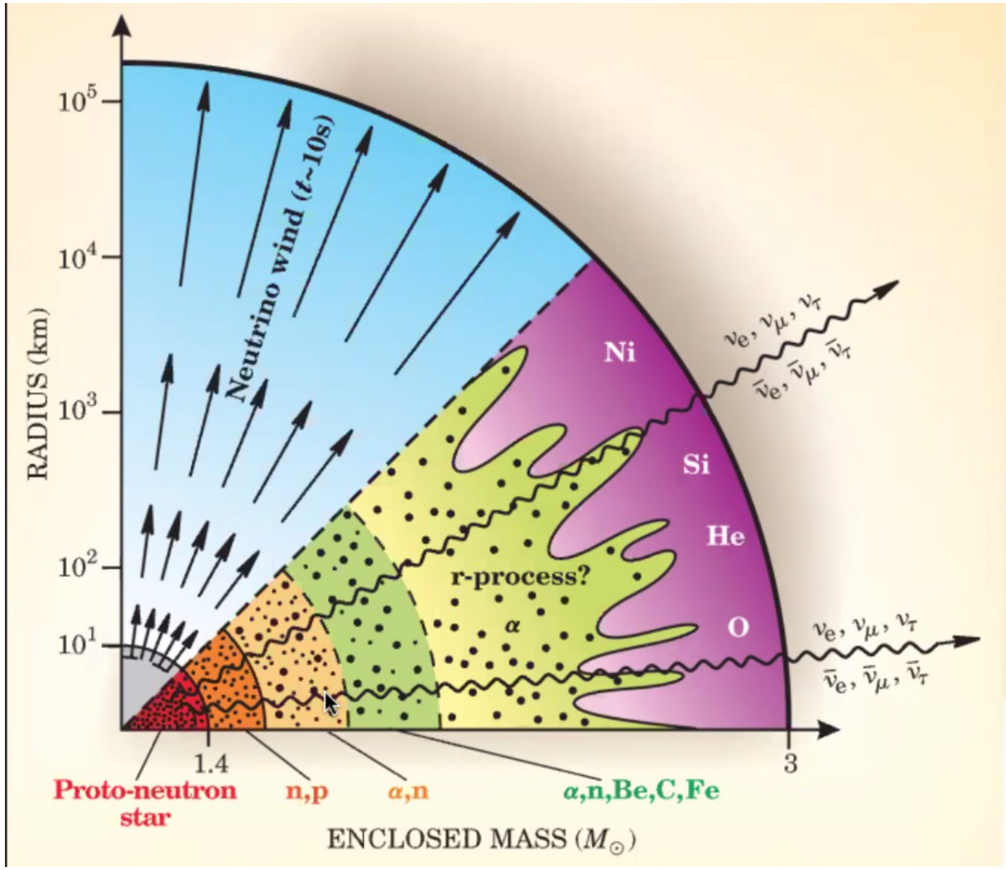
Neutrinos and heavy-element nucleosynthesis in supernovae



Woosley, Janka 2005

$$\boxed{\begin{array}{l} \nu_e + n \rightleftharpoons p + e^- \\ \bar{\nu}_e + p \rightleftharpoons n + e^+ \end{array}}$$

Neutrino physics shapes the

- Electron fraction

$$Y_{e,f} \approx \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

- Entropy per baryon

$$S_f \approx 235 C^{-1/6} L_{\bar{\nu}_e,51}^{-1/6} \epsilon_{\bar{\nu}_e,\mathrm{MeV}}^{-1/3} R_6^{-2/3} \left(\frac{M}{1.4\, M_\odot}\right) \text{ for } S_f \gg S_N$$

$$S_{\mathrm{tot}} \approx S_f + S_N \approx S_f + \ln S_f + 10$$

Qian, Woosley 1996

Collective Neutrino Oscillation

- Many body:
    - a system of N neutrinos with discrete energies quantized in a box of volume V
    - two-flavor approximation

$$H = \sum_p \omega_p \vec{B} \cdot \vec{J}_p + \sum_{p,q} \mu_{pq} \vec{J}_p \cdot \vec{J}_q$$

$$i \frac{d}{dt} |\Psi\rangle = H |\Psi\rangle$$

Neutrino "polarization vectors"

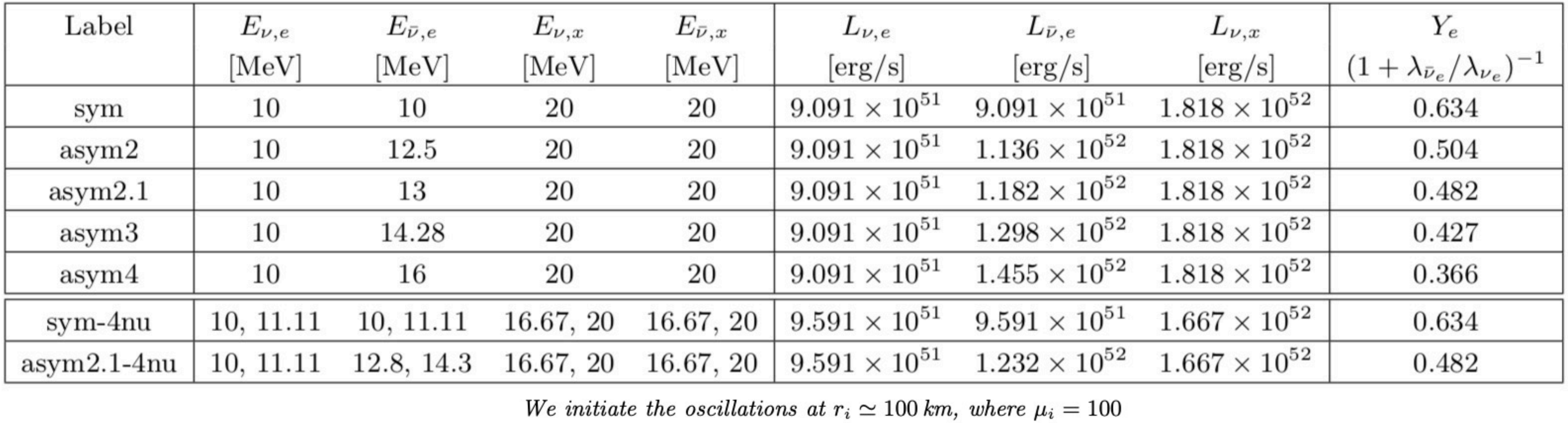
$$\vec{P}_q = 2\langle \vec{J}_q \rangle$$

- Mean field

$$H = \sum_p \omega_p \vec{B} \cdot \vec{J}_p + \sum_{p,q} \mu_{pq} \left[\vec{J}_p \cdot \langle \vec{J}_q \rangle + \langle \vec{J}_p \rangle \cdot \vec{J}_q - \langle \vec{J}_p \rangle \cdot \langle \vec{J}_q \rangle \right]$$

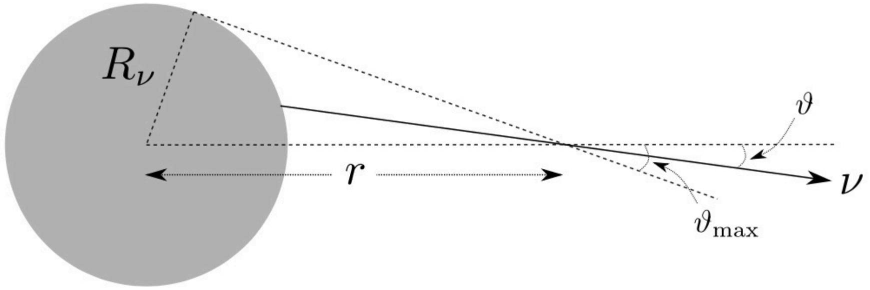
$$\frac{d\vec{P}_q}{dt} = \omega_q \vec{B} \times \vec{P}_q + 2 \sum_p \mu_{pq} \vec{P}_p \times \vec{P}_q$$

Collective oscillations in supernovae



Label	$E_{\nu,e}$ [MeV]	$E_{\bar{\nu},e}$ [MeV]	$E_{\nu,x}$ [MeV]	$E_{\bar{\nu},x}$ [MeV]	$L_{\nu,e}$ [erg/s]	$L_{\bar{\nu},e}$ [erg/s]	$L_{\nu,x}$ [erg/s]	Y_e $(1+\lambda_{\bar{\nu}_e}/\lambda_{\nu_e})^{-1}$
sym	10	10	20	20	9.091×10^{51}	9.091×10^{51}	1.818×10^{52}	0.634
asym2	10	12.5	20	20	9.091×10^{51}	1.136×10^{52}	1.818×10^{52}	0.504
asym2.1	10	13	20	20	9.091×10^{51}	1.182×10^{52}	1.818×10^{52}	0.482
asym3	10	14.28	20	20	9.091×10^{51}	1.298×10^{52}	1.818×10^{52}	0.427
asym4	10	16	20	20	9.091×10^{51}	1.455×10^{52}	1.818×10^{52}	0.366
sym-4nu	10, 11.11	10, 11.11	16.67, 20	16.67, 20	9.591×10^{51}	9.591×10^{51}	1.667×10^{52}	0.634
asym2.1-4nu	10, 11.11	12.8, 14.3	16.67, 20	16.67, 20	9.591×10^{51}	1.232×10^{52}	1.667×10^{52}	0.482

We initiate the oscillations at $r_i \simeq 100\,km$, where $\mu_i = 100$



"neutrino bulb" geometry
--single angle approximation

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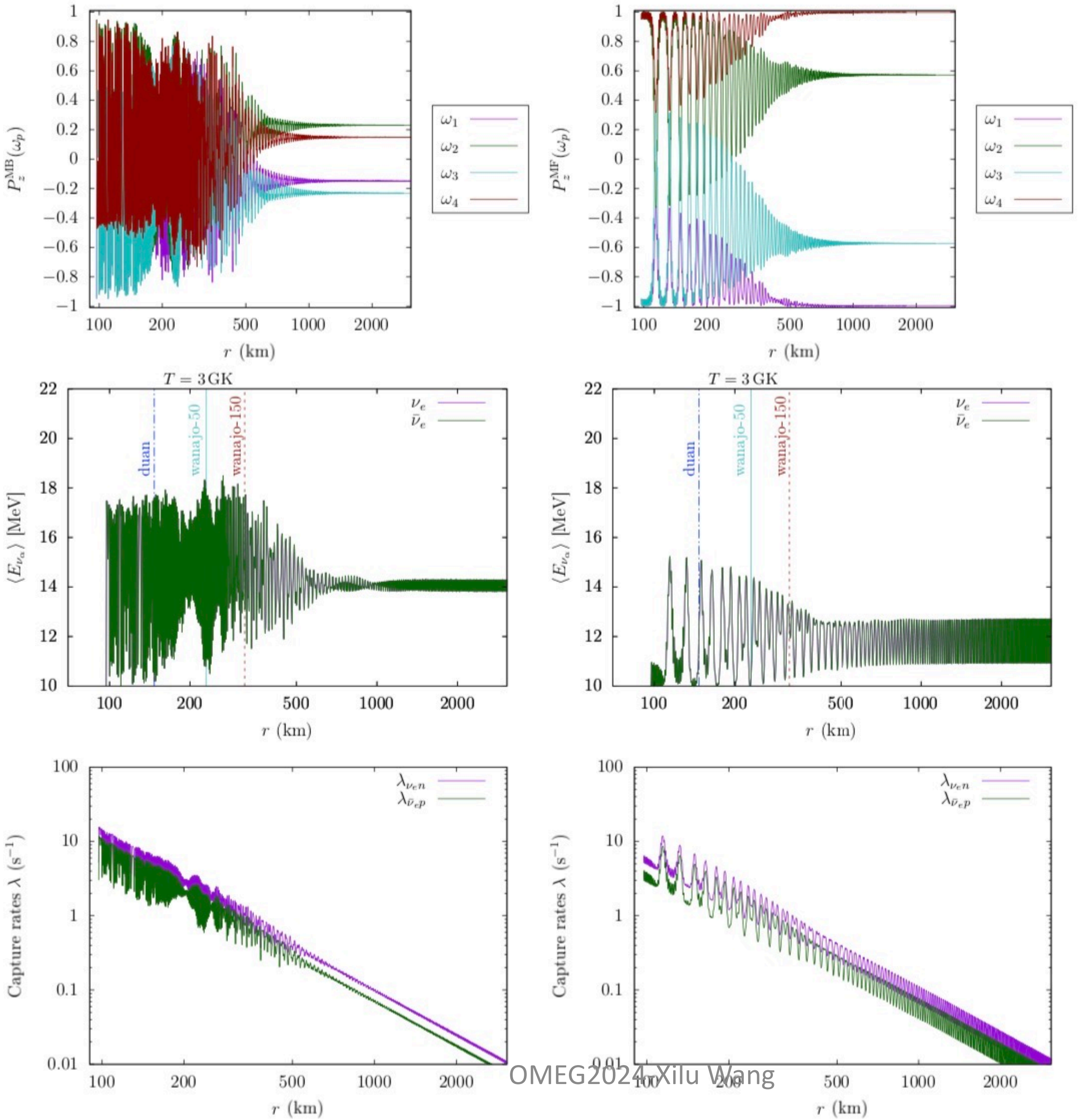
Collective oscillations in supernovae



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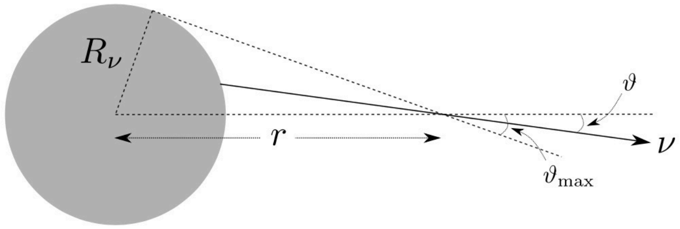
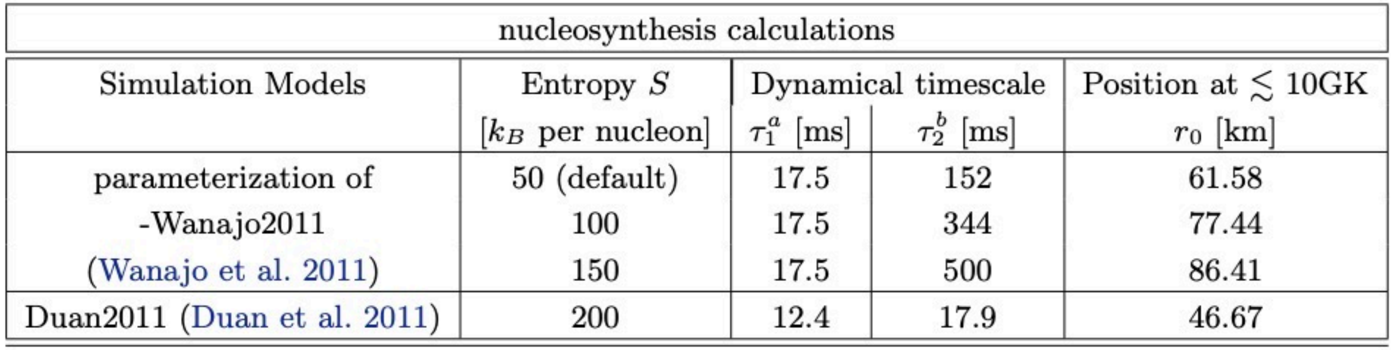
Collective oscillations in supernovae



SN neutrino-driven wind trajectories:
1) parameterized slow NDW trajectory adapted from Wanajo2011 with various entropy values;
2) parameterized high entropy and fast NDW trajectory adapted from Arcones+2007 as in Duan+2011.



nucleosynthesis calculations

Simulation Models	Entropy S [k_B per nucleon]	Dynamical timescale τ_1^a [ms]	τ_2^b [ms]	Position at $\lesssim$ 10GK r_0 [km]
parameterization of -Wanajo2011 (Wanajo et al. 2011)	50 (default)	17.5	152	61.58
	100	17.5	344	77.44
	150	17.5	500	86.41
Duan2011 (Duan et al. 2011)	200	12.4	17.9	46.67

Nucleosynthesis simulation with PRISM

1) four neutrino treatments (nn, nosc, mf, mb) are implemented into PRISM in the form of external $\nu_e + n$ and $\bar{\nu}_e + p$ capture rates; neutrino-nuclei interactions are not included
2) Nuclear data: REACLIB reaction rates (Cyburt et al. 2010) + NUBASE β-decay properties (Kondev et al. 2021)

PRISM (**P**ortable **R**outines for **I**ntegrated nucleo**S**ynthesis **M**odeling): Trevor Sprouse (ND) & Matthew Mumpower (LANL)

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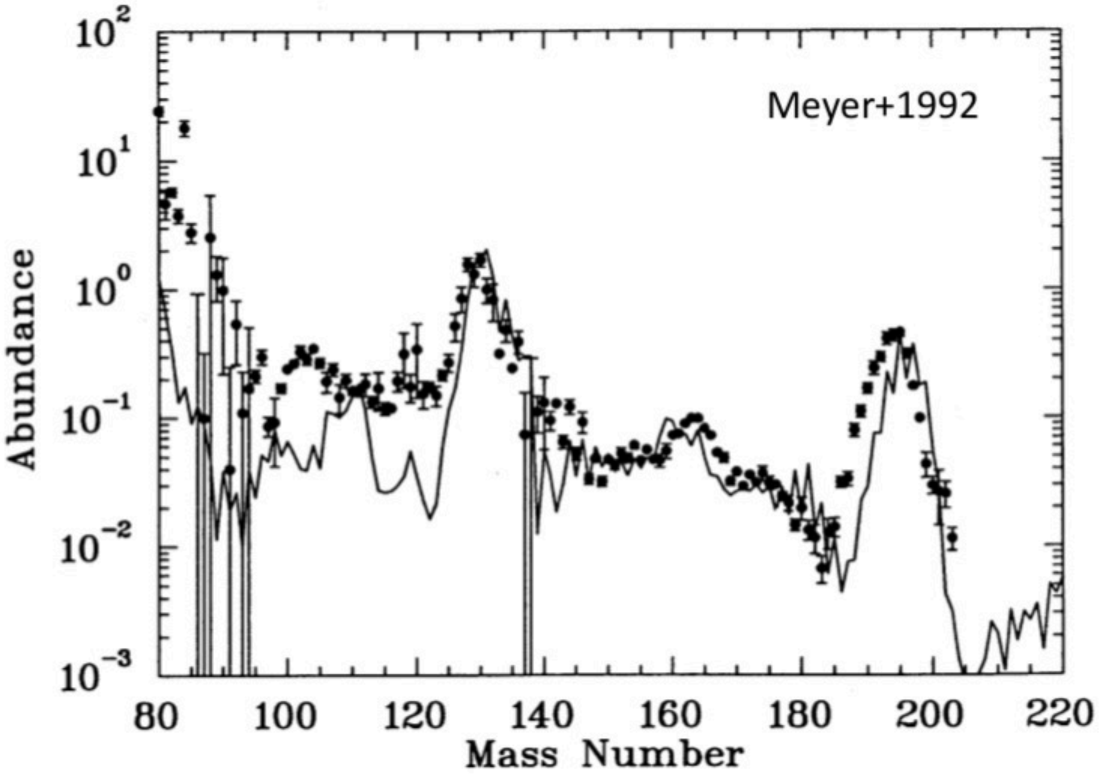
r-process astrophysical sites: supernovae?

SN neutrino-driven wind



$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

Does this work?

- Yes

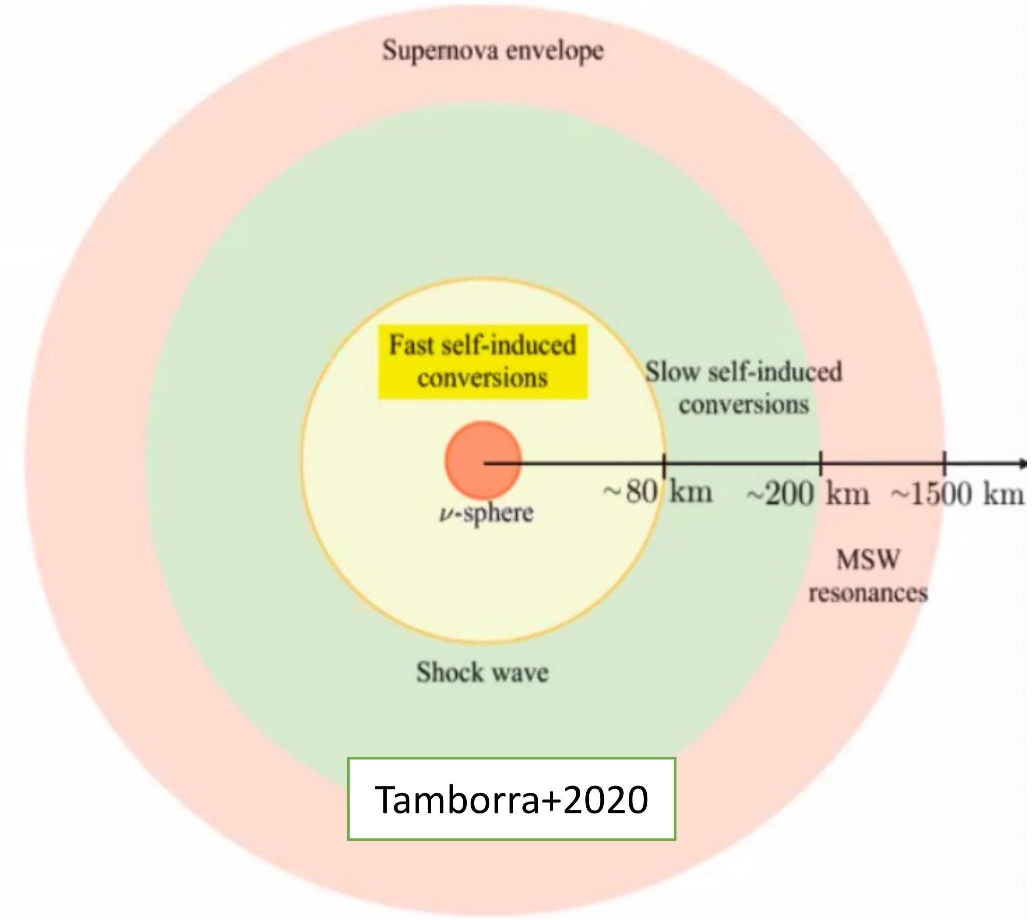
Meyer+1992, Woosley+1994

- No

Takahashi+1994, Witti+1994, Fuller, Meyer 1995, McLaughlin+1996, Qian & Woosley 1996, Hoffman+1997, Otsuki+2000, Thompson+2001, Terasawa+2002, Liebendorfer+2005, Wanajo 2006, Arcones+2007, Huedepohl+2010, Fischer+2010, Roberts, Reddy 2012, Martinez-Pinedo+2014, Chakraborty+ 2015, Goriely, Janka 2016, etc., etc.

r-process astrophysical sites: supernovae?

SN neutrino-driven wind:



Tamborra+2020

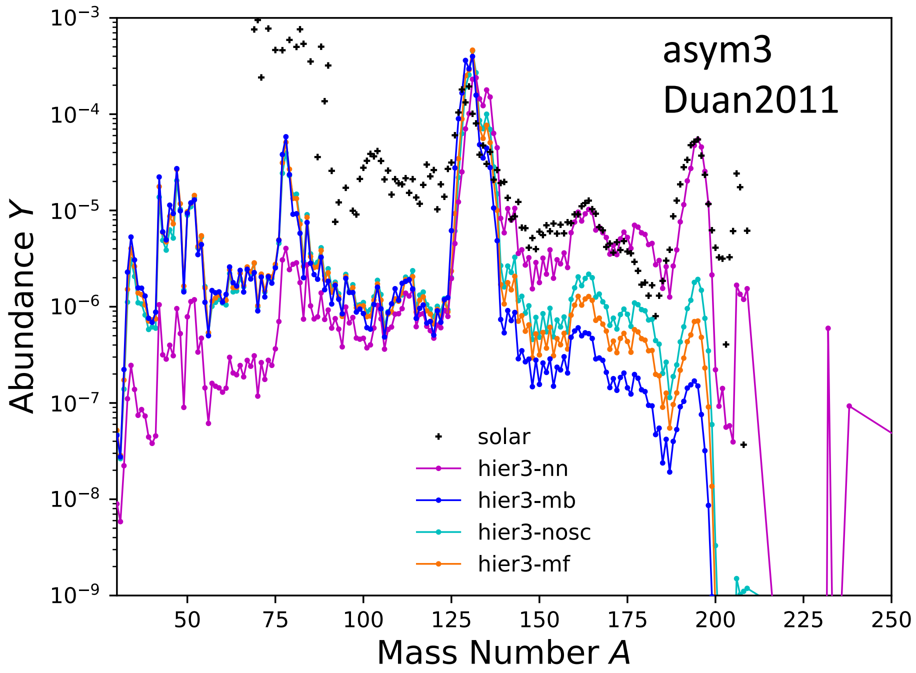
$$\boxed{\begin{array}{l}\nu_e + n \rightleftharpoons p + e^- \\ \bar{\nu}_e + p \rightleftharpoons n + e^+\end{array}}$$

a weak r-process (up to A~125) might be possible, with the ultimate extent of nucleosynthesis sensitively depends on neutrino physics (Fuller, Meyer 1995, Balantekin, Yuksel 2005, Johns+2020, Xiong+2020):

- Neutrinos determines the initial neutron richness (Y_e) for r process
- During alpha particle formation: ν_e reduce free neutrons --- alpha effect (Fuller+1995, McLaughlin+1996, Meyer+1998 ……)
- Collective neutrino oscillations raise the effective energy of ν_e and $\bar{\nu}_e$, to readjust the Y_e value at early time (mostly free nucleons), and enhance the alpha effect (Duan+2011, Wu+2015, Pllumbi+2015, Just+2022…)
- Active-sterile conversions may also has an effect (McLaughlin+1999, Beun+2006, Wu+2014, Pllumbi+2015)

Existence of neutrinos: less robust r-process productions

Collective oscillations and r process

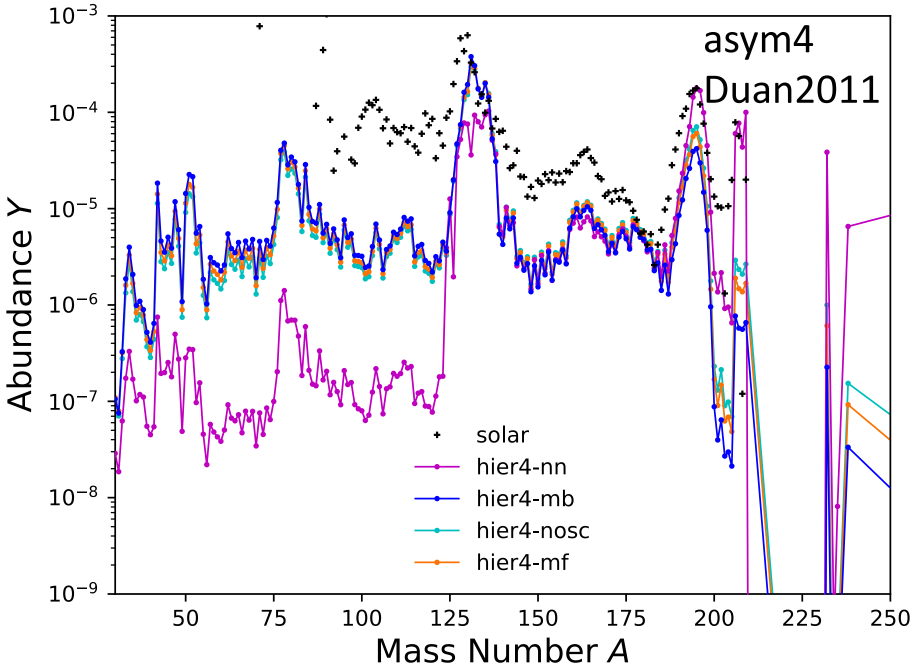


purple: no neutrino (nn)

cyan: no neutrino oscillation (nosc)

blue: many-body calculation of oscillation (mb)

orange: mean-field calculation of oscillation (mf)



r process: neutrinos hinder the synthesis of heavier nuclei, and mainly affect the 3rd peak and beyond region;

for asym3 case with r-process nucleosynthesis barely reach the 3rd peak and beyond → Biggest effect of the difference in SN NDW neutrino treatments on the r-process yields: move to weak r-process;

many-body treatment has the biggest effect for normal mass hierarchy;

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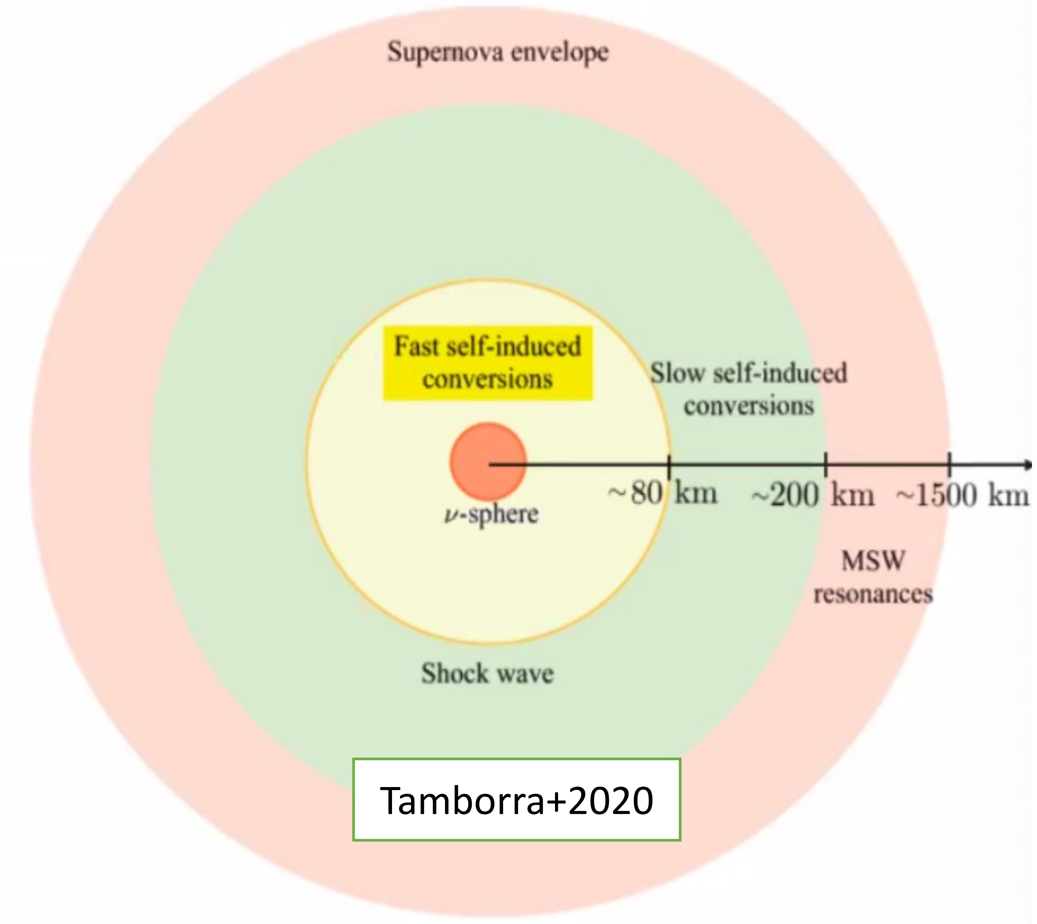
νp-process in supernovae



Tamborra+2020

SN neutrino-driven wind:

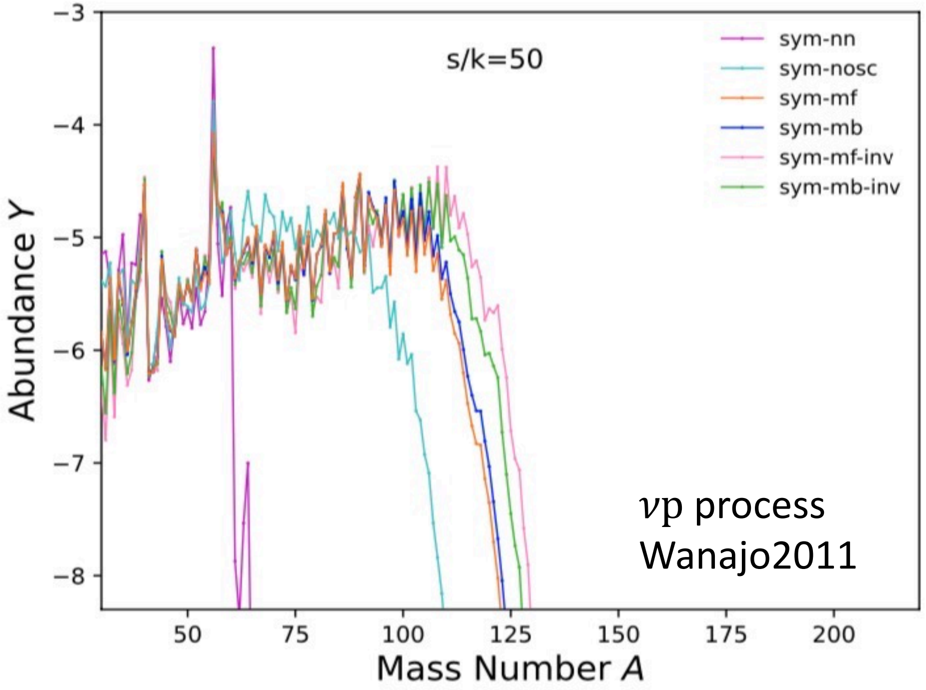
$$\boxed{\begin{array}{l} \nu_e + n \rightleftharpoons p + e^- \\ \bar{\nu}_e + p \rightleftharpoons n + e^+ \end{array}}$$

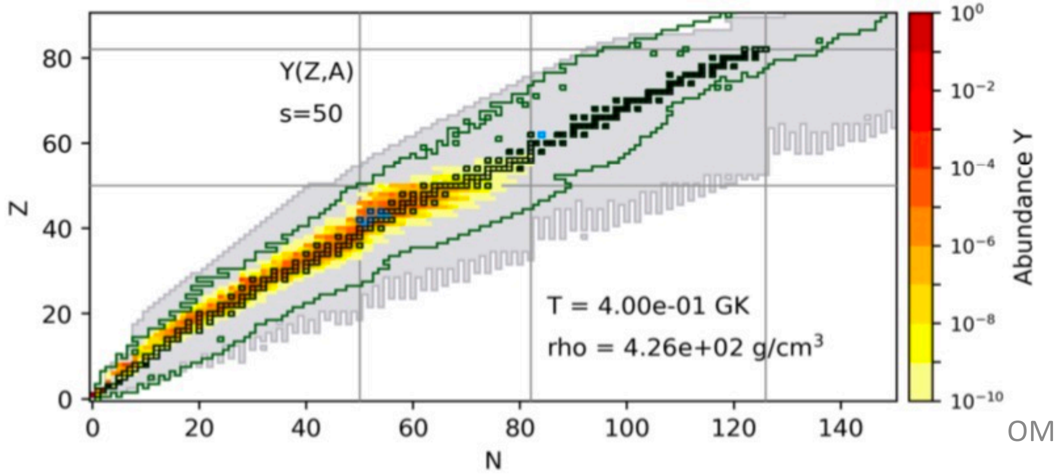
Neutrinos for νp process :

- Determines the initial proton-rich status of NDW at T~10GK
- $\bar{\nu}_e$ captures on free protons give rise to a tiny amount of free neutrons, which are captured on the seed nuclei ^{56}Ni from the nuclear quasi-equilibrium (QSE), initiating the νp process (Frohlich+2006, Wanajo+2006, Pruet+2006)
- Collective neutrino oscillations act to increase the $\bar{\nu}_e$ flux and create a more robust νp process (Martinez-Pinedo+2011, Martinez-Pinedo+2017, Sasaki+2017, Balantekin 2018…)
- Fast flavor conversion could potentially increase mass loss rate and enhance the νp process (Xiong+2020)
- Active-sterile neutrino flavor conversion could also help νp process reach heavier elements between Zr and Cd (Wu+2014)

Existence of neutrinos: enhance heavier elements productions in νp process

Collective oscillations and νp process





purple: no neutrino (nn)

cyan: no neutrino oscillation (nosc)

blue: many-body calculation of oscillation (mb)

orange: mean-field calculation of oscillation (mf)

green: inverted mass hierarchy with mb

pink: inverted mass hierarchy with mf

νp process: neutrinos boost the synthesis of heavier nuclei; The difference in SN NDW neutrino treatments brings a difference in yields: many-body treatment has the biggest effect for normal mass hierarchy; Inverted mass hierarchy introduces bigger neutrino effect

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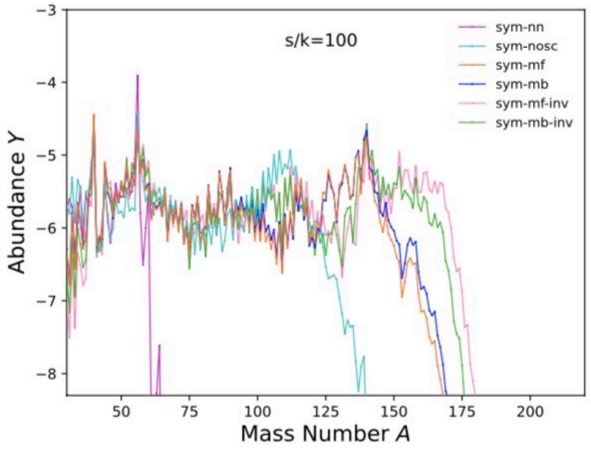
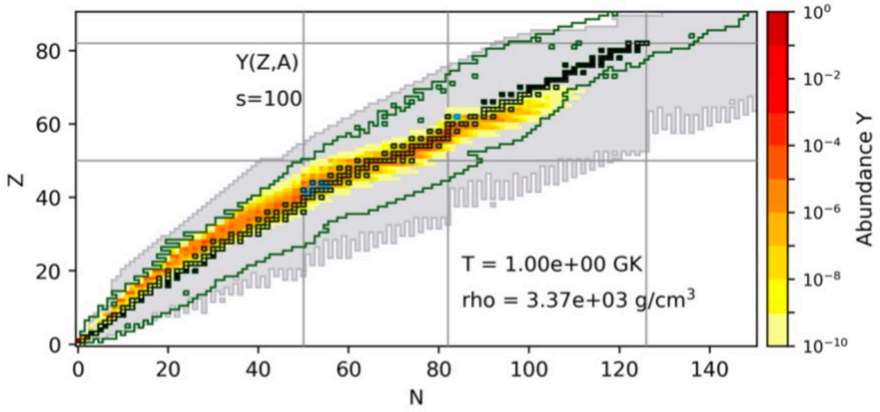
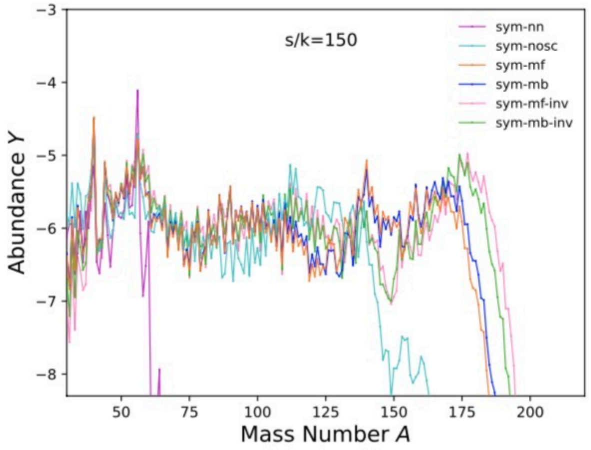
Collective oscillations and νp process with various entropy

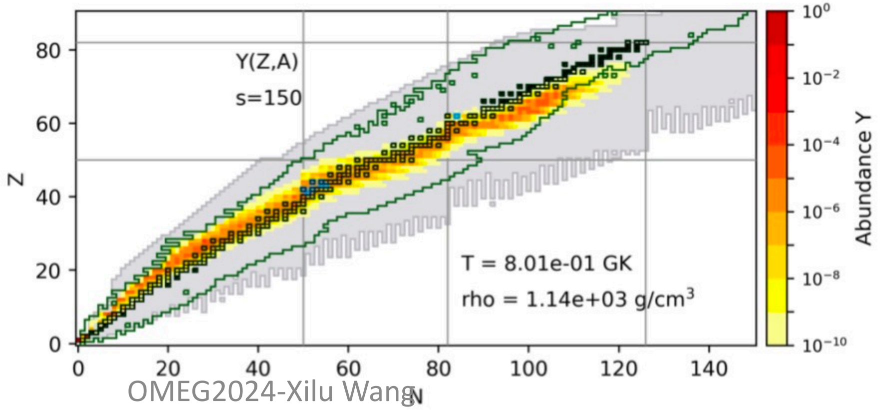
- Initial proton-rich condition(νp process): with the increased initial entropy, s/k_B =50, 100, 150, the collective neutrino oscillation push the synthesis of heavier nuclei, moving towards the neutron-rich region





Special abundance yields for s/k_B >~150: light proton-rich nuclei + heavy neutron-rich nuclei





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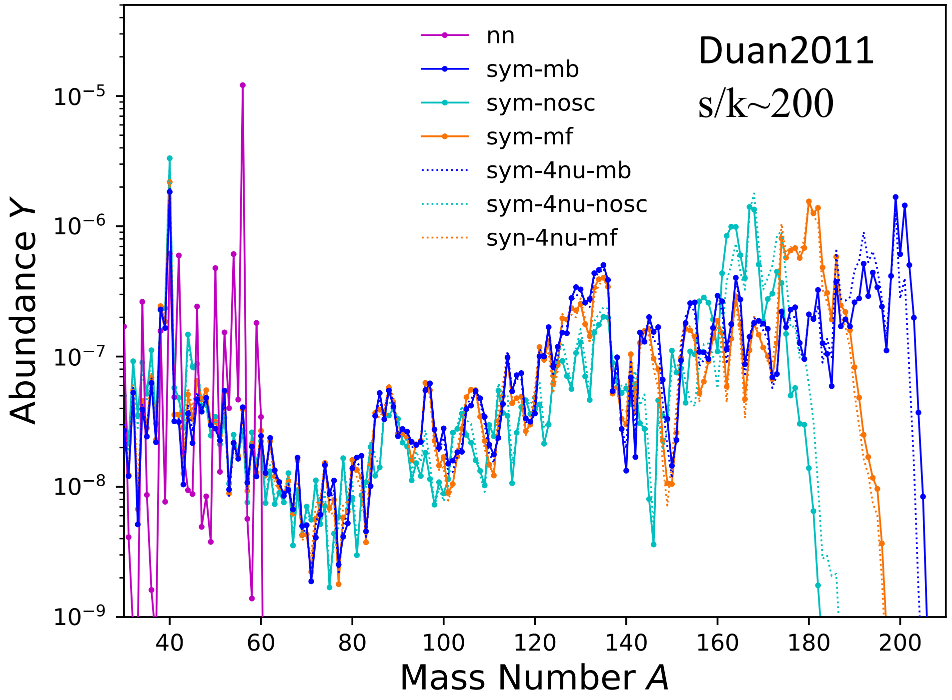
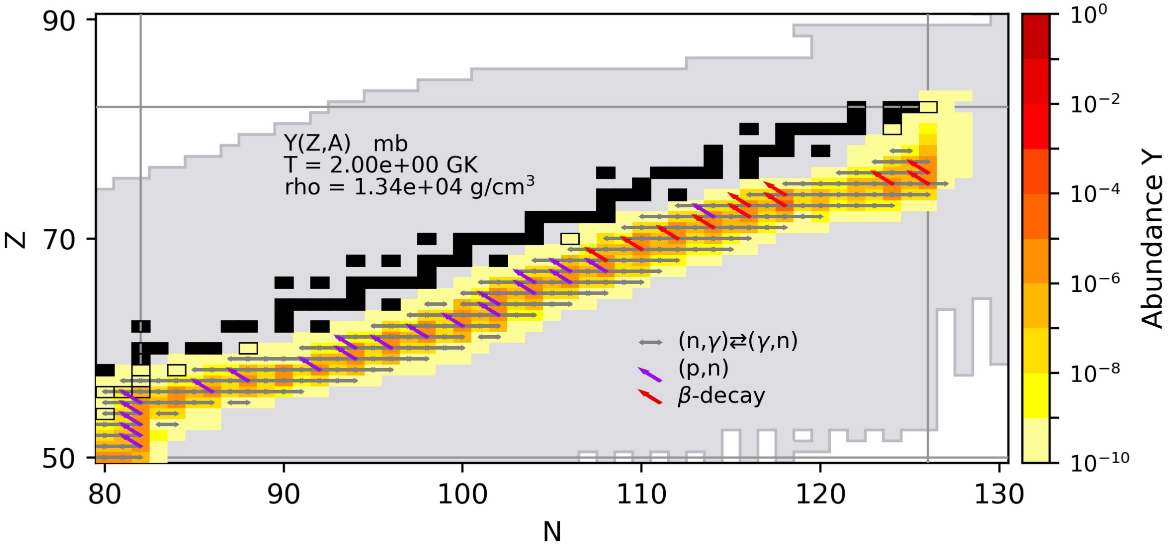
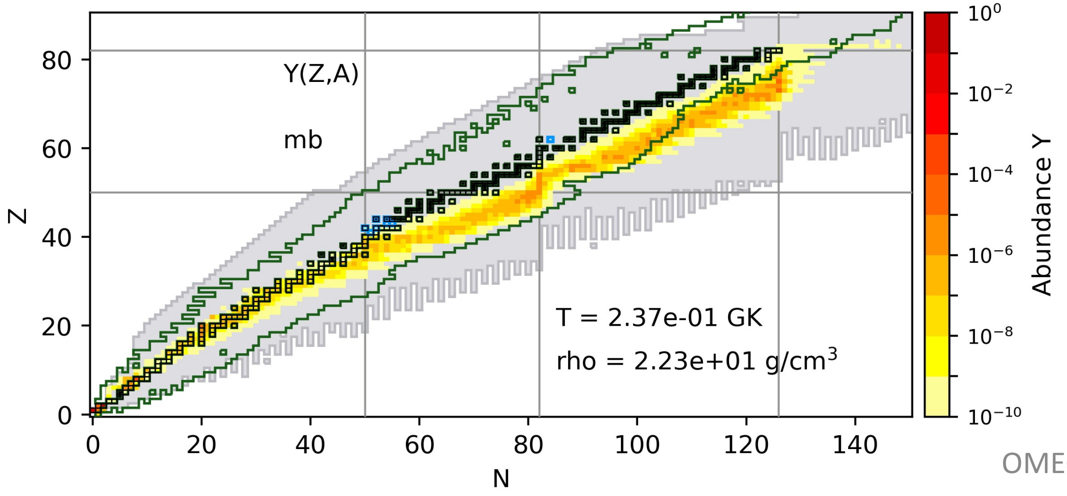
Collective oscillations and νi process







νi process: new nucleosynthesis process and path

- Occur in a high entropy proton-rich environment with abundant neutrinos: supernovae, hypernovae
- Abundance yields: a mixture of lighter νp-process-type pattern and heavier i-process-like pattern, or a fully i-process-like pattern at the highest entropies.
- The nucleosynthetic pathway is clearly distinct from an i process that occurs in mildly neutron-rich conditions

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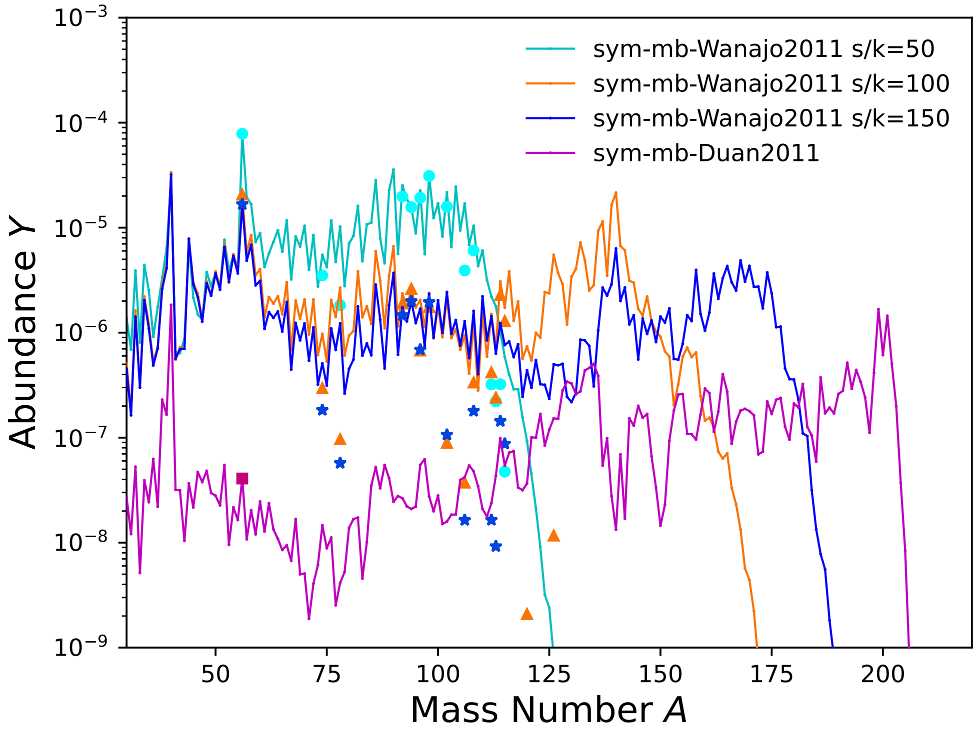
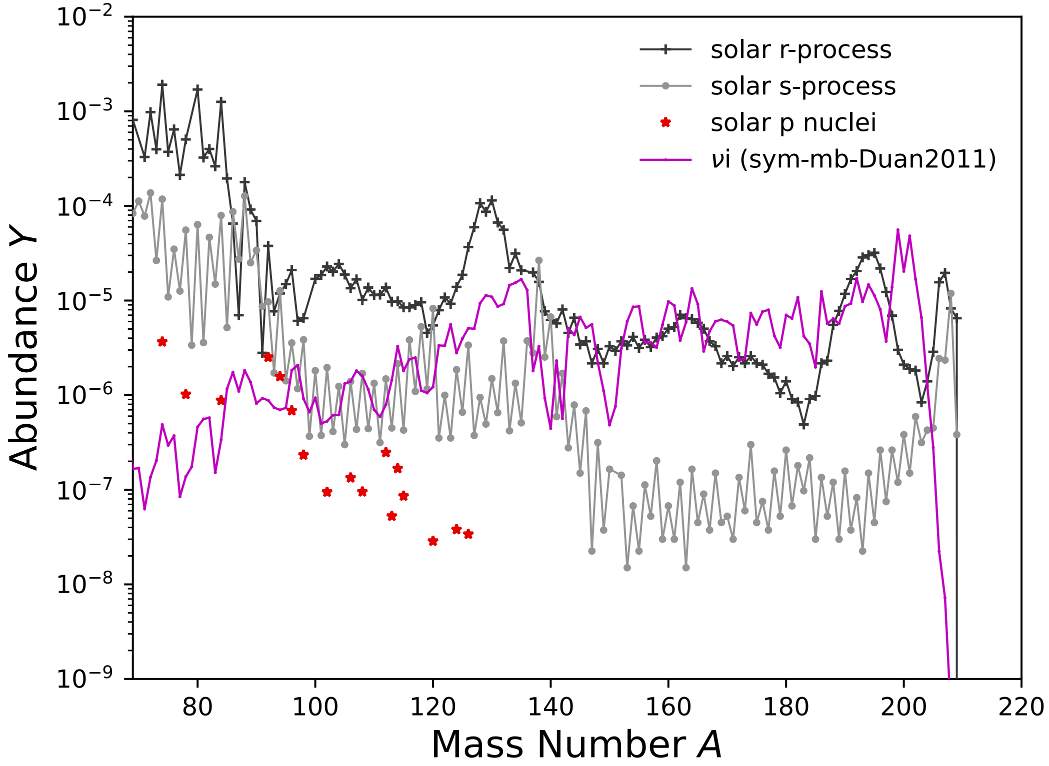
Collective oscillations and νi process





- the abundance pattern of Wanajo2011 s/k = 50 case follows a typical νp process where p nuclei are dominantly produced, while the abundance patterns resulting from larger initial entropy values shift from a νp process at lower mass to a neutron-rich pattern for heavier nuclei ($A \gtrsim 115$ for s/k = 100, $A \gtrsim 100$ for s/k = 150, $A \gtrsim 70$ for Duan2011).

- the νi process abundances are distinct from those of both the solar s process and r process, showing shifted neutron closed shell features and a distinctly higher lanthanide production than the s process.---New astrophysical sources for lanthanides

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Summary

- Neutrinos play a key role in heavy-element nucleosynthesis in supernovae.
- However, the neutrino physics in candidate heavy-element nucleosynthesis events remains poorly understood. Different treatments of the collective neutrino oscillations can have a non-negligible impact on the the operation of the νp-process and r-process nucleosynthesis in supernovae.
- We found that the difference in the neutrino treatments has the largest impact on proton-rich nucleosynthesis, particularly at high entropies. Indeed, neutrino interactions, especially when neutrino oscillations are included, can nudge an initial νp process neutron rich, resulting in a unique combination of proton-rich low-mass nuclei as well as neutron-rich high-mass nuclei. We describe this novel neutrino-induced neutron capture process as the "νi process".

- Thanks for your attention. Questions?