

Collective Neutrino Oscillations and Heavy-element Nucleosynthesis in Supernovae

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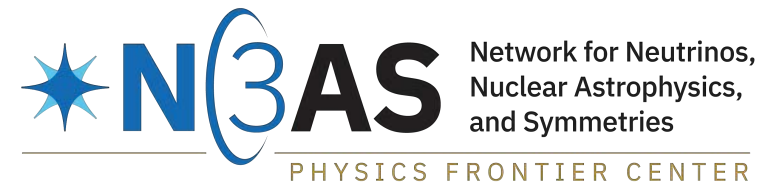
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@Neutrinos in Physics and Astrophysics

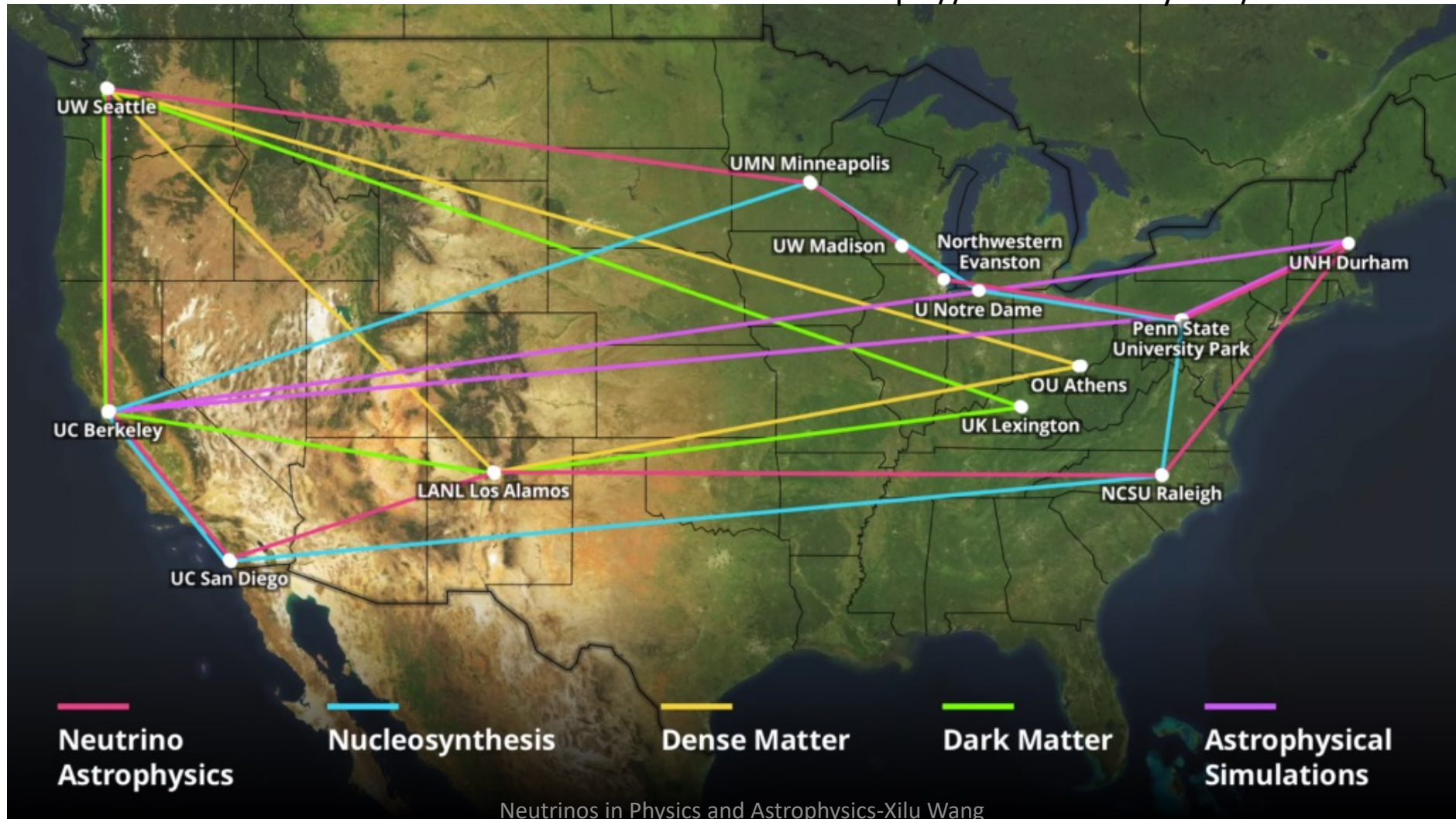


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The Network in Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS)

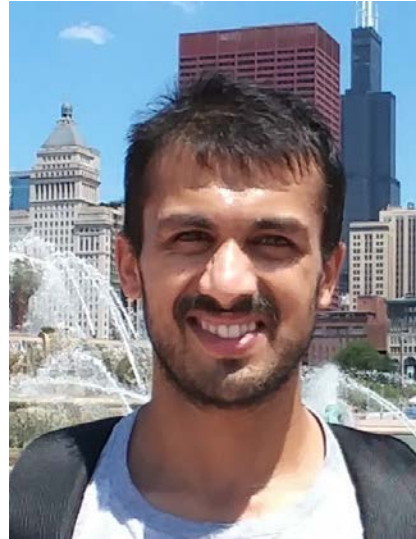
*Now a NSF Physics Frontier Center
<https://n3as.berkeley.edu/>



Collaborators



Baha Balantekin



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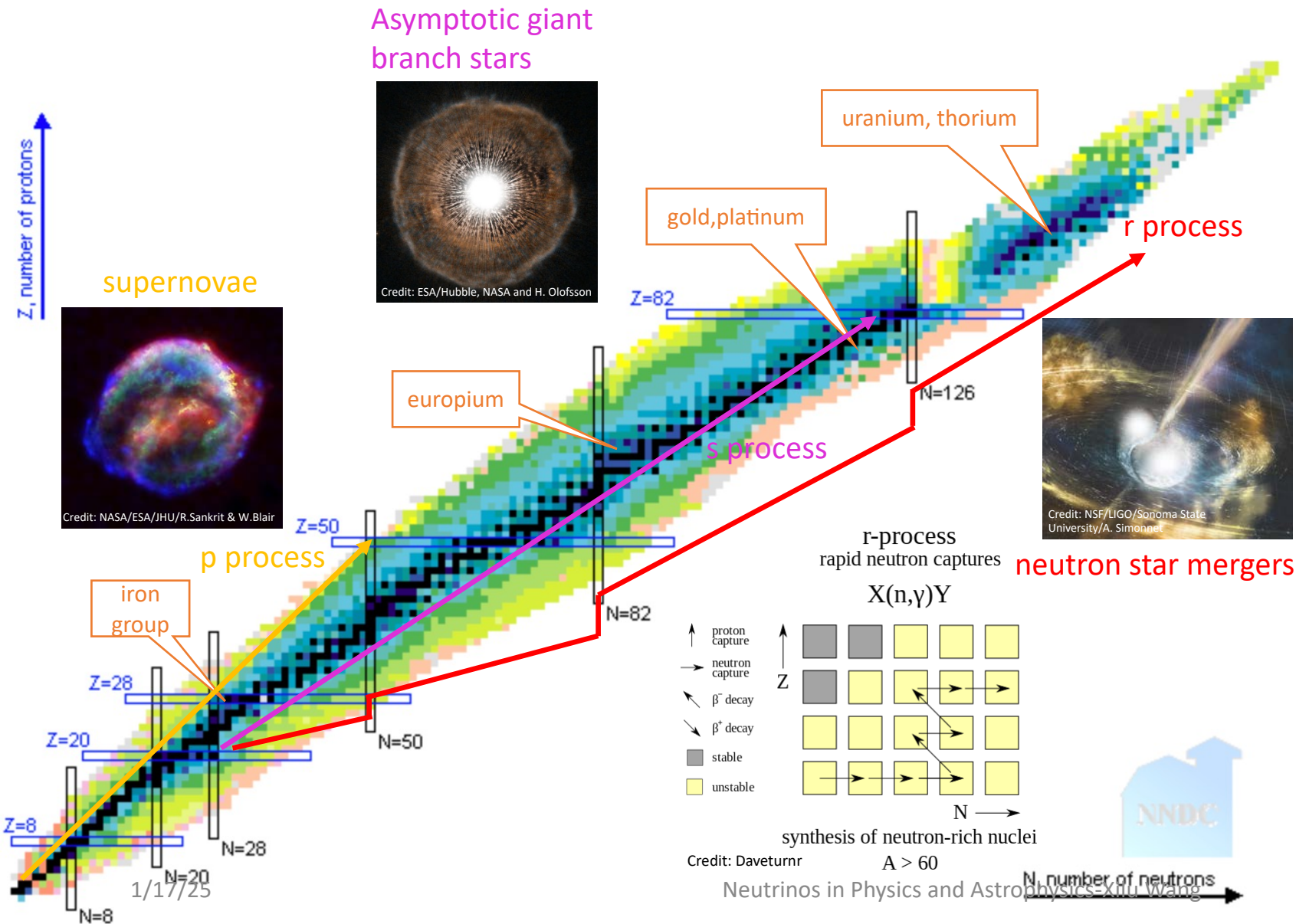

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Rebecca Surman



Nucleosynthesis-heavy elements



Heavy elements (heavier than iron):
the nucleosynthesis was a mystery for decades

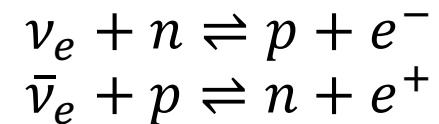
Main processes:
Proton-rich process (**p process**)-
~0.1%-1% ;
neutron capture process:
s process (slow neutron capture)
~50%, up to ²¹⁰Bi;
r process (rapid neutron capture)
~50%

**Heavy element nucleosynthesis---
multi-messenger astronomy**



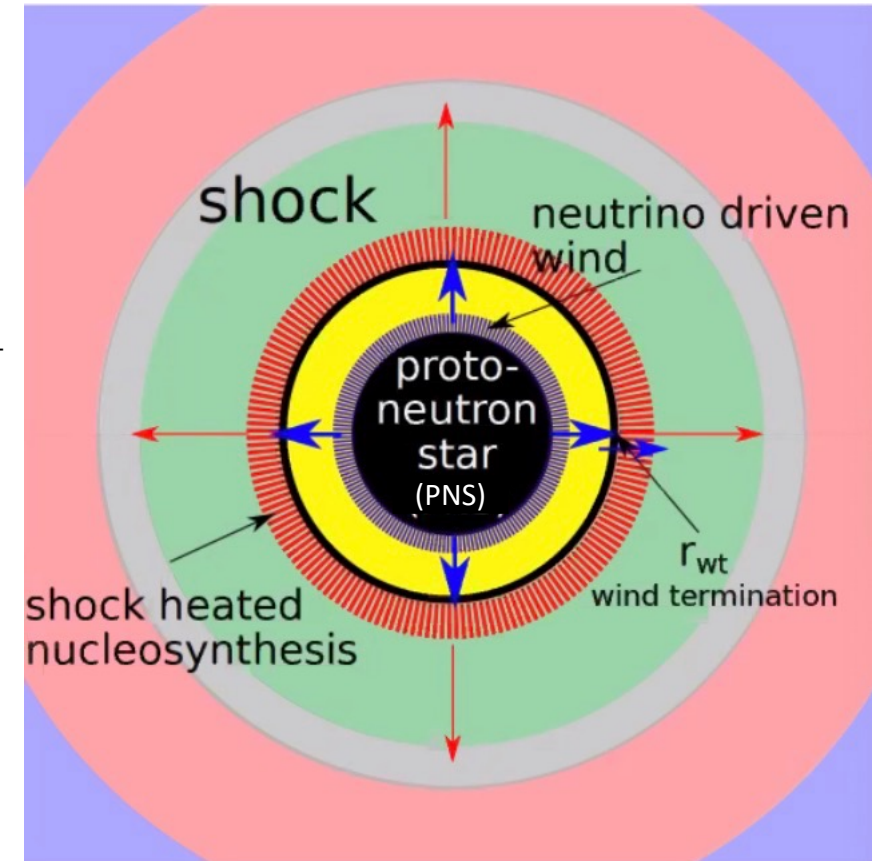
Heavy-element nucleosynthesis affected by neutrinos

- Neutron-rich side: **r process**
- Proton-rich side: ν process and **νp process**
- Supernova neutrino driven wind (NDW):
 - fast, hot matter outflow from the PNS surface \sim few 10^{-5} - 10^{-3} solar mass
 - NDW is determined by long-term neutrino cooling of the PNS
 - Neutrinos determine Y_e of the ejecta



electron fraction $Y_e = \frac{1}{1+n_n/n_p}$:

smaller Y_e , more neutron richness



Inset from Pan et al. (2016)

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

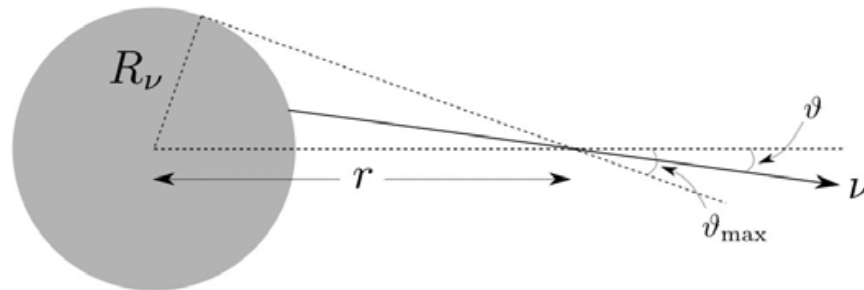
$$H = \sum_p \omega_p \vec{B} \cdot \vec{J}_p + \sum_{p,q} \mu_{pq} [\vec{J}_p \cdot \langle \vec{J}_q \rangle + \langle \vec{J}_p \rangle \cdot \vec{J}_q - \langle \vec{J}_p \rangle \cdot \langle \vec{J}_q \rangle]$$

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

Collective oscillations in supernovae

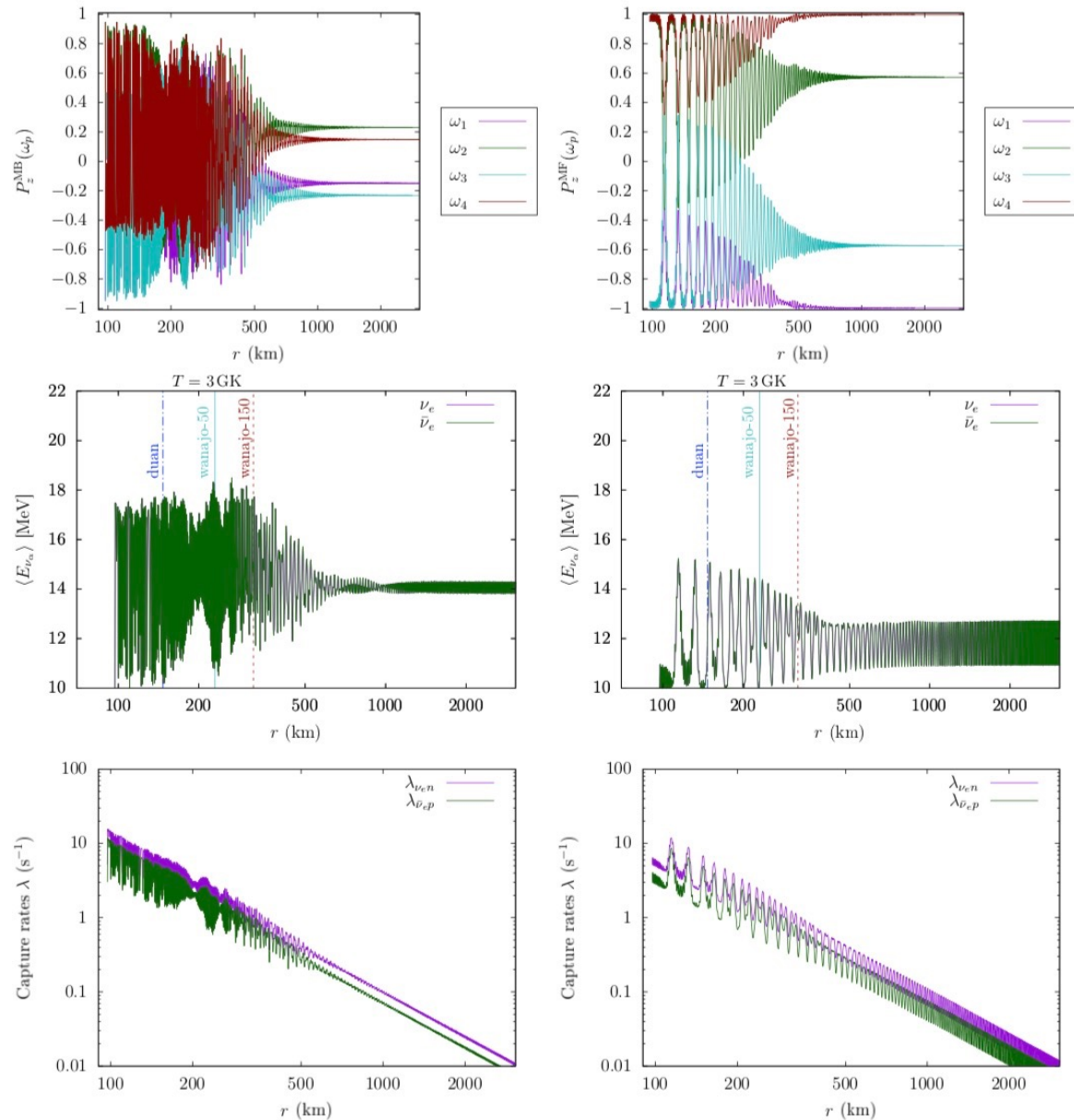
Label	$E_{\nu,e}$ [MeV]	$E_{\bar{\nu},e}$ [MeV]	$E_{\nu,x}$ [MeV]	$E_{\bar{\nu},x}$ [MeV]	$L_{\nu,e}$ [erg/s]	$L_{\bar{\nu},e}$ [erg/s]	$L_{\nu,x}$ [erg/s]	Y_e $(1 + \lambda_{\bar{\nu}_e}/\lambda_{\nu_e})^{-1}$
sym	10	10	20	20	9.091×10^{51}	9.091×10^{51}	1.818×10^{52}	0.634
asym2	10	12.5	20	20	9.091×10^{51}	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 $\mu_i = 100$



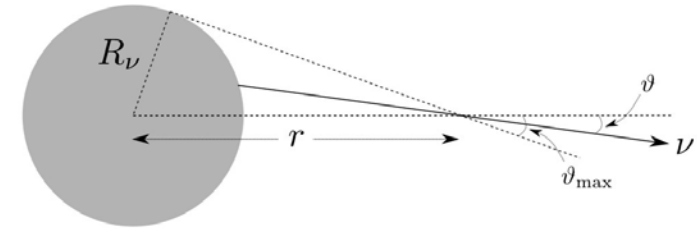
“neutrino bulb” geometry
--single angle approximation

Collective oscillations in supernovae



Balantekin, B.,..., Wang, X., 2024,
ApJ 967, 146, arXiv: 2311.02562

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		Position at $\lesssim 10\text{GK}$ r_0 [km]
		τ_1^a [ms]	τ_2^b [ms]	
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**

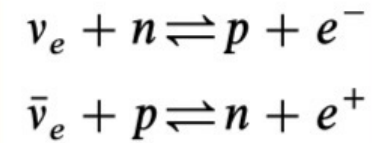
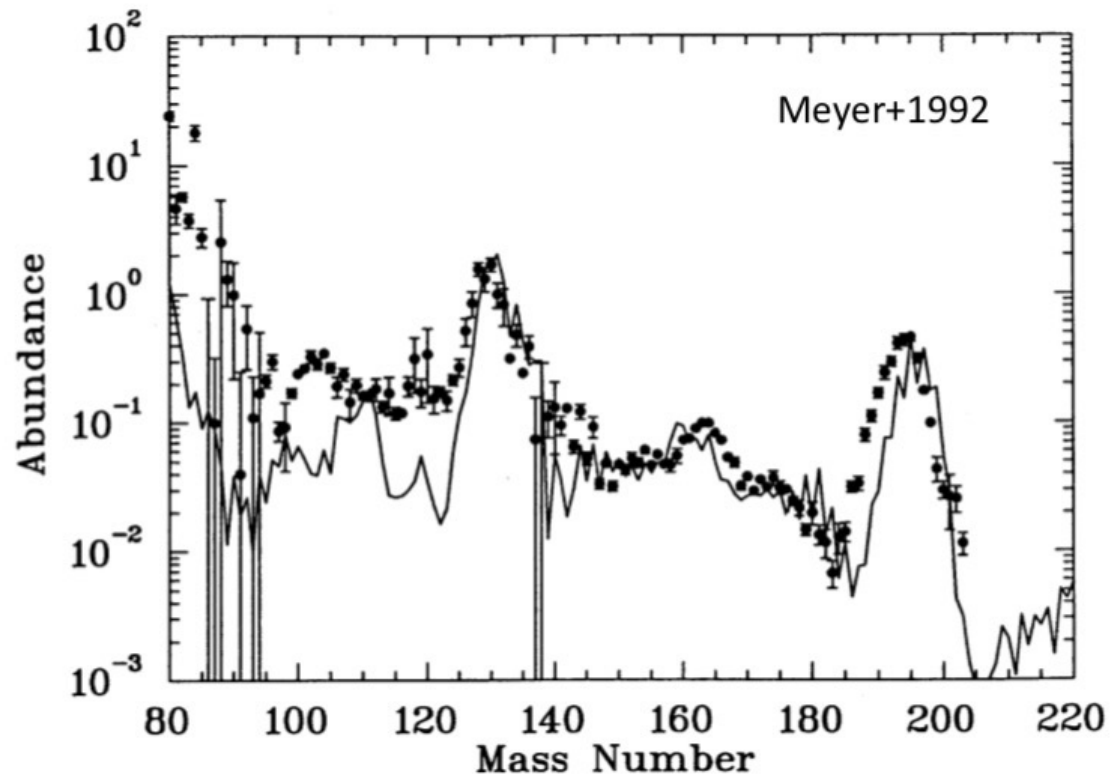
- 1) four neutrino treatments (nn, nosc, mf, mb) are implemented into PRISM in the form of external $\nu_e + n$ and $\bar{\nu}_e + p$ capture rates; neutrino-nuclei interactions are not included
- 2) Nuclear data: REACLIB reaction rates ([Cyburt et al. 2010](#)) + NUBASE β -decay properties ([Kondev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

PRISM (**P**ortable **R**outines for **I**ntegrated **n**ucleo**S**ynthesis **M**odeling):

Trevor Sprouse (ND) & Matthew Mumpower (LANL)

r-process astrophysical sites: supernovae?

SN neutrino-driven wind



Does this work?

- Yes

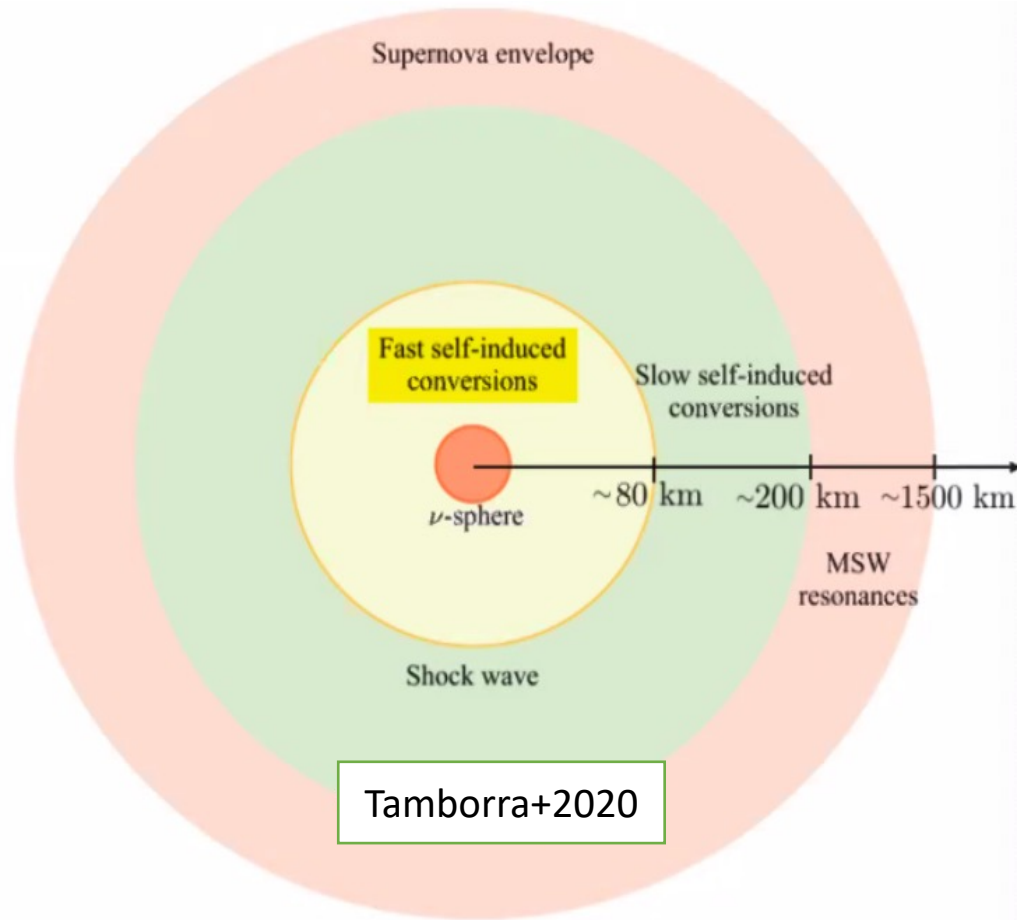
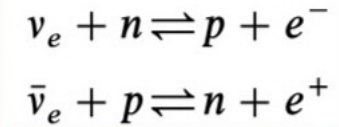
Meyer+1992, Woosley+1994

- 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?

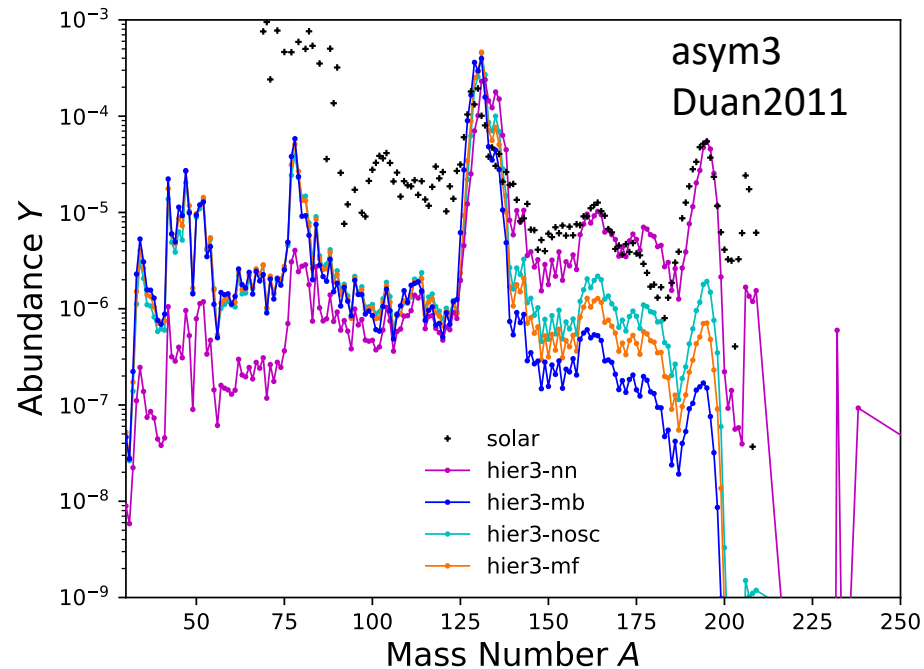
SN neutrino-driven wind:



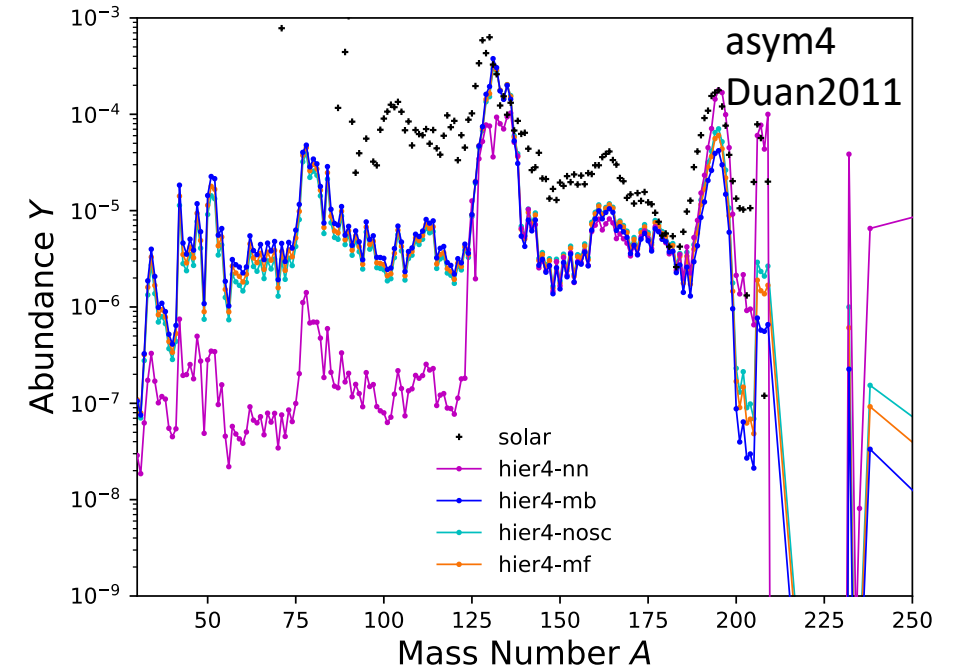
a **weak r-process** (up to $A \sim 125$) might be possible, with the ultimate extent of nucleosynthesis sensitively depends on neutrino physics (Fuller, Meyer 1995, Balantekin, Yuksel 2005, Johns+2020, Xiong+2020):

- 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)

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)

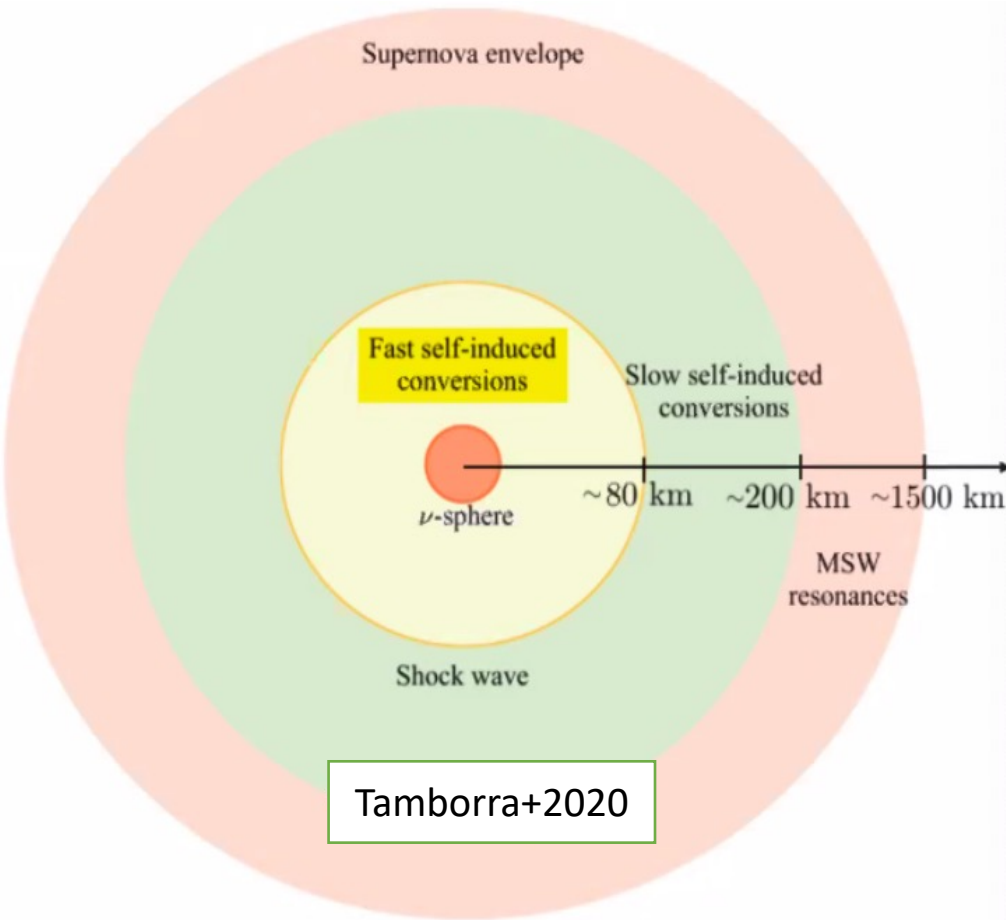


r process: neutrinos **hinder** the synthesis of heavier nuclei, and mainly affect the 3rd peak and beyond region;

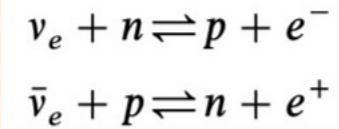
for asym3 case with r-process nucleosynthesis **barely reach the 3rd peak and beyond** → **Biggest** effect of the difference in SN NDW neutrino treatments on the r-process yields: move to weak r-process;

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

νp -process in supernovae



SN neutrino-driven wind:

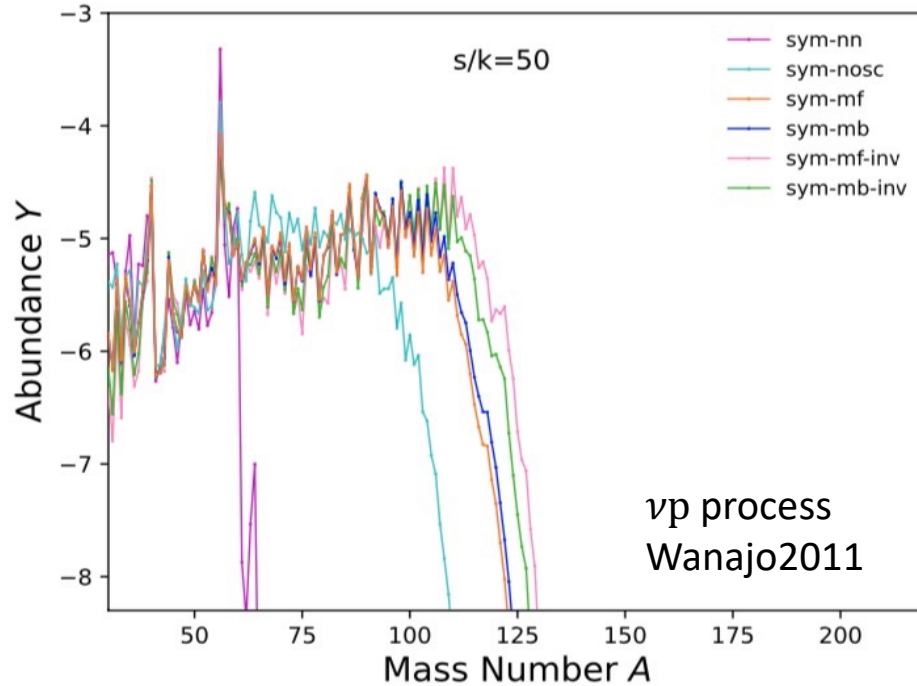


Neutrinos for νp process :

- Determines the initial proton-rich status of NDW at $T \sim 10\text{GK}$
- $\bar{\nu}_e$ 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)

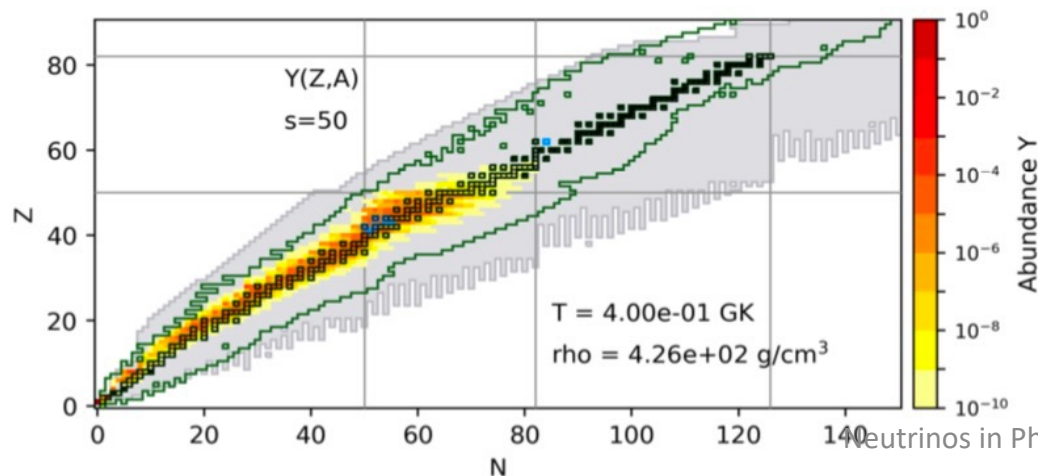
blue: many-body calculation of oscillation (mb)

orange: mean-field calculation of oscillation (mf)

green: inverted mass hierarchy with mb

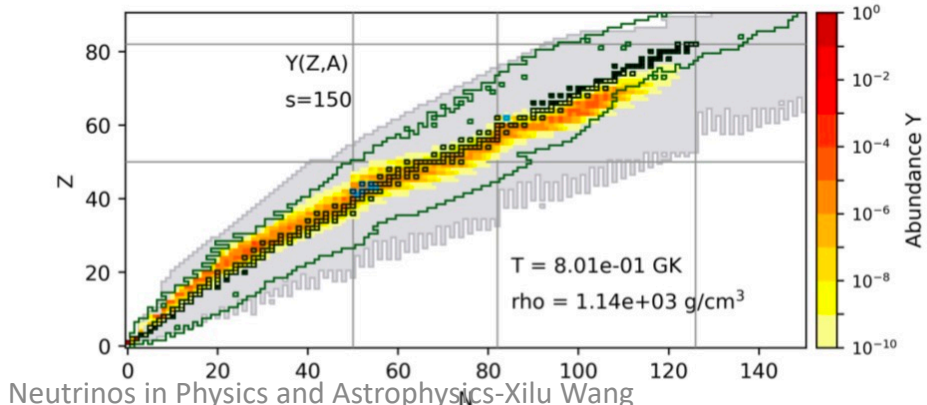
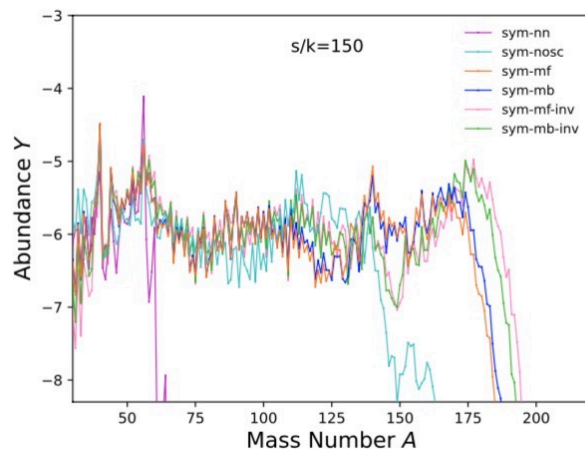
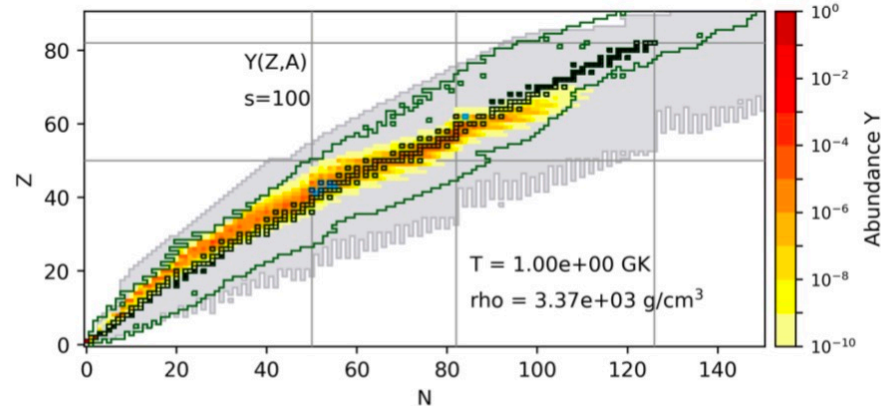
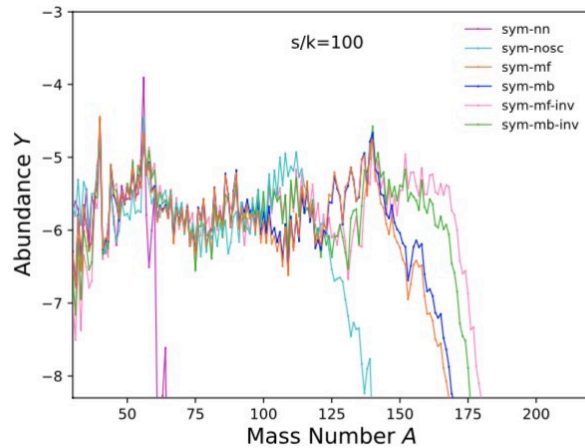
pink: inverted mass hierarchy with mf

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



Collective oscillations and νp process with various entropy

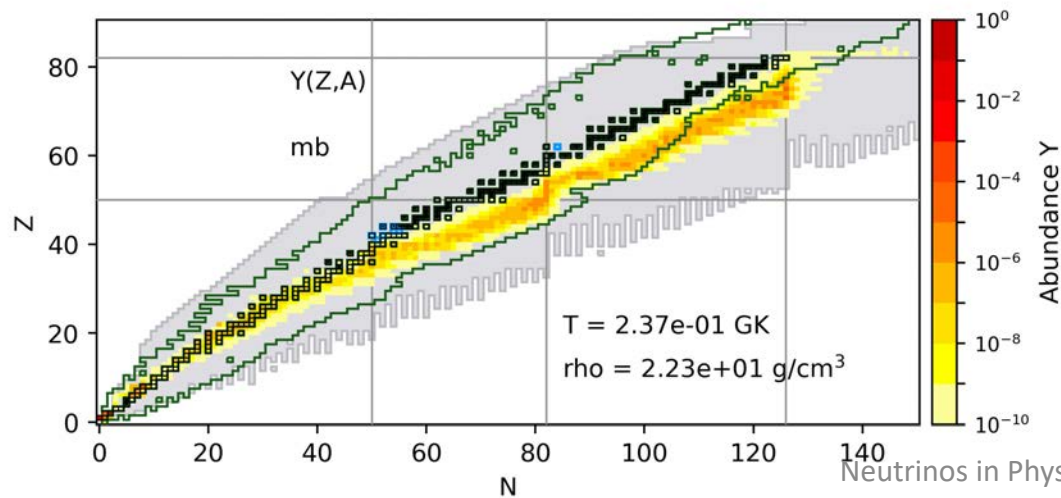
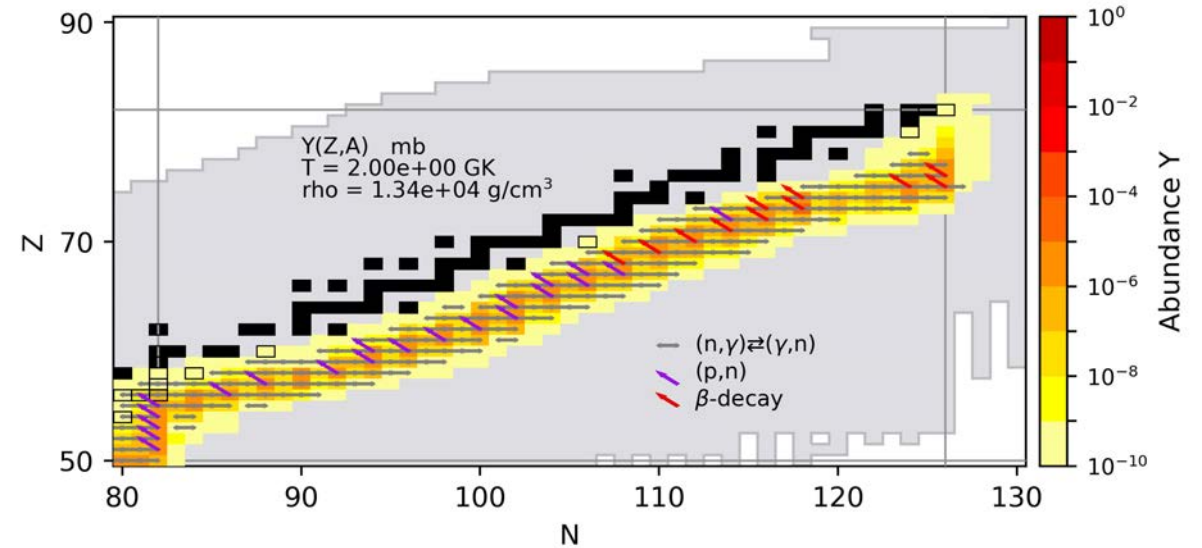
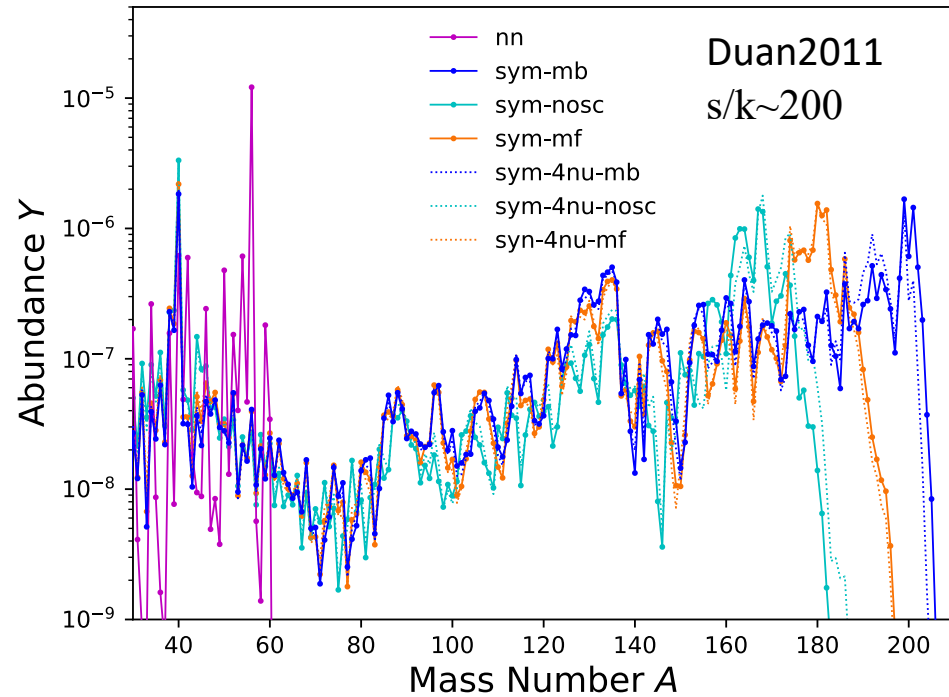
- ❖ Initial **proton-rich** condition(νp process): with the **increased initial entropy**, $s/k_B = 50, 100, 150$, the **collective neutrino oscillation** push the synthesis of **heavier nuclei**, moving towards the **neutron-rich** region



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

Balantekin, B.,..., Wang, X., 2024, ApJ 967, 146, arXiv: 2311.02562

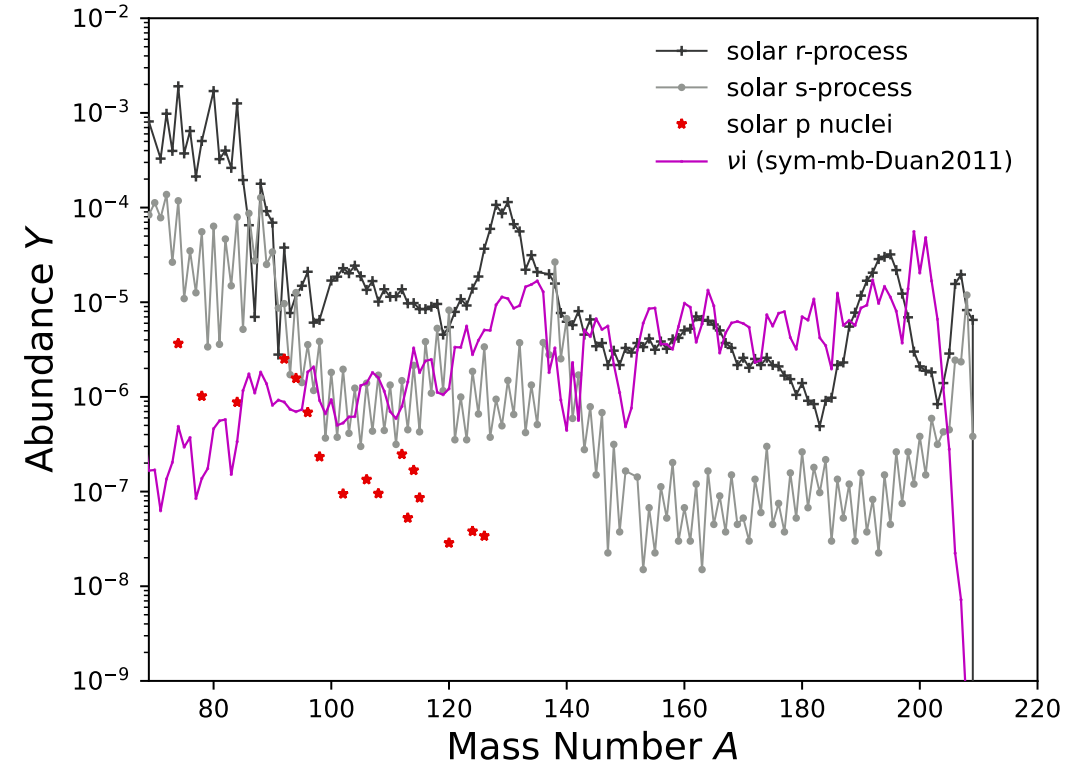
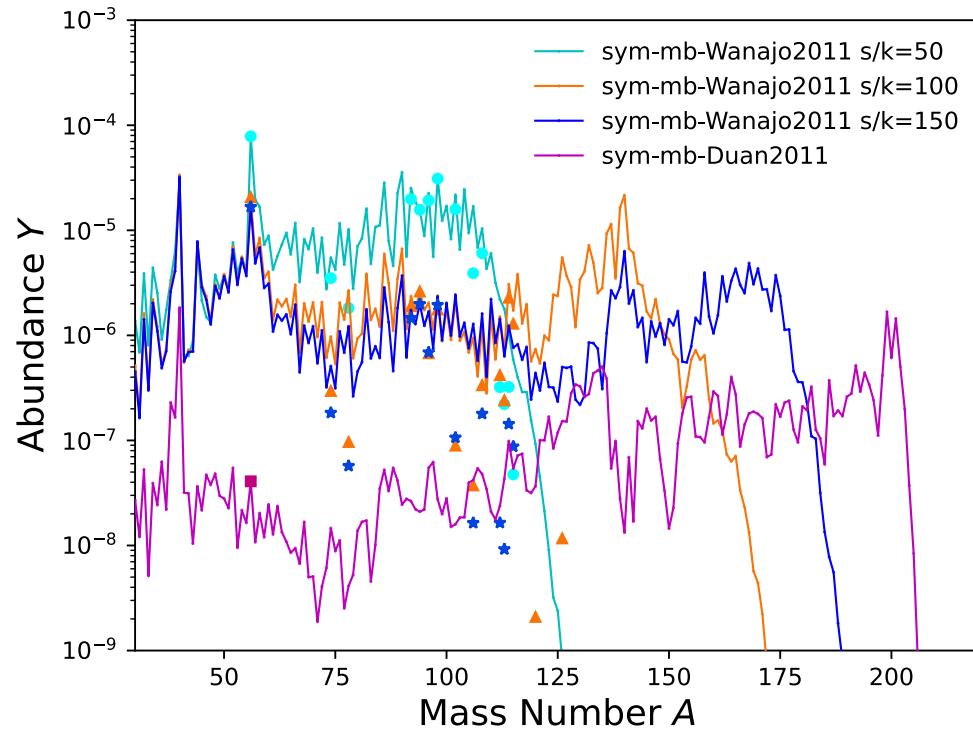
Collective oscillations and νi process



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

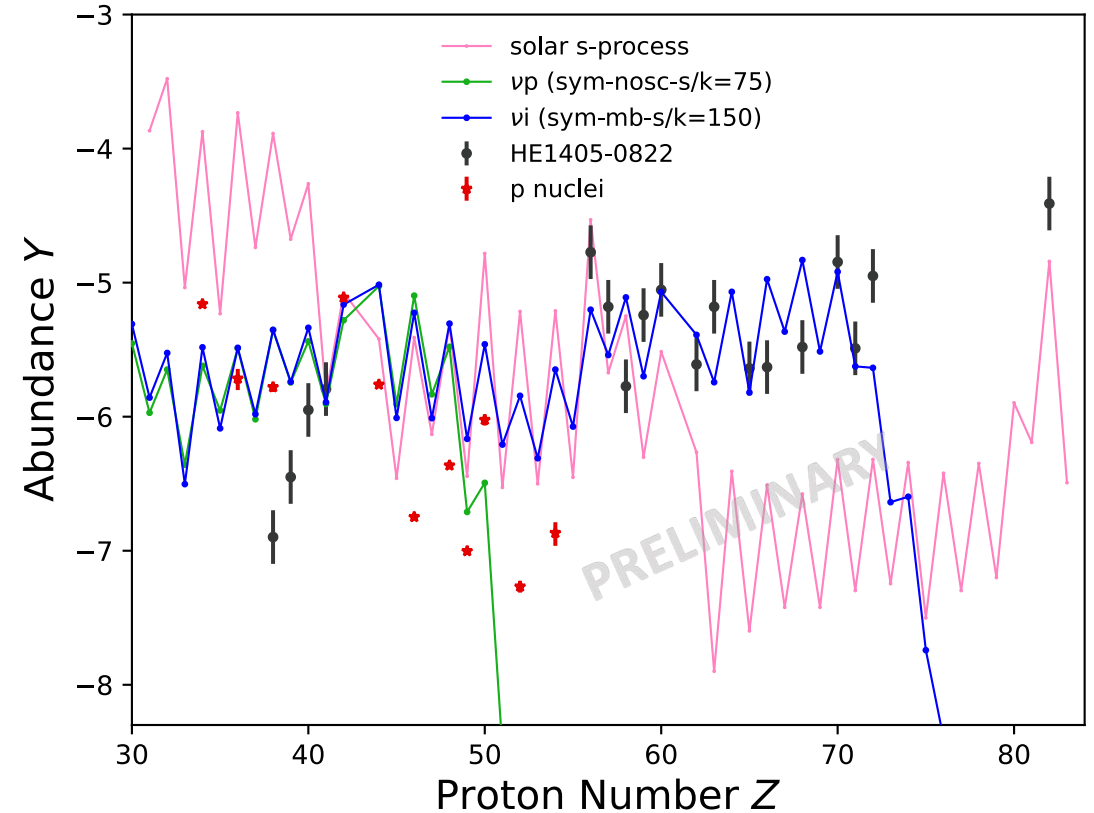
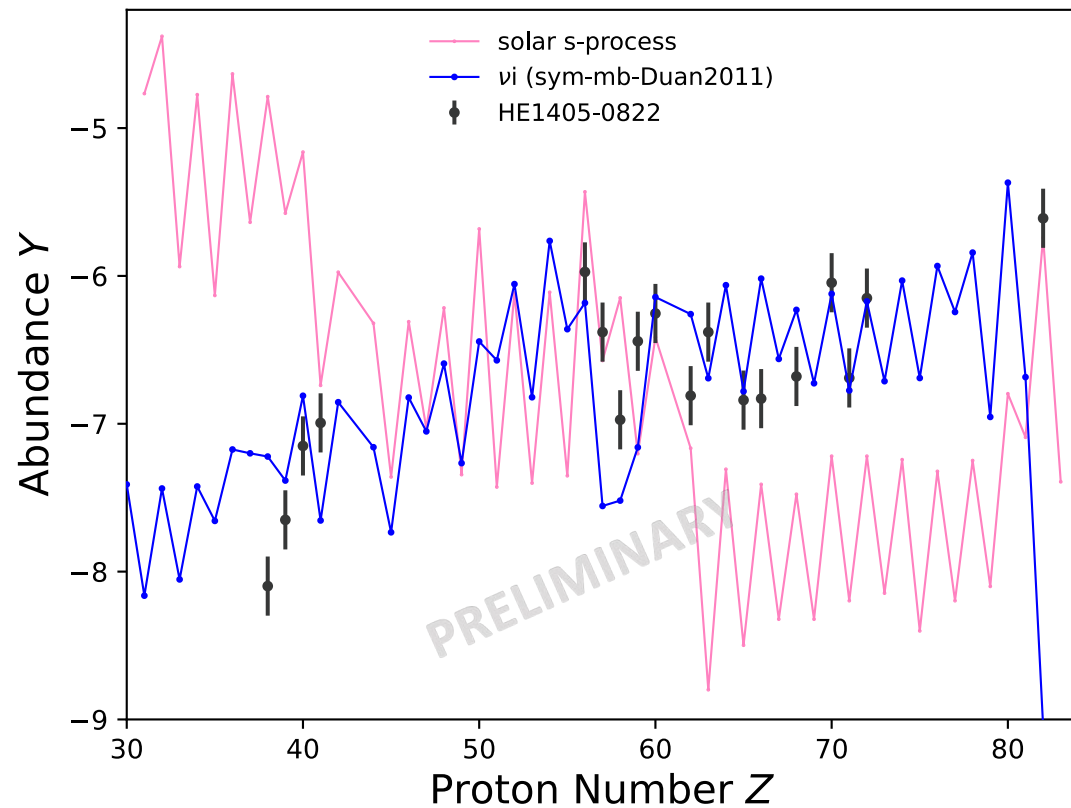
Collective oscillations and νi process



- 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 a flatter pattern and a distinctly higher lanthanide production than the s process.---New astrophysical sources for lanthanides

νi process elemental pattern and stellar observation



- the νi process elemental pattern can be an alternative explanation for some CEMP r/s stars, especially in the lanthanide region

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 **vp-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 vp 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 “**vi process**”.

On-going work:

- vi process elemental pattern analysis and comparison with metal poor stars
- Test uncertainty of vi due to nuclear physics variations

- Thanks for your attention. Questions?