PHY 7097 | Modern Astrophysics

Lecture III.

Stellar birth, life and death

Imre Bartos
Department of Physics

UNIVERSITY of FLORIDA

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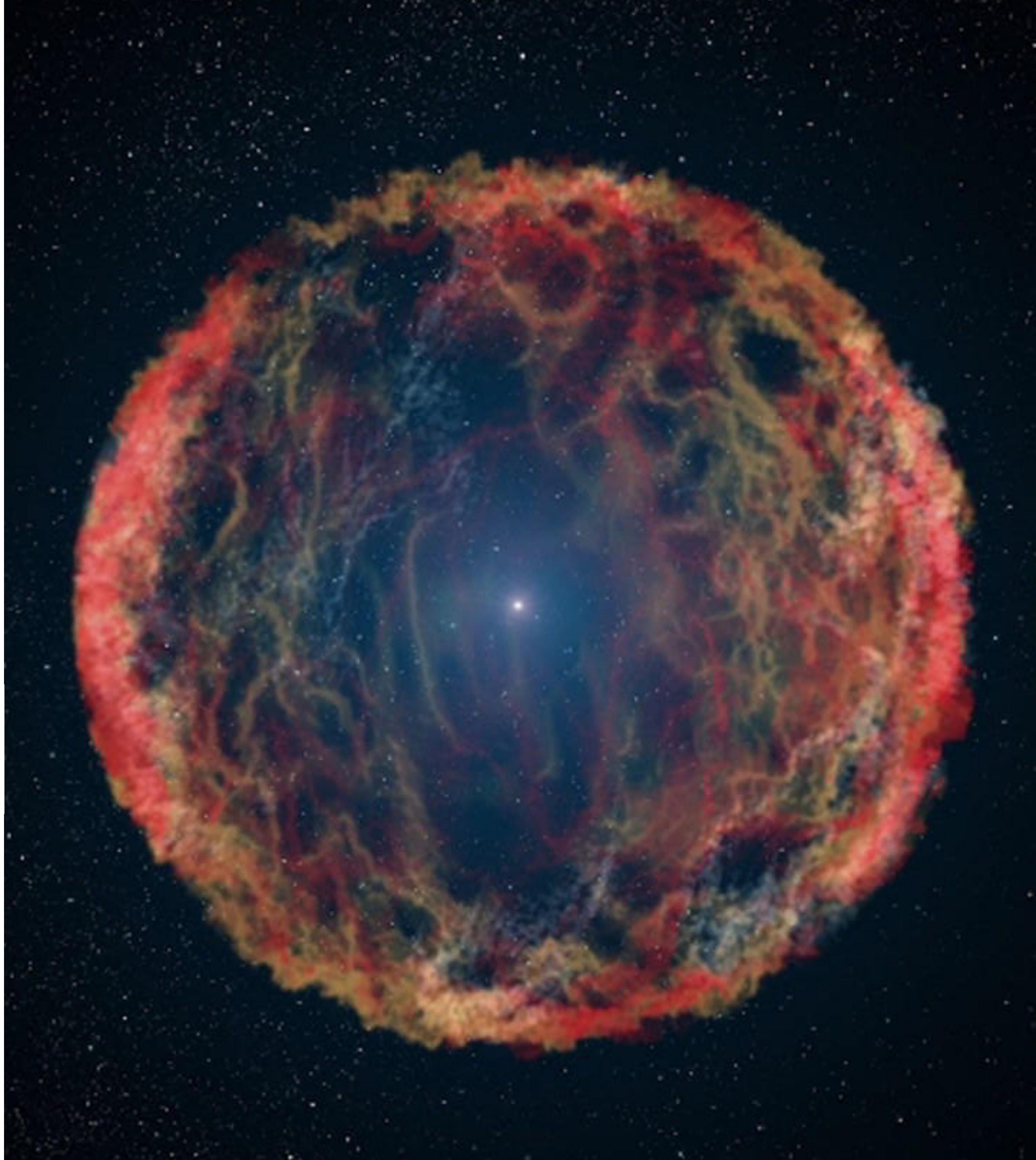


Star formation

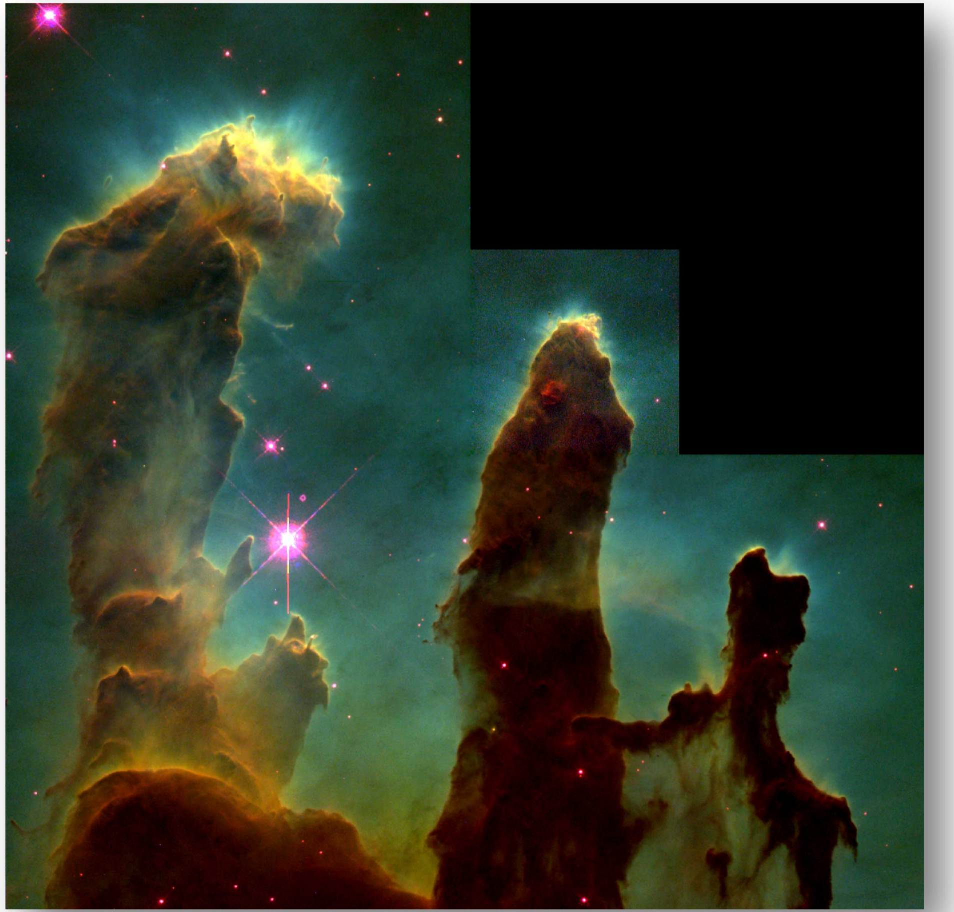
<u>Origin:</u>
- Molecular clouds
- Interstellar gas (MW: 1 particles / cm^3)

Cloud collapses (gravity) and heats up (work)

<u>Can be triggered:</u>
- Galaxy collisions
- Supernova shocks
- Milky Way – arms have higher SF

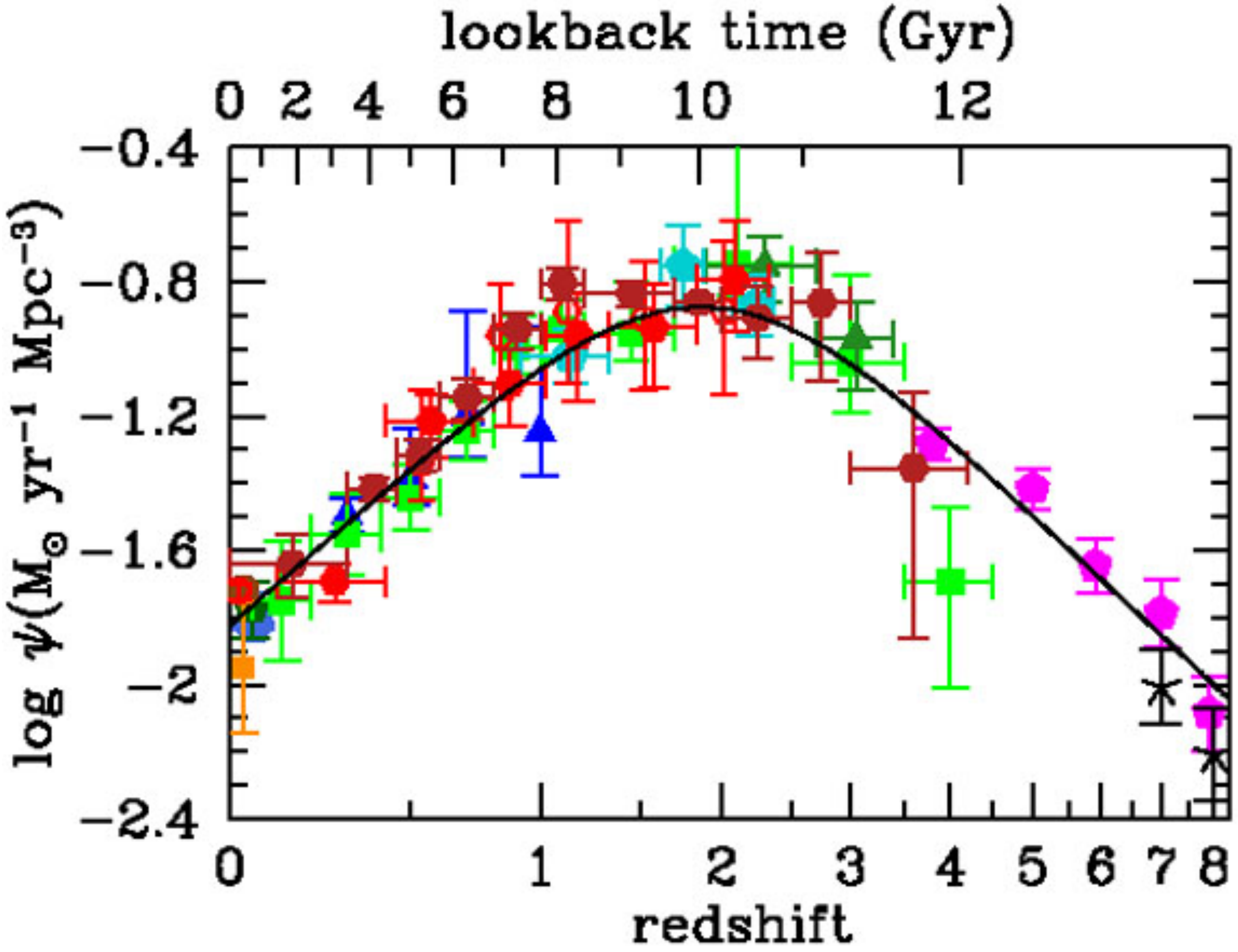
Accreting Supermassive BHs drive relativistic jets that can limit SF.

Massive stars form in binaries (angular momentum)



HST image of Eagle Nebula.
Credit: NASA, Jeff Hester, and Paul Scowen (Arizona State U.)

Cosmic star formation rate



Non-uniform, higher in the past.

Peaks around z~2

Needs to be taken into account when studying star formation / supernovae / BH formation / etc.

Depends on many things. E.g., less gas is available today.

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} \; M_\odot \, \mathrm{year}^{-1} \, \mathrm{Mpc}^{-3}$$

Madau & Dickinson 2014 (1403.0007)

Initial mass function

Salpeter function (1955):

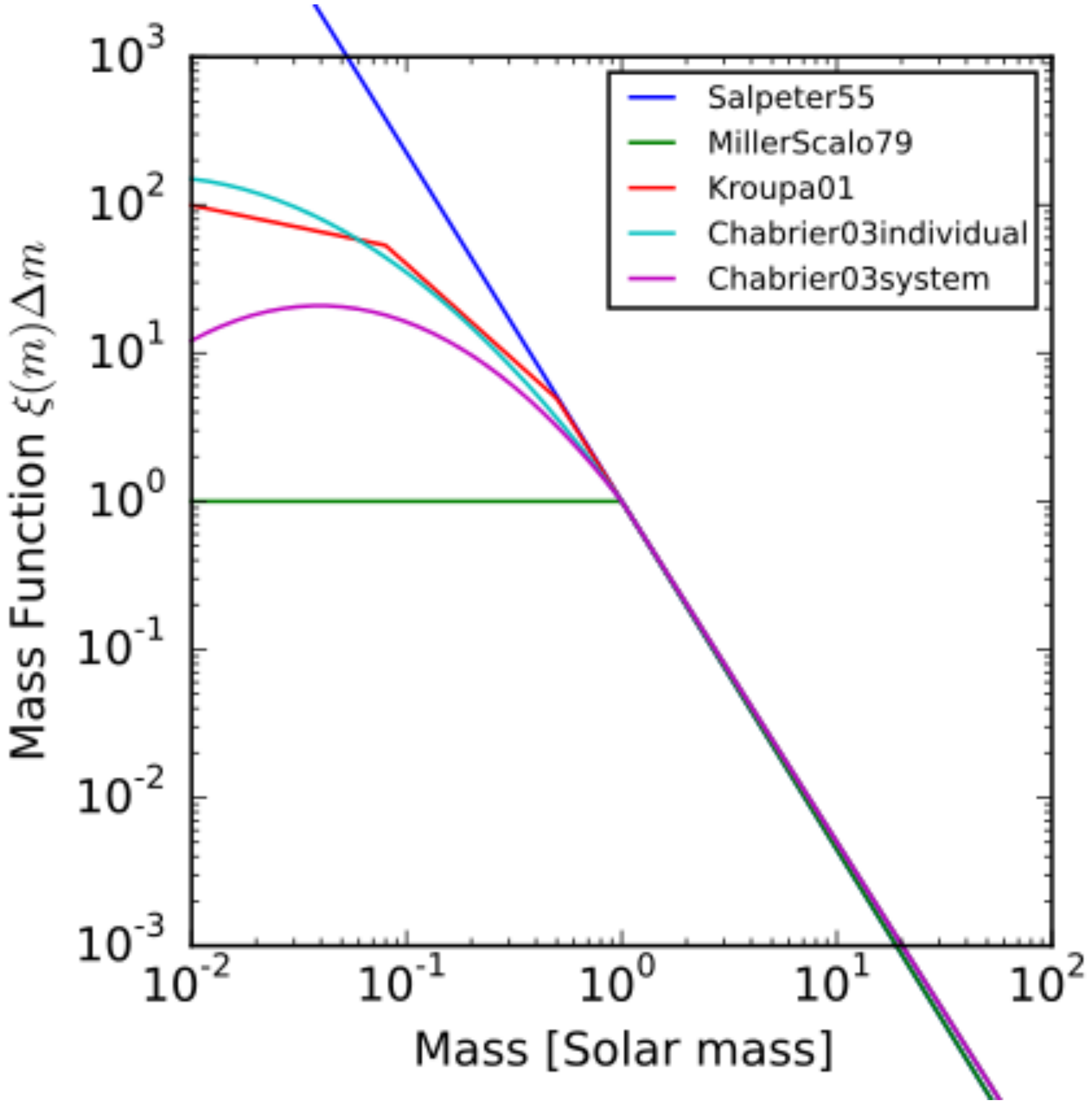
$$\xi(m)\Delta m = \xi_0 \left(\frac{m}{M_{\rm sun}}\right)^{-2.35} \left(\frac{\Delta m}{M_{\rm sun}}\right)$$

only applicable ~ above stellar mass

Substellar population is uncertain (see varying models).

Will be important for the distribution of stellar remnants (WD, NS, BH).

Will be important for the BH mass distribution (uncertain).



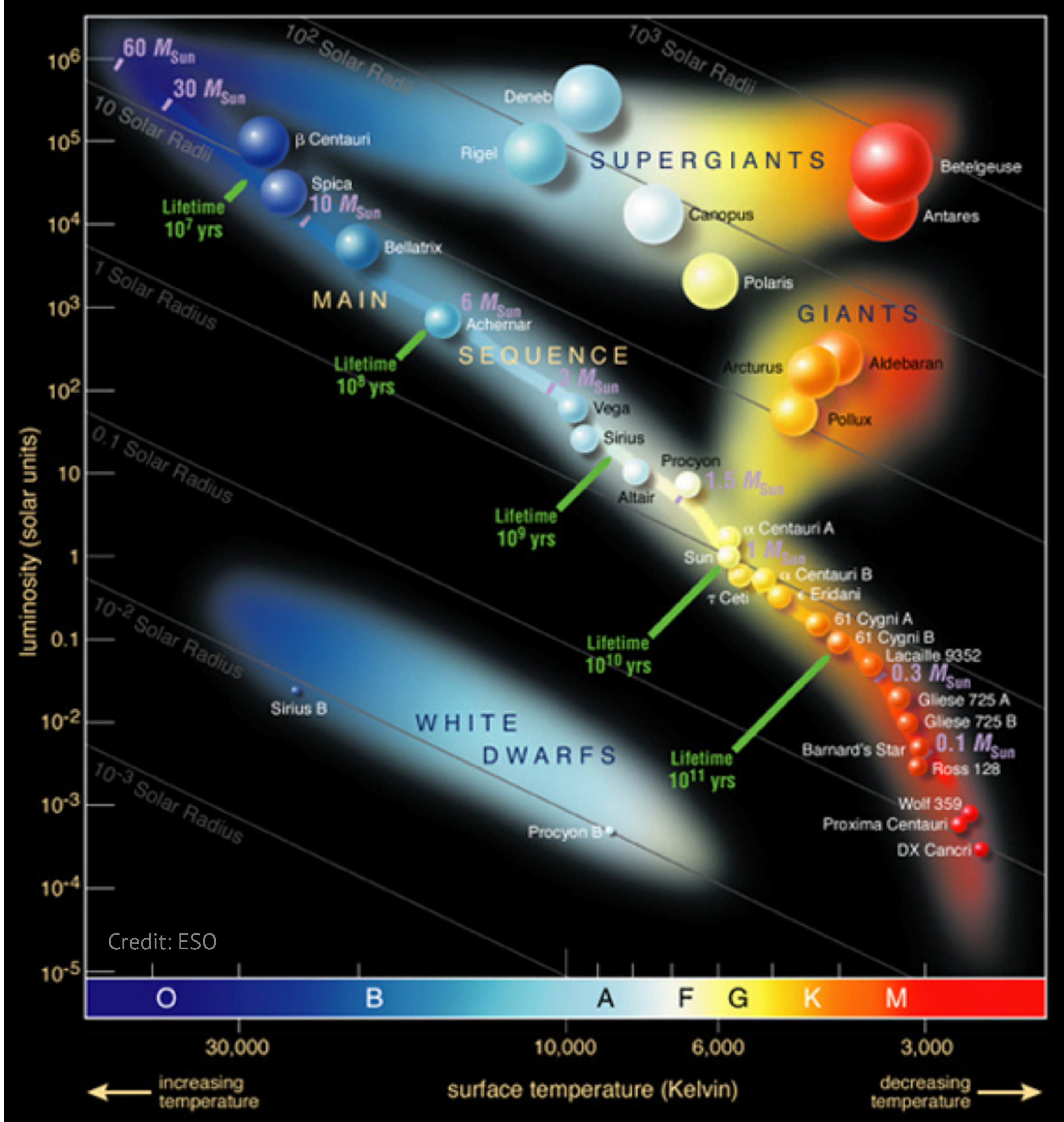
Stellar Evolution

Not everyone will be a star…
Below 0.08 $M_\odot$, pressure is too small for fusion.
→ Brown dwarfs

Stars are ~70% H, 30% He, and a trace of "metal."
→ Hydrogen fusion.

Fusion produces heat that halts gravitational collapse.
→ Hydrostatic equilibrium.

Hertzsprung–Russell diagram
Stars stay on the same point for most of their lives.



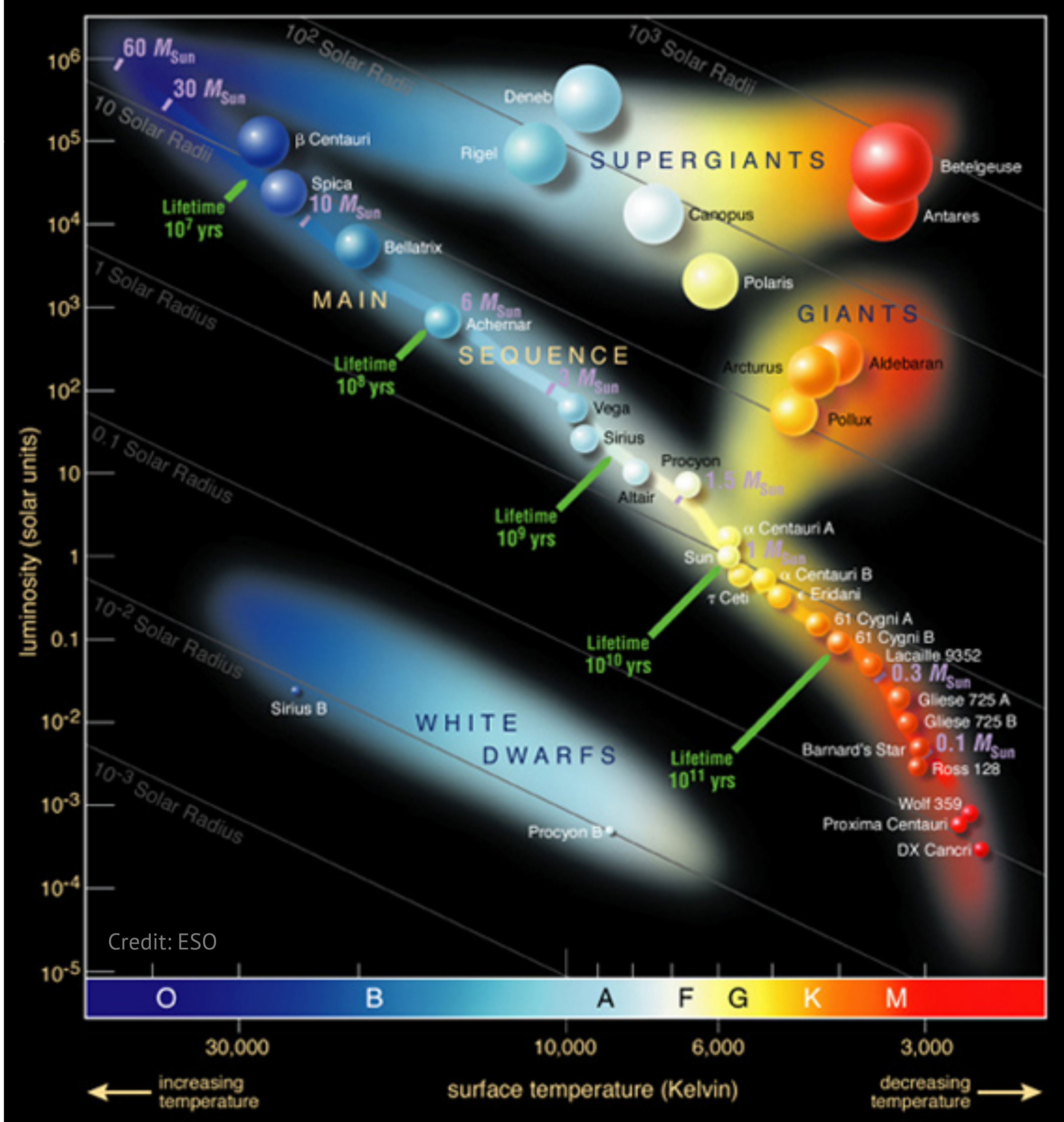
When H starts running out stars move off of the main sequence.

Stellar Evolution II.

Massive stars live fast and die young.

Mass (solar masses)	Time (years)	Spectral type
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000s billions	M7

http://www.worldscientific.com/worldscibooks/10.1142/8573

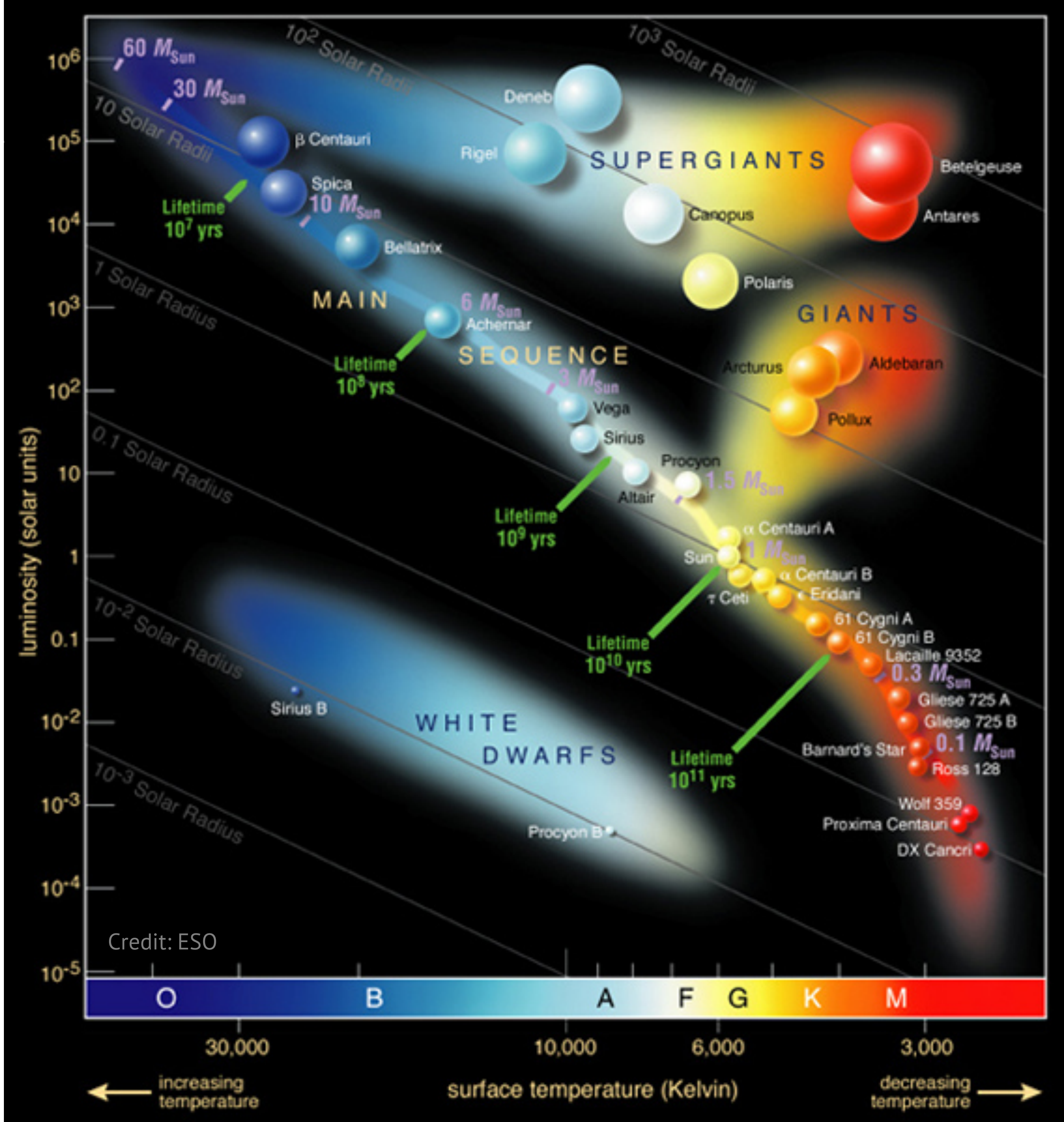


Stellar Evolution III.

White dwarfs – low mass (< 8-10 $M_{\odot}$) stars run out of fuel → no thermal pressure → shrink.

Giants – e.g. helium burning introduces different equilibrium: increased temperature → stars grow in size and redden.

Supergiants – from the heaviest stars. There are also hypergiants.



Stellar winds

Radiation pressure blows off gas/dust from the outer layers of stars.

Metallicity: fraction of elements heavier than He.
Typically defined in comparison to Solar metallicity.

More metallicity → more stellar winds.

Higher stellar mass → more wind.

Winds will limit the end-of-life mass of massive stars, especially for high-metallicity stars.

Wolf-Rayet stars: massive stars that lost ~all of their hydrogen envelope to winds.

Population III (Pop III) stars: extremely massive stars only in the early universe (first stars), with no metals.

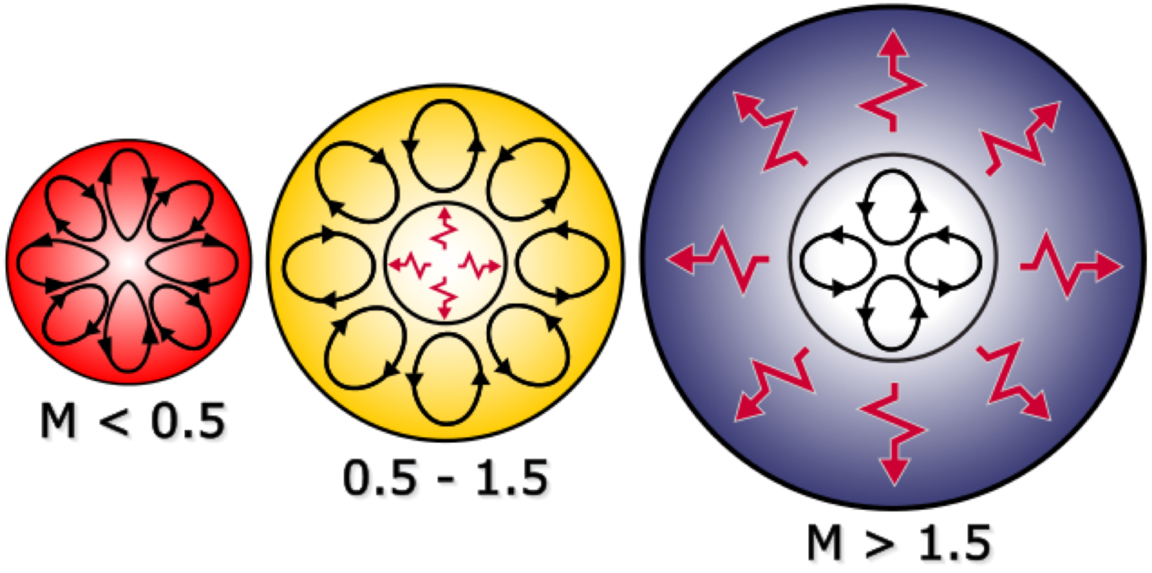
Credit: ESA/Hubble & NASA Acknowledgement: M. Novak

Chemical mixing

There can be convection within the star due to temperature difference / fast rotation / etc.

e.g. in a binaries can align orbit and spin → fast spinning → chemical mixing.

Can affect what is being fused, giant phase as well as stellar winds.



Death

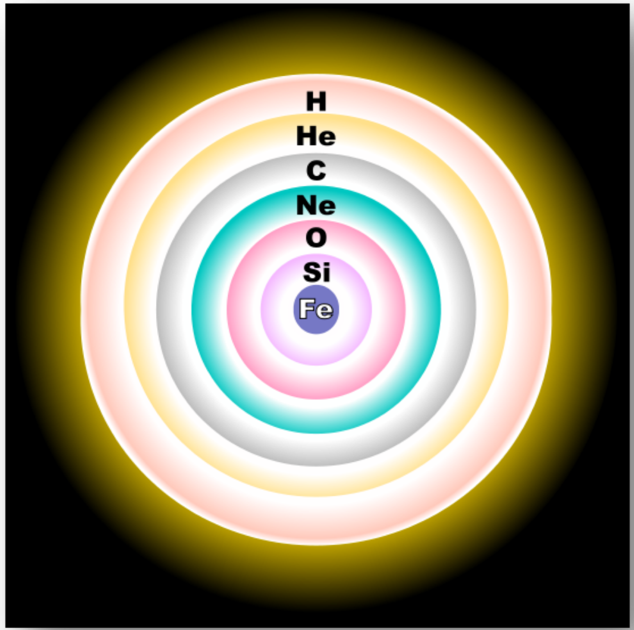
Low mass stars – runs out of fuel --> radiation pressure reduced → shrinks → white dwarf

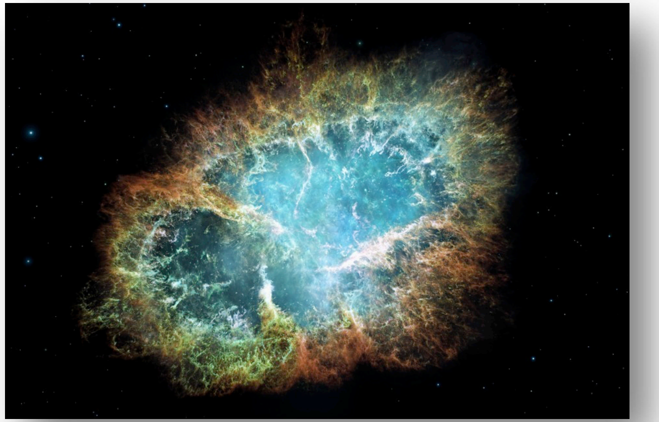
High mass stars – fusion down to iron → iron core → gravitational core collapse → supernova / collapsar

Very high mass stars – high pressure → gamma rays energetic for electron+positron pair production → reduced pressure → gravitational collapse → pair-instability supernova

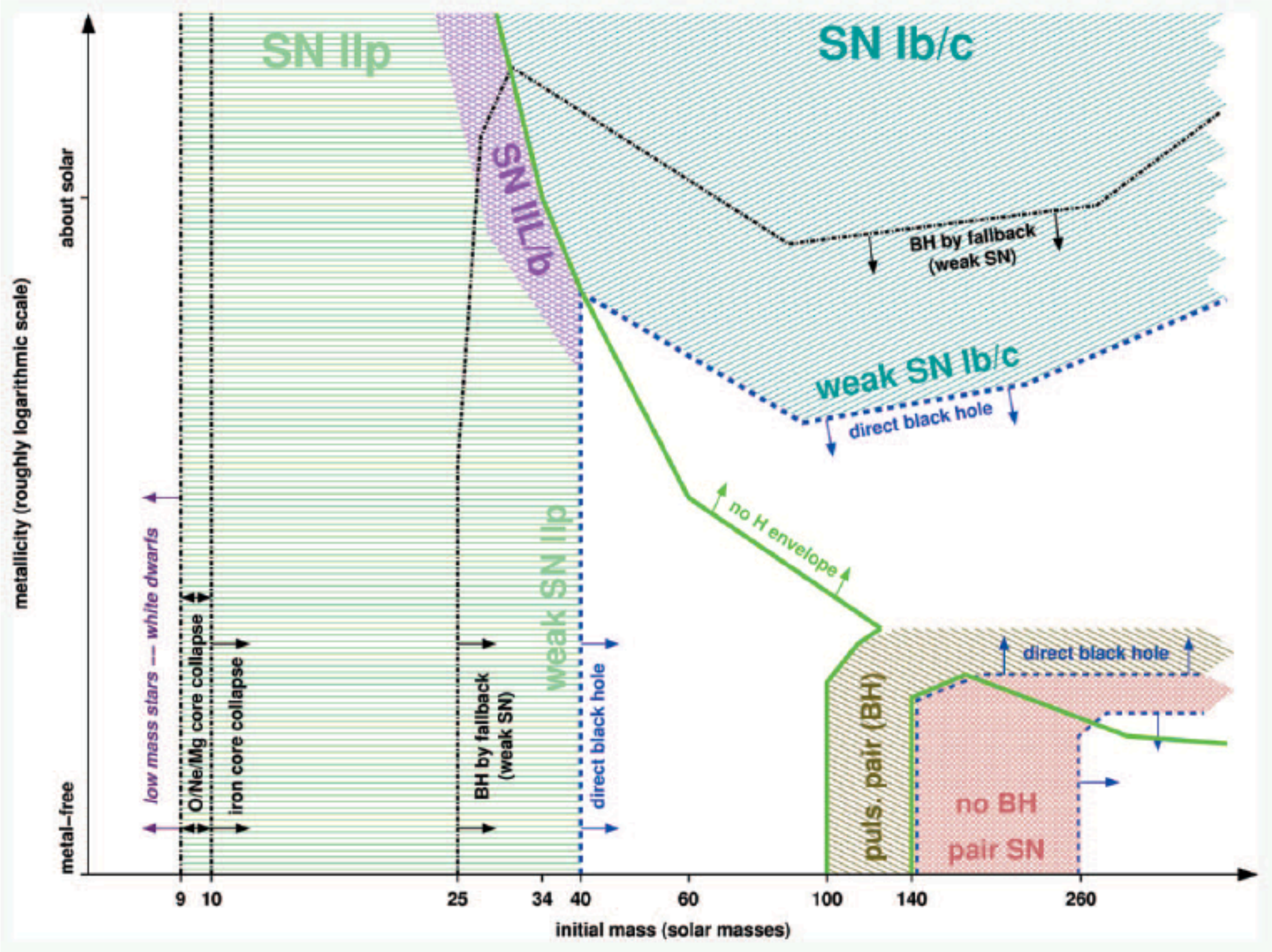
Very high mass stars – high pressure → gamma rays energetic for photodisintegration→ reduced pressure → gravitational collapse → black hole

Infalling matter – needs to get rid of angular momentum → relativistic jet



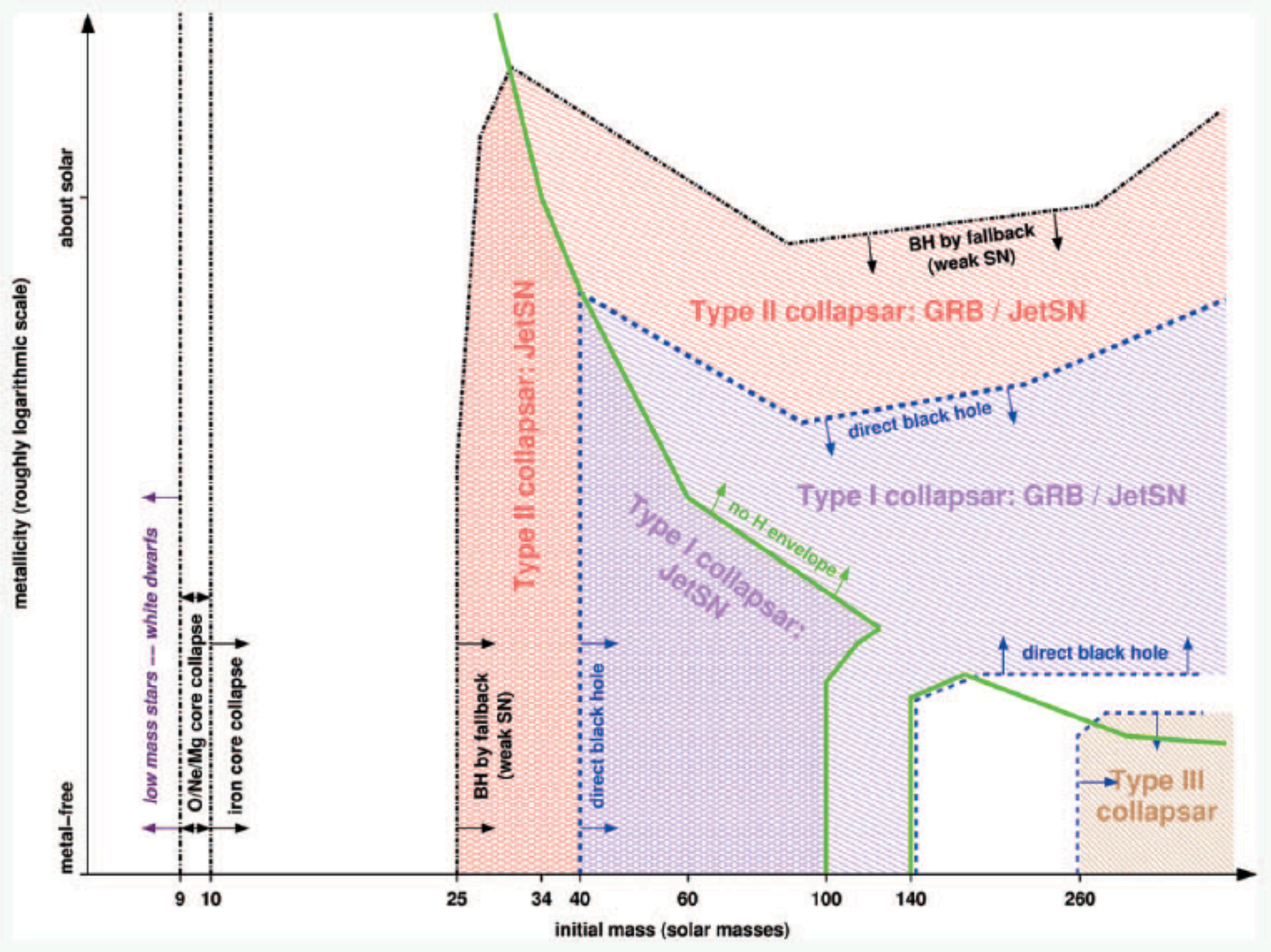


Supernova explosion



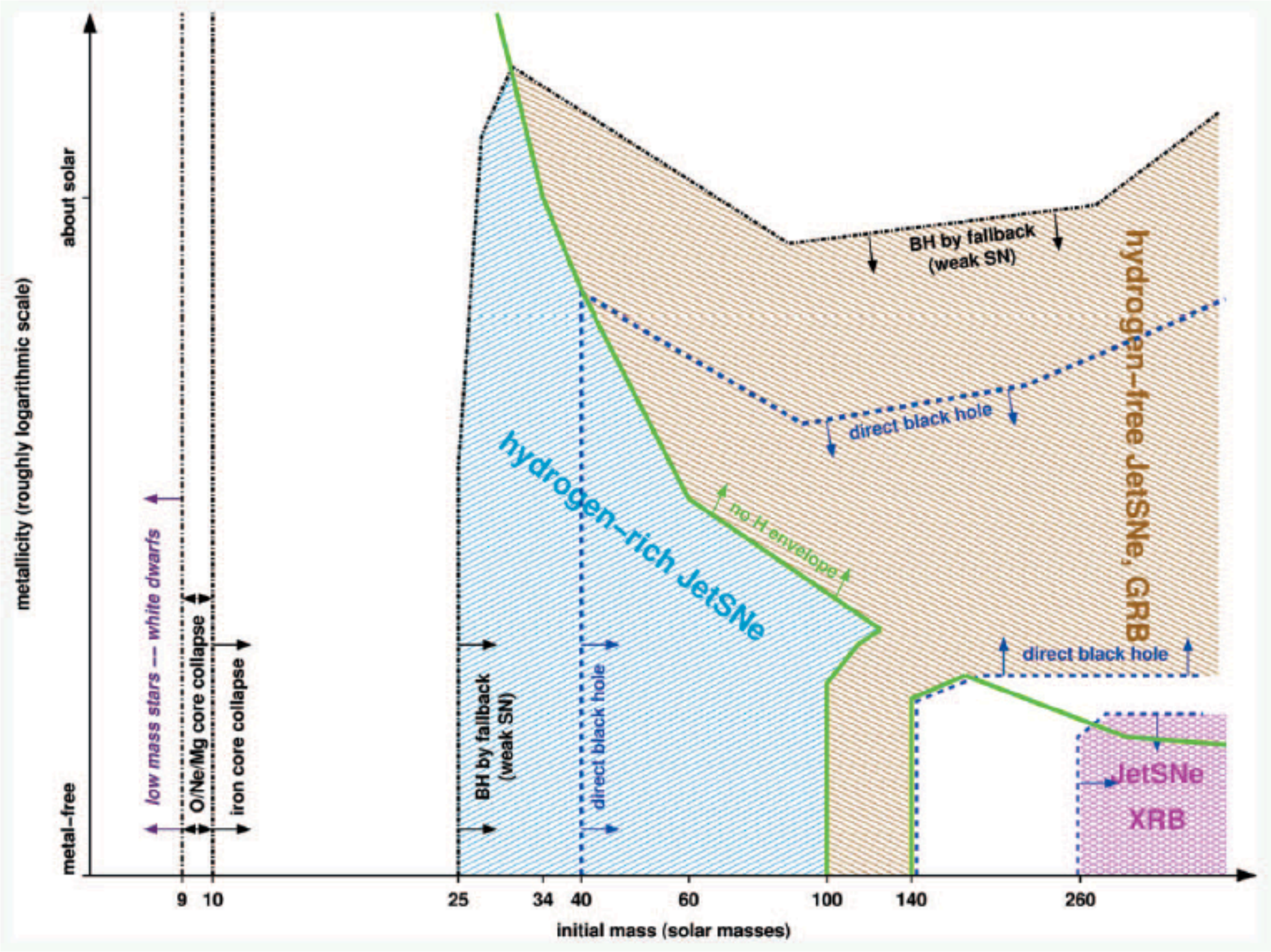
Heger+ ApJ 2003

Collapsars



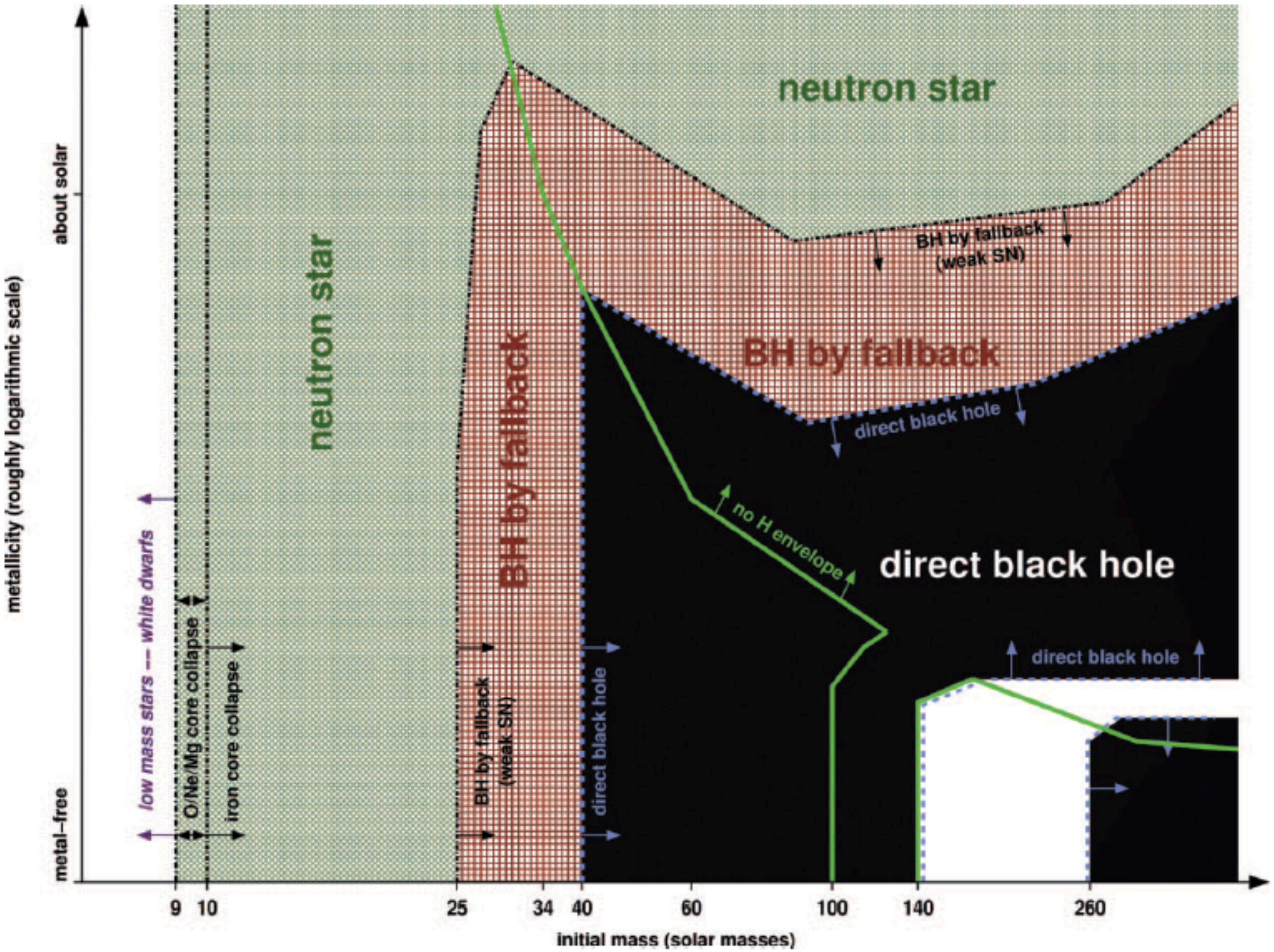
Heger+ ApJ 2003

Beamed outflow (jet)



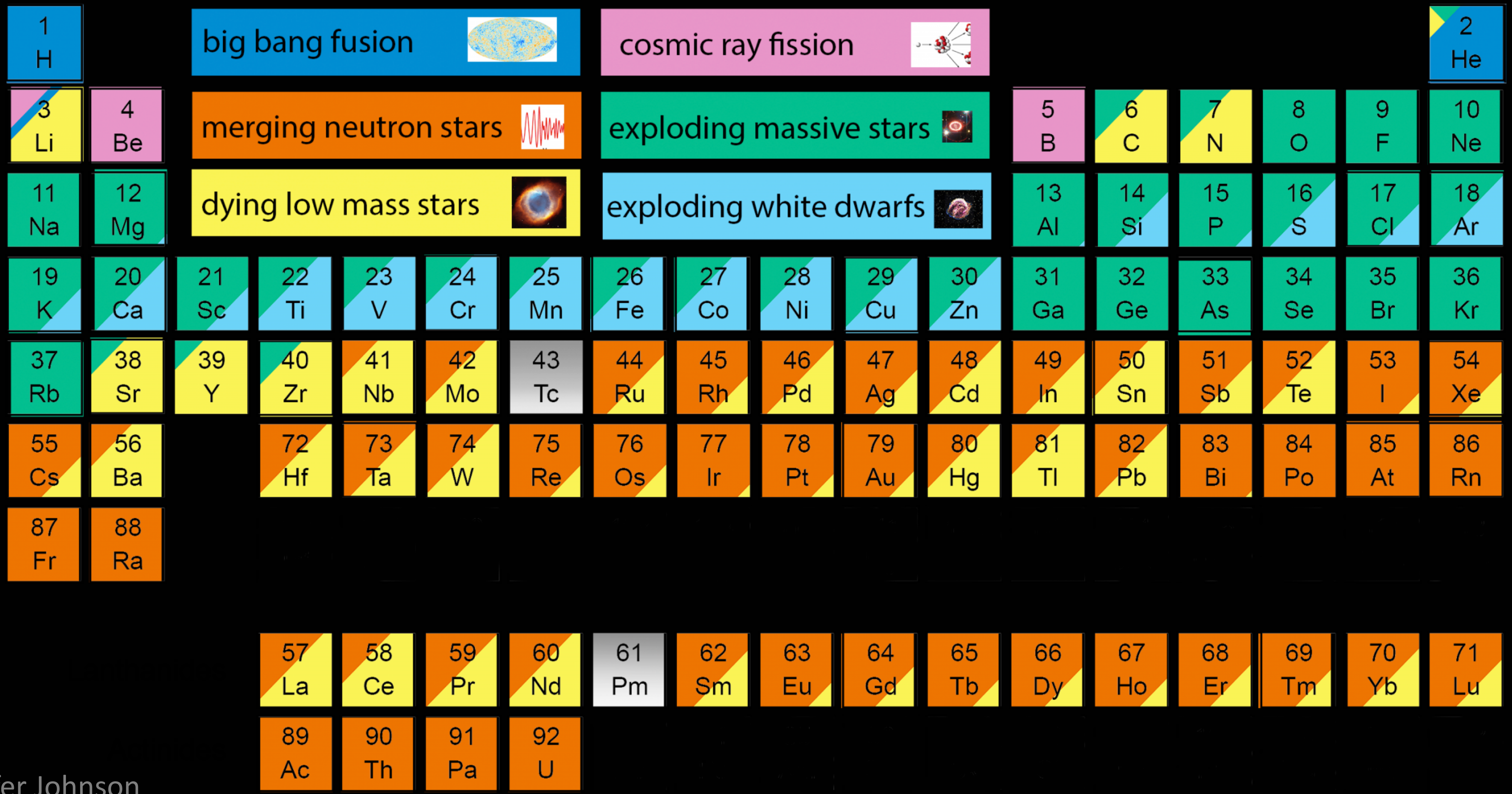
Heger+ ApJ 2003

Remnant



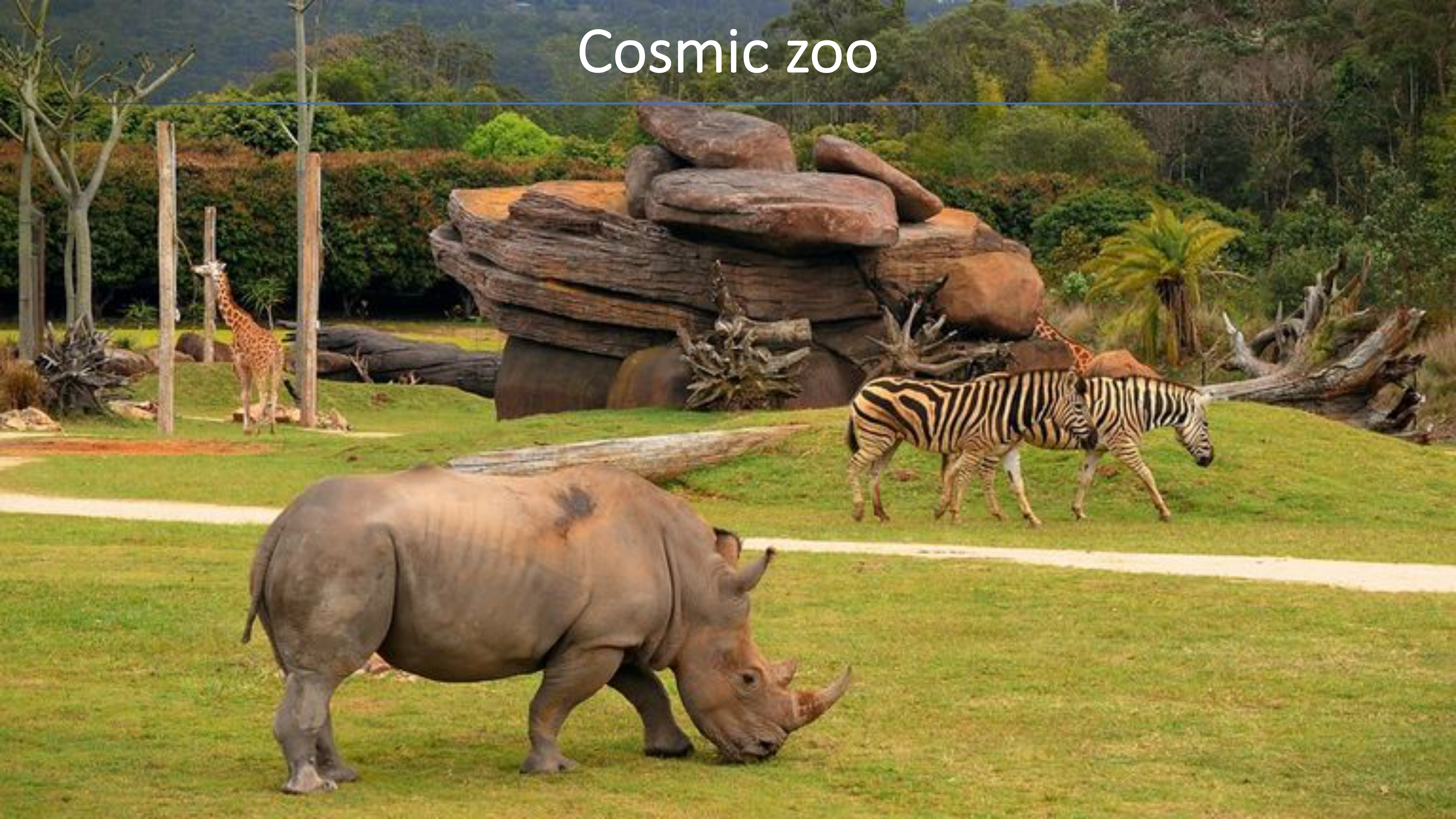
Heger+ ApJ 2003

The Origin of the Solar System Elements

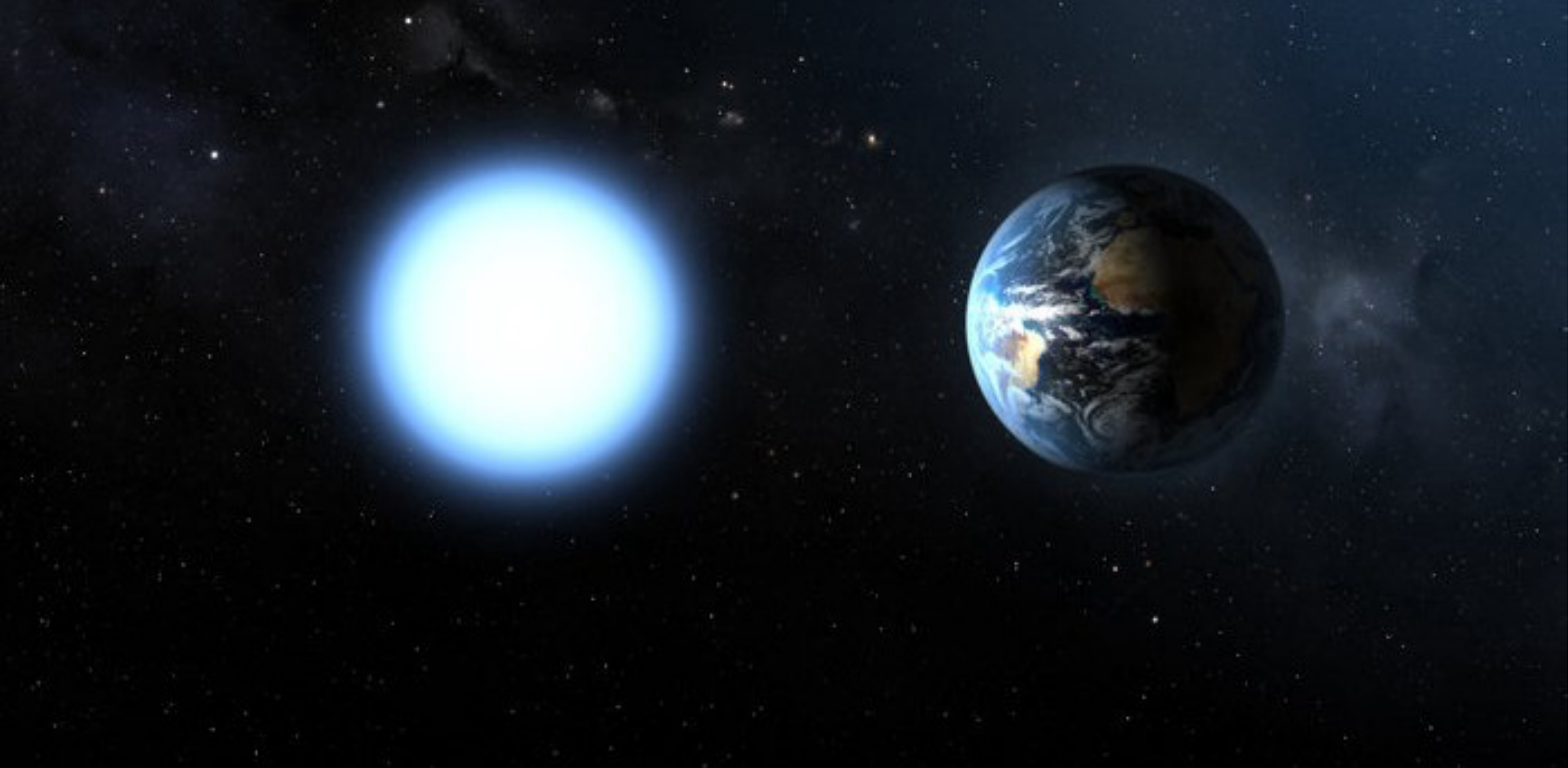


Jennifer Johnson

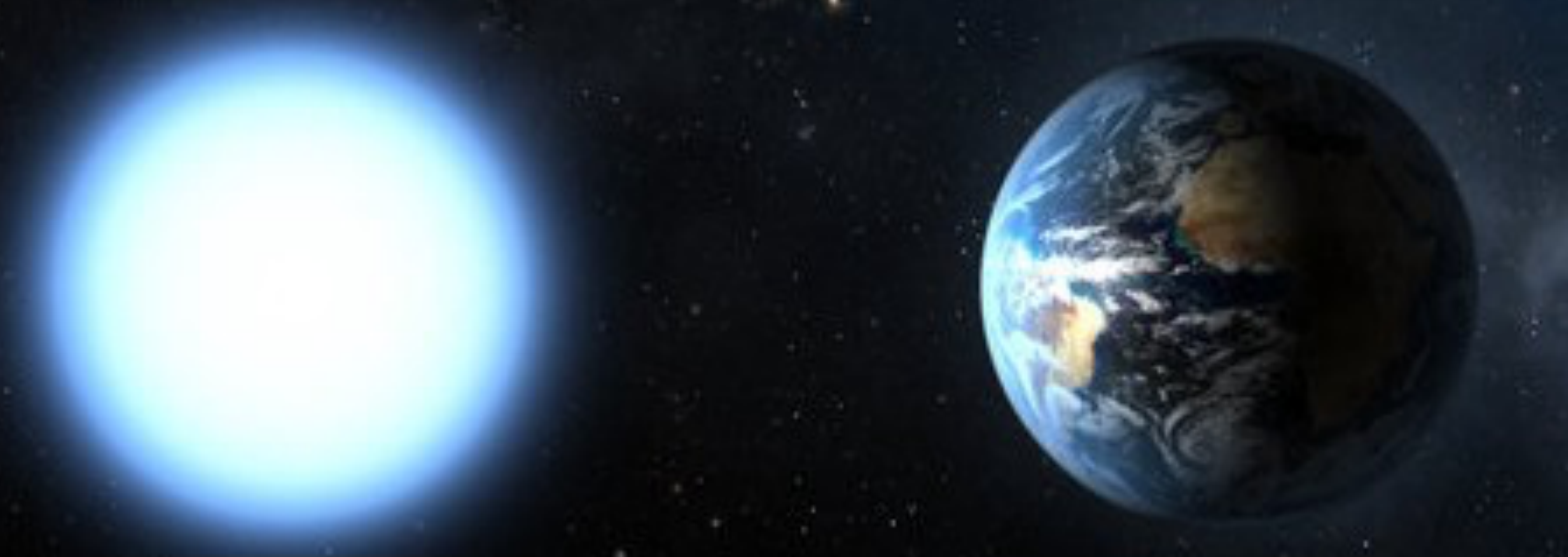
Cosmic zoo



White dwarfs



White dwarfs



$$T = 2\pi\sqrt{\frac{a^3}{G\left(M_1 + M_2\right)}}$$

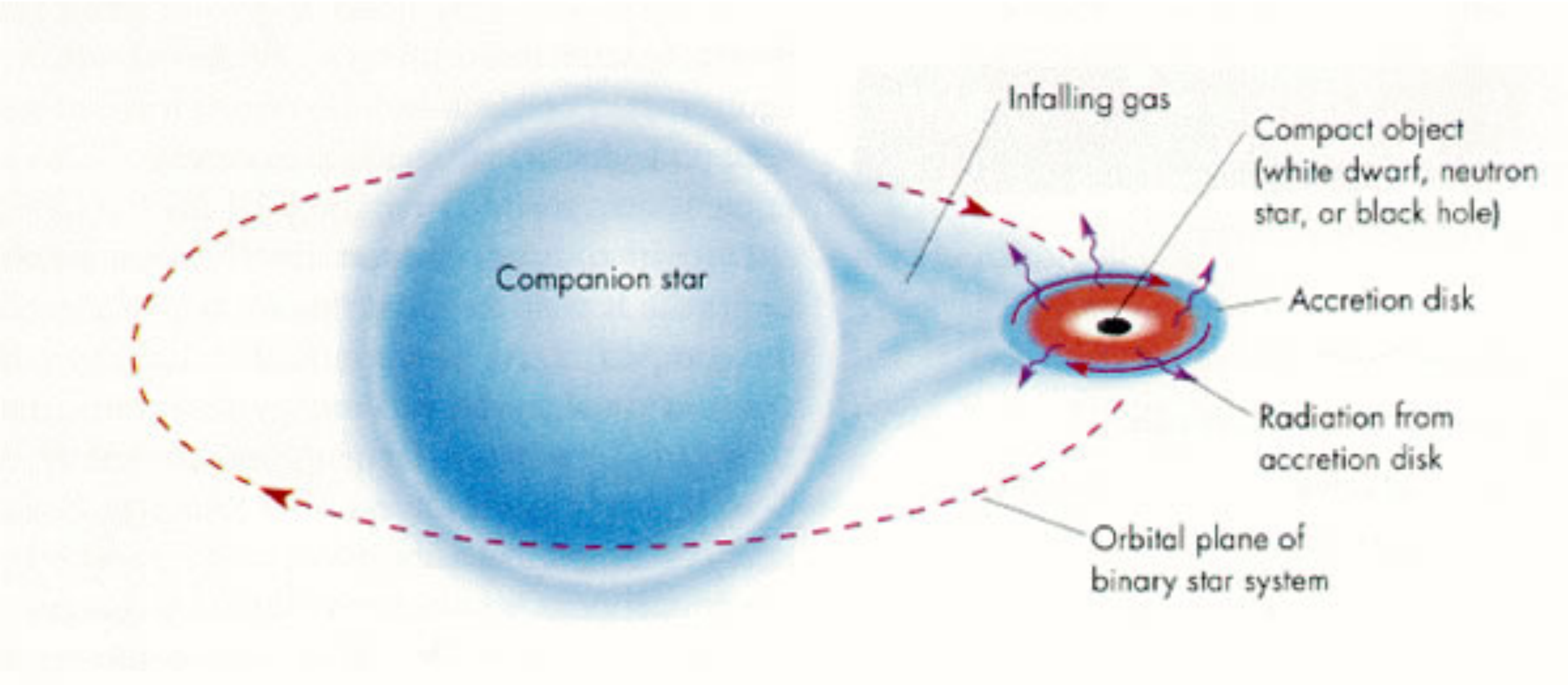
Classification

Absorption line and light curve

<table>
<tr><td rowspan="3">Type I
No hydrogen</td><td colspan="3">Type Ia
Presents a singly ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light</td><td>Thermal runaway</td></tr>
<tr><td rowspan="2">Type Ib/c
Weak or no silicon absorption feature</td><td colspan="2">Type Ib
Shows a non-ionized helium (He I) line at 587.6 nm</td><td rowspan="6">Core collapse</td></tr>
<tr><td colspan="2">Type Ic
Weak or no helium</td></tr>
<tr><td rowspan="4">Type II
Shows hydrogen</td><td rowspan="3">Type II-P/L/N
Type II spectrum throughout</td><td rowspan="2">Type II-P/L
No narrow lines</td><td>Type II-P
Reaches a "plateau" in its light curve</td></tr>
<tr><td>Type II-L
Displays a "linear" decrease in its light curve (linear in magnitude versus time).[47]</td></tr>
<tr><td colspan="2">Type IIn
Some narrow lines</td></tr>
<tr><td colspan="3">Type IIb
Spectrum changes to become like Type Ib</td></tr>
</table>

https://en.wikipedia.org/wiki/Supernova

Novae



http://astro.hopkinsschools.org

Core collapse supernovae

Most relevant:
Iron-core collapse

When iron core reaches Chandrasekhar mass (1.4 Msun) when it overcomes electron degeneracy

Typical energy released: 10^53 erg

Can we estimate this?

99% is released as neutrinos

What is the neutrino flux at Earth?

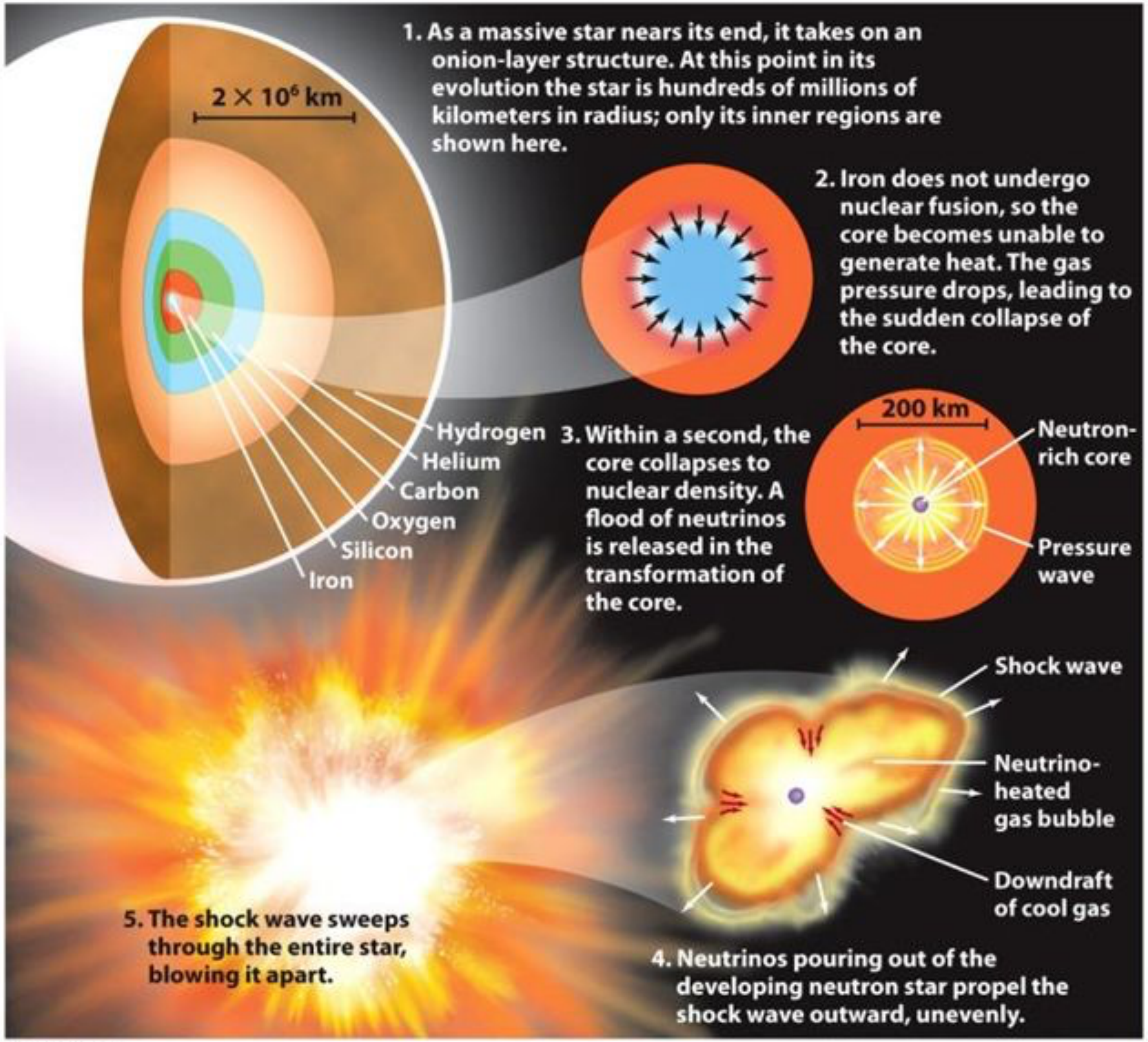


Figure 20-14
Universe, Tenth Edition
Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006

SN 1987A

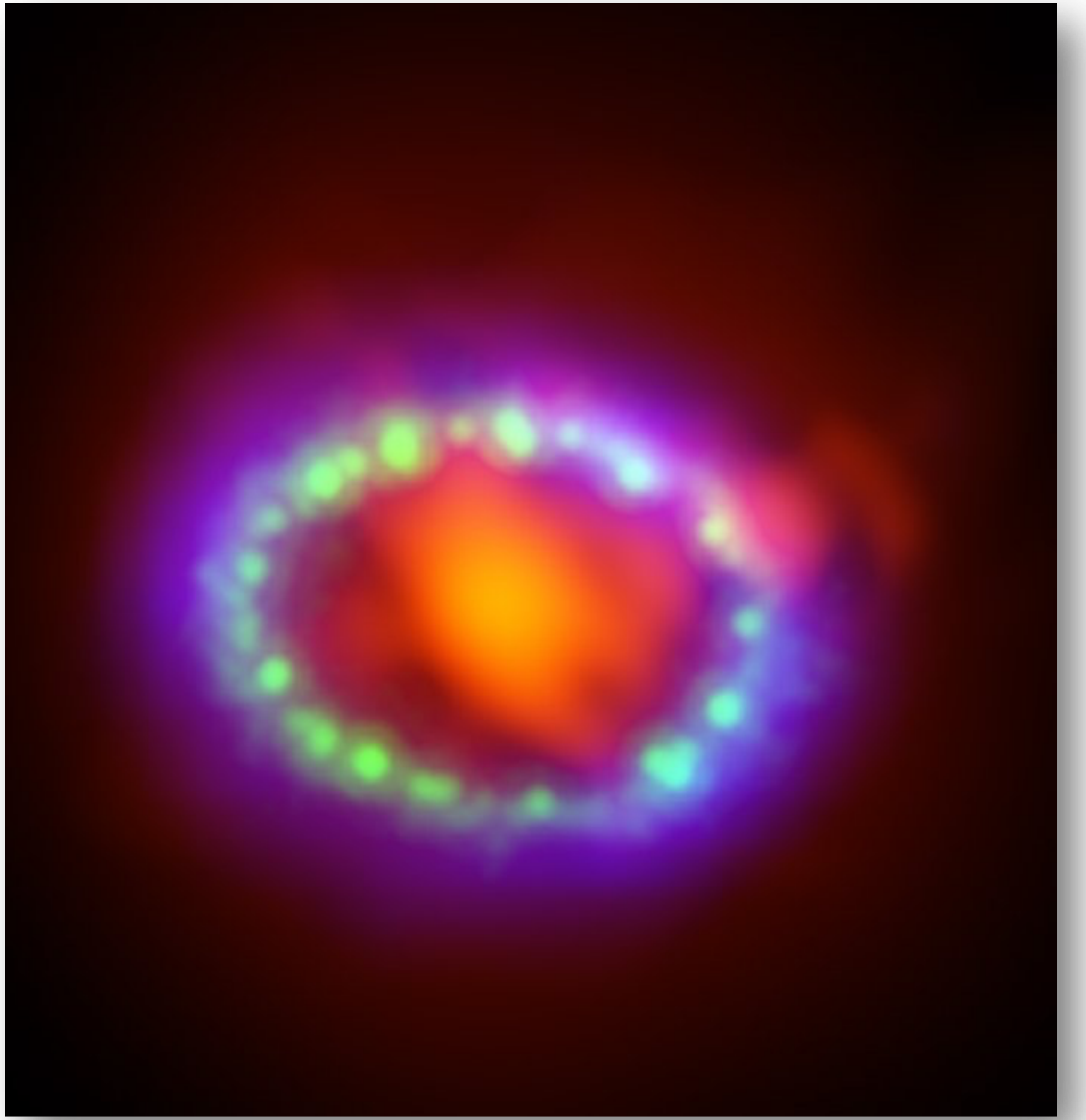
In Large Magellanic Cloud at ~50 kpc

Progenitor star: blue supergiant

Visible to the naked eye from the Southern hemisphere

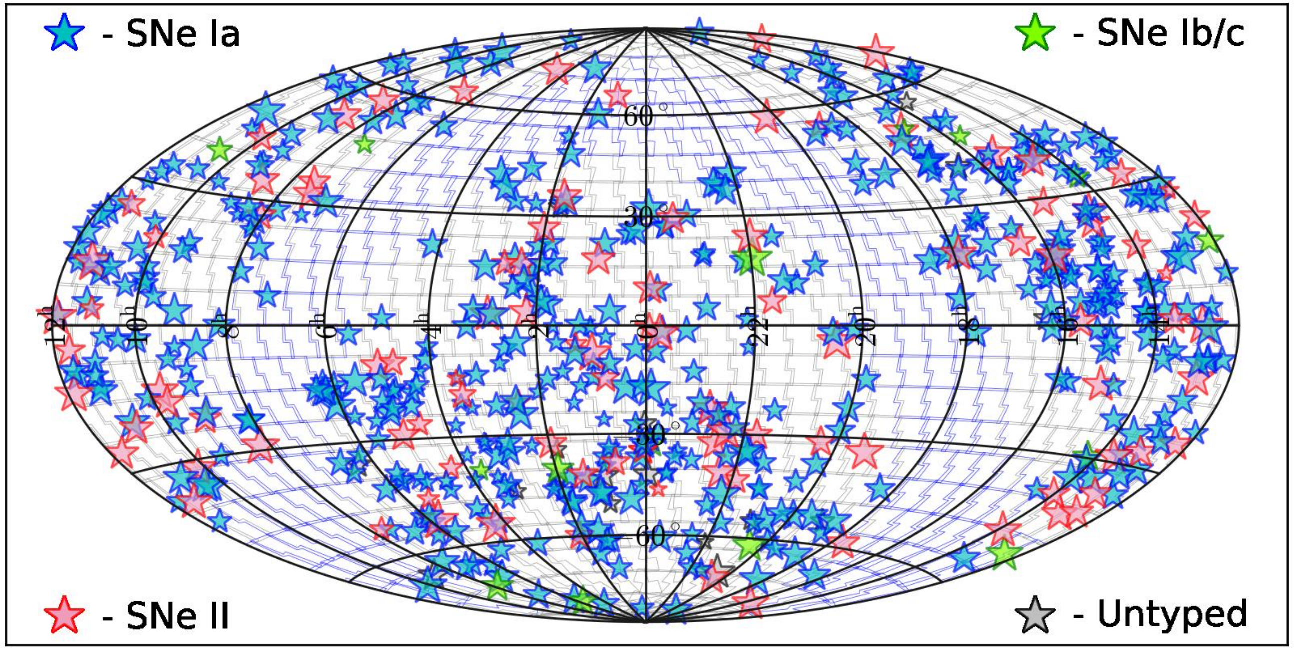
Detection of 25 neutrinos
2-3 hours before the first light was detected

No NS remnant has been observed



Observations

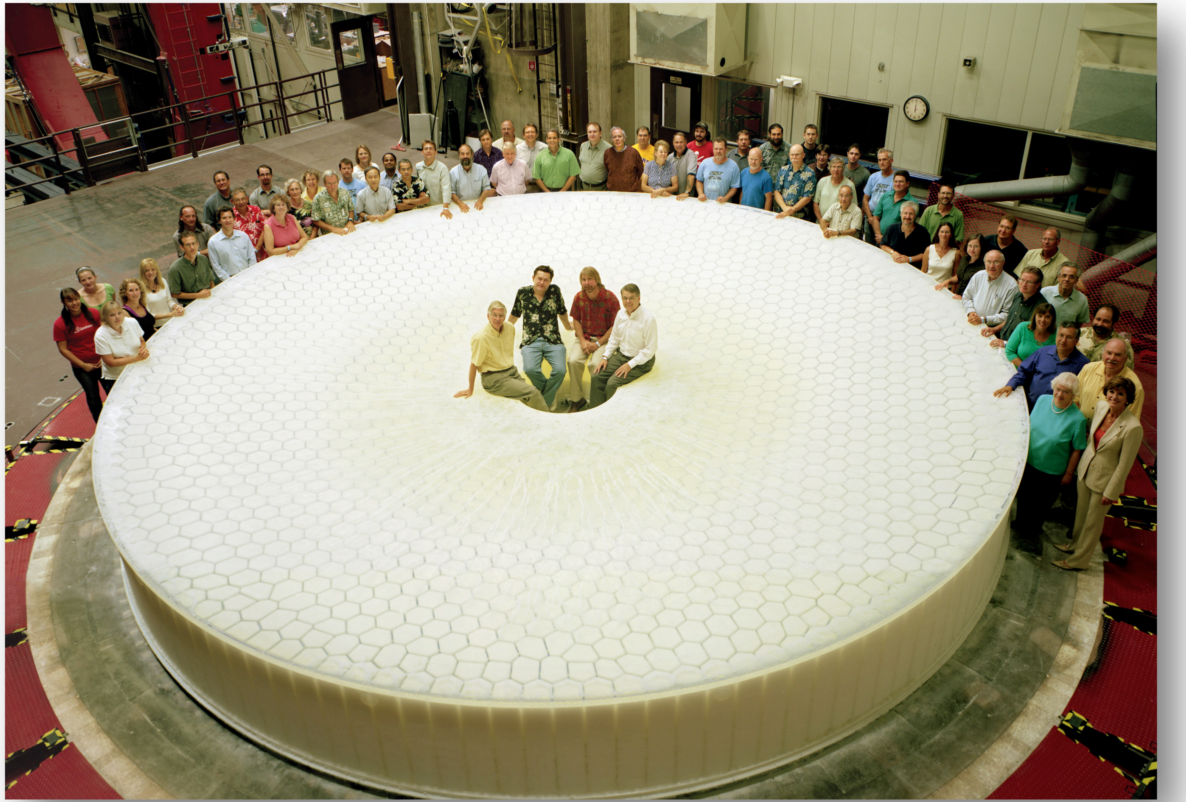
ASAS-SN

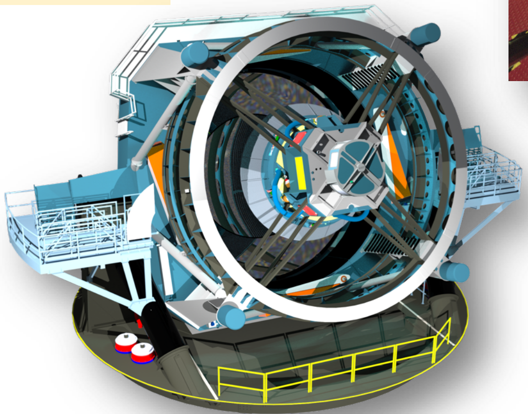


Multiple, very small telescopes that scan the whole sky every night.

Observations

Zwicky Transient Facility (ZTF)
Regular scans of the sky, rapid ToO response





Large Synoptic Survey Telescope (LSST, 2022)
Regular scans of the sky, very high sensitivity (9m)

Detections

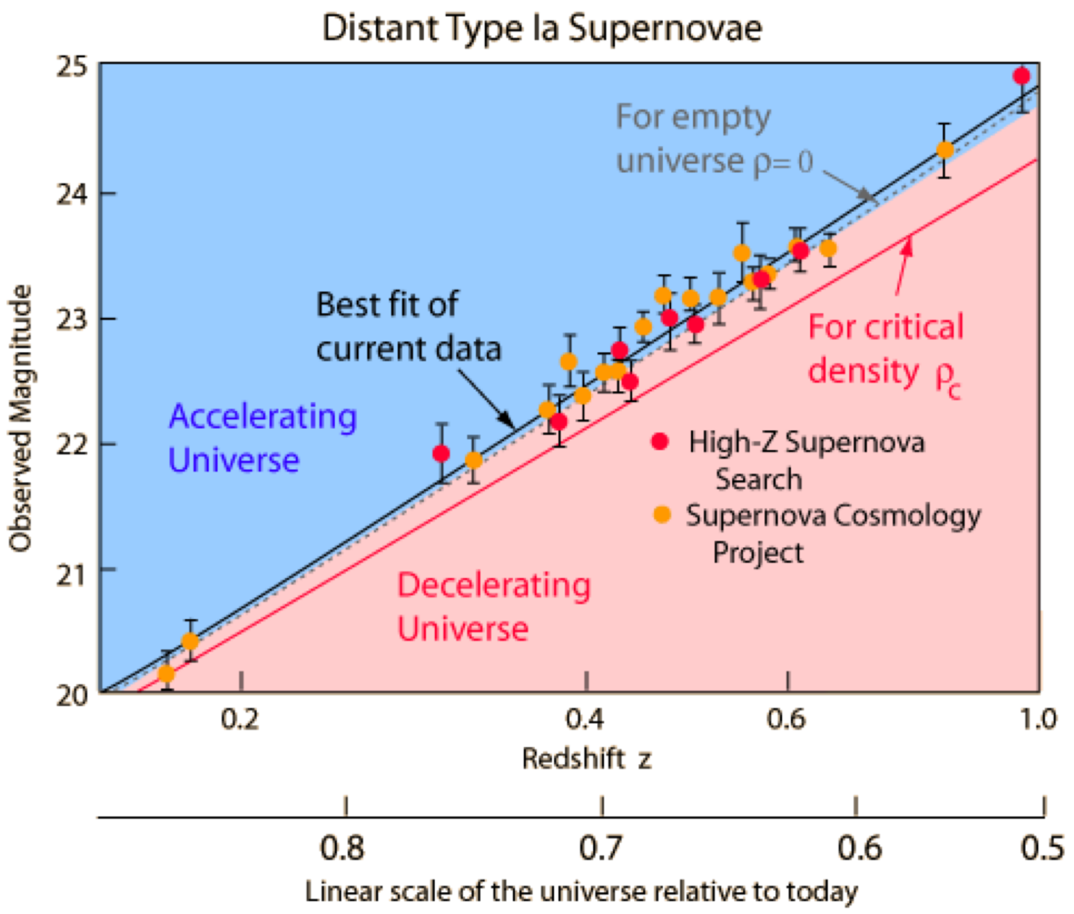
Type Ia --- standard candle for cosmic distance ladder

Gravitational waves --- maybe only from galactic CCSNe?

Neutrino observations

Process	Typical $\|h\|$ (at 10 kpc)	Typical f (Hz)	Duration Δt (ms)	E_{GW} ($10^{-10}\,M_\odot c^2$)	Limiting factors or processes
Prompt convection	10^{-23}–10^{-21}	50–1000	0 to $\sim$30	$\lesssim$ 0.01–10	Seed perturbations, entropy/lepton gradient, rotation
	(Emission characteristics depend on seed perturbations.)				
PNS convection	2–5 $\times 10^{-23}$	300–1500	500 to several 1000	$\lesssim 1.3\left(\frac{\Delta t}{1s}\right)$	Rotation, BH formation, strong PNS g-modes
Neutrino-driven convection and SASI	10^{-23}–10^{-22} (peaks up to 10^{-21})	100–800	100 to $\gtrsim$1000	$\gtrsim 0.01\left(\frac{\Delta t}{100\text{ ms}}\right)$ $\lesssim 15\left(\frac{\Delta t}{100\text{ ms}}\right)$	Rotation, explosion, BH formation

Ott CQG 2008



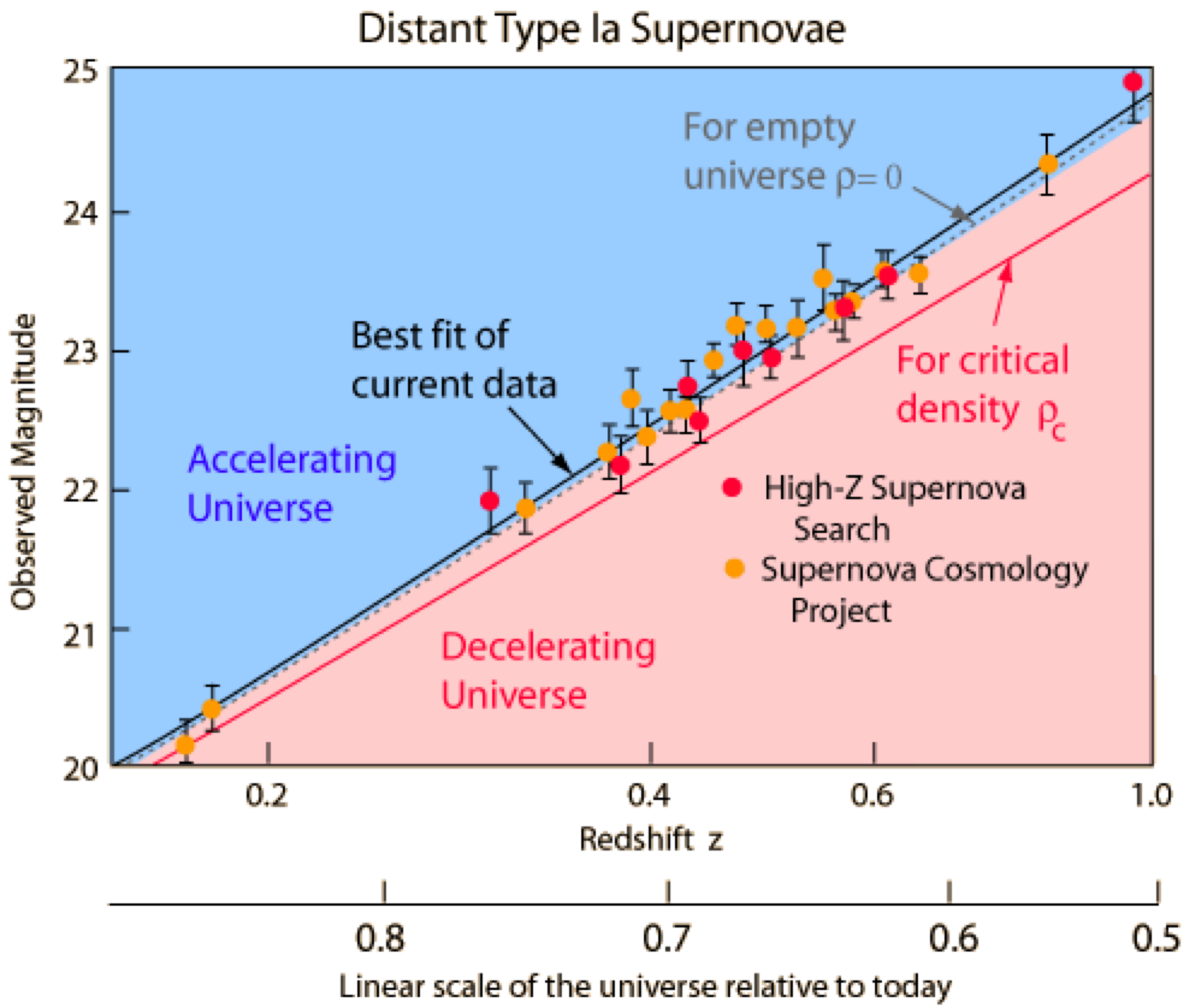
Cosmology with Type Ia Supernovae

"Standard candle"
always the same peak luminosity

Allows reconstruction of
luminosity distance

vs. host galaxy redshift

→ Rate of expansion of the universe



Gravitational waves

"messy" waveform
stochastic with dominant frequency

Emission essentially stars with core bounce

Duration: 10s of ms

Waveform will depend on:

- Mass
- Nuclear equation of state (EoS)
- Rotation
- …

Ott 2008

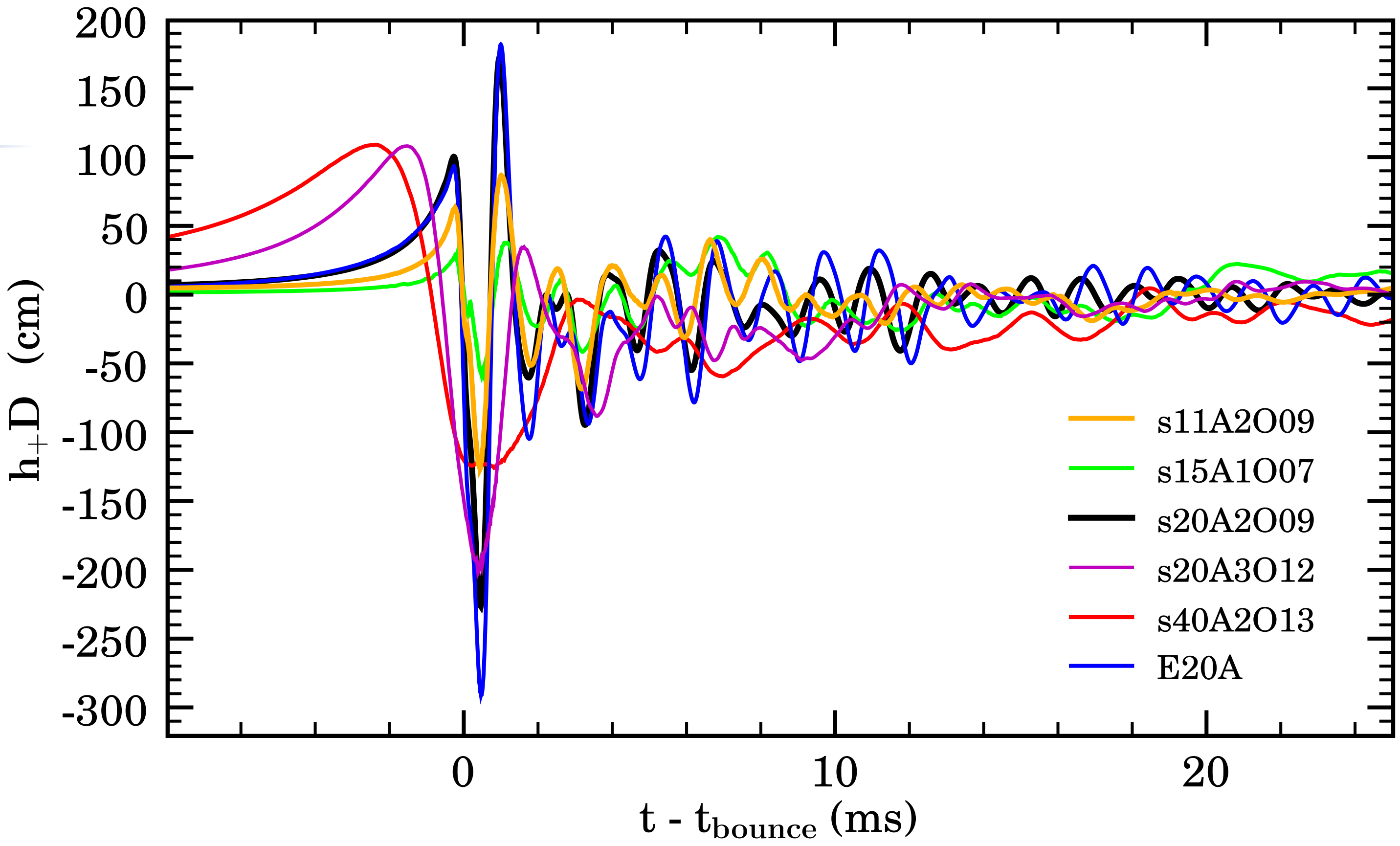
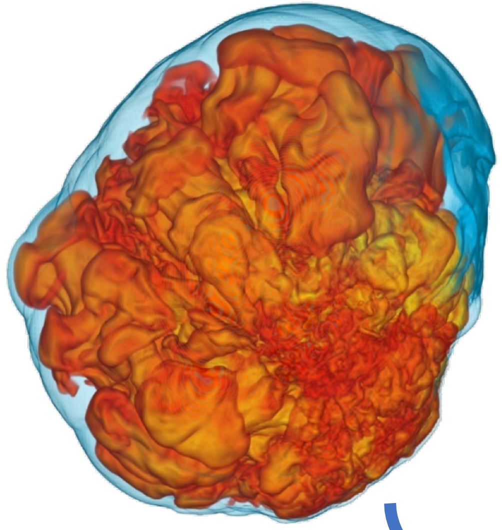
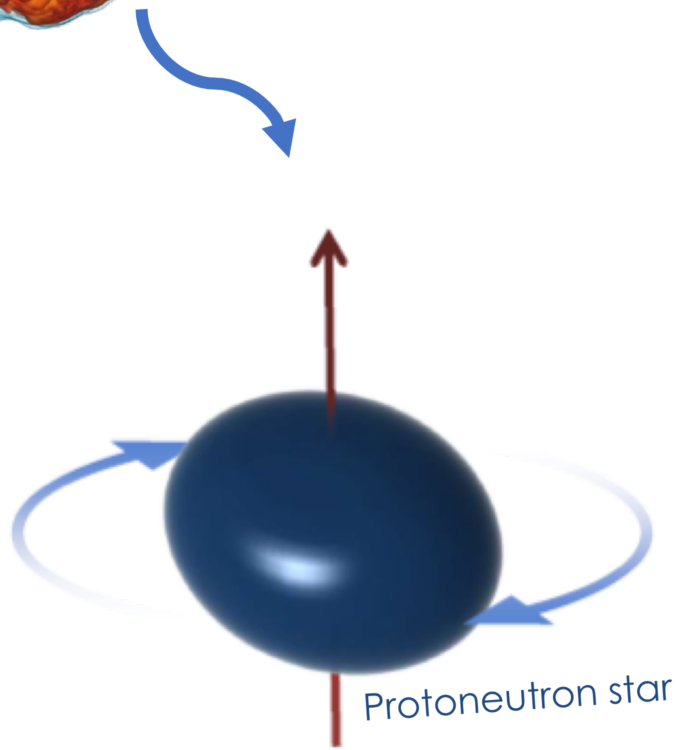


Figure 2. GW signals ($h_+ D$ in units of cm, where D is the distance of the source) for a few examples from the 2D GR model set of Dimmelmeier et al. [108]. The models shown here were computed with the Shen EOS [135, 136] and employ 1D presupernova models of [137], spanning the progenitor mass range from 11.2 $M_\odot$ (s11) to 40 $M_\odot$ (s40). The models were set up with precollapse central angular velocities $\Omega_{\mathrm{c,i}}$ from $\sim$ 1.5 rad s^{-1} to $\sim$ 11 rad s^{-1}. For details of the rotational setup, see [108]. Model E20A uses a 20-$M_\odot$ presupernova model that was evolved by [138] with a 1D prescription for rotation. Note the generic shape of the waveforms, exhibiting one pronounced spike at core bounce and a subsequent ring down. Very rapid precollapse rotation ($\Omega_{\mathrm{c,i}} \gtrsim 6$ rad s^{-1}; models s20A3O12 and s40A2O13 in this plot) results in a significant slow-down of core bounce, leading to a lower-amplitude and lower-frequency GW burst. The GW signal data are available for download from [126].

Rapidly rotating core





Bartos, Brady, Marka 2013

GWs from rapidly rotating cores?

Relevant distance scale:

Low-luminosity GRB / CCSN with jets: 10^2-10^3 Gpc^{-3} yr^{-1}

(Guetta & della Valle 2006; Soderberg+ Nature 2010)

(Beaming factor ~ 10)

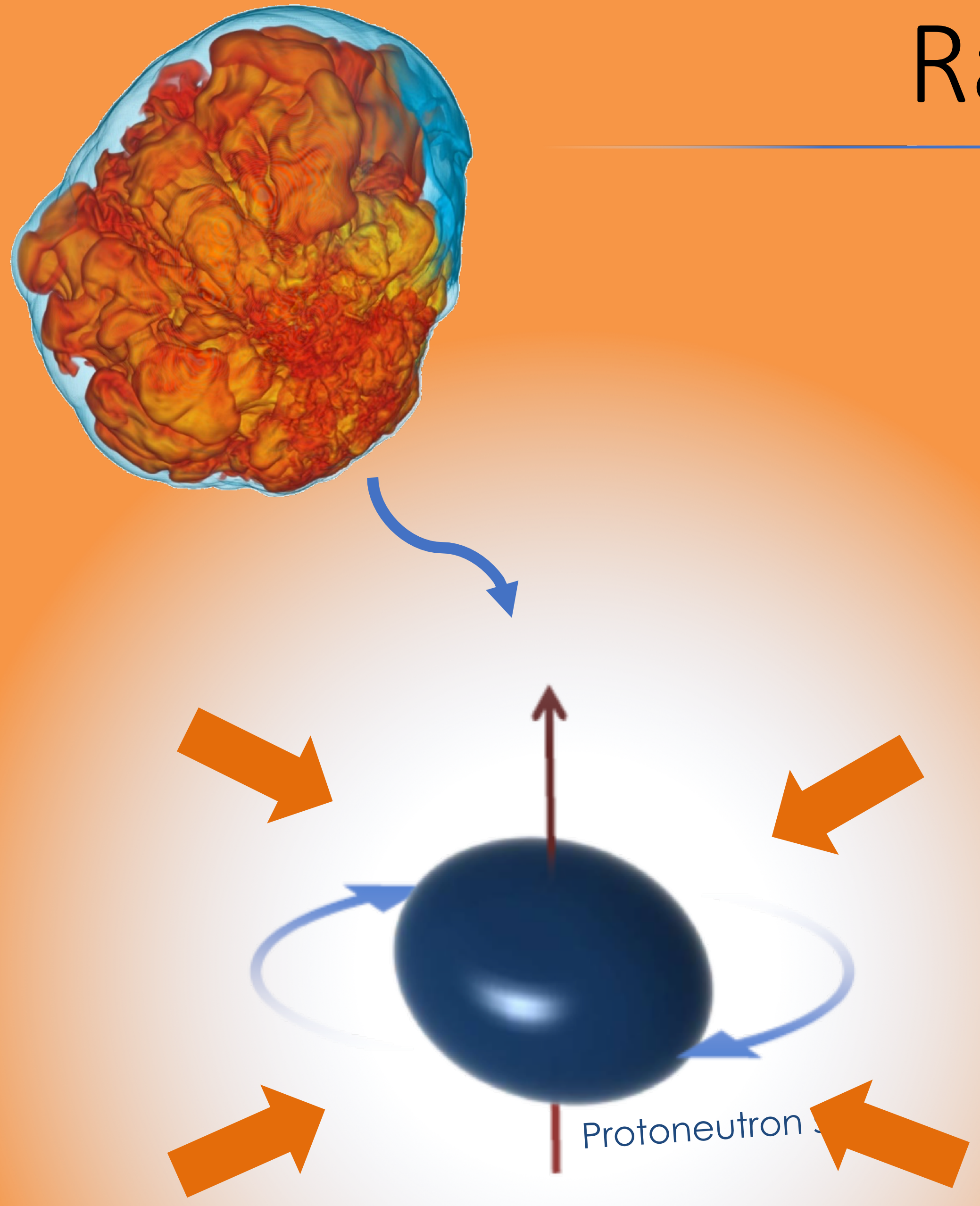
→ 50-100 Mpc

Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

$$E_{\rm GW} \approx 10^{-2} M_\odot c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,{\rm kHz}}\right)^6 \left(\frac{M}{1.4\,M_\odot}\right) \left(\frac{R}{12\,{\rm km}}\right)^2 \left(\frac{\tau}{0.1\,{\rm s}}\right)$$

Rapidly rotating core



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Fallback accretion? *(Piro, Thrane, 2012)*

$$E_{\rm GW} \approx 10^{-2} M_{\odot} c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,\mathrm{kHz}}\right)^6 \left(\frac{M}{1.4\,M_{\odot}}\right) \left(\frac{R}{12\,\mathrm{km}}\right)^2 \left(\frac{\tau}{0.1\,\mathrm{s}}\right)$$

Bartos, Brady, Marka 2013