Supernovae From Red Super Giant Stars

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Overview

Explosion Mechanism

- In the last stages of its life, a massive star consists of concentric shells, with a core composed mostly by iron and lighter elements all around.
- The collapse of the inner core of a massive star forming a neutron star (NS) releases a huge amount of gravitational binding energy

$$\Delta E_b \approx \frac{GM_{core}^2}{R} = 3 \times 10^{53} \left(\frac{M_{core}}{M_\odot} \right) \left(\frac{R}{10km} \right)^{-1} erg. \tag{1}$$

- Only a few percent of this energy needs to be trapped to power the outflow of a supernova (SN) explosion.

The Key Role of Neutrinos

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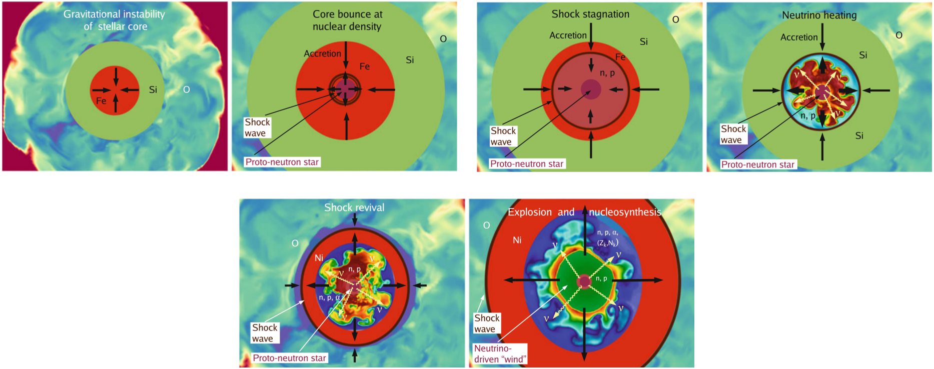
Solution

Neutrinos coming from the cooling proto-neutron star revive the stalled shock (Colgate & White 1966, Wilson 1985).

This idea was confirmed by simulations first (Wilson 1985), and by the observation of SN1987A later.

Phases of the Explosion (Wongwathanarat et al. 2013, Müller et al. 2016)



Numerical Setup

- `PROMETHEUS-HOTB` (Janka & Müller 1996, Gabler et al. 2021)
- Models: 7 red super giant (RSG) stars, with $12.5 M_\odot \leq M \leq 27 M_\odot$.
- Grid: $400(r) \times 45(\theta) \times 135(\phi) \times 2$ zones.
- $\Delta\theta = \Delta\phi = 2^\circ$.
- `rib` = 3.5e6 cm.
- `gridlx` = 4.0e10 cm.
- $t_f = 2.5s$.
- Expansion in the stellar wind of the progenitor star

$$\rho_e = \rho_0 \left(\frac{R_{prog}}{r}\right)^2, \quad T_e = T_0 \left(\frac{R_{prog}}{r}\right)^2. \tag{2}$$

Explodability

Compactness (O'Connor & Ott 2011):

$$\xi_M = \left.\frac{M/M_\odot}{R(M_{bary} = M)/1000\ \text{km}}\right|_{t=t_b} \quad (3)$$

100% accuracy if a two-parameter description is used (Ertl et al. 2015).

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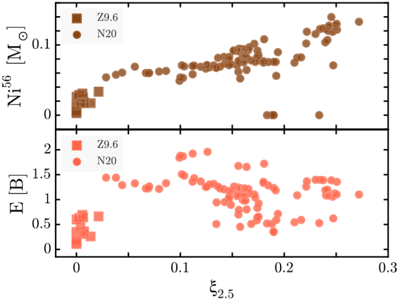
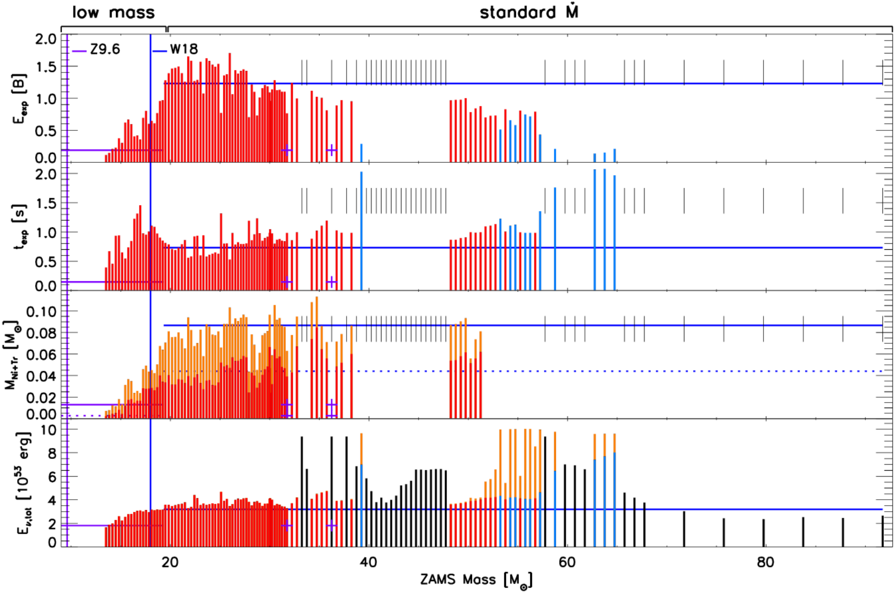


Figure: *Figure 16 from Sukhbold et al. 2016*

Explsion Rate (Ertl et al. 2020)



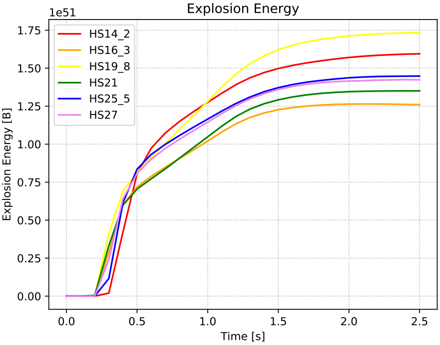
Overview

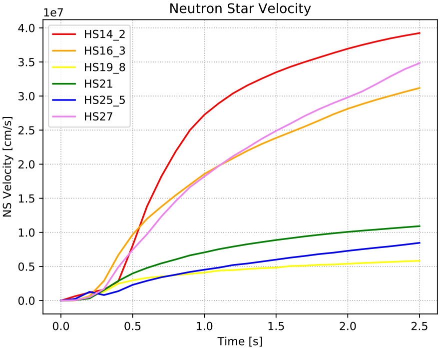
We identified 7 models that can lead to a SN explosion:

Model	t_{exp} [ms]	E_{exp} [B]	M_{Ni} [$M_\odot$]	M_{ns} [$M_\odot$]	v_{ns} [km/s]
W12.5	*Currently running*				
HS14.2	285	1.59	0.121	1.52	392.28
HS16.3	207	1.26	0.097	1.35	311.72
HS19.8	193	1.73	0.077	1.36	58.27
HS21	190	1.35	0.093	1.35	109.14
HS25.5	250	1.45	0.107	1.60	84.68
HS27	203	1.42	0.110	1.46	348.26

Calibration of E_{exp} and ^{56}Ni mass on 1D models by Sukhbold et al. 2016 (calibration models: SN1054 and SN1987A).

Explosion Energy and Remnant Kick



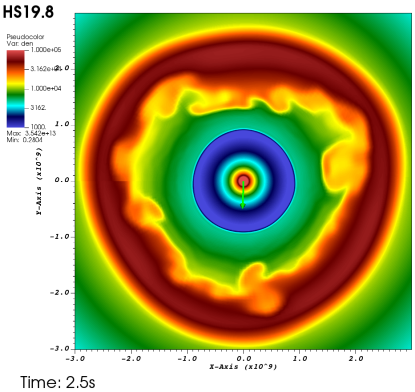


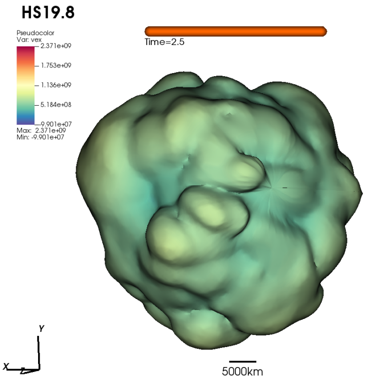
Following Sheck et al. 2006, $\mathbf{v}_{NS}(t) = -\mathbf{P}_{gas}(t)/M_{NS}(t)$, where

$$\mathbf{P}_{gas} = \int_{R_{ib}}^{R_{ob}} dV \rho \mathbf{v}.$$

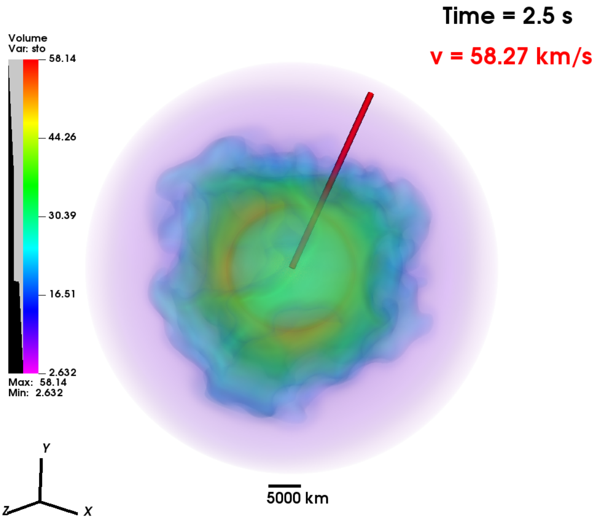
Model HS19.8

Density and ^{56}Ni distribution



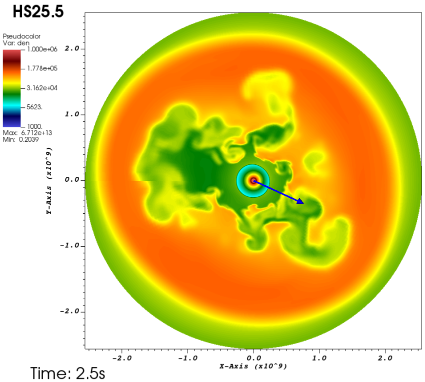


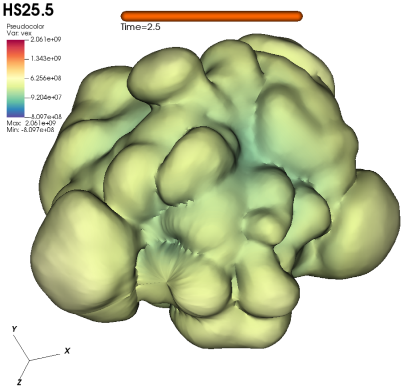
Volume plot of the entropy



Model HS25.5

Density and ^{56}Ni distribution





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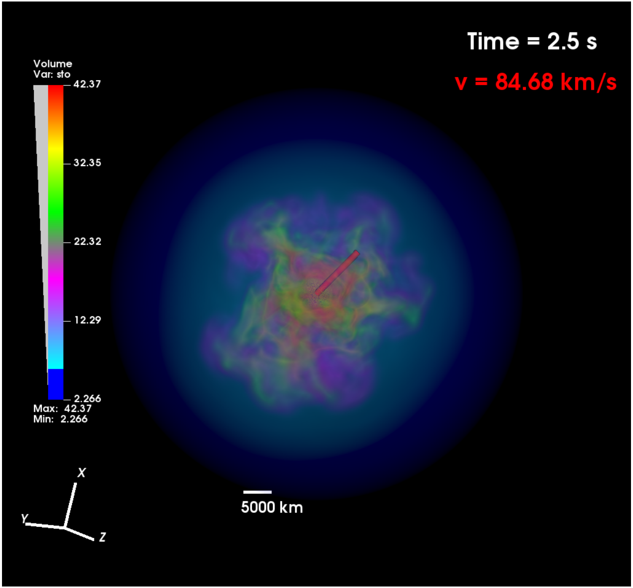
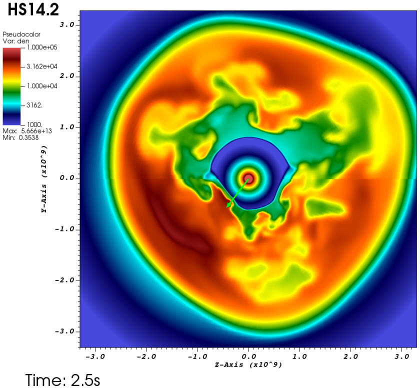
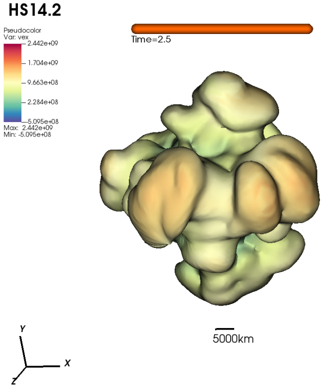


Model HS14.2

Density and ^{56}Ni distribution





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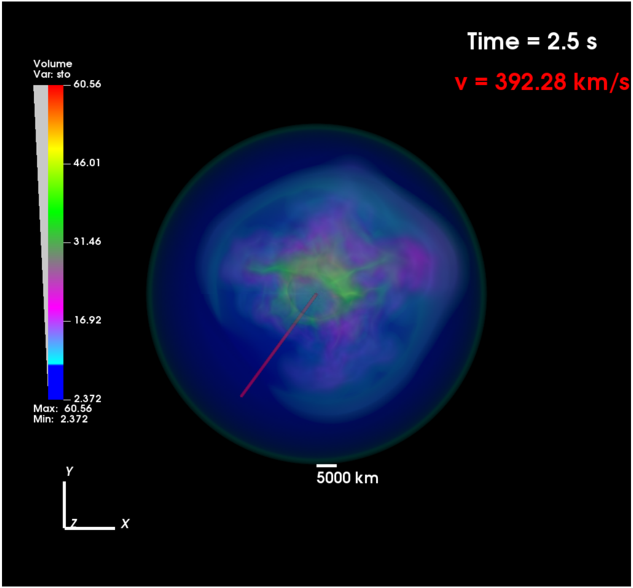

Conclusion

Summary:

- The explodability of a star is severely linked to its compactness.
- Supernova explosions are affected by hydrodynamical instabilities from very early stages, and this cause a deviation from spherical symmetry.
- The HD kick velocity does not contradict observations.

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Prospects:

- Prolong the simulations until the shock breakout.
- Extensive study of the dicotomy NS-SNR.
- The results of this study can be compared with observation to understand the nature of SNe.

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THANK YOU!!!

Yin-Yang Grid (Kageyama & Sato 2004)

$$\theta = \left[\frac{\pi}{4} - \delta, \frac{3}{4}\pi + \delta\right] \cap \phi = \left[-\frac{3}{4}\pi - \delta, \frac{3}{4}\pi + \delta\right], \quad \delta \equiv \Delta\theta = \Delta\phi$$

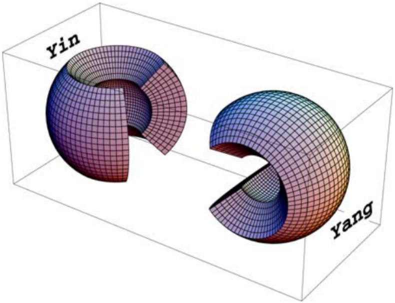

Figure: *Figure 3 from Kageyama & Sato 2004.*

- Eases the severe restriction of the time step size.
- Easy and straightforward implementation in a code that already uses spherical polar coordinates.
- It eliminates flaws near coordinate symmetry axis of the polar grid $\rightarrow$ No evidence of preferred radial direction.
- Reduced computational cost.