Li, Be, and B Production in Core-Collapse SNe

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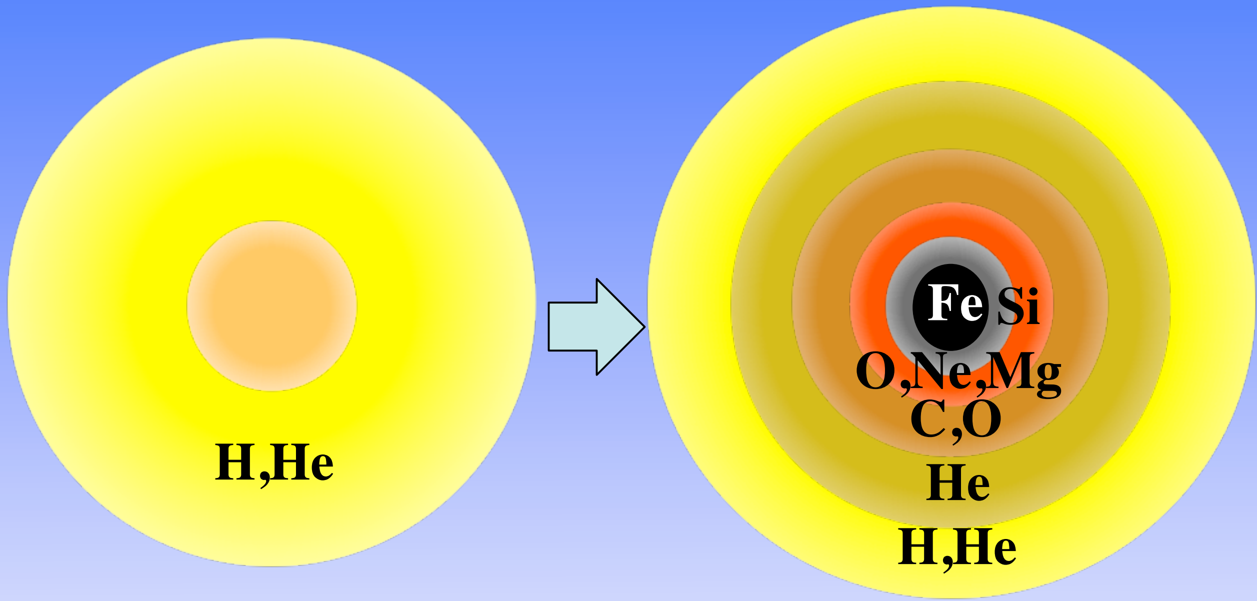
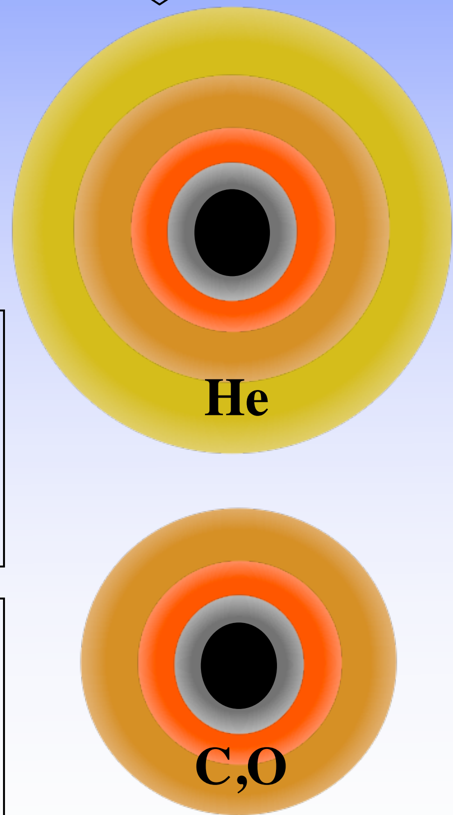
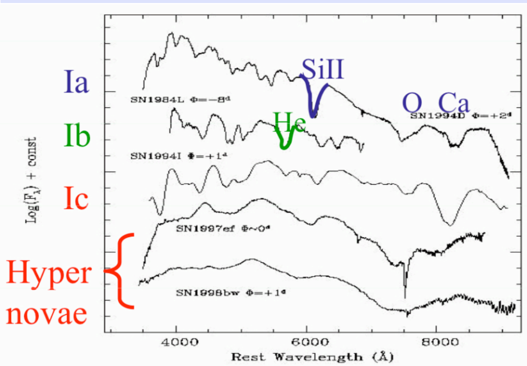
Type of core-collapse SNe



Stellar wind
or
binary effect





(Mazzali)

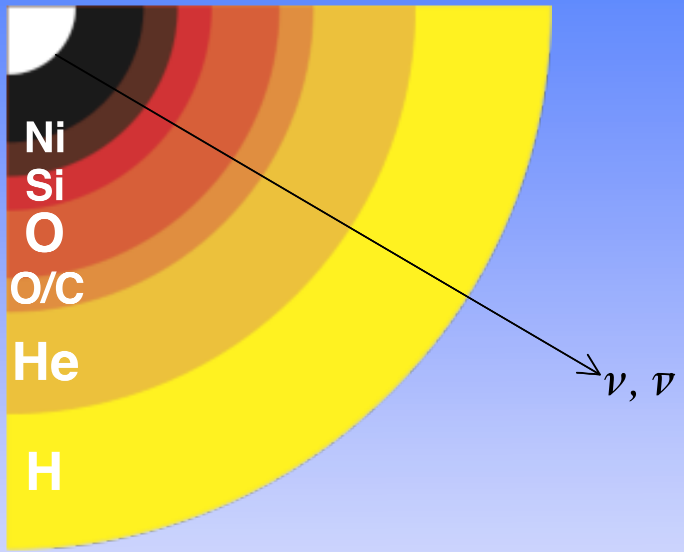
Type II (with H line)

- SN 1987A
- v ～ a few × 1,000 km/s

Type Ib/Ic (without H/He line)

- SN 1984L (Ib); 94I, 98bw (Ic)
- v > 10,000 km/s
- associated with GRB/HN

Neutrinos

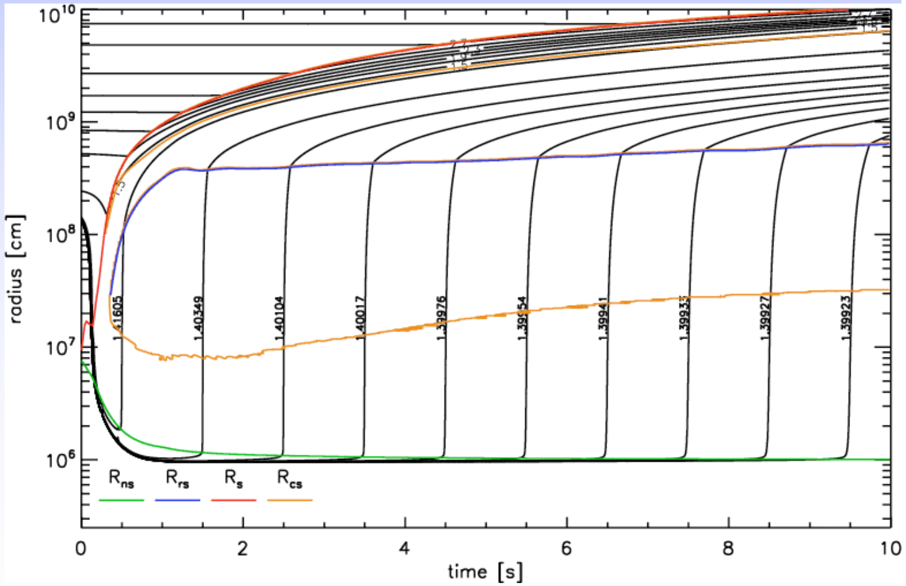


- $\nu_e, \bar{\nu}_e, \nu_{\mu\tau} = (\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

  $\langle \varepsilon_{\nu e} \rangle < \langle \varepsilon_{\bar{\nu} e} \rangle < \langle \varepsilon_{\nu\mu\tau} \rangle$
- emitted from the central remnant
- hardly interact with materials
- carry away almost all (99%) energy

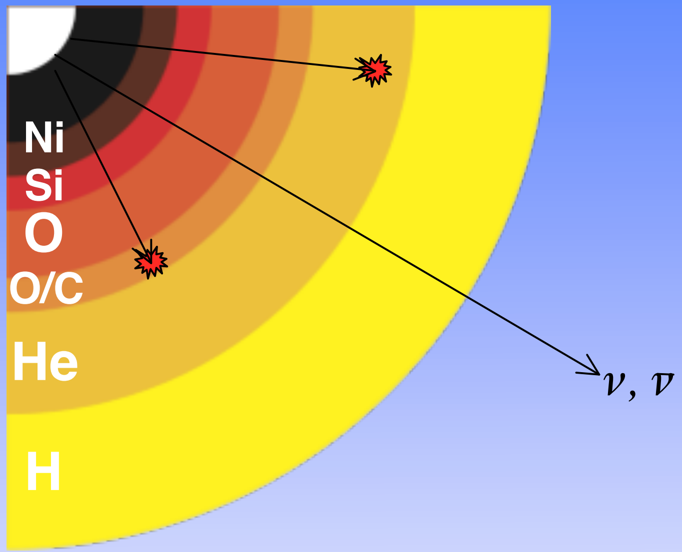
Neutrino - material interactions

- Simulations have failed to explode SNe
- Neutrinos may supply energy with stalled shock
- AND…



Arcones, Janka, & Scheck, 2007

Neutrino-induced nucleosynthesis



- Huge number of neutrinos ($>10^{58}$!)
- Some interact with materials and induce nucleosynthesis

  => The ν-process (Woosley+ 1990)
- ^{7}Li in He layer & ^{11}B in C layer

➢ The ν-process

- Neutral current reaction:

  $(Z, A) + \nu \rightarrow (Z\text{-}1, A\text{-}1) + \nu' + p$

  $(Z, A) + \nu \rightarrow (Z, A\text{-}1) + \nu' + n$

- Charged current reaction:

  $(Z, A) + \nu_e \rightarrow (Z+1, A) + e^-$

  $(Z, A) + \bar{\nu}_e \rightarrow (Z\text{-}1, A) + e^+$

- Boron production

  $^{12}C(\nu, \nu' n)^{11}C$, $^{12}C(\nu, \nu' p)^{11}B$

  $^{12}C(\nu_e, e^- p)^{11}C$, $^{12}C(\bar{\nu}_e, e^+ n)^{11}B$

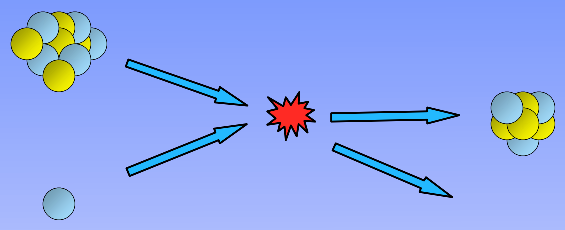
  ↓

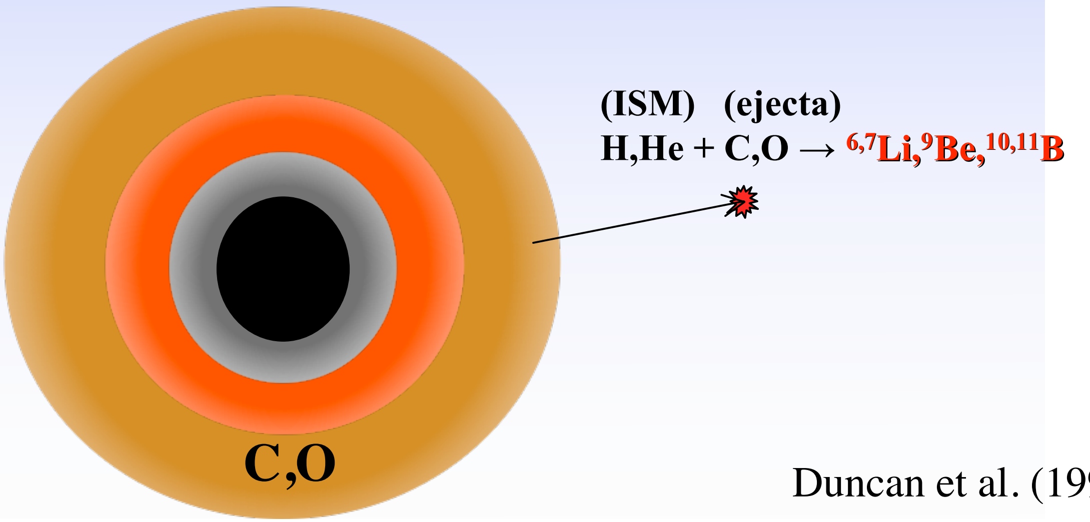
  ^{11}B in 20 min.

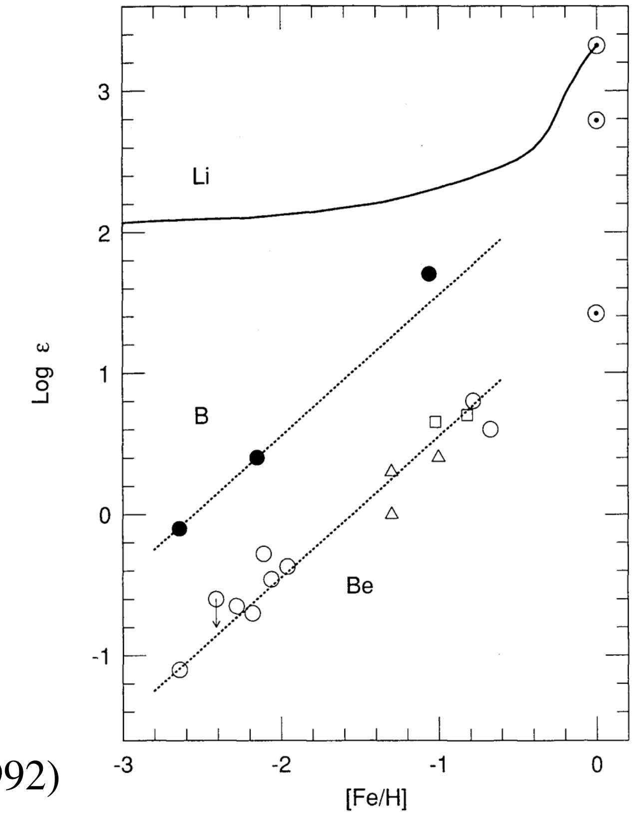
Spallation reactions around CCSNe

- Spallation production of **LiBeB**
- Outermost layers of SNe Ib/c are accelerated to v > 10,000 km/s (5 MeV/A).
- Ejected **C,O** into the interstellar matter (**H,He**) produce **LiBeB** via spallations.
- Fields+ 96,02 ; KN+ 04,06
- This mechanism does not conflict with observational trends of **Be** and **B**.

H,He + C,N,O → ^{6,7}Li, ^{9}Be, ^{10,11}B







Duncan et al. (1992)

Calculations: SN Ic explosion

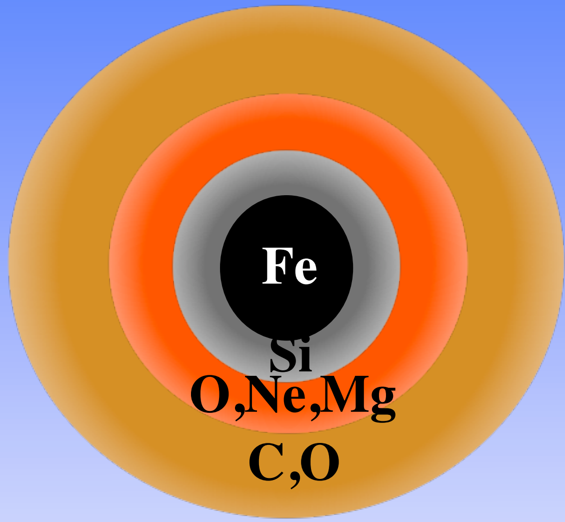
- Progenitor model:
  - SN 1998bw model (Nakamura+ 01)
    WR type (C/O) star
    M=15$M_\odot$, E_{ex}=3×10^{52} erg
- Numerical code:
  - 1-dimensional hydrodynamic code
  - effects of special relativity
- Equations: (KN & Shigeyama 2004)
  - Relativistic hydrodynamic eq.

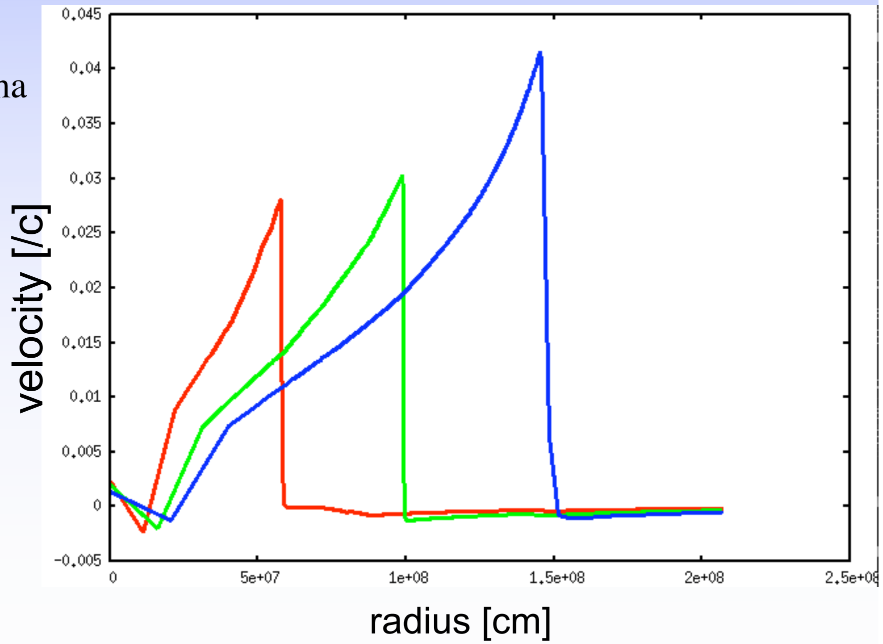
$$\partial_\mu \left(\rho v^\mu \right) = 0$$

$$\partial_\mu T^{\nu\mu} = 0$$

  - EOS

$$p = \frac{a}{3} T^4 + \frac{k\rho T}{\mu m_H}$$





Calculations: the ν-process

- Neutrino luminosity (Woosley+ 90) :

$$L_{\nu i}(t) \propto \frac{E_\nu}{\tau_\nu} \exp\left(-\frac{t - r/c}{\tau_\nu}\right)$$

$$\nu_i : \nu_{e\mu\tau}, \bar{\nu}_{e\mu\tau}$$

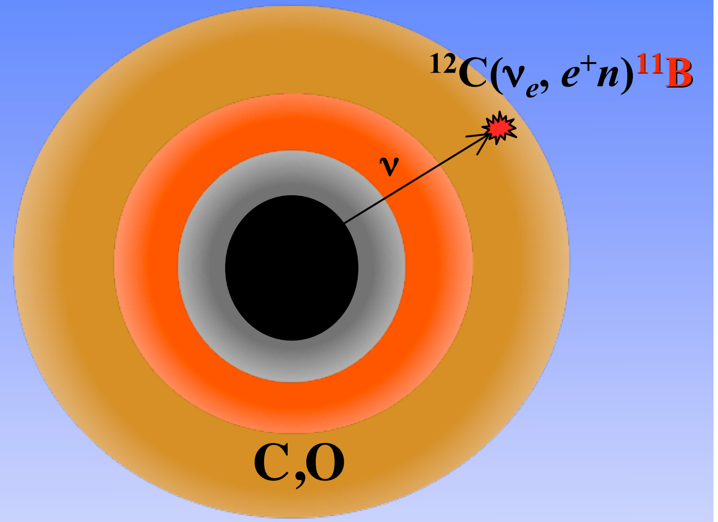
- decay time: $\tau_\nu = 3$ s
- total neutrino energy: $E_\nu = 3\times 10^{53}$ ergs
- Energy spectra:

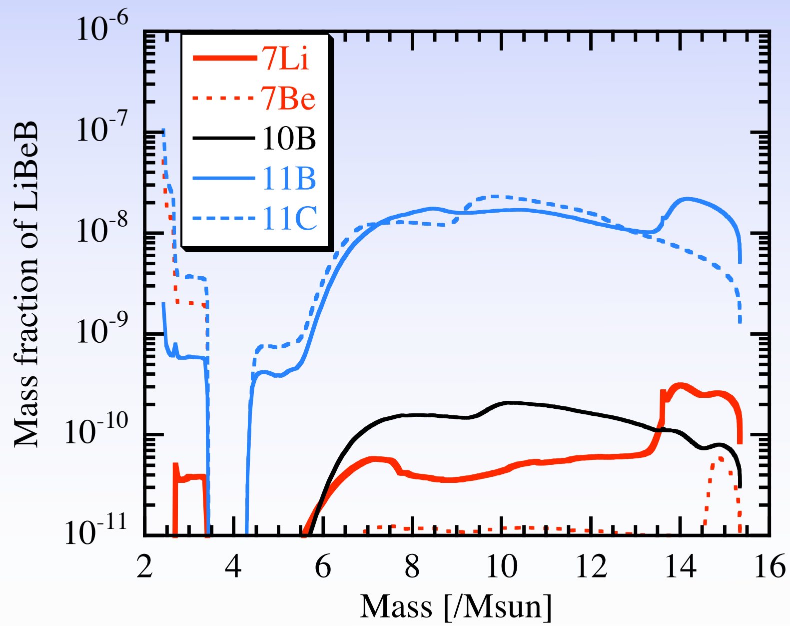
$(kT\nu_e, kT\bar{\nu}_e, kT\nu_{\mu\tau}) =$

(3.2, 5, 6) MeV <= normal $T\nu_{\mu\tau}$

(3.2, 5, 8) MeV <= high $T\nu_{\mu\tau}$

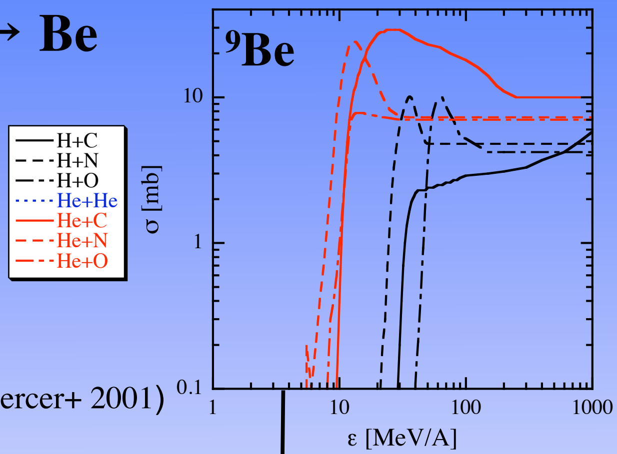
- Using nuclear reaction network consisting of 291 species of nuclei



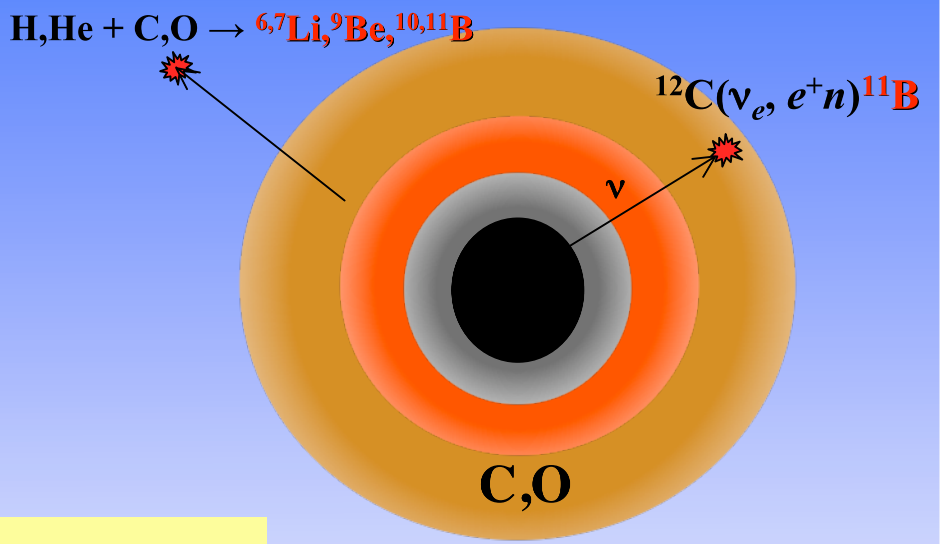


Calculations: spallation reactions

ex.) **O+H → Be**



Cross sections
(Read & Viola 1984; Mercer+ 2001)



$$\frac{dN_{Be}}{dt} = n_H \int \sigma^{Be}{}_{O,H}(E) \frac{F_O(E,t)}{A_O m_H} v_O(E)\, dE$$

number density of target (**H**) in ISM

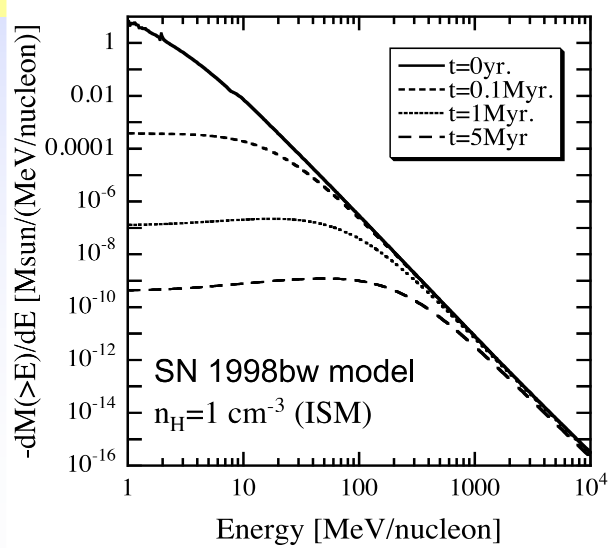
number of ejecta (**O**) with energy ***E*∽*E*+*dE*** at time ***t***

Transport equation

$$\frac{\partial F_i(E,t)}{\partial t} = \frac{\partial[\omega_i(E) F_i(E,t)]}{\partial E} - \frac{F_i(E,t)}{\Lambda} \rho v_i(E)$$

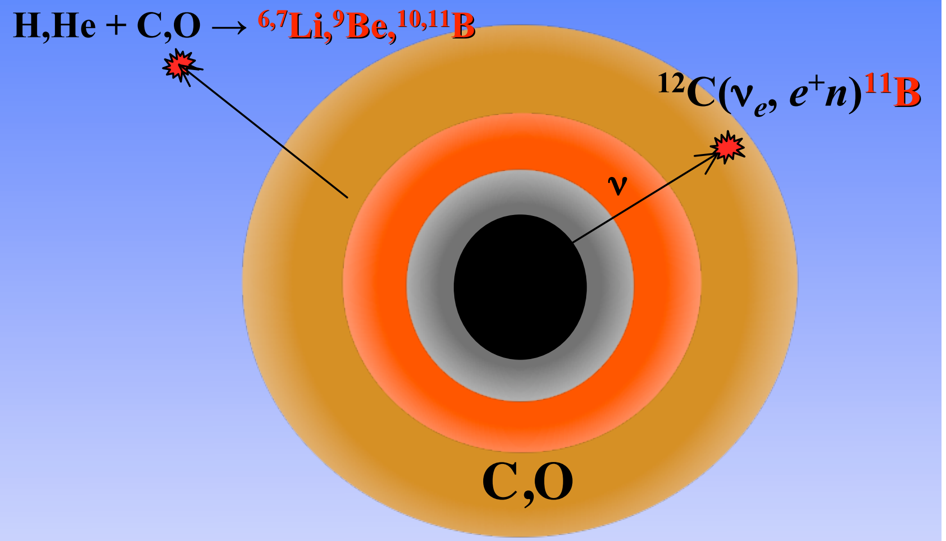
ω_i : energy loss rate (ionization)

Λ : loss length (spallation & escape)



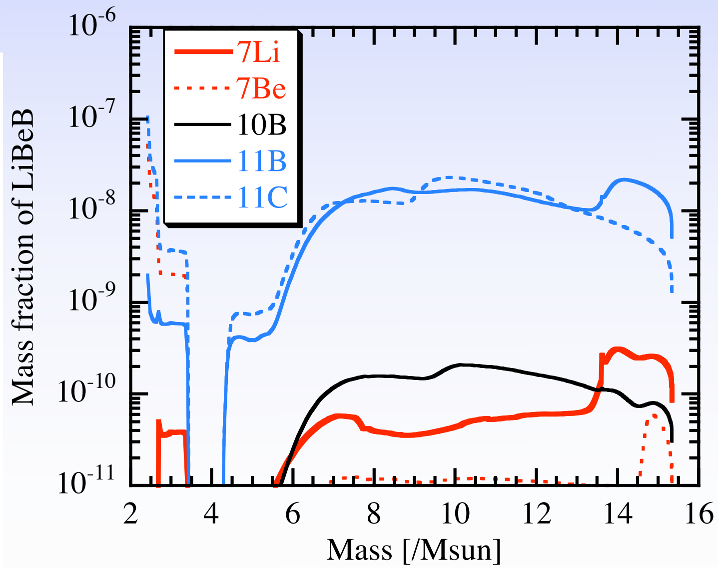
Results

- **LiBeB** from the ν-process
  - plenty of ^{11}**B**
  - production in **C**-rich layers
  - … and in the innermost region (including ^{7}**Li** !)
  - more **LiBeB** in high $T\nu_{\mu\tau}$ model



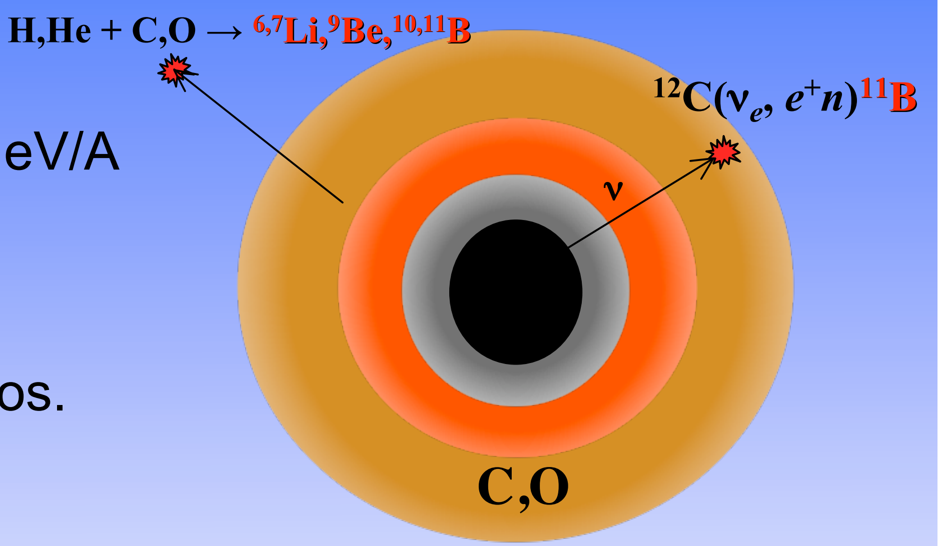
Light Element Yields from SN Ic Model

Species	Normal $T_{\nu_{\mu,\tau}}$ ($M_\odot$)	High $T_{\nu_{\mu,\tau}}$ ($M_\odot$)	Spallation ($M_\odot$)
^{6}Li	1.67×10^{-11}	5.91×10^{-11}	2.38×10^{-7}
^{7}Li	7.41×10^{-9}	2.50×10^{-8}	3.31×10^{-7}
^{9}Be	4.49×10^{-11}	1.08×10^{-10}	9.99×10^{-8}
^{10}B	1.29×10^{-9}	2.78×10^{-9}	4.38×10^{-7}
^{11}B	2.69×10^{-7}	5.46×10^{-7}	1.34×10^{-6}



Results

- **LiBeB** from spallations
  - 0.03$M_\odot$ of ejecta attain E > 10 MeV/A
  - plenty of **LiBeB**
  - predominantly from **O** spallation
  - cross sections determine the ratios.



LIGHT ELEMENT YIELDS FROM SN IC MODEL

Species	Normal $T_{\nu_{\mu,\tau}}$ ($M_\odot$)	High $T_{\nu_{\mu,\tau}}$ ($M_\odot$)	Spallation ($M_\odot$)
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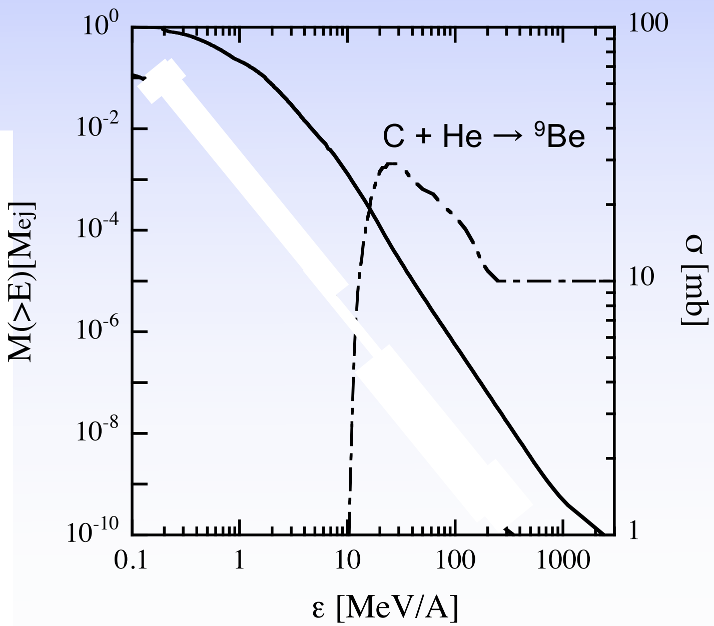
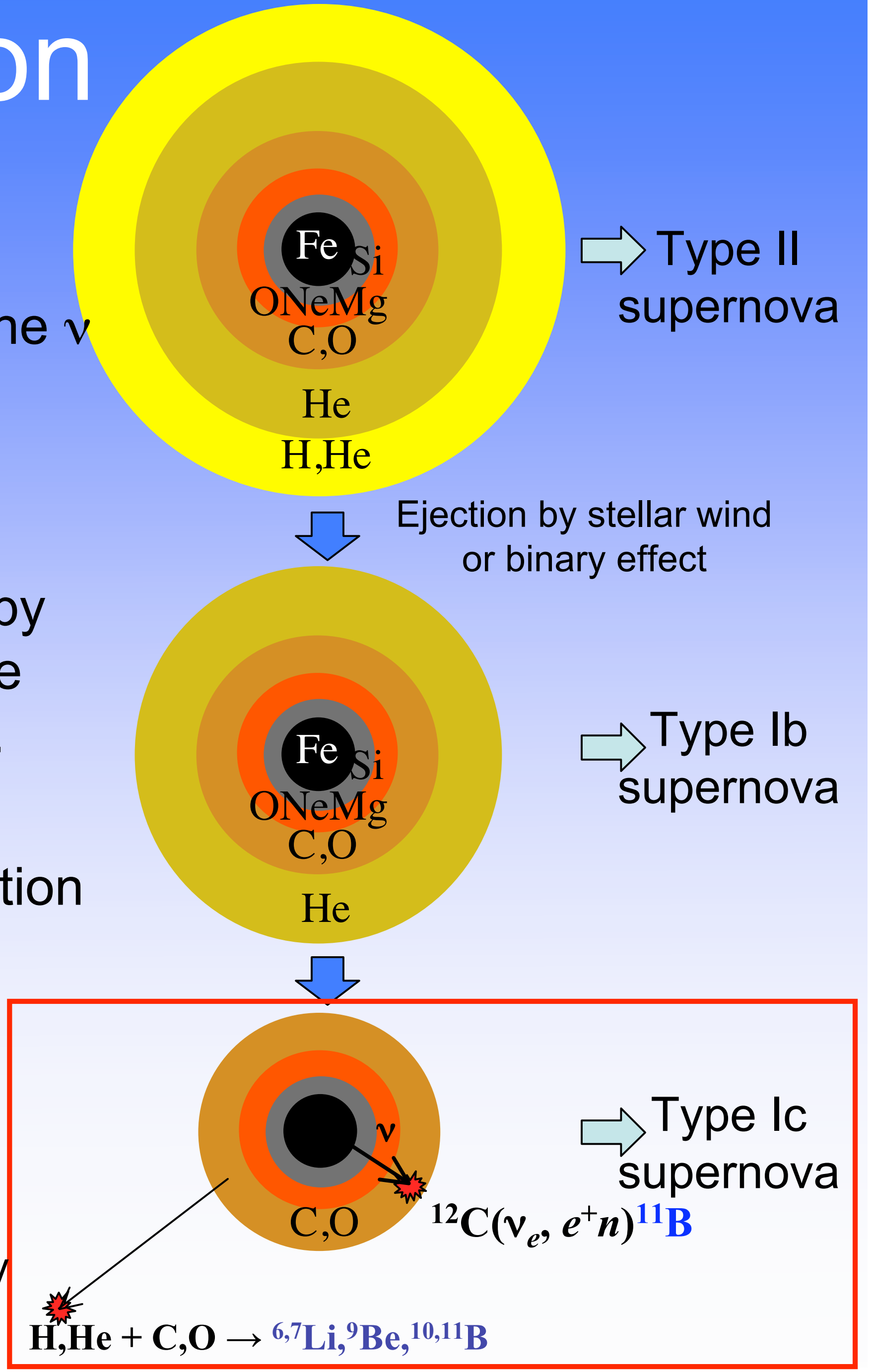


Summary/Discussion

- SNe Ic : a class of CCSNe
- We investigated LiBeB production via the ν -process and spallations in SNe Ic.
- The ν-process synthesizes ^{11}B in C/O layer.
- The outermost C/O nuclei accelerated by explosion interact with ISM and produce $^{6,7}Li$, ^{9}Be, $^{10,11}B$ via spallation reactions.
- $^{11}B/^{10}B$ (ν-process +spallations) = 3.67-4.28
- Dense CSM => localized LiBeB production and star formation => anomalous star
- How about SNe Ib ?
  - the ν-process produces ^{7}Li in the He layer
  - fusion reaction of α-particles produces Li isotopes
  - nitrogen may be included if low-Z and rapidly rotating, leading to rich LiBeB production



Results

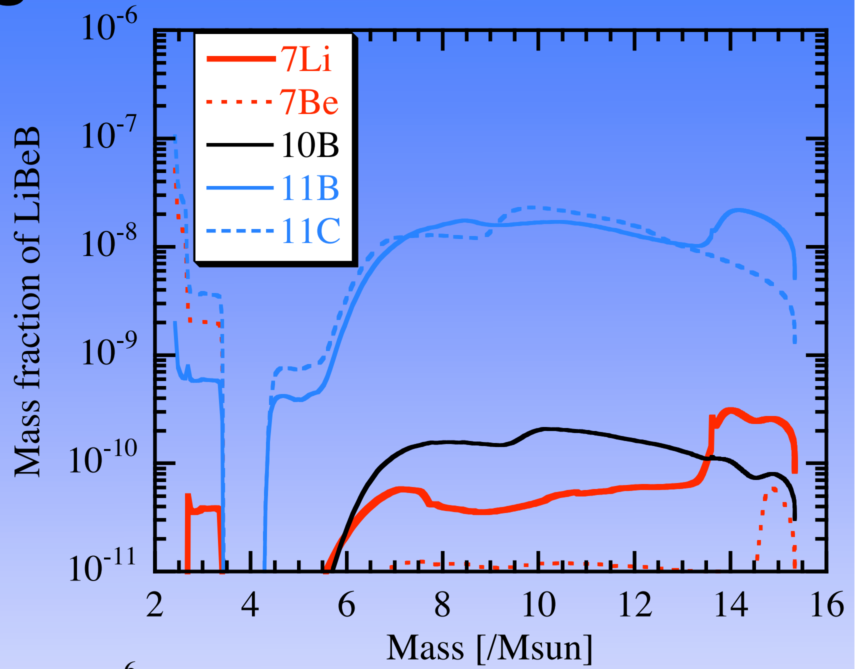
- Neutrino process
  - case 1: $(T\nu e, T\bar{\nu}e, T\nu\mu\tau)$ = (3.2 MeV, 5 MeV, 6 MeV)

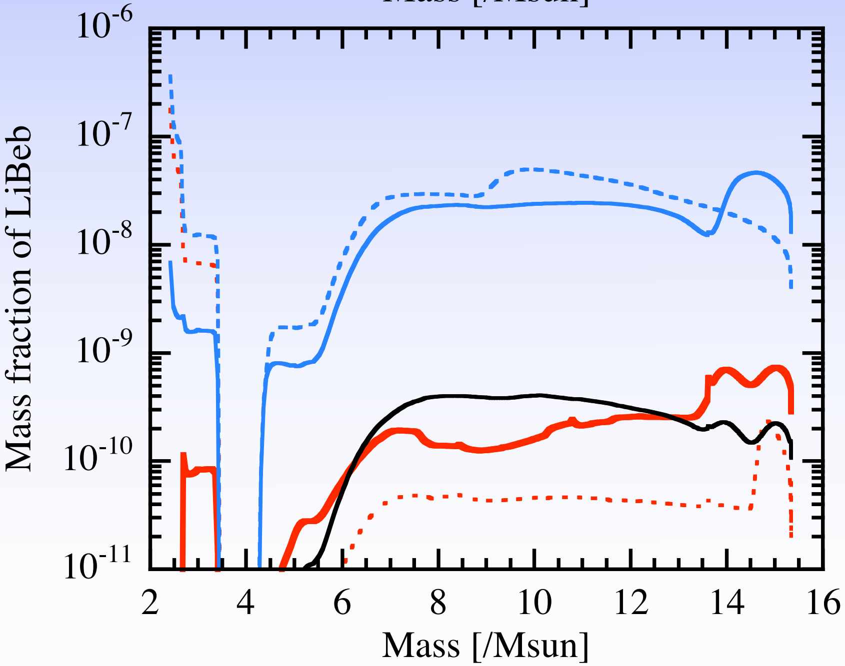
    $M(^6Li)$ = 1.67E-11
    $M(^7Li+^7Be)$= 7.41E-09
    $M(^9Be)$= 4.49E-11
    $M(^{10}B)$= 1.29E-09
    $M(^{11}B+^{11}C)$= 2.69E-07
  - case 2: $(T\nu e, T\bar{\nu}e, T\nu\mu\tau)$ = (3.2 MeV, 5 MeV, 8 MeV)

    $M(^6Li)$= 5.91E-11
    $M(^7Li+^7Be)$= 2.50E-08
    $M(^9Be)$= 1.08E-10
    $M(^{10}B)$= 2.79E-09
    $M(^{11}B+^{11}C)$= 5.46E-07

- Spallation reactions (KN & Shigeyama 04)

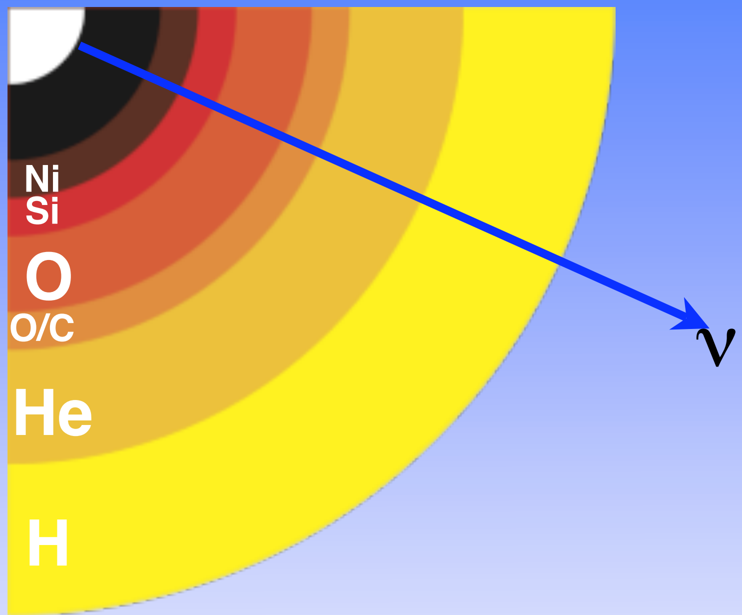
  $M(^6Li)$= 2.38E-07
  $M(^7Li+^7Be)$= 3.31E-07
  $M(^9Be)$= 1.00E-07
  $M(^{10}B)$= 4.38E-07
  $M(^{11}B+^{11}C)$= 1.34E-06





Neutrino-induced nucleosynthesis(ν-process)

Supernova neutrinos



- ν_e, $\bar{\nu}_e$, $\nu_{\mu\tau}=(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

  $\langle \varepsilon_{\nu_e} \rangle < \langle \varepsilon_{\bar{\nu}_e} \rangle < \langle \varepsilon_{\nu_{\mu\tau}} \rangle$

- $E_\nu \sim E_{grav} \sim 10^{53}$ ergs

  ➡ $N_\nu \sim 10^{58}$

- $O(t_\nu) \sim 10$ s

Neutrino Reactions

- $\sigma_\nu \sim 10^{-42}$ cm^2
- $\phi_\nu dt \sim N_\nu/4\pi r^2 \sim 10^{58}/4\pi(10^9 \text{cm})^2 \sim 10^{37}$ cm^{-2}

  ➡ $N_{product}/N_{target} \sim \sigma_\nu \phi_\nu dt \sim 10^{-5}$

  ➡ production of rare elements

Neutrino-induced nucleosynthesis(ν-process)

Neutrino reactions

- **Neutral current reactions**

$$(Z, A) + \nu \rightarrow (Z\text{-}1, A\text{-}1) + \nu' + p$$

$$(Z, A) + \nu \rightarrow (Z, A\text{-}1) + \nu' + n$$

- **Charged current reactions**

$$(Z, A) + \nu_e \rightarrow (Z+1, A) + e^-$$

$$(Z, A) + \bar{\nu}_e \rightarrow (Z\text{-}1, A) + e^+$$

➡ ^{7}Li, ^{11}B, ^{19}F, ^{55}Mn, ^{138}La, ^{180}Ta

^{11}B production

➡ $^{12}C(\nu, \nu' n)^{11}C$, $^{12}C(\nu, \nu' p)^{11}B$

$^{12}C(\nu_e, e^- p)^{11}C$, $^{12}C(\bar{\nu}_e, e^+ n)^{11}B$

SN neutrino model

Neutrino luminosity

$$L_{\nu i}(t) = \frac{1}{6}\frac{E_\nu}{\tau_\nu}\exp\left(-\frac{t-r/c}{\tau_\nu}\right)\Theta(t-r/c) \quad \nu_i : \nu_{e\mu\tau}, \bar{\nu}_{e\mu\tau}$$

- $\tau_\nu = 3$ s
- $E_\nu = 3\times 10^{53}$ erg

(after Woosley et al. 1990, ApJ 356, 272)

Neutrino energy spectra

- Fermi distribution: $\eta_\nu = \mu_\nu/kT_\nu = 0$

$(kT_{\nu e}, kT_{\bar{\nu} e}, kT_{\nu\mu\tau}) = (3.2\ \text{MeV}, 5\ \text{MeV}, 6\ \text{MeV})$

(e.g., Yoshida et al. 2005, 2006, 2008)

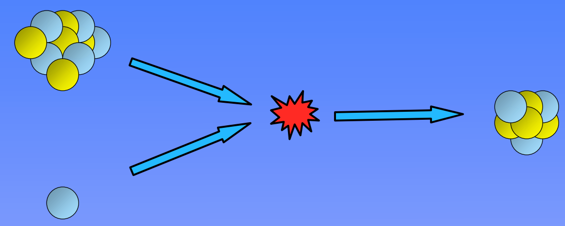
$(3.2\ \text{MeV}, 5\ \text{MeV}, 8\ \text{MeV})$

Cosmic-Ray Spallation

- Spallation reactions

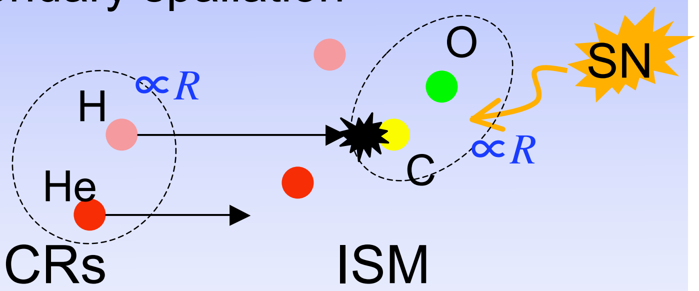
$$\mathrm{H,He + CNO} \rightarrow {}^{6,7}\mathrm{Li}, {}^{9}\mathrm{Be}, {}^{10,11}\mathrm{B}$$

CR	target	····	Secondary spallation
target	CR	····	Primary spallation

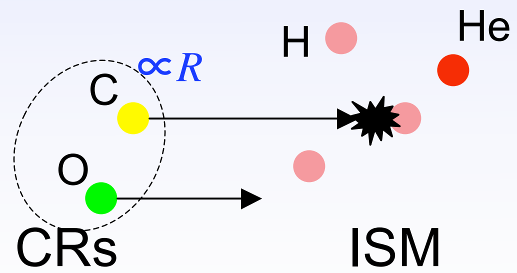


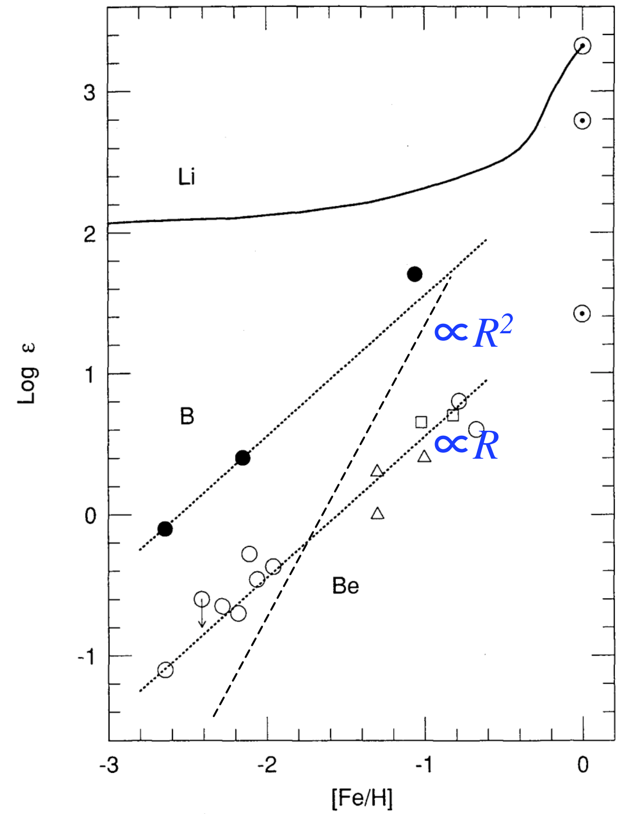
Assuming CRs from SN (rate=R)

- Secondary spallation



- Primary spallation





Duncan et al. (1992)