Nucleosynthesis in Ultra-Stripped Supernovae

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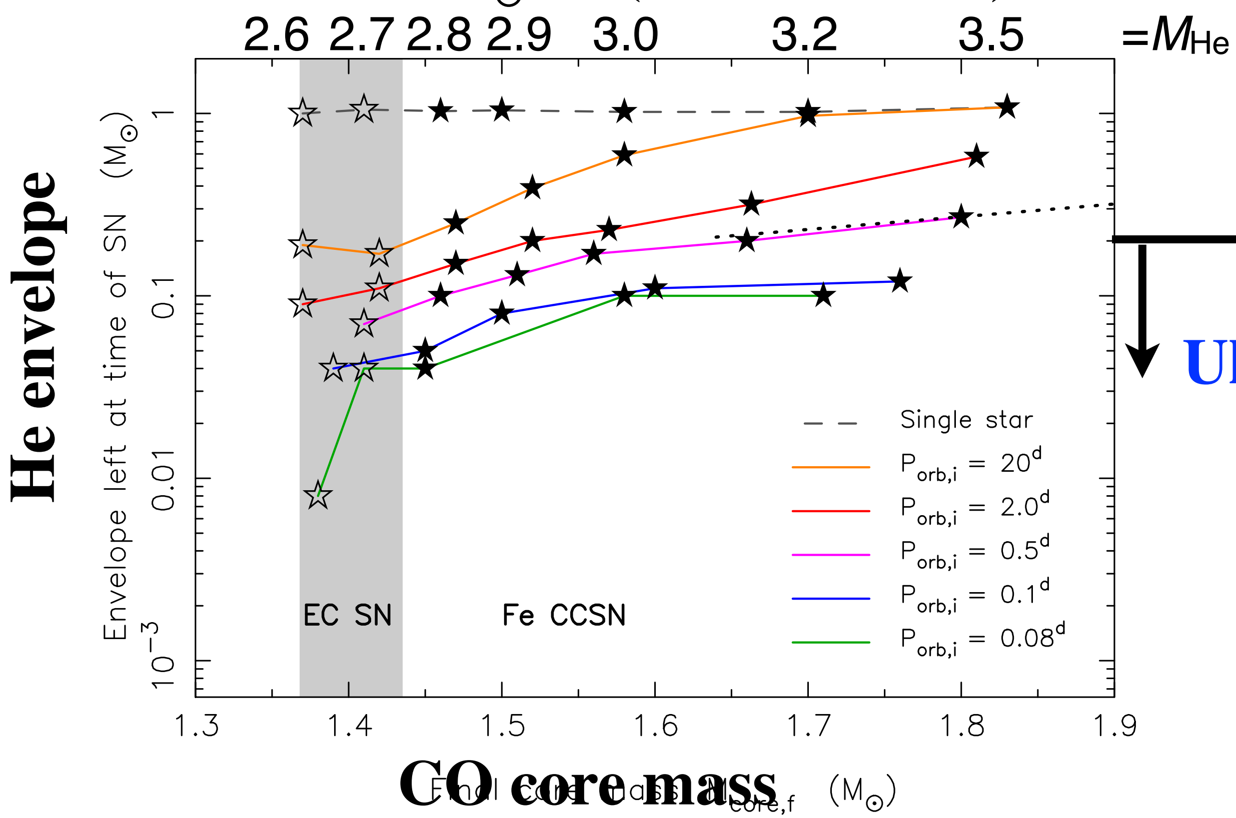
Physics of Core-Collapse Supernovae and Compact Star Formation

March 19th, 2018, Waseda University

Ultra-Stripped Supernova

- **Ultra-stripped SN**
  - ➡ **SN of which H and He envelope has been lost in binary system**
  - **Small ejecta mass** (Tauris et al. 2013; Suwa, TY et al. 2015; Moriya et al. 2017)
    - ➡ **A possible generation site of binary neutron stars and neutron star mergers**
      (Ejection of a half of the total mass disrupts a binary system.)

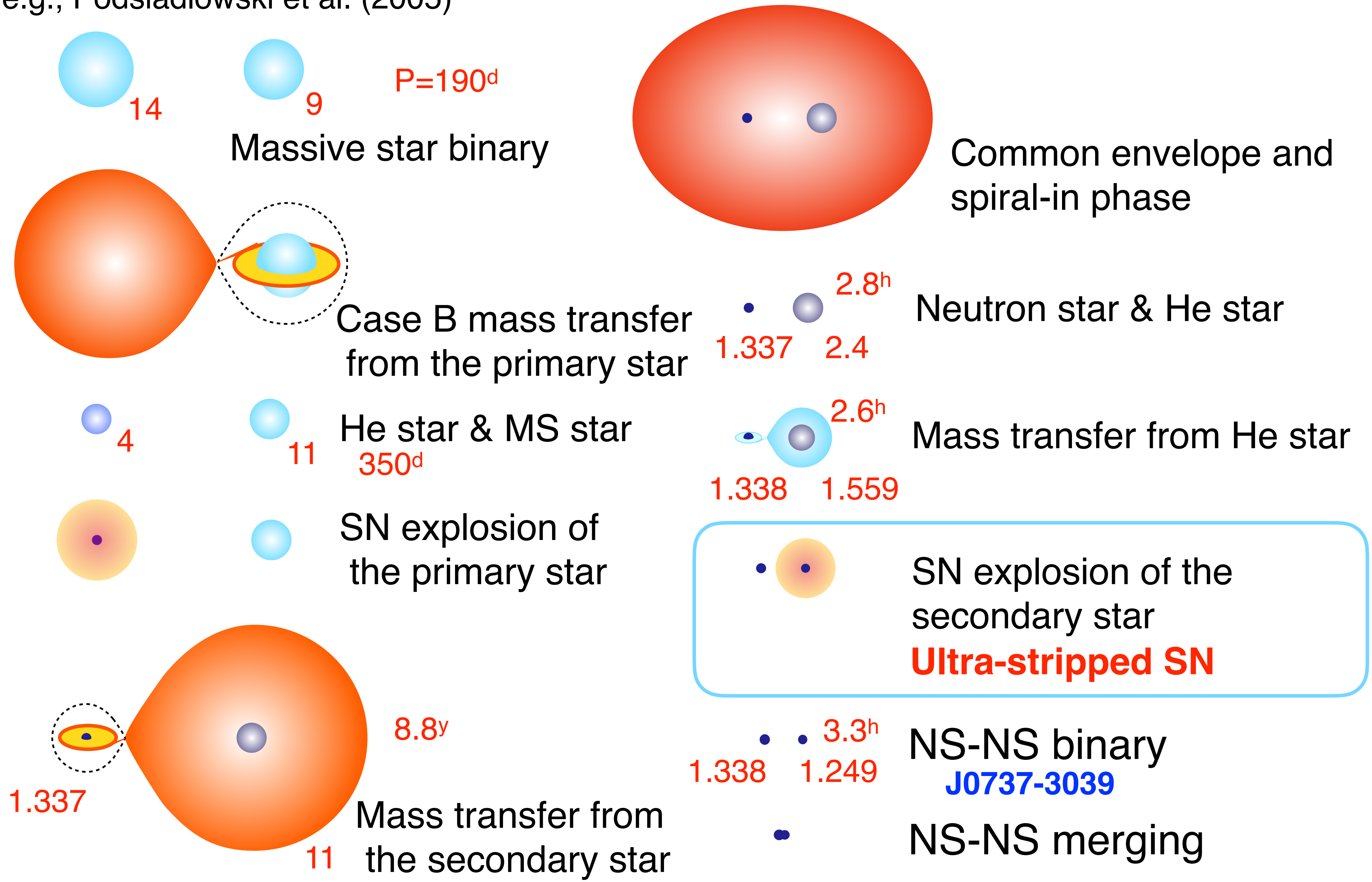
- **He star + 1.35 $M_\odot$ NS** (Tauris et al. 2015)



Ultra-stripped SNe

Standard channel producing NS-NS binary

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



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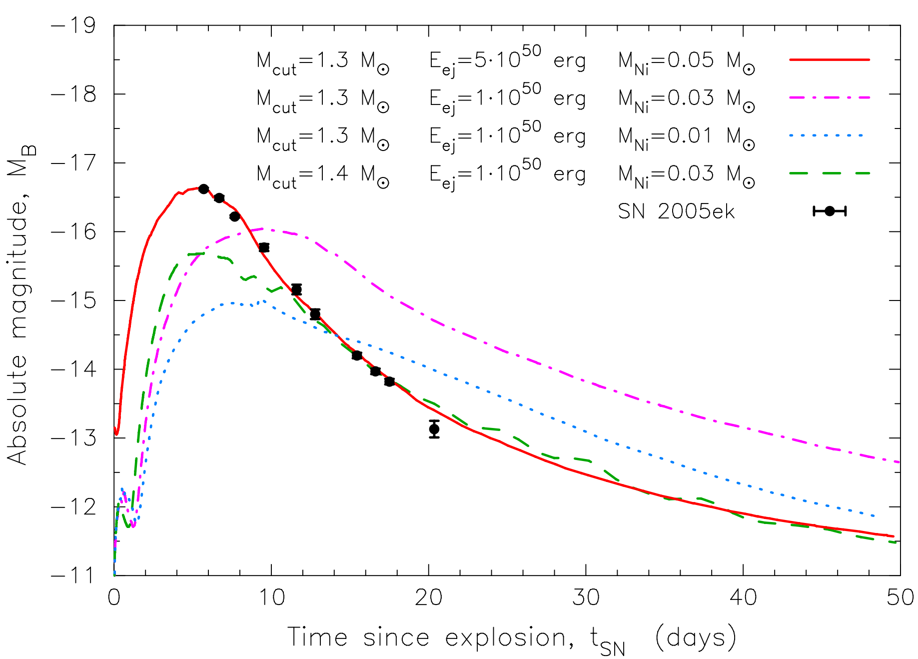
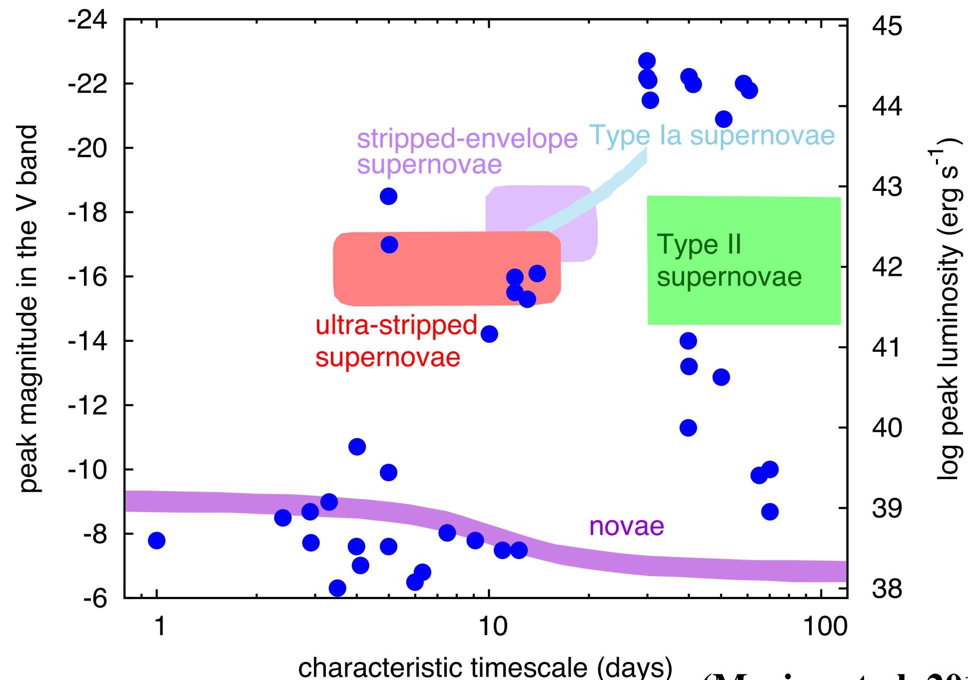
Rapidly decaying optical transients

- **Ultra-stripped SNe**
  - ➡ **A candidate of *rapidly-decaying faint 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 CC SNe is ~ 0.001 - 0.01.** **(Tauris et al. 2013)**



(Tauris et al. 2013)



(Moriya et al. 2017)

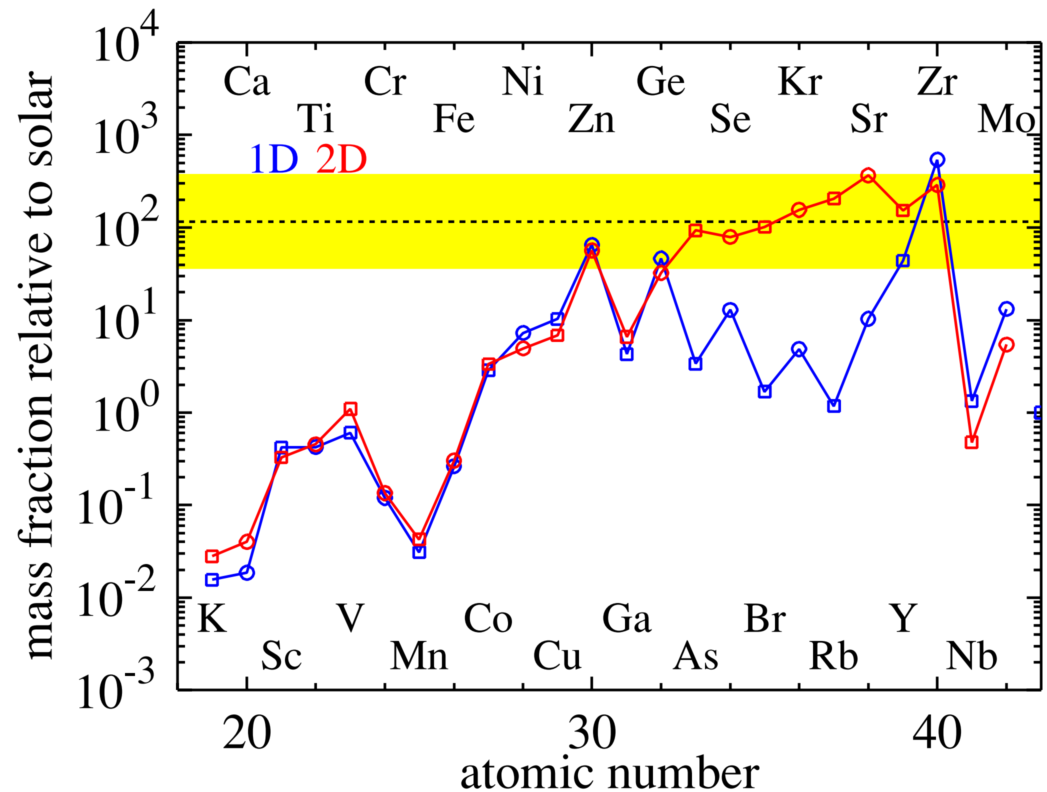
Similarity to electron-capture SNe

- Ultra-stripped SNe having a small CO core
  - → Weak explosion and small ejecta mass
    (Suwa, TY et al. 2015)
  - → *A possibility of the nucleosynthesis similar to EC SNe*

- Nucleosynthesis in EC SNe
  (Wanajo et al. 2011)
  - Small ^{56}Ni amount
  - Production of light trans-iron elements from *n*-rich matter

Electron fraction: Y_e

$(0.404 < Y_e, < 0.55)$



(Wanajo et al. 2011)

→ Ultra-stripped SNe could be a site of light trans-iron elements.

Nucleosynthesis in ultra-stripped Type Ic SNe

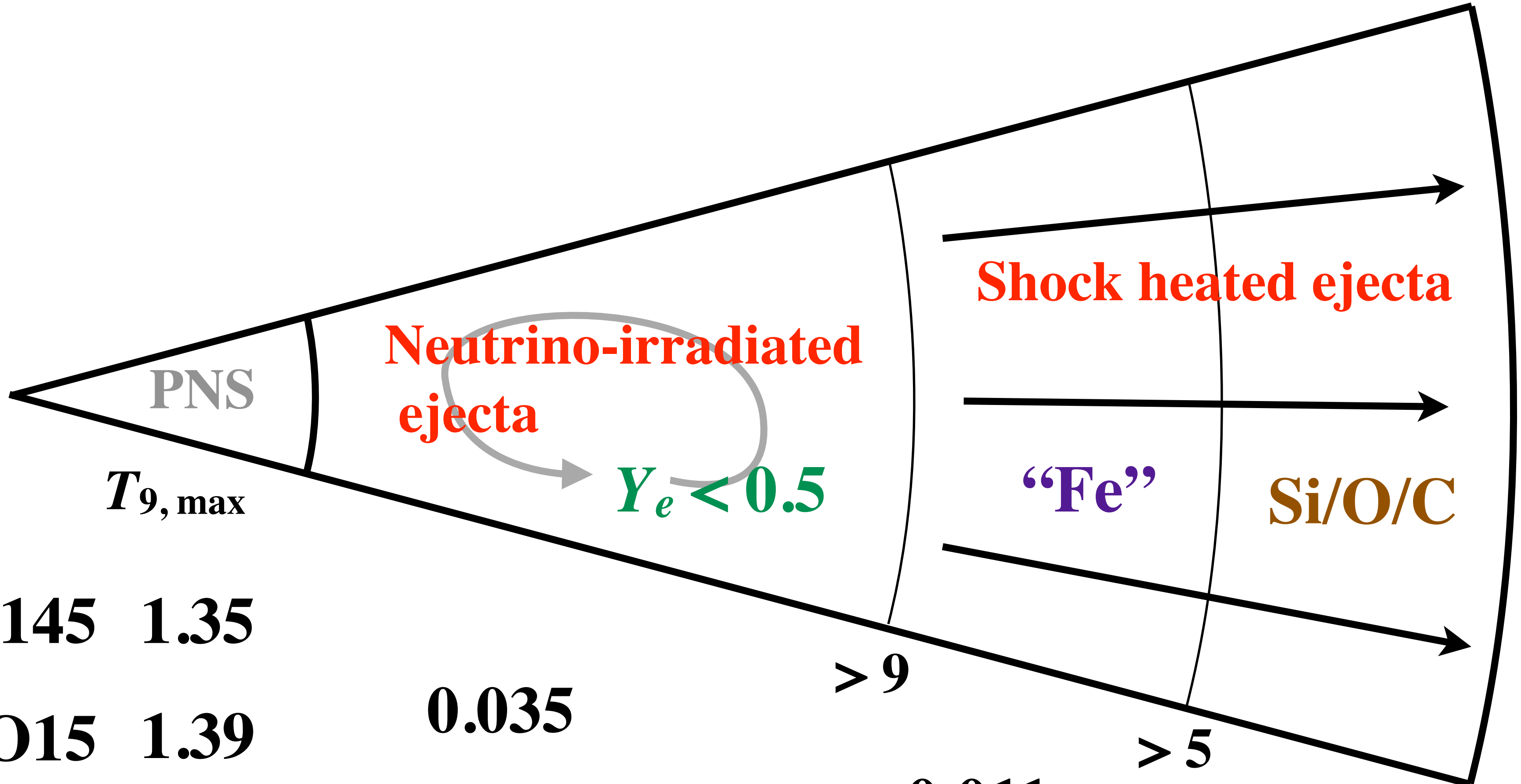
We investigate the nucleosynthesis in ultra-stripped Type Ic SNe.

- **Production of trans-iron elements**
- **^{56}Ni amount and light curve**

Nucleosynthesis in ultra-stripped Type Ic SNe

- **Stellar evolution of 1.45 and 1.5 $M_{\odot}$ CO stars (CO145 and CO15)**
  (Suwa, TY et al. 2015)
- **2D ν-radiation hydrodynamics simulation of SN explosions for 1.3 s**
- **Postprocessing nucleosynthesis of ~10,000 traced fluid particles of SN ejecta using a nuclear reaction network of 1651 nuclei up to Ce**

Ejected mass distribution

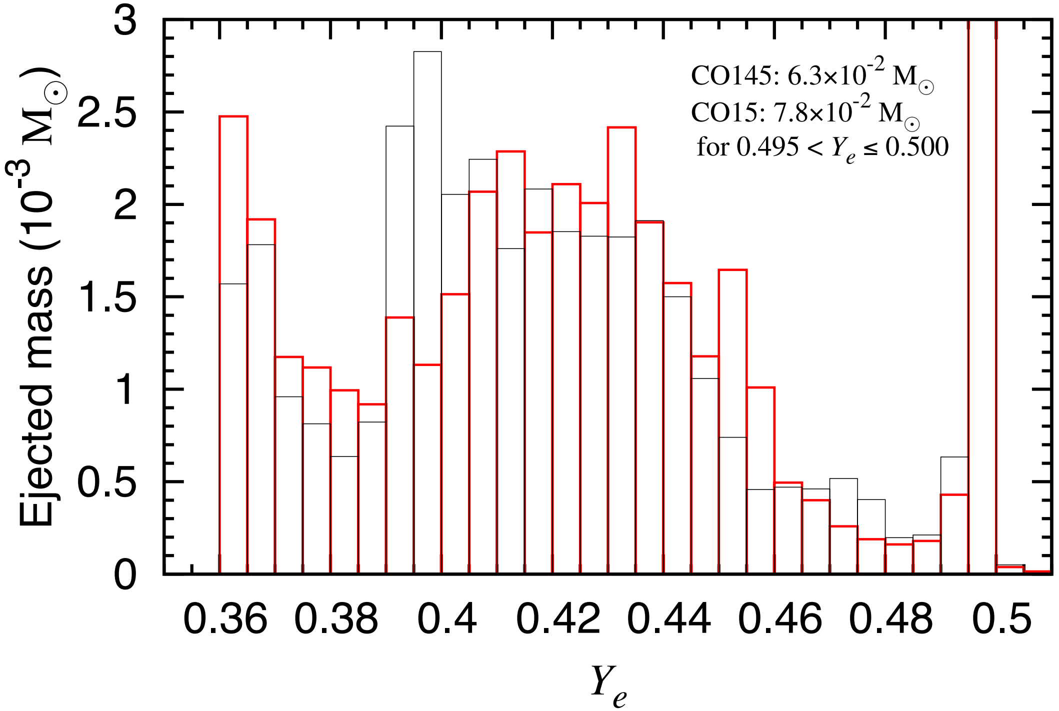


	$T_{9,\mathrm{max}}$	Neutrino-irradiated ejecta	"Fe"	Si/O/C	Total ejecta
CO145	1.35	0.035	0.011	0.052	0.098
CO15	1.39	0.034	0.006	0.072	0.112

$M_\odot$

Ejected mass distribution

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

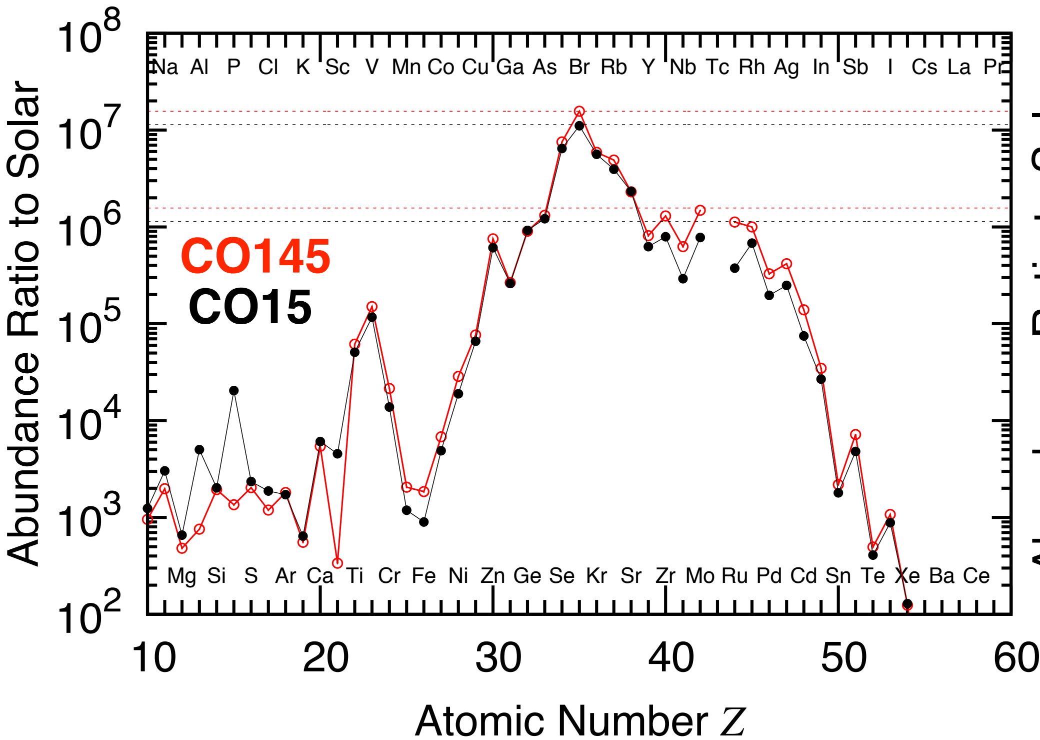


- $Y_e = n_e / (n_p + n_n) = n_p / (n_p + n_n)$

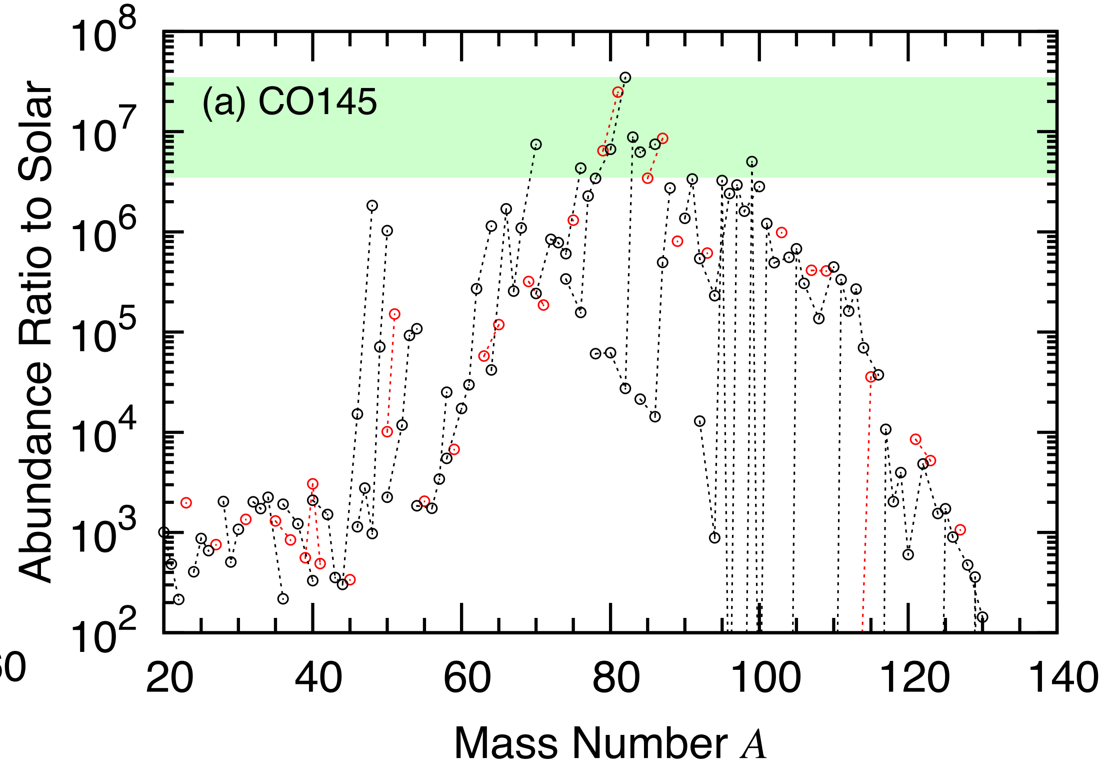
- **The Y_e range** → **$0.36 \le Y_e \le 0.505$ for CO145 and CO15 models**

We will discuss the uncertainty in the Y_e range later.

Abundance ratios to the Solar composition



Elemental distribution



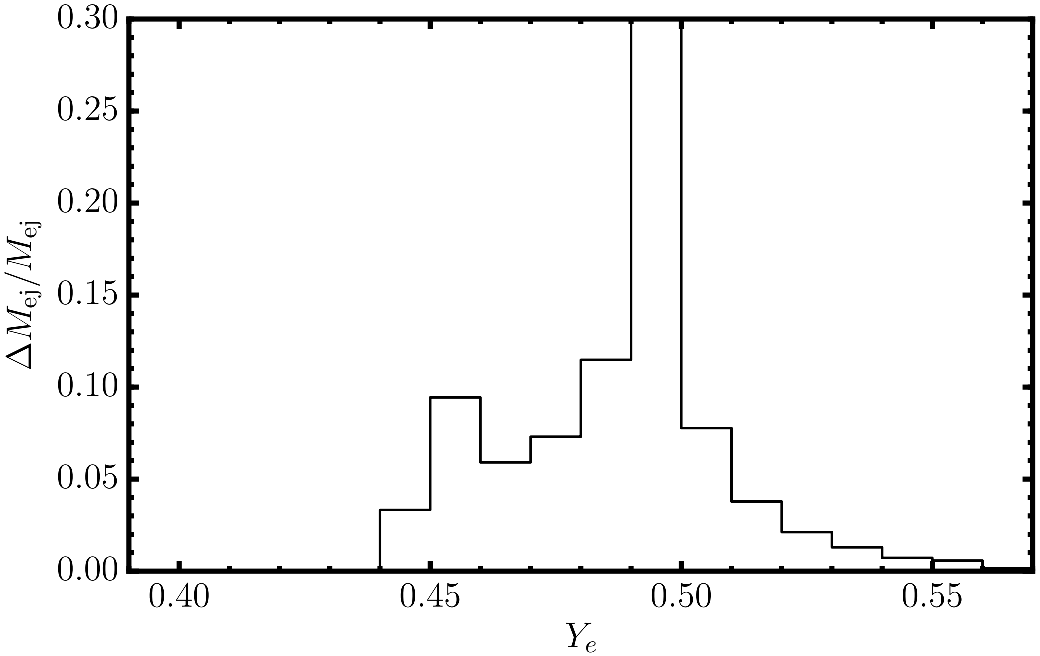
Isotopic distribution

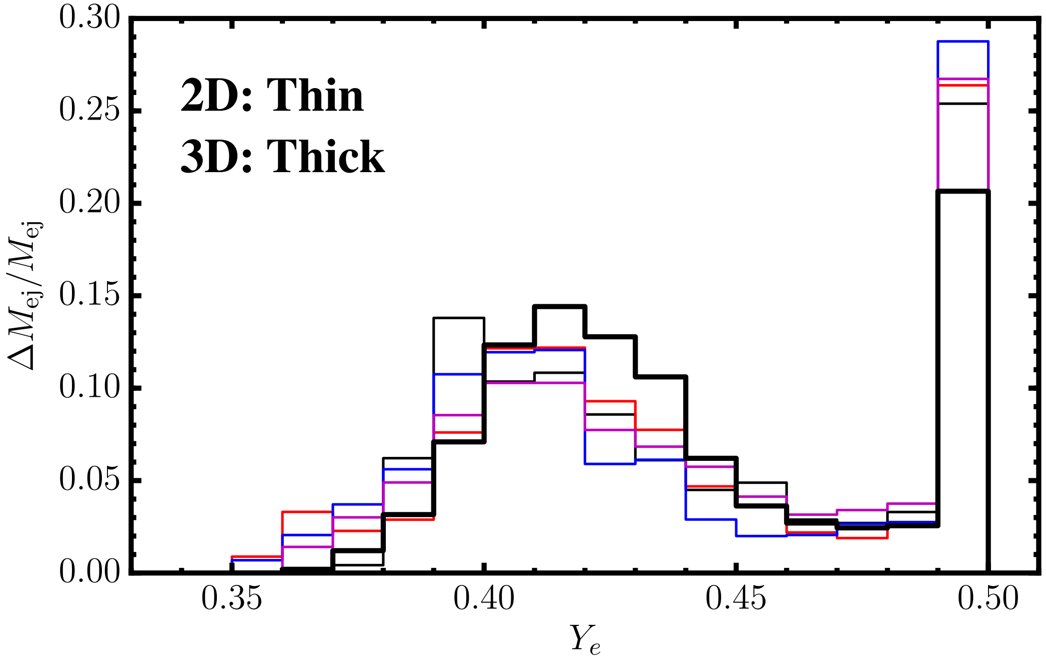
- **The abundance ratios of the SN ejecta to the solar composition** $Y(Z)/Y_{\rm solar}(Z)$; $Y(^AZ)/Y_{\rm solar}(^AZ)$
- **Large abundance ratios to the solar composition are shown for light tran-iron elements.**

$M(Z>30) = 0.012\, M_\odot$ (CO145, CO15)

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**





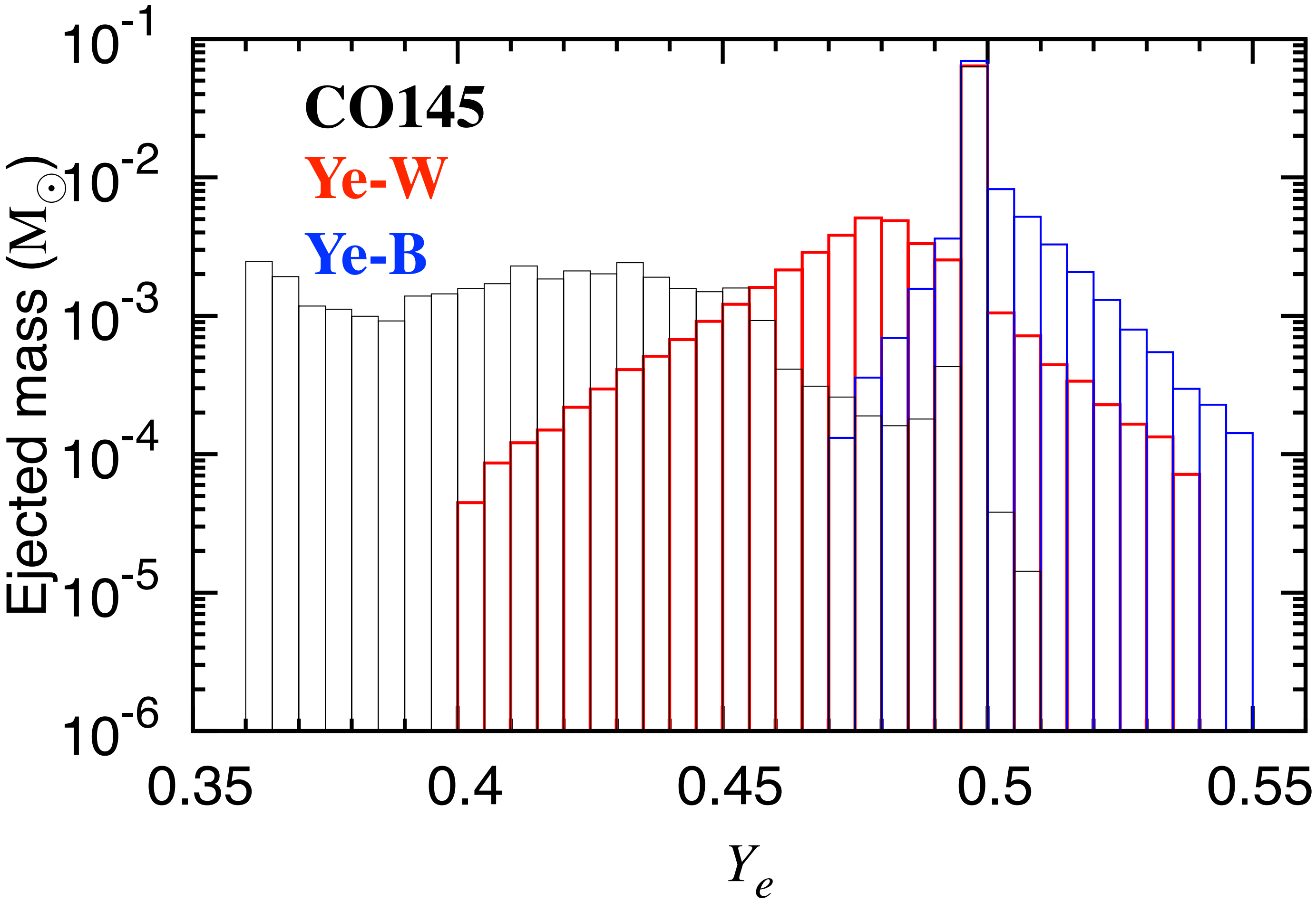
Vertex-CoCoNuT
(Two-moment scheme with variable Eddington factors from a model Boltzmann equation.)
Sophistication of the microphysics

CoCoNuT-FMT
(Dynamic one-moment closure scheme)

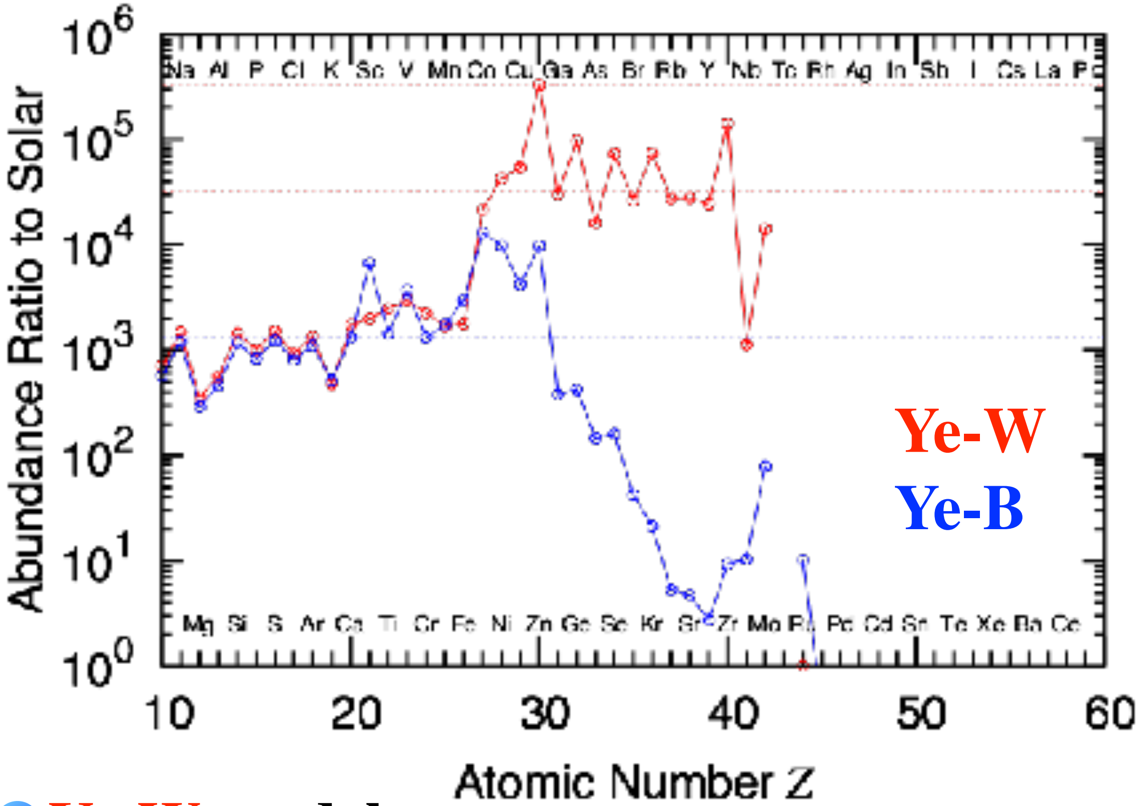
→ **Systematic differences by neutrino transport treatments**
Y_e distribution also depends on microphysics (e.g. Roberts et al. 2012)

Y_e modification

- **Y_e distributions having similar distributions of EC SN and normal SN for *neutrino-irradiated materials* of CO145 model**
  - **Ye-W model → EC SN-like (Wanajo et al. 2011)**
  - **Ye-B model → Normal SN-like (Buras et al. 2006)**



Y_e modification



$M(Z>30)$ =

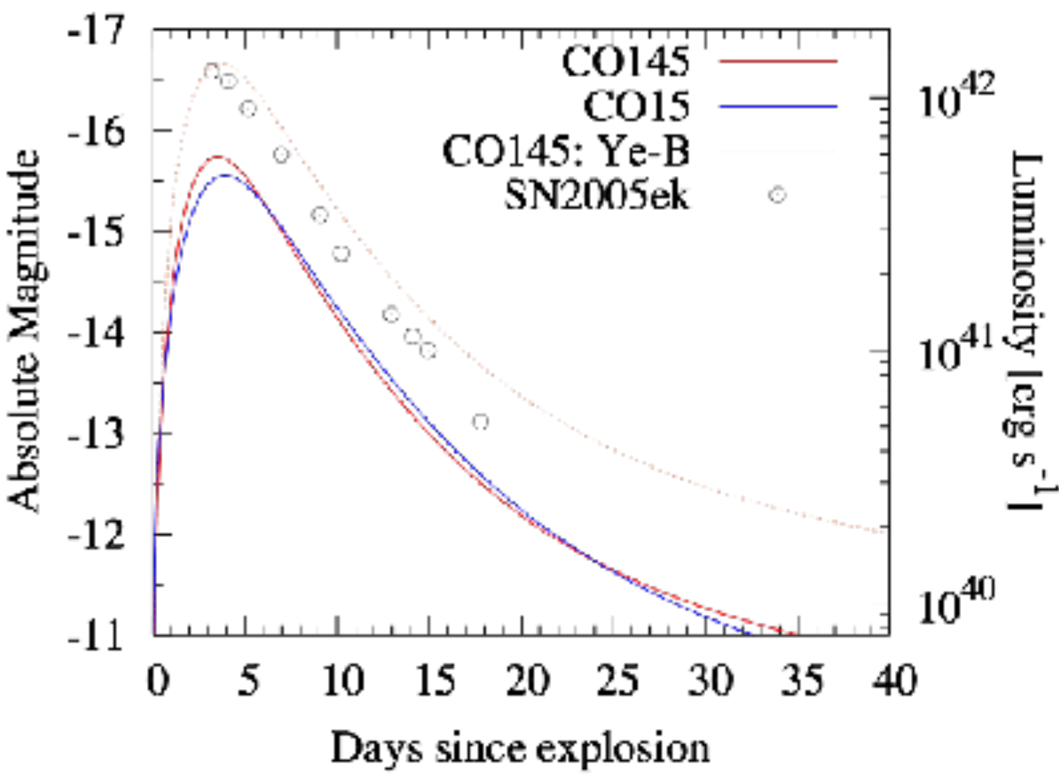
0.01 $M_\odot$ (CO145)

3.0×10^{-4} $M_\odot$ (Ye-W)

1.1×10^{-6} $M_\odot$ (Ye-B)

- **Ye-W model**
  - ➡ **Ga-Zr are produced**
  - **Zr is the largest ratio in light trans-iron elements**
- **Ye-B model**
  - ➡ **Contribution to the iron-peak elements in the solar composition**
    - **$M(^{56}\mathrm{Ni}) = 2.9\times10^{-2}$ $M_\odot$**
    - **Sc is produced in *p*-rich ejecta.** (Pruet et al. 2006; Fröhlich et al. 2006)

Light curves of modified Y_e models



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

$M(^{56}\mathrm{Ni}) = 9.7\times10^{-3}\ M_\odot$ (CO145)
$= 5.7\times10^{-3}\ M_\odot$ (CO15)
$= 2.9\times10^{-2}\ M_\odot$ (Ye-B)

- The peak magnitude is ~ -16.5 for CO145 Ye-B model.

➡ The peak value is close to SN 2005ek.

Y_e distribution in neutrino-irradiated ejecta is also important for light curve.

Summary

- **Nucleosynthesis of ultra-stripped Type Ic SNe**
  1.45 and 1.5 $M_\odot$ CO star progenitors
- **Explosions of the ultra-stripped SNe**
  ➡ **Weak explosion ($E \sim 10^{50}$ ergs)**
  Small ejecta mass ($M_{\rm ej} \sim 0.1\ M_\odot$) and ^{56}Ni yield ($< 0.01\ M_\odot$)
  ➡ **Rapidly-decaying faint light curve**
- **Light trans-iron elements are produced in neutrino-irradiated ejecta**
  - **Produced in mildly neutron-rich materials ($Y_e > 0.36$)**
- **Uncertainties in the Y_e distribution of the SN ejecta**
  ➡ **Yield and abundance distribution of light trans-iron elements**
  ➡ **Magnitude of light curve through ^{56}Ni yield**

TY et al. (2017): *Mon. Not. R. Astron. Soc.* **471**, 4275