中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

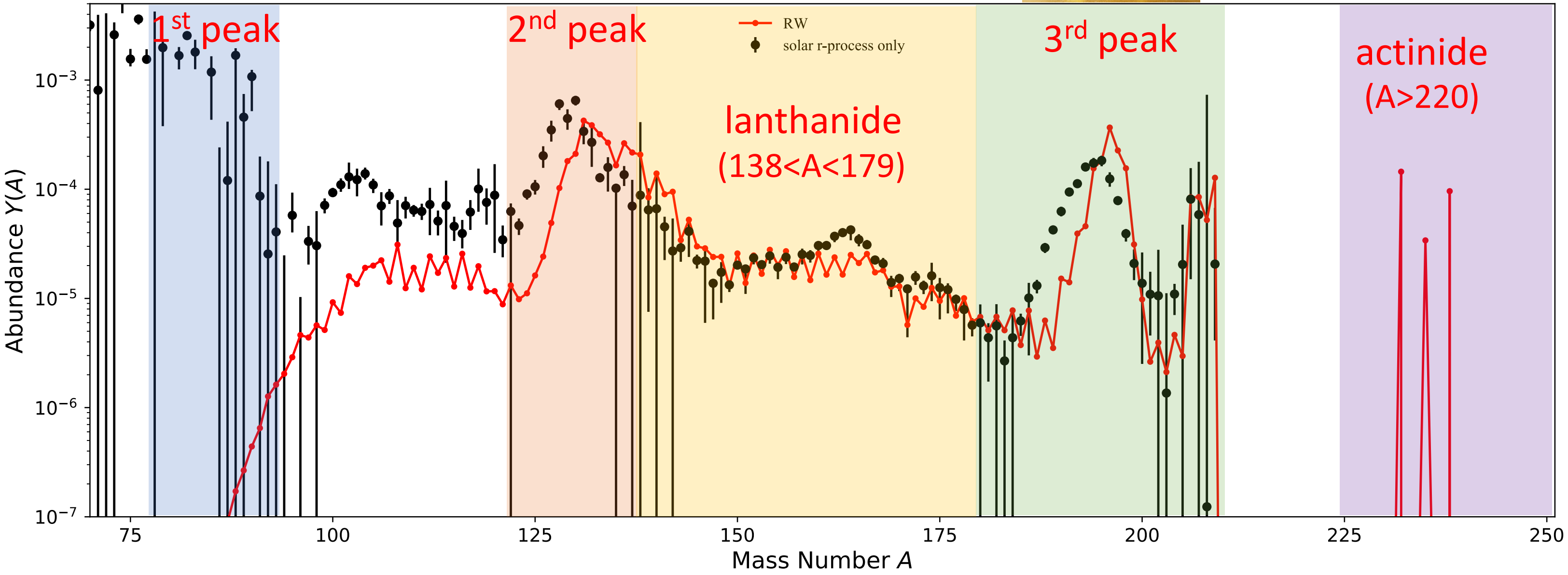
Using Astrophysical Observations of the r-Process Radioisotopes to Probe Nucleosynthesis Sites

Xilu Wang
Institute of High Energy Physics,
Chinese Academy of Sciences

@EMMI+IReNA Workshop “Remnants of neutron-star mergers – Connecting hydrodynamics models to nuclear, neutrino and kilonova physics”

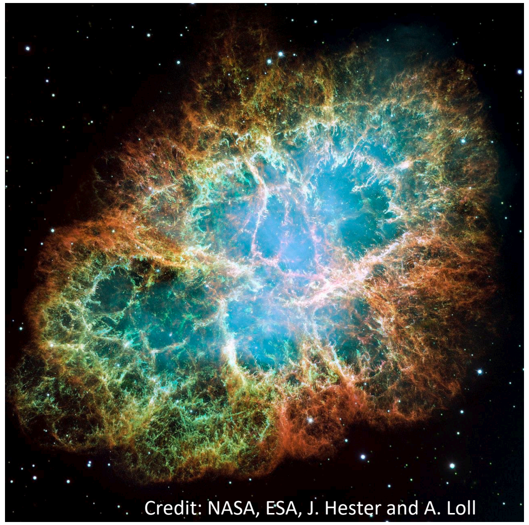
r-process nucleosynthesis

- 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)

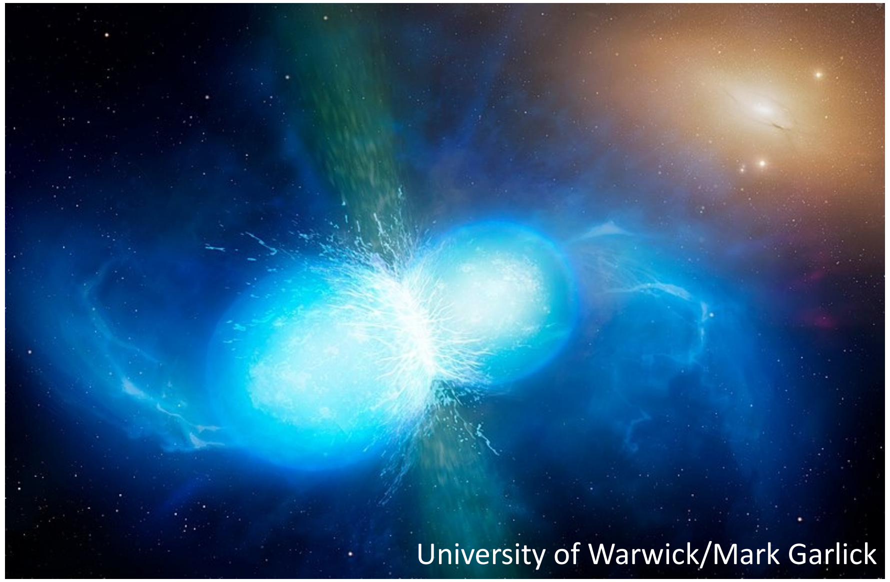


r-process sites: a mystery

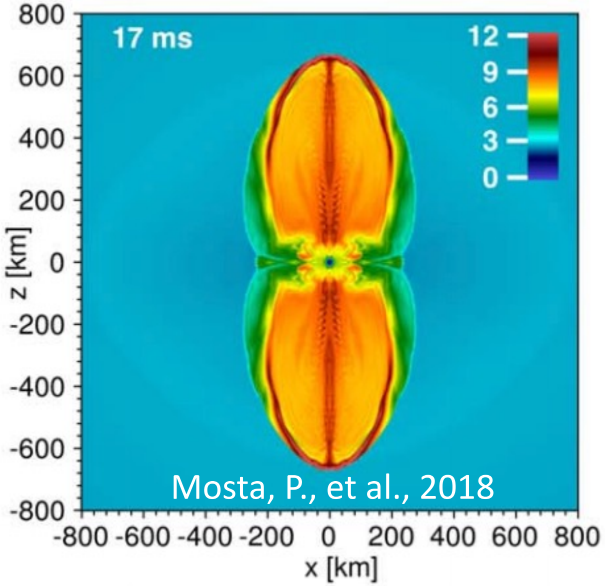
Core collapse Supernovae?
(e.g., Meyer+1992, Roberts+2012)



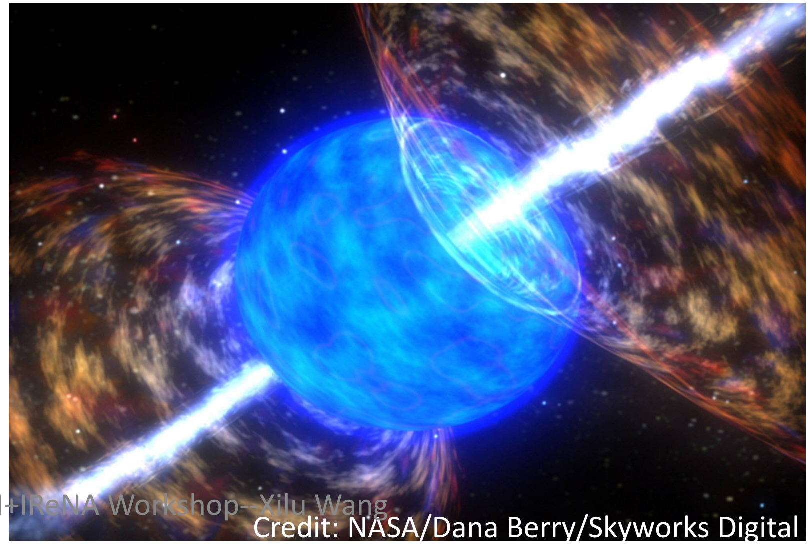
Neutron star + neutron star/black hole mergers
(e,g, Nedora+2020, Foucart+2020, George+2020, etc.)



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

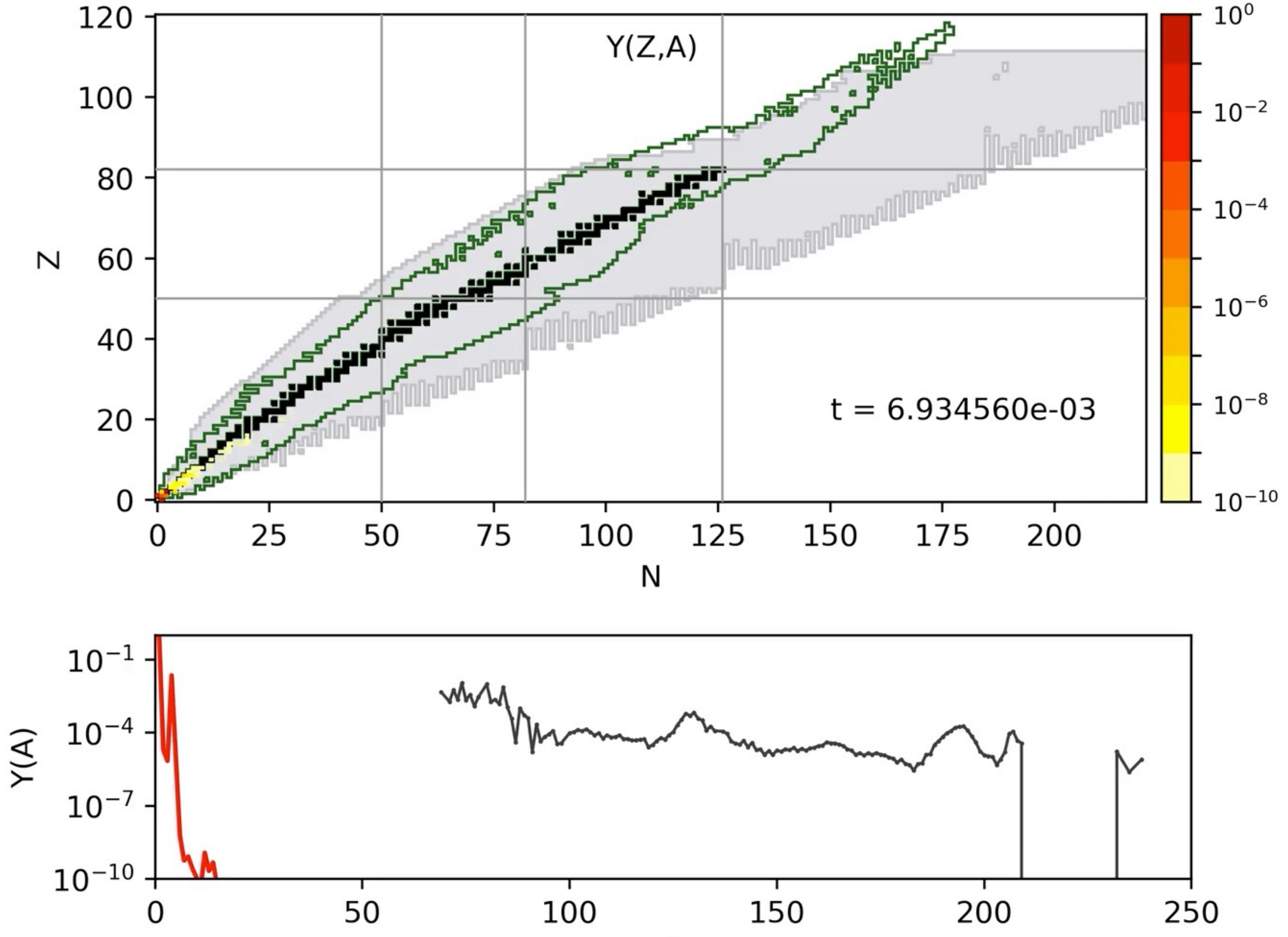


Collapsars
(e.g., Siegel+2019, Miller+2019)



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

r process nucleosynthesis simulation with PRISM



Thousands of nuclei far from stability, or radioisotopes, are created and decay via alpha decay, beta decay and fission over timescales raging from seconds to Myrs →radioisotopes can serve as a direct trace to their nucleosynthesis sites

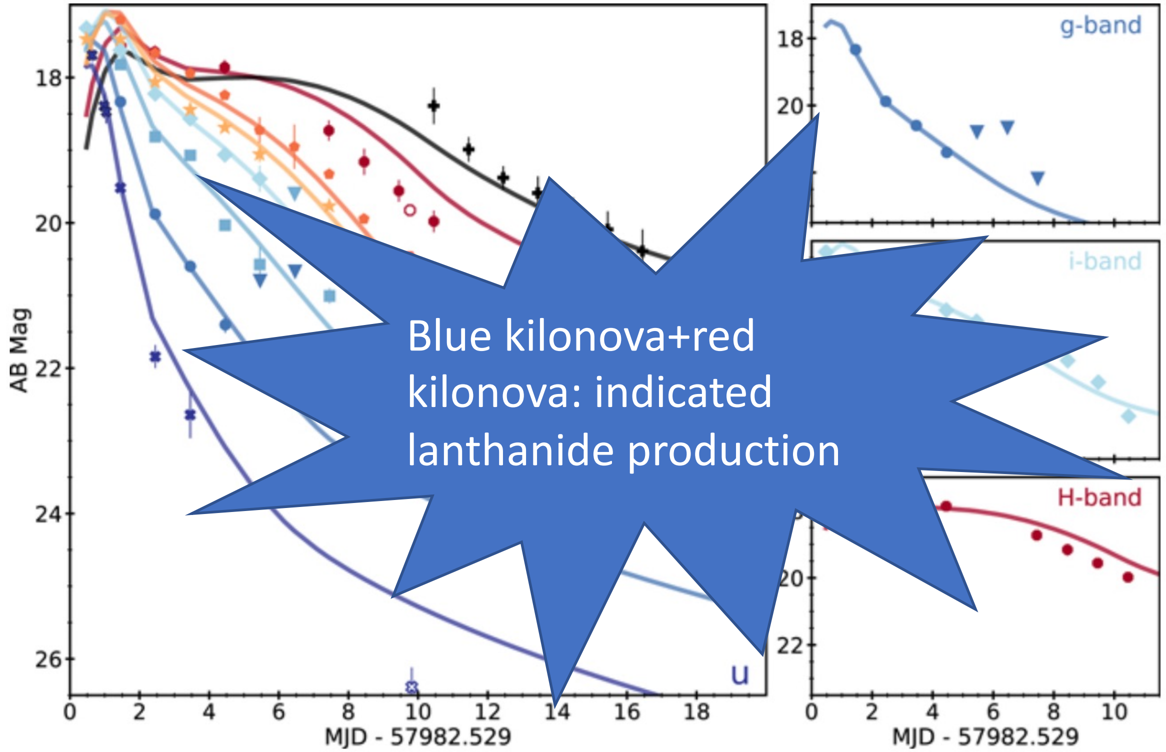
Cold, neutron-rich dynamical ejecta from an NSM event

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

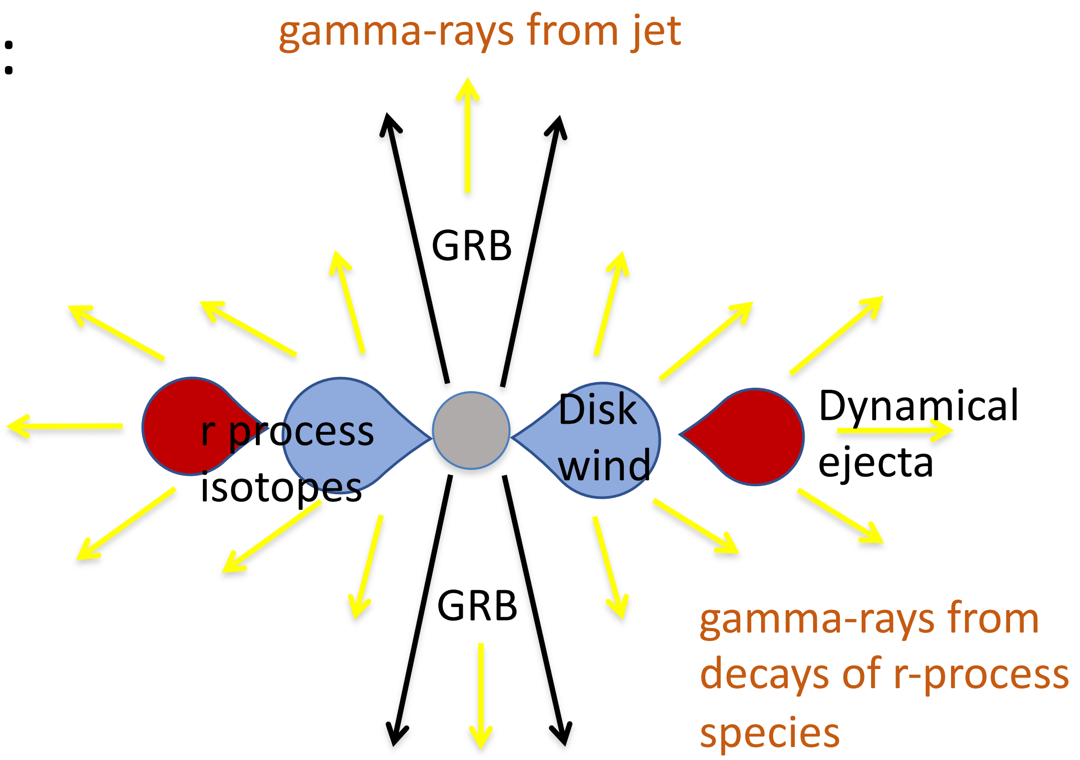
Astrophysical observations of the r-process radioisotopes

1. Prompt gamma-ray emissions from the synthesized radioisotopes

Take neutron star mergers for example:



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

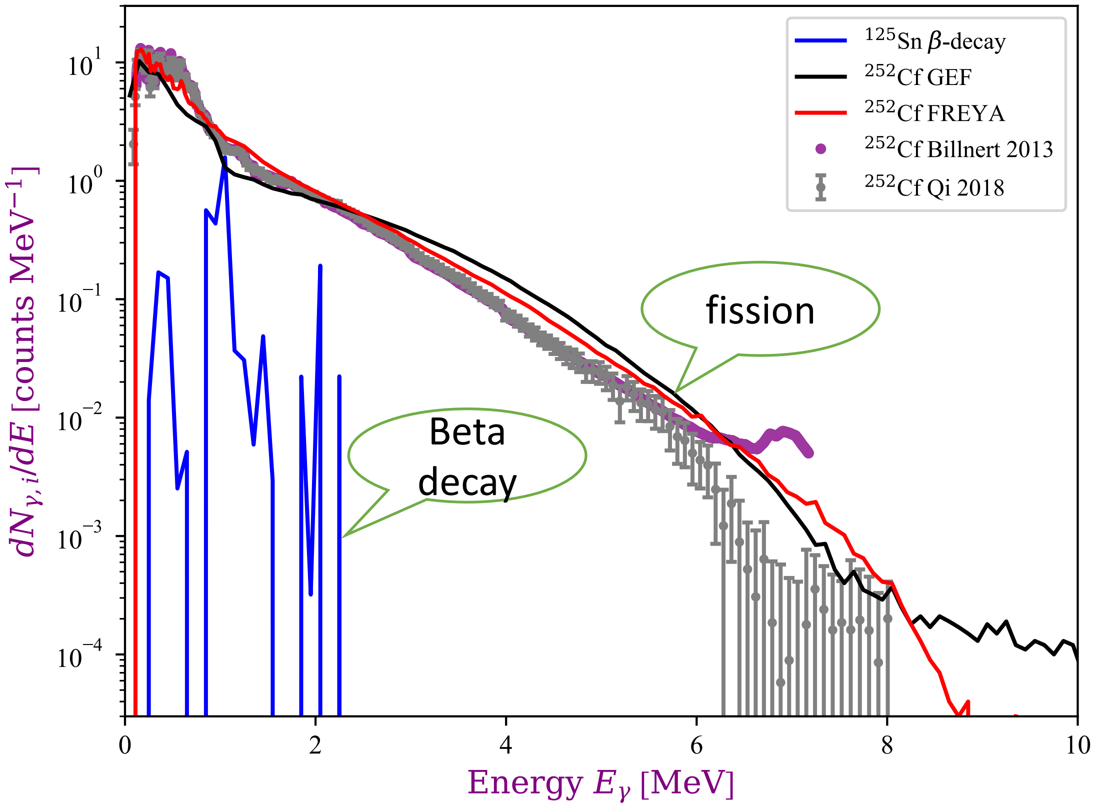


alpha decay, beta decay and nuclear fission

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

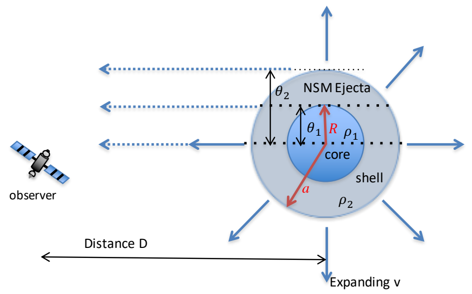
Prompt gamma-ray spectra from r process

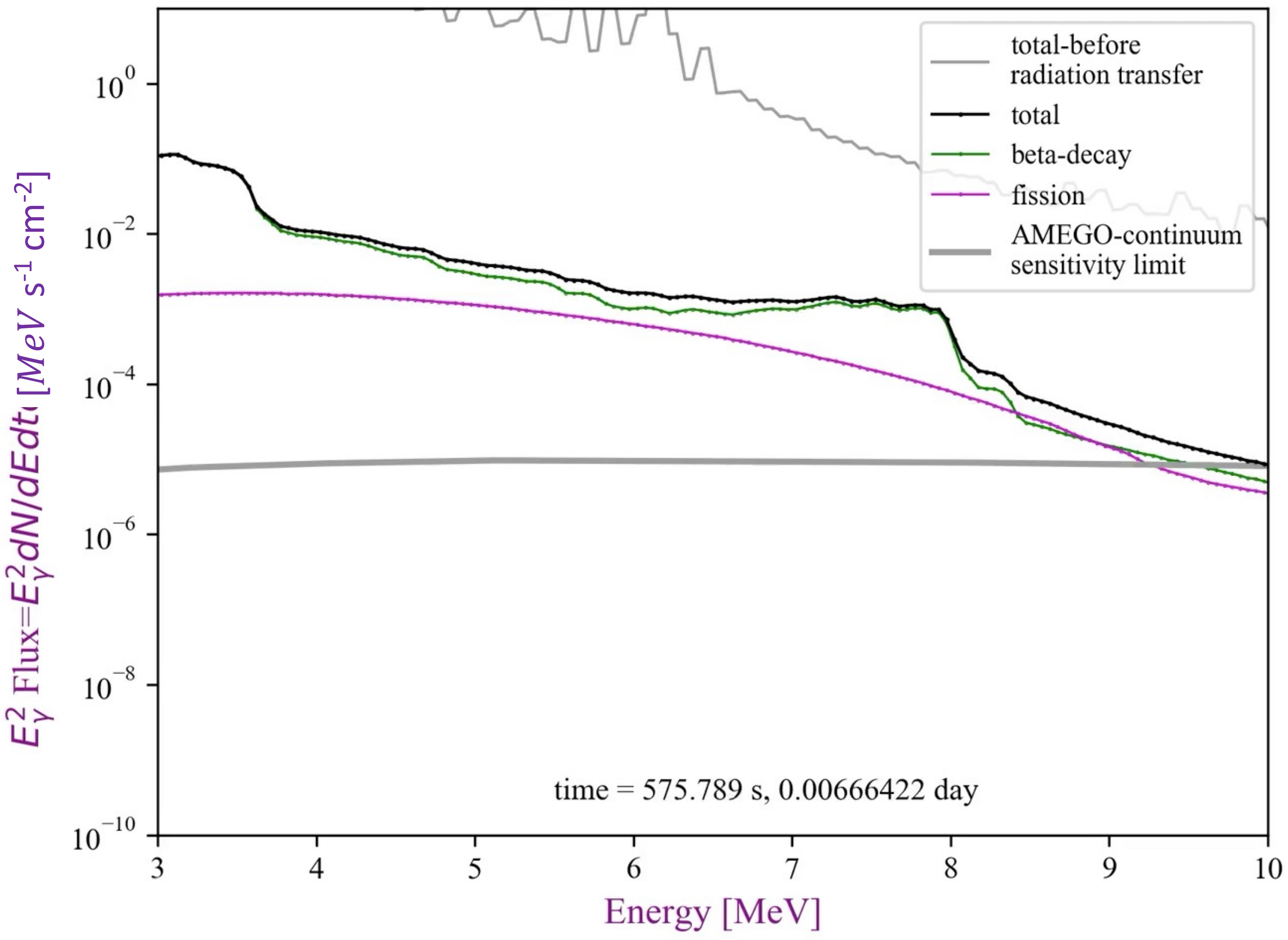
- Prompt gamma-ray photons emitted from r-process:
  - Beta decays, experimental data from ENDF/B-VIII.03 (Brown et al. 2018), theoretical calculations from LANL work (Korobkin et al., 2020)
  - Fission, theoretical calculation from GEF (Schmidt et al. 2016) and FREYA (Vogt & Randrup 2017) as in Vassh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



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

MeV gamma-ray spectrum evolution





Total signal: black

Beta-decay: green

Fission: purple

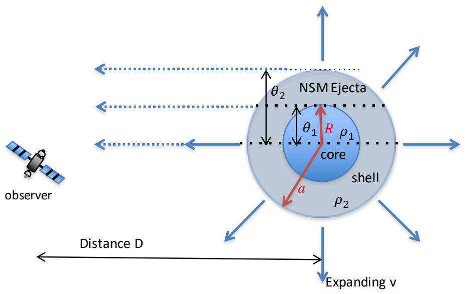
$$Y_e = \frac{n_e}{n_b} = 1 - \frac{n_n}{n_n + n_p} \sim 0.015$$

Smaller Y_e: more neutron rich

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



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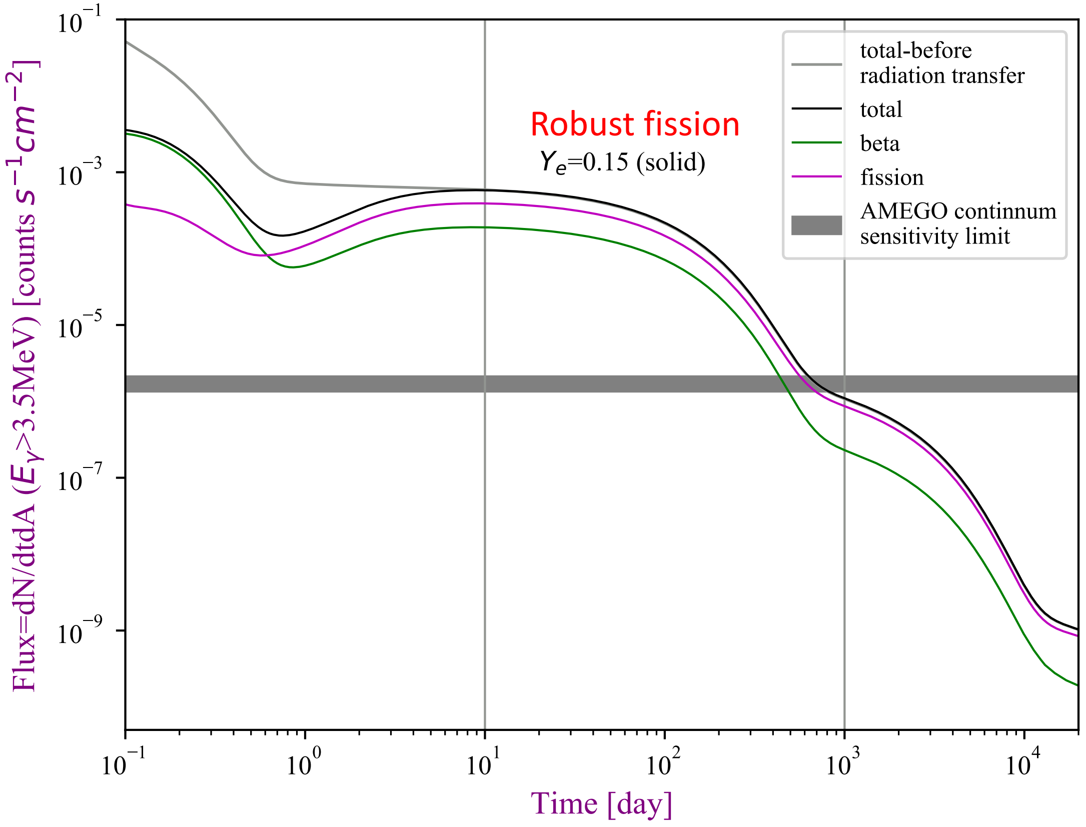

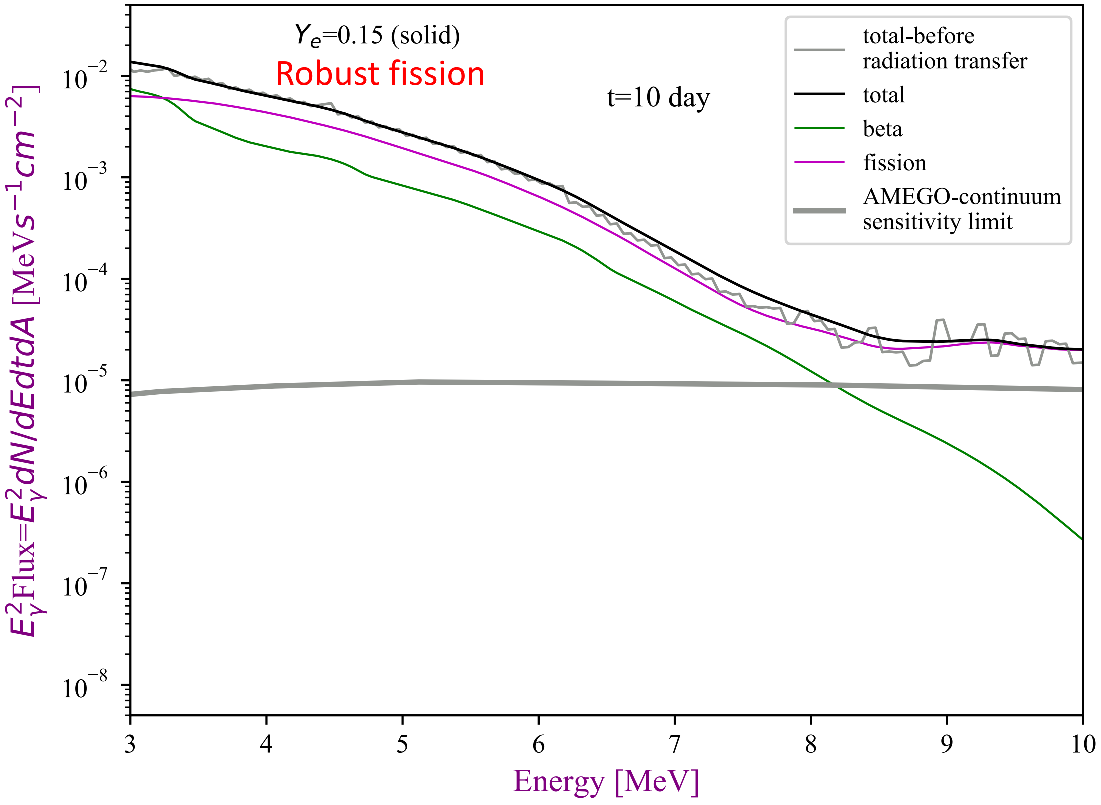

Low entropy parameterized outflow found in Radice et al., 2018, Just et al., 2015.
Nuclear data based on FRDM and FRLDM nuclear models

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

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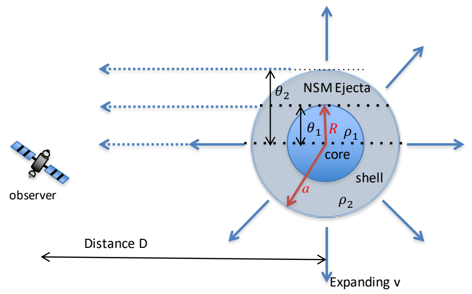

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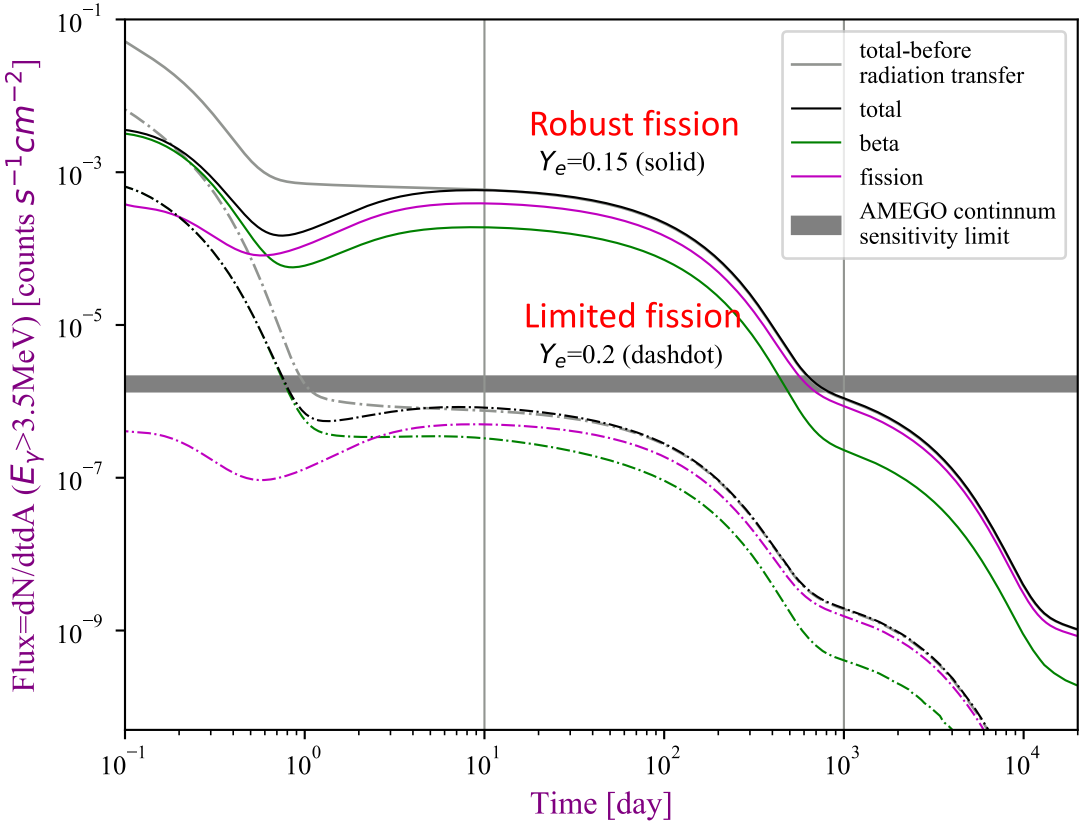

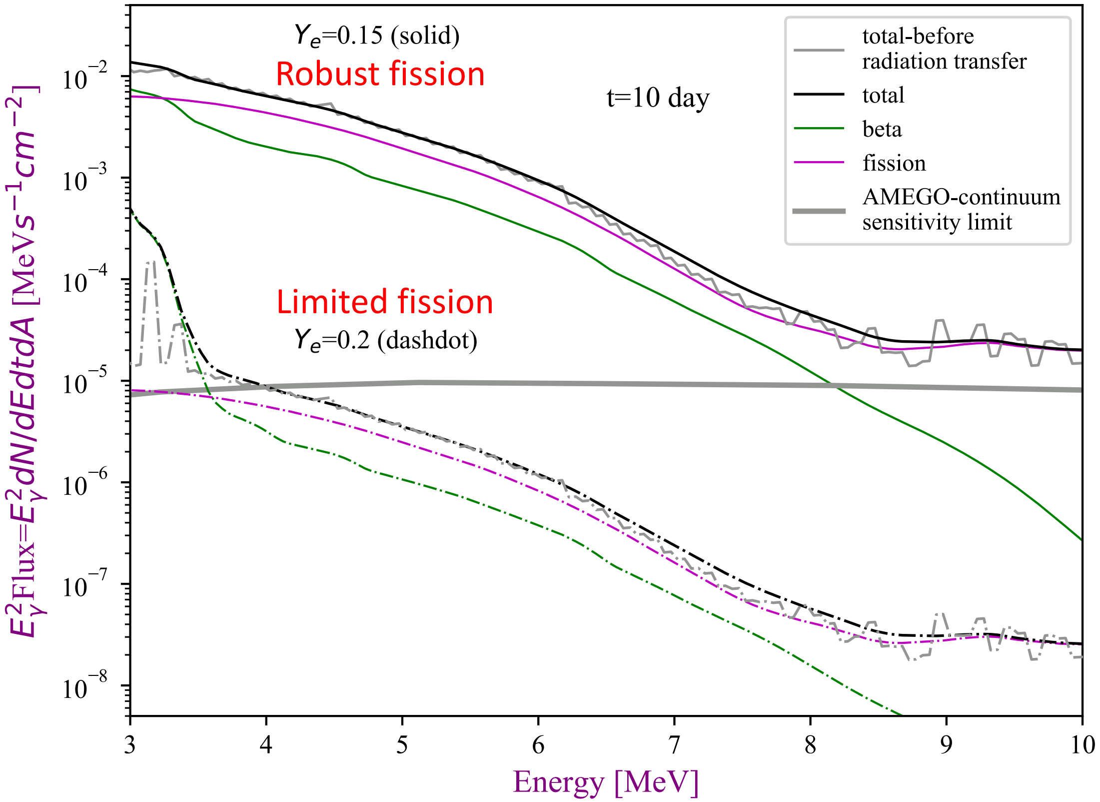

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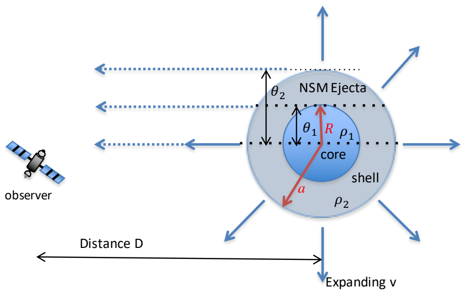

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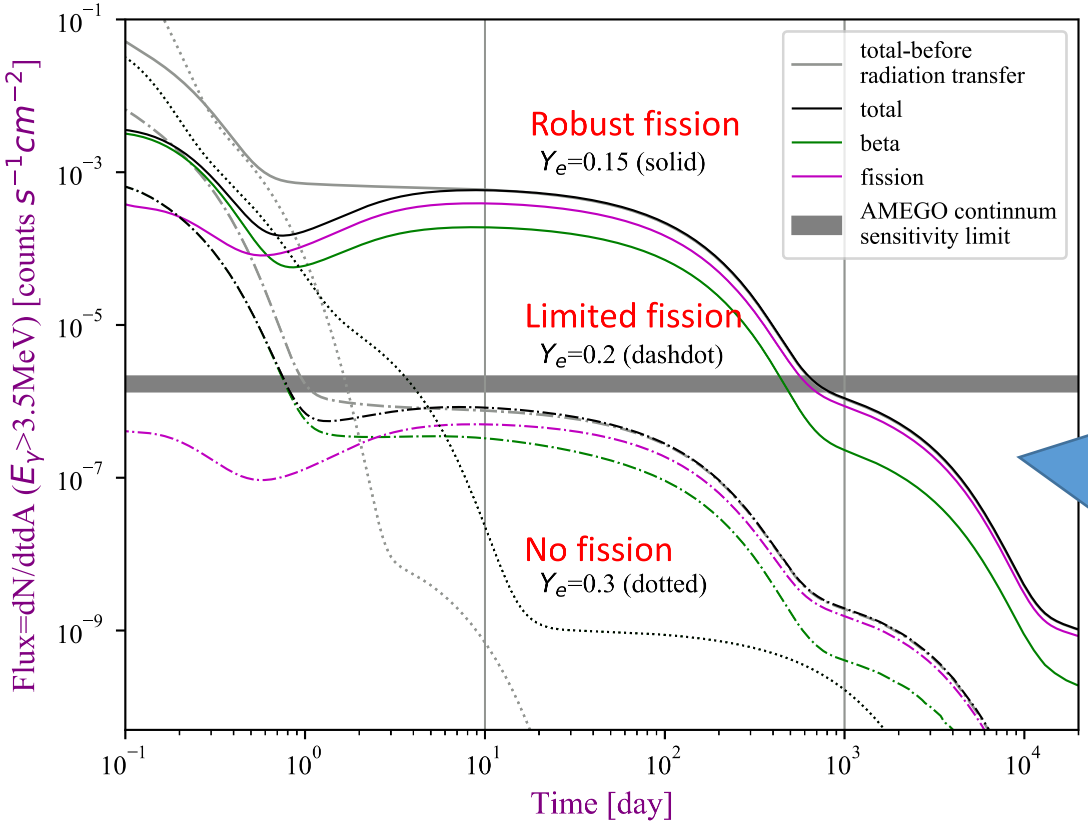
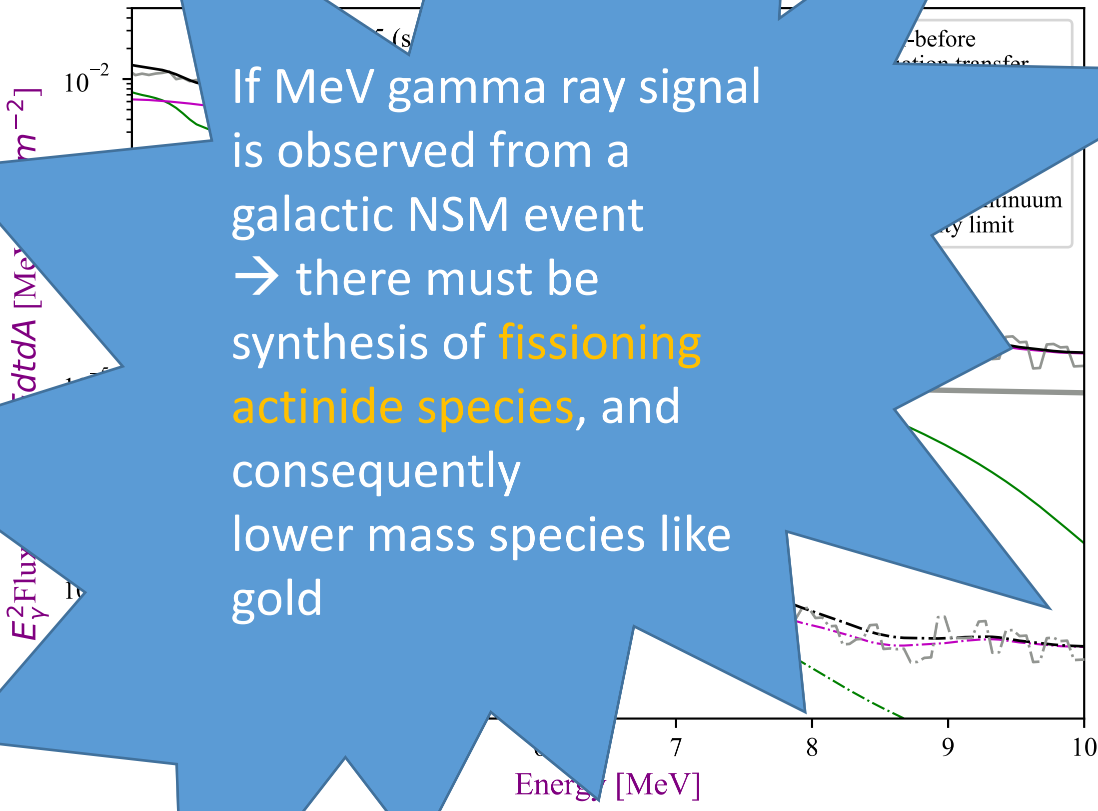




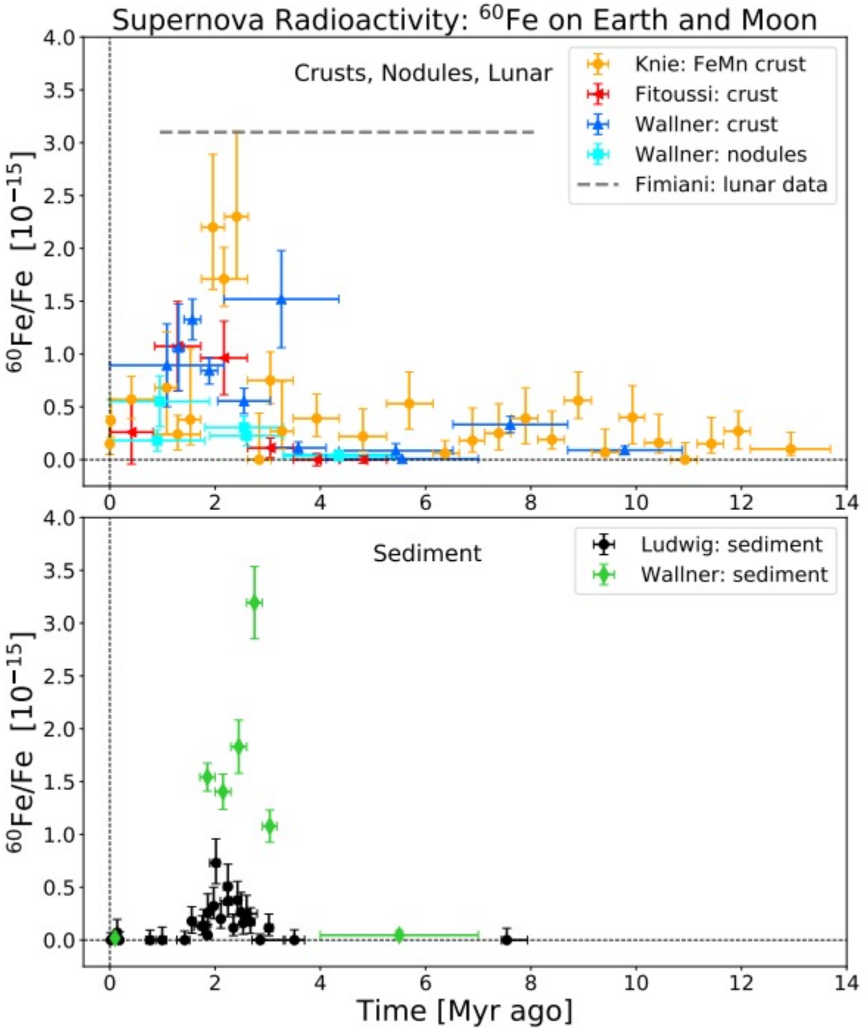
If MeV gamma ray signal is observed from a galactic NSM event → there must be synthesis of fissioning actinide species, and consequently lower mass species like gold

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

Astrophysical observations of the r-process radioisotopes

2. Direct measurements of the live radioisotopes on the Earth and moon:



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

60Fe Sample Sites

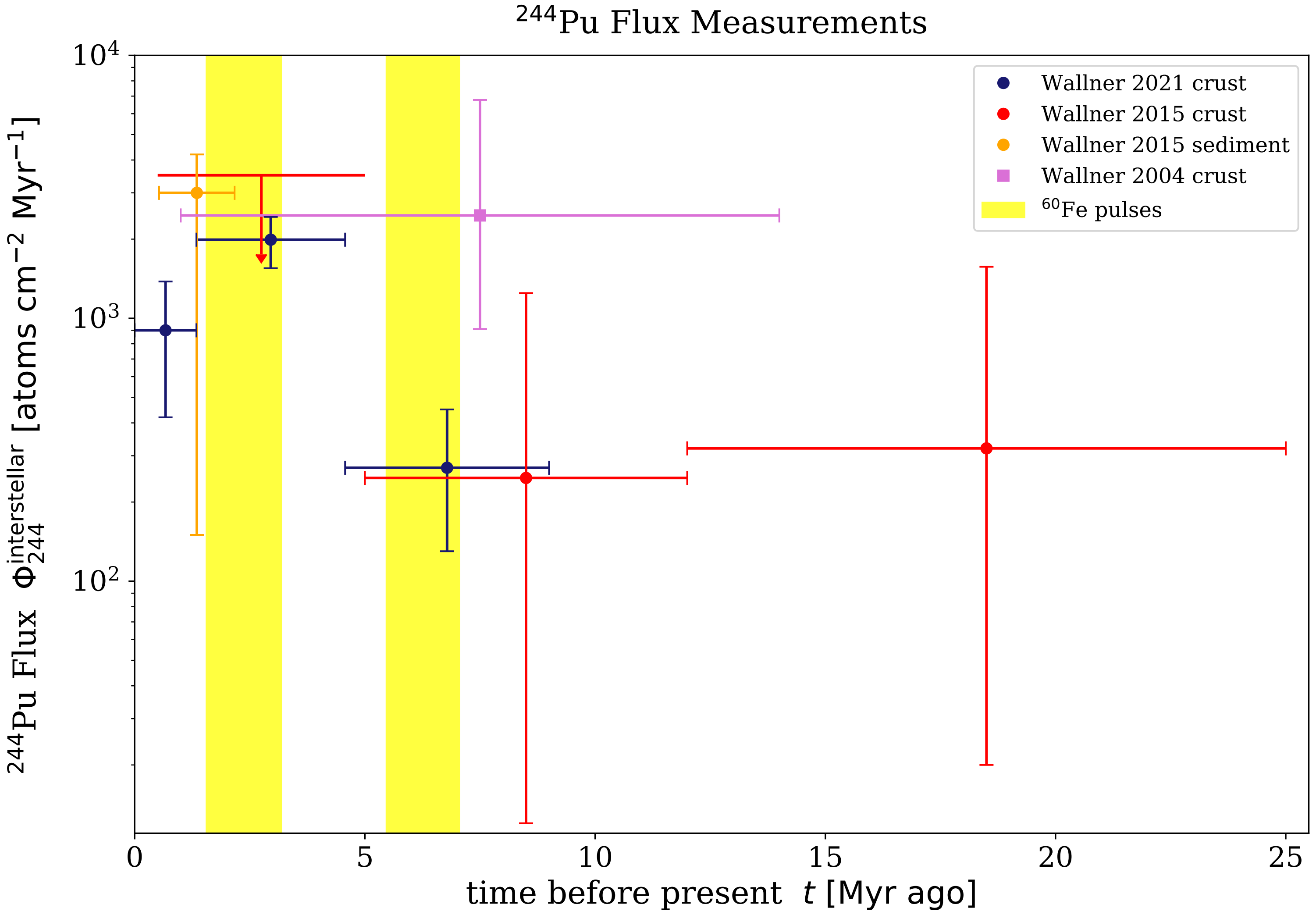
$$t_{mean,{}^{60}_{26}Fe} = 3.78\ Myr$$

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

Credit: Brian Fields

Geological Signatures

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



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

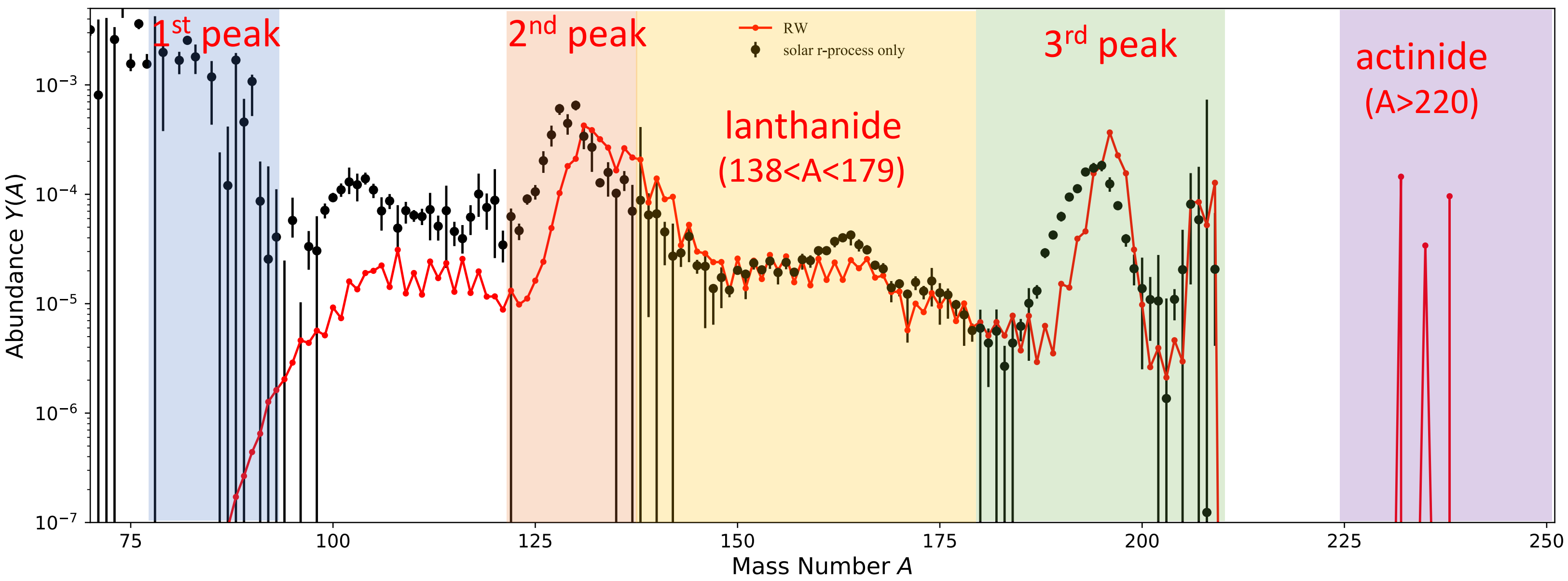
$t_{mean,{}^{244}_{94}Pu} = 115\ Myr$

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

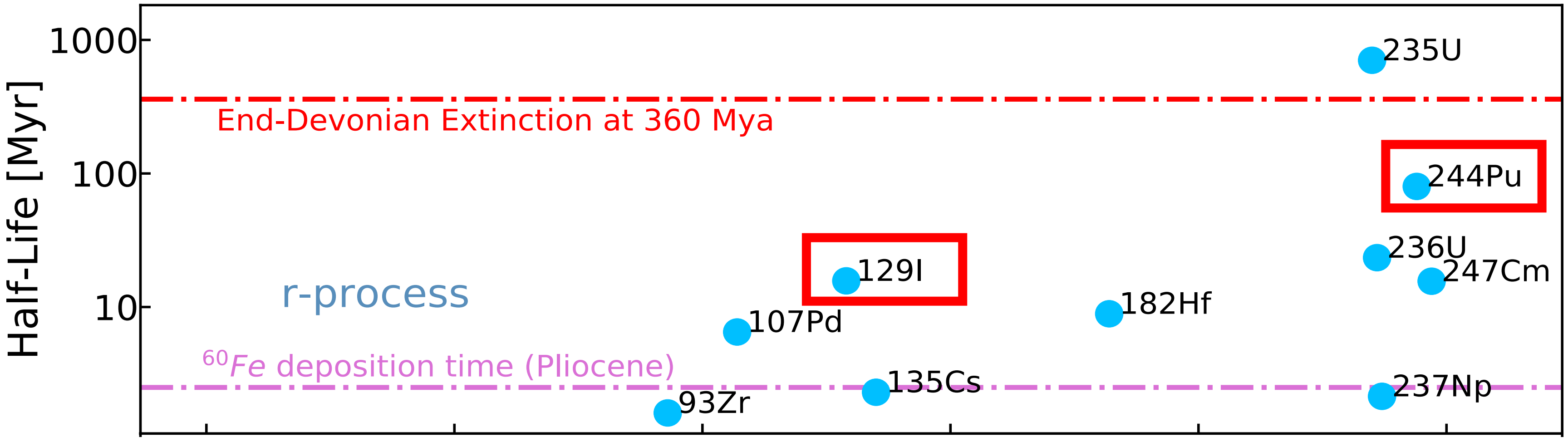
Wang, X., et al., 2021, ApJ 923, 219

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

Long lived r-process radioisotopes



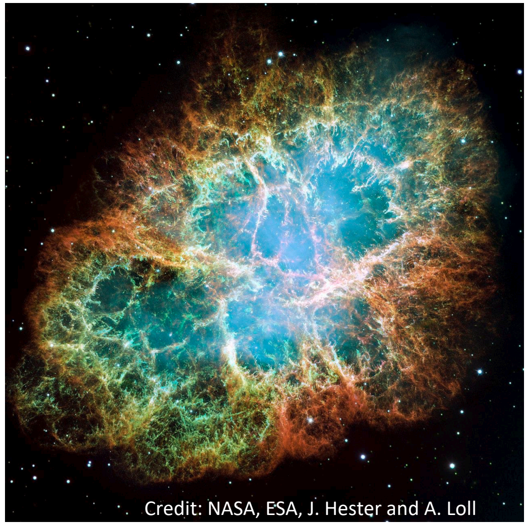
Isotopes with half-lives $t_{1/2}$ ~ 1 Myr to 1 Gyr



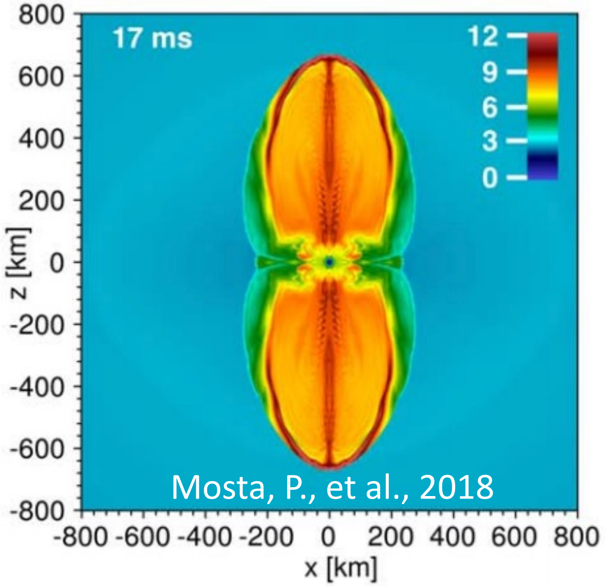
Wang, X., et al., 2021, ApJ 923, 219

r-process calculations

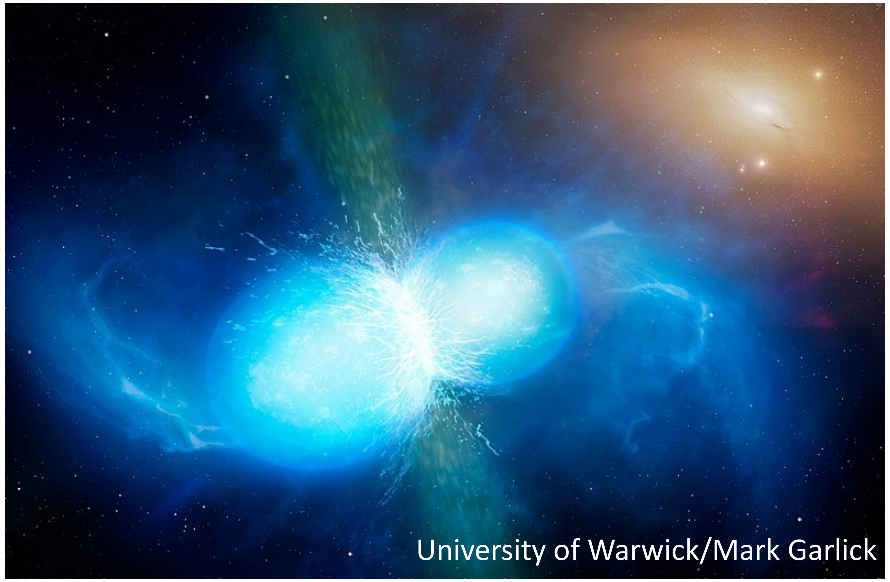
	Supernova (SN) Models		Kilonova (KN) Models	
Label	SA ($\nu\star$)	SB (MHD)	KA	KB
Simulations	SN *forced* neutrino-driven wind: 4 trajectories from Arcones et al. (2007); Arcones & Janka (2011b) with modified $Y_e = 0.31, 0.35, 0.42, 0.48$	MHD SN: 2 trajectories from Mösta et al. (2018b)	KN dynamical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



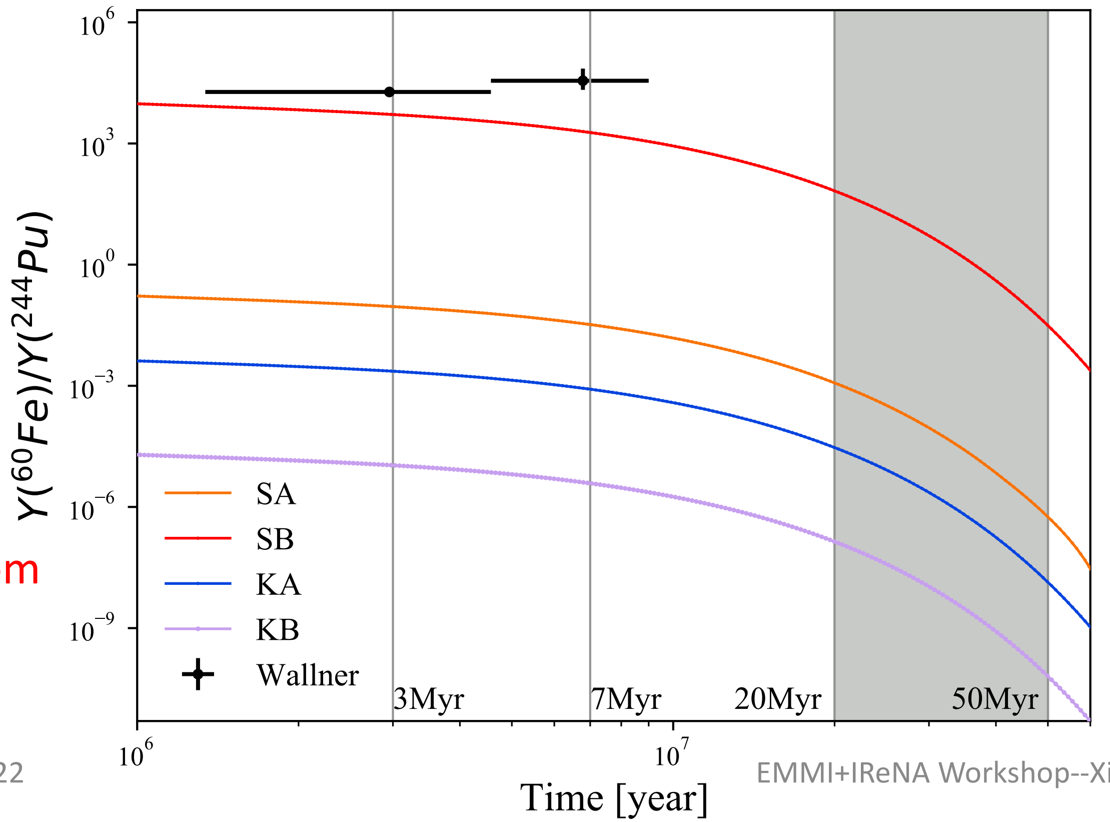
Magneto-rotational supernovae (MHD)



Neutron star mergers (kilonovae)

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

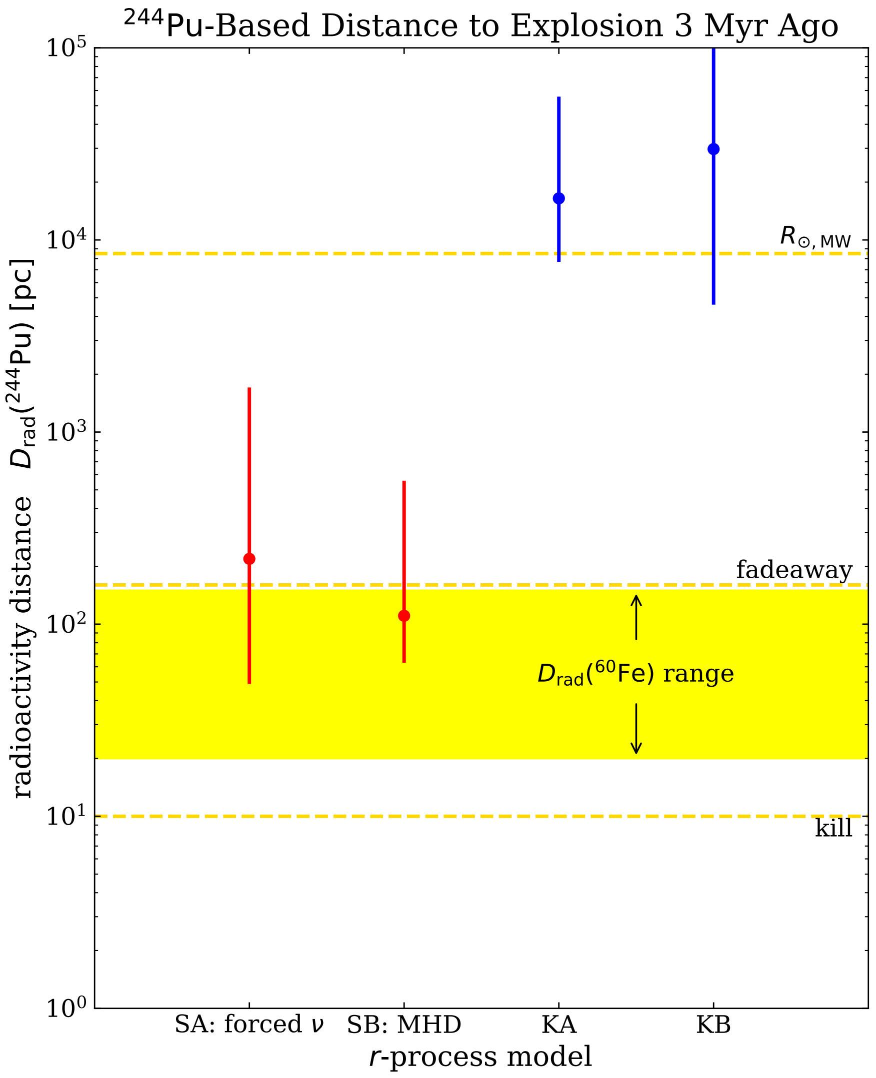


^{60}Fe only from r process

- 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

Wang, X., et al., submitted, arXiv:2112.09607

^{244}Pu: Near-Earth Supernovae or Kilonovae?



- The influence (time-integrated flux) of ^{244}Pu from an explosion at distance r and time t in the past:

$$\mathcal{F}_{^{244}Pu}^{interstellar} \propto f_{dust} M_{^{244}Pu,eject} / r^2 e^{-t/\tau_{244Pu}}$$

→"Radioactivity distance" from ^{244}Pu yield:

$$D \sim \sqrt{f_{dust} M_{^{244}Pu,eject} / \mathcal{F}_{^{244}Pu}^{interstellar}}$$

  - ✓ "forced" SN neutrino driven wind and MHD SN can work → must be rare SN
  - ✓ KN >> 1kpc → fail
- Could there be a prior event?

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

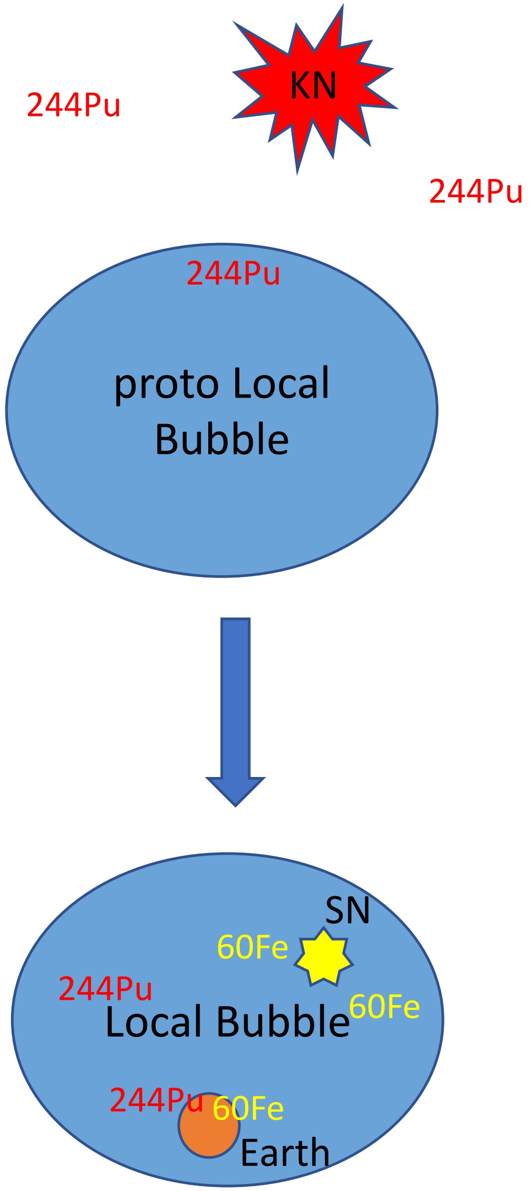
^{244}Pu: Two-Step Kilonova Scenario

Kilonovae/Neutron Star mergers:

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

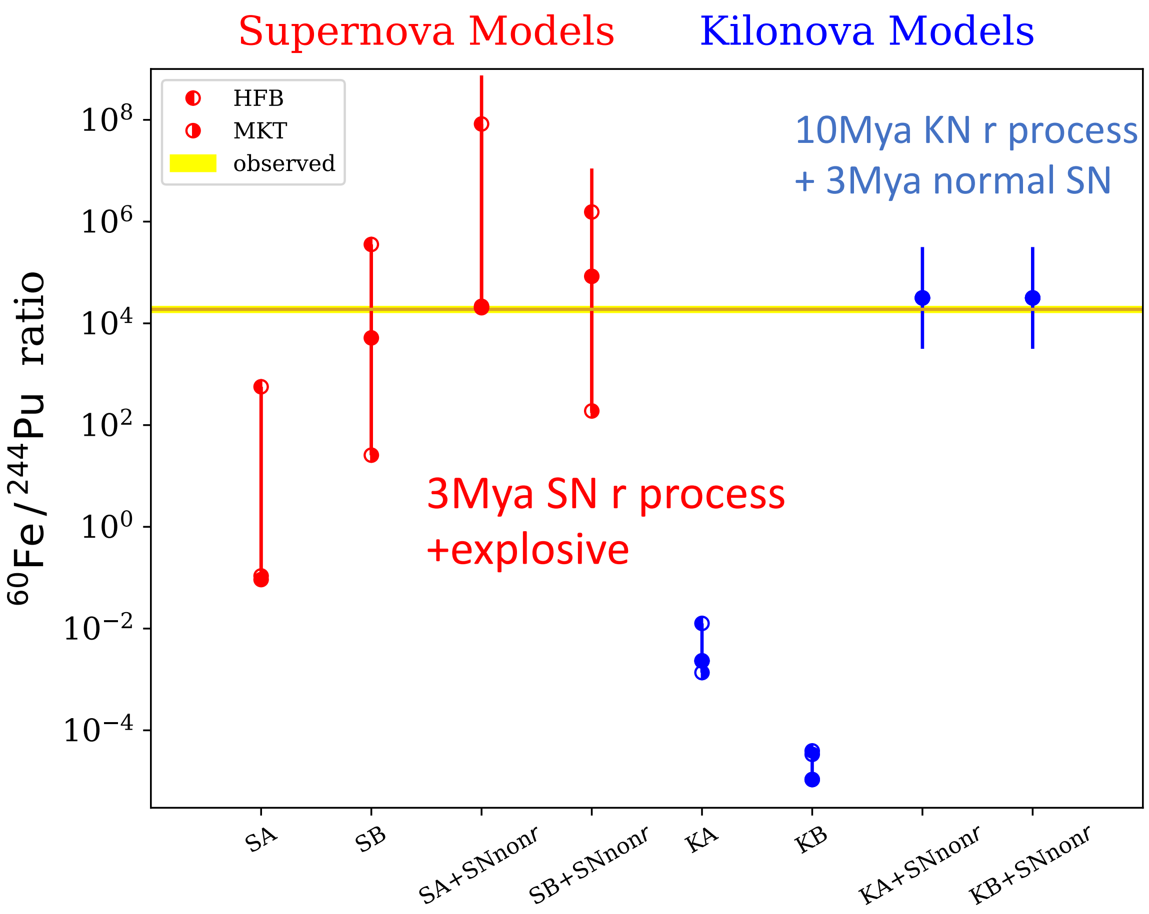
"Two-step" scenario for Kilonovae:

- 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 and Kilonovae



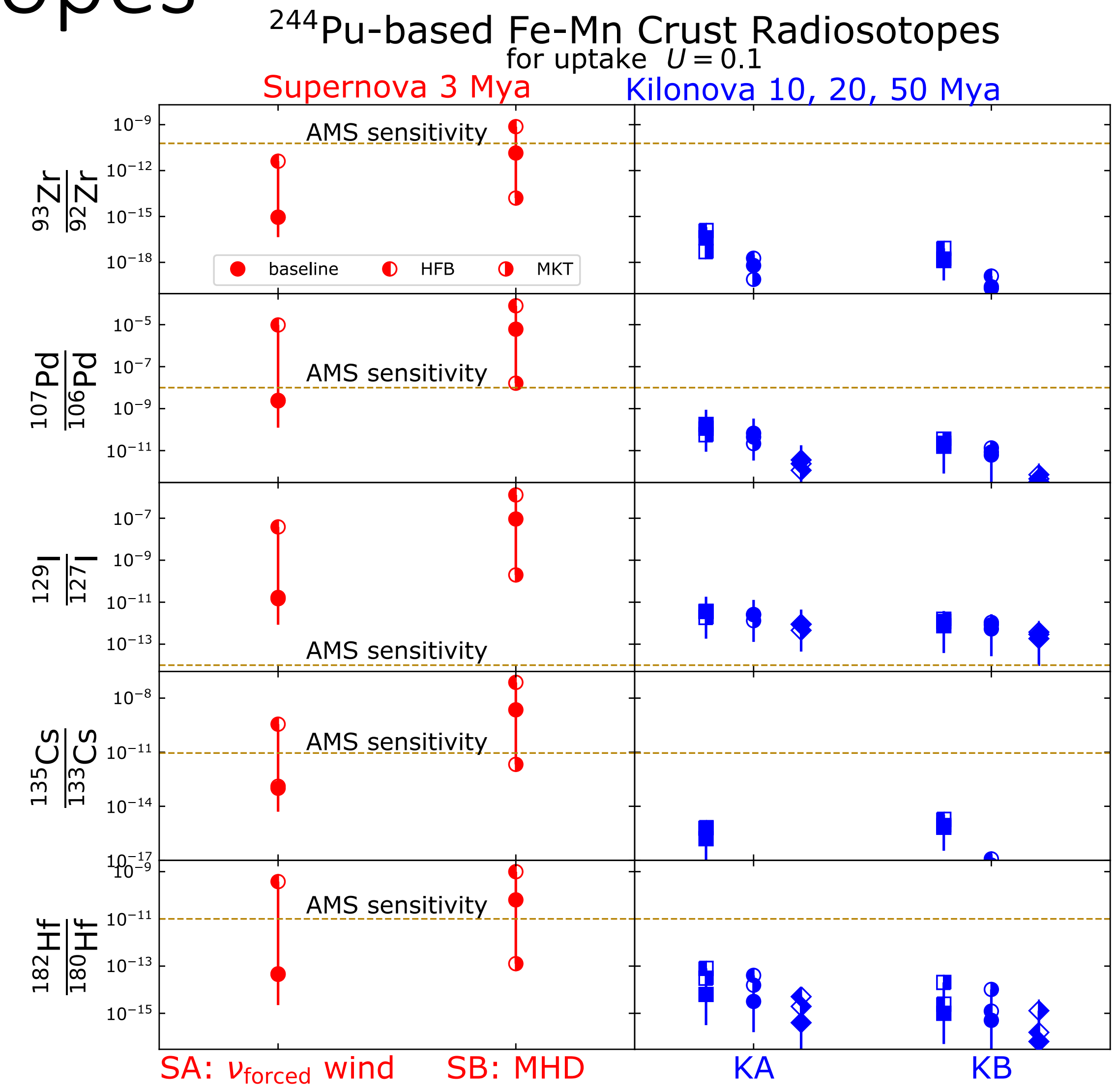
- $^{60}Fe/^{244}Pu$ measurement :
  - Direct deposition: "modified " SN neutrino driven wind and MHD SN can work → must be rare SN
  - Two step KN scenario: 10Mya-50Mya KN + a normal non-r-process SN

- Tests: other long-lived r-process species ^{129}I, ^{182}Hf, ^{247}Cm....

Wang, X., et al., submitted, arXiv: 2112.09607

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

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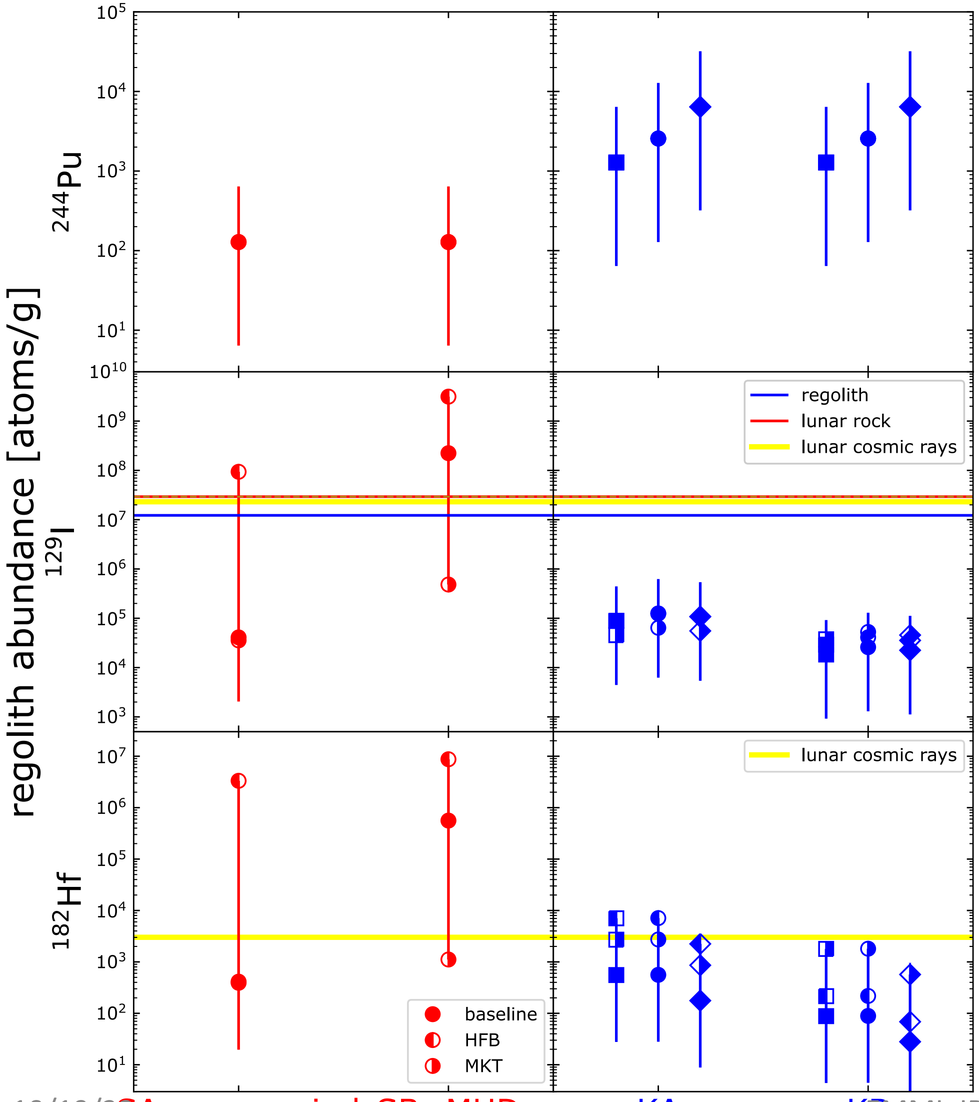

Table 2. Lunar Regolith *r*-Process Radioisotopes From Near-Earth Explosions

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	

Lunar regolith samples

→ Avoid anthropogenic contamination

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

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Summary

- *r*-process sites: a mystery
- Astrophysical observations of *r*-process radioisotopes
    - ❖ Observations of the prompt gamma-ray emissions from the *r*-process sites.
        - ✓ MeV gamma-ray signals from kilonova: a direct signature of actinide production in neutron star mergers
    - ❖ Direct measurement of the radioisotopes in deep-ocean Fe-Mn crusts, and in the lunar regolith samples.
        - ✓ The near-earth r-process event responsible for the ^{244}Pu detection on the earth: rare supernovae (direct deposition) or two-step kilonovae scenario.
        - ✓ Future AMS searches needed

- Thanks for you attention! Questions?