Did a kilonova set off in our Galactic backyard 3.5 Myr ago?

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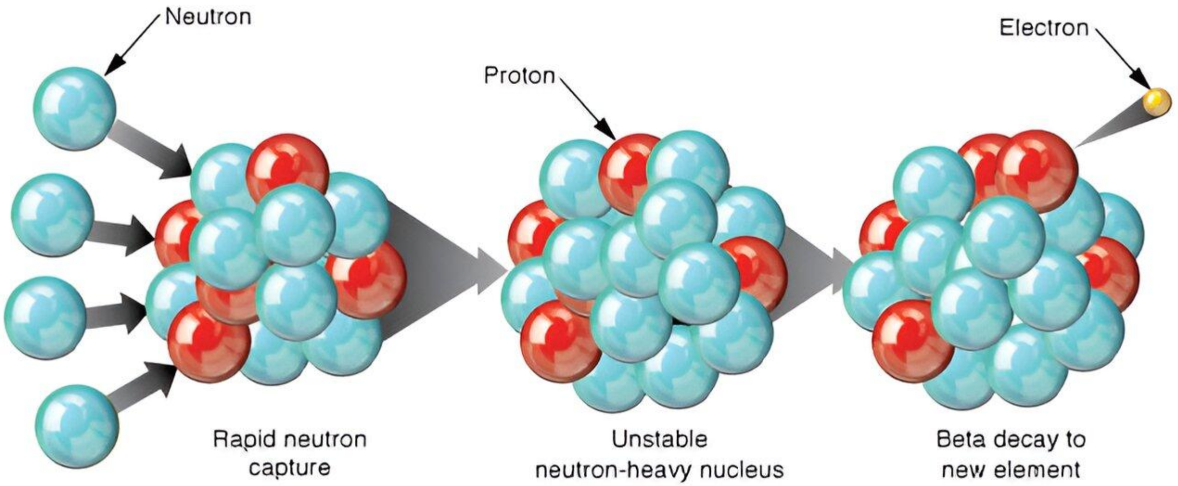
ApJL **962** L24 (2024)

Sesto Incontro Nazionale di Fisica Nucleare
INFN2024 - Trento

February 26, 2024

r-process nucleosynthesis

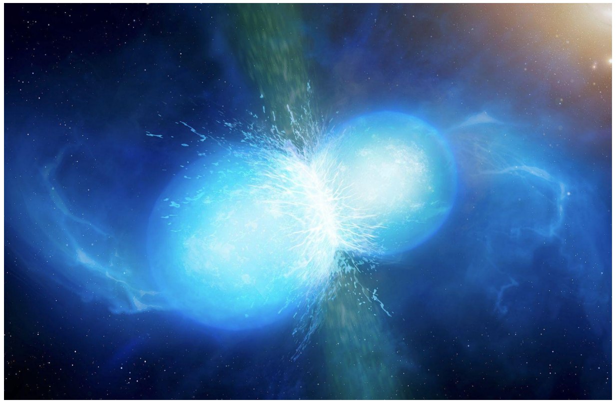
- Half of heavy elements in the Universe from rapid neutron capture process **(*r*-process)** ⇒ **neutron-rich** astrophysical sites!



★ Special types of supernovae (SN)
⇒ e.g. magneto-rotational, collapsars…

★ Binary Neutron Star mergers
Black Hole - Neutron Star mergers

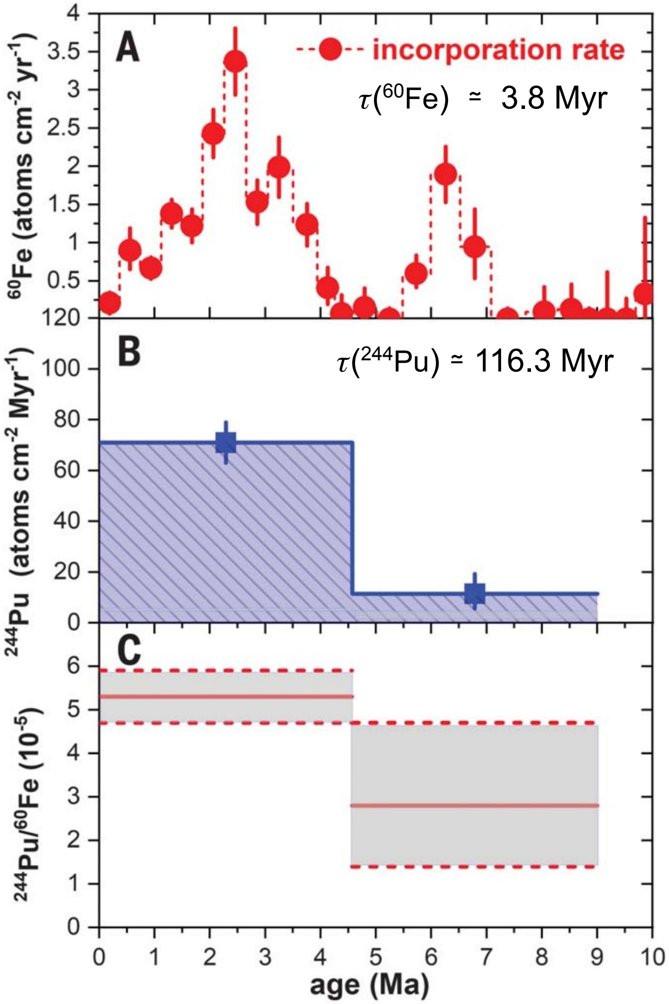
⇒ GW170817 + AT2017gfo



Live radioactive isotopes

- **Live radioactive isotopes** in meteorites, lunar samples, deep-sea sediments…

Wallner et al., *Science* (2021)



➔ Isotopic signatures in deep-sea crust ≤ 10 Myr old

^{60}Fe ➢ usually associated with SN explosions

^{244}Pu ➢ solely from *r*-process events

^{244}Pu / ^{60}Fe atoms (t < 4.6 Myr) = (56 ± 6) $\times 10^{-6}$

- ☐ not compatible with a single BNS event
- ☐ nearby SN with enhanced r-process production or alternative explanation

Wang+2021
Wang+2023

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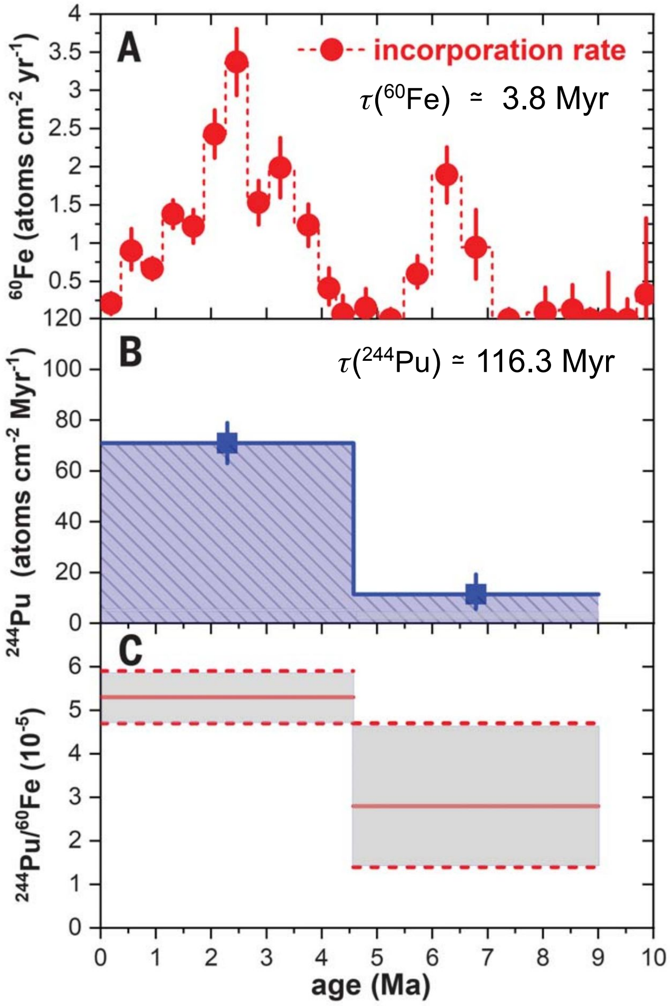

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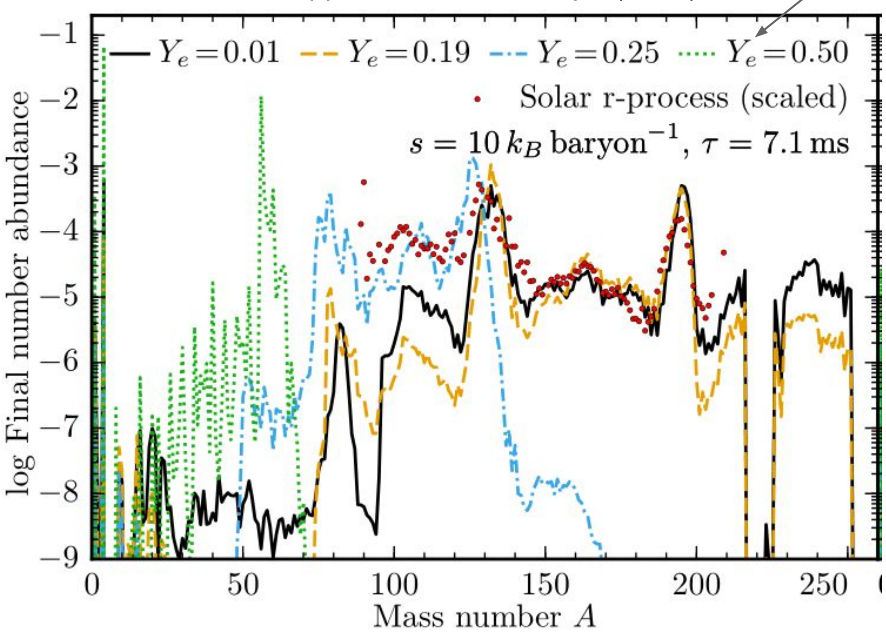

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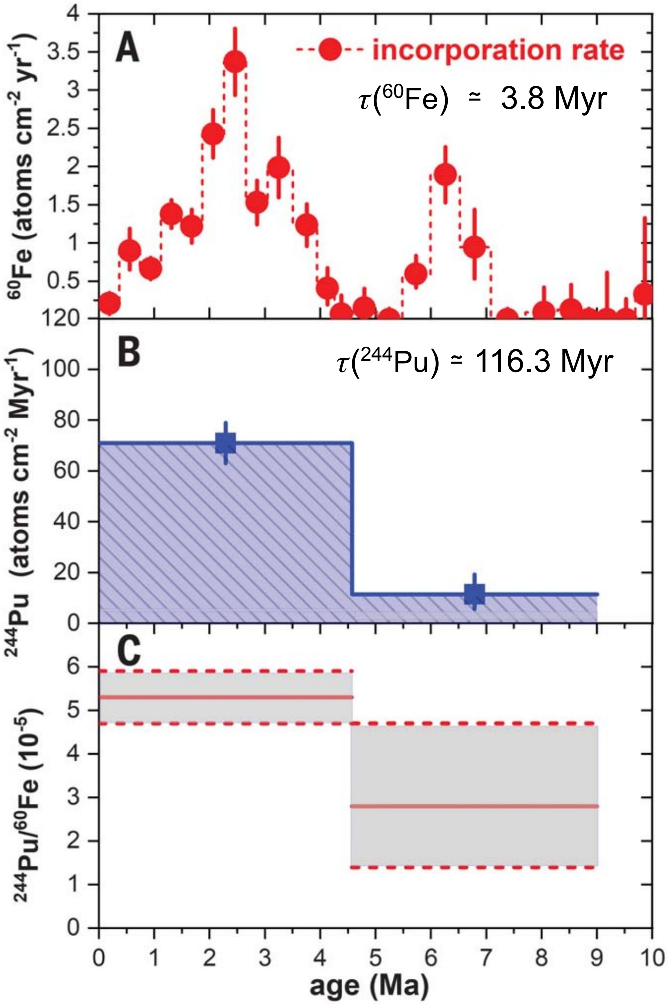

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***ν* irradiation** from NS remnant in a BNS merger boosts the production of light elements in the ejecta

BNS merger model with long-lived NS remnant could predict a much higher ^{60}Fe/^{244}Pu ratio!

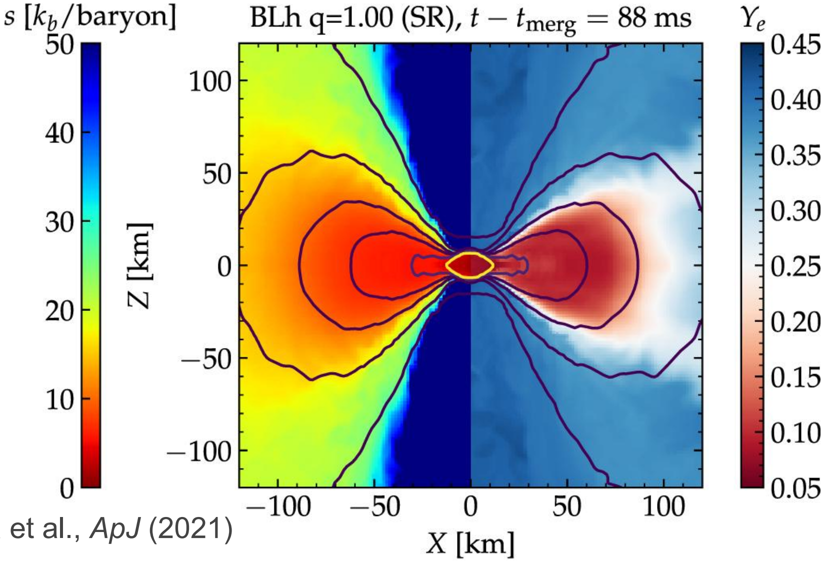
Methods

- Modeling of BNS ejecta with NR simulations (WhiskyTHC)

  long-lived remnant (50-100 ms)

  ★ EOS ⇒ DD2, BLh, SFHo, SLy4

  ★ neutrinos ⇒ LK + M0 scheme

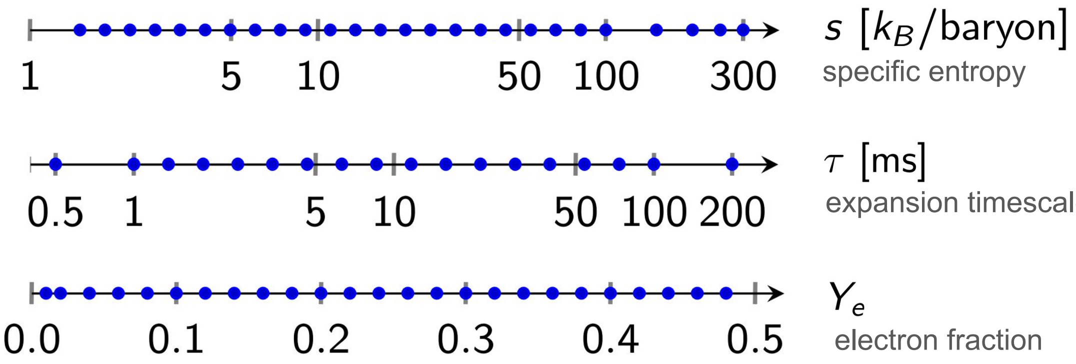


Nedora et al., *ApJ* (2021)

- Parametric nuclear reaction network calculations for Lagrangian trajectories

Sky Net
bitbucket.org/jlippuner/skynet

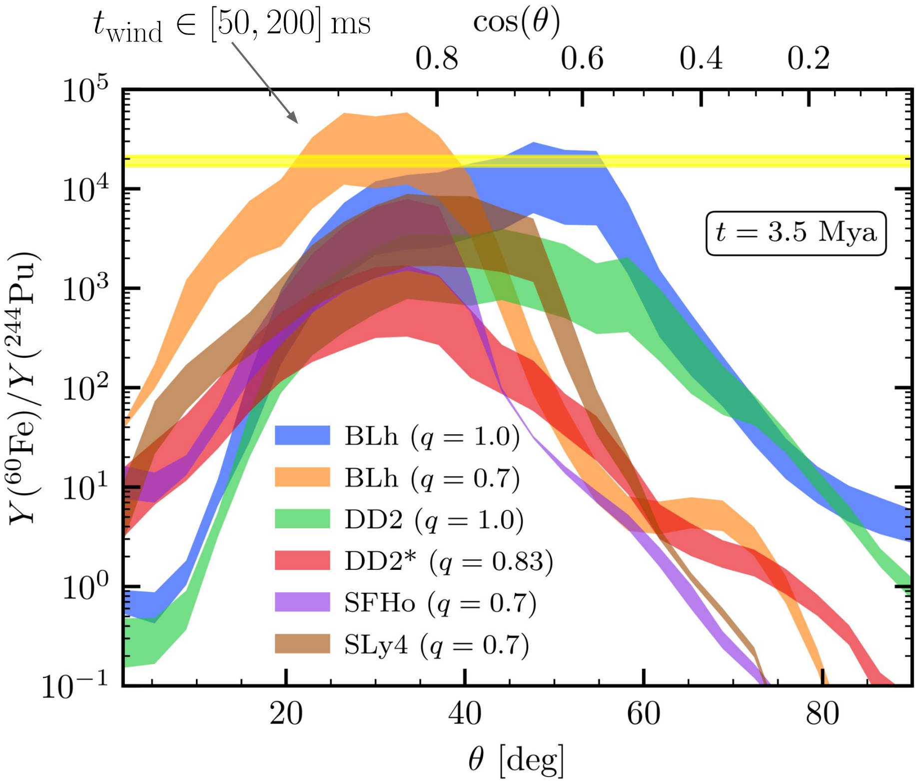
Lippuner & Roberts (2017)



$$m_{\mathrm{ej},i}(\theta, t_{\mathrm{wind}}) = m^{\mathrm{dyn}}_{\mathrm{ej},i}(\theta) + \frac{t_{\mathrm{wind}}}{t_{\mathrm{sim}}} m^{\mathrm{wind}}_{\mathrm{ej},i}(\theta)$$

30 yrs post-merger

Results



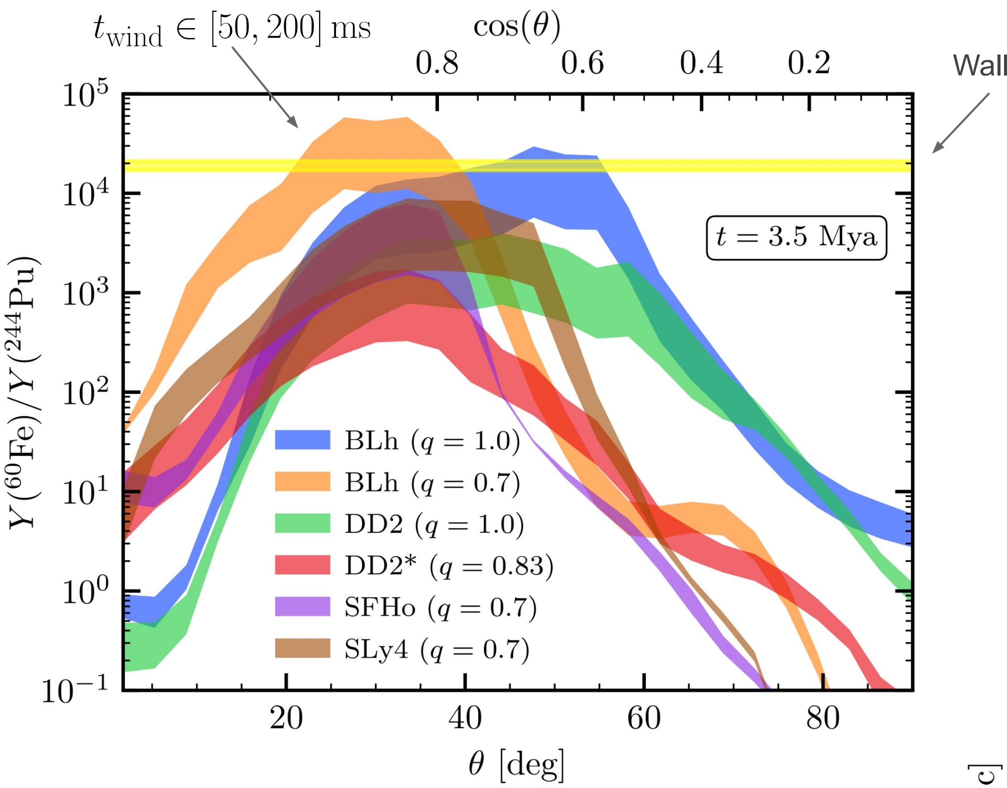
$t_{\mathrm{wind}} \in [50, 200]$ ms

Wallner+2021

➔ Some BNS models can reproduce the measured ratio for $20° \lesssim \theta \lesssim 60°$

↳ distance from Earth?

Results



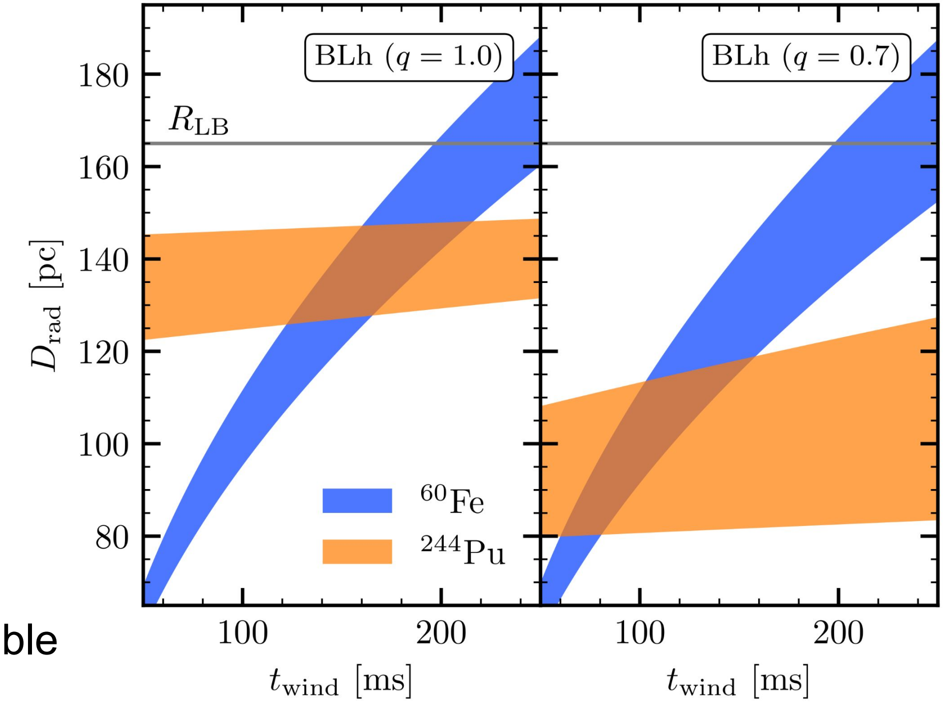
Wallner+2021

➔ Some BNS models can reproduce the measured ratio for 20° ≲ θ ≲ 60°

distance from Earth?

$$\mathcal{F}_i = f_{\text{dust},i} \frac{m^{\text{iso}}_{\text{ej},i}(\tilde{\theta}, t_{\text{wind}}) / (A_i m_u)}{4\pi D^2_{\text{rad},i}} e^{-t/\tau_i}$$

fluence (atoms cm^{-2})
Wallner+2021



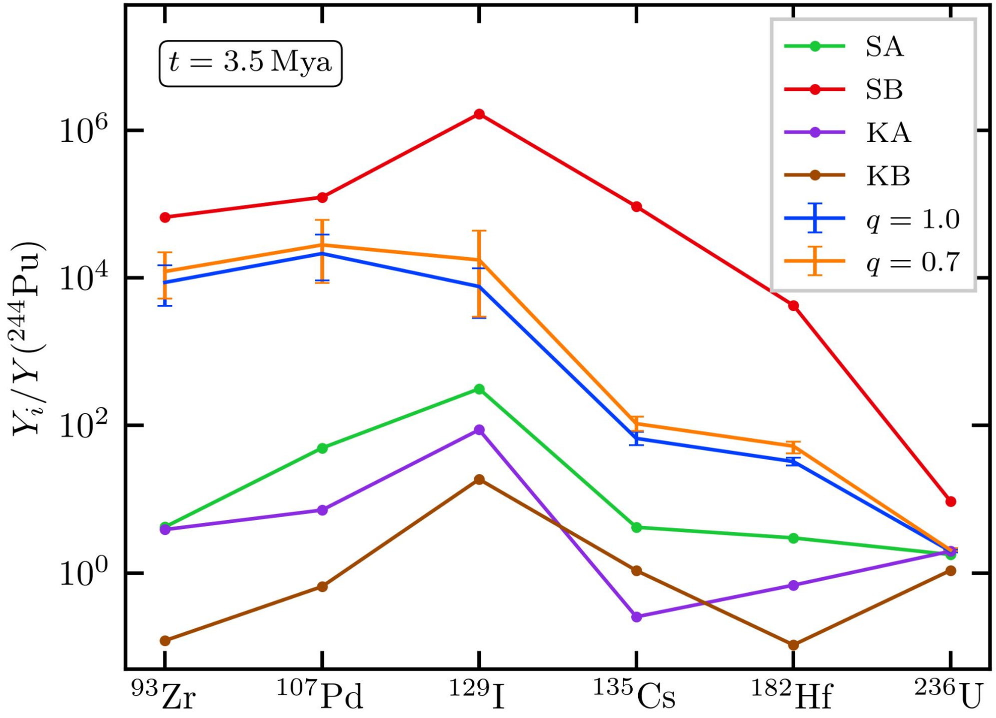
➔ Radioactivity distances are mutually compatible

Conclusions and outlook

^{244}Pu and ^{60}Fe isotopic signatures compatible with a **single (long-lived) BNS** merger occurring **~ 3.5 Myr ago** at ~ **80-150 pc** from Earth

isotopic ratios over ^{244}Pu

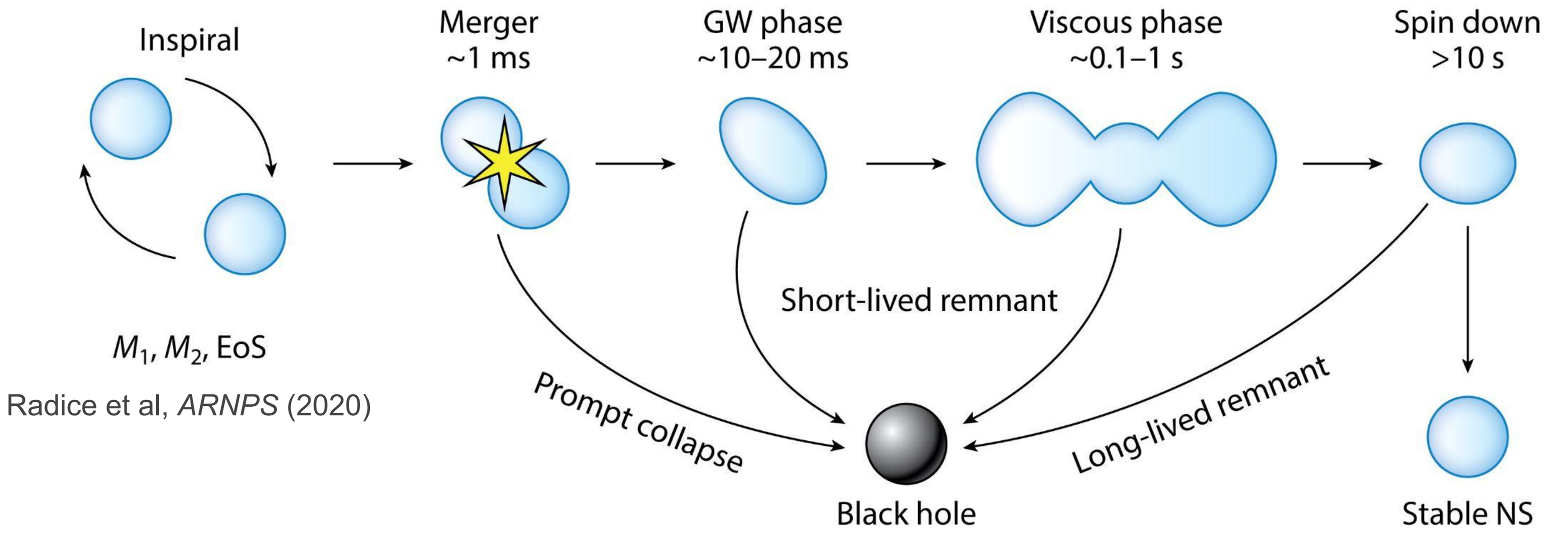
Wang+2021 models
vs BLh q = 0.7,1.0



➔ Further isotopic measurements required to distinguish between different scenarios

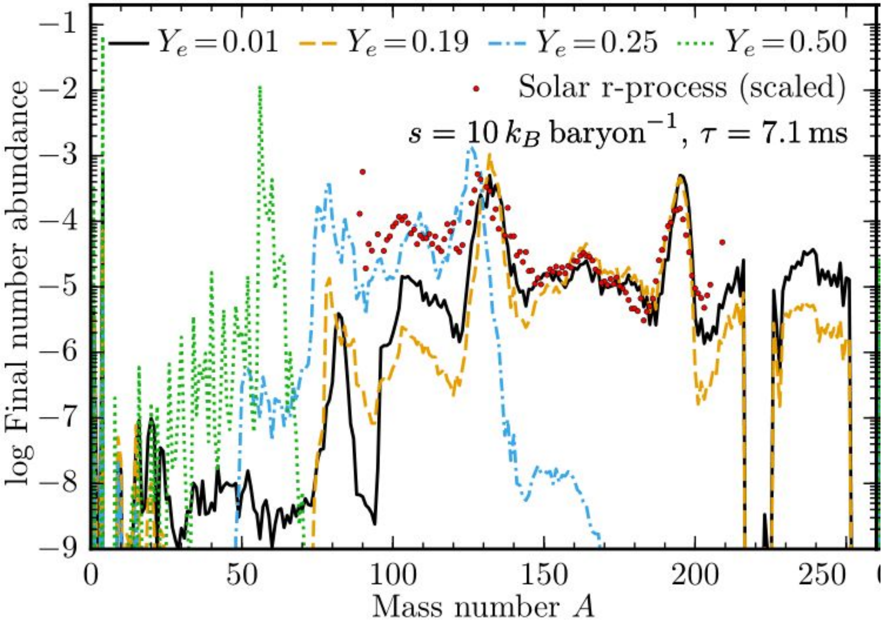
Backup slides

Binary neutron-star mergers



Radice et al, *ARNPS* (2020)

Lippuner & Roberts, *ApJ* (2015)



- ➢ Dynamical ejecta (tidal + shock-heated)
- ➢ Disk-wind ejecta (e.g. spiral-wave wind)

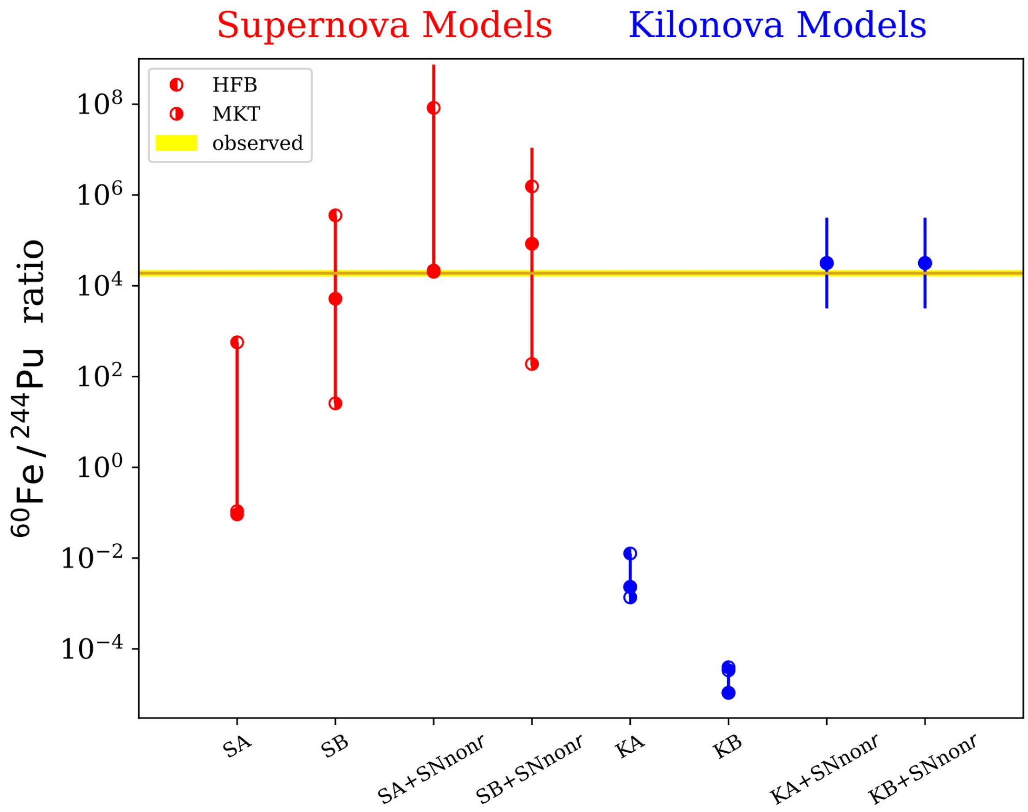
  matter can be reprocessed to higher Y_e by ν from the remnant

electron fraction distribution $\Big\}$ $\boxed{0.05 \lesssim Y_\mathrm{e} \lesssim 0.4}$

Nucleosynthesis models for ^{60}Fe / ^{244}Pu

Different nsys models to explain the observed ^{60}Fe over ^{244}Pu ratio:

- one-step scenario
  - ➔ SN ✓
  - ➔ BNS (KN) ✗
- two-step scenario
  - ➔ ^{244}Pu enrichment of LB from earlier BNS event ✓



Wang et al., *ApJ* (2021)
Wang et al., *ApJ* (2023)

KN model limitations ⇨

1. isotropic ejecta
2. combination of few BNS trajectories fitted to experimental data

BNS models

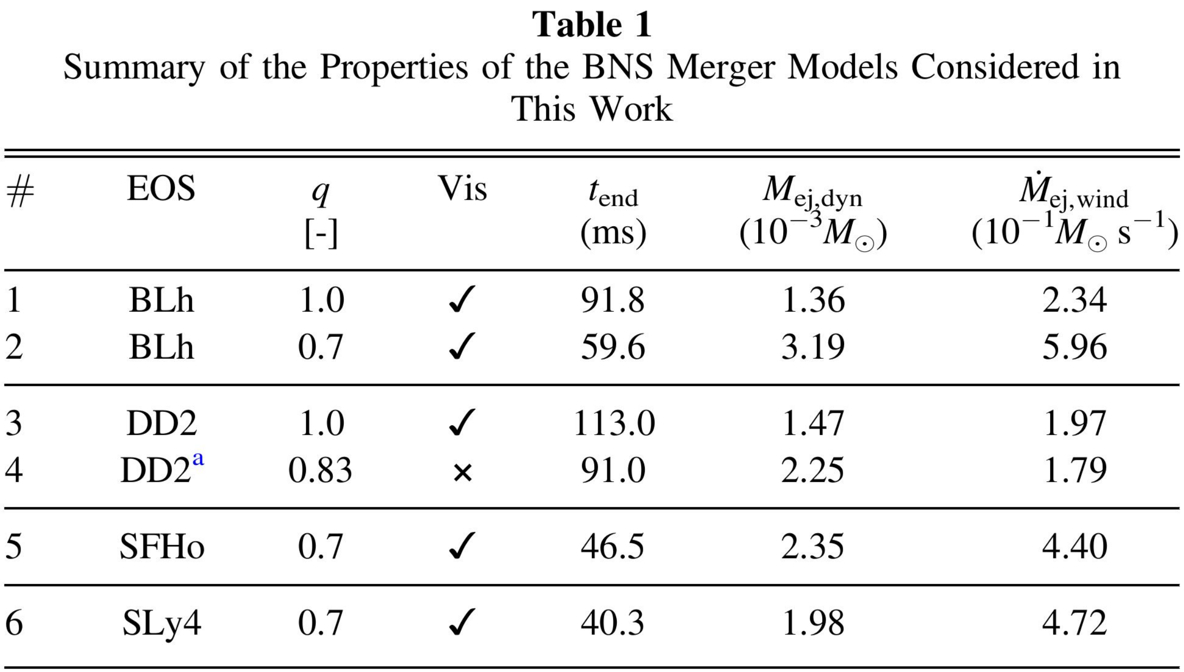


Table 1
Summary of the Properties of the BNS Merger Models Considered in This Work

#	EOS	q [-]	Vis	$t_{\rm end}$ (ms)	$M_{\rm ej,dyn}$ ($10^{-3}M_\odot$)	$\dot{M}_{\rm ej,wind}$ ($10^{-1}M_\odot\ {\rm s}^{-1}$)
1	BLh	1.0	✓	91.8	1.36	2.34
2	BLh	0.7	✓	59.6	3.19	5.96
3	DD2	1.0	✓	113.0	1.47	1.97
4	DD2[a]	0.83	×	91.0	2.25	1.79
5	SFHo	0.7	✓	46.5	2.35	4.40
6	SLy4	0.7	✓	40.3	1.98	4.72

1. Massive NS remnant for ~100-200 ms ⇒ dynamical (^{244}Pu) and spiral-wave (^{60}Fe)

   $\gtrsim$ 50% of the events (Margalit & Metzger 2019)

2. Mid-high latitudes: $30^\circ \lesssim \tilde{\theta} \lesssim 50^\circ \Rightarrow \frac{\Delta\Omega}{4\pi} \approx 0.18{-}0.27$

^{60}Fe and ^{244}Pu nucleosynthesis

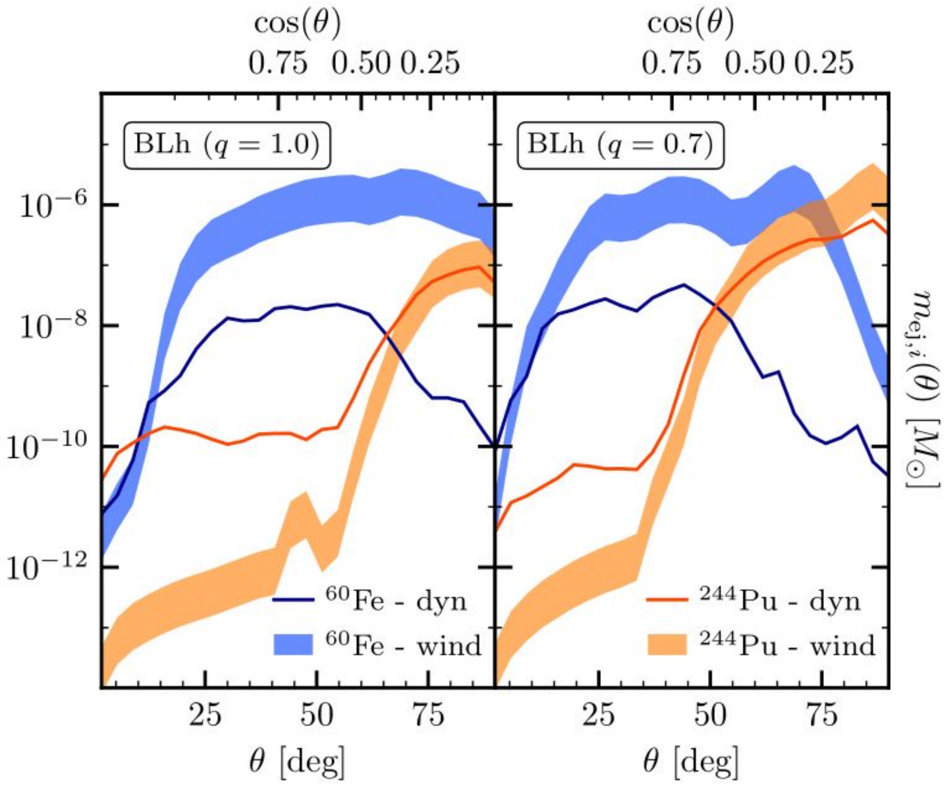
- Angular dependence is relevant!

  large-scale mixing is inefficient for such nearby events

^{60}Fe ➢ wide θ range (wind)

^{244}Pu ➢ equatorial region (dyn + wind)

$$\frac{Y_i}{Y_j}(\tilde{\theta}, t_{\mathrm{wind}}) = \frac{A_j}{A_i}\frac{m_{\mathrm{ej},i}(\tilde{\theta}, t_{\mathrm{wind}})}{m_{\mathrm{ej},j}(\tilde{\theta}, t_{\mathrm{wind}})}\, e^{t(1/\tau_j - 1/\tau_i)}$$



★ BLh models match the observed ratio at mid-high latitudes

★ DD2 models: spiral-wave wind is not rich enough in ^{60}Fe

★ SFHo and SLy4 models: amount of ^{244}Pu is one order of magnitude larger

Explosion time uncertainty

- BNS ejecta expands after merger to ~100 pc within ~1 Myr

$$R_{\mathrm{fade}} \simeq 240\,\mathrm{pc}$$

Bonetti et al. (2019)
Beniamini et al. (2018)

⇨ isotopic ratio can accommodate such explosion time uncertainty (± 1 Myr)