Reverse construction of initial conditions: from supernovae to progenitors

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Key observables characterizing supernovae

* **Explosion energy:** $\sim 10^{51}$ **erg**
* **Ni mass:** $\sim 0.1 M_\odot$
* **Ejecta mass:** $\sim M_\odot$

measured by fitting SN light curves

related

* **NS mass:** $\sim 1 - 2\ M_\odot$

measured by binary systems

final goal of first-principle (*ab initio*) simulations

Brief history of supernova theory

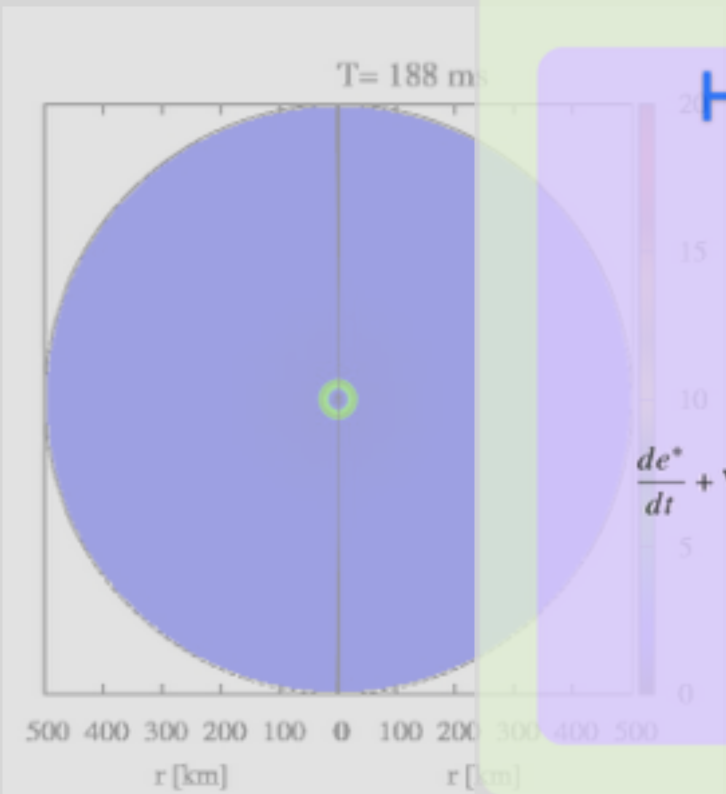
- **1980s**
  - **two explosion scenarios (prompt/delayed)**
  - **delayed scenario (neutrino-driven exp.) was preferred and became standard**
- **2000s**
  - **non-exploding supernova problem (1D)**
- **since 2006**
  - **exploding simulations (2D/3D)!**
    but explosion energy is too small (~10^{50} erg)
  - **many 2D explosions (~O(100)), a few 3D explosions**
  - **1D<3D<2D?** still controversial
- **since 2013**
  - **Initial condition dependence** ← today's topic

Supernova simulation is an initial value problem

stellar evolutionary calculations

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

Time integration



Suwa+ 2011 (2D)

Hydrodynamic equations

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

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

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

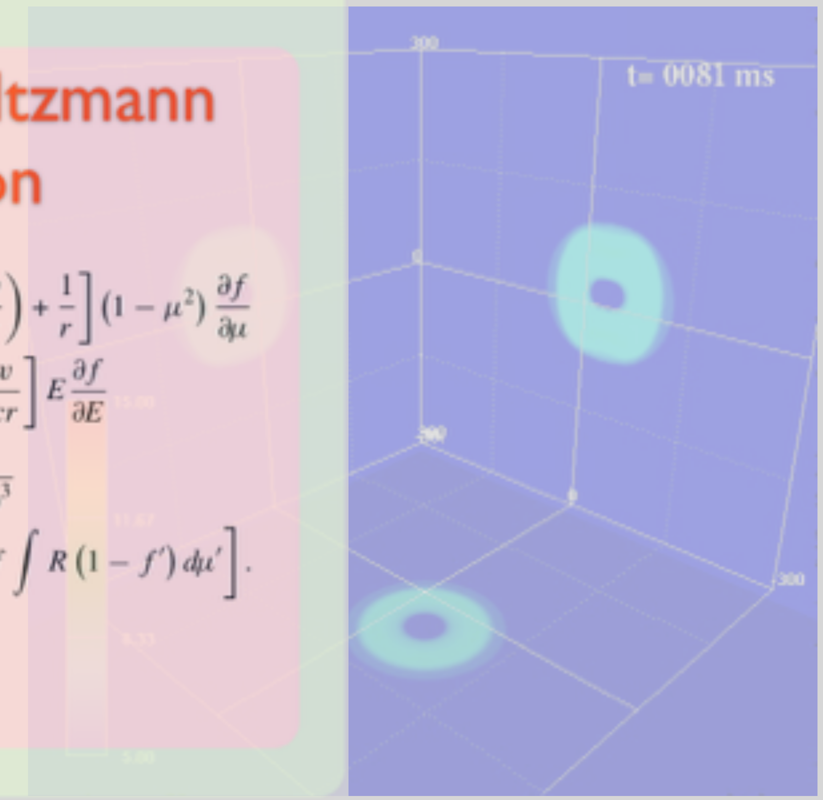
$$\frac{dY_e}{dt} = Q_N,$$

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

Solve simultaneously

Neutrino Boltzmann equation

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

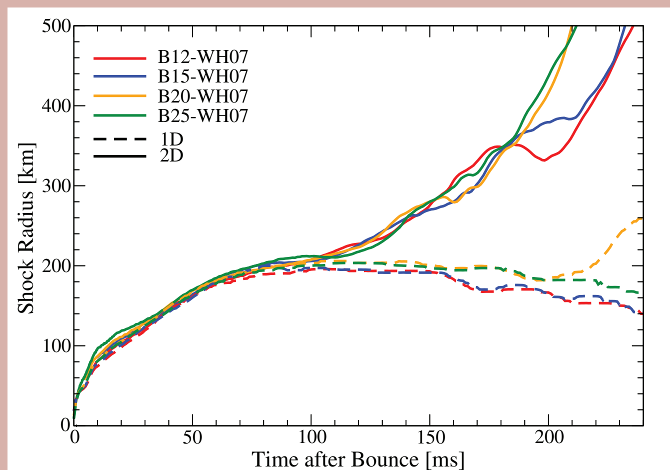


Takiwaki, Kotake, Suwa 2016 (3D)

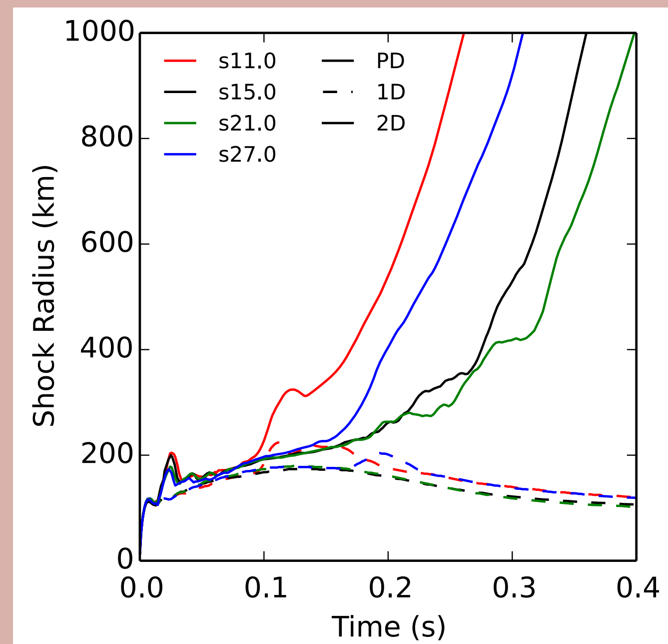
supernova explosions

Initial condition dependences of SN simulations

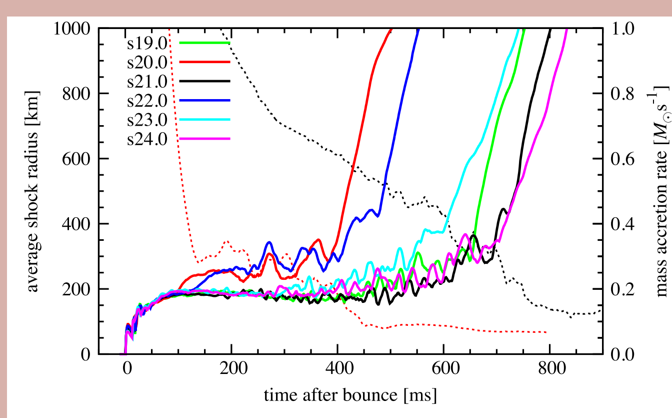
2D-hydro+ν transfer



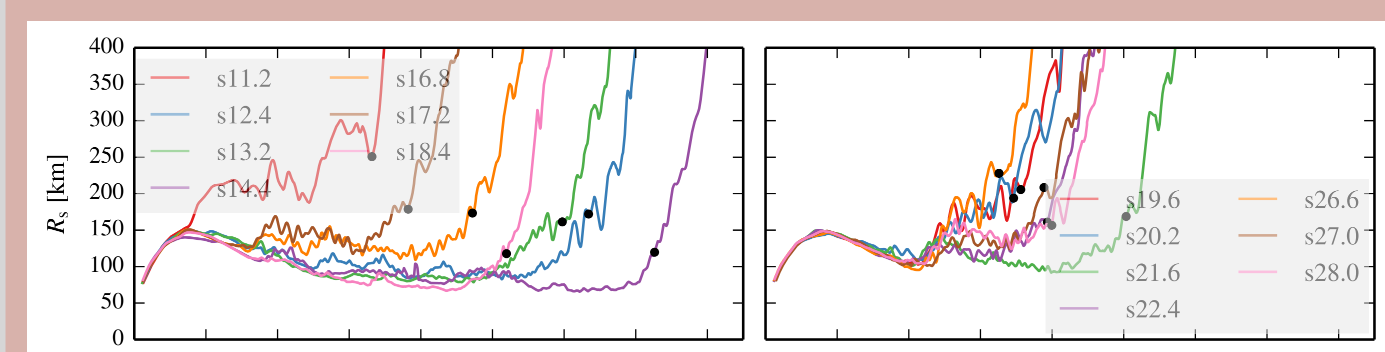
Bruenn+ 2013
4 models



Pan+ 2016
6 models

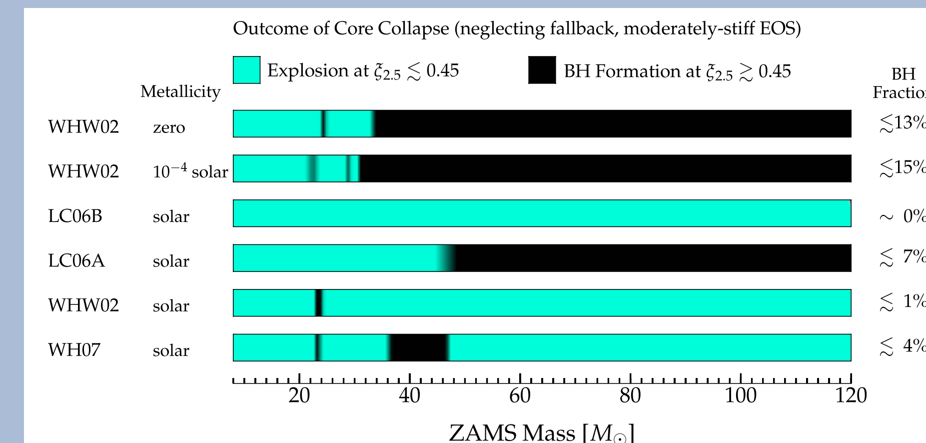


Nakamura+ 2015
378 models

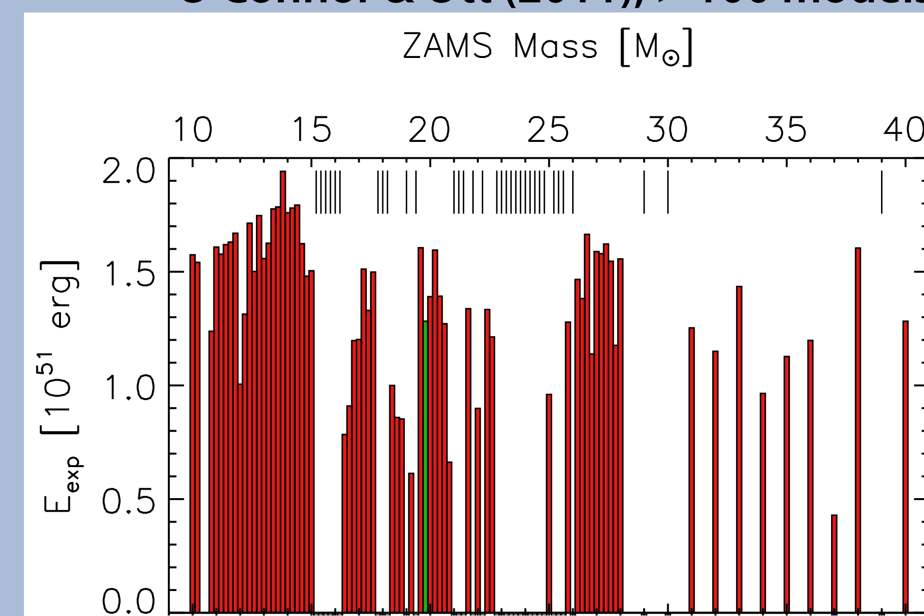


Summa+ 2016, 18 models

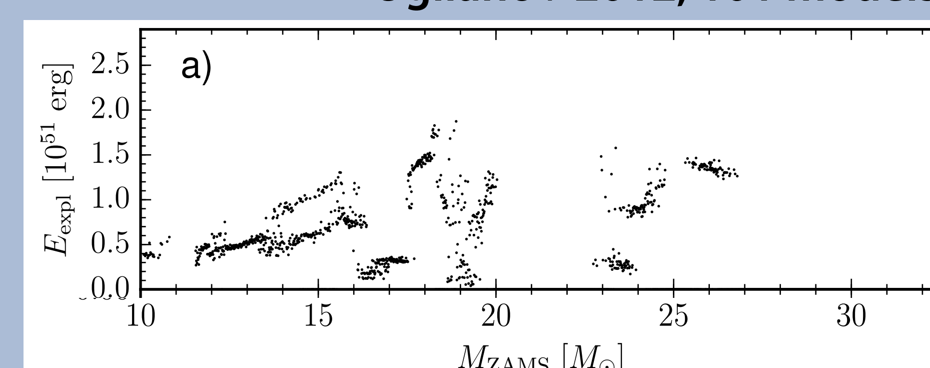
1D-hydro+approx. ν treatment



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



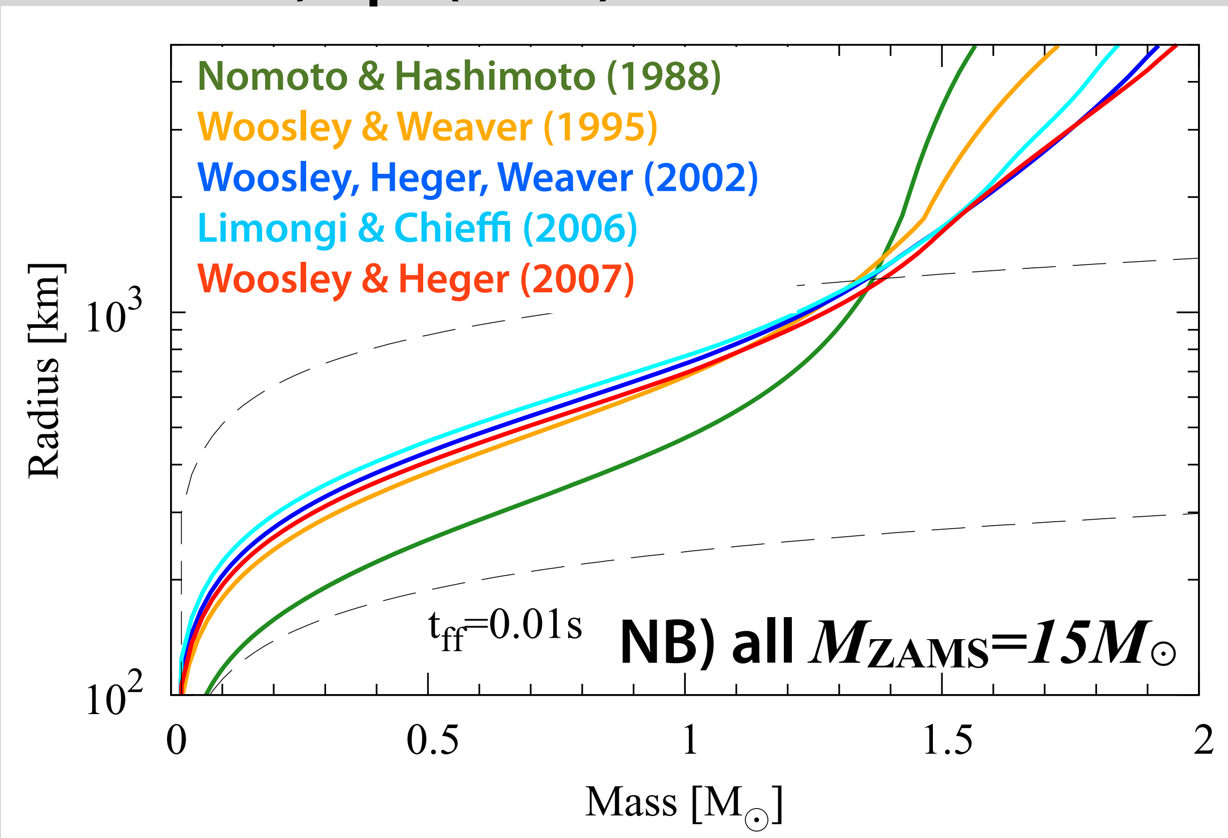
Ugliano+ 2012, 101 models



Müller+ 2016, 2120 models

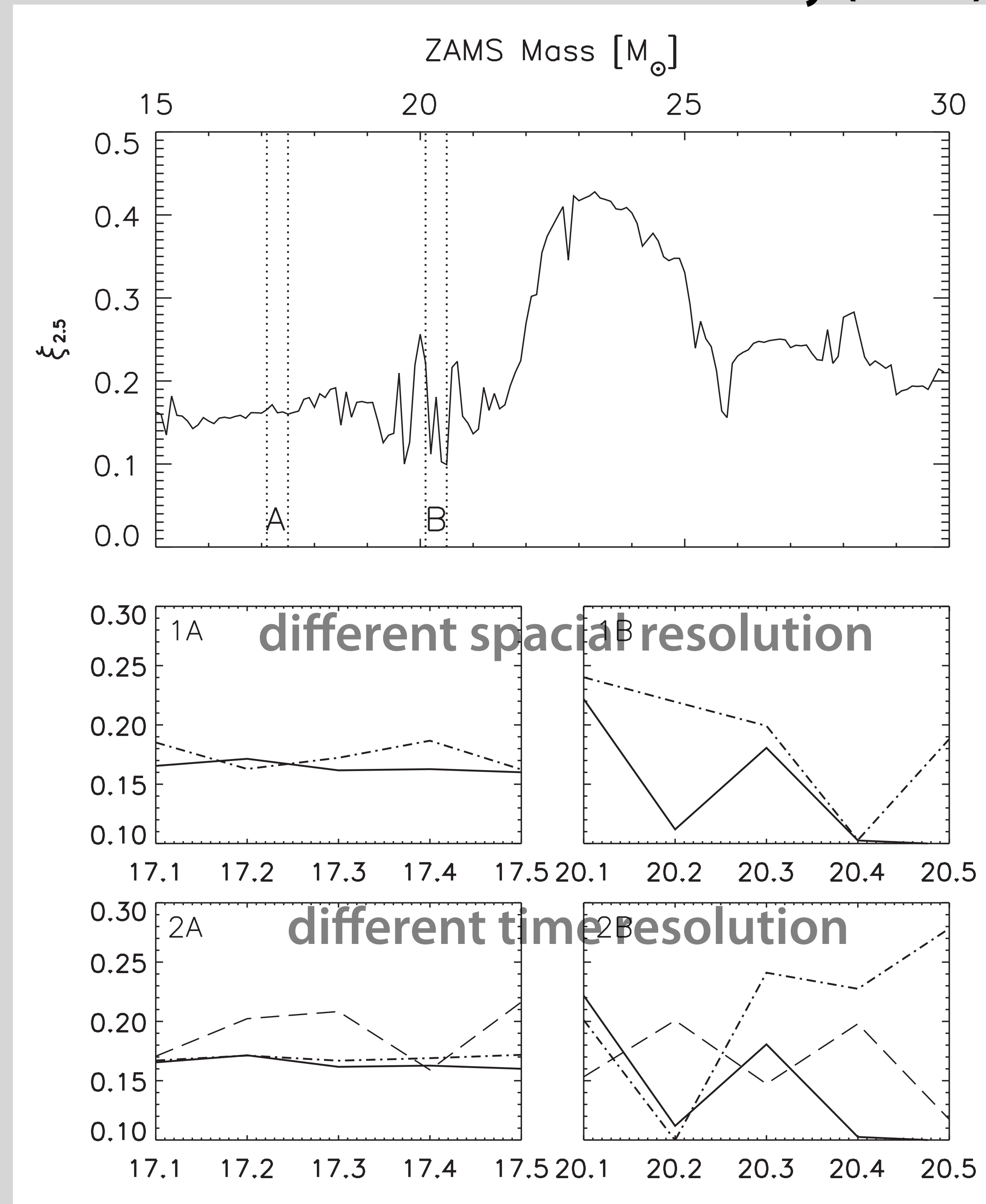
Uncertainties in stellar evolutionary calculations

Suwa+, ApJ (2016)



Different codes lead to different structure

Sukhbold & Woosley (2014)



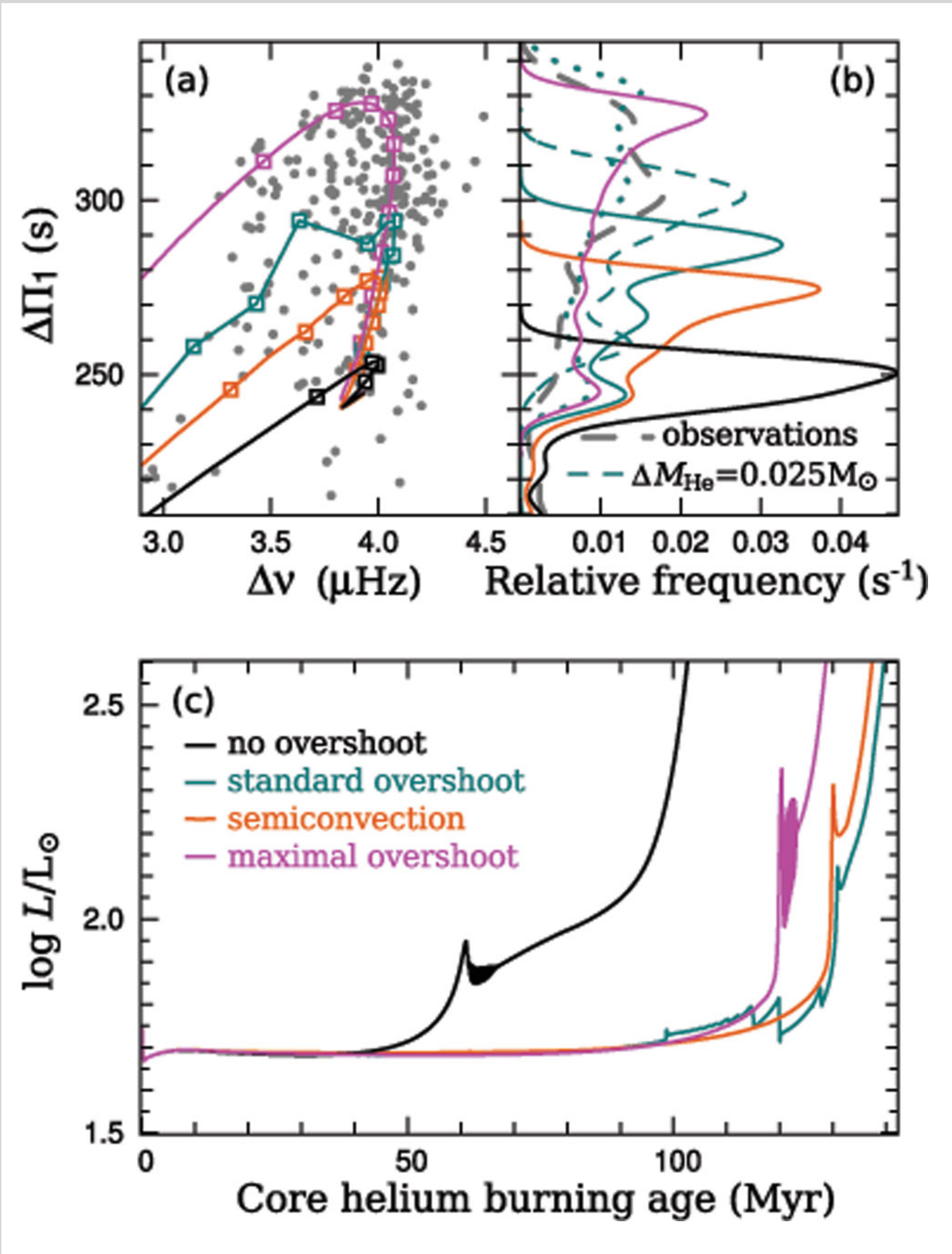
Even with the *same* code, different (time or space) resolutions lead to different structure

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

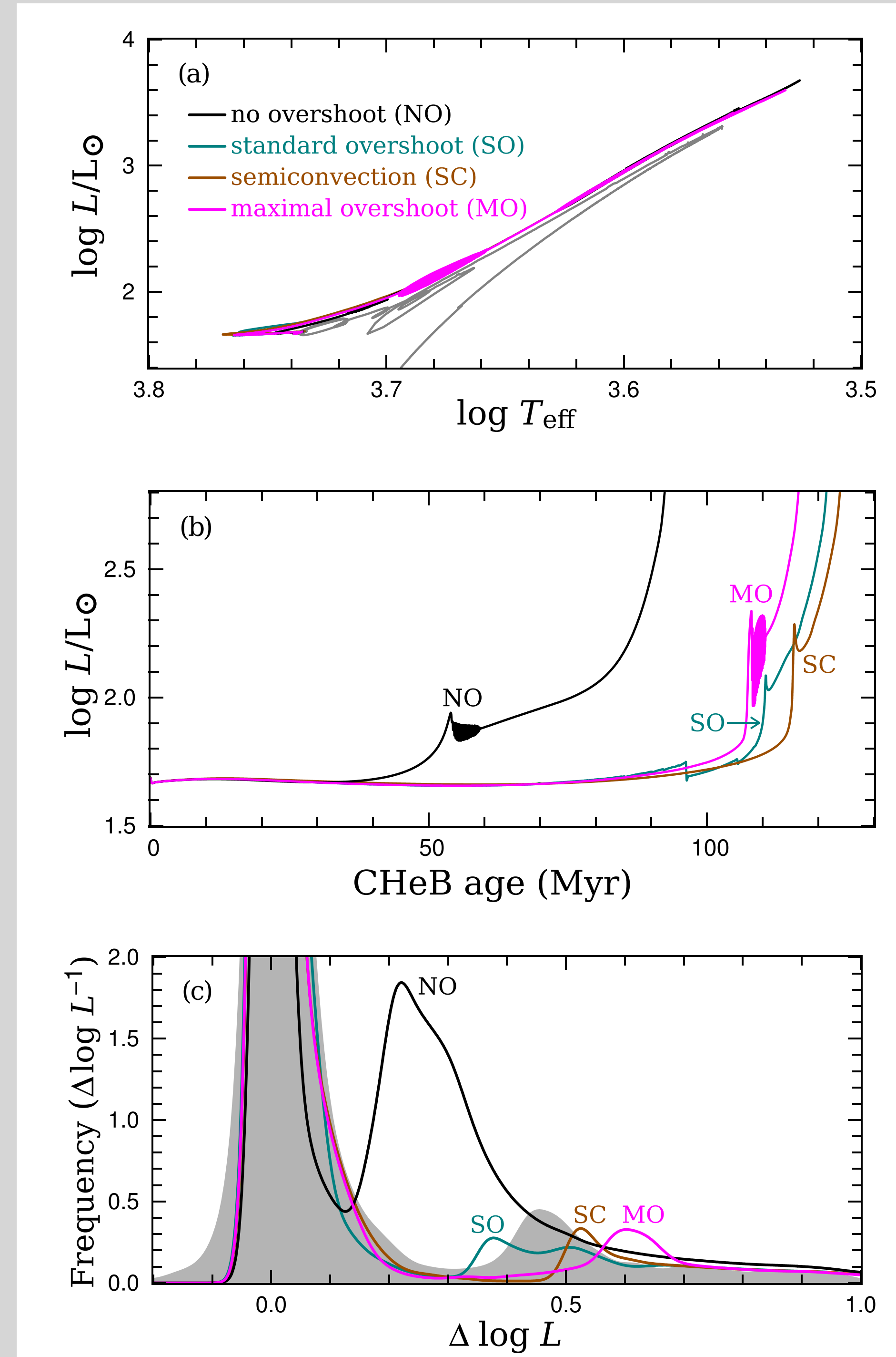
"Compactness parameter"
O'Connor & Ott (2011)

Asteroseismology and overshoot treatments

Constantino+ 2015



Constantino+ 2016



core helium burning (CHeB) stars

An example of initial value problem

given equation

$$\ddot{x} - x = 0$$

initial conditions

$$x(0) = 1$$

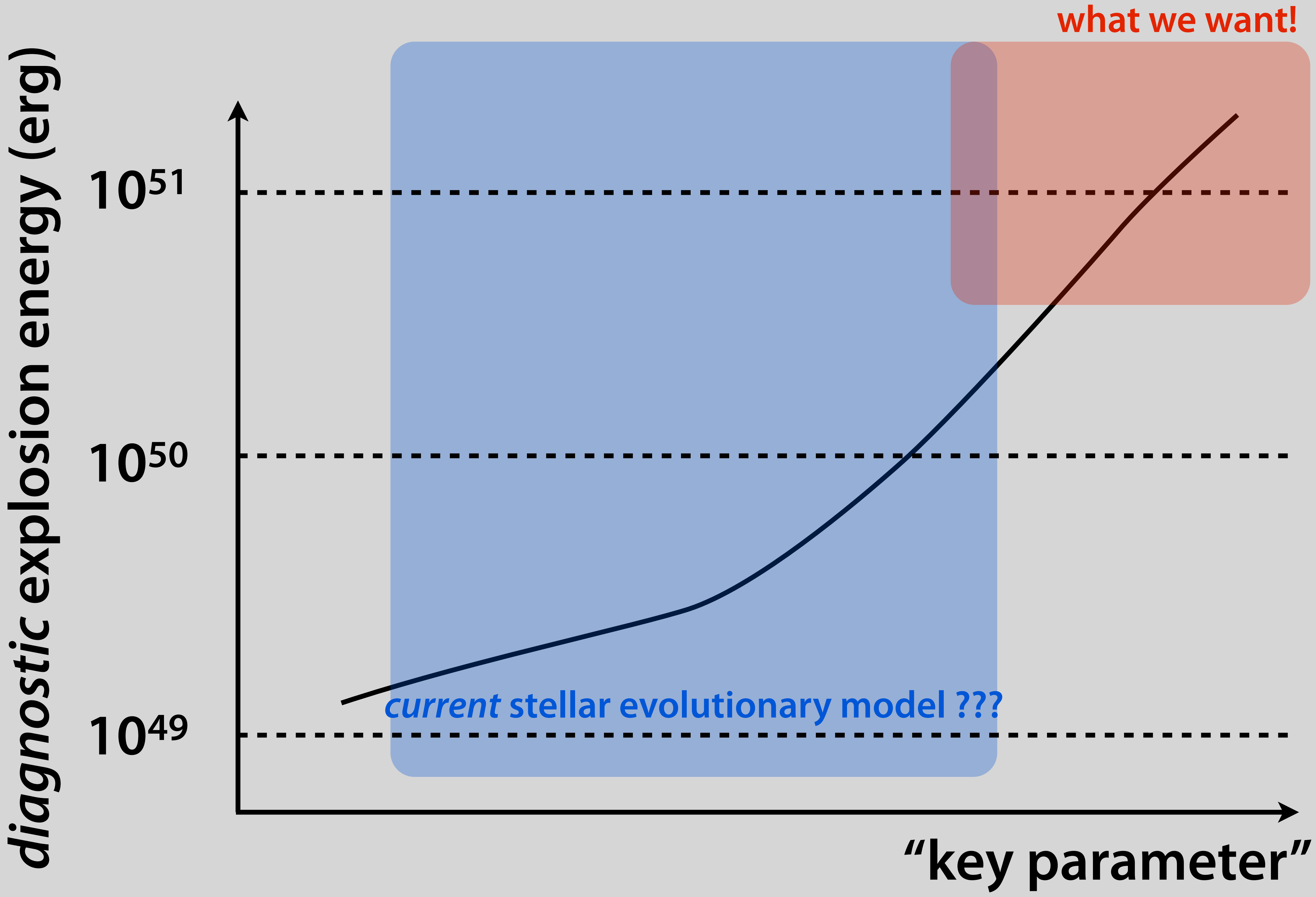
and

$$\dot{x}(0) = 1 \quad \text{or} \quad \dot{x}(0) = -1$$

solutions

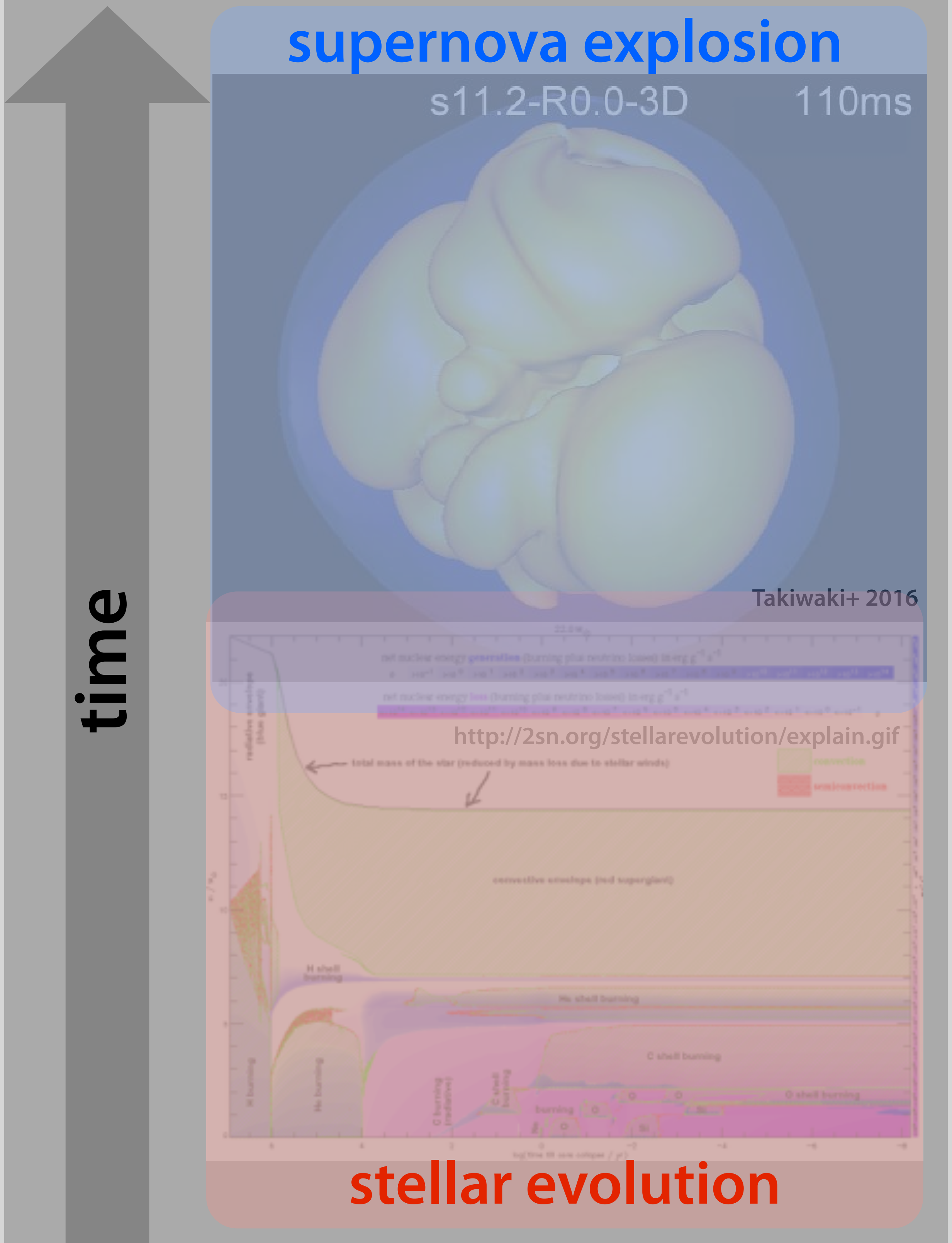
$$x(t) = e^{t} \qquad x(t) = e^{-t}$$

A possibility



Problem reduction

traditional approach



new approach

supernova explosion

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

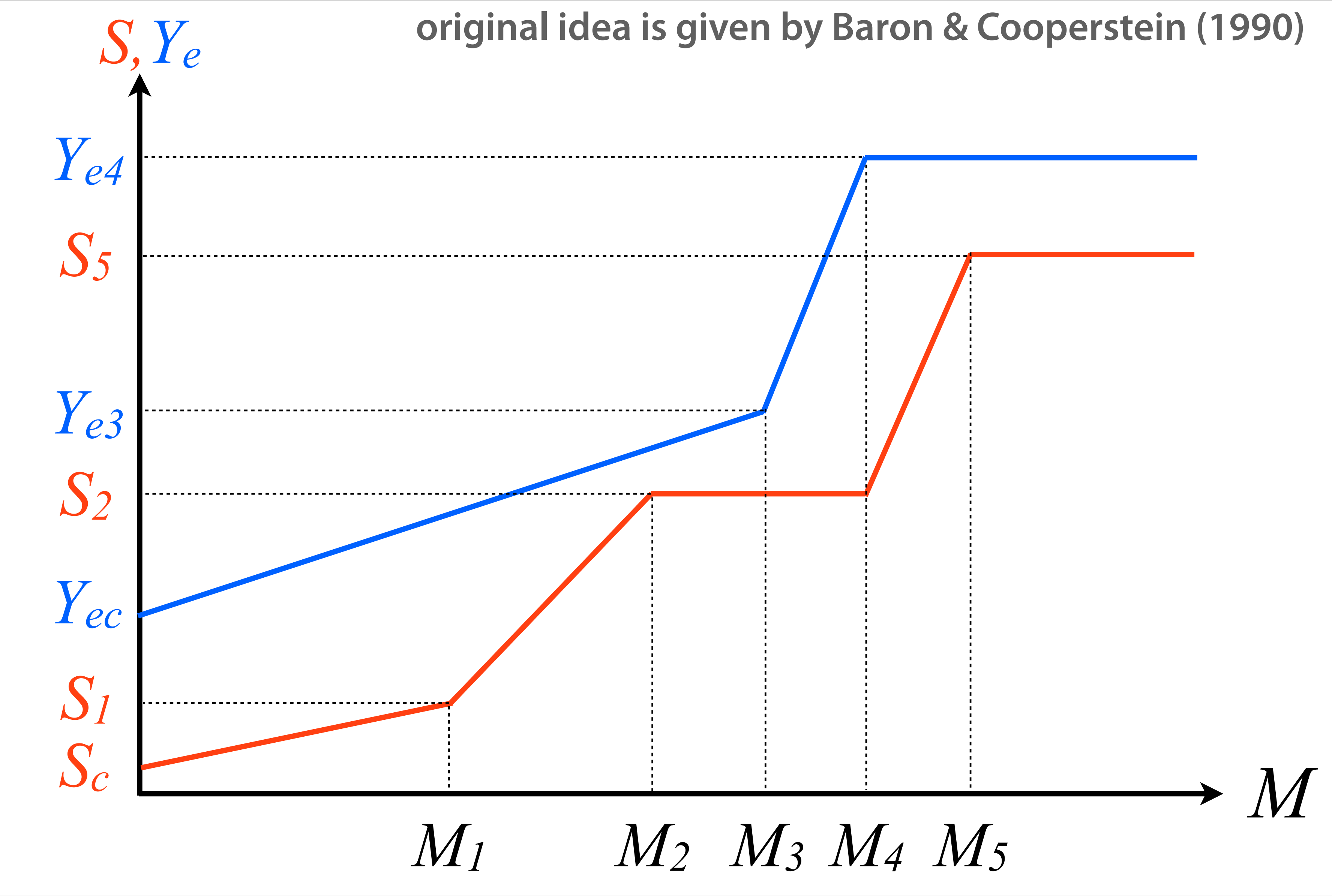
stellar structure

↑ Q2. *Is it possible to produce such structure?*

stellar evolution

Parametric initial conditions

[Suwa & E. 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

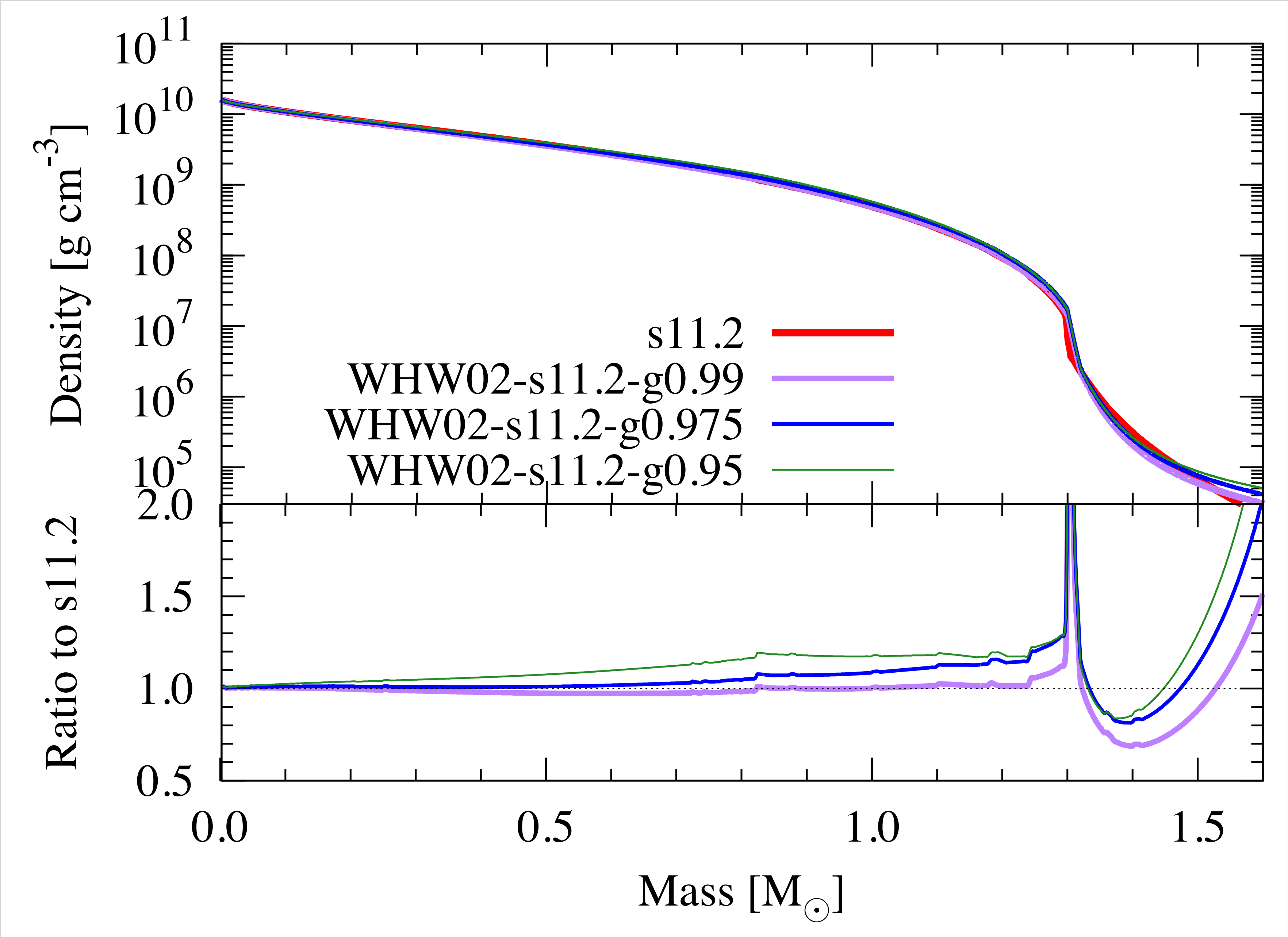
[Suwa & E. Müller, MNRAS, 460, 2664 (2016)]

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

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

+

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



Parametric initial conditions

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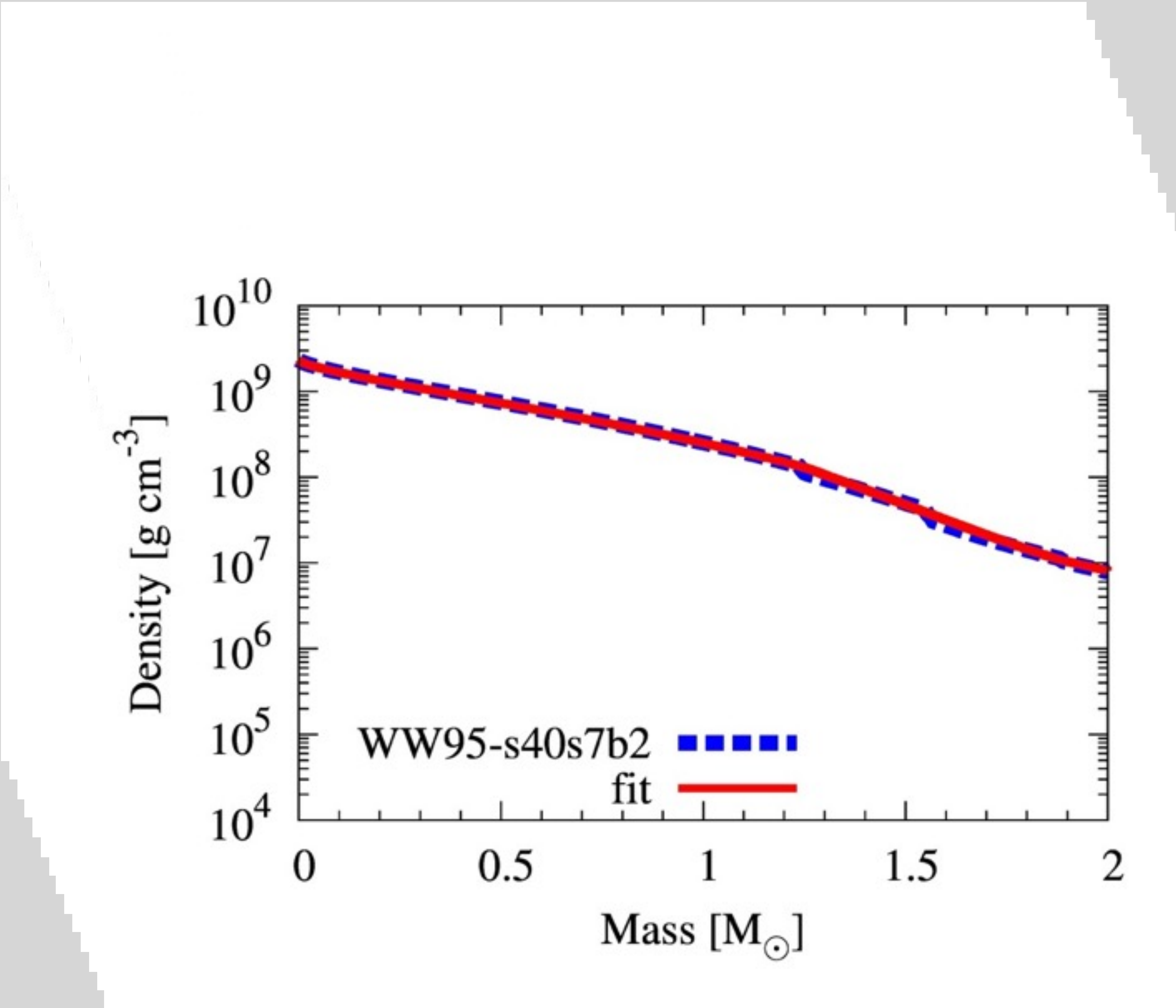
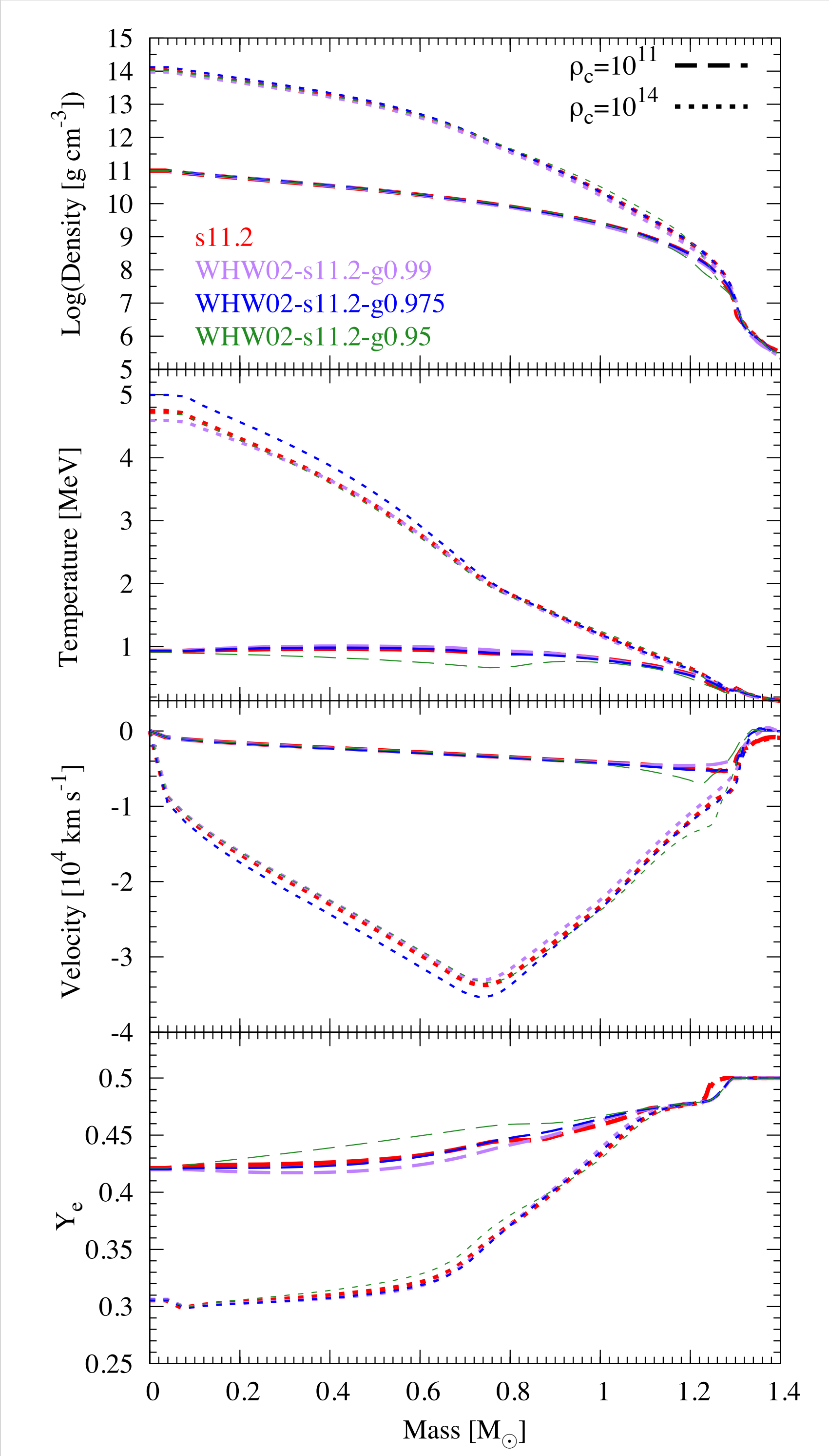


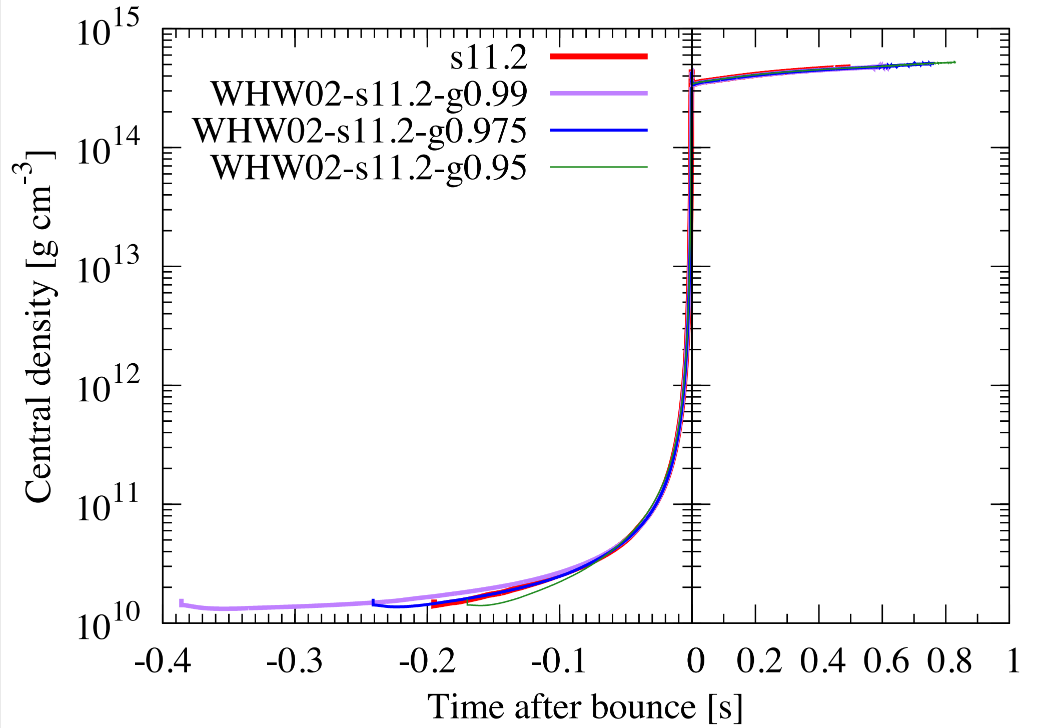
Hydrodynamics simulations

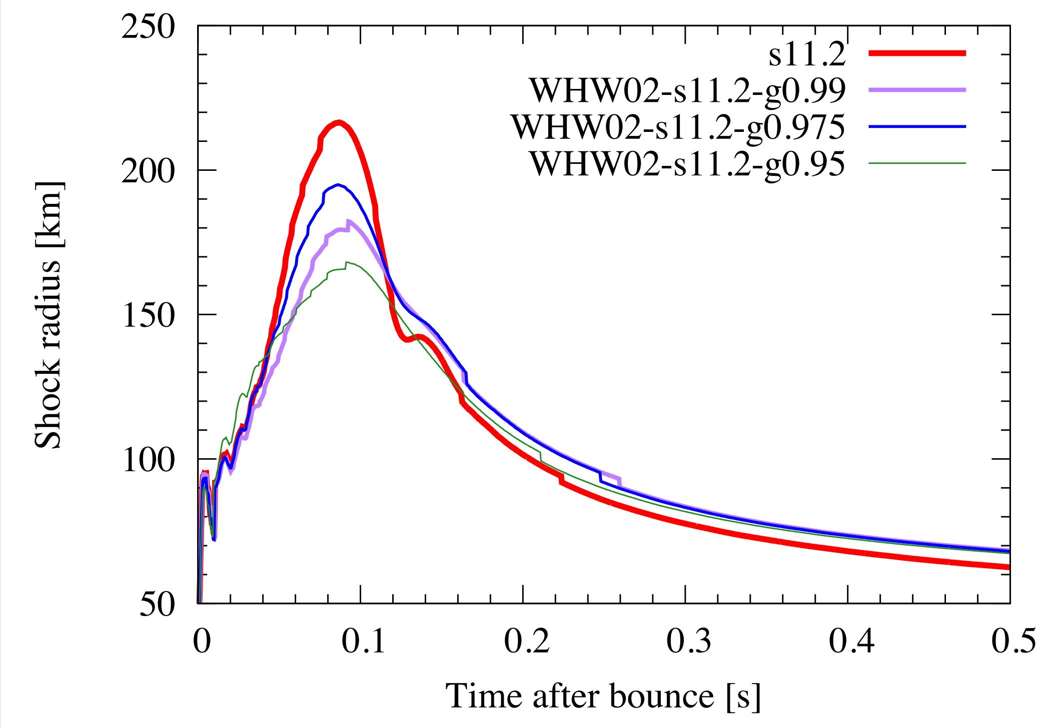
[Suwa & E. Müller, MNRAS, **460**, 2664 (2016)]

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

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







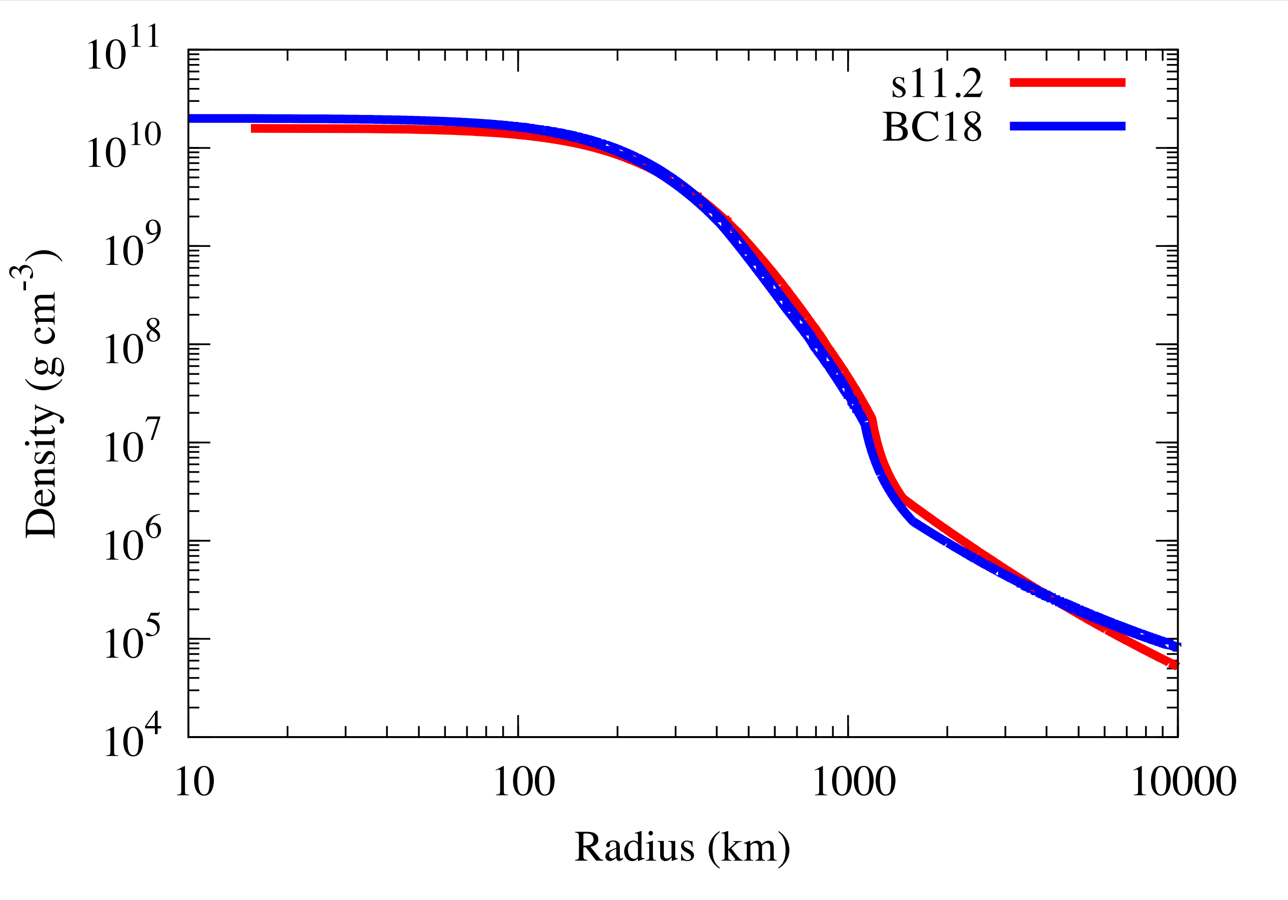
Parameter regime beyond evolution models

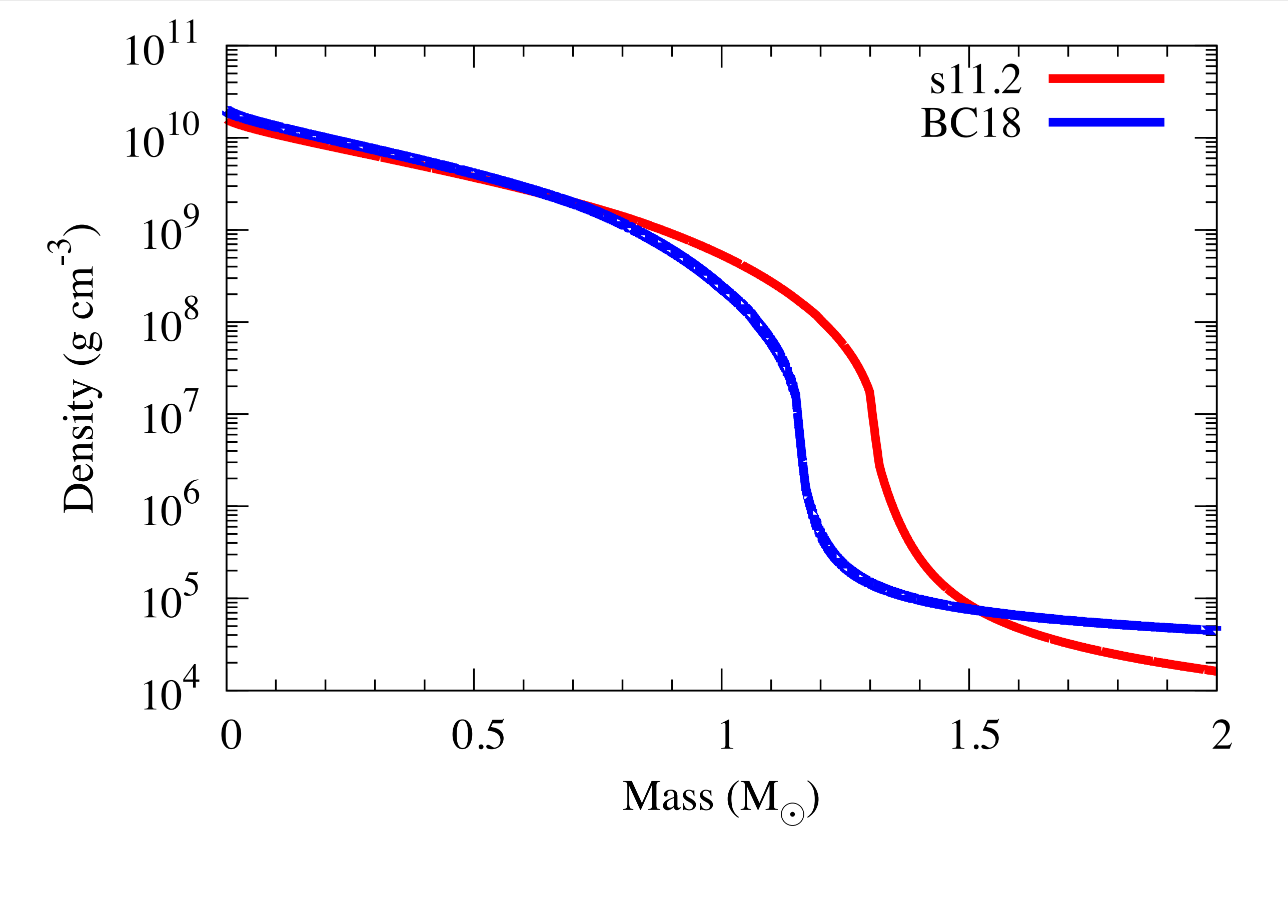
[Suwa & E. Müller, MNRAS, **460**, 2664 (2016)]

Model	S_c	S_1	S_2	S_5	Y_{ec}	Y_{e3}	ρ_c
		$[k_B/\mathrm{baryon}]$					$[10^{10}\,\mathrm{g\,cm^{-3}}]$
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

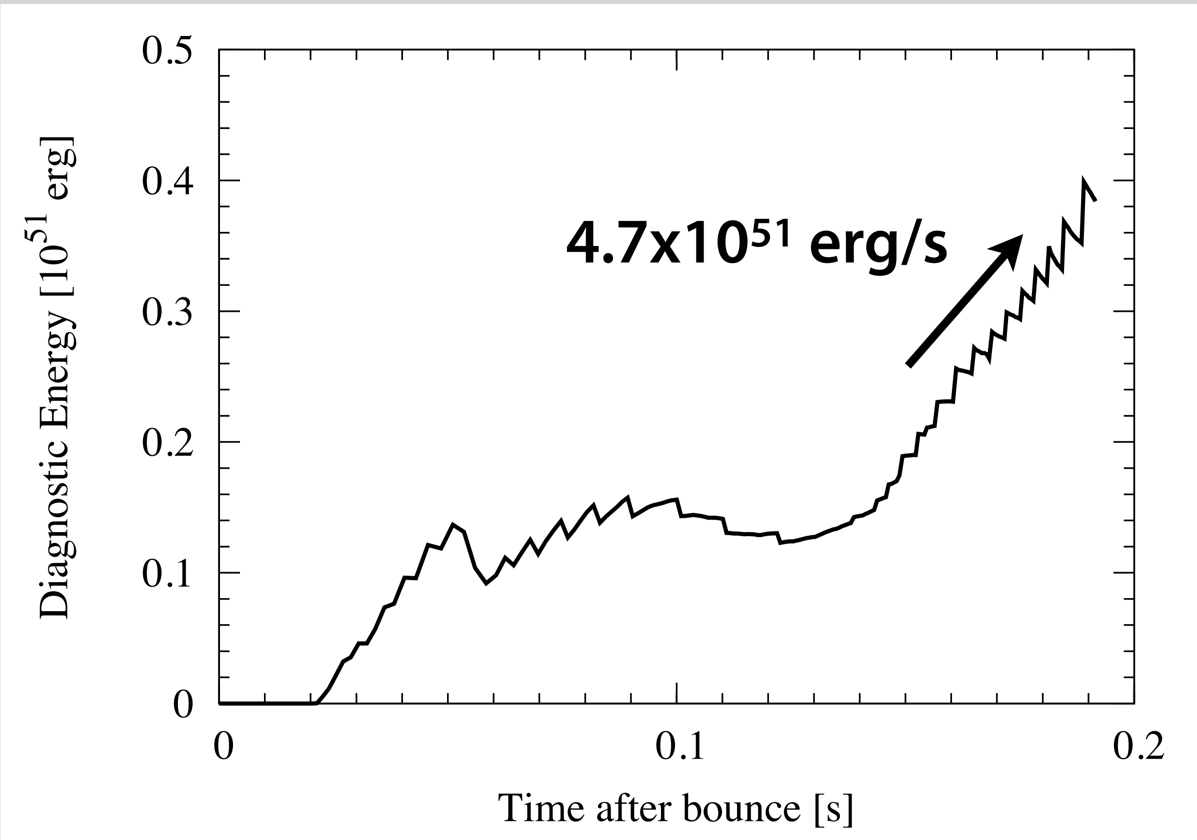
[Suwa & E. Müller, MNRAS, 460, 2664 (2016)]

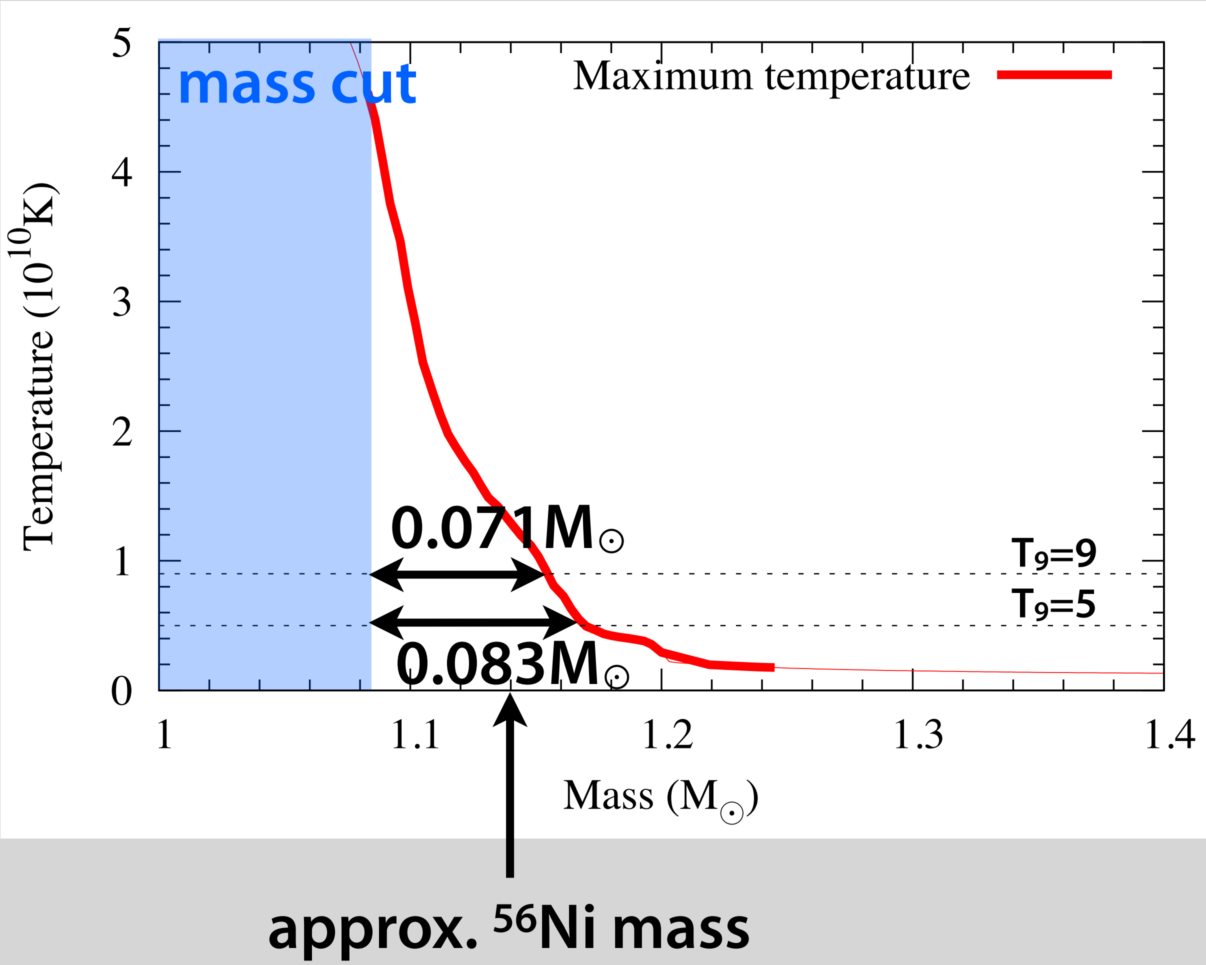




Explosions in 1D

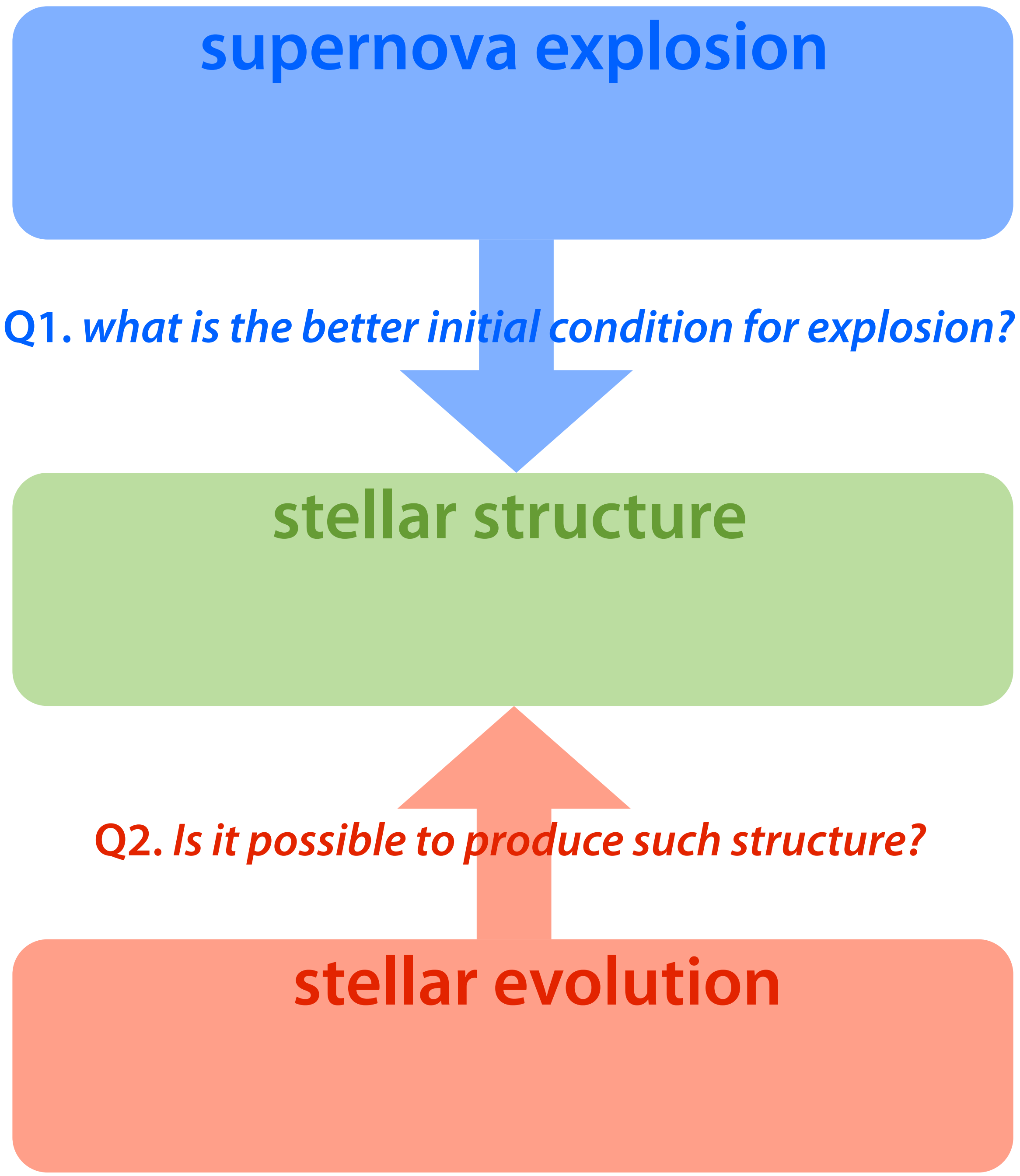
[Suwa & E. Müller, MNRAS, 460, 2664 (2016)]





Prospects

new approach



What's next step?:
Broader parameter study
2D/3D simulations

What can I do?:
MESA

Summary

Question:

How can we produce strong (E_{exp}~10^{51} erg) explosion?

Possible Answer:

Change initial conditions. By starting from specific initial conditions, strong explosions are obtained *without* any change of simulation codes.

Next Question:

Which kind of stellar evolutionary calculations can produce these *preferable* presupernova structure?