Roles of Neutrino in Core-collapse Supernovae

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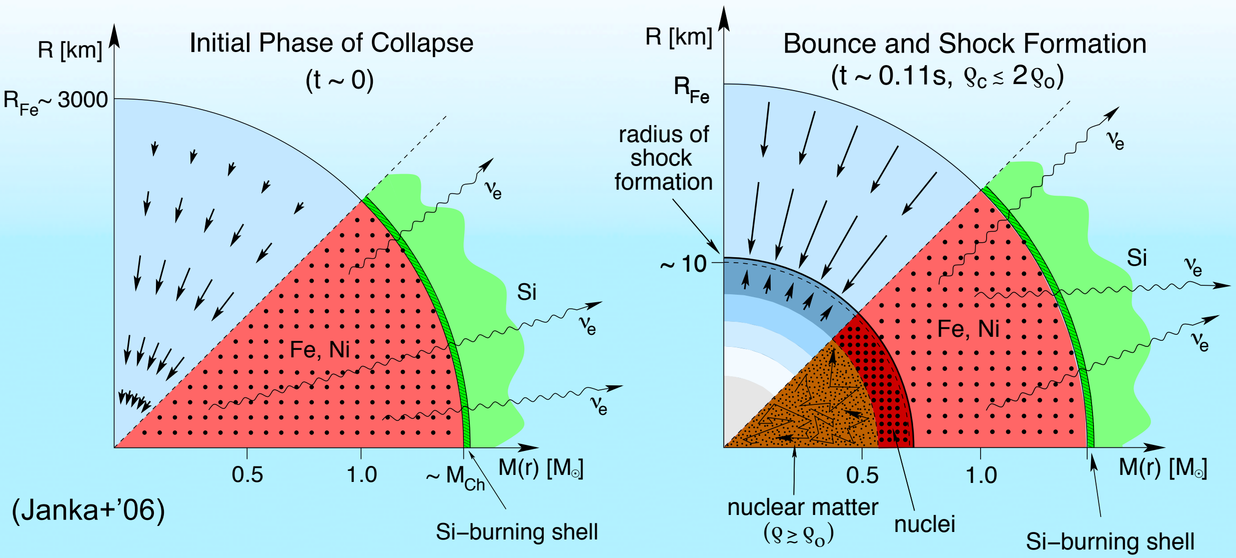
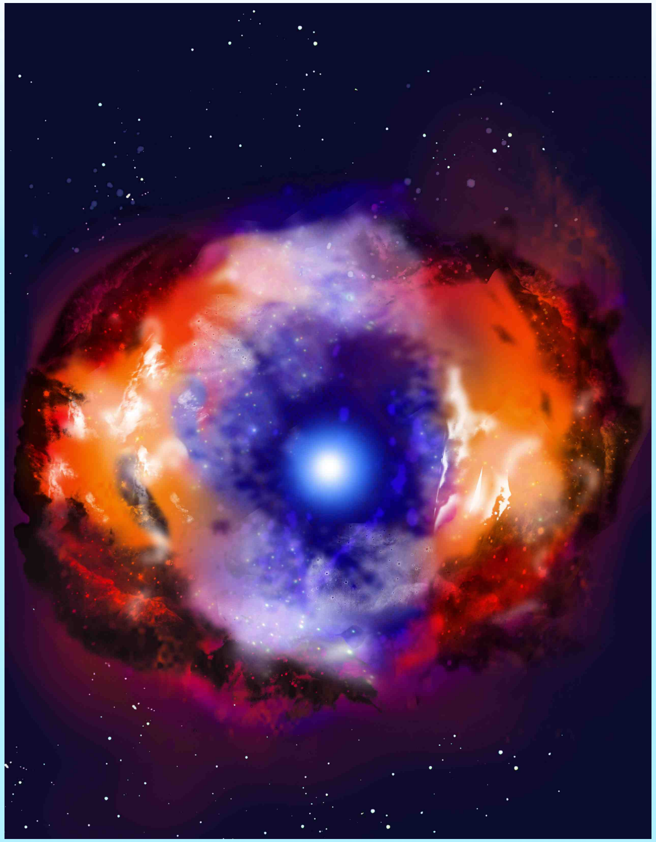
Outline

- Core-collapse supernova explosion
  - collapse, bounce, and stalled
- Neutrino-driven explosion model
  - by neutrino heating (and cooling)
  - with some hydrodynamic instabilities
- Neutrino-induced nucleosynthesis
  - Light elements (Li & B)
  - Heavy elements (Nb, La, & Ta)
- Summary

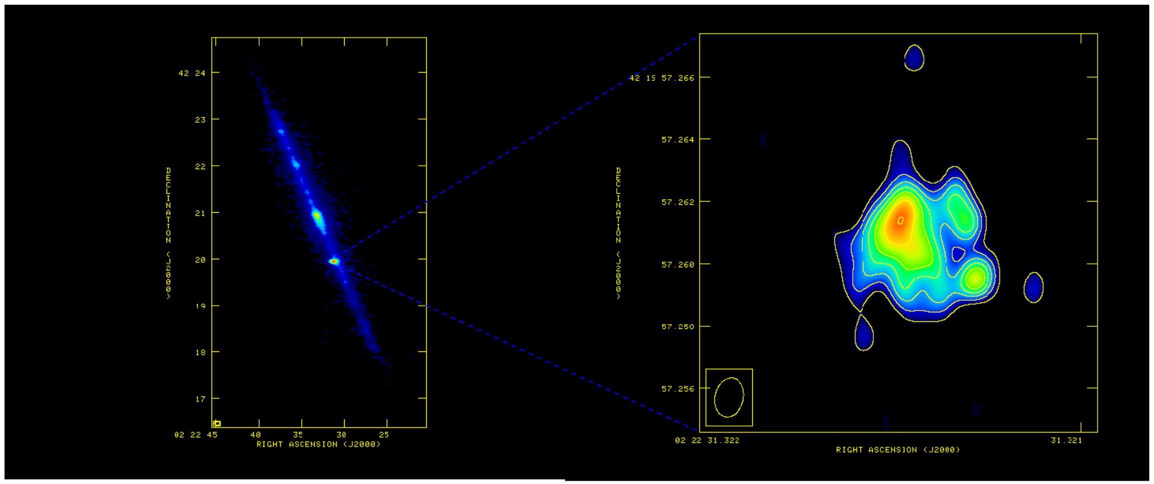
Core-collapse Supernova Explosions



(Janka+'06)



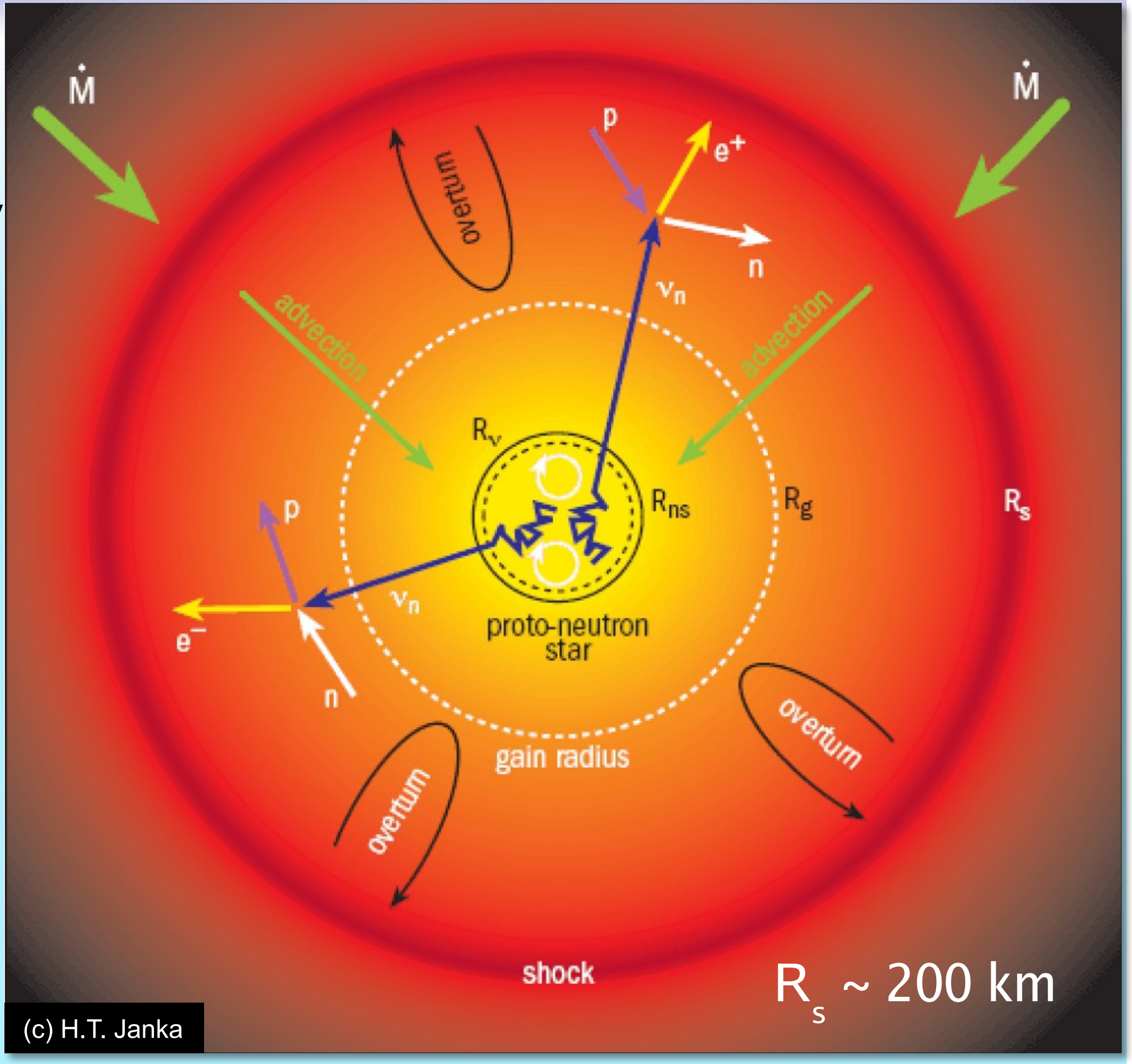
An artist's impression of SN 1986.
(c) N. Bartel, M. Bietenholz, G. Arguner



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

Neutrino-driven SN explosion mechanism

- Gravitational binding energy of the collapsing core (>～10^{53} erg) >> Typical SN explosion energy (～10^{51} erg)
- Neutrinos carry away most of the energy, but ..
- A small fraction of emitted neutrinos can interact with the matter behind a shock, deposit energy, and revive the stalled shock wave.
- Hydrodynamic instabilities enhance the neutrino heating.



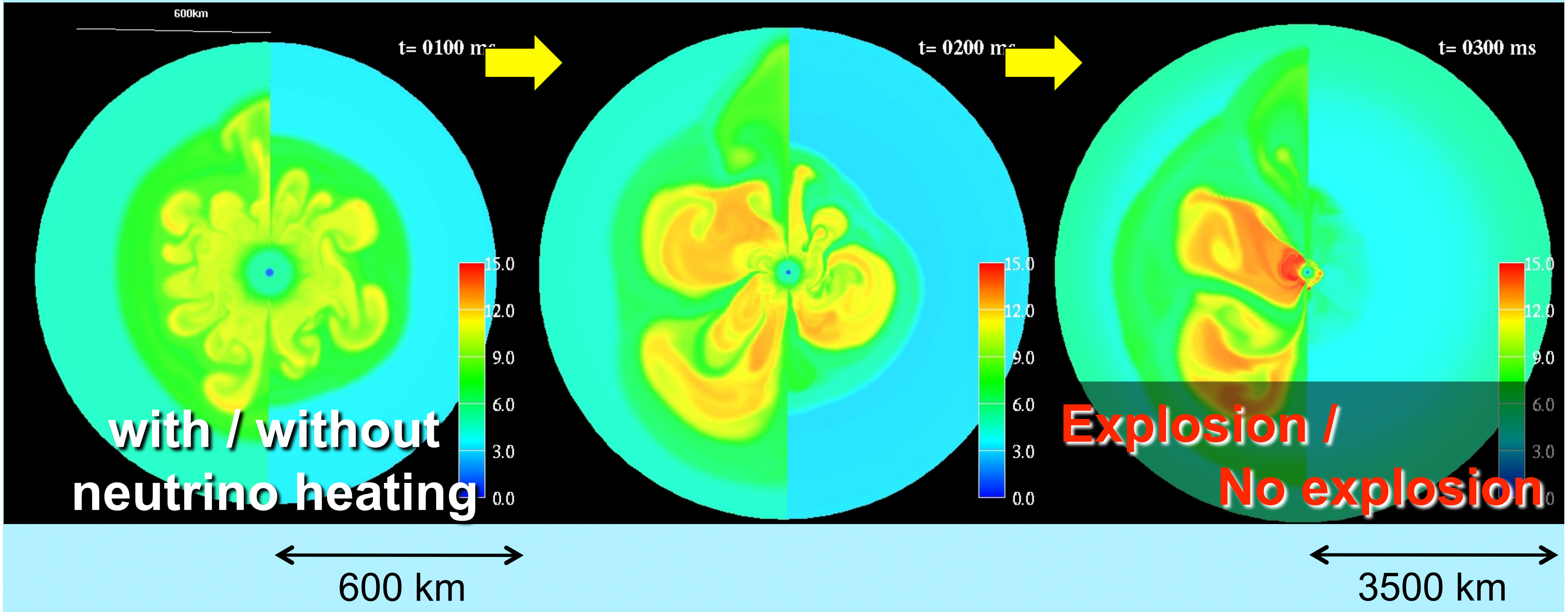
Neutrino-induced explosion model (2-D)

Snap shots of entropy distributions from our simulations with (*left*) and without (*right*) neutrino heating.

Example) $L\nu_e = L_0 \exp(-t_{pb}/t_d) \leftarrow L_0 = 2.4\times10^{52}$ erg/s, $t_d = 1.1$ s

Time after core bounce:

100 ms 200 ms 300 ms

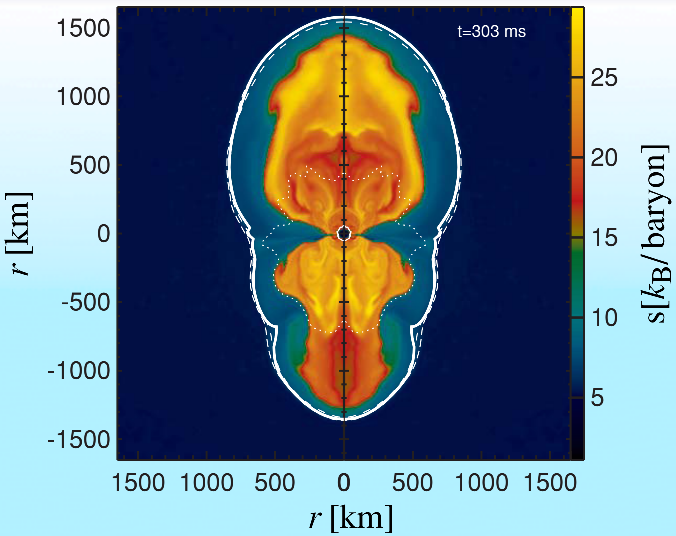


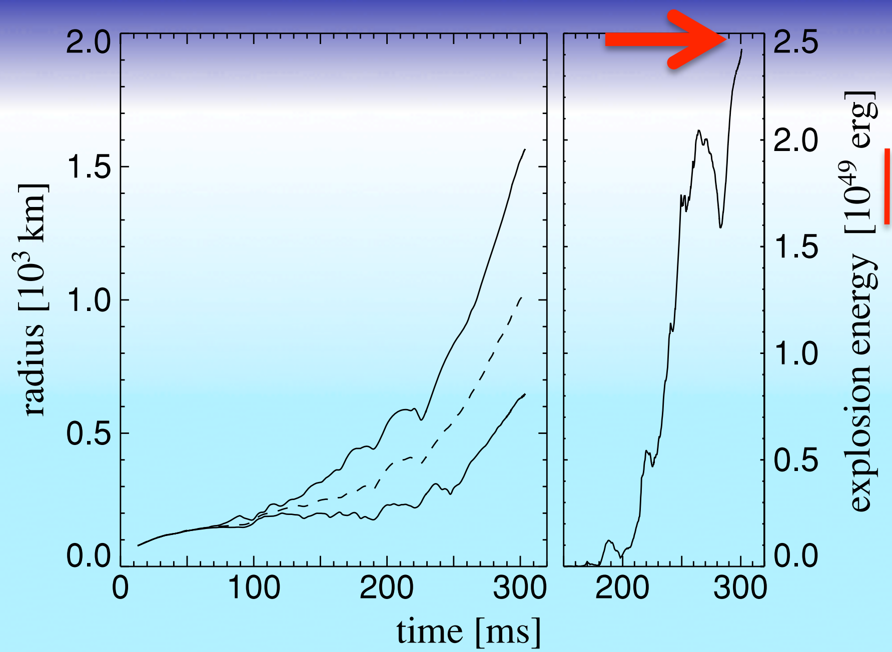
Neutrino-induced explosion model (3-D)

- 3-dimensional MPI-AMR code
- High-performance computer (XT4) @ NAOJ
- KN+ (in preparation)
- => Movie

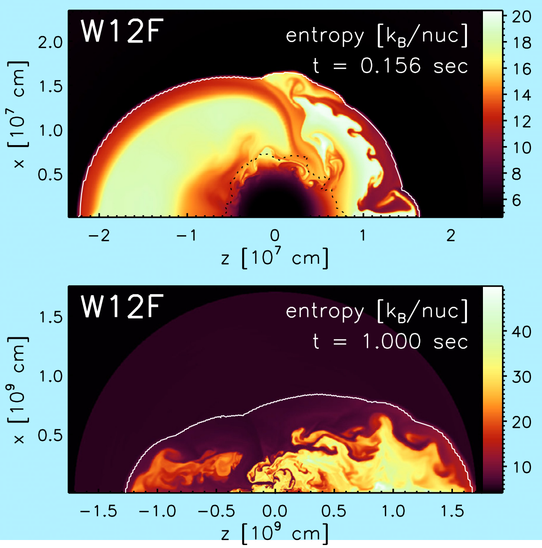
Previous studies of SASI+ν-induced explosion

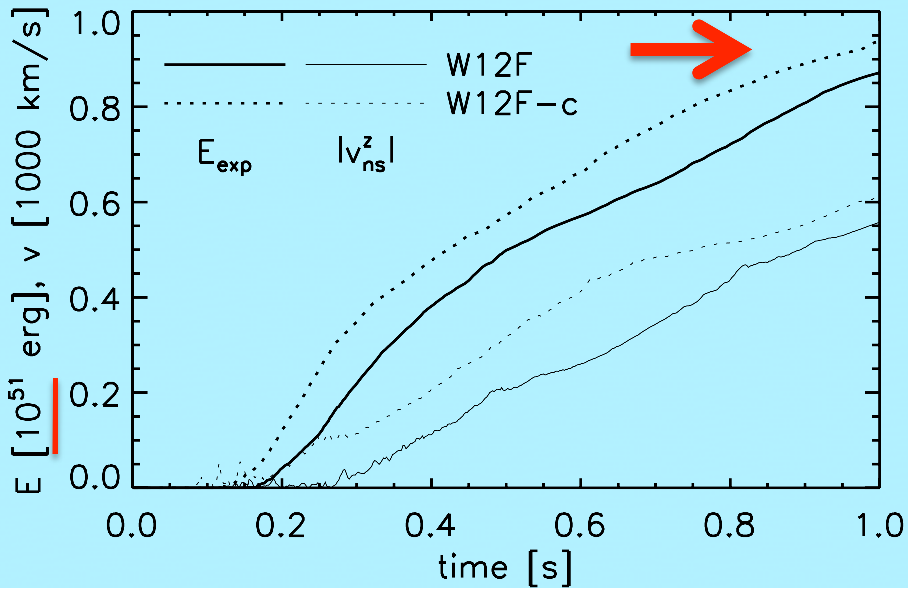
- Marek & Janka (2009)





- Scheck et al. (2008)

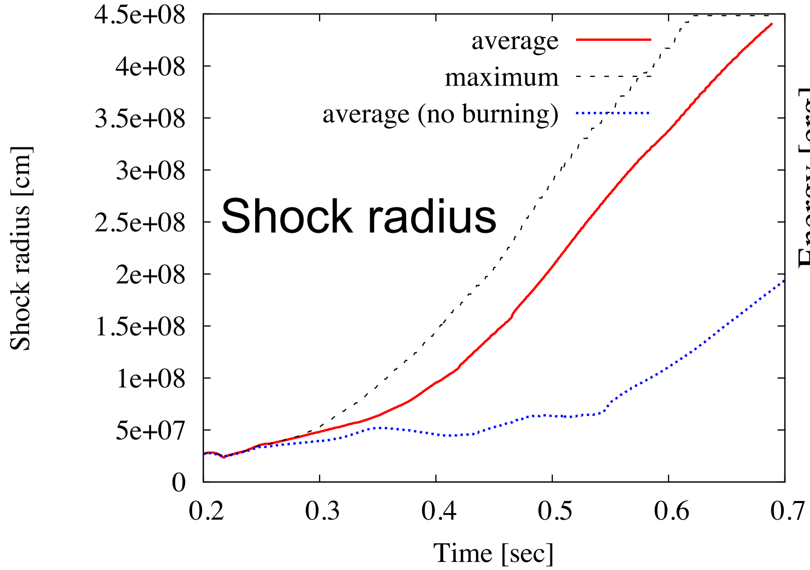


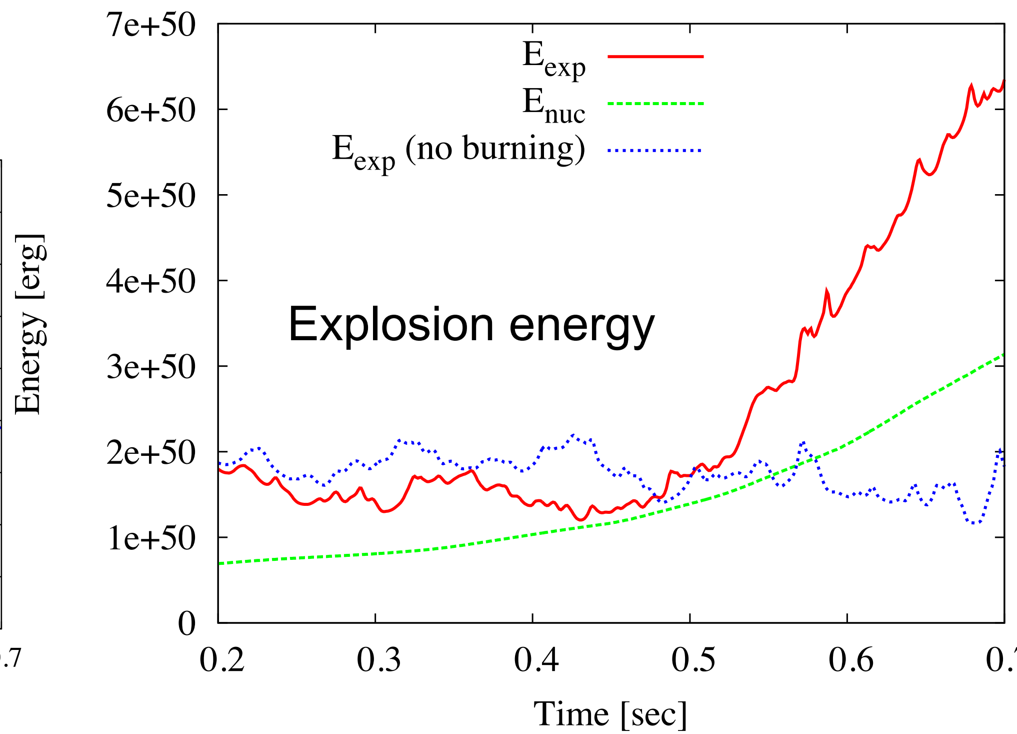


Contribution of nuclear reactions to explosion energy

- Explosion energy
  - red: explosion energy = $\Sigma(Ekin + Eint + Egrv)_i$ for vr_i & $Etot_i > 0$
  - green: net burning energy
  - blue-dotted: explosion energy in the case without nuclear burning

Ln_0 = 2.1e52 [erg/s]
t_d = 2.0 [s]





Short summary

- We can reproduce SN explosion based on neutrino-heating model if we assume high neutrino luminosity (and simple treatment of neutrino transport).

How can we solve the full Boltzmann equation?

Theory

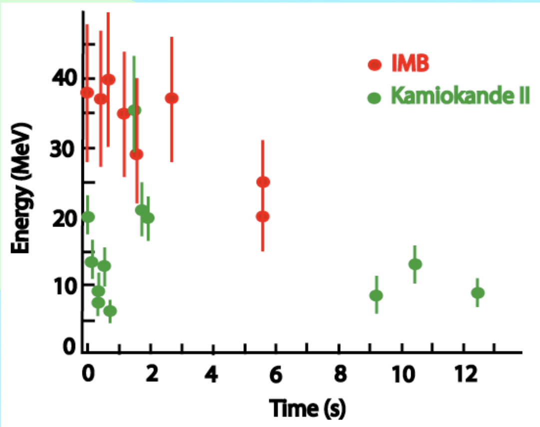
With some assumptions: Fermi distribution, exponential decay, ..

Parameter study

REAL properties of SN neutrinos (luminosity, spectra)

Observations

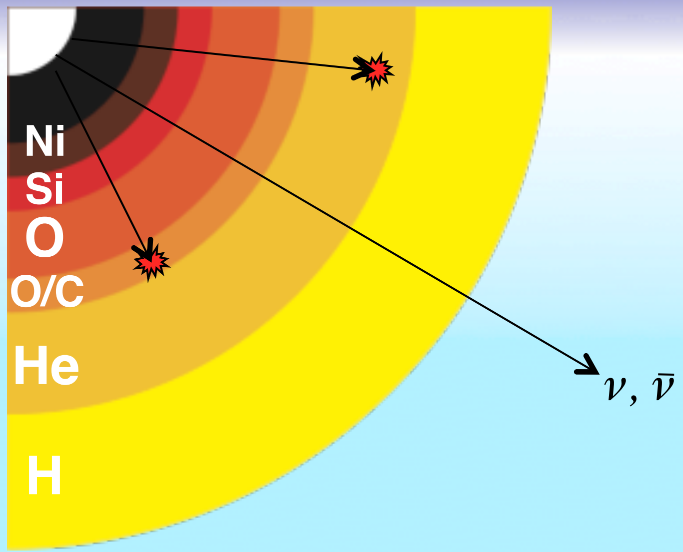
When will the next Galactic SN explode?



Nucleosynthesis

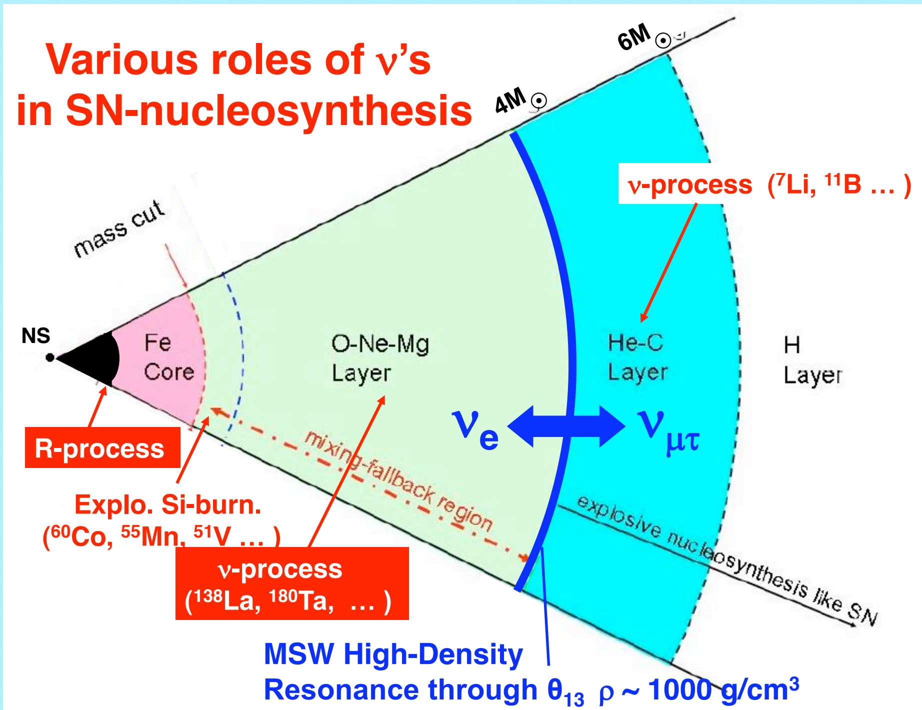
The neutrino-process

Neutrino-induced Nucleosynthesis

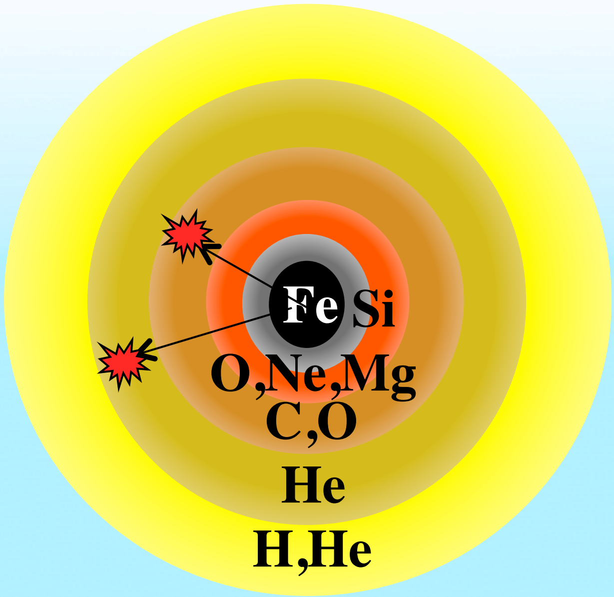


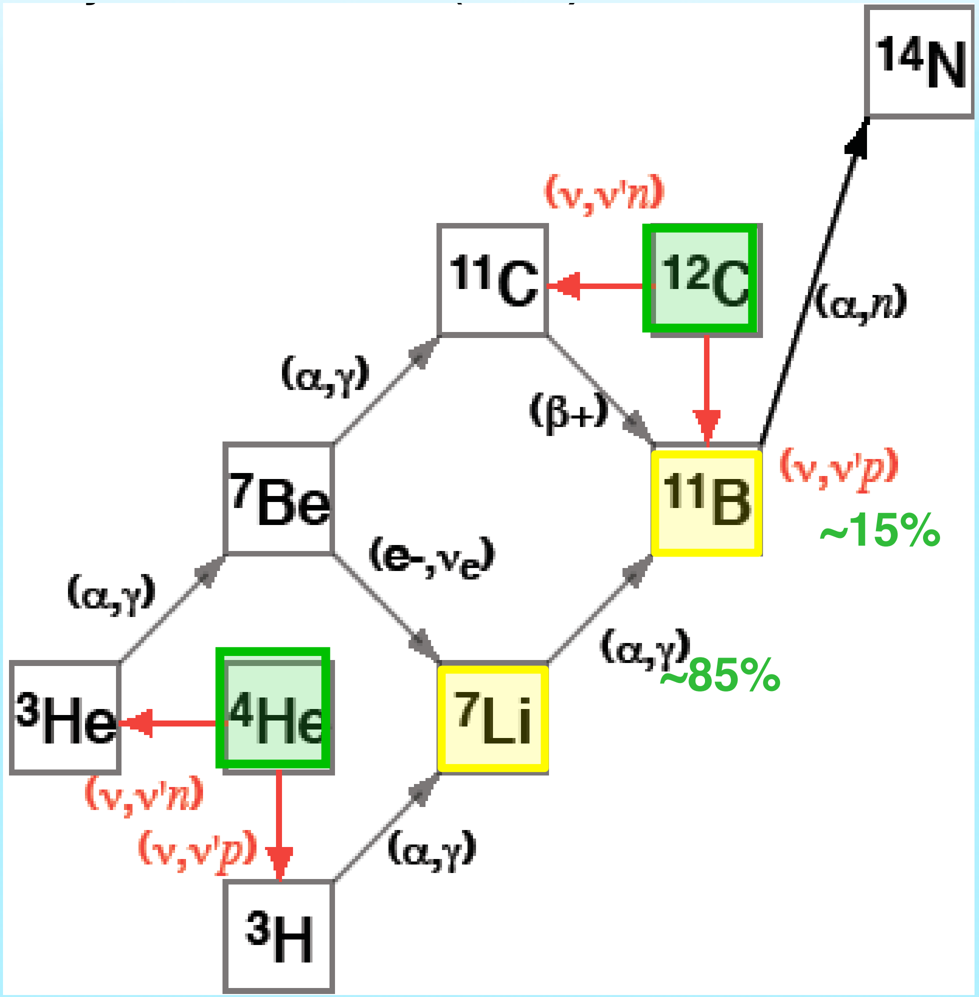
- Huge number of neutrinos (>10^{58} !)
- $\sigma_\nu \sim O(10^{-42})$ cm^2
- Some interact with materials and induce nucleosynthesis
  → "ν-process" (Woosley+ 1990)
- **^{7}Li, ^{11}B, ^{19}F, ^{138}La, ^{180}Ta**

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



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





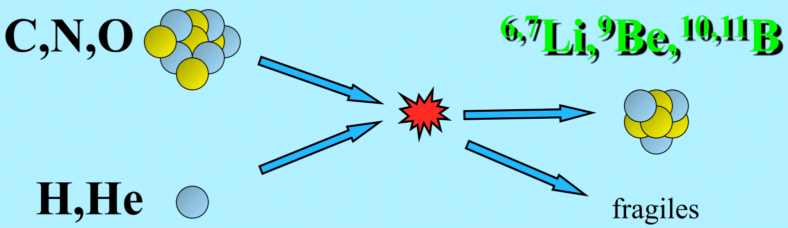
Example)

^{4}He(ν, $\nu'p$)^{3}H(α, γ) ^{7}Li

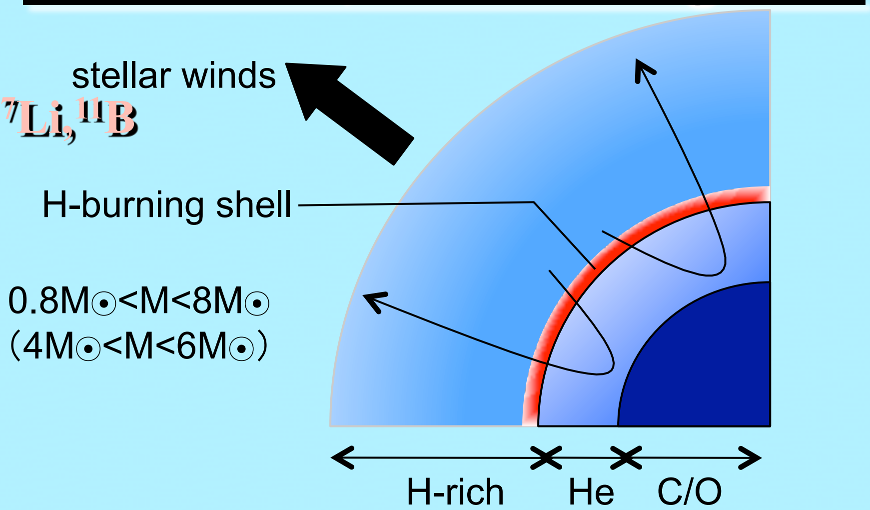
^{12}C(ν_e, e^+n)^{11}B

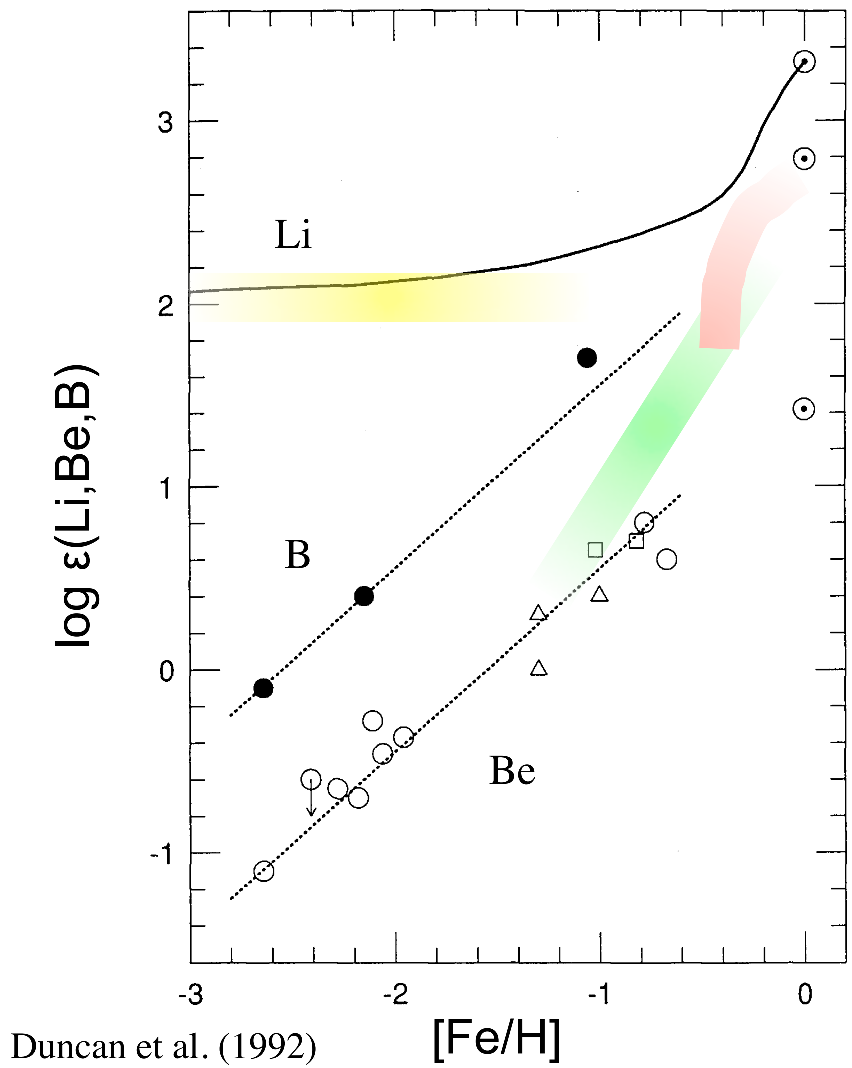
Production Sites of ^{6,7}Li, ^{9}Be, ^{10,11}B

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



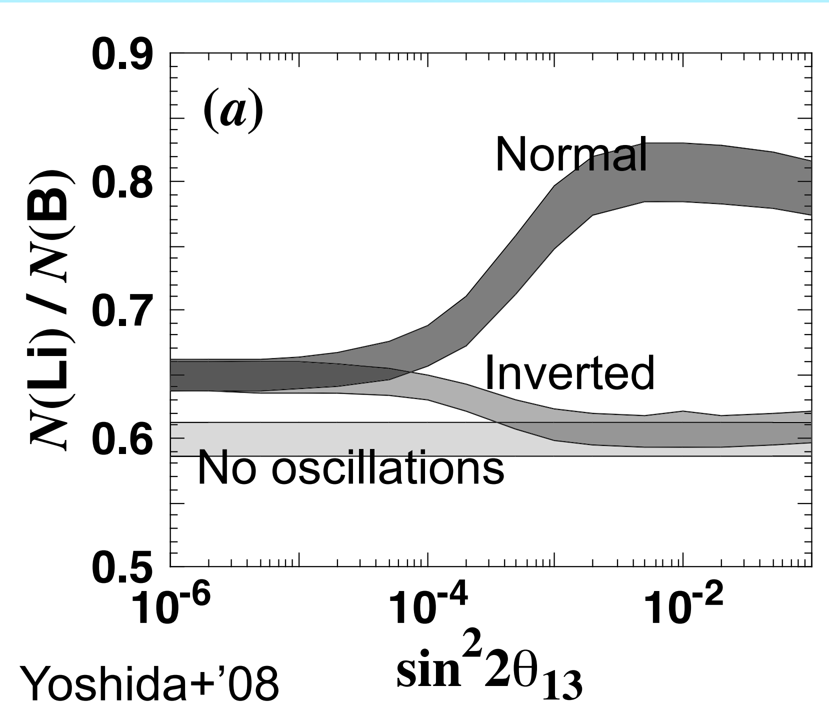
- **AGB stars, low mass giants**

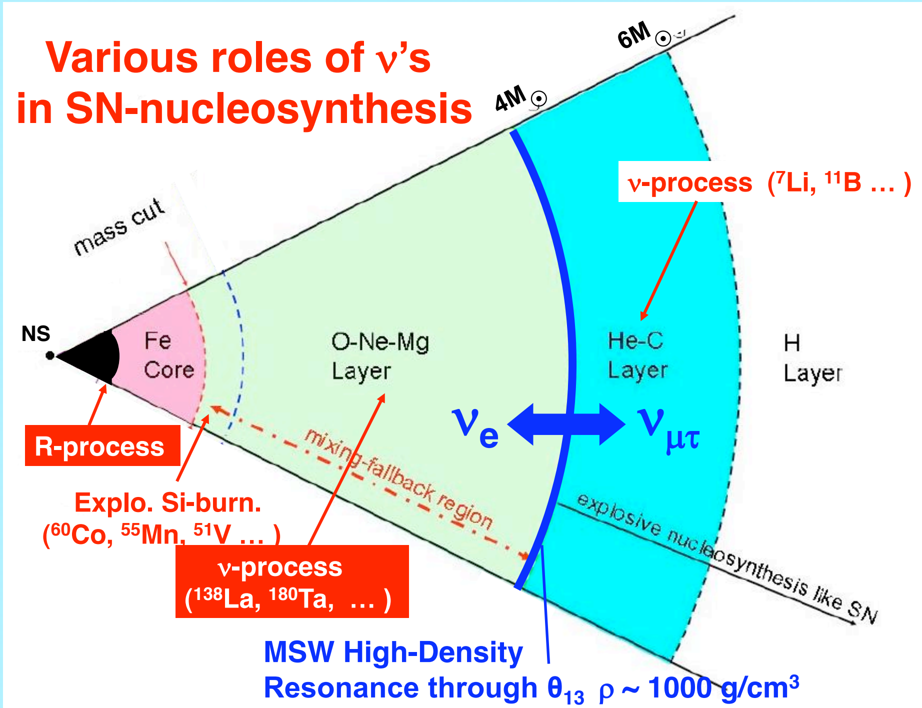




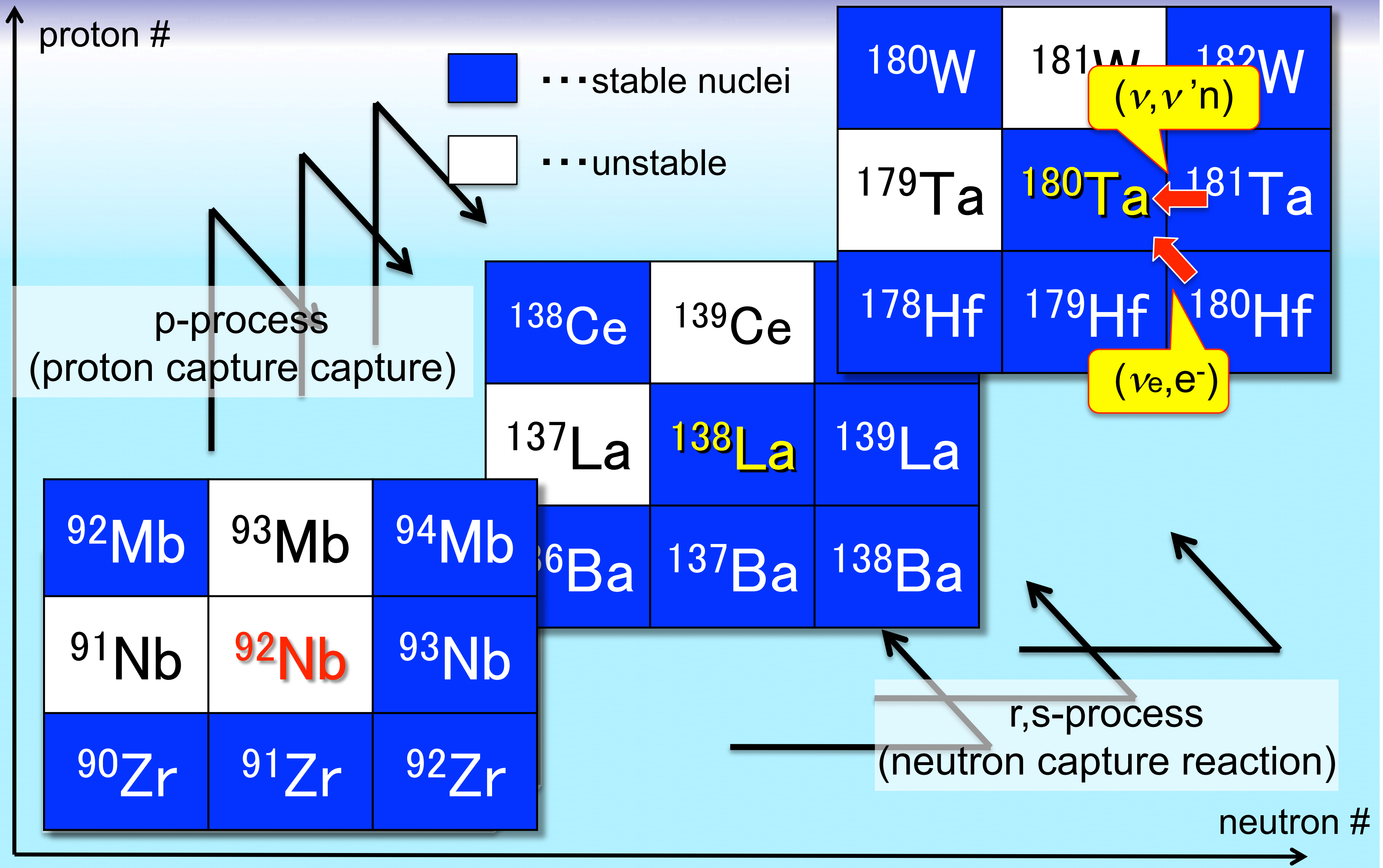
SN neutrino properties deduced from Li & B

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





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

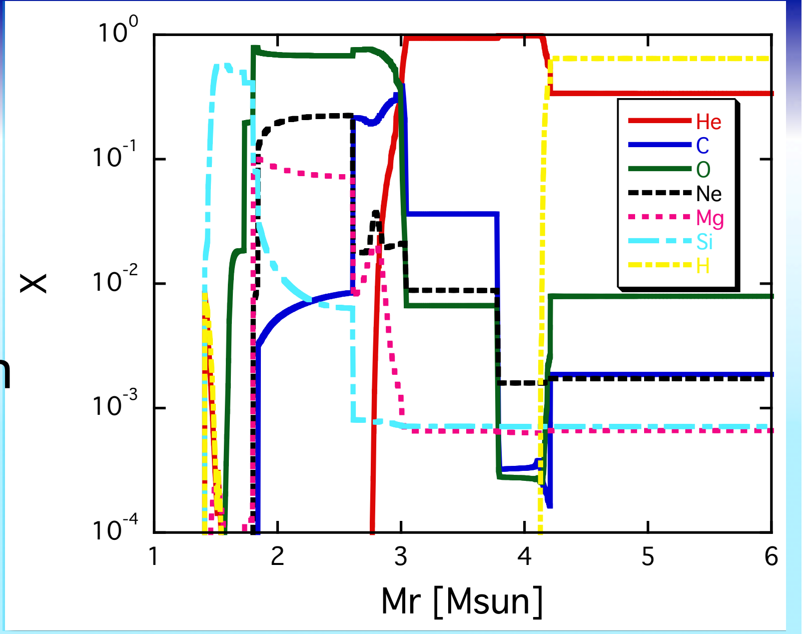


Why niobium-92?

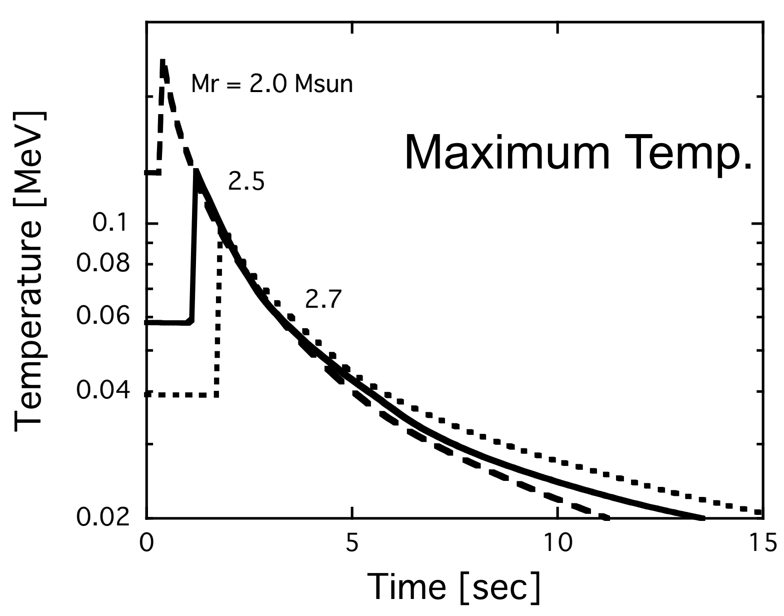
- Radioactive **^{92}Nb** :
  - observed in meteorites as its daughter nucleus ^{92}Zr
  - useful as a chronometer during the solar system formation
  - unlikely produced through p-process and gamma-process
- We propose that the **ν-process** can produce ^{92}Nb !
  - similar environment to ^{138}La & ^{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 (CCSN)

Numerical scheme (1)

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

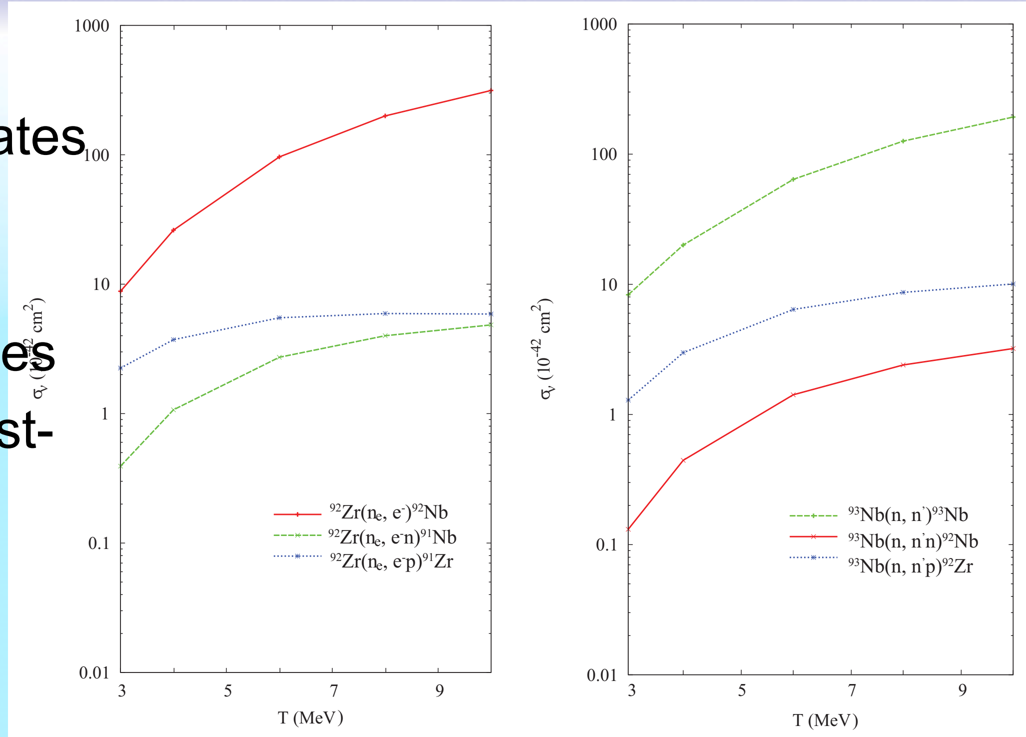


- Hydrodynamics:
  - 1-D spherical code
  - $E_{ex} = 10^{51}$ ergs



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

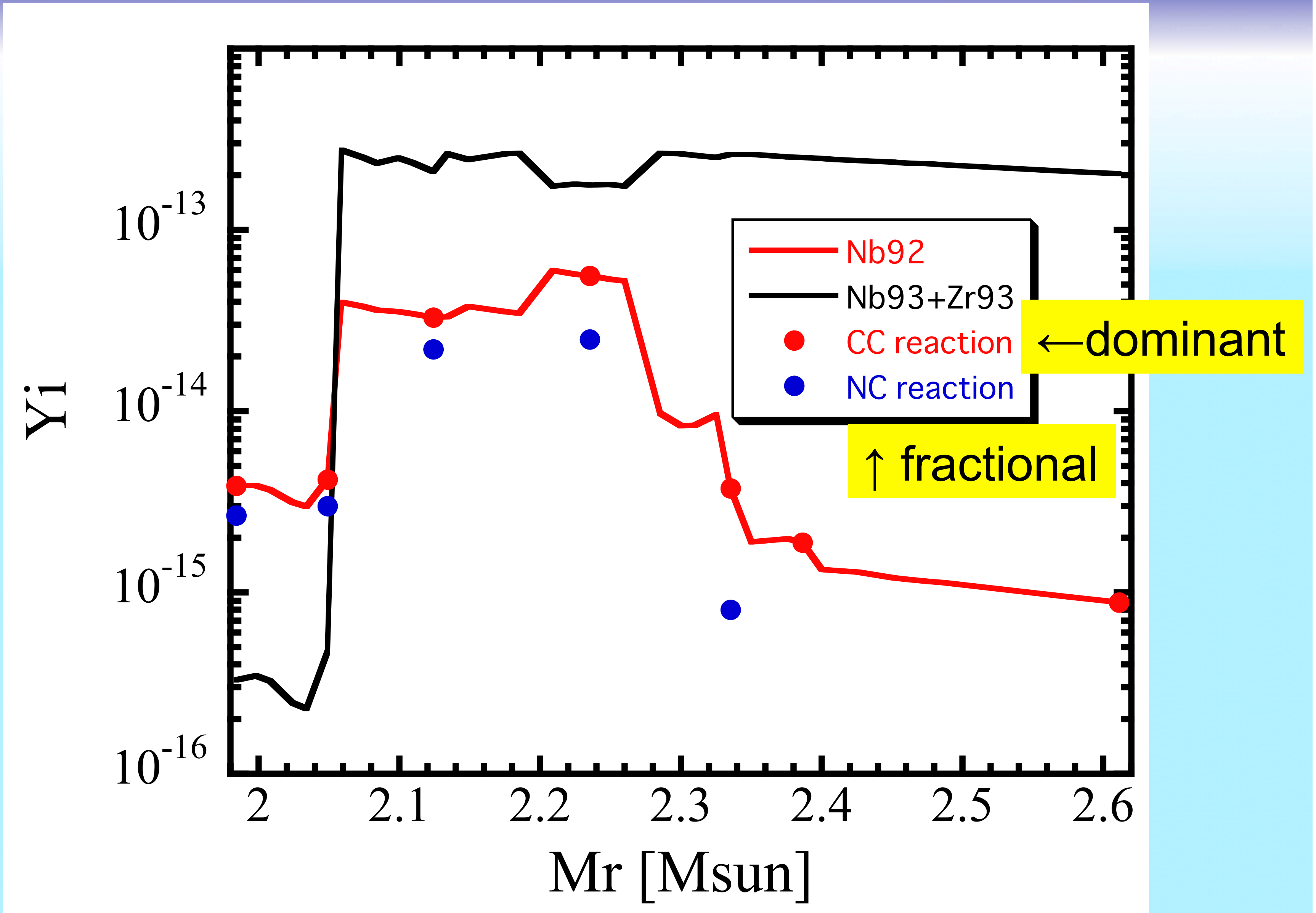
E_ν : total neutrino energy
= 3×10^{53} ergs

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



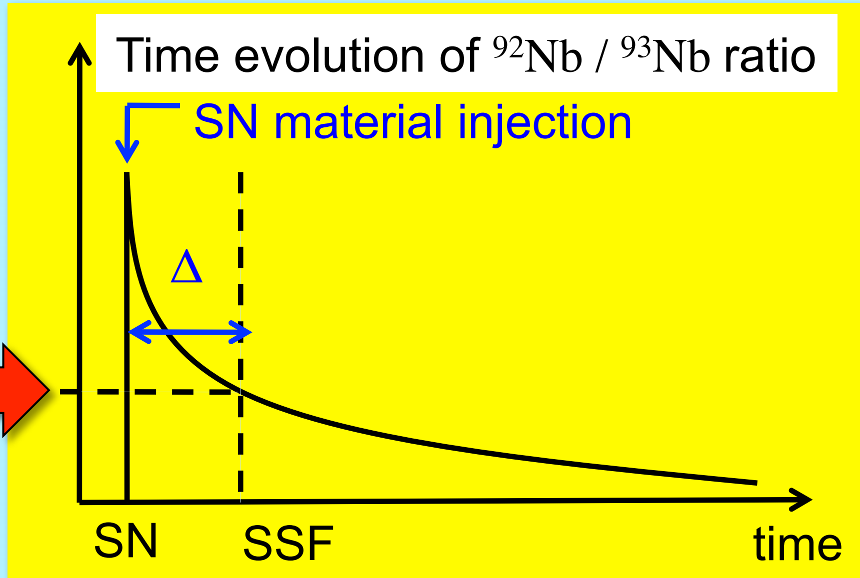
92Nb as a chronometer during SSF

- $(^{92}\mathrm{Nb} / ^{93}\mathrm{Nb})_{SSF} = (^{92}\mathrm{Nb} / ^{93}\mathrm{Nb})_{SN\text{-}\nu} \times \exp(-\Delta / \tau)$
  - $(^{92}\mathrm{Nb} / ^{93}\mathrm{Nb})_{SN\text{-}\nu}$: 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}Pd, ^{129}I, ^{182}Hf ; Dauphas+'05)
  - τ: mean life time of ^{92}Nb = (35Myr / ln 2)

$(^{92}\mathrm{Nb} / ^{93}\mathrm{Nb})_{SSF} = (3.5\text{-}0.86) \times 10^{-5}$

for Δ = 30-100Myr

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



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With some assumptions:
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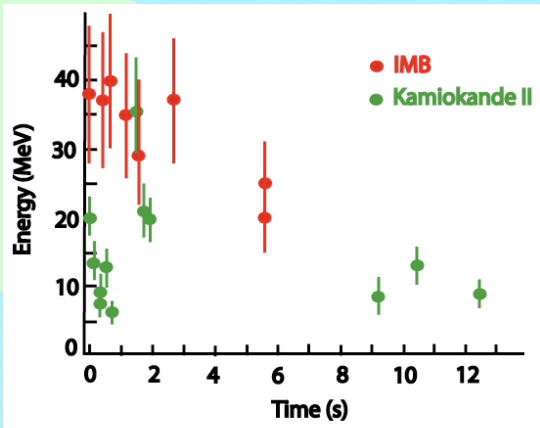

<u>Nucleosynthesis</u>

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