PHY 7097 | Modern Astrophysics

Lecture IV.

Supernovae

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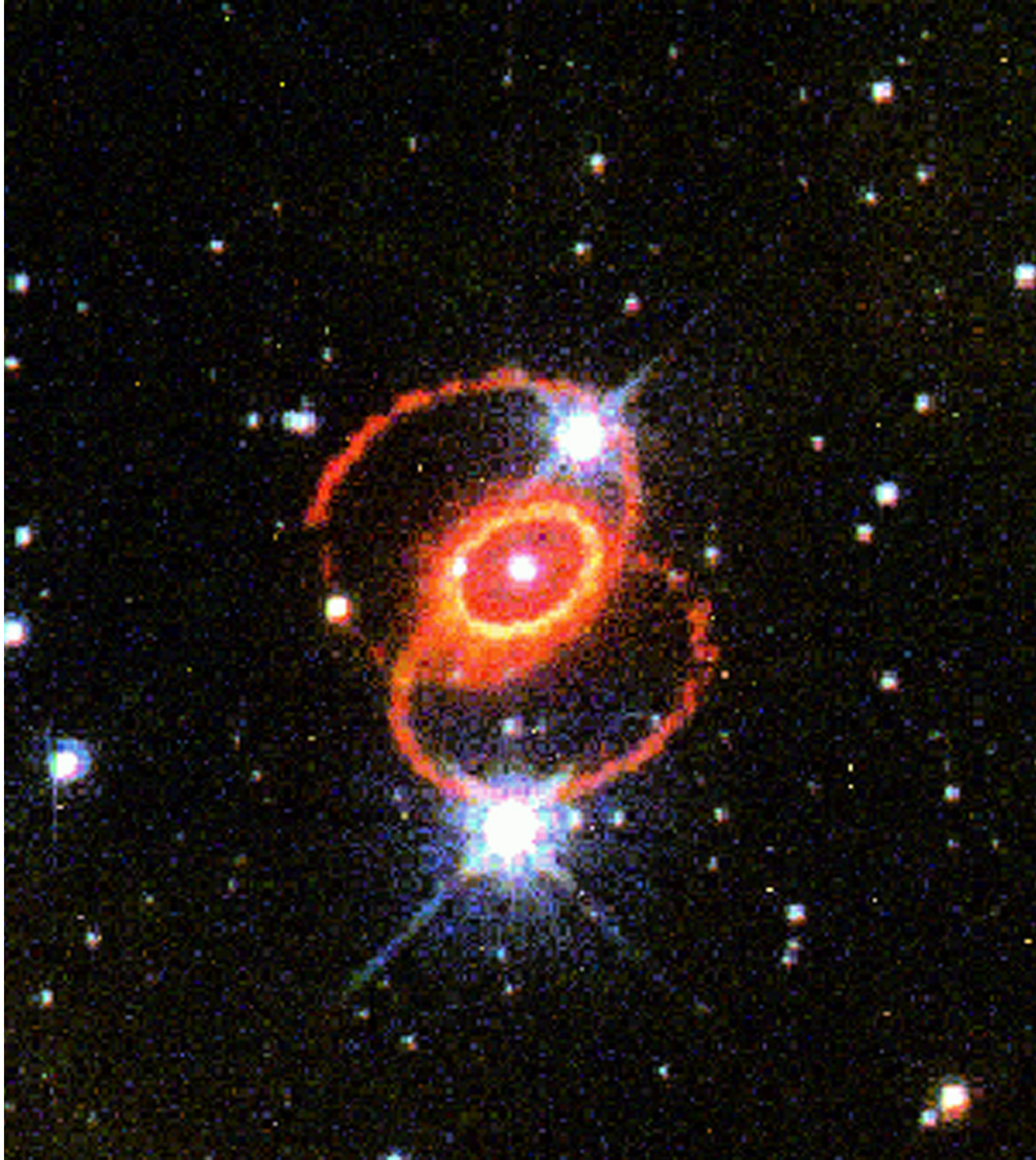


Stellar Evolution

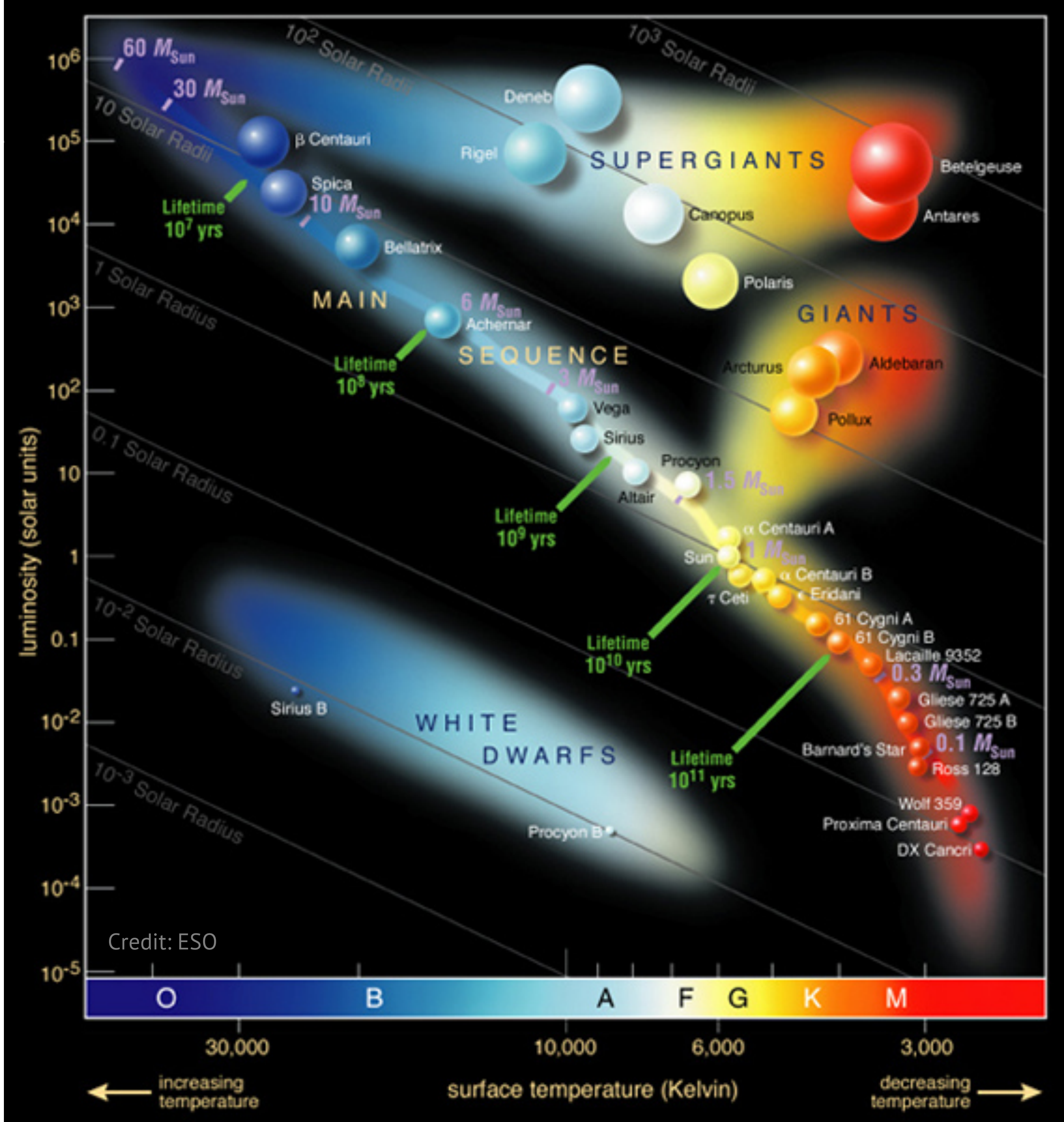
Not everyone will be a star…
Below 0.08 $M_{\odot}$, pressure is too small for fusion.
→ <u>Brown dwarfs</u>

Stars are ~70% H, 30% He, and a trace of “metal.”
→ <u>Hydrogen fusion.</u>

Fusion produces heat that halts gravitational collapse.
→ <u>Hydrostatic equilibrium.</u>

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

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



Death

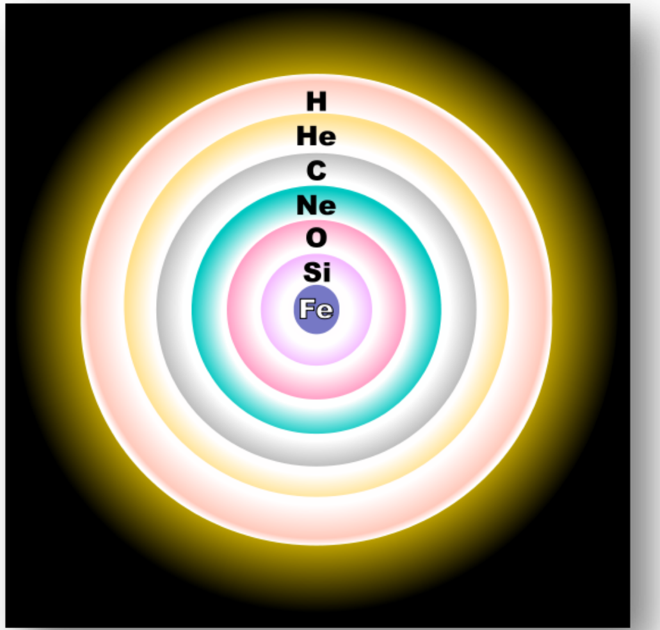
Low mass stars – runs out of fuel --> radiation pressure reduced → shrinks → white dwarf

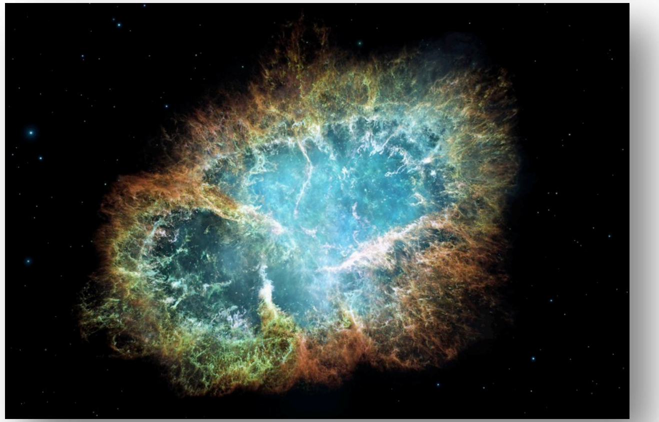
High mass stars – fusion down to iron → iron core → gravitational core collapse → supernova / collapsar

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

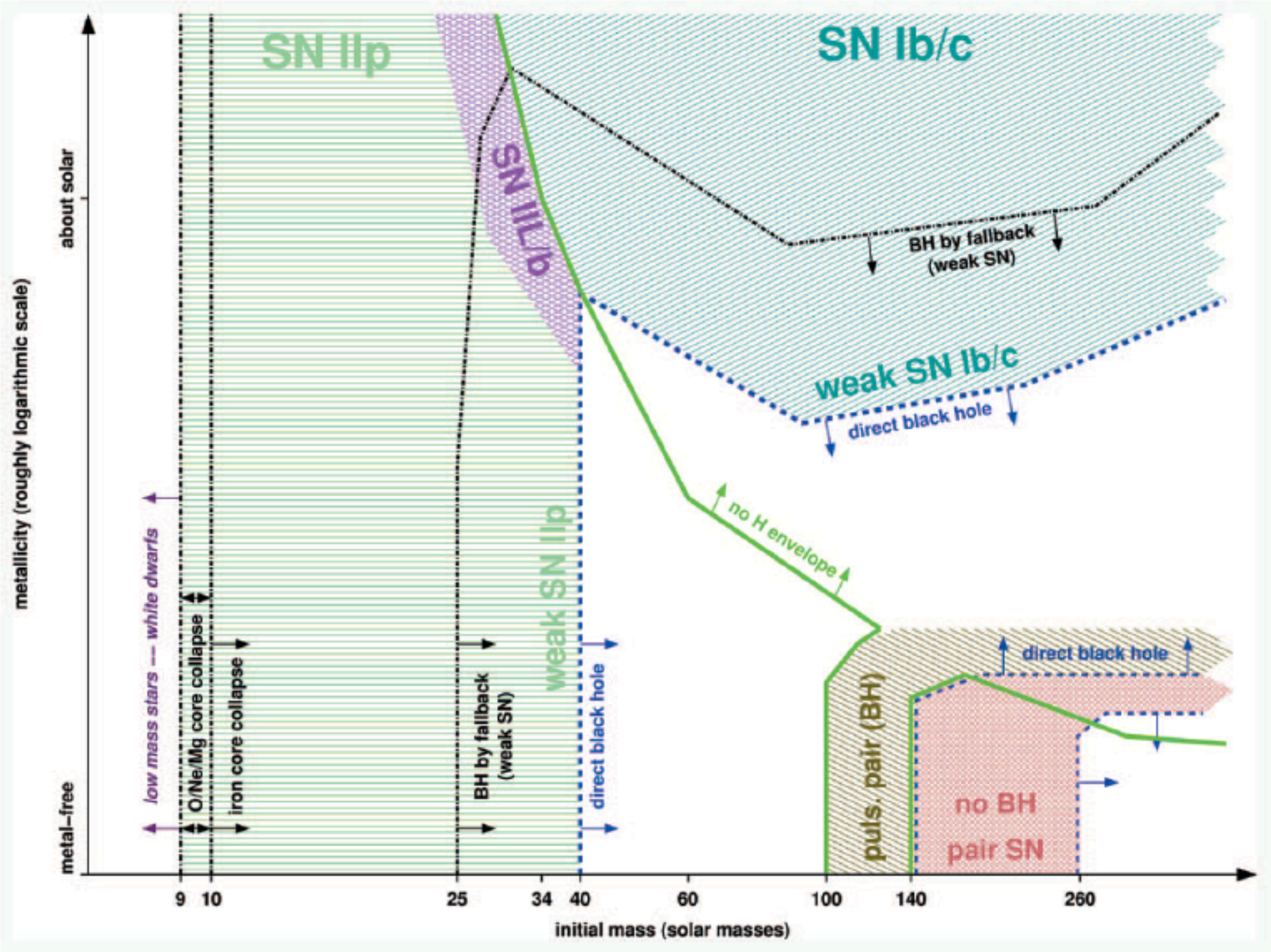
Very high mass stars – high pressure → gamma rays energetic for photodisintegration→ reduced pressure → gravitational collapse → black hole

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



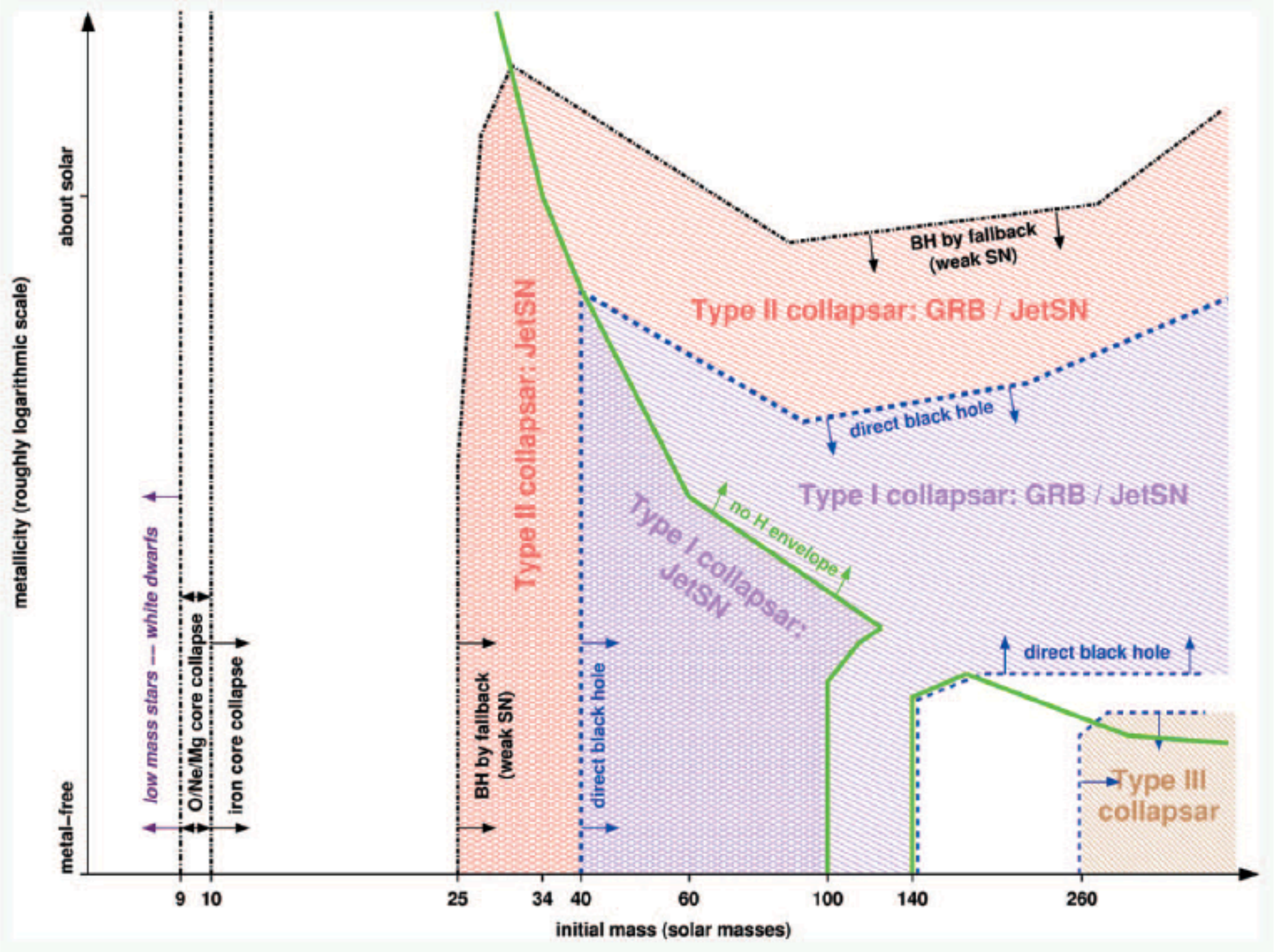


Supernova explosion



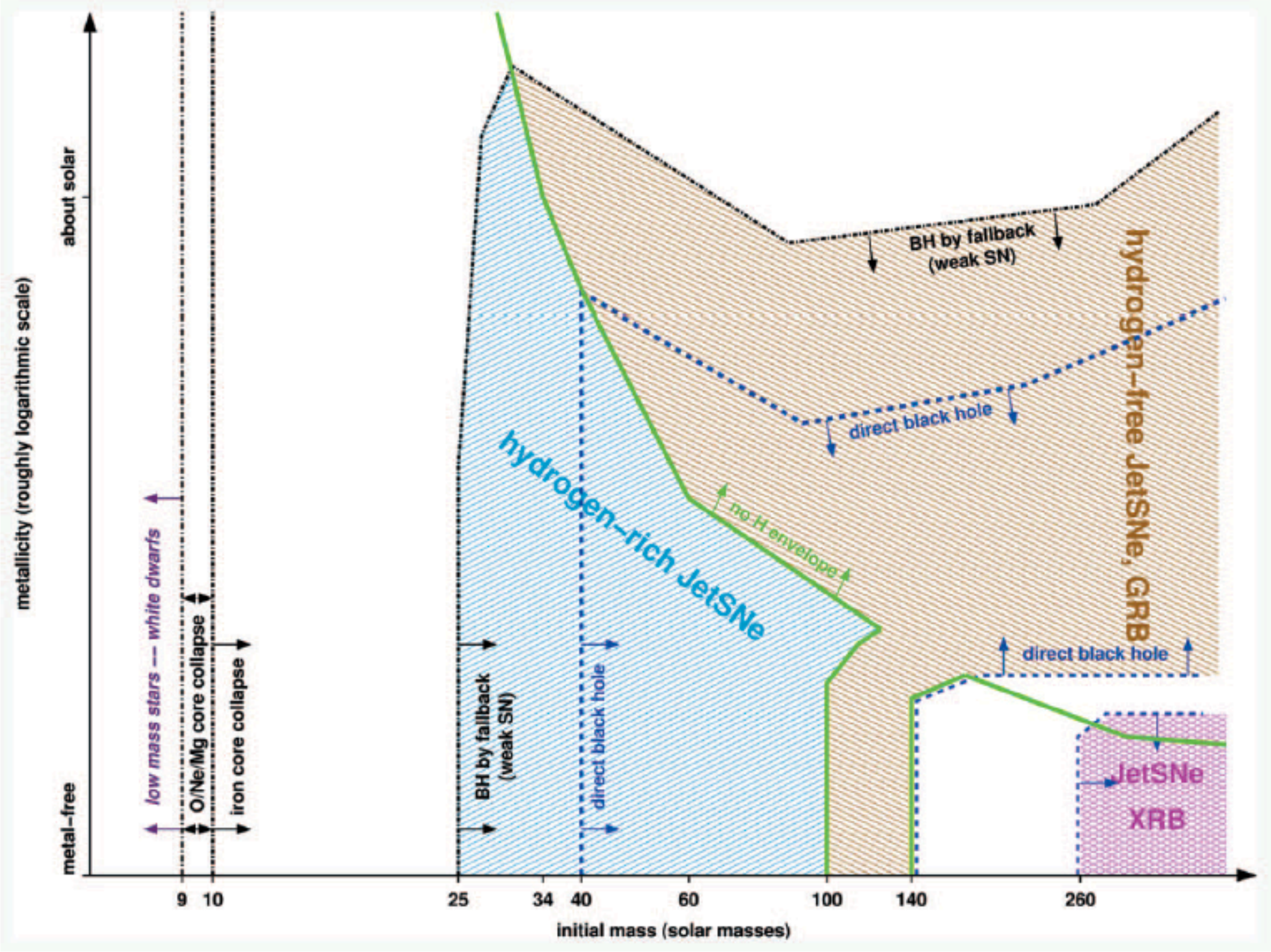
Heger+ ApJ 2003

Collapsars



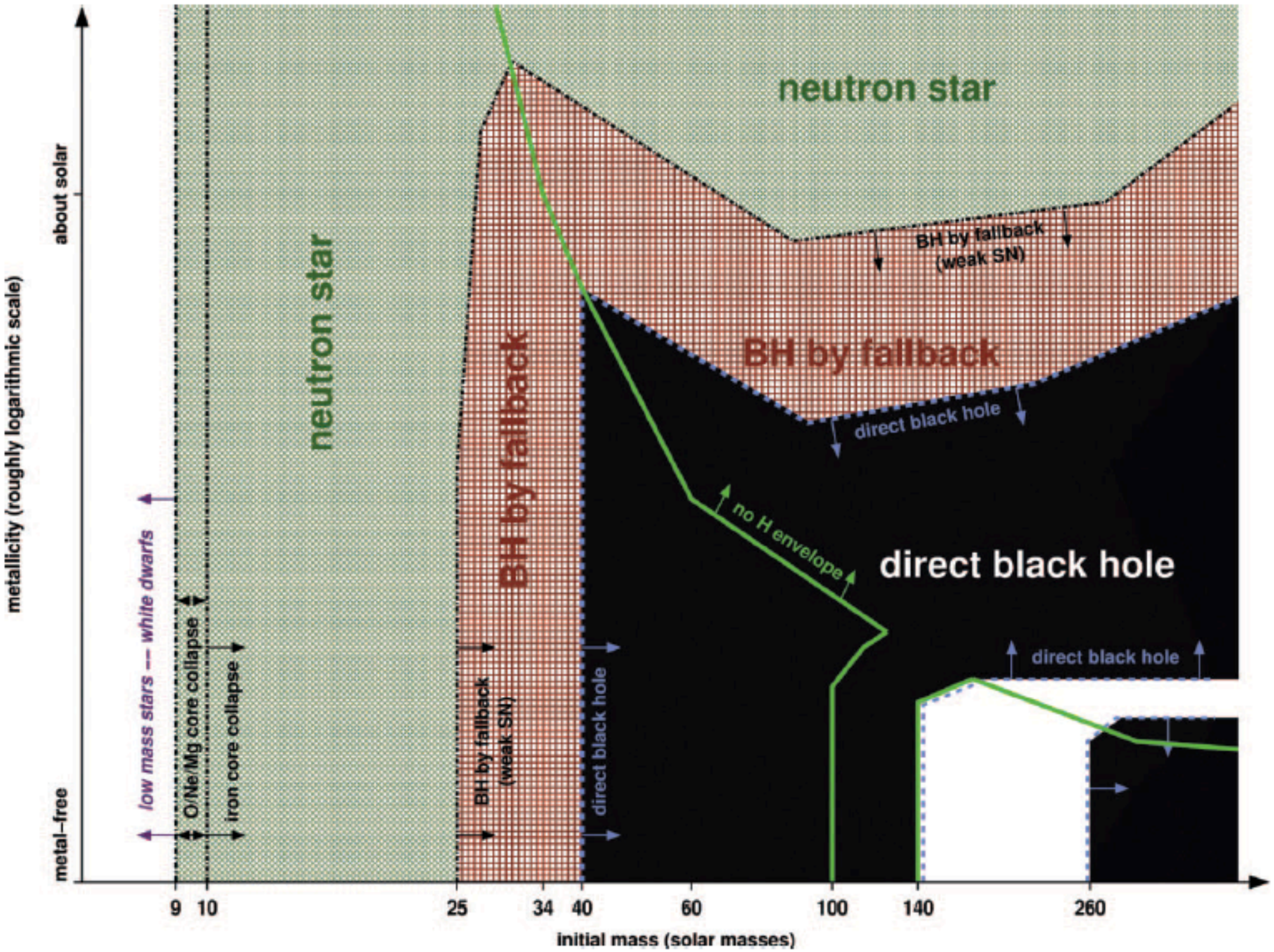
Heger+ ApJ 2003

Beamed outflow (jet)



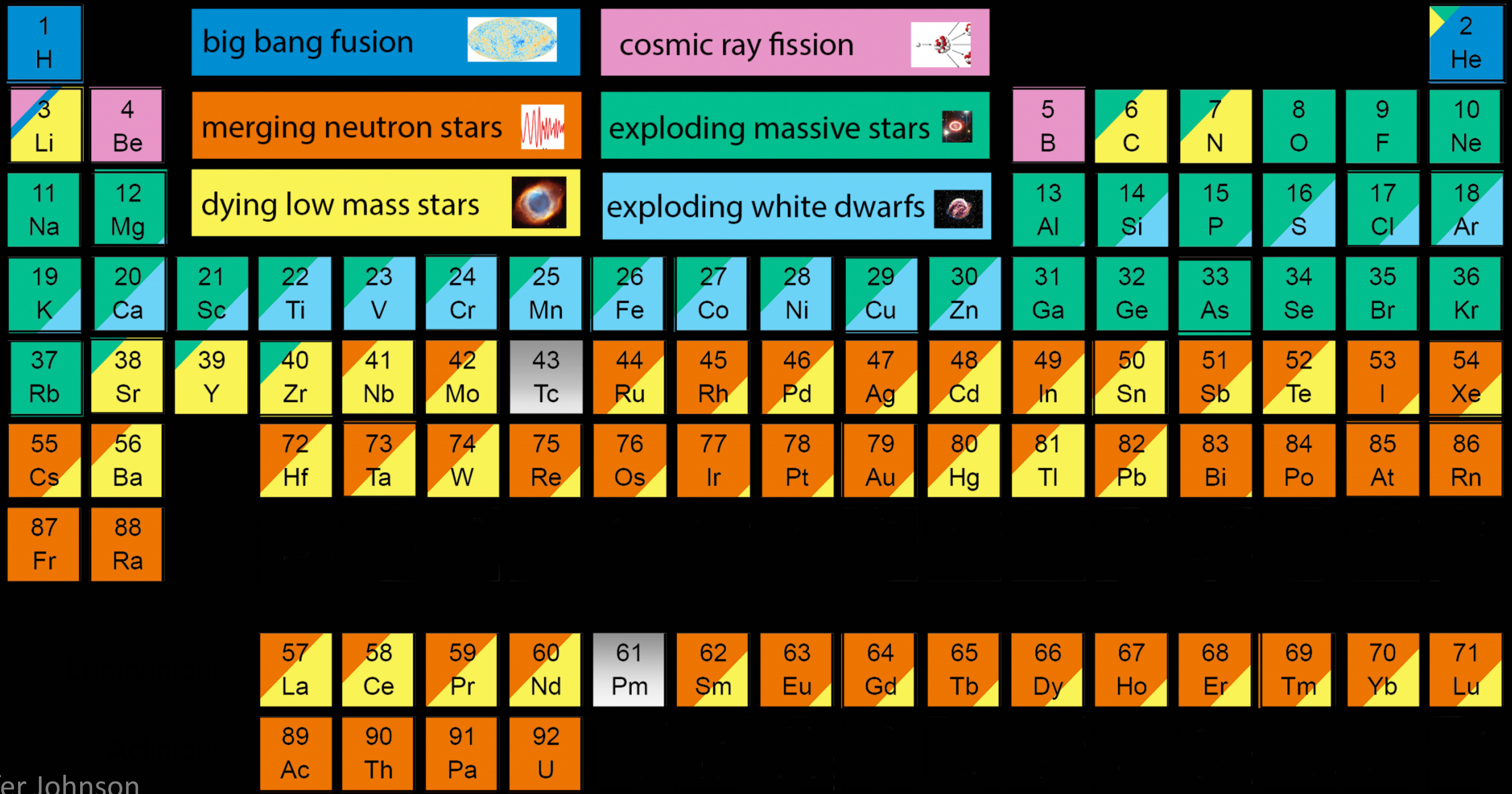
Heger+ ApJ 2003

Remnant



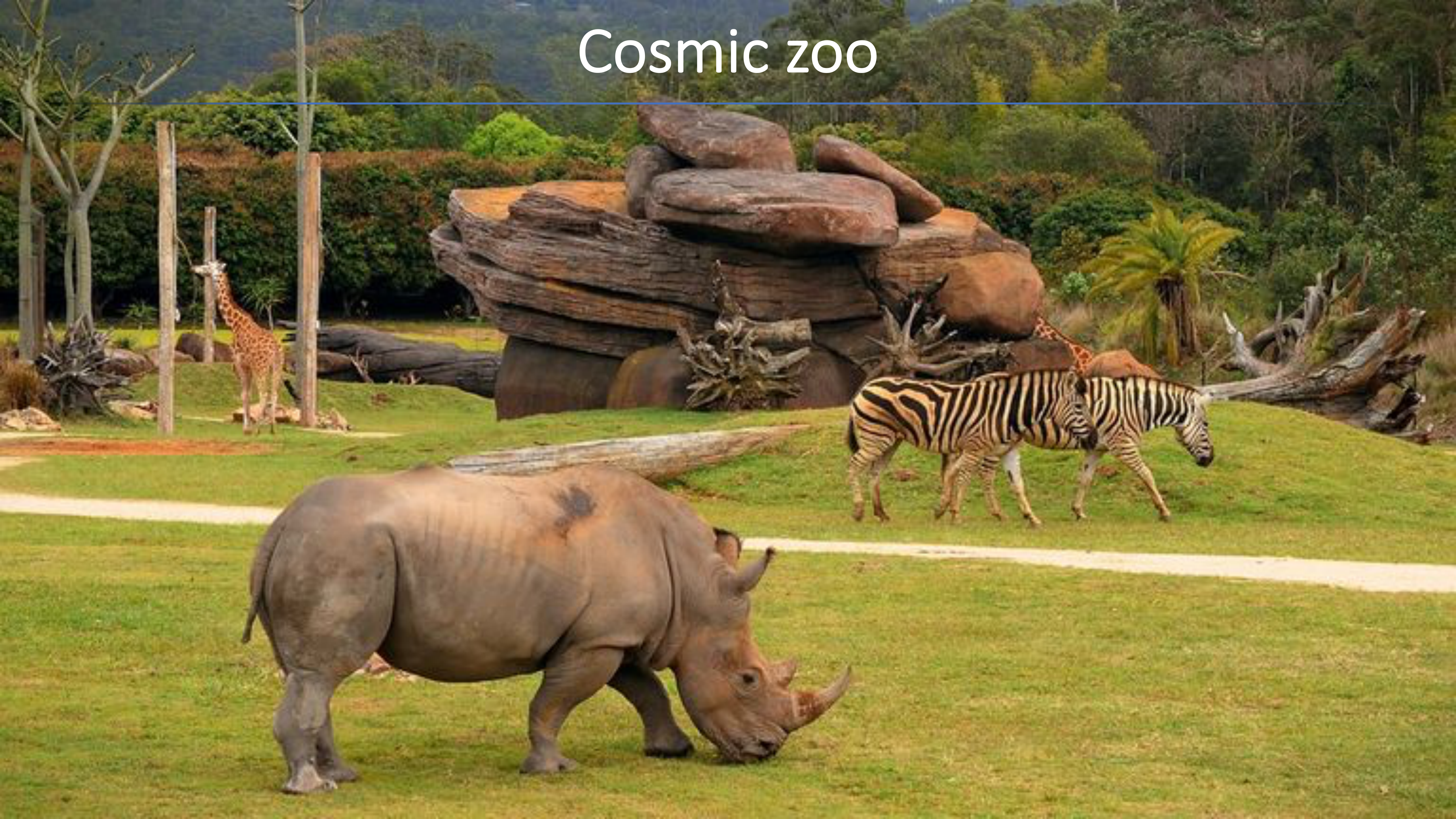
Heger+ ApJ 2003

The Origin of the Solar System Elements

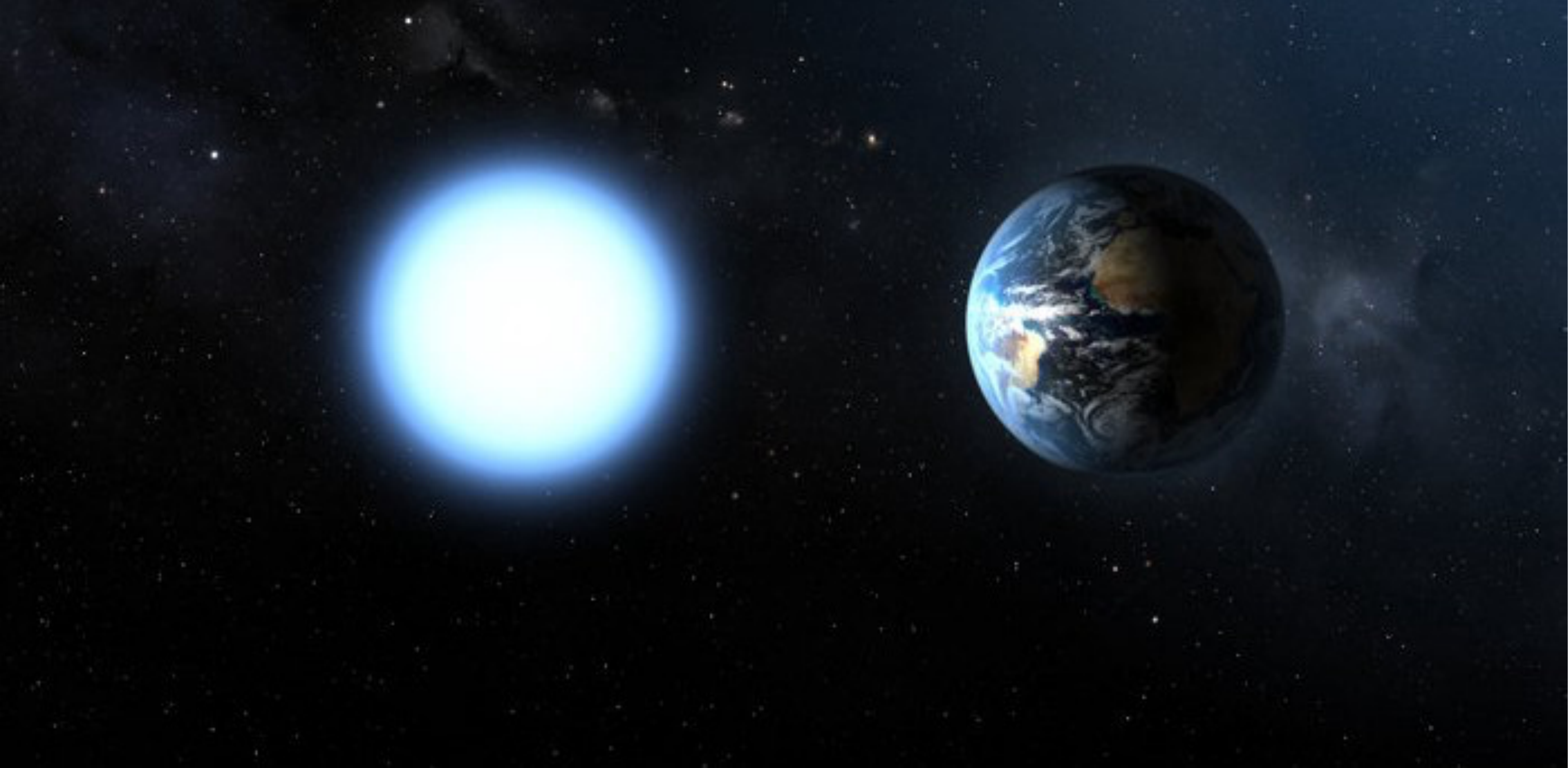


Jennifer Johnson

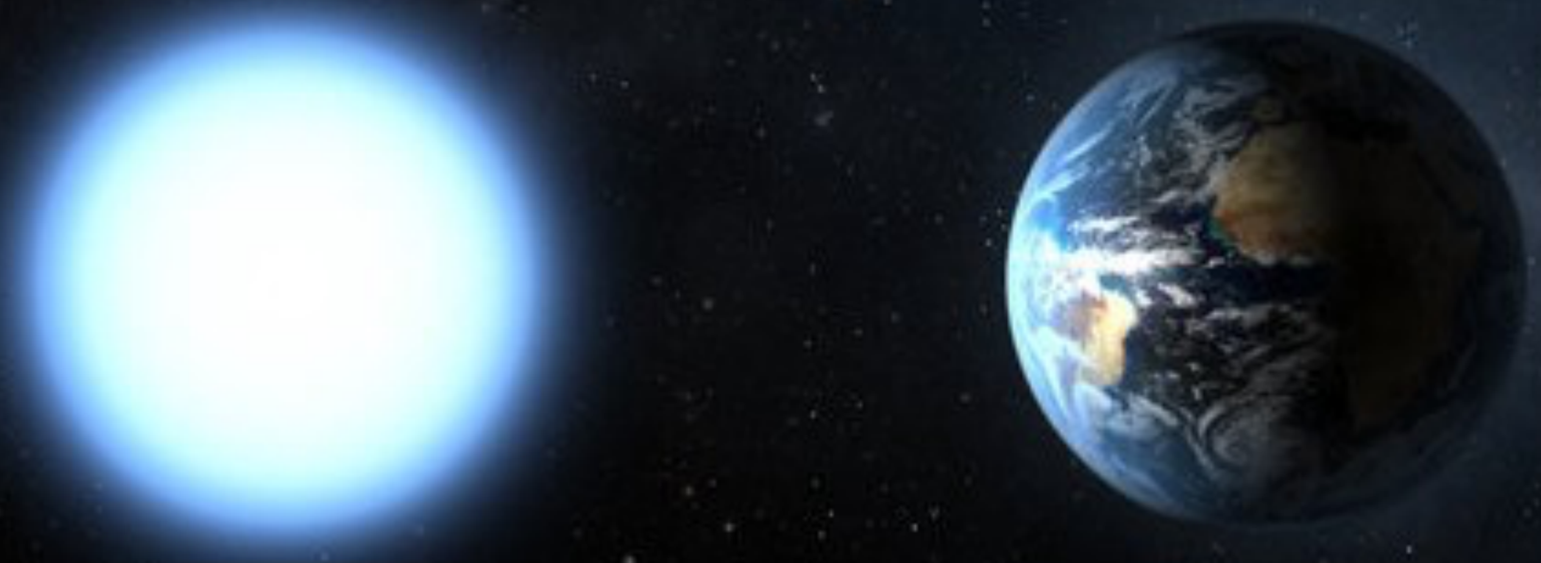
Cosmic zoo



White dwarfs



White dwarfs



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

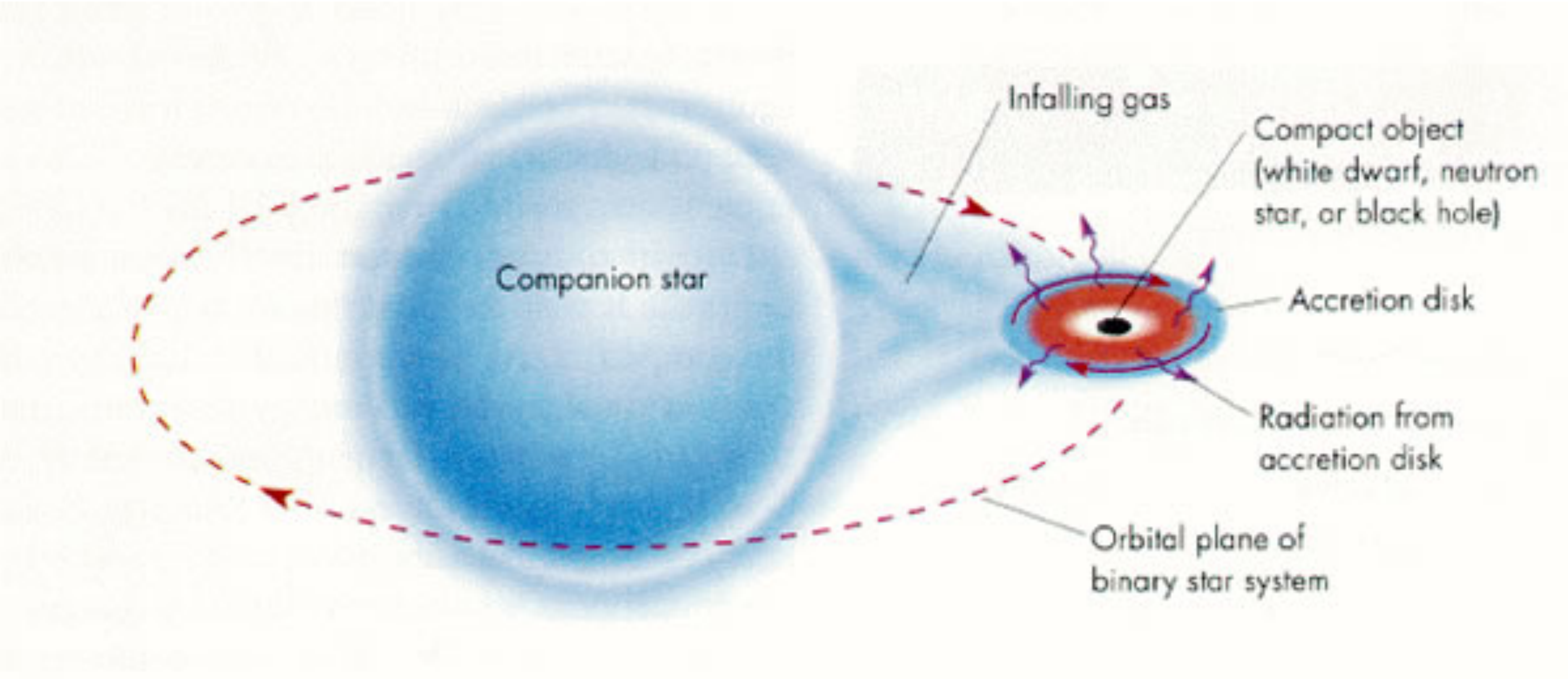
Classification

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?

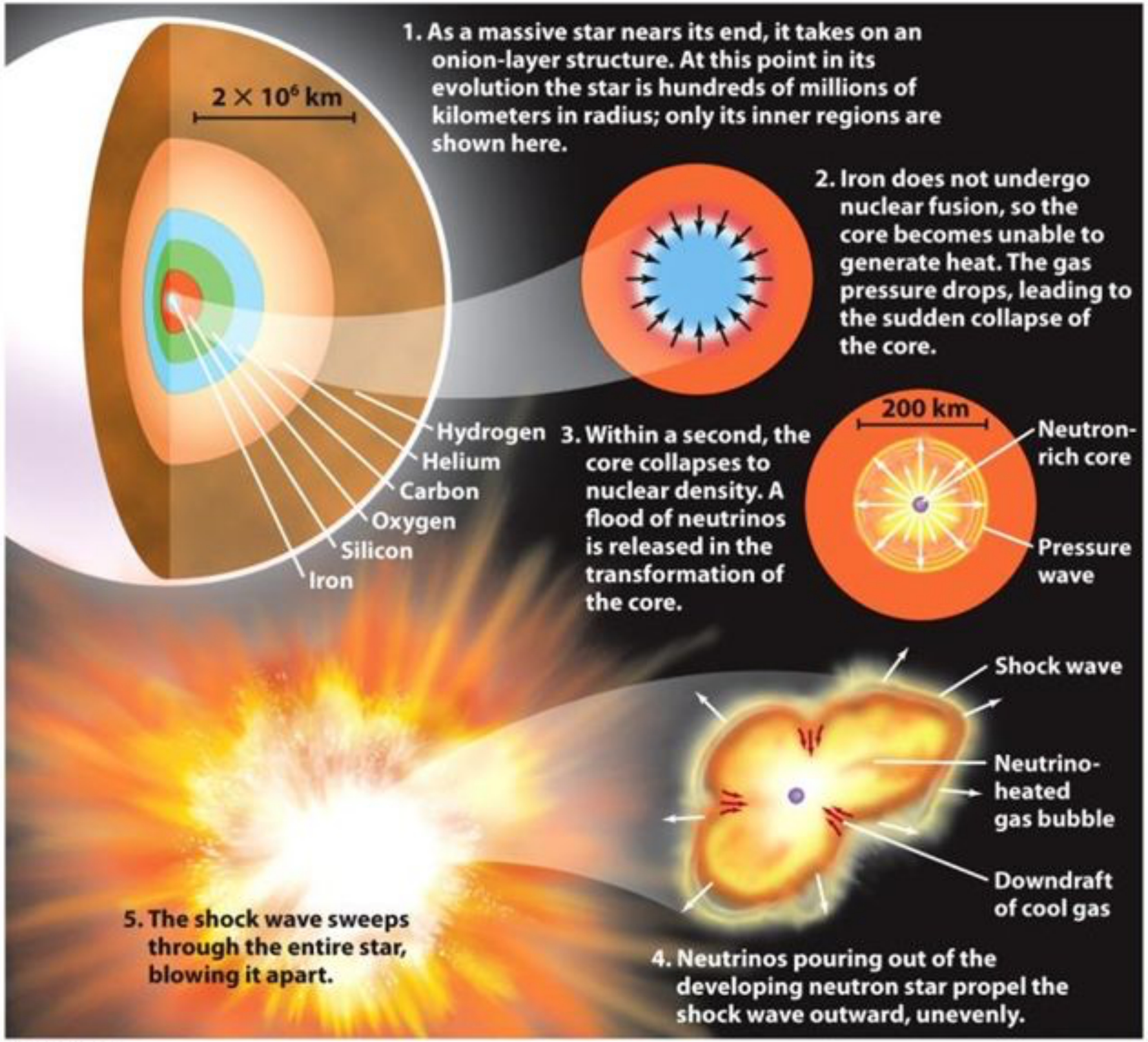


Figure 20-14
Universe, Tenth Edition
Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006

SN 1987A

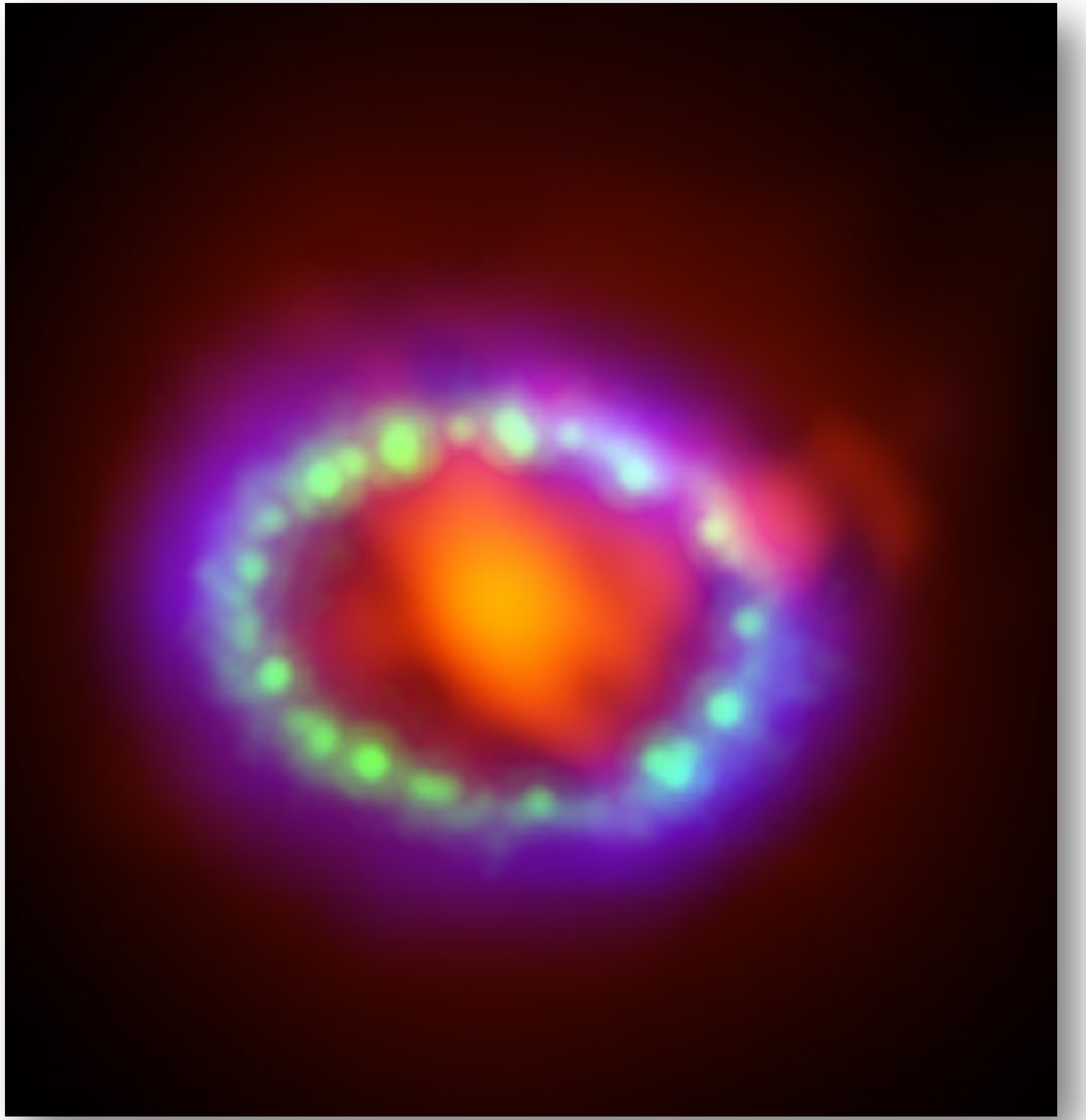
In Large Magellanic Cloud at ~50 kpc

Progenitor star: blue supergiant

Visible to the naked eye from the Southern hemisphere

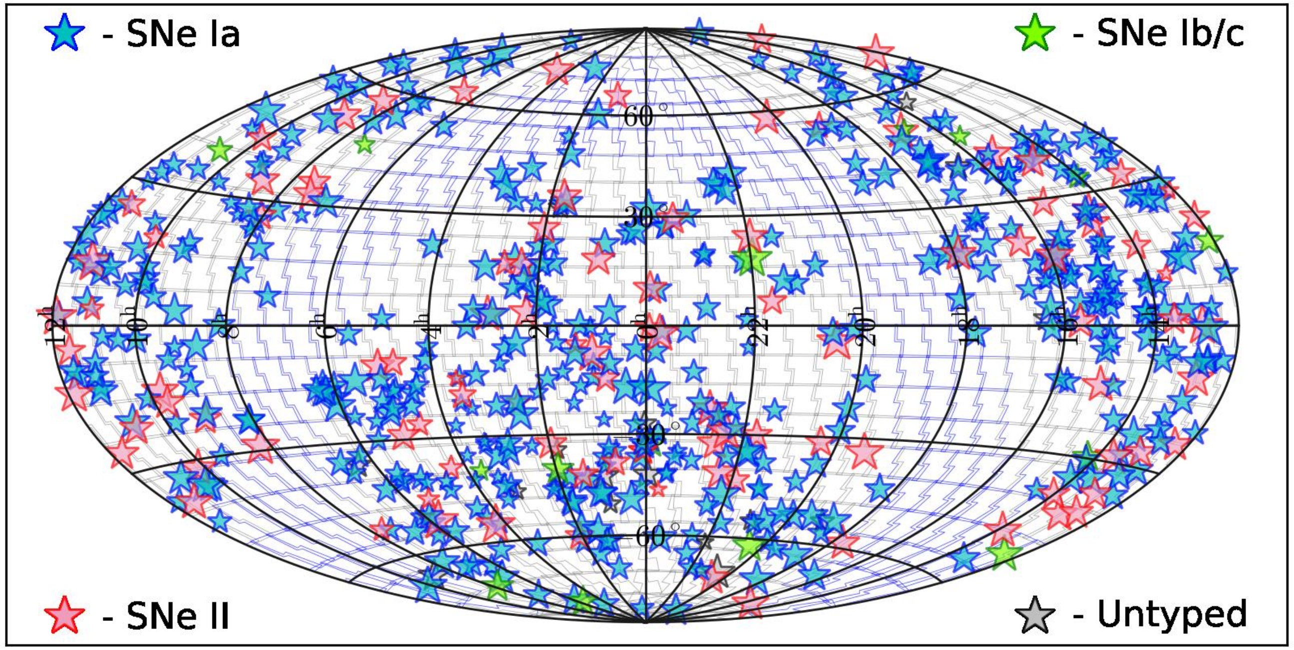
Detection of 25 neutrinos
2-3 hours before the first light was detected

No NS remnant has been observed



Observations

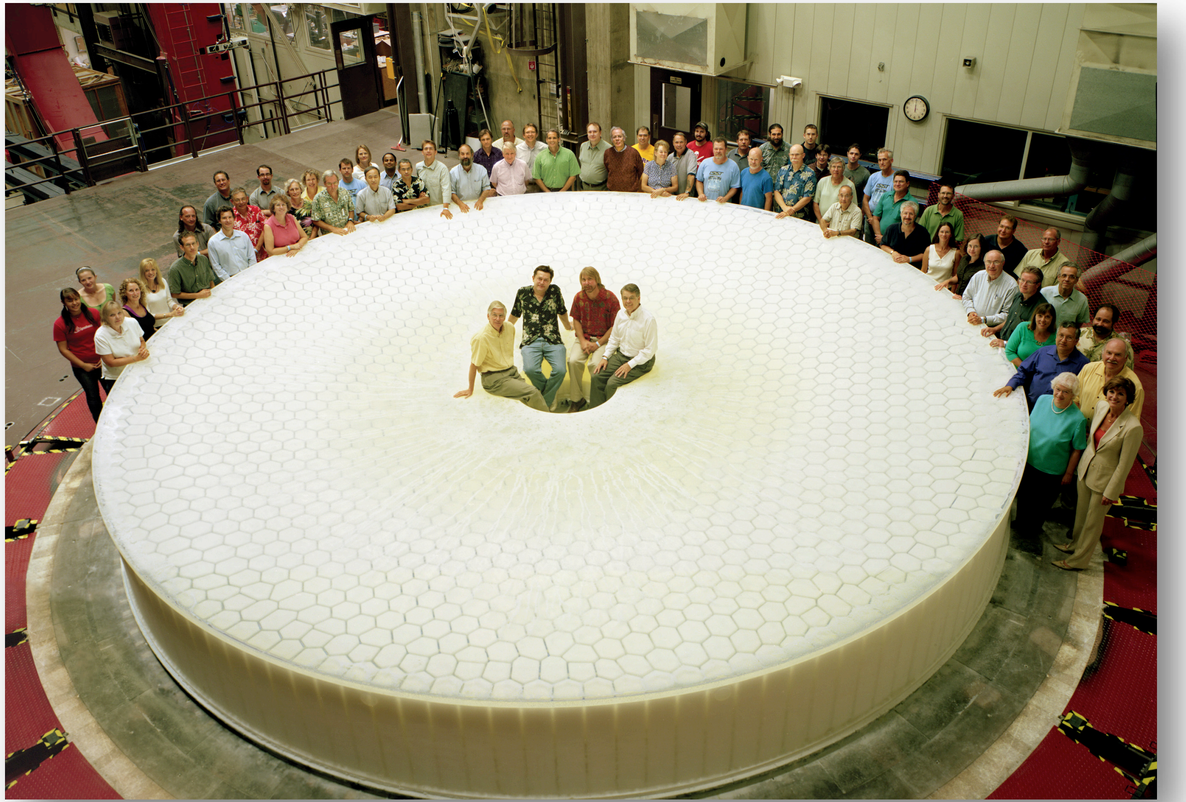
ASAS-SN

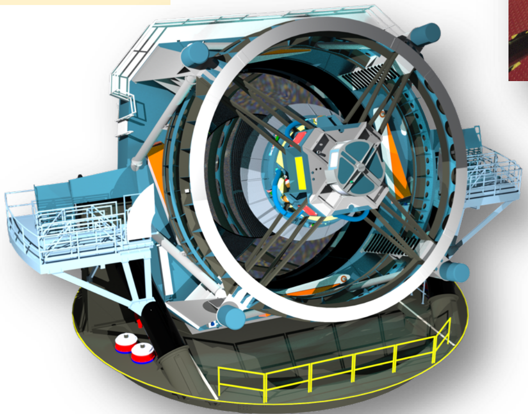


Multiple, very small telescopes that scan the whole sky every night.

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

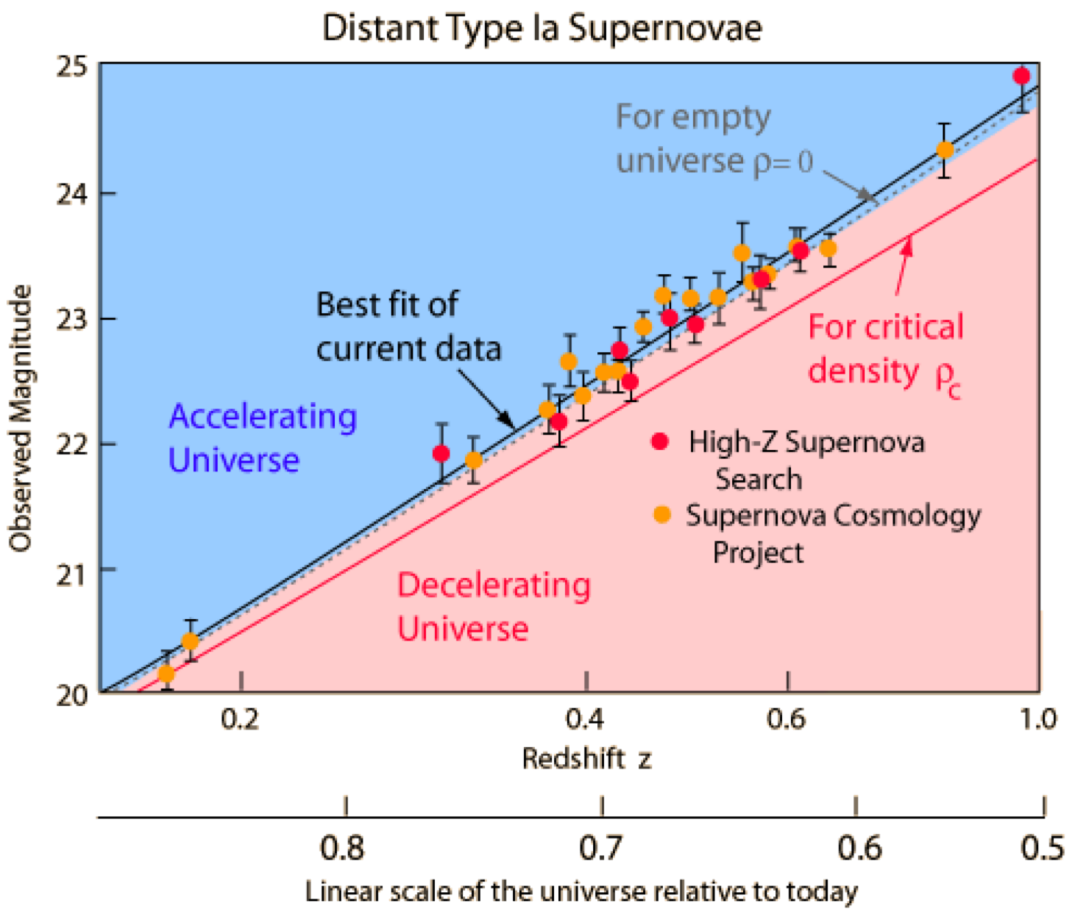
Type Ia --- standard candle for cosmic distance ladder

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



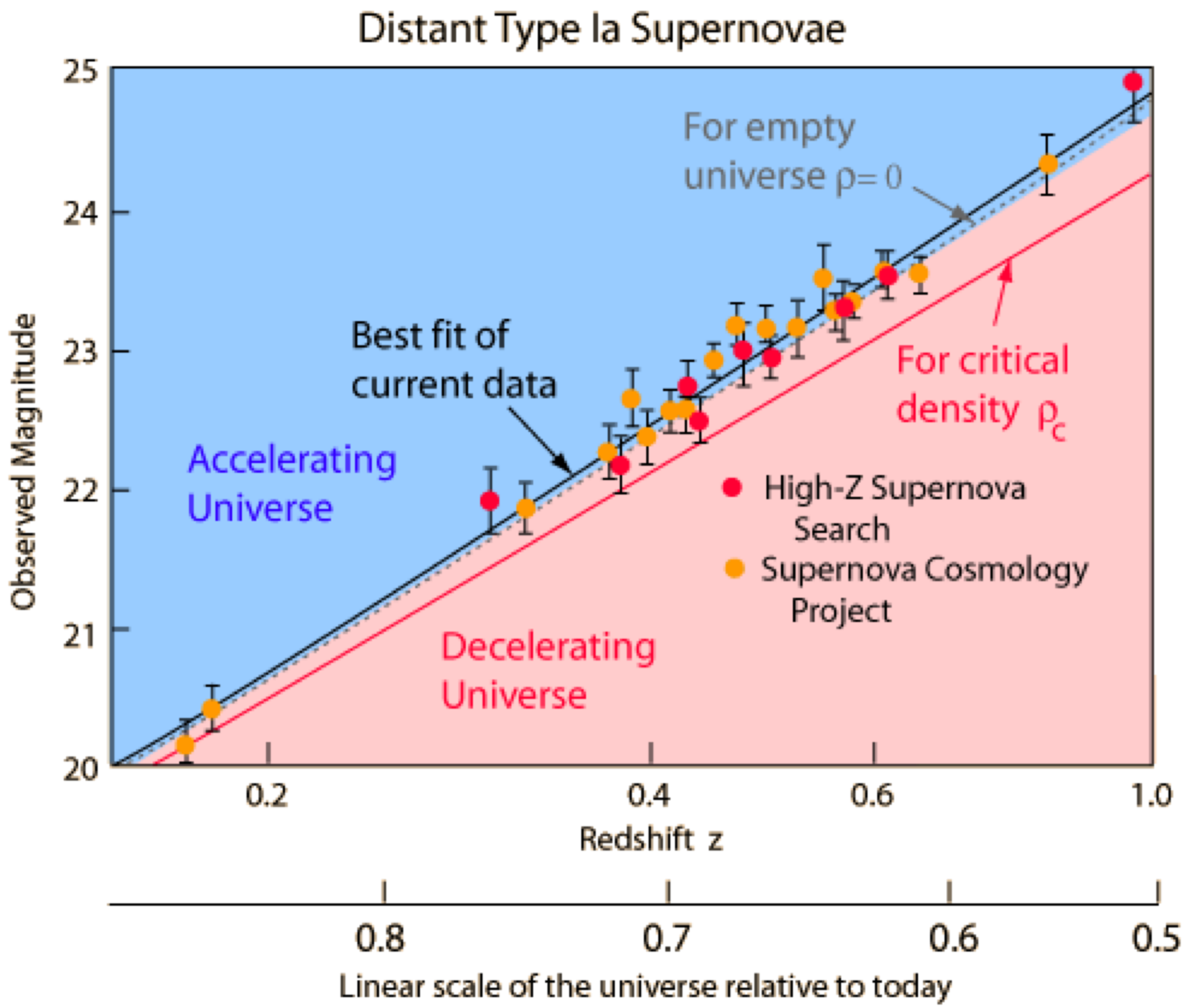
Cosmology with Type Ia Supernovae

"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

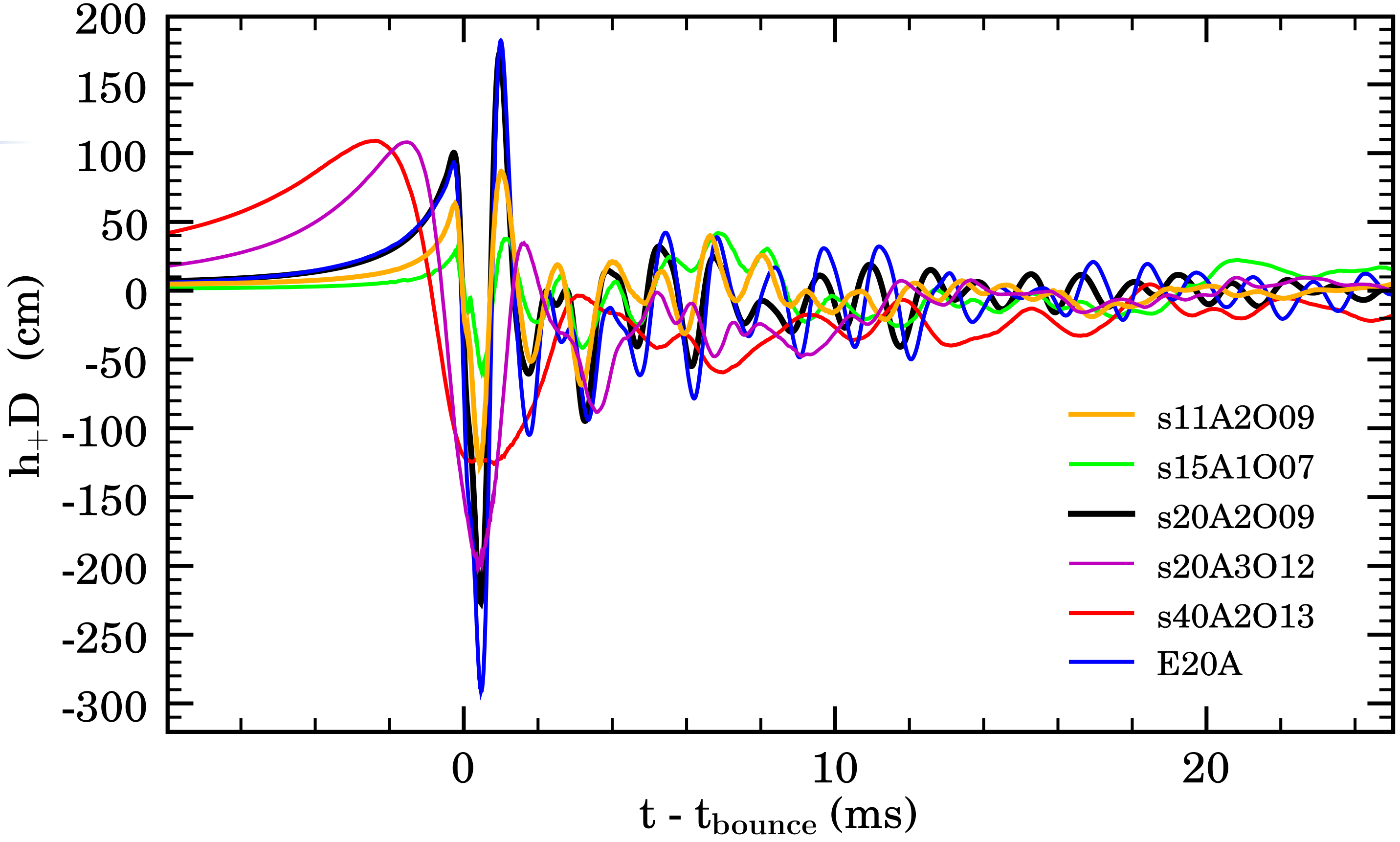
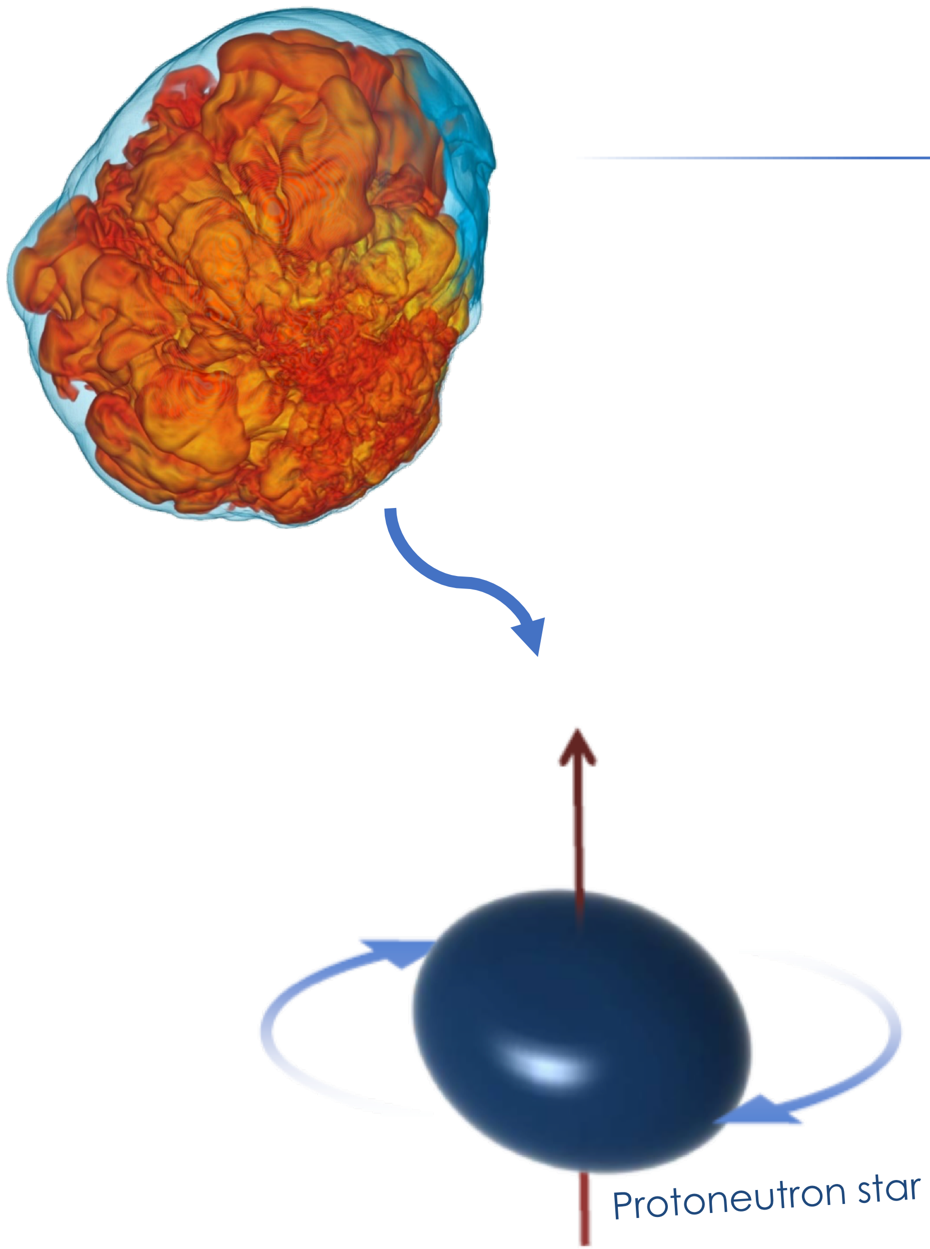


Figure 2. GW signals (h_+ D in units of cm, where D is the distance of the source) for a few examples from the 2D GR model set of Dimmelmeier et al. [108]. The models shown here were computed with the Shen EOS [135, 136] and employ 1D presupernova models of [137], spanning the progenitor mass range from 11.2 $M_\odot$ (s11) to 40 $M_\odot$ (s40). The models were set up with precollapse central angular velocities $\Omega_{\rm c,i}$ 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 ($\Omega_{\rm c,i} \gtrsim 6$ 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



GWs from rapidly rotating cores?

<u>Relevant distance scale:</u>

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

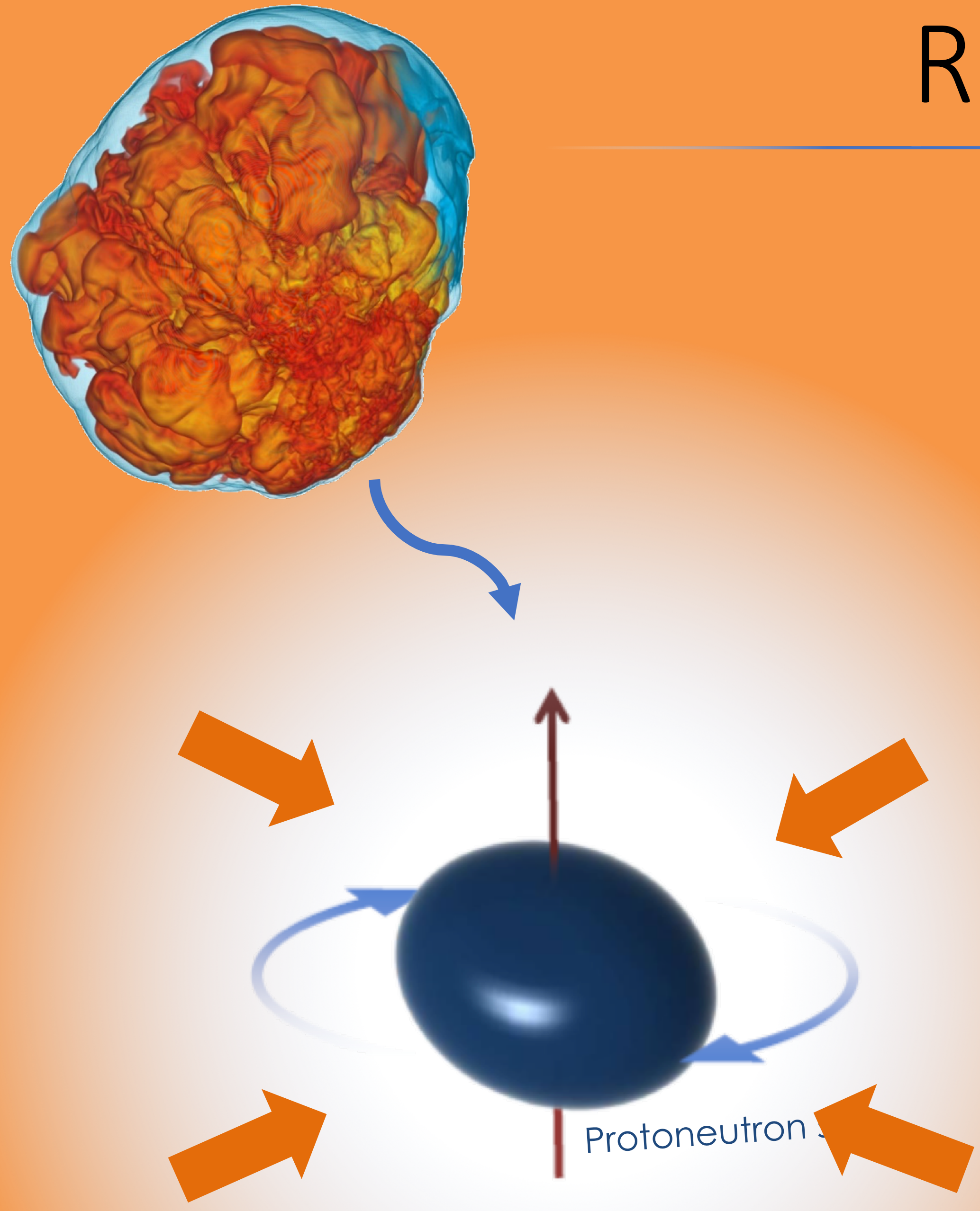
Differential rotation (e.g. Corvino+ 2010)

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

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

Bartos, Brady, Marka 2013

Rapidly rotating core



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

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