Einführung in die Astronomie II

Jörn Wilms

Wintersemester 2011/2012

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Friedrich–Alexander–Universität
Erlangen–Nürnberg

Introduction

Astronomie im Bachelorstudiengang Physik

NF im Bachelor/Master: Zwei Module (Je 10 ECTS):
    NW1 kann gewählt werden im 1./2., 3./4. oder 5./6. Semester

PW im Bachelorstudium: Modul für PW-1, PW-2, oder PW-3

PW im Masterstudium: geplant: PW-1, PW-2 und/oder PW-3 alternativ im Masterstudiengang

Astronomie für LAG-Physik, BA Informatik und Mathematik

physikalisches Wahlfach im LAG: NW-1 (10 ECTS):
    kann vorzugsweise gewählt werden im 5./6. Semester

NF im Bachelor Informatik: Erweitertes NW-1 (15 ECTS):
    Besteht aus NW1 plus verpflichtende Übungen und kann gewählt werden im 5./6. Semester

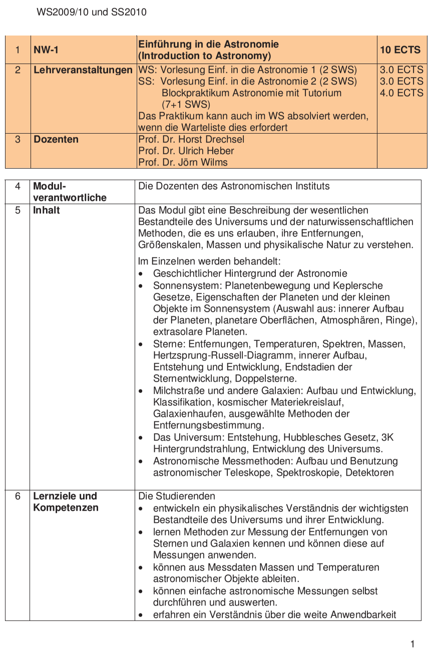
NF im Bachelor Mathematik: 35 ECTS:

1. und 2. Semester: Einführung in die Experimentalphysik I und 2 (je 7.5 ECTS)

3. und 4. Semester: Astronomie NW-1 (10 ECTS)

5. und 6. Semester: Astronomie NW-2 (10 ECTS), PW-1 (5 ECTS)

weitere Fächer: Anfrage beim jeweiligen Prüfungsamt



WS2009/10 und SS2010

1	**NW-1**	**Einführung in die Astronomie (Introduction to Astronomy)**	**10 ECTS**
2	**Lehrveranstaltungen**	WS: Vorlesung Einf. in die Astronomie 1 (2 SWS) SS: Vorlesung Einf. in die Astronomie 2 (2 SWS) Blockpraktikum Astronomie mit Tutorium (7+1 SWS) Das Praktikum kann auch im WS absolviert werden, wenn die Warteliste dies erfordert	3.0 ECTS 3.0 ECTS 4.0 ECTS
3	**Dozenten**	Prof. Dr. Horst Drechsel Prof. Dr. Ulrich Heber Prof. Dr. Jörn Wilms	

4	**Modulverantwortliche**	Die Dozenten des Astronomischen Instituts
5	**Inhalt**	Das Modul gibt eine Beschreibung der wesentlichen Bestandteile des Universums und der naturwissenschaftlichen Methoden, die es uns erlauben, ihre Entfernungen, Größenskalen, Massen und physikalische Natur zu verstehen. Im Einzelnen werden behandelt: • Geschichtlicher Hintergrund der Astronomie • Sonnensystem: Planetenbewegung und Keplersche Gesetze, Eigenschaften der Planeten und der kleinen Objekte im Sonnensystem (Auswahl aus: innerer Aufbau der Planeten, planetare Oberflächen, Atmosphären, Ringe), extrasolare Planeten. • Sterne: Entfernungen, Temperaturen, Spektren, Massen, Hertzsprung-Russell-Diagramm, innerer Aufbau, Entstehung und Entwicklung, Endstadien der Sternentwicklung, Doppelsterne. • Milchstraße und andere Galaxien: Aufbau und Entwicklung, Klassifikation, kosmischer Materiekreislauf, Galaxienhaufen, ausgewählte Methoden der Entfernungsbestimmung. • Das Universum: Entstehung, Hubblesches Gesetz, 3K Hintergrundstrahlung, Entwicklung des Universums. • Astronomische Messmethoden: Aufbau und Benutzung astronomischer Teleskope, Spektroskopie, Detektoren
6	**Lernziele und Kompetenzen**	Die Studierenden • entwickeln ein physikalisches Verständnis der wichtigsten Bestandteile des Universums und ihrer Entwicklung. • lernen Methoden zur Messung der Entfernungen von Sternen und Galaxien kennen und können diese auf Messungen anwenden. • können aus Messdaten Massen und Temperaturen astronomischer Objekte ableiten. • können einfache astronomische Messungen selbst durchführen und auswerten. • erfahren ein Verständnis über die weite Anwendbarkeit

1

Benotung

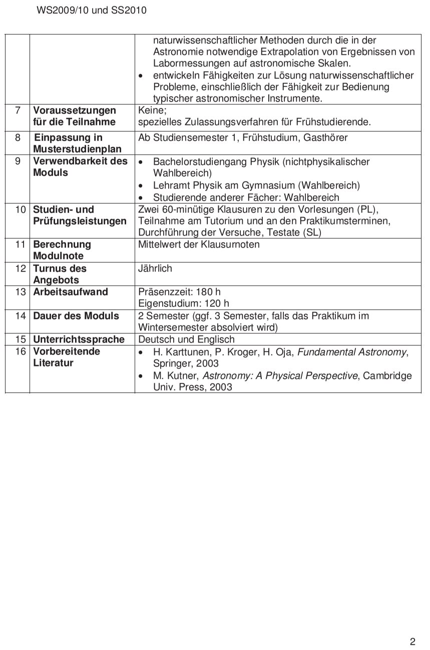
Idee: Kumulative Abschlüsse in den Nebenfächern, keine modulübergreifende Prüfung.

$\Longrightarrow$ Impliziert Notengebung!

$\Longrightarrow$ KLAUSUR am 31. Januar 2012

Klausur führt zu einer *Note*

Physiker: Noten aus dem 1. & 2. Bachelor-Semester gehen *NICHT* in die Bachelor-Note ein.



WS2009/10 und SS2010

		naturwissenschaftlicher Methoden durch die in der Astronomie notwendige Extrapolation von Ergebnissen von Labormessungen auf astronomische Skalen. • entwickeln Fähigkeiten zur Lösung naturwissenschaftlicher Probleme, einschließlich der Fähigkeit zur Bedienung typischer astronomischer Instrumente.
7	**Voraussetzungen für die Teilnahme**	Keine; spezielles Zulassungsverfahren für Frühstudierende.
8	**Einpassung in Musterstudienplan**	Ab Studiensemester 1, Frühstudium, Gasthörer
9	**Verwendbarkeit des Moduls**	• Bachelorstudiengang Physik (nichtphysikalischer Wahlbereich) • Lehramt Physik am Gymnasium (Wahlbereich) • Studierende anderer Fächer: Wahlbereich
10	**Studien- und Prüfungsleistungen**	Zwei 60-minütige Klausuren zu den Vorlesungen (PL), Teilnahme am Tutorium und an den Praktikumsterminen, Durchführung der Versuche, Testate (SL)
11	**Berechnung Modulnote**	Mittelwert der Klausurnoten
12	**Turnus des Angebots**	Jährlich
13	**Arbeitsaufwand**	Präsenzzeit: 180 h Eigenstudium: 120 h
14	**Dauer des Moduls**	2 Semester (ggf. 3 Semester, falls das Praktikum im Wintersemester absolviert wird)
15	**Unterrichtssprache**	Deutsch und Englisch
16	**Vorbereitende Literatur**	• H. Karttunen, P. Kroger, H. Oja, *Fundamental Astronomy*, Springer, 2003 • M. Kutner, *Astronomy: A Physical Perspective*, Cambridge Univ. Press, 2003

2

Übungen und Hausaufgaben

Um den Stoff zu vertiefen gibt es freiwillige Übungen, verpflichtend für BA-Informatik.

Terminfindung:

25 Oktober, 17:45 (Nach der Vorlesung)

Betreuung: Maria Obst

Wir werden Übungsblätter austeilen, die in den Übungen besprochen werden.

Ebenso sind Vorschläge und Fragen für die Übungen sehr erwünscht.

Praktikum

Praktikum wird an der Dr. Karl Remeis-Sternwarte, Bamberg, als Blockpraktikum durchgeführt werden.

Termine:

- 20.02.–02.03.2012
- 05.03.–16.03.2012
- 19.03.–30.03.2012

$\Longrightarrow$ 21 Plätze pro Termin, Vorbesprechung am 17.01.2012

Anmeldung: Bestätigung der Teilnehmerliste *jetzt*, Einteilung in Gruppen findet Anfang Januar statt, hängt aber von Bestehen der Klausur ab. Leute auf der Warteliste können noch bis 29.02. für den 2. und 3. Termin abgerufen werden.

Zum Bestehen des Moduls sind für *alle* das Praktikum sowie Bestehen der zwei Klausuren Astronomie I und II erforderlich.

Textbooks

Kartunnen, Kröger, Oja, Poutanen & Donner , 2007, *Fundamental Astronomy*, 5th ed., Heidelberg: Springer, €64 (hardcover), 510 pp.
Good general overview of astronomy.
Recommended, especially for exam preparation.

Kutner, 2003, *Astronomy: A Physical Perspective*, 2nd ed., Cambridge: Cambridge Univ. Press, €51, 600 pp.
Modern physics based textbook, easy to read. Recommended.

Bennett et al., 2009, *Astronomie: Die kosmische Perspektive*, Pearson Studium, €79.95, 1200 pp.
Modern and good; German translation is not bad, Recommended.

Textbooks

Unsöld & Baschek, 2006, *Der neue Kosmos. Einführung in die Astronomie und Astrophysik*, 7. Auflage, Berlin: Springer, €60, 577 pp.
Intermediate level: Good overview of stellar astronomy
Good secondary reading.

Zeilik & Gregory, 1998, *Introductory Astronomy & Astrophysics*, 4th ed., Thomson Learning, ca. €65, 672 pp.
Intermediate level, self contained, but sometimes chaotic order.

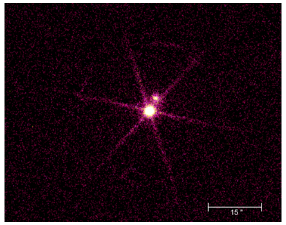
Carroll & Ostlie, 2006, *An Introduction to Modern Astrophysics*, 2nd ed., Reading: Addison-Wesley, ca. €100 (hardcover), 1400 pp.
Advanced level, expects good physics background.
Recommended if you want to specialize in astronomy.

Contents

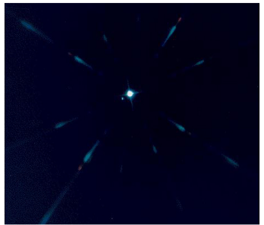
18 Oct	Reminders, stellar evolution
25 Oct	White Dwarfs, Supernovae
08 Nov	Neutron stars, black holes
15 Nov	Binary Evolution & Gamma Ray Bursts
22 Nov	Milky Way and Galactic Center
29 Nov	Galaxies: classification, properties
06 Dec	Extragalactic distance scale
13 Dec	Galaxy masses, dark matter
20 Dec	Active Galaxies
10 Jan	Galaxy Clusters
17 Jan	Cosmology I, Lab meeting
24 Jan	Cosmology II
31 Jan	Klausur
07 Feb	Evolution of the Universe

Stellar Death

White Dwarfs



Sirius A+B: *Chandra*
(X-rays; *WD is bright*)

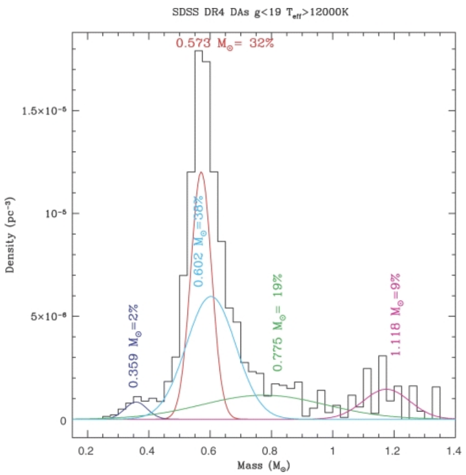


McDonald Observatory
(optical; *WD is faint*)

White Dwarfs: Sirius B

- Companion to the brightest star Sirius
- cannot be seen with the naked eye.
- Analyzing the motion of Sirius from 1833 to 1844, Friedrich Wilhelm Bessel (1844) concluded that Sirius must have an unseen companion.
- Sirius B was not actually observed until 1862 January 31 by Alvan Graham Clark.
- Star B's peculiar high temperature, small size, and great density were not established until 1925 by Walter Adams.

White Dwarfs

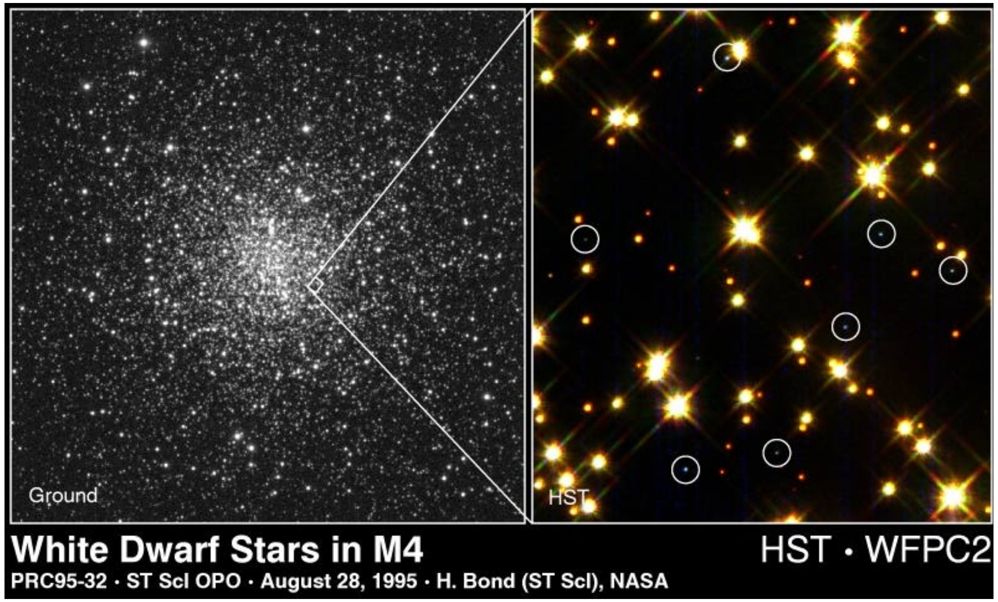


mass distribution of 1733 white dwarfs

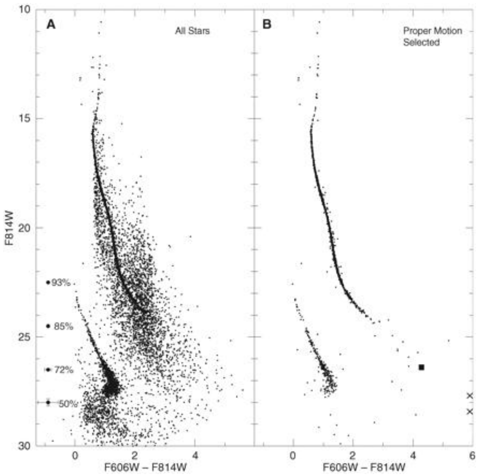
(Kepler et al. 2007, MNRAS 375, 1315)

White Dwarfs

1. End stages of evolution of stars born with $M \lesssim 8\,M_\odot$
2. typically $M \sim 0.6 M_\odot$
3. mainly consist of C and O
4. Radius $\sim$ Earth
5. typical density $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$



White Dwarfs



Color-magnitude diagram of the NGC 6397 White Dwarf sequence (Richer et al. 2006, Science 313, 936)

globular clusters are the oldest building blocks of the Galaxy

$\Longrightarrow$ many stars have already died

$\Longrightarrow$ GCs must host a large number of white dwarfs

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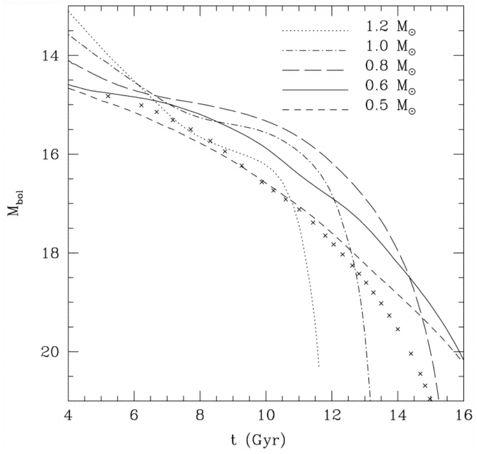
White Dwarfs



white dwarf cooling tracks
Chabrieyer et al. 2005 (ApJ 542, 216)

- white dwarfs are stabilized by the pressure of the degenerate electron gas
- they can not shrink
- cooling of the ionic gas takes a very long time
- at low temperature: crystalization, crystal structure similar to diamond

“White dwarfs are diamonds in the sky”

White Dwarfs

For a degenerate gas, the equation of state ($P = P(T, \rho)$) is

$$P \propto \begin{cases} \rho^{5/3} & \text{(non-relativistic gas)} \\ \rho^{4/3} & \text{(relativistic gas)} \end{cases} \tag{15.1}$$

independent of T!

WD structure can be determined from hydrostatic equilibrium alone:

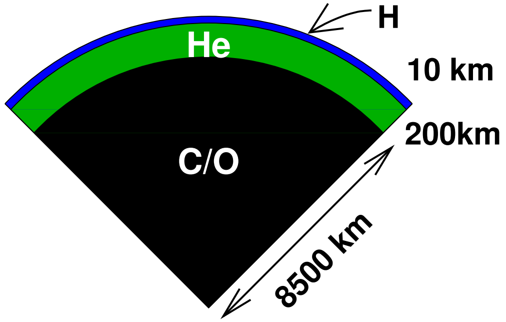
Mass structure
(mass conservation)

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \rho(r)$$

Pressure structure
(hydrostatic equilibrium)

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)\frac{GM(r)}{r^2}$$

White Dwarfs



White dwarfs come in two flavors:

DA: H present in spectrum
(~80% of all WD)

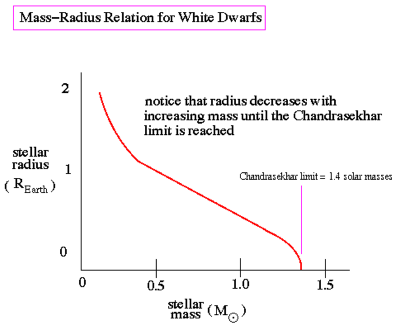
DB: He present in spectrum (~ the rest)

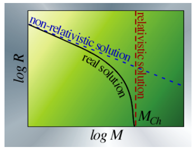
plus a few oddballs

Structure: gravitationally settled, so DB’s really do not have any H since it would “swim on top”

$\Longrightarrow$ layered, “onion-like” structure

White Dwarfs



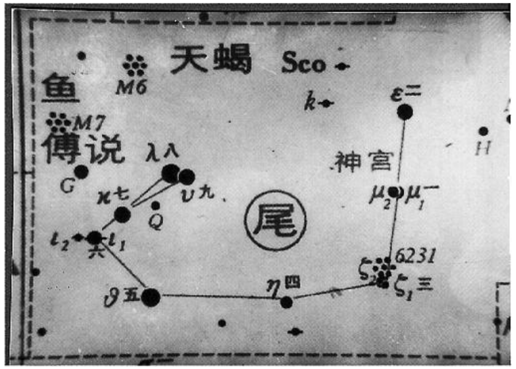


- Subrahmanyan Chandrasekhar, 1910–1995
- Nobel prize 1983
- Radius decreases with increasing mass: $R \propto M^{1/3}$
- Chandrasekhar limit: relativistic limit:

Mass must be less than 1.4 $M_\odot$

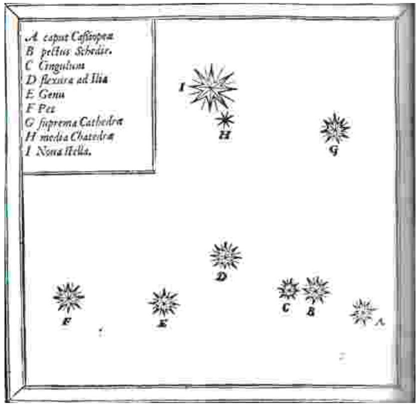
Historical Supernovae

Supernovae (term coined by Baade & Zwicky, 1934) increase in magnitude by 20 mag

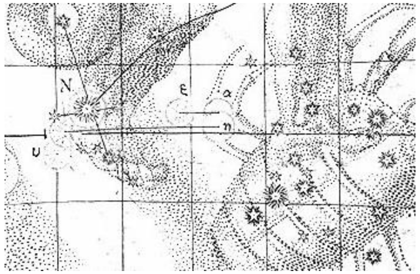


The guest star of AD 386, Wang, Yu & Chen (1997, A&A 318, L59)

Historical Supernovae



Tycho Brahe's Supernova 1572

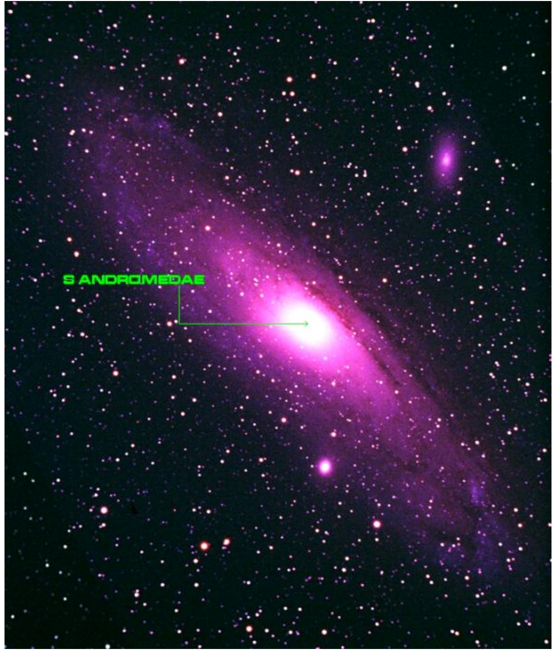


Johannes Kepler's Supernova 1604

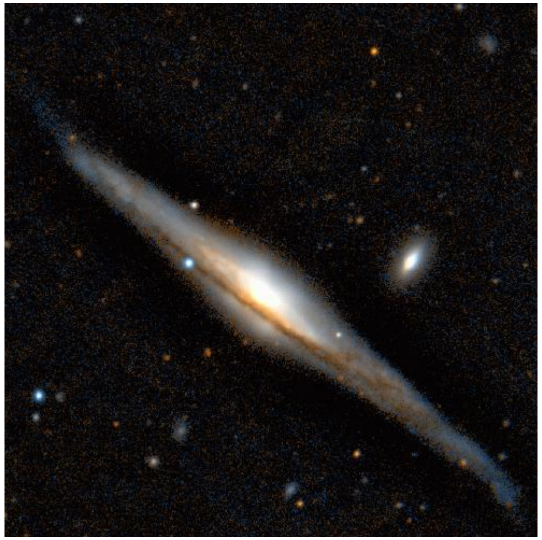
Galactic supernovae

Year of appearance	constellation	magnitude	visibility months
185	Centaurus	−8	6?
386	Sagitarius	+1.5	
393	Scorpius	0	
1006	Lupus	−7.5	24
1054	Taurus	−6	24
1181	Cassiopeia	0	6
1572	Cassiopeia	−6	16
1604	Ophiuchus	−3	12
1667	Cassiopeia	obscured	-
∼1850	G1.9+0.3	obscured	–

S Andromedae = Supernova 1885 in the Andromeda galaxy



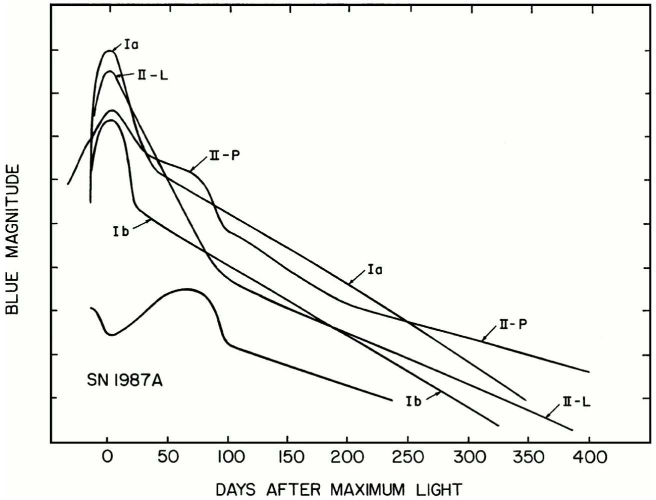
Ernst Hartwig (Dorpat = Tartu)
20.08.1885: discovery of S And
01.01.1886: director of Remeis observatory Bamberg



Type II SN2001cm in NGC5965 (2.56 m NOT, Håkon Dahle; NORDITA)

SN1994d (HST WFPC)

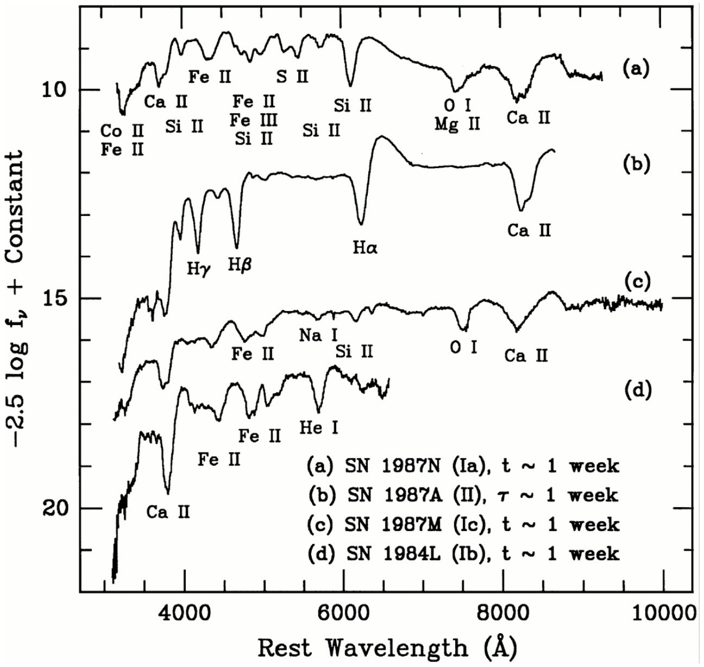
Extragalactic Supernovae



(Filippenko, 1997, ARAA Fig. 1)

Light curves of SNe I all very similar,
SNe II have much more scatter.

SNe II-L (“linear”) resemble SNe I
SNe II-P (“plateau”) have const. brightness to within 1 mag for extended period of time.



(Filippenko et al., 1997, Fig. 1); t: time after maximum light; τ: time after explosion; P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

Rough classification (Minkowski, 1941):

Type I: no hydrogen
in spectra;
subtypes Ia, Ib, Ic

Type II: hydrogen
present, subtypes
II-L, II-P

Note: pre 1985 subtypes Ia, Ib had different definition than today $\Longrightarrow$ beware when reading older texts.

Supernova Statistics

Clue on origin from supernova statistics:

- SNe II, Ib, Ic: never seen in elliptical galaxies, which are void of gas and have no new star formation; generally associated with spiral arms and H II regions in spiral galaxies, i.e., with star forming regions

$\Longrightarrow$ progenitor of SNe II, Ib, Ic: massive stars ($\gtrsim 8\,M_\odot$)

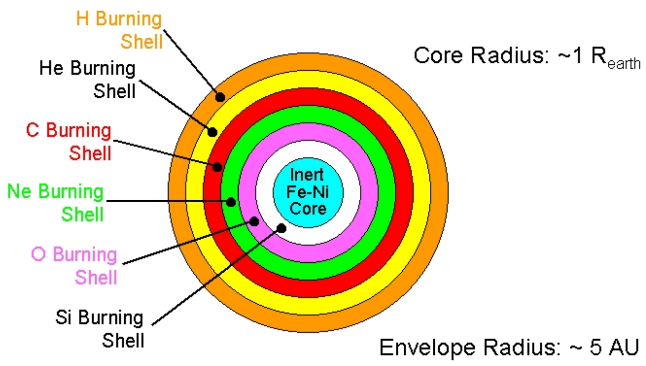
$\Longrightarrow$ “core collapse supernova”

- SNe Ia: all types of galaxies, coming from both young and old stellar populations.

$\Longrightarrow$ stellar progenitors of SNe Ia can not be massive stars, because such stars do no longer exist in old stellar populations.

common model: accreting carbon-oxygen white dwarfs undergoing thermonuclear runaway

Core Collapse Supernovae



Successive stages of nuclear burning in a massive star:

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni

Final state: “onion-shell”

Core Collapse Supernovae

Standard core-collapse supernova model:

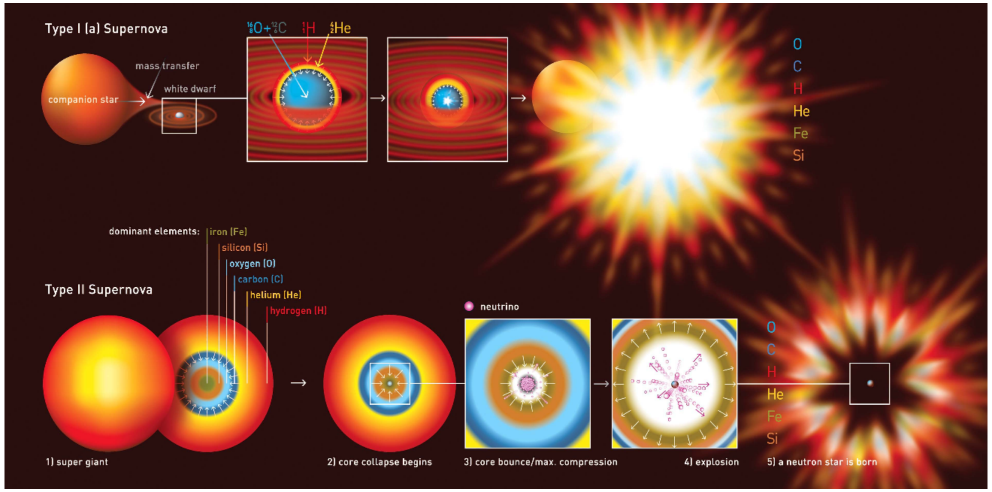
$t = 0$ **s:** Collapse of Fe core of star with main sequence mass $>10\,M_\odot$, triggered by electron capture and photodisintegration of Fe ($T \sim 10^{10}$ K, $\rho \sim 10^{10}\,\mathrm{g\,cm^{-3}}$).

rebound: outer material rebounds off core, looses velocity because of photodisintegration and neutrino loss

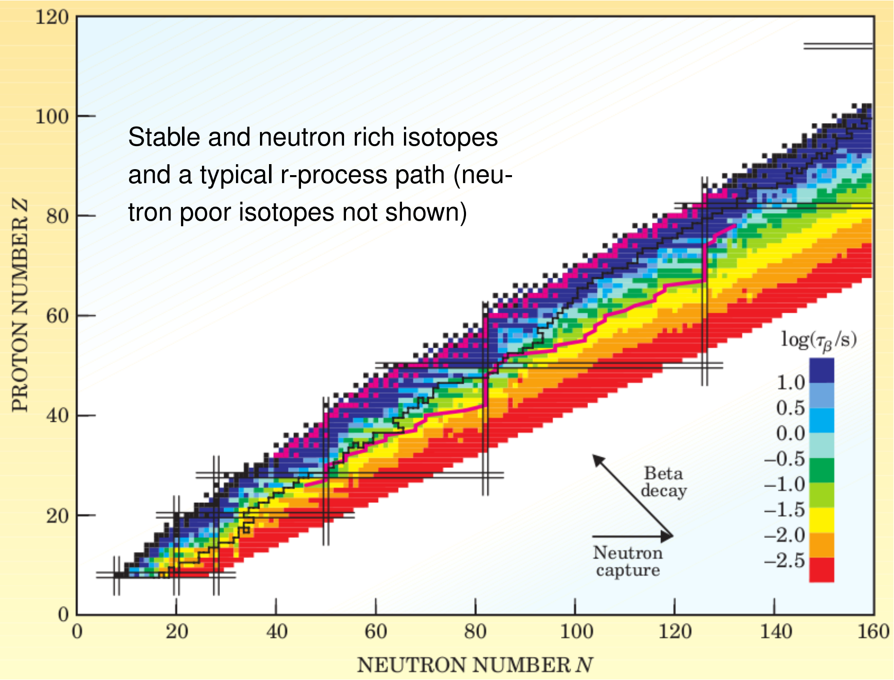
$t = 0.1$ **s:** proto-neutron star formed with $R \sim 30$ km, $M = 1.4\,M_\odot$, standing shock ~150 km above neutron star

$t = 0.1$ **s until** $t = 0.2$ **s:** start to radiate $\sim 10^{53}\,\mathrm{erg\,s^{-1}}$ as neutrinos, triggers convection, heats material by depositing 10^{51} erg ($\longrightarrow$ convection)

$t = 0.2$ **s:** SN explosion is triggered

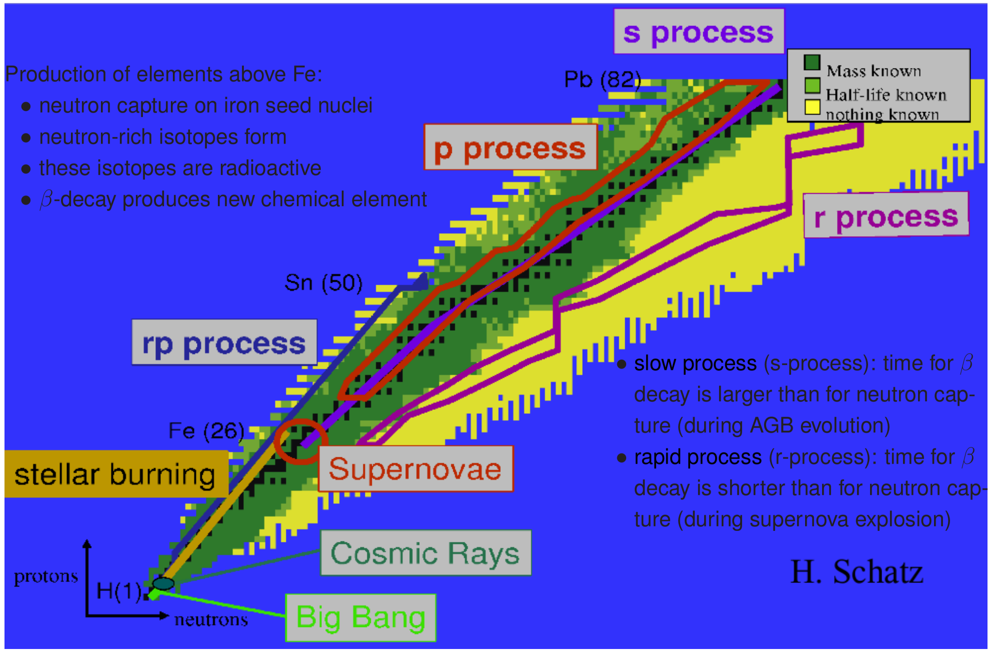


F.K. Thielemann



Stable and neutron rich isotopes and a typical r-process path (neutron poor isotopes not shown)

(Cowan & Thielemann, 2004, Physics Today, 46; after P. Möller)



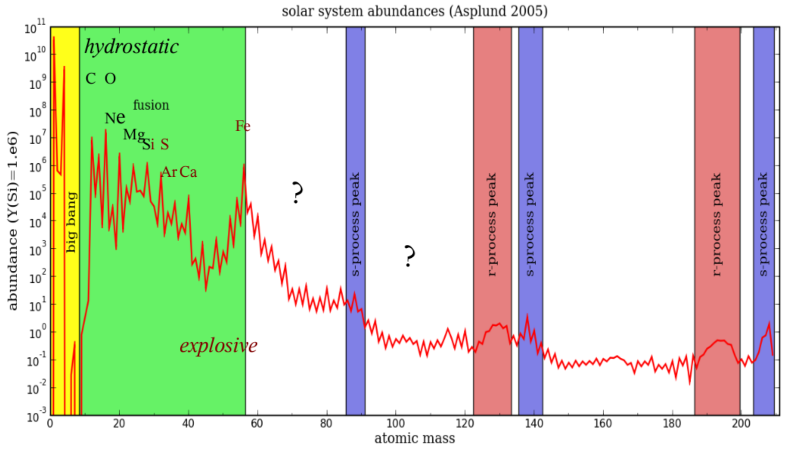
Production of elements above Fe:

- neutron capture on iron seed nuclei
- neutron-rich isotopes form
- these isotopes are radioactive
- β-decay produces new chemical element

- slow process (s-process): time for β decay is larger than for neutron capture (during AGB evolution)
- rapid process (r-process): time for β decay is shorter than for neutron capture (during supernova explosion)

H. Schatz

Nucleosynthesis



With SN calculations and fusion mechanisms in stars, it is possible to explain the observed elemental abundance pattern of the solar system.

First work on these processes: Burbidge, Burbidge, Fowler, Hoyle, 1957 (B^2FH)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SN1987a

SN1987A in the Large Magellanic Cloud, 1987 February 23

- distance well known = 50 kpc
- visible to the naked eye ($V_{max} = 4.5$ mag), first after 300 yrs
- for the first time it was possible to identify the progenitor star
- progenitor Sanduleak −69 202 = massive star, i.e., blue supergiant
- supports core collapse model
- light curve has been measured over 20 yrs, presently $V = 21$ mag
- spectral changes have been monitored over many years


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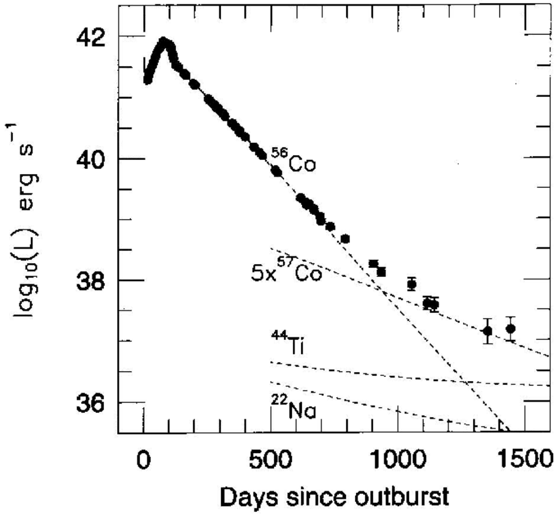
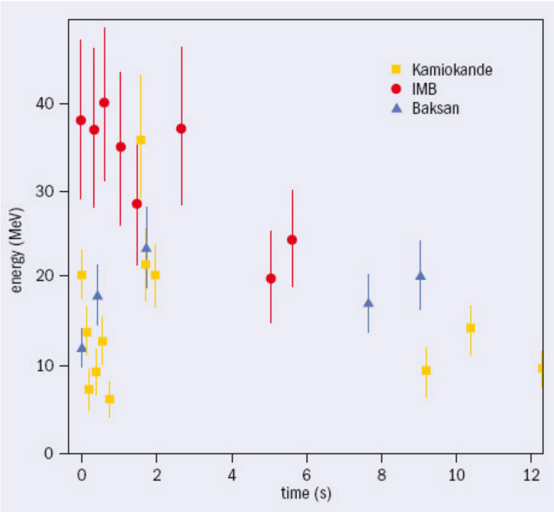
SN1987a



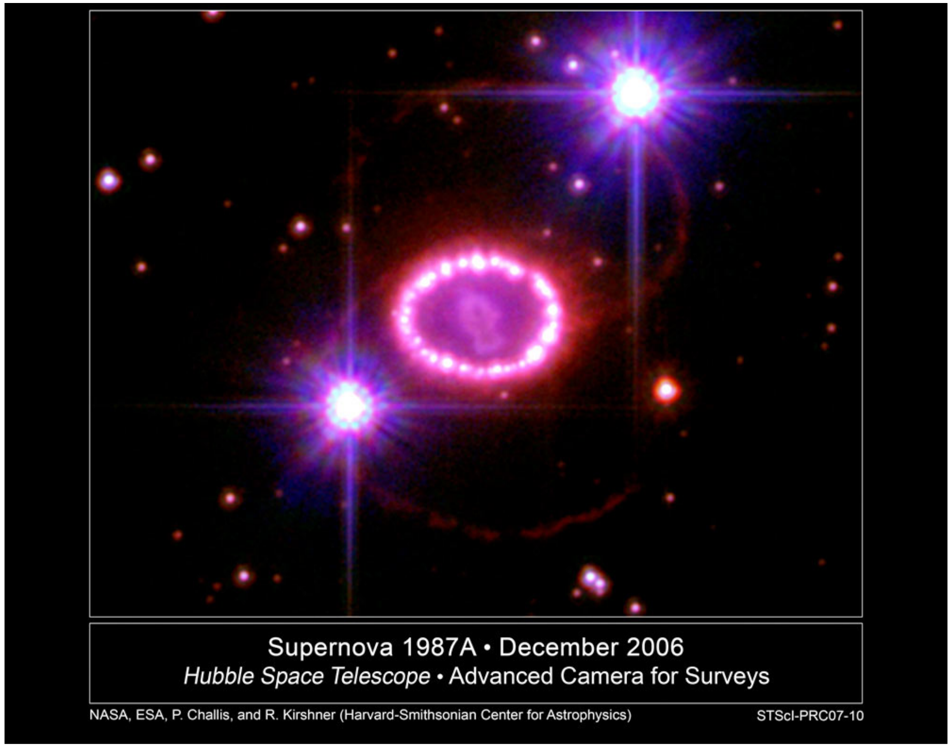
Expanding envelope powered by radioactive decay of short lived isotopes created in the core collapse

SN1987a



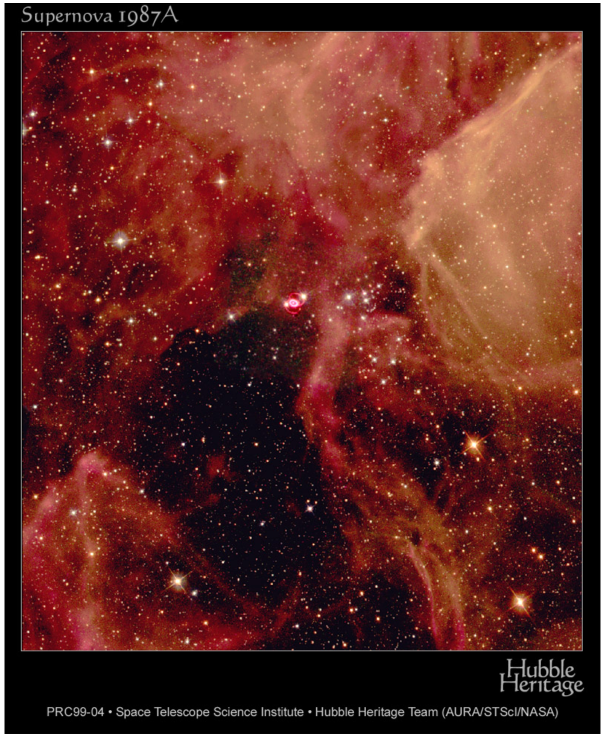
Neutrinos detected as predicted by core collapse model

Cern Courier


Supernova 1987A • December 2006

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC07-10


Supernova 1987A

Hubble Heritage

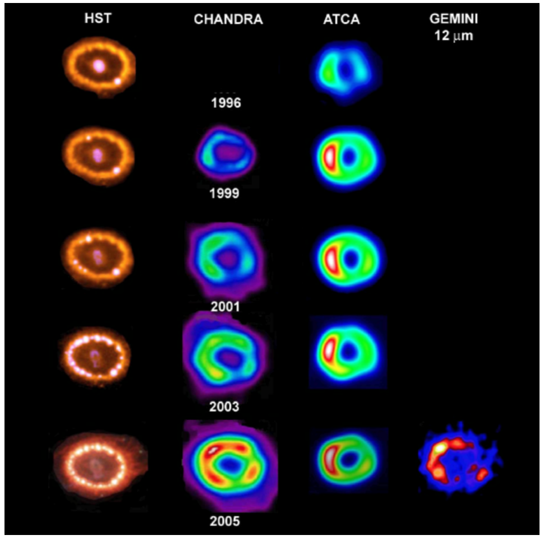
PRC99-04 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

Additional features:

The mysterious rings

- central ring, light year across due to impact of a shock wave on circumstellar material, ejected from progenitor star; started to glow after more than 15 years.
- outer rings, possibly due to ionization of material illuminated by SN light. Material possibly from bipolar outflow during blue supergiant phase (fast blue SG wind colliding with slower RG wind); material ejected ∼20000 years before explosion.

SN1987a

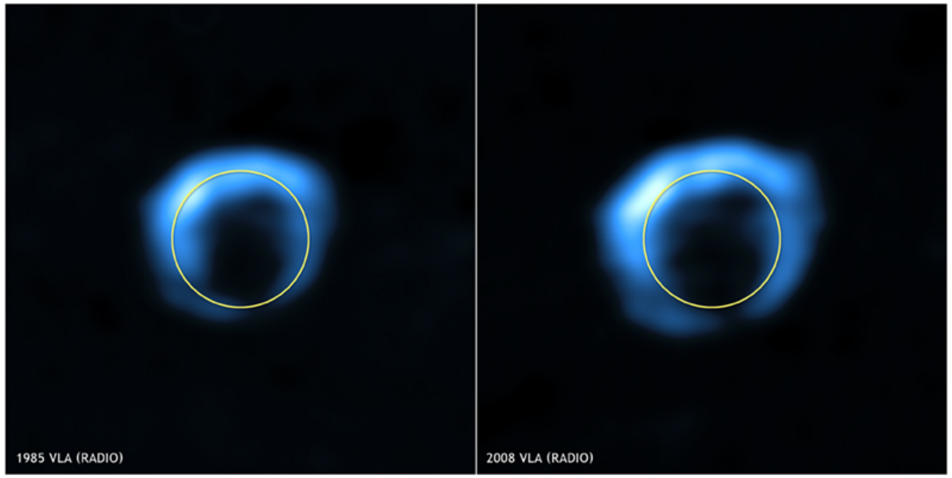


McCray 2007, Fig. 6

Late time light curve due to radioactive decay of Cobalt.

- Day 125–1100: dominated by decay of ^{56}Co
- After ∼ 3 years: radioactive decays of long-lived ^{57}Co and later of ^{44}Ti start to heat the system
- Today: Light curve almost flat and $\sim 10^{-7}$ fainter than at maximum! Ring still brightening!

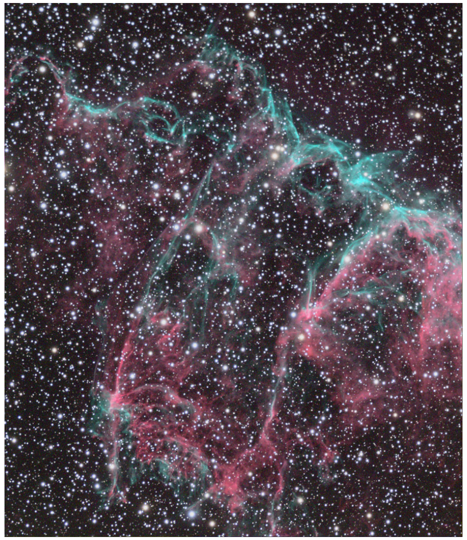
SN 1987A has made the transition to a young Supernova Remnant!



G1.9+0.3: Youngest Galactic SN remnant. While known since long time, it was only in 2008 that the fast expansion was noted $\Longrightarrow$ age: 140 ± 30 years Due to strong extinction by dust in MW, explosion was not observed.

(ESO VLT/FORS 2)

Crab nebula: young remnant of SN of 1054, observed light due to synchrotron radiation (radiation emitted by electrons accelerated in magnetic field)



5000–10000 year old IC 1340/Veil Nebula/Cygnus Loop (©Loke Kun Tan)

Older supernova remnants: “wispy structure” due to interaction with interstellar medium, radiation (line emission) mainly caused by heating due to shocks.

Neutron Stars

Neutron stars form after the core collapse of massive stars.

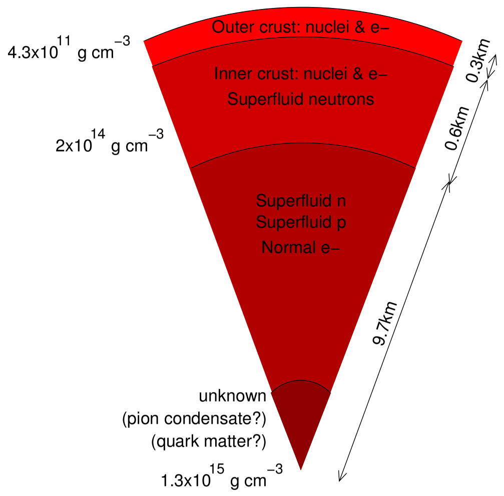
During the supernova, densities get so high that neutronization sets in:

$$\mathrm{p} + \mathrm{e}^- \longrightarrow \mathrm{n} + \nu_\mathrm{e}$$

General properties:

- Pressure mainly through degenerate neutrons (similar to degenerate electrons for WD!).
- Typical density: $\rho \sim 10^{14}\,\mathrm{g\,cm^{-3}}$ (nuclear densities)
- Typical radius: 10...15 km (Nuremberg!)
- surface gravity $\sim 10^{11}\times$ Earth
- Detailed structure not yet fully understood

Neutron Stars: Structure



Crust: perhaps crystallized?

Atoms become elongated along B-field line on surface

Internal structure unclear:

- Supraconducting matter
- Suprafluidity (i.e., fluid with no viscosity)
- central composition unknown

(after Shapiro & Teukolsky)

Neutron Stars: Rotation

During collapse, angular momentum is conserved (Explosion: symmetric)

Total angular momentum of homogeneous sphere:

$$J = I\omega \quad \text{where} \quad I = \frac{2}{5}MR^2$$

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Angular momentum conservation ($J_{\text{before}} = J_{\text{NS}}$):

$$\frac{2}{5}M_{\text{before}}R^2_{\text{before}}\omega_{\text{before}} = \frac{2}{5}M_{\text{NS}}R^2_{\text{NS}}\omega_{\text{NS}}$$

or

$$\omega_{\text{NS}} = \left(\frac{M_{\text{before}}}{M_{\text{NS}}}\right)\left(\frac{R_{\text{before}}}{R_{\text{NS}}}\right)^2\omega_{\text{before}} \quad \text{or} \quad P_{\text{NS}} \sim \left(\frac{R_{\text{NS}}}{R_{\text{before}}}\right)^2 P_{\text{before}}$$

(where P: rotation period)

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(where P: rotation period)

Example: $R_{\text{before}} = 700000\,\text{km}$ (sun), $R_{\text{NS}} = 15\,\text{km}$, $P_{\text{Sun}} = 27\,\text{d} \Longrightarrow P_{\text{NS}} = 0.001\,\text{s}$

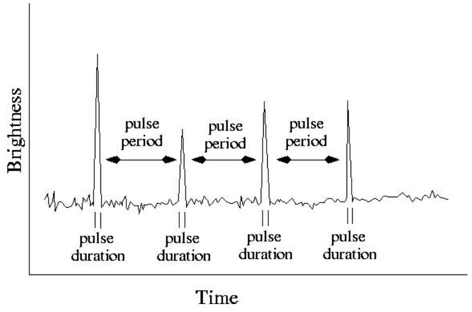
Neutron Stars are extremely fast rotators.

close to break-up speed!

Pulsars

Discovery: Bell & Hewish (1967):

Radio Pulsar

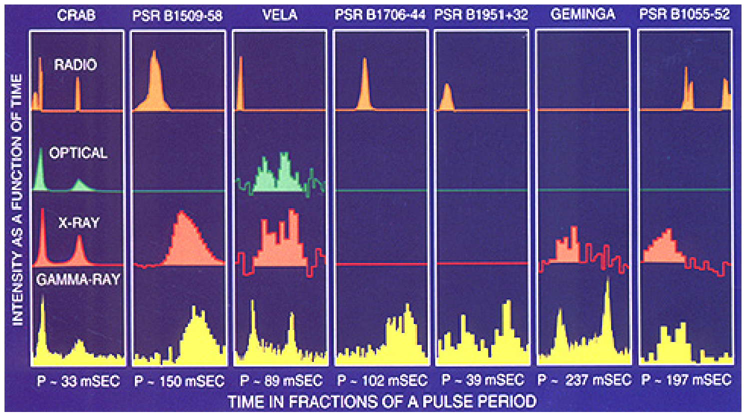


radio emission is pulsed,

very short periods: milliseconds to a few seconds

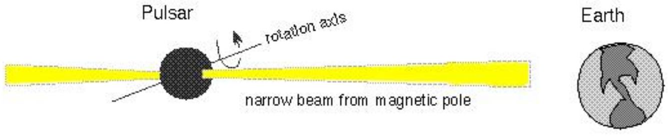
Pulsars

Pulsars at different wavelengths



Pulsations not only in the radio regime, but also at optical, X-ray, and γ-ray wavelength, but not in all cases.

Pulsars



If the narrow synchrotron beam passes over the Earth, we see the neutron star flash on and off like a lighthouse beam does for ships at sea.

Pulses due to the lighthouse effect caused by rapid rotation.

Rotation period:

$$P = \frac{2\pi R}{v_{\text{rot}}} \tag{15.2}$$

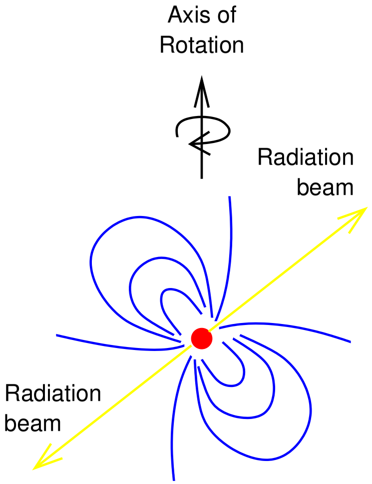
Rotation speed at the surface must be smaller the speed of light. $\Longrightarrow R < \frac{Pc}{2\pi}$

Shortest periods observed: $P \sim 1\,\text{ms}$

$\Longrightarrow R < 50\,\text{km}$

Pulsars are neutron stars!

Pulsars



“Lighthouse model” for pulsars

Another conserved observable: magnetic flux: $\Phi = BR^2$

Magnetic field after SN:

$$B_{\text{NS}} = \left(\frac{R_{\text{before}}}{R_{\text{NS}}}\right)^2 B_{\text{before}}$$

$\Longrightarrow$ neutron stars have strong magnetic fields (typical: $B \sim 10^6 \ldots 10^8\,\text{T}$)

Radio pulsars are fast rotating (isolated) neutron stars with strong magnetic fields.

The sounds of pulsars

- PSR 0329 – a normal pulsar ($P = 0.714519$ s)
- PSR 0833 – the Vela pulsar, a faster, younger pulsar in the Vela supernova remnant ($P = 89$ msec)
- Crab pulsar – the youngest pulsar ($P = 33$ ms)
- B1937 – one of the fastest pulsars ($P = 0.00155780644887275$ s)

See/hear `http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html` for more examples.

Black Holes

Degenerate neutron gas: Chandrasekhar theory applies.

However, modified hydrostatic equation (GRT)

equation of state much more complicated than for white dwarfs

Neutron stars also have upper mass limit: Oppenheimer Volkoff limit.

Detailed mass limit unknown, causality considerations give $M \sim 3\,M_\odot$ (for "stiff equation of state" the sound speed becomes greater than speed of light at this mass)

Compact objects with mass above Oppenheimer Volkoff limit: Black Holes

More conservative astronomers: "Black Hole Candidates".

Black Holes

In more modern usage (but still Newtonian!):

Total energy of a mass m:

$$E = E_{\text{pot}} + E_{\text{kin}} = -\frac{GMm}{R} + \frac{1}{2}mv^2$$

Mass m is unbound if $E > 0$, i.e., for

$$v \geq v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

Black Hole: Body of mass M and radius R for which $v_{\text{escape}} > c$, where c is the speed of light.

This is the case if

$$R \leq R_{\text{S}} = \frac{2GM}{c^2} \sim 3\,\text{km}\frac{M}{M_\odot}$$

the Schwarzschild Radius.

Einstein

Albert Einstein (1879–1955)

Special Relativity (1905):

- Speed of light has the same value in *all* frames of reference
- Observer with constant velocity measure the same physical laws

From these axioms follows:

$\Longrightarrow$ Space and time are relative ("4D-space-time")

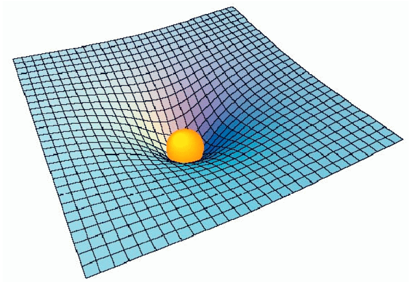
$\Longrightarrow E = mc^2$ ("Mass and Energy are equivalent")

Einstein


Albert Einstein (1879–1955)

General relativity (1916):

- Mass curves space (“Metric”)

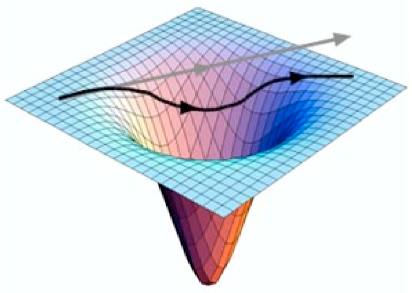


Einstein


Albert Einstein (1879–1955)

General relativity (1916):

- Mass curves space (“Metric”)
- Light moves through curved space



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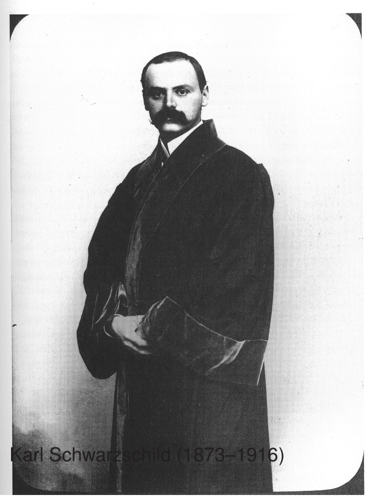
post-Einstein


Karl Schwarzschild (1873–1916)

Directly after publication of GRT:

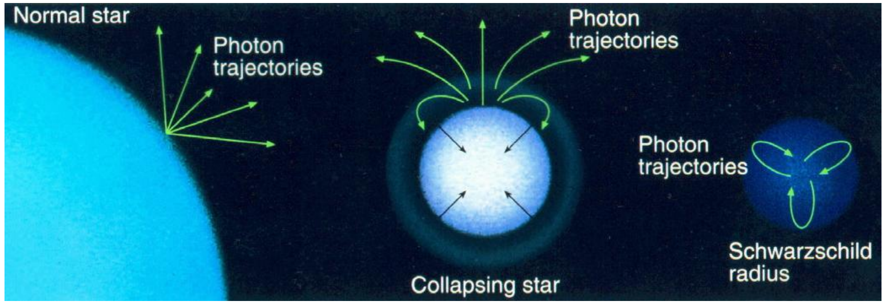
$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2$$

(Schwarzschild Metric).

Describes “shape of space” in vicinity of mass M.

---

post-Einstein



$R > R_S$ $R \sim R_S$ $R < R_S$

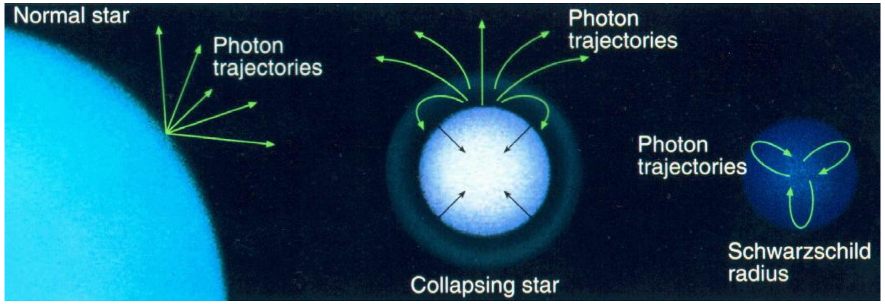
Behavior of light is determined from location of emission, in dependence from the Schwarzschild Radius:

$$R_S = \frac{2GM}{c^2} \sim 3\,\text{km}\,\frac{M}{M_\odot}$$

Same value as in Newtonian derivation!

J.N. Imamura

post-Einstein



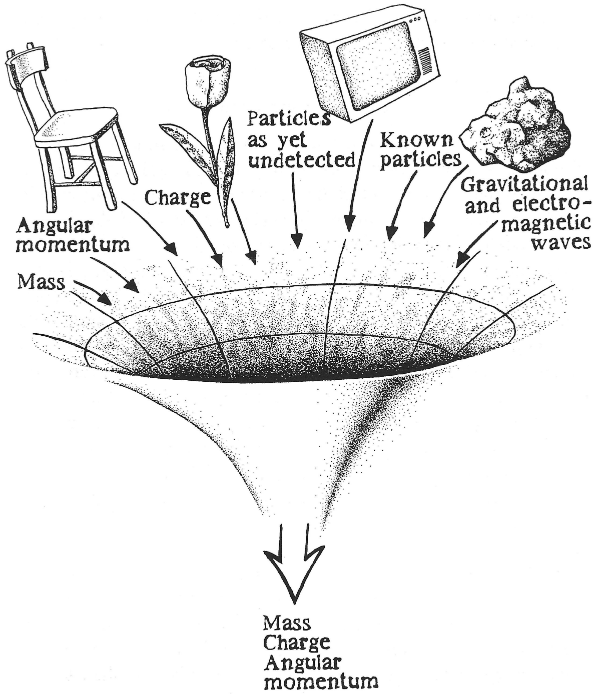
$R > R_S$ $R \sim R_S$ $R < R_S$

Black hole in GRT: Bodies smaller than their Schwarzschild radius.

J.N. Imamura

"It's black, and it looks like a hole. I'd say it's a black hole."

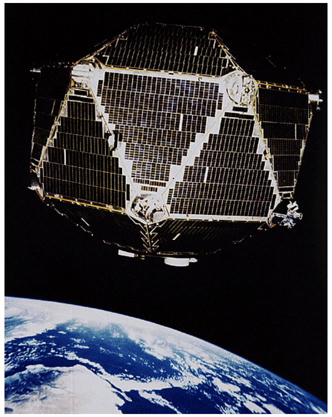
x



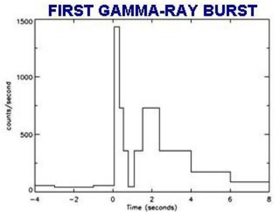
Black holes are very simple physical objects, determined by

- Mass
- (Charge)
- Angular momentum

Discovery



Sketch of one of the Vela satellites to search for violations of the nuclear test ban treaty.



1967: Vela satellites find extremely bright flares from the sky, with durations of a few seconds: Gamma-Ray Bursts (GRBs; total of 73 GRBs found between).

Reported in 1973 only (Klebesadel et al., 1973).

During the burst, GRBs are the *brightest* gamma-ray objects in the sky, brighter than the Sun!

1990s: CGRO era

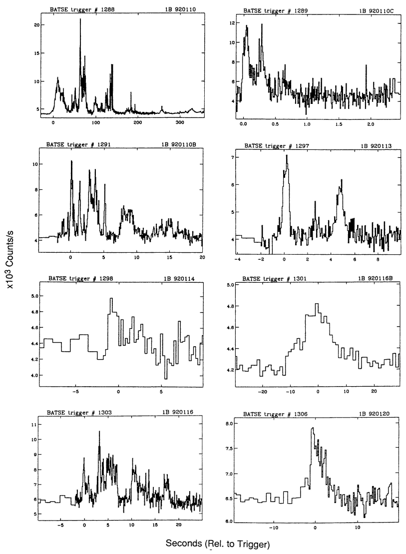
Due to short duration of bursts, no detailed studies were available for a long time.

This changed with the Burst and Transient Science Experiment (BATSE) on the Compton Gamma-Ray Observatory (*CGRO*; launch 1991): All Sky Monitor, first systematic study of Gamma-Ray Bursts.

Gamma-Ray Bursts are very common: BATSE saw 1 GRB day^{-1}, taking into account BATSE covering factor: 600 GRB year^{-1}

Movie time: `grbmovies/grb_animation.gif`

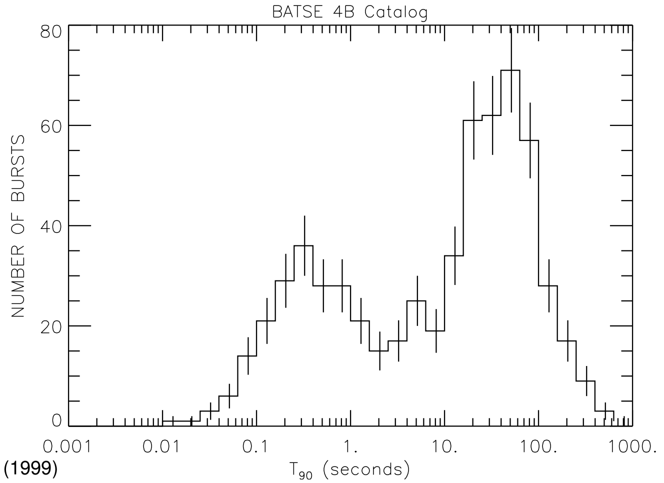
1990s: CGRO era



There is a wide variety of burst lightcurves, both in duration and morphology.

(Fishman et al., 1995, Fig. 1)

1990s: CGRO era

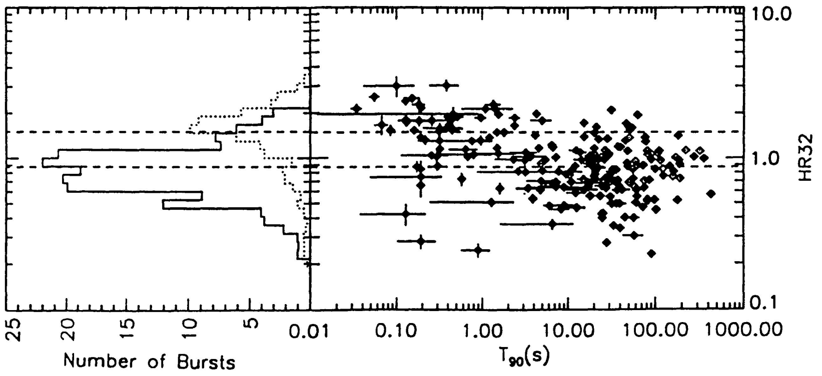


Paciesas et al. (1999)

Kouveliotou et al. (1993): There are two classes of Gamma-Ray Bursts:

long bursts ($t_\gamma > 2\,\mathrm{s}$) and short bursts ($t_\gamma < 2\,\mathrm{s}$).

1990s: CGRO era

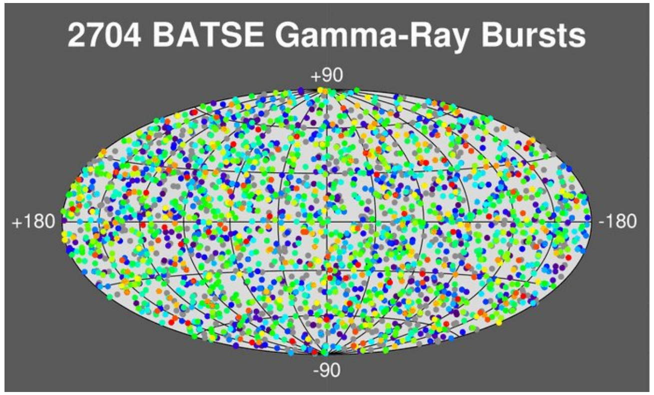


(Kouveliotou et al., 1993)

There is a correlation between spectral shape and duration of the burst:

Shorter bursts tend to have harder X-ray/gamma-ray spectra.

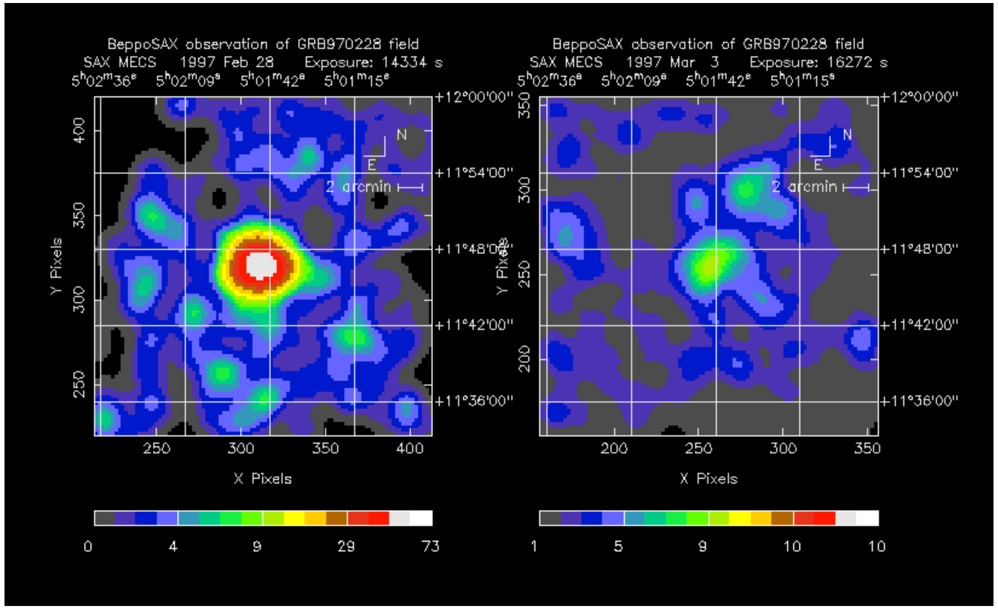
1990s: CGRO era



9 years of *CGRO*-BATSE GRBs

Bursts are distributed isotropically on sky:

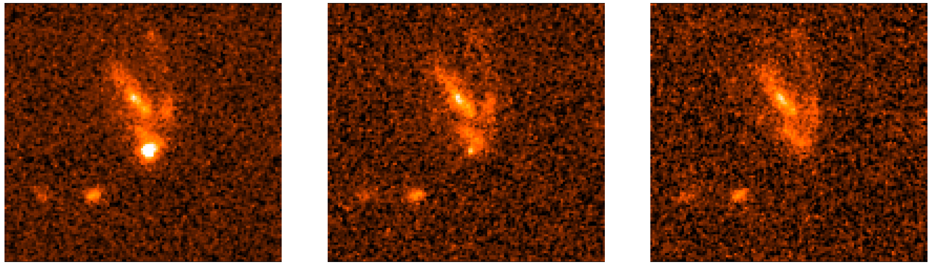
they are either very close (solar system) or at cosmological distances).



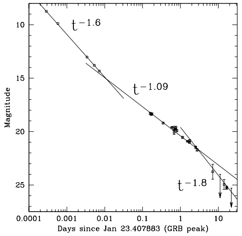
GRB 970228: *BeppoSAX* finds first GRB afterglow (Costa et al., 1997)

⟹ Allows precise localization of burst

GRB 990123

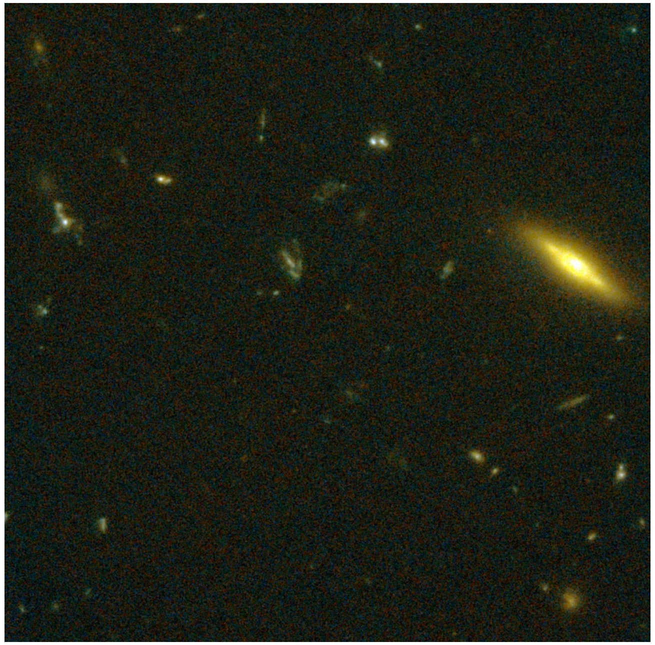


Feb 1999 Mar 1999 Feb 2000



Fading of the optical transient of GRB 990123.
Lightcurve is also a power law.

Fruchter et al. (1999) and `http://www.stsci.edu/~fruchter/GRB/990123/index.html`



26.3″ × 26.3″ HST image of field of GRB 990123 (A. Fruchter; priv. comm.)

Host galaxy is peculiar, blueish

GRB 990123

Bright and prompt optical flashes and radio flares are associated with some GRBs

First seen for GRB 990123

X-ray afterglows (seen in long bursts) allow localization of GRB

BeppoSaX/ground based: Galaxies hosting GRB 970508 and GRB 971214 have large redshifts

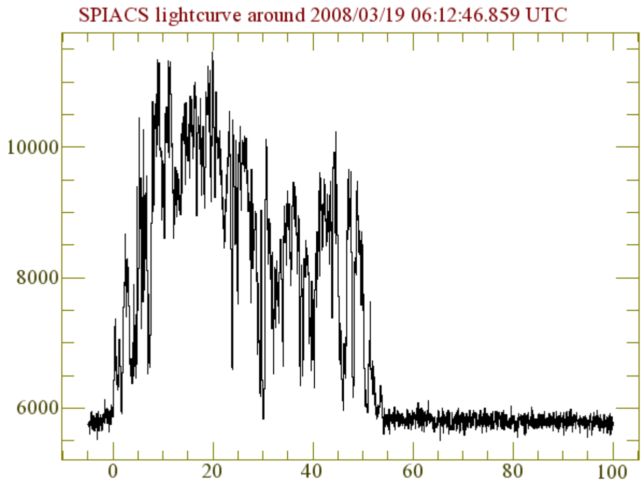
Gamma-Ray Bursts are at cosmological distances.

Redshifts known for >50 GRBs to date, typical $z \sim 1$, but there are extremes, e.g., GRB 050904 with $z = 6.29$ (end of cosmological dark ages!).

$\Longrightarrow$ Gives fluences $\sim 10^{53\dots 54}(\Omega_\gamma/4\pi)$ erg, varying by about 1 order of magnitude.

Ω_γ is correction factor for beaming.

GRB 080319



INTEGRAL/V. Beckmann

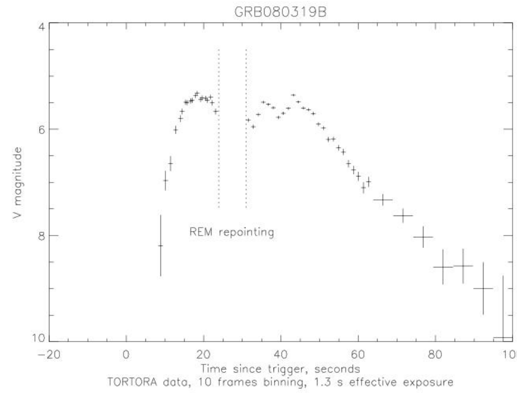
GRB 080319B (one of four GRBs seen on that date!)

GRB 080319

REM and TORTORA

ESO Press Photo 08a/08 (2 April 2008)

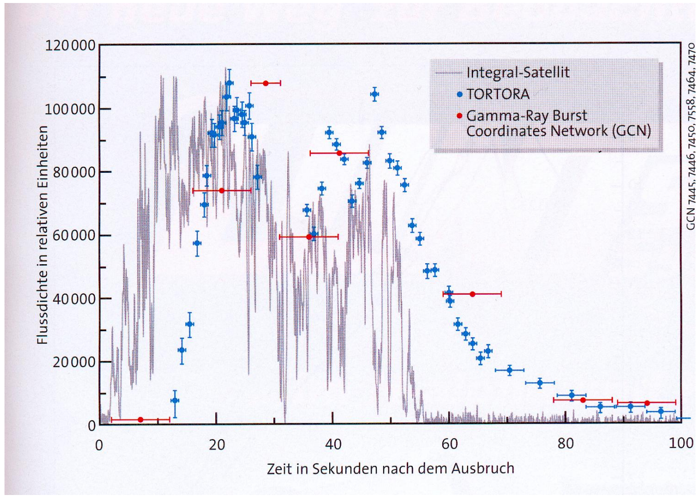
Tortora Video camera on REM: one image every 0.13 s



Karpov et al. (2008; GCN 7558)

GRB080319B: 1st GRB confirmed to be visible to the naked eye!

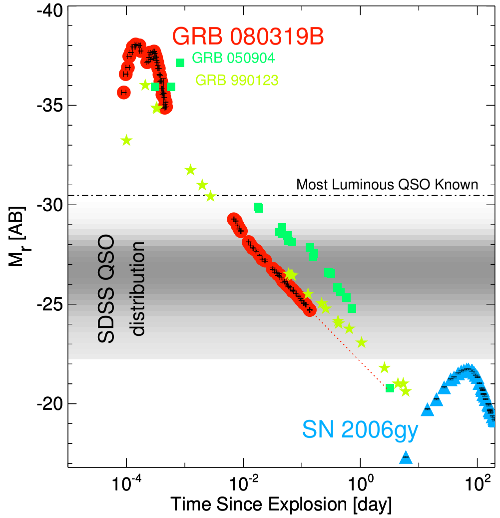
GRB 080319



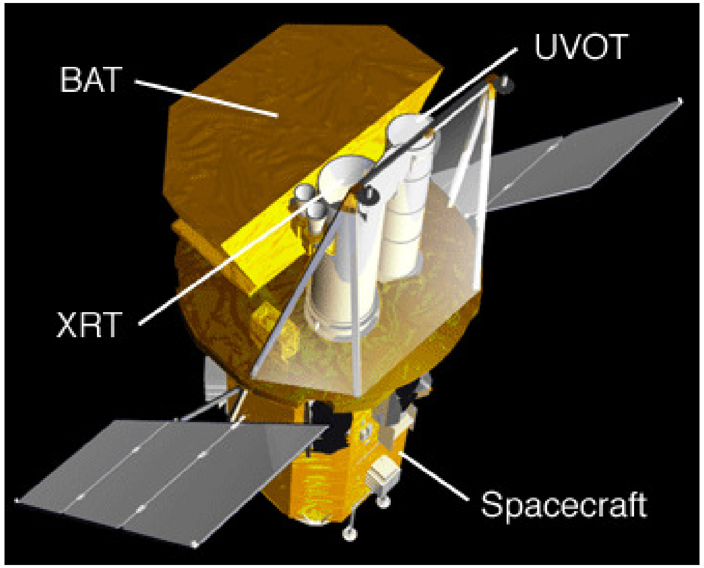
Long duration GRB, optical afterglow 6 s after the GRB (SuW 5/2008)

Movie time: grb080319b.avi (`http://vo.astronet.ru/~karpov/`)

GRB 080319



GRB080319B = the biggest bang since the Big Bang

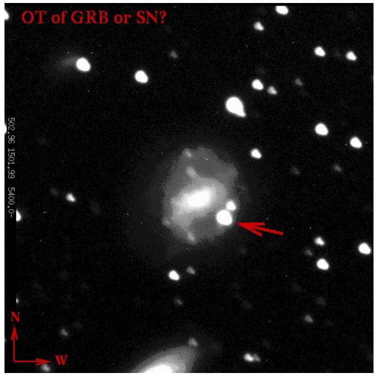


(Gehrels et al., 2004, Fig. 2)

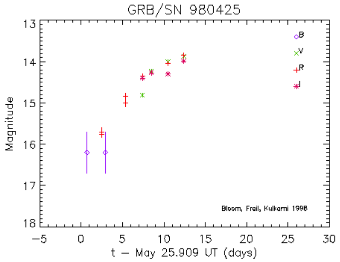
Swift: Launch November 2004, allows broad band monitoring of GRBs

Since *CGRO* and *Beppo-SAX* only some progress through observations with *HETE*-2 and Gamma-ray detectors on interplanetary probes.

GRB–SN association



UvA



Bloom et al. (IAUC 6899)

- 26 April 1998: IAUC 6884: GRB 980425 detected with *BeppoSAX*-WFC
- 29 April 1998: Galama et al. (GCN Report 60): GRB 980425 located off center on arms of in barred spiral ESO 184-82

- Several GCNs: nothing seen in optical
- 7 May 1998: Galama et al. (IAUC 6895): Point source at GRB position, brightens

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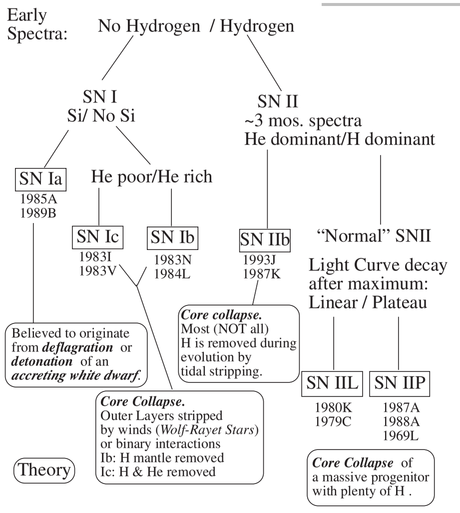
GRB–SN association



Early Spectra: No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

"Normal" SNII

Light Curve decay
after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf.***

Core collapse. Most (NOT all) H is removed during evolution by tidal stripping.

Core Collapse. Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

Core Collapse of a massive progenitor with plenty of H .

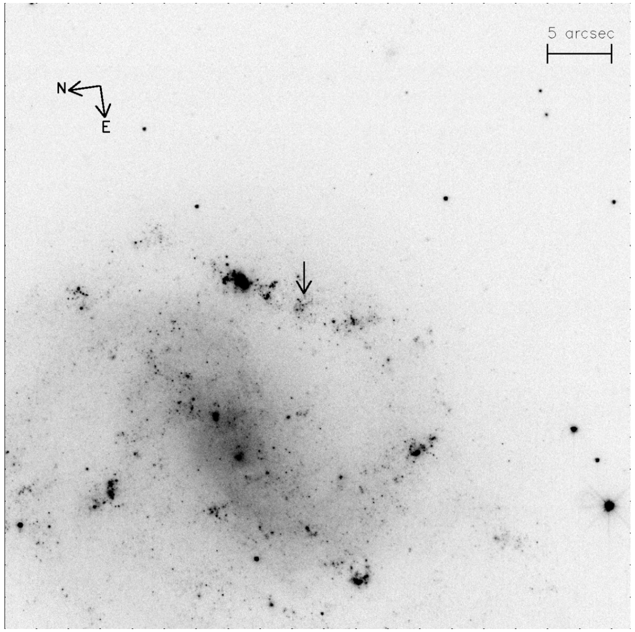
Theory

courtesy M.J. Montes

- 7 May 1998: Lidman et al. (IAUC 6895): Spectroscopy: point source at location of GRB 980425 is possibly a supernova, designated *SN 1998bw*:
  - no H-lines
    $\Longrightarrow$ not a type-II supernova
  - no Si lines
    $\Longrightarrow$ not regular Ia Supernova.

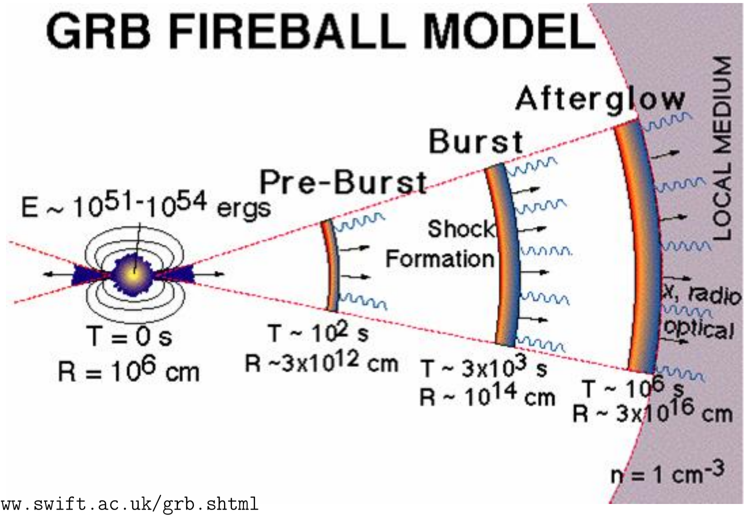
  $\Longrightarrow$ peculiar SN Ic

  "The nature of this puzzling object still evades identification, as does its relation to GRB 980425 or to the galaxy.".



Fynbo et al. (2000): ESO 184-G82 is a star-forming SBc galaxy
GRB was located in star forming region

GRB–SN association



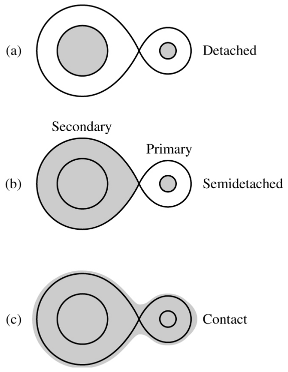
`http://www.swift.ac.uk/grb.shtml`

GRB model: Relativistic fireball model (Rees & Mészáros, 1992)

Evolution of Binary Stars

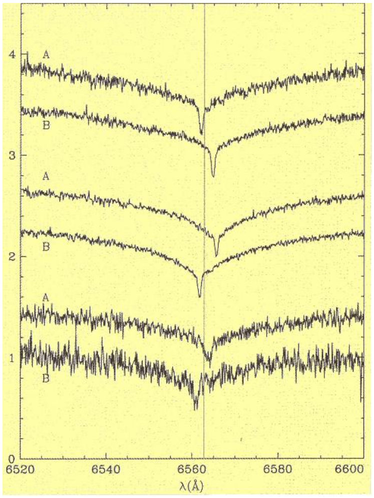
How to detect a compact object?

Binaries!



- Detached binaries:
  Doppler motion of the visible star (as for Exo-Planets).
- Interacting binaries (semi-detached):
  Mass transfer from the normal star and accretion onto the companion

Carroll & Ostlie Fig. 18.4



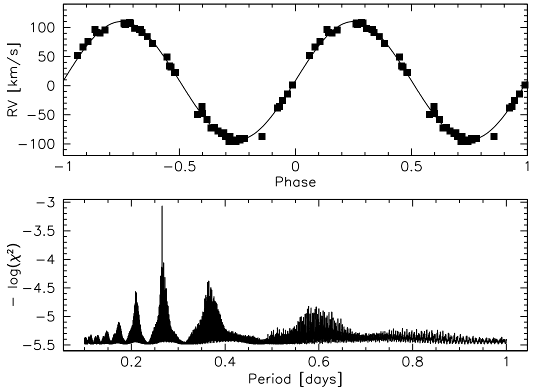
Reminder: Spectroscopic binaries: Mass of compact invisible object (as for the exo-planets) from 3rd Kepler:

$$\frac{a^3}{P^2} = \frac{G(M_1+M_2)}{4\pi^2} \qquad (16.1)$$

(a: semi-major axis, P: orbital period, $M_{1,2}$: Masses).

Derive from this: Mass function

$$\mathrm{MF} = \frac{M_2^3 \sin^3 i}{(1+(M_1/M_2))^2} = \frac{K_1^2 P}{2\pi G} \qquad (16.2)$$



C. Karl, U. Heber, R. Napiwotzki, S. Geier, Balt. Ast. 15, 1

measurement K_2 : velocity amplitude, P: period (power spectrum)

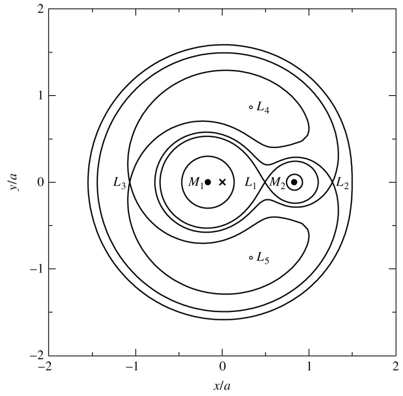
Mass function gives lower limit for M_2

How to distinguish between white dwarf, neutron star and black hole?

- If the lower limit to M_2 is less than the Chandrasekhar mass: no distinction possible.
- If the lower limit to M_2 is larger than Chandrasekhar mass but less than the Oppenheimer-Volkoff limit: Neutron star or black hole
- If the lower limit to M_2 is larger than the Oppenheimer-Volkoff limit: black hole
- If the companion is a pulsar: neutron star

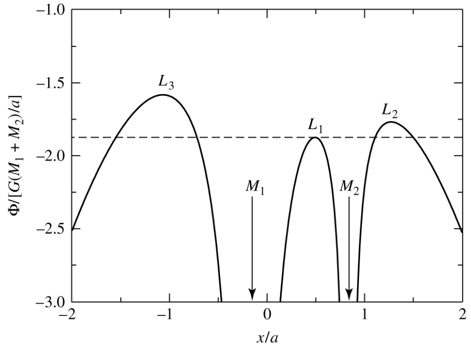
Semi-detachted systems

Gravitational potential of a binary



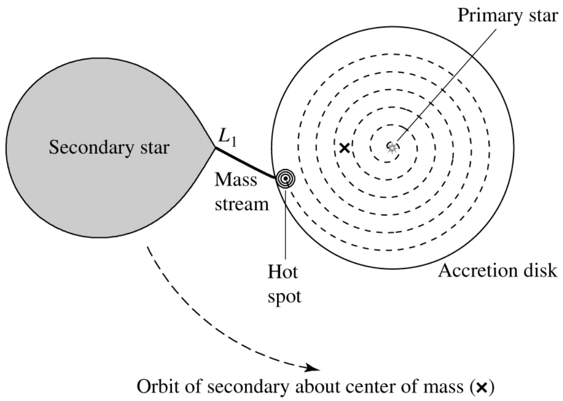
Equipotential contours, Carroll & Ostlie Fig. 18.3

$L_1 \ldots L_5$: Lagrange points.

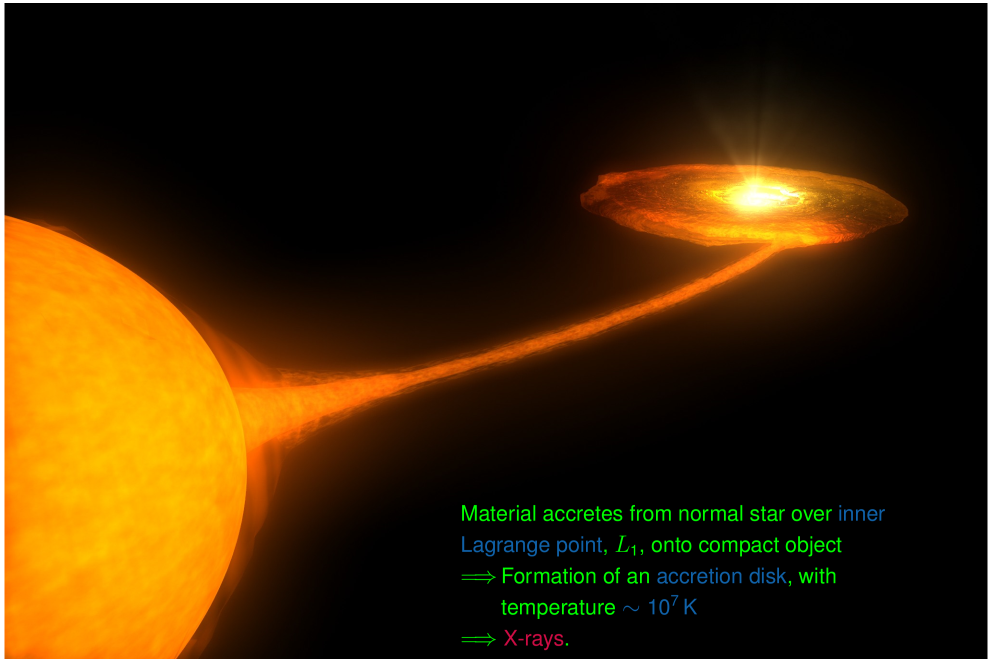


Effective gravitational potential, Carroll & Ostlie Fig. 18.2 Dashed line: Total energy rquired for material to flow through L1.

Semi-detachted systems



- Visible star = secondary = normal star
- Cataclysmic variable: primary is white dwarf
- X-ray binary: primary is a neutron star or black hole.



Material accretes from normal star over inner Lagrange point, L_1, onto compact object
$\Longrightarrow$ Formation of an accretion disk, with temperature $\sim 10^7$ K
$\Longrightarrow$ X-rays.

Accretion

Astrophysical energy sources:

1. Nuclear fusion
Reactions à la

$$4\text{p} \longrightarrow {}^4\text{He} + \Delta E_\text{nuc}$$

Energy released:

Fusion produces $\sim 6 \times 10^{11}\,\text{J}\,\text{g}^{-1}$

(i.e., $\Delta E_\text{nuc} \sim 0.007 m_\text{p} c^2$)

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2. Gravitation
Accretion of mass m from ∞ to R_S on black hole with mass M gives

$$\Delta E_\text{acc} = \frac{GMm}{R_\text{S}} \quad \text{where} \quad R_\text{S} = \frac{2GM}{c^2}$$

Accretion produces $\sim 10^{13}\,\text{J}\,\text{g}^{-1}$

(i.e., $\Delta E_\text{acc} \sim 0.1\, m_\text{p} c^2$)

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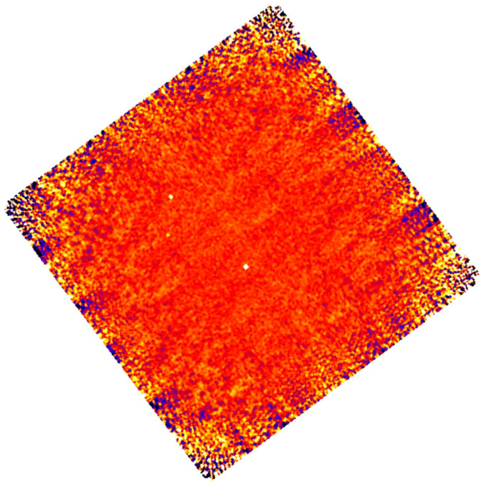
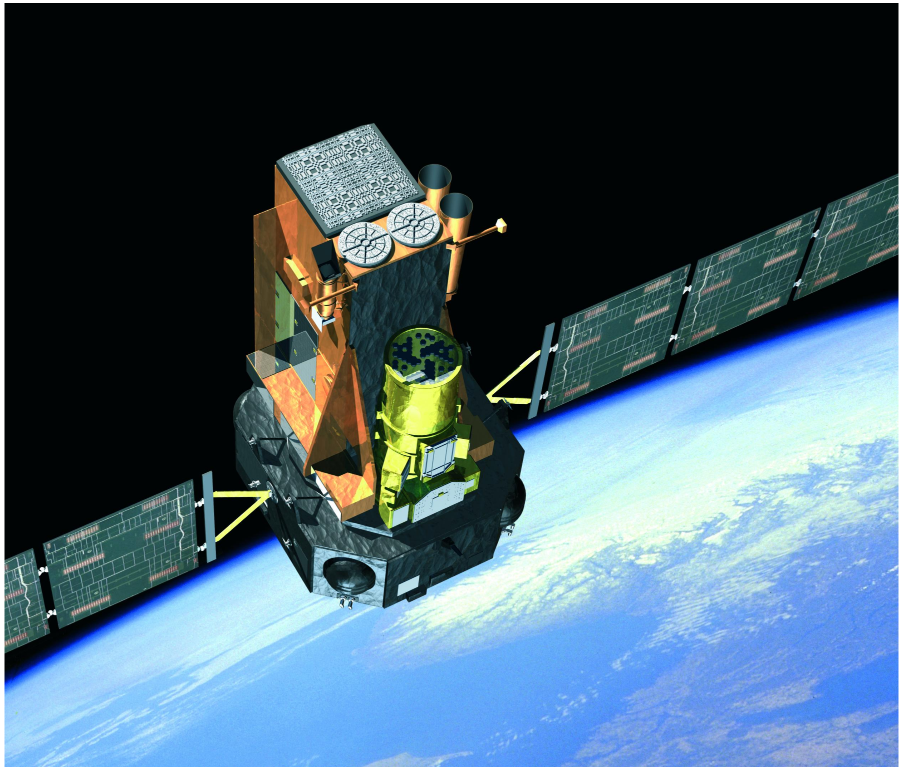
(i.e., $\Delta E_{\mathrm{acc}} \sim 0.1\, m_{\mathrm{p}} c^2$)

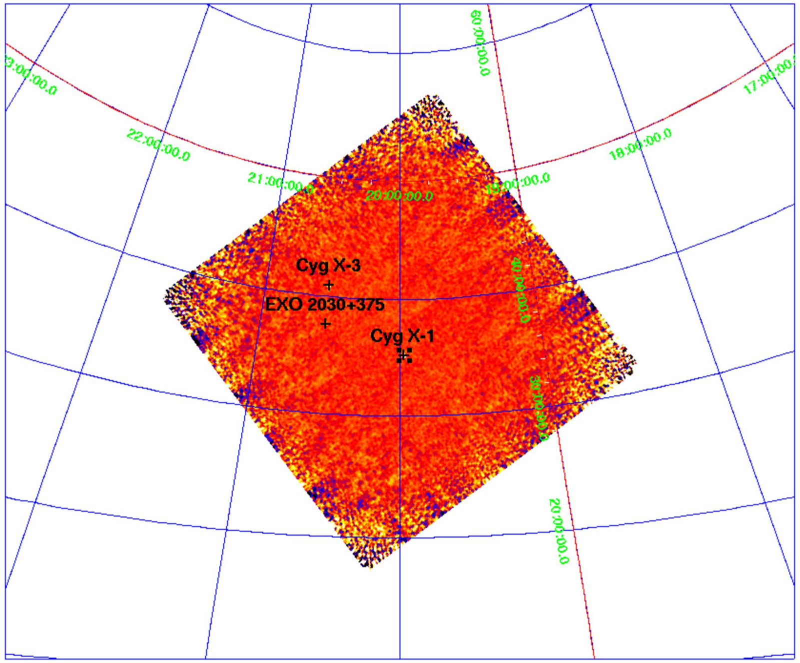
$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source.

…thus accreting objects are the most luminous in the whole universe.

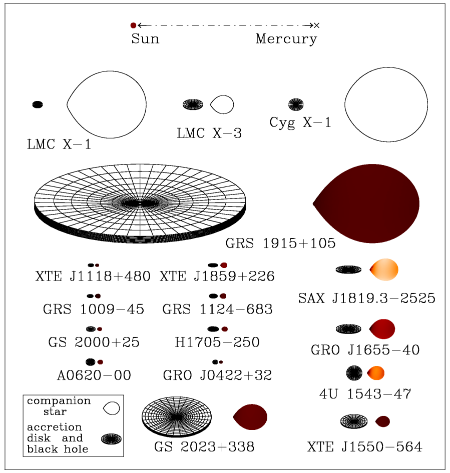
Note: energy gets radiated away from *outside* the Schwarzschild radius!

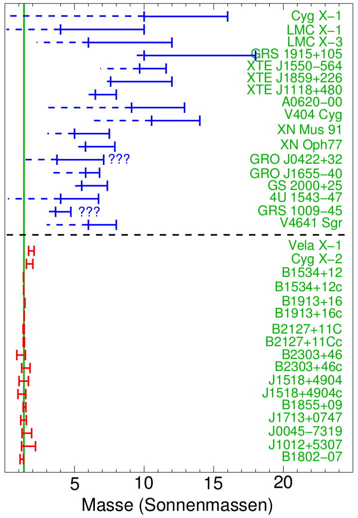






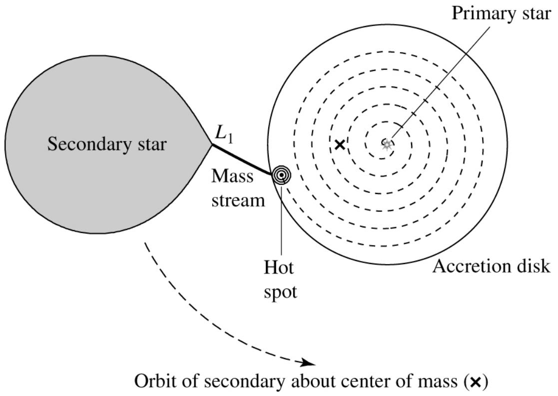
Mass determination





Orosz, 2003, priv. comm.

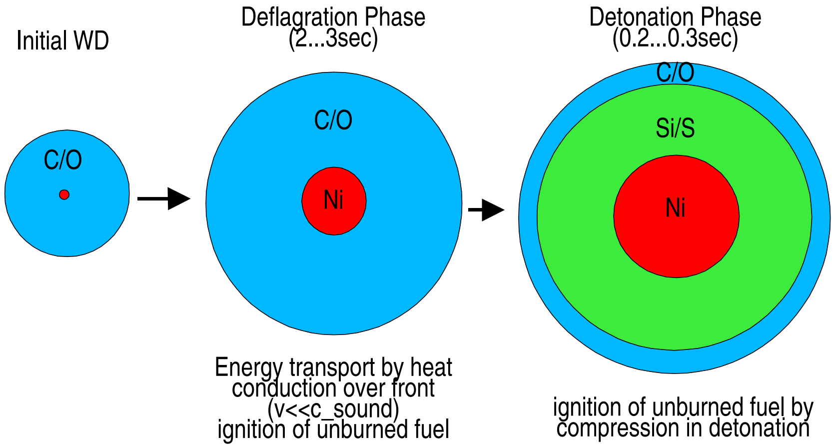
Explosions in binary systems: Novae



Novae: accretion of hydrogen onto the surface of a white dwarf:

- $10^{-5}M_\odot \dots 10^{-4}M_\odot$ Hydrogen accumulate.
- Electron gas is degenerate
- Temperature of a few million K
- hydrogen burning in the CNO cycle starts
- thermal run-way as in the core helium flash at the tip of the RGB
- explosion expell almost all accreted material

Explosions in binary systems: Supernovae– Type Ia



Energy transport by heat conduction over front (v<<c_sound) ignition of unburned fuel

ignition of unburned fuel by compression in detonation

after P. Höflich

SNe Ia: thermonuclear runaway in carbon-oxygen white dwarfs close to Chandrasekhar limit

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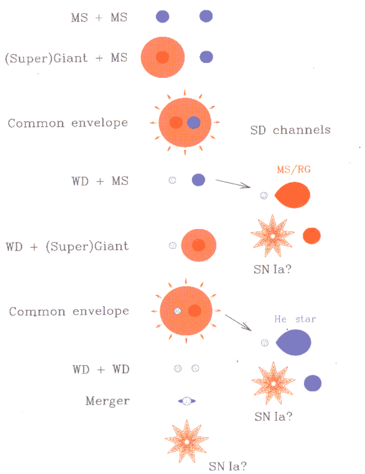
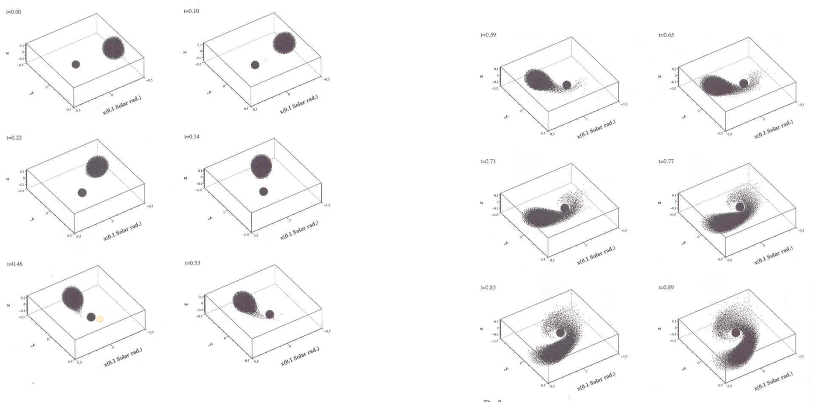
Explosions in binary systems: Supernovae– Type Ia

Thermonuclear explosion of a white dwarf at the Chandrasekhar limit



- orbital shrinkage by common envelope ejection
- single degenerate scenario: continous mass transfer to the white dwarf
  - white dwarf & normal star
  - white dwar & helium star
- Double degenerate scenario:
- two white dwarfs: orbital shrinkage by gravitational wave radiation: white dwarf merger.

White dwarf merger

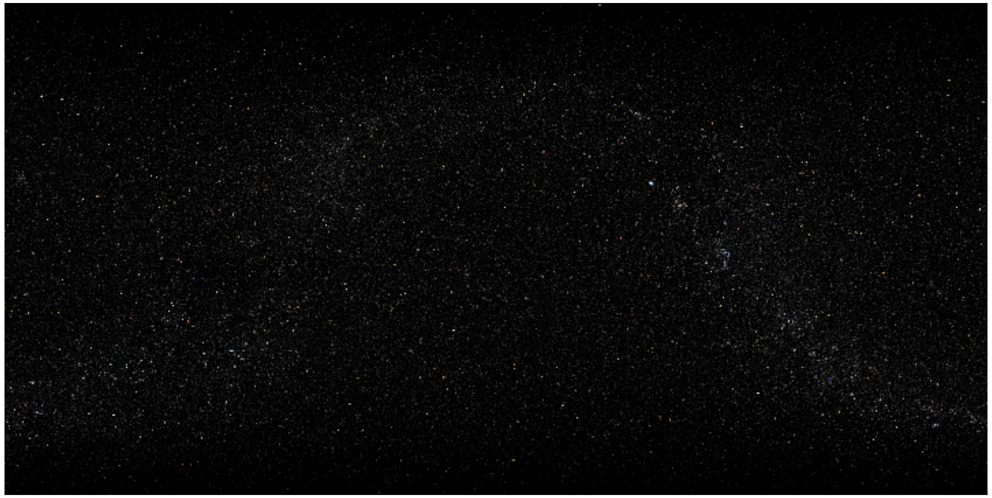


The less massive (larger) white dwarf is disrupted with in one final orbit and acrreted by the more massive one. Explosion starts when approaching the Chandrasekhar limit.

D.Seal/JPL

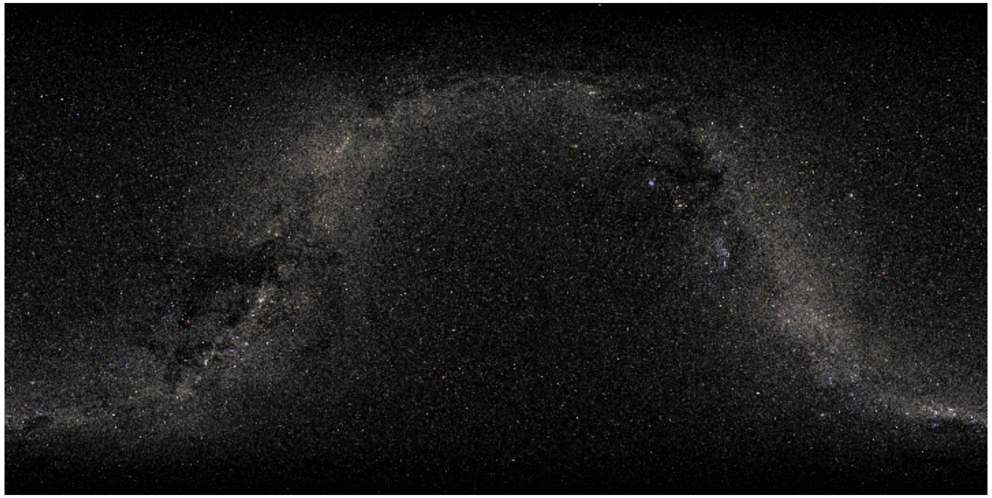
The Yale Bright Star Catalogue (9110 brightest stars)

The Galaxy



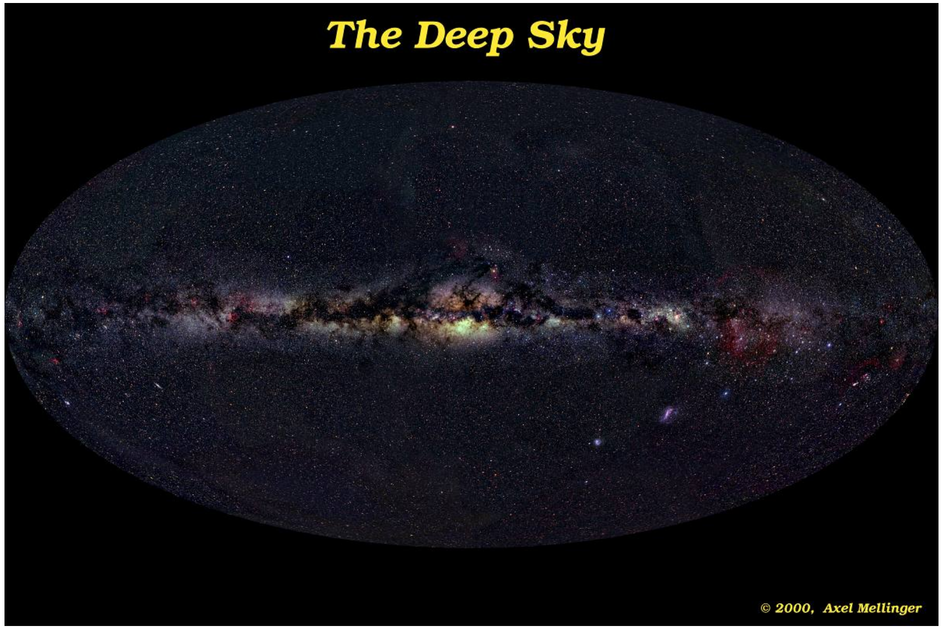
D.Seal/JPL

The Hipparcos Catalogue (118000 stars)

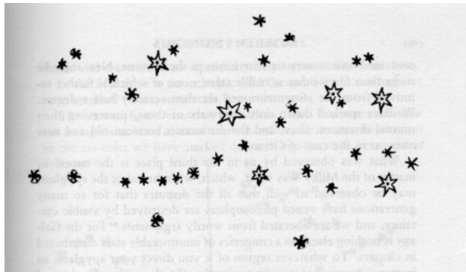


D.Seal/JPL

The second Tycho Catalogue (2.5 million stars)



The Night Sky



Galileo Galilei (1564–1642; Sidereus Nuncius): Telescope resolves (part of) the milky way in stars, discovers new stars $\Longrightarrow$ Milky way is not “milky”!

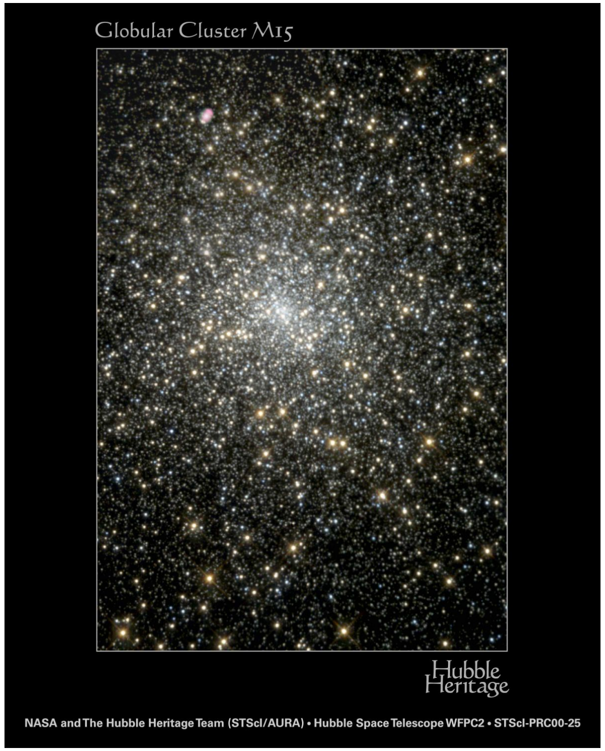
The Night Sky

Charles Messier (1730–1817) searched for comets but found nebula which did not move. Created a catalog of 110 nebulae.

- diffuse nebulae: M 42 = Orion nebula
- Planetary nebulae: M 57 = Ring nebula
- Supernova remnants M 1 = Crab nebula
- Open star clusters: M 45 = Pleiades
- Globular star clusters: M 13 in Hercules
- Galaxies: M31 = Andromeda galaxy

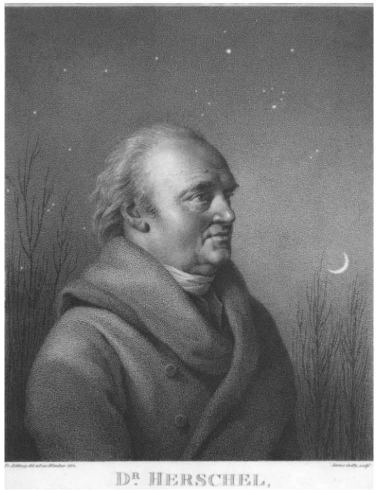
Open clusters = Galactic clusters, young, e.g. Pleiades 100 Myrs

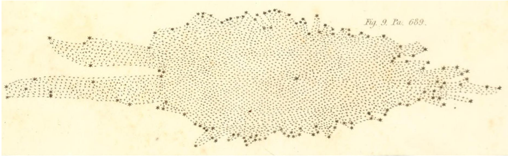
Globular clusters: very old: 9–12 Gyrs



NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC00-25

The Night Sky

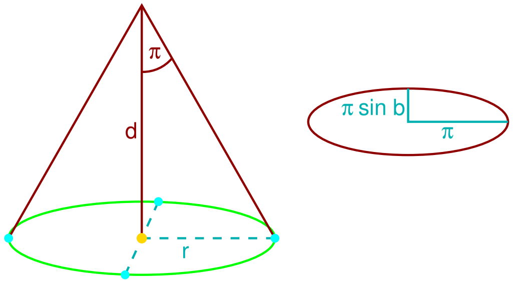




William Herschel (1738–1822): First attempts to determine morphology of the Galaxy.

Note: heliocentric!

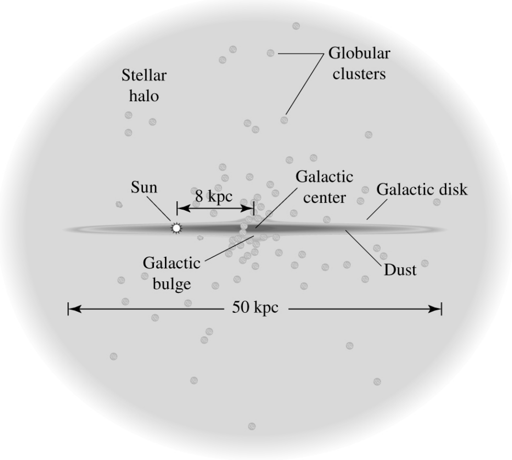
The Night Sky



Wilhelm Bessel (1784–1846): First determination of a stellar parallax

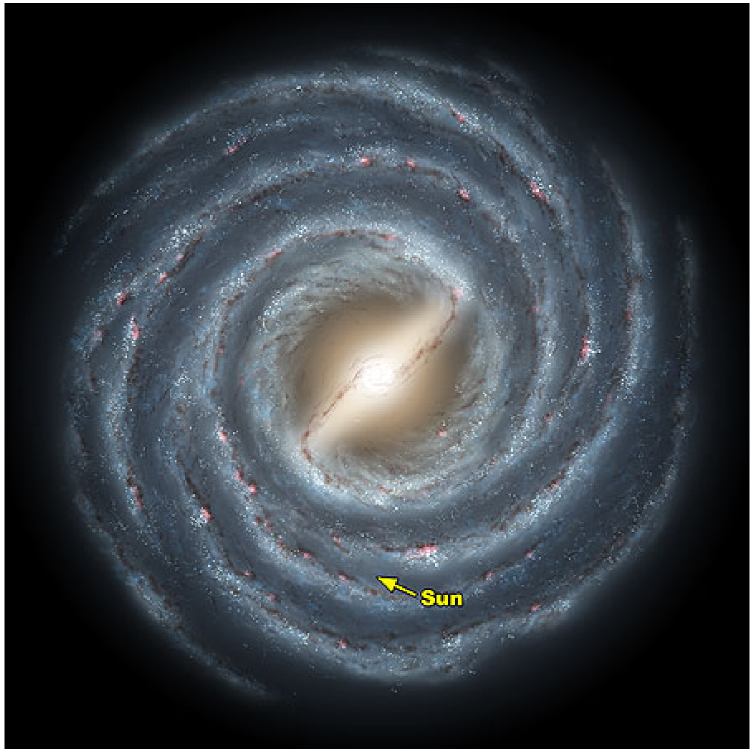
reminder: 1 parsec = 3.26 Lj = 3 × 10^{13} km

The Milky Way

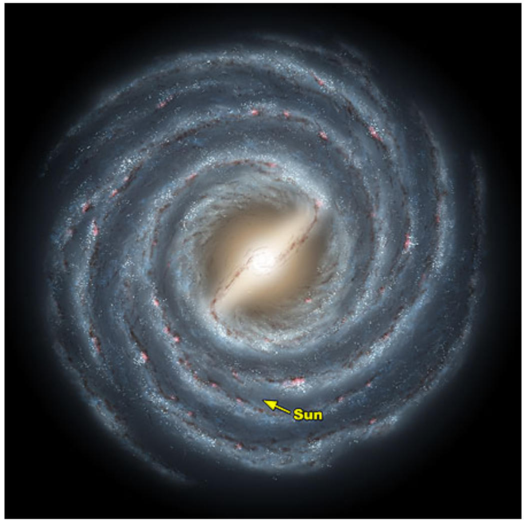


components of the Milky Way:

- Galactic disk:
  - rotating
  - young & old stars, open star clusters
  - gas & dust
- Galactic halo:
  - non-rotating,
  - old stars only, globular clusters
  - no gas, no dust
- Galactic bulge: rigid rotation

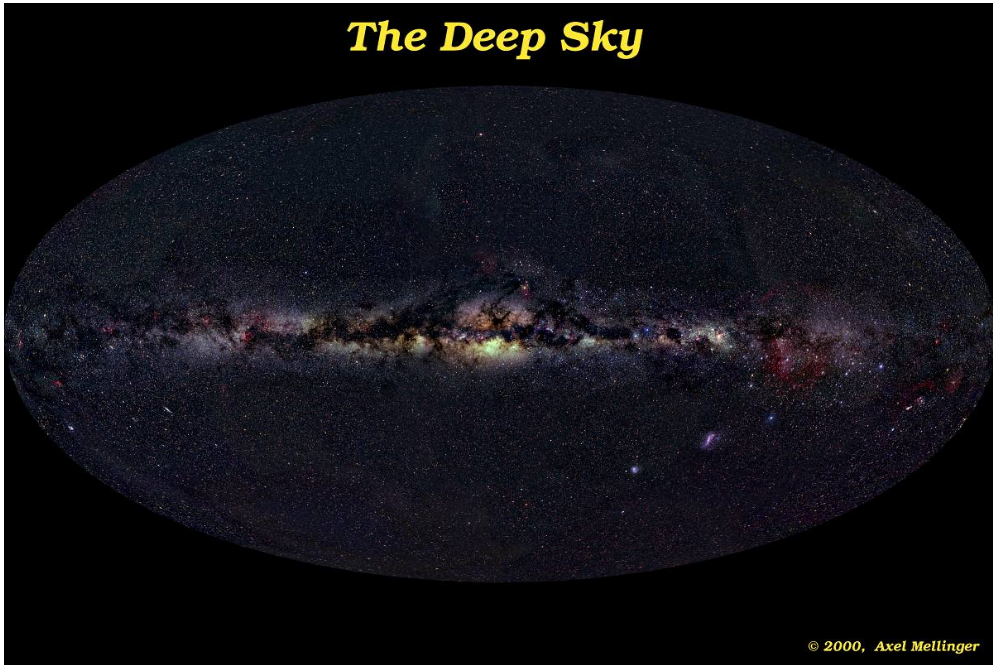


The Milky Way

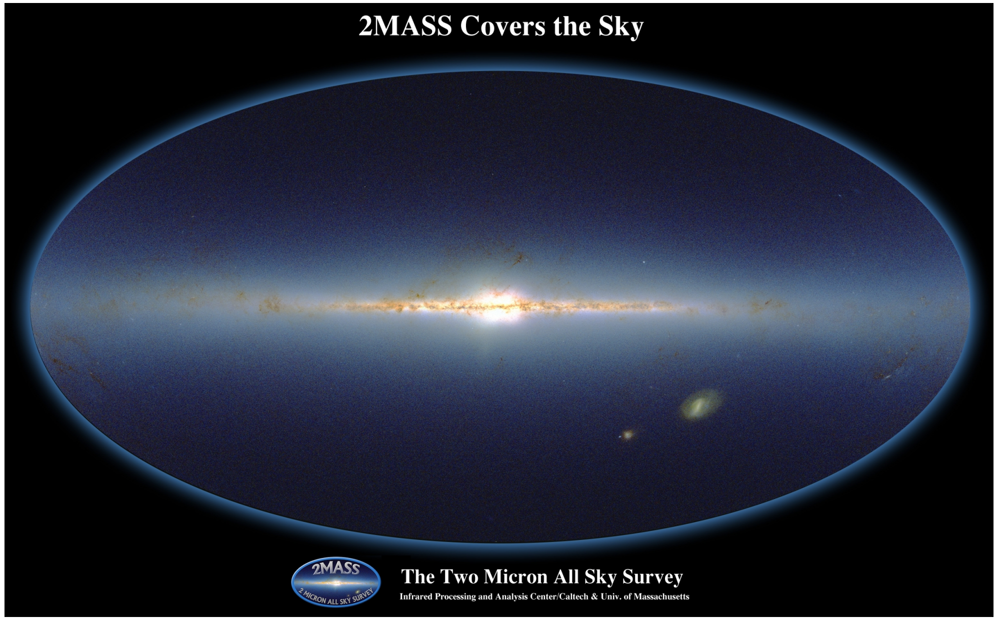


Milky Way is a barred spiral galaxy Luminosity:
$\sim 2\times 10^{10}\,L_\odot$
Mass: $\sim 10^{11}\,M_\odot$ (radiating)
$\sim 10^{12}\,M_\odot$ (total)
Stellar density: $\sim 0.3\,M_\odot\,\mathrm{pc}^{-3}$

$1\,M_\odot = 2\times 10^{33}\,\mathrm{g} = 2\times 10^{30}\,\mathrm{kg}$,
$1\,L_\odot = 4\times 10^{33}\,\mathrm{erg\,s^{-1}} = 4\times 10^{26}\,\mathrm{W}$



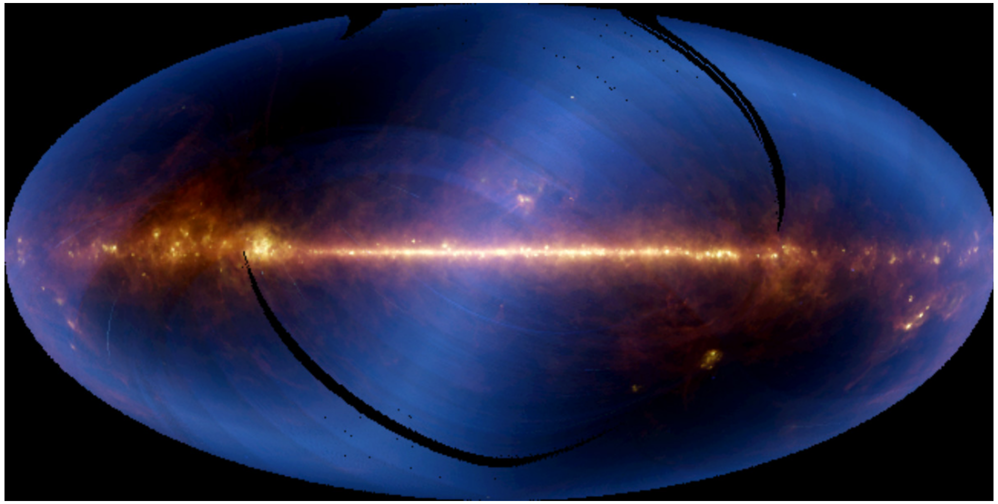
Milky Way in Optical



Infra red: Dust becomes transparent!

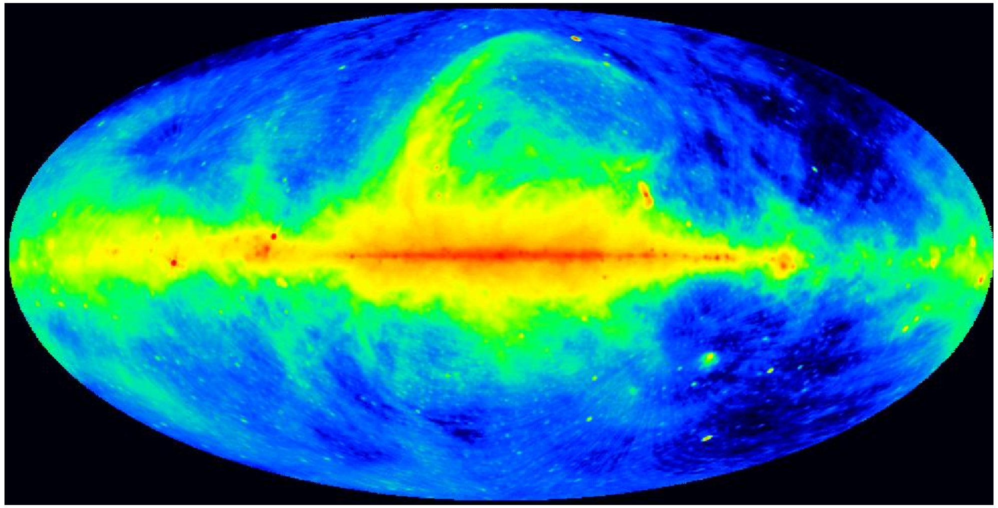
2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)

Milky Way in Near Infra Red



Milky Way in far Infra Red

IRAS: 3 IR Bands: blue (12 μm), green (60 μm), red (100 μm)



G.T. Haslam et al., MPI für Radioastronomie 1982

Milky Way in radio ($\lambda = 73\,\mathrm{cm}$, $\nu = 408\,\mathrm{MHz}$)

Continuum radiation (bremsstrahlung, synchrotron radiation)

Multi Wavelength

From the available maps the Galaxy looks like a spiral galaxy.

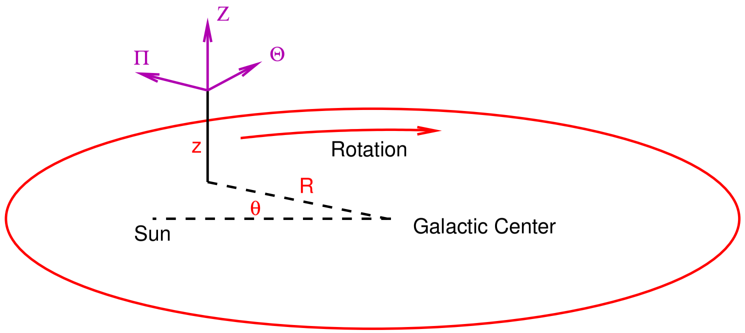
$\Longrightarrow$ How can we determine the structure of the Galaxy in more detail?

Derivation of Galaxy structure is somewhat complicated since we are sitting in it and since the solar system participates with the motion of the Galaxy.

$\Longrightarrow$

1. Galactic Rotation Curve
2. Distribution of gas
3. Evidence for spiral arms

Local Standard of Rest



after Carroll & Ostlie (Fig. 22.21)

Introduce cylindrical coordinate system R, θ, z

$\Longrightarrow$ Velocity components of a star in a cartesian coordinate system:

$$\Pi = \frac{dR}{dt} \qquad \Theta = R\frac{d\theta}{dt} \qquad Z = \frac{dz}{dt} \tag{17.1}$$

Local Standard of Rest

All observations of Galaxy are made from position of Sun.

But Sun moves through space

$\Longrightarrow$ define a *local* coordinate system centered on Sun, which moves on a circular orbit around the center of the Galaxy: Local Standard of Rest (LSR)

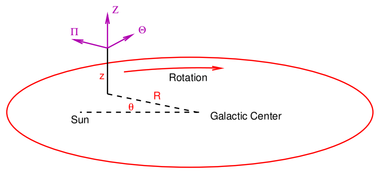
By definition, velocity components of the LSR are:

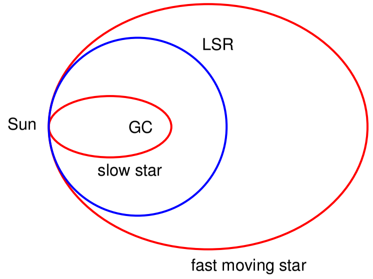
$$\Pi_{\mathrm{LSR}} = 0 \qquad \Theta_{\mathrm{LSR}} =: \Theta_0 \qquad Z = 0 \tag{17.2}$$

Therefore, after measuring motion with respect to LSR, we can convert to Galactic system provided we know Θ_0.

Note that Sun *moves with respect to LSR*!

Motion of the Sun





Velocity of stars relative to LSR: peculiar motion. *Velocity components:*

$$u = \Pi - \Pi_{\mathrm{LSR}} = \Pi$$
$$v = \Theta - \Theta_{\mathrm{LSR}} = \Theta - \Theta_0 \qquad (17.3)$$
$$w = Z - Z_{\mathrm{LSR}} = Z$$

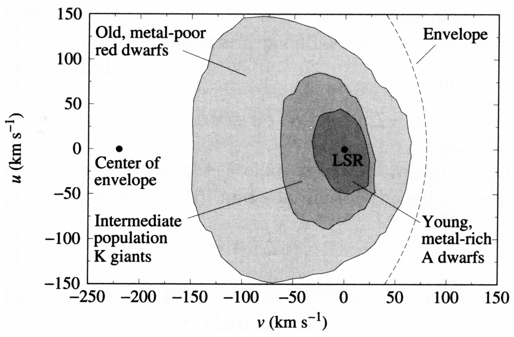
Now look at average u, v, w of stars in solar neighborhood:

- motion in Π and Z should average to zero: $\langle u \rangle = 0$, $\langle w \rangle = 0$, because of symmetry,
- $\langle v \rangle < 0$ because of elliptical motion of stars around Galactic center. Since there are more stars towards GC, more stars move slower than LSR.

From this one can deduce Sun's peculiar velocity:

$$u_\odot = -9\,\mathrm{km\,s^{-1}}, \quad v_\odot = 12\,\mathrm{km\,s^{-1}}, \quad w_\odot = 7\,\mathrm{km\,s^{-1}} \qquad (17.4)$$

Motion of the Sun



Carroll & Ostlie (Fig. 22.23)

The distribution objects in u-v-plane ("velocity ellipsoid") depends on type of object. velocity–metallicity relation: The oldest objects in Galaxy, which have lowest metallicity, have the largest velocity dispersion.

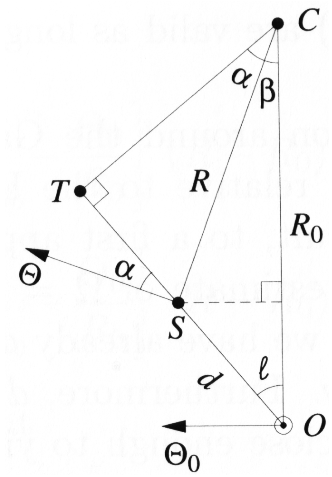
Velocity ellipsoids are asymmetric, oldest objects centered on $v \sim -220\,\mathrm{km\,s^{-1}}$.

Assumption: these objects do not participate in Galactic rotation

The orbital speed of the LSR is 220 km s^{-1}.

Confirmed by looking at motion with respect to other galaxies.

Galaxy Rotation Curve



Carroll & Ostlie (Fig. 22.24)

To determine rotation of Galaxy ($= \Theta(R)$), our observables are the radial velocities and the transversal velocities of a star S:

$$v_{\mathrm{r}} = \Theta\cos\alpha - \Theta_0 \sin\ell = \Omega R\cos\alpha - \Omega_0 R_0 \sin\ell \qquad (17.5)$$
$$v_{\mathrm{t}} = \Theta\sin\alpha - \Theta_0 \cos\ell = \Omega R\sin\alpha - \Omega_0 R_0 \cos\ell \qquad (17.6)$$

where ℓ: galactic longitude, $\Omega = \Theta/R$: angular velocity
But from geometry of $\triangle OTC$:

$$R\cos\alpha = R_0 \sin\ell \qquad (17.7)$$
$$R\sin\alpha = R_0 \cos\ell - d \qquad (17.8)$$

such that

$$v_{\mathrm{r}} = (\Omega - \Omega_0) R_0 \sin\ell \qquad (17.9)$$
$$v_{\mathrm{t}} = (\Omega - \Omega_0) R_0 \cos\ell - \Omega d \qquad (17.10)$$

$\Longrightarrow$ We can determine Ω from v_{r}!

Gas Distribution

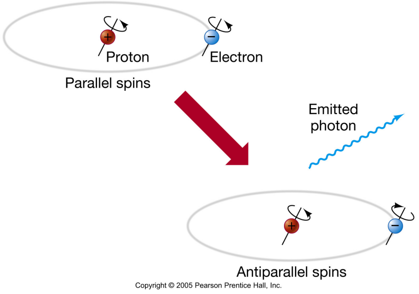
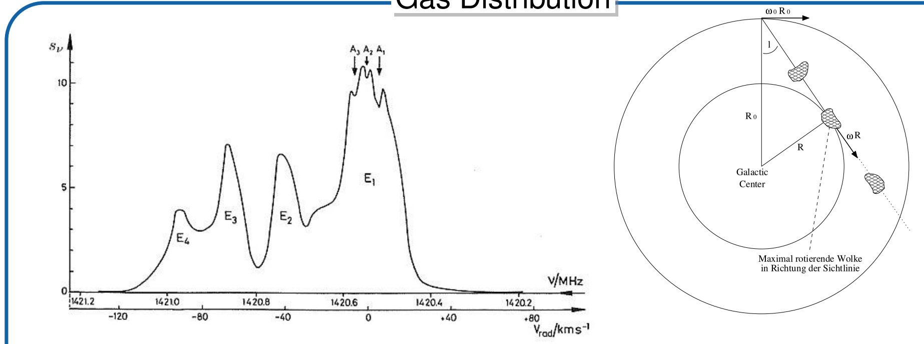


Image: 2005, Pearson Prentice Hall, Inc.

- Spins of electron and proton may be parallel ($F = 1$) or antiparallel ($F = 0$) ("hyperfine levels"); energy difference of $\Delta E \sim 6 \times 10^{-6}$ eV, corresponding to $\lambda = 21$ cm or $\nu = 1.4$ GHz.
- $F = 1$ is metastable, i.e., long life time (10^7 years); transition to $F = 0$ *dipole forbidden* in quantum mechanics, transition rate 10^{-6} smaller than for permitted transitions.
- Laboratory: $F = 1$ state is depopulated by collisions; no line is seen.
- ISM: low densities, i.e., no collisions; radiative transitions possible.

Because of the ubiquity of hydrogen, 21 cm line traces gas extremely well. Self-absorption of the line is extremely unlikely $\Longrightarrow$ line visible from everywhere except for the most dense regions.

Gas Distribution



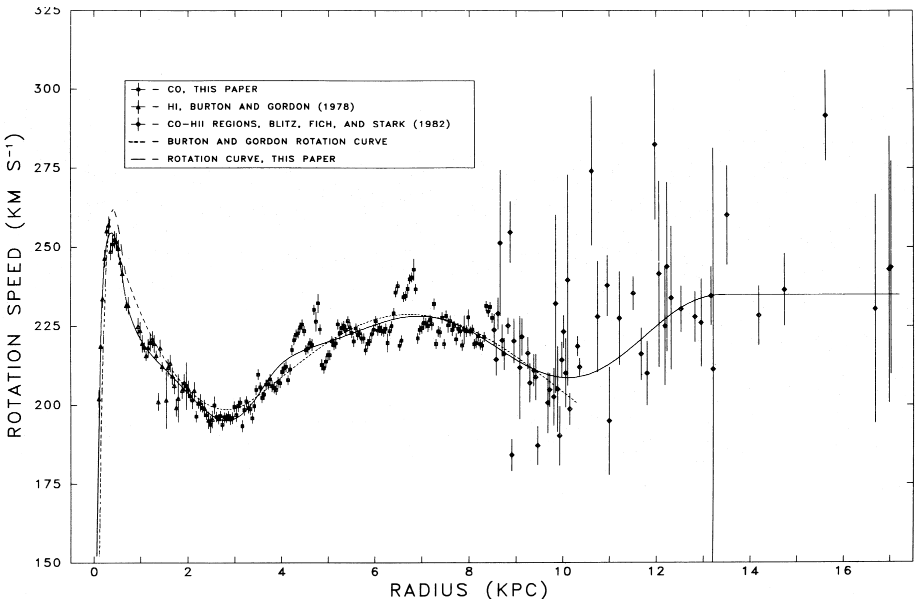
Sketch of a typical H I emission line profile. Note: v-axis has wrong sign!

In general multiple hydrogen clouds along the line of sight. Differential rotation ⇒ Differential Doppler shift, allows to obtain $\Omega(R)$ (note: maximum v_r at $R = R_0 \sin \ell$!).

Overall: Probe of ISM structure and dynamics!

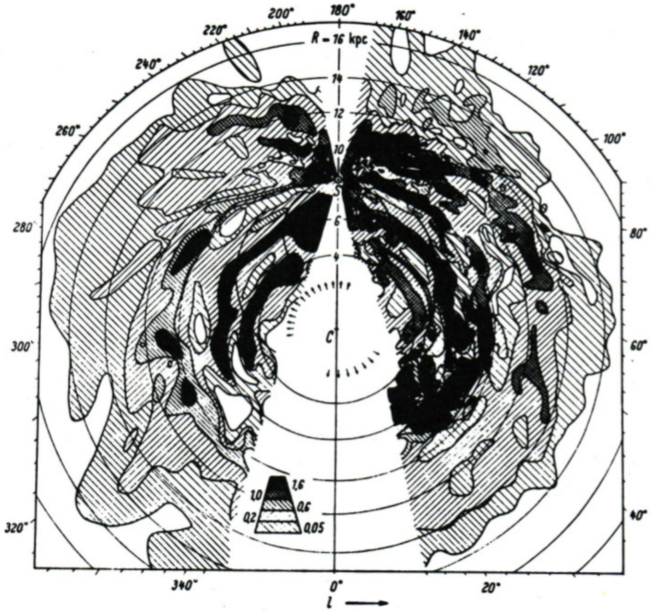
Integration over the full profile gives the column density of neutral hydrogen in this direction. Typical values: $10^{18}\,\mathrm{cm}^{-2}$ (at large gal. latitudes) to $10^{22}\,\mathrm{cm}^{-2}$ (in the gal. plane).

State of the art is the Leiden-Argentine-Bonn Survey (Kalberla et al., 2005).



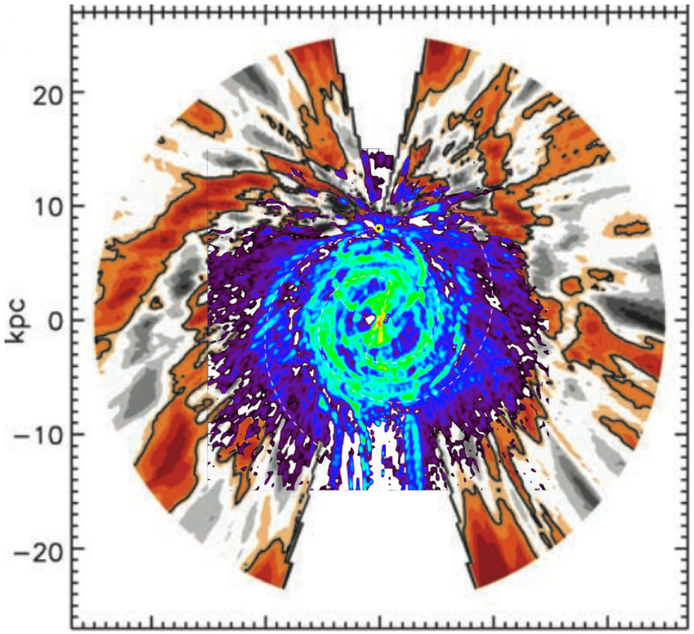
Clemens (1985, Fig. 3)

The rotation curve of the galaxy is approximately flat.



from Englmaier, Pohl, Bissanz (2008, Fig. 1)

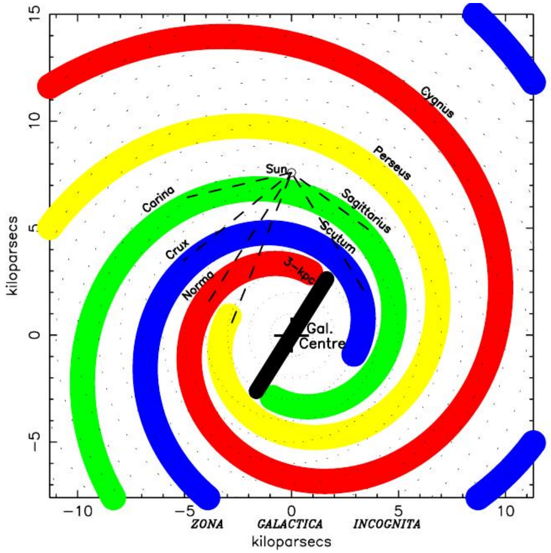
Oort (1958): First map of H distribution in Galaxy: structure!



from Englmaier, Pohl, Bissanz (2008, Fig. 2; Sun is yellow dot)

Distribution of CO and H gas shows clearly the spiral structure.

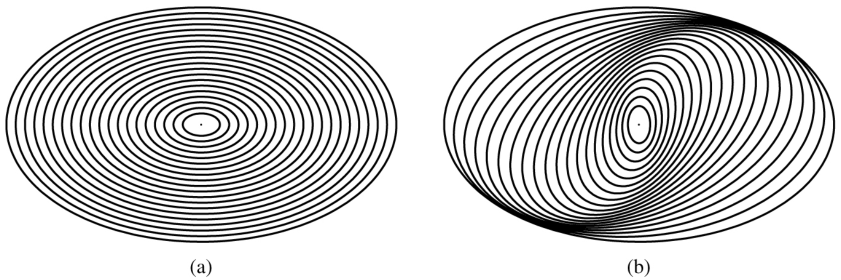
Evidence for Spiral Arms

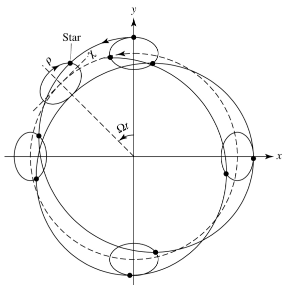


The spiral arm structure of Galaxy is now rather well understood

Vallee (2008)

Spiral Arms





Carroll & Ostlie

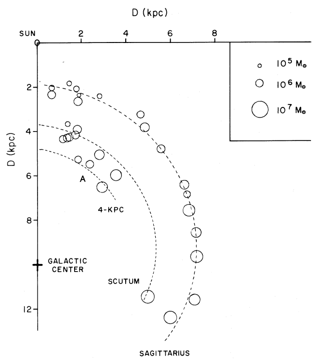
Spiral structure and density waves:

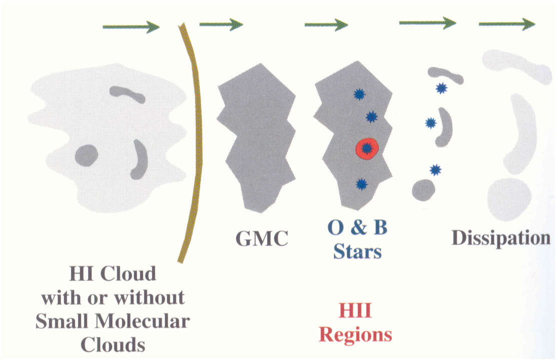
Stars do not move on circles but on “nested ovals”

If each oval is rotated relative to the orbit immediately interior to it: spiral density wave

First order approximation: combination of a retrograde motion about an epicycle and a prograde circular orbit of the epicycle centre

Spiral Arms





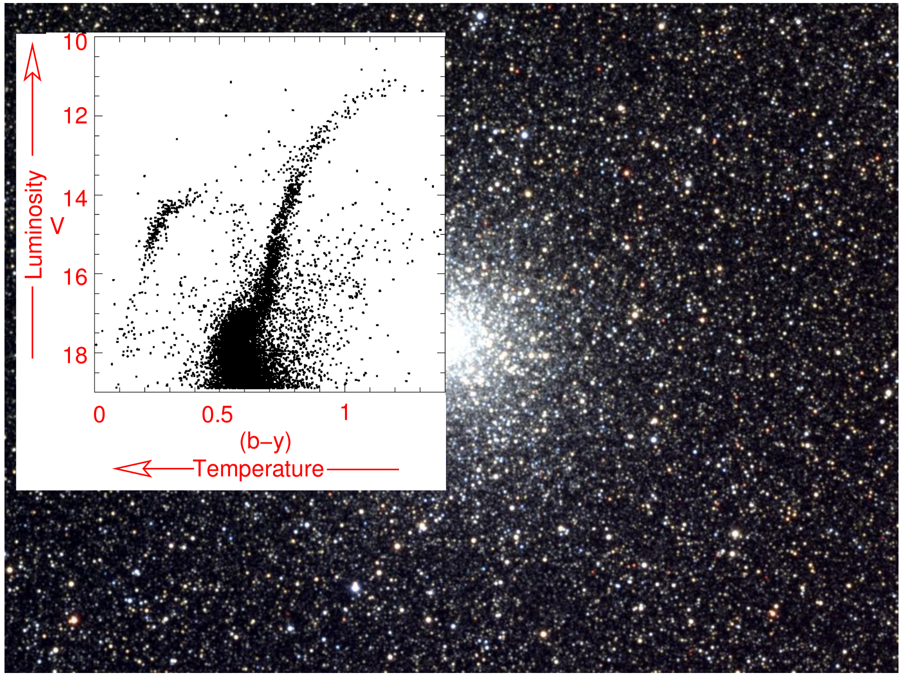
Dame et al. (1986, Fig. 9)

Carroll & Ostlie

Star formation induced by density wave:

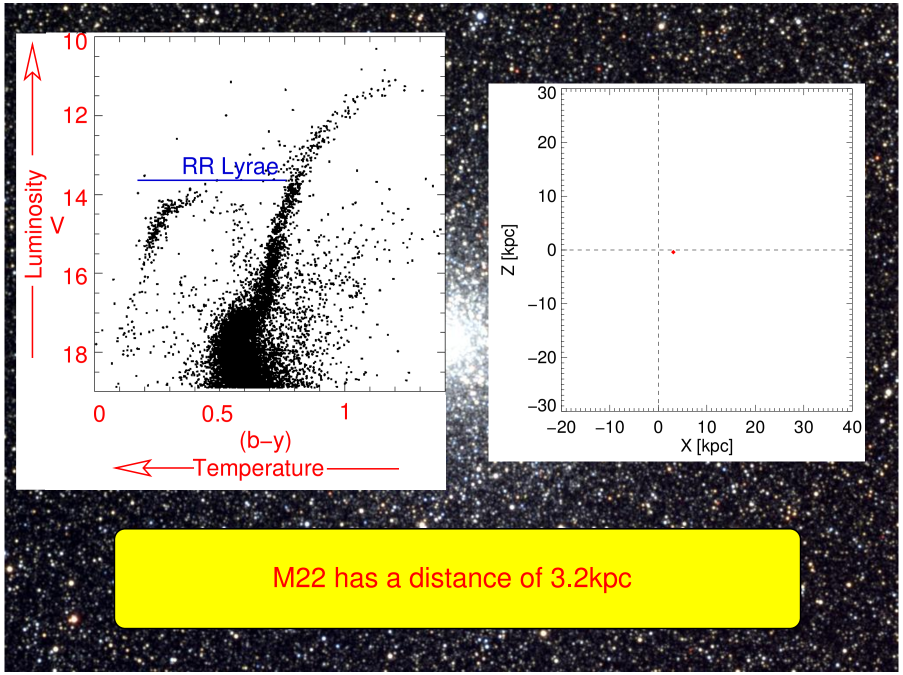
- A cloud of gas passes through a density wave
- compression induces collapse
- stars of all masses form
- massive stars dissipate the cloud by their strong UV radiation

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



Richter et al., 1999, A&A 350, 476

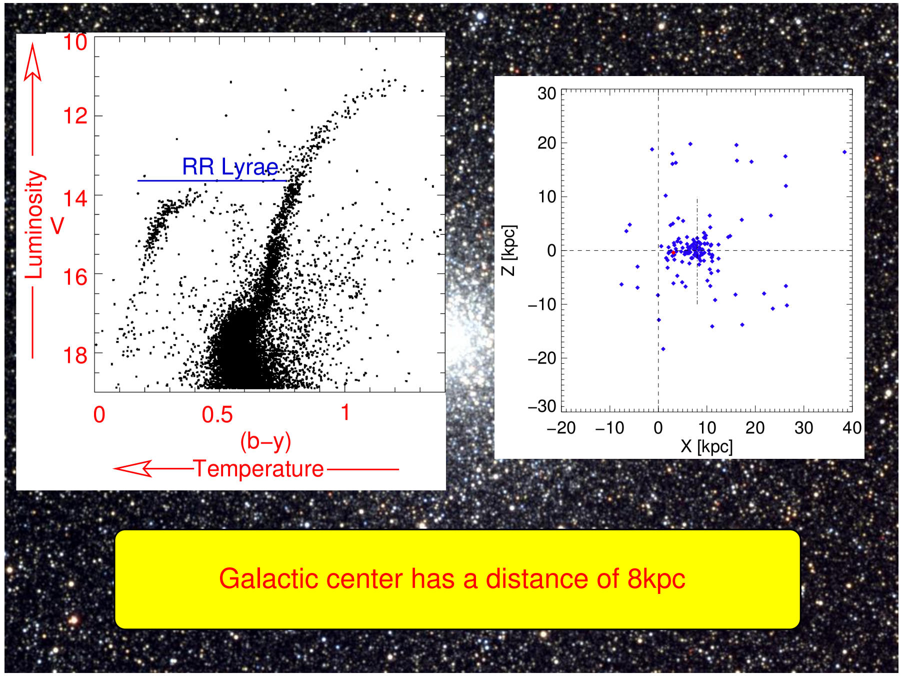
M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



M22 has a distance of 3.2kpc

Richter et al., 1999, A&A 350, 476

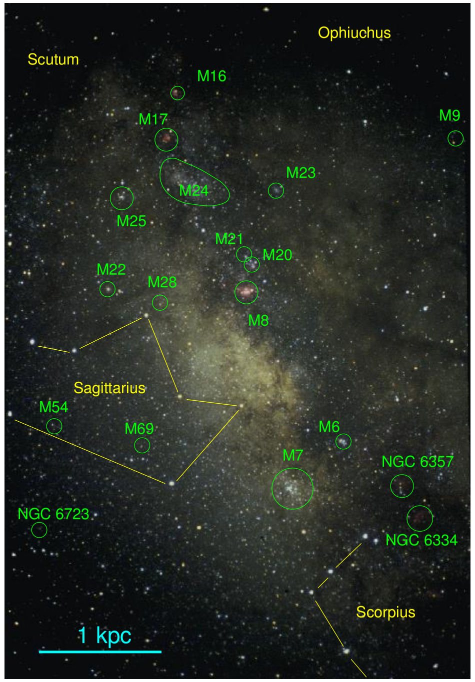
M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



Galactic center has a distance of 8kpc

Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)



W. Keel (U Alabama)

Milky way in Saggitarius

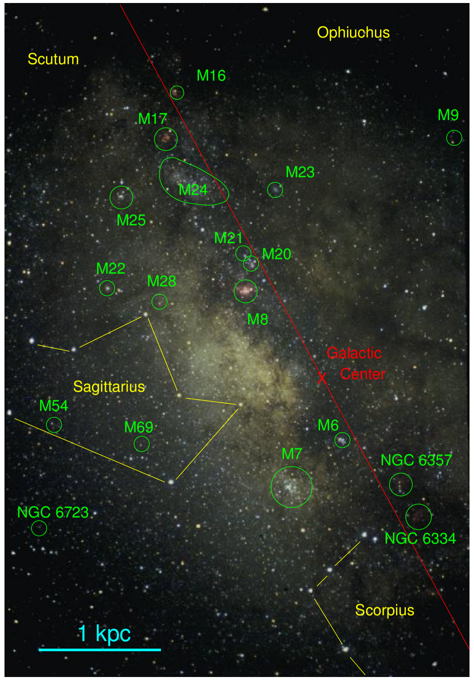
$27^\circ \times 40^\circ$

Distance: 8 kpc

$\Longrightarrow 1^\circ \sim 140\,\mathrm{pc}$

$\Longrightarrow 1' \sim 2\,\mathrm{pc}$

$\Longrightarrow 1'' \sim 0.03\,\mathrm{pc}$



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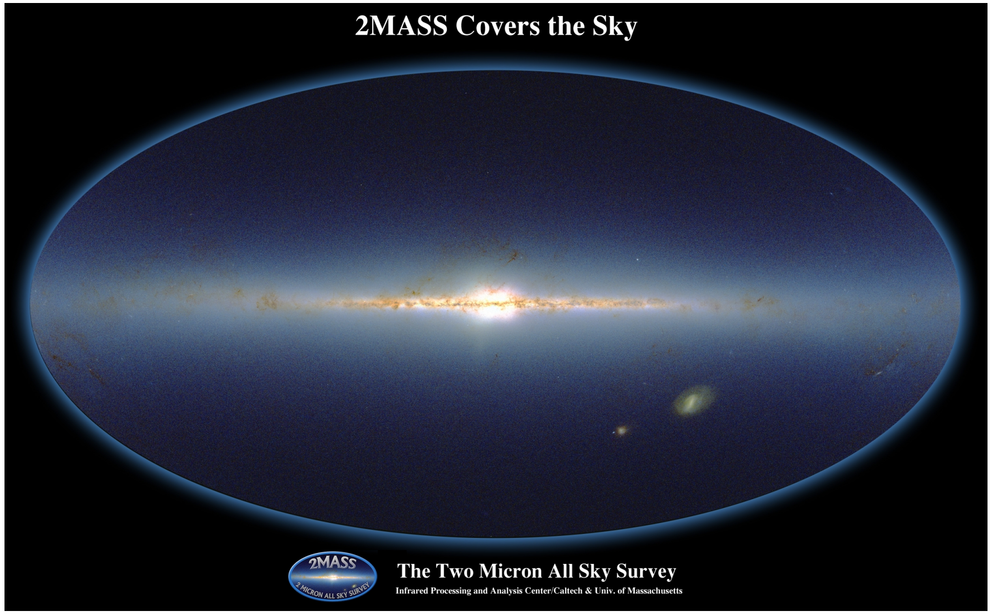
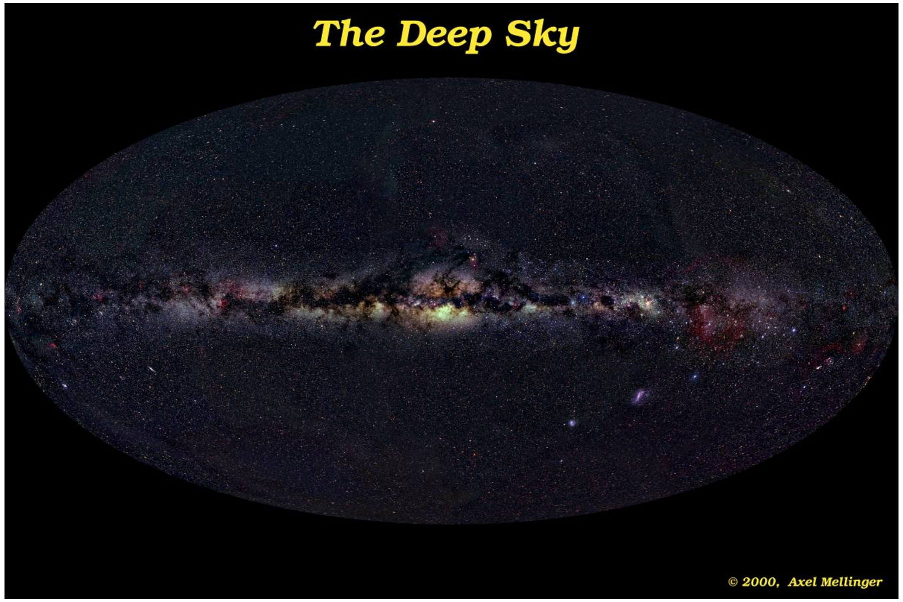
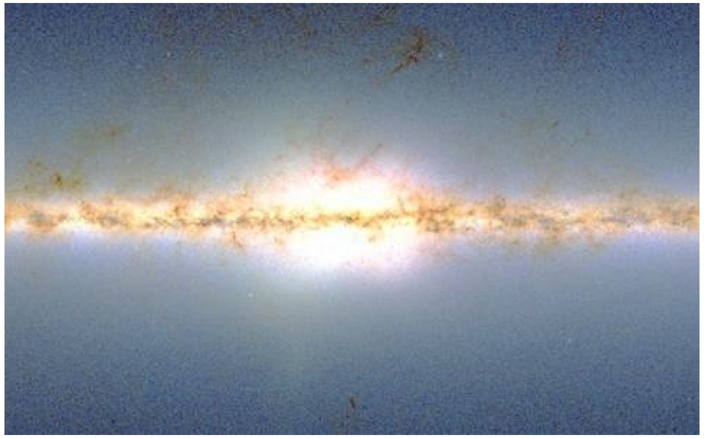


Infra red: Dust becomes transparent!

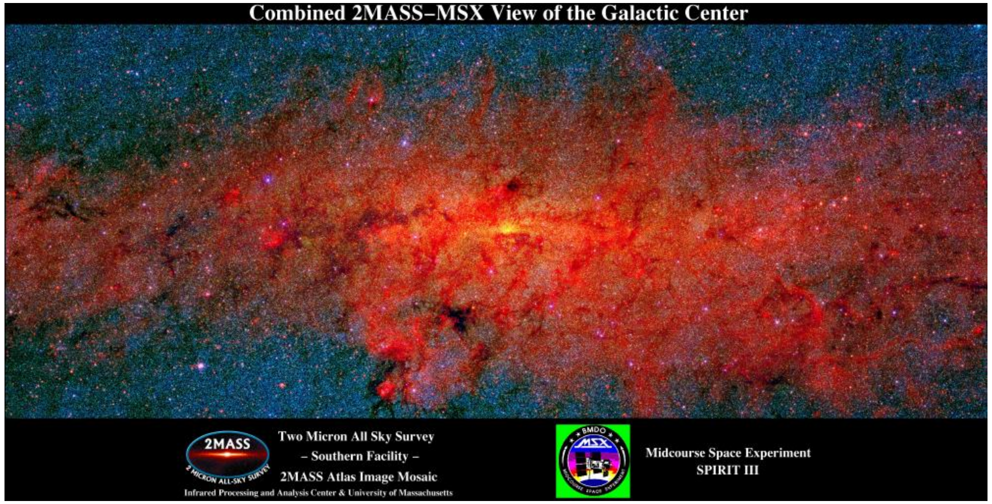
2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)



Problem: strong extinction due to dust
($A_V \sim 30$ mag: 10^{12} times reduction in the optical!)
$\Longrightarrow$ Multiwavelength astronomy!



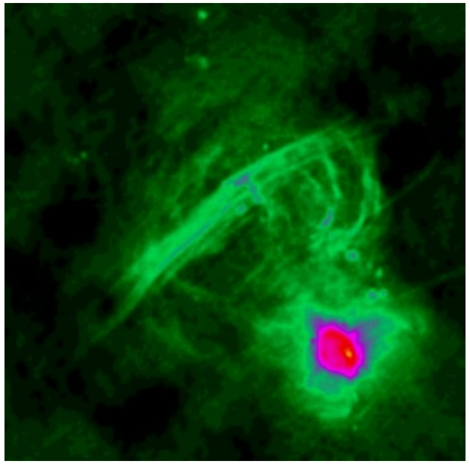
2MASS: inner $60^\circ \times 45^\circ$



2MASS/MSX: Inner 4° × 2°

2MASS (J [1.25 μm], red), (K [2.17 μm], green), MSX (A [6–11 μm], blue)

The Galactic nucleus



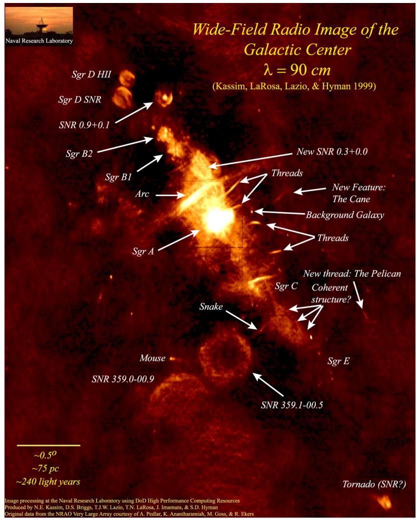
70 pc × 70 pc, VLA (F. Yusef-Zadeh et al., 1982–1984)
ⒸNRAO/AUI

Radio source Sgr A:
Sgr A (West) (Arc): broad radio filaments, part of a much larger Ω-shaped structure $\perp$ galactic plane.

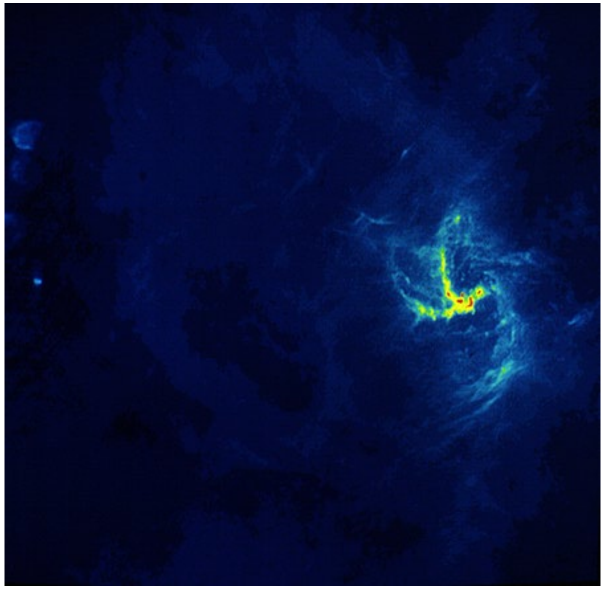
polarized, steep radio spectrum $\Longrightarrow$ synchrotron radiation (nonthermal electrons; $n_\mathrm{e}(E) \propto E^{-p}$)!
caused by shocks from supernovae?

central radio point source, unresolved: Sgr A*

The Galactic nucleus



- the stellar density rises towards a sharp central peak.
- Galactic gas disc has a central hole of 3 kpc radius
- dense nuclear gas disc (R=1.5 kpc) within the central gas hole
  - neutral hydrogen
  - mostly molecular clouds concentrated within central 300pc: 10^8 M$_\odot$ = 5% of the total Galactic molecular mass!
  - embedded in very hot gas (10^8K)
  - supernova remnants
- central 10pc are dominated by radio source Sgr A



Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West (“spiral”):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
northern arm falls on centre, east and south arms rotate.

The Inner Parsec: Central Cluster

Centre of Sgr A contains massive and dense cluster ($> 10^6\,M_\odot\,\mathrm{pc}^{-3}$, compare solar neighborhood: $0.1\,M_\odot\,\mathrm{pc}^{-3}$)

Spectroscopy: Stars are rich in Helium, early type (=massive), strong winds ($v_{\mathrm{Wind}} \sim 1000\,\mathrm{km\,s}^{-1}$).

The Inner Parsec: Central Cluster

Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7''$=0.2 pc)

The Inner Parsec: Central Cluster

Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7''$=0.2 pc)

. . . which can be corrected by adaptive optics

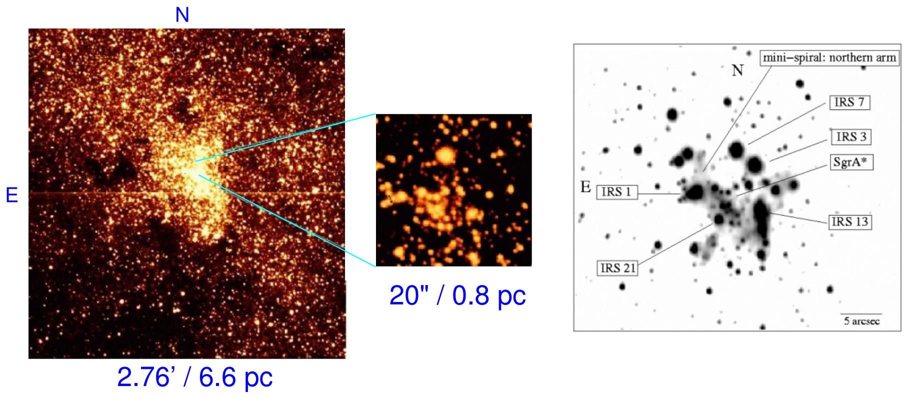
$\Longrightarrow$ resolution: diffraction limit!

$$\theta = 1.22\,\mathrm{rad} \cdot \lambda/d \sim 1\,\mathrm{mas}$$

(for $d = 8$ m, $\lambda = 2.2\,\mu$m)

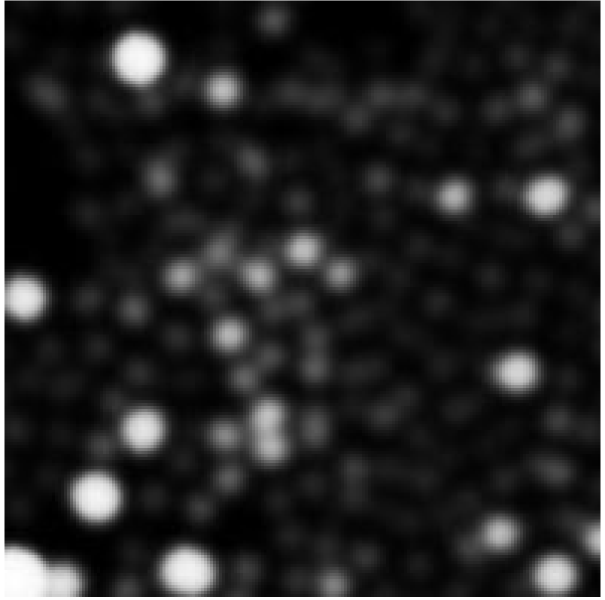
$\Longrightarrow$ 140 AU for gal. centre!

The Inner Parsec: Central Cluster



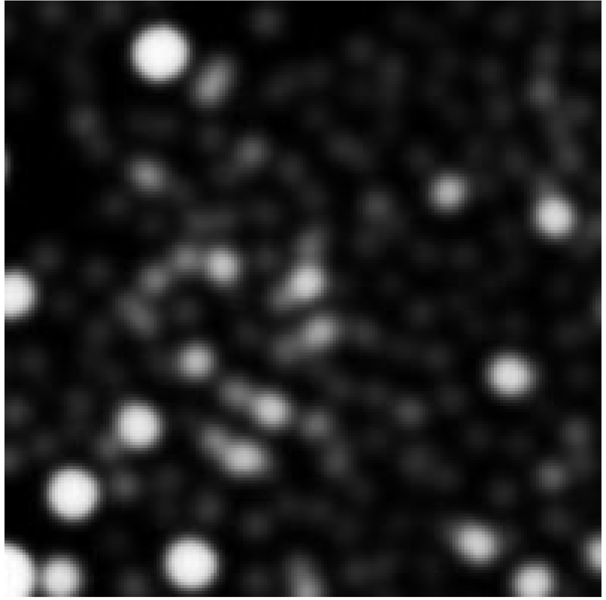
VLT ISAAC K-Band (2.2 μm) (Genzel/Eckart)

1994



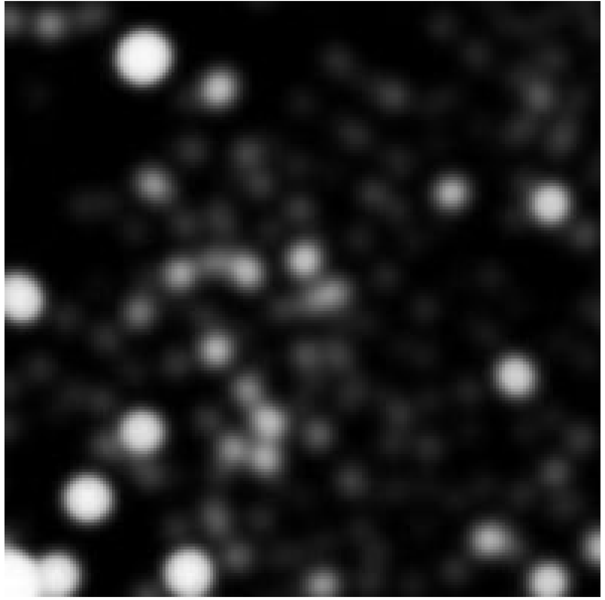
Genzel/Eckart

2000

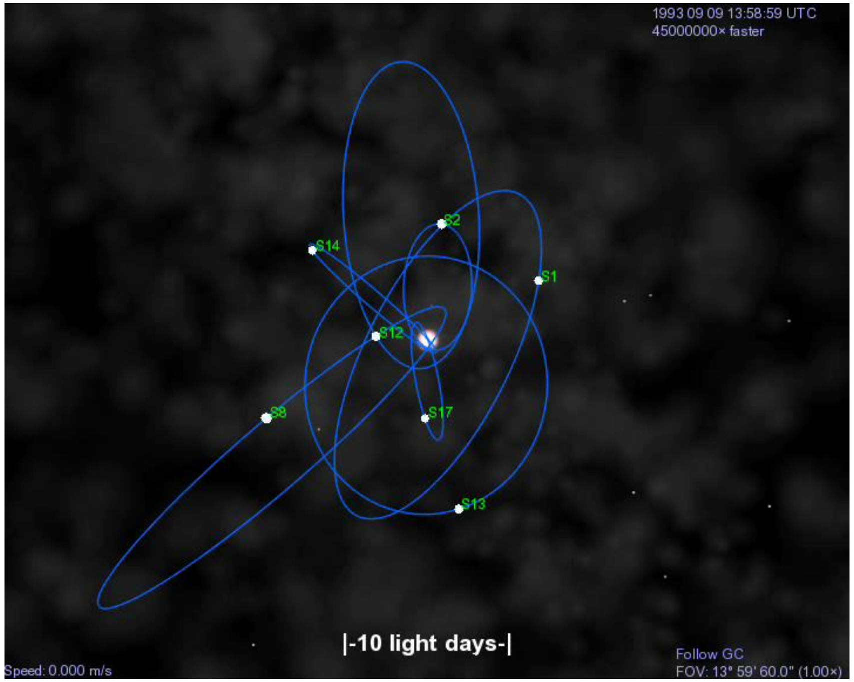


Genzel/Eckart

1996

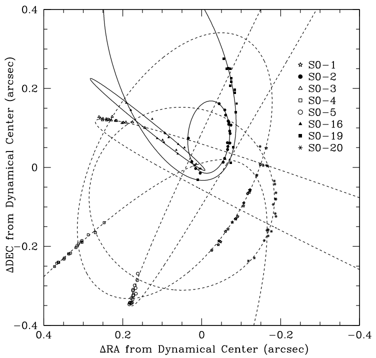


Genzel/Eckart

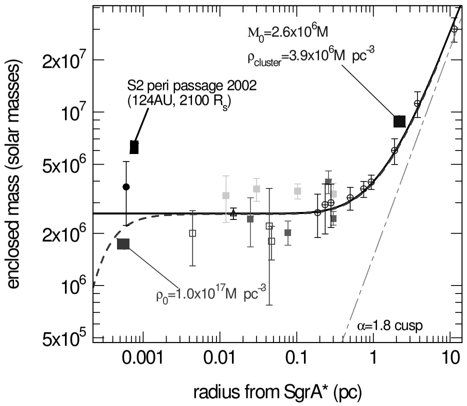


Movie time: movies/gcmovies/orbits3d.avi

The inner parsec: mass determination



Ghez et al. (2003)

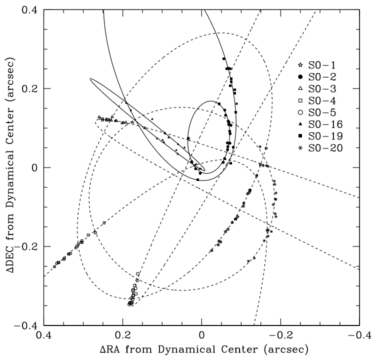


Schödel et al. (2002)

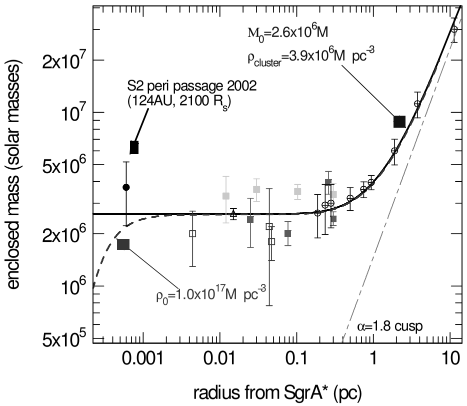
Mass determination: 3. Kepler

$$a = 5.5\,\text{light days} \qquad P = 15.2\,\text{years} \quad \Longrightarrow \quad \frac{P^2}{a^3} = \frac{4\pi^2}{G(m_* + M_{\text{BH}})}$$

The inner parsec: mass determination



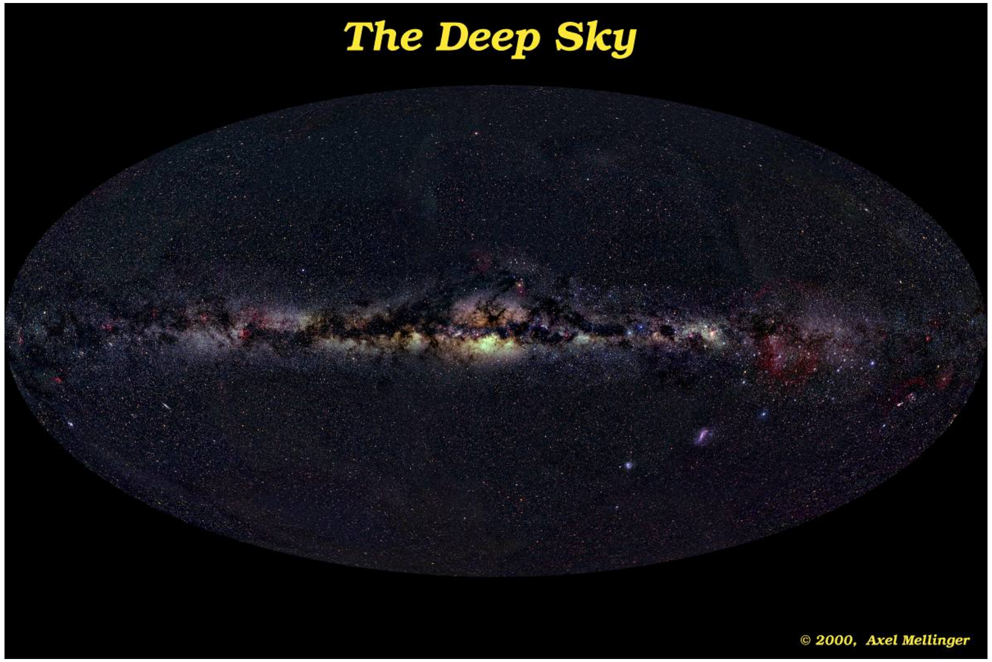
Ghez et al. (2003)



Schödel et al. (2002)

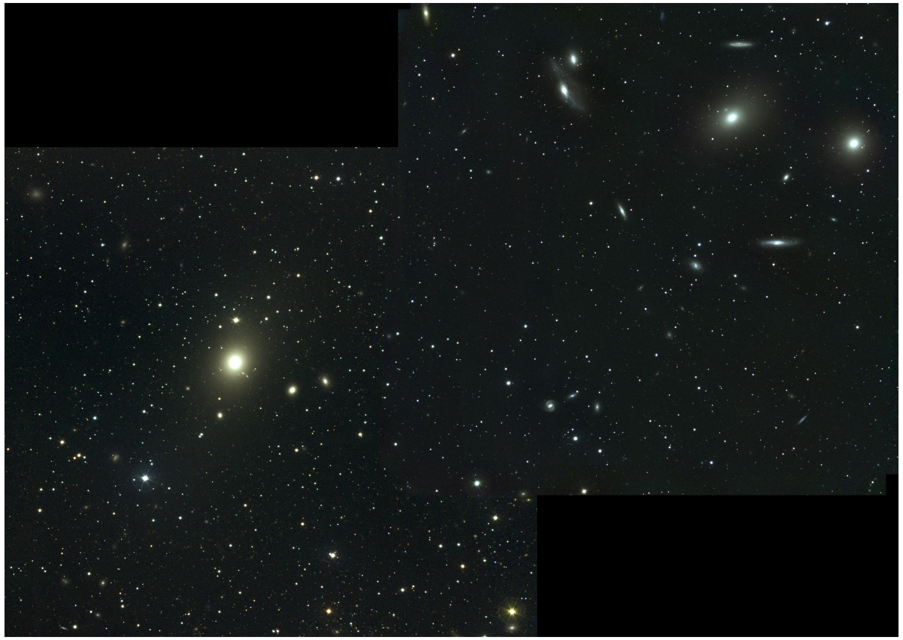
The center of the Galaxy harbors a black hole with $M_{\text{BH}} = (3.7 \pm 1.0) \times 10^6\,M_\odot$

Galaxies



Optical image of the whole sky

Andromeda galaxy (closest real neighbour galaxy, diam. 20kpc, distance: 675 kpc), NOAO/AURA/NSF

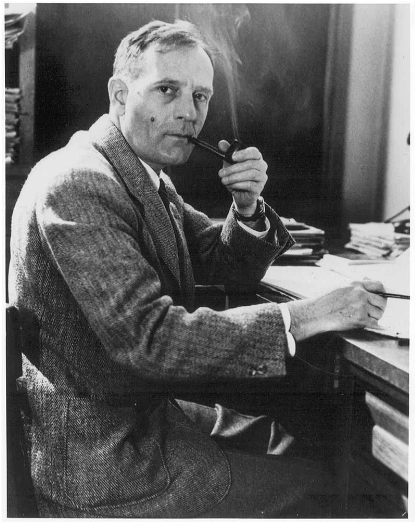


Virgo cluster, Burnell Schmidt telescope, NOAO/AURA/NSF

Deep looks in the universe: galaxies as building blocks

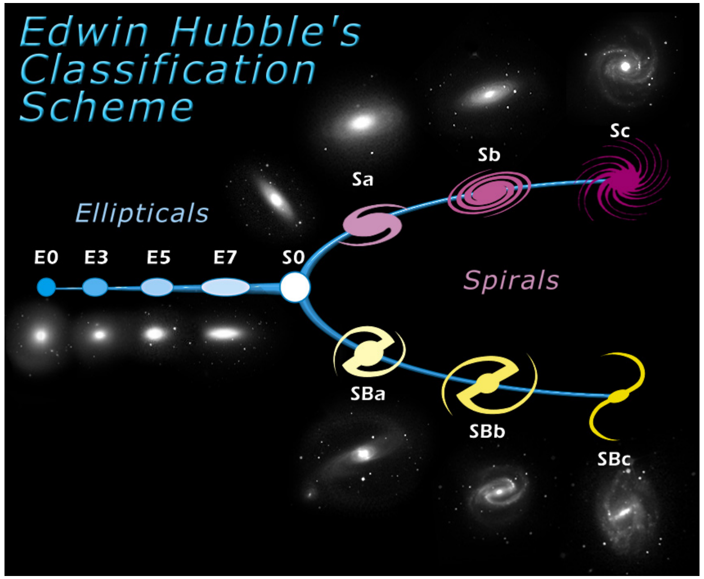
Deep image of Virgo cluster, 4 m Mayall telescope, NOAO/AURA/NSF

Galaxy Classification



1920s: Hubble and others: classification of galaxies

- Morphology: Appearance on photographs, photographic emulsion is blue sensitive
- *Warning:* scheme is in parts not so well defined, incomplete, and not unique
- Note: photometric (colors) and spectroscopic information are not part of the Hubble scheme.

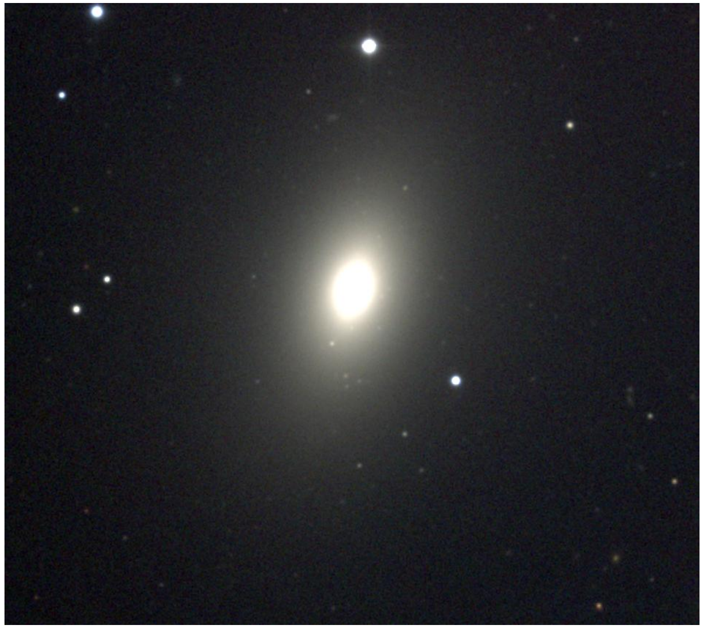


SDSS

Galaxy classification via the Hubble “tuning fork diagram”: “early types”: elliptical galaxies; “late types”: spiral galaxies, Not an evolutionary sequence!

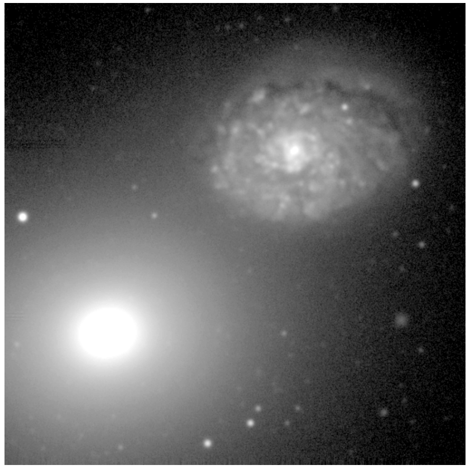
M49 (E4), NOAO/AURA/NSF

M87 (=Virgo A, note jet; E0), NOAO/AURA/NSF

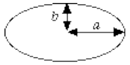


M59 (E5; color image), NOAO/AURA/NSF

Elliptical Galaxies



M60 (NGC 4649), E1, U. of Alabama

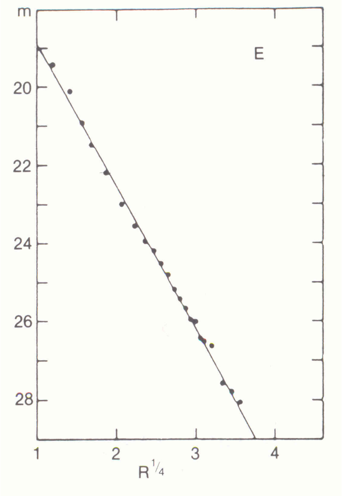


Elliptical galaxies: Classification as Ex where $x = 10(a-b)/a$ (integer part; between 0 and 7)

Ellipticals are low on dust and gas, reddish color (=old stars!), typically low luminosity and low mass ($10^6\,M_\odot$)

Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\,M_\odot$, designated cD.

Elliptical Galaxies

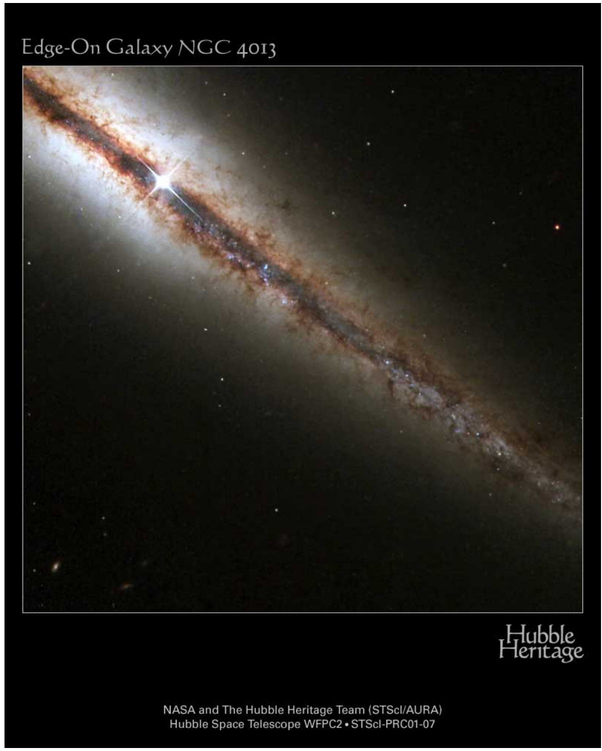


Radial brightness distribution in ellipticals is given by de Vaucouleurs' law:

$$\log\left(\frac{I(R)}{I_\mathrm{e}}\right) = -3.3307\left[\left(\frac{R}{R_\mathrm{e}}\right)^{1/4} - 1\right] \tag{18.1}$$

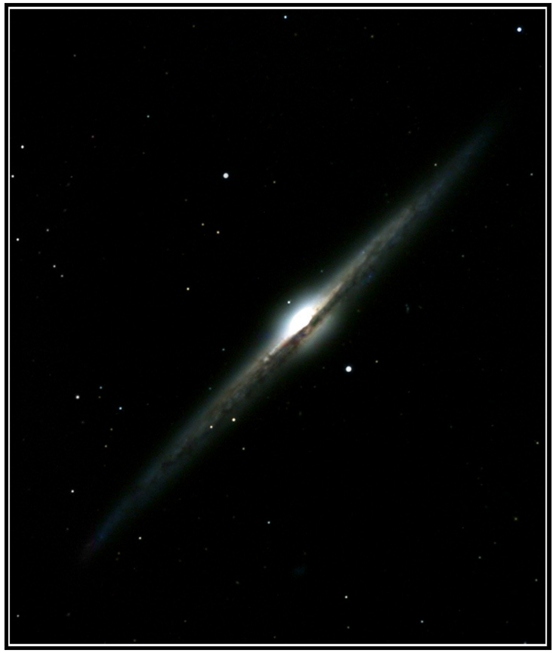
where

- $I(R)$: surface brightness, e.g., in $L_\odot\,\mathrm{pc}^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity



NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

edge on Spiral NGC 4013 (Sa; NASA/HST)



NGC 4565 (Sb, seen edge on), McLaughlin

M51 (Sc; center), HST/NASA

M51 (Sc, “Whirlpool galaxy”), NOAO/AURA/NSF, T. Rector

Spiral Galaxies

M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

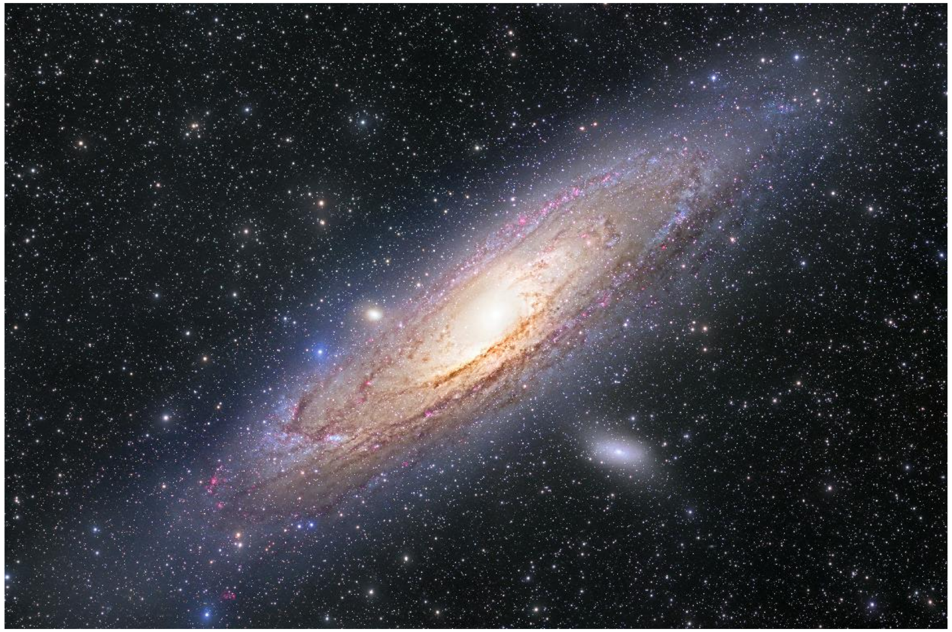
Spiral Galaxies: Elliptical nucleus (“bulge”) plus disk with spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10^\circ$, Sc: $\sim 20^\circ$) and dominance of nucleus.

Bluer than ellipticals.

Mass content $\sim 3 \times 10^{11}\,M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.



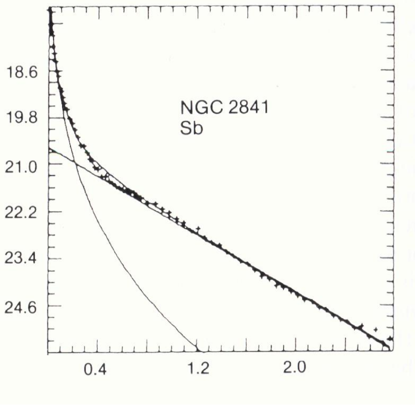
M31 (Sb; “Andromeda galaxy”),
`http://www.rosa-obs.com/images/ccd/M31C_karel_full.jpg`

M90 (Sb), NOAO/AURA/NSF

Spiral Galaxy NGC 300
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 18a/02 (7 August 2002)

Spiral Galaxies



Radial intensity profile:

Bulge: de Vaucouleurs’ law (same as ellipticals!):

$$\log\left(\frac{I(R)}{I_\mathrm{e}}\right) = -3.3307\left[\left(\frac{R}{R_\mathrm{e}}\right)^{1/4} - 1\right] \tag{18.2}$$

where

- $I(R)$: surface brightness, e.g., in $L_\odot\,\mathrm{pc}^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity

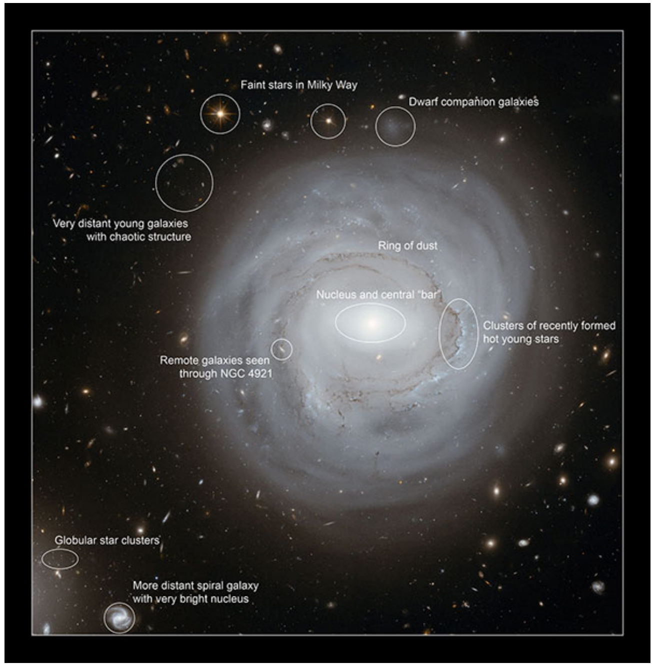
Disk: Exponential law:

$$I(R) = I_0 \exp -R/R_0 \tag{18.3}$$

where R_0: scale length (typical, e.g., thin disk of Milky Way: 3 kpc)

NGC 4921 (SBab; but note low star formation! HST/STScl)

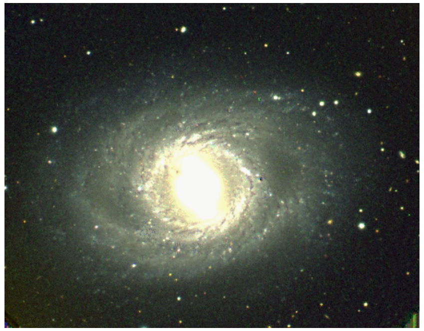
M58 (SBb), NOAO/AURA/NSF



NGC 4921 (SBab; but note low star formation! HST/STScl)

M83 (SBc, ESO)

Barred Galaxies



M95 (NGC 3351), SBb, INT

Barred Galaxies: Classification as SBa, SBb, SBc similar to Sx galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.

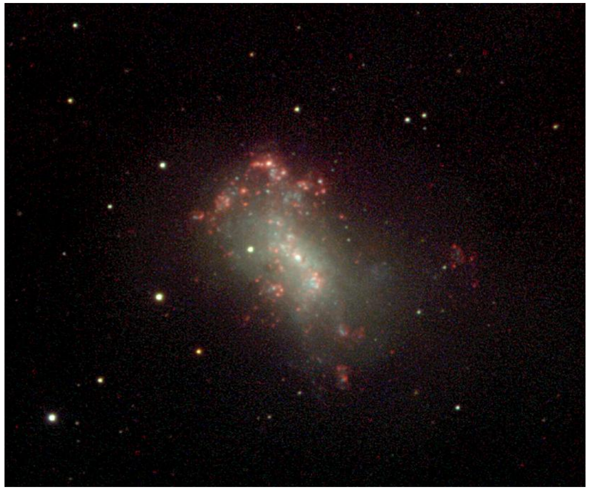
NGC 1365 (SBb, VLT/FORS/ANTU): note old “reddish” bar, young spiral arms

M86 (lenticular, S0), NOAO/AURA/NSF

S0 = eliptical galaxy + disk

S0 = spiral galaxy without spirals

Irregular Galaxies: Irr I

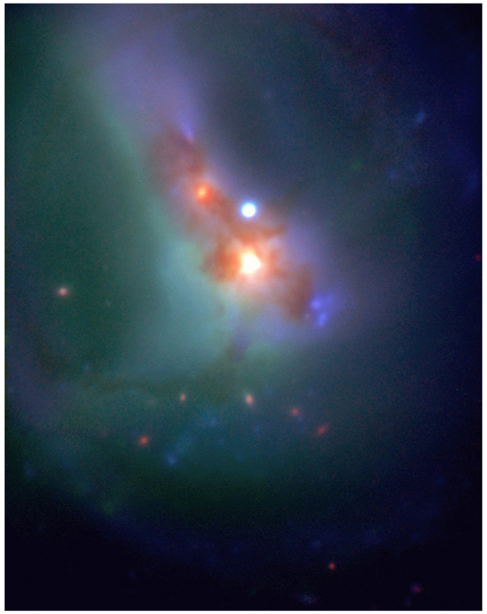


NGC 4449, Univ. Bonn

Irr I: no symmetry or spiral arms, bright knots of O- and B-type stars, very blue ($B-V\sim 0.5$), high dust content ($\sim$ 16%), $M/L\sim 3$, masses vary appreciably from 10^6 to $10^{10}\,M_\odot$.

Examples: SMC, LMC
$\Longrightarrow$ “Magellanic type irregulars”.

Large Magellanic Cloud (LMC; Irr I), Loke Kun Tan

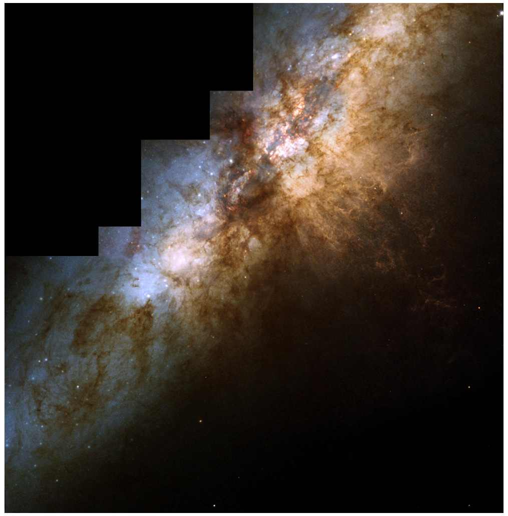


IR/Optical Colour Composite of
Center of Merging Galaxy System ESO202-G23 (VLT UT1 + ISAAC)
ESO PR Photo 46e/98 (26 November 1998)
©European Southern Observatory

ESO202-G23 (VLT UT1/ISAAC/ESO)

Large Magellanic Cloud (LMC; Irr I), AURA/NOAO/NSF

Irregular Galaxies: Irr II



M82, HST-WFPC

Irr II: asymmetrical and “abnormal”

$\Longrightarrow$ All objects that do not fit in the rest of the classification: starburst galaxies, interacting galaxies, Seyfert galaxies,. . .

NGC 6946, T. Rector/AURA/Gemini

I Zwicky 18, Y. Izotov/T. Thuan/HST

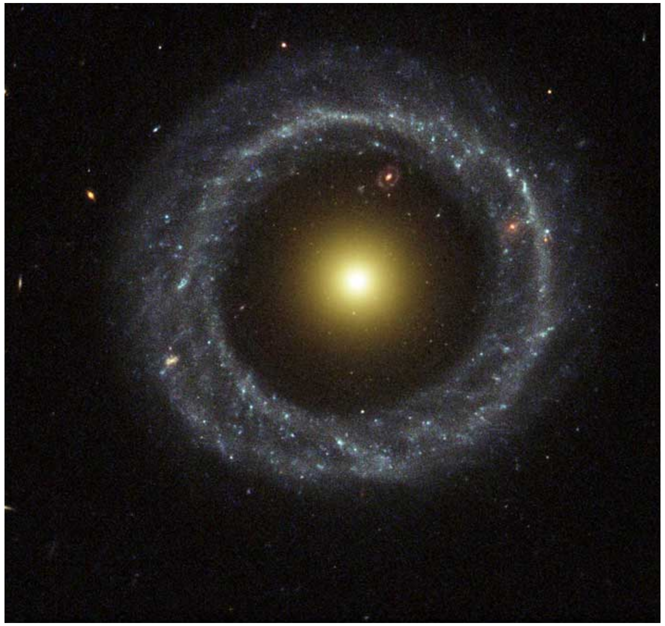
NGC 6946, T. Rector/AURA/Gemini

NGC 6946 is a SABc galaxy (note very small bar).

I Zwicky 18, Y. Izotov/T. Thuan/HST

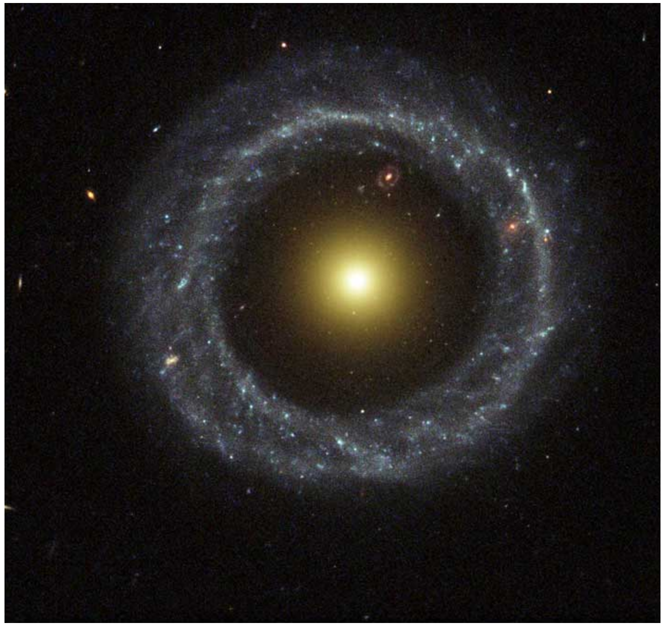
I Zw 18 is a irregular galaxy

(and one of the smallest galaxies known, merely 1.2 kpc across).



Hoag's Object, HST

NGC 1300, HST

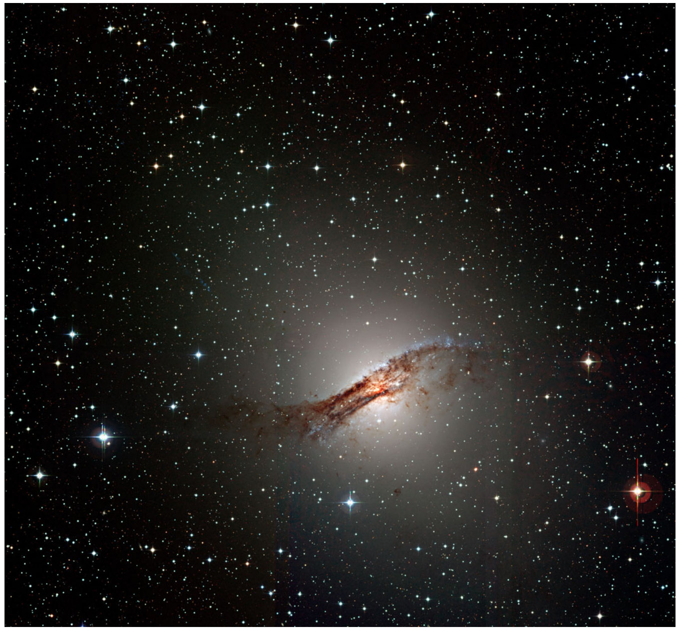


Hoag's Object, HST

Hoag's object an irregular galaxy

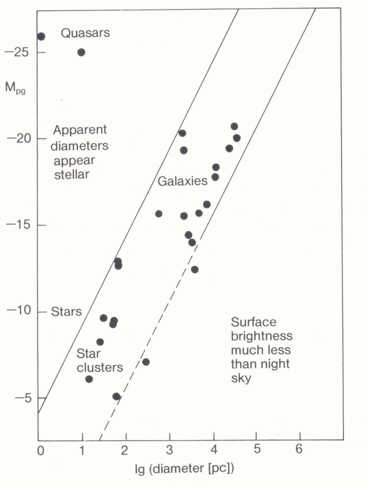
NGC 1300, HST

NGC 1300 is a SBbc galaxy



Cen A, ESO/WFI

Caveats: Selection Effects

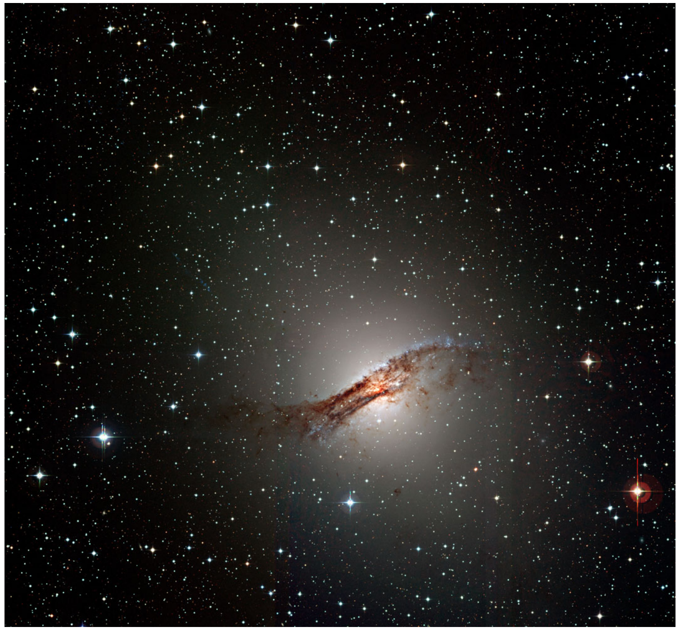


Karttunen

- diameter: edge of a galaxy is not well defined as intensity decreases strongly from center.

  Wide range of observed radii: 0.1 . . . 10 kpc (dwarf galaxies) to 30 kpc (normal spirals) and 50 kpc (ellipticals)
- Angular diameters depend on sky brightness

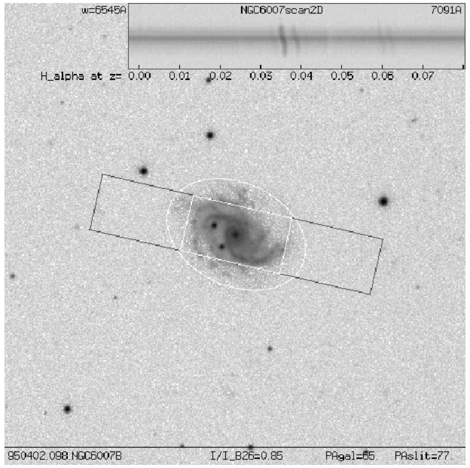
  Often used: D_{21} contour (= isophotal contour where galaxy becomes fainter than 21 mag arcsec^{-2})
- Small Galaxies can not be distinguished from stars
- Low surface brightness galaxies can not be seen against sky background.



Cen A, ESO/WFI

Cen A is a (peculiar) S0 galaxy

Spiral Galaxies



NGC 6007 (Jansen; `http://www.astro.rug.nl/~nfgs/`)

Spectra of galaxies: sum of all constituent spectra (mainly stars plus some contribution from nebulae).

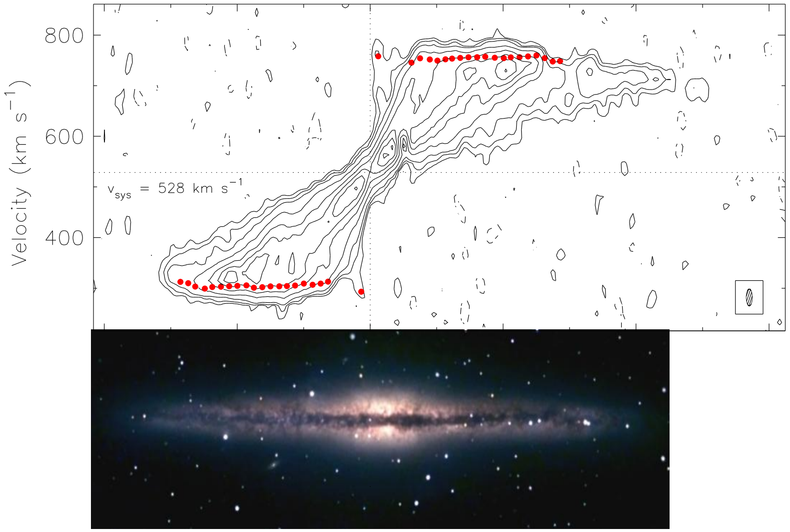
Absorption lines show clear shift $\Longrightarrow$ Doppler effect due to motion of stars around centre:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_\mathrm{r}}{c} = \frac{v}{c}\sin i$$

where v_r: radial velocity, i: inclination (angle measured with respect to plane of sky).

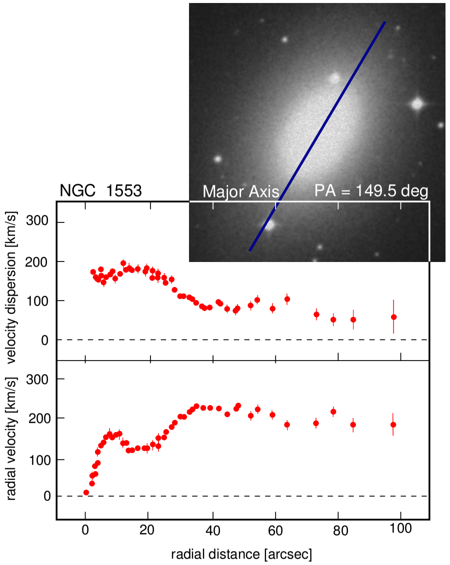
Typical rotation speeds are a few 100 km s^{-1}.

Spiral Galaxies



NGC 891 (Swaters et al., 1997, ApJ 491, 140 / Paul LeFevre, S&T Nov. 2002)

Spiral Galaxies



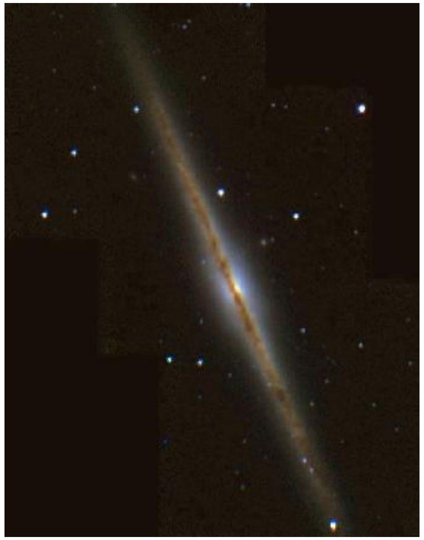
Spiral galaxy rotation curves are flat!

“Galaxy rotation problem”, first discovered by Vera Rubin (1970)

©Astron. Soc. Pacific

← NGC 1553 (S0) (after Kormendy, 1984, ApJ 286, 116)

Rotation Curves: Interpretation



Newtonian interpretation of galaxy rotation curves:

Motion because of mass within r:

$$\frac{GM(\leq r)}{r^2} = \frac{v_{\text{rot}}^2(r)}{r}$$

such that

$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

therefore:

$v \sim$ const. implies $M(\leq r) \propto r$.

This assumption is approximately true even for nonspherical mass distributions.

NGC 891, KPNO 1.3 m
Barentine & Esquerdo

Rotation Curves: Interpretation

What mass distribution do we expect?

Intensity profile of disk in spiral galaxies can be well described by

$$I(r) = I_0 \exp(-r/h)$$

where r: distance from centre, h: “scale length”.

Luminosity emitted within radial distance r_0:

$$L(r < r_0) = I_0 \int_0^{r_0} \exp(-r/h)\, 2\pi r\, \mathrm{d}r = 2\pi I_0 \left(h^2 - \exp(-r_0/h) h (h + r_0)\right)$$

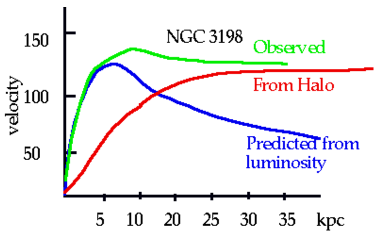
i.e., for $r_0 \longrightarrow \infty$: $L(r < r_0) \to$ const..

If all light comes from stars, i.e., light traces mass,

and the population of stars does not change with position

then $M/L \sim$ const., such that $M(< r) \sim$ const. outside a certain radius and $v \propto r^{-1/2} \Longrightarrow$ not what is observed!

Rotation Curves: Interpretation



Distribution of dark matter

- luminosity to mass ratio: $L/M = 4$ (solar neighbourhood)
- convert luminosity to mass
- compute expected rotation curve form the mass distribution $v_{\mathrm{lum}}(R)$
- distribution of dark matter: $M_{\mathrm{dark}}(R) = \frac{M}{G}[v^2(R) - v^2_{\mathrm{lum}}(R)]$

Canonical interpretation: a large fraction of gravitating material does not emit light $\Longrightarrow$ spiral galaxies have large and massive halos made of dark matter

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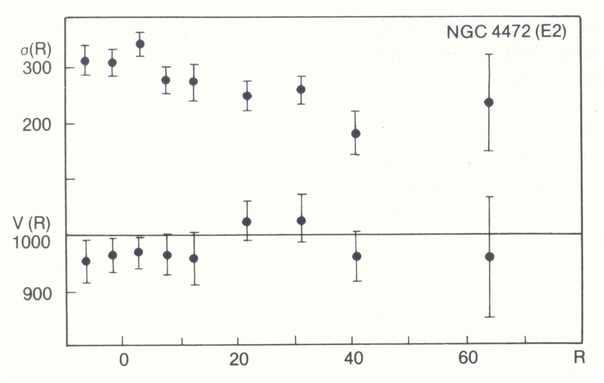
Elliptical Galaxies

What determines the shape of elliptical galaxies?



Karttunen

No rotation!

Large velocity dispersion

statistical motion of stars

correlation of the central velocity dispersion with absolute brightness

$L \sim \sigma_c^4$

(Faber-Jackson-relation)

Masses of Elliptical Galaxies

Ellipticals do not rotate. We can estimate their masses from the virial theorem assuming that the stars in ellipticals are in statistical equilibrium:

The virial theorem says that on average

$$\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2} \langle E_{\mathrm{pot}} \rangle \tag{18.4}$$

For an elliptical galaxy,

$$M_{\mathrm{G}} \langle v^2 \rangle = G \int_0^{R_{\mathrm{G}}} \frac{M(R) dM(R)}{R} = a \frac{G M_{\mathrm{G}}^2}{R_{\mathrm{G}}} \tag{18.5}$$

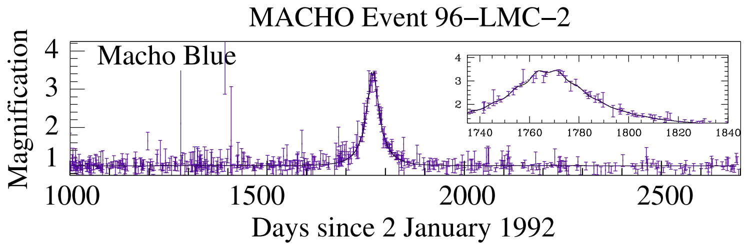
where for a homogeneous sphere $a = 3/5$. Therefore

$$\langle v^2 \rangle = \sigma^2 = a \frac{G M_{\mathrm{G}}}{R_{\mathrm{G}}} \tag{18.6}$$

Measurements show that also for ellipticals the kinematical mass is significantly larger than the mass of luminous matter.

Dark Matter is present also in Elliptical Galaxies

Dark Matter: MACHOS



after Alcock et al. (2001, Fig. 2)

MACHOS (Massive Compact Halo Objects): White dwarfs in the galaxy's halo

Pro:

1. very low luminosity objects $\Longrightarrow$ *very* difficult to detect
2. detected by microlensing towards SMC and LMC (see figure) $\Longrightarrow$ MW halo consists of 50% white dwarfs

Contra:

1. possible "self-lensing" (by stars in MW or SMC/LMC; confirmed for a few cases)
2. inferred white dwarf formation rate too high (100 $\mathrm{year}^{-1}\,\mathrm{Mpc}^{-3}$ instead of <1 as previously assumed)

Dark Matter: Nonbaryonic

Nonbaryonic dark matter:

Requirements:

- gravitating
- no or very weak other interaction with baryons (=“us”)

$\Longrightarrow$ Grab-box of elementary particle physics:

1. Neutrinos with non-zero mass

   Pro: It exists, mass limits are a few eV, need only $\langle m_\nu c^2\rangle \sim 10\,\mathrm{eV}$

   Contra: ν are relativistic ($v \sim c$), this has implications for galaxy formation that make it unlikely that they form a major part of dark matter.

2. Axions ($mc^2 \sim 10^{-5\ldots-2}\,\mathrm{eV}$) and WIMPs (weakly interacting massive particles; masses $mc^2 \sim \mathrm{GeV}$)

   Pro: help with cosmology as well

   Contra: We do not know they exist. . . (but they might soon be detectable)

$\Longrightarrow$ Jury is still out, question on origin of flat rotation curves is still open.

MOND

Modified Newtonian Dynamics (Milgrom, 1983ff.; MOND): Alternative to Dark Matter

Reviews: Sanders & McGaugh, 2002, Ann. Rev. Astron. Astrophys. 40, 263; Milgrom, 2001, astro-ph/0112069

Idea: Modify Newton’s Laws:

Acceleration on particle in gravitational field:

$$a = \frac{GM}{r^2} \cdot \frac{1}{\mu(a/a_0)} \quad \text{with} \quad \mu(x) \longrightarrow \begin{cases} 1 & \text{for } x \to \infty \\ x & \text{for } x \to 0 \end{cases}$$

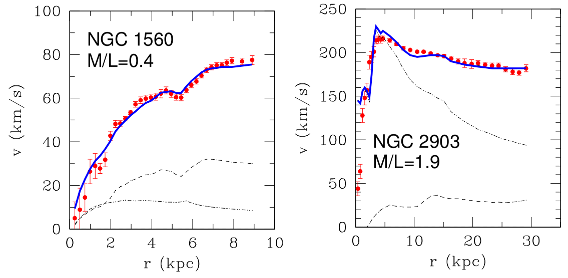
i.e., for accelerations $a \ll a_0$, $a \longrightarrow \sqrt{GMa_0/r^2}$, giving circular motion in the limit of small accelerations:

$$\sqrt{\frac{GM(\le r)a_0}{r^2}} = \frac{v^2}{r} \quad \Longrightarrow \quad M(\le r) = \frac{v^4}{Ga_0}$$

and therefore independent of r!

MOND can explain the flat rotational curves (by construction!).

MOND



after Sanders & McGaugh (2002)

Fits of rotational curves give

$$a_0 = 1.2\times10^{-8}\,\mathrm{cm\,s^{-2}}$$

and $M/L \sim 1$, so not bad!

BUT:

- where is the physics behind a_0?
- violation of the strong equivalence principle

  (“outcome of any physical experiment is independent of where and when in the universe it is performed, and it is independent on whether the experimental apparatus is free falling or stationary”)

$\Longrightarrow$ At the moment MOND does not seem to be a viable alternative to other theories of dark matter.

. . . but it shows that even today people are not afraid to attack Newton’s laws, and this is good for progress of physics as a whole

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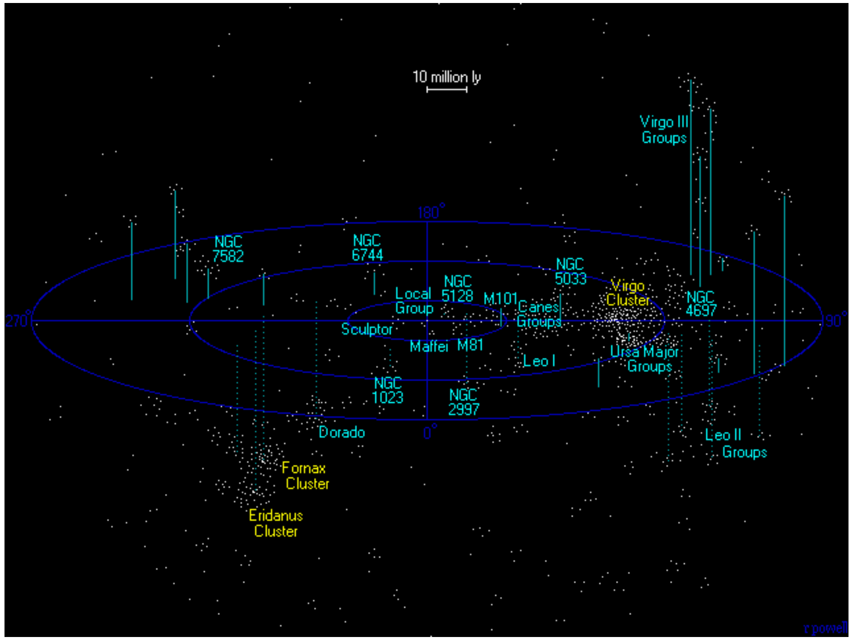
Clusters of Galaxies



The universe out to the Virgo Cluster
source: `http://www.atlasoftheuniverse.com`

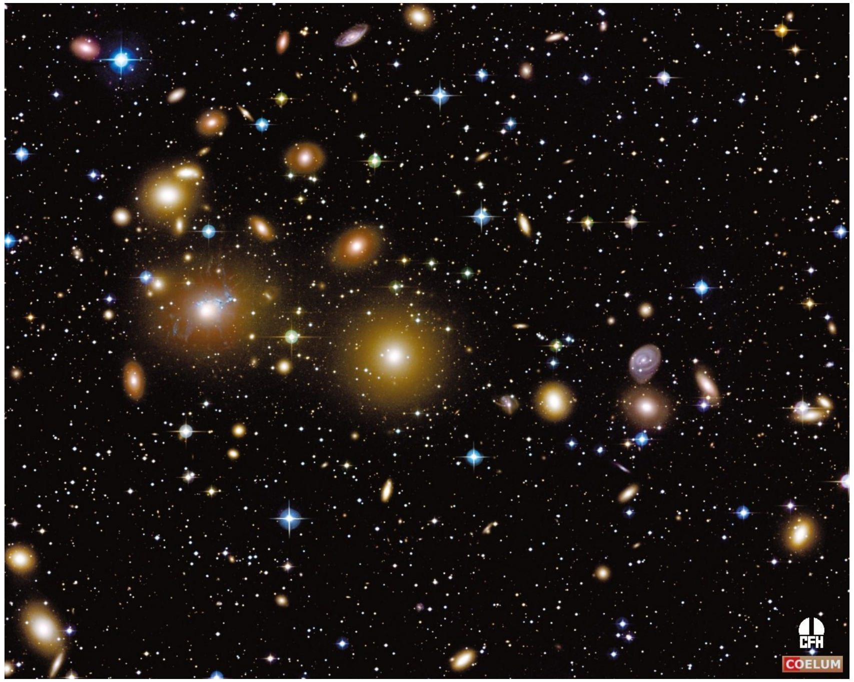
Coma cluster of galaxies (Misti/APOD)

Clusters of Galaxies: largest gravitationally bound structures in the universe.

Typical numbers: up to a few 1000 galaxies, masses: 10^{14} to $10^{15}\,M_\odot$

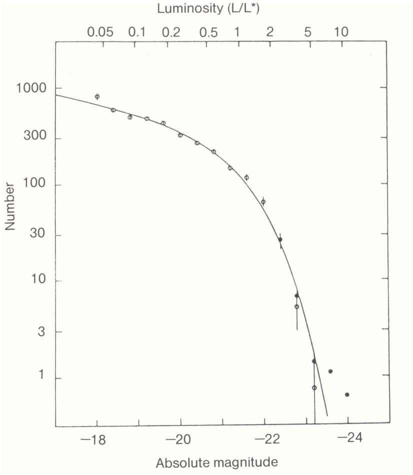
Densest clusters: visually found, “Abell clusters”

Groups of galaxies: few MPc, few 10s of galaxies



Perseus Cluster: 660 gal in field, number of spirals increases outwards

Luminosity Function



“Schechter Function” of 13 clusters (Karttunen)

Analysis of clusters finds that galaxies have wide distribution of absolute magnitudes

Generally described in terms of the luminosity function, $\Phi(L)$, where $\Phi(L)dL$ = number of galaxies per unit volume in luminosity bin $[L, L + dL]$, can be described by the Schechter function:

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*}\right)^\alpha \exp\left(-\frac{L}{L^*}\right)\frac{dL}{L} \quad (19.1)$$

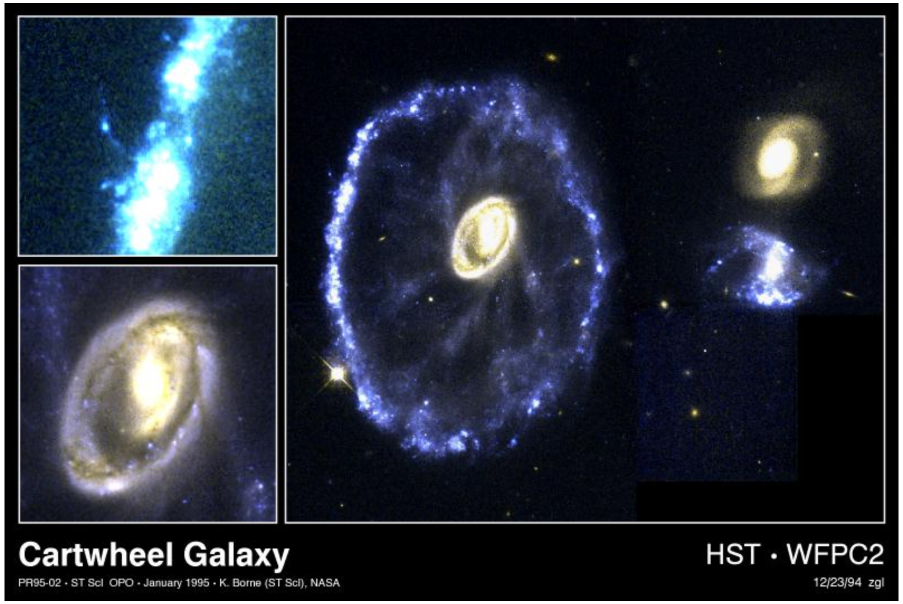
where typically $\Phi^* \sim 4 \times 10^{-2}\,\mathrm{Mpc}^{-3}$, $\alpha \sim -1$ and where L^* is a characteristic luminosity (in magnitudes, $M^* \sim -20$ mag)

Masses of Clusters of Galaxies

Fritz Zwicky

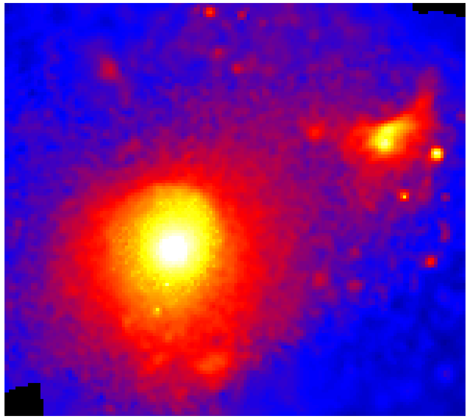
- Virial masses (as for elliptical galaxies)
- Zwicky (1933): Coma cluster: $\sigma \sim 1000\,\mathrm{km\,s^{-1}}$
- virial mass 10 times larger than luminous mass
- Dark Matter halo
- Masses of clusters of galaxies: $10^{12} \dots 10^{15} M_\odot$
- Masses of stars: 5% of the cluster mass

Dark Matter also in clusters of Galaxies



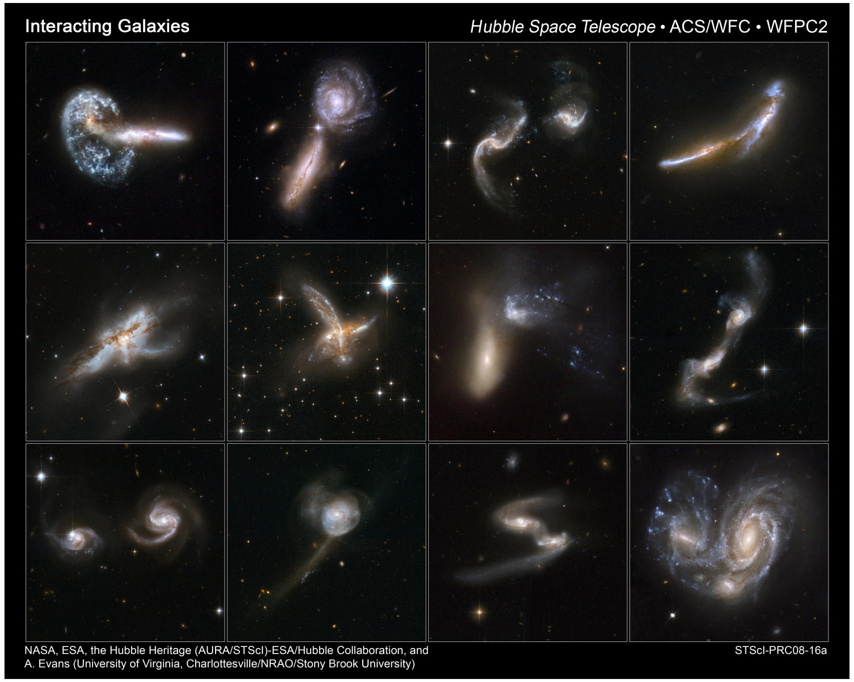
colliding galaxies: Cartwheel Galaxy (HST)

Hot X-ray gas in clusters of Galaxies



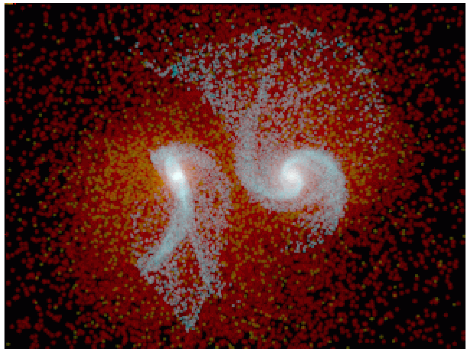
Virgo cluster in X-ray light (ROSAT)

- Diffuse intra cluster X-rays detected
- Temperatures: 10...100 Million K
- Mass: 10% of total mass of galaxy cluster
- Dark Matter required to keep X-ray intracluster gas bound to the cluster



Interacting Galaxies (HST)

Interacting Galaxies

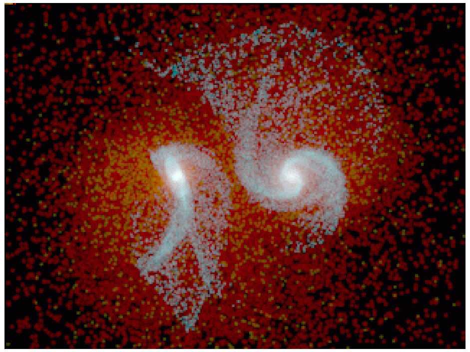


Numerical Merger Experiments

- two identical spiral galaxies
- bulge : disc : halo = 1 : 3 : 16
- gas: 10% of disc mass
- exponential scale length: 3.3 kpc
- rotation curve as in Milky Way
- parabolic orbit
- closest encounter: 8.8 kpc after 250 Myrs

`http://ifa.hawaii.edu/~barnes/transform.html`

Interacting Galaxies



Numerical Merger Experiments: Results

- gas collapses into the central 100pc of the merger
- tidal arms form; bridges between galaxies
- morphology of peculiar galaxies (e.g. The Mice) can be explained by two merging disc galaxies

Elliptical galaxy results from a merger of two disc galaxies

`http://ifa.hawaii.edu/~barnes/transform.html`

The Astronomical Distance Ladder

Introduction

Distances are required to determine properties such as the luminosity or the size of an astronomical object.

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Most other methods based on “standard candles”, i.e., use known absolute magnitude of an object to derive distance via distance modulus.

2. Main Sequence Fitting
3. Variable stars: RR Lyrae and Cepheids
4. Type Ia Supernovae
5. Tully-Fisher for spiral galaxies
6. D_n-σ for ellipticals
7. Brightest Cluster Galaxies

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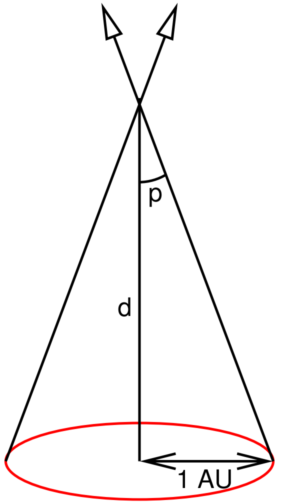
Methods are calibrated using distances from the previous step of the distance ladder.

Trigonometric Parallax



Motion of Earth around Sun $\Longrightarrow$ Parallax

Produces apparent motion of star; projected on sky see angular motion, opening angle

$$\tan p \sim p = \frac{r_{\text{Earth}}}{d} = \frac{1\,\text{AU}}{d}$$

p is called the trigonometric parallax.

Note: requires several at several positions of the Earth

Measurement difficult: $\pi \lesssim 0.76''$ (α Cen).

Define unit for distance:

Parsec: Distance where 1 AU has $p = 1''$.

$$\boxed{1\,\text{pc} = 206265\,\text{AU} = 3.086 \times 10^{16}\,\text{m} = 3.26\,\text{ly}}$$

Trigonometric Parallax

Best measurements to date: Hipparcos satellite (1989–1993)

- systematic error of position: ~0.1 mas
- effective distance limit: 1 kpc
- standard error of proper motion: ~1 mas/yr
- photometry
- magnitude limit: 12
- complete to mag: 7.3–9.0

Results available at `http://astro.estec.esa.nl/Hipparcos/`:

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

Tycho catalogue: 10^6 stars with 20–30 mas precision, two-band photometry

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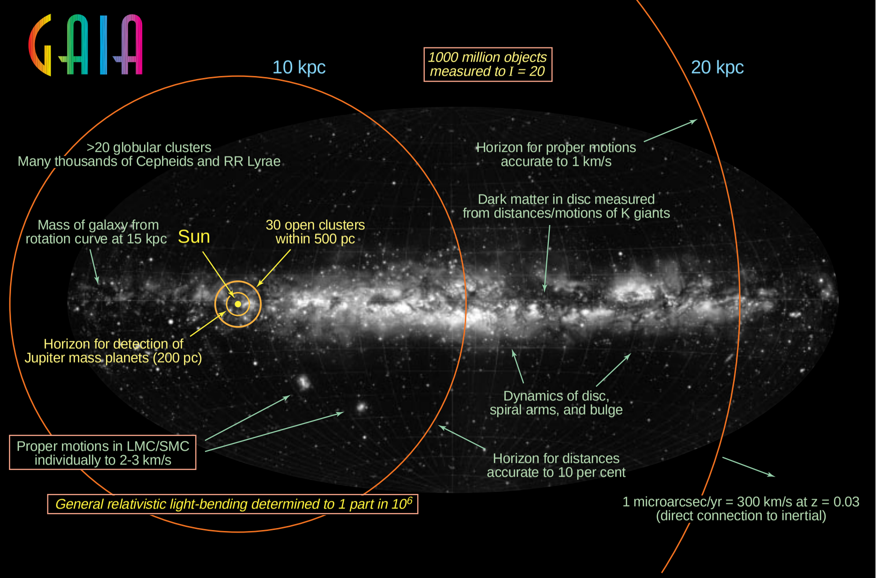
Plans for the future: (ESA mission, launch ~ End 2012):



GAIA: ~ 4μarcsec precision, 4 color to $V = 20$ mag, 10^9 objects.

Standard Candles

Assuming isotropic emission, the flux measured at distance d from object with luminosity L is given by the "inverse square law",

$$f(d) = \frac{L}{4\pi d^2}$$

note that f is a function of the d.

Remember that the magnitude is defined through comparing two fluxes,

$$m_2 - m_1 = 2.5 \log_{10}(f_1/f_2) = -2.5 \log_{10}(f_2/f_1)$$

To allow the comparison of sources at different distances, define

$$\boxed{\text{absolute magnitude } M = \text{magnitude if star were at distance } 10\,\text{pc}}$$

Because of this

$$M - m = -2.5 \log_{10}\left(f(10\,\text{pc})/f(d)\right) = -2.5 \log_{10}\left(\frac{L/(4\pi(10\,\text{pc})^2)}{L/(4\pi d^2)}\right) = -2.5 \log_{10}\left(\frac{d}{10\,\text{pc}}\right)^2$$

The difference $m - M$ is called the distance modulus,

$$m - M = 5 \log_{10}\left(\frac{d}{10\,\text{pc}}\right)$$

Standard Candles

To obtain distance, use standard candles

Standard candles are defined to be objects for which their absolute magnitude is known.

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- physics of standard candle well understood (i.e., need to know *why* object has certain luminosity).
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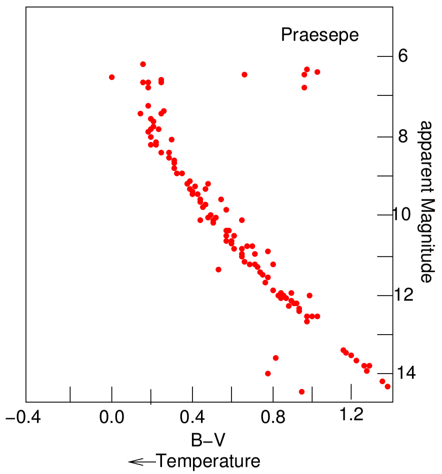
To determine distance to astronomical object:

1. find standard candle(s) in object,
2. measure their m
3. determine $m - M$ from known M of standard candle
4. compute distance d

Often, distances are given in terms of $m - M$, and not in pc, so last step is not always performed.

Main Sequence Fitting



MS fitting applied to Praesepe
(after VandenBerg & Bridges 1984)

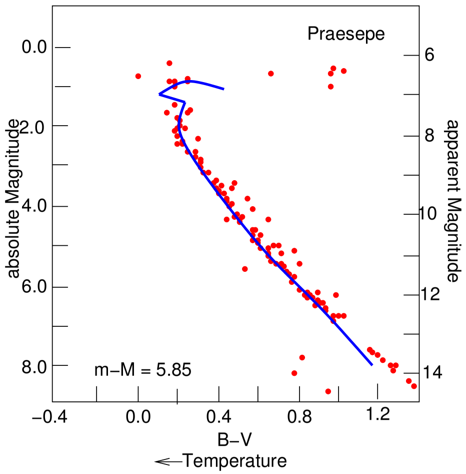
Clusters: if Main Sequence in Hertzsprung Russell Diagram determinable:

Shift observed HRD until main sequence agrees with location of MS measured for stars in solar vicinity $\Longrightarrow$ distance modulus.

Currently: distances to ∼200 open clusters known

Distance limit ∼7 kpc.

Main Sequence Fitting



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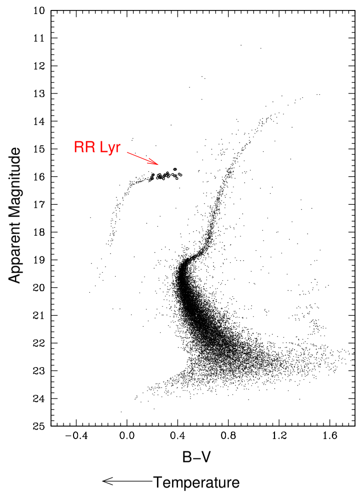
RR Lyrae



HRD of Globular Cluster M2
(after Lee et al., 1999, Fig. 2)

RR Lyrae variables:

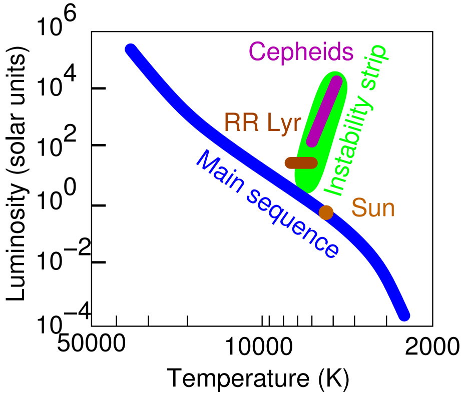
- Variability ($P \sim 0.2 \ldots 1$ d)
- Mainly temperature change
- RR Lyr gap clearly observable in globular cluster HRD

Absolute magnitude of RR Lyr gap: $M_\mathrm{V} = 0.6$ mag, $M_\mathrm{B} = 0.8$ mag, i.e., $L_\mathrm{RR} \sim 50\,L_\odot$.

Works out to LMC ($d \sim 50$ kpc) and other dwarf galaxies of local group, mainly used for globular clusters and local group.

Example: M5: gap at $m = 16$ mag $\Longrightarrow m - M = 15.4$ mag $\Longrightarrow d = 12$ kpc.

Introduction



Instability strip in the Hertzsprung-Russell Diagram

Certain regions of HRD: stars prone to instability:

Ionization of Helium: transparency of outer parts of star changes

$\Longrightarrow$ size of star changes

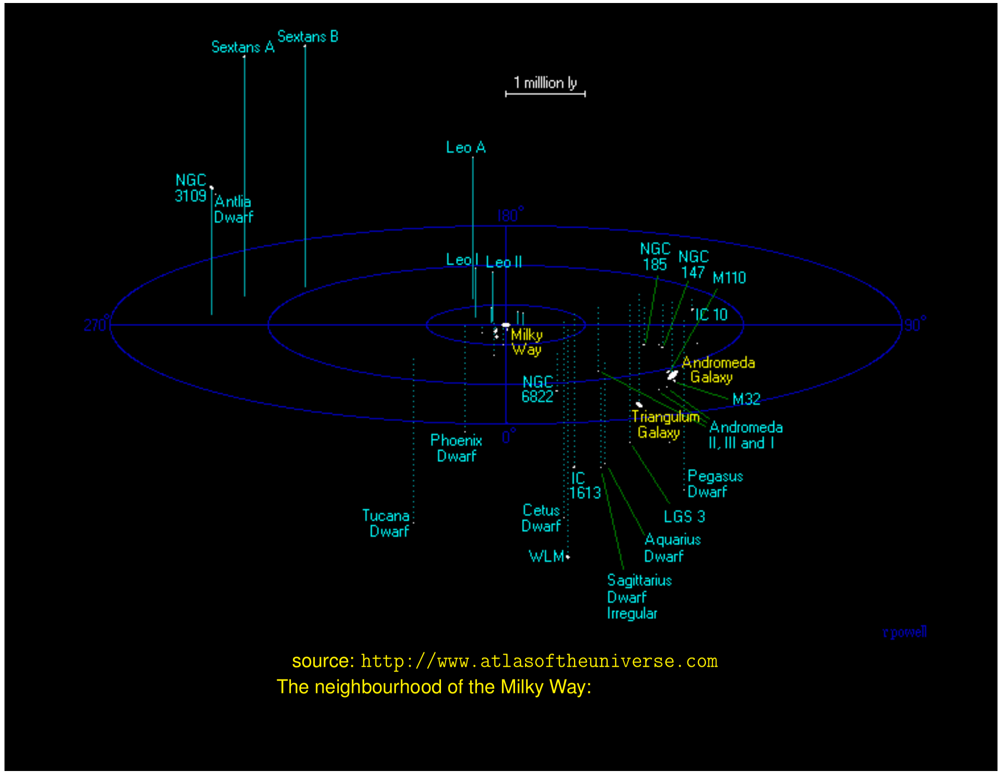
$\Longrightarrow$ surface temperature and luminosity variations

Most important variables of this kind:

1. RR Lyr variables

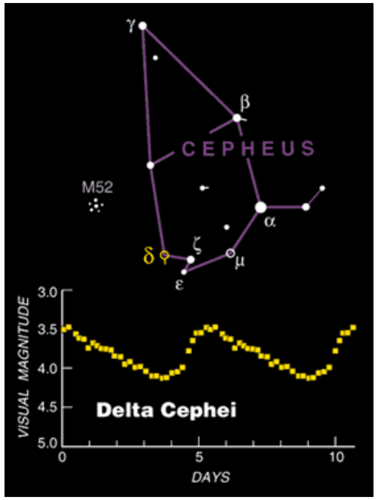
   mainly in globular clusters: lower metallicity of clusters (“population II”) allows stars to enter instability strip

2. δ Cepheids



source: `http://www.atlasoftheuniverse.com`
The neighbourhood of the Milky Way:

Cepheids



John Goodricke (1764–1786):

- deaf after scarlet fever at the age of five
- special education at Edinburgh
- at the age of 13 academy near York
- 1781: worked with Edward Pigott as astronomer
- 1782: discovery of Algol as eclipsing binary
- 1784: discovery of δ Cep

Cepheids

© ASP

Henrietta Leavitt (1868–1921):

- Graduated from Radcliffe College
- from 1895: volunteer at Harvard Observatory
- was ill and partially deaf from that
- 1902: back at Harvard Obs
- discovered 1777 variable stars in LMC
- 1912: discovered Period-Luminosity relation of Cepheids in SMC, but was not allowed (!) to follow this up
- later: defined Harvard photographic magnitude system
- died of cancer in 1921

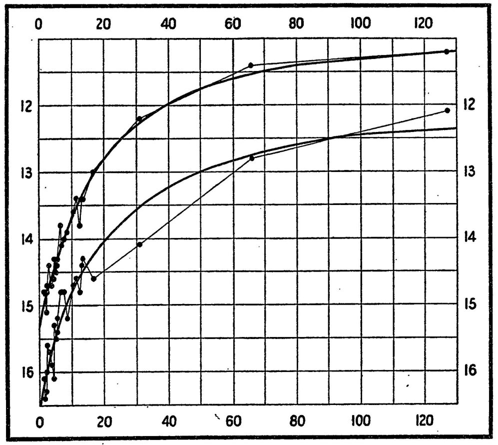


Fig. 1.

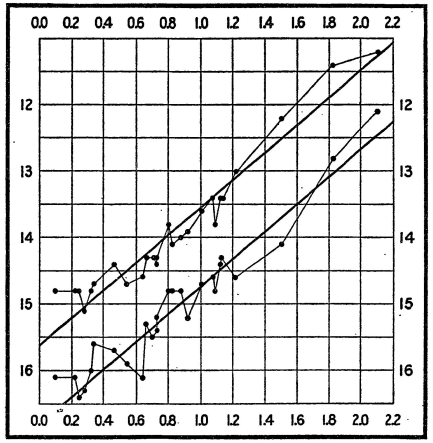
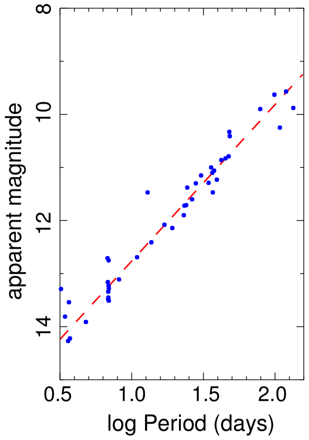


Fig. 2.

X-axis: period in days, Y-axis: magnitude

Leavitt & Pickering, 1912, Periods of 25 Variable Stars in the Small Magellanic Cloud, Harvard College Observatory Circular, vol. 173, pp. 1–3

Cepheids



Period-Luminosity relation for the LMC Cepheids

after Mould et al. (2000, Fig. 2)

Henrietta Leavitt(1912):

Cepheids have a period luminosity relationship: $M \propto -\log P$

Low luminosity Cepheids have lower period

Observations find:

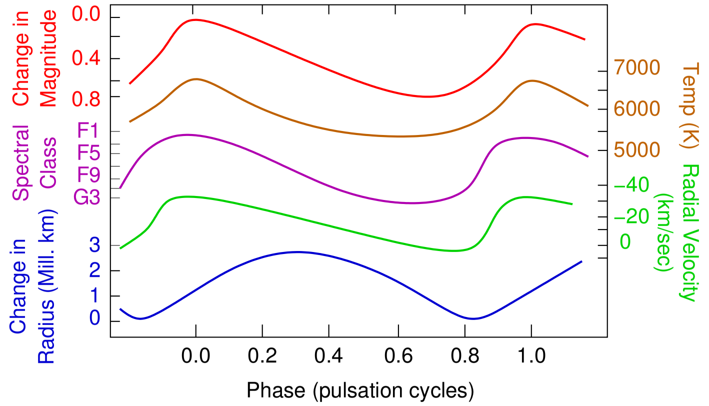
$$\langle M\rangle = -2.76\log P - 1.40$$

(P in days)

Calibrated from observing Large Magellanic Cloud Cepheids (see figure), and determining LMC distance from other means (MS fitting, RR Lyr,...) to find absolute magnitudes...

With HST: works out to Virgo cluster ($d = 18.5$ Mpc).

Cepheids

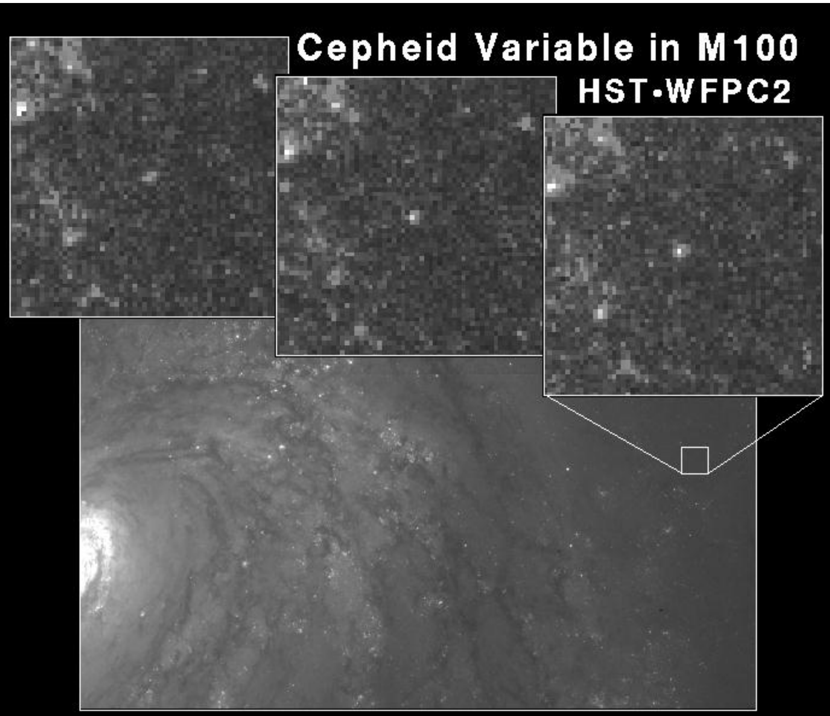


after `http://csep10.phys.utk.edu/astr162/lect/index.html`

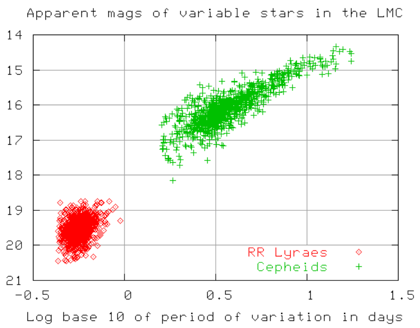
Cepheids: Luminous stars ($L \sim 1000\,L_\odot$) in instability strip with large luminosity amplitude variation, $P \sim 2\ldots150\,\mathrm{d}$ (easily measurable).

Cepheid Variable in M100

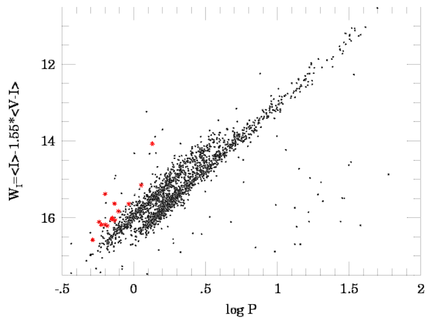
HST•WFPC2



The distance to the LMC



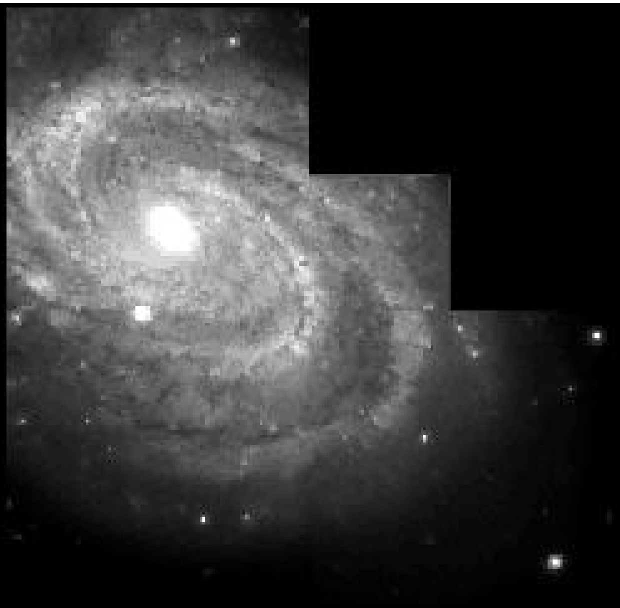
RR Lyra (old stellar population) & δ Cep stars (young population)



problem: overtone pulsators

Additional methods: Eclipsing binaries, star clusters, Miras, tip of red giant branch, Supernova 1987A,...

Distance to the LMC: 50 kpc



Movie: `movies/cosmomovies/1999-19-b-low_quicktime.mov`

The origin of the Period-Luminosity relationship is in the Helium ionization instability discussed before. The details of this are rather messy, however, it is easy to see that a Period-Luminosity relationship as that observed for the Cepheids is a simple consequence of the fact that the pulsating star is not disrupted by its oscillation.

For the outer parts of the star to remain bound, the kinetic energy of the pulsating outer parts of the stars has to remain smaller than their binding energy:

$$\frac{1}{2}mv^2 \lesssim \frac{GMm}{R}$$

But we know that for the velocity

$$v < \frac{2R}{P}$$

where P is the period of the star and R its radius at maximum extension (we observe the star to expand to a radius R once every P seconds, so the maximum distance the expanding material can go during that time is $2R$). Inserting v into the above equation gives

$$\frac{1}{2}\frac{4R^2}{P^2} \lesssim \frac{GM}{R} \quad \Longleftrightarrow \quad P^2 \gtrsim \frac{2}{G}\frac{R^3}{M} = \frac{2}{G}\frac{1}{M/R^3}$$

If we assume that the pulsation is close to the break-up speed, and noting that M/R^3 is proportional to the average density of the star, then it is easy to see that

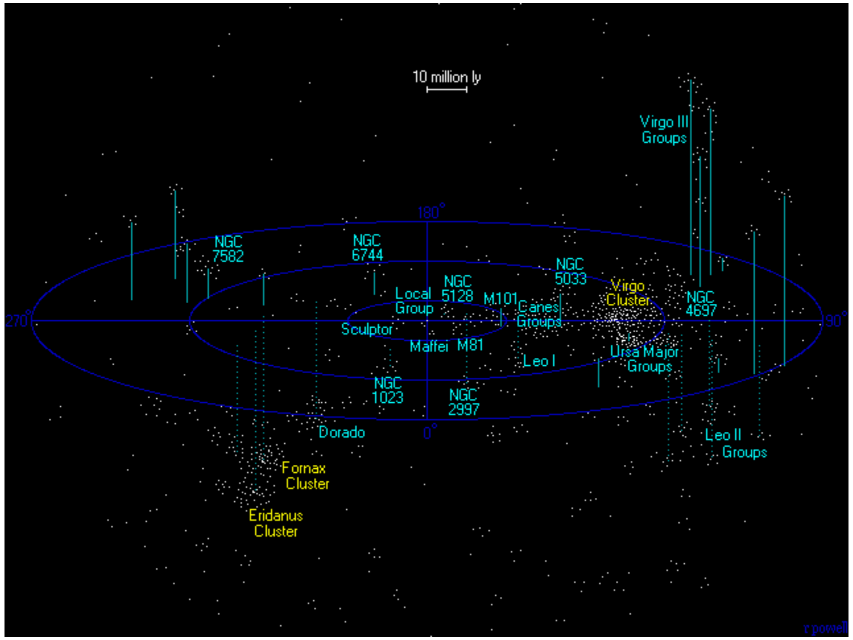
$$P \propto (G\rho)^{-1/2}$$

In the homework for this week you are asked to convince yourself that $(G\rho)^{-1/2}$ has the dimension of a period, i.e., for all gas balls oscillating close to the break up speed, we expect that $P \propto \rho^{-1/2}$. To obtain the period luminosity relationship, you need to remember that the emissivity per square-metre of the surface of a star with temperature T is σT^4 (per the Stefan-Boltzmann law), while the surface of the star is proportional to R^2. Therefore, the luminosity of the star is $L \propto R^2T^4$.

This week's homework asks you to use $L \propto R^2T^4$ and $P \propto \rho^{-1/2}$ to show that from these the absolute magnitude of a pulsating star is related to the period through

$$\log P \propto -m$$

as observed for Cepheids.

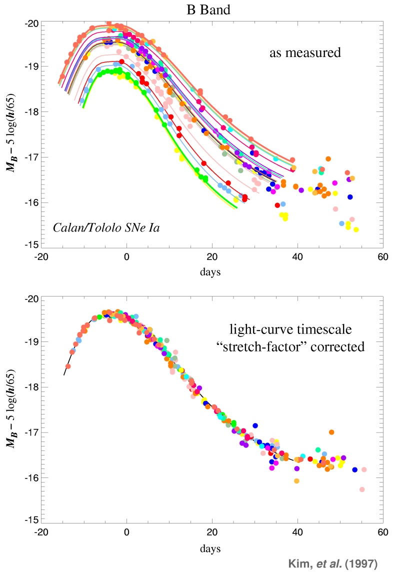


The universe out to the Virgo Cluster
source: `http://www.atlasoftheuniverse.com`

SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim 10^{51}$ erg/s in light, 100× more in neutrinos.

Supernovae



After correction of systematic effects and time dilatation (expansion of the universe, see later):

SN Ia lightcurves all look the same $\Longrightarrow$ standard candle

Supernovae

SN Ia: Explosion of CO white dwarf when pushed over Chandrasekhar limit (1.4 $M_\odot$) (via accretion?).

$\Longrightarrow$ Always similar process

$\Longrightarrow$ Very characteristic light curve: fast rise, rapid fall, exponential decay ("FRED") with half-time of 77 d.

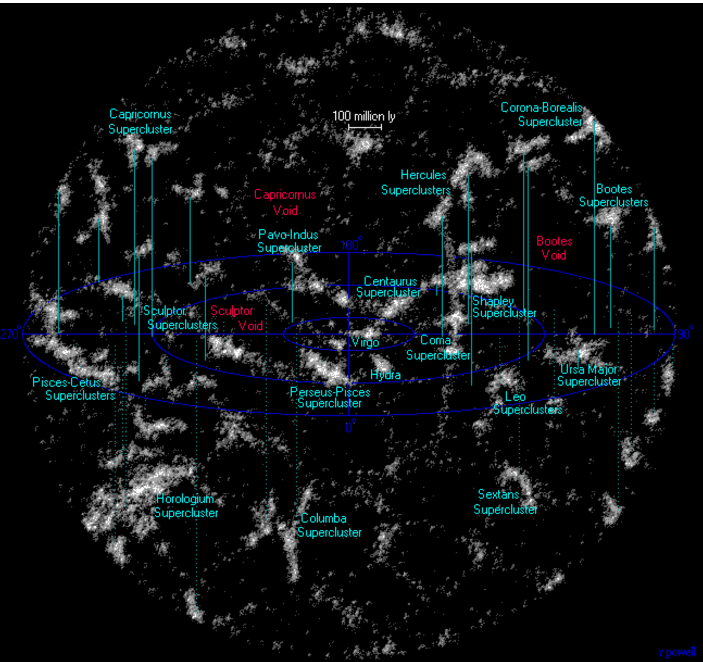
77 d time scale from radioactive decay $\mathrm{Ni}^{56} \rightarrow \mathrm{Co}^{56} \rightarrow \mathrm{Fe}^{56}$
("self calibration" of lightcurve if same amount of Ni^{56} produced everywhere)

Calibration: SNe Ia in nearby galaxies where Cepheid distances known.

At maximum light:

$$M_\mathrm{B} = -19.3 \pm 0.11 \quad \Longleftrightarrow \quad L \sim 10^{9\ldots10}\,L_\odot$$

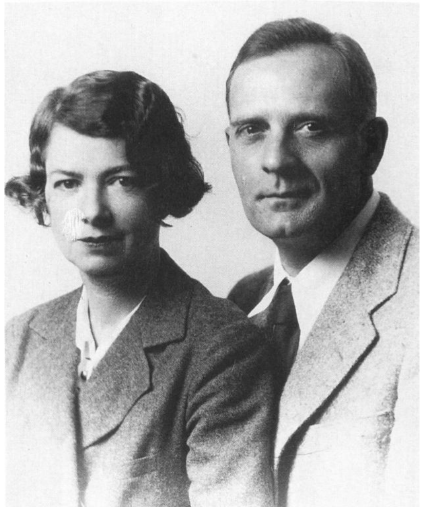
Observable out to $\gtrsim$1 Gpc $\Longrightarrow$ covers almost the whole universe...



Superclusters in our vicinity

source: `http://www.atlasoftheuniverse.com`

Edwin Hubble



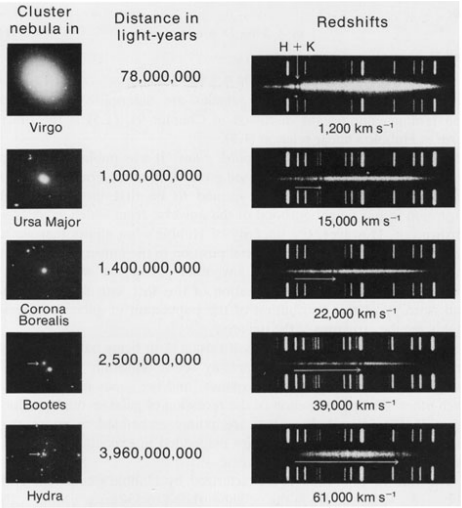
Christianson, 1995, p. 165

Edwin Hubble (1889–1953):

- Realization of galaxies as being outside of the Milky Way
- Discovery that universe is expanding

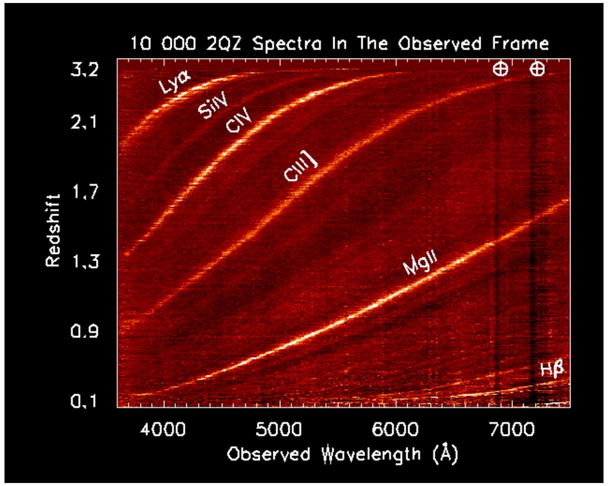
Founder of modern extragalactic astronomy

Redshifts



Hubble: spectral lines in galaxies are more and more redshifted with increasing distance.

Redshifts



2dF QSO Redshift survey

Redshift:

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

interpreted as velocity:

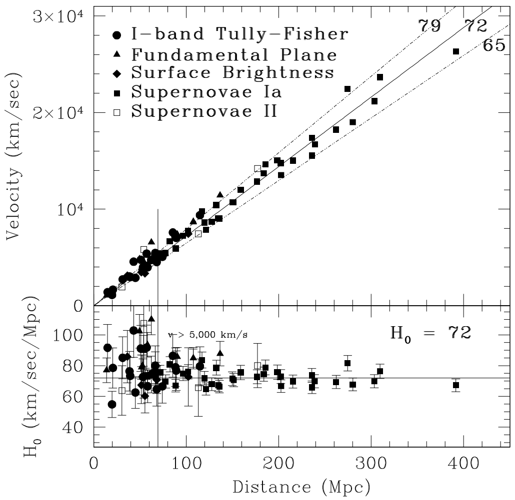
$$v = cz$$

where

$c = 300000\,\text{km}\,\text{s}^{-1}$

(speed of light)

Hubble Relation



(Freedman, 2001, Fig.4)

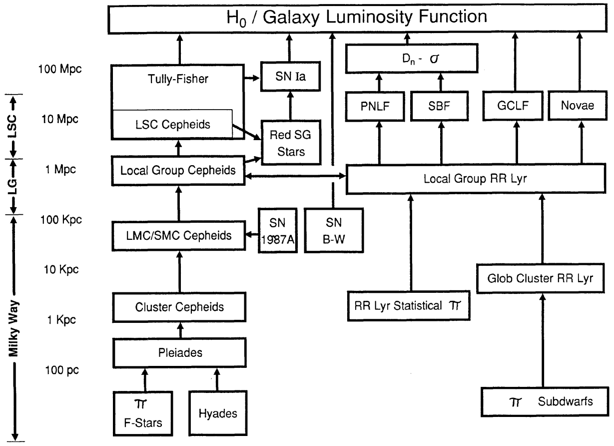
Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

where H_0: "Hubble constant".
Measurement: determine v from redshift (easy), d with standard candles (difficult)
$\Longrightarrow$ H_0 from linear regression.
Hubble Space Telescope key project finds

$H_0 = 72 \pm 8\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$

Summary: Distance Ladder

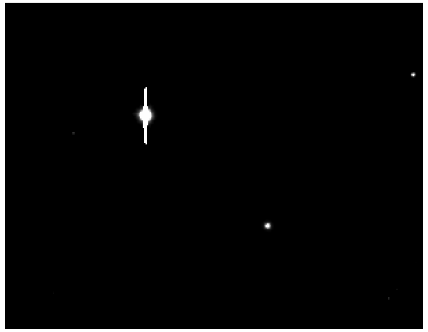


Pathways to Extragalactic Distances

Jacoby (1992, Fig. 1)

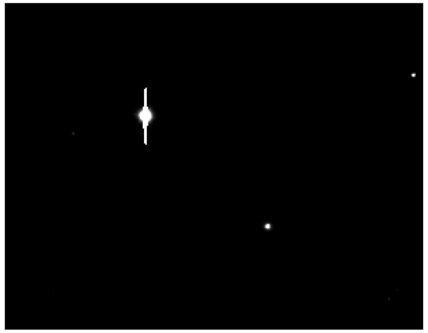
Active Galactic Nuclei

AGN

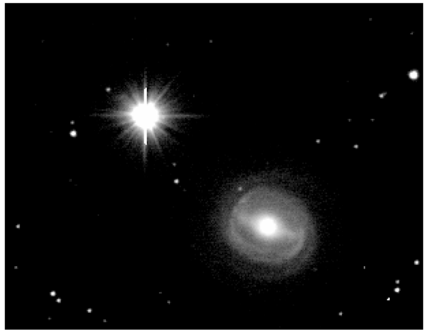


NGC 3783: *linear* intensity scale

AGN

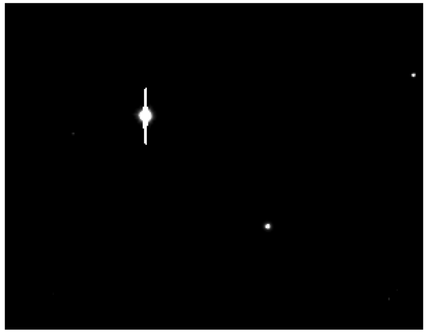


NGC 3783: *linear* intensity scale

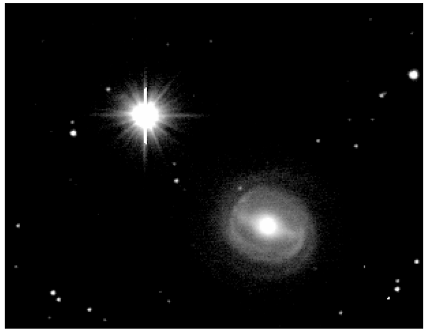


logarithmic intensity scale

AGN



NGC 3783: *linear* intensity scale



logarithmic intensity scale

Active Galactic Nuclei (AGN): supermassive black holes ($M \sim 10^{6\ldots8}\,M_\odot$), accreting $1\ldots2\,M_\odot/\text{year}$

$\Longrightarrow$ Luminosity $\sim 10^{10}\,L_\odot$ (comparable to galaxy luminosity)

AGN

Astrophysical energy sources:

1. Nuclear fusion

Reactions à la

$$4\text{p} \longrightarrow {}^4\text{He} + \Delta E_\text{nuc}$$

Energy released:

$$\boxed{\text{Fusion produces} \sim 6 \times 10^{11}\,\text{J}\,\text{g}^{-1}}$$

(i.e., $\Delta E_\text{nuc} \sim 0.007 m_\text{p} c^2$)

AGN

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(i.e., $\Delta E_{\mathrm{nuc}} \sim 0.007 m_{\mathrm{p}} c^2$)

2. Gravitation

Accretion of mass m from ∞ to R_{S} on black hole with mass M gives

$$\Delta E_{\mathrm{acc}} = \frac{GMm}{R_{\mathrm{S}}} \quad \text{where} \quad R_{\mathrm{S}} = \frac{2GM}{c^2}$$

Accretion produces ∼$10^{13}\,\mathrm{J\,g^{-1}}$

(i.e., $\Delta E_{\mathrm{acc}} \sim 0.1\, m_{\mathrm{p}} c^2$)

NGC 1068 (M77)
courtesy Nordic Optical
Telescope

AGN

Astrophysical energy sources:

1. Nuclear fusion

Reactions à la

$$4\mathrm{p} \longrightarrow {}^4\mathrm{He} + \Delta E_{\mathrm{nuc}}$$

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Accretion produces ∼$10^{13}\,\mathrm{J\,g^{-1}}$

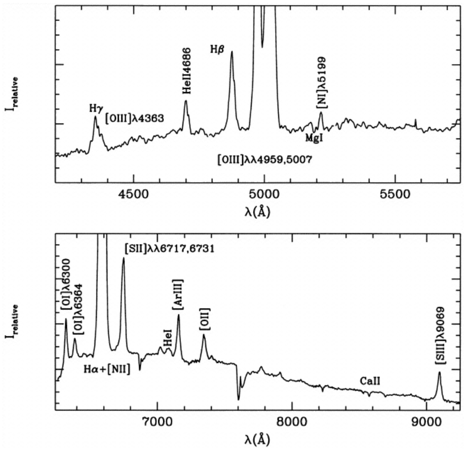
(i.e., $\Delta E_{\mathrm{acc}} \sim 0.1\, m_{\mathrm{p}} c^2$)

$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source.

…thus accreting objects are the most luminous in the whole universe.

Note: energy gets radiated away from *outside* the Schwarzschild radius!

1908: E. Fath



Optical spectrum of NGC 1068

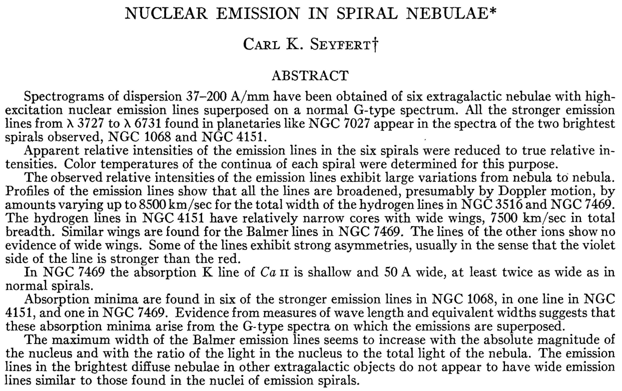
(García-Lorenzo et al., 1999, Fig. 4)

1908: Edward A. Fath: There are emission lines in NGC 1068, similar to planetary nebulae.

This was part of Fath's PhD!

Note: High ionization levels, large width of lines

1943: C. Seyfert



NUCLEAR EMISSION IN SPIRAL NEBULAE*

Carl K. Seyfert†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

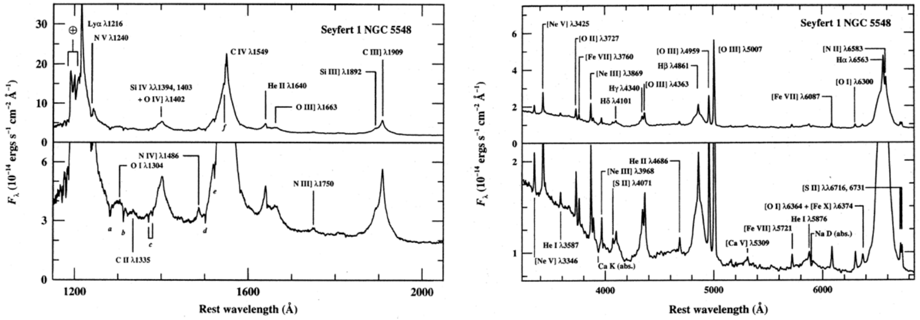
The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.

(Seyfert, 1943)

1943: Carl Seyfert: Recognization of spiral galaxies with optical emission lines as a class $\Longrightarrow$ Seyfert galaxies

---

Seyfert 1

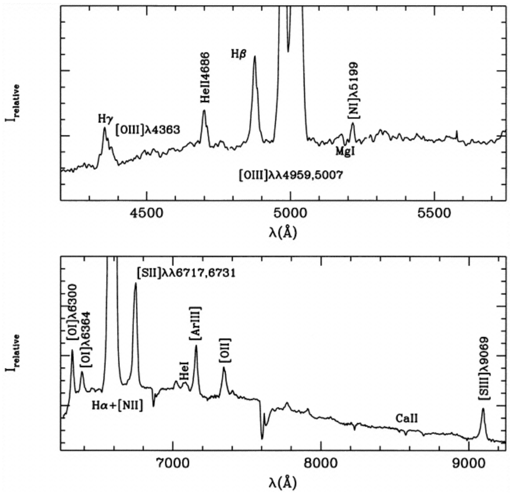


Seyfert 1 galaxies:

- broad dipole allowed lines (e.g., Balmer series), Full width at half maximum (FWHM) up to $10^4\,\mathrm{km\,s^{-1}}$ from high density medium ($n_\mathrm{e} \gtrsim 10^9\,\mathrm{cm^{-3}}$).
- narrow dipole forbidden lines (e.g., [O III5007]), FWHM $\sim$ few $\cdot\ 10^2\,\mathrm{km\,s^{-1}}$ from a low density medium ($n_\mathrm{e} \sim 10^3\,\mathrm{cm^{-3}} \dots 10^6\,\mathrm{cm^{-3}}$).

Reminder: From the Doppler effect: $\Delta\lambda/\lambda = v/c$.

Seyfert 2

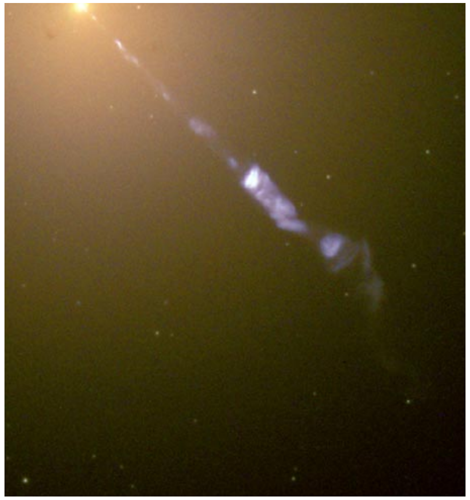


(García-Lorenzo et al., 1999, Fig. 4)

Optical spectrum of the Seyfert 2 Galaxy NGC 1068:

- Weak continuum (compared to Seyfert 1s).
- Narrow forbidden lines, FWHM $\sim$ few $\cdot\ 10^2\,\mathrm{km\,s^{-1}}$.
- No broad lines
- Absorption lines from underlying galaxy (mainly late-type giants).

1918: H. Curtis



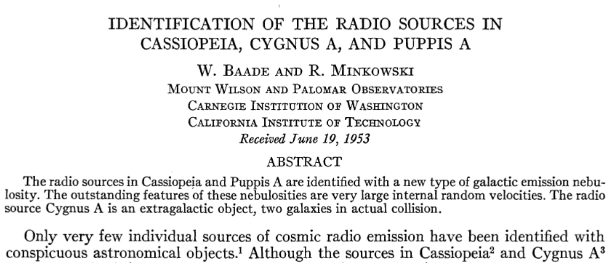
HST

1918: Heber D. Curtis: “[M87 exhibits] a curious straight ray…apparently connected with the nucleus by a thin line of matter”.
$\Longrightarrow$ M87 contains an optical jet

1954: W. Baade and R. Minkowski

W. Baade

(Mt. Wilson Obs.)



IDENTIFICATION OF THE RADIO SOURCES IN CASSIOPEIA, CYGNUS A, AND PUPPIS A

W. Baade and R. Minkowski
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology
Received June 19, 1953

ABSTRACT

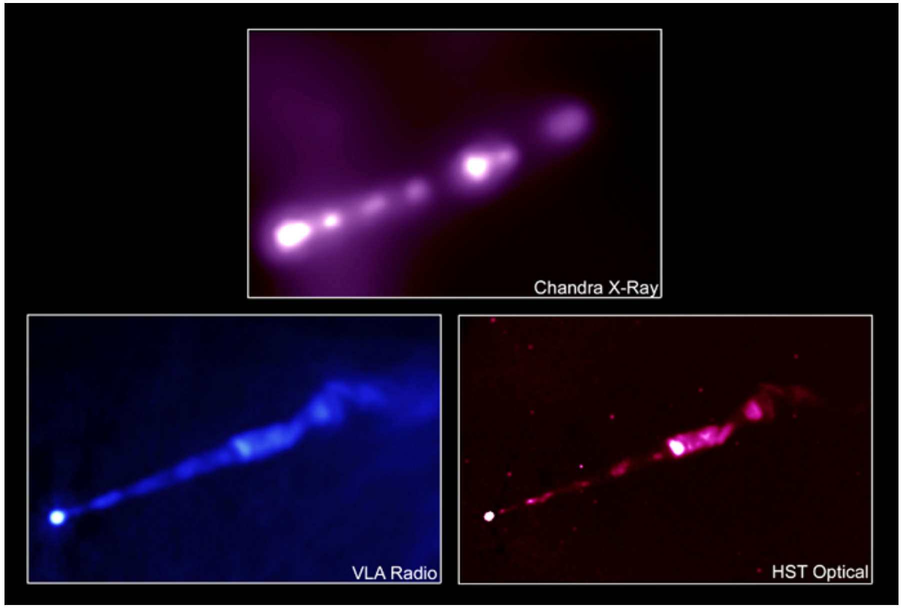
The radio sources in Cassiopeia and Puppis A are identified with a new type of galactic emission nebulosity. The outstanding features of these nebulosities are very large internal random velocities. The radio source Cygnus A is an extragalactic object, two galaxies in actual collision.

Only very few individual sources of cosmic radio emission have been identified with conspicuous astronomical objects.[1] Although the sources in Cassiopeia[2] and Cygnus A[3]

(Baade & Minkowski, 1954)

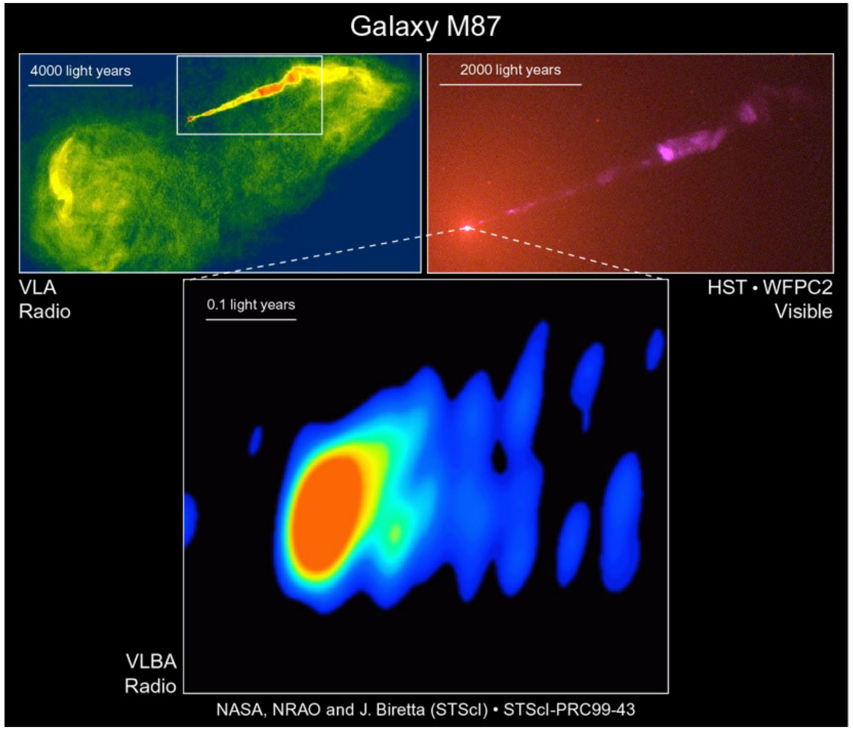
1954: Walter Baade and Rudolph Minkowski: optical counterparts to radio sources Cyg A (3C 405), Vir A (M87), Per A (NGC 1275).

Cyg A: First ultra-luminous AGN (2nd brightest radio source in the sky; $L \sim 10^{45}\,\mathrm{erg\,s^{-1}}$).

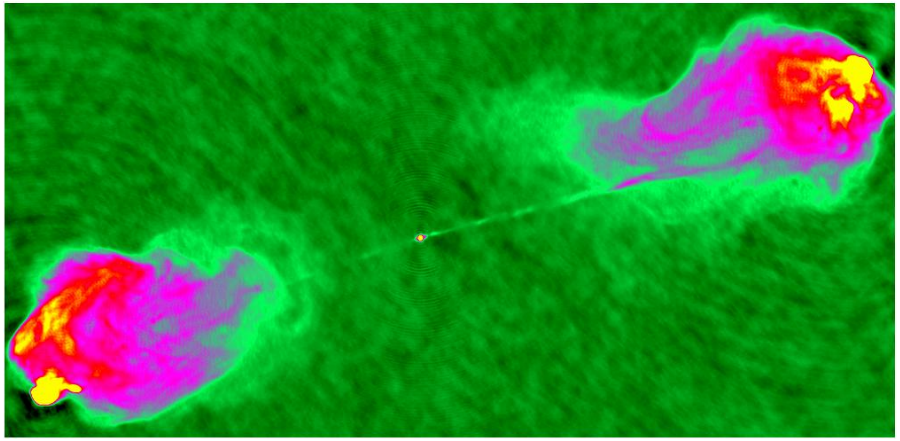


X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F.Zhou, F.Owen (NRAO), J.Biretta (STScI)
Optical: NASA/STScI/UMBC/E.Perlman et al.

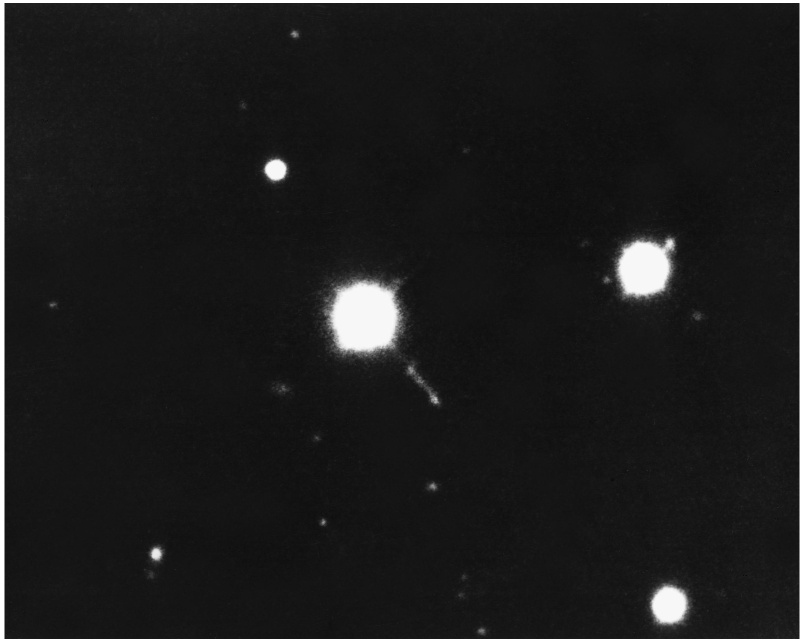
Jets are visible in all wavebands



NASA/NRAO/STScI

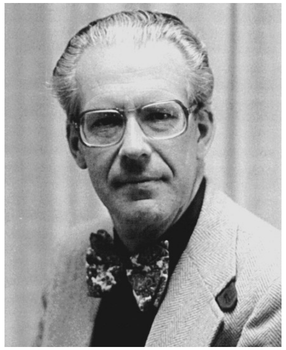


Cyg A in radio ($\lambda = 6\,\mathrm{cm}$, VLA, Perley et al. 1984)

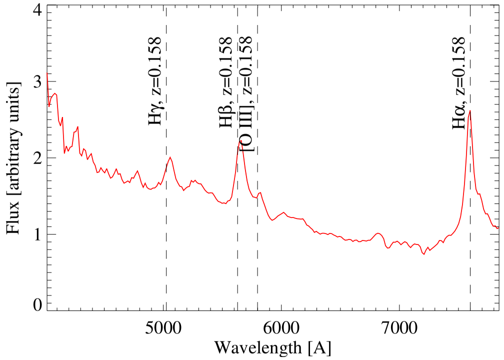


3C273 (4 m Myall telescope, NOAO/AURA/NSF)

Schmidt 1963



M. Schmidt (Caltech)



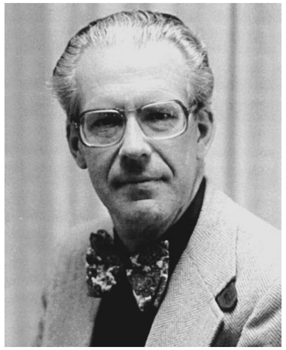
3C273 (Rondi et al., Pic du Midi)

1963: Maarten Schmidt: 3C273 has $z = 0.158 \Longrightarrow$ AGN are far away!

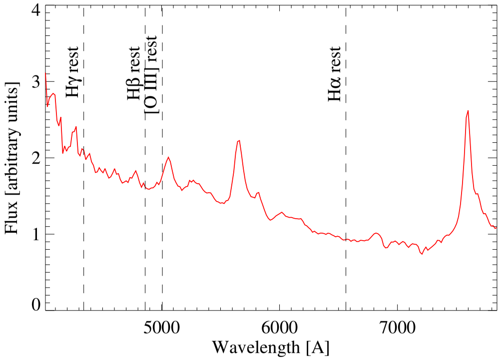
shortly later: 1963: J. Greenstein and Th. Matthews: 3C48 has $z = 0.368$

Nomenclature: Quasar/QSO (from “quasi stellar radio source”: radio emitting AGN)

Schmidt 1963

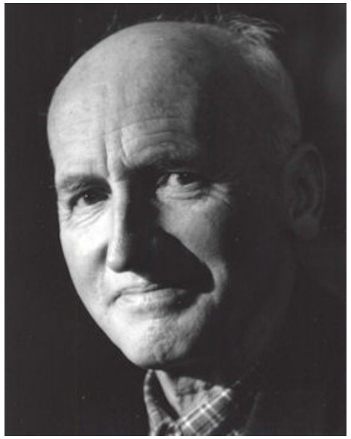


M. Schmidt (Caltech)

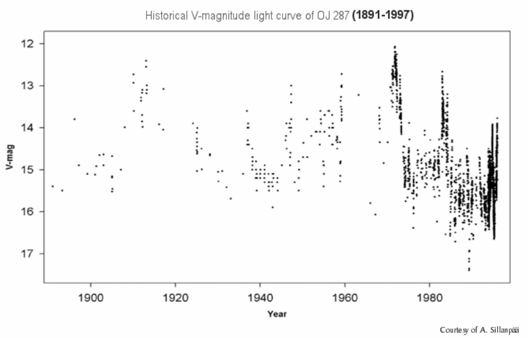


3C273 (Rondi et al., Pic du Midi)

BL Lac Objects

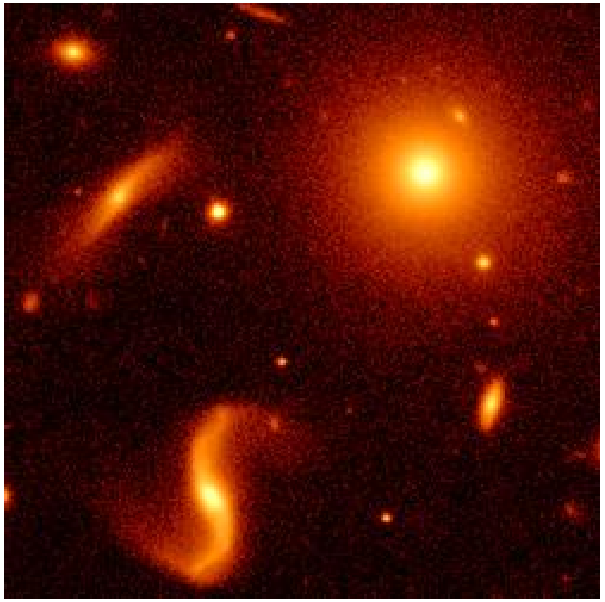


Cuno Hoffmeister
(Sonneberg Obs., Thüringen),
1915–1918: Assistant at
Dr. Remeis-Sternwarte Bamberg



1929: BL Lac: variable star

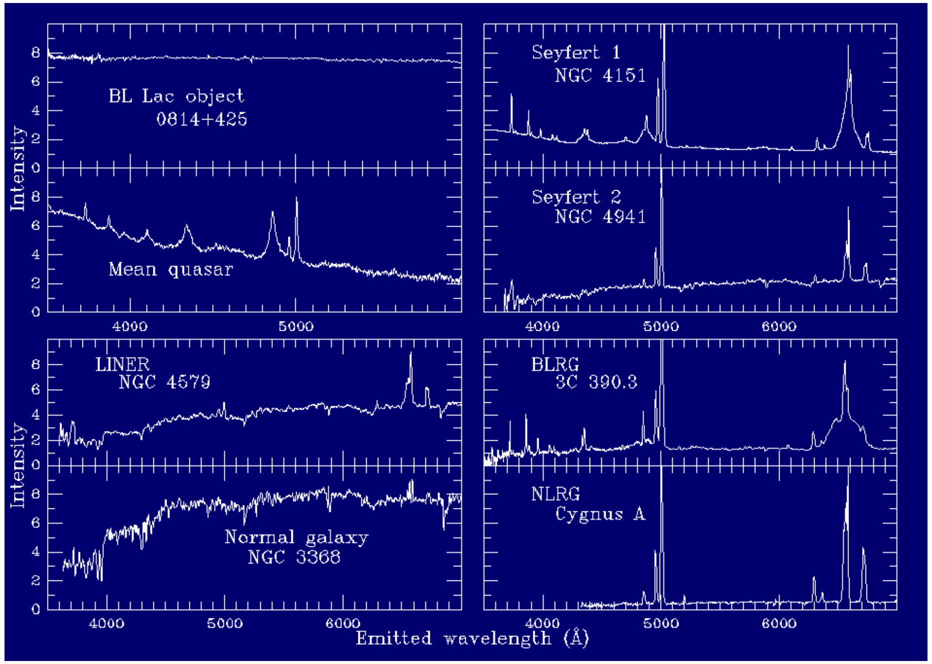
1968: BL Lac is strong radio source

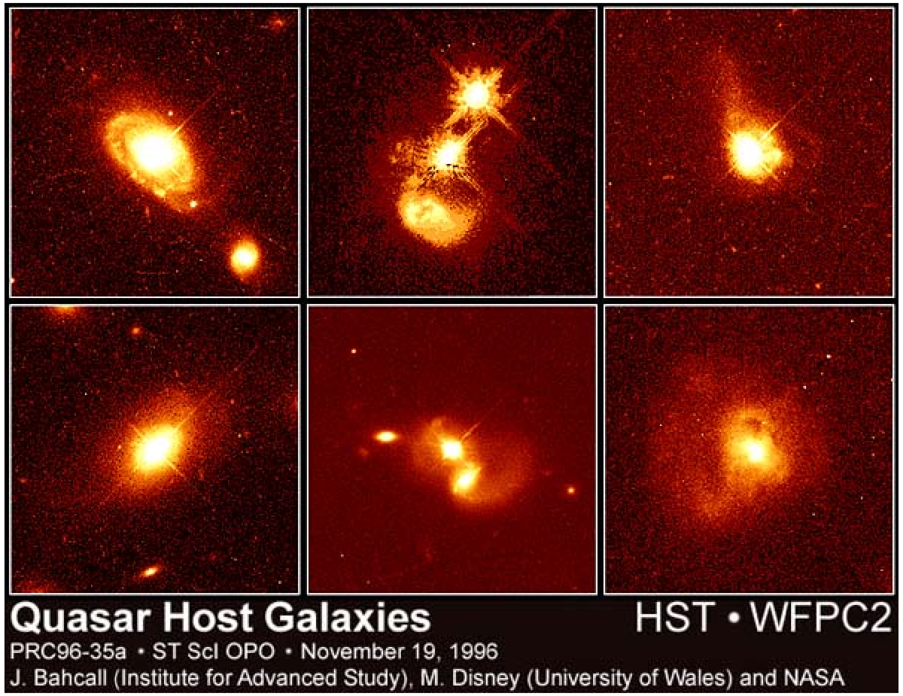


BL Lac object lives in an elliptical galaxy

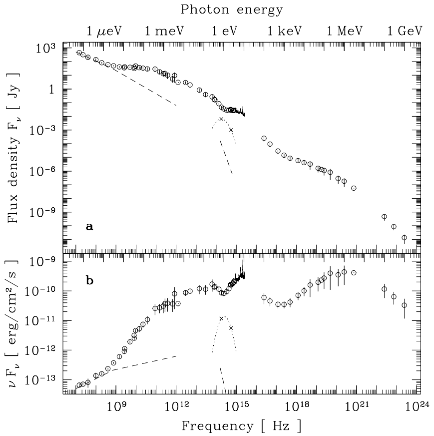
`www.astro.utu.fi/tuorla/new/nilsson.s.jpg`

BL Lac: spectrum of host galaxy: redshift $z = 0.069$





Spectral energy distribution



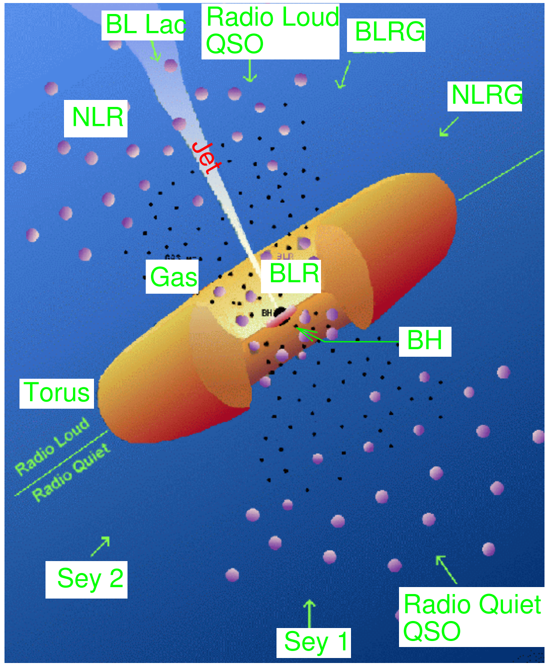
Türler et al. (1999): Spectral energy distribution of 3C273

- dashed line: Jet (synchrotron emission)
- dotted line: Host galaxy

AGN Spectral energy distribution is a power law

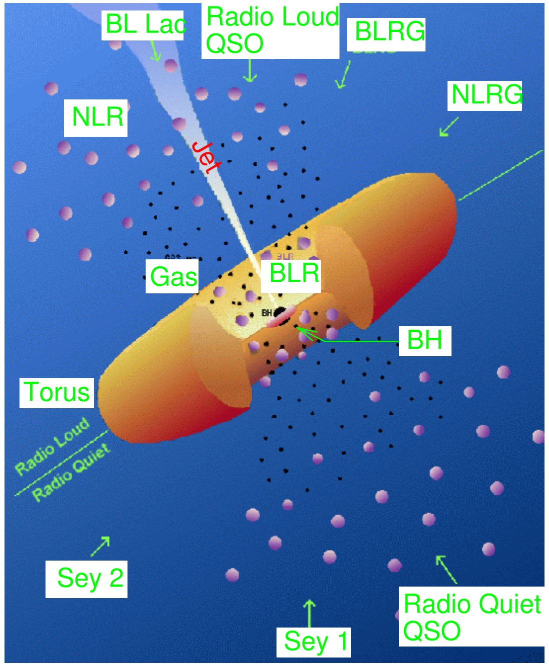
$$F(\nu) = \nu^{-\alpha}$$

$\alpha \sim 1$, i.e. $\nu \times F(\nu)$ is flat



Unified Model: All AGN types are due to the same physics, different phenomenology just due to different viewing angle.

(Urry & Padovani, 1995, NOTE: logarithmic length scale!)



Physical properties of components:

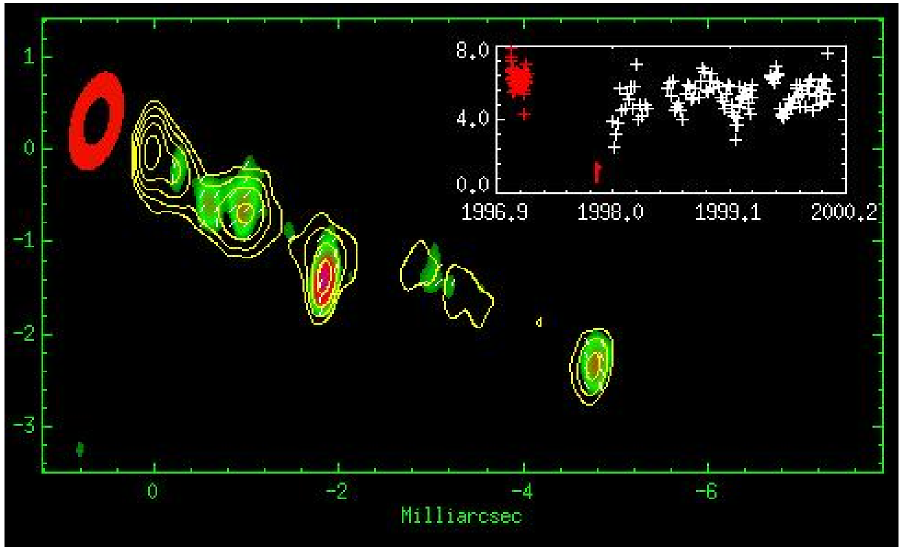
Accretion disk: $r \sim 10^{-3}$ pc,
$n \sim 10^{15}\,\mathrm{cm}^{-3}$,
$kT \sim 50\,\mathrm{eV} \cdot r^{-3/4}$,
$v \sim 0.3c$ at inner edge.

Broad Line Region (BLR):
$r \sim 0.01$–0.1 pc (=light days),
$n \sim 10^{10}\,\mathrm{cm}^{-3}$,
$v \sim 1000$–$5000\,\mathrm{km\,s}^{-1}$,
$T \sim 10^4\,\mathrm{K}$

Torus: $r \sim 1$– few 10 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
T: cold

Narrow Line Region (NLR):
$r \sim 100$–1000 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
$v \sim$ few $\cdot$ $100\,\mathrm{km\,s}^{-1}$,
$T \sim 10^4\,\mathrm{K}$

See, e.g., Antonucci (1993) for a review.



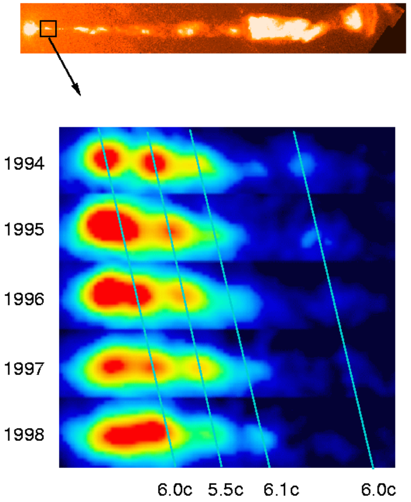
Movie time: jetmovies/3c120rx.avi

Jet motion in 3C120 (Marscher et al., 2002)

3C120: Sy 1, $M_{\mathrm{BH}} = 3 \times 10^7\,M_\odot$ from reverberation mapping

Superluminal Motion

Superluminal Motion in the M87 Jet



3C120: Apparent speed of jet: $\sim 5c$

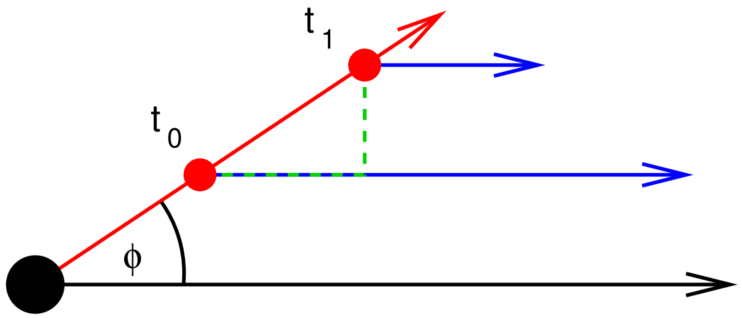
M87: Apparent speed of jet: $\sim 6c$

Superluminal motion: The apparent velocities measured in many AGN jets are $v > c$.

First discovered in 1971 in 3C273.

Biretta/STScI

Superluminal Motion



Consider blob moving towards us with speed v and angle ϕ with respect to line of sight, emitting light signals at t_0 and $t_1 = t_0 + \Delta t_\mathrm{e}$

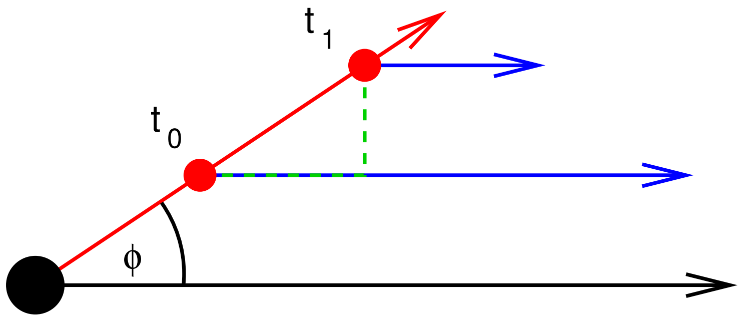
Light travel time: Observer sees signals separated by

$$\Delta t_\mathrm{o} = \Delta t_\mathrm{e} - \Delta t_\mathrm{e} \frac{v}{c}\cos\phi = \left(1 - \frac{v}{c}\cos\phi\right)\Delta t_\mathrm{e} \qquad (21.1)$$

Observed distance traveled in plane of sky:

$$\Delta \ell_\perp = v \Delta t_\mathrm{e} \sin\phi \qquad (21.2)$$

Superluminal Motion

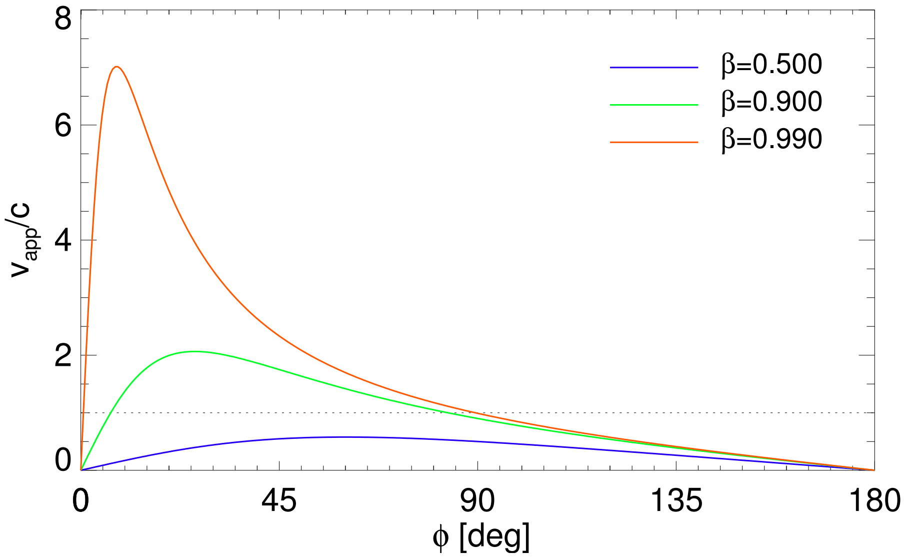


Apparent velocity deduced from observations:

$$v_\mathrm{app} = \frac{\Delta \ell_\perp}{\Delta t_\mathrm{o}} = \frac{v \Delta t_\mathrm{e} \sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)\Delta t_\mathrm{e}} = \frac{v\sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)} \qquad (21.3)$$

$\Longrightarrow$ For v/c large and ϕ small: $v_\mathrm{app} > c$

Superluminal Motion



AGN Summary

- The zoo of Active Galactic Nuclei:
  - Seyfert galaxies: Typ I (narrow- and broad-lined), Type II (narrow-lined), in spiral galaxies, radio-quiet
  - radio galaxies: elliptical galaxy in the center of (double) radio lobes: relativistic jet
  - BL Lac objects: continuous, polarized spectra, highly variable, in elliptical galaxies
  - quasars: extremely luminous nucleus, radio-loud (QSR), radio-quiet (QSO)
- Unified Model:
  - Supermassive Black Hole
  - accretion disk
  - Narrow- and broad-line region: clouds orbiting around Black Hole
  - dust torus
- Superluminal Motions: highly relativistic jet seen at a low angle

Antonucci, R., 1993, Ann. Rev. Astron. Astrophys., 31, 473

Baade, W., & Minkowski, R. 1954, ApJ, 119, 206

García-Lorenzo, B., Mediavilla, E., & Arribas, S. 1999, ApJ, 518, 190

Marscher, A. P., Jorstad, S. G., Gómez, J.-L., et al. 2002, Nature, 417, 625

Perley, R. A., Dreher, J. W., & Cowan, J. J. 1984, ApJ, 285, L35

Seyfert, C. K., 1943, ApJ, 97, 28

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

World Models

Introduction

Cosmology: science of the universe as a whole

How did the universe evolve to what it is today?

Based on four basic facts:

The universe
- expands,
- is isotropic,
- and is homogeneous.

Isotropy and homogeneity of the universe: “*cosmological principle*”.

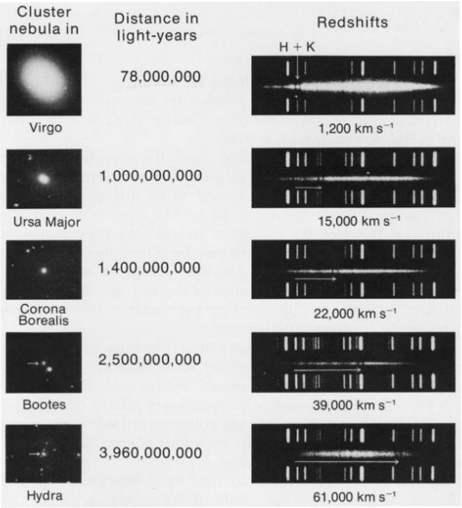
Perhaps (for us) the most important fact is:

- The universe is habitable for humans.

(“*anthropic principle*”)

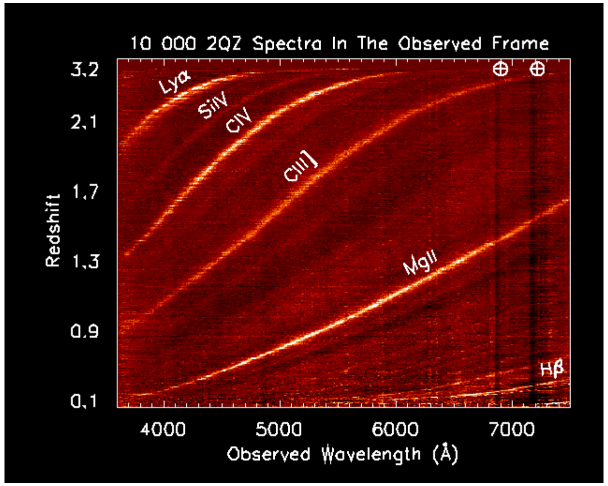
The one question cosmology does not attempt to answer is: How came the universe into being?
$\Longrightarrow$ Realm of theology!

Redshifts



Hubble: spectral lines in galaxies are more and more redshifted with increasing distance.

Redshifts



2dF QSO Redshift survey

Redshift:

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

interpreted as velocity:

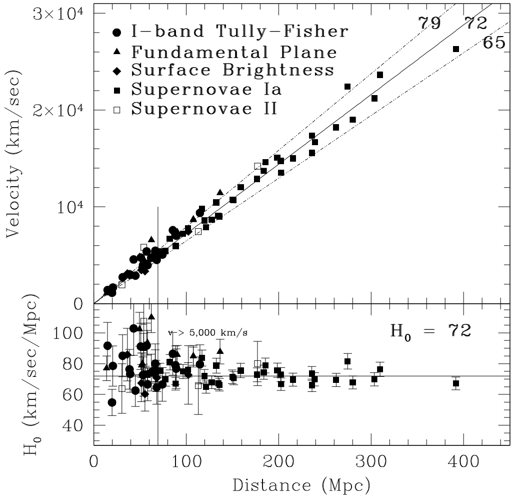
$$v = cz$$

where

$c = 300000\,\text{km}\,\text{s}^{-1}$

(speed of light)

Hubble Relation



(Freedman, 2001, Fig.4)

Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

where H_0: "Hubble constant".

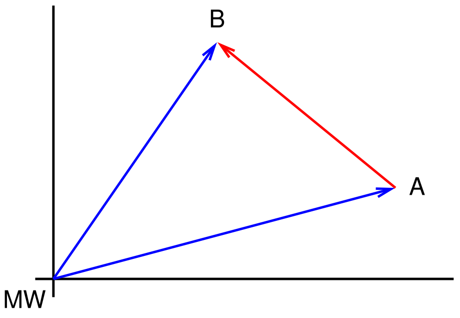
Measurement: determine v from redshift (easy), d with standard candles (difficult)

$\Longrightarrow H_0$ from linear regression.

Hubble Space Telescope finds

$$H_0 = 72 \pm 8\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$$

Hubble Relation



The expansion law $\mathbf{v} = H_0\mathbf{r}$ is unchanged under rotation and translation: isomorphism.

Proof: consider two galaxies at positions $\mathbf{r}_A$ and $\mathbf{r}_B$:

Hubble: $\mathbf{v}_A = H_0\,\mathbf{r}_A$ and $\mathbf{v}_B = H_0\,\mathbf{r}_B$

Galaxy B as seen from galaxy A:

$\mathbf{v}_B - \mathbf{v}_A = H_0\,\mathbf{r}_B - H_0\,\mathbf{r}_A = H_0\,(\mathbf{r}_B - \mathbf{r}_A)$

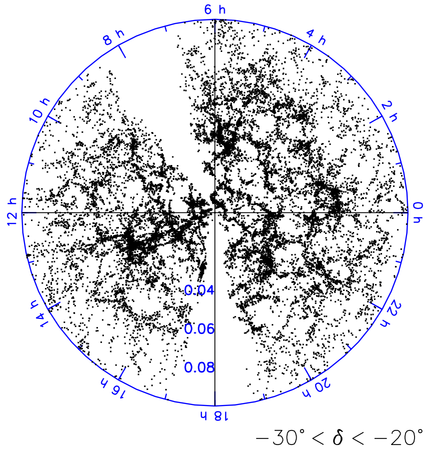
$\Longrightarrow$ observer at A derives the same Hubble law as we on Milky Way.

This is a direct consequence of the homogeneity of the universe.

Despite everything receding from us, we are not at the center of the universe $\Longrightarrow$ Copernicus principle still holds.

Copernicus principle: We are not at a special place in the universe in time or space.

Homogeneity

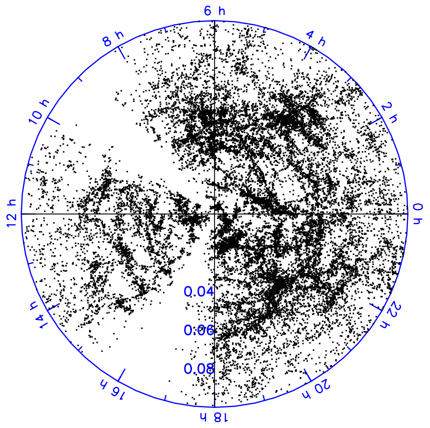


$-30^\circ < \delta < -20^\circ$

Homogeneity: "The universe looks the same, regardless from where it is observed" (on scales $\gg$100 Mpc).

6dF QSO Redshift survey

Homogeneity

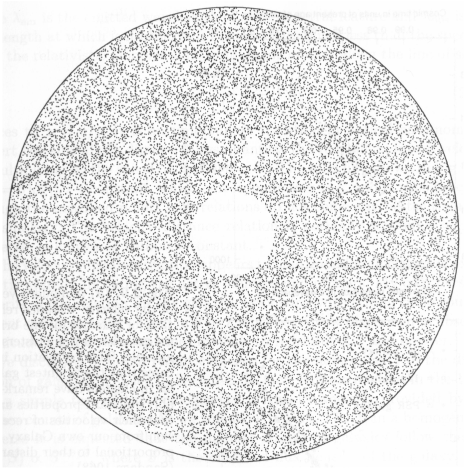


$-60^\circ < \delta < -40^\circ$

Homogeneity: “The universe looks the same, regardless from where it is observed” (on scales ≫100 Mpc).

6dF QSO Redshift survey

Isotropy

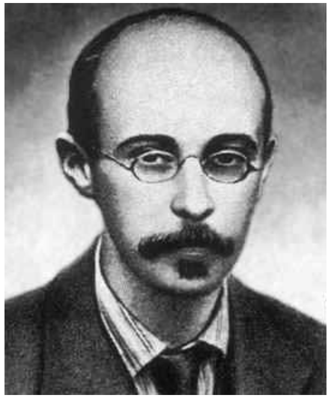


Peebles (1993): Distribution of 31000 radio sources on northern sky (wavelength $\lambda = 6\,\mathrm{cm}$)

Isotropy $\Longleftrightarrow$ The universe looks the same in all directions.

N.B. Homogeneity *does not* imply isotropy, and isotropy around one point does not imply homogeneity!

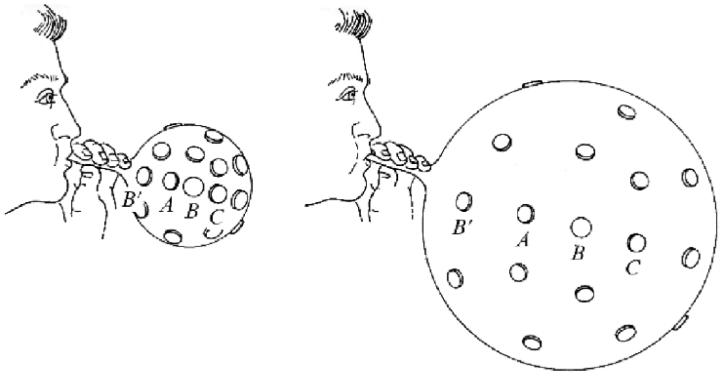
World Models



A.A. Friedmann (1888–1925)

Friedmann: Mathematical description of the Universe using normal “fixed” coordinates (“comoving coordinates”), plus scale factor R which describes evolution of the Universe.

World Models

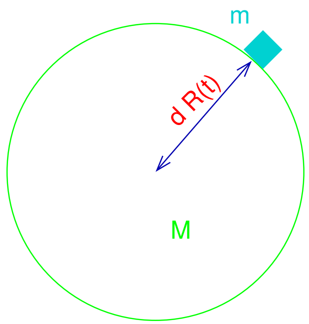


R small

R large

Friedmann: Mathematical description of the Universe using normal “fixed” coordinates (“comoving coordinates”), plus scale factor R which describes evolution of the Universe.

Friedmann Equations



Evolution of universe described with Friedmann equations: Dynamics of a mass element on the surface of sphere of density $\rho(t)$ and comoving radius d, i.e., proper radius $d \cdot R(t)$ (McCrea, 1937)

Mass of sphere:

$$M = \frac{4\pi}{3}(d\,R)^3\rho(t) = \frac{4\pi}{3}d^3\rho_0 \quad \text{where} \quad \rho(t) = \frac{\rho_0}{R(t)^3} \tag{22.1}$$

Force on mass element:

$$m\frac{\mathrm{d}^2}{\mathrm{d}t^2}\big(d\,R(t)\big) = -\frac{GMm}{(dR(t))^2} = -\frac{4\pi G}{3}\frac{d\rho_0}{R^2(t)}m \tag{22.2}$$

Canceling $m \cdot d$ gives momentum equation:

$$\ddot{R}(t) = -\frac{4\pi G}{3}\frac{\rho_0}{R(t)^2} = -\frac{4\pi G}{3}\rho(t)R(t) \tag{22.3}$$

Multiplying Eq. (22.3) with $\dot{R}$ and integrating yields the energy equation:

$$\frac{1}{2}\dot{R}(t)^2 = +\frac{4\pi G}{3}\frac{\rho_0}{R(t)} + \text{const.} = +\frac{4\pi G}{3}\rho(t)R^2(t) + \text{const.} \tag{22.4}$$

where the constant can only be obtained from GR.

Friedmann Equations

General relativistic approach: Insert metric into Einstein equation to obtain differential equation for $R(t)$:

Einstein equation:

$$\underbrace{R_{\mu\nu} - \frac{1}{2}\mathscr{R}g_{\mu\nu}}_{G_{\mu\nu}} = \frac{8\pi G}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu} \tag{22.5}$$

where

$g_{\mu\nu}$**:** Metric tensor ($\mathrm{d}s^2 = g_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu$)

$R_{\mu\nu}$**:** Ricci tensor (function of $g_{\mu\nu}$)

$\mathscr{R}$**:** Ricci scalar (function of $g_{\mu\nu}$)

$G_{\mu\nu}$**:** Einstein tensor (function of $g_{\mu\nu}$)

$T_{\mu\nu}$**:** Stress-energy tensor, describing curvature of space due to fields present (matter, radiation,…)

Λ**:** Cosmological constant

$\Longrightarrow$ greatly simplified by cosmolgical principle: Robertson-Walker metric

---

Friedmann Equations

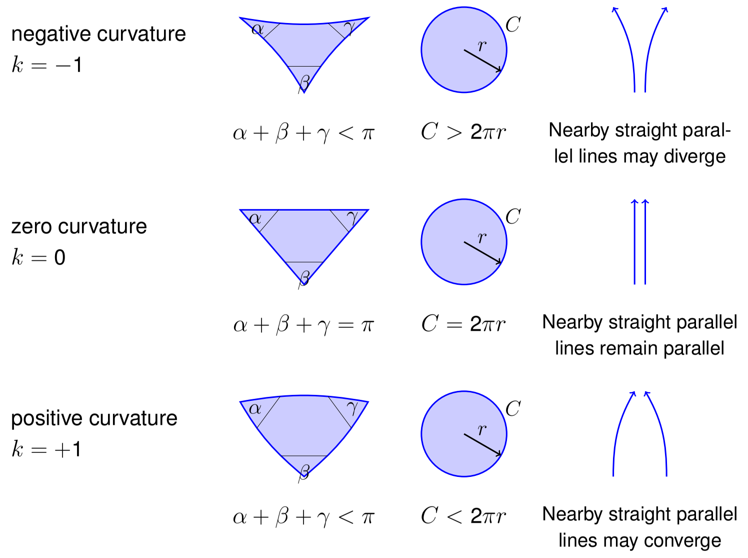
The exact GR derivation of Friedmanns equation gives:

$$\begin{aligned}\ddot{R} &= -\frac{4\pi G}{3}R\left(\rho + \frac{3p}{c^2}\right) + \left[\frac{1}{3}\Lambda R\right]\\ \dot{R}^2 &= +\frac{8\pi G\rho}{3}R^2 - kc^2 + \left[\frac{1}{3}\Lambda c^2 R^2\right]\end{aligned} \tag{22.6}$$

Notes:

1. For $k = 0$: Eq. (22.6) $\longrightarrow$ Eq. (22.4).
2. k determines the curvature of space:
    - $k > 0$: closed universe (finite volume)
    - $k = 0$: flat universe
    - $k < 0$: open universe (infinite volume)
3. The density, ρ, includes the contribution of all different kinds of energy (remember mass-energy equivalence!).
4. cosmological constant Λ introduced by Einstein to ensure stability of the universe. Physics unknown.

Friedmann Equations



after Jones & Lambourne: An Introduction to Galaxies and Cosmology

Hubble's Law

The variation of $R(t)$ implies Hubble's Law:

Small scales $\Longrightarrow$ Euclidean geometry

Proper distance between two observers with comoving distance d:

$$D(t) = d \cdot R(t) \tag{22.7}$$

Expansion $\Longrightarrow$ D changes:

$$\frac{\Delta D}{\Delta t} = \frac{R(t+\Delta t)d - R(t)d}{\Delta t} \quad \text{and for } \lim_{\Delta t \to 0} \quad v = \frac{\mathrm{d}D}{\mathrm{d}t} = \dot{R}\,d = \frac{\dot{R}}{R}\,D =: H\,D \tag{22.8}$$

$\Longrightarrow$ Identify local Hubble "constant" as

$$H = H(t) = \frac{\dot{R}(t)}{R(t)} \tag{22.9}$$

$\Longrightarrow$ Hubble "constant" is time-dependent! $\Longrightarrow$ "Hubble parameter"

Hubble's Law

The cosmological redshift is a consequence of the expansion of the universe:

The comoving distance is constant, thus in terms of the proper distance:

$$d = \frac{D(t = \text{today})}{R(t = \text{today})} = \frac{D(t)}{R(t)} = \text{const.} \tag{22.10}$$

Set $a(t) = R(t)/R(t = \text{today})$, then eq. (22.10) implies

$$\lambda_{\text{obs}} = \frac{\lambda_{\text{emit}}}{a_{\text{emit}}} \tag{22.11}$$

(λ_{obs}: observed wavelength, λ_{emit}: emitted wavelength)

Thus the observed redshift is

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1 = \frac{\nu_{\text{emit}}}{\nu_{\text{obs}}} - 1 \tag{22.12}$$

$$\Longrightarrow \quad 1 + z = \frac{1}{a_{\text{emit}}} = \frac{R(t = \text{today})}{R(t)} = \frac{\nu_{\text{emit}}}{\nu_{\text{obs}}} \tag{22.13}$$

Light emitted at $z = 1$ was emitted when the universe was half as big as today!

z: measure for *relative size* of universe at time the observed light was emitted.

Critical Density

Looking at the energy equation for $\Lambda = 0$,

$$\dot{R}^2 = +\frac{8\pi G\rho}{3}R^2 - kc^2 \tag{22.14}$$

we find that the evolution of the Hubble parameter is:

$$\left(\frac{\dot{R}}{R}\right)^2 = H(t)^2 = \frac{8\pi G\rho(t)}{3} - \frac{kc^2}{R^2} \tag{22.15}$$

and therefore

$$k \cdot \frac{c^2}{R(t)^2 H(t)^2} = \frac{8\pi G}{3H(t)^2}\rho(t) - 1 = \frac{\rho(t)}{\rho_{\text{crit}}} - 1 = \Omega - 1 \tag{22.16}$$

where Ω is called the critical density:

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} \quad \text{where} \quad \rho_{\text{crit}} = \frac{3H^2}{8\pi G} \tag{22.17}$$

currently: $\rho_{\text{crit}} \sim 1 \times 10^{-23}\,\text{g}\,\text{cm}^{-3}$ (3…10 H-Atoms m^{-3}).

Ω describes the curvature of the universe:

$\Omega > 1 \Longrightarrow k > 0$: closed ❙ $\Omega = 1 \Longrightarrow k = 0$: flat ❙ $\Omega < 1 \Longrightarrow k < 0$: open

Critical Density

World Model: Evolution of R as a function of time

Solution of Friedmann equations depends on boundary conditions:

1. Value of H as measured today (H is time dependent!)
2. Density Parameter of universe

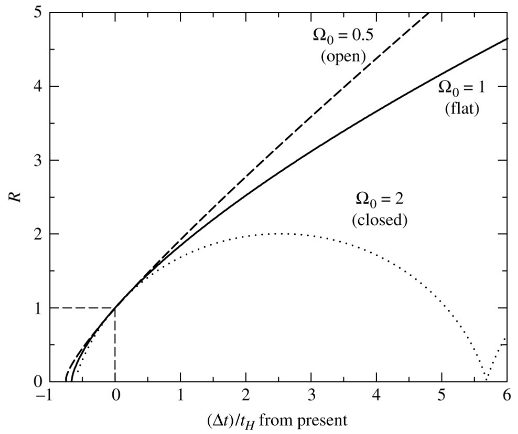
Note: total Ω is sum of:

1. Ω_{m}: Matter, i.e., everything that leads to gravitative effects
   Ω_{m} in baryonic matter is $\lesssim$3%, but note there might be "nonbaryonic dark matter" as well!
2. $\Omega_\Lambda = \Lambda c^2/3H^2$: contribution by cosmological constant Λ
   (Λ is often called "dark energy" for PR reasons)

Hubble time: Assume an empty universe ($\omega = 0$): linear expansion

$\Longrightarrow$ age of the Universe: $t_{\text{H}} = v/d = 1/H_0$ is called Hubble time

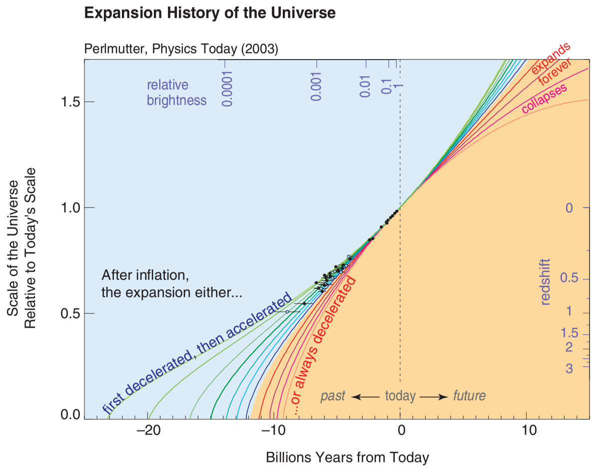
Critical Density



Carroll & Ostlie, Fig. 29.5

- $\Omega > 1 \Longrightarrow$ finite life
- $\Omega = 1 \Longrightarrow$ expands forever
- $\Omega < 1 \Longrightarrow$ expands forever

Age of the Universe

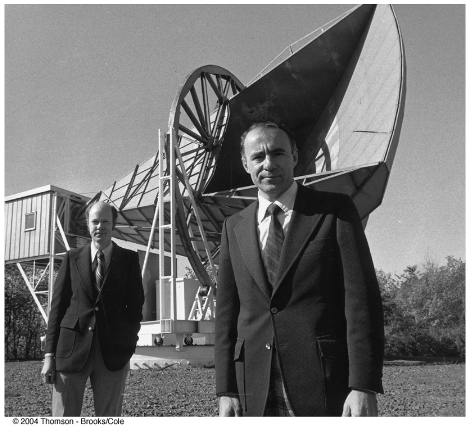


Note: Extrapolation backwards gives age of universe as *roughly* $1/H_0$!

for $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}} = 2.3 \times 10^{-18}\,\mathrm{s^{-1}}$, giving an age of 13.6 Gyr.

The Big Bang

CMBR

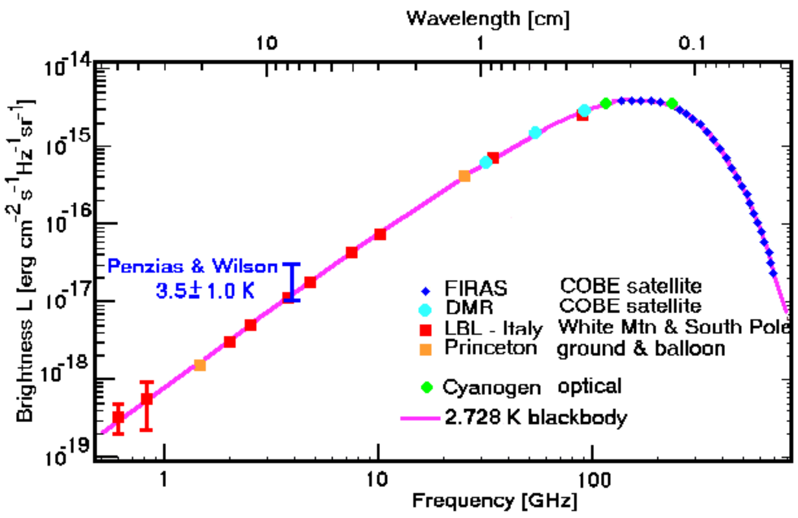


Arno Penzias & Robert Wilson
(Nobel prize 1978)

Discovery of the Cosmic Microwave Background (CMB):

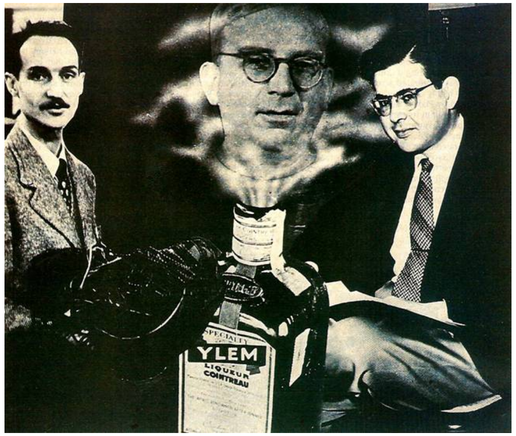
“A Measurement of Excess Antenna Temperature at 4080 Mc/s.”
A.A. Penzias & R.W. Wilson (1965, ApJ 142, 419):
Abstract: *Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna . . . at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value of about 3.5 K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 – April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.*

CMBR



NASA COBE: CMB is a perfect black body with $T = 2.725 \pm 0.002\,\mathrm{K}$

CMBR



Gamov called original state the ylem. This term has (thankfully) not caught on.

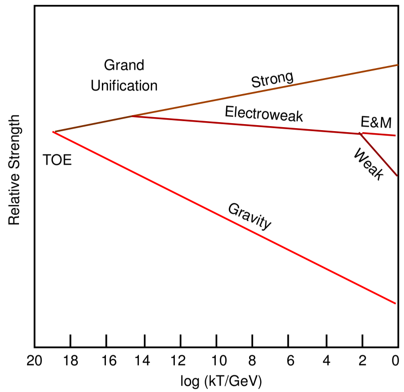
George Gamov:
Thermodynamics implies that the young, dense Universe must have been extremely hot
$\Longrightarrow$ The Big Bang

Temperature then decreased after BB as universe expanded,

$$T(z) = T_0(1 + z) \qquad (23.1)$$

The very early universe

Big Bang Theory: Initially, the universe was very hot and as it expanded, it cooled down. Theory gives $T(t) = 1.52 \times 10^{10}\,\mathrm{K} \cdot (t/1\,\mathrm{s})^{-1/2}$



after Carroll & Ostlie, Fig. 30.2

Fundamental physics: unification of forces

- $t = 10^{-44}$ s: GUT & gravitation
  $\Longrightarrow$ Theory of Everything (TOE)
- $t = 10^{-34}$ s: electroweak & strong nuclear force
  $\Longrightarrow$ Grand Unifying Theory (GUT)
- $t = 10^{-11}$ s: electromagnetic & weak nuclear forces
  $\Longrightarrow$ electroweak force

Physics is understood from $t = 10^{-11}$ s after the Big Bang

---

The hot Big Bang

- 10^{-4} s after Big Bang: Temperature has decreased to $T = 10^{12}\,\mathrm{K}$, corresponding energy $E = kT = 86\,\mathrm{MeV}$
- Universe consists of only a few particle types:
  - photons γ, electrons e^-, positrons e^+, neutrinos: $\nu_\mathrm{e}, \nu_\mu, \nu_\tau$ and anti-neutrinos $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
  - few hadrons: protons p & neutrons n: $N(p) \sim 5 \times 10^{-10} N(\gamma)$
- reactions at work:
  - pair formation and annihilation:

$$\gamma \rightleftharpoons \mathrm{e}^- + \mathrm{e}^+ \quad \text{and} \quad \gamma \rightleftharpoons \nu_\mathrm{e} + \bar{\nu}_\mathrm{e}$$

  - transformation of particles:

$$\begin{aligned} \mathrm{n} &\rightleftharpoons \mathrm{p} + \mathrm{e}^- + \nu_\mathrm{e} \\ \mathrm{n} + \mathrm{e}^+ &\rightleftharpoons \mathrm{p} + \bar{\nu}_\mathrm{e} \\ \mathrm{n} + \nu_\mathrm{e} &\rightleftharpoons \mathrm{p} + \mathrm{e}^- \end{aligned}$$

- resulting thermodynamic equilibrium: neutron-proton-ratio:

$$\frac{N(\mathrm{n})}{N(\mathrm{p})} = \exp\left(-\frac{(m_\mathrm{p} - m_\mathrm{n})c^2}{kT}\right) \qquad (23.2)$$

where $(m_\mathrm{p} - m_\mathrm{n})c^2 = 1.293\,\mathrm{MeV} \Longrightarrow N_\mathrm{n}/N_\mathrm{p} = 0.985$

The hot Big Bang

- $t \sim 2\,\text{s}$: Temperature has decreased to $t \sim 2 \times 10^{10}\,\text{K}$.
  At this time: Timescale for nuclear reactions < Expansion time scale

Result: End of thermodynamical equilibrium, "freeze out"

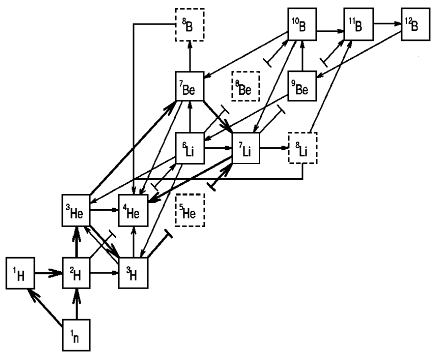
  - neutron-proton ratio now $N_\text{n}/N_\text{p} = 0.223$
  - Neutrino freeze-out: neutrinos decouple, no interaction with other particles
  - electron-positron pair formation stops at threshold 1.22 MeV (1.4×10^{10} K)
  - electrons and positrons annihilate ⟹ very few electrons remain
  - ⟹ no neutrons can be formed neutrons decay to protons (half-life 10.3 min.)
- $T = 10^9\,\text{K}$, $t = 230\,\text{s}$:
  - Deuterium formation: $p + n \rightleftharpoons d + \gamma$
  - Helium formation:

$$\text{d} + \text{d} \rightleftharpoons \text{t} + \text{p} \quad \text{and then} \quad \text{t} + \text{d} \rightleftharpoons {}^4\text{He} + \text{n}$$

and also

$$\text{d} + \text{d} \rightleftharpoons {}^3\text{He} + \text{n} \quad \text{and} \quad {}^3\text{He} + \text{d} \rightleftharpoons {}^4\text{He} + \text{p}$$

The hot Big Bang



Ohio State University

- Helium formation: neutrons start to decay

$$N_\text{n}(t) = 0.223 \exp\left(-\lambda\, t\right) \qquad (23.3)$$

where $\lambda = \ln 2/\tau$. Nucleosynthesis starts once $N_\text{n}/N_\text{p} = 0.164$.

Most neutrons still around manage to get bound in He before they decay:

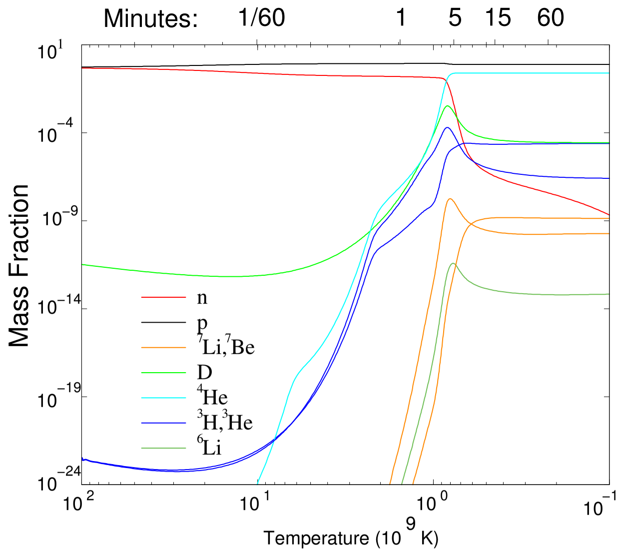
$$N_\text{He}/N_\text{H} \sim 0.1 \qquad (23.4)$$

(turns out to be almost independent of Ω)

- Some higher elements are also formed, especially ^{7}Li Abundances of deuterium, tritium, ^{3}He and ^{7}Li arestrongly dependent on Ω

Since there are no stable nuclei with A = 5 & 8, heavier elements can not form in Big Bang Nucleosynthesis.

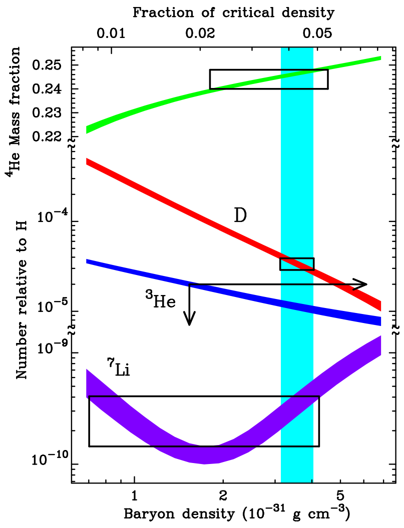
The hot Big Bang



Big Bang Nucleosynthesis finishes after a quarter of an hour!

(Burles, 1999)

The hot Big Bang



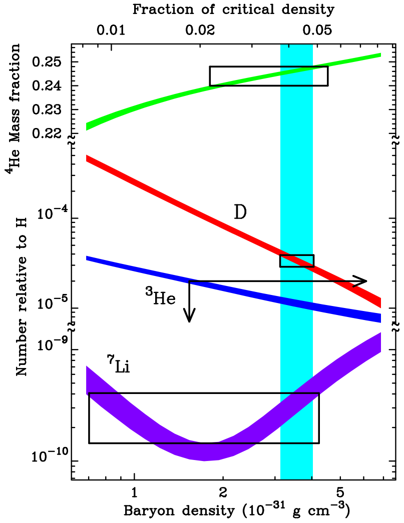
(Burles, 1999)

Synthesis of the elements in stars: Burbidge, Burbidge, Fowler & Hoyle (1957, B^{2}FH):

Stars produce much less He than observed

⟹ The helium (^{4}He) abundance is a smoking gun for the hot big bang

The hot Big Bang



(Burles, 1999)

Deuterium, ^{3}He & Lithium abundances: primordial abundances are very difficult to determine as these elements are easily destroyed in stars by thermonuclear reactions.

Can be approximately measured from old stars and the intergalactic medium

Result:

Density parameter $\Omega_{\mathrm{m}} = 0.04$: Normal matter (“baryons”) contributes 4% of the critical density.

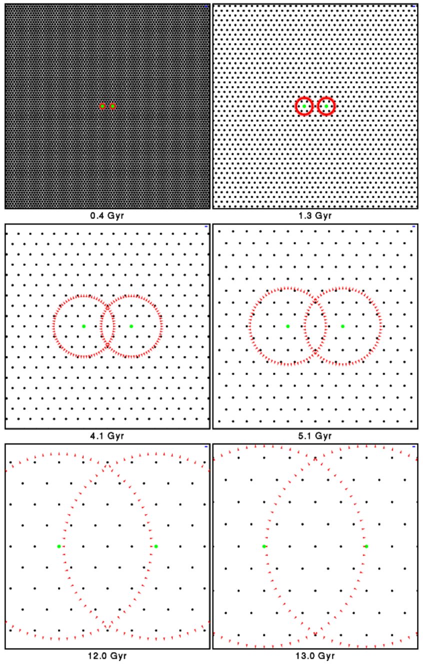
The hot Big Bang

BB works remarkably well in explaining the observed universe.

However, there are many problems with classical BB theory:

- Horizon problem:
  Why ist the CMB so isotropic?
- Flatness problem:
  Why is and was the density so close to critical, i.e., $\Omega = 1$?
- Baryogenesis:
  Why is there virtually no antimatter in the universe?
- What is the nature of Dark Matter & Dark Energy?
- Structure formation:
  The fluctuations of the cosmic microwave background are too small to allow stars & galaxies to form as early as observed. Why?

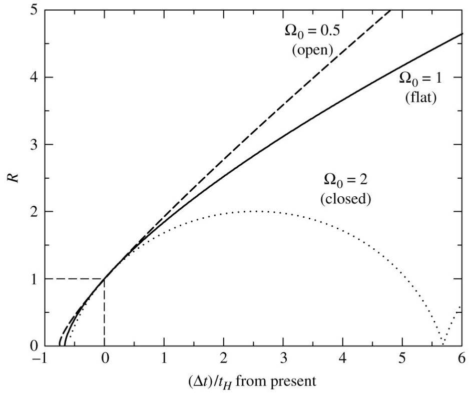
Inflation attempts to answer all of these questions.



courtesy E. Wright.

Expansion of horizon in an expanding universe.

The Flatness Problem



Carroll & Ostlie, Fig. 29.5

Because of expansion, Ω is changing with time:

$$\frac{1}{\Omega_0} - 1 = \left(\frac{1}{\Omega} - 1\right) \cdot (1 + z) \qquad (23.5)$$

What was Ω at time when radiation and matter decoupled ($T_{\mathrm{dec}} = 380000$ yrs; $z = 1100$)?

$\Longrightarrow$ assume $\Omega(T_{\mathrm{dec}}) = 2$:
Results in big crunch after $\sim$ 3 milllion years

$\Longrightarrow$ assume $\Omega(T_{\mathrm{dec}}) = 0.5$:
Results in a very fast evolution of the universe, no stars & galaxies can form.

Why is the universe (nearly) flat?

The matter/antimatter problem

The matter/antimatter problem

Early universe was in thermodynamic equilibrium

$\Longrightarrow$ there should have been as much matter as antimatter

But: If there were as much matter as antimatter formed in the Big Bang, they would have annihilated very soon.

$\Longrightarrow$ Only photons would have remained, we should not exist.

Observations of Big Bang nucleosynthesis: ratio of hadrons to photons: $\sim 5 \cdot 10^{-10}$

$\Longrightarrow$ slightly more matter than antimatter must have been formed.

There is no observational evidence for antimatter

(except for production by high energy cosmic rays)

$\Longrightarrow$ There must have been some kind of symmetry breaking in the production of elementary particles in the very early universe!

Inflation

Possible solution of these problems: inflation

Basic assumption of inflationary cosmology:

During the big bang there was a phase where Λ dominated the Friedmann equation.

Use the Friedmann equation with a cosmological constant:

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{23.6}$$

where $a = R(t)/R_0$

For $\Lambda =$ const. this gives

$$H(t) = \frac{\dot{a}}{a} = \sqrt{\frac{\Lambda}{3}} = \text{const.} \tag{23.7}$$

Solution of Eq. (23.7):

$$a \propto \mathrm{e}^{Ht} \tag{23.8}$$

Inflation

When and why did inflation happen?

Typical assumption: Inflation = phase transition of a scalar field (“inflaton”) associated with Grand Unified Theories = GUT.

(GUT predicts that the electromagnetic, weak nuclear, and strong nuclear forces are fused into a single unified field at energies above 10^{14} GeV)

$\Longrightarrow$ temperature $kT_{\mathrm{GUT}} = 10^{15}$ GeV, when $1/H \sim 10^{-34}$ sec ($t_{\mathrm{start}} \sim 10^{-34}$ s).

$\Longrightarrow$ inflation lasted for 100 Hubble times, i.e., for $\Delta T = 10^{-32}$ s.

With Eq. (23.8): Inflation: Expansion by factor $\mathrm{e}^{100} \sim 10^{43}$... corresponding to a volume expansion by factor $\sim 10^{130}$

$\Omega \neq 1$ (curved) before inflation $\Longrightarrow \Omega = 1$ (flat) thereafter.

Universe was so small before inflation that all parts of it were in causal contact.

Inflation solves horizon, antimatter, and flatness problem.

...but it was *constructed* to do so, and the real physical cause for inflation is still unclear.

Determination of Ω

Motivation

While most of the things happening during the Big Bang are rather insensitive to the detailed value of Ω, the evolution of the universe depends on

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} = \Omega_{\text{m}} + \Omega_{\Lambda} \tag{24.1}$$

where

$\Omega_{\mathbf{m}}$**:** Ω due to gravitating stuff (baryons and other things).
Ω_{Λ}**:** Ω due to vacuum energy or other exotic stuff.

Furthermore: inflation predicts $\Omega = 1$.

To decide whether that is true:

- need inventory of gravitating material in the universe,
- need to search for evidence of non-zero Λ

Will now work on Ω_{m}.

Motivation

Remember that

$$\Omega_{\text{m}} = \frac{\rho_{\text{m}}}{\rho_{\text{crit}}} = \frac{8\pi G\rho}{3H^2} \tag{22.17}$$

For a typical ensemble of stars,

$$\frac{M}{L} \approx \text{const.} \tag{24.2}$$

we therefore often express Ω in terms of a mass to luminosity ratio:

Using canonical luminosity density of universe, one can show that

$$\left.\frac{M}{L}\right|_{\text{crit}} = 1390\, h \frac{M_{\odot}}{L_{\odot}} \tag{24.3}$$

. . . which means that there *must* be lots of dark matter if $\Omega = 1$.

$h = H/100\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$

Introduction

Constituents of Ω_{m}:

- Radiation (3 K radiation)
- Neutrinos
- Baryons (“normal matter”, Ω_{b})
- Other, non-radiating, gravitating material (“dark matter”)

Radiation: From temperature of 3 K radiation, using $u = \rho c^2 = a_{\text{rad}} T^4$:

$$\Omega_{\gamma} h^2 = 2.480 \times 10^{-5} \tag{24.4}$$

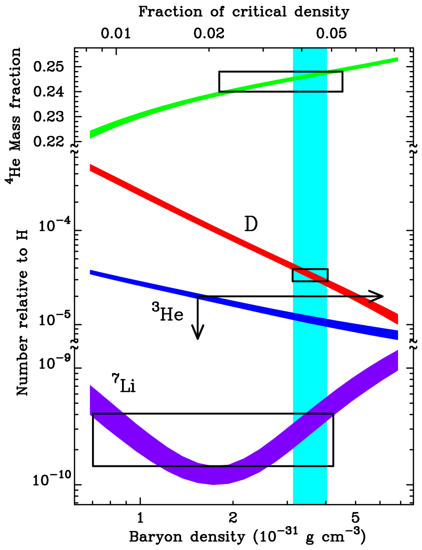
for $h = 0.72$: $\Omega_{\gamma} = 4.8 \times 10^{-5}$

Massless Neutrinos have

$$\Omega_{\nu} = 3 \cdot \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \Omega_{\gamma} = 0.68\, \Omega_{\gamma} \tag{24.5}$$

Photons and neutrinos are unimportant for todays Ω.

Baryons



Best evidence for mass in baryons, Ω_{b}: primordial nucleosynthesis.

$$\Omega_{\mathrm{b}} h^2 = 0.02 \pm 0.002 \qquad (24.6)$$

(Burles et al., 1999, Fig. 1)

Coma Cluster (O. Lopez-Cruz, I. K. Shelton, & KPNO)

Galaxy Clusters

For mass of galaxy clusters, make use of the virial theorem (see earlier homework):

$$E_{\mathrm{kin}} = -E_{\mathrm{pot}}/2 \qquad (24.7)$$

in statistical equilibrium.

Measurement: assume isotropy, such that

$$\left\langle v^2 \right\rangle = \left\langle v_x^2 \right\rangle + \left\langle v_y^2 \right\rangle + \left\langle v_z^2 \right\rangle = 3 \left\langle v_\parallel^2 \right\rangle \qquad (24.8)$$

Assuming that the velocity dispersion is independent of m_i gives:

$$E_{\mathrm{kin}} = \frac{1}{2} \sum_i m_i \mathbf{v}_i^2 = \frac{3}{2} M \left\langle v_\parallel^2 \right\rangle \qquad (24.9)$$

where M is the total mass.

If the cluster is spherically symmetric $\Longrightarrow$ Define weighted mean separation R_{cl}, such that

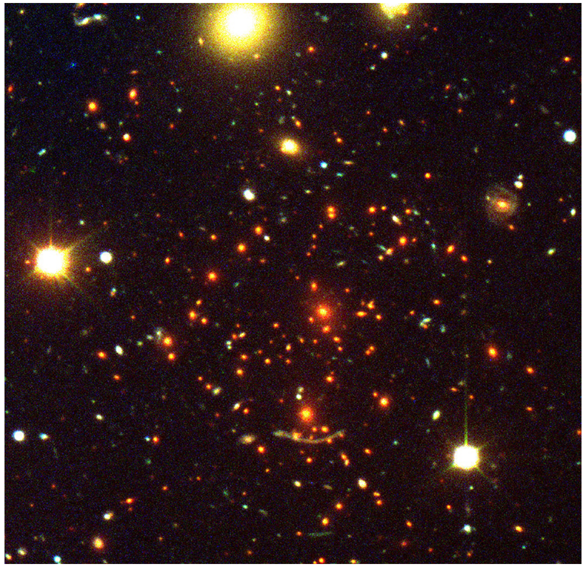
$$E_{\mathrm{pot}} = \frac{GM^2}{R_{\mathrm{cl}}} \qquad (24.10)$$

From Eqs. (24.9) and (24.10):

$$M = \frac{3}{G} \left\langle v_\parallel^2 \right\rangle R_{\mathrm{cl}} \qquad (24.11)$$

E.g.: $v_\parallel \sim 1000\,\mathrm{km\,s^{-1}}$, $R \sim 1\,\mathrm{Mpc} \Longrightarrow M = 1.4 \times 10^{48}\,\mathrm{g} = 7 \times 10^{14}\,M_\odot$ (MW: $6 \times 10^{11}\,M_\odot$).

Galaxy Clusters



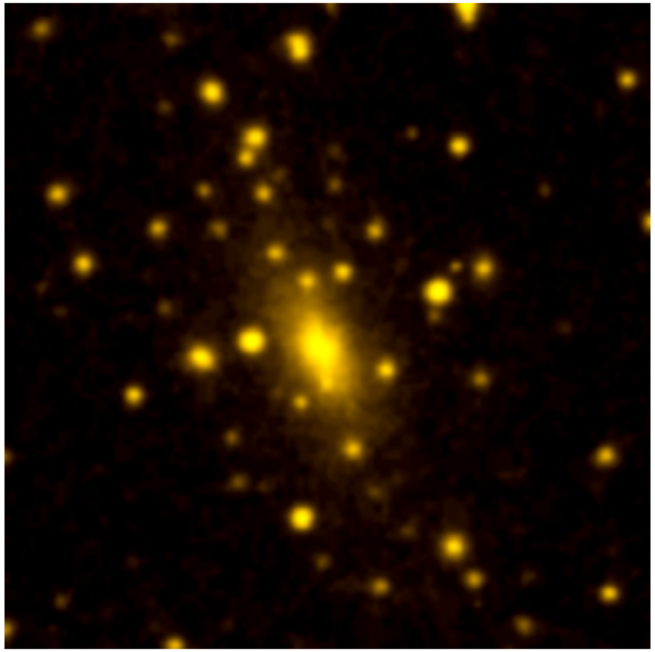
More detailed analysis using more complicated mass models gives (Merritt, 1987):

$$\frac{M}{L} \sim 350 h^{-1} \frac{M_\odot}{L_\odot} \qquad (24.12)$$

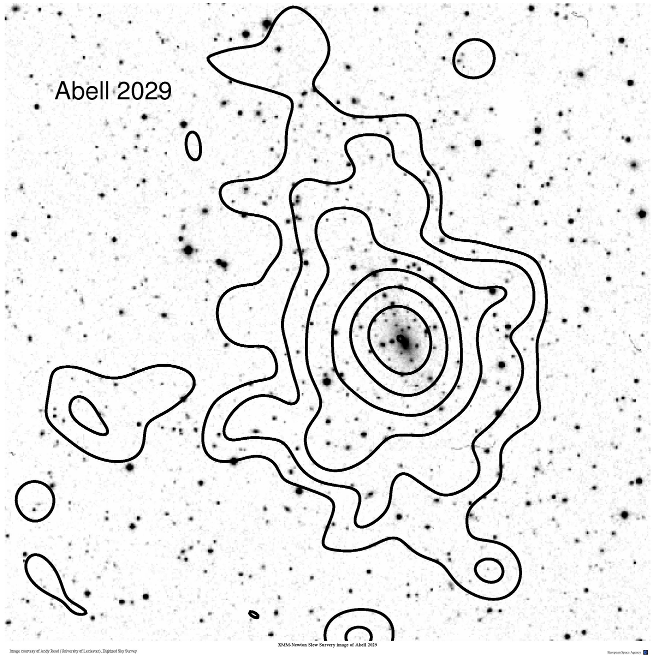
while we would have expected $M/L = 10 \ldots 20$ as for galaxies

Dark matter is an important constituent in galaxy clusters

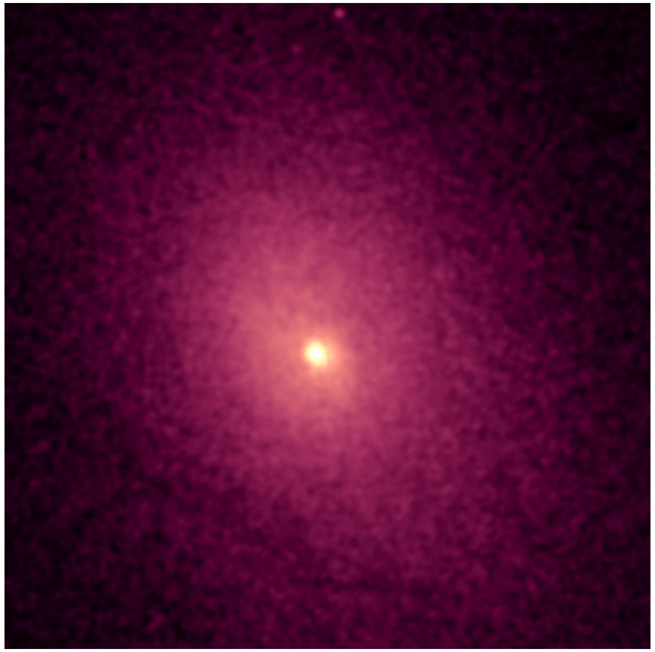
Abell 370 (VLT UT1+FORS)



Abell 2029, Palomar Schmidt [DSS]



Abell 2029, Optical and X-rays (*XMM-Newton*; Andy Read [Leicester]/DSS/ESA; larger FoV)



Abell 2029, Soft X-rays (*Chandra*; NASA/CXC/UCI/A.Lewis et al.)

X-ray emission

X-ray emission from galaxy clusters gives mass to higher precision:

Assume gas in potential of galaxy cluster. If gas is in hydrostatic equilibrium:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM_r\rho}{r^2} \tag{24.13}$$

where the pressure P:

$$P = nkT = \frac{\rho kT}{\mu m_\mathrm{H}} \tag{24.14}$$

where m_H: mass of H-atom, μ mean molecular weight of gas ($\mu = 0.6$ for fully ionized).

Differentiating Eq. (24.14) wrt r gives

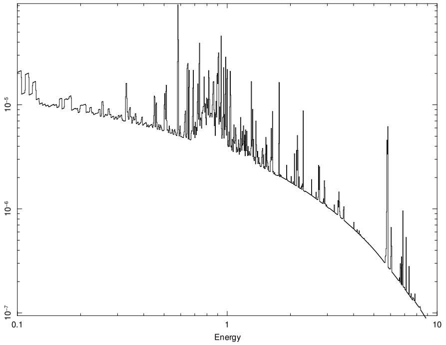
$$\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{k}{\mu m_\mathrm{H}}\left(T\frac{\mathrm{d}\rho}{\mathrm{d}r} + \rho\frac{\mathrm{d}T}{\mathrm{d}r}\right) = \frac{\rho kT}{\mu m_\mathrm{H}}\left(\frac{\mathrm{d}\log\rho}{\mathrm{d}r} + \frac{\mathrm{d}\log T}{\mathrm{d}r}\right) \tag{24.15}$$

Inserting d$P/$dr into Eq. (24.13) and solving for M_r gives

$$M_r = -\frac{kTr^2}{G\mu m_\mathrm{H}}\left(\frac{\mathrm{d}\log\rho}{\mathrm{d}r} + \frac{\mathrm{d}\log T}{\mathrm{d}r}\right) \tag{24.16}$$

X-ray emission

To determine M_r, we need to measure $T(r)$ and $\rho(r)$. These quantities can be obtained from the observed X-ray spectrum:



Theoretical X-ray spectrum of a cluster.

Cluster gas mainly radiates by bremsstrahlung emission, with a spectral continuum shape

$$\epsilon(E) \propto \left(\frac{m_\mathrm{e}}{kT}\right)^{1/2} g(E,T)\, n\, n_\mathrm{e} \exp\left(-\frac{E}{kT}\right) \tag{24.17}$$

where

n: number density of nuclei,

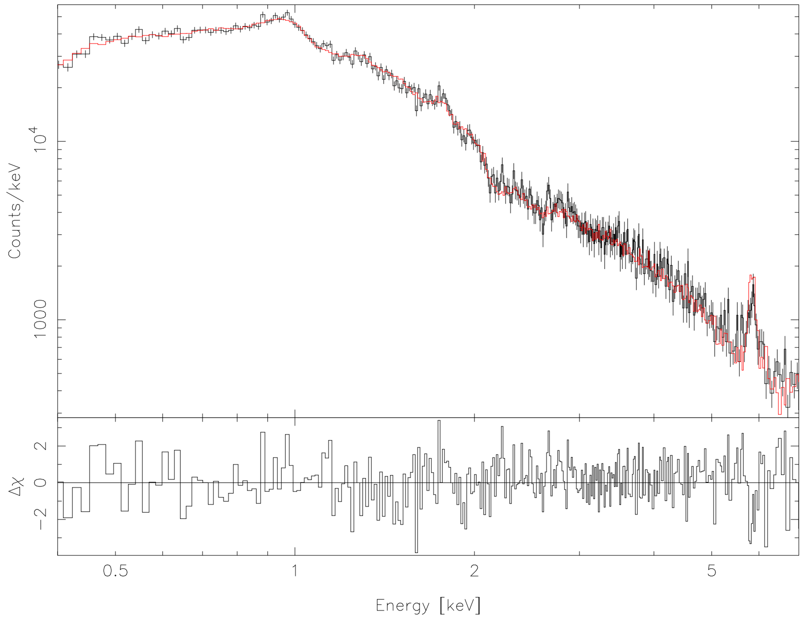
n_e: number density of electrons,

$g(E,T)$: Gaunt factor (QM correction factor, roughly constant).

plus emission lines. . .

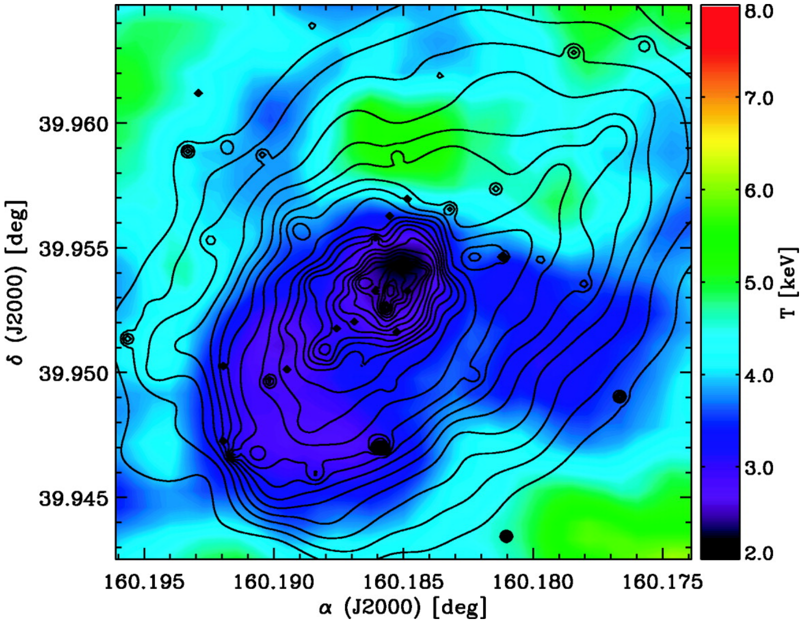
$\Longrightarrow$ $T(r)$ can be obtained from the X-ray spectral shape, n and n_e from the measured flux

$\Longrightarrow$ M_r.



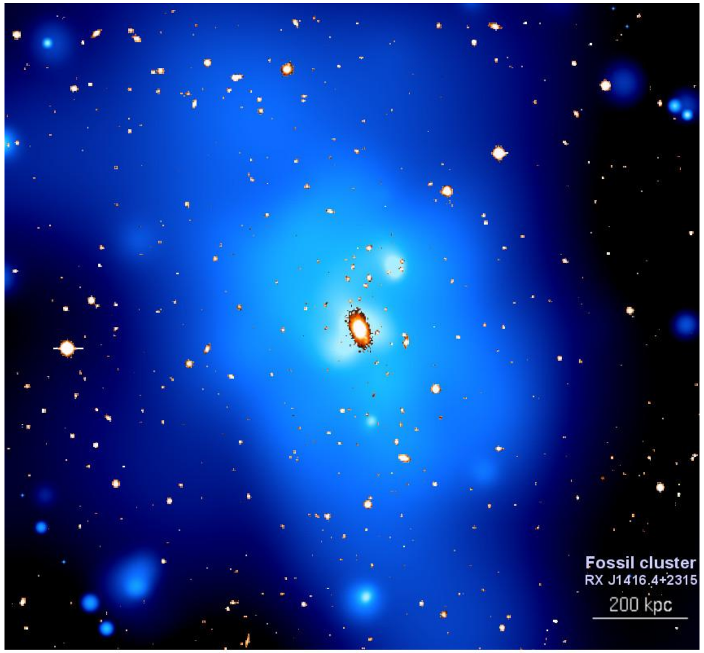
(Wise et al., 2004, Fig. 2)

X-ray spectrum of A1068 obtained from *Chandra*



(Wise et al., 2004, Fig. 8)

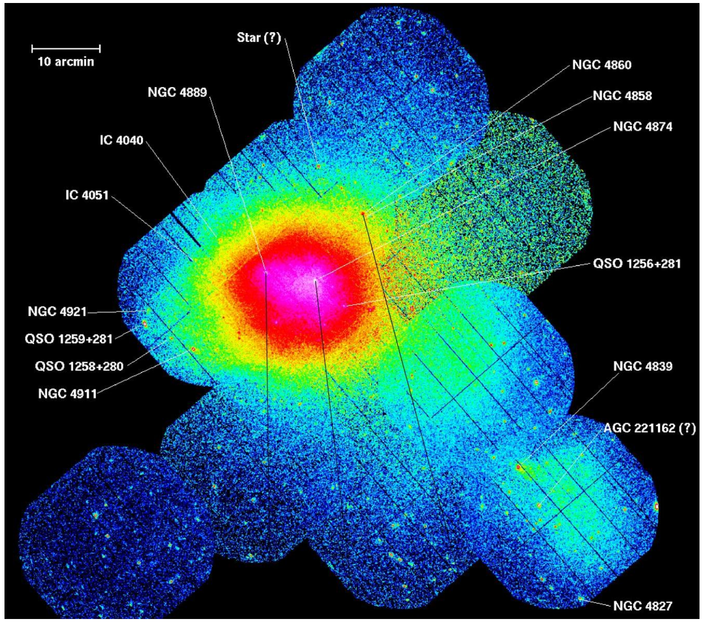
Temperature distribution in A1068 obtained with *Chandra*



XMM-Newton explores the fossil galaxy cluster RX J1416.4+2315

Image courtesy of Habib Khosroshahi (University of Birmingham)

European Space Agency



Technical problems:

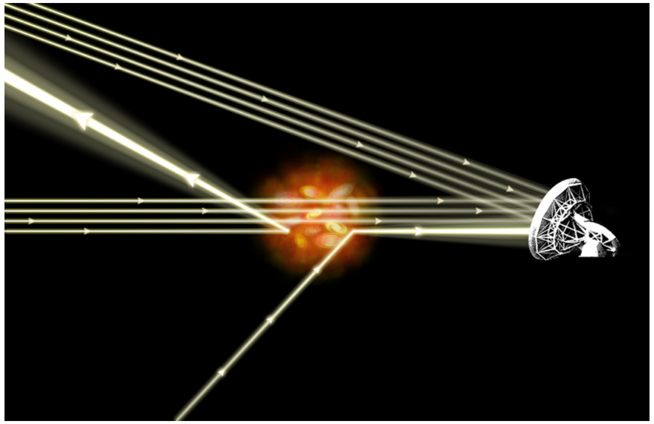
- see through cluster $\Longrightarrow$ integrate over line of sight, assuming spherical geometry.
- spherical geometry is assumed
- it is unclear whether gas is in hydrostatic equilibrium (cooling flows? – but note, there is sparse evidence for a "flow")

XMM-Newton, EPIC-pn

General Result:

$$\Omega_\mathrm{m} = \Omega_\mathrm{b}/f_\mathrm{gas} = (0.3 \pm 0.05)\,h^{-1/2} \qquad (24.18)$$

Sunyaev-Zeldovich



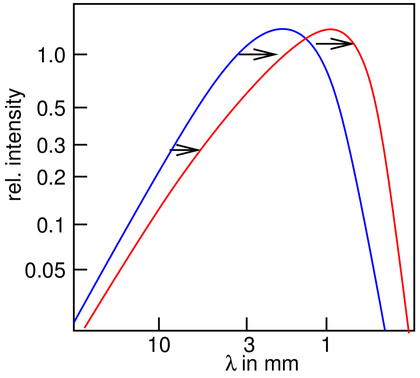
NASA/CXC/M.Weiss

Gas in cooling flow influences CMBR by Compton upscattering

$\Longrightarrow$ Sunyaev-Zeldovich effect (1970).

Sunyaev-Zeldovich

The quantitative derivation of the SZ-effect cannot be done in an introductory lecture.



after Schneider

The basic ingredients are the optical depth for Compton scattering (Compton y-parameter):

$$y = \int \left(\frac{kT_\mathrm{e}}{m_\mathrm{e}c^2}\right) \sigma_\mathrm{T} N_\mathrm{e}\,\mathrm{d}l \qquad (24.19)$$

From this follows in the Rayleigh-Jeans regime that the intensity due to Compton upscattering changes as follows:

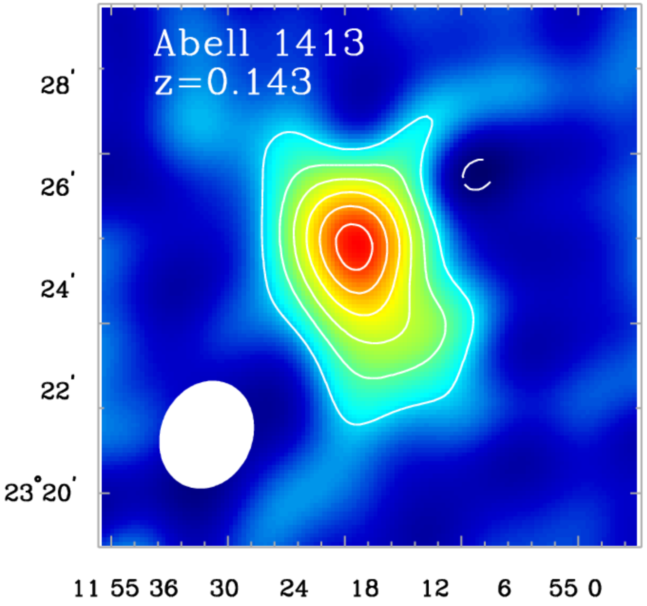
$$\frac{\Delta I}{I} = -2y \sim 10^{-4} \qquad (24.20)$$

(for typical parameters).

$\Longrightarrow$ ΔI allows to measure of $\int N_\mathrm{e} T_\mathrm{e}\,\mathrm{d}l$

$\Longrightarrow$ Mass!

T is known from X-ray spectrum.



(temperature decrement from 3 K background, Carlstrom et al., 2000, Fig. 3)

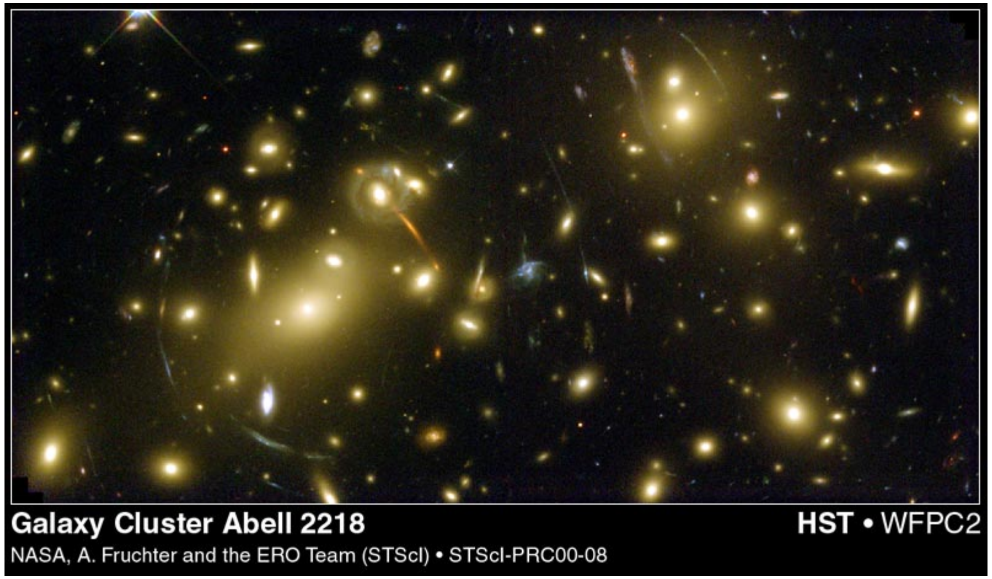
SZ analysis gives gas fraction for 27 clusters

$$f_\mathrm{gas} = (0.06 \pm 0.006) h^{-3/2} \qquad (24.21)$$

remarkably similar to X-ray result $\Longrightarrow$ clumping of gas does not influence results! (SZ only traces real gas...)

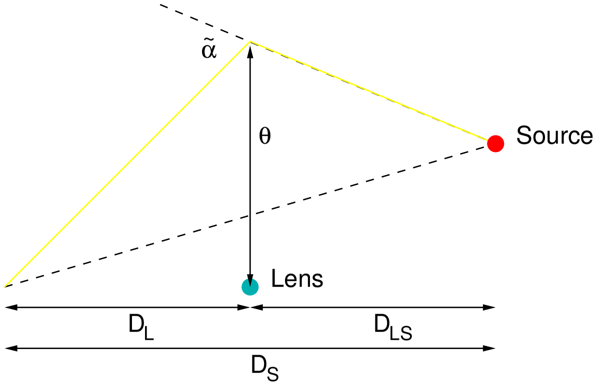
f_gas translates to

$$\Omega_\mathrm{m} = (0.25 \pm 0.04)\,h^{-1} \qquad (24.22)$$


Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Gravitational Lenses

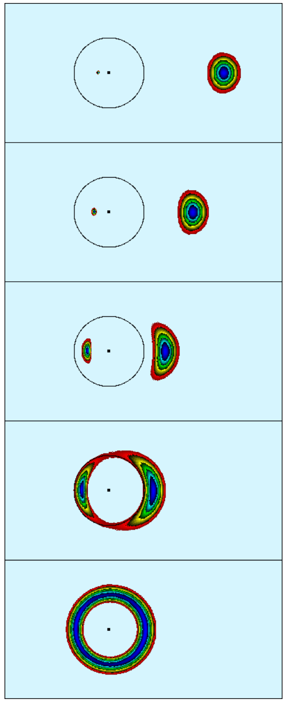


(after Longair, 1998, Fig. 4.8a)

GR: Angular deflection of light due to presence of mass M:

$$\tilde{\alpha} = \frac{4GM}{\theta c^2} = \frac{2}{c^2} \cdot \frac{2GM}{\theta} \qquad (24.23)$$

where θ: distance of closest approach (*twice* the classical result).



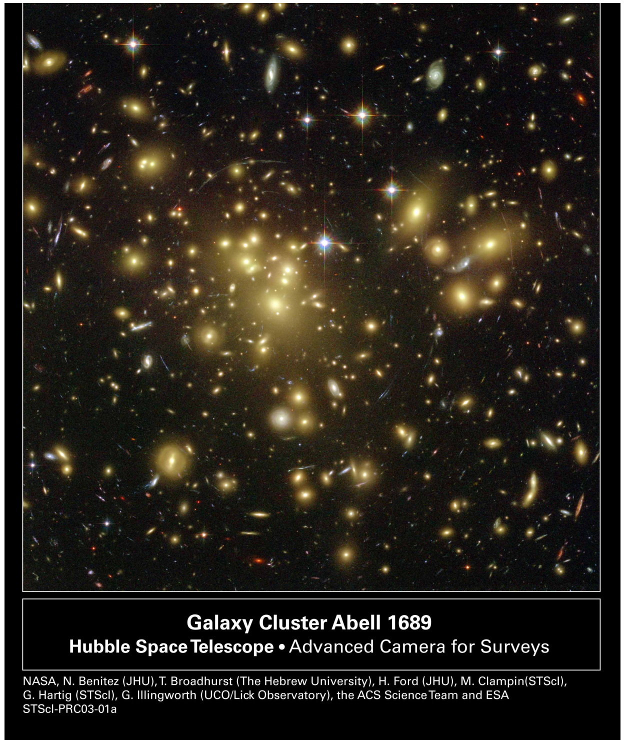
Einstein ring: source directly behind lens, Lens Radius is found to be:

$$\theta_{\text{E}}^2 = \frac{4GM}{c^2}\frac{1}{D} \qquad (24.24)$$

i.e.,

$$\theta_{\text{E}} = 98.9'' \left(\frac{M}{10^{15}\,M_\odot}\right)^{1/2} \frac{1}{(D/1\,\text{Gpc})^{1/2}} \qquad (24.25)$$

Mass measurements possible by observing “giant luminous arcs” and Einstein rings.


Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

General results of mass determinations from lensing agree with other methods.

Summary

So far, we have seen:

Photons:

$$\Omega_\gamma h^2 = 2.480 \times 10^{-5} \tag{24.26}$$

Neutrinos:

$$\Omega_\nu h^2 = 1.69 \times 10^{-5} \tag{24.27}$$

Baryons (from nucleosynthesis):

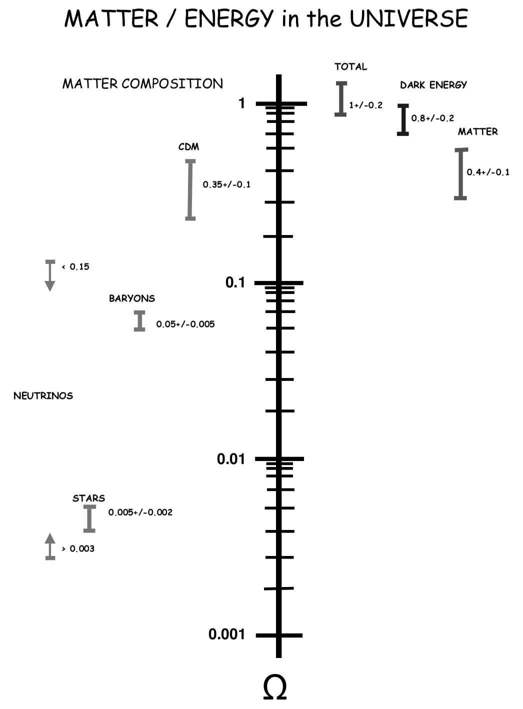
$$\Omega_\mathrm{b} h^2 = 0.02 \quad \text{where} \quad \Omega_\text{stars} \sim 0.005 \ldots 0.01 \tag{24.28}$$

Baryons+dark matter (from clusters):

$$\Omega_\mathrm{m} \sim 0.25 \tag{24.29}$$

(of which $\sim 10\%$ in baryons)

If we believe in $\Omega_\text{total} \equiv 1 \Longrightarrow \Omega_\Lambda \sim 0.7$.



(Turner, 1999, Fig. 1, numbers slightly different to ours. . .)

The Nature of Dark Matter

Big Bang Nucleosynthesis:

Normal (baryonic) matter density: only ∼ 4% of the critical density ($\Omega_m \sim 0.04$).

Observed (concordance) model: $\Omega = 0.28$

What is the missing Dark Matter?

Nonbaryonic dark matter

Requirements:

- gravitating
- no or very weak other interaction with baryons (="us")

The Nature of Dark Matter

$\Longrightarrow$ Grab-box of elementary particle physics:

1. Neutrinos with non-zero mass

   Pro: It exists, mass limits are a few eV, need only $\langle m_\nu c^2 \rangle \sim 10\,\mathrm{eV}$

   Contra: ν are relativistic ($v \sim c$), this has implications for galaxy formation that make it unlikely that they form a major part of dark matter.

2. WIMPs (weakly interacting massive particles; masses $mc^2 \sim$ GeV)

   Pro: may be identified with Super-symmetric particles predicted by elementary particle theory.

   Contra: We do not know they exist. . . (but they might soon be detectable by the Large Hadron collider (LHC) at CERN.)

WIMPS are heavy and therefore non-relativistic ("move slowly") $\Longrightarrow$ helps to explain formation of first stars and galaxies.

WIPMS = Cold Dark Matter

Burles, S., Nollett, K. M., & Turner, M. S. 1999, Big-Bang Nucleosynthesis: Linking Inner Space and Outer Space, APS Centennial Exhibit, astro-ph/9903300

Carlstrom, J. E., Joy, M. K., Grego, L., et al. 2000, Phys. Scr., T85, 148

Merritt, D., 1987, ApJ, 313, 121

Turner, M. S., 1999, in The Third Stromlo Symposium: The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, M. E. Putmann, Astron. Soc. Pacific, Conf. Ser., ASP), in press (astro-ph/9811454)

Wise, M. W., McNamara, B. R., & Murray, S. S. 2004, ApJ, 601, 184

Determination of Λ

Friedmann with $\Lambda \neq 0$

$\Longrightarrow$ So far we have ignored Λ

Friedmann equation with $\Lambda \neq 0$:

$$H^2(t) = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3} \tag{23.6}$$

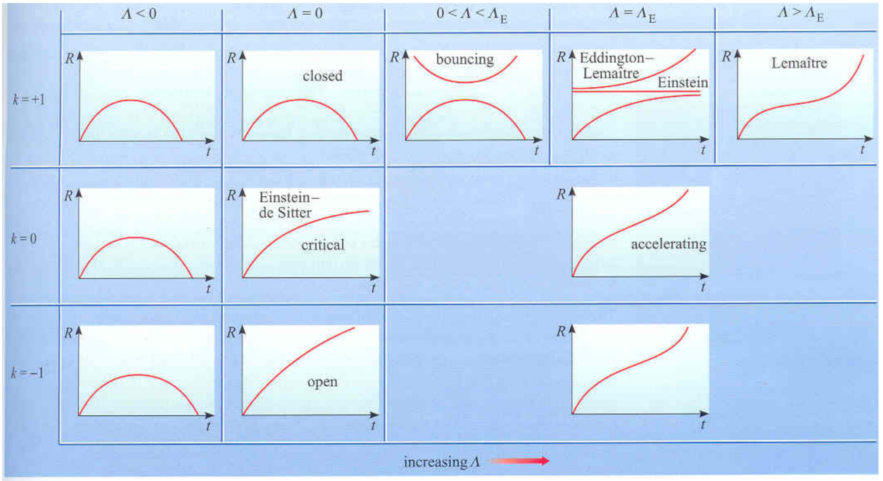
And define the Ωs:

$$\Omega_\mathrm{m} = \frac{8\pi G\rho_\mathrm{m}}{3H_0^2}, \qquad \Omega_\Lambda = \frac{\Lambda c^4}{3H_0^2}, \qquad \Omega_k = -\frac{kc^2}{R_0^2H_0^2} \tag{25.1}$$

Because of Eq. (23.6),

$$\Omega_\mathrm{m} + \Omega_\Lambda + \Omega_k = \Omega + \Omega_k = 1 \tag{25.2}$$

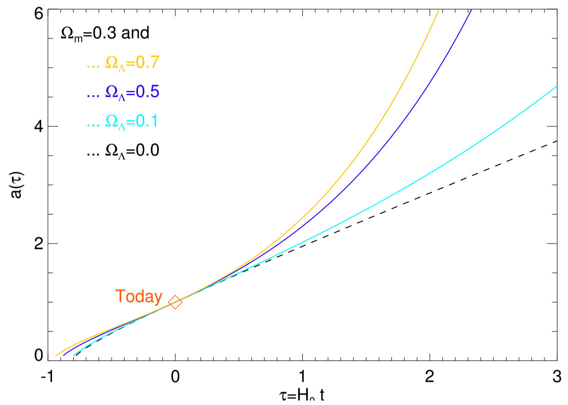
Friedmann with $\Lambda \neq 0$



Jones & Lambourne: An Introduction to Galaxies and Cosmology

Many different kinds of world models are possible, depending on Ω und Λ.

$\Omega_\Lambda < 1$



For $\Omega_\Lambda < 1$: first matter domination, similar to earlier results, then Λ domination, exponential rise.

Universes with $\Omega_\Lambda > 0$ are *older* than those with $\Omega_\Lambda = 0$.

This solves the age problem, that some globular clusters have age comparable to age of universe if $\Omega_\Lambda = 0$.

Motivation

We have already seen that evolution of the universe depends on

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} = \Omega_{\text{m}} + \Omega_\Lambda \qquad (25.3)$$

where

$\Omega_{\mathbf{m}} = 0.3$**:** Ω due to gravitating stuff,
Ω_Λ**:** Ω due to vacuum energy or other exotic stuff.

If inflation is true and $\Omega = 1$, then

$$\Omega_\Lambda = \frac{\rho_{\text{vac}}}{\rho_{\text{crit}}} = \frac{\rho_{\text{vac}}}{3H^2/8\pi G} = \frac{\Lambda c^4}{3H^2} = 0.7 \qquad (25.4)$$

Influence of Λ is most prominent at large distances!

$\Longrightarrow$ Expect influence on Hubble Diagram.

Luminosity Distance

For Hubble diagram: Need to find relation between measured flux, emitted luminosity, and redshift.

Assume source with luminosity L at comoving coordinate r, emitting isotropically into 4π sr.

At time of detection today, photons are

- on sphere with proper radius $R_0 r$,
- redshifted by factor $1 + z$,
- spread in time by factor $1 + z$.

$\Longrightarrow$ observed flux is

$$F = \frac{L}{4\pi R_0^2 r^2 (1+z)^2} =: \frac{L}{4\pi d_{\text{L}}^2} \quad \text{where} \quad d_{\text{L}} = R_0 \cdot r \cdot (1+z) \qquad (25.5)$$

where d_{L} is called the luminosity distance

The calculation of d_{L} is somewhat technical, one can show that (Carroll et al., 1992):

$$d_{\text{L}} = \frac{c}{H_0} |\Omega_k|^{-1/2} \cdot S_{-\text{sgn}(\Omega_k)} \left\{ |\Omega_k|^{1/2} \int_0^z \left[(1+z)^2 (1 + \Omega_{\text{m}} z) - z(2+z)\Omega_\Lambda \right]^{1/2} \, \mathrm{d}z \right\} \qquad (25.6)$$

Supernovae

Best way to determine Ω_Λ:

Type Ia supernovae

The distance modulus is

$$m - M = 5 \log \left(\frac{d_{\text{L}}}{1\,\text{Mpc}} \right) + 25 \qquad (25.7)$$

Use SNe as standard candles $\Longrightarrow$ Deviations from $d_{\text{L}} \propto z$ are indicative of Λ.

Two projects:

- High-z Supernova Team (STSCI, Riess et al.)
- Supernova Cosmology Project (LBNL, Perlmutter et al.)

Both find SNe out to $z \sim 1$.

Supernovae

Basic observations: easy:

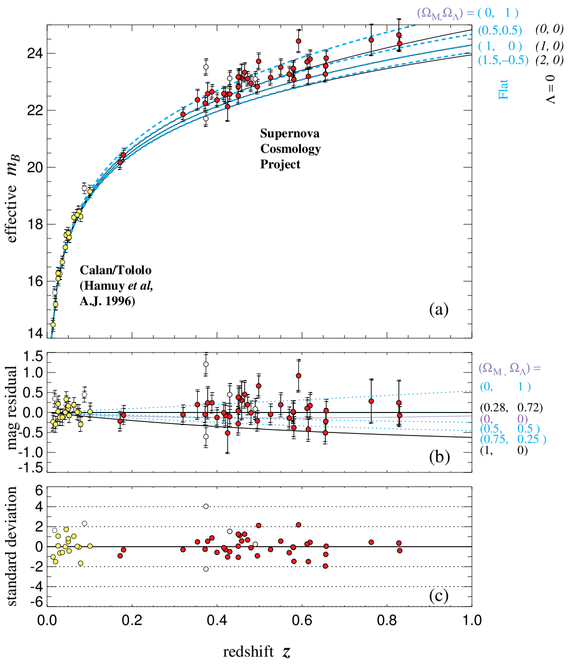
- Detect SN in rise $\Longrightarrow$ CTIO 4 m
- Follow SN for $\sim$ 2–3 months with 2–4 m class telescopes, HST, Keck. . .

More technical problems in data analysis: Conversion into source frame:

- Correction of photometric flux for redshift: “K-correction”
- Correct for time dilatation in SN light curve

Further things to check

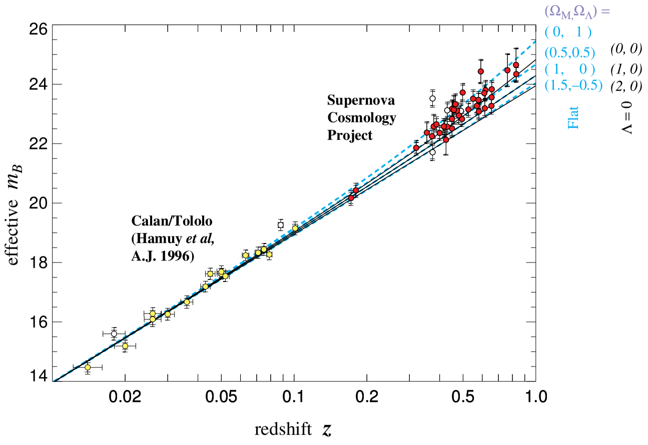
- SN internal extinction
- Galactic extinction
- Galactic reddening
- Photometric cross calibration
- Peculiar motion of SN



Best fit: $\Omega_{\mathrm{m,\,flat}} = 0.28^{+0.09}_{-0.08}$,
$\chi^2/\mathrm{DOF} = 56/50$
corresponding best free fit:
$(\Omega_{\mathrm{m}}, \Omega_\Lambda) = (0.73, 1.32)$.

(Perlmutter et al., 1999, Fig. 2)

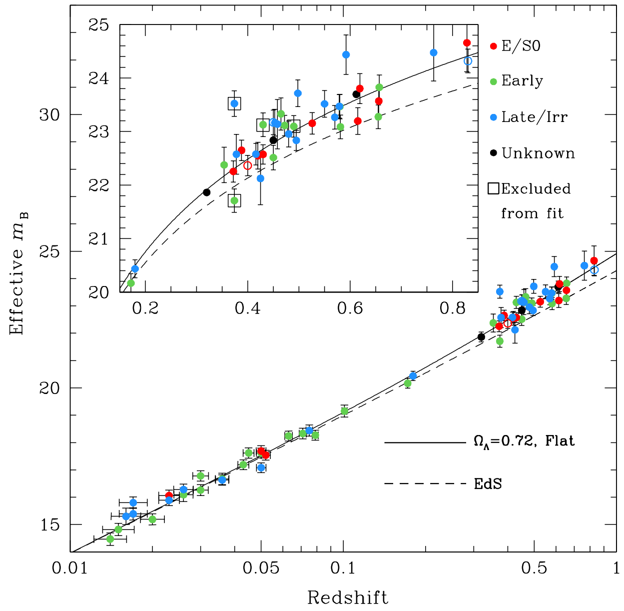
Supernovae



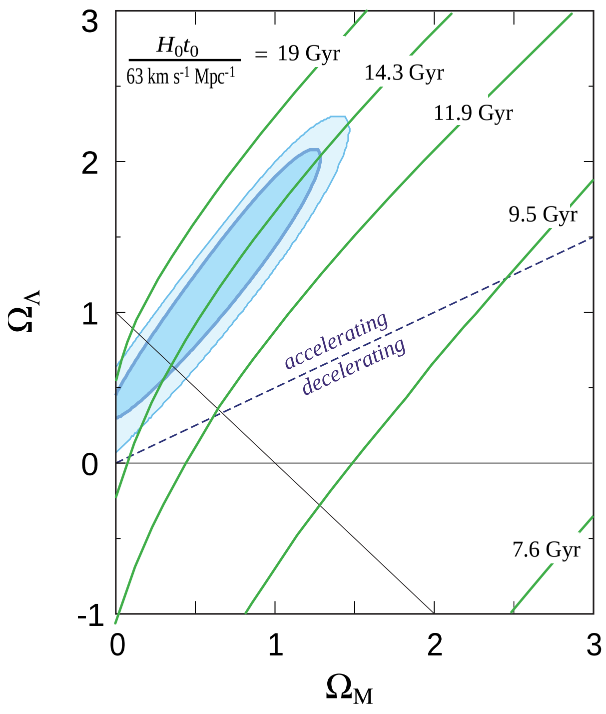
Vertical error bars:
measurement
uncertainty *plus*
0.17 mag intrinsic mag.
dispersion
Horizontal error bars:
300 km s^{-1} peculiar
velocity uncertainty

(Perlmutter et al., 1999, Fig. 1)

42 SNe from SCP, 18 low redshift from Calán/Tololo SN Survey



Updated 2002 Hubble diagram for SN Iae confirms Perlmutter (1999).



Isochrones for age of universe for $H_0 = 63\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (for $h = 0.7$: age 10% smaller).
$\Longrightarrow$ Consistent with globular cluster ages!

(Perlmutter et al., 1999, Fig. 9)

Summary

For all practical purposes, currently the best values of Ω_m and Ω_Λ are

$\Omega_\mathrm{m} \sim 0.3$ and $\Omega_\Lambda = 0.7$

Even if $\Omega \neq 1$:

$\Omega_\Lambda \neq 0$

And therefore

Baryons are an energetically unimportant constituent of the universe.

The Nature of Dark Energy

- What is the physical meaning of Einstein's cosmological constant Λ?
- candidate: vacuum energy (Ground state energy of the universe)
- Equation of state:

$$P_\mathrm{vac} = -\rho_\mathrm{vac} \cdot c^2 = -u_\mathrm{vac} \qquad (25.8)$$

  where u_vac = energy density $\Longrightarrow$ negative pressure!
- quantum field theory predicts a huge energy density: $u_\mathrm{vac} = 10^{111}\,\mathrm{J\,m^{-3}}$
- Observation: $u_\mathrm{dark} = \rho_\Lambda \cdot c^2 = 6 \cdot 10^{-10}\,\mathrm{J\,m^{-3}}$
- mismatch by 120 orders of magnitude

The Nature of Dark Energy

Currently discussed to solve vacuum energy problem: quintessence: “rolling scalar field”, corresponding to very lightweight particle ($\lambda_\text{de Broglie} \sim 1$ Mpc), looks like time varying cosmological “constant”.

Why? $\Longrightarrow$ More naturally explains why Ω_Λ so close to 0 (i.e., why matter and vacuum have so similar energy densities)

Motivated by string theory and M theory…

Still VERY SPECULATIVE, decision Λ vs. quintessence should be possible in next 5…10 years when new instruments become available.

Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 50, 499

Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565

Evolution of the Universe

Structures

So far: looked at smooth universe (determination of Ω, Λ,...).

But in reality: Universe has structure: humans, stars, galaxies, galaxy clusters

Question: how did structures form in the universe?

Better definition for “structure”: density perturbations

> “Structure formation”: Study of the formation of density perturbations in an initially approximately smooth universe and of their evolution

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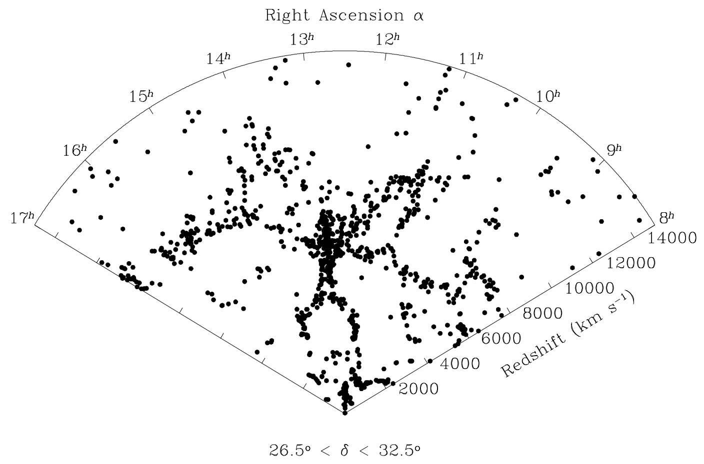
Introduction



(limiting mag $m_\mathrm{B} = 15.6$, Lapparent, 1986)

Lumpy universe: spatial distribution of galaxies and greater structures.

Introduction

How do we study the structure of the Universe?

$\Longrightarrow$ We need distance information for many ($10^4 \dots 10^7$) objects

$\Longrightarrow$ Large redshift surveys

Review: Strauss, 1995

Redshift survey: Survey of (patch of) sky determining galaxy z and position to predefined magnitude or z.

First larger survey: Lapparent et al., (1986)

Classification:

1D-surveys: very deep exposures of small patch of sky, e.g., HST Deep Field, Lockman Hole Survey, COSMOS Field, Marano Field.

2D-surveys: cover long strip of sky, e.g., CfA-Survey ($1.5 \times 100^\circ$), 2dF-Survey (“2 degree Field”).

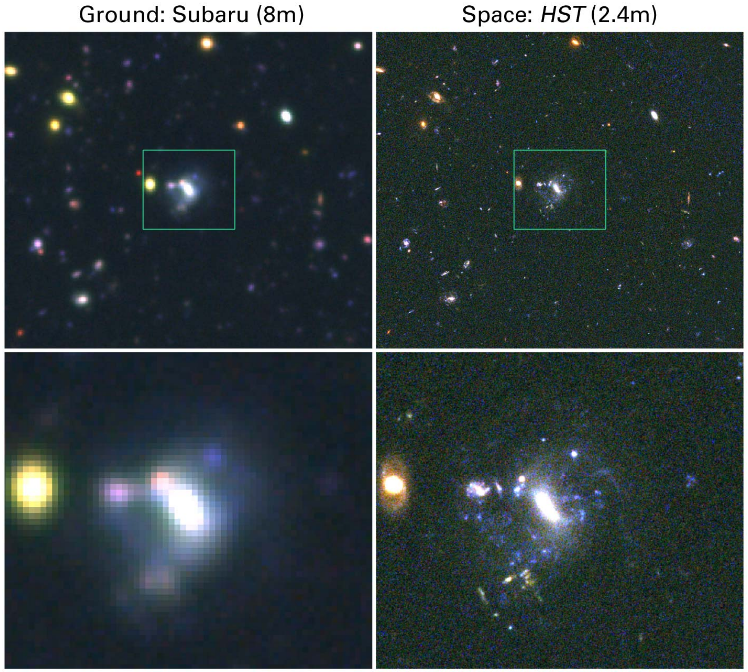
3D-surveys: cover part of the sky, e.g., Sloan Digital Sky Survey.

These surveys attempt to go to certain limit in z or m.

Other approaches: use pre-existing galaxy catalogues (e.g., QDOT Survey [IRAS galaxies], APM survey,…).

We will concentrate here on the larger surveys based on no other catalogue.

STScI



To go deep one needs to go to space

Hubble Space Telescope

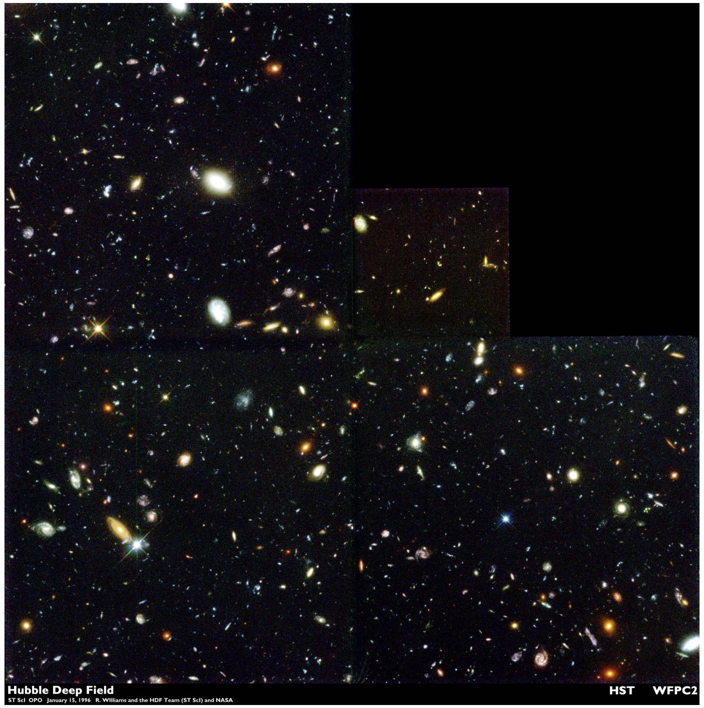
The Hubble Space Telescope has a large set of instruments well suited for cosmological observations:

Current HST Instruments :

- WFC3: Wide Field Camera 3 (05.2009–)
- COS: Cosmic Origins Spectrograph (05.2009–)
- ACS: Advanced Camera for Surveys (03.2002–)
- STIS: Space Telescope Imaging Spectrograph (02.1997–)
- NICMOS: Near Infrared Camera and Multi Object Spectrometer (02.1997–)
- FGS: Fine Guidance Sensors

Former Generation Instruments :

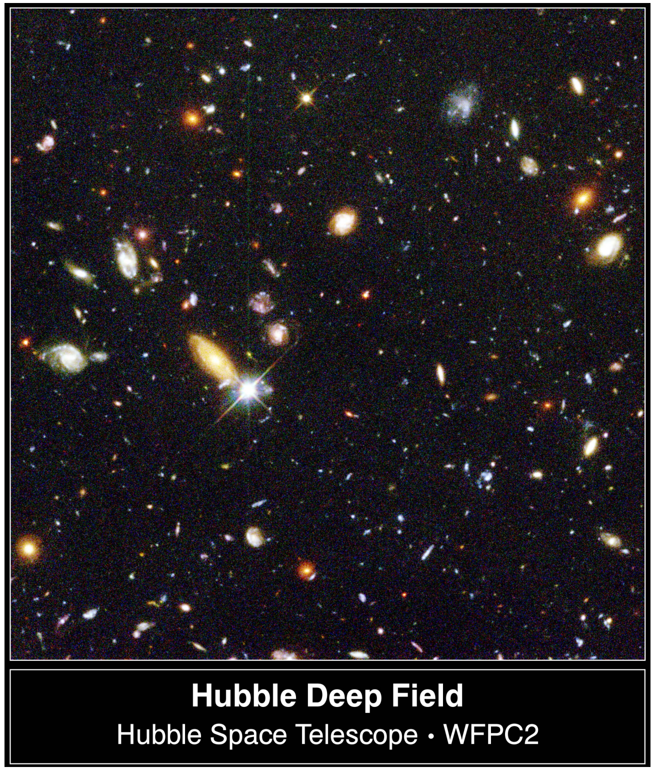
- FOC: The Faint Object Camera (04.1990–03.2002)
- FOS: The Faint Object Spectrograph (04.1990–02.1997)
- GHRS: The Goddard High Resolution Spectrograph (04.1990–02.1997)
- HSP: The High Speed Photometer (04.1990–10.1993)
- WF/PC-1: Wide Field Planetary Camera 1 (04.1990–10.1993)
- WFPC2 The Wide Field Planetary Camera 2 (12.1993–05.2009)

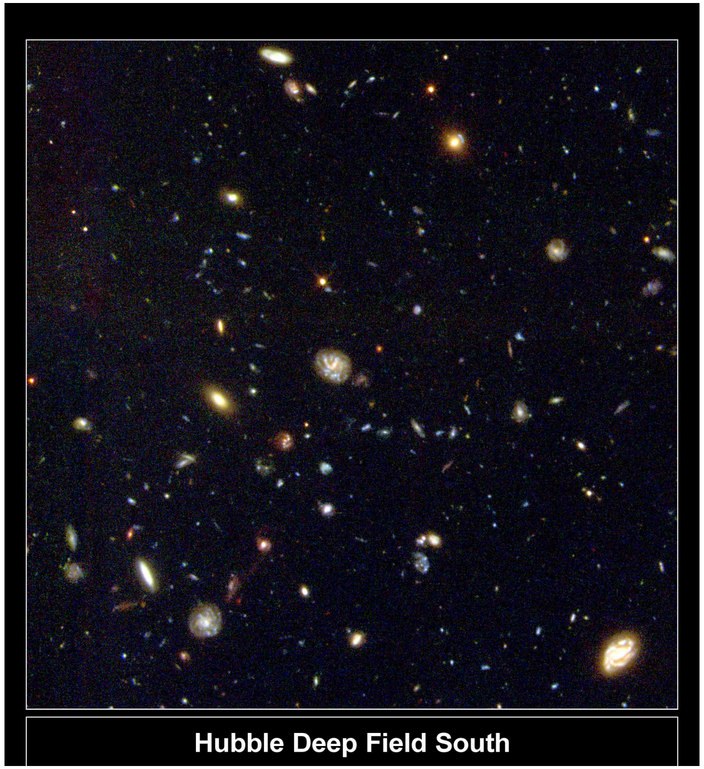


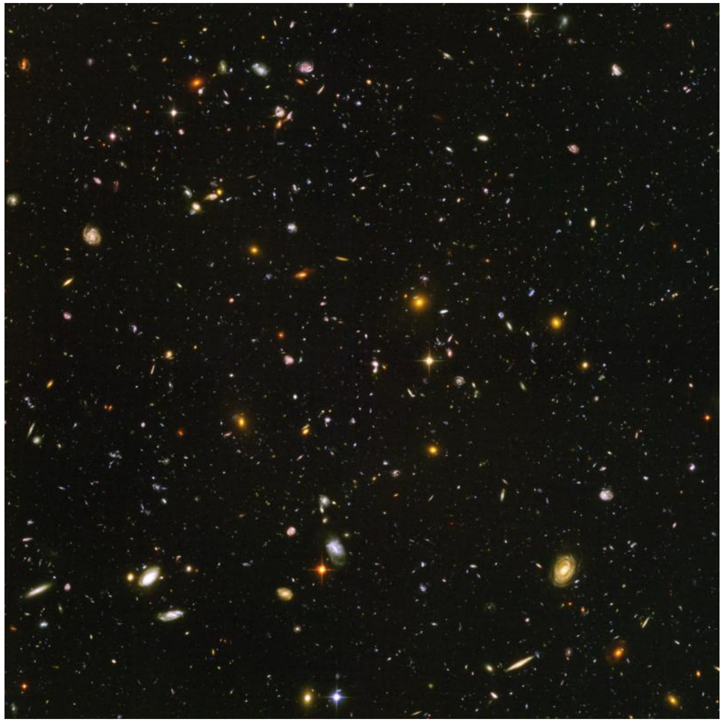
1995 December: Hubble Deep Field: $\sim$ 150 ksec/Filter for four HST Filters

Many galaxies with weird shapes $\Longrightarrow$ protogalaxies!

Redshifts: $z \in [0.5, 5.3]$ (Fernández-Soto et al., 1999)



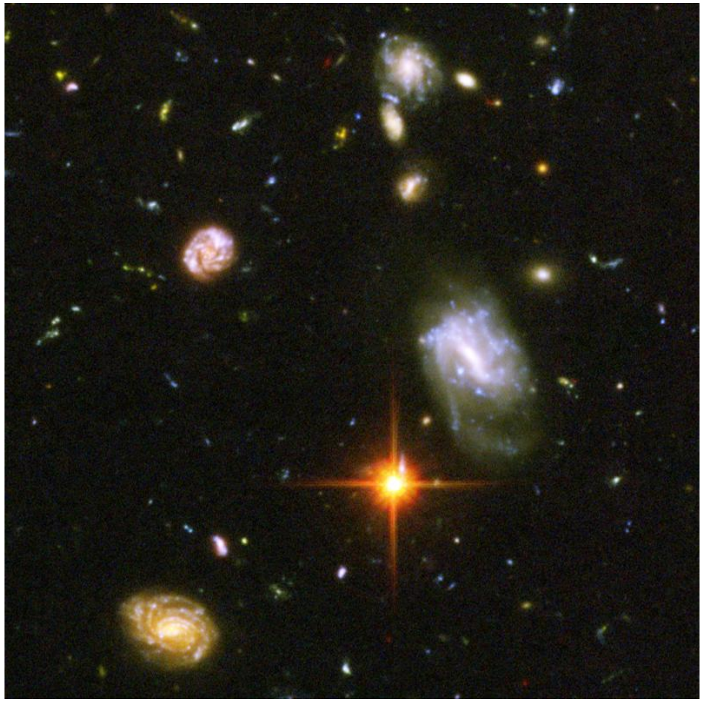


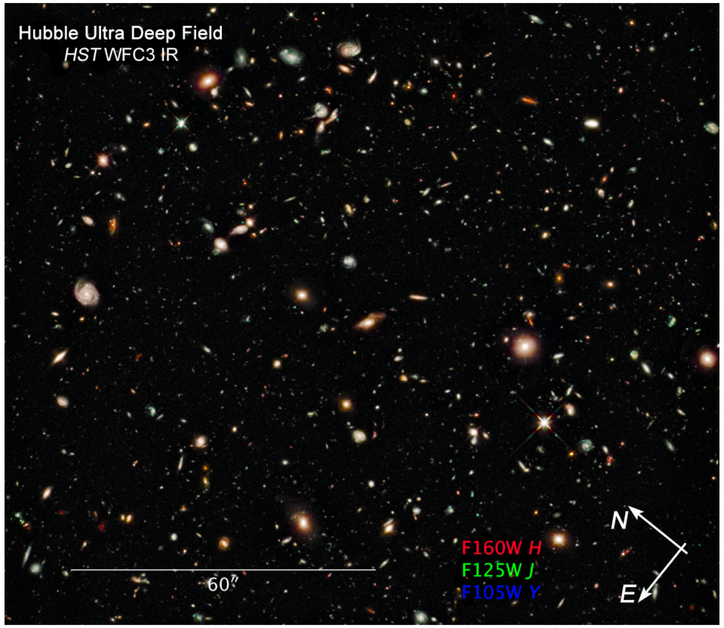


2004: Hubble Ultra Deep Field, 1 Msec long exposure of field in Fornax. Uses updated HST with Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS); diameter: $3'$ ($2\times$ HDF)

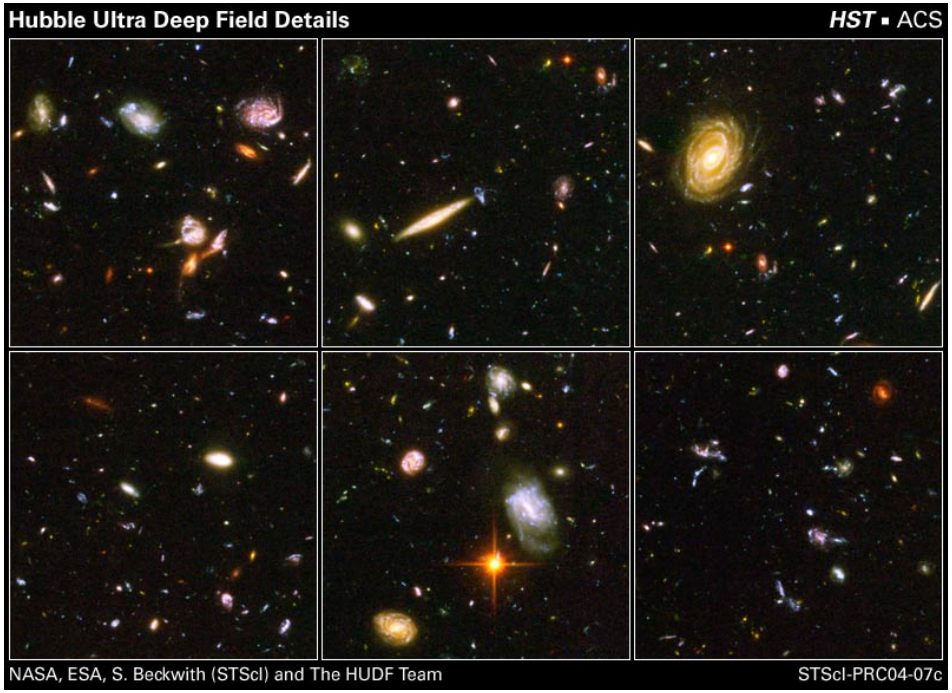
Limiting magnitude: 30 mag, $\sim$10000 galaxies visible, up to $z \gtrsim 7$

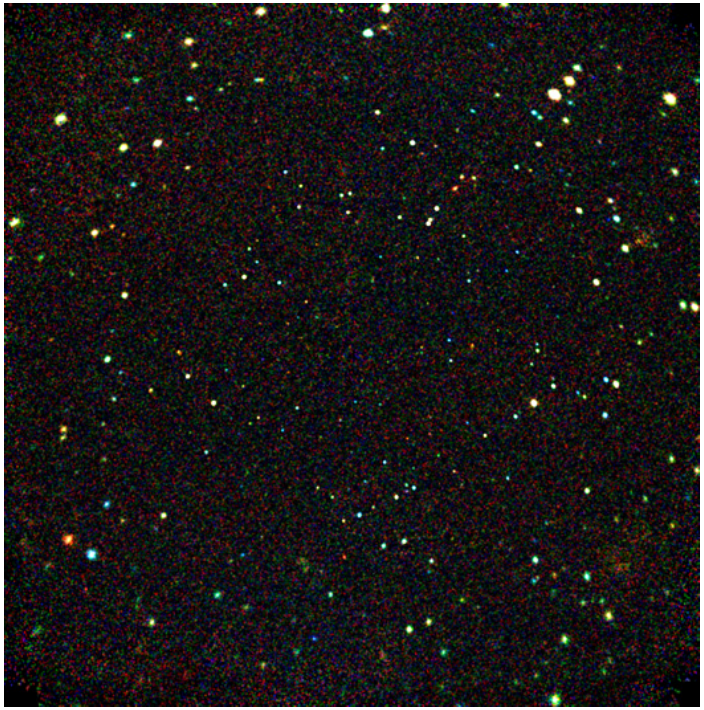
IR reveals many reddened objects





2009 August 26 – 2009 September 2009: WFC3 pushes HUDF even deeper (data taken in same region as HUDF, “Hubble Ultra Deep Field Infrared”). Exposure: 48 h



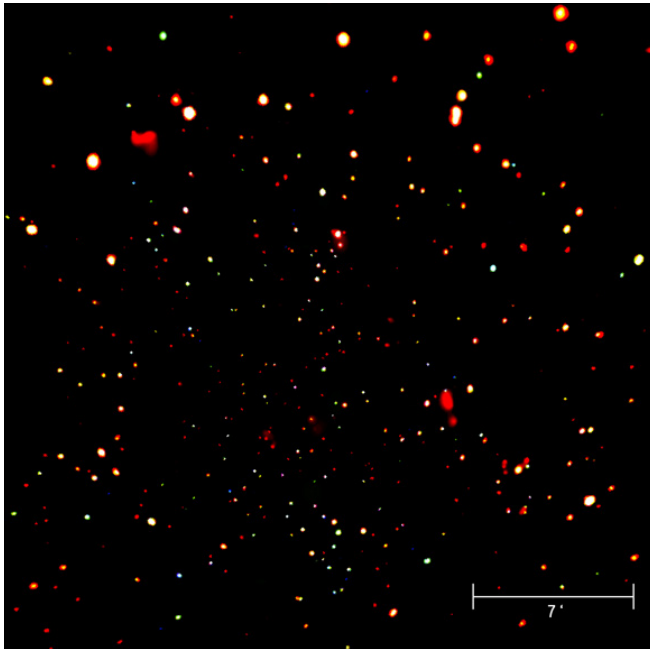


Chandra Deep Field South: 1 Msec (10.8 days) on one region in Fornax ($\alpha_{\mathrm{J2000.0}} = 3^{\mathrm{h}}32^{\mathrm{m}}28.0^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = -27^{\circ}48'30''$, coaligned with HDF-S

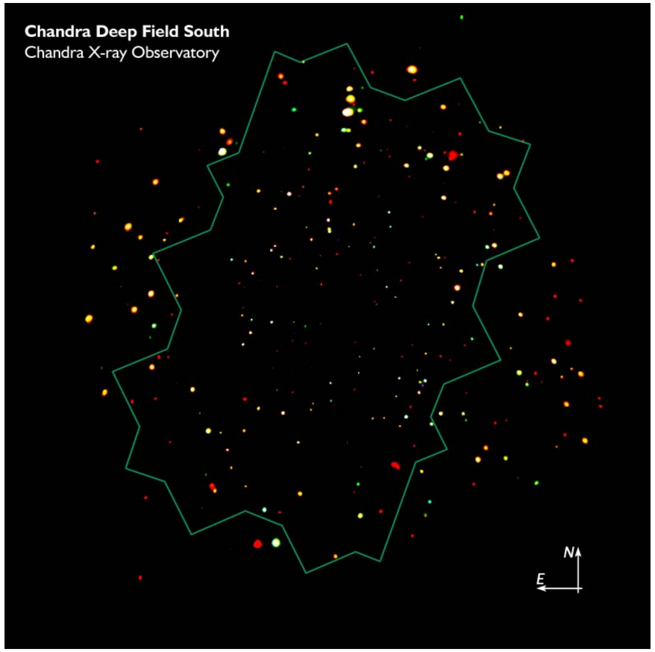
Deepest X-ray field ever

color code: spectral hardness

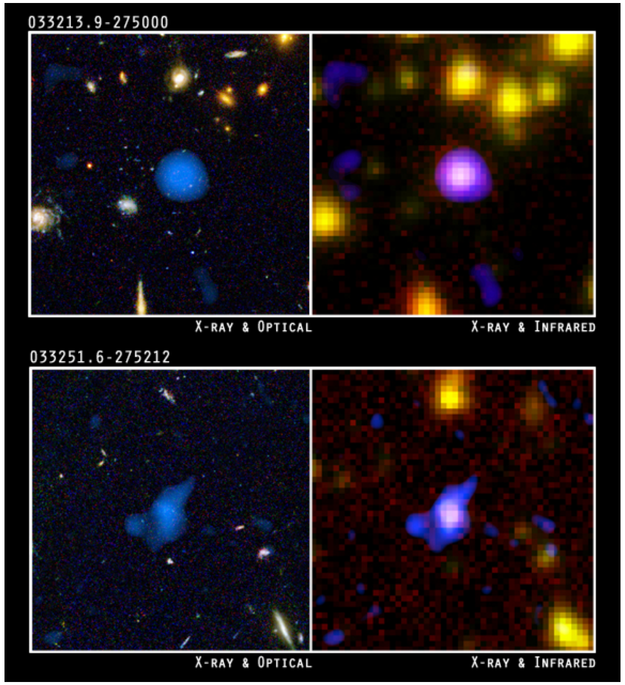
scale: $15' \times 15'$; courtesy NASA/JHU/AUI/R.Giacconi et al.



⟹ GOODS-Survey (Great Observatories Origins Deep Survey), centered on CDF-S
(same image as before, this time smoothed)



Chandra and HST fields aligned



IR, optical, and X-ray image of small fraction of GOODS

CXC/NASA

2D/3D Surveys: Technology

Future for Large Scale Structure: 2D and 3D Surveys observing large part of sky with dedicated instruments.

Currently largest surveys:

Las Campanas Redshift Survey (LCRS): 26418 redshifts in six $1.5\times80^\circ$ slices around NGP and SGP, out to $z=0.2$.

CfA Redshift Survey: 30000 galaxies

APM: (Oxford University) $2\sim10^6$ galaxies, 10^7 stars around SGP, 10% of sky, through $B=21$ mag.

2MASS: IR Survey of complete sky (Mt. Hopkins/CTIO) completed 2000 October 25), 3 bands, $\sim 2\times10^6$ galaxies, accompanying redshift survey (8dF, CfA)

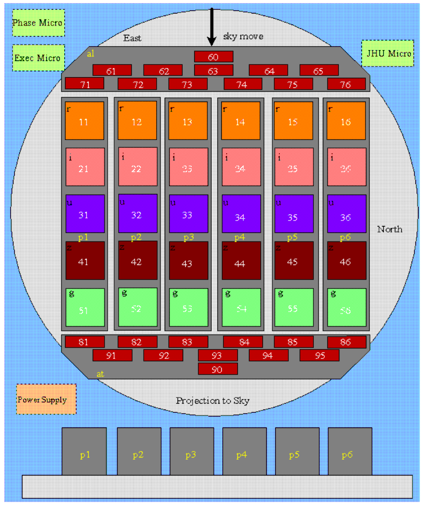
Sloan Digital Sky Survey (SDSS): dedicated 2000 October 5, Apache Point Obs., NM, 25% of whole sky, $\sim10^8$ objects, now in Google Earth

And many more (e.g., Keck, ESO, LSST,...).

SDSS 2.5 m telescope at Apache Point Observatory

courtesy SDSS

2D/3D Surveys: Technology



CCD alignment of SDSS:

- focal plane: 2.5°,
- 5 rows of 2048 × 2048 CCDs with r, i, u, z, g filters, saturation at $r = 14$
- 22 2048 × 400 CCD, saturation at $r = 6.6$ for astrometry

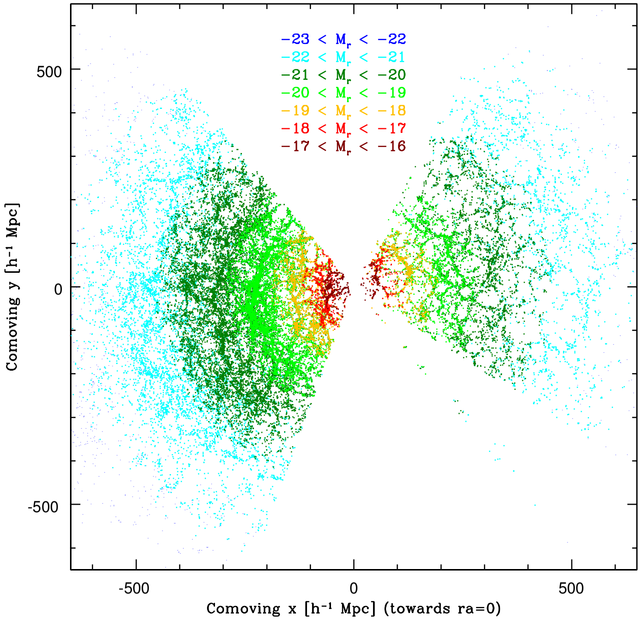
Imaging by slewing over CCD Array

SDSS

2D/3D Surveys: Technology

courtesy SDSS

Spectroscopy with grism (combination of prism and grating), light from objects via optical fibers and plug plate.



Galaxy distribution from the SDSS

(Tegmark et al., 2004)

Jeans Mass

How do structures form?

Consider a collapsing sphere of gas in a *non-expanding* universe.

Potential energy, U, and kinetic energy content, T, of sphere:

$$U = -\frac{1}{2}\int \rho(x)\Phi(x)\,\mathrm{d}^3x \sim -\frac{16\pi^2}{15}G\rho^2 r^5 \quad\text{and}\quad T \sim \frac{c_\mathrm{s}^2}{2}\frac{4\pi r^3\rho}{3} \tag{26.1}$$

c_s: speed of sound; for neutral Hydrogen, $c_\mathrm{s} = \sqrt{5T/3m_\mathrm{p}}$.

Sphere collapses for $|U| > T$, i.e., when

$$2r \gtrsim \sqrt{\frac{5}{2\pi}}\sqrt{\frac{c_\mathrm{s}^2}{G\rho}} \sim c_\mathrm{s}\sqrt{\frac{\pi}{G\rho}} =: \lambda_\mathrm{J} \tag{26.2}$$

λ_J is called the Jeans length, the corresponding mass is the Jeans mass,

$$M_\mathrm{J} = \frac{\pi}{6}\rho\lambda_\mathrm{J}^3 \tag{26.3}$$

Structures with $m < M_\mathrm{J}$ cannot grow.

Note that c_s is time dependent $\Longrightarrow$ M_J can change with time! $\Longrightarrow$ thermal history of the universe!

Theory is identical to that used in formation of stars

General structure formation

General idea of all theories of structure formation:

1. Big Bang generates initial density perturbations (=potential wells)
   density perturbations caused by Poisson statistics in the early universe, e.g., decay of inflaton or similar
2. Those density fluctuations that can grow, grow.
3. Those density fluctuations that cannot grow get smoothed out by expansion and disappear.

How fluctuations grow depends on properties of material forming structures:

Early theory (Zeldovich, 1960s): structures=baryons; large structures must form first $\Longrightarrow$ this is not what is observed.

New theory: dark matter is important:

1. DM forms initial potential wells
2. Wells develop as universe expands
3. Baryons fall into potential wells once radiation and matter decouple
4. galaxies formed first, clusters still forming

Dark Matter

Detailed theory of structure formation uses numerical simulations, using CMB boundary conditions and assumptions on dark matter:

Hot Dark Matter: relativistic particles (e.g., neutrinos): moving with $v \sim c$. Fast particles

$\Longrightarrow$ smears out small density perturbations

$\Longrightarrow$ “top down structure formation”

Not what is observed

(observed: galaxies were there first, clusters are still forming)

Cold Dark Matter: slow particles, condense first, forming potential wells while baryonic matter is still coupled to radiation.

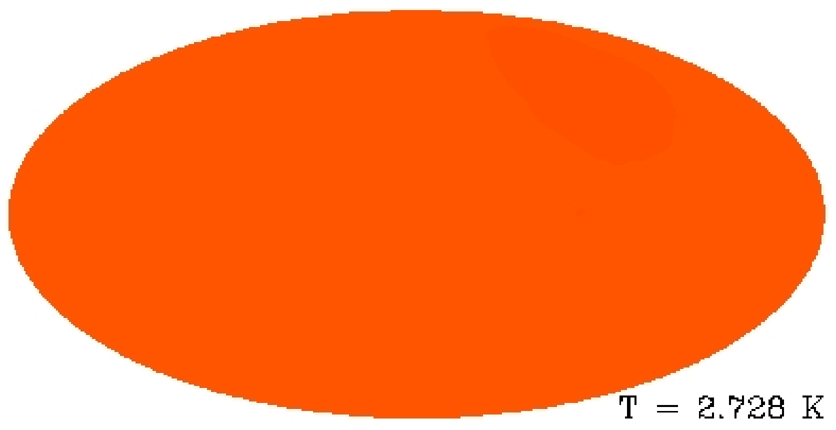
Once radiation decouples from matter (when universe is cold enough), matter falls in gravity wells.

$\Longrightarrow$ “bottom up structure formation”

Closer to what is observed

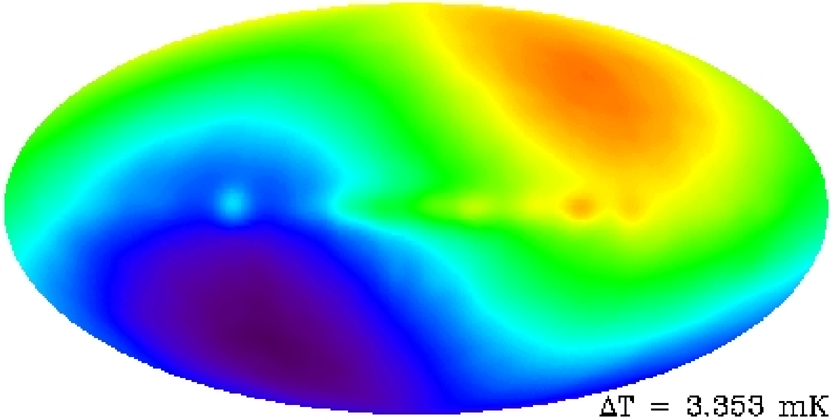
Luminous baryonic mass traces Dark Matter

CMB



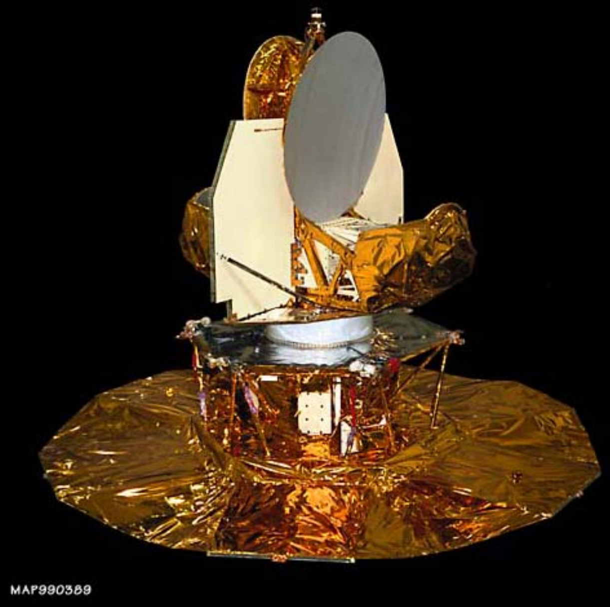
COBE (1992): 1st map of 3K-radiation
$T = 2.728\,\mathrm{K}$

CMB



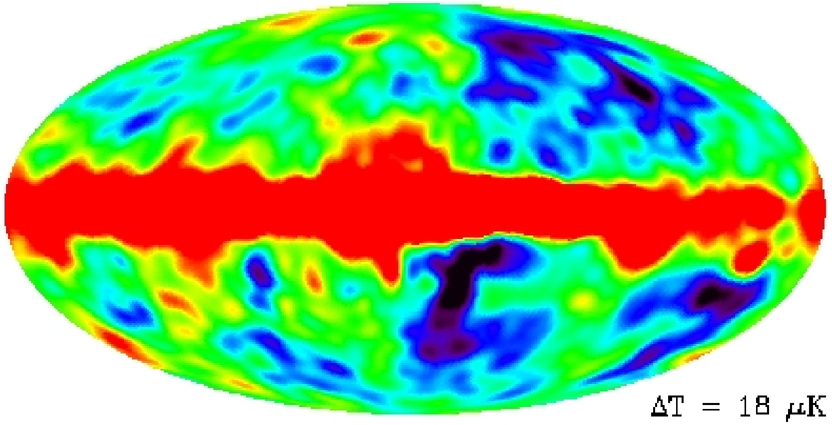
Overlay: Dipole-Anisotropy due to motion of Sun

Temperature fluctuation: $\Delta T/T \sim 10^{-4}$

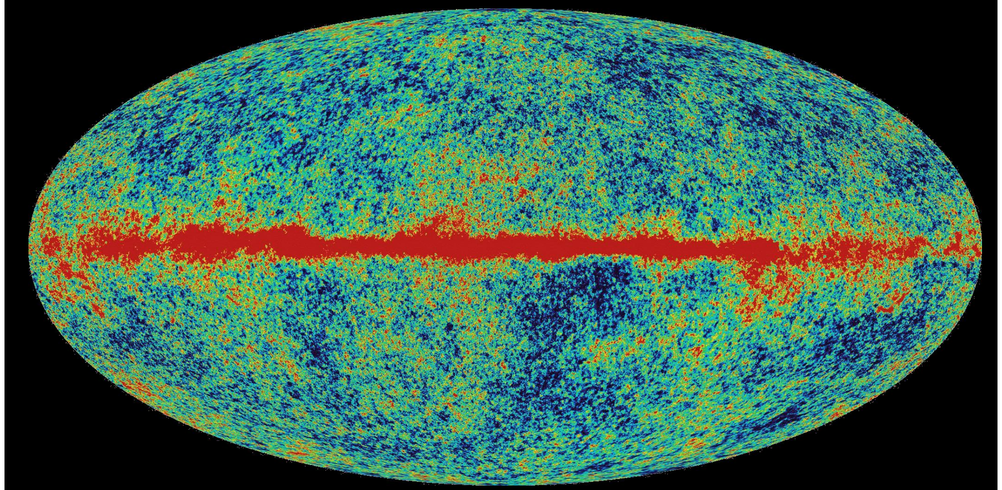


(WMAP): Launch 2001 Juni 30

CMB

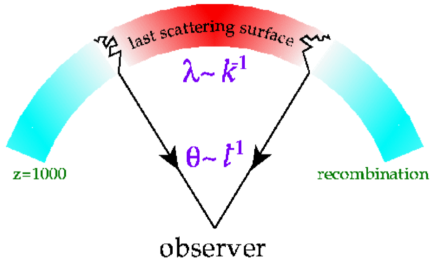


At a level of $\Delta T/T \sim 10^{-5}$: Deviations from isotropy because of structure formation



WMAP, W-Band, $\lambda = 3.2\,\text{mm}$, $\nu = 93.5\,\text{GHz}$, resolution 0.21°

CMB



After BB: Universe is dense (“forry”), photons scatter efficiently off electrons $\Longrightarrow$ coupling of matter and radiation

Universe cools: recombination of protons and electrons to form hydrogen
$\Longrightarrow$ no free electrons
$\Longrightarrow$ no scattering
$\Longrightarrow$ photons stream freelty

courtesy Wayne Hu

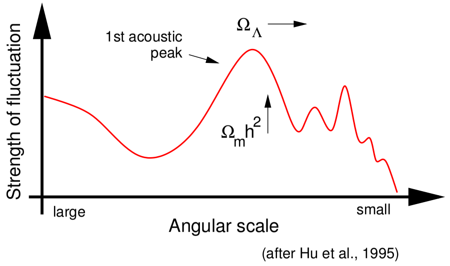
Photons leaving overdense regions loose energy (gravitational red shift)

$\Longrightarrow$ visible as a temperature fluctuation (Sachs-Wolfe-Effect)

CMB fluctuations $\sim$ gravitational potential at $z \sim 1100$ (380000 yr after big bang) $\Longrightarrow$ structure

---

CMB

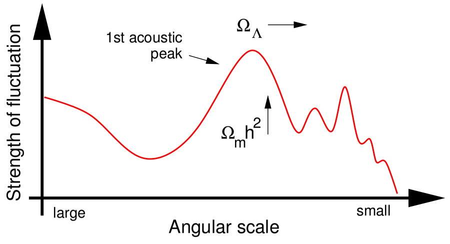


(after Hu et al., 1995)

Power spectrum of CMB depends on

$$\Omega_m \quad H_0 \quad \Omega_\Lambda$$

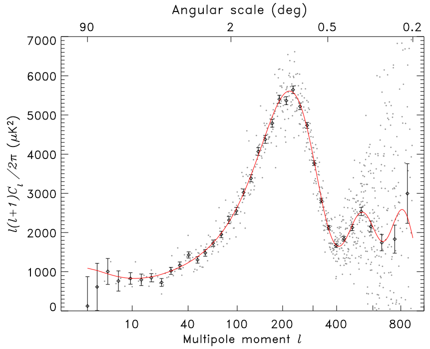
CMB



(after Hu et al., 1995)

Power spectrum of CMB depends on

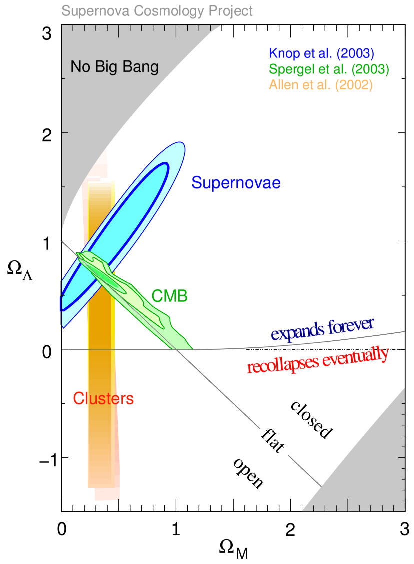
$$\Omega_m \quad H_0 \quad \Omega_\Lambda$$



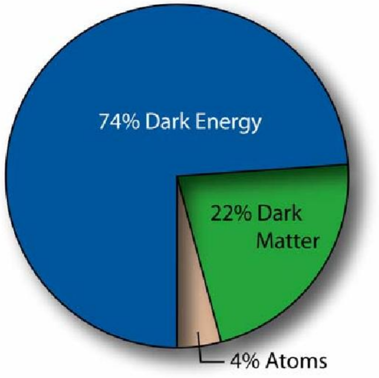
WMAP best fit parameters (assuming $\Omega = 1$, $H_0 =: h \cdot 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$):

$$h = 0.72 \pm 0.05$$
$$\Omega_m h^2 = 0.14 \pm 0.02$$

CMB

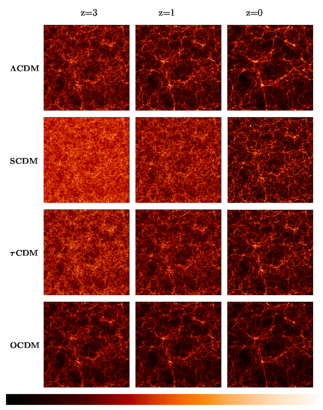


concordance model:



age of the universe: 13.7 Mrd. Jahre.

Numerical Structure Formation



The VIRGO Collaboration 1996

Detailed theory: numerical simulations in expanding universe:

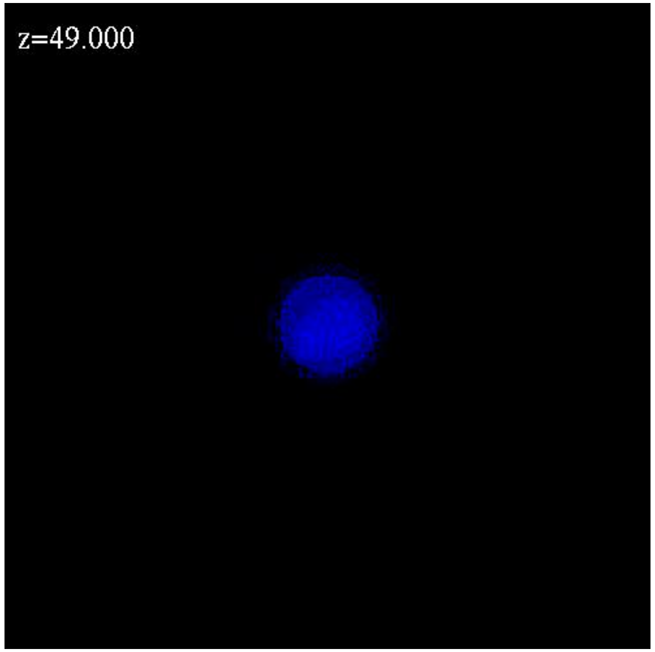
Inputs:

- Cosmological parameters (H_0, Ω, Λ)
- CMB properties as boundary condition
- Assumed properties of DM (CDM, HDM)

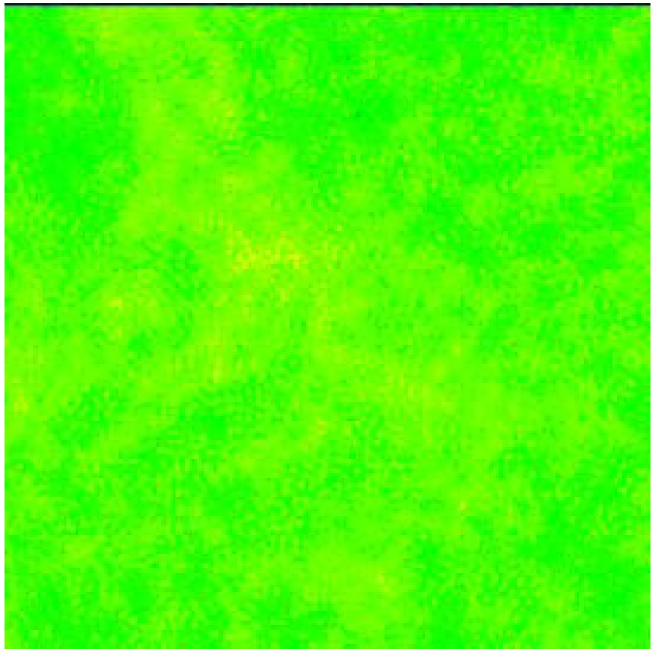
ΛCDM-models to predict how galaxies form and evolve in the universe.

Models with $\Lambda = 0$ do *not* reproduce the structure observed in todays universe, i.e., we *need* the expansion to be driven by Λ!

Numerical simulation of structure formation (Virgo collaboration)

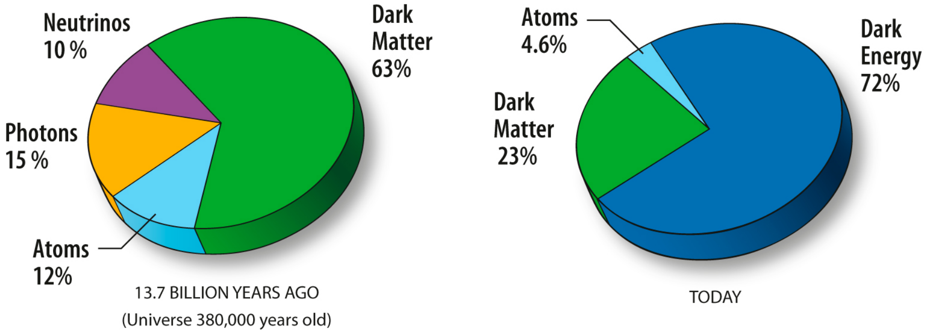


Structure evolution in a CDM universe (Virgo collaboration)



Structure evolution in a CDM universe

Numerical Structure Formation



WMAP Science team

$\Longrightarrow$ Conclusion of Ω, Λ, and structure formation: As universe expanded, its energetic contents changed dramatically

The Future

So far we have looked in the past and have seen that physics “works”

$\Longrightarrow$ We can use this knowledge to extrapolate into the future.

Overview article: F.C. Adams & G. Laughlin, Sky&Telescope, 96(2), 32

see also

L. Krauss & R.J. Scherrer, “The return of a static universe and the end of cosmology”, General Relativity and Gravitation, in press (arXiv:0704.0221 [www.arxiv.org])

The first article has been beautifully summarized by a talk by Lucyna Kedziora-Chudczer (Institute of Astronomy, University of Sydney), which will be shown on the next viewgraphs.

The End