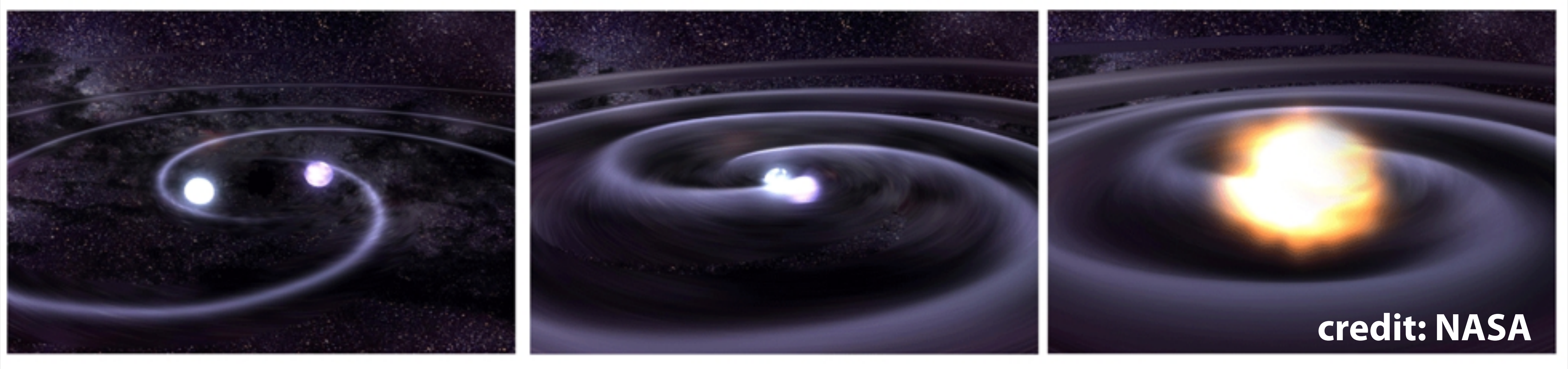
Neutrino-driven explosions of ultra-stripped type Ic supernovae generating binary neutron stars

Yudai Suwa[1, 2]

[1]Yukawa Institute for Theoretical Physics, Kyoto U.
[2]Max Planck Institute for Astrophysics, Garching

Collaboration with: T. Yoshida, M. Shibata (YITP), H. Umeda, K. Takahashi (U. Tokyo)

Binary neutron stars

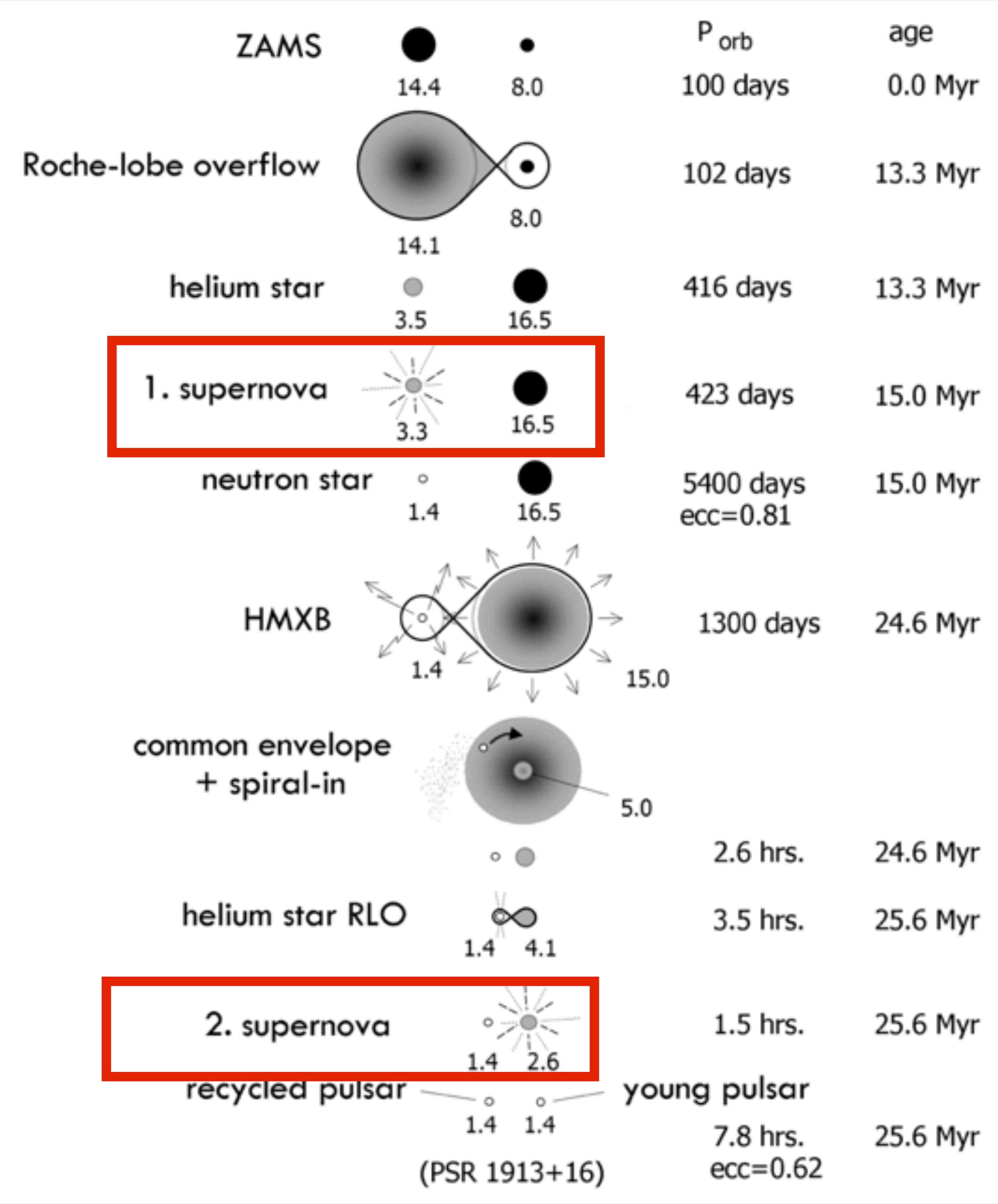

credit: NASA

- 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)**

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **451,** 2123–2144 (2015) doi:10.1093/mnras/stv990

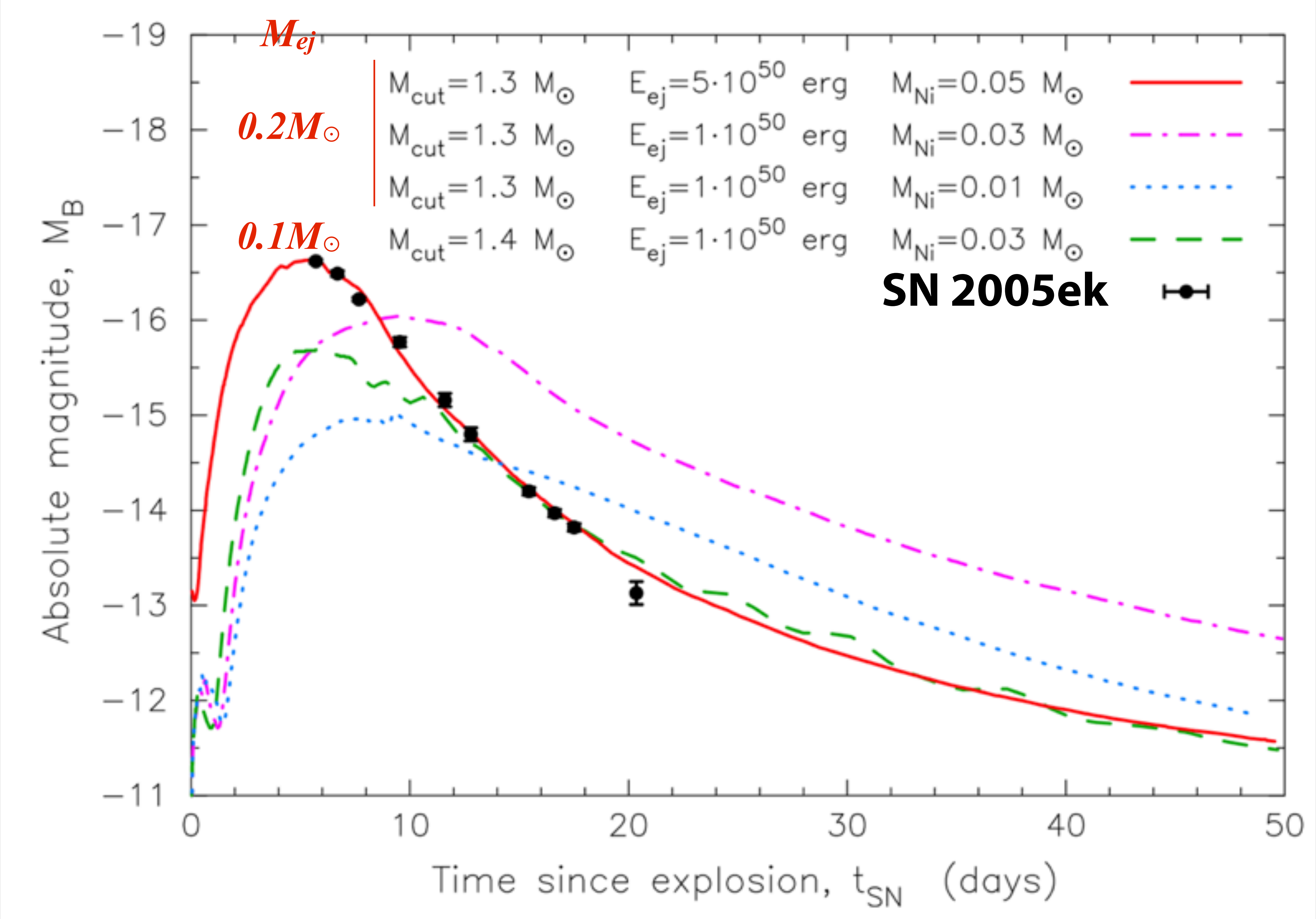
Ultra-stripped supernovae: progenitors and fate

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."*

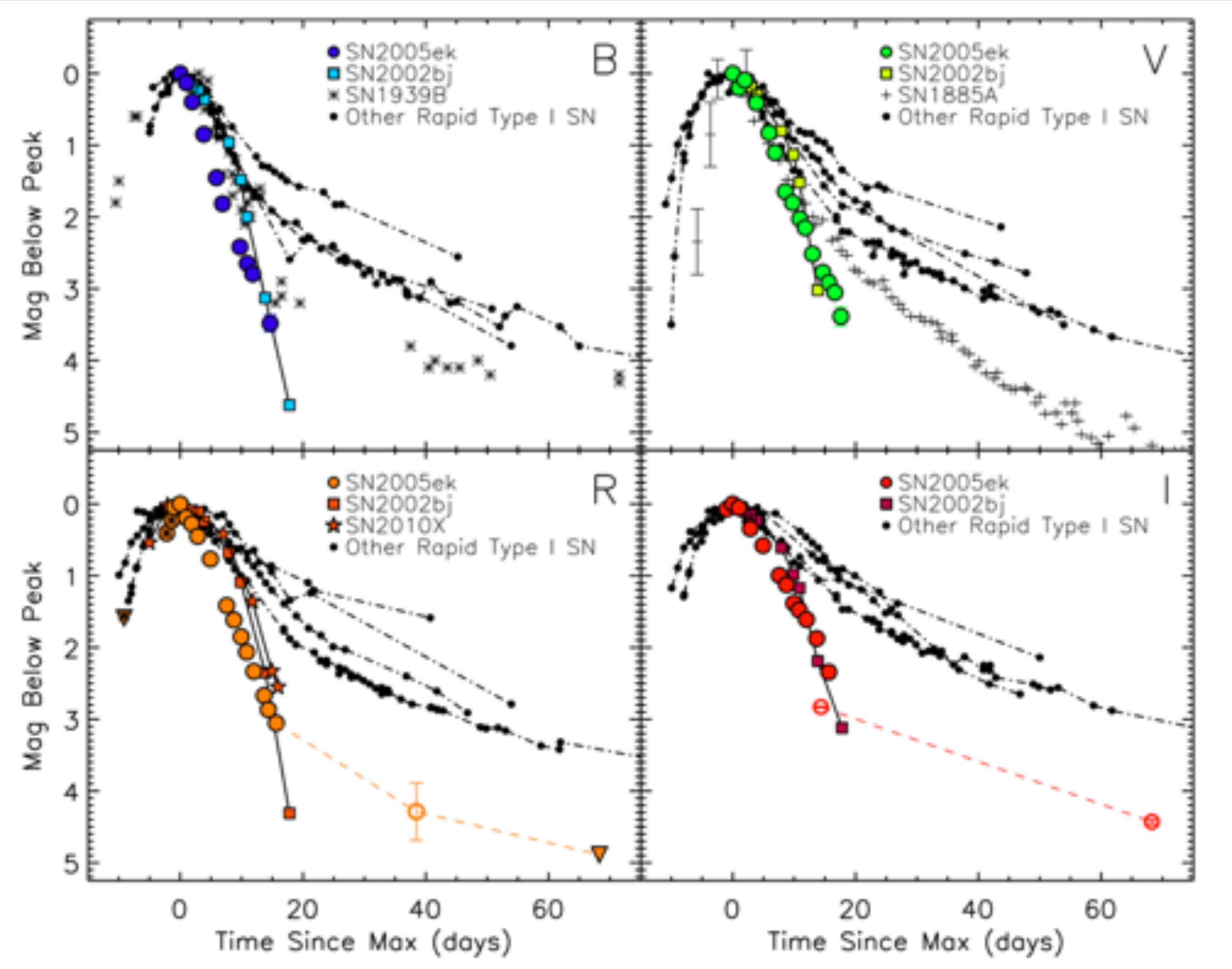
Small ejecta mass

Tauris+ 2013

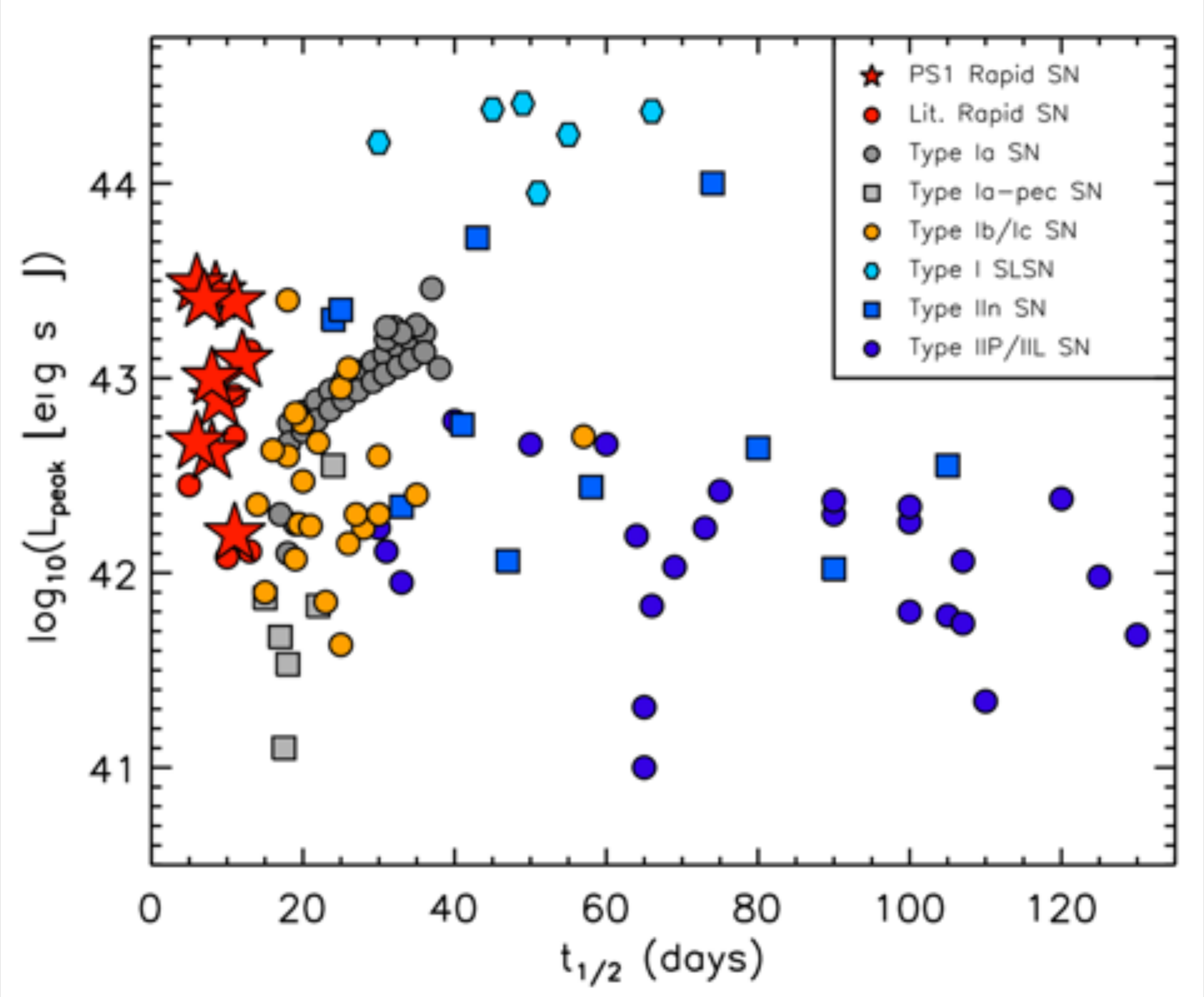


Rapidly evolving supernovae

Drout+ 2013

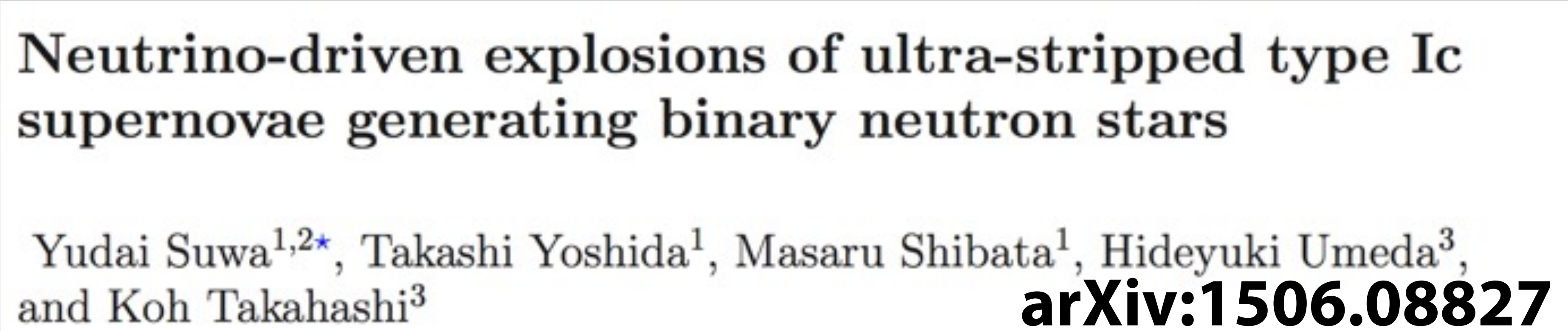


Drout+ 2014



- **early samples (05ek, 10X, 05E)+10 more discoveries by Pan-STARRS**
- $t_{1/2}<12$ **day**
- **diffusion time;** $\tau_c \propto M_{\mathrm{ej}}^{3/4} E_{\mathrm{K}}^{-1/4}$ **(Arnett 1982)**
- **small** M_{ej}

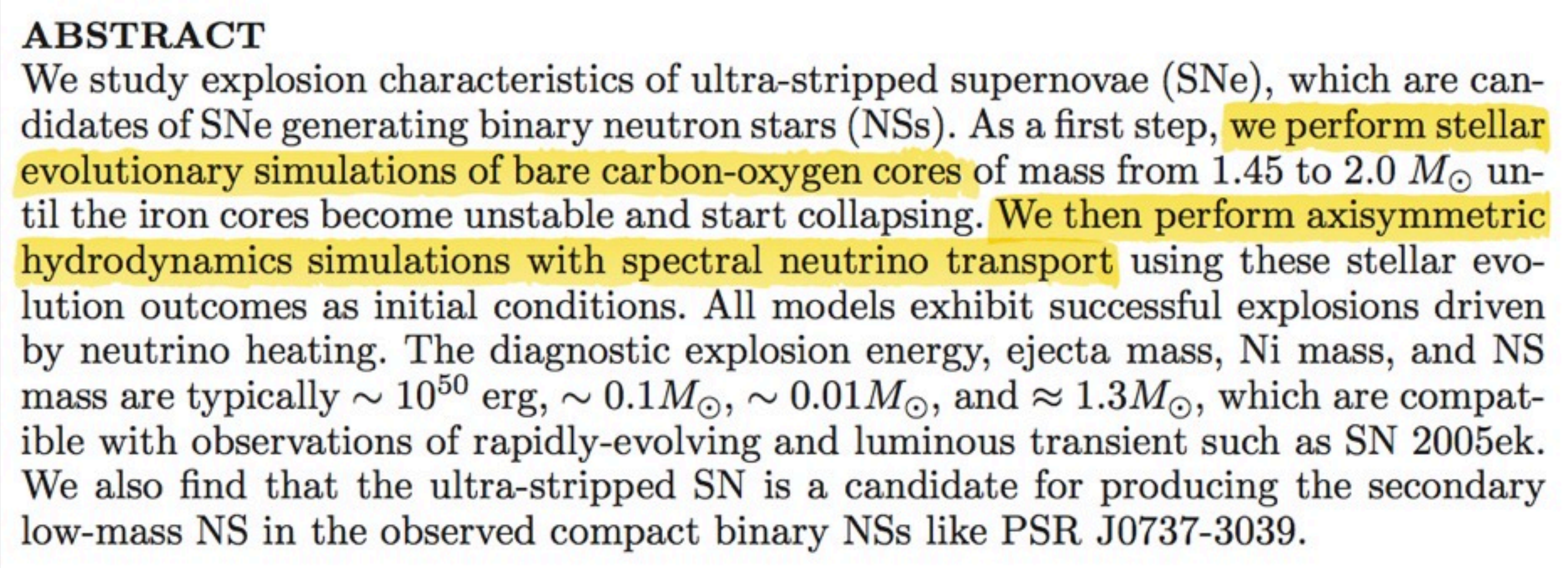
What we have done



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

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

arXiv:1506.08827



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.

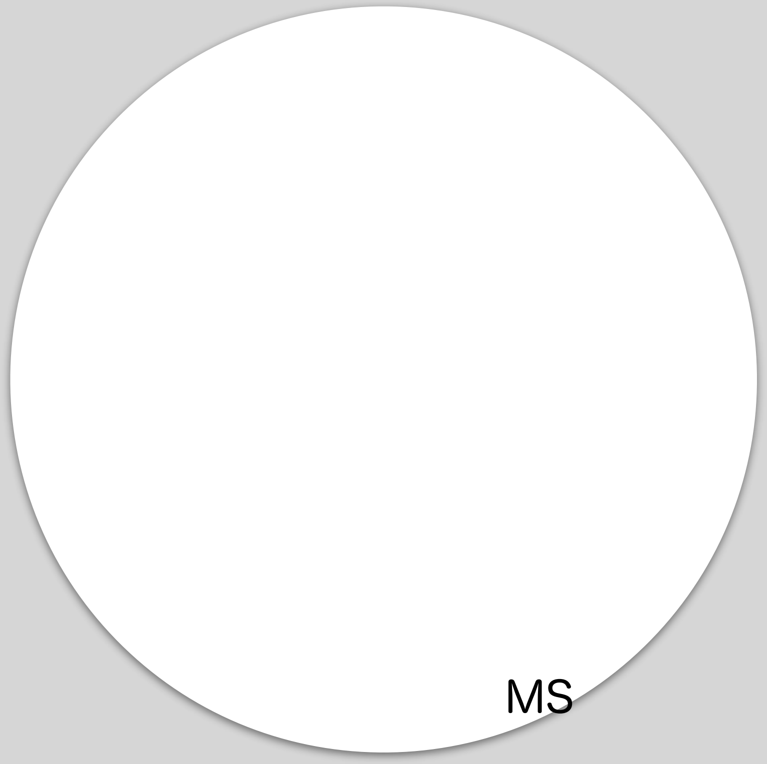
Stellar evolutionary simulations-1: setups

- **Stellar evolution code for massive stars**

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

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

- **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 $M_\odot$



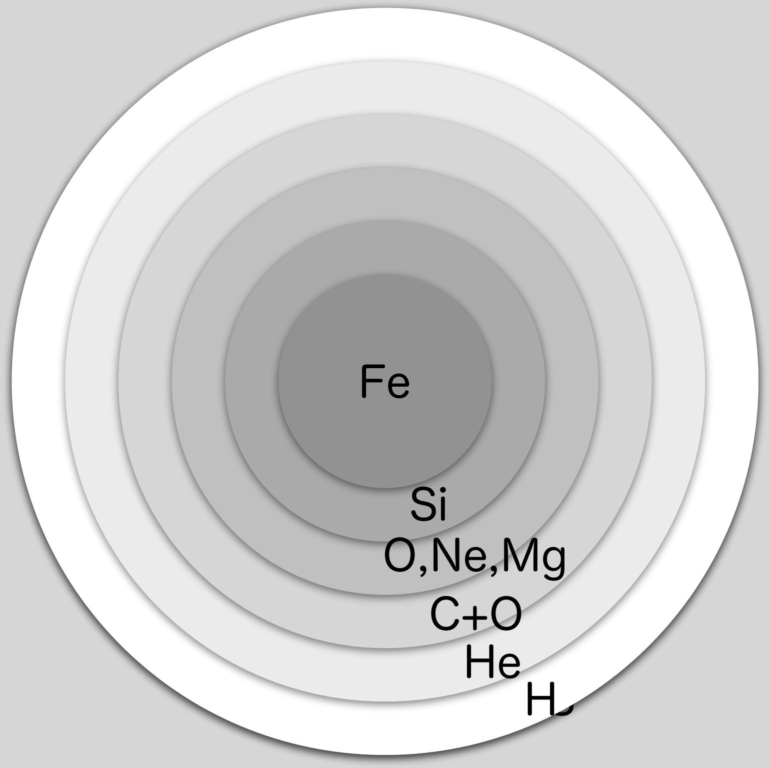
Stellar evolutionary simulations-1: setups

- **Stellar evolution code for massive stars**

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

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

- **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-1: setups

- **Stellar evolution code for massive stars**

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

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

- **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 $M_\odot$

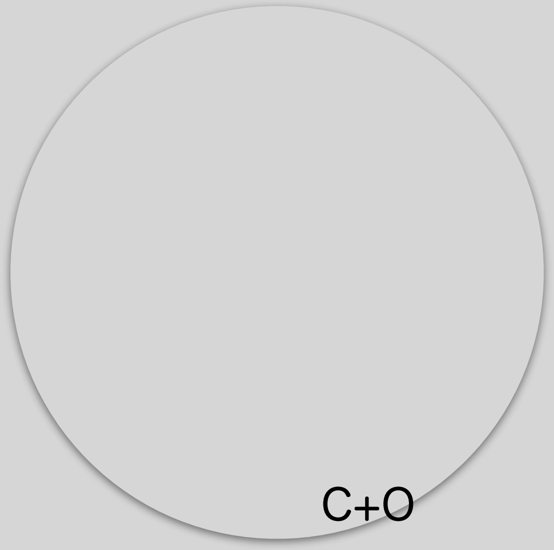
Stellar evolutionary simulations-1: setups

- **Stellar evolution code for massive stars**

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

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

- **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
  - $X_{\mathrm{C}}(\mathrm{C}) = 0.33 - 0.36$
  - M_{CO}=1.45, 1.5, 1.6, 1.8 and 2.0 $M_\odot$



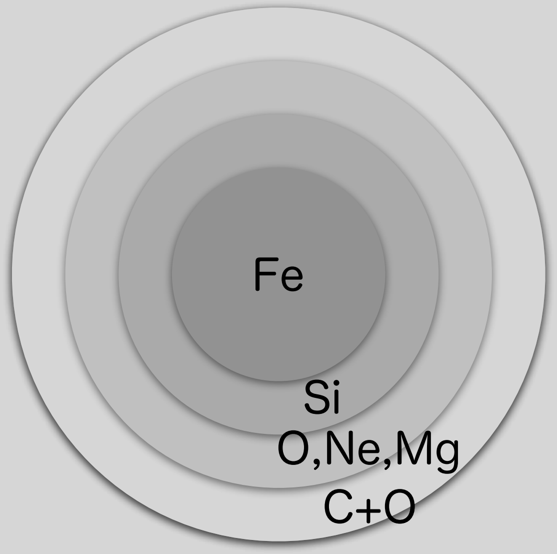
Stellar evolutionary simulations-1: setups

- **Stellar evolution code for massive stars**

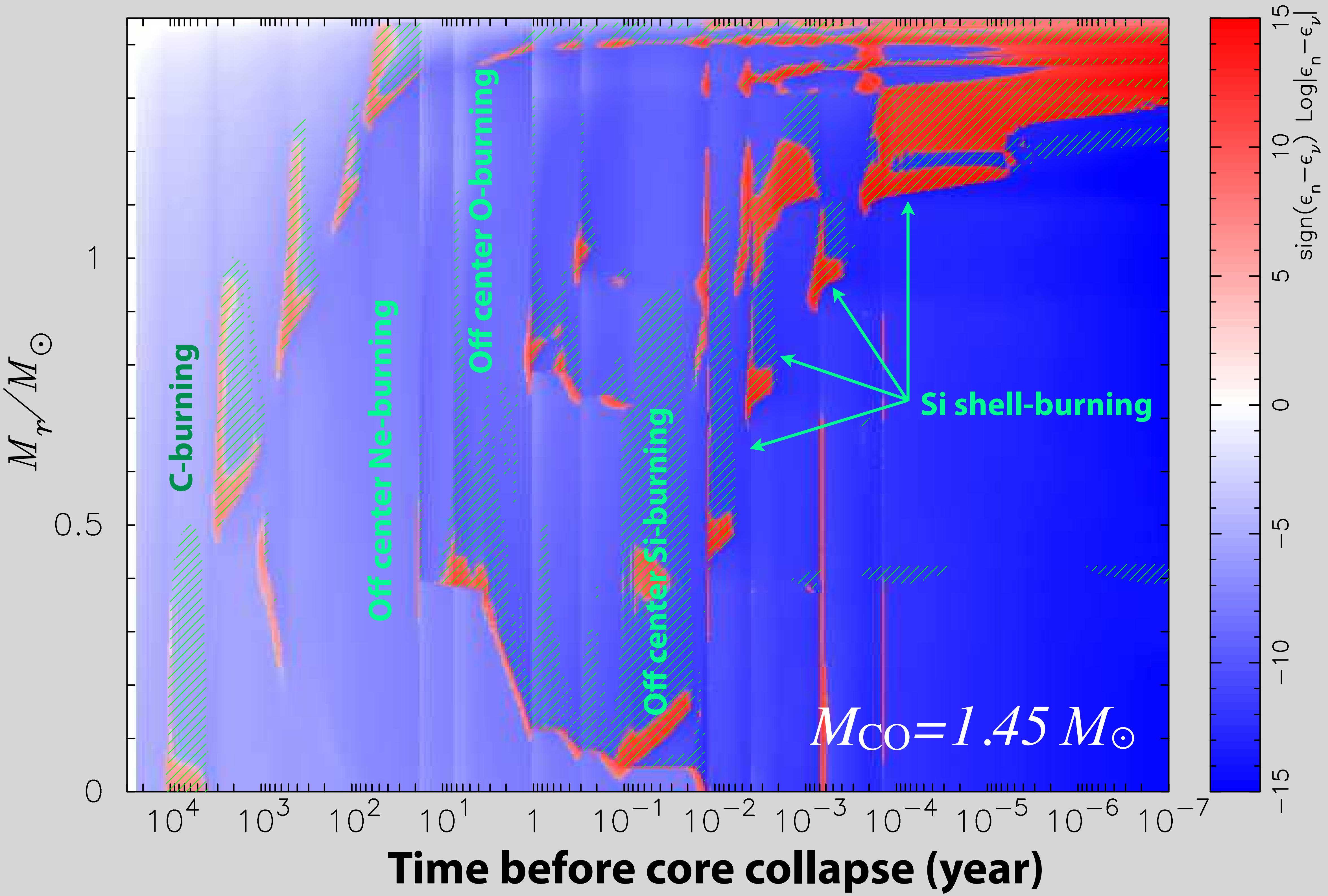
  (Umeda, Yoshida, Takahashi 2012; Takahashi, Yoshida, Umeda 2013; Yoshida, Okita, Umeda 2014)

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

- **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



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., arXiv:1406.6414
Suwa et al., arXiv:1506.08827
for more details

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

hydrodynamics

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

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

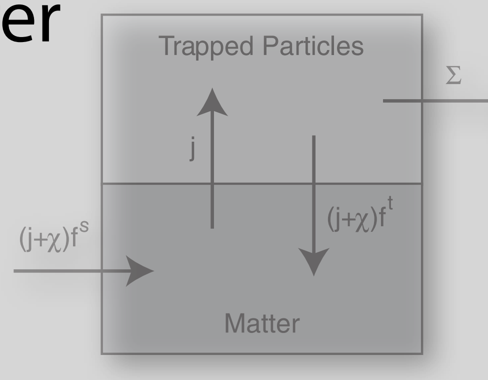
$$\frac{\partial e^*}{\partial t} + \nabla\cdot[(e^* + P)\mathbf{v}] = -\rho\mathbf{v}\cdot\nabla\Phi + Q_\nu,$$

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

ν transfer

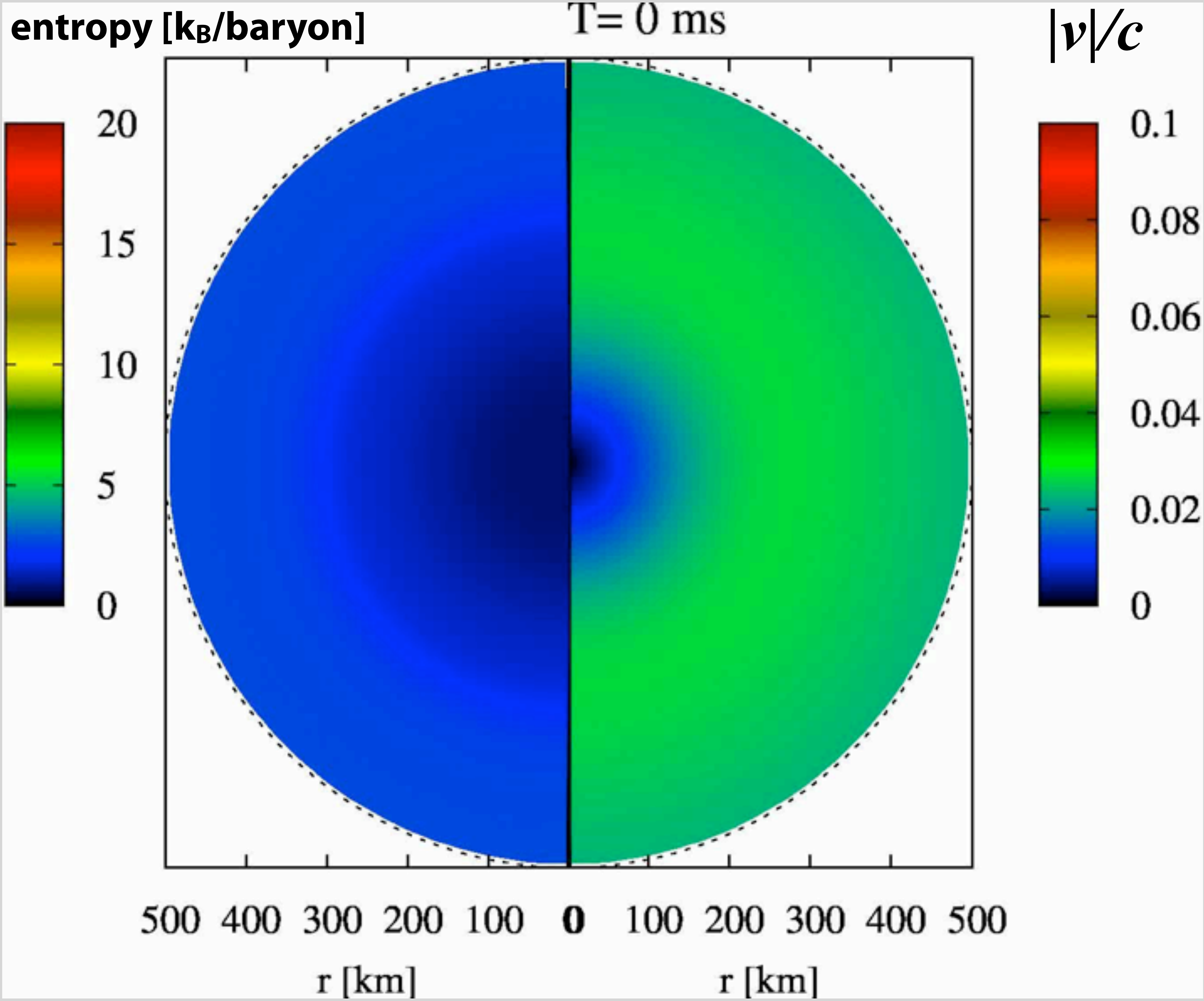
$$\begin{aligned}
&\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right](1-\mu^2)\frac{\partial f}{\partial\mu}\\
&\quad + \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]E\frac{\partial f}{\partial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

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

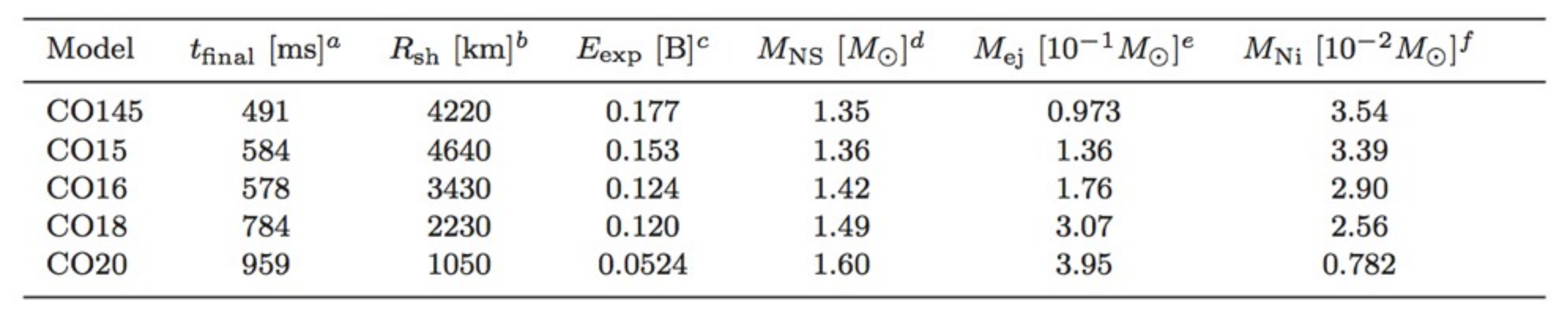


- **EOS: Lattimer-Swesty** (K=180,**220**,375MeV) / H. Shen

Explosion simulations-2: movie



Explosion simulations-3: results

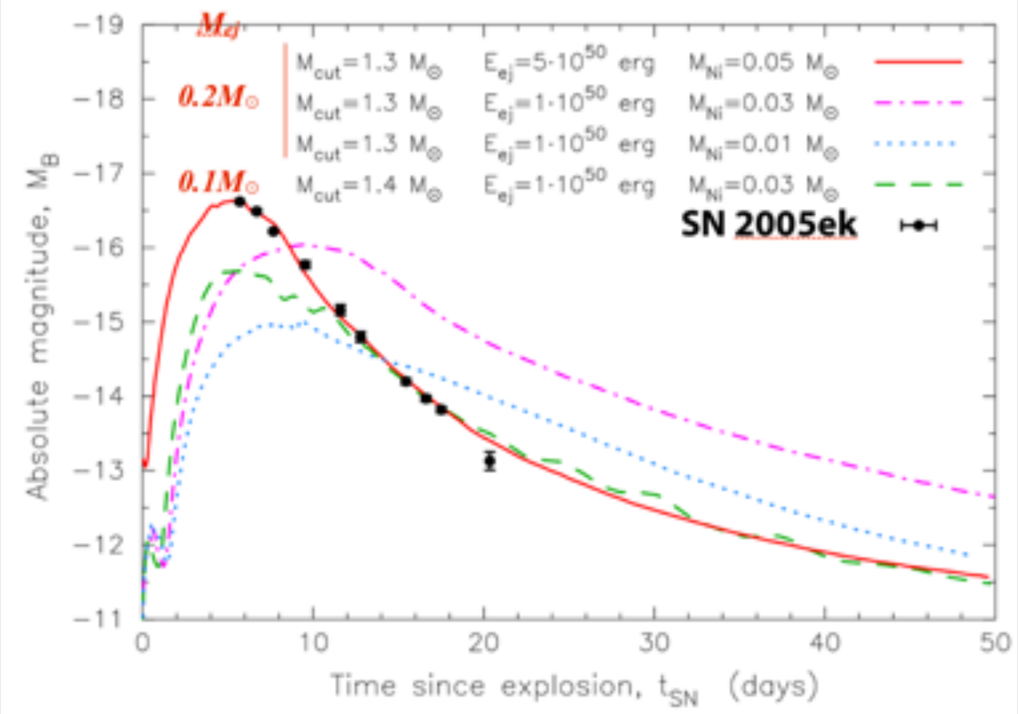


Model	$t_{\rm final}$ [ms]^a	$R_{\rm sh}$ [km]^b	$E_{\rm exp}$ [B]^c	$M_{\rm NS}$ [$M_\odot$]^d	$M_{\rm ej}$ [$10^{-1}M_\odot$]^e	$M_{\rm Ni}$ [$10^{-2}M_\odot$]^f
CO145	491	4220	0.177	1.35	0.973	3.54
CO15	584	4640	0.153	1.36	1.36	3.39
CO16	578	3430	0.124	1.42	1.76	2.90
CO18	784	2230	0.120	1.49	3.07	2.56
CO20	959	1050	0.0524	1.60	3.95	0.782

- **ALL models explode**
- **Final NS mass ~1.3-$1.6M_\odot$ (baryonic)**

  ~1.2-$1.4M_\odot$ (gravitational)
- **Ejecta mass=M_{CO}-M_{NS} ~ $O(0.1)M_\odot$**
- **Explosion energy ~$O(10^{50})$ erg**
- **Ni mass ~$O(10^{-2})M_\odot$**

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
- **even 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

- **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
  - hydrodynamic simulations for neutrino-driven explosions
- **Compatible with parameters explaining observations**
  - $E_{\mathrm{exp}}=O(10^{50})$ erg
  - $M_{\mathrm{ej}}\sim O(0.1)\ M_\odot$
  - $M_{\mathrm{Ni}}\sim O(10^{-2})M_\odot$
  - $M_{NS}\sim 1.2\text{-}1.4M_\odot$ (gravitational)

Drout+ 13, Tauris+13

See
Suwa, Yoshida, Shibata, Umeda, Takahashi
arXiv:1506.08827
for more details