超新星の第一原理シミュレーションで十分な量のニッケルは生成可能か

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First principle simulations

Key observables characterizing supernovae

* **Explosion energy:** $\sim 10^{51}$ **erg**
* **Ni mass:** $\sim 0.1 M_\odot$
* **Ejecta mass:** $\sim M_\odot$
* **NS mass:** $\sim 1 - 2\ M_\odot$

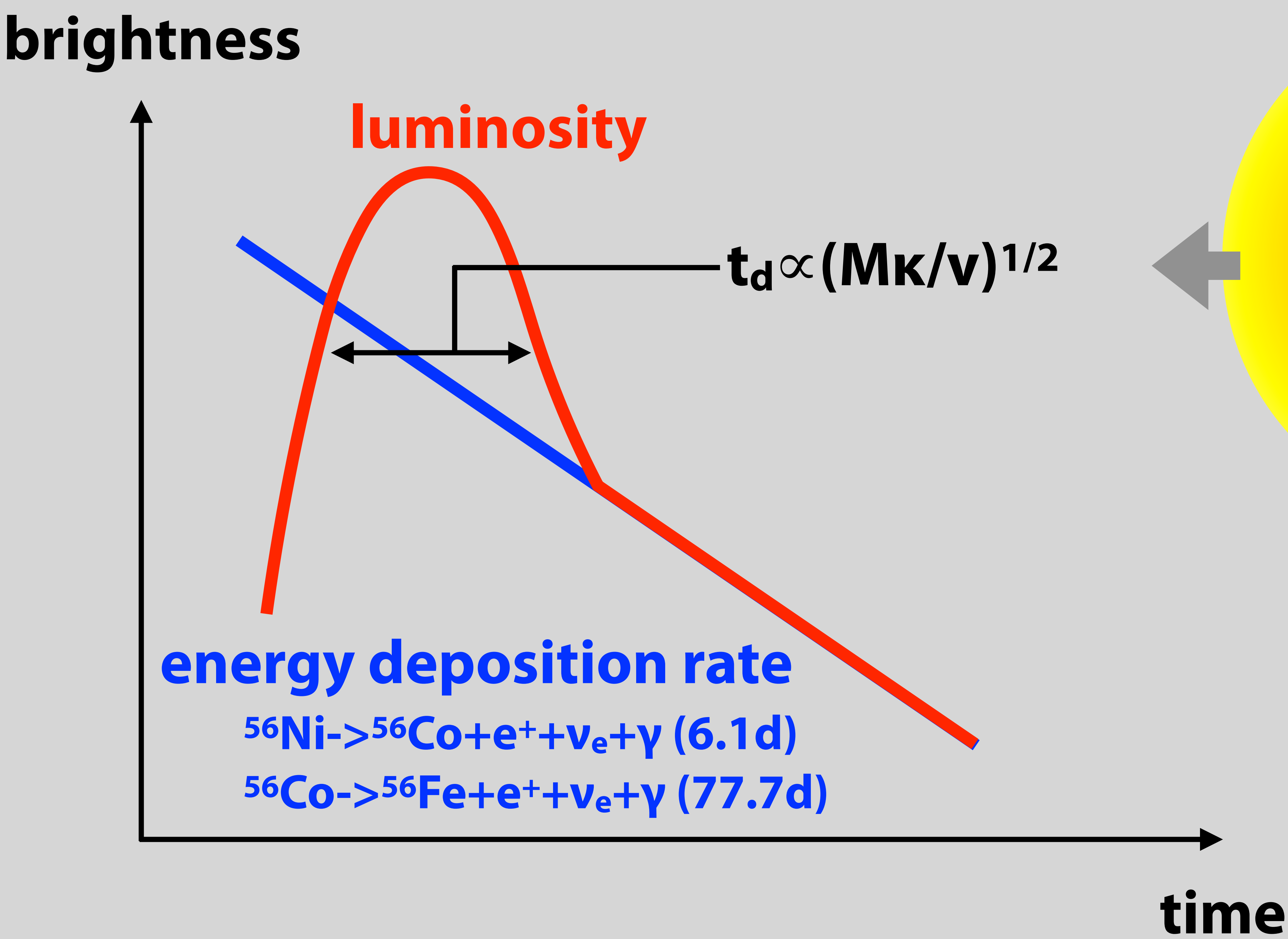
related

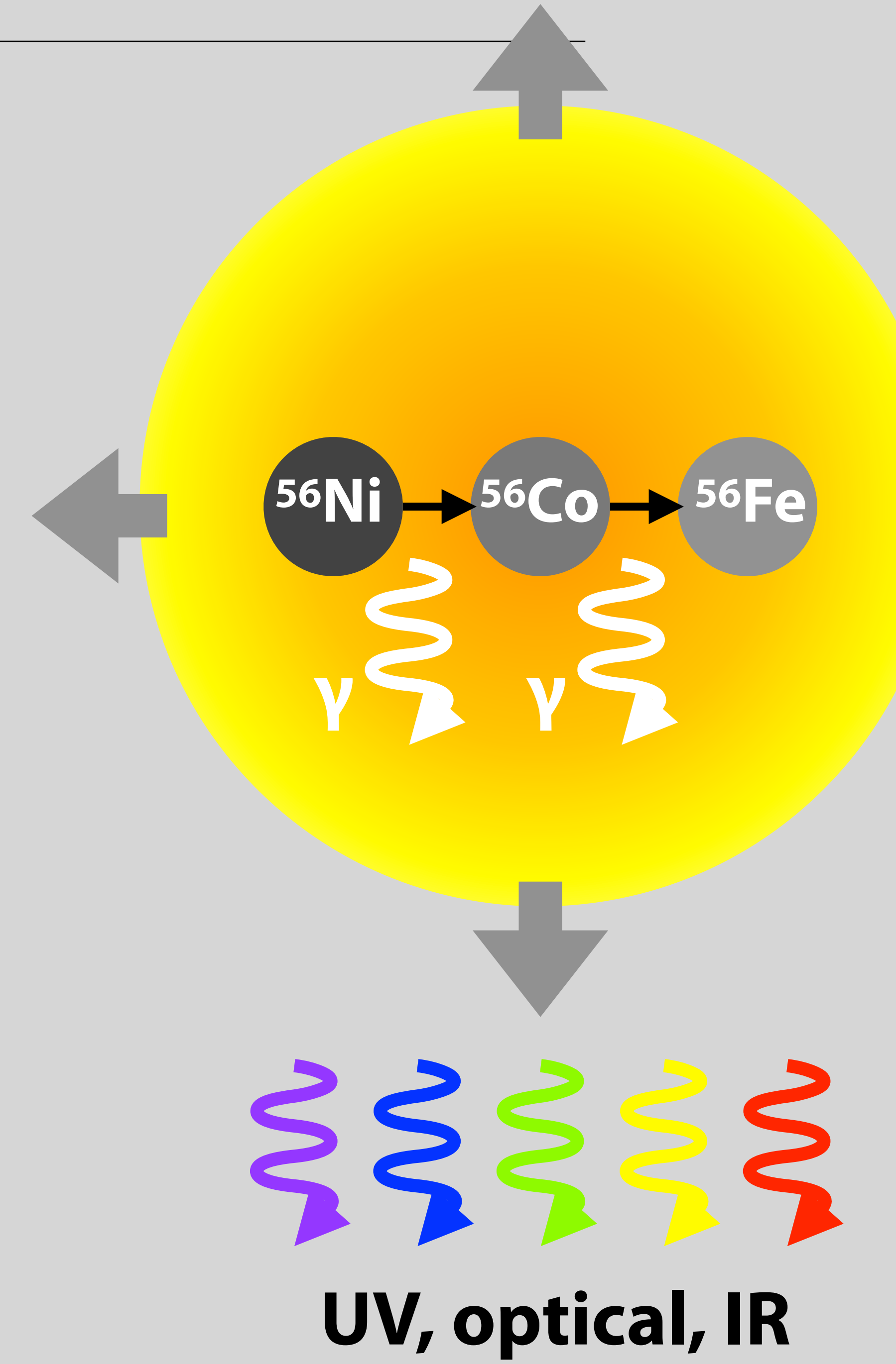
measured by fitting SN light curves

measured by binary systems

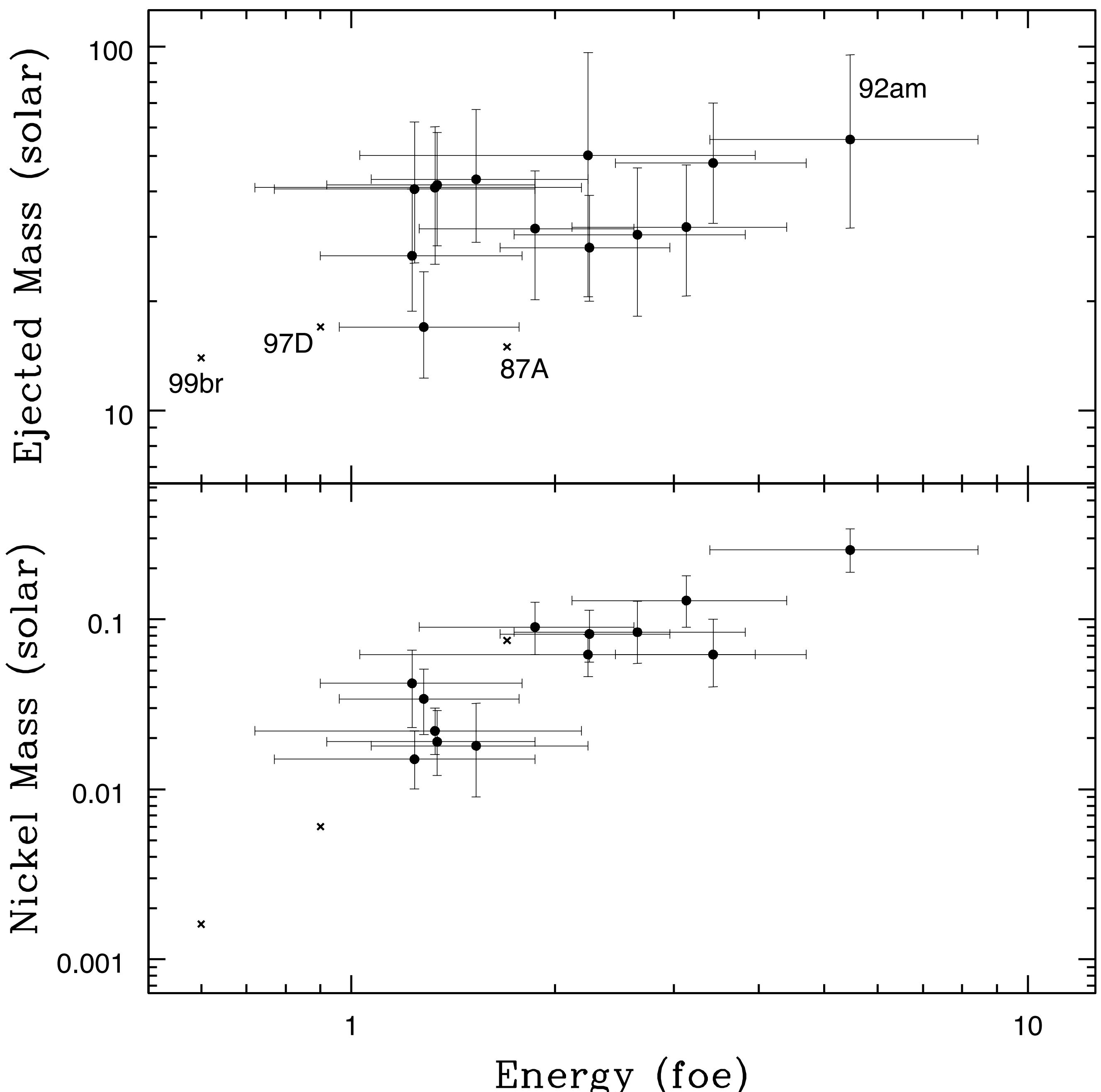
final goal of first-principle (*ab initio*) simulations

SN light curve





Explosion energy and Ni amount

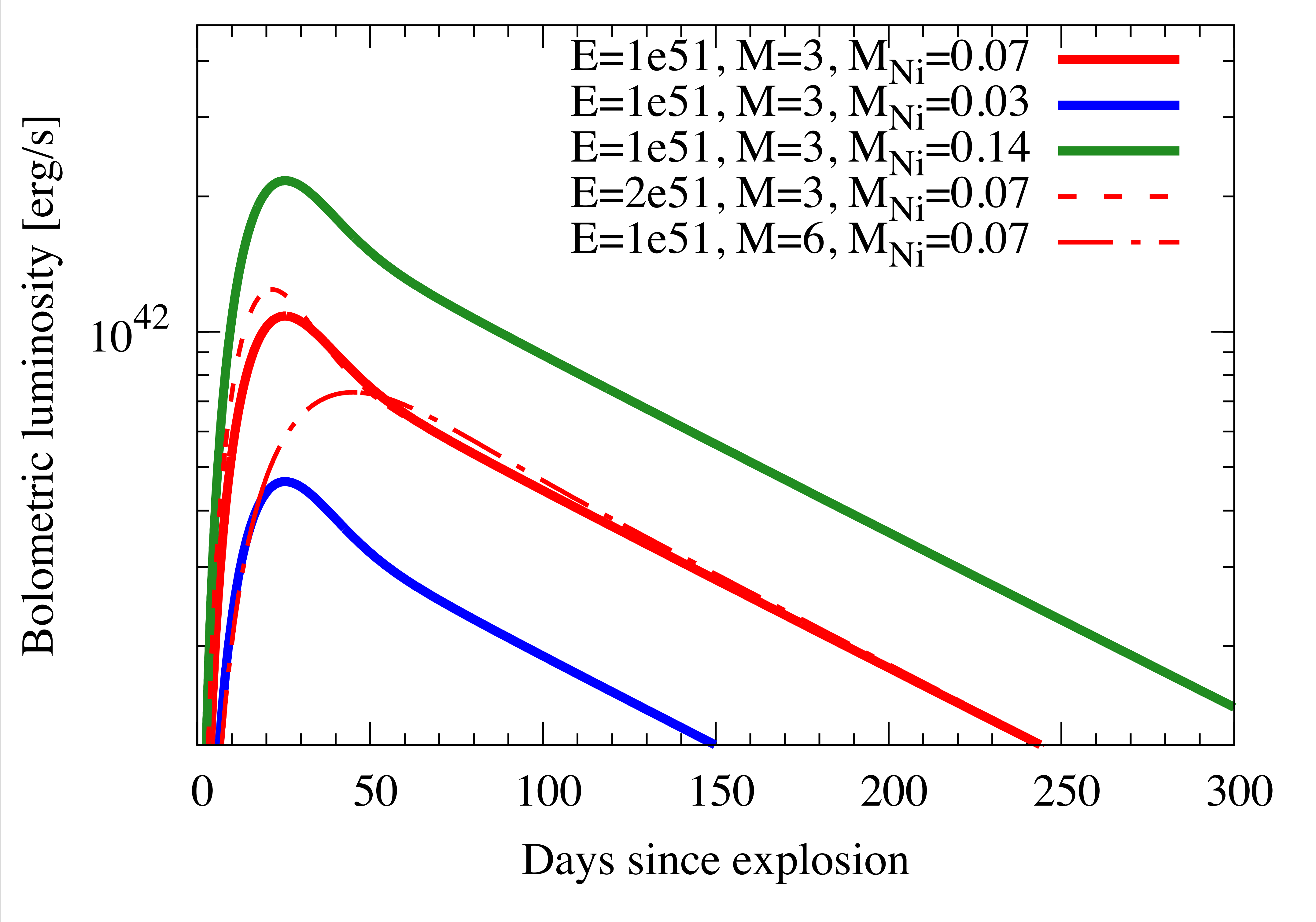


Hamuy 03

Ni mass has a *smaller error* than expl. energy

foe=fifty-one-erg, 10^{51} erg

Light curves and parameter dependences



One-zone model based on Arnett (1982)

^{56}Ni production

- $M(^{56}Ni)=O(0.01)M_\odot$
- **T>5x10^9 K is necessary for ^{56}Ni production**

Woosley+ 02

  - $E=(4\pi/3)r^3 aT^4$ ➡ $T(r_{sh})=1.33\times10^{10}(E/10^{51}erg)^{1/4}(r_{sh}/1000km)^{-3/4}$ K
  - With $E=10^{51}$erg, r_{sh}<3700km for $T>5\times10^9$K (Woosley+ 2002)
- **^{56}Ni amount is more difficult to explain than explosion energy**
  - Explosion energy can be topped up late after the onset of explosion (~O(1)s)
  - ^{56}Ni should be synthesized just after the onset of the explosion (before shock passes O(1000)km, i.e. O(0.1) s)
- **It would be a benchmark test for explosion simulations**

Numerical simulation

1D Lagrangian simulation w/ heating and cooling terms by ν

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho},$$
$$\frac{Dv}{Dt} = -\frac{Gm}{r^2} - 4\pi r^2 \frac{\partial P}{\partial m},$$
$$\frac{D\epsilon}{Dt} = -P\frac{D}{Dt}\left(\frac{1}{\rho}\right) + \mathcal{H} - \mathcal{C}.$$

$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\mathrm{erg\,s^{-1}}}\right)\left(\frac{r}{100\mathrm{km}}\right)^{-2}\left(\frac{T_{\nu_e}}{4\mathrm{MeV}}\right)^2,$$

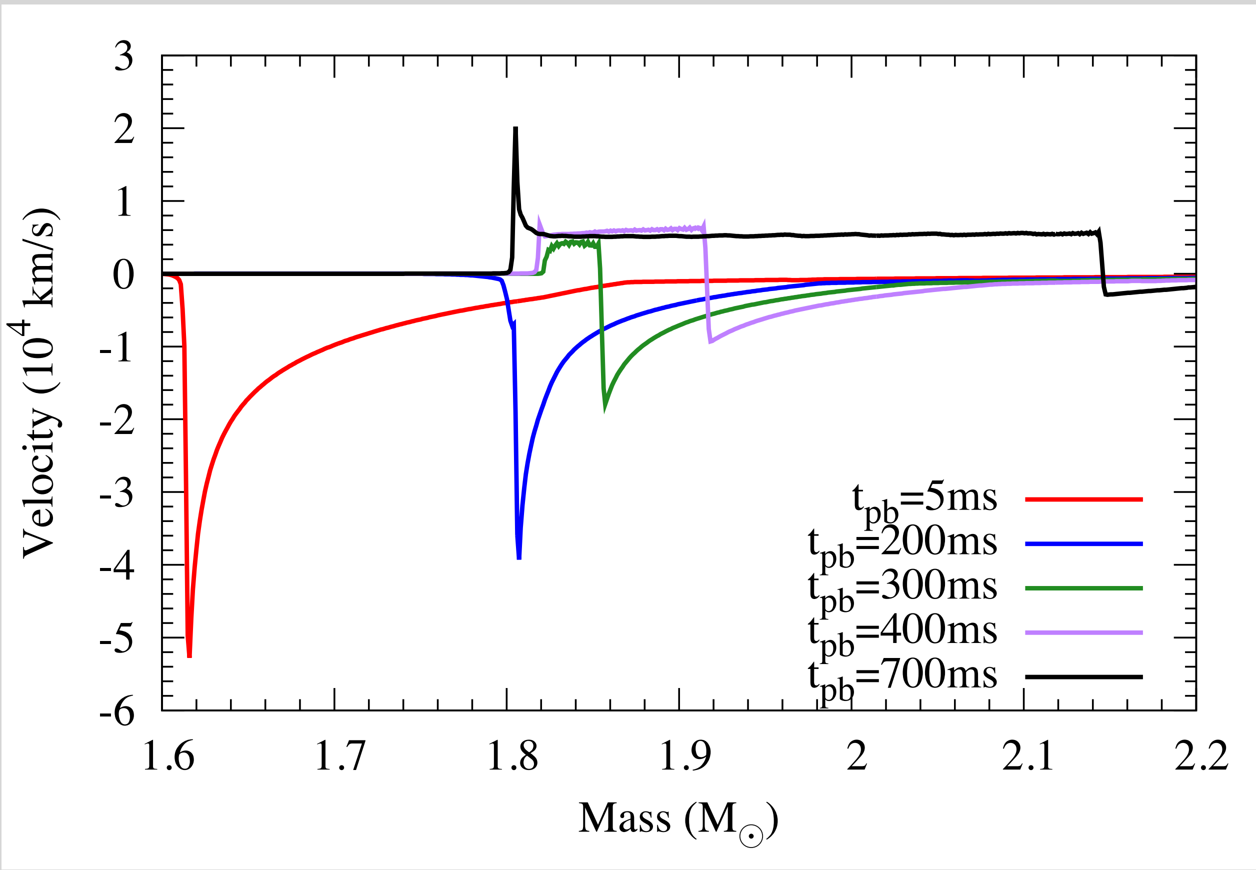
$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\mathrm{MeV}}\right)^6.$$

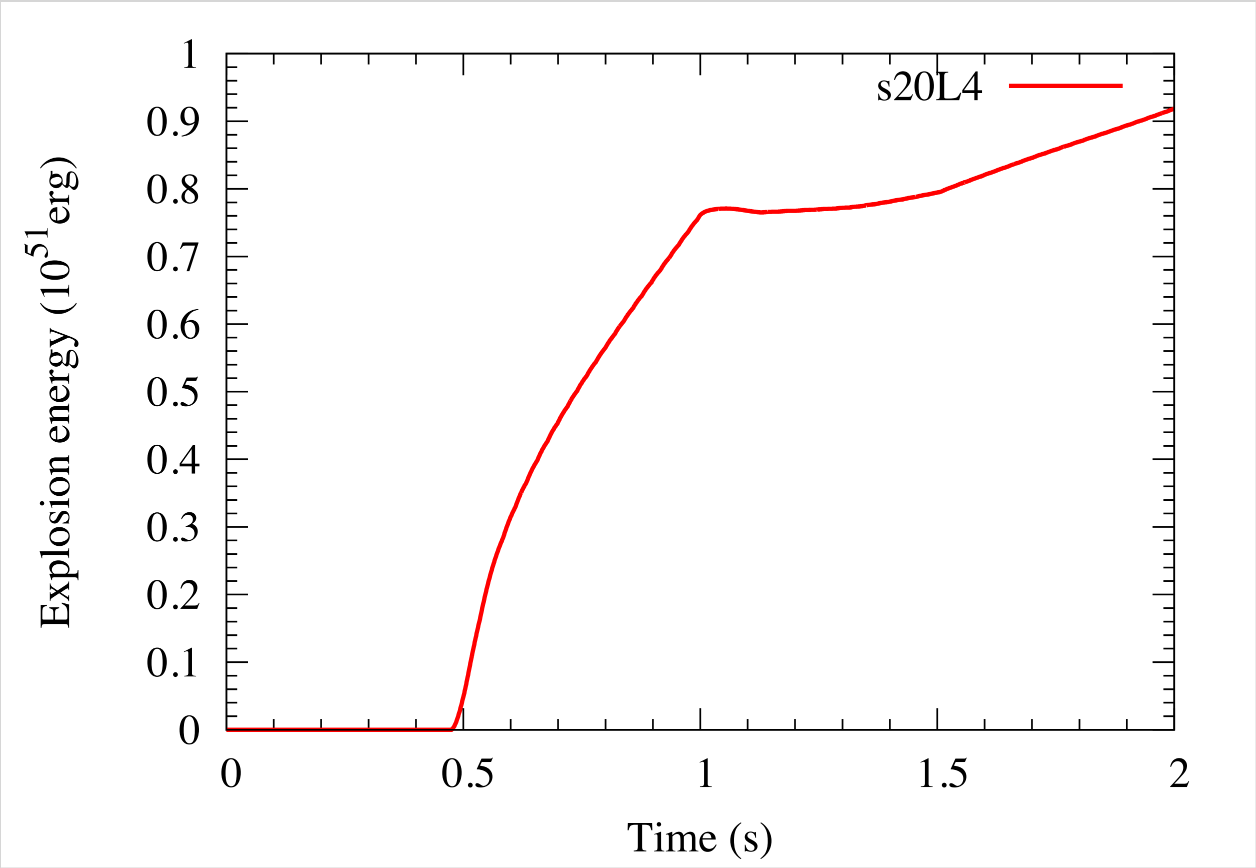
Light-bulb approx.

EOS: Helmholtz EOS (Timmes & Arnett 1999)
Progenitor: M_{ZAMS}=12$M_\odot$, 15$M_\odot$, 20$M_\odot$, 25$M_\odot$ by Woosley & Heger (2007)
R_{in}=50km (fixed)
M_{cut}=1.3 (12), 1.6 (15, 20), 1.7 (25) $M_\odot$
(determined by inner edge of Si/O layer, which has density jump)
$L_{\nu e}$=[1,4]x10^{52} erg/s
$T_{\nu e}$=4MeV (fixed)

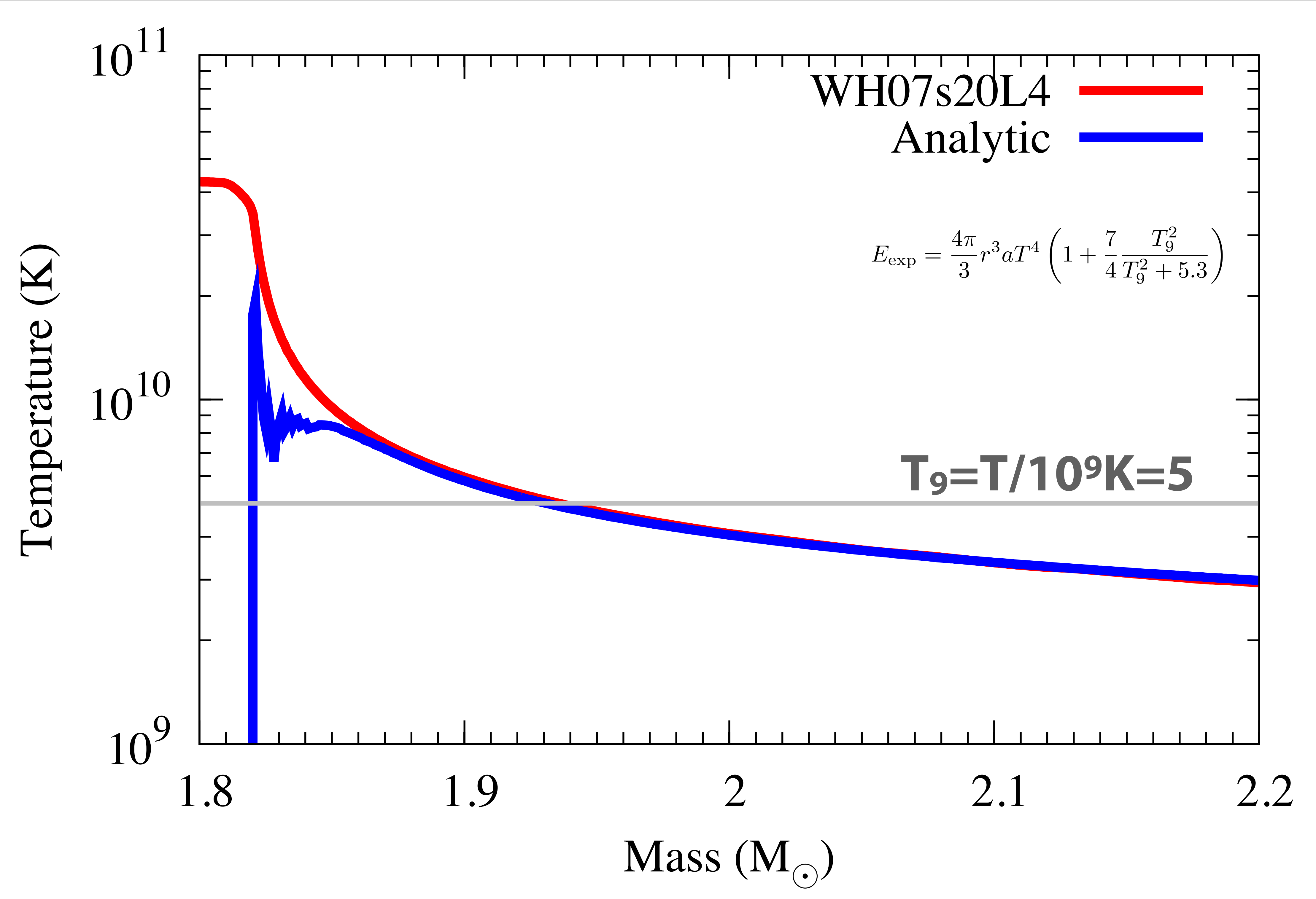
Numerical results

20M☉, $L_{\nu e}$=4x10^{52} erg/s





Maximum temperature



Analytic model

shock velocity (Matzner & McKee 1999)

$$v_s = 0.794 \left(\frac{E_{\rm exp}}{M_{\rm ej}}\right)^{1/2} \left(\frac{M_{\rm ej}}{\rho(r_s) r_s^3}\right)^{0.19}$$

$$M_{\rm ej}(t, r_s) = \dot{M} t + \int_{r_{\rm mc}}^{r_s} 4\pi r^2 \rho(r) dr \qquad E_{\rm exp} = Lt$$

Density structure in pre-shock regime (Shu 1977, Suto & Silk 1988)

$$\rho(r) = \rho_R \left(\frac{r}{R}\right)^{-3/2}$$

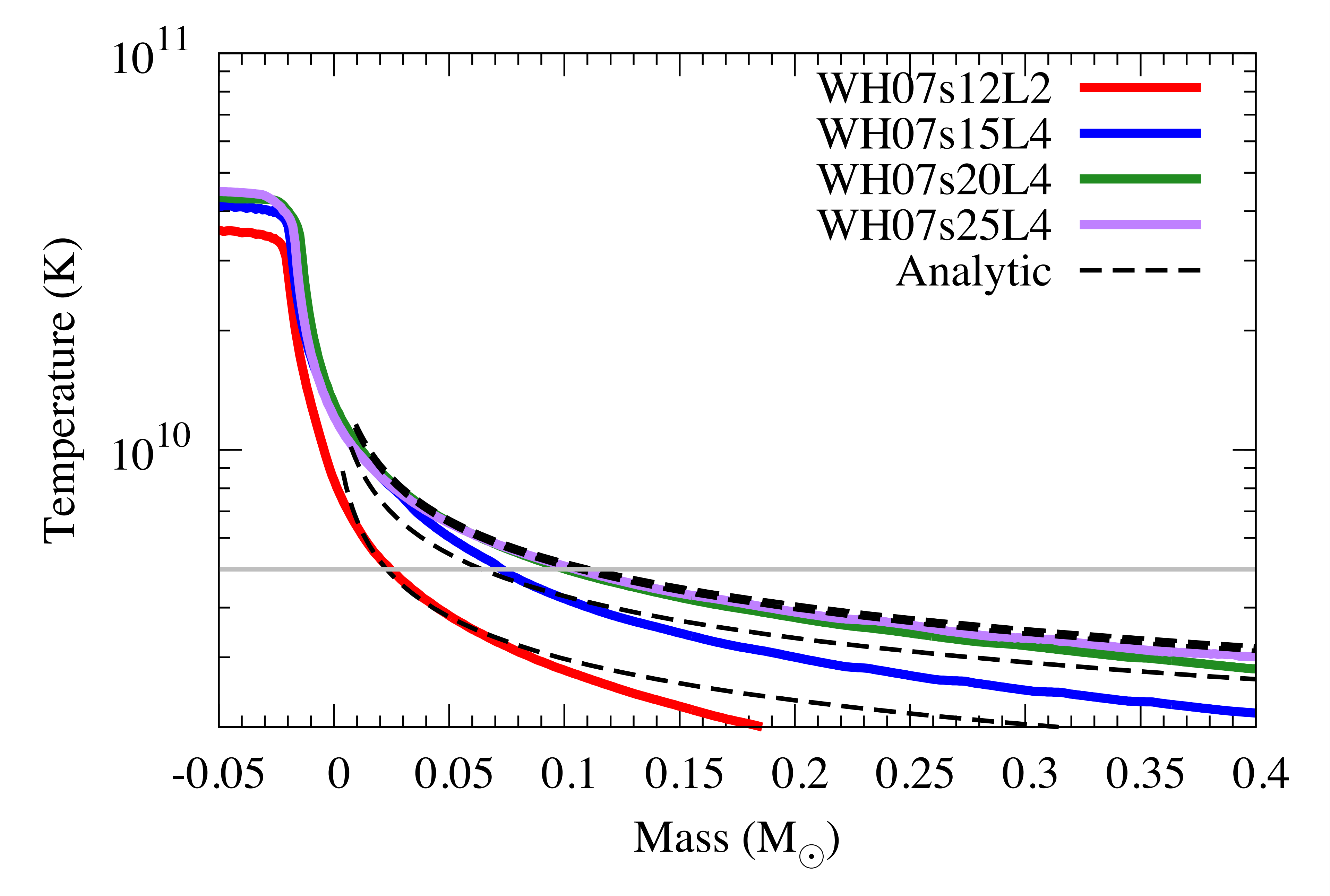
ρ_R and R are determined by progenitor structure

Temperature evolution

$$\frac{4\pi}{3} r_s^3 a T^4 = E_{\rm int} + Lt$$

$E_{\rm int}$ is initial internal energy, which is given by pressure balance at shock launch

Comparison



Model	$M_{s=4}$ ($M_\odot$)	$R_{M_{s=4}}$ (1000 km)	$\rho_{M_{s=4}}$ (10^7 g cm^{-3})	$M_{s=4}+0.1M_\odot$ ($M_\odot$)	$R_{M_{s=4}+0.1M_\odot}$ (1000 km)	$\rho_{M_{s=4}+0.1M_\odot}$ (10^7 g cm^{-3})
s12	1.530	2.813	0.168	1.630	4.655	0.035
s15	1.818	3.770	0.129	1.918	4.924	0.051
s20	1.824	2.654	0.268	1.924	3.646	0.133
s25	1.901	2.803	0.317	2.001	3.771	0.131

Ni amount and growth rate

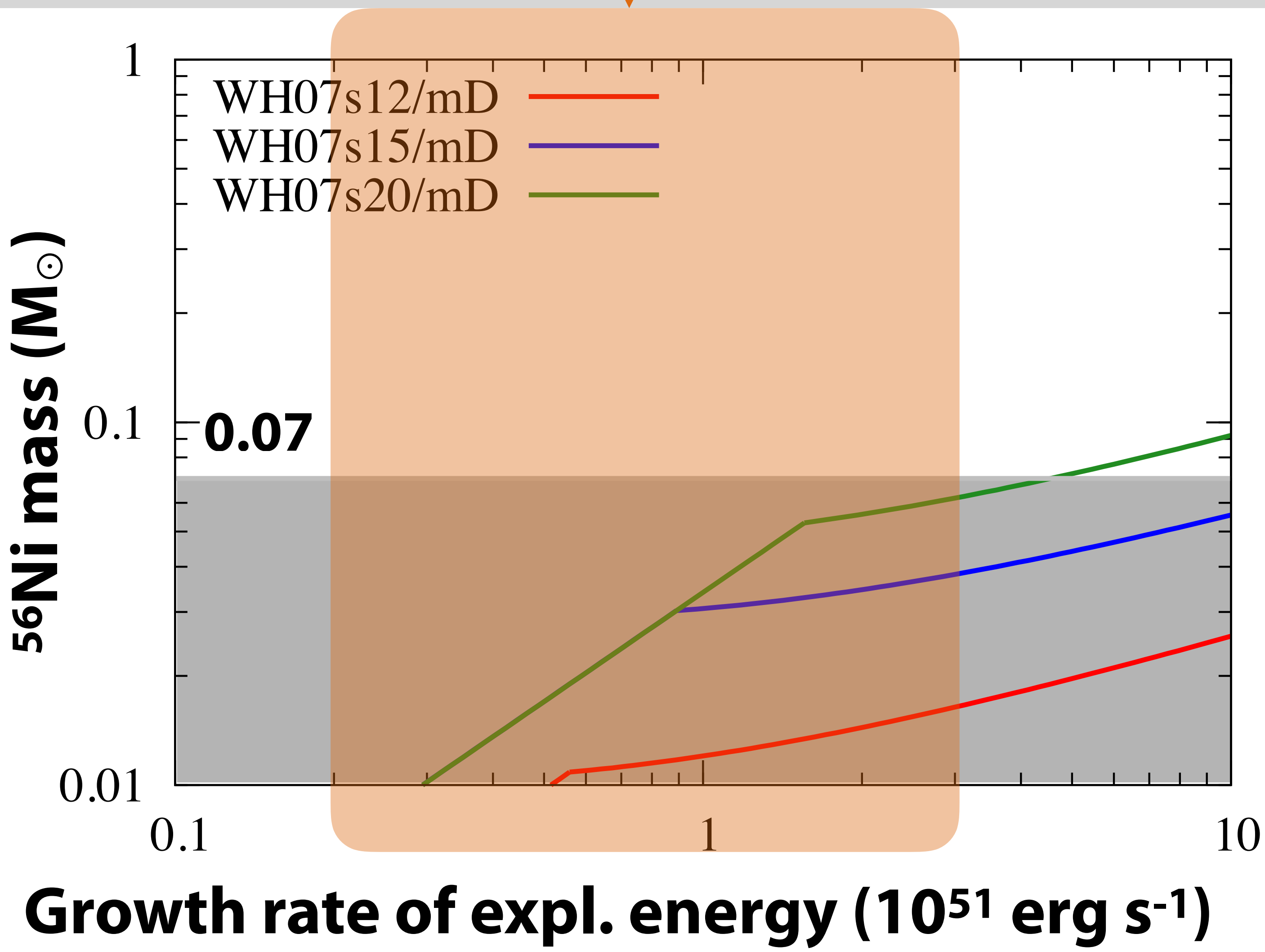


Table 1. Properties of recent explosion simulations

Author(s)	ZAMS mass [a] ($M_\odot$)	$\dot{E}_{\rm exp}$ [b] (Bethe s^{-1})
2D (axisymmetric)		
Bruenn et al. (2016)	12, 15, 20, 25	1.5 – 3
Suwa et al. (2016)	12 – 100	0.5 – 0.7
Pan et al. (2016)	11, 15, 20, 21, 27	1 – 5
O'Connor & Couch (2015)	12, 15, 20, 25	0.5 – 1
Nakamura et al. (2016)	17	0.4
Summa et al. (2016)	11.2 – 28	1
Burrows et al. (2016)	12, 15, 20, 25	1 – 3
3D		
Lentz et al. (2015)	15	0.2
Melson et al. (2015)	9.6	0.6
Müller (2015)	11.2	0.4
Takiwaki et al. (2016)	11.2, 27	0.4 – 2

^{56}Ni amount cannot be explained…

Summary

- ^{56}Ni is primary observable of SNe
- To synthesize enough amount of ^{56}Ni (~0.07$M_{\odot}$), ***rapid growth of explosion energy*** is necessary

- Based on light-bulb approx., we develop
  - Numerical simulation
  - Analytic model

- The Ni amount is unexplainable with the current standard simulations. ***What are we missing?***