Neutrinos and Nucleosynthesis

The effect of neutrinos on nucleosynthesis in core-collapse supernovae

by Franziska Treffert

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- Core-Collapse Supernovae and Nucleosynthesis
- Neutrino Matter Interactions
- Proton-to-Nucleon Ratio
- Nucleosynthesis
  - Neutrino driven Winds
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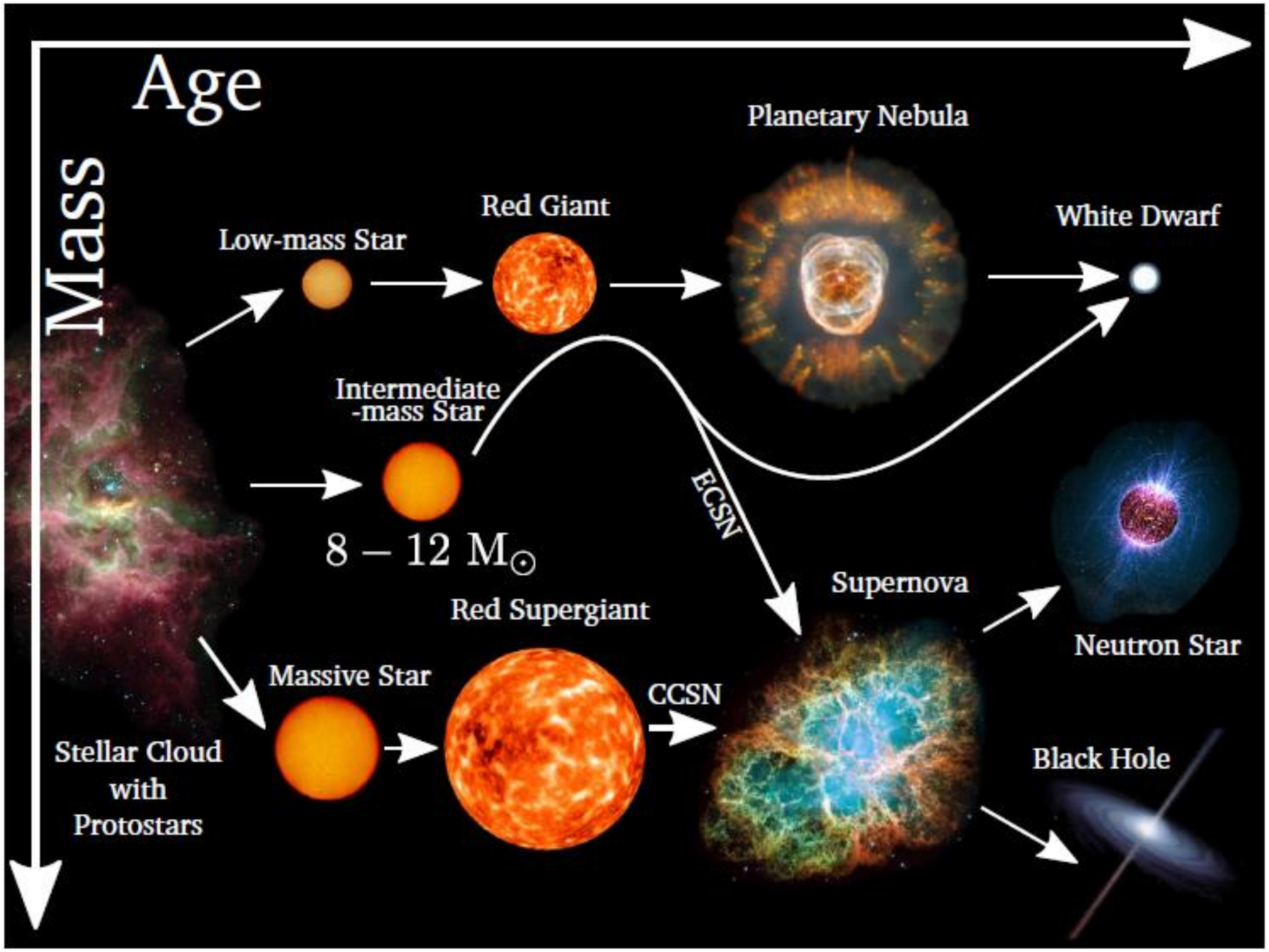
Stellar Evolution



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Core-Collapse Supernova

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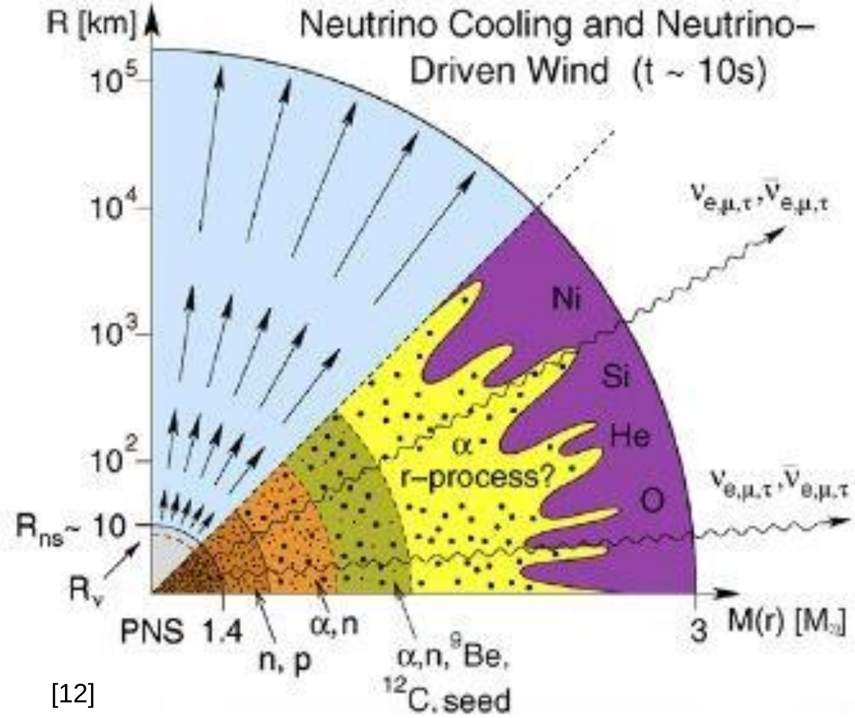
- collapse stops when nuclear densities reached
- shock triggers explosion
- emission of 10^{59} neutrinos from the cooling core of ~10 MeV
- neutrinos can influence the ongoing nucleosynthesis



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Nucleosynthesis

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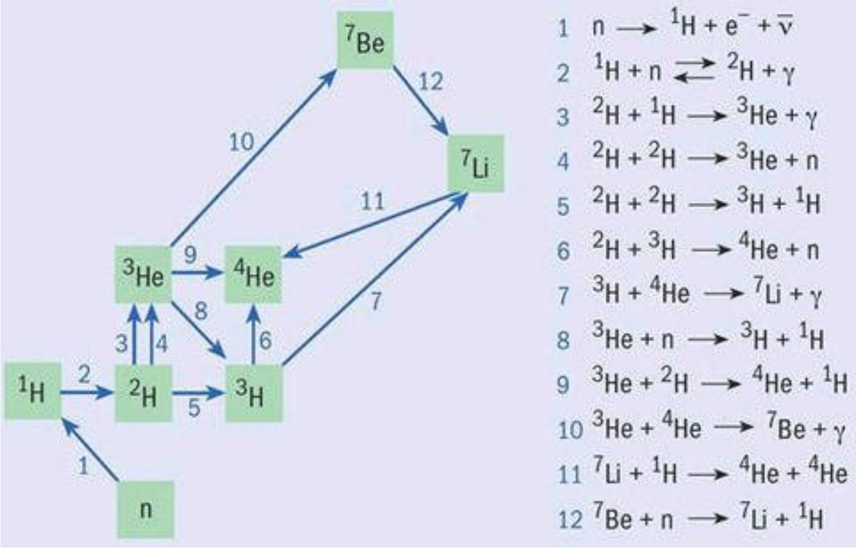
- **Big Bang Nucleosynthesis**
  - first 3 minutes after Big Bang
  - mainly H and He



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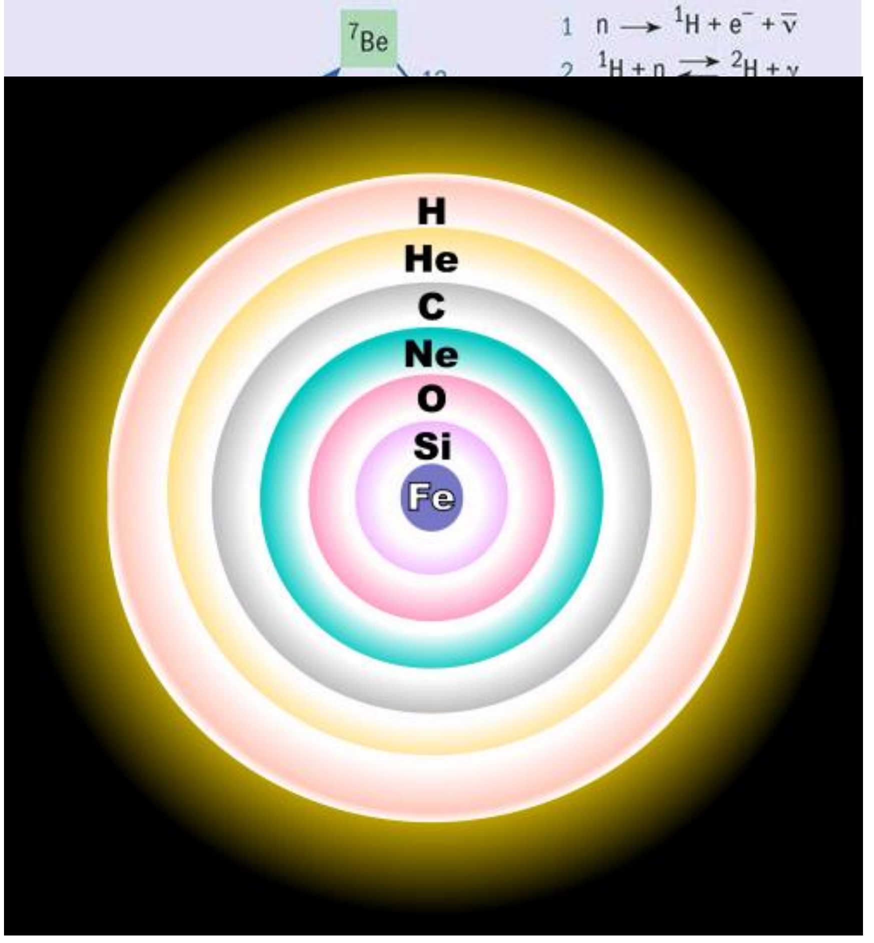
Nucleosynthesis

- **Big Bang Nucleosynthesis**
  - first 3 minutes after Big Bang
  - mainly H and He

- **Stellar Nucleosynthesis**
  - creation of nuclei up to Fe



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Nucleosynthesis

- **Big Bang Nucleosynthesis**
  - first 3 minutes after Big Bang
  - mainly H and He
- **Stellar Nucleosynthesis**
  - creation of nuclei up to Fe
- **Supernova Nucleosynthesis**
  - nuclei heavier than Fe produced

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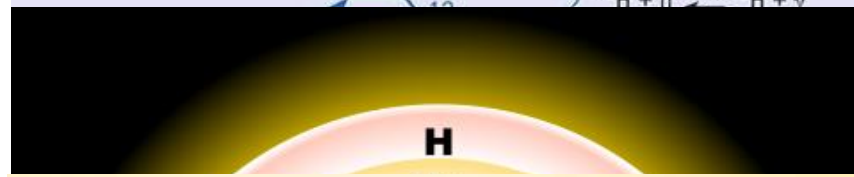

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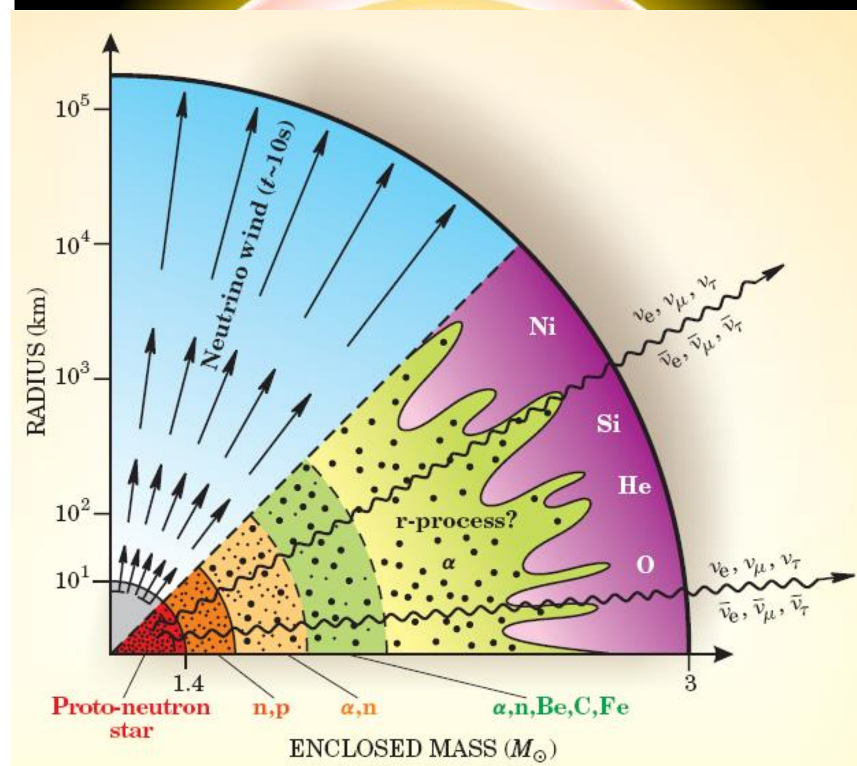

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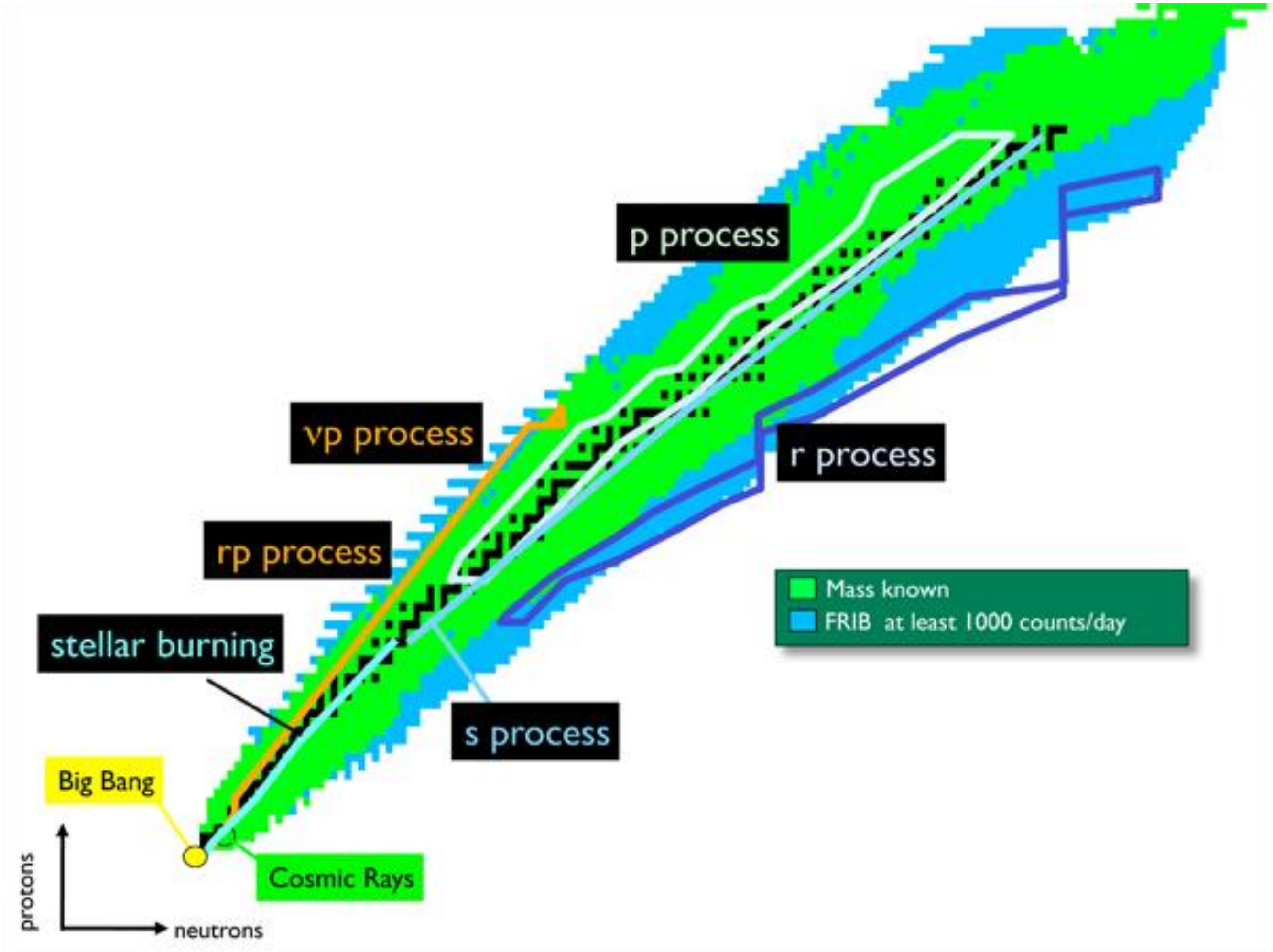
Nucleosynthesis



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charged-current
W^+ , W^-

neutral-current
Z^0

Neutrino Matter Interactions

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- charged-current interactions
  - interactions near the proto neutron star

$$n + \nu_e \leftrightarrow p + e^-$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

  - interactions in the outer shells

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

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

Neutrino Matter Interactions

- neutral-current interactions
  - neutrino Bremsstrahlung

$$N + N \to N + N + \overline{\nu} + \nu$$

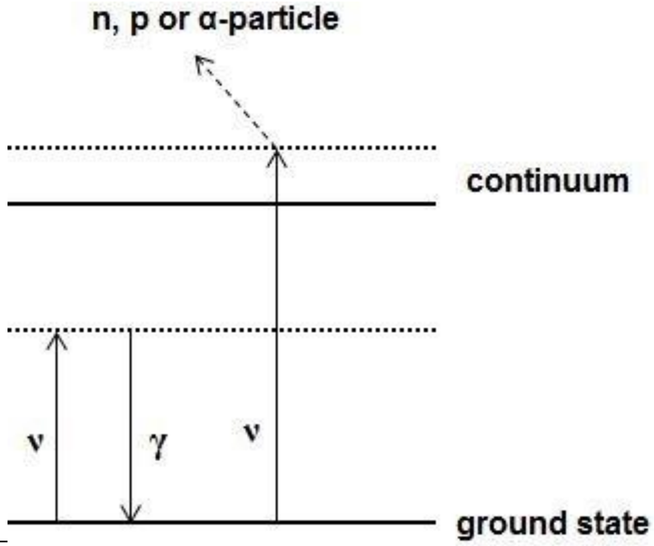
  - neutrino pair production

$$A^*(Z,N) \to A(Z,N) + \bar{\nu} + \nu$$

  - neutrino scattering

$$\nu + A \to \nu + A^*$$

    - A* decays



Neutrino Matter Interactions

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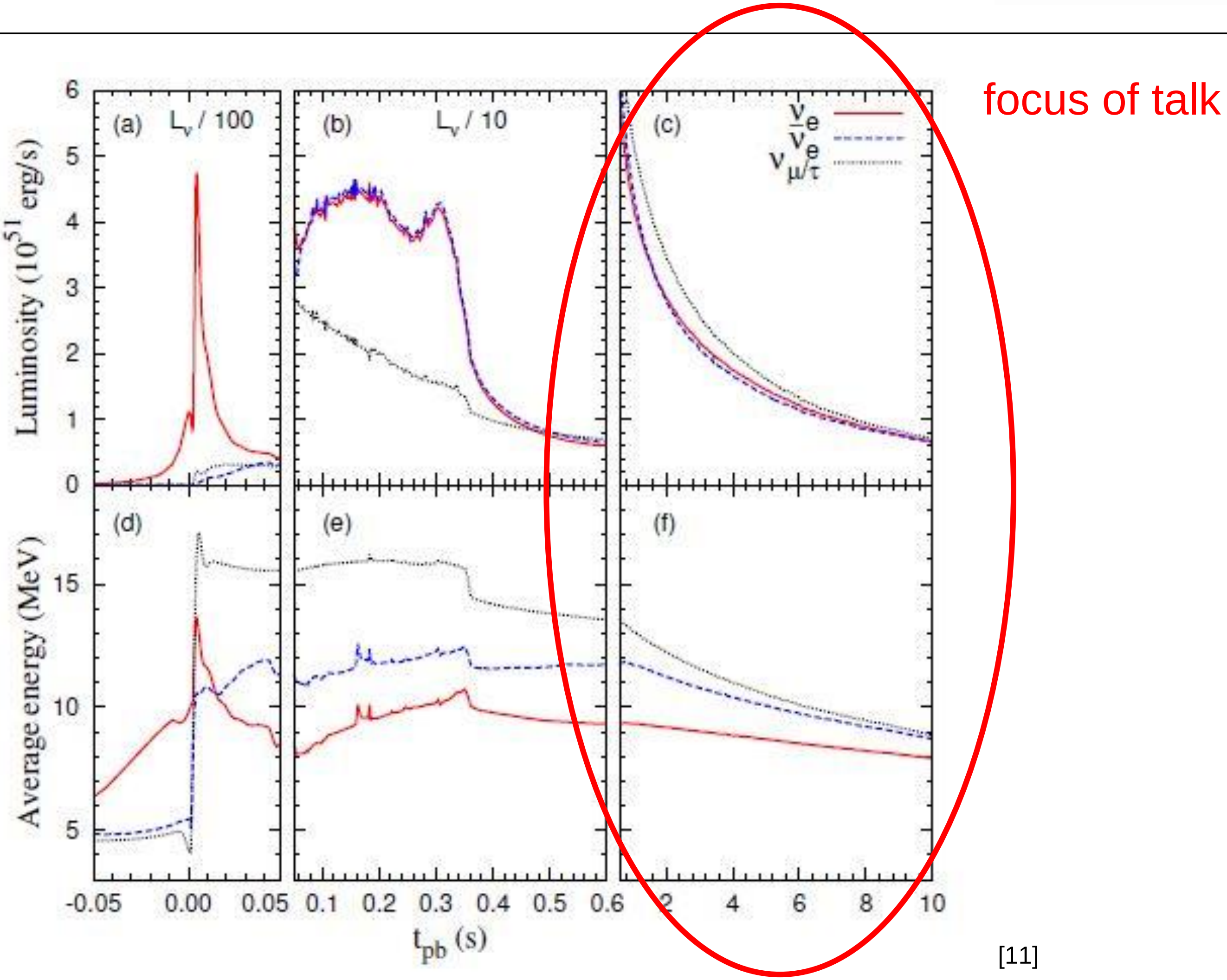
- consider neutrinos produced in neutron star
  - ν_e and $\bar{\nu}_e$ interact via charged-current and neutral-current
  - $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ interact via neutral-current
    - ➢ $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ have less interactions and thus a higher energy
  - composition mainly consists of neutrons
    - ➢ ν_e absorbation more likely than $\bar{\nu}_e$ absorbation

➢ hierarchy in energy

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau},\bar{\nu}_{\mu,\tau}} \rangle$$

Neutrino Matter Interactions



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Proton-to-Nucleon Ratio

- proton-to-nucleon ratio Y_e determines nucleosynthesis processes
- Y_e determined by charge current interactions
- $Y_e > 0.5$ ⟶ proton-rich matter $\lambda_{\bar{\nu}_e p} < \lambda_{\nu_e n}$
- $Y_e < 0.5$ ⟶ neutron-rich matter $\lambda_{\bar{\nu}_e p} > \lambda_{\nu_e n}$

$$\dot{Y}_e = \lambda_{\nu_e n} Y_n - \lambda_{\bar{\nu}_e p} Y_p$$

$$n + \nu_e \leftrightarrow p + e^-$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$Y_e = Y_p \quad , \quad Y_n = 1 - Y_e$$

$$Y_{e,eq} = \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}}$$

Proton-to-Nucleon Ratio

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$$\lambda_{\nu_e n} = \Phi_{\nu_e} \cdot \sigma_{\nu_e n}$$

$$\lambda_{\bar{\nu}_e p} = \Phi_{\bar{\nu}_e} \cdot \sigma_{\bar{\nu}_e p}$$

$$\sigma_0 = 2.569 \times 10^{-44}\,\mathrm{cm}^2$$

$$\Phi_{\nu_e} = \frac{L_{\nu_e}}{4\pi r^2 \langle E_{\nu_e} \rangle} \qquad \sigma_{\nu_e n} = \frac{\sigma_0}{m_e c^2} E_{e^-}^2 = \frac{\sigma_0}{m_e c^2} (E_{\nu_e} + \Delta)^2$$

$$\Phi_{\bar{\nu}_e} = \frac{L_{\bar{\nu}_e}}{4\pi r^2 \langle E_{\bar{\nu}_e} \rangle} \qquad \sigma_{\bar{\nu}_e p} = \frac{\sigma_0}{m_e c^2} E_{e^+}^2 = \frac{\sigma_0}{m_e c^2} (E_{\bar{\nu}_e} - \Delta)^2$$

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2 (m_e c^2)^2} \sigma_0 \left(\epsilon_{\nu_e} + 2\Delta + \frac{\Delta^2}{\langle E_{\nu_e} \rangle} \right)$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2 (m_e c^2)^2} \sigma_0 \left(\epsilon_{\bar{\nu}_e} - 2\Delta + \frac{\Delta^2}{\langle E_{\bar{\nu}_e} \rangle} \right)$$

$$\epsilon_\nu = \frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle}$$

Proton-to-Nucleon Ratio

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2 (m_e c^2)^2} \sigma_0 \left(\epsilon_{\nu_e} + 2\Delta + \frac{\Delta^2}{\langle E_{\nu_e} \rangle} \right)$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2 (m_e c^2)^2} \sigma_0 \left(\epsilon_{\bar{\nu}_e} - 2\Delta + \frac{\Delta^2}{\langle E_{\bar{\nu}_e} \rangle} \right)$$

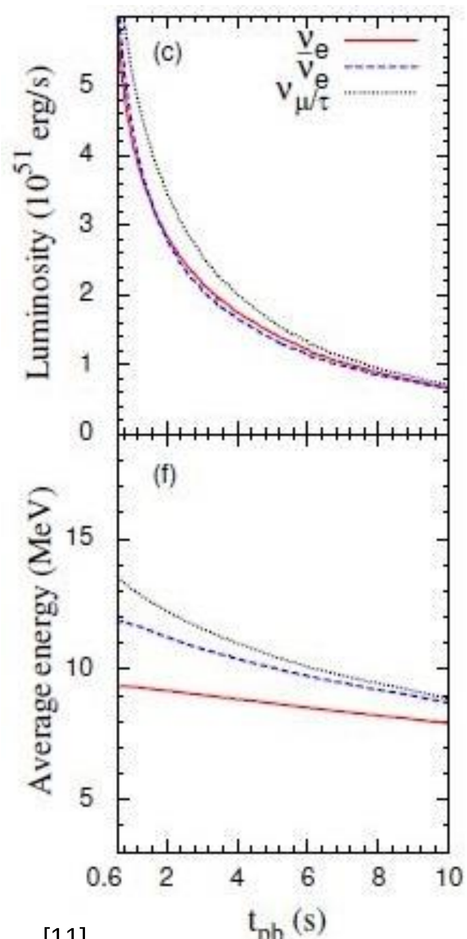
- neutron-rich condititons

$$\lambda_{\bar{\nu}_e p} > \lambda_{\nu_e n}$$

$$\epsilon_\nu = \frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle}$$

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1 \right] (\epsilon_{\bar{\nu}_e} - 2\Delta)$$

- matter proton-rich most of the time
- might be slightly neutron-rich at the beginning



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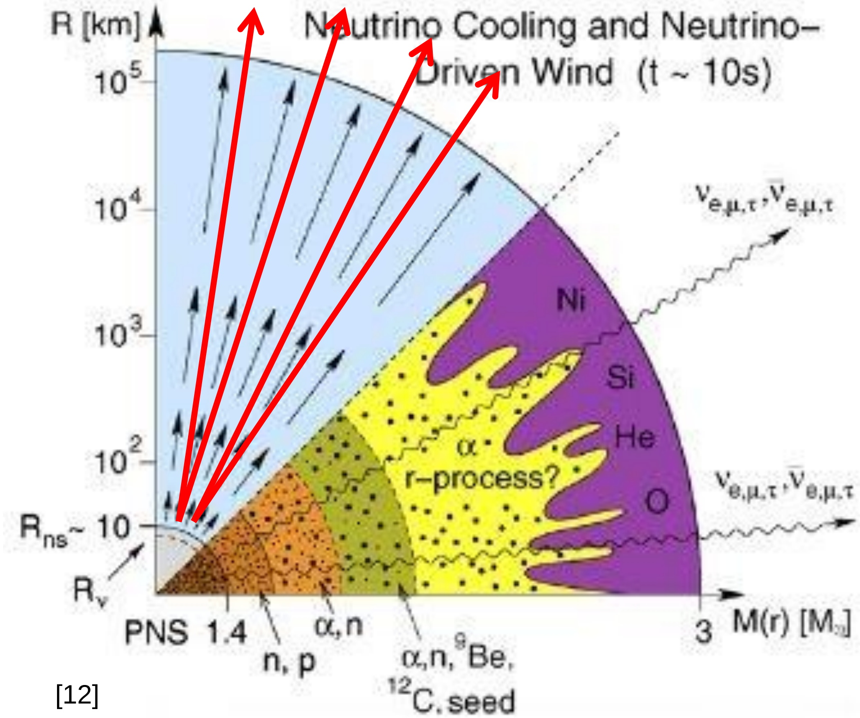

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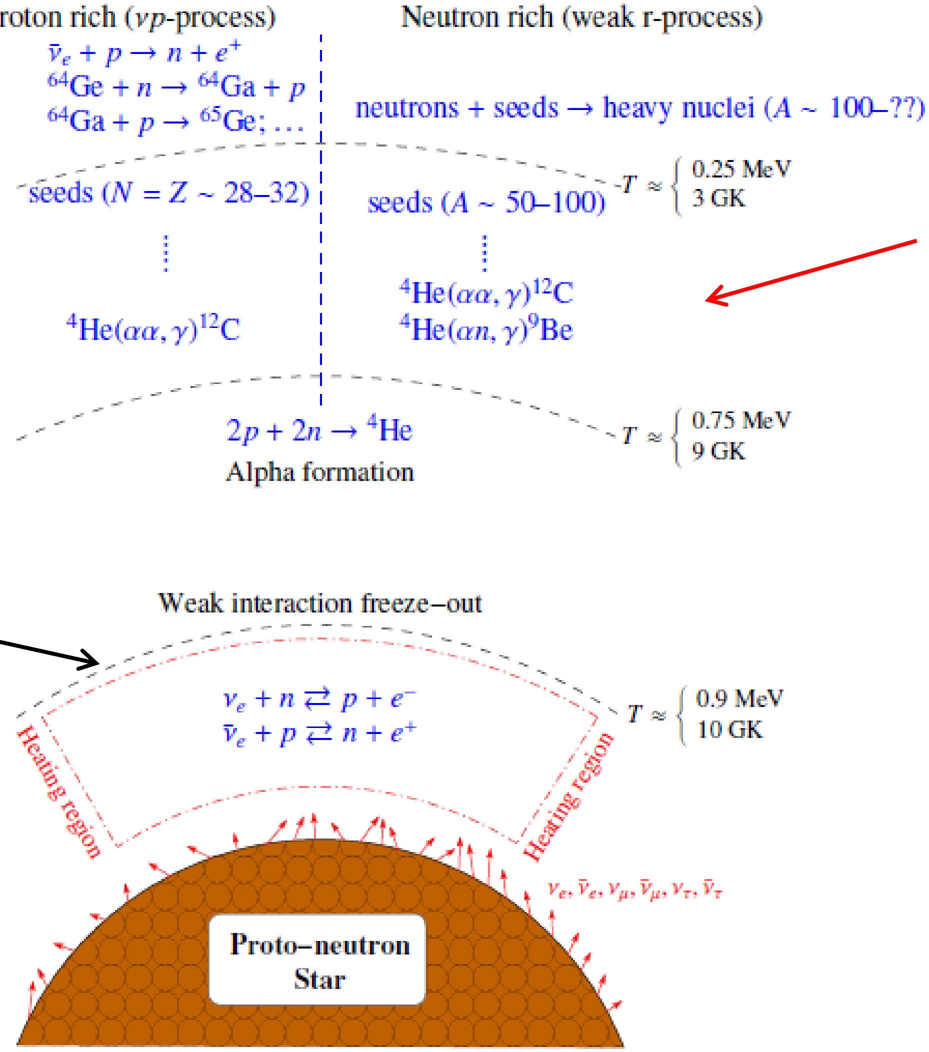
Nucleosynthesis – Neutrino driven Winds

seed production

Y_e fixed



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Nucleosynthesis – Neutrino driven Winds –

νp-process

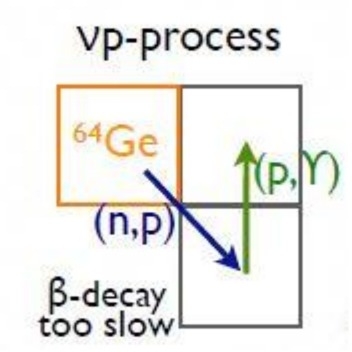
- $Y_e > 0.5$ → proton-rich
- after alpha rich freeze-out N=Z nuclei and free protons produced

➢ proton capture supplied by β^+-decay

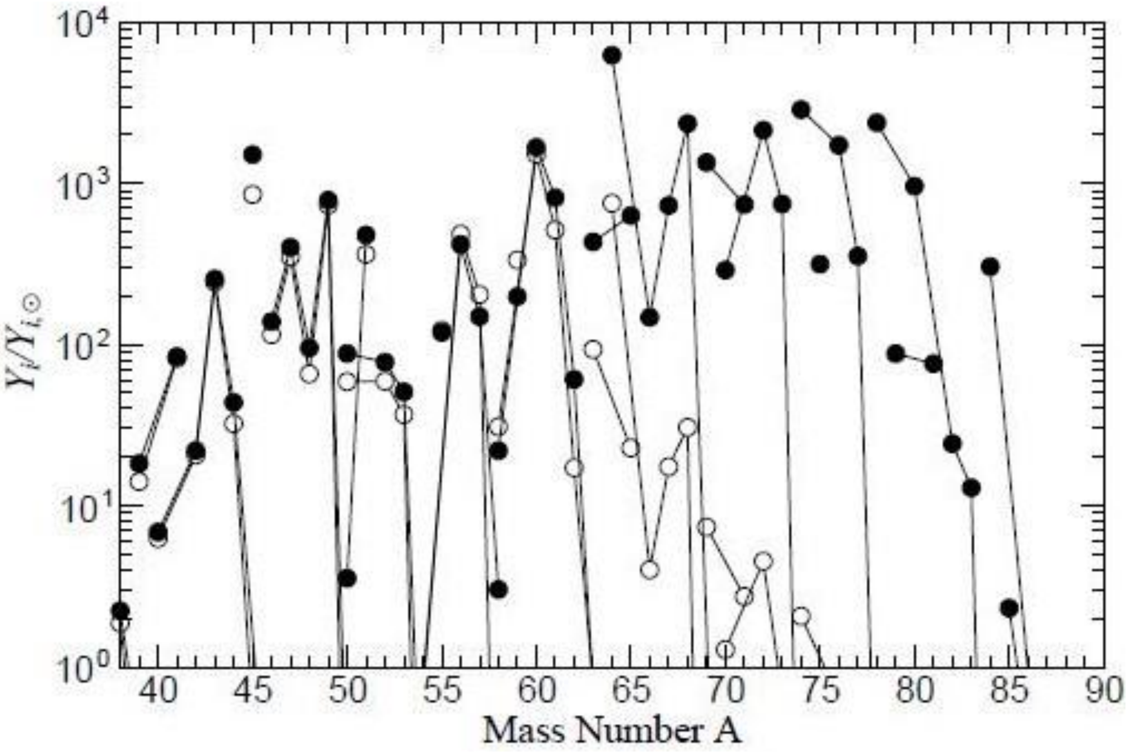
- high coulomb barrier limits proton capture
- proton capture until ^{64}Ge

$$\tau_{\beta+} \gg \tau_{expansion}$$

- $\bar{\nu}_e + p \rightarrow n + e^+$
- (n,p) supplies (p, γ)
- up to A~80-100



Nucleosynthesis – Neutrino driven Winds – νp-process



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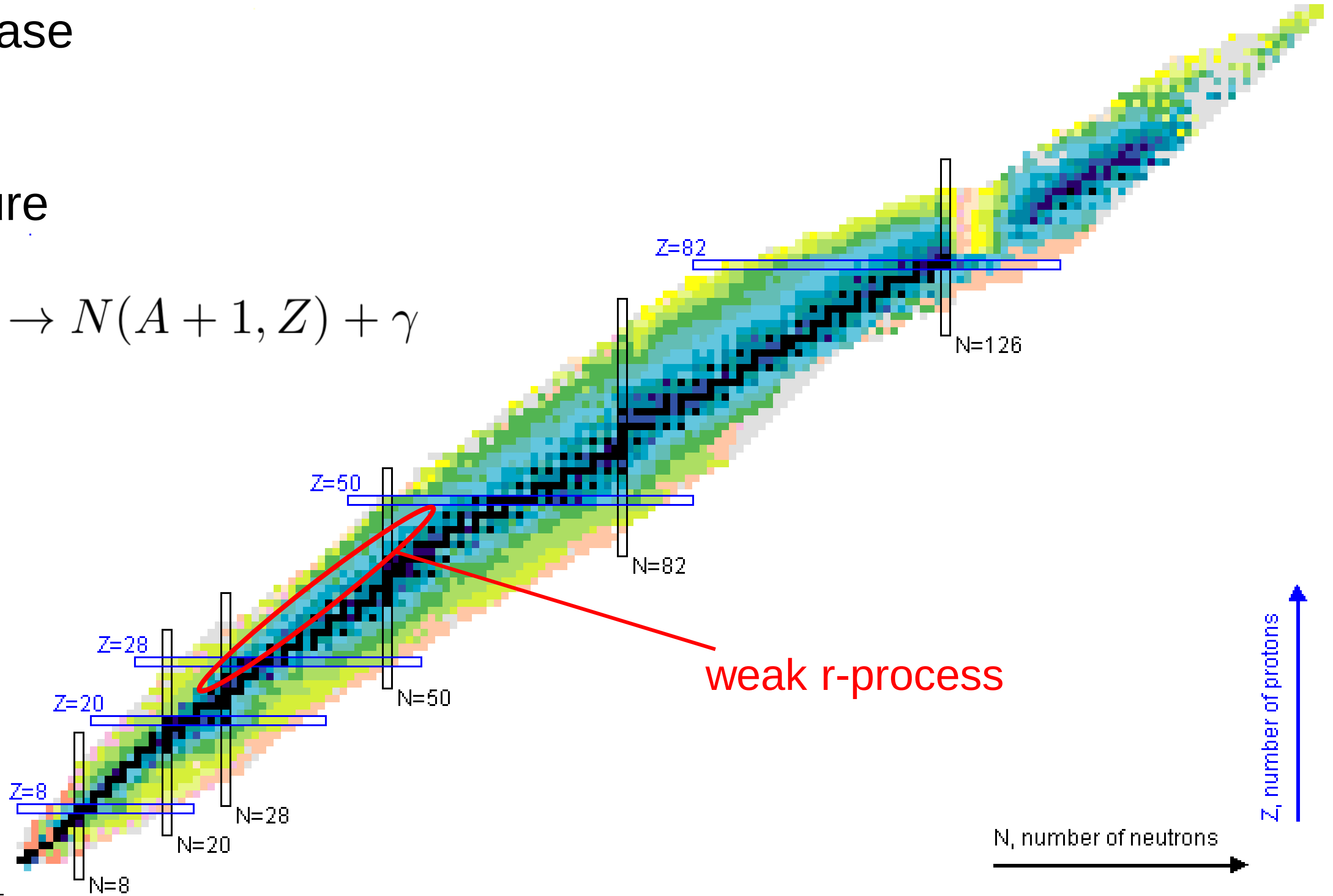
Nucleosynthesis – Neutrino driven Winds –
weak r-process

- early wind phase
- $Y_e \sim 0{,}48$
- neutron capture

$$N(A,Z) + n \rightarrow N(A+1,Z) + \gamma$$



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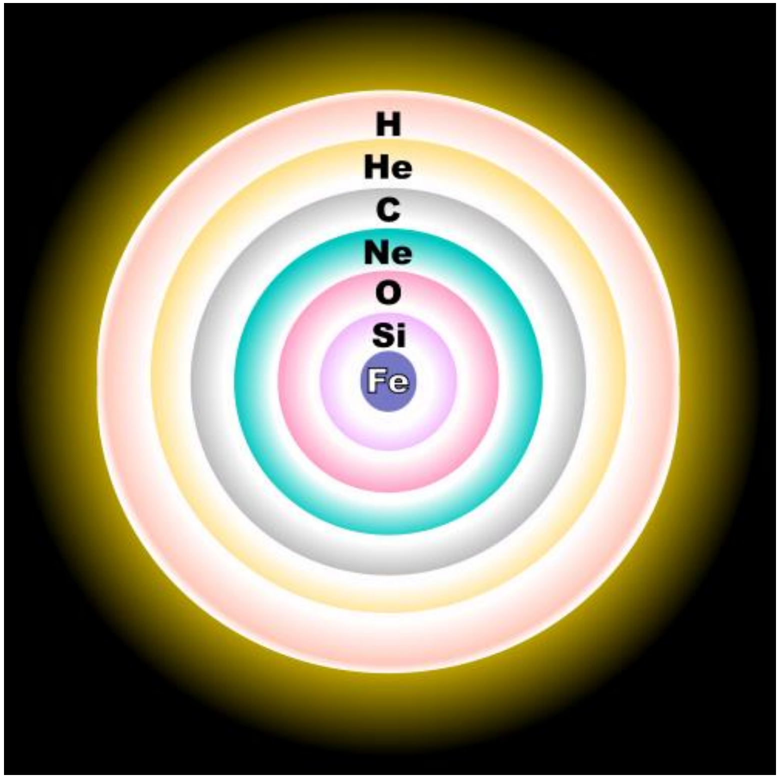

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Nucleosynthesis – Outer Shells–

ν-process

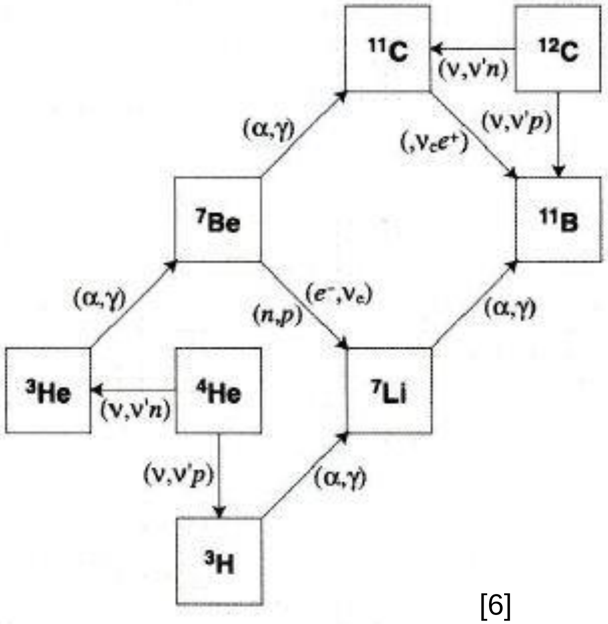
- $^4He(\nu, \nu'p)^3H(\alpha,\gamma)^7Li$ or

  $^4He(\nu, \nu'n)^3He(\alpha,\gamma)^7Be(e^-,\nu_e)^7Li$

- induced by $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$
  - $^{12}C(\nu,\nu'p)^{11}B$ and $^{20}Ne(\nu,\nu'n)^{19}F$

- ^{22}Na and ^{26}Al produced

- Induced by ν_e and $\bar{\nu}_e$
  - $^{138}Ba(\nu,e^-)^{138}La$ and $^{180}Hf(\nu,e^-)\,^{180}Ta$



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Summary

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- proton-to-nucleon ratio Y_e determines processes
- in core collapse supernovae
  - neutrino driven winds
    - mainly by νp-process
    - possibly weak r-process during early wind phase
  - outer shells
    - ν-process
    - just distinct nuclei

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Thank you for your attention!

Any questions?