# Towards linking core-collapse supernova simulations with observations


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CEA/DAp seminar, 23 October 2018

# Outline

- Brief introduction
  - What is core-collapse supernova ?
  - The delayed neutrino-driven mechanism
  - How do we model it ?

- What happen after the explosion ?
  - State-of-the-art long-time modeling of CCSNe
  - Mixing instabilities in progenitor envelope

- Extracting observables from simulations
  - Light curves
  - Pulsar kicks
  - Element distributions

- Conclusions

# What is CCSNe ?

Figure from Janka et al. (2012)

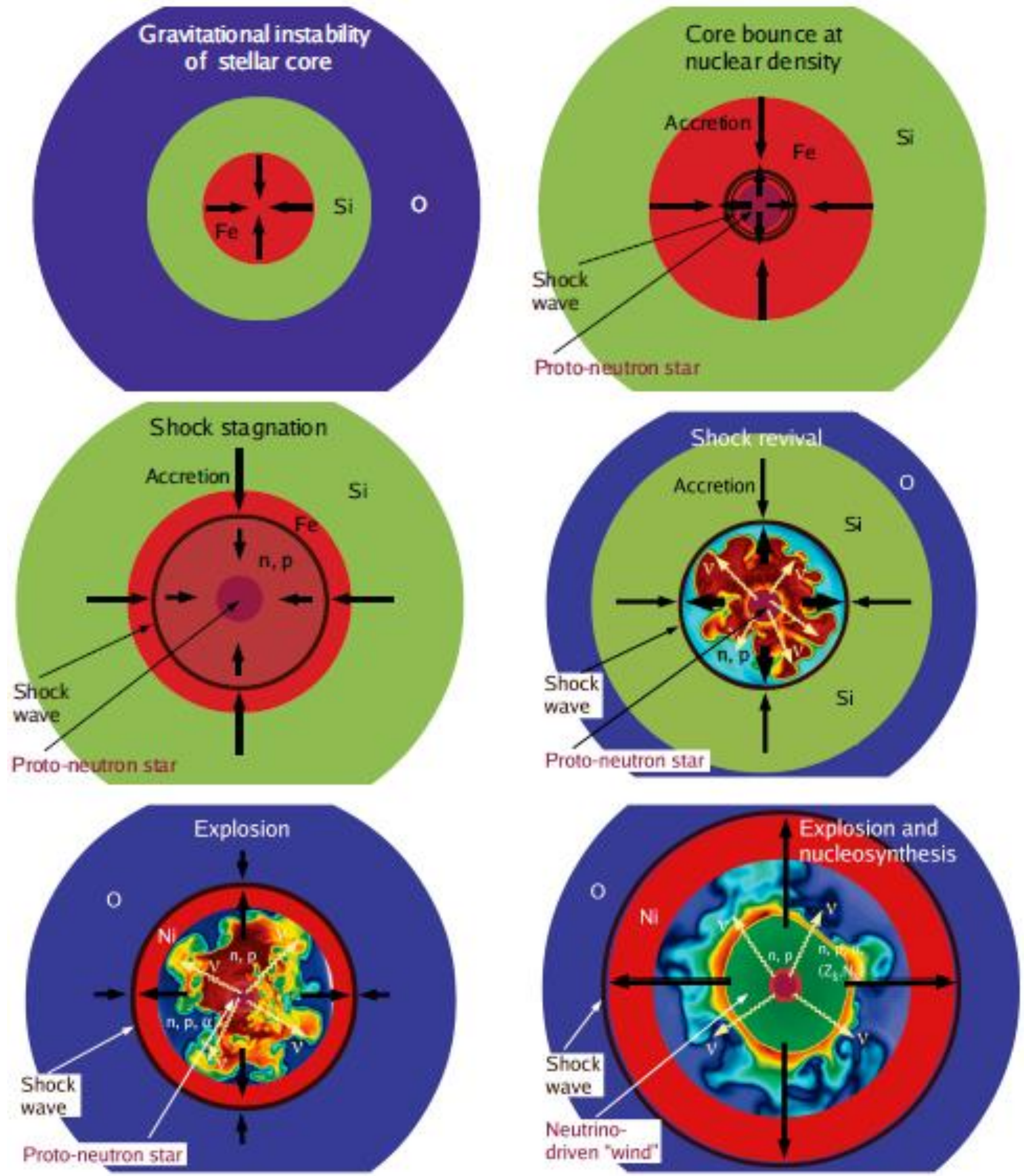
CCSNe = death of massive stars > 8-10 Msun

collapse >> bounce >> shock formation >> stalled accretion shock

how to revive the stalled shock???

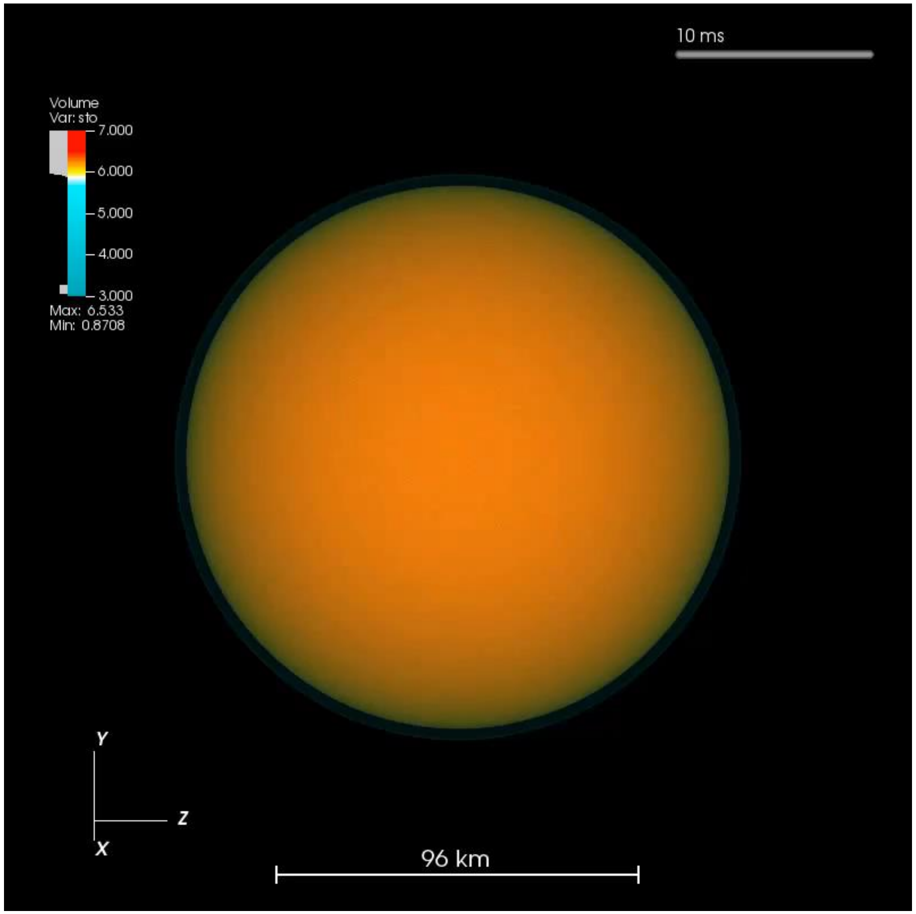
delayed neutrino-driven mechanism

multi-D effects play important roles !!!



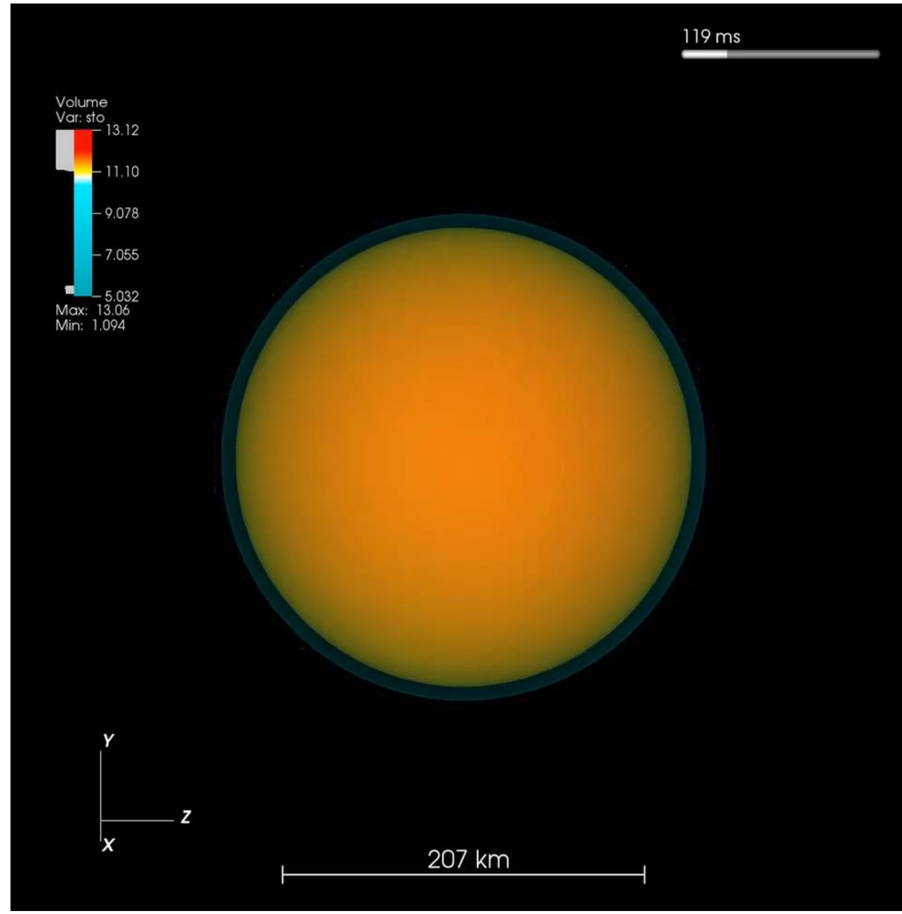
# Convection and SASI

## 9.6 solar masses star




Melson et al. (2015a), ApJL 801

## 20 solar masses star




Melson et al. (2015b), ApJL 808

# Half a century problem

- **How to revive the shock ???**
- **Delayed neutrino-driven mechanism**

| | |
|---|---|
| Beta processes: | $e^- + p \rightleftharpoons n + \nu_e$ |
| | $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ |
| | $e^- + A \rightleftharpoons \nu_e + A^*$ |
| Neutrino scattering: | $\nu + n, p \rightleftharpoons \nu + n, p$ |
| | $\nu + A \rightleftharpoons \nu + A$ |
| | $\nu + e^\pm \rightleftharpoons \nu + e^\pm$ |
| Thermal pair processes: | $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ |
| | $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$ |
| Neutrino-neutrino reactions: | $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ ($\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau$, or $\bar{\nu}_\tau$) |
| | $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$ |

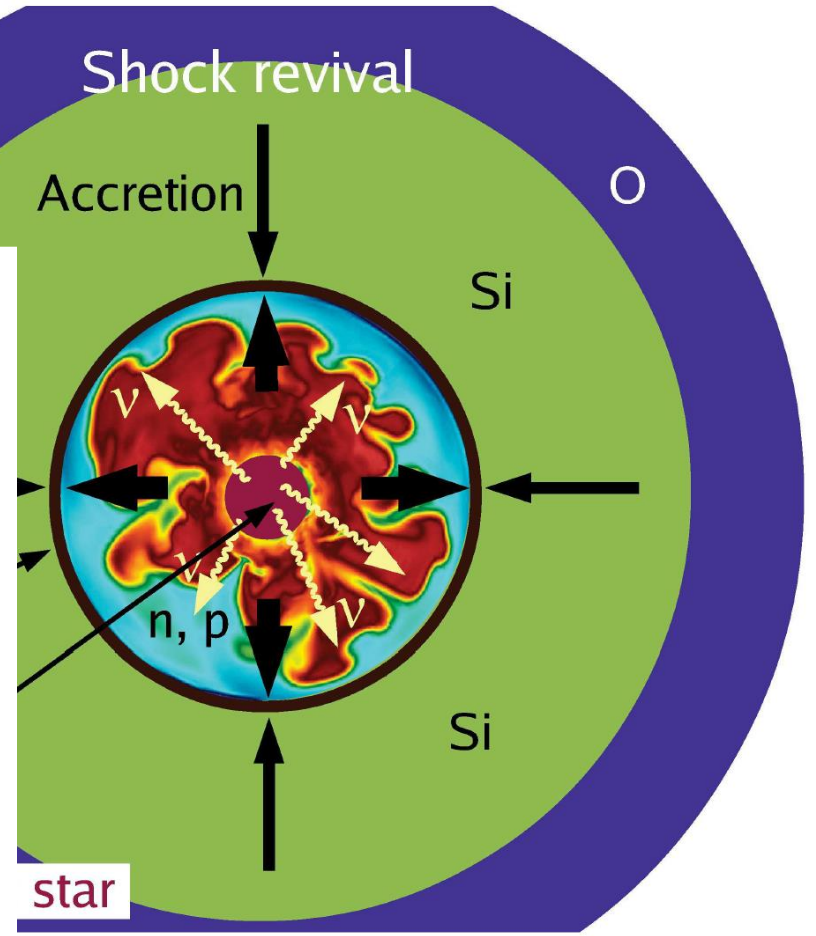



Figure from Janka et al. (2012)

# Ingredients in CCSN models and observables

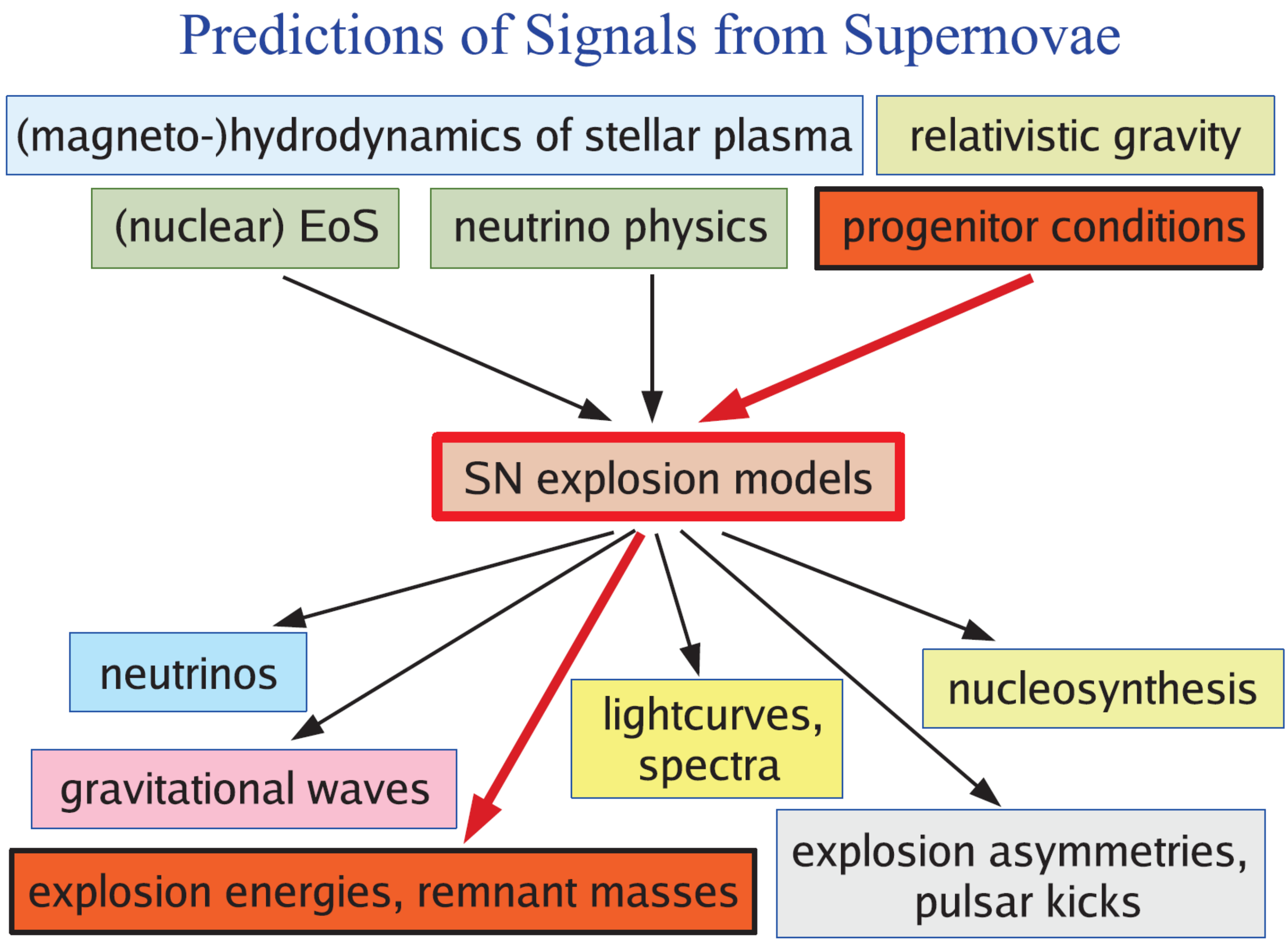
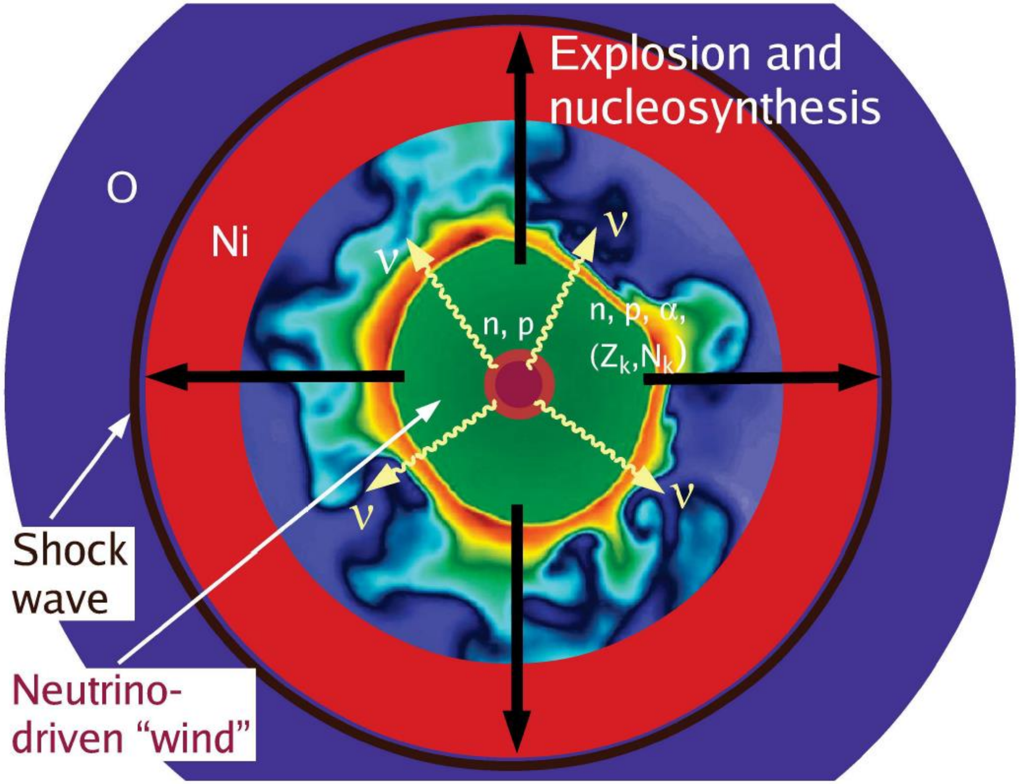
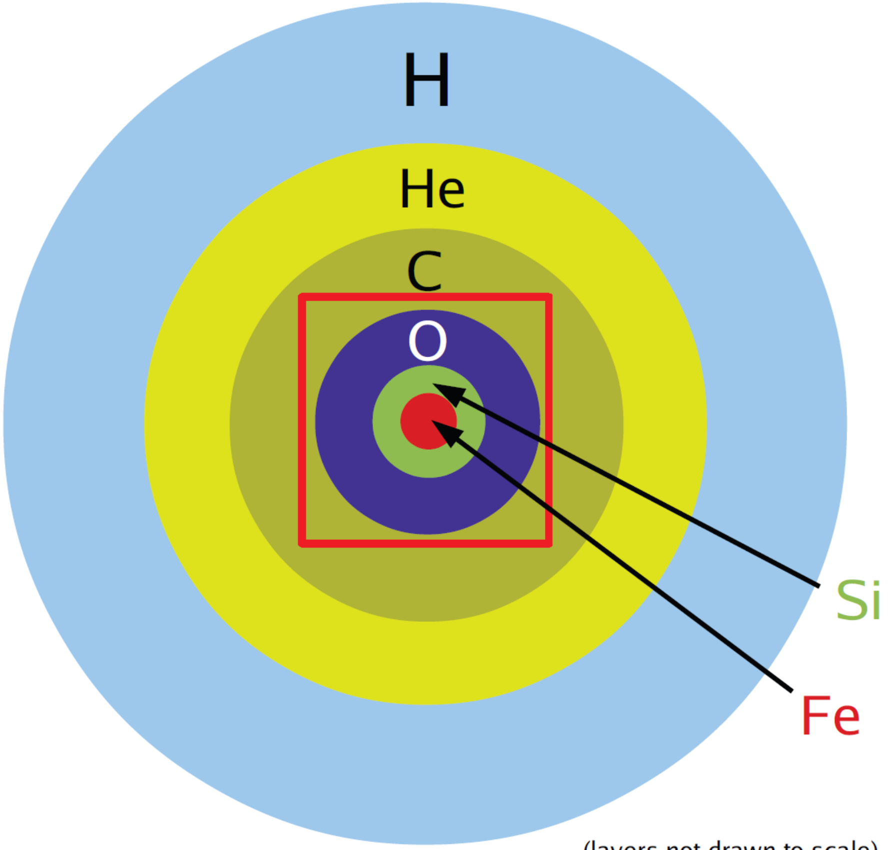



Figure from Janka et al. (2012)

# What happens after the explosions?




Onion-shell structure of pre-collapse star

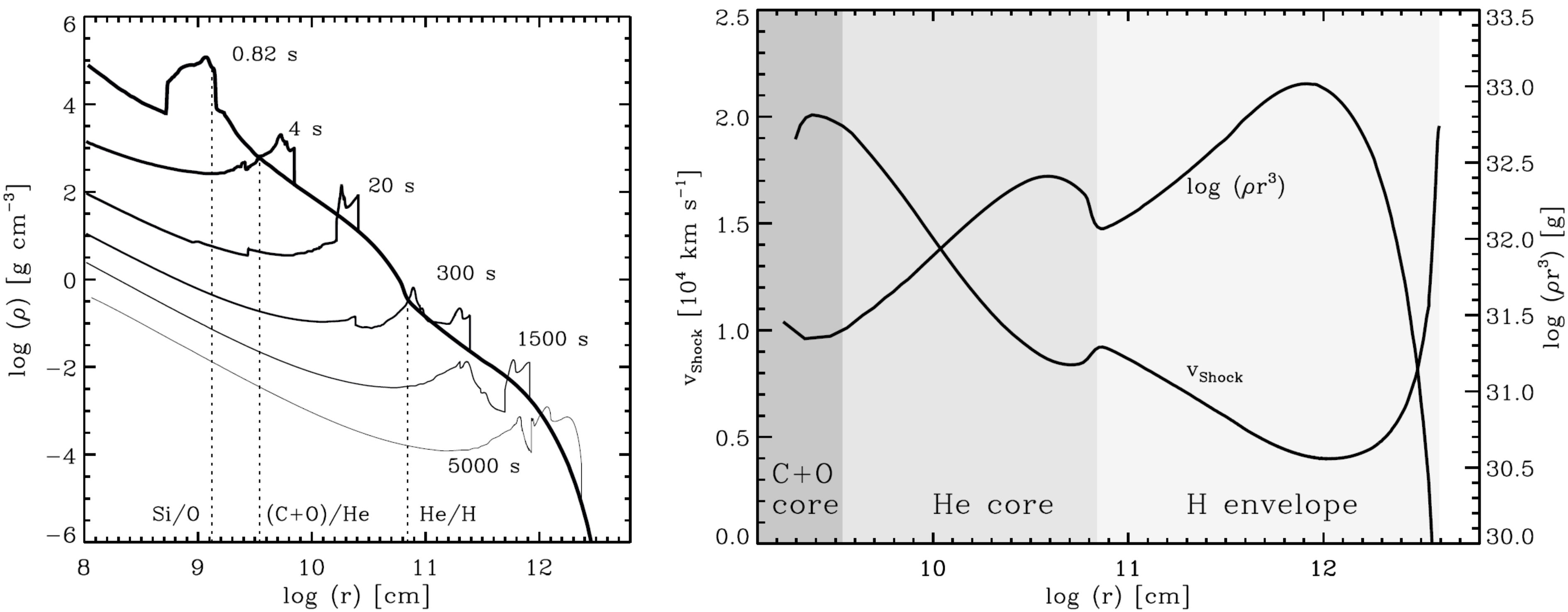



(layers not drawn to scale)

**Figure from Janka et al. (2012)**

# SN shock propagation

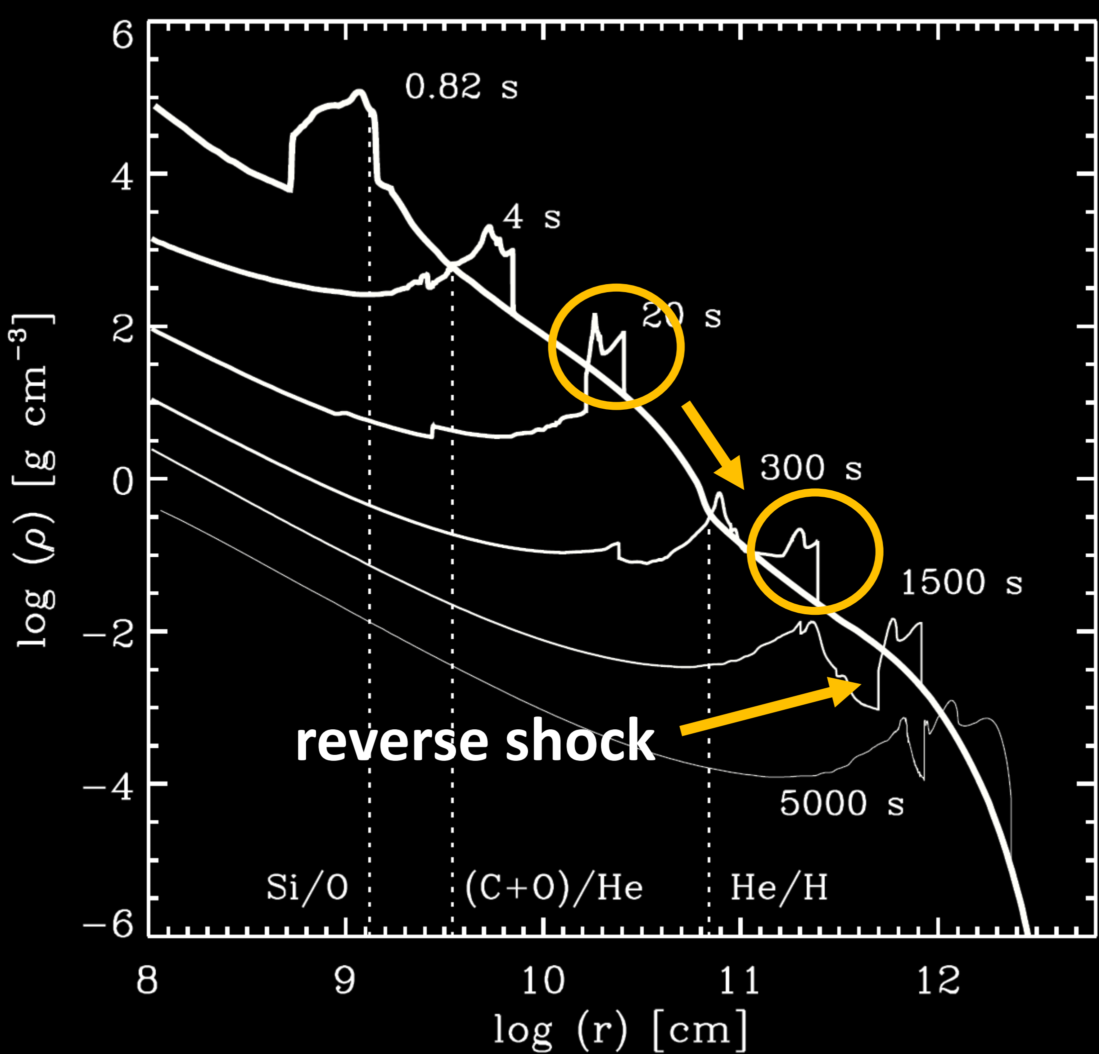
**Kifonidis+ (2003)**

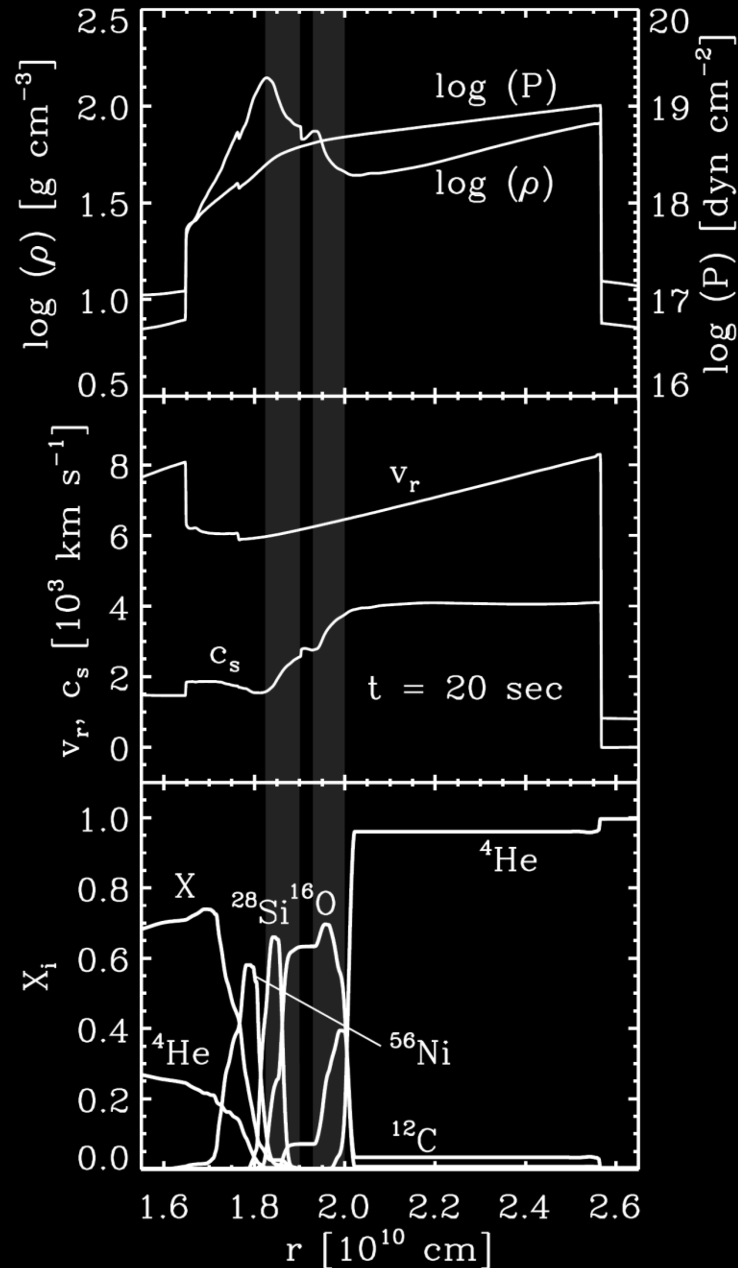



**Shock propagation follows Sedov-Taylor blast wave solution**

**Shock acceleration when $\rho r^3$ profile decreases, and vice versa**

# Rayleigh-Taylor instabilities induce mixing

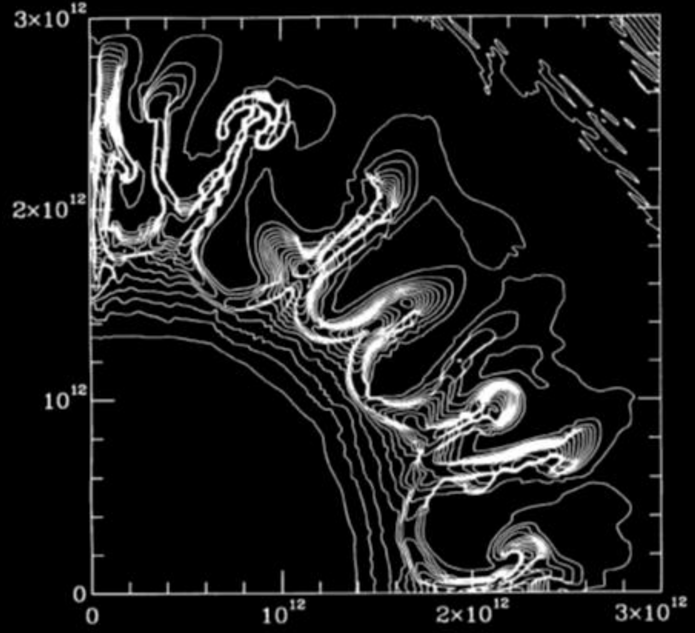


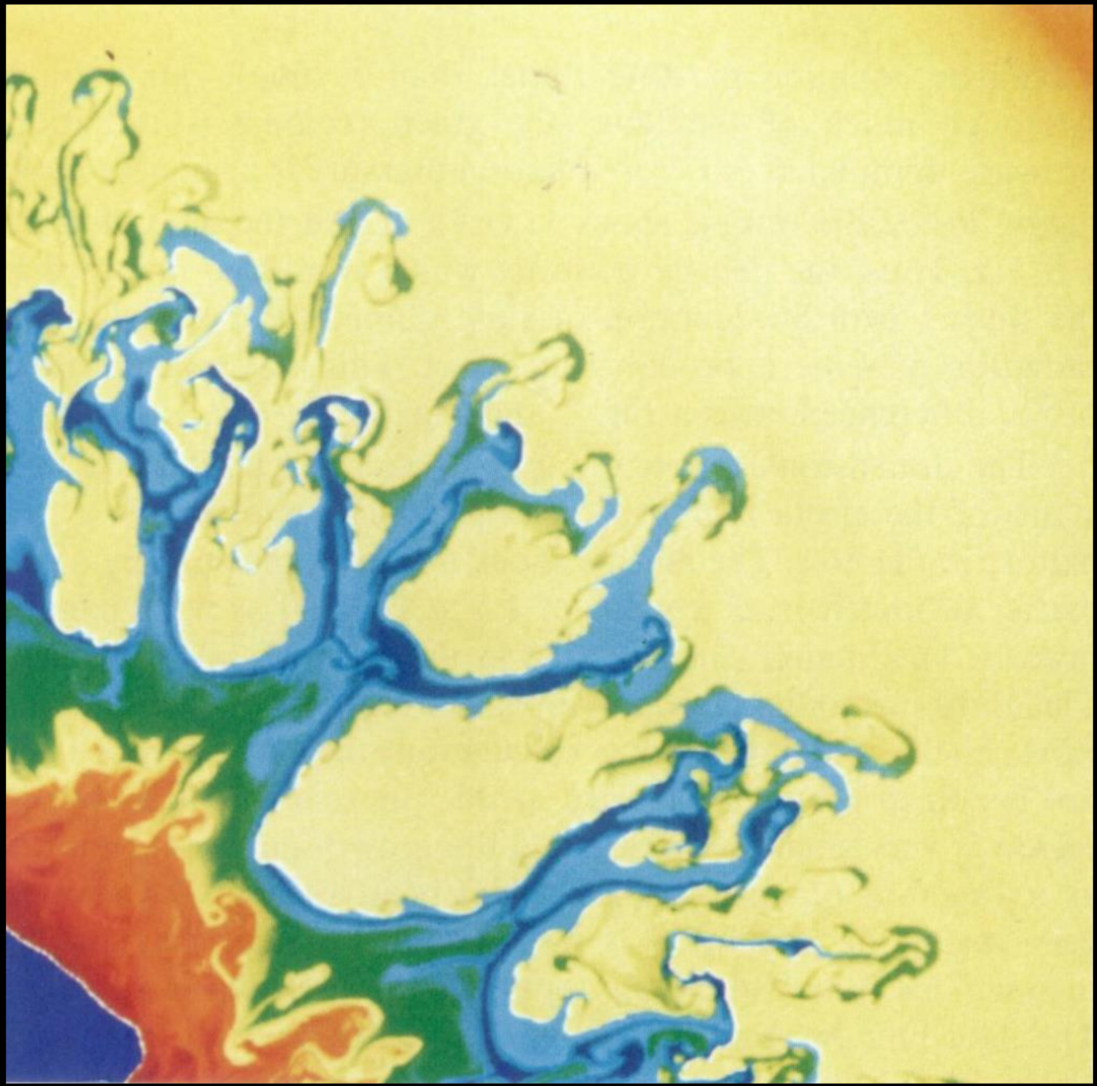




Kifonidis+ 2003

# Rayleigh-Taylor instabilities induce macroscopic mixing

2D simulation by Müller et al. (1991) using PROMETHEUS



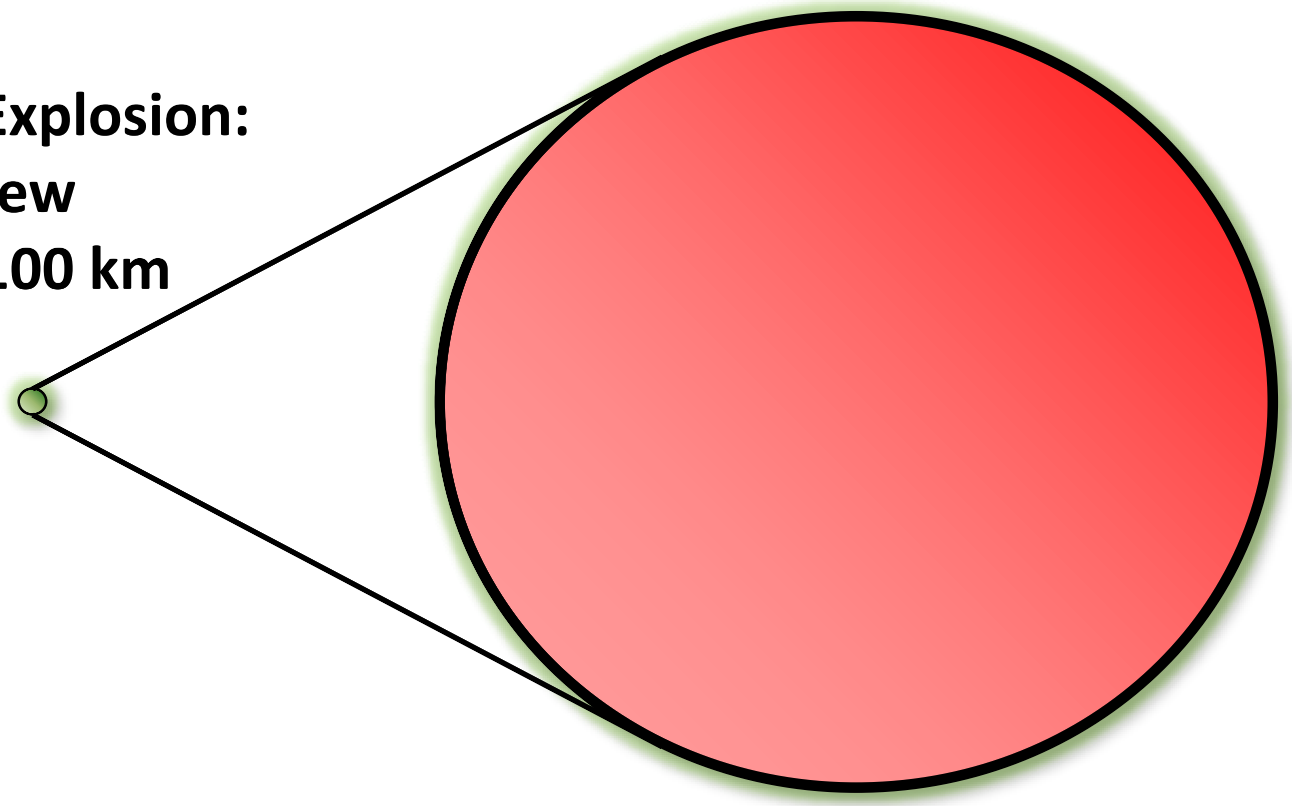



2D simulation by Arnett et al. (1989) using PROMETHEUS

15 $M_\odot$ progenitor by Arnett (1987)

# Challenges in long time simulations

Explosion:
few
100 km



Star:
few 100
millions
km

Remnants:
few 10
trillions
km

Time scale: ms >>> hours, day >>>>>>>>>>>>>>>>>>>>>>>> 100 years

# Standard approach in 90s

**Motivated by observations of SN1987A**
**Nickel required to mix beyond ~3000 km/s**

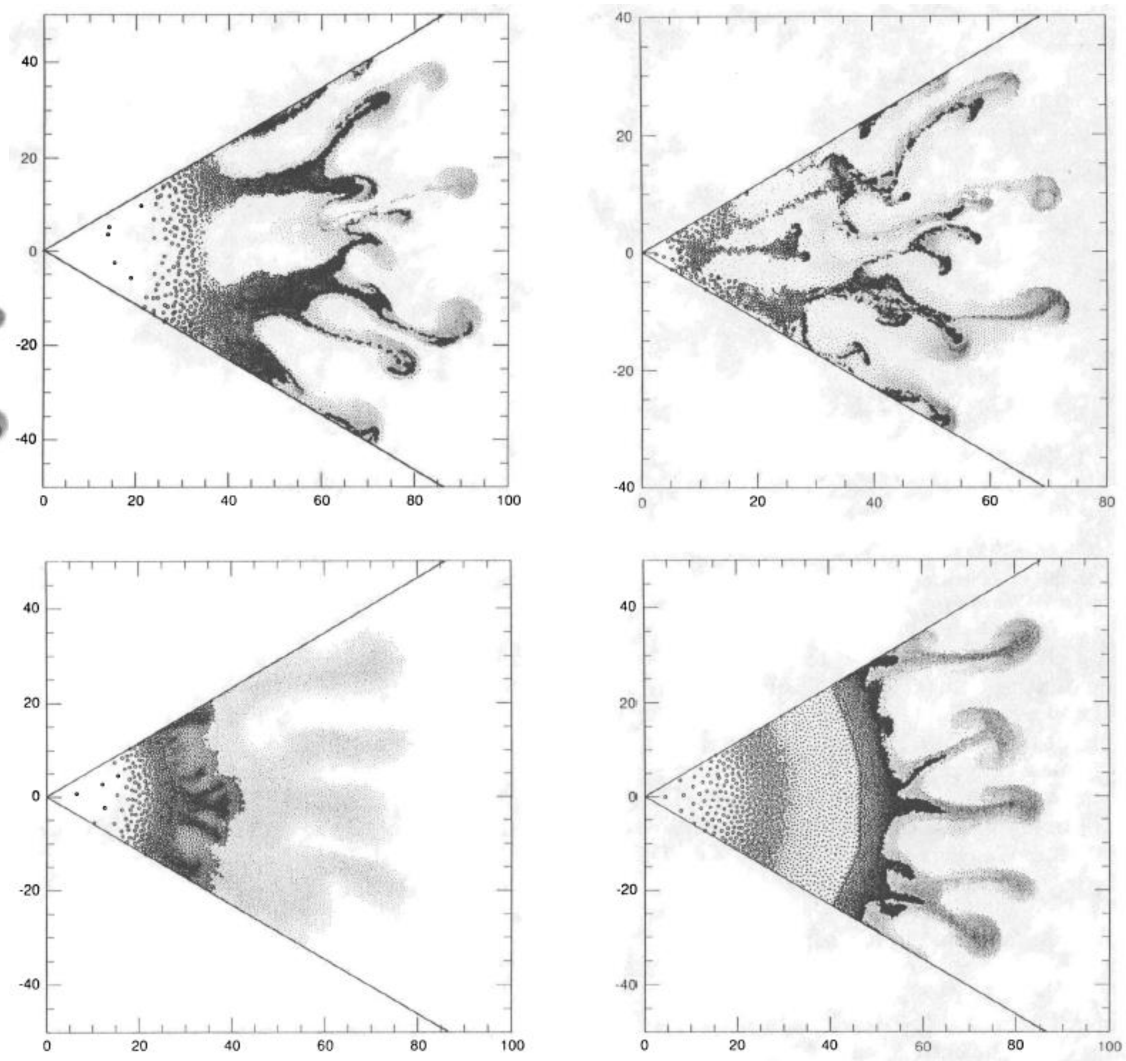
**2D simulations + thermal bomb + perturbation**

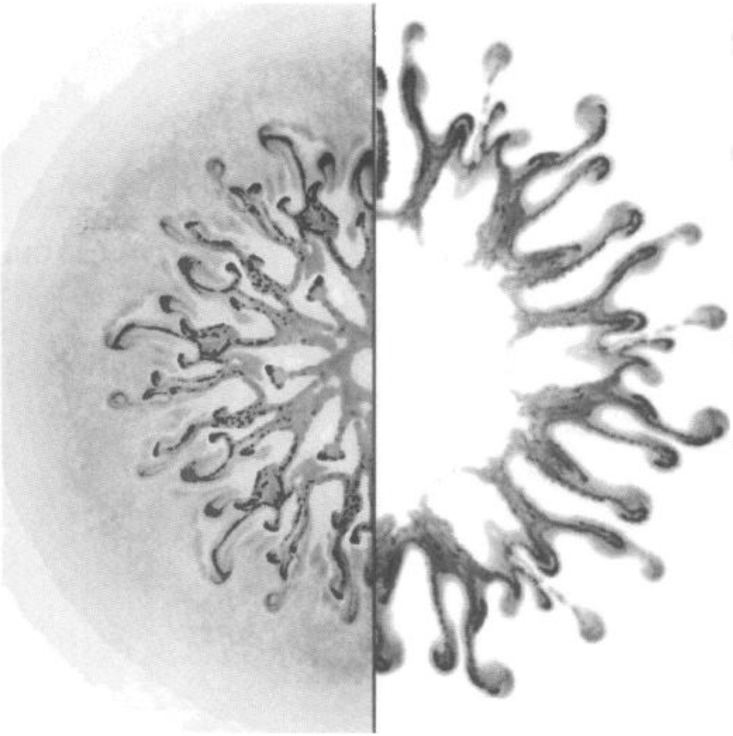
Arnett+ 1989b; Fryxell+ 1991; Müller+ 1991b,a,c; Hachisu+ 1990, 1991, 1992, 1994;Yamada & Sato 1990, 1991; Herant & Benz 1991; Herant & Benz 1992;Herant & Woosley 1994; Shigeyama+ 1996; Iwamoto+ 1997; Nagataki+ 1998; Kane+ 2000

**But, failed to solve "Nickel discrepancy"**
**>> Nickel confined to velocities below 2000 km/s**
**>> Nickel not mixed far enough**

# Progenitors

Herant&Benz 92



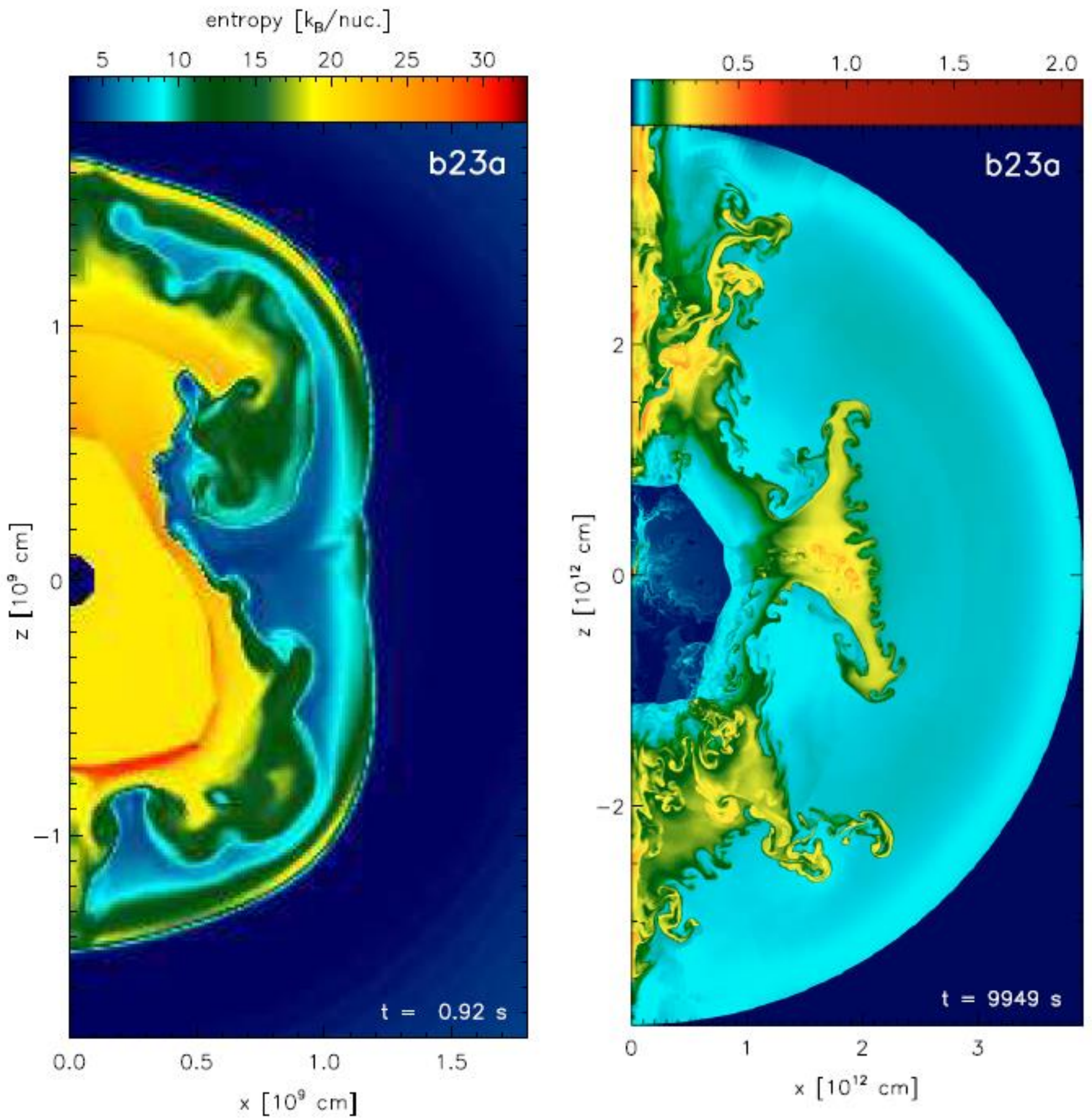
Herant&Benz 91

Different growth of RTIs depending on progenitor structure

# Explosion physics

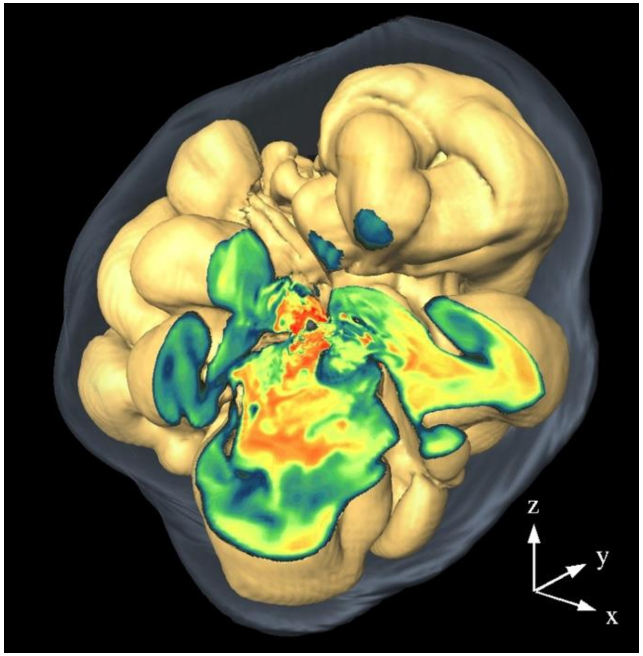
Kifonidis+ 2000, 2003, 2006 were first to consider explosions in Multi-D

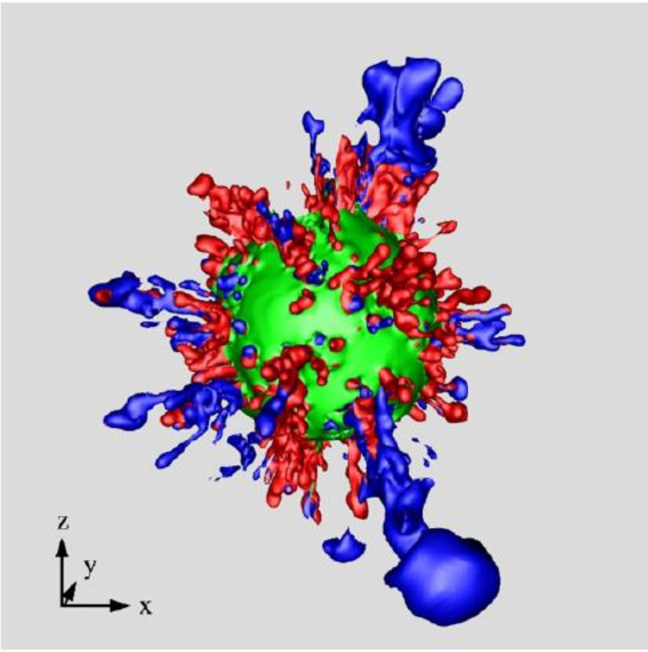
Low mode instabilities in SN cores make large-scale large-amplitude perturbation



# Dimensionality

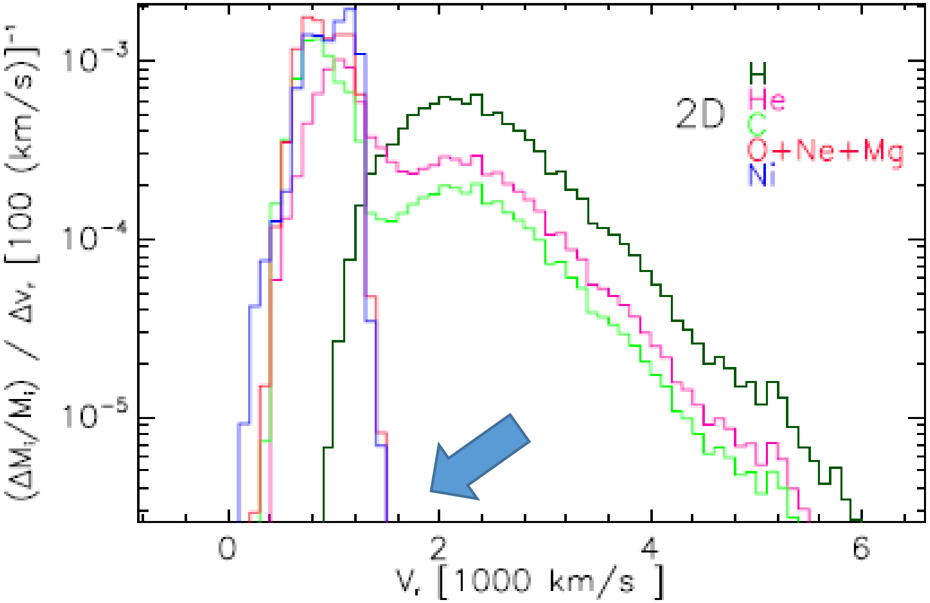
**2D VS 3D**

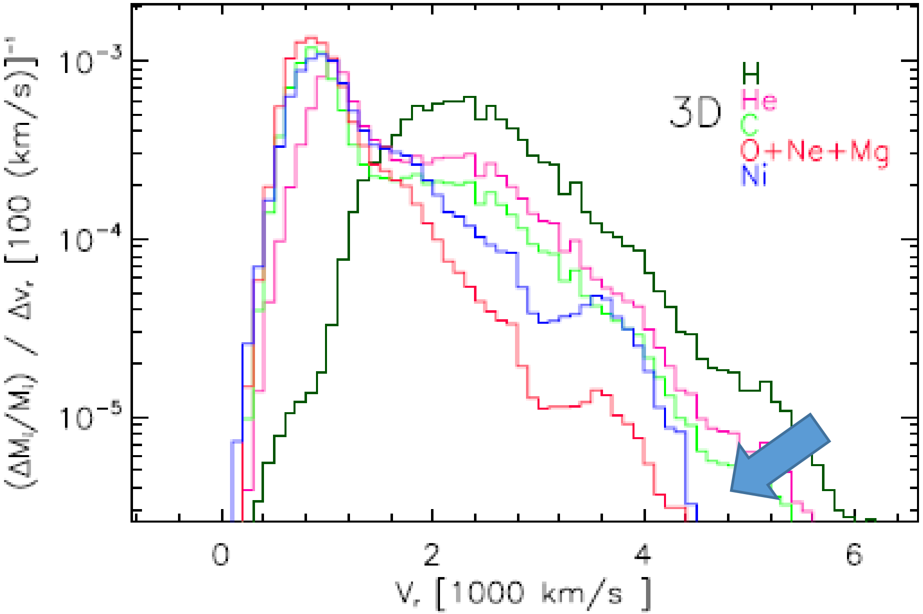


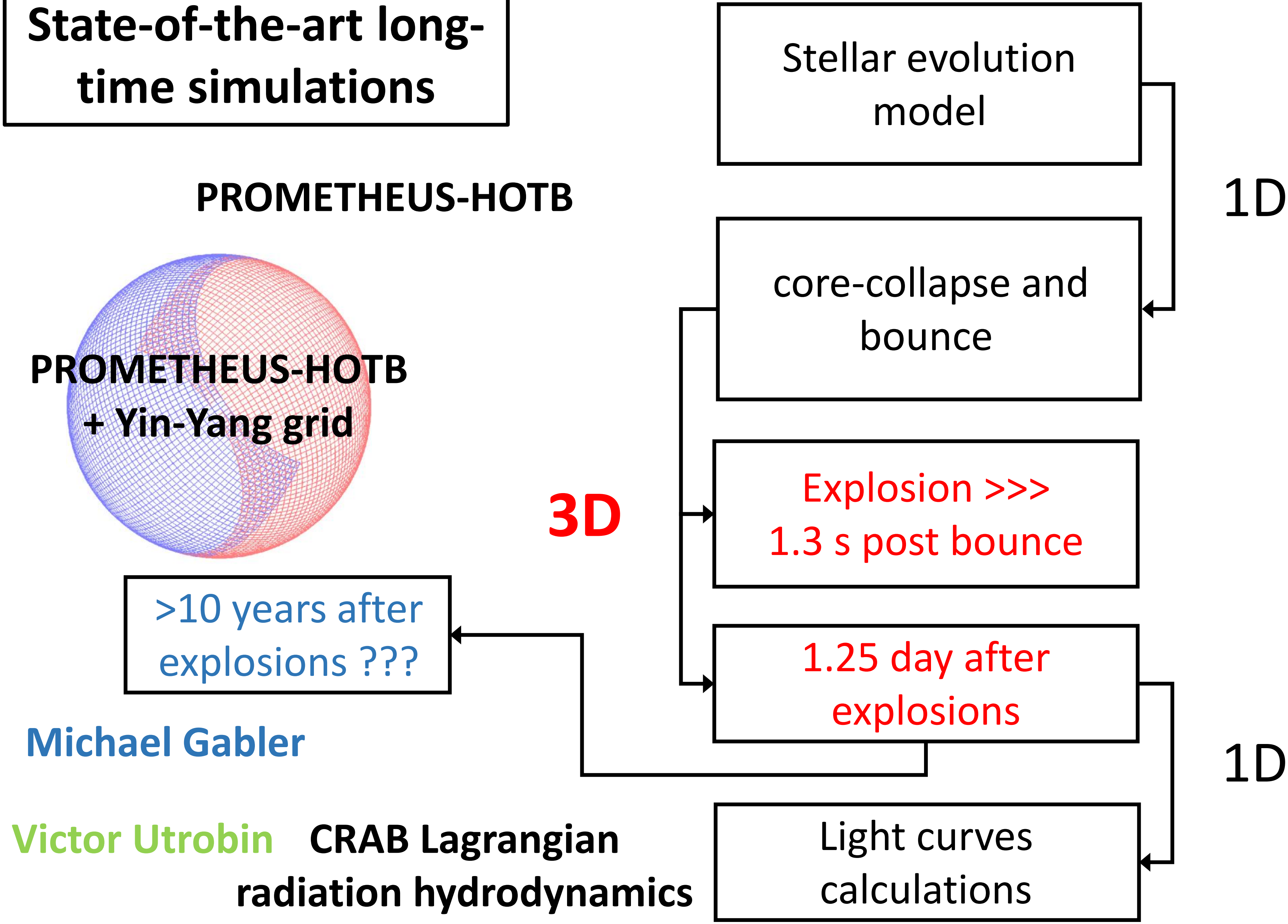

**Scheck 2008**

**Hammer+ 2010**



# State-of-the-art long-time simulations



# Numerics

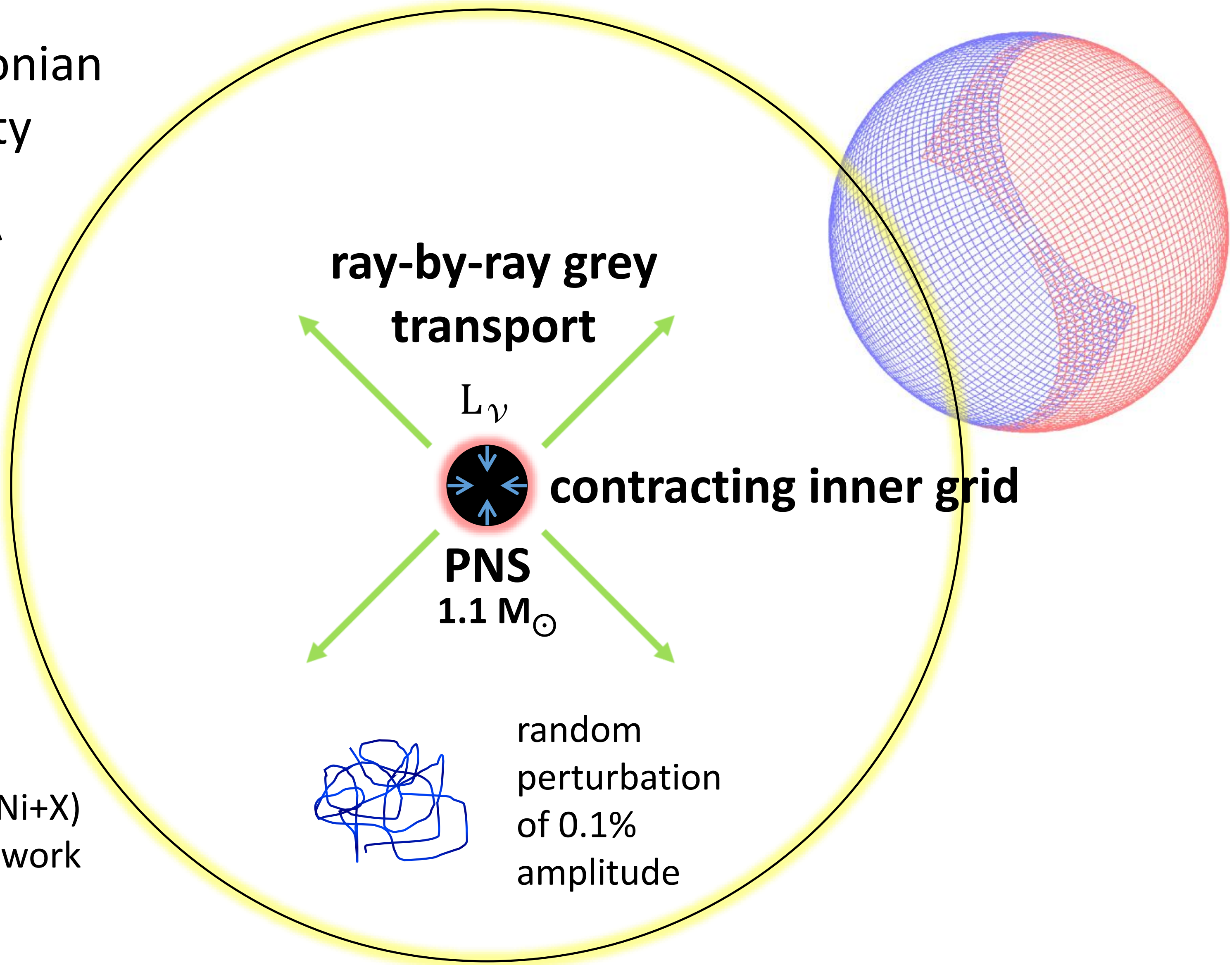
3D Newtonian self-gravity

monopole GR correction

tabulated EOS by Janka & Müller (1996)

4 nuclear species in NSE (n, p, $^{4}$He, $^{54}$Mn)

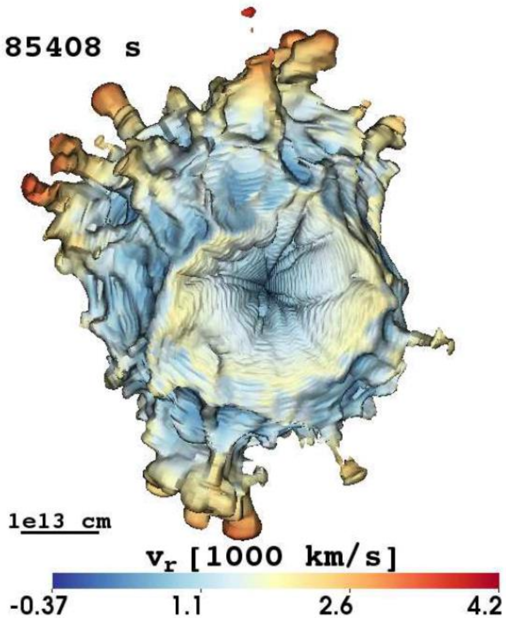
14 species ($^{4}$He- $^{56}$Ni+X) alpha-reactions network

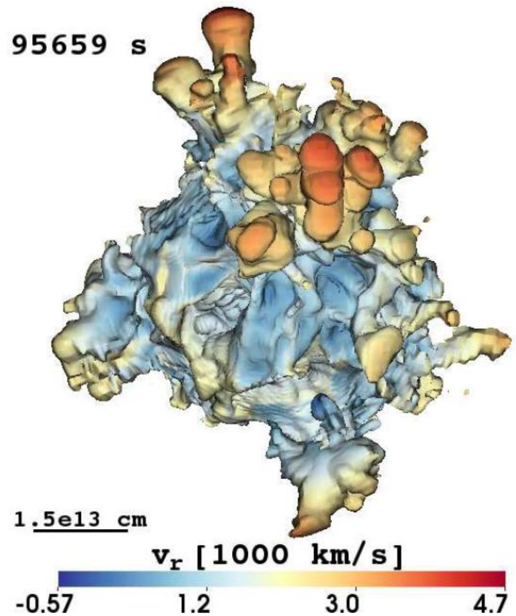


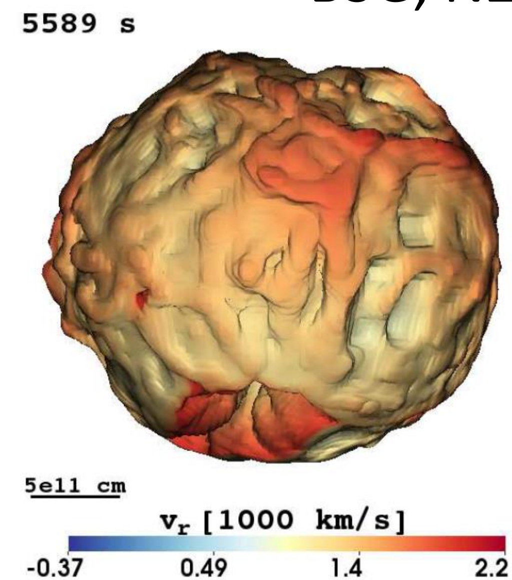
# How explosion asymmetries evolve

Shigeyama&Nomoto (1990)

BSG, N20



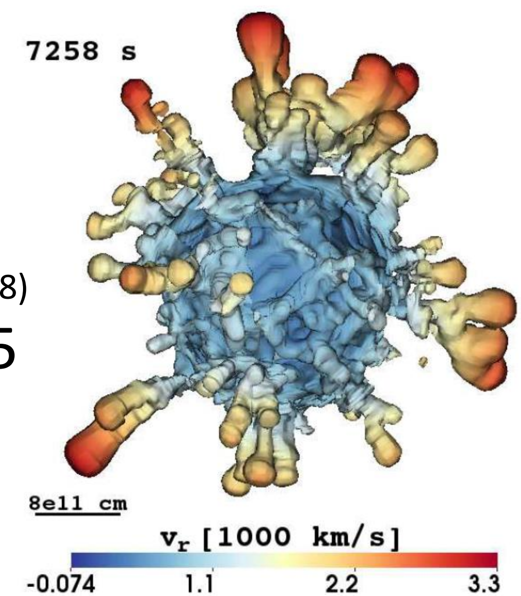




RSG, W15

Woosley & Weaver (1995)

RSG, L15

Limongi+ (2000)

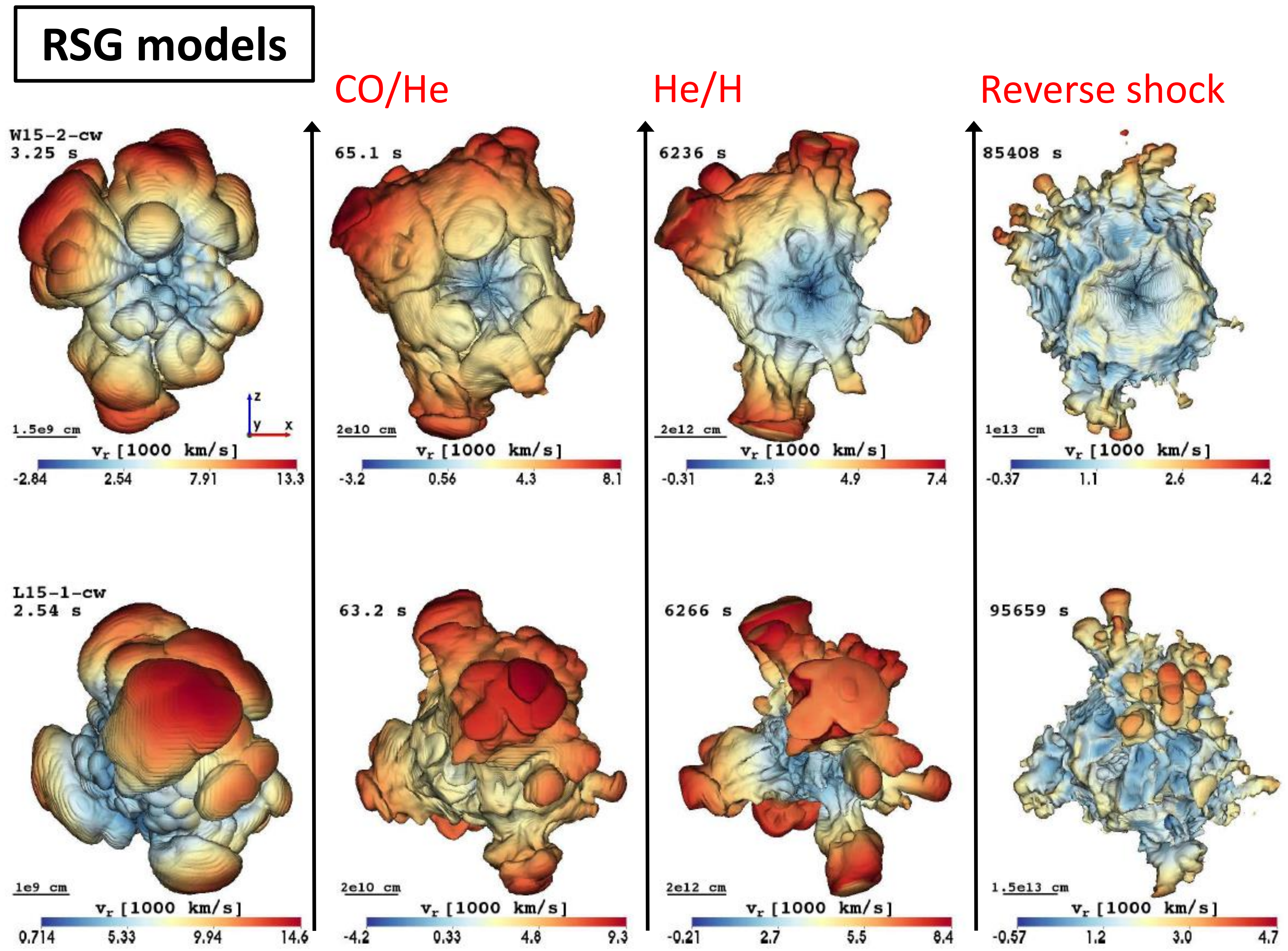



**Isosurfaces of 3% Ni color coded by velocities**

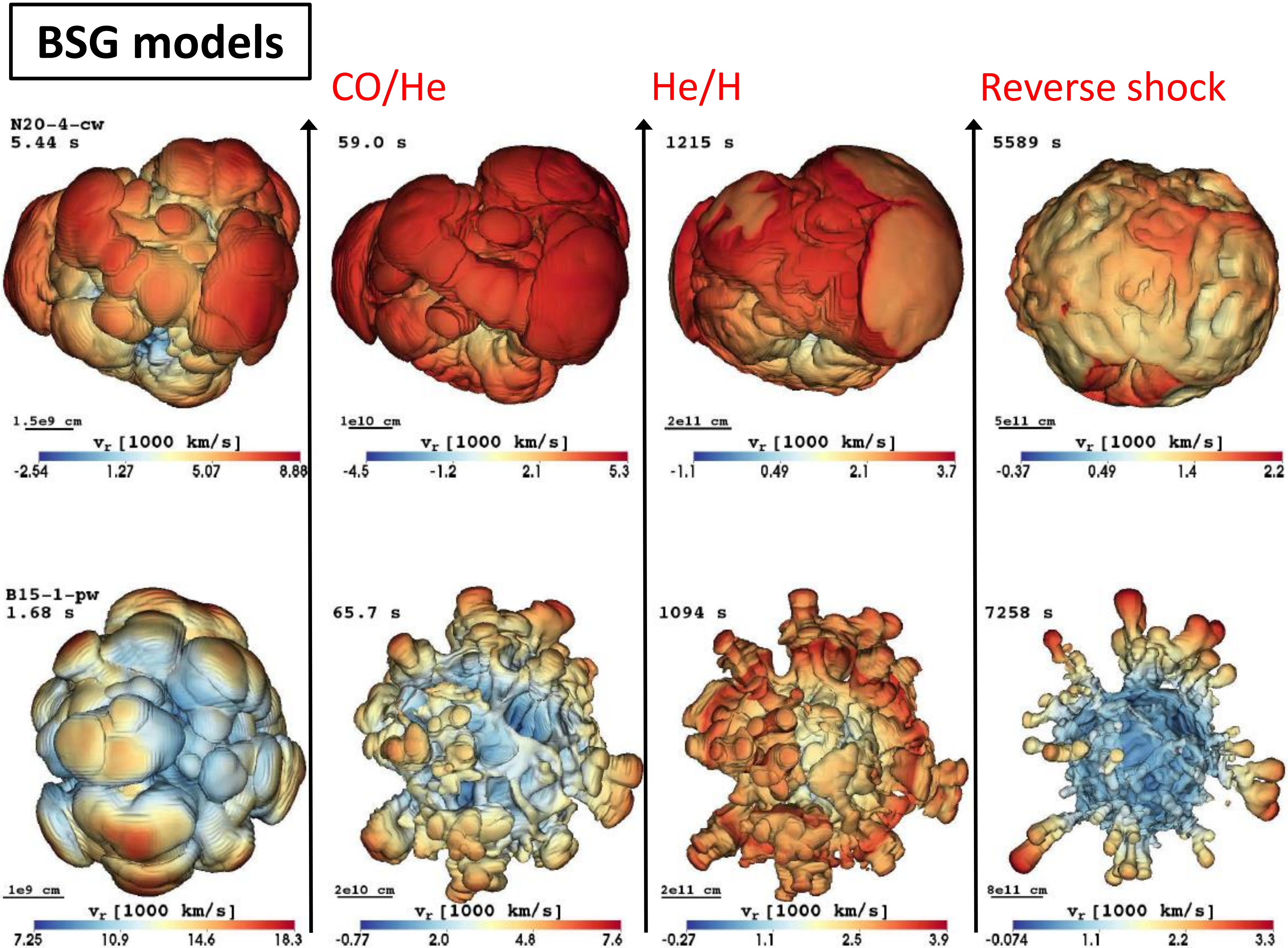
Woosley+ (1988)

BSG, B15

Wongwathanarat+ (2015)

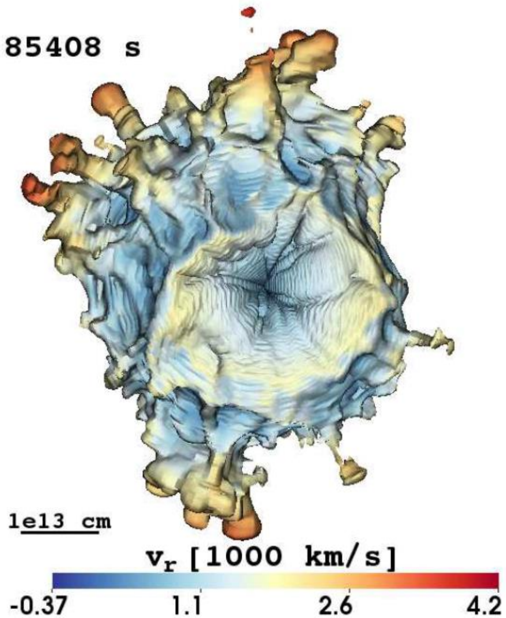


RSG models
CO/He
He/H
Reverse shock
W15-2-cw
3.25 s
65.1 s
6236 s
85408 s
1.5e9 cm
2e10 cm
2e12 cm
1e13 cm
v_r [1000 km/s]
-2.84 2.54 7.91 13.3
-3.2 0.56 4.3 8.1
-0.31 2.3 4.9 7.4
-0.37 1.1 2.6 4.2
L15-1-cw
2.54 s
63.2 s
6266 s
95659 s
1e9 cm
2e10 cm
2e12 cm
1.5e13 cm
0.714 5.33 9.94 14.6
-4.2 0.33 4.8 9.3
-0.21 2.7 5.5 8.4
-0.57 1.2 3.0 4.7



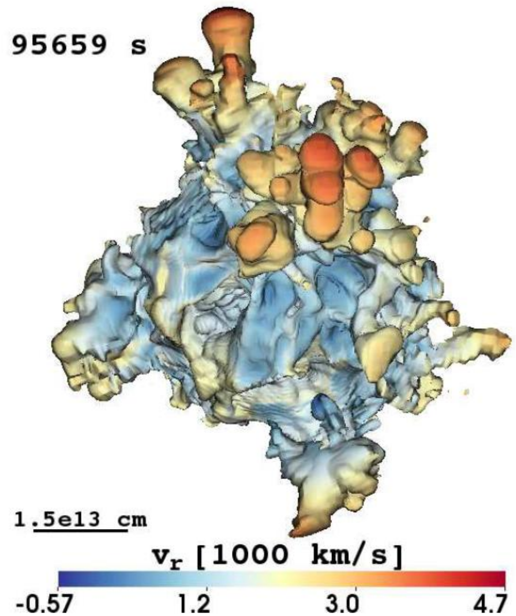
BSG models
CO/He
He/H
Reverse shock
N20-4-cw
5.44 s
59.0 s
1215 s
5589 s
1.5e9 cm
1e10 cm
2e11 cm
5e11 cm
v_r [1000 km/s]
-2.54 1.27 5.07 8.88
-4.5 -1.2 2.1 5.3
-1.1 0.49 2.1 3.7
-0.37 0.49 1.4 2.2
B15-1-pw
1.68 s
65.7 s
1094 s
7258 s
1e9 cm
2e10 cm
2e11 cm
8e11 cm
7.25 10.9 14.6 18.3
-0.77 2.0 4.8 7.6
-0.27 1.1 2.5 3.9
-0.074 1.1 2.2 3.3

# Nickel-rich ejecta at shock breakout




RSG, W15

Woosley & Weaver (1995)

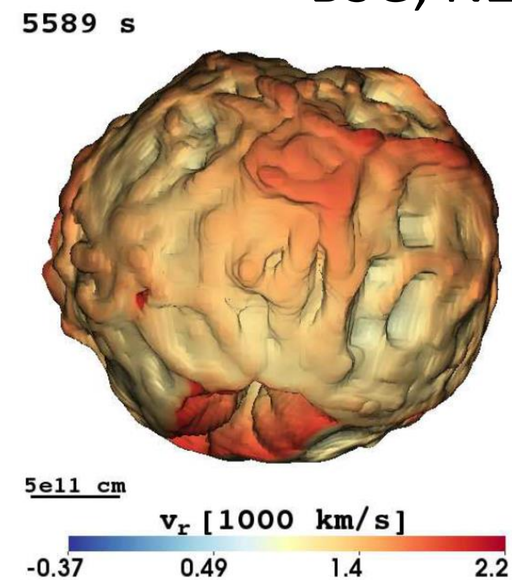



RSG, L15

Limongi+ (2000)

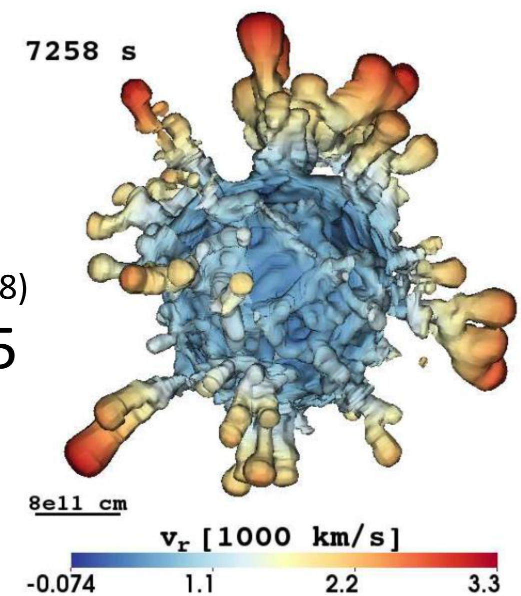
Shigeyama&Nomoto (1990)

BSG, N20



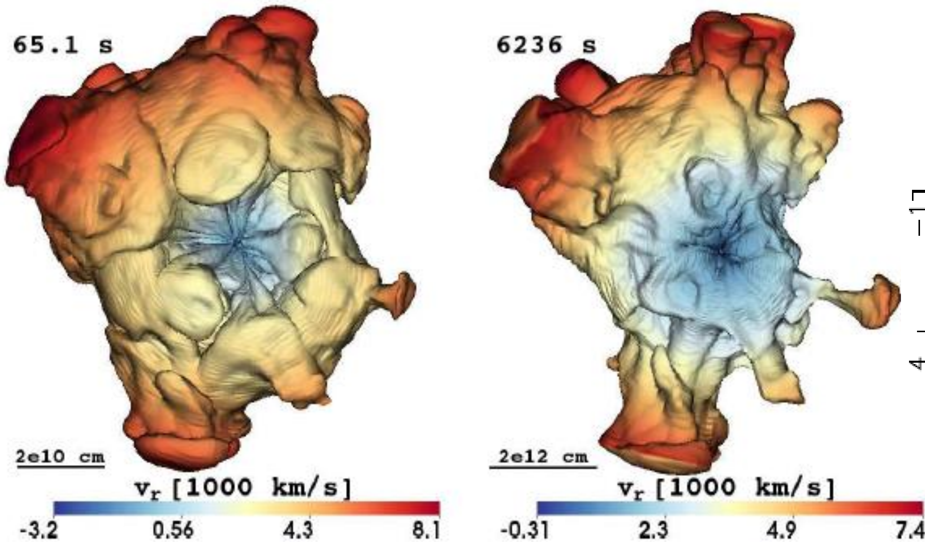

Woosley+ (1988)

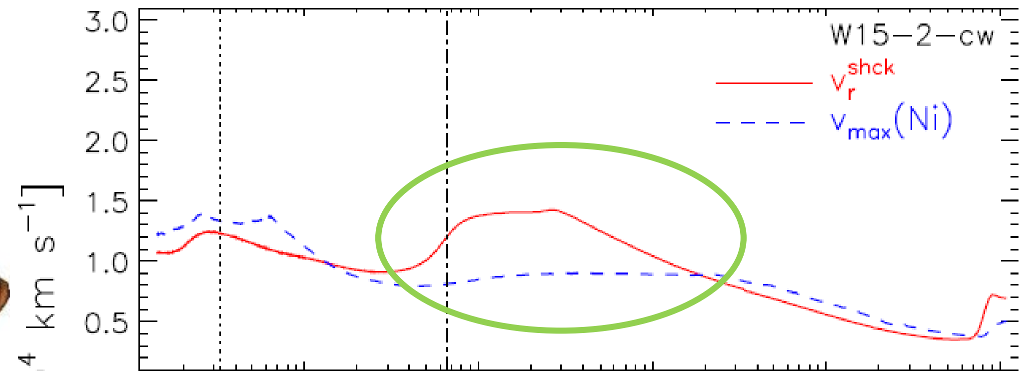
BSG, B15




**Dynamical interplay between the propagation of the forward SN shock, the reverse shock, and the Ni-rich ejecta determines the morphology of Ni-rich ejecta at shock breakout**

# RSG model



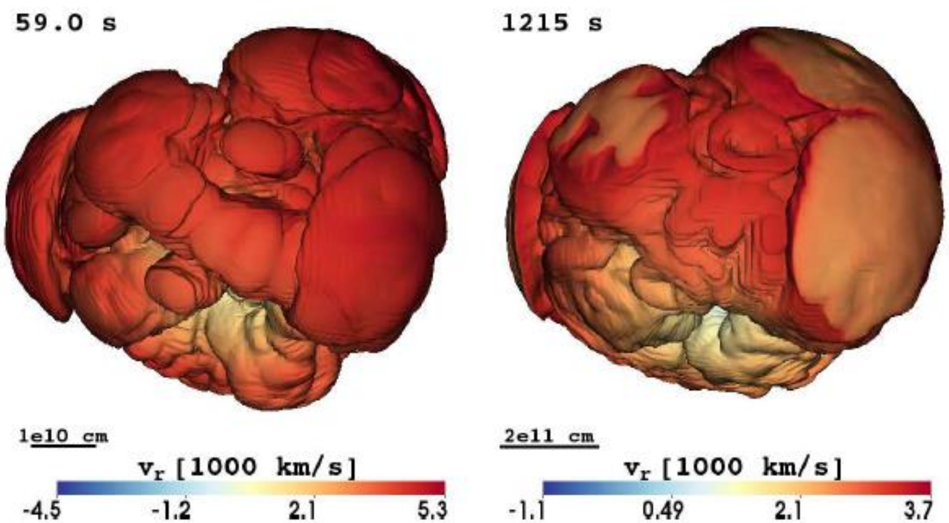



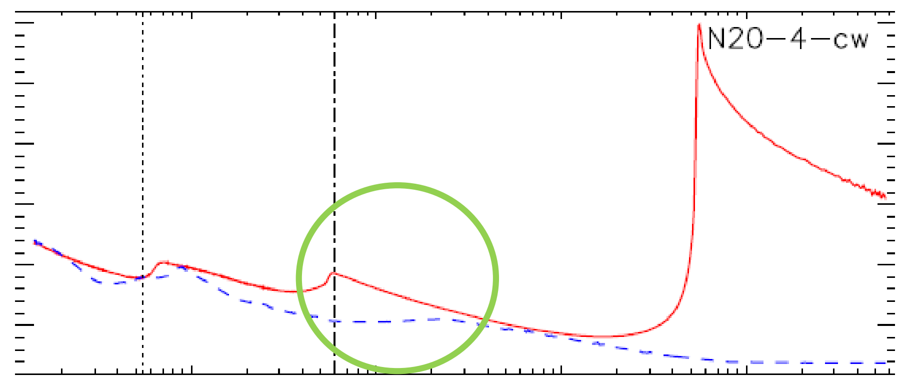

at He/H interface

→ meet reverse shock

Shock strongly accelerates --> RTI fingers stretch --> Reverse shock forms --> RTI fingers collide with Reverse shock

# N20 model



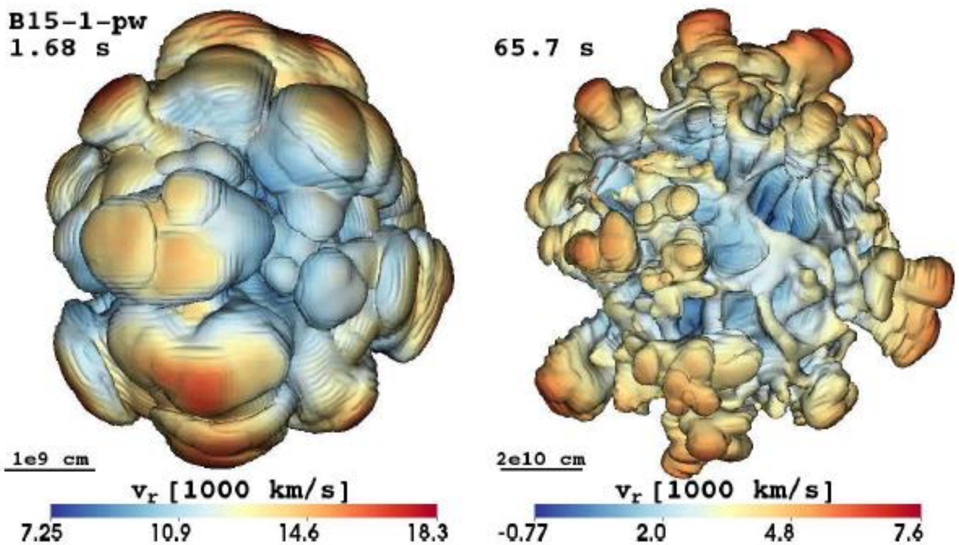



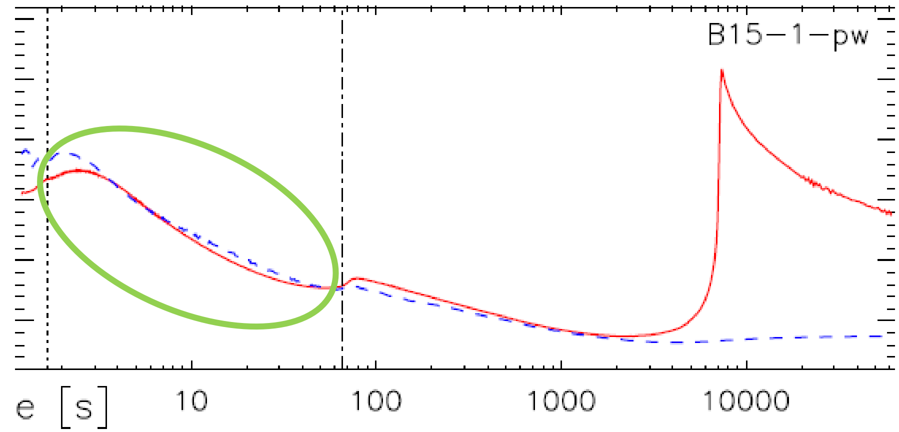

at He/H interface

→ meet reverse shock

Shock accelerates briefly --> Reverse shock forms --> Slow nickel bubbles collide with reverse shock and flattened

# B15 model



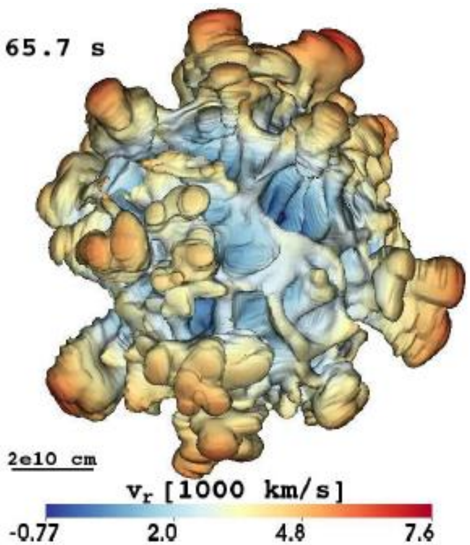



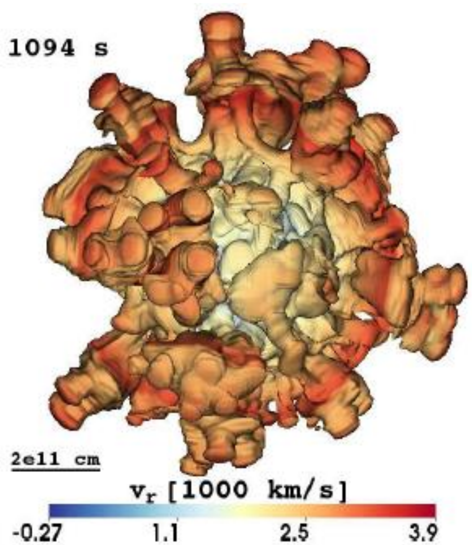

at C+O/He interface

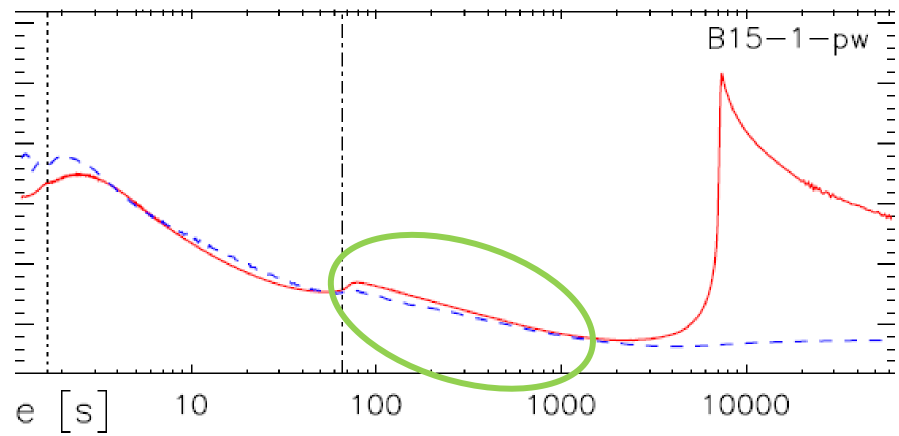
→ at He/H interface

Significant growth of RTIs --> fragmentation of nickel bubbles

# B15 model



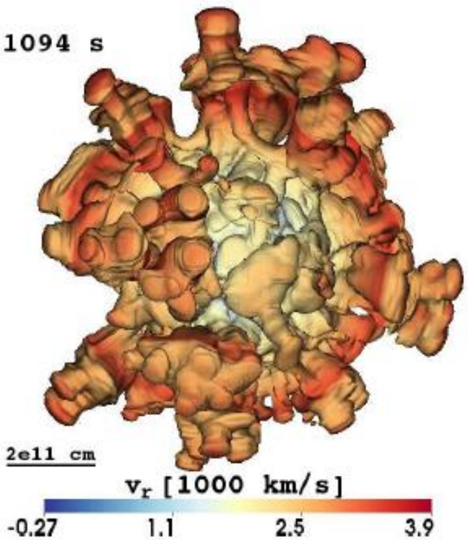

at He/H interface

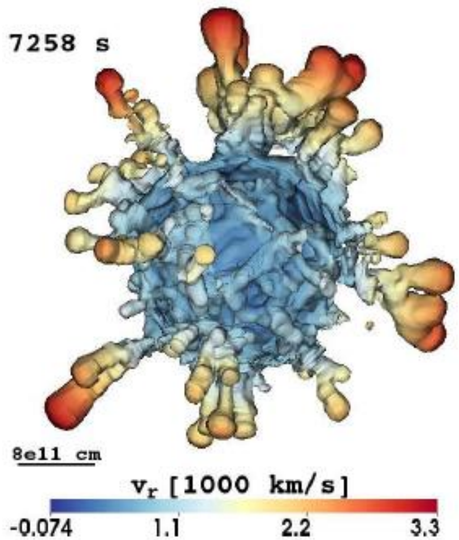
→ meet reverse shock

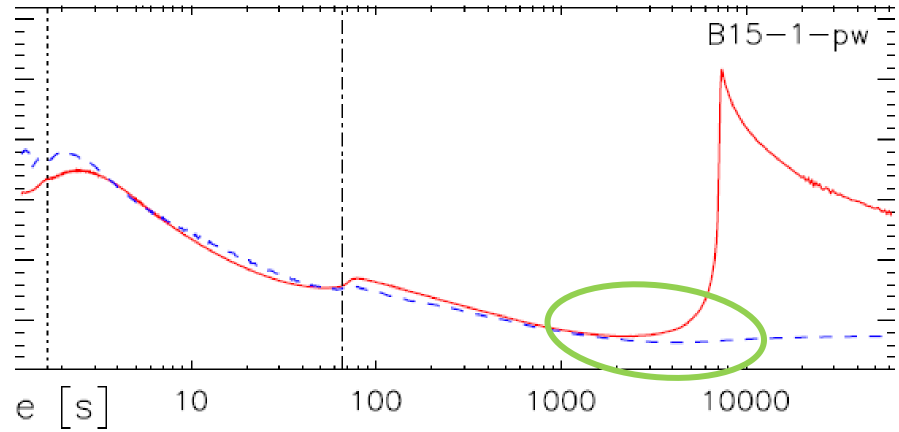
Shock accelerates briefly --> Reverse shock forms -->

Fast nickel fingers ahead of reverse shock !!!

# B15 model




meet reverse shock

→ shock breakout

Fast nickel fingers stretch --> inner part of ejecta trapped by reverse shock

# Connections to observations

# SN1987A

**Core-collapse supernova**

**Type**: IIP-pec

**Discovery**: Feb 23, 1987

**Position**: Large Magellanic Cloud (LMC)

**Progenitor**: Sanduleak -69$^o$ 202

**Luminosity**: 3-6 x $10^{38}$ erg/s

$T_{eff}$: 15000-18000 K

**Progenitor type**: Blue Supergiant

*****************************

**ZAMS**: 18-21 $M_{\odot}$

Woosley (1988), Shigeyama & Nomoto (1990)

**M(He core)**: 6 $M_{\odot}$

Saio et al. (1988), Woosley (1988)

**Explosion Energy**: $(1.1\pm0.3)\times10^{51}$ erg

Blinnikov et al. (2000)

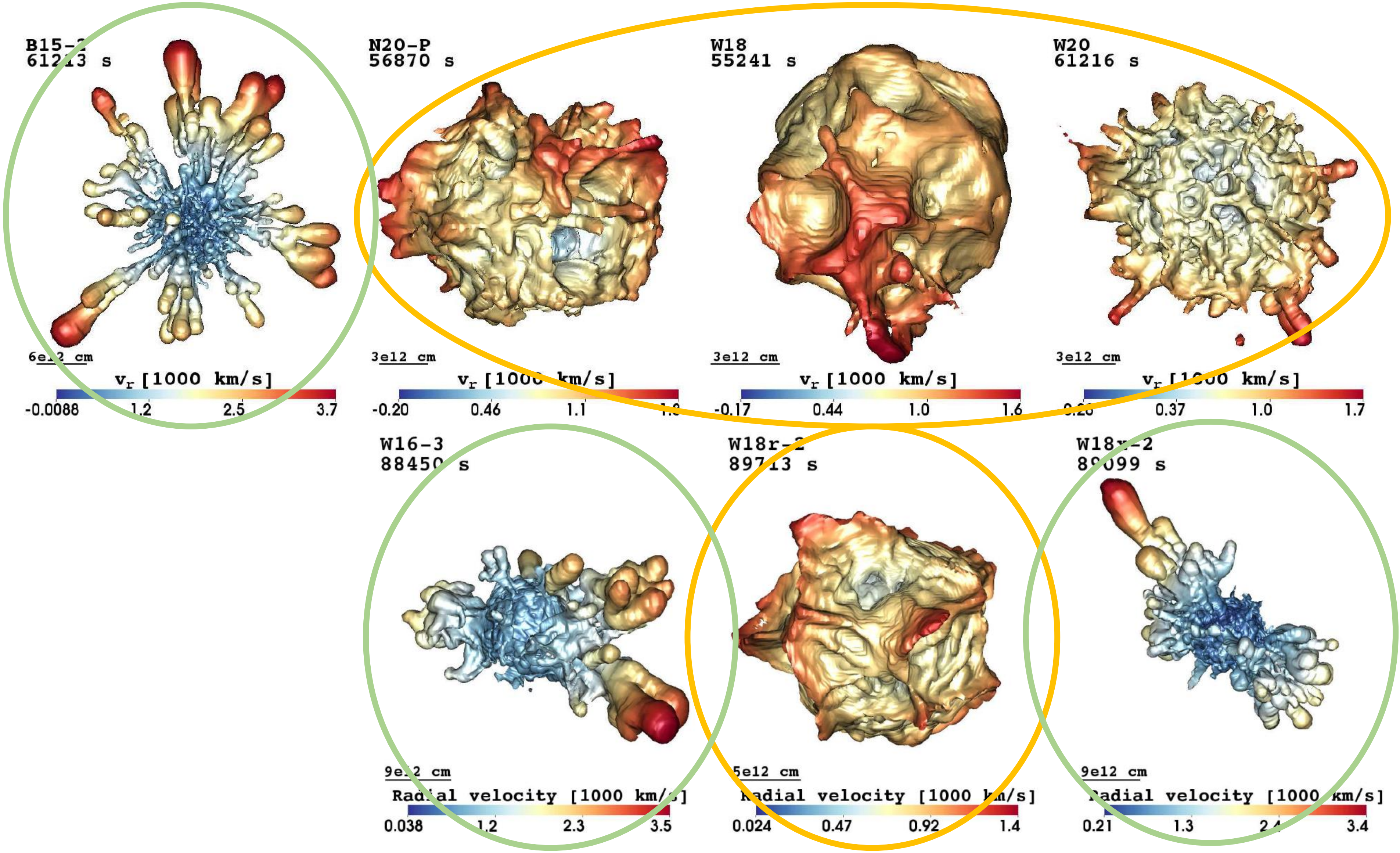
**M(56Ni)**: $(7.1\pm0.3)\times10^{-2}$ $M_{\odot}$

**M(44Ti)**:$(0.55\pm0.17)\times10^{-4}$ $M_{\odot}$

Seitenzahl et al. (2014)

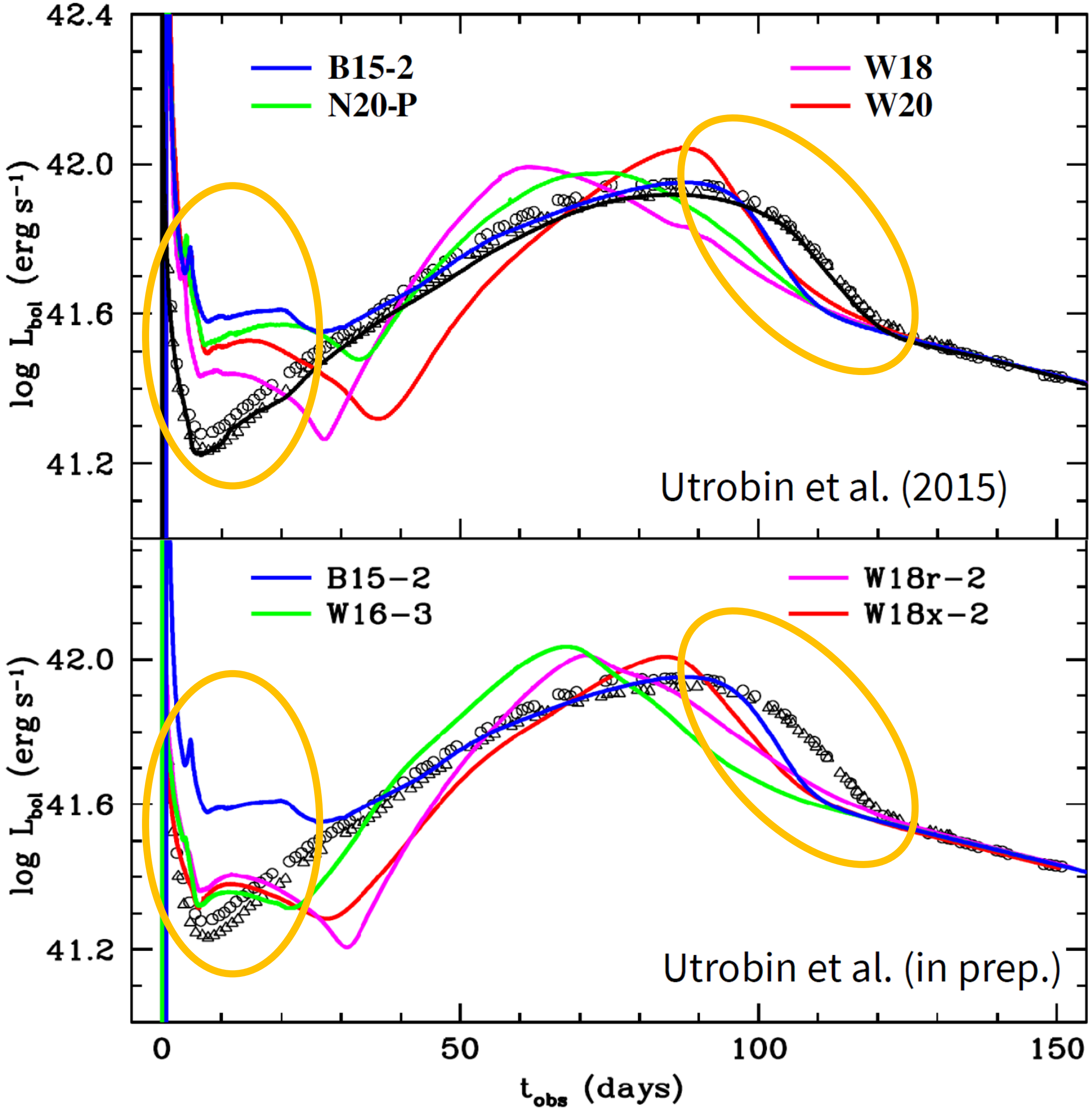
# SN1987A models

Wongwathanarat+ (2015), Utrobin+ (2015)



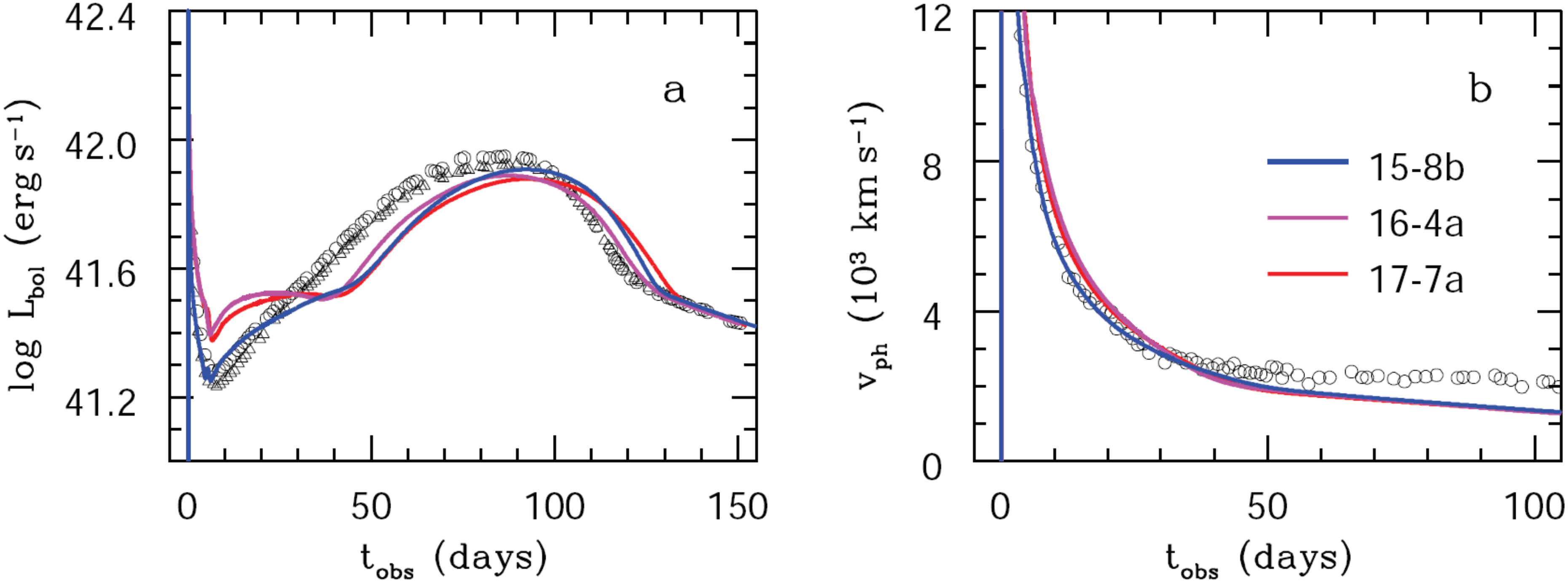

Utrobin+ (in prep.)

# Light Curves of SN1987A




- **B15** model reproduces the dome of light curve
- Light curve deficits due to progenitor structure

# Preliminary results from Binary merger models




- **Consider binary merger models by Menon & Heger (2017)**

- **First results look promising**

Utrobin et al. (in prep.)

**Courtesy of Victor Utrobin**

Neutron star kicks

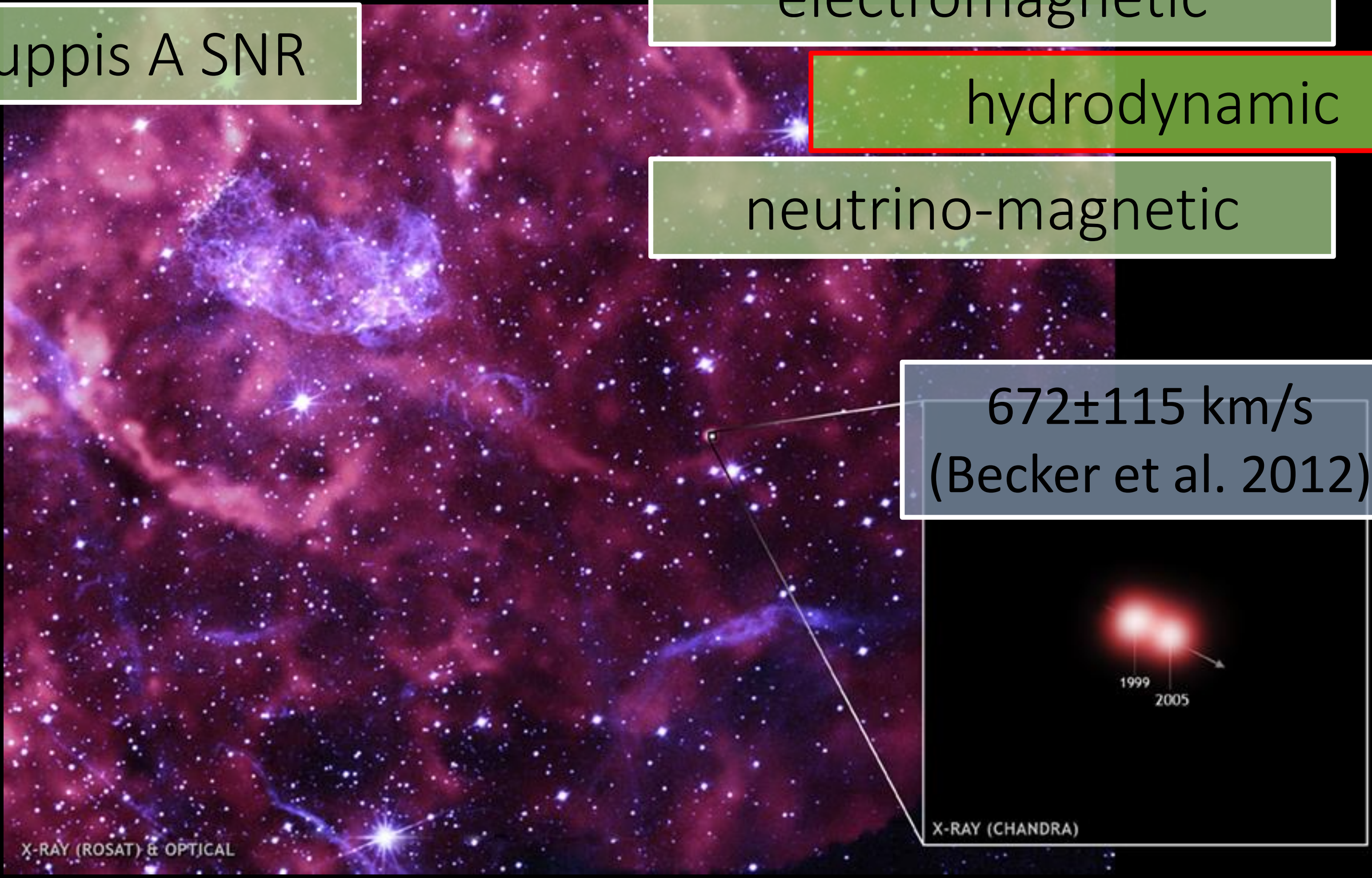
Kick mechanism??

electromagnetic

hydrodynamic

neutrino-magnetic

Puppis A SNR



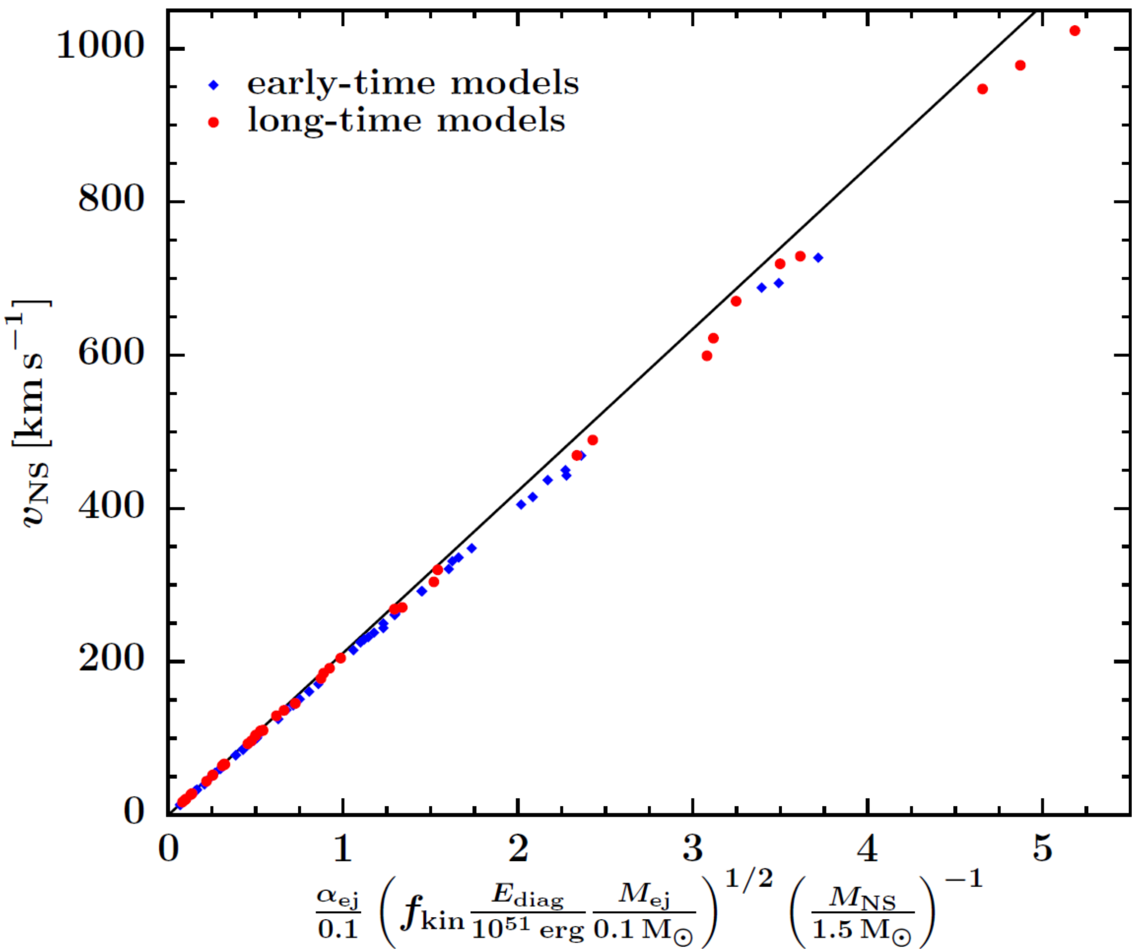

672±115 km/s
(Becker et al. 2012)

average pulsars velocity: 200-500 km/s (e.g., Hobbs et al. 2005)

# Pulsar kicks

39 long-time models in 3D

Wongwathanarat & Janka (in prep.)




$$v_{NS} = \alpha_{ej}\sqrt{2 f_{kin} E_{exp} M_{ej}}\, M_{NS}^{-1}$$
$$= 211\ \mathrm{km\,s^{-1}}\, f_{kin}^{1/2}\, \frac{\alpha_{ej}}{0.1}\left(\frac{E_{exp}}{10^{51}\ \mathrm{erg}}\right)^{1/2} \times \left(\frac{M_{ej}}{0.1\ M_\odot}\right)^{1/2}\left(\frac{M_{NS}}{1.5\ M_\odot}\right)^{-1}.$$

Janka (2017)

Momentum asymmetry parameter

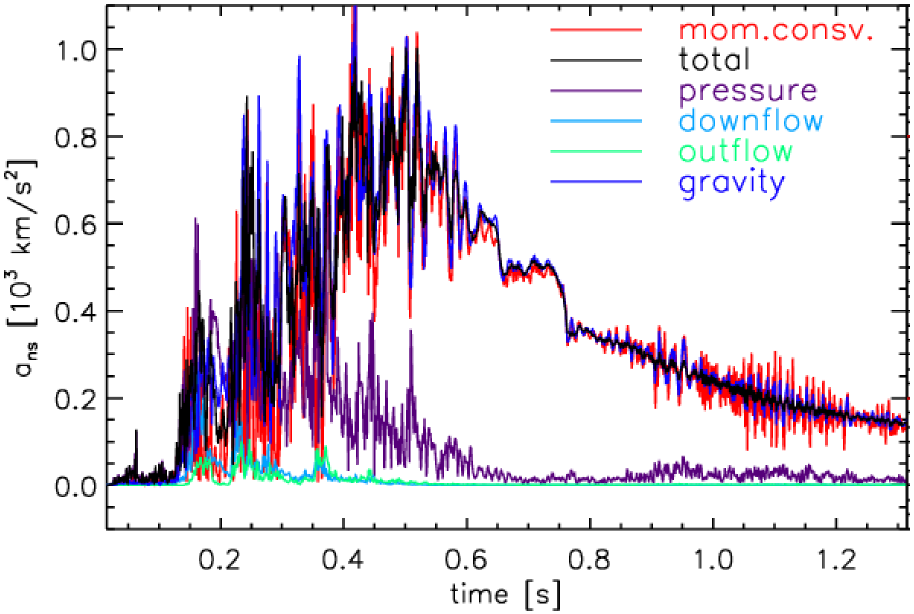
$$\alpha_{ej} = \frac{|\boldsymbol{P}_{gas}|}{P_{ej}},$$

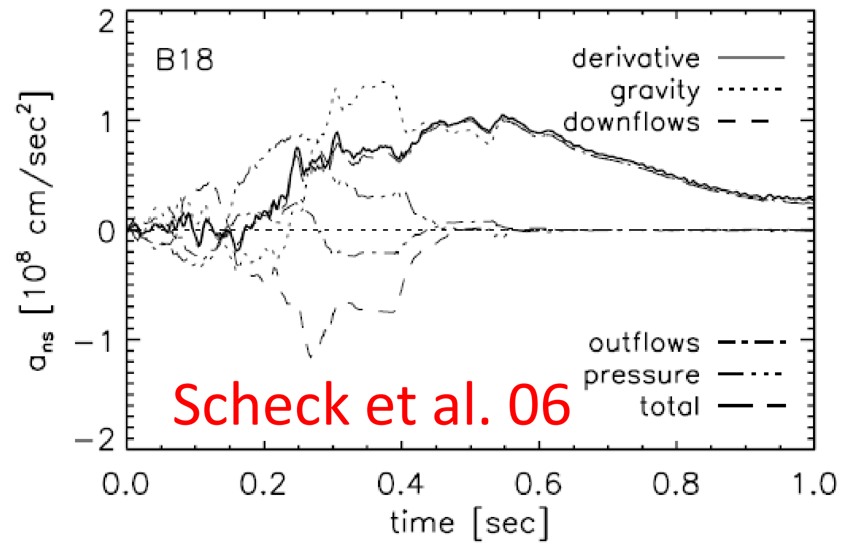
$$f_{kin} E_{exp} = E_{kin}$$

$$\vec{v}_{ns}(t) = -\vec{P}_{gas}(t)/M_{ns}(t)$$

Simulation results show for the first time a NS kick beyond 1000 km/s

$$\dot{\vec{P}}_{ns} \approx -\oint_{r=r_0} P\, d\vec{S} - \oint_{r=r_0} \rho \vec{v} v_r dS + \int_{r>r_0} \frac{G M_{ns} \vec{r}}{r^3}\, dm$$

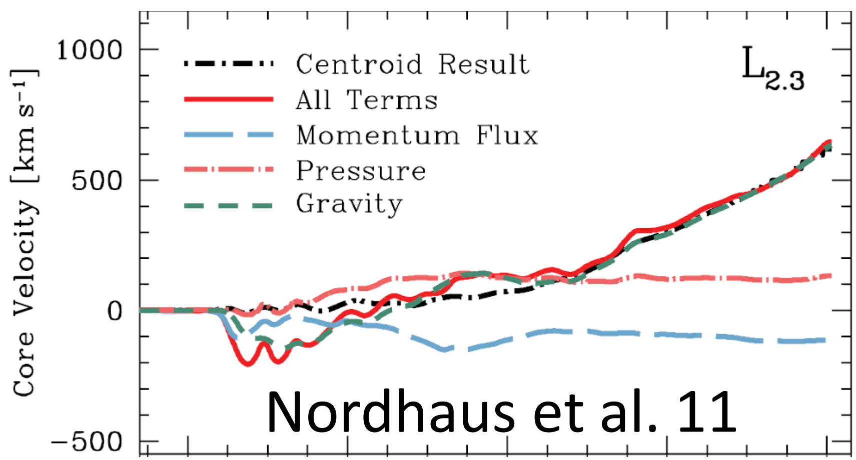


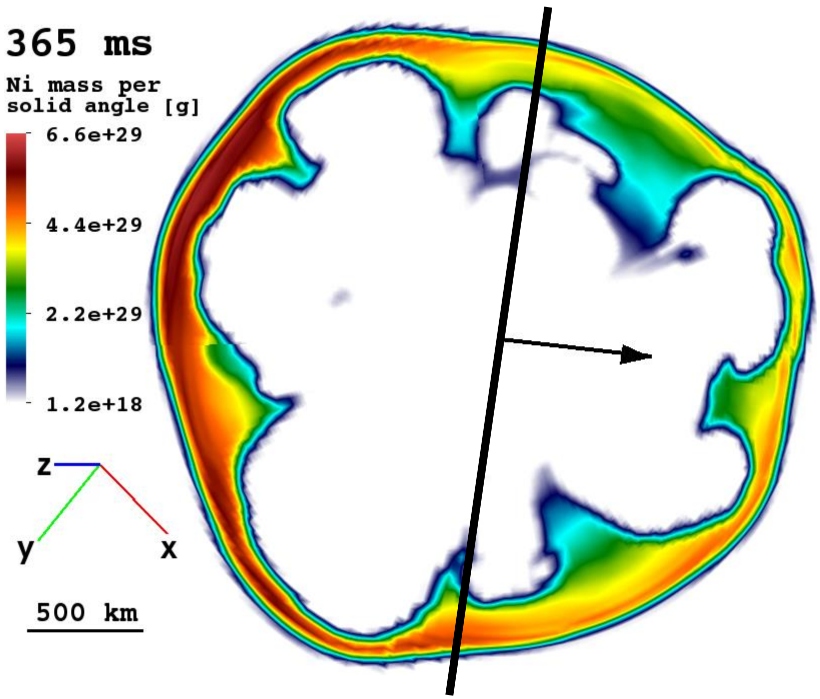

Gravitational drag term is dominant

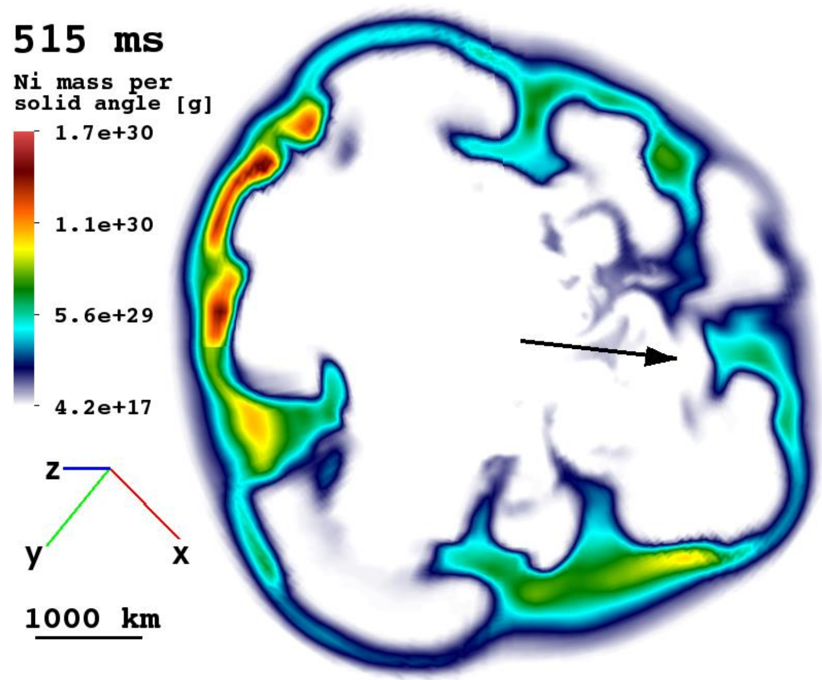
Hence the name

"gravitational tug-boat mechanism"



# Element distribution



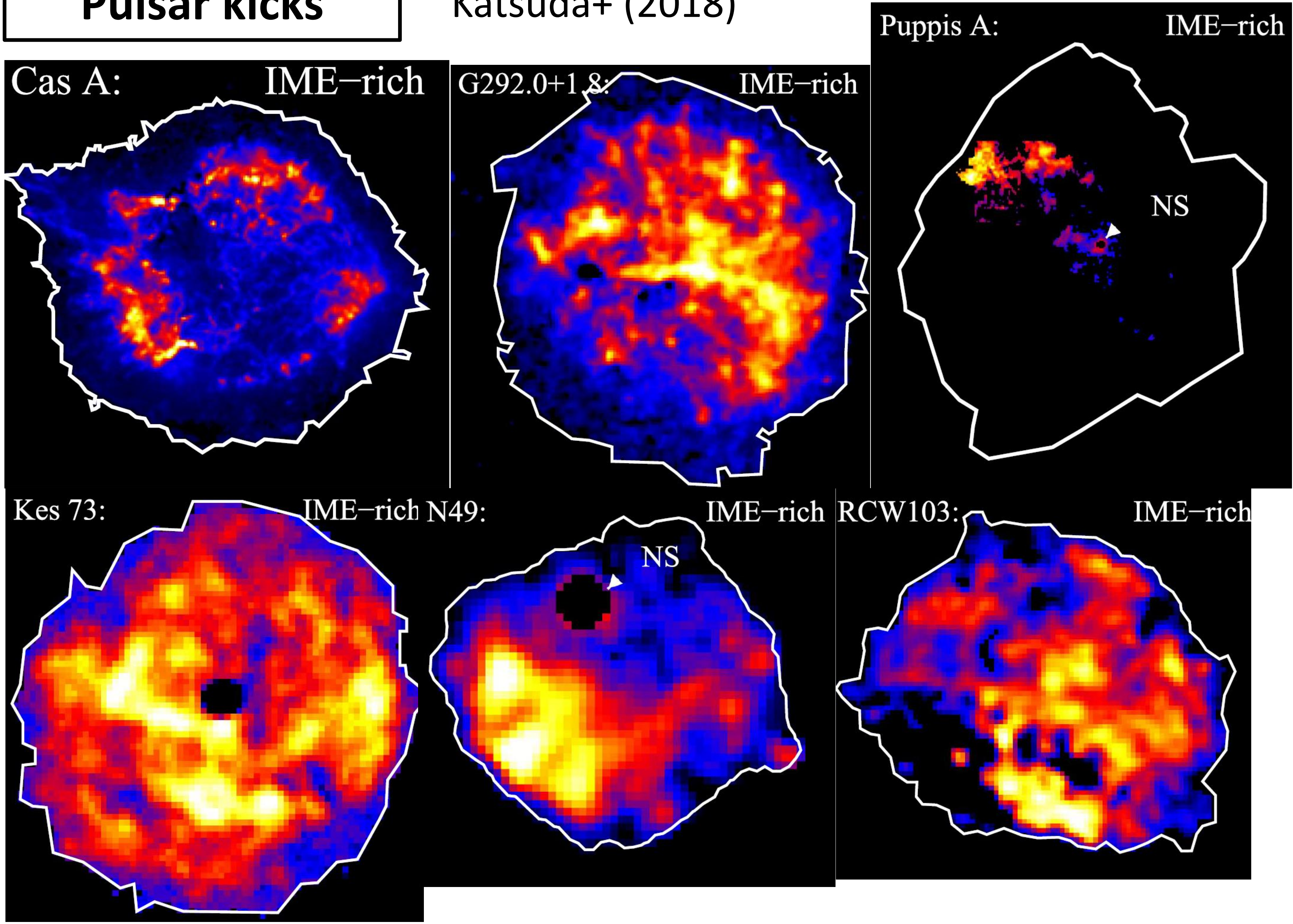

Ni shows hemispheric asymmetry

asymmetry can be as large as 50%

observed??? Constrain kick mechanism???

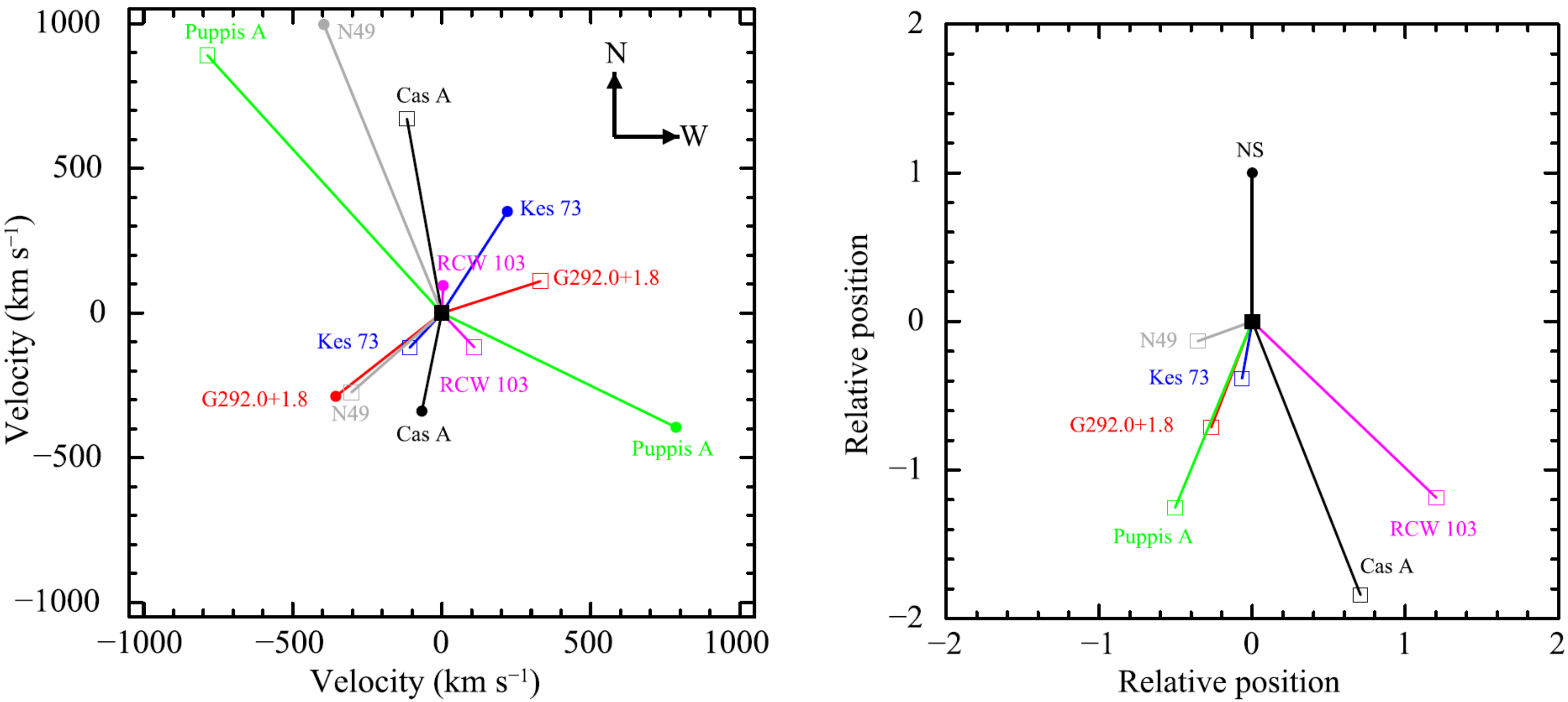
# Pulsar kicks

Katsuda+ (2018)



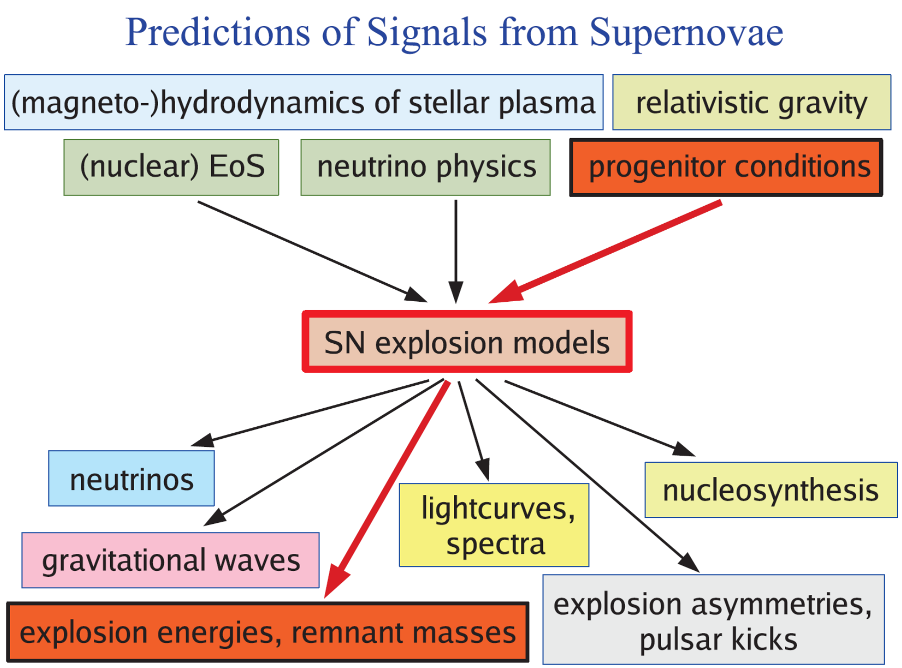
# Pulsar kicks

Katsuda+ (2018)




- IME ejecta ejected preferentially opposite to the NS kick direction
- Strong support for hydrodynamic kick mechanism

# Conclusions




- We are now making progresses towards direct comparison with SN/SNR observations !!!

- perform 3D simulations of CCSN from shortly after core bounce until shock breakout
- Compute bolometric light curves based on 3D hydrodynamic models and compare with data from SN1987A
- results from 7 single star progenitor models are still unable to reproduce the observed light curve
- Calculate NS kicks by gravitational tug boat mechanism
- Obtain kick beyond 1000 km/s which can explain even the fastest pulsar velocity observed