Explosive Nucleosynthesis in Ultra-Stripped Supernovae

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Ultra-stripped SNe relating to NS mergers

- **Neutron star (NS) mergers will be observed by Advanced LIGO, VIRGO, and KAGRA soon!**

- **Neutron star mergers**

  → **A promising site of r-process nucleosynthesis**
  (e.g., Wanajo et al. 2014; Just et al. 2015; Goriely et al. 2015)

  → **A fate of *massive star* binary systems**

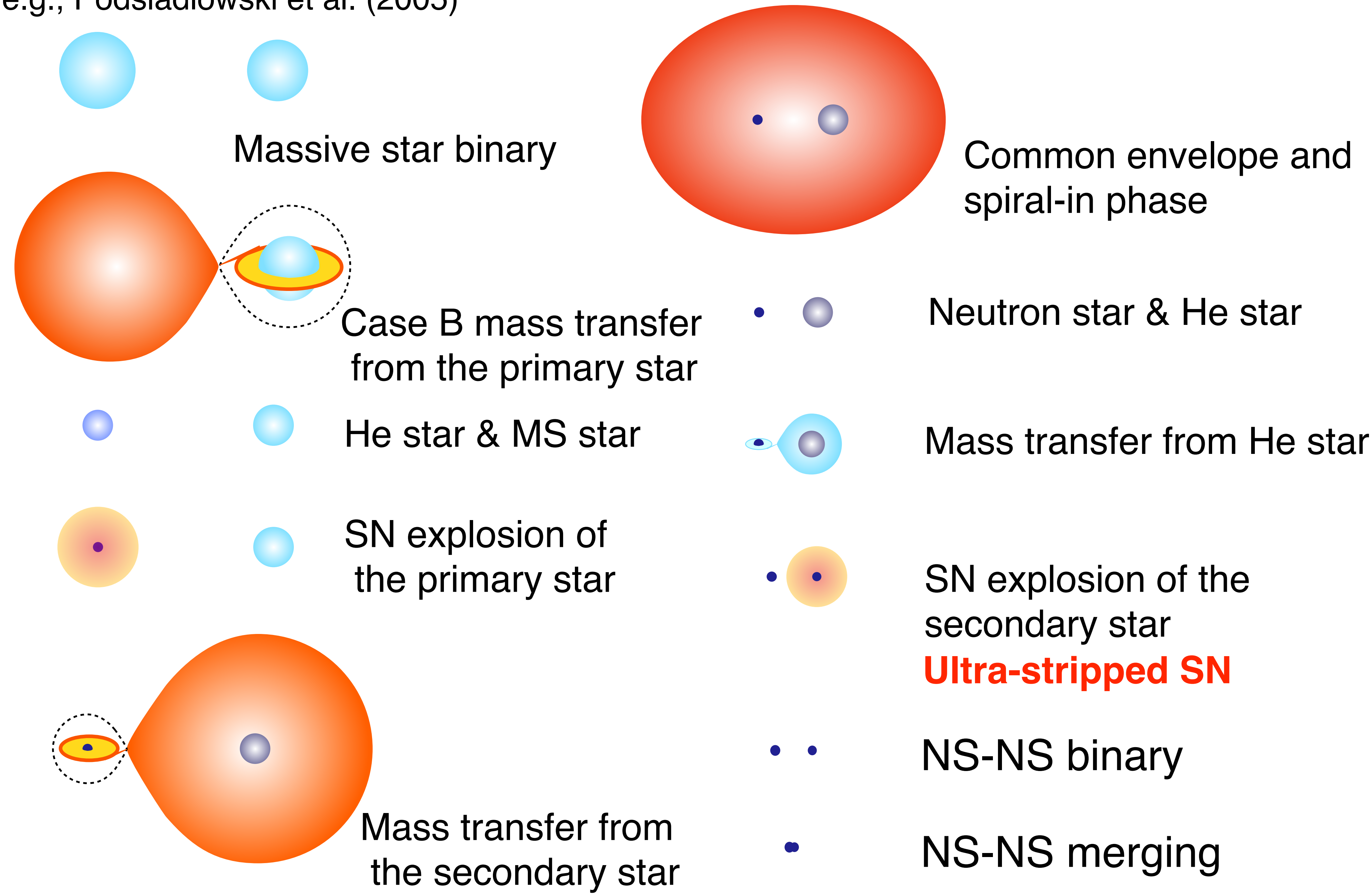
- **Ultra-stripped supernova (SN)**

  → **The progenitors have been stripped more than what is possible with a non-degenerate companion.** (Tauris et al. 2015)
  SN containing envelope masses $\lesssim 0.2\ M_{\odot}$ and having a compact star companion (Yoon et al. 2010; Tauris et al. 2015)

  → **A generation site of *binary neutron stars***

Standard channel producing NS-NS binary

e.g., Podsiadlowski et al. (2005)



Rapidly decaying optical transients

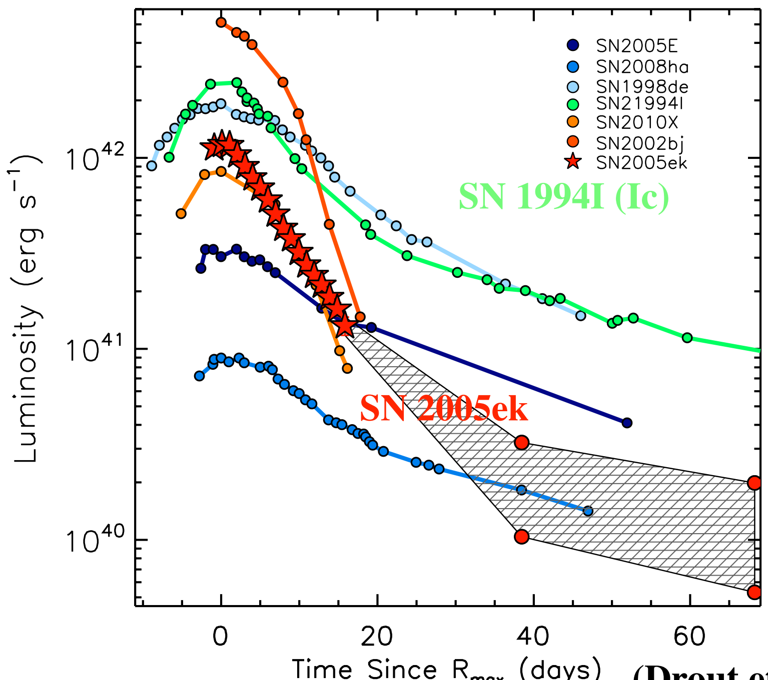
- Ultra-stripped SNe

➡ A candidate of *faint and rapidly decaying optical transients*

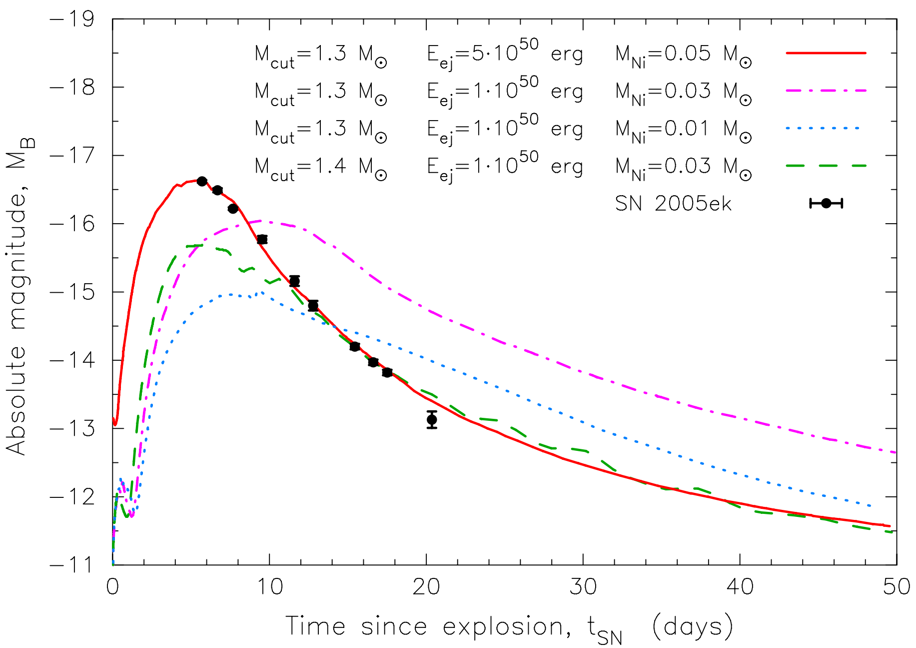
- SN 2005ek (Ic): $M_{ej} \sim 0.3 M_\odot$, $M(^{56}Ni) \sim 0.03 M_\odot$ (Drout et al. 2013)
  SN 2010X (.Ia) (Kasliwal et al. 2010), SN 2005E (Ib) (Perets et al. 2010)

- The rate of rapidly decaying SNe is 4%-7% of CC SNe.
  (Drout et al. 2014)

- The ratio of ultra-stripped SNe to all SNe is ~ 0.001 - 0.01.
  (Tauris et al. 2013)



(Drout et al. 2013)



(Tauris et al. 2013)

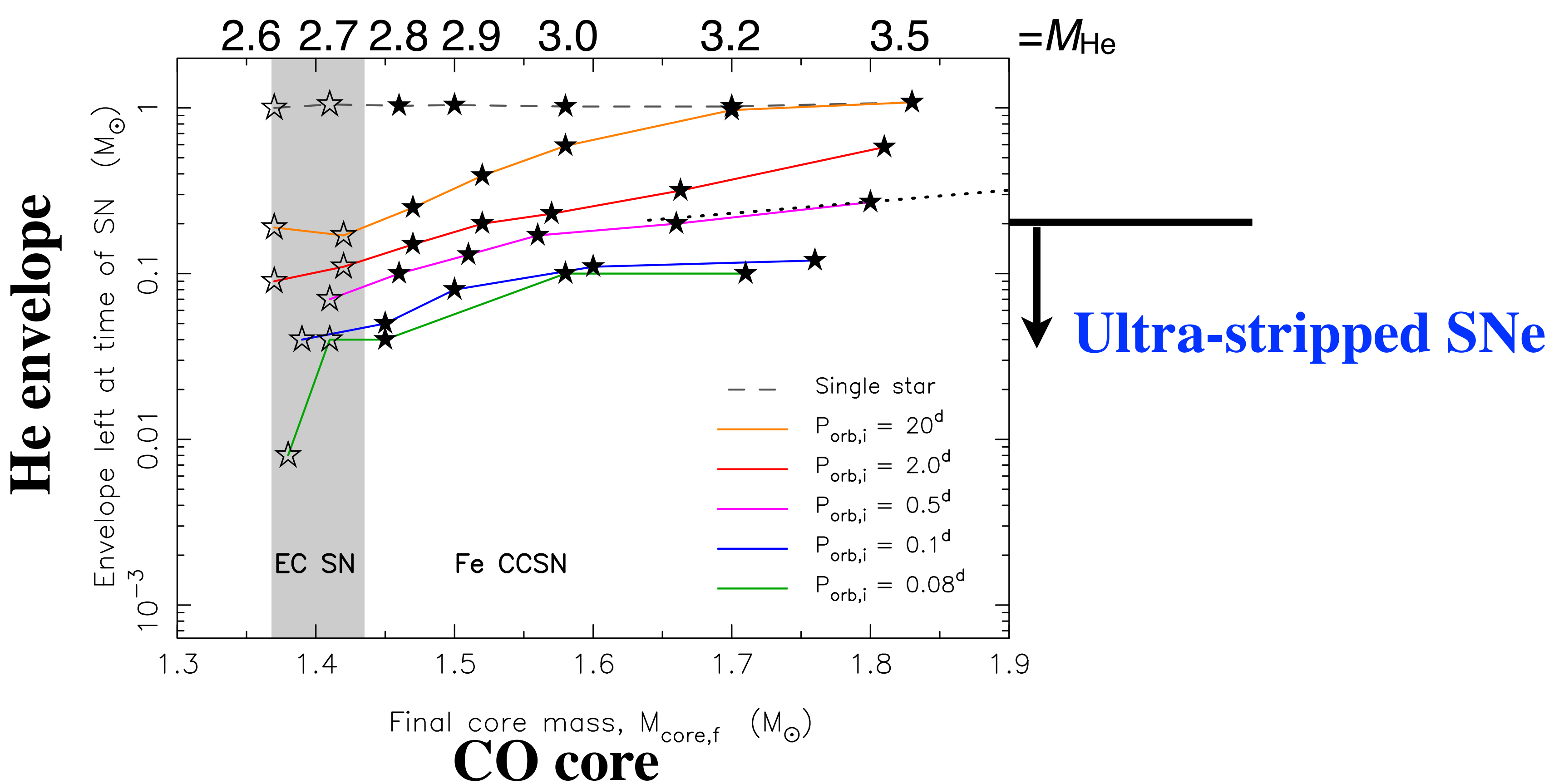
Generation site of binary neutron stars

- **Ultra-stripped SNe**
  - ➡ **Small ejecta mass** (Tauris et al. 2013; Suwa et al. 2015)

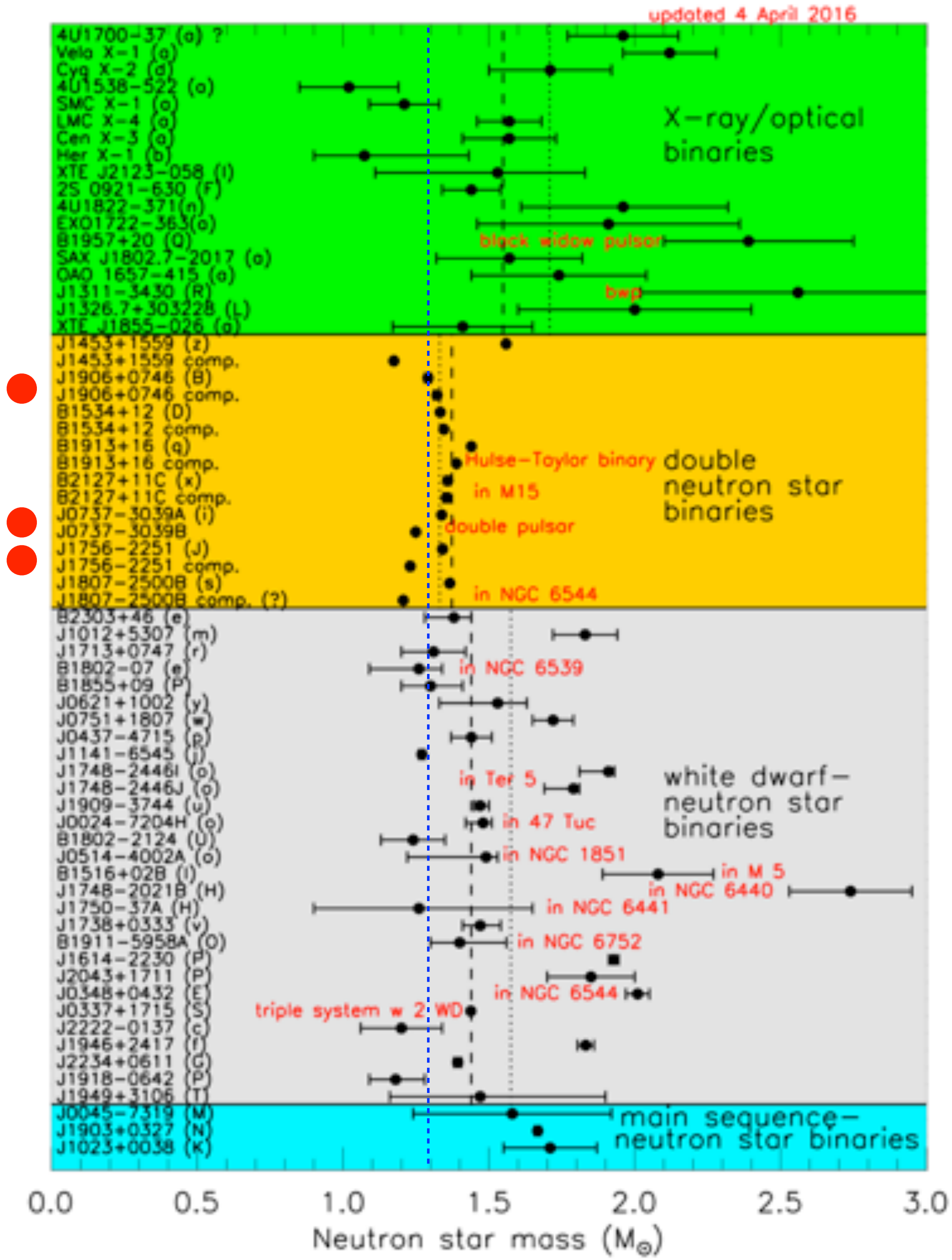
    Ejection of a half of the total mass disrupts a binary system.

    ➡ **A possible generation site of binary neutron stars and neutron star mergers**

- **He star + 1.35 $M_\odot$ NS** (Tauris et al. 2015)



NS-NS binary system



http://www.stellarcollapse.org/nsmasses

- **NS-NS binaries**

  J1906+0746

  → **1.291$M_\odot$ + 1.322$M_\odot$**

  J0737-3039

  → **1.3381$M_\odot$ + 1.2489$M_\odot$**

  J1756-2251

  → **1.312$M_\odot$ + 1.258$M_\odot$**

  J0453-1559 **(Martinez et al. 2015)**

  → **1.559$M_\odot$ + 1.174$M_\odot$**

- **Small CO-core models**

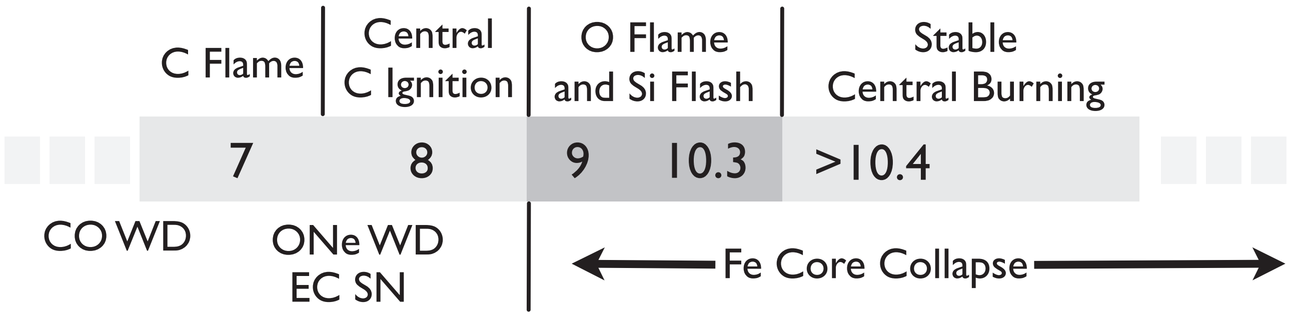
  → **Small neutron-star mass**

  (Suwa et al. 2015)

How to make a small NS in binary systems?

- **Fates of $M_{ini} \sim$ 9-11 $M_{\odot}$ single stars**

(e.g., Woosley 1986; Nomoto & Hashimoto 1988; Umeda et al. 2012; Woosley & Heger 2015)



(Woosley & Heger 2015)

➡ **Electron-capture (EC) SNe and EC SN-like (weak) core-collapse (CC) SNe will make small neutron stars.**

***But note*: fallback**

- **He star - NS binaries**

➡ **Ultra-stripped SN progenitors having a small CO-core could become EC SNe or weak CC SNe.**

➡ **They will make a small NS in the NS-NS binary.**

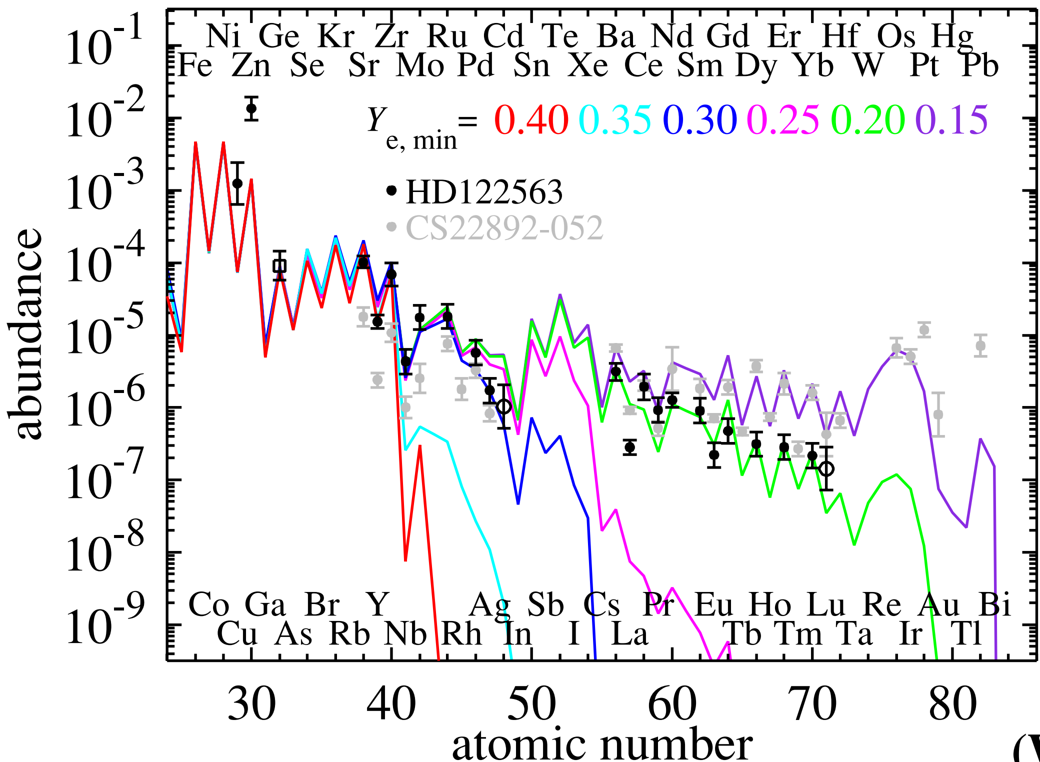
Similarity to electron-capture SNe

- **Ultra-stripped SNe having a small CO core**

➡ **Weak explosion and small ejecta mass**

(Suwa et al. 2015)

➡ ***A possibility of the nucleosynthesis similar to EC SNe***



(Wanajo et al. 2011)

Nucleosynthesis in EC SNe

- **Small ^{56}Ni amount**
- **Production of light r-process elements**

➡ **Ultra-stripped SNe could be a site of (weak) r-process elements**

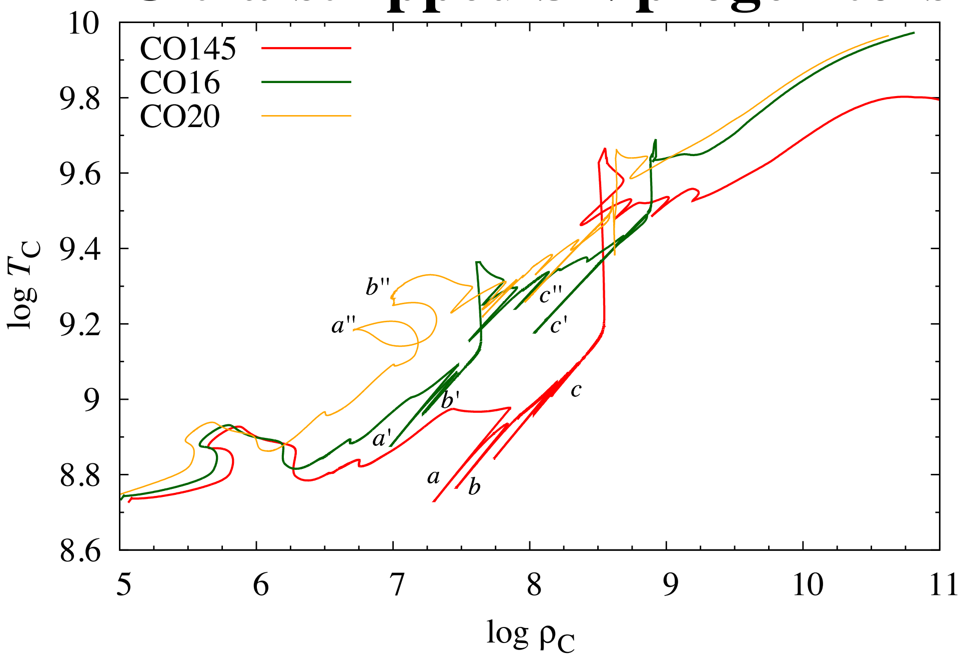
CC SNe of single stars having a low-mass Fe core

- **The advanced evolution of single stars forming a low-mass Fe-core ($M_{ini} \sim$ 9-11 $M_\odot$?) is similar to ultra-stripped SN progenitors.**
  (e.g., Woosley 1986; Nomoto & Hashimoto 1988; Umeda et al. 2012; Woosley & Heger 2015)

➡ ***Fe-core structure and explosions similar to ultra-stripped SNe are expected.***

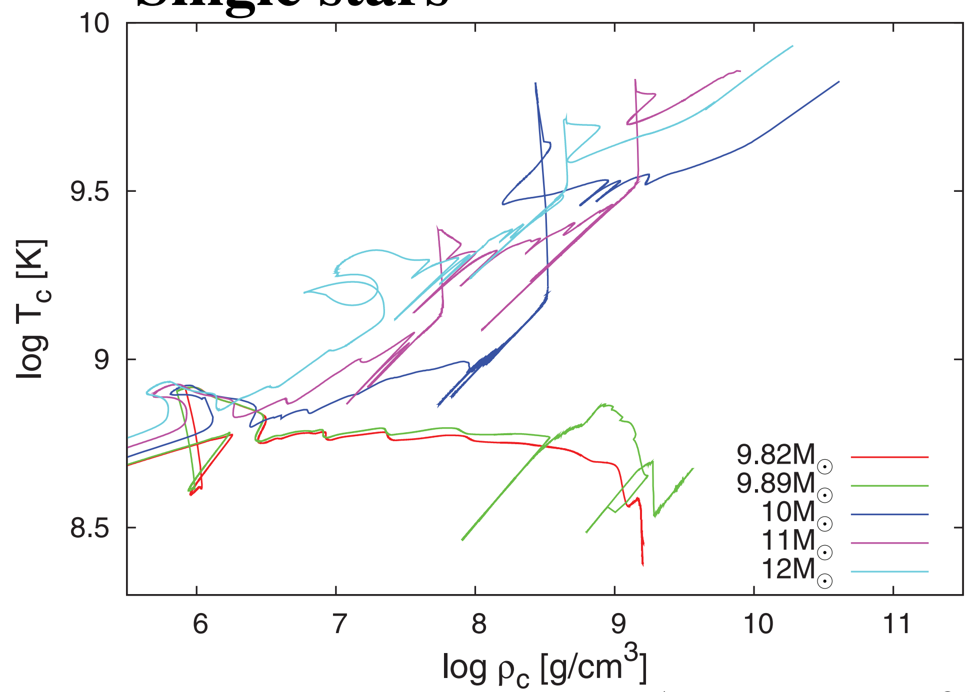
➡ **The nucleosynthesis products of such explosions could affect the Galactic chemical evolution.**

Ultra-stripped SN progenitors



(Suwa et al. 2015)

Single stars



(Umeda et al. 2012)

Nucleosynthesis of ultra-stripped SNe

- Ultra-stripped SNe having a small CO core

  → Small ejecta mass and weak explosions

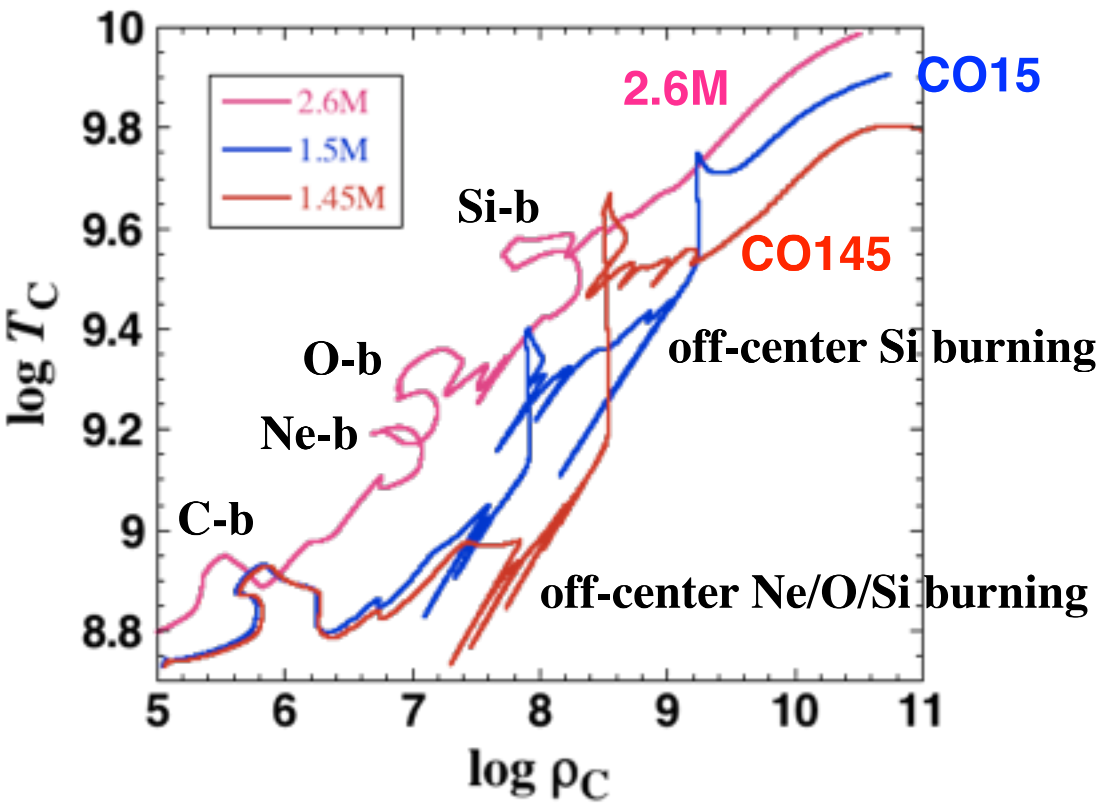
    - Similarity to EC SNe
      - Small ^{56}Ni amount
      - A possibility of weak r-process
    - Similarity to CC SNe having a small Fe core
      - Contribution to the Galactic chemical evolution from single CC SNe having a small Fe core

- We investigate the explosive nucleosynthesis of ultra-stripped Type Ic SNe evolved from 1.45 and 1.5 $M_{\odot}$ CO cores.

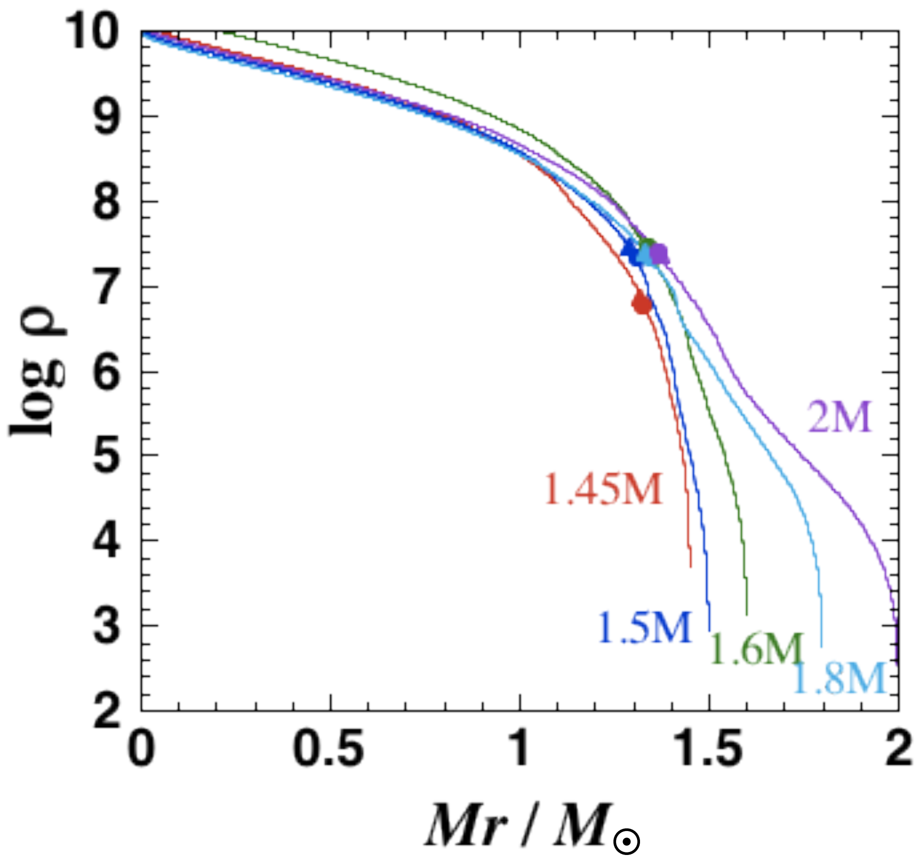
Advanced evolution of CO stars

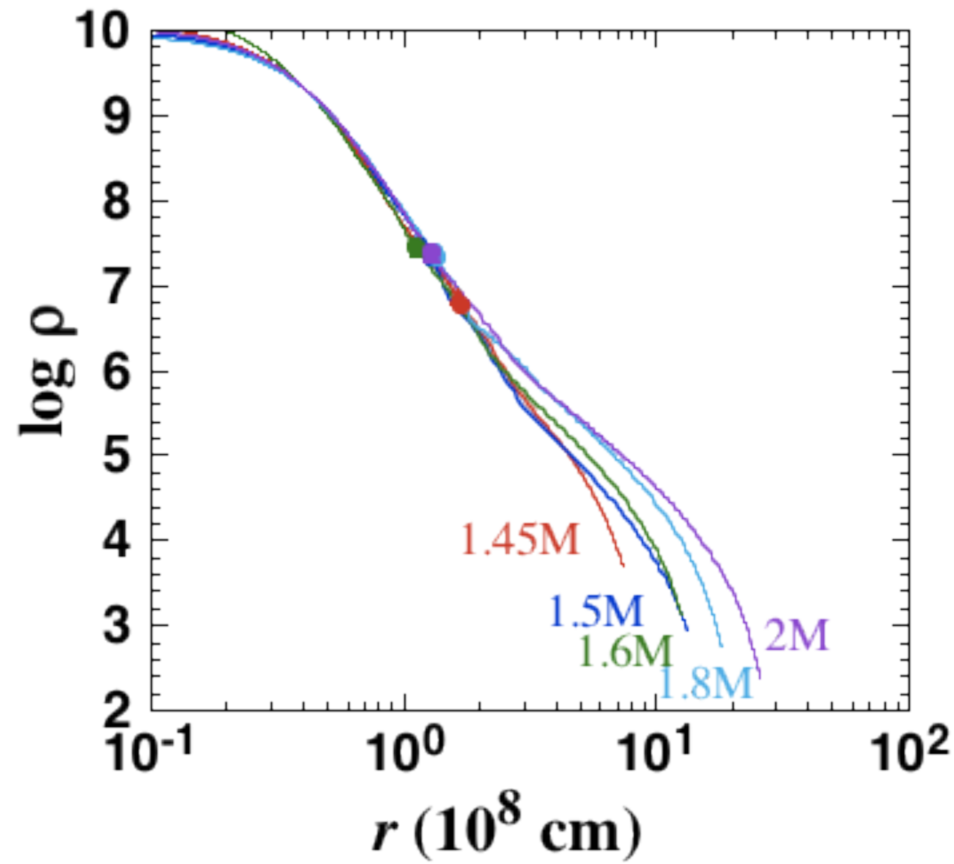
- Advanced evolution of CO stars (Suwa et al. 2015)
  - 1.45, 1.5, 1.6, 1.8, 2.0 $M_\odot$ models
    (CO145, CO15, CO16, CO18, CO20)

➡ **All models form a small Fe core.**
Off-center Ne/O and/or Si burnings occur in the degenerate core.



Density distributions of the progenitors





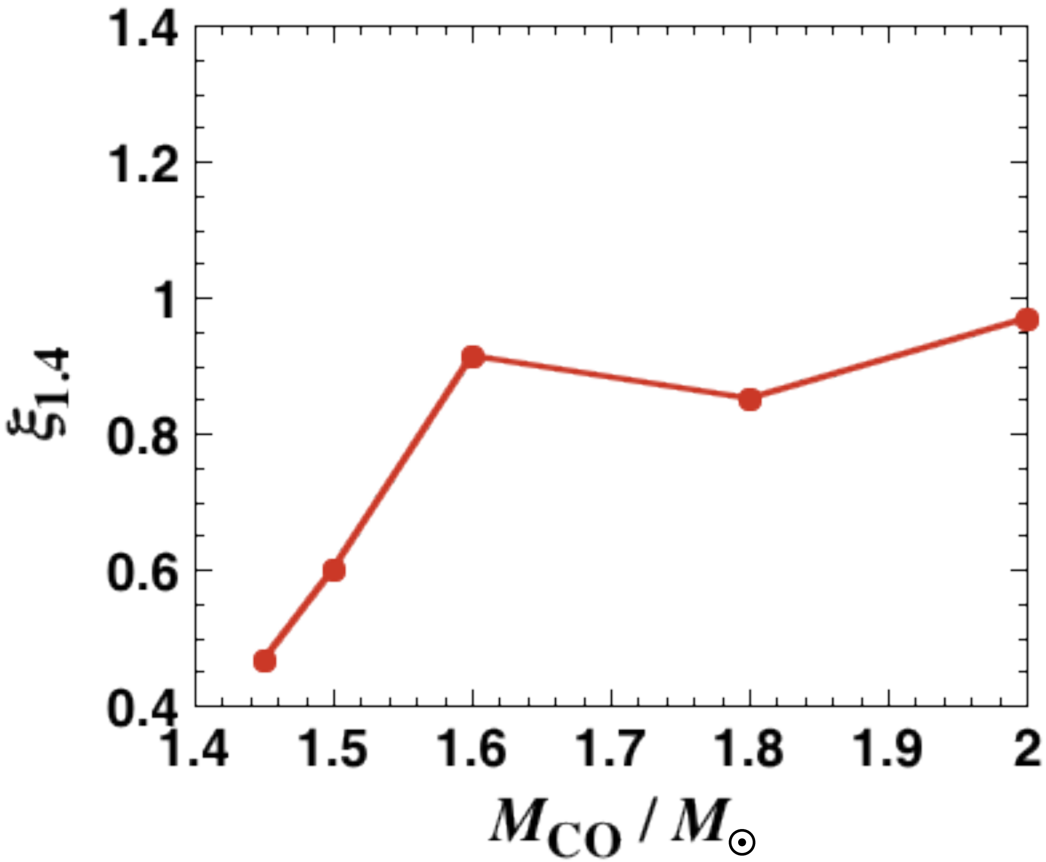
• Ye < 0.495; ▲ *X*("Fe") > *X*("Si")

- **Light CO cores ➡ Steep density decrease outside Fe core**
- $r_{\mathrm{Fe\ core}} = (1.34 - 1.77) \times 10^8$ cm

Compactness parameter

- **Compactness parameter**

  $\xi_{1.4} = 1.4 / (r[Mr = 1.4M_\odot]/1000\text{km})$ @ $\log \rho_C \sim 10$



- **Light CO core** → **Less central concentration**

  $\xi_{1.4} = 0.468 - 0.968$

Explosions of ultra-stripped SNe

- **2D axial symmetry simulation of SN explosions**

(Suwa et al. 2010, 2011, 2013, 2014; Suwa et al. 2015 for details)

→ **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

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

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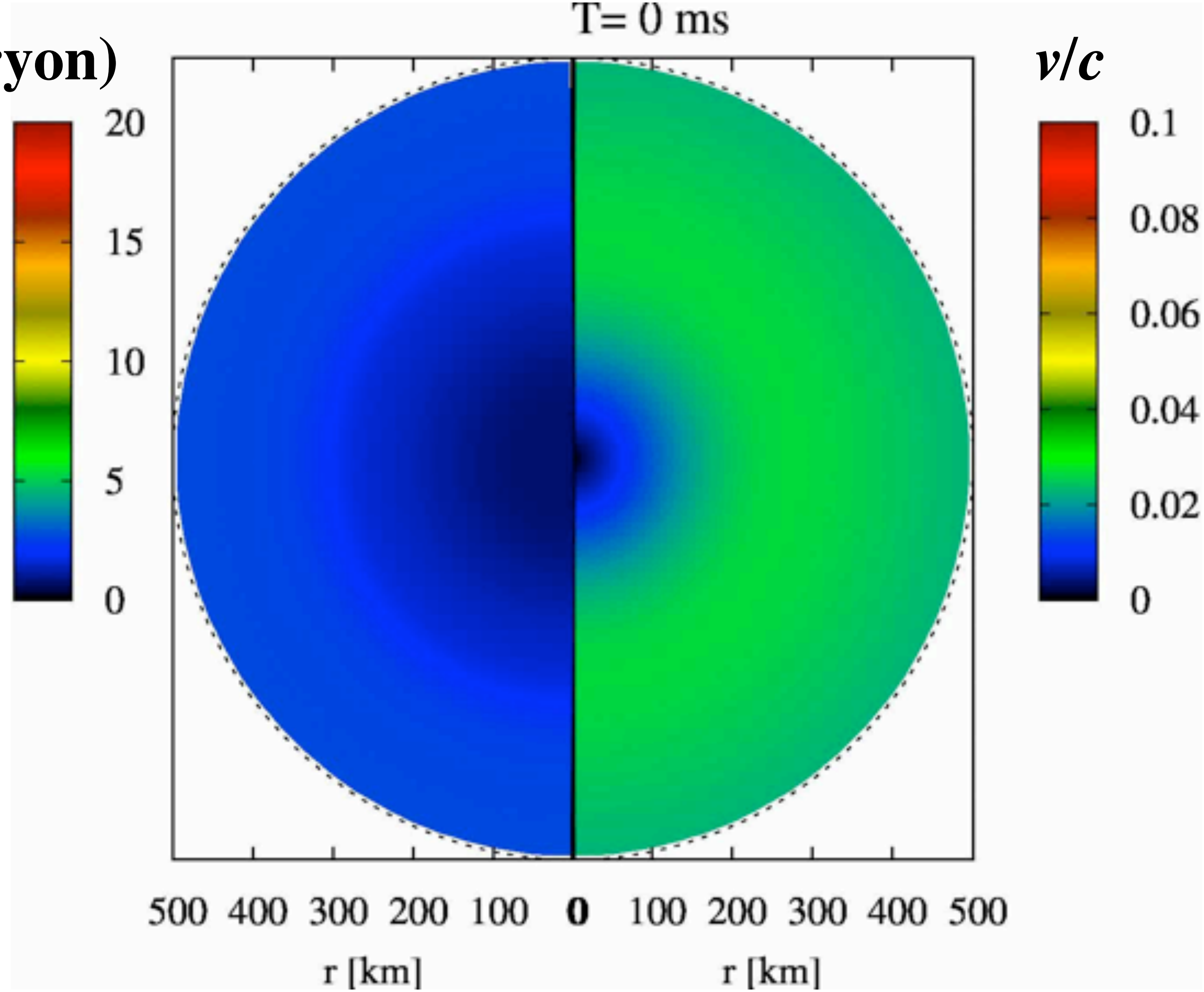
- **EOS: Lattimer & Swesty (*K*=220 MeV)**

Explosion of CO145 model



(Suwa et al. 2015)

- Rapidly exploding phase at ~ 200 ms

Explosions of ultra-stripped SNe

- E_{exp}, M_{NS}, M(^{56}Ni), and v_{kick} (Suwa et al. 2015 for details)

Model	t_{final} [a] [ms]	R_{sh} [b] [km]	E_{exp} [c] [B]	$M_{NS,baryon}$ [d] $[M_\odot]$	$M_{NS,grav}$ [e] $[M_\odot]$	M_{ej} [f] $[10^{-1} M_\odot]$	M_{Ni} [g] $[10^{-2} M_\odot]$	v_{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	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

($M_{Ni}{}^{g}$=M(T_{max}>5GK))

- **Explosion energy** → $O(10^{50})$ erg
- **Final NS mass** → $M_{baryon} \sim 1.35 - 1.60\ M_\odot$
  $M_{grav} \sim 1.24 - 1.44\ M_\odot$
- **Ejecta mass** → $M_{ej} \sim 0.1\text{-}0.4\ M_\odot$
- **NS kick velocity** → $v_{kick} < 100$ km s^{-1}

Nucleosynthesis calculation of ultra-stripped SNe

- **Explosive nucleosynthesis of ultra-stripped SNe**
  - **The explosions follow for ~1.3 s using a 2D ν-RHD code.**
  - **CO145 and CO15 models**

    → **Thermal evolution of ~10,000 tracer particles of ejecta**

  - **Nuclear reaction network of 1,651 nuclear species to Ce**
    - **Initial composition**

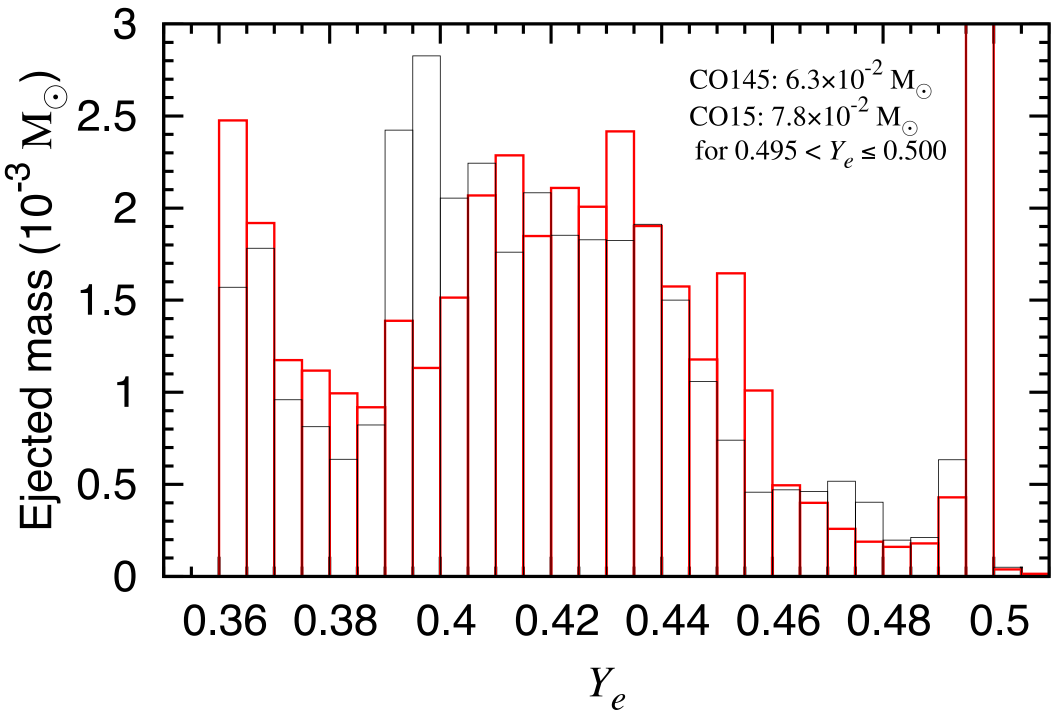
      → **NSE composition with a given Y_e ($T_{max} > 7\times10^9$ K)**

      Progenitor composition ($T_{max} < 7\times10^9$ K)

Ejected mass distribution

- Ejected mass distribution about Y_e at the initial time of the nucleosynthesis calculation

$$Y_e = n_e / (n_p + n_n) = n_p / (n_p + n_n)$$



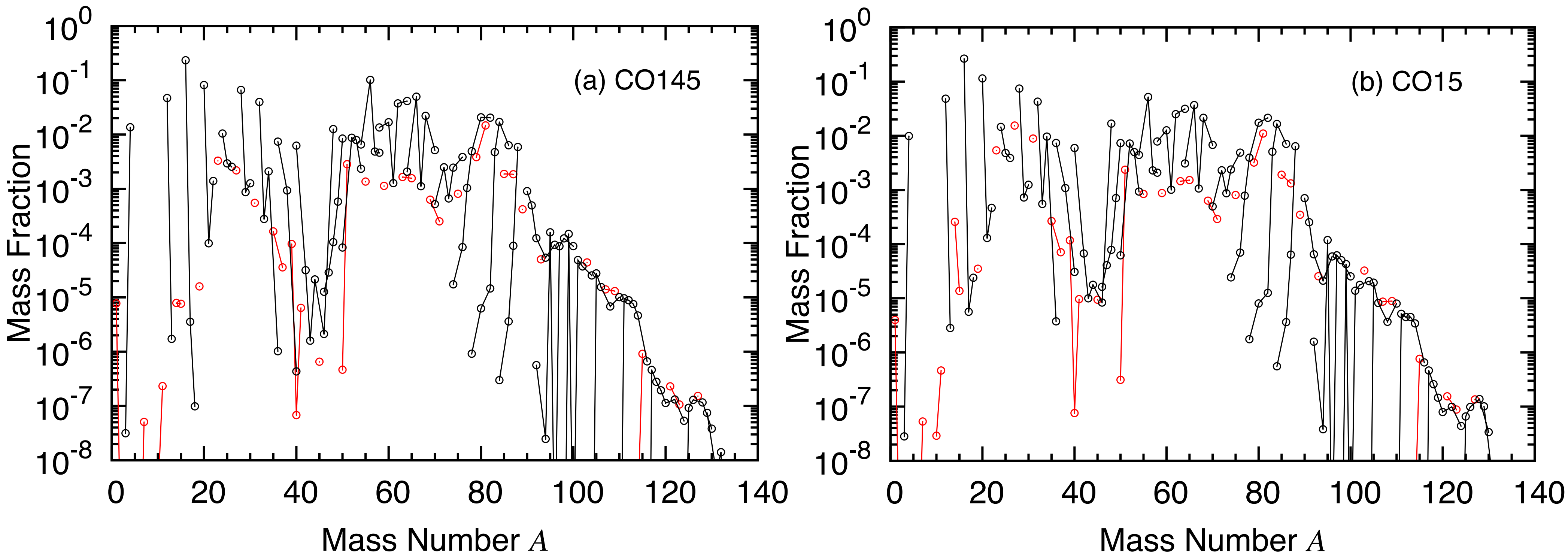
- $T_{9,max} > 9$:
  The calculation starts at T_9=9.
- $7 < T_{9,max} \leq 9$:
  The calculation starts at $T_9 = T_{9max}$.
- $T_{9,max} \leq 7$:
  The calculation starts before the shock arrival.

$T_9 \equiv T/10^9$ K

- The Y_e range ➡ $0.36 \leq Y_e \leq 0.505$
  for CO145 and CO15 models

We will discuss the uncertainty in the Y_e range later.

Mass fraction distribution

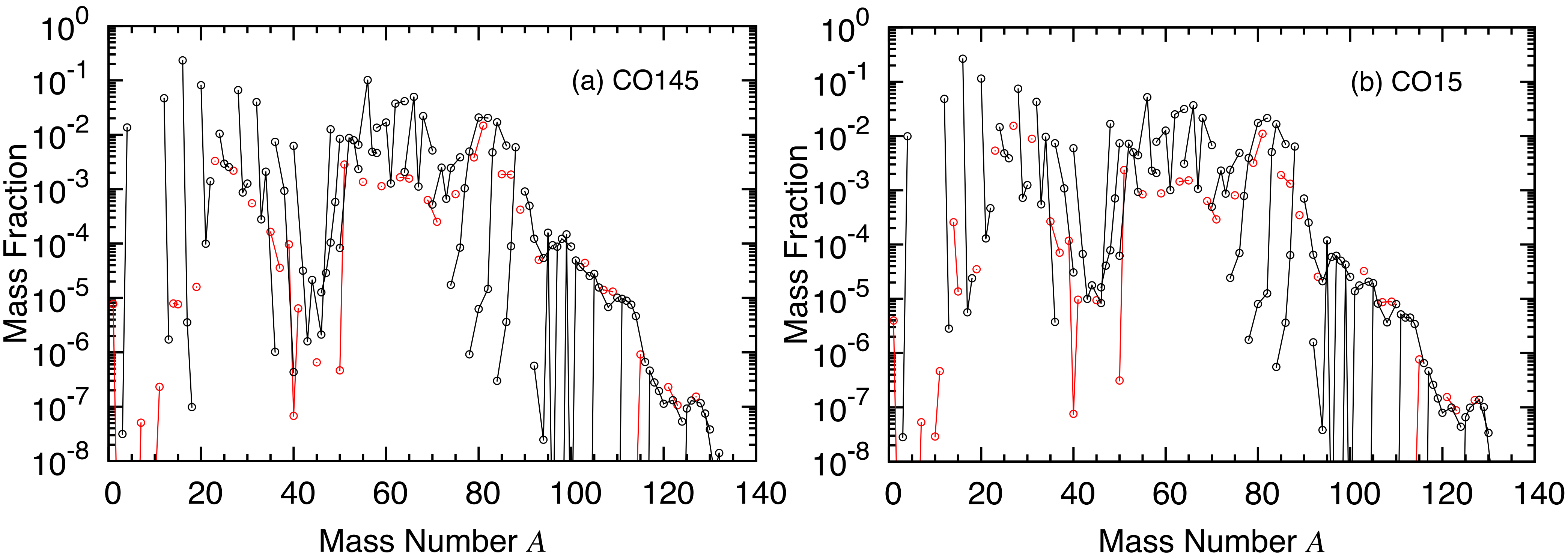


- M_{ej} = 0.098 $M_\odot$ (CO145), 0.112 $M_\odot$ (CO15)
- Shock heated materials ($Y_e \sim 0.5$)

➡ C, O, α-elements, Fe-peak elements

$M(^{56}Ni) = 9.7\times10^{-3}\ M_\odot$ (CO145) , $5.7\times10^{-3}\ M_\odot$ (CO15)

Mass fraction distribution

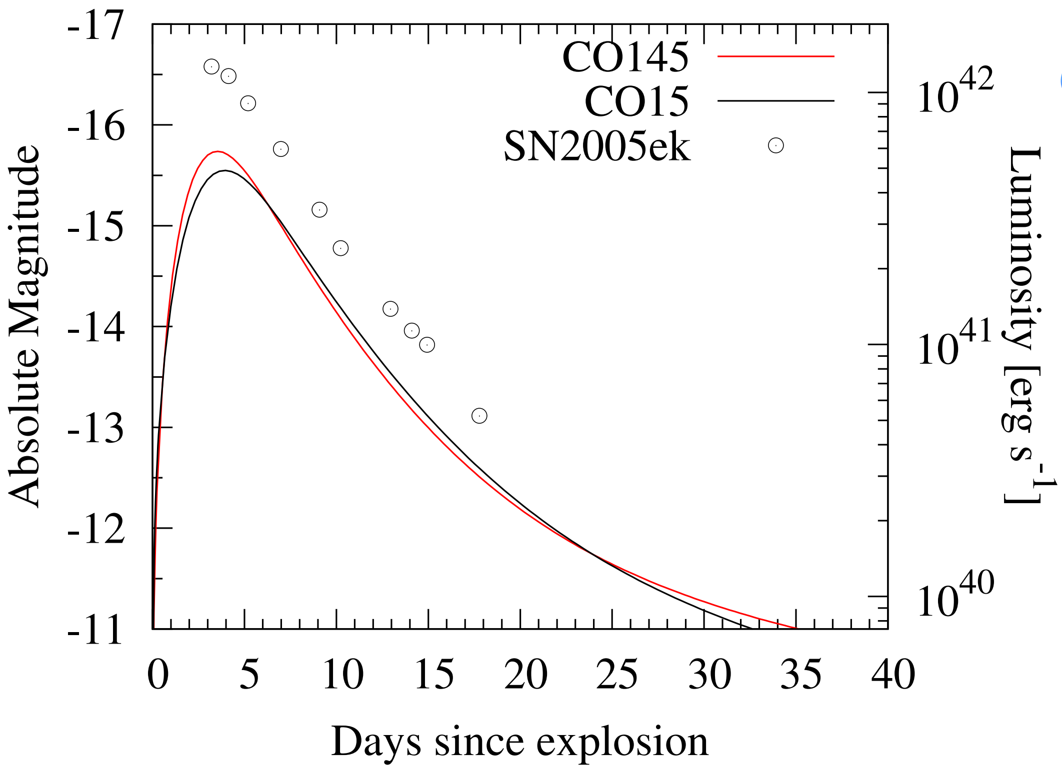


- $M_{ej} = 0.098\, M_\odot$ **(CO145), 0.112** $M_\odot$ **(CO15)**
- **Shock heated materials ($Y_e \sim 0.5$)**
- **Hot-bubble materials ($Y_e < 0.5$)**

➡ **The 1st peak r-process elements**
***n*-rich intermediate isotopes (^{48}Ca, ^{50}Ti)**

(c.f. Wanajo et al. 2013 for EC SN)

Light curves



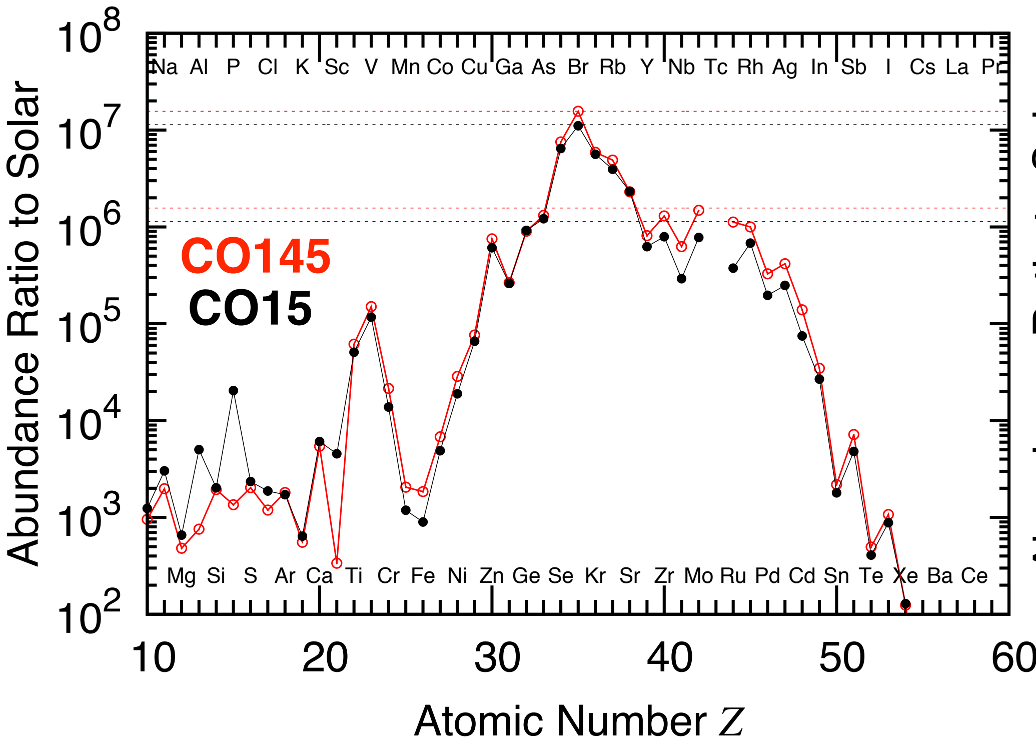
- **Light curves are evaluated using the analytical solution shown in Arnett (1982).**

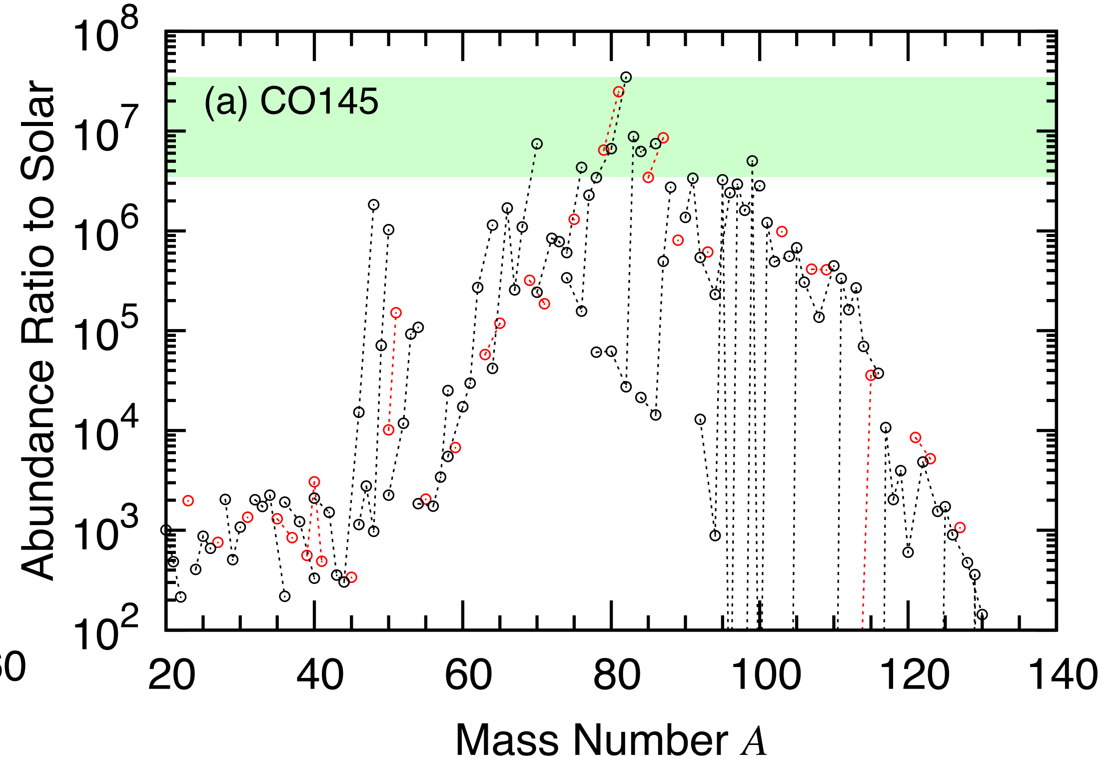
$M(^{56}Ni)$ = 9.7×10^{-3} $M_\odot$(CO145)
= 5.7×10^{-3} $M_\odot$(CO15)

SN 2005ek: Drout et al. (2013)

- **The decline time scale is close to fast-decaying faint SN 2005ek.**
- **The peak magnitude is ~ -15.5.**
- **The radioactive decays of intermediate and heavy unstable isotopes partly contribute to the optical emission.**

Abundance ratios to the Solar composition



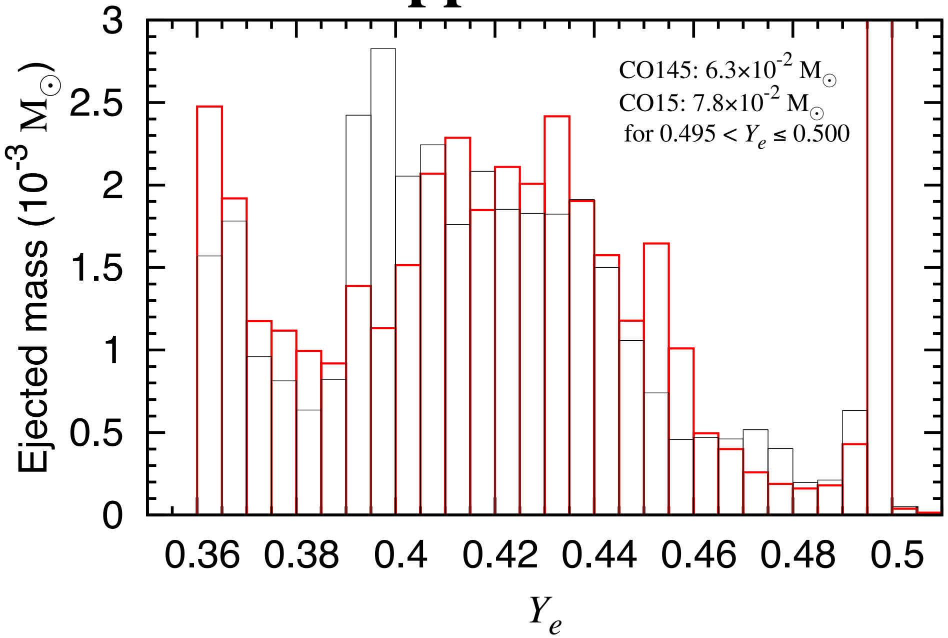


- **The abundance ratios of the SN ejecta to the solar composition $Y(Z)/Y_{\text{solar}}(Z)$; $Y(^{A}Z)/Y_{\text{solar}}(^{A}Z)$**
- **Large abundance ratios to the solar composition are shown for the 1st peak r-process elements (As - Sr).**
- ***n*-rich intermediate isotopes (^{48}Ca, ^{50}Ti)**

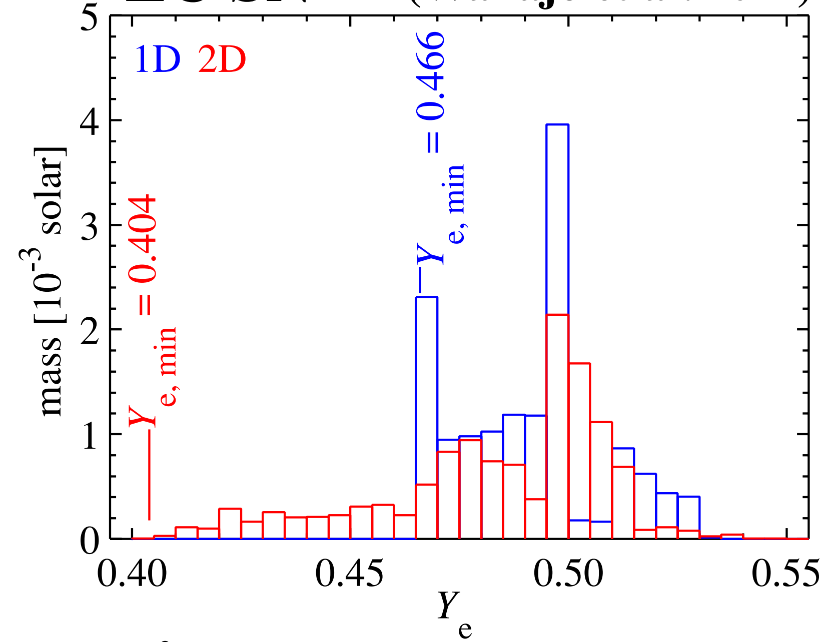
Uncertainty in ejected mass distribution on Y_e

- The Y_e range ➡ $0.36 \le Y_e \le 0.505$
  for CO145 and CO15 models
- Electron-capture SN
  ➡ $Y_{e,\mathrm{min}} = 0.46$ in 1D explosion model
  (Wanajo et al. 2009)
  $Y_{e,\mathrm{min}} = 0.34$ - 0.40 for different 2D RHD treatments
  (Wanajo et al. 2011; Janka-san's talk on Nov. 1)

Ultra-stripped SNe



EC SN (Wanajo et al. 2011)

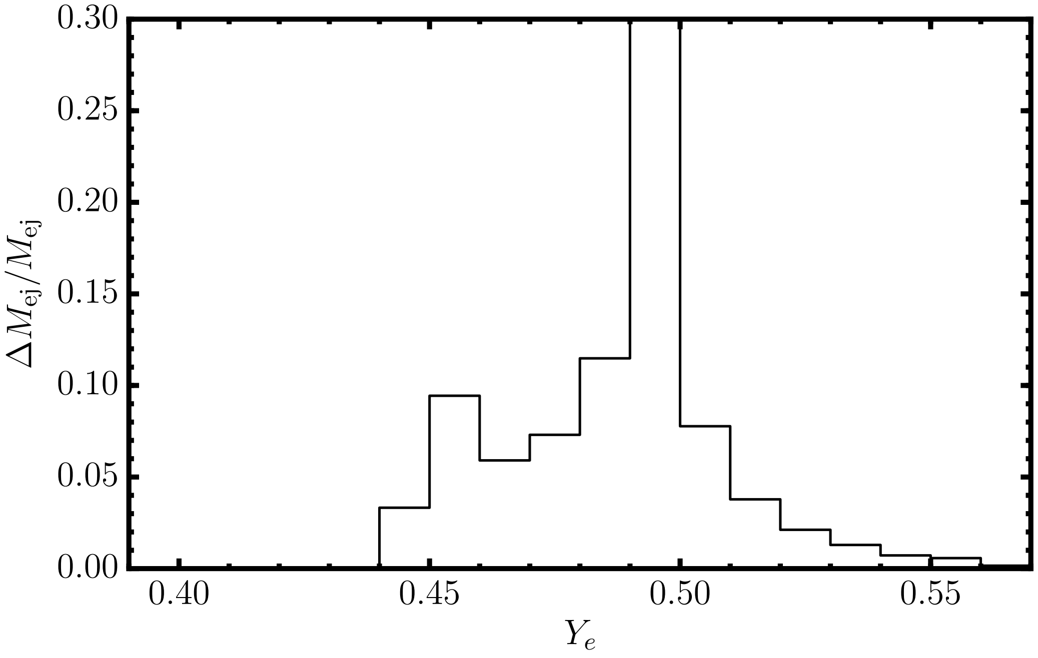


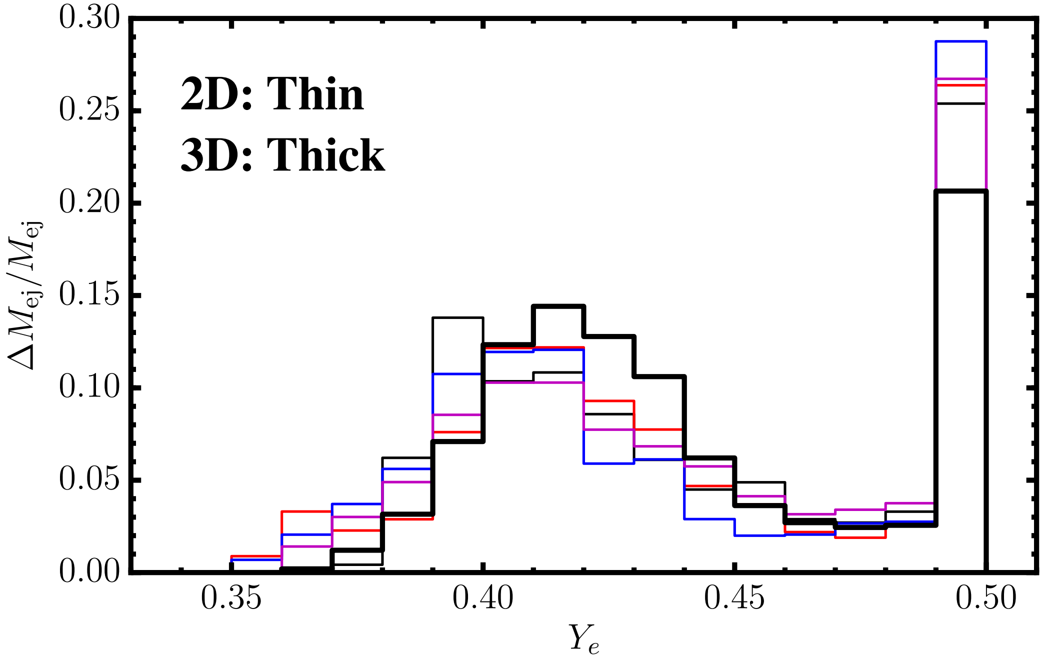
➡ **Systematic differences by neutrino transport treatments**

Uncertainty in ejected mass distribution on Y_e

- **SN explosion of a 9.6 $M_\odot$ star** (Müller 2016)

  ➡ **$Y_{e,\,\mathrm{min}}$ of 0.35 - 0.44**





Vertex-CoCoNuT
(Two-moment scheme with variable Eddington factors from a model Boltzmann equation.)
Sophistication of the microphysics

CoCoNuT-FMT
(Dynamic one-moment closure scheme)

➡ **Systematic differences by neutrino transport treatments**

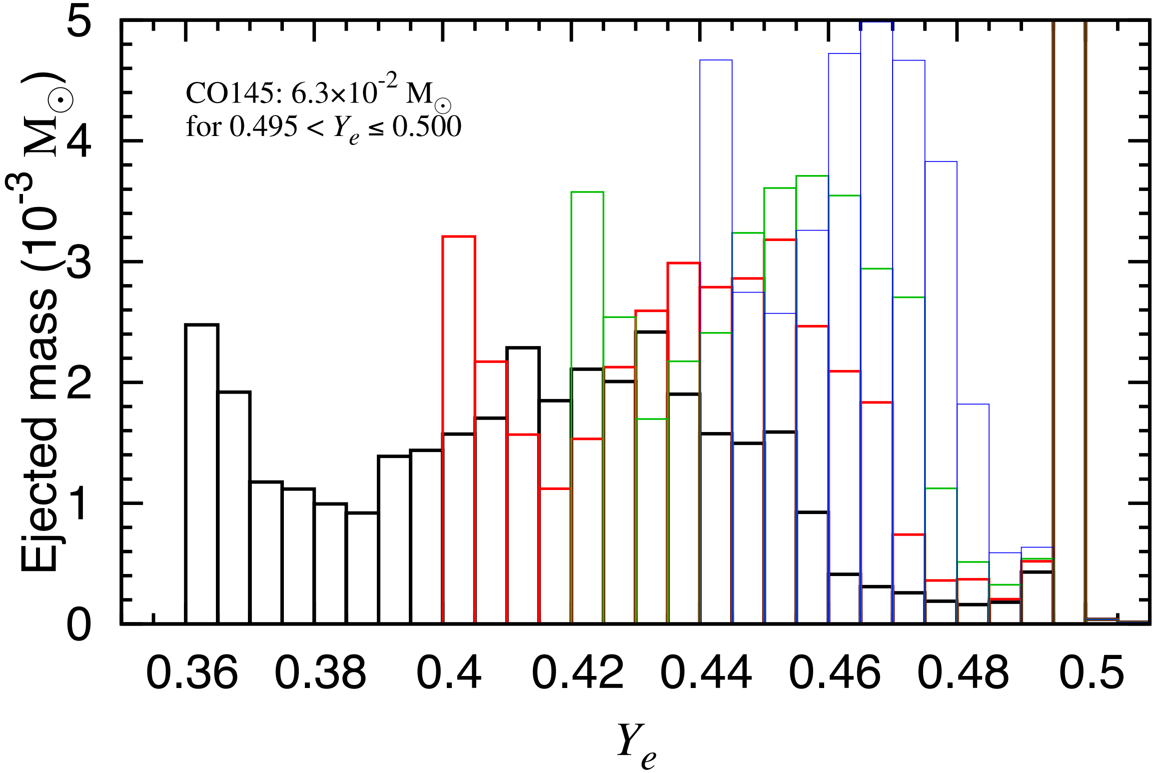
Uncertainty in ejected mass distribution on Y_e

- The Y_e range ➡ $0.36 \le Y_e \le 0.505$
  for CO145 and CO15 models

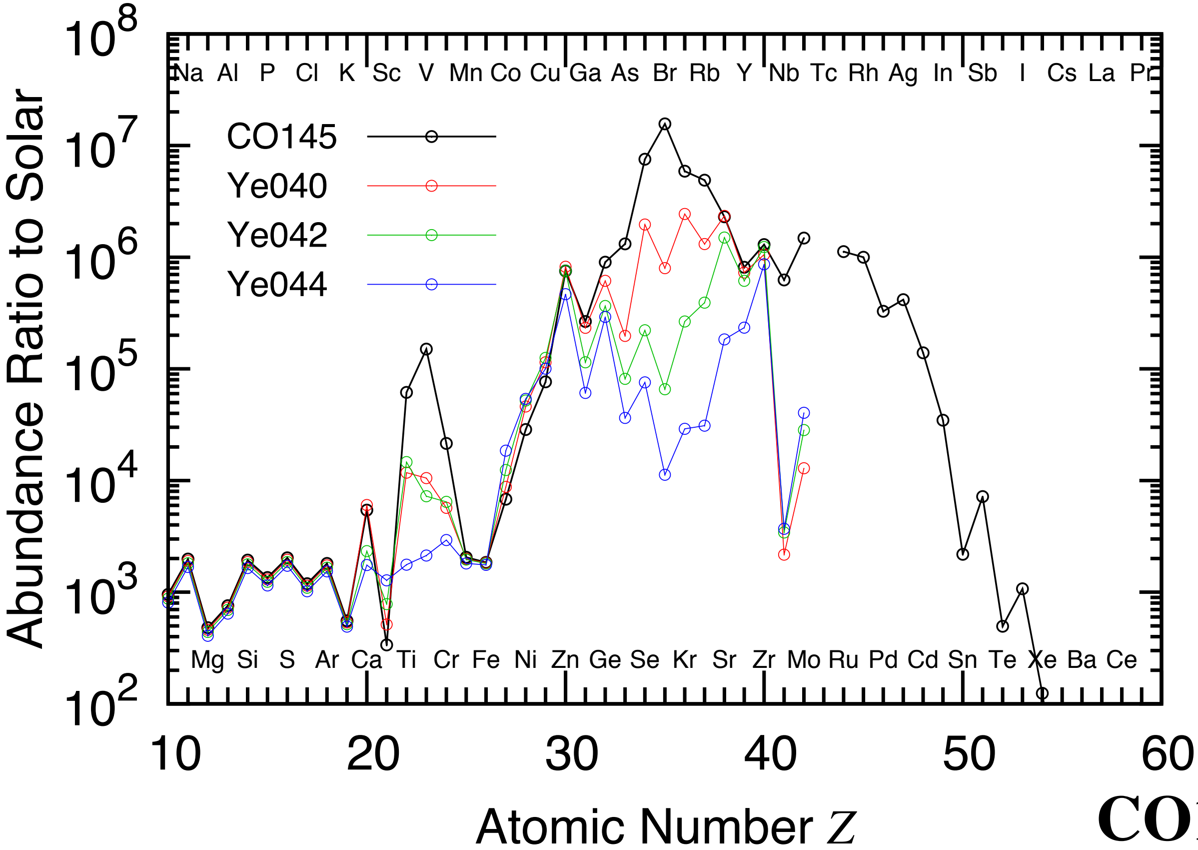
The Y_e distribution could be affected by neutrino transport treatments.

- We investigate the effects of Y_e uncertainties to the nucleosynthesis.

➡ $Y_{e,\mathrm{min}} = 0.36 \rightarrow 0.40$ (Ye040), 0.42 (Ye042), 0.44 (Ye044)
for CO145 model



Uncertainty in abundance distribution

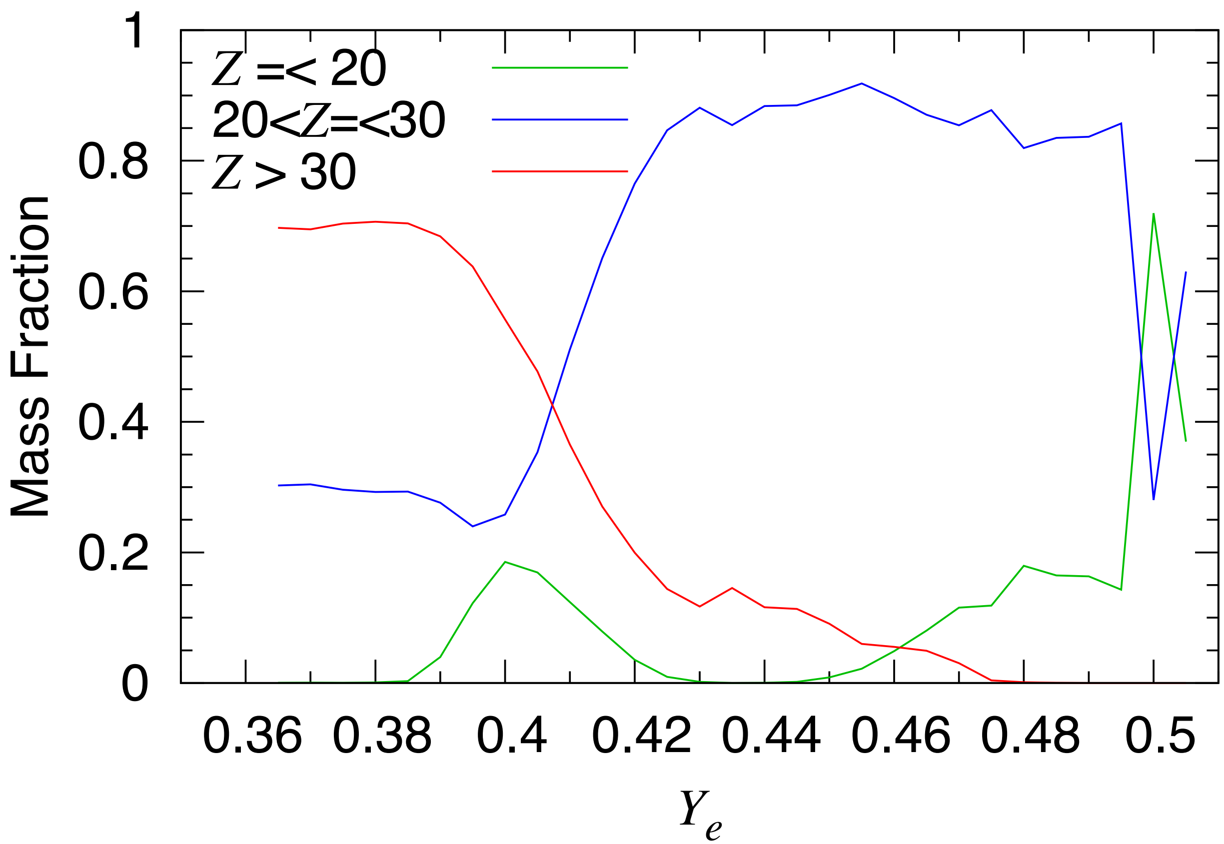


CO145, Ye040, Ye042, Ye044 models

- **Less *n*-rich distributions**
  - **➡ Different distributions of the 1st peak r-process elements**
    Less abundant in Ga-Rb
- **Yield of the 1st peak r-process elements ($Z > 30$)**
  - **➡ 6×10^{-4} (Ye044) ~ 0.01 (CO145) $M_\odot$**

Y_e dependence of heavy element abundances

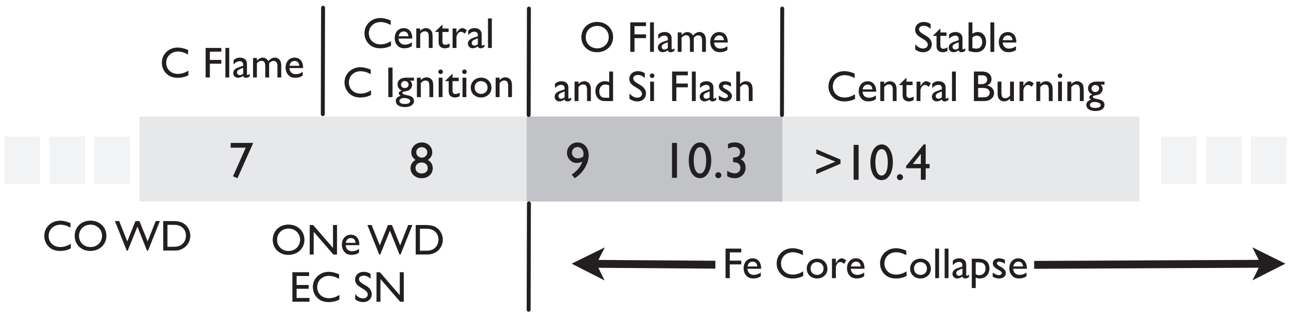
- **Mass fractions in fluid particles with each Y_e (0.005) bin**



- **Heavy elements are produced in $Y_e < 0.42$.**
- **Neutron-rich Ca isotopes are produced in $Y_e \sim 0.40$.**

Contribution of low-mass massive stars

- $M_{ini} \sim 9\text{-}11\ M_\odot$ **single stars**
  (e.g., Woosley 1986; Nomoto & Hashimoto 1988; Umeda et al. 2012; Woosley & Heger 2015)



(Woosley & Heger 2015)

➡ **Electron-capture (EC) SNe and EC SN-like (weak) core-collapse (CC) SNe will make small neutron stars.**

***But note*: fallback**

- **A possible site for the 1st peak r-elements in the Galaxy**
  - **Stellar mass range?**
  - **Production/ejection of the 1st peak r-elements?**

Concluding remarks

- We investigated explosive nucleosynthesis of ultra-stripped SNe evolved from 1.45 and 1.5 $M_\odot$ CO core progenitors using thermal history calculated by 2D ν-RHD simulations.
- $M_{ej} \sim 0.1\ M_\odot$, $M(^{56}Ni) = 9.7\times10^{-3}\ M_\odot$(CO145), $5.7\times10^{-3}\ M_\odot$(CO15)
- Small ejecta mass, small ^{56}Ni amount, and weak explosion deduce faint and fast-decaying light curves.
- The 1st peak r-process elements such as As-Sr can be produced in hot-bubble materials.
- The 1st peak r-element yield and the r-element distribution depend on the uncertainty of the Y_e distribution of the SN ejecta.
- Weak core-collapse SNe having a small Fe core could eject the products similar to EC SN and affect the Galactic chemical evolution.