Neutrino-driven explosions of ultra-stripped type Ic supernovae generating binary neutron stars

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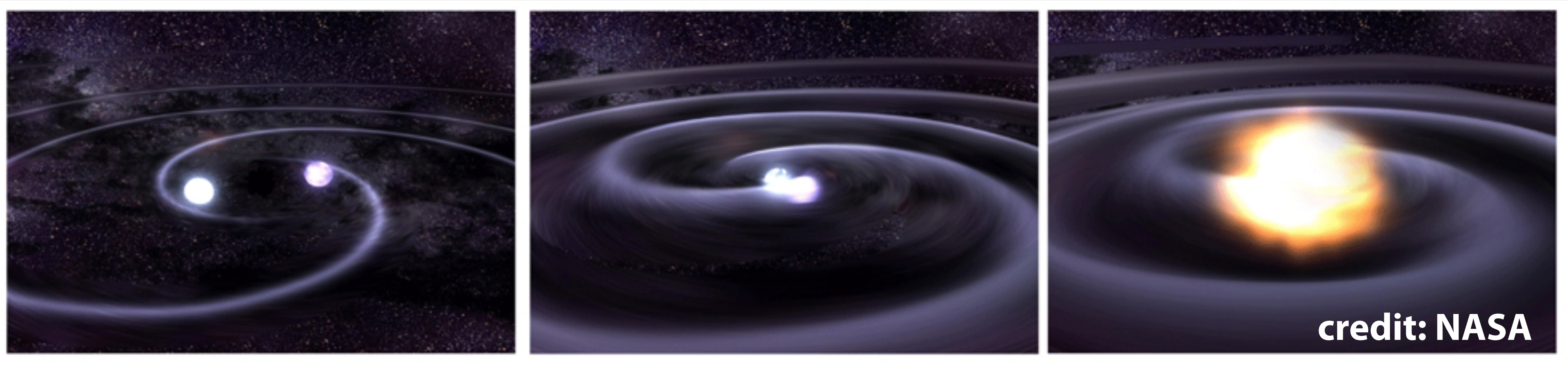
Binary neutron stars

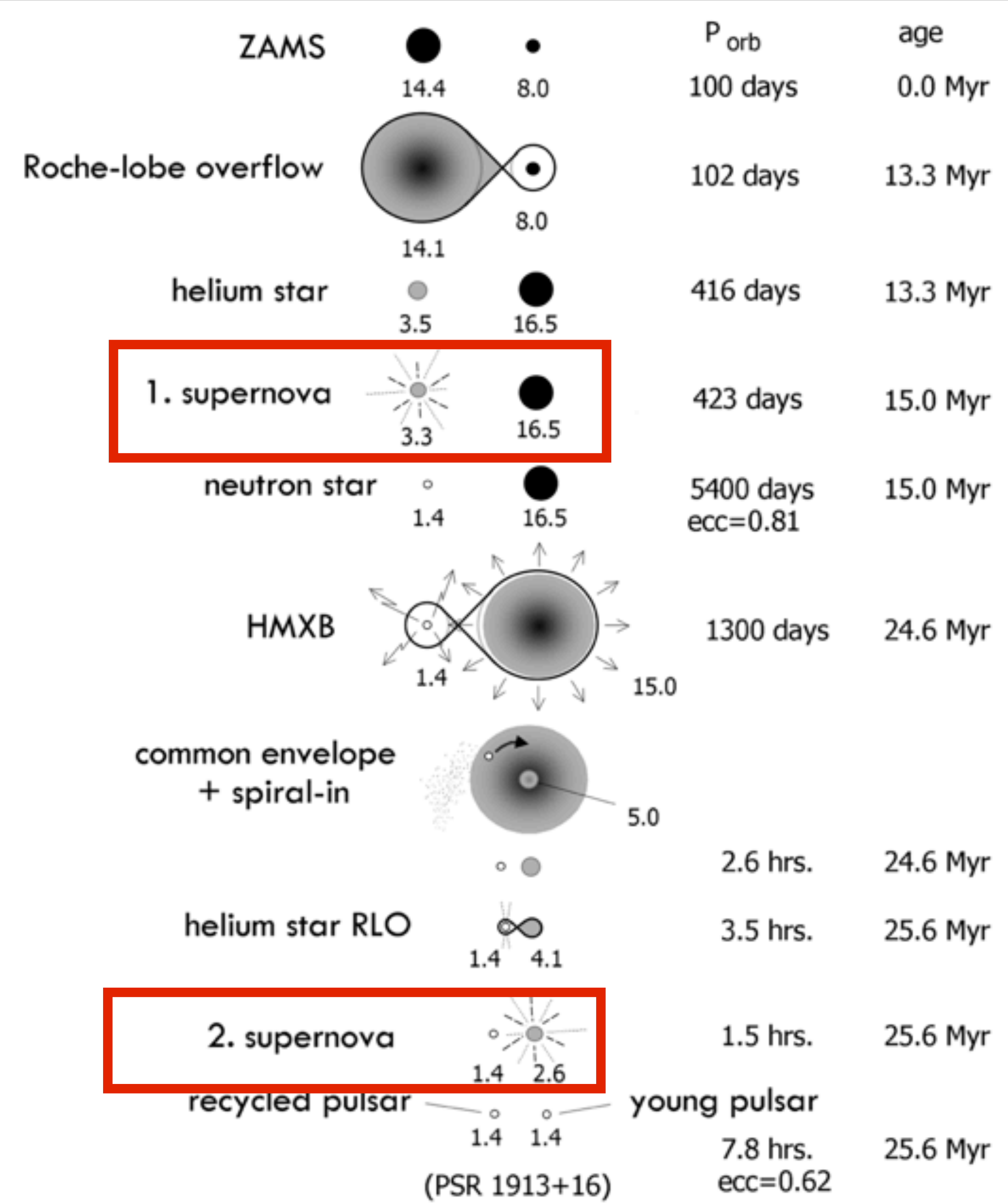


* one of the best candidates of strong gravitational wave (GW) sources
* will be detected by GW in a couple of years (?)
* estimated merger rates ~1-4000 /gal/Myr, **large uncertainty!**

  Abadie+ 2010

* let me remind you that **NSs are born to supernovae (SNe)**
* supernova surveys might be able to give constraint on NS merger rates

Binary evolutions



- **There are *two* SNe**
  - first one may be usual (type-Ibc or type II)
  - second one explodes after close binary interactions, e.g. common envelope phase (if they are close enough)
- **How does a second SN look like? Is there any difference from normal SNe?**

Tauris & van den Heuvel 2006

Ultra-stripped supernovae?

- **Tauris, Langer, Podsiadlowski (2015)**

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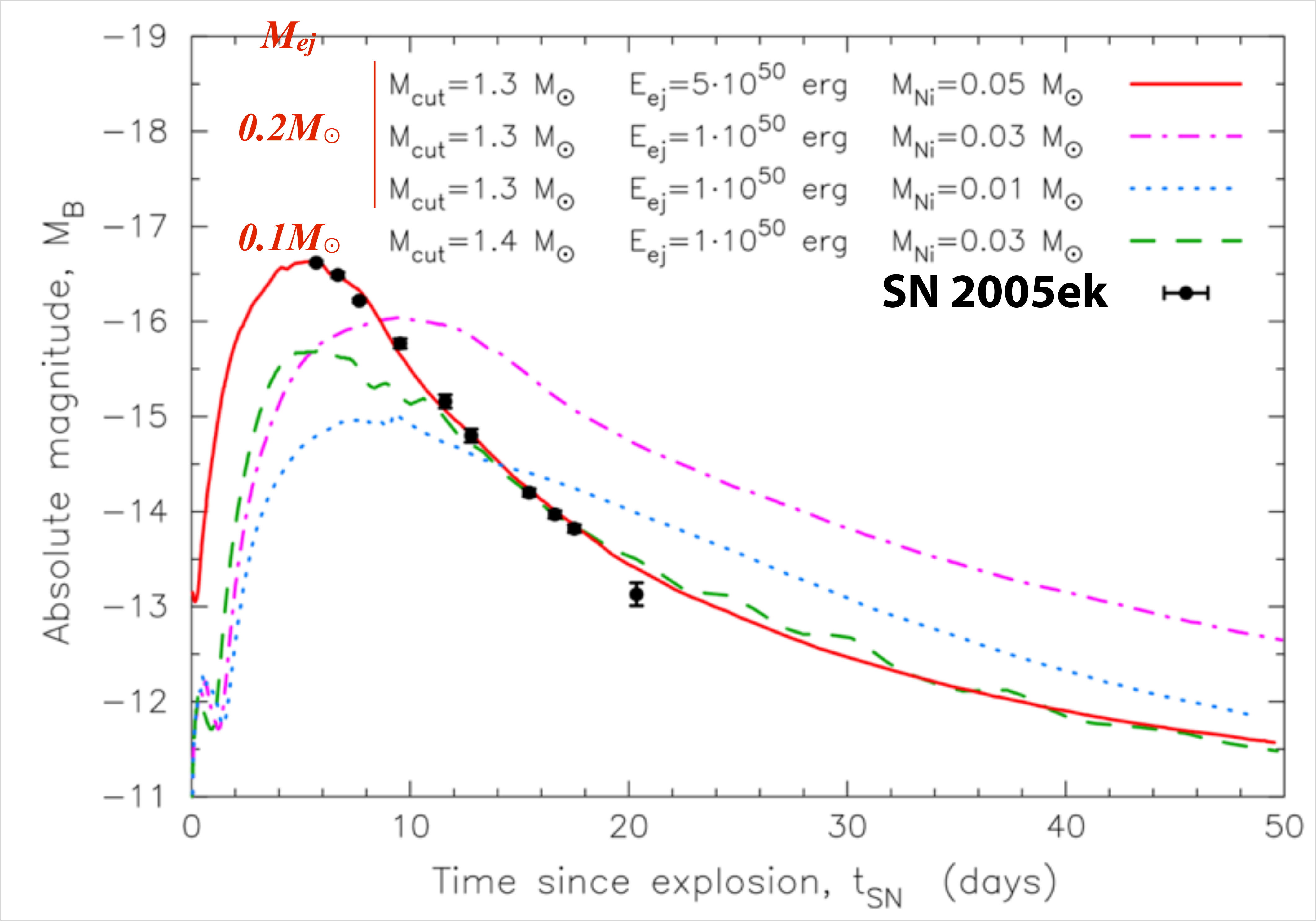
Ultra-stripped supernovae: progenitors and fate

Thomas M. Tauris,[1,2★] Norbert Langer[1] and Philipp Podsiadlowski[3]

- *"We therefore suggest to define ultra-stripped SNe as exploding stars whose progenitors are stripped more than what is possible with a non-degenerate companion. In other words, ultra-stripped SNe are exploding stars which contain envelope masses $\lesssim 0.2\ M_\odot$ and having a compact star companion."*

Small ejecta mass

Tauris, Langer, Moriya, Podsiadlowski, Yoon, Blinnikov 2013



What we have done

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]

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Neutrino-driven explosions of ultra-stripped Type Ic supernovae generating binary neutron stars

Yudai Suwa,[1,2]★ Takashi Yoshida,[1,3] Masaru Shibata,[1] Hideyuki Umeda[3] and Koh Takahashi[3]

ABSTRACT

We study explosion characteristics of ultra-stripped supernovae (SNe), which are candidates of SNe generating binary neutron stars (NSs). As a first step, we perform stellar evolutionary simulations of bare carbon–oxygen cores of mass from 1.45 to 2.0 $M_\odot$ until the iron cores become unstable and start collapsing. We then perform axisymmetric hydrodynamics simulations with spectral neutrino transport using these stellar evolution outcomes as initial conditions. All models exhibit successful explosions driven by neutrino heating. The diagnostic explosion energy, ejecta mass, Ni mass, and NS mass are typically $\sim 10^{50}$ erg, $\sim 0.1\ M_\odot$, $\sim 0.01\ M_\odot$, and $\approx 1.3\ M_\odot$, which are compatible with observations of rapidly evolving and luminous transient such as SN 2005ek. We also find that the ultra-stripped SN is a candidate for producing the secondary low-mass NS in the observed compact binary NSs like PSR J0737−3039.

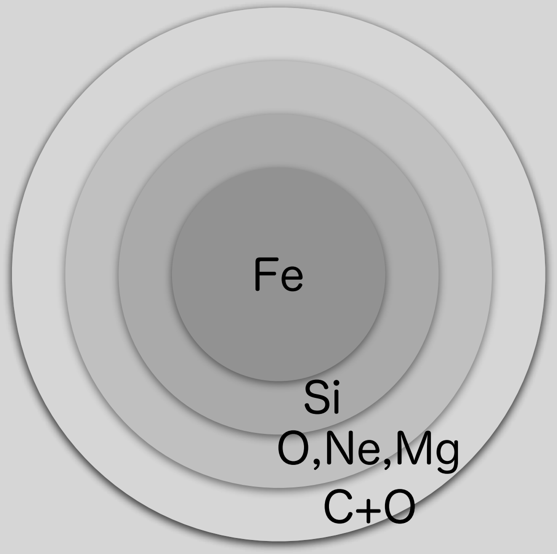
Stellar evolutionary simulations-1: setups

- **Stellar evolution code for massive stars**

  (Umeda, Yoshida, Takahashi 2012; Takahashi, Yoshida, Umeda 2013; Yoshida, Okita, Umeda 2014)

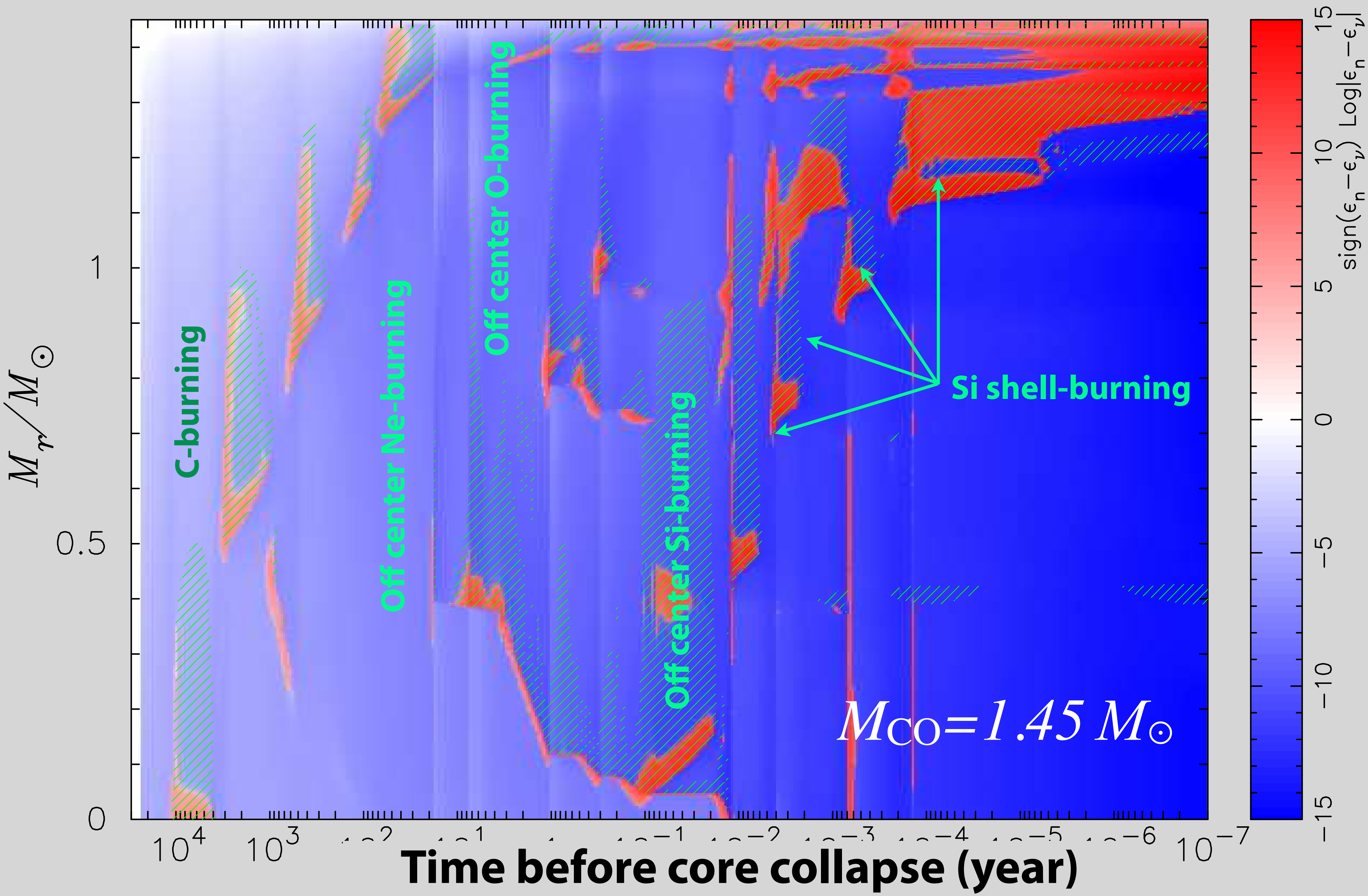
$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4} - \frac{1}{4\pi r^4}\frac{\partial^2 r}{\partial t^2},$$
$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho},$$
$$\frac{\partial \ln T}{\partial \ln P} = \min(\nabla_{\rm ad}, \nabla_{\rm rad}),$$
$$\frac{\partial L_r}{\partial M_r} = \epsilon_{\rm nucl} - \epsilon_\nu + \epsilon_{\rm grav}.$$

- **Nucleosynthesis and energy generation**
  - network with ~300 species
- **Initial condition**
  - bare CO cores (mimicking mass loss)
  - composition: central abundance of massive stars just after He burning
  - $X_{\rm C}({\rm C})$ = 0.33 - 0.36
  - $M_{\rm CO}$=1.45, 1.5, 1.6, 1.8 and 2.0 $M_\odot$



Stellar evolutionary simulations-2: results

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]



Explosion simulations-1: setups

See
- Suwa et al., PASJ, **62**, L49 (2010)
- Suwa et al., ApJ, **738**, 165 (2011)
- Suwa et al., ApJ, **764**, 99 (2013)
- Suwa, PASJ, **66**, L1 (2014)
- Suwa et al., ApJ in press [arXiv:1406.6414]
- **Suwa et al., MNRAS, 454, 3073(2015)**

for more details

- **2D (axial symmetry)** (ZEUS-2D; Stone & Norman 92)
- **MPI+OpenMP hybrid parallelized**
- **Hydrodynamics+spectral neutrino transfer**
  (***neutrino-radiation hydrodynamics***)

hydrodynamics

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

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

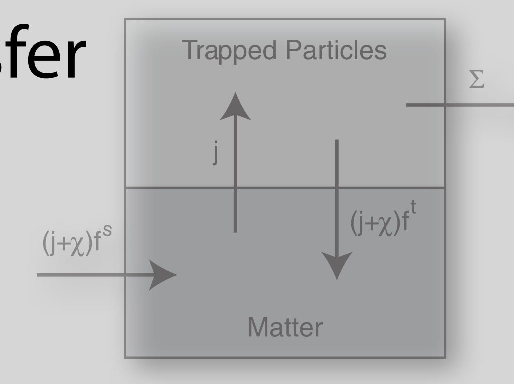
$$\frac{\partial e^*}{\partial t} + \nabla \cdot [(e^* + P)\mathbf{v}] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_\nu,$$

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

ν transfer

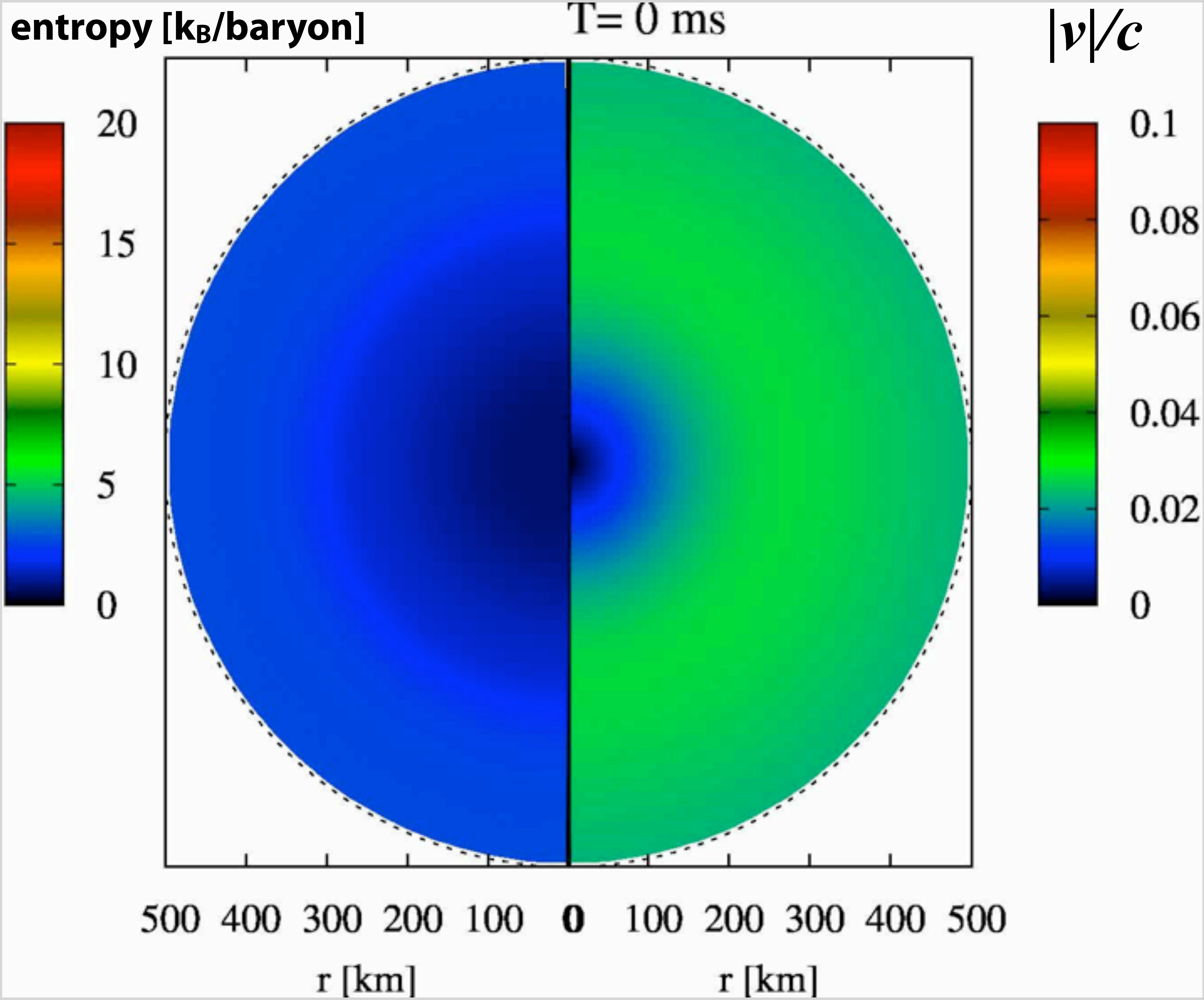
$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right](1-\mu^2)\frac{\partial f}{\partial \mu}$$
$$+ \left[\mu^2 \left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right] E \frac{\partial f}{\partial E}$$
$$=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

- Isotropic diffusion source approximation (***IDSA***) for neutrino transfer (Liebendörfer+ 09)
- ***Ray-by-ray plus*** approximation for multi-D transfer (Buras+ 06)



- **EOS: Lattimer-Swesty** (K=180,**220**,375MeV) / H. Shen

Explosion simulations-2: movie



Explosion simulations-3: results

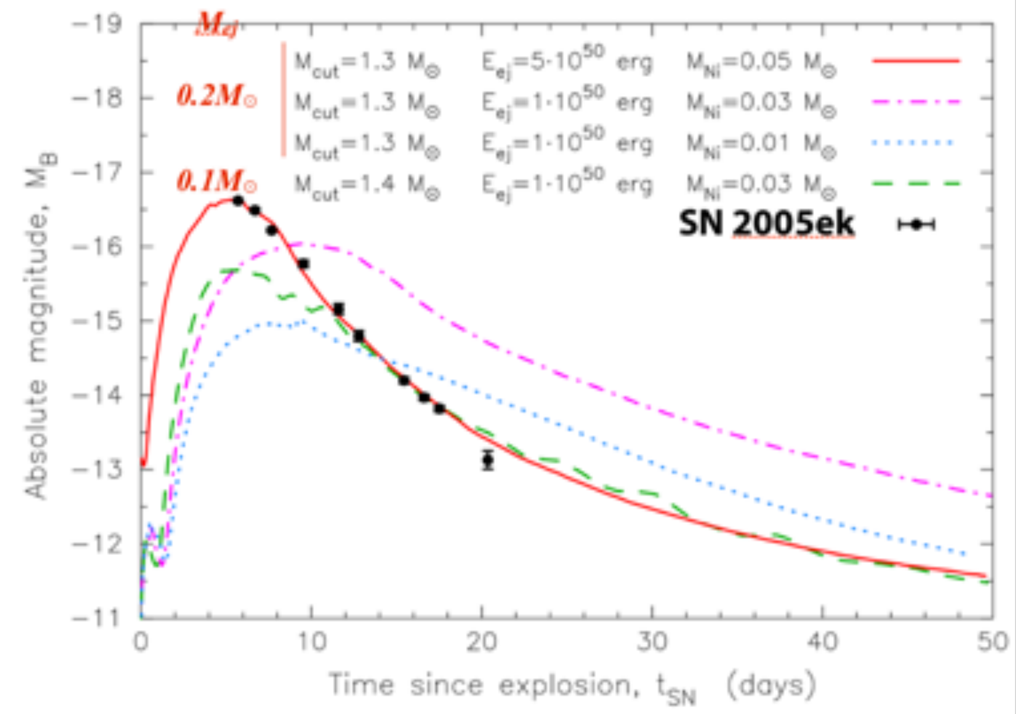
[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]

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

- **ALL models explode**
- **Final NS mass $\sim 1.35\text{-}1.6M_\odot$ (baryonic)**

  $\sim 1.24\text{-}1.44M_\odot$ (gravitational)
- **Ejecta mass=M_{CO}-M_{NS} ~ $O(0.1)M_\odot$**
- **Explosion energy $\sim O(10^{50})$ erg**
- **Ni mass $\sim O(10^{-2})M_\odot$**

Tauris+ 2013



Implications

* **small kick velocity due to small ejecta mass**
* **small eccentricity (e~0.1), compatible with binary pulsars J0737-3039 (e=0.088 now and ~0.11 at birth of second NS)**
  Piran & Shaviv 05
* **event rate (~1% of core-collapse SN)** Tauris+13, 15, Drout+ 13, 14
  * **SN surveys (e.g., HSC, PTF, Pan-STARRS, and LSST) will give constraint on NS merger rate**

* **nucleosynthesis calculations and radiation transfer simulations will be done based on our model**

Summary

- **Ultra-stripped SN might be second explosion in close binary forming binary NSs**
- **To test this conjecture, we performed**
  - stellar evolutionary simulations of bare C/O cores
  - hydrodynamics simulations for neutrino-driven explosions
- **Compatible with parameters explaining observations**

  Drout+ 13, Tauris+13

  - $E_{\mathrm{exp}}=O(10^{50})$ erg
  - $M_{\mathrm{ej}} \sim O(0.1)\ M_{\odot}$
  - $M_{\mathrm{Ni}} \sim O(10^{-2}) M_{\odot}$
  - $M_{NS} \sim 1.2\text{-}1.4 M_{\odot}$ (gravitational)

See
Suwa, Yoshida, Shibata, Umeda, Takahashi
MNRAS, 454, 3073 (2015)
for more details