^{56}Ni as probes for supernova interior

Yudai Suwa

(U. of Tokyo & YITP, Kyoto U.)

YS, Tominaga, MNRAS, 451, 282 (2015)
YS, Tominaga, Maeda, MNRAS, 483, 3607 (2019)
Sawada, YS, ApJ, 908, 6 (2021)
Sawada, Kashiyama, YS, to appear soon

Contents

* **Observational findings**

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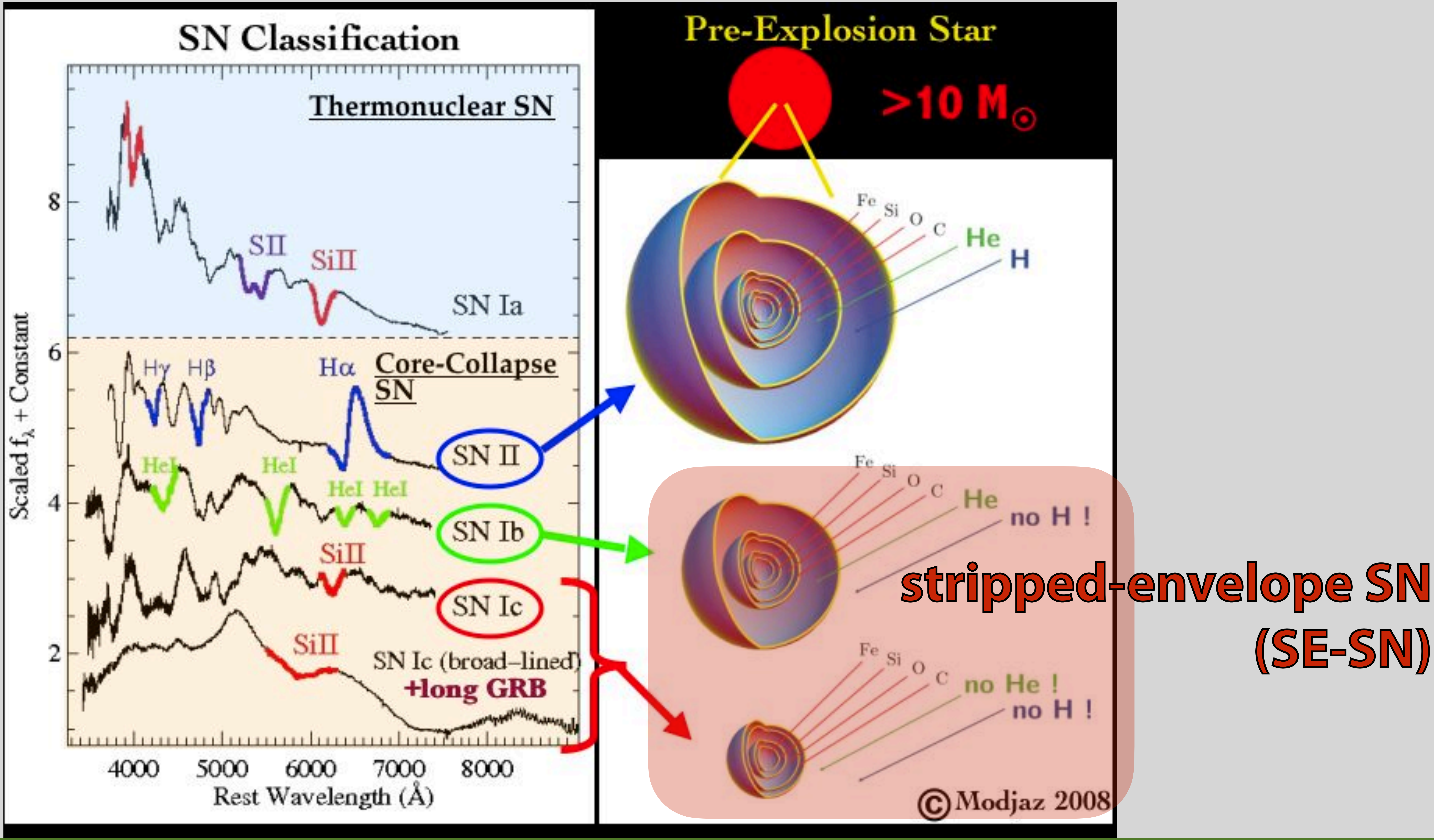
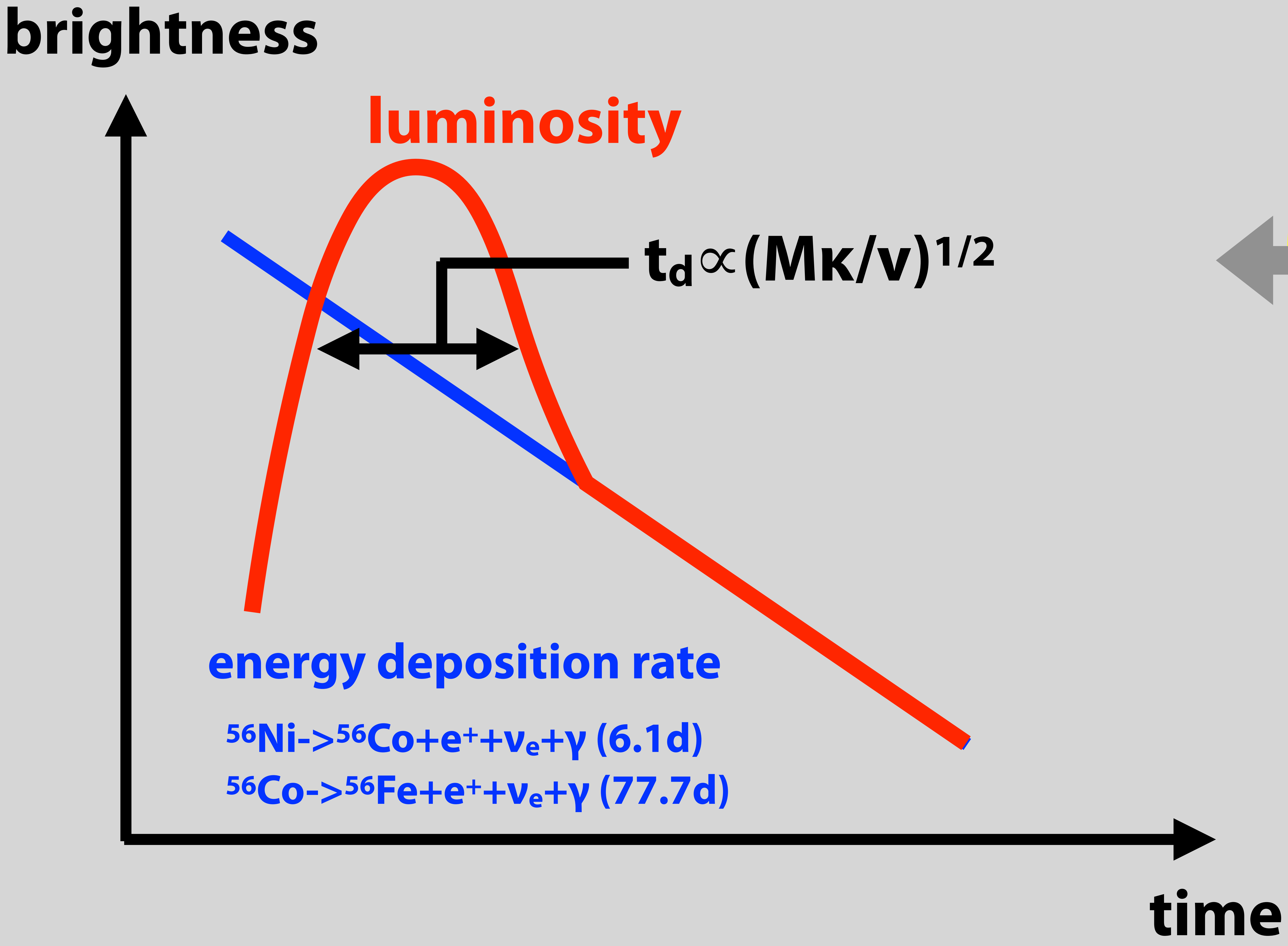
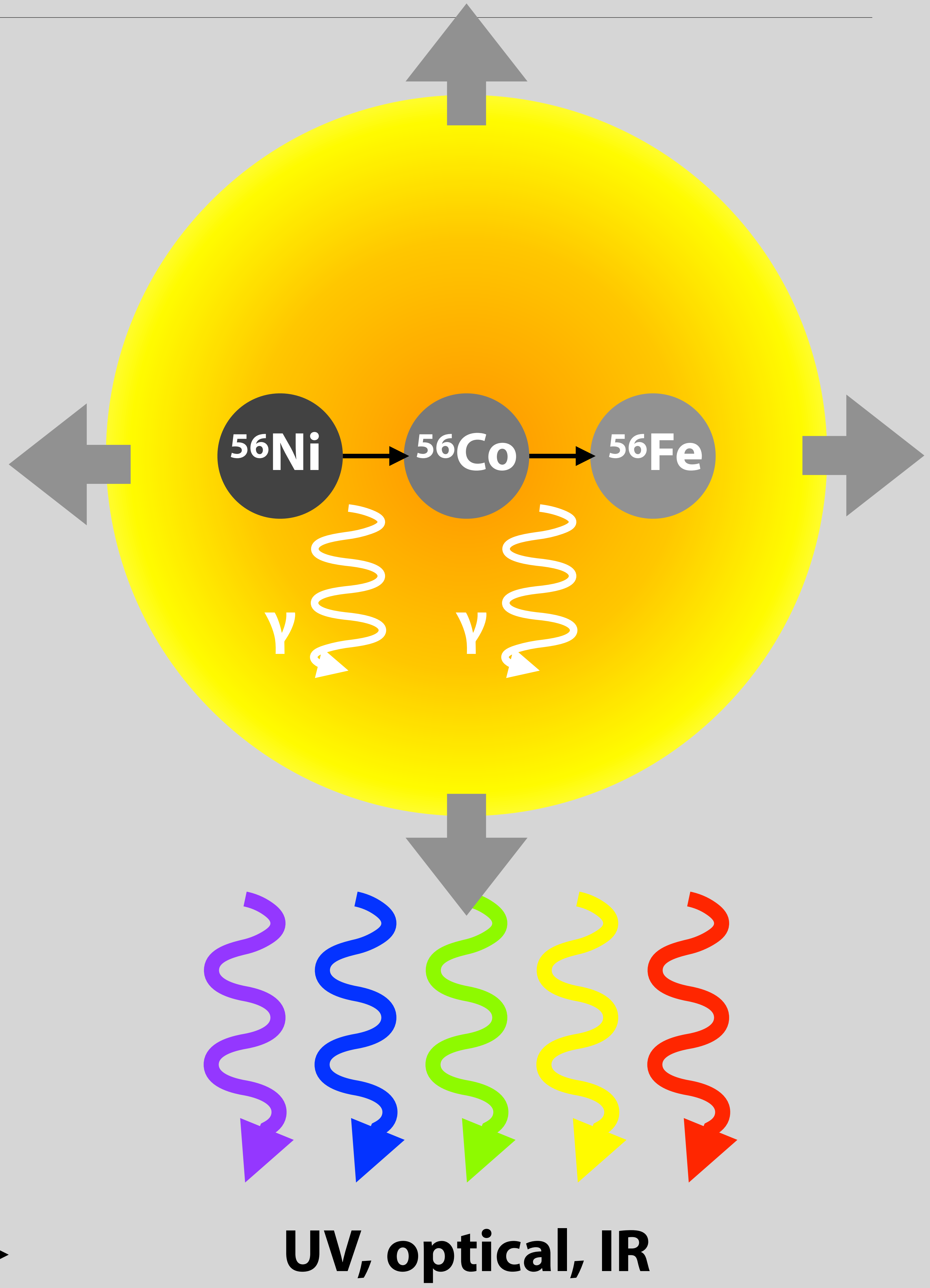
Observational findings

Types of supernovae



Supernova light curves (LC)





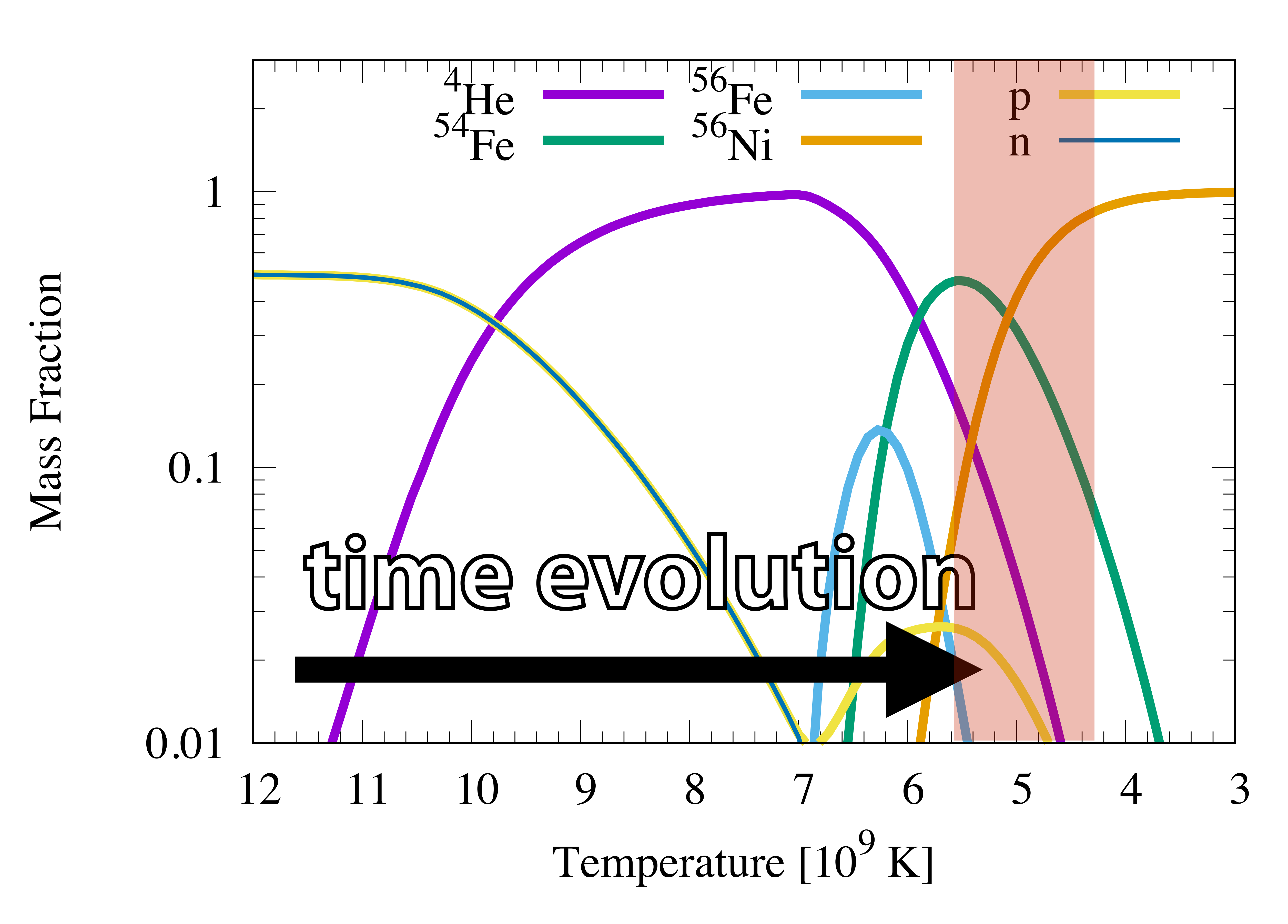
^{56}Ni

* Z=28, N=28, A=56 → Y_e=0.5
* ^{56}Ni is mainly produced in supernova (SN) ejecta
* ^{56}Ni is produced if Nuclear Statistical Equilibrium (NSE) is achieved, typically $T>5\times10^9$ K
* Enough amount of ^{56}Ni needs to be produced to explain SN LC brightness

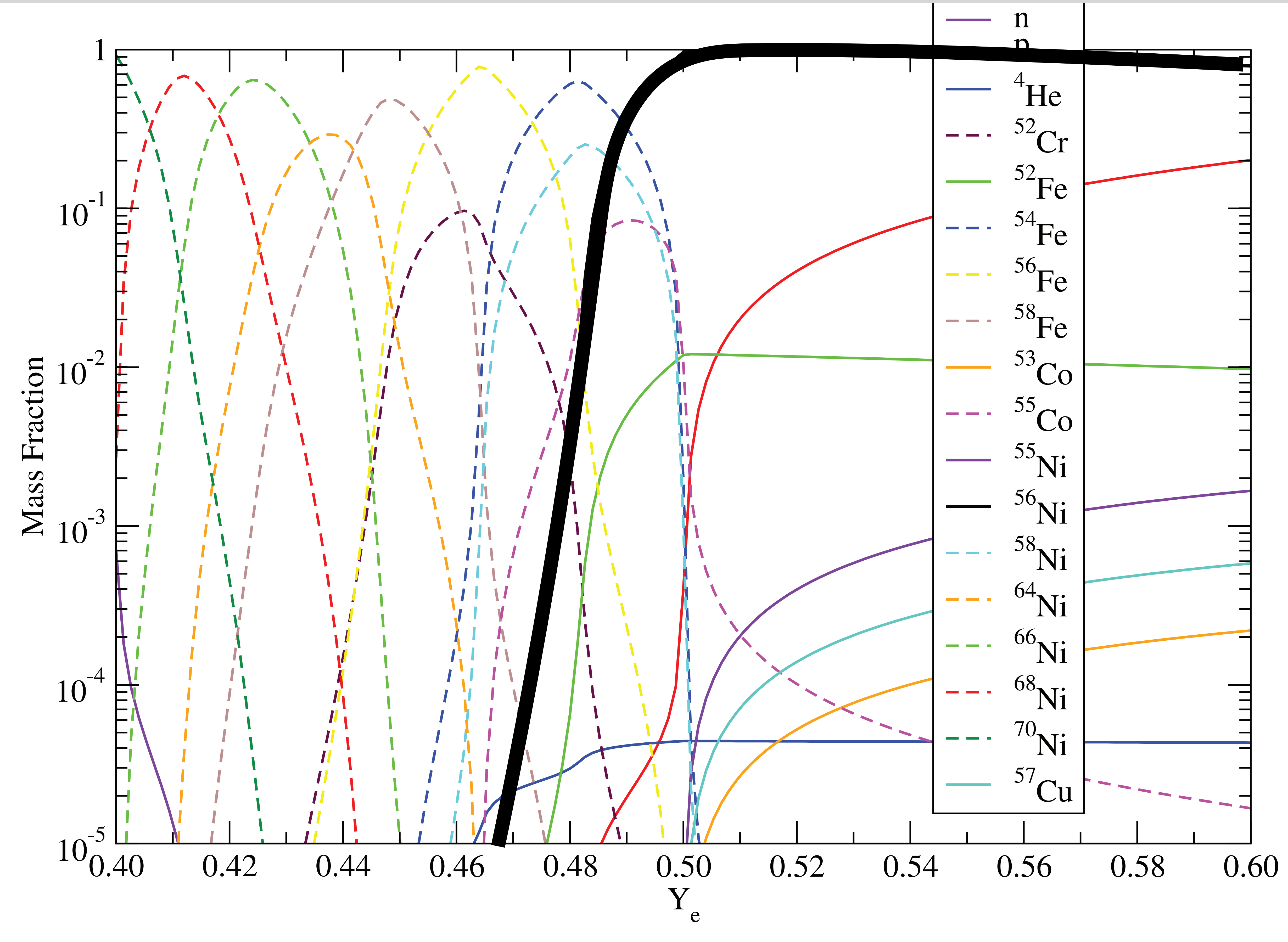
Nuclear Statistical Equilibrium (NSE)

NSE: chemical equilibrium of mixture of nucleons (n, p) and nuclei

$\rho=10^7$ g cm^{-3}、 $Y_e=0.5$

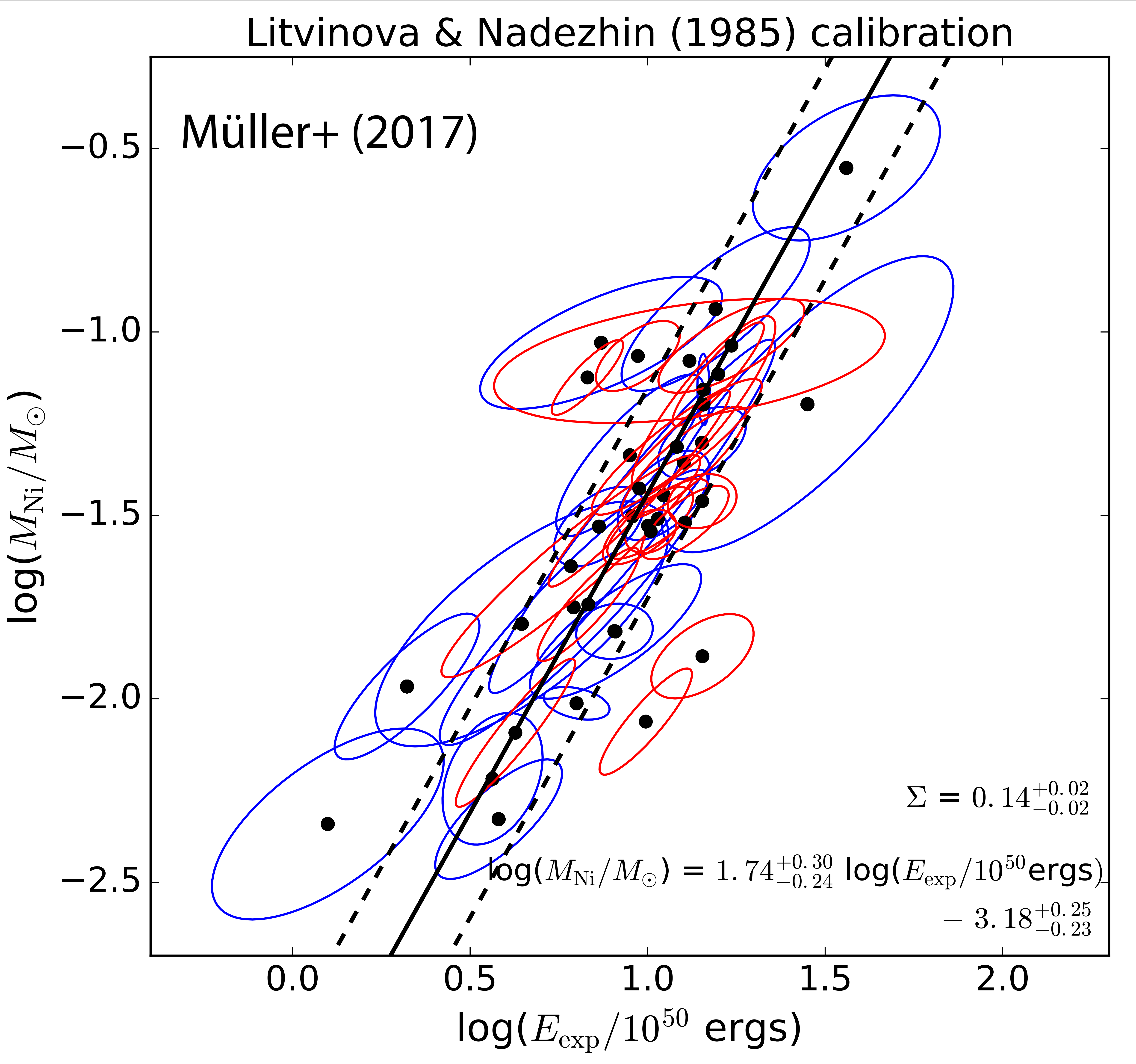


Seitenzahl+ 08 ($\rho=10^7$ g cm^{-3}、 $T=3.5\times10^9$K)



^{56}Ni is major element in SN ejecta for $Y_e \gtrsim 0.5$

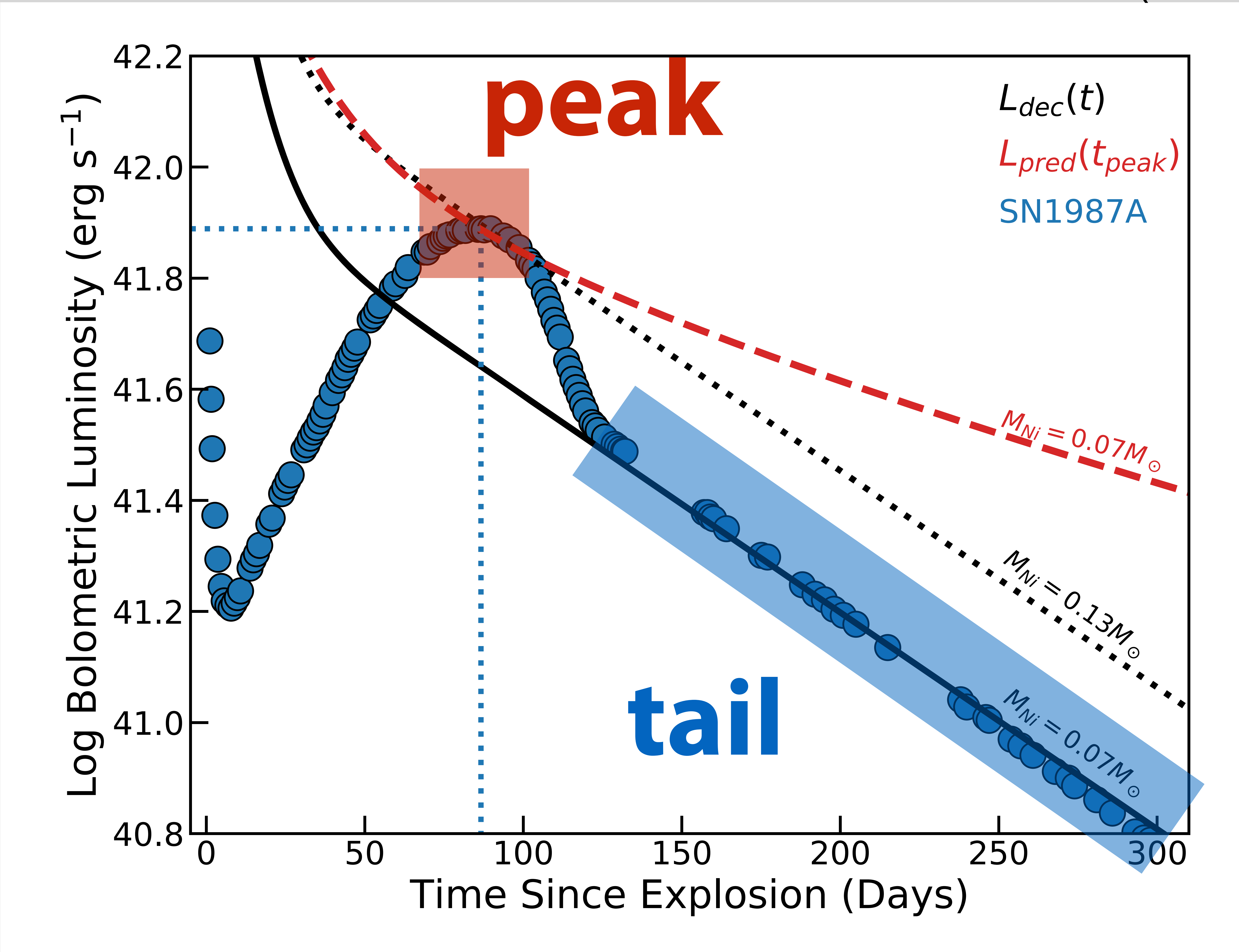
Explosion energy - M_{Ni} correlation



- E_{exp}-M_{Ni} correlation for SN-II
  - Fit multi-band LC w/ approximate model provides M_{Ni}
- M_{Ni} distribution:
  - between $0.005M_\odot$ and $0.280M_\odot$
  - median of $0.031M_\odot$
  - mean of $0.046M_\odot$
- NB: error is large for SN-II, since the initial thermal energy contributes the brightness in early LC
- Nearby SNe has similar M_{Ni} of $\sim 0.07M_\odot$: 1987A (51kpc), 1993J (3.6Mpc), 1994I (8Mpc)

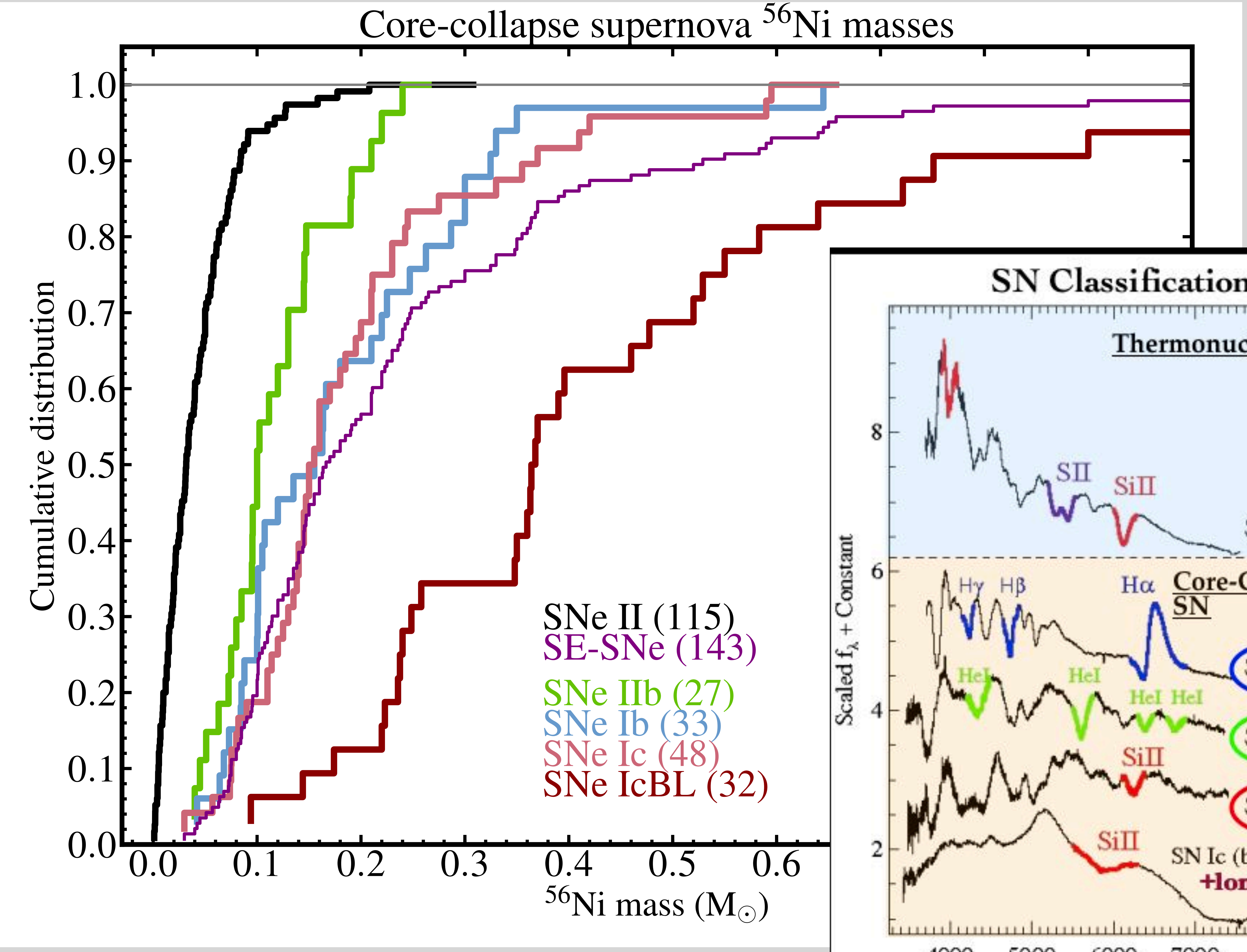
Two ways to measure ^{56}Ni amount in SE-SN

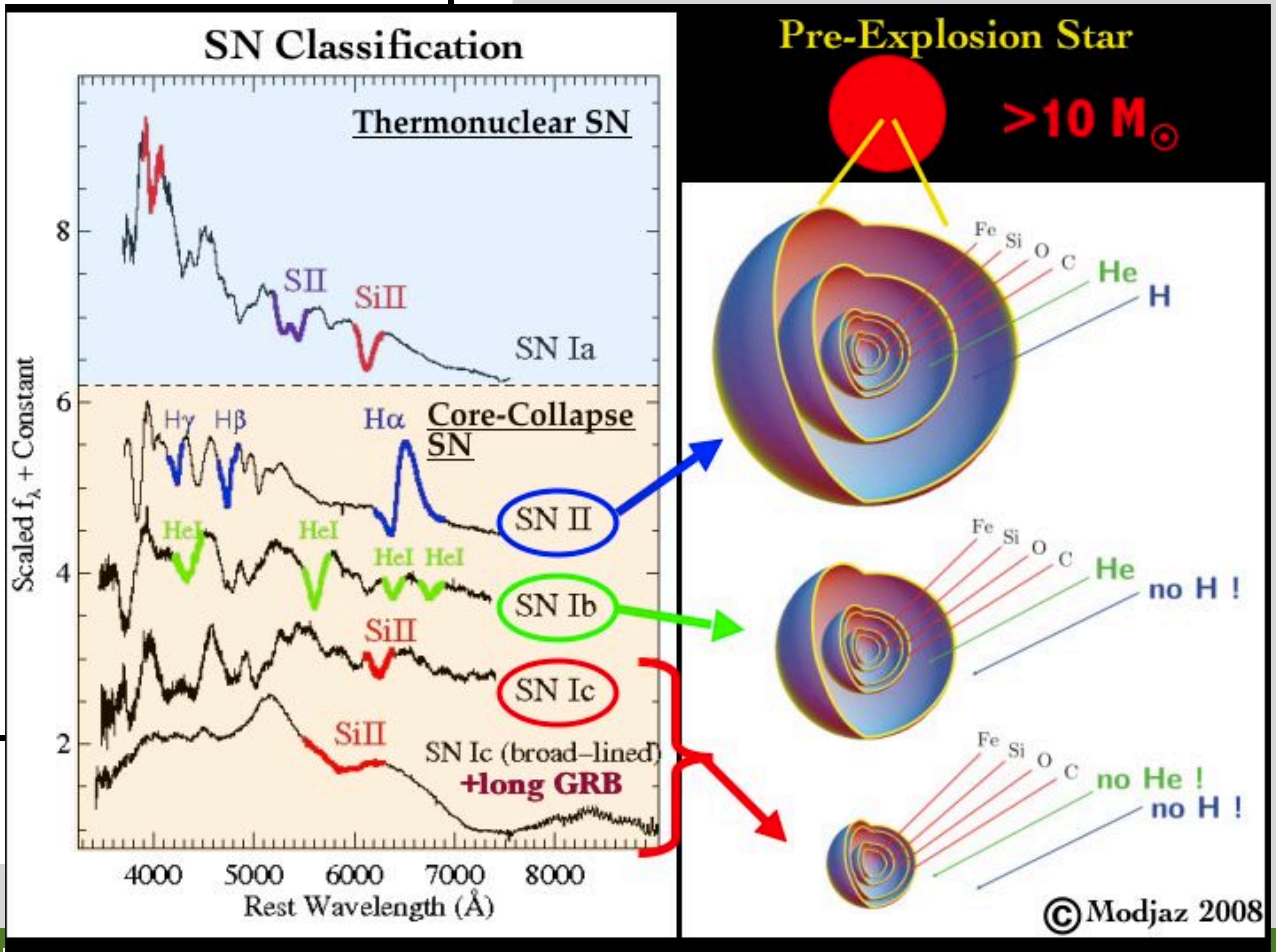
Khatami & Kasen (2019)



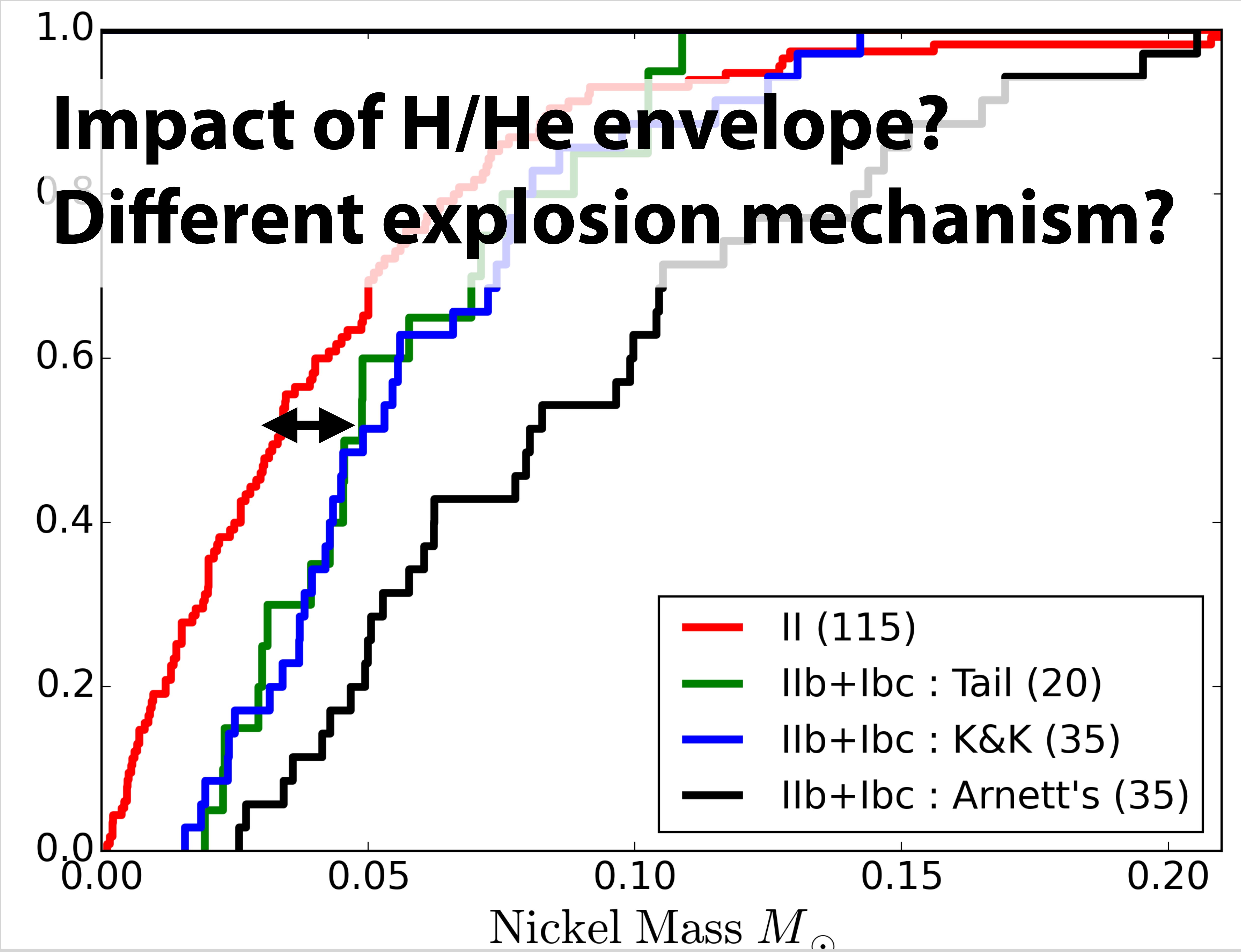
^{56}Ni distribution

Anderson (2019)

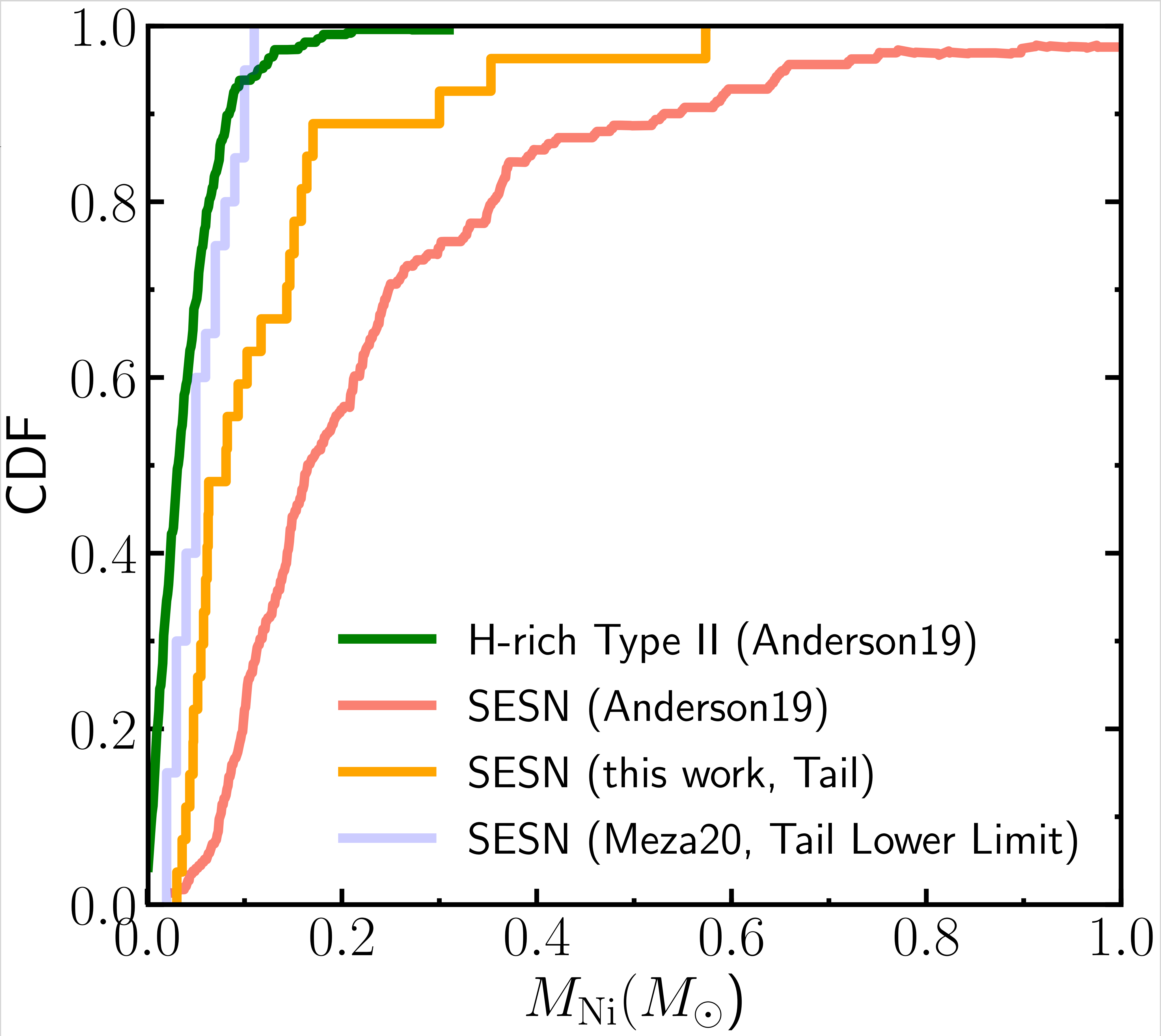




^{56}Ni distribution updated



Meza & Anderson (2020)



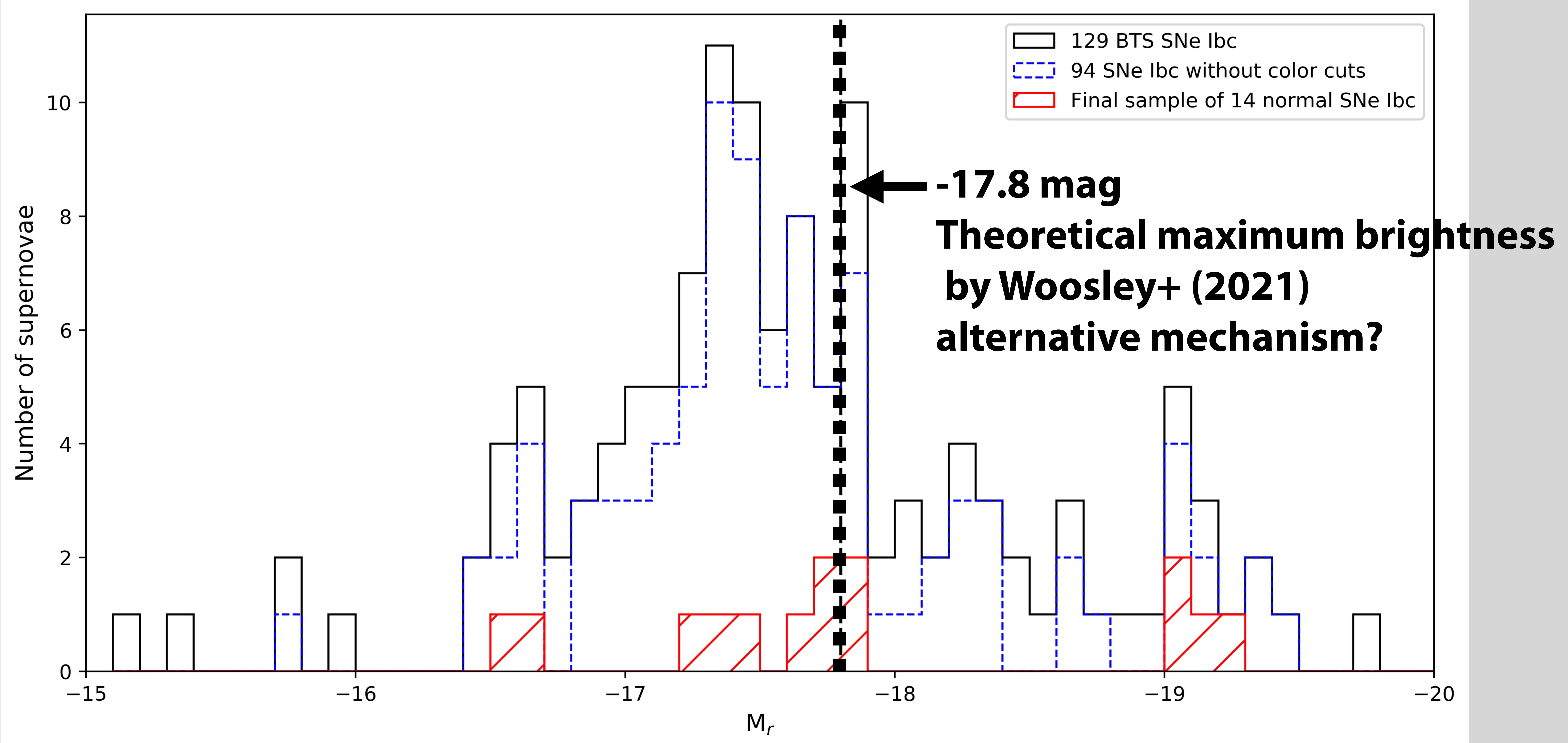
Afsariardchi+ (2021)

	Tail $M_{\rm Ni}$ $(M_\odot)$			Arnett $M_{\rm Ni}$ $(M_\odot)$			KK19 $M_{\rm Ni}$ $(M_\odot)$		
SN Type	Mean	Median	Std	Mean	Median	Std	Mean	Median	Std
IIb	0.06	0.06	0.02	0.13	0.13	0.04	0.07	0.07	0.02
Ib	0.11	0.06	0.11	0.20	0.11	0.19	0.12	0.08	0.1
Ic	0.20	0.10	0.22	0.26	0.16	0.22	0.15	0.11	0.11
Ic-BL	0.15	0.15	0.07	0.31	0.29	0.16	0.15	0.15	0.07
All	0.12	0.08	0.12	0.22	0.16	0.17	0.12	0.09	0.09

Mean $M_{\rm Ni}$ (SE-SN) ~ 3x $M_{\rm Ni}$ (SNII)

Maximum brightness of SE-SN

Sollerman+ (2021)

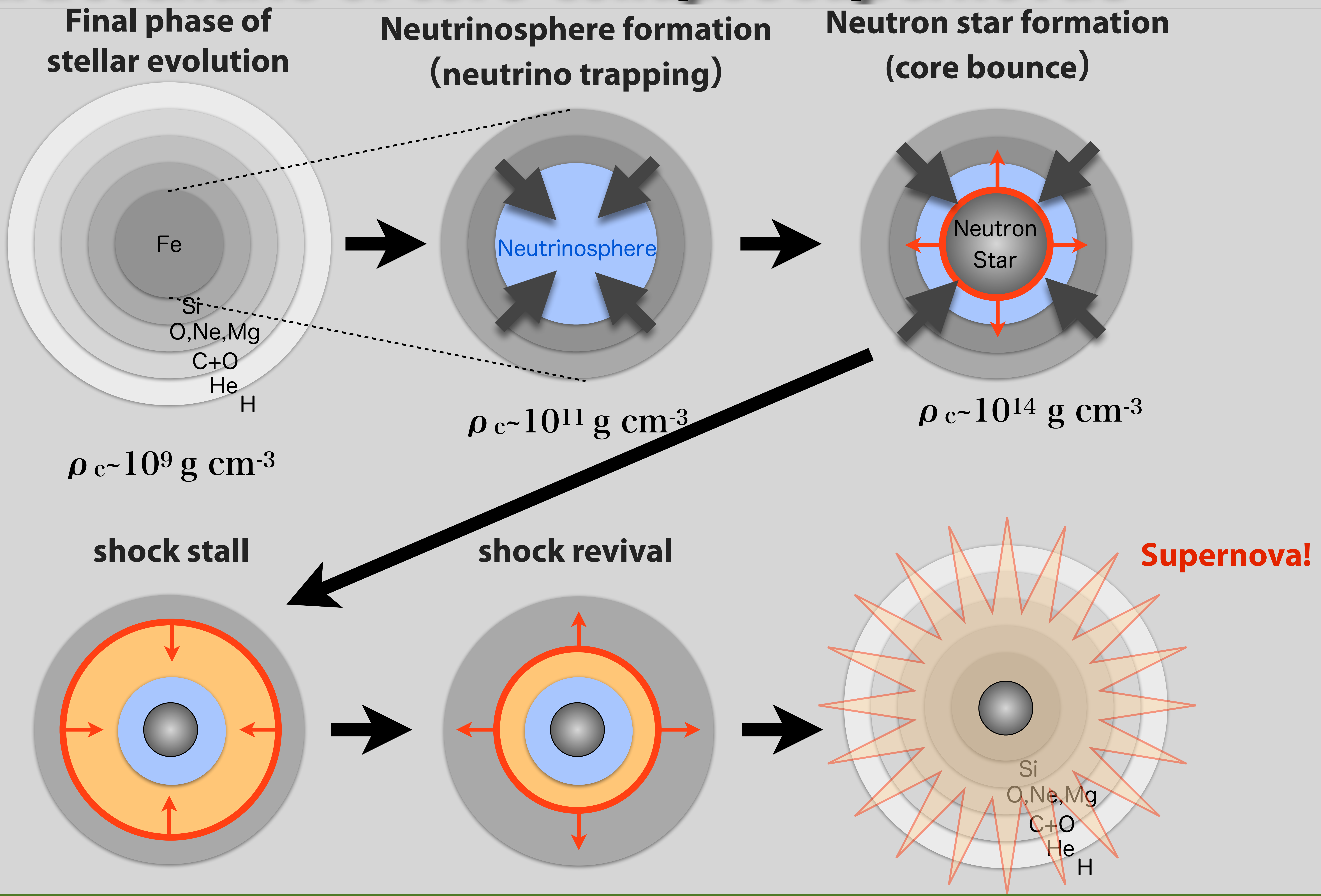


Summary of observational findings

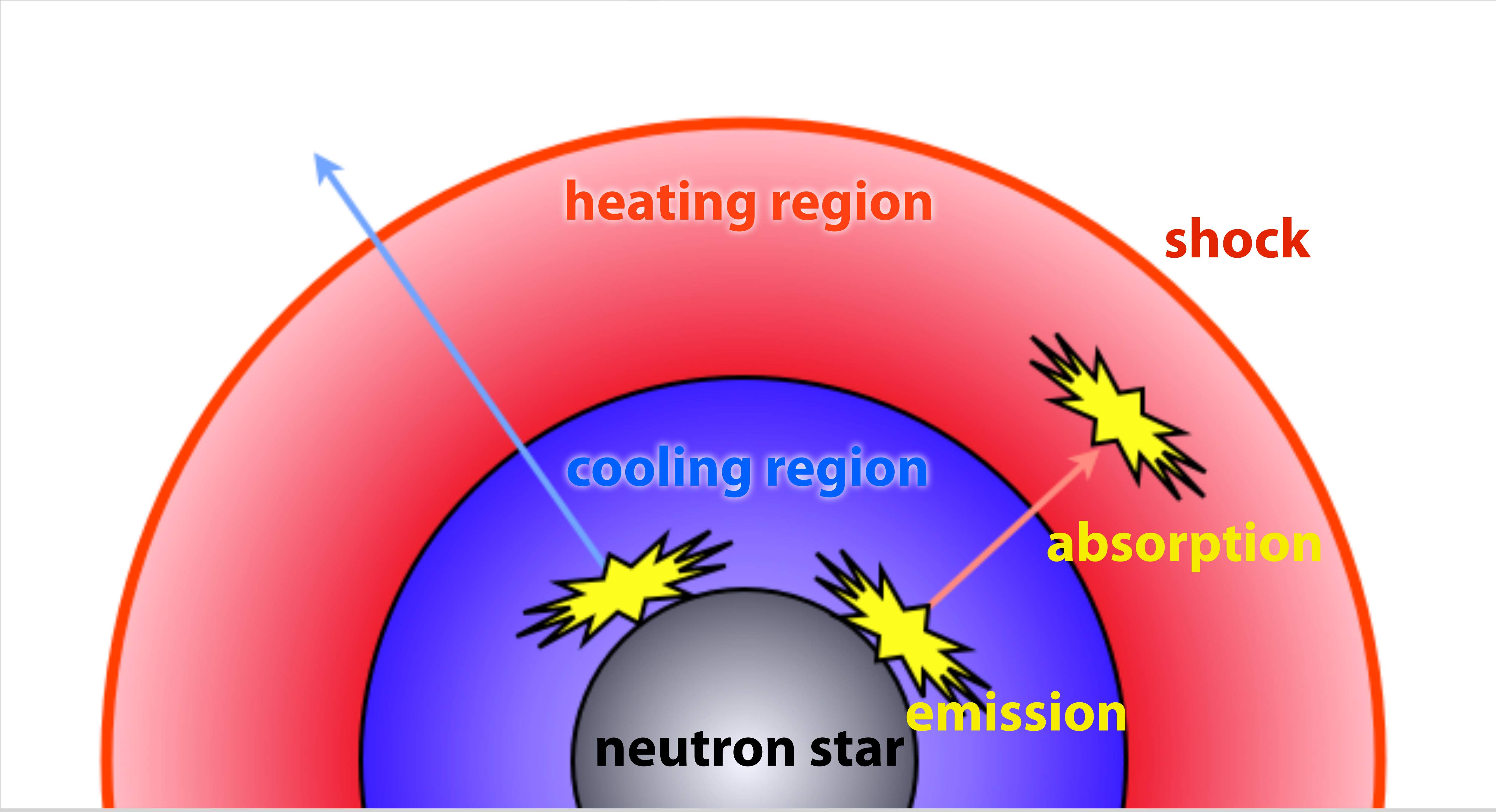
- ^{56}Ni is energy source of SN light curves
- Two different methods become consistent
  - peak luminosity
  - tail emission
- $M_{^{56}\mathrm{Ni}}$ for SE-SN is larger than type-II SN
  - fallback induced by massive envelope?
  - different explosion properties?
- Typical $M_{^{56}\mathrm{Ni}} \gtrsim 0.04 M_\odot$
  - depending on SN types
  - Ic-BL > Ic > Ib/IIb >II

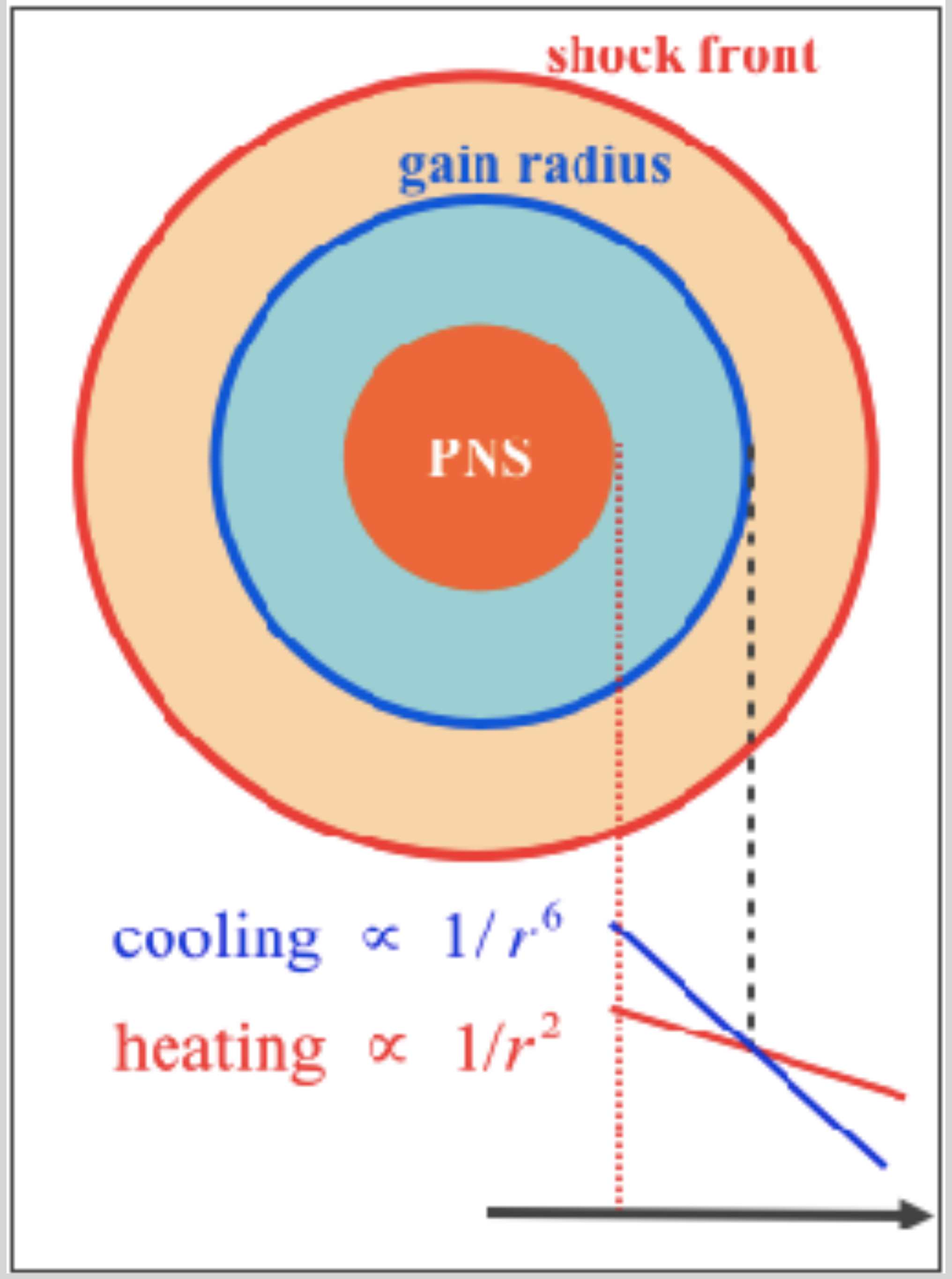
Theoretical understandings

Standard scenario of core-collapse supernovae



Current paradigm: neutrino-heating mechanism

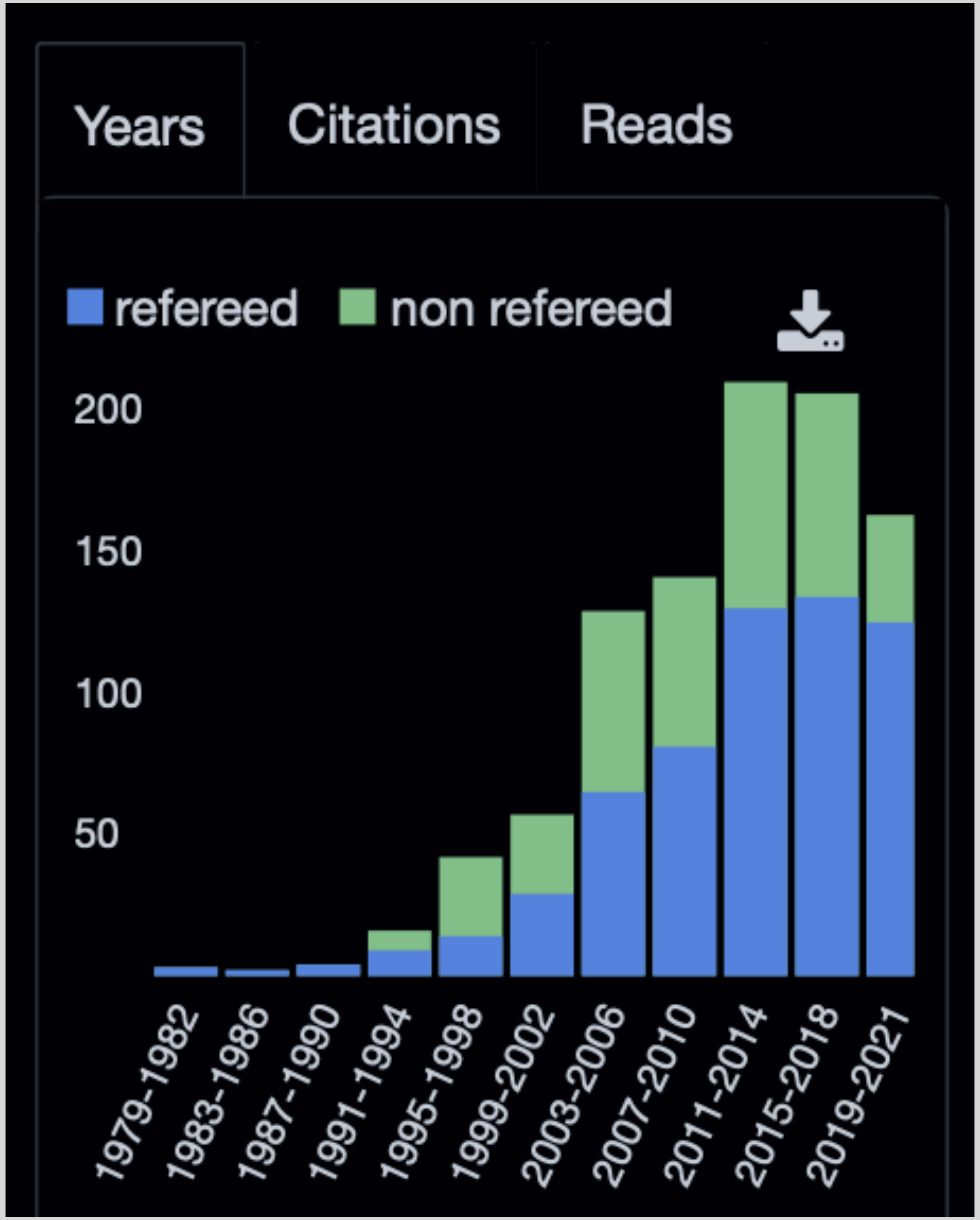




- **A CCSN emits $O(10^{58})$ of neutrinos with $O(10)$ MeV.**
- **Neutrinos transfer energy**
  - **Most of them are just escaping from the system (cooling)**
  - **Part of them are absorbed in outer layer (heating)**
- **Heating overwhelms cooling in heating (*gain*) region**

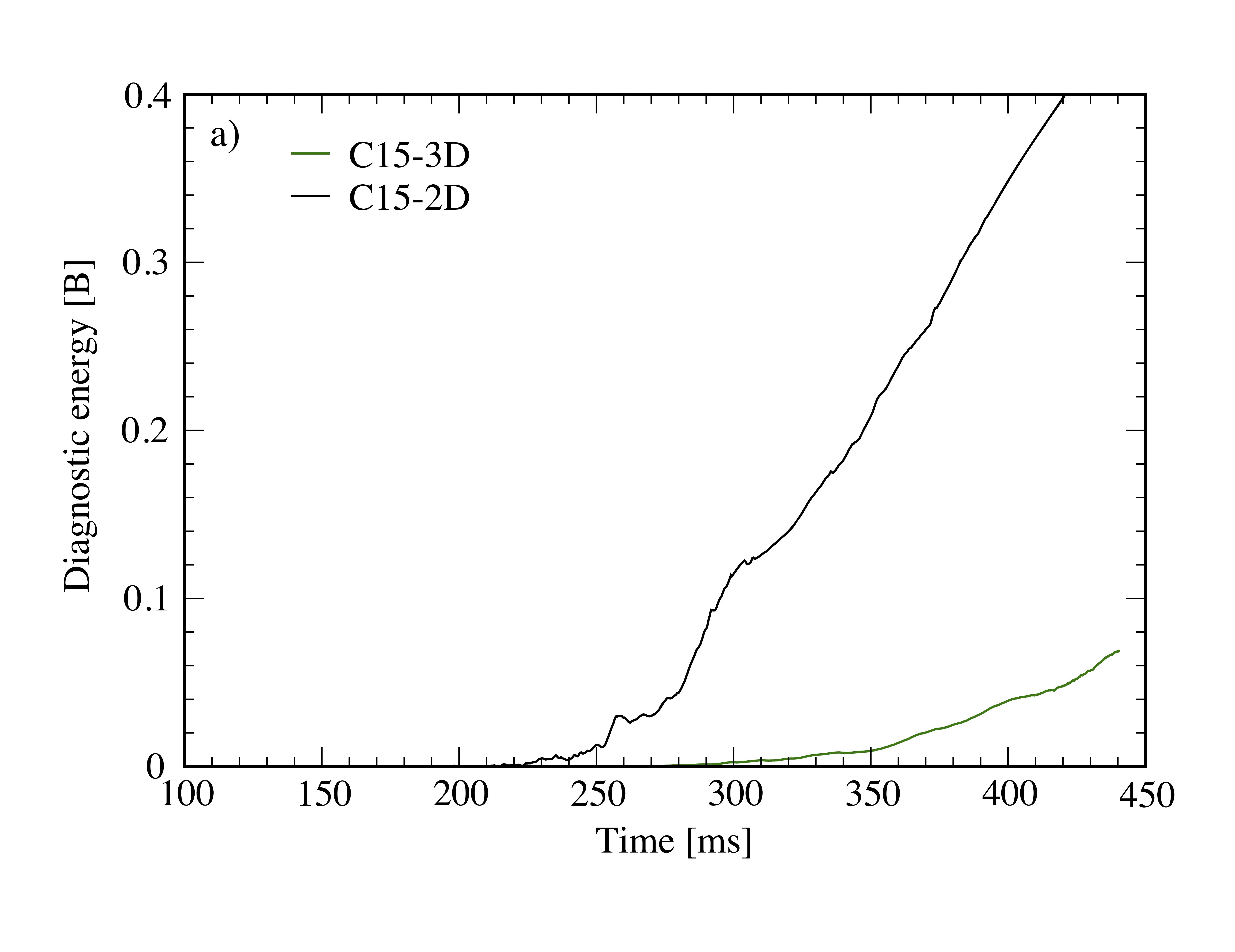
Exploding numbers of exploding models

- **Many papers reported successful explosions by neutrino heating in the past ~15 years**
- **Breakthroughs;**
  - Buras+ 2006: 1st neutrino driven explosion in 2D
  - Marek & Janka (2009): long-term (700ms) 2D sim.
  - Takiwaki+ (2012): 1st neutrino driven explosion in 3D
- **So far, ~10 independent codes that solve multi-energy neutrino-radiation hydrodynamics in multi-D, are present**
  - 4 codes are compared in O'Connor+ 2018 as well as 2 1D codes



At ADS, search with "core-collapse supernova hydrodynamics simulations"

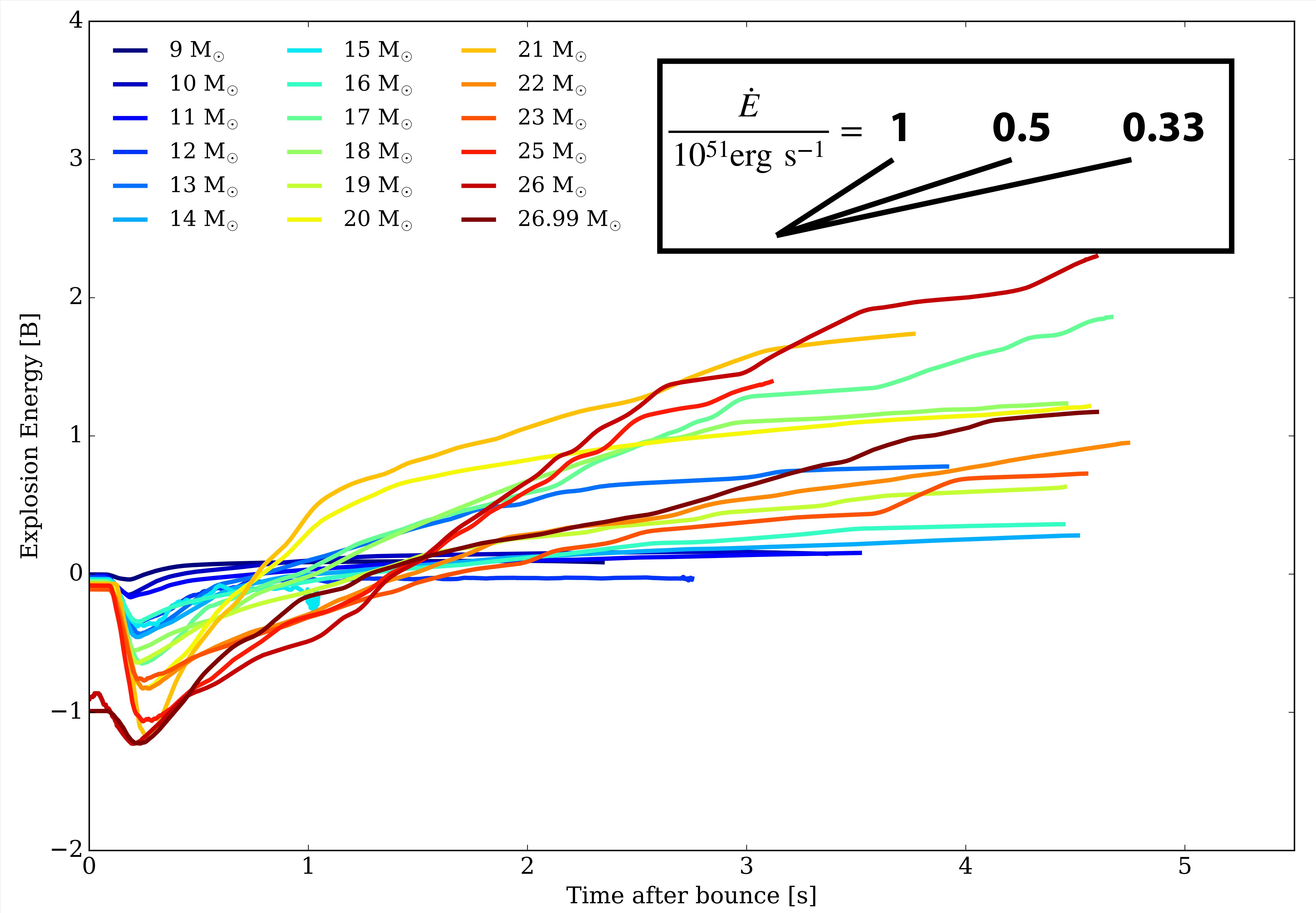
Explosion energy problem



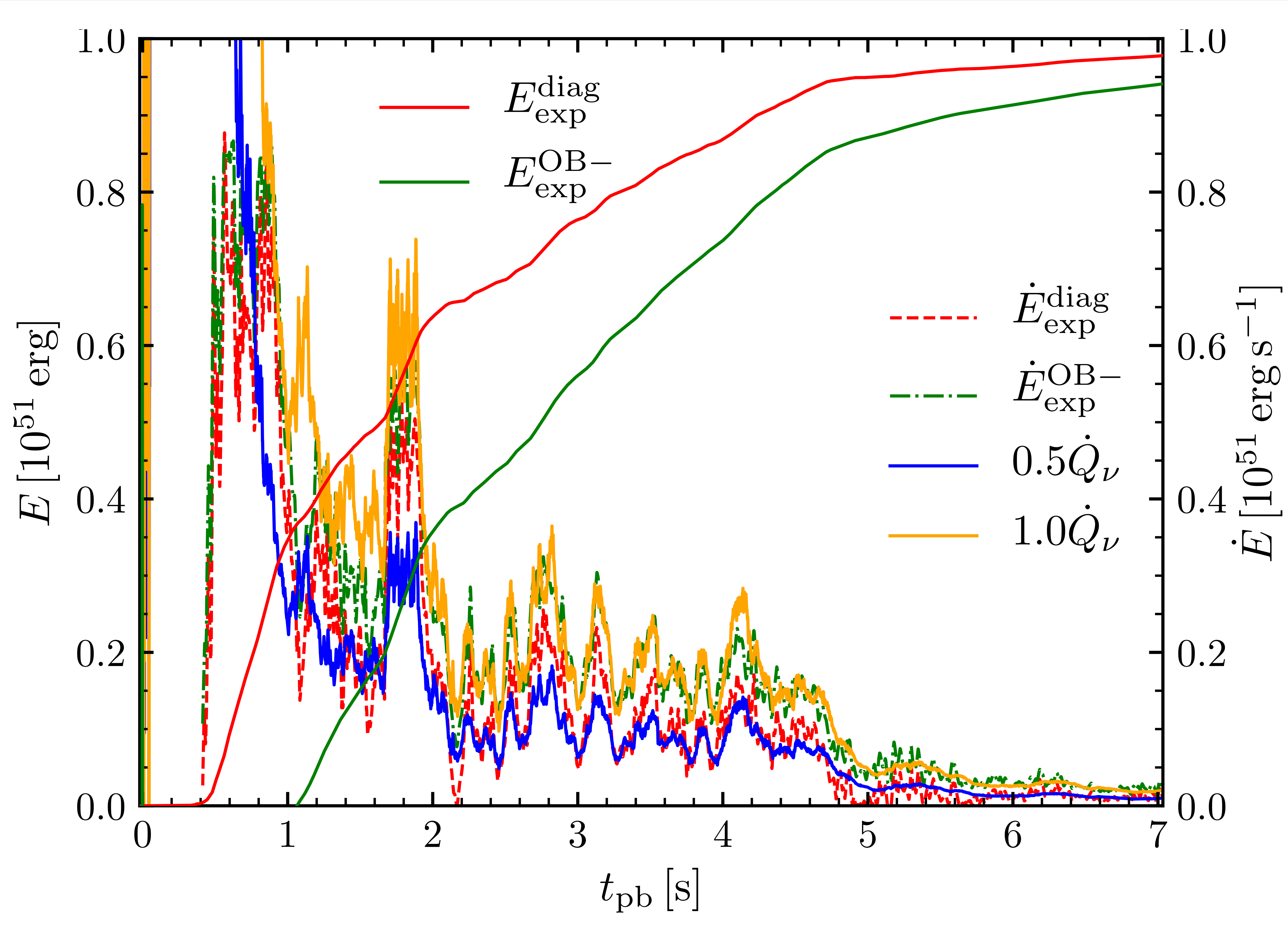
Lentz+ (2015)

Recent simulations with explosion energy ~10^{51} erg

Burrows & Vartanyan (2021) [2D, systematic]

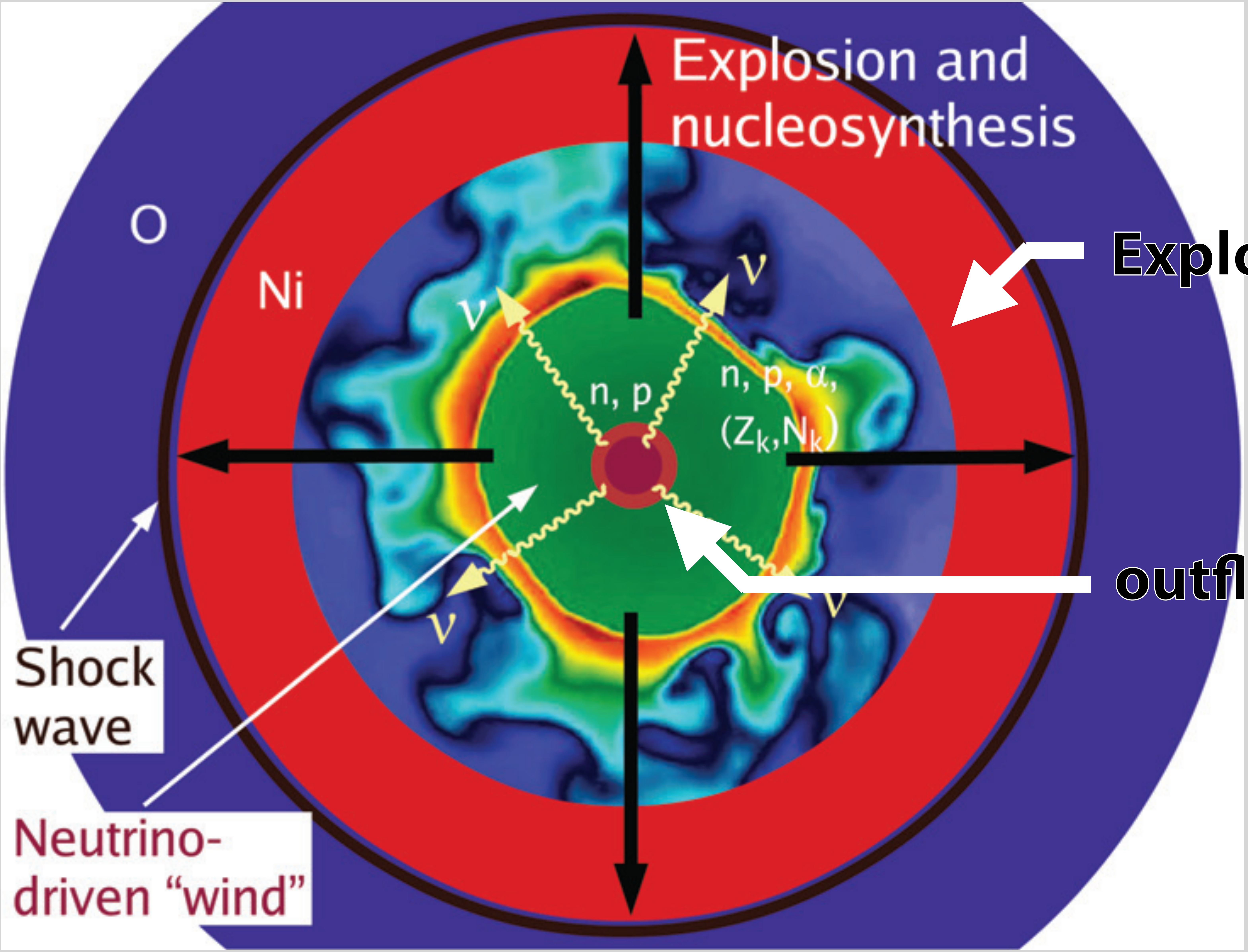


Bollig+ (2021) [3D, 1 model]



$$\dot{E} = \mathcal{O}\left(10^{50}\right)\ \mathrm{erg\,s^{-1}}$$

Where is ^{56}Ni produced?



Explosive nucleosynthesis

outflow from PNS

Janka (2012)

Condition of ^{56}Ni production in explosive nucleosynthesis

* **In radiation dominant gas,**

$$E = \frac{4\pi}{3} r_s^3 a T^4$$

$$\Rightarrow T(r) = 1.33 \times 10^{10}\,\mathrm{K} \left(\frac{E}{10^{51}\,\mathrm{erg}}\right)^{1/4} \left(\frac{r_s}{10^8\,\mathrm{cm}}\right)^{-3/4}$$

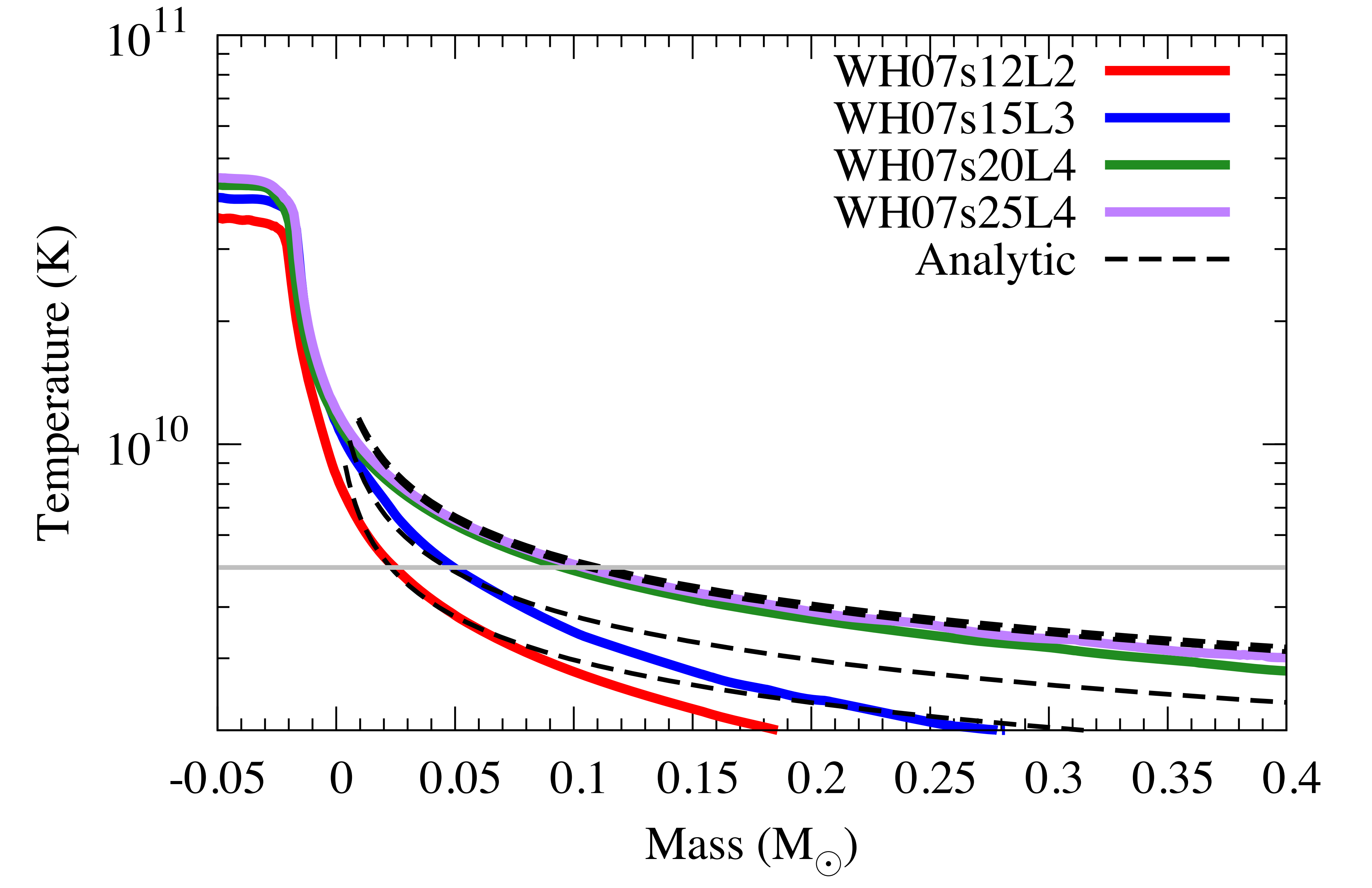
* **For NSE ($T>5\times10^9$K),**

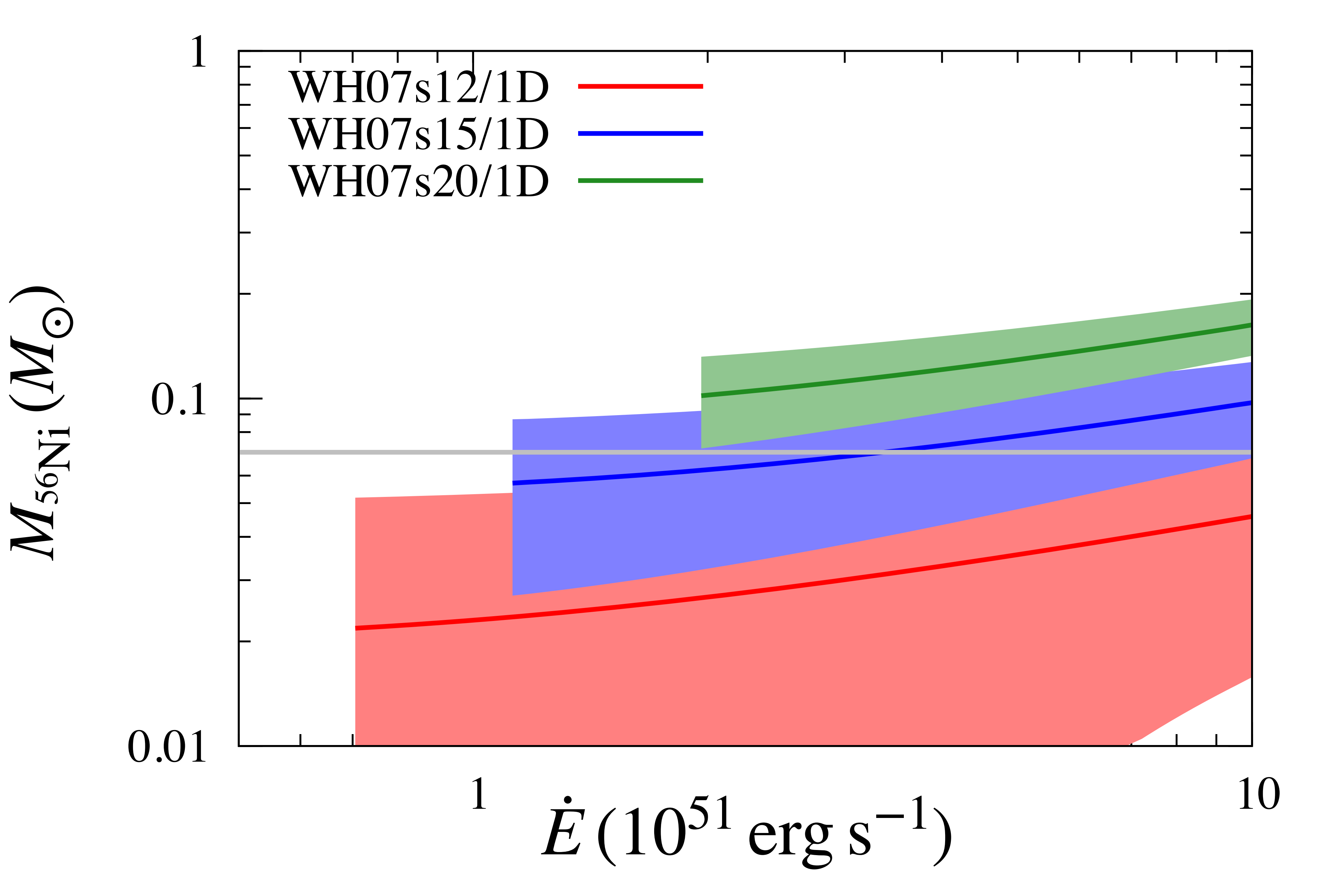
$$r_s < 3700\,\mathrm{km} \left(\frac{E}{10^{51}\,\mathrm{erg}}\right)^{1/3}$$

* **Large energy deep inside is necessary => $\dot{E}$ needs to be large!**

^{56}Ni production in explosive nucleosynthesis

[Suwa, Tominaga, Maeda, MNRAS, 483, 3607 (2019)]



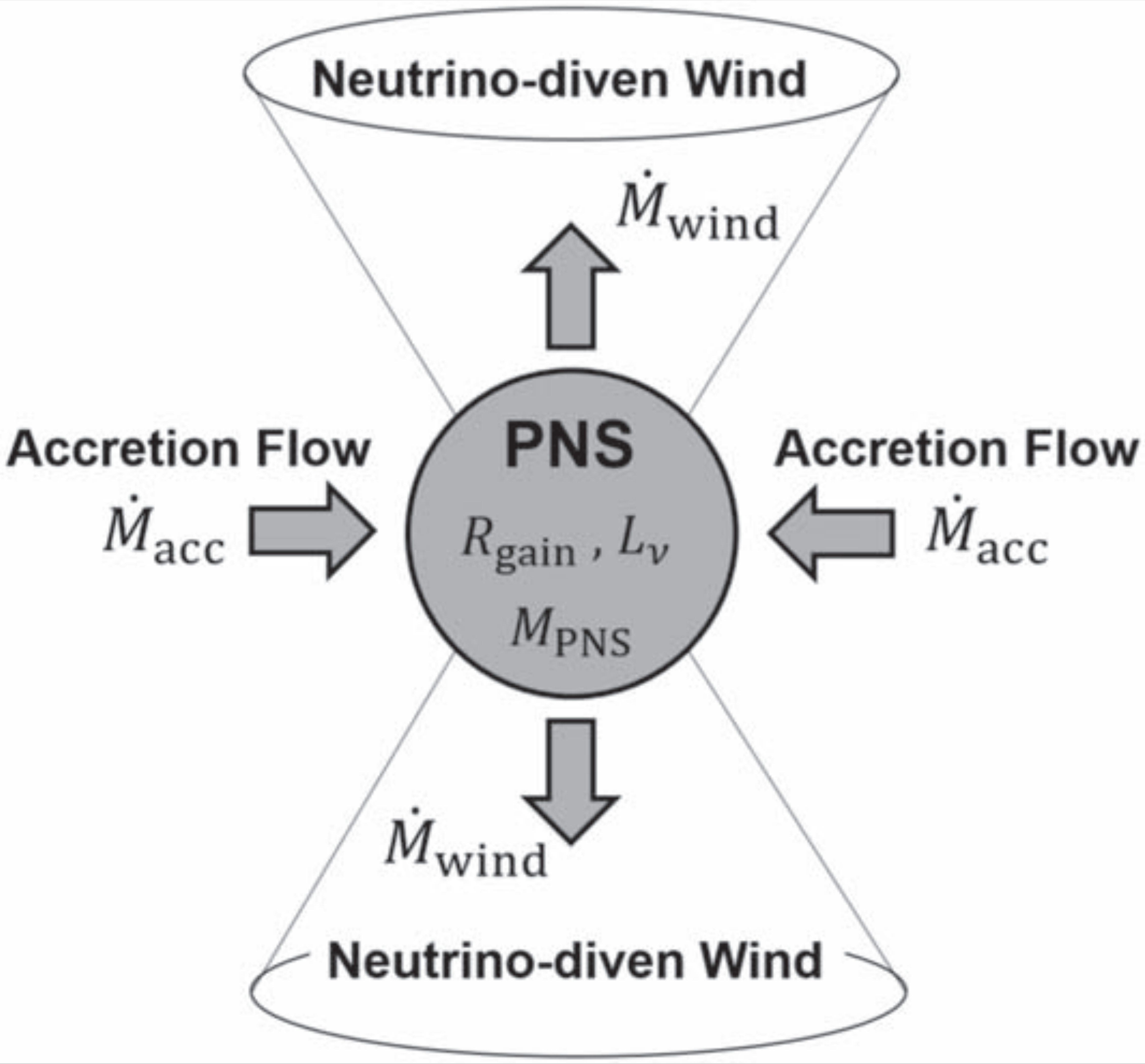


* **1D Lagrangian hydro. sim.**
* **heating/cooling by ν taken into account with light bulb**
* **12, 15, 20, 25 $M_\odot$**
* **Analytic model is provided**

* $M_{^{56}\mathrm{Ni}}$ **is correlated to** $\dot{E}$
* **Compact stars produce larger** $M_{^{56}\mathrm{Ni}}$
* $\dot{E} \gtrsim 10^{51}\,\mathrm{erg\,s^{-1}}$ **is necessary for** $M_{^{56}\mathrm{Ni}} \approx 0.07 M_\odot$ (see also Sawada & Maeda 2019)

^{56}Ni production in neutrino-driven wind

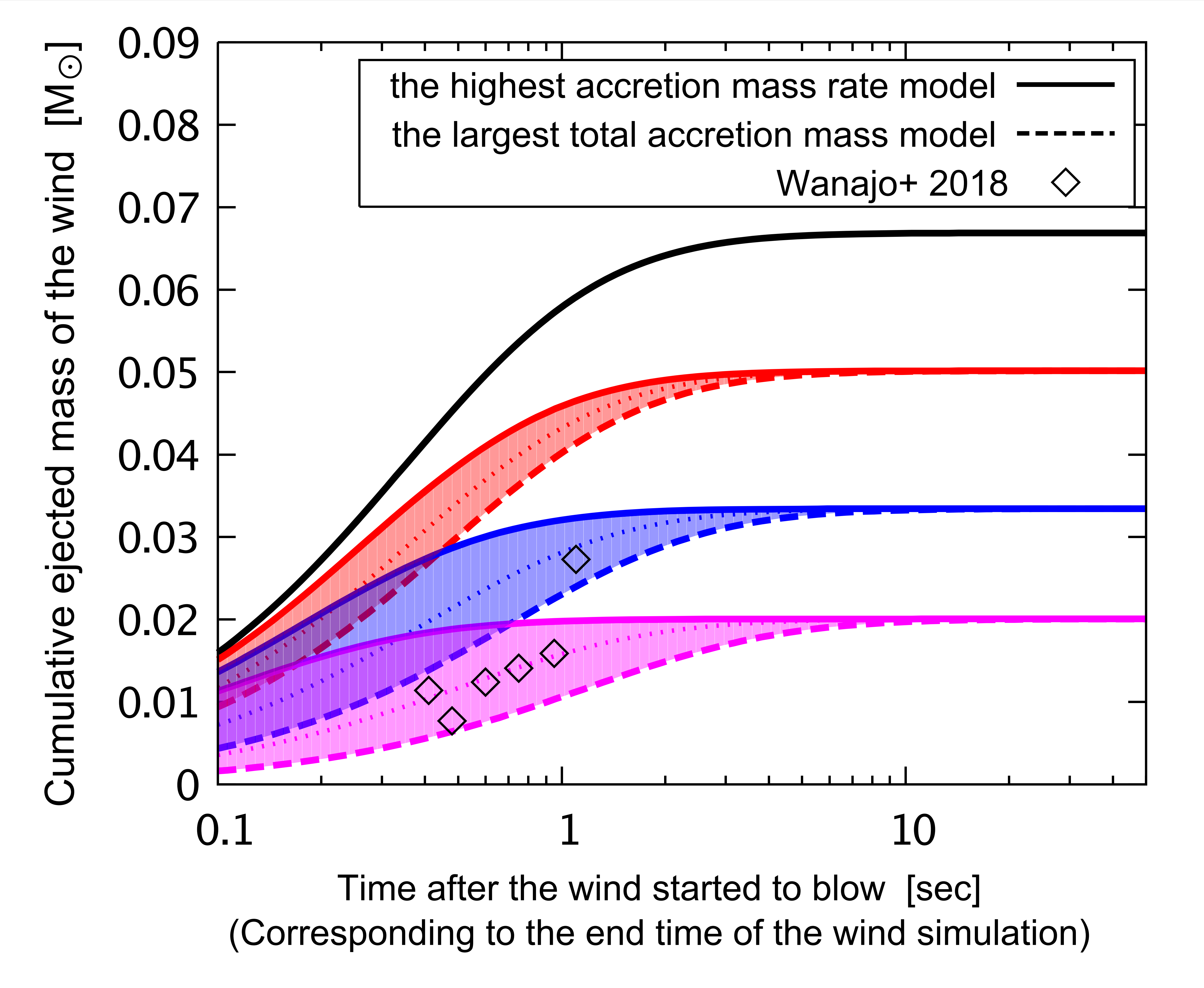
[Sawada, Suwa, ApJ, 908, 6 (2021)]



- **Construct model of neutrino-driven wind powered by mass accretion onto PNS**
  - Steady-state solution of neutrino-driven wind (e.g., Otsuki+ 2000, Wanajo+ 2001, Fujibayashi+ 2015)
  - $\dot{M}$ with progenitor models from Sukhbold+ (2018)
  - L_ν and $R_{\rm gain}$ are estimated based on hydrodynamics simulations

^{56}Ni production in neutrino-driven wind

[Sawada, Suwa, ApJ, 908, 6 (2021)]



- $M_{^{56}\mathrm{Ni}} \lesssim 0.067 M_\odot$
  - initial PNS mass: $1.4 M_\odot$
  - total accretion mass: $< 0.7 M_\odot$
- **Mass is converged in 2 s**
  - consistent with neutrino-rad. hydro. simulation (Wanajo+ 2018)
- **Difficult to provide enough ^{56}Ni with neutrino-driven wind**

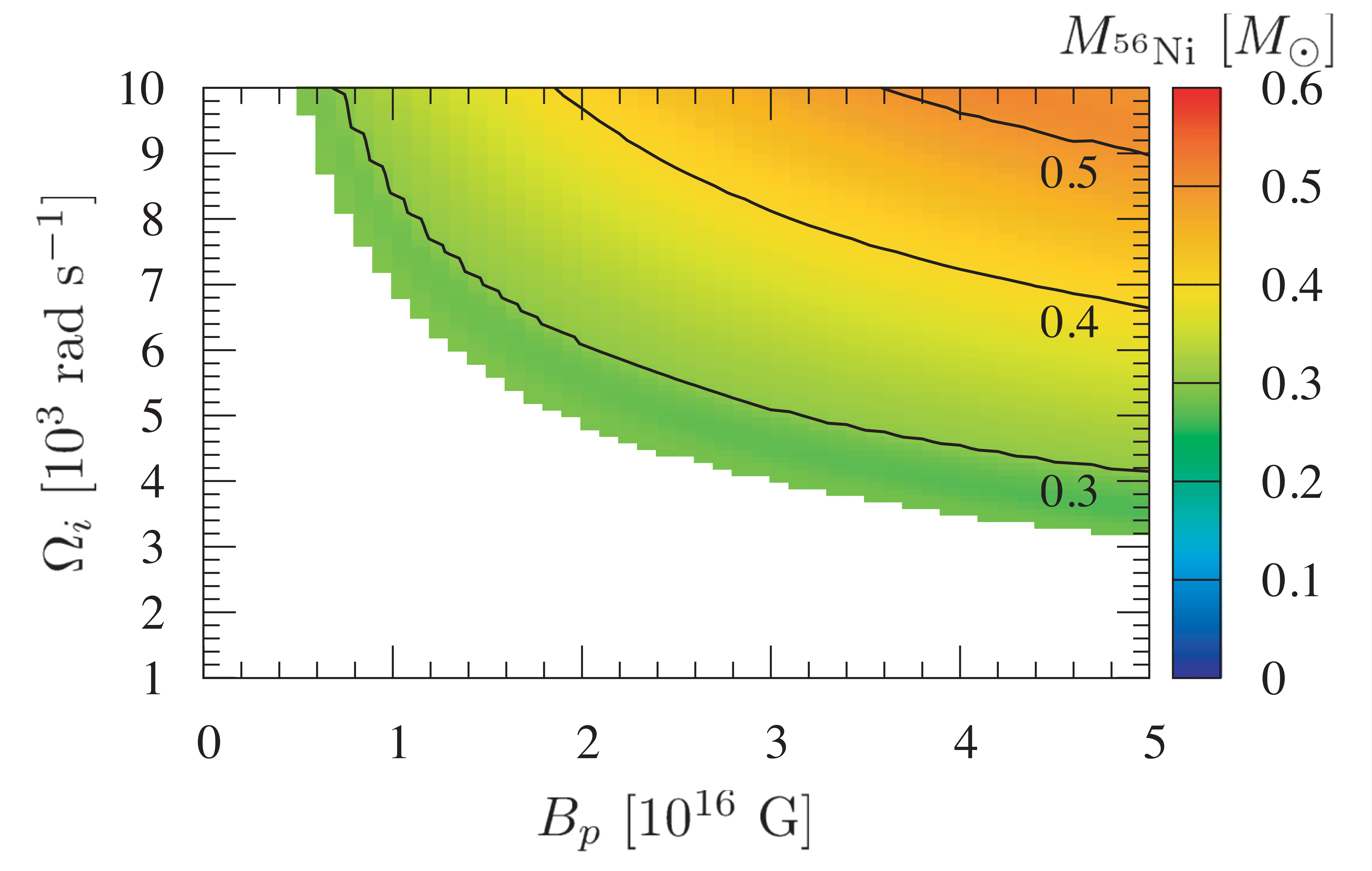
^{56}Ni problem is ubiquitous

* The ^{56}Ni problem exists besides canonical supernova

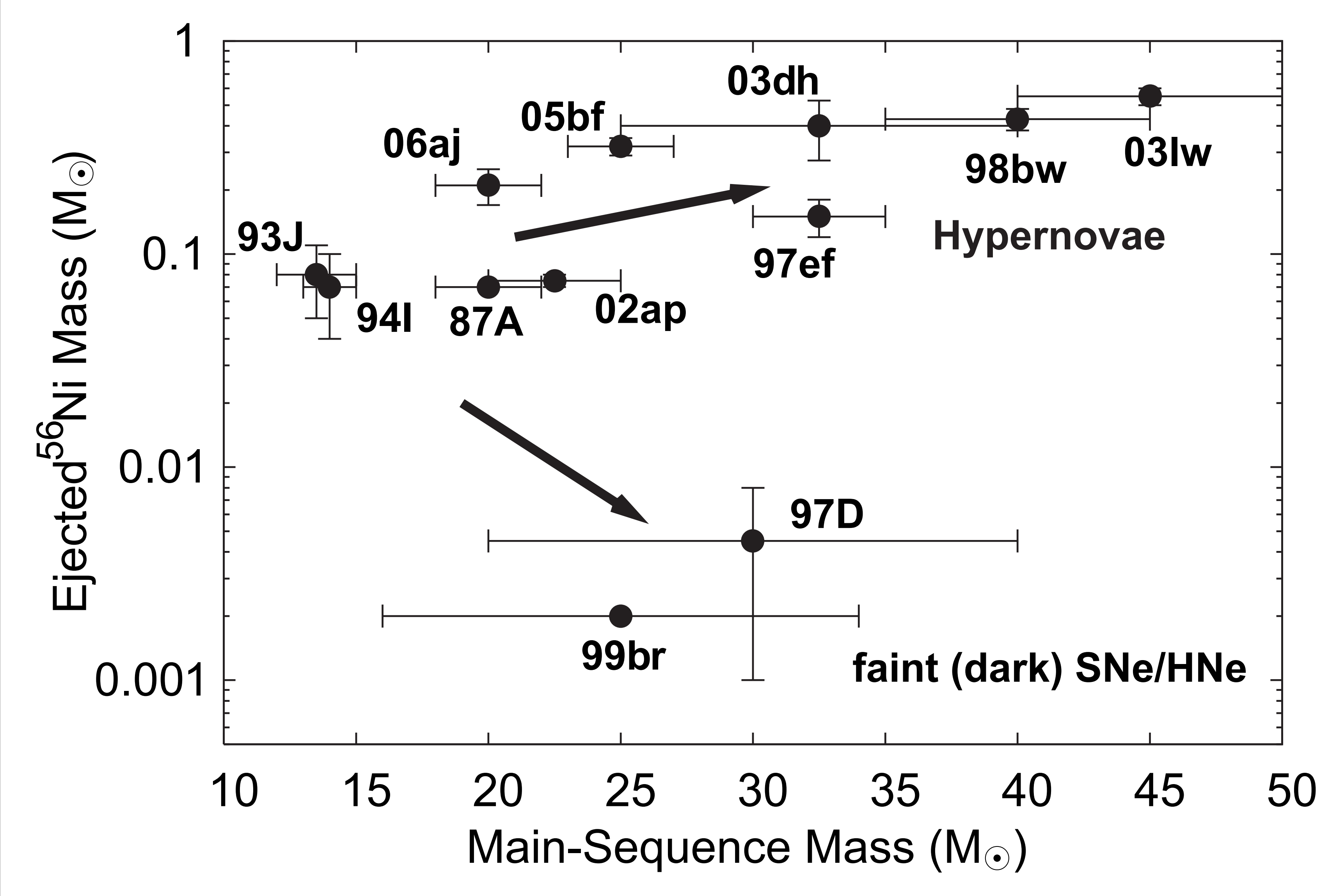
* Hypernova a.k.a. SN Ic-BL
* Ultrastripped-envelope SN

^{56}Ni production for hypernovae with magnetar engine

[Suwa, Tominaga, MNRAS, 451, 282 (2015)]



Nomoto+ (2006)



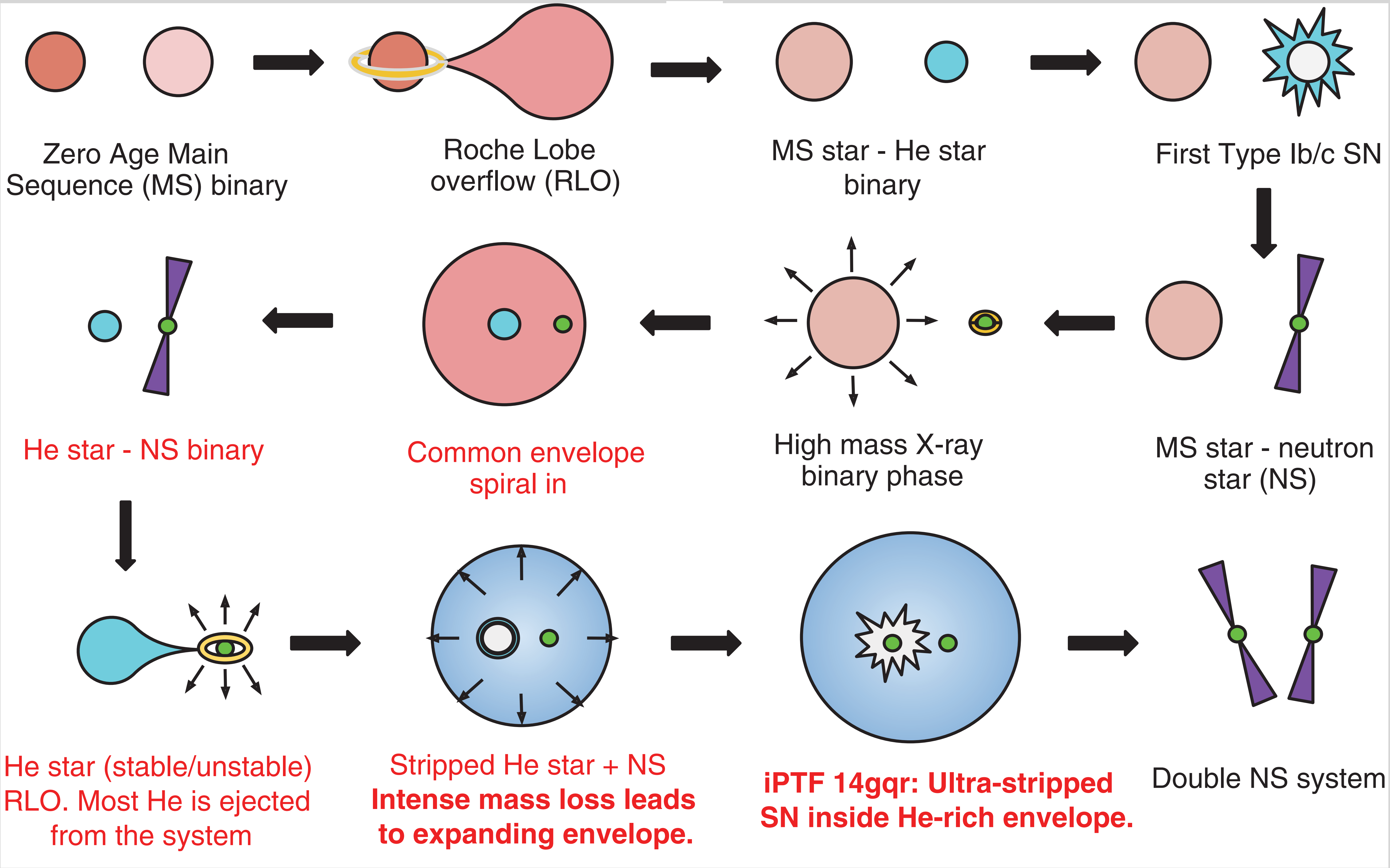
For $M_{^{56}\mathrm{Ni}} \gtrsim 0.2 M_\odot$**,**

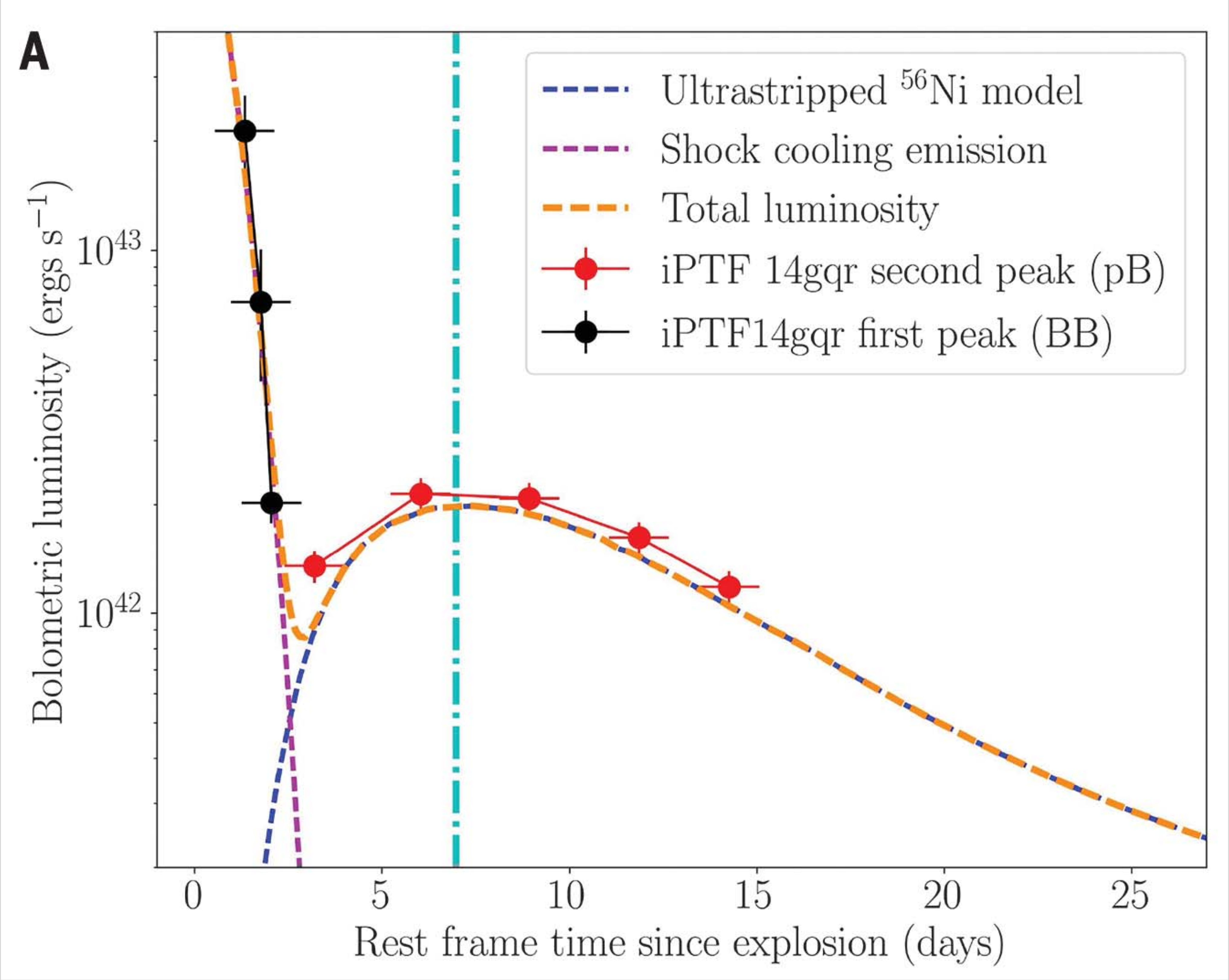
$$\left(\frac{B_p}{10^{16}\mathrm{G}}\right)^{1/2}\left(\frac{\Omega_i}{10^4 \mathrm{rad\,s^{-1}}}\right) \gtrsim 1.$$

It is compatible with prompt emission of GRBs , but is incompatible with late activity like X-ray flares during afterglow…

^{56}Ni problem in ultra-stripped supernova

De+ (2018)



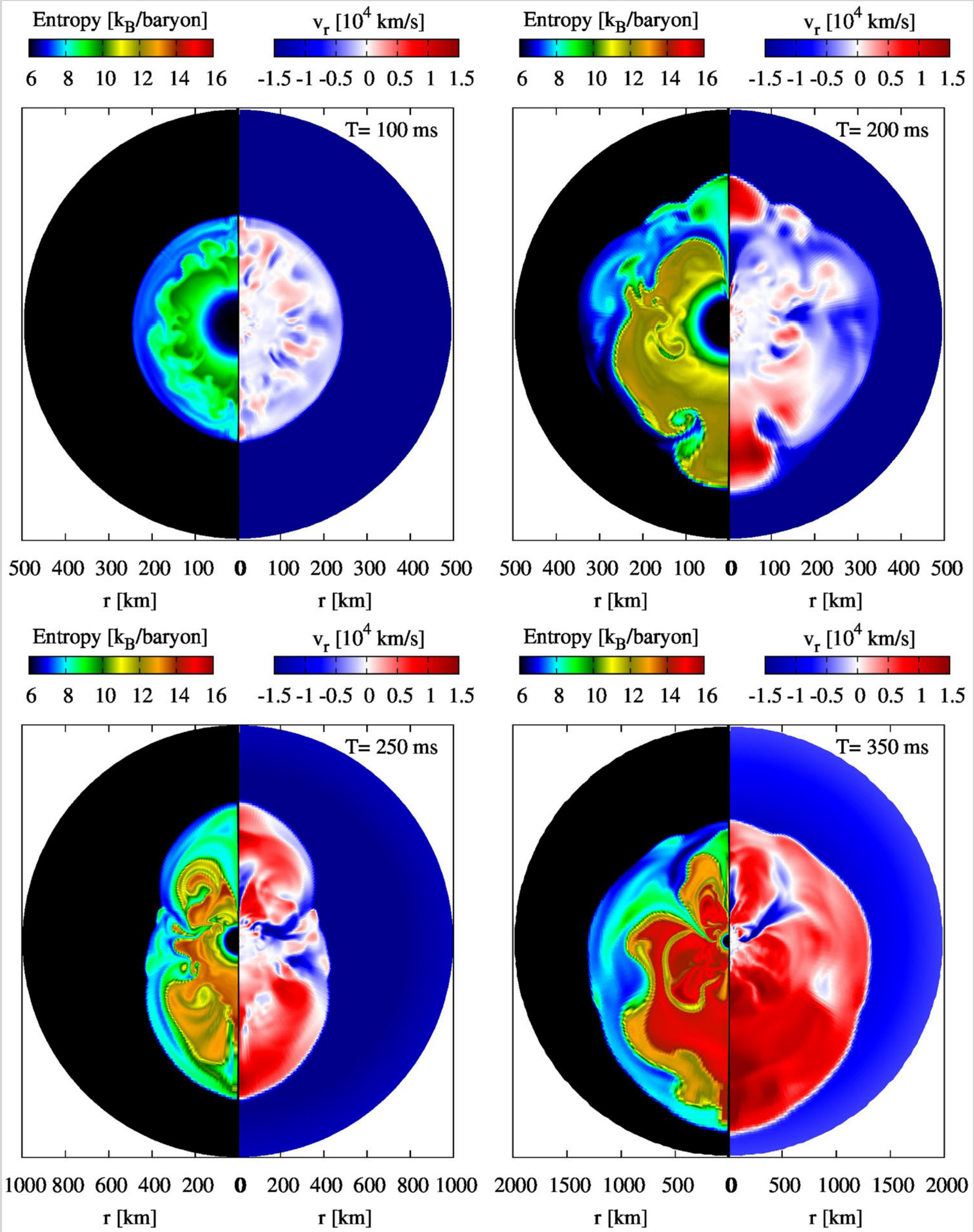


$$M_{\rm ej} = 0.2 M_\odot, E_{\rm K} = 2 \times 10^{50} {\rm erg},$$

$$M_{^{56}{\rm Ni}} = 0.05 M_\odot$$

Neutrino-driven explosion and nucleosynthesis in USSN

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, 454, 3073 (2015)]
[Yoshida, Suwa, Umeda, Shibata, Takahashi, MNRAS, 471, 4275 (2017)]



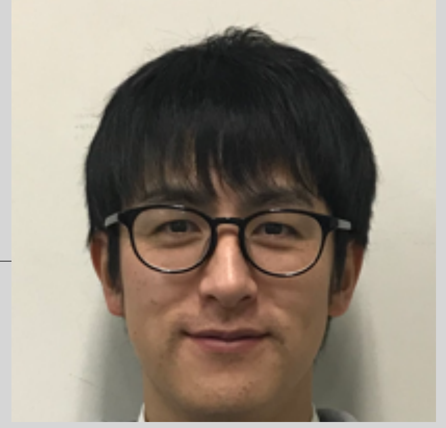
Model	$t_{\rm final}$[a] (ms)	$R_{\rm sh}$[b] (km)	$E_{\rm exp}$[c] (B)	$M_{\rm NS,\,baryon}$[d] ($M_\odot$)	$M_{\rm NS,\,grav}$[e] ($M_\odot$)	$M_{\rm ej}$[f] ($10^{-1}\,M_\odot$)	$M_{\rm Ni}$[g] ($10^{-2}\,M_\odot$)	$v_{\rm kick}$[h] (km s^{-1})
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20[i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

looks ok

Since this amount is based on temperature alone, we performed detailed nucleosynthesis study in which Ye is also taken into account, and found that $M_{Ni}<0.01M_\odot$

Combined w/ compatible expl. ener., Ni problem in USSN is more problematic

Systematic study of Ni amount in USSN



[Sawada, Kashiyama, Suwa, to appear soon]

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Summary

* ^{56}Ni is the most important element in SN
* ^{56}Ni provides thermal condition deep inside SN engine
* To produce enough amount of ^{56}Ni, we need rapid growth of the explosion energy as $\dot{E} \gtrsim 10^{51}\,\mathrm{erg\,s^{-1}}$, which is much larger than numerical results (Ni problem)
* Neutrino-driven wind is difficult to solve Ni problem
* Not only canonical SN, other types also have Ni problem

* We may need more efficient energy transfer mechanism, or additional energy source