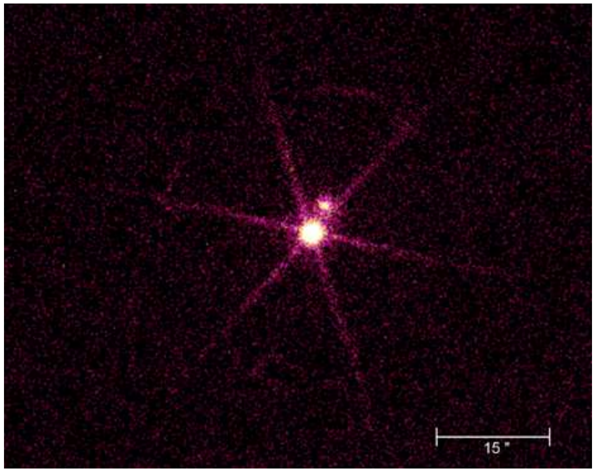
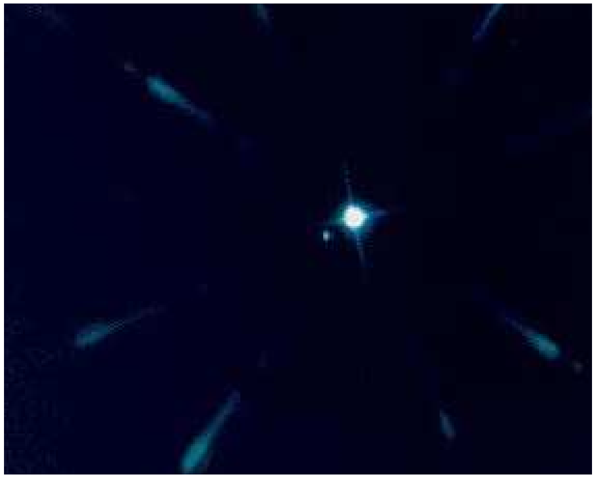
White Dwarfs



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

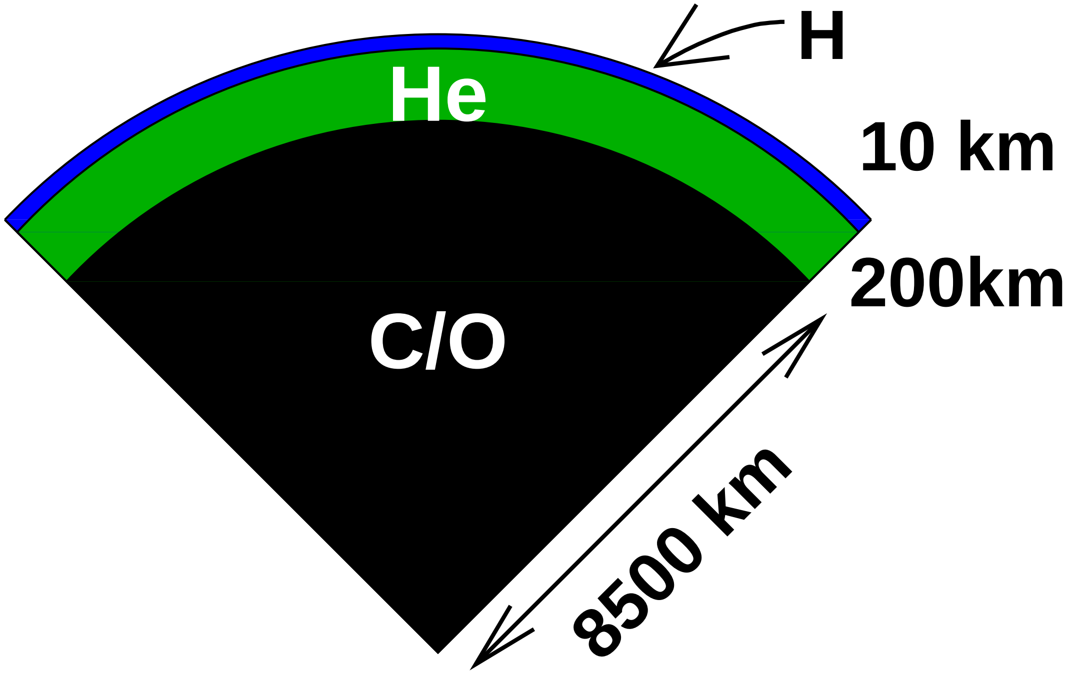


McDonald Observatory
(optical; *WD is faint*)

White Dwarfs:

1. End stages of evolution of stars with $M \lesssim 10\,M_\odot$ on main sequence
2. typically $M \sim 0.6\ldots0.8\,M_\odot$, and always $M < 1.44\,M_\odot$ (Chandrasekhar mass); above that: relativistic degenerate gas ($P \propto \rho^{4/3}$), can show that under these circumstances WD is not stable.
3. mainly consist of C and O
4. Radius $\sim$ Earth
5. Typical density $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$
6. interior temperature $\sim 10^7\,\mathrm{K}$, atmosphere $\sim 10^4\,\mathrm{K}$, slowly cooling down (observable for $\gtrsim 10^9$ years).

White Dwarfs



White dwarfs come in two flavors:

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

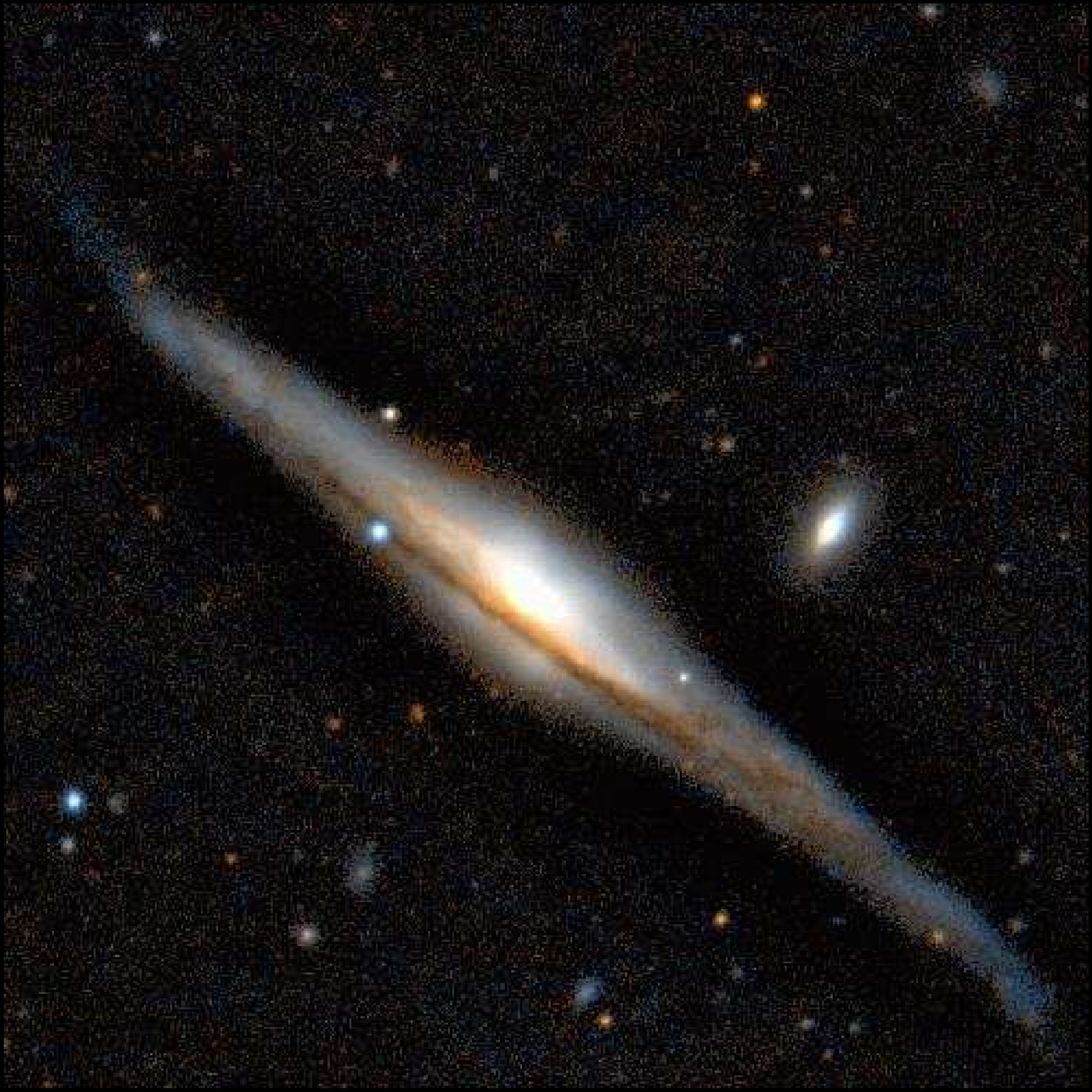
DB: He present in spectrum (∼ the rest)

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

SN1994d (HST WFPC)

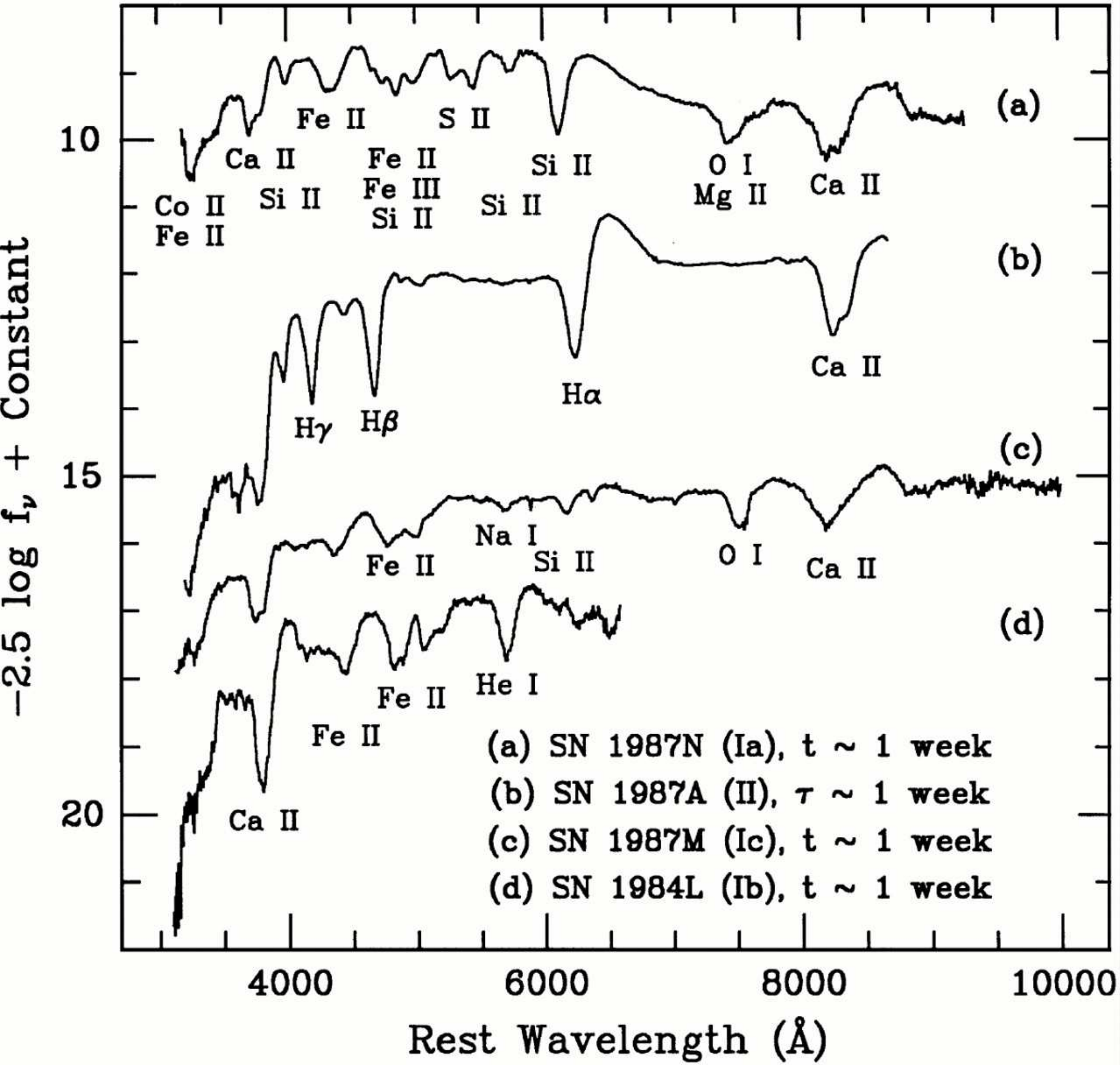


Type II SN2001cm in NGC5965 (2.56 m NOT, Håkon Dahle; NORDITA)

Evolution of more massive stars: fusion up to ^{56}Fe, then no energy gain

$\Longrightarrow$ no pressure balance in centre $\Longrightarrow$ supernova explosion of type II.

energy release: 10^{46} W ($10^{20} L_\odot$; about 1% in light, rest in neutrinos)



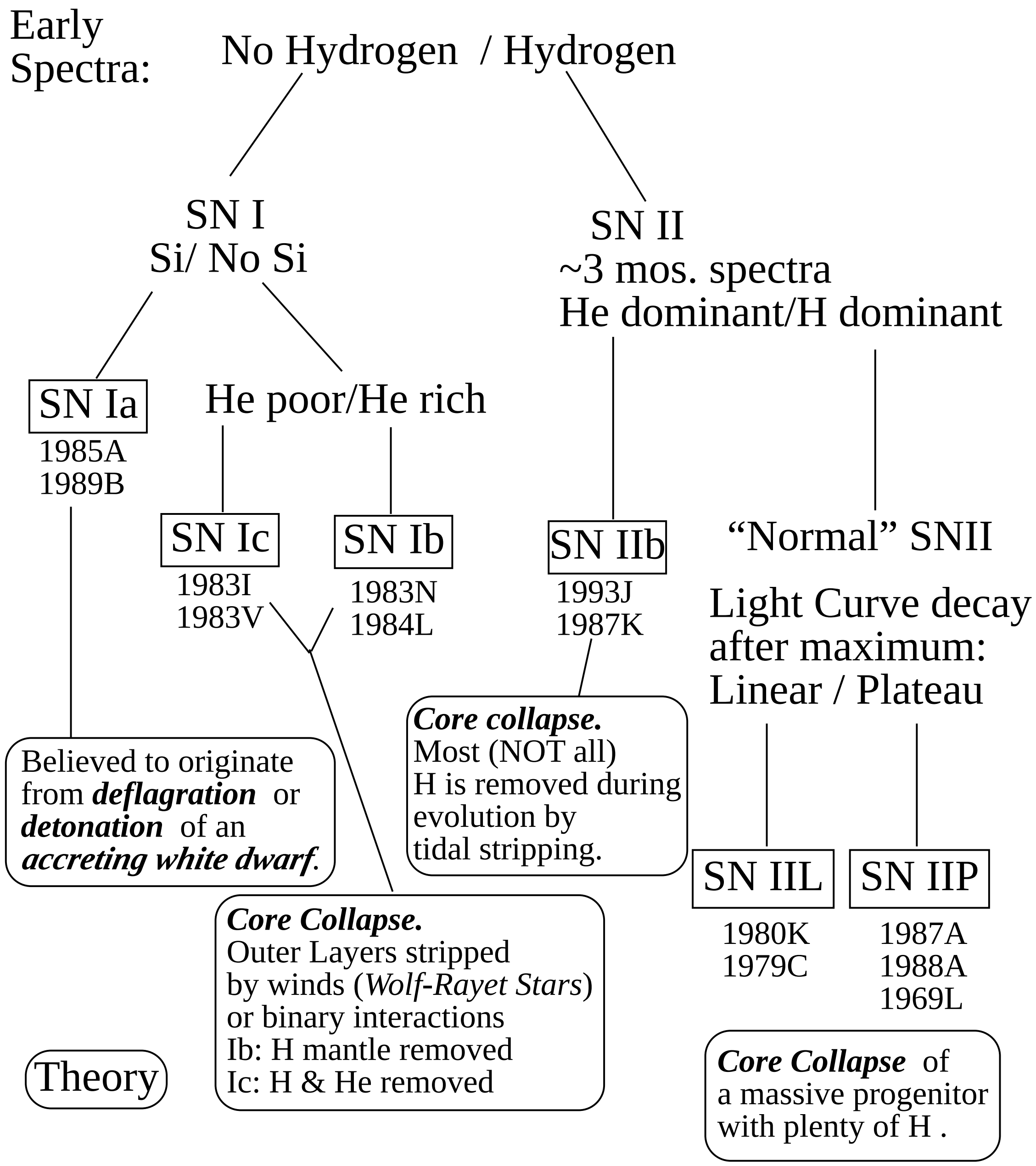
(Filippenko, 1997, Fig. 1); t: time after maximum light; τ: time after explosion;
P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

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 ⟹ beware when reading older texts.



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

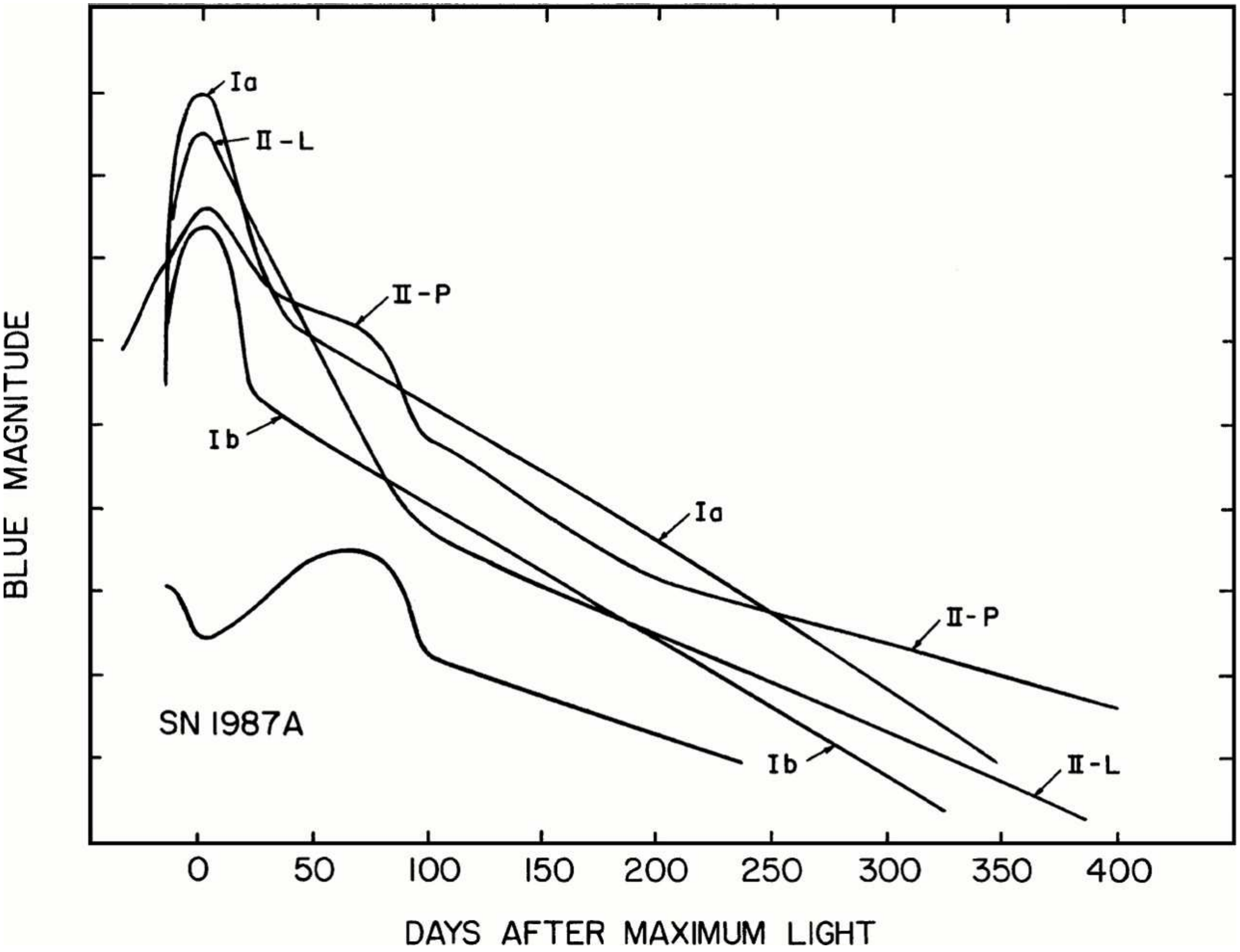
Core collapse.
Most (NOT all)
H is removed during
evolution by
tidal stripping.

Core Collapse of
a massive progenitor
with plenty of H .

Theory

courtesy M.J. Montes

Supernovae, V

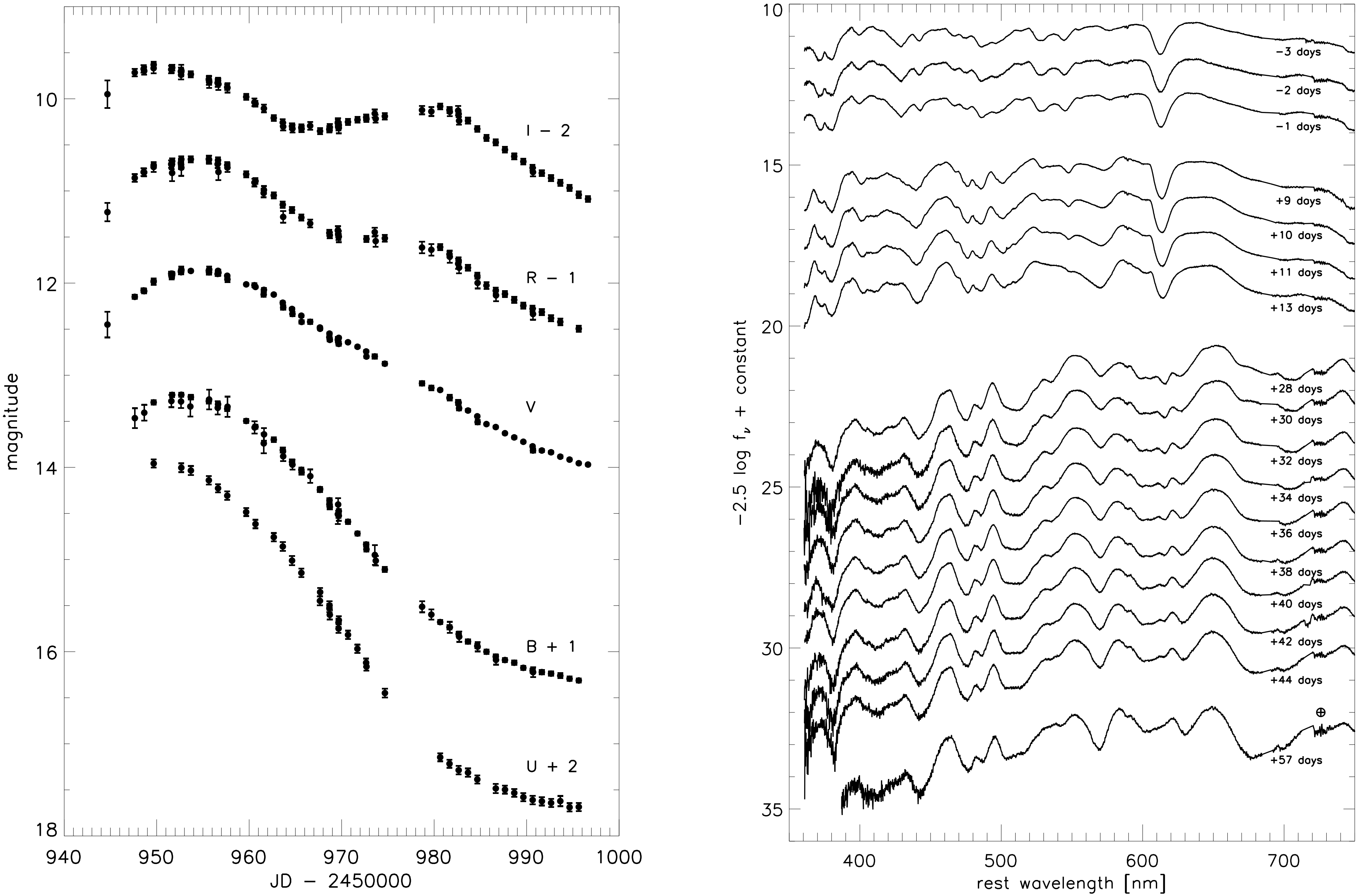


(Filippenko, 1997, Fig. 3)

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.



(SN 1998bu in M96, Jha et al., 1999, Figs. 2 and 4)

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, no preference for arms.

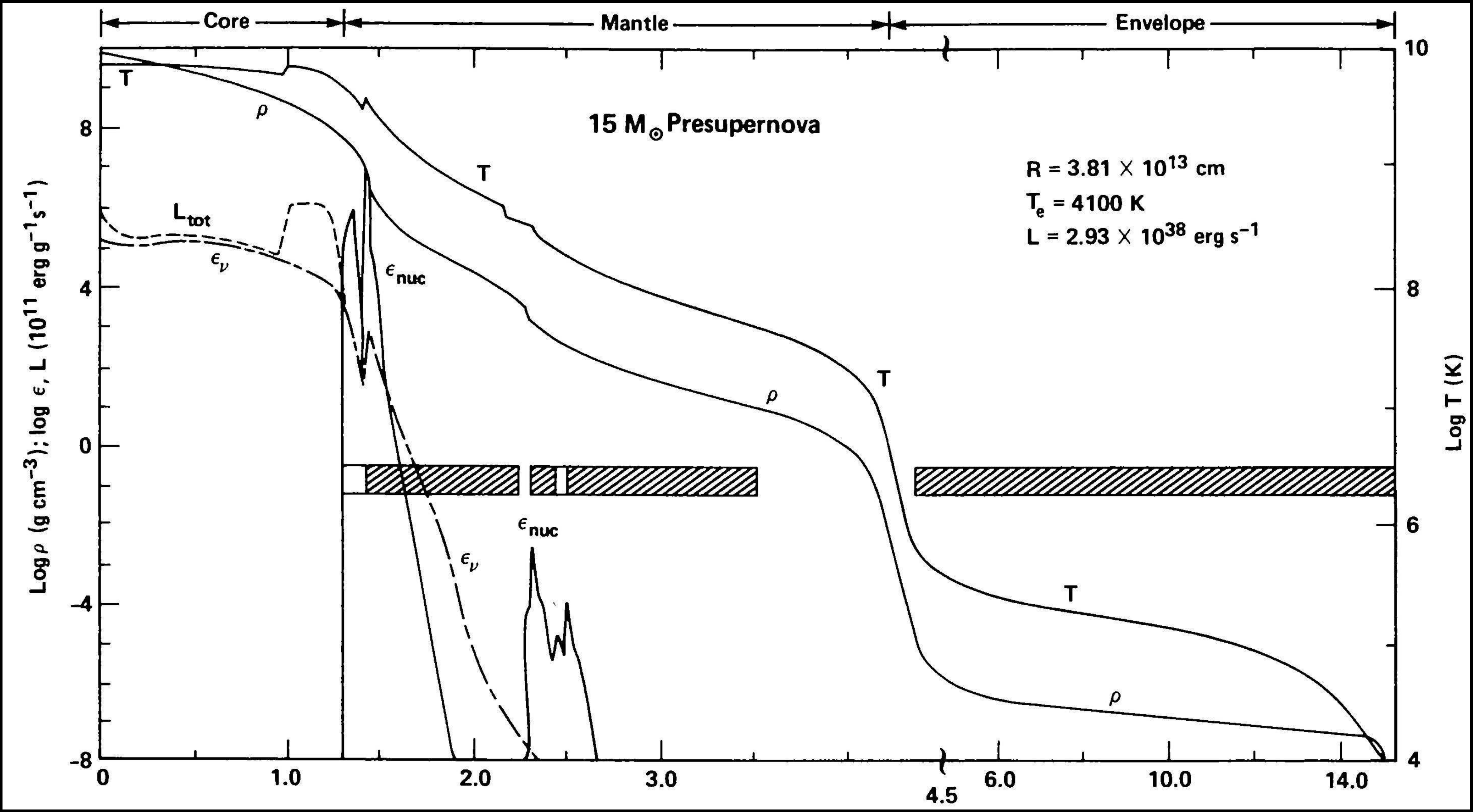
$\Longrightarrow$ progenitor of SNe Ia: accreting carbon-oxygen white dwarfs, undergoing thermonuclear runaway (see later)

© Anglo-Australian Observatory

Core Collapse SNe, III

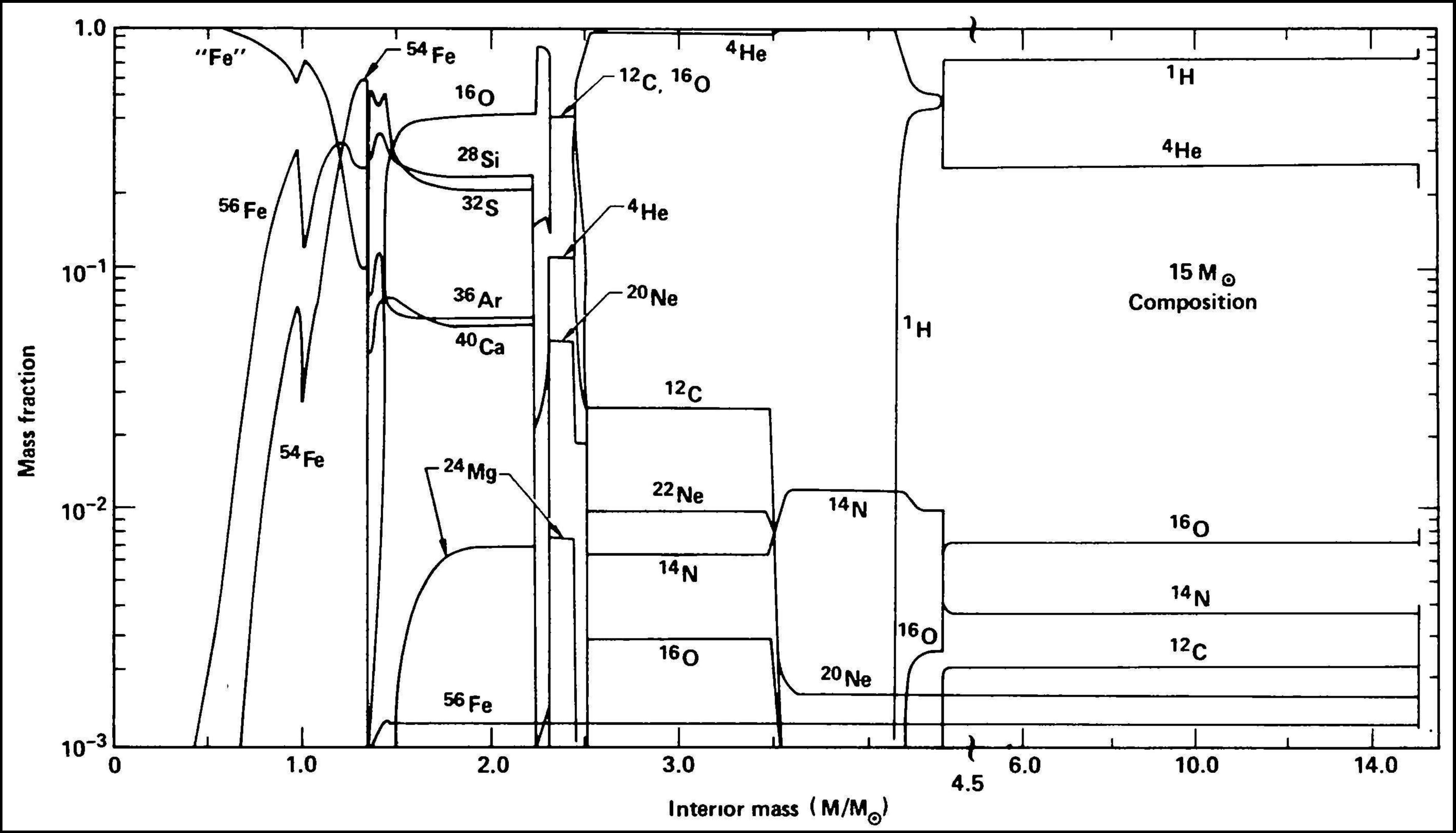
Nuclear reactions in massive ($> 8\,M_\odot$) stars:

Reaction	above T $[10^6\,\mathrm{K}]$	Energy gain [MeV]
Hydrogen burning		
$4\,^1\mathrm{H} \longrightarrow {}^4\mathrm{He}$	4	6.55
Helium burning		
$3\,^4\mathrm{He} \longrightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$	100	<0.61
Carbon burning		
${}^{12}\mathrm{C} + {}^4\mathrm{He} \longrightarrow {}^{16}\mathrm{O}$	600	<0.54
$2\,^{12}\mathrm{C} \longrightarrow {}^4\mathrm{He} + {}^{20}\mathrm{Ne}$		
${}^{20}\mathrm{Ne} + {}^4\mathrm{He} \longrightarrow \mathrm{n} + {}^{23}\mathrm{Mg}$		
Oxygen burning		
$2\,^{16}\mathrm{O} \longrightarrow {}^4\mathrm{He} + {}^{28}\mathrm{Si}$	1000	<0.3
$2\,^{16}\mathrm{O} \longrightarrow 2\,^4\mathrm{He} + {}^{24}\mathrm{Mg}$		
Silicon burning		
$2\,^{28}\mathrm{Si} \longrightarrow {}^{56}\mathrm{Fe}$	3000	< 0.18



Woosley & Weaver, 1988, Fig. 1

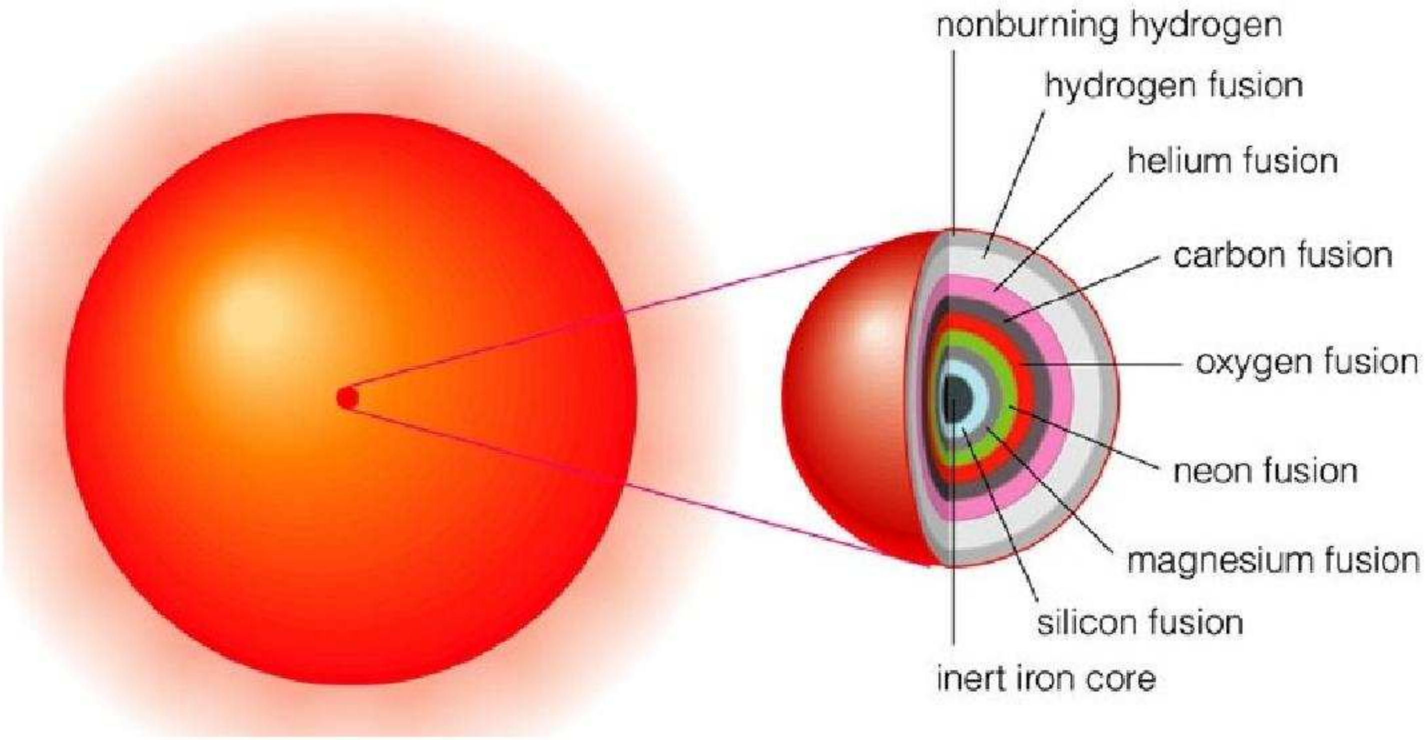
Structure of a 15 $M_\odot$ pre-supernova star



Woosley & Weaver, 1988, Fig. 1

Structure of a 15 $M_\odot$ pre-supernova star

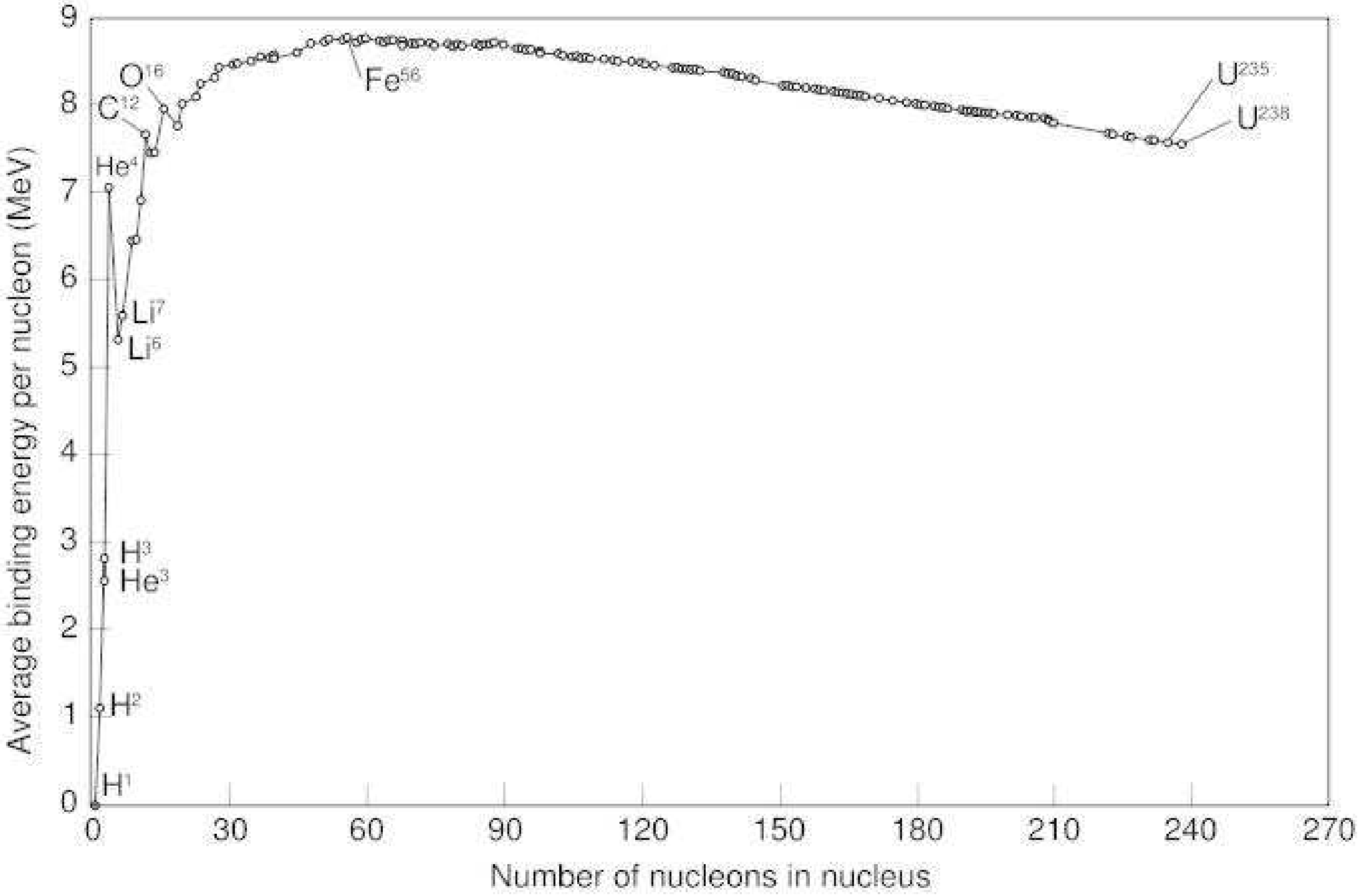
Core Collapse SNe, VI



Core collapse supernovae:

- SNe II: progenitors are stars with mass 8–40 $M_\odot$ (approximate).
- SNe Ib, Ic: more massive stars, which lost their H shell due to strong stellar winds

Core Collapse SNe, VII



^{56}Fe is one of the most tightly bound nucleons $\Longrightarrow$ Star has a problem once ^{56}Fe reached: fusion processed become endotherm

Core Collapse SNe, VIII

Iron core starts to shrink $\Longrightarrow$ T increases $\Longrightarrow$ ^{56}Fe starts photodisintegration:

$$^{56}\mathrm{Fe} + \gamma \longrightarrow 13\,^{4}\mathrm{He} + 4\mathrm{n}$$
$$^{4}\mathrm{He} + \gamma \longrightarrow 2\mathrm{p} + 2\mathrm{n}$$

Typical core masses are between 1.3 $M_\odot$ (for 10 $M_\odot$ on ZAMS) and 2.5 $M_\odot$ (for 50 $M_\odot$ on ZAMS).

Until now, free electrons have degeneracy pressure and hold star

BUT: once core temperature increases to $T_\mathrm{c} \sim 8 \times 10^{9}\,\mathrm{K}$ and density to $\rho_\mathrm{c} \sim 10^{10}\,\mathrm{g\,cm^{-3}}$: neutronization:

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

$\Longrightarrow$ rapid energy loss (for a 20 $M_\odot$ star: $4.4 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ in photons, but $3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ in neutrinos!) $\Longrightarrow$ COLLAPSE

Core Collapse SNe, IX

Once pressure support is gone:

$\Longrightarrow$ collapse (free fall)

$\Longrightarrow$ speeds are fast (outer core: $\sim$70000 km s^{-1}!)

$\Longrightarrow$ supersonic, so outer parts don't realize what's happening

$\Longrightarrow$ inner core compresses further through neutronization

$\Longrightarrow$ once $\rho_\mathrm{c} \sim 8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$: Neutron star forms (degeneracy pressure of neutrons)

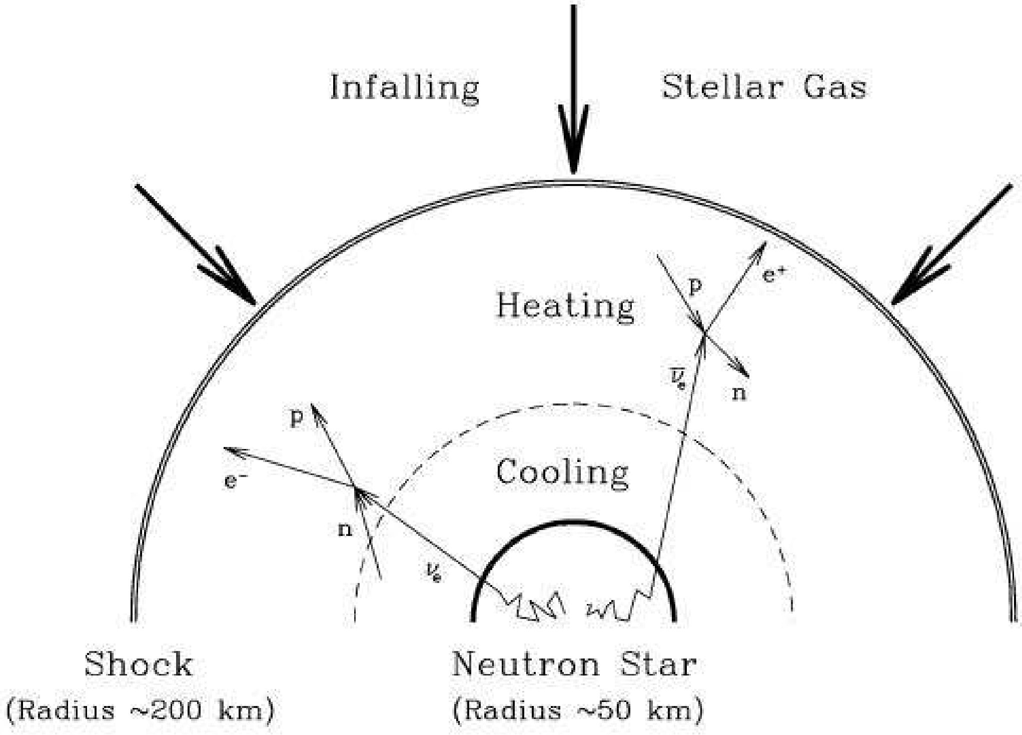
$\Longrightarrow$ "solid surface forms", resulting in bounce back

$\sim$20 msec for shock wave to pass through core

$\Longrightarrow$ further photodesintegration

$\Longrightarrow$ shock moves outwards $\Longrightarrow$ explosion ("prompt hydrodynamic explosion")

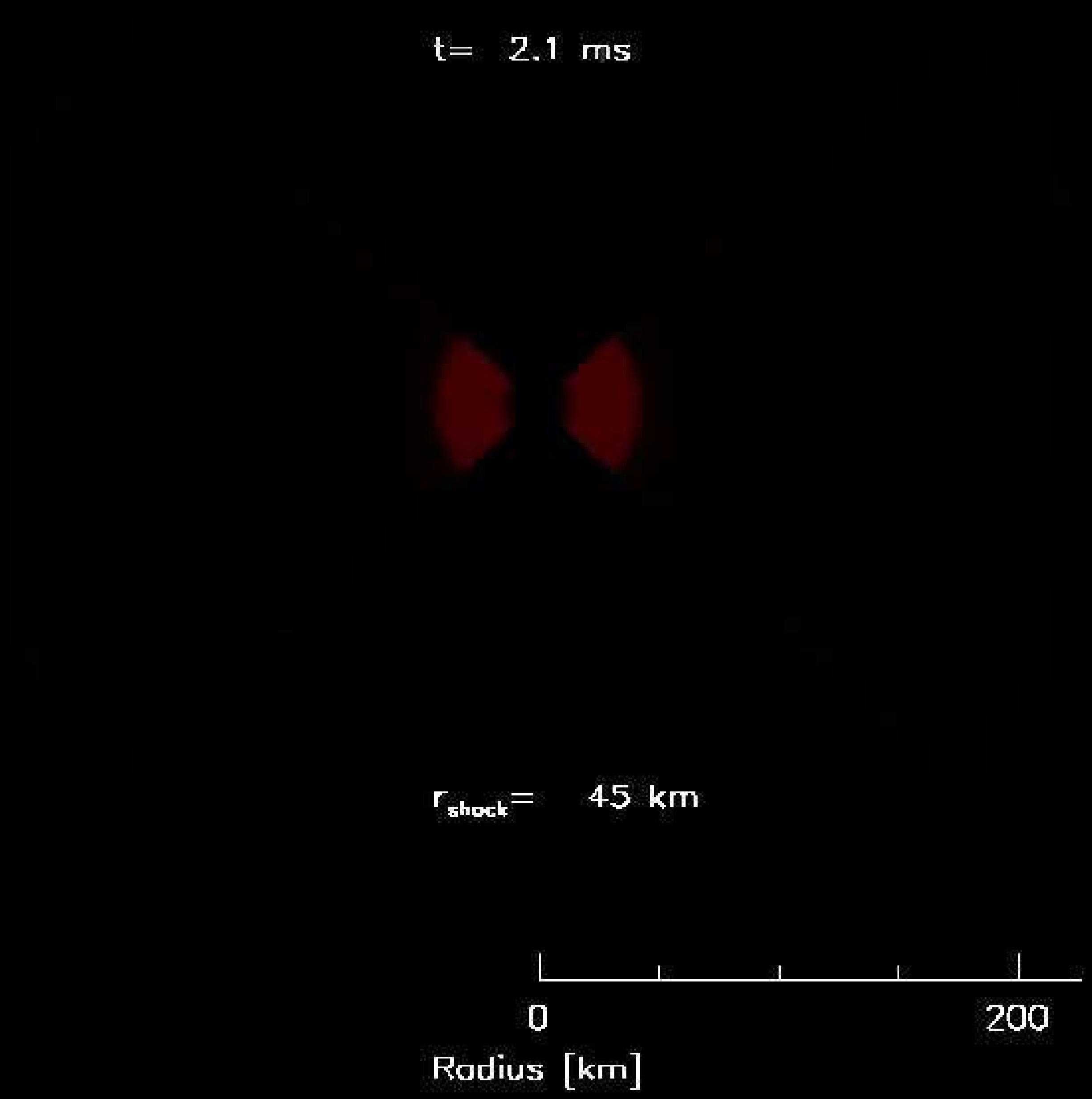
Core Collapse SNe, X



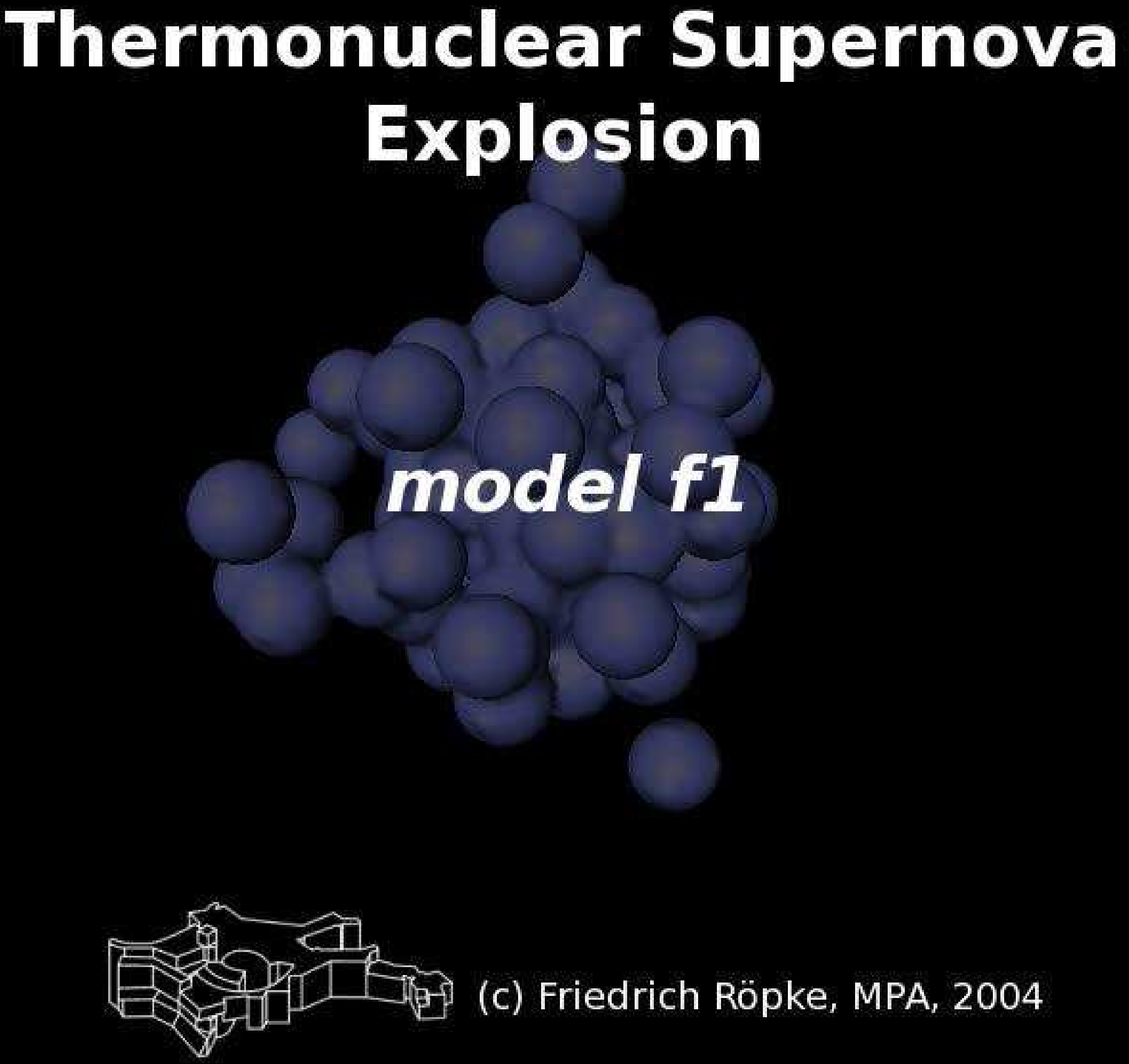
H.-T. Janka

For Fe core mass of $\gtrsim$1.2 $M_\odot$: Infalling gas damps expansion of shock $\Longrightarrow$ need sufficient heating by neutrinos to trigger explosion! (takes $\sim$1 s $\Longrightarrow$ “delayed explosion mechanism”)

energy loss $\sim$1.7 × 10^{51} ergs s^{-1} per 0.1 $M_\odot$ of Fe

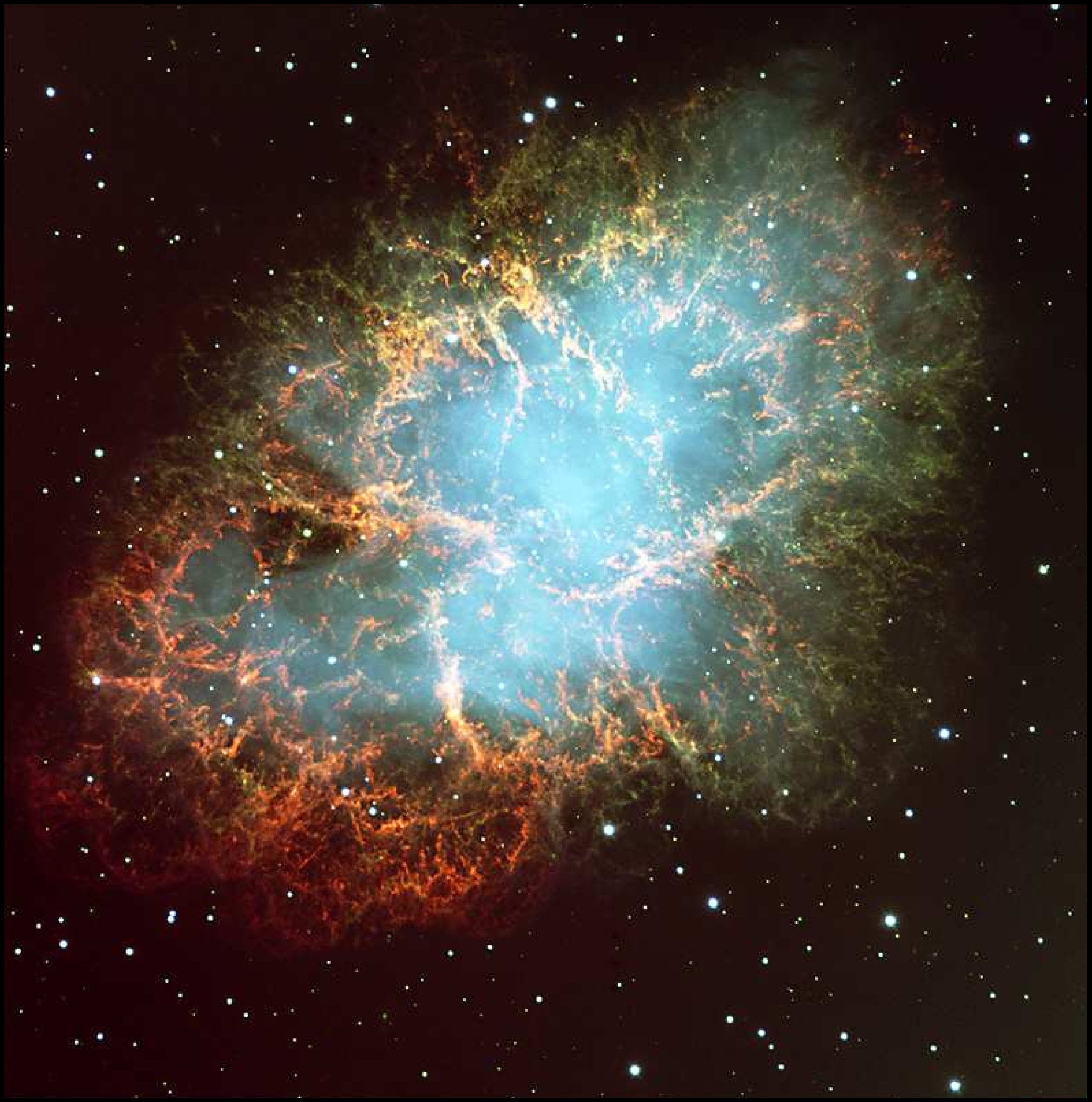


W. Hillebrandt/MPA



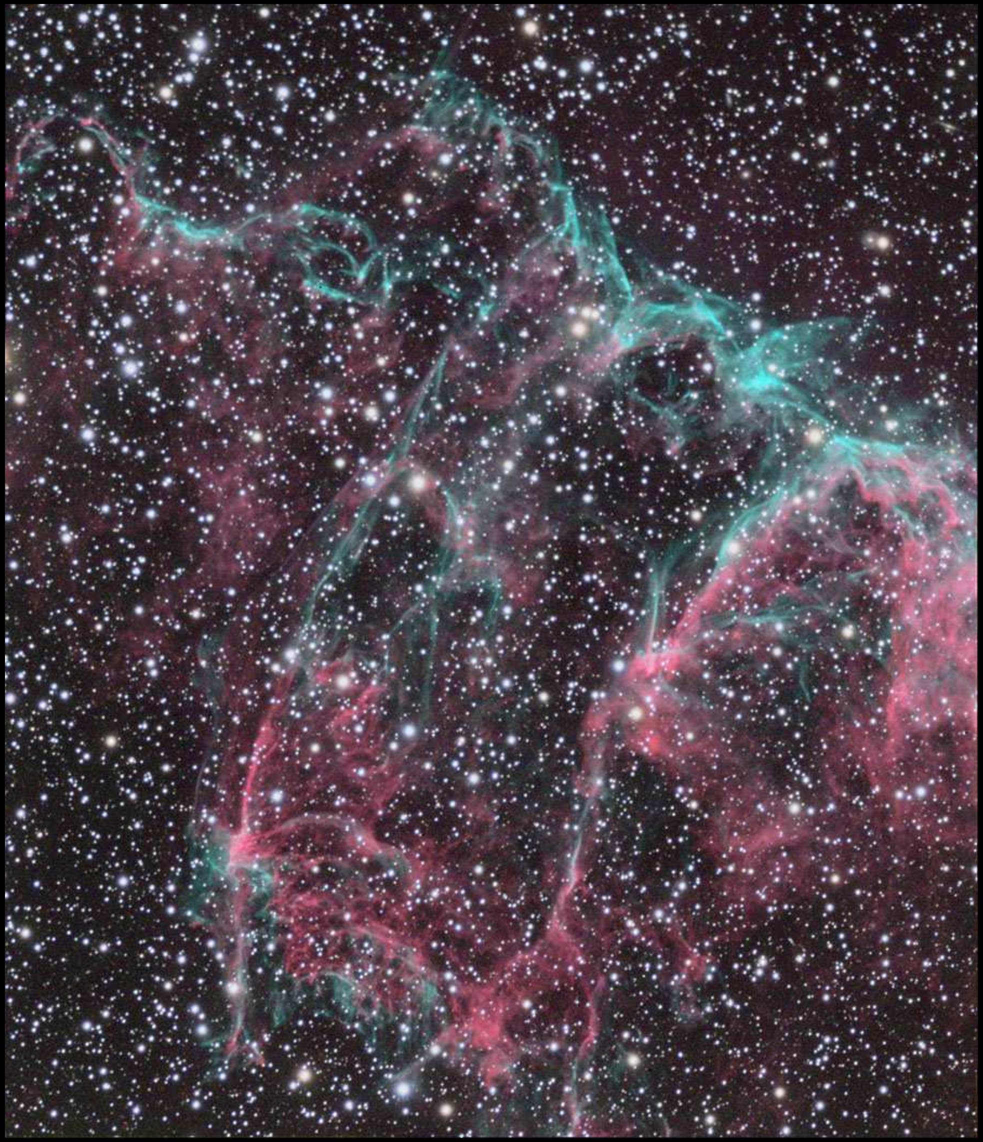
3D-simulations show strong asymmetry of supernova explosion.

CXC



(ESO VLT/FORS 2)

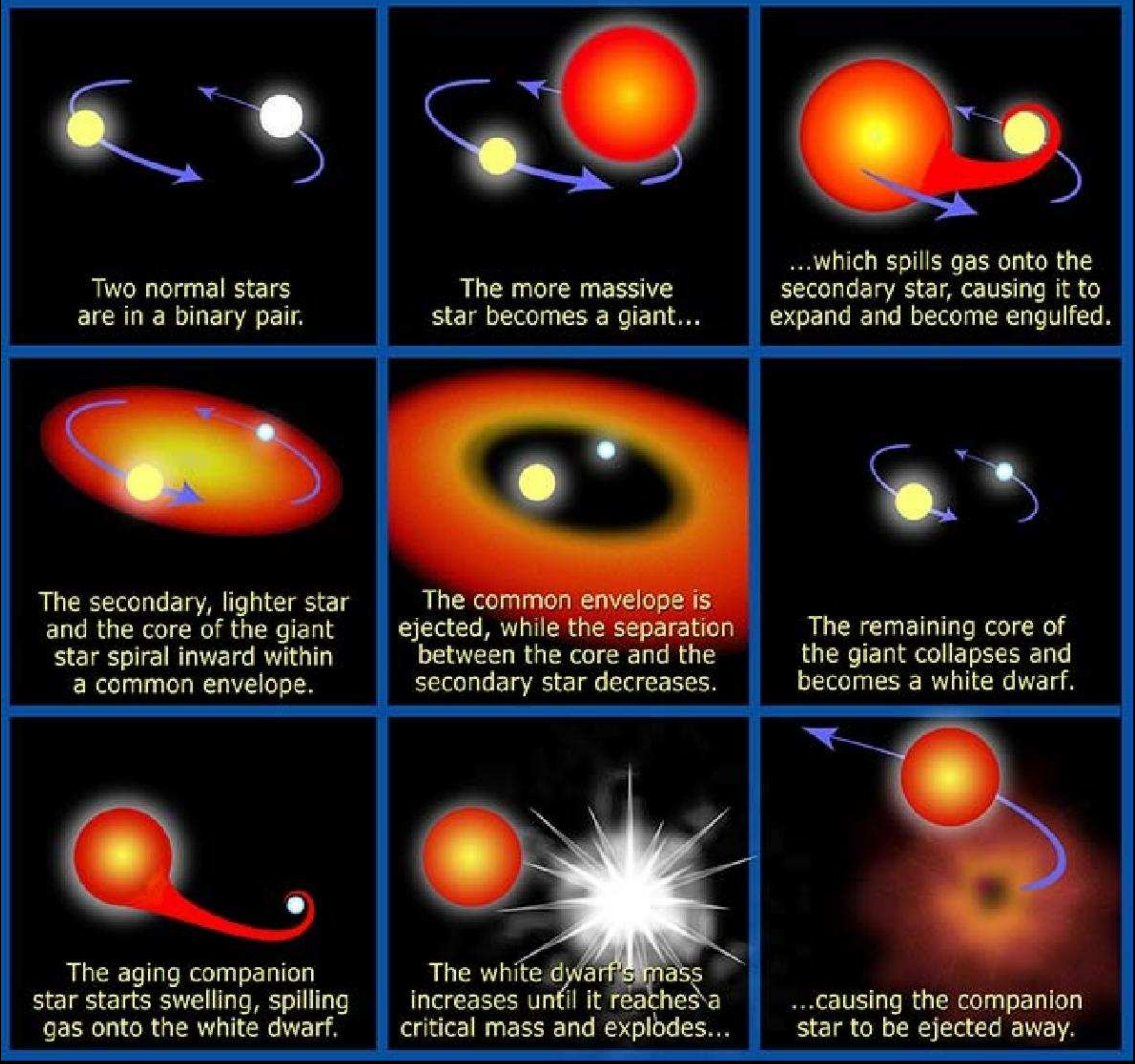
Crab nebula: young remnant of SN of 1054, observed light due to synchrotron radiation (radiation emitted by electrons accelerated in magnetic field)



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.

The progenitor of a Type Ia supernova



Two normal stars are in a binary pair.

The more massive star becomes a giant...

...which spills gas onto the secondary star, causing it to expand and become engulfed.

The secondary, lighter star and the core of the giant star spiral inward within a common envelope.

The common envelope is ejected, while the separation between the core and the secondary star decreases.

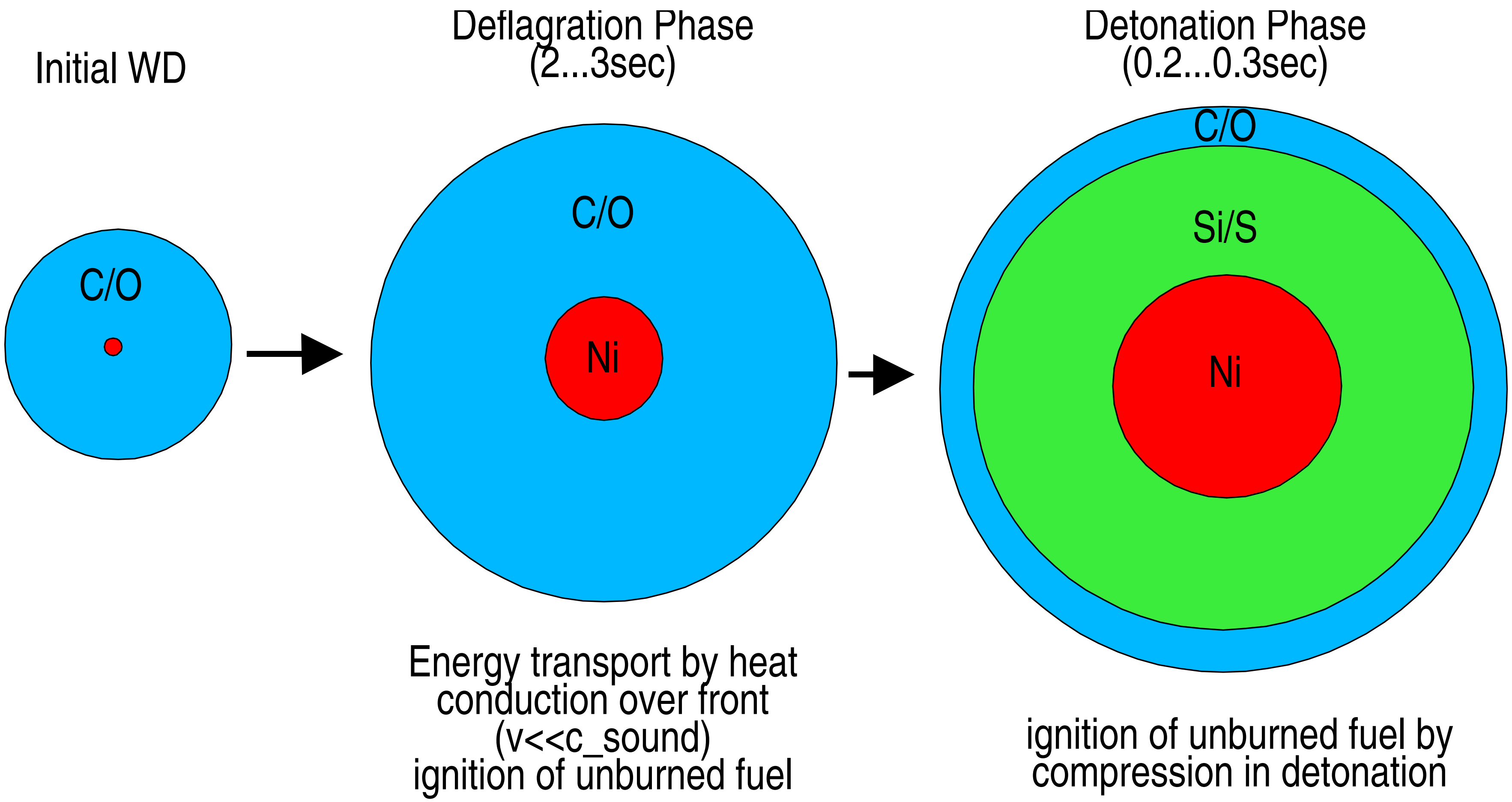
The remaining core of the giant collapses and becomes a white dwarf.

The aging companion star starts swelling, spilling gas onto the white dwarf.

The white dwarf's mass increases until it reaches a critical mass and explodes...

...causing the companion star to be ejected away.

Supernova Mechanisms – Ia



after P. Höflich

SNe Ia: thermonuclear runaway in carbon-oxygen white dwarfs (See later for details)

Neutron Stars

During SN explosion:

Core of exploding star above Chandrasekhar limit $\Longrightarrow$ core collapses

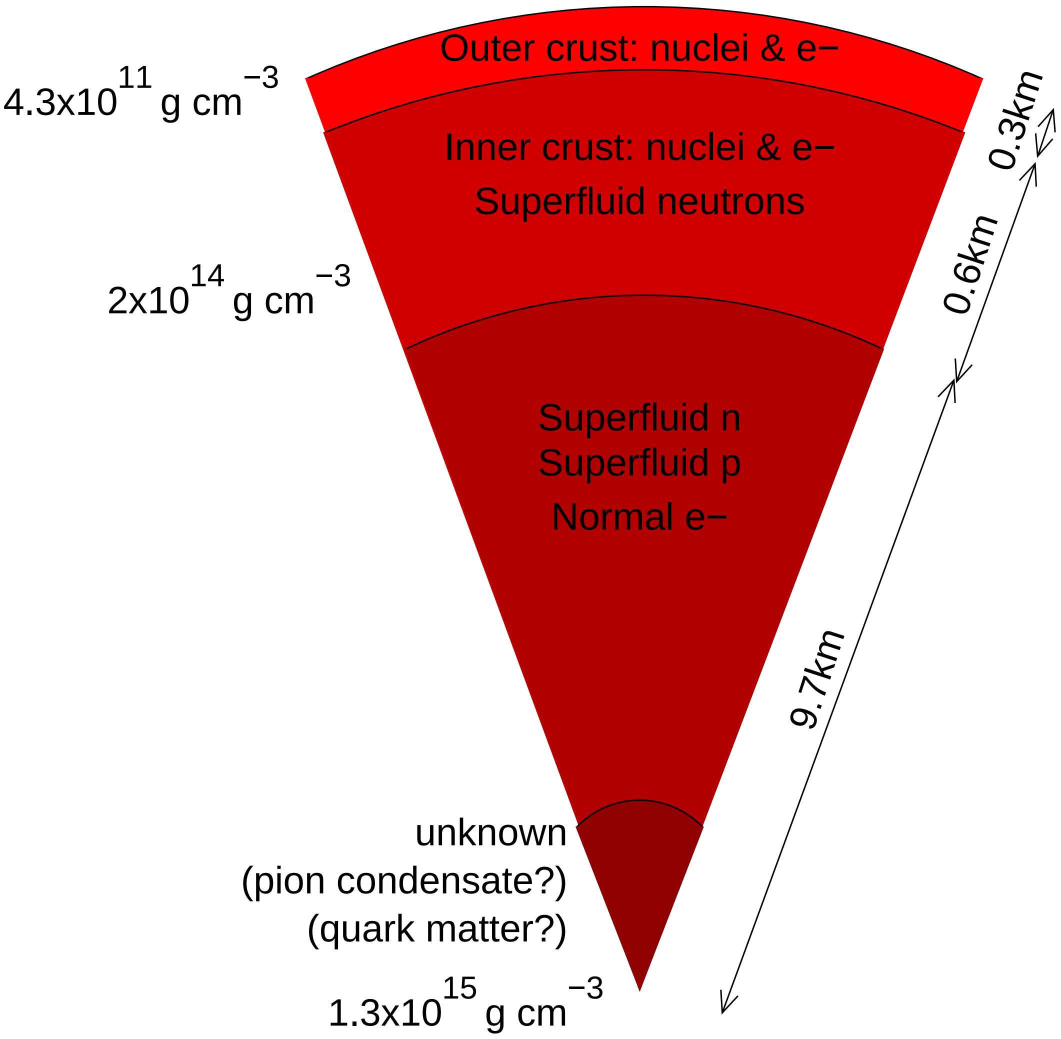
Densities get so high that neutronization sets in:

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

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: $10\ldots15\,\mathrm{km}$ (Nuremberg!)
- surface gravity $\sim 10^{11}\times$ Earth
- Detailed structure not yet fully understood

Neutron Stars: Structure, I



Crust: perhaps crystallized?

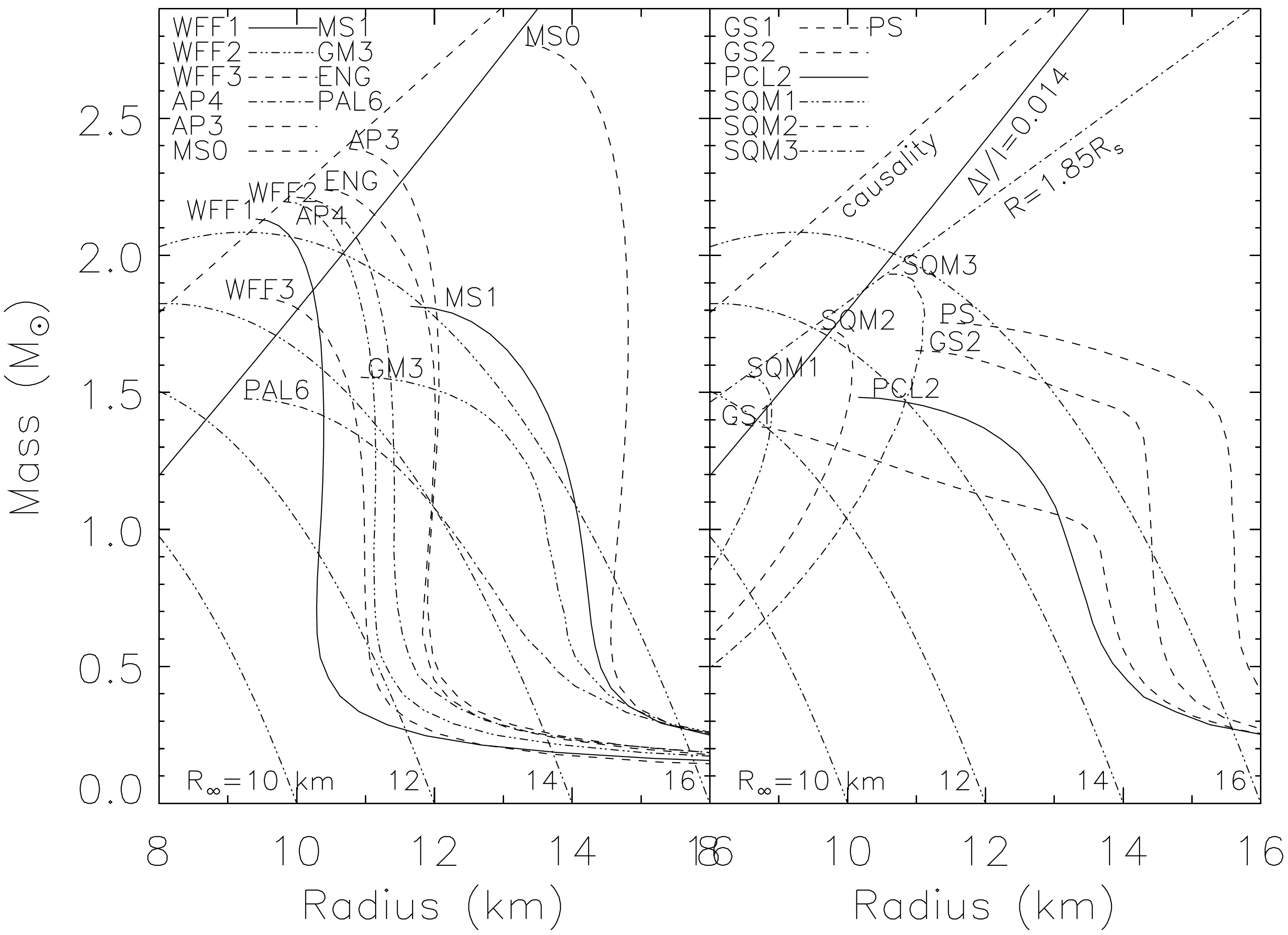
Atoms become elongated along B-field line on surface

Internal structure unclear:

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

(after Shapiro & Teukolsky, 1983)

Neutron Stars: Structure, II



(Lattimer & Prakash, 2001)

The structure and size of neutron stars depends strongly on the unknown properties of matter at very high densities.

Neutron Stars: Rotation, I

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

Total angular momentum of homogeneous sphere:

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

Neutron Stars: Rotation, II

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

Total angular momentum of homogeneous sphere:

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

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)

Neutron Stars: Rotation, III

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

Total angular momentum of homogeneous sphere:

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

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

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

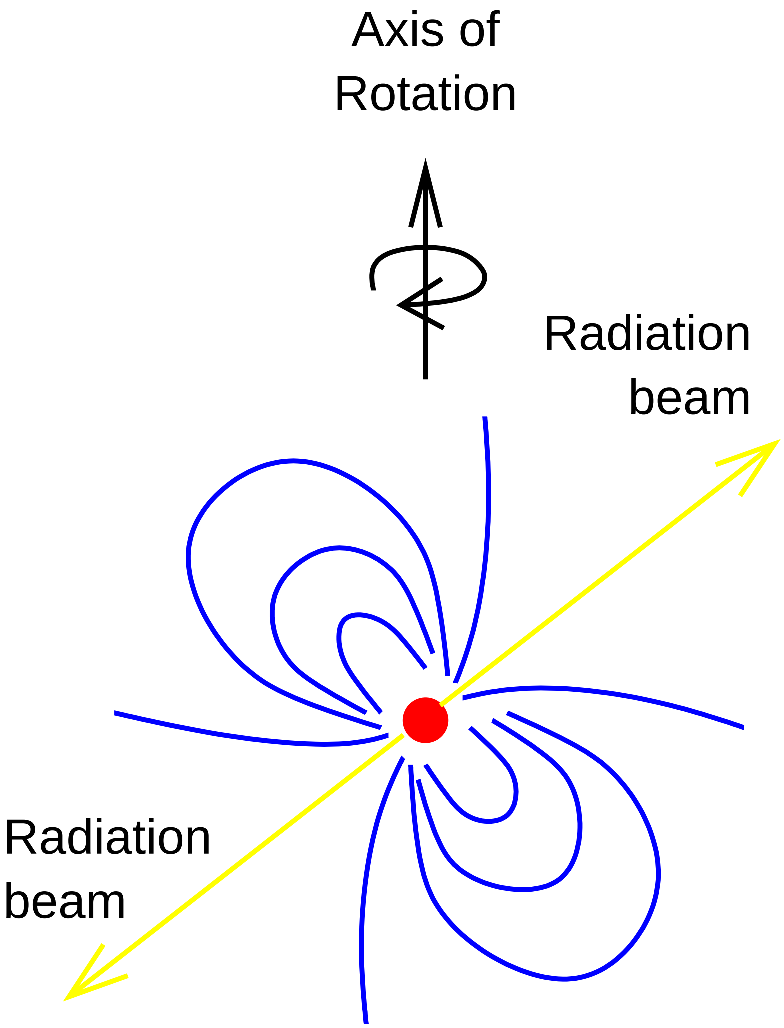
(where P: rotation period)

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!

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: $B \sim 10^6 \ldots 10^8$ T)

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

The sounds of pulsars

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

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

Black Holes, I

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

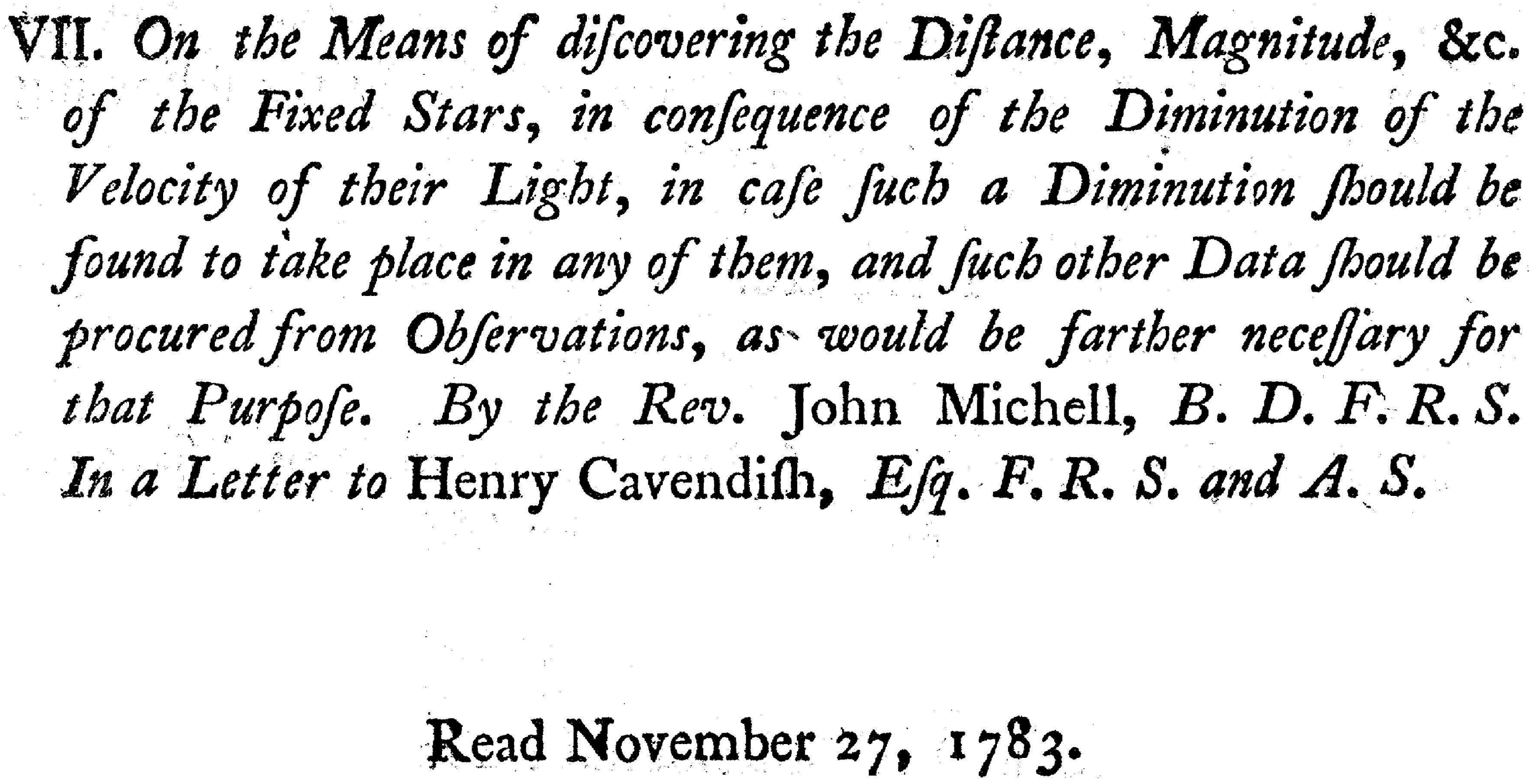
Detailed mass limit unknown, causality considerations give $M \sim 3\,M_\odot$ (for “stiff equation of state” the sound speed becomes greater than speed of light at this mass)

Compact objects with mass above Oppenheimer Volkoff limit: Black Holes

More conservative astronomers: “Black Hole Candidates”.

Black Holes, II

Rev. John Michell: *Phil. Trans. R. Soc. London*, ***74***, *35–57 (1784)*:

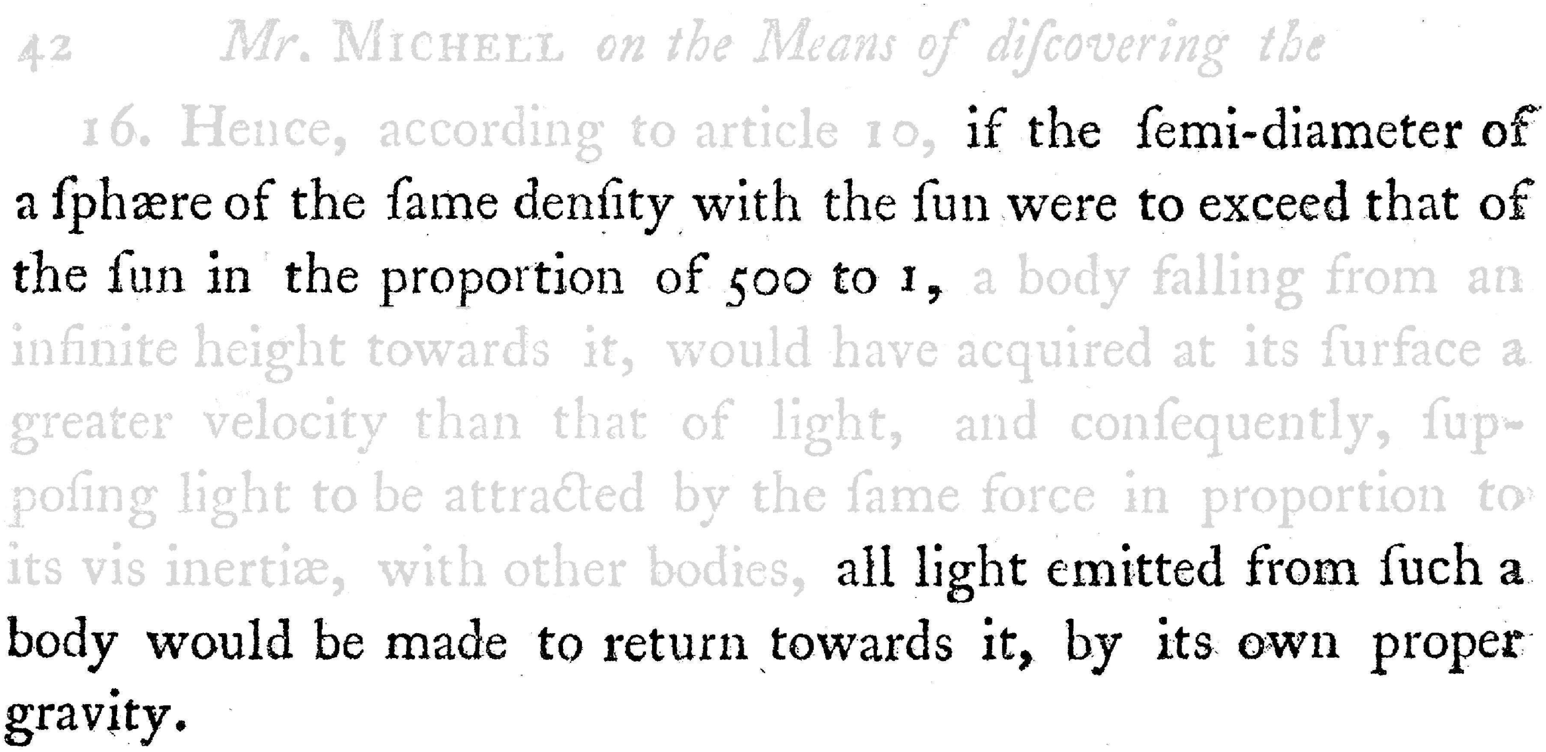


VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

Read November 27, 1783.

Black Holes, III

Rev. John Michell: *Phil. Trans. R. Soc. London*, ***74***, *35–57 (1784)*:



42 Mr. Michell on the Means of diſcovering the

16. Hence, according to article 10, if the ſemi-diameter of a ſphære of the ſame denſity with the ſun were to exceed that of the ſun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its ſurface a greater velocity than that of light, and conſequently, ſuppoſing light to be attracted by the ſame force in proportion to its vis inertiæ, with other bodies, all light emitted from ſuch a body would be made to return towards it, by its own proper gravity.

Black Holes, IV

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, I

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")

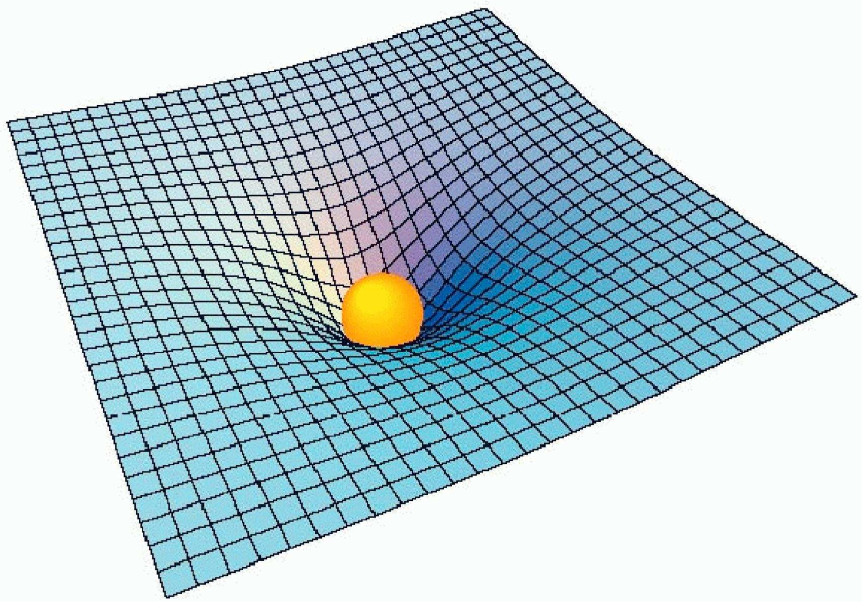
$\Longrightarrow E = mc^2$
("Mass and Energy are equivalent")

Einstein, II

Albert Einstein (1879–1955)

General relativity (1916):

- Mass curves space ("Metric")

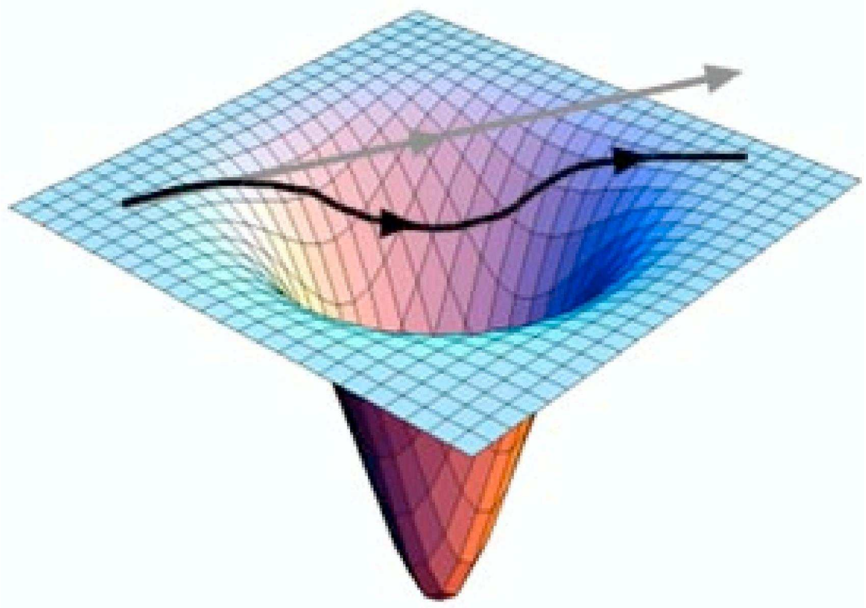


Einstein, III

Albert Einstein (1879–1955)

General relativity (1916):

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



post-Einstein, I


Karl Schwarzschild (1873–1916)

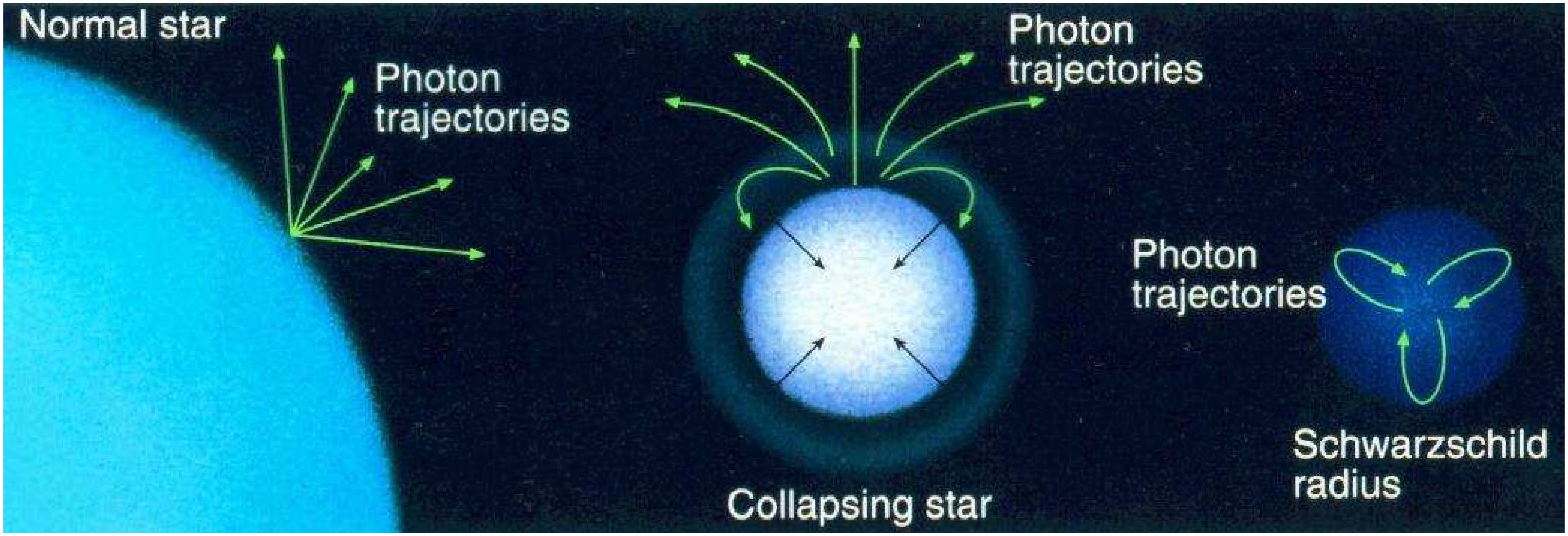
Directly after publication of GRT:

$$\mathrm{d}s^2 = \left(1 - \frac{2GM}{c^2r}\right) c^2\mathrm{d}t^2 - \left(1 - \frac{2GM}{c^2r}\right)^{-1} \mathrm{d}r^2$$

(Schwarzschild Metric).

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

post-Einstein, II



$R > R_\mathrm{S}$ $R \sim R_\mathrm{S}$ $R < R_\mathrm{S}$

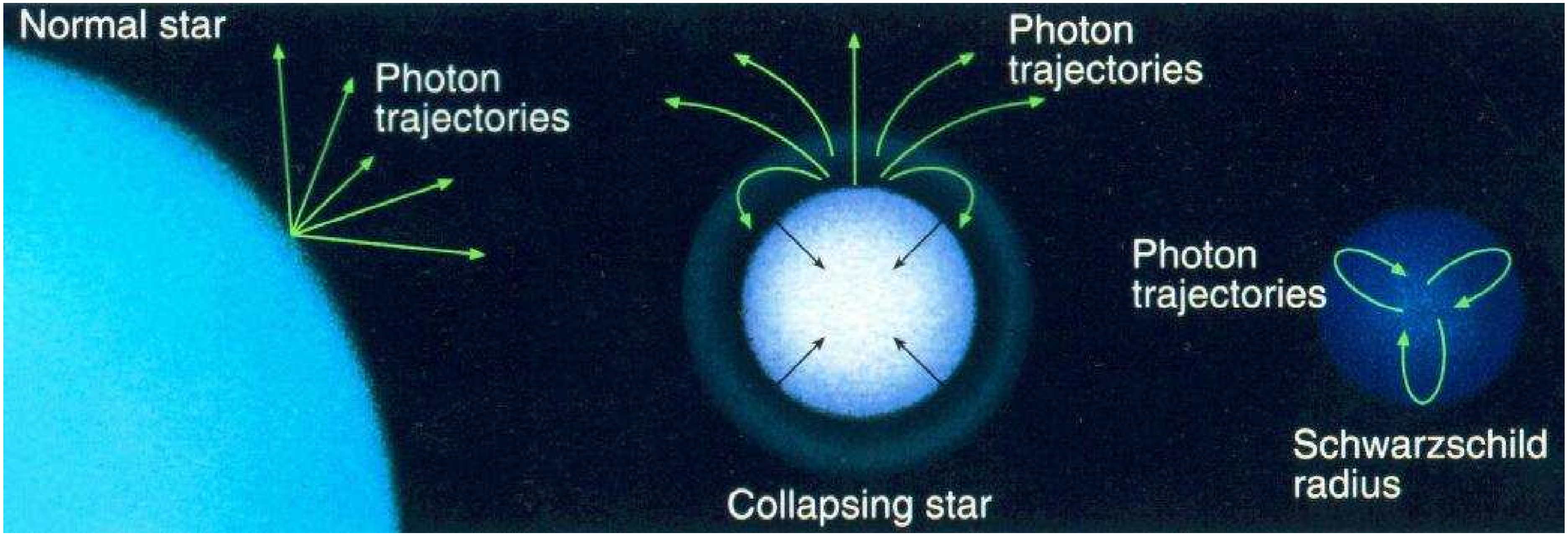
Behavior of light is determined from location of emission, in dependence from the Schwarzschild Radius:

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

Same value as in Newtonian derivation!

J.N. Imamura

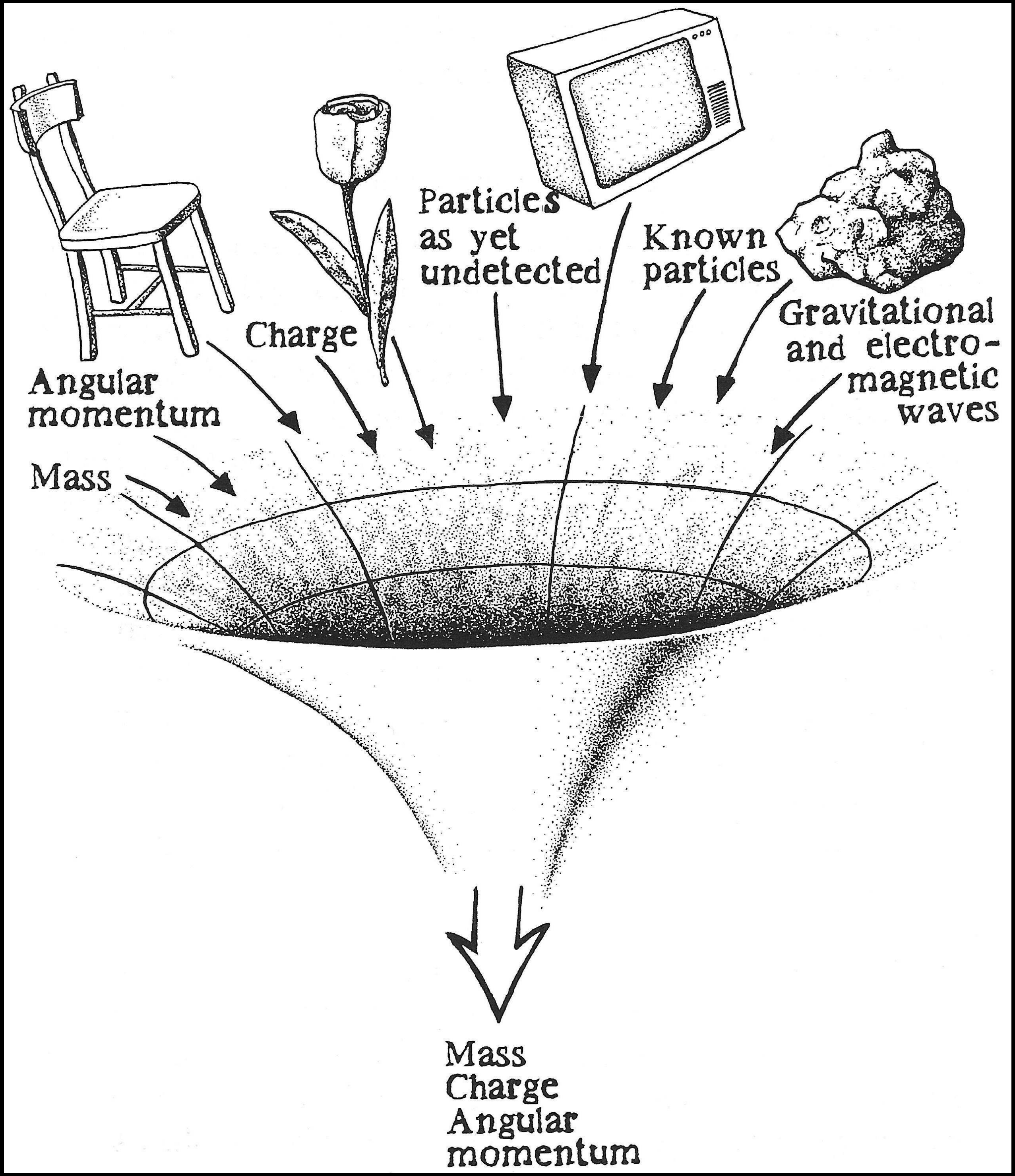
post-Einstein, III



$R > R_\mathrm{S}$ $R \sim R_\mathrm{S}$ $R < R_\mathrm{S}$

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

J.N. Imamura



Black holes are very simple physical objects, determined by

- Mass
- (Charge)
- Angular momentum

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

Black Holes: Accretion, I

Astrophysical energy sources:

1. Nuclear fusion

Reactions à la

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

Energy released:

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

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

Black Holes: Accretion, II

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2. Gravitation

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

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

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

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

Black Holes: Accretion, III

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

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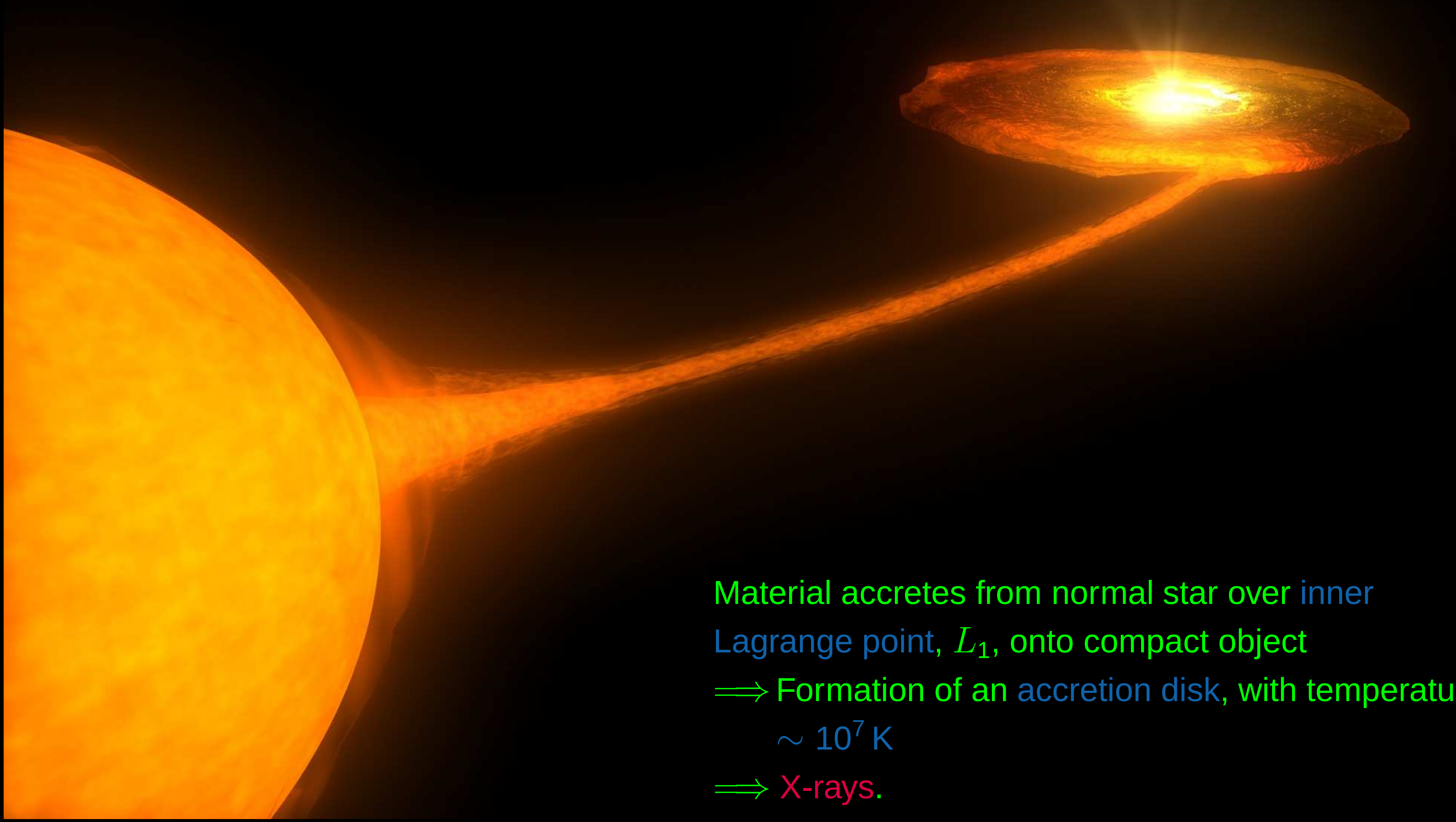
$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source.

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

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



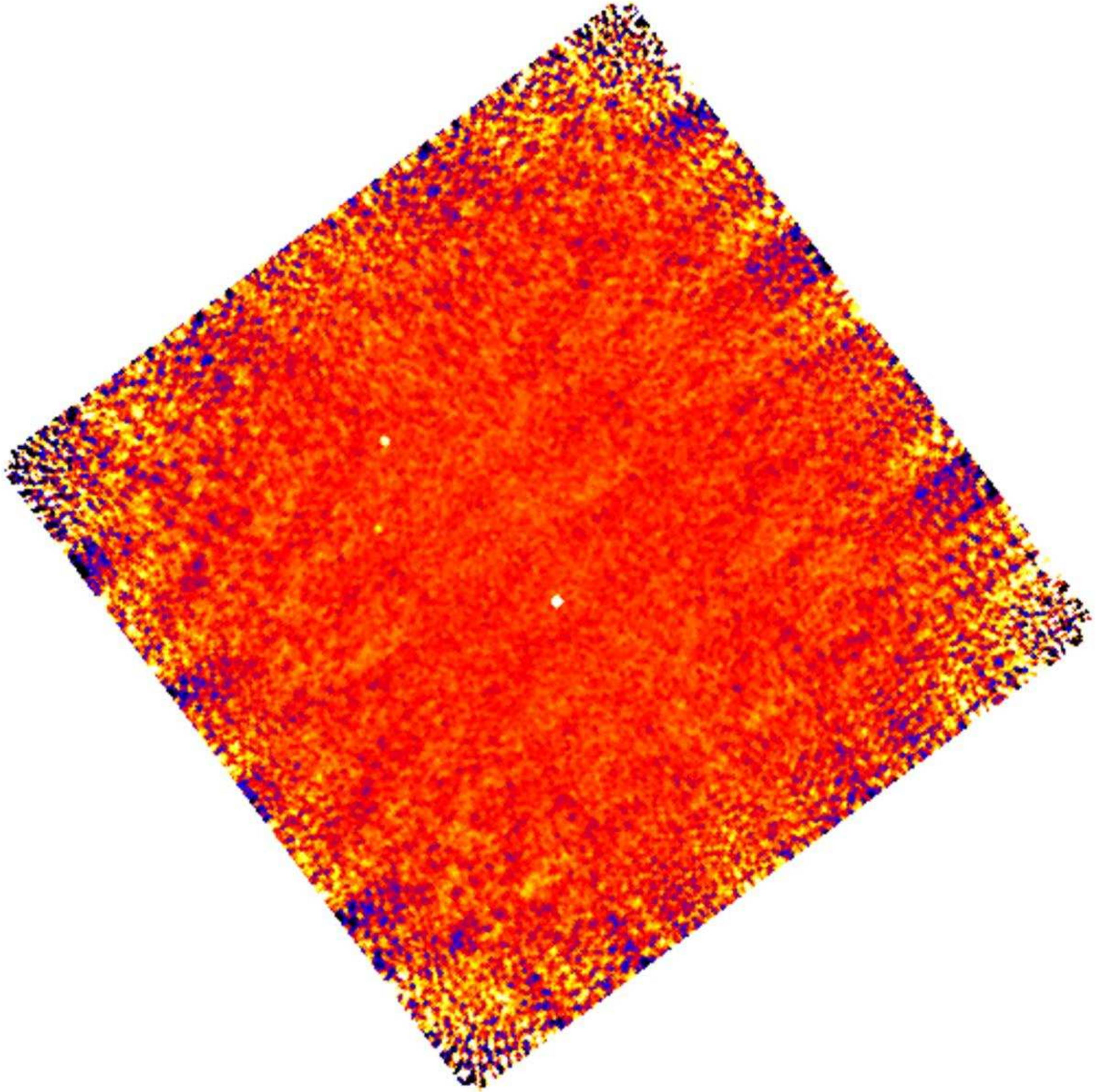
Material accretes from normal star over inner Lagrange point, L_1, onto compact object

$\Longrightarrow$ Formation of an accretion disk, with temperature $\sim 10^7$ K

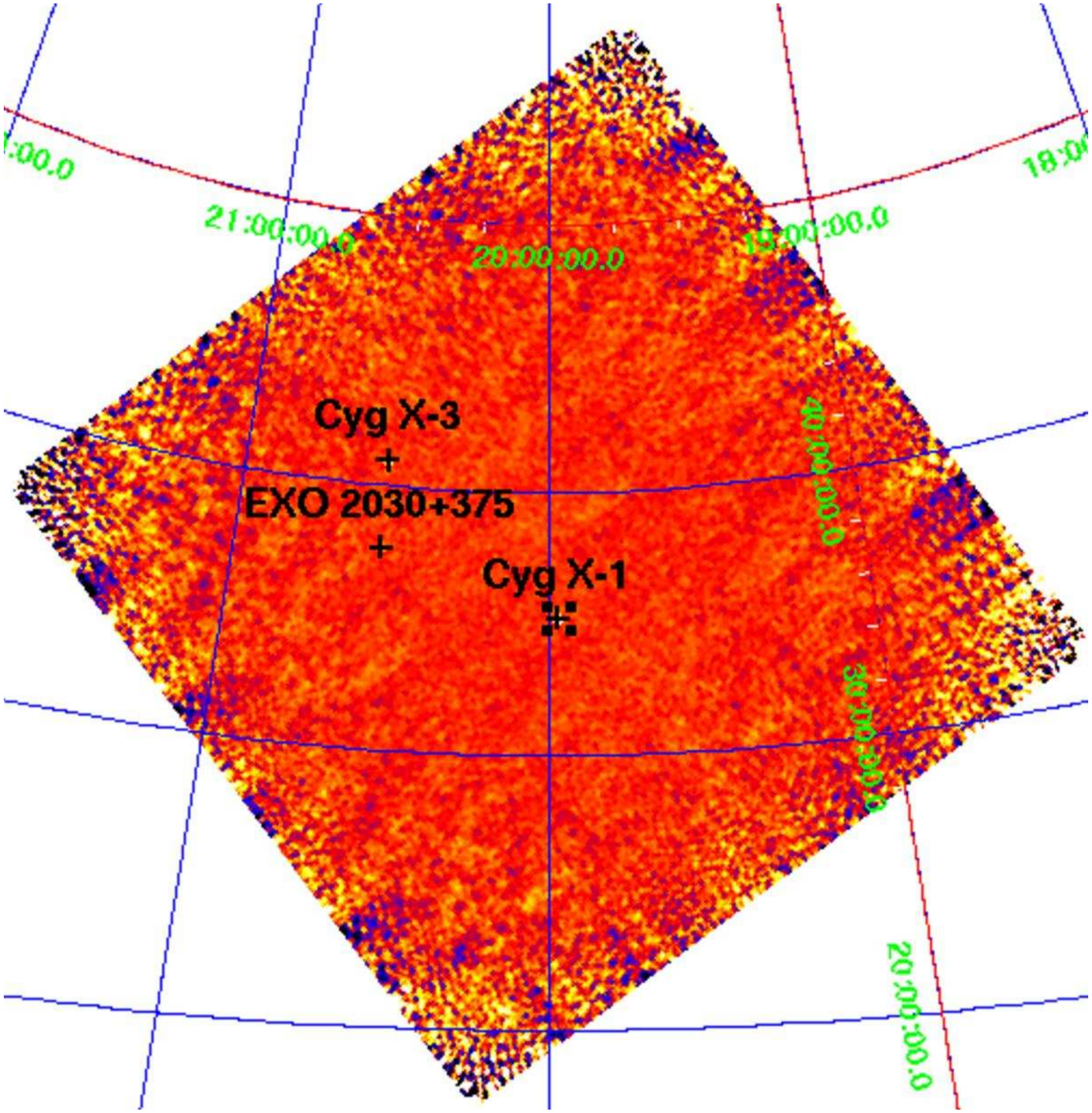
$\Longrightarrow$ X-rays.

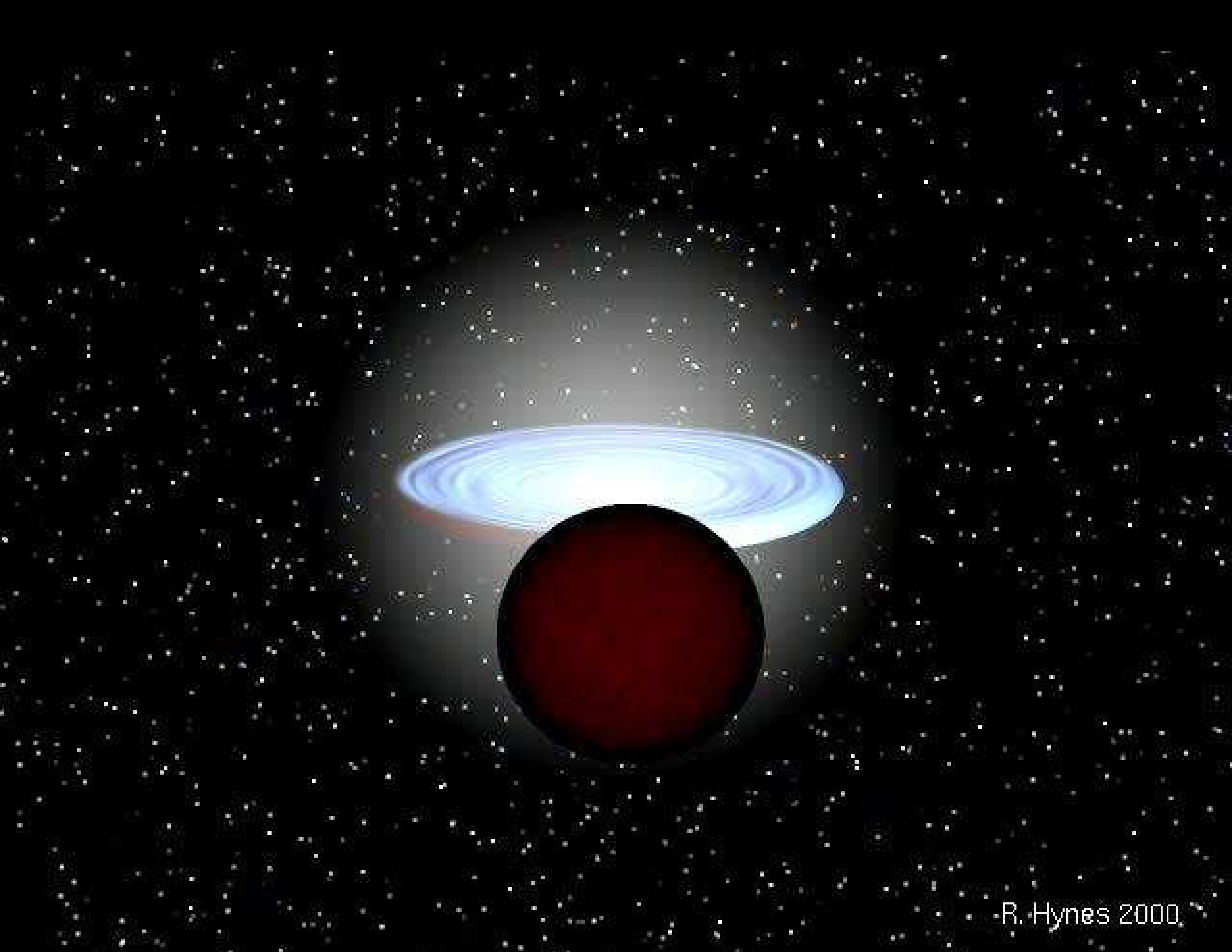
INTEGRAL

Black Holes: Accretion, VI



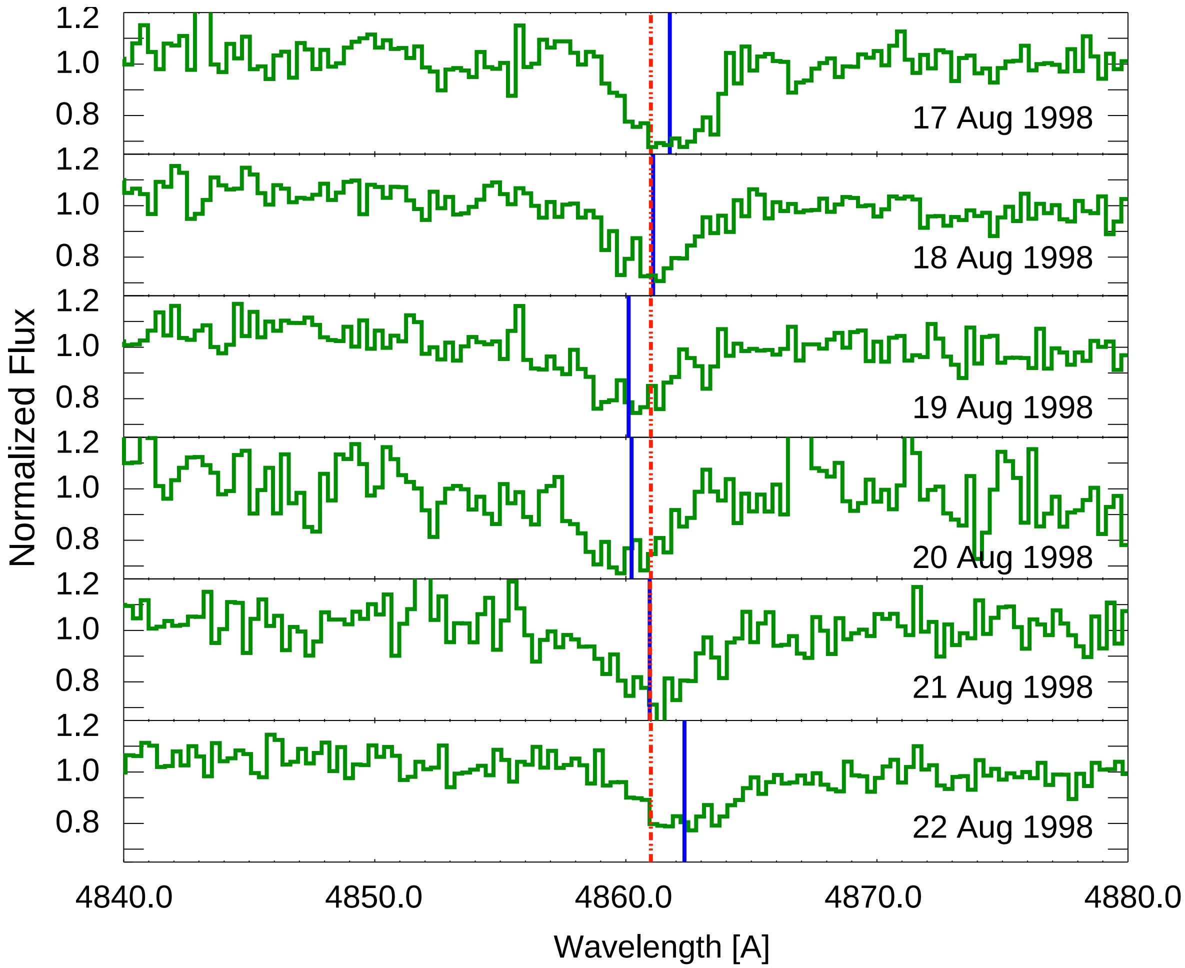
Black Holes: Accretion, VII





R. Hynes 2000

Mass determination, II



Motion of Hβ linie in HDE 226868/Cyg X-1 (Pottschmidt, Wilms)

Reminder: In binary systems: Mass of compact object from 3rd Kepler:

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

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

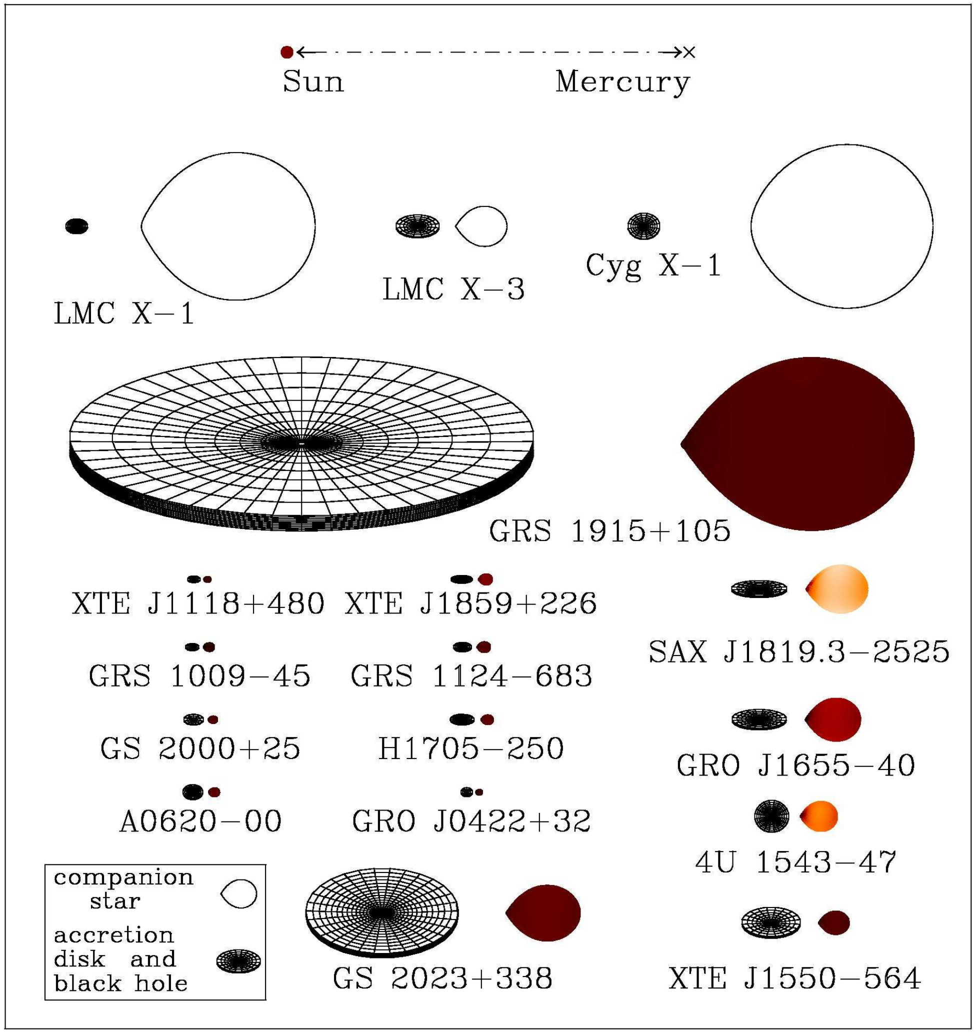
Derive from this: Mass function

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

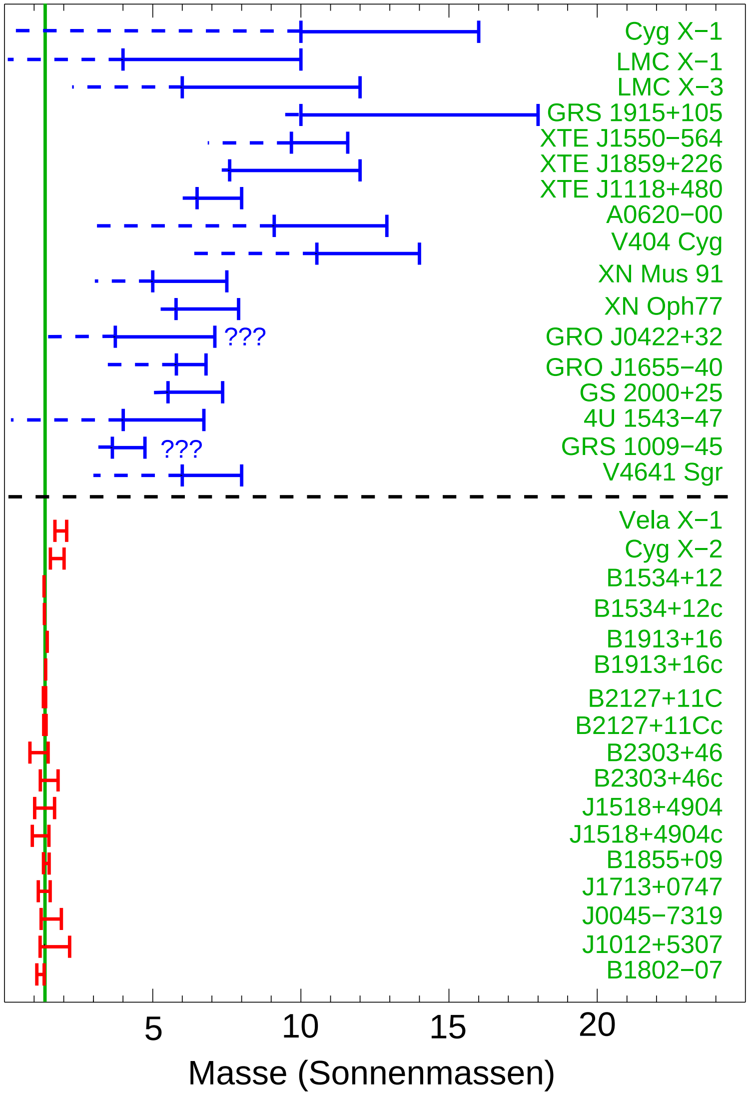
MF is lower limit for M_2.

(K_2 : velocity amplitude,
P: period)

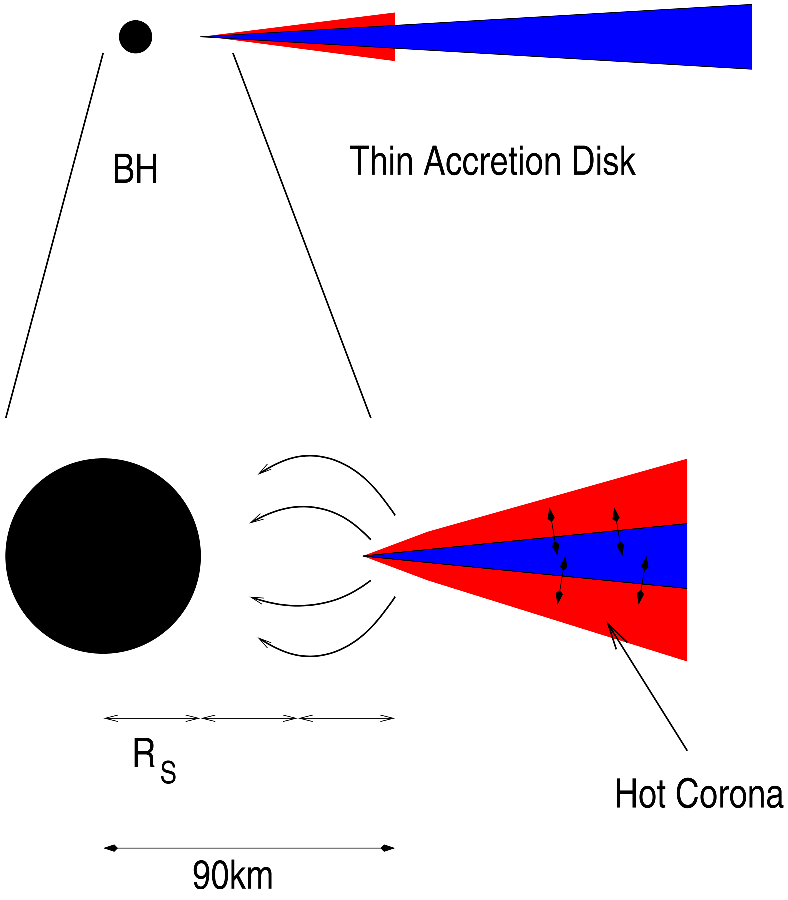
Mass determination, III

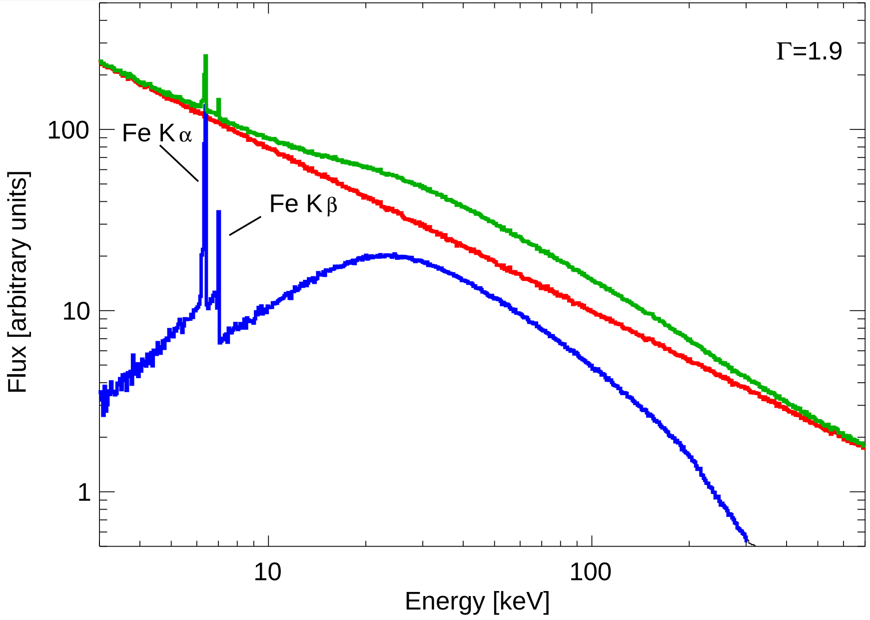


Orosz, 2003, priv. comm.



Relativistic Lines

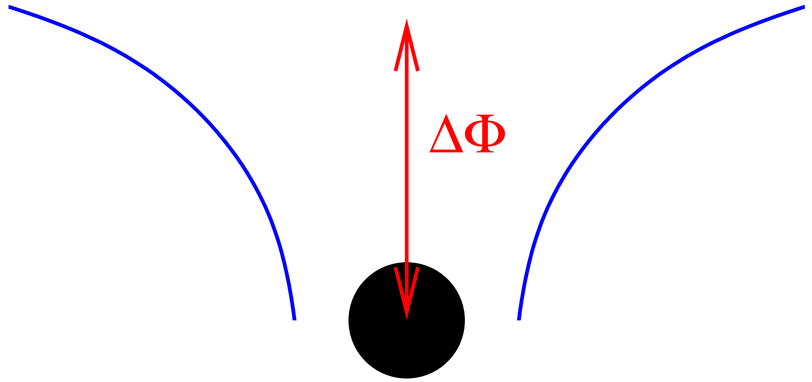


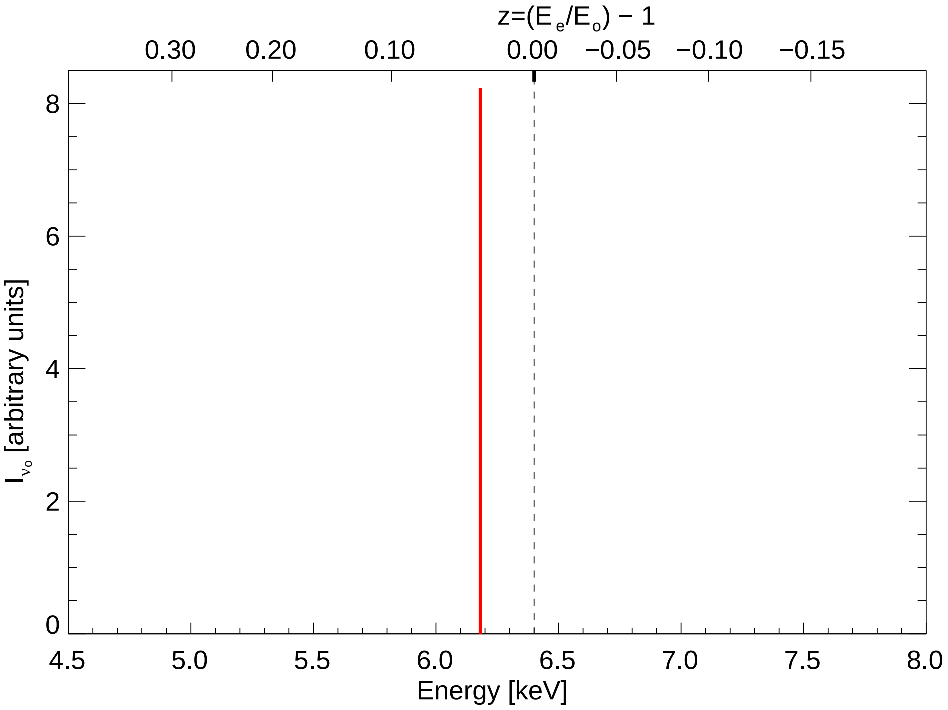


Black Hole X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump
- Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at ~6.4 keV

Relativistic Lines

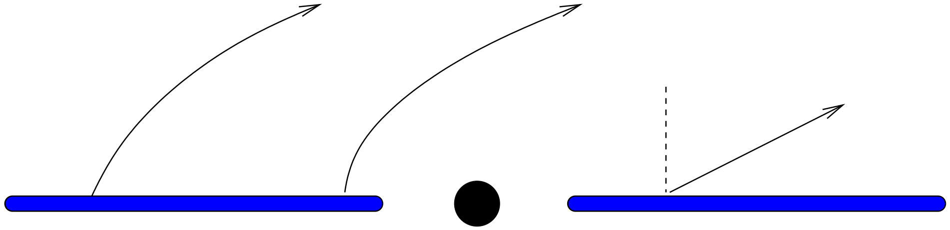


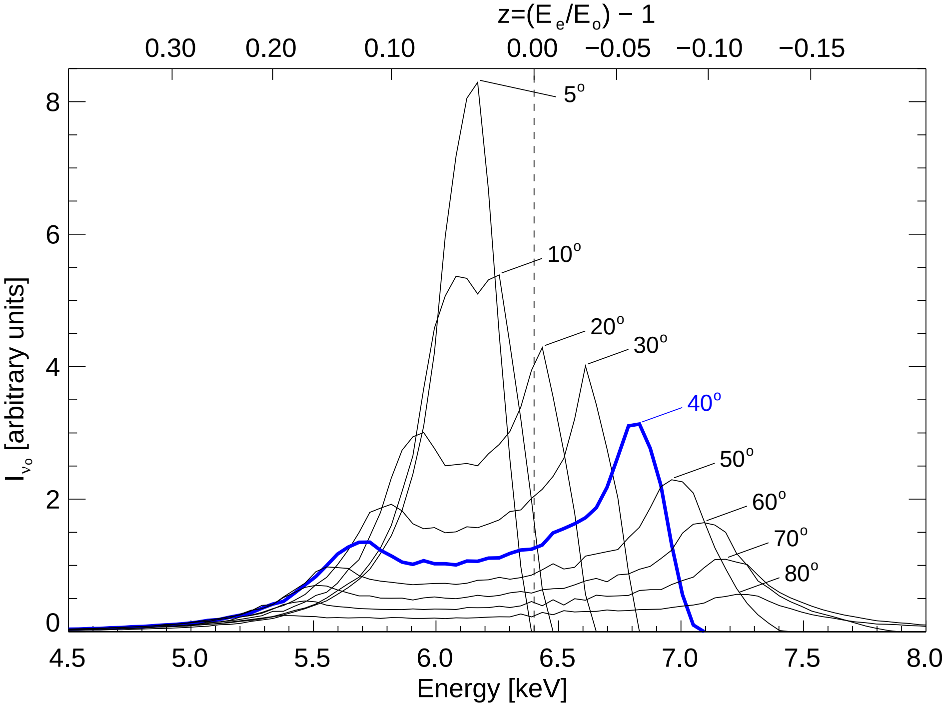


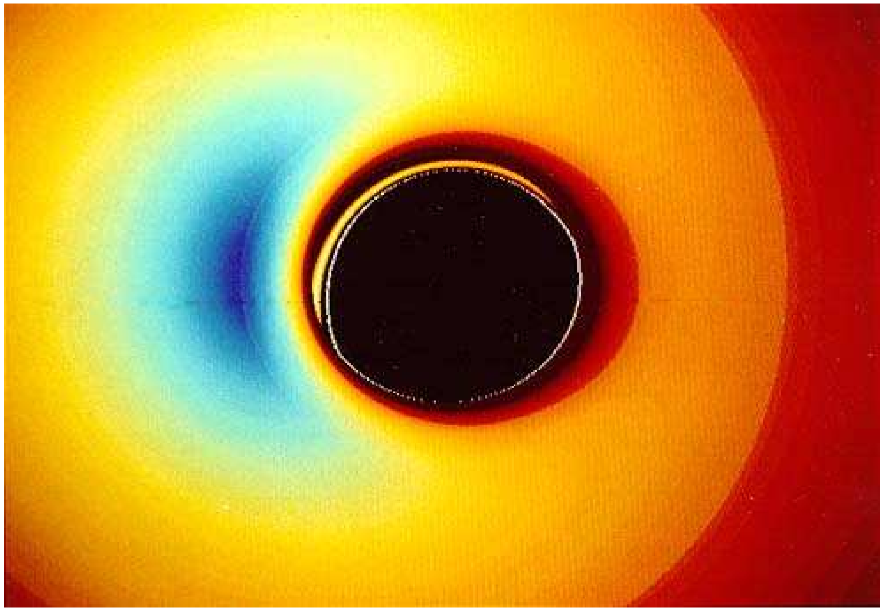
Total observed line profile affected by

- grav. Redshift

Relativistic Lines



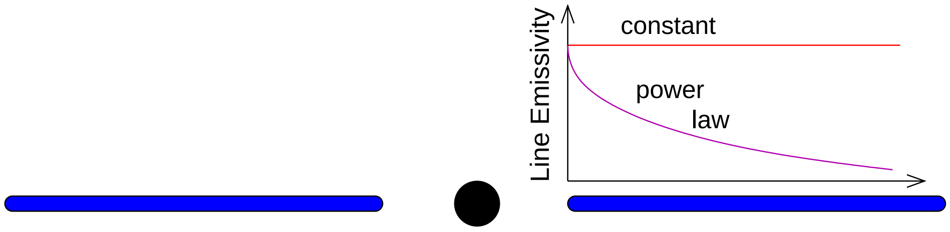


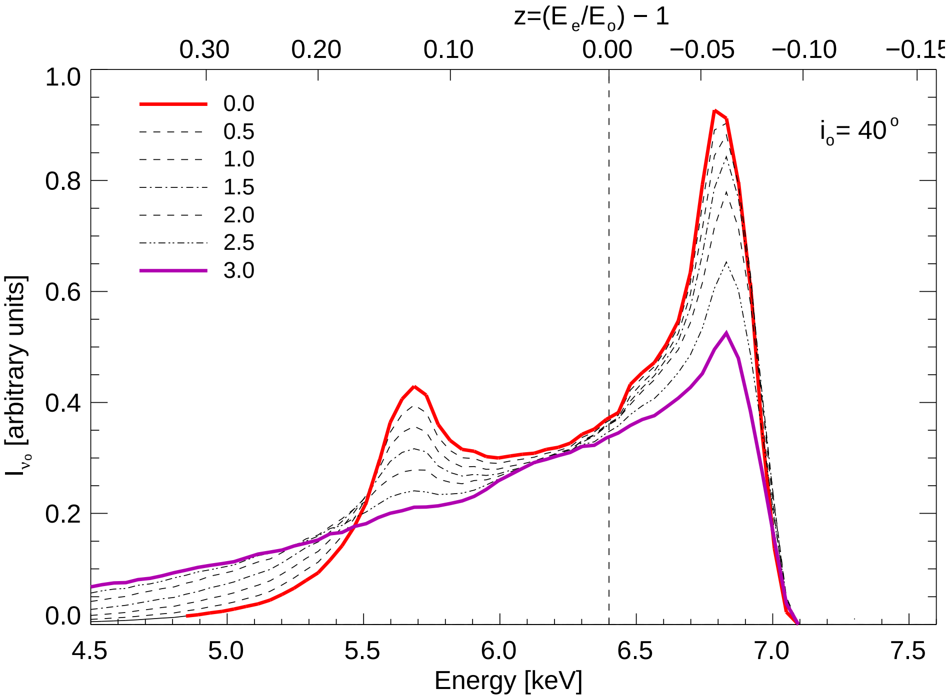


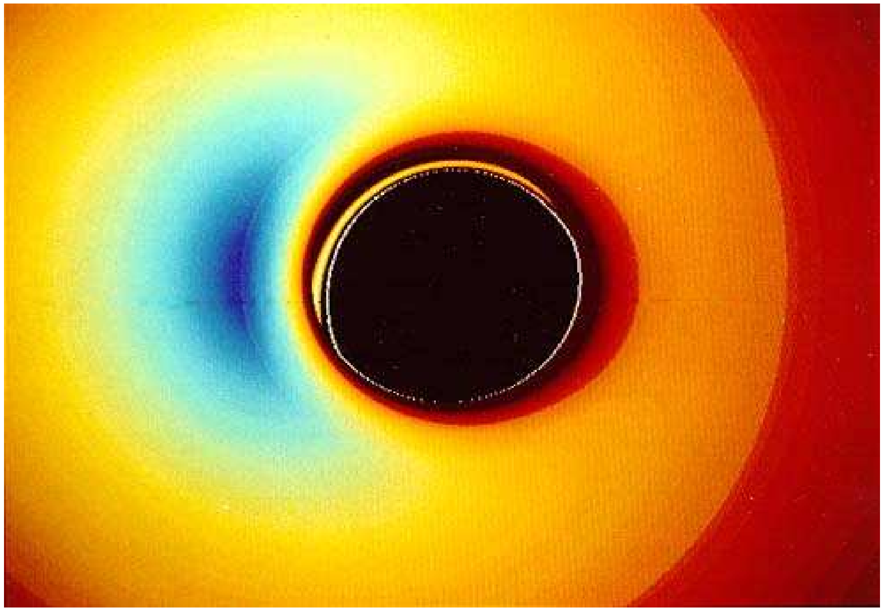
Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift

Relativistic Lines







Total observed line profile affected by

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- Light bending
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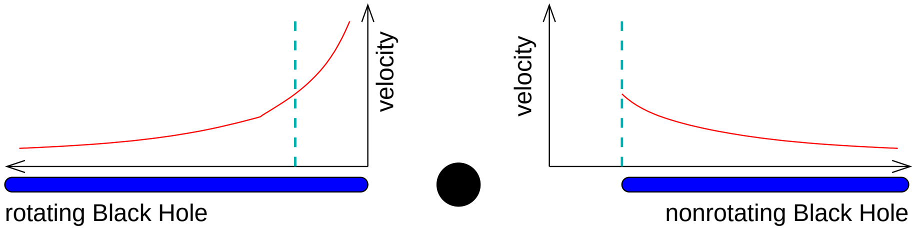
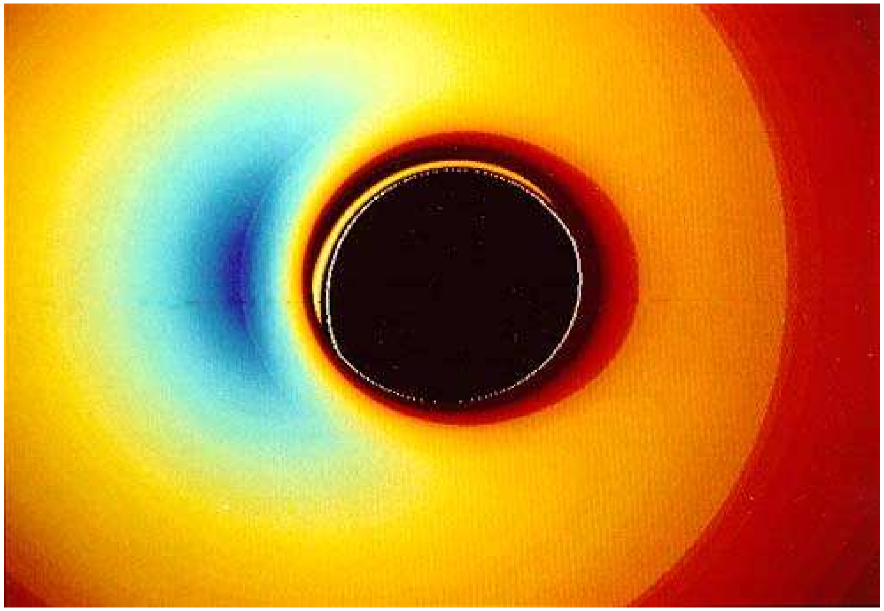
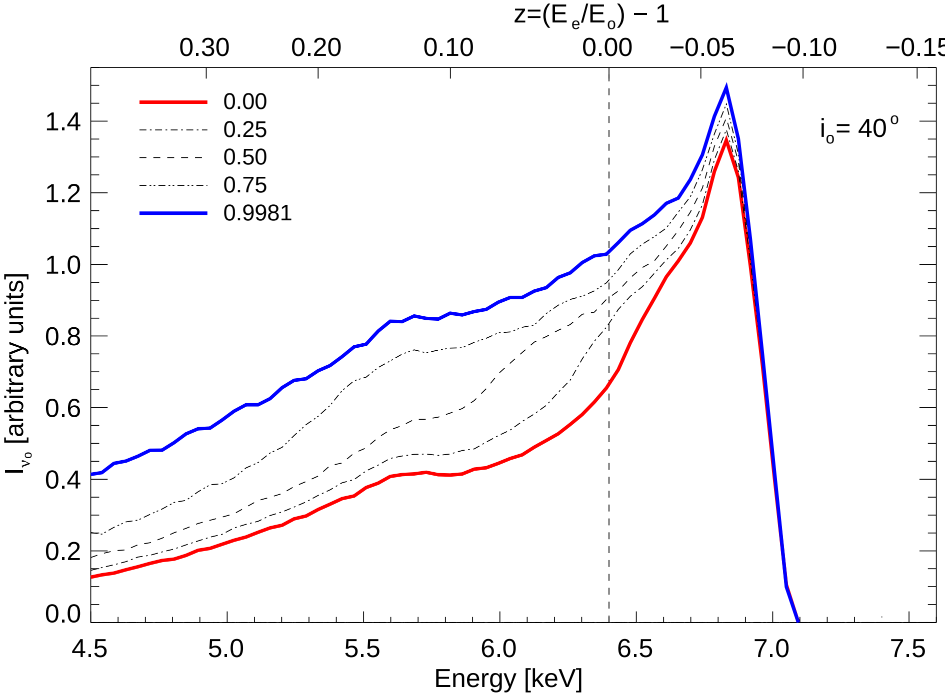
- emissivity profile

Relativistic Lines





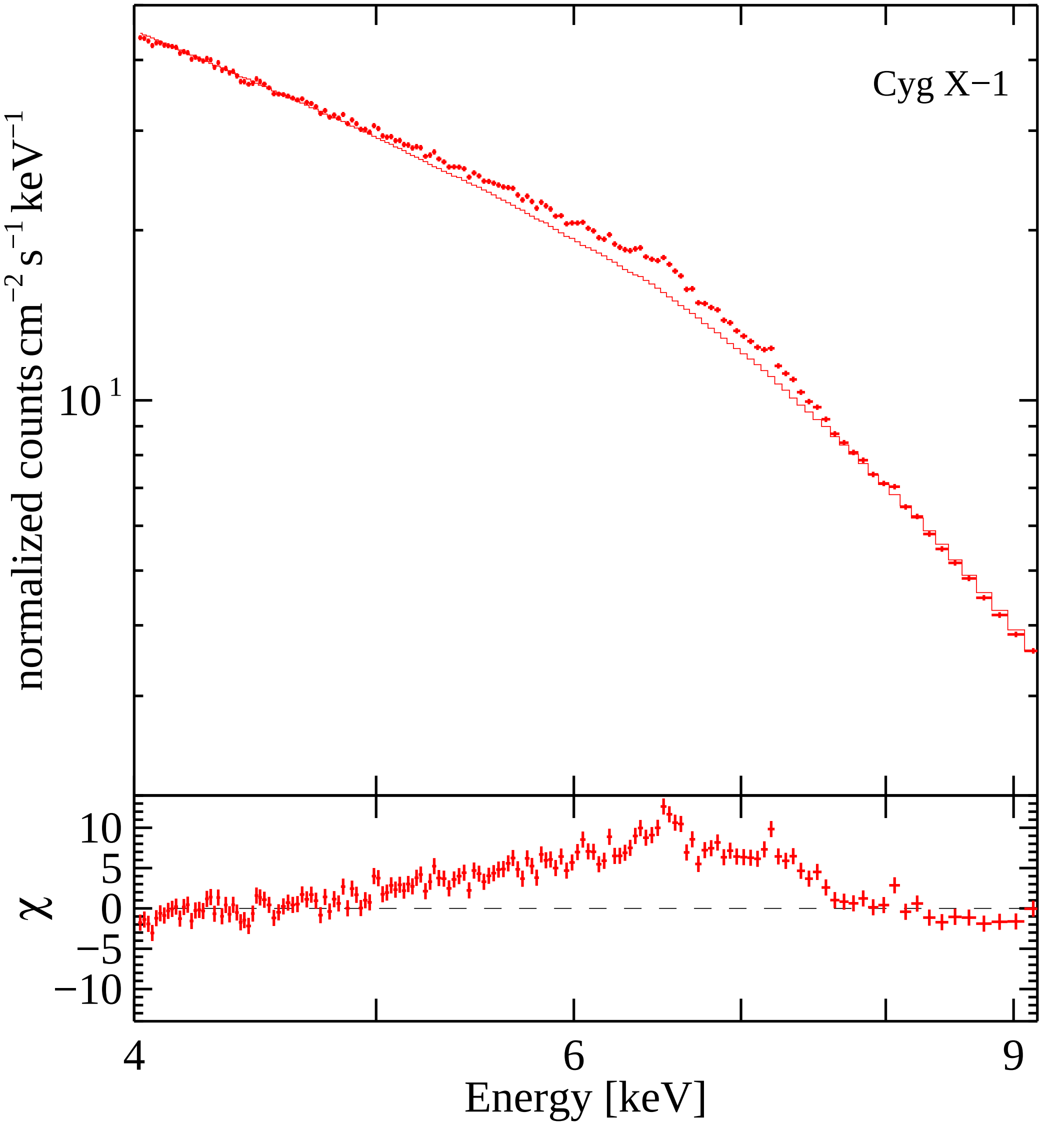


Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile
- spin of black hole

XMM-Newton

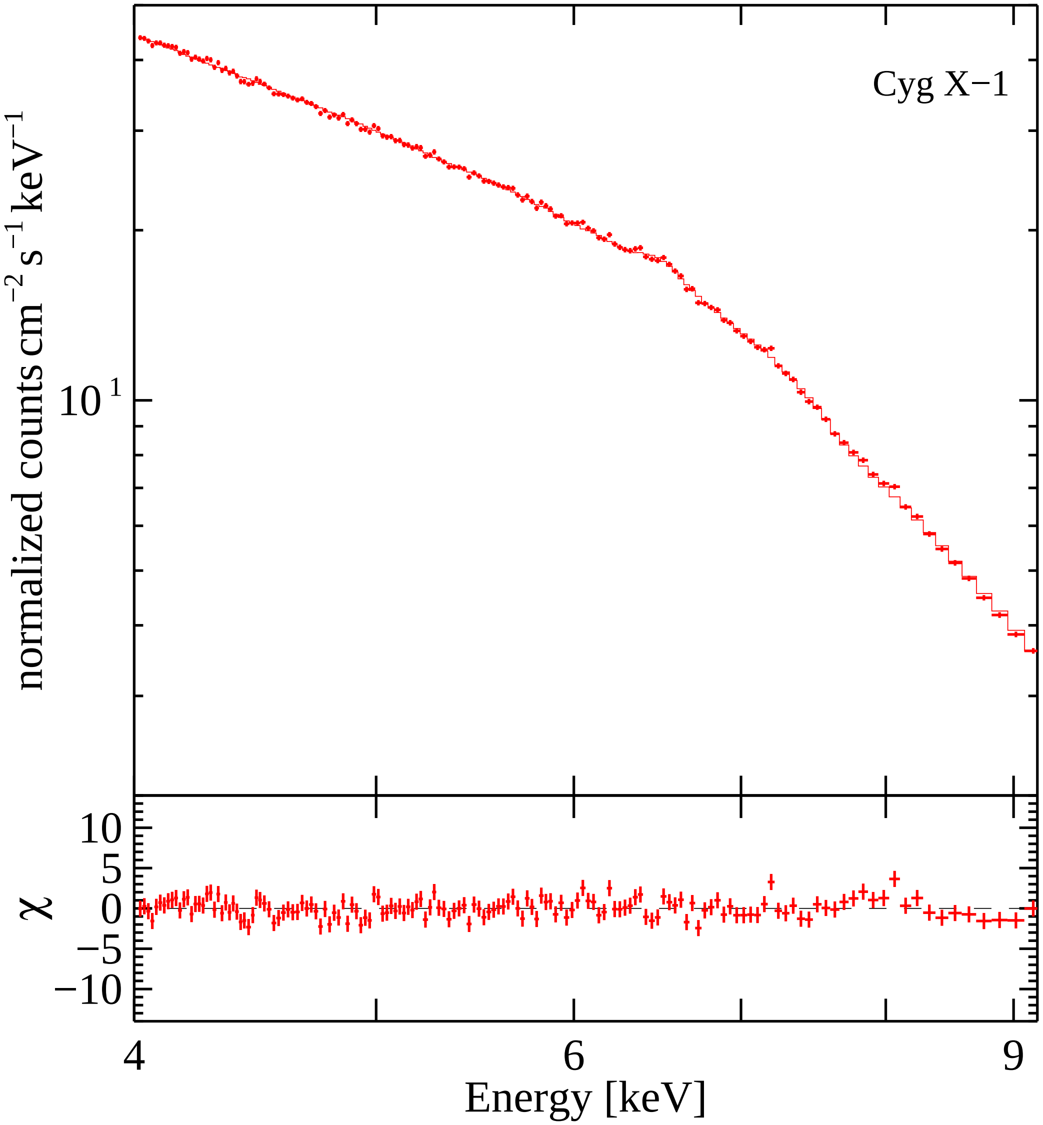
Relativistic Lines



Wilms et al. (2006)

XMM-Newton Observation of Cyg X-1: Power-law fit to $E \leq 5$ keV and $E \geq 8$ keV: strong residuals in Fe Kα region

Relativistic Lines



Wilms et al. (2006)

4–9 keV spectrum: well explained ($\chi^2_{\text{red}} = 1.3$) with:

- Power law

  $\Gamma = 1.90 \pm 0.01$

- narrow line

  $E = 6.52 \pm 0.02$ keV,
  $\sigma = 80 \pm 35$ eV,
  EW=14 eV

- relativistic line (Kerr)

  $E = 6.76 \pm 0.1$ keV,
  emissivity $\propto r^{-4.3\pm0.1}$ (strongly centrally peaked!).

Parameters similar (but not equal) to *Chandra* intermediate state observations (Miller et al., 2002)

Summary

Stars end their lifes as one of three kinds of compact objects:

White Dwarf: $R \sim R_{\mathrm{Earth}}$, $\rho \sim 10^{5\ldots6}\,\mathrm{g\,cm^{-3}}$

$M < 1.44\,M_\odot$ (Chandrasekhar Limit)

Equilibrium between gravitation and pressure of degenerate electrons

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Black Hole: Above OV-Limit no stable configuration known

$\Longrightarrow$ star collapses

$\Longrightarrow$ Black Hole

$M \gtrsim 4\,M_\odot$

Event horizon at $R_\text{S} = 2GM/c^2 = 3(M/M_\odot)\,\text{km}$ (Schwarzschild radius)

Filippenko, A. V., 1997, Ann. Rev. Astron. Astrophys., 35, 309

Jha, S., et al., 1999, ApJS, 125, 73

Lattimer, J. M., & Prakash, M., 2001, ApJ, 550, 426

Shapiro, S. L., & Teukolsky, S. A., 1983, Black Holes, White Dwarfs, and Neutron Stars, (New York: Wiley)