MeV nuclear gamma-rays from kilonovae and supernovae as *r*-process sites

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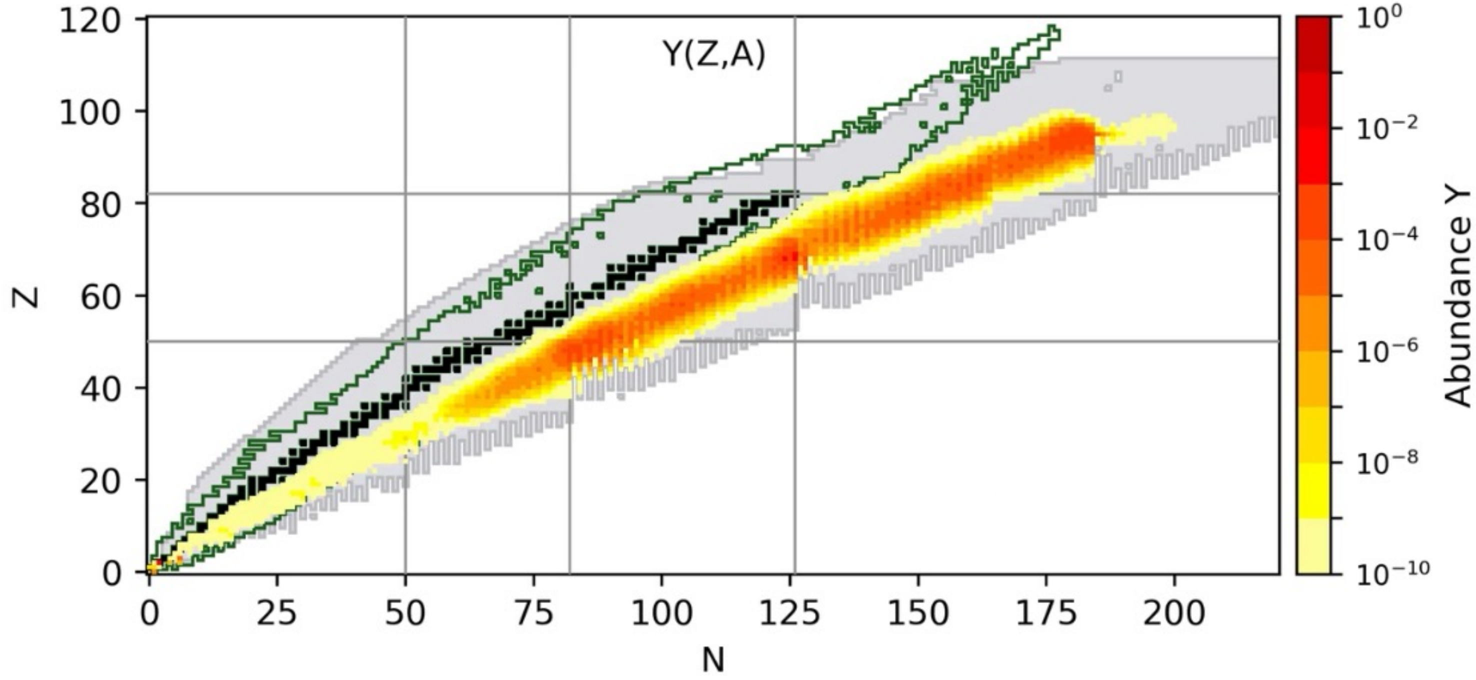
r-process nucleosynthesis

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



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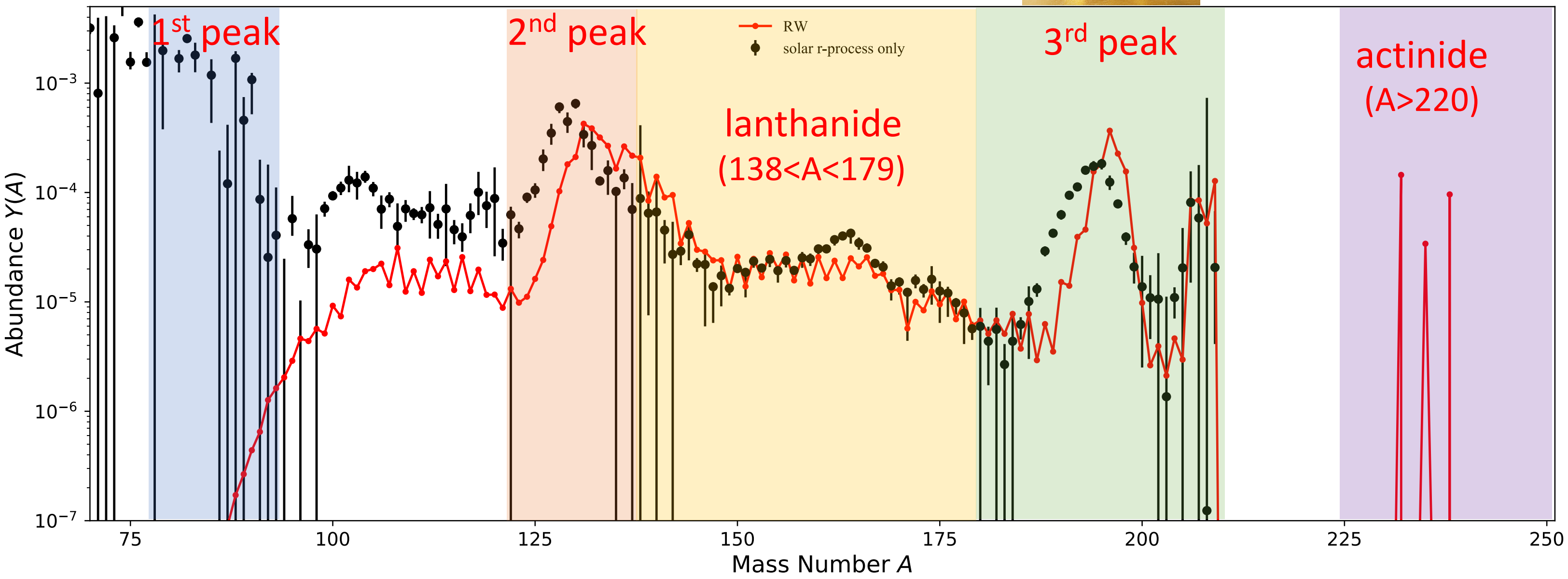
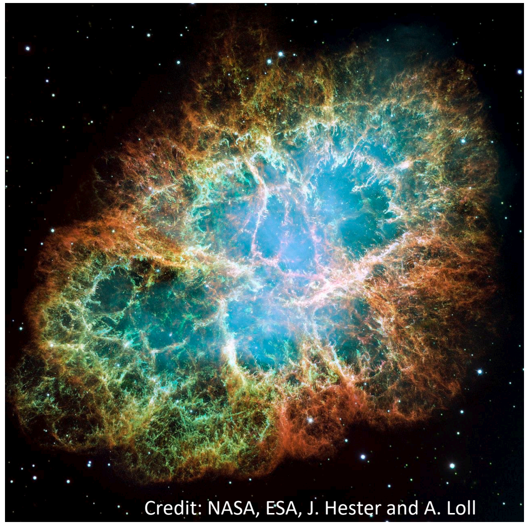
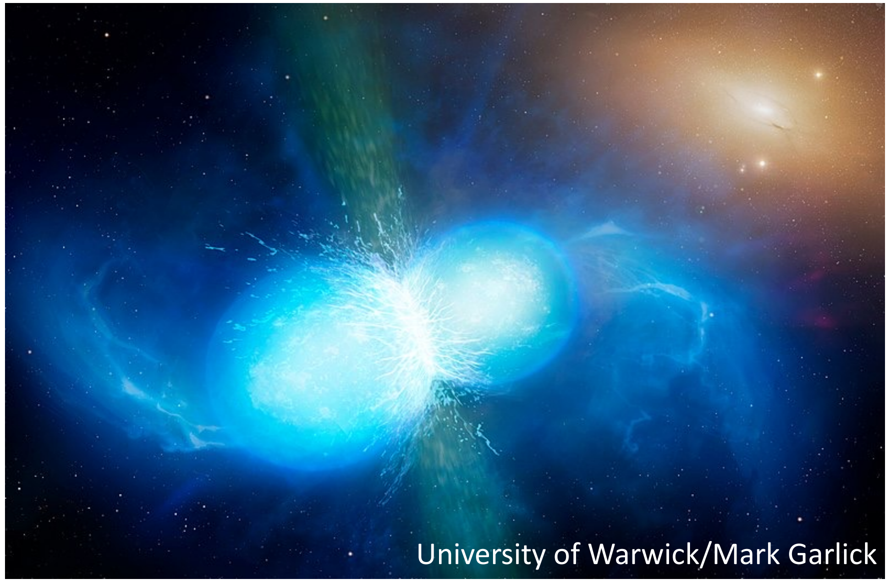


r-process sites: a mystery

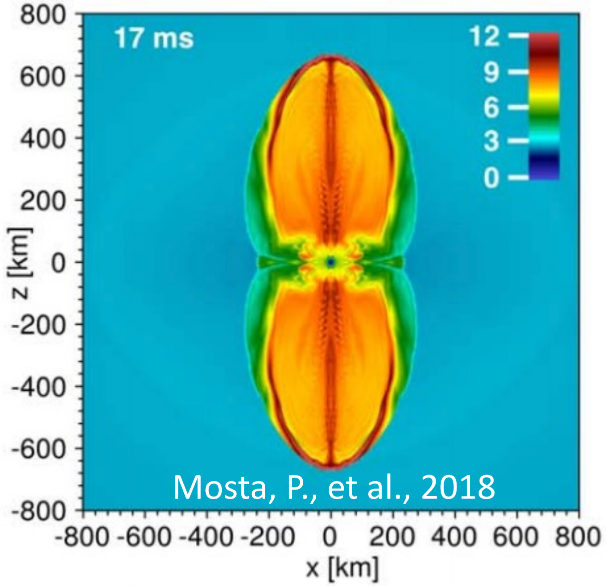
Core collapse Supernovae?
(e.g., Meyer+1992, Roberts+2012)



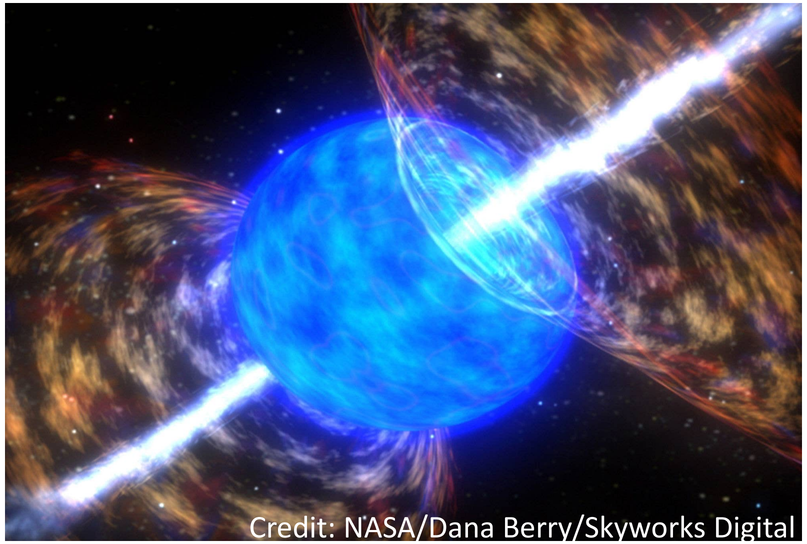
Neutron star + neutron star/black hole mergers
(e,g, Nedora+2020, Foucart+2020, George+2020, etc.)



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



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



Magnetar giant flare
(Patel+2025)

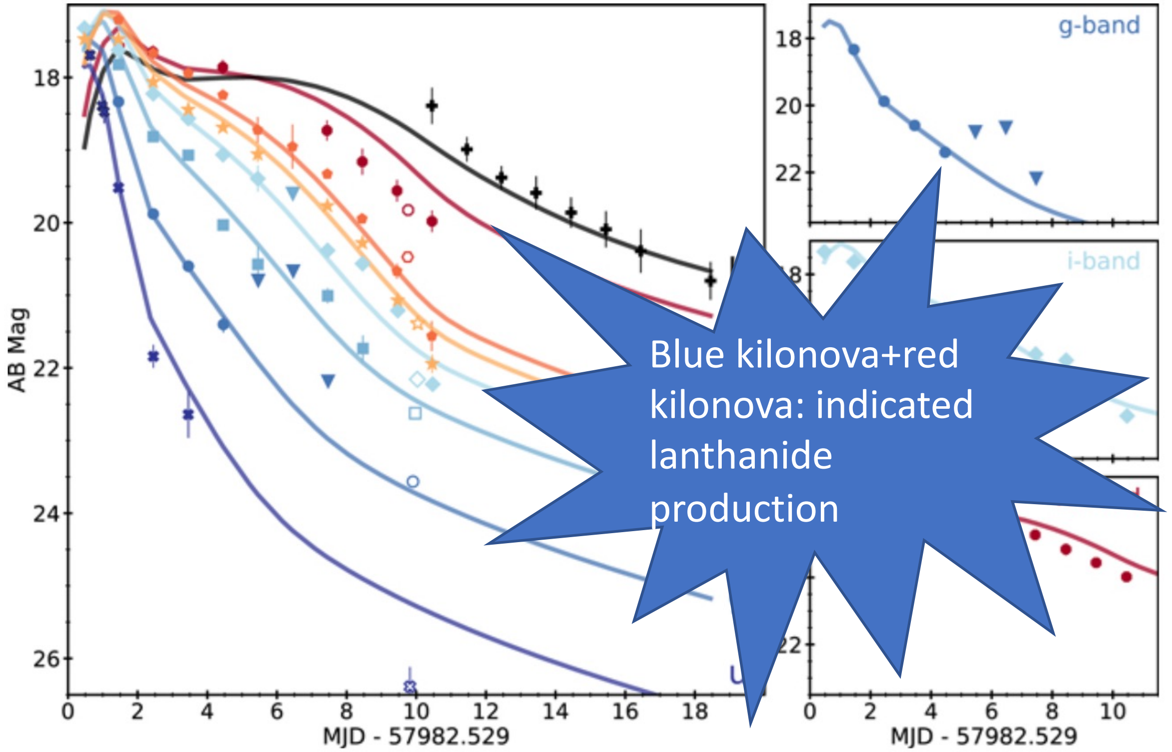
exotic supernovae
(e.g., Fischer+2020)

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

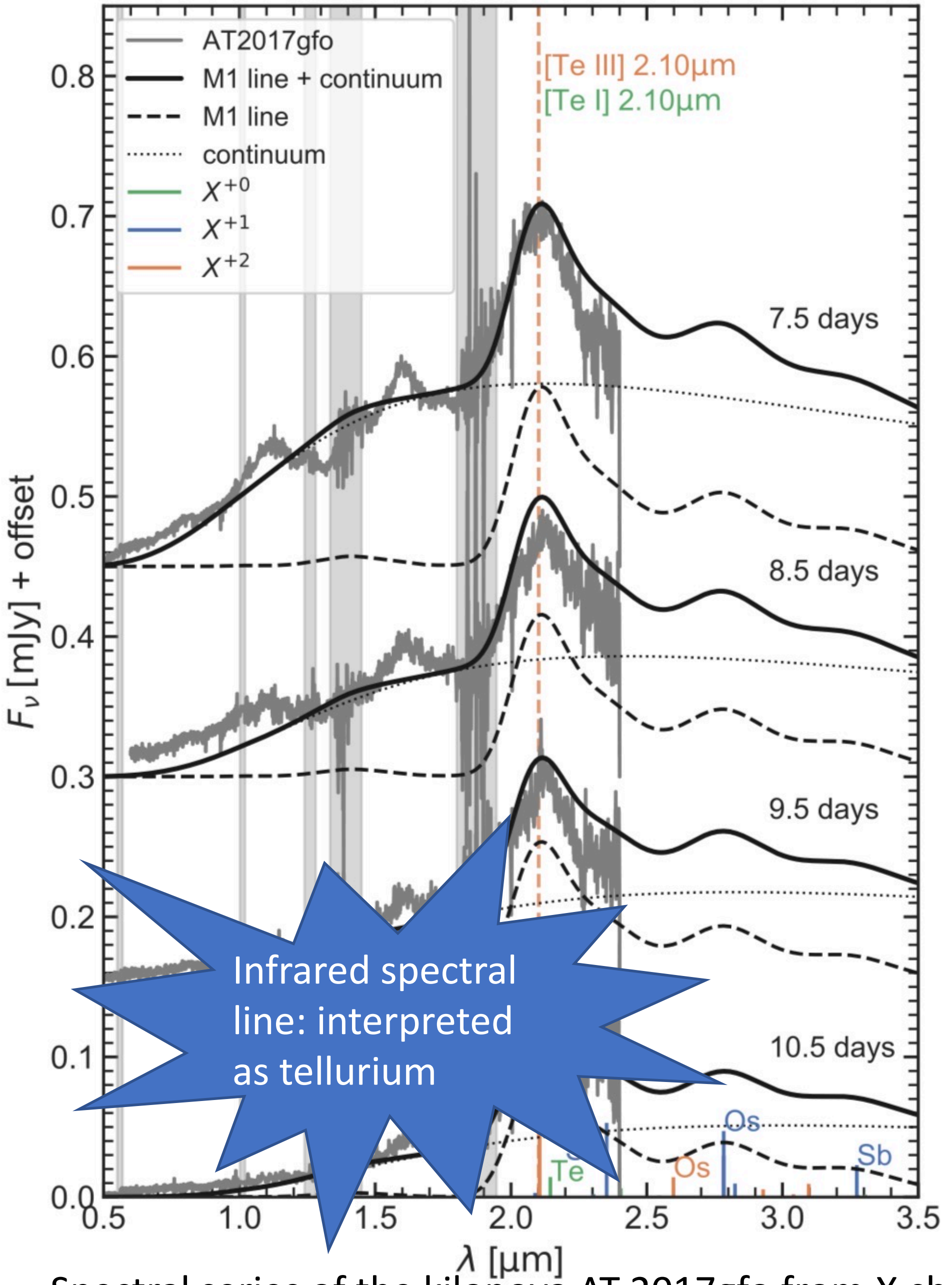
etc.

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

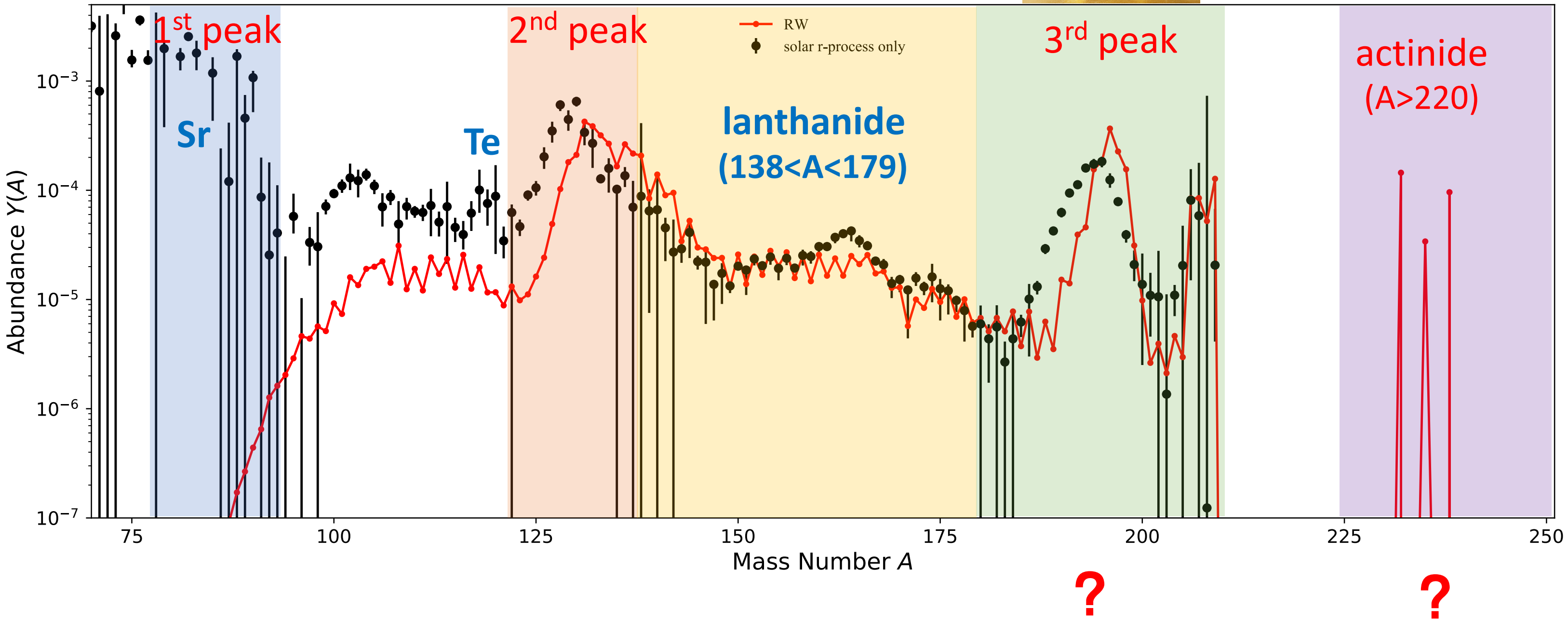


UV, optical, and NIR light curves of the counterpart of GW170817. (Cowperthwaite, P. S., et al., 2017)



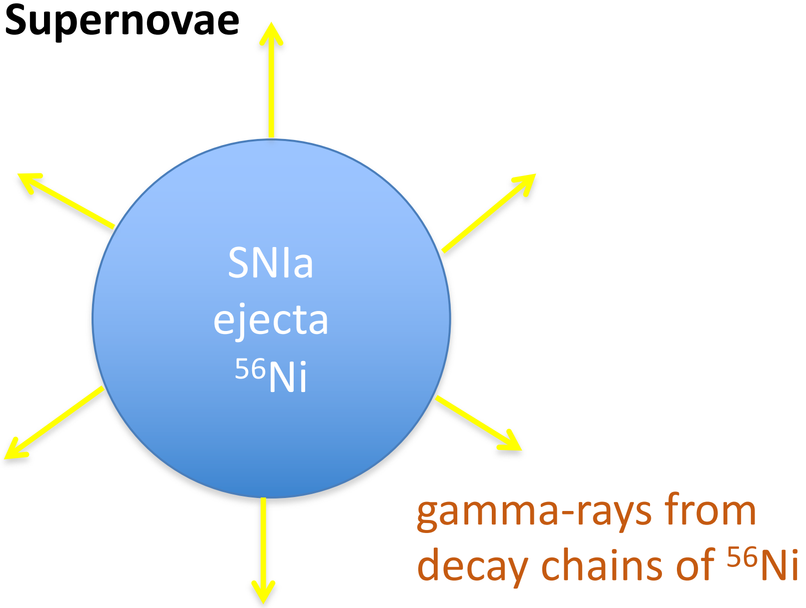
Spectral series of the kilonova AT 2017gfo from X-shooter on VLT. (Hotokezaka, K., et al., 2023)

Did the GW170817 merger produce actinides?



Gamma rays from Neutron Star Mergers

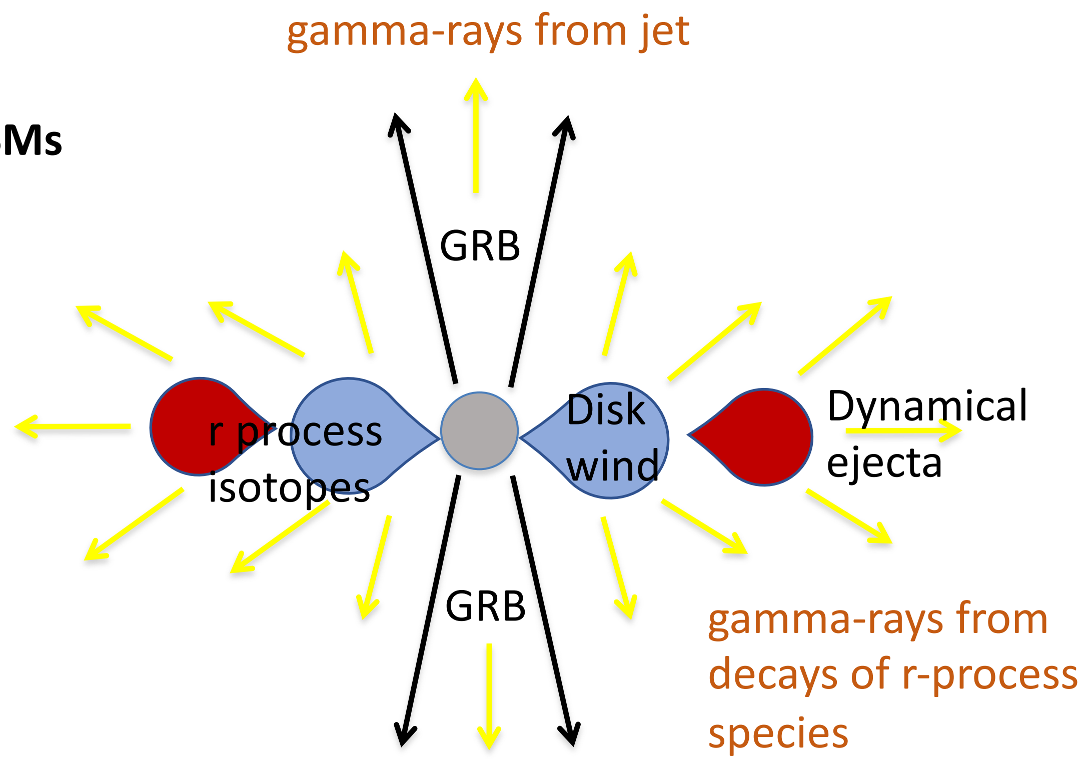
Type Ia Supernovae (SNIa)



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

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

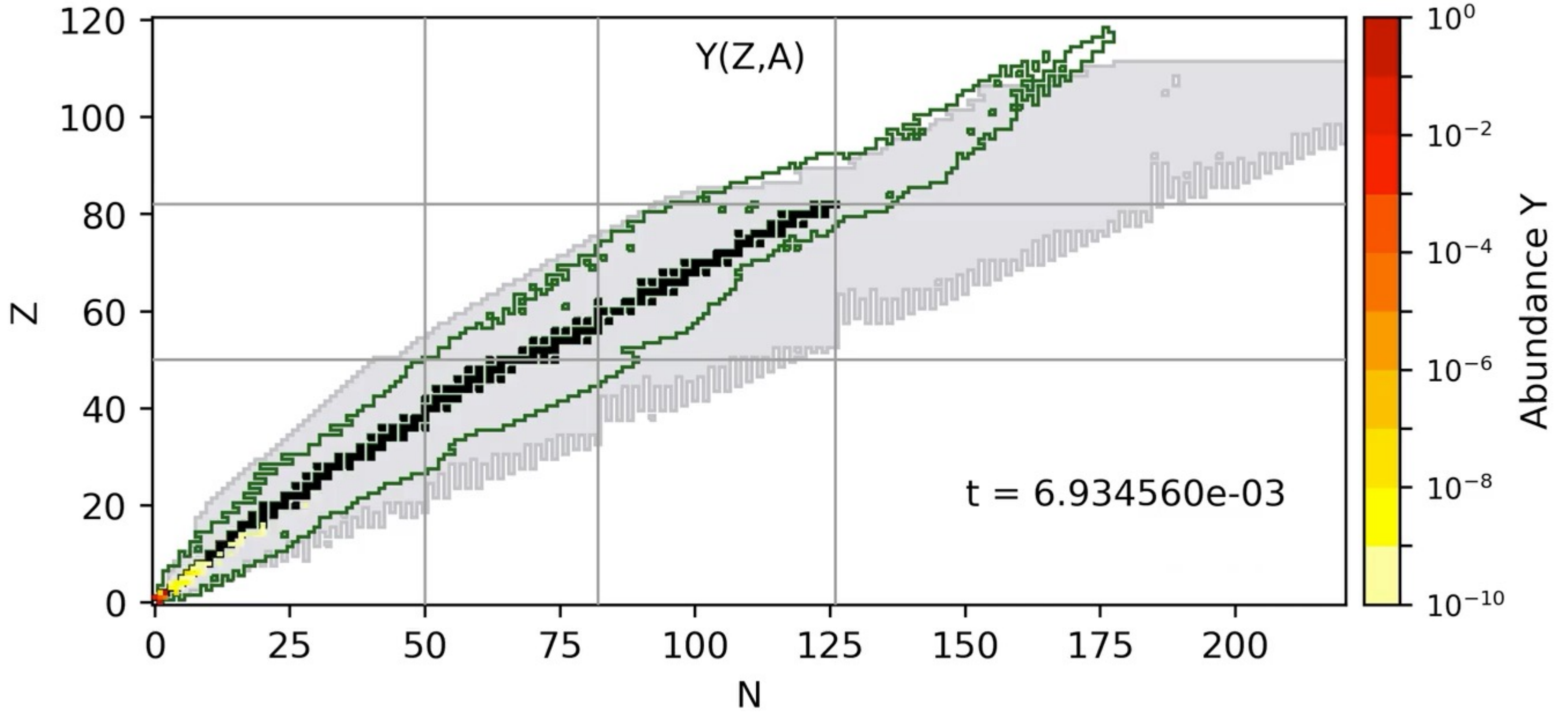
NSMs

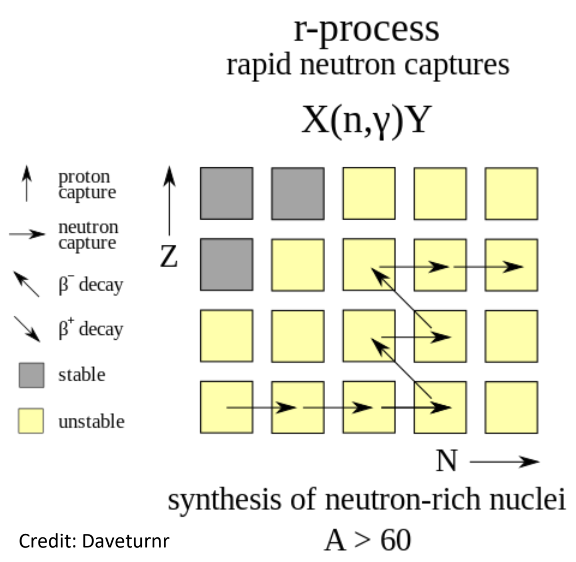


alpha decay, beta decay and nuclear fission

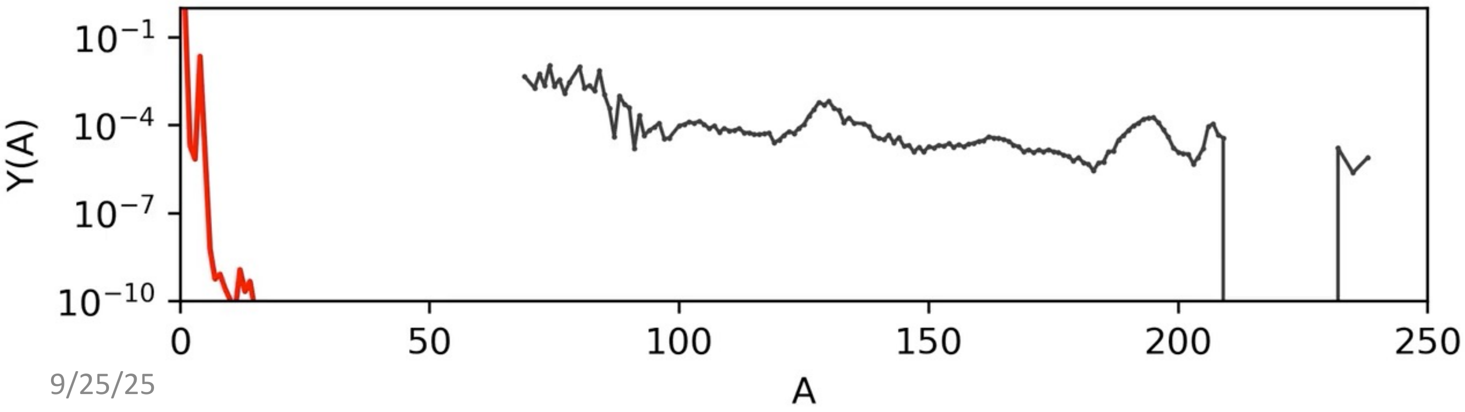
Wang, X., et al. 2020,
ApJL, 903, L3,
arXiv:2008.03335

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!

Incident neutron strikes

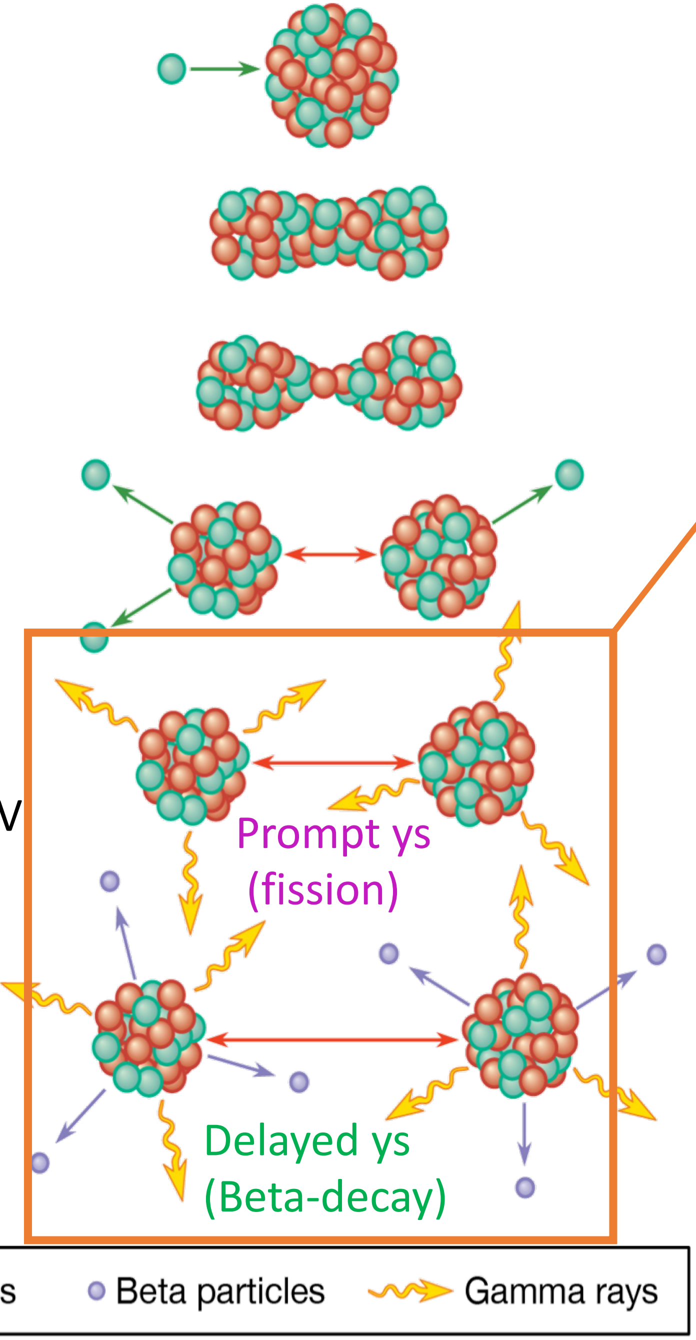
Deformation

Scission

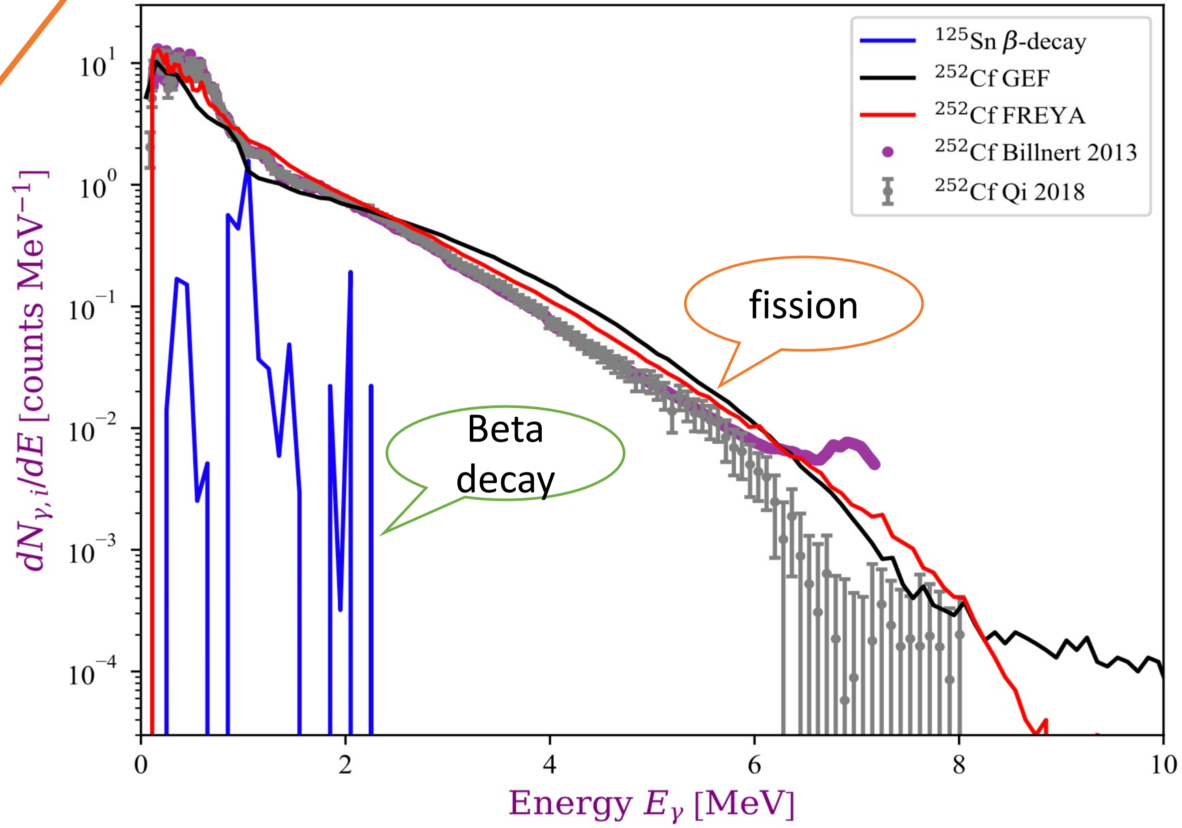
Prompt Neutron Emission

Energy release
Q~200 MeV, TKE~170 MeV

β-delayed emission from n-rich fission products



Credit: Nicole Vassh

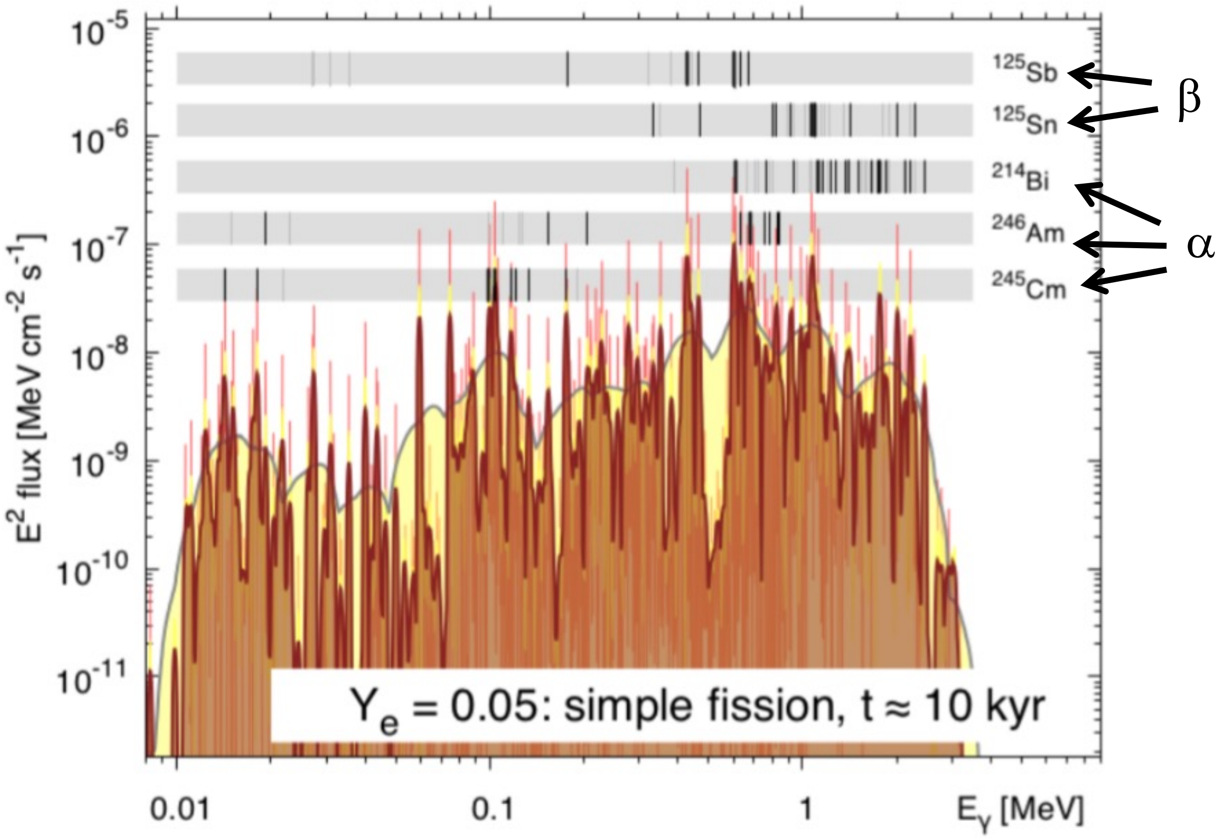


Wang, X., et al. 2020, ApJL, 903, L3,

Gamma rays from neutron star mergers

Emission from NSM remnants

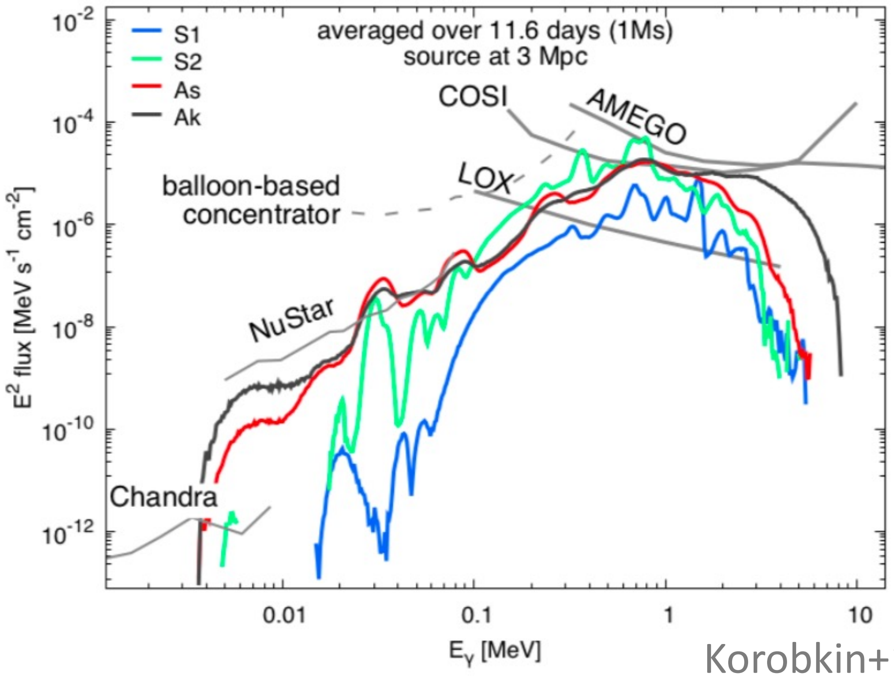
Influential γ emitters from alpha and beta-decay



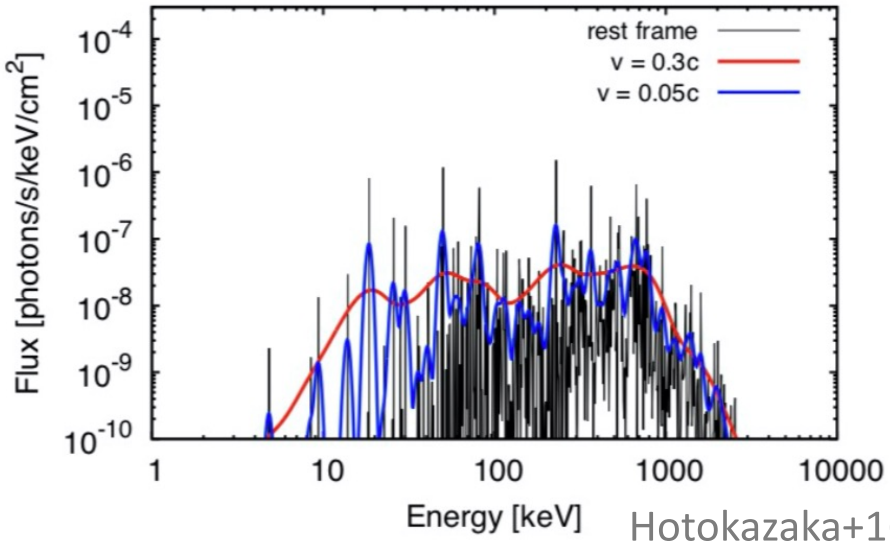
D=10 kpc

Korobkin+19; see also Wu+19

Emission from a nearby kilonova

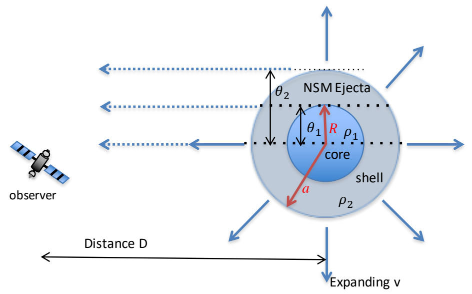


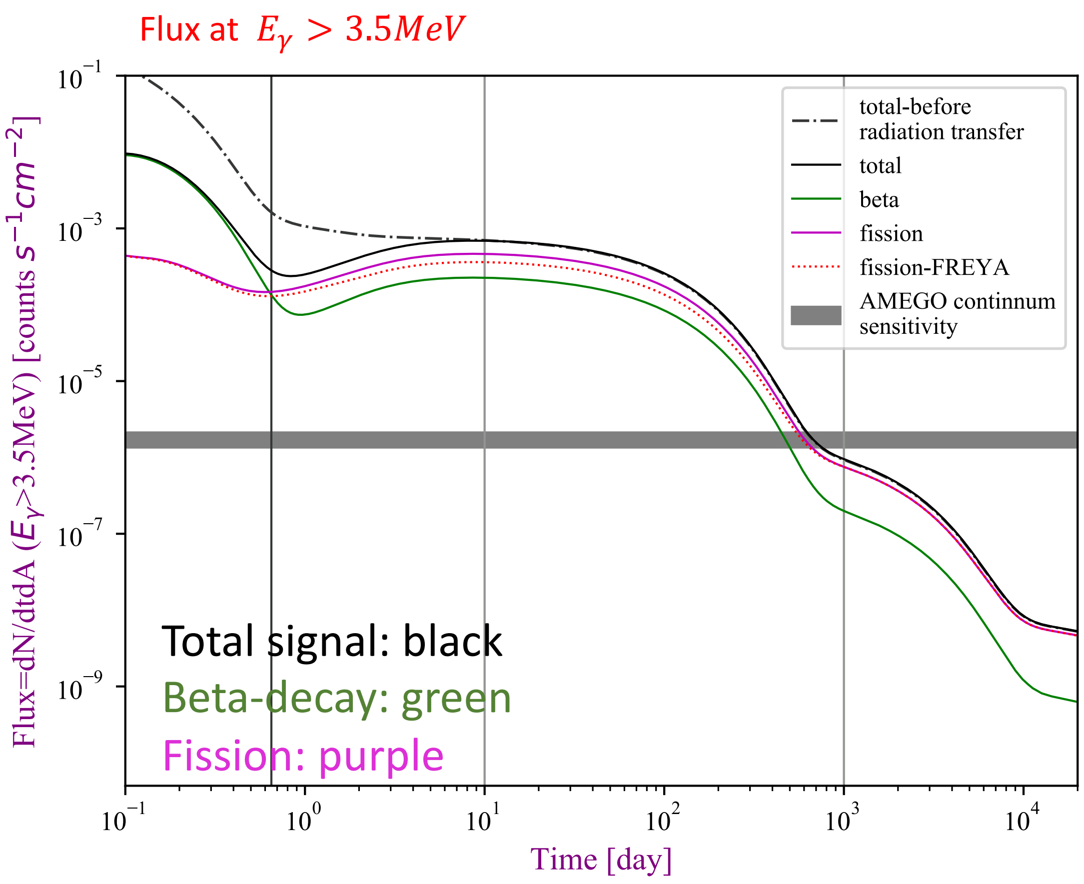
Korobkin+19

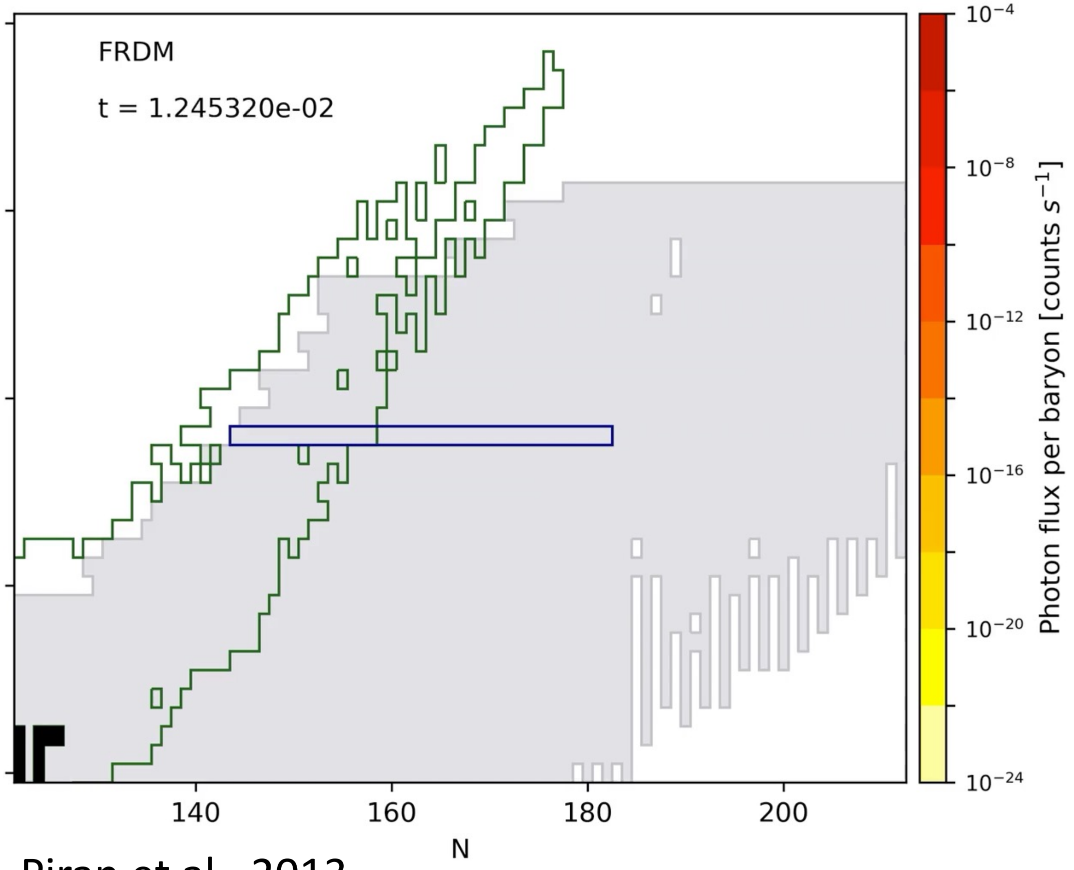


Hotokazaka+16

MeV light curve and contributions from individual fissioning nuclei



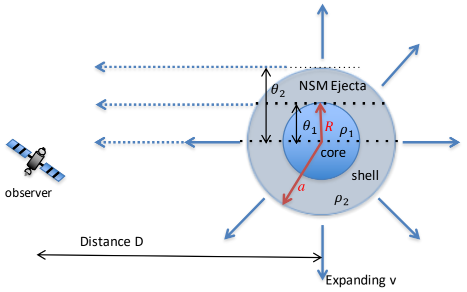




Very neutron rich dynamical ejecta from Rosswog et al., 2013, Piran et al., 2013.
Nuclear data based on FRDM and FRLDM nuclear models

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

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



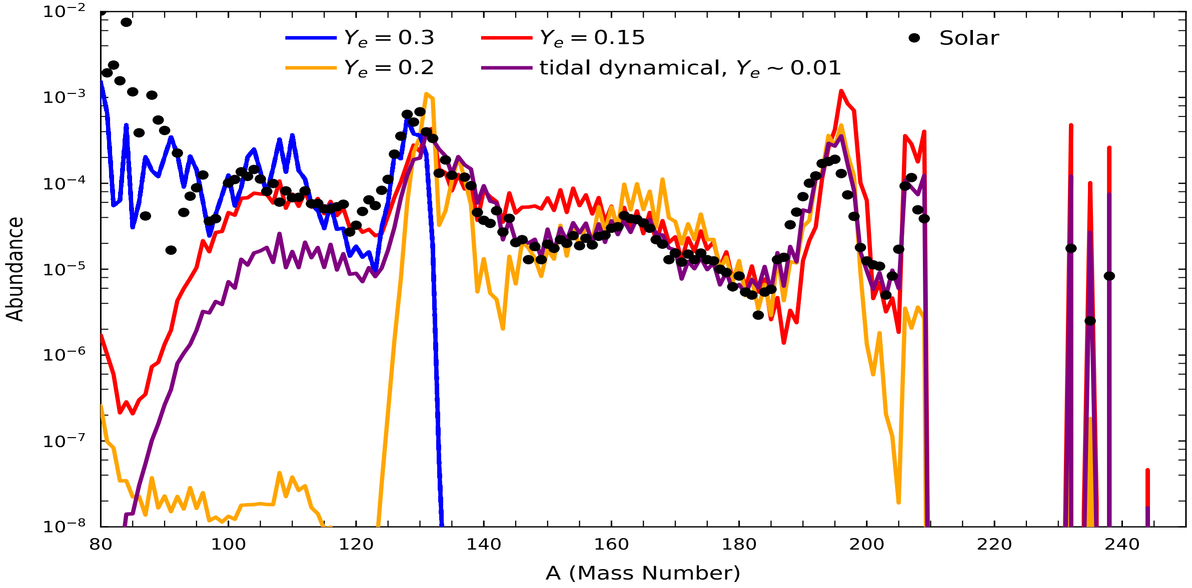
$$Y_e = \frac{n_e}{n_b} = 1 - \frac{n_n}{n_n + n_p} \sim 0.015$$

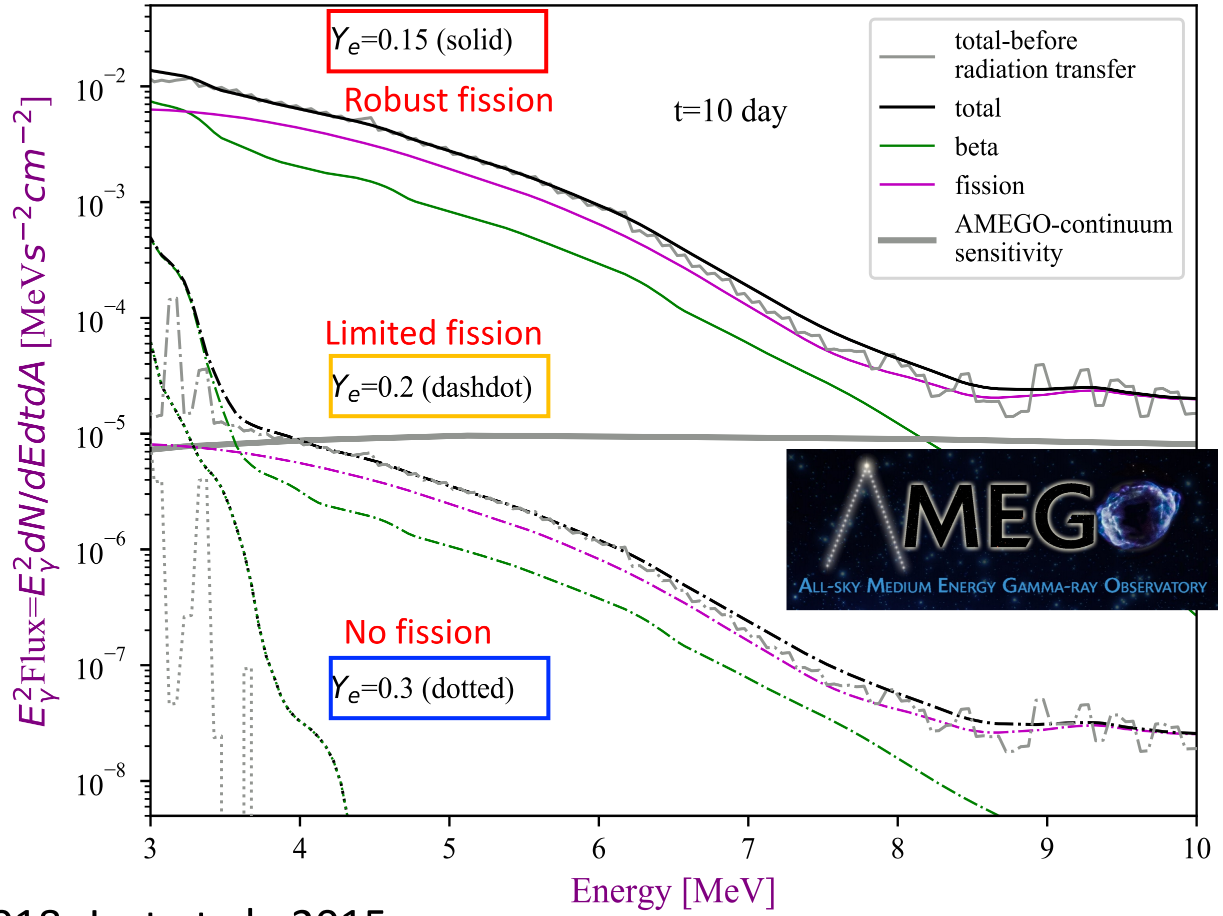
Smaller Y_e: more neutron rich

Total signal: black

Beta-decay: green

Fission: purple





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

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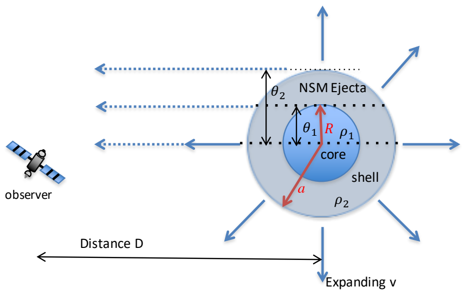

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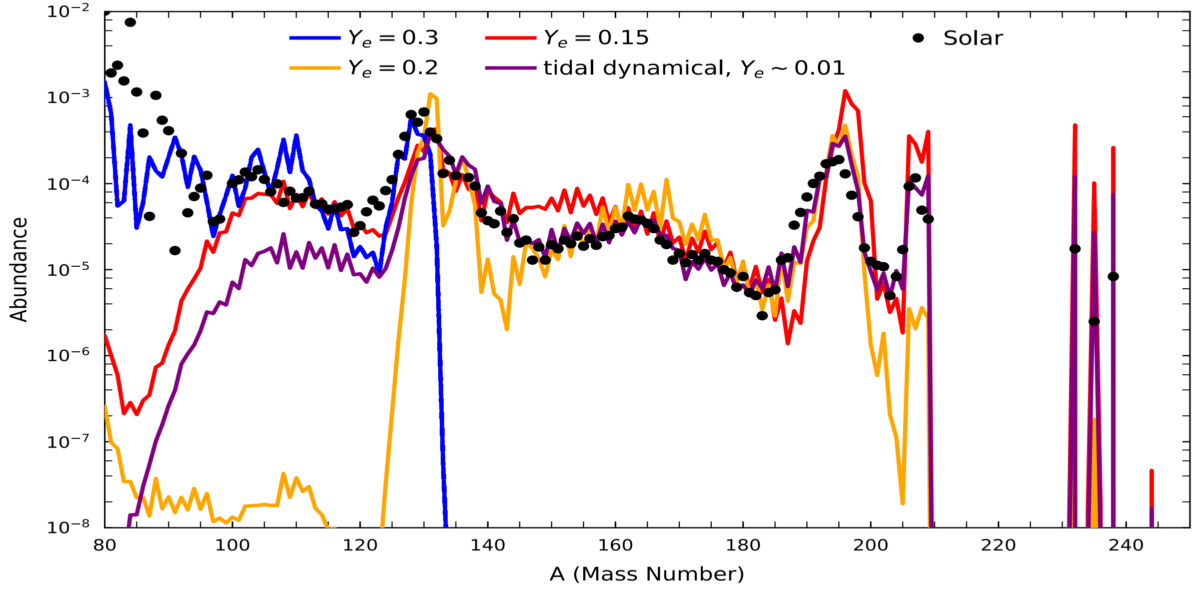

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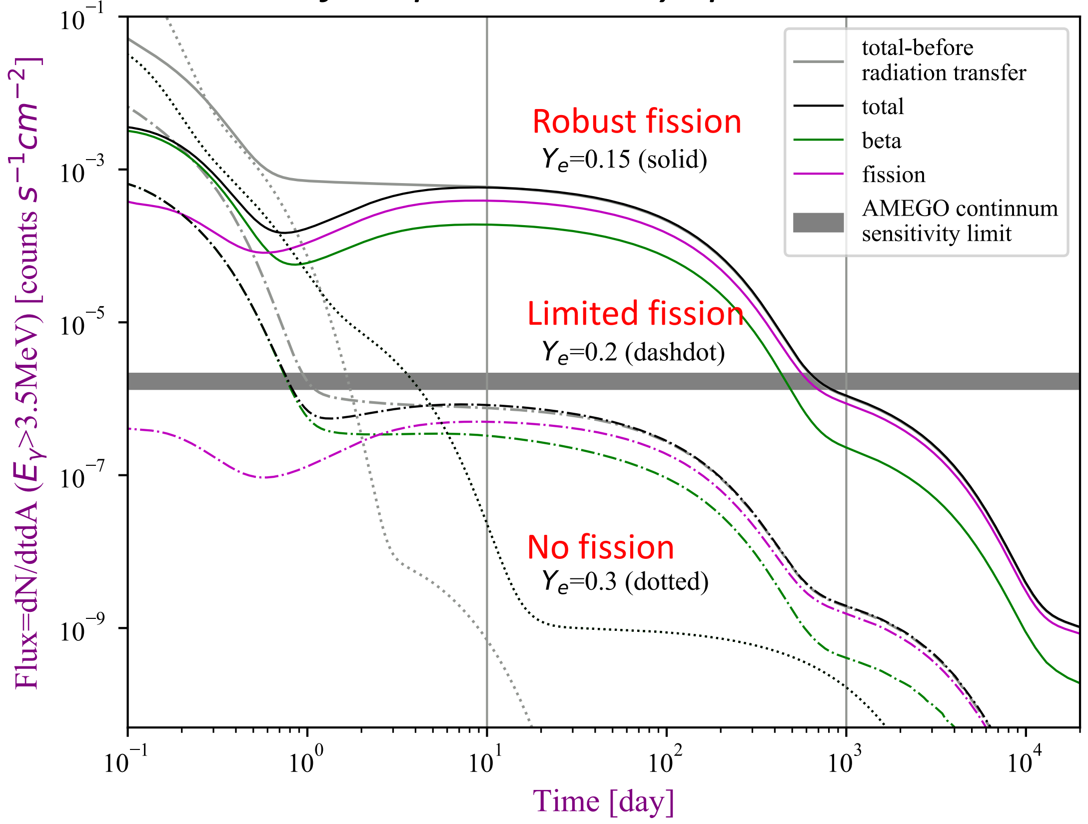
Fission: purple

Visible for up to 1000 days post-event



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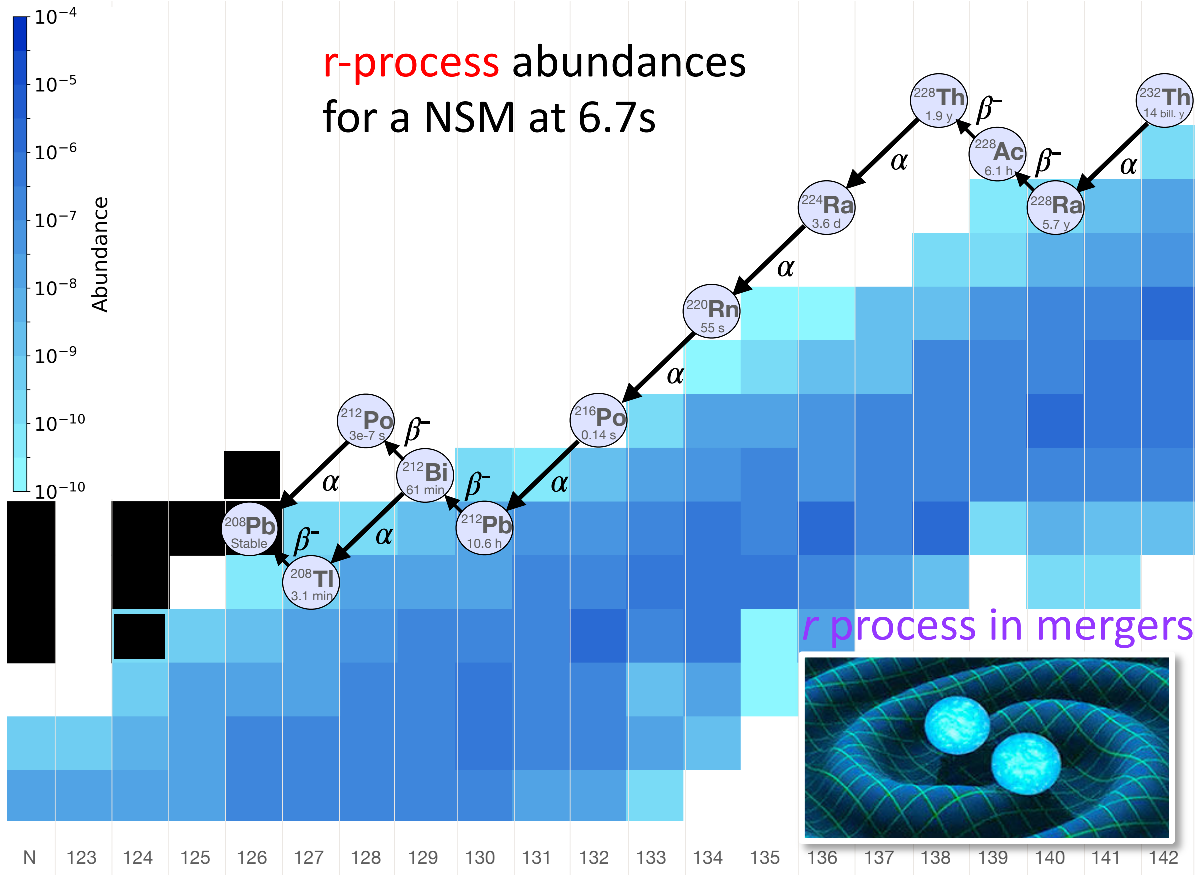
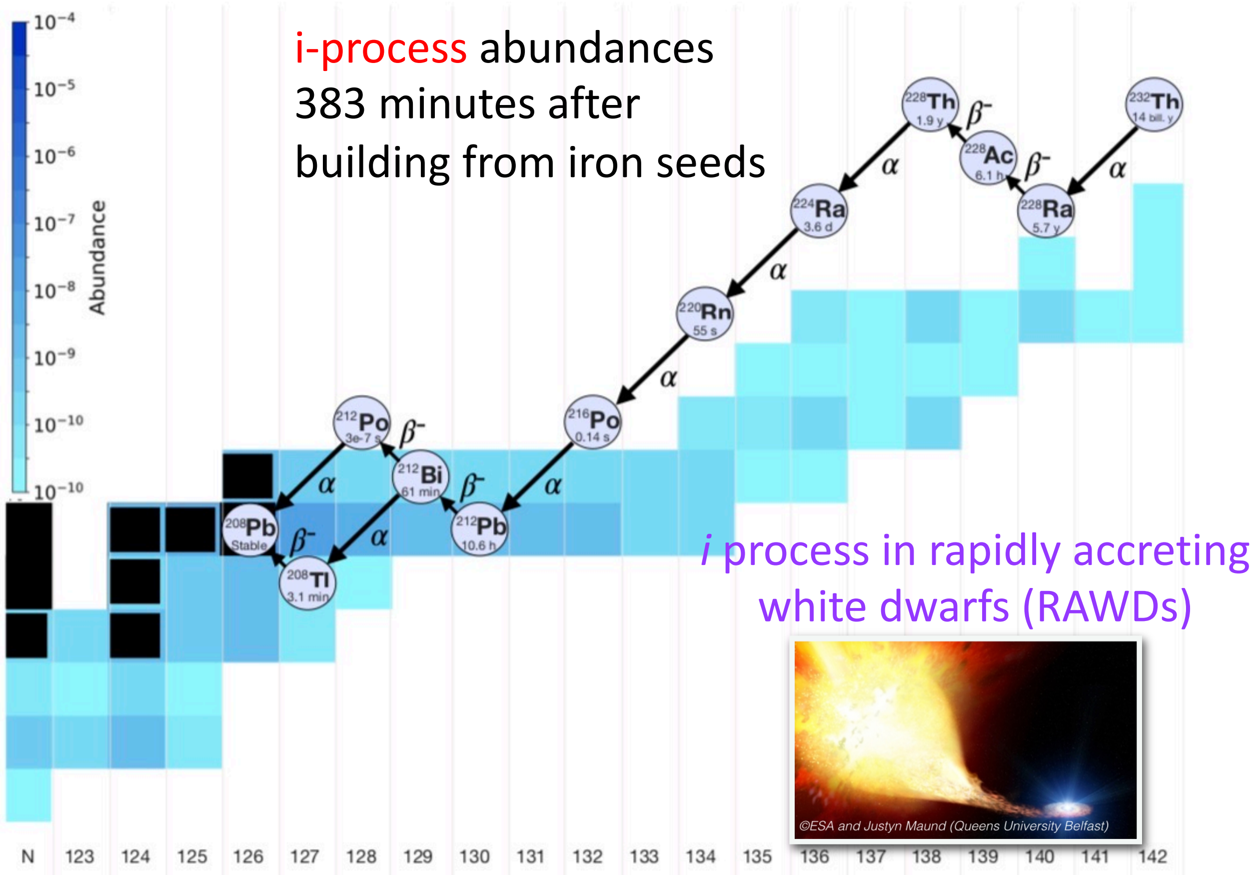
Thallium-208: A Beacon of In Situ Neutron Capture Nucleosynthesis



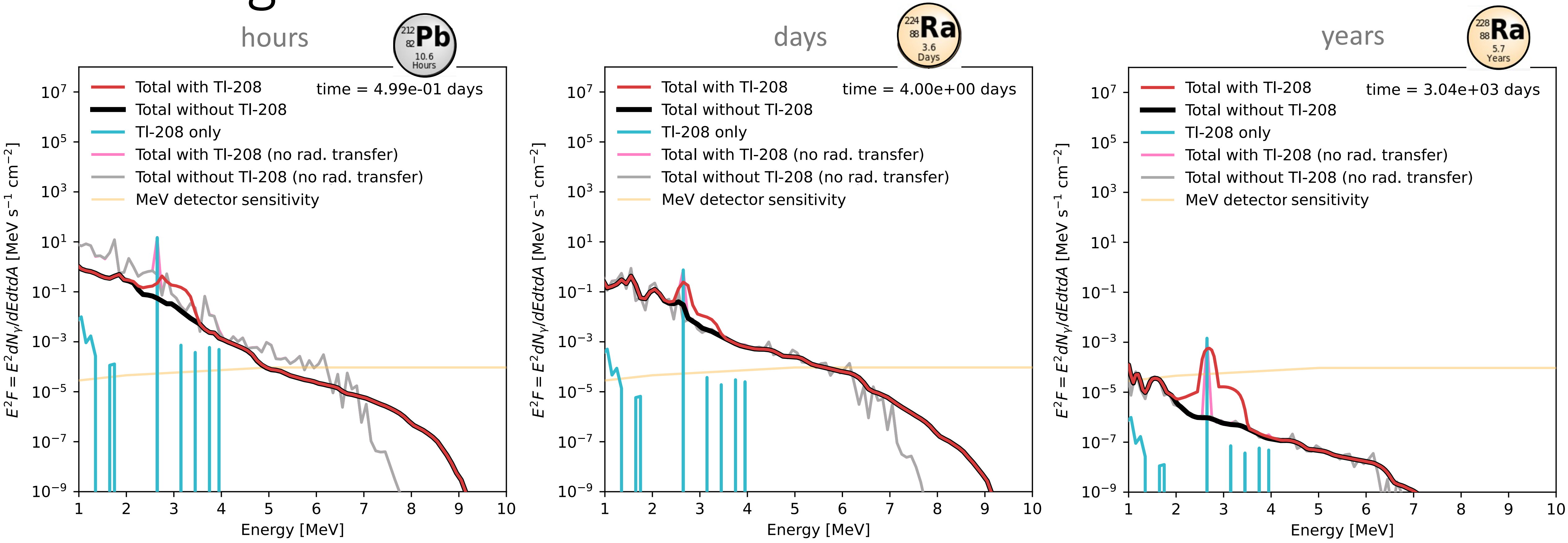


neutron capture processes can populate species along the well-known Th-232 decay chain → yielding Tl-208;

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

2.6 MeV Tl-208 lines emitted from neutron star mergers

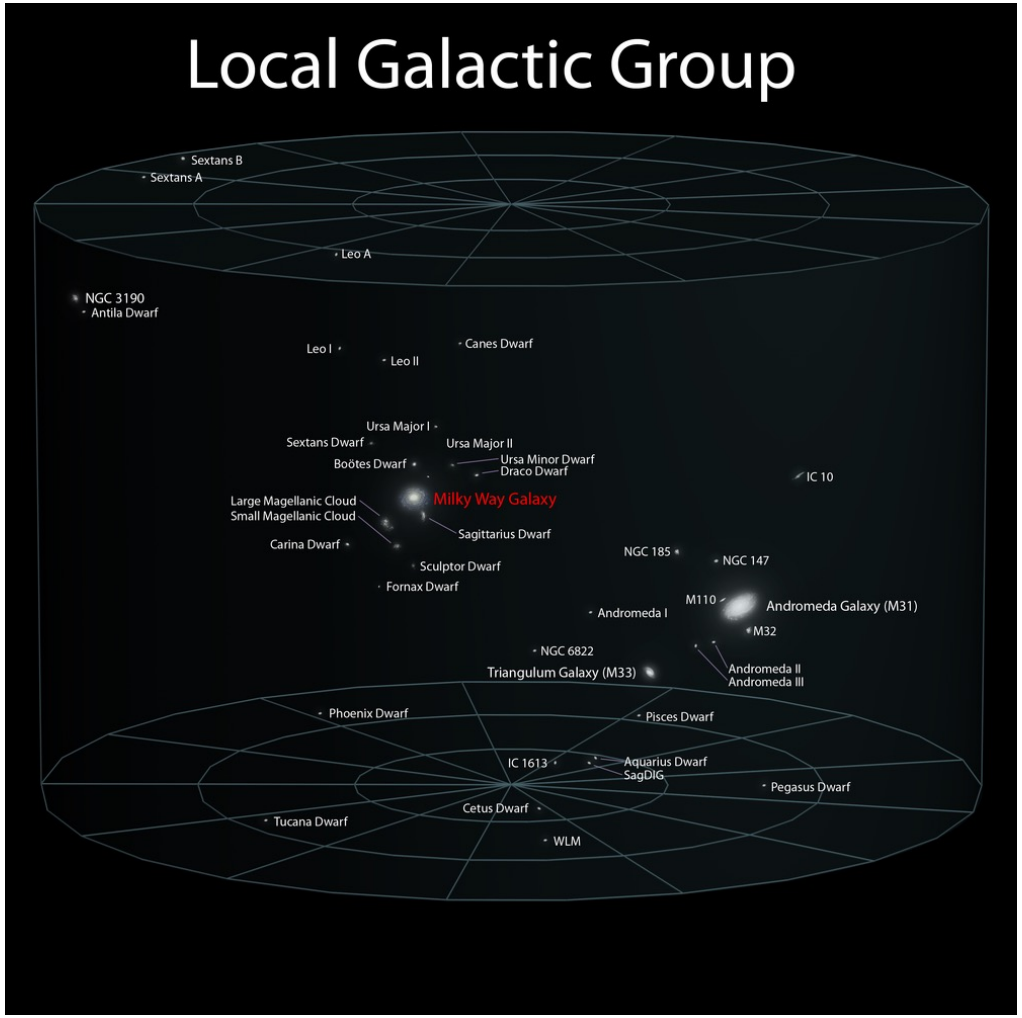


@ 10 kpc (Galactic)

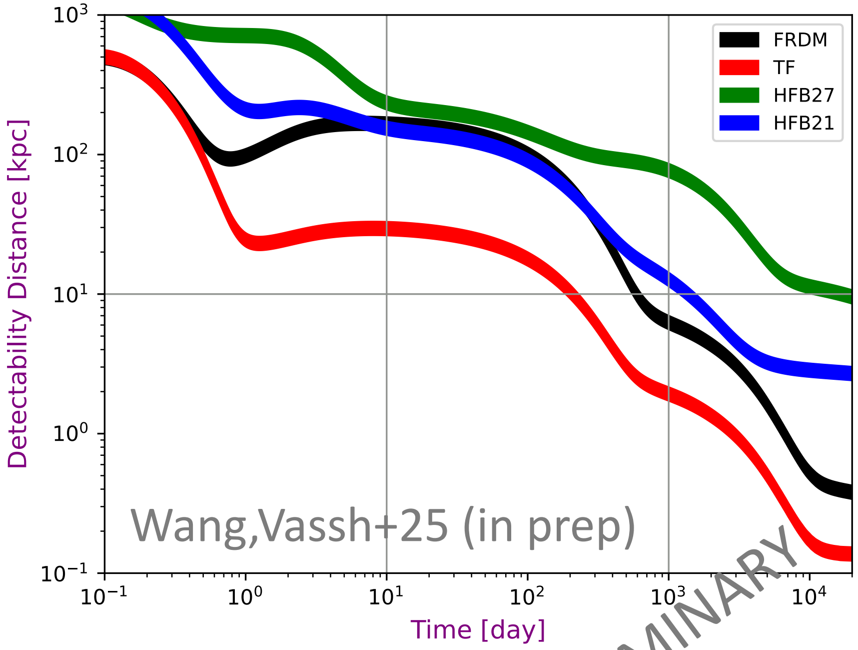
- the 2.6 MeV Tl-208 line explicitly show itself in the spectrum at the timescales: ~12hours - ~10days (after Tl is populated by Pb-212 and Ra-224 decays); 1-20 years (Ra-228 decays);
- Next generation MeV gamma-ray detectors will be able to detect the Tl-208 lines from NSM in Milky Way or nearby galaxies at these timescales.

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

From how far could we see signals given projected detector sensitivity?

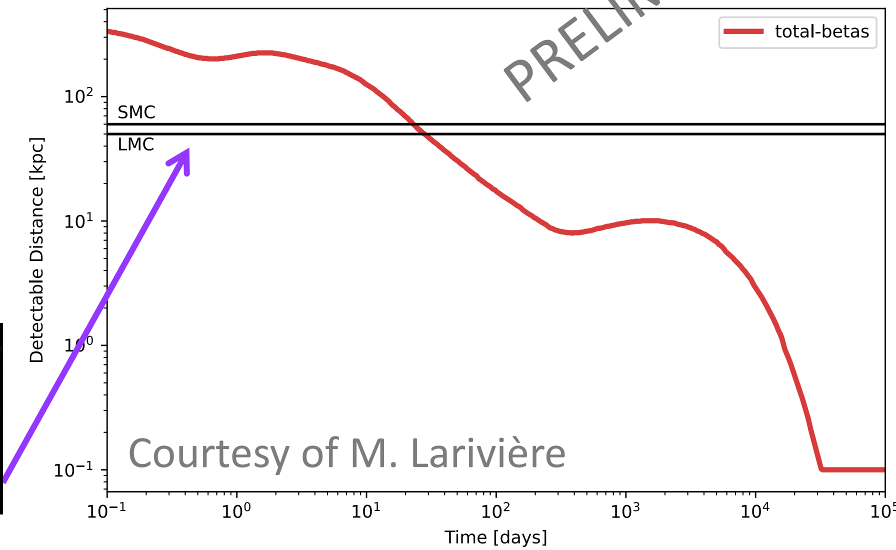


Detectability of **fission gammas** (>3.5 MeV) with the next general MeV telescope:
predicted detectability distance depends on nuclear model assumptions



Detectability of **Tl-208 2.6 MeV gamma line**

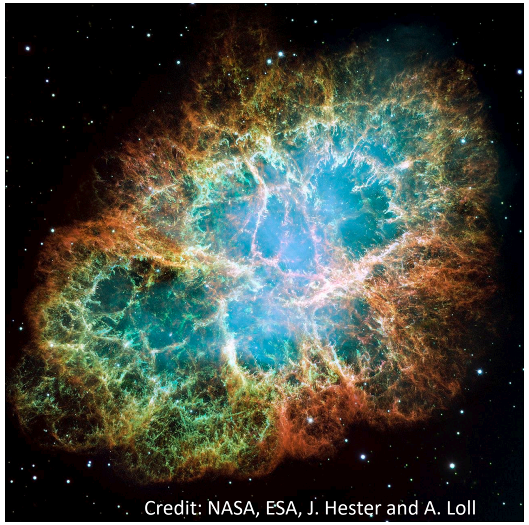
SN1987A



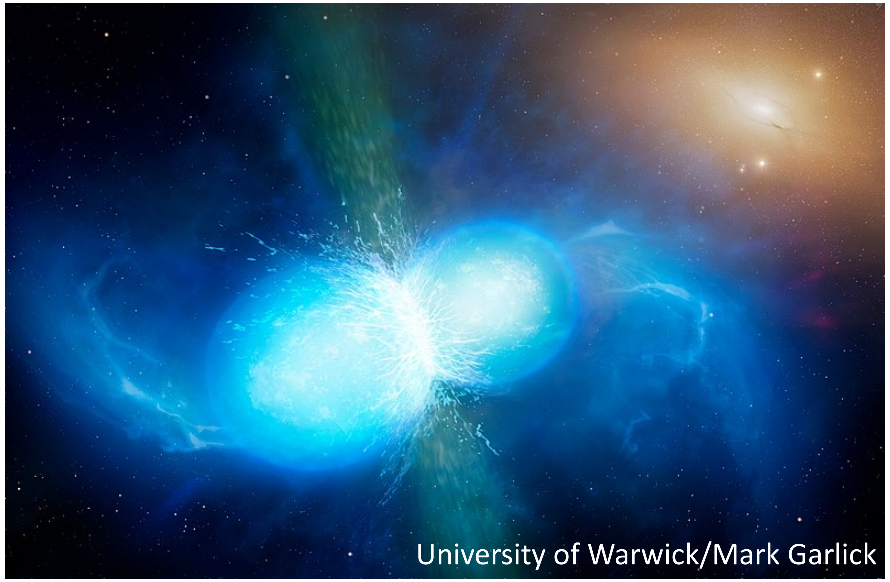
Credit: Nicole Vassh

r-process sites: a mystery

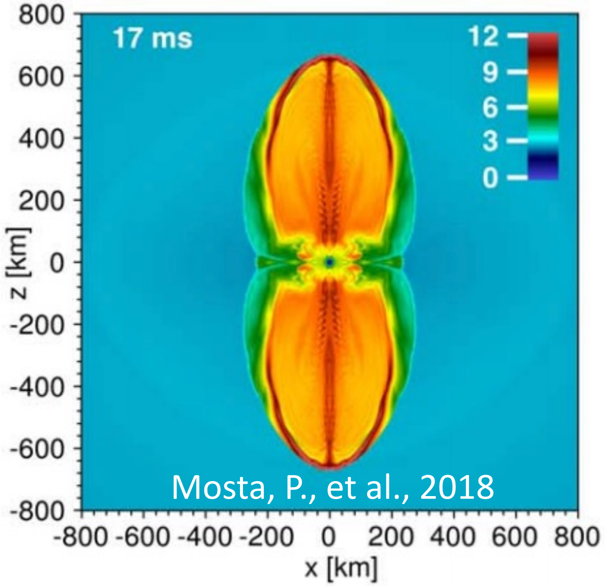
Core collapse Supernovae?
(e.g., Meyer+1992, Roberts+2012)


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

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

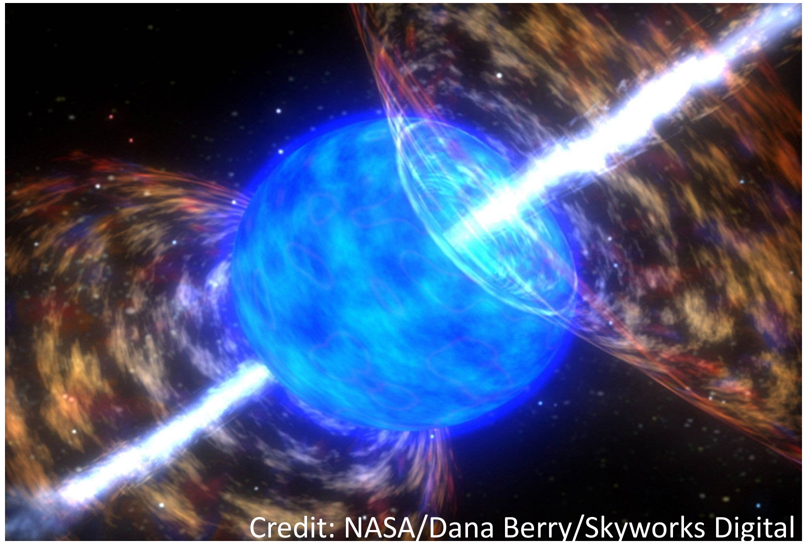

University of Warwick/Mark Garlick

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

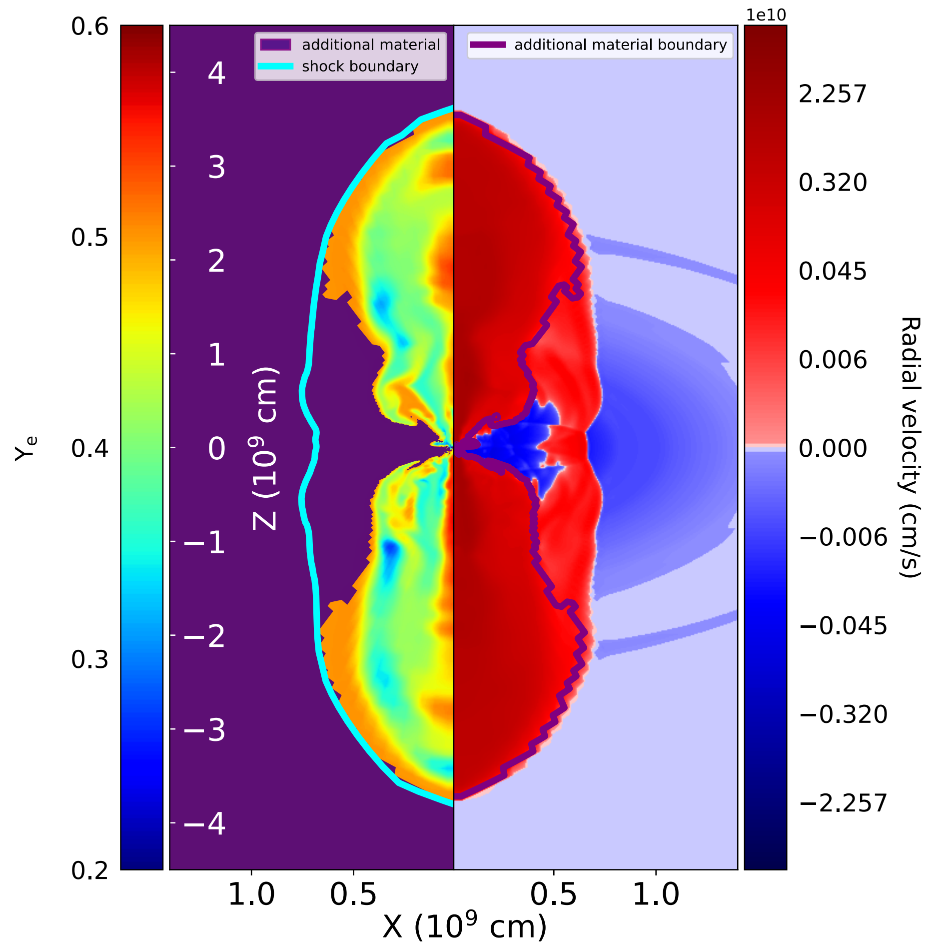
Magnetar giant flare
(Patel+2025)

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

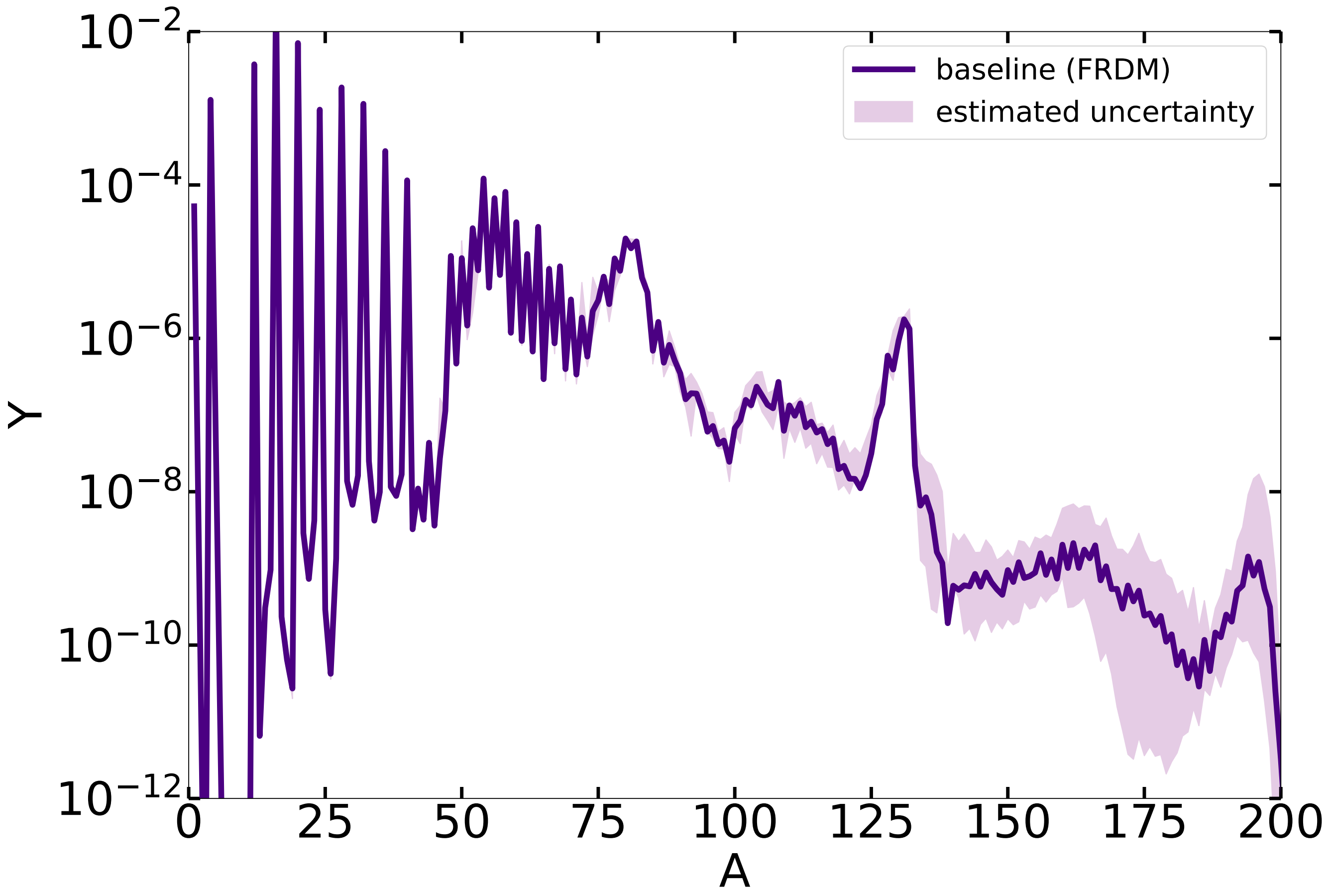
primordial black hole + neutron star (e.g., Fuller+2017)

etc.

MeV gamma-ray from rare supernovae with r-process

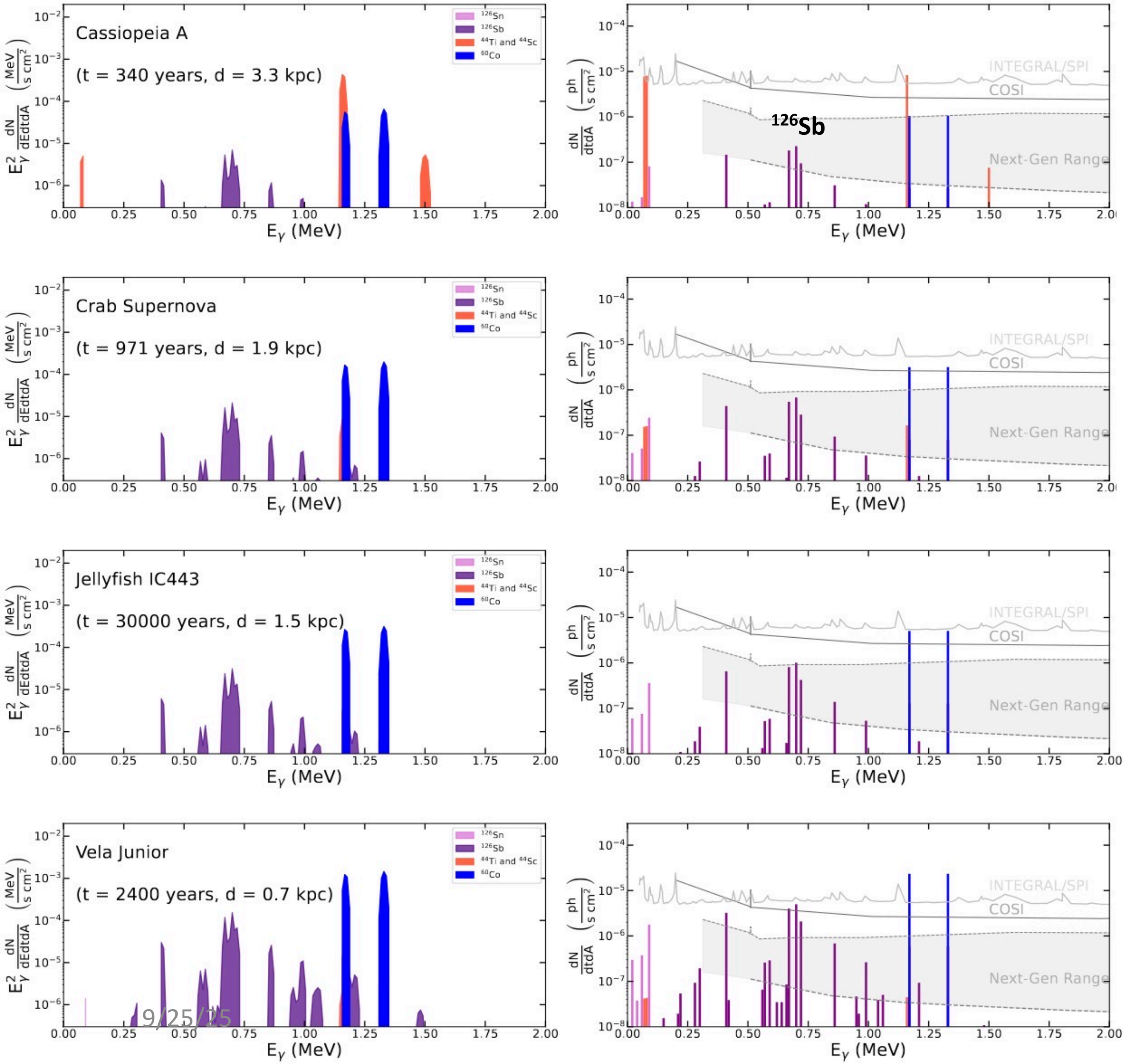


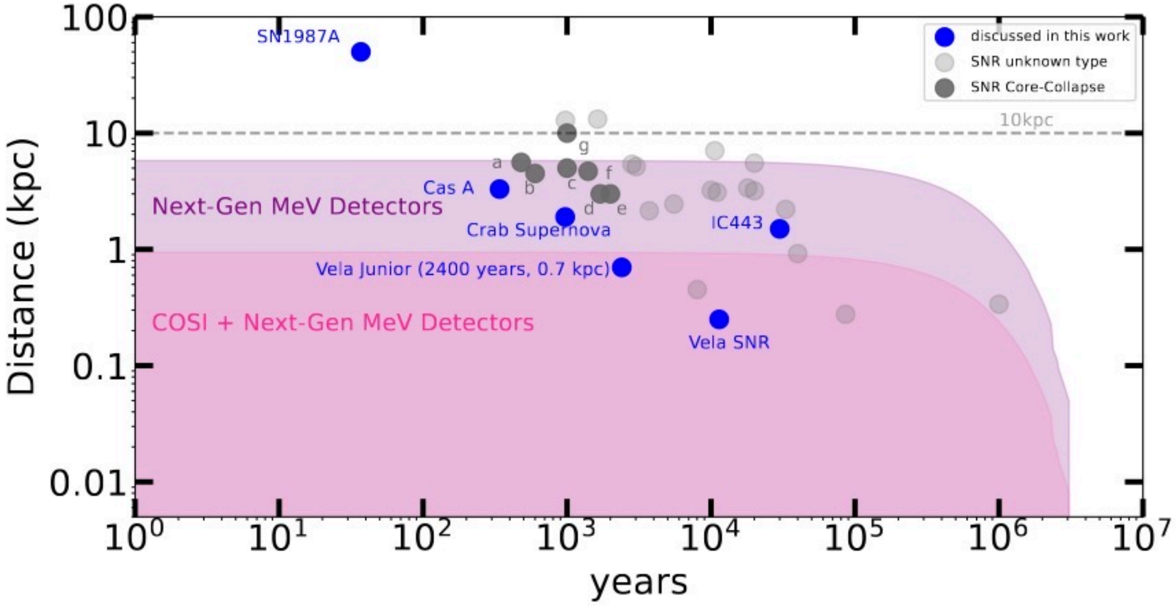
Snapshot of the MR-SN model 35OC-RS from Reichert et al. (2021) at the end of the simulation time (1.306 s).



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

MeV gamma-ray from rare supernovae with r-process



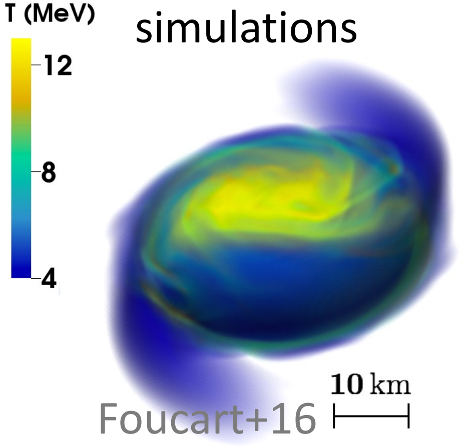


Observability of ^{126}Sb 666 keV line with COSI and next-generation MeV telescopes if a supernova remnant originated from a rare magneto-rotational-SN with r-process occurs.

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

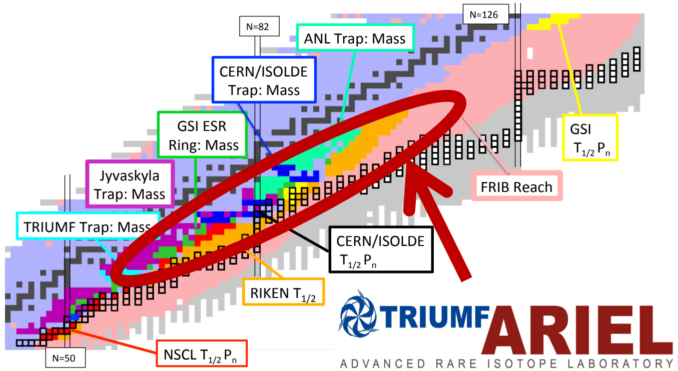
An international and multi-disciplinary community working to illuminate heavy element origins

Advances in computational simulations



Foucart+16

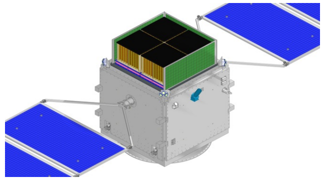
Experimental campaigns



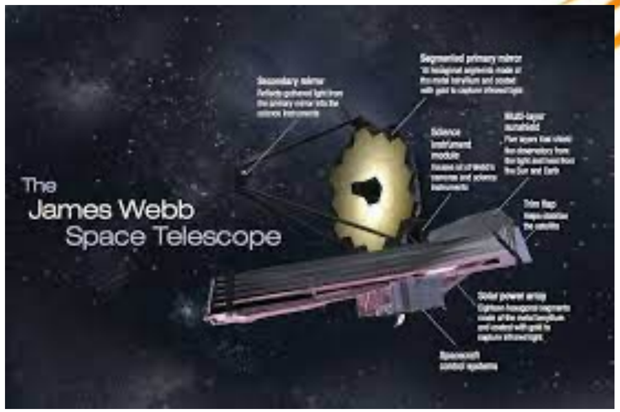
TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

Horowitz+18

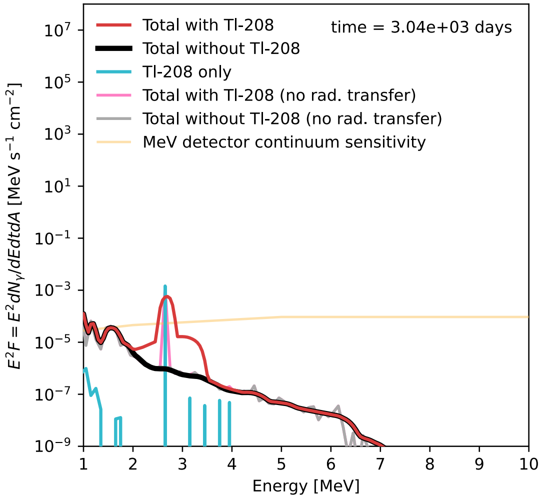
Observational campaigns



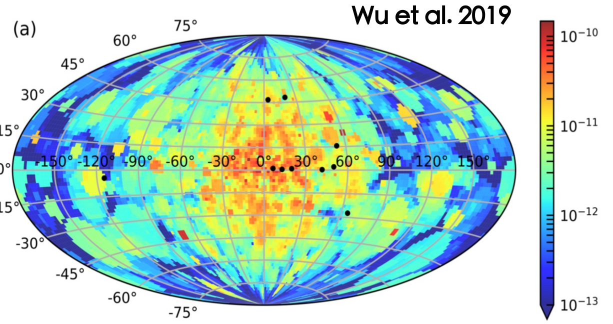
LIGO VIRGO



MeV gammas are especially interesting to search for specific element fingerprints

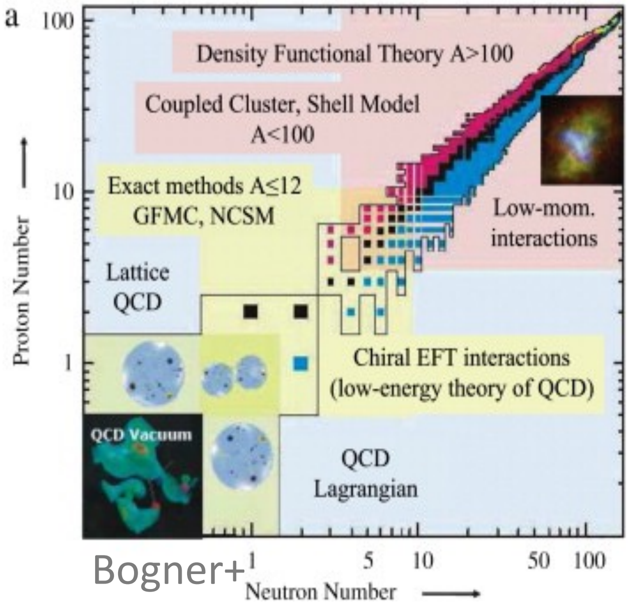


Vassh,Wang+24



^{182}Hf gamma-lines (1121keV)
flux Galactic distribution

Advances in nuclear theory



Bogner+

Credit: Nicole Vassh

- Thanks for your attention. Questions?