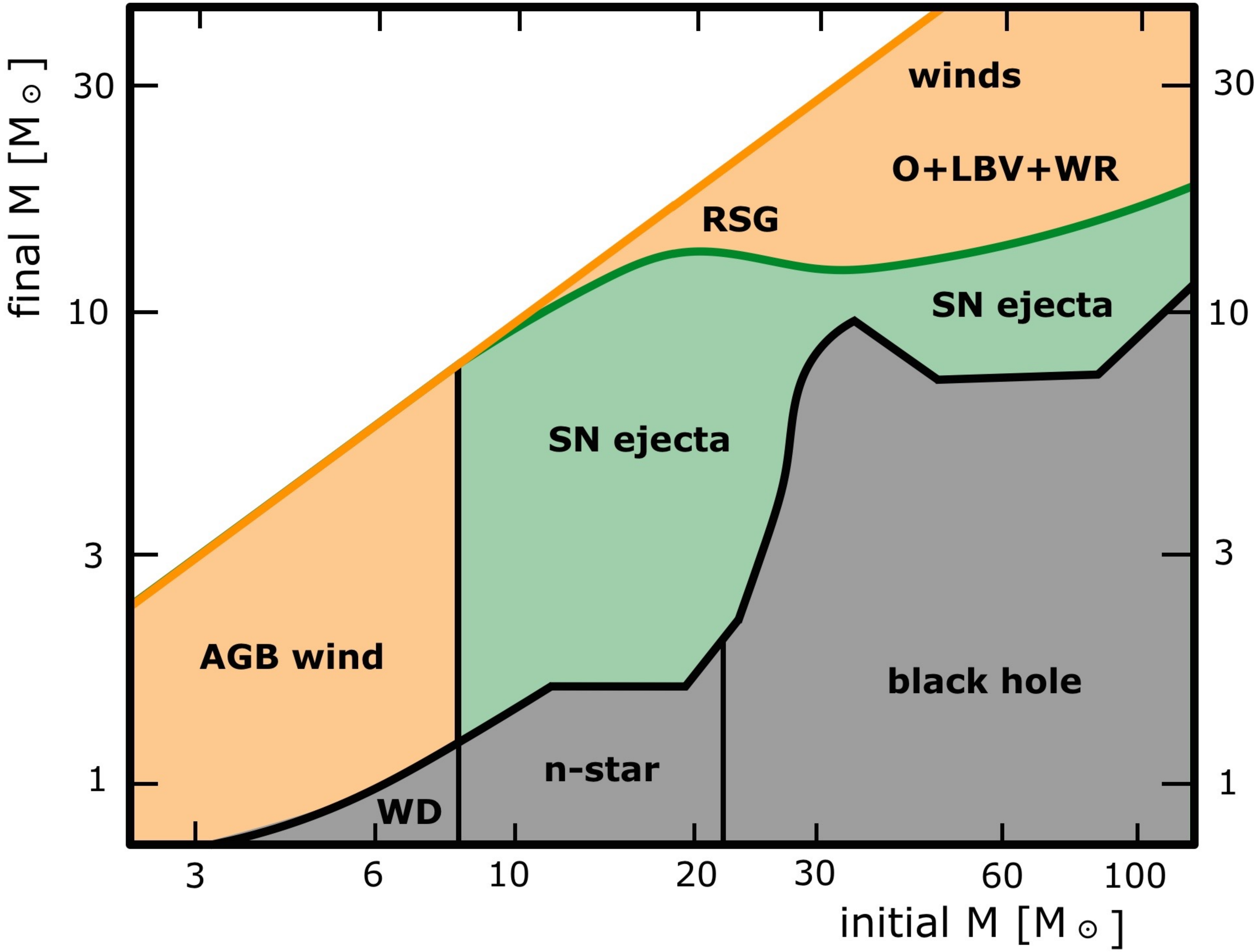
(core-collapse supernovae) (neutron stars & black holes)

Lecture 17: CC SN & compact remnants

Phillips Ch. 6.2-4; Lamers & Levesque Ch. 27



More mass, more problems

1. rotation

see L&L Chapter 25, Ekström et al. (2012)

no convection in outer layers → no dynamo to produce strong B fields
→ no magnetic braking of rotation → fast rotation throughout lifetime
→ changes structure & (differential) rotational mixing

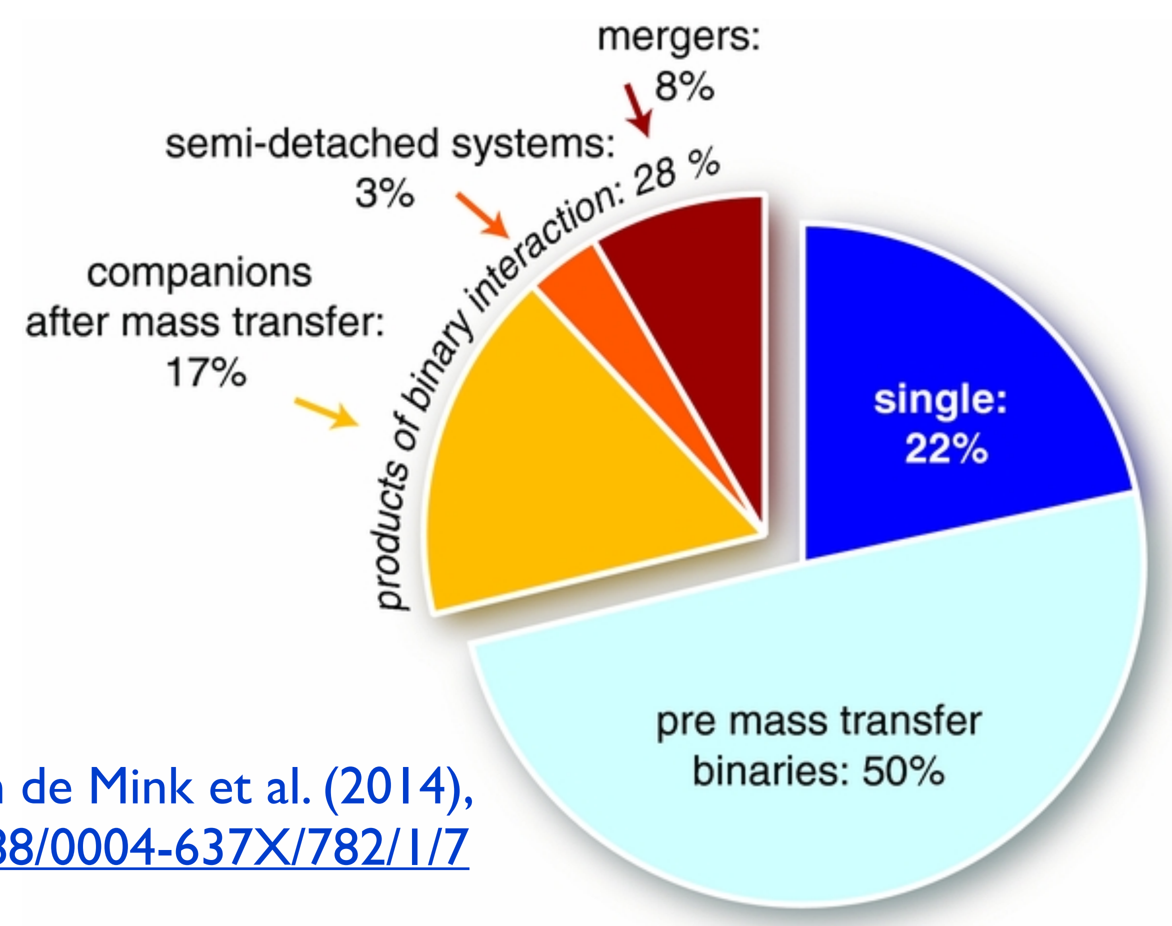
2. mass loss

see L&L Chapters 22, 24

high luminosity → radiation pressure driven stellar winds
→ significant mass loss → changes structure, evolution, & lifetime of star

3. binaries

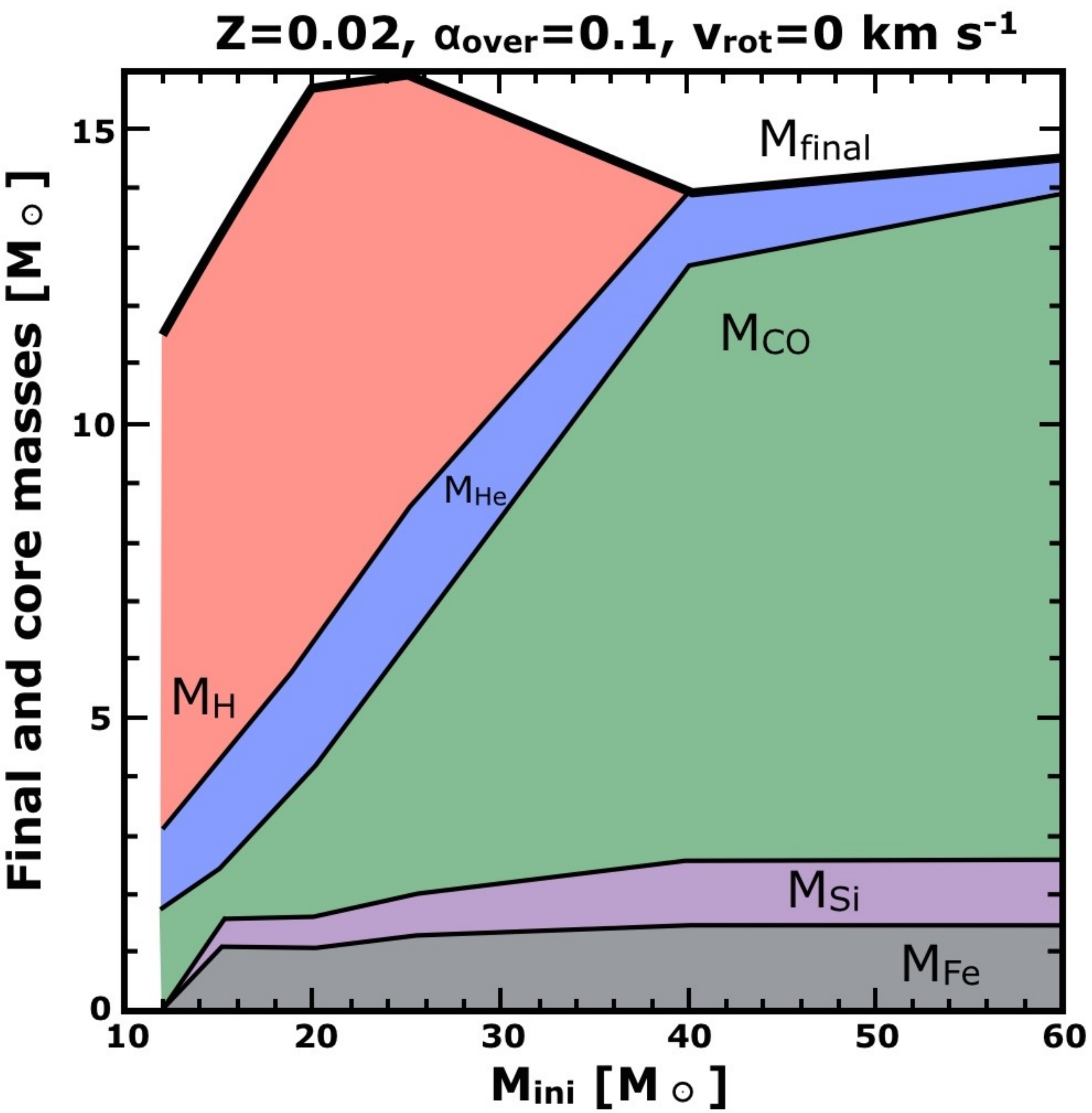
next week; see L&L Chapters 29, 30
70-80% of massive stars are in binary systems that will interact

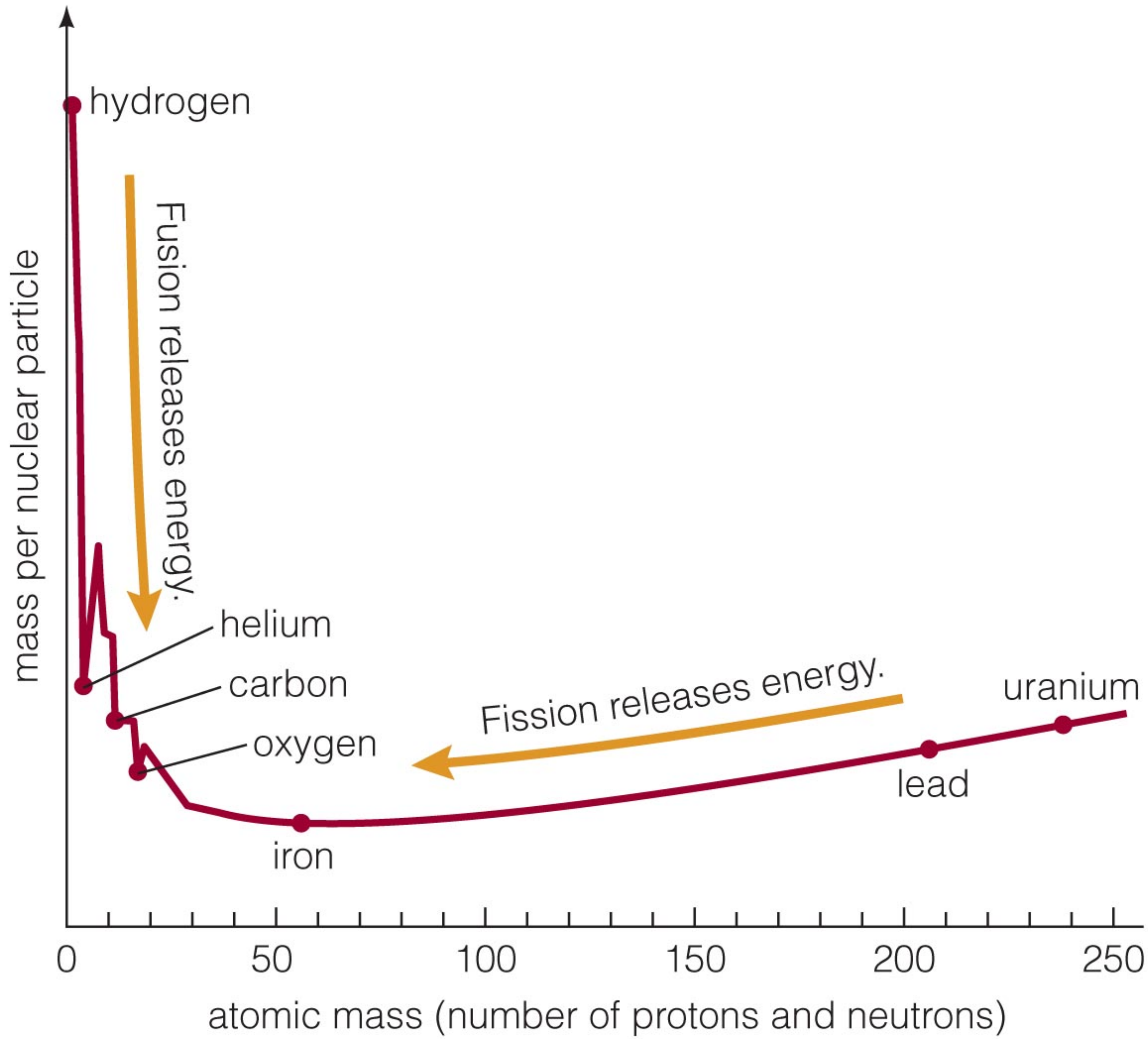


from de Mink et al. (2014),
http://dx.doi.org/10.1088/0004-637X/782/1/7

Massive Stars - pre-SN stages...

The mass distribution at the end of Si fusion (as a function of M_i) for solar metallicity stars that are non-rotating (left) and rapidly rotating (right).

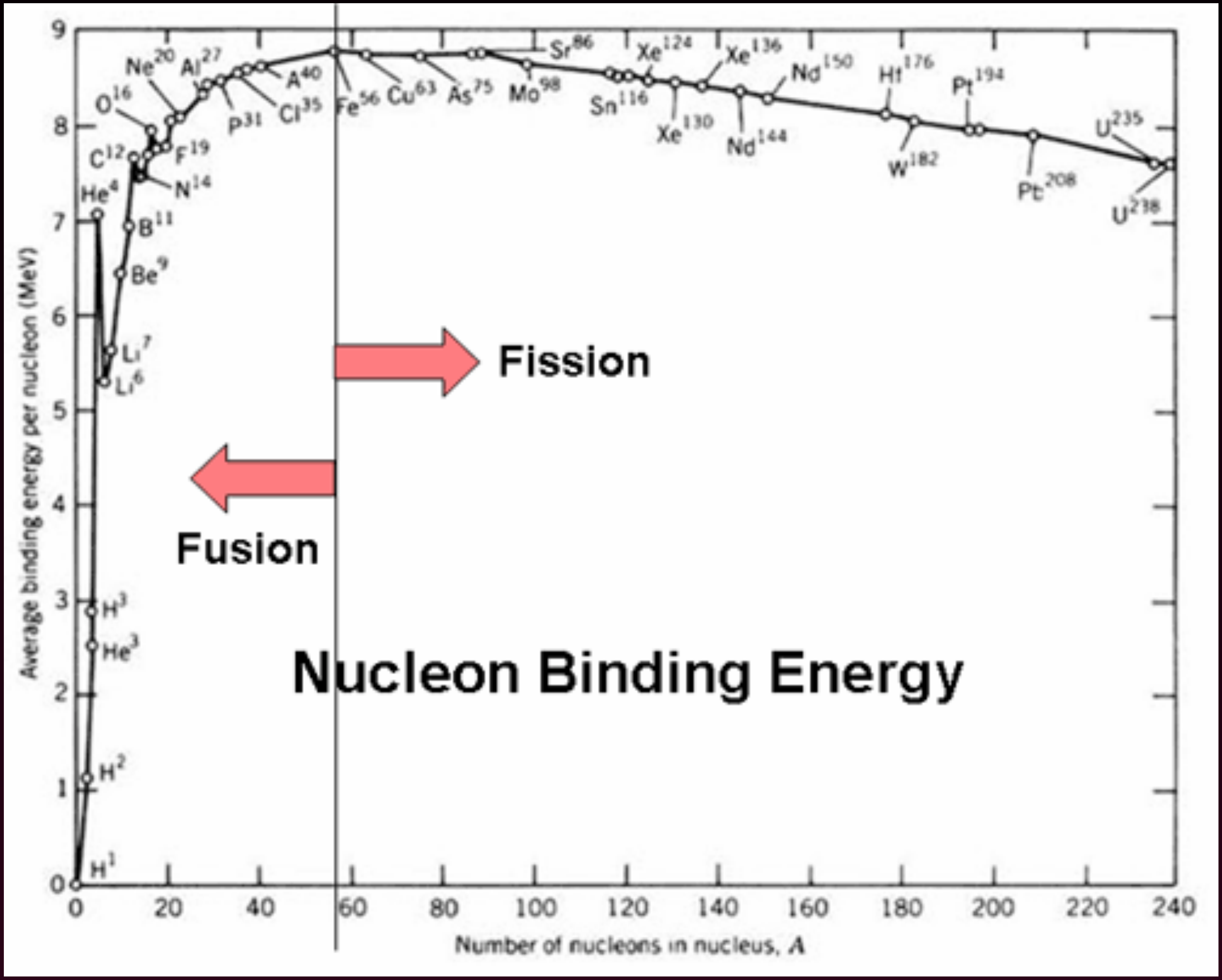




Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(This is because iron has lowest mass per nuclear particle.)

binding energy per nucleon



from http://www.mpoweruk.com/nuclear_theory.htm

Supernovae - energetics

Let's take a star with $M_* = 11.4 M_\odot$ ($M_{env} = 10 M_\odot$ and $M_c \sim 1.4 M_\odot$) collapsing to a NS with $R_{cf} \sim 20$km.

$$\mathbf{E}_{\mathbf{env}}^{\mathbf{pot}} \sim 10^{50} \text{ erg}$$

$$\boldsymbol{E}_{\mathbf{env}}^{\mathbf{kin}} = \frac{1}{2} M_{\text{env}} V^2 \sim 6 \times 10^{51} \text{erg}$$

$$+ \quad \mathbf{E}_{\mathbf{rad}} \sim 10^{48}\text{-}10^{49} \text{ erg}$$

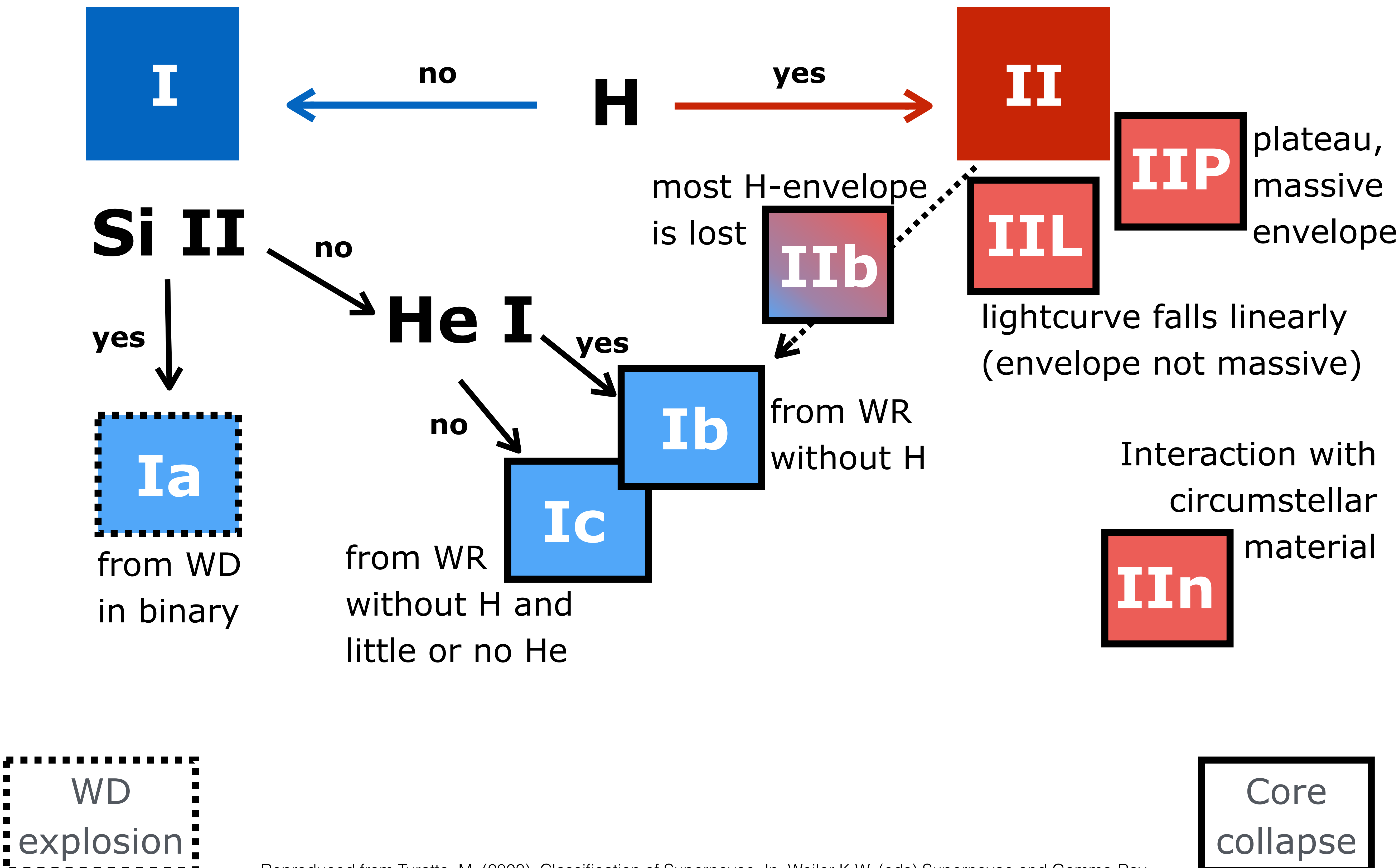
$\ll$
much less than

$$\boldsymbol{E}_{\mathbf{collapse}} \simeq -\frac{GM_c^2}{R_{ci}} + \frac{GM_c^2}{R_{cf}} \simeq \frac{GM_c^2}{R_{cf}} \sim 3 \times 10^{53} \text{ erg}$$

$$\boxed{E_{\text{env}}^{\text{pot}} + E_{\text{env}}^{\text{kin}} + E_{\text{rad}} \ll E_{\text{collapse}}}$$

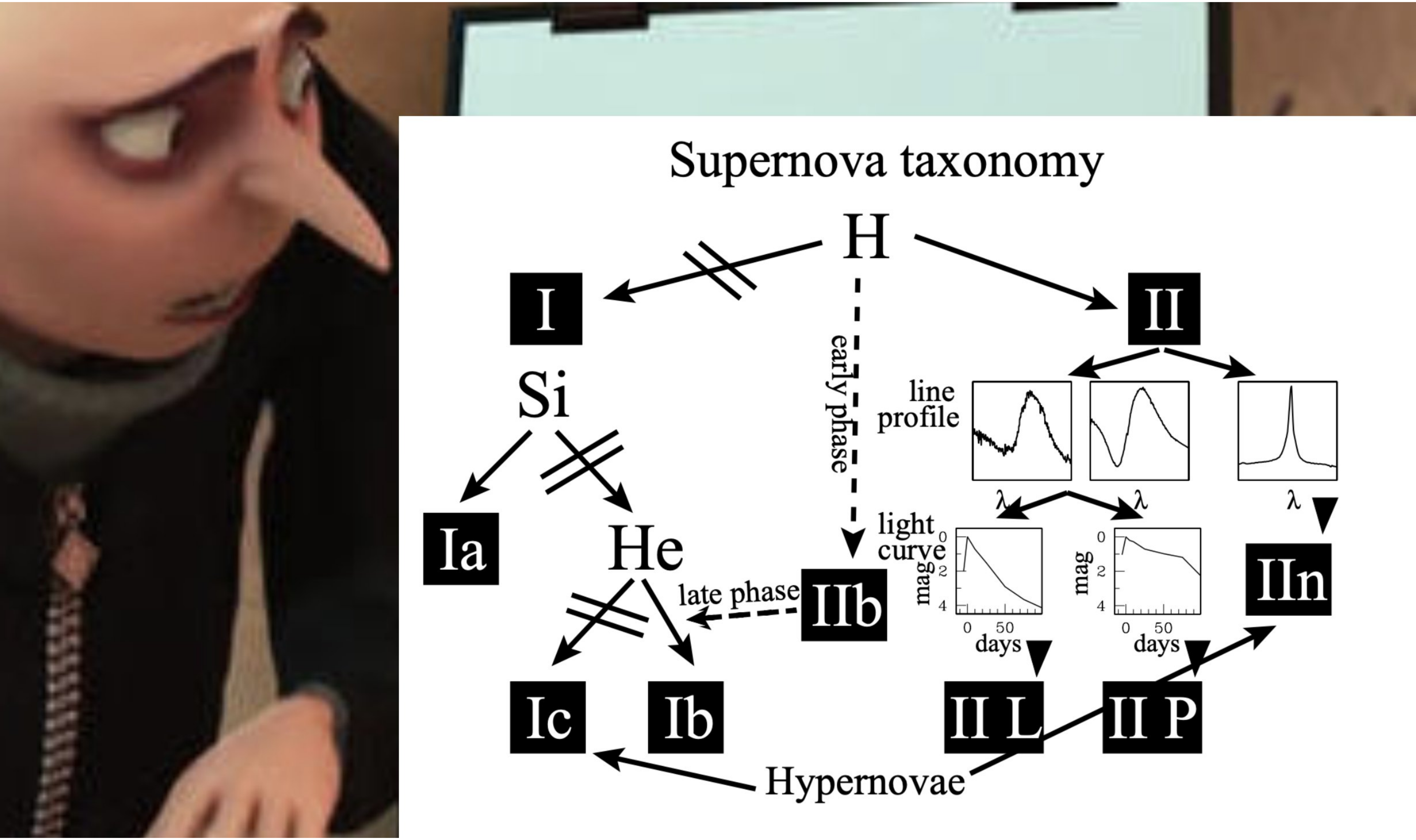
Only a small fraction of the energy released in core collapse is used to eject the envelope and emit light. Most energy comes out as neutrinos.

Supernovae - Types



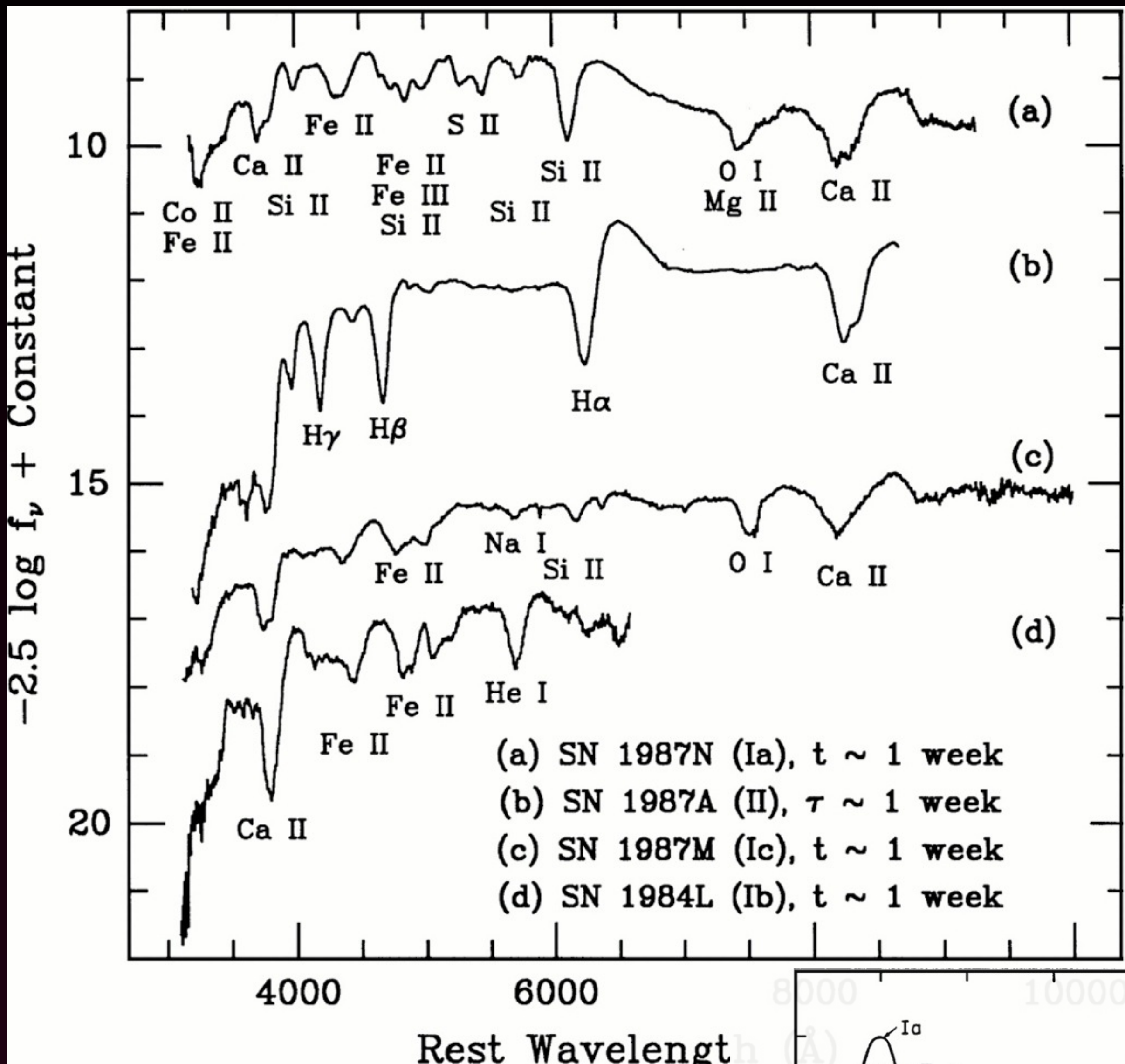
Reproduced from Turatto, M. (2003). Classification of Supernovae. In: Weiler K.W. (eds) Supernovae and Gamma-Ray Bursters. Lecture Notes in Physics, vol 598. Springer, Berlin, Heidelberg. © Springer-Verlag Berlin Heidelberg 2003.

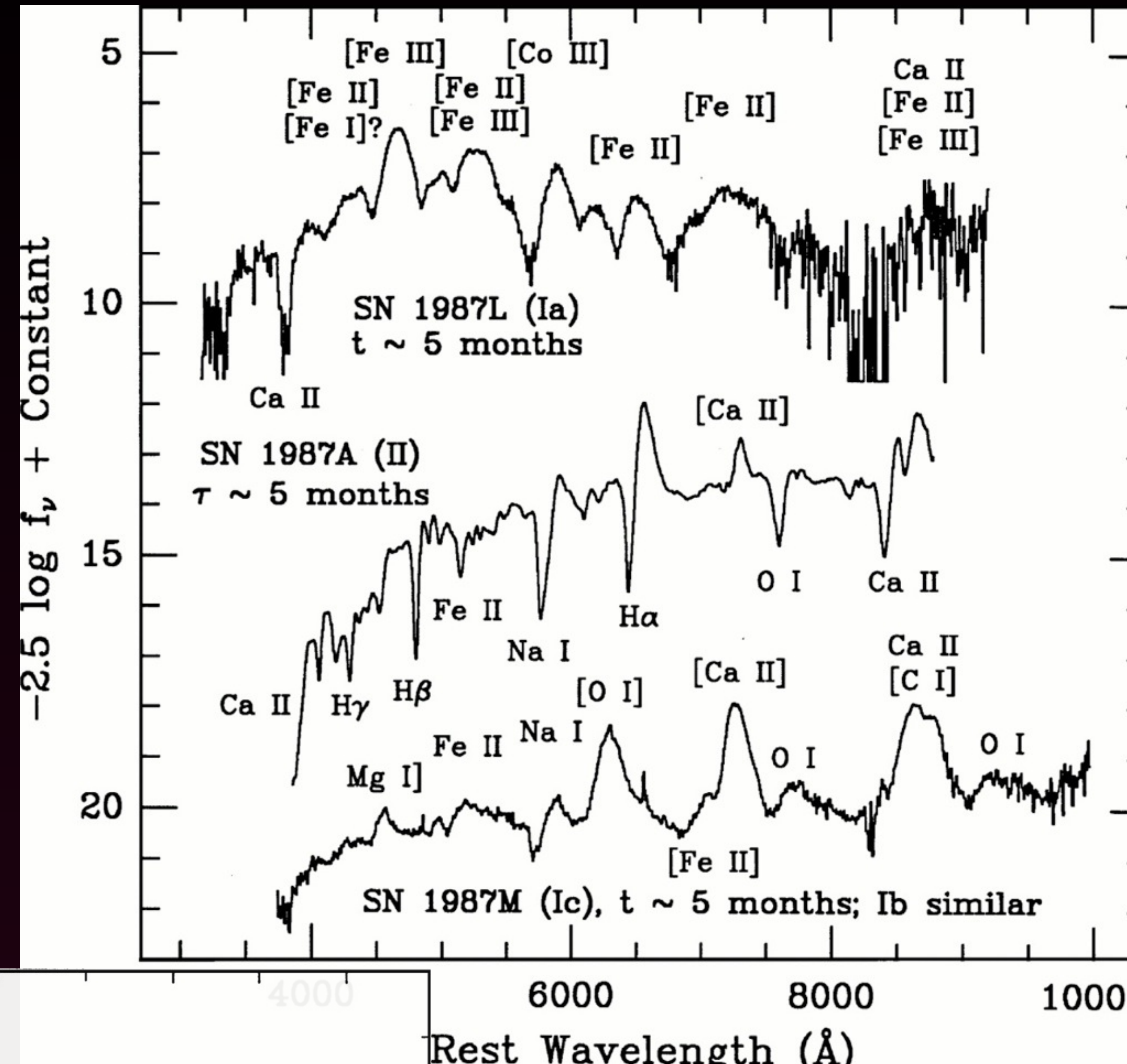
Supernovae - Types

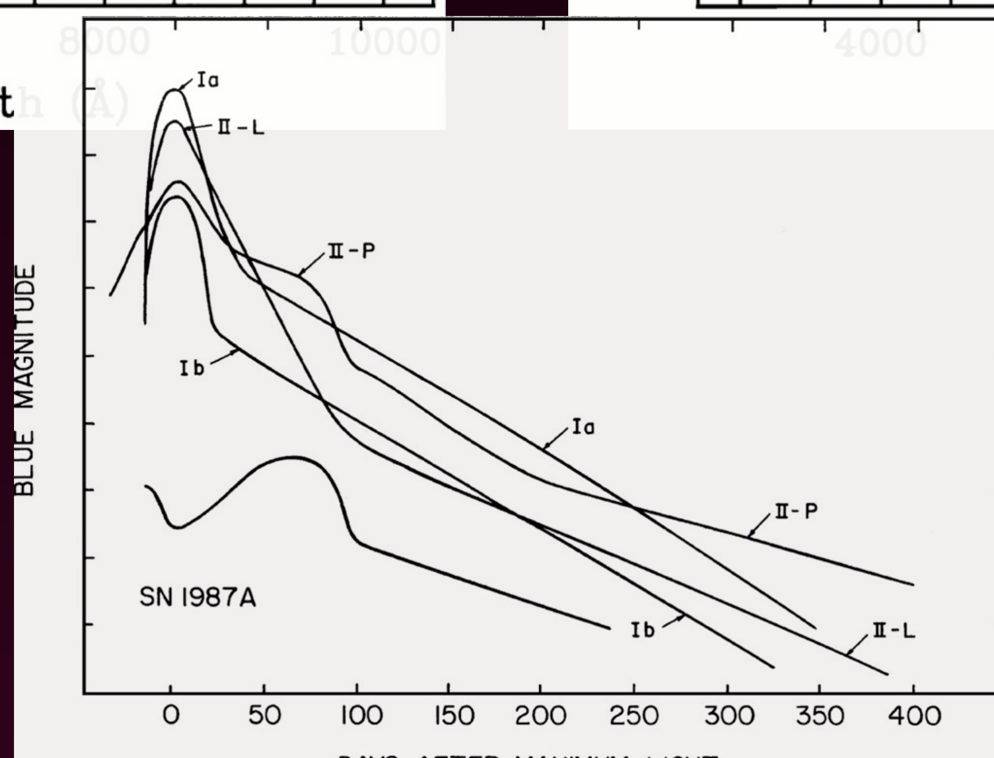


https://twitter.com/RealTime1987A/status/1499852183726141443?s=20&t=HmgPrrObXXyWxvTcgLy6Vw

Supernova Types





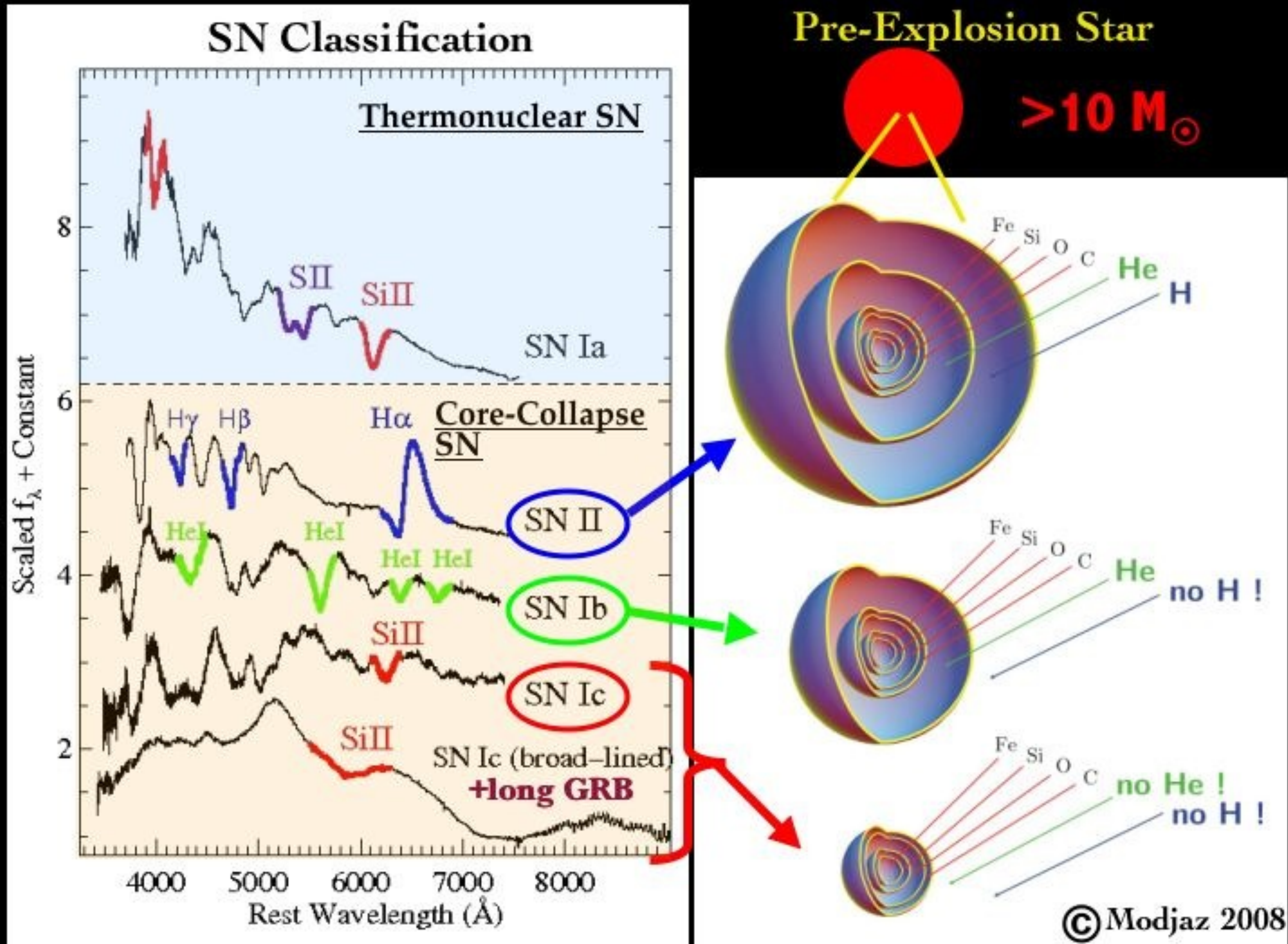


maximum light spectral features:
H: Type II
He: Type Ib
Si: Type Ia
else: Type Ic

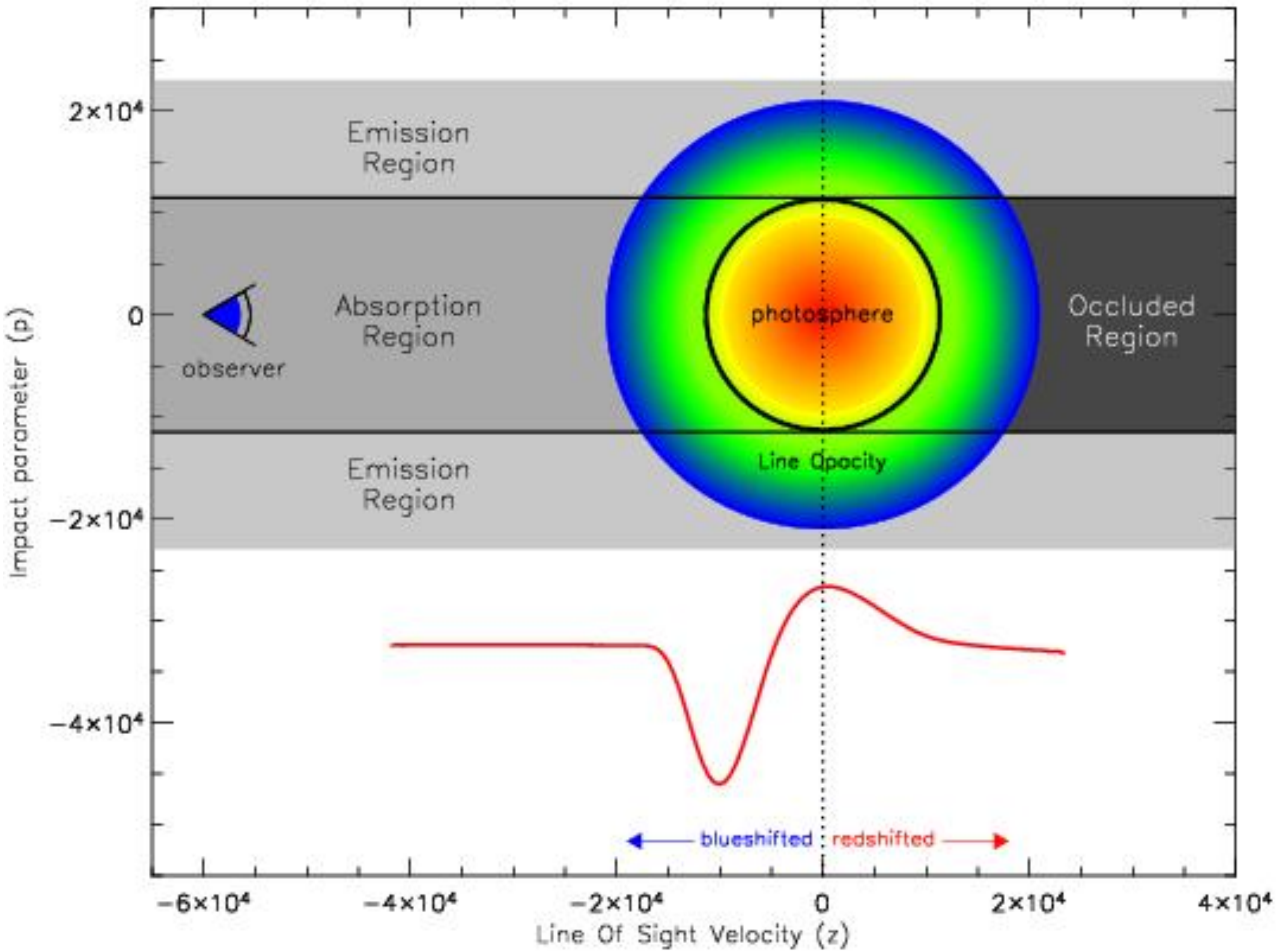
Filippenko (1997)

light curve power
CC: thermal

SN Ia: radioactivity
($^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$)

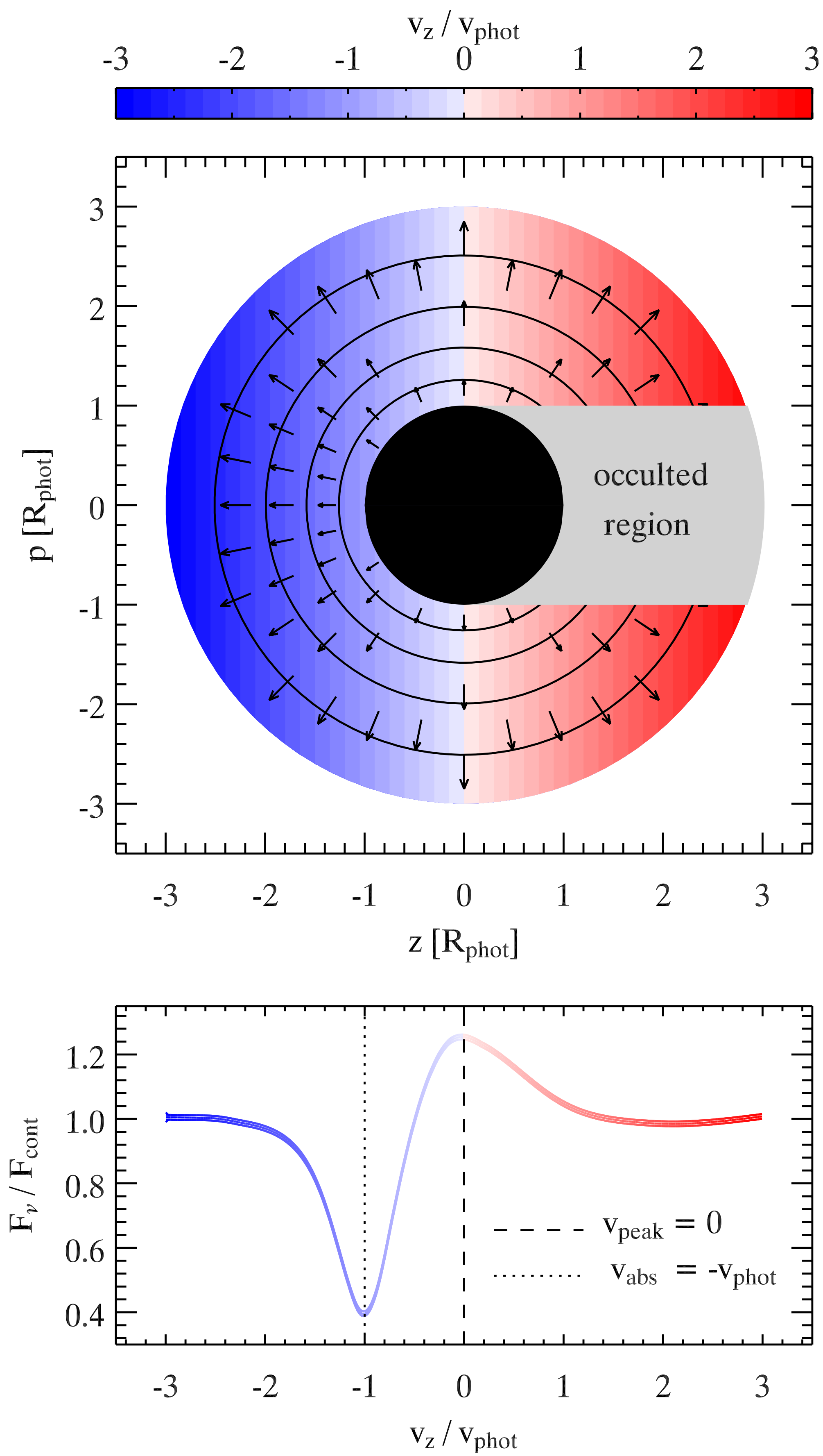

SN Classification
Thermonuclear SN
SII
SiII
SN Ia
Core-Collapse SN
Hγ Hβ
Hα
SN II
HeI HeI HeI HeI
SN Ib
SiII
SN Ic
SiII
SN Ic (broad-lined)
+long GRB
Scaled f_λ + Constant
Rest Wavelength (Å)
Pre-Explosion Star
>10 $M_\odot$
Fe Si O C He H
Fe Si O C He no H !
Fe Si O C no He ! no H !
© Modjaz 2008

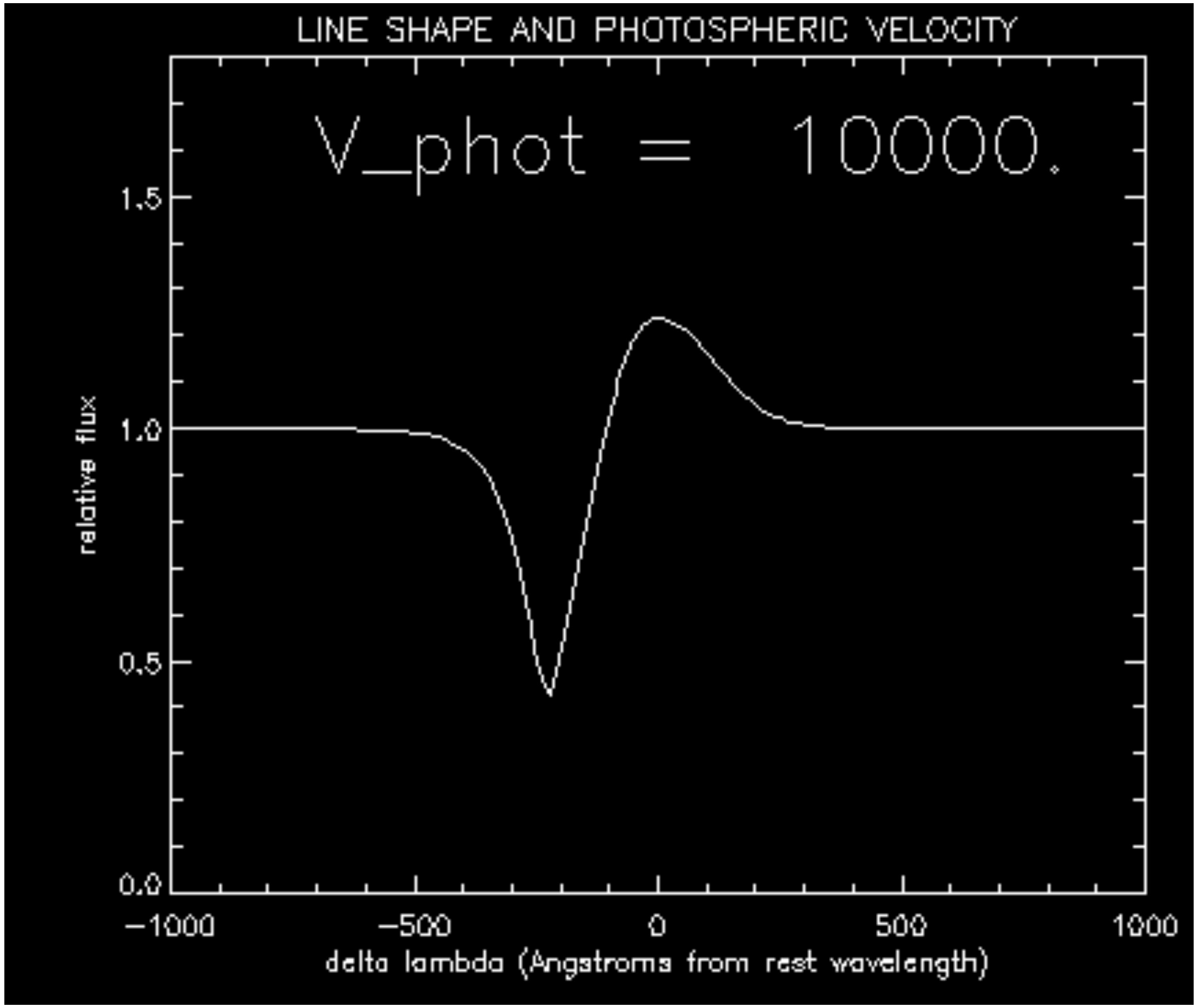
P-Cygni line profiles



from Dan Kasen, http://supernova.lbl.gov/~dnkasen/tutorial/

P-Cygni line profiles





from Stéphane Blondin https://people.lam.fr/blondin.stephane/graphics/ and Dan Kasen, http://supernova.lbl.gov/~dnkasen/tutorial/

supernova!

March 14, 1997

May 18, 1998

http://twanight.org/newTWAN/photos.asp?ID=3004502

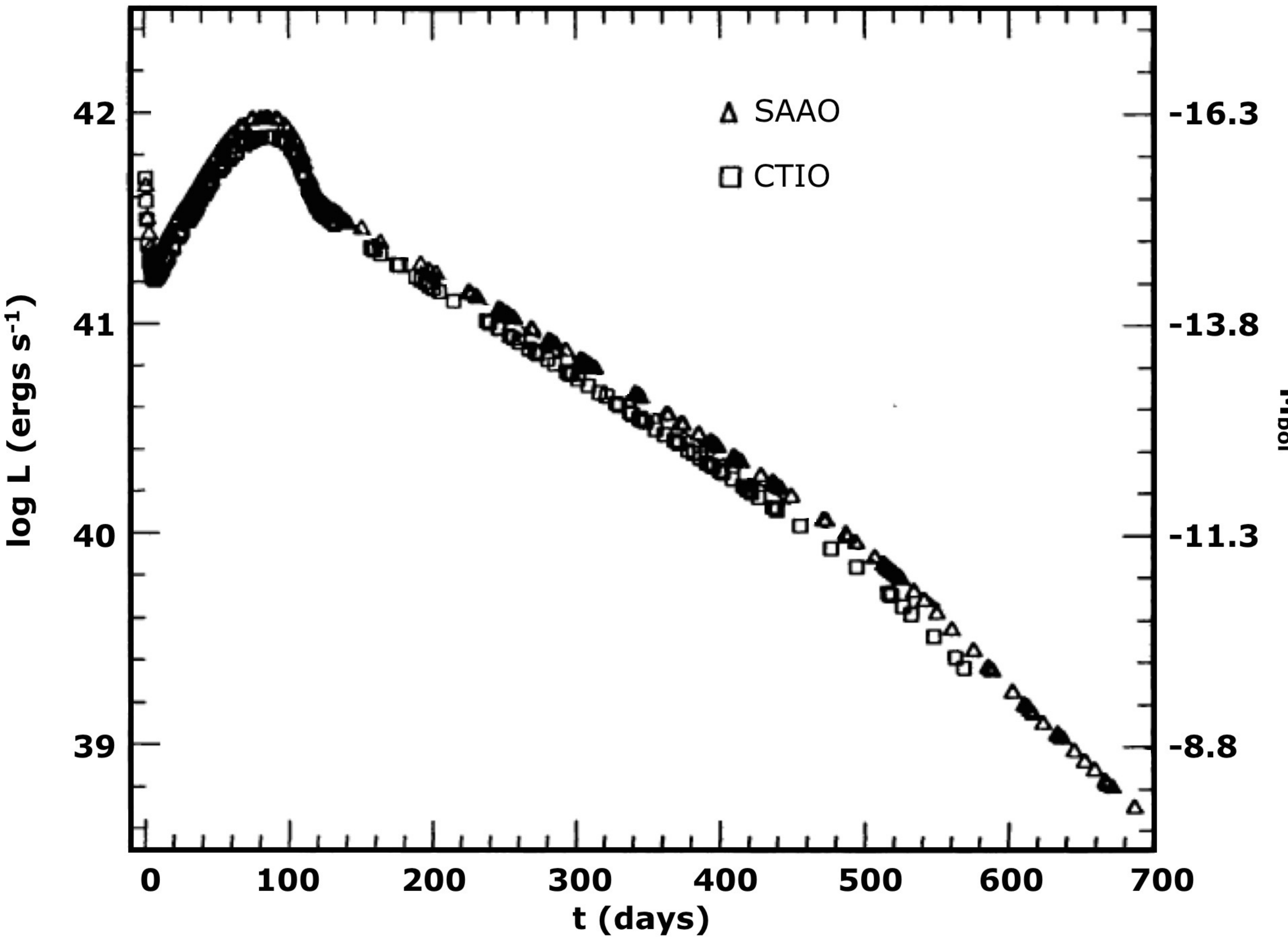
http://www.space.com/25450-large-magellanic-cloud.html

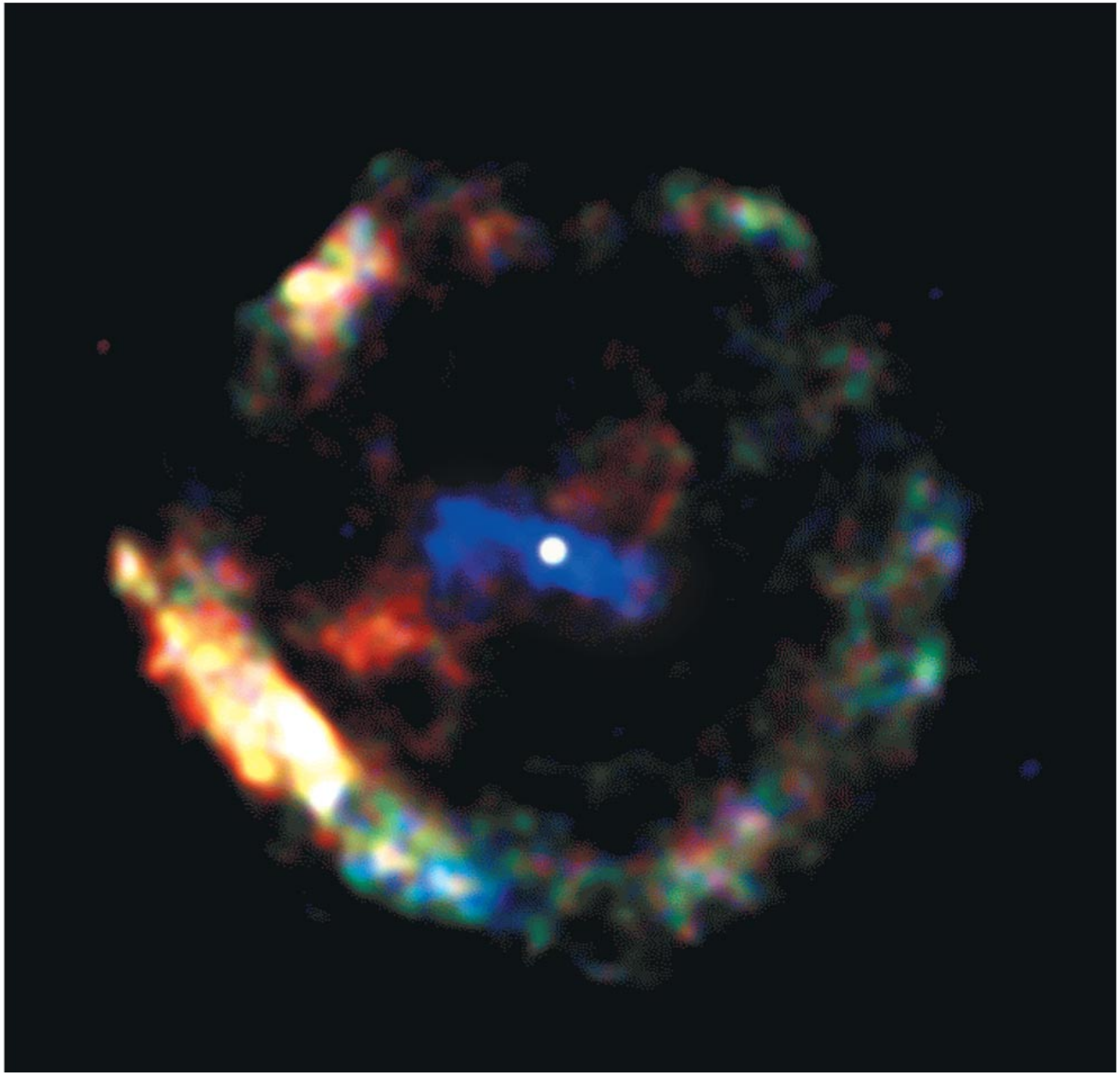
SN 1987A in the LMC

after and before image of SN 1987A in the Large Magellanic Cloud, discovered on February 23, 1987
from the Anglo-Australian Telescope, http://cosmos.colorado.edu/stem/courses/common/documents/chapter6/l6S6.htm

Supernovae - 1987A

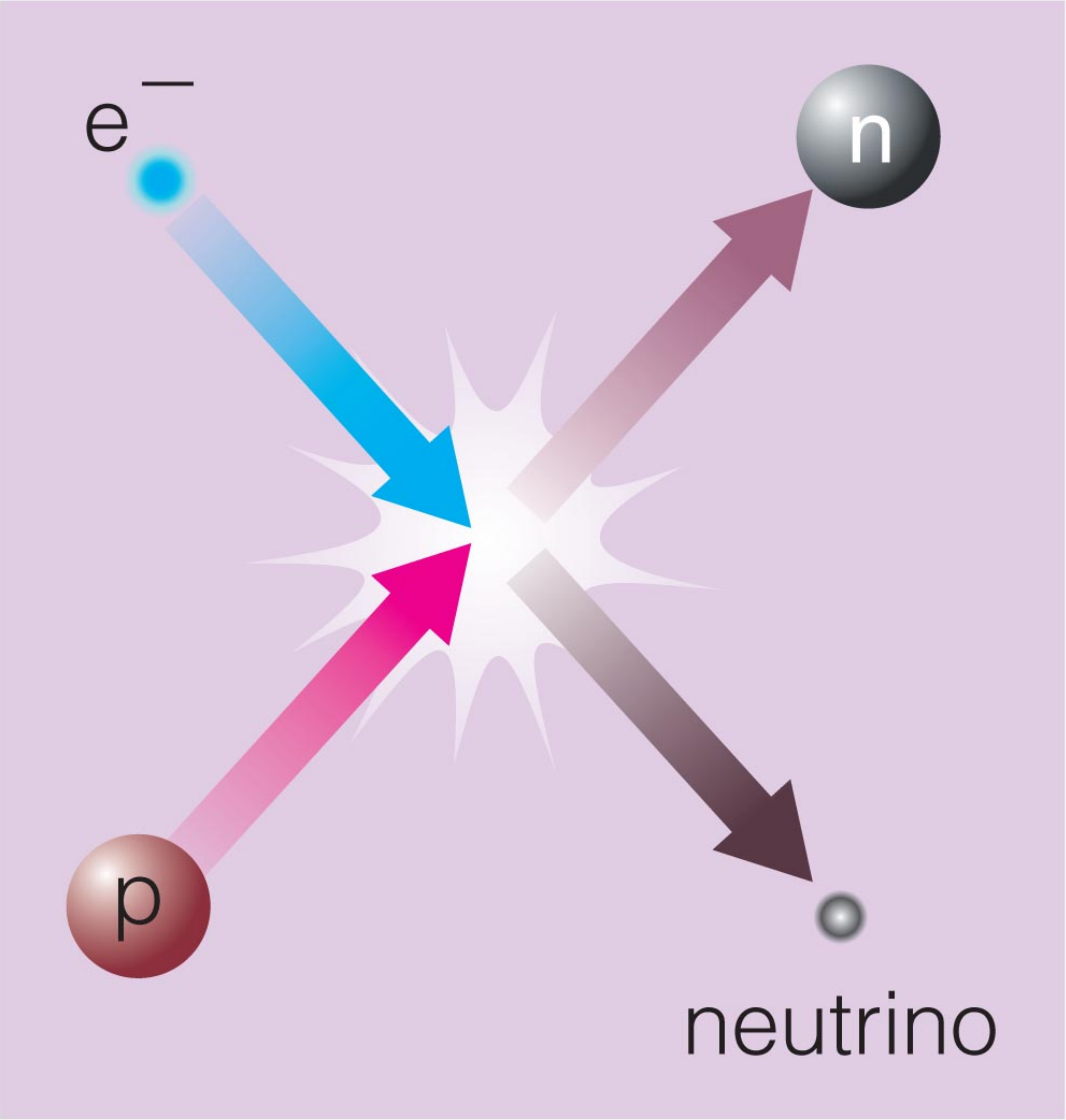
SN 1987A in the LMC is the closest and best-studied example of a core-collapse supernova:





A neutron star is the ball of neutrons left behind by a massive-star supernova.

Degeneracy pressure of neutrons supports a neutron star against gravity.

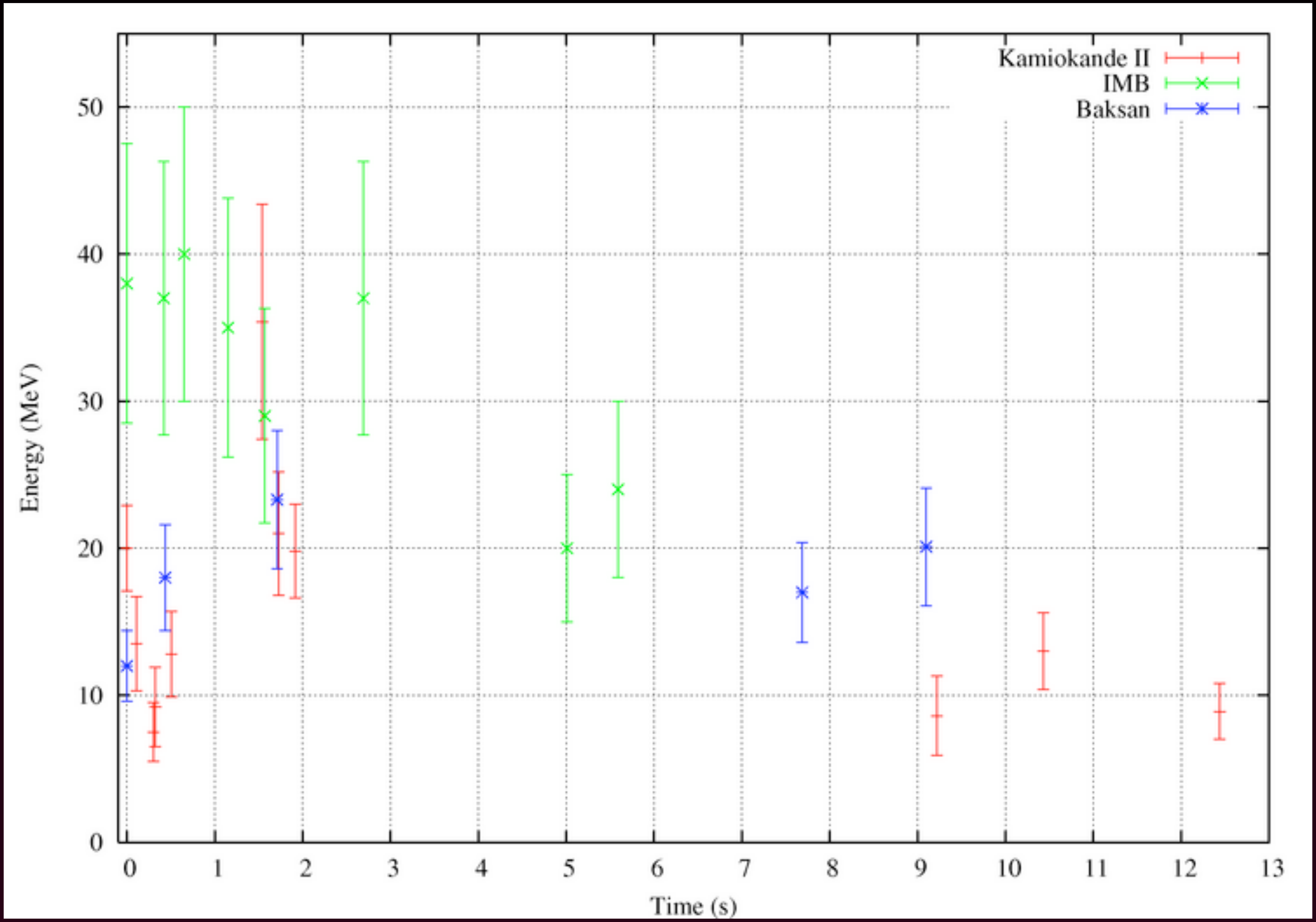


Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

Neutrons collapse to the center, forming a ***neutron star***.

We **know** this happens, because we detected neutrinos from massive star supernova 1987A

neutrinos from SN 1987A



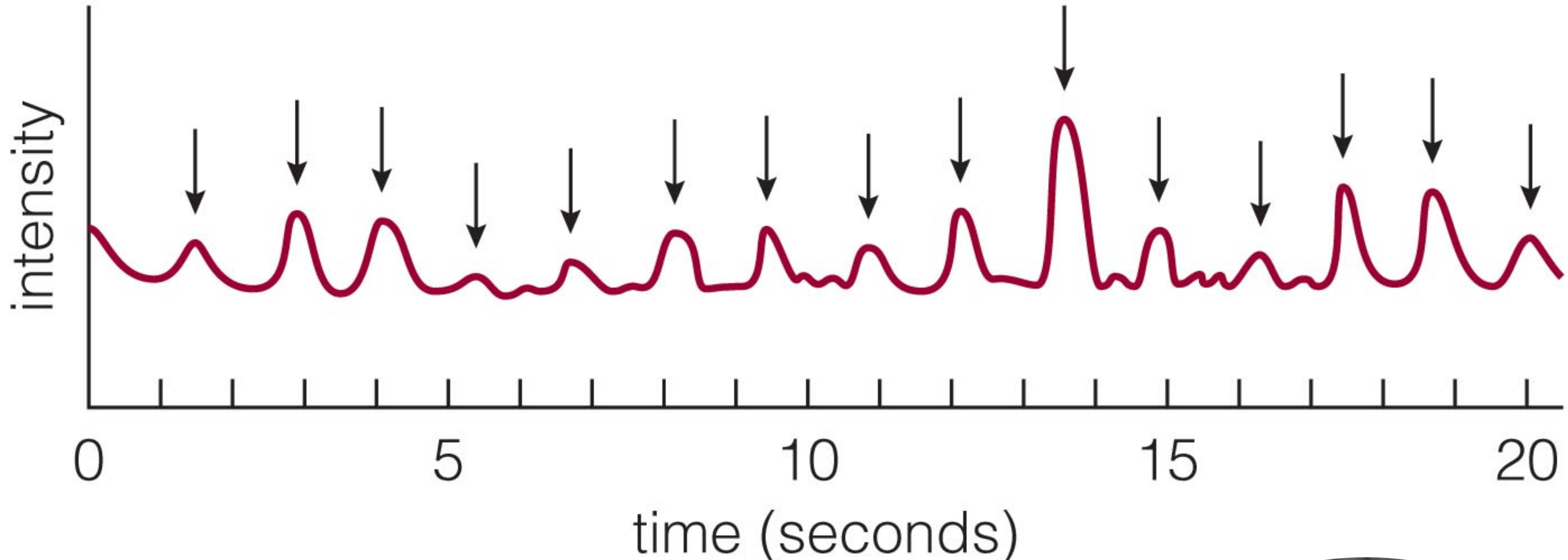
from http://nu.phys.laurentian.ca/%7Efleurot/supernova/
similar plot in Phillips Figure 6.3

Neuton stars: formation

production of neutrinos and anti-neutrinos:

$$p + e^- \to n + \nu_e \qquad p + \bar{\nu}_e \to n + e^+ \quad e^+ e^- \to \gamma\gamma \text{ or } \nu\bar{\nu}$$

Discovery of Neutron Stars

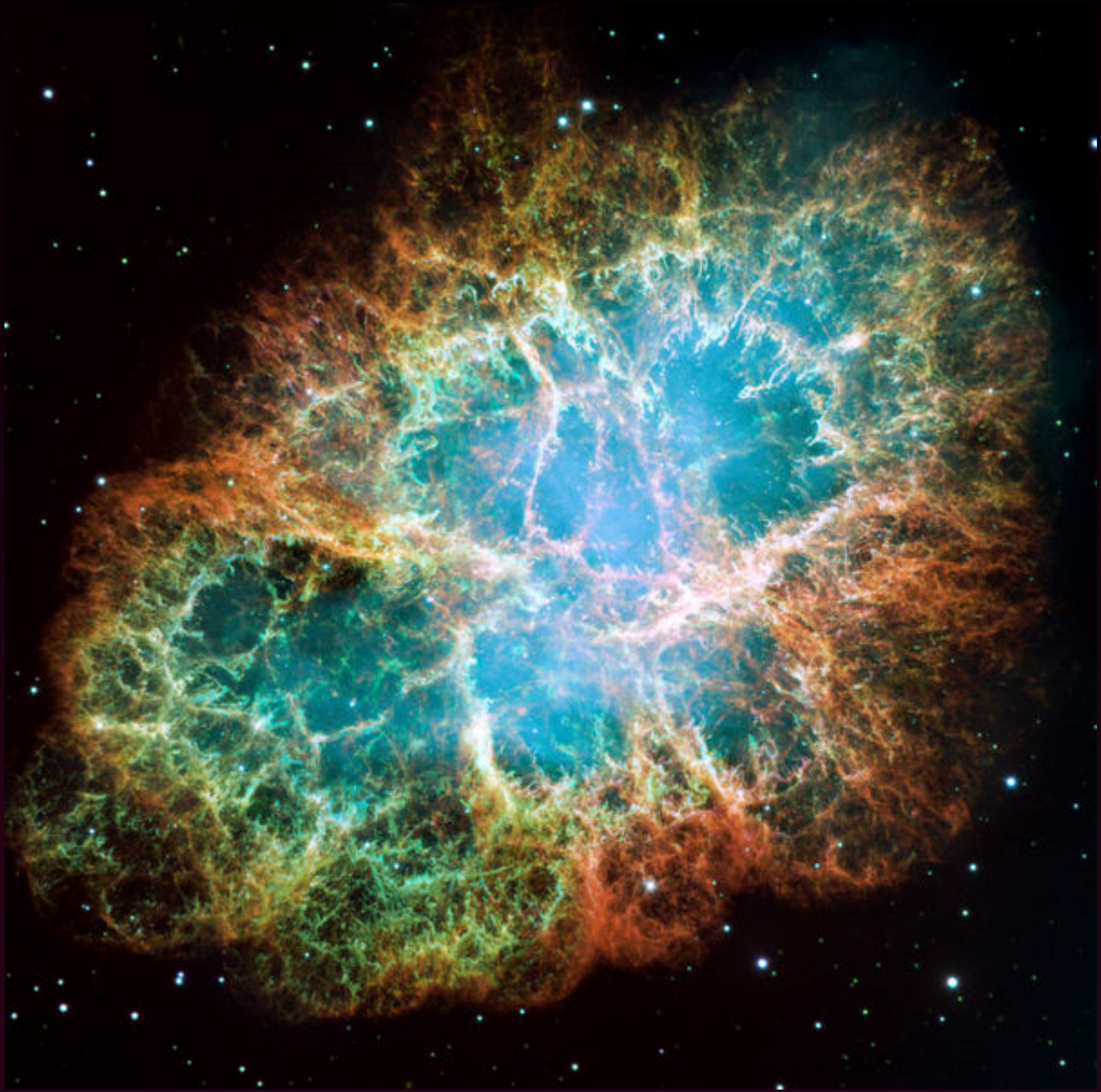


- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.

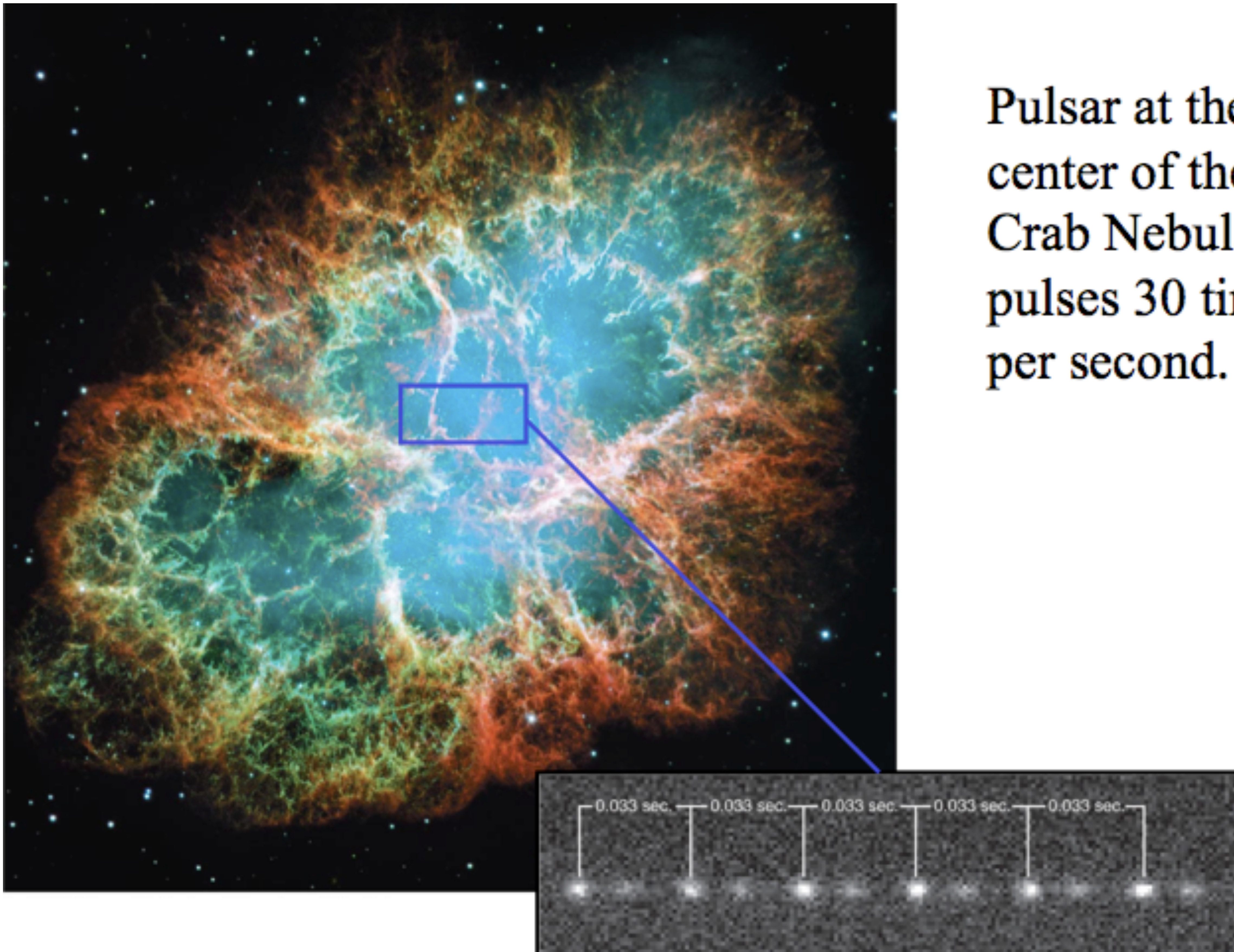
- The pulses were coming from a spinning neutron star—a *pulsar.*

Rutgers 2016 commencement

Crab Nebula, remnant of SN 1054

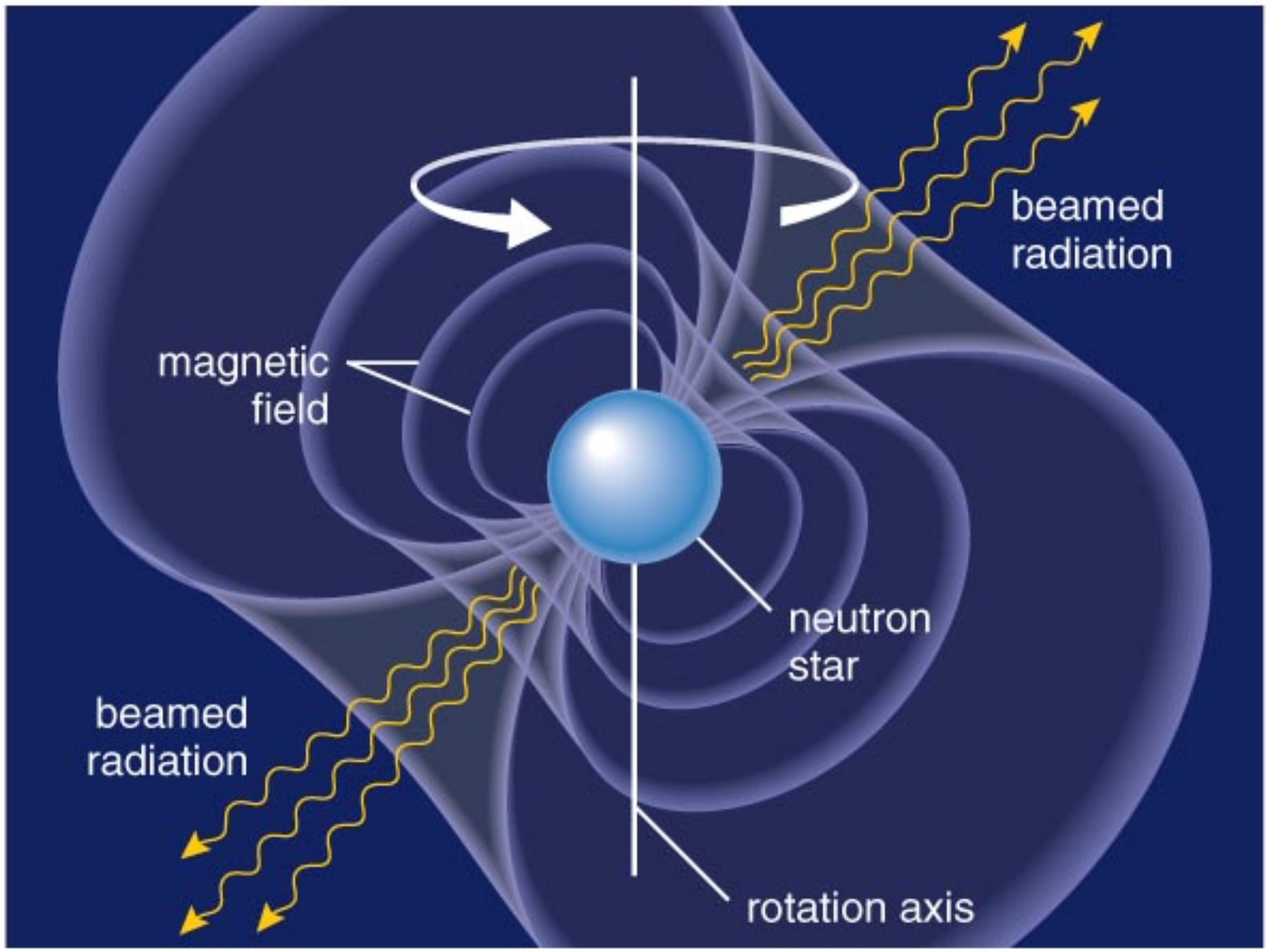


from http://en.wikipedia.org/wiki/File:Crab_Nebula.jpg



Pulsar at the center of the Crab Nebula pulses 30 times per second.

Pulsars



- A ***pulsar*** is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

Review: degeneracy pressure

non-relativistic

$$P = \frac{h^2}{5m_e}\left[\frac{3}{8\pi}\right]^{2/3} n^{5/3}$$

ultra-relativistic

$$P = \frac{hc}{4}\left[\frac{3}{8\pi}\right]^{1/3} n^{4/3}$$

these limits correspond to polytropes

$$\gamma = 5/3 \quad n = 3/2$$

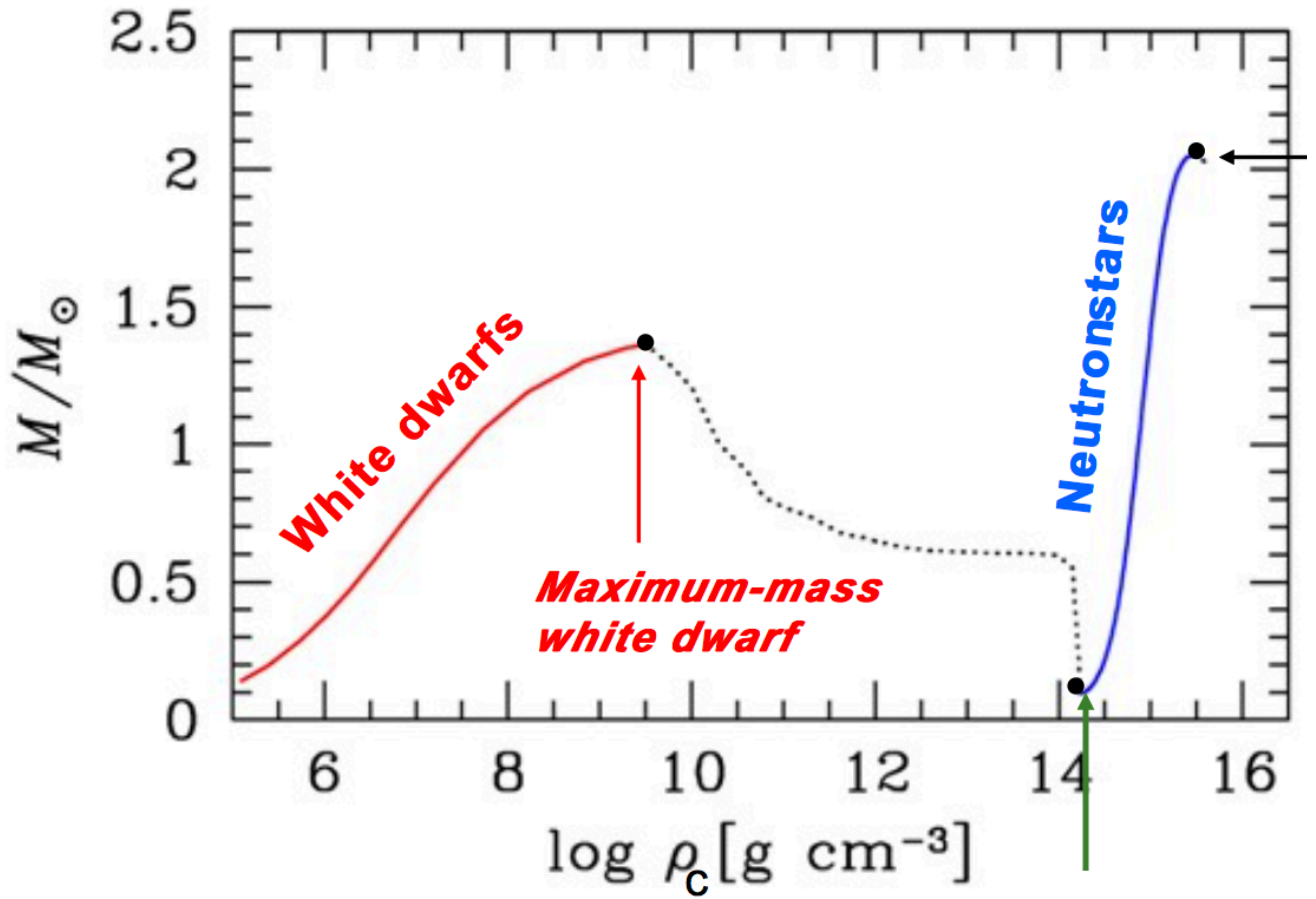
$$\gamma = 4/3 \quad n = 3$$

$$R \propto M^{\frac{1-n}{3-n}} \qquad R \propto M^{-1/3}$$

Replace m_e, n_e from white dwarfs with m_n, n_n for neutron stars

For NR case replacing m_e with m_n means n_n must be much higher than n_e was to give same pressure.
So R must be much smaller: 1 M_{Sun} neutron star ~ 10–20 km

Neutron stars: density



from Soldan http://slideplayer.com/slide/3852443/

Neutron star maximum mass

non-relativistic

$$P = \frac{h^2}{5m_e}\left[\frac{3}{8\pi}\right]^{2/3} n^{5/3}$$

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Replace m_e, n_e from white dwarfs with m_n, n_n for neutron stars

Note ultra-relativistic case does not depend on m! Why?

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recall derivation: rest mass is negligible compared to KE

Neutron star maximum mass

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Replace m_e, n_e from white dwarfs with m_n, n_n for neutron stars

Note ultra-relativistic case does not depend on m! Why?

recall derivation: rest mass is negligible compared to KE

So we get the same derivation as for the Chandrasekhar mass

$$M_{\mathrm{Ch}} = 5.8\ M_\odot \left(\frac{1}{\mu_e}\right)^2$$

except replace μ_e with μ_n (avg particle mass per neutron). It's all neutrons! So $\mu_n = 1$.

Thus maximum mass of a neutron star should be 5.8 $M_\odot$

Neutron star maximum mass

The maximum mass of a neutron star should be 5.8 $M_\odot$

Not so fast! Need to switch from Newtonian gravity to GR!

hydrostatic equilibrium:

see Phillips section 6.3

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\rho}{r^2}, \longrightarrow \frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\rho}{r^2} \times \frac{(1 + P/\rho c^2)(1 + 4\pi r^3 P/mc^2)}{(1 - 2Gm/rc^2)}.$$

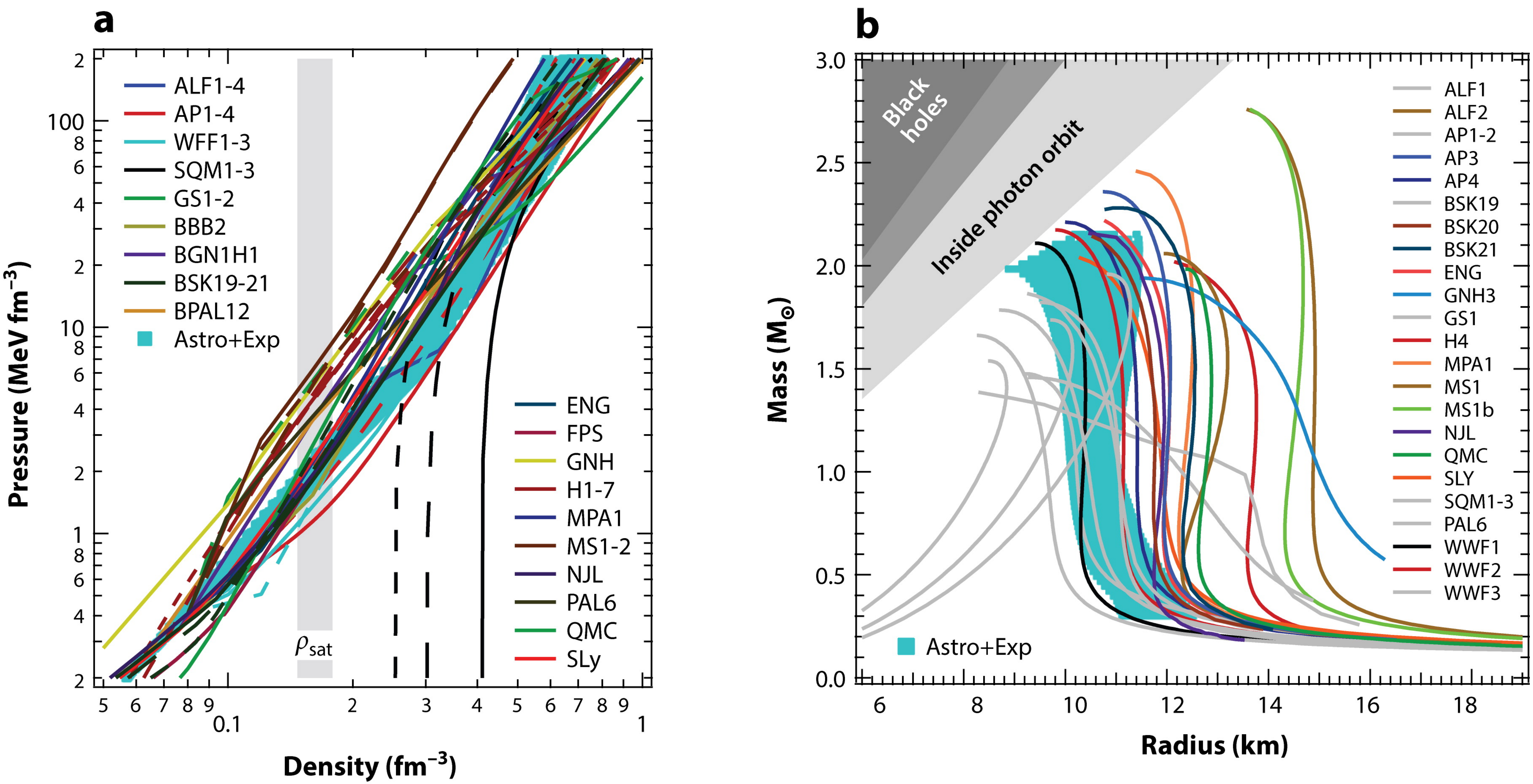
Newtonian General Relativity

In GR, all forms of energy gravitate!
Not just rest mass, but kinetic energy (pressure) as well.

So faster-moving neutrons have more pressure,
but also more gravity to overcome!

This plus strong nuclear force effects lowers maximum mass of a neutron star to be somewhere between 2–3 $M_\odot$

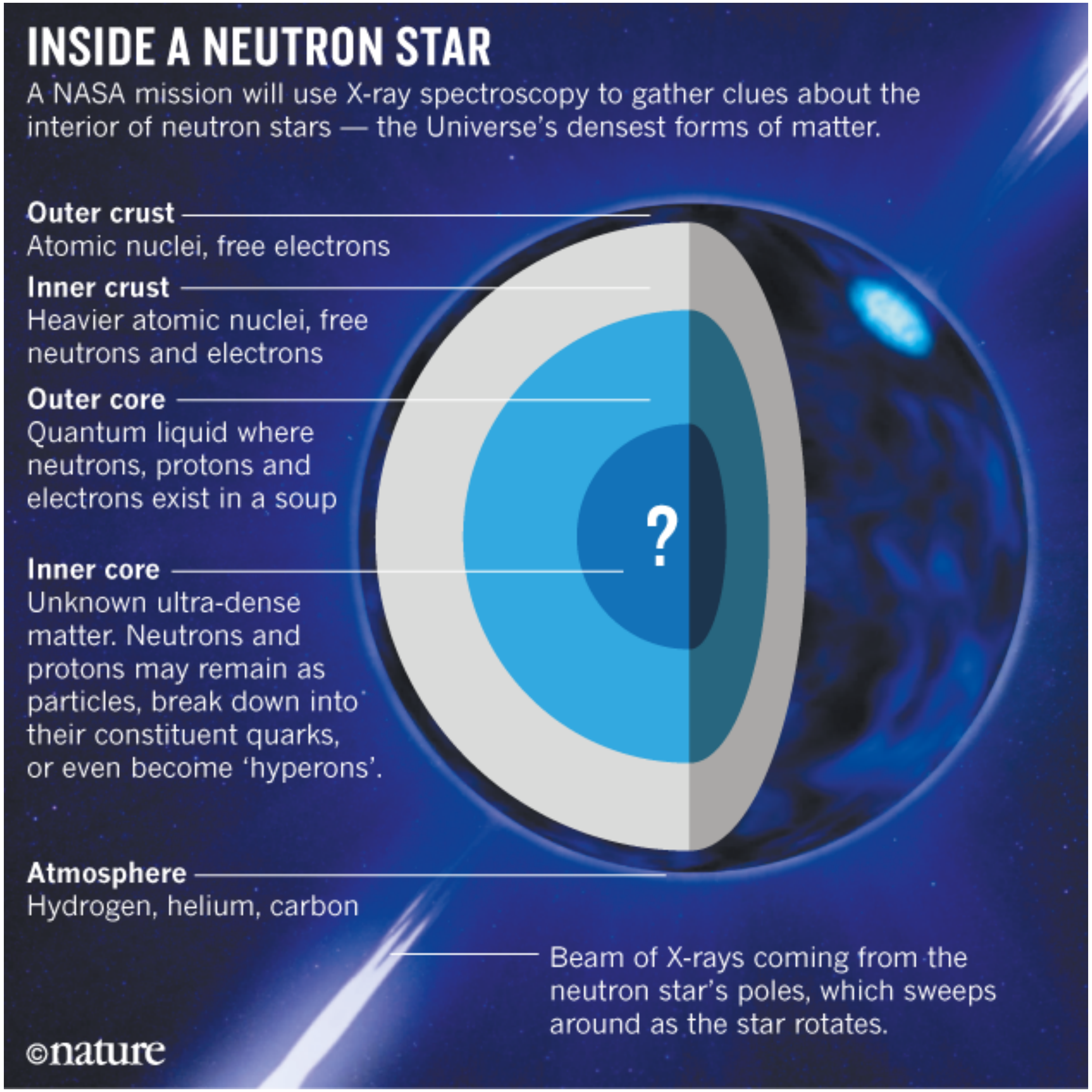
Neutron stars: mass & radius



Özel F, Freire P. 2016.

Annu. Rev. Astron. Astrophys. 54:401–40

Neutron stars: interior structure

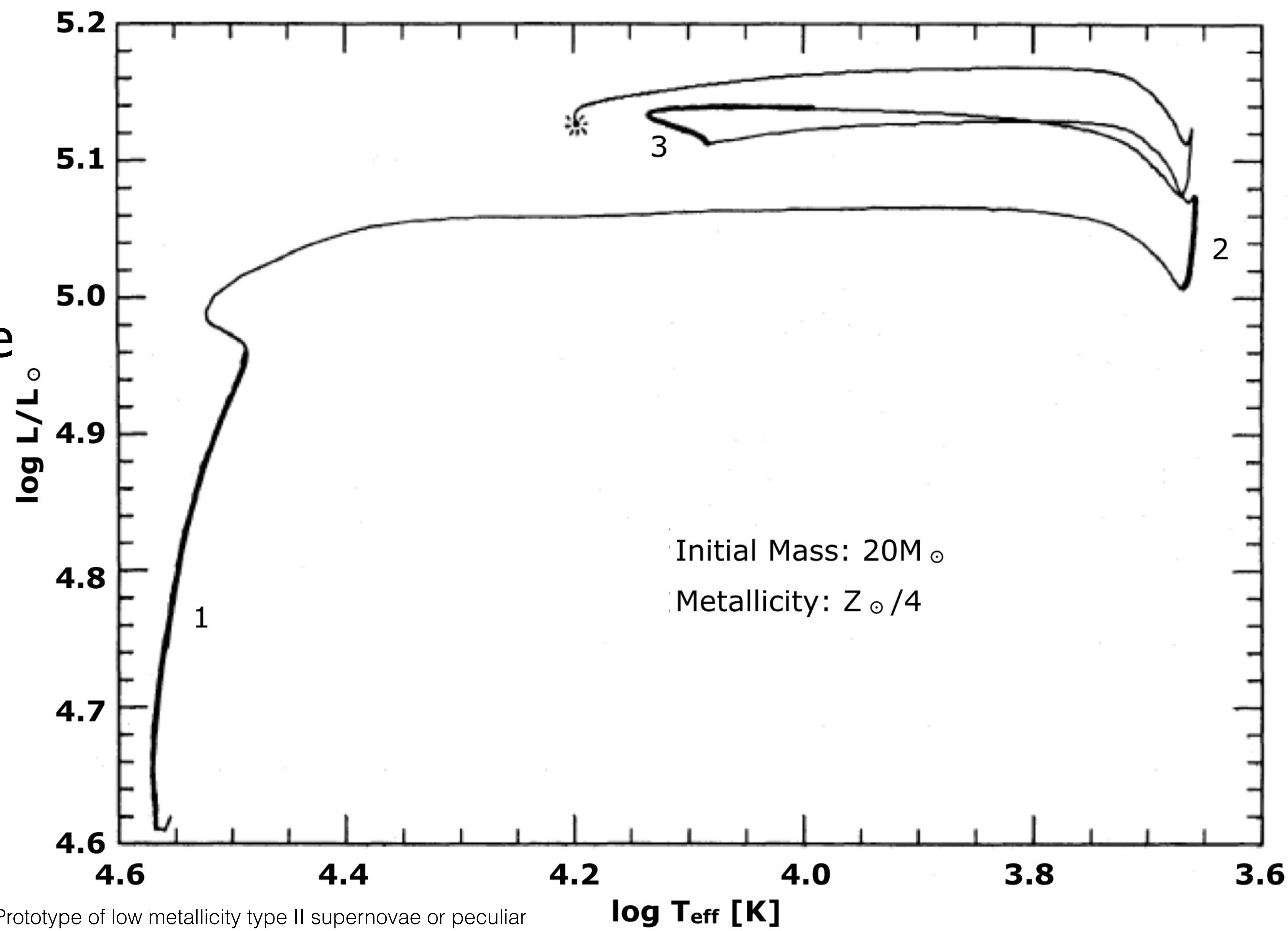


from https://www.nature.com/news/neutron-stars-set-to-open-their-heavy-hearts-1.22070

Supernovae - 1987A

SN 1987A in the LMC is the closest and best-studied example of a core-collapse supernova:

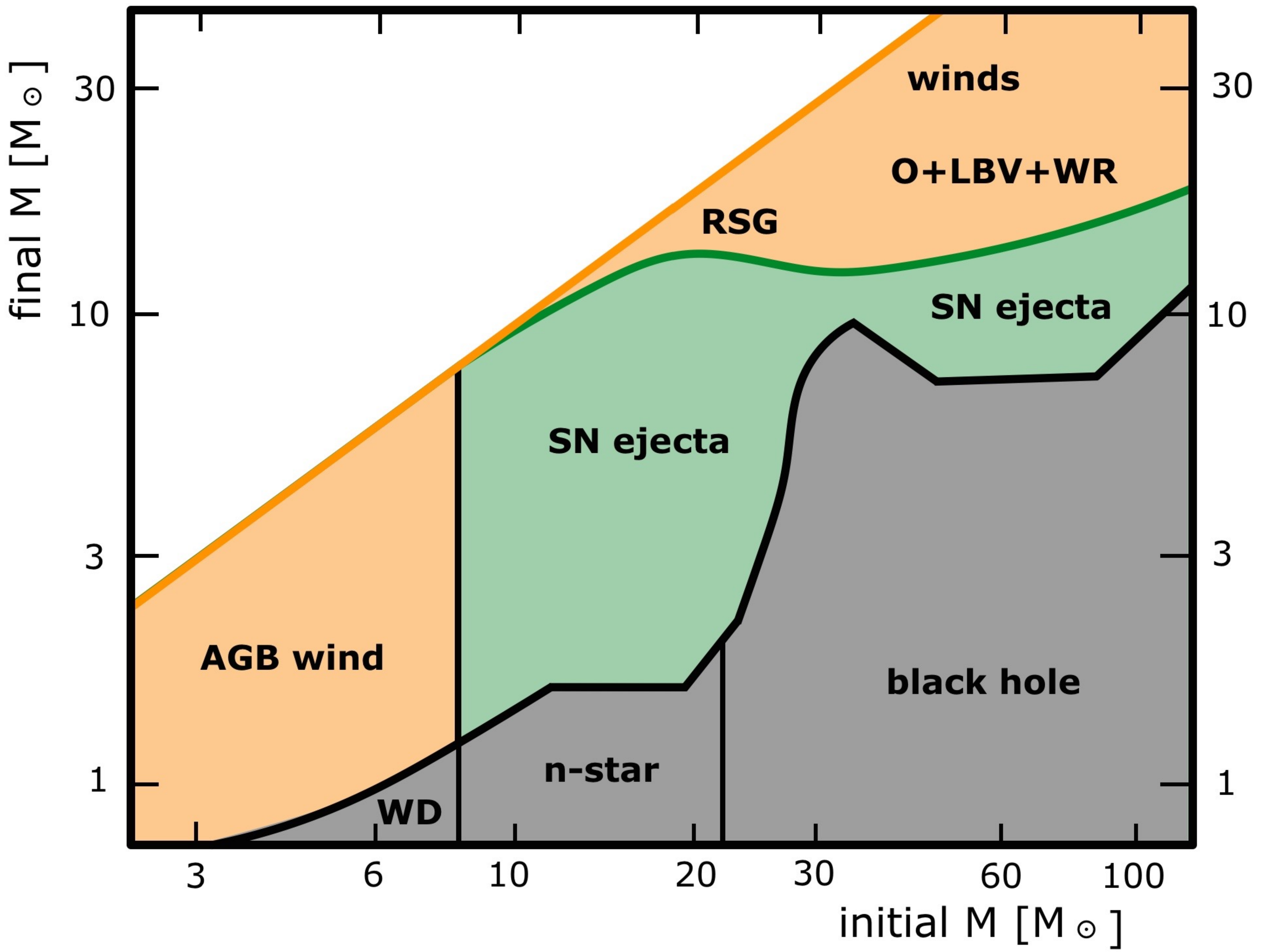
A single-star model can match the progenitor star but is dependent on the blue loop. More recent models adopt a pre-SN merger model with a binary companion…



Reproduced from N. Langer 'Supernova 1987 A - Prototype of low metallicity type II supernovae or peculiar exception? ', Astronomy & Astrophysics, vol 243, p 155-159, 1991. Reproduced with permission. © ESO.

Supernovae - remnants

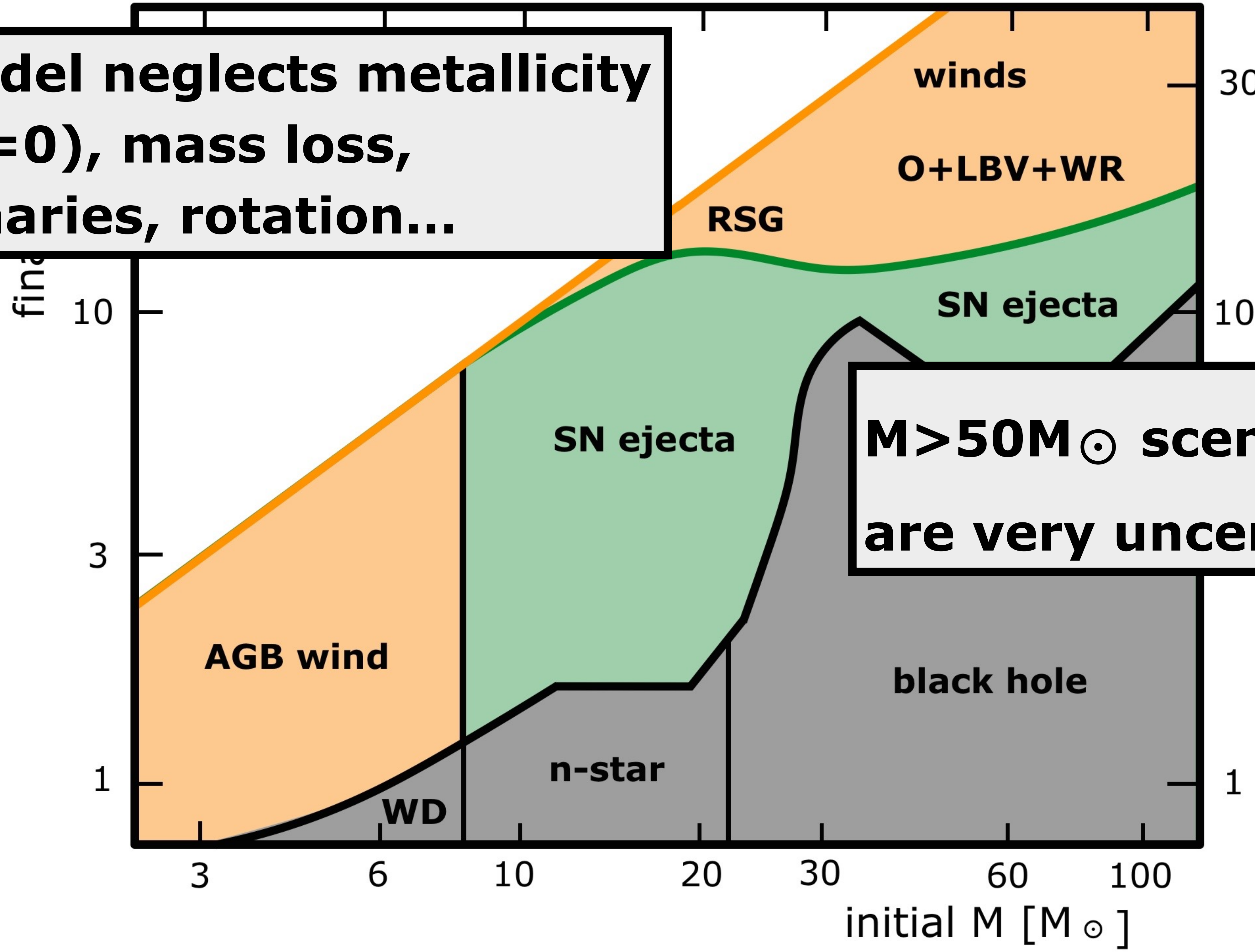
Our simplified model illustrates that stars with different initial masses end their lives differently…



Supernovae - remnants

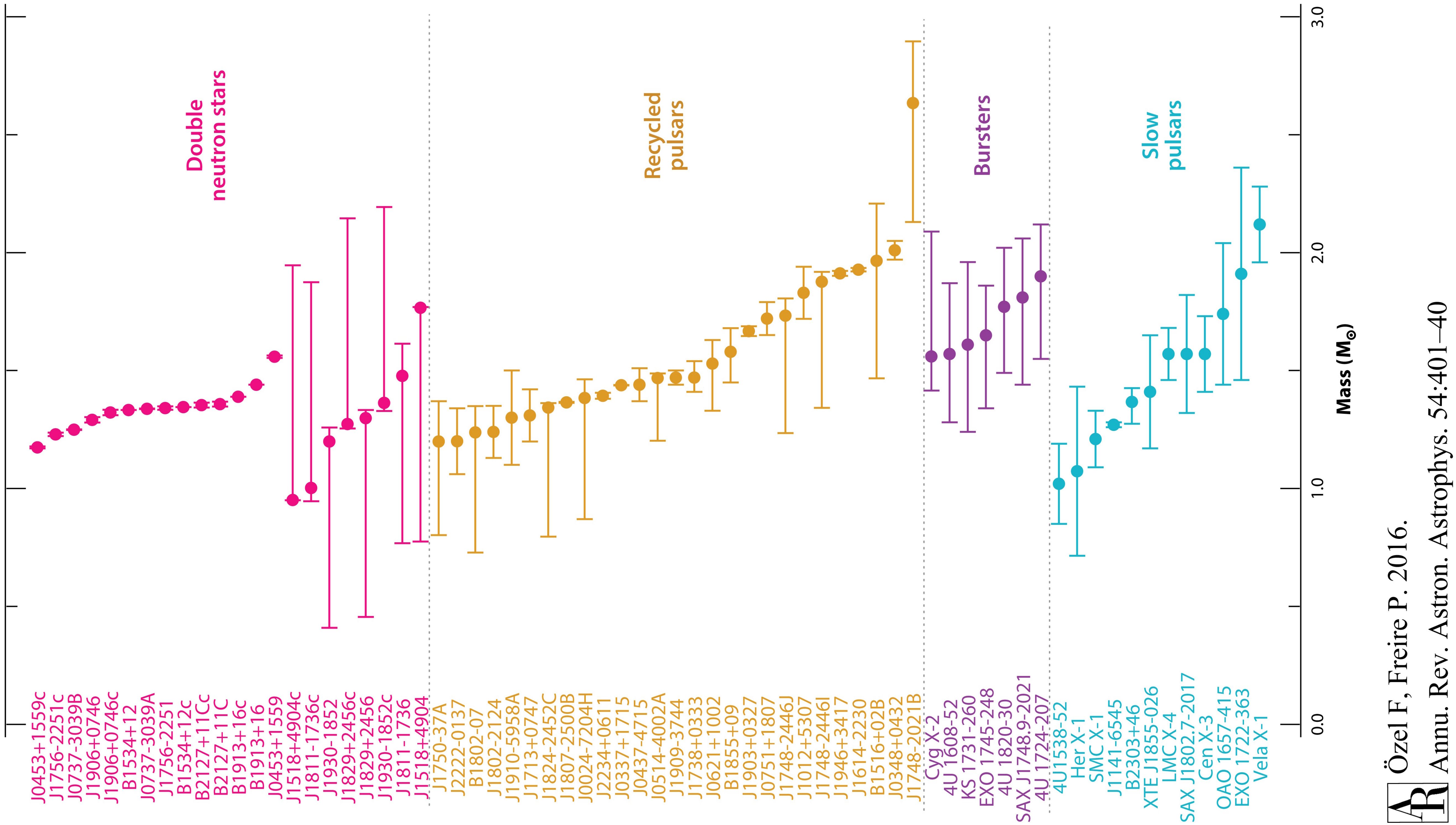
Our simplified model illustrates that stars with different initial masses end their lives differently…however…

Model neglects metallicity (Z=0), mass loss, binaries, rotation…



M>50M$_\odot$ scenarios are very uncertain

Neutron stars: masses



Supernovae - remnants

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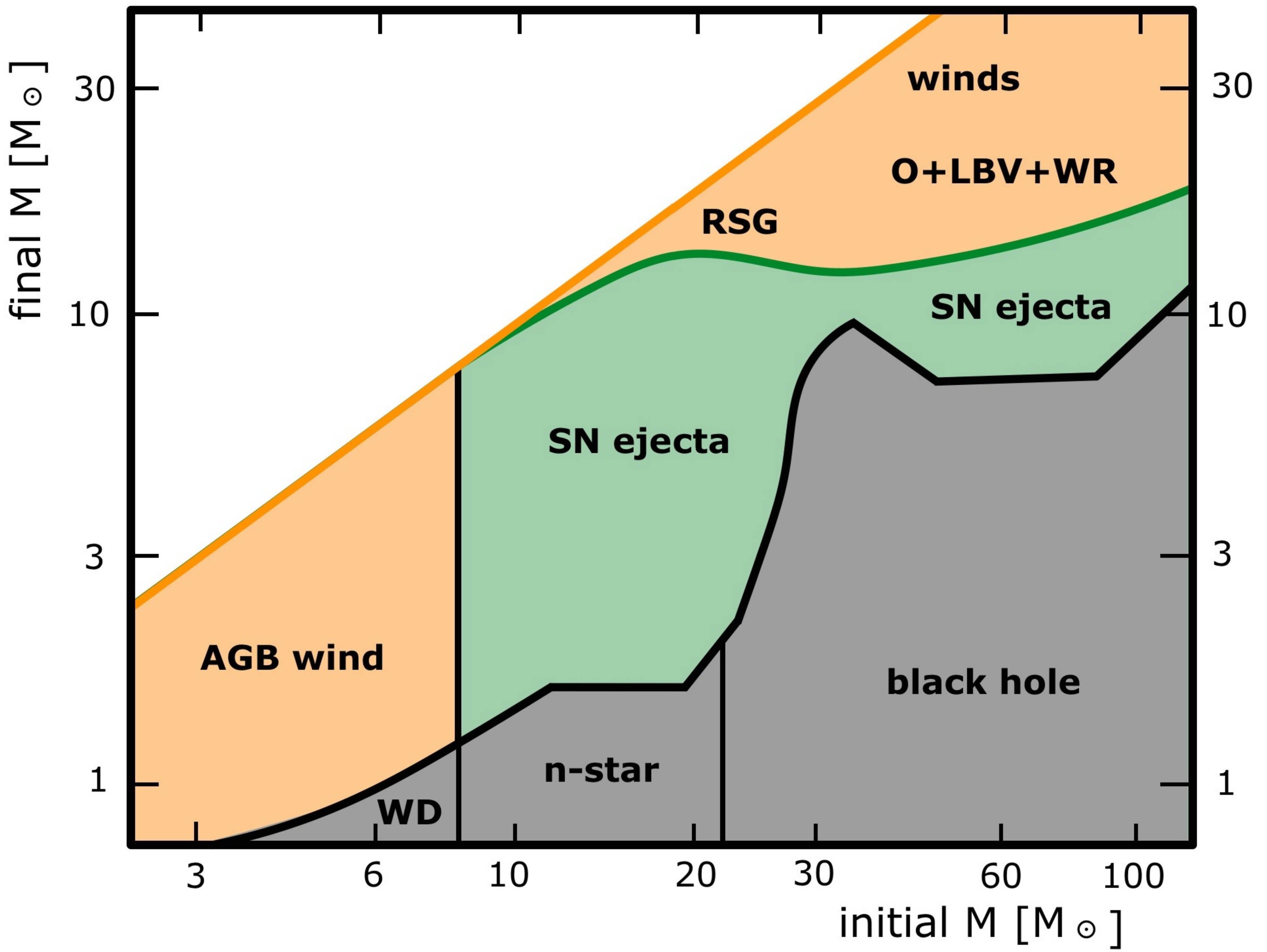
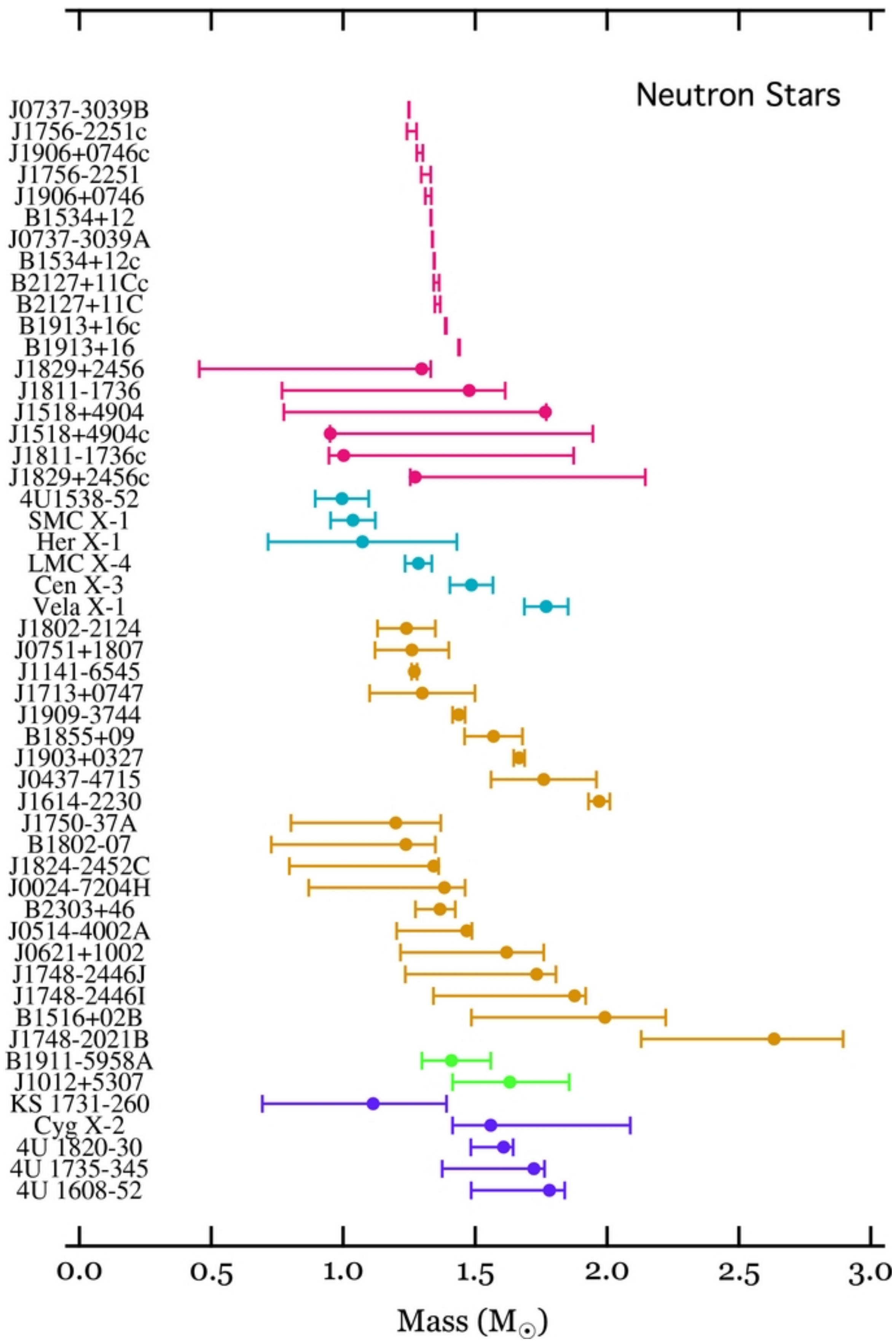
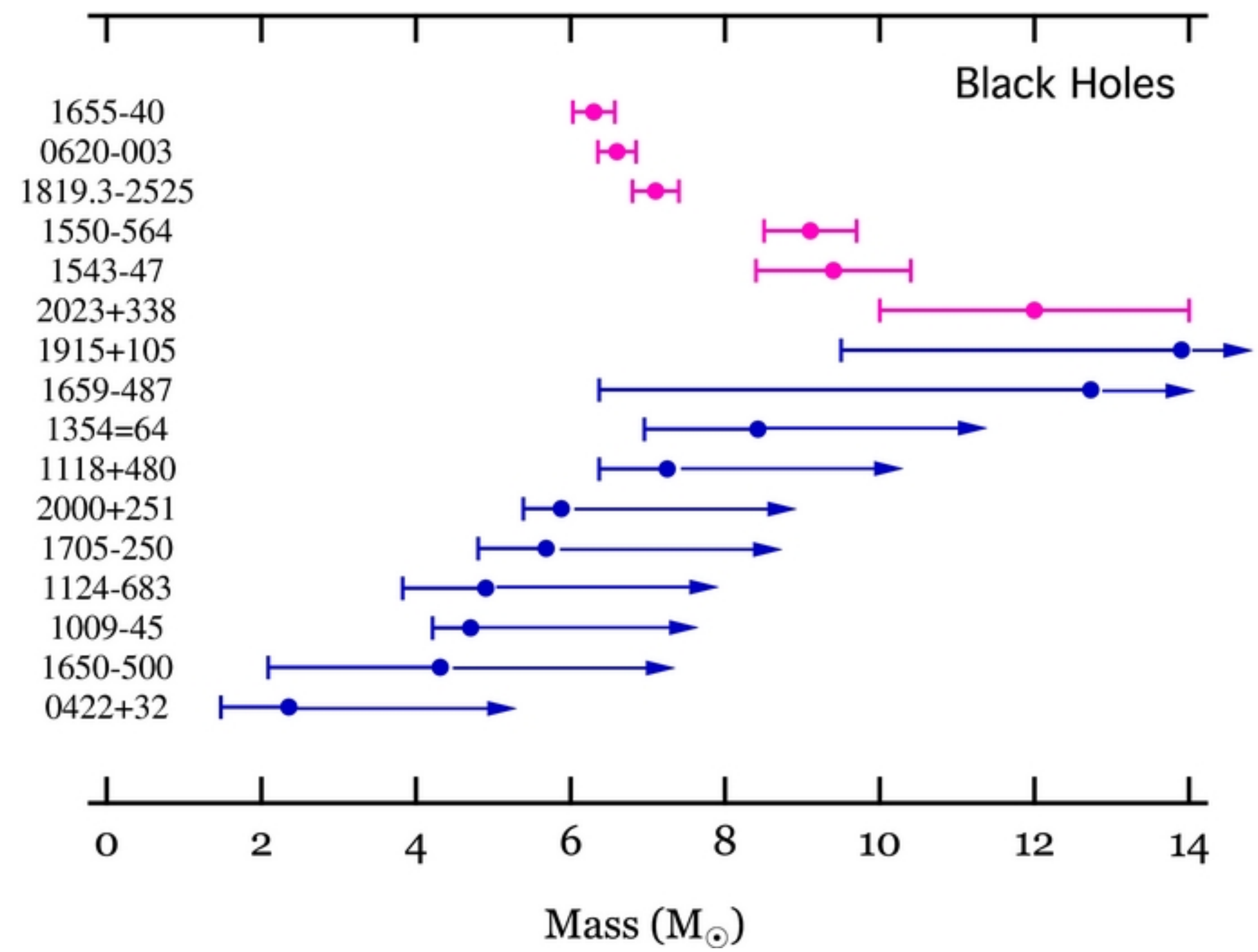


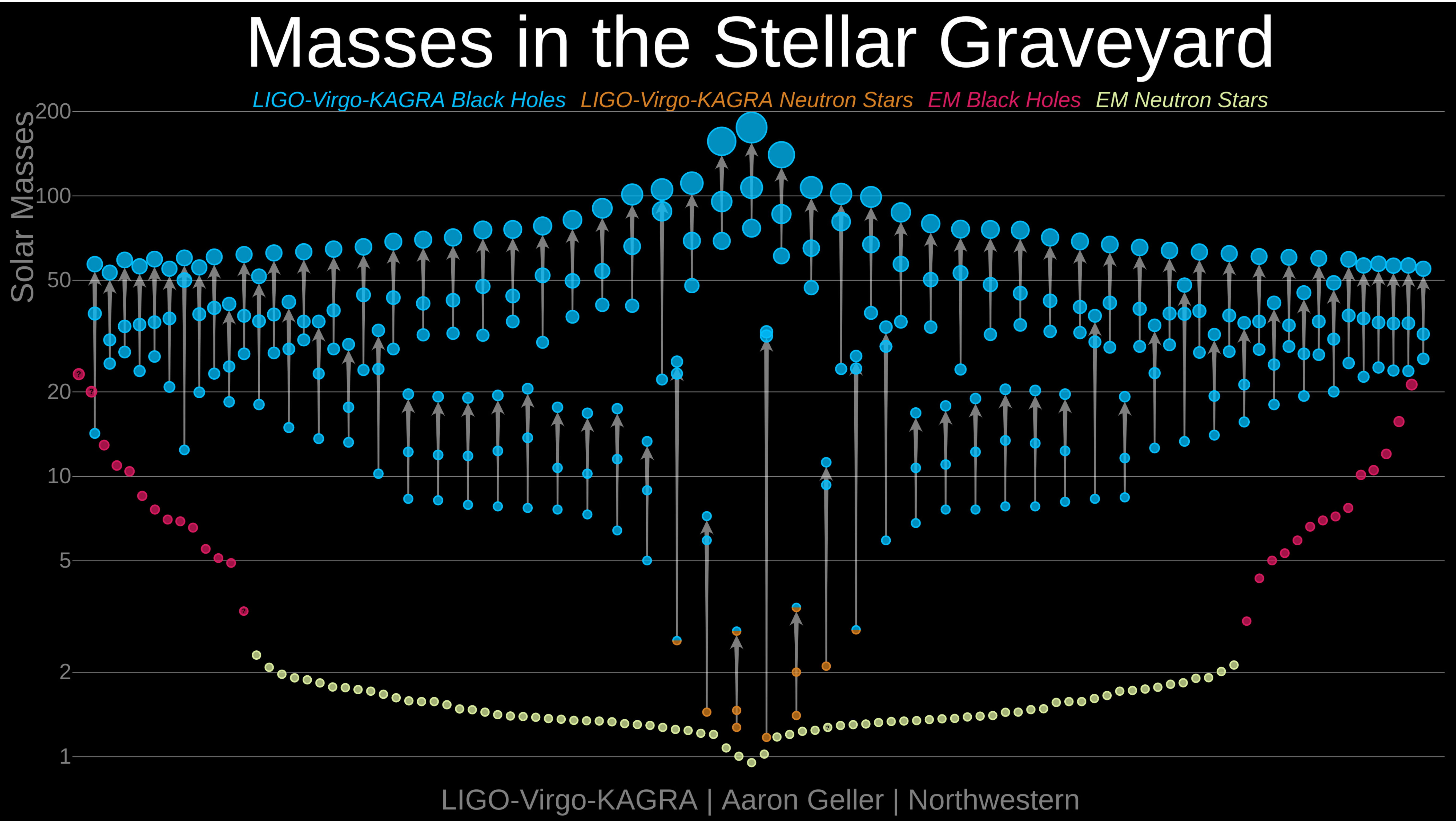
Neutron stars & black holes



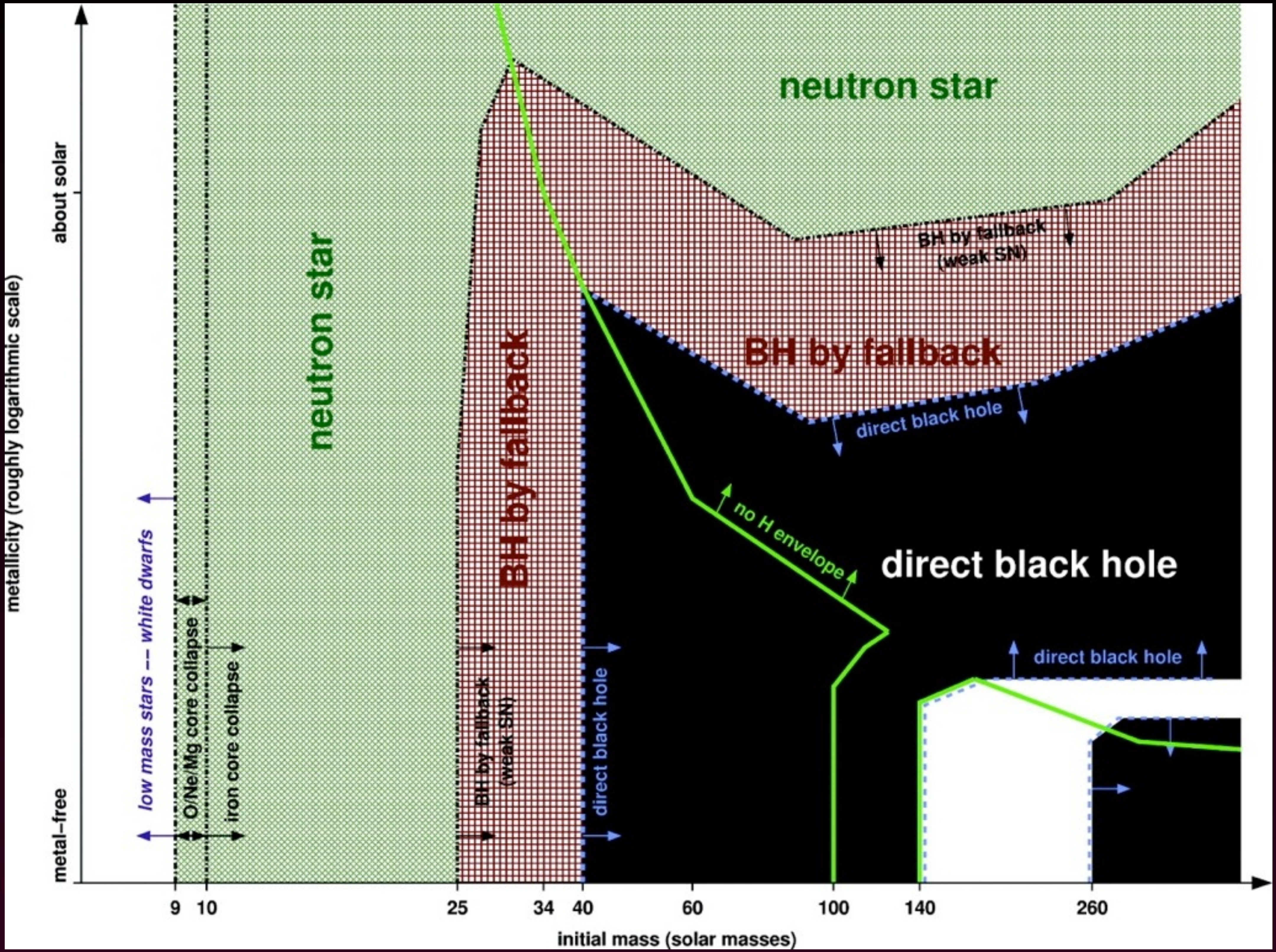


from Özel et al. (2012)

Neutron stars & black holes

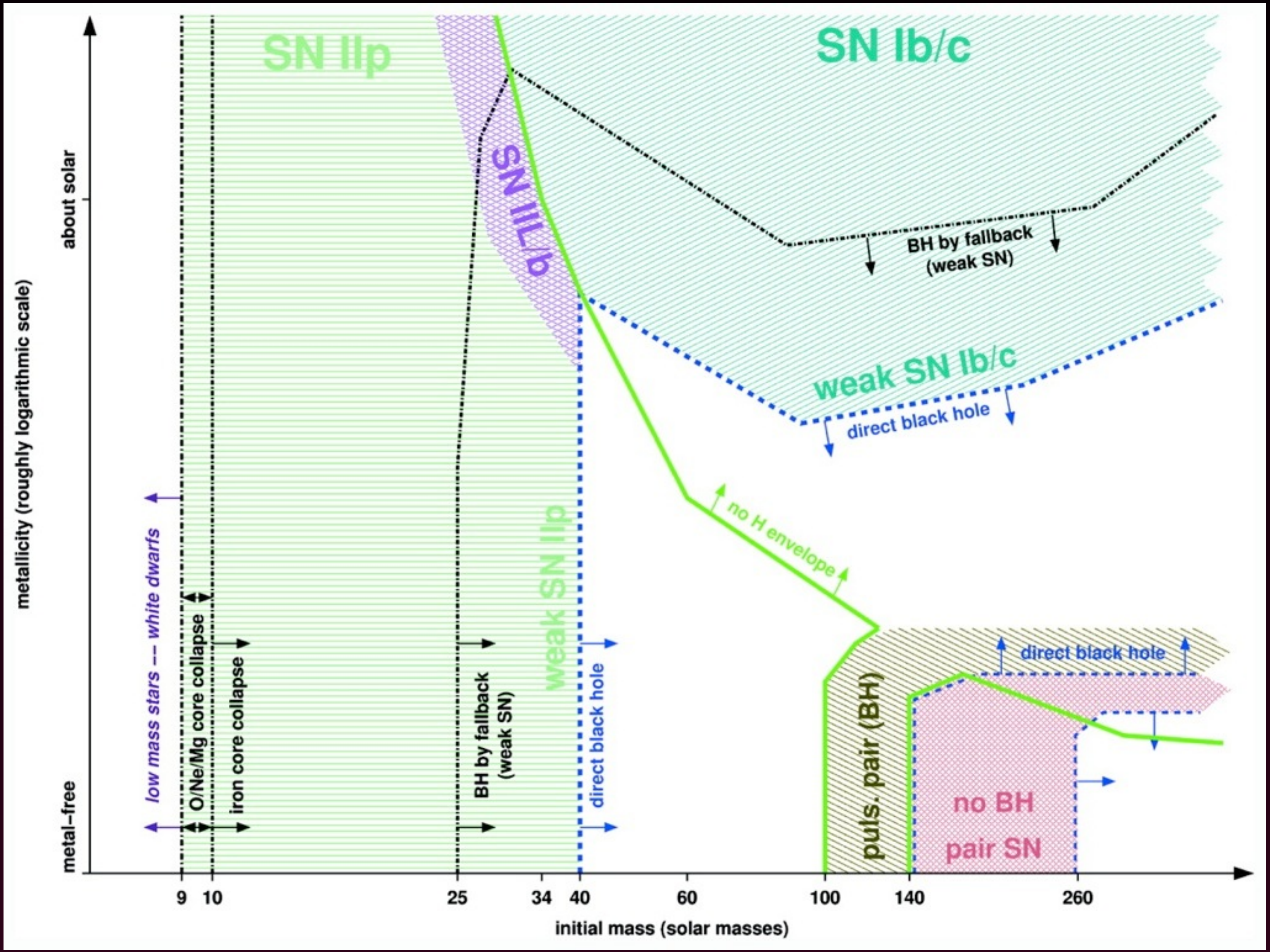


The End of Single Massive Stars (in theory)

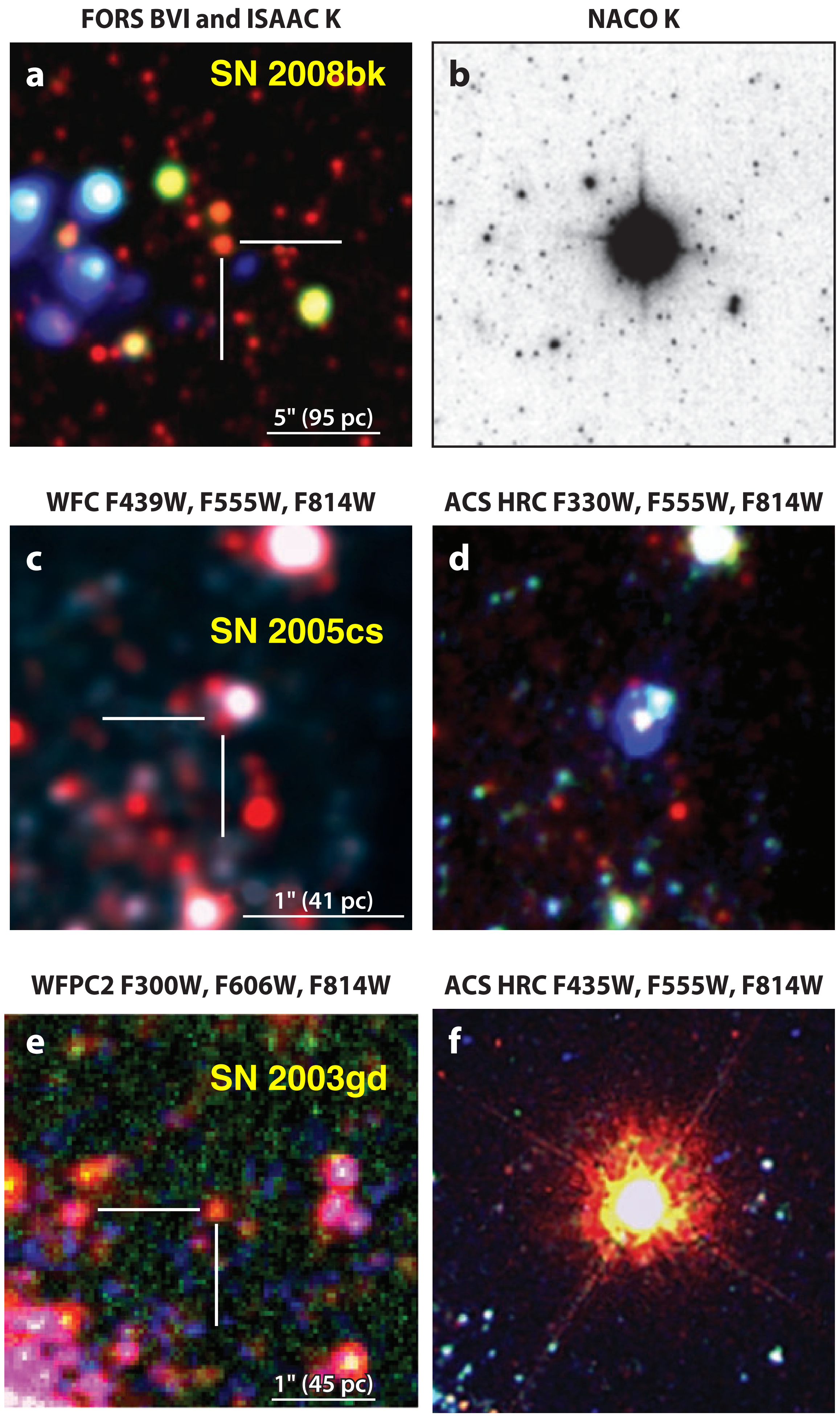


Heger et al. (2003)

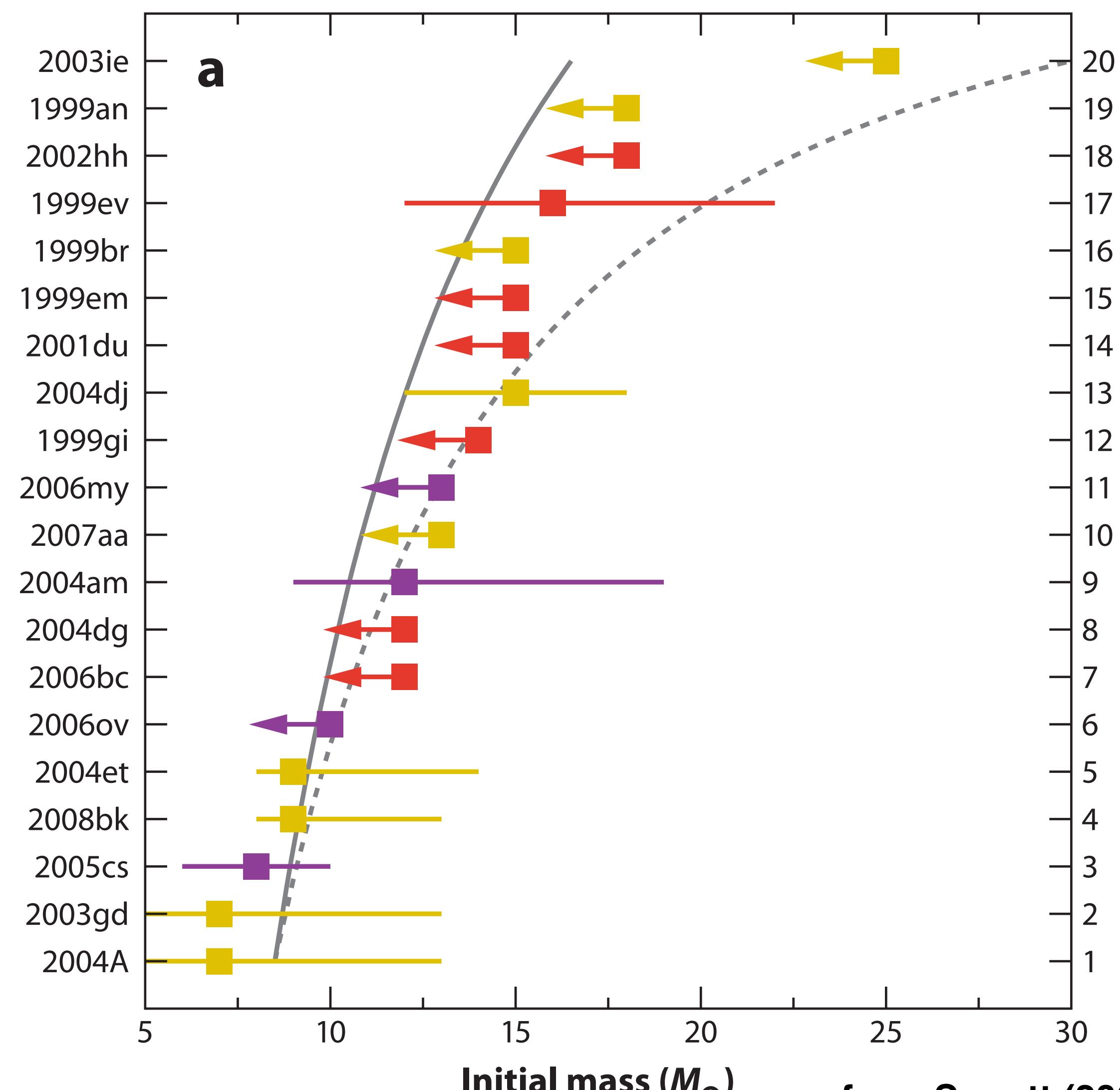
The End of Single Massive Stars (in theory)



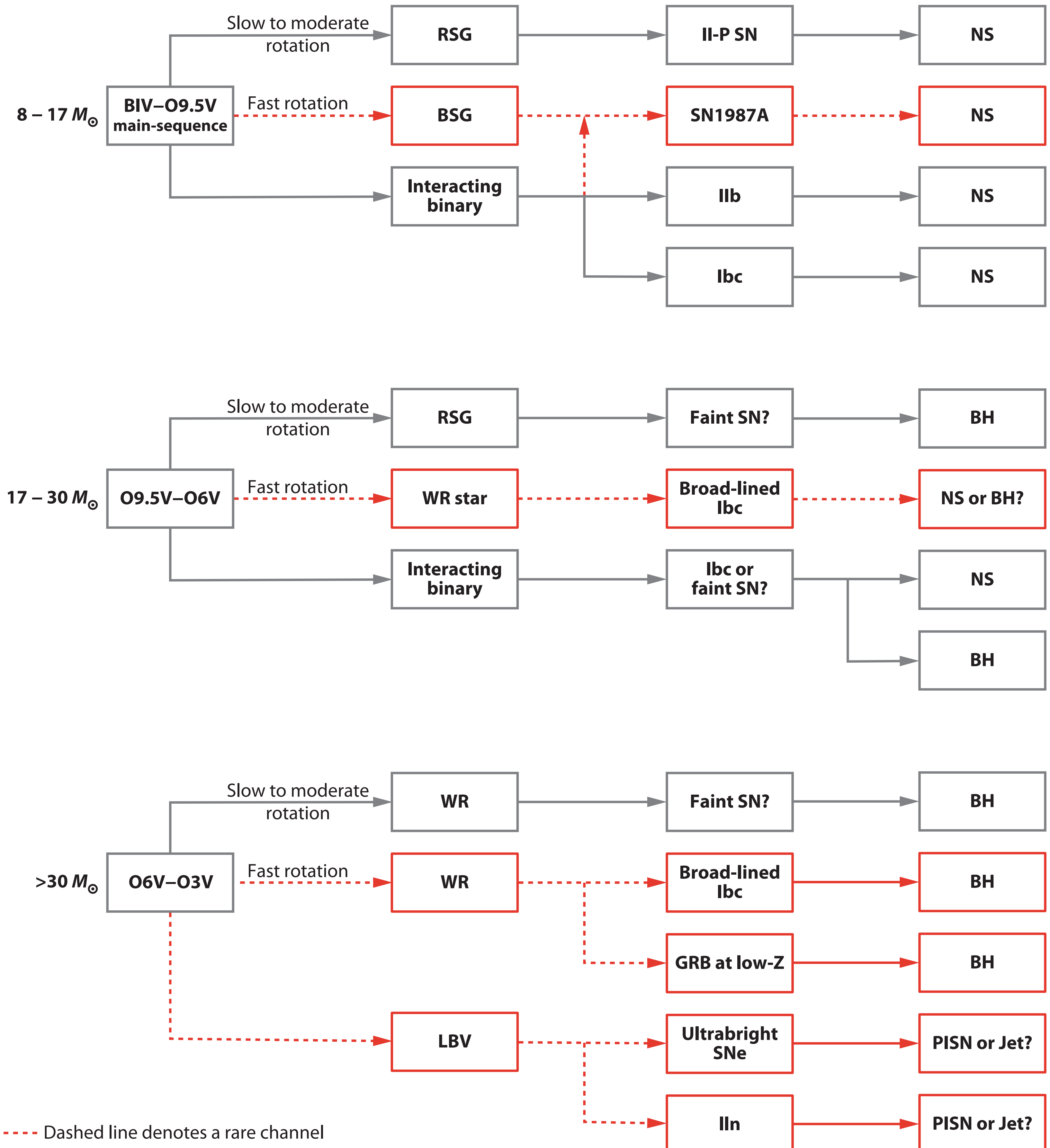
Heger et al. (2003)



SN 1987A in the Large Magellanic Cloud

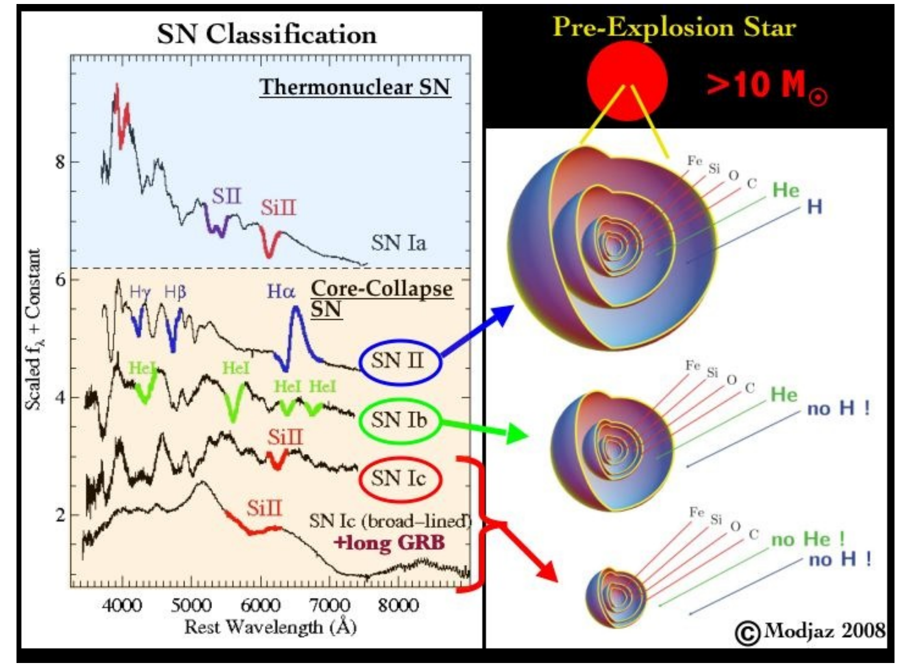


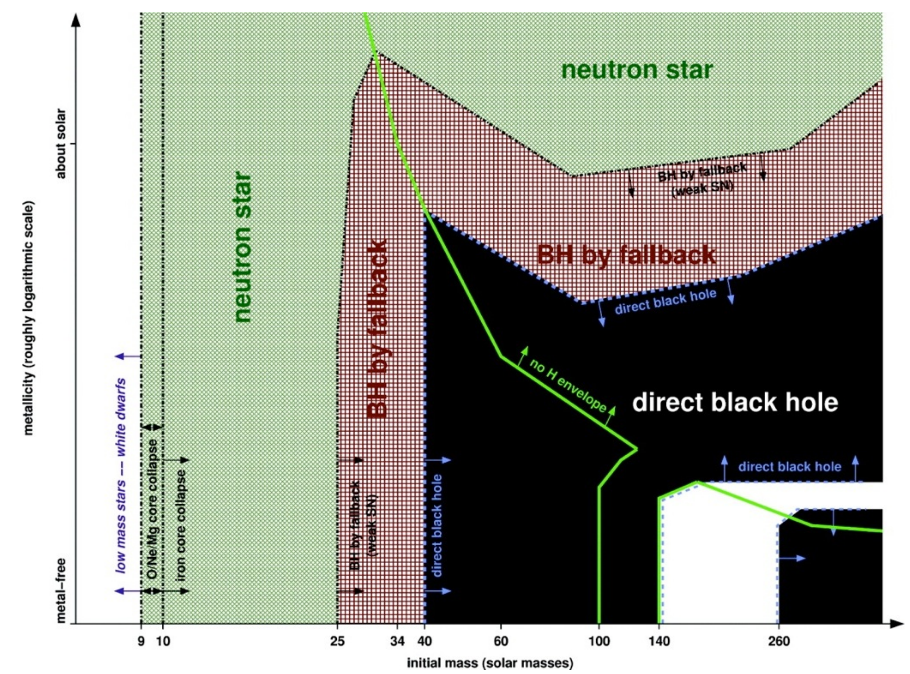
from Smartt (2009)

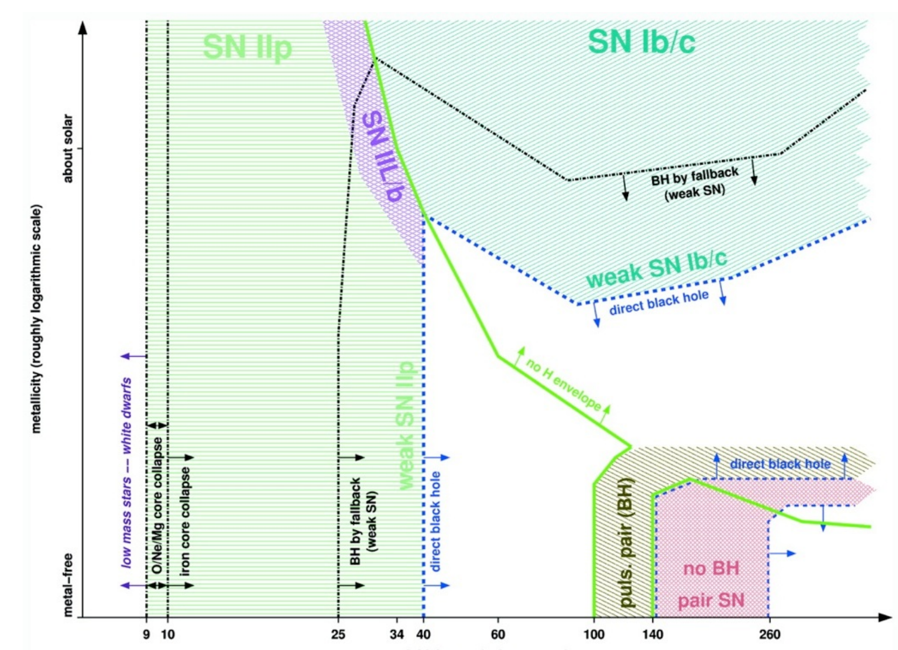


Dashed line denotes a rare channel

from Smartt (2009)







Massive Stars - high mass

The Conti scenario

Description that connects observations and theories to describe an evolutionary sequence for massive stars

$M_i / M_\odot$	Spectral types	Supernova

Massive Stars - high mass

The Conti scenario

Description that connects observations and theories to describe an evolutionary sequence for massive stars

$M_i / M_\odot$	Spectral types	Supernova
	Always Blue	
$\gtrsim 90$	: O – Of – WNL – (WNE) – WCL – WCE -	SN (Hypernova?)
60 - 90	: O – Of/WNL – LBV - WNL – WCL - WCE -	SN IIn ?
40 - 60	: O – BSG – LBV - WNL – (WNE) - WCL - WCE -	SN Ib
	WCL – WCE – WO -	SN Ic
limits uncertain		SNe uncertain
		(LBVs + IIn?)
	Blue – Red – Blue	
30 - 40	: O – BSG – RSG – WNE – WCE –	SN Ib
	Blue - Red	
25 – 30	: O - BSG – RSG – BLG –blue loop- RSG –	SNIIL
15 – 25	: O – RSG -	SNIIp
10 – 15	: O – RSG – blue loop Cepheid – RSG -	SNIIp

binaries??

?

?

?