The neutrino-process and light element production

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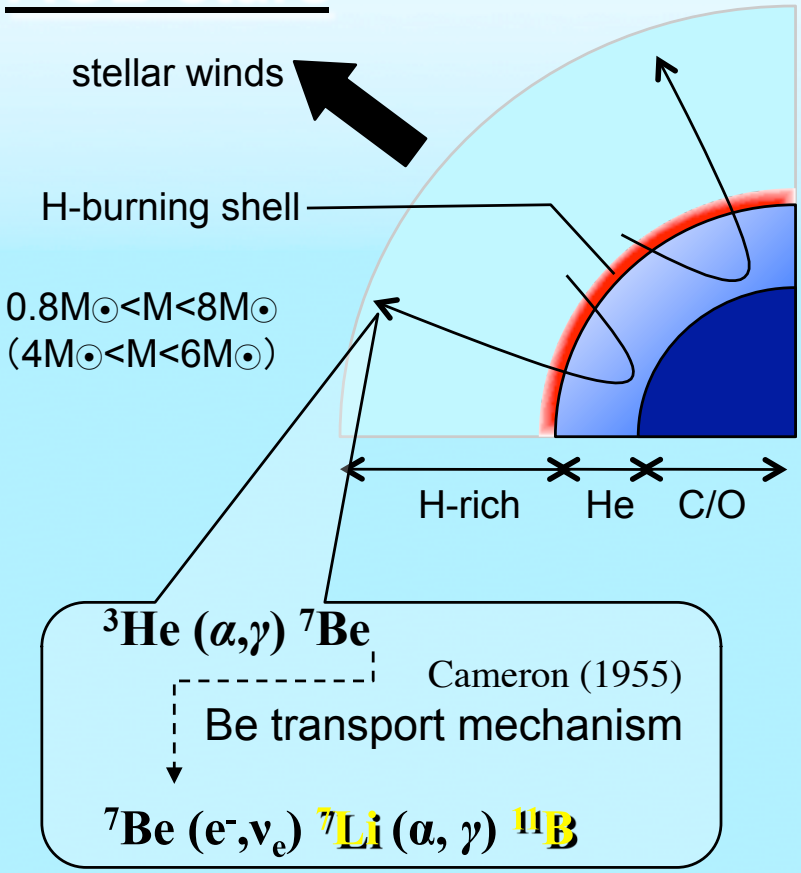
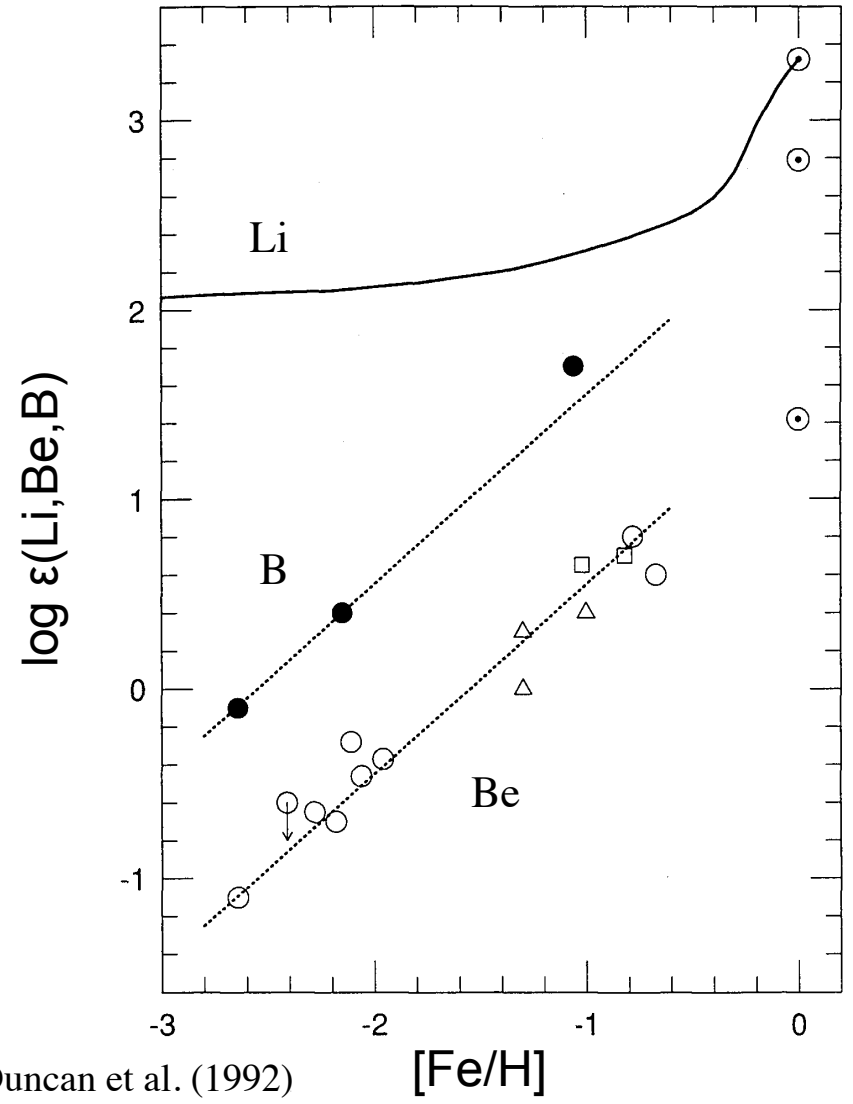
Production Sites of ^{6,7}Li, ^{9}Be, ^{10,11}B

- **Big Bang Nucleosynthesis**
  - Primordial ^{7}Li (Spite plateau)
- **AGB stars**





Duncan et al. (1992)

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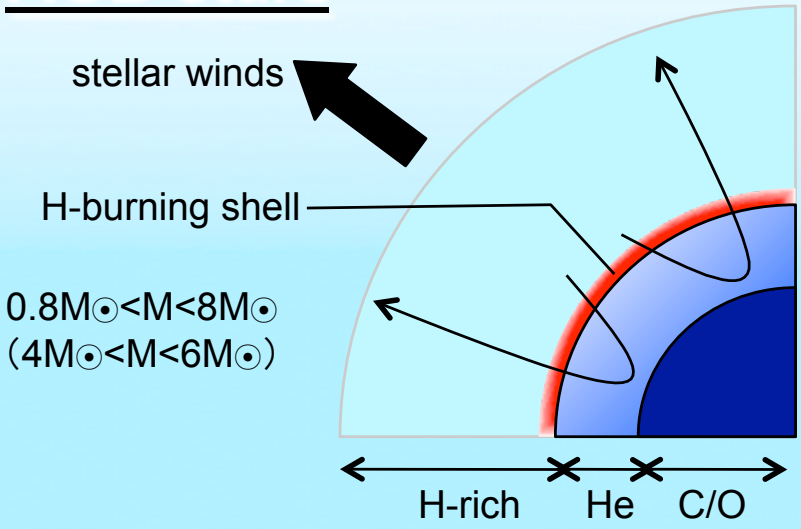
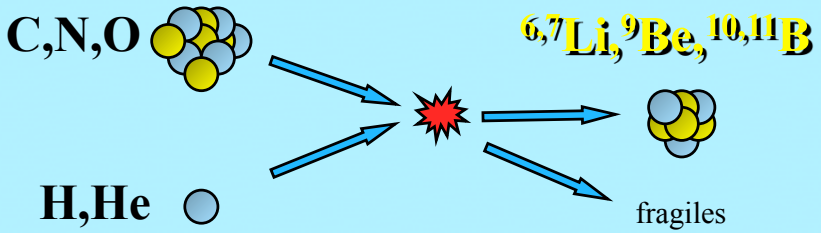
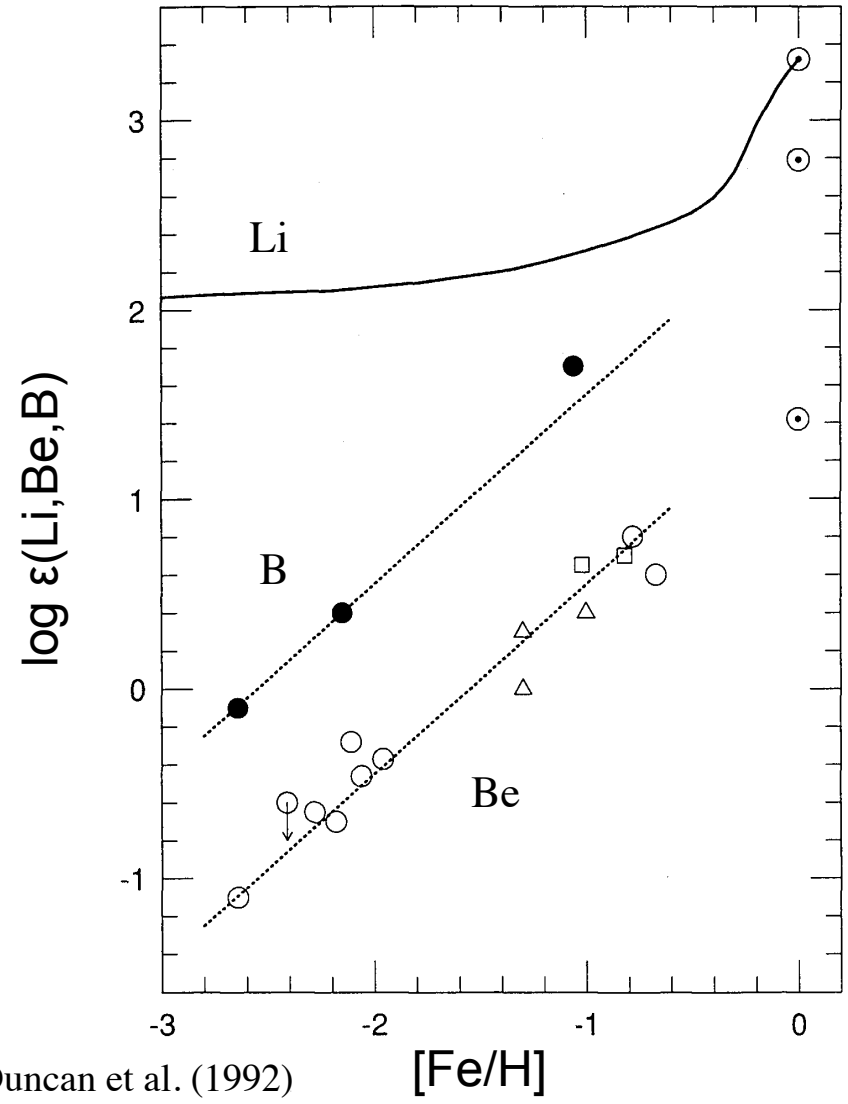


- **Cosmic-ray interactions**
  - Spallation reactions





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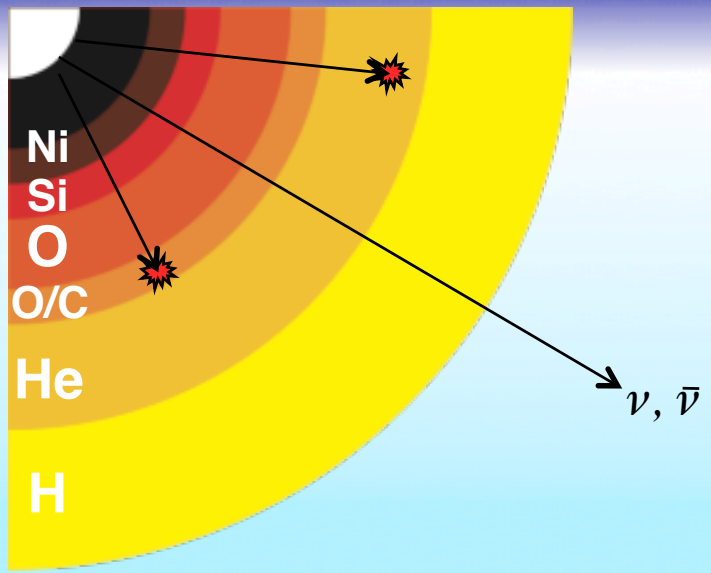
Neutrino-induced Nucleosynthesis



- Huge number of neutrinos (>10^{58} !)
- $\nu_e, \bar{\nu}_e, \nu_{\mu\tau} = (\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

  $\langle\varepsilon_{\nu e}\rangle < \langle\varepsilon_{\bar{\nu} e}\rangle < \langle\varepsilon_{\nu\mu\tau}\rangle$
- Some interact with materials and induce nucleosynthesis

  => The ν-process (Woosley+ 1990)
- ^{7}Li, ^{11}B, ^{19}F, …, ^{138}La, ^{180}Ta

➢ 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:

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

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

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

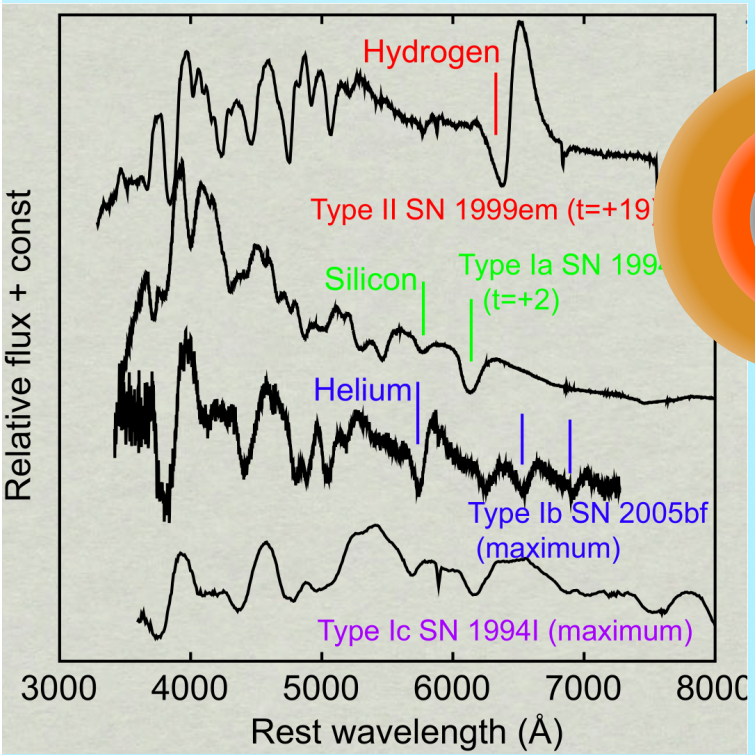
  $^{12}C(\nu_e, e^- p)^{11}C$, $^{12}C(\bar{\nu}_e, e^+ n)^{11}B$

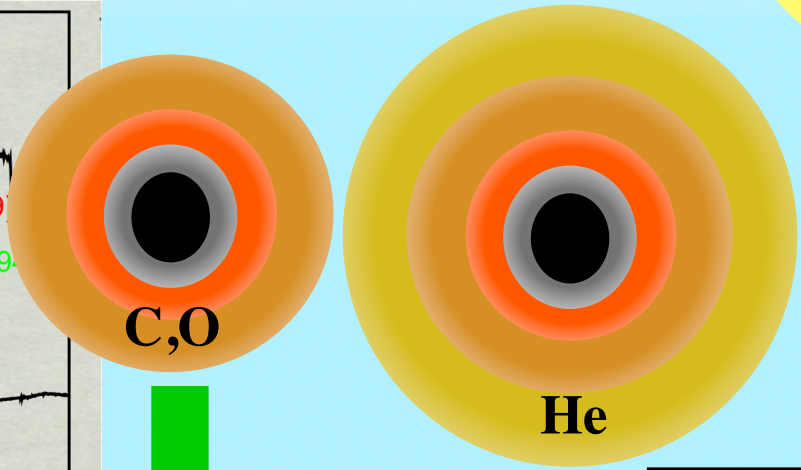
  ↓

  ^{11}B in 20 min.

LiBeB production in/around CCSNe

Stellar wind or binary effect
10-40 % (Cappellaro+ 99)

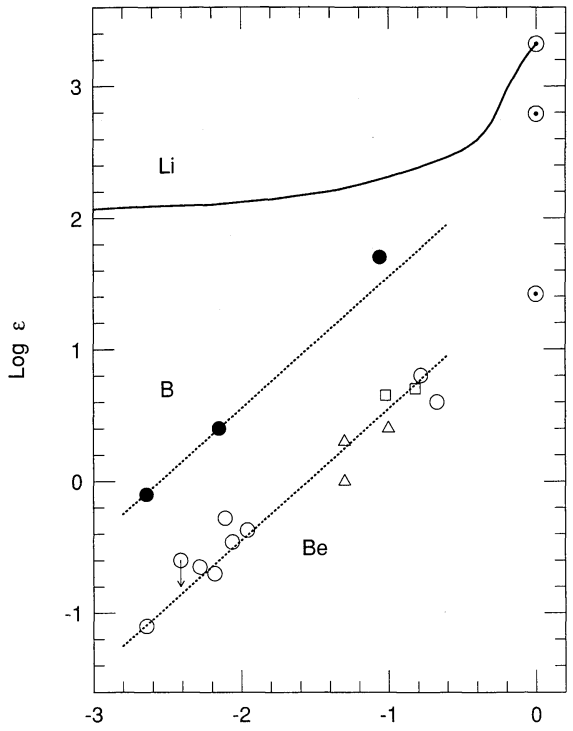




Type II (with H line)
- SN 1987A, 99em
- v ~ 1,000 km/s

Type Ib(c) (w/o H(He) line)
- SN 1984L (Ib); 98bw (Ic)
- v > 10,000 km/s
- associated with GRB/HN

ction in/around CCSNe



Duncan et al. (1992)

(neutrino process)

^{7}Li, ^{11}B

Fe Si
O,Ne,Mg
C,O
He
H,He

(spallation reactions)

^{6,7}Li, ^{9}Be, ^{10,11}B

C,O

He

H,He
in ISM

Type II (with H line)
- SN 1987A, 99em
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Calculations: SN Ic Explosion

- Progenitor model:

Type	$M_{ms}[M_{sun}]$	$M[M_{sun}]$	Eex	SN
Ib	12	4	1	---
Ic	15	4	1	1994I
Ic	25	6	4	2002ap
Ic	40	15	30	1998bw
II	16	16	1	1987A

- Numerical code:
  - 1-dimensional hydrodynamic code
  - incl. effects of special relativity

    (KN & Shigeyama 2004)

  - Relativistic hydrodynamic eq.
- Outputs:
  - time evolution of physical quantities: $\rho(t)$, $T(t)$
  - energy spectra of ejecta: $M(>E)$

Calculations: The ν-process

- Neutrino luminosity (Woosley+ 90) :

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

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

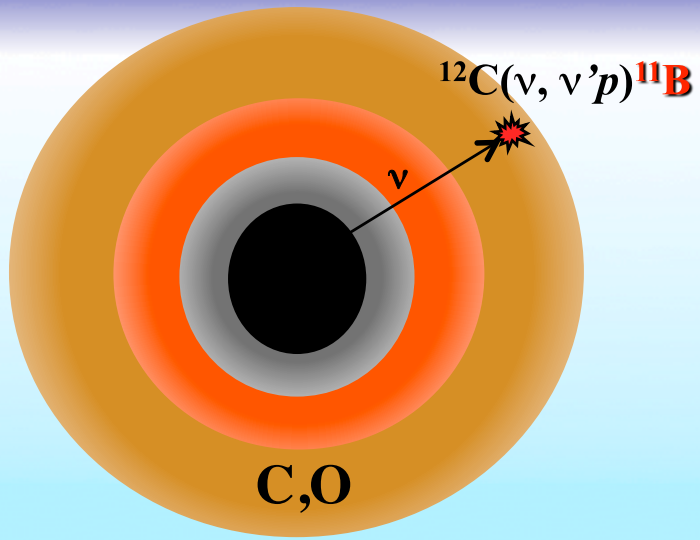
- decay time: $\tau_\nu = 3$ s
- total neutrino energy: $E_\nu = 3\times 10^{53}$ ergs
- Energy spectra: Fermi-Dirac distribution

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

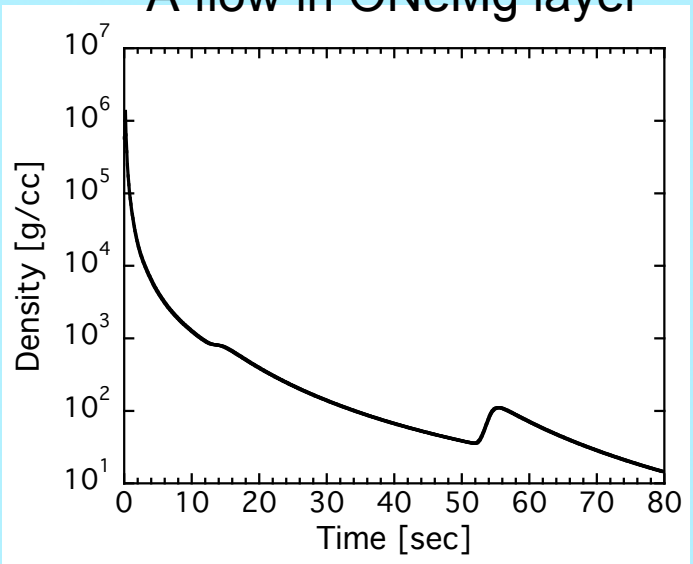
$$(3.2,\ 5.0,\ 6.0)\ \text{MeV} \leftarrow \text{normal } T\nu_{\mu\tau}$$

$$(3.2,\ 5.0,\ 8.0)\ \text{MeV} \leftarrow \text{high } T\nu_{\mu\tau}$$

- Nuclear reaction network consisting of 291 species of nuclei

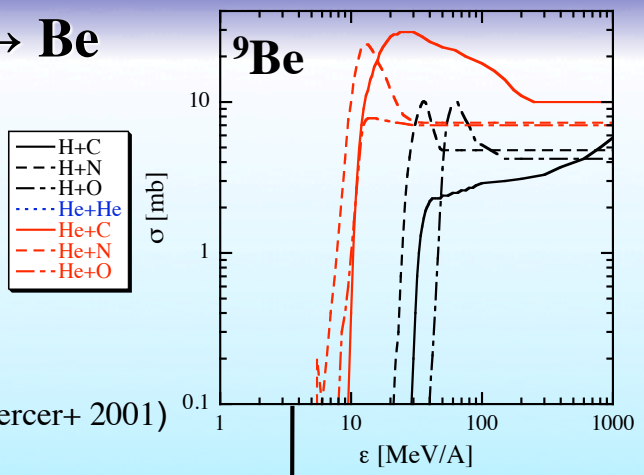


A flow in ONeMg layer



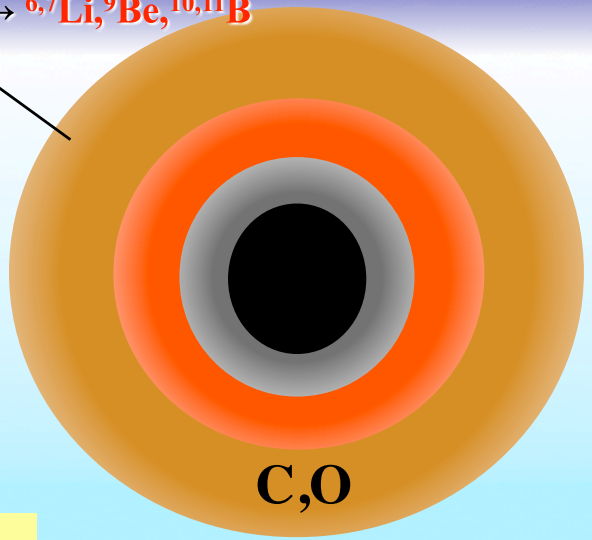
Calculations: Spallation Reactions

ex.) **O+H → Be**



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

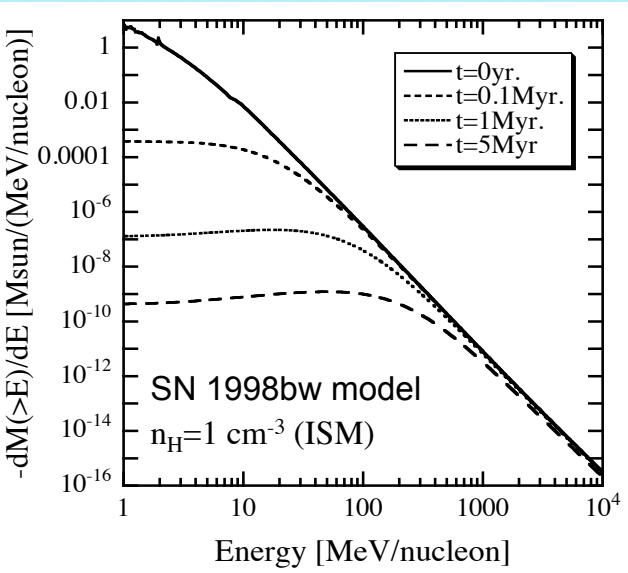
H,He + C,O → ^{6,7}Li,^{9}Be,^{10,11}B



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

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

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



Transport equation

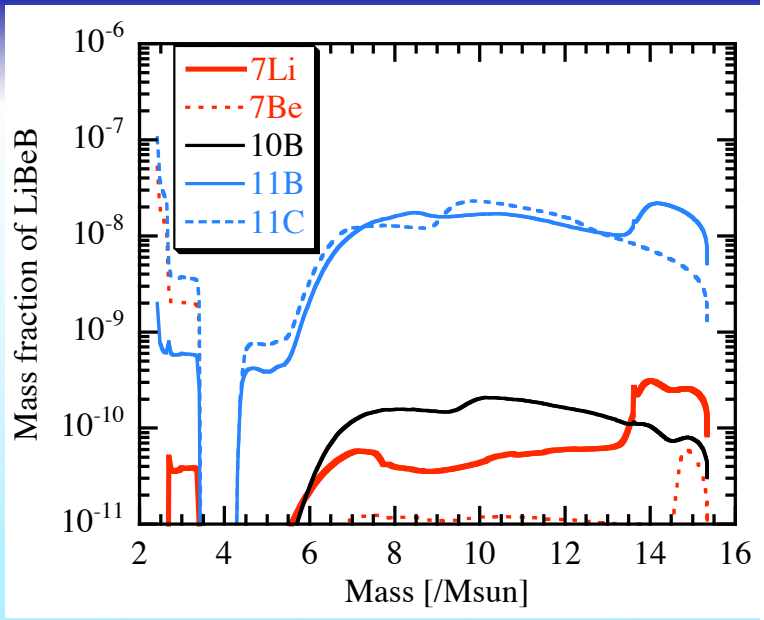
$$\frac{\partial F_i(E,t)}{\partial t} = \frac{\partial[\omega_i(E) F_i(E,t)]}{\partial E} - \frac{F_i(E,t)}{\Lambda} \rho v_i(E)$$

ω_i : energy loss rate (ionization)

Λ : loss length (spallation & escape)

Results - process dependence (98bw)

- **LiBeB** from the ν-process
  - ^{11}**B** production in **C**-rich layers
  - … and in the innermost region (incl. ^{7}**Li** !)
  - more **LiBeB** in high $T\nu_{\mu\tau}$ model
- **LiBeB** from spallations
  - 0.04$M\odot$ of ejecta attain ε > 10 MeV/A
  - plenty of **LiBeB**
  - predominantly from **O** spallation



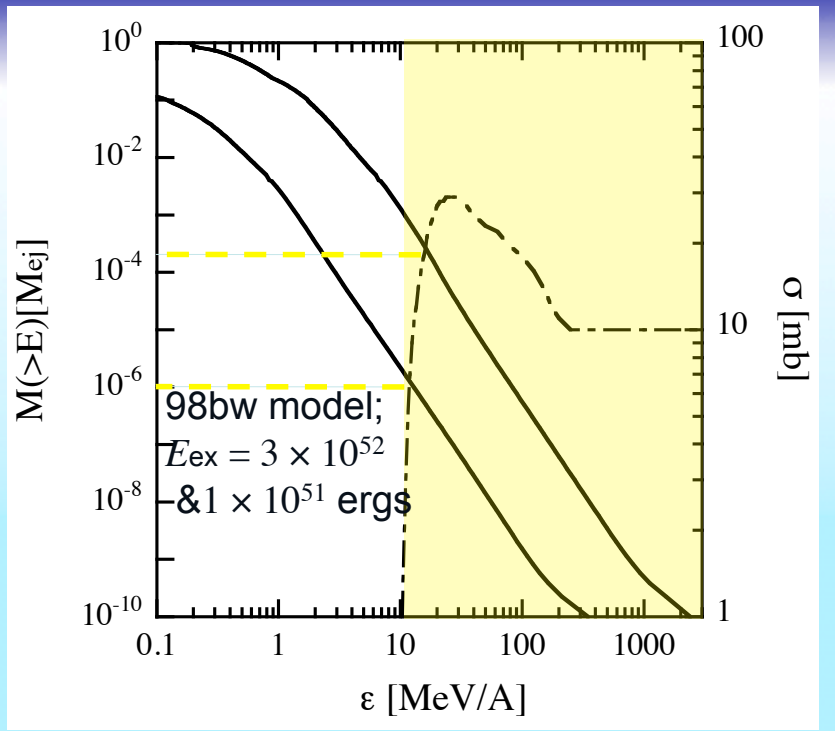
LiBeB from each process (1998bw model)

process	^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B
ν (low Tv)	1.7(-11)	7.4(-9)	4.5(-11)	1.3(-9)	2.7(-7)
ν (high Tv)	5.9(-11)	2.5(-8)	1.1(-10)	2.8(-9)	5.5(-7)
spallation	2.4(-7)	3.3(-7)	1.0(-7)	4.4(-7)	1.3(-6)

*** 2.5(-10) = 2.5×10^{-10} Msun**

Results - model dependence (^{11}B)

- ^{11}B from the ν-process in SNe Ibc
  - as much as SNe II
  - favors less energetic explosion
  - production (ν) and destruction (shock)
- ^{11}B from spallations in SNe Ic
  - strongly dependent on E_{ex}
  - little contribution from Ib (He) & II (H)



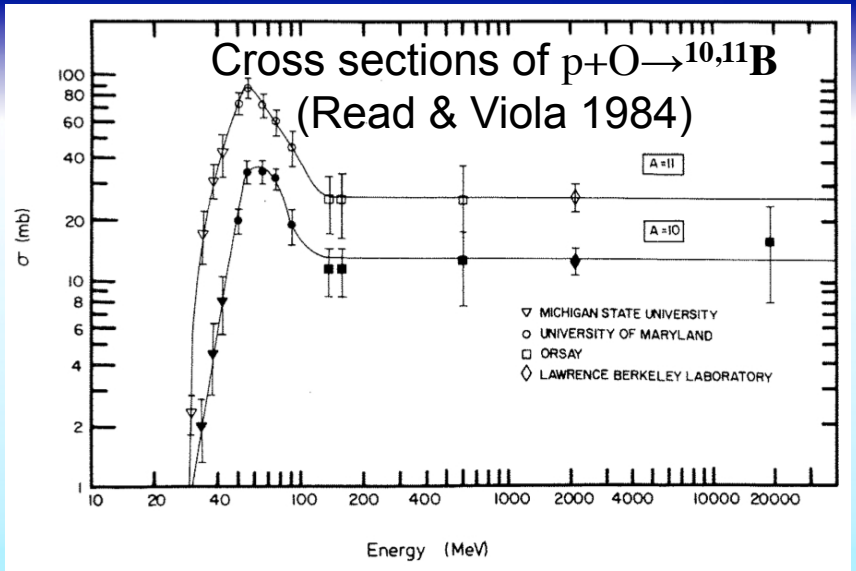
^{11}B from each model

process	(b)	94I(c)	02ap(c)	98bw(c)	87A(II)
ν (low Tv)	4.3(-7)	1.2(-7)	1.3(-7)	2.7(-7)	7.1(-7)
ν (high Tv)	1.1(-6)	2.8(-7)	3.1(-7)	5.5(-7)	---
spallation	negligible	7.8(-9)	4.5(-8)	1.3(-6)	negligible

*** 2.5(-10) = 2.5×10^{-10} Msun**

Results - compared with observation

- **B** isotope ratios (^{11}**B**/^{10}**B**)
  - 4.05 ± 0.05 (meteorites)
  - ~3 (spallations)
  - ~200 (the ν-process)
  - ν-process (^{11}B) + spallation (^{11,10}B)



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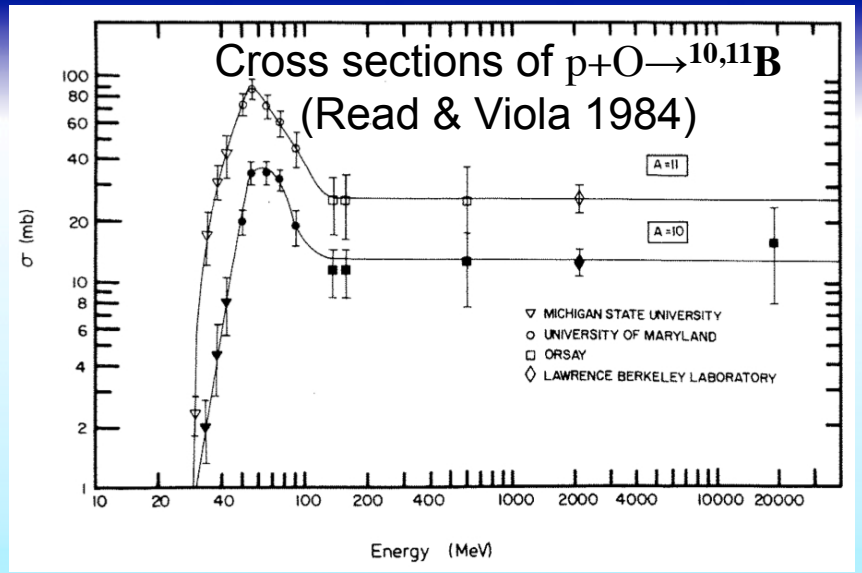
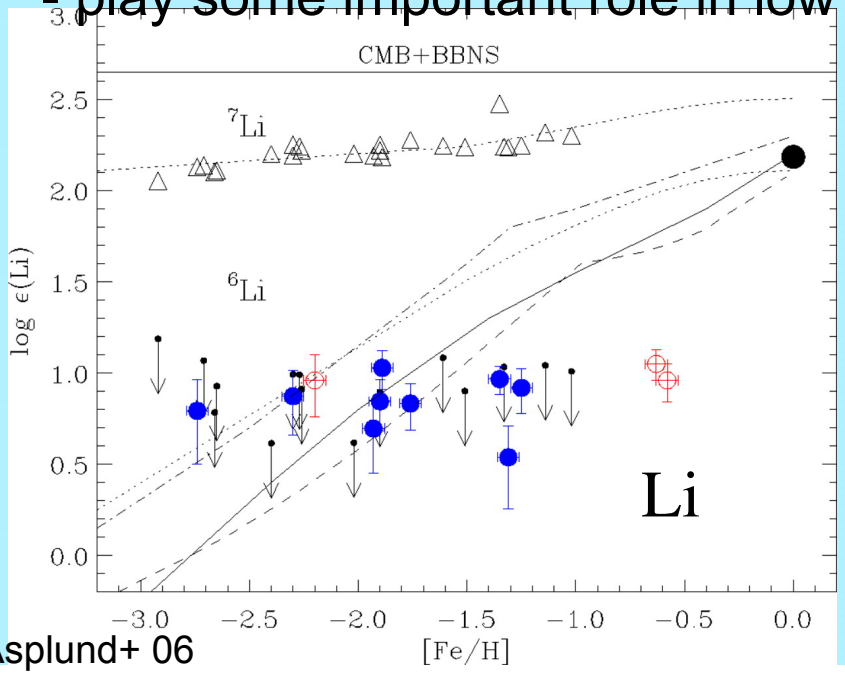
  - ν-process (^{11}B) + spallation ($^{11,10}B$)
- HNe contribution is low
- SNe Ib/c might …
  - play some important role in low Z
  - make some anomalous stars





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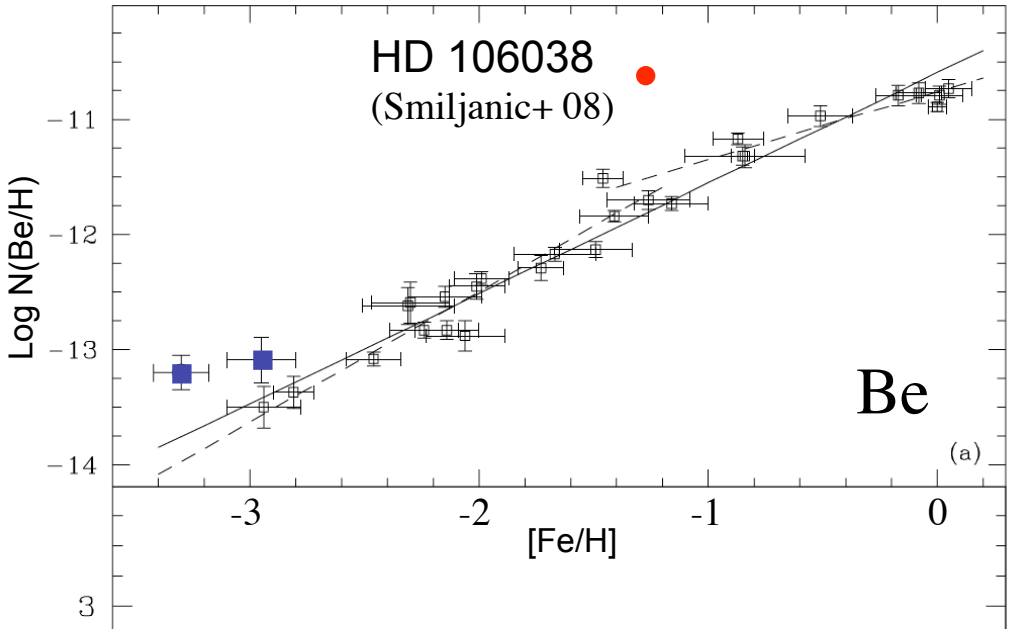

Summary

- Core-collapse SNe: SNe Ib, Ic, II
- We investigated **LiBeB** production via the ν-process and spallations in CCSNe.
- The ν-process synthesizes ^{11}B in C/O layer.
- The outermost nuclei accelerated by explosion interact with ISM and produce ^{6,7}Li, ^{9}Be, ^{10,11}B via spallation reactions.
- Dense CSM surrounding SNe Ib/c
  → localized synthesis and star formation
  → LiBeB-rich star (HD 106038) ?
- Key discriminator: Isotope ratios
  - BBN => ^{7}Li >> ^{6}Li
  - CRs => ^{7}Li ~ ^{6}Li, ^{10}B ~ ^{11}B
  - ν-process => ^{11}B >> ^{10}B