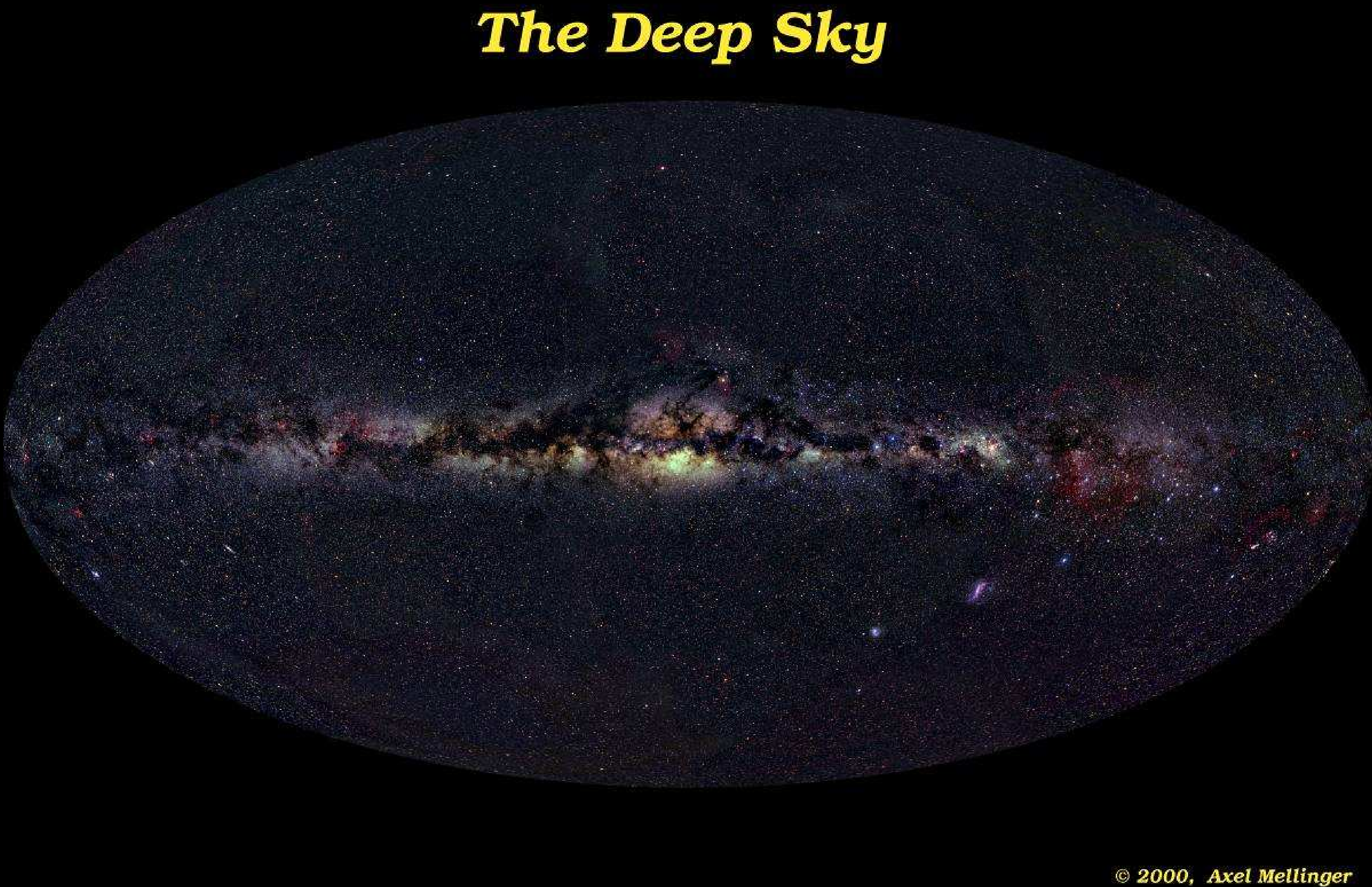
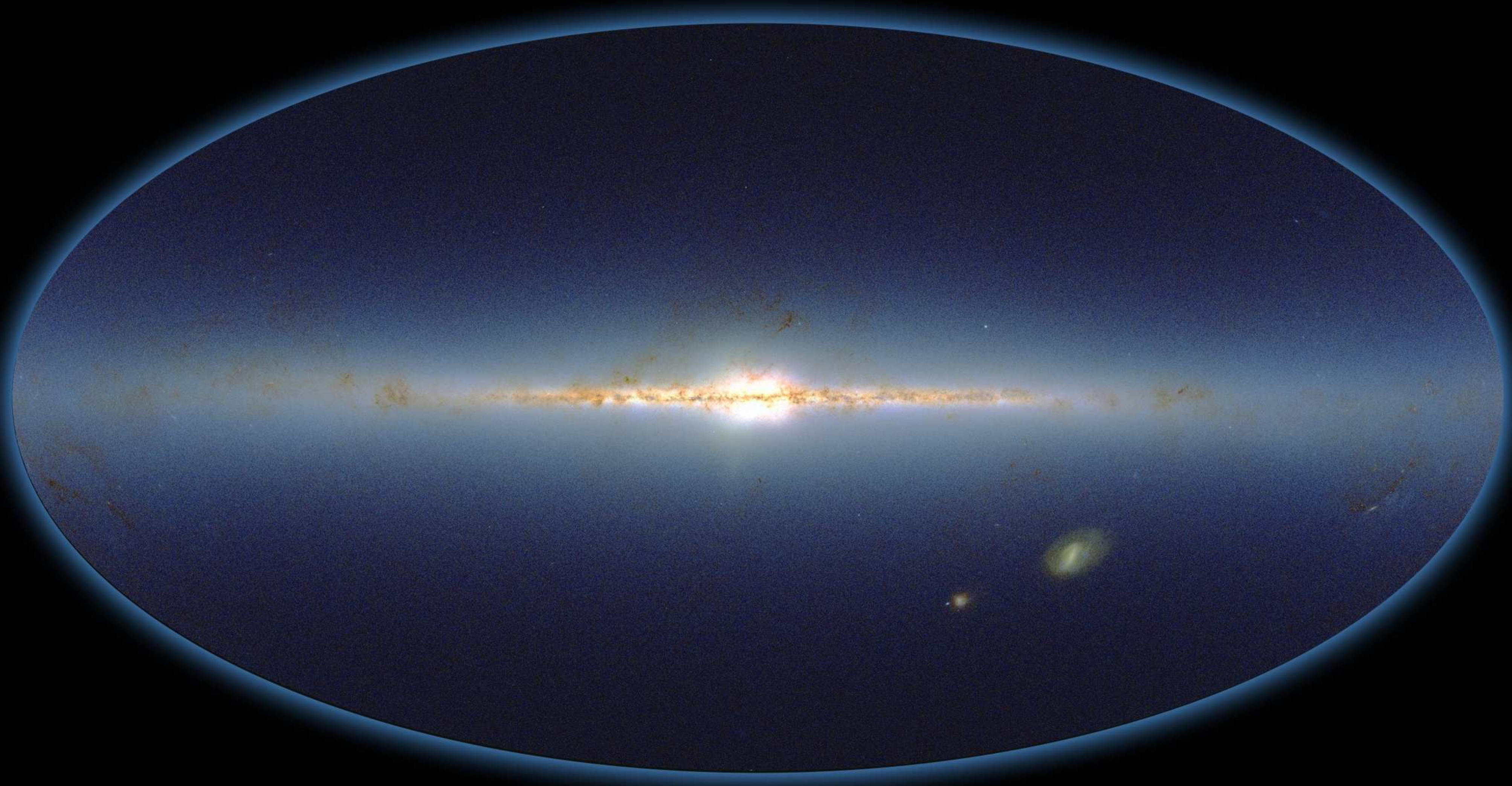
Galaxies



Optical image of the whole sky

2MASS Covers the Sky

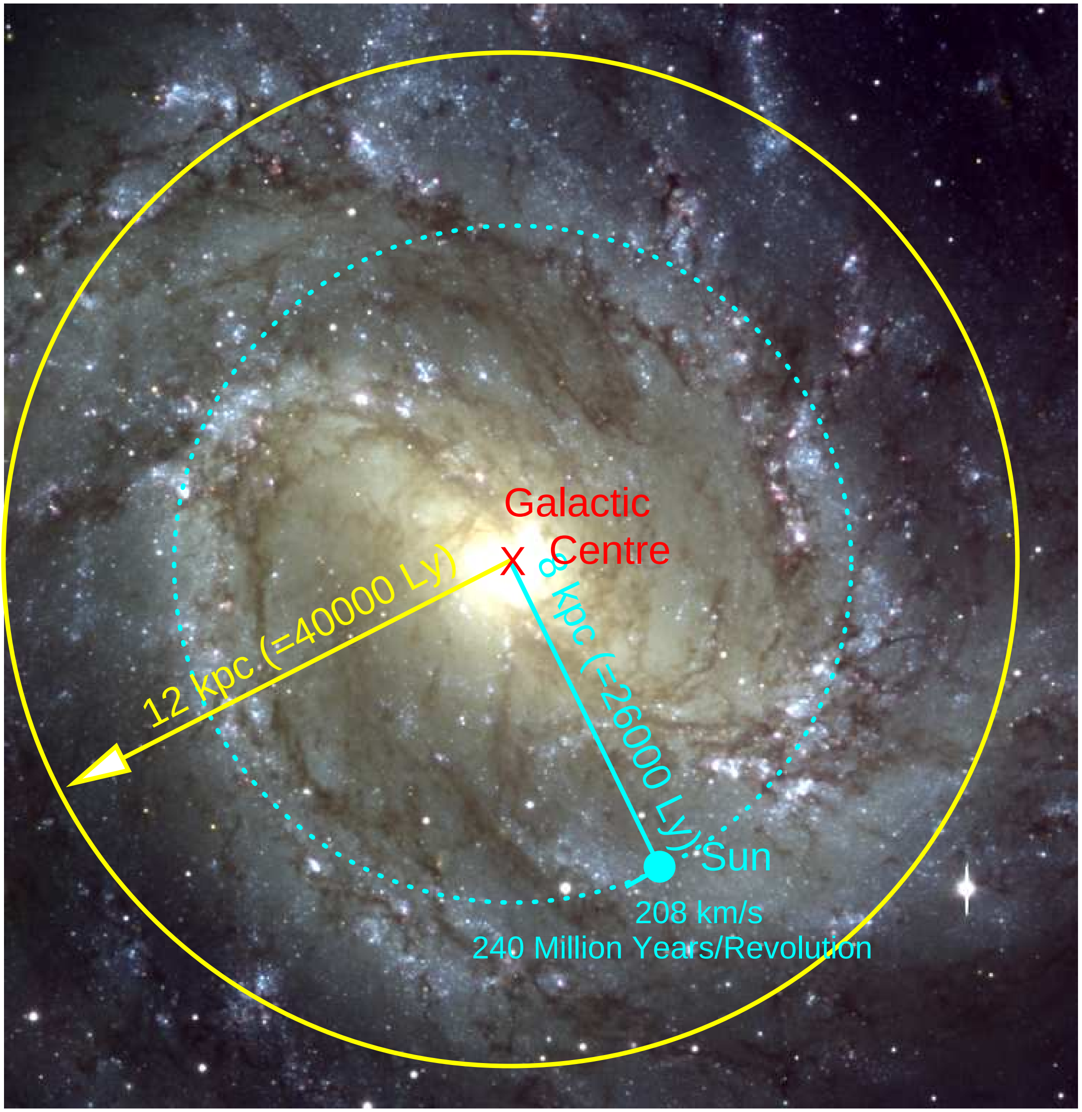


The Two Micron All Sky Survey

Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

Infrared view of the whole sky

Milky Way, III



M83: ESO [VLT ANTU+FORS1]

Luminosity: $\sim 2 \times 10^{10}\, L_\odot$

Mass: $\sim 10^{11}\, M_\odot$ (radiating)

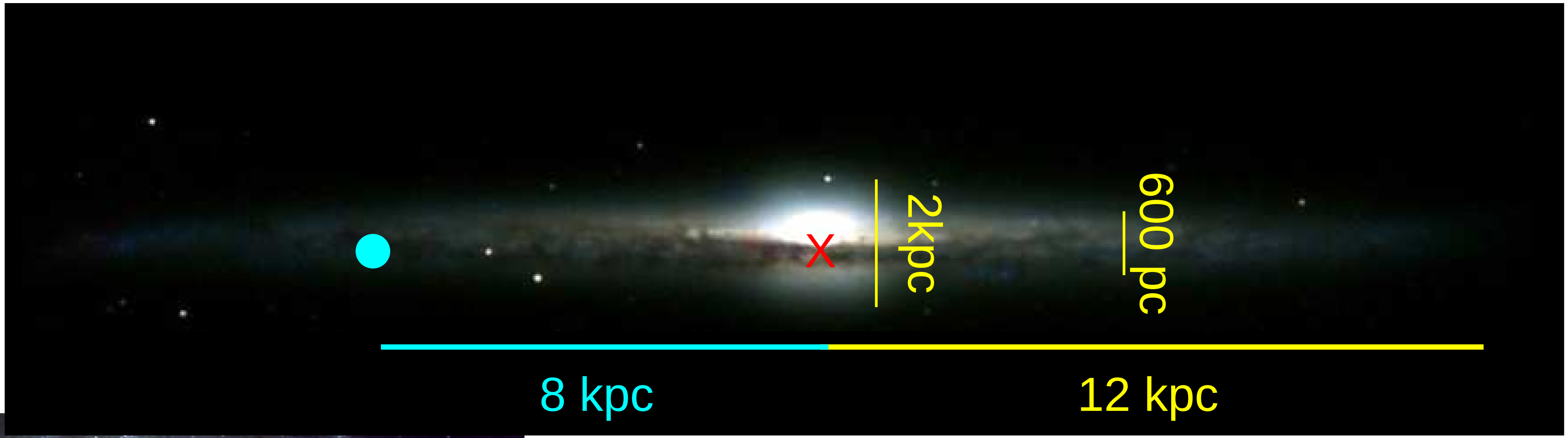
$\sim 10^{12}\, M_\odot$ (total)

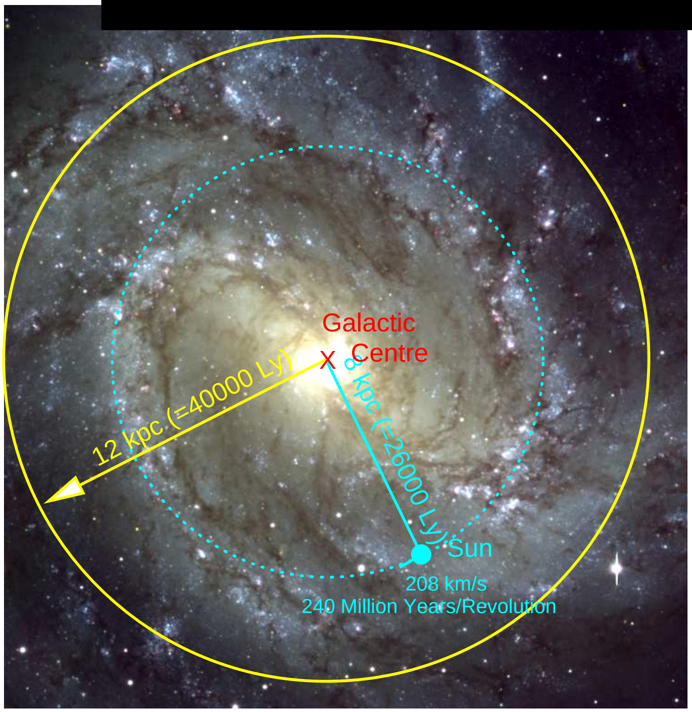
Stellar density:

$\sim 0.3\, M_\odot\,\mathrm{pc}^{-3}$

$1\, M_\odot = 2 \times 10^{30}$ kg,
$1\, L_\odot = 4 \times 10^{26}$ W

Milky Way, IV





NGC 4565: W. McLaughlin

Luminosity: $\sim 2 \times 10^{10}\, L_\odot$

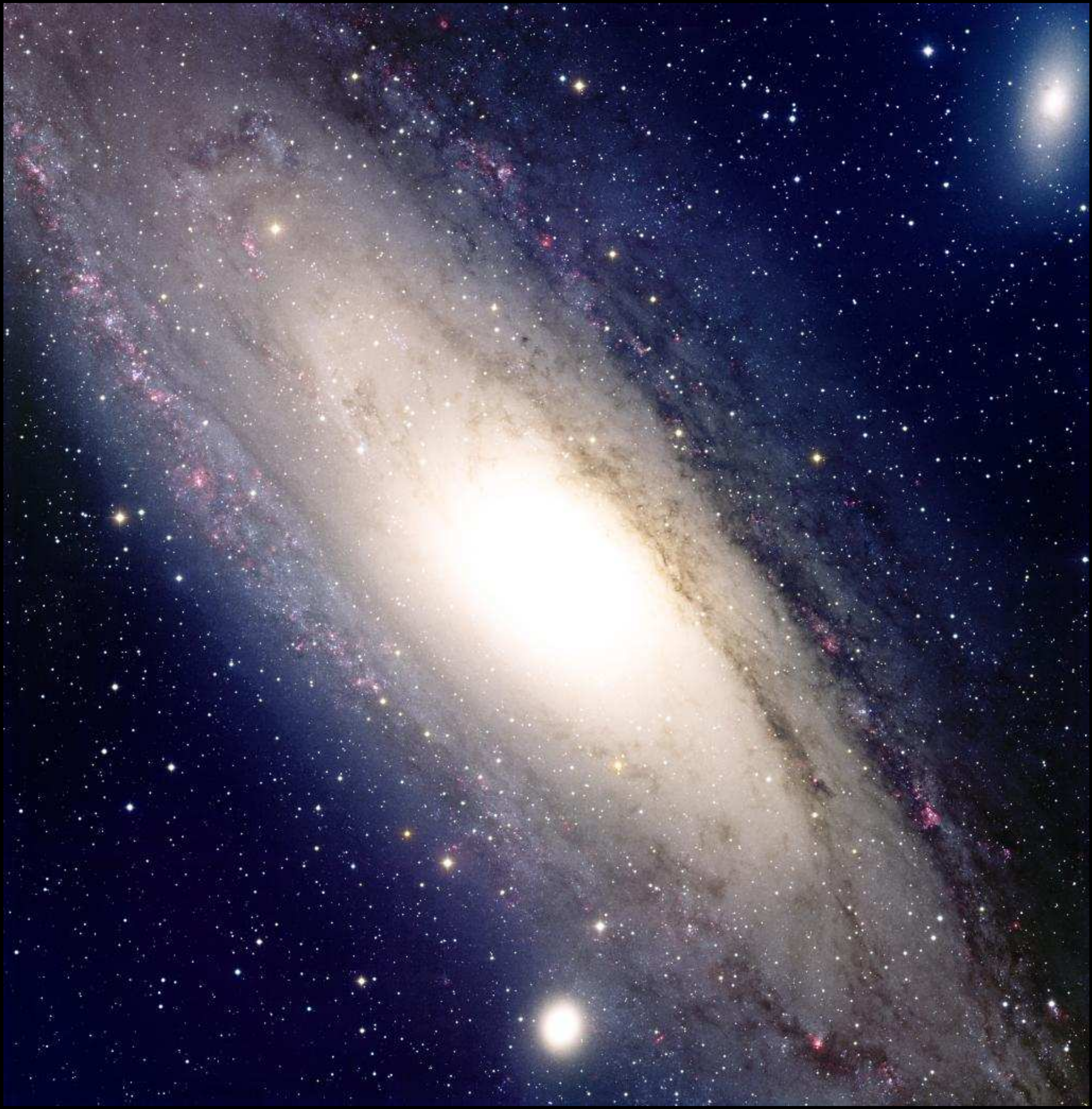
Mass: $\sim 10^{11}\, M_\odot$ (radiating)

$\sim 10^{12}\, M_\odot$ (total)

Stellar density:

$\sim 0.3\, M_\odot\,\mathrm{pc}^{-3}$

$1\, M_\odot = 2 \times 10^{30}$ kg,
$1\, L_\odot = 4 \times 10^{26}$ W

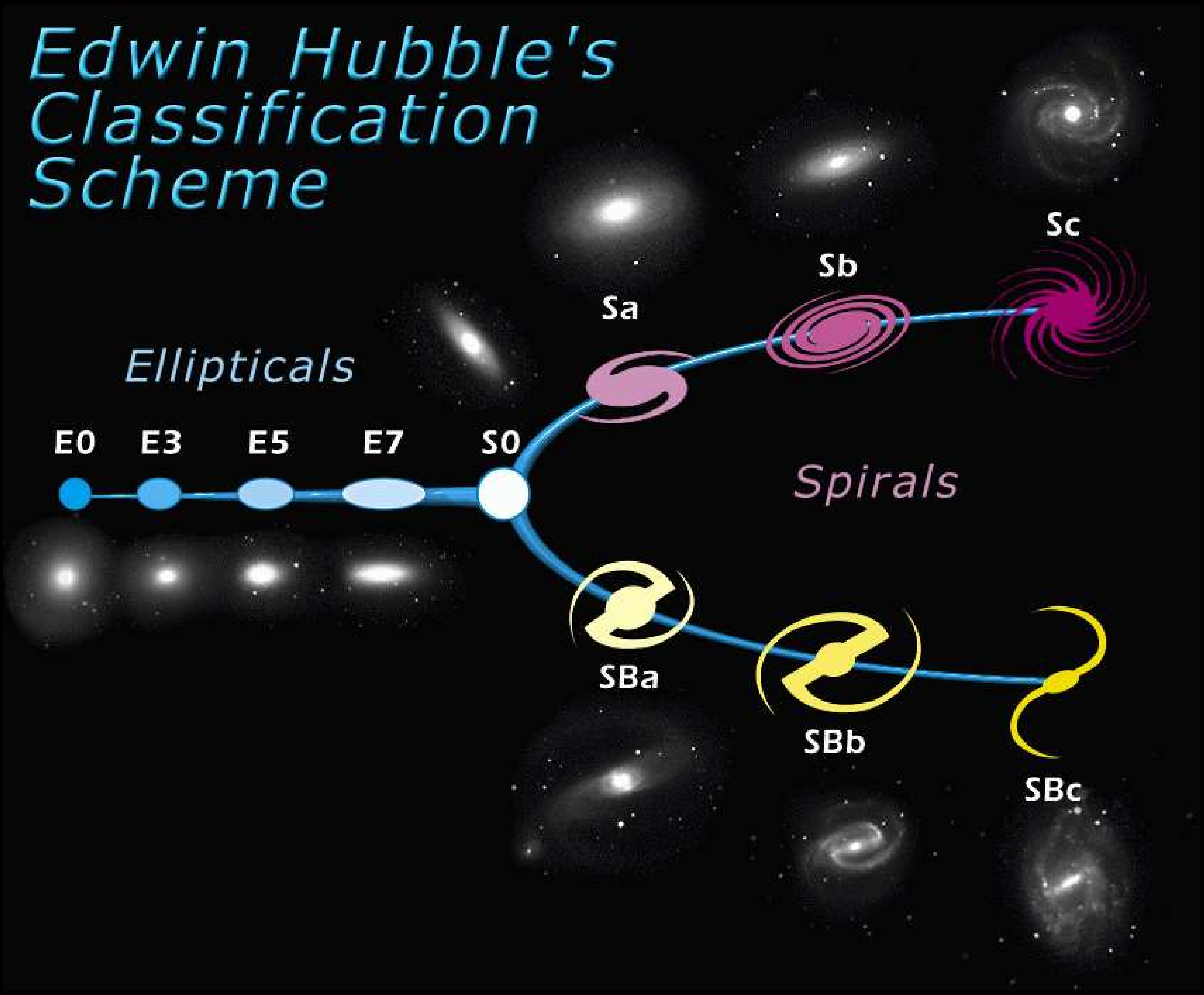


Andromeda galaxy (closest real neighbour galaxy, diam. 20kpc, distance: 675 kpc), NOAO/AURA/NSF

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



SDSS

Galaxy classification via the Hubble "tuning fork diagram"

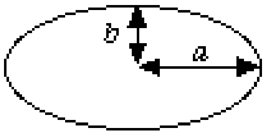
M87 (=Virgo A, note jet; E0), NOAO/AURA/NSF

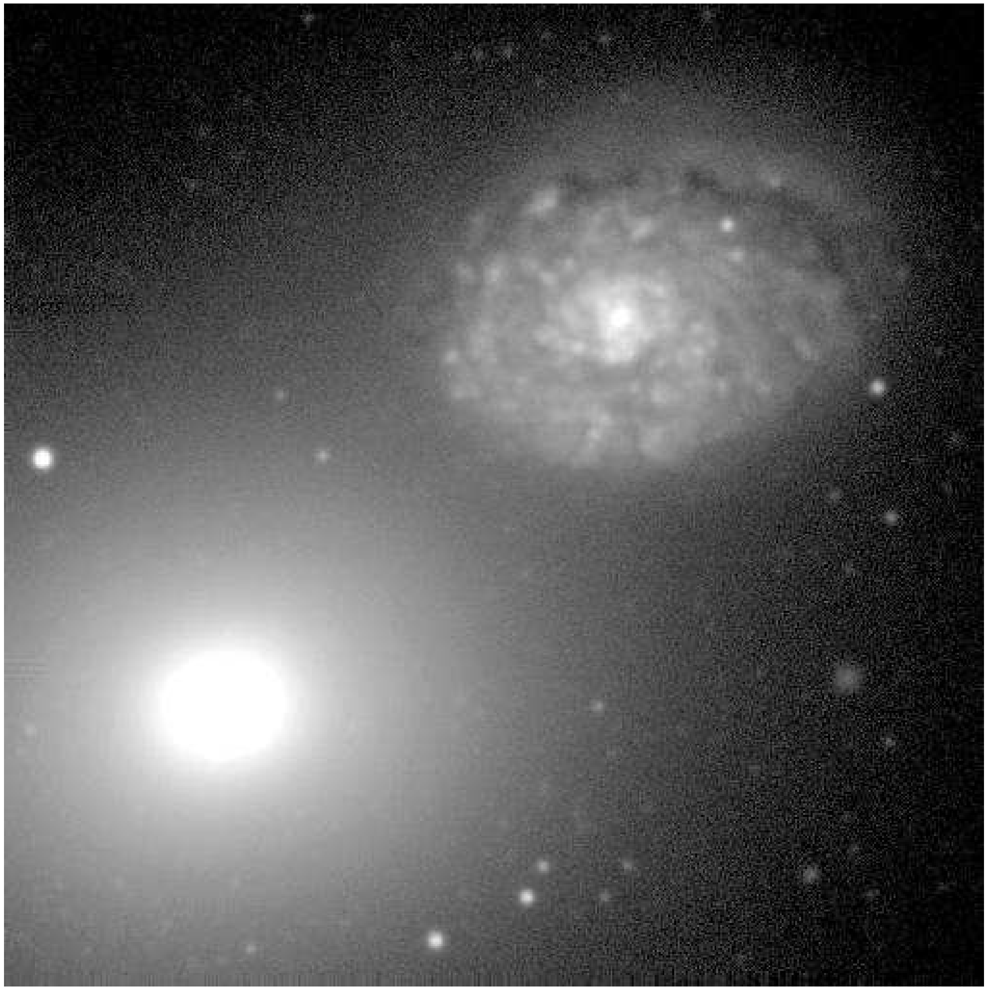
M49 (E4), NOAO/AURA/NSF

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

M86 (lenticular, S0), 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.

M104 (Sa; “Sombrero galaxy), HST/NASA

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

M90 (Sb), NOAO/AURA/NSF

NGC 4565 (Sb, seen edge on), McLaughlin

M51 (Sc), NOAO/AURA/NSF, T. Rector

M51 (Sc; centre), HST/NASA

NGC 300 (Sc), M. Schirmer/ESO/2.2 m

Spiral Galaxies

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

Spiral Galaxies: Elliptical nucleus plus 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.

M83 (SABc, ESO)

M58 (SBb), NOAO/AURA/NSF

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

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).

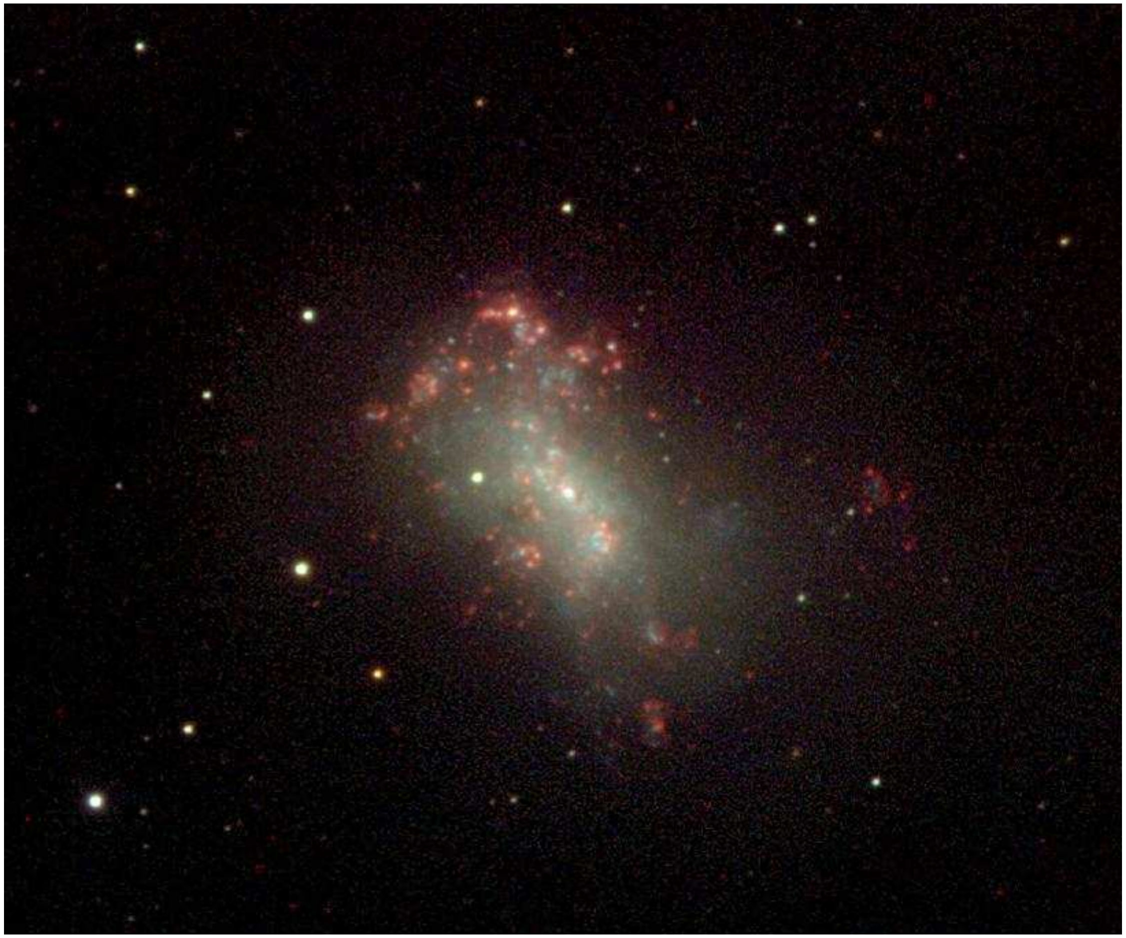
Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.

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

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

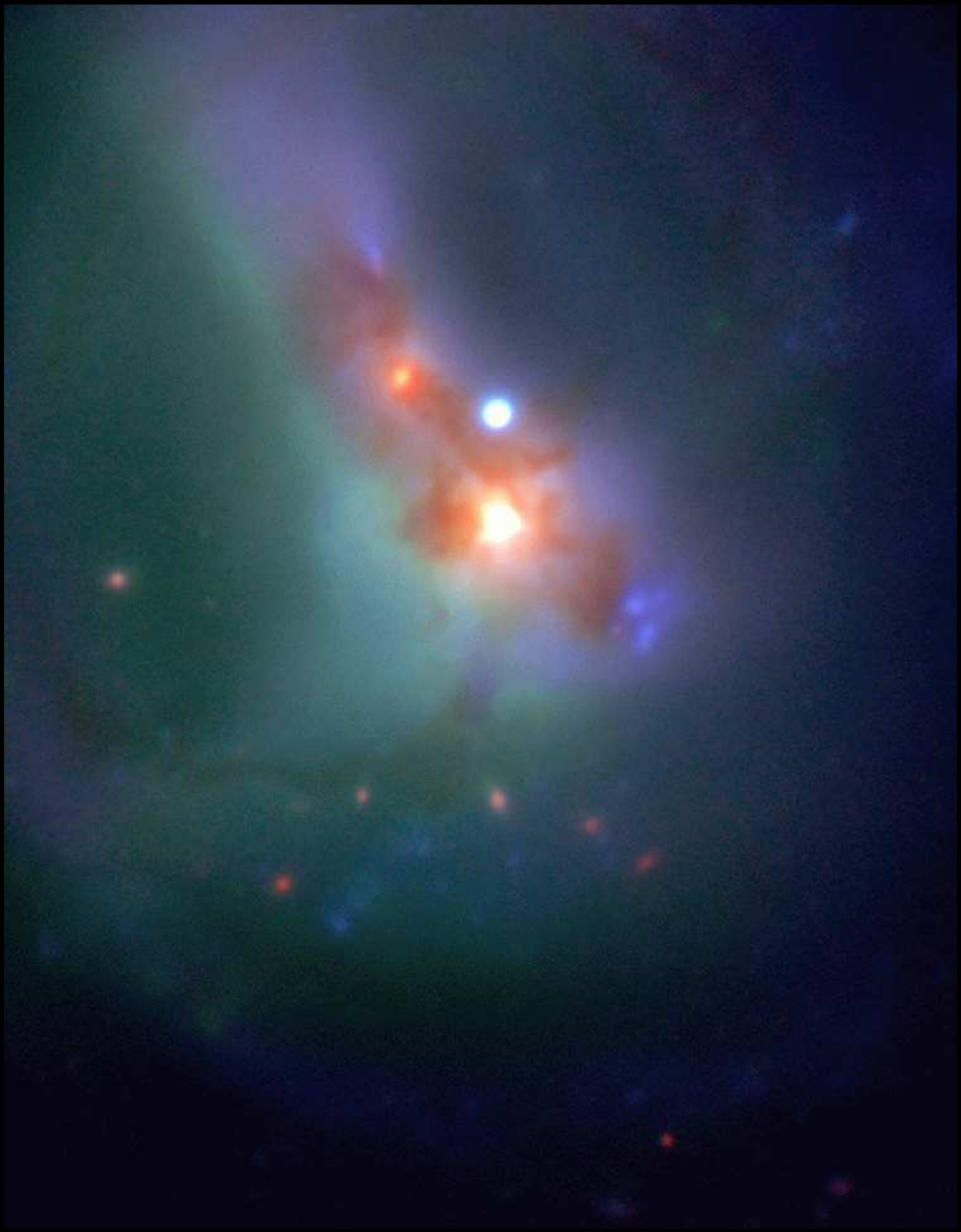
Irregular Galaxies: Irr I



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".



ESO202-G23 (VLT UT1/ISAAC/ESO)

Irregular Galaxies: Irr II

M82, HST-WFPC

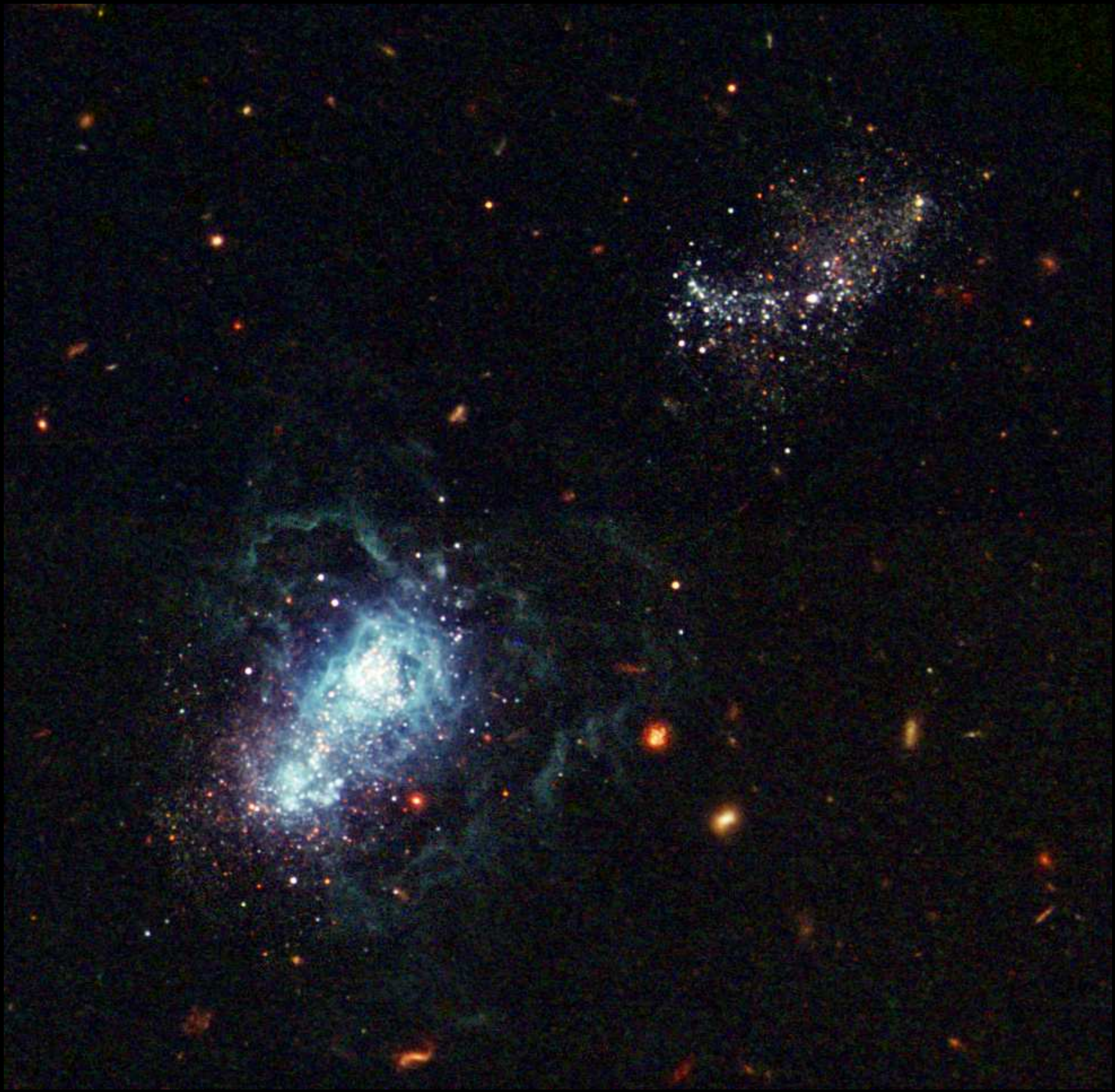
Irr II: unsymmetrical and "abnormal"

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

NGC 6946, T. Rector/AURA/Gemini

NGC 6946, T. Rector/AURA/Gemini

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

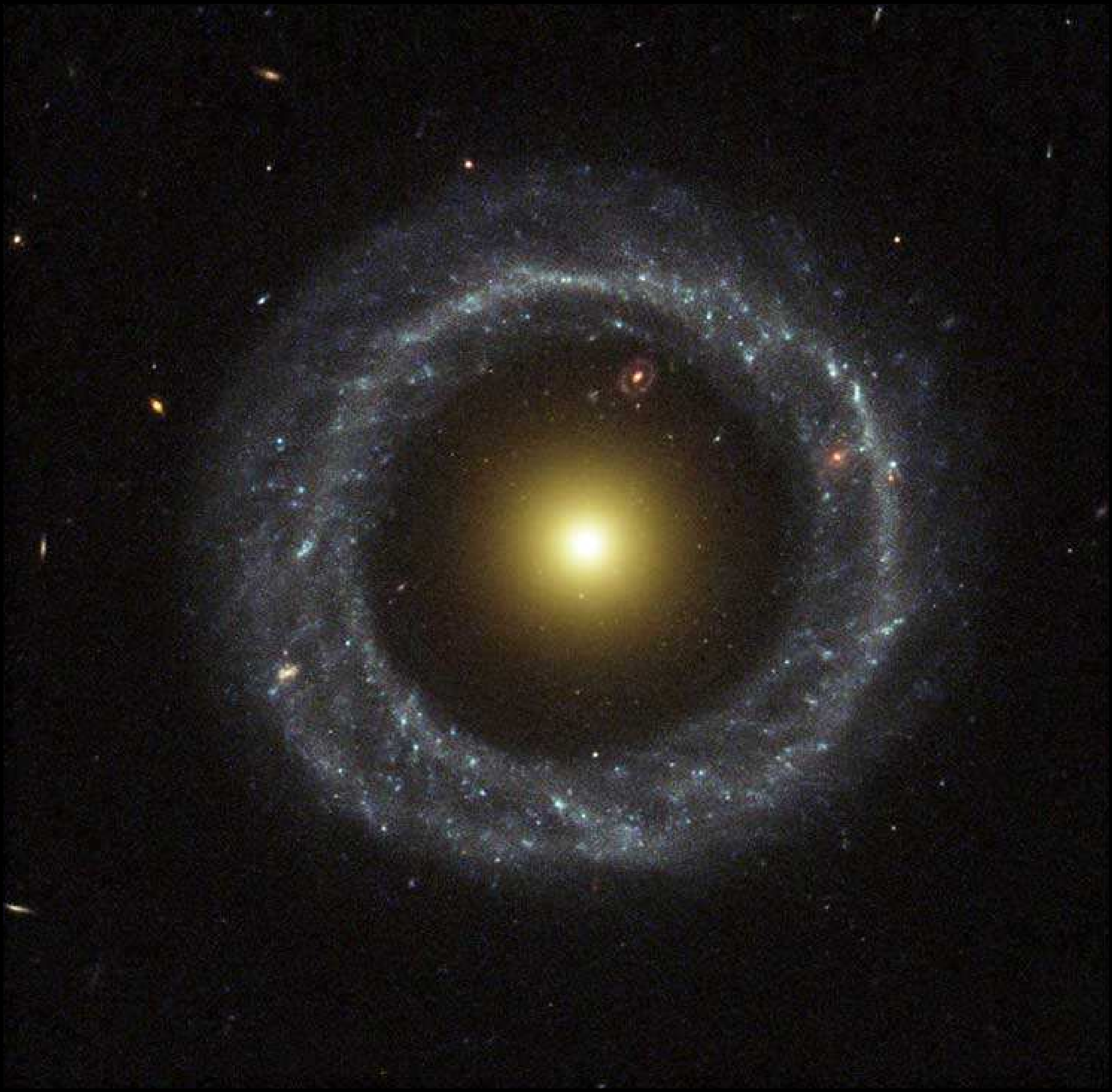


I Zwicky 18, Y. Izotov/T. Thuan/HST

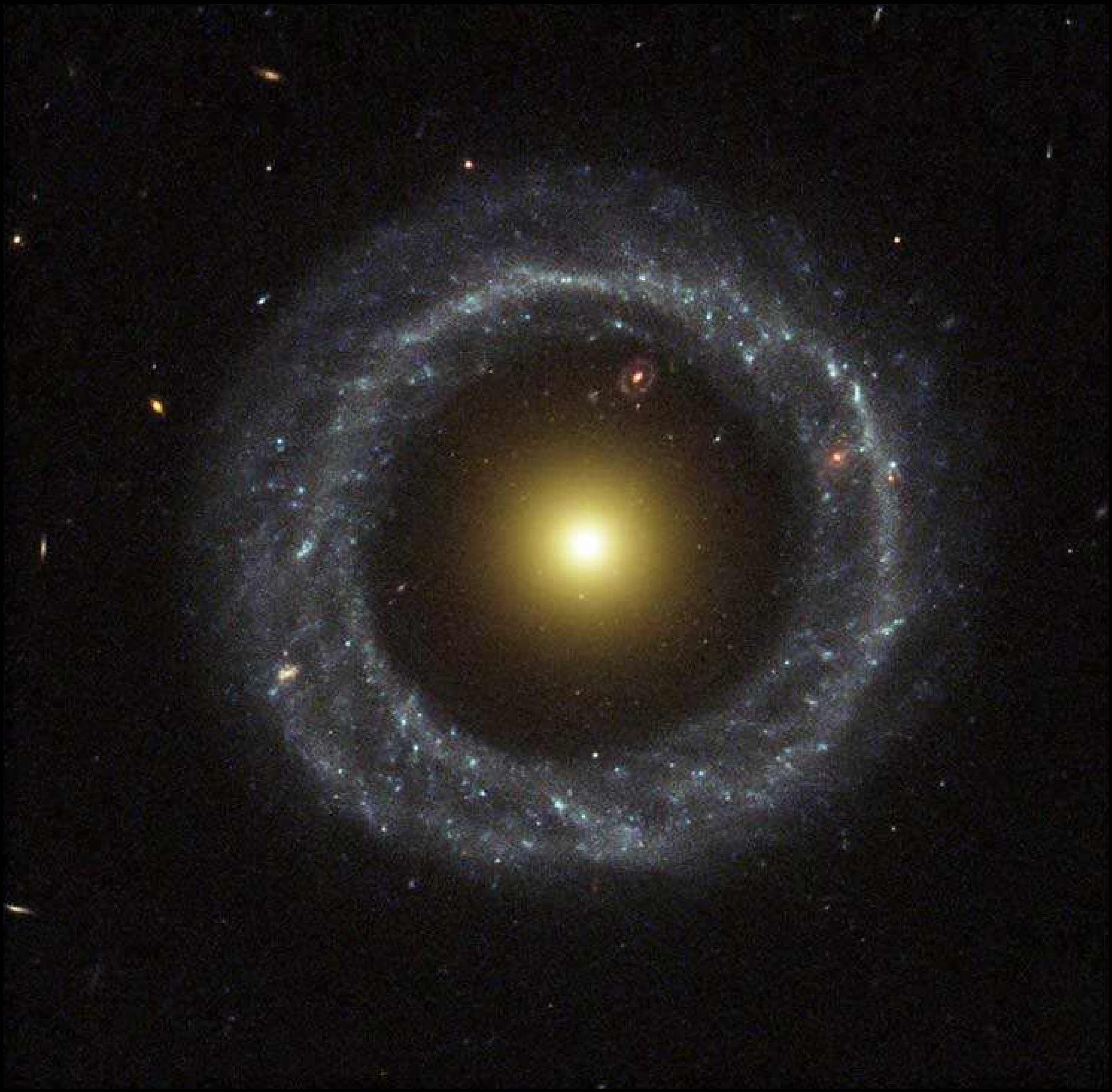
I Zwicky 18, Y. Izotov/T. Thuan/HST

I Zw 18 is a irregular galaxy

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



Hoag’s Object, HST



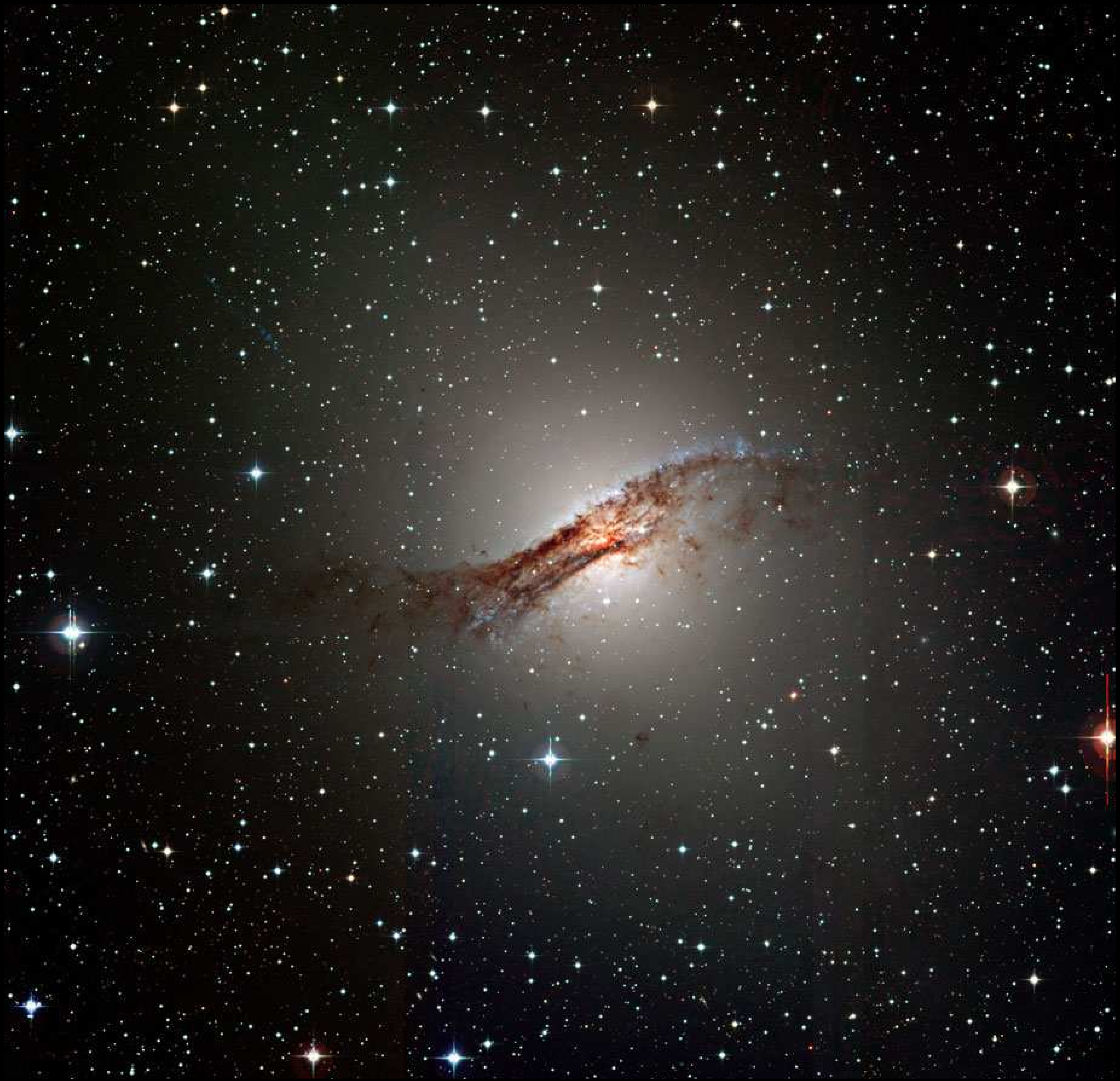
Hoag’s Object, HST

Hoag’s object an irregular galaxy

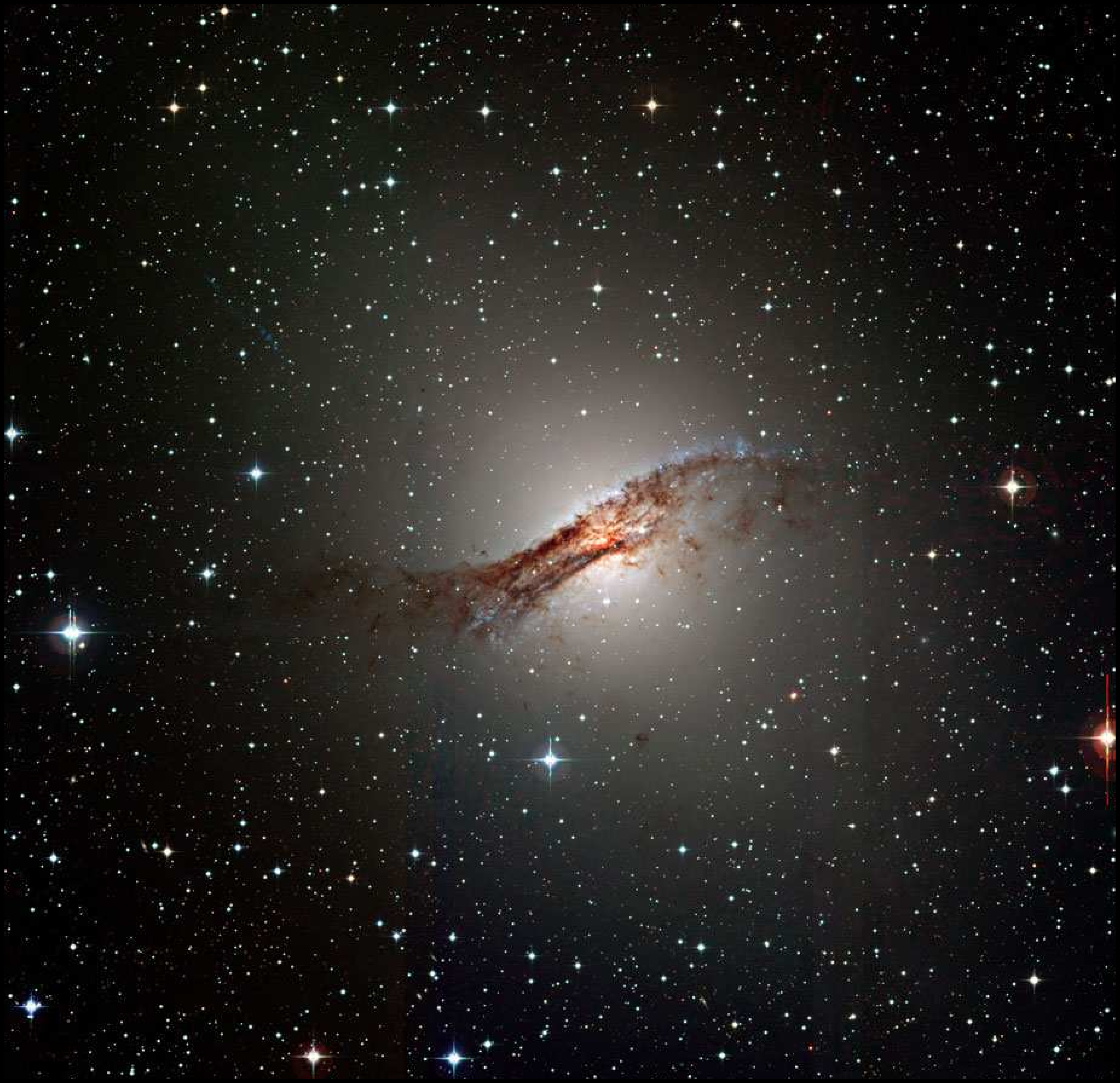
NGC 1300, HST

NGC 1300, HST

NGC 1300 is a SBbc galaxy



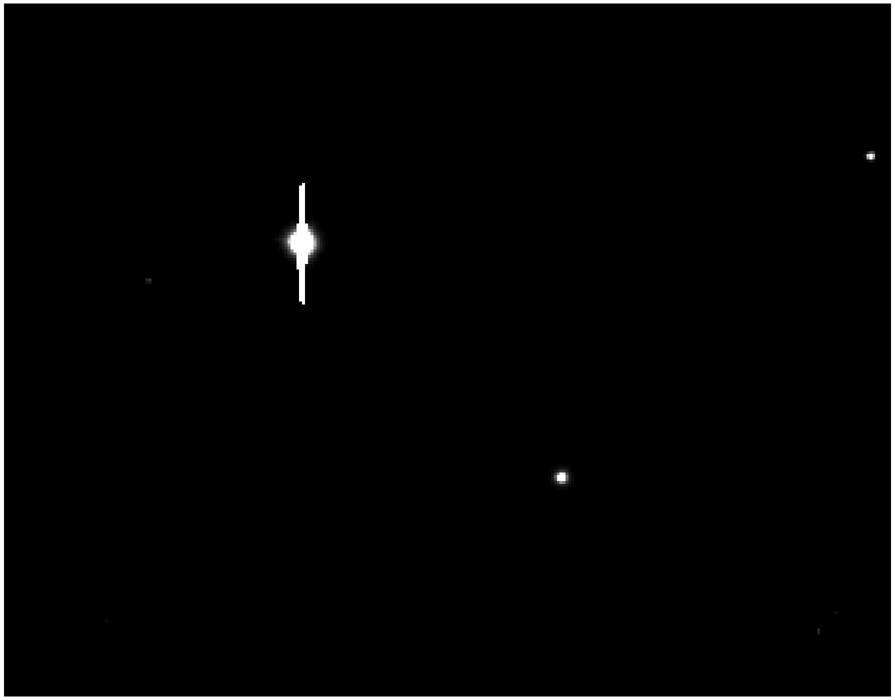
Cen A, ESO/WFI



Cen A, ESO/WFI

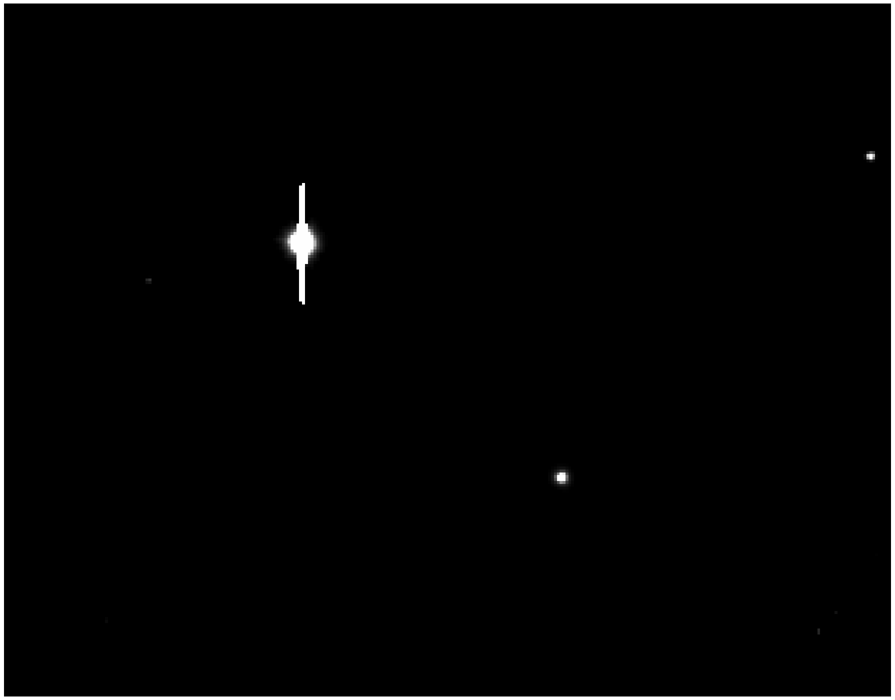
Cen A is a (peculiar) S0 galaxy

AGN

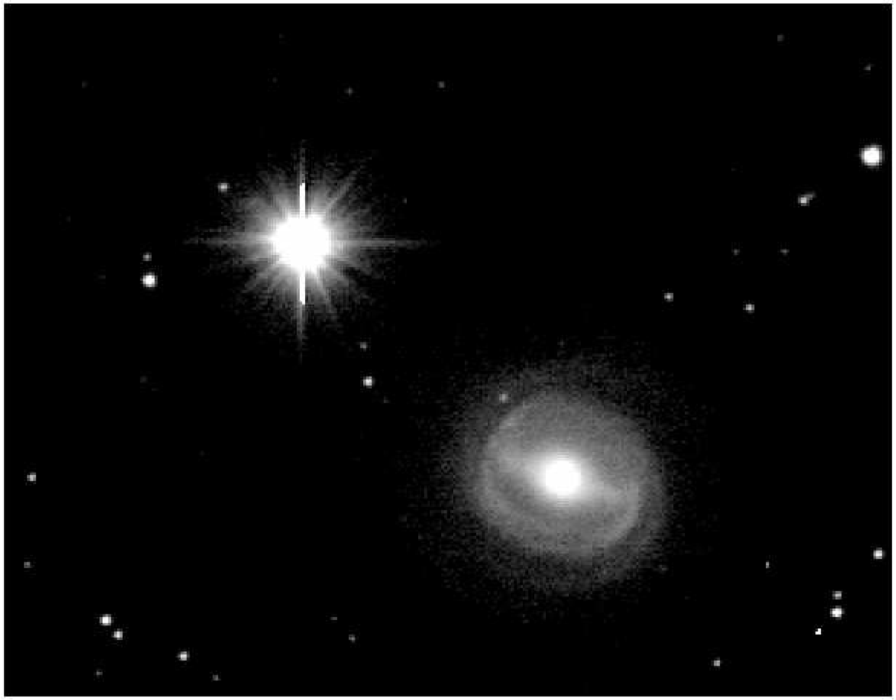


NGC 3783: *linear* intensity scale

AGN

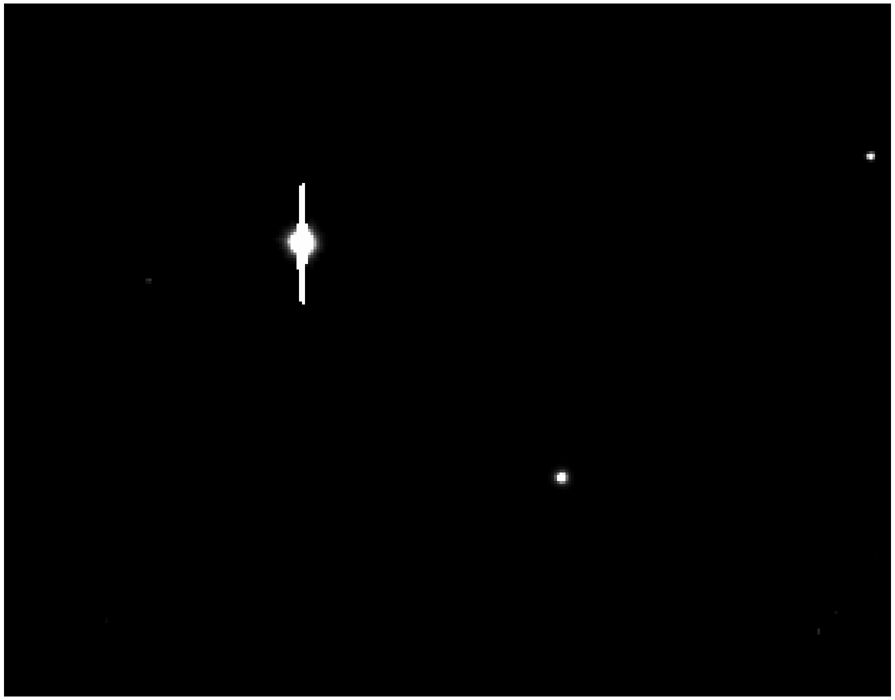


NGC 3783: *linear* intensity scale

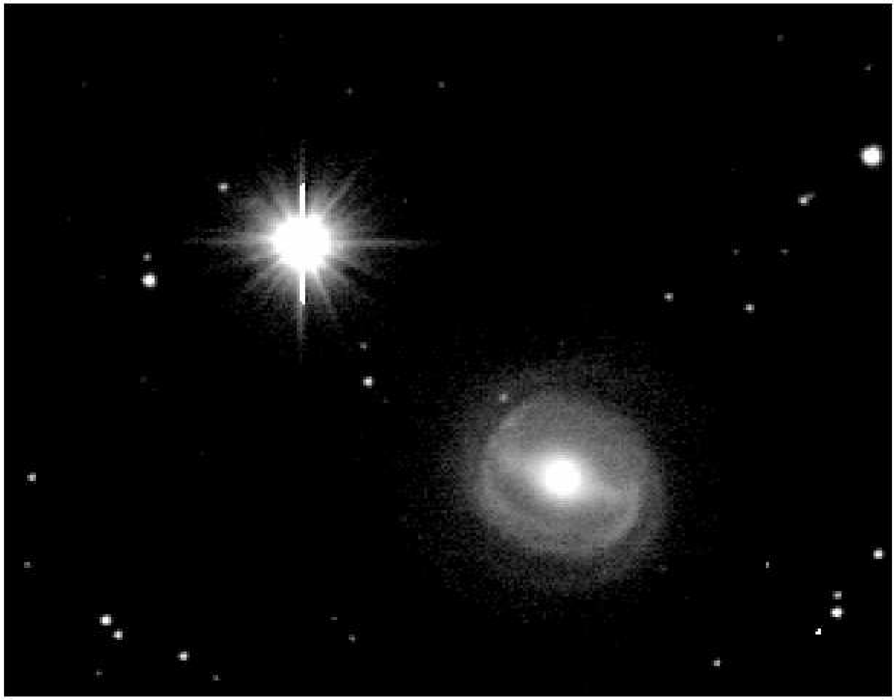


logarithmic intensity scale

AGN



NGC 3783: *linear* intensity scale

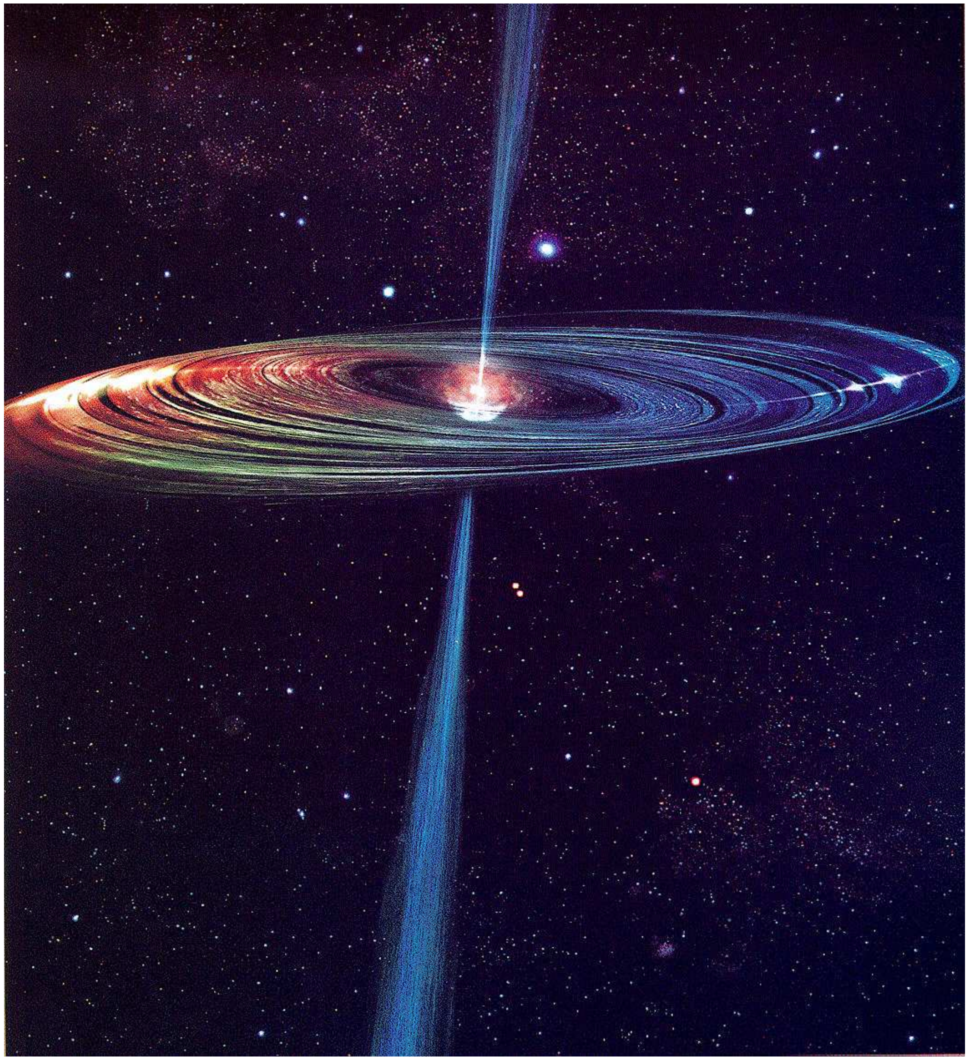


logarithmic intensity scale

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)

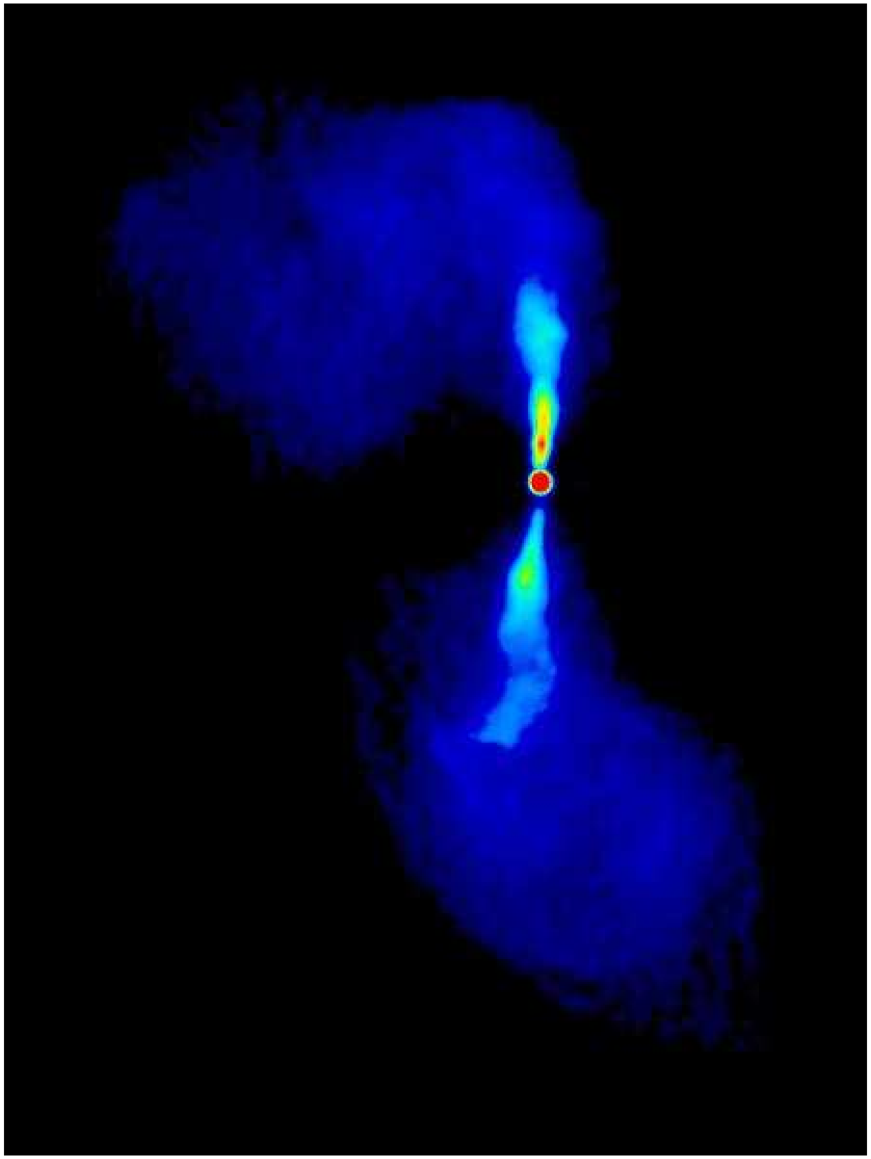
AGN



Structure of active galactic nuclei similar to galactic black holes (although somewhat scaled up. . .)

- supermassive black hole ($10^7\ M_\odot$)
- accretion disk ($\dot{M} \sim 1 \ldots 2\ M_\odot\,\mathrm{yr}^{-1}$)
- large luminosity ($L \sim 10^{10}\ L_\odot$)
- Schwarzschild radius now $\sim$ 1 AU

AGN

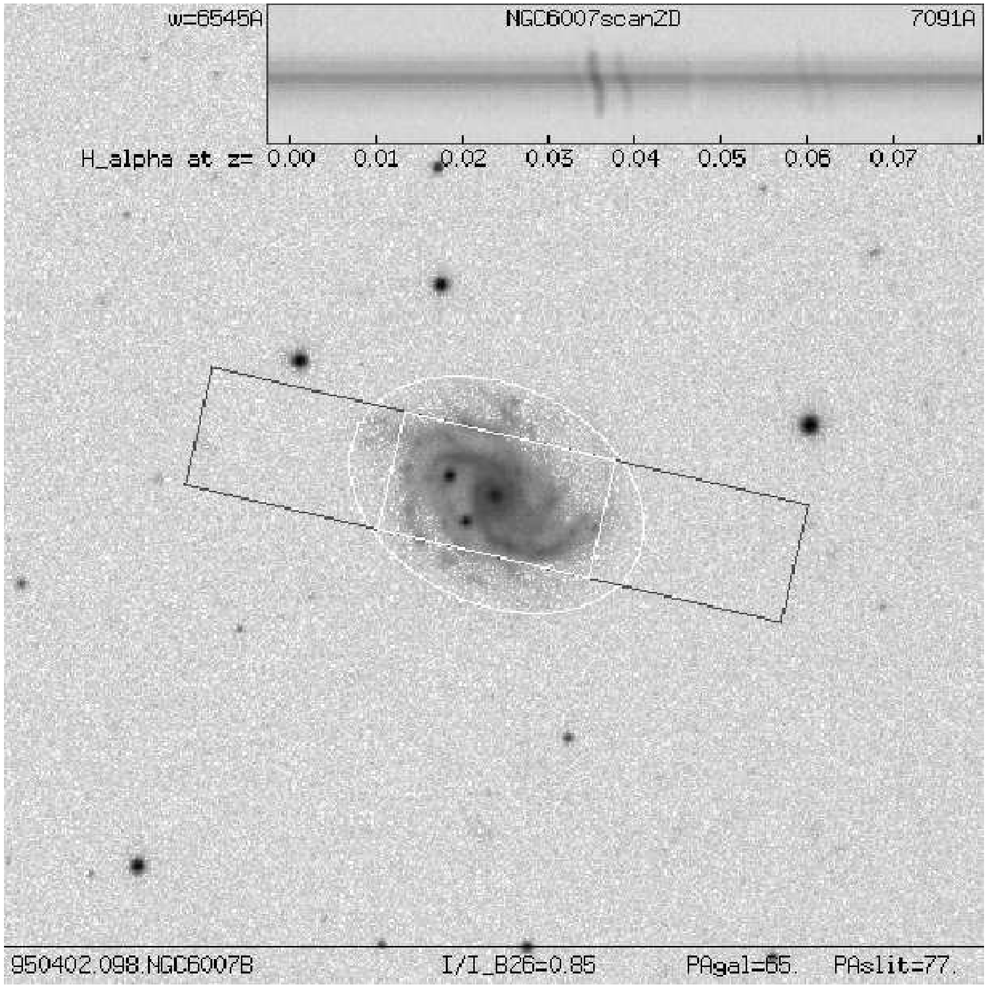


Structure of active galactic nuclei similar to galactic black holes (although somewhat scaled up...)

- supermassive black hole ($10^7\,M_\odot$)
- accretion disk ($\dot{M} \sim 1\ldots 2\,M_\odot\,\mathrm{yr}^{-1}$)
- large luminosity ($L \sim 10^{10}\,L_\odot$)
- Schwarzschild radius now $\sim$ 1 AU
- often relativistic jets, where material is accelerated to the speed of light

AGN *with* jets: quasars, blazars...
AGN *without* jets: Seyfert galaxies

Mass Determination, I



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

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

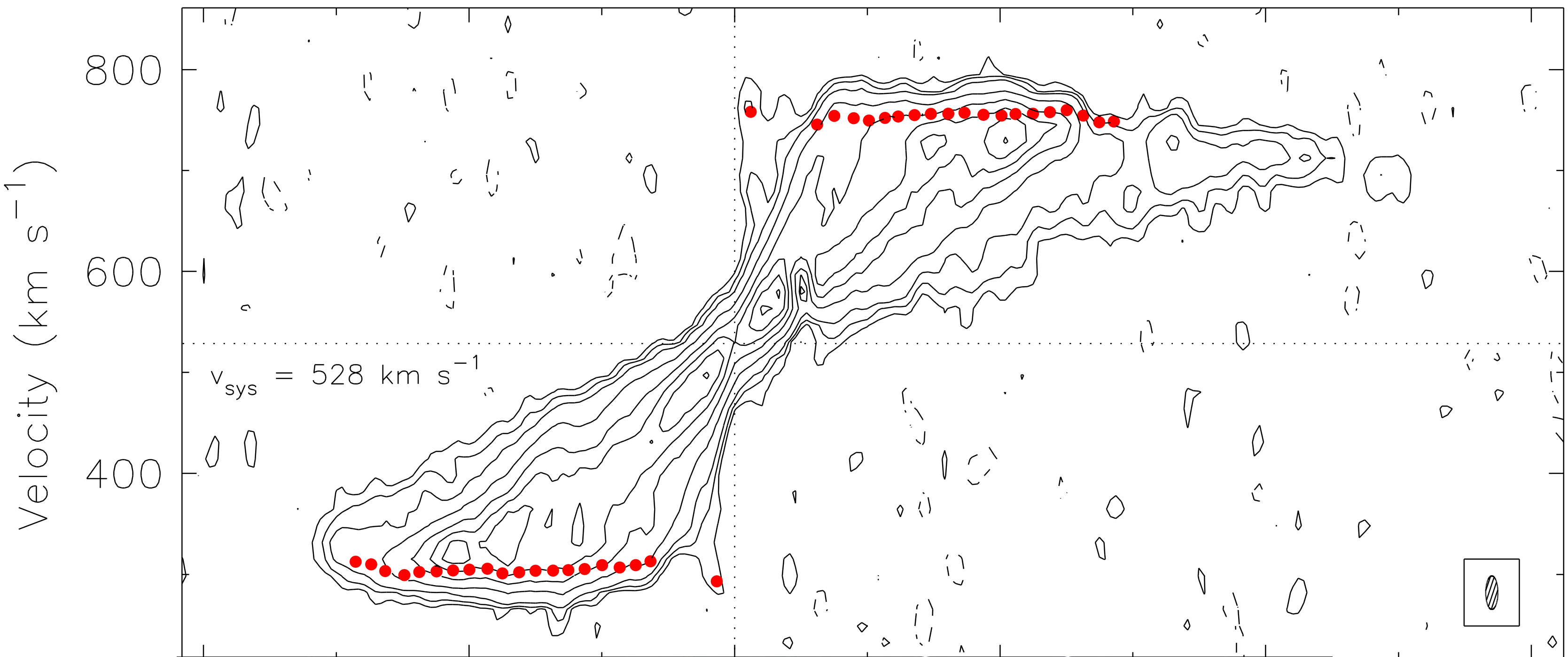
Absorption lines show clear shift $\Longrightarrow$ Doppler effect due to motion of stars around centre:

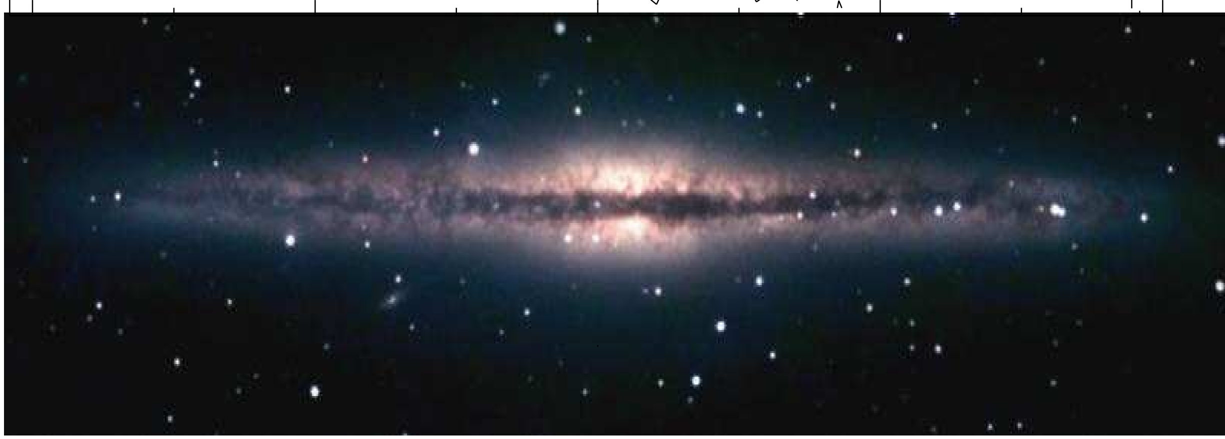
$$\frac{\Delta\lambda}{\lambda} = \frac{v_{\mathrm{r}}}{c} = \frac{v}{c}\sin i$$

where v_{r}: radial velocity, i: inclination (angle measured with respect to plane of sky).

Typical rotation speeds are a few $100\,\mathrm{km\,s^{-1}}$.

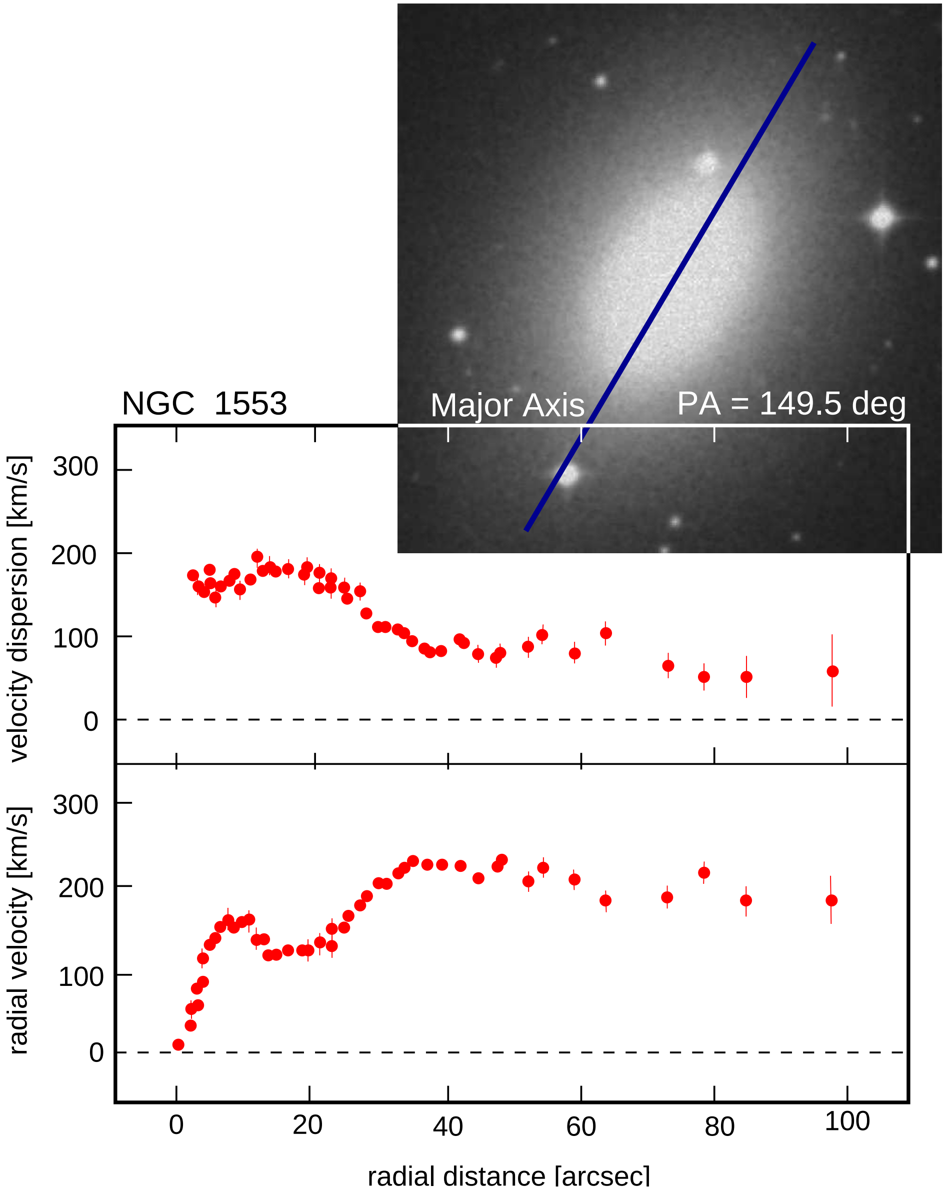
Mass Determination, II





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

Mass Determination, III



Spiral galaxy rotation curves are flat!

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

← 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

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

r: distance from centre, h: “scale height”.

Luminosity emitted within radial distance r_0:

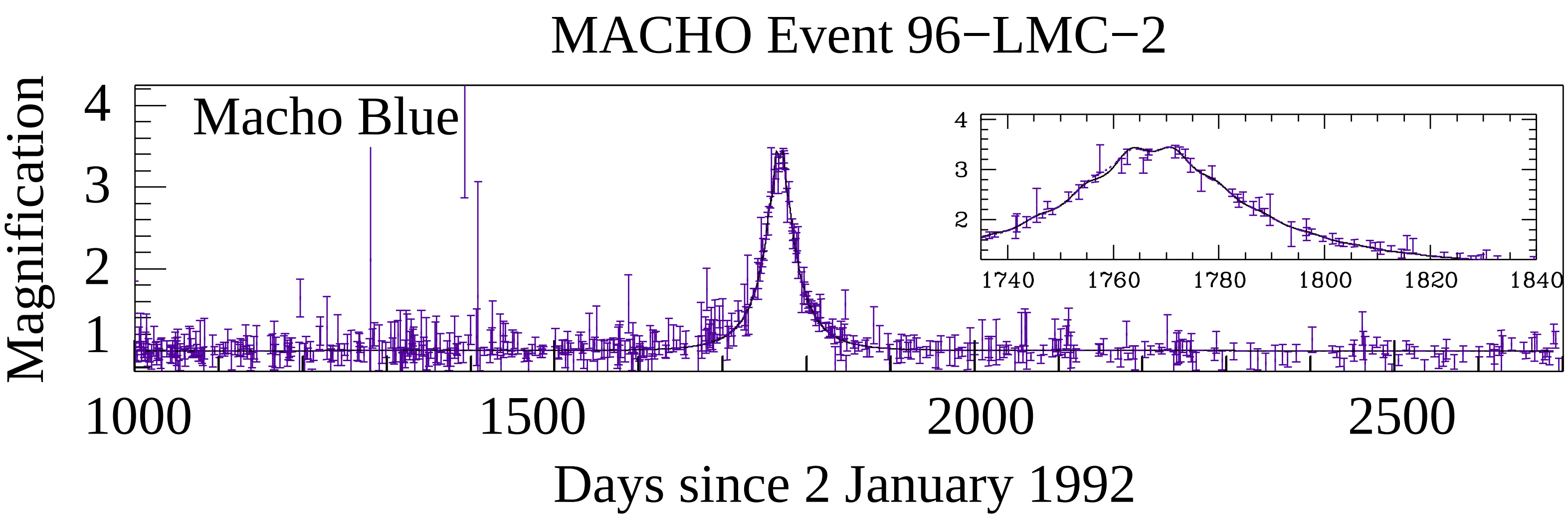
$$L(r < r_0) = I_0 \int_0^{r_0} \exp(-r/h)\, 2\pi r\, \mathrm{d}r = 2\pi I_0 \left(h^2 - \exp(-r_0/h)h(h + r_0)\right)$$

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

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

Canonical interpretation: a large fraction of gravitating material does not emit light $\Longrightarrow$ spiral galaxies have large and massive halos made of dark matter, resulting in $M/L \sim 30$.

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 year^{-1} 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 ($mc^2 \sim 10^{-5\ldots-2}$ eV) and WIMPs (weakly interacting massive particles; masses $mc^2 \sim$ 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:

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

and therefore independent of r!

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

MOND

Fits of rotational curves give

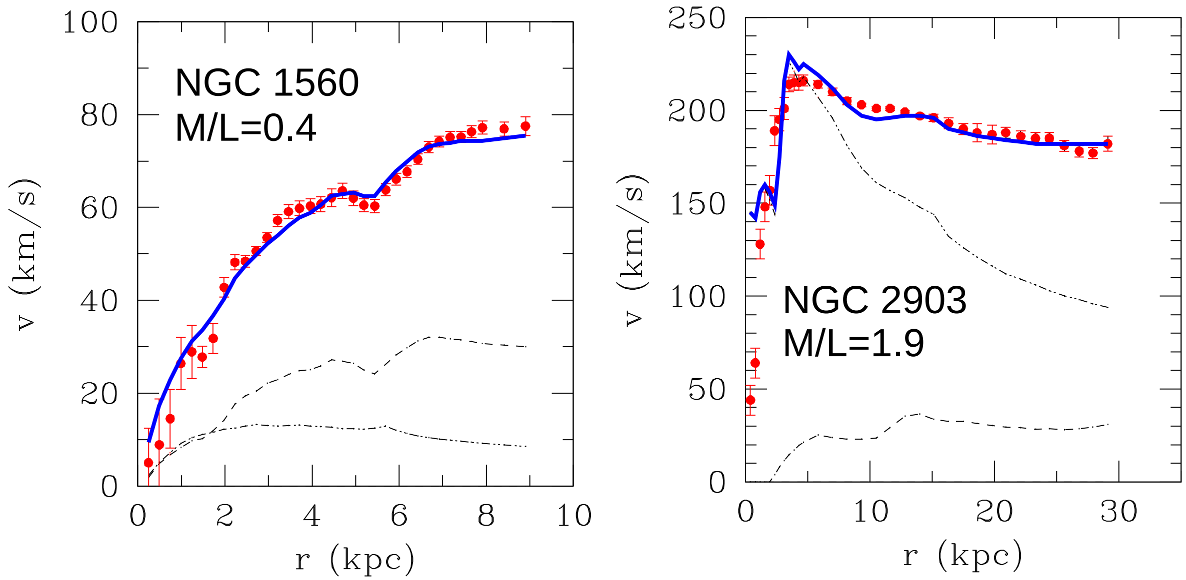
$$a_0 = 1.2\times10^{-8}\,\mathrm{cm\,s^{-2}}$$

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")



after Sanders & McGaugh (2002)

$\Longrightarrow$ 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