



TECHNISCHE
UNIVERSITÄT
DARMSTADT

The Impact of Heavy-Flavor Neutrinos on the νr -Process

Heamin Ko

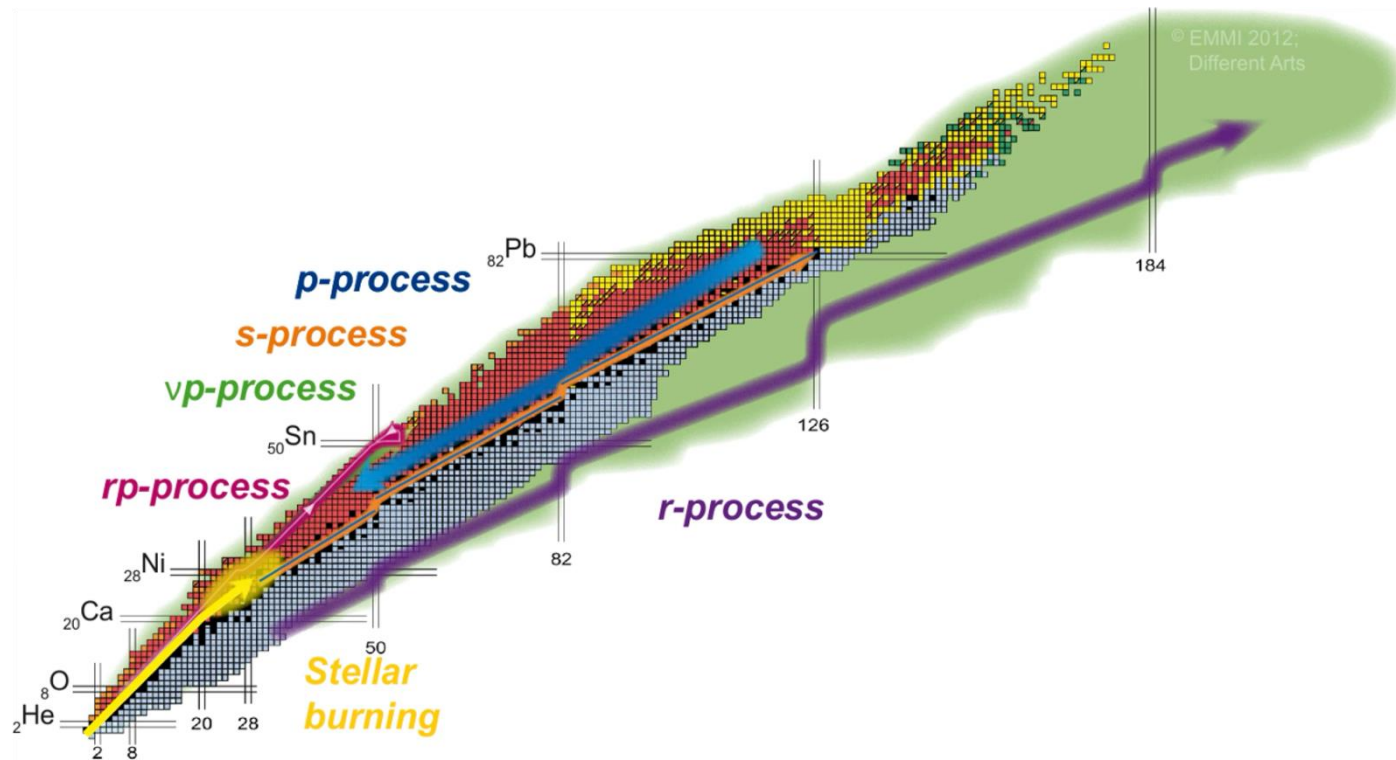
Technical University of Darmstadt

In collaboration with

Gabriel Martínez-Pinedo and Zewei Xiong

Introduction

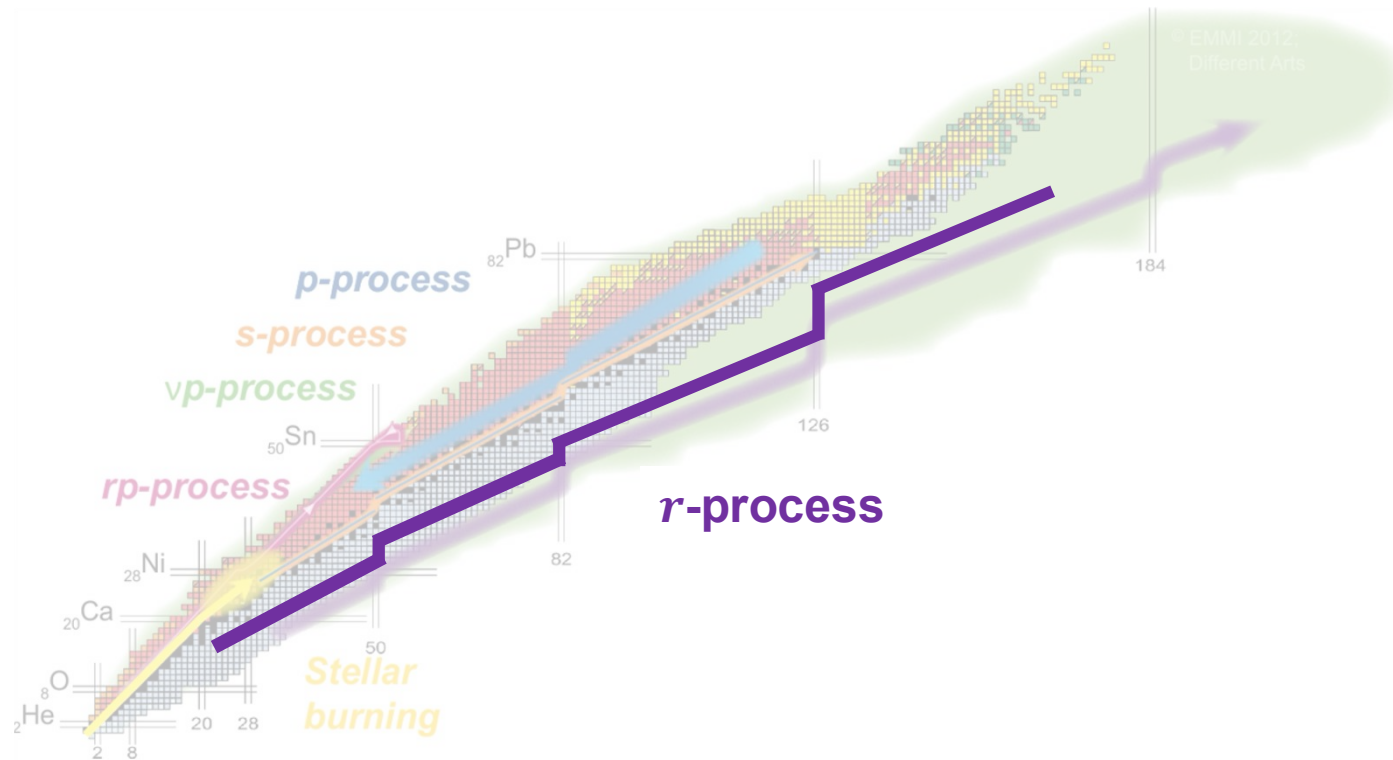
Several processes contribute to the nucleosynthesis beyond Iron: s-process, r-process and p-process (γ -process)



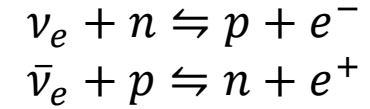
| | | | | | | | | | | | | | | |
|----|------------------|-----------------|------------------|------------------|------------------------------|------------------|------------------|-------------------|-----------------------------------|-------------------|-----------------------------------|-------------------|-------------------|--------------------|
| 10 | Sn 100 0.94 s | Sn 101 3 s | Sn 102 3.8 s | Sn 103 7.0 s | Sn 104 20.6 s | Sn 105 34 s | Sn 106 2.1 m | Sn 107 2.9 m | Sn 108 10.3 m | Sn 109 18.0 m | Sn 110 4.11 h | Sn 111 35.3 m | Sn 112 0.97 | Sn 113 21.4 m |
| 9 | In 99 3.1 s | In 100 5.9 s | In 101 16 s | In 102 22.1 s | In 103 34 s | In 104 60 s | In 105 1.8 m | In 106 4.8 m | In 107 5.5 m | In 108 32.4 m | In 109 39.8 m | In 110 1.34 h | In 111 4.2 h | In 112 66.1 m |
| 8 | Cd 98 9.2 s | Cd 99 16 s | Cd 100 49.1 s | Cd 101 1.2 m | Cd 102 5.5 m | Cd 103 7.3 m | Cd 104 57.7 m | Cd 105 5.5 m | Cd 106 1.25 | Cd 107 6.5 h | Cd 108 0.89 | Cd 109 462.6 d | Cd 110 12.49 | Cd 111 49 m |
| 7 | Ag 97 25.3 s | Ag 98 46 s | Ag 99 1.7 m | Ag 100 21.4 m | Ag 101 3.7 d | Ag 102 1.2 m | Ag 103 7.3 m | Ag 104 55.5 m | Ag 105 7.3 m | Ag 106 41.29 d | Ag 107 8.3 d | Ag 108 24 m | Ag 109 44.3 s | Ag 110 51.639 s |
| 6 | Pd 96 2.0 m | Pd 97 3.1 m | Pd 98 17.7 m | Pd 99 21.4 m | Pd 100 3.7 d | Pd 101 8.47 h | Pd 102 1.02 | Pd 103 16.96 d | Pd 104 11.14 | Pd 105 22.33 | Pd 106 27.33 | Pd 107 21.8 s | Pd 108 10.9 s | Pd 109 26.46 |
| 5 | Rh 95 1.96 s | Rh 96 5.8 m | Rh 97 17.7 m | Rh 98 21.4 m | Rh 99 3.7 d | Rh 100 8.47 h | Rh 101 1.02 | Rh 102 16.96 d | Rh 103 11.14 | Rh 104 22.33 | Rh 105 27.33 | Rh 106 21.8 s | Rh 107 10.9 s | Rh 108 26.46 |
| 4 | Ru 94 51.8 m | Ru 95 1.65 h | Ru 96 5.54 | Ru 97 2.9 d | Ru 98 1.87 | Ru 99 12.76 | Ru 100 12.60 | Ru 101 17.06 | Ru 102 31.55 | Ru 103 39.35 d | Ru 104 18.62 | Ru 105 4.44 h | Ru 106 373.6 d | Ru 107 3.1 |
| 3 | Tc 93 43.5 m | Tc 94 2.7 h | Tc 95 60 d | Tc 96 20 h | Tc 97 42 m | Tc 98 4.3 d | Tc 99 92.2 d | Tc 100 4.9 s | Tc 101 4.2 · 10 ⁸ a | Tc 102 6.6 h | Tc 103 2.1 · 10 ⁵ a | Tc 104 8.6 h | Tc 105 15.8 s | Tc 106 15.8 s |
| 2 | Mo 92 14.77 | Mo 93 3.5 h | Mo 94 9.23 | Mo 95 15.90 | Mo 96 16.68 | Mo 97 9.56 | Mo 98 24.19 | Mo 99 56.0 h | Mo 100 14.6 m | Mo 101 11.2 m | Mo 102 7.1 s | Mo 103 67.5 s | Mo 104 1.0 m | Mo 105 35 |
| 1 | Nb 90 96.9 d | Nb 91 860 a | Nb 92 3.19 h | Nb 93 98.5 d | Nb 94 2.10 ⁴ a | Nb 95 6.28 m | Nb 96 23.4 h | Nb 97 23.4 h | Nb 98 2.8 m | Nb 99 2.8 m | Nb 100 1.5 s | Nb 101 1.5 s | Nb 102 4.3 s | Nb 103 1.5 s |
| 0 | Zr 90 51.45 | Zr 91 11.22 | Zr 92 17.15 | Zr 93 17.38 | Zr 94 17.38 | Zr 95 64.0 d | Zr 96 64.0 d | Zr 97 17.38 | Zr 98 2.8 m | Zr 99 30.7 s | Zr 100 30.7 s | Zr 101 7.1 s | Zr 102 2.1 s | Zr 103 2.1 s |
| 0 | Y 89 15.0 m | Y 90 184 h | Y 91 49.7 m | Y 92 3.54 h | Y 93 10.1 h | Y 94 18.7 m | Y 95 10.3 m | Y 96 18.7 m | Y 97 10.3 m | Y 98 3.78 s | Y 99 1.47 s | Y 100 0.94 s | Y 101 0.94 s | Y 102 0.94 s |

- Origin of p-nuclei is unclear
- Can neutrino-nucleus reactions help producing p-nuclei?

Introduction: r – process



- **Weak freeze-out**



determine $Y_e = n_p / (n_n + n_p)$

- **Seed production**

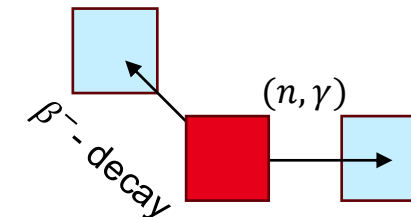
Charged particle reaction produce the seed nuclei and neutrons

- **Neutron capture phase**

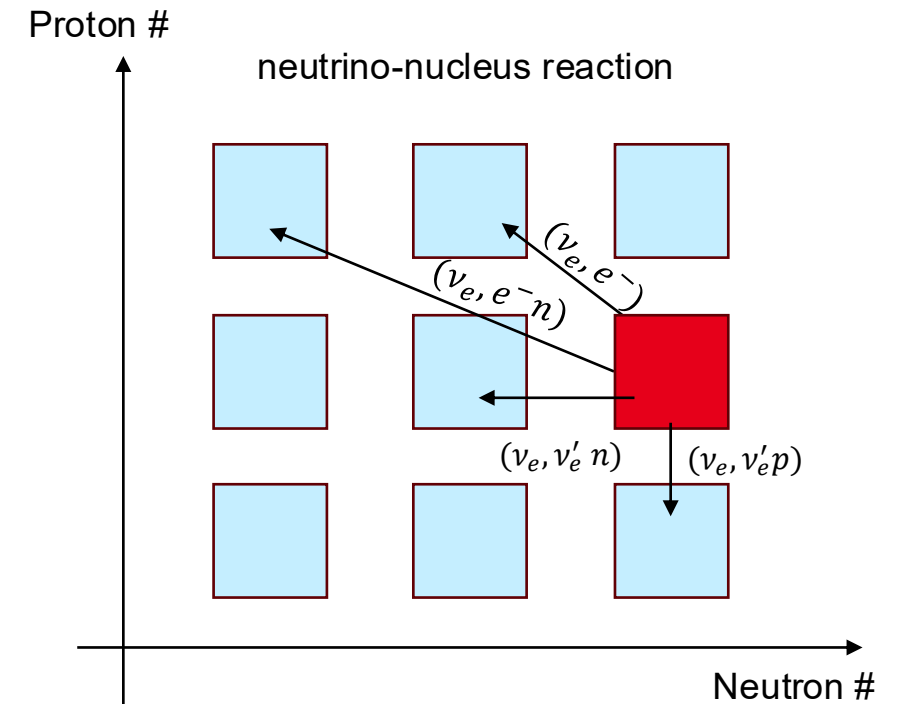
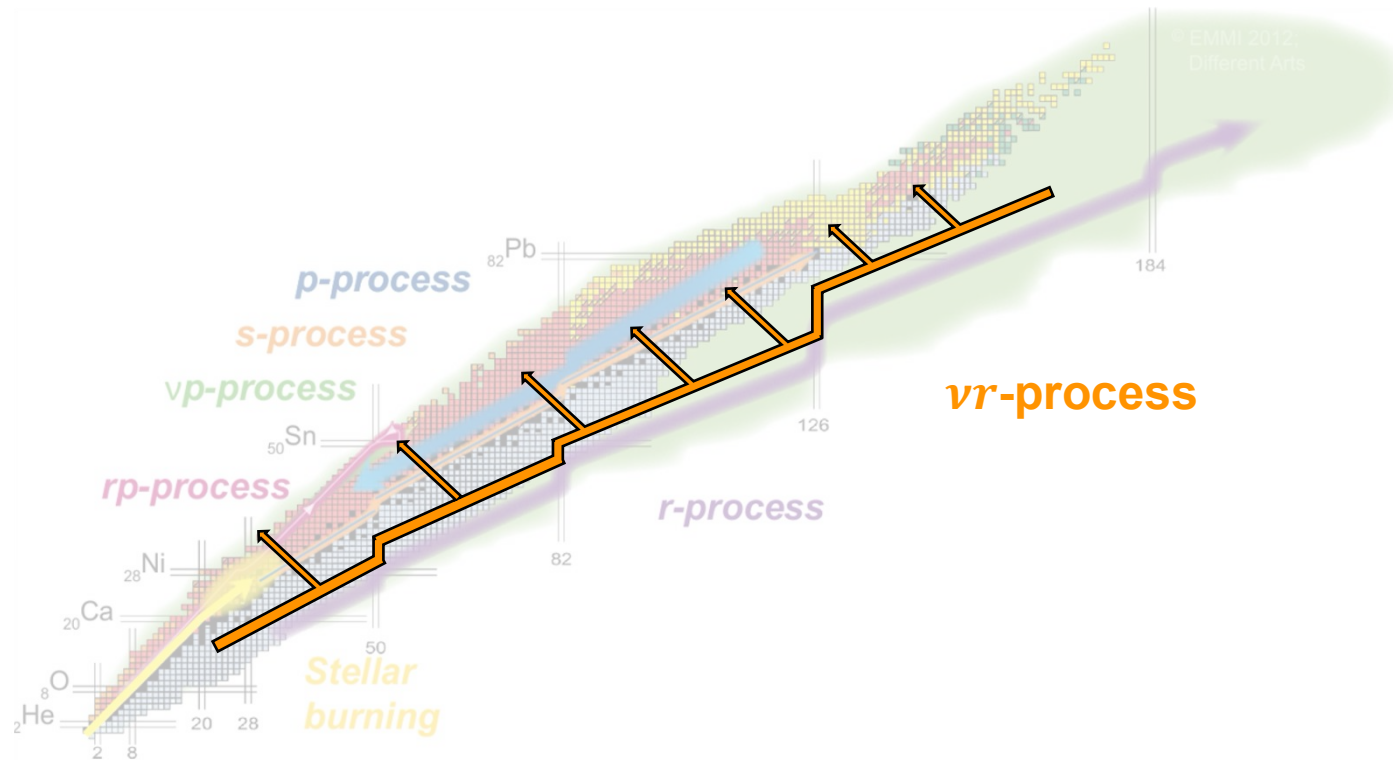
$(n, \gamma) \rightleftharpoons (\gamma, n)$ in equilibrium

- **Freeze-out and decay to stability**

Competition between (n, γ) and β – decay



Introduction: νr – process



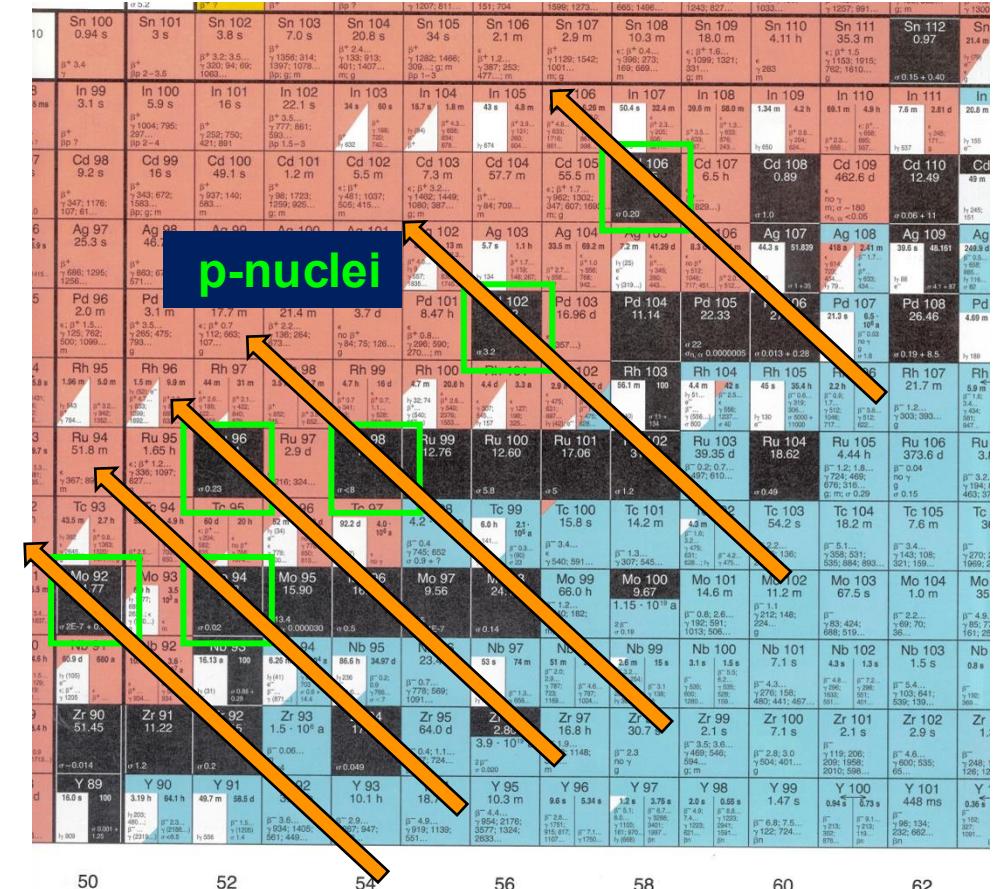
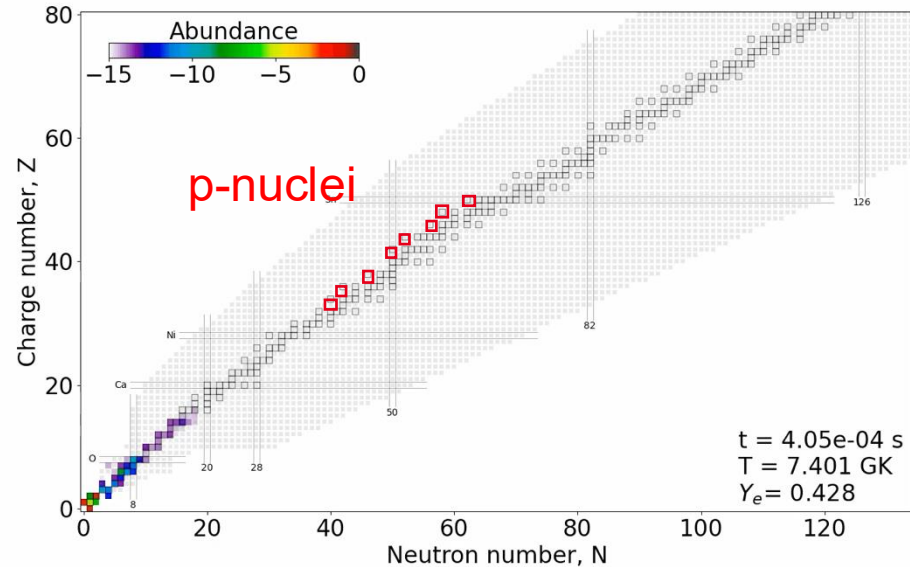
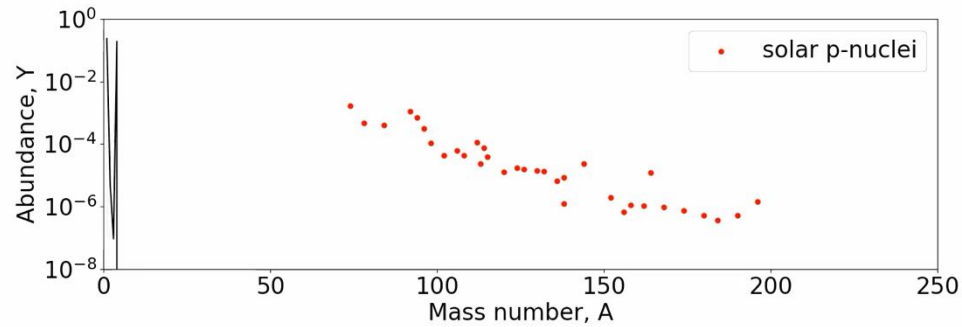
- Charged current reaction:
 $A(\nu_e, e^- X)B$, where $X = (\gamma, n, p, \alpha)$
 $n(\nu_e, e^-)p$: protons are used for $A(p, n)B$ in medium mass nuclei
- Neutral current reaction: $A(\nu_e, \nu'_e X)B$, where $X = (n, p, \alpha)$

Z. Xiong, G. Martínez-Pinedo, O. Just and A. Sieverding, *PRL* 132.192701 (2024)

Introduction: νr – process

Production of p-nuclei

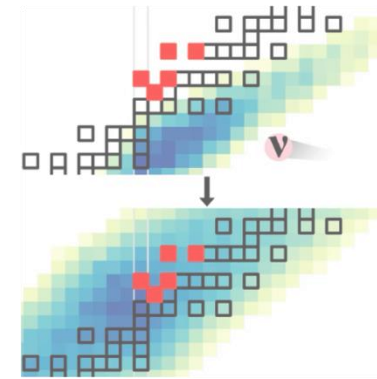
ν reaction flow



νr -process

p-nuclei from neutron-rich outflows

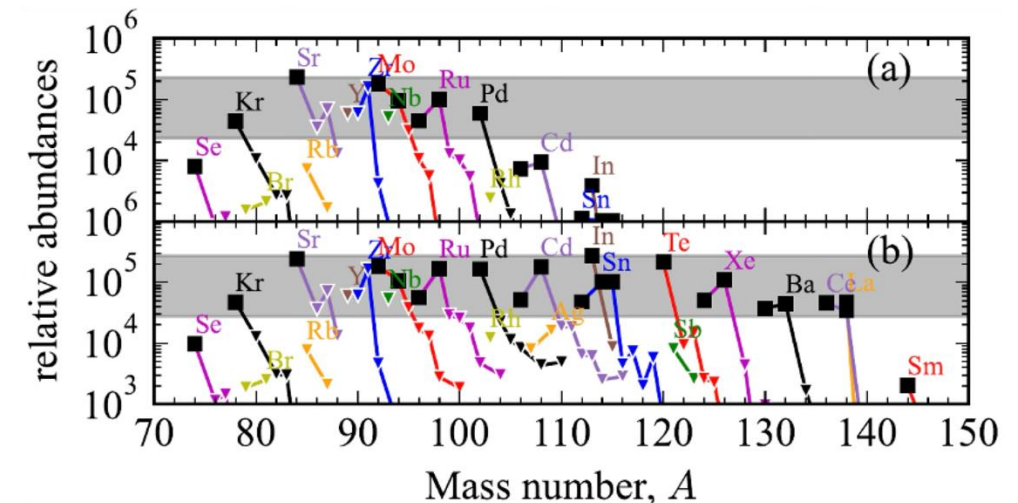
- Novel nucleosynthesis process that operates under strong neutrino fluxes
- Sequence of neutron captures and charged-current neutrino-nucleus reactions
- Co-production of p-nuclei from $A=88-138$
- May require high magnetic fields as found in magnetars (see *Tejas Prasanna et al ApJ 973 91(2024)*)
- Electron neutrinos are included in previous study
- **Effects of neutral current reactions by heavy lepton neutrinos ($\nu_\mu, \nu_\tau, \bar{\nu}_\mu$ and $\bar{\nu}_\tau$) to be checked**



In neutron-rich condition ($Y_e \approx 0.4 - 0.5$)

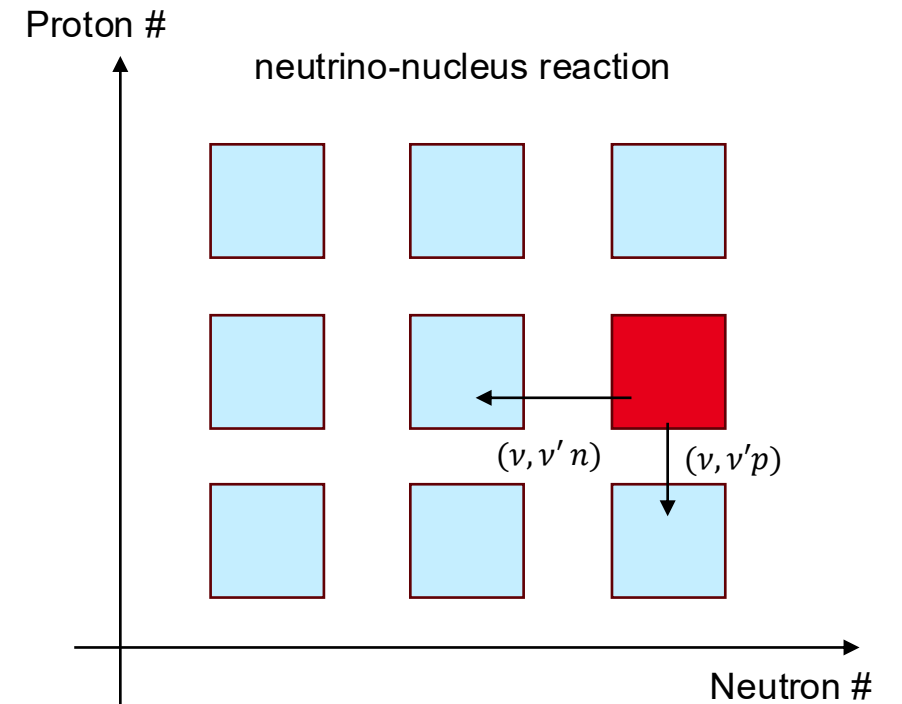
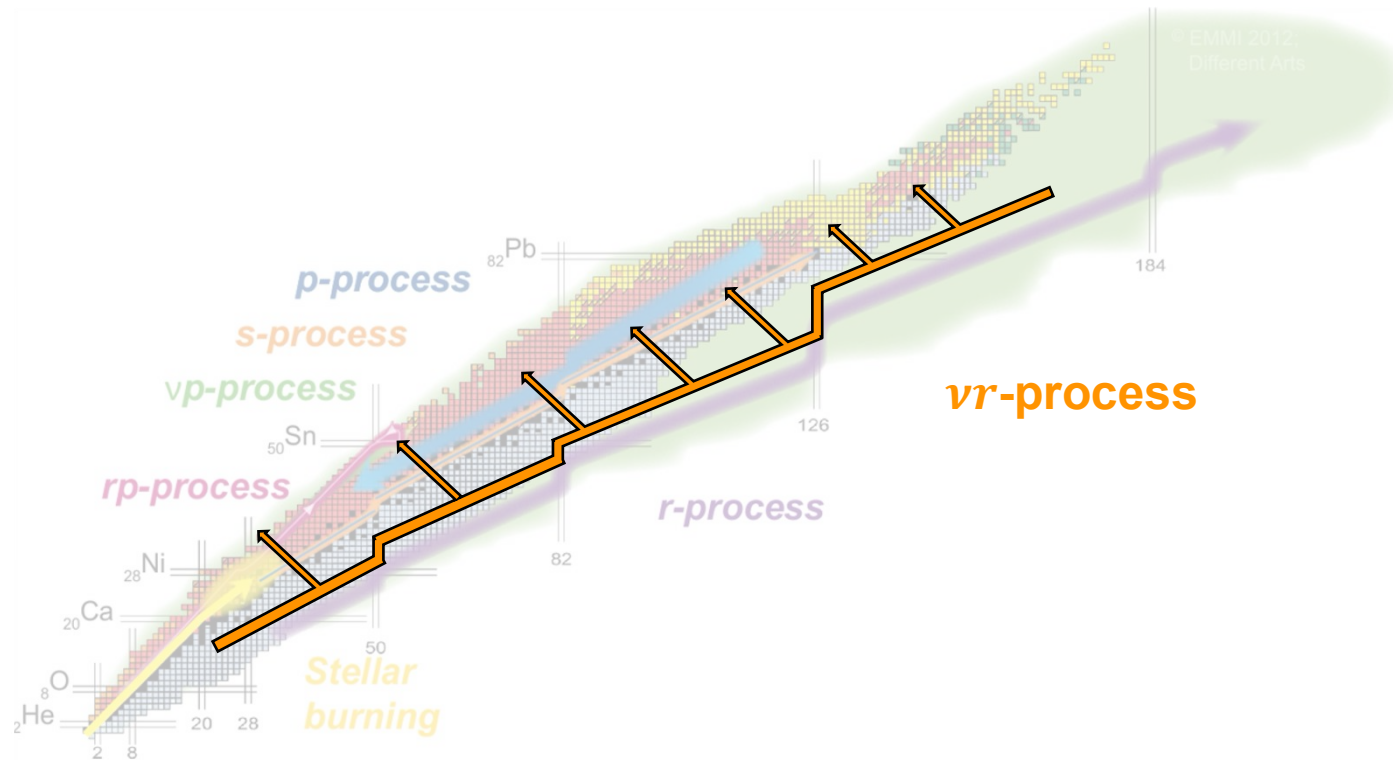
ν -A reactions ($\nu_e + (A, Z) \rightarrow (A, Z + 1) + e^-$) drive material towards and across stability

Production of p-nuclei from neutron-rich nuclei.



Z. Xiong, G. Martínez-Pinedo, O. Just and A. Sieverding, *PRL* 132.192701 (2024)

Introduction: νr – process

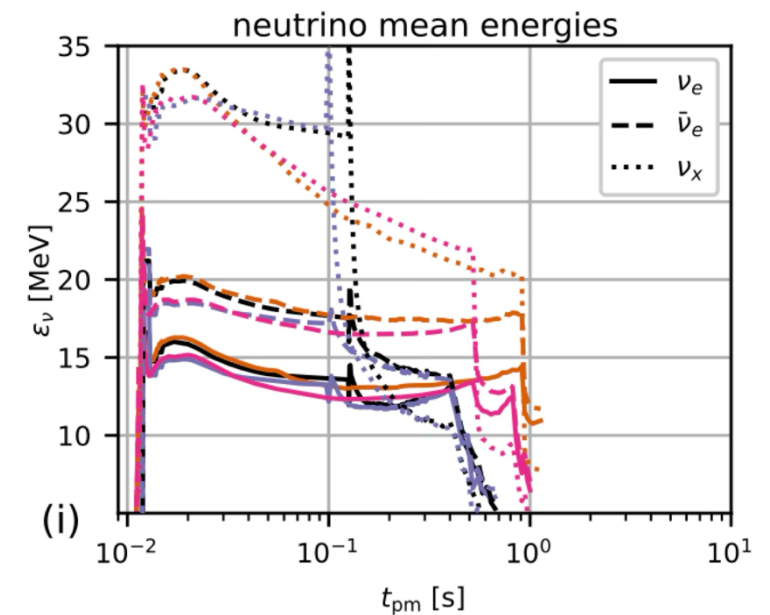
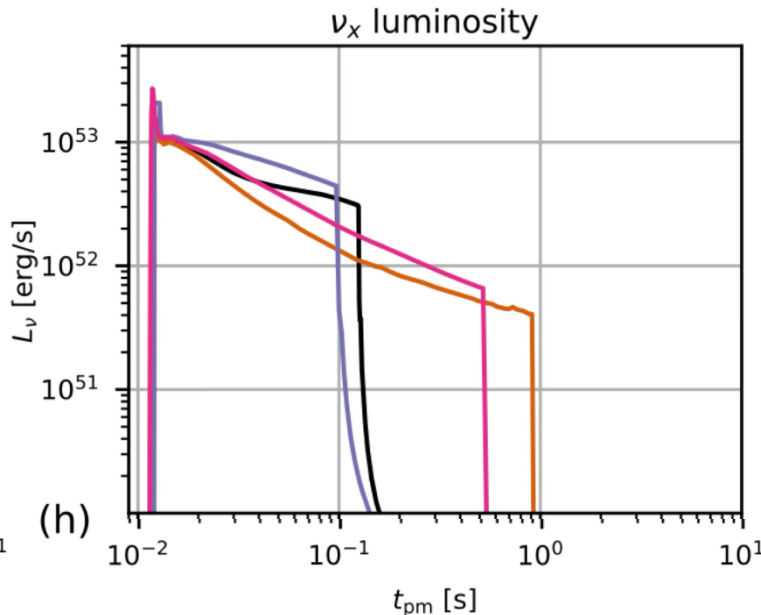
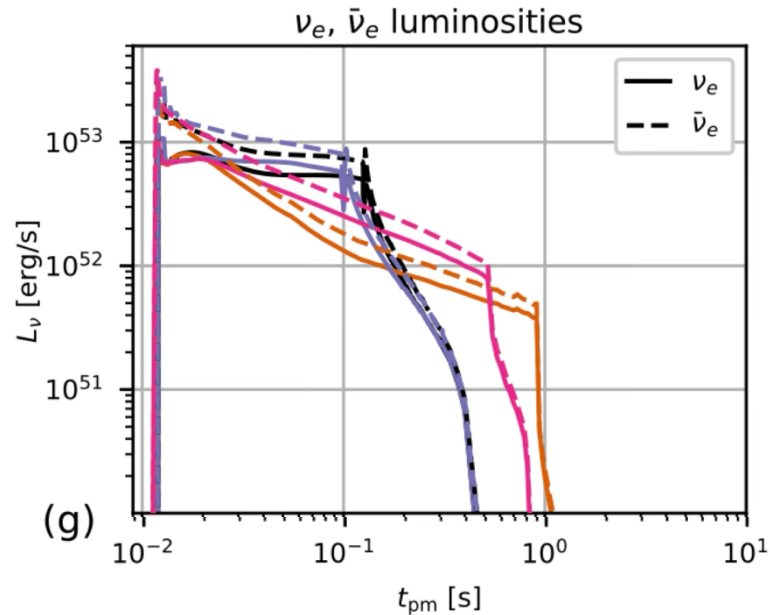


- Neutral current reaction: $A(\nu, \nu' X)B$, where $X = (n, p, \alpha)$

Parameters

Neutrino luminosity and average energy

O. Just et al. ApJL 951 L12 (2023)



Our parameter sets:

$$n_{\nu_e} = 10^{33} \text{ (1/cm}^3\text{)}$$

$$\langle E_{\nu_e} \rangle \sim 16 \text{ MeV}$$

$$n_{\bar{\nu}_e} = 1.2 n_{\nu_e}$$

$$\langle E_{\bar{\nu}_e} \rangle \sim 20 \text{ MeV}$$

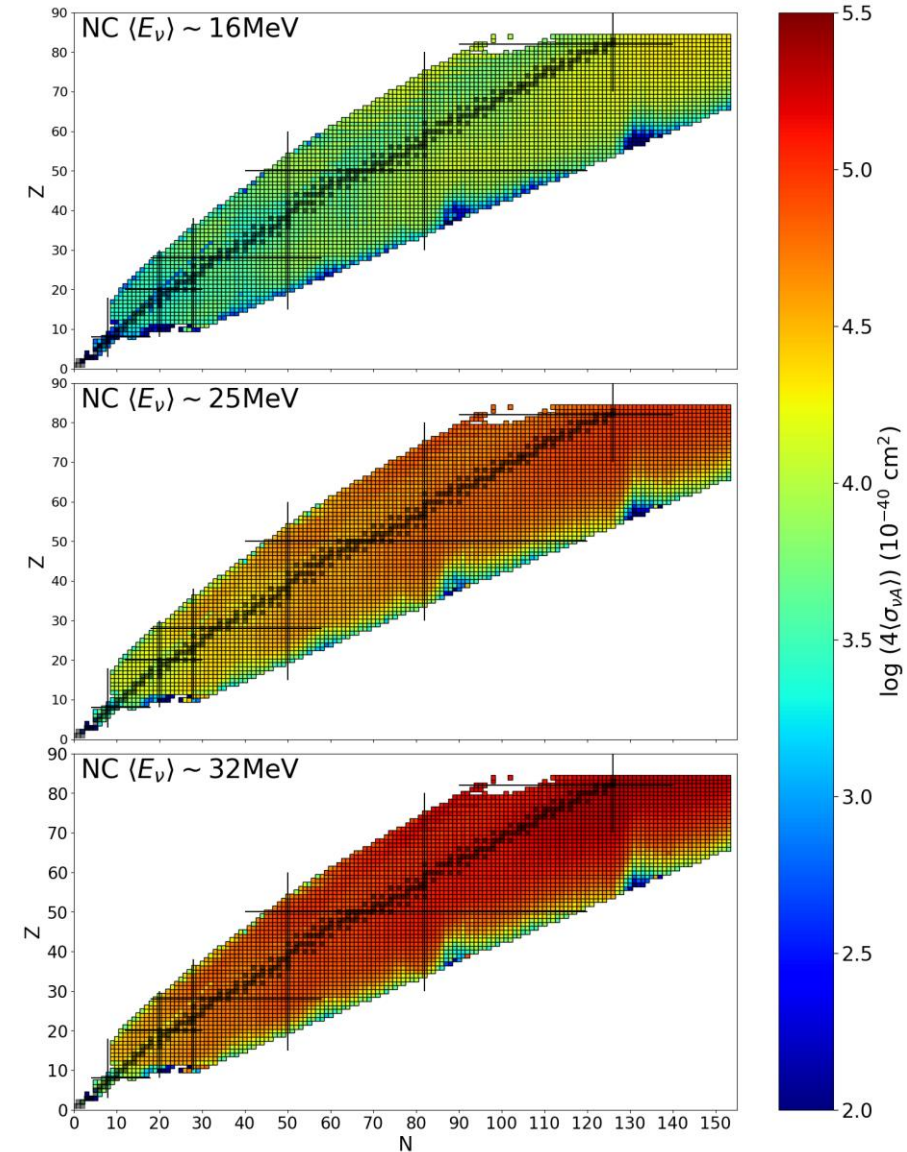
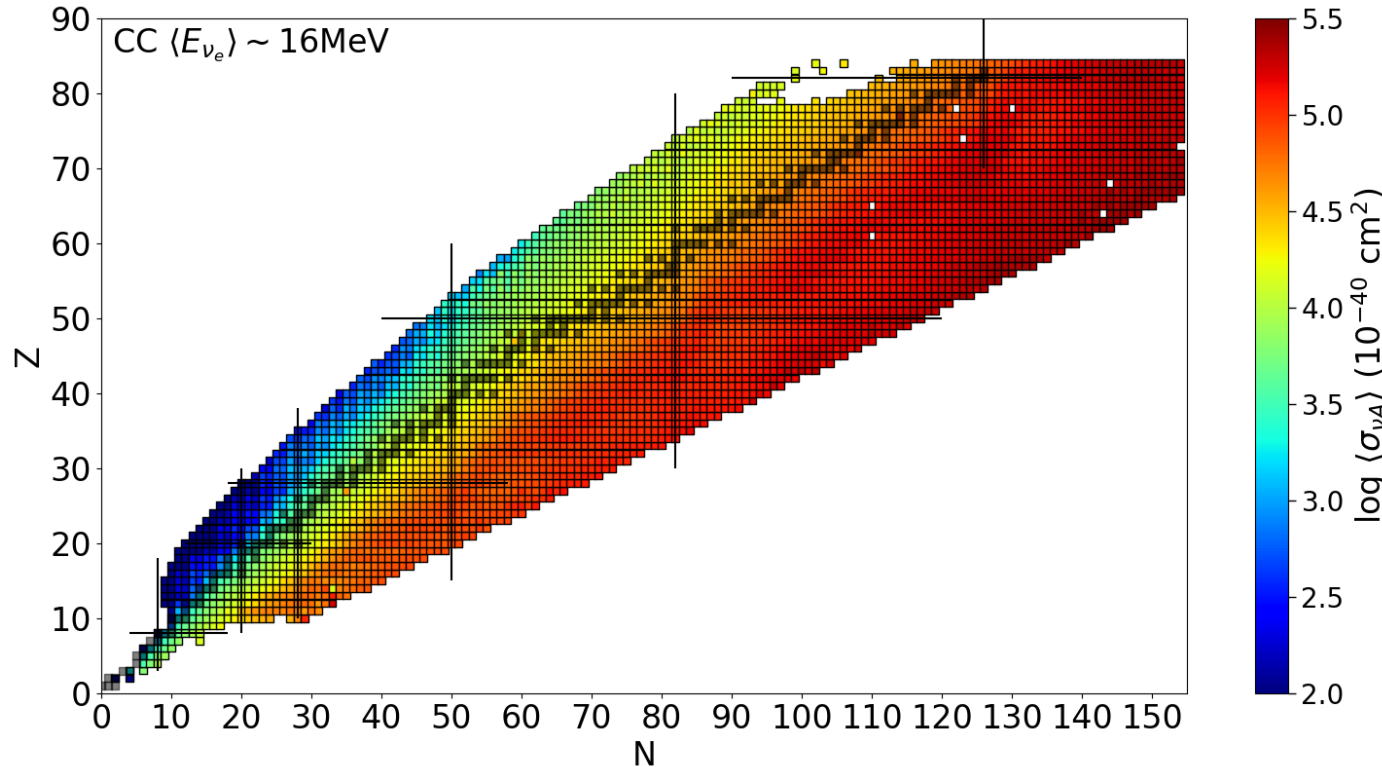
$$n_{\nu_\mu} = n_{\nu_\tau} = n_{\bar{\nu}_\mu} = n_{\bar{\nu}_\tau} = 1.25 n_{\nu_e}$$

$$\langle E_{\nu_\mu} \rangle = \langle E_{\nu_\tau} \rangle = \langle E_{\bar{\nu}_\mu} \rangle = \langle E_{\bar{\nu}_\tau} \rangle \sim 25 - 47 \text{ MeV}$$

Cross section

The average neutrino-nucleus cross-section

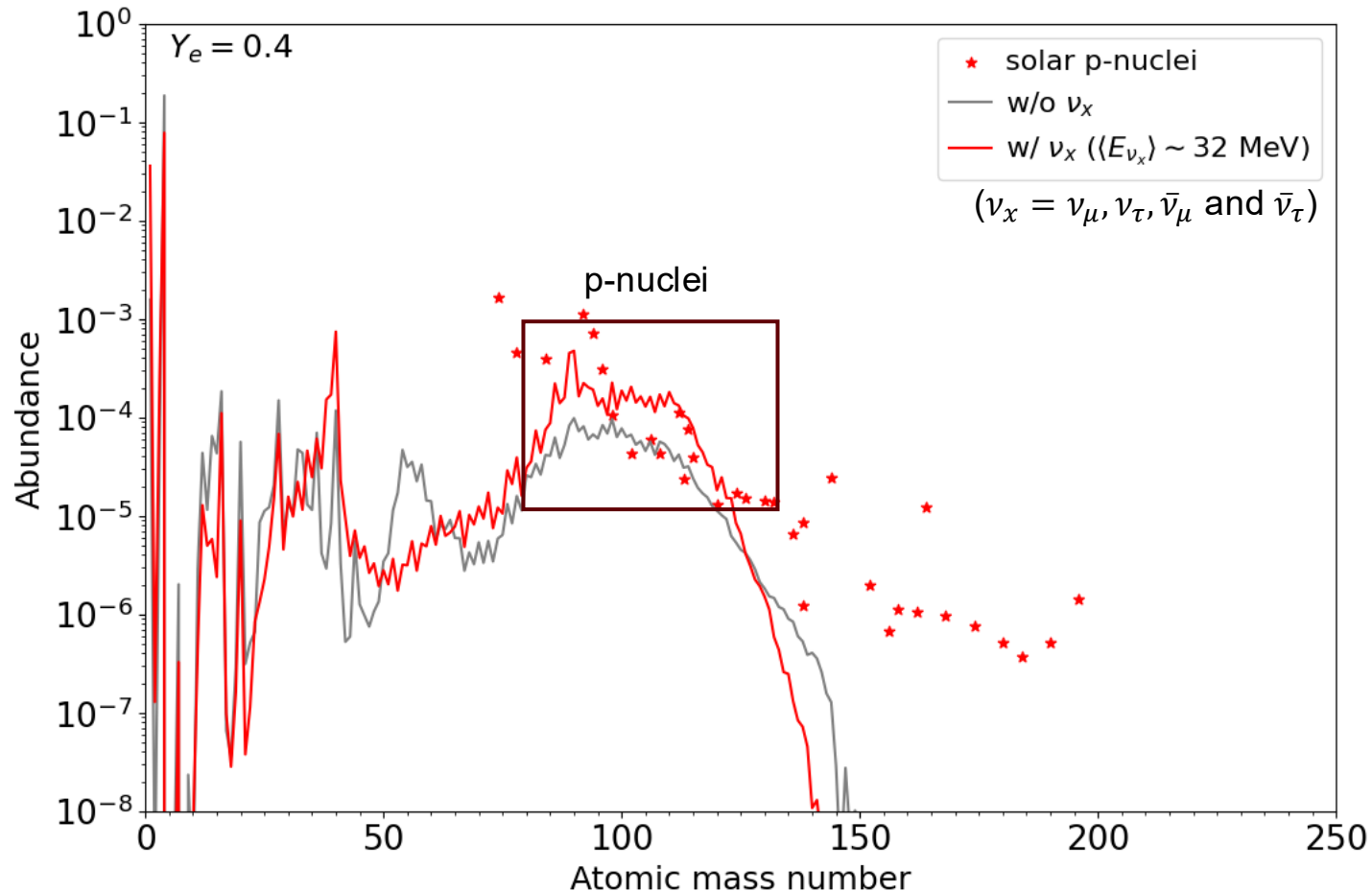
A. Severing et al. APJ 865, 143 (2018)



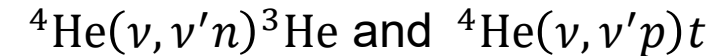
- Charged current (CC) reactions increase the charge number of heavy nuclei
- **Neutral current (NC; $\nu + A \rightarrow \nu' + A^* \rightarrow B + (n, p, \alpha)$) reactions (spallation)**

Final abundance

Neutral current depends on average neutrino energy

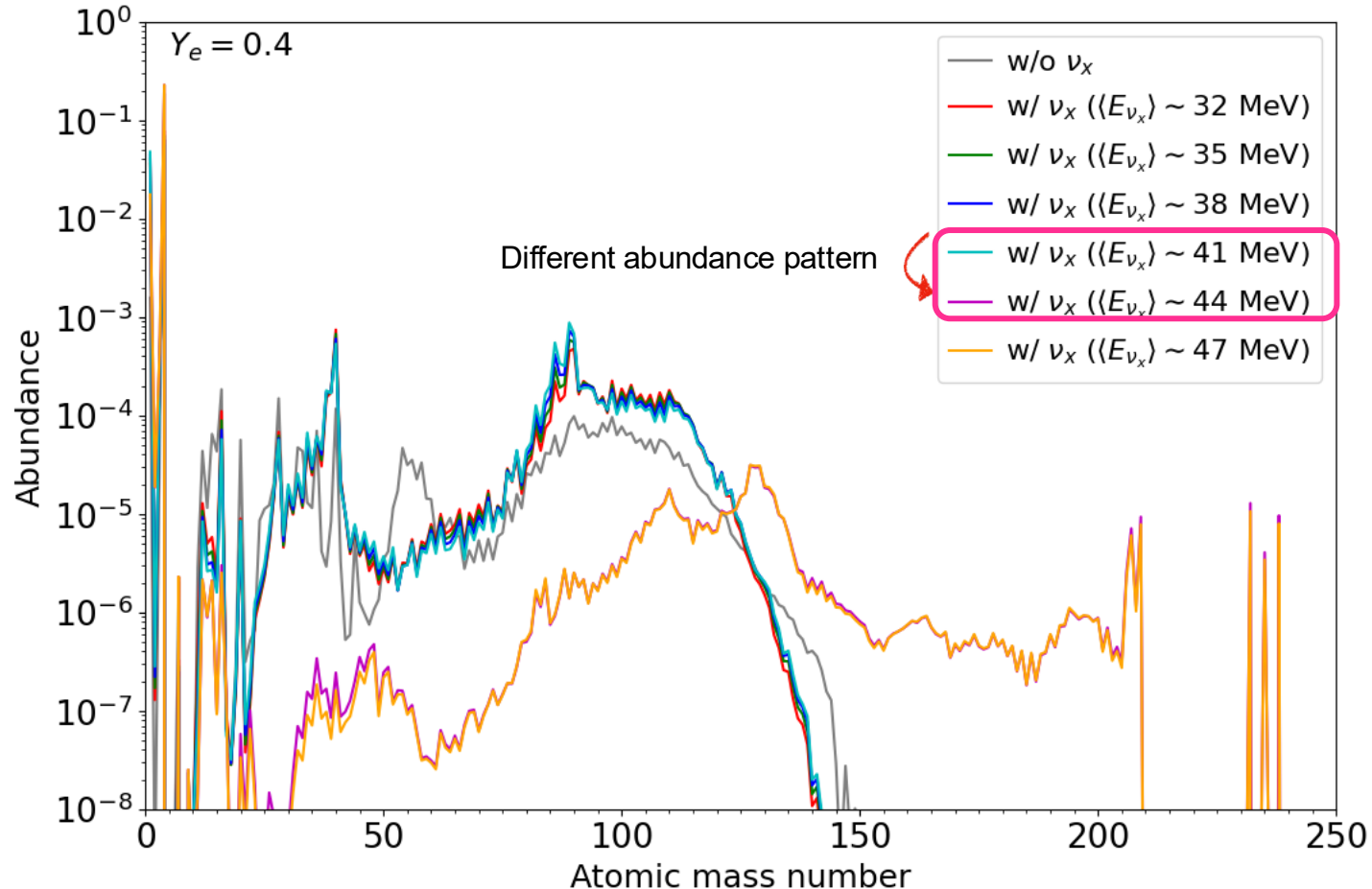


- Neutral current (NC) by ν_μ and ν_τ increases the p-nuclei abundance.
- NC interactions can produce additional nucleons.



Final abundance

Neutral current depends on average neutrino energy

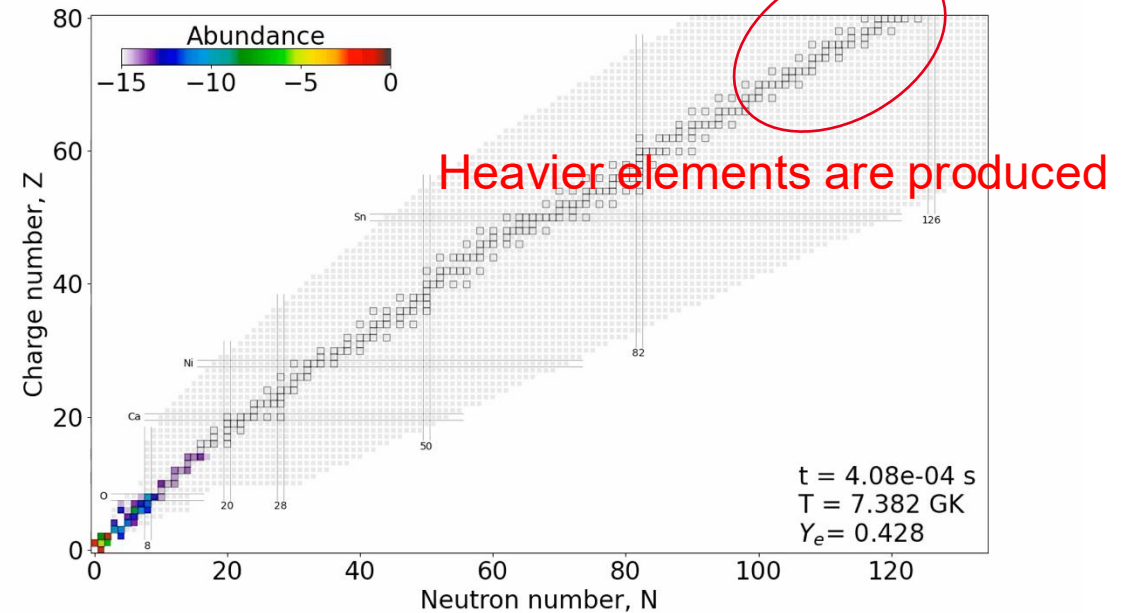
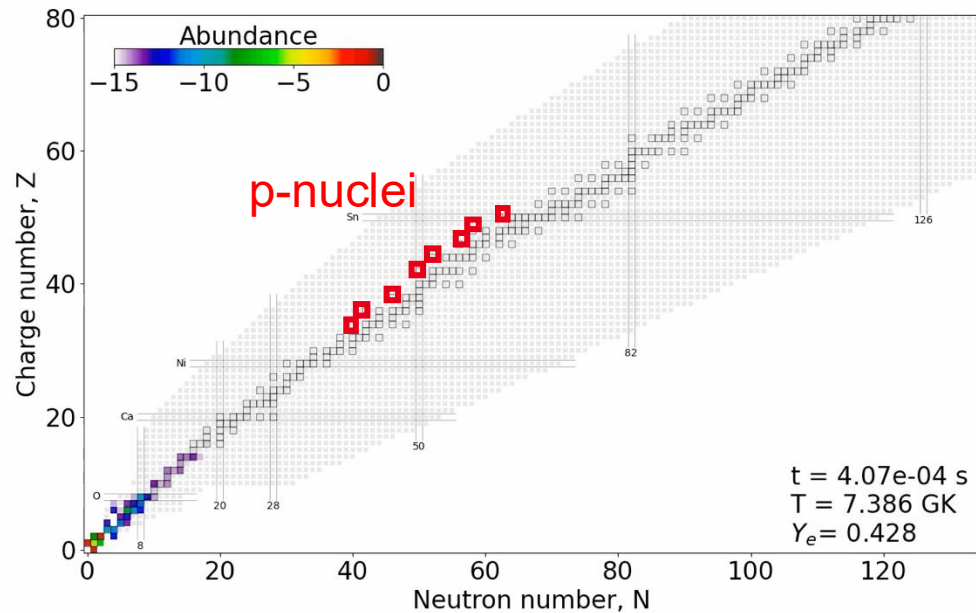
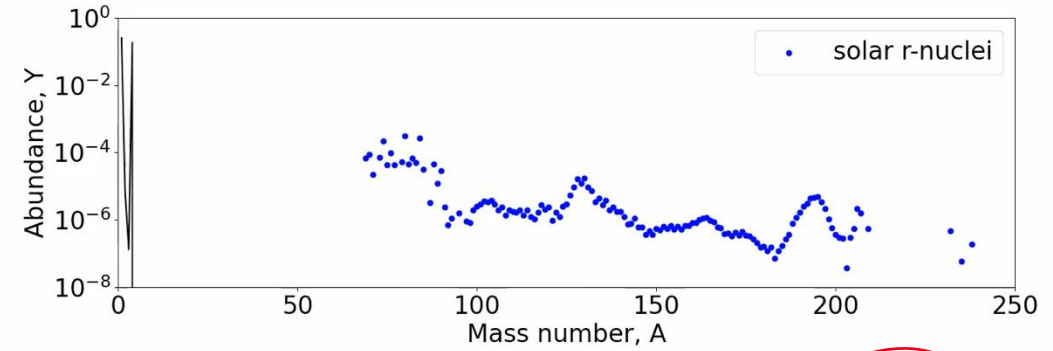
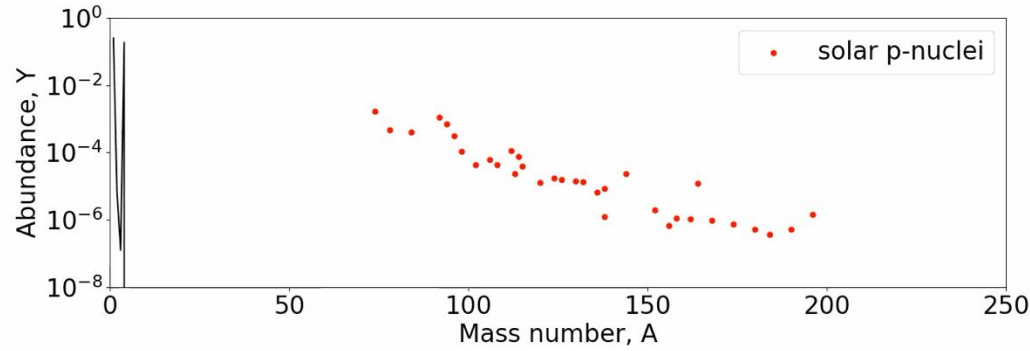


- Neutral current by ν_μ and ν_τ increases the p-nuclei abundance.
- For $\langle E_{\nu_x} \rangle \lesssim 41 \text{ MeV}$ case, the p-nuclei $A \sim 88 - 138$ are produced
- For $\langle E_{\nu_x} \rangle > 44 \text{ MeV}$ case, the p-nuclei production decreases but it shows r-process like pattern.

The origin of two different evolutions

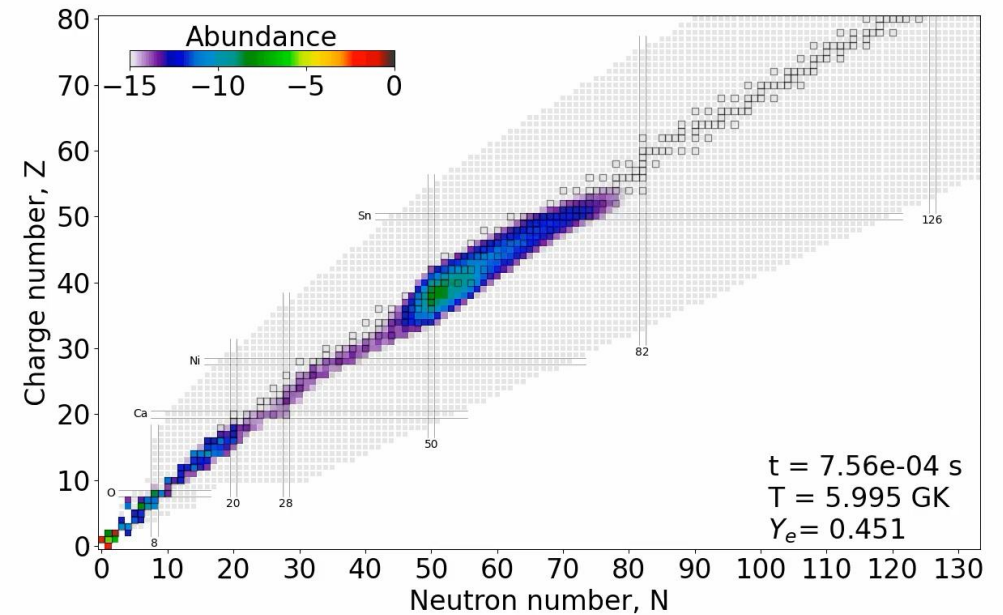
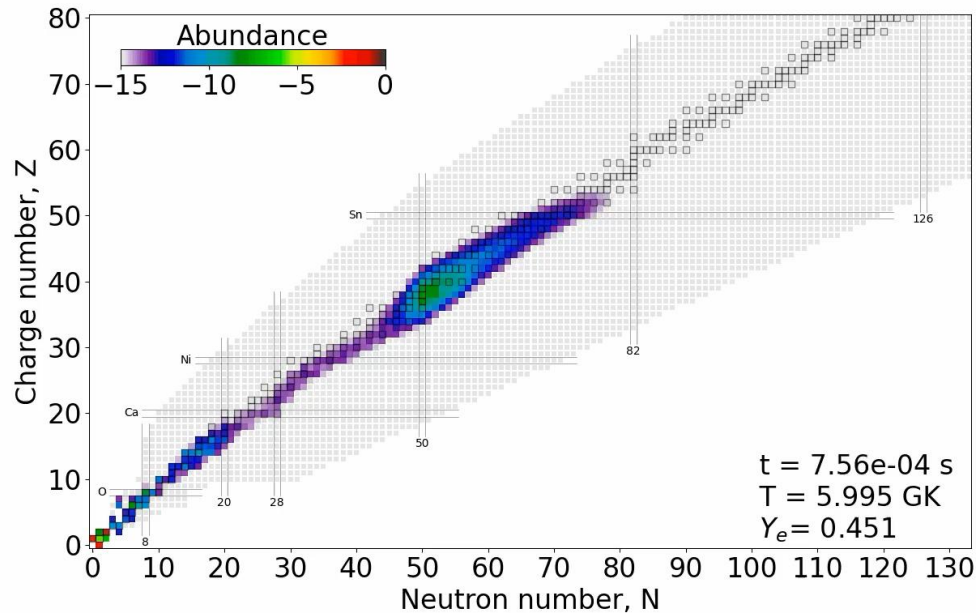
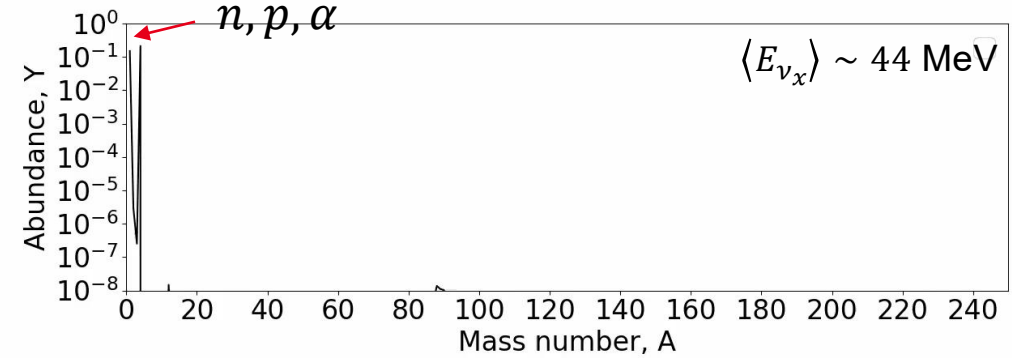
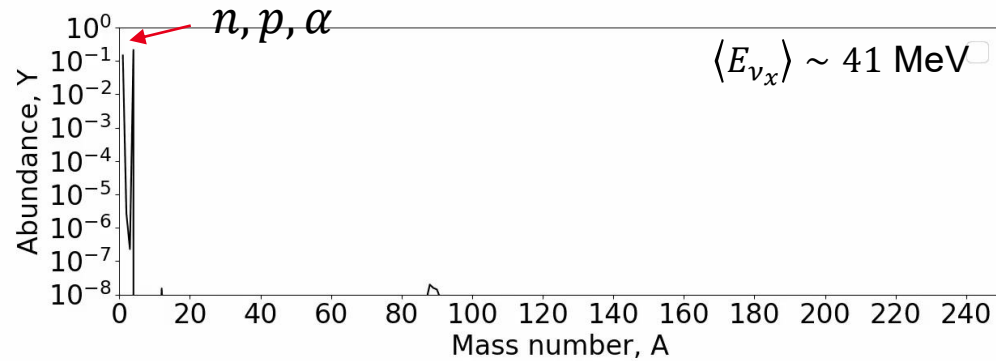
$\langle E_{\nu_x} \rangle \sim 41 \text{ MeV}$

$\langle E_{\nu_x} \rangle \sim 44 \text{ MeV}$



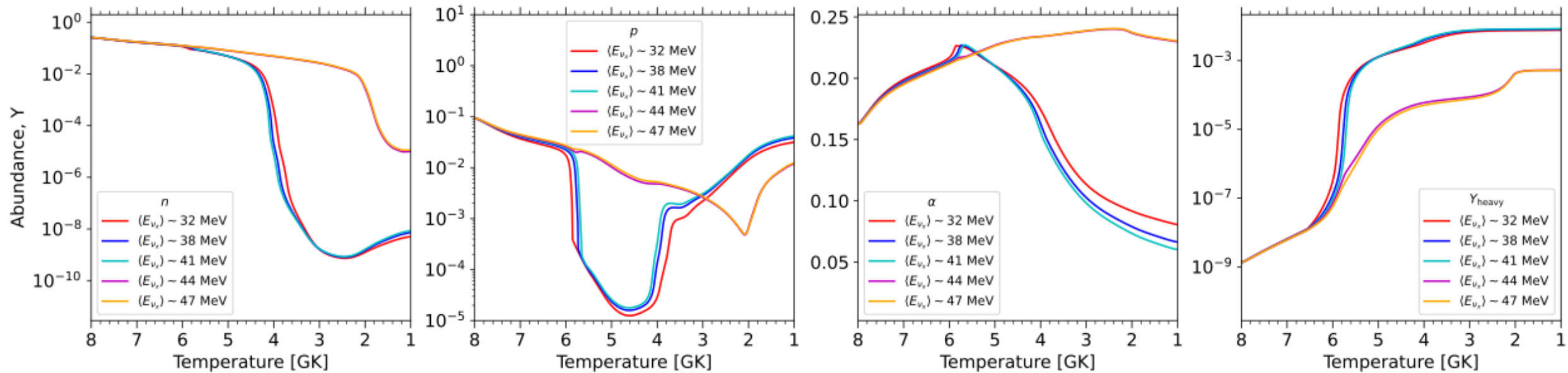
Evolutions from $T = 4-6$ GK

The patterns starts to deviate at $T \sim 5.5$ GK



Abundances

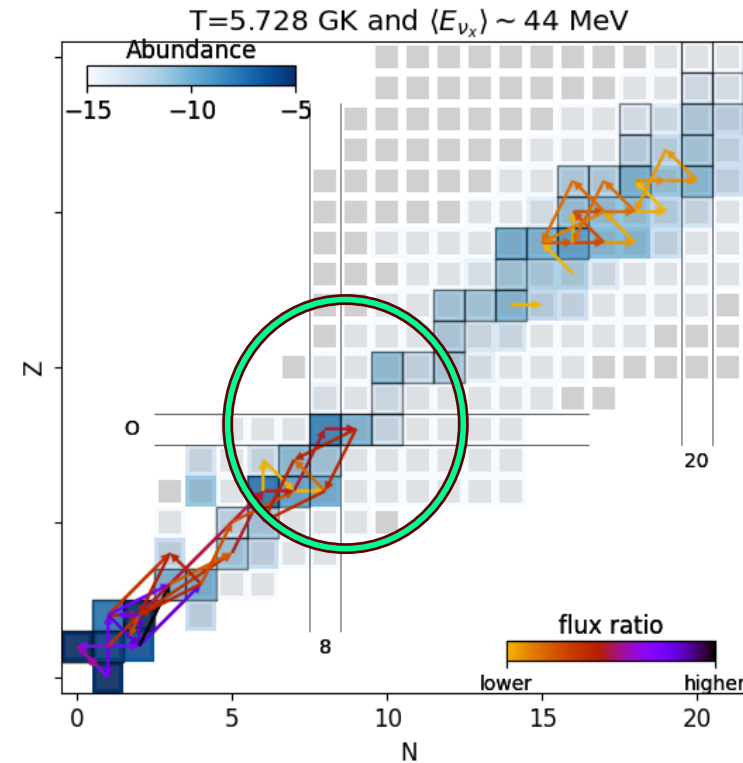
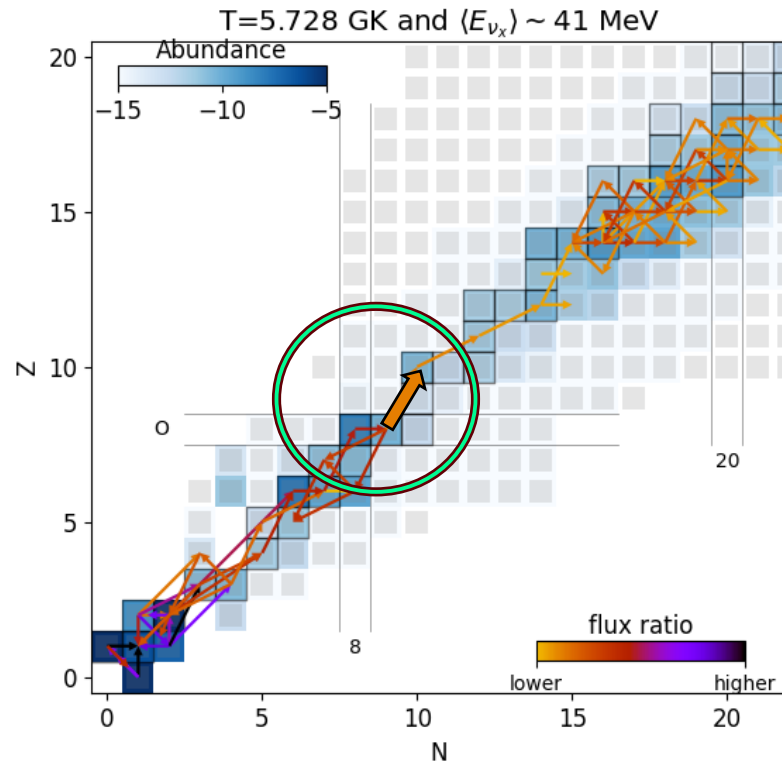
The abundances of neutron, proton, alpha and heavy nuclei



- There are two trends in abundances between $\langle E_{\nu_x} \rangle \sim 41$ MeV and $\langle E_{\nu_x} \rangle \sim 44$ MeV.
- For the higher $\langle E_{\nu_x} \rangle$, there are more free n, p and α .
- Alpha particles are used to form a heavier element.

The difference in ^{17}O

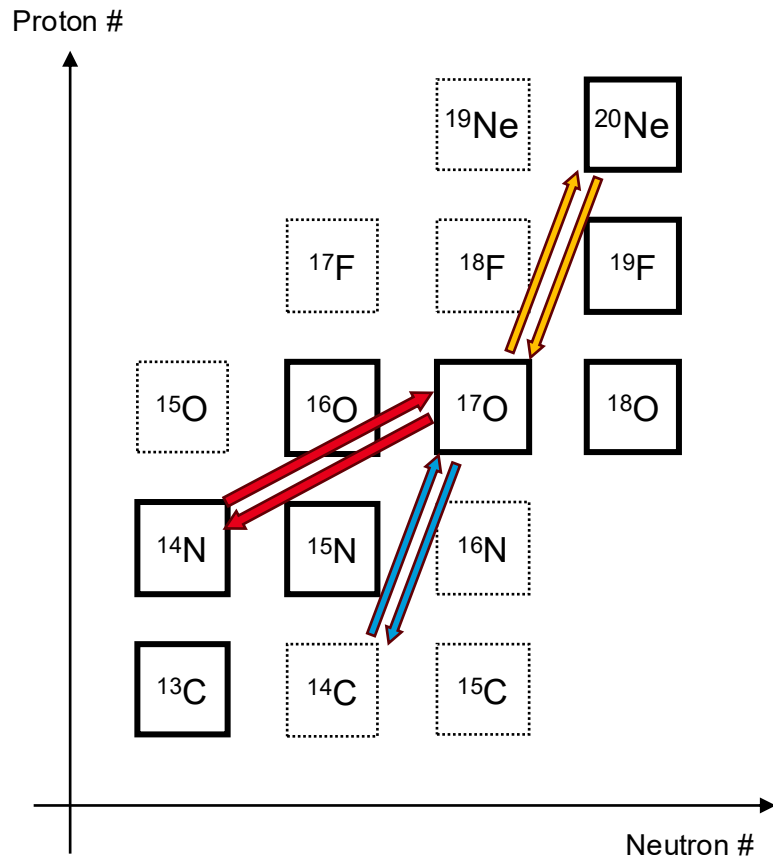
Flow of the flux



- $\langle E_{\nu_x} \rangle \sim 41 \text{ MeV}$ case supports to produce again the heavier elements over ^{17}O .
- While $\langle E_{\nu_x} \rangle \sim 44 \text{ MeV}$ case, the light elements are stock below ^{17}O

The flux on ^{17}O

$^{17}\text{O}(\alpha, n)^{20}\text{Ne}$, $^{17}\text{O}(n, \alpha)^{14}\text{C}$ and $^{17}\text{O}(p, \alpha)^{14}\text{N}$ reactions



(Yellow) $\alpha + ^{17}\text{O} \rightleftharpoons n + ^{20}\text{Ne}$

$$\text{Flux} = Y_\alpha Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha + ^{17}\text{O}} - Y_n Y_{^{20}\text{Ne}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{n + ^{20}\text{Ne}}$$

(Blue) $\alpha + ^{14}\text{C} \rightleftharpoons n + ^{17}\text{O}$

$$\text{Flux} = Y_\alpha Y_{^{14}\text{C}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha + ^{14}\text{C}} - Y_n Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{n + ^{17}\text{O}}$$

(red) $\alpha + ^{14}\text{N} \rightleftharpoons p + ^{17}\text{O}$

$$\text{Flux} = Y_\alpha Y_{^{14}\text{N}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha + ^{14}\text{N}} - Y_p Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{p + ^{17}\text{O}}$$

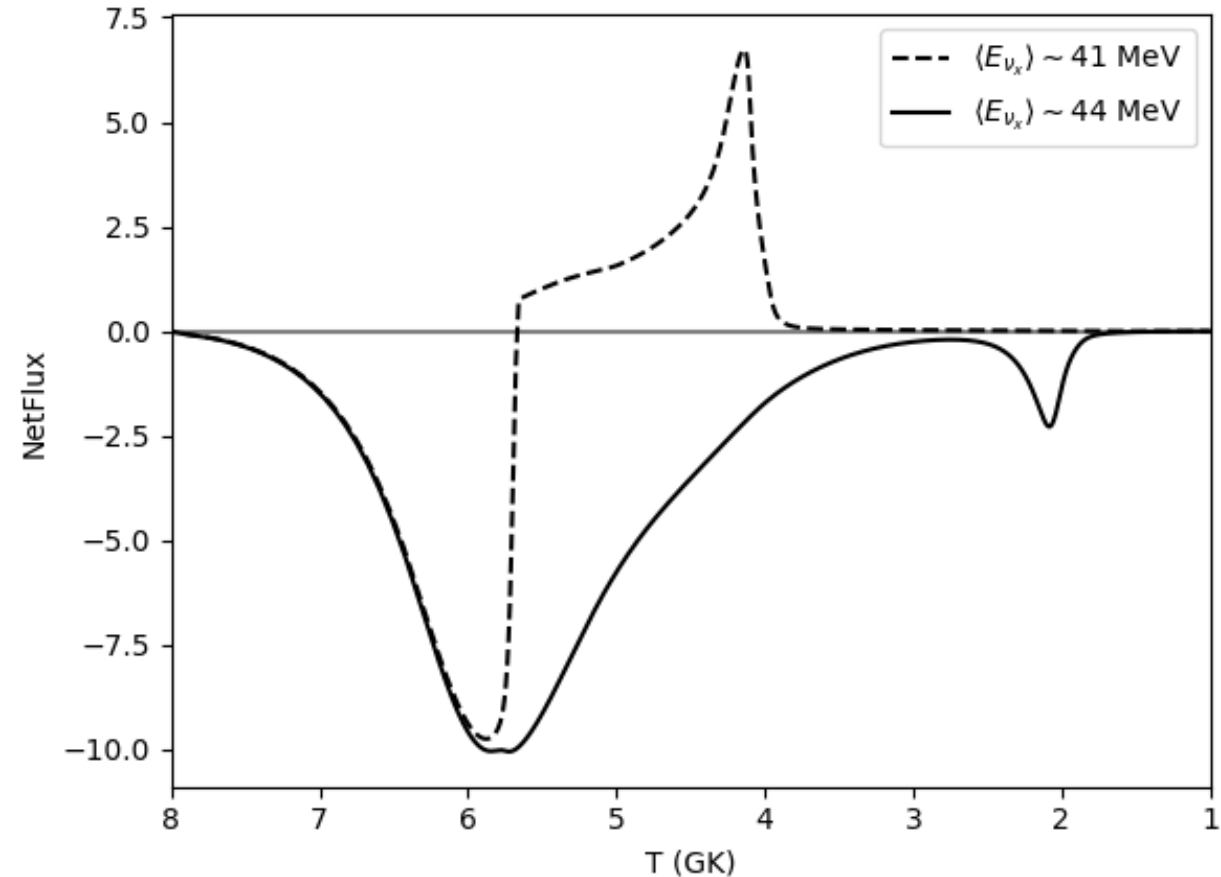
Flux > 0: flow is directed towards producing heavier elements
Reaction rate from JINA reaclib

The flow of net flux for ^{17}O

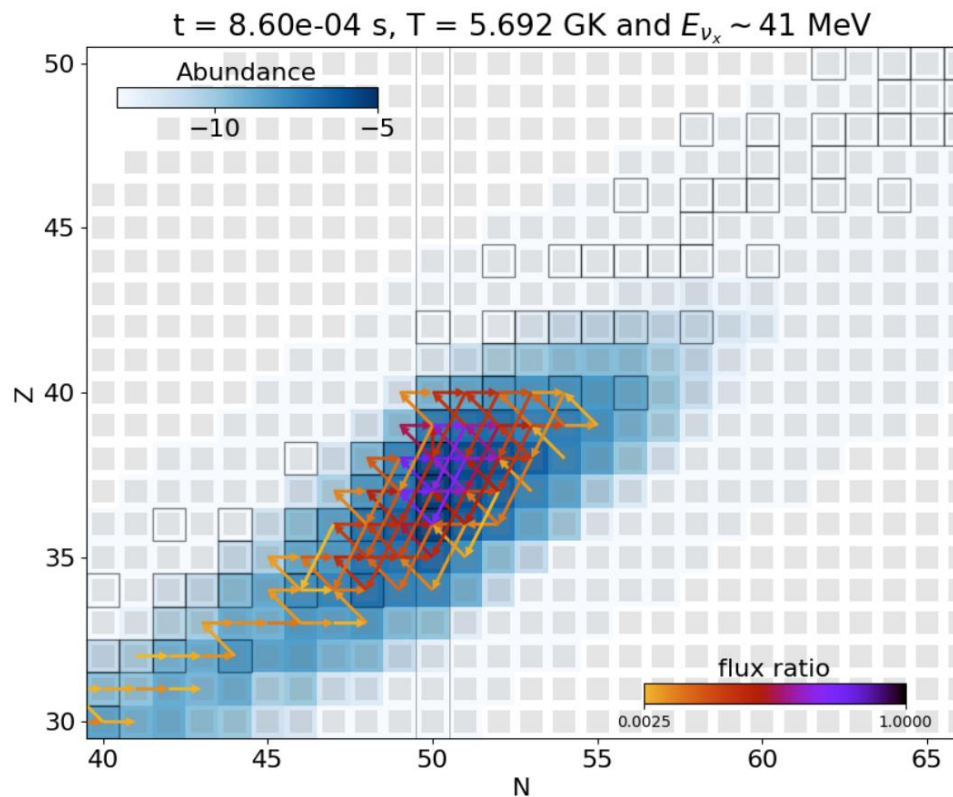
- $$\text{Net Flux} \equiv +Y_\alpha Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha+^{17}\text{O}} - Y_n Y_{^{20}\text{Ne}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{n+^{20}\text{Ne}}$$

$$+Y_\alpha Y_{^{14}\text{C}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha+^{14}\text{C}} - Y_n Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{n+^{17}\text{O}}$$

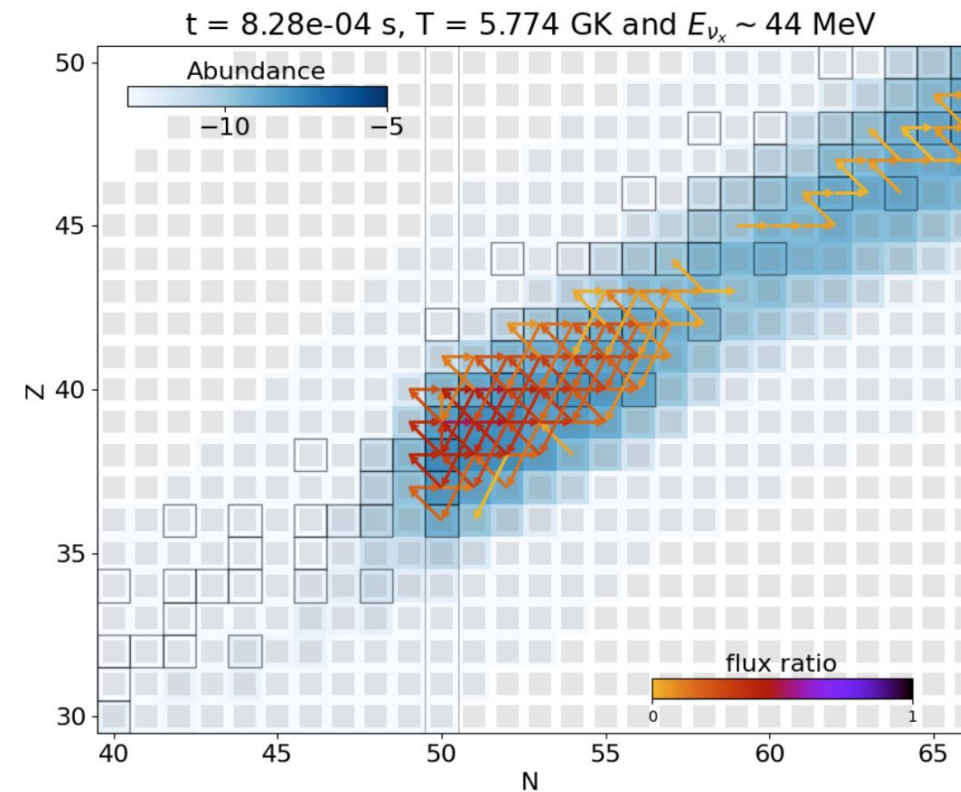
$$+Y_\alpha Y_{^{14}\text{N}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{\alpha+^{14}\text{N}} - Y_p Y_{^{17}\text{O}} \frac{\rho_b}{m_u} \langle \sigma v \rangle_{p+^{17}\text{O}}$$
- For Net Flux > 0 , the evolution proceeds in direction of synthesizing element heavier than ^{17}O .
- $T \gtrsim 5.7 \text{ GK}$, $\langle E_{\nu_x} \rangle \lesssim 41 \text{ MeV}$ case starts to produce again heavier elements.



Connection to lighter elements

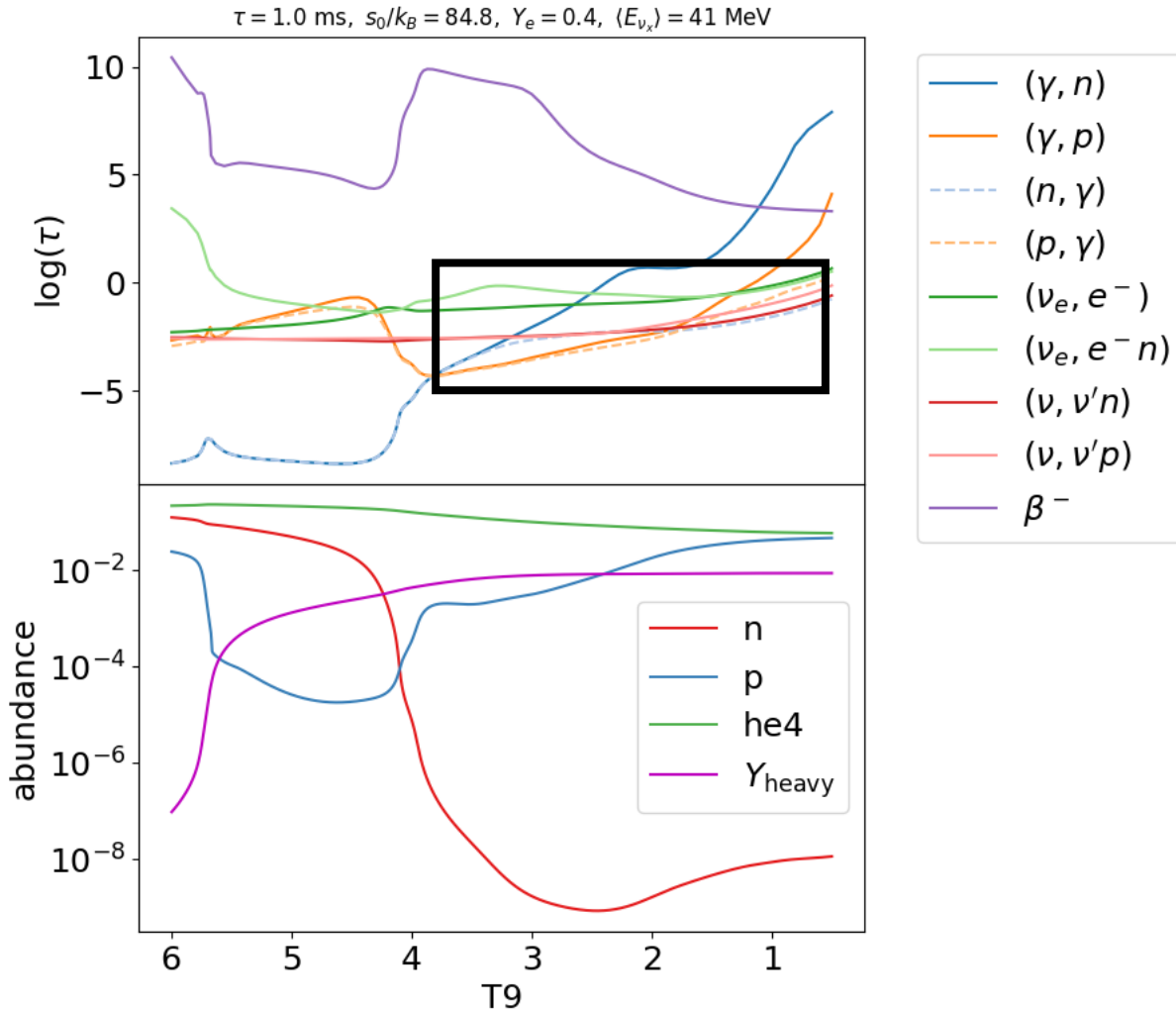


Additional seed production



Suppressed seed production

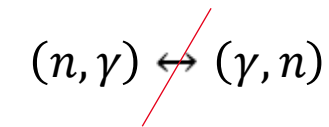
Reaction timescales



Lower time scale means faster reaction

$$\tau \propto \frac{1}{\lambda} \quad \text{or} \quad \tau \propto \frac{1}{\sum Y_i \langle \sigma v \rangle_i}$$

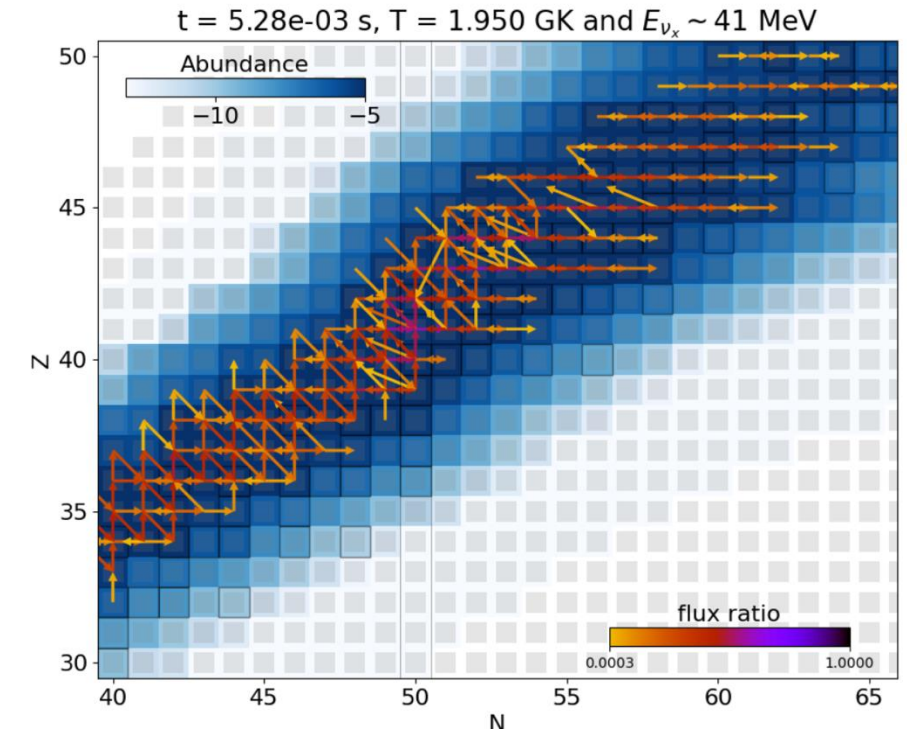
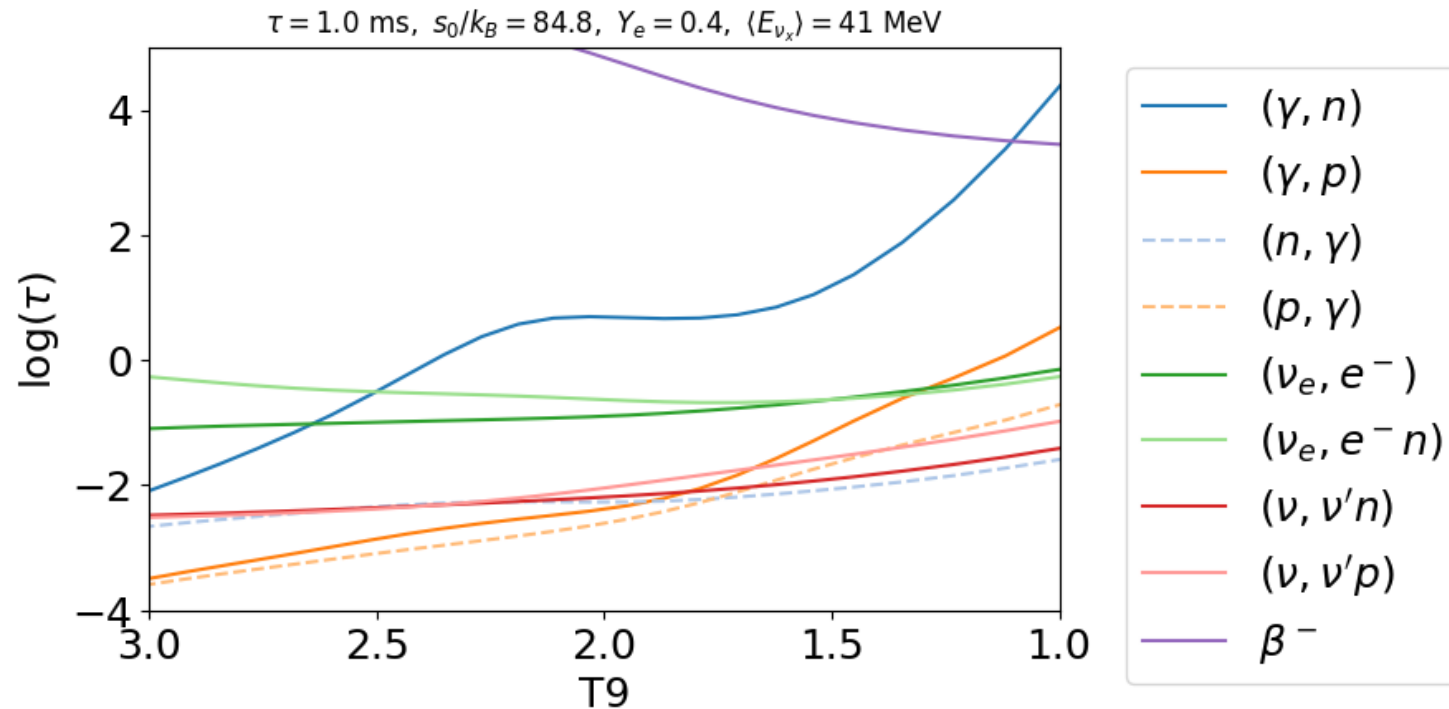
Below $T \sim 4 \text{ GK}$



Reaction timescales

Lower time scale means faster reaction

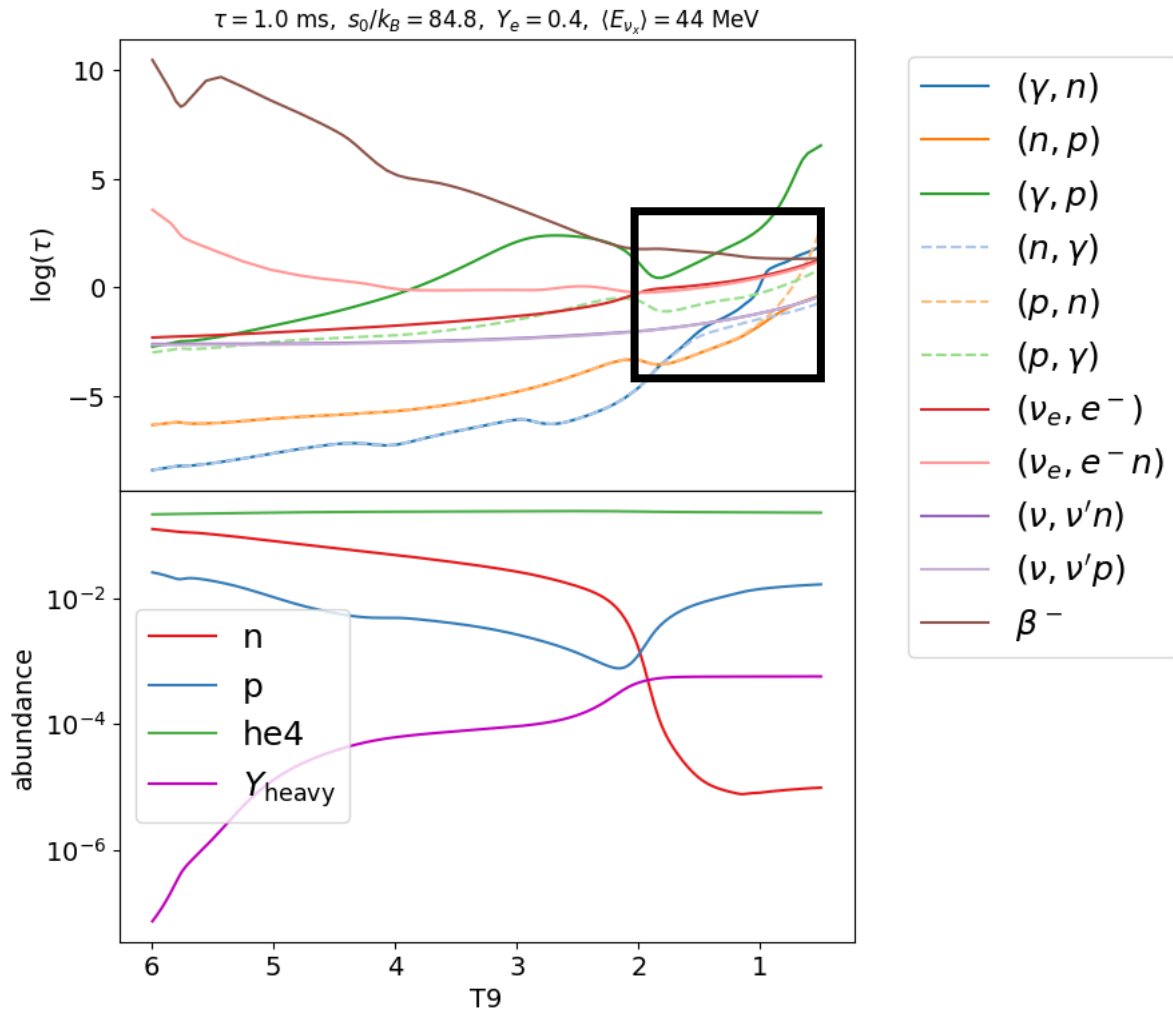
$$\tau \propto \frac{1}{\lambda} \quad \text{or} \quad \tau \propto \frac{1}{\sum Y_i \langle \sigma v \rangle_i}$$



$$\tau_{(n,\gamma)} \sim \tau_{(p,\gamma)} \sim \tau_{CC}(\nu_e) \sim \tau_{NC}(\nu) > \tau_{\beta^-}$$

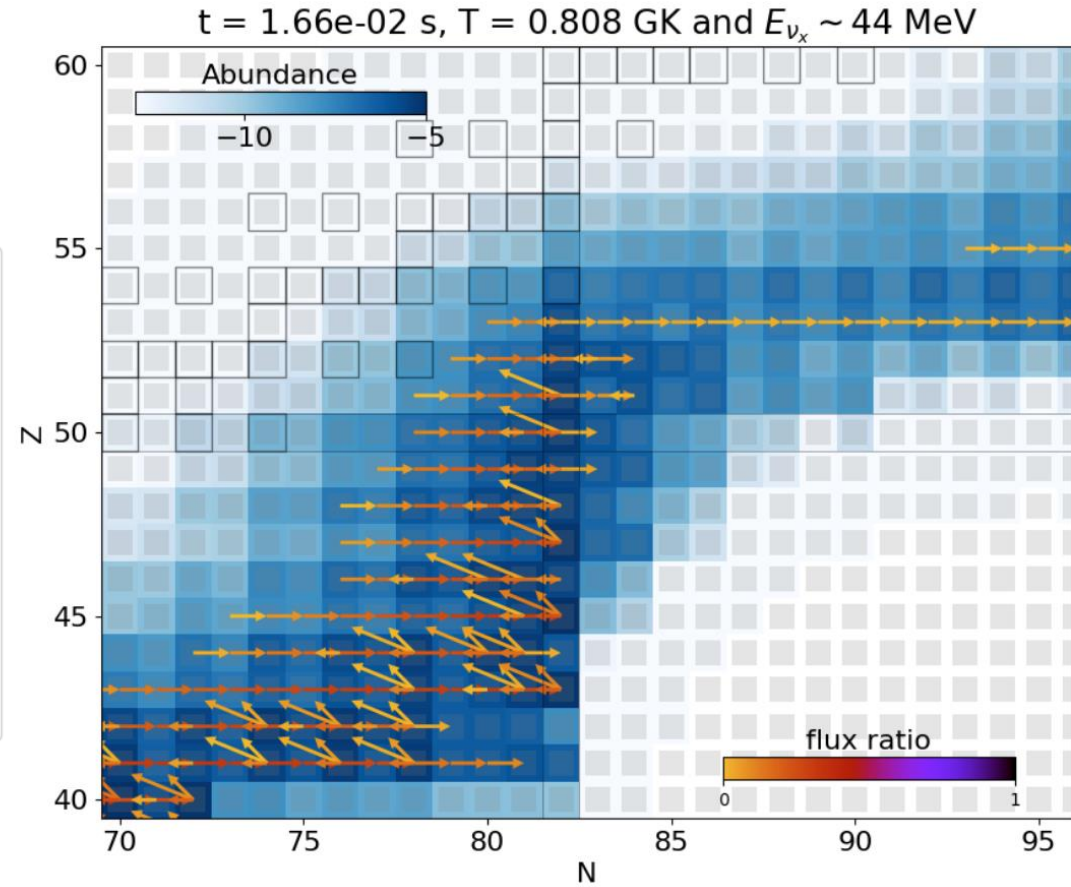
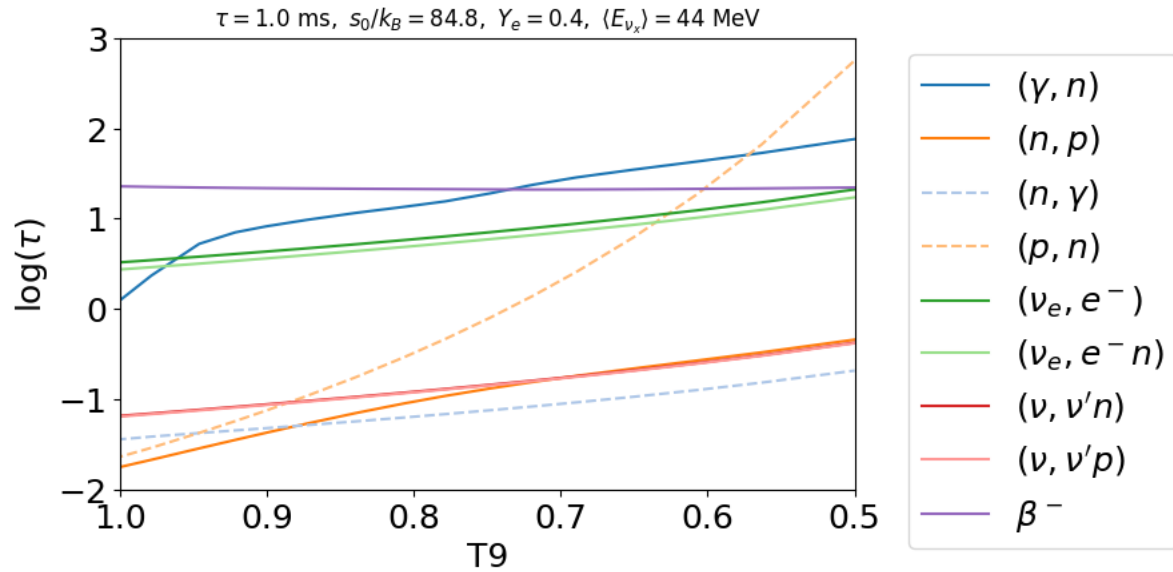
→
↑
↖
←


Reaction timescales



$$\tau_{(n,\gamma)}, \tau_{\text{CC}(\nu_e)}, \tau_{\text{NC}(\nu)} > \tau_{\beta^-}$$

Reaction timescales



$$\tau_{(n,\gamma)}, \tau_{CC}(\nu_e), \tau_{NC}(\nu) > \tau_{\beta^-}$$


By neutrino energy ordering

Previous neutrino energy ordering

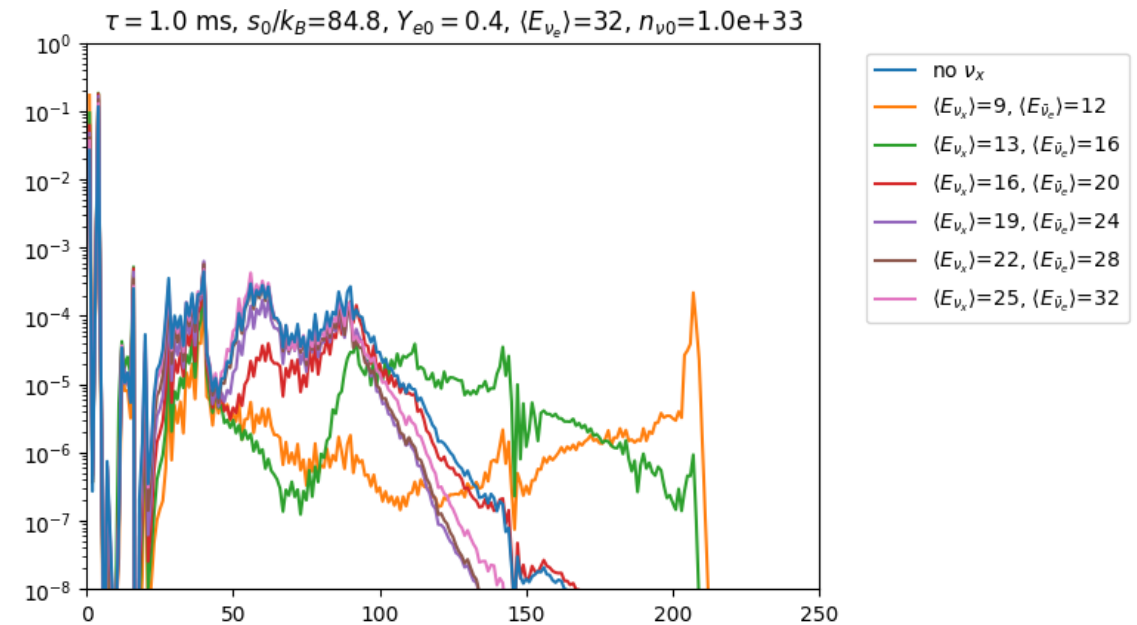
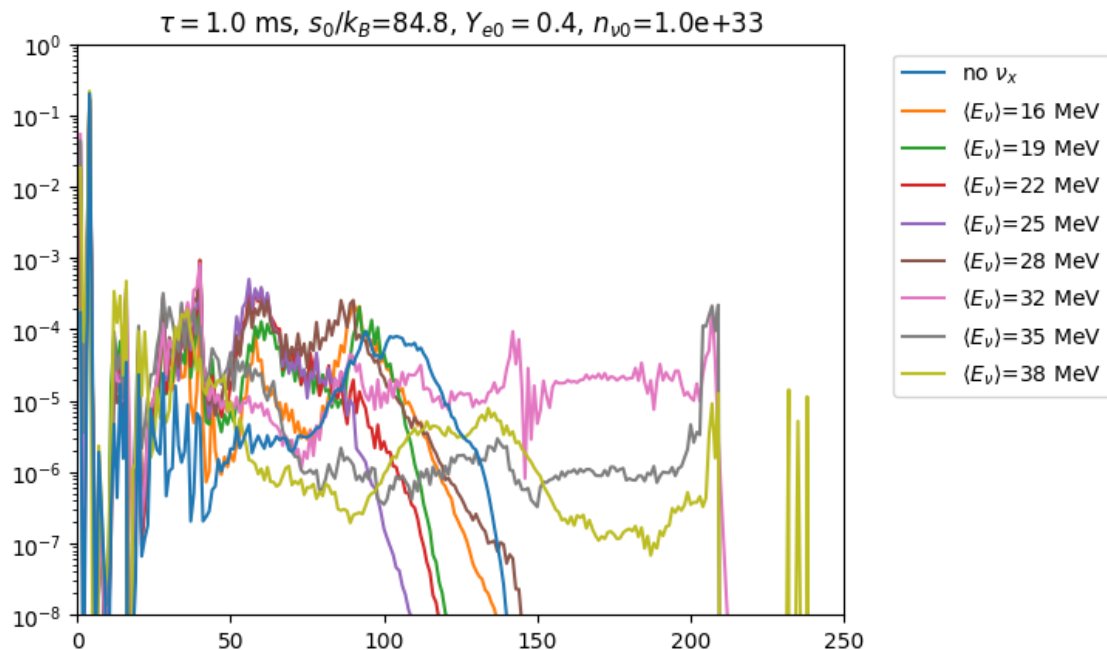
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \ll \langle E_{\nu_x} \rangle$$

For the case of flavor equipartition

$$\langle E_{\nu_e} \rangle = \langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu_x} \rangle$$

Full flavor conversion between $\nu_e \leftrightarrow \nu_x$

$$\langle E_{\nu_e} \rangle > \langle E_{\nu_x} \rangle$$



Summary

- νr -process: A large neutrino flux in a neutron-rich environment produces p-nuclei through the charged current (CC) interaction with the nucleus.
- The average cross section ($\langle \sigma_{\nu_x} \rangle$) by ν_μ and ν_τ is comparable to that of lower-energy electron neutrino CC interactions.
- There are enhancement on p-nuclei by NC
- (extreme case $\langle E_{\nu_x} \rangle > 44$ MeV) neutrino spallation on α changes the dynamics into r-process like pattern.
- We found that extreme case can not produce p-nuclei but instead produce heavier r-process element. Additionally, a bifurcation occurs in the light nuclei.
- ^{17}O is a key nucleus to build up again the production chain from the light element.