星の死：超新星爆発

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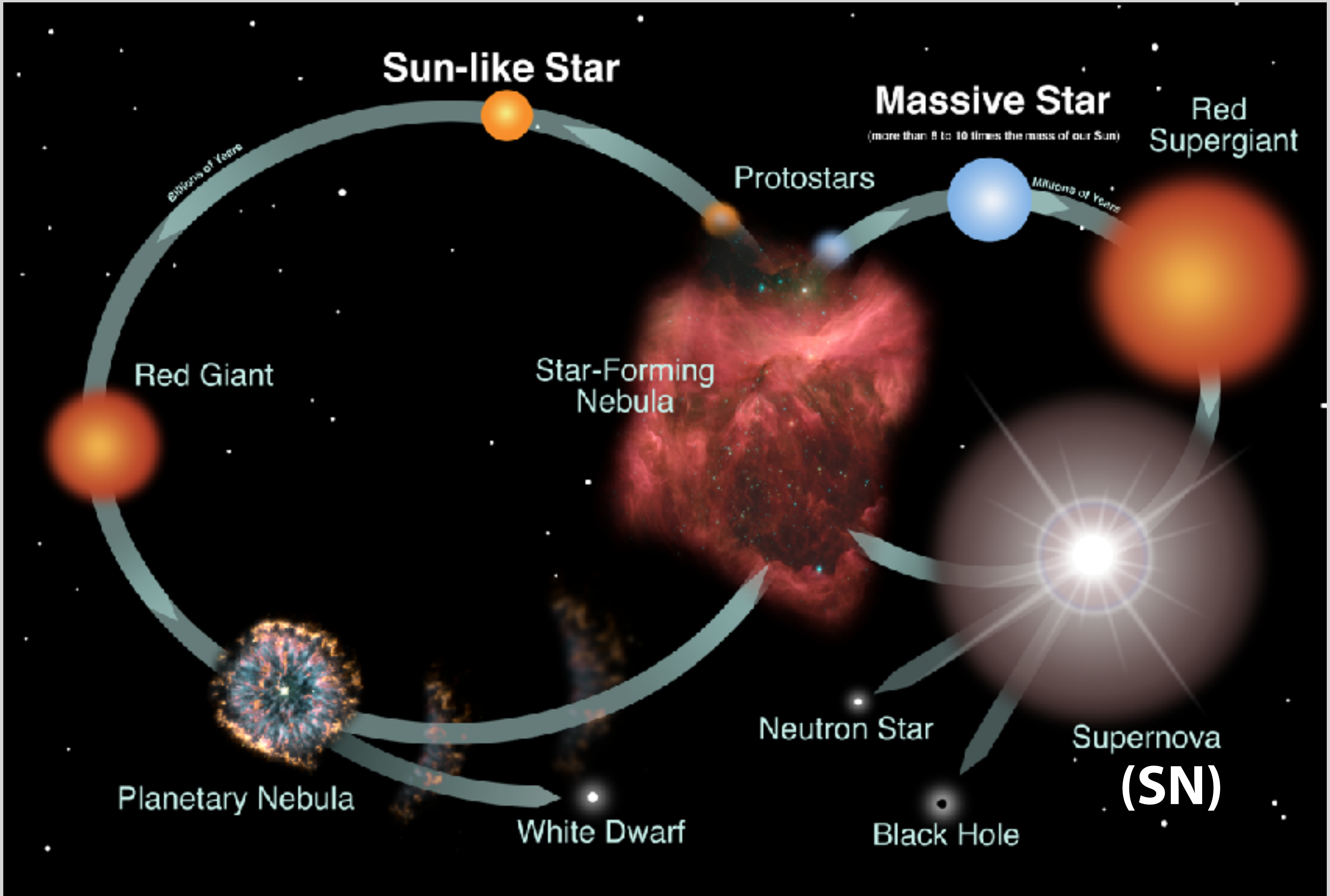
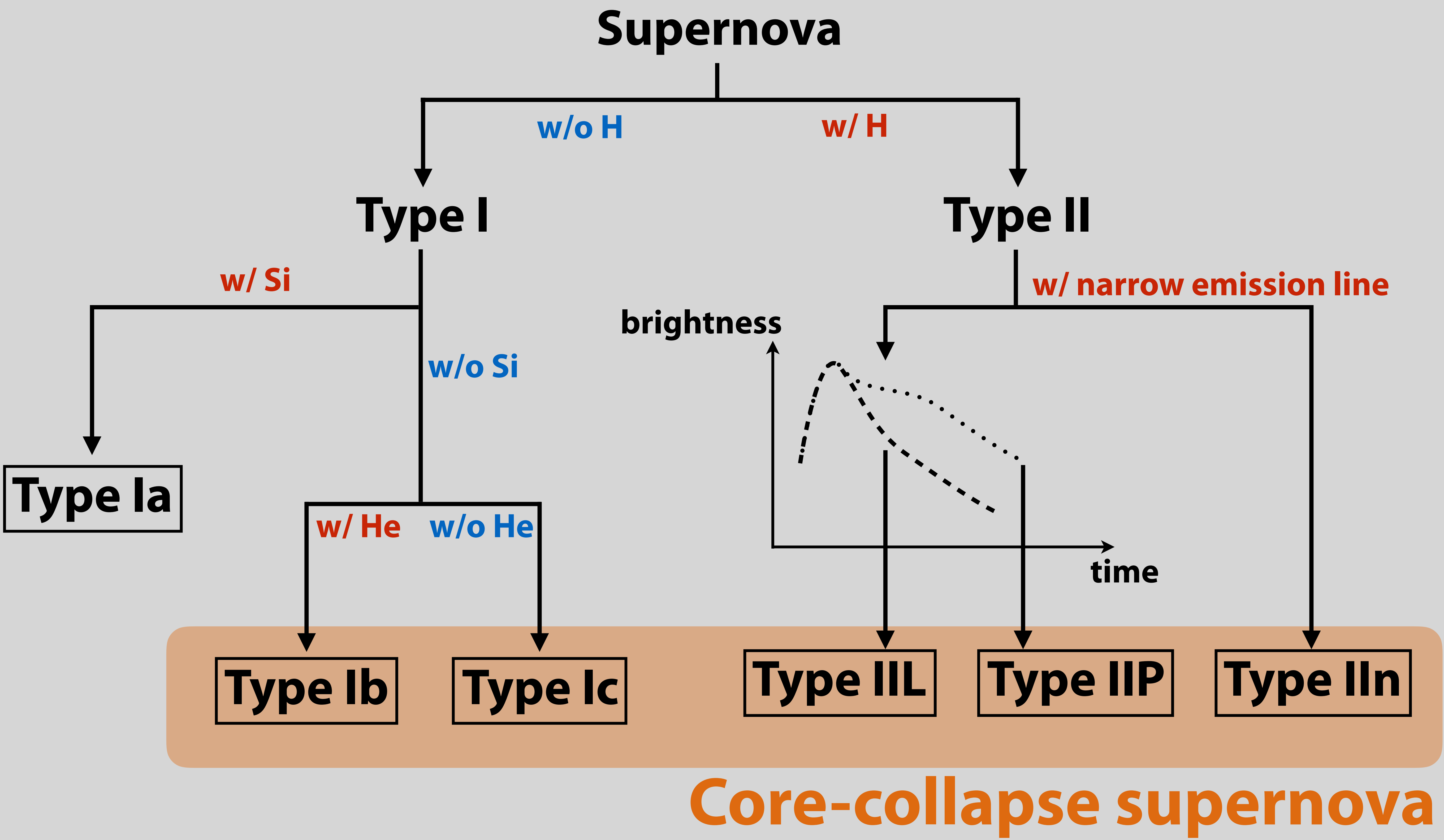
Life cycle of stars



(c) NASA and the Night Sky Network

Types of SNe


Supernova
w/o H
w/ H
Type I
Type II
w/ Si
w/o Si
w/ narrow emission line
brightness
time
Type Ia
w/ He
w/o He
Type Ib
Type Ic
Type IIL
Type IIP
Type IIn
Core-collapse supernova

Contents

* **Observation**
* **Theory**
* **Prospects**

Observation

Supernovae are made by neutron star formation

Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE
F. ZWICKY

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

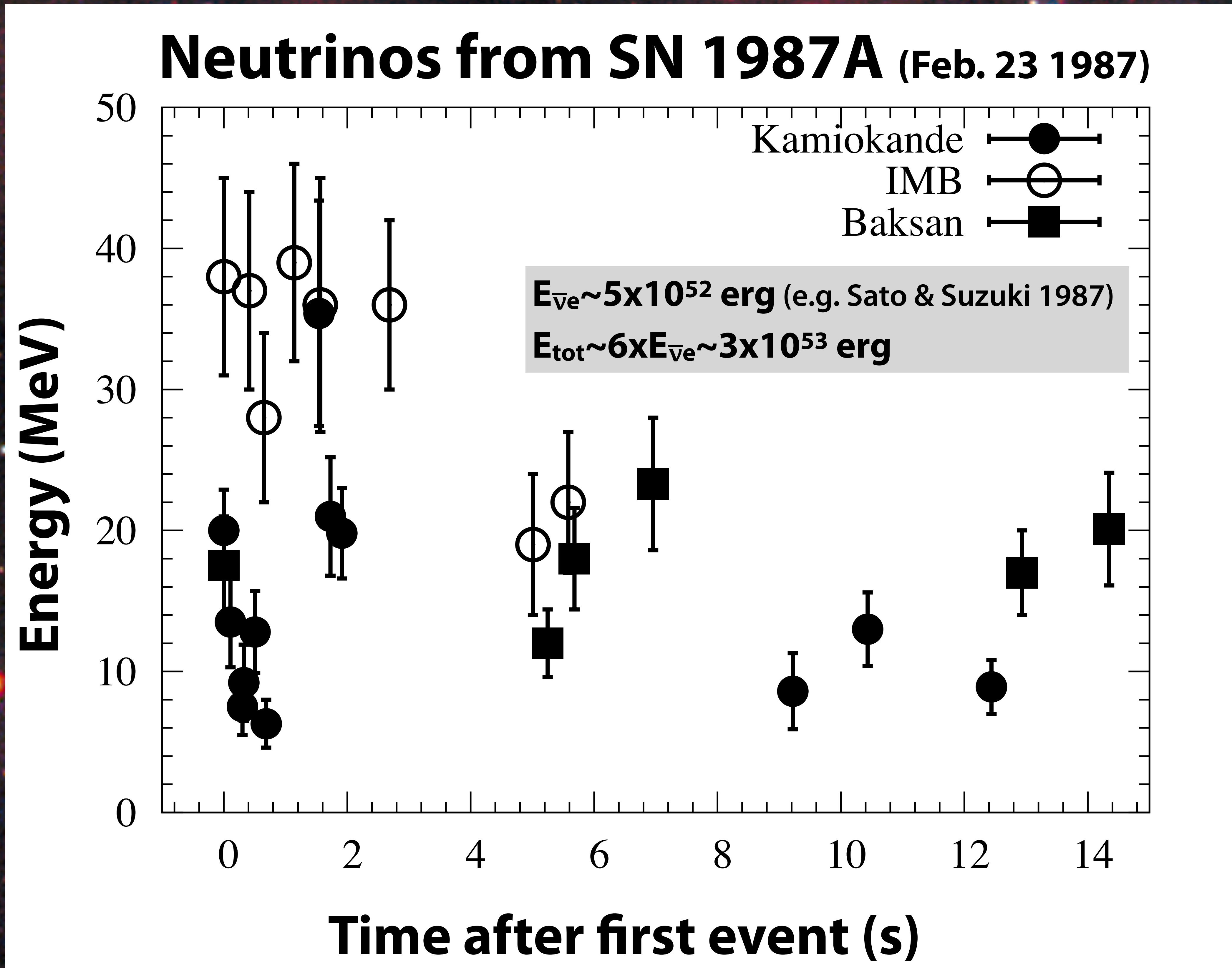
Baade & Zwicky (1934)

Evidence: Crab nebula

- **SN observed in 1054**
- **Pulsar inside SNR**

© NASA/ESA

Evidence: SN1987A

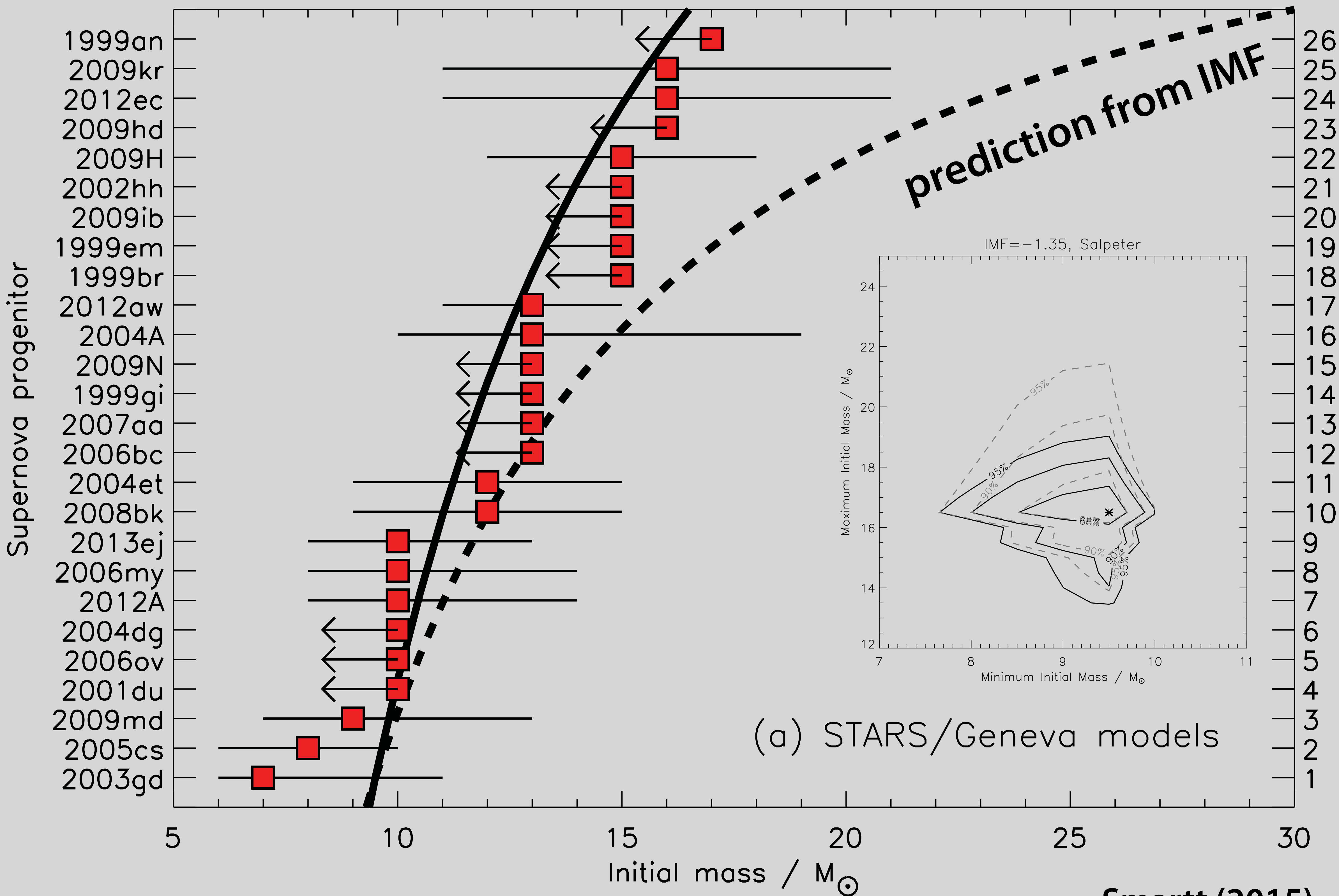


NASA/ESA

Galactic supernova rate

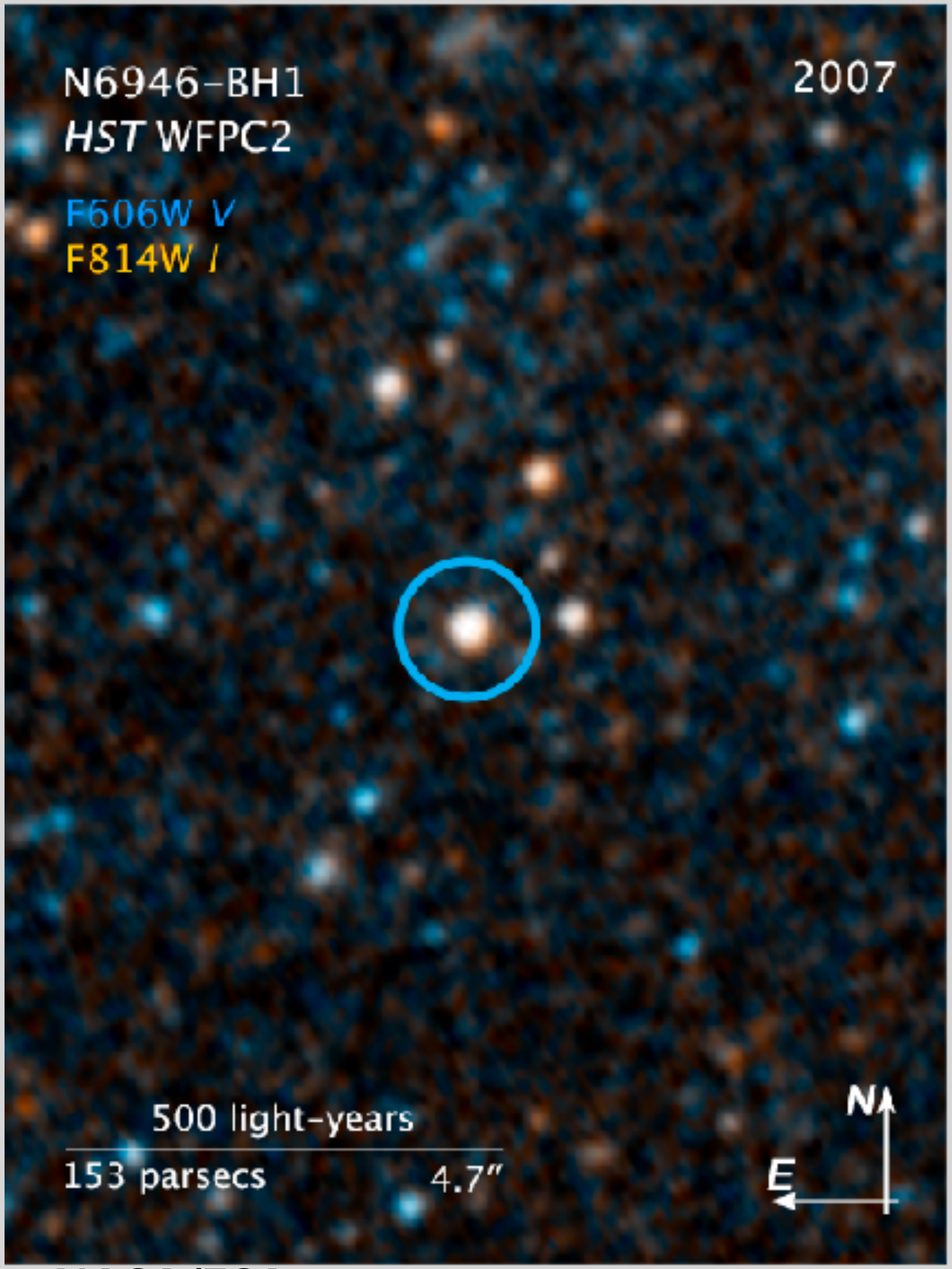
- **Estimate from historical events**
  - $R_{SN}=3.2^{+7.3}_{-2.6}$ century^{-1} (Adams et al. 2013)
- **Estimate from pulsar birth rate**
  - R_{pulsar}~2.8 century^{-1} (Faucher-Giguère & Kaspi 2006)
- **No galactic SN from 1992, based on neutrino observation**
  (Ikeda et al. 2007, Agafonova et al. 2015)

Progenitors of SNe: pre-SN images

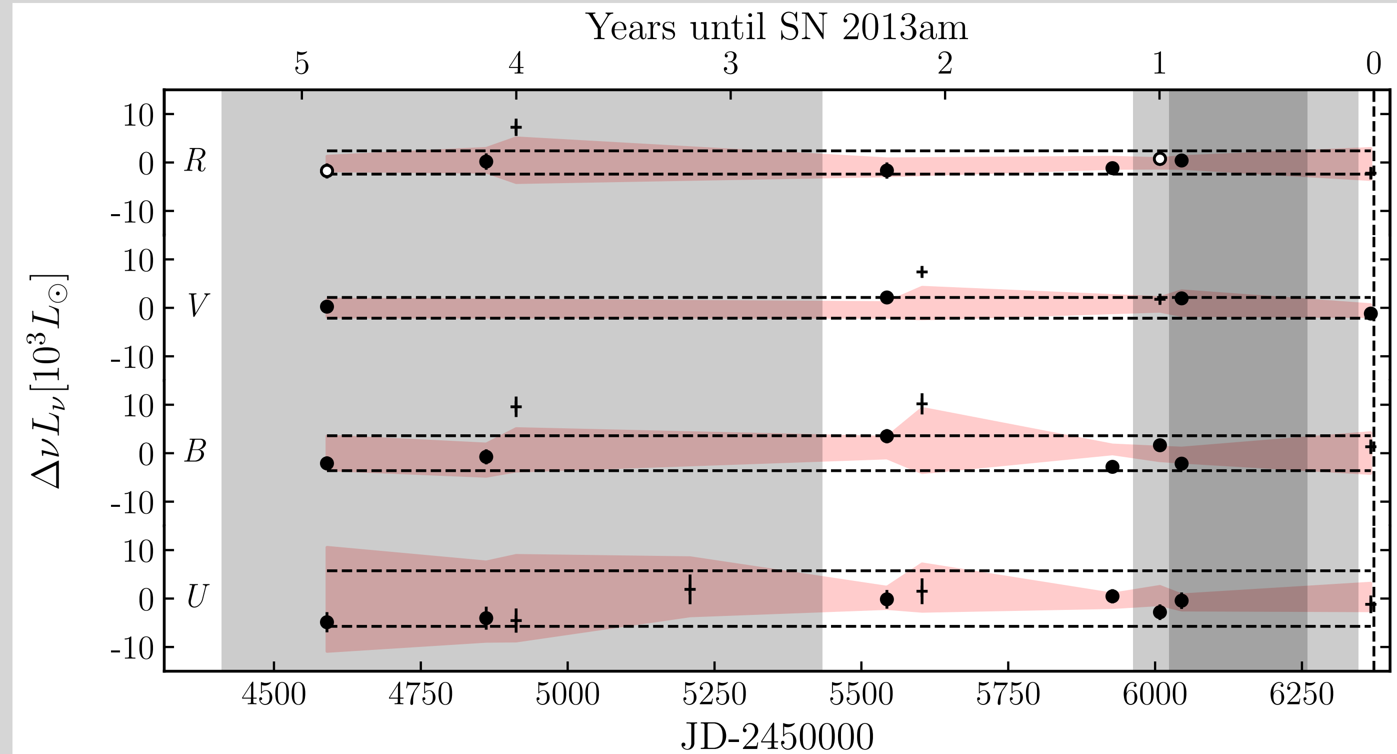


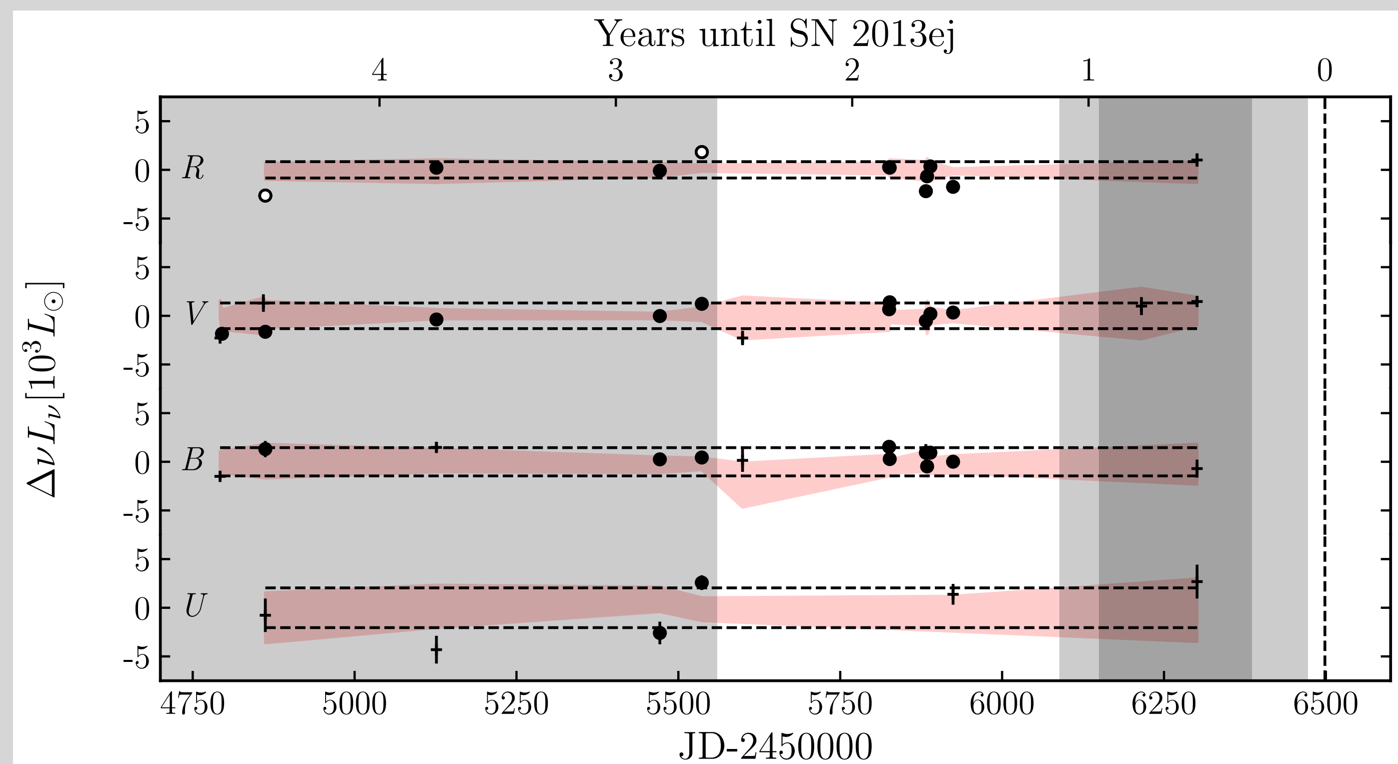
Smartt (2015)

Related interesting topics w/ pre-SN images



© NASA/ESA
Adams et al. (2017)

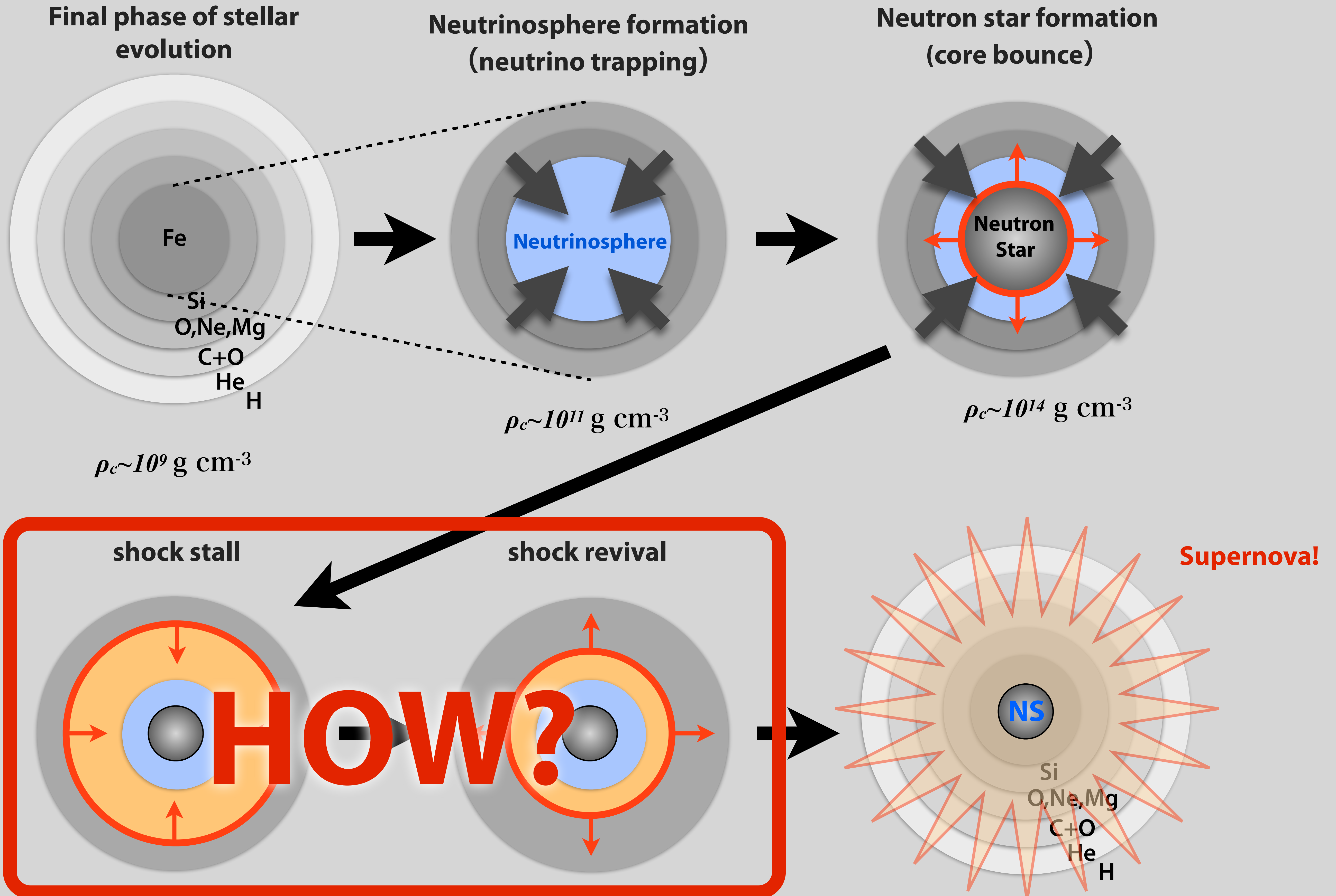




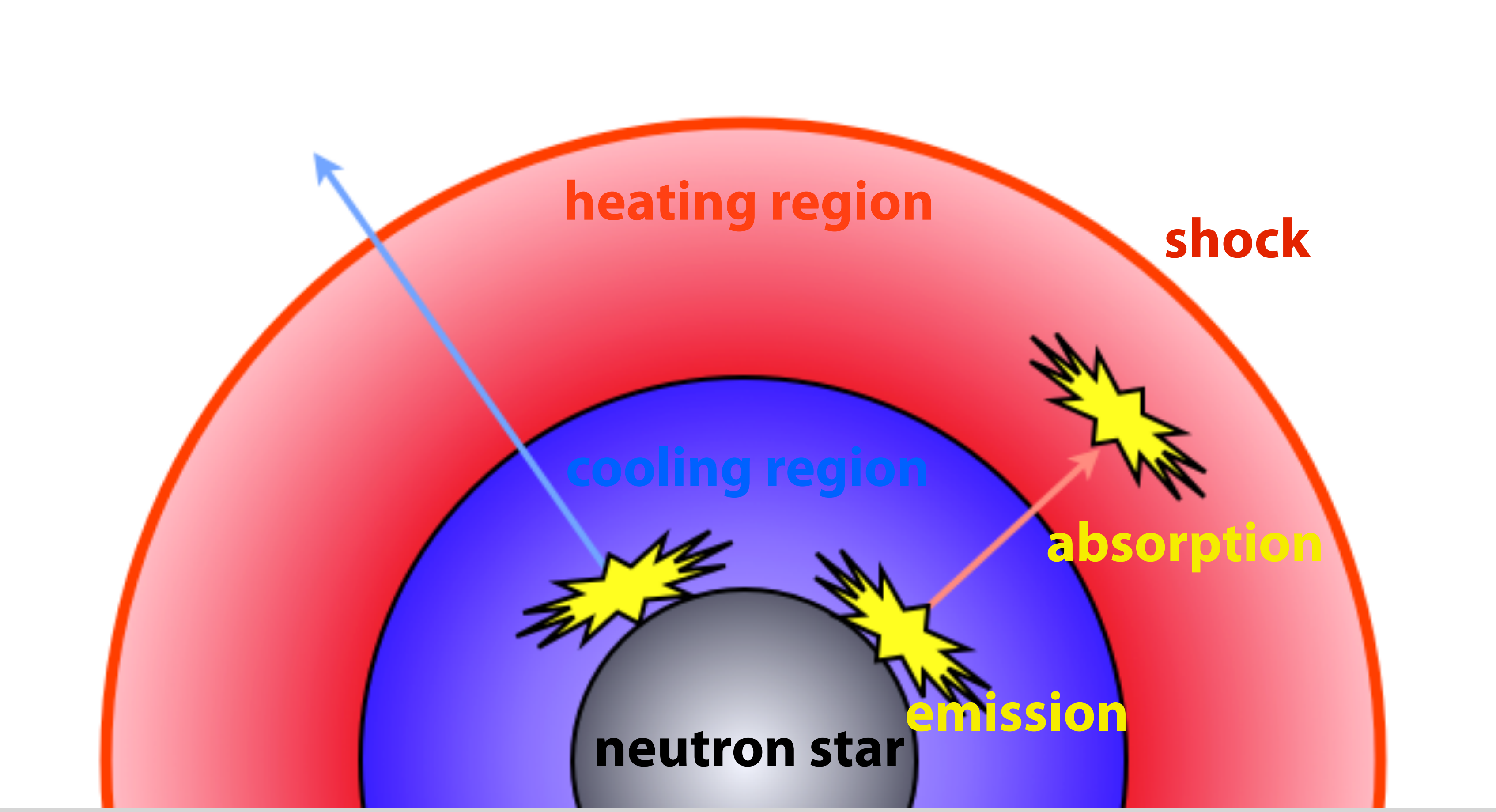
Johnson et al. (2017)

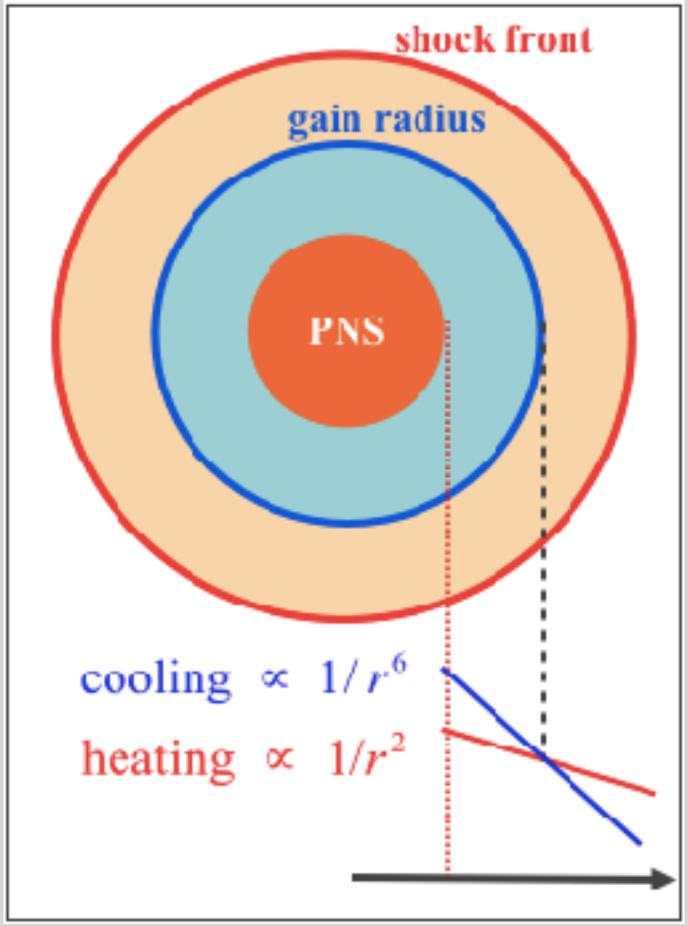
Theory

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

What do simulations solve?

stellar evolution

input: $\rho(r)$, $T(r)$, $Z_i(r)$, $v_r(r)$

Numerical table based on nuclear physics

e.g.) 10^3 g cm^{-3} < ρ < 10^{15} g cm^{-3}

0.1 MeV < T < 100 MeV

0.03 < Y_e <0.56

general relativity

Gravity

strong interaction

Nuclear equation of state

electro-magnetic interaction

(Magneto-)hydrodynamics

weak interaction

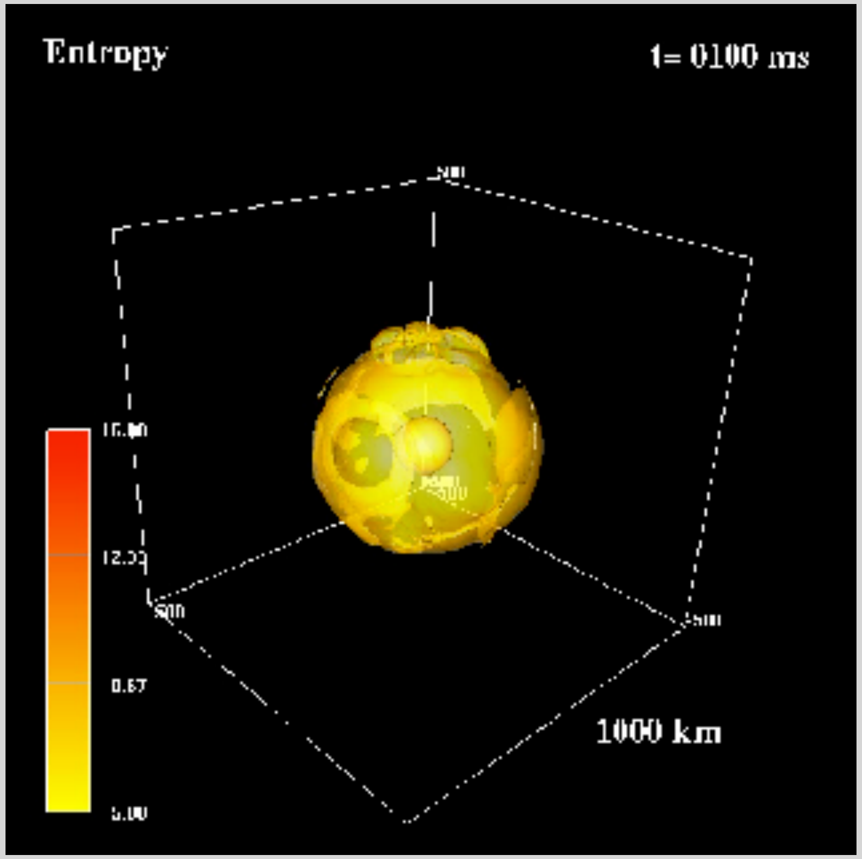
Neutrino transfer

Number of interactions;

$pe^- \leftrightarrow n\nu_e$, $ne^+ \leftrightarrow p\bar{\nu}_e$

$\nu e^\pm \leftrightarrow \nu e^\pm$, $\nu A \leftrightarrow \nu A$, $\nu N \leftrightarrow \nu N$

$\nu\bar{\nu} \leftrightarrow e^-e^+$, $NN \leftrightarrow \nu\bar{\nu}NN$, $\nu\bar{\nu} \leftrightarrow \nu\bar{\nu}$



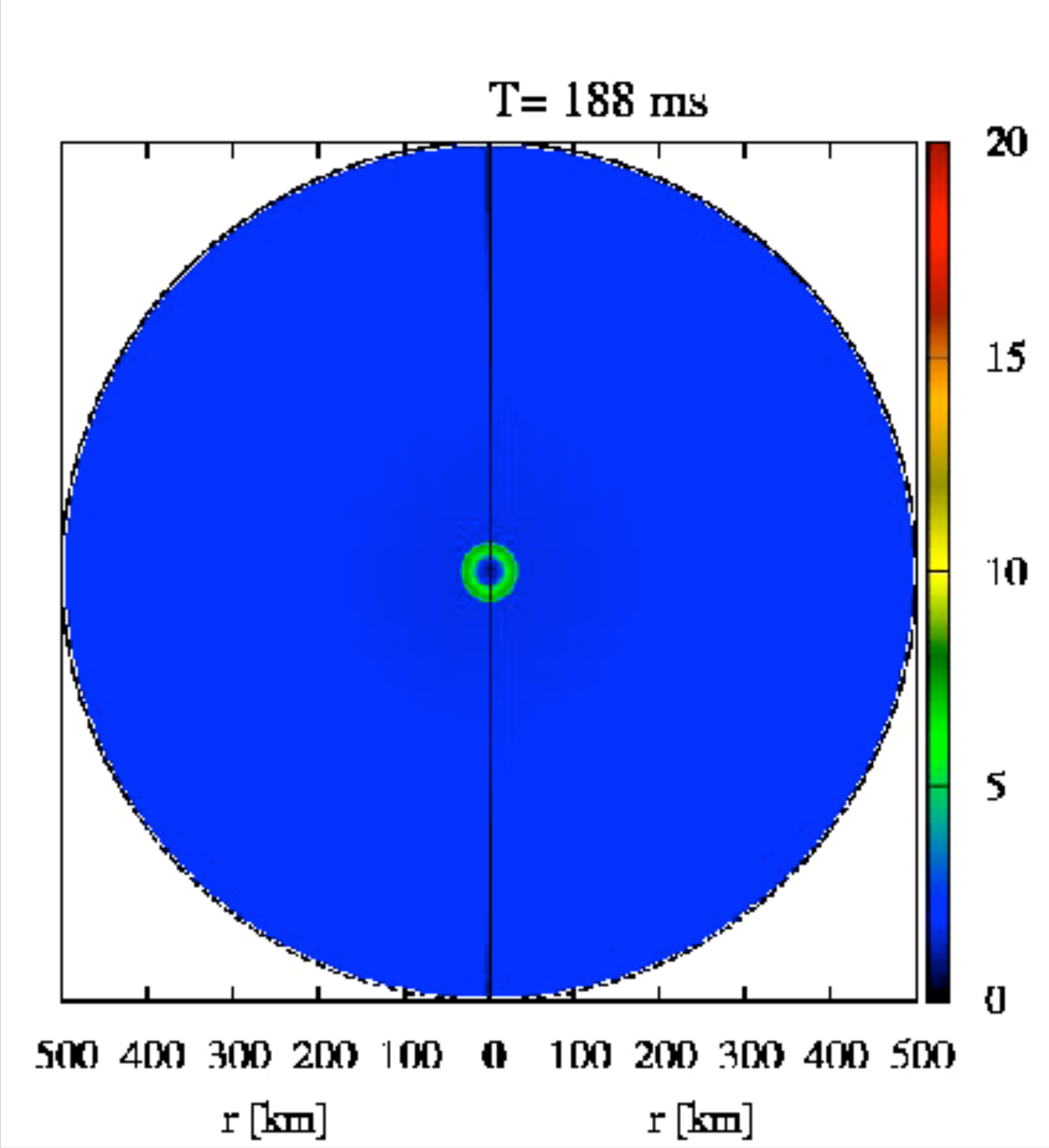
Takiwaki, Kotake, Suwa (2014)

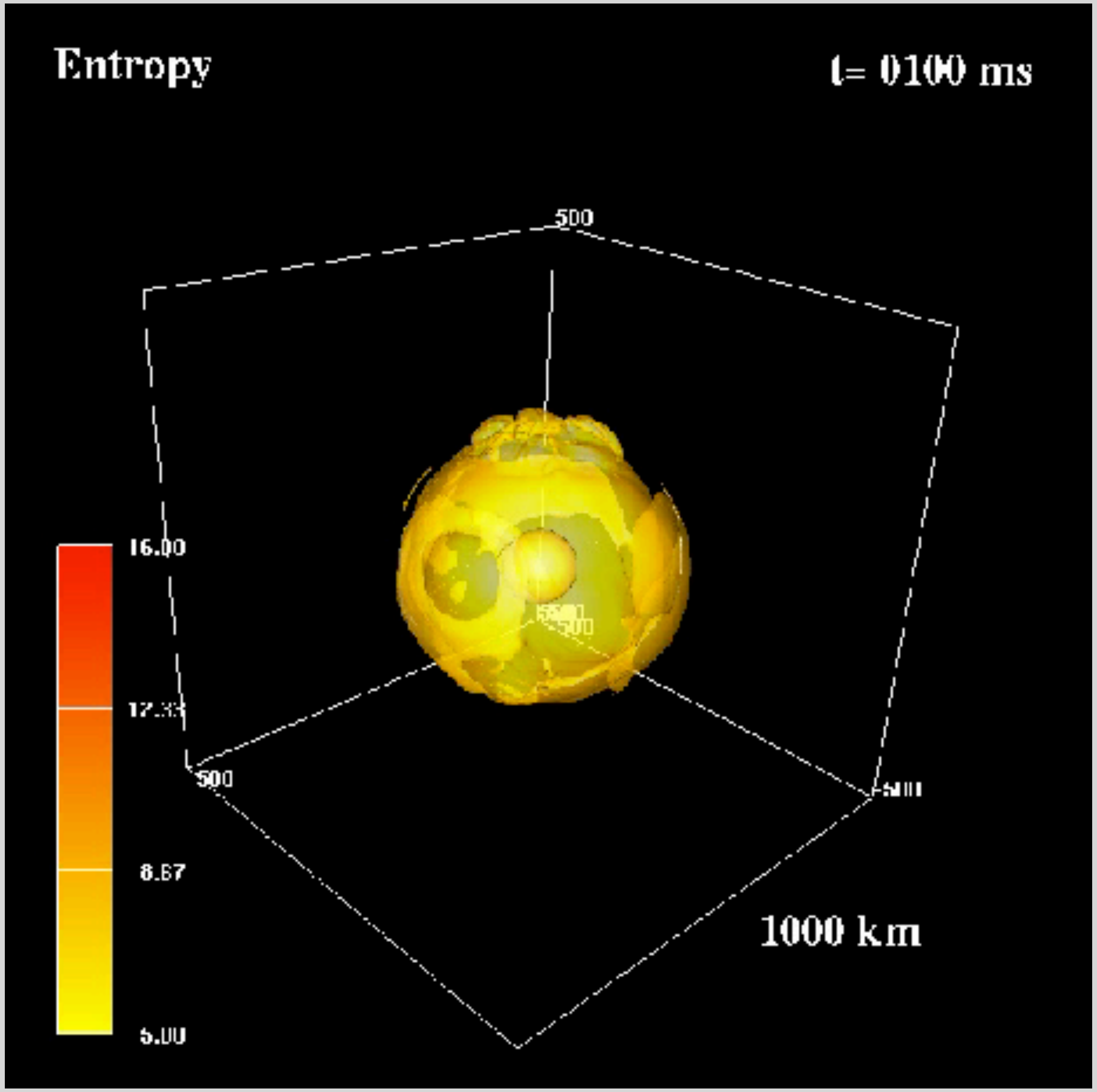
as first-principles as possible.

parameter free simulation!

Neutrino-driven explosion in multi-D simulation

Exploding models driven by neutrino heating with 2D/3D simulations





see also, e.g.,
Marek & Janka (2009), Müller+ (2012), Bruenn+ (2013), Obergaulinger+ (2014), Pan+ (2016), O'Connor & Couch (2015), Nagakura+ (2017)

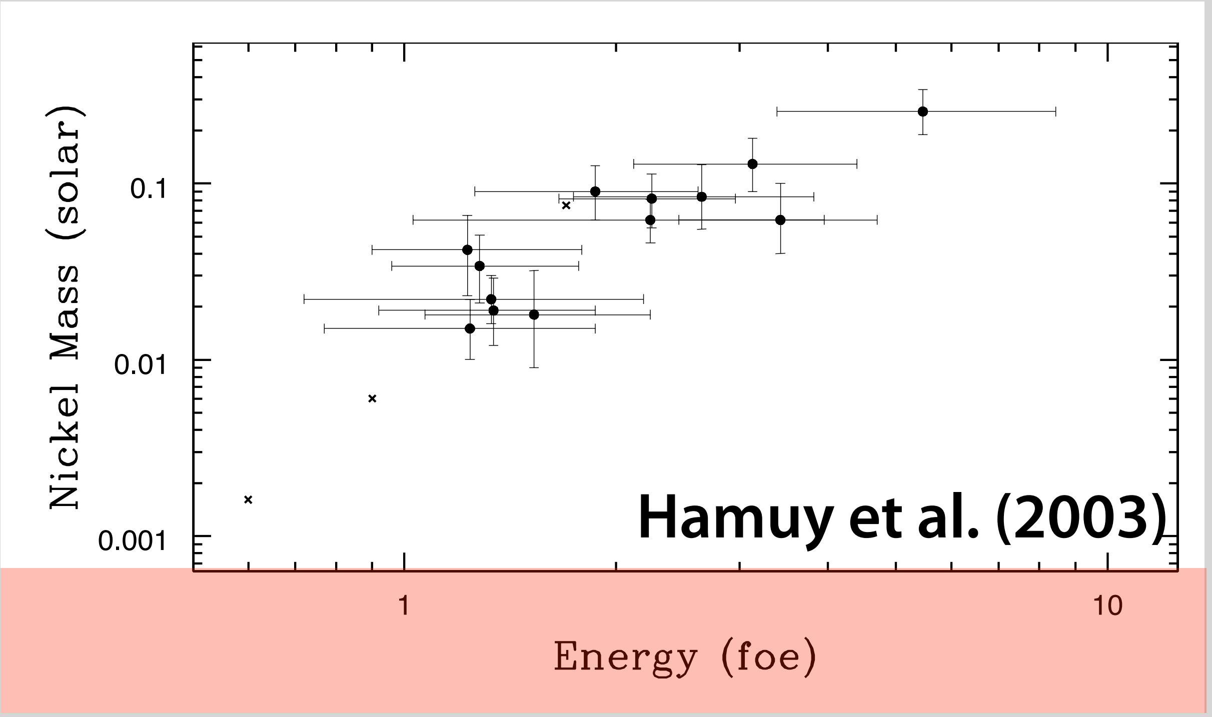
Suwa+ (2D)
- PASJ, **62**, L49 (2010)
- ApJ, **738**, 165 (2011)
- ApJ, **764**, 99 (2013)
- PASJ, **66**, L1 (2014)
- MNRAS, **454**, 3073 (2015)
- ApJ, **816**, 43 (2016)

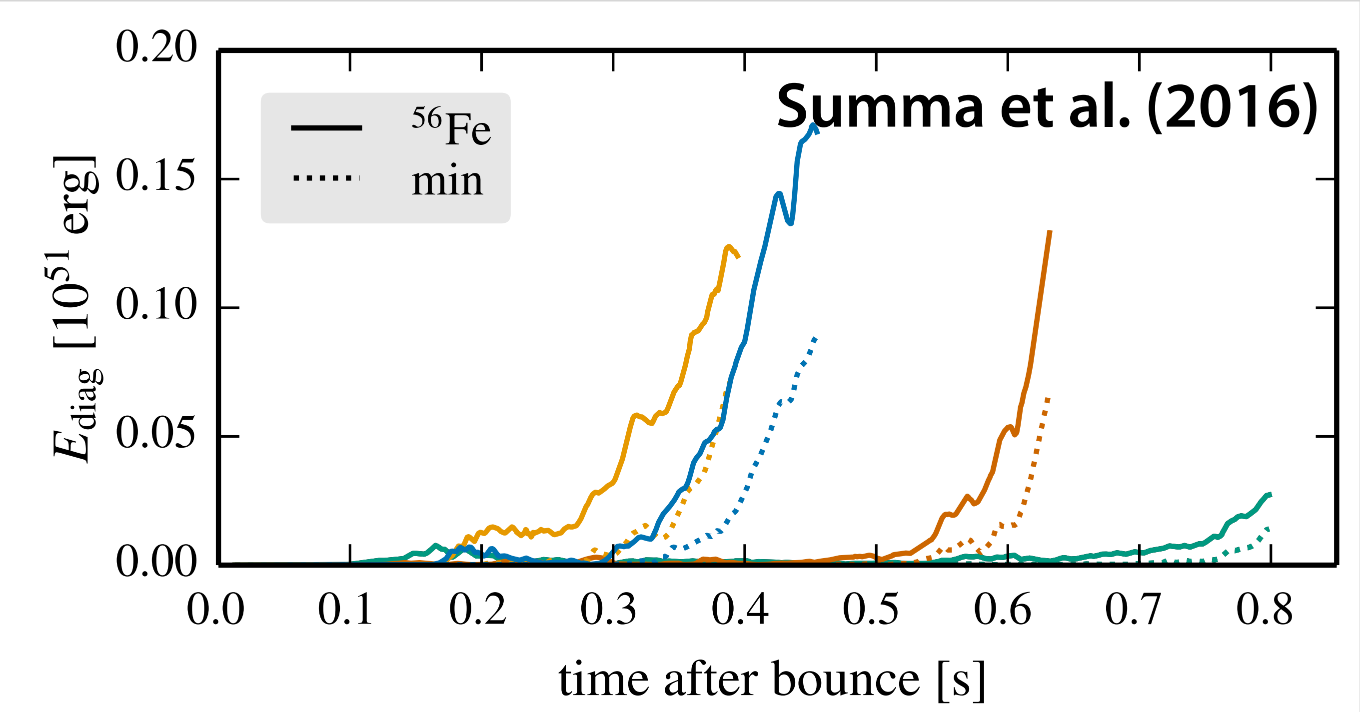
Takiwaki+ (3D)
- ApJ, **749**, 98 (2012)
- ApJ, **786**, 83 (2014)
- MNRAS, **461**, L112 (2016)

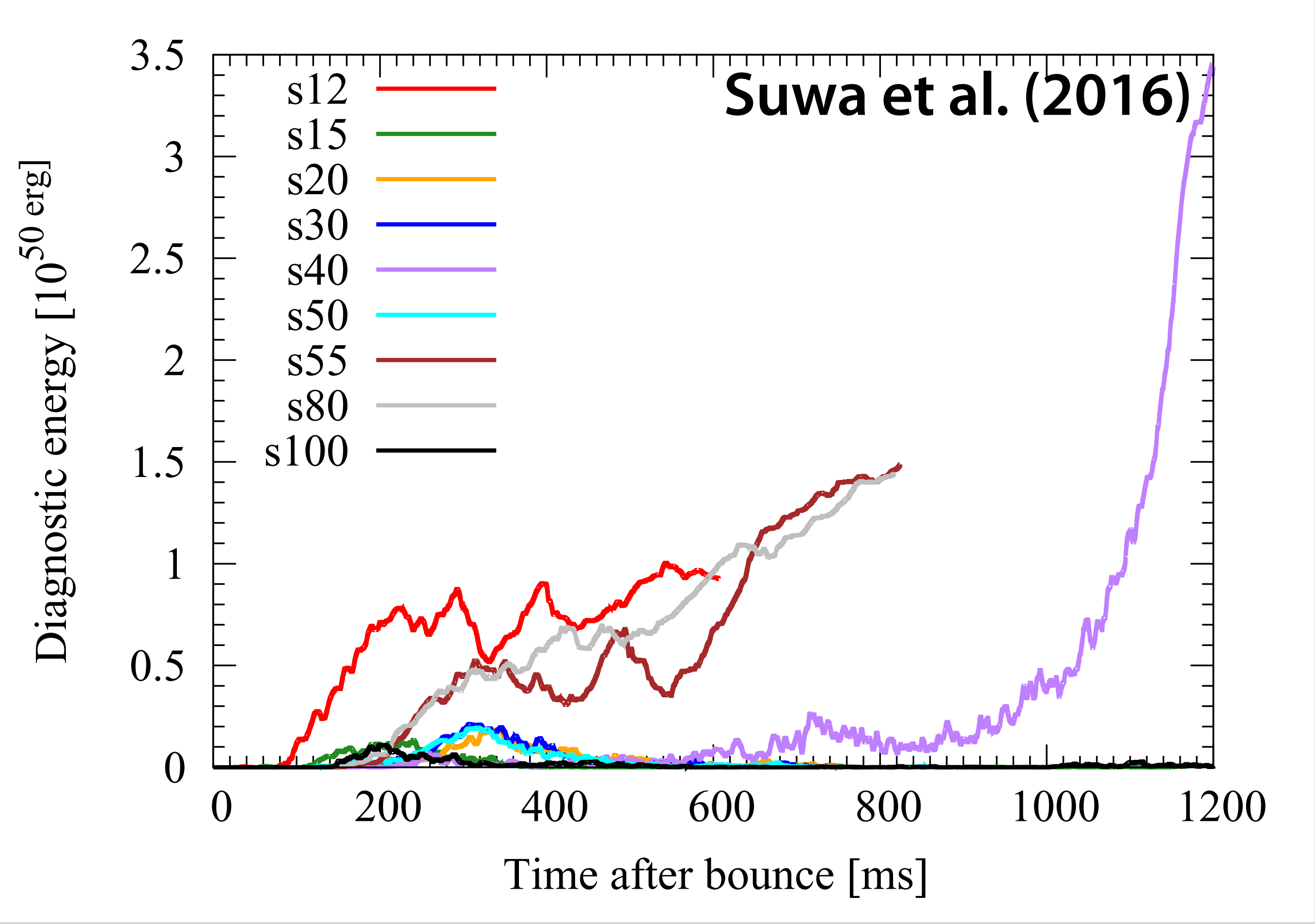
see also, e.g.,
Hanke+ (2013), Lentz+ (2015), Melson+ (2015), Müller (2015), Roberts+ (2016)

Explosion, explosion, and explosion

Problem 1: Insufficient explosion energy

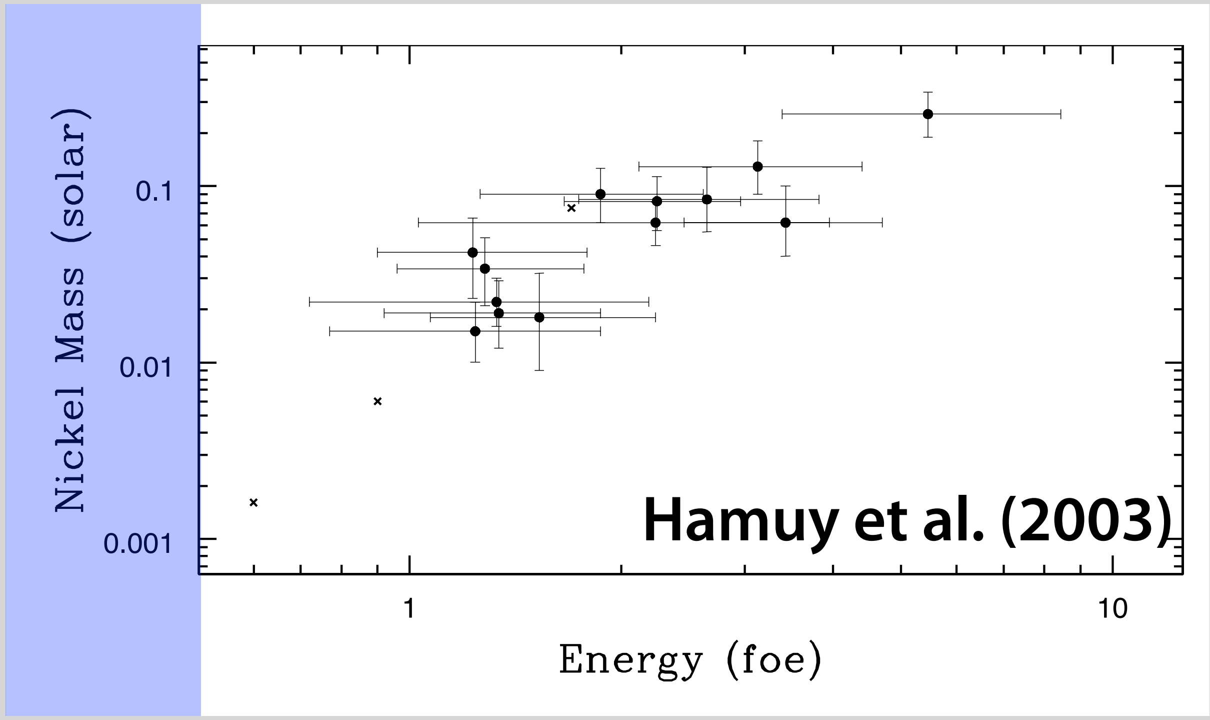


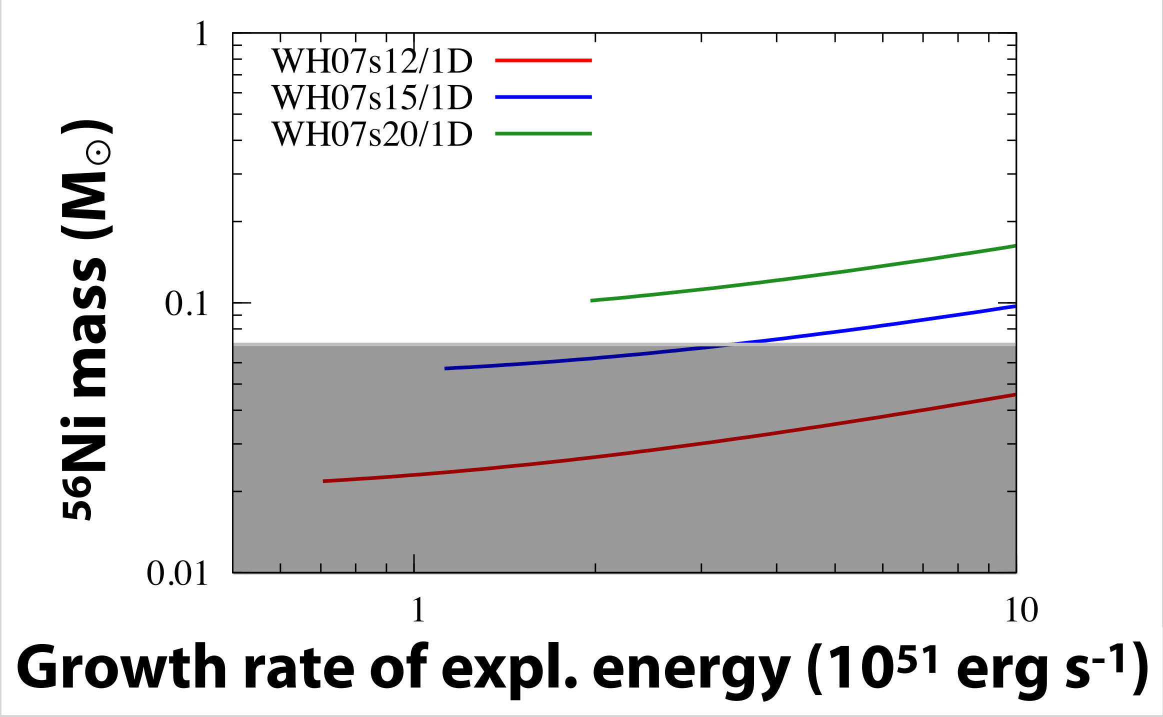




- **1 foe=10^{51} erg is necessary**
- **~10^{50}erg in simulations**
  - Can we extrapolate the growth of expl. ene. up to 10^{51} erg?

Problem 2: Insufficient ^{56}Ni mass





Suwa, Tominaga, Maeda (2017)

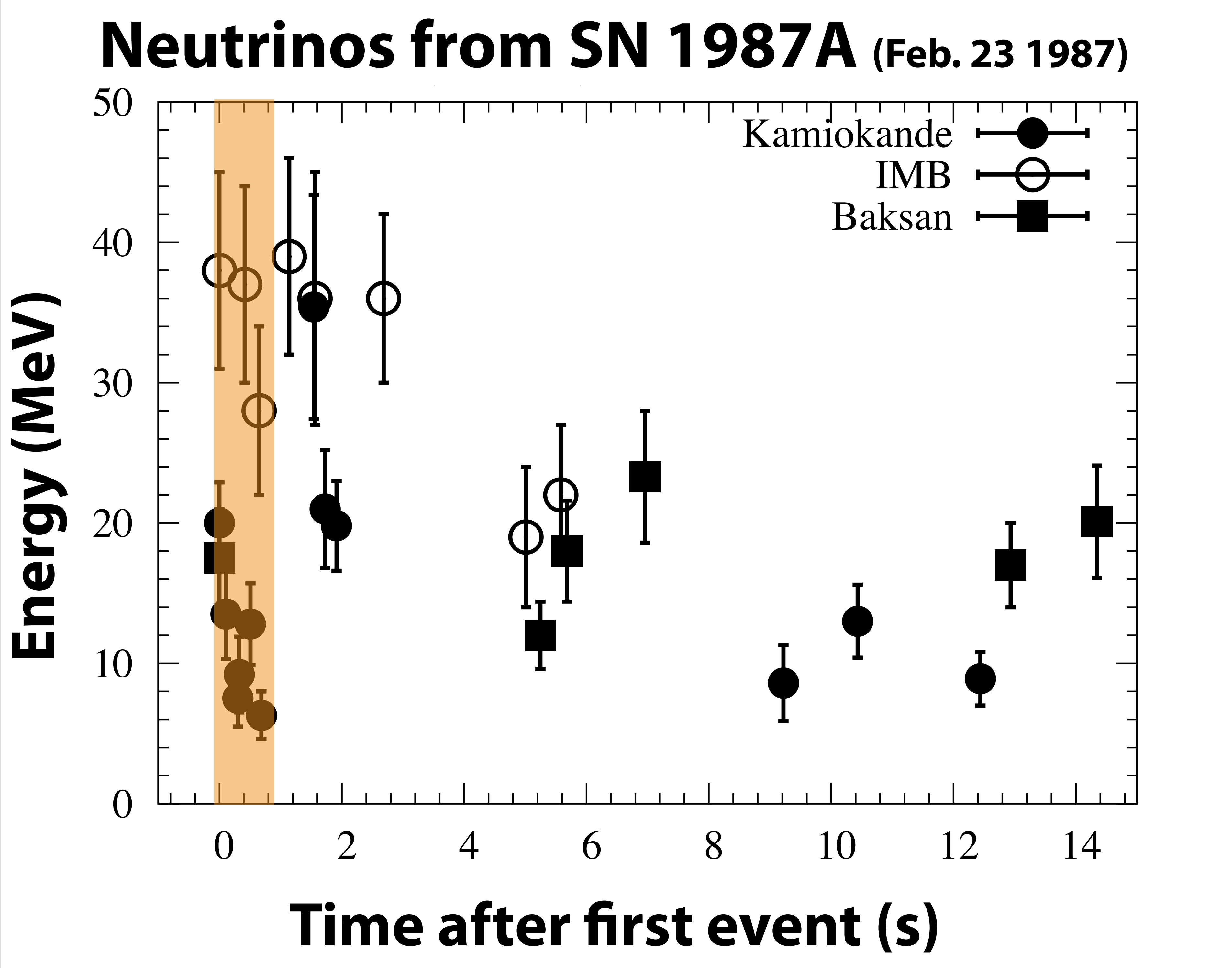
- **M(^{56}Ni) is primary observable of SN**
- **M(^{56}Ni)~0.1M$_\odot$ (typically 0.07M$_\odot$)**
- **T>5x10^9 K is necessary for ^{56}Ni production**
  - $E=(4\pi/3)r^3 aT^4 \Rightarrow T(r_{sh})=1.33\times10^{10}(E/10^{51}\mathrm{erg})^{1/4}(r_{sh}/1000\mathrm{km})^{-3/4}$ K
  - With E=10^{51}erg, r_{sh}<3700km for T>5x10^9K (Woosley et al. 2002)
- **^{56}Ni amount is more difficult to explain than explosion energy**

Personal prospects

* **Long-term simulations**
* **Binary interaction**
* **Progenitor structure**
* **Supernova forecast**

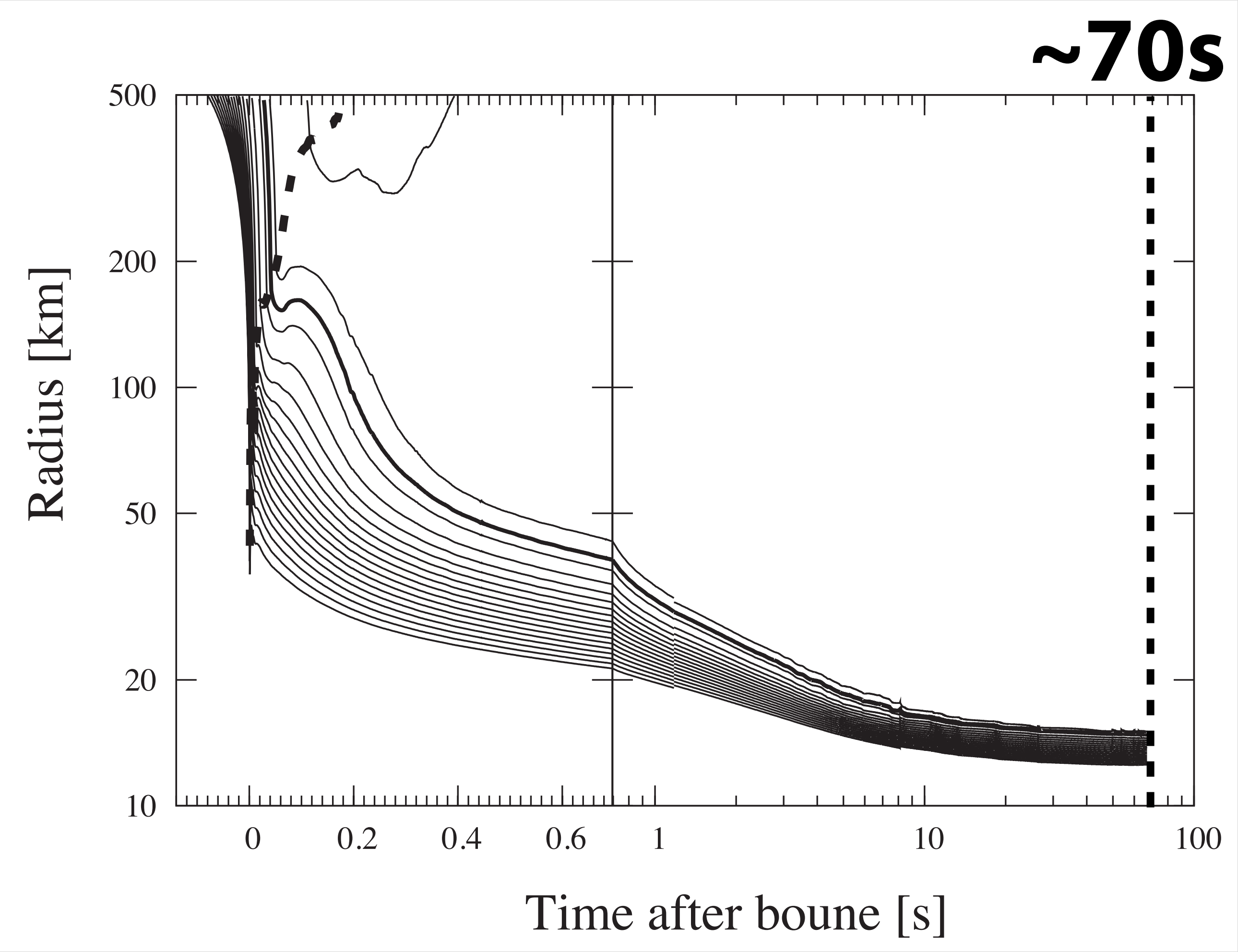
Long-term simulations are necessary

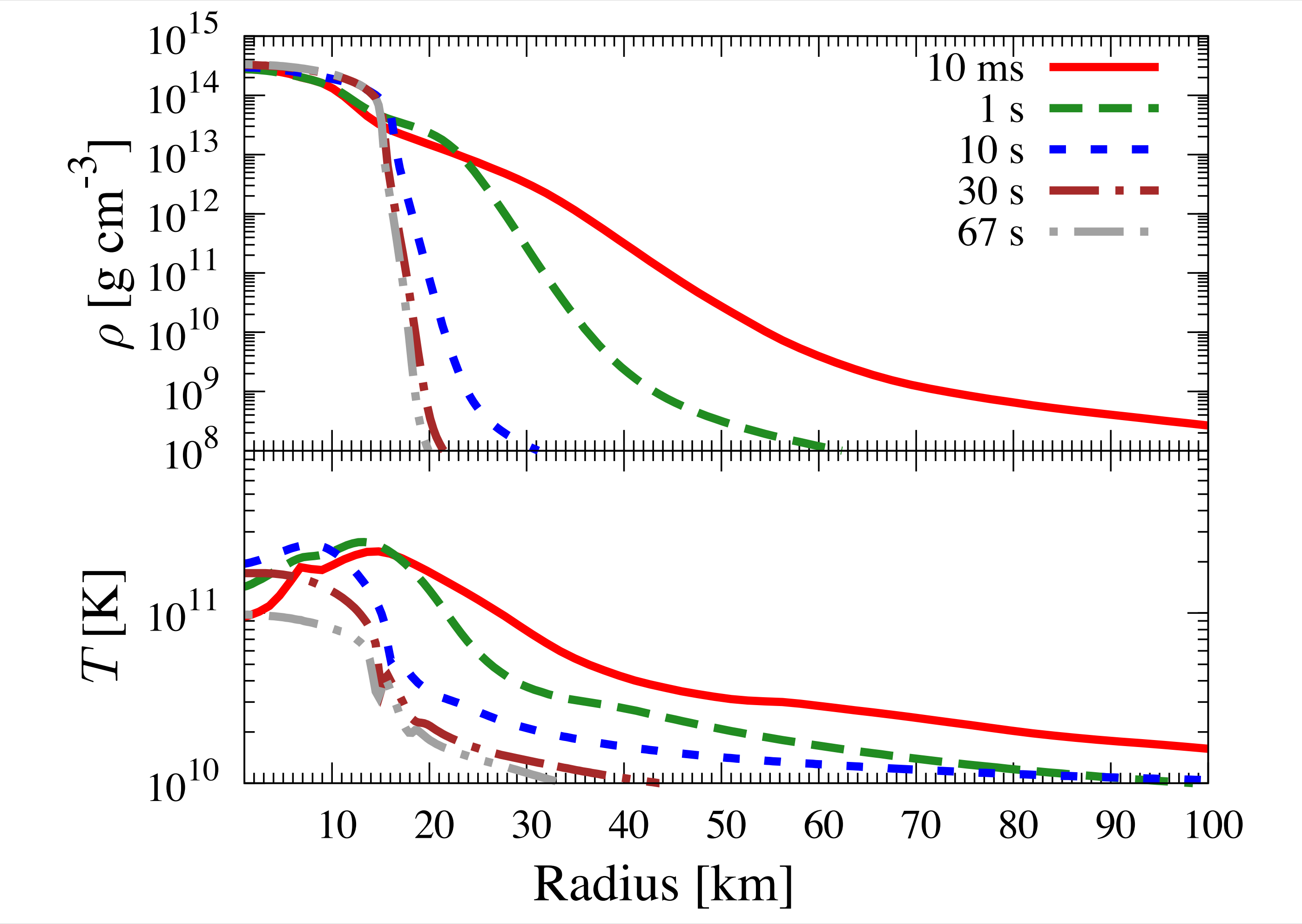
* **Detailed multi-D simulations are only available < ~1 s**



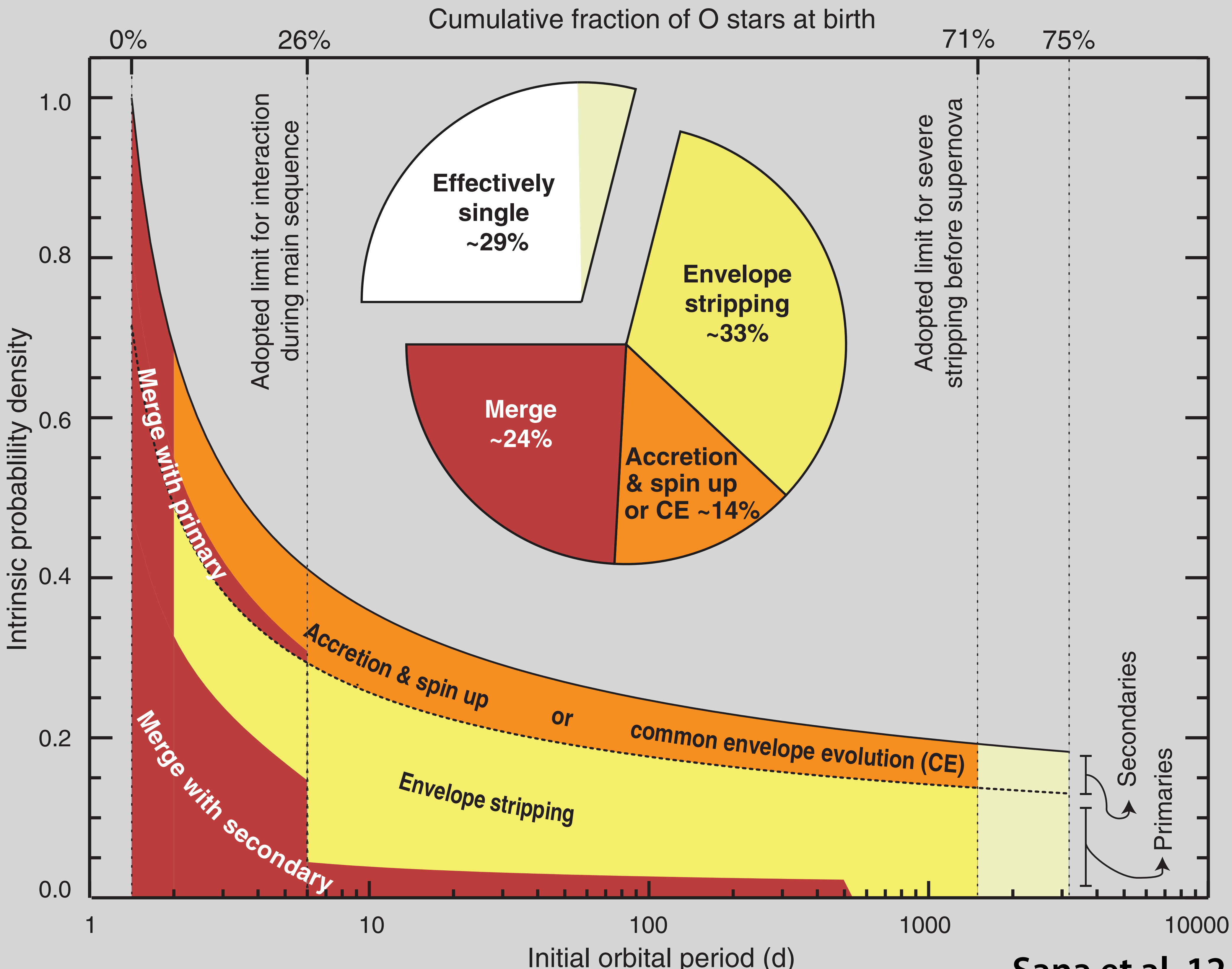
Long-term simulation is doable now

[Suwa, PASJ, 66, L1 (2014)]





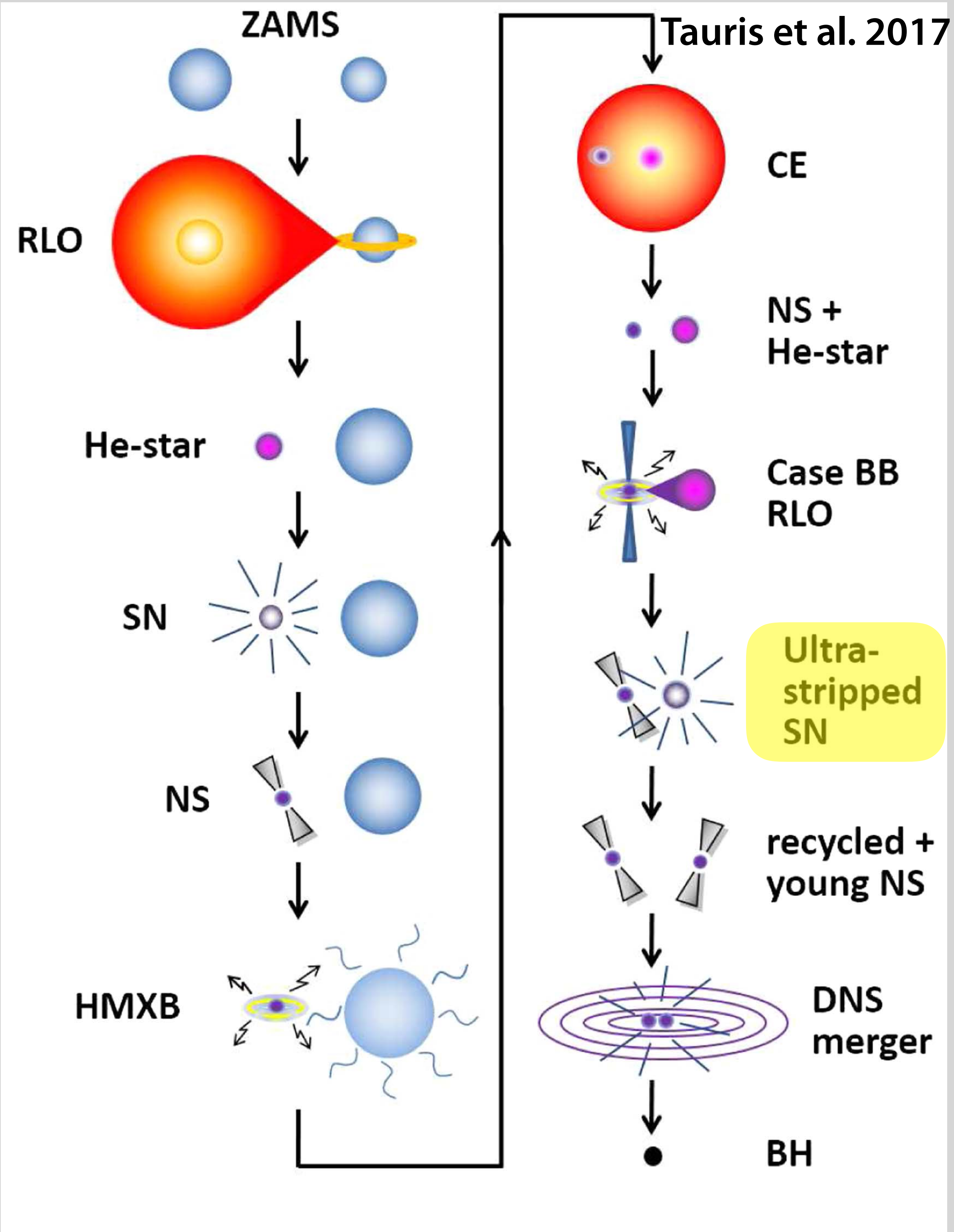
>70% of massive stars are in binary systems

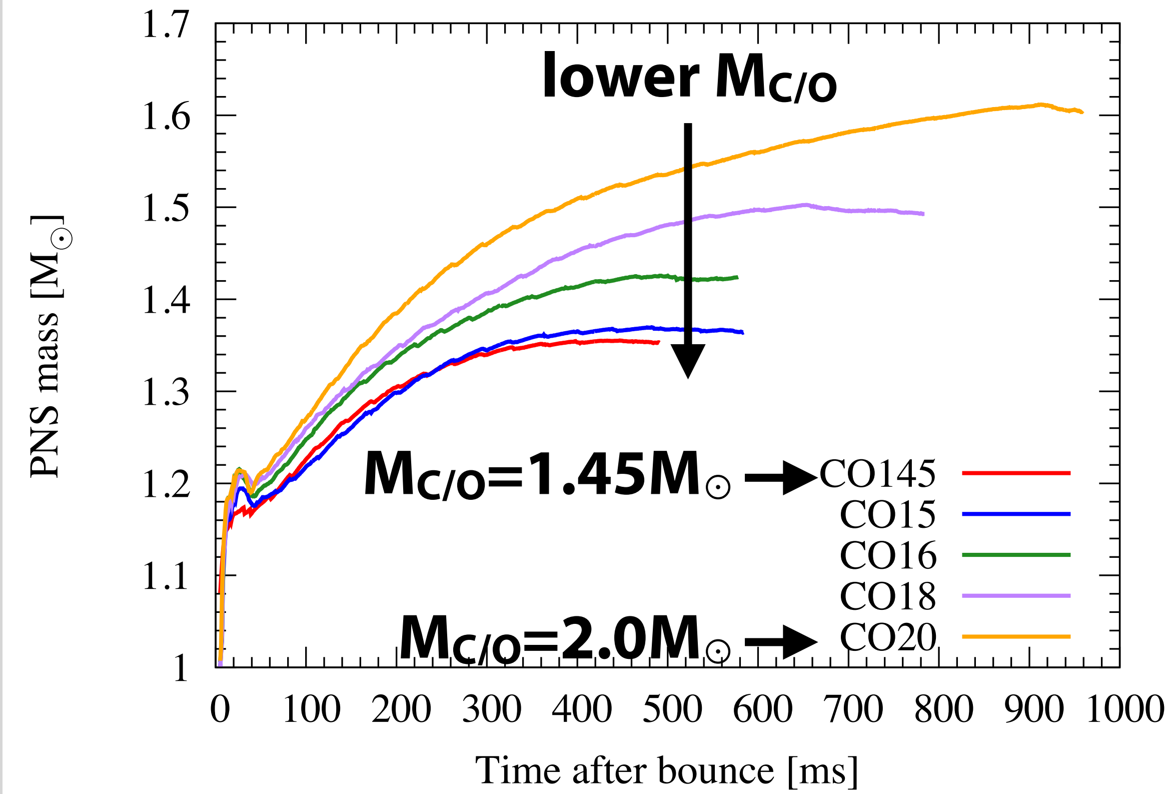


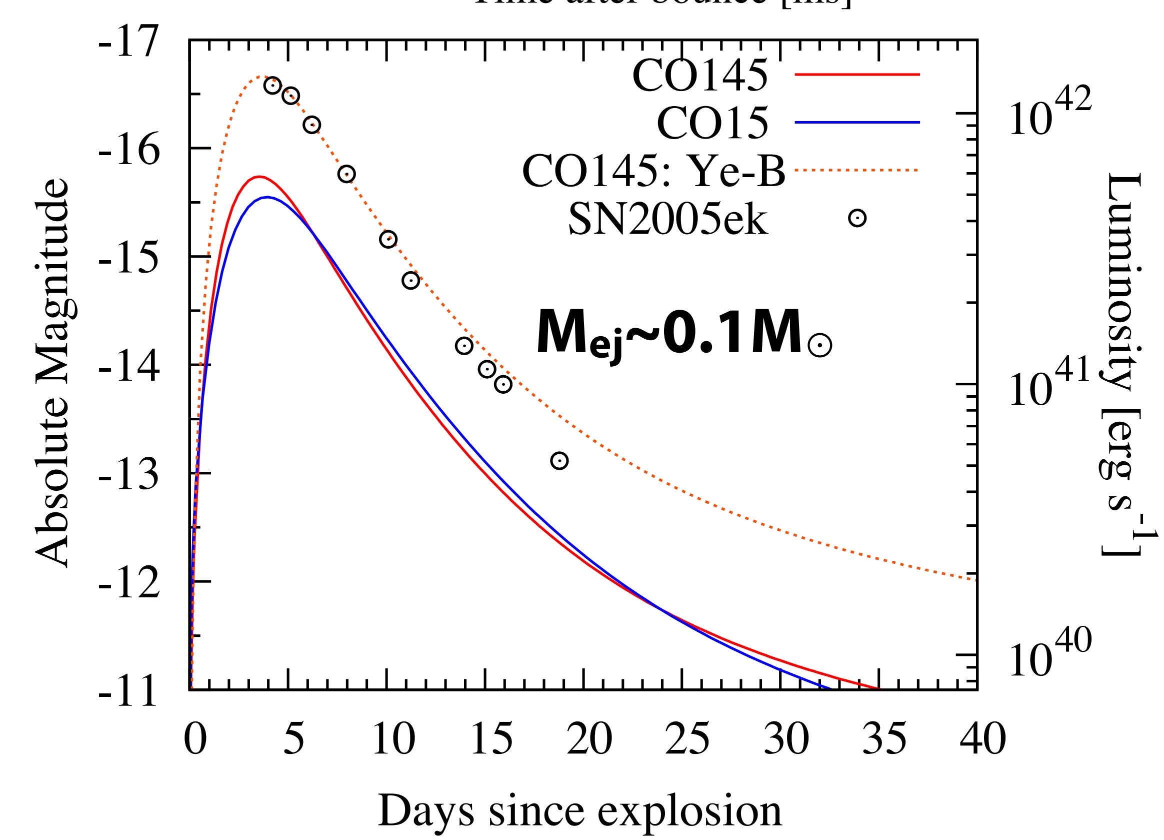
Sana et al. 12

SN after binary interaction: Ultra-stripped SN

[Suwa et al., MNRAS, 454, 3073 (2015); Yoshida et al., MNRAS, 471, 4275 (2017)]

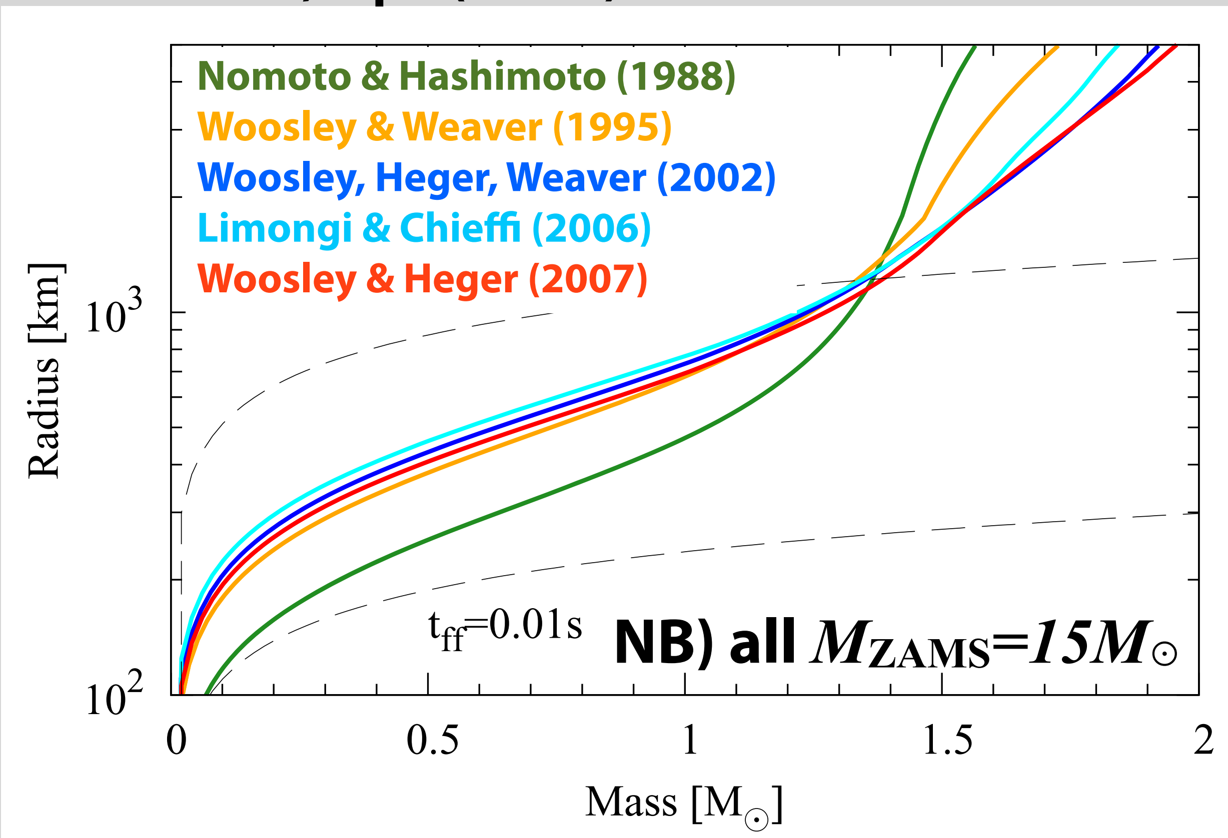






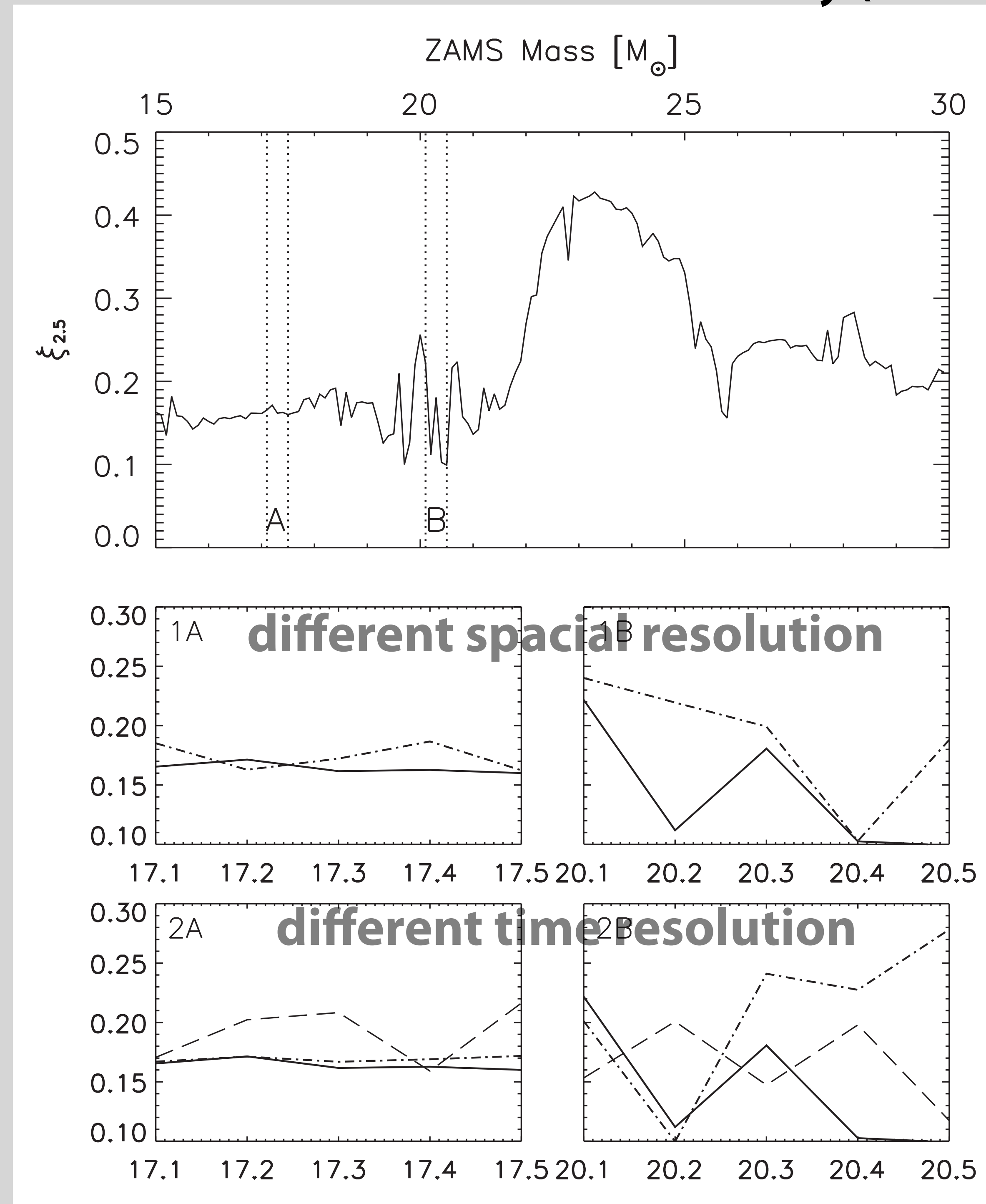
Uncertainties in stellar evolutionary calculations

Suwa et al., ApJ (2016)



Different codes lead to different structure

Sukhbold & Woosley (2014)

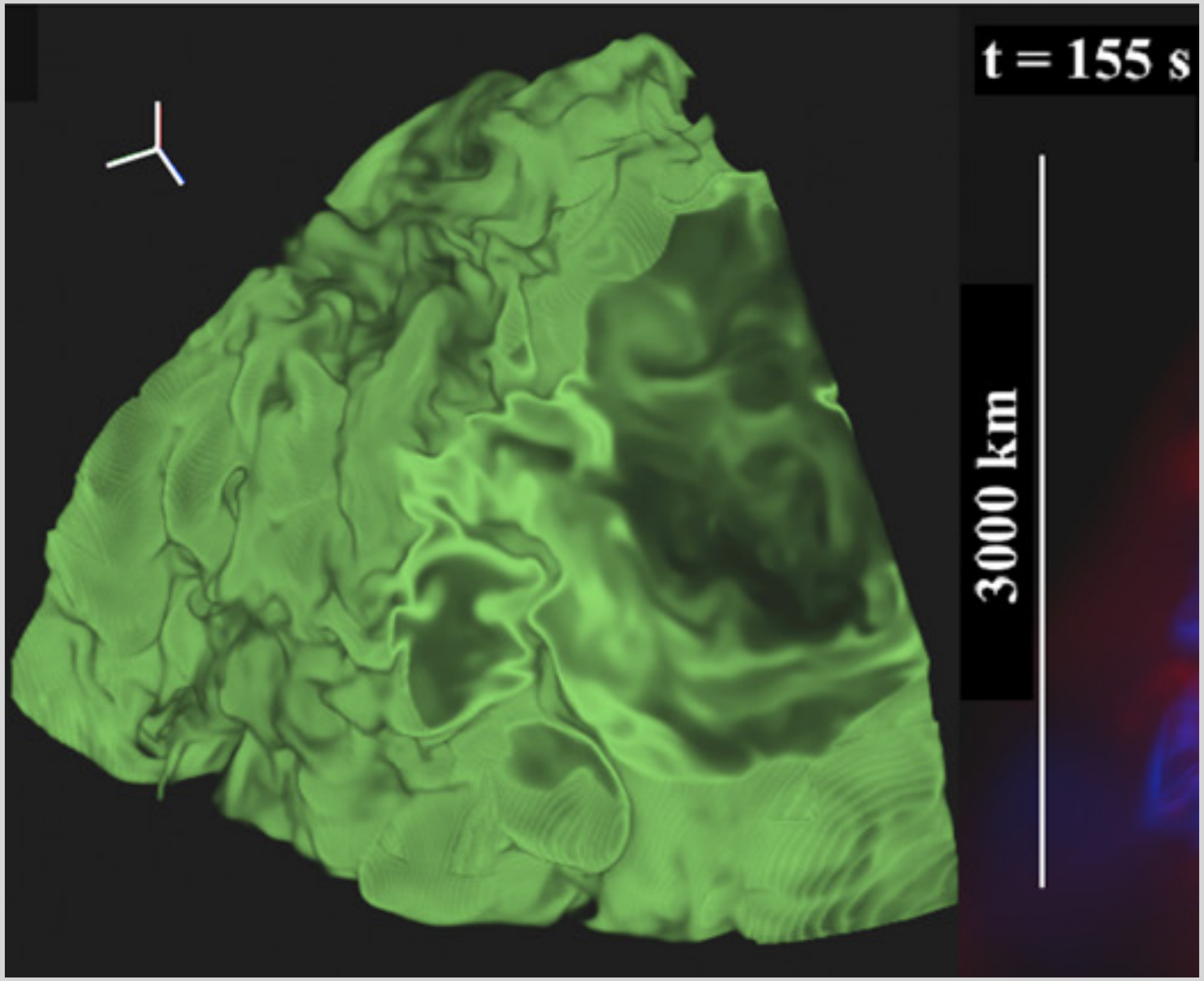


Even with the *same* code, different (time or space) resolutions lead to different structure

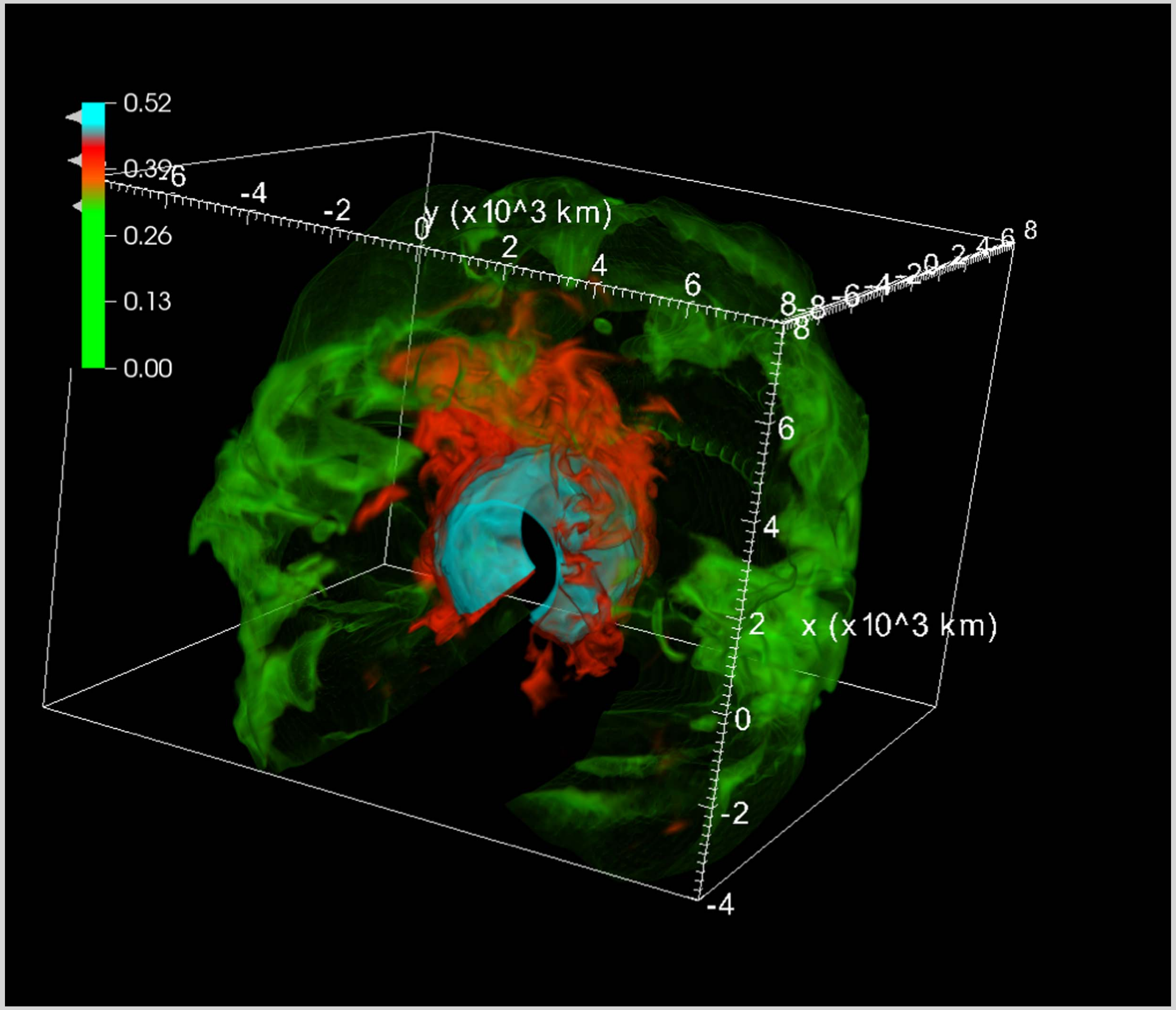
$$\xi_M = \frac{M/M_\odot}{r_M/1000\,\mathrm{km}}$$

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

Progenitor models in 3D



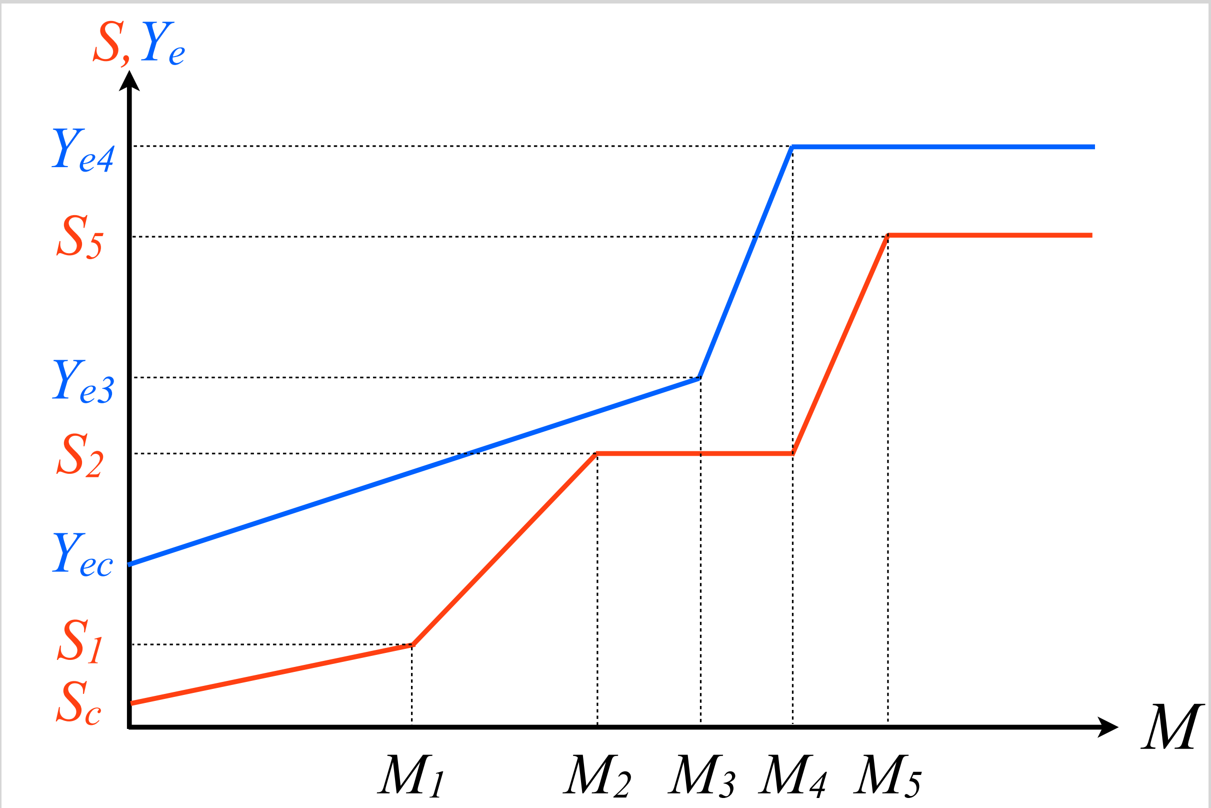
Couch et al. (2015)

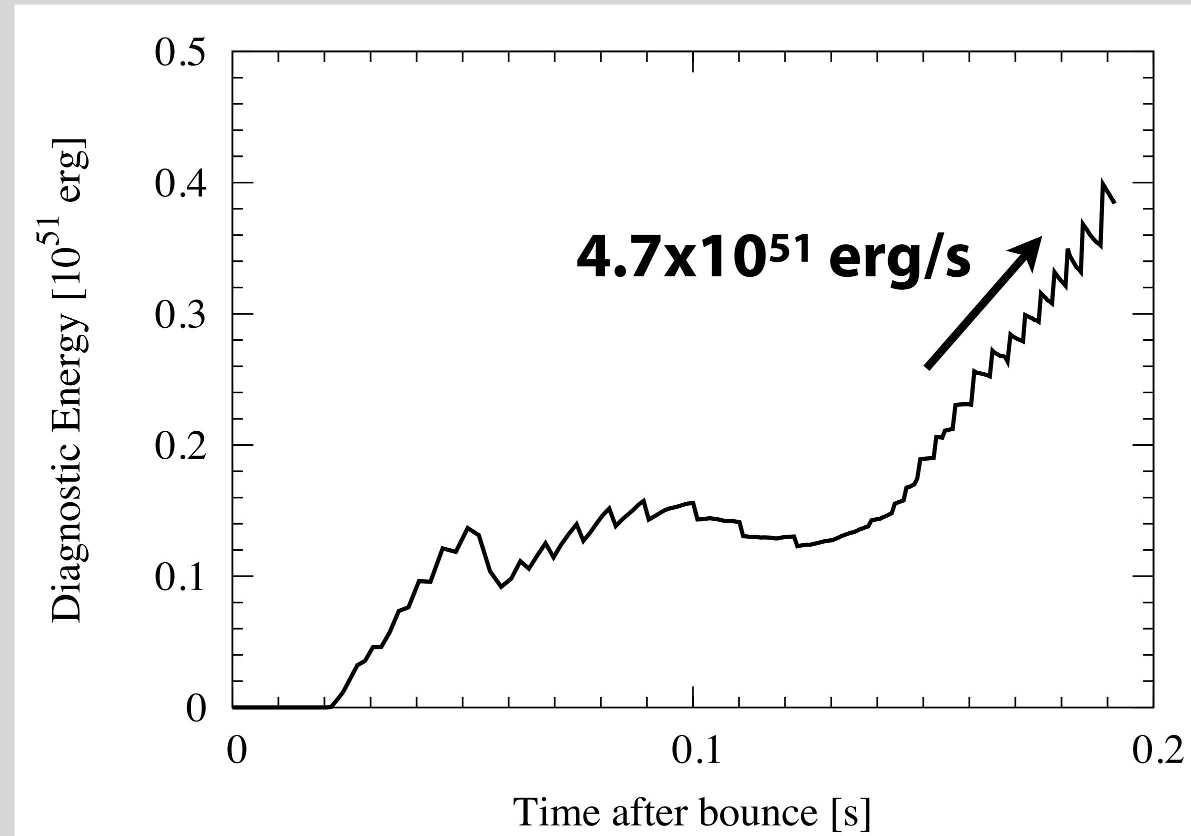


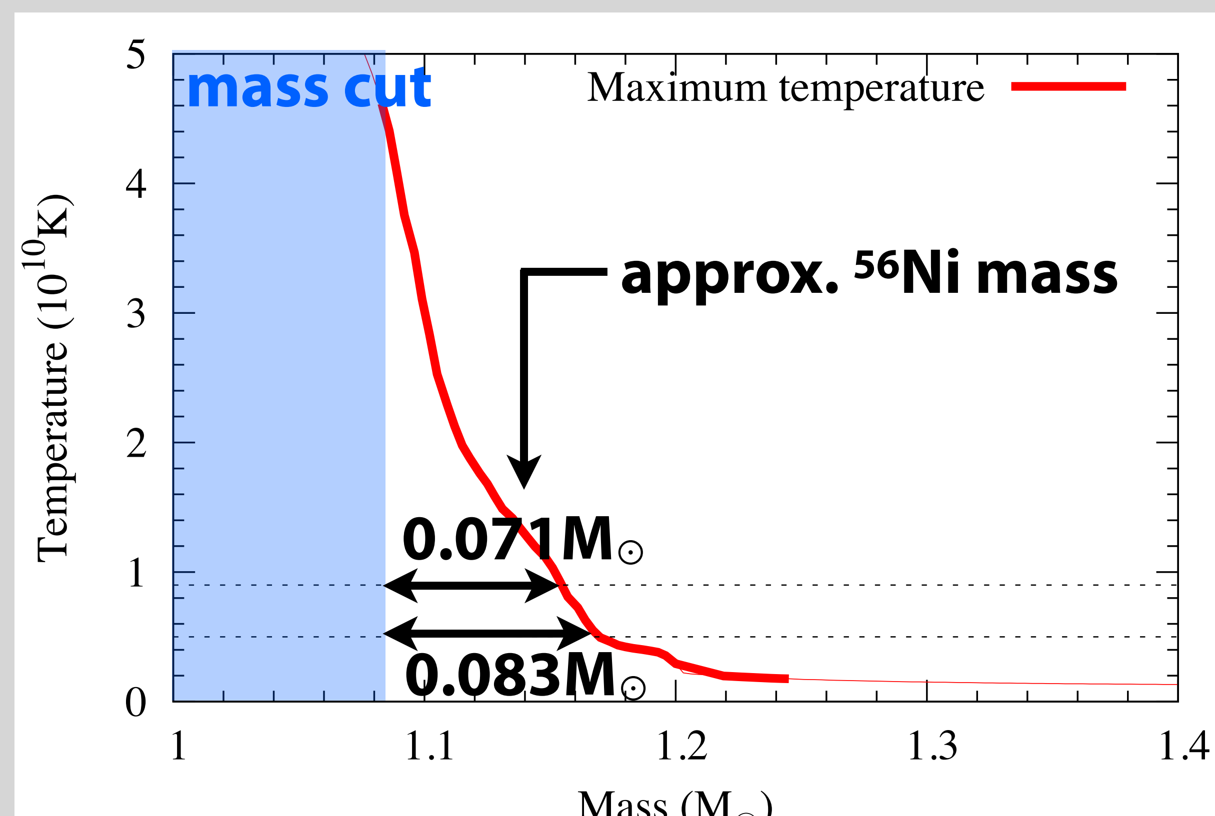
Müller et al. (2016)

Parametric progenitor model

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



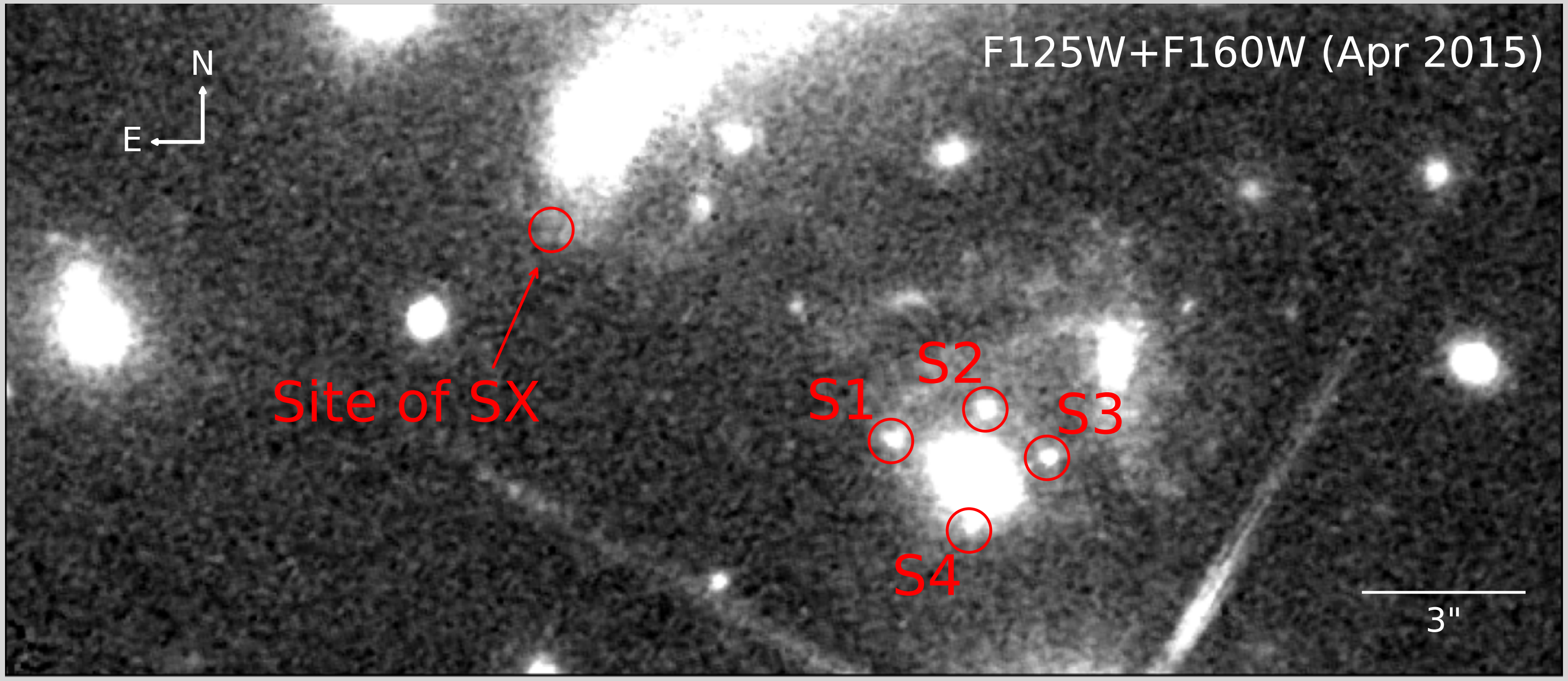




- New initial conditions for SN sim. (w/o stellar evol.)
- Reproduces stellar evol. results
- Strong explosion (in 1D!) is found
- Systematic study is needed

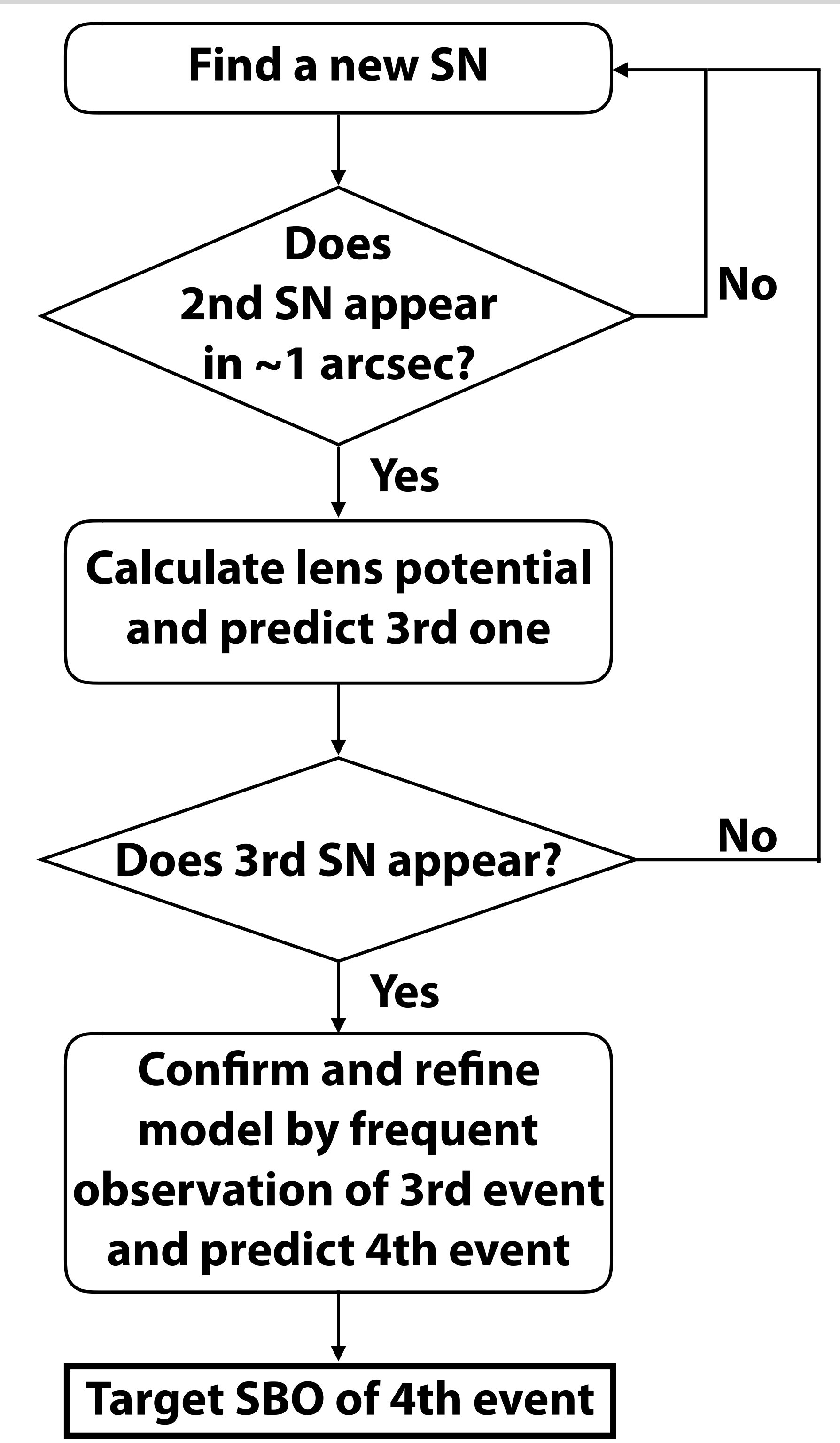
Strongly lensed SN

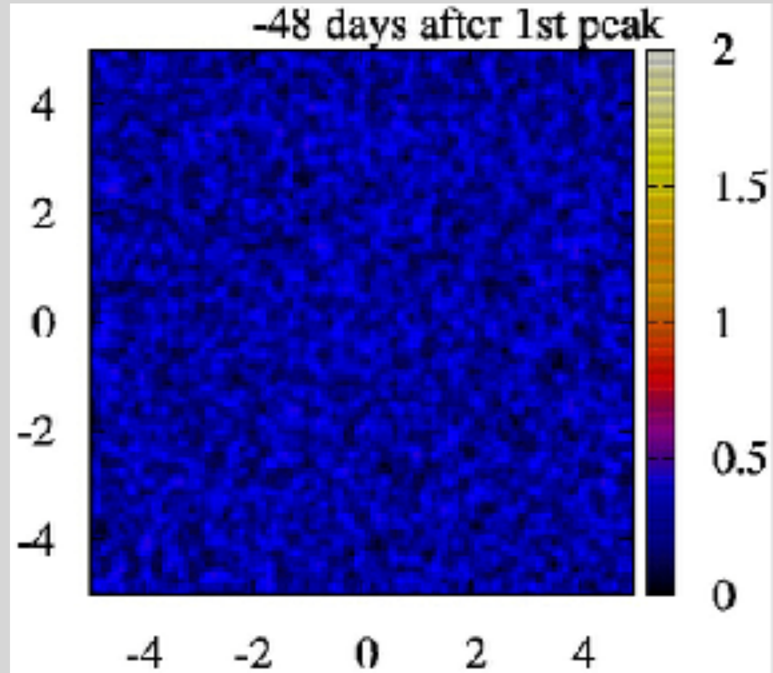
- **There have been *three* lensed SN observations so far**
  - **PS1-10afx (Ia; Quimby et al. 2013), SN Refsdal (CC; Kelly et al. 2015), iPTF16geu (Ia; Goobar et al. 2017)**
- **SN Refsdal**
  - **four images were found at the same time**
  - **one more event had been predicted one year *after* the images**
  - **another image indeed appeared! (Kelly+ 2016)**

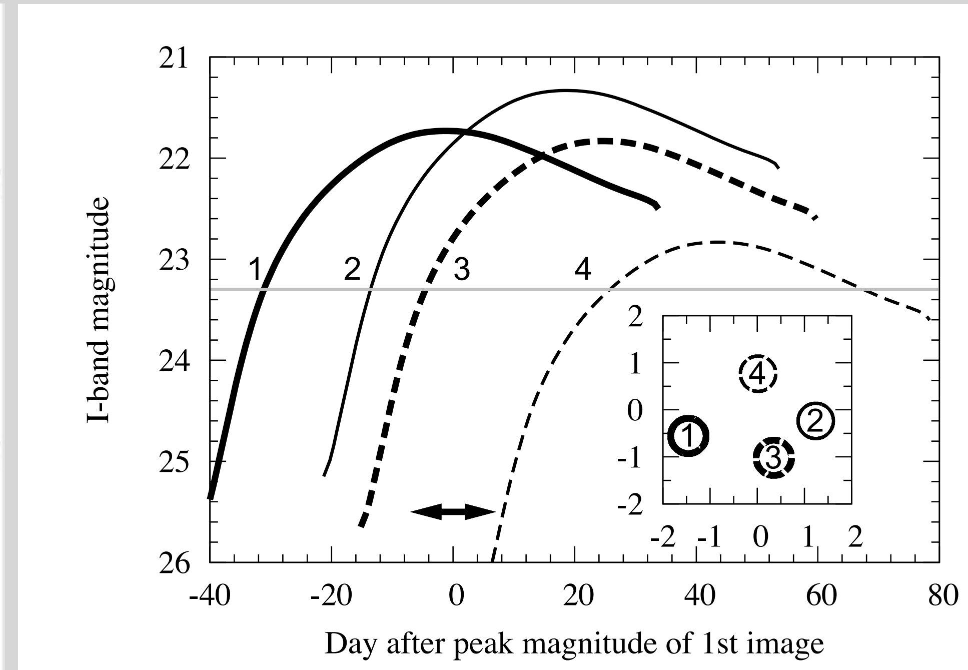


Supernova forecast

[Suwa, MNRAS, 474, 2612 (2018)]







- By LSST, >10 lensed SNe will be found annually (Oguri & Marshall 2010)
- With previous 3 images, 4th image delay time can be estimated
  - Lensing parameters determined with 3 images
  - Precision of prediction? **Δt<1day!**
- **ToO observations of shock breakout in multi wavelength are possible!**

Summary

* **Observation**
  - SN is powered by NS formation
  - SN rate
  - pre-SN images
* **Theory**
  - Explosion, explosion and explosion
  - Explosion energy problem
  - ^{56}Ni mass problem
* **Prospects**
  - long-term simulation, binarity, initial condition, forecast, etc.