SN neutrino-nucleosynthesis, Laboratory for fundamental physics (2)

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3. Roles of neutrinos in the Universe
4. Neutrino reactions in supernovae (SNe)

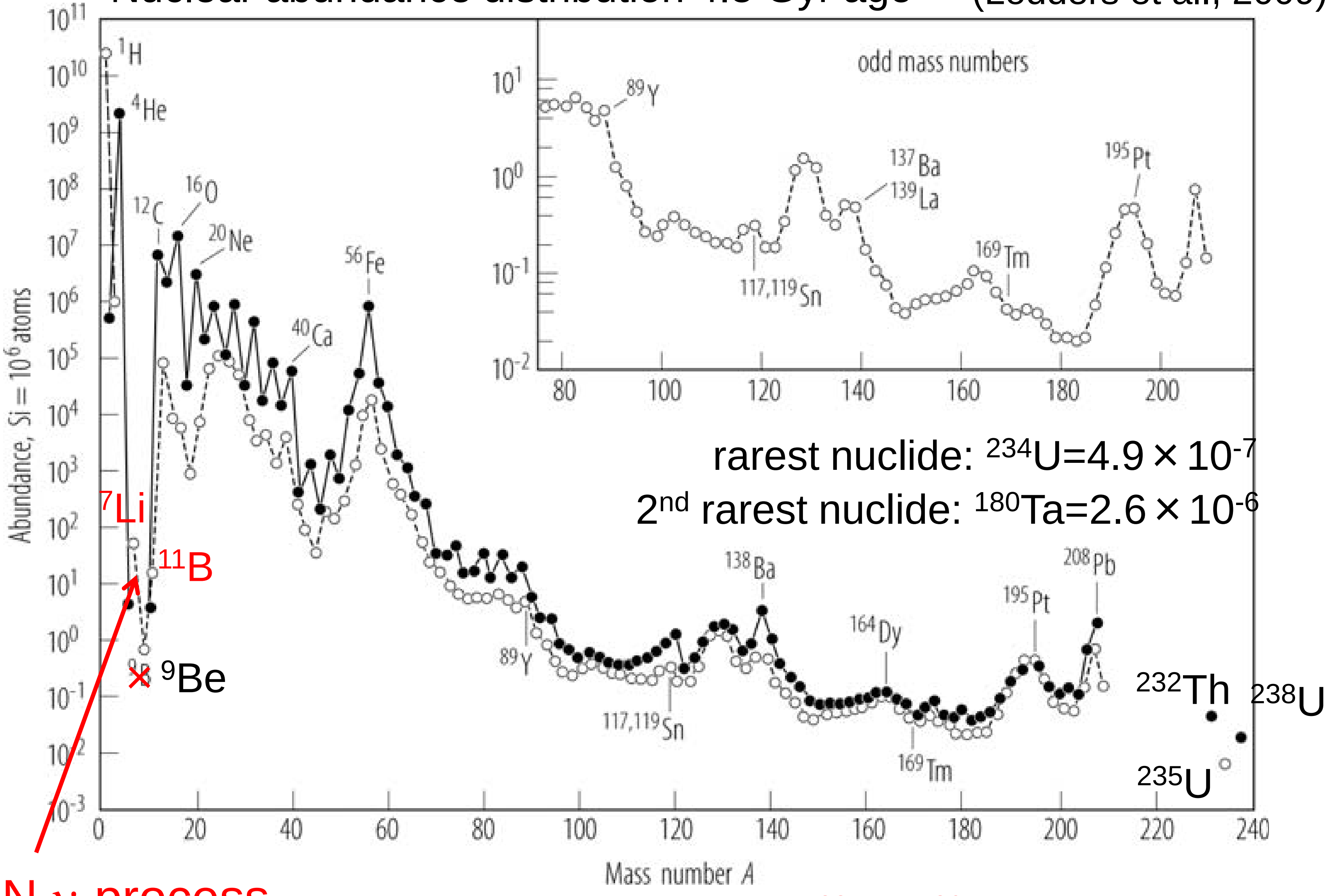
The 16th Nuclei in Cosmos School

2021/9/16

3. Roles of neutrinos in the Universe

1. Solar abundance

Nuclear abundance distribution 4.5 Gyr ago (Lodders et al., 2009)



rarest nuclide: ^{234}U=4.9 × 10^{-7}

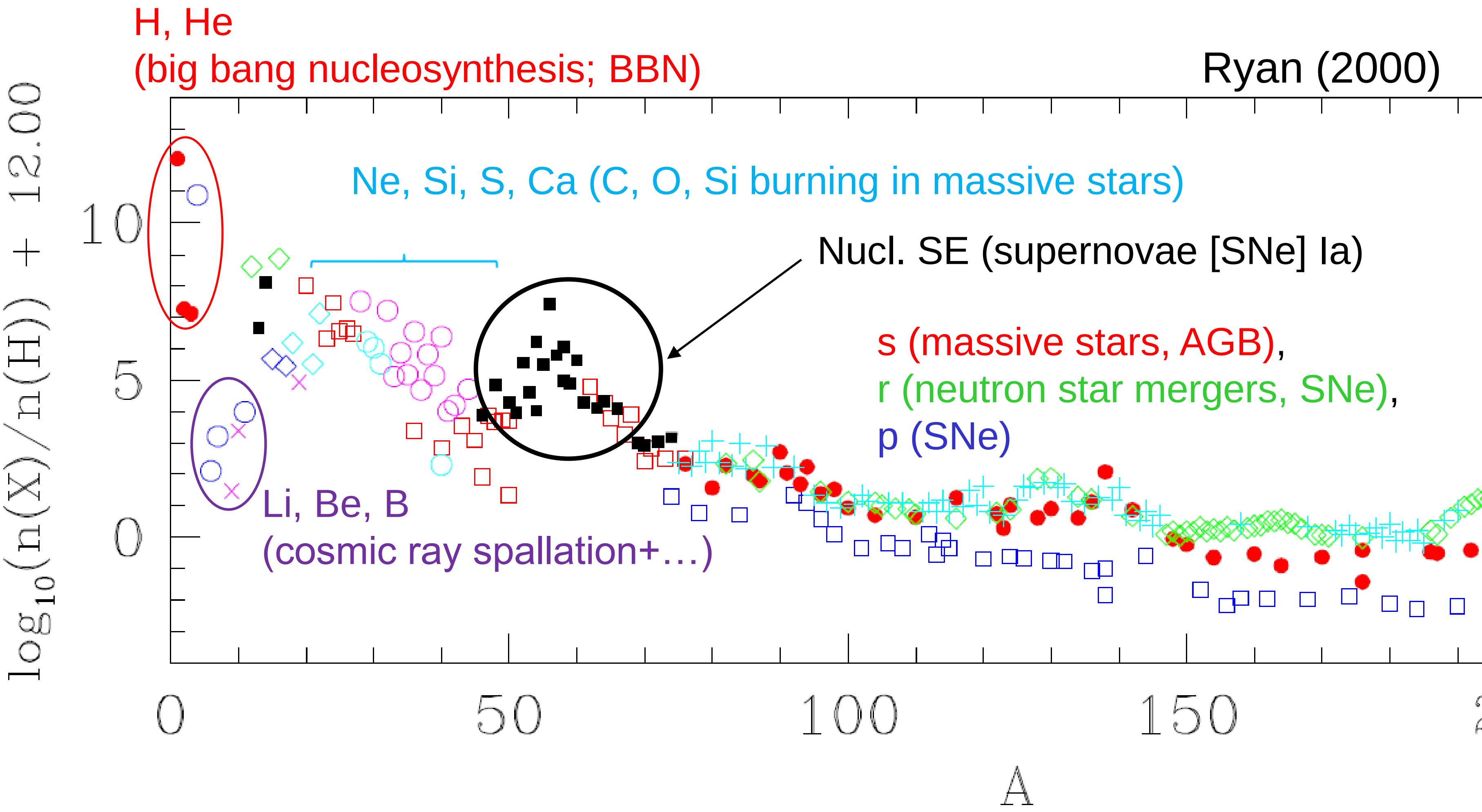
2nd rarest nuclide: ^{180}Ta=2.6 × 10^{-6}

SN ν-process

Rare p-nuclides (^{138}La, ^{180}Ta)

Short-lived (^{92}Nb, ^{98}Tc)

1. Solar abundance



H, He
(big bang nucleosynthesis; BBN)

Ryan (2000)

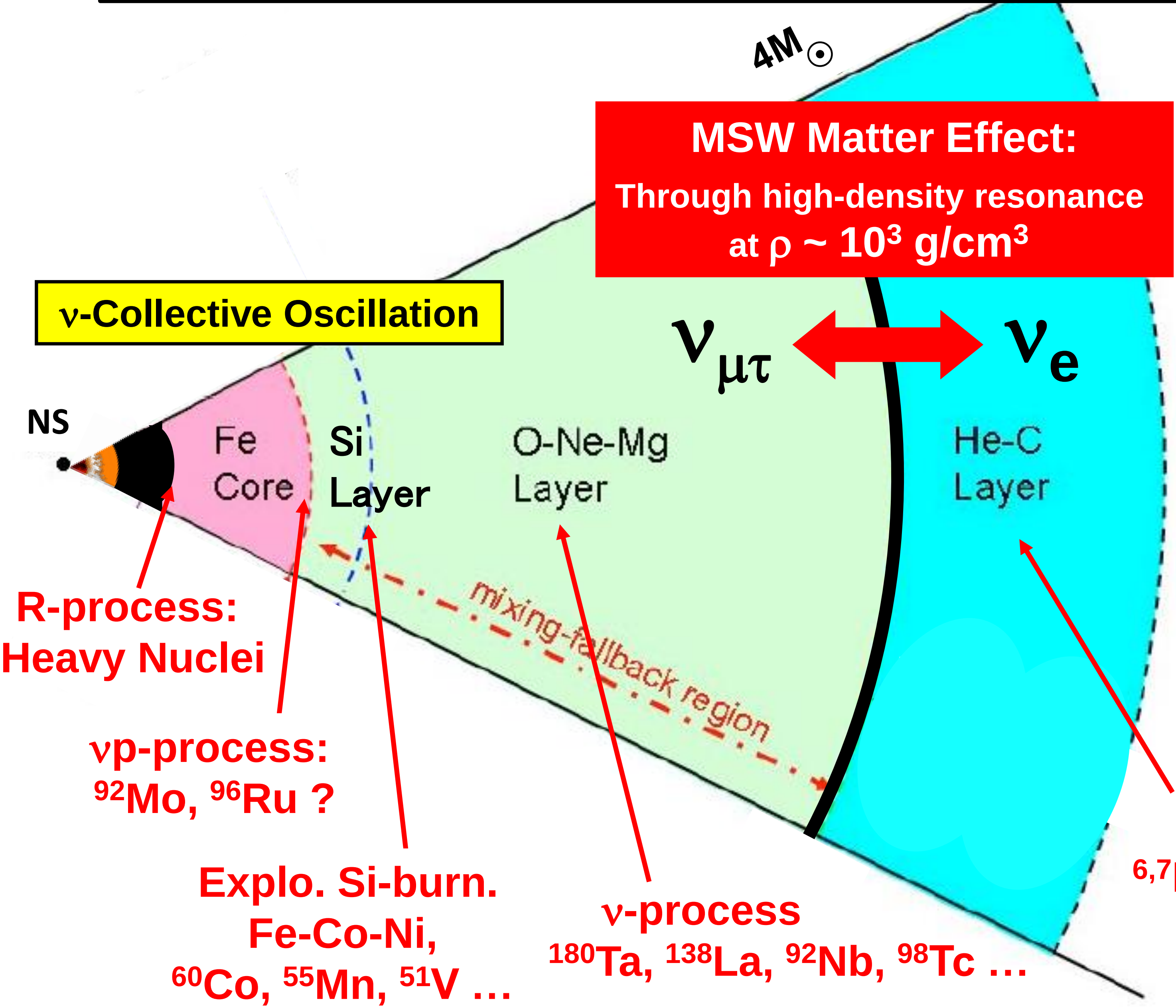
Ne, Si, S, Ca (C, O, Si burning in massive stars)

Nucl. SE (supernovae [SNe] Ia)

s (massive stars, AGB),
r (neutron star mergers, SNe),
p (SNe)

Li, Be, B
(cosmic ray spallation+…)

Various roles of ν's in SN-nucleosynthesis



MSW Matter Effect:

Through high-density resonance at ρ ~ 10^3 g/cm^3

ν-Collective Oscillation

R-process: Heavy Nuclei

νp-process: ^{92}Mo, ^{96}Ru ?

Explo. Si-burn. Fe-Co-Ni, ^{60}Co, ^{55}Mn, ^{51}V …

ν-process ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

ν-process: ^{6,7}Li, ^{9}Be, ^{10,11}B …

From T. Kajino's presentation in OMEG2003

2. Contributions of ν-process to solar abundances

Nuclide	**Fraction (%)**	**Other sources**	**Methods**
^{7}Li	18	AGB, novae, cosmic ray (CR)	Subtractions for AGB, novae, CR
^{11}B	6	CR	
^{92,94}Mo & ^{96,98}Ru	$\sim\leq 100$	p-process in SNe	Subtractions for p-process & CR
^{138}La	$\sim\leq 100$	p-process	
^{180}Ta	~ 80	p-process, CR	

Based upon CR studies by
Prantzos A&A 448, 665 (2006) for Li & B
MK & Mathews, ApJ 854, 183 (2018) for other nuclei

3. ^{7}Li & ^{11}B: messenger of ν parameters

- ➢O(10) % of ^{7}Li & ^{11}B originate from SN ν-process

- ➢SN yields depend on ν parameters (Yoshida, Kajino, et al. 2004-):
  - ✓ Mass hierarchy
  - ✓ Temperatures & luminosity ν's coming from neutron stars.
  - ✓ Electron density profile → ν oscillation is affected

- ➢If grains form in the SN ejecta,
Li/B ratio in the yield may be measured
in pre-solar grains in meteorites.

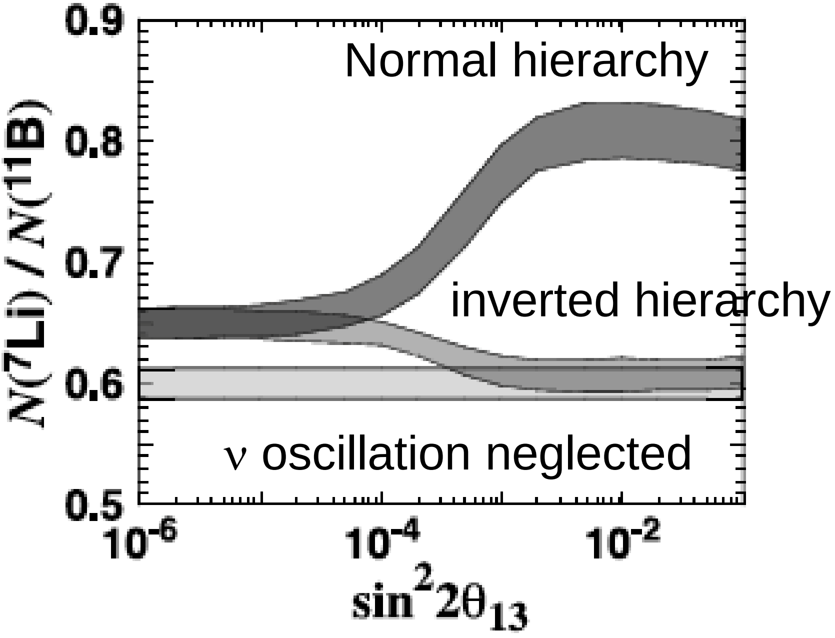


Fig. 10.—^{7}Li/^{11}B abundance ratio as a function of the mixing angle $\sin^2 2\theta_{13}$. Dark and medium shaded regions correspond to normal and inverted mass hierarchies, respectively. The lightly shaded region indicates the ratio obtained without neutrino oscillations. Each range is drawn using the results of models 1, 2, LT, and ST.

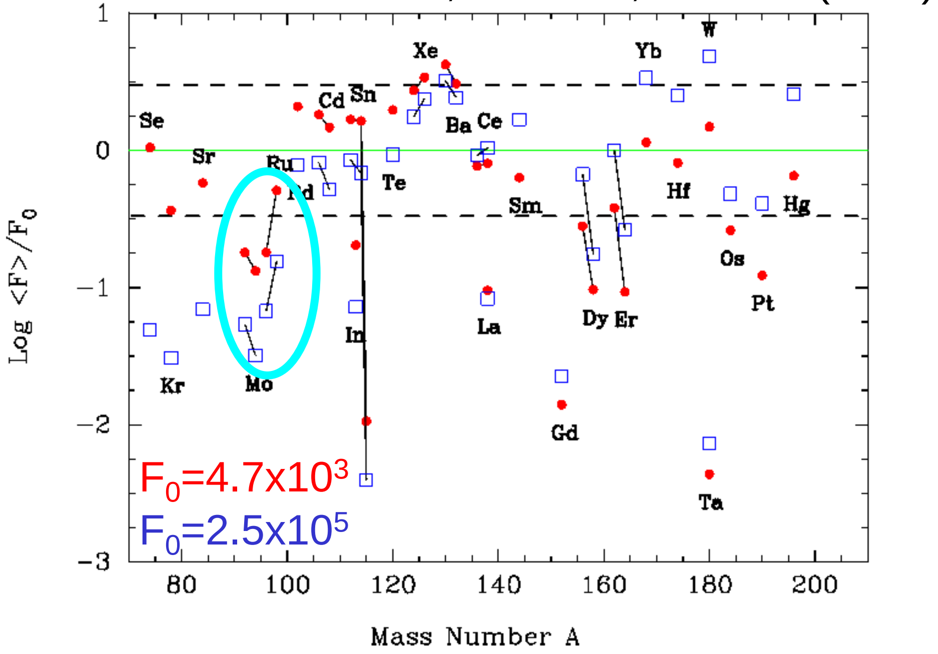
(Yoshida et al. ApJ 686, 448, 2008)

4. ^{92,94}Mo & ^{96,98}Ru: produced in νp-process?

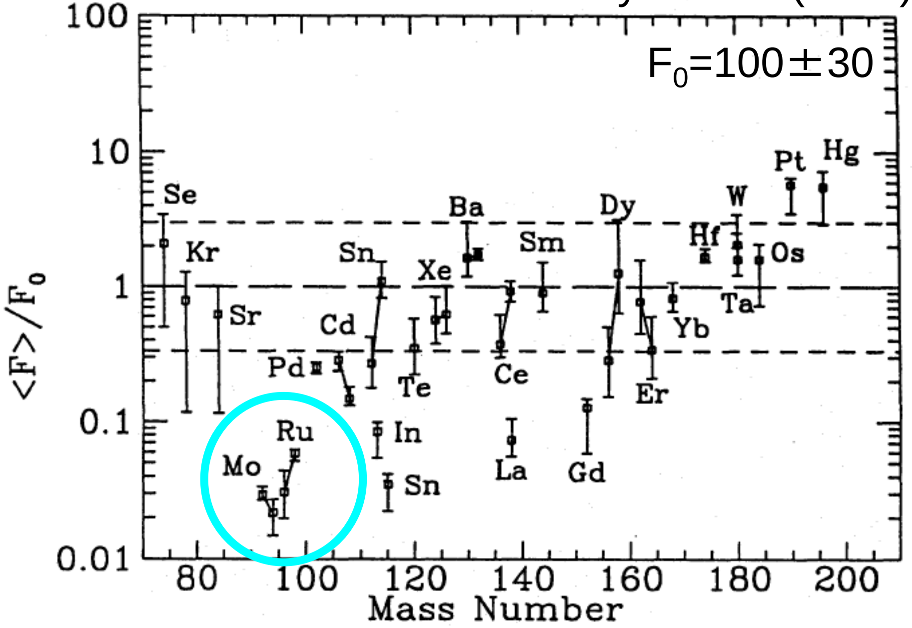
➢Underproduction problem in the p-process in SNe Ia & II

➢(p,γ) & (n,p) reactions produces p-rich nuclei in SNe II
using neutrons from the $\bar{\nu}_e$+p reaction
(Pruet et al. 2005-; Fröhlich et al. 2006-; Wanajo 2006-)

SN Ia MK, Iwamoto, Nomoto (2011)



SN II Rayet et al. (1995)



➢**Mo and Ru are more produced than in a SN II**

➢Sensitive to uncertain s-abundance

overproduction factor :

$\langle F \rangle \equiv \langle X \rangle / X_{\odot}$

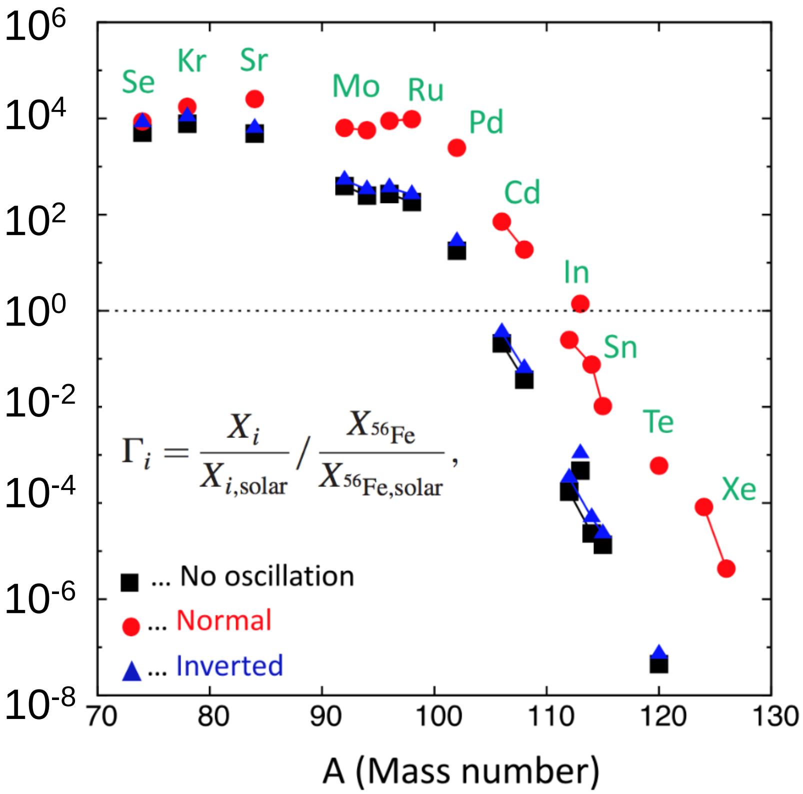
yield of a p-nuclide

4. ^{92,94}Mo & ^{96,98}Ru: produced in νp-process?

- ➢Underproduction problem in the p-process in SNe Ia & II

- ➢(p,γ) & (n,p) reactions produces p-rich nuclei in SNe II
  using neutrons from the $\bar{\nu}_e$+p reaction
  (Pruet et al. 2005-; Fröhlich et al. 2006-; Wanajo 2006-)

νp process (T_9=2-3, Y_e > 0.5)



$$\boxed{\overline{\nu}_\mathrm{e} + p \leftrightarrow n + \mathrm{e}^+}$$

^{64}Ge (n,p)^{64}Ga(p,γ)…

^{92,94}Mo, ^{96,98}Ru,.. p-nuclei

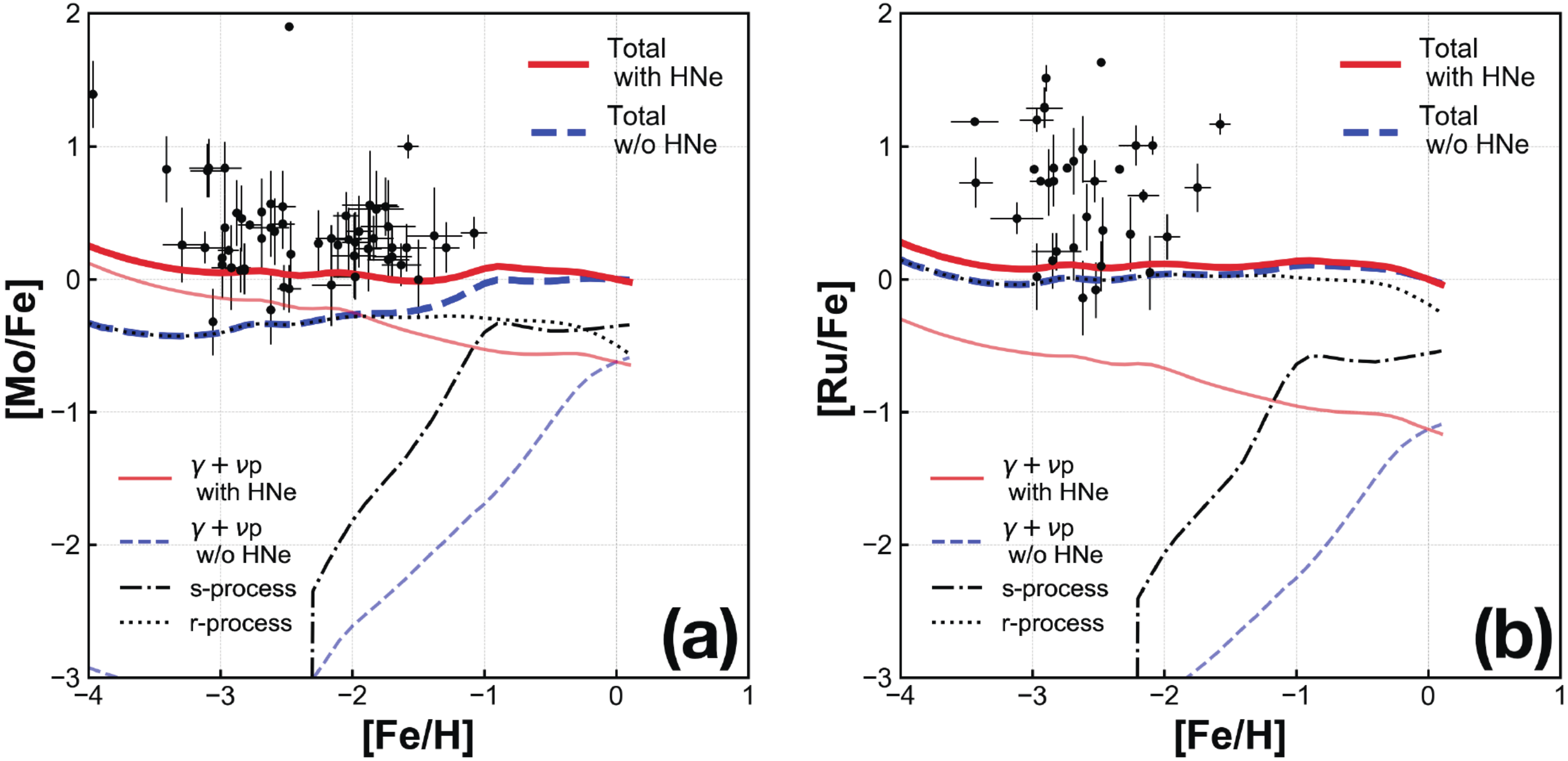
In the normal hierarchy, p-nuclei are enriched by a factor of ~1-10^4

Sasaki, et al., Phys. Rev. D 96, 043013 (2017)

4. ^{92,94}Mo & ^{96,98}Ru: produced in νp-process?

➢Galactic chemical evolution (GCE) taking into account p-nuclei of Mo & Ru
(H. Sasaki, Y. Yamazaki, et al. arXiv:2106.01679)

- ✓ νp process in hypernovae dominates the production of ^{92,94}Mo & ^{96,98}Ru.
- ✓ Refinement of GCE theory by consistently accounting for isotopic abundances of p-nuclei

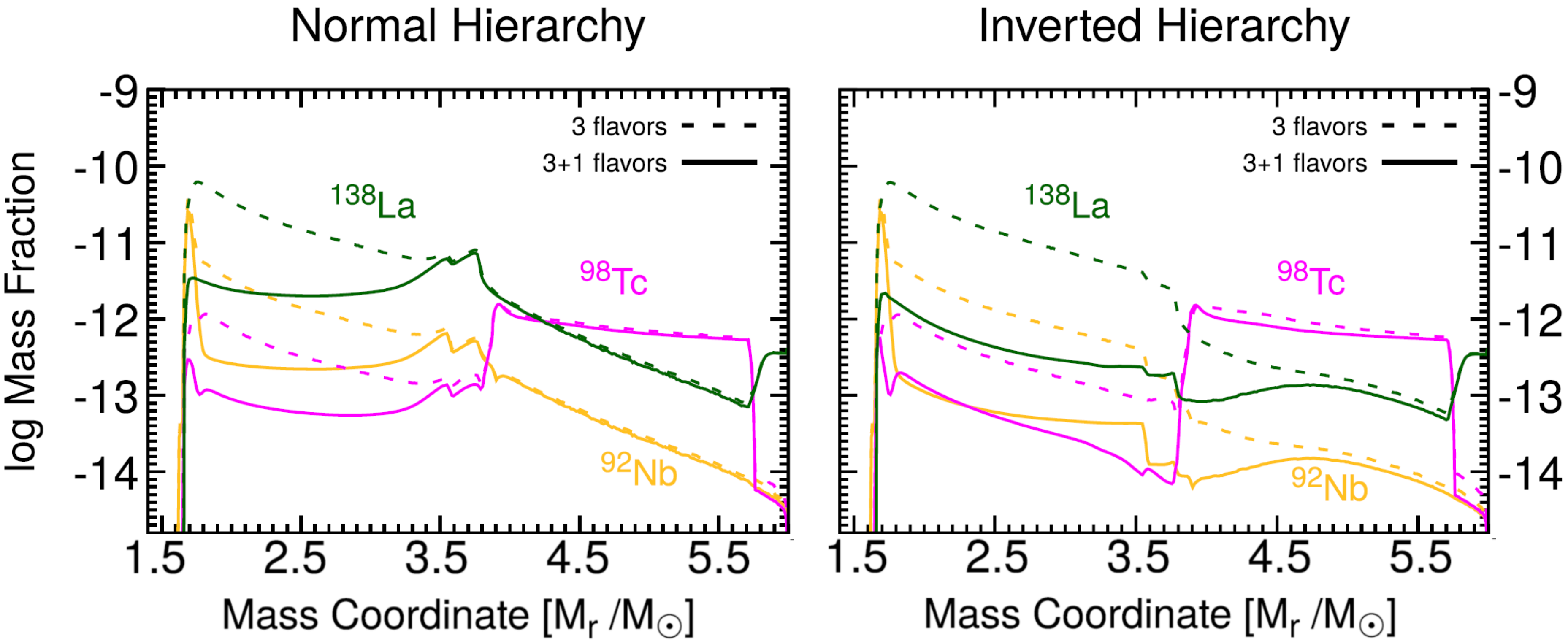


5. ^{138}La & ^{180}Ta: produced in ν_e-process

- Underproduction in the p-process in SNe Ia & II

- Production via $^{138}\mathrm{Ba}(\nu_e,e)^{138}\mathrm{La}$, $^{180}\mathrm{Hf}(\nu_e,e)^{180}\mathrm{Ta}$
  - ✓ Yields sensitive to ν-self interaction (Ko et al., ApJL 2020)
  - ✓ Also sensitive to hypothetical sterile neutrino (Ko et al., ApJ 2020)

Ko, Jang, MK, Cheoun, Astrophys. J. (2020)

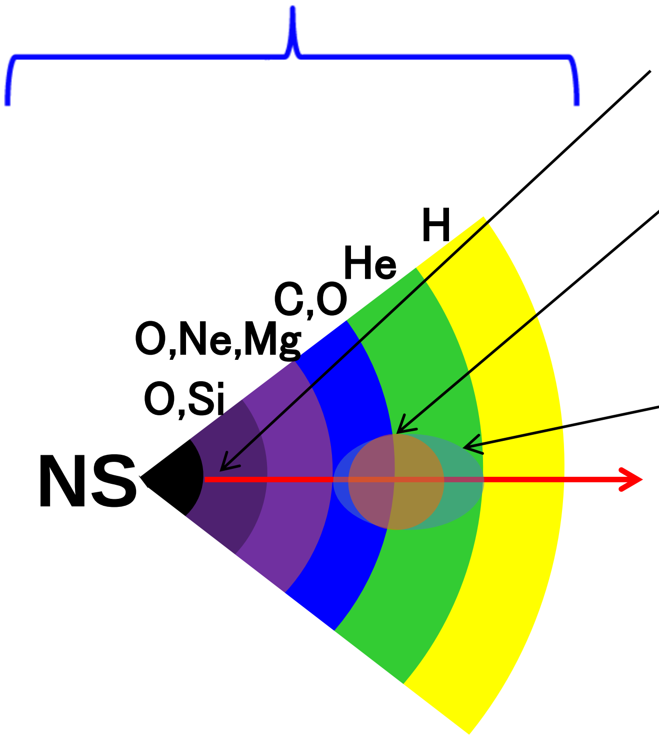


4. Neutrino reactions in SNe

Model

1. Structure of numerical code

- Stellar model [$\rho(r)$, $Y_i(r)$]



ν's emitted
from ν spheres

①ν spectra $\phi_{\nu\alpha}(E_{\nu\alpha})$ is assumed

H resonance of the MSW effect
$\nu_e \rightleftarrows \nu_\mu, \nu_\tau$

②ν spectra is changed to $\phi'_{\nu\alpha}(E_{\nu\alpha})$

light element (^{7}Li & ^{11}B) synthesis

- ✓ nuclear reactions
- ✓ β-decays
- ✓ ν-nuclear reactions

JINA Reaclib V2.0
Elements up to $_{87}$Fr
3080 nuclides, 38197 reactions

reaction

$$N_i({}^{A_i}Z_i) + N_j({}^{A_j}Z_j) \leftrightarrow N_k({}^{A_k}Z_k) + N_l({}^{A_l}Z_l)$$

N_i : # of nuclide i
A_i : atomic # of i

Rate equation
$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left(- \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} [ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} [lk]_j \right)$$
+(1 body)+(3 body)+(4 body)

$X_i = \rho_i / \rho_B \quad Y_i = X_i / A_i$

Reaction rate [$\rho(r,t)$, $T(r,t)$] ←hydrodynamic calculation

2. Why ν-process depends on physical quantities of ν?

- ν-reactions at T ~ MeV:
  - Neutral current: $\nu_\alpha + X \rightarrow \nu_\alpha + X$ ($\alpha = e, \mu, \tau$)
  - Charged current: $\nu_e + n \rightarrow e^- + p^+$
    $\bar{\nu}_e + p^+ \rightarrow e^+ + n$

- Reaction rates at neutron star surface: $\lambda_e > \lambda_{\bar{e}} > \lambda_x$ ($x = \mu, \tau$)

- ν-decoupling radius (ν-sphere): $R_e > R_{\bar{e}} > R_x$ ($x = \mu, \tau$)
- Temperature of decoupled ν: $T_e < T_{\bar{e}} < T_x$ ($x = \mu, \tau$)

➡ Emitted ν spectra depend on flavors ($\alpha = e, \mu, \tau$)

- ν flavor evolve during propagation inside a star
- ν-induced nuclear reaction rates are affected by the flavor evolution

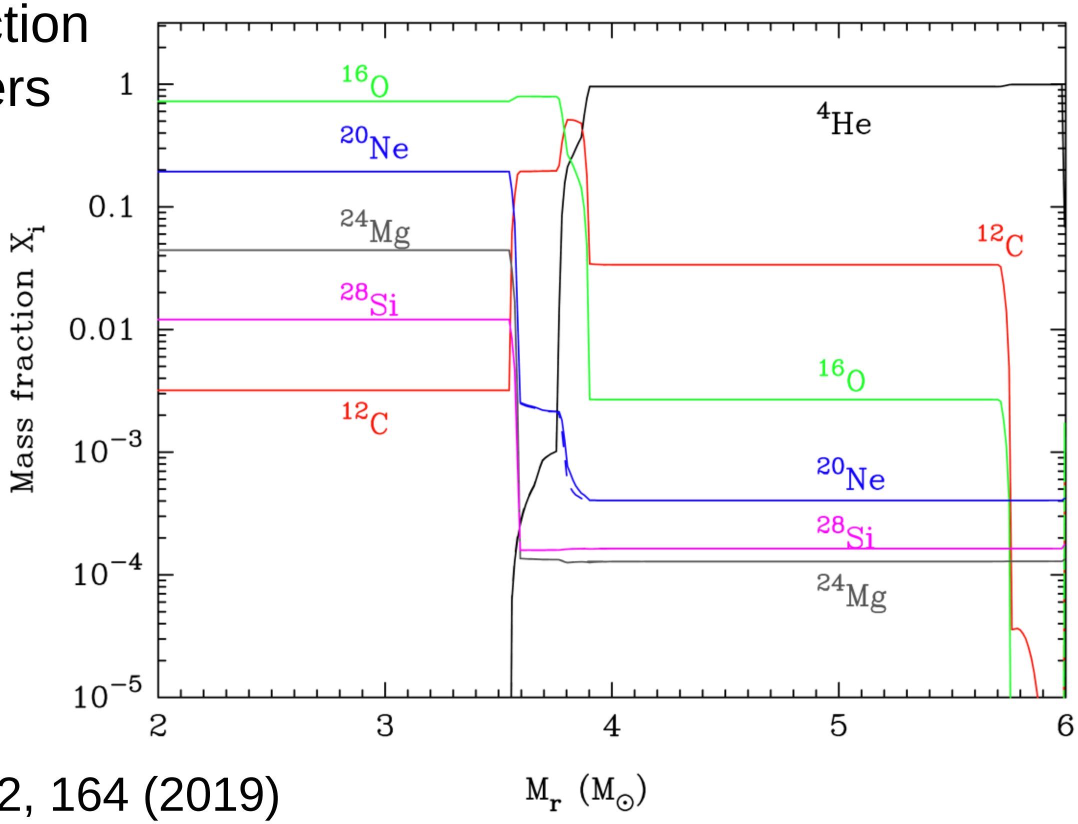
➡ Yields of the ν-process depend on ν-flavor change

3. Initial nuclear abundances

- s-nuclides:
  - ✓ s-process during He burning

- new calculation of stellar evolution
  for Z =$Z_\odot$/4 with the method (Kikuchi et al, PTEP 2015, 063E01)

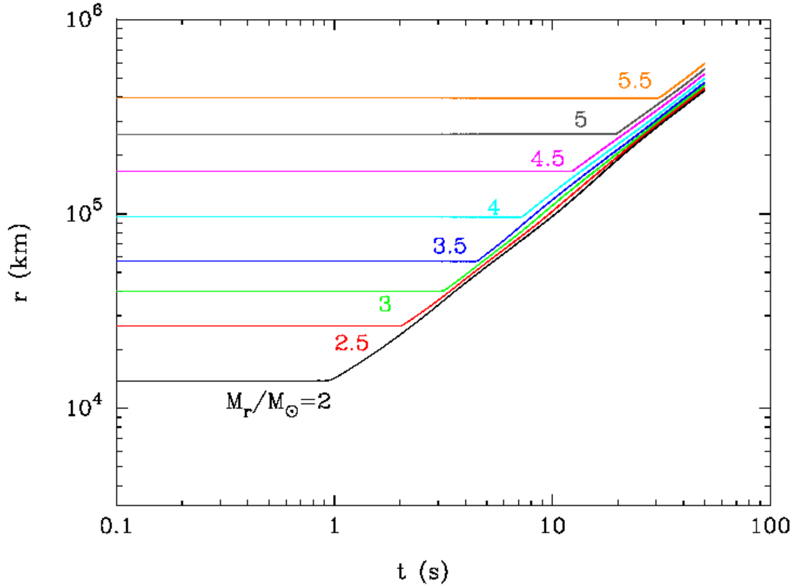
- Main region of Li and B production
  →C-rich and He-rich layers

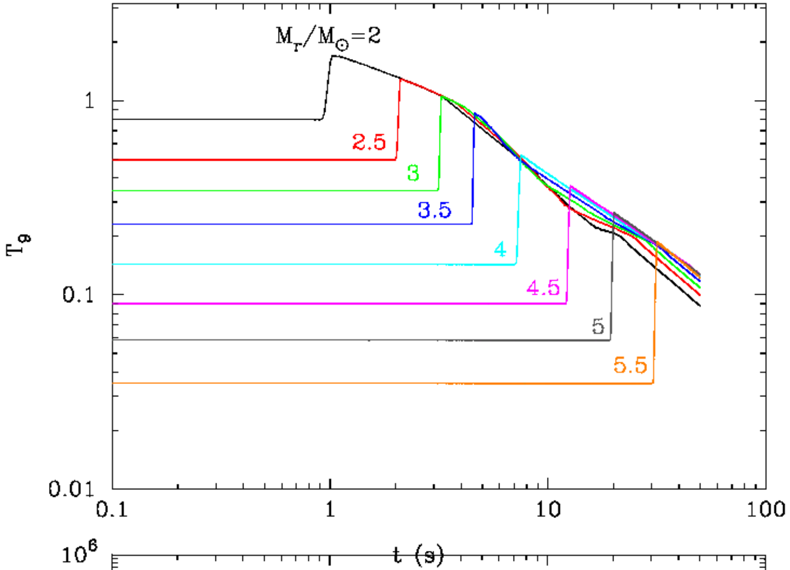


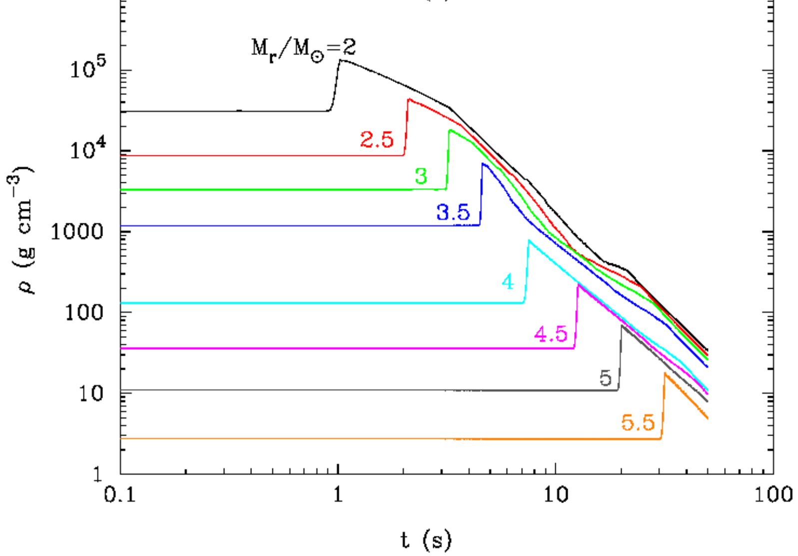
MK, Cheoun, Kim, et al., ApJ 872, 164 (2019)

4. Evolutions of density, temperature & radius

Evolutions in Lagrangian coordinates [M(<r)=const.]







- ➢ Hydrodynamical calculation
- ➢ blcode (Ott, Morozova, Piro)
- ➢ Thermal bomb

  (E=1 × 10^{51} erg for SN1987A)

←large pressure is assumed in the center, and explosion is solved

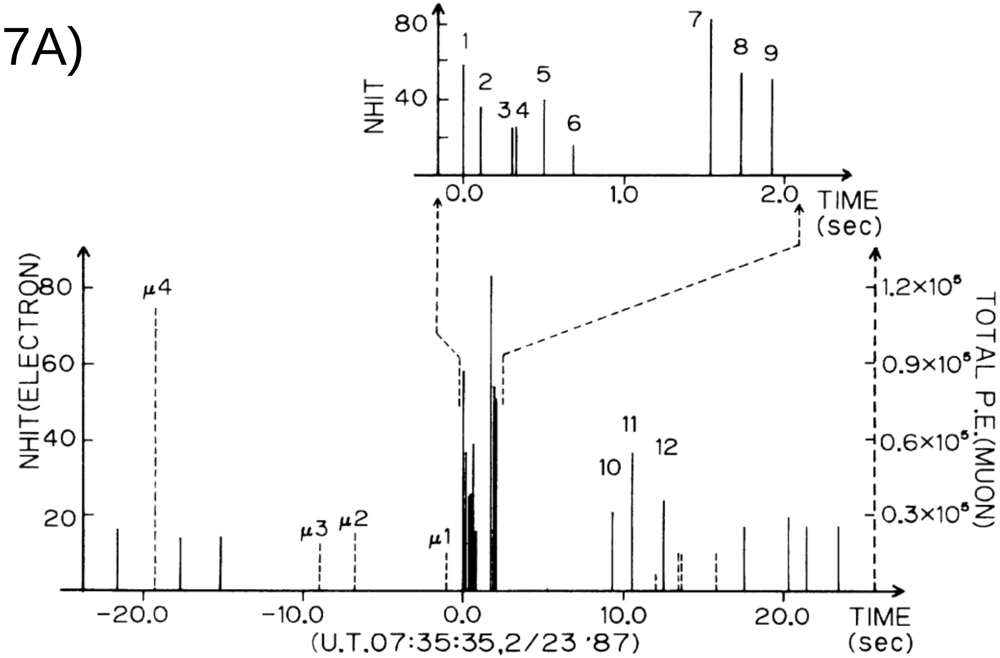
5. ν-luminosity

$$L_{\nu_\alpha}(r;t) = \frac{1}{6}\,\frac{E_\nu^{\mathrm{SN}}}{\tau_\nu}\,\exp\left(-\frac{t-r/c}{\tau_\nu}\right)\Theta\left(t-\frac{r}{c}\right)$$

$$= 1.04025\times 10^{58}\ \mathrm{MeV\ s^{-1}}\ \frac{E^{\mathrm{SN}}_{\nu,\ 10^{53}\ \mathrm{erg}}}{\tau_{\nu,\ \mathrm{s}^{-1}}}\,\exp\left(-\frac{t-r/c}{\tau_\nu}\right)\Theta\left(t-\frac{r}{c}\right),$$

(Woosley et al., ApJ 356, 272, 1990, Woosley & Weaver, ApJS, 101, 181, 1995, Yoshida et al., ApJ 600, 204, 2004)

- The same luminosity for all ν flavors
- Total ν energy E_ν=3 × 10^{53} erg
  (from ν detections of SN1987A)
- Exponential decrease with τ_ν=3 s



Hirata et al., PRL, 58, 1490 (1987)

6. ν-reaction cross sections

- ν-reaction rates
  - ✓ Spallation of ^{4}He & ^{12}C:
    - Yoshida et al. ApJ 686, 448 (2008)

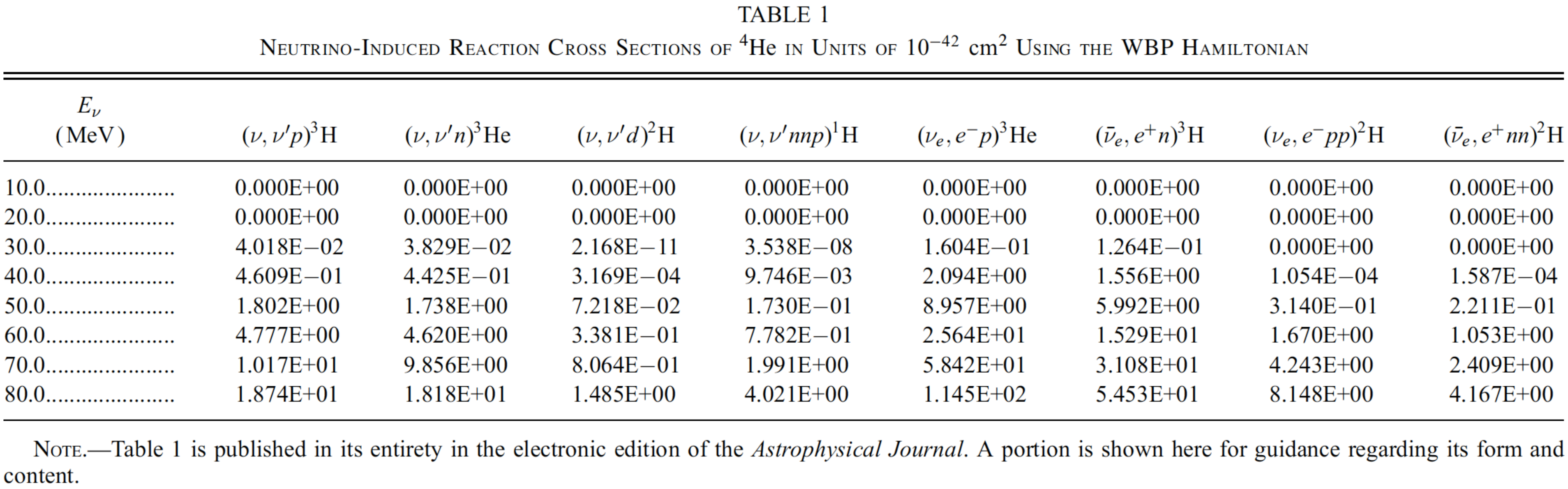


TABLE 1

NEUTRINO-INDUCED REACTION CROSS SECTIONS OF ^{4}He IN UNITS OF 10^{-42} cm^2 USING THE WBP HAMILTONIAN

E_ν (MeV)	$(\nu,\nu' p)^3$H	$(\nu,\nu' n)^3$He	$(\nu,\nu' d)^2$H	$(\nu,\nu' nnp)^1$H	$(\nu_e,e^- p)^3$He	$(\bar{\nu}_e,e^+ n)^3$H	$(\nu_e,e^- pp)^2$H	$(\bar{\nu}_e,e^+ nn)^2$H
10.0.....................	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
20.0.....................	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
30.0.....................	4.018E−02	3.829E−02	2.168E−11	3.538E−08	1.604E−01	1.264E−01	0.000E+00	0.000E+00
40.0.....................	4.609E−01	4.425E−01	3.169E−04	9.746E−03	2.094E+00	1.556E+00	1.054E−04	1.587E−04
50.0.....................	1.802E+00	1.738E+00	7.218E−02	1.730E−01	8.957E+00	5.992E+00	3.140E−01	2.211E−01
60.0.....................	4.777E+00	4.620E+00	3.381E−01	7.782E−01	2.564E+01	1.529E+01	1.670E+00	1.053E+00
70.0.....................	1.017E+01	9.856E+00	8.064E−01	1.991E+00	5.842E+01	3.108E+01	4.243E+00	2.409E+00
80.0.....................	1.874E+01	1.818E+01	1.485E+00	4.021E+00	1.145E+02	5.453E+01	8.148E+00	4.167E+00

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

- Difference between ν and ν̄ cross sections: MK, et al. (2019)

- ✓ Reactions for ^{98}Tc production: Cheoun et al. PRC 85, 065807 (2012)

- ✓ Other reactions: Hoffmann & Woosley (A =~[12,80], 4186 reactions)

http://dbserv.pnpi.spb.ru/elbib/tablisot/toi98/www/astro/hw92 1.htm

7. SN ν-reaction rate

- energy spectra depend on ν flavors $T_{\nu_e} = 3.2,\ T_{\bar{\nu}_e} = 5.0, \text{ and } T_{\nu_x} = 6.0 \text{ MeV}$

→ν oscillation changes the ν energy spectra

flux of ν_i with the energy E_ν

$$\frac{d\phi_{\nu_\alpha}}{dE_\nu} = \frac{L_{\nu_\alpha}}{4\pi r^2} \frac{1}{F_3(\eta_{\nu_\alpha})\,(kT_{\nu_\alpha})^4} \underline{\frac{E_\nu^2}{\exp(E_\nu/kT_{\nu_\alpha} - \eta_{\nu_\alpha}) + 1}}$$

$$\eta_{\nu_\alpha} = \mu_{\nu_\alpha}/kT_{\nu_\alpha}$$

$$F_n(\eta_{\nu_\alpha}) = \int_0^\infty \frac{x^n}{\exp(x - \eta_{\nu_\alpha}) + 1} dx,$$

Fermi-Dirac distribution

$$\lambda_{\nu_\alpha}(r) = \int_0^\infty \sum_{\beta=e,\mu,\tau} \frac{d\phi_{\nu_\beta}}{dE_\nu} P_{\beta\alpha}(r; E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu$$

$$= \sum_{\beta=e,\mu,\tau} \left[\frac{L_{\nu_\beta}}{4\pi r^2} \frac{1}{F_3(\eta_{\nu_\beta})\,(kT_{\nu_\beta})^4} \int_0^\infty \frac{E_\nu^2 P_{\beta\alpha}(r; E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu}{\exp(E_\nu/kT_{\nu_\beta} - \eta_{\nu_\beta}) + 1} \right]$$

$$= \sum_{\beta=e,\mu,\tau} \left[\frac{L_{\nu_\beta}}{4\pi r^2} \frac{1}{kT_{\nu_\beta}} \frac{F_2(\eta_{\nu_\beta})}{F_3(\eta_{\nu_\beta})} \langle P_{\beta\alpha}\sigma_{\nu_\alpha}\rangle(T_{\nu_\beta}; r) \right],$$

$P_{\beta\alpha}(r; E_\nu)$ probability of change β→α

$$\langle P_{\beta\alpha}\sigma_{\nu_\alpha}\rangle(T_{\nu_\beta}; r) = \frac{1}{F_2(\eta_{\nu_\beta})\,(kT_{\nu_\beta})^3} \int_0^\infty \frac{E_\nu^2 P_{\beta\alpha}(r; E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu}{\exp(E_\nu/kT_{\nu_\beta} - \eta_{\nu_\beta}) + 1}$$

$$= \frac{1}{F_2(\eta_{\nu_\beta})} \int_0^\infty \frac{P_{\beta\alpha}(r; E_\nu)\sigma_{\nu_\alpha}(E_\nu)x^2 dx}{\exp(x - \eta_{\nu_\beta}) + 1}.$$

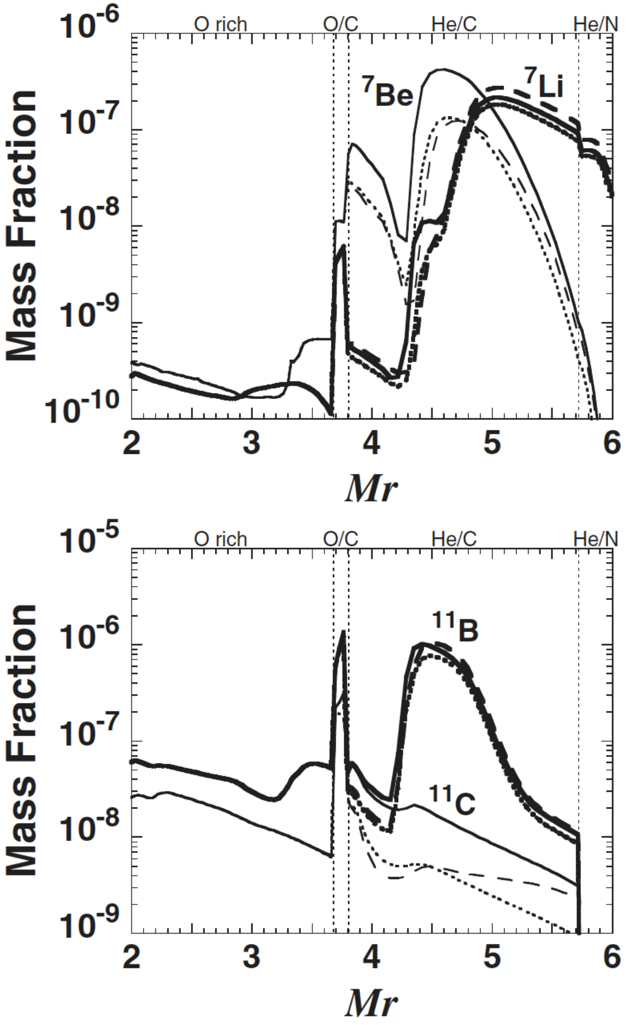
- For $\eta_{\nu_j} = 0$ Reaction rate of nuclei

$$\lambda_{\nu_\alpha}(r) = 1.263 \times 10^{-7}\ \mathrm{s}^{-1} \sum_{\beta=e,\mu,\tau} \left[\frac{L_{\nu_\beta,\ 10^{58}\mathrm{MeV/s}}}{r^2_{,2\times10^{10}\mathrm{cm}}} \frac{1}{(kT_{\nu_\beta})_{,5\mathrm{MeV}}} \langle P_{\beta\alpha}\sigma_{\nu_\alpha}\rangle_{,10^{-42}\ \mathrm{cm}^2}(T_{\nu_\beta}; r) \right],$$

$$\lambda^{\mathrm{NC}}_{\nu,\mathrm{tot}}(r) = 1.263 \times 10^{-7}\ \mathrm{s}^{-1} \sum_{\beta=e,\mu,\tau} \left[\frac{L_{\nu_\beta,\ 10^{58}\mathrm{MeV/s}}}{r^2_{,2\times10^{10}\mathrm{cm}}} \frac{1}{(kT_{\nu_\beta})_{,5\mathrm{MeV}}} \langle \sigma^{\mathrm{NC}}_\nu\rangle_{,10^{-42}\ \mathrm{cm}^2}(T_{\nu_\beta}) \right],$$

8. Effect of ν oscillation on ^{7}Li & ^{11}B production (1)

- Yields of Li & B depend on neutrino parameters
  (Yoshida et al. PRL 96, 091101, 2006)



(Yoshida et al. 2006) $\sin^2 2\theta_{13} = 2 \times 10^{-2}$

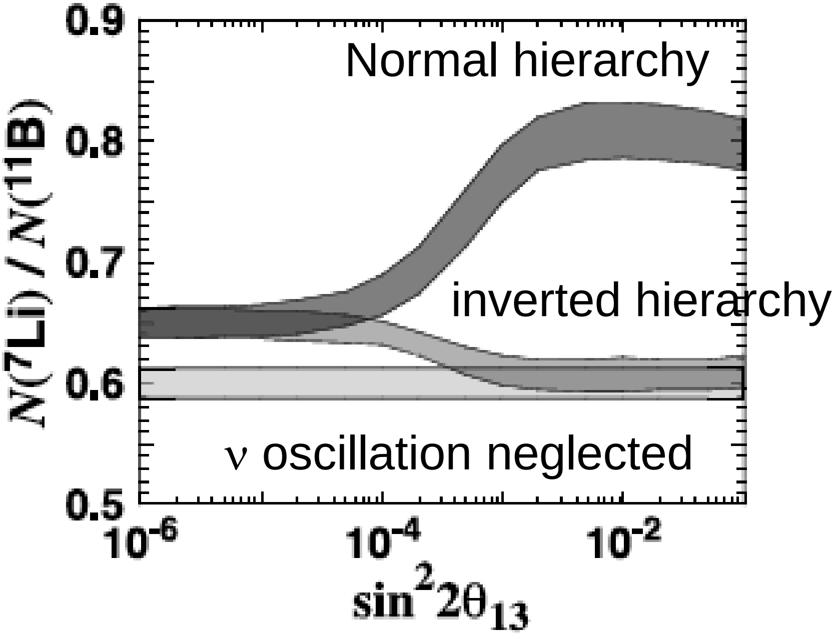
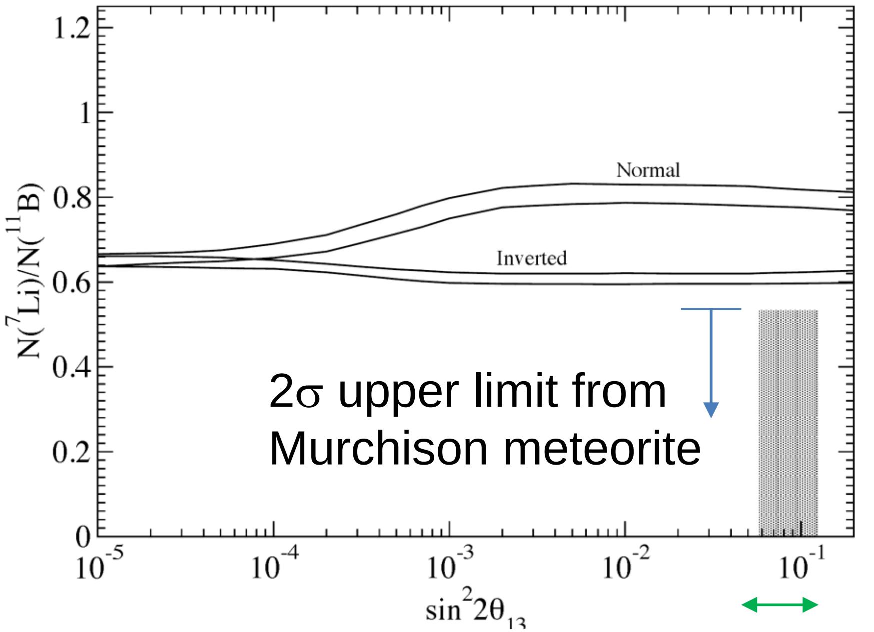


FIG. 10.—^{7}Li/^{11}B abundance ratio as a function of the mixing angle $\sin^2 2\theta_{13}$. Dark and medium shaded regions correspond to normal and inverted mass hierarchies, respectively. The lightly shaded region indicates the ratio obtained without neutrino oscillations. Each range is drawn using the results of models 1, 2, LT, and ST.

(Yoshida et al. ApJ 686, 448, 2008)

9. Effect of ν oscillation on ^{7}Li & ^{11}B production (2)

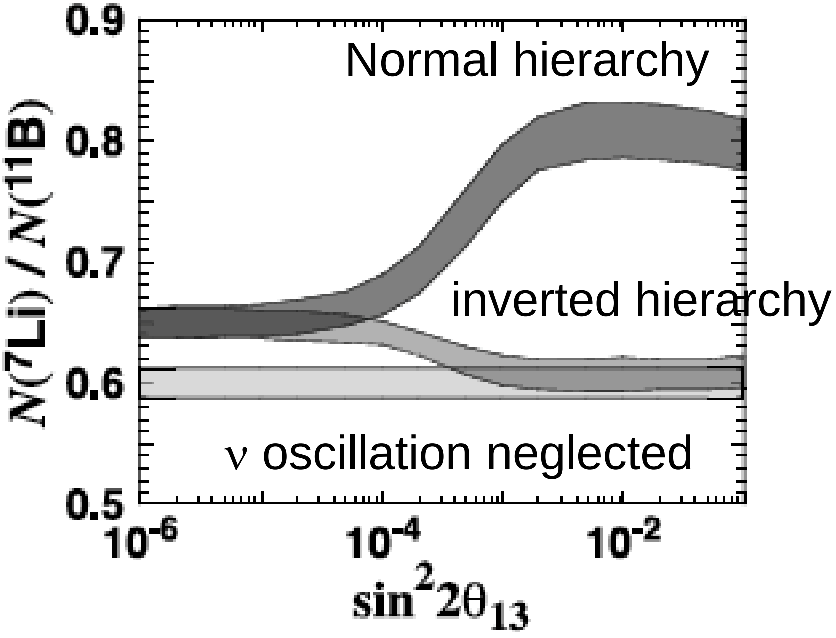
- Yields of Li & B depend on neutrino parameters
  (Yoshida et al. PRL 96, 091101, 2006)



2σ upper limit from Murchison meteorite

Daya Bay
(Ann et al, 2012)

(Mathews et al, PRD 85, 105023, 2012)



Normal hierarchy

inverted hierarchy

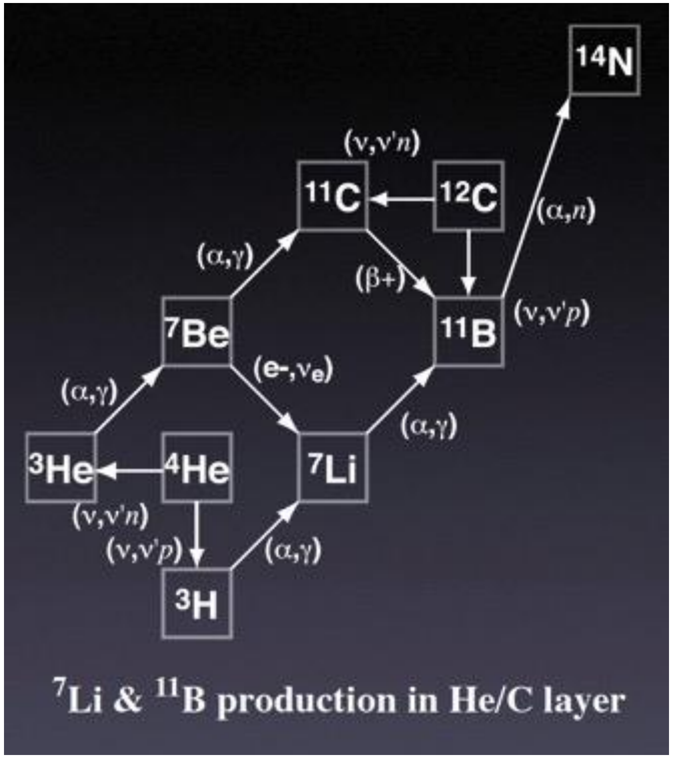
ν oscillation neglected

FIG. 10.—^{7}Li/^{11}B abundance ratio as a function of the mixing angle $\sin^2 2\theta_{13}$. Dark and medium shaded regions correspond to normal and inverted mass hierarchies, respectively. The lightly shaded region indicates the ratio obtained without neutrino oscillations. Each range is drawn using the results of models 1, 2, LT, and ST.

- Observational constraint on ^{7}Li/^{11}B yield of SN ν-process
  (Mathews et al, PRD 85, 105023, 2012)

10. Specific reactions for SN ν-process

- ν-process for Li, B & ^{98}Tc



^{7}Li & ^{11}B production in He/C layer

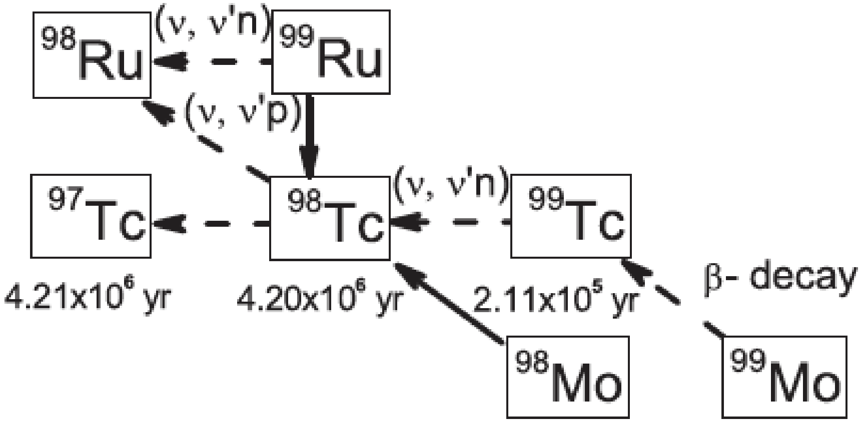


FIG. 2. Partial nuclear chart around ^{98}Tc indicating the main ν-process production from the ^{98}Mo$(\nu_e, e^-)^{98}$Tc CC reaction and the ^{99}Ru$[\nu(\bar{\nu}), \nu'(\bar{\nu})'\ p]^{98}$Tc NC reaction.

(Cheoun et al., PRC 85, 065807, 2012,
Ko et al. 2018, Hayakawa et al. 2018)

(Yoshida, in OMEG 2003)
Domogatskii et al. (1978), Woosley et al. (1990),
Woosley & Weaver (1995), Yoshida et al. (2004)

- Variable order Bader & Deuflhard method
- Sparse matrix solver MA38 (cf. Timmes ApJS 124, 241, 1999)

Before seeing results

- results of Li & B yields are different from Yoshida et al. (2008).
- Differences in the two calculations:
  - (i) initial abundance
  - (ii) nuclear reaction rates
  - (iii) input data from hydrodynamical calculation
  - (iv) neutrino parameters (slightly different)
  - (v) nucleosynthesis calculation

Appendix 1: ν-reaction rates in network

- For a reaction $N_i({}^{A_i}Z_i) + N_j({}^{A_j}Z_j) \leftrightarrow N_k({}^{A_k}Z_k) + N_l({}^{A_l}Z_l)$

N_i : # of nuclide i
A_i : atomic # of nuclide i

abundance change rates:

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!}[ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!}[lk]_j \right)$$

$Y_i = X_i/A_i$

destruction

production

- Example:

(1) ${}^2H + {}^2H \rightarrow {}^3He + n$

i $= {}^2H$ $N_i = 2$
k $= {}^3He$ $N_k = 1$
l $= n$ $N_l = 1$

2-body reaction

$$\frac{dY_d}{dt} \ni -2\frac{Y_d{}^2}{2!}\varrho N_A \langle \sigma v \rangle_{d\,+\,d} + Y_{3\mathrm{He}} Y_n \varrho N_A \langle \sigma v \rangle_{3\mathrm{He}\,+\,n}$$

(2) $\gamma + {}^2H \rightarrow p + n$

i $= {}^2H$ $N_i = 1$
k $= p$ $N_k = 1$
l $= n$ $N_l = 1$

As a 1-body reaction

$$\frac{dY_d}{dt} \ni -Y_d \lambda_{\gamma\,+\,d} + Y_p Y_n \varrho N_A \langle \sigma v \rangle_{p\,+\,n}$$

Appendix 1: ν-reaction rates in network

- Photodisintegration

(2) $\gamma + {}^{2}H \rightarrow p + n$

As a 1-body reaction

$$\frac{dY_d}{dt} \ni -Y_d \lambda_{\gamma + d} + Y_p Y_n \varrho N_A \langle \sigma v \rangle_{p + n}$$

$$\lambda_{\gamma + d} = n_\gamma \langle \sigma c \rangle_{\gamma + d}$$
$$= \frac{1}{\pi^2 (\hbar c)^3} \int \frac{{E_\gamma}^2 dE_\gamma}{e^{E_\gamma / kT} - 1} \sigma(E_\gamma) c$$

$f(E_\gamma)$: Planck distribution of γ

- ν-reactions

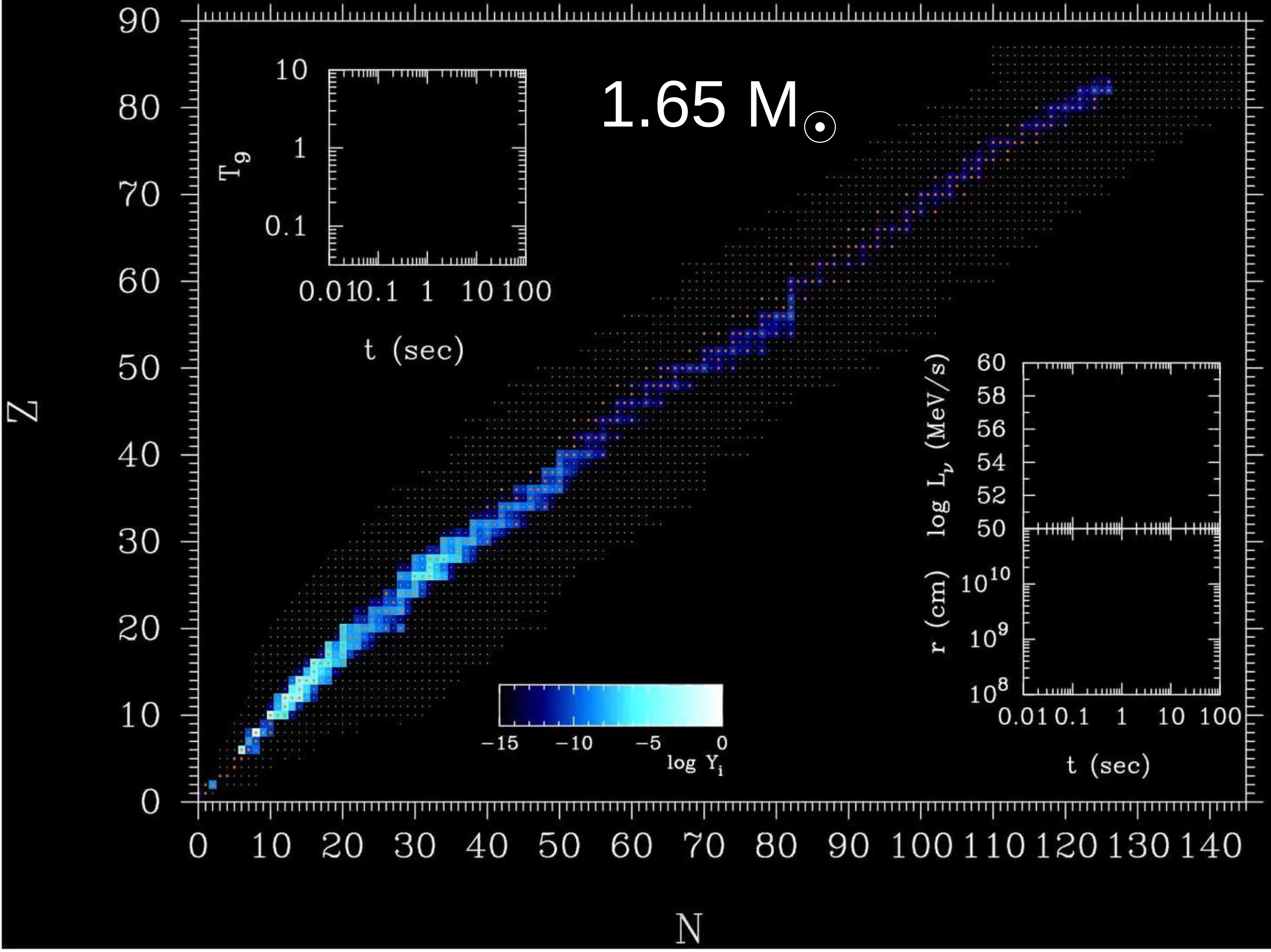
$\nu_e + {}^{4}He \rightarrow {}^{3}He + n + \nu_e$

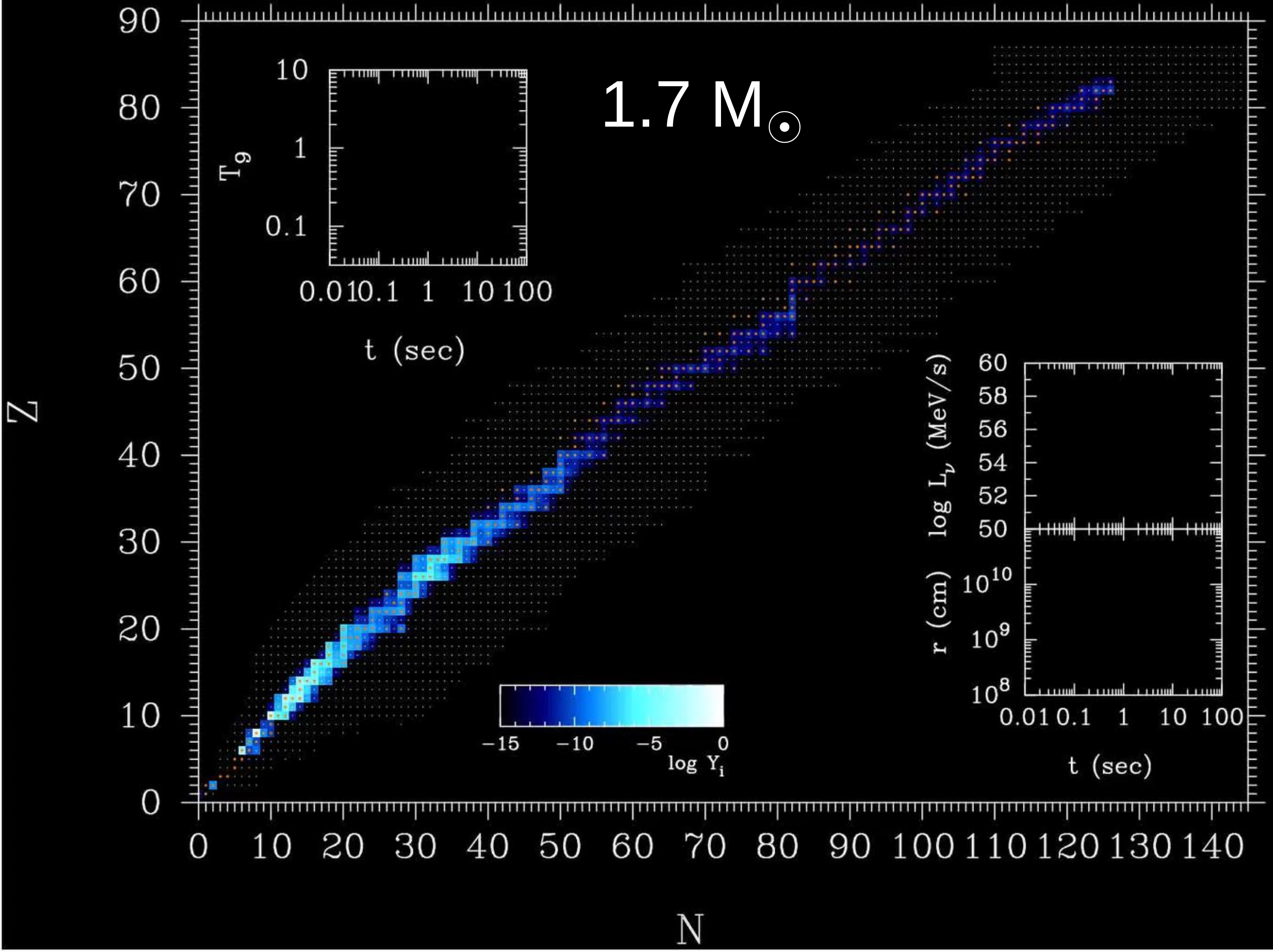
As a 1-body reaction

$$\frac{dY_d}{dt} \ni -Y_\alpha \lambda_{\nu + \mathrm{4He}} + (\text{inverse reaction})$$

$$\lambda_{\nu + \mathrm{4He}} = n_\nu \langle \sigma c \rangle_{\nu + \mathrm{4He}}$$
$$= \int f_e(E_\nu, r, t) dE_\nu \, \sigma(E_\gamma) c$$

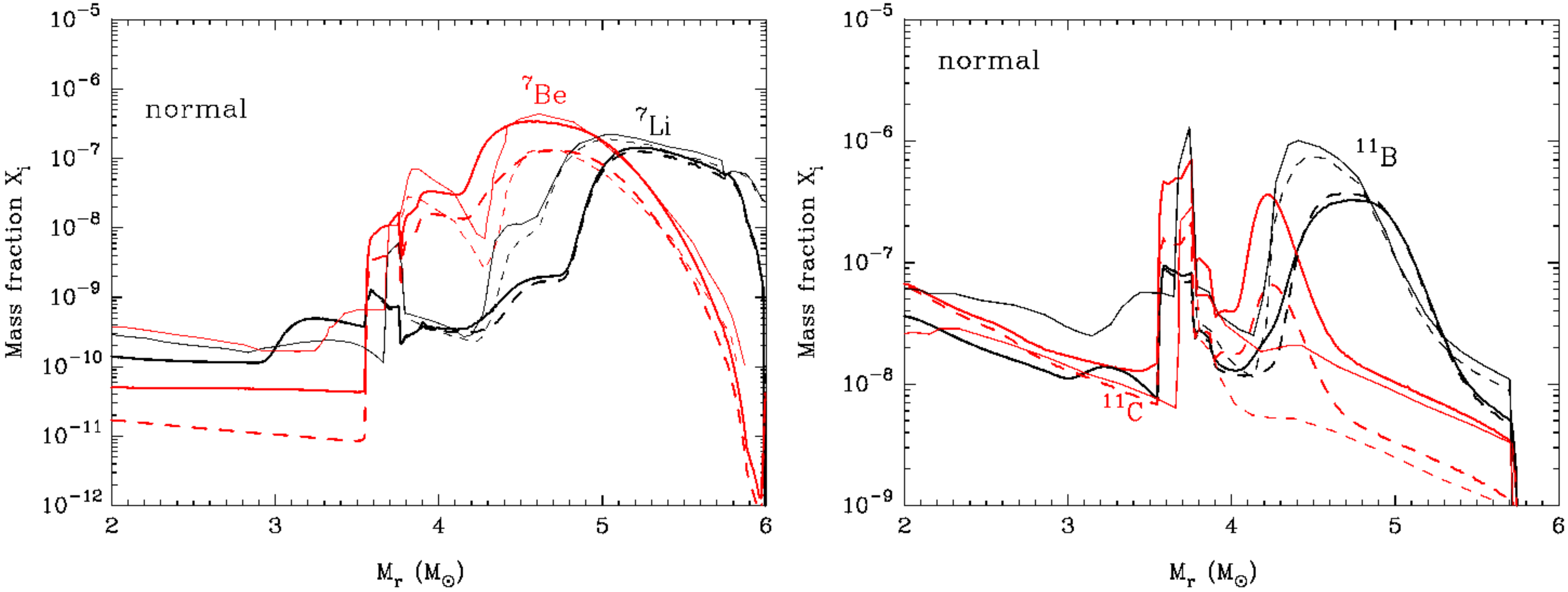
$f_e(E_\nu, r, t)$: Distribution function of ν_e


1.65 $M_\odot$
90
80
70
60
50
40
30
20
10
0
Z
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
N
10
1
0.1
T_9
0.01
0.1
1
10
100
t (sec)
60
58
56
54
52
50
log L_ν (MeV/s)
10^{10}
10^9
10^8
r (cm)
0.01
0.1
1
10
100
t (sec)
−15
−10
−5
0
log Y_i


1.7 $M_\odot$
Z
N
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
T_9
10
1
0.1
0.01
0.1
1
10
100
t (sec)
log L_ν (MeV/s)
60
58
56
54
52
50
r (cm)
10^{10}
10^9
10^8
0.01
0.1
1
10
100
t (sec)
−15
−10
−5
0
log Y_i

Results

1. Li & B (normal hierarchy)



MK, et al., ApJ 872, 164 (2019)

—— Normal

- - - No oscillation

MSW → ν_e rates increase

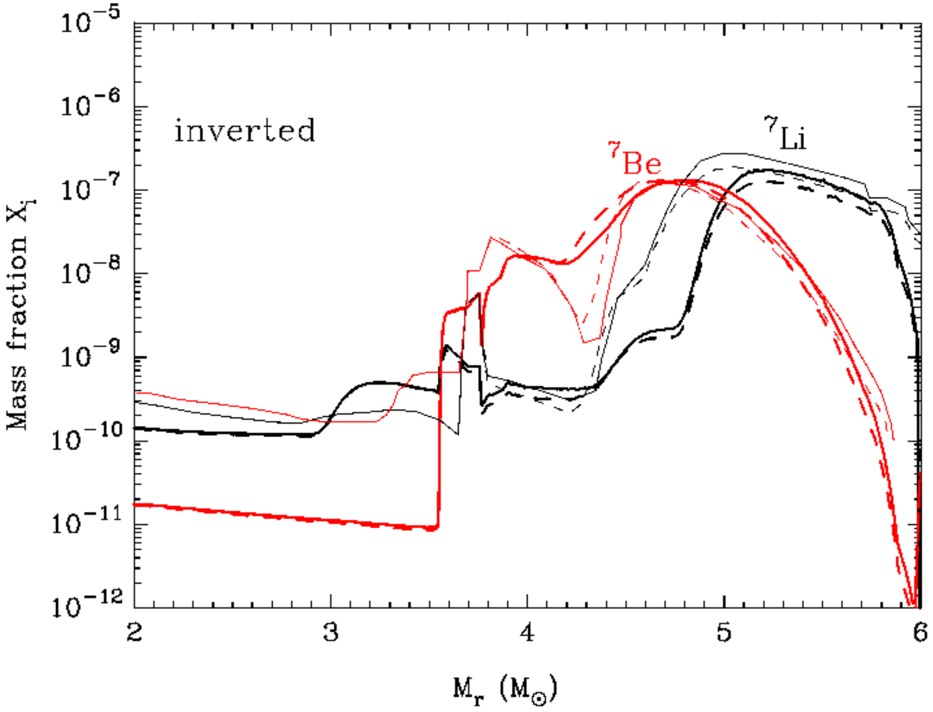
→yields of p & ^{3}He via ν+^{4}He reaction increase

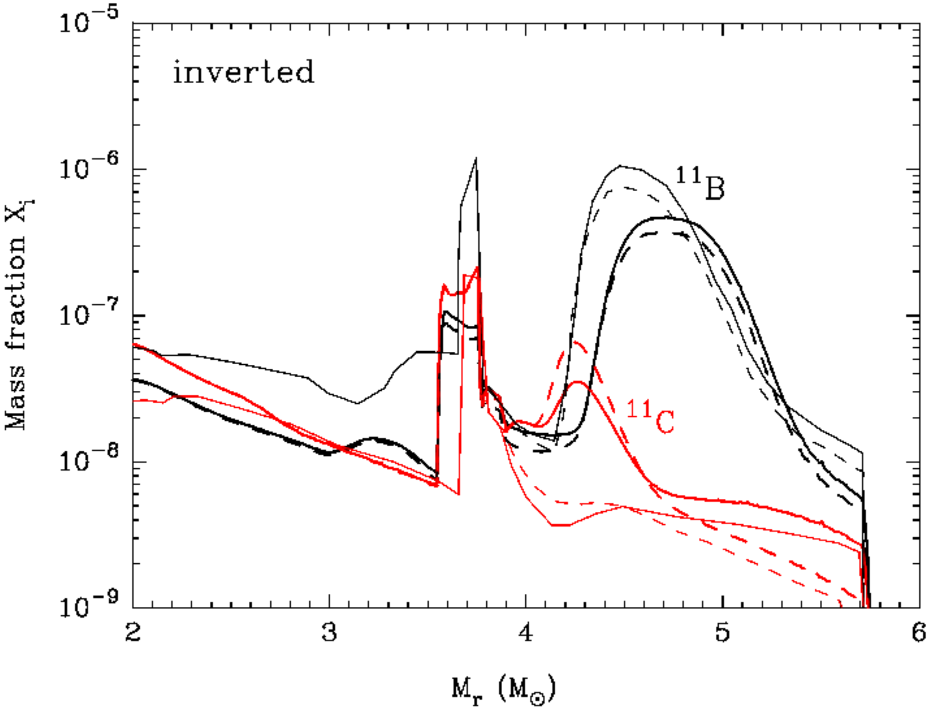
→enhanced ^{3}He$(\alpha,\gamma)^7$Be$(\alpha,\gamma)^{11}$C

stronger destruction ^{11}B(p,2α)^{4}He

- Thin lines: Yoshida et al. (2008)
  different yields ←different explosion models

2. Li & B (inverted hierarchy)





MK, et al., ApJ 872, 164 (2019)

———— Inverted

– – – – No oscillation

MSW → $\bar{\nu}_e$ rates increase

→yields of n & ^{3}H via ν+^{4}He reaction increase

→enhanced ^{3}H(α,γ)^{7}Li(α,γ)^{11}B

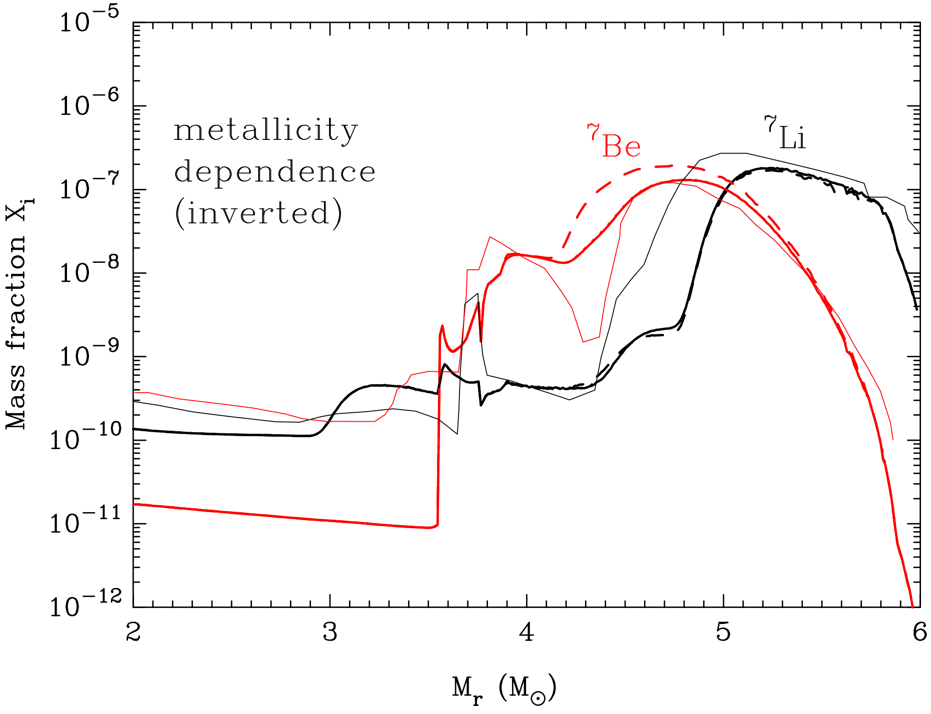
stronger destruction ^{3}He(n,p)^{3}H & ^{7}Be(n,p)^{7}Li

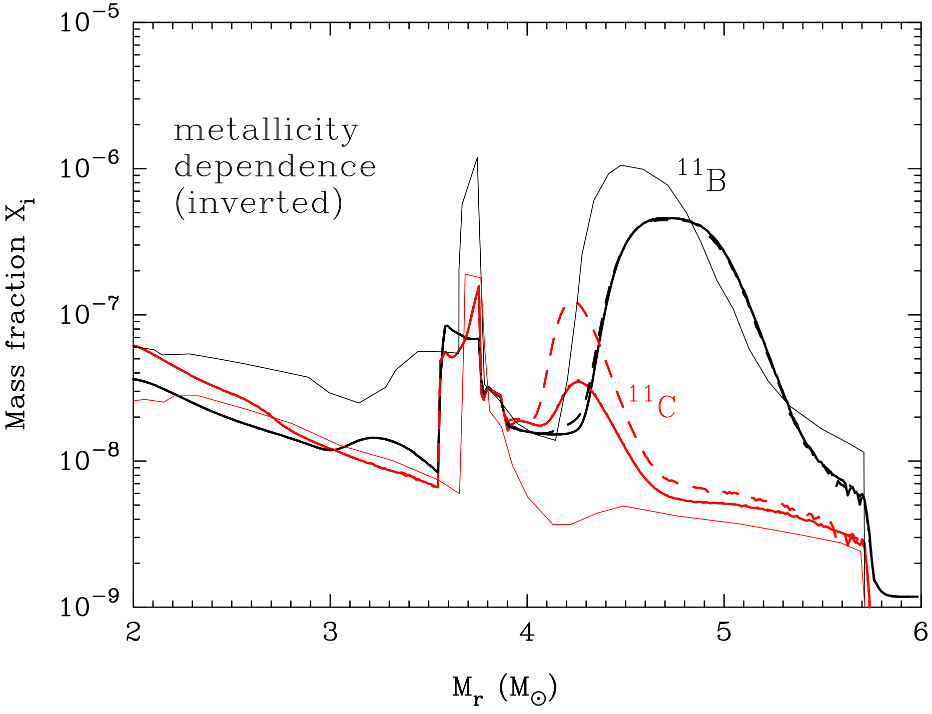
(M_r=4.2 - 4.7 $M_\odot$)

- Thin lines: Yoshida et al. (2008)

  different yields ←different explosion models

3. Li & B (metallicity effect)





—— Stellar s-abundance

- - - - - $Z_\odot$ for heavy nuclei

✓ Evolved star with Z =$Z_\odot$/4
✓ Thermal bomb (E=10^{51} erg)
✓ ν energy $E_\nu=3\times10^{53}$ erg
✓ Luminosity decays with τ_ν=3 s

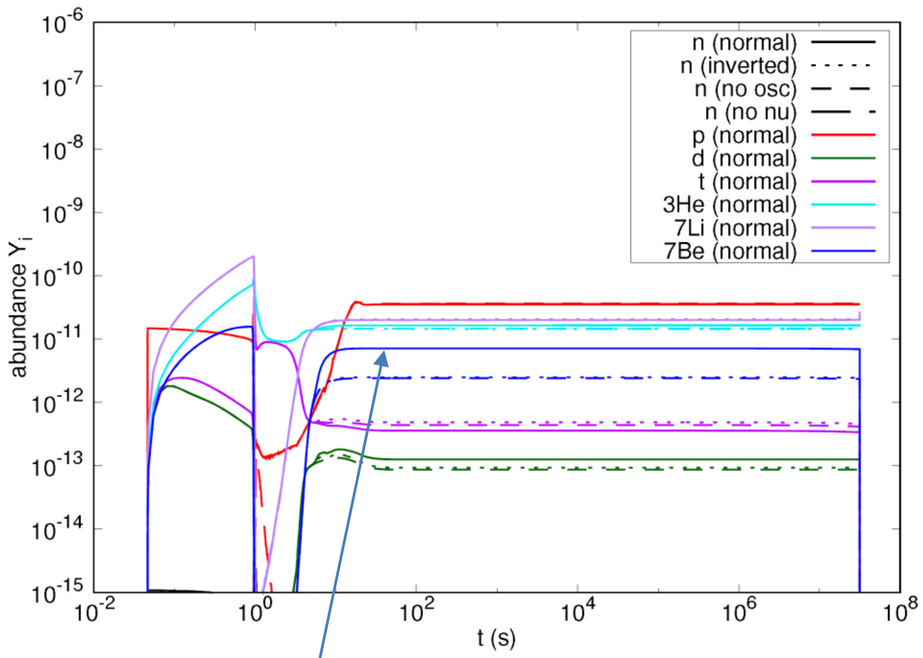
➢ Y_n depend on initial nuclear abundances

➢ solar abundance→**higher metallicity**
→many neutron absorbers
→n-poor

➢ at M_r=4.5 $M_\odot$, **Y_n determines ^{7}Be yields through ^{7}Be(n,p)^{7}Li rate**

MK, Cheoun, Kim, et al., ApJ 872, 164 (2019)

4. abundance evolution (M_r =2 $M_\odot$)



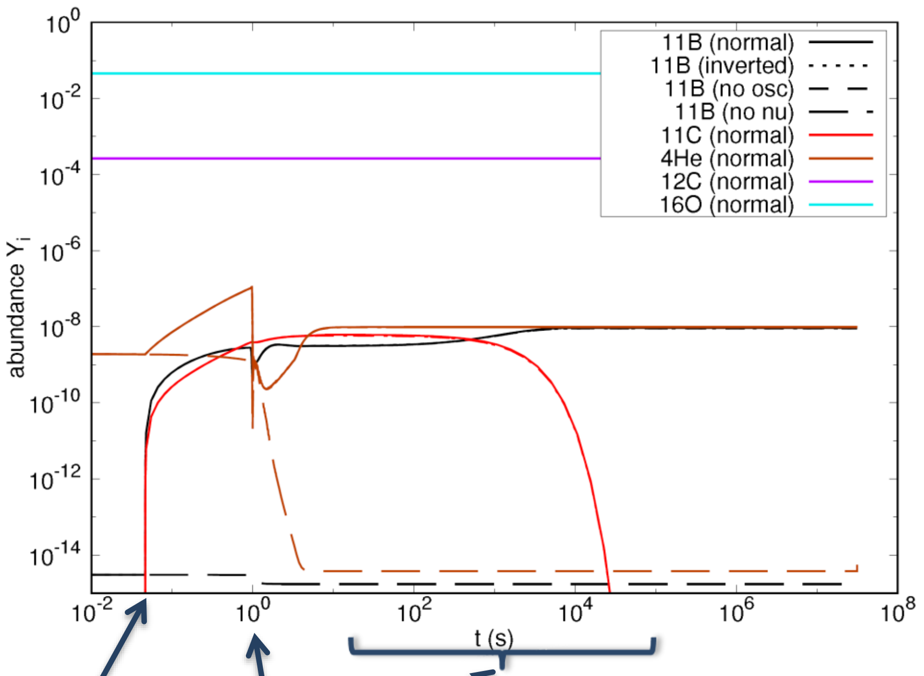
^{7}Be: ^{12}C+ν_e (CC)

←higher rate in the Normal hierarchy:

ν_x←>ν_e

→spallation products are more p-rich

(^{3}He, ^{7}Be, ^{11}C)



ν arrives

→ν-process

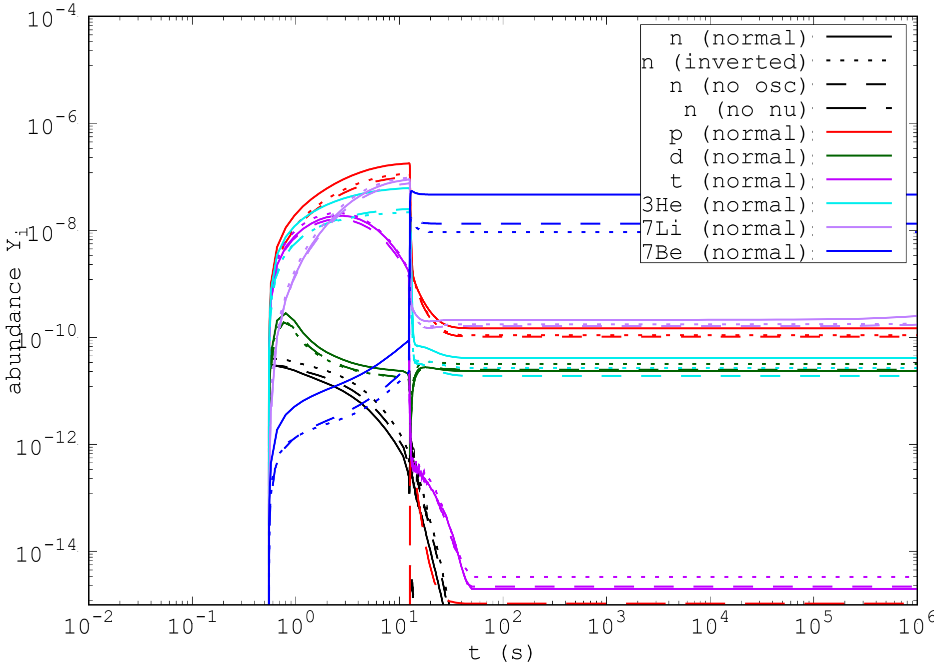
β-decay of unstable nuclides

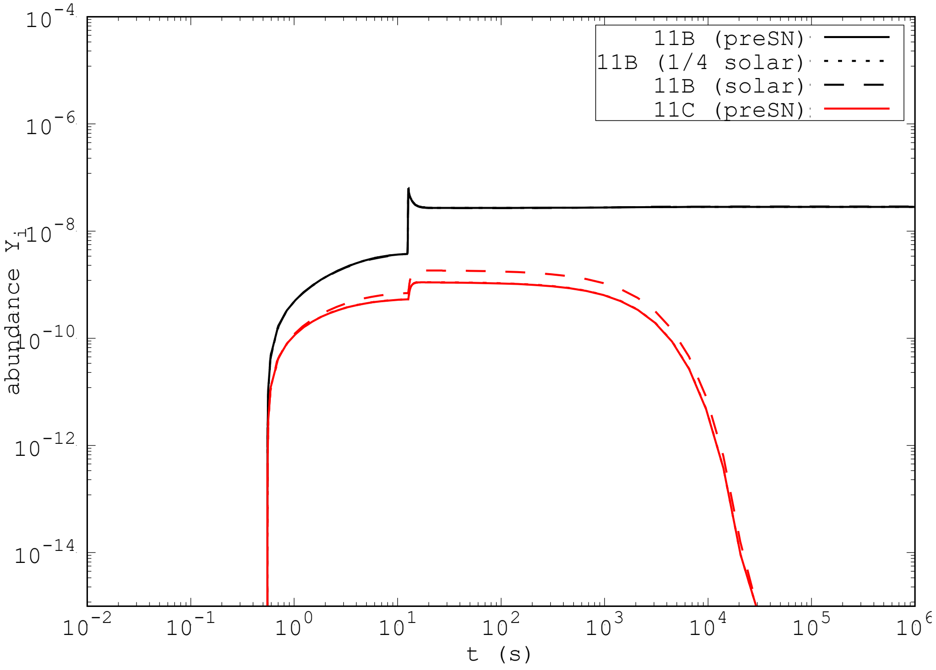
SN shock arrives

→high T_9→nucleosynthesis

MK, et al., ApJ 872, 164 (2019)

5. abundance evolution (M$_r$ =4.5 M$_\odot$)





[before shock arrival]

^{4}He spallation → ^{3}H & ^{3}He production

→ ^{3}H(α,γ)^{7}Li

^{3}He(α,γ)^{7}Be

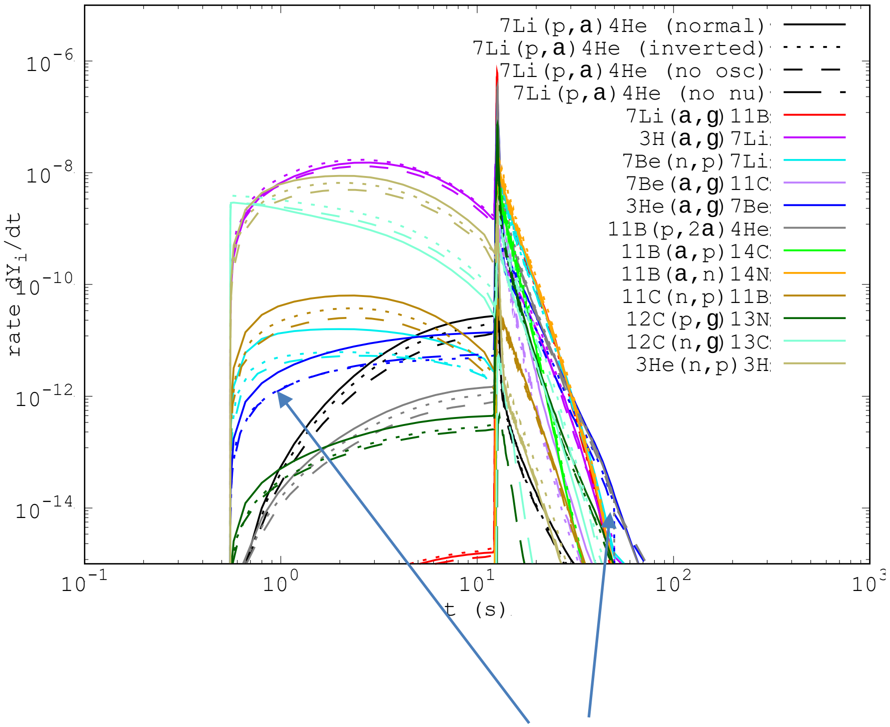
^{12}C spallation → ^{11}B, ^{11}C

[after shock heating]

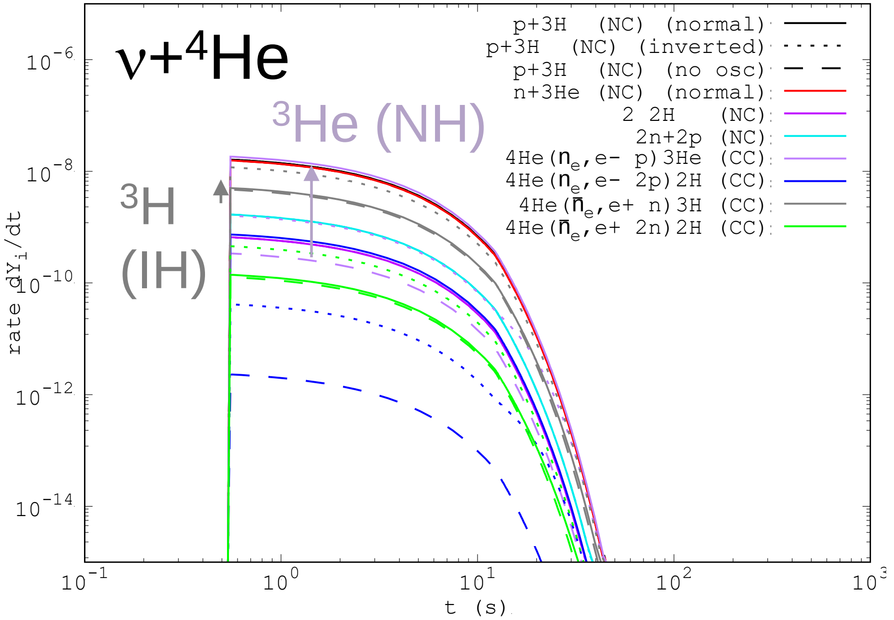
^{3}He(α,γ)^{7}Be

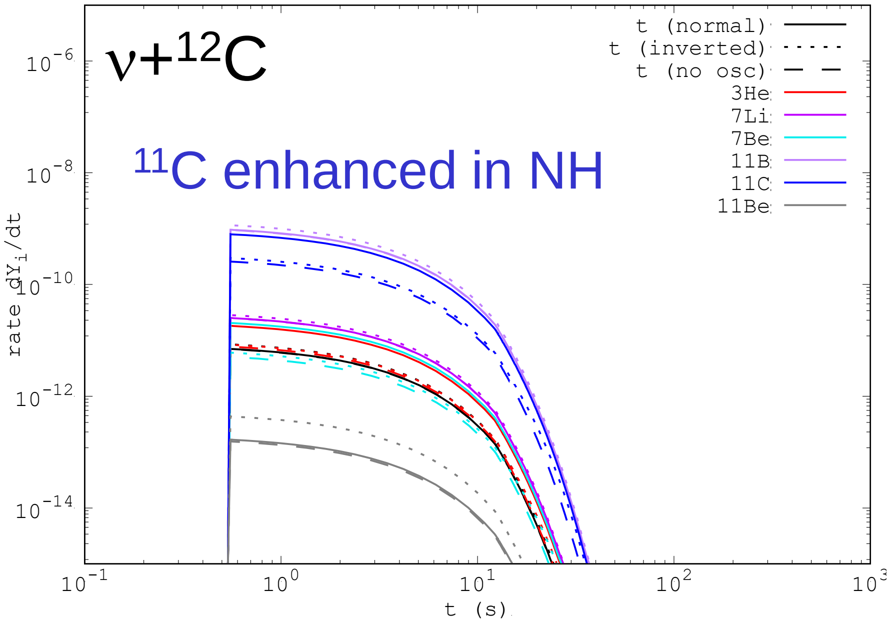
^{7}Li(α,γ)^{11}B

6. production & destruction rates ($M_r = 4.5\ M_\odot$)



^{3}He$(\alpha,\gamma)^7$Be





[before shock]

$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$ and $^3\mathrm{He}(n,p)^3\mathrm{H}$

[after shock]

$^{11}\mathrm{B}(\alpha,n)^{14}\mathrm{N}$, $^7\mathrm{Li}(\alpha,\gamma)^{11}\mathrm{B}$, $^7\mathrm{Be}(n,p)^7\mathrm{Li}$,
$^{11}\mathrm{B}(p,2\alpha)^4\mathrm{He}$, $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$, $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$,
$^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}$, $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

7. effects of mass hierarchy & initial abundances

MK, Cheoun, Kim, et al., ApJ 872, 164 (2019)

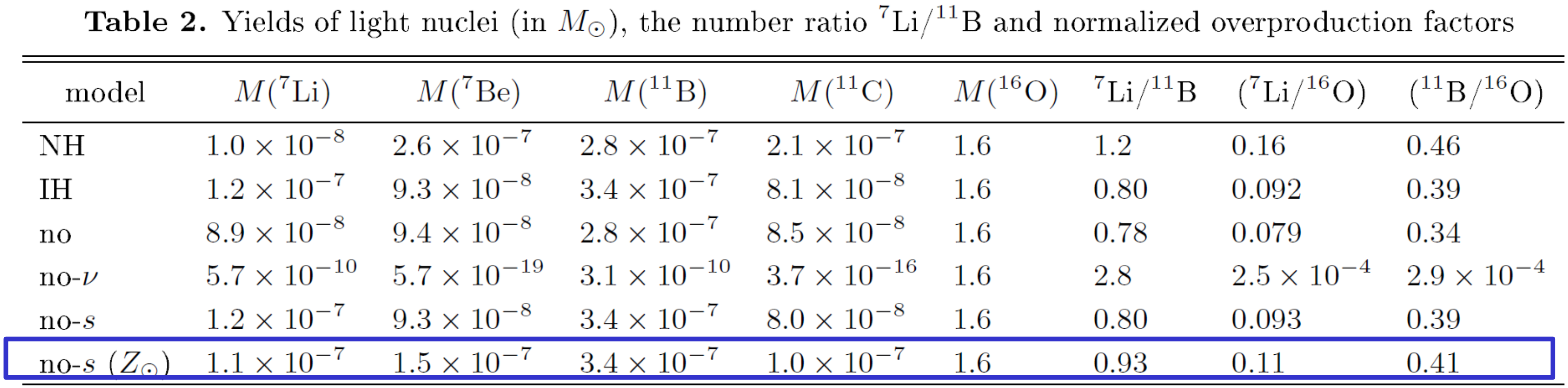


Table 2. Yields of light nuclei (in $M_\odot$), the number ratio ^{7}Li/^{11}B and normalized overproduction factors

model	$M(^7\mathrm{Li})$	$M(^7\mathrm{Be})$	$M(^{11}\mathrm{B})$	$M(^{11}\mathrm{C})$	$M(^{16}\mathrm{O})$	$^7\mathrm{Li}/^{11}\mathrm{B}$	$(^7\mathrm{Li}/^{16}\mathrm{O})$	$(^{11}\mathrm{B}/^{16}\mathrm{O})$
NH	1.0×10^{-8}	2.6×10^{-7}	2.8×10^{-7}	2.1×10^{-7}	1.6	1.2	0.16	0.46
IH	1.2×10^{-7}	9.3×10^{-8}	3.4×10^{-7}	8.1×10^{-8}	1.6	0.80	0.092	0.39
no	8.9×10^{-8}	9.4×10^{-8}	2.8×10^{-7}	8.5×10^{-8}	1.6	0.78	0.079	0.34
no-ν	5.7×10^{-10}	5.7×10^{-19}	3.1×10^{-10}	3.7×10^{-16}	1.6	2.8	2.5×10^{-4}	2.9×10^{-4}
no-s	1.2×10^{-7}	9.3×10^{-8}	3.4×10^{-7}	8.0×10^{-8}	1.6	0.80	0.093	0.39
no-s $(Z_\odot)$	1.1×10^{-7}	1.5×10^{-7}	3.4×10^{-7}	1.0×10^{-7}	1.6	0.93	0.11	0.41

Yields of stars with $Z_\odot$

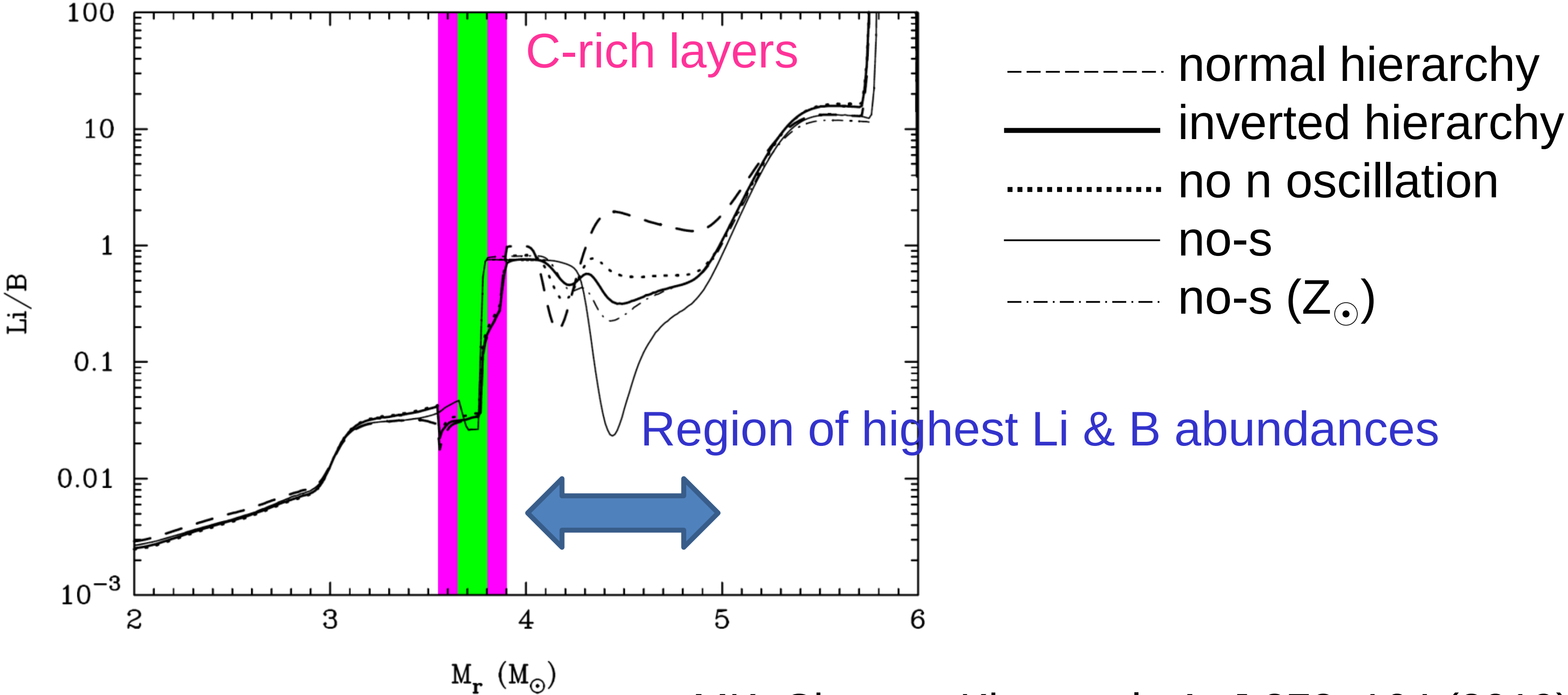
- ➢ **Li and B yields are independent of the abundance pattern of s-nuclei**
- ➢ **Li and B yields depends on the metallicity significantly**

- ➢ However, probably dust formations occurs before mixing of SN ejecta
  →not the total yield ratio, but local values are retained in presolar grains

8. Li/B ratio in SN dusts

[evolution of SN ejecta until dust formation of ~O(1) yr]

- Mixing within layers →no
  - ✓ Mixing time scale is long (Deneault, Clayton, Heger, 2003)
  - ✓ Positional change of materials with different compositions is possible
  - ✓ SN observations support no-mixing (Cas A)
- Then, Li/B ratios in grains depend on position



C-rich layers

Region of highest Li & B abundances

MK, Cheoun, Kim, et al., ApJ 872, 164 (2019)

Appendix 2. Chronology of the Solar System Formation

- Solar system (SS)→made of mixture of many SN ejecta
- Existences of p-process short-lived radioactive nuclides ($T_{1/2}$~100 Myr) have been found in solar material
- Constraint on a time scale of the SS formation
  - ✓ Possibility of a triggered formation by a SN shock (Cameron & Truran 1977, Cameron 1993)
  - ✓ Possibility that the last SN, ejecting p-nuclei, triggered the SS formation

Radioactive nuclei

Decay mode	**$T_{1/2}$ (Myr)**	**Reference**	**Process**
$^{53}\mathrm{Mn}\rightarrow{}^{53}\mathrm{Cr}$	3.7	$^{55}\mathrm{Mn}$	NSE
$^{92}\mathrm{Nb}\rightarrow{}^{92}\mathrm{Zr}$	36.	$^{92}\mathrm{Mo}$	p-process
$^{97}\mathrm{Tc}\rightarrow{}^{97}\mathrm{Mo}$	2.6	$^{92}\mathrm{Mo}$	p-process
$^{146}\mathrm{Sm}\rightarrow{}^{142}\mathrm{Nd}$	103.	$^{144}\mathrm{Sm}$	p-process

Extinct nuclides in meteorites

(ex.) $^{92}_{41}\mathrm{Nb} \rightarrow {}^{92}_{40}\mathrm{Zr}$ (e^- capture)

present Nb/Zr : large (much Nb)

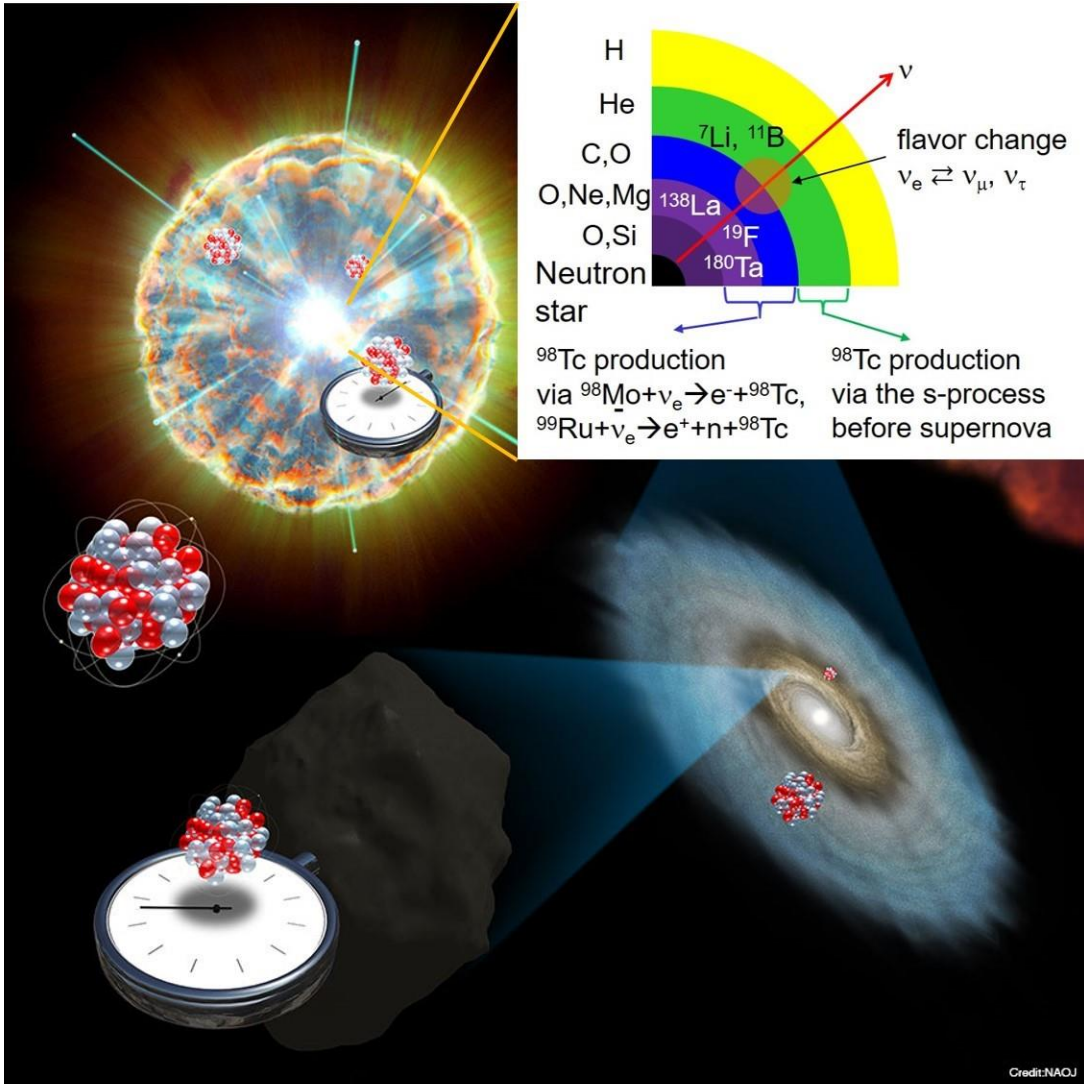
➔ $^{92}_{40}\mathrm{Zr}$ isotopic ratio : large

anomaly ⇩

Verification of $^{92}_{41}\mathrm{Nb}$ at the condensation

- ✓ Constrain the formation from nucleosynthesis calculation and meteoritic analyses

9. Short-lived ^{98}Tc (1)



^{98}Tc is produced in SNe
via the ν-process ($\bar{\nu}_e$)

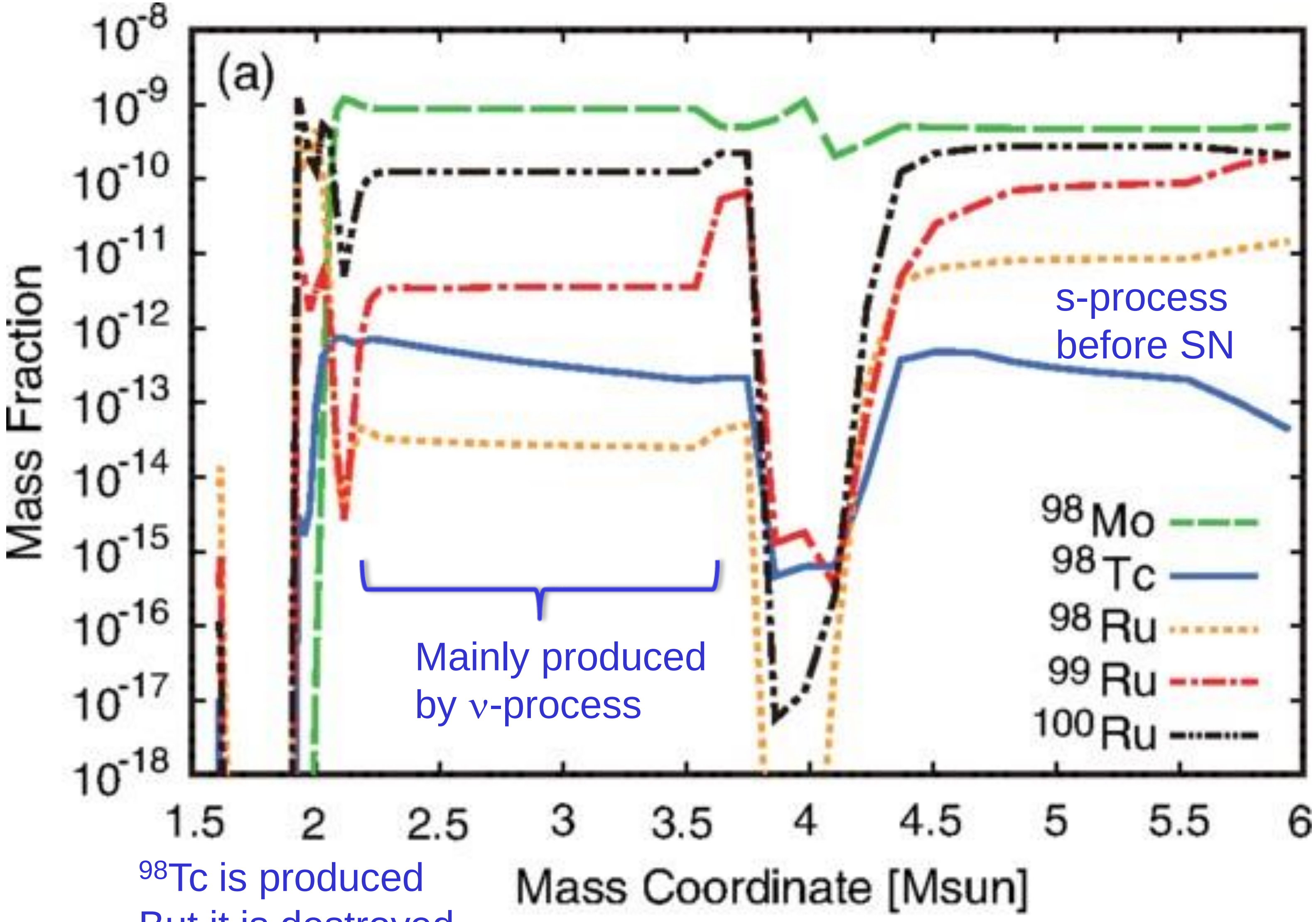
^{98}Tc decays with $T_{1/2}$ =4.2 Myr
until it is confined in meteorites
at the solar system formation

^{98}Tc→^{98}Ru
isotopic anomaly in meteorites
→time between the SN and
the solar system formation

→nuclear chronology
宇宙年代学

(国际交叉科学研究院院刊 in BUAA)

9. Short-lived ^{98}Tc (2)



s-process before SN

Mainly produced by ν-process

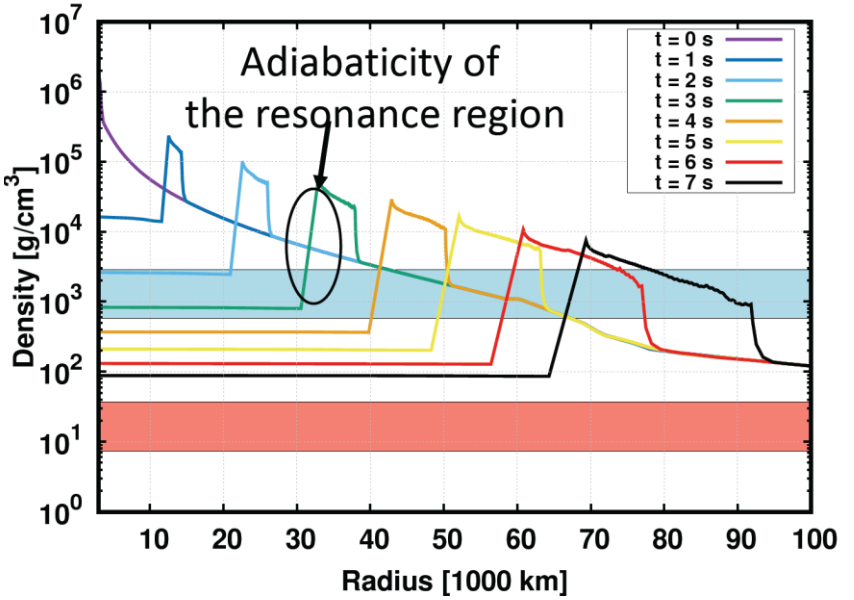
^{98}Tc is produced
But it is destroyed

Peak $T_9 = T/(10^9$ K) ←

(Hayakawa, Ko, Cheoun, et al., PRL 121, 102701, 2018)

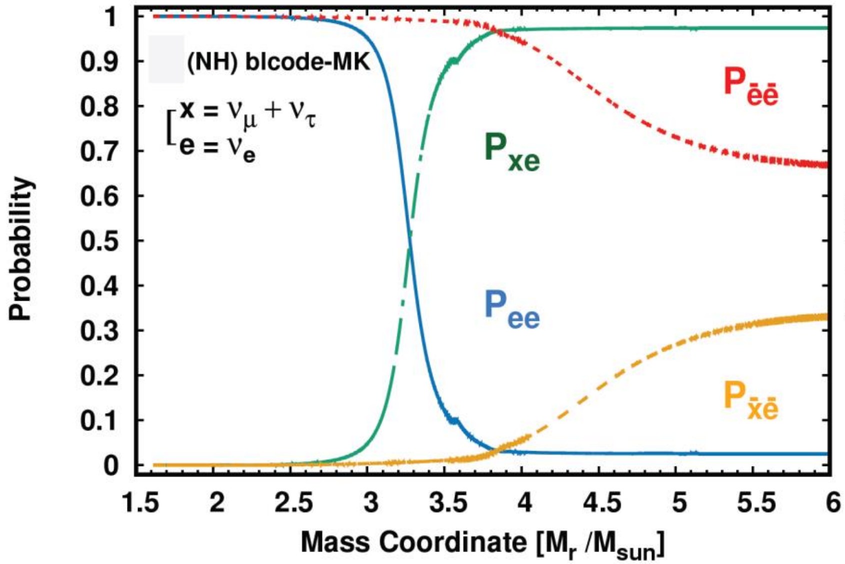
10. Effect of density evolution by a shock

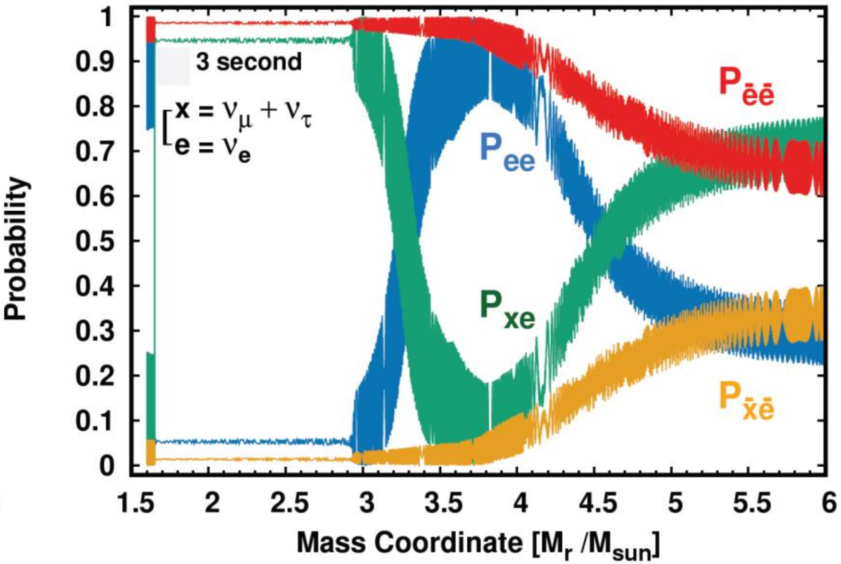
Heamin Ko, in Beihang workshop (2018)



ν-heating
→low density region expands

Density change occurs at 3 positions
→flavor change occurs 3 times.





11. Effects of sterile neutrino (ν_s)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \hat{H}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix},$$

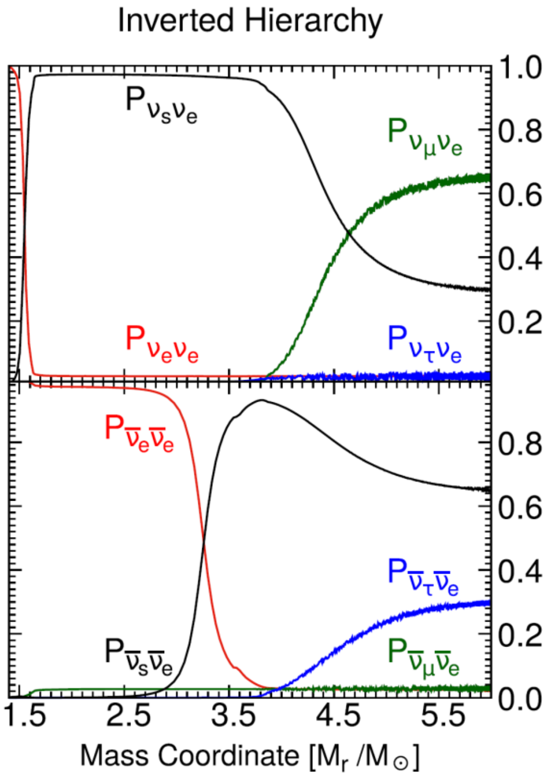
$$\hat{H}_{\rm vacuum} = U{\rm diag}\left(0,\ \frac{\Delta m^2_{21}}{2E_\nu},\ \frac{\Delta m^2_{31}}{2E_\nu},\ \frac{\Delta m^2_{41}}{2E_\nu}\right)U^\dagger,$$

$$\hat{H}_{\rm matter} = {\rm diag}(V_{\rm CC} + V_{\rm NC},\ V_{\rm NC},\ V_{\rm NC},\ 0),$$

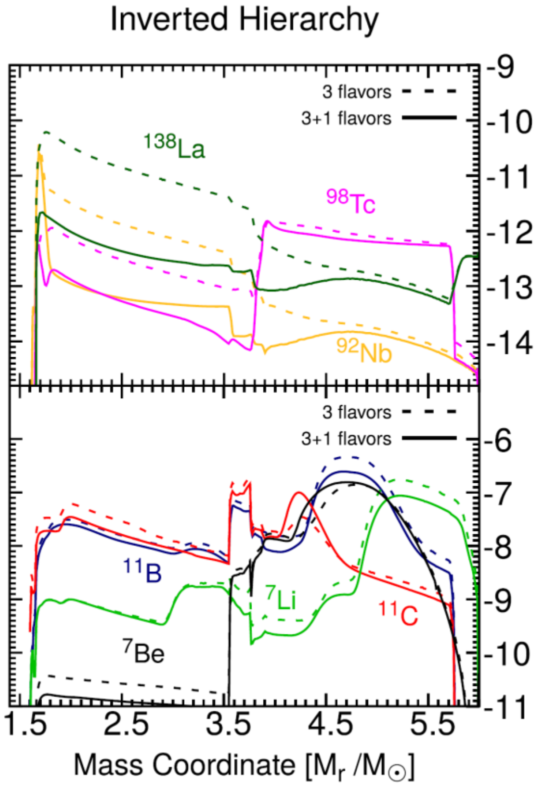
$$V_{CC} = \sqrt{2}\,G_F n_e$$

$$V_{NC} = -\sqrt{2}\,G_F n_n/2$$

flavor change with ν_s



Nuclear yields

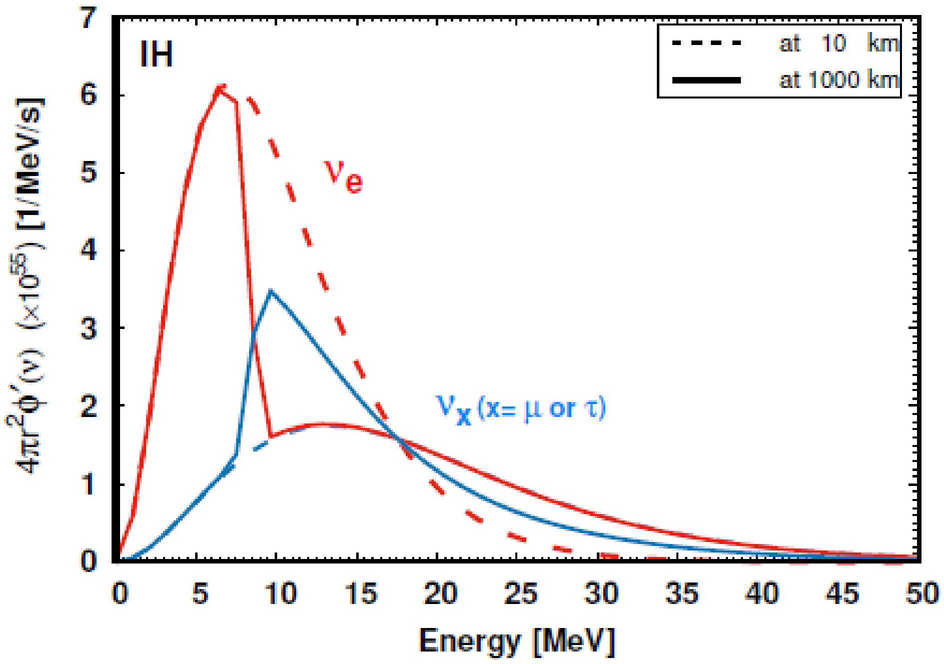


- If ν_s luminosity is zero in the center, the flavor change of ν_e→ν_s leads to smaller ν-reaction rate →**excluded**
- If ν_s luminosity is as large as other ν's, **Li/B ratio can constrain ν_s temperature**

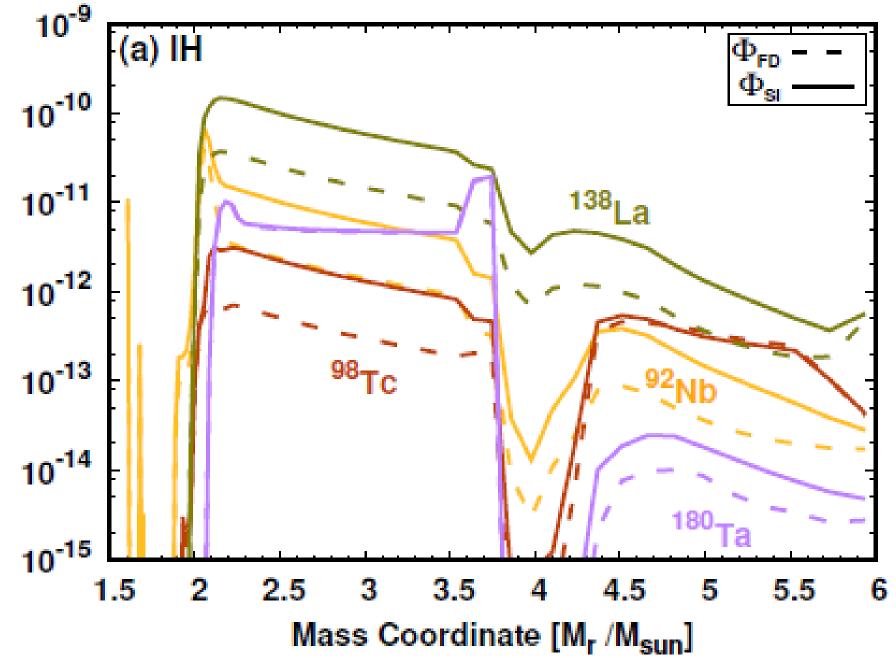
(Ko, Jang, MK, Cheoun, Astrophys. J. 894, 99, 2020)

12. Effects of collective ν-oscillation

ν-flavor change of e↔x



Yields of ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta



- ν_e spectrum is increased at high E
  →ν_e reaction rates are larger
  → ^{92}Nb, ^{138}La, ^{98}Tc abundances are enhanced

- ^{180}Ta is produced before the SN in the inner region
  →its yield is insensitive to ν oscillation

(Ko, Cheoun, Ha, et al., Astrophys. J. Lett. 891, 24, 2020)

Summary

3. Some nuclei originate from neutrino reactions
    - Fragile light nuclei ^{7}Li & ^{11}B, rare p-nuclides ^{138}La & ^{180}Ta
    - Short-lived nuclei ^{92}Nb & ^{98}Tc
    - ^{92,94}Mo & ^{96,98}Ru via νp-process

4. SN ν-process have observables
    - Li & B production
        - ✓ Yields are sensitive to ν mass hierarchy & flavor changes in stars
        - ✓ The ratio ^{7}Li/^{11}B increases with metallicity
    - Yields of ^{92}Nb, ^{98}Tc, ^{138}La & ^{180}Ta are sensitive to collective ν-oscillation.
    - It is desired that we obtain better understanding of SN ν-process by accurate SN modeling, precise nuclear cross sections & neutrino experiments, and meteoritic analyses.

→ Let's get ready and wait for the next nearby SN!

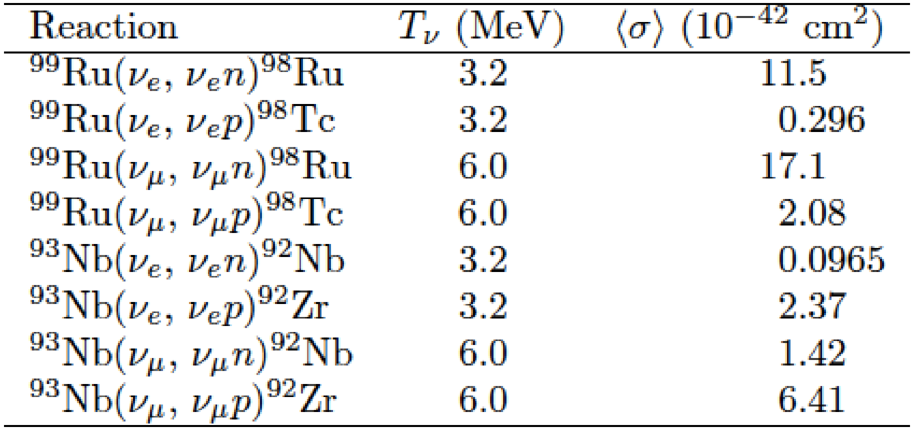
Backup

2. SN ν-reaction rate (1)

1. Hydrodynamical calculation
    - blcode (Ott, Morozova, Piro)
    - Thermal bomb (E=1 × 10^{51} erg for SN1987A)
      ←large pressure is assumed in the center, and explosion is solved

2. ν-luminosity
    - Total ν energy E_ν=3 × 10^{53} erg
    - Exponential decrease with τ_ν=3 s

3. ν-cross sections
    - Spallation cross section of ^{4}He & ^{12}C
      (Yoshida et al. ApJ 686, 448, 2008)
    - ^{98}Tc (& ^{92}Nb) production
      (Cheoun et al. 2012)
      Reactions complimented



Reaction	T_ν (MeV)	$\langle\sigma\rangle$ (10^{-42} cm^2)
$^{99}\mathrm{Ru}(\nu_e, \nu_e n)^{98}\mathrm{Ru}$	3.2	11.5
$^{99}\mathrm{Ru}(\nu_e, \nu_e p)^{98}\mathrm{Tc}$	3.2	0.296
$^{99}\mathrm{Ru}(\nu_\mu, \nu_\mu n)^{98}\mathrm{Ru}$	6.0	17.1
$^{99}\mathrm{Ru}(\nu_\mu, \nu_\mu p)^{98}\mathrm{Tc}$	6.0	2.08
$^{93}\mathrm{Nb}(\nu_e, \nu_e n)^{92}\mathrm{Nb}$	3.2	0.0965
$^{93}\mathrm{Nb}(\nu_e, \nu_e p)^{92}\mathrm{Zr}$	3.2	2.37
$^{93}\mathrm{Nb}(\nu_\mu, \nu_\mu n)^{92}\mathrm{Nb}$	6.0	1.42
$^{93}\mathrm{Nb}(\nu_\mu, \nu_\mu p)^{92}\mathrm{Zr}$	6.0	6.41

4. ν-process of nuclei

- ν-reaction rates
  - ✓ Spallation of ^{4}He & ^{12}C: Yoshida et al. ApJ 686, 448 (2008)

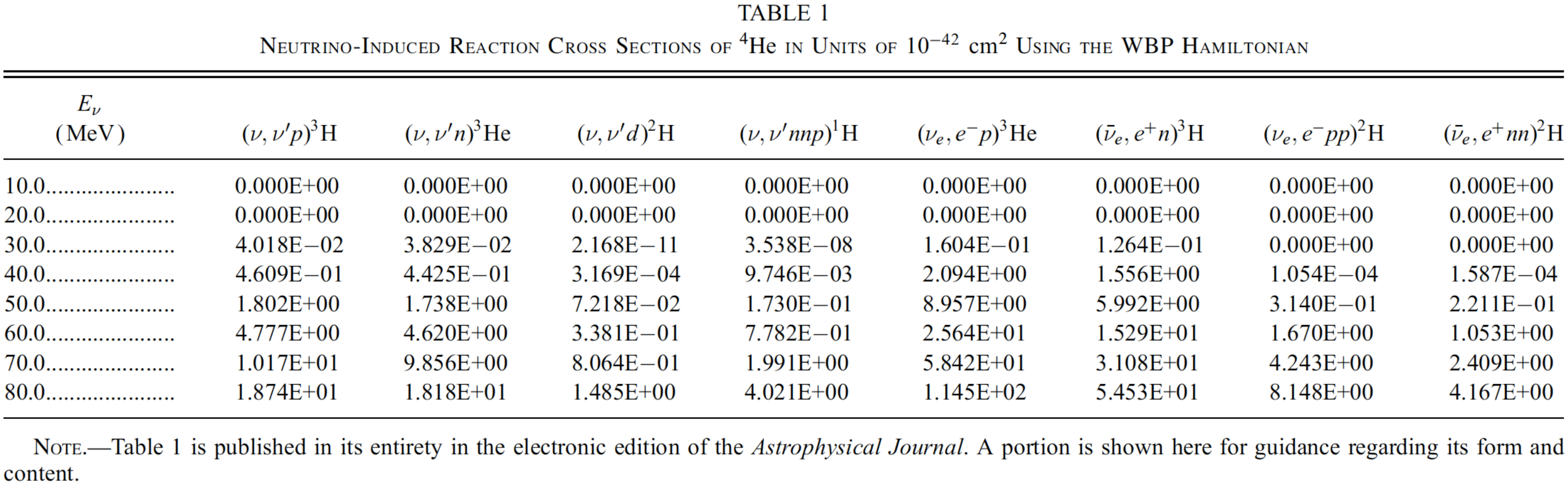


TABLE 1

Neutrino-Induced Reaction Cross Sections of ^{4}He in Units of 10^{-42} cm^2 Using the WBP Hamiltonian

E_ν (MeV)	$(\nu,\nu'p)^3$H	$(\nu,\nu'n)^3$He	$(\nu,\nu'd)^2$H	$(\nu,\nu'nnp)^1$H	$(\nu_e,e^-p)^3$He	$(\bar{\nu}_e,e^+n)^3$H	$(\nu_e,e^-pp)^2$H	$(\bar{\nu}_e,e^+nn)^2$H
10.0.....................	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
20.0.....................	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
30.0.....................	4.018E−02	3.829E−02	2.168E−11	3.538E−08	1.604E−01	1.264E−01	0.000E+00	0.000E+00
40.0.....................	4.609E−01	4.425E−01	3.169E−04	9.746E−03	2.094E+00	1.556E+00	1.054E−04	1.587E−04
50.0.....................	1.802E+00	1.738E+00	7.218E−02	1.730E−01	8.957E+00	5.992E+00	3.140E−01	2.211E−01
60.0.....................	4.777E+00	4.620E+00	3.381E−01	7.782E−01	2.564E+01	1.529E+01	1.670E+00	1.053E+00
70.0.....................	1.017E+01	9.856E+00	8.064E−01	1.991E+00	5.842E+01	3.108E+01	4.243E+00	2.409E+00
80.0.....................	1.874E+01	1.818E+01	1.485E+00	4.021E+00	1.145E+02	5.453E+01	8.148E+00	4.167E+00

Note.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

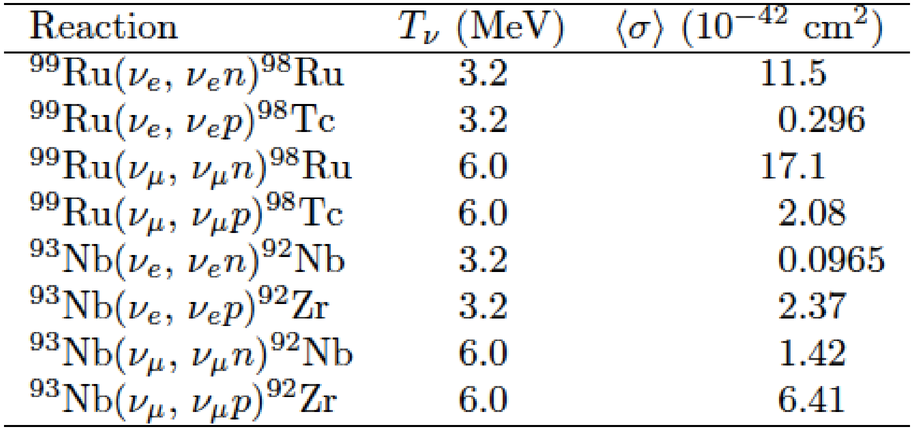
- ✓ Reactions for ^{98}Tc production: Cheoun et al. PRC 85, 065807 (2012)

- ✓ Other reactions: Hoffmann & Woosley (A =~[12,80], 4186 reactions)

  http://dbserv.pnpi.spb.ru/elbib/tablisot/toi98/www/astro/hw92 1.htm

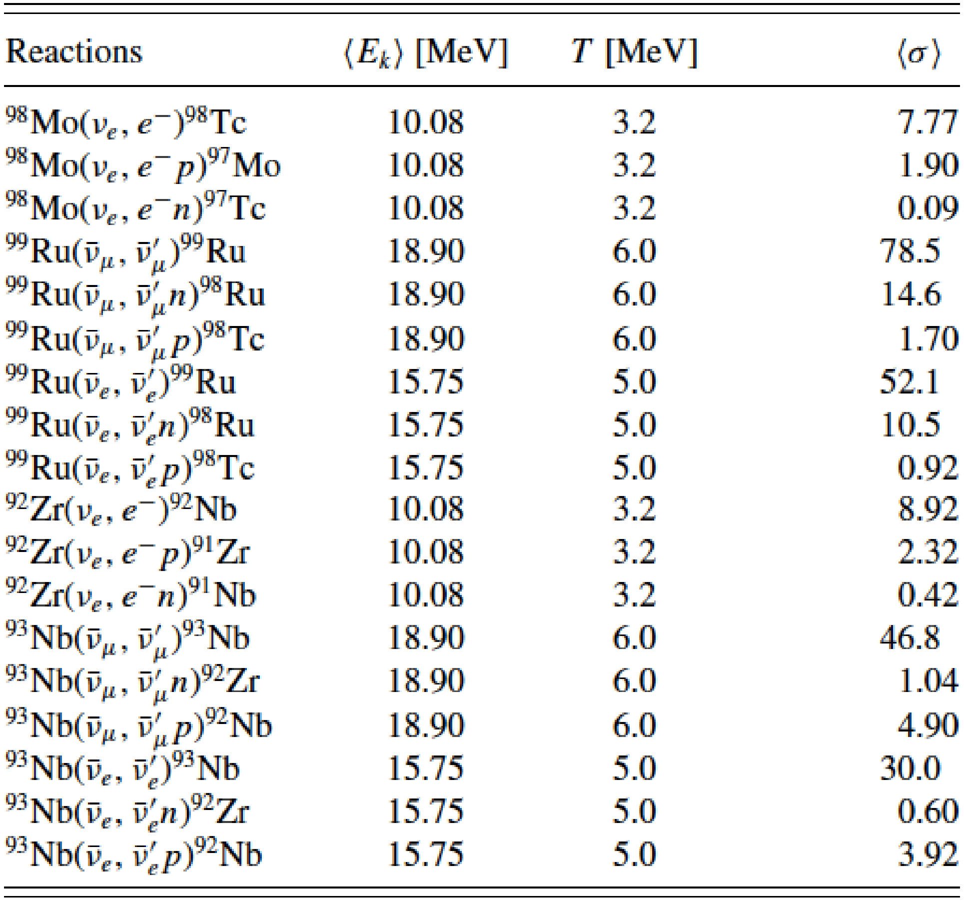
6. Revised calculations

- ➢ ^{98}Tc (& ^{92}Nb) production
  - ✓ Reactions are complimented



Reaction	T_ν (MeV)	$\langle\sigma\rangle$ (10^{-42} cm^2)
^{99}Ru(ν_e, $\nu_e n$)^{98}Ru	3.2	11.5
^{99}Ru(ν_e, $\nu_e p$)^{98}Tc	3.2	0.296
^{99}Ru(ν_μ, $\nu_\mu n$)^{98}Ru	6.0	17.1
^{99}Ru(ν_μ, $\nu_\mu p$)^{98}Tc	6.0	2.08
^{93}Nb(ν_e, $\nu_e n$)^{92}Nb	3.2	0.0965
^{93}Nb(ν_e, $\nu_e p$)^{92}Zr	3.2	2.37
^{93}Nb(ν_μ, $\nu_\mu n$)^{92}Nb	6.0	1.42
^{93}Nb(ν_μ, $\nu_\mu p$)^{92}Zr	6.0	6.41

Cheoun et al. (2012)



Reactions	$\langle E_k\rangle$ [MeV]	T [MeV]	$\langle\sigma\rangle$
^{98}Mo(ν_e, e^-)^{98}Tc	10.08	3.2	7.77
^{98}Mo(ν_e, e^-p)^{97}Mo	10.08	3.2	1.90
^{98}Mo(ν_e, e^-n)^{97}Tc	10.08	3.2	0.09
^{99}Ru($\bar\nu_\mu$, $\bar\nu'_\mu$)^{99}Ru	18.90	6.0	78.5
^{99}Ru($\bar\nu_\mu$, $\bar\nu'_\mu n$)^{98}Ru	18.90	6.0	14.6
^{99}Ru($\bar\nu_\mu$, $\bar\nu'_\mu p$)^{98}Tc	18.90	6.0	1.70
^{99}Ru($\bar\nu_e$, $\bar\nu'_e$)^{99}Ru	15.75	5.0	52.1
^{99}Ru($\bar\nu_e$, $\bar\nu'_e n$)^{98}Ru	15.75	5.0	10.5
^{99}Ru($\bar\nu_e$, $\bar\nu'_e p$)^{98}Tc	15.75	5.0	0.92
^{92}Zr(ν_e, e^-)^{92}Nb	10.08	3.2	8.92
^{92}Zr(ν_e, e^-p)^{91}Zr	10.08	3.2	2.32
^{92}Zr(ν_e, e^-n)^{91}Nb	10.08	3.2	0.42
^{93}Nb($\bar\nu_\mu$, $\bar\nu'_\mu$)^{93}Nb	18.90	6.0	46.8
^{93}Nb($\bar\nu_\mu$, $\bar\nu'_\mu n$)^{92}Zr	18.90	6.0	1.04
^{93}Nb($\bar\nu_\mu$, $\bar\nu'_\mu p$)^{92}Nb	18.90	6.0	4.90
^{93}Nb($\bar\nu_e$, $\bar\nu'_e$)^{93}Nb	15.75	5.0	30.0
^{93}Nb($\bar\nu_e$, $\bar\nu'_e n$)^{92}Zr	15.75	5.0	0.60
^{93}Nb($\bar\nu_e$, $\bar\nu'_e p$)^{92}Nb	15.75	5.0	3.92

7. Initial nuclear abundance

- s-nuclides:
  - ✓ s-process during He burning (Ono & Hashimoto)

- new calculation of stellar evolution
  for Z =$Z_\odot$/4 with the method (Kikuchi et al, PTEP 2015, 063E01)

Results (Li & B)

- results are different from Yoshida et al. (2008).
- Differences in the two calculations:
  - (i) initial abundance
  - (ii) nuclear reaction rates
  - (iii) input data from hydrodynamical calculation
  - (iv) neutrino parameters (slightly different)
  - (v) nucleosynthesis calculation

5. Code development

- Rate equation

$$\frac{d\boldsymbol{Y}}{dt} = \boldsymbol{f}(t, \boldsymbol{Y})$$

When this is solved with semi-implicit extrapolation method, we need to evaluate $\partial \boldsymbol{f} / \partial t$

$$f_i = \sum_a f_{i,a}.$$

$$f_{i,a} = \pm \frac{n_i}{\prod_{k=1}^{N_{\rm nuc}} n_k!} [N_{\rm A} \rho_{\rm b}(t)]^{\sum_{j=1}^{N_{\rm nuc}} n_j - 1} \prod_{k=1}^{N_{\rm nuc}} Y_k^{n_k} \langle {\rm rate} \rangle (t),$$

$$\frac{\partial f_{i,a}}{\partial t} = f_{i,a} \left[\left(\sum_{j=1}^{N_{\rm nuc}} n_j - 1 \right) \underbrace{\frac{d \ln \rho_{\rm b}}{dt}}_{\text{Hydrodynamics}} + \overbrace{\boxed{\frac{1}{\langle {\rm rate} \rangle} \frac{d \langle {\rm rate} \rangle}{d T_9}}}^{\text{Reaction rates}} \underbrace{\frac{d T_9}{dt}}_{\text{Hydrodynamics}} \right]$$

For ν-reactions, $\partial \boldsymbol{f} / \partial t$ ~0

Appendix 2: Advanced scheme of finite differentiation

- Many methods for integration of rate equations….

$$\frac{Y(t+\Delta t)-Y(t)}{\Delta t}=(1-\Theta)\dot{Y}(t+\Delta t)+\Theta\dot{Y}(t).$$

- Explicit Euler (Θ=1; 1st-order accurate)

$$\frac{Y(t+\Delta t)-Y(t)}{\Delta t}=\dot{Y}(t).$$

→Unstable for large Δt

- **Implicit Euler (Θ=0; 1st-order accurate) →best**

$$\frac{Y(t+\Delta t)-Y(t)}{\Delta t}=\dot{Y}(t+\Delta t)$$

→Stable for large Δt
→no warranty for accuracy

- Trapezoidal (Θ=1/2; 2nd-order accurate)

→adopted in a BBN code (Kawano 1992)
→not good for astrophysical nucleosynthesis (MK's experience)

Hix & Thielemann, J. Comp. App. Math. 109, 321 (1999)

Appendix 2: Advanced scheme of finite differentiation

- Semi-implicit Euler method

←Solving the implicit method with linearization

$$\mathbf{y}_{n+1} = \mathbf{y}_n + h\mathbf{f}(\mathbf{y}_{n+1})$$

Taylor expansion up to 1st order

$$\mathbf{y}_{n+1} = \mathbf{y}_n + h\left[\mathbf{f}(\mathbf{y}_n) + \left.\frac{\partial \mathbf{f}}{\partial \mathbf{y}}\right|_{\mathbf{y}_n} \cdot (\mathbf{y}_{n+1} - \mathbf{y}_n)\right]$$

$$\mathbf{y}_{n+1} = \mathbf{y}_n + h\underline{\left[\mathbf{1} - h\frac{\partial \mathbf{f}}{\partial \mathbf{y}}\right]^{-1}} \cdot \mathbf{f}(\mathbf{y}_n)$$

Matrix inversion

- Nucleosynthesis calculation →**stiff set of equations**
- **Stiff:** On 2 or more very different scales of the independent variable (t), dependent variables (Y_i) change

→we must set Δt small enough that Y_i evolution is followed properly.

- Variable-order Bader & Deuflhard method to minimize the computation time

(See e.g. Chap. 16 in Numerical Recipes in Fortran 77, 2nd Ed.)

Appendix 3: derivation of inverse matrix

- Easiest one: Gaussian elimination after making a triangularized matrix

$$(A_{ij})[\bar{Y}_j(t)] = [\tilde{Y}_i(t-\Delta t)]$$

$$\Longrightarrow \begin{pmatrix} A'_{11} & A'_{12} & A'_{13} & \cdots & A'_{1n} \\ 0 & A'_{22} & A'_{23} & \cdots & A'_{2n} \\ 0 & 0 & A'_{33} & \cdots & A'_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & A'_{nn} \end{pmatrix} \cdot \begin{pmatrix} \bar{Y}_1 \\ \bar{Y}_2 \\ \bar{Y}_3 \\ \vdots \\ \bar{Y}_n \end{pmatrix} = \begin{pmatrix} \tilde{Y}'_1 \\ \tilde{Y}'_2 \\ \tilde{Y}'_3 \\ \vdots \\ \tilde{Y}'_n \end{pmatrix} \Longrightarrow$$

$$\bar{Y}_n = \tilde{Y}'_n / A'_{nn}$$

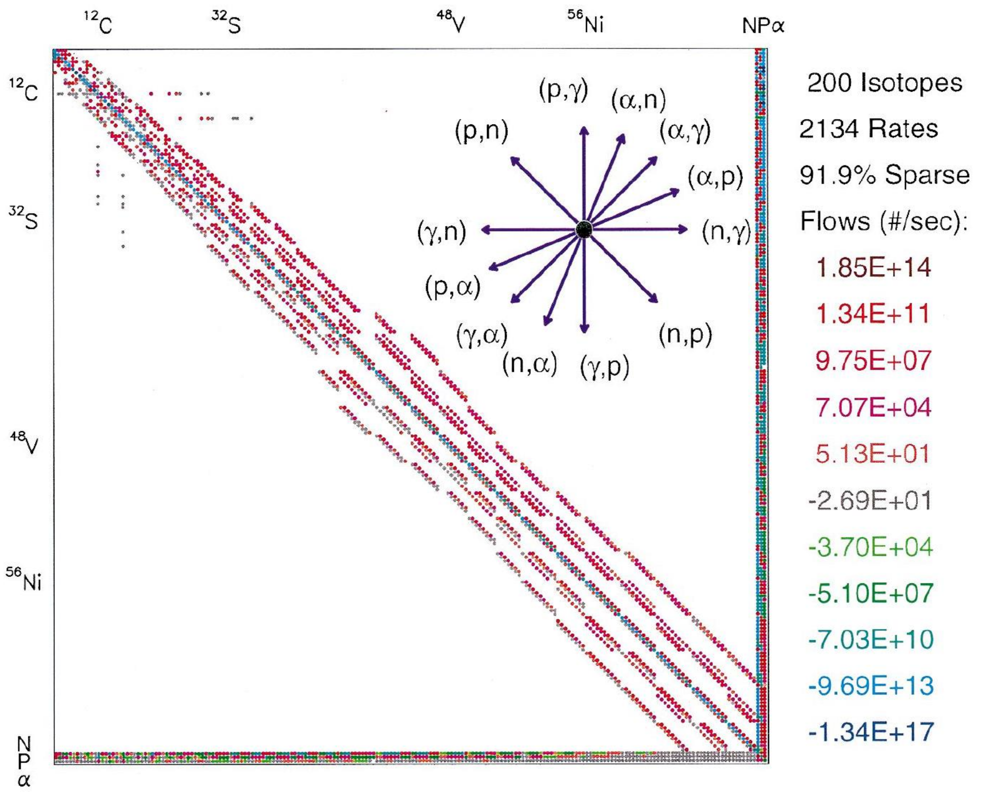
$$\bar{Y}_i = \frac{1}{A'_{ii}} \left[\tilde{Y}'_i - \sum_{j=i+1}^{N} A'_{ij} \bar{Y}_j \right]$$

- Save time with better techniques
  →sparse matrix solver

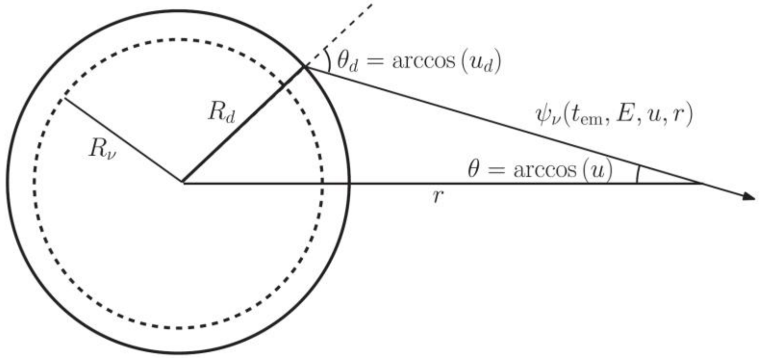
dense:
[LAPACK, LUDCMP, LEQS, GIFT]
Sparse:
[MA28, UMFPACK, Y12M]

Timmes, ApJS 124, 241 (1999)

MA38 is used in our code:
MK et al. ApJ 872, 164 (2019)



9. Effect of ν collective oscillation



$$i\frac{d\psi_\nu}{dt} = (H_{\rm v} + H_e + H_\nu)\psi_\nu(t_{\rm em}, E, u, r),$$

$$H_{\rm v} = U\frac{M^2}{2E}U^\dagger, \qquad (6a)$$

$$H_e = \sqrt{2}G_F \underline{n_e(r)}{\rm diag}(1,0,0), \qquad (6b)$$

electron # density

$$H_\nu = \sqrt{2}G_F\sum_\alpha\int dE'd\Omega'(1-\underline{uu'})$$

Angles of neutrinos

$$\times\left[\frac{d^2n_{\nu_\alpha}}{dE'd\Omega'}\rho_{\nu_\alpha}(t'_{\rm em}, E', u', r) - \frac{d^2n_{\bar\nu_\alpha}}{dE'd\Omega'}\rho^*_{\bar\nu_\alpha}(t'_{\rm em}, E', u', r)\right].$$

density of ν

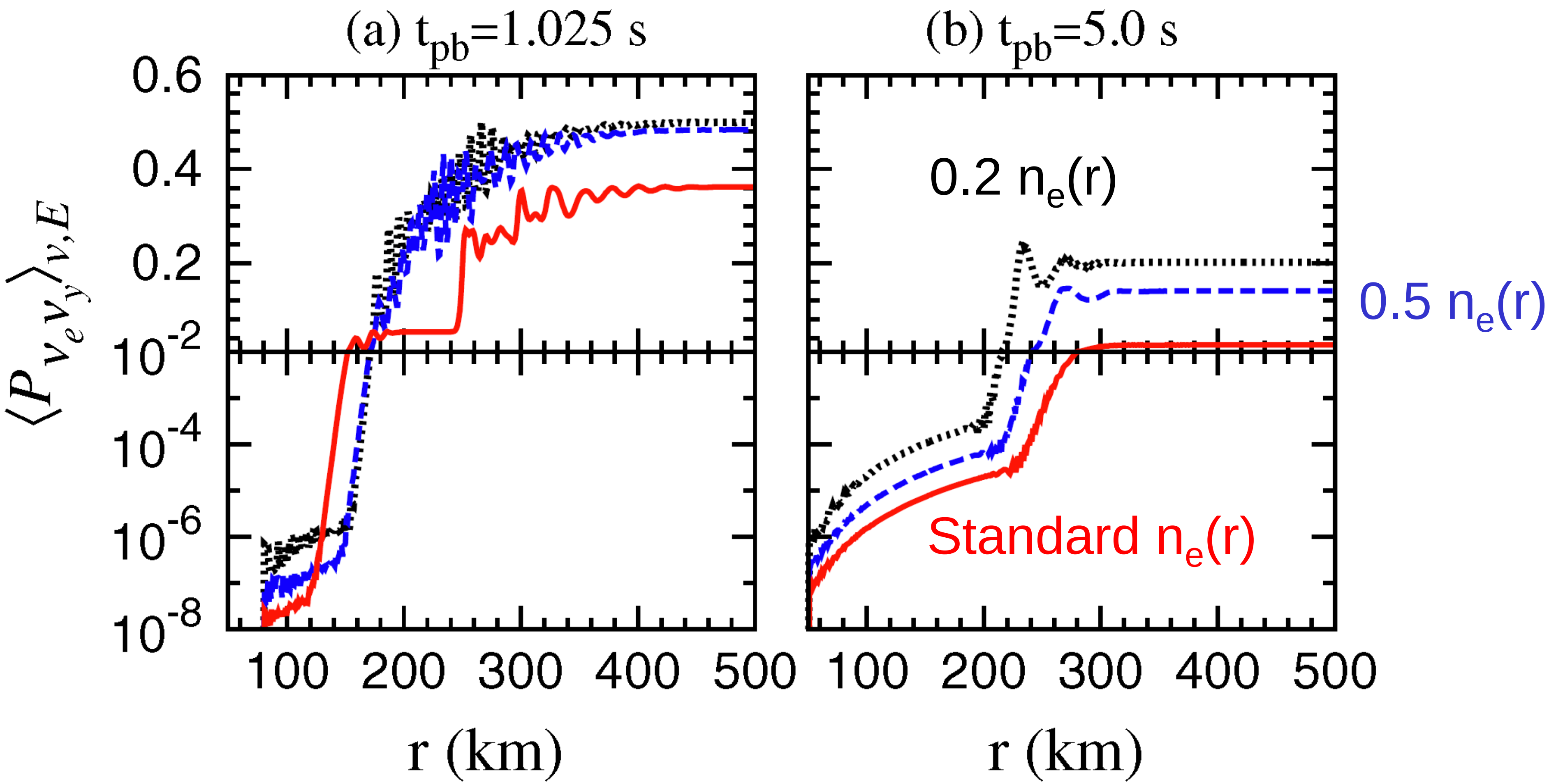
density of $\bar{\nu}$

- ➢ν spectra are changed
  - →reaction rates of ν-process (^{7}Li, ^{11}B, ^{138}La, ^{180}Ta, …) are affected (Wu et al, PRD 91, 065016, 2015)
- ➢ For analysis with collision terms, Hansen & Smirnov, JCAP 04 (2018) 057

Effect of ν collective oscillation 2

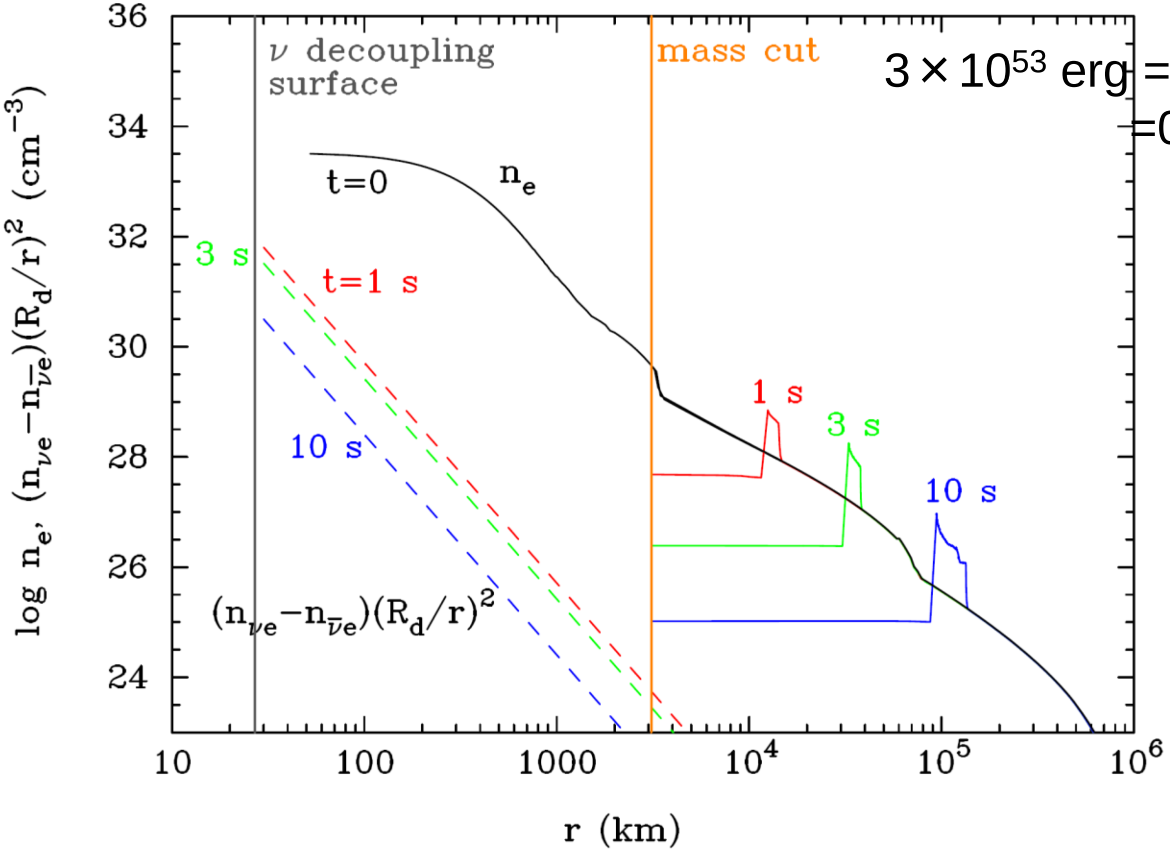
- Small n_e →large self-interaction effect
- Large t →luminosity decreases →small self-interaction effect

(Wu et al, PRD 91, 065016, 2015)



$$(|\nu_e\rangle, |\nu_x\rangle, |\nu_y\rangle)^T = R_{23}^{-1}(\theta_{23})(|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle)^T, \qquad v \equiv u_d^2$$

On effect of ν collective oscillation



3×10^{53} erg $=1.87\times10^{56}$ GeV

$=0.168\ M_\odot$

- How small can the inner electron density can become?

  →if $n_e \le n_\nu^{eff}$, the collective oscillation is effective

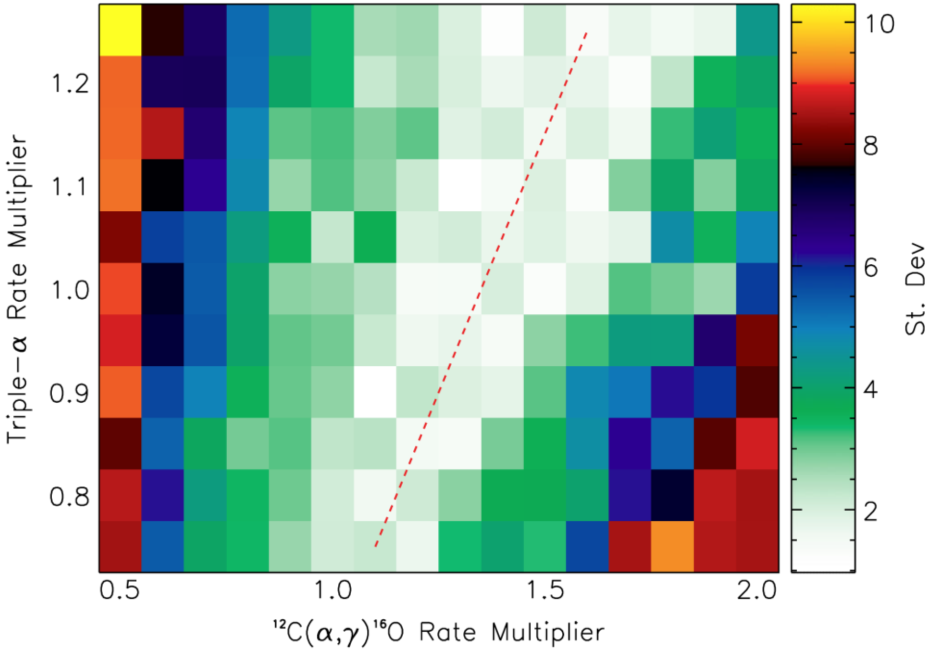
- (H. Sasaki, priv. comm.) the ν self interaction does not always change flavors depending on the density profile

Effect of 3α & $^{12}C(\alpha,\gamma)$ via stellar nucleosynthesis 1

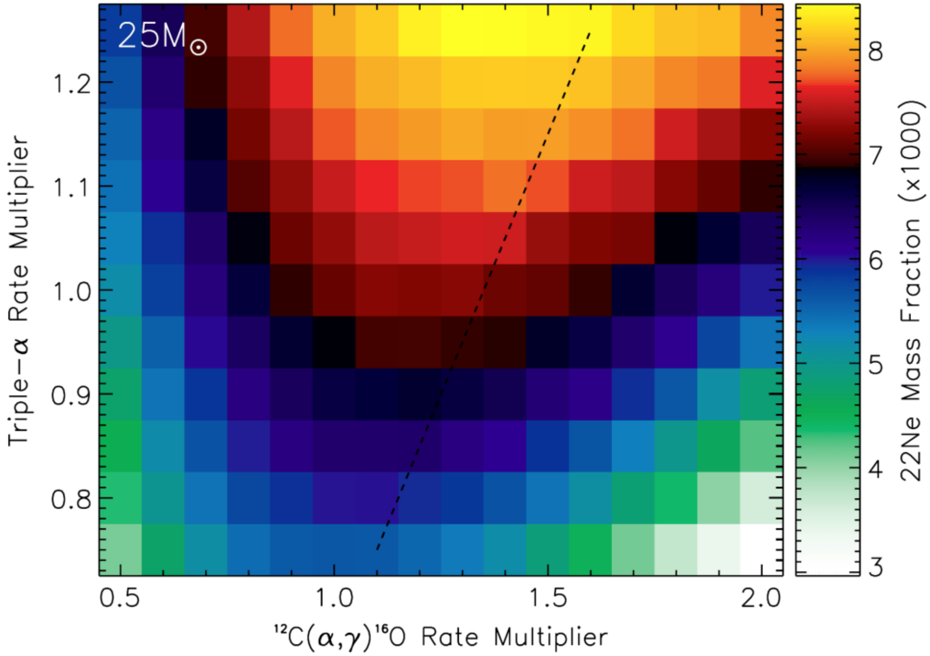
- Constraint from IMF averaged production factors of
  intermediate-mass $^{16,18}O$, ^{20}Ne, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca
  s-only nuclei (^{70}Ge, ^{76}Se, $^{80,82}Kr$, $^{86,87}Sr$)

(Austin, West, Heger, PRL 112, 111101, 2014)

Deviation derived from overproduction factors



Amount of ^{22}Ne after the core He burning of 25 $M_\odot$ star



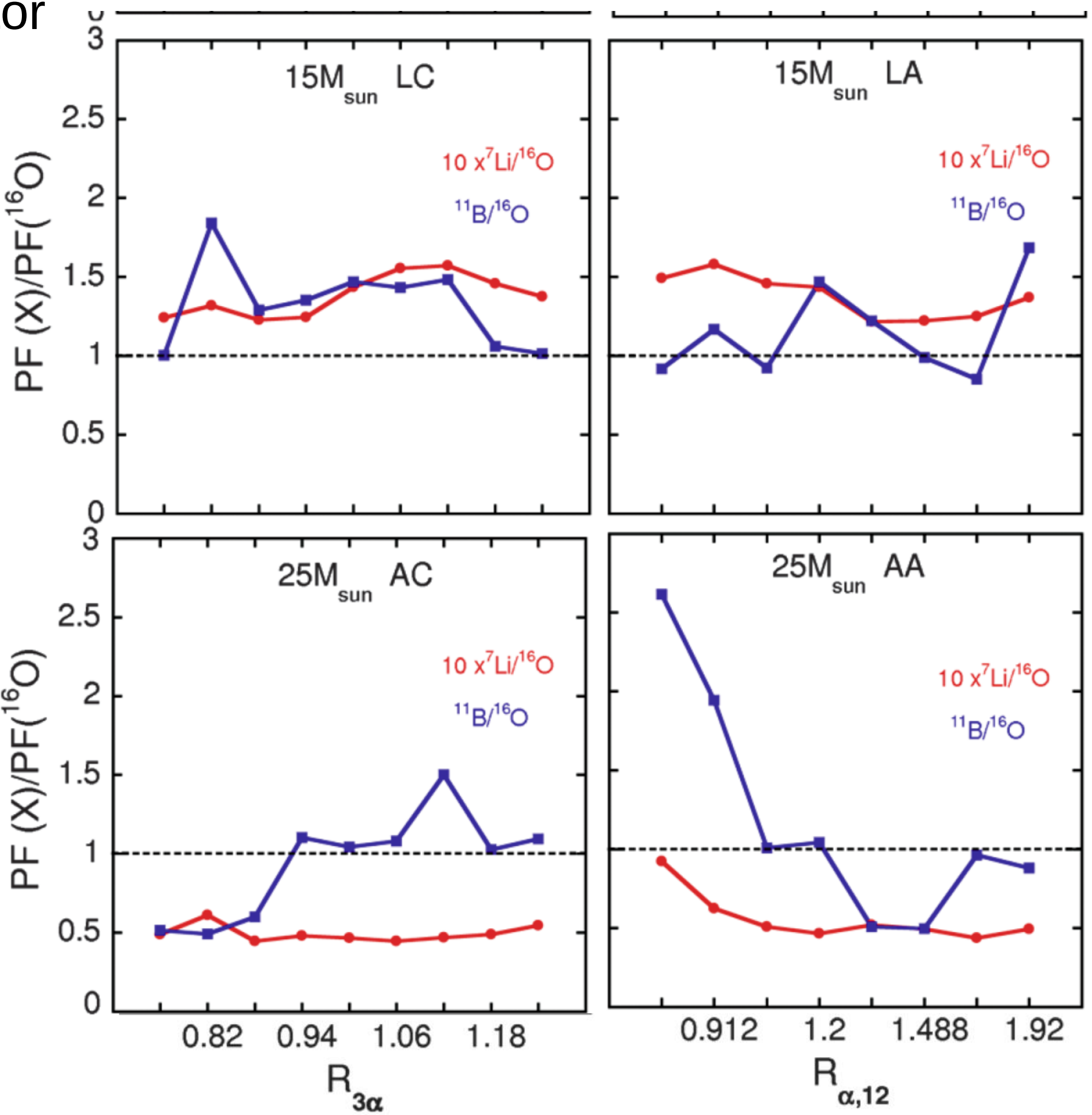
- Variations in reaction rates are constrained

Effect of 3α & $^{12}C(\alpha,\gamma)$ via stellar nucleosynthesis 1

- Uncertainties in reaction rates affect ^{11}B abundance by a factor of ≤2

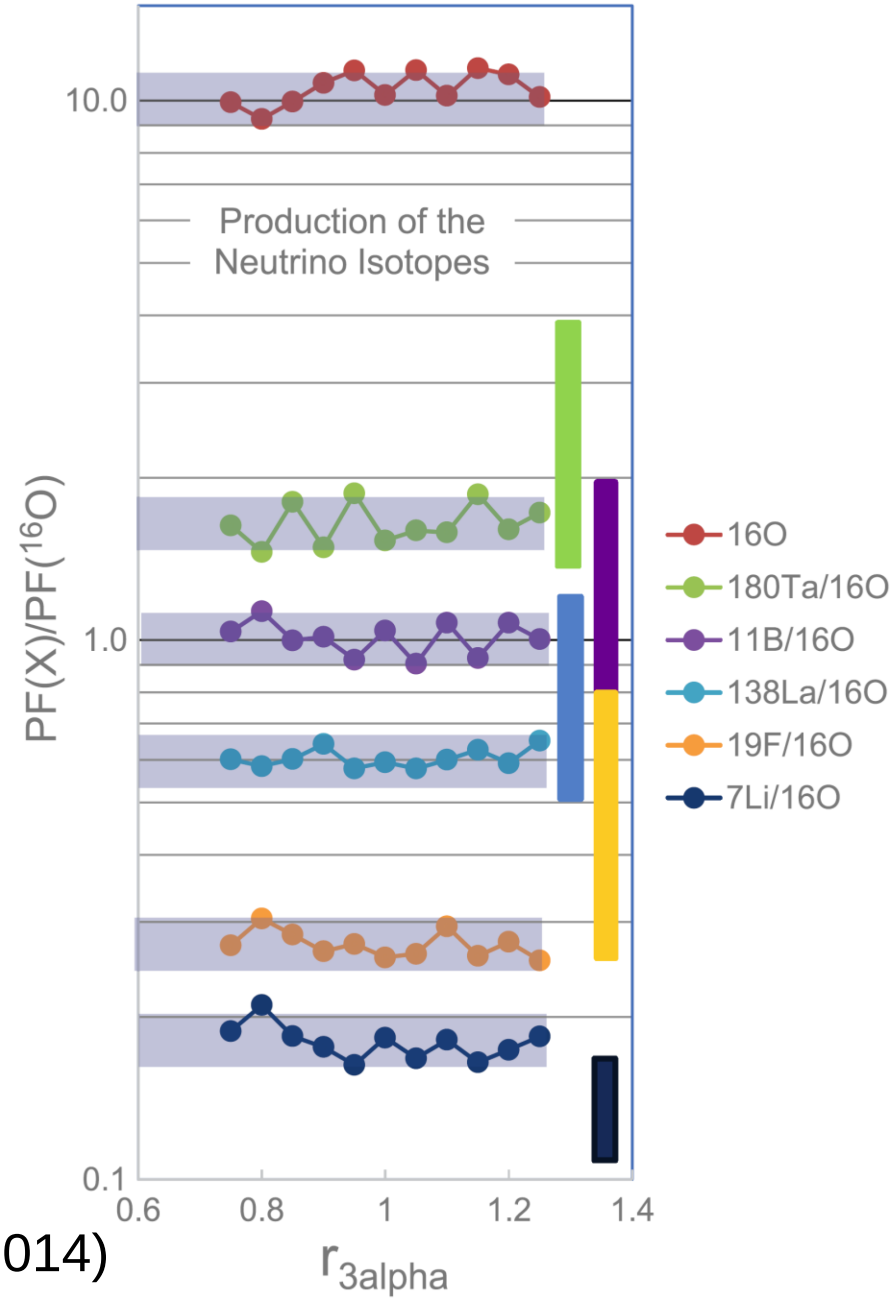
- 3α (Caughlan & Fowler , 1988)
- $^{12}C(\alpha,\gamma)$ (Buchmann, 1996)
- 2 σ uncertainties

(Austin, Heger, Tur, PRL 106, 152501, 2011)



Effect of 3α & $^{12}C(\alpha,\gamma)$ via stellar nucleosynthesis 2

- Along the minimum deviation line:
- 2 σ uncertainty
  → Li and B abundances change by about 10 %



(Austin, West, Heger, PRL 112, 111101, 2014)

Backup 2

Effects of neutrinos on supernovae (SNe)

- Neutrino flavors (e, μ, τ) changes during propagation
  until an overlap of wave packets is lost

- ν spectra determine the n/p ratio →suppression of the r-process

- ν-spallation of ^{4}He produces neutrons →mini r-process in outer He shell

- ν-nuclear reactions produce rare nuclei
  →possible constraints from elemental abundances
  "production of ^{7}Li, ^{11}B, & ^{98}Tc"

Topic I. n/p ratio in SNe

- ν-driven wind →n/p ratio is low (Balantekin & Yüksel, ., New J. Phys. 7, 51, 2005)

n↔p conversion via

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + \mathrm{e}^-$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + \mathrm{e}^+$$ ← endoergic

$$\langle E_{\nu_e} \rangle \leqslant \langle E_{\bar{\nu}_e} \rangle \leqslant \langle E_{\nu_x, \bar{\nu}_x} \rangle$$ energetic

$$\frac{\mathrm{d}X_p}{\mathrm{d}t} = -\underbrace{(\lambda_{\bar{\nu}_e} + \lambda_{e^-})}_{}X_p + \underbrace{(\lambda_{\nu_e} + \lambda_{e^+})}_{}X_n$$

Mass fraction $X_j = \frac{N_j A_j}{\sum_i N_i A_i}$

Mole fraction $Y_j = \frac{X_j}{A_j} = \frac{N_j}{\sum_i N_i A_i}$

$$Y_e = (n_{e^-} - n_{e^+})/n_B$$

$\mathrm{d}Y_e/\mathrm{d}t = \mathrm{d}X_p/\mathrm{d}t$ ←ν effect on α is small due to tight binding

$$\frac{\mathrm{d}Y_e}{\mathrm{d}t} = \lambda_n - (\lambda_p + \lambda_n)Y_e + \frac{1}{2}(\lambda_p - \lambda_n)X_\alpha \quad X_p + X_n + X_\alpha = 1$$

➡ $$Y_e = \frac{\lambda_n}{\lambda_p + \lambda_n} + \frac{1}{2}\frac{\lambda_p - \lambda_n}{\lambda_p + \lambda_n}X_\alpha$$

- **ν-spectra affect Y_e → Y_e determines the r-process**
- High n/p for heavy r-nuclei →difficult

  →less-ν condition (neutron star mergers…)

Topic II. ν-induced n-capture in He shell

- Core-collapse supernovae with $Z \lesssim 10^{-3} Z_\odot$, M_{ZAMS} ~11-15 $M_\odot$
- Neutrinos from ^{4}He($\bar{\nu}_e$,e$^+$n)^{3}H in He shells → production of nuclei with A~200

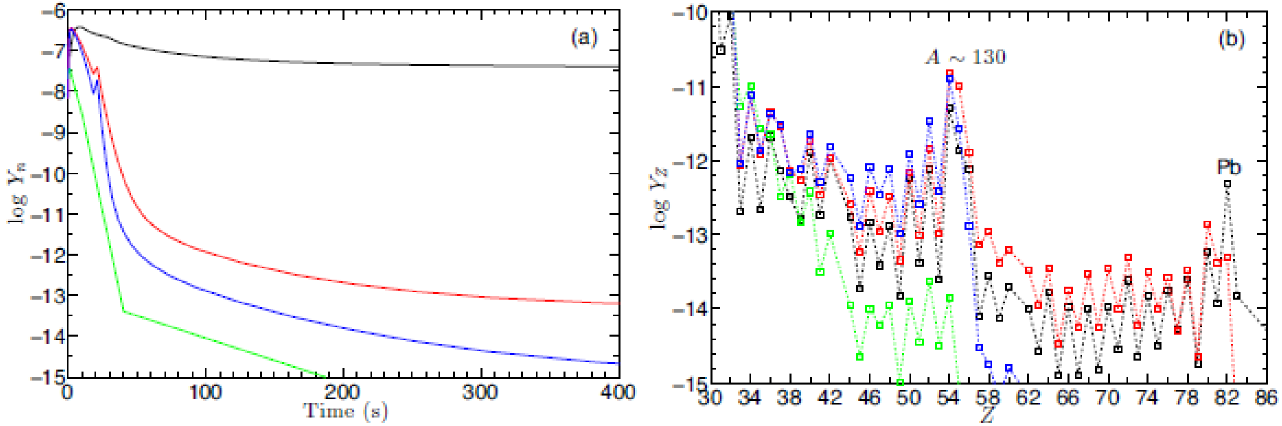


Figure 1. (a) Evolution of neutron abundance Y_n with time for a typical zone in the outer He shell for y11$\bar{\mathrm{H}}$.1 (*black*), u11*$\bar{\mathrm{H}}$.1 (*red*), u11$\bar{\mathrm{H}}$.1 (*blue*), and v11$\bar{\mathrm{H}}$.1 (*green*). (b) Final elemental abundance pattern produced by y11$\bar{\mathrm{H}}$.1 (*black*), u11*$\bar{\mathrm{H}}$.1 (*red*), u11$\bar{\mathrm{H}}$.1 (*blue*), and v11$\bar{\mathrm{H}}$.1 (*green*).

Table 1. Yields of Be, Sr, and Ba in $M_\odot$ [$X(Y) \equiv X \cdot 10^Y$] and the corresponding [Sr/Ba] with log (Sr/Ba)$_\odot$ = 0.70

Model	Be	Sr	Ba	[Sr/Ba]
y11$\bar{\mathrm{H}}$.1	1.48(−8)	3.02(−10)	1.14(−9)	−1.09
y11$\bar{\mathrm{H}}$.3	7.90(−9)	2.35(−10)	3.21(−10)	−0.65
y15$\bar{\mathrm{H}}$.1	1.07(−8)	3.43(−11)	1.05(−10)	−1.00
y15$\bar{\mathrm{H}}$.3	1.01(−9)	6.91(−11)	1.40(−10)	−0.82
u11*$\bar{\mathrm{H}}$.1	1.20(−8)	6.50(−10)	1.87(−9)	−0.97
u11*$\bar{\mathrm{H}}$.3	2.48(−9)	5.70(−10)	1.90(−9)	−1.03
u15*$\bar{\mathrm{H}}$.1	2.44(−9)	1.32(−10)	4.86(−11)	−0.08
u15*$\bar{\mathrm{H}}$.3	8.46(−10)	1.22(−10)	9.50(−11)	−0.40
u11$\bar{\mathrm{H}}$.1	2.72(−9)	5.99(−10)	1.95(−10)	−0.02
u11$\bar{\mathrm{H}}$.3	7.13(−10)	4.92(−10)	1.84(−10)	−0.09
u15$\bar{\mathrm{H}}$.1	9.92(−10)	2.18(−10)	3.27(−12)	1.31
u15$\bar{\mathrm{H}}$.3	2.23(−10)	3.34(−10)	7.33(−12)	1.14

- ✓ ^{9}Be production (Banerjee et al. PRL 2013)
- ✓ ``mini-r process" ^{7}Li(n,γ)^{8}Li(n,γ)^{9}Li(,e$^-\bar{\nu}_e$)^{9}Be

Banerjee, Qian, Heger, Haxton,
EPJ Web. Conf. 109, 06001 (2016)

Topic III. mixing between He and C, O, Ne shells

- ^{4}He+ν reactions for the weak r-process nuclei with A $\lesssim$ 130
- Convective mixing assumed during the core-collapse

  →large effects for low Z stars if He is moved down to r $\lesssim 10^9$ cm

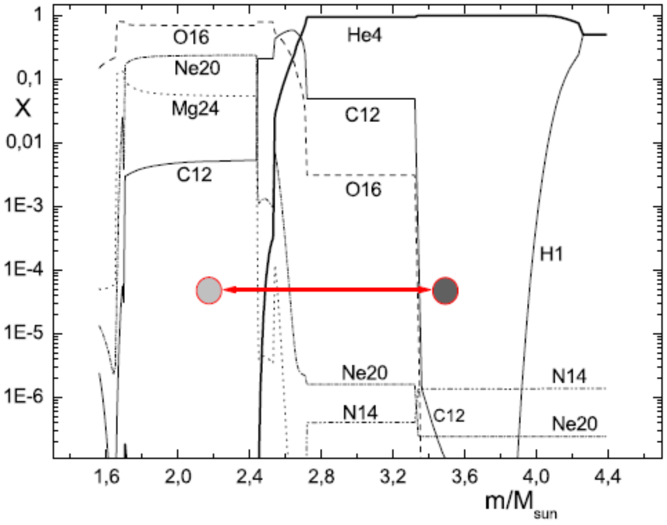


Figure 1. The composition of the He and C–O–Ne shells of a 15 M$_\odot$ low-metallicity (0.0001 Z$_\odot$) pre-supernova model from Woosley et al. (2002).

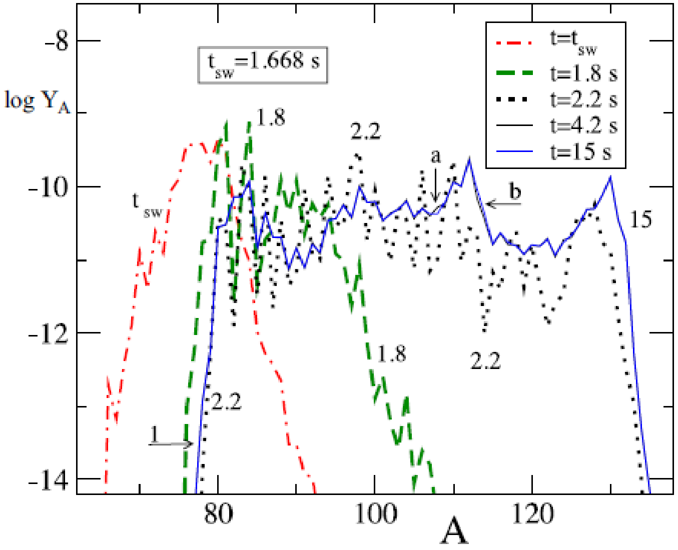


Table 2. The neutrino–nuclear interactions and their mean cross-sections per target nucleus.

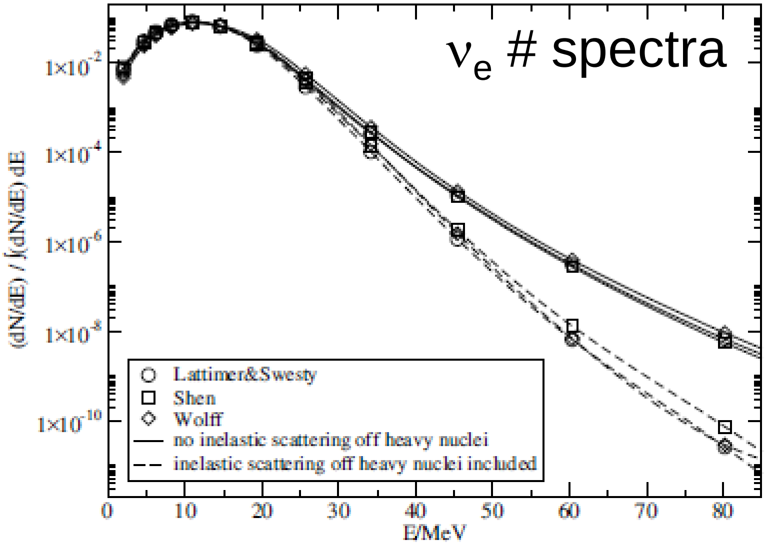
Reaction	Mean cross-section $\langle\sigma_{A\nu}\rangle$ (10^{-42} cm^2)
^{4}He(ν, ν' n)^{3}He	0.403
^{4}He(ν, ν' p)^{3}H	0.441
^{12}C(ν, ν' n)^{11}C	0.512
^{12}C(ν, ν' p)^{11}B	1.86
^{12}C(ν, ν' ^{3}He)^{9}Be	0.0024
^{13}C(ν, ν' α)^{9}Be	0.714
^{14}N(ν, ν' α)^{10}B	0.312
^{16}O(ν, ν' n)^{15}O	0.747
^{16}O(ν, ν' p)^{15}N	2.68
^{20}Ne(ν, ν' n)^{19}Ne	1.05
^{20}Ne(ν, ν' p)^{19}F	7.31
p($\bar{\nu}_e$, e$^+$)n	9.70

Nadyozhin & Panov, MNRAS 441, 733 (2014)

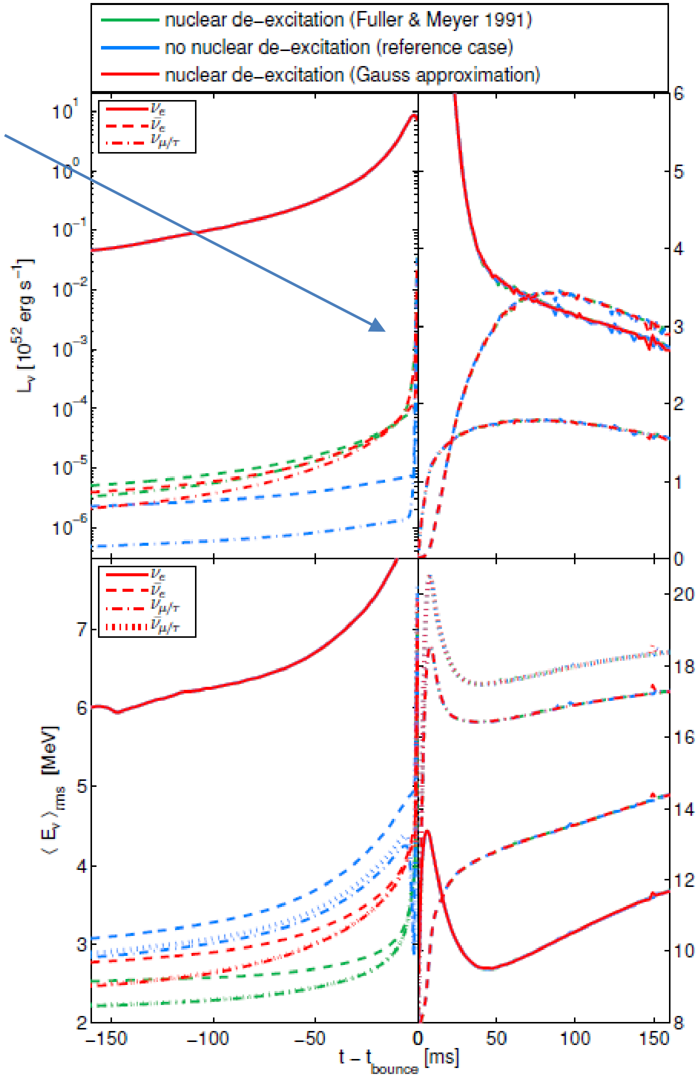
Topic IV. ν-spectra of SNe

- during the collapse, **de-excitation via ν-pair production** is the dominant source of ν_e, ν_x
- N-N bremsstrahlung is a strong source of $\bar{\nu}_e$, ν_x

- **Inelastic ν-scattering off nuclei**
  - →energy loss of high E neutrinos
  - →event rates can be reduced by up to 50 % for NC ^{16}O spallation in Super-K



Langanke et al., PRL 100, 011101 (2008)



Fischer et al., PRC 88, 065804 (2014)