Relativistic outflows in binary neutron star mergers

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PoToR Annual Meeting

Będlewo, August 7, 2026

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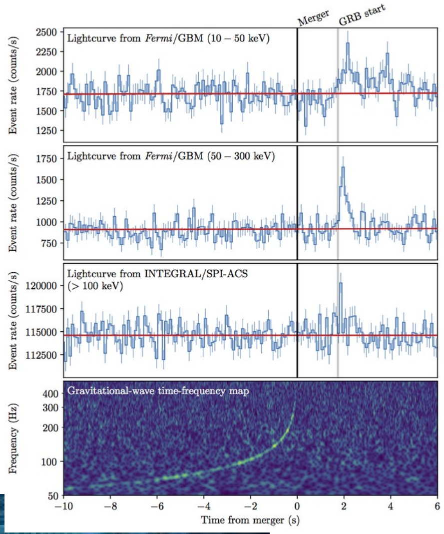
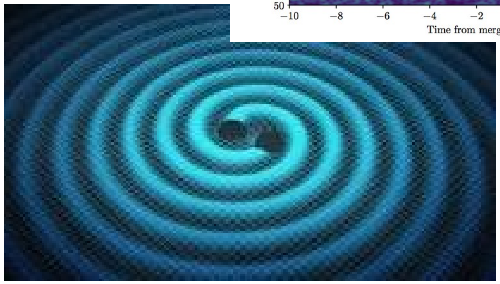
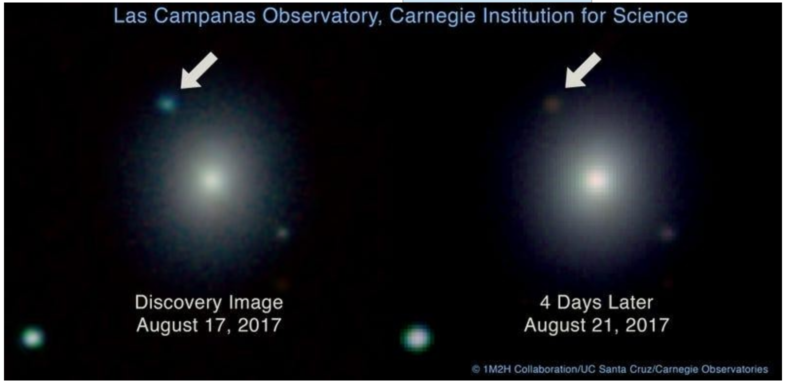
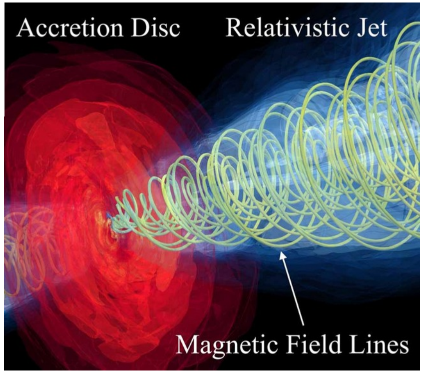
Multimessenger appearance of BNS mergers

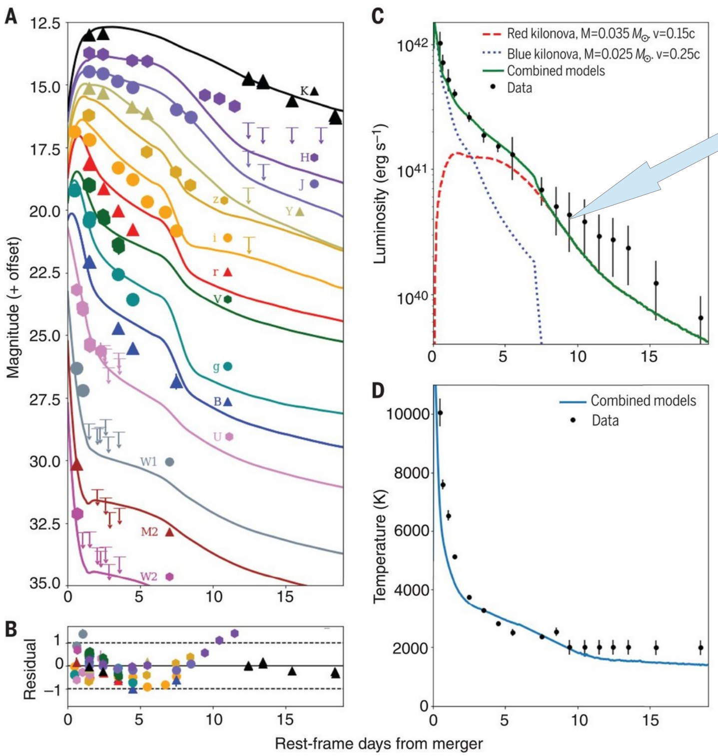




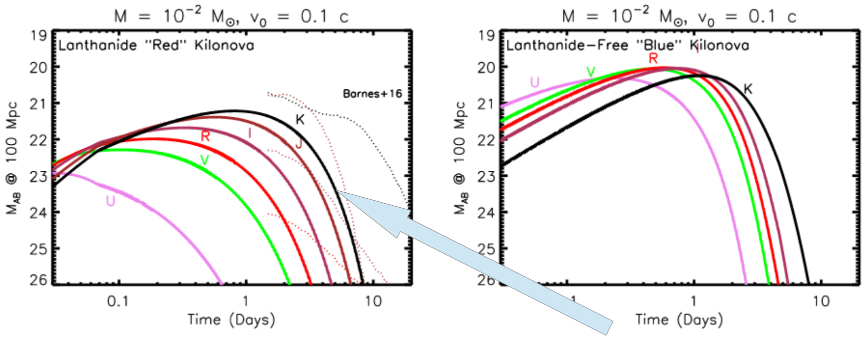




GW170817 and its colors

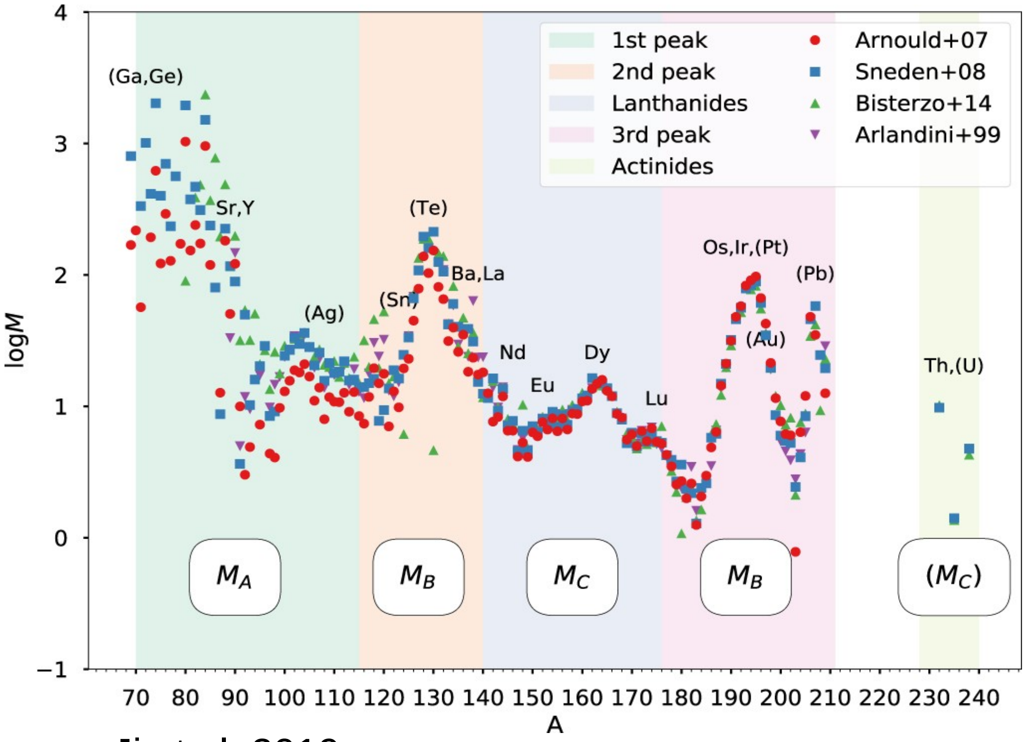


Blue and the red kilonova associated with GW170817 (Kilpatrick et al. 2017).



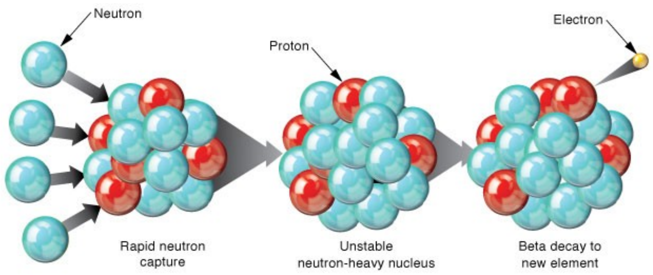
Interpreted from radiation transfer calculations, due to absorption in the media of various composition

Nucleosynthesis of heavy elements: r-process



Ji et al. 2019

Ye = $n_p/(n_p + n_n) < 0.5$

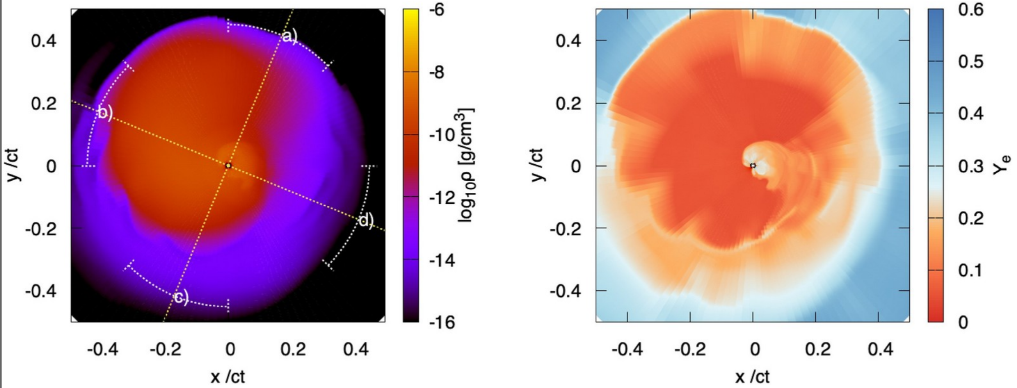


$Y_e > 0.25$: 1st peak

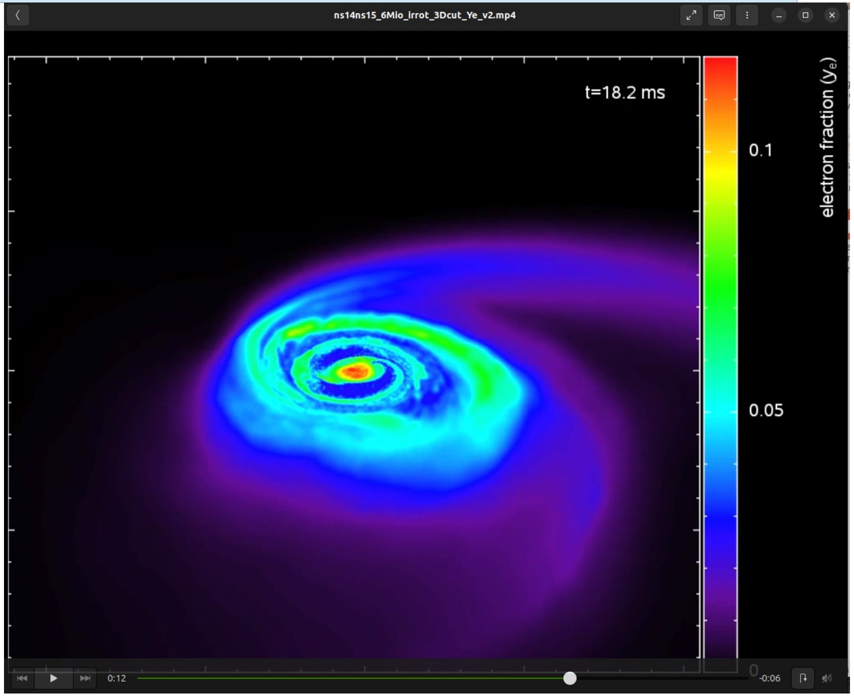
$Y_e = 0.15\text{-}0.25$: 2nd peak, Lanthanides

$Y_e < 0.15$: 3rd peak, Actinides

Compact binary merger simulations



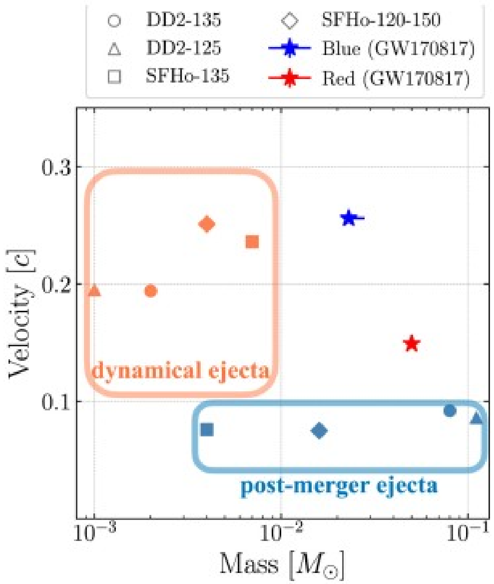
BH-NS merger
Kawaguchi et al. 2024



NS-NS merger
Korobkin et al. 2021

Multi-component picture

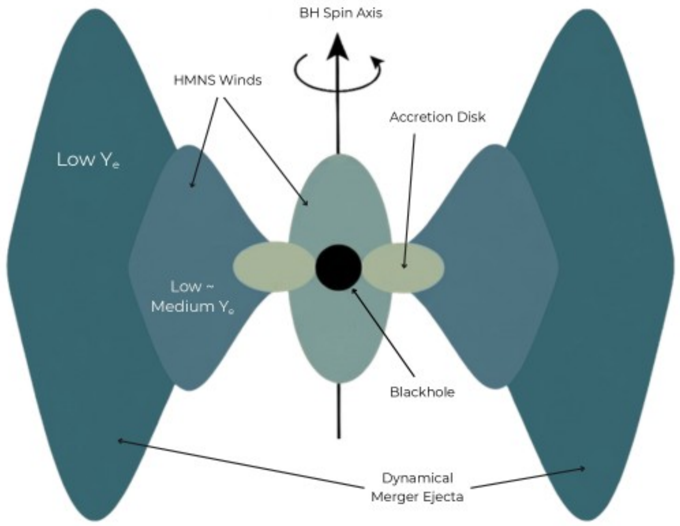
- Pre-merger phase: dynamical ejecta
- Post-merger phase: spherical winds from HMNS
- Data need another component → disk wind?
- HMNS wind properties depend on its lifetime (tbc...)



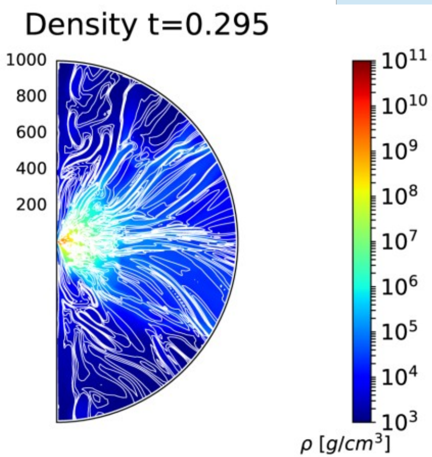
Kitamura et al. 2025

Disk winds regulate the transient

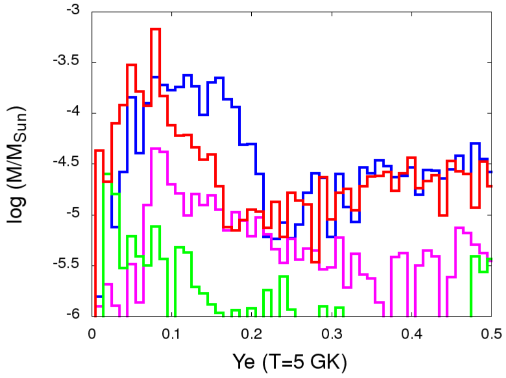
- Disk winds are bridge between kilonovae and GRBs
- They regulate lanthanide opacity through stratified Y_e and provide baryonic medium that shapes relativistic jets
- Their properties are tightened with engine parameters and nature of progenitor → central for multimessenger interpretation

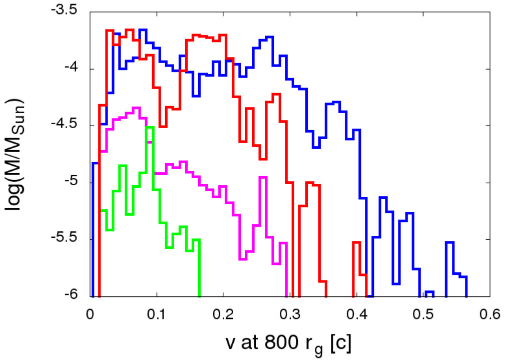


Disk wind thermodynamics



- Fast wind (v=c ∼ 0.11 − 0.23), broad range of electron fraction Ye ∼ 0.1 − 0.4.
- Mass loss via unbound outflows between 2% and 17% of the initial disk mass.
- Details sensitive to engine parameters: BH spin and magnetisation of the disk
- More magnetized disk produce faster outflows. BH spin dependence





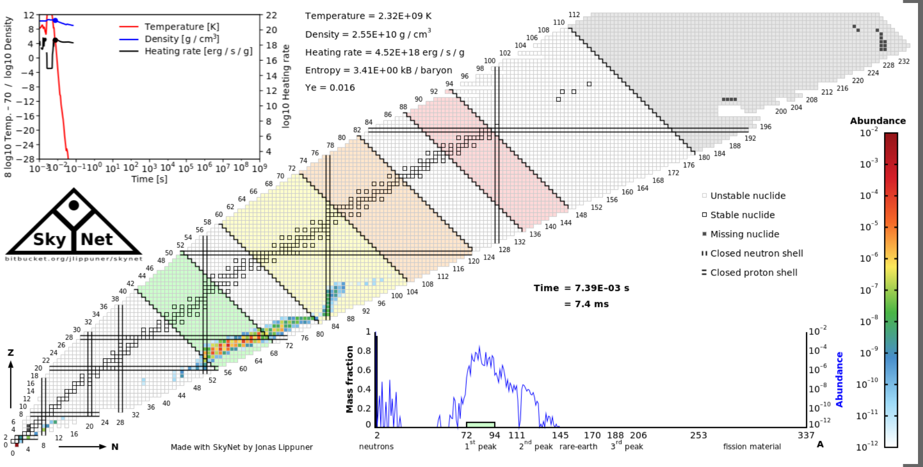
A. Janiuk (2019, ApJ)

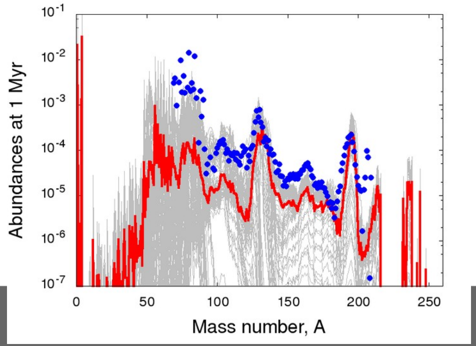
Disk wind nucleosynthesis

- Heavy elements up to A ~ 200
  (incl. Platinum, Gold) produced in disk winds

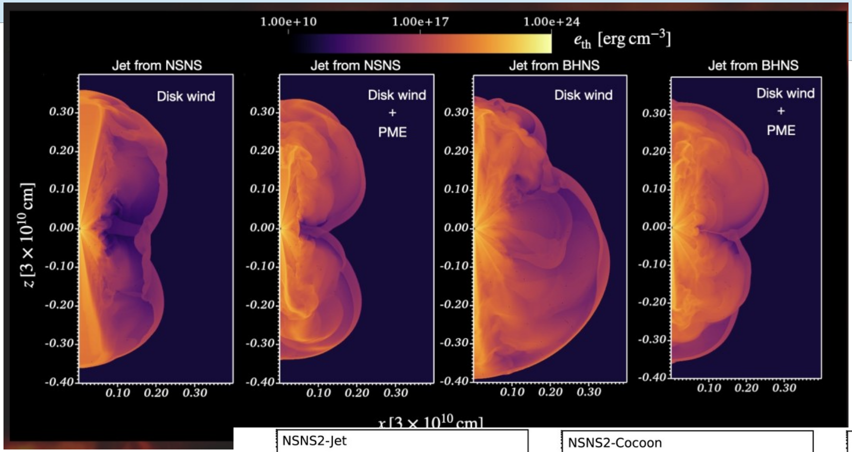
- Correlation between the black hole's spin and ejected wind mass (Nouri, Janiuk Przerwa, 2023)

- Link to population studies: only a fraction (~20%) of BH-NS binaries gain a high BH spin (cf. Drozda et al. 2022)



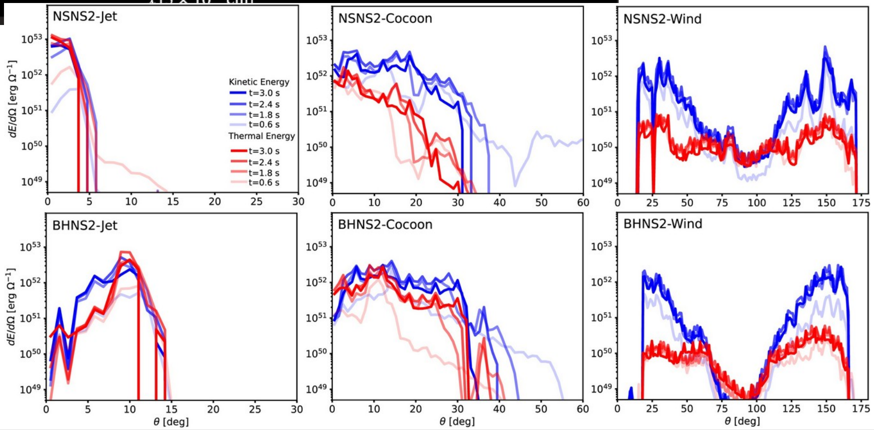


Jet interactions with disk winds



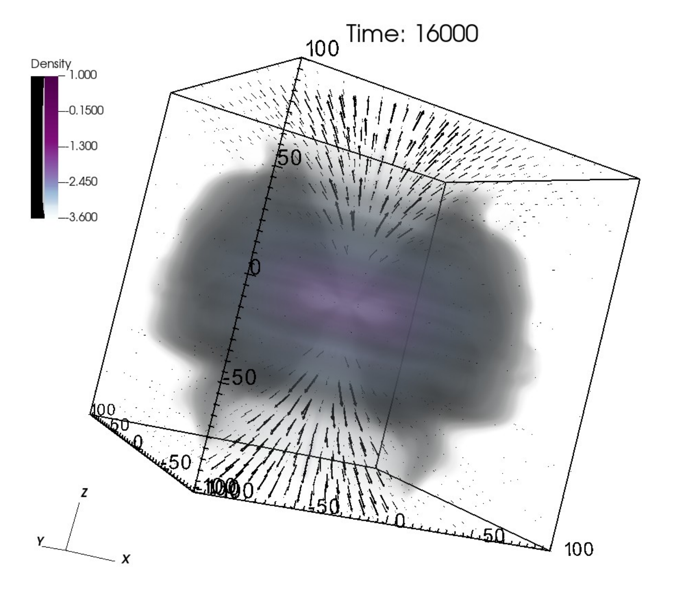
- Interaction of a relativistic jet with postmerger ejecta and accretion disk wind shapes the structure of outflow and its radiation properties.

- Distribution of thermal and kinetic energy in jet, cocoon and wind, depend on our (implicit) binary merger scenario and presence of postmerger (HMNS) ejecta.

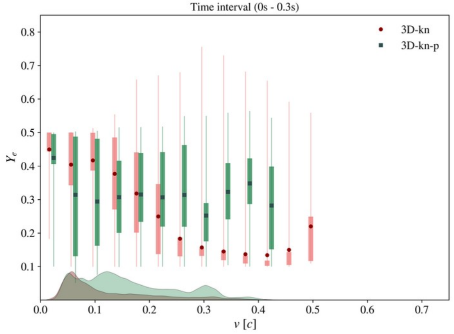


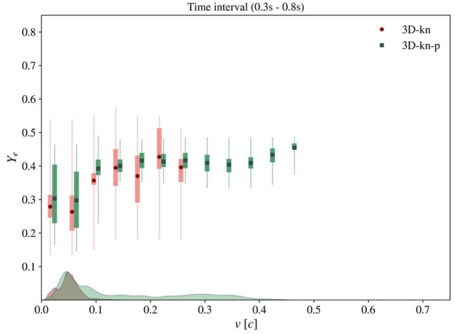
Urrutia, G. Janiuk A., Nouri F.H., 2025, MNRAS, 358, 124

Launching disk winds



- HARM-EOS (3-parameter tabulated ‘Helmholtz’ EOS, neutrino leakage (Rosswog & Liebendoerfer 2003; Fernandez & Metzger 2013)
- Magnetised winds and weak jets launched, chemical evolution of winds followed by tracers.
- Low- and high-Y_e media, stratification and geometries depending on (disk-BH mass ratio, magnetisation, BH spin)

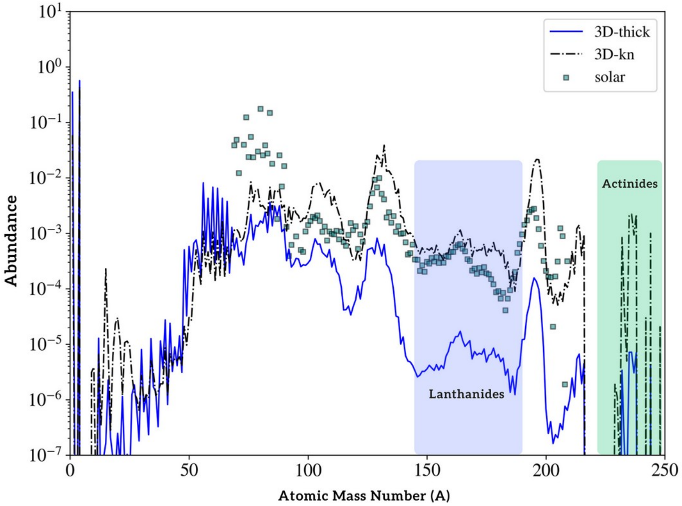




Janiuk A., Saji, J, Urrutia G. 2026, A&A, 707, 307

Nucleosynthetic output across different engine configurations

Lanthanide mass fraction spans nearly two orders of magnitude between small and massive disks

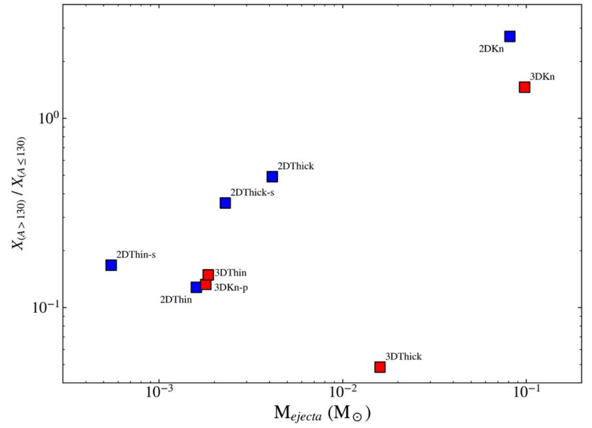


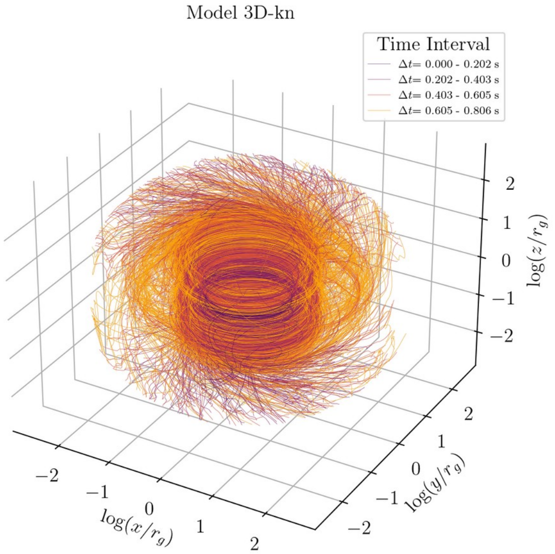
Model	Total outflow mass [$M_\odot$]	$\langle Y_e \rangle_{tr}$ $T = 10\,GK$	$\langle Y_e \rangle_{tr}$ $T = 5\,GK$	$\langle v \rangle$[c] at 500 r_g	Eu/Fe	$X(57 \leq Z \leq 72)$ (Lanthanides)
2D-Thick-s	2.3×10^{-3}	0.388	0.424	0.125	8.2×10^{-3}	0.0011
2D-Thin-s	5.5×10^{-4}	0.382	0.444	0.089	4.6×10^{-3}	0.0007
2D-Thick	4.2×10^{-3}	0.328	0.389	0.097	1.7×10^{-2}	0.0020
2D-Thin	1.6×10^{-3}	0.378	0.448	0.111	5.5×10^{-3}	0.0007
2D-kn	8.2×10^{-2}	0.160	0.189	0.073	1.04	0.0509
3D-Thick	1.6×10^{-2}	0.420	0.485	0.132	8.3×10^{-4}	0.0003
3D-Thin	1.9×10^{-3}	0.377	0.445	0.100	1.2×10^{-2}	0.0008
3D-kn	9.8×10^{-2}	0.191	0.262	0.074	5.7×10^{-1}	0.0265
3D-kn-p	1.8×10^{-3}	0.372	0.420	0.193	4.6×10^{-2}	0.0016

Notes. Model parameters are listed in Table 1. The total mass and angle-averaged electron fraction are computed for unbound tracers cooled to the NSE-breakdown temperature. The velocity (in units of c) is measured at 500 r_g. Europium-to-iron number ratios are calculated across all isotopes (not normalized to Solar). The lanthanide-abundance fraction is summed over $57 \leq Z \leq 72$.

Chemical enrichment from disk winds

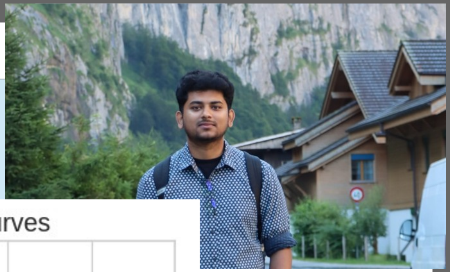
- Ejecta masses 0.01 – 0.1 M_{sun}
- Broad range of Y_e,
- Velocities up to 0.2 c
- [Eu/Fe] : 8.3×10^{-4} – 5.7×10^{-1}
- Heavy-to-light ratio depend on CE properties



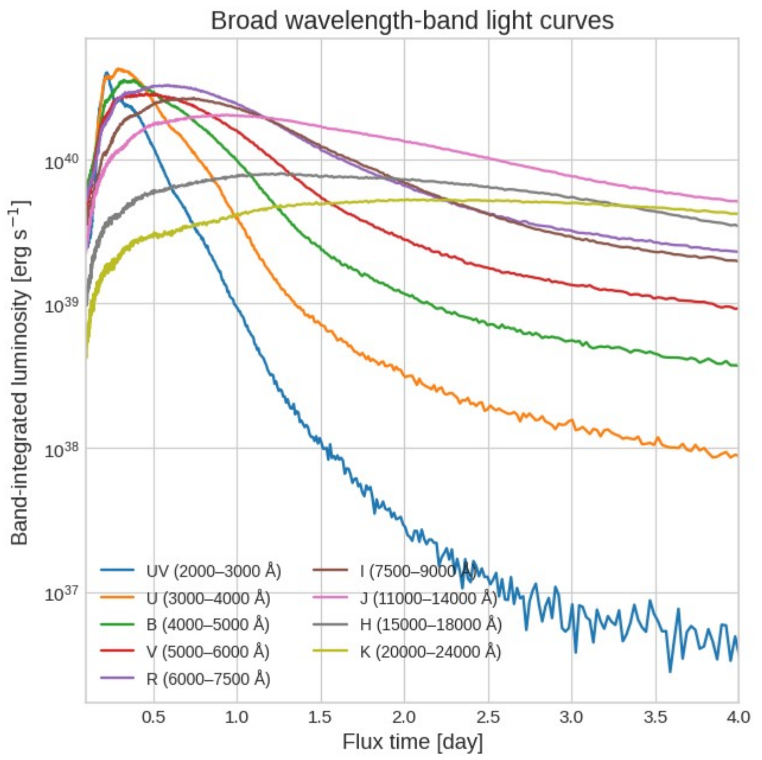


→ Favored models for rich-red-KN contribution: a=0.6, M_{BH}/M_{disk} = 8.2/0.78 ~ 10, optically thin to neutrino
→ Tuned for ‘peculiar’ GRB211211A

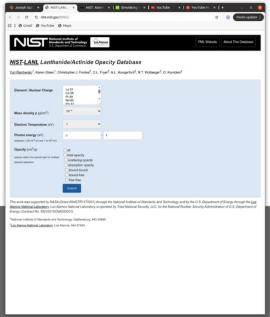
Radiation transport calculations



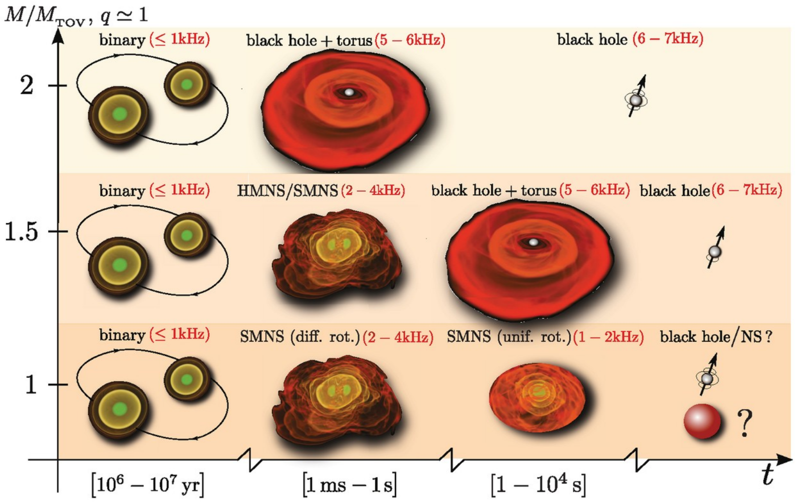
- Radiative transfer: multidimensional, multigroup Monte Carlo code SuperNu (Wollaeger et al. 2013; Wollaeger & van Rossum 2014),
- Tabulated, line-binned opacities from the LANL suite of relativistic atomic physics codes.
- Detailed lanthanide and actinide opacities (Fontes et al. 2020, 2023) and iron-group/light r-process elements (Wollaeger et al. 2018).



Saji et al. (2026, in prep.)



HMNS: a short-lived remnant



For GW170817, the collapse time is still indirectly constrained;

Estimates around ∼1 s are model dependent.

cf. review by Baiotti & Rezolla 2017

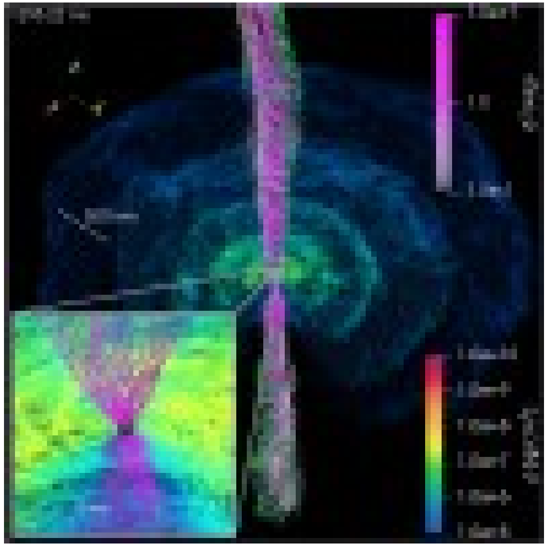
Recent numerical relativity simulations

- **Nedora et al. (2021)** connects remnant survival with persistent spiral-wave winds, relatively high-Y_e ejecta, remnant disk properties, and nucleosynthesis

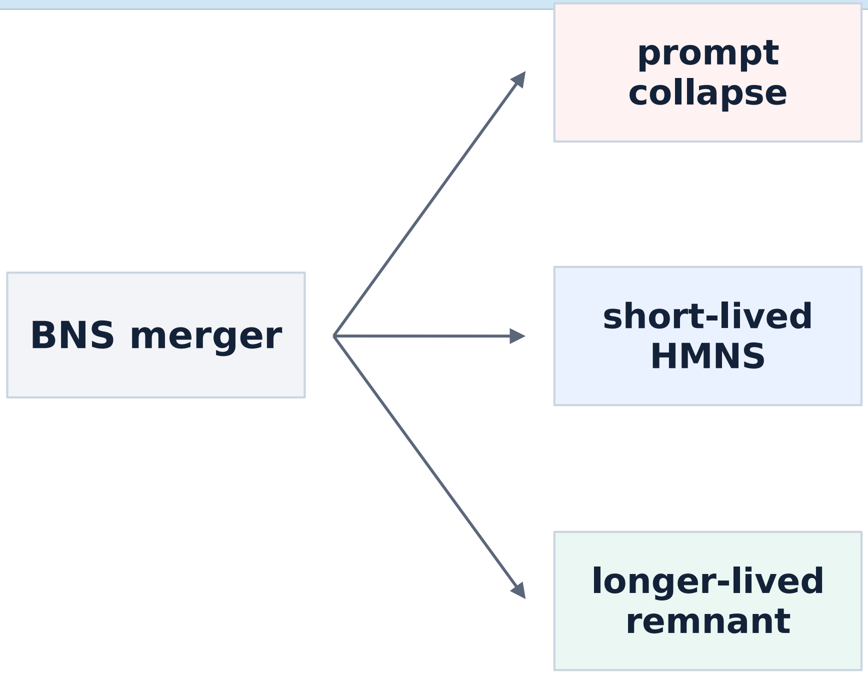
- **Fujibayashi et al. (2023)** present remnants collapsing within approximately 20 ms and separate dynamical ejecta from post-merger ejecta.

- **Bernuzzi, Magistrelli et al. (2025)** present long-lived-remnant calculation with neutrino-radiation hydrodynamics

- **Hayashi et al. (2025)** present long, self-consistent neutrino-radiation GRMHD simulation of an asymmetric merger undergoing prompt BH formation.



From remnant evolution to kilonovae



Remnant fate: disk mass, ejecta geometry, composition.

Longer-lived remnants allow stronger neutrino/thermal processing, producing high Ye, high entropy winds.

Prompt or short-lived collapse leaves a cleaner BH–disk system, but usually less polar blue ejecta.

NR-based fitting studies show that ejecta and disk properties depend on mass ratio, tidal deformability (EOS), and microphysics (neutrino transport).

Summary

1. Post-merger disk winds contribute to r-process ejecta and kilonova emission.
2. The same wind and surrounding ejecta reshape the jet collimation, cocoon, and angular structure.
3. Disk, tidal ejecta, HMNS winds retain the information on the remnant lifetime
4. Numerical Relativity informed lifetime survey connects remnant evolution to jet emission, propagation, nucleosynthesis and kilonovae

BH accretion disk simulations - Post-merger system

$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$

$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$

$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

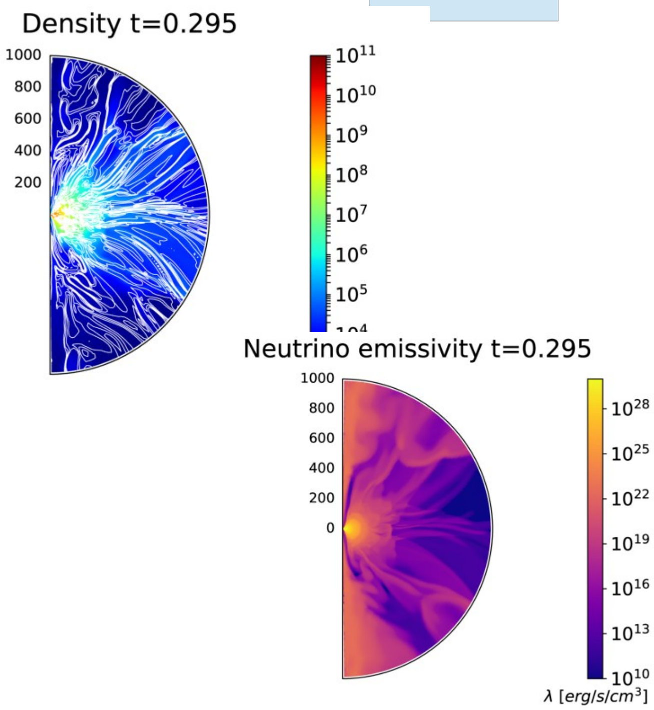
$$(\rho u_\mu)_{;\nu} = 0$$

$$T^\mu_{\nu;\mu} = 0.$$

HARM= High Accuracy Relativistic MHD
(cf. Gammie et al. 2003).

HARM-COOL: Fermi gas EOS is computed numerically and tabulated during dynamical simulation with P(ρ, T), e(ρ,T)
Postprocessing by nuclear reaction networks.
Implemented on tracer particles.

https://github.com/agnieszkajaniuk/HARM_COOL



A. Janiuk (2017; 2019)

Collapsar disk winds

- Collapsars can also have neutron-rich disk outflows and have been proposed as major r-process sites (Siegel, Barnes & Metzger, 2019)
- Collapsar accretion disks can eject enough r-process material to be important for cosmic heavy-element production.
- Their optical/IR emission may be kilonova-like, but it is embedded in a massive-star explosion environment and can be masked by supernova light.
- Still, LGRB-associated kilonova events, 2011211A, and 230307A, re-opened the debate on the collapsar-driven engines

Ristic et al.

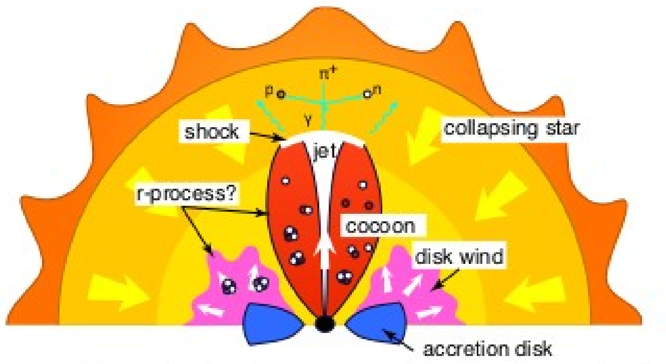
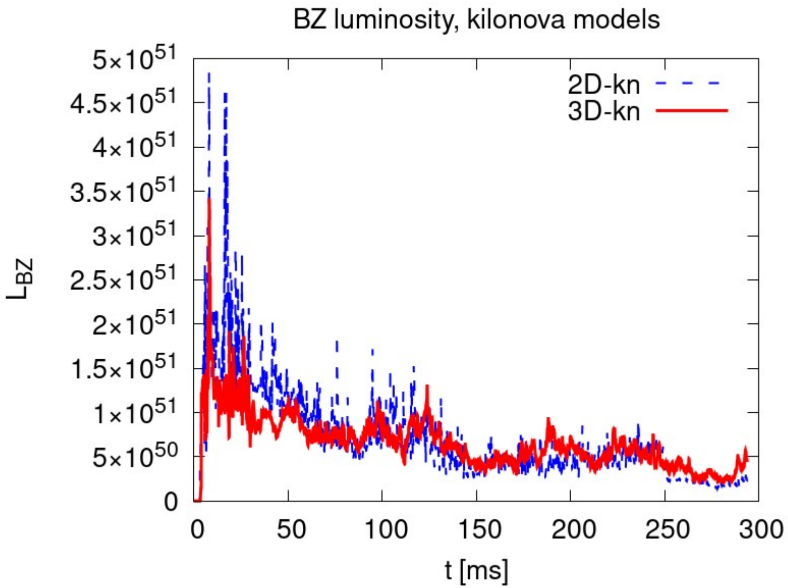
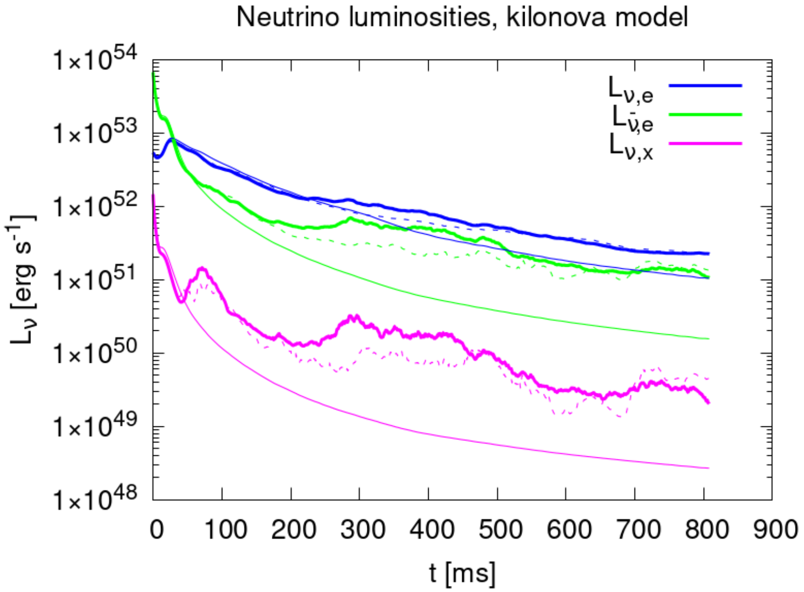


Figure 1. Schematic of a collapsar showing the two proposed sites for neutron-rich nucleosynthesis, emanating from the jet/cocoon or from the disk wind.

Ristic et al. (2026, ApJL)

GRB source of power





→ The jet in kilonova-related GRB may be driven by neutrino annihillation, rather than BZ

→ SANE evolution of the disk leads to powerful wind outflows, but a weak jet

(Janiuk, Saji, Urrutia, 2026, A&A, 707, 307)

Kilonova: mergers as safe channel

♠ Binary neutron star mergers eject material rich in heavy radioactive isotopes.

♠ Can power an electromagnetic signal called a kilonova
(Li & Paczynski 1998; Tanvir et al. 2013)

♠ Dynamical ejecta from compact binary mergers, $M_{ej} \sim 0.01\ M_{Sun}$, can emit about 10^{40}-10^{41} erg/s in a timescale of 1 week.

♠ Subsequent accretion can provide bluer emission, if it is not absorbed by precedent ejecta
(Tanaka, 2016, Berger 2016, Siegel & Metzger 2017)