超新星爆発研究の光と影

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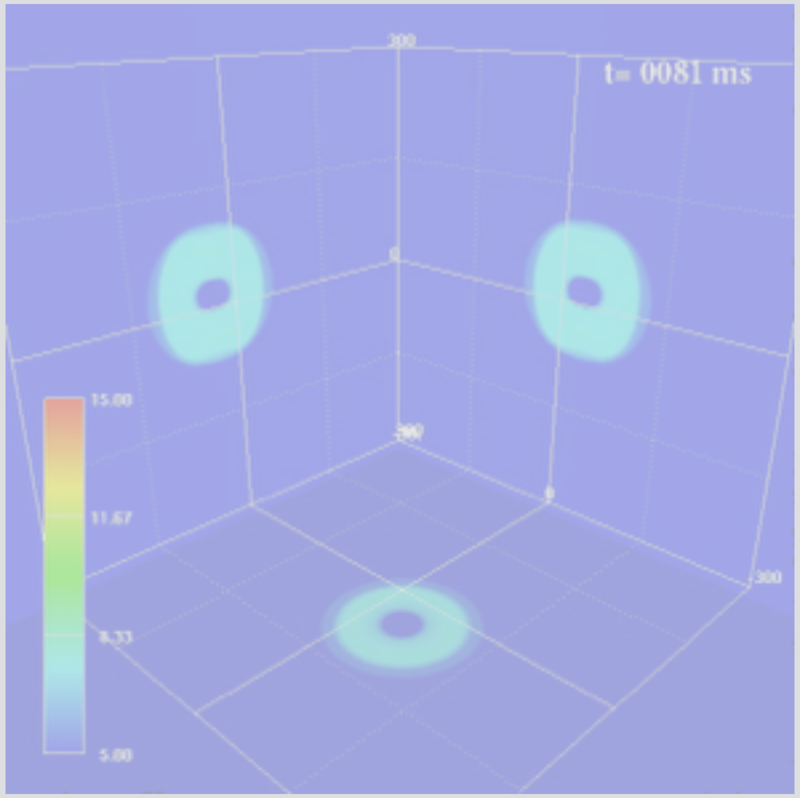
Bright side of SN simulations

* **Success of simulations**
  * detailed ν interactions and transfer (2000~)
  * hydro: 2D (2006~) and 3D (2012~)
  * multi-D GR+ν transfer (2010~)
  * 6D Boltzmann solver (2012~)

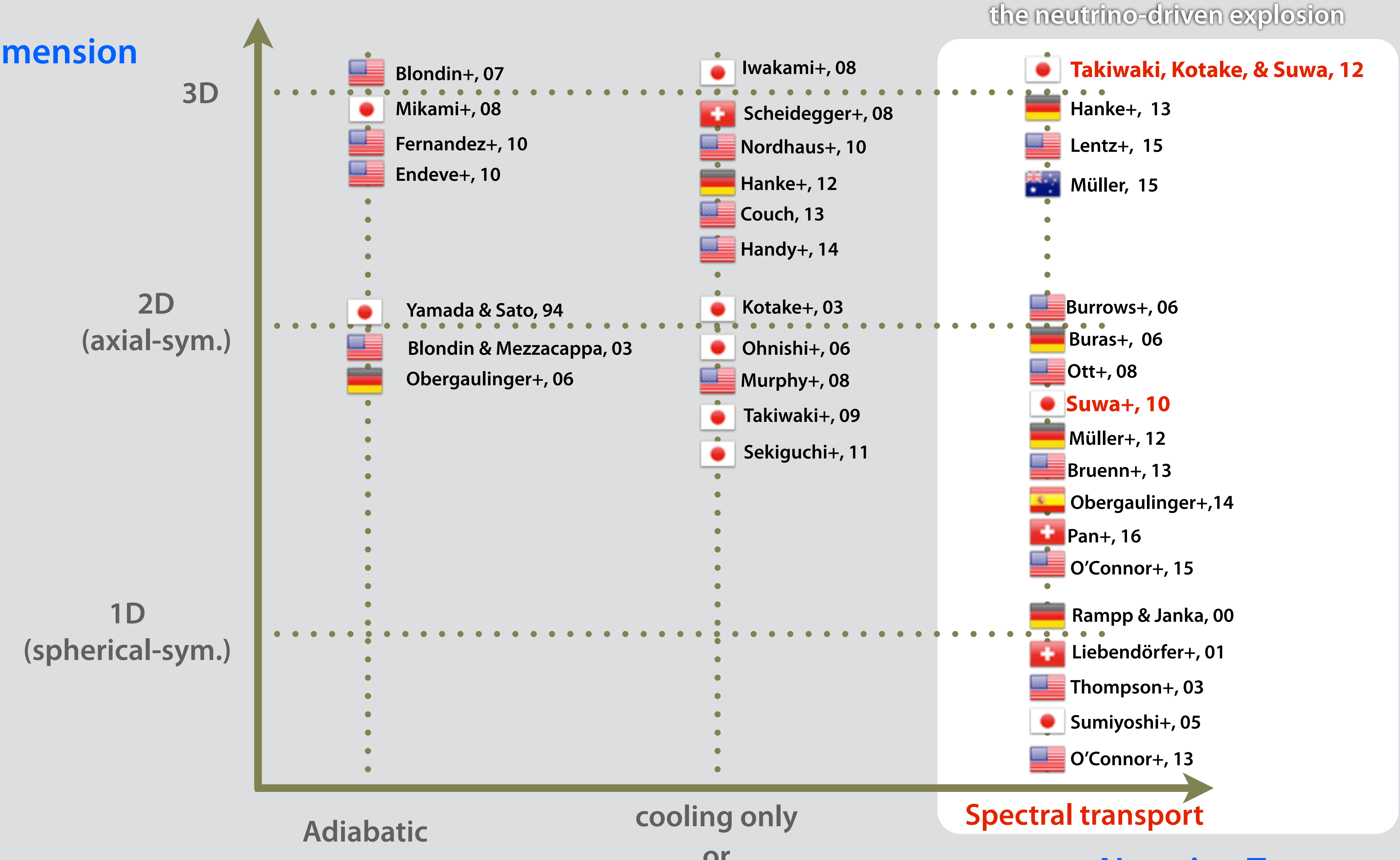
* **Success of explosion**
  * driven by neutrino heating (delayed exp.)
  * multiple groups have obtained explosions
  * multi-D effects amplify neutrino heating efficiency



Takiwaki, Kotake, Suwa (2016)

Increasing number of codes

※grid-based codes only, not completed



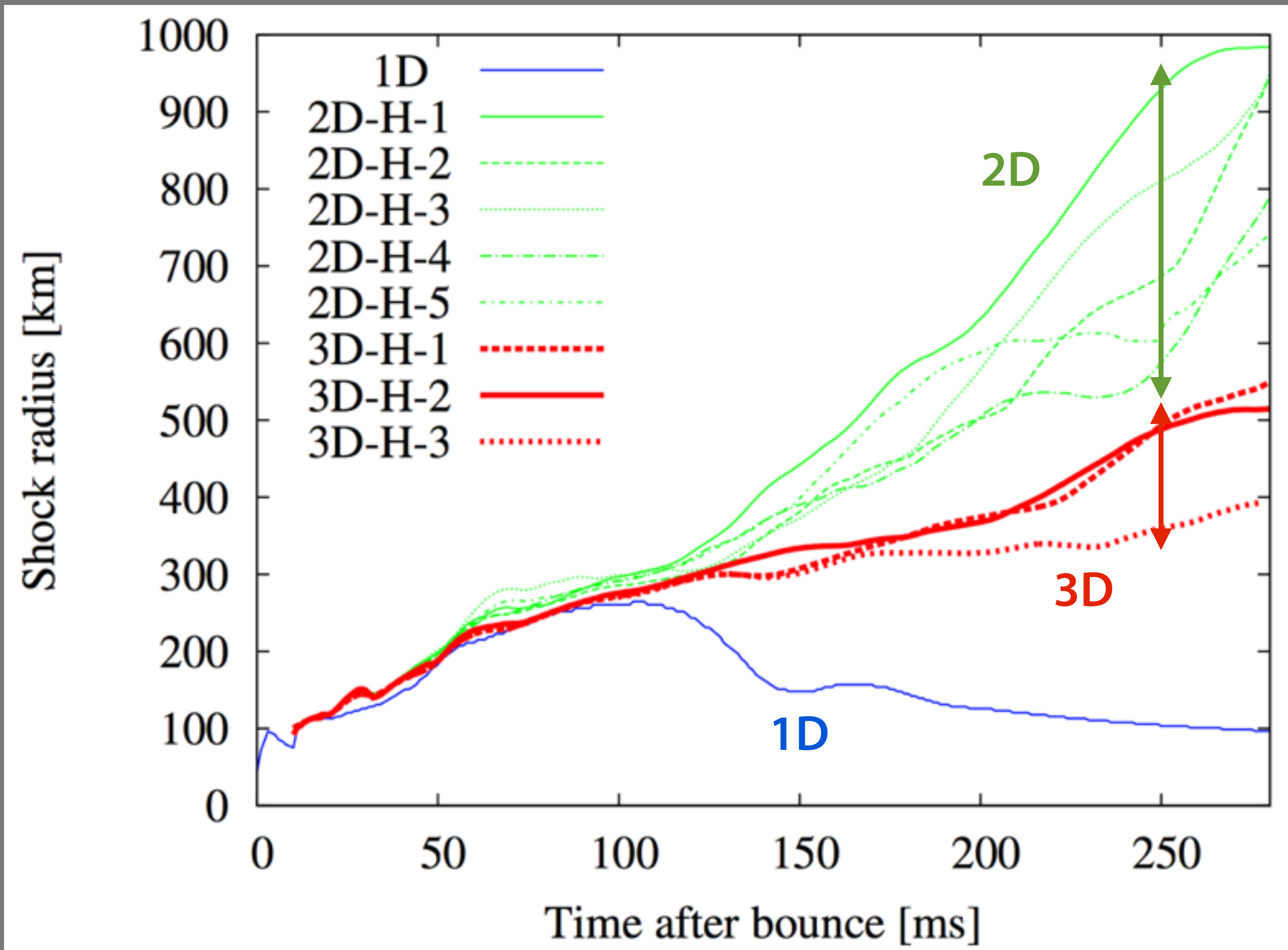
flags are taken from http://icondrawer.com/flag-icons.php

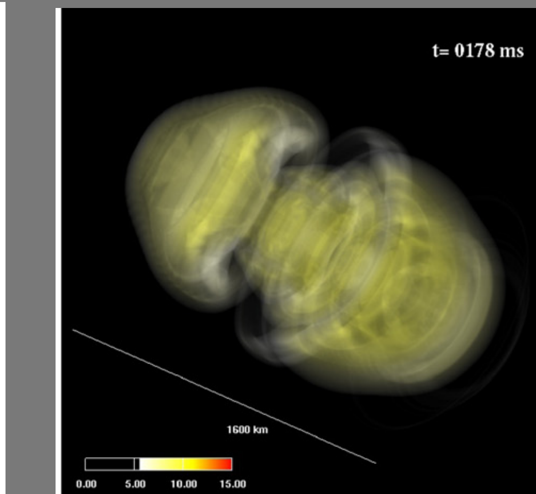
Explosion, explosion, and explosion

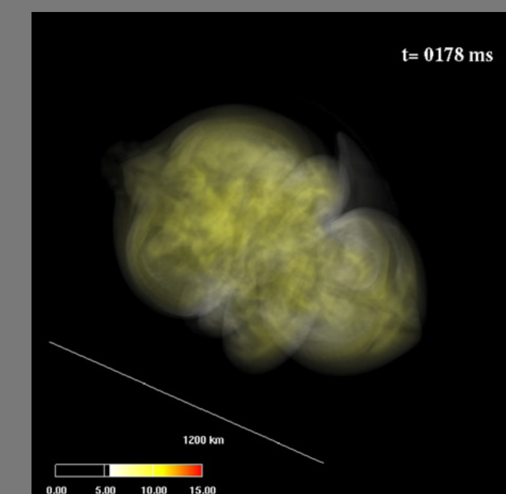
Dark side

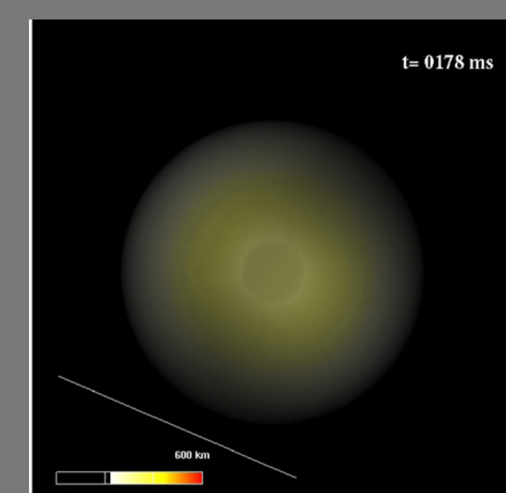
☯ 2D is better than 1D, but 3D is not better than 2D

[Takiwaki, Kotake, & Suwa, ApJ, **786**, 83 (2014)]

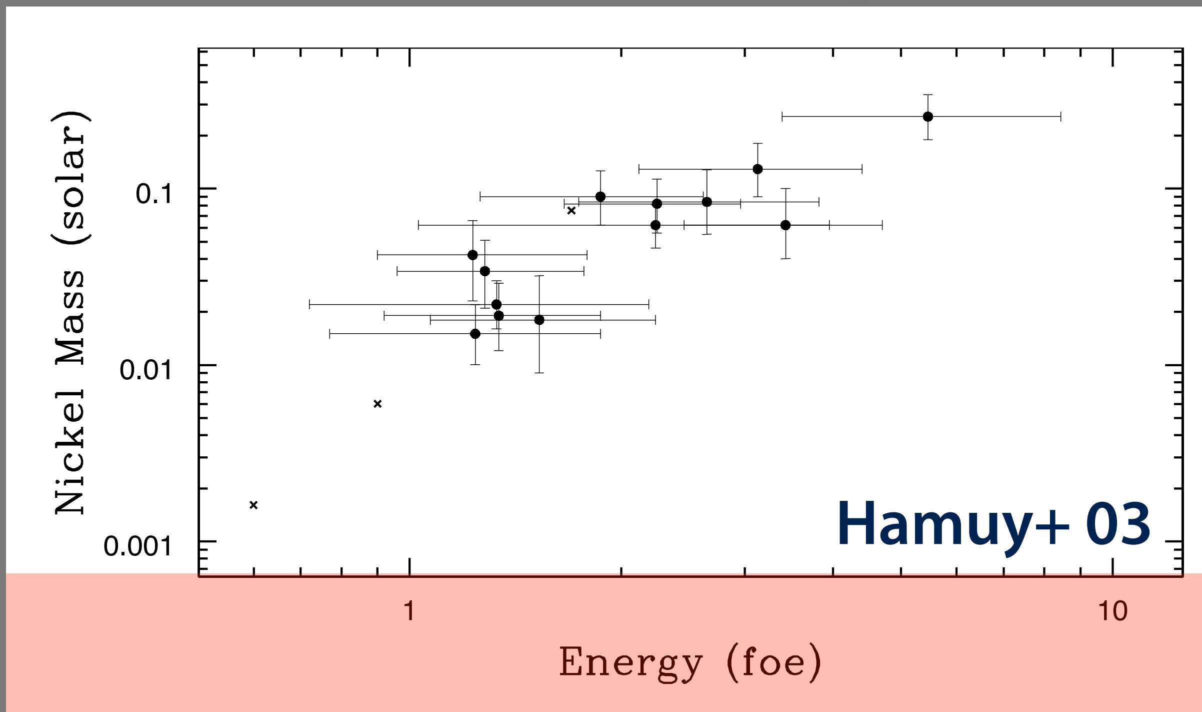


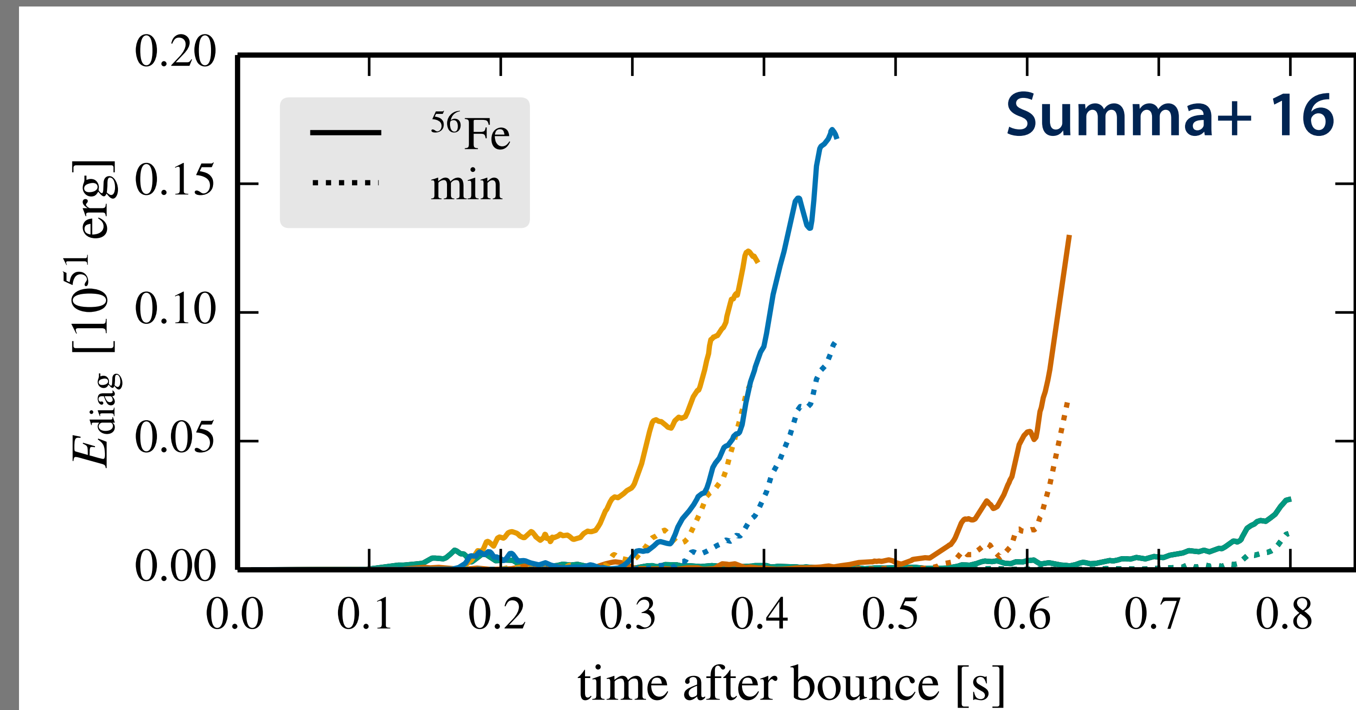


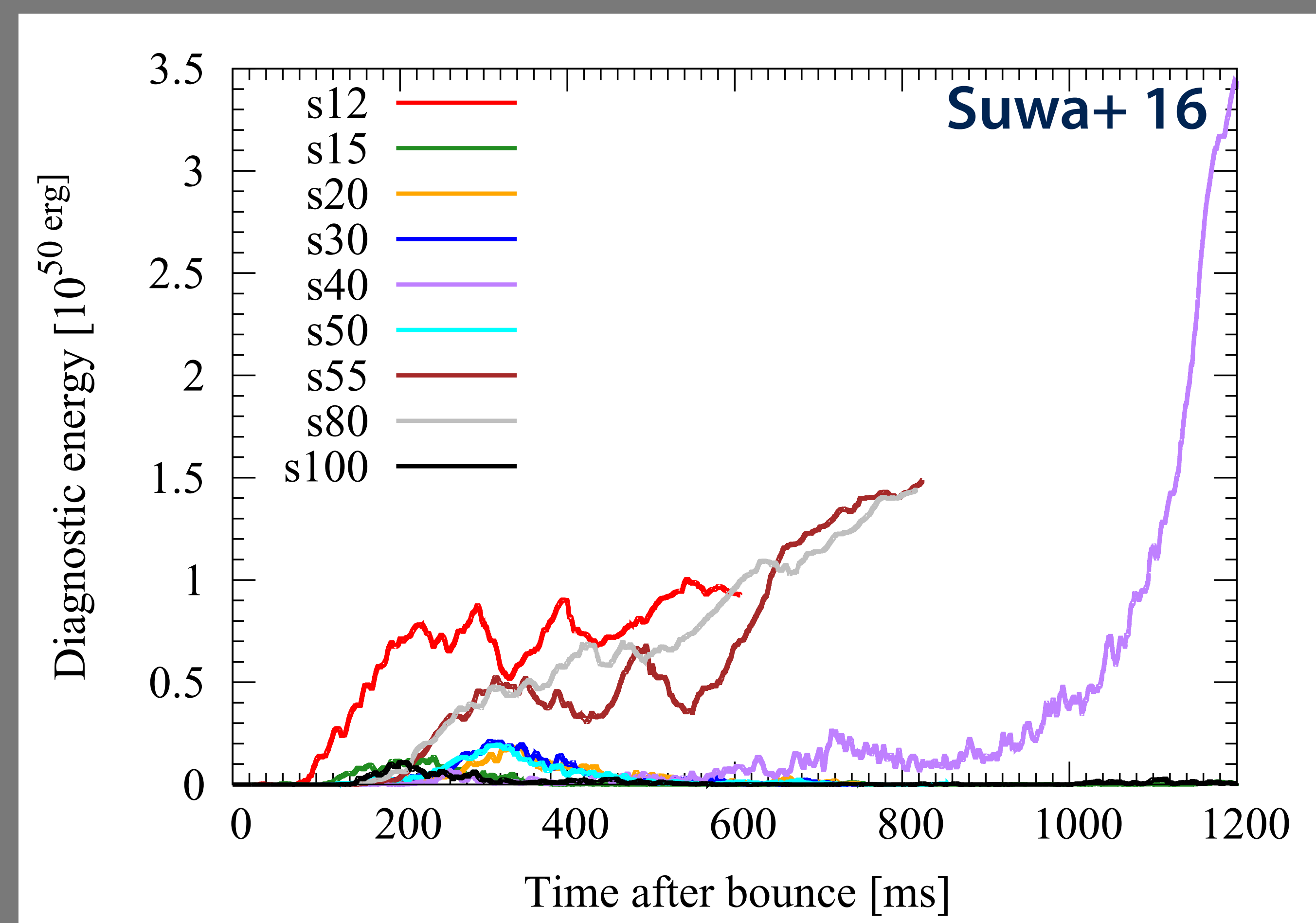




Insufficient explosion energy

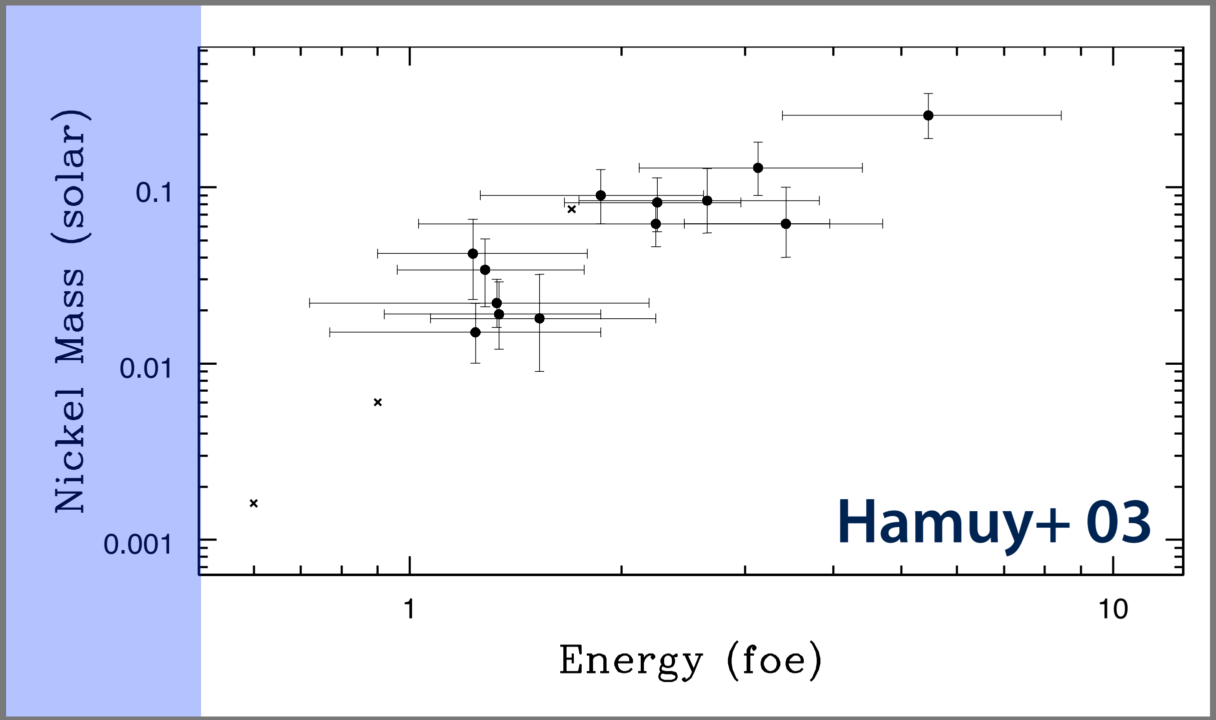


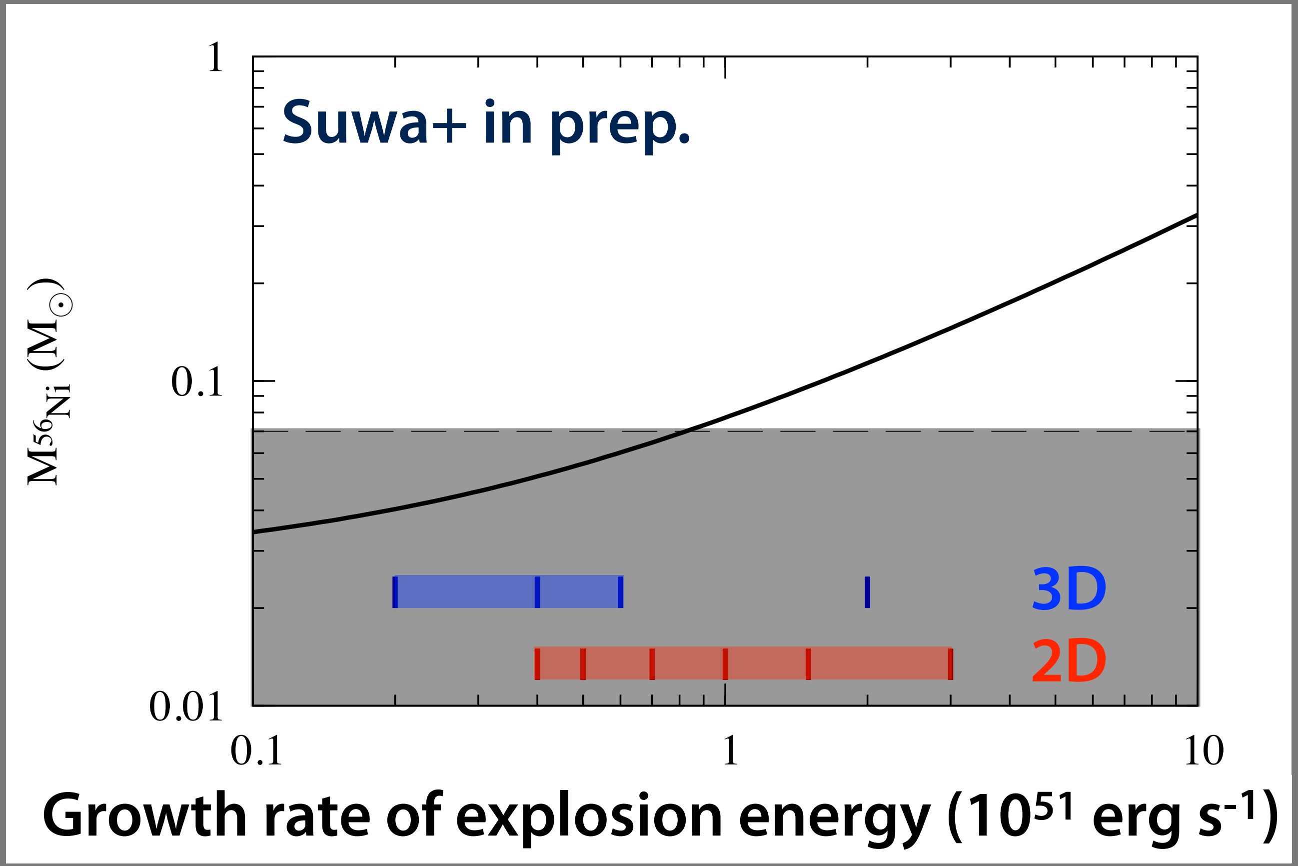




- **1 foe=10^{51} erg is necessary from obs.**
- **~10^{50}erg in simulations**
  - Can we extrapolate the growth of expl. ene. up to 10^{51} erg?

Insufficient ^{56}Ni





- $M(^{56}Ni) \sim 0.1 M_\odot$
- $T > 5\times10^9$ K is necessary for ^{56}Ni production

Woosley+ 02

  - $E = (4\pi/3) r^3 a T^4 \Rightarrow T(r_{sh}) = 1.33\times10^{10} (E/10^{51}\mathrm{erg})^{1/4} (r_{sh}/1000\mathrm{km})^{-3/4}$ K
  - With $E = 10^{51}$ erg, $r_{sh} < 3700$ km for $T > 5\times10^9$ K
- ^{56}Ni amount is more difficult to explain than explosion energy

What should we do next?

* **More detailed simulations**
  * accumulating 10% effects?
* **Looking for missing physics**
  * importing something from other communities?
* **Reconsidering initial value problem**
  * how reliable progenitor models?

Initial condition may solve problem

Supernova simulation is an initial value problem

stellar evolutionary calculations

$\rho(r)$, $T(r)$, $Y_e(r)$, $v_r(r)$

Time integration

Hydrodynamic equations

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi,$$

$$\frac{de^*}{dt} + \nabla \cdot \left[(e^* + P)\, \mathbf{v} \right] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_E,$$

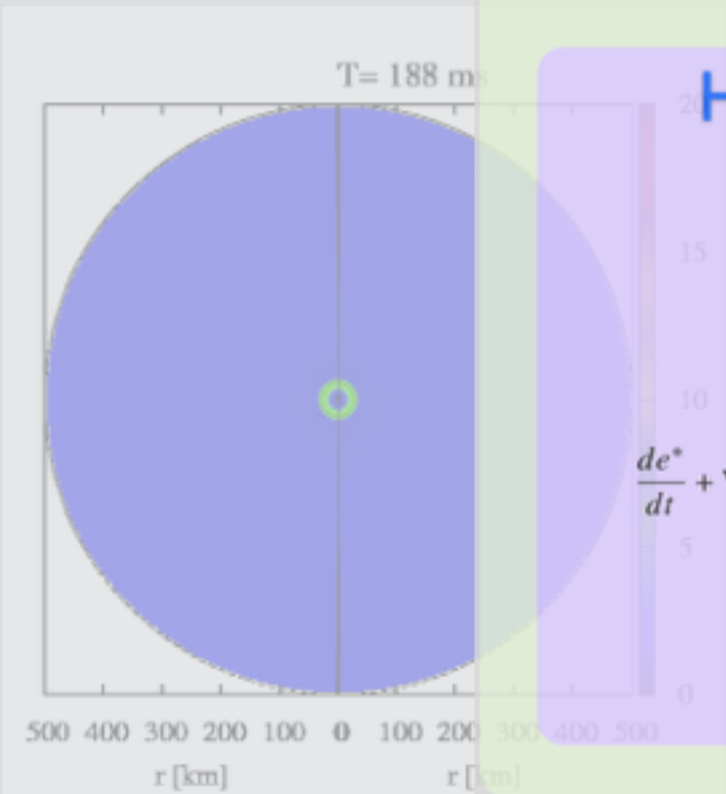
$$\frac{dY_e}{dt} = Q_N,$$

$$\Delta \Phi = 4\pi G \rho,$$

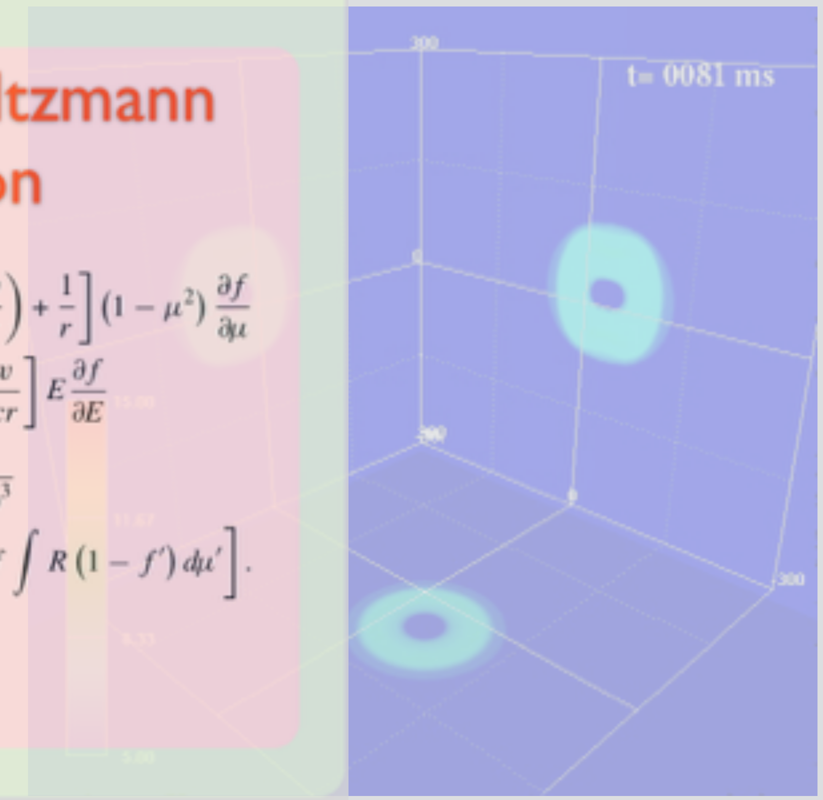
Solve simultaneously

Neutrino Boltzmann equation

$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) + \frac{1}{r} \right] (1-\mu^2) \frac{\partial f}{\partial \mu} + \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) - \frac{v}{cr} \right] E \frac{\partial f}{\partial E} = j(1-f) - \chi f + \frac{E^2}{c(hc)^3} \times \left[(1-f) \int R f' d\mu' - f \int R (1-f') d\mu' \right].$$



Suwa+ 2010 (2D)

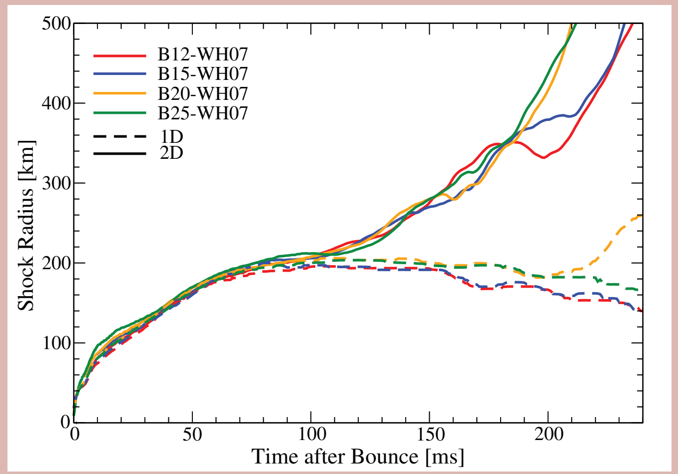


Takiwaki, Kotake, Suwa 2016 (3D)

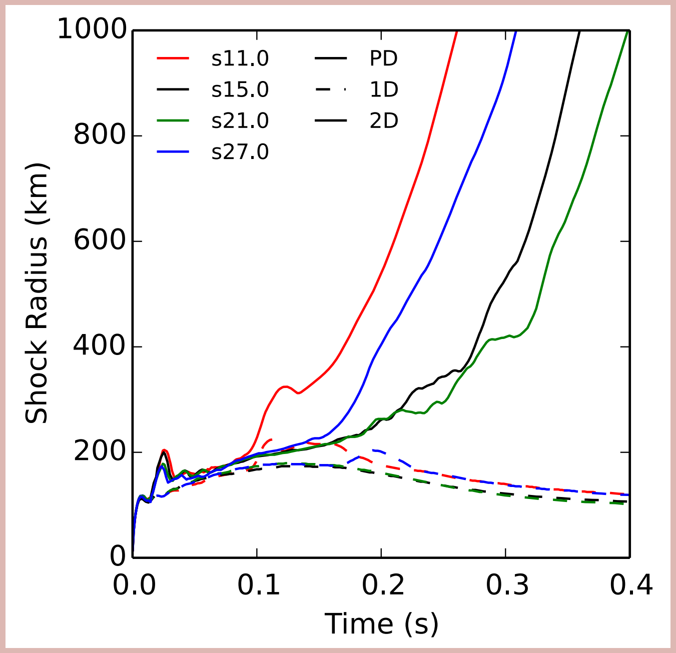
supernova explosions

Initial condition dependences of SN simulations

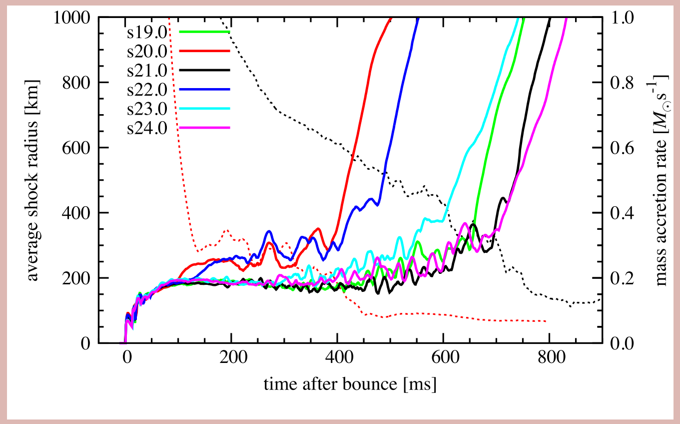
2D-hydro+ν transfer



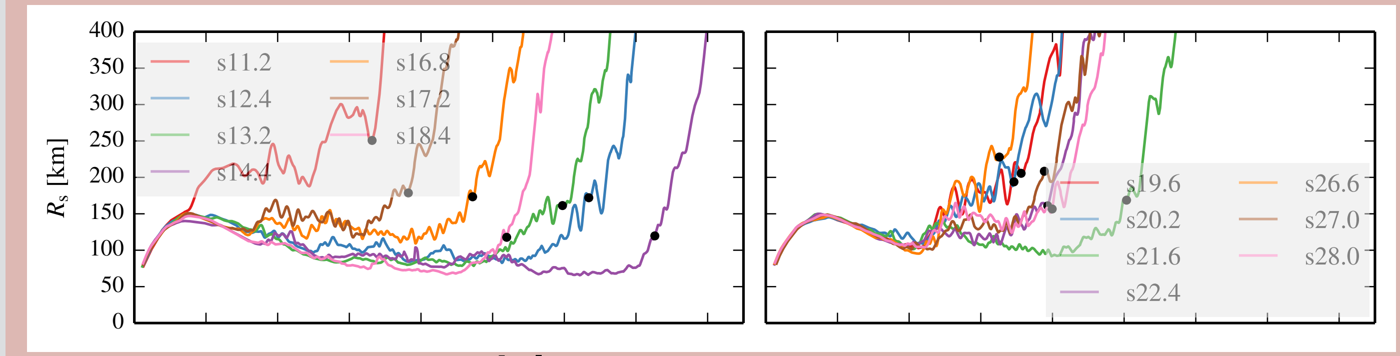
Bruenn+ 2013
4 models



Pan+ 2016
6 models

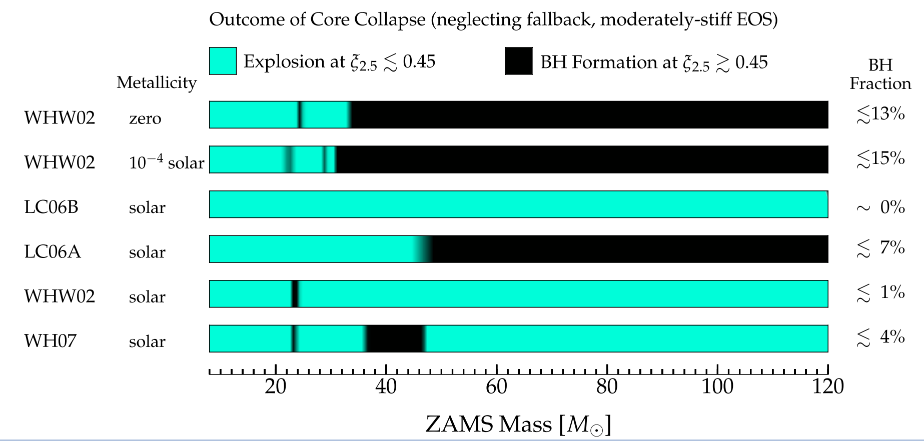


Nakamura+ 2015
378 models

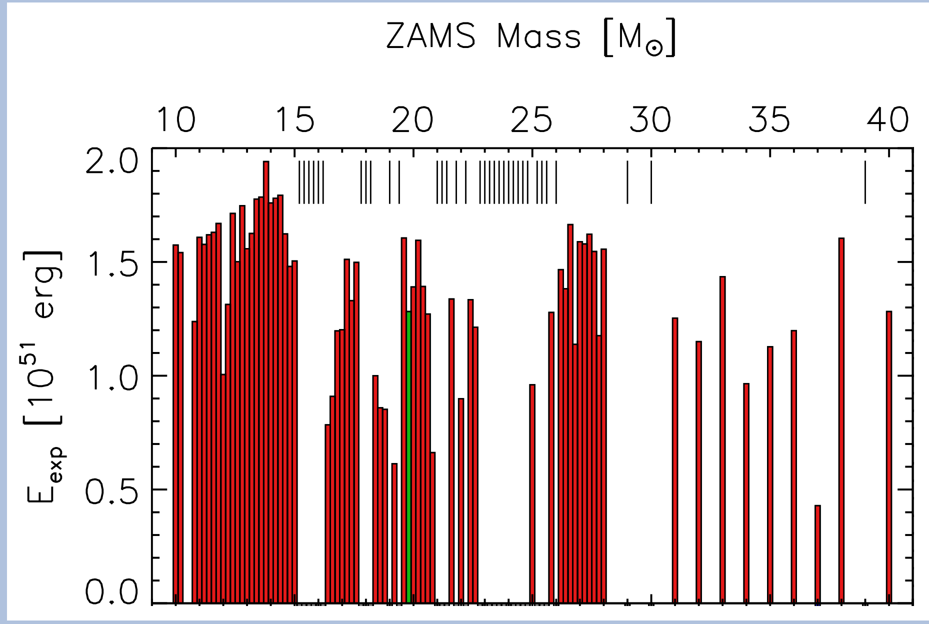


Summa+ 2016, 18 models

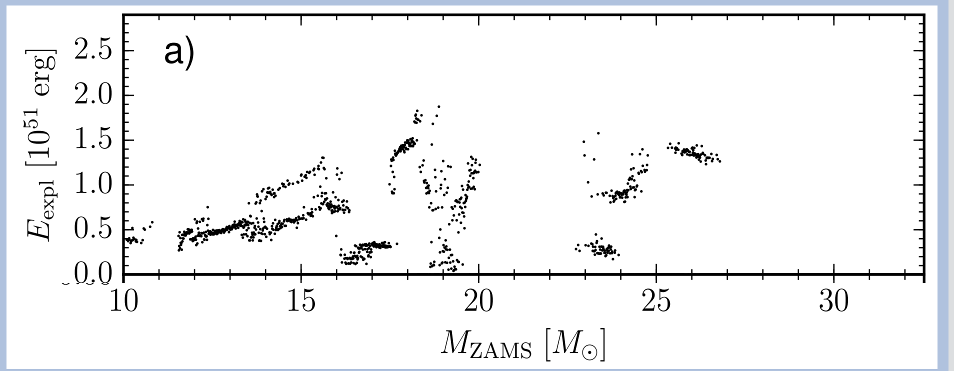
1D-hydro+approx. ν treatment



O'Connor & Ott (2011), > 100 models



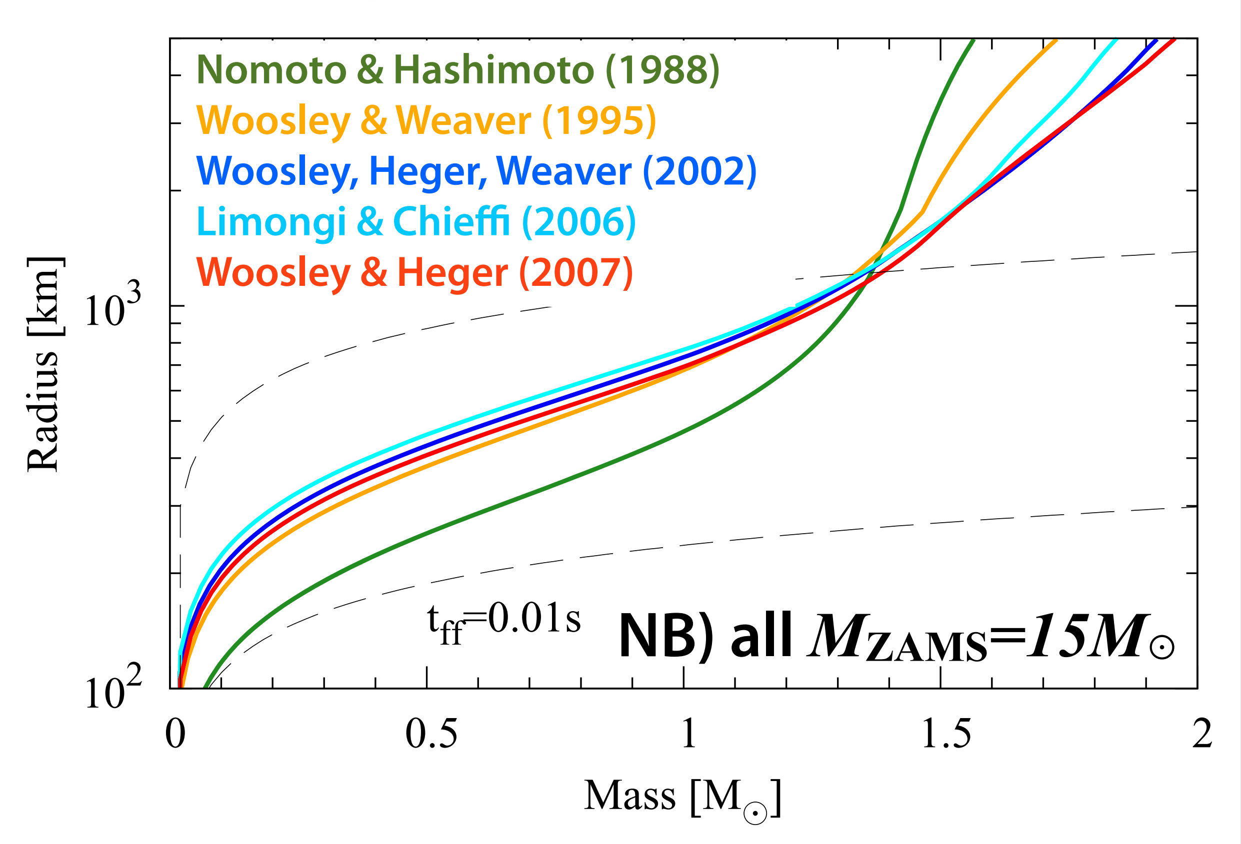
Ugliano+ 2012, 101 models



Müller+ 2016, 2120 models

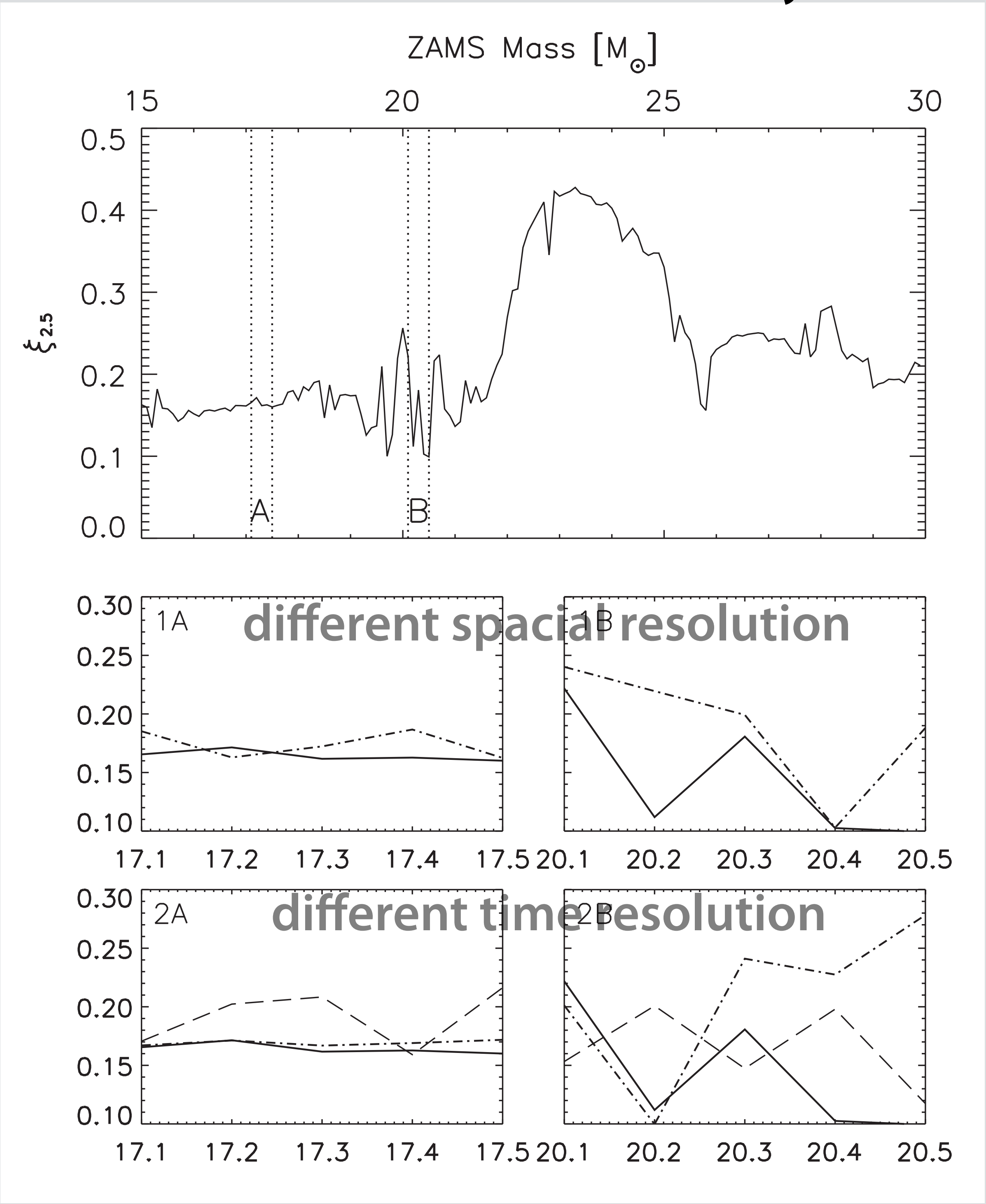
Uncertainties in stellar evolutionary calculations

Suwa+, ApJ (2016)



Different codes lead to different structure

Sukhbold & Woosley (2014)

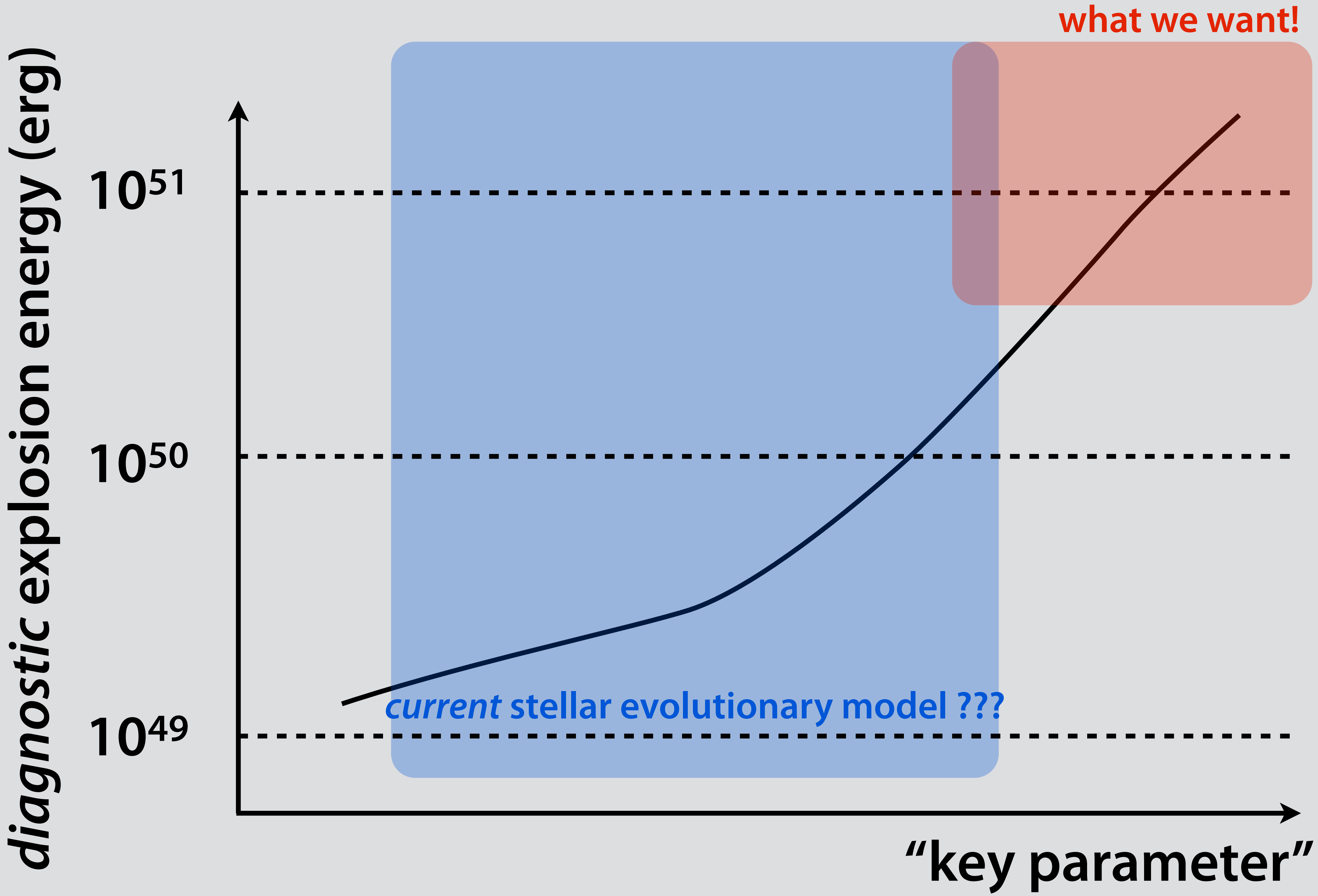


Even with the *same* code, different (time or space) resolutions lead to different structure

$$\xi_M = \frac{M/M_\odot}{r_M/1000\,\mathrm{km}}$$

"Compactness parameter"
O'Connor & Ott (2011)

A possibility

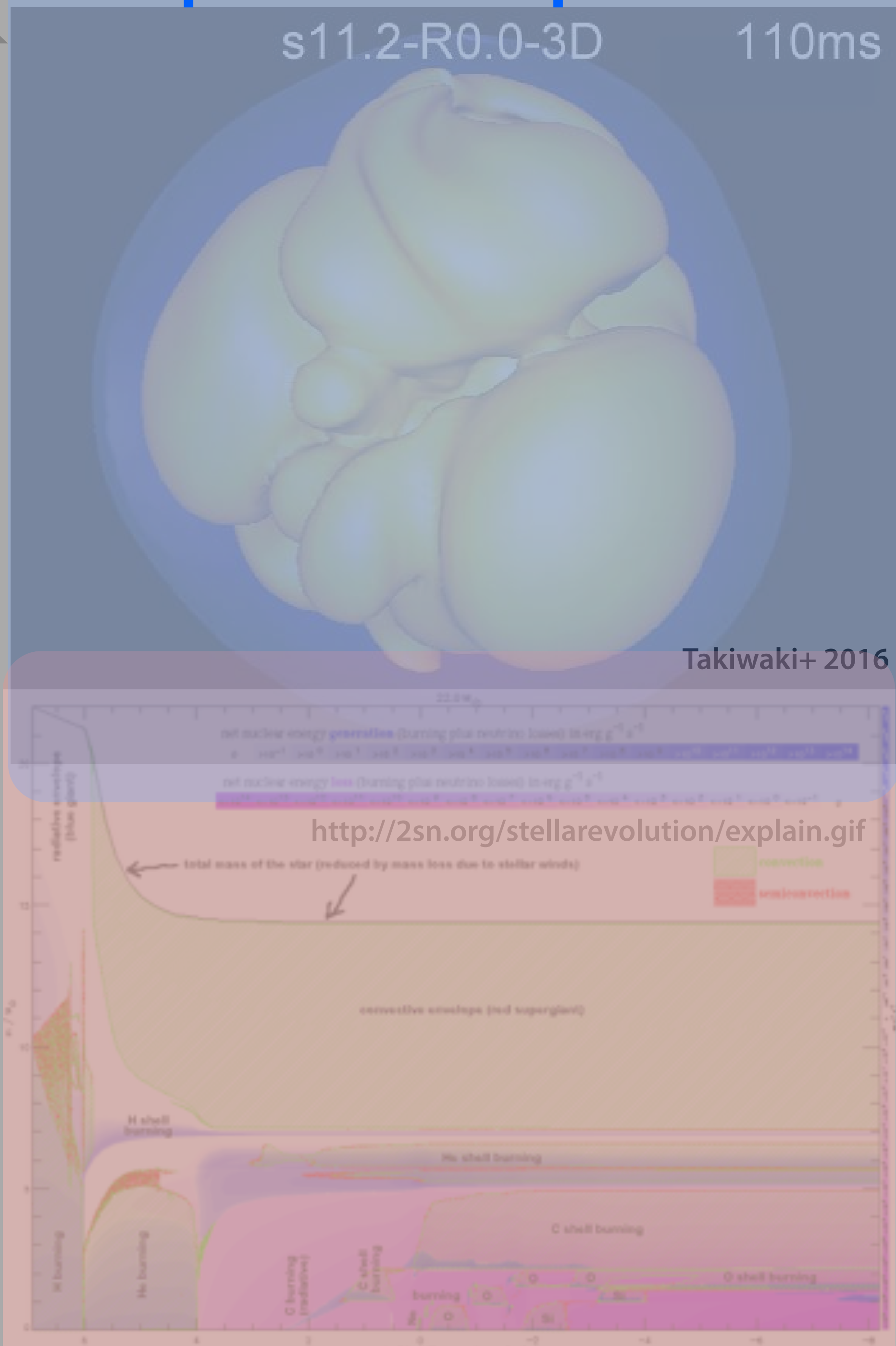


Problem reduction

traditional approach

time

supernova explosion



stellar evolution

new approach

supernova explosion

Q1. *what is the better initial condition for explosion?*

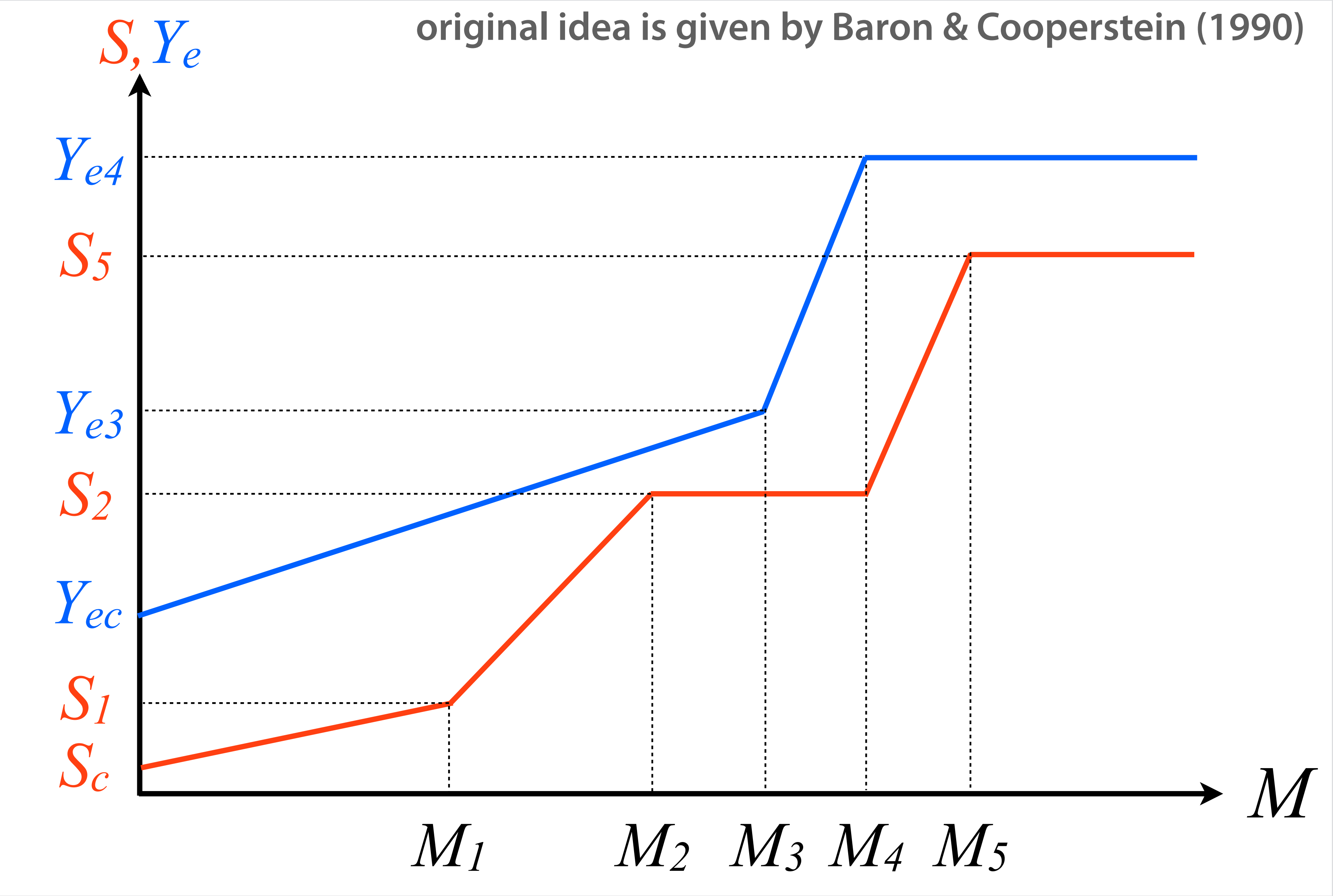
stellar structure

Q2. *is it possible to produce such structure?*

stellar evolution

Parametric initial conditions

[Suwa & Müller, MNRAS, 460, 2664 (2016)]



M_1: the edge of the final convection in the radiative core

M_2: the inner edge of the convection zone in the iron core

M_3: the NSE core

M_4: the iron core mass

M_5: the base of the silicon/oxygen shell

Parametric initial conditions

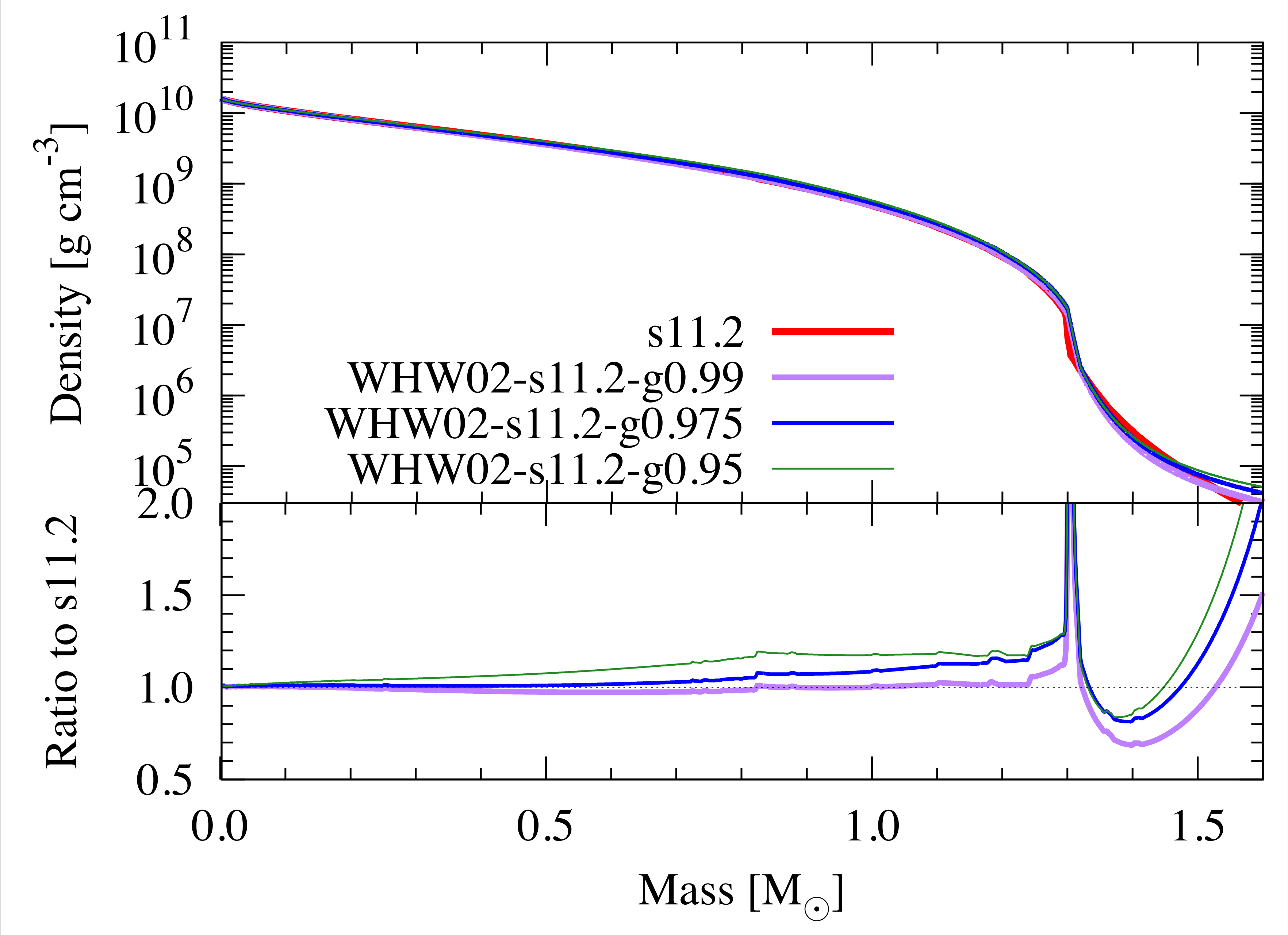
[Suwa & Müller, MNRAS, 460, 2664 (2016)]

$s(M_r)$ → $P(\rho, s, Y_e)$ ← $Y_e(M_r)$

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

+

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

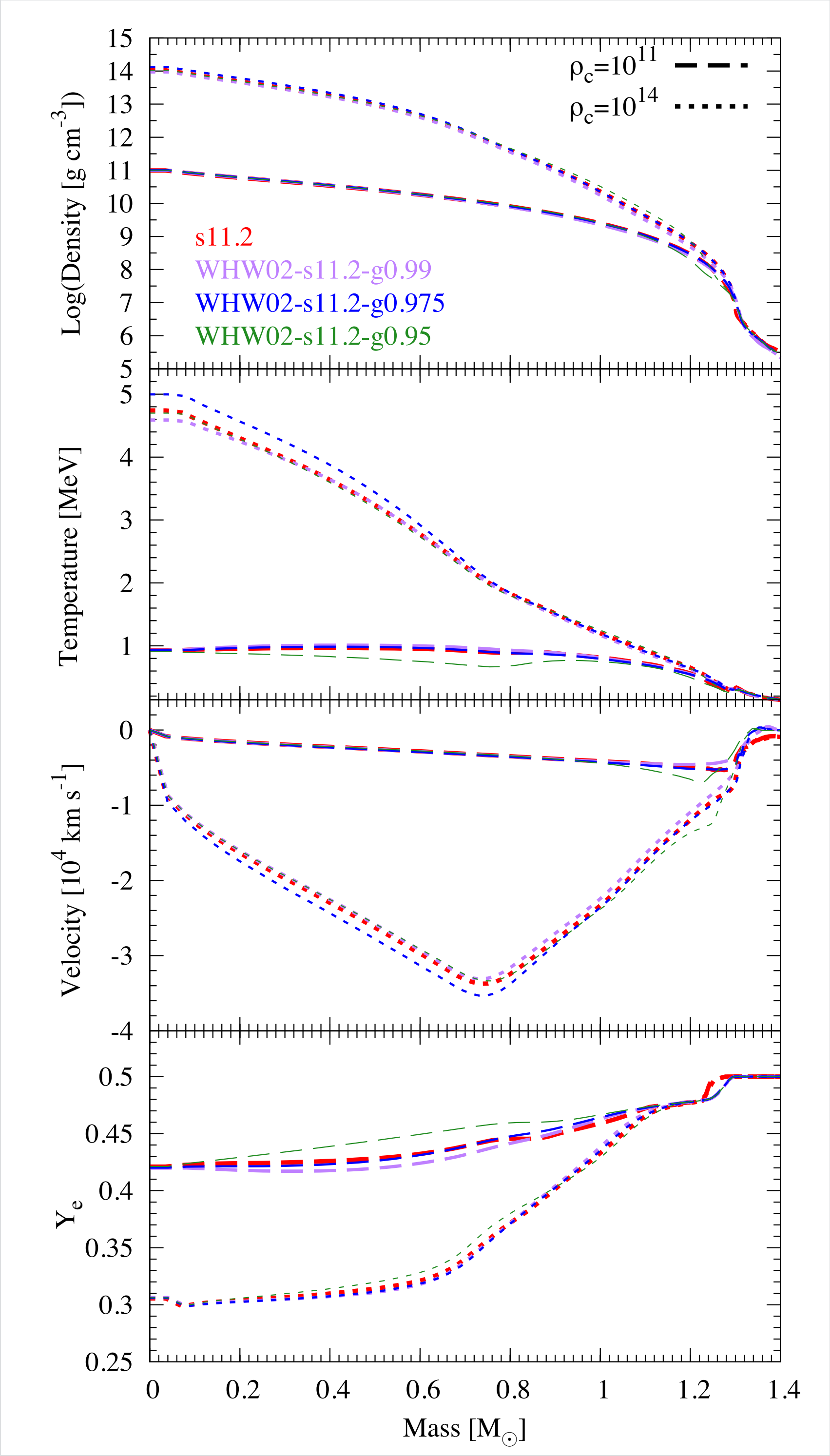


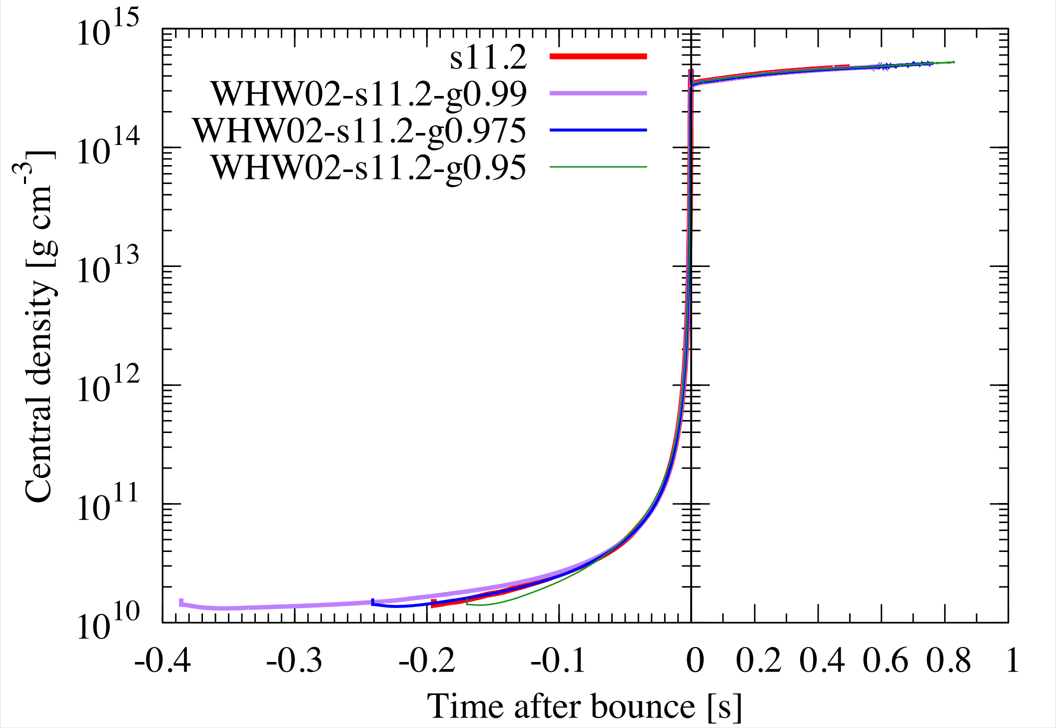
Hydrodynamics simulations

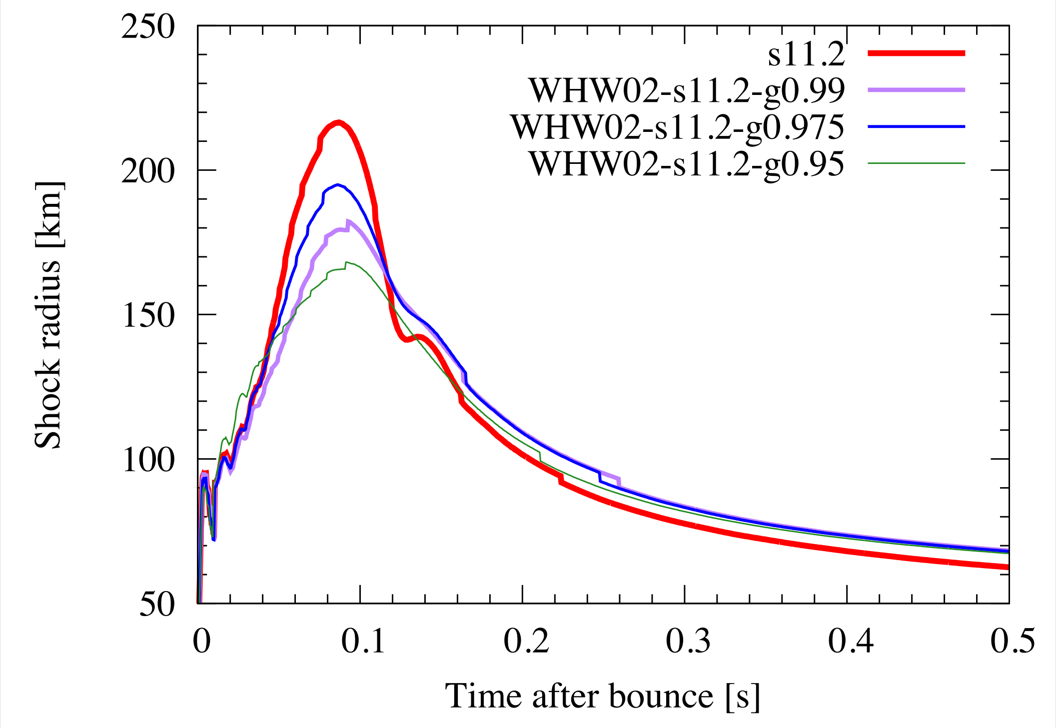
[Suwa & Müller, MNRAS, 460, 2664 (2016)]

https://physik.unibas.ch/~liebend/download/

Agile-IDSA: 1D/GR/neutrino-radiation hydro code, publicly available







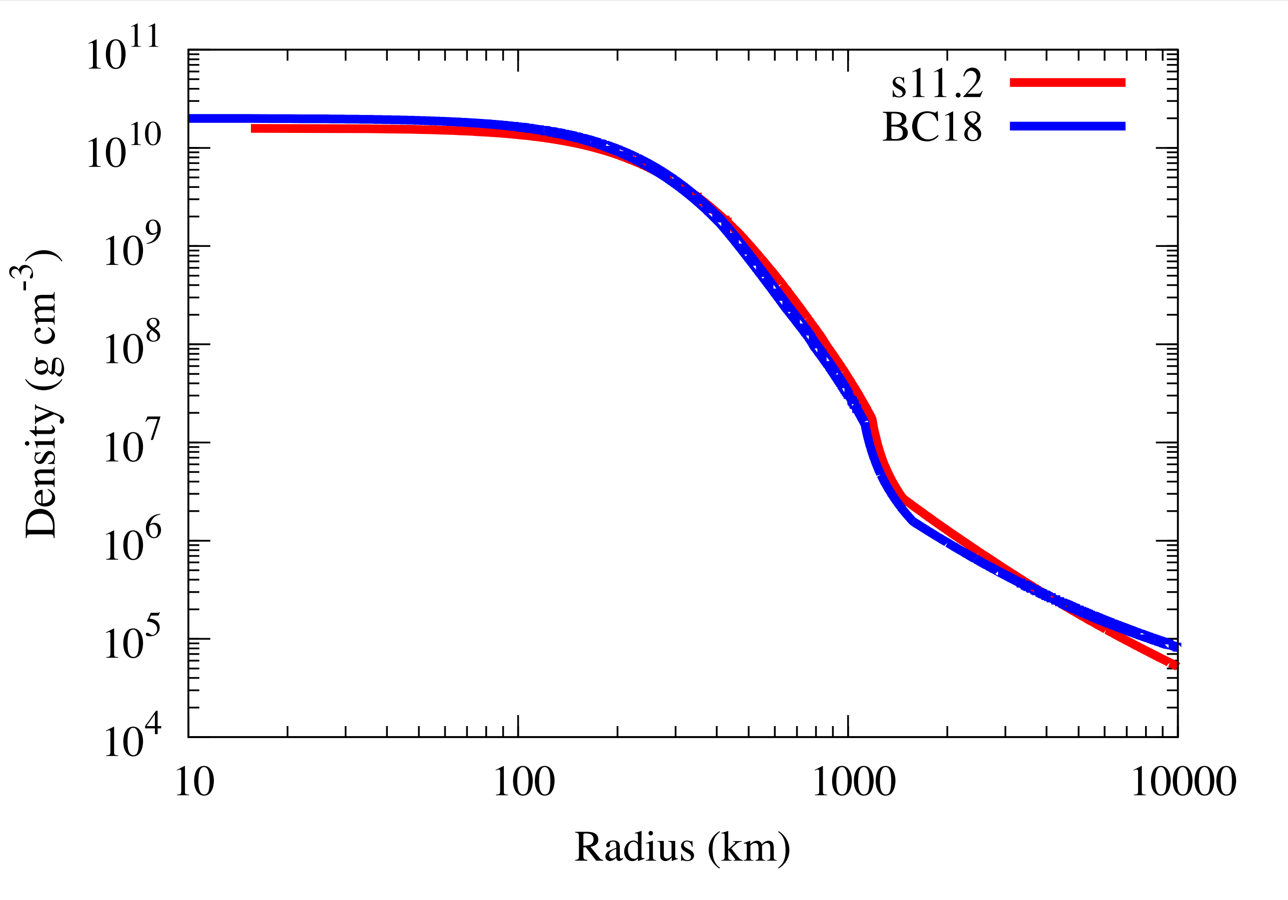
Parameter regime beyond evolution models

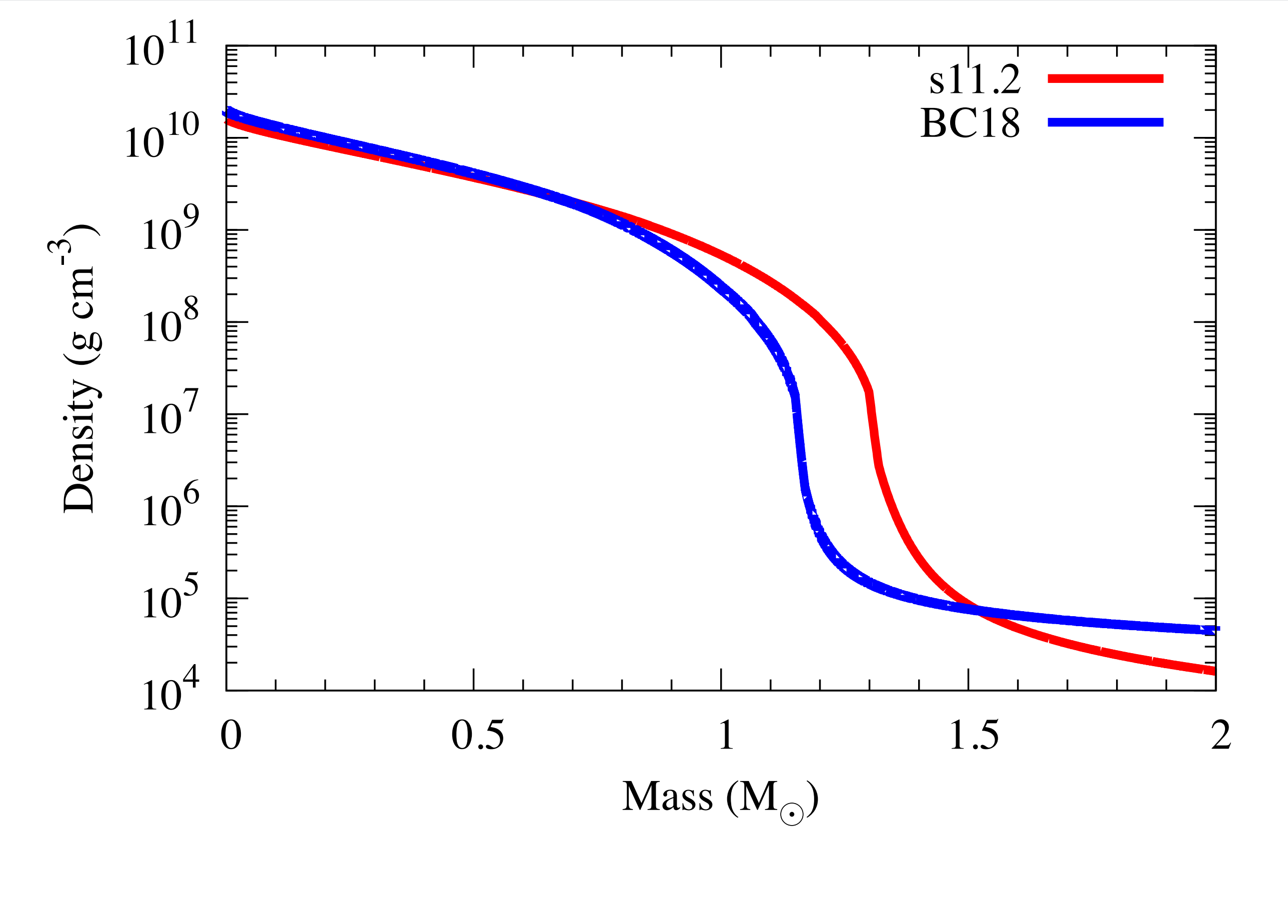
[Suwa & Müller, MNRAS, 460, 2664 (2016)]

Model	S_c	S_1	S_2 [k_B/baryon]	S_5	Y_{ec}	Y_{e3}	ρ_c [10^{10} g cm^{-3}]
BC01	0.5	0.63	1.6	4.0	0.415	0.46	2.0
BC02	**0.4**	0.63	1.6	4.0	0.415	0.46	2.0
BC03	**0.6**	0.63	1.6	4.0	0.415	0.46	2.0
BC04	0.5	**0.53**	1.6	4.0	0.415	0.46	2.0
BC05	0.5	**0.73**	1.6	4.0	0.415	0.46	2.0
BC06	0.5	0.63	**1.5**	4.0	0.415	0.46	2.0
BC07	0.5	0.63	**1.7**	4.0	0.415	0.46	2.0
BC08	0.5	0.63	1.6	**3.0**	0.415	0.46	2.0
BC09	0.5	0.63	1.6	**6.0**	0.415	0.46	2.0
BC10	0.5	0.63	1.6	4.0	**0.411**	0.46	2.0
BC11	0.5	0.63	1.6	4.0	**0.425**	0.46	2.0
BC12	0.5	0.63	1.6	4.0	0.415	**0.452**	2.0
BC13	0.5	0.63	1.6	4.0	0.415	**0.47**	2.0
BC14	0.5	0.63	1.6	4.0	0.415	0.46	**1.0**
BC15	0.5	0.63	1.6	4.0	0.415	0.46	**3.0**
BC16	**0.4**	**0.73**	1.6	4.0	0.415	0.46	2.0
BC17	**0.4**	0.63	**1.7**	4.0	0.415	0.46	2.0
BC18	**0.4**	0.63	1.6	**6.0**	0.415	0.46	2.0
BC19	**0.4**	0.63	1.6	4.0	**0.425**	0.46	2.0
BC20	**0.4**	0.63	1.6	4.0	0.415	**0.47**	2.0
BC21	**0.4**	0.63	1.6	4.0	0.415	0.46	**1.0**
BC22	**0.4**	0.63	1.6	4.0	0.415	0.46	**3.0**

Density structures

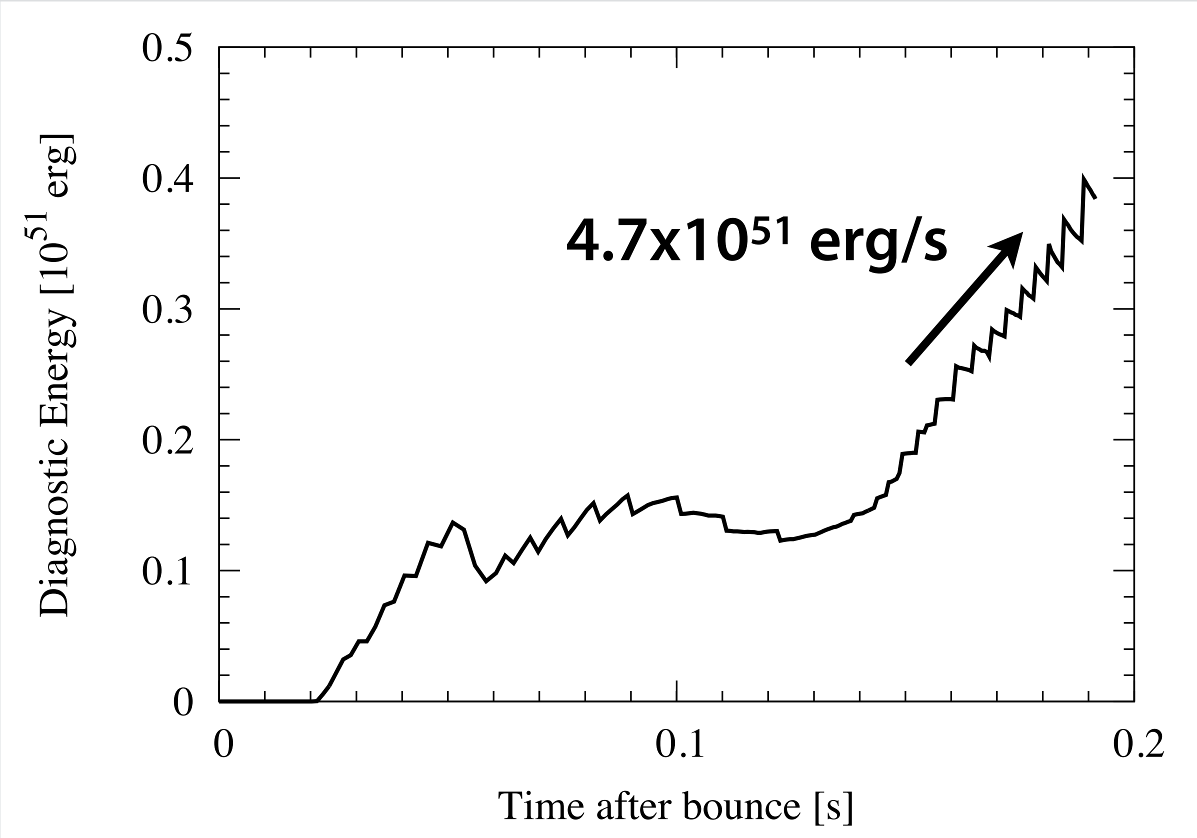
[Suwa & Müller, MNRAS, 460, 2664 (2016)]

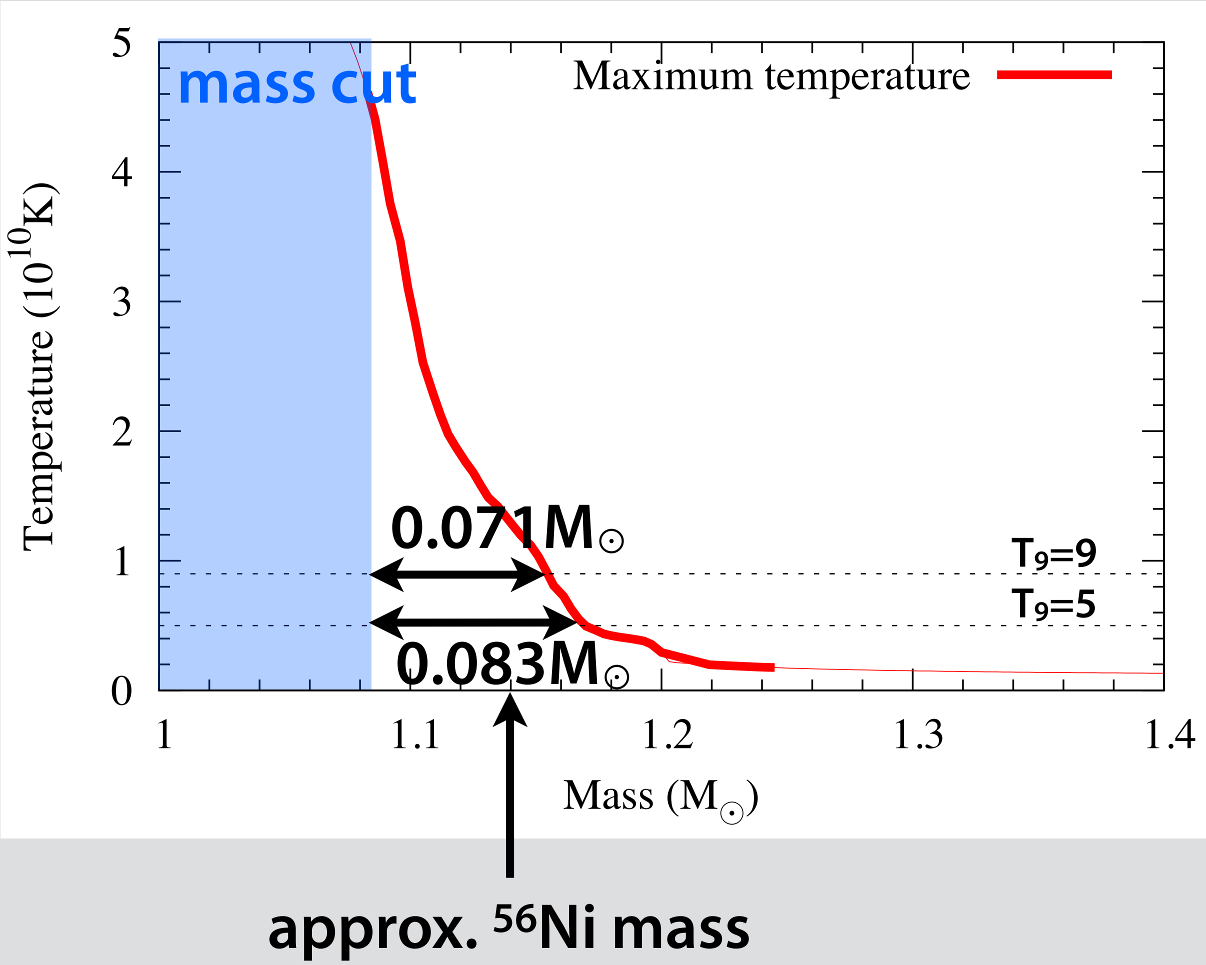




Explosions in 1D

[Suwa & Müller, MNRAS, 460, 2664 (2016)]





Summary

* **Bright side**
  * success of detailed numerical simulations
  * Many exploding models
* **Dark side**
  * insufficient explosion energy and ^{56}Ni mass
  * 2D>1D, but 3D<2D (probably)
* **Initial condition may solve problem**