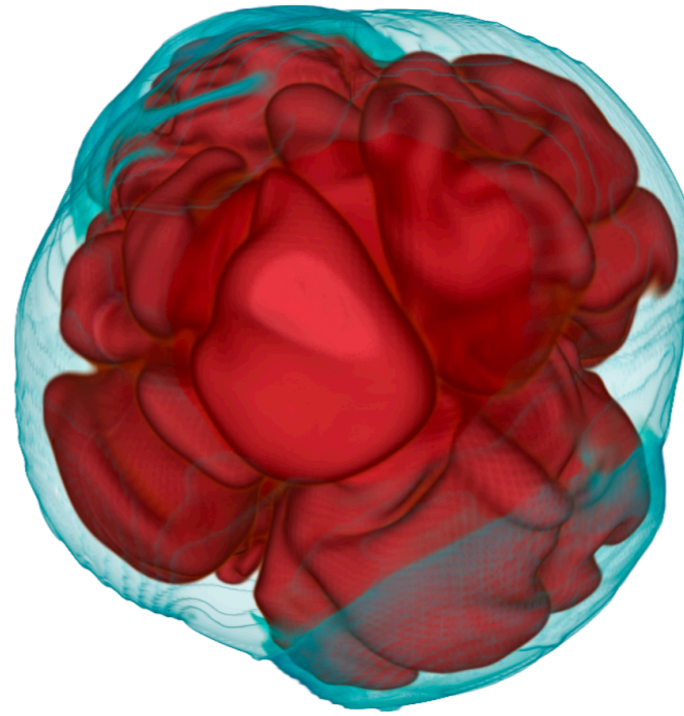
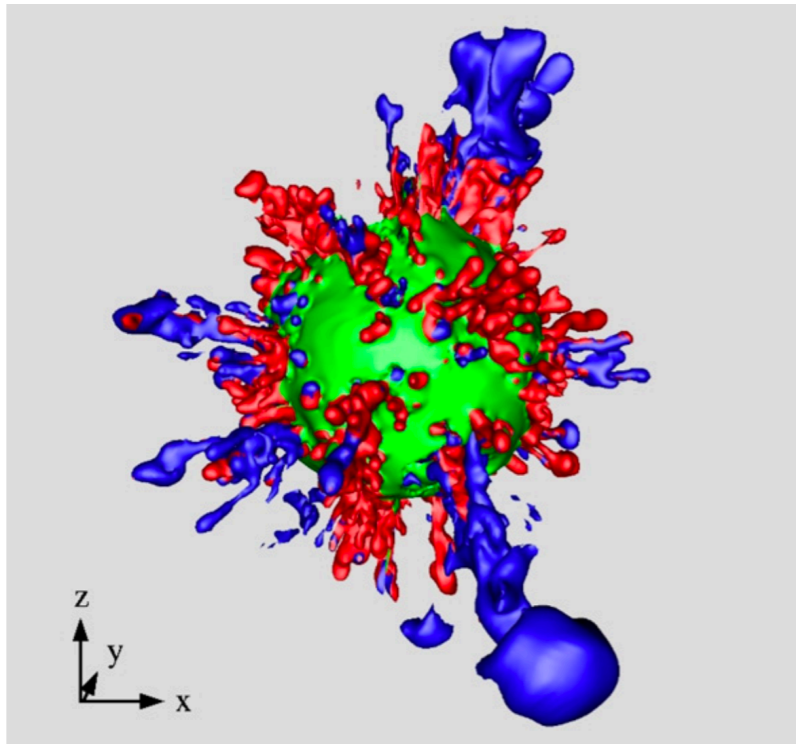
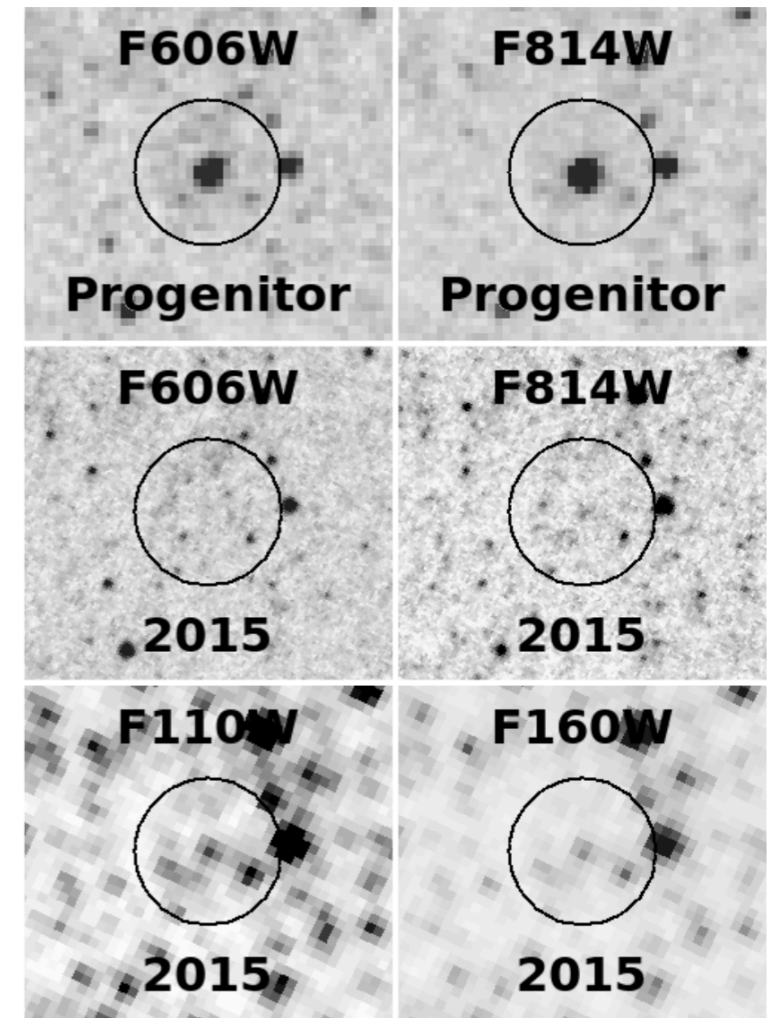


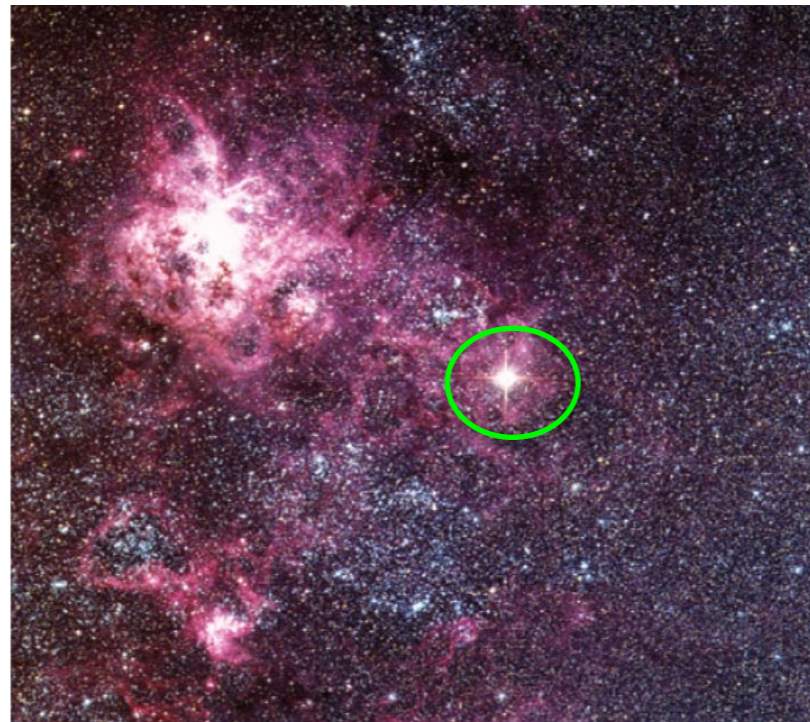
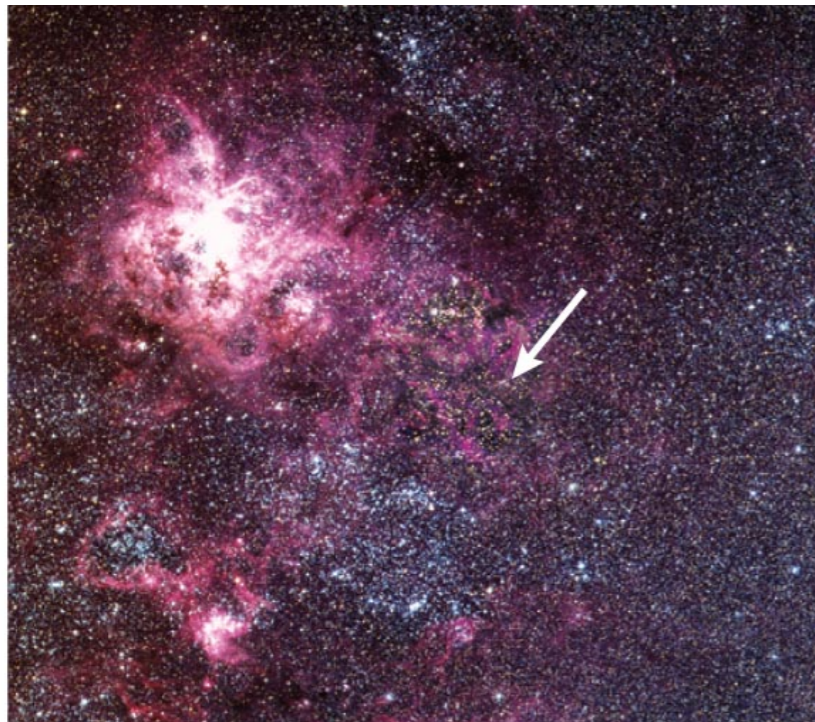
Hammer et al. (2009)



Vartanyan et al. (2022)



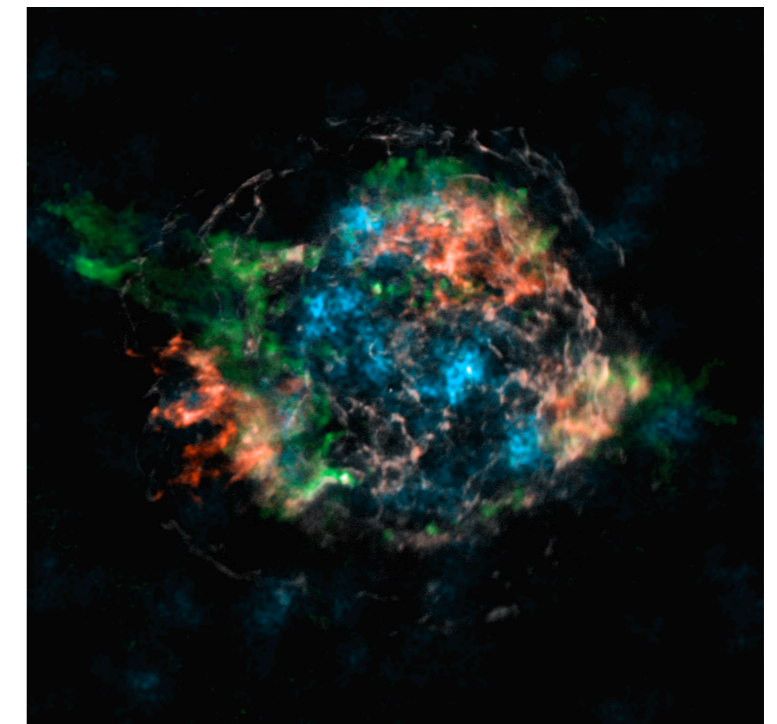
Adams+ (2017): N6946-BH1



SN 1987A (ESO)

Supernovae I

Rodrigo Fernández (University of Alberta)



Grefenstette et al. (2014)

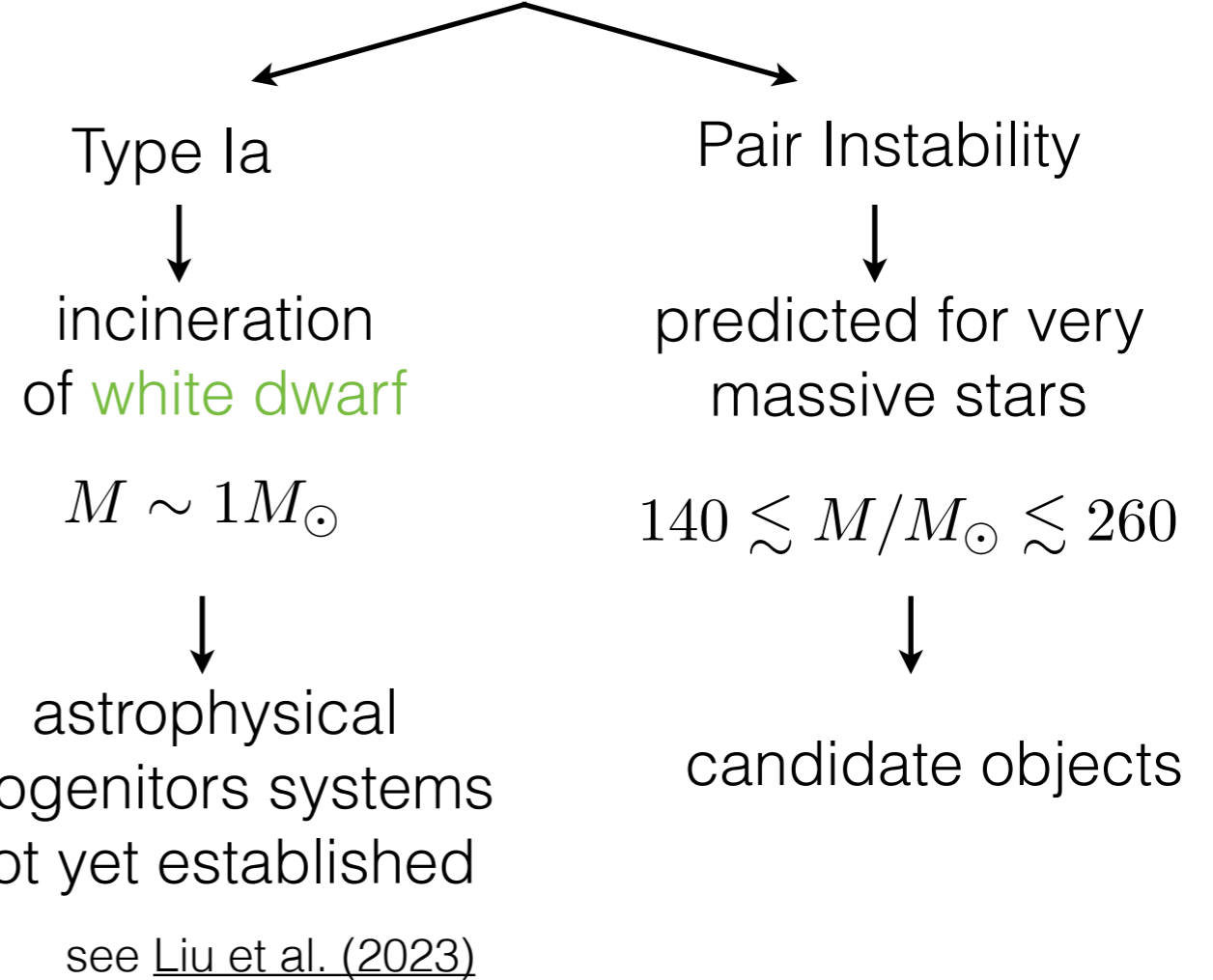
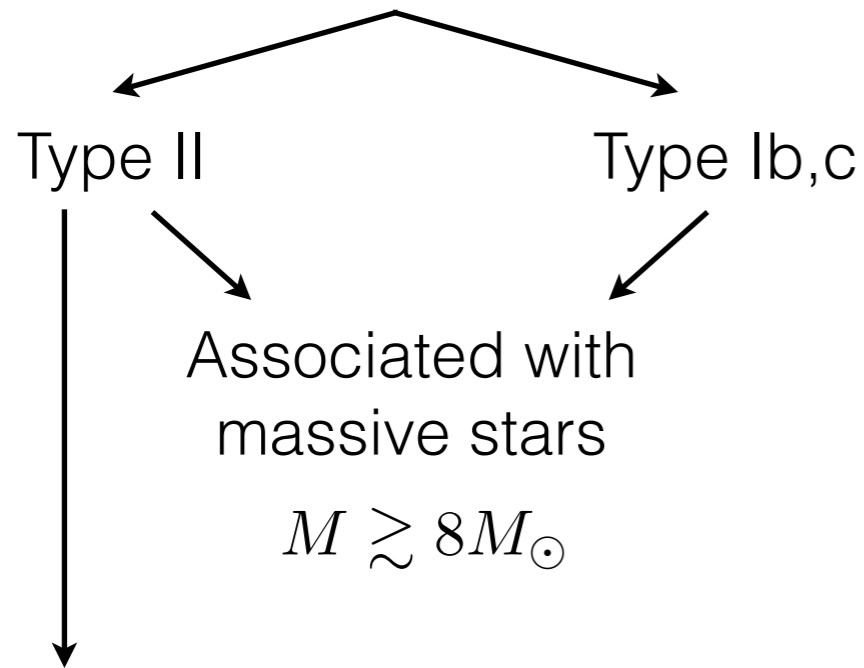
Outline

- 1) Supernovae: Thermonuclear vs Gravitational
- 2) Pair-Instability Supernovae
- 3) Progenitors & Core-Collapse
- 4) Delayed Neutrino Explosions
- 5) Shock propagation into stellar envelope
- 6) BH-forming Supernovae
- 7) Phase Transition aided Explosions
- 8) Remnants: NS or BH & Kicks

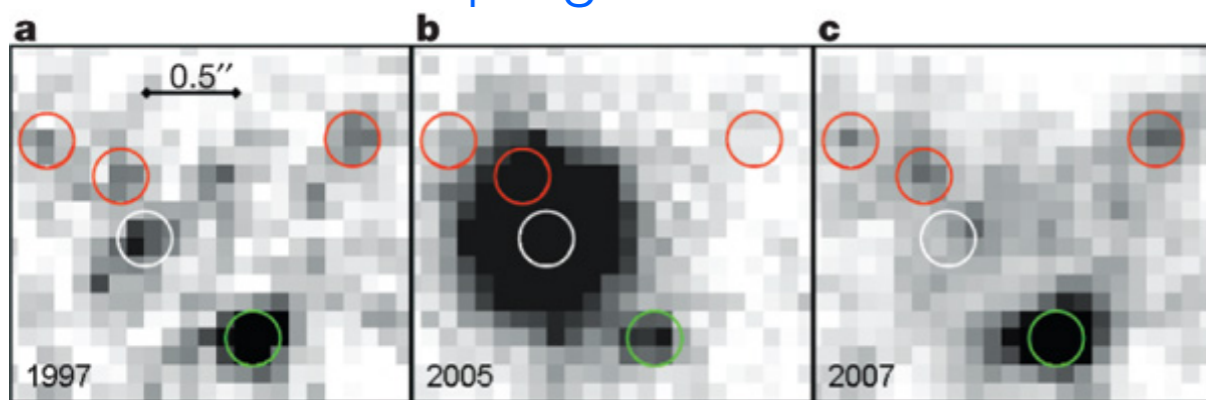
Supernovae: Classification

Core-Collapse

Thermonuclear



several systems with confirmed progenitors:



SN 2005gl (Gal-Yam & Leonard 2009)

see [Liu et al. \(2023\)](#)

Pair Instability Supernovae

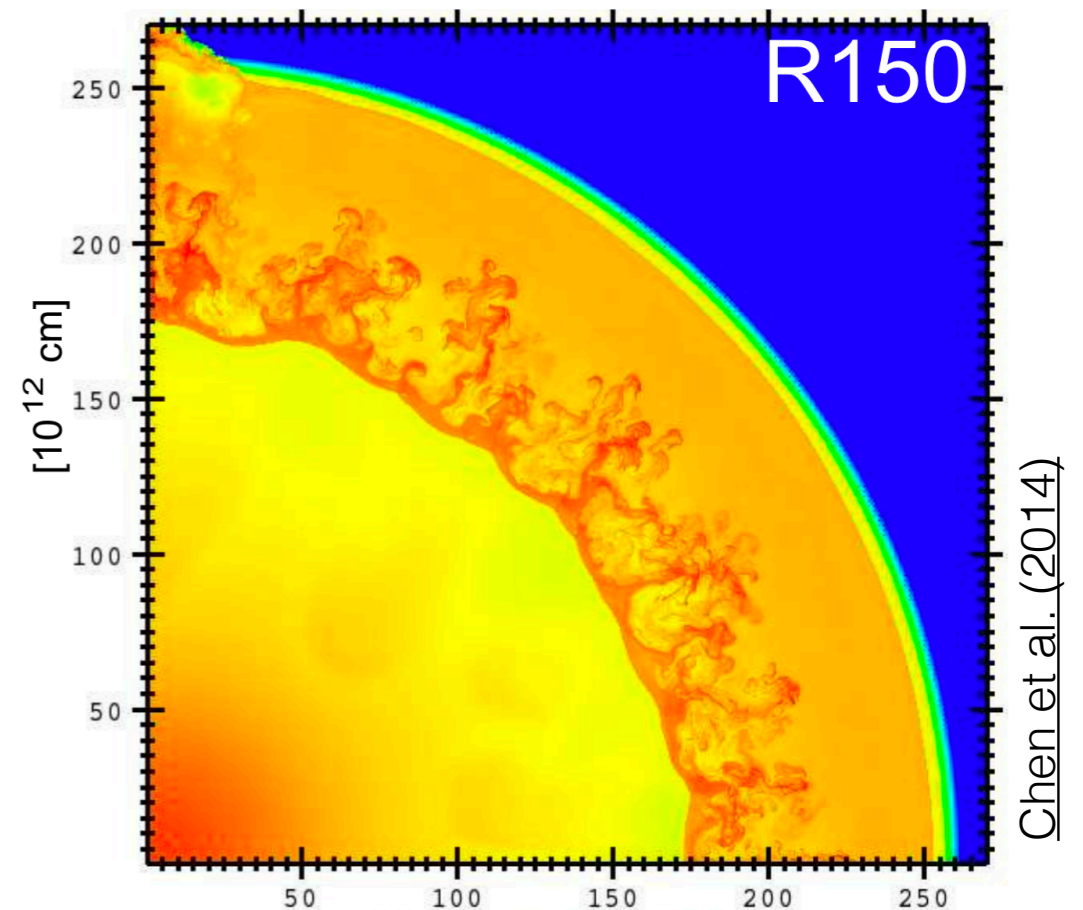
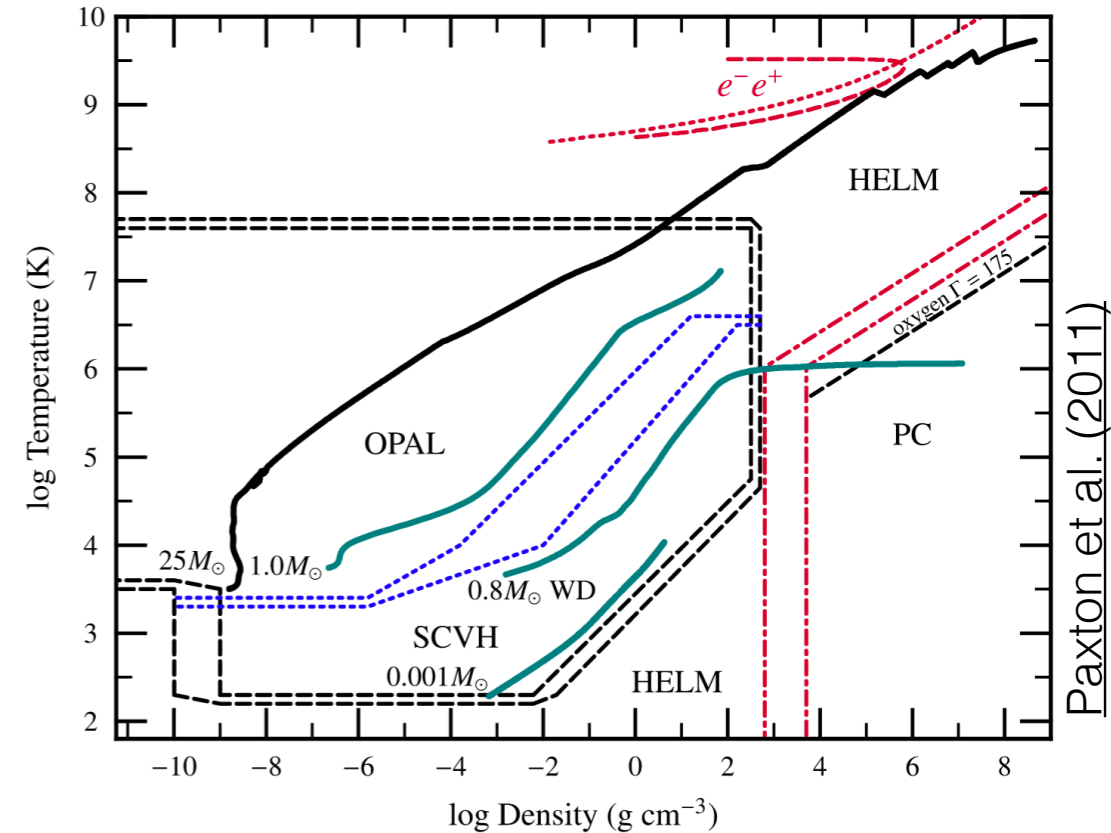
Stars in the ZAMS range:

$$140 \lesssim M/M_{\odot} \lesssim 260$$

(for solar metallicity), encounter a region of thermodynamic space where it is energetically convenient to **convert photons to e^+e^- pairs, which removes pressure support** and causes the star to collapse ($pc/E < 1$ for non-zero m).

Explosive burning of oxygen or silicon (depending on mass) due to the temperature overshoot from hydrostatic equilibrium then explode the star, leaving no remnant behind. **For masses above the upper limit, explosive burning cannot reverse the collapse and a BH forms with no mass ejection.**

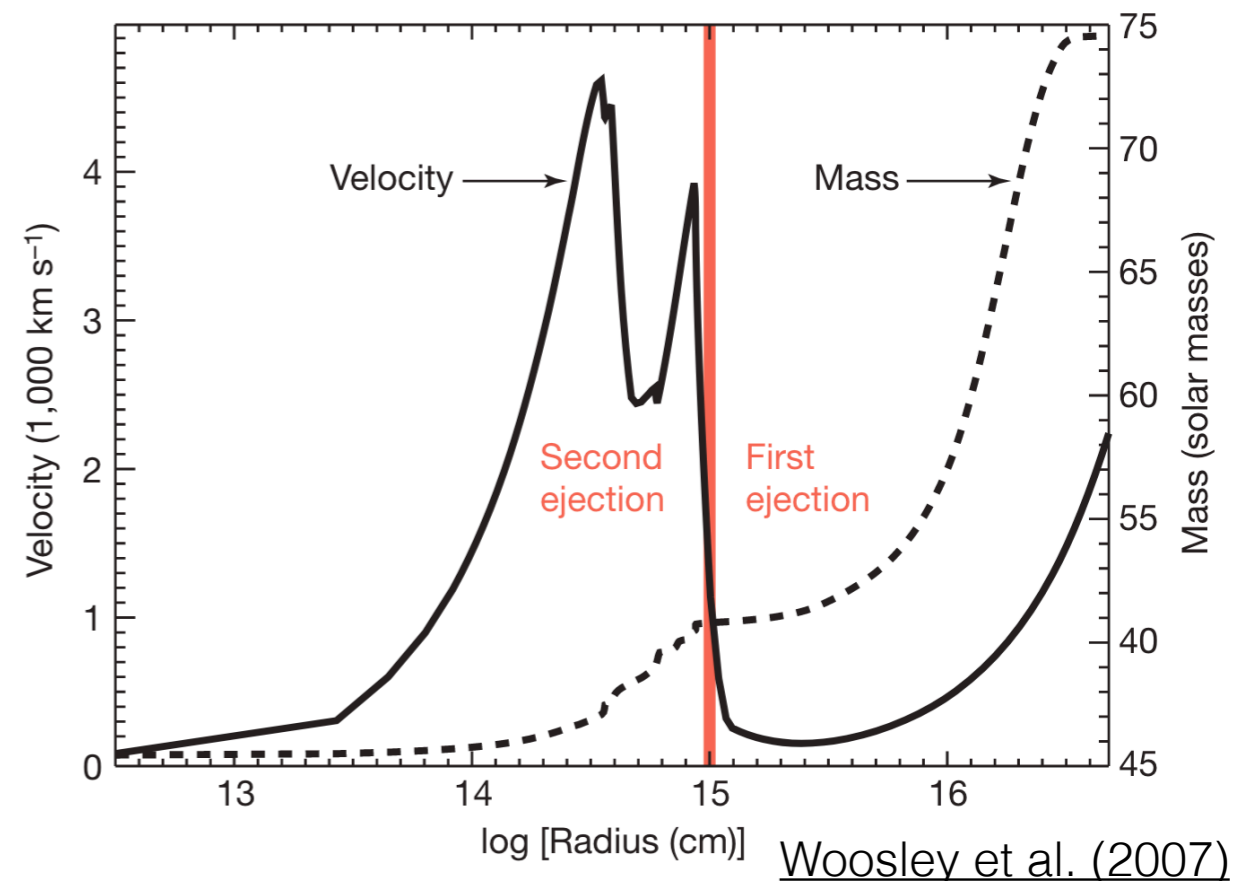
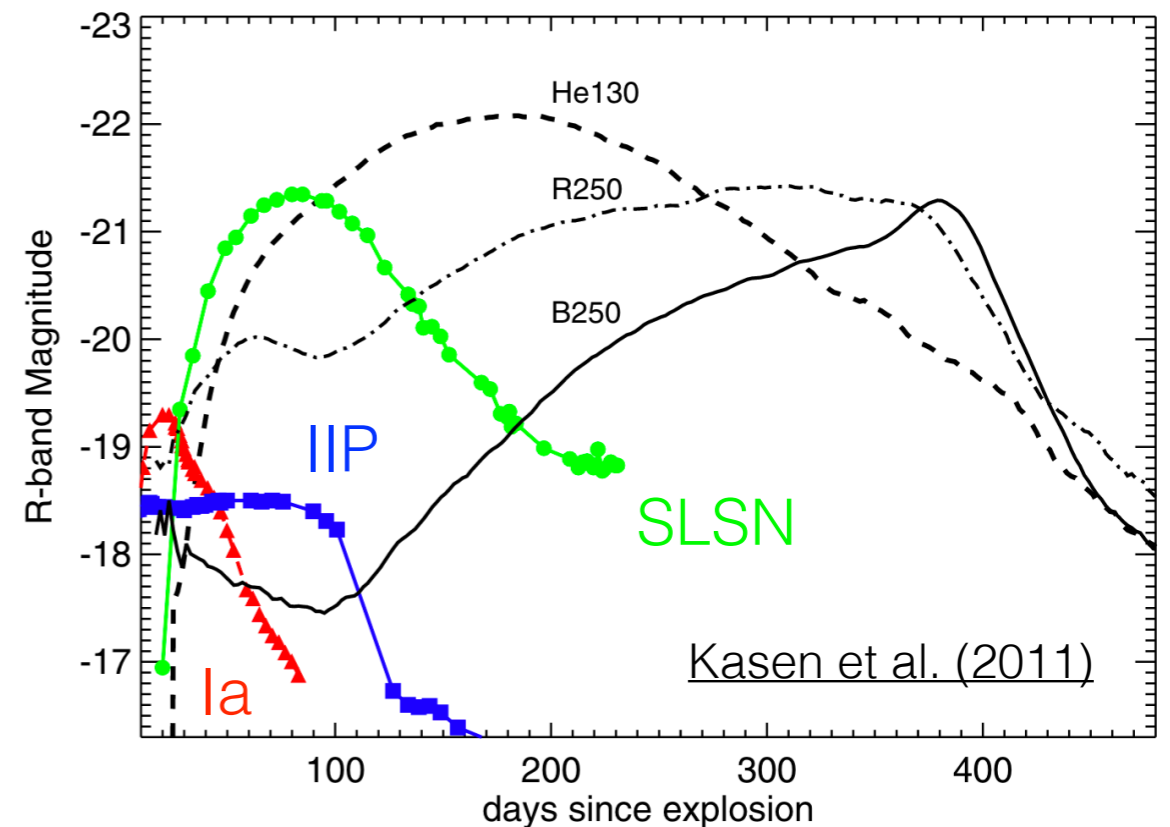
Fryer et al. (2001)



Pair Instability Supernovae

PISN produce **large ejecta masses** ($> 50M_{\text{sun}}$) hence their light curves peak over a timescale of $\sim 1\text{yr}$. The ^{56}Ni mass ejected can range from zero to several $10M_{\text{sun}}$, hence there is a **very wide range in (predicted) luminosities**, even exceeding the most luminous supernovae yet observed.

Around the lower mass end, explosive burning does not disrupt the star, leading to a subsequent collapse(s) due to pair instability, and more explosive burning. These are called **pulsational pair instability supernovae** when a terminal pulse occurs (stars can also move to regular core-collapse evolution).

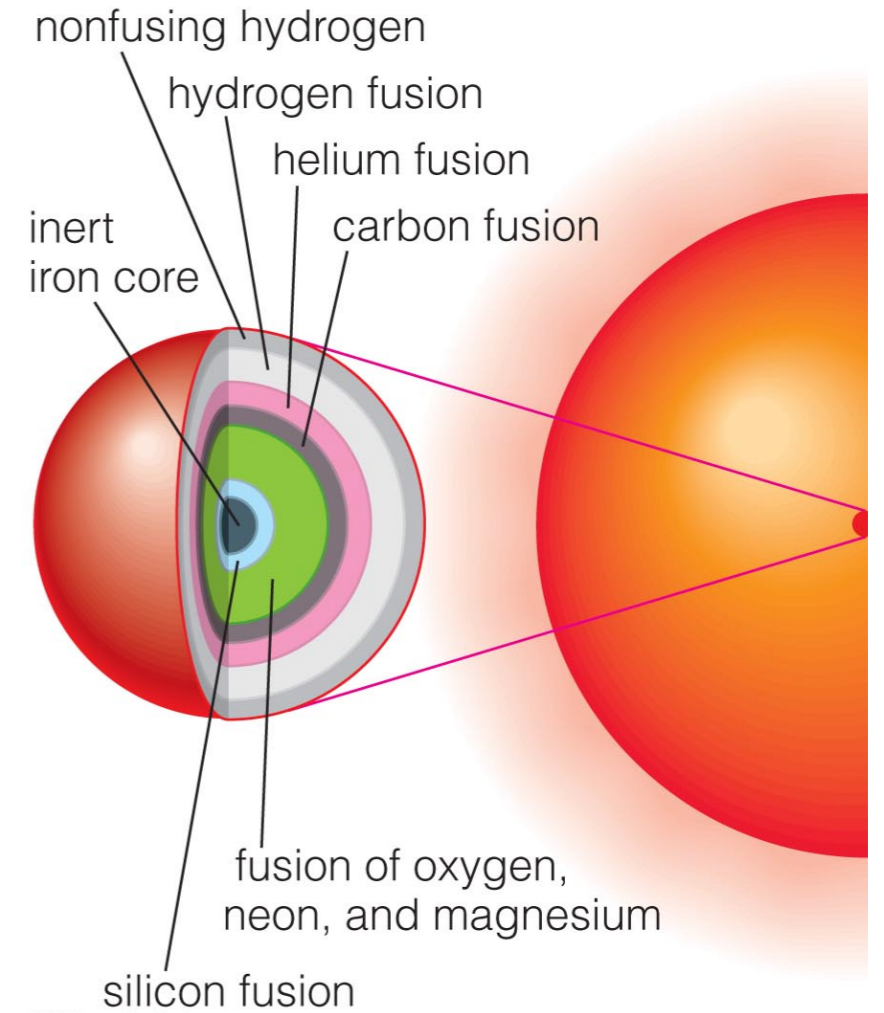


Pre-supernova Evolution

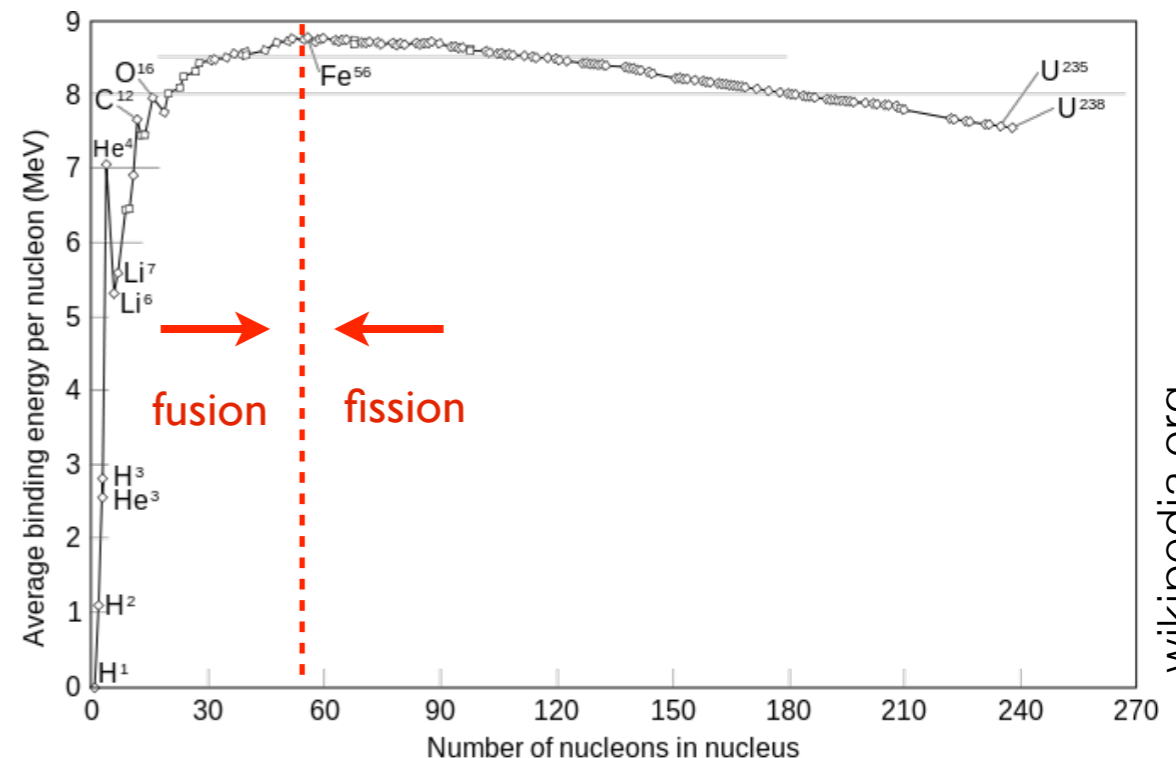
Stars that do not encounter the pair instability, go through advanced burning stages of increasingly heavier elements.

Stars more massive than about $10M_{\text{sun}}$ at solar metallicity reach silicon burning, generating a **degenerate iron core**.

Since iron and surrounding elements are the most tightly bound nuclei, **no more energy can be produced by nuclear fusion**, and the core grows in mass (due to continuous silicon burning), being supported against gravity primarily by electron degeneracy pressure.



credit: Pearson Education



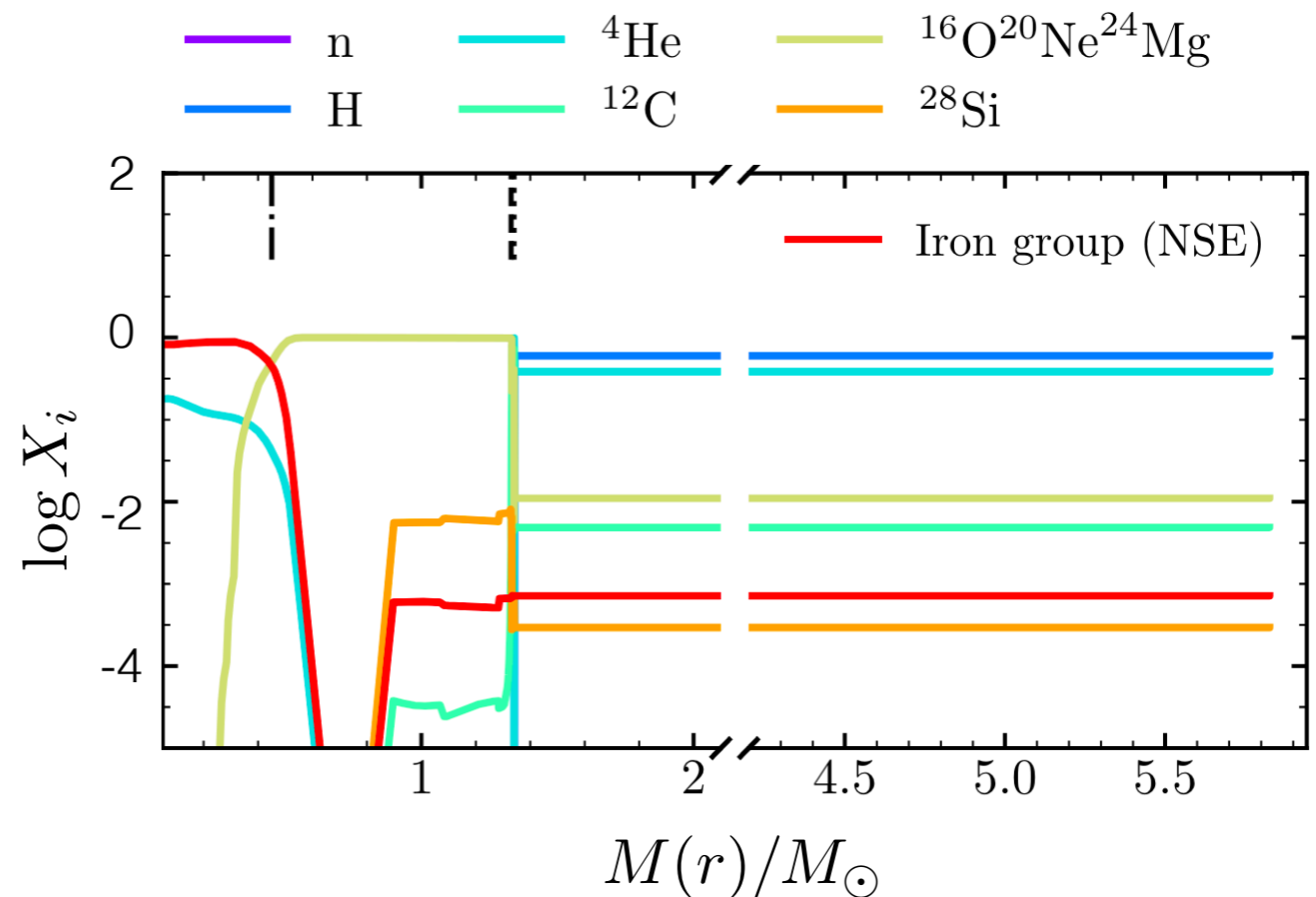
wikipedia.org

Pre-supernova Evolution

Stars with initial masses in the range $8-10M_{\text{sun}}$ at solar metallicity form a **degenerate ONeMg core**. Two things can happen:

1) At the lower mass end, an **ONeMg white dwarf** is left behind, ejecting the outer stellar layers. This is usually called a “super-AGB” star.

2) For higher masses, the ONeMg core undergoes runaway electron capture and collapses on a dynamical time. This outcome is usually called an **electron-capture supernovae (ECSN)**. The evolution after collapse is **conceptually similar to iron core-collapse**, with some notable differences due to the stellar structure outside the core that justify the use of the nomenclature.



Stockinger et al. (2020)

Pre-supernova Progenitors: Evolution

There are 3 main uncertainties in stellar evolution of pre-supernova progenitors:

1) **Mass loss**, particularly episodic mass ejection prior to explosion, there's evidence for mass loss beyond what can be accounted for by traditional line-driven winds.

e.g., [Smith \(2014\)](#)

2) **Binary evolution**: broad parameter space, and some processes like common-envelope are not well understood at a fundamental level.

e.g., [Laplace et al. \(2021\)](#), [Marchant & Bodensteiner \(2023\)](#)

3) **Turbulent transport processes**: 1D stellar models that advance on the thermal time scale treat convection and other mixing processes using Mixing Length Theory (MLT) and diffusion approximations. Multi-dimensional simulations that resolve the hydrodynamic timescale have shown that these approximations must be improved upon.

e.g., [Lecoanet & Edelmann \(2023\)](#), [Herwig et al. \(2023\)](#)

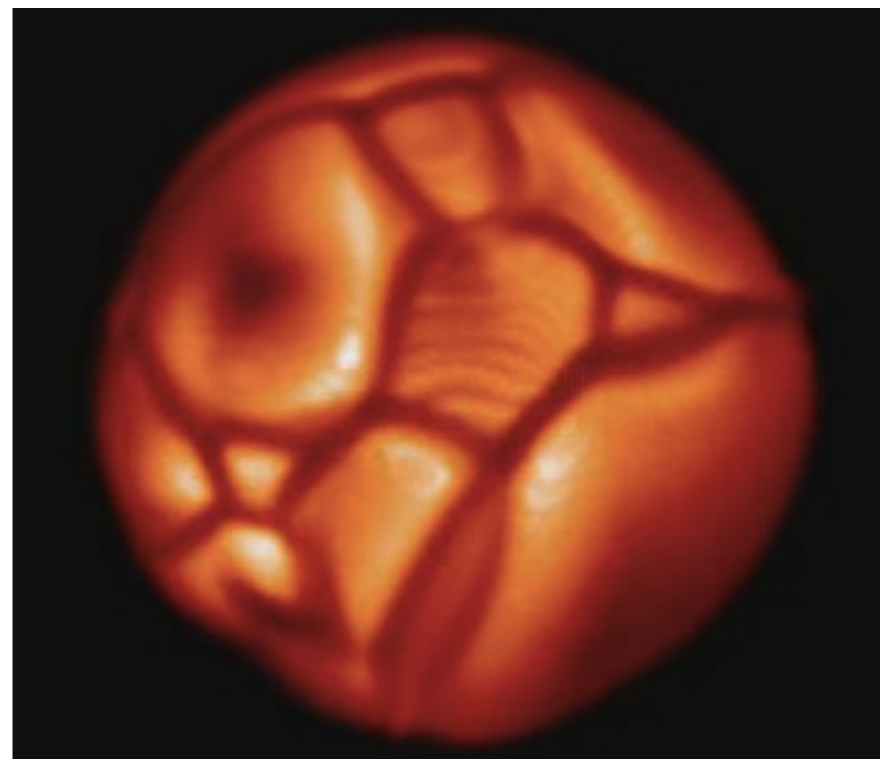
Pre-supernova Progenitors: Envelopes

Depending on the mass and composition (luminosity and opacity), there are 3 possible post main sequence states:

- 1) **Red Supergiant**: convective H envelope, like a red giant or AGB but with much higher luminosity (i.e. Betelgeuse).
At solar metallicity, occurs for about $8 < M/M_{\text{sun}} < 20$

Surface temperatures
of red supergiants
are in the range
3000K - 5000K

e.g., [Woosley et al. \(2002\)](#)



credit: Bernd Freytag

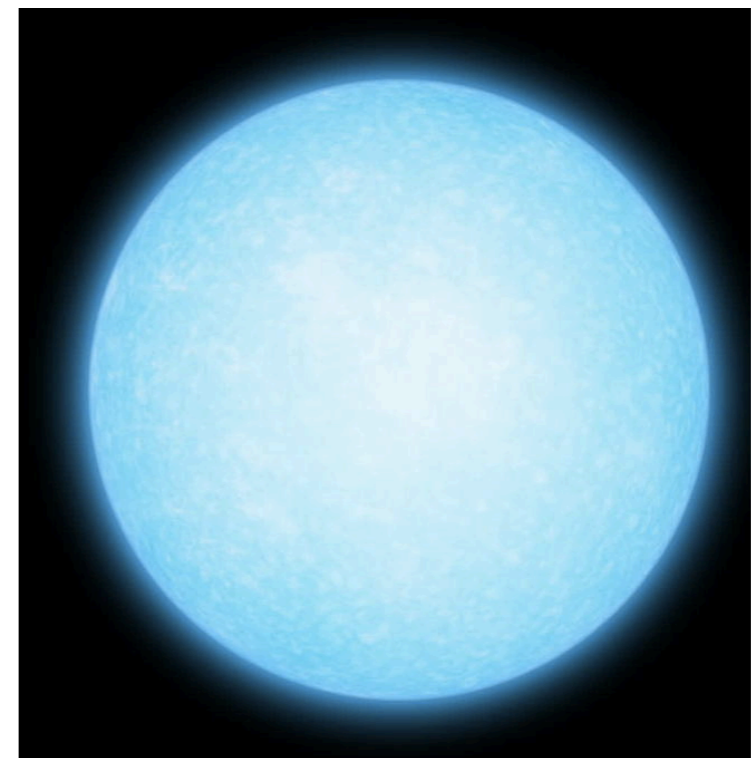
Pre-supernova Progenitors: Envelopes

Depending on the mass and composition (luminosity and opacity), there are 3 possible post main sequence states:

2) **Blue Supergiant**: radiative envelope, need lower opacity so it is more frequent in lower metallicity stars and some in the range $\sim 20\text{-}30M_{\text{sun}}$, sensitive to treatment of mixing in stellar models (example: Rigel)

Surface temperatures of blue supergiants are in the range 10,000K - 50,000K

e.g., [Woosley et al. \(2002\)](#)



credit: sciencesource.com

Pre-supernova Progenitors: Envelopes

Depending on the mass and composition (luminosity and opacity), there are 3 possible post main sequence states:

3) **Wolf-Rayet**: ejected all of its H envelope due to powerful stellar winds, so it is much hotter and compact than blue or red supergiants. At solar metallicity, occur above $\sim 30M_{\text{sun}}$

Surface temperatures of Wolf-Rayet stars can exceed 100,000K

e.g., [Woosley et al. \(2002\)](#)



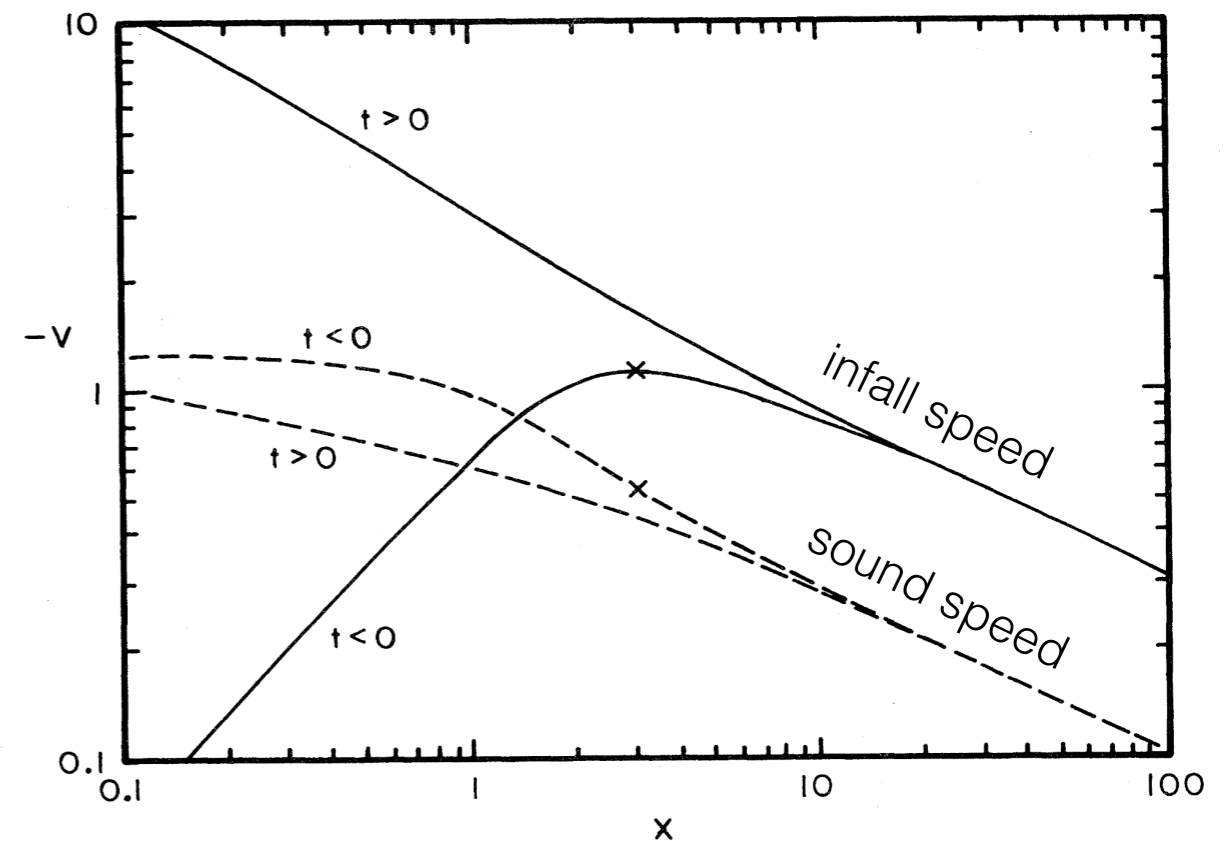
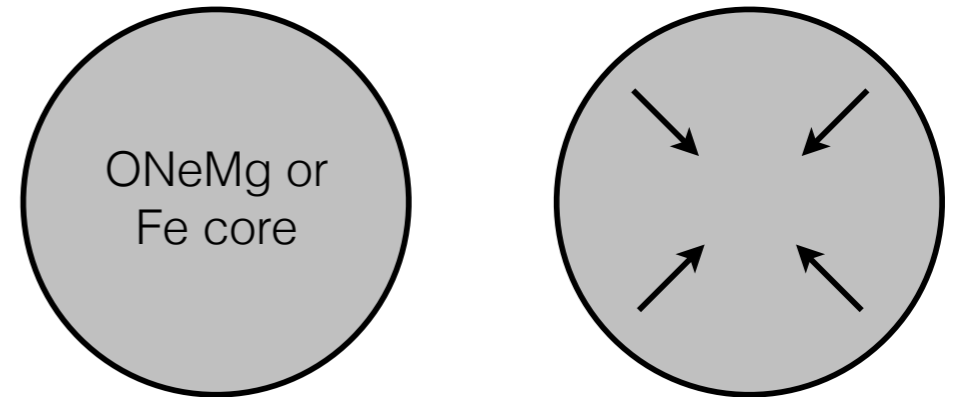
nasa.gov (M1-67, WR 124)

Core Collapse and Bounce

Once collapse sets in, the dynamics proceeds on the dynamical time for a core of mass $\sim 1.4M_{\text{sun}}$ and radius 2000km:

$$t_{\text{dyn}} \sim 1 \text{ s} \left(\frac{M}{1.4 M_{\odot}} \right)^{-1/2} \left(\frac{R}{2000 \text{ km}} \right)^{3/2}$$

Collapse proceeds self-similarly, with the inner regions contracting subsonically and with velocity proportional to radius (“homologous collapse”). The contraction speed reaches a peak above the sound speed: **the outer core collapses supersonically.**



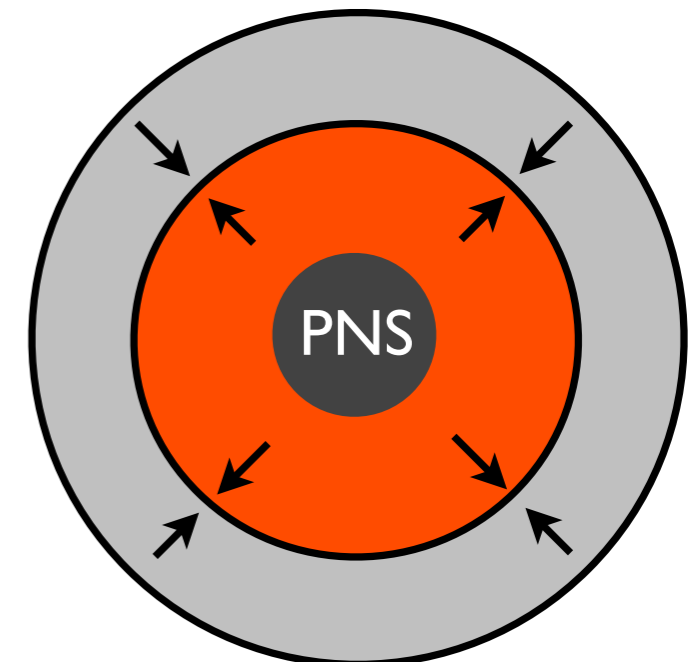
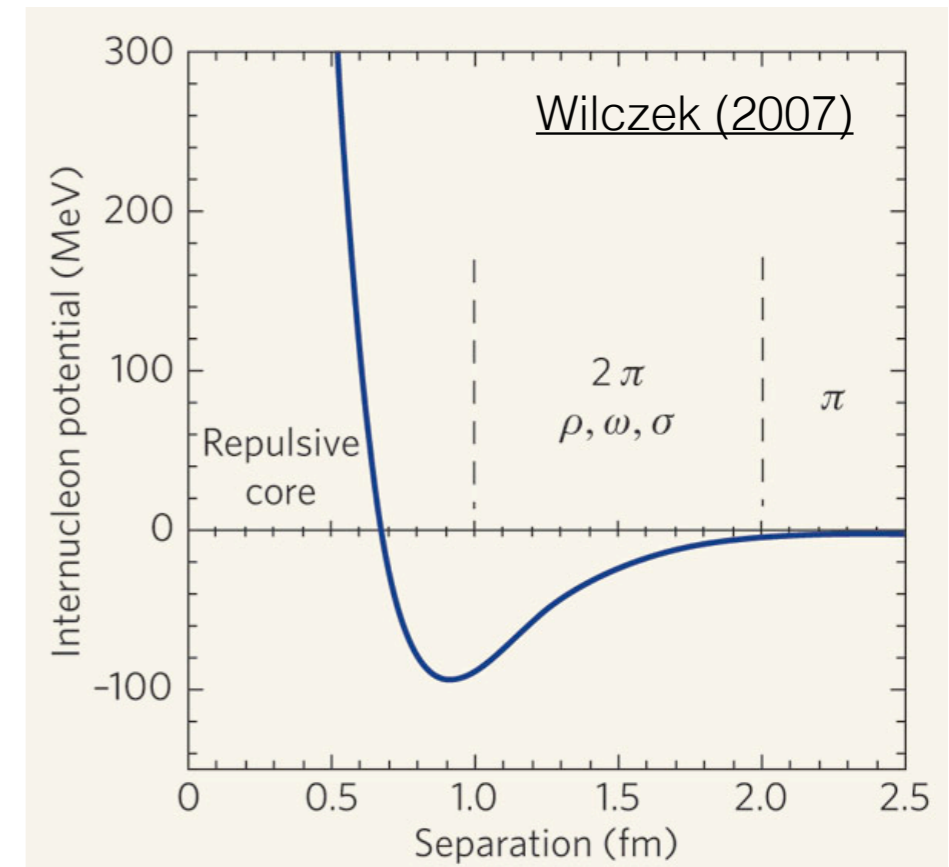
Core Collapse and Bounce

When the center of the core reaches densities around those of atomic nuclei

$$\rho_{\text{nuc}} \simeq 2.5 \times 10^{14} \text{ g cm}^{-3}$$

the equation of state stiffens, increasing the pressure faster for a given density change, relative to lower densities. This is quantified by the adiabatic index $\Gamma \sim \rho \frac{dP}{d\rho}$. This stiffening is due to the fact that the **strong interaction becomes repulsive at very short distances**.

This results in a **hydrodynamic pulse (sound wave) emerging from the core** due to the slow down. The sound wave stiffens into a shock once it reaches the supersonically collapsing regions (the “bounce shock”).

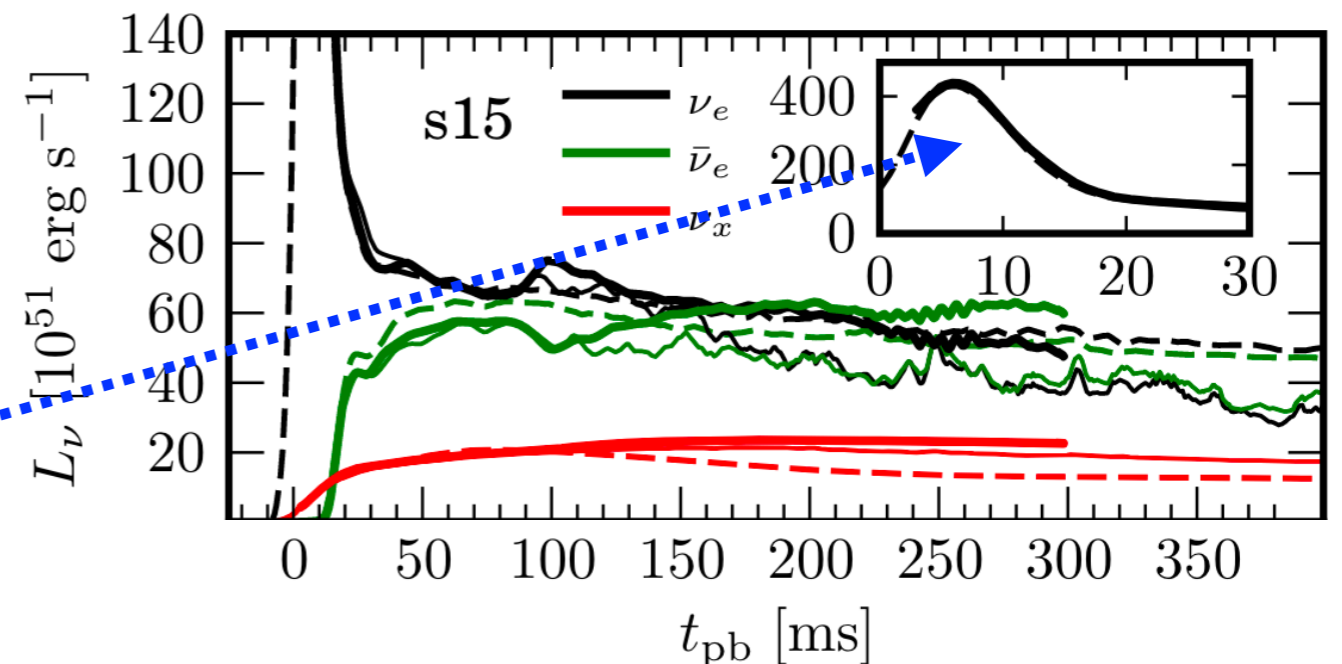
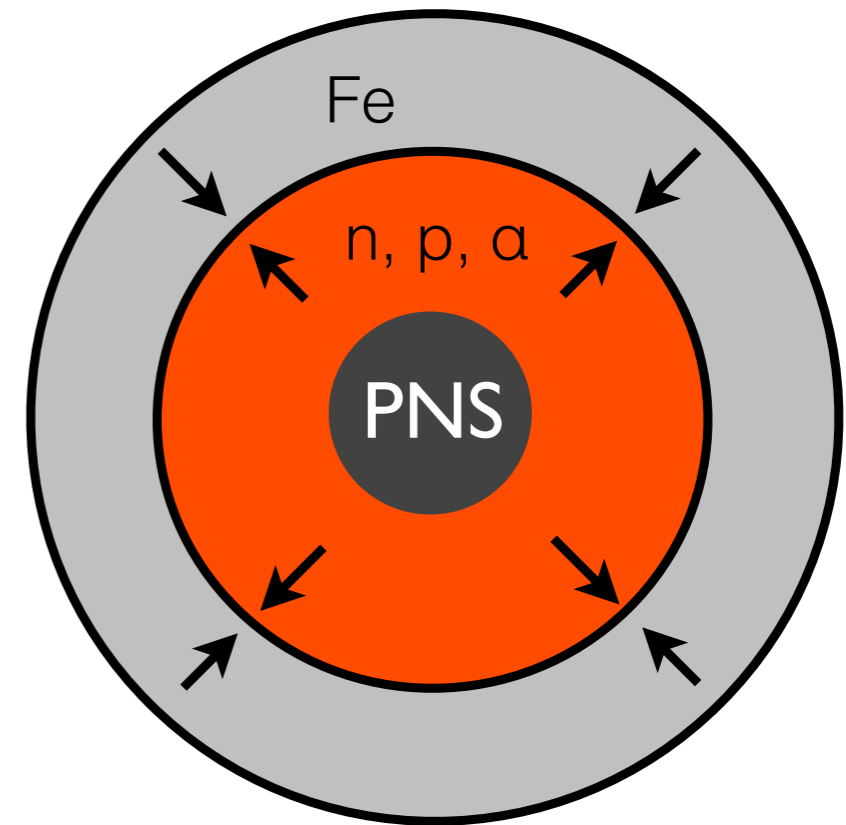


Core Collapse and Bounce

The outgoing shock stalls on its way out due to energy losses from dissociation of heavy nuclei falling through it and neutrino emission.

Dissociation of a heavy nucleus **costs the nuclear binding energy of the nucleus** ($\sim 8-9$ MeV/nucleon), which decreases the internal energy.

Electron neutrinos (produced by e^- capture on p) initially trapped behind the shock, are suddenly released once the shock reaches optically thin regions: **electron neutrino burst**.

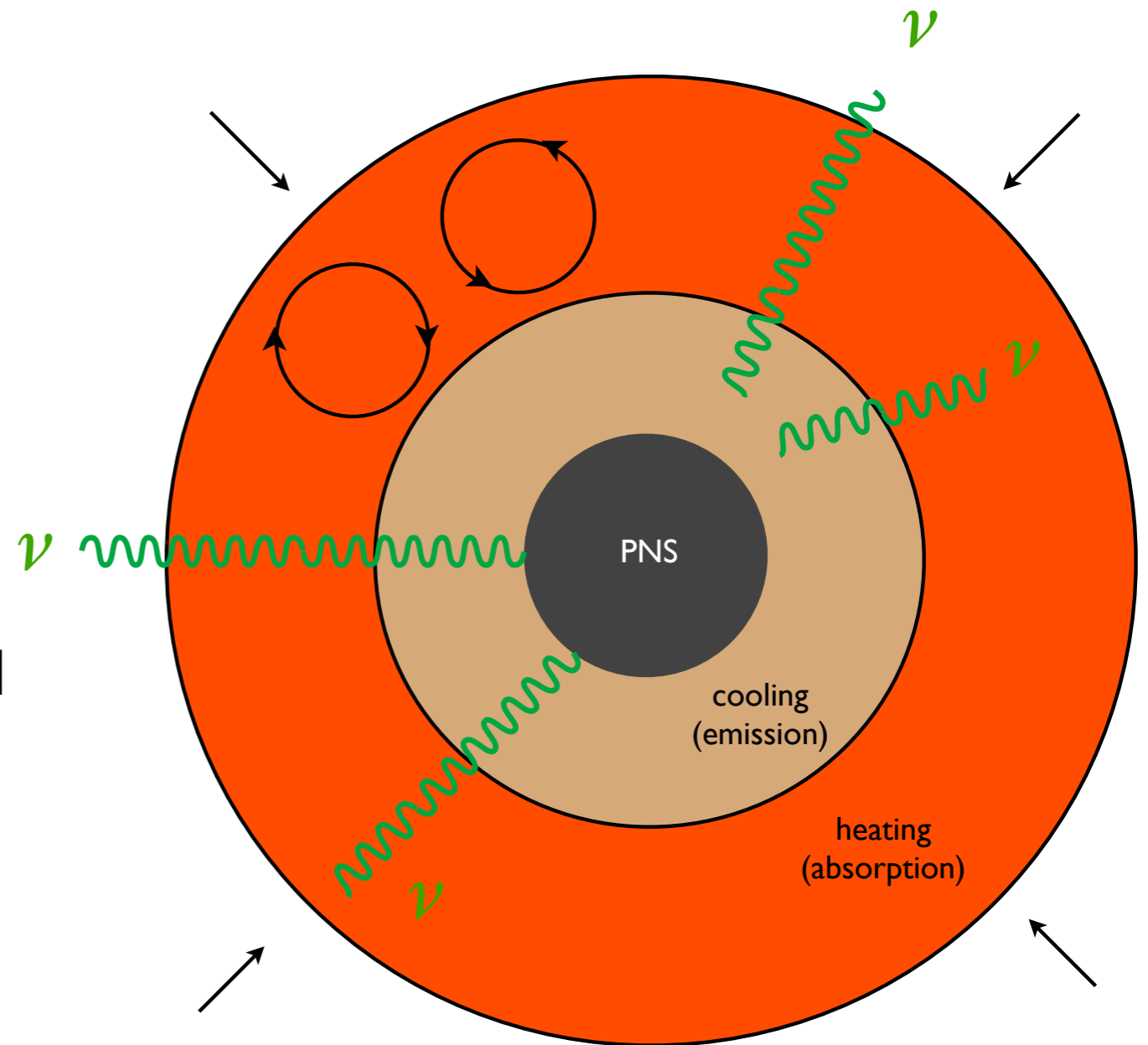


Delayed Neutrino Mechanism

The stalled shock **needs additional energy to be revived** in order for a successful explosion to occur.

In the absence of additional effects like rapid rotation, the default explosion mode is the **delayed neutrino mechanism**.

A fraction $\sim 1\%$ of neutrinos emitted by the dense core (proton-neutron star) and by accretion, are re-absorbed **in a layer just behind the shock where heating dominates cooling** (the “gain” layer).



Delayed Neutrino Mechanism: Numbers

Available energy: $\frac{GM_{\text{PNS}}^2}{R_{\text{PNS}}} \sim 10^{53} \left(\frac{M_{\text{PNS}}}{M_{\odot}}\right)^2 \left(\frac{30 \text{ km}}{R_{\text{PNS}}}\right) \text{ erg}$ plenty!

Average density: $\bar{\rho} \sim \frac{M_{\text{PNS}}}{R_{\text{PNS}}^3} \sim 10^{14} \left(\frac{M_{\text{PNS}}}{M_{\odot}}\right) \left(\frac{30 \text{ km}}{R_{\text{PNS}}}\right)^3 \text{ g cm}^{-3} \sim \rho_{\text{nuc}}$ nuclear physics

Neutrinos: $\sigma_{\nu} \simeq 10^{-42} \left(\frac{\varepsilon_{\nu}}{10 \text{ MeV}}\right)^2 \text{ cm}^2$

$$\tau_{\text{PNS}} \sim \frac{R_{\text{PNS}}}{\ell_{\text{mfp}}} \sim \left(\frac{\bar{\rho}}{m_n}\right) \sigma_{\nu} R_{\text{PNS}} \sim 100$$

neutrino transport
(radiation hydro)

$$\tau_{\text{shock}} \sim 0.01 \left(\frac{\rho_{\text{shock}}}{10^9 \text{ g cm}^{-3}}\right) \left(\frac{R_{\text{shock}}}{150 \text{ km}}\right)$$

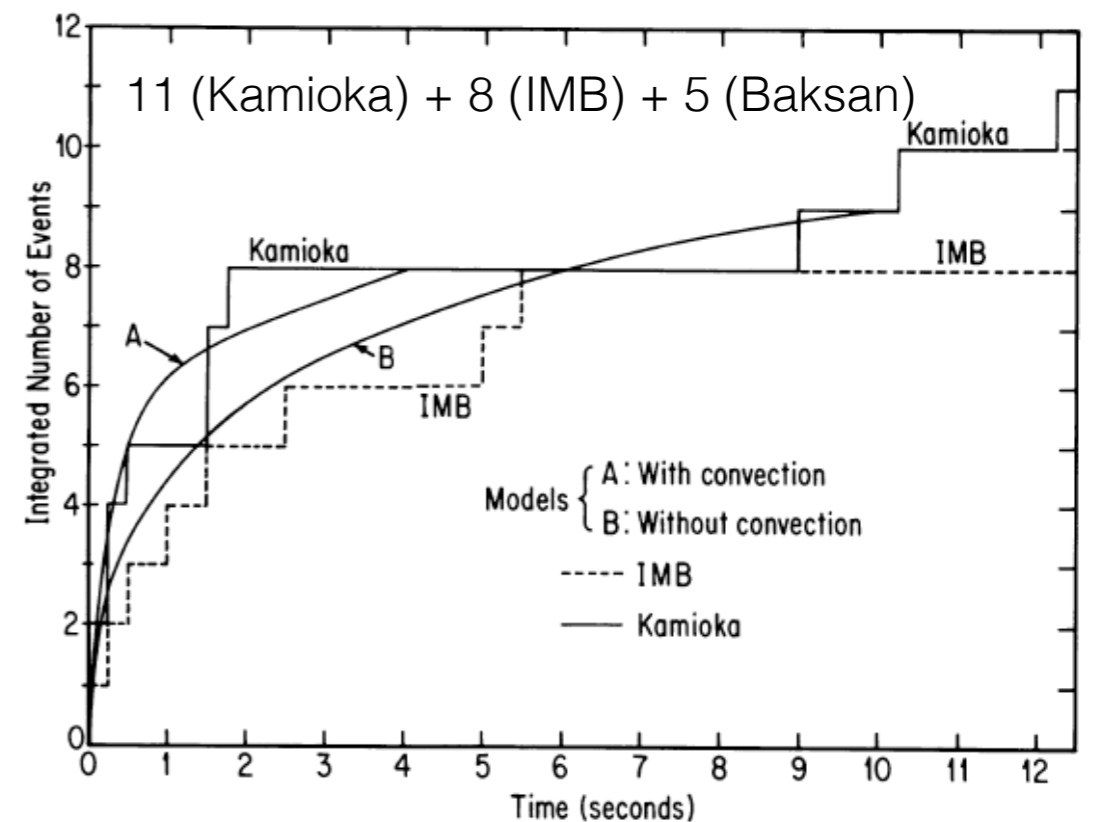
↑
small number: sensitive to details

Delayed Neutrino Mechanism: Evidence

Evidence for the delayed neutrino mechanism comes from **SN 1987A**, the closest core-collapse supernova in the modern era, and the first multi-messenger astrophysical source!



A total of **24 neutrinos** were detected, with a timing consistent with what is expected from the delayed neutrino mechanism (a few hours before electromagnetic detection when the shock breaks out of the stellar surface).



Burrows & Lattimer (1987)

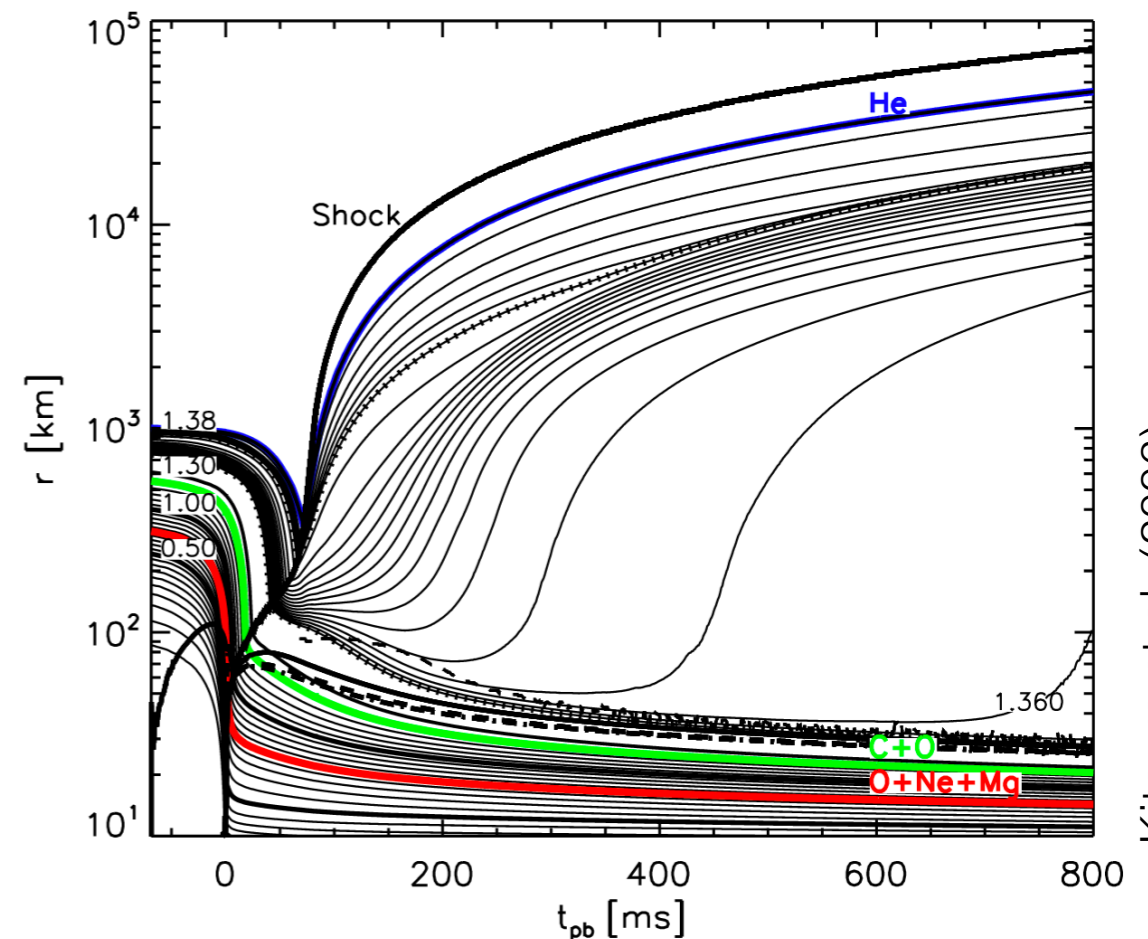
Neutrino Mechanism: ONeMg cores

The delayed neutrino mechanism produces **successful and robust explosions of ONeMg cores**.

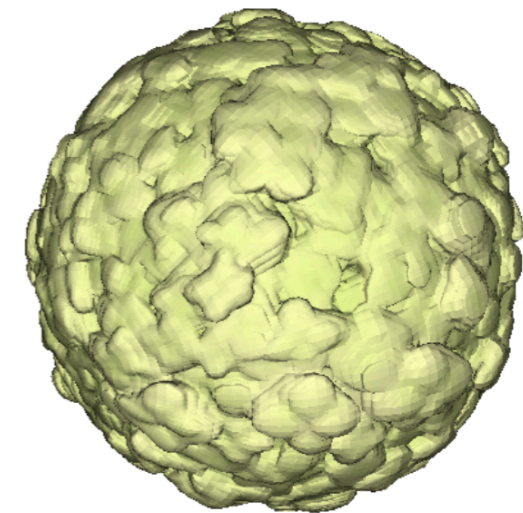
This success is because a **steep decrease of the density outside the degenerate core** makes it easy for the shock to propagate out.

State-of-the-art 3D simulations with neutrino transport have shown that:

- 1) The explosion remains mostly spherical. The low asymmetries imply low NS kick speeds.
- 2) Explosion energies are low, typically 10^{50} erg.



Kitaura et al. (2006)



Ni+Tr 4.7 d e8.8

1.05e09 km

Stockinger et al. (2020)

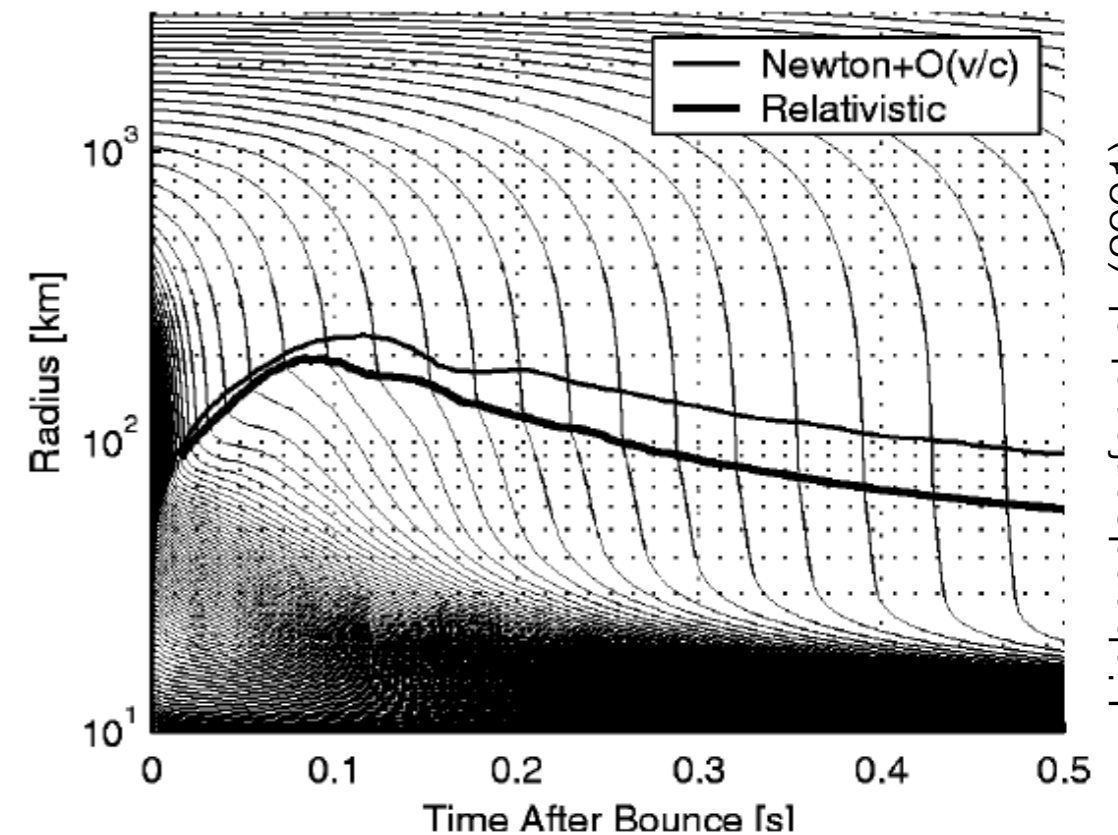
Neutrino Mechanism: Iron cores

In contrast, Fe cores **fail to explode in spherical symmetry (1D)**. All supernova groups that achieved Boltzmann neutrino transport in general relativity obtained the same result.

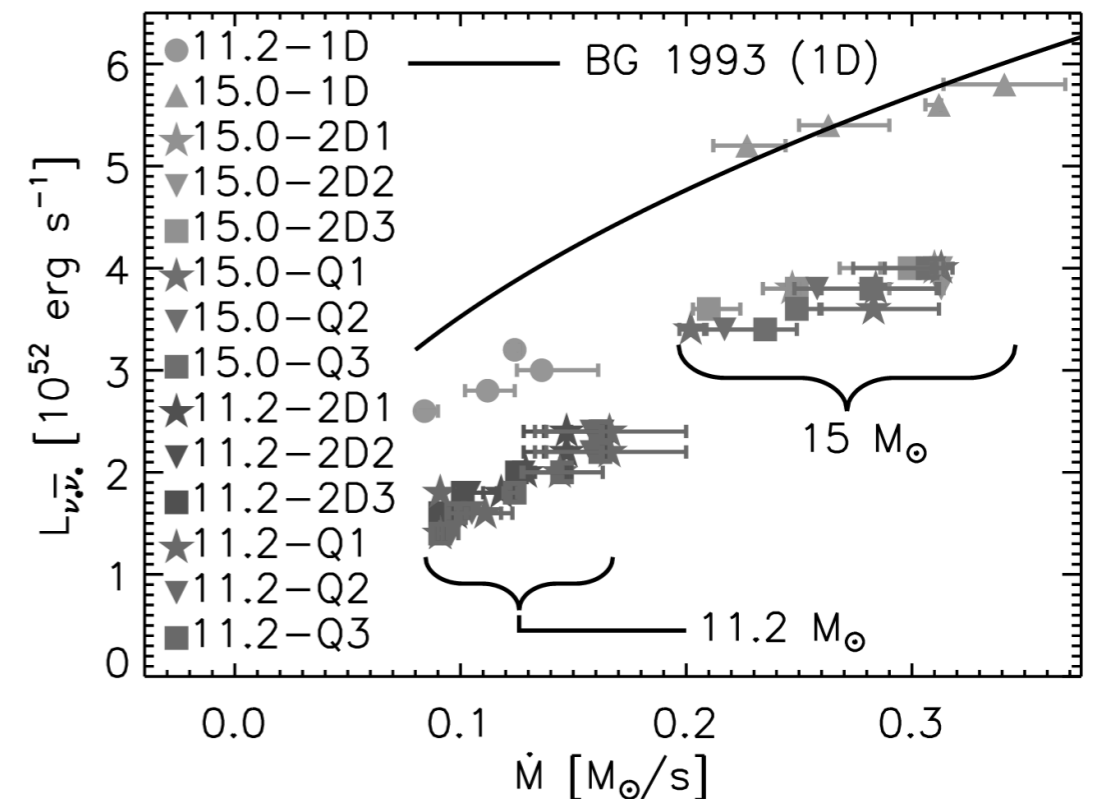
([Liebendörfer et al. 2001](#), [Thompson et al. 2003](#), [Rampp & Janka 2002](#), [Sumiyoshi et al. 2005](#))

The physical reason for the failure is that **in 1D, explosion shuts off accretion and its contribution to the neutrino luminosity** (roughly comparable to that from the core in ν_e and anti- ν_e).

Significant work has been done since the mid 1990s to model CCSNe in 2D or 3D. Parametric models showed that multi-D effects had promise in leading to success.



Liebendörfer et al. (2001)



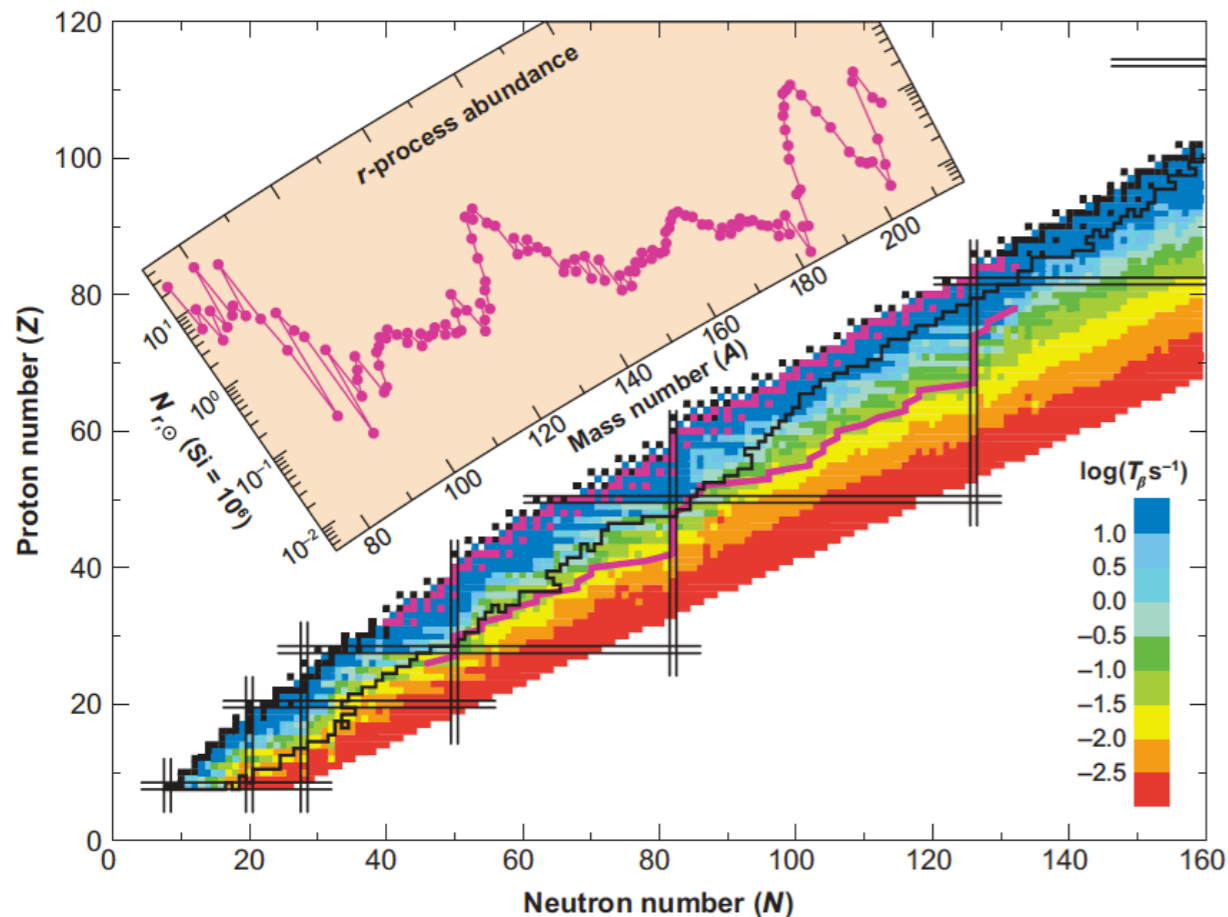
Murphy & Burrows (2008)

r-Process Nucleosynthesis

~50% of elements heavier than Zinc (Z=30) require formation by 'rapid' neutron capture (r-process)

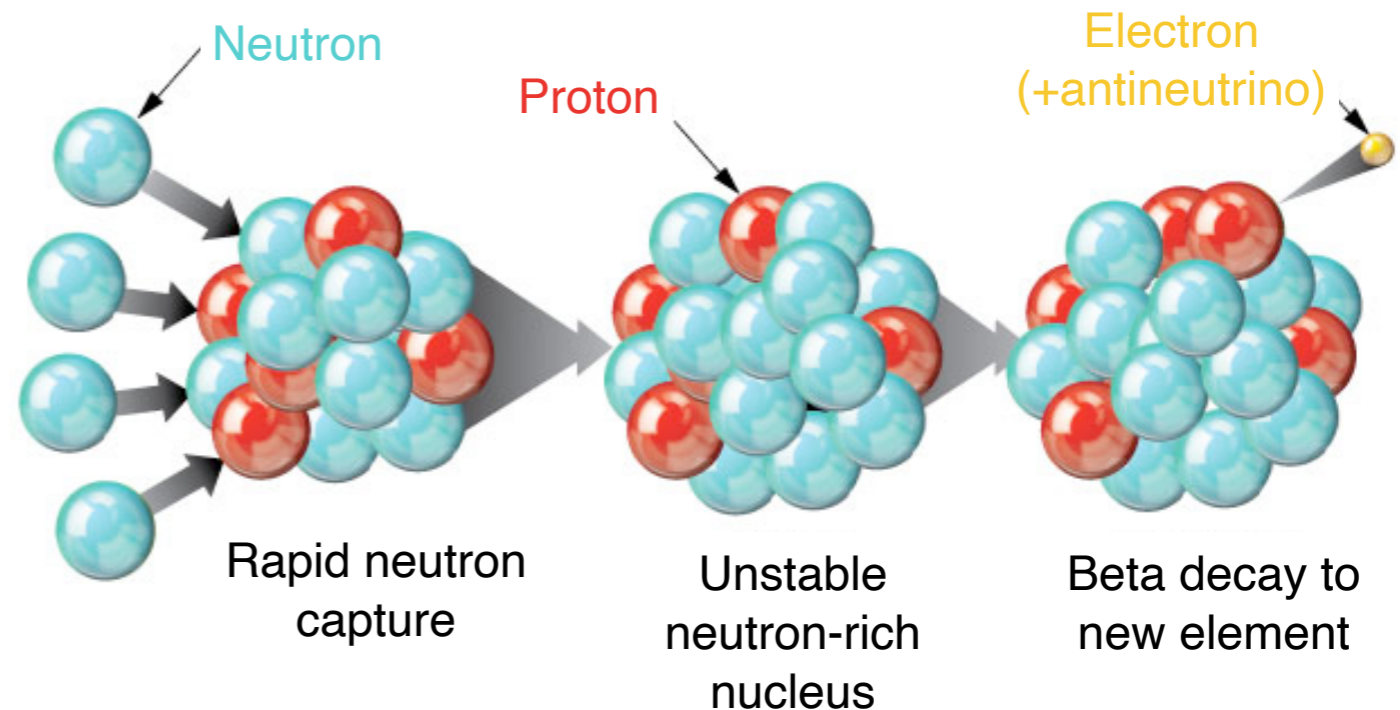
Burbidge et al. (1957), Cameron (1957)

Nuclear Chart & Solar System abundances:



Möller, Nix, & Kratz (1997)

$$t_{n\text{-capture}} \ll t_{\beta\text{-decay}}$$



llnl.gov

Astrophysical sites that meet the conditions:

- 1) Neutron Star Mergers
- 2) Core-Collapse Supernovae