# 超新星爆発計算のための
# 新しい初期条件の作り方

## 諏訪雄大

（京都大学基礎物理学研究所）

共同研究者：E. Müller （マックスプランク宇宙物理研究所）

# *Key observables characterizing supernovae*

* **Explosion energy:** $\sim 10^{51}$ **erg**

* **Ni mass:** $\sim 0.1 M_{\odot}$

* **Ejecta mass:** $\sim M_{\odot}$

   **related**

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

measured by fitting
SN light curves

measured by
binary systems

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

# *Supernova simulation is an initial value problem*

stellar evolutionary calculations

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



Time integration

Hydrodynamic equations

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

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

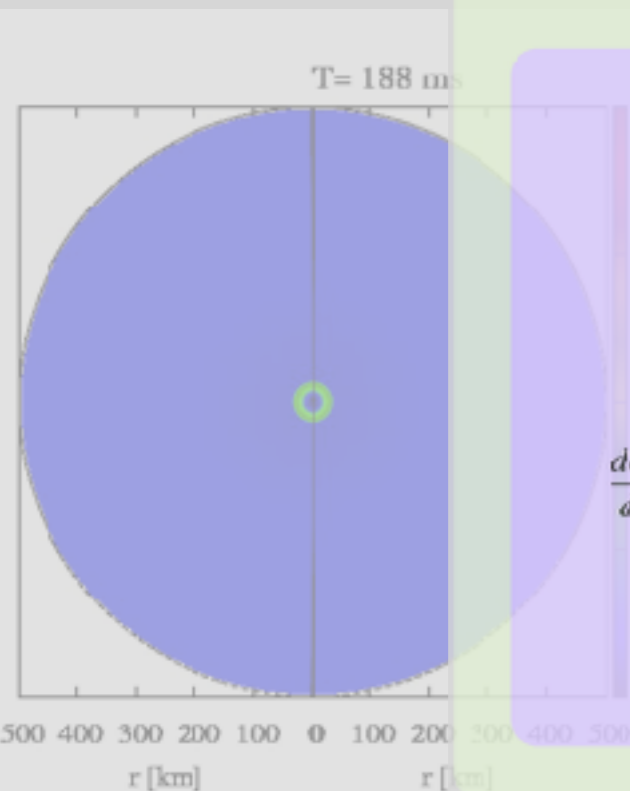$$\frac{de^*}{dt} + \nabla \cdot \left[ (e^* + P) \mathbf{v} \right] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_E,$$

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

$$\triangle \Phi = 4\pi G\rho,$$
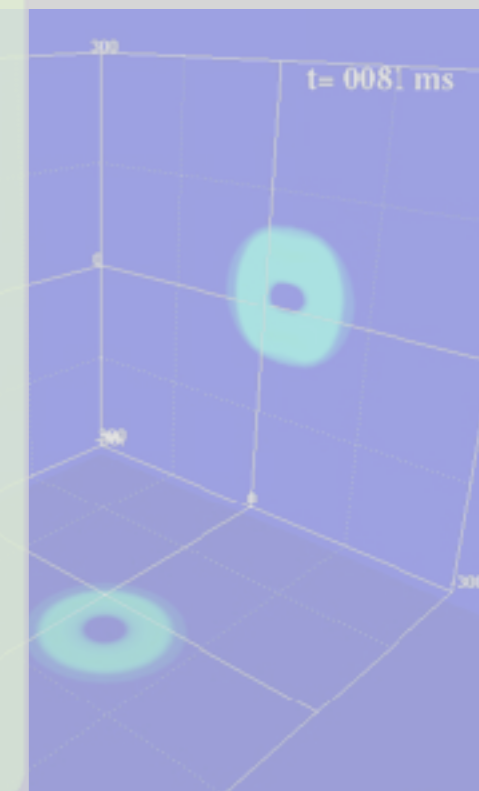
Solve simultaneously

Neutrino Boltzmann equation

$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[ \mu \left( \frac{d\ln\rho}{cdt} + \frac{3v}{cr} \right) + \frac{1}{r} \right] (1-\mu^2) \frac{\partial f}{\partial \mu}$$

$$+ \left[ \mu^2 \left( \frac{d\ln\rho}{cdt} + \frac{3v}{cr} \right) - \frac{v}{cr} \right] F \frac{\partial f}{\partial E}$$

$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3}$$

$$\times \left[ (1-f) \int R f' d\mu' - f \int R (1-f') d\mu' \right].$$
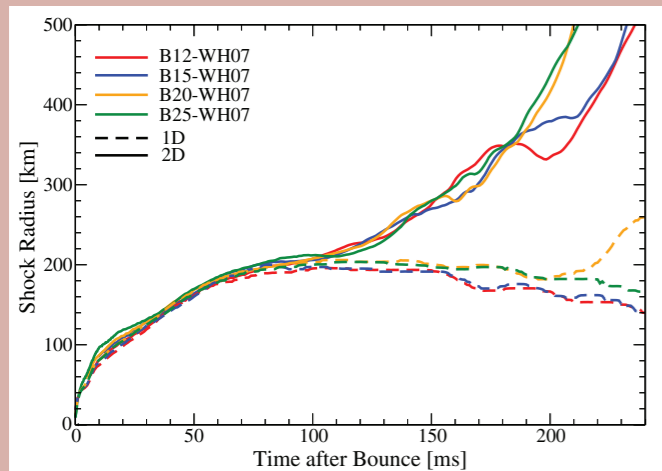
**Suwa+ 2011 (2D)**

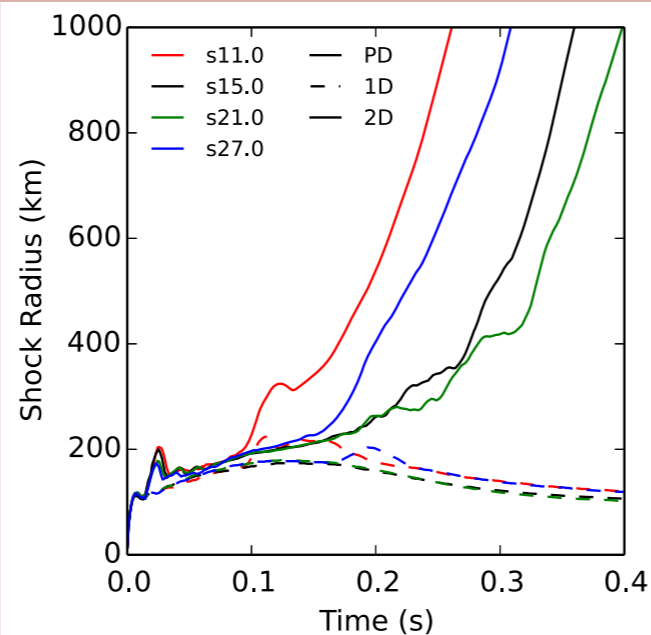**Takiwaki, Kotake, Suwa 2016 (3D)**

supernova explosions
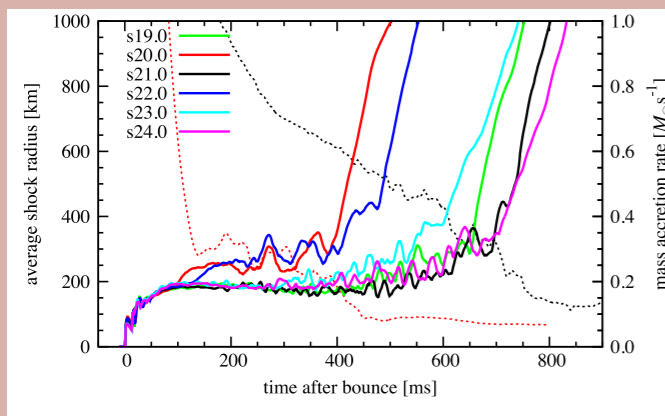
# Initial condition dependences of SN simulations

## 2D-hydro+ν transfer



Bruenn+ 2013

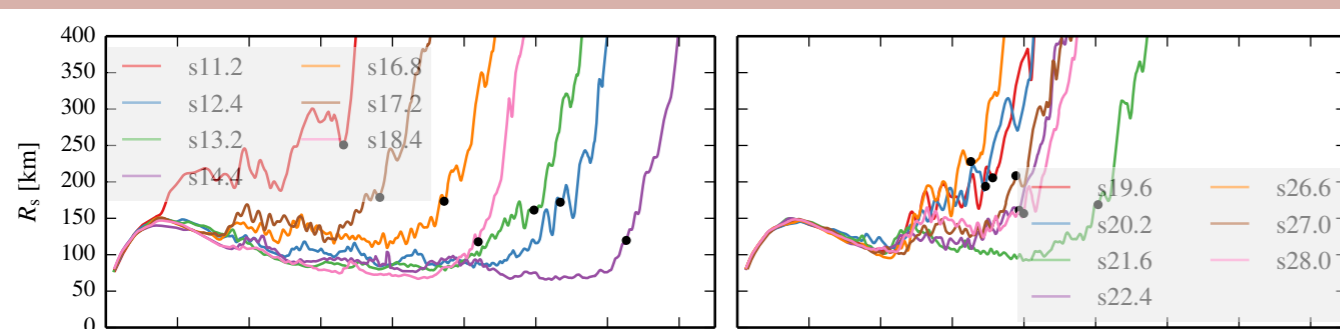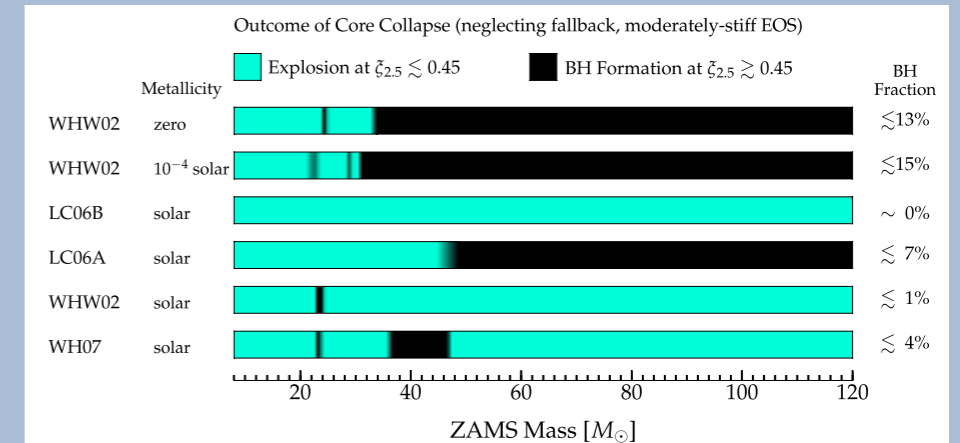**4 models**



Pan+ 2016

**6 models**



Nakamura+ 2015
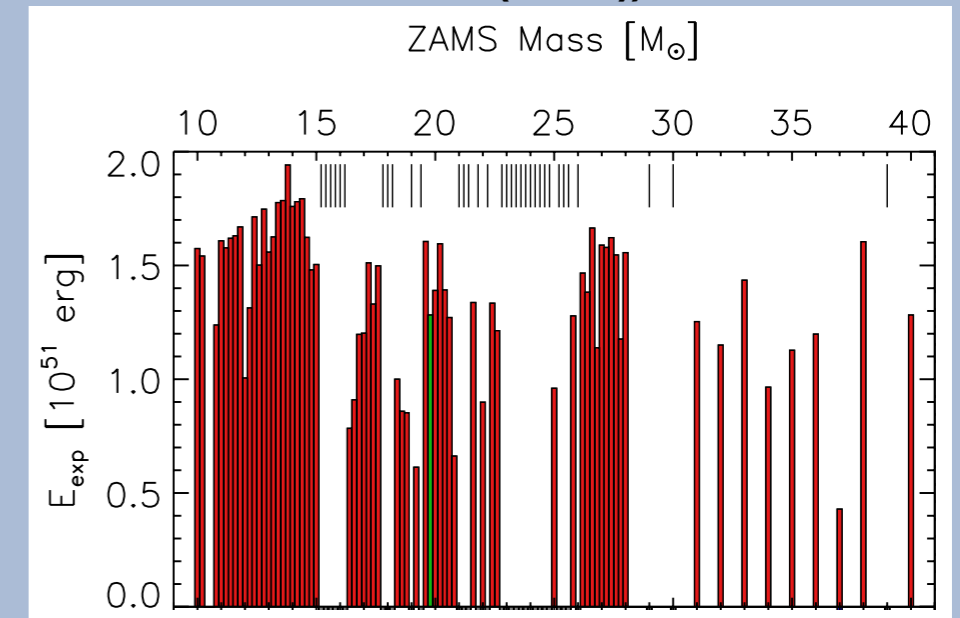
**378 models**



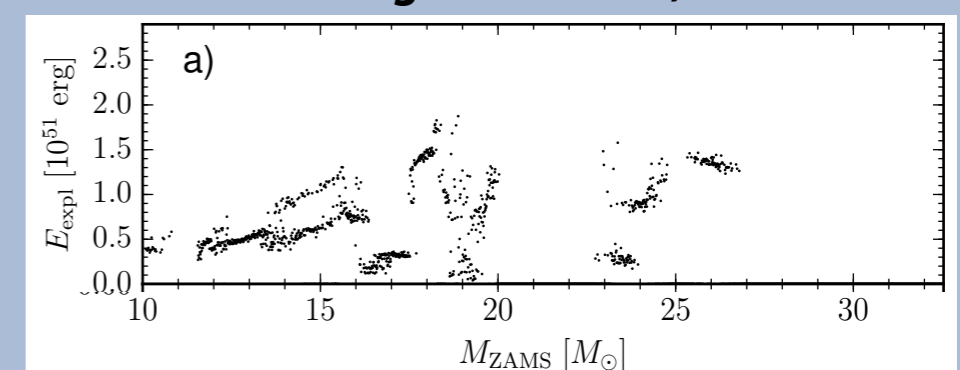**Summa+ 2016, 18 models**

## 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)**

**Sukhbold & Woosley (2014)**
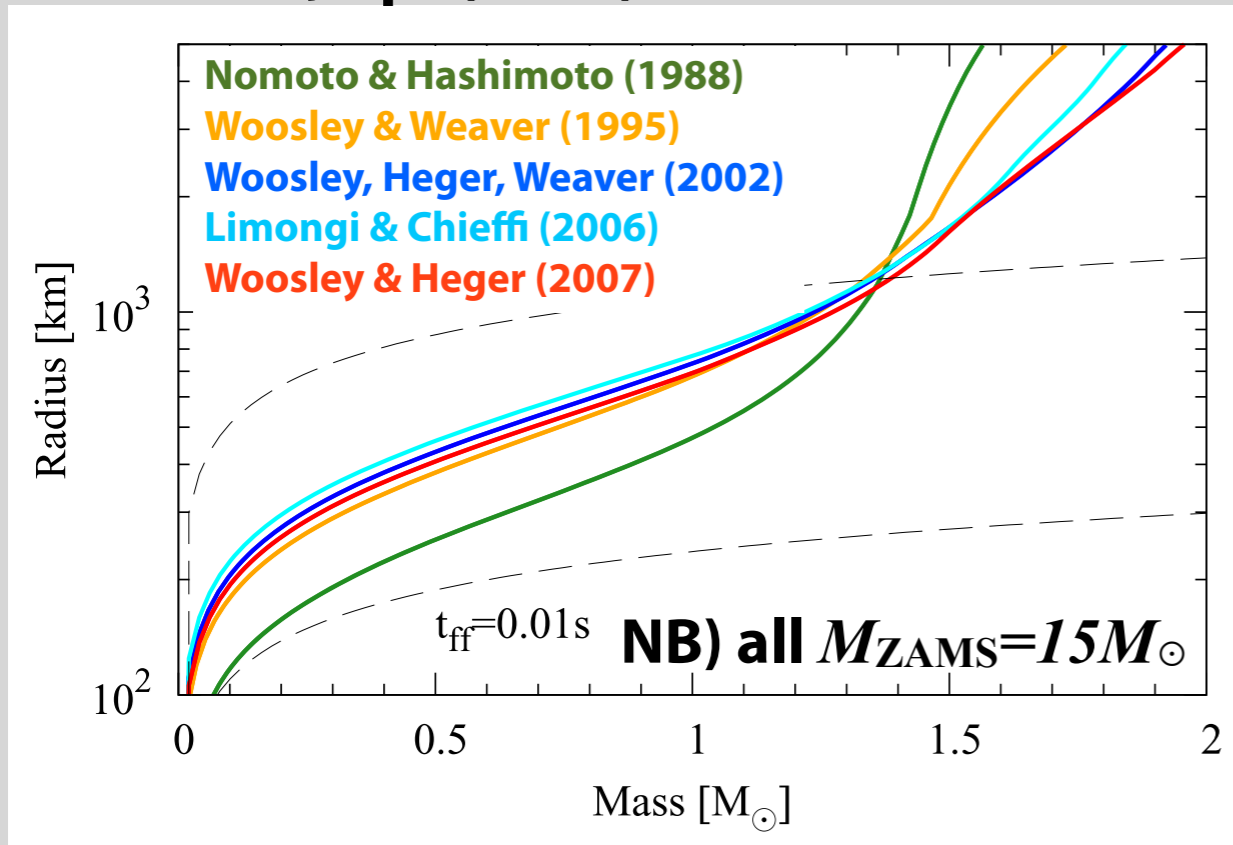


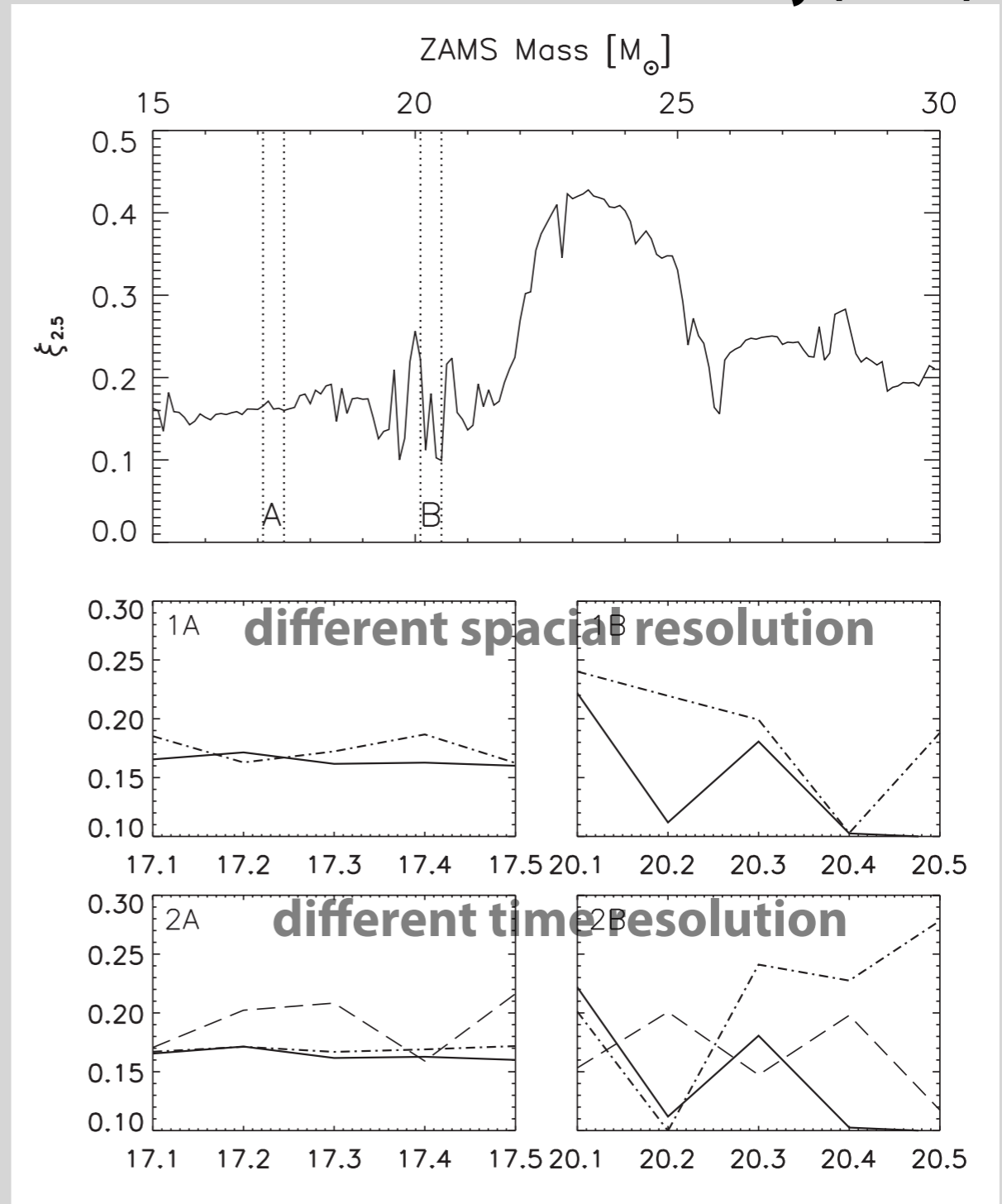**Different codes lead to different structure**

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

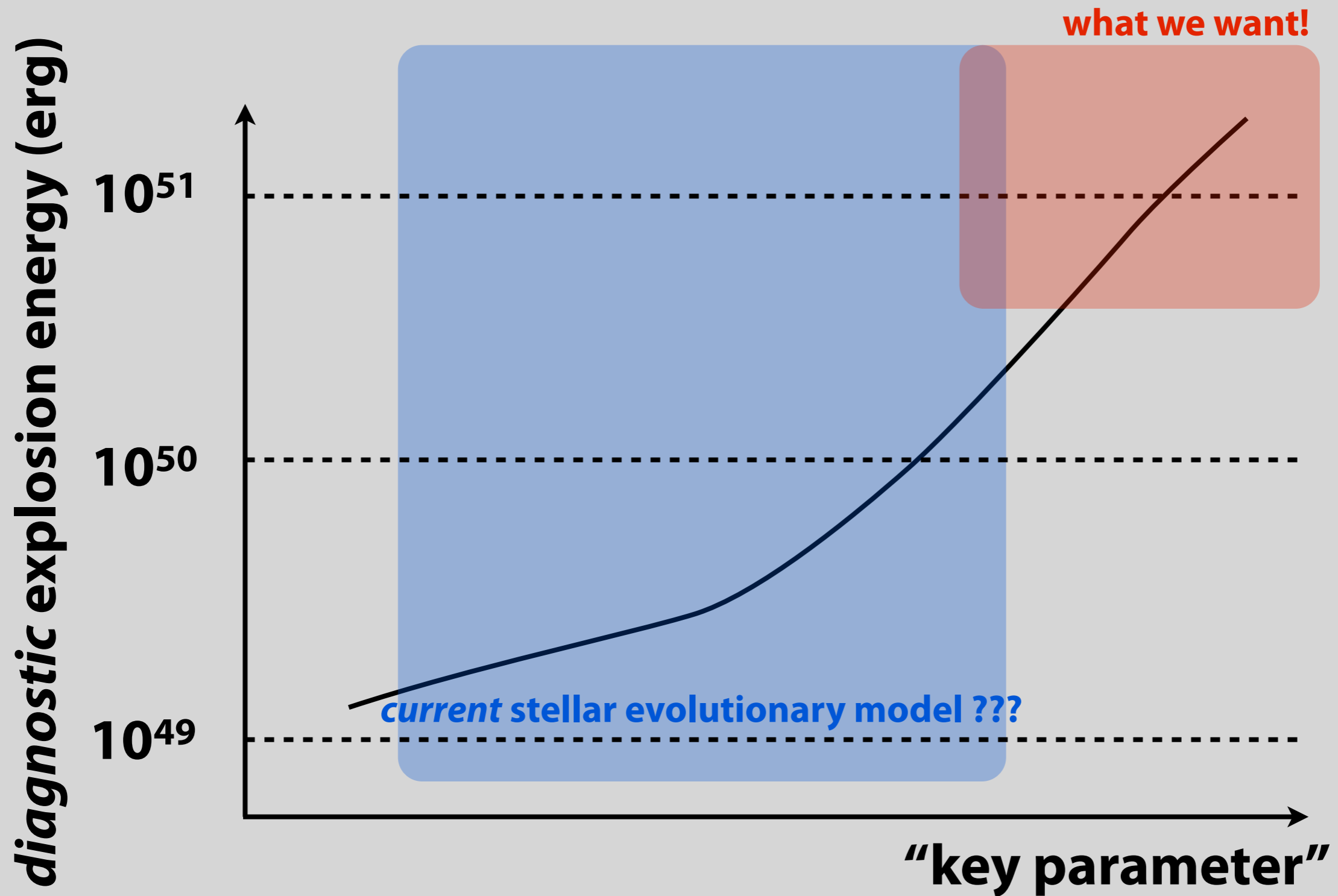$$\xi_M = \frac{M/M_\odot}{r_M/1000\,\mathrm{km}}$$

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

# *A possibility*



what we want!

diagnostic explosion energy (erg)

$10^{51}$

$10^{50}$

$10^{49}$

*current* stellar evolutionary model ???

"key parameter"

# *Problem reduction*

**traditional approach**

**supernova explosion**

s11.2-R0.0-3D                110ms

Takiwaki+ 2016

http://2sn.org/stellarevolution/explain.gif
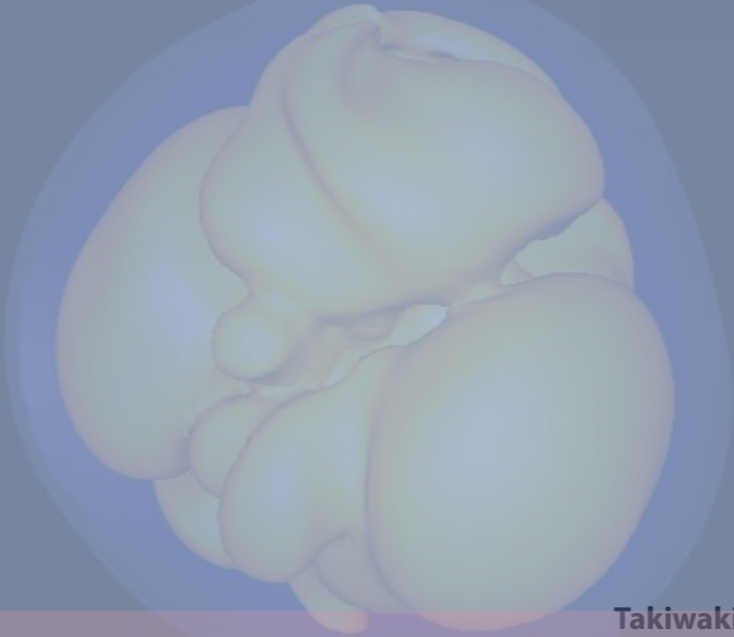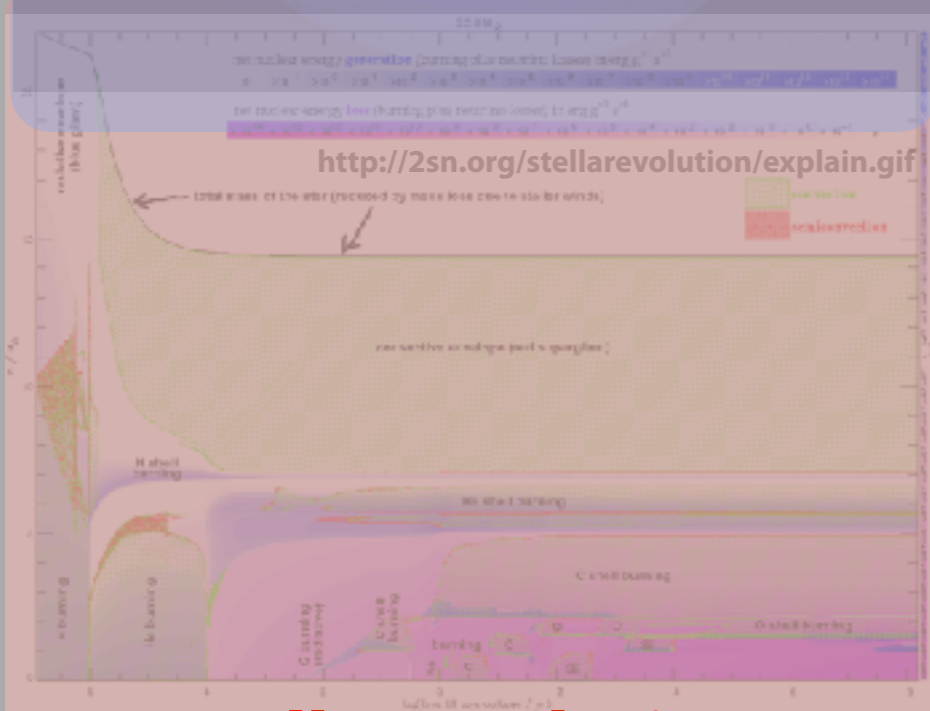
**time**

**stellar evolution**

**new approach**

**supernova explosion**

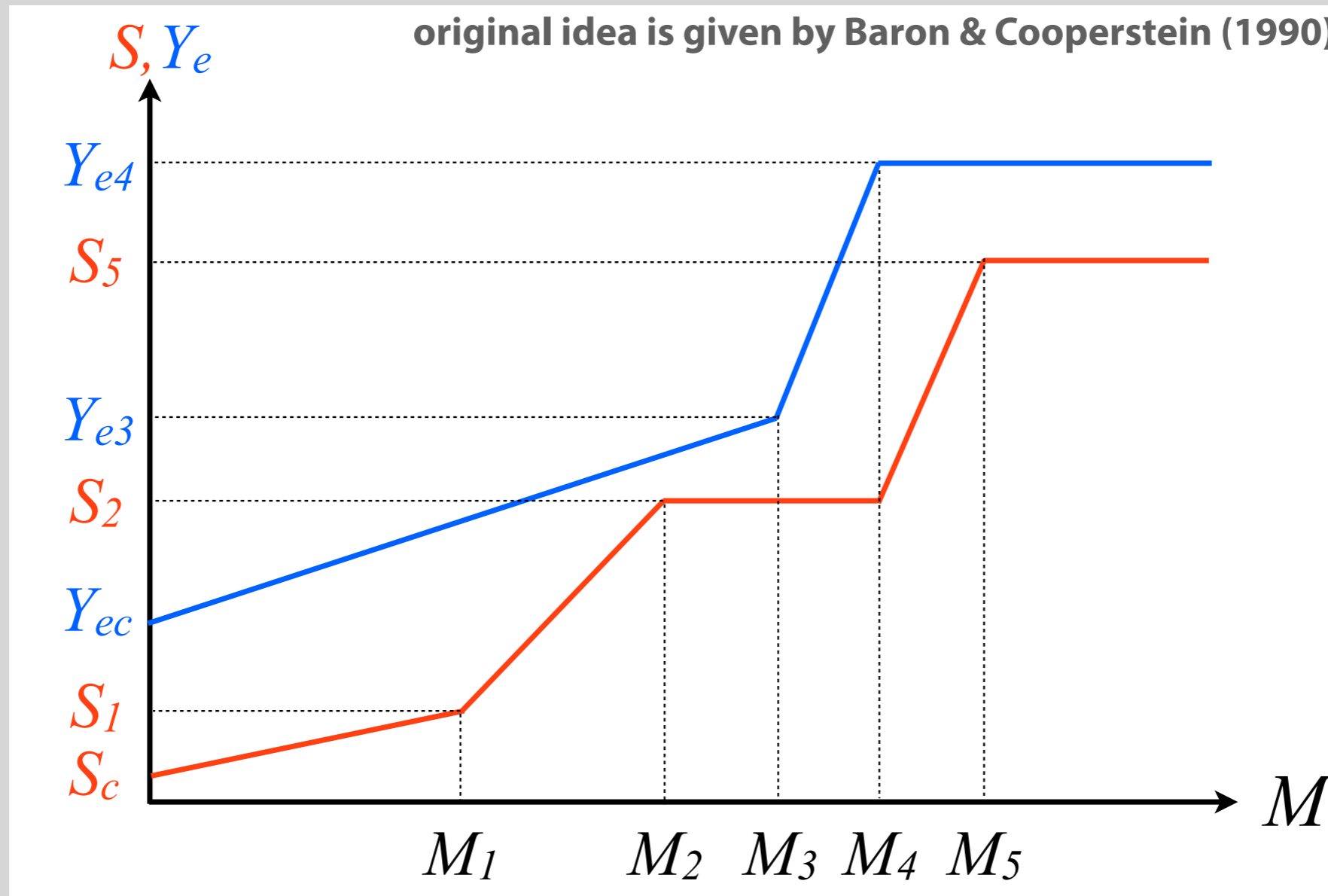**Q1.** *what is the better initial condition for explosion?*

**stellar structure**

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

**stellar evolution**

# *Parametric initial conditions*

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

original idea is given by **Baron & Cooperstein (1990)**

$S, Y_e$

$Y_{e4}$

$S_5$

$Y_{e3}$

$S_2$

$Y_{ec}$

$S_1$

$S_c$

$M$

$M_1$   $M_2$   $M_3$   $M_4$   $M_5$

$M_1$: 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

**see also next talk**

# *Parametric initial conditions*

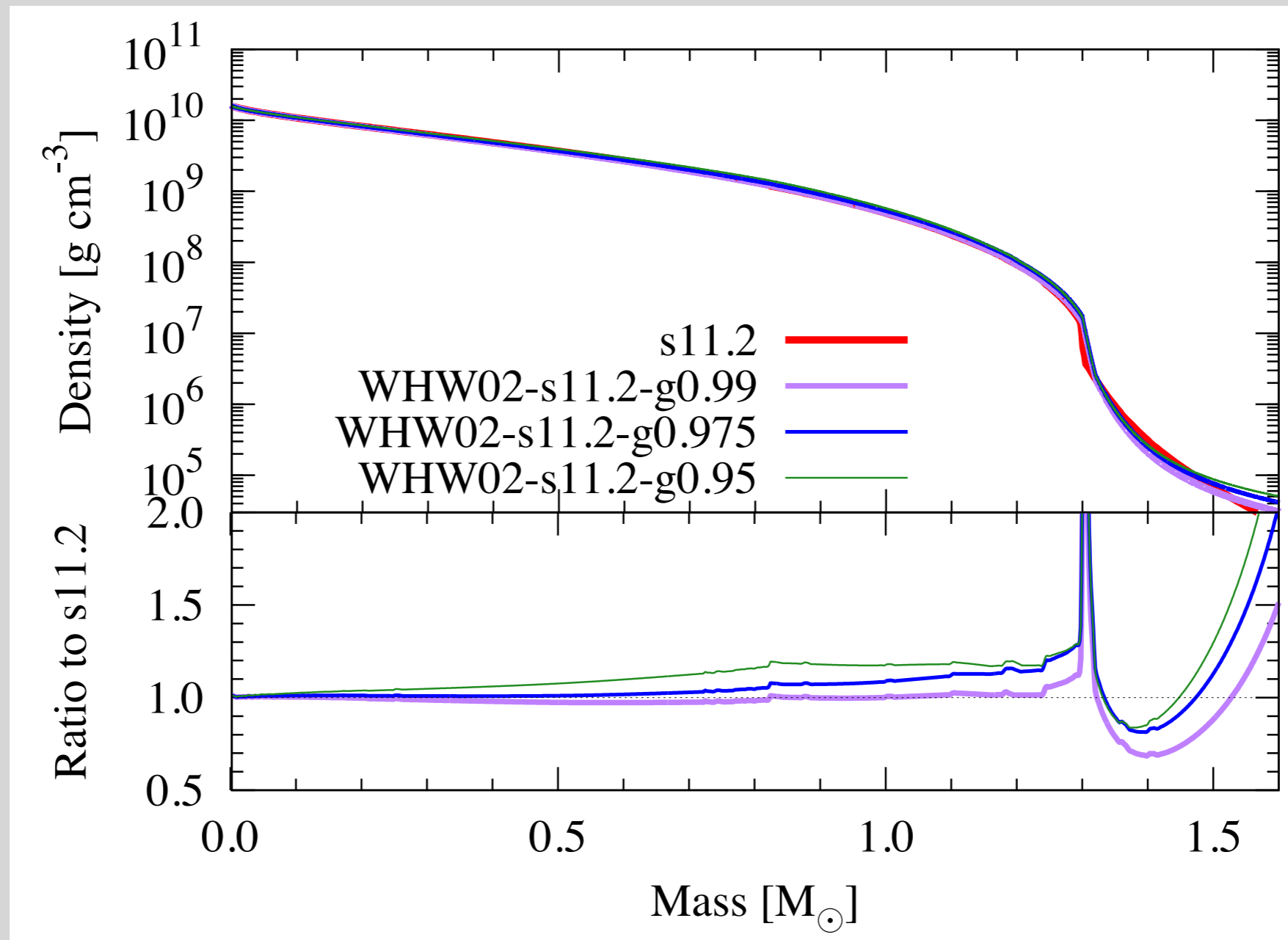**[Suwa & E. Müller, MNRAS, 460, 2664 (2016)]**

$$s(M_r) \qquad Y_e(M_r)$$

$$P(\rho, s, Y_e)$$

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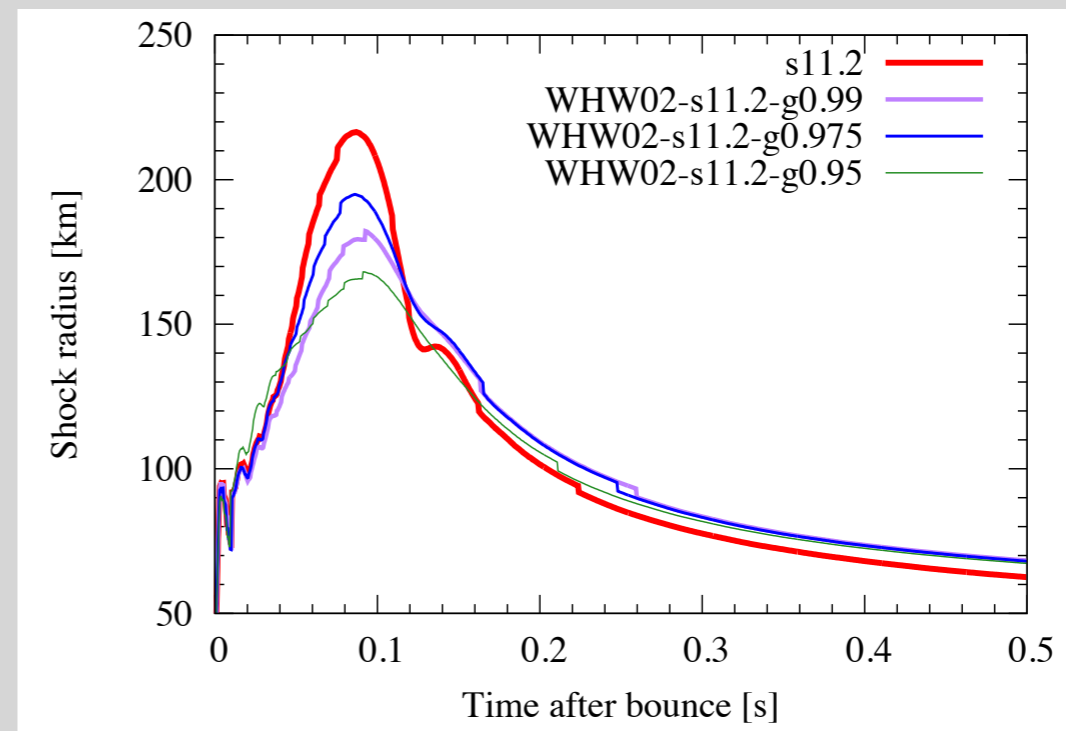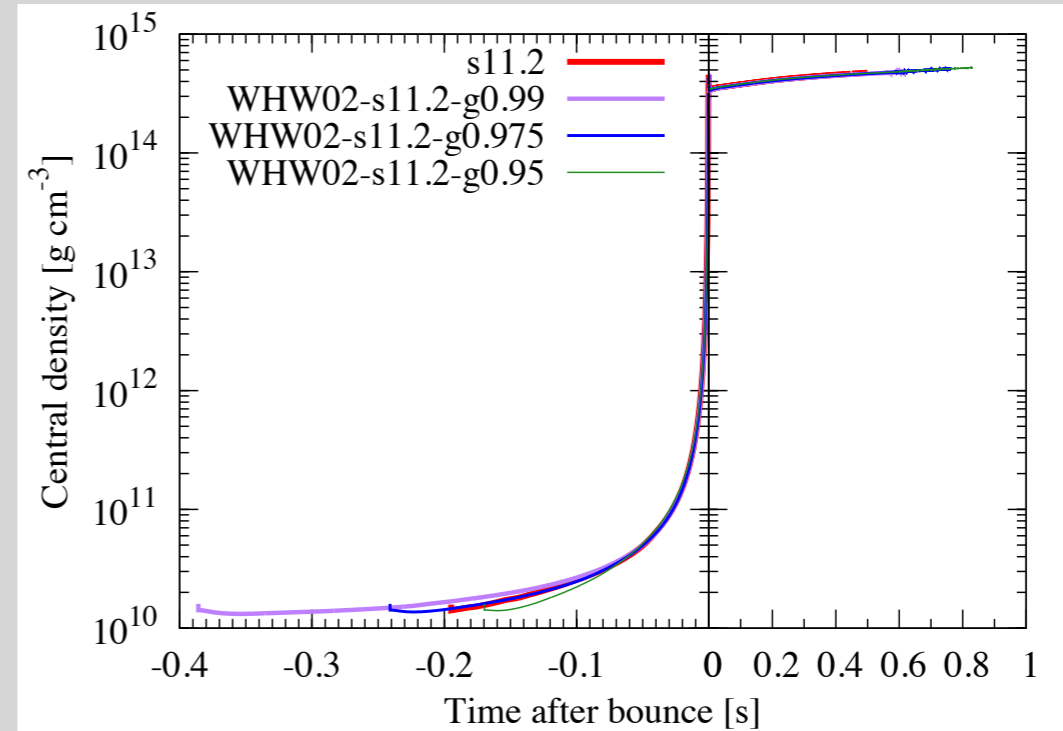
**+**

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

# 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**
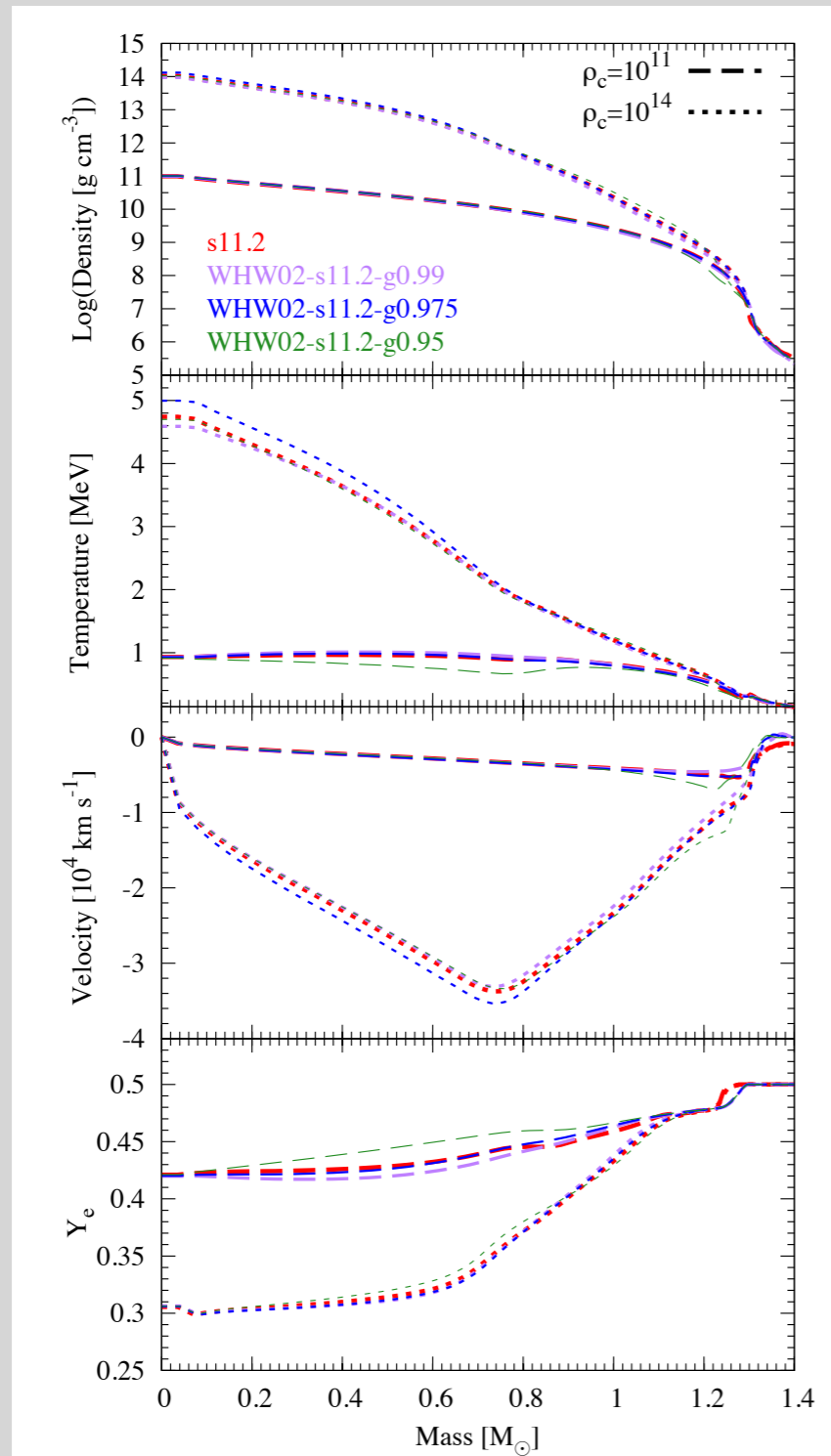
# Parameter regime beyond evolution models

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

| Model | $S_c$ | $S_1$ | $S_2$ | $S_5$ | $Y_{ec}$ | $Y_{e3}$ | $\rho_c$ |
|-------|-------|-------|-------|-------|----------|----------|----------|
|       |       | $[k_B/\mathrm{baryon}]$ | | | | | $[10^{10}\,\mathrm{g\,cm}^{-3}]$ |
| 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)]**
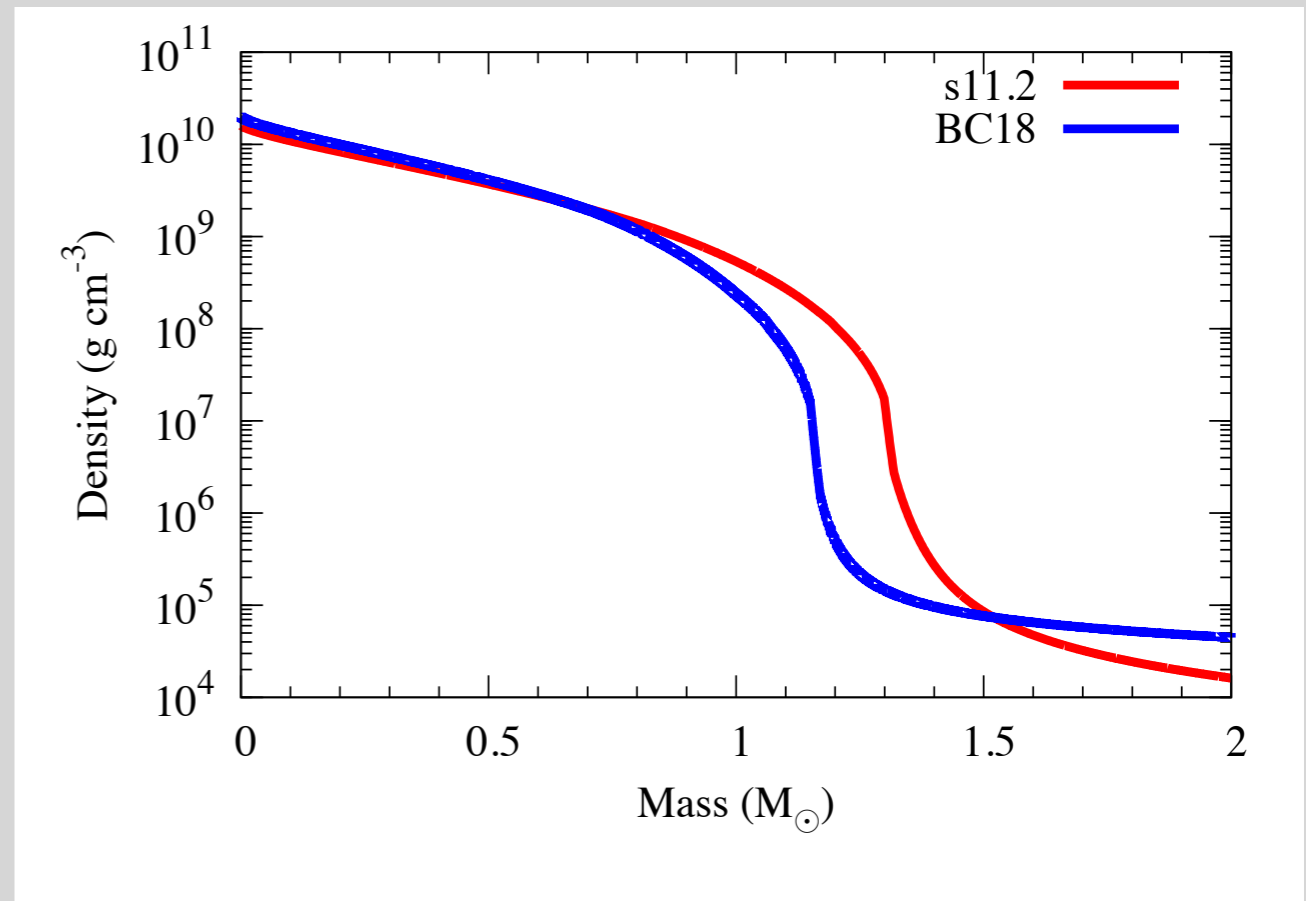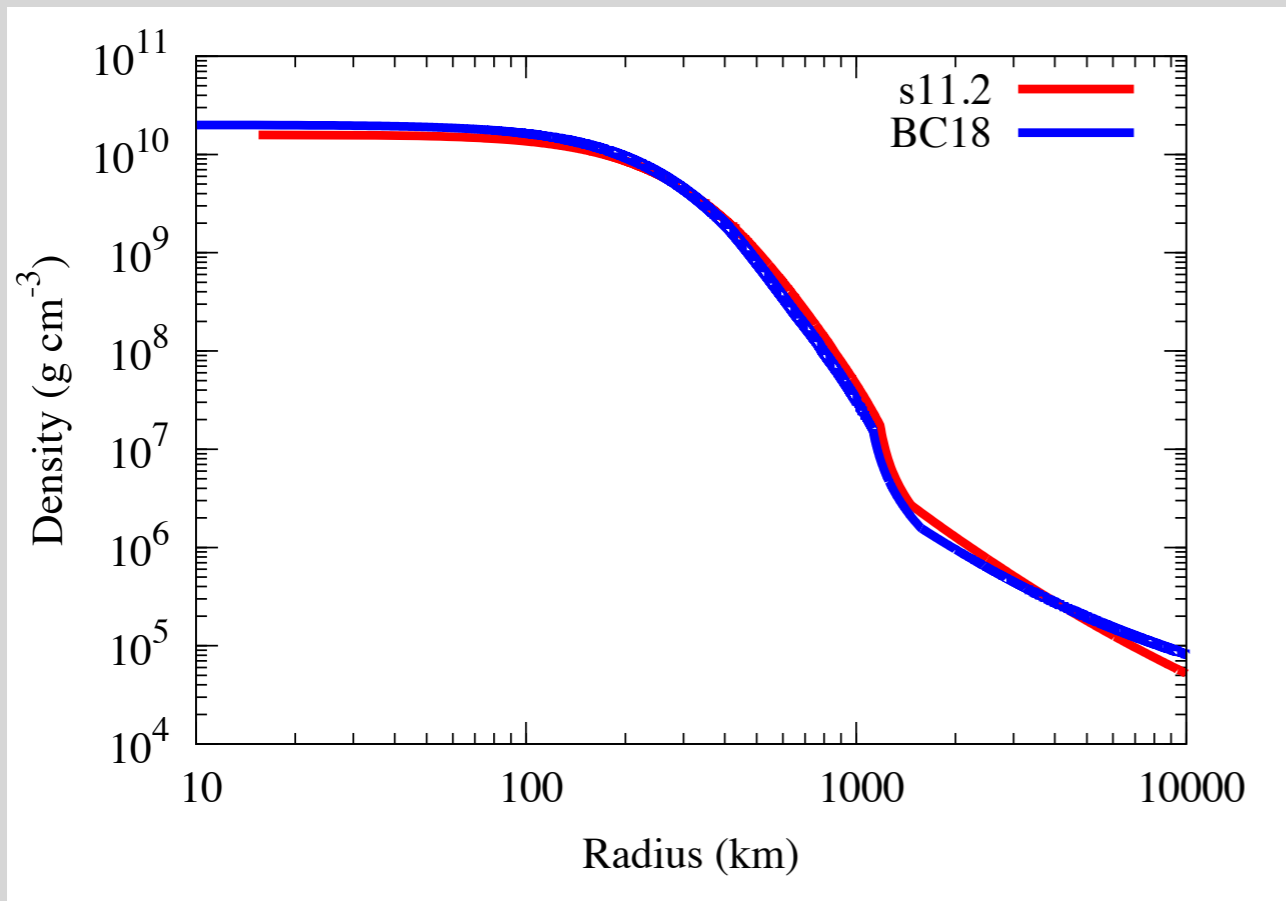
# *Explosions in 1D*

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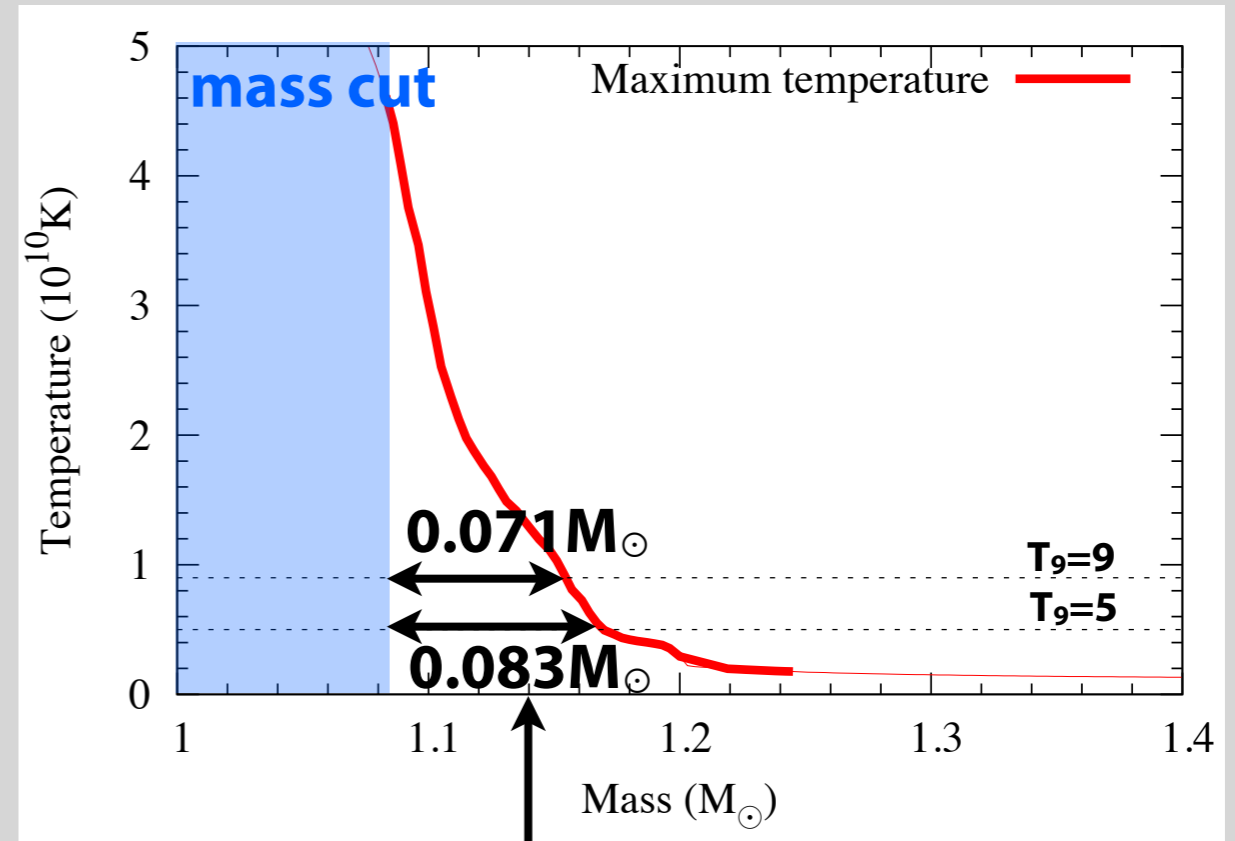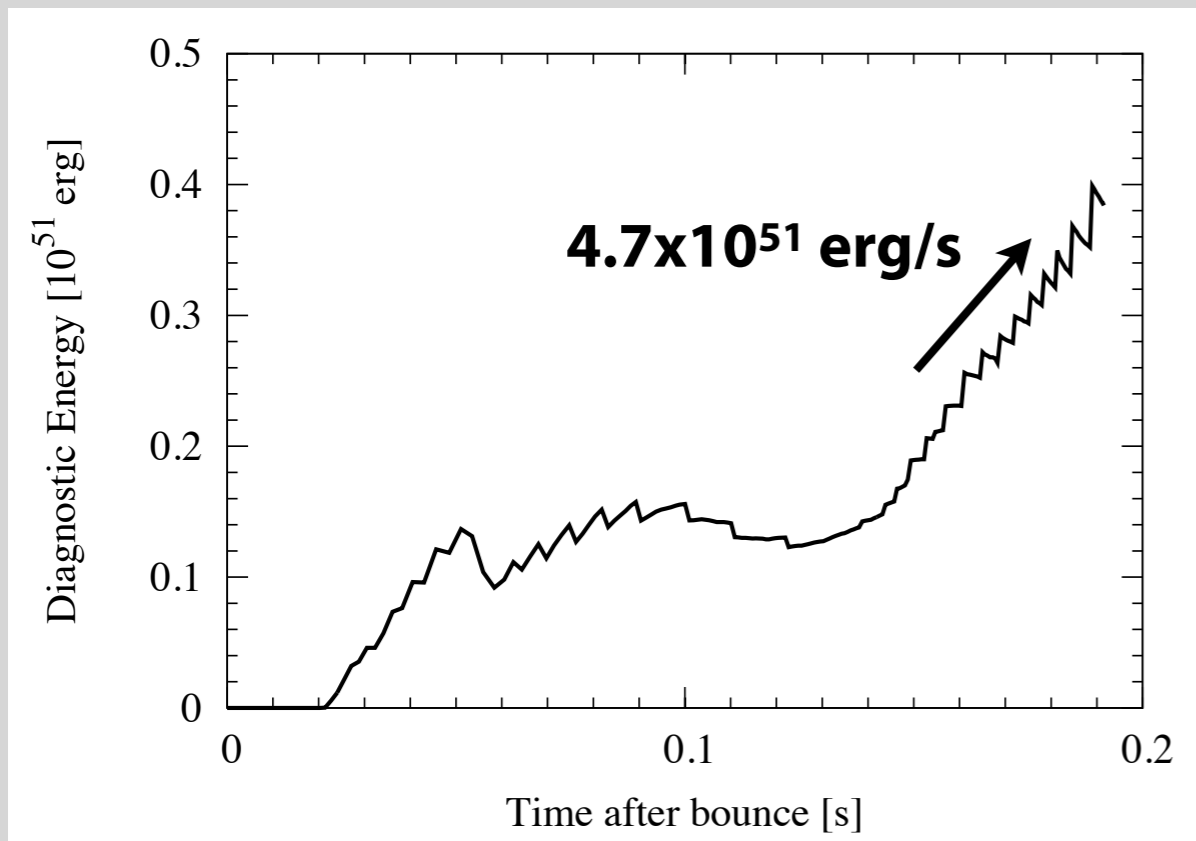
# *Summary*

*Question:*

**How can we produce strong ($E_{exp} \sim 10^{51}$ 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?**