PennState
Eberly College of Science

Explosive Astrophysics: Supernovae

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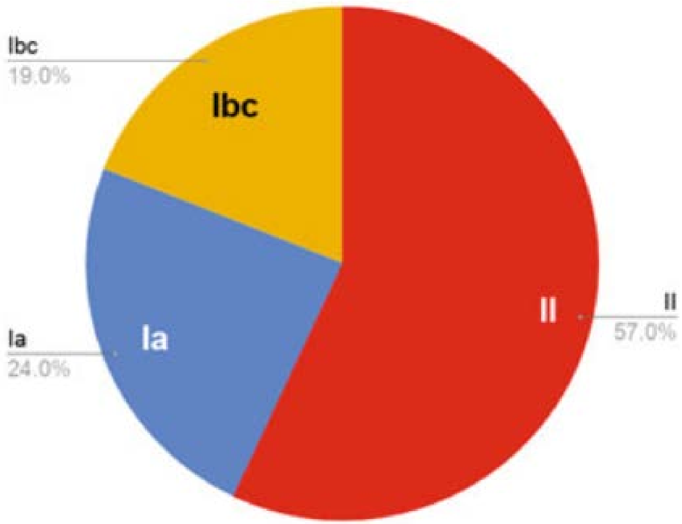
NP3M

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER



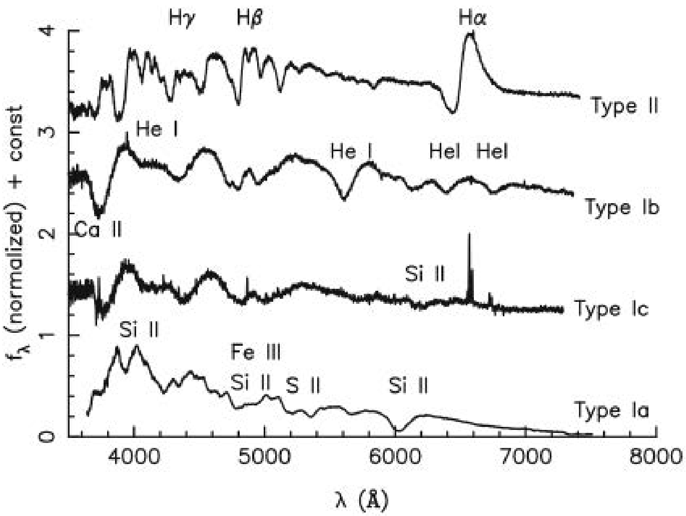
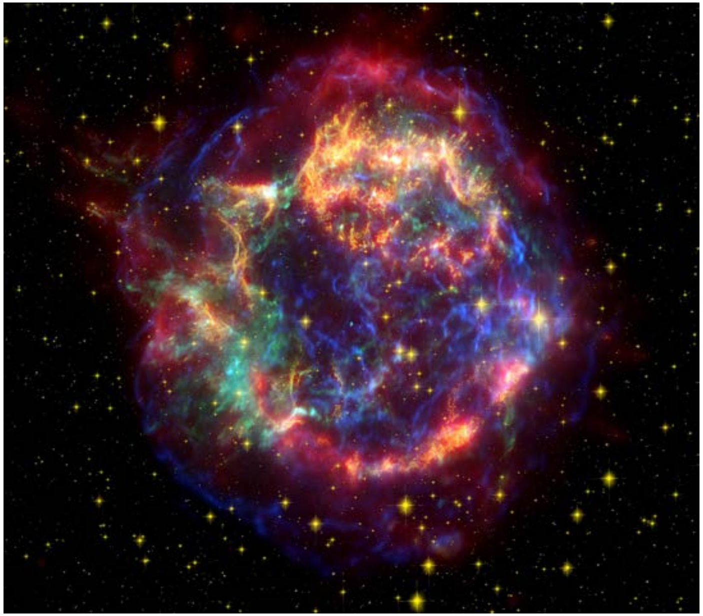


Figure. From Vink, *Physics and Evolution of Supernova Remnants*

Learning objectives

- The physics of core-collapse supernova explosion
- Gravitational waves and neutrino signals from core-collapse supernovae
- Supernova light curves

Core-collapse supernovae in numbers



- $\sim (30\,\mathrm{yr})^{-1}$ in our galaxy
- O(few millions) to be discovered by LSST
- peak luminosity $L_{\mathrm{SN}} \sim 10^{10}\, L_\odot$
- $t_{\mathrm{peak}} \sim$ few weeks $\sim 10^6\,\mathrm{sec}$

The radiated energy is

$$E_{\mathrm{EM}} \sim t_{\mathrm{peak}}\, L \sim 10^{48}\,\mathrm{erg}.$$

- $T_{\mathrm{eff}} \sim 2\, T_\odot \approx 12{,}000\,\mathrm{K}$

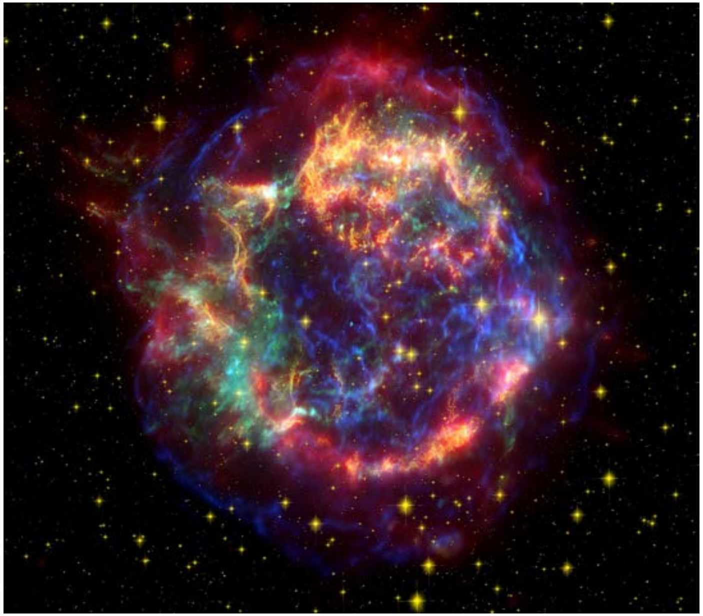
For a black body we have

$$L_{\mathrm{SN}} = 4\,\pi\,\sigma\, R_{\mathrm{SN}}^2\, T_{\mathrm{eff}}^4 \Longrightarrow R_{\mathrm{SN}} \sim 10^{15}\,\mathrm{cm} \gg R_\star.$$

The typical expansion velocity is

$$v \sim \frac{R_{\mathrm{SN}}}{t_{\mathrm{peak}}} = \frac{10^{15}\,\mathrm{cm}}{10^6\,\mathrm{s}} = 10^9\,\mathrm{cm\,s^{-1}} \Longrightarrow K = \frac{1}{2} M v^2 \sim 10^{51} \left(\frac{M}{M_\odot}\right) \mathrm{erg} \gg E_{\mathrm{EM}}.$$

Core-collapse supernovae energy budget



- $10^{45}\,\mathrm{erg}$ in GW
- $10^{48}\,\mathrm{erg}$ EM radiation
- $10^{51}\,\mathrm{erg} \equiv 1\mathrm{B}$ kinetic energy
- $10^{53}\,\mathrm{erg} \sim 0.1\,M_\odot\,c^2$ in neutrinos

Where does this energy come from?

The gravitational binding energy of a NS is

$$U = -\frac{3}{5}\frac{G\,M^2}{R} = -\frac{3}{5}\frac{G\,M}{R\,c^2}\,M\,c^2 \sim 0.1\,M_\odot\,c^2.$$

The SN problem: can we transfer $\sim$1% of the binding to the envelope of the star?

Massive star evolution

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, ...	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, ...	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

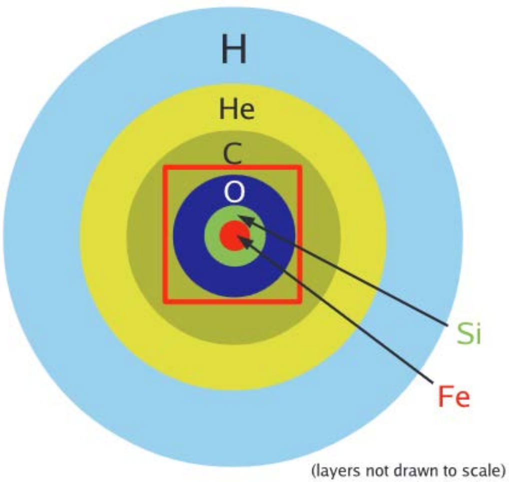
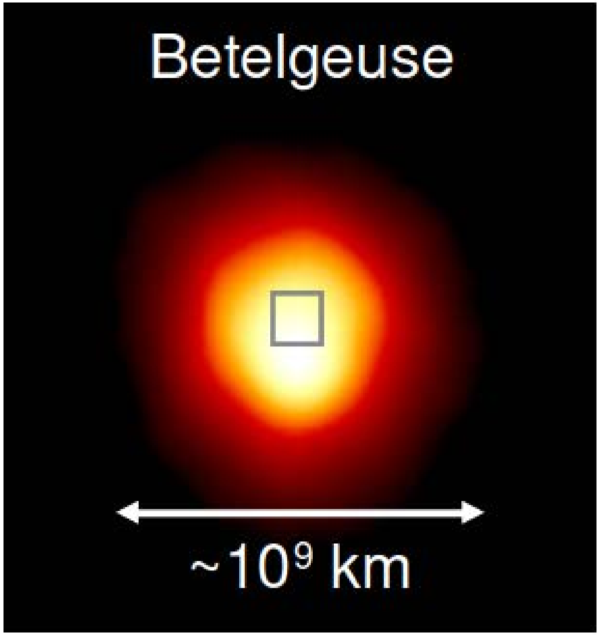
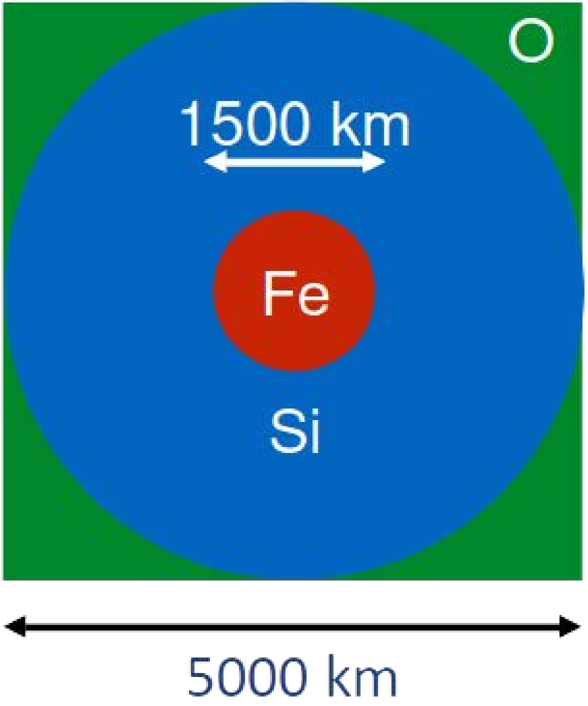


Table. From Woosley and Janka 2005.
Figure. From Janka et al 2012.

- Massive stars burn bright and fast
- A degenerate iron core is created at the center of the star
- Once the mass of the iron core goes above the Chandrasekhar mass the core collapses.

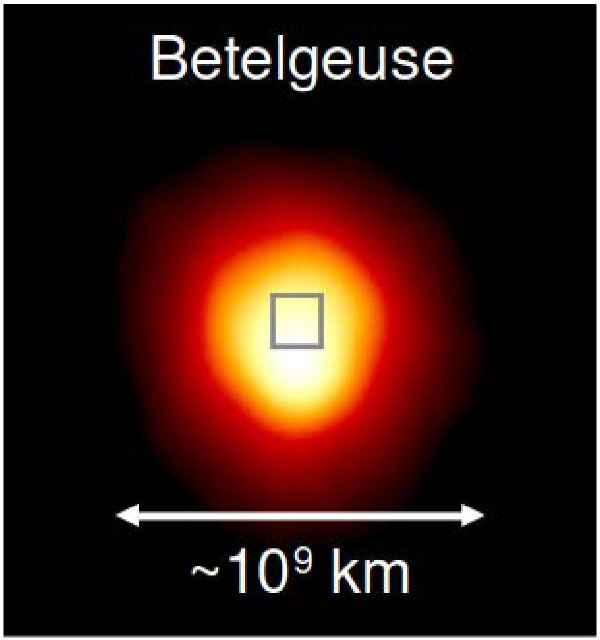
Explosion mechanism (I)

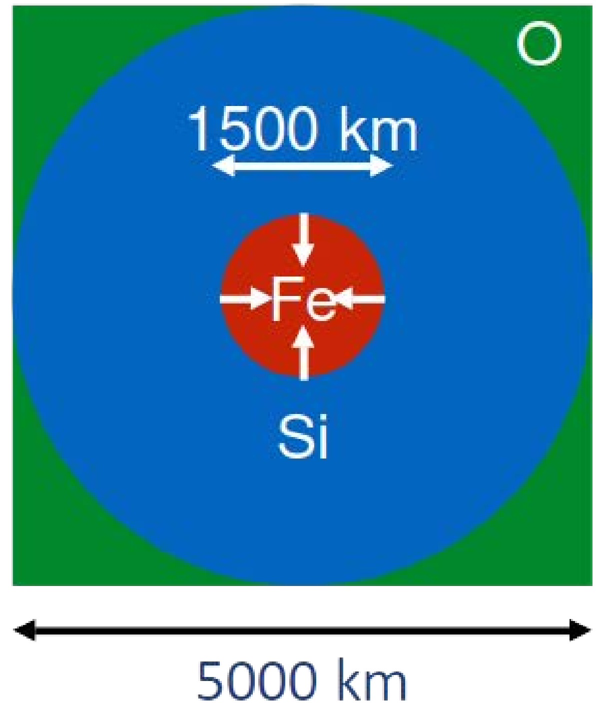




1. An iron core is formed in the star

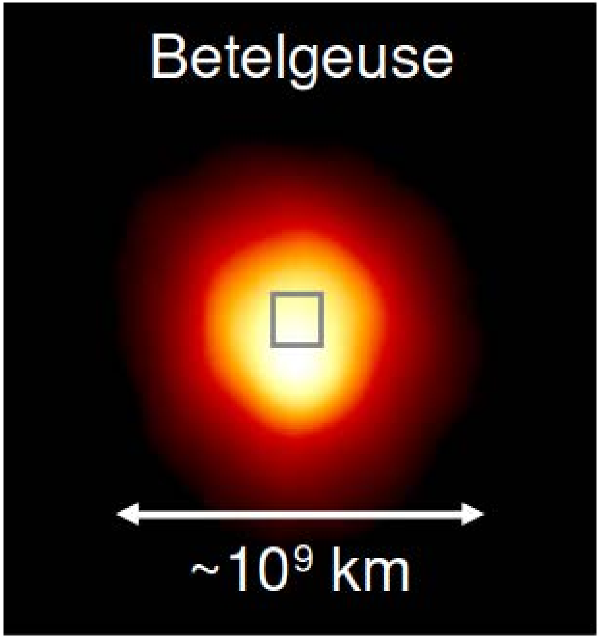
Explosion mechanism (II)

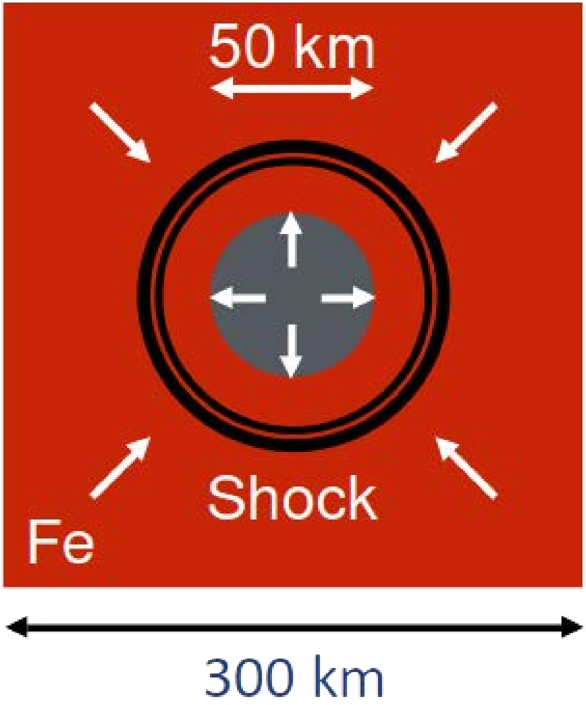




2. The iron core becomes unstable and collapses under its own self-gravity

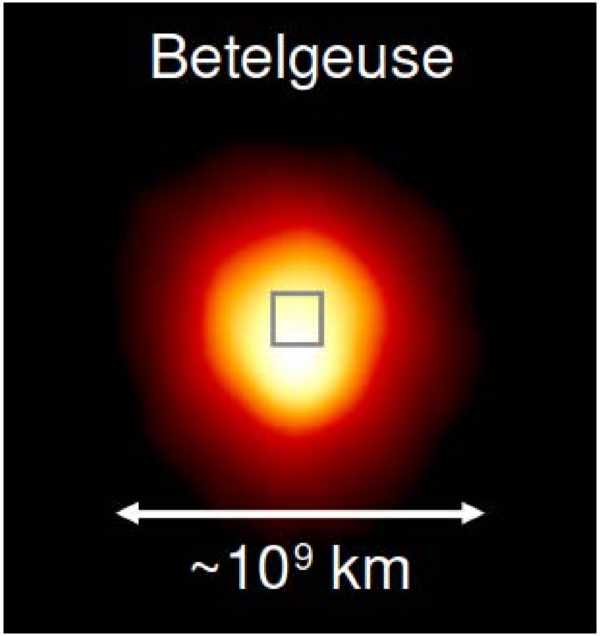
Explosion mechanism (III)

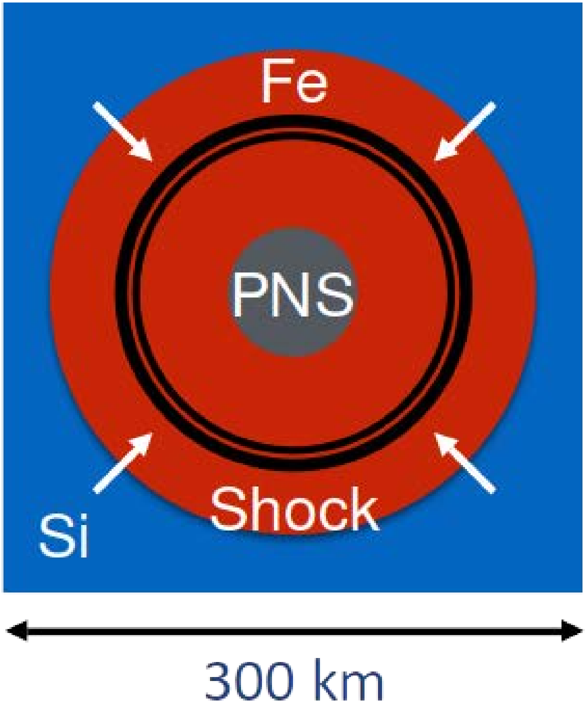




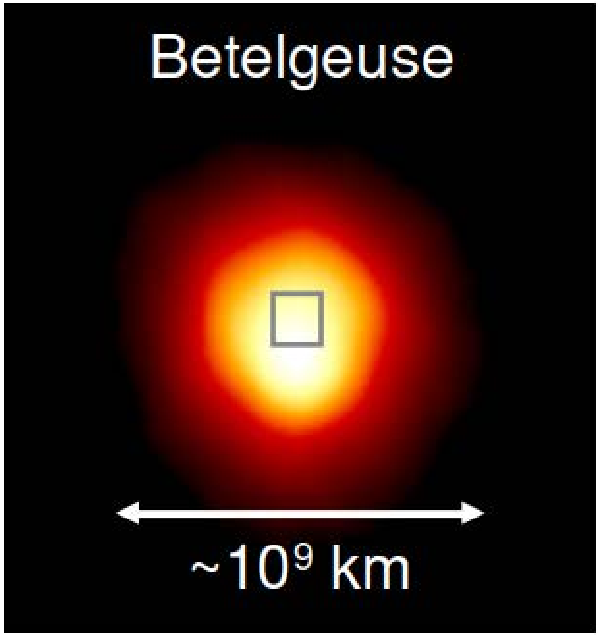
3. The inner-core bounces once it reaches nuclear density and launches a shock wave

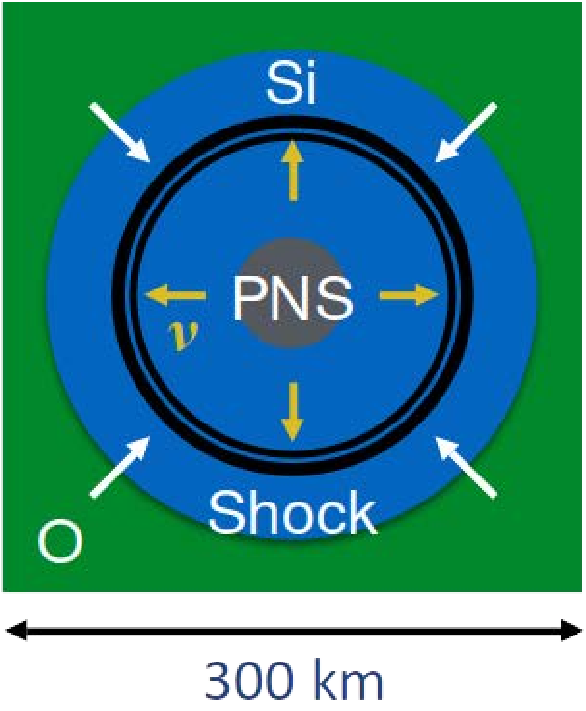
Explosion mechanism (IV)





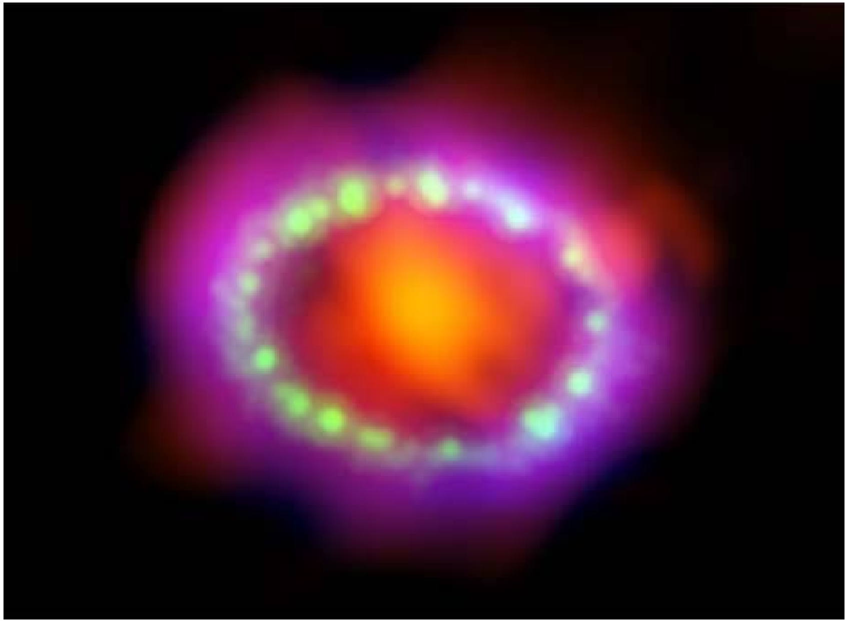
4. The shock runs out of energy and stalls

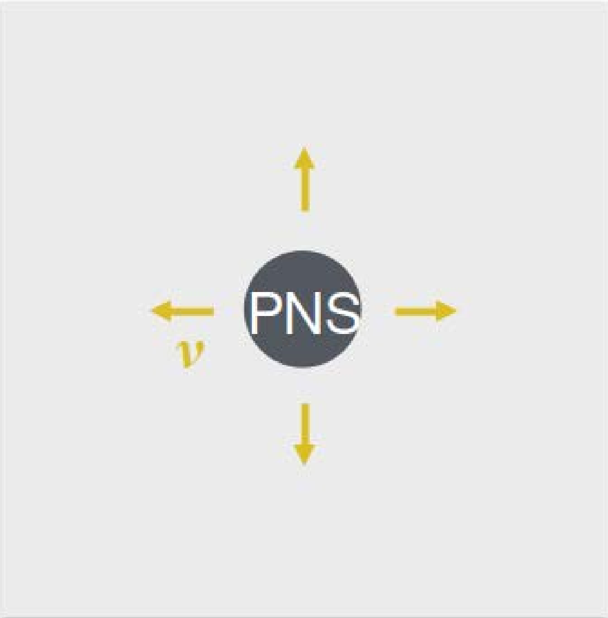




5. Neutrinos revive the shock?

Explosion mechanism (VI)





6. The proto-neutron star cools down over a minute
7. The shock wave reaches the surface in $\sim$12h to a day

Core collapse and bounce

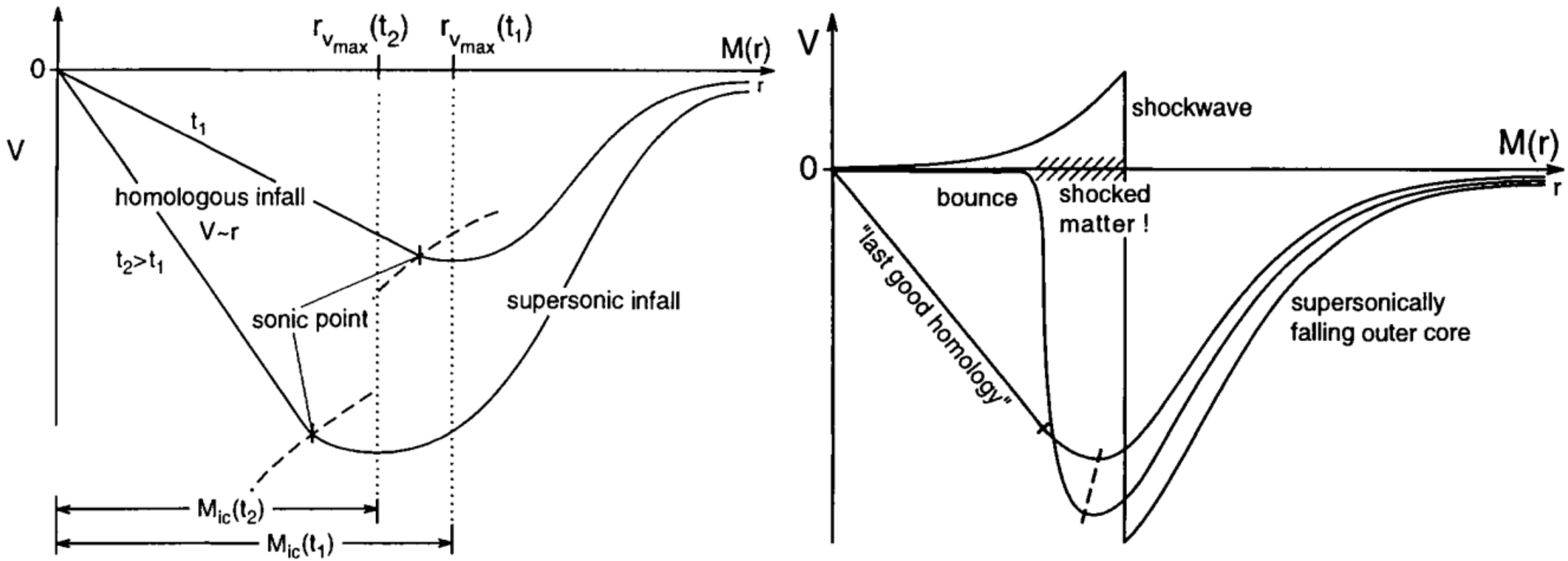


Figure. From E. Müller, Saas-Fee Advanced Course 27 (1997).

- Neutrinos are trapped when $\rho \gtrsim 10^{12}\,\mathrm{g}/\mathrm{cm}^3 \Longrightarrow$ core-collapse is close to adiabatic.
- Inner core mass is $M_{\mathrm{IC}} \sim 0.5\,M_\odot$, independent on the progenitor, it is set by nuclear physics.
- Core bounce is triggered by transition from electron-dominated $\Gamma = \frac{\mathrm{d}\log p}{\mathrm{d}\log \rho} = \frac{4}{3}$ to nuclear repulsion force $\Gamma = 2-3$.

Post-bounce phase

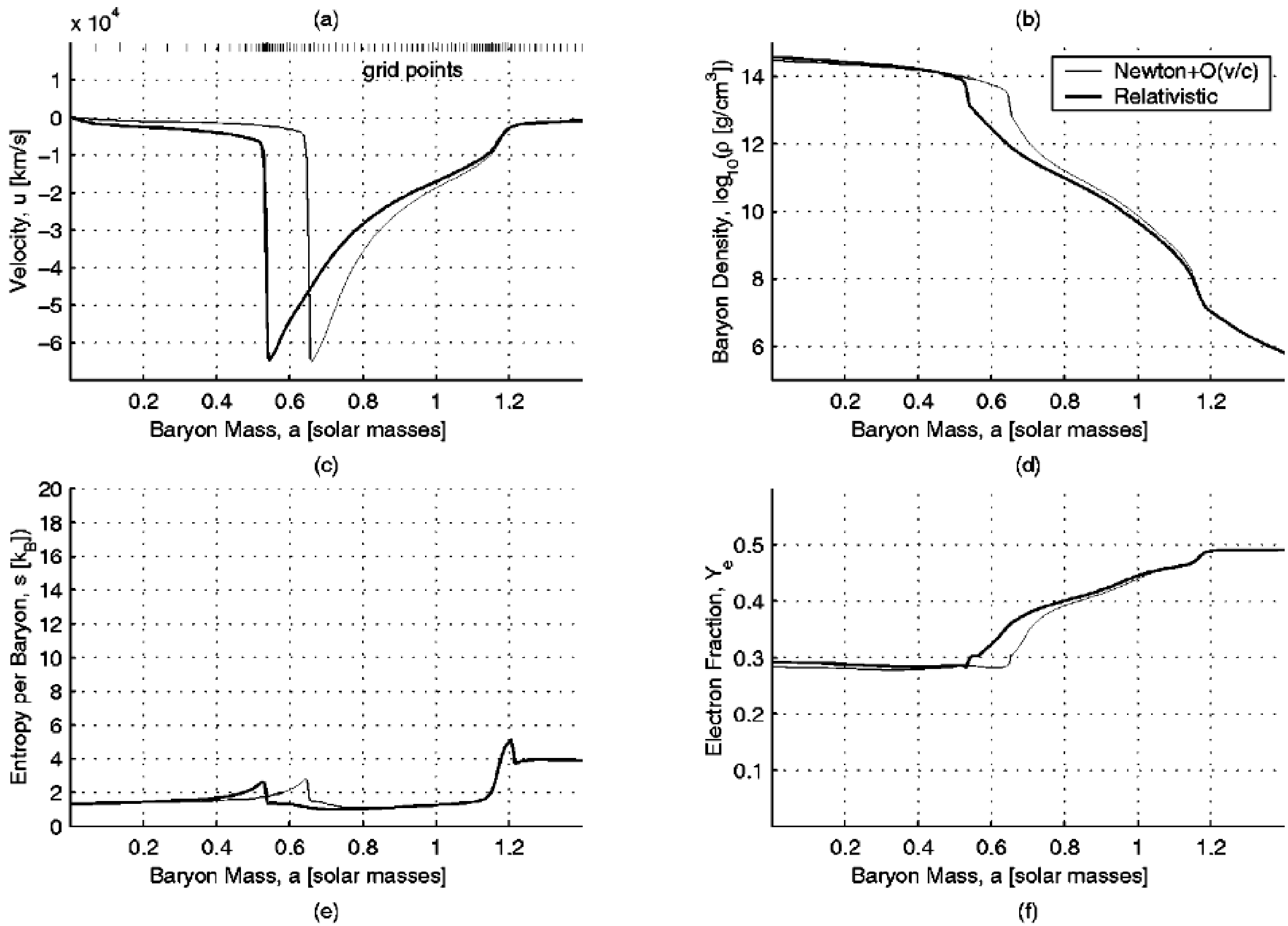


Figure. $t - t_{\mathrm{bounce}} = 0$. From Liebendörfer et al. (2001).

Post-bounce phase

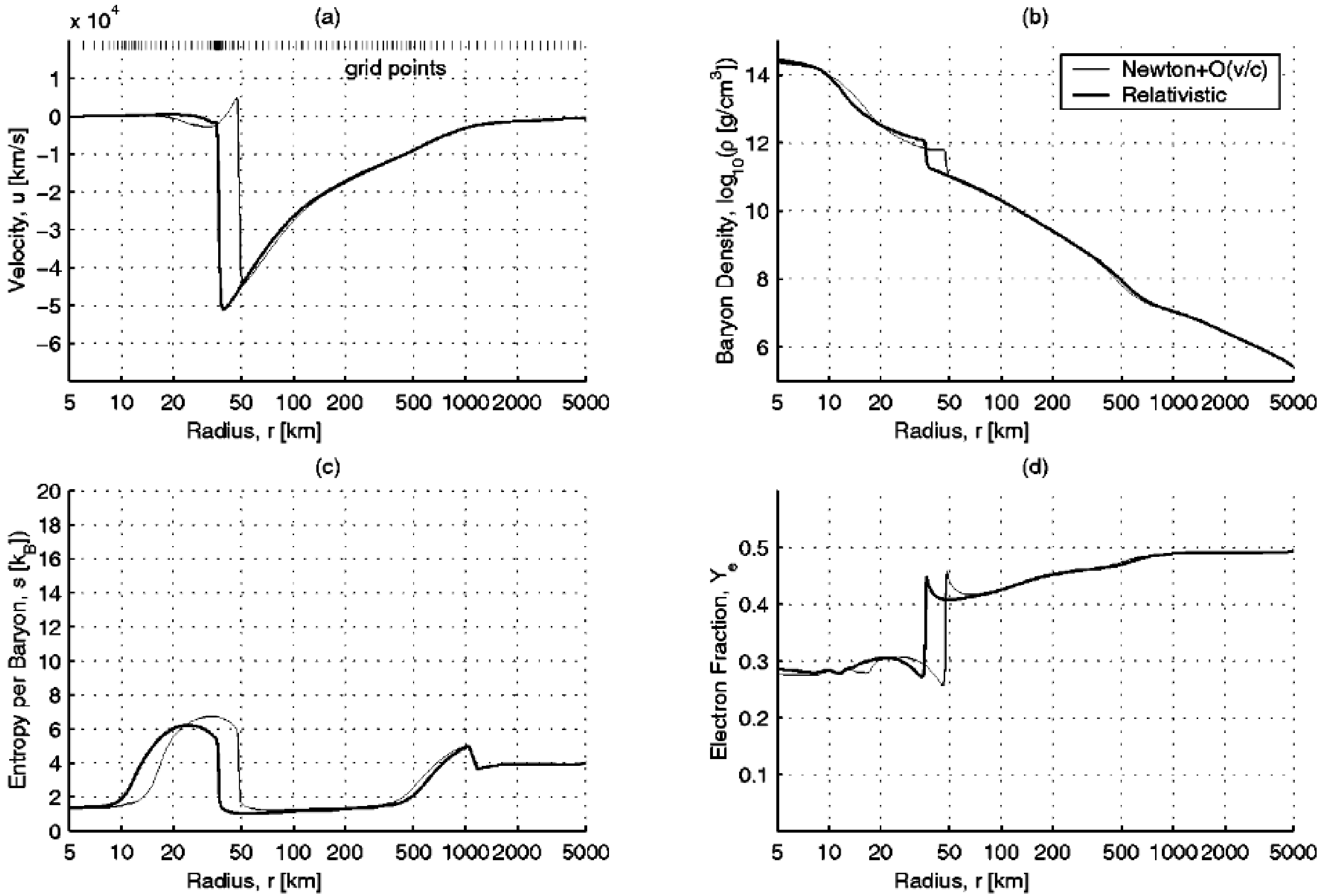


Figure. $t - t_{\mathrm{bounce}} = 1\,\mathrm{ms}$. From Liebendörfer et al. (2001).

Post-bounce phase

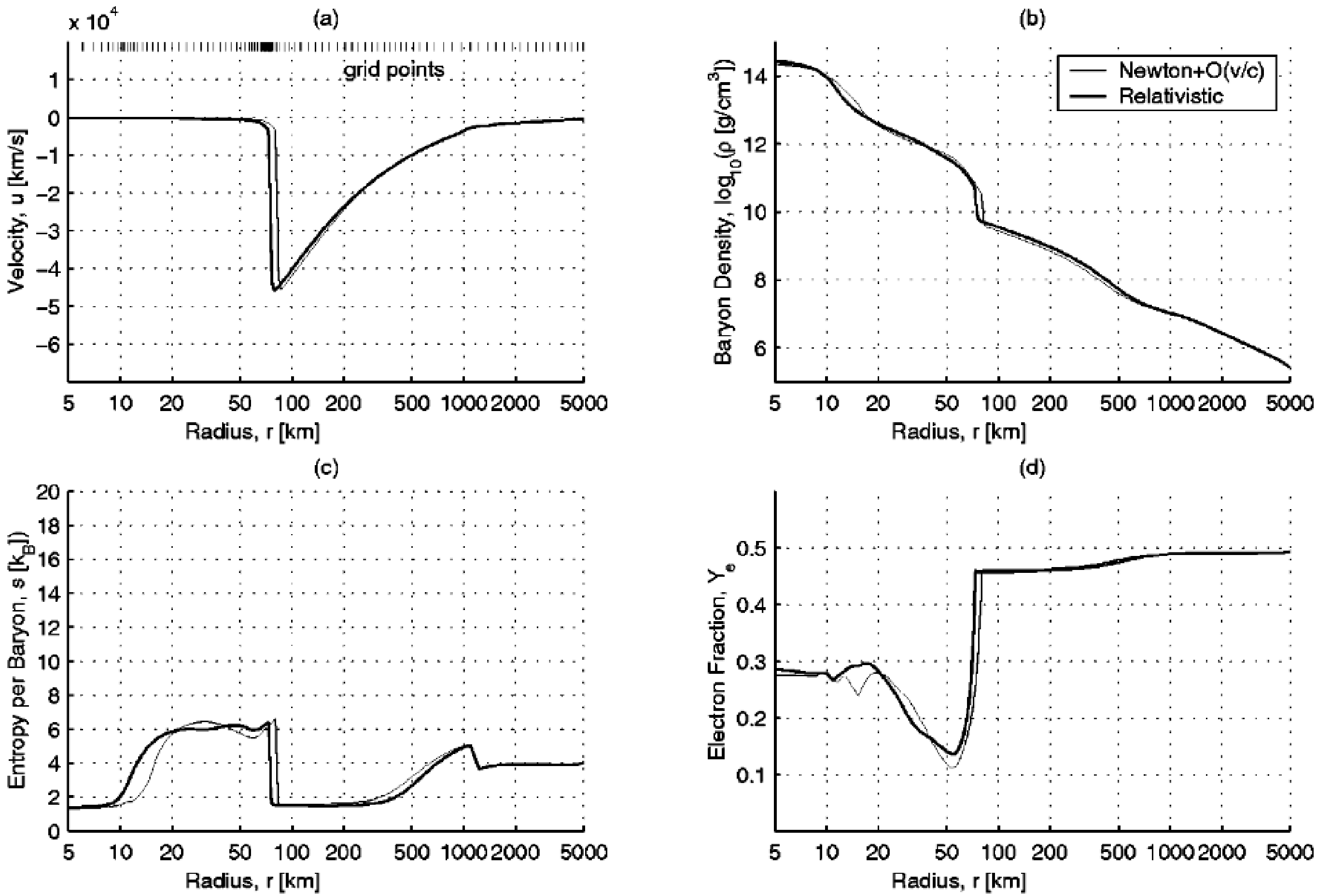


Figure. $t - t_{\text{bounce}} = 10\,\text{ms}$. From Liebendörfer et al. (2001).

Post-bounce phase

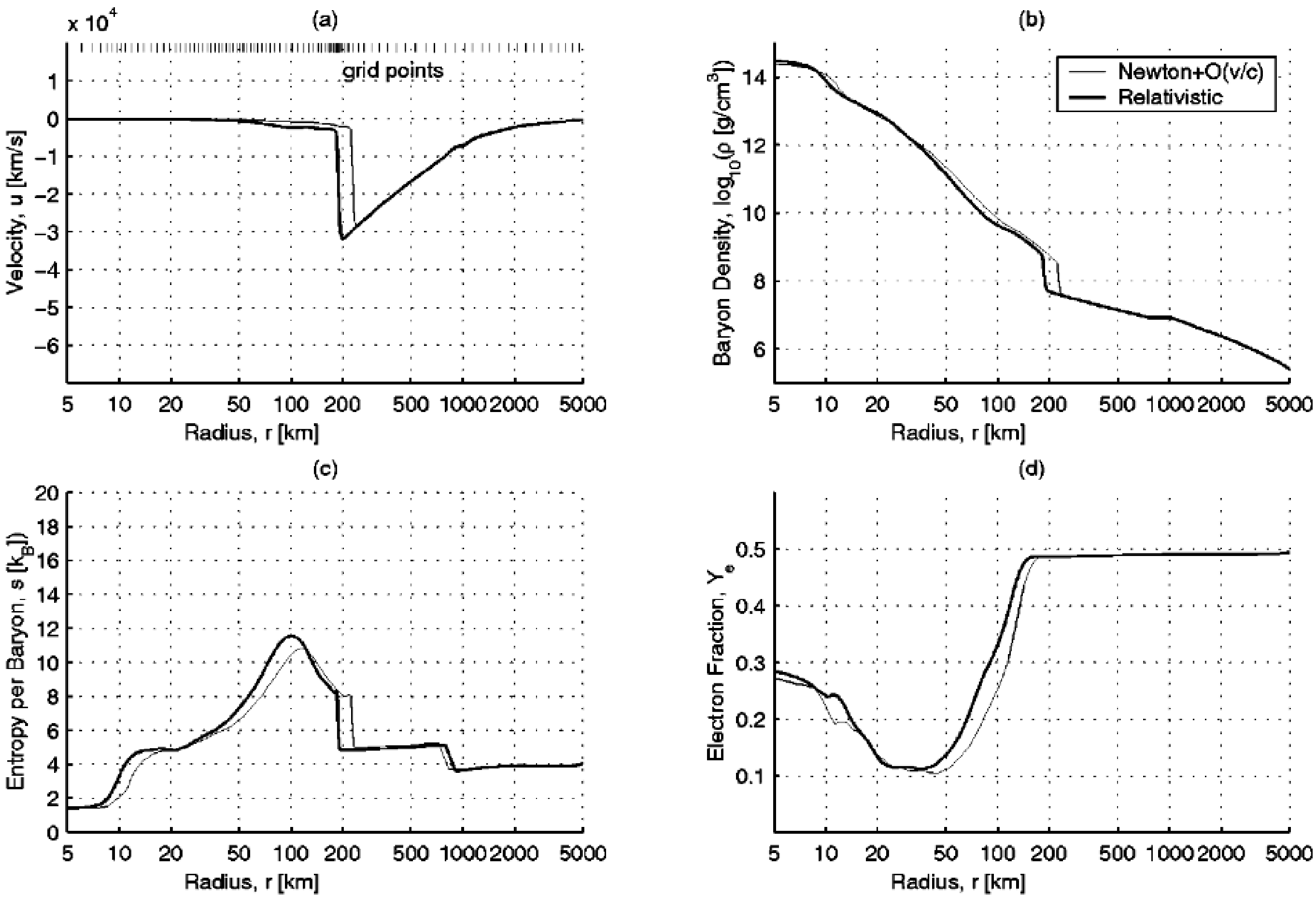


Figure. $t - t_{\text{bounce}} = 100\,\text{ms}$. From Liebendörfer et al. (2001).

Accretion phase

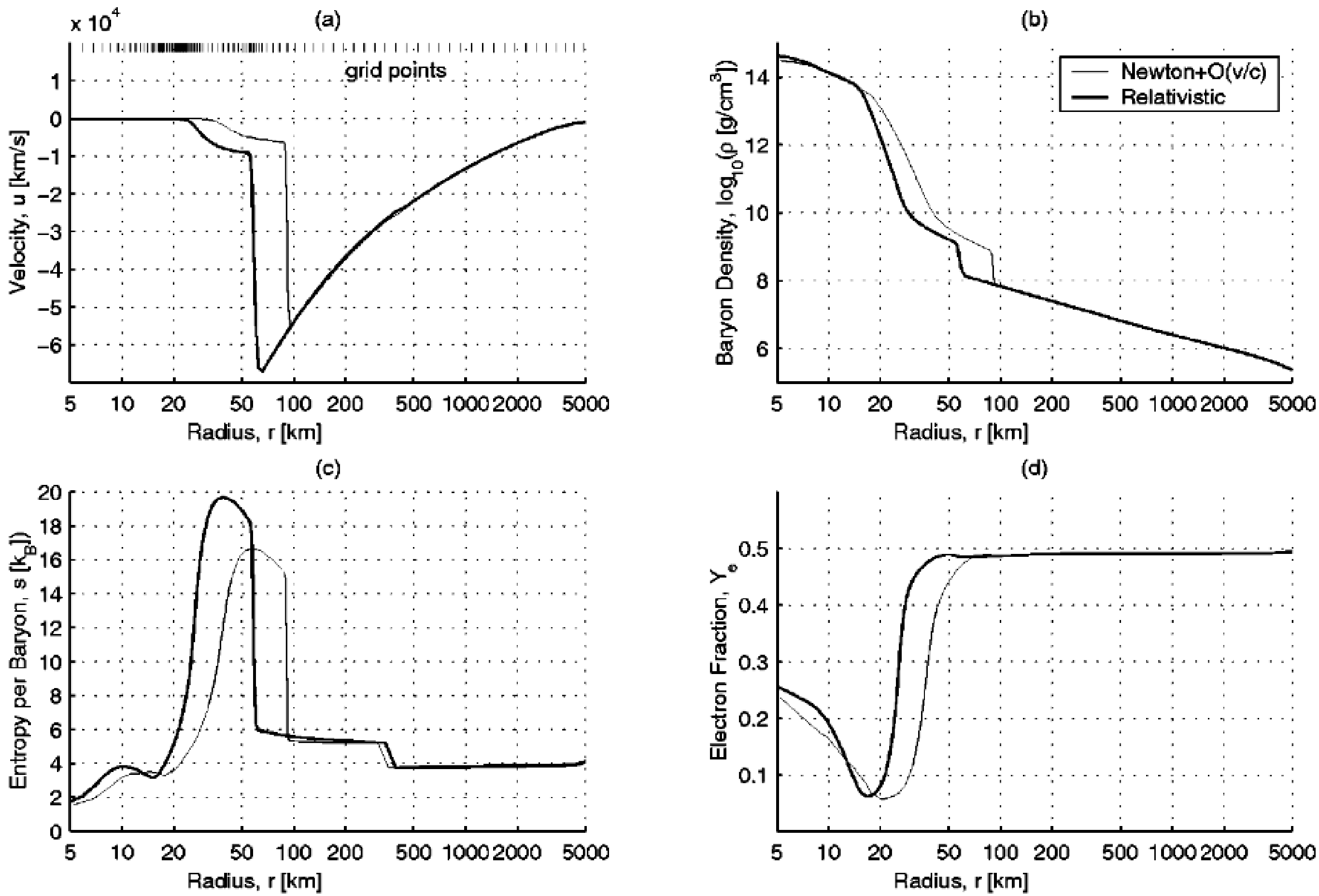


Figure. $t - t_{\mathrm{bounce}} = 500\,\mathrm{ms}$. From Liebendörfer et al. (2001).

Why does the shock stall?

- $\sim$2B lost to the neutrino burst
- Energy lost to dissociation

$$\dot{E}_{\rm diss} \sim 1.7\, \dot{M}_{-1}\, {\rm B}$$

Key neutrino processes

$$e^- + p \leftrightarrow \nu_e + n$$
$$e^+ + n \leftrightarrow \bar{\nu}_e + p$$

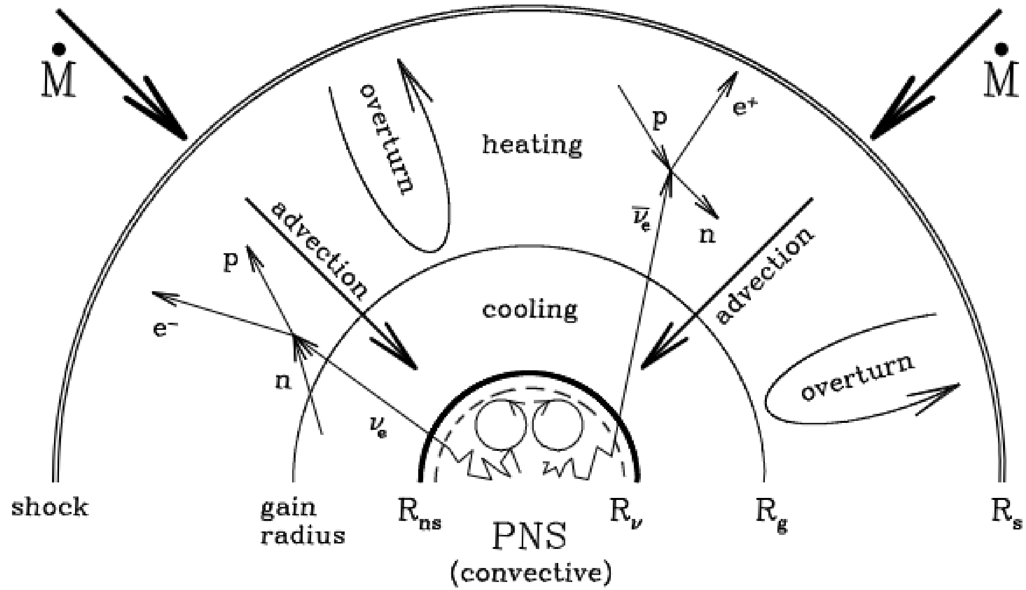


Figure. From Janka (2001).

Heating and cooling are:

$$Q^-_{\nu_e,\bar{\nu}_e} \approx 2.4 \cdot \left(\frac{T}{1\,{\rm MeV}}\right)^6 Y_{n,p} \left[\frac{\rm MeV}{\rm s \cdot nucleon}\right], \qquad Q^+_{\nu_e,\bar{\nu}_e} \approx 110 \cdot \frac{L_{52}}{r_7^2} \frac{\langle \epsilon_\nu^2 \rangle}{(15\,{\rm MeV})^2} Y_{p,n} \left[\frac{\rm MeV}{\rm s \cdot nucleon}\right].$$

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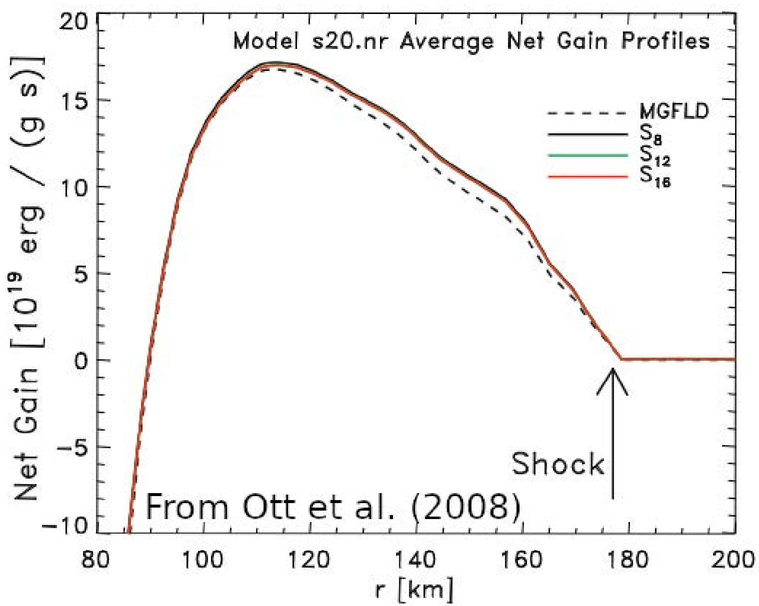
The pressure is dominated by radiation and relativistic e^-, e^+: $p \propto \rho^{4/3} \propto T^4$.
The subsonic accretion flow has $v_r \propto r$, $\rho\, v_r\, r \sim \mathrm{const}$, so $\rho \propto r^{-3}$ and $T \propto r^{-1}$. Then

$$Q^-_{\nu_e,\bar{\nu}_e} \sim r^{-6}, \qquad Q^+_{\nu_e,\bar{\nu}_e} \sim r^{-2},$$

so there is a region where heating > cooling (gain layer)!



Critical luminosity

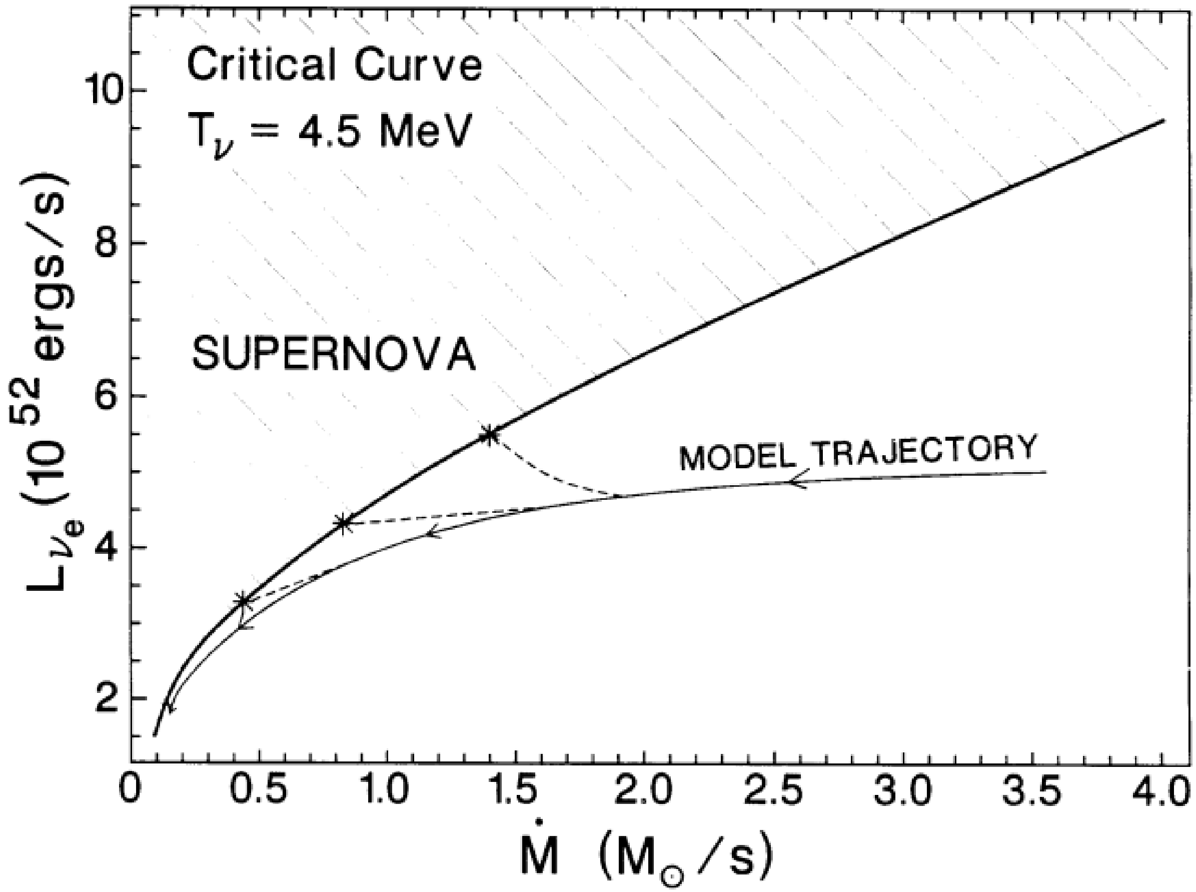
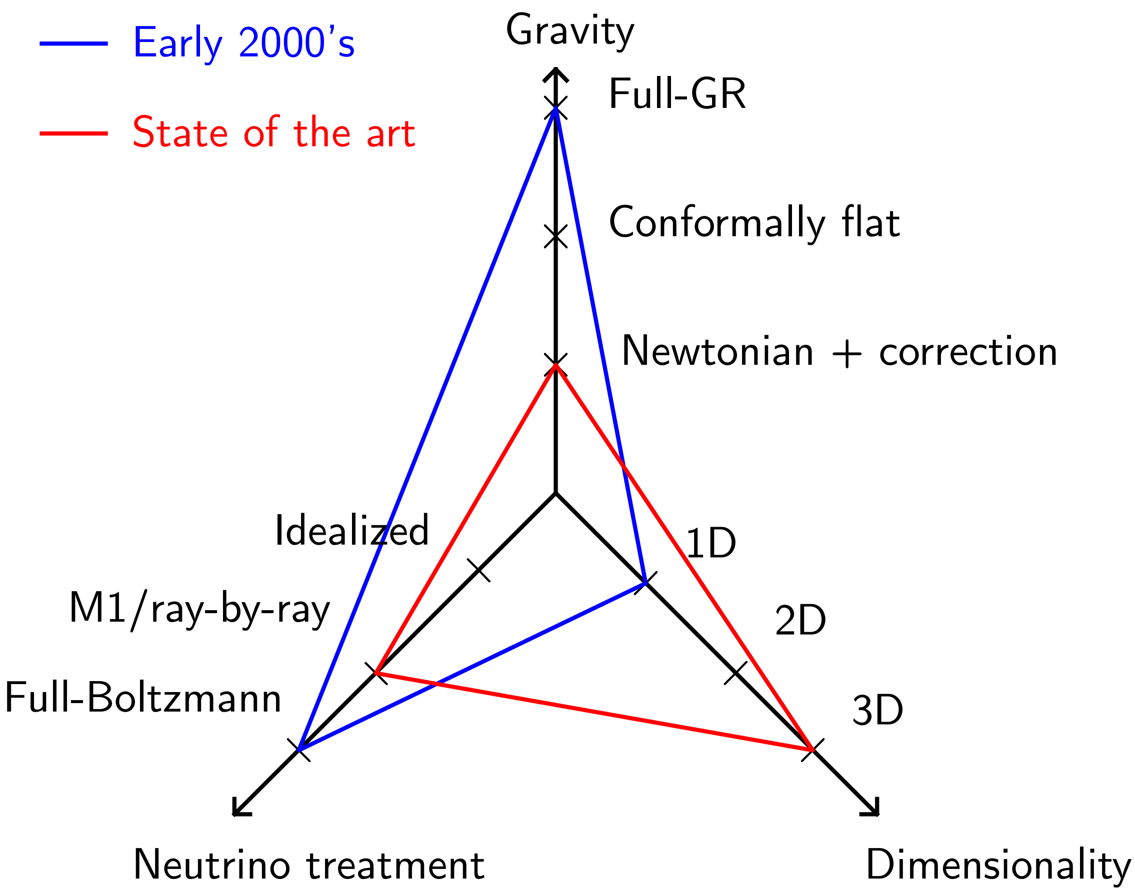
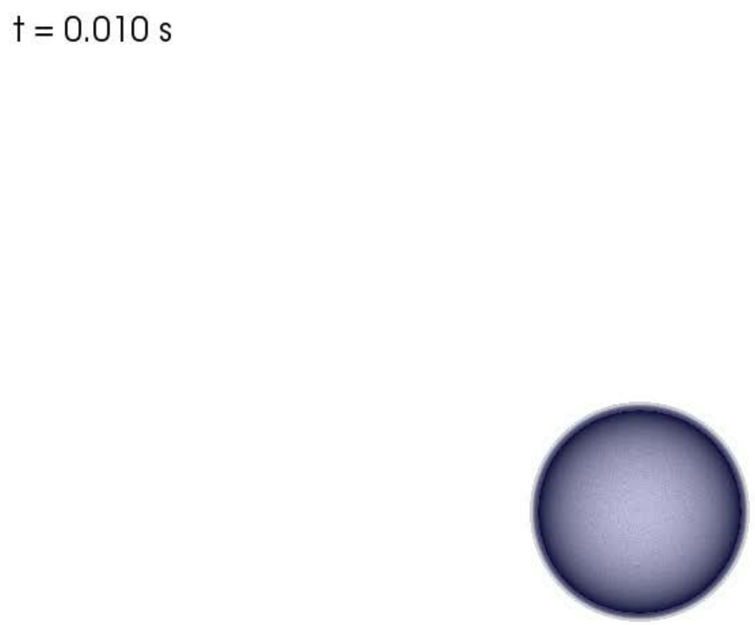


Figure. From Burrows and Ghosy 1993.

Modeling requirements



- Gravity
  - General relativity
- Microphysics
  - EOS of dense matter
  - NSE, nuclear burning, electron capture rates
- Neutrino-radiation hydro
  - Must solve Boltzmann equation in 7D
  - Oscillations?
  - MHD effects
- Multi-dimensional effects and turbulence


t = 0.010 s

Shock radii

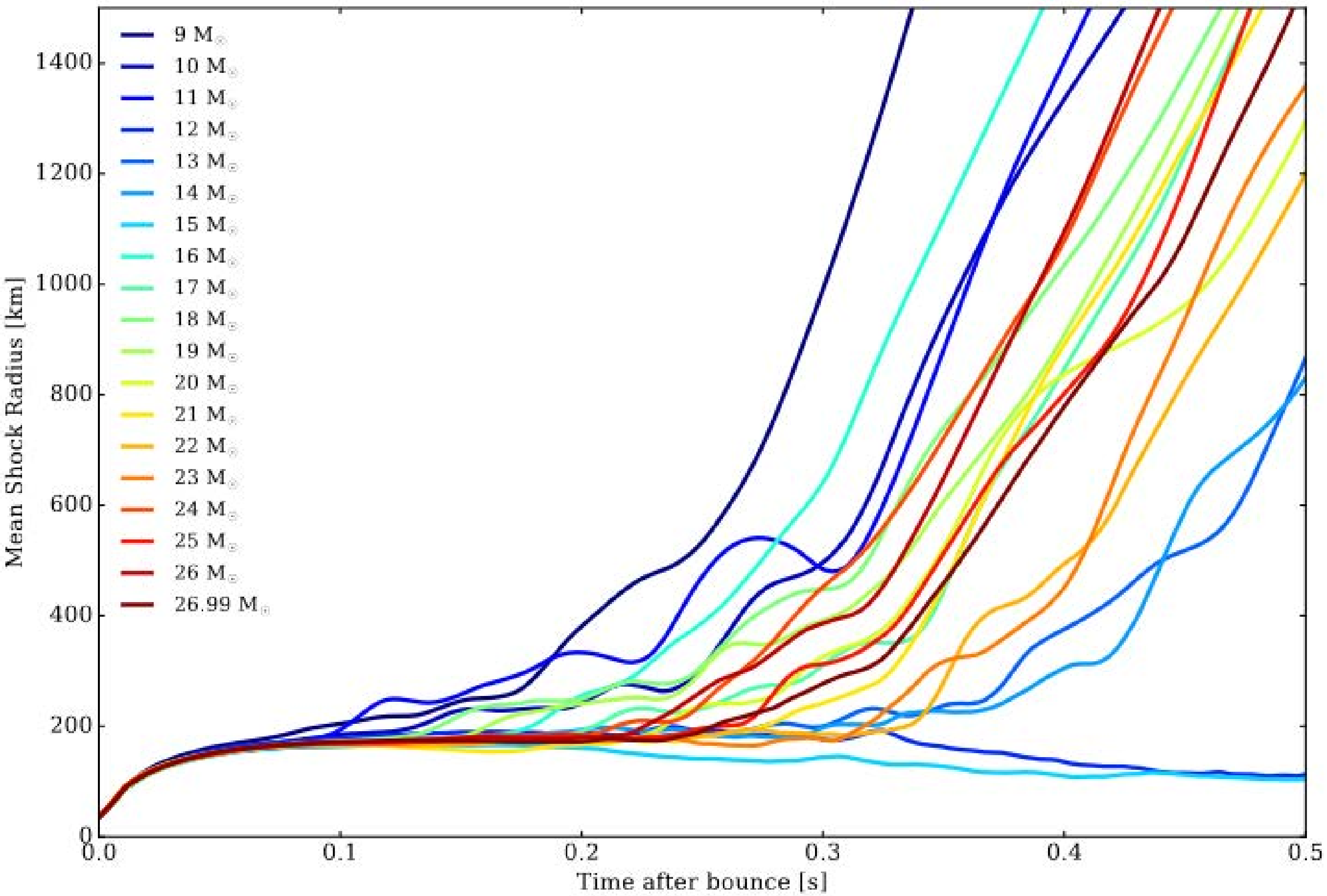


Figure. From Burrows and Vartanyan (2020).

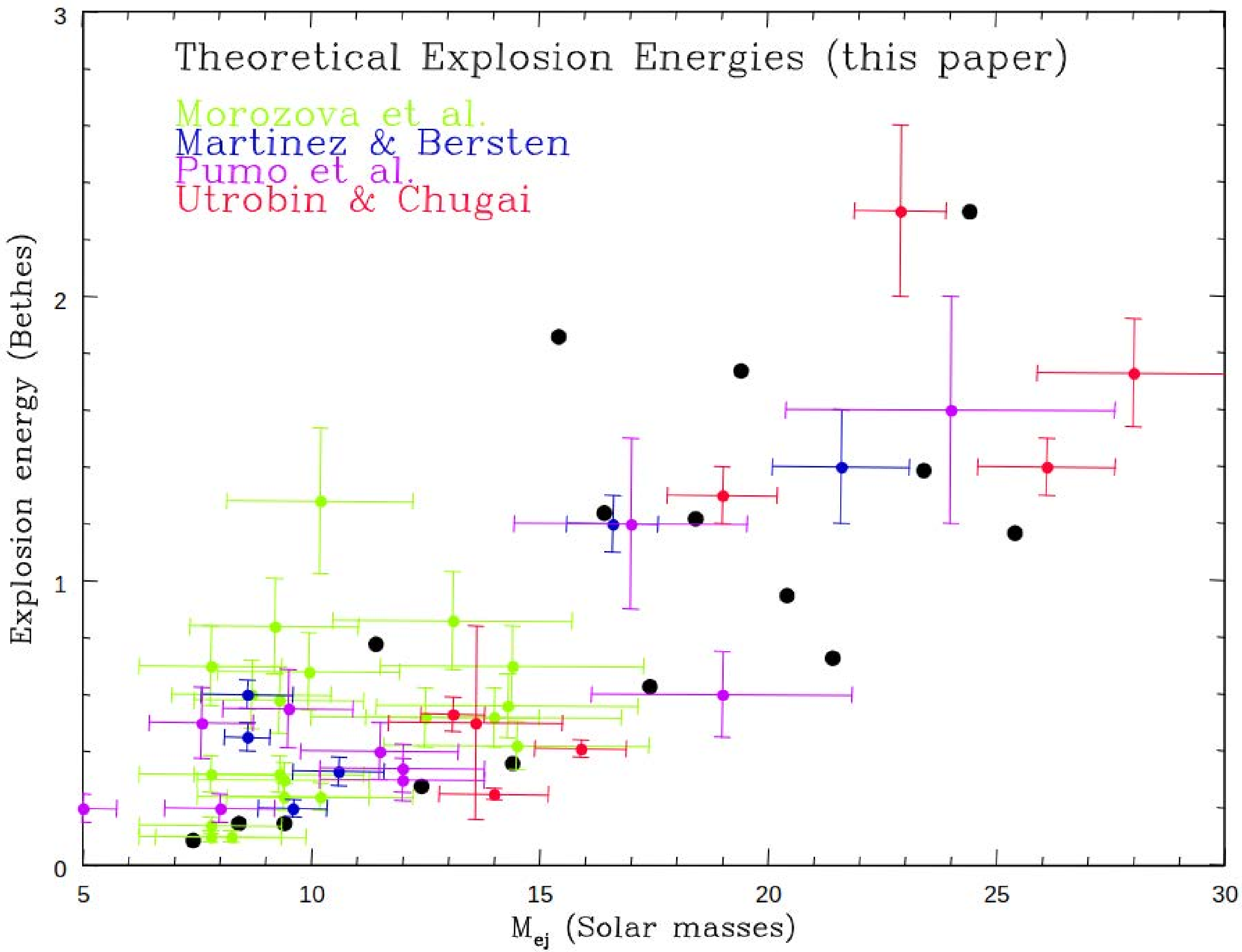


Figure. From Burrows and Vartanyan (2020).

Which stars explode?

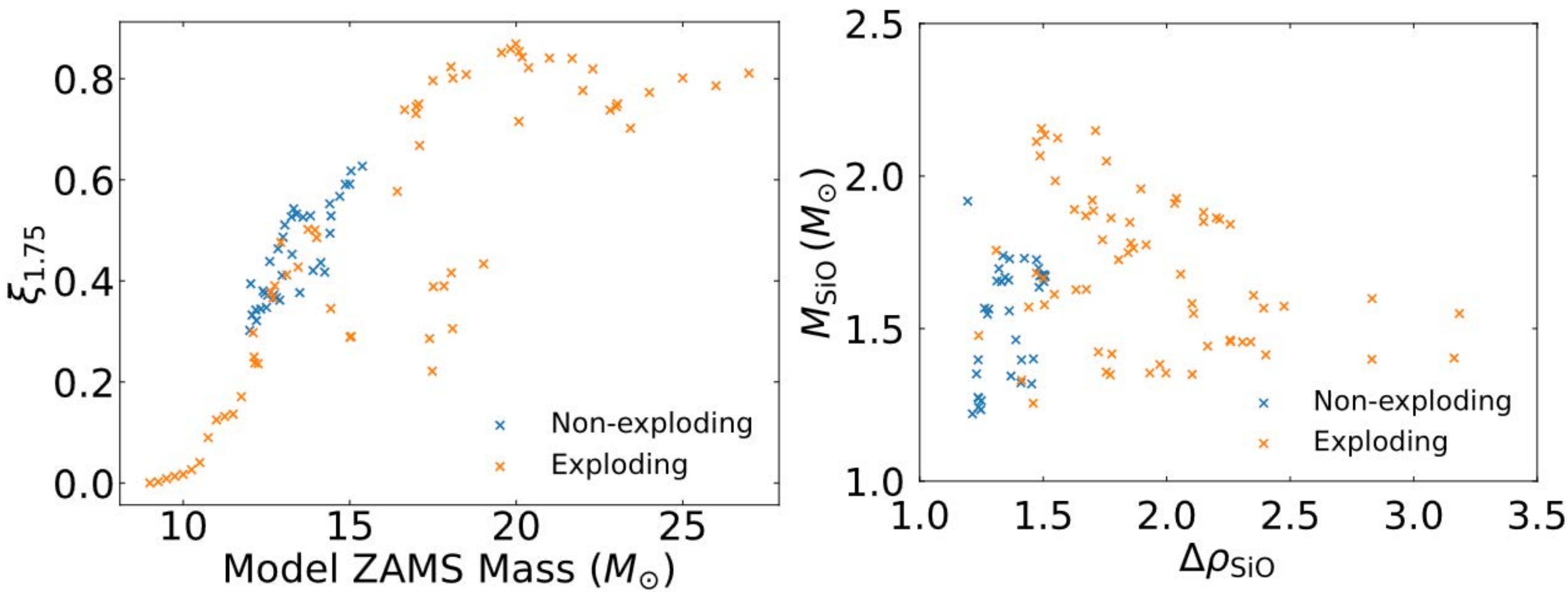


Figure. From Tsang et al. (2022)

- Compactness or ZAMS mass are not useful criteria for explodability.
- The Si-O density drop is critical to trigger an explosion.
- Explosion does not mean no black hole formation.

Problem solved?

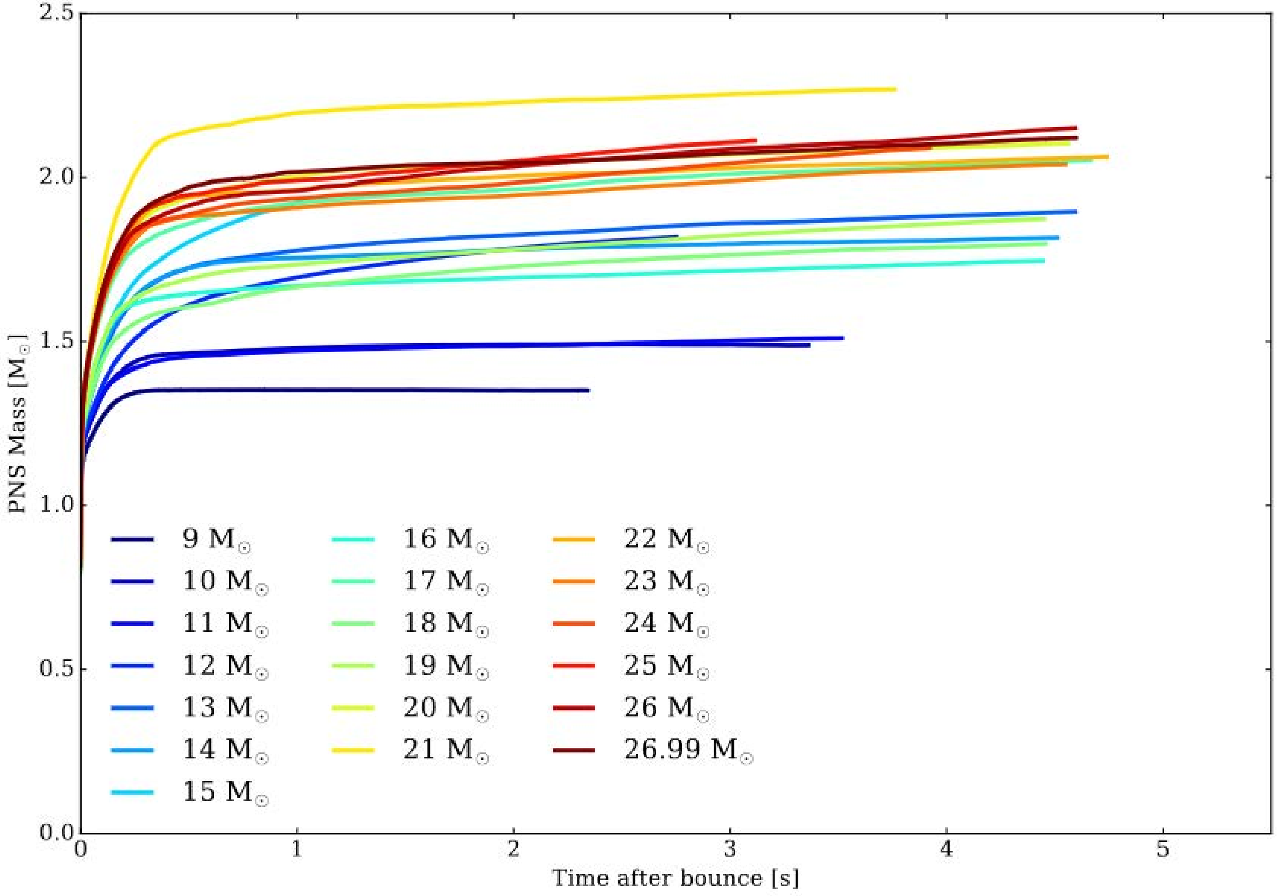


Figure. From Burrows and Vartanyan (2020).

SN1987a

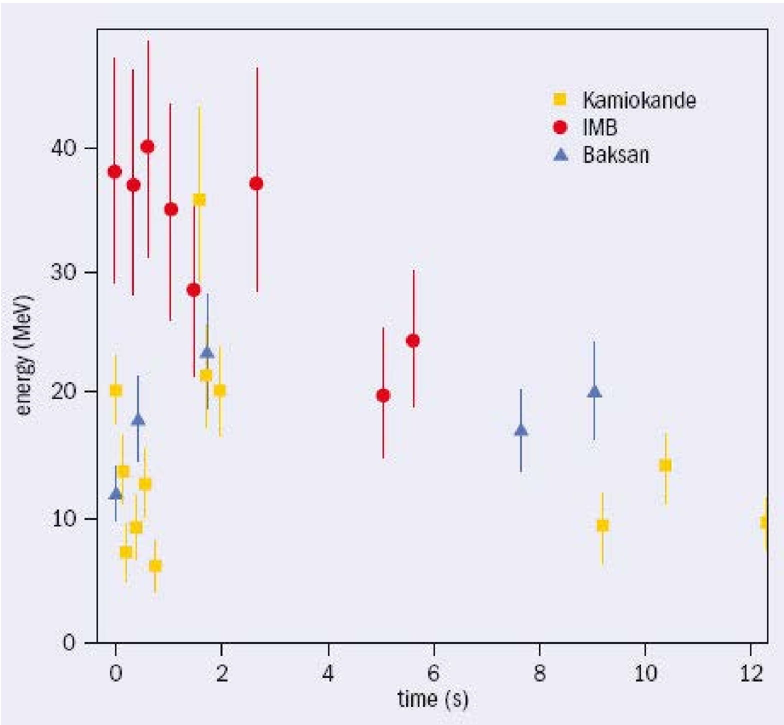


Image credit: CERN

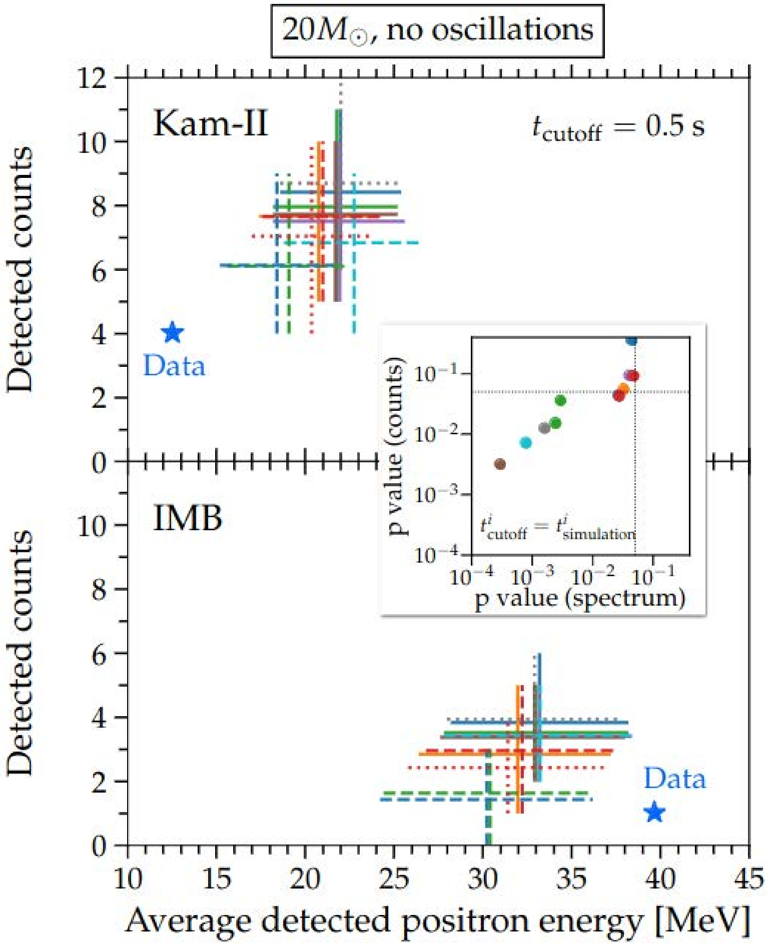
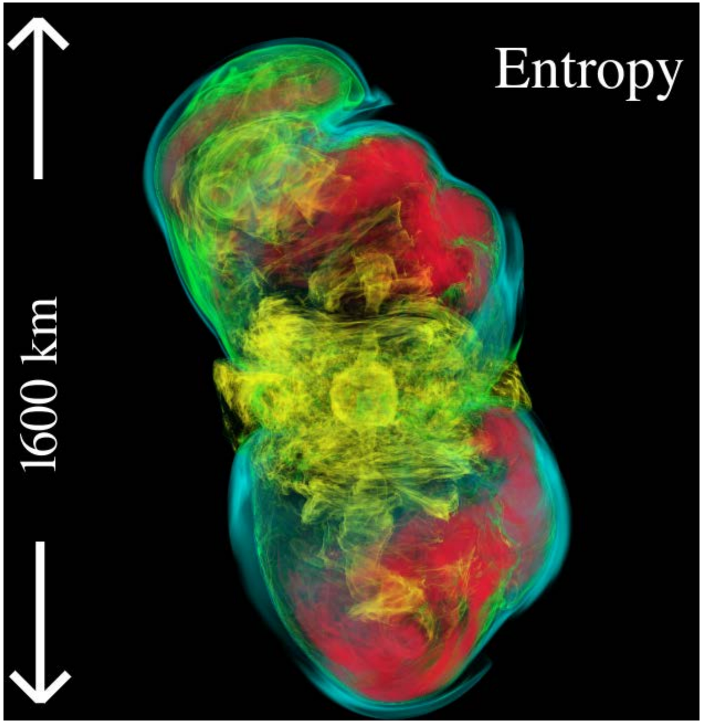


Figure. From Li, Beacom, et al. (2023)

Supernova theory status

- What is missing?
  - Magnetic fields?
  - Better progenitor models and rotation?
  - Quantum effects in the neutrino sector?
  - BSM physics?
- Other open questions
  - Weird supernovae, GRB connection
  - Origin of pulsar magnetic fields
  - Connection with SN remnants morphology
  - Nucleosynthesis from CCSNe



From Mösta et al. (2014).

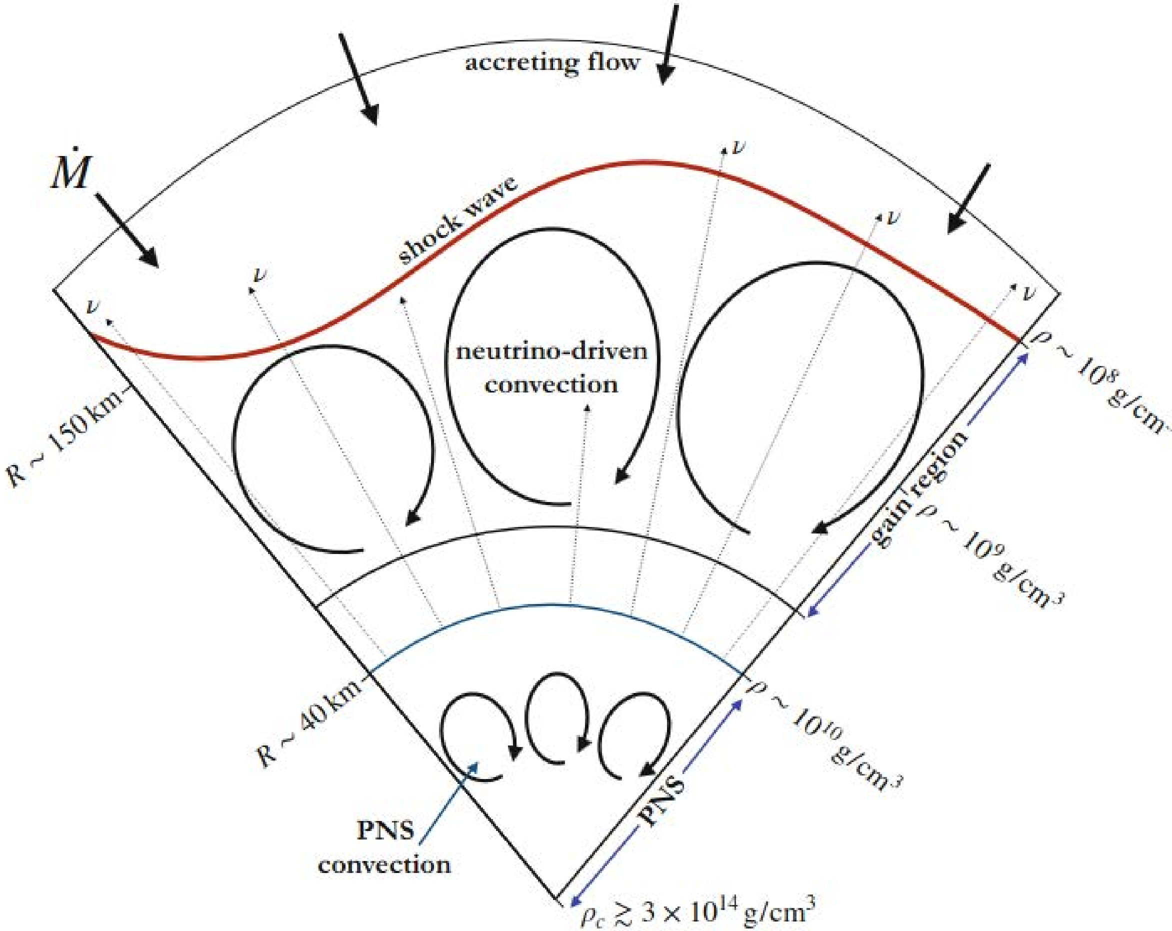


Figure. From Abdikamalov, Pagliaroli, & Radice (2020).

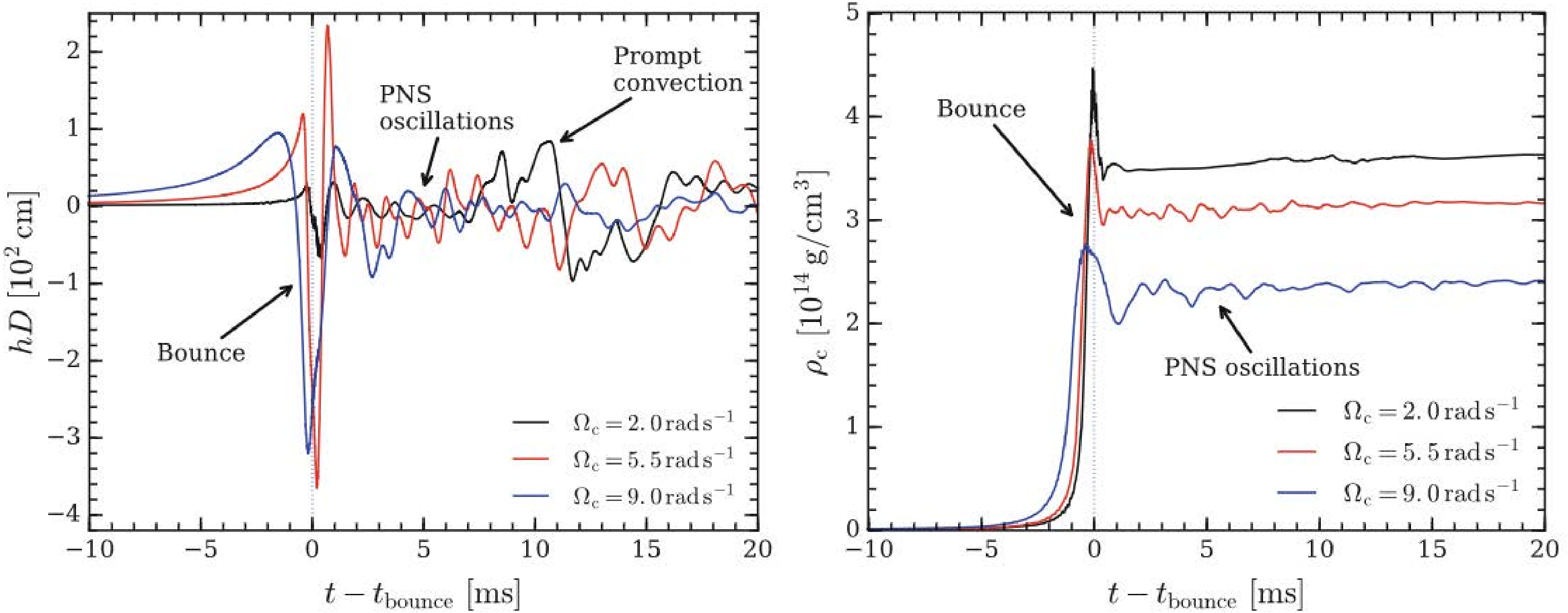


Figure. From Abdikamalov, Pagliaroli, & Radice (2020).

Low-$T/|W|$ instability

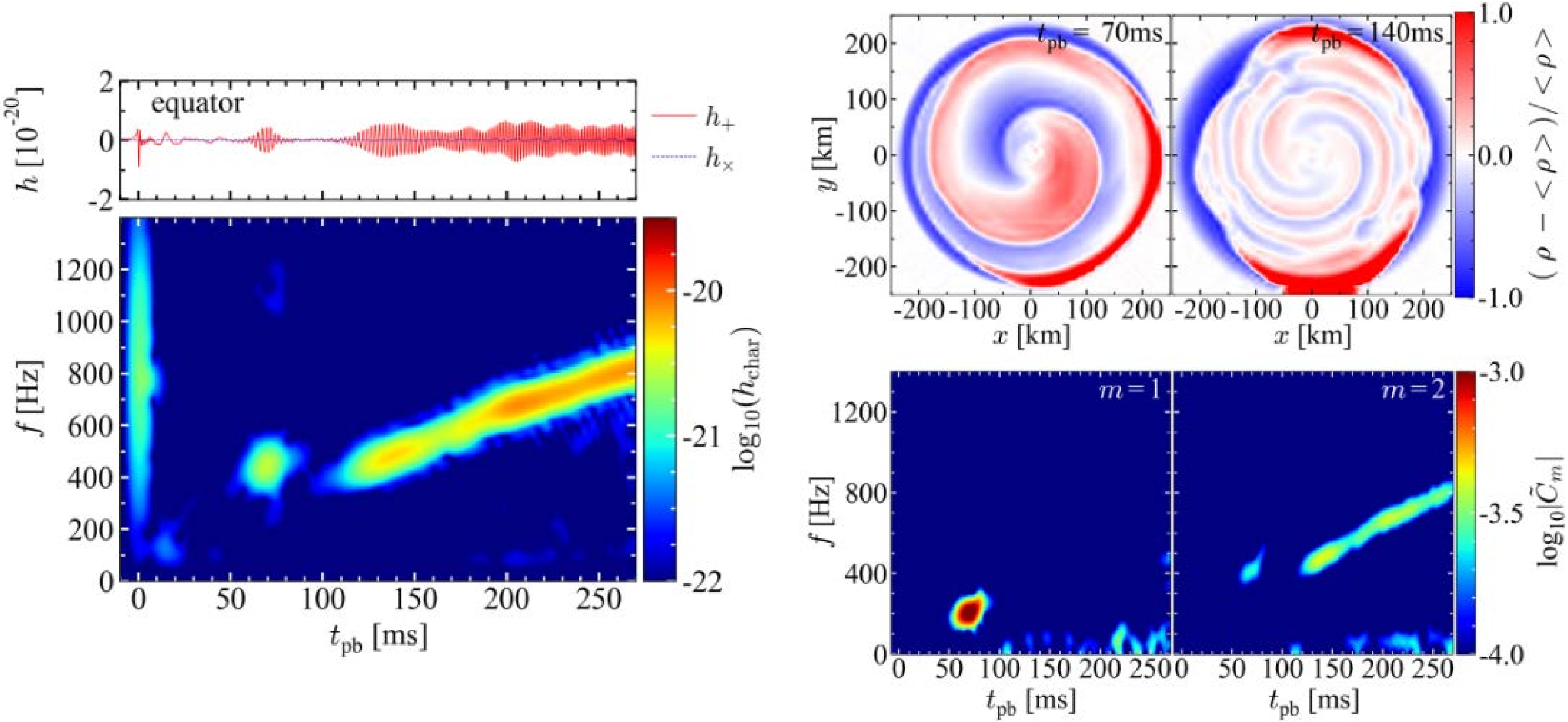
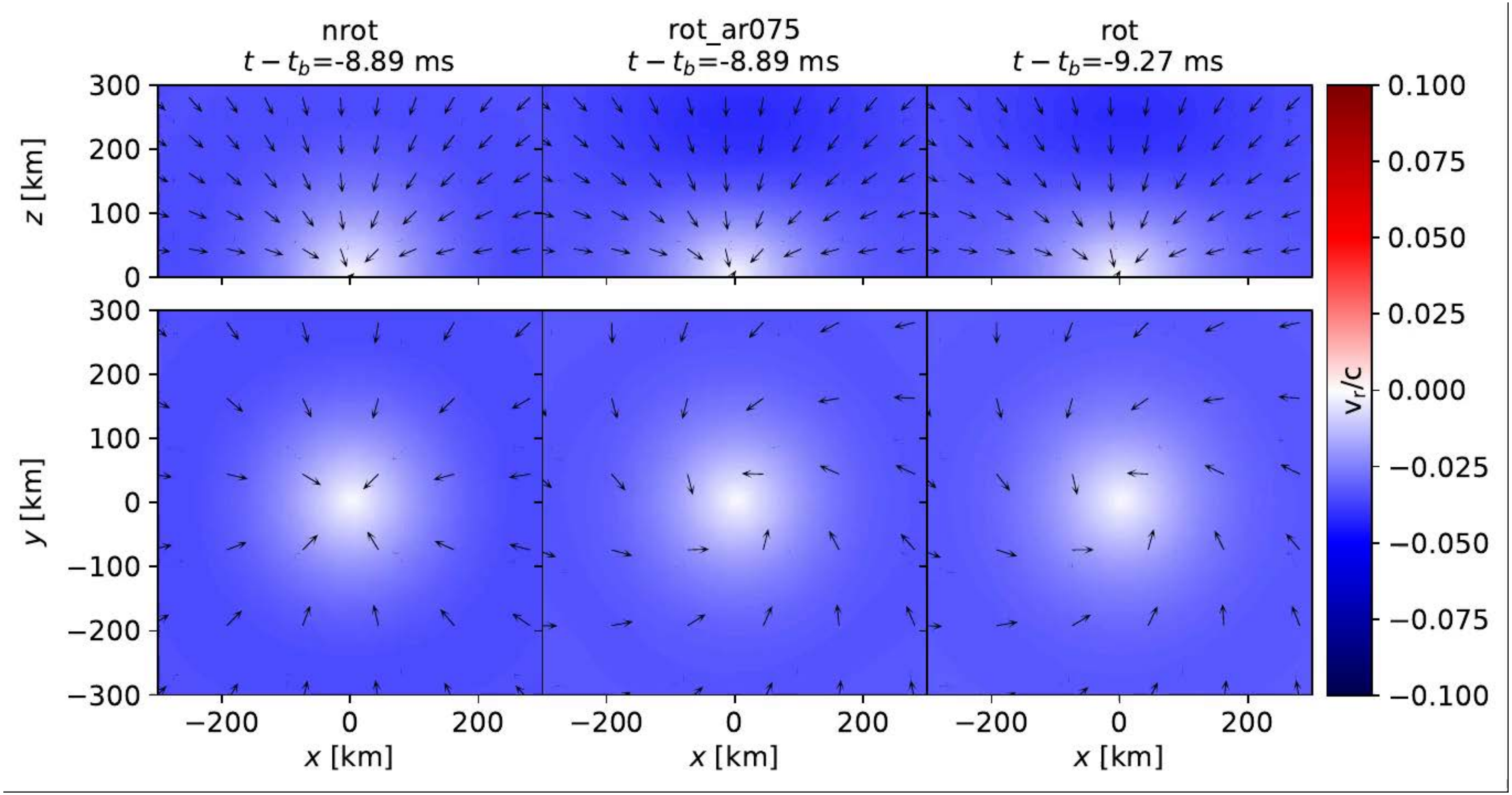
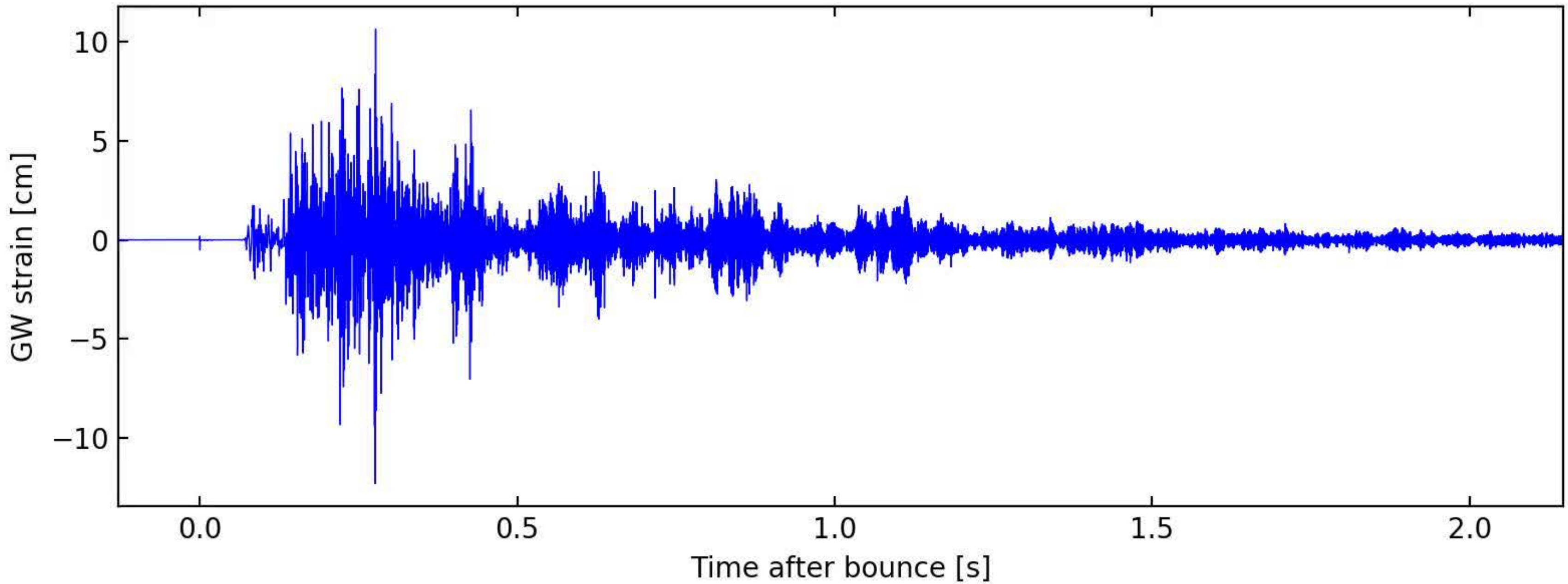


Figure. From Shibagaki et al. (2020).

Low-$T/|W|$ instability



Gravitational waves from nonrotating SNe



Gravitational waves from nonrotating SNe

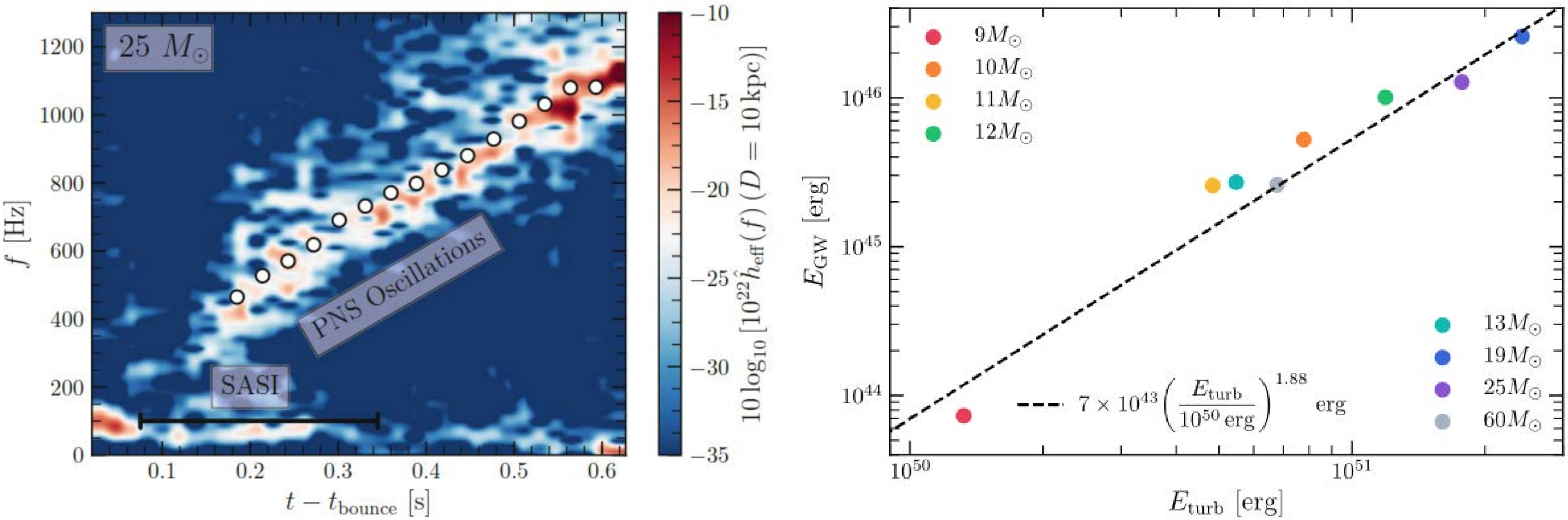
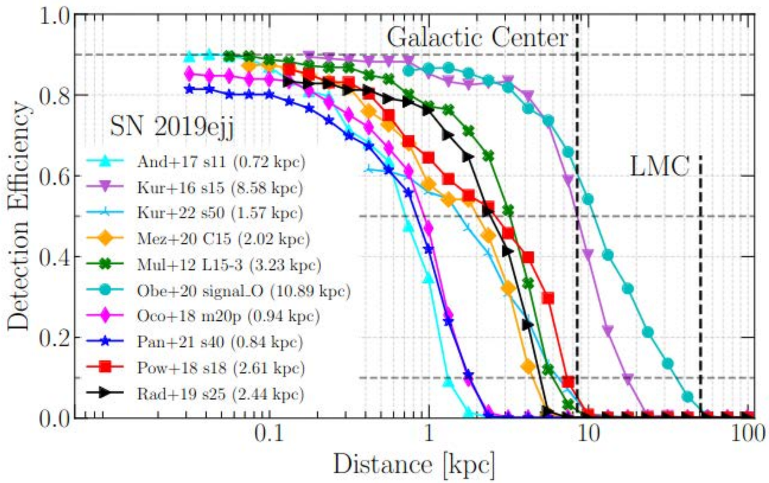


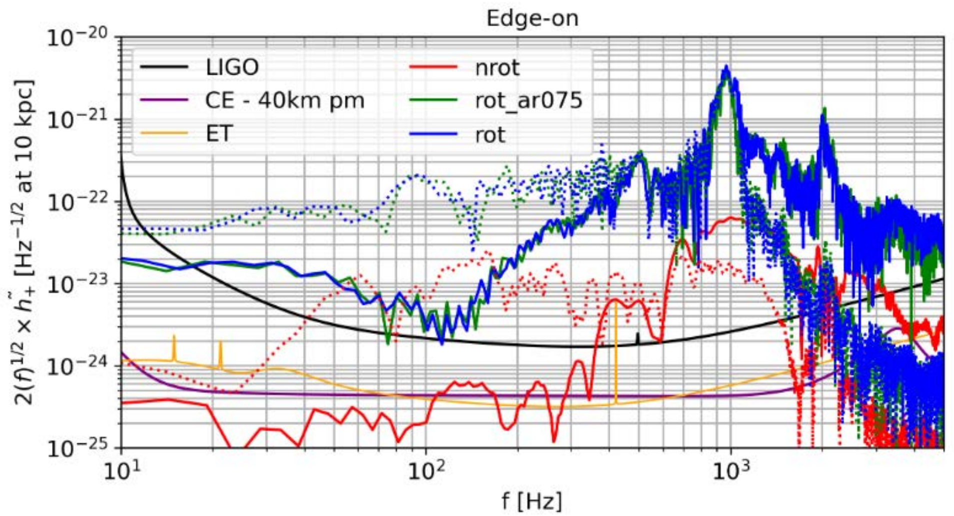
Figure. From Radice et al. (2019).

- Signal is dominated by the oscillation modes of the PNS
- Excitation mechanism? Chaotic accretion [Radice+ 2019, Andresen+ 2021] vs PNS inner convection [Andresen+ 2017, 2019; Mezzacappa+ 2022].

Detections prospects



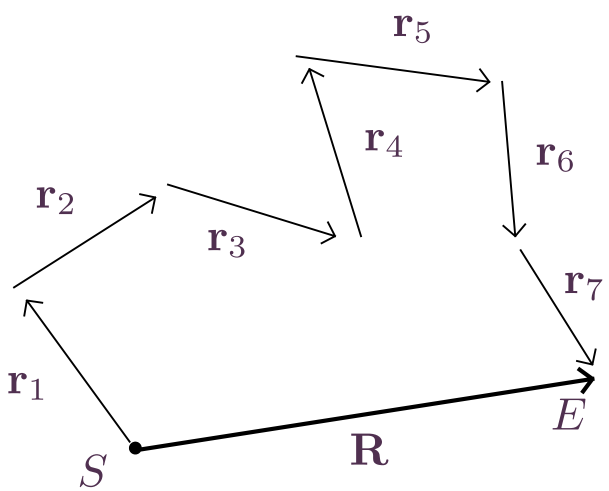
From Szczepańczyk et al. (2023)



From Longo et al. (2023)

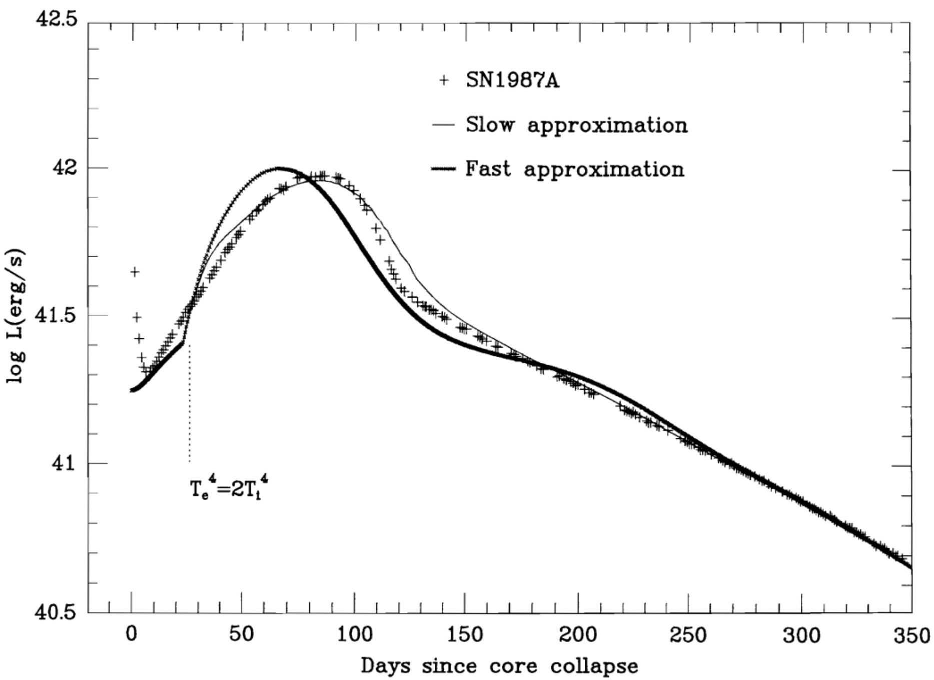
- Prospects for detection are not great with current gen observatories
- Next-generation detectors (ET, CE, NEMO) can detect nonrotating CCSNe in the galaxy at high-SNR, and fast rotating collapse to distances of a few Mpc.

On the blackboard: bolometric light curves



$$\langle \mathbf{R} \rangle = \langle \mathbf{r}_1 + \mathbf{r}_2 + \mathbf{r}_3 + \cdots \rangle = 0$$

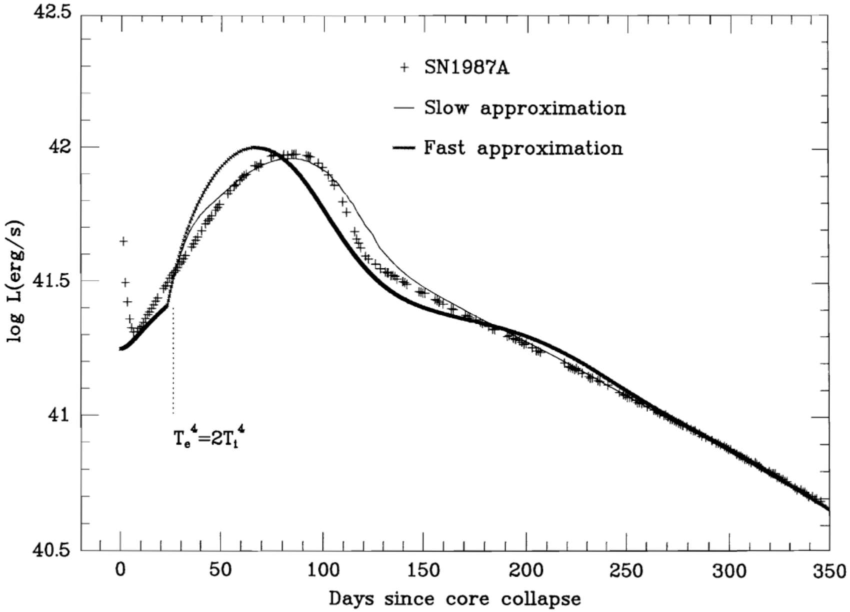
$$\begin{aligned} \langle \mathbf{R}^2 \rangle &= \langle (\mathbf{r}_1 + \mathbf{r}_2 + \cdots) \cdot (\mathbf{r}_1 + \mathbf{r}_2 + \cdots) \rangle \\ &= \langle \mathbf{r}_1^2 \rangle + \langle \mathbf{r}_2^2 \rangle + \cdots + 2 \langle \mathbf{r}_1 \cdot \mathbf{r}_2 \rangle = N \lambda \end{aligned}$$



From Arnett, *Supernovae and Nucleosynthesis*, 1999

The peak timescale for the light curve can be estimated as

$$t_p = \left(\frac{\kappa M}{\beta c v} \right)^{1/2}, \qquad \beta \approx 13.8.$$



For Thompson scattering in an hydrogen rich, ionized gas $\kappa = 0.4\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, so

$$t_p \;=\; 1.4 \cdot 10^6\,\mathrm{s}\,M_1^{1/2}\,\kappa_{0.4}^{1/2}\,v_9^{-1/2}$$

For SN1987a $v \sim 0.3 \cdot 10^9\,\mathrm{cm\,s}^{-1}$ and the peak time is $t_p \approx 100\,\mathrm{days}$.

Question. What is R at peak? What is M_1? What is the explosion energy?

Answer.

A “one-zone” model: Arnett’s law

We derive on the blackboard a one-zone model:

$$\dot{E} + p\,\dot{V} = \dot{Q}_{\mathrm{heat}} - L.$$

We show two important results

1. Most of the initial energy is lost to adiabatic expansion, so $K \gg E_{\mathrm{EM}}$.
2. The peak luminosity if $\dot{Q}_{\mathrm{heat}} \approx 0$ is

$$L \approx \frac{E_p}{\tau_{d,p}} = \frac{\beta\, R_p\, c}{\kappa\, M}\, E_p = 5.2 \cdot 10^{43}\,\mathrm{erg\,s^{-1}}\, E_{p,50}\, R_{p,15}\, M_1^{-1}\, \kappa_{0.4}^{-1}.$$

3. **Arnett’s law**: at peak $\dot{Q}_{\mathrm{heat}} \approx L$.

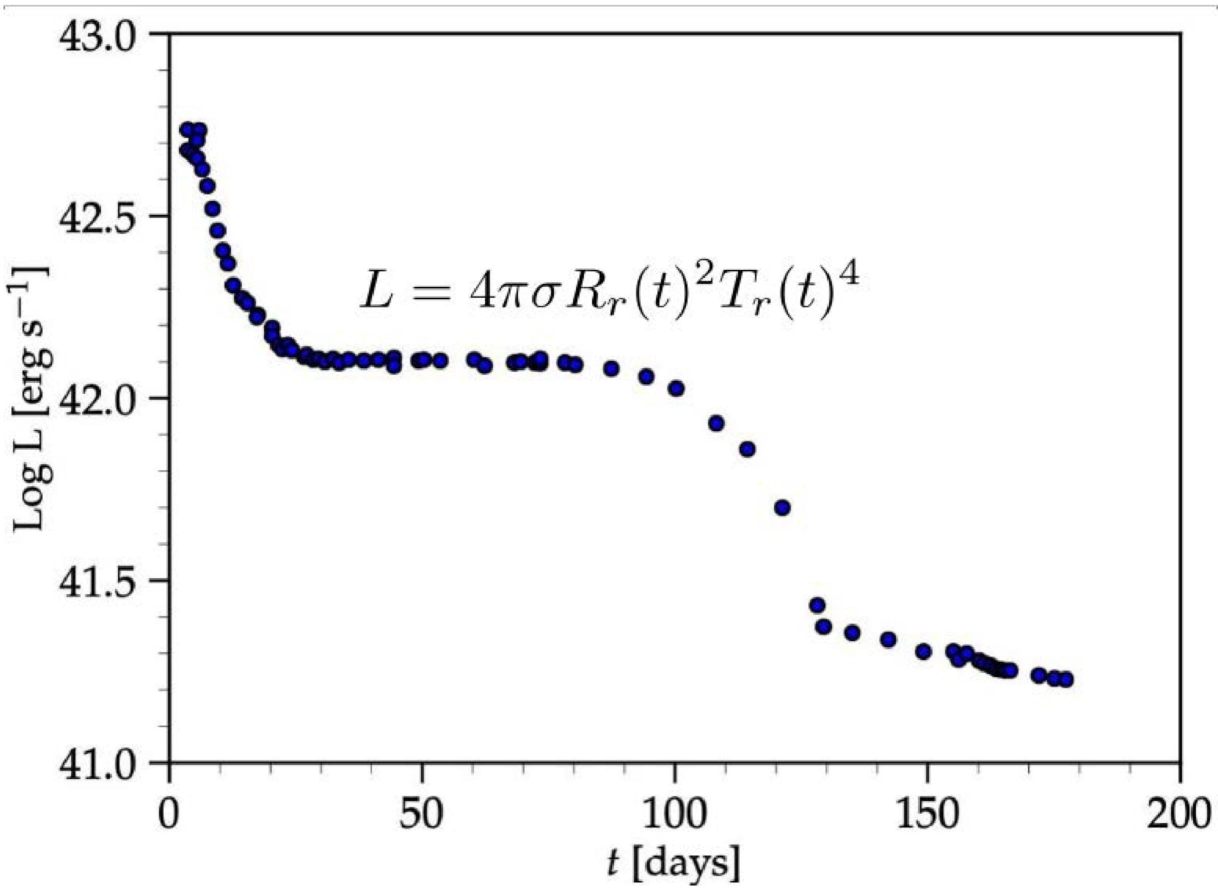
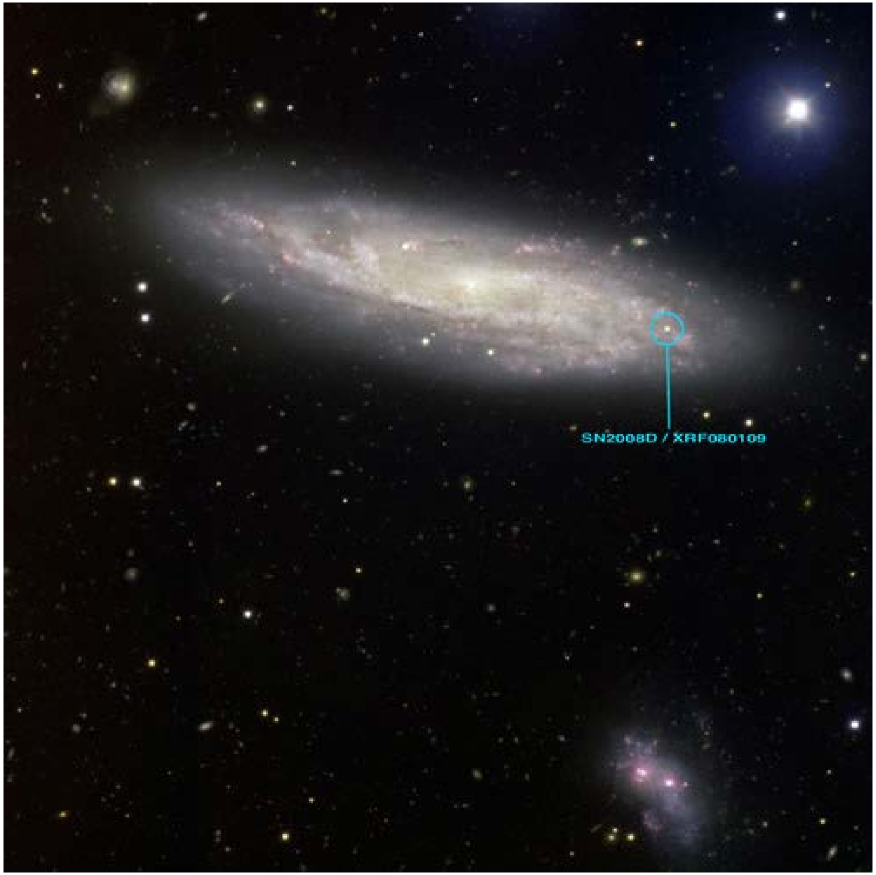


Figure. Bolometric light curve for SN1999em, a classical example of a Type II-P supernova. Data from Elmhamdi et al., MNRAS **338**, 939-956 (2003), figure courtesy of Dr. Giryanskaya.



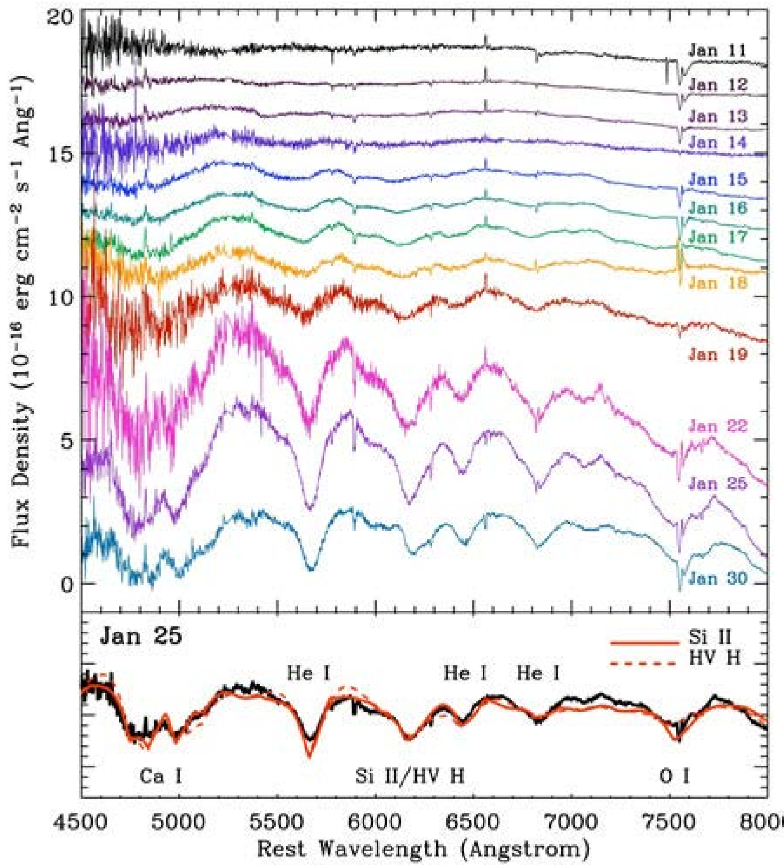


Figure. SN2008D optical (left) and spectra evolution (right). Credit: Gemini observatory.

Future directions

- Better supernova models
  - Inclusion of GR, magnetic fields, better neutrino transport, nuclear burning
  - More realistic "3D" stellar evolution models, binary stellar evolution
  - Extension to several seconds and then to breakout
- Observational data
  - Light curves from millions of supernovae, many spectra, progenitor images, etc.
  - Preparing for the next galactic CCSN
- Peculiar supernovae
  - Hypernovae, BH forming supernovae, LGRB
  - Ultra-stripped supernovae, accretion-induced collapse of white dwarfs
  - White-dwarf neutron-star mergers

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