Astrophysical observables of heavy-element nucleosynthesis

and nuclear physics

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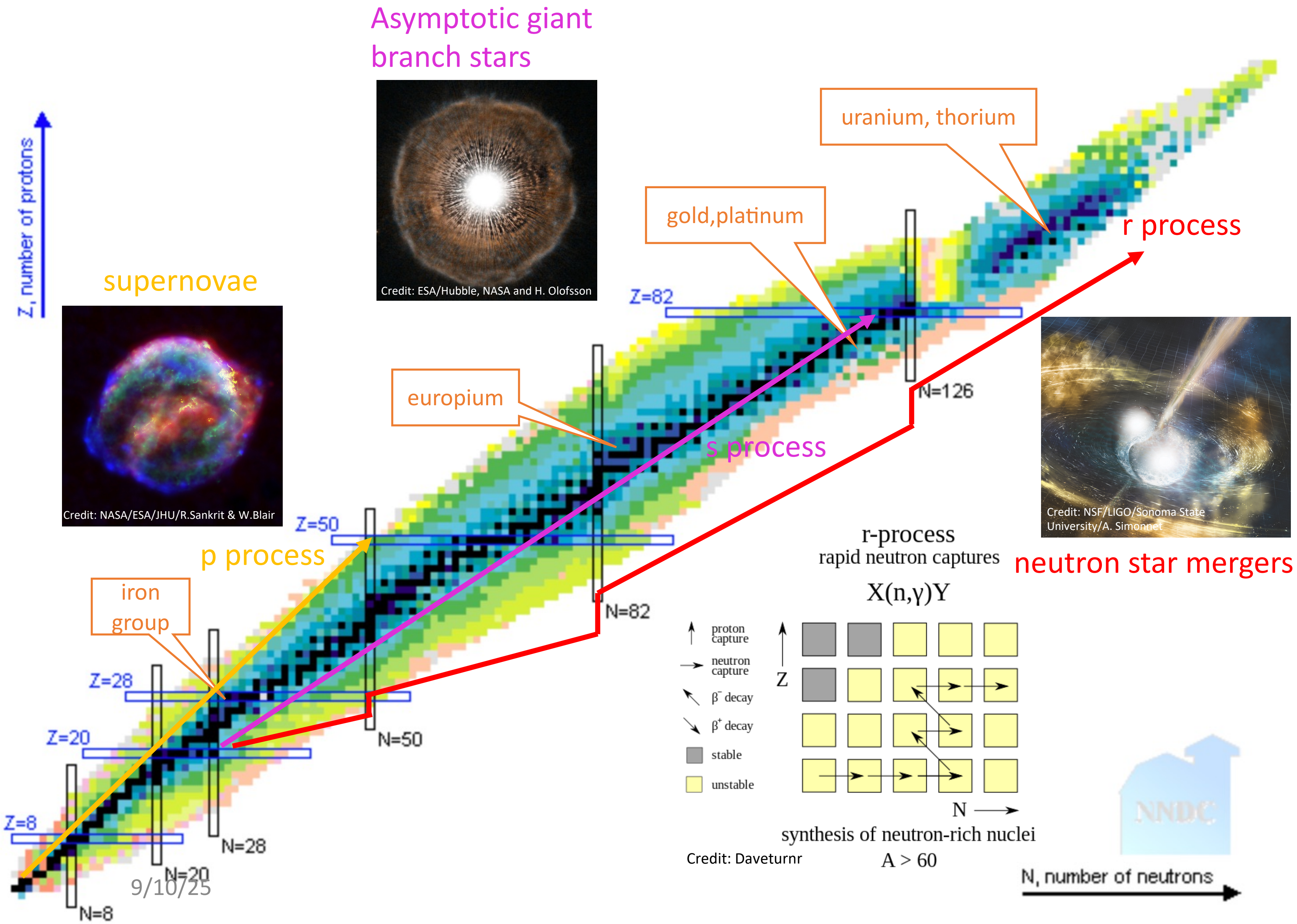
Nucleosynthesis-heavy elements



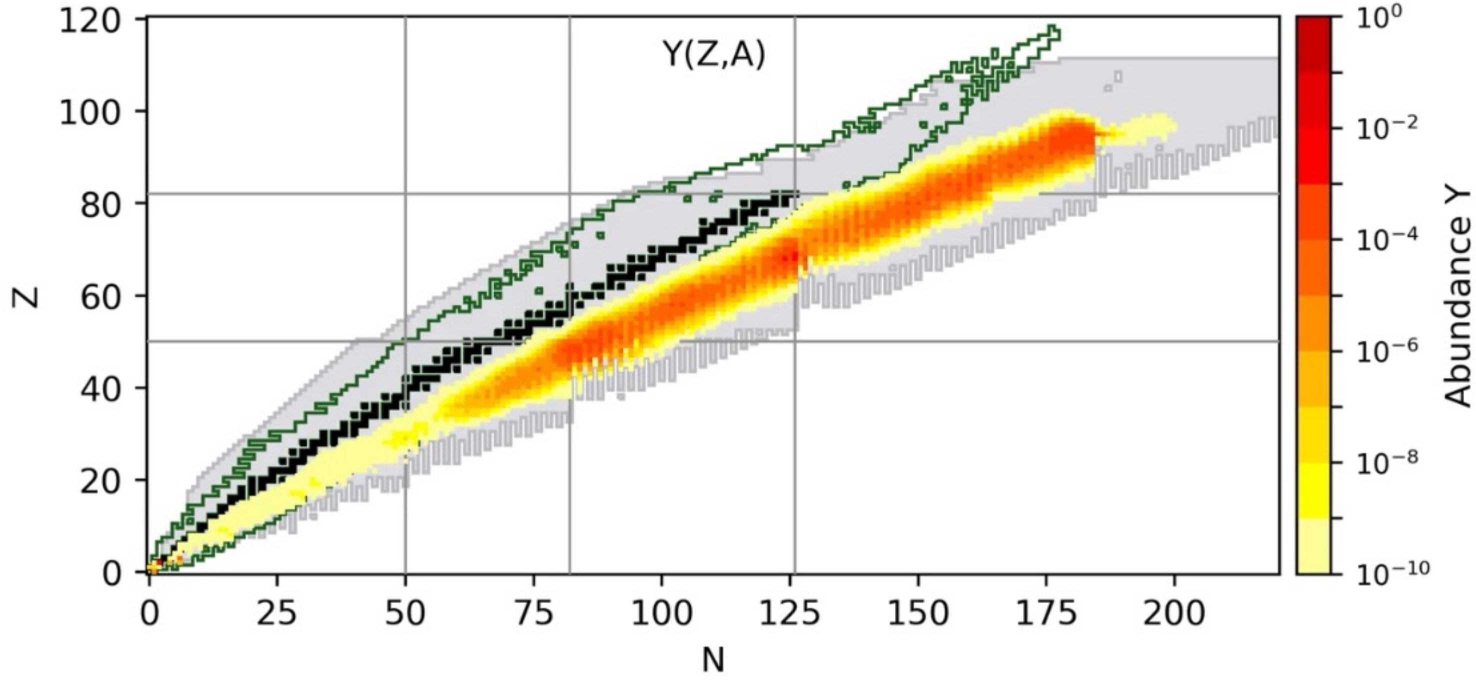
Heavy elements (heavier than iron):
the nucleosynthesis was a mystery for decades

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

r-process nucleosynthesis

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



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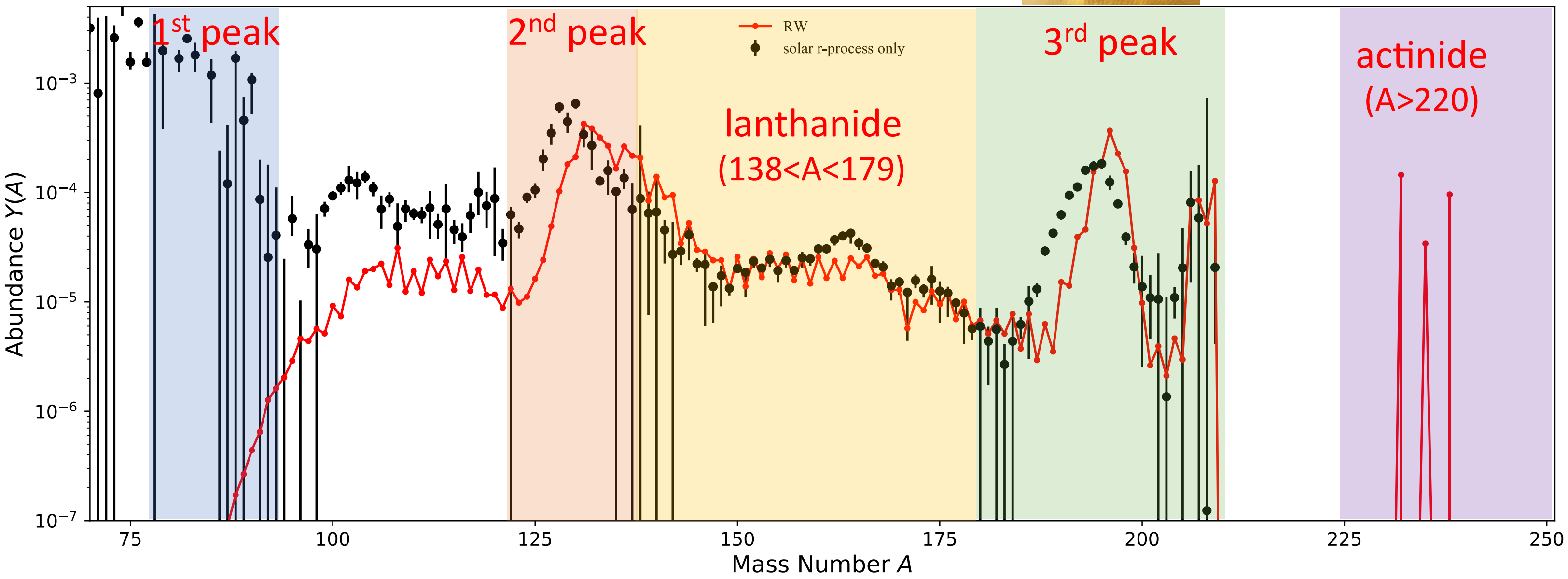
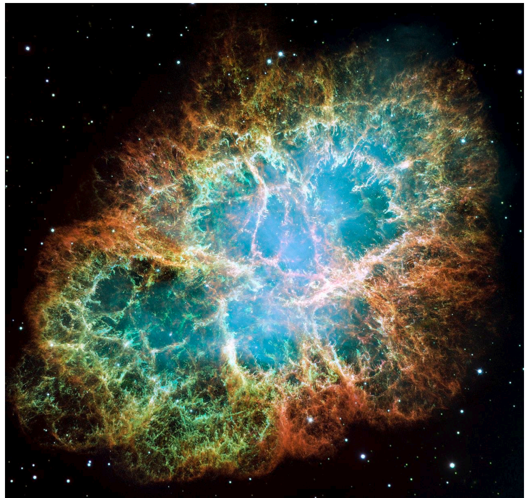


r-process sites: a mystery

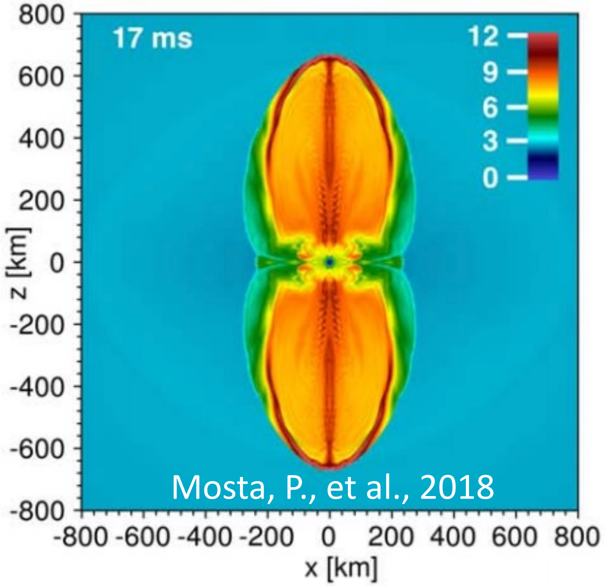
Core collapse Supernovae?
(e.g., Meyer+1992, Roberts+2012)


Credit: NASA, ESA, J. Hester and A. Loll

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

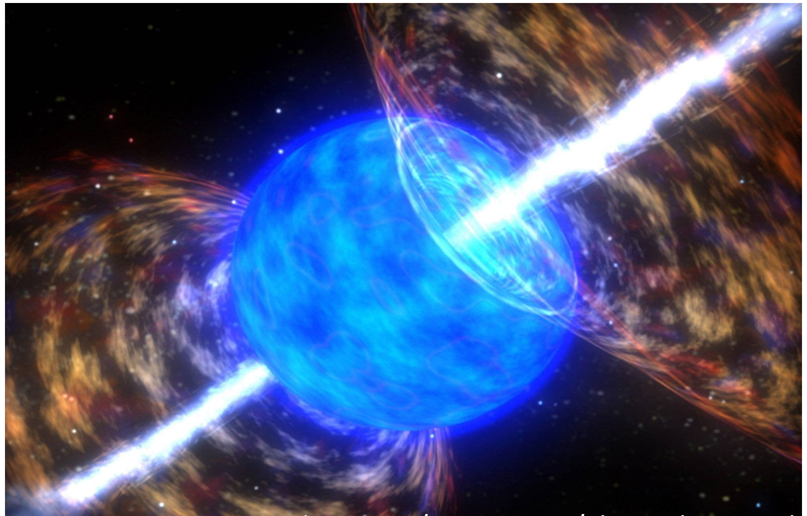

University of Warwick/Mark Garlick

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



Mosta, P., et al., 2018

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


Credit: NASA/Dana Berry/Skyworks Digital

Magnetar giant flare (Patel+2025)

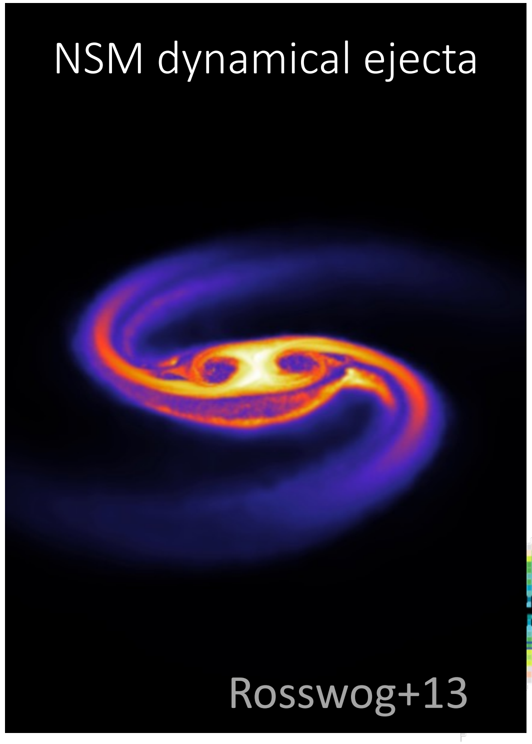
exotic supernovae (e.g., Fischer+2020)

primordial black hole + neutron star (e.g., Fuller+2017)

etc.

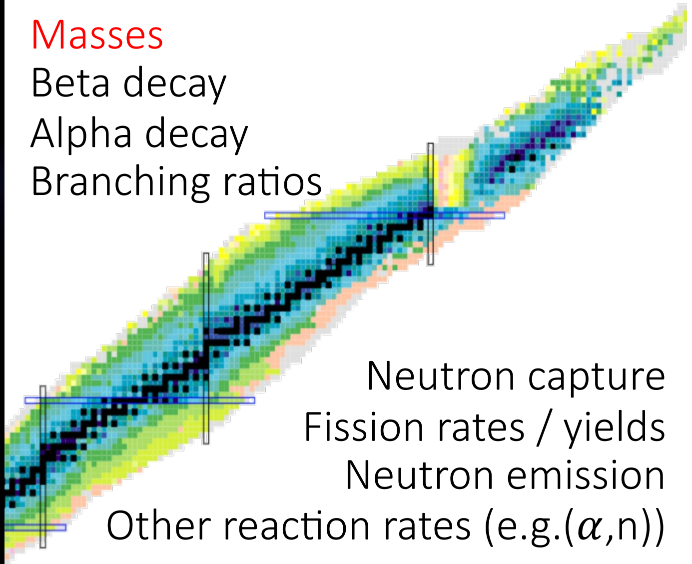
Modeling the *r*-process: **nucleosynthesis** networks and post-processing

Hydrodynamic simulations provide us with a "trajectory":
density / temperature / position
as a function of time



Both experimental + theoretical nuclear inputs:

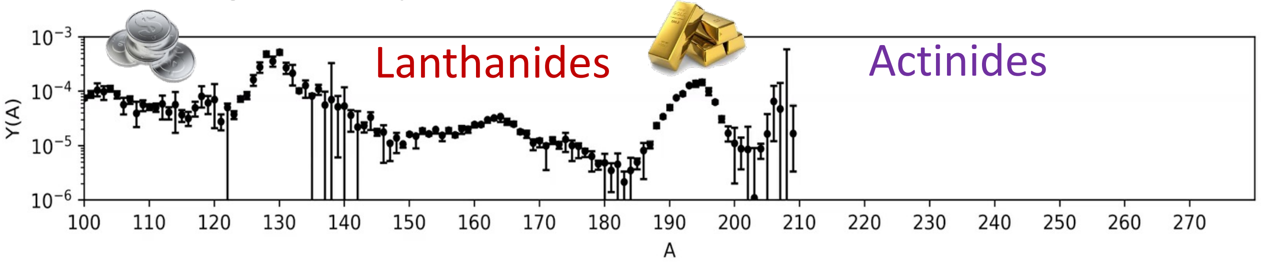
Masses
Beta decay
Alpha decay
Branching ratios

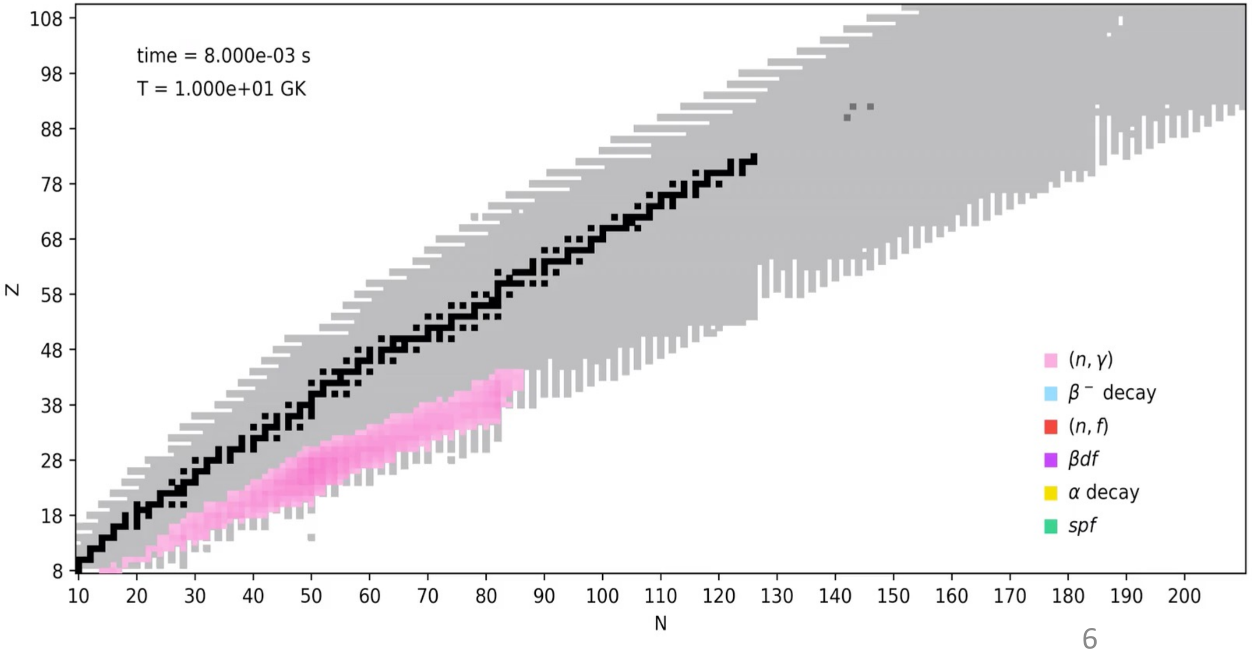


Neutron capture
Fission rates / yields
Neutron emission
Other reaction rates (e.g.(α,n))

The need for nuclear inputs is not isolated to reactions and decays in the network:

- input initial composition dependent on EOS
- outputs are post-processed to evaluate nuclear heating, light curves, gamma spectra…

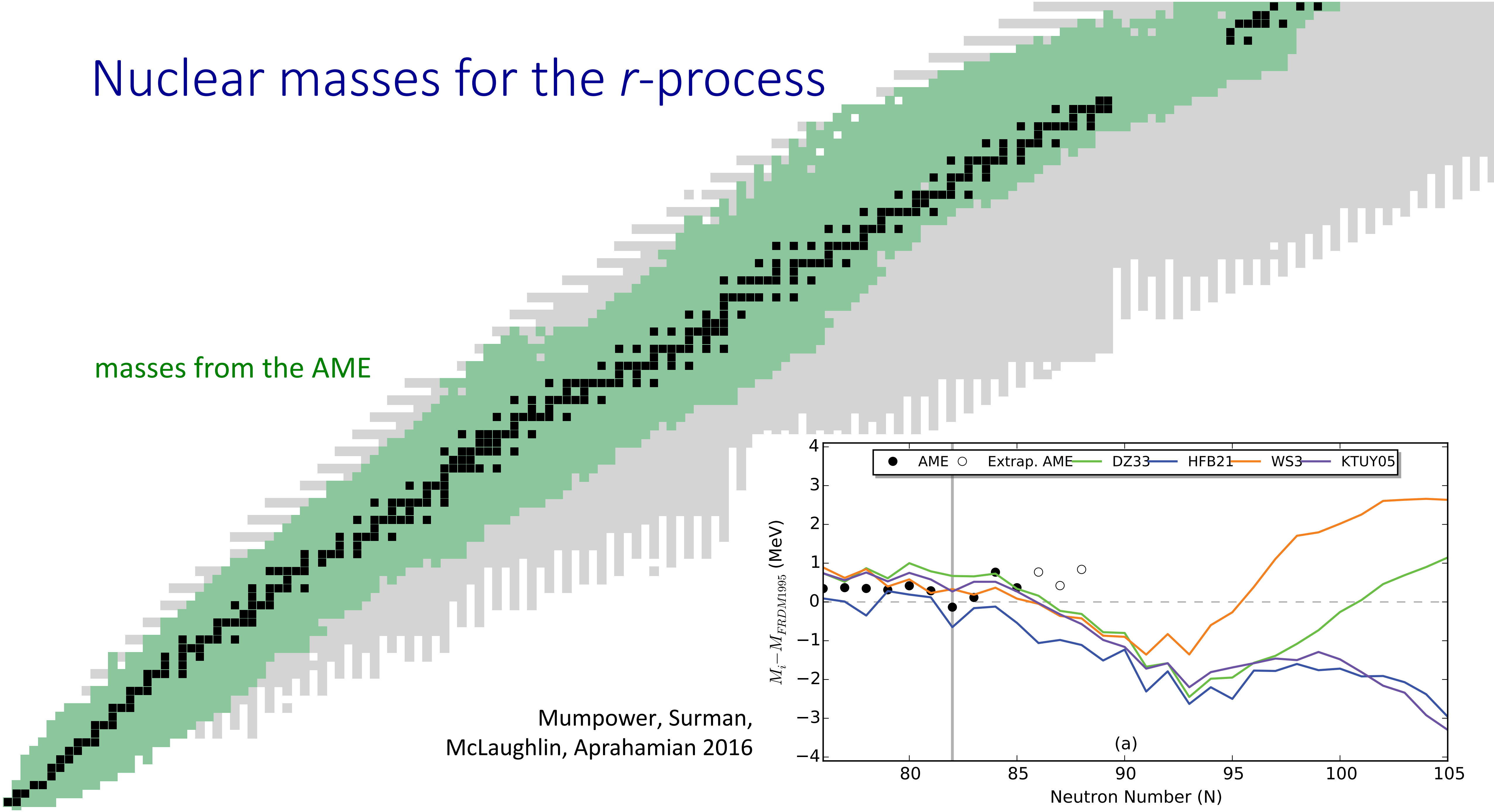




Credit: Nicole Vassh

Nuclear masses for the *r*-process

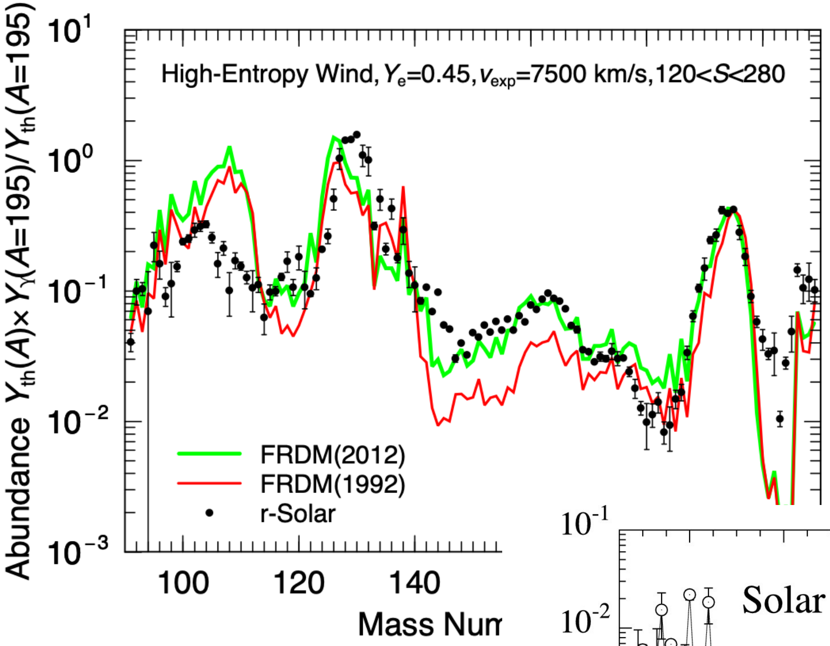
masses from the AME



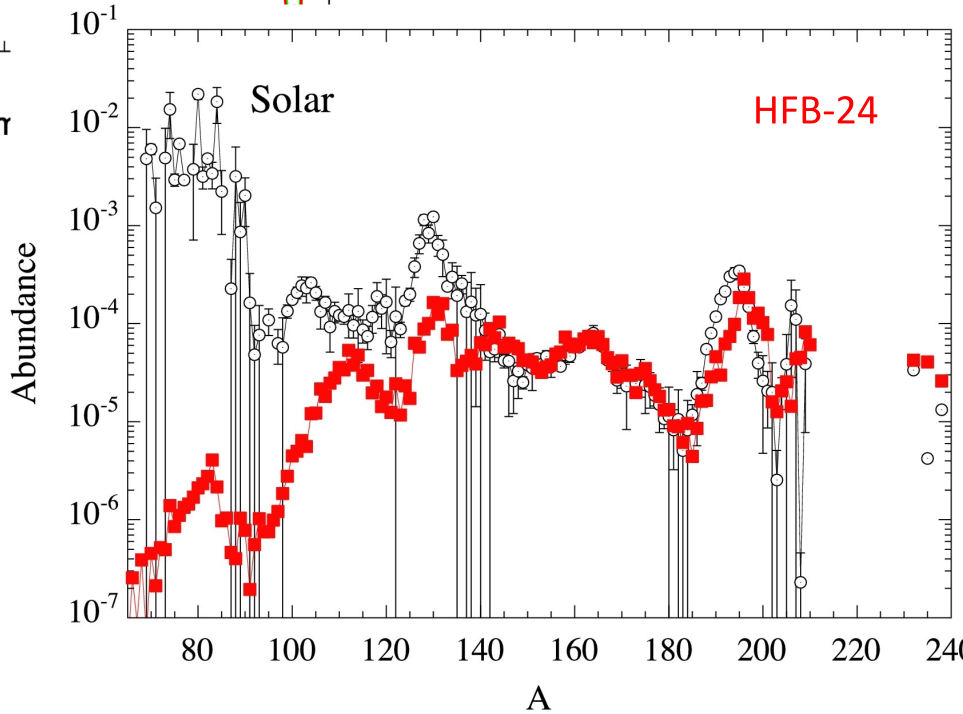
Mumpower, Surman, McLaughlin, Aprahamian 2016

Credit: Rebecca Surman

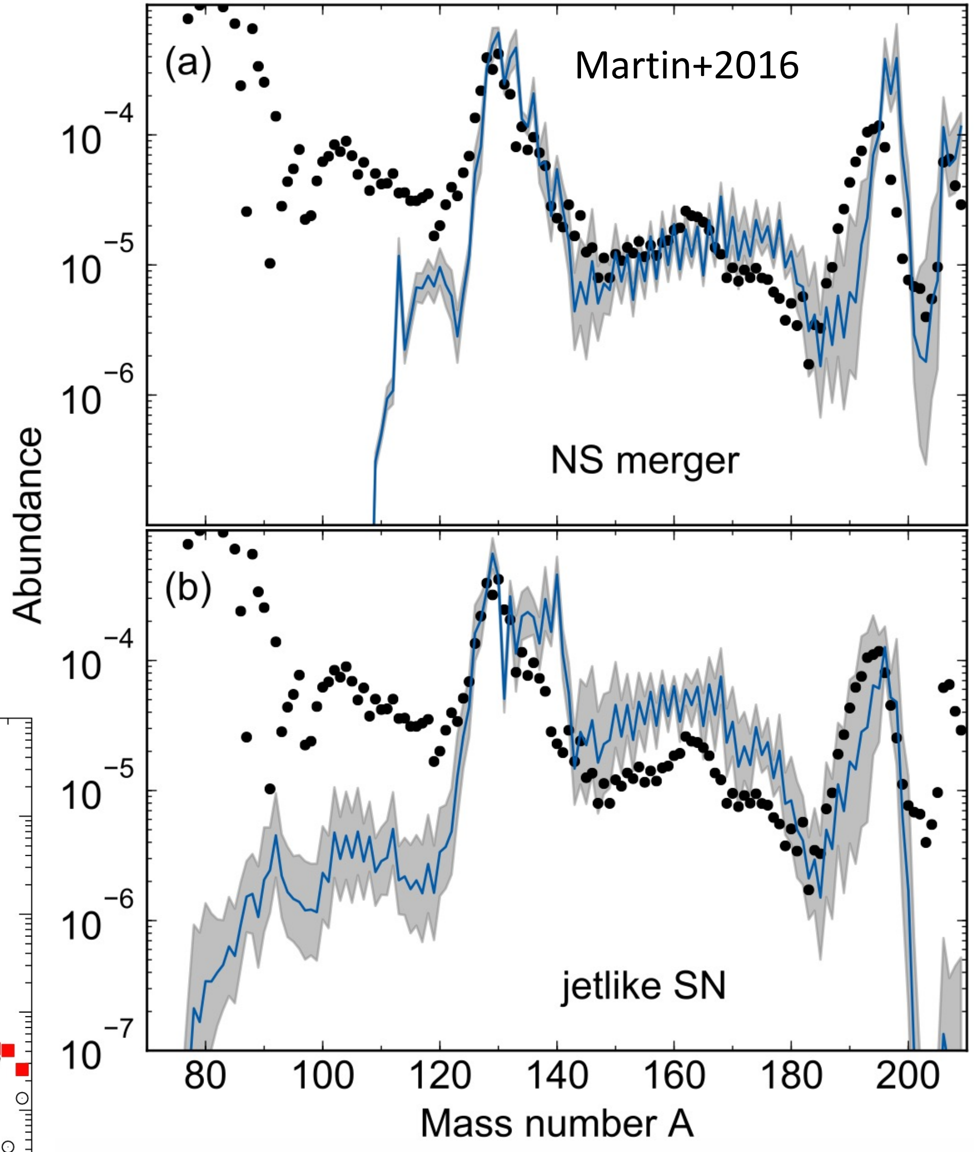
Nuclear mass model systematics



Kratz+2014



Goriely, Martínez
Pinedo 2015

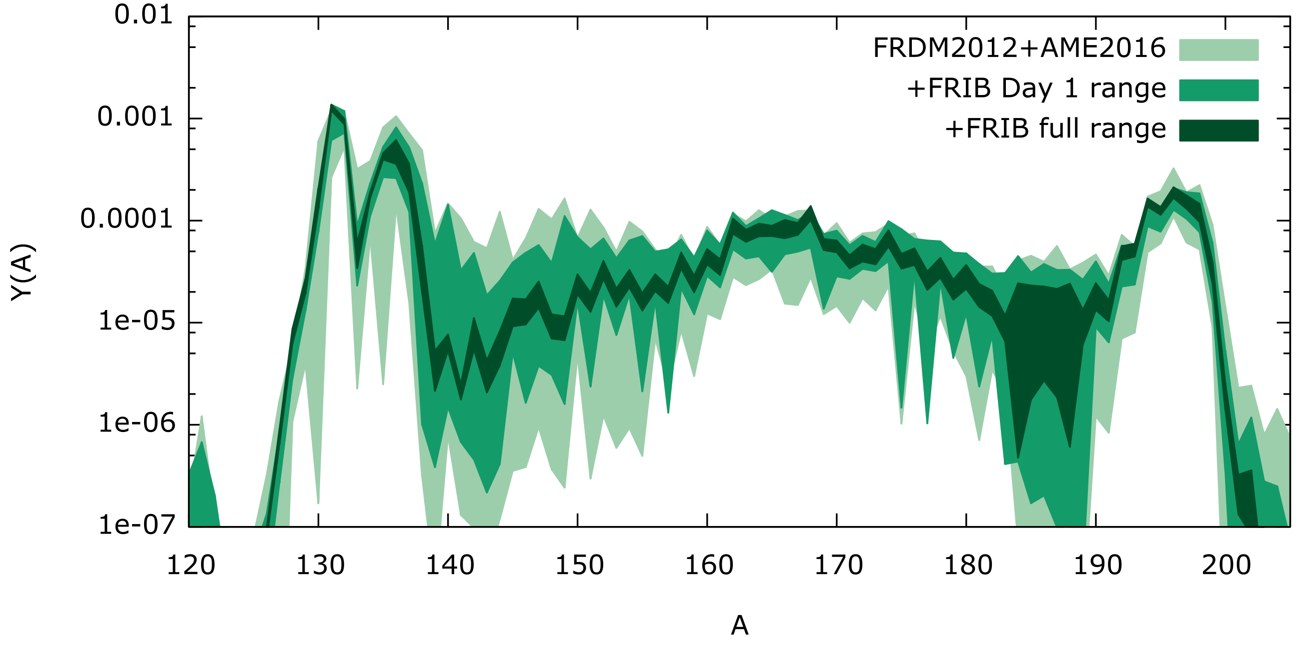


Skyrme EDFs: SkM*, SkP, SLy4,
SV-min, UNEDF0, UNEDF1

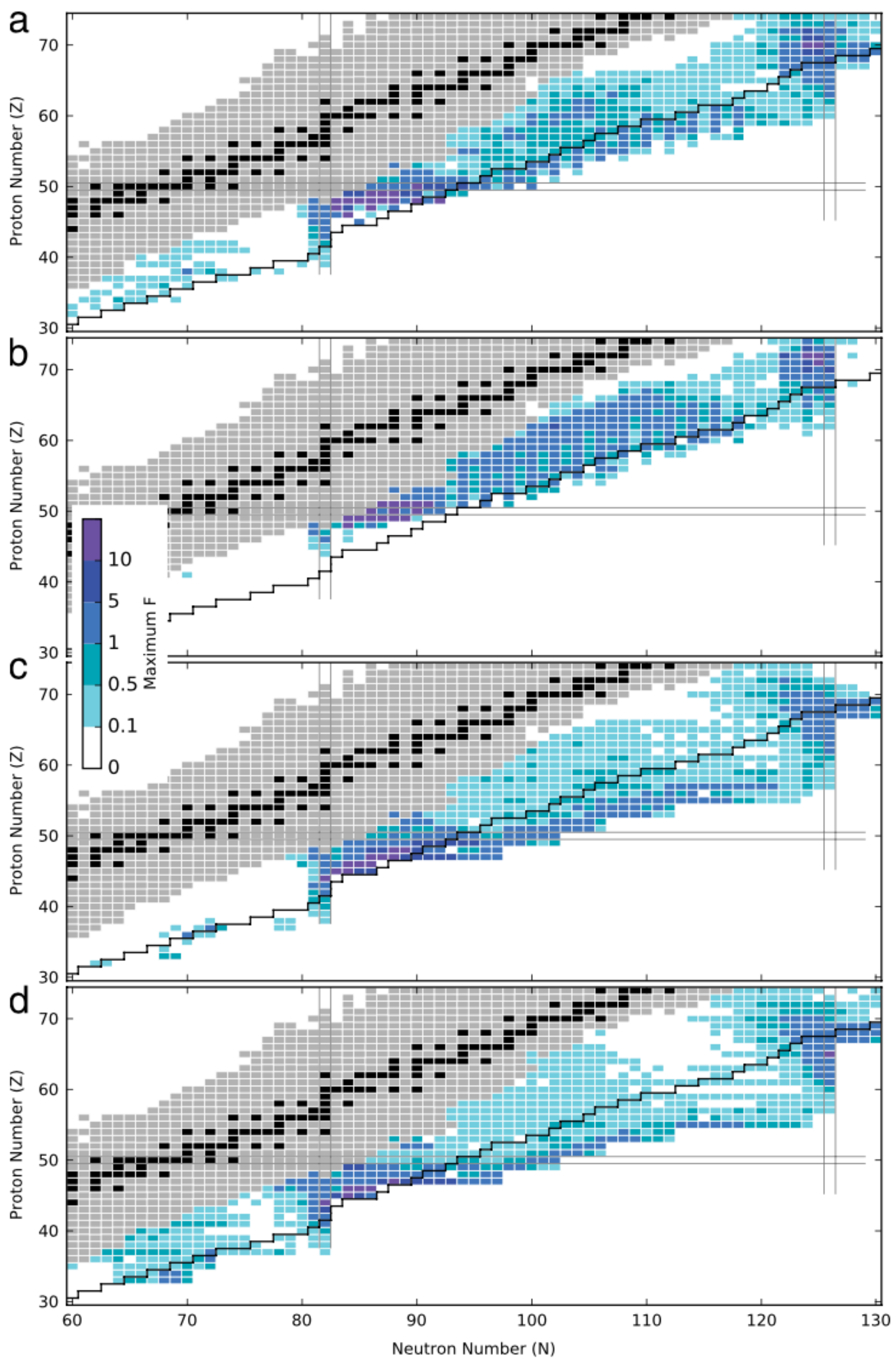
Credit: Rebecca Surman

Nuclear mass sensitivity studies

Mumpower, Surman, McLaughlin, Aprahamian 2016



Surman, Mumpower 2018



Credit: Rebecca Surman

Nuclear mass sensitivity studies

NSAC LRP document, 2013

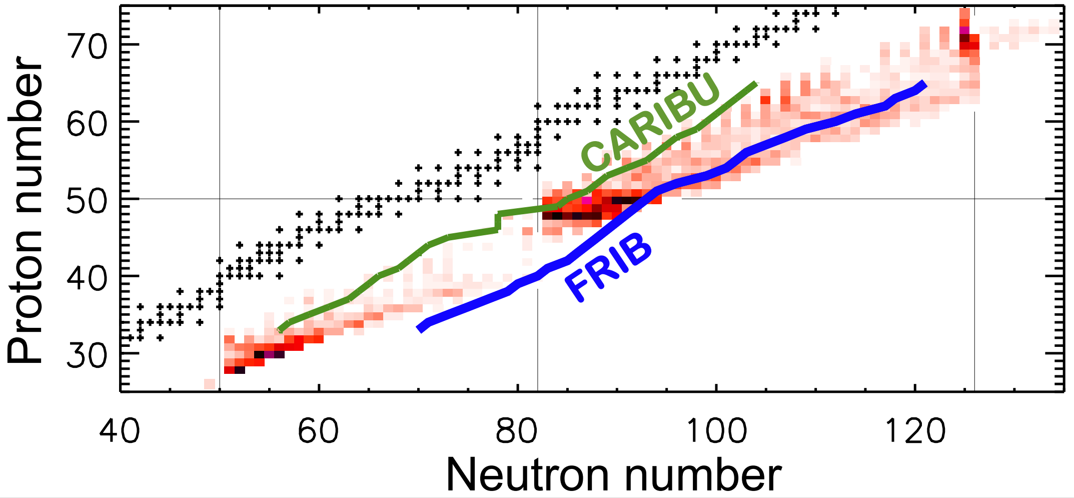
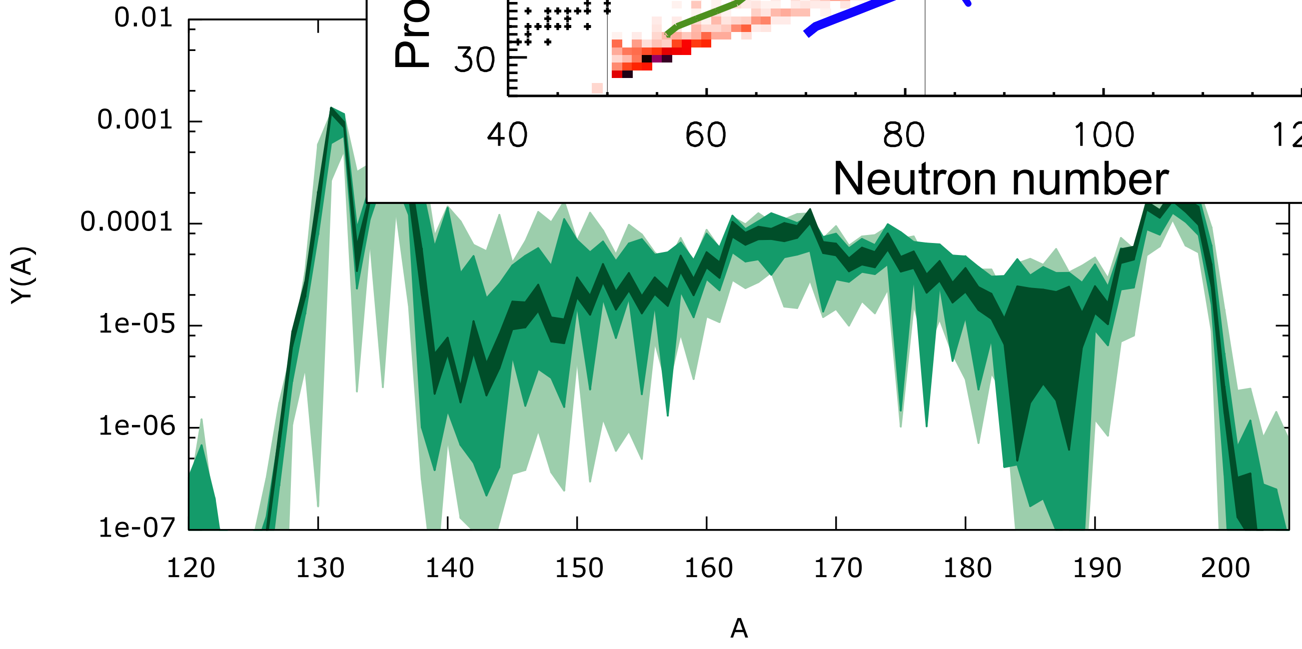
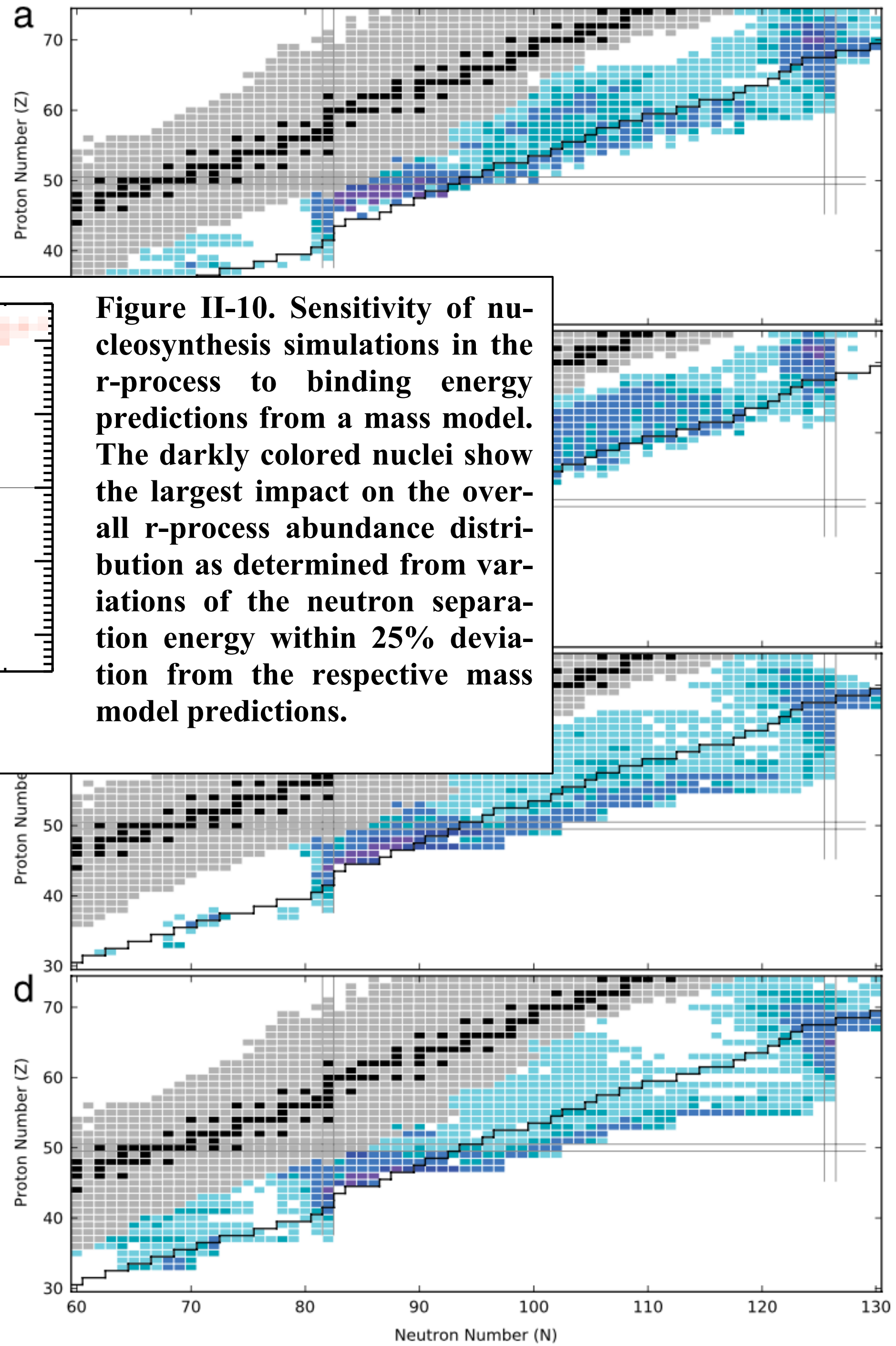


Figure II-10. Sensitivity of nucleosynthesis simulations in the r-process to binding energy predictions from a mass model. The darkly colored nuclei show the largest impact on the overall r-process abundance distribution as determined from variations of the neutron separation energy within 25% deviation from the respective mass model predictions.



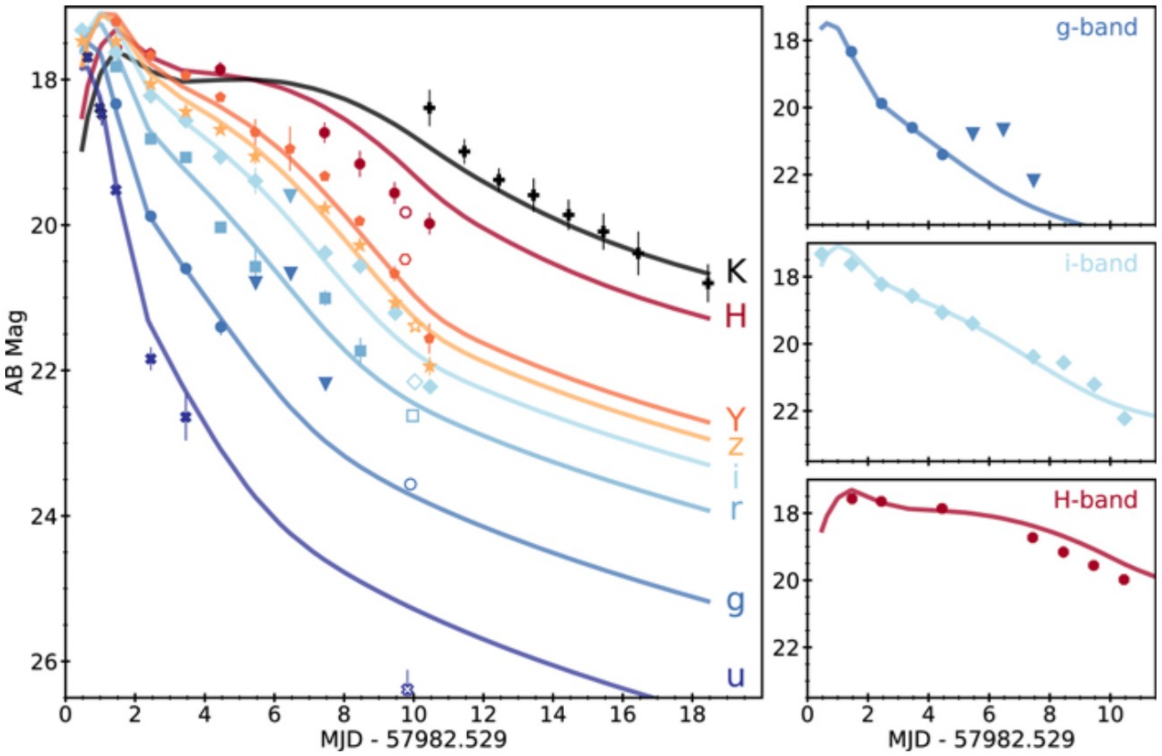
Surman, Mumpower 2018



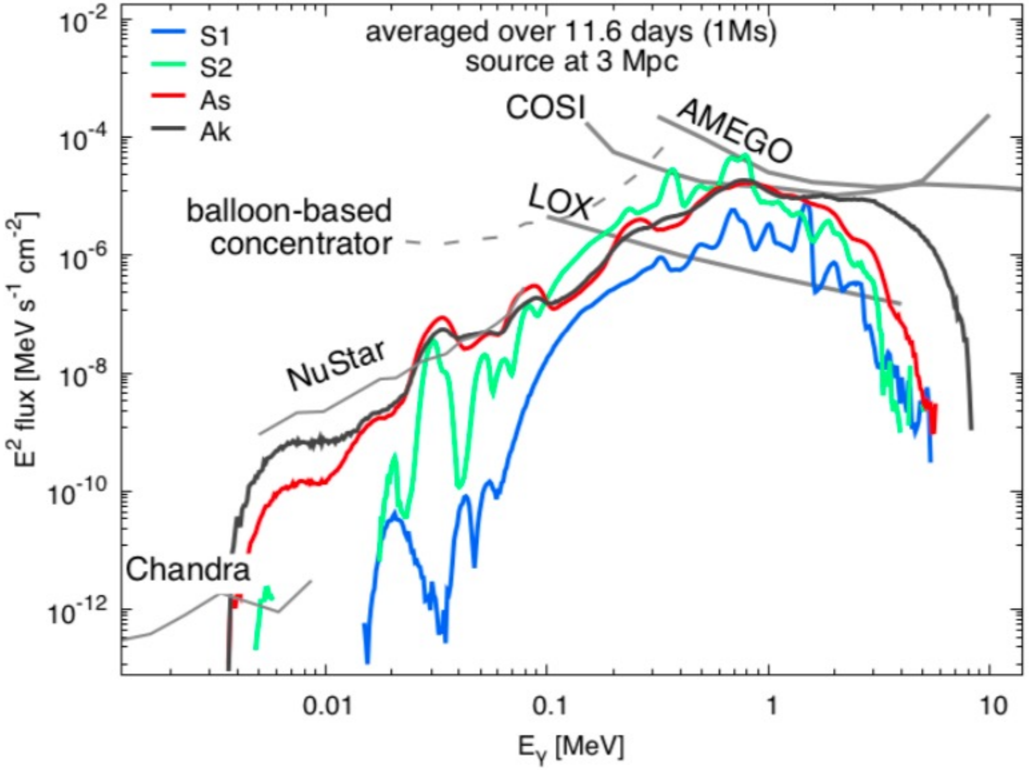
Credit: Rebecca Surman

Astrophysical observables of heavy-element nucleosynthesis

- Prompt electromagnetic emissions
  - Kilonova: a transient powered by the radioactive decay of the r-process elements synthesized from the r-process sites like neutron star merger



UV, optical, and NIR light curves of the counterpart of GW170817. (Cowperthwaite, P. S., et al., 2017)



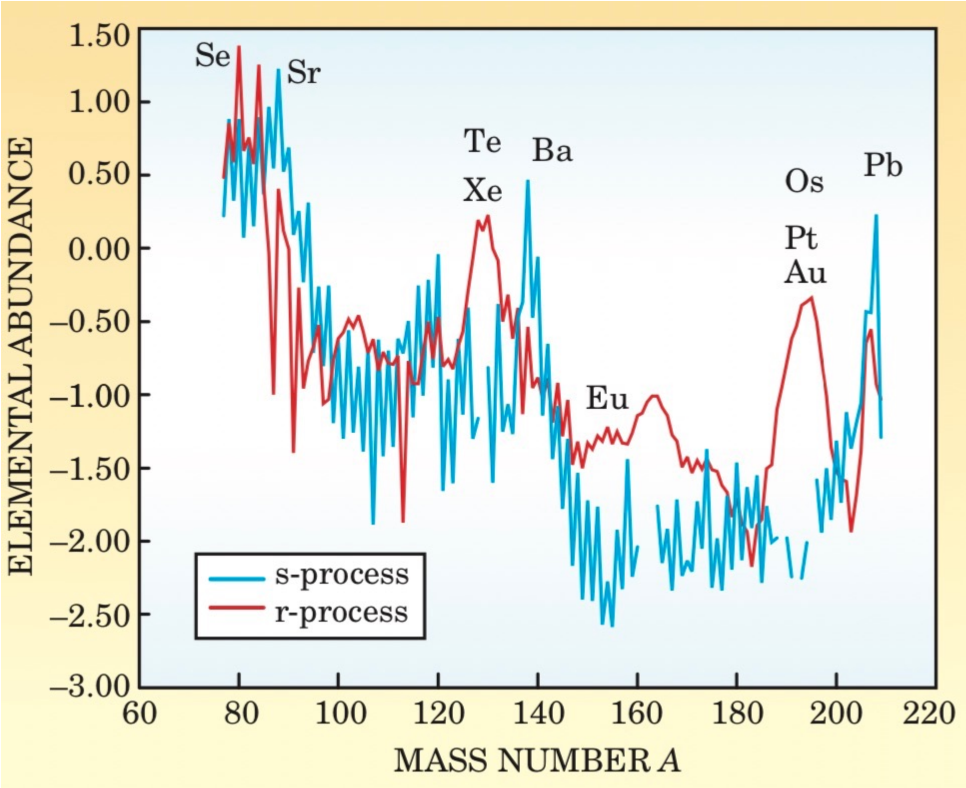
Gamma rays from a nearby kilonova. (Korobkin. O., et al., 2020)

Astrophysical observables of heavy-element nucleosynthesis

- Long-lived abundance yields

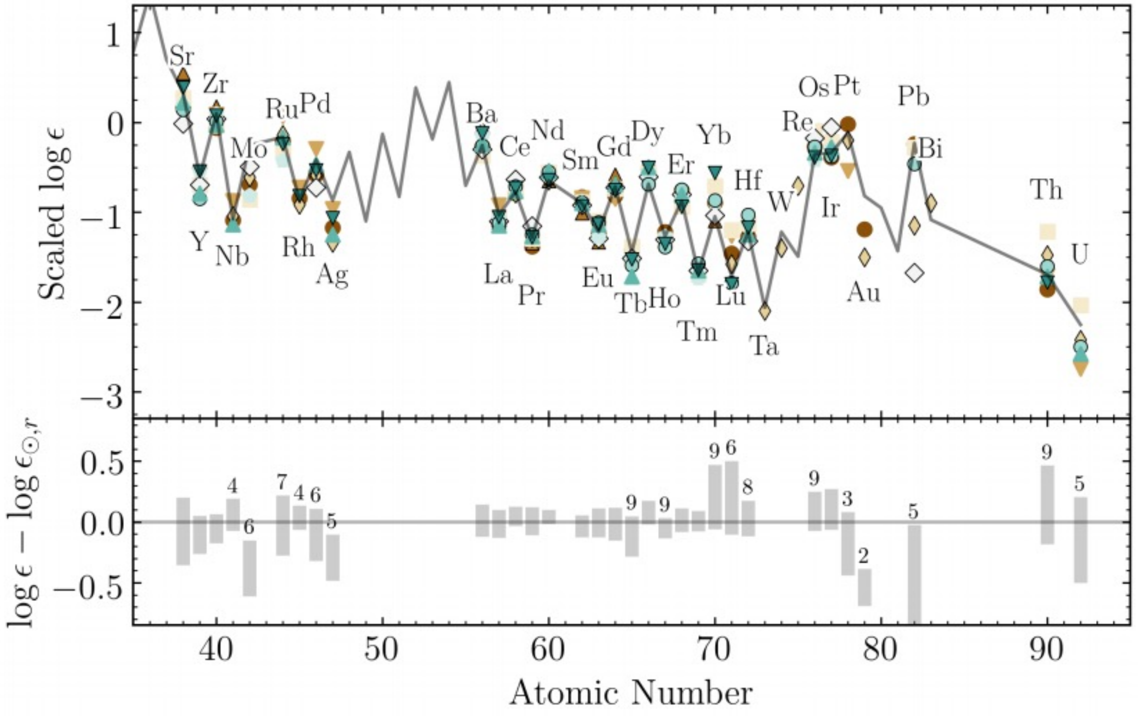
Solar system abundances of heavy elements:

Cowan, J.& Thielemann, F. 2004



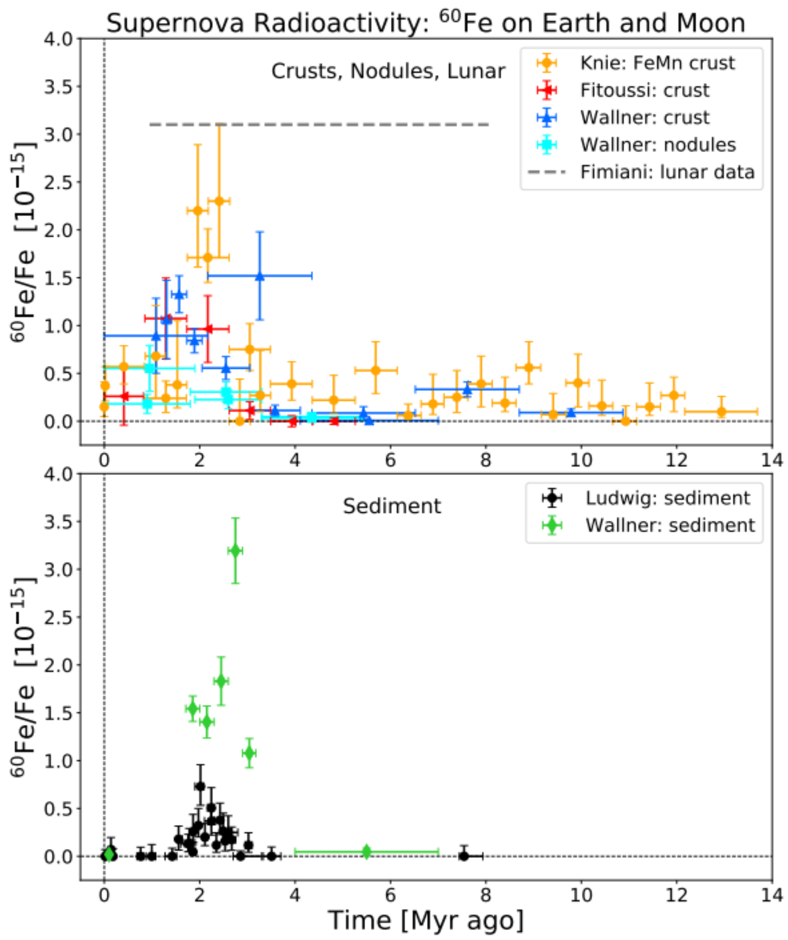
Stellar observations of metal-poor stars:

Holmbeck, E., et al 2020



Astrophysical observables of heavy-element nucleosynthesis

- isotope measurements in the solar system samples (Earth, moon, meteorites)

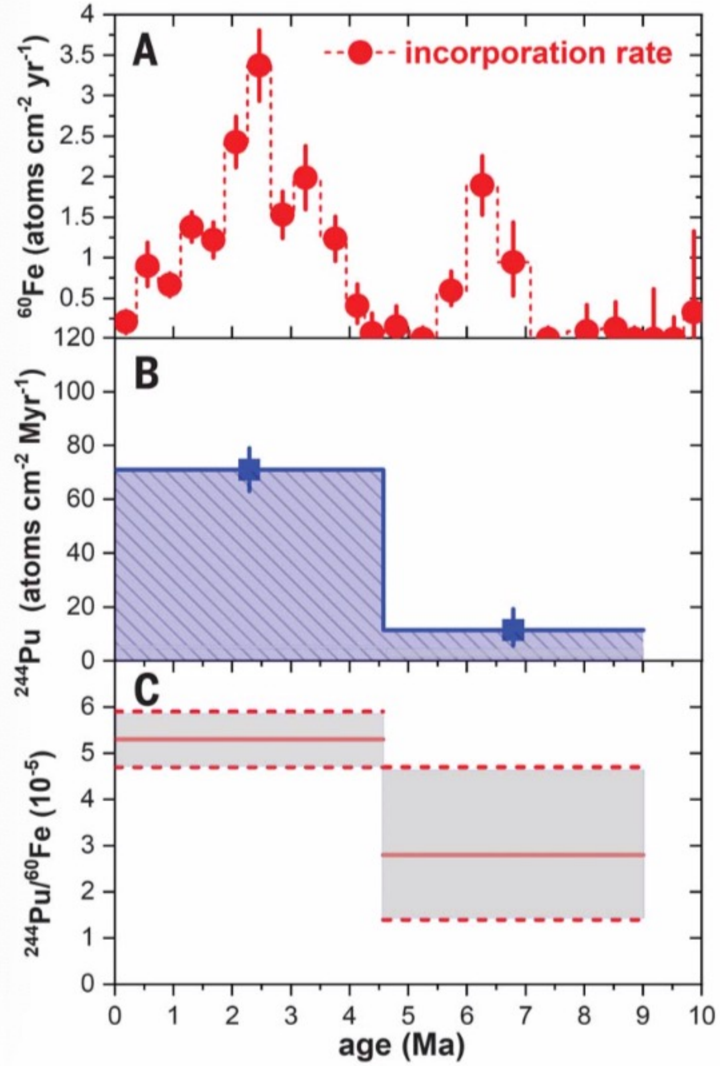


Fields, B., et al. 2019, BAAS, 51,410

$$t_{mean,{}^{60}_{26}Fe} = 3.78\ Myr$$

$$t_{mean,{}^{244}_{94}Pu} = 115\ Myr$$

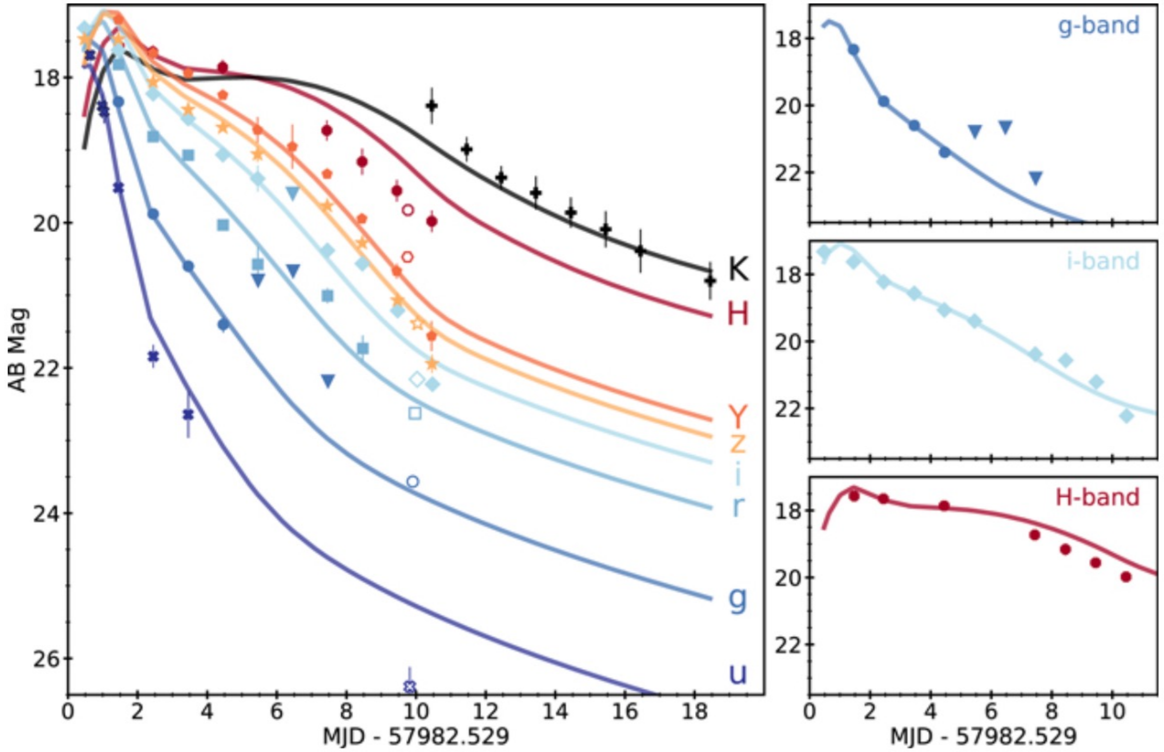
Near-earth event: within~100pc; occur ~ 3Myr ago



Wallner, A., et al. 2021, Science, 372, 6543

Neutron star mergers (NSM)

- **GW170817**: multi-wavelength observations →confirmed r-process nucleosynthesis sites
  - ➢ Kilonova light curve: Lanthanides production
  - ➢ Strontium and Tellurium elements indicated from spectroscopy
- GRB211211A and GRB230307A: kilonova lightcurve; tellerium



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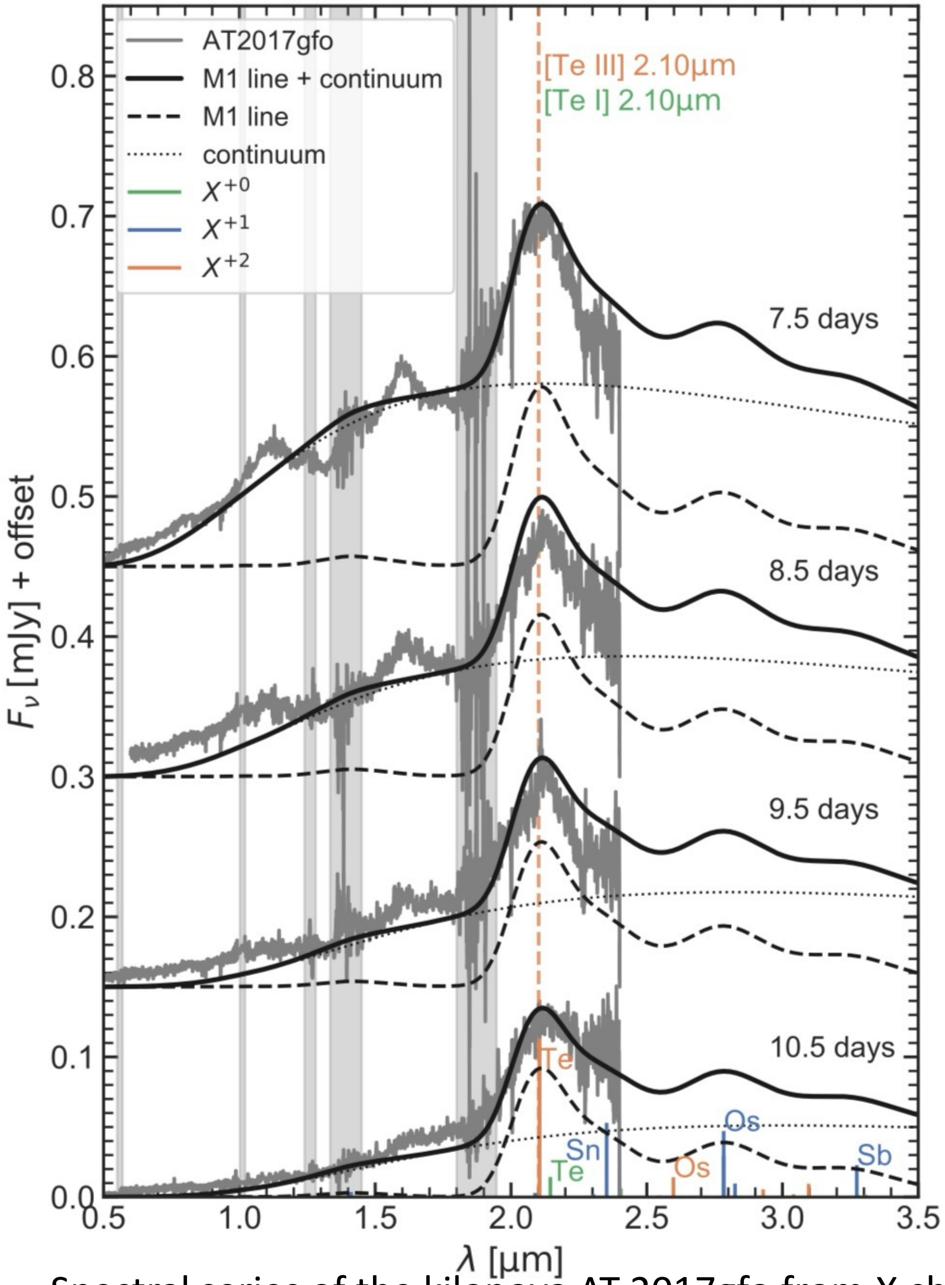
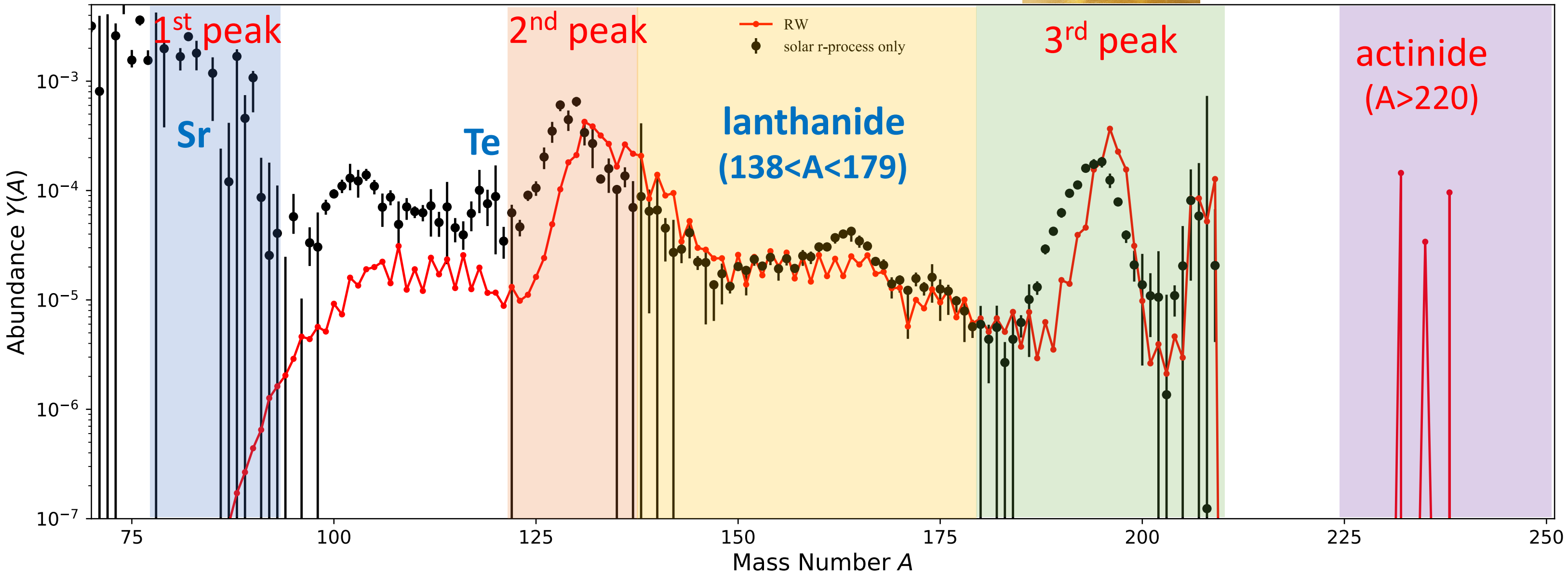


Spectral series of the kilonova AT 2017gfo from X-shooter on VLT. (Hotokezaka, K., et al., 2023)

Did the GW170817 merger produce actinides?



Fission in astrophysical environments

Incident neutron strikes

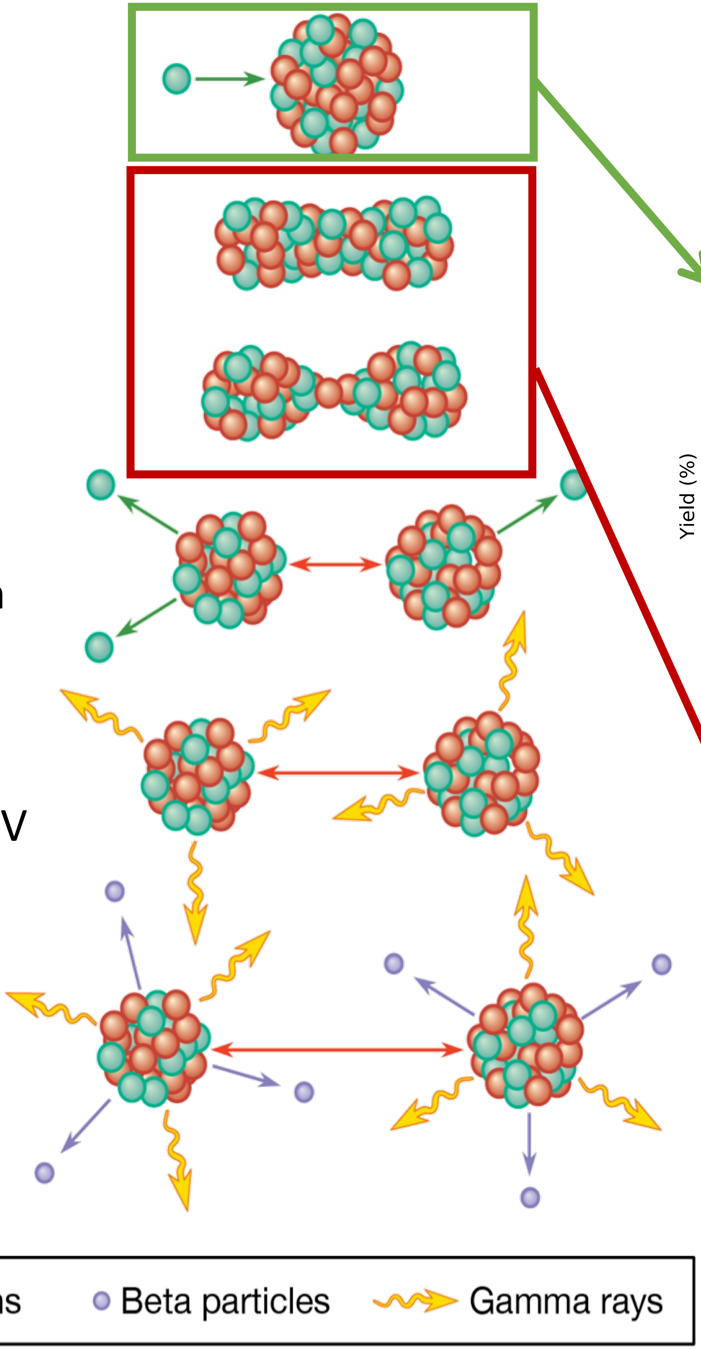
Deformation

Scission

Prompt Neutron Emission

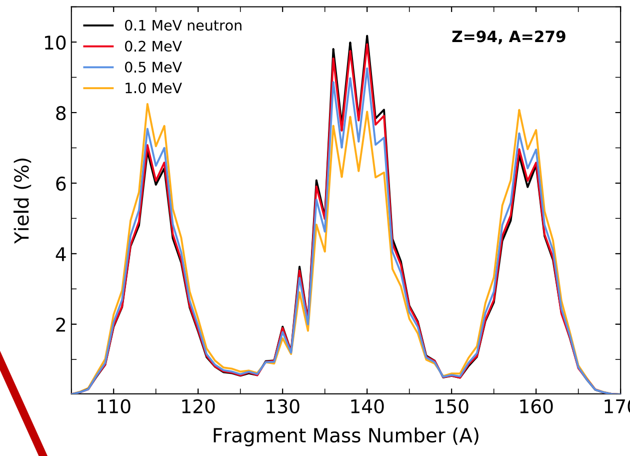
Energy release
Q~200 MeV, TKE~170 MeV

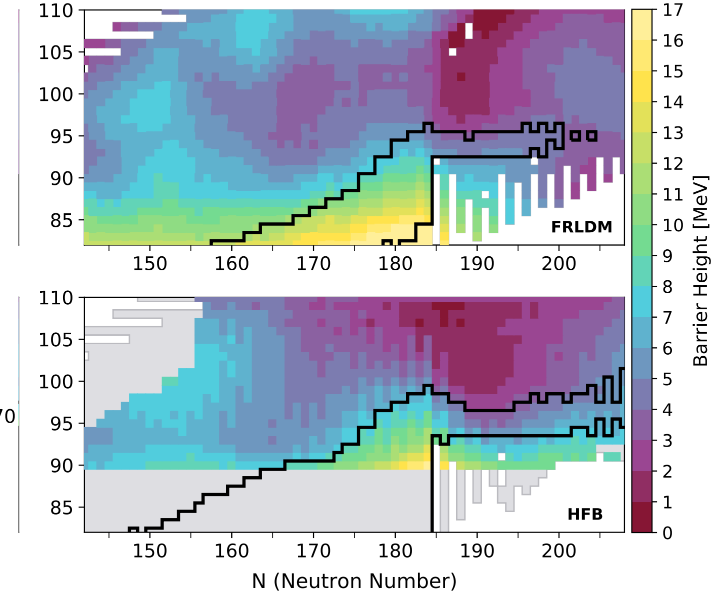
β-delayed emission from
n-rich fission products



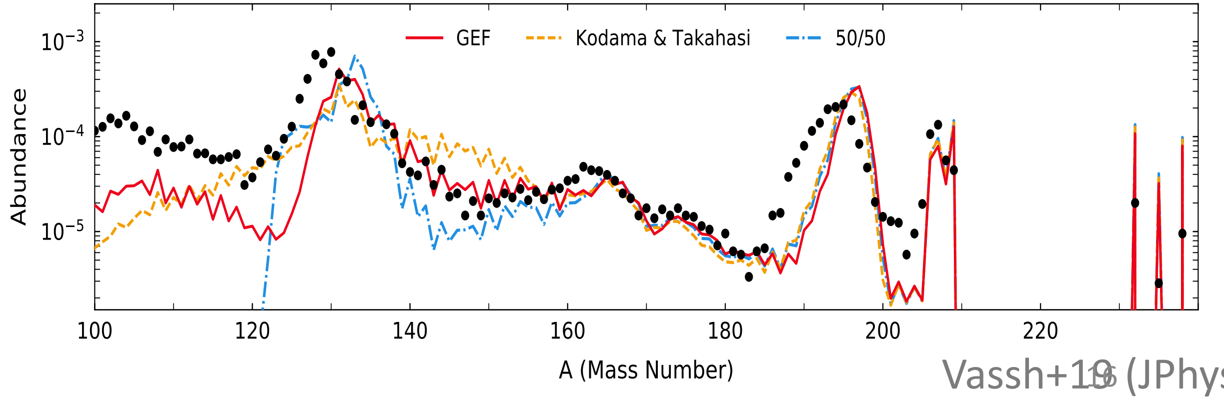
Credit: Nicole Vassh

Fission yields and **rates** depend on incident energy and barrier height ((n,f), βdf, sf distinct)





Predicted abundance dependence on yield model



Vassh+19 (JPhysG)

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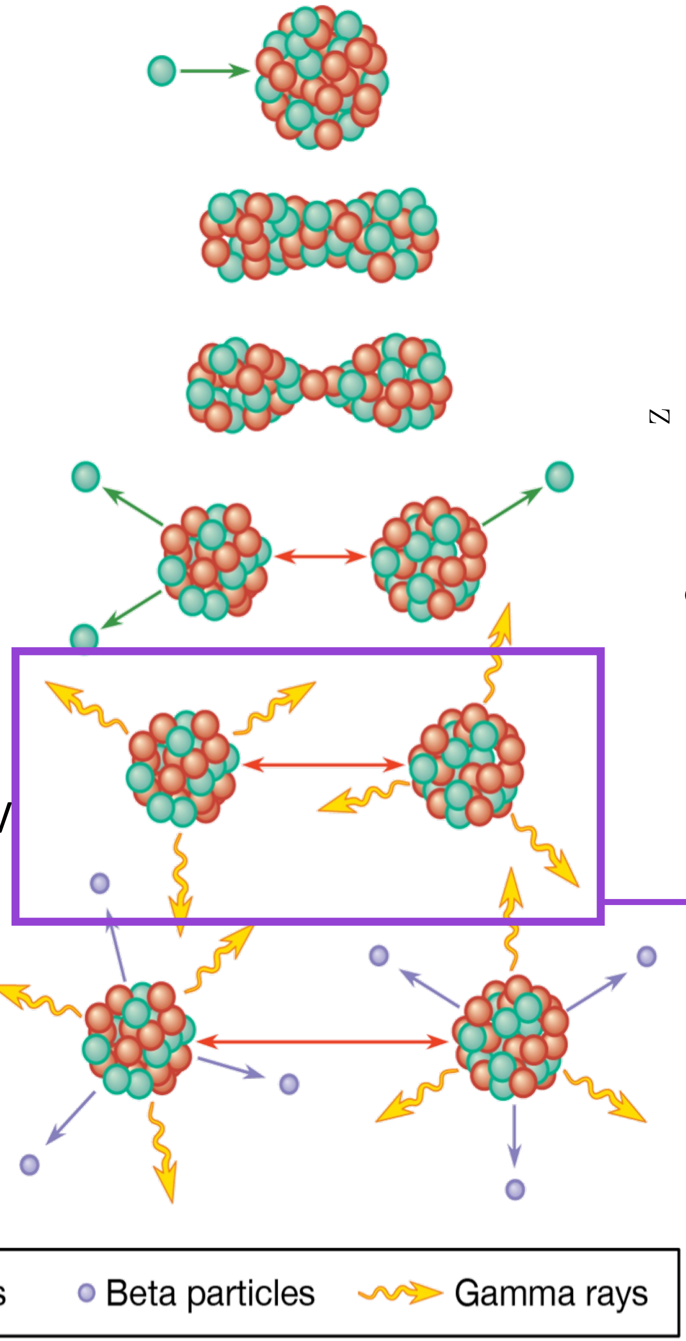
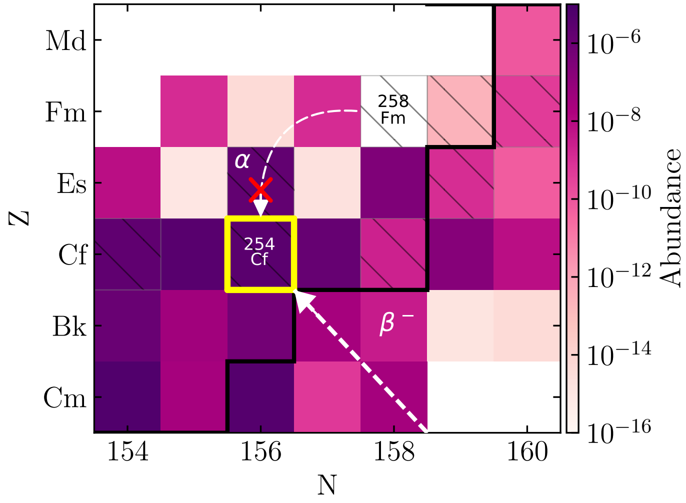
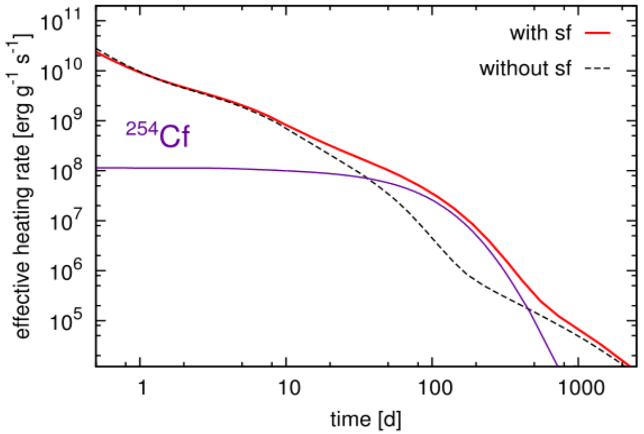


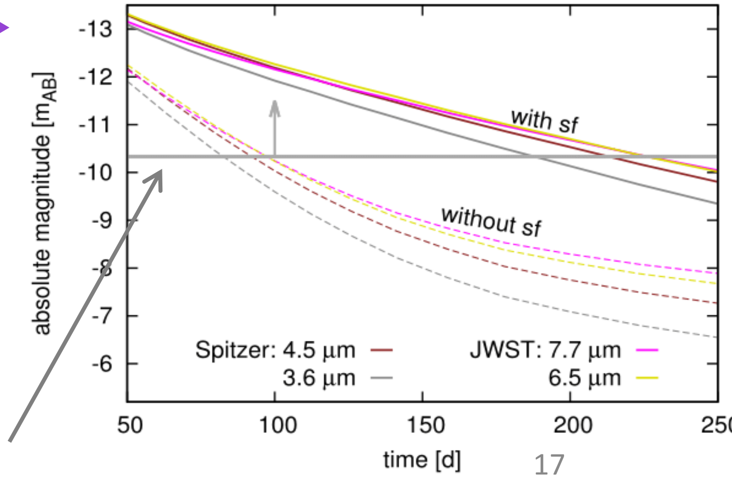
Credit: Nicole Vassh



Cf-254 has measured half-life ~60 days with SF branching 100%

Predicted **kilonova light curve** with and without late time Cf heating

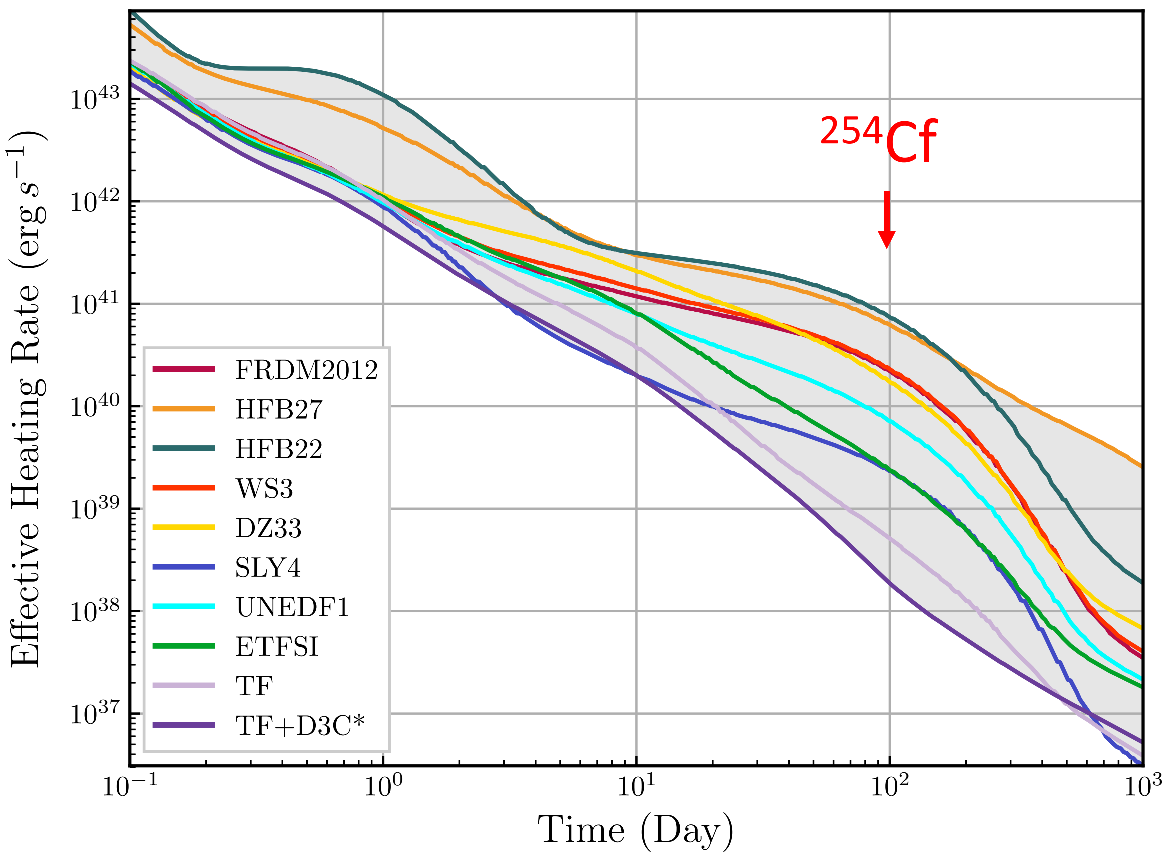




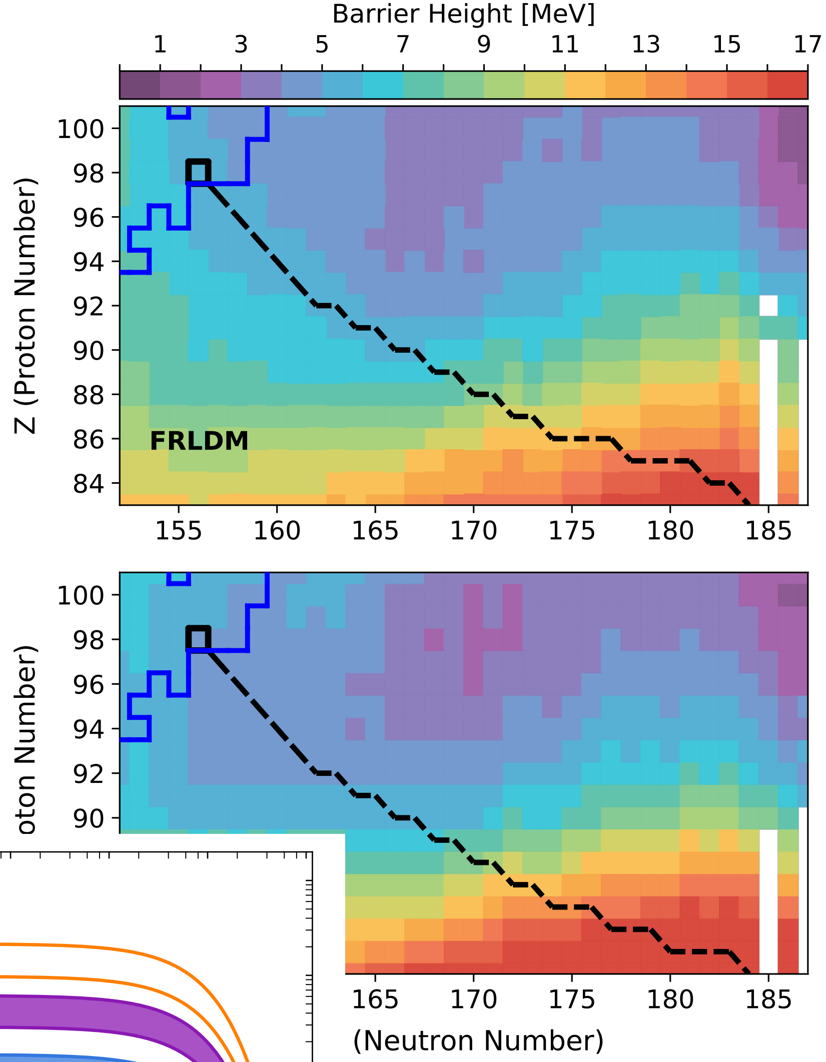
James Webb Space Telescope

Zhu+18 (including Vassh)(ApJ Letters)

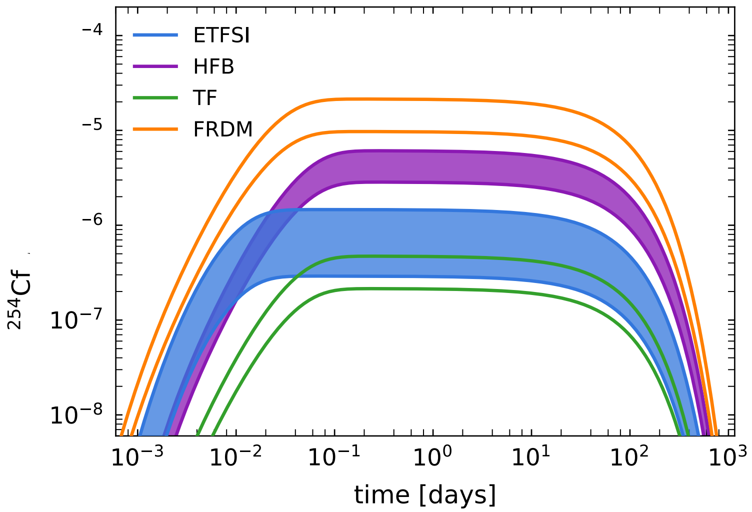
^{254}Cf: dependence on nuclear inputs



Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021



Vassh, Vogt, Surman, Randrup, Sprouse, Mumpower, Jaffke, Shaw, Holmbeck, Zhu, McLaughlin, 2018

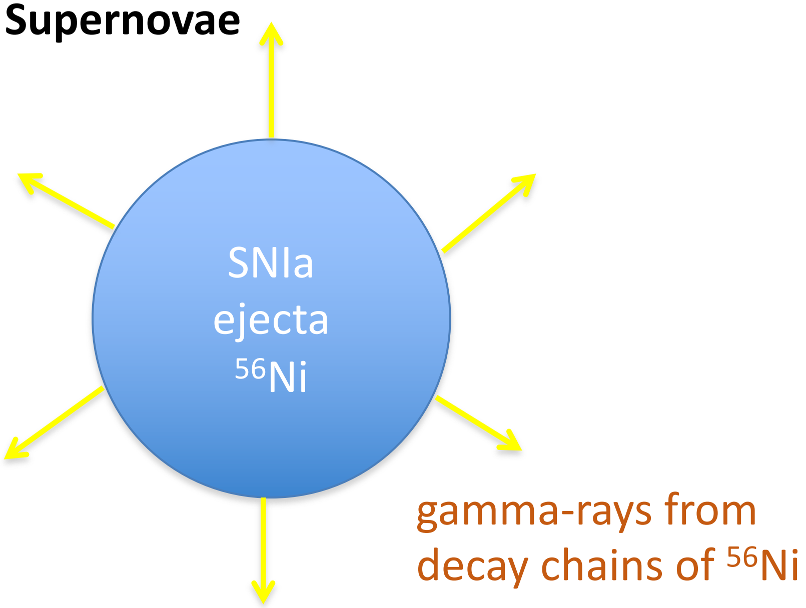


Credit: Rebecca Surman

Can we directly probe the heaviest elements made in NSMs?

Gamma rays from Neutron Star Mergers

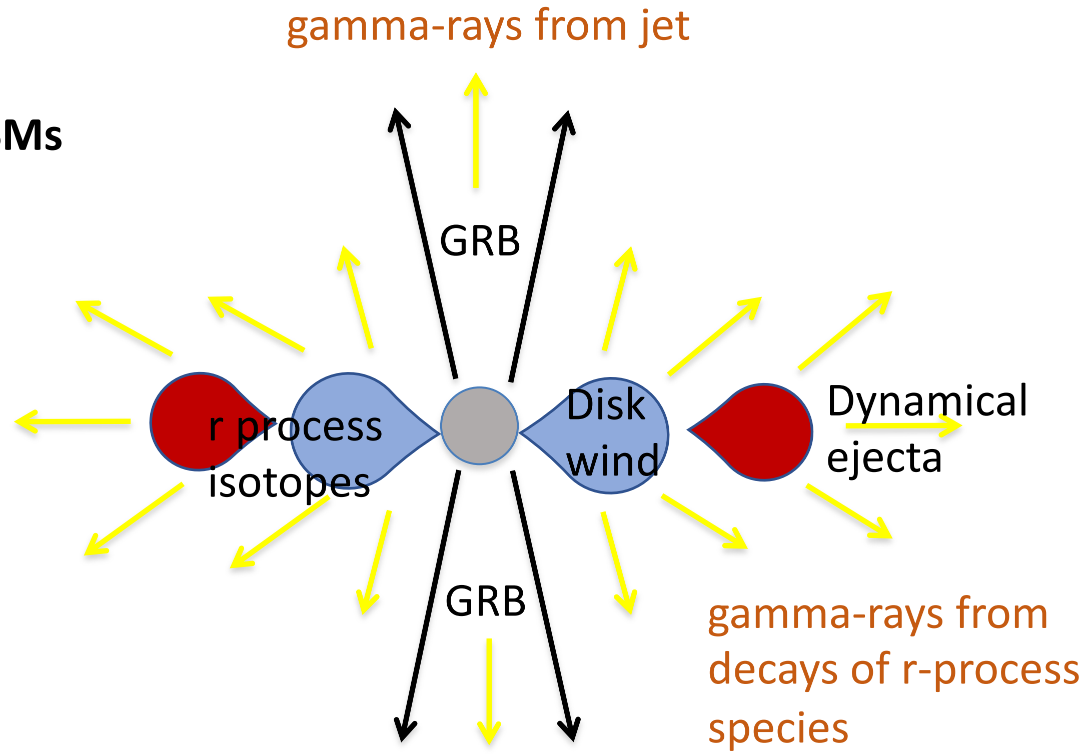
Type Ia Supernovae (SNIa)



$$^{56}Ni \xrightarrow{t_{mean}=8.8\,days} {}^{56}Co + \gamma$$

$$^{56}Co \xrightarrow{t_{mean}=111.3\,days} {}^{56}Fe + \gamma$$

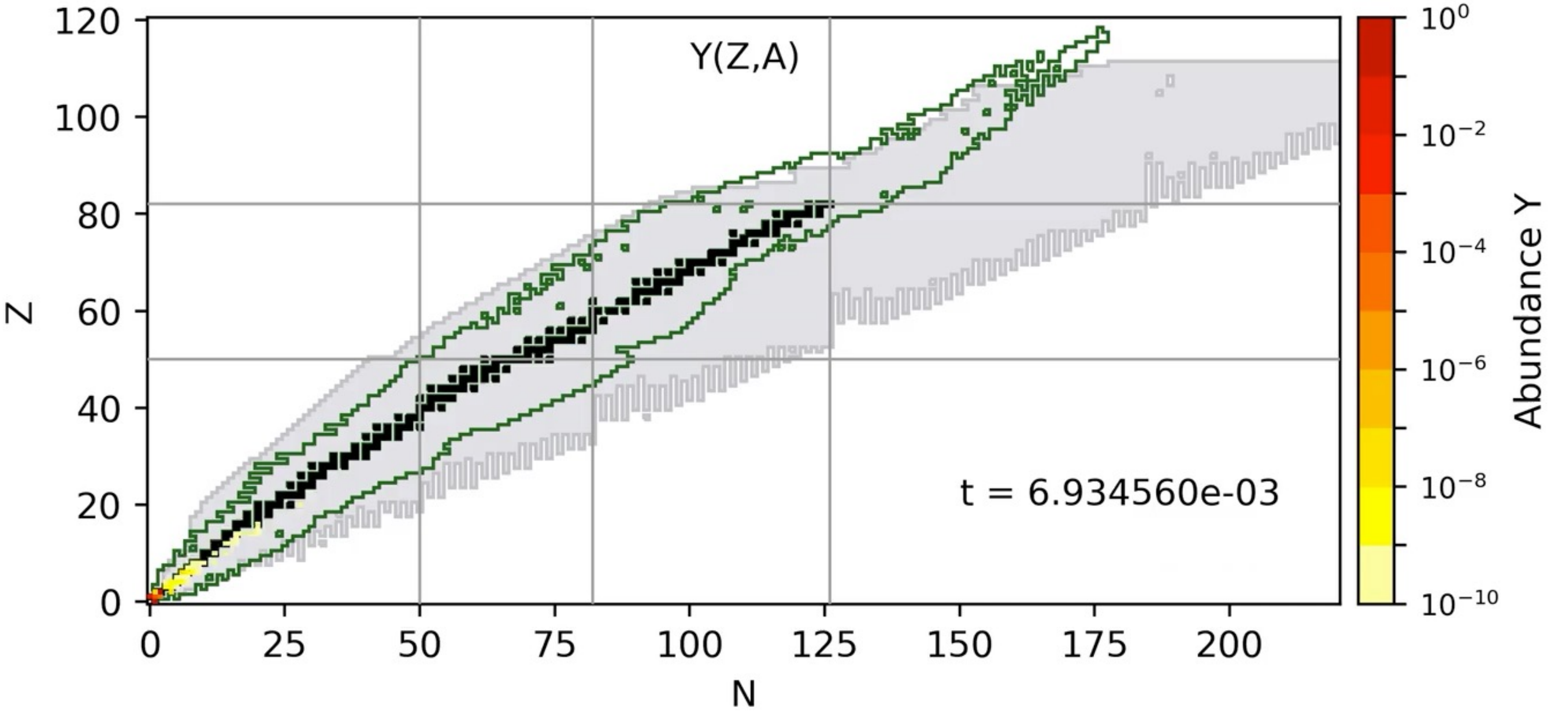
NSMs

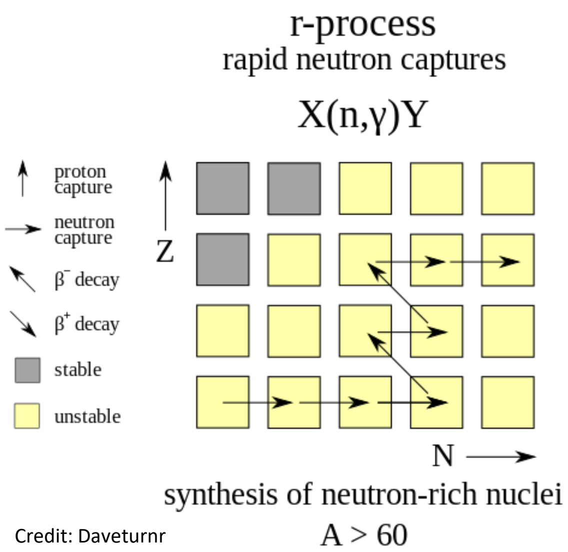


alpha decay, beta decay and nuclear fission

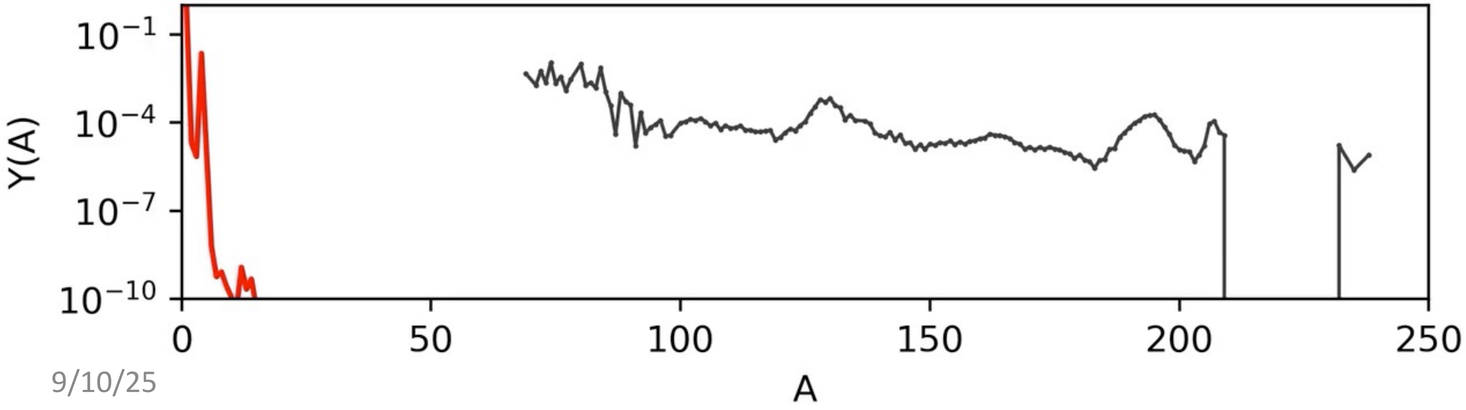
Wang, X., et al. 2020,
ApJL, 903, L3,
arXiv:2008.03335

r process nucleosynthesis simulation with PRISM





Credit: Daveturnr

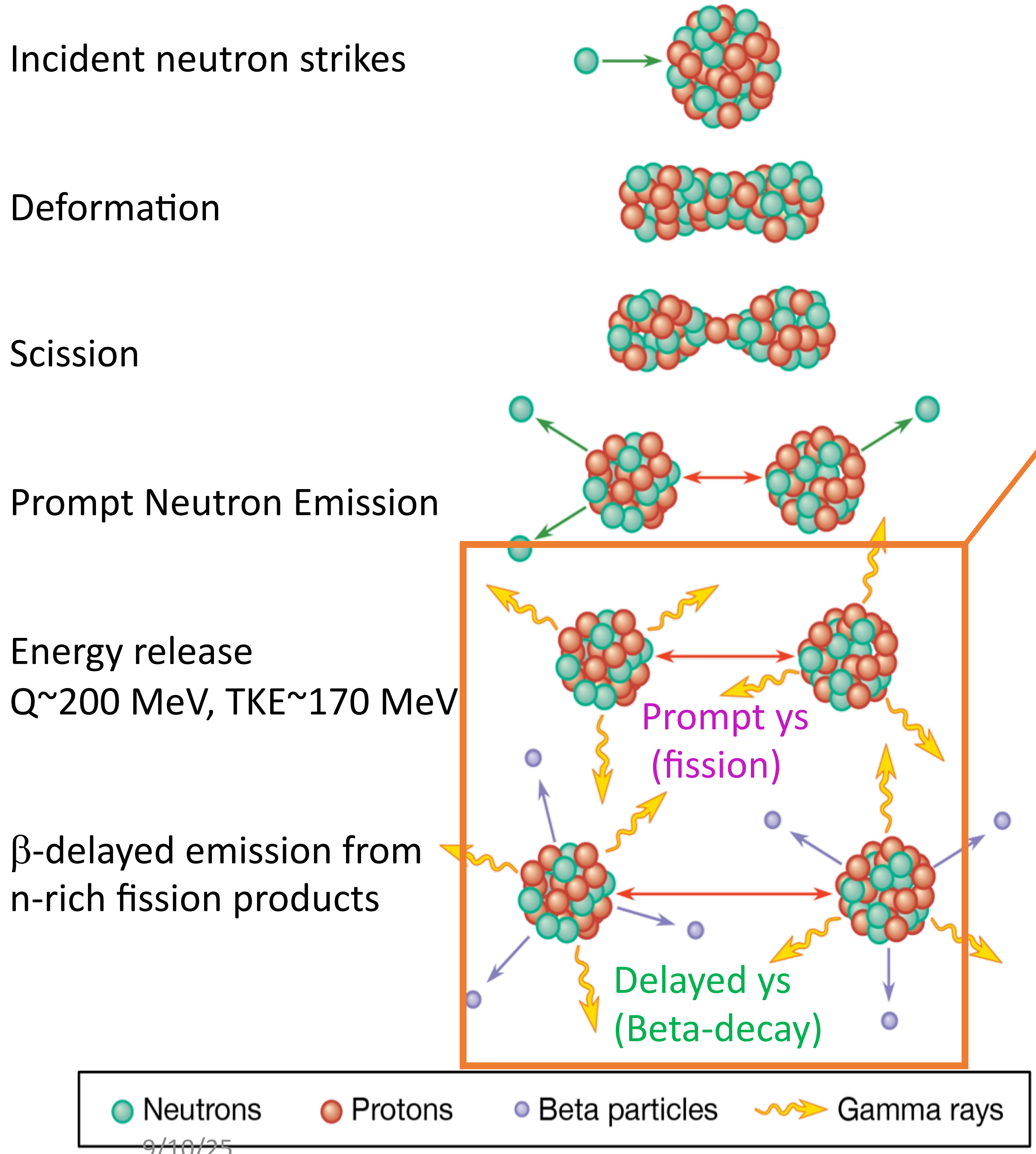


Cold, neutron-rich dynamical ejecta from an NSM event

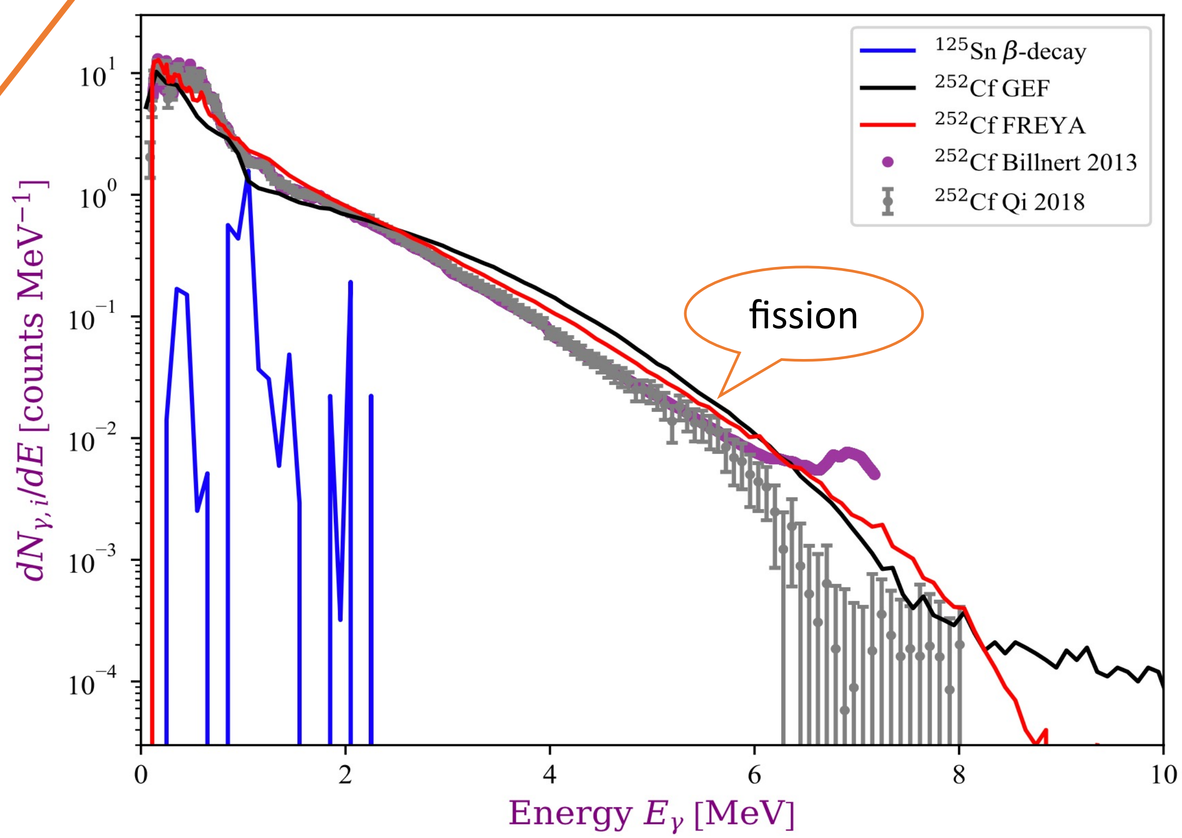
PRISM (**P**ortable **R**outines for **I**ntegrated nucleo**S**ynthesis **M**odeling): Trevor Sprouse (ND) & Matthew Mumpower (LANL)

Fission in astrophysical environments

Gammas > 3.5 MeV: signature of prompt and delayed **fission gammas** in an astrophysical event!



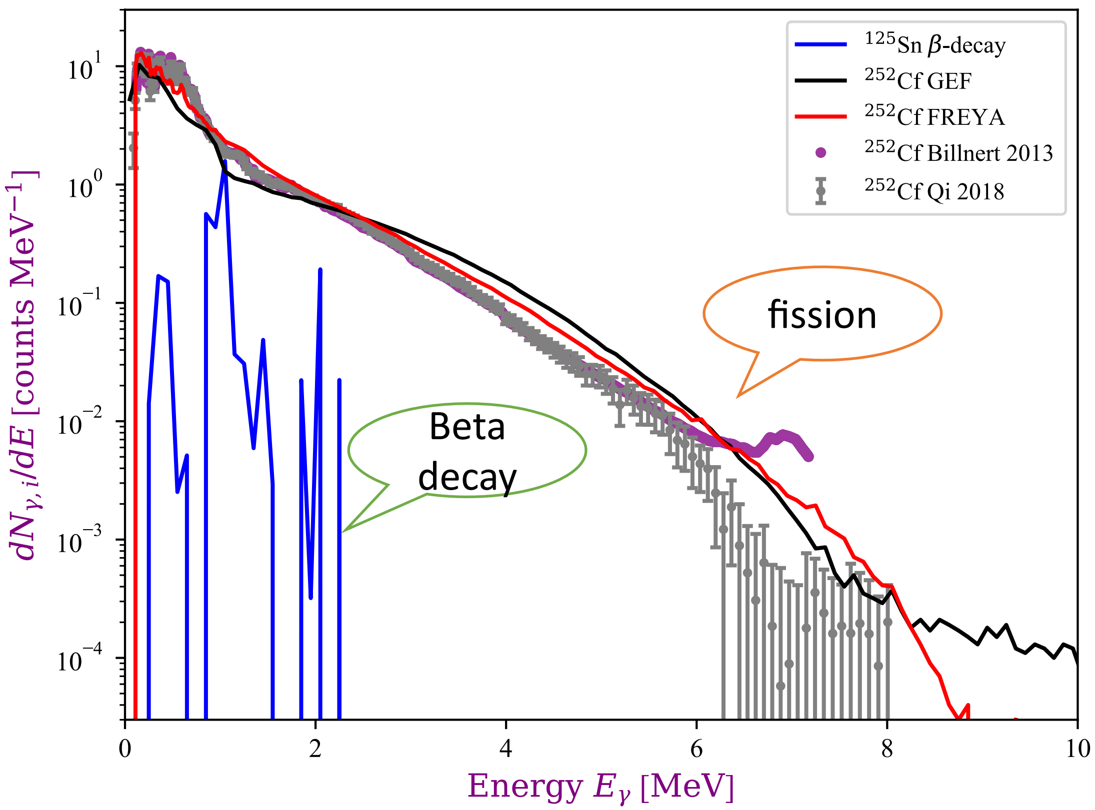
Credit: Nicole Vassh



Wang, X., et al. 2020, ApJL, 903, L3,

Prompt gamma-ray spectra from r process

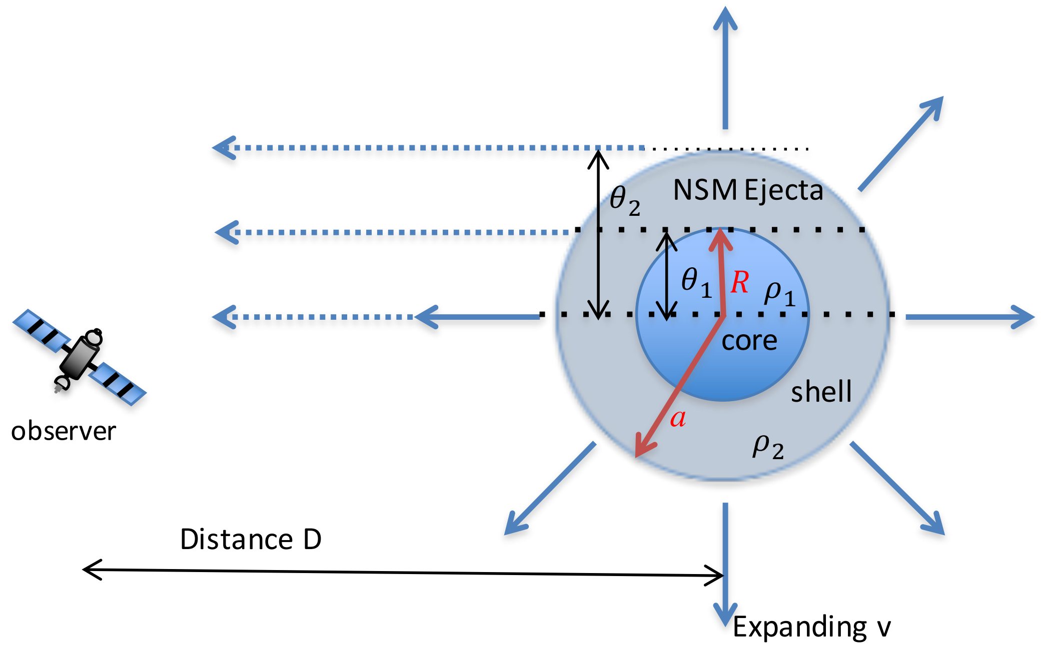
- Prompt gamma-ray photons emitted from r-process:
  - Beta decays, experimental data from ENDF/B-VIII.03 (Brown et al. 2018), theoretical calculations from LANL work (Korobkin et al., 2020)
  - Fission, theoretical calculation from GEF (Schmidt et al. 2016) and FREYA (Vogt & Randrup 2017) as in Vassh et al., 2019.

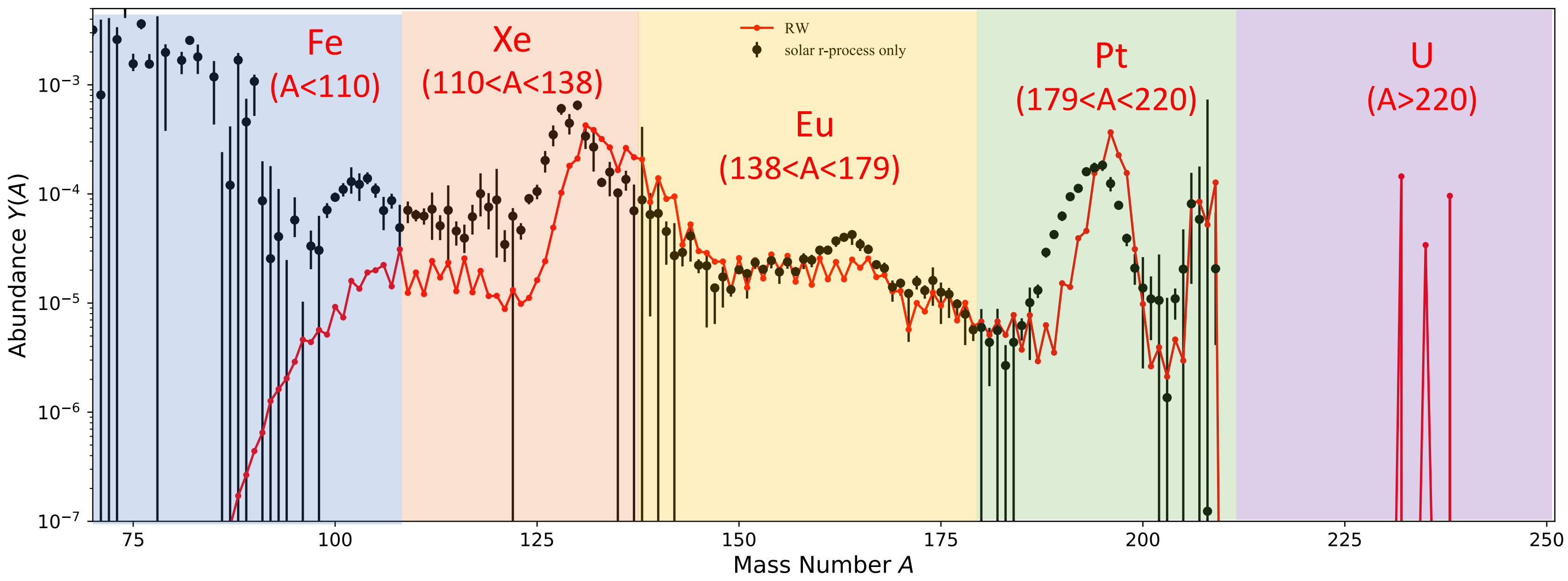


Wang, X., et al. 2020, ApJL, 903, L3,

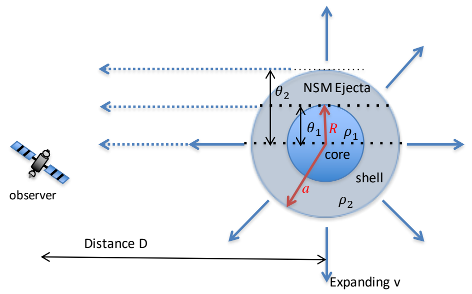
Radiation transfer calculation

- Semi-analytical gamma-ray radiation transfer calculation adapted from Wang, X., et al 2019, MNRAS, 486, 2910
- Opacity calculation based on the ejecta composition; NIST XCOM Photon Cross Sections Database: opacity for individual element
- radiation transfer interactions include: Rayleigh scattering, Compton scattering, photoelectric absorption, and pair production

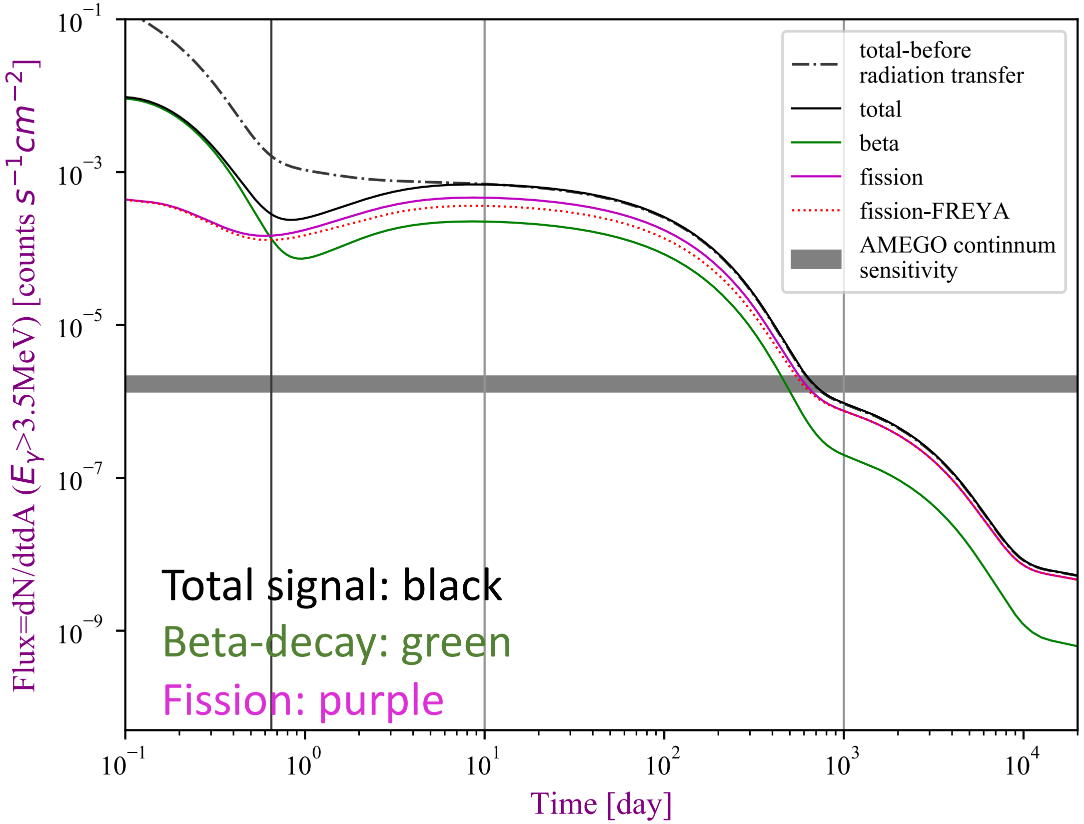


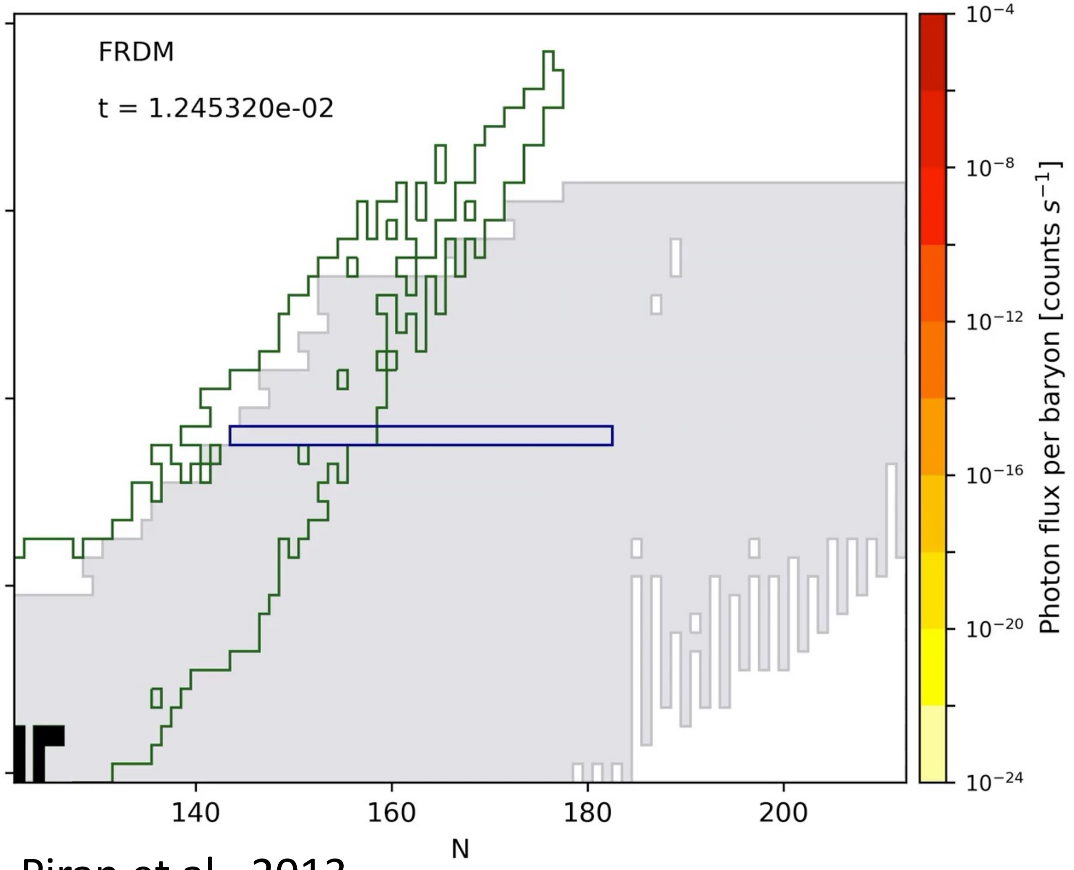


MeV light curve and contributions from individual fissioning nuclei



Flux at $E_\gamma > 3.5 MeV$

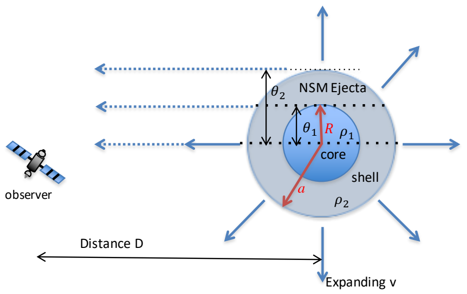




Very neutron rich dynamical ejecta from Rosswog et al., 2013, Piran et al., 2013.
Nuclear data based on FRDM and FRLDM nuclear models

Wang, X., et al. 2020 , ApJL, 903, L3, arXiv:2008.03335

Variations on neutron-richness (Y_e) and the actinide production



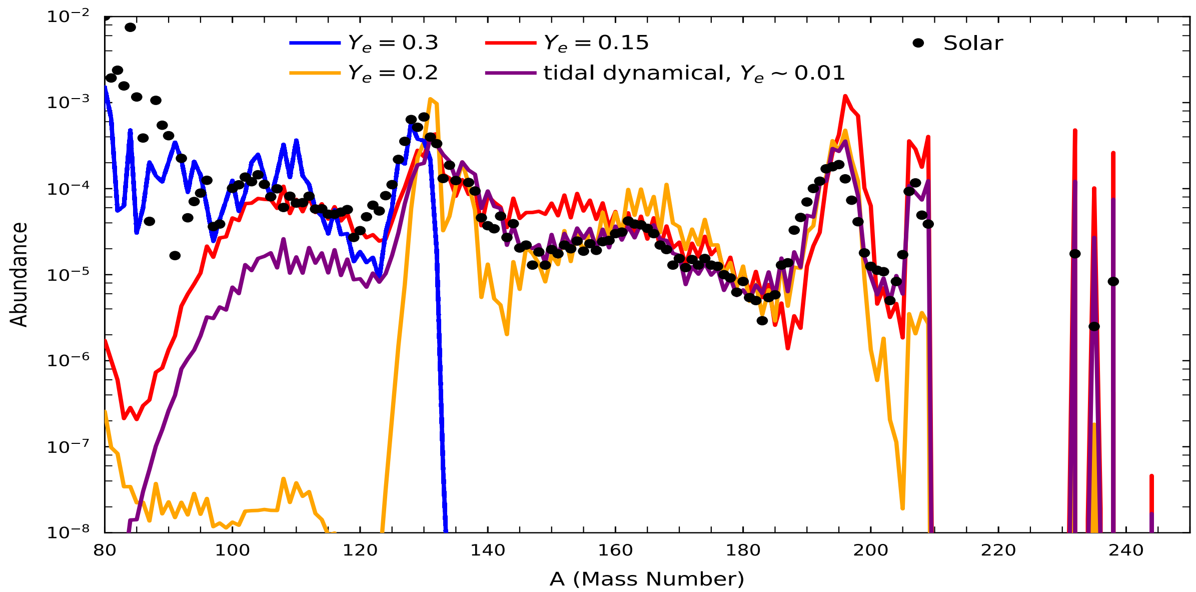
$$Y_e = \frac{n_e}{n_b} = 1 - \frac{n_n}{n_n + n_p} \sim 0.015$$

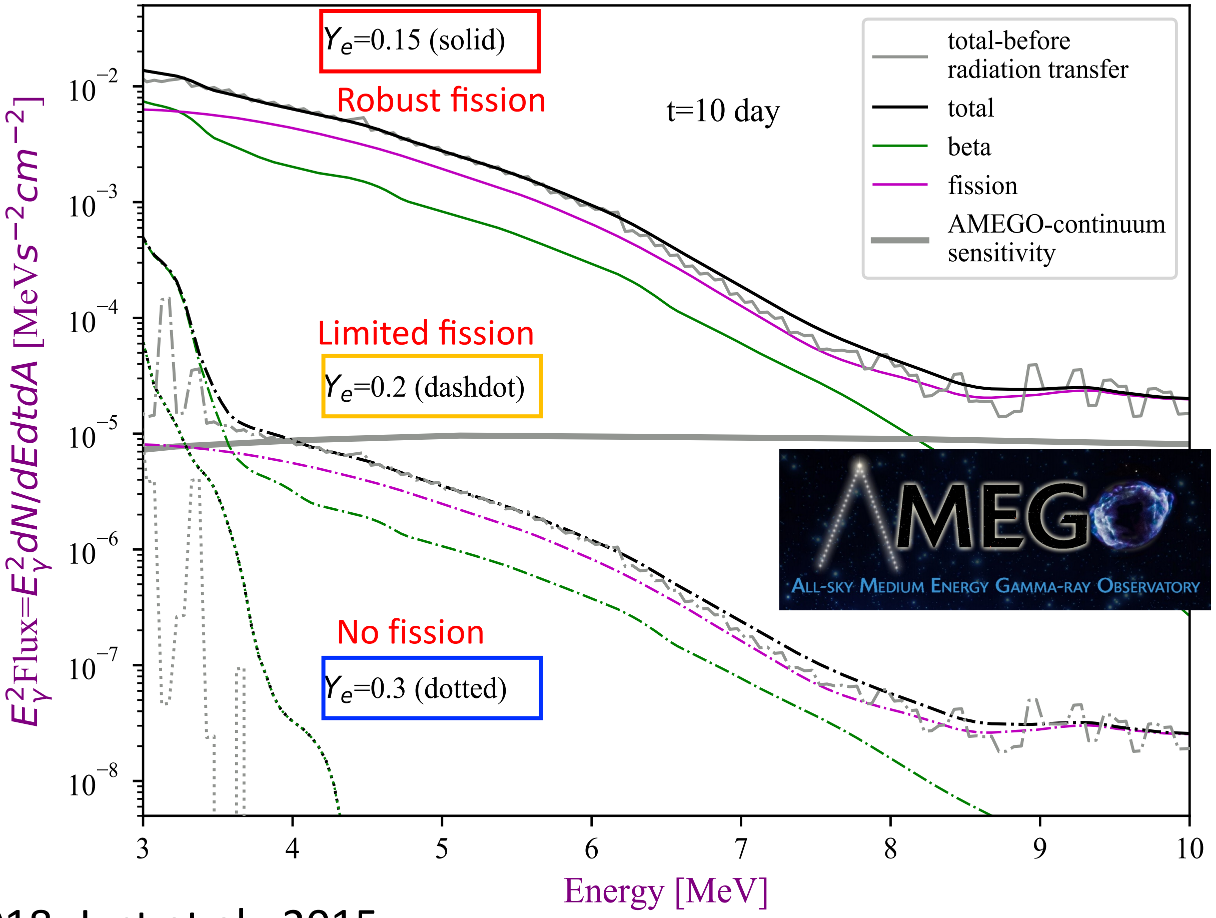
Smaller Y_e: more neutron rich

Total signal: black

Beta-decay: green

Fission: purple



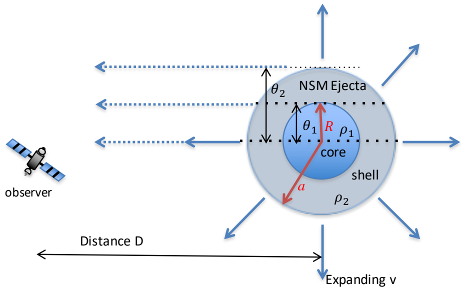


Low entropy parameterized outflow found in Radice et al., 2018, Just et al., 2015.

Nuclear data based on FRDM and FRLDM nuclear models

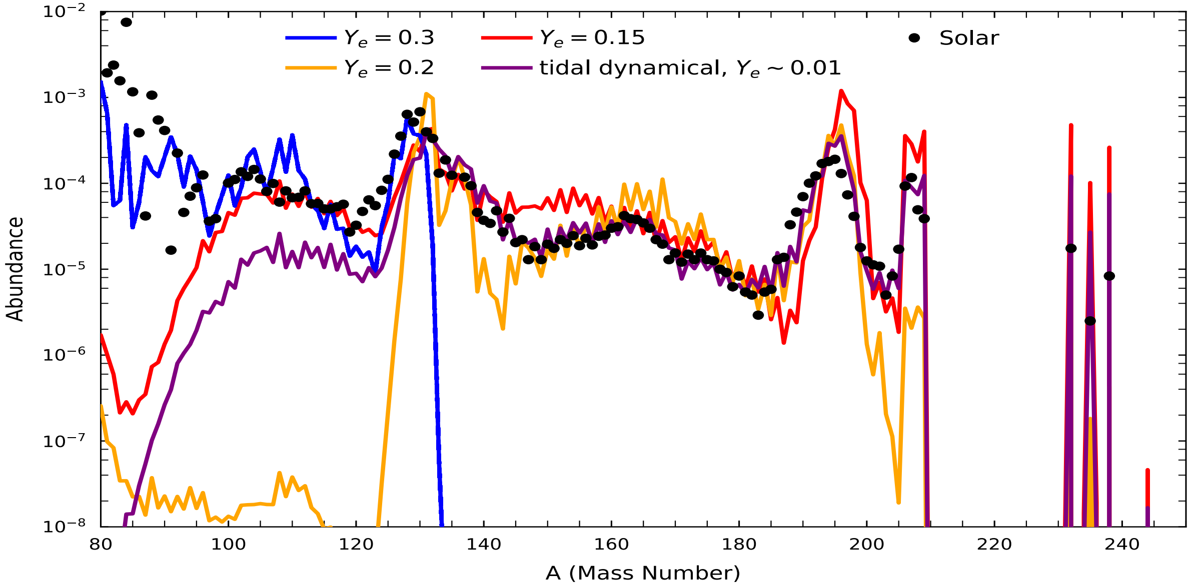
Wang, X., et al. 2020 , ApJL, 903, L3, arXiv:2008.03335

Variations on neutron-richness (Y_e) and the actinide production



$$Y_e = \frac{n_e}{n_b} = 1 - \frac{n_n}{n_n + n_p} \sim 0.015$$

Smaller Y_e: more neutron rich

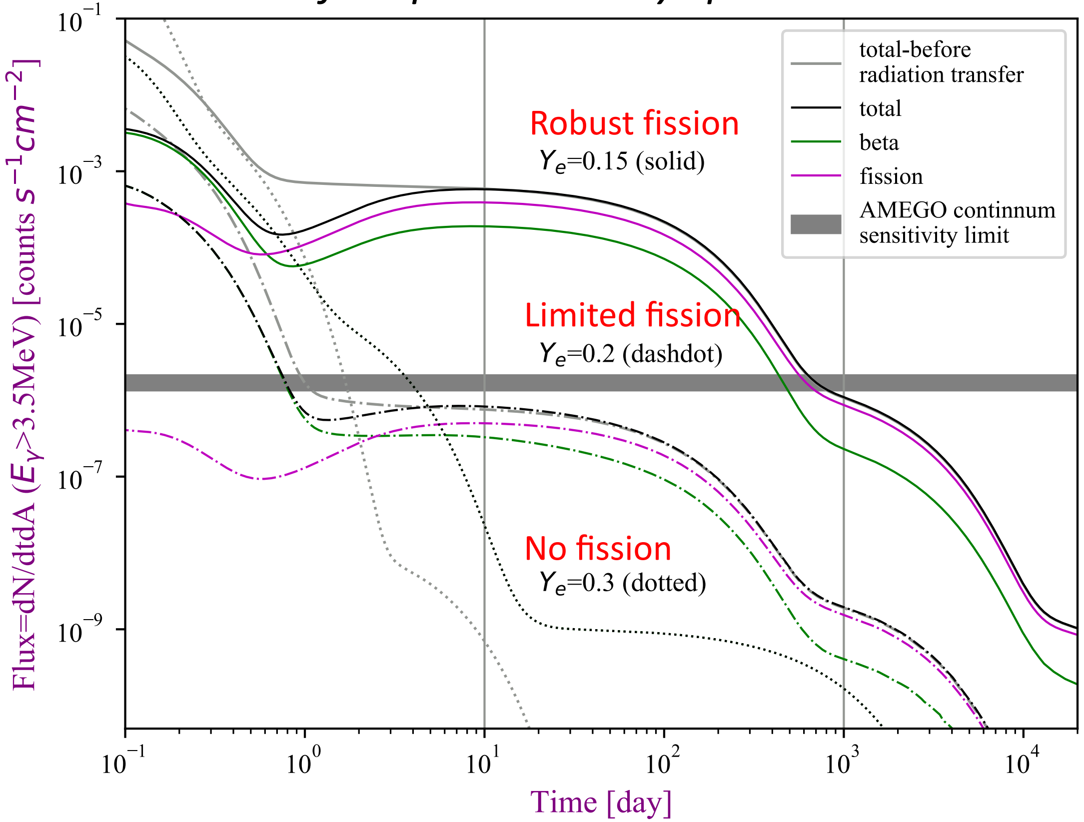


Total signal: black

Beta-decay: green

Fission: purple

Visible for up to 1000 days post-event

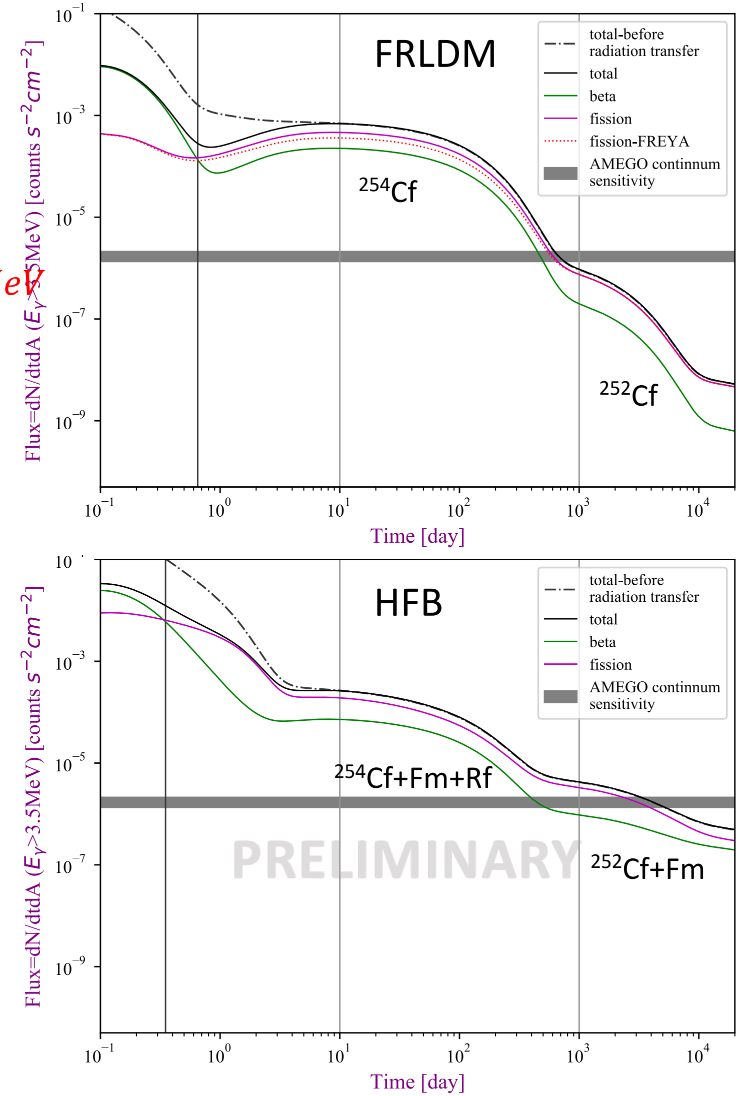


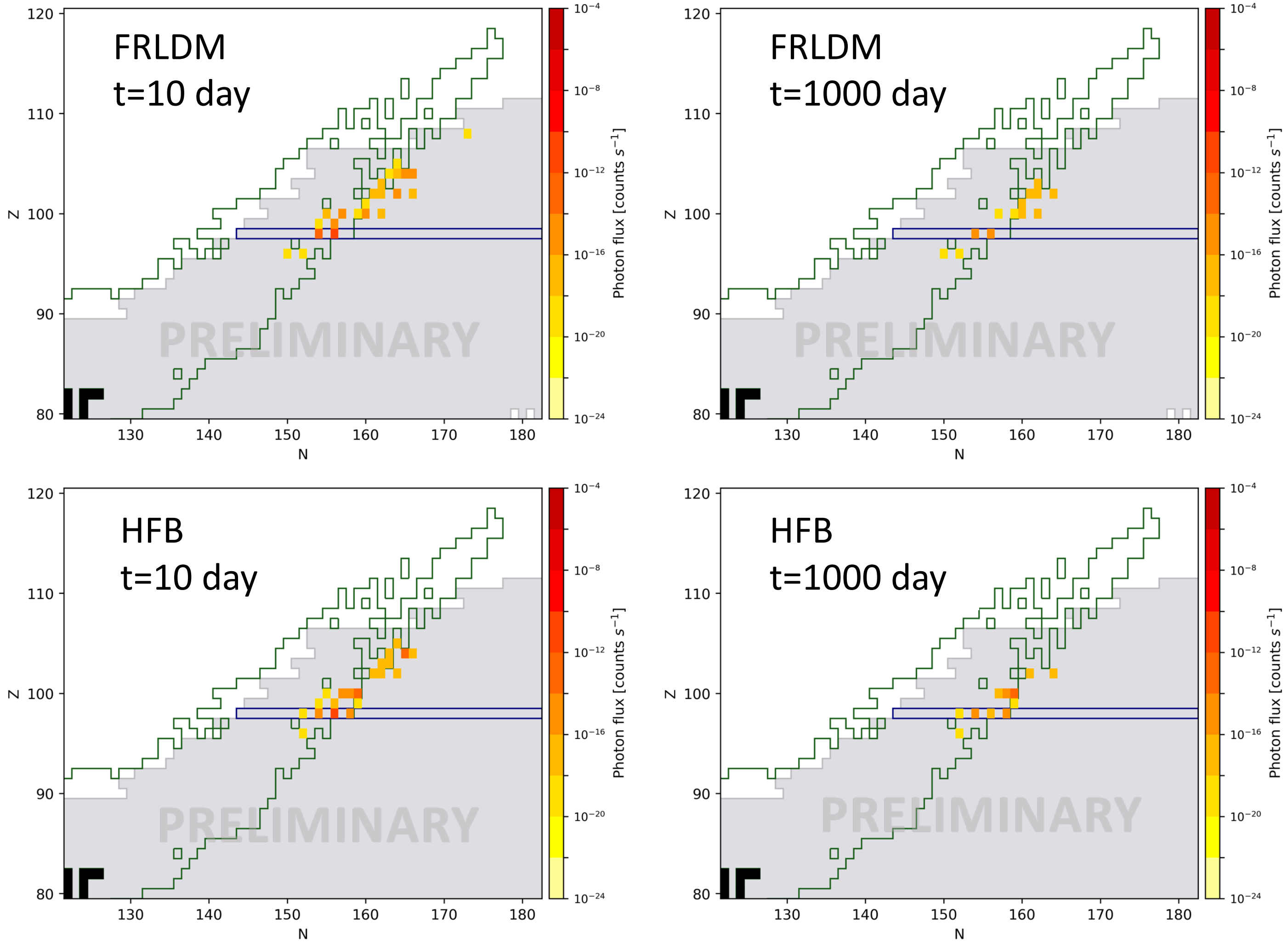
Low entropy parameterized outflow found in Radice et al., 2018, Just et al., 2015.
Nuclear data based on FRDM and FRLDM nuclear models

Wang, X., et al. 2020 , ApJL, 903, L3, arXiv:2008.03335

Variations on nuclear models: fission barriers

Flux at $E_\gamma > 3.5MeV$

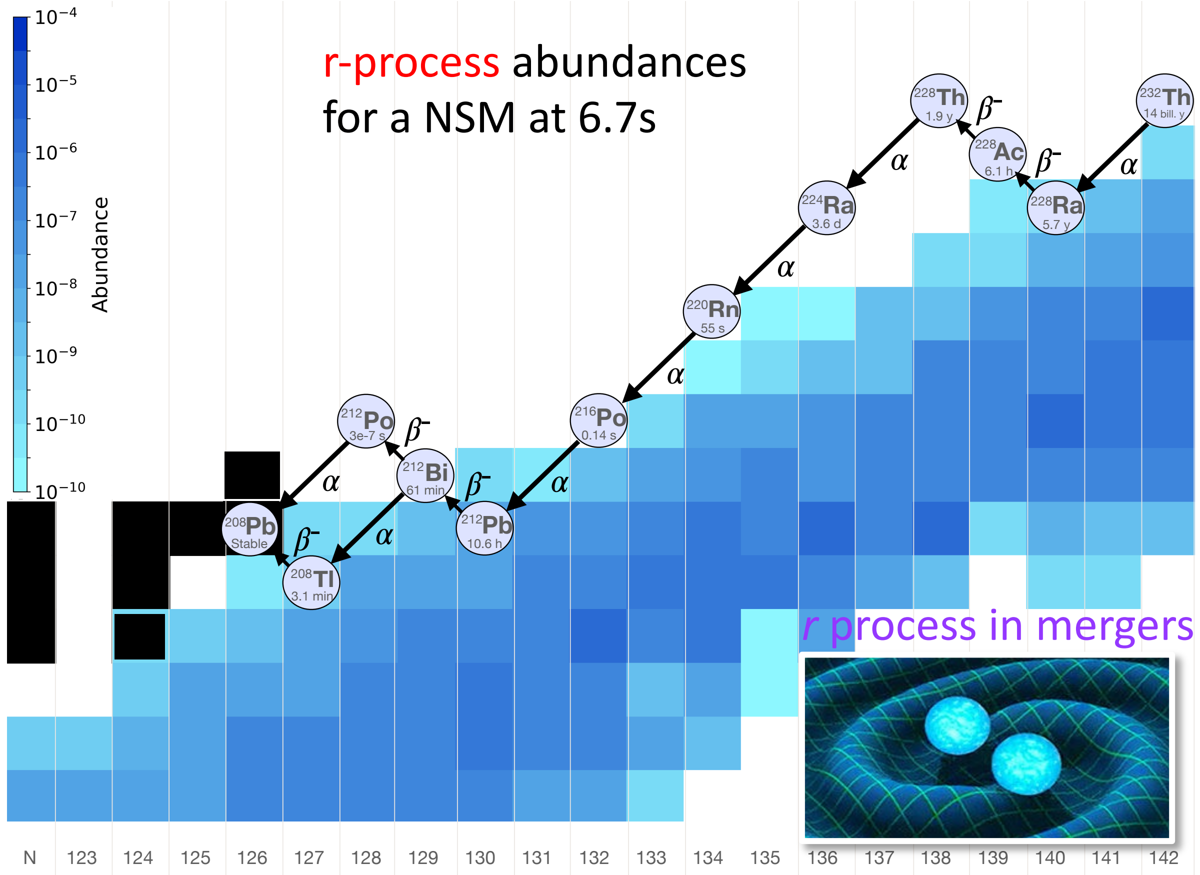


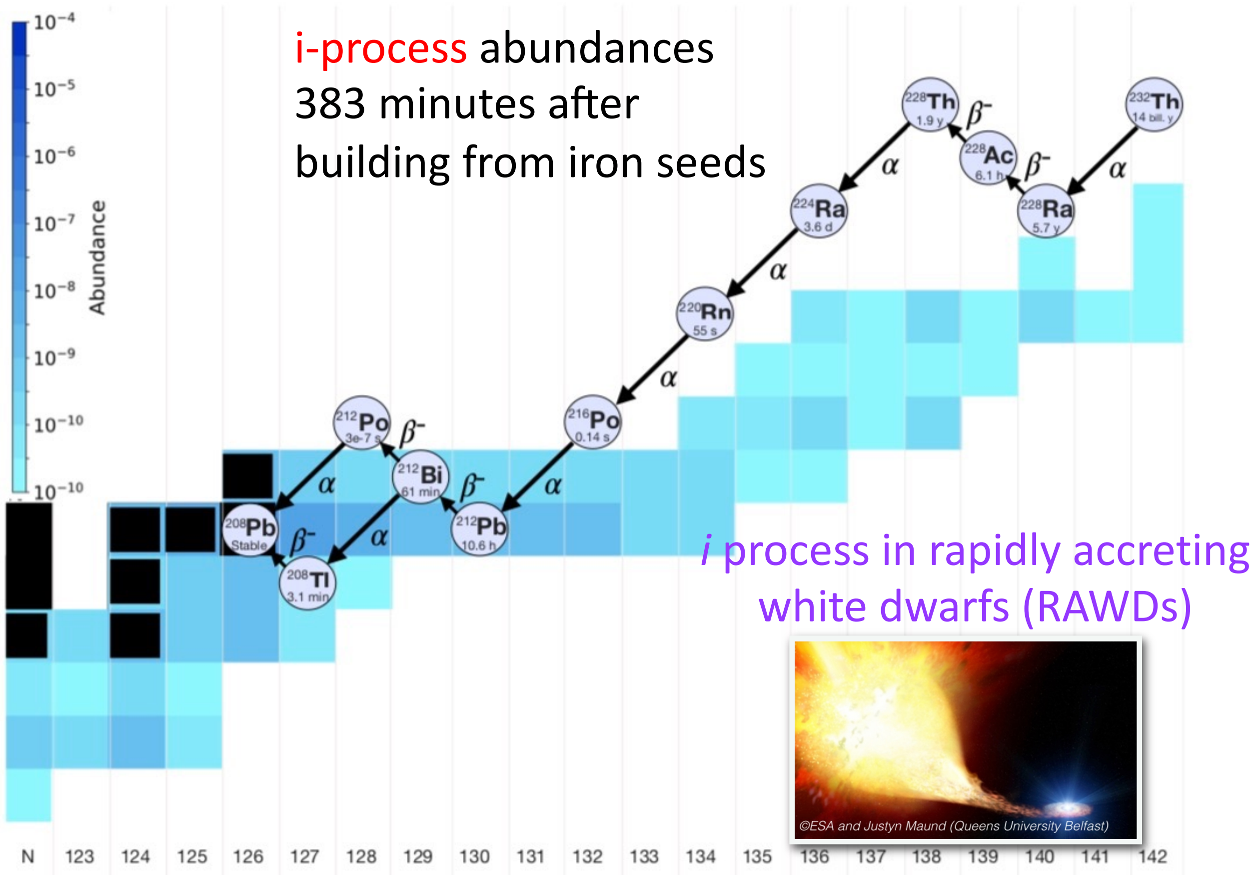


Very neutron rich dynamical ejecta from Rosswog et al., 2013, Piran et al., 2013.
Nuclear data based on FRDM and FRLDM nuclear models, and HFB nuclear models

Wang, X., Vassh, N., et al., 2025, in prep

Thallium-208: A Beacon of In Situ Neutron Capture Nucleosynthesis

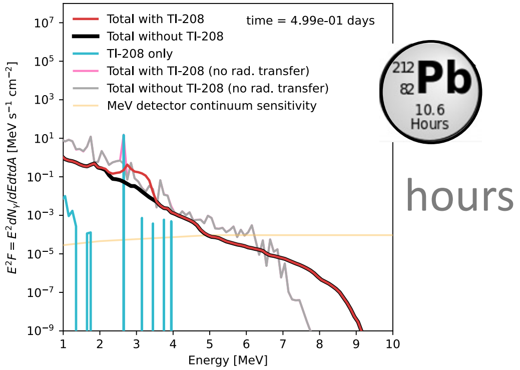


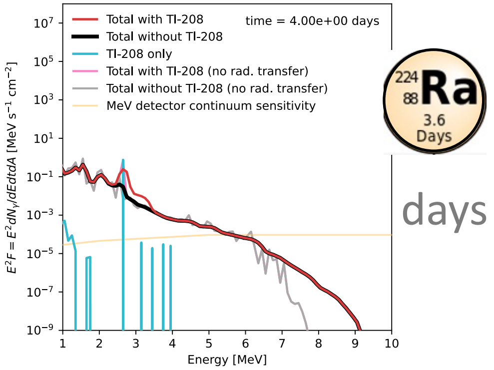


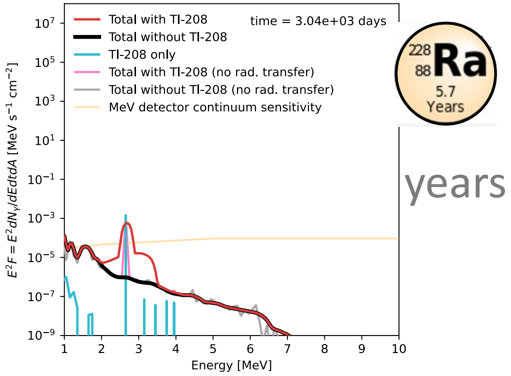
neutron capture processes can populate species along the well-known Th-232 decay chain → yielding Tl-208;
Detection of Tl-208 represents the only identified prospect for a direct signal of lead production (implying 3rd r-process peak synthesis like gold) in a real-time event.

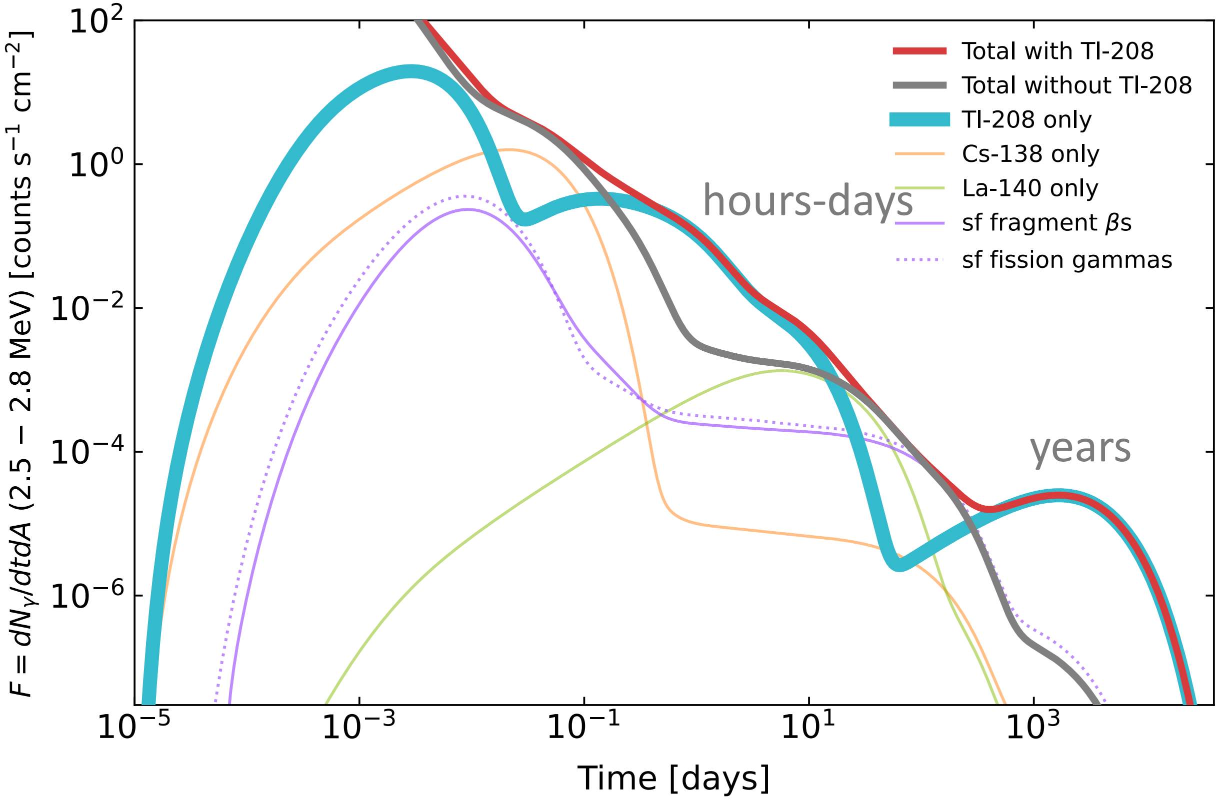
Vassh, N., **Wang, X.**, et al., 2024, PRL, 132, 052701
arXiv:2311.10895

Comparison with other nuclei with decays emitting in the 2.5-2.8 MeV energy range









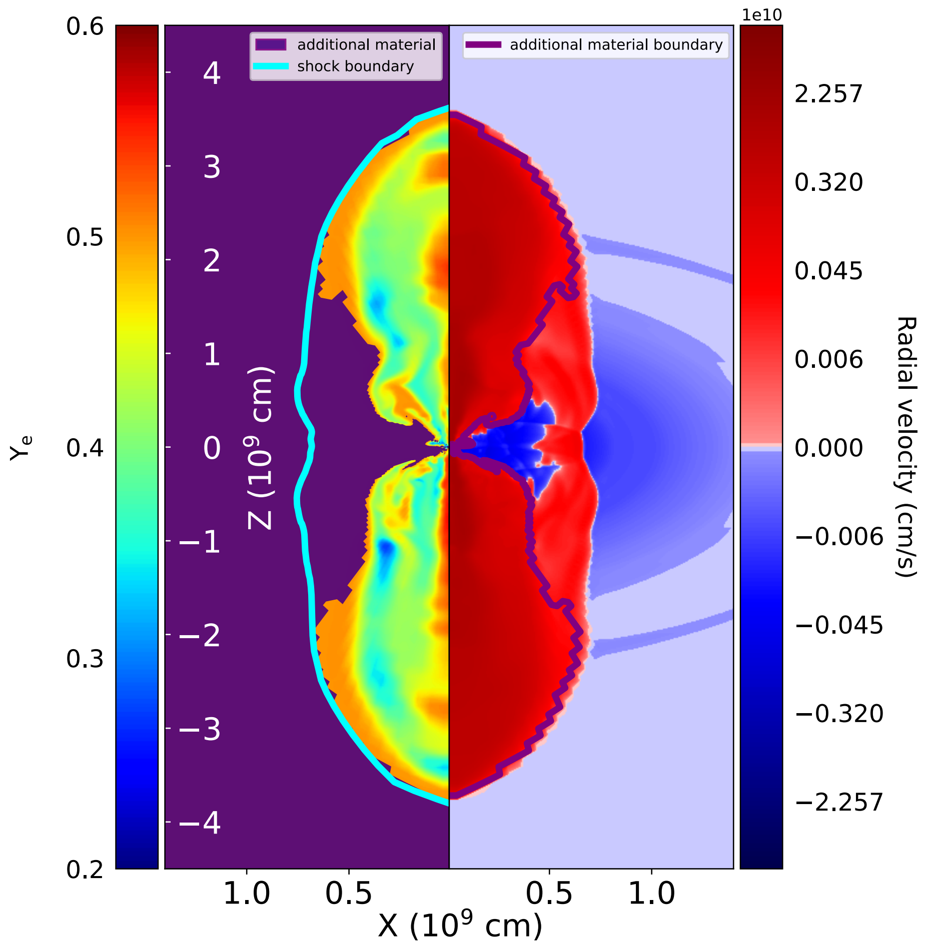
➢the 2.6 MeV Tl-208 line explicitly show itself in the spectrum at the timescales: ~12hours - ~10days (after Tl is populated by Pb-212 and Ra-224 decays); 1-20 years (Ra-228 decays);

➢Next generation MeV gamma-ray detectors will be able to detect the Tl-208 lines from NSM in Milky Way or nearby galaxies at these timescales.

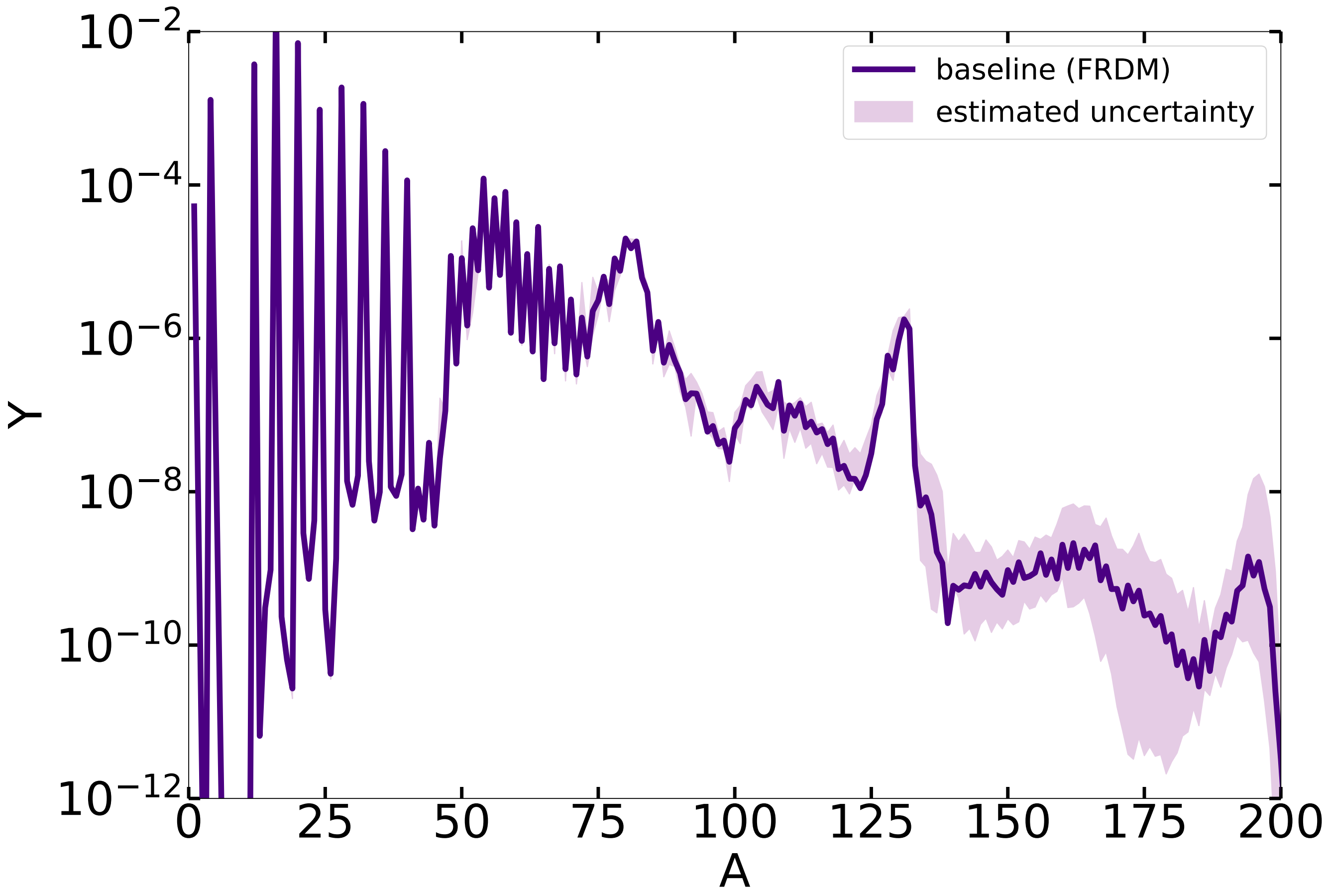
Very neutron rich dynamical ejecta from Rosswog et al., 2013, Piran et al., 2013.
Nuclear data based on FRDM and FRLDM nuclear models

Vassh, N., **Wang, X.**, et al., 2024, PRL, 132, 052701

MeV gamma-ray from rare supernovae with r-process

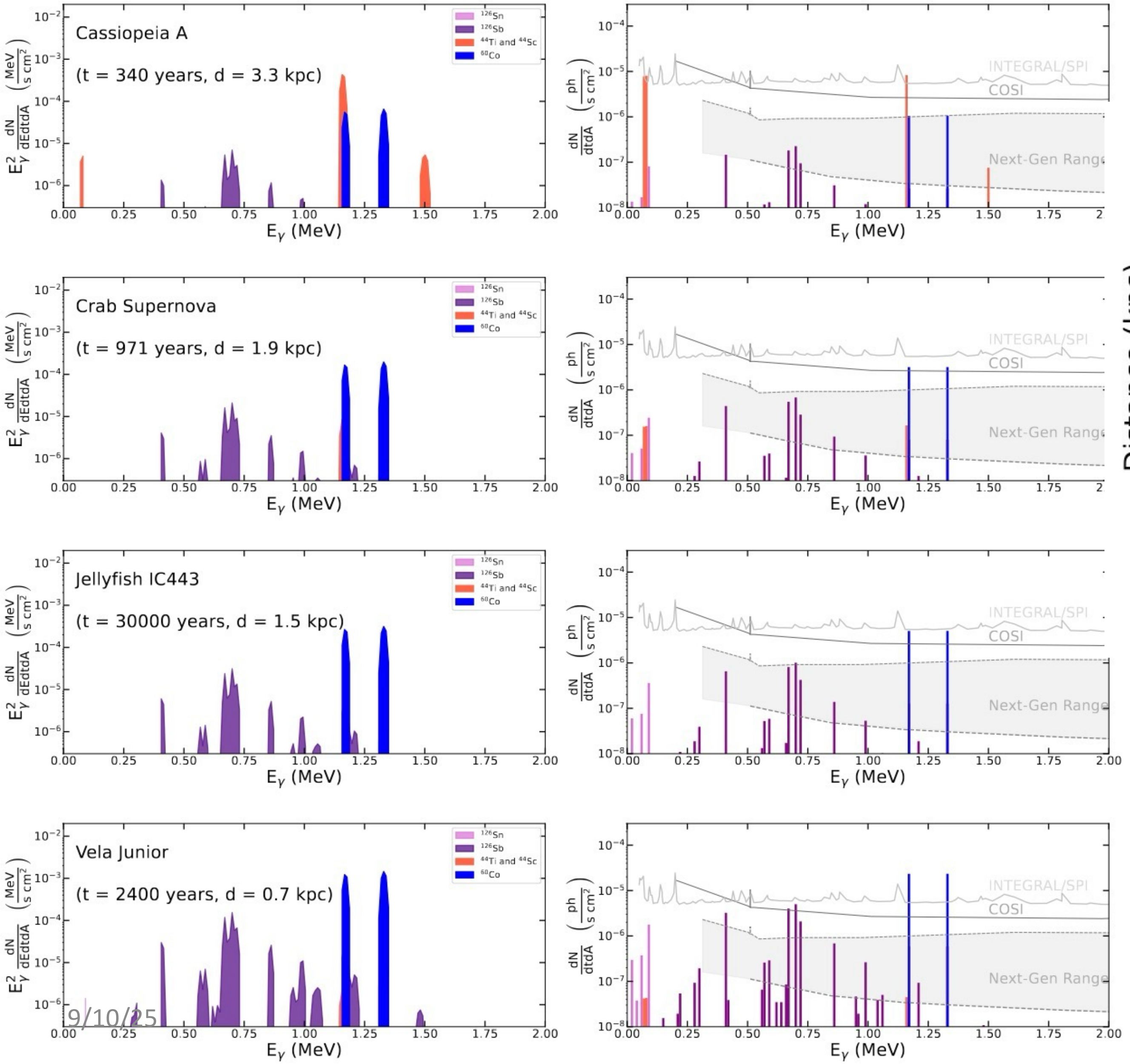


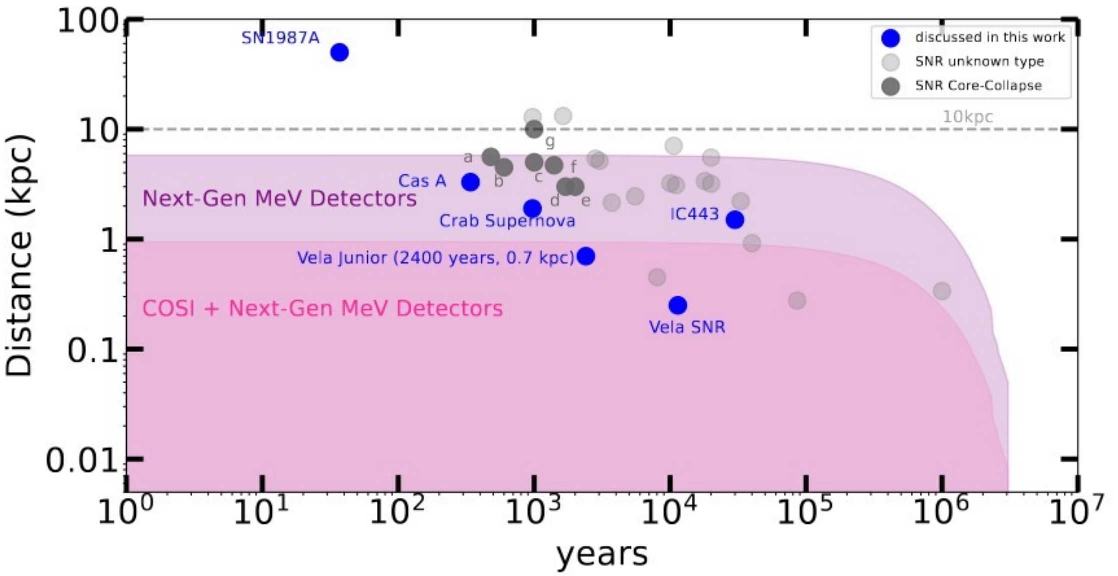
Snapshot of the MR-SN model 35OC-RS from Reichert et al. (2021) at the end of the simulation time (1.306 s).



(Liu, Z., et al., 2025, *submitted to ApJ*)

MeV gamma-ray from rare supernovae with r-process





Observability of ^{126}Sb 666 keV line with COSI and next-generation MeV telescopes if a supernova remnant originated from a rare magneto-rotational-SN with r-process occurs.

(Liu, Z., et al., 2025, *submitted to ApJ*)

An important astrophysical conditions that affect the heavy-element abundance yields: neutrinos

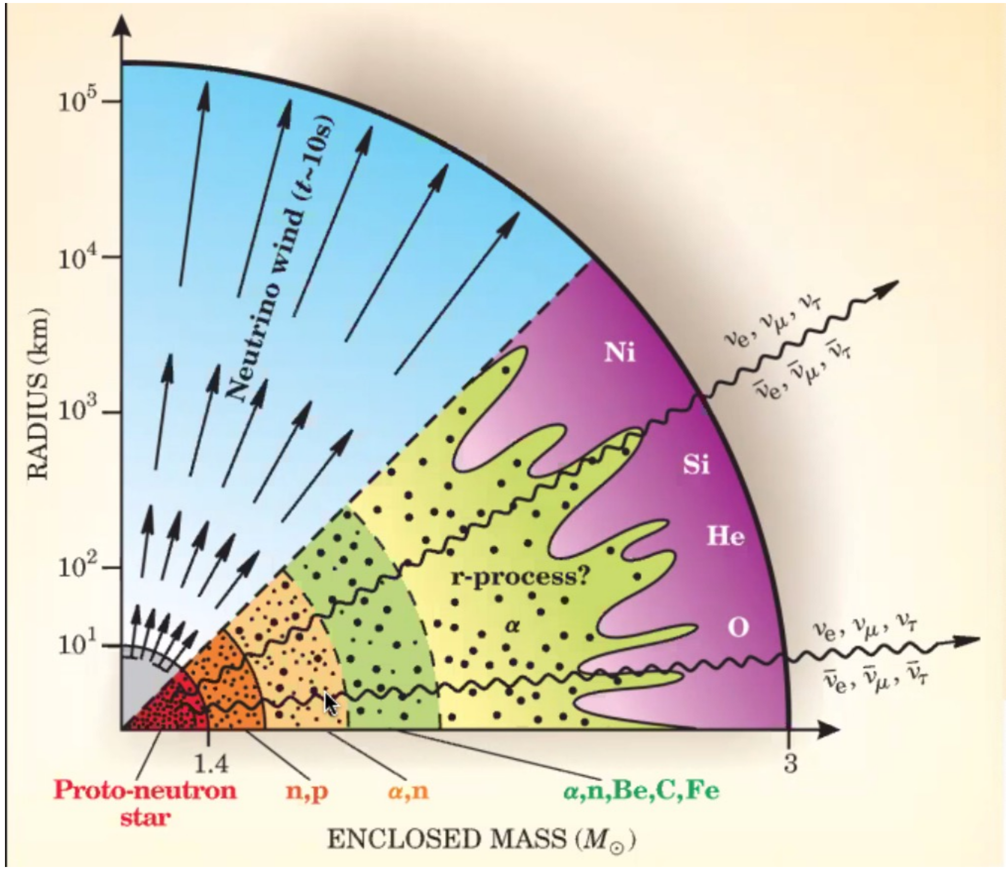
Heavy-element nucleosynthesis affected by neutrinos

- 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^{-2} 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



Woosley, Janka 2005

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

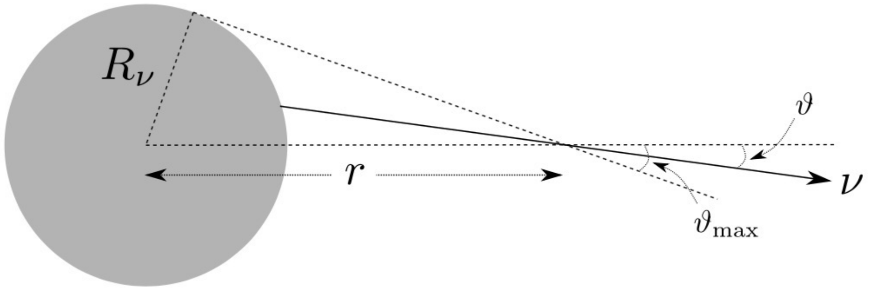
$$H = \sum_p \omega_p \vec{B} \cdot \vec{J}_p + \sum_{p,q} \mu_{pq} \left[\vec{J}_p \cdot \langle \vec{J}_q \rangle + \langle \vec{J}_p \rangle \cdot \vec{J}_q - \langle \vec{J}_p \rangle \cdot \langle \vec{J}_q \rangle \right]$$

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

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

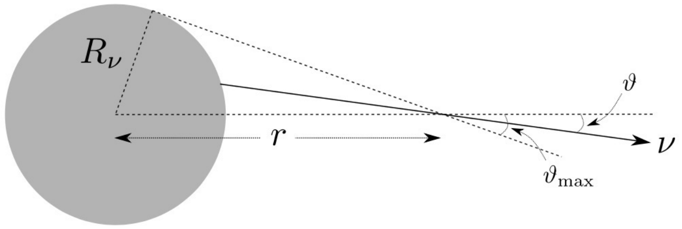
We initiate the oscillations at $r_i \simeq 100\,km$, *where* $\mu_i = 100$



"neutrino bulb" geometry
--single angle approximation

Balantekin, B.,.., Wang, X., 2024, ApJ 967, 146

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	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

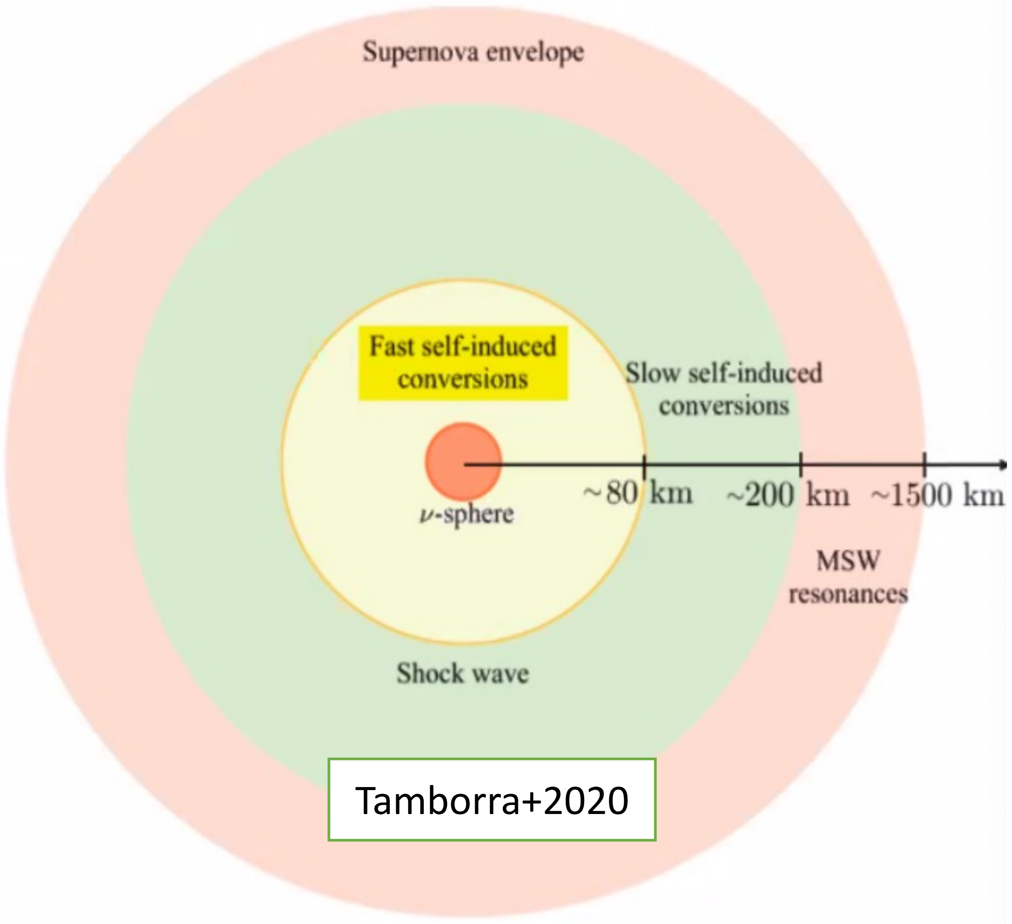
Nucleosynthesis simulation with PRISM
1) four neutrino treatments (nn, nosc, mf, mb) are implemented into PRISM in the form of external $\nu_e + n$ and $\bar{\nu}_e + p$ capture rates; neutrino-nuclei interactions are not included
2) Nuclear data: REACLIB reaction rates (Cyburt et al. 2010) + NUBASE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

→only 1 set nuclear database available for proton-rich region:
variations in ncap rates? (n,p) (n, gamma) (n, alpha)

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

Balantekin, B.,.., Wang, X., 2024, ApJ 967, 146

νp-process in supernovae



Existence of neutrinos: enhance heavier elements productions in νp process

SN neutrino-driven wind:

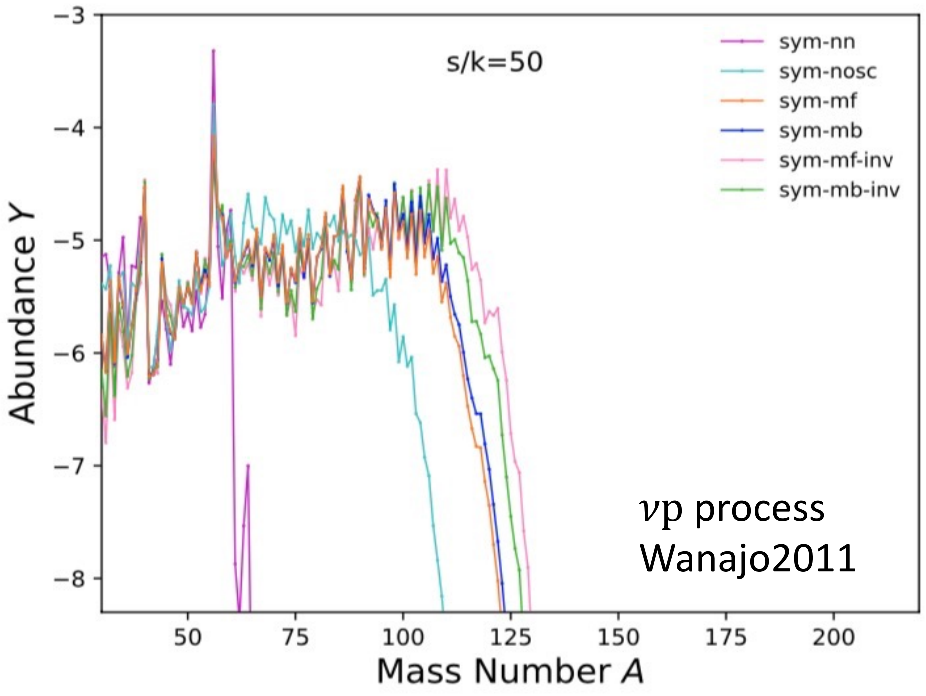
~~$\nu_e + n \rightleftharpoons p + e^-$~~

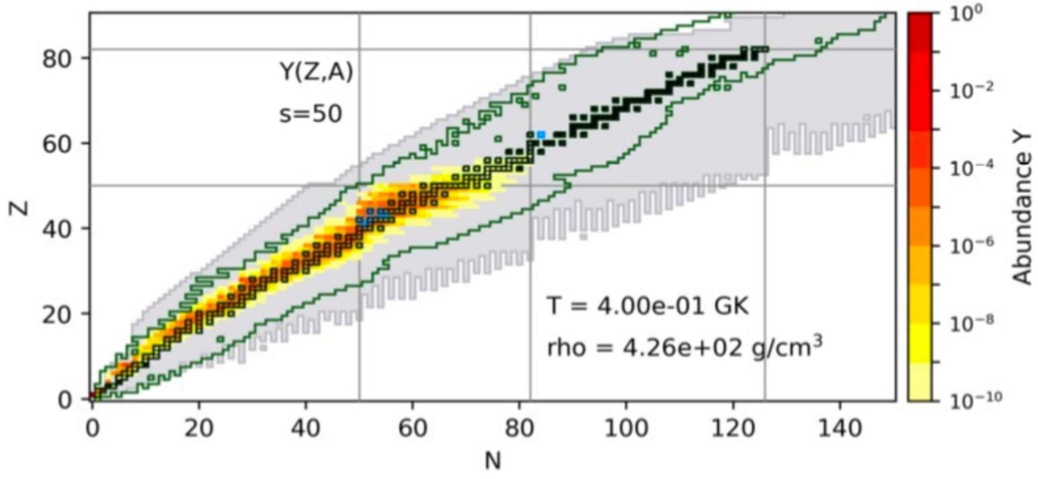
$\bar{\nu}_e + p \rightleftharpoons n + e^+$

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, Arcones+2012…)
- 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 or Ye and enhance the νp process (Xiong+2020, Xiong+2025)
- Active-sterile neutrino flavor conversion could also help νp process reach heavier elements between Zr and Cd (Wu+2014)

Collective oscillations and νp process





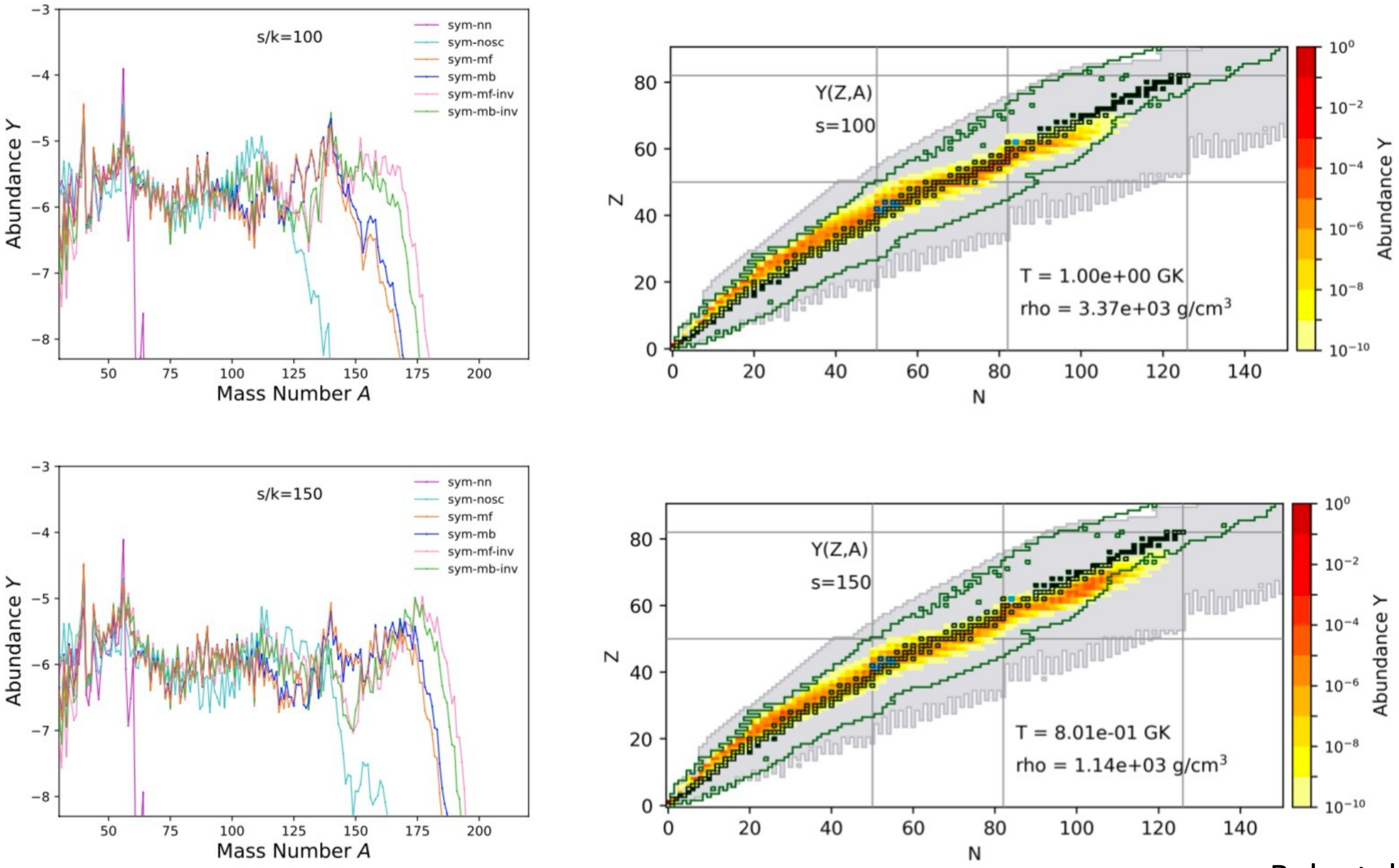
purple: no neutrino (nn)
cyan: no neutrino oscillation (nosc)
blue: many-body calculation of oscillation (mb)
orange: mean-field calculation of oscillation (mf)
green: inverted mass hierarchy with mb
pink: inverted mass hierarchy with mf

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

Balantekin, B.,.., Wang, X., 2024, ApJ 967, 146

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

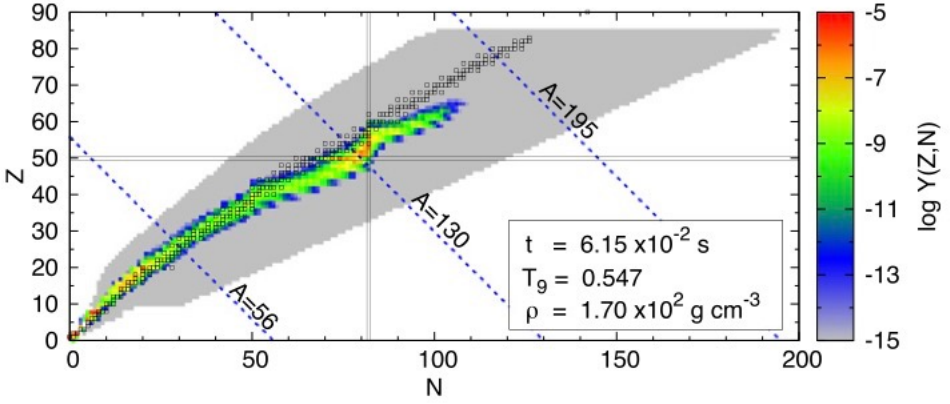


Special abundance yields for s/k_B >~150: light proton-rich nuclei + heavy neutron-rich nuclei

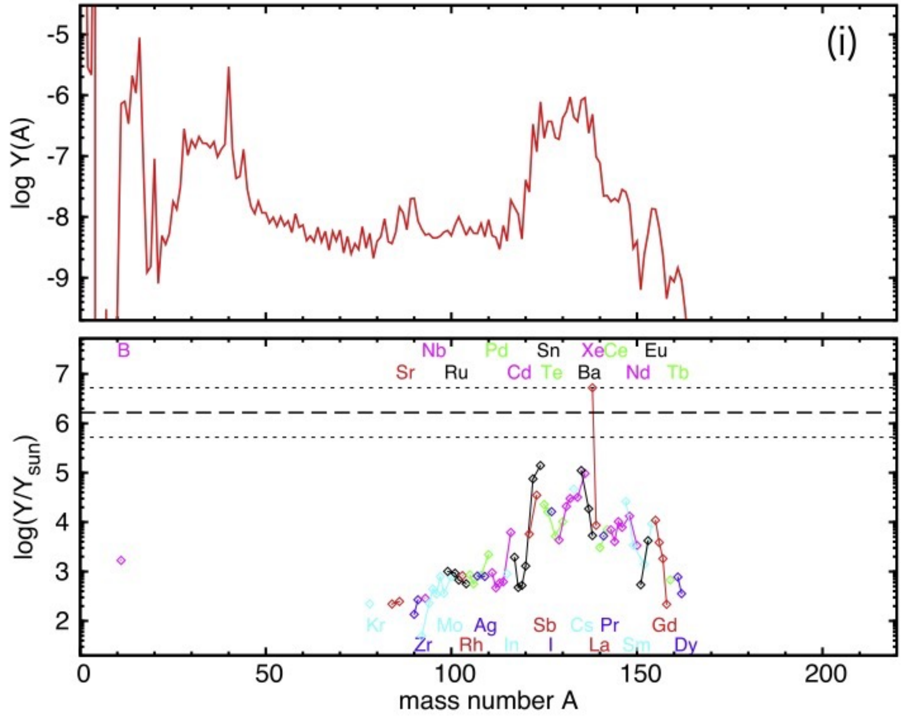
Balantekin, B.,.., Wang, X., 2024, ApJ 967, 146

A robust νp process → neutron rich at late time

- First pointed out: Wanajo et al. (2011), Arcones et al. (2012), Nishimura et al. (2019)
- Observed in a hypernova neutrino-driven wind with higher (~10x) $L\nu e \sim 1.65\text{x}10^{53}$erg s^{-1} (Fujibayashi et al. 2015):

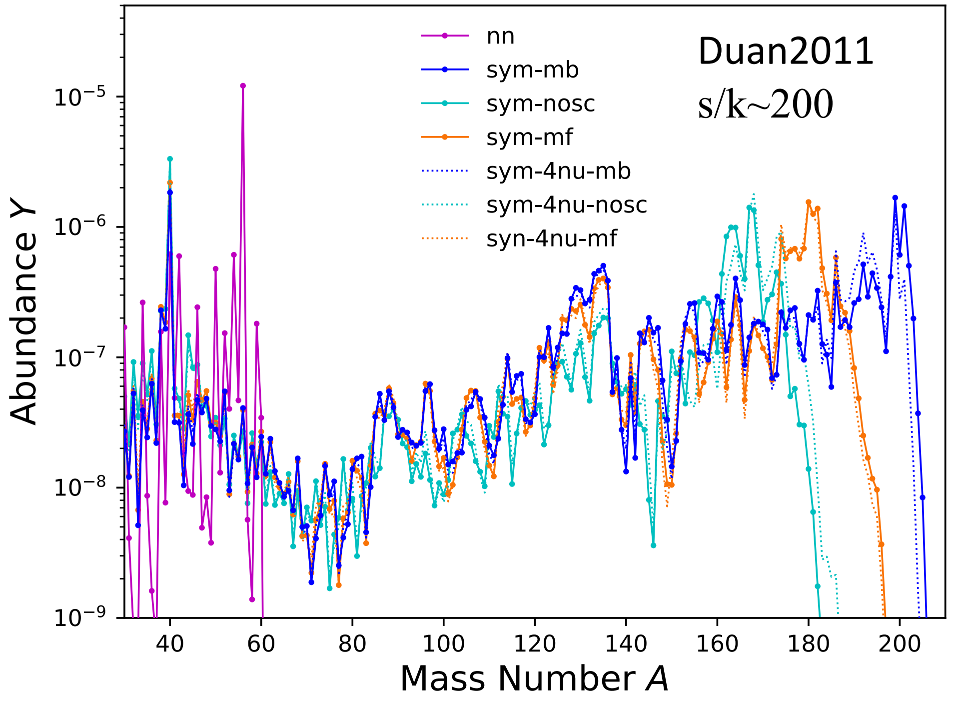


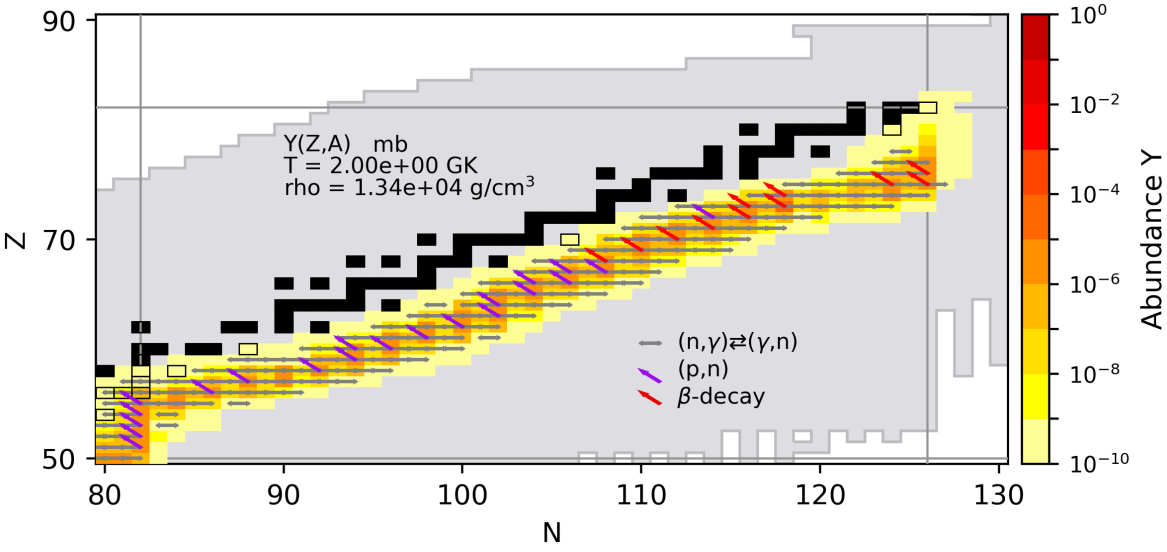
Hypernova wind condition:
M_{pns}=3M_{sol} ,$E_{\nu e}$=11.0 MeV, Y_e=0.587,
s/k_B=141(Fujibayashi et al. 2015)

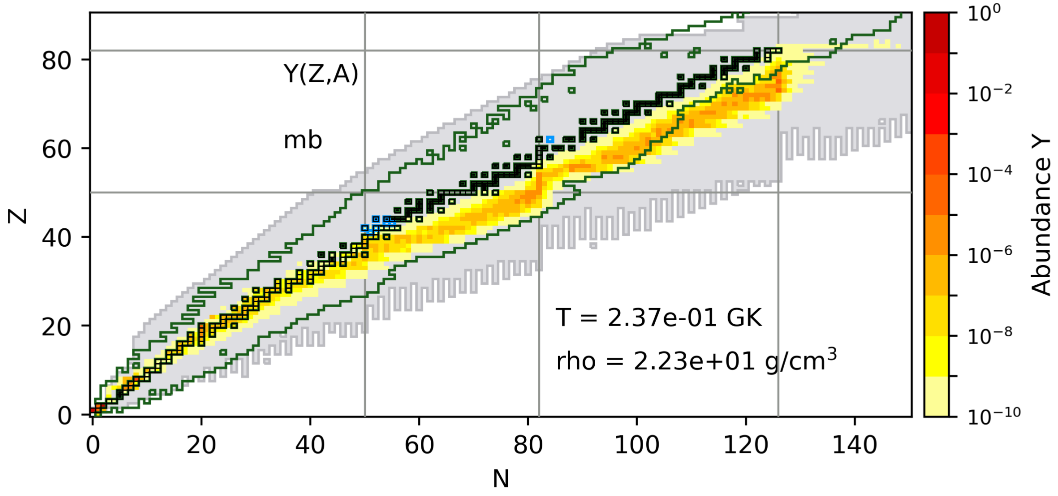


- We find neutrino oscillations **amplify** the shift from proton-rich to neutron-rich nucleosynthesis

Collective oscillations and νi process





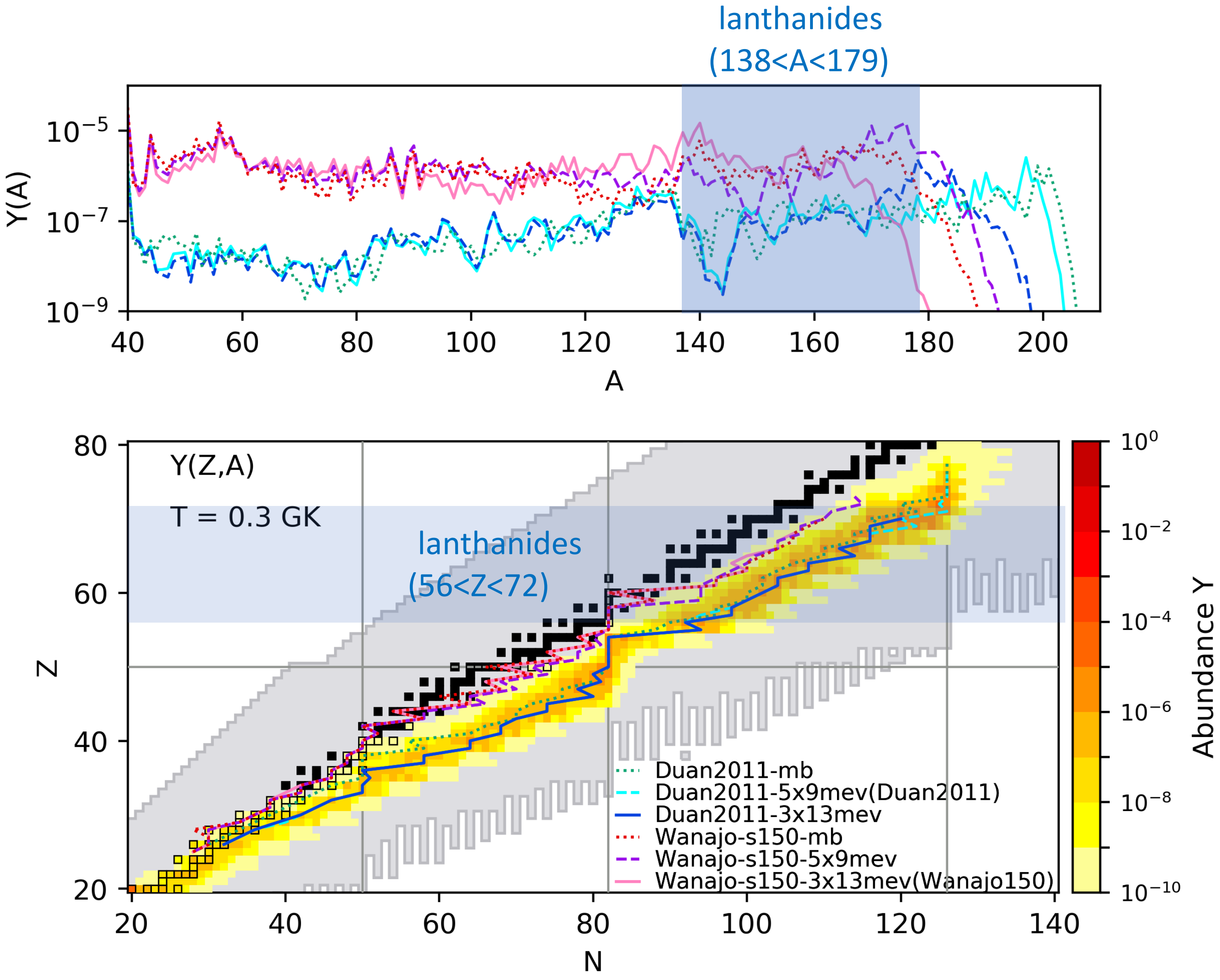


νi process: new nucleosynthesis process and path

- 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.

Balantekin, B.,.., Wang, X., 2024, ApJ 967, 146

νi process nucleosynthesis



green: duan2011 with neutrinos of many-body (mb) oscillation calculations

cyan: duan2011 with neutrinos of $\langle E_\nu \rangle$=9MeV, L_ν=5x$L_{\nu,0}$=5x9x10^{51}erg/s

blue: duan2011 with neutrinos of $\langle E_\nu \rangle$=13MeV, L_ν=3x$L_{\nu,0}$

purple: wanajo-s150 with neutrinos of $\langle E_\nu \rangle$=9MeV, $L_{\nu,0}$=5x$L_{\nu,0}$

pink: wanajo-s150 with neutrinos of $\langle E_\nu \rangle$=13MeV, $L_{\nu,0}$=3x$L_{\nu,0}$

red: wanajo-s150 with neutrinos of mb oscillation calculations

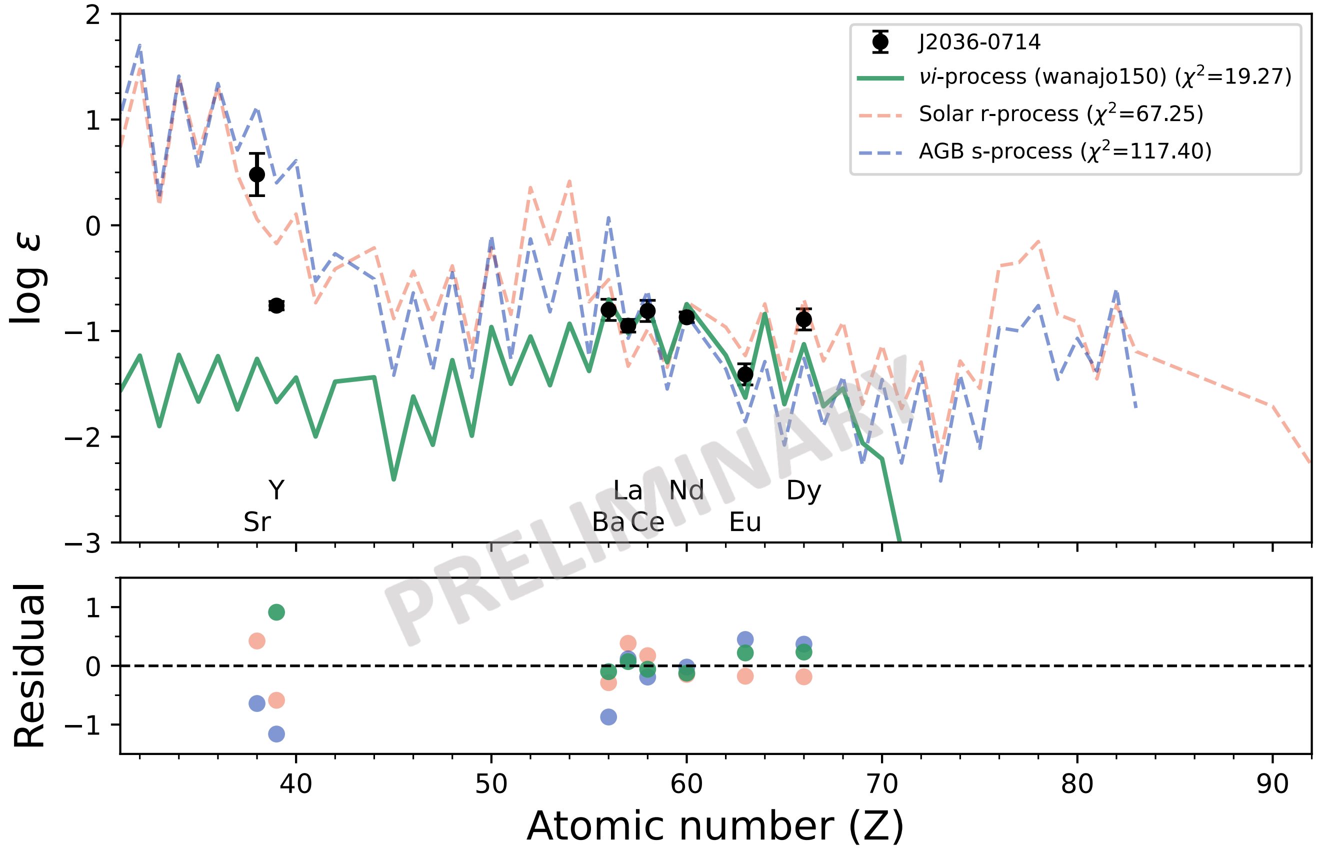
νi process:

Occur in a high entropy proton-rich environment with abundant neutrinos: supernovae, hypernovae

- Neutrino oscillations facilitate the νi process, or a larger amount of neutrinos (3-5x higher luminosity) is needed to result in the νi process from initial robust the νp process
- New astrophysical sources for lanthanides

Wang, X., et al., 2025, *in preparation*

νi process elemental patterns and stellar observations



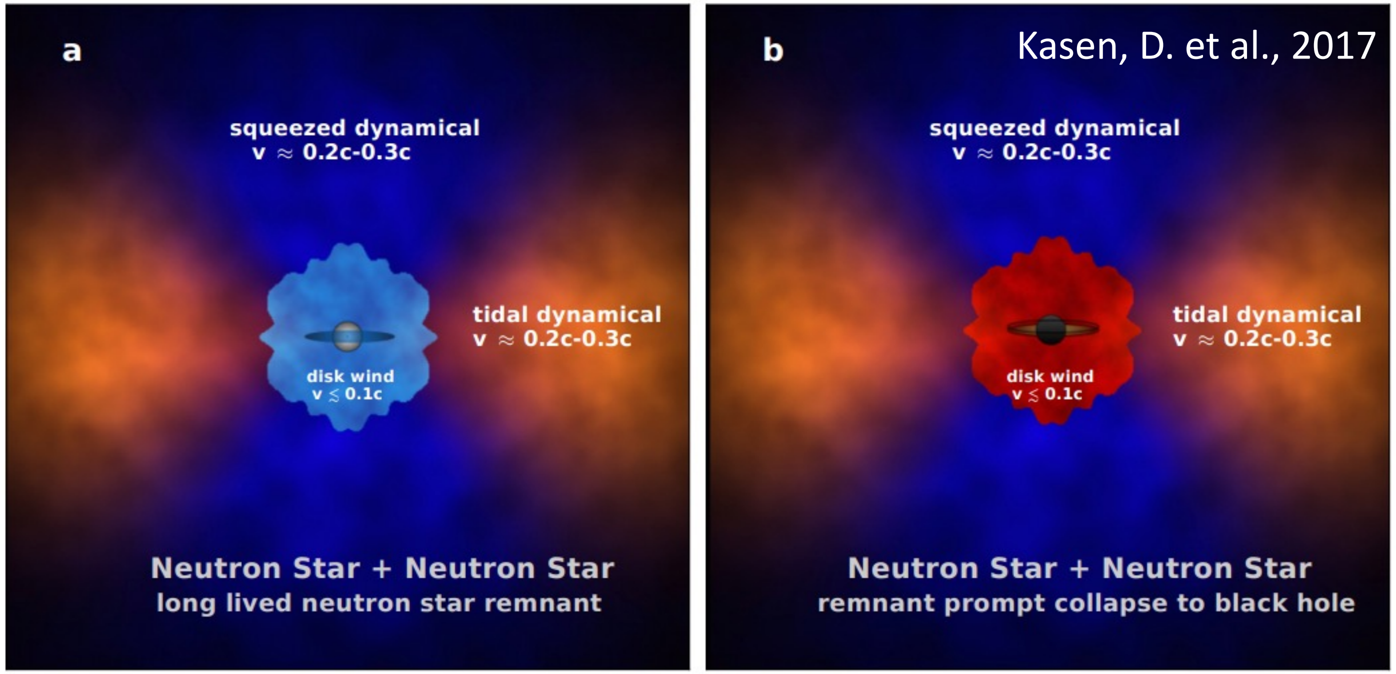
- the νi process abundances are distinct from those of both the solar r process and the AGB s process, showing a flatter pattern with no lead production and a lower abundance of Sr, Y and Zr.
- the νi process can provide a equally good fit to the elemental pattern CEMP-r star J2036-0714 in the lanthanide region, compared with the solar r process or AGB s process.

Wang, X., et al., 2025, *in preparation*

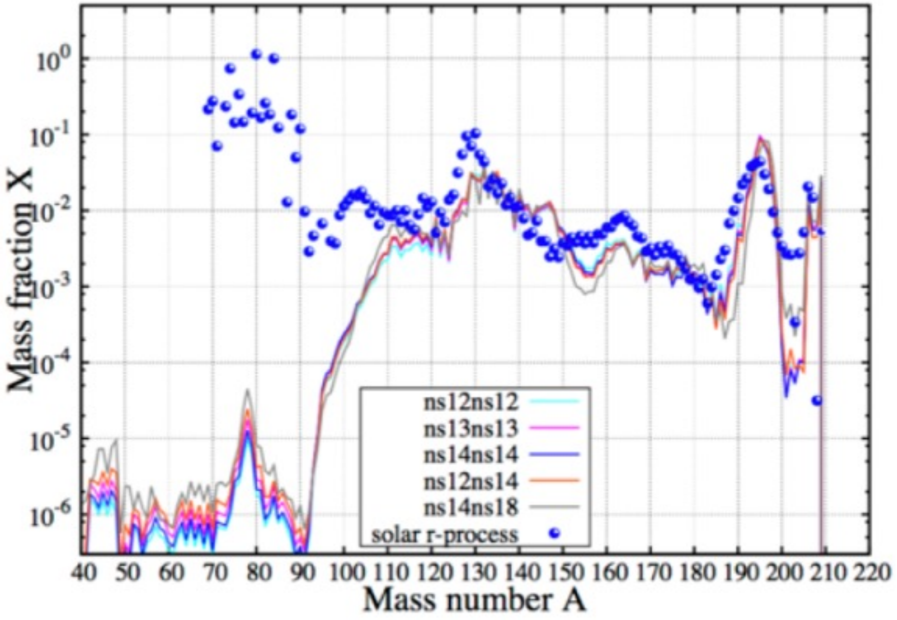
What happens if a stream of energetic heavy particles is traveling through the interstellar medium? Will the propagation affect r-process abundance patterns?

Neutron star mergers

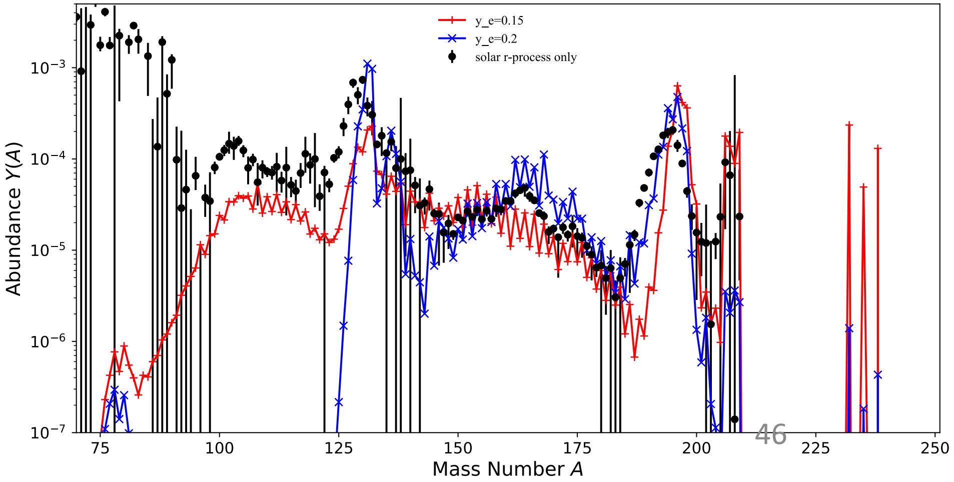
- GW170817: multi-wavelength observation
- r-process nucleosynthesis sites
- Matter ejected at high velocity: <v>~0.1c-0.3c



Nucleosynthesis for dynamic ejecta
(Rosswog et al. 2017)

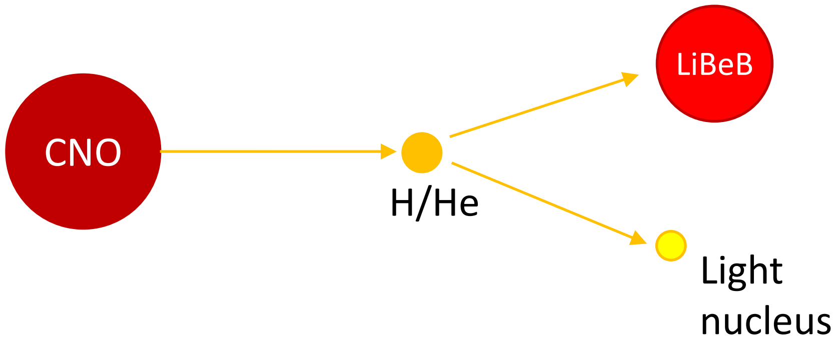


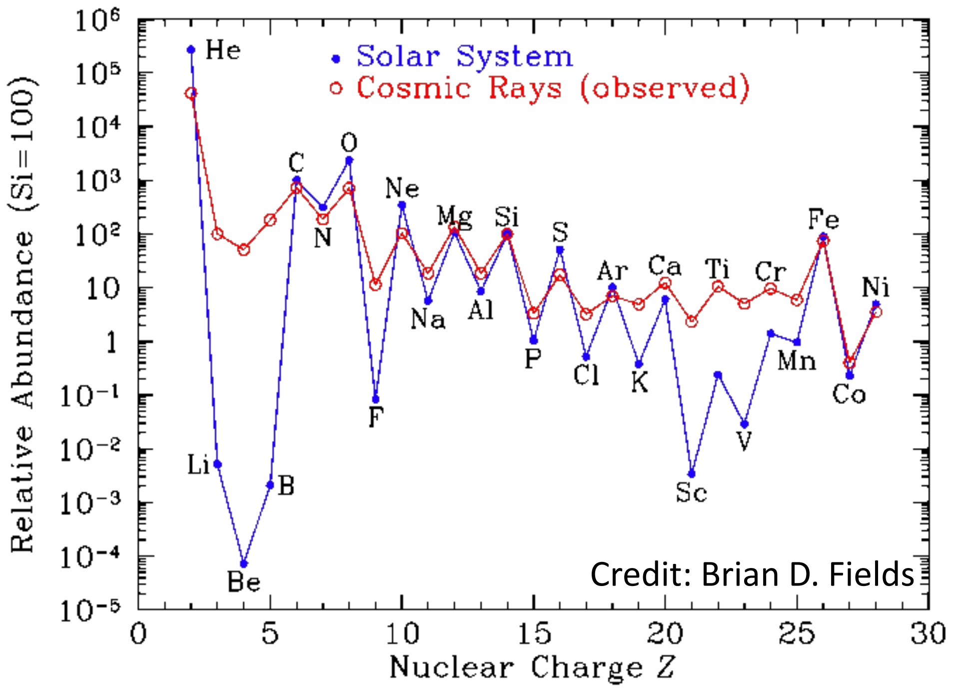
Nucleosynthesis for disk wind



Cosmic-ray spallation

- Cosmic-ray spallation "fill in the valley" at Li-Be-B, at the expense of a small reduction in the neighboring C-N-O peak on the abundance pattern.



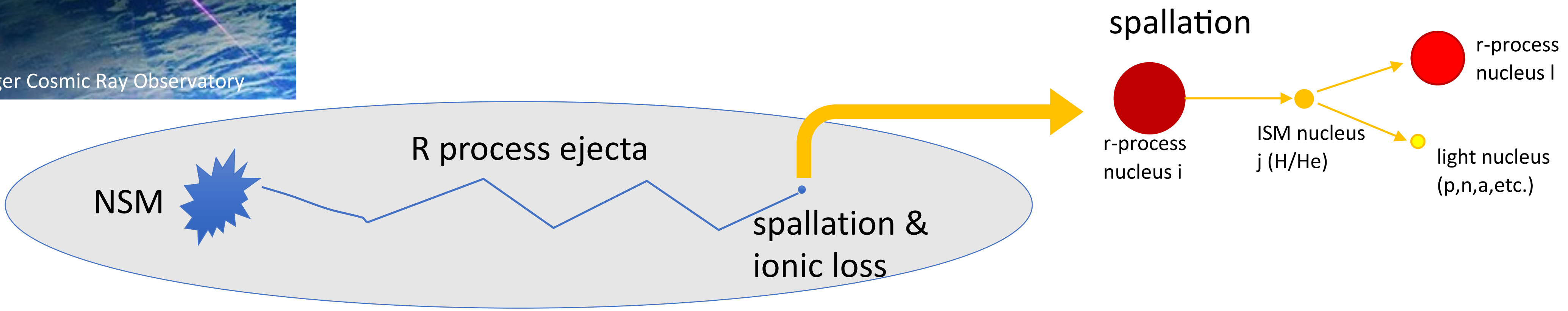


Spallation of r-process nuclei ejected from a NSNS event

- What happens if a stream of energetic heavy particles is travelling through the interstellar medium?

→ **Spallation!** (nuclear fragmentation)

- r-process ejecta transport calculation adapted from Wang, X. & Fields, B., 2018, MNRAS, 474, 4073



Wang, X., et al. 2020,
ApJ, 893, 92,
arXiv: 1909.12889

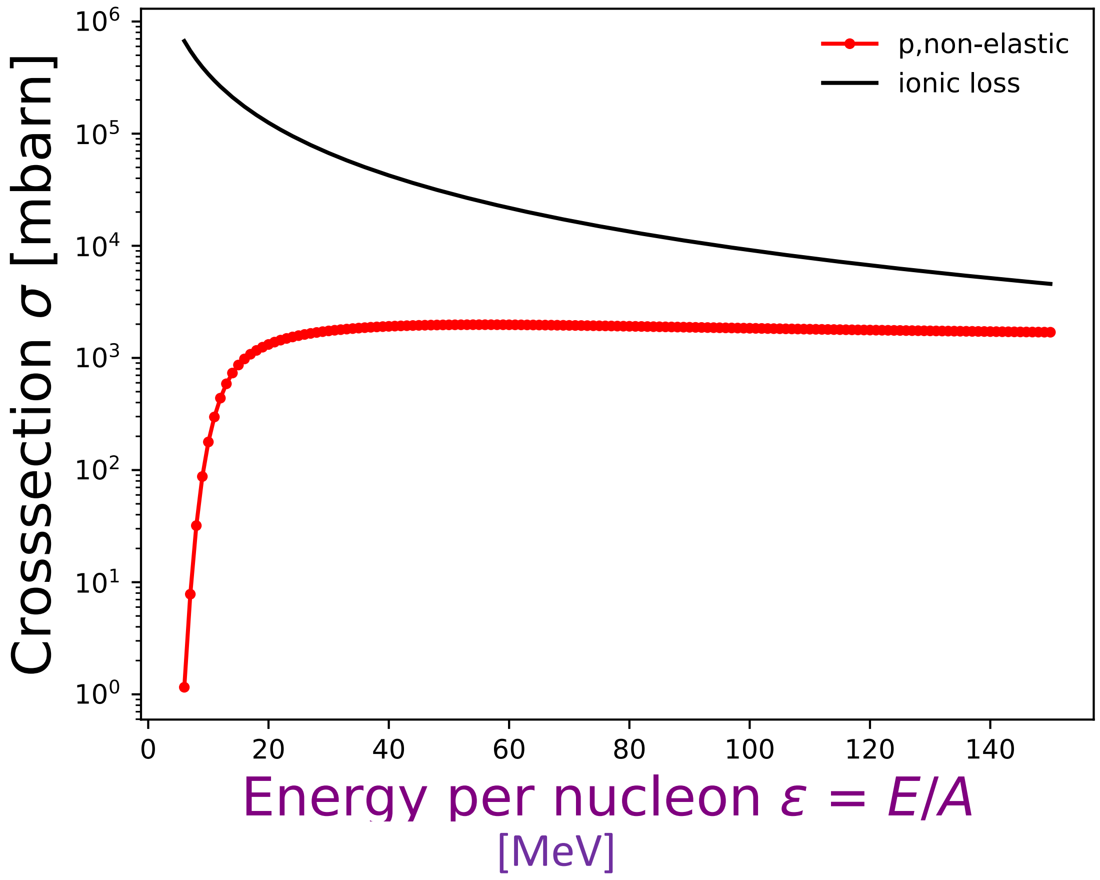
TALYS---generate nuclear data for spallation

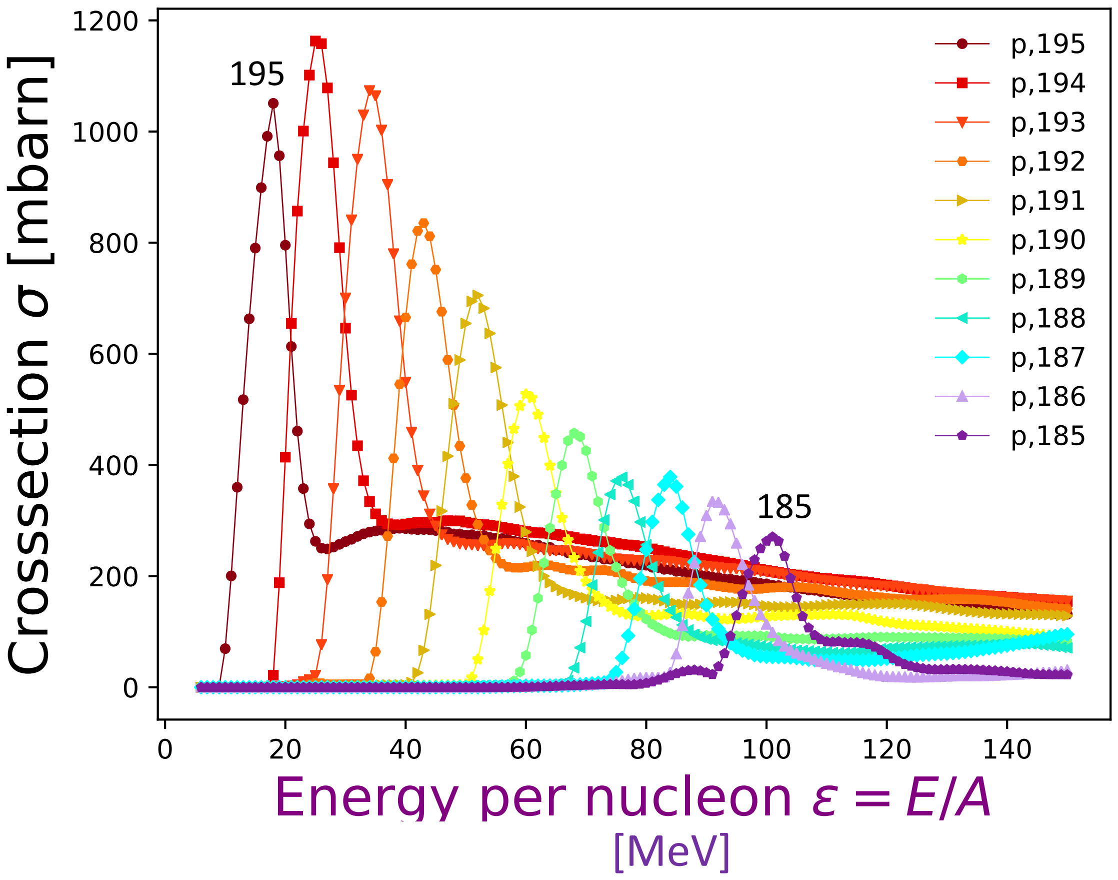
Wang, X., et al. 2020,
ApJ, 893, 92,
arXiv: 1909.12889

$p+^{196}Pt$

^{196}Pt

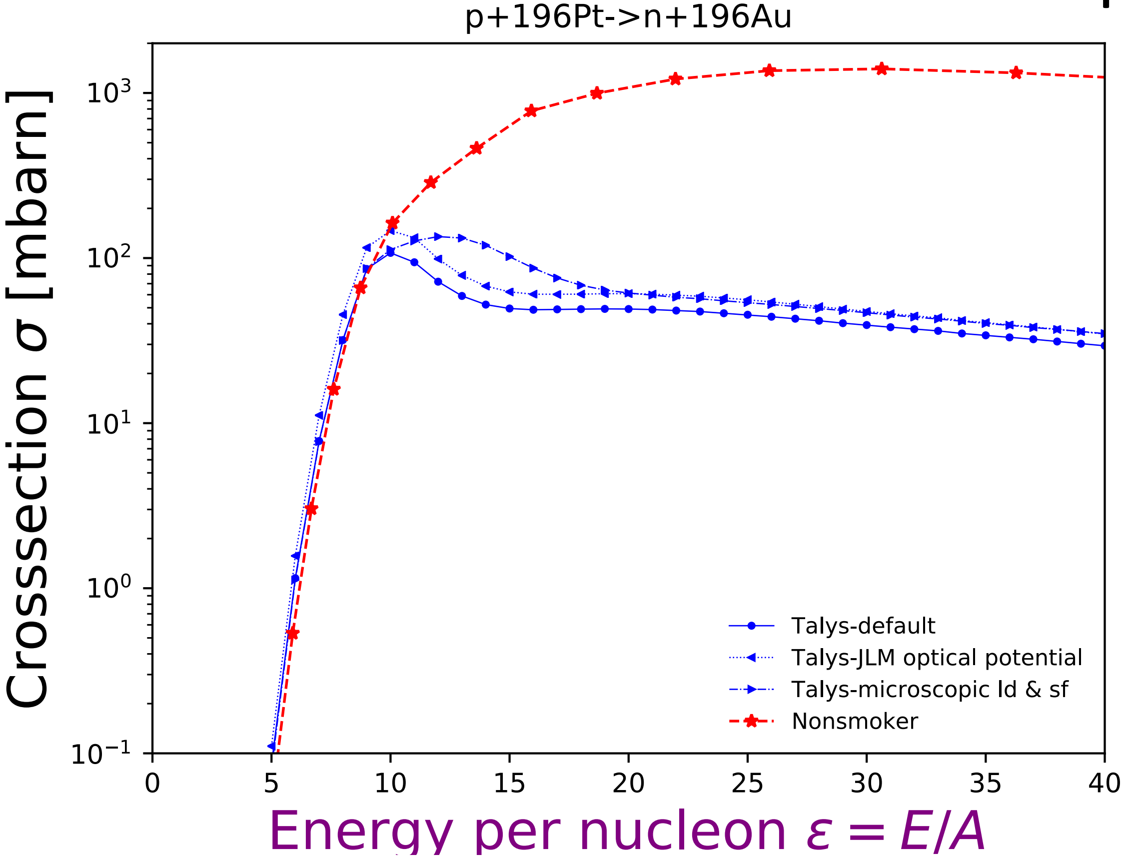
Non-elastic/spallation cross-section: Talys
Ionic loss: Schlickerser 2013

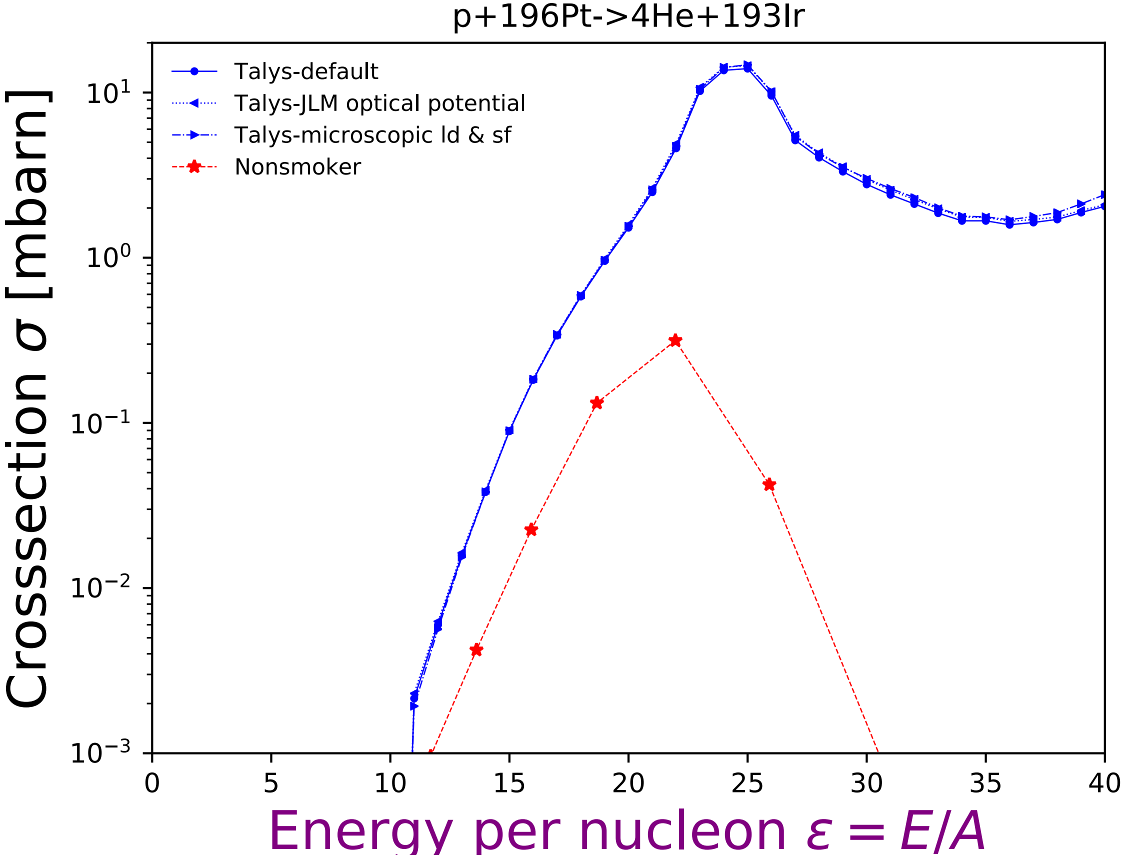




Spallation cross-sections from TALYS and NONSMOKER

p+^{196}Pt



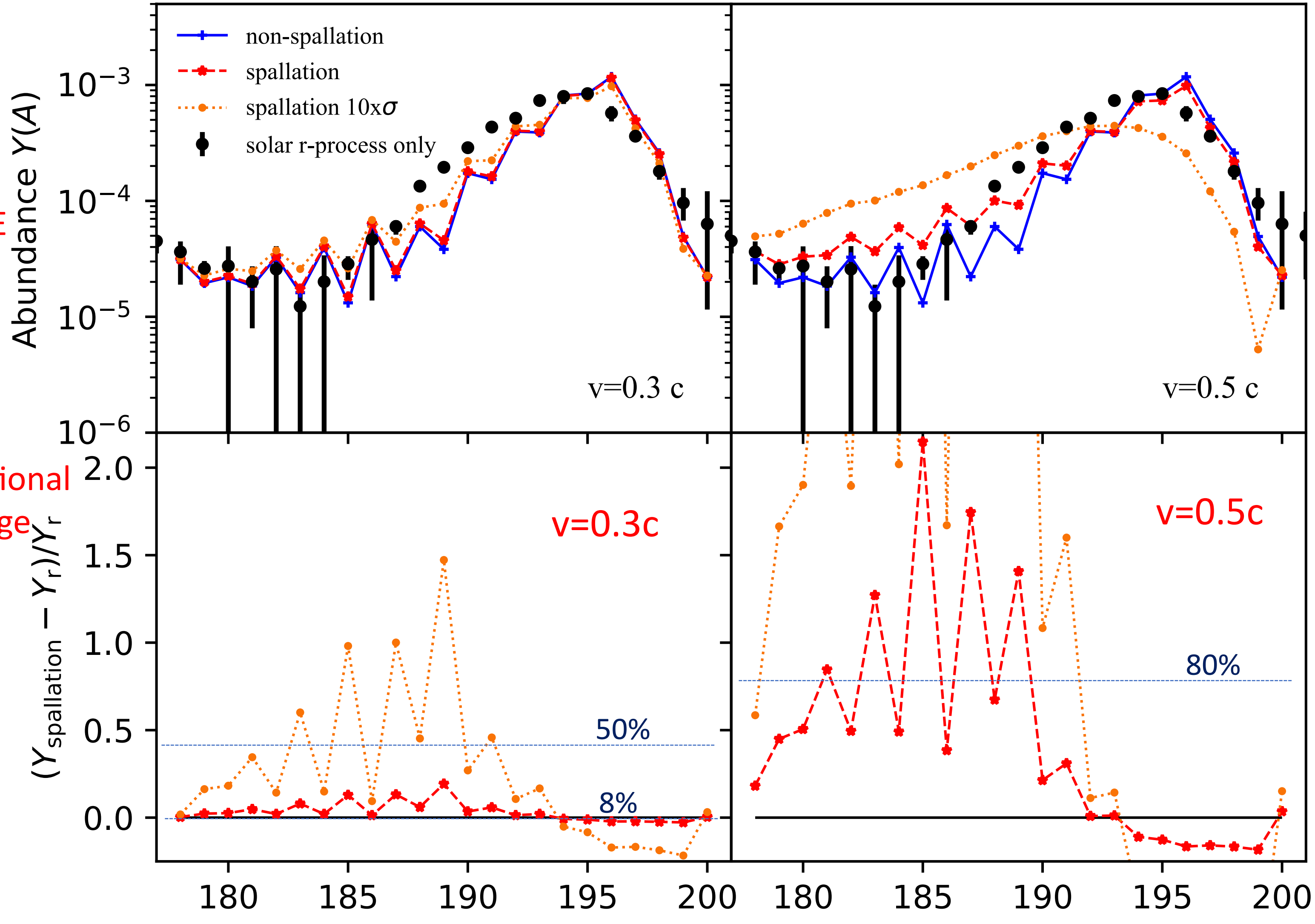


Wang, X., et al. 2020, JPhCS, 1668, 012049, arXiv: 2003.06370

Spallation in the third peak with various speeds and 10x spallation cross-section

ABUNDANCE

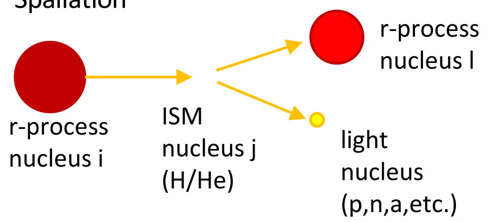
Fractional change



Mass Number A

Wang, X., et al. 2020, ApJ, 893, 92, arXiv: 1909.12889

Cold NSM dynamical ejecta



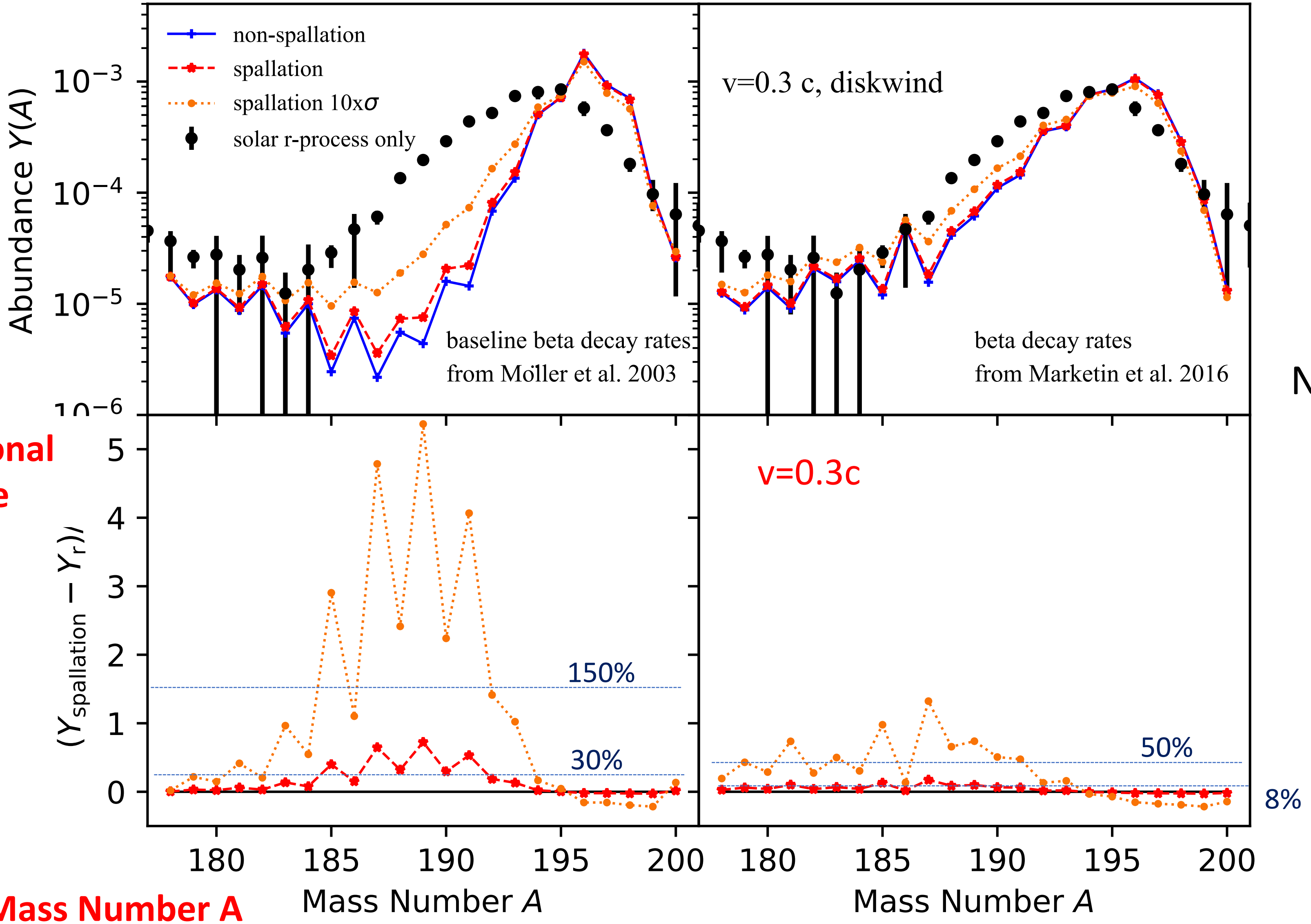
Solar r-process only abundance data of from Arnould, M. et al., 2007

Spallation in the third peak
with various nuclear physics inputs

Wang, X., et al. 2020, JPhCS, 1668, 012049, arXiv: 2003.06370

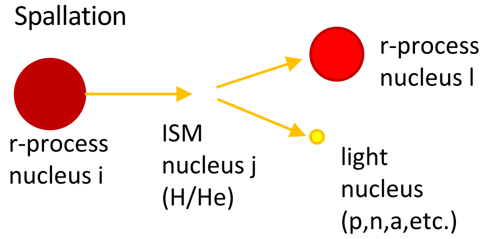
ABUNDANCE

Fractional change



Mass Number A

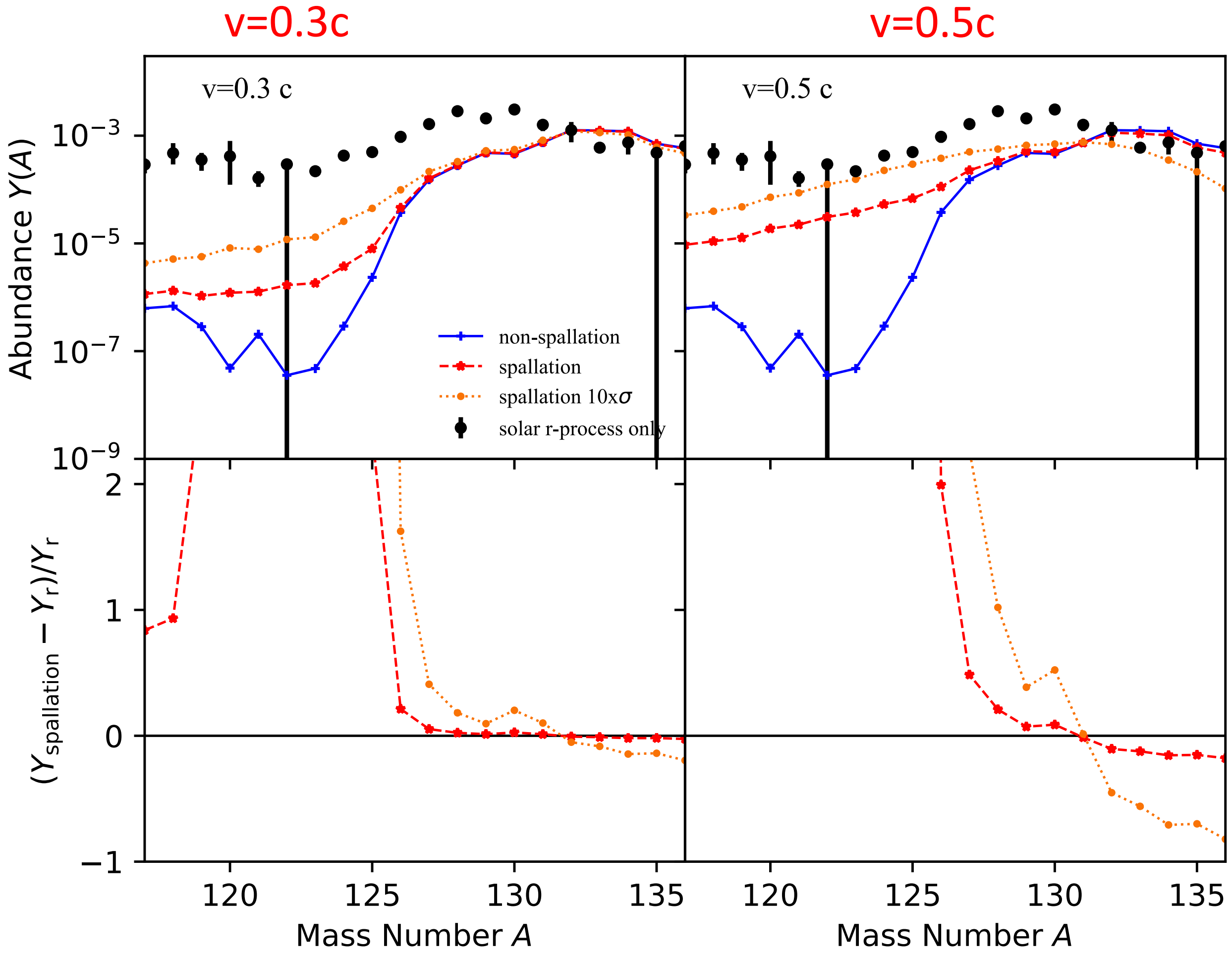
NSM disk wind

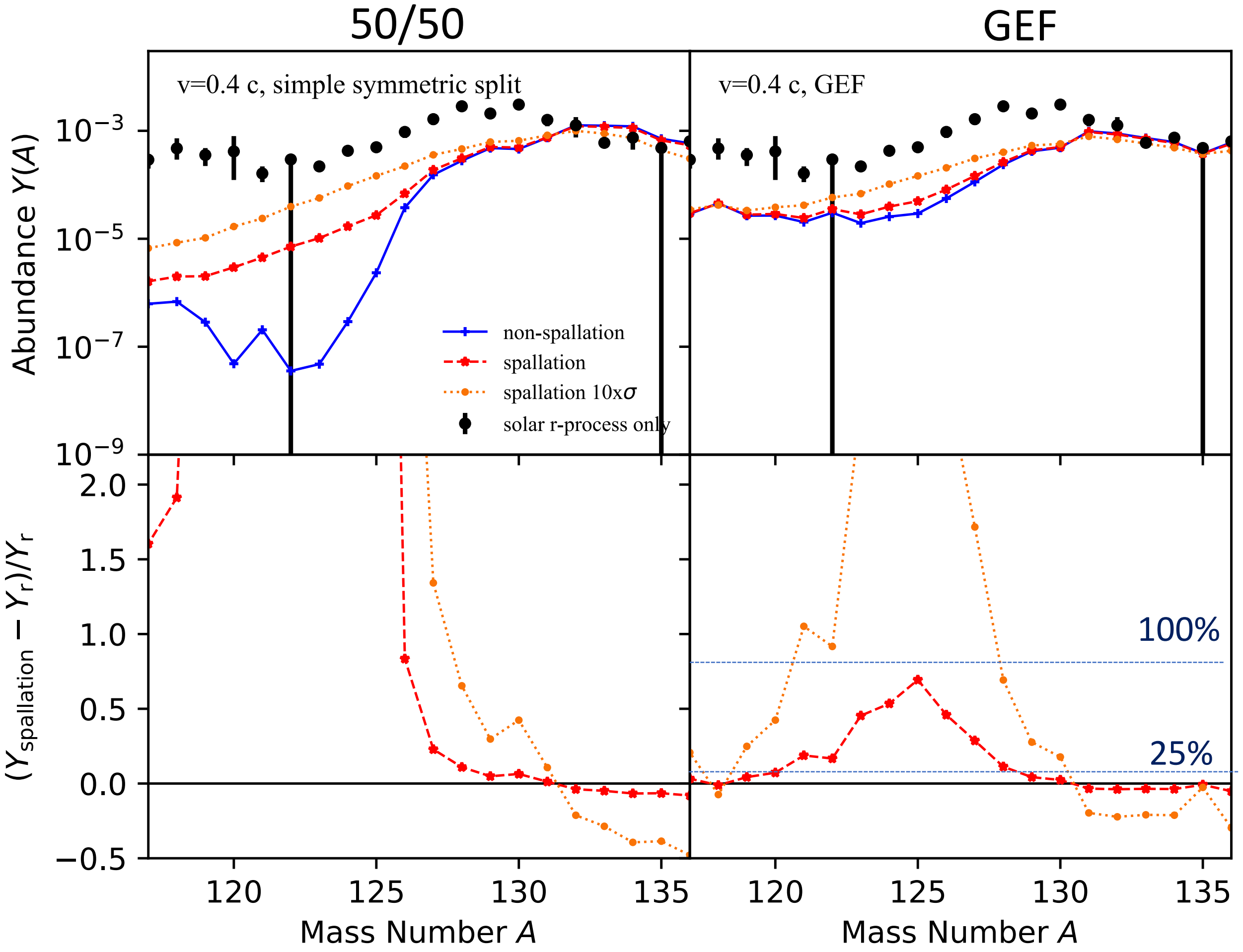


Solar r-process only abundance data of from Arnould, M. et al., 2007

Spallation in the second peak
with various initial speeds and fission yields

Cold NSM dynamical ejecta

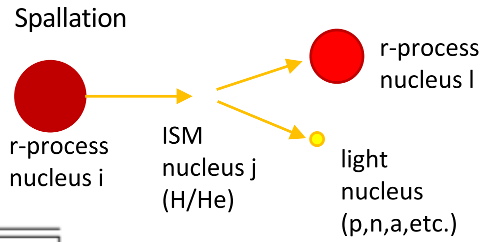


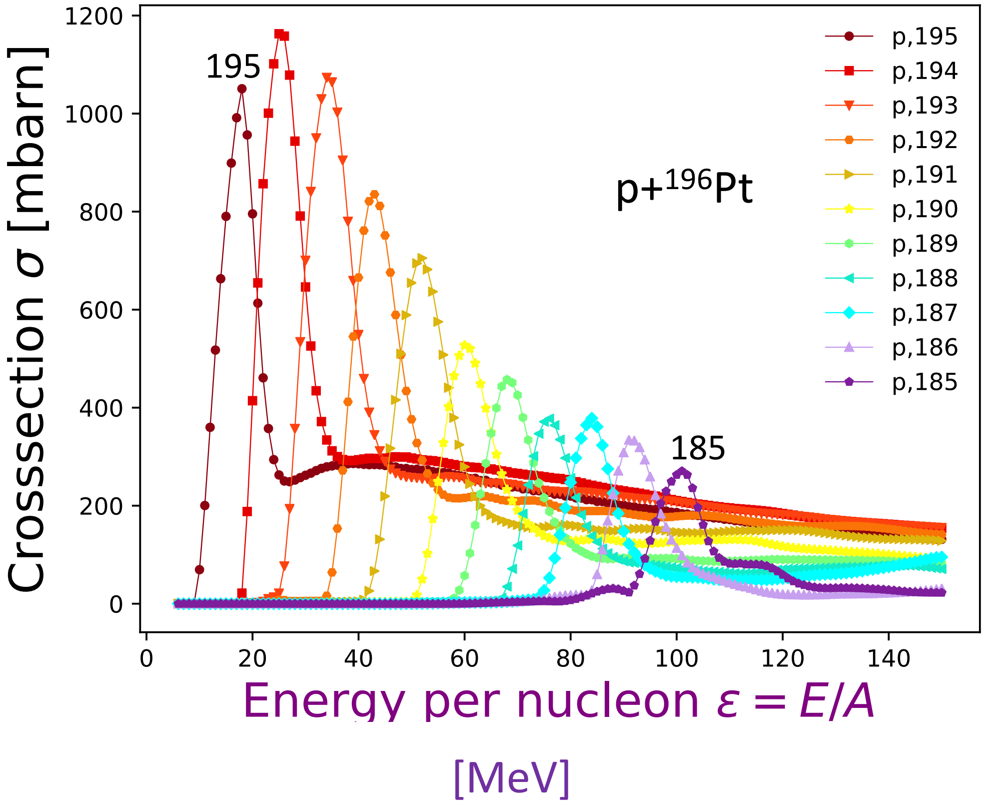


Wang, X., et al. 2020, ApJ, 893, 92, arXiv: 1909.12889

R-process abundance data with GEF fission yields from Vassh, N. et al., 2018

Spallation Cross-sections Sensitivity Study





Wang, X., et al. 2020,
NPA-IX proceedings,
arXiv: 2003.06370

Adopted Cross Sections $\sigma_{\text{spallation}}$		Spallation Effect [percentage]
TALYS value (1×) (original)		23.99
10× for all nuclei (all-increased)		138.19
10× for each individual nucleus	^{198}Pt	114.18
	^{197}Au	112.54
	^{196}Pt	108.91
	^{195}Pt	106.98
	^{194}Pt	91.78
	^{193}Ir	64.00
	^{192}Os	45.49
	^{191}Ir	54.67
	^{190}Os	46.22
	^{189}Os	33.55

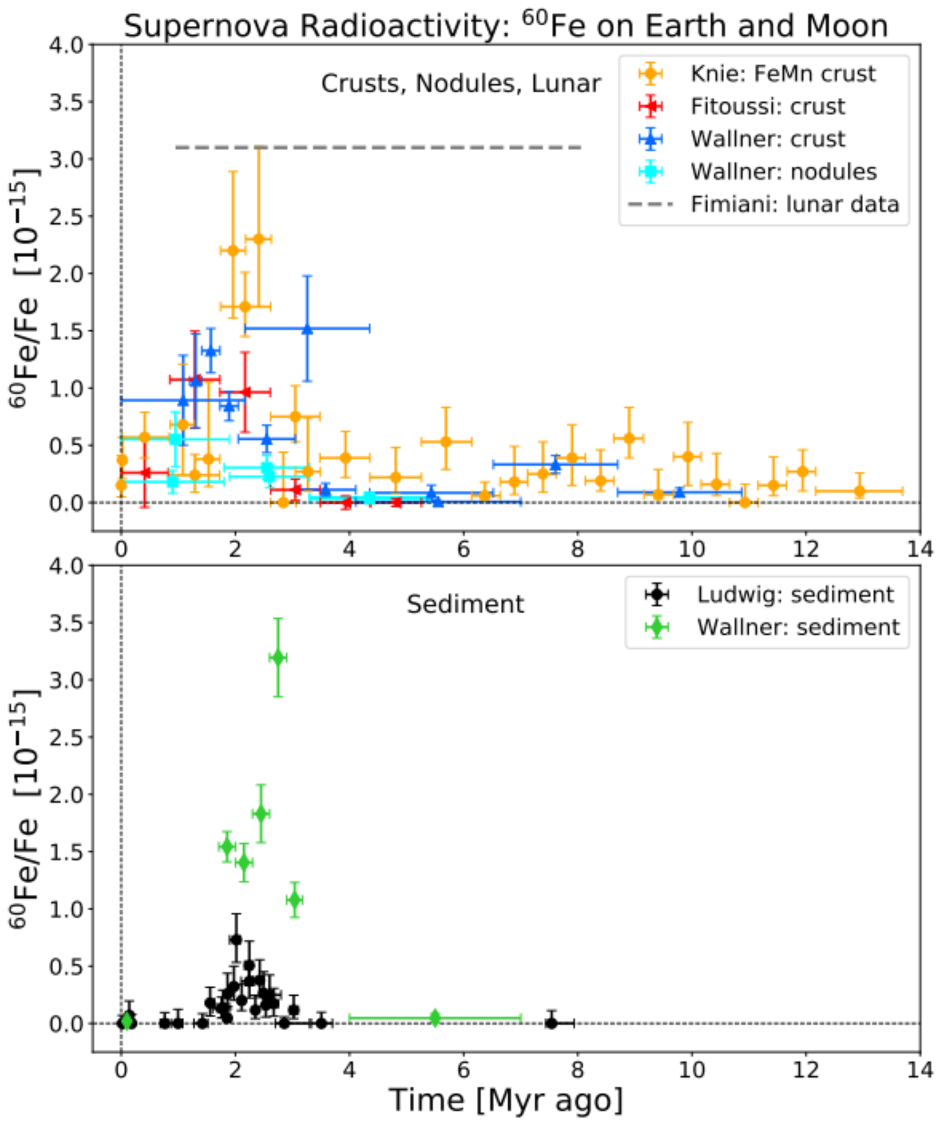
NSM dynamical ejecta with *v*=0.4*c*

Stable beam facilities, FRIB, FAIR and RIKEN

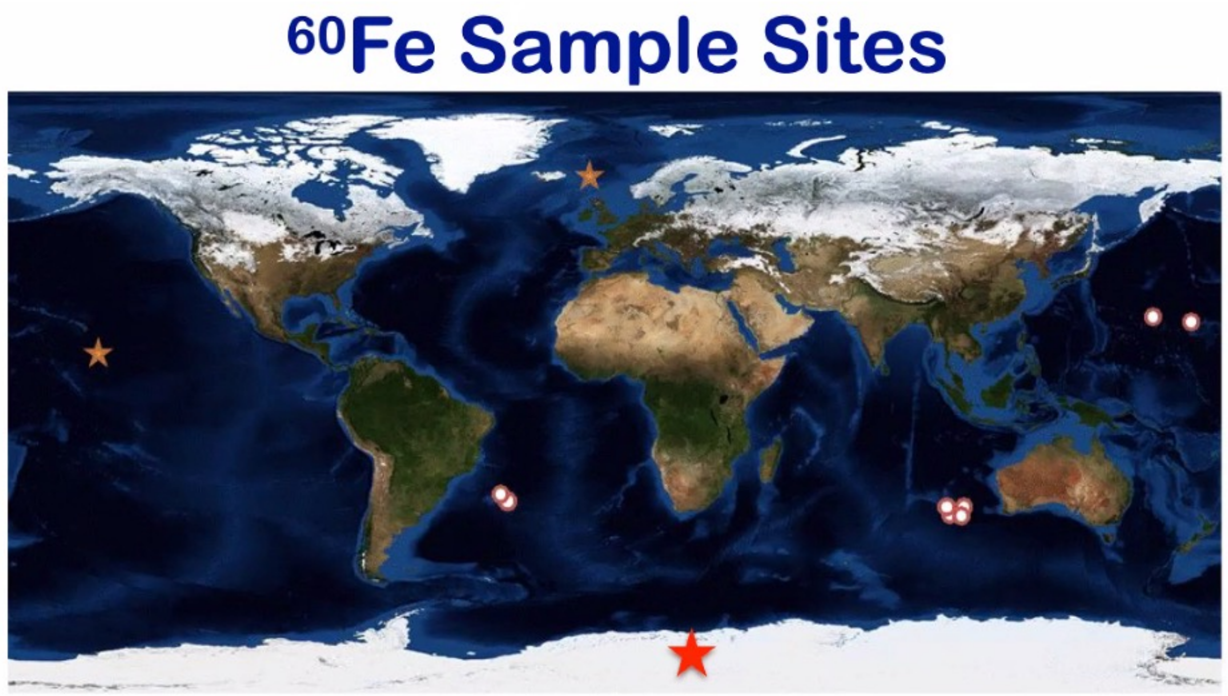
Wang, X., et al. 2020, ApJ, 893, 92

Another interesting astrophysical observables to be explored……

Live radioisotope measurements on the Earth and moon --- ^{60}Fe



Fields, B., et al. 2019, BAAS, 51,410



$t_{mean,{}^{60}_{26}Fe} = 3.78\ Myr$

Near-earth event:
within~100pc;
occur ~ 3Myr ago

Credit: Brian Fields

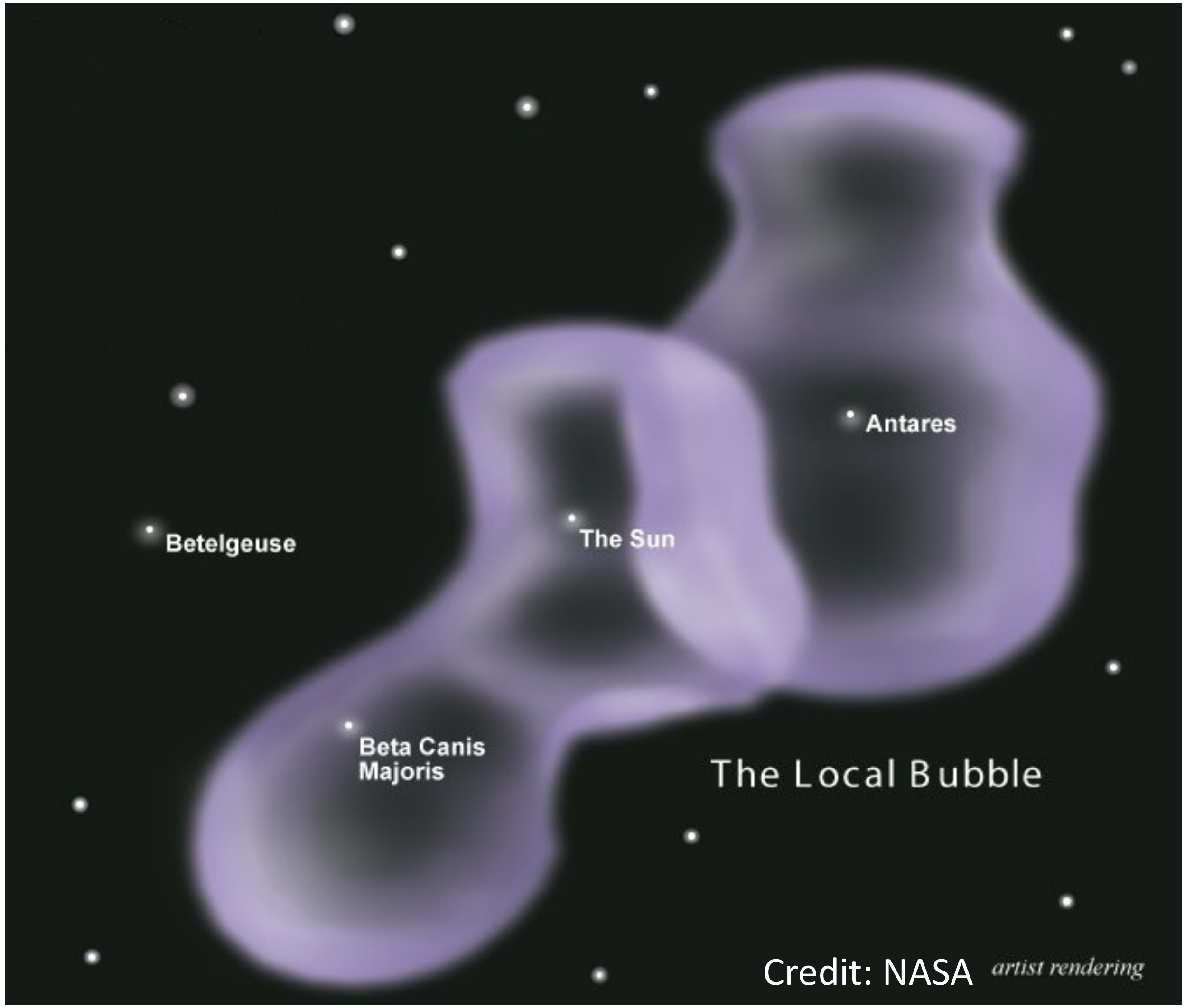
Live radioisotope measurements on the Earth and moon --- ^{60}Fe

The Local Bubble:

- Hot cavity in the interstellar medium
- ~50pc in radius
- Exceptionally sparse gas → due to the supernovae(SN) exploded within the past 10-20 Myr → we live inside SN remains

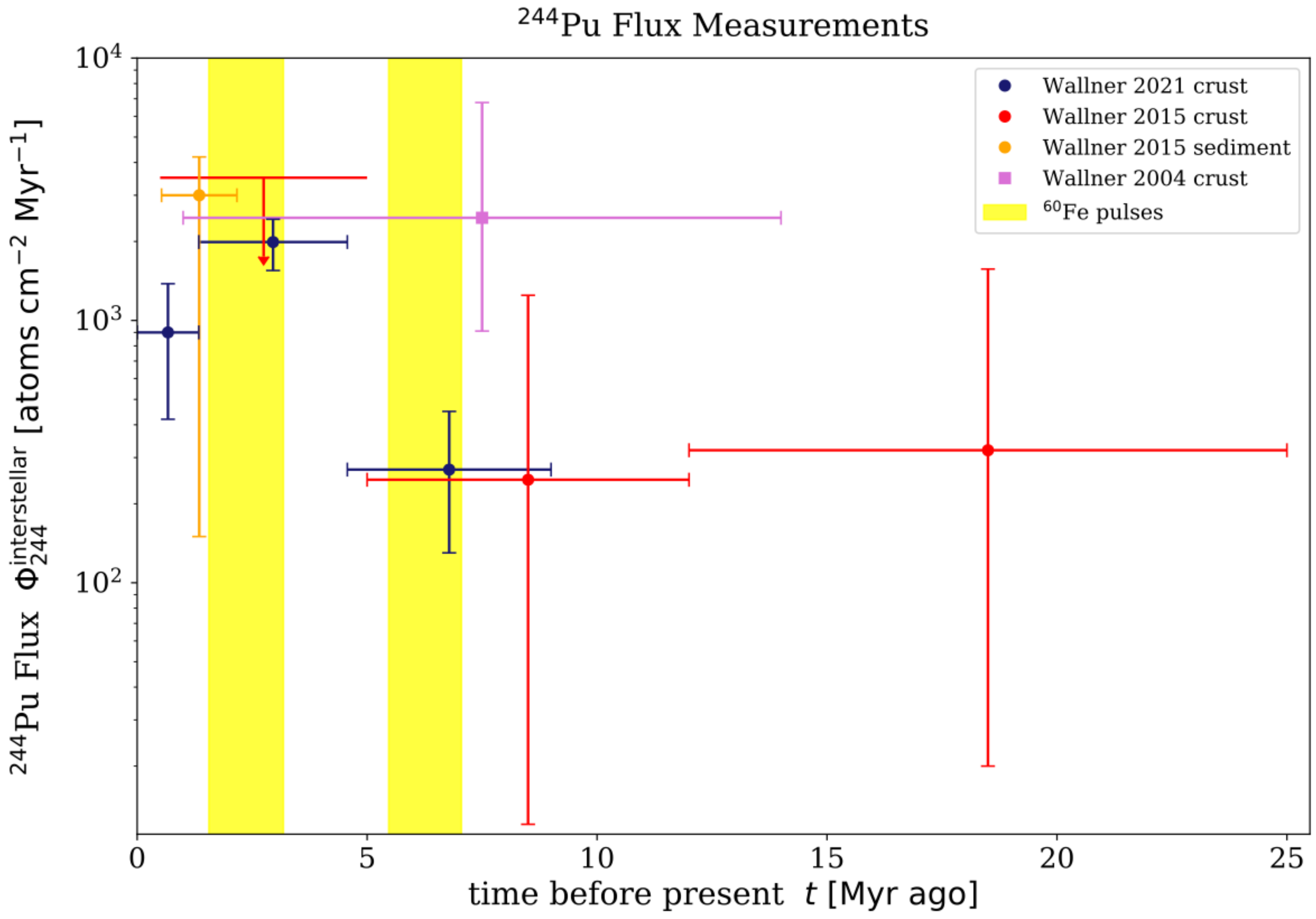
Nearby Supernovae for ^{60}Fe deposition:

- ✓ SN eject plows through interstellar matter
- ✓ Earth shielded by solar wind
- ✓ SN blast is close enough to push plasma to inner Solar System
- ✓ Dust decouples and rains on Earth → accumulates in deep ocean



Geological Signatures

Live radioisotope measurements on the Earth and moon --- ^{244}Pu



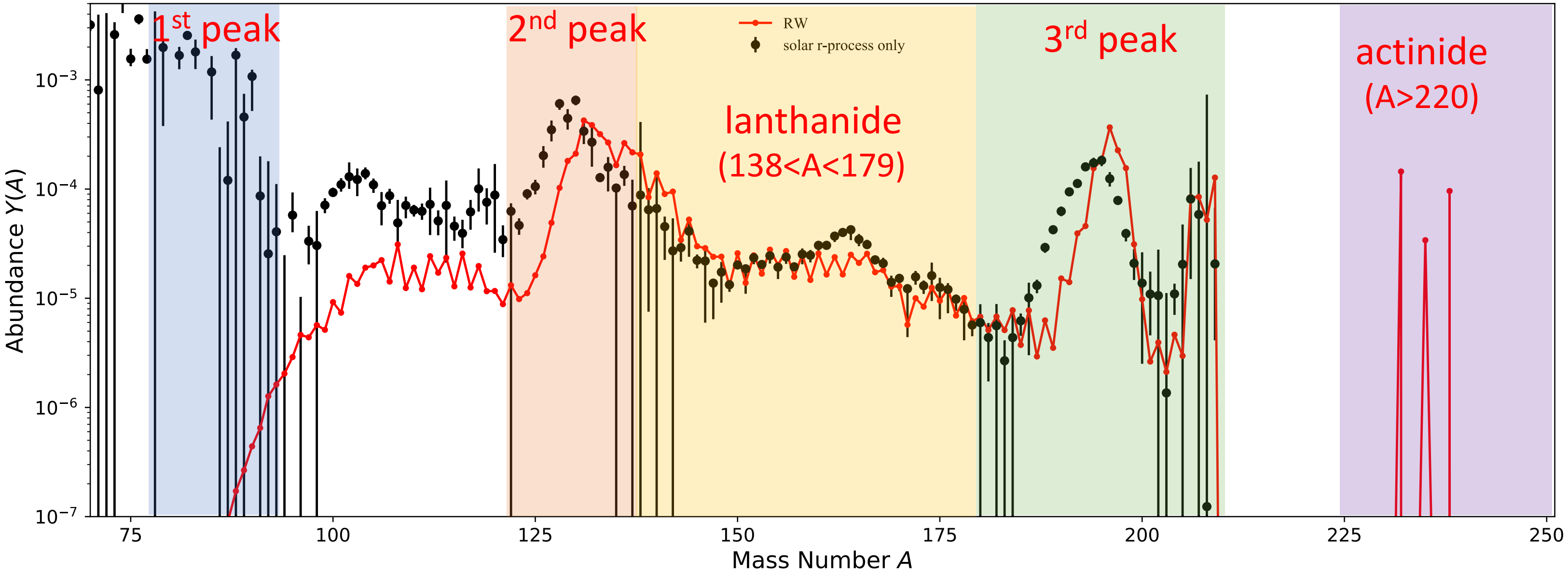
^{244}Pu: only made in r-process

$t_{mean,{}^{244}_{94}Pu} = 115\ Myr$

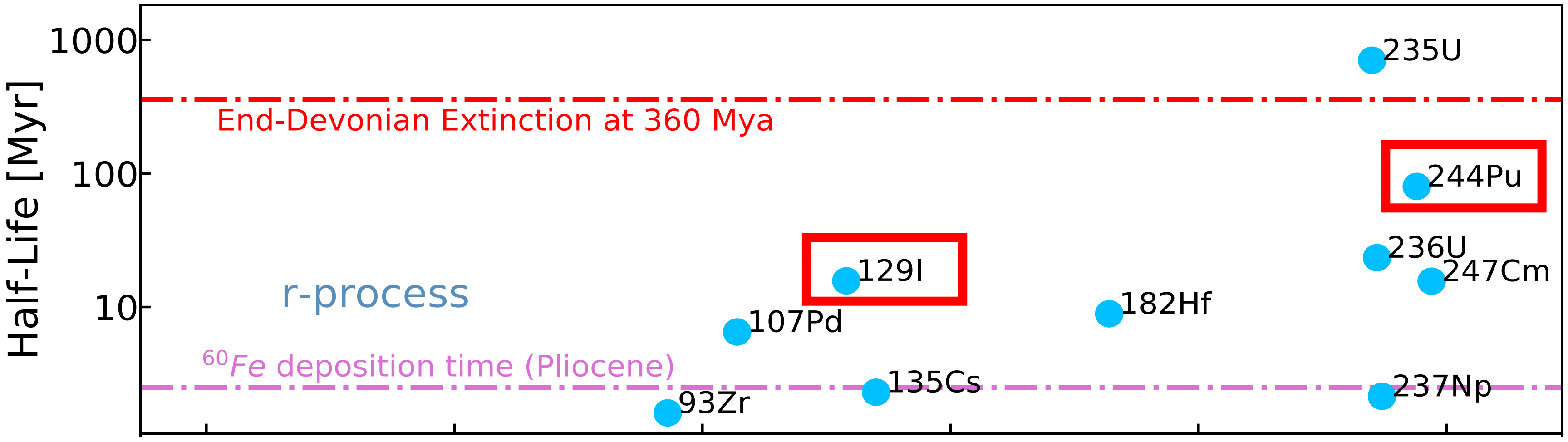
→ other long-lived r-process radioisotopes should also be present

Wang, X., et al., 2021, ApJ 923, 219

Long lived r-process radioisotopes



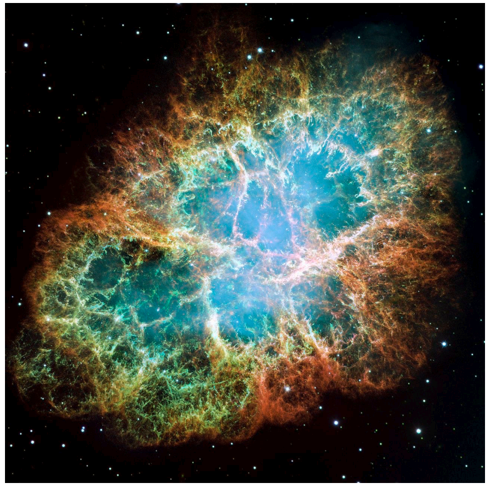
Isotopes with half-lives $t_{1/2} \sim$ 1 Myr to 1 Gyr



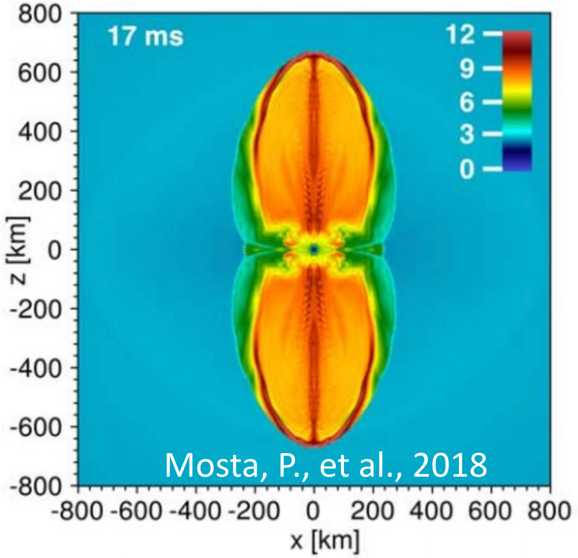
Wang, X., et al., 2021, ApJ 923, 219

r-process calculations

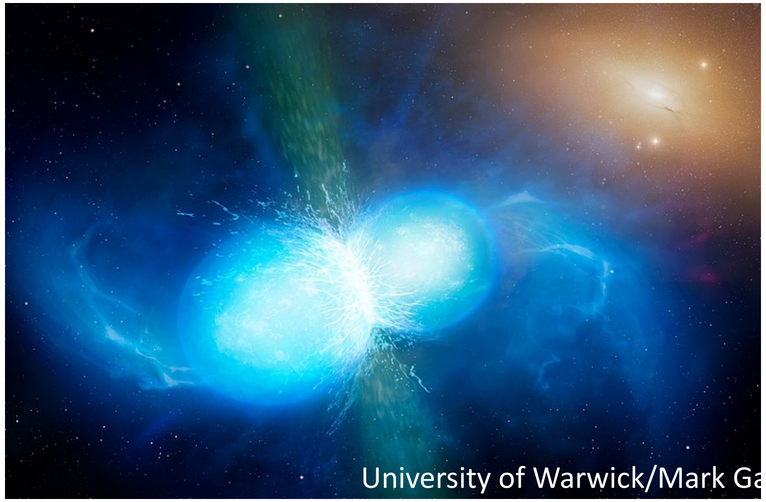
	Supernova (SN) Models		Kilonova (KN) Models	
Label	SA ($\nu\star$)	SB (MHD)	KA	KB
Simulations	SN *forced* neutrino-driven wind: 4 trajectories from Arcones et al. (2007); Arcones & Janka (2011b) with modified $Y_e = 0.31, 0.35, 0.42, 0.48$	MHD SN: 2 trajectories from Mösta et al. (2018b)	KN dynamical ejecta: 2 trajectories from Bovard et al. (2017) diskwind: 2 trajectories from Just et al. (2015)	
Scaling	HD160617: Yb, Te, Cd and Zr	HD160617: Yb and Zr	HD160617: Yb and Zr	J0954+5246: Yb and Zr
Mixing fractions f	$f_{0.35}$=0.757, $f_{0.42}$=1.778, $f_{0.48}$=0.770	3.137	3.980	0.819



Core collapse Supernovae



Magneto-rotational supernovae (MHD)



Neutron star mergers (kilonovae)

Nucleosynthesis simulation with PRISM

1) Baseline: AME2016 + FRDM2012 masses; Nubase2016 spontaneous fission and β decay rates; theoretical calculations from LANL (HF for n capture and n-induced fission; QRPA+HF for β-delayed fission and β-delayed neutron emission); symmetric split fission yields.

2) Variations: HFB masses (Goriely et al. 2009); β-decay rates from Marketin et al. (2016) (MKT); fission yields from Kodama & Takahashi (1975).

r-process calculations

	Supernova (SN) Models		Kilonova (KN) Models	
Label	SA ($\nu\star$)	SB (MHD)	KA	KB
Simulations	SN *forced* neutrino-driven wind: 4 trajectories from Arcones et al. (2007); Arcones & Janka (2011b) with modified $Y_e = 0.31, 0.35, 0.42, 0.48$	MHD SN: 2 trajectories from Mösta et al. (2018b)	KN dynamical ejecta: 2 trajectories from Bovard et al. (2017) diskwind: 2 trajectories from Just et al. (2015)	
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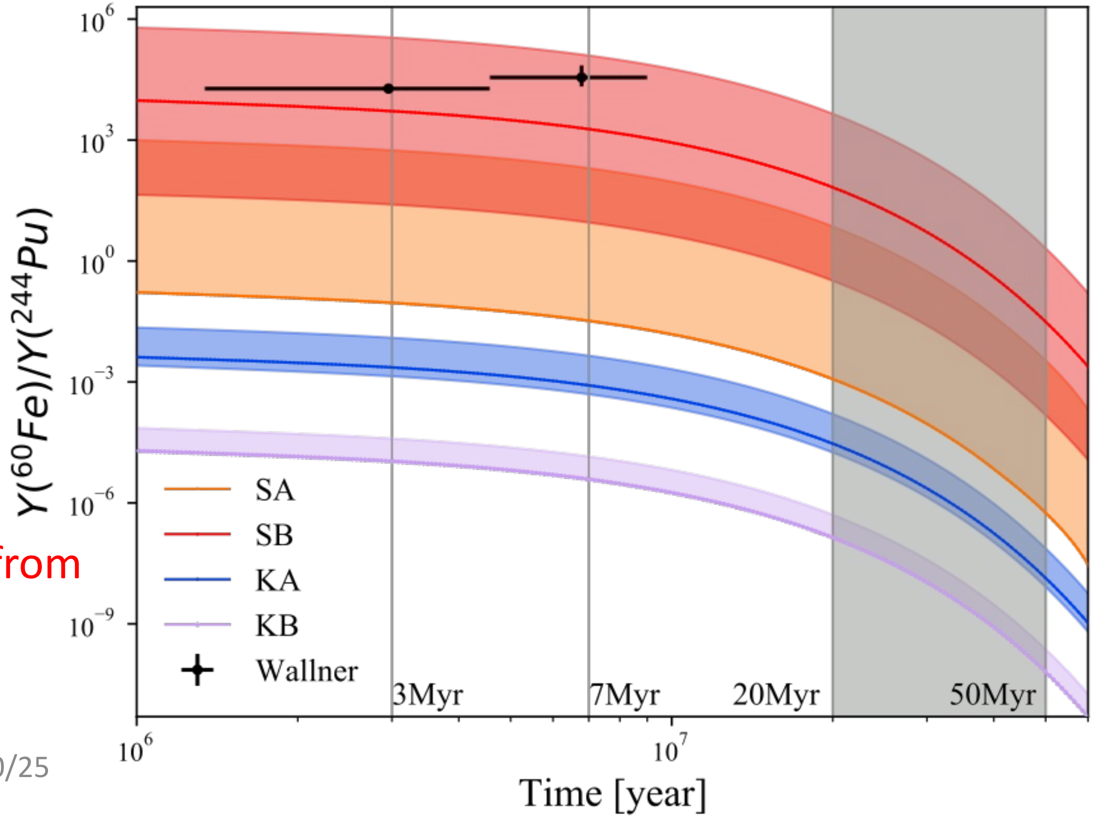


^{60}Fe only from r process

- SN: ^{60}Fe mostly comes from explosive nucleosynthesis and stellar burning → ^{60}Fe in r process production serve as a lower limit for SN models SA and SB
- For direct deposition, ^{60}Fe/^{244}Pu:
  - ➢ KN models fail
  - ➢ "modified " SN neutrino driven wind and MHD SN can work → must be rare SN

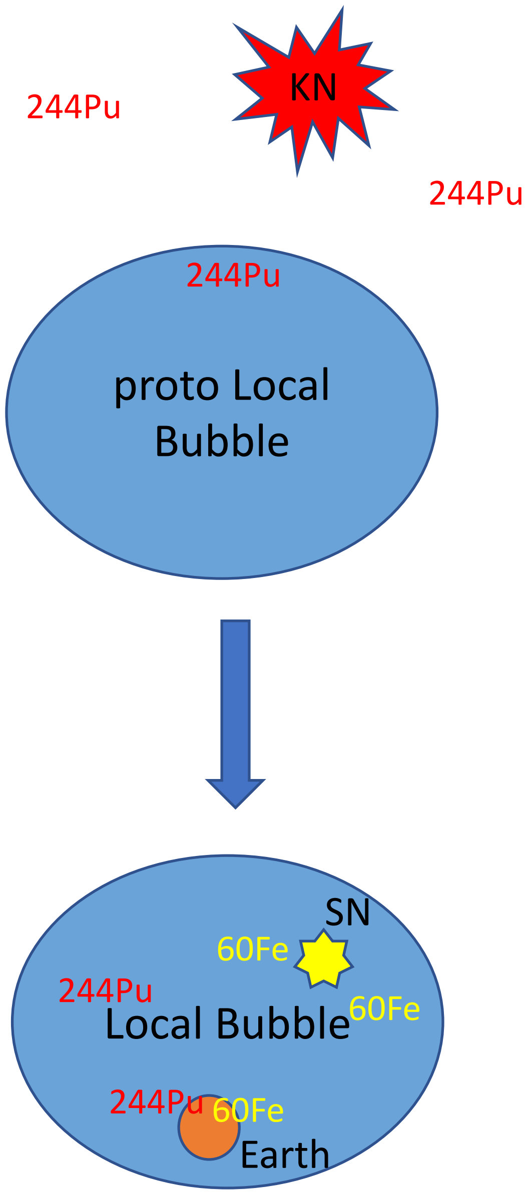
^{244}Pu: Two-Step Kilonova Scenario

Kilonovae/Neutron Star mergers:

- ➢ Robust r-process sites → ample ^{244}Pu productions
- ➢ Rare events
- ➢ Unlikely within Local Bubble

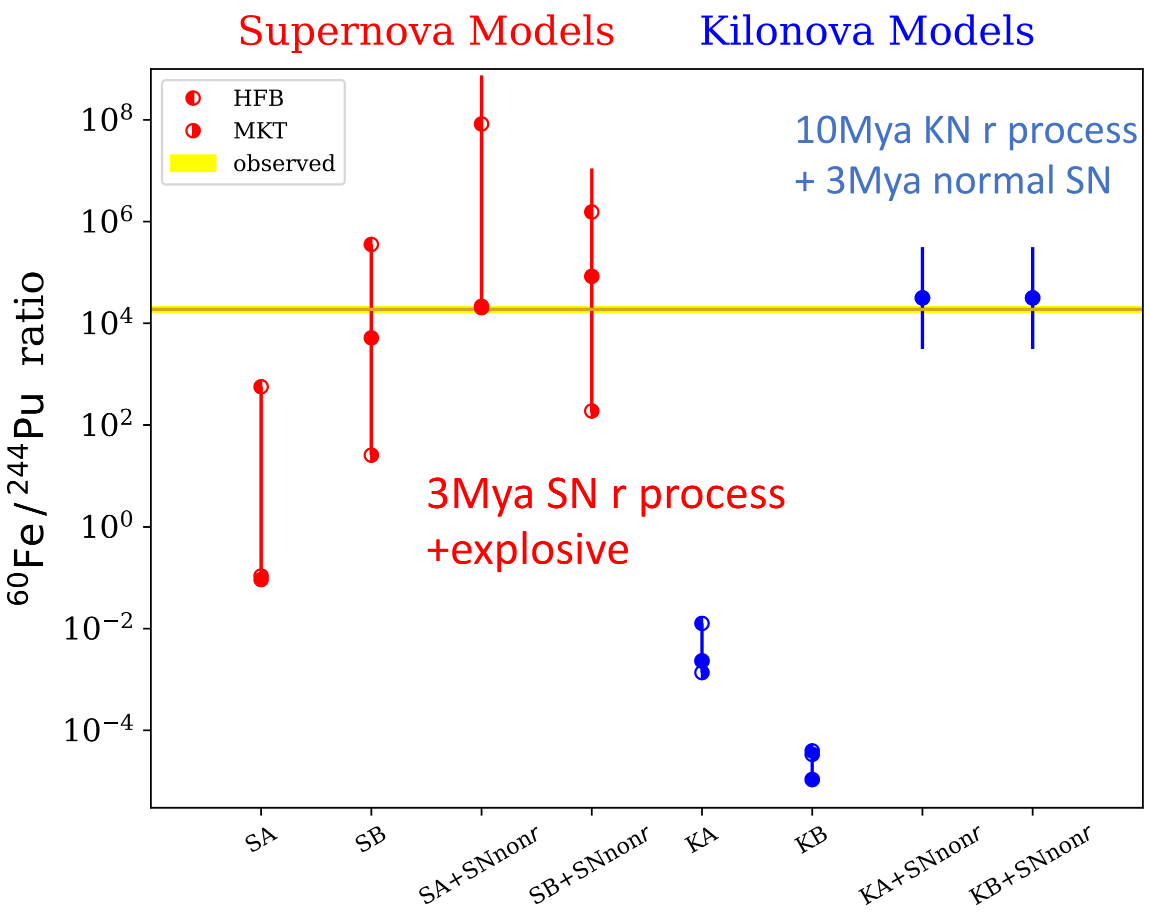
"Two-step" scenario for Kilonovae:

- ❖ More than ~10-20 Mya, a KN exploded, ejecting ^{244}Pu-bearing r-process material
- ❖ Some of the KN ejecta collided with and was mixed into the molecular cloud giving rise to the Local Bubble
- ❖ Some of the ^{244}Pu was incorporated into dust grains, and a more recent SN swept the ^{244}Pu-bearing dust to bombard the Earth.



Wang, X., et al., 2021, ApJ 923, 219

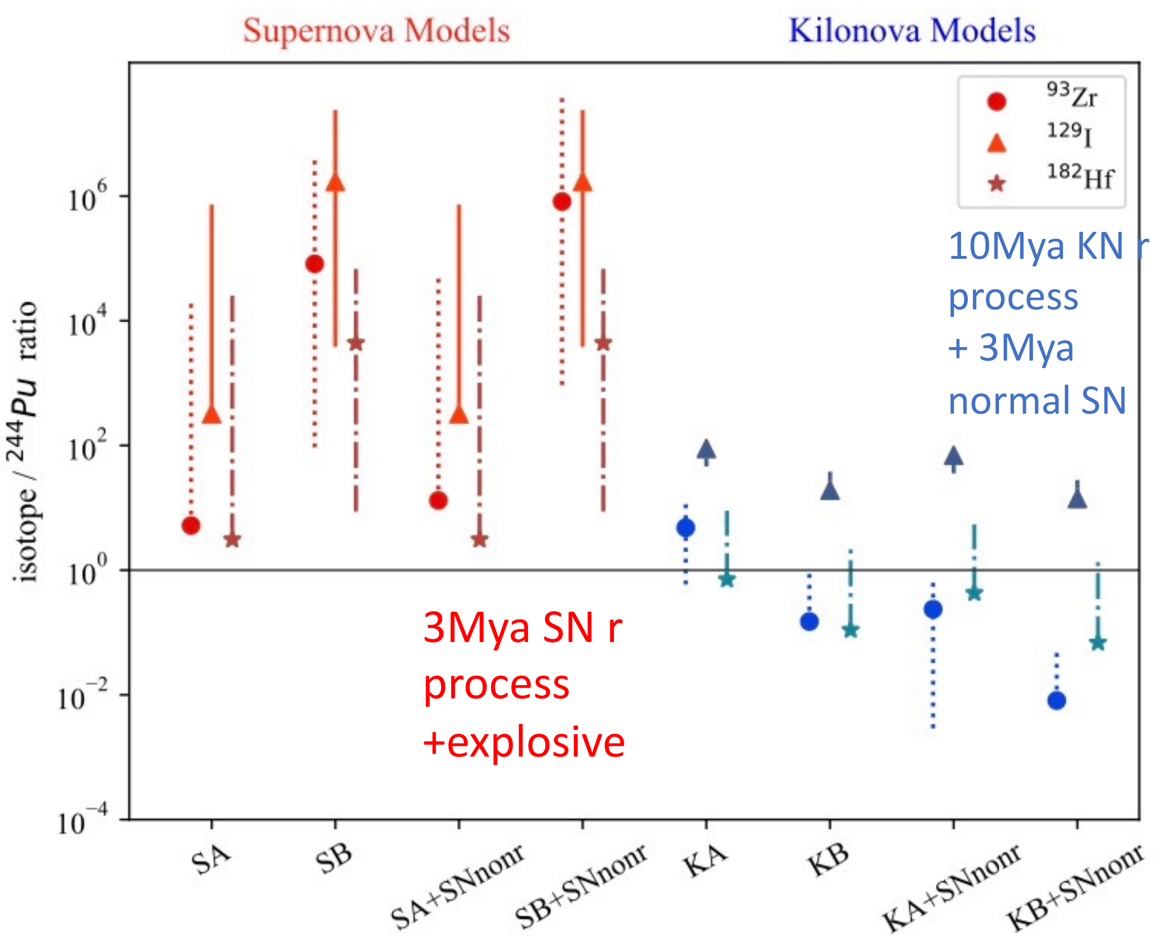
^{244}Pu from Near-Earth Supernovae or Kilonovae



- ^{60}Fe/^{244}Pu measurement :
  - Direct deposition: "modified " SN neutrino driven wind and MHD SN can work → must be rare SN
  - Two step KN scenario: 10Mya-50Mya KN + a normal non-r-process SN
- Tests: other long-lived r-process species ^{93}Zr, ^{129}I, ^{182}Hf….

Wang, X., et al., 2023, ApJ 948, 113

^{244}Pu from Near-Earth Supernovae or Kilonovae



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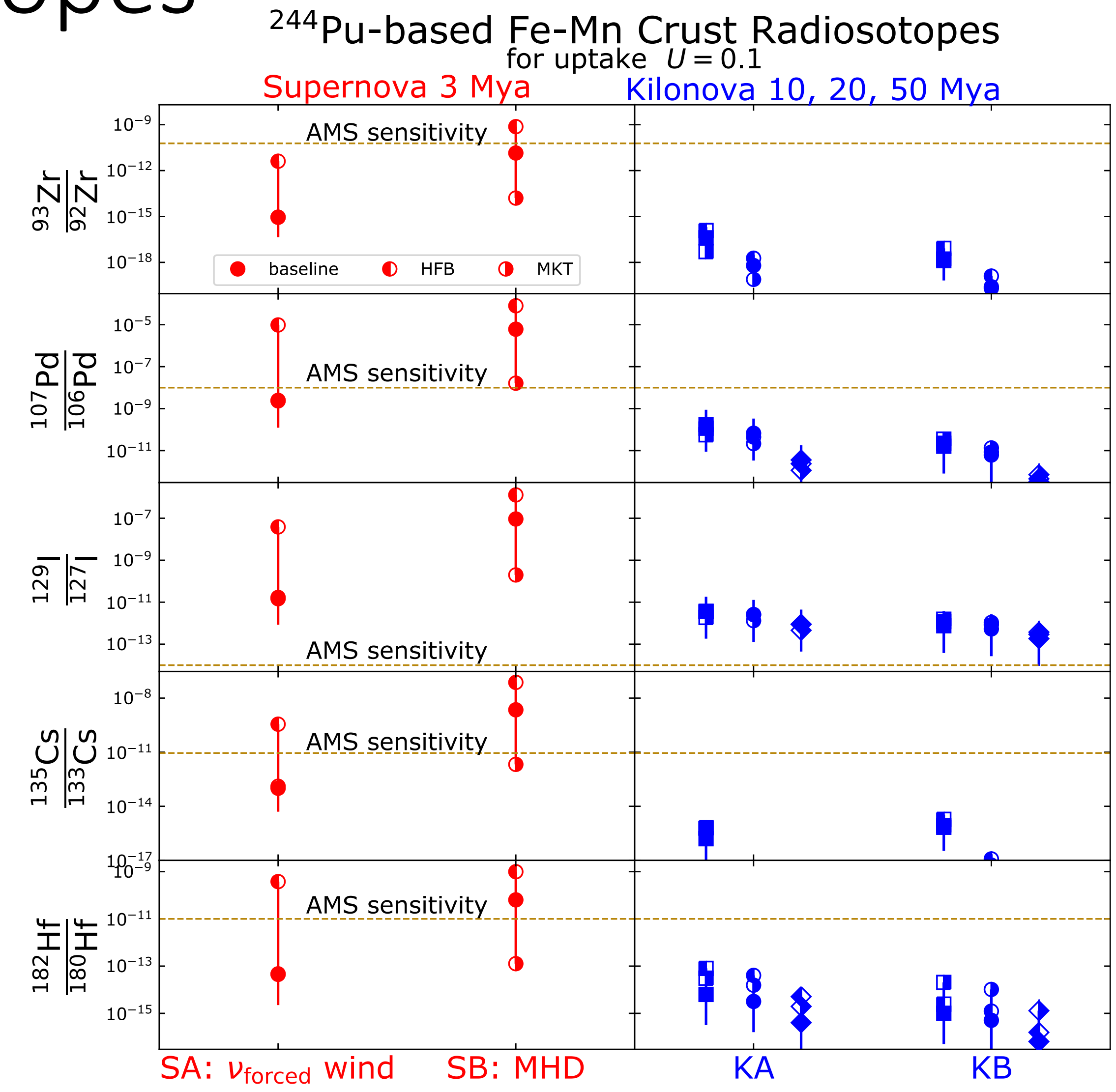
Wang, X., et al., 2023, ApJ 948, 113

Predictions for future measurement of the r-Process Radioisotopes

Wang, X., et al., 2021, ApJ 923, 219



Deep-ocean crusts

→With current AMS sensitivities, ^{129}I is the most promising.

Predictions for future measurement of the r-Process Radioisotopes

Lunar regolith samples

→ Avoid anthropogenic contamination

→ Future measurements of the samples from Chang'e and Artemis missions

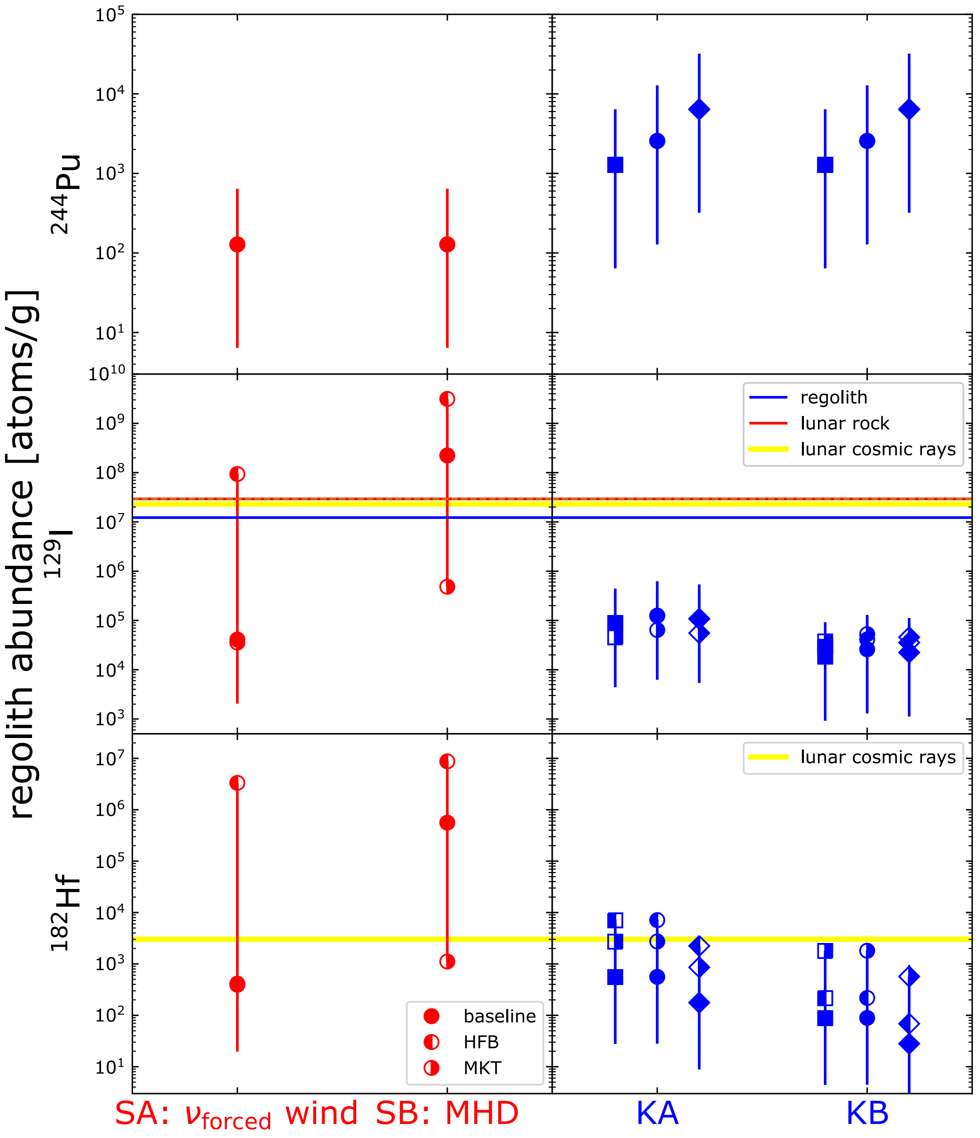


Table 2. Lunar Regolith *r*-Process Radioisotopes From Near-Earth Explosions

Isotope	Cosmic-Ray Targets	AMS Sensitivity [atoms]	Background [atoms/g]	Sample Mass [g] SN	Sample Mass [g] KN
^{129}I	Te, Ba, La	10^5	10^7	$10^{-1} - 10^3$	1–10
^{182}Hf	^{183}W, ^{184}W, ^{186}W	10^7	3×10^3	$2 - 5 \times 10^5$	$3 \times 10^3 - 10^6$
^{244}Pu	–	10^2	–	10	

Wang, X., et al., 2023, ApJ 948, 113

Outlooks

- What are the origins of the heaviest elements in our universe?
  - ➢Solution: Combination of theory, simulations, and observations & experiments

❖more multi-messenger observations of NSMs and supernovae: LIGO, VIRGO, KAGRA, Fermi, JUNO, COSI…

❖more stellar observations of metal-poor stars: Las Campanas Observatory, RAVE, Hubble, JWST, LAMOST…

❖more nuclear data for r-process isotopes: HIAF, FRIB, FAIR, RIKEN…

❖more AMS measurements of heavy radioisotopes on Earth and moon: VERA, NSL, HZDR, CIAE …

- Thanks for your attention. Questions?