Neutrino-induced Nucleosynthesis in Core-collapse Supernovae

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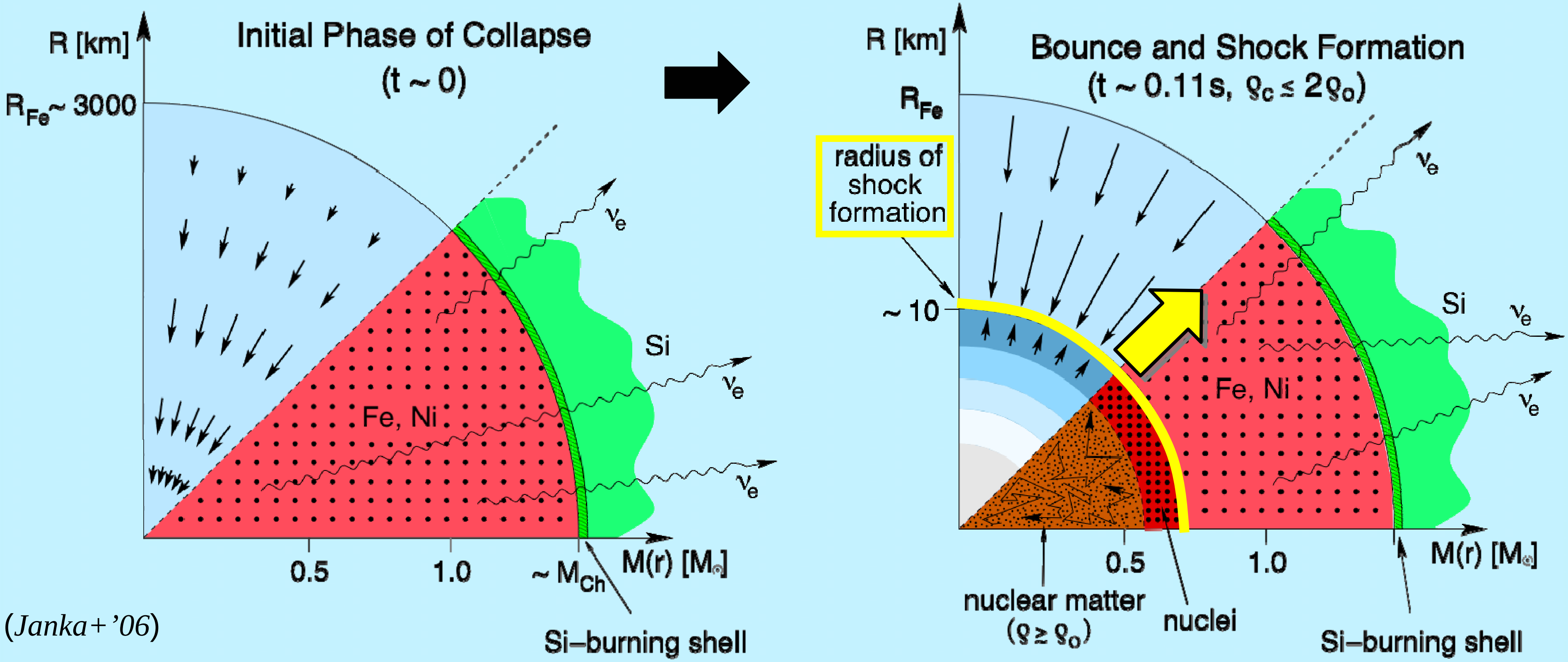
NDM12 @ Nara **June 11-15, 2012**

Core-collapse supernova explosions

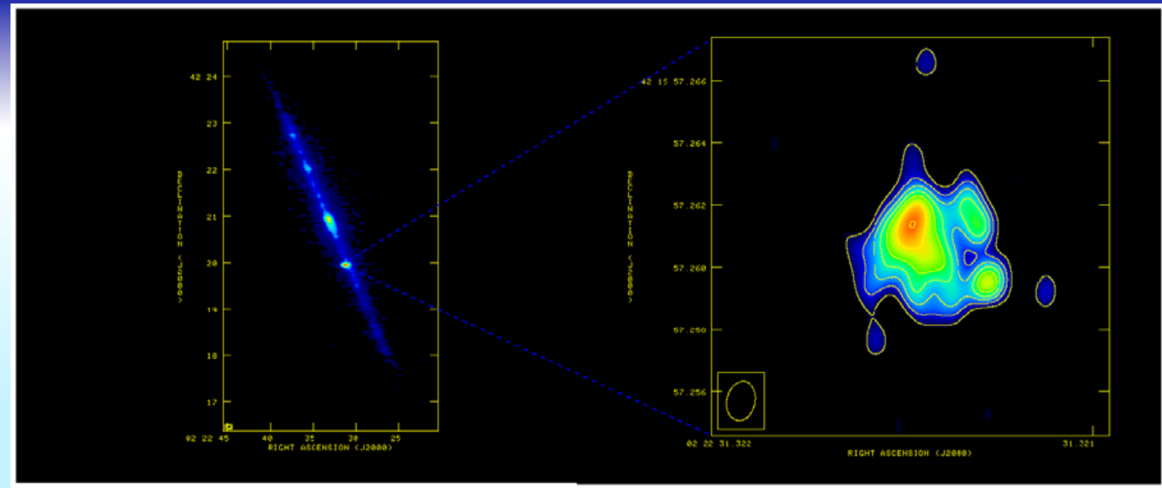
- Death of massive stars (> 10 Msun)
- Collapse of Fe core
- Core bounce and shock formation
- The shock will push accreting materials outward and induce explosion



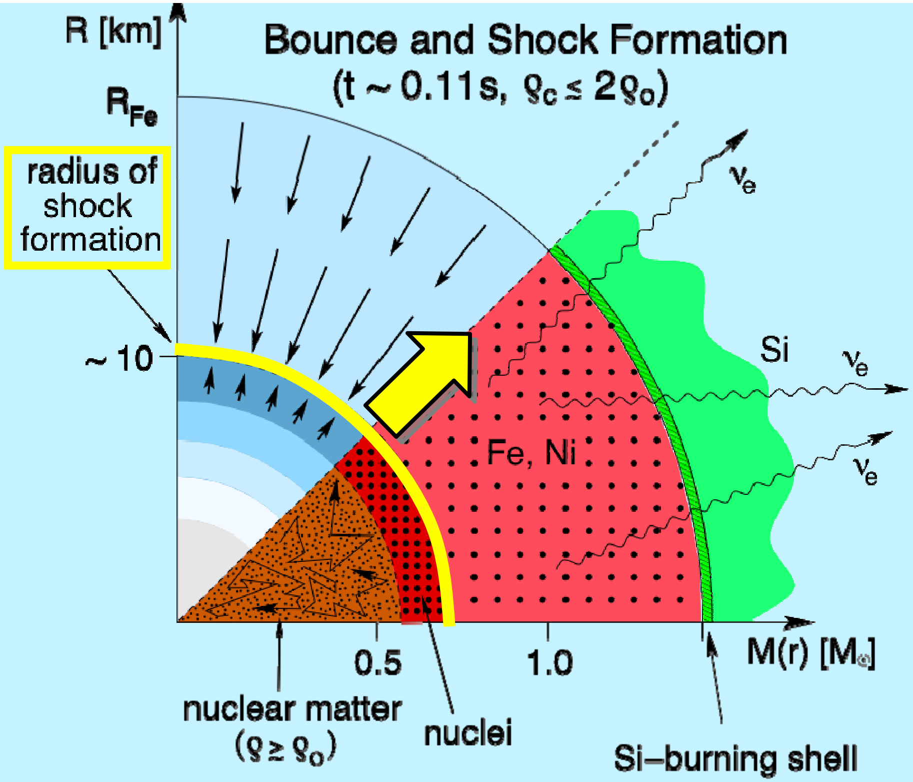
(*Janka+'06*)

Core-collapse supernova explosions

A VLA image of SN 1986J in the galaxy NGC 891.

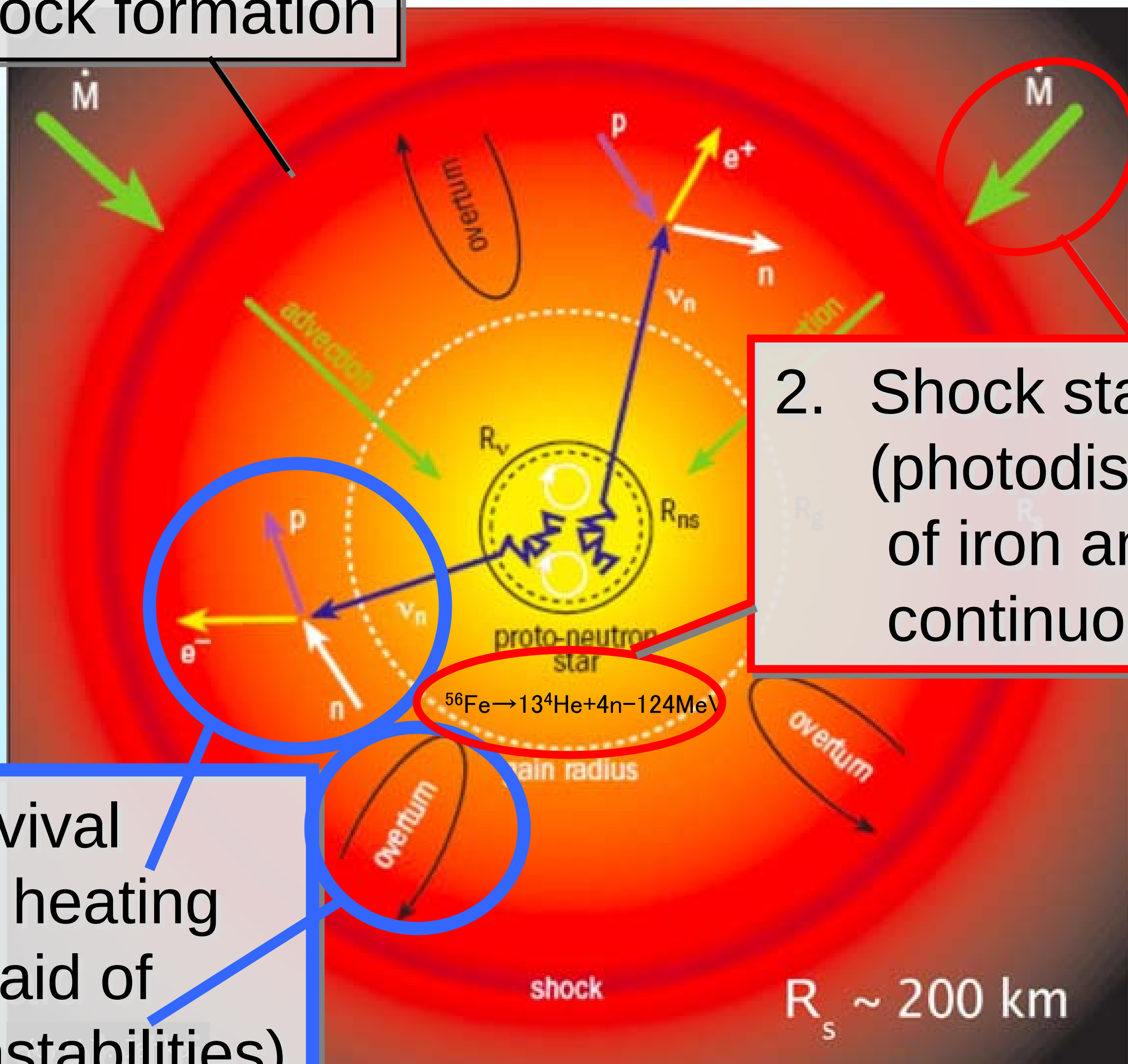


An artist's impression of SN 1986.
(c) N. Bartel, M. Bietenholz, G. Arguner



Theoretical trial to reproduce SN explosions

1. Core bounce
   and shock formation

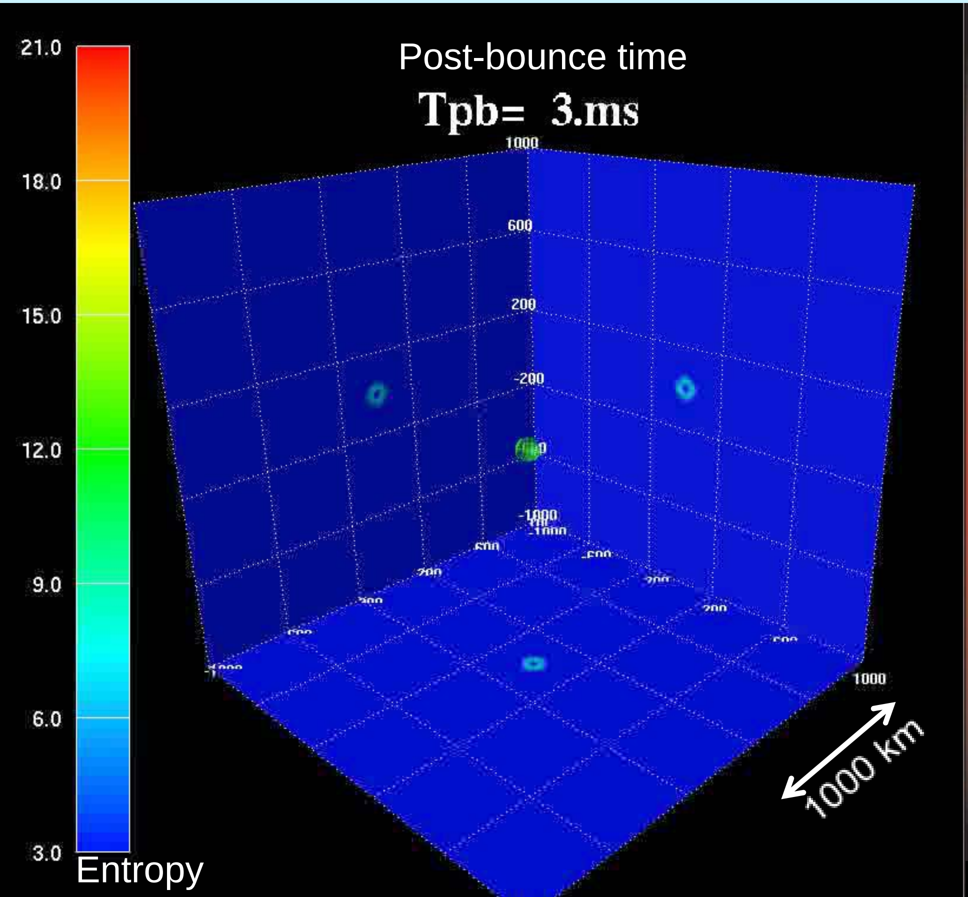


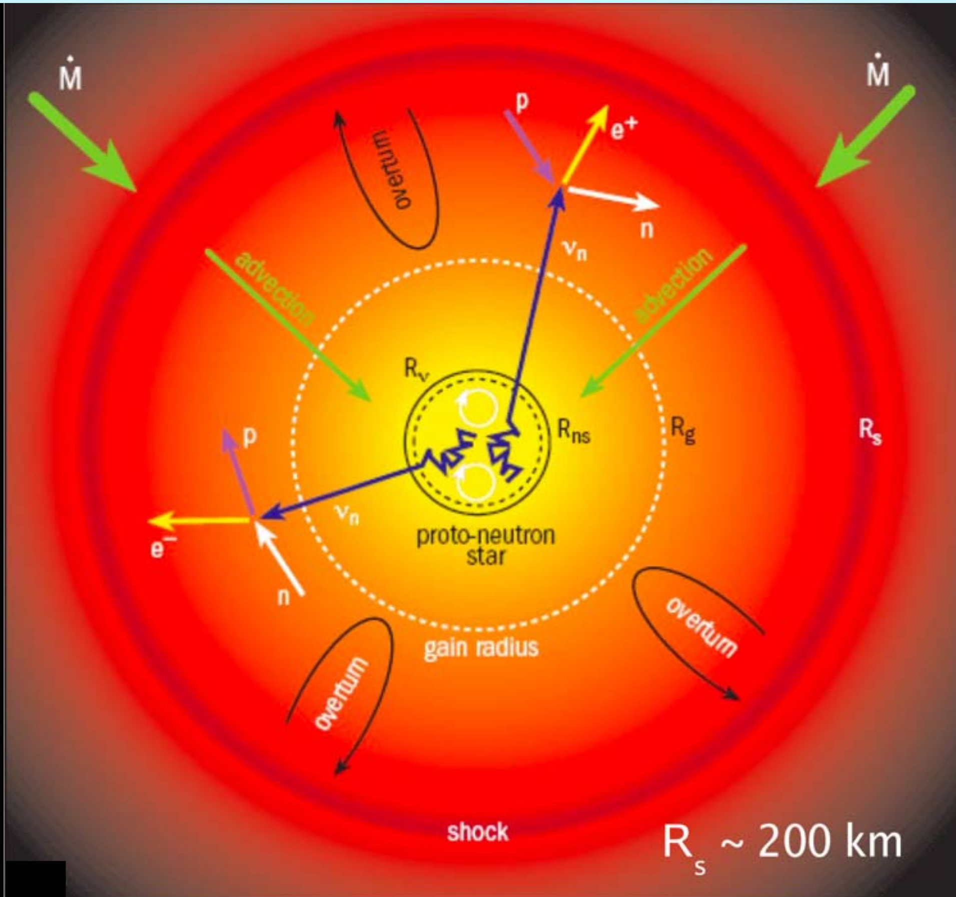
2. Shock stall problem
   (photodisintegration
   of iron and
   continuous accretion)

3. Shock revival
   (neutrino heating
   with the aid of
   hydro. instabilities)

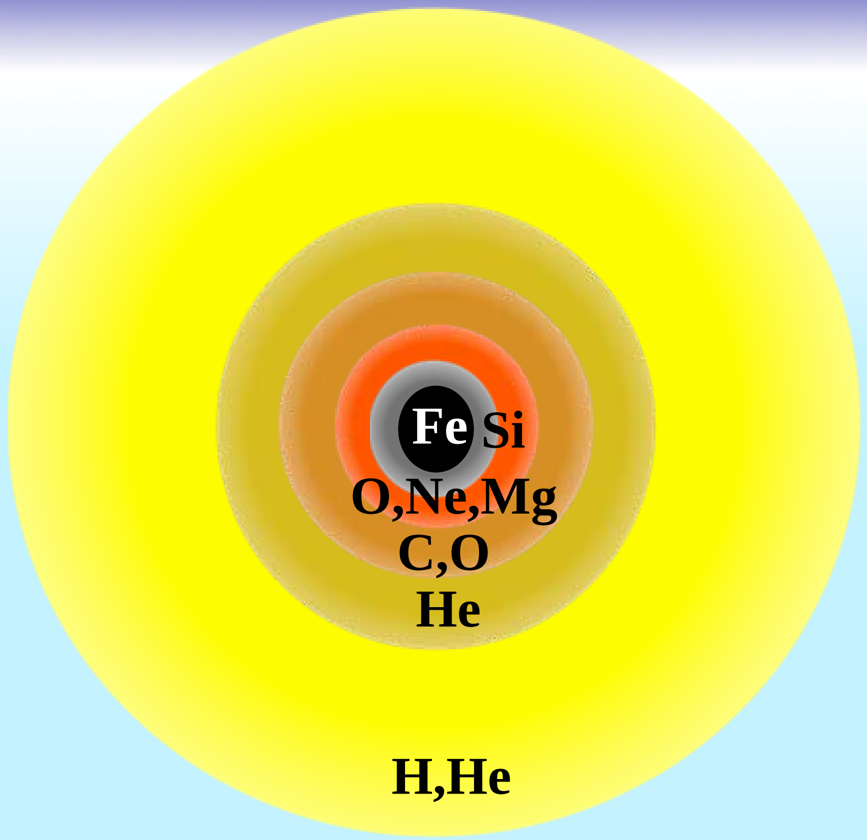
3D numerical simulation of CCSN

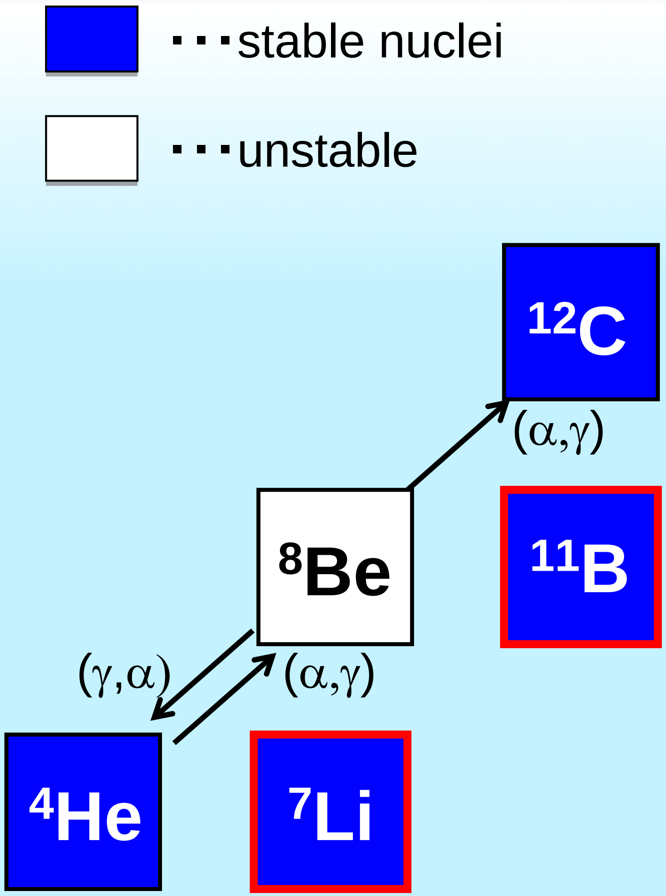
- ***<u>KN</u>**, Kuroda, Takiwaki, & Kotake (in prep.)*
- 15 Msun progenitor with solar metallicity
- No rotation, no magnetic field
- Light-bulb scheme (ex., *Janka & Muller '96, Murphy & Burrows '08*)





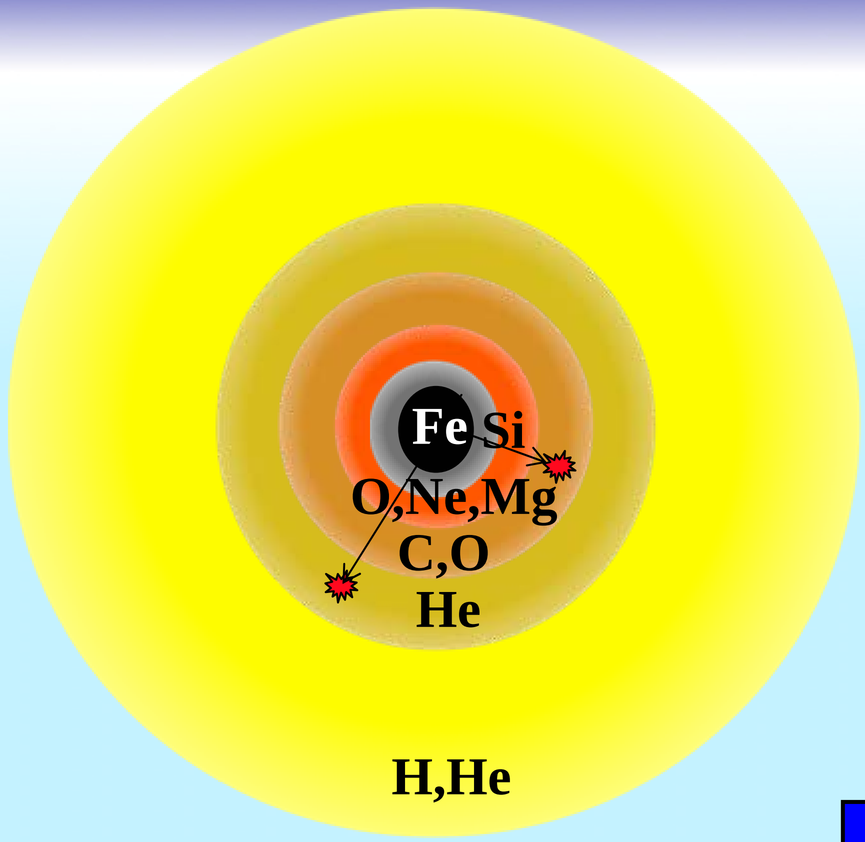
Light ν-processed elements: ^{7}Li & ^{11}B

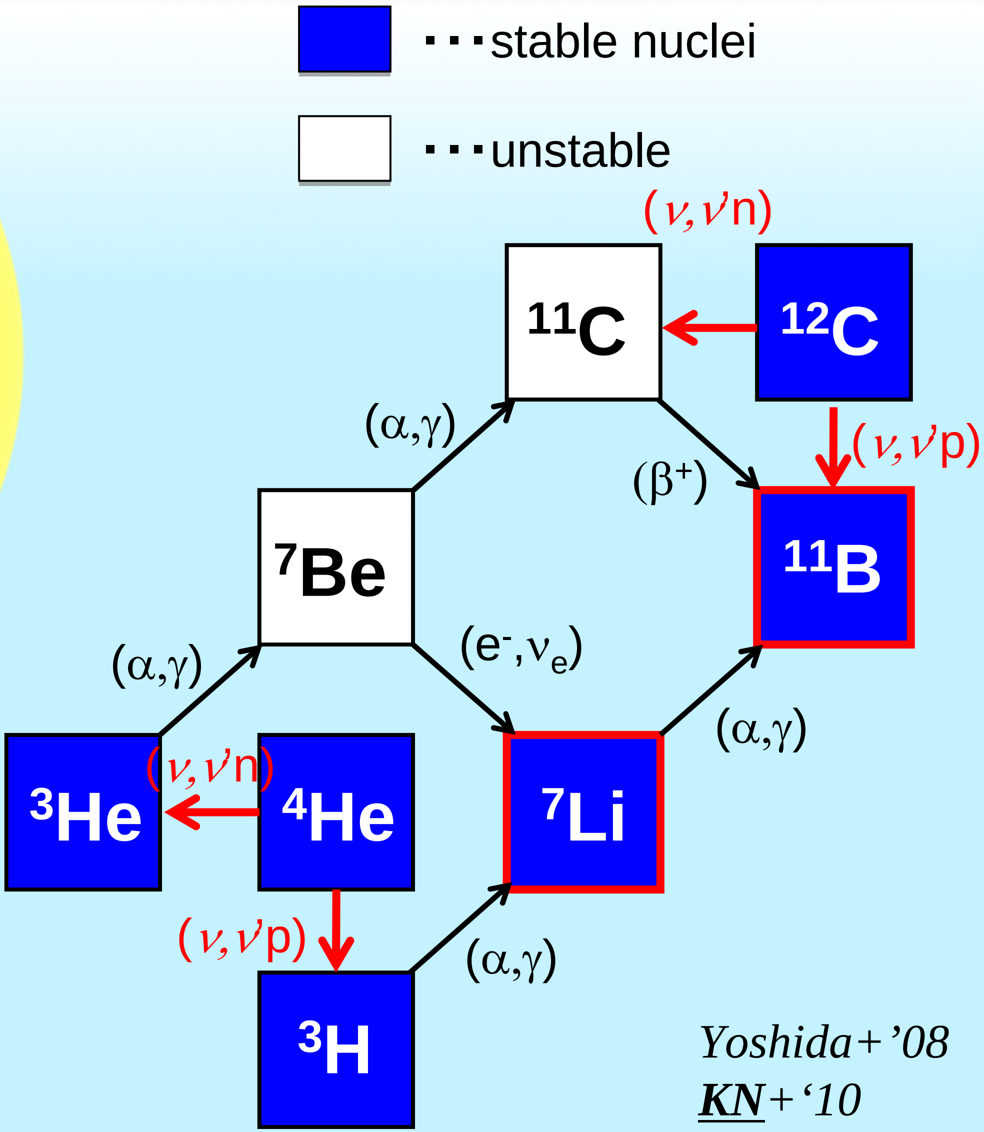




Lithium (and boron) isotopes are hardly produced through nuclear burning reactions in stellar evolution because of the absence of stable nuclei with mass number of 8.

Light ν-processed elements: ^{7}Li & ^{11}B

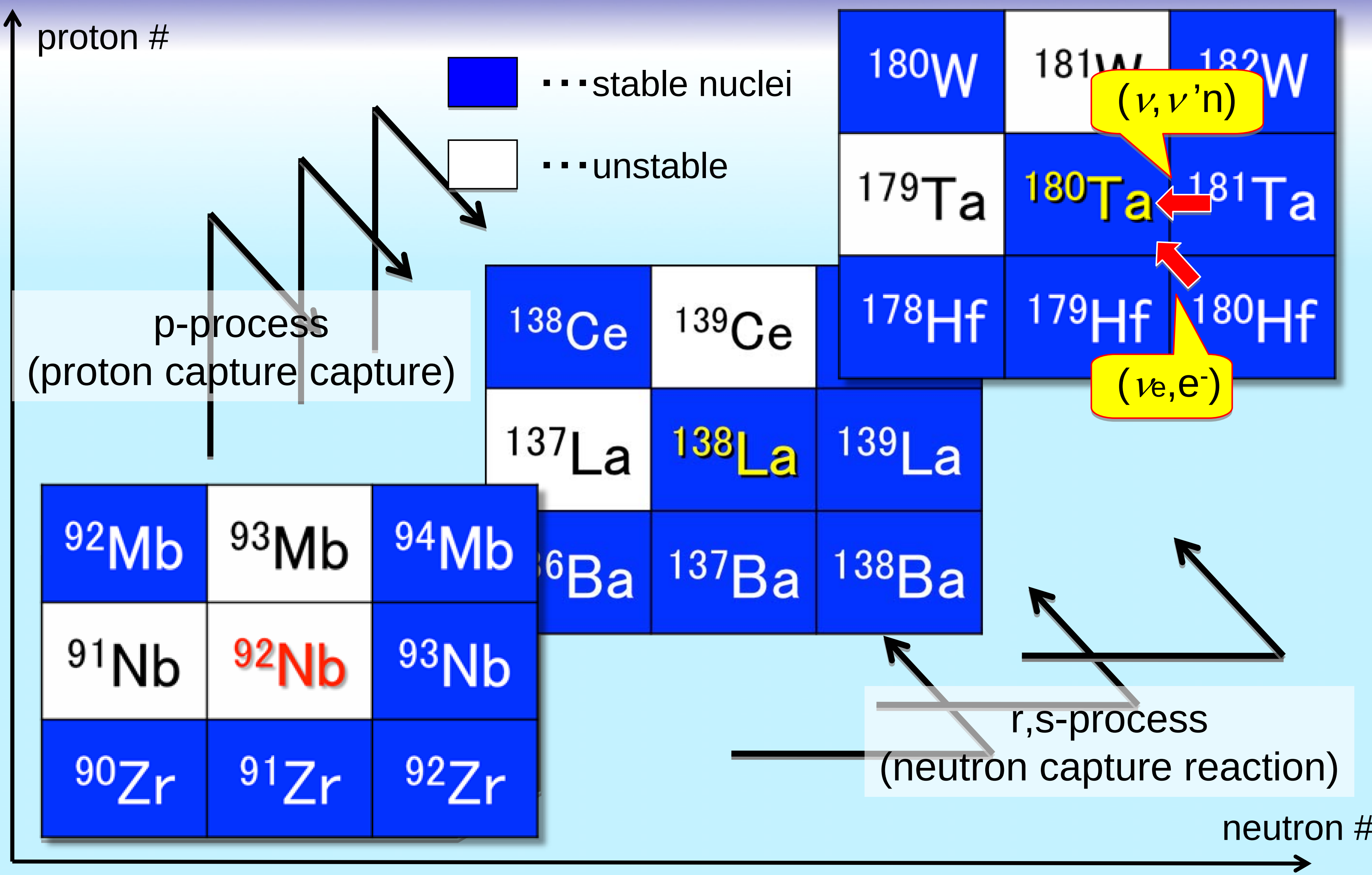




^{7}Li /^{11}B production in He / C layer.
They are hardly affected (destroyed) by shock heating.

Yoshida+'08
***KN**+'10*

Heavy ν-process elements: ^{138}La & ^{180}Ta

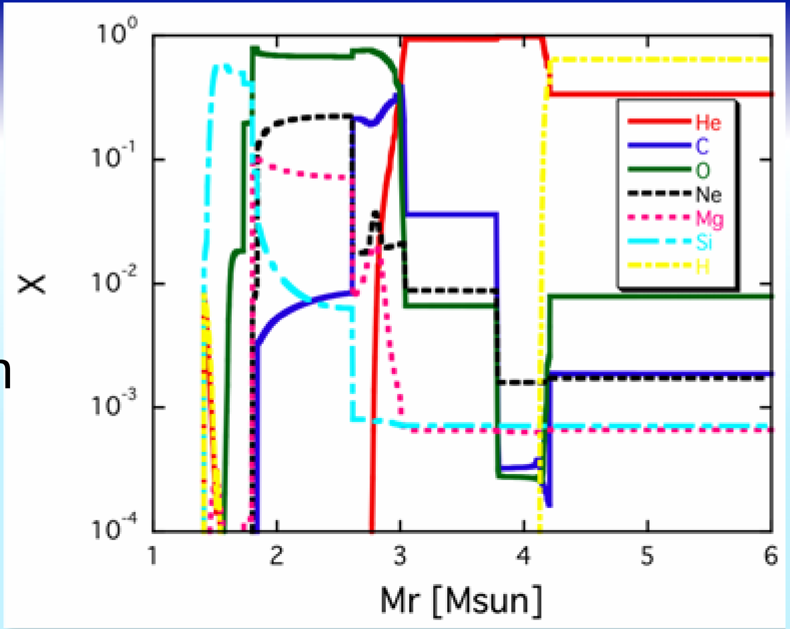


Why niobium-92?

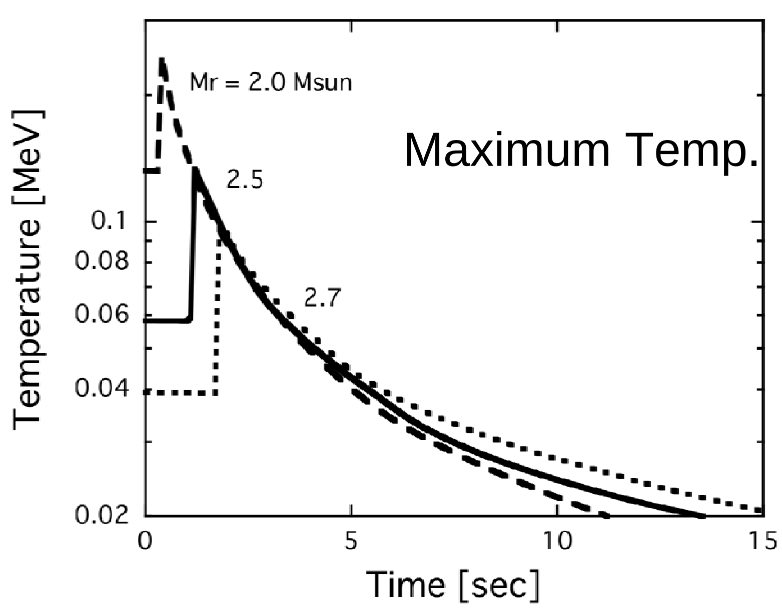
- Radioactive **^{92}Nb** :
  - observed in meteorites as its daughter nucleus ^{92}Zr
  - useful as a chronometer during the solar system formation
  - unlikely produced through p-process and gamma-process
- We propose that the **ν-process** can produce ^{92}Nb !
  - similar environment to ^{138}La & ^{180}Ta in the nuclear chart
- Advantages over other chronometers (ex., r-process):
  - simple and direct nuclear reactions makes the estimation robust
  - contribution from ISM is negligible
  - astrophysical site is clear (CCSNe)

Numerical scheme (1)

- Progenitor model:
  - M = 15Msun, Z = Zsun
    (s15a28 model of Heger+02)
  - 1 zone weak s-process calculation
    (Iwamoto+)

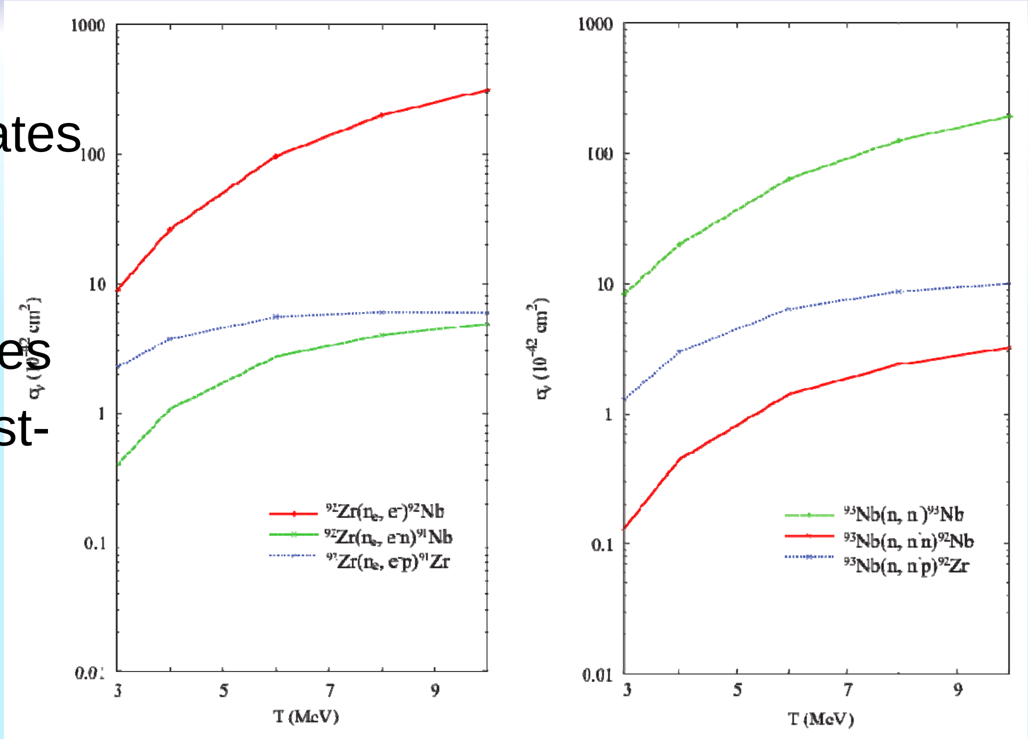


- Hydrodynamics:
  - 1-D spherical code
  - $E_{\mathrm{ex}} = 10^{51}$ ergs



Numerical scheme (2)

- Nuclear reactions:
  - neutrino-induced reaction rates (MK Cheoun, KN+)
  - nuclear network code including about 3000 isotopes
  - network calculation as a post-process



Neutrino parameters

E_ν: total neutrino energy

$= 3 \times 10^{53}$ ergs

τ : decay time scale

$= 3$ sec

$T_{\nu i}$: neutrino temperature

$T_{\nu e} = 3.2$ MeV (r)

$T_{\nu e} = 4.0$ MeV (heavy ν)

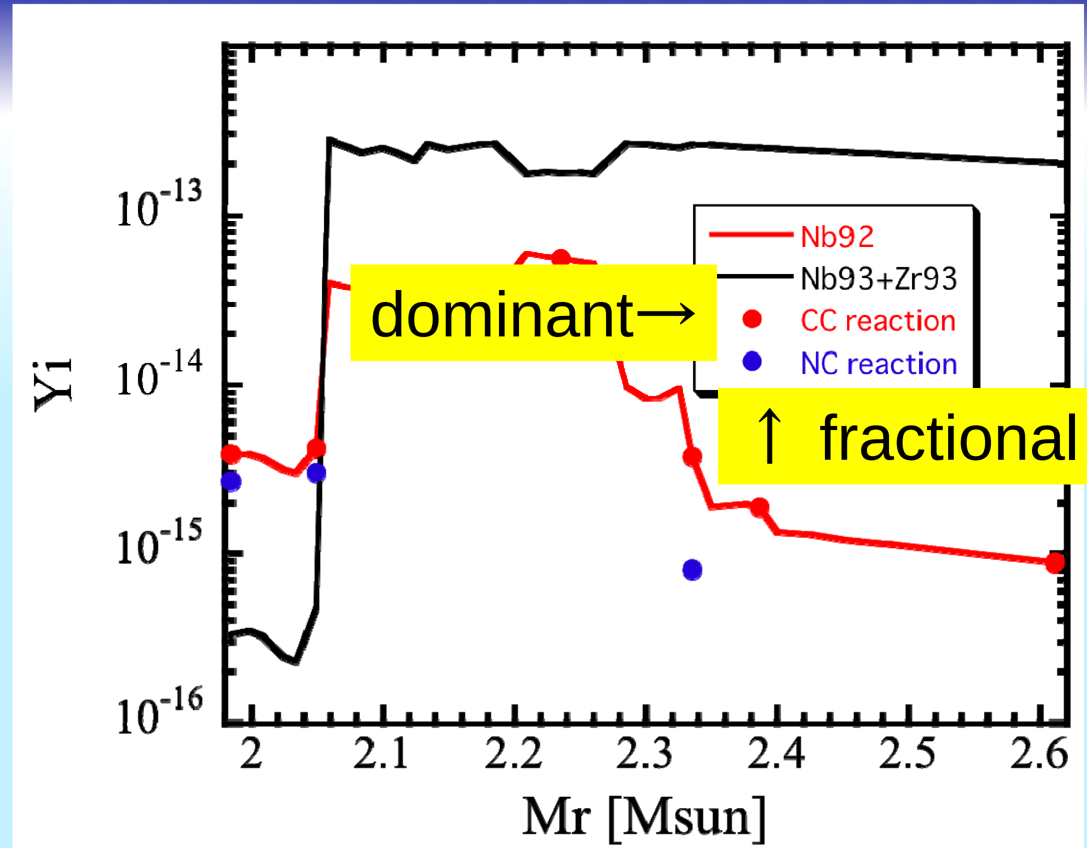
$T_{\nu x} = 6.0$ MeV (heavy ν)

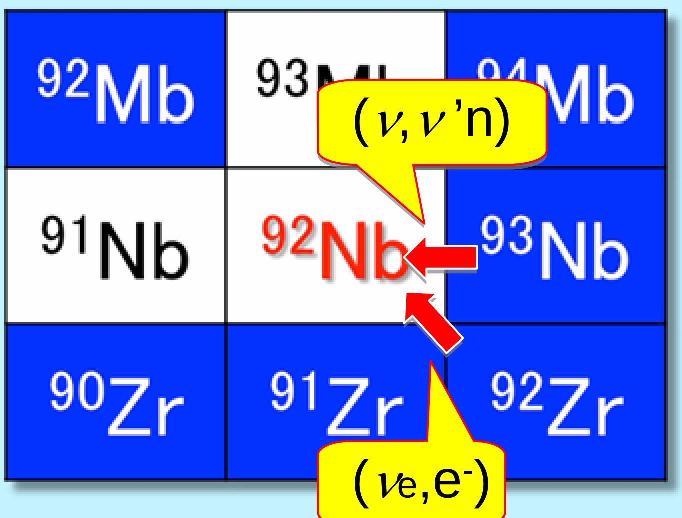
- Neutrino model:
  - $L_{\nu i} \propto (E_\nu/6) \times \exp(-t/\tau)$
  - Fermi distribution ($T_{\nu i}$ = const.)

Results - ^{92}Nb production in ONeMg layer

Charged current reaction:
$^{92}Zr(\nu_e,e^-)^{92}Nb$

Neutral current reaction:
$^{93}Nb(\nu,\nu'n)^{92}Nb$





Gamma process $^{93}Nb(\gamma,n)^{92}Nb$ does not contribute to ^{92}Nb production because ^{92}Nb is unstable.
It can destroy newly synthesized ^{92}Nb.

92Nb as a chronometer during SSF

- $({}^{92}\mathrm{Nb} / {}^{93}\mathrm{Nb})_{\mathrm{SSF}} = ({}^{92}\mathrm{Nb} / {}^{93}\mathrm{Nb})_{\mathrm{SN}\text{-}\nu} \times \exp(-\Delta / \tau)$

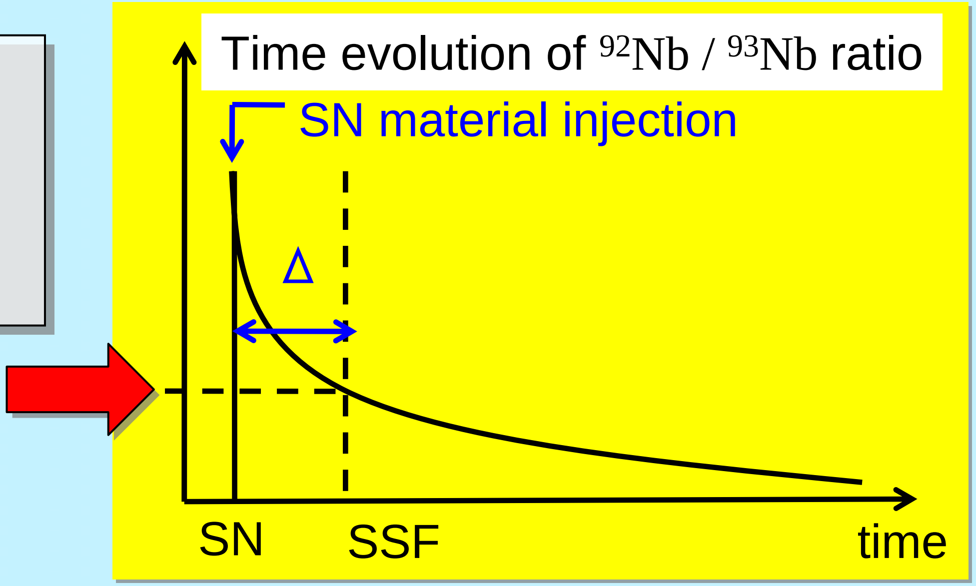
  – $({}^{92}\mathrm{Nb} / {}^{93}\mathrm{Nb})_{\mathrm{SN}\text{-}\nu}$: Nb isotopic ratio derived from our simulation

  – Δ : time delay between the last SN and SSF = 30-100Myr
  (estimated from short-lived r-proc. ${}^{107}\mathrm{Pd}$, ${}^{129}\mathrm{I}$, ${}^{182}\mathrm{Hf}$; Dauphas+'05)

  □ τ : mean life time of ${}^{92}\mathrm{Nb}$ = (35Myr / ln 2)

$({}^{92}\mathrm{Nb} / {}^{93}\mathrm{Nb})_{\mathrm{SSF}}$
$= (\underline{3.5}\text{-}\underline{0.86}) \times 10^{-5}$
for $\Delta = \underline{30}\text{-}\underline{100}$Myr

consistent with $\sim 10^{-5}$
(Schoenbachler+'02,'05)

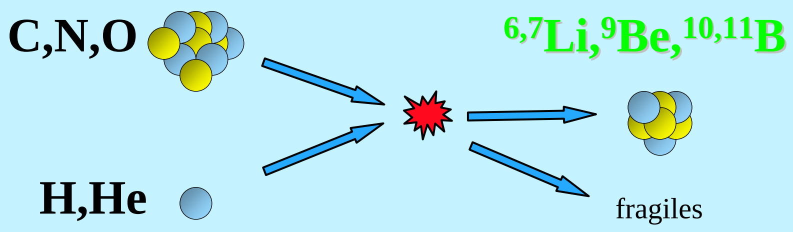


Summary

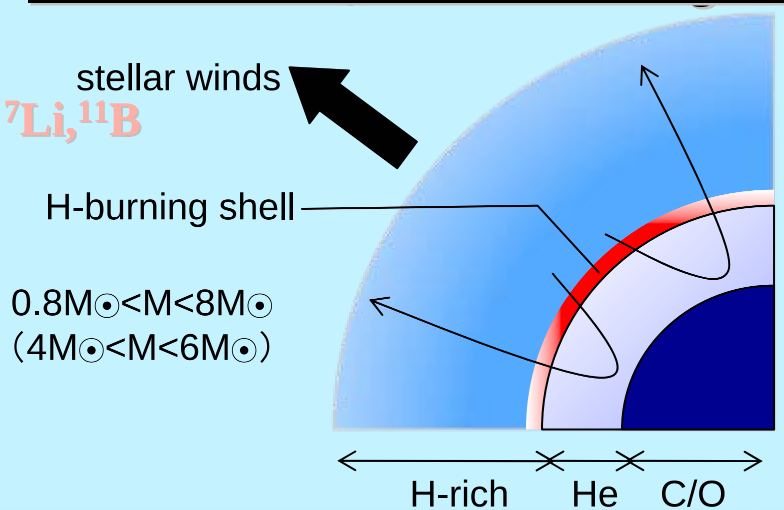
- Neutrinos play a crucial role in supernova explosion mechanism
  - neutrino heating behind a stalled shock wave
- Neutrinos leave characteristic isotopes via the neutrino-process (neutrino-induced nucleosynthesis)
  - possible source of relatively rare elements
- ^{7}Li and ^{11}B production in He/C layers
  - shock heating is negligible
  - but there exist other production sites and entangled with each other
- ^{92}Nb (, ^{138}La, and ^{180}Ta) production in ONeMg layer
  - production and destruction by shock heating (γ,n) is negligible
  - contribution of the neutral current reaction ^{93}Nb(ν,ν'n)^{92}Nb is small
  - charged current reaction ^{92}Zr(ν_e,e$^-$)^{92}Nb is dominant

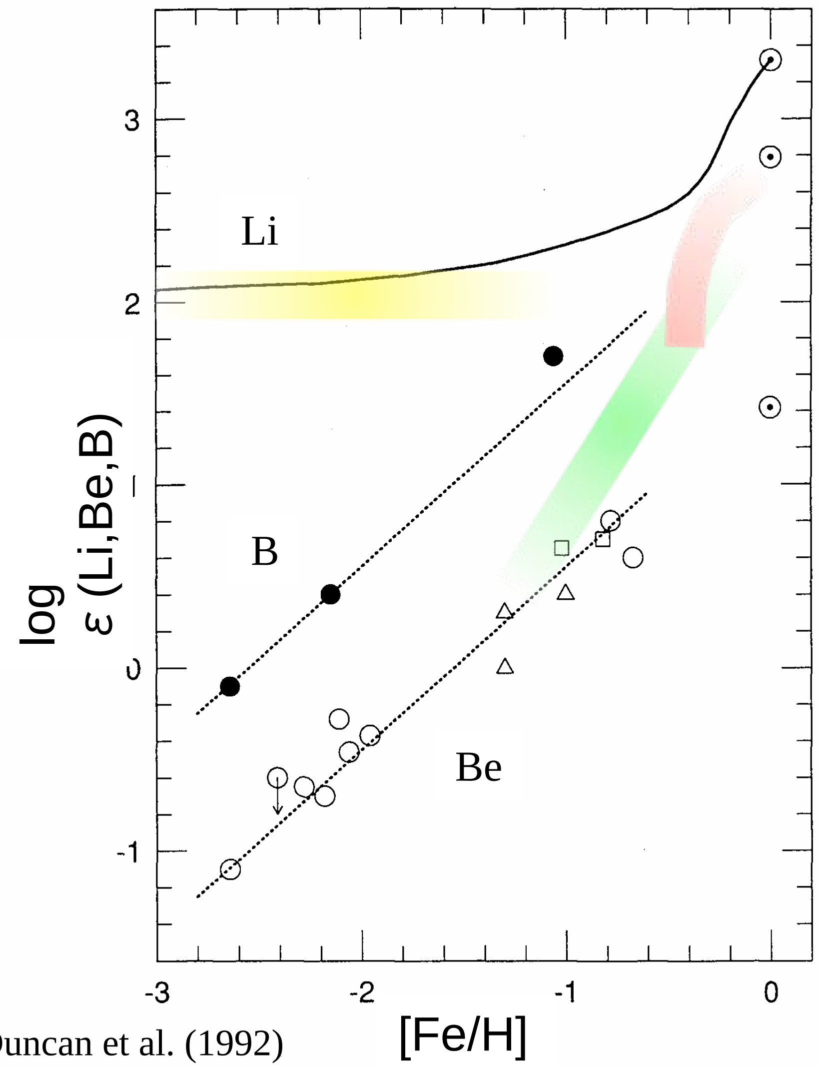
Production Sites of ^{6,7}Li, ^{9}Be, ^{10,11}B

- **Big Bang Nucleosynthesis**
  - Primordial ^{7}Li (Spite plateau)
- **Cosmic-ray interactions**
  - Spallation reactions



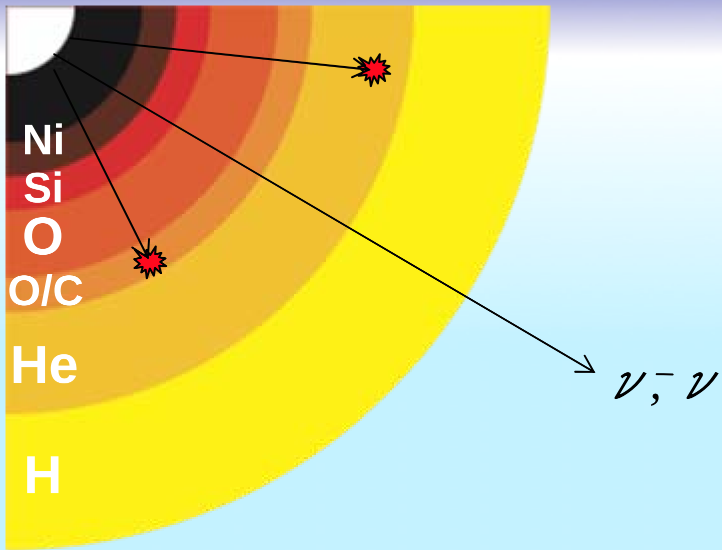
- **AGB stars, low mass giants**





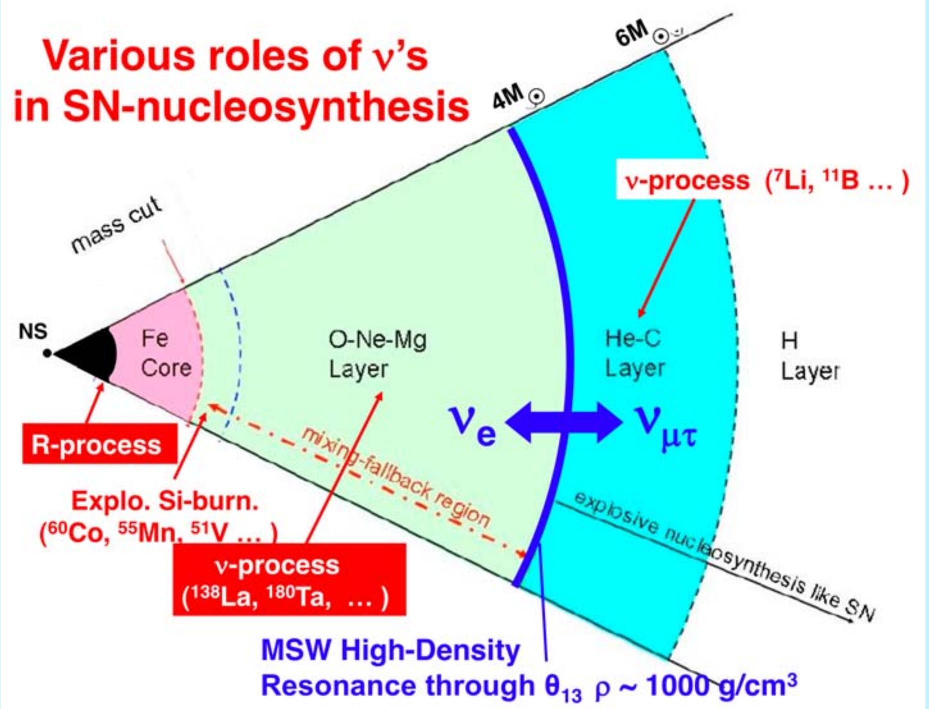
Duncan et al. (1992)

Neutrino-induced Nucleosynthesis



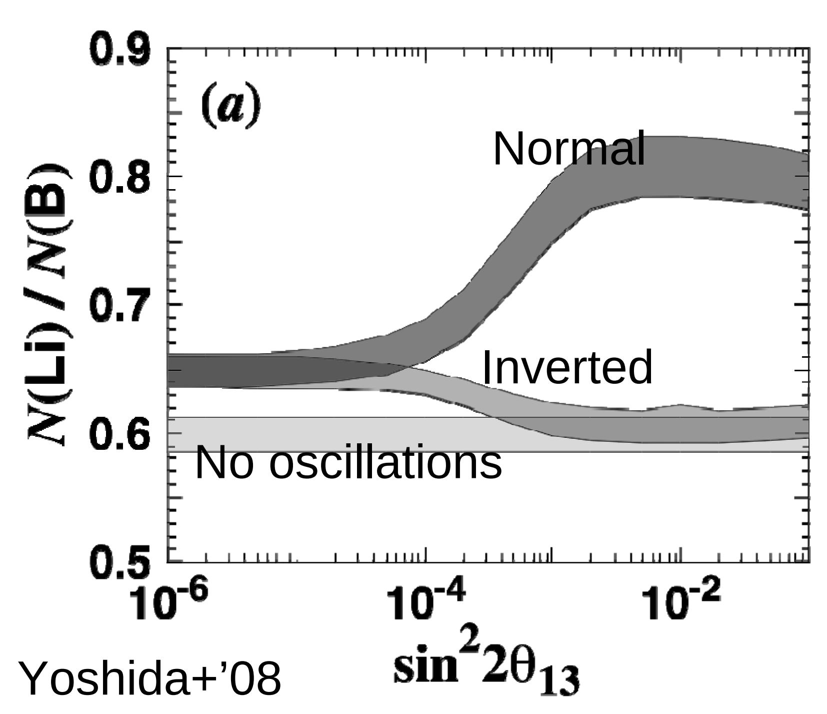
- Huge number of neutrinos ($>10^{58}$!)
- $\sigma_\nu \sim O(10^{-42})$ cm^2
- Some interact with materials and induce nucleosynthesis
  → "ν-process" (Woosley+ 1990)
- ^{7}Li, ^{11}B, ^{19}F, ^{138}La, ^{180}Ta

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



SN neutrino properties deduced from Li & B

- Production site is out of the resonance radius.
  - mixing angle and hierarchies
- We have to squeeze out information from entangled stellar abundances.



Yoshida+'08