Collective Neutrino Oscillation and Heavy-element Nucleosynthesis in Supernovae

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N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
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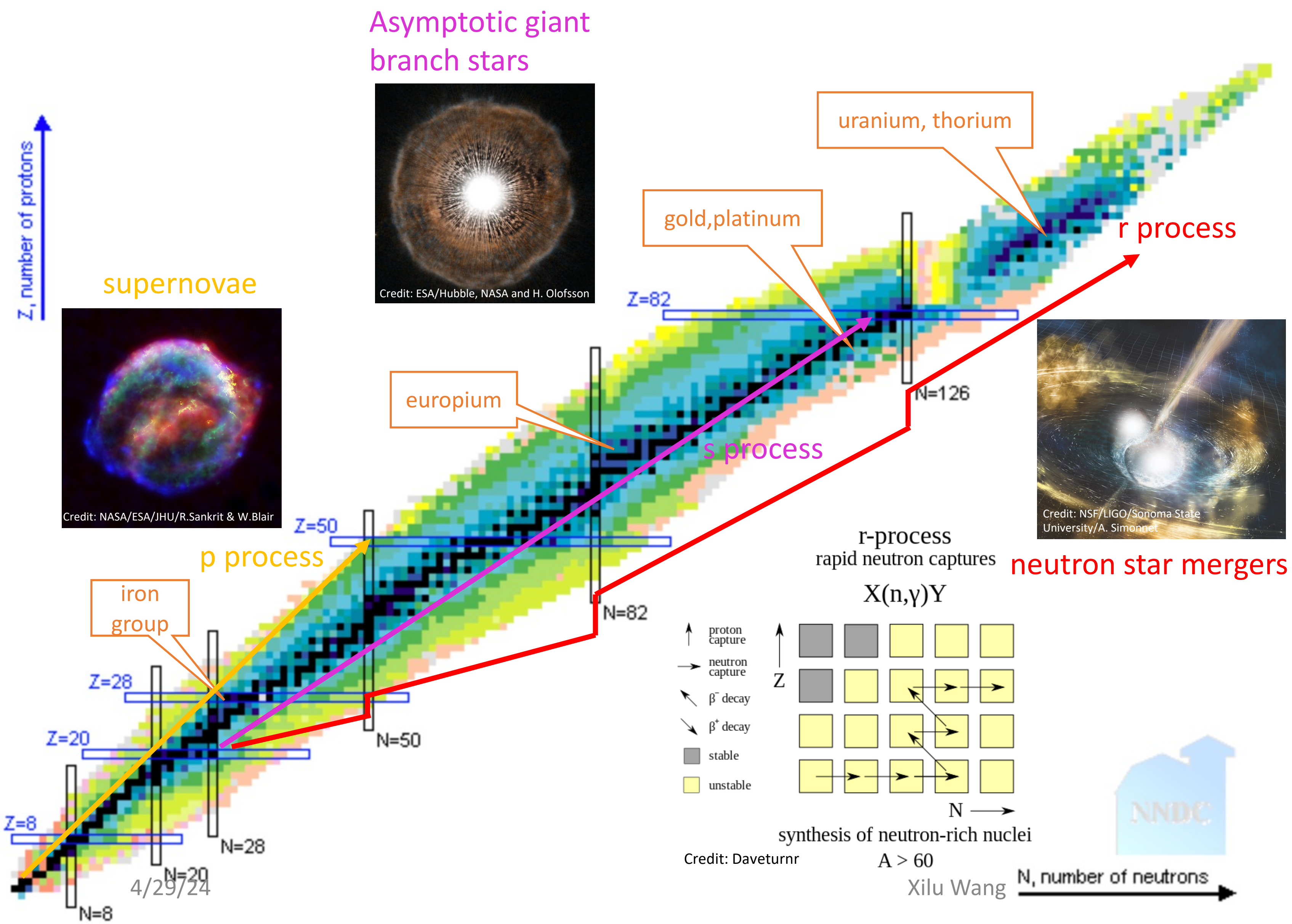
Nucleosynthesis-heavy elements



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 ^{210}Bi;
r process (rapid neutron capture) ~50%

Heavy element nucleosynthesis---multi-messenger astronomy

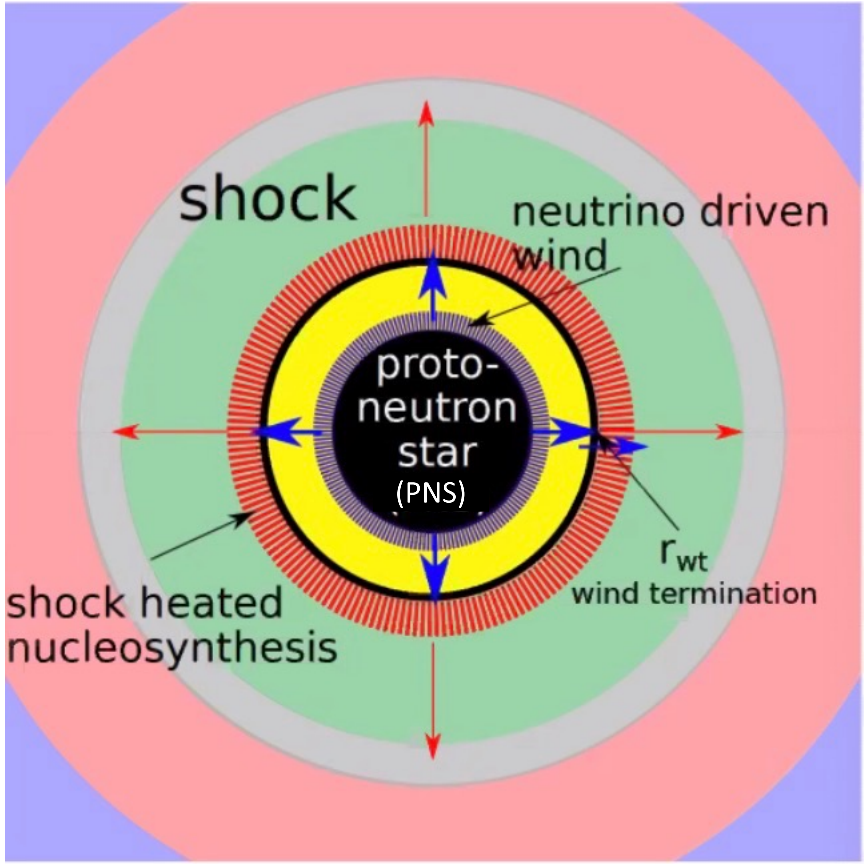
Heavy-element nucleosynthesis affected by neutrinos

- 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 ~ 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

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

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"

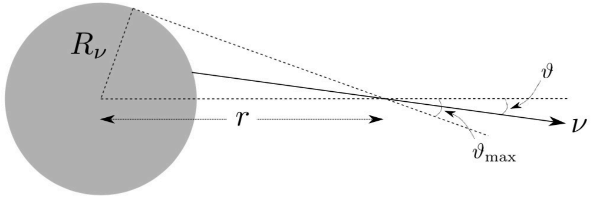
$$\vec{P}_q = 2\langle \vec{J}_q \rangle$$

- Mean field

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

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

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* $\mu_i = 100$

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	50 (default)	17.5	152	61.58
-Wanajo2011	100	17.5	344	77.44
(Wanajo et al. 2011)	150	17.5	500	86.41
Duan2011 (Duan et al. 2011)	200	12.4	17.9	46.67

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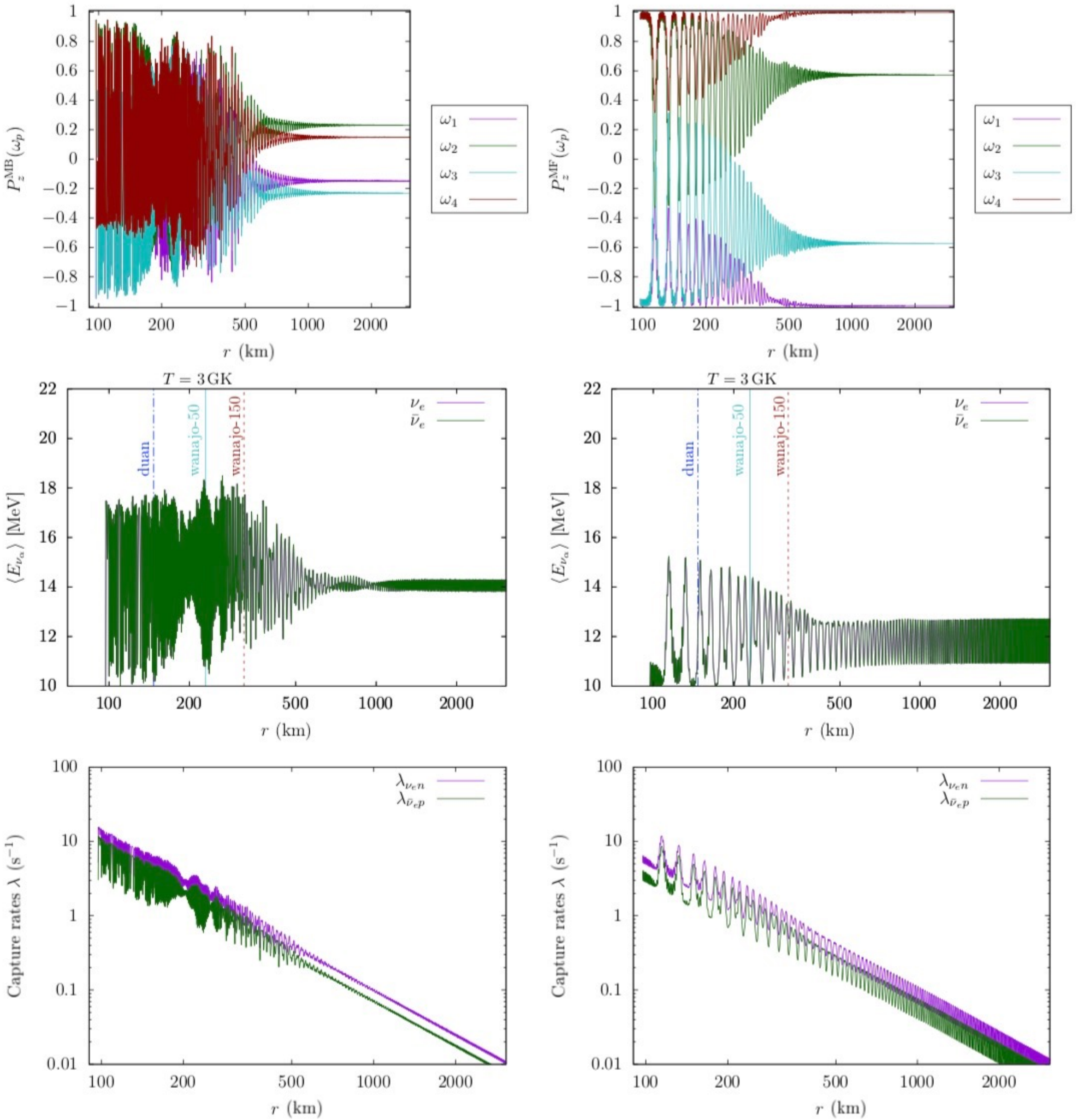
Collective oscillations in supernovae



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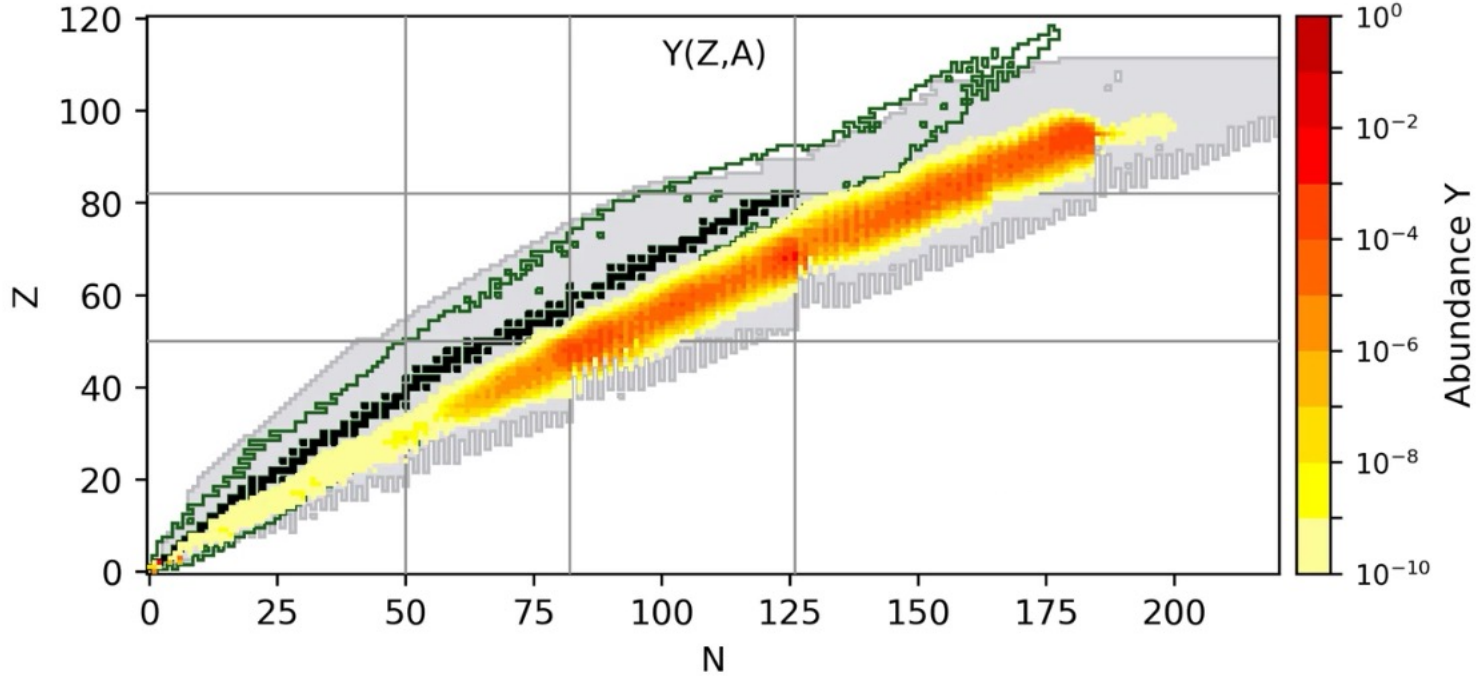
r-process nucleosynthesis

- Rapid neutron-capture process (r process):
  - ✓ Create ~half of the nuclei heavier than iron
  - ✓ Occurs in neutron-rich environments, when neutron capture rates >> beta decay rates
  - ✓ Abundance peaks: A~82, A~130, A~196 (closed shell structures at N = 50, N = 82, and N = 126)



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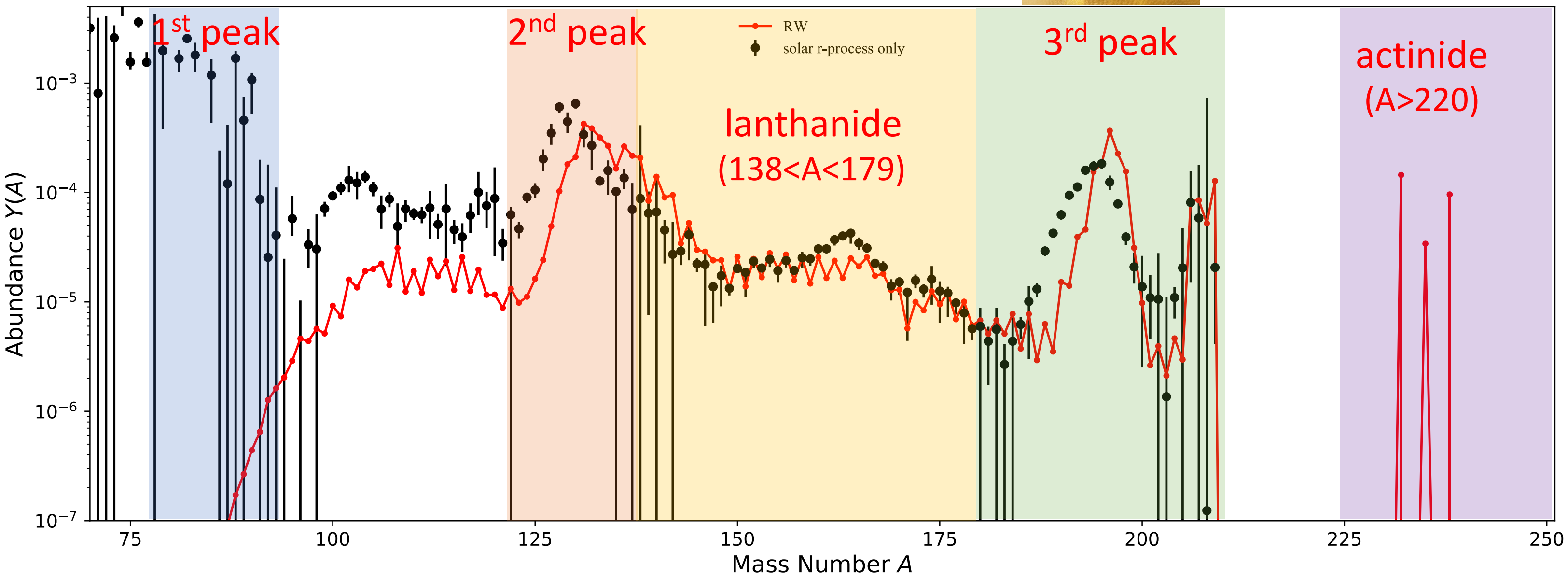
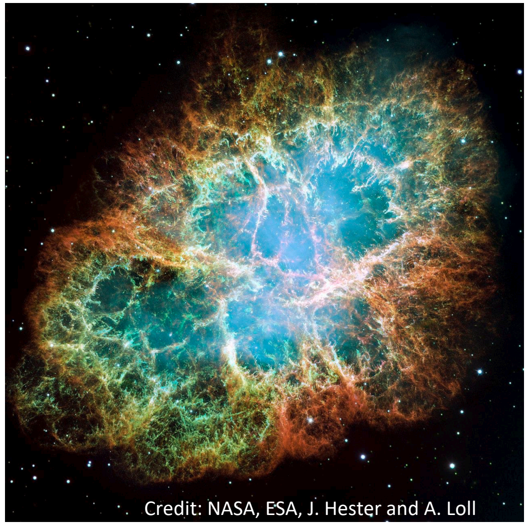


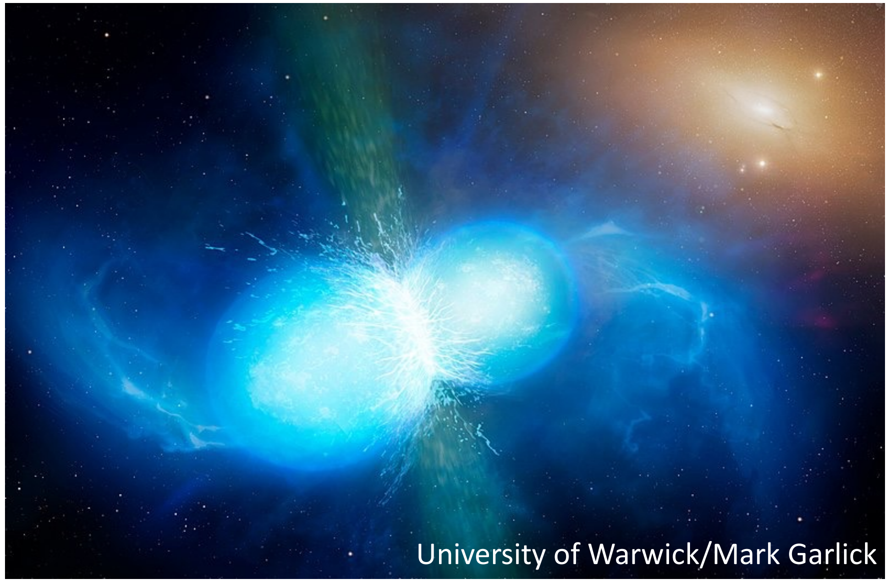
Solar r-process residuals data from Arnould+2007, Sneden+2008

r-process astrophysical sites: a mystery

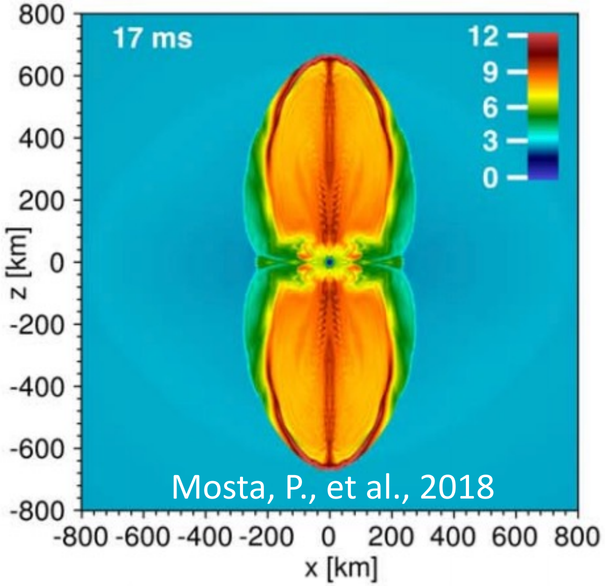
Core collapse Supernovae?
(e.g., Meyer+1992, Roberts+2012)



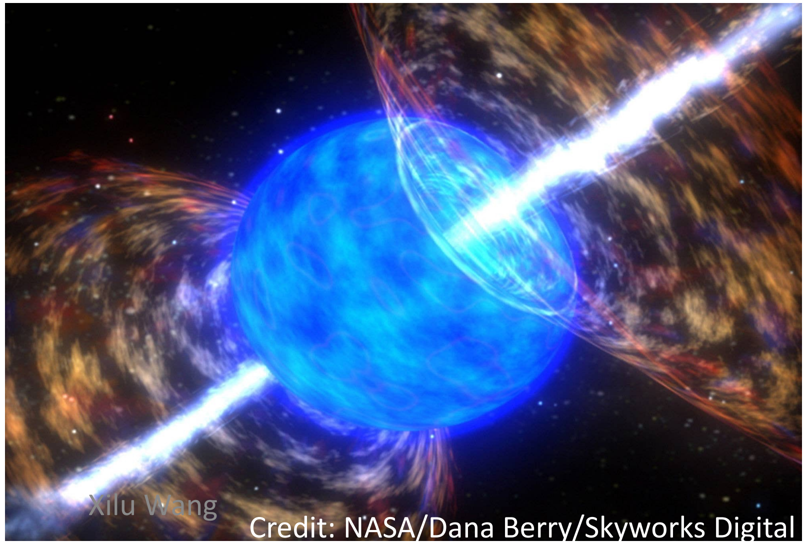
Neutron star + neutron star/black hole mergers
(e,g, Nedora+2020, Foucart+2020, George+2020, etc.)



Magneto-rotational supernovae
(e.g., Reichart+2020, Nishimura+2017, Mosta+2018)

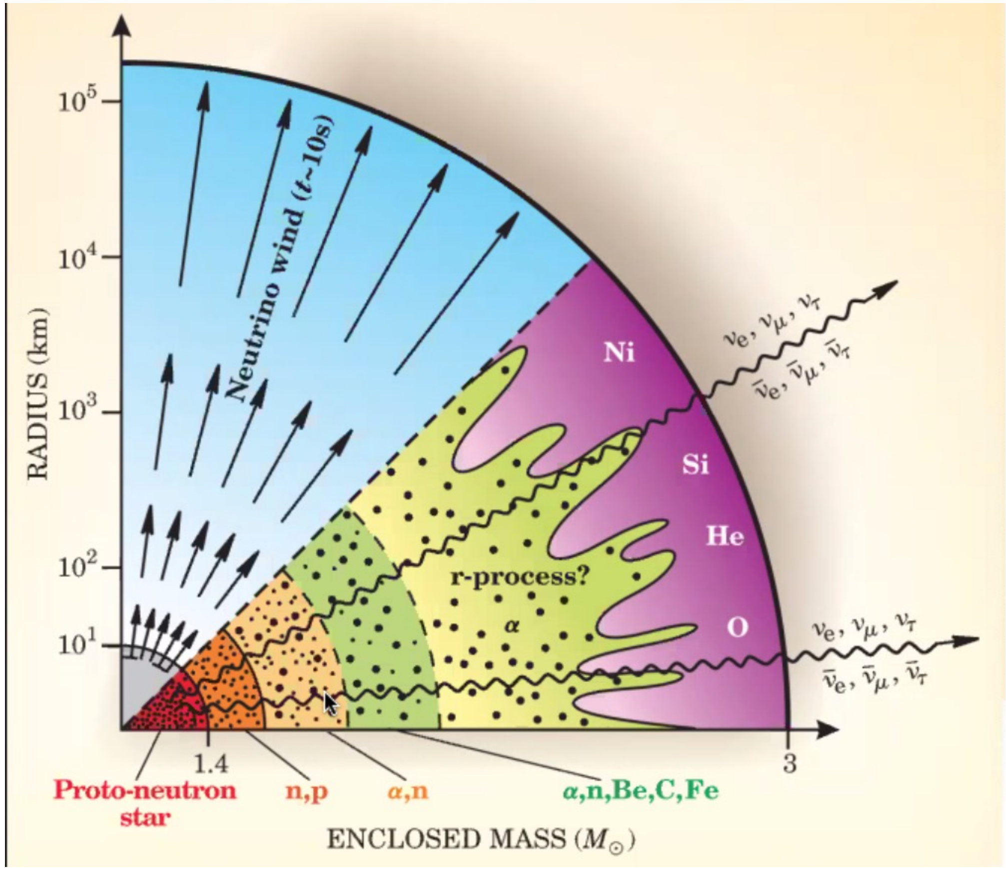


Collapsars
(e.g., Siegel+2019, Miller+2019)



exotic supernovae
(e.g., Fischer+2020)
primordial black hole + neutron star (e.g., Fuller+2017)
etc.

r-process astrophysical sites: supernovae?



Woosley, Janka 2005

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

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

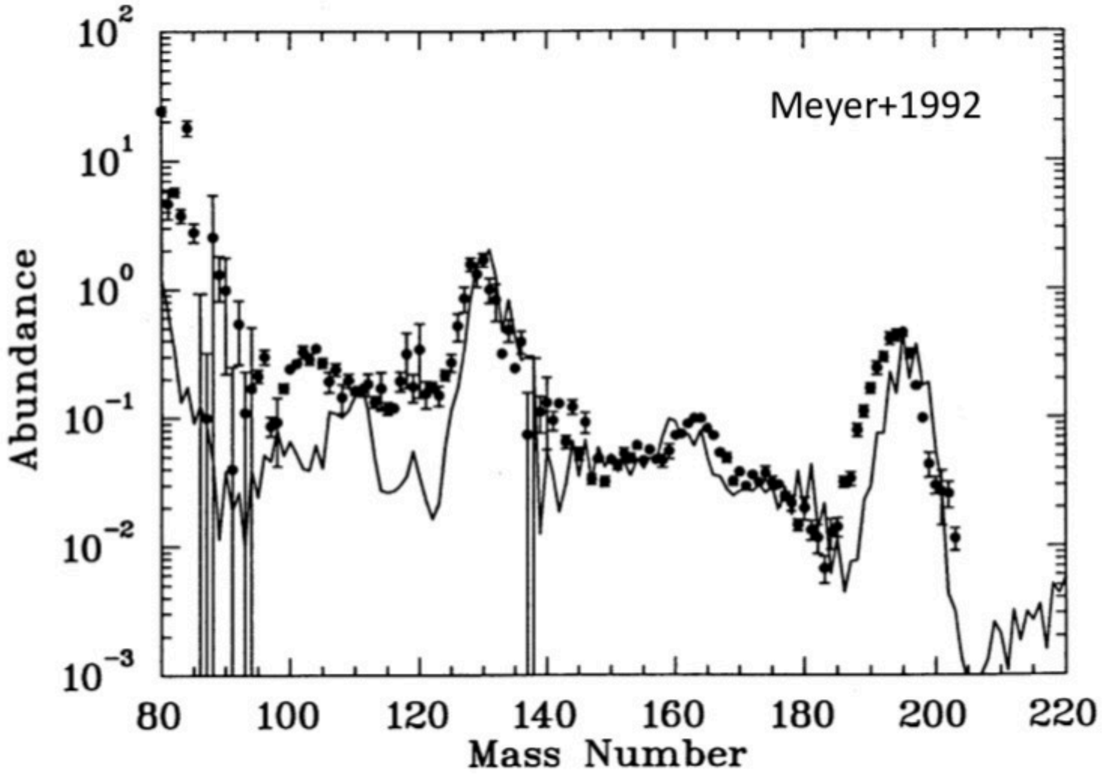
$$S_f \approx 235 C^{-1/6} L_{\bar{\nu}_e,51}^{-1/6} \epsilon_{\bar{\nu}_e,\mathrm{MeV}}^{-1/3} R_6^{-2/3} \left(\frac{M}{1.4\ M_\odot}\right) \text{ for } S_f \gg S_N$$

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

Qian, Woosley 1996

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?

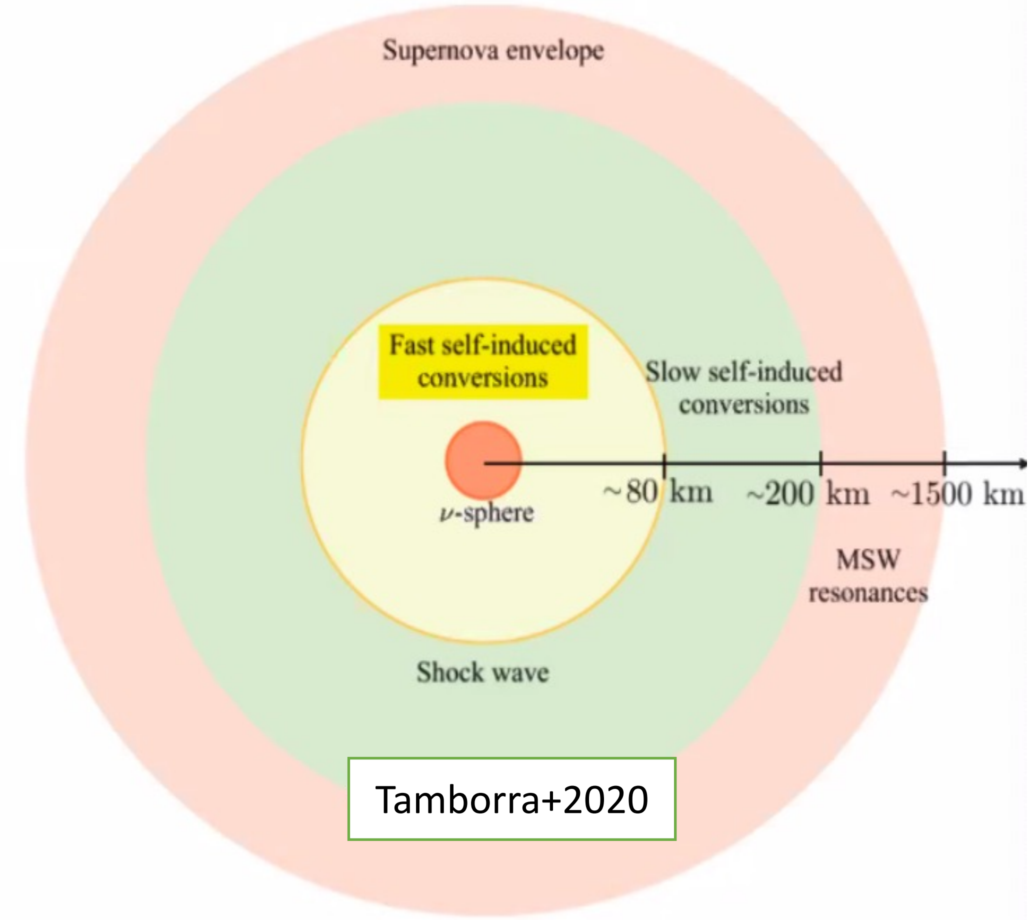
- Yes

  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?



Tamborra+2020

SN neutrino-driven wind:

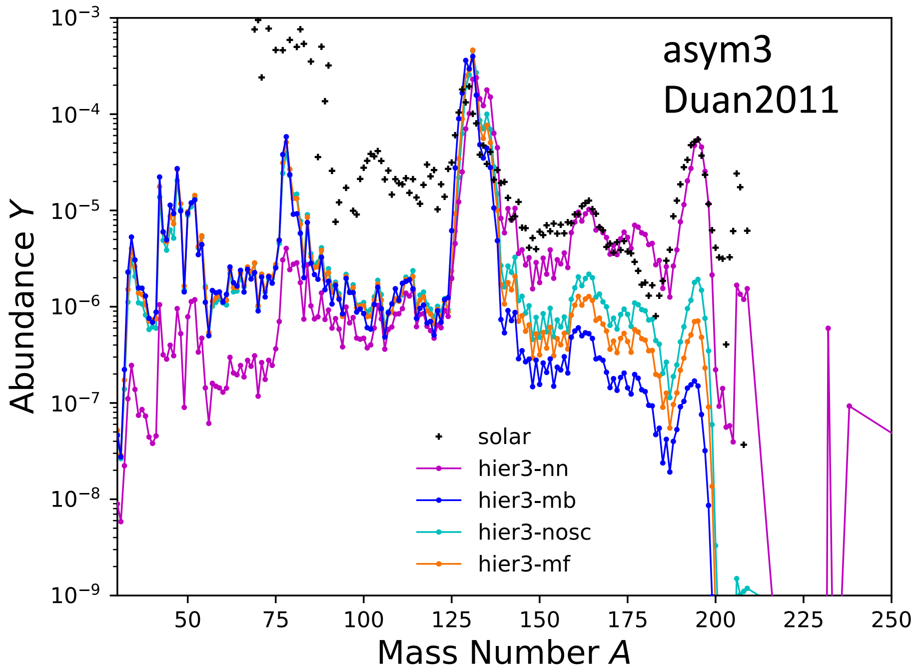
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

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):

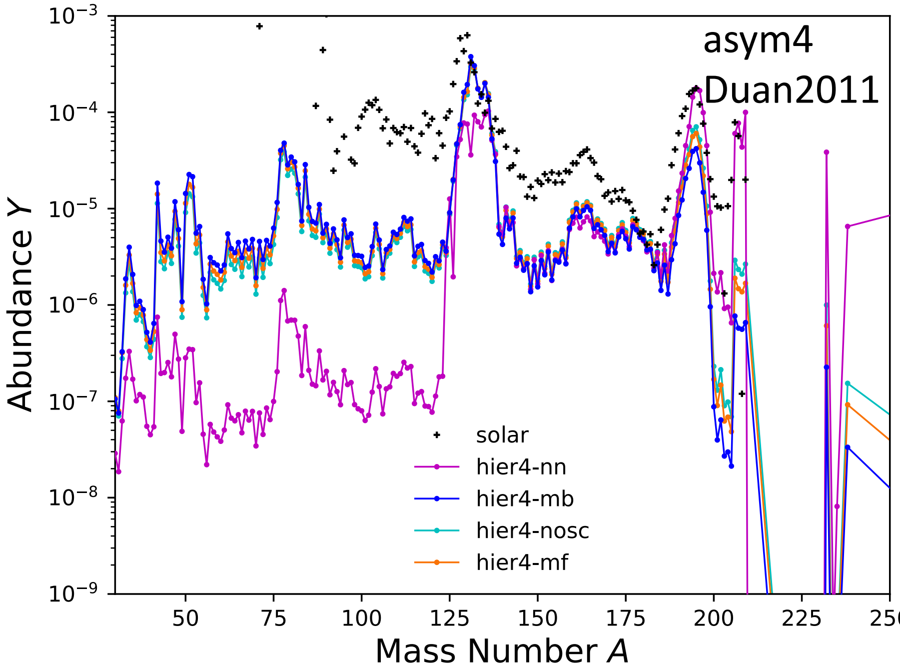
- Neutrinos determines the initial neutron richness (Y_e) for r process
- During alpha particle formation: ν_e reduce free neutrons --- alpha effect (Fuller+1995, McLaughlin+1996, Meyer+1998 ……)
- Collective neutrino oscillations raise the effective energy of ν_e and $\bar{\nu}_e$, to readjust the Y_e 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;
inverted mass hierarchy introduces bigger neutrino effect

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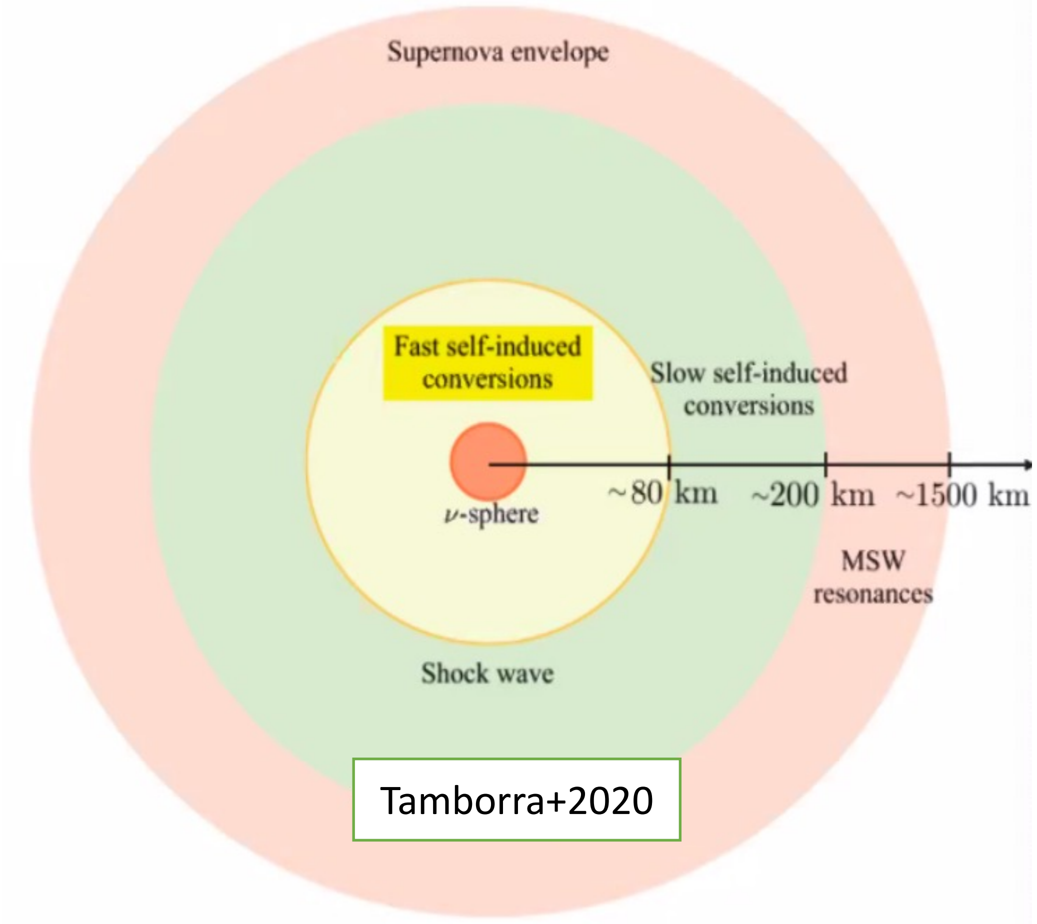
νp-process in supernovae



Existence of neutrinos: enhance heavier elements productions in νp process

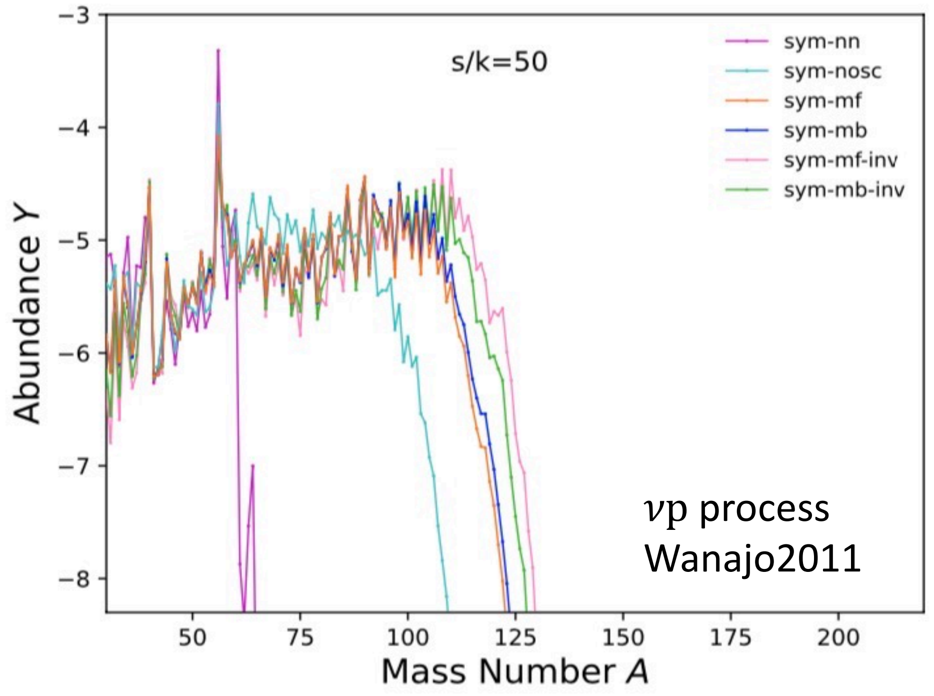
SN neutrino-driven wind:

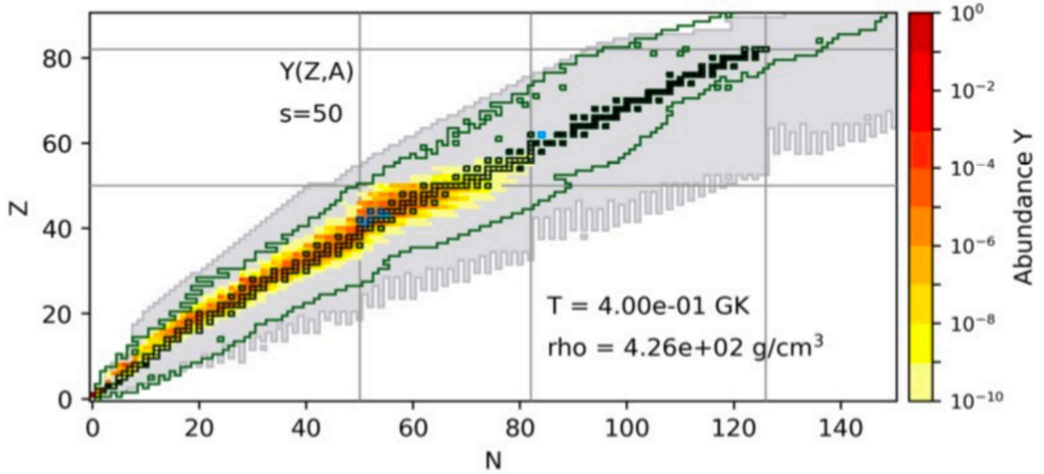
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

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)

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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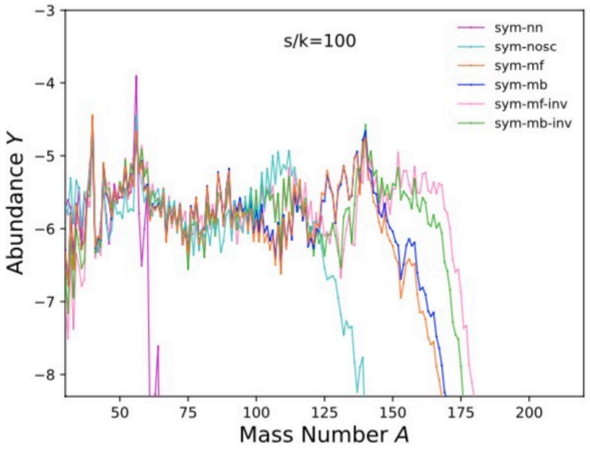
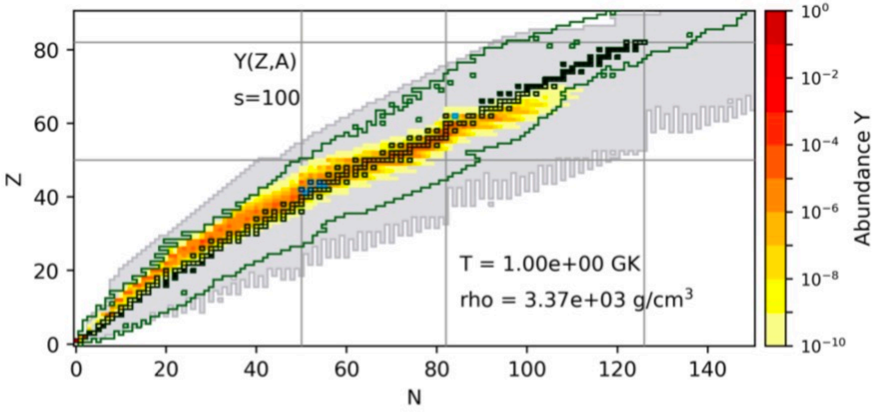
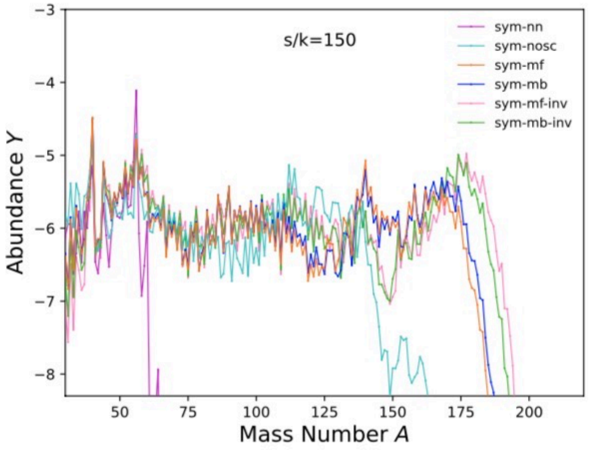
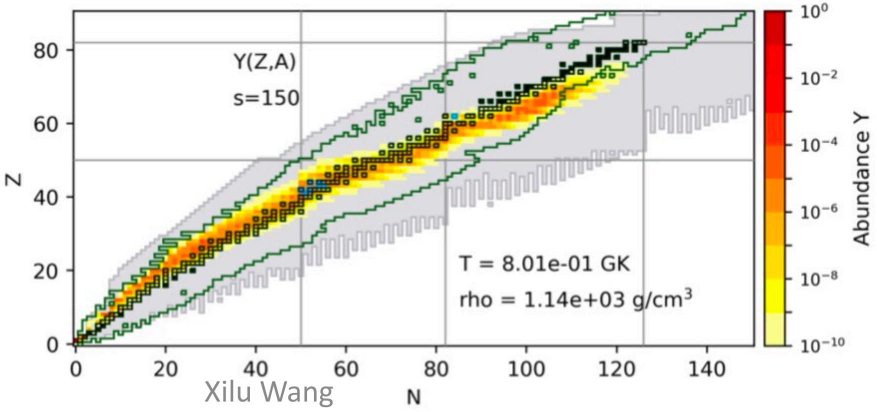
Collective oscillations and νp process with various entropy

- 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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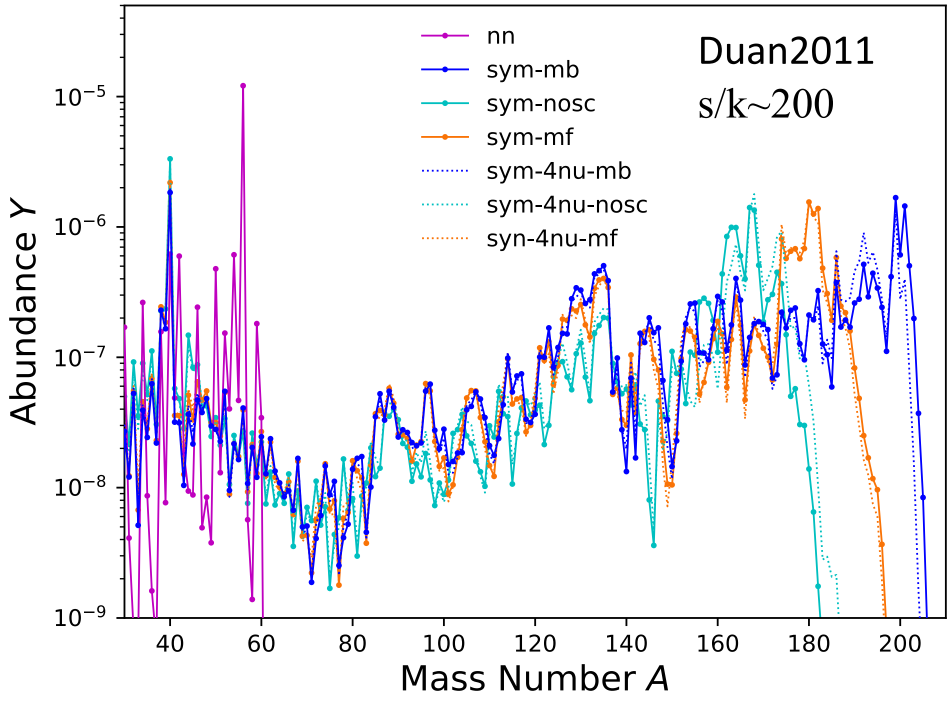
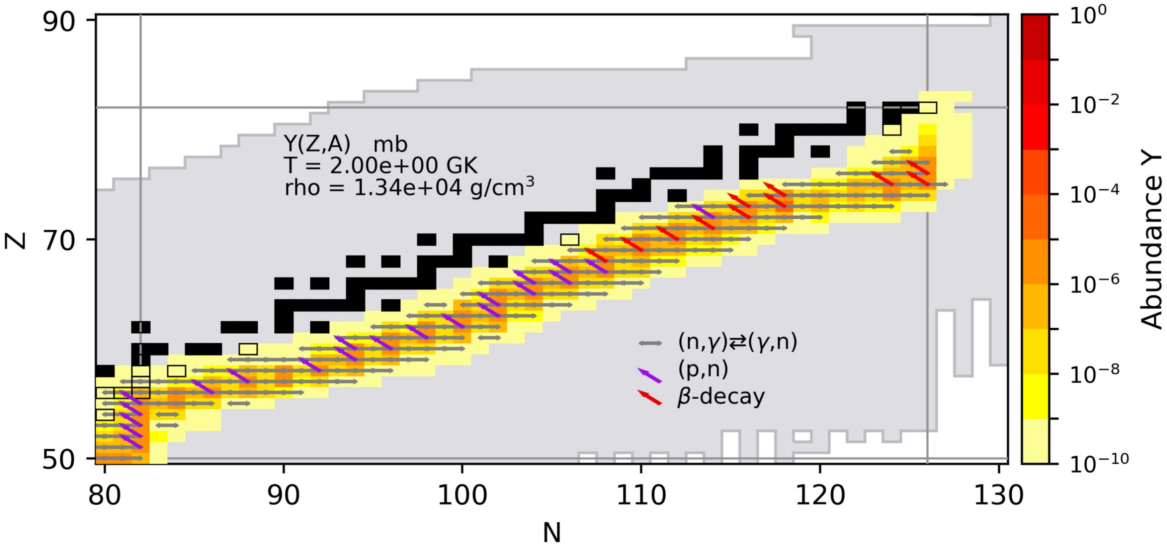
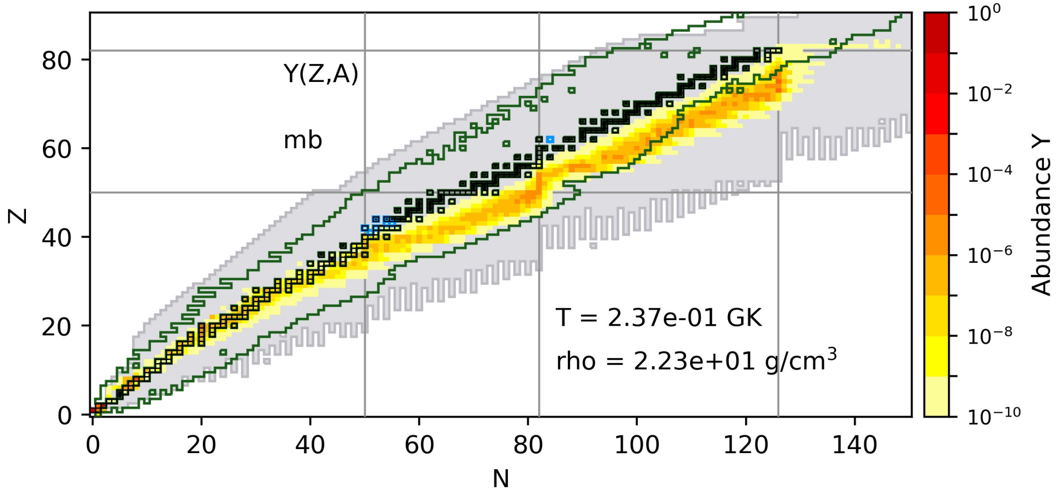
Collective oscillations and νi process







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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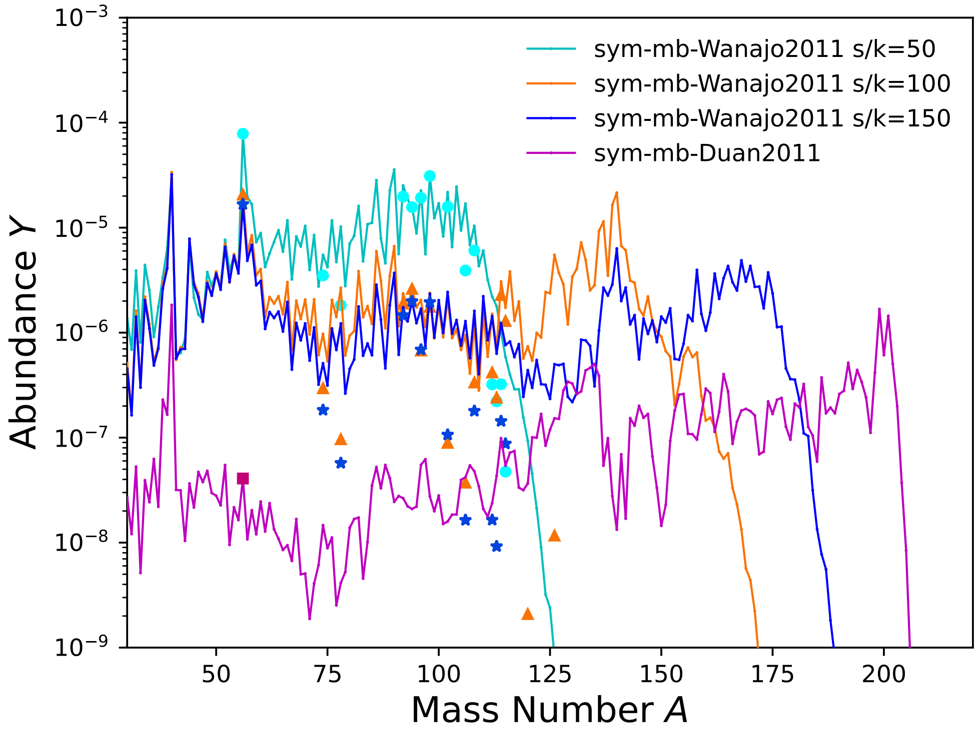
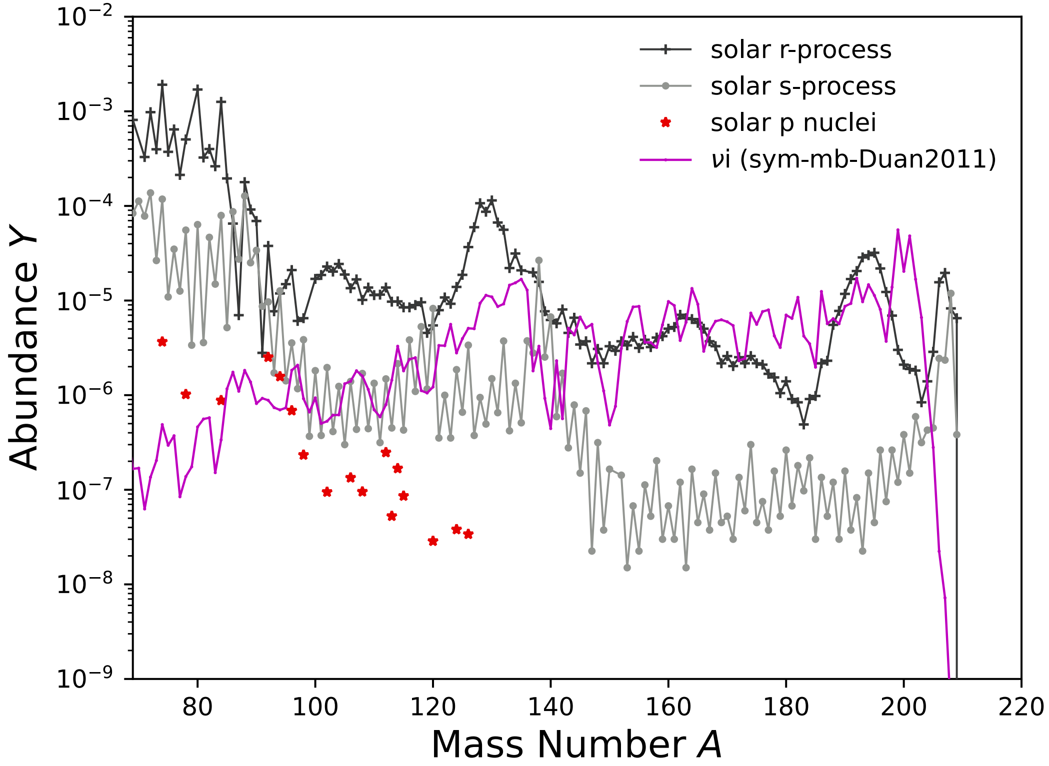
Collective oscillations and νi process





- 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".
- Future JUNO neutrino measurement will provide important information for neutrino interactions to help us better understand the heavy-element nucleosynthesis in supernovae.

- Thanks for your attention. Questions?