Chemical Evolution and Ejecta Diversity in Post-Merger Black Hole Accretion Disk Outflows

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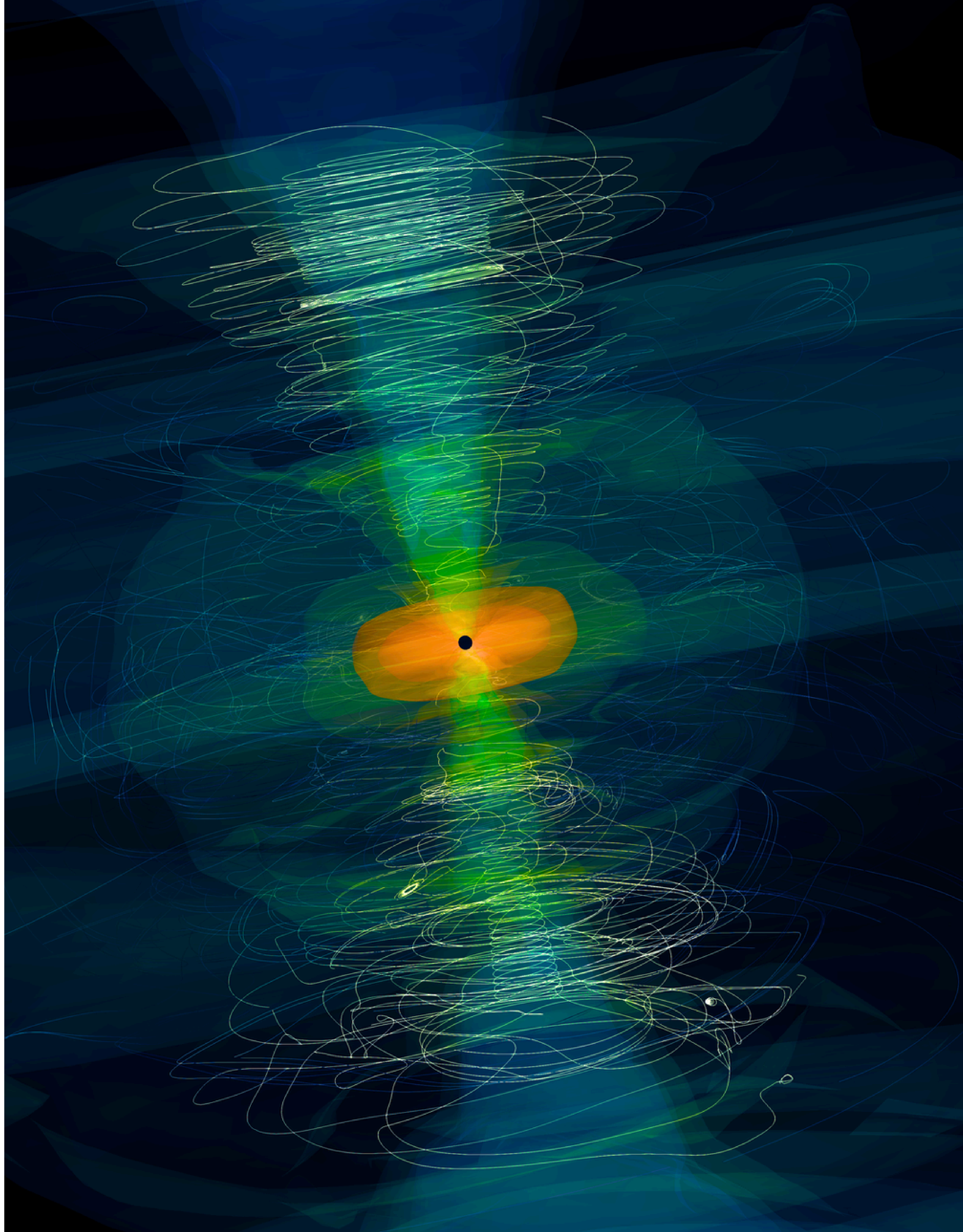
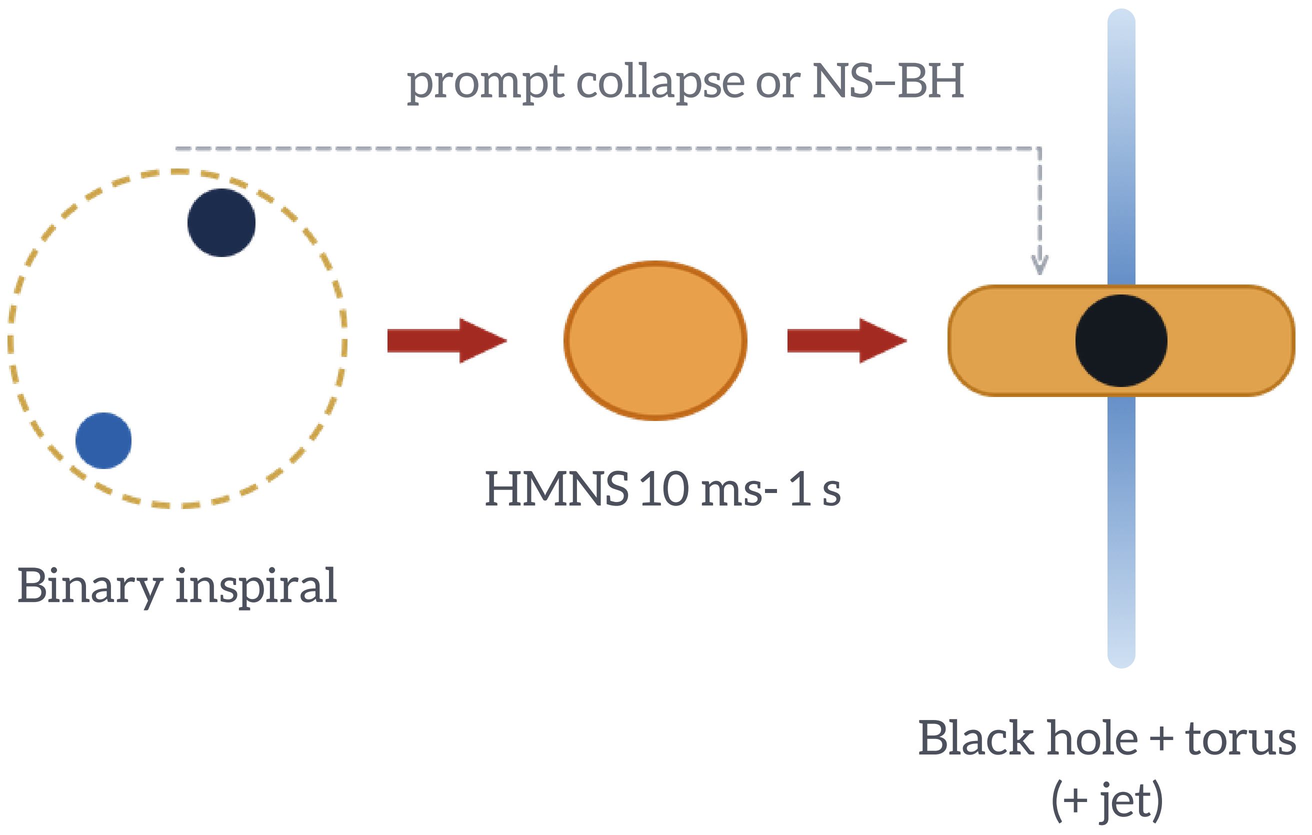


Compact-object mergers leave a spinning black hole behind

- NS–NS or NS–BH coalescence ends the inspiral within milliseconds.
- **BNS merger** → BH may form promptly or after the collapse of a transient neutron-star remnant.
- **NS-BH merger** → NS can be tidally disrupted before being swallowed.
- Matter remaining outside the black hole can form a hot, dense accretion torus, sustaining activity after the merger.

What happens next? The black hole–torus system powers jets and drives outflows.



merger schematics

The post-merger engine: black hole, torus, jets and winds

Dynamical ejecta

Tidal + shock driven, launched within milliseconds of contact; fast and highly neutron-rich (low Y_e).

10^{-4}–10^{-2} M⊙ · 0.15–0.3c · $Y_e \approx 0.05$–0.1

HMNS ejecta (if such a remnant is formed)

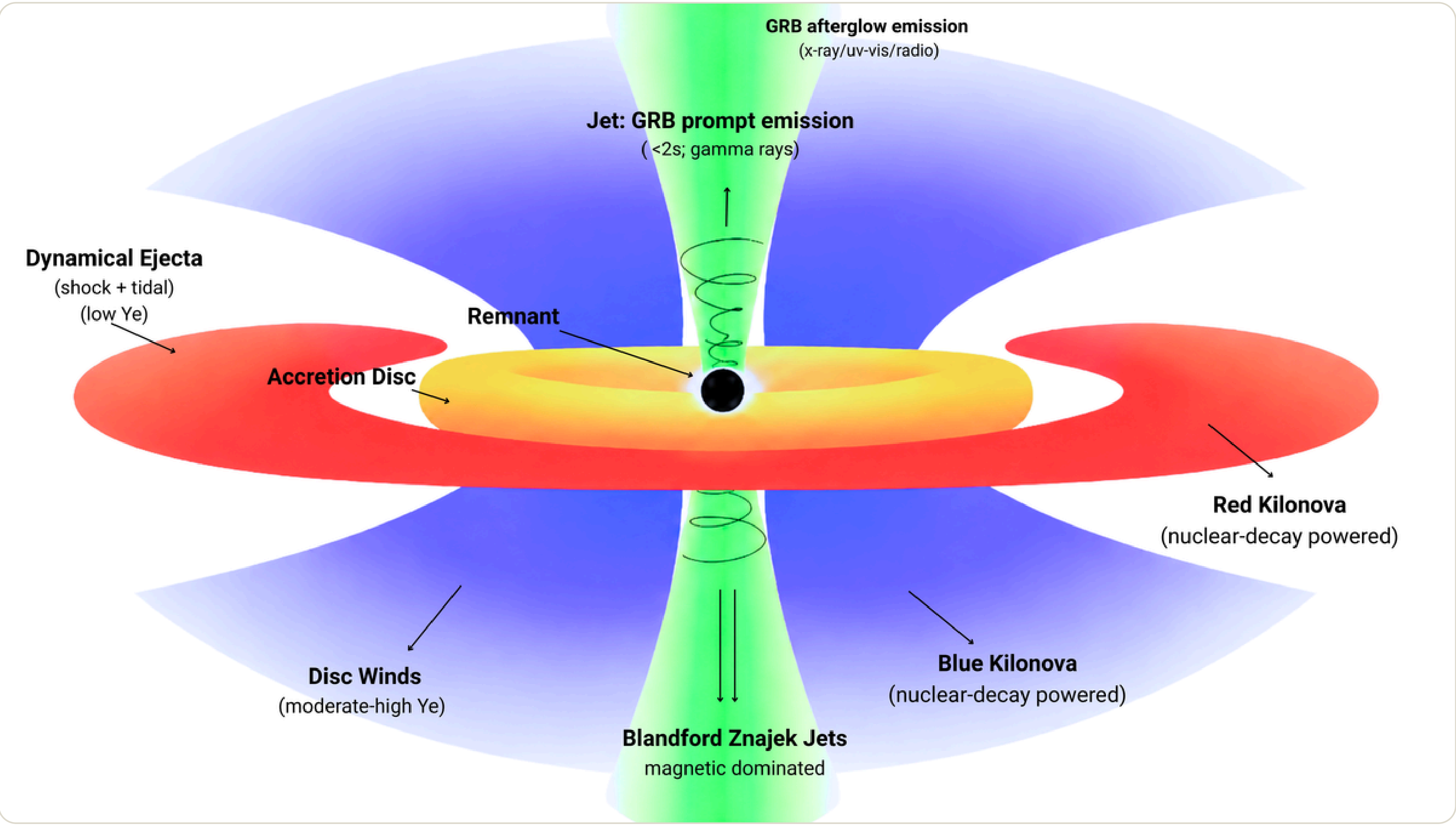
Neutrino-driven and magnetised winds, 10 ms–1 s

10^{-3}–10^{-2} M⊙ · 0.1–0.3c · $Y_e \approx 0.25$–0.4

Post-merger disk wind (our focus)

Launched over ~10s–100s of ms by MHD stresses and neutrino heating/cooling in the torus around the black hole; ~20–40% of the torus · 0.05–0.1c · $Y_e \approx 0.1$–0.4, broad

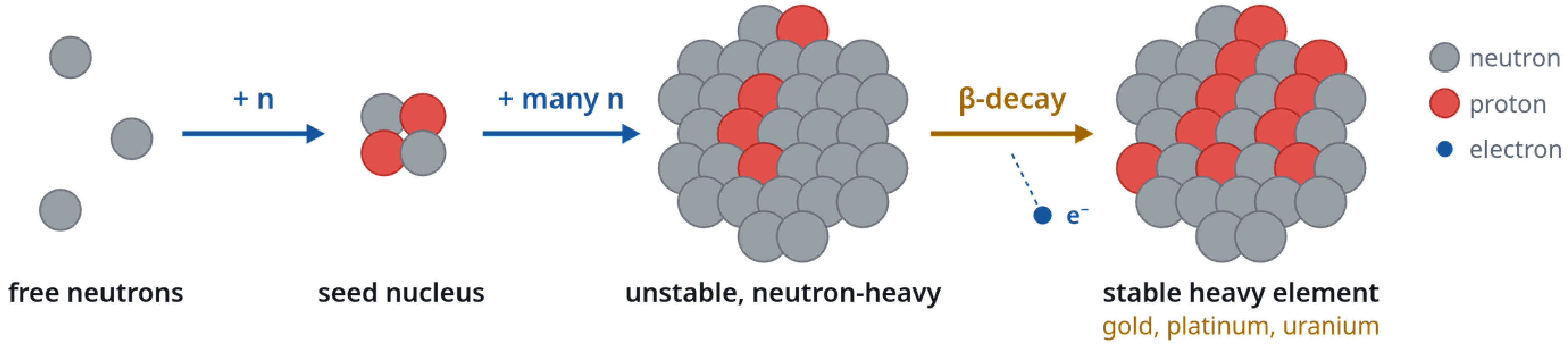
Observed jointly as: gravitational waves + GRB (prompt & afterglow) + kilonova.



Schematic: post-merger environment

Rapid neutron capture: building heavy nuclei

merger ejecta is heavily neutron-rich, enabling heavy-element synthesis through rapid neutron capture: the r-process.



1. Capture

Neutrons arrive faster than the nucleus can decay.

2. Decay

When the neutron-to-seed ratio runs out, β-decays carry nuclei back to stability: gold, platinum, uranium.

3. EM emission

β-decay, α-decay and fission heat the gas; the heat leaks out over days as a kilonova.

Y_e Protons per nucleon.

$Y_e \lesssim 0.25$ → 2nd + 3rd peaks, lanthanides & actinides

$0.25 \lesssim Y_e \lesssim 0.35$ → up to the 2nd peak, few lanthanides

$Y_e \gtrsim 0.35$ → 1st peak only ("weak" r-process)

Kilonova emission: radioactive heating and opacity

Radioactive heating
Unstable r-process nuclei decay and heat the expanding ejecta.

Thermal radiation diffuses out, producing the kilonova.
The light curve peaks approximately when the photon diffusion time matches the expansion time

$$t_{\mathrm{peak}} \propto \left(\frac{\kappa M_{\mathrm{ej}}}{v\,c}\right)^{1/2}$$

Higher opacity delays the peak and shifts emission toward redder wavelengths.

Ejecta mass, velocity, and composition shapes the kilonova's light curve and spectrum

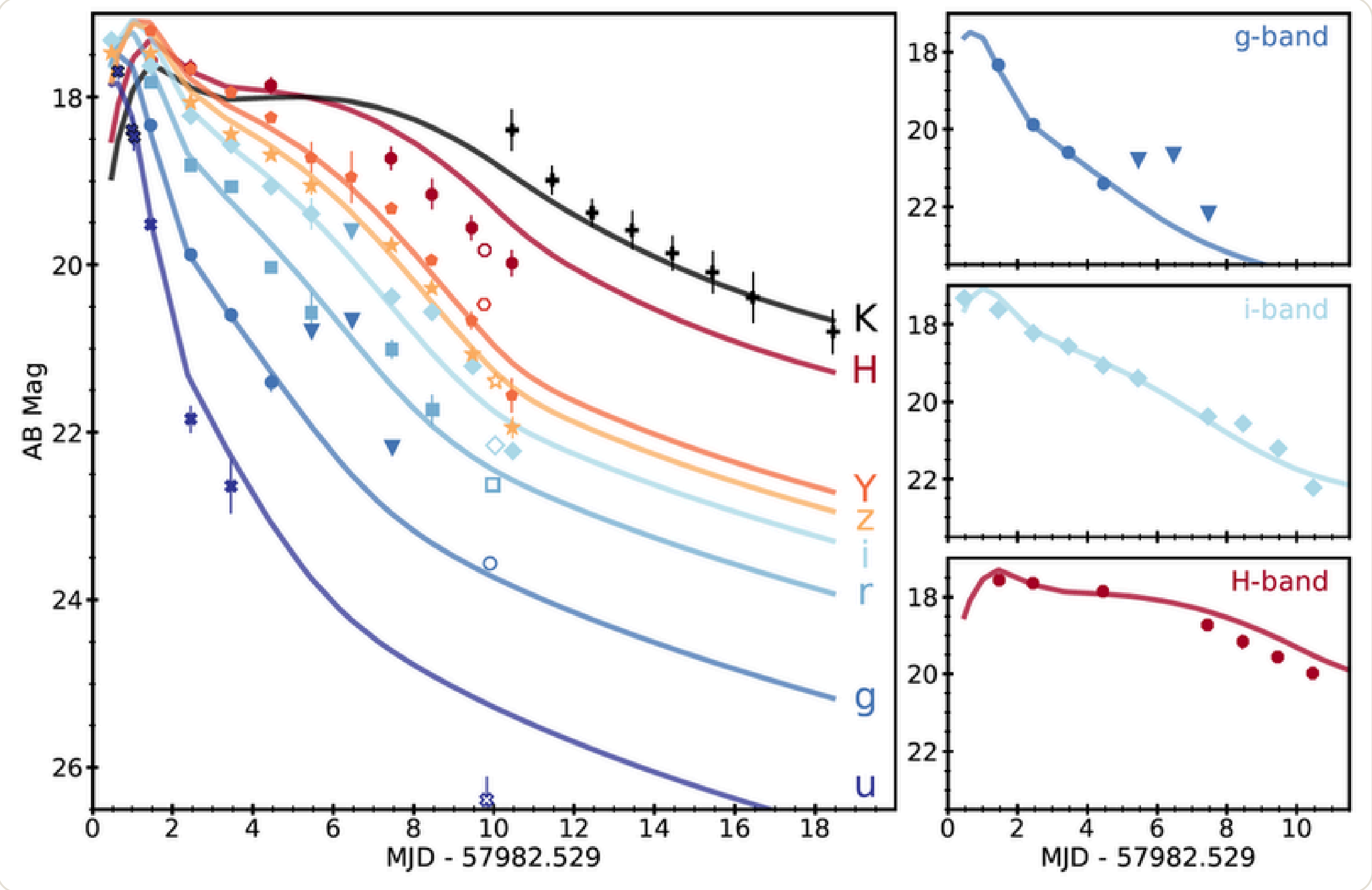
Blue · lanthanide-poor
Fast, polar · early UV/optical, ~1 day

Purple · intermediate
Disk winds · optical–near-IR, days

Red · lanthanide-rich
late, near-IR, ~1 week

Lanthanide-rich ejecta have higher opacity, producing a later, redder kilonova.

AT2017gfo: what the fits tell us



AT2017gfo light curves with the three-component fit (Villar+ 2017): **fast fading, blue → red**

Component	**M_ej ($M_\odot$)**	**v/c**
Blue	0.020	0.27
Purple	0.047	0.15
Red	0.011	0.14

Each component assumes a constant grey opacity; the inferred ejecta properties depend on these assumptions. (Villar+ 2017)

- $\approx 0.08\,M_\odot$ of r-process ejecta in total.
- Purple + red $\approx 0.06\,M_\odot$ exceeds typical dynamical ejecta ($\lesssim 10^{-2}\,M_\odot$) → most likely a **post-merger disk wind**.

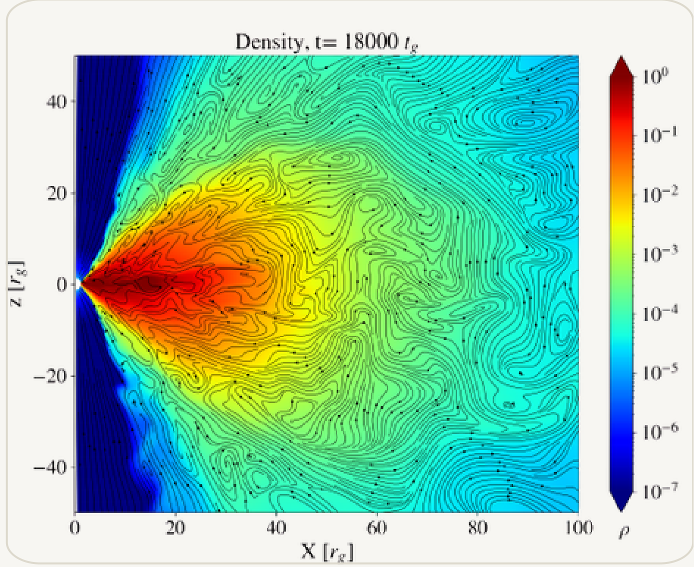
Numerical framework: from a Kerr black hole to observables

A multi-physics, multi-scale problem: general relativity, MHD, neutrino transport and nuclear reactions, in sequence.

1 · GRMHD

HARM-MULTIEOS

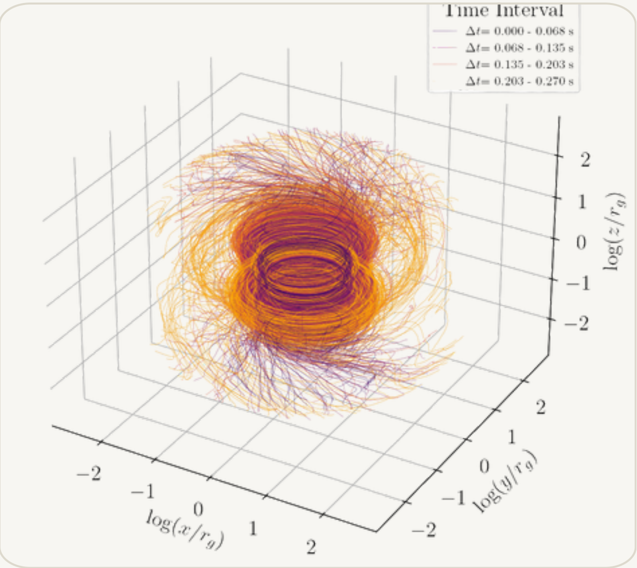
Kerr BH + magnetised torus; tabulated nuclear EOS, Y_e evolution, neutrino leakage.



2 · TRACERS

Lagrangian tracers

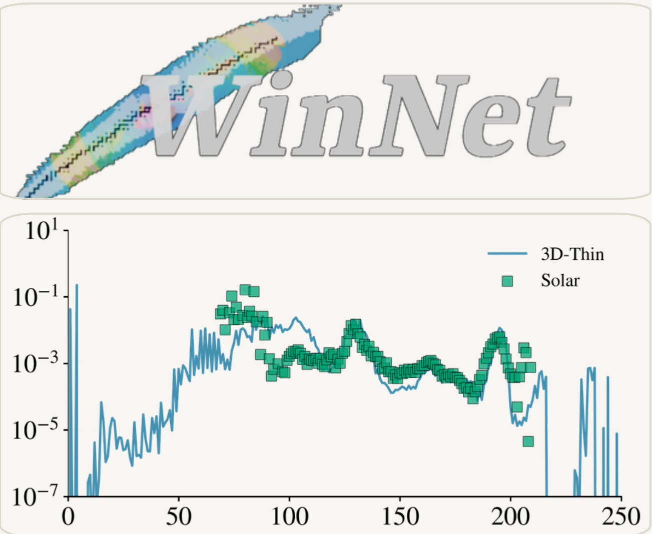
Outflow trajectories recording ρ(t), T(t), Y_e(t), v(t) for every unbound tracer.



3 · NETWORK

WinNet

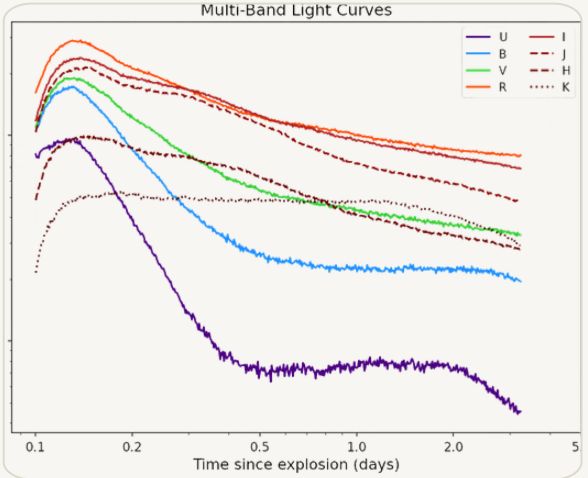
Nuclear reaction network along each trajectory: isotope mass fractions, lanthanides, actinides, radioactive heating.



4 · RADIATIVE TRANSFER

SuperNu

Time-dependent multigroup MCRT; composition- & wavelength-dependent opacity → synthetic spectra and light curves.



What sets the disk-wind nucleosynthesis?

- **Electron fraction, Ye**

Sets the neutron richness and therefore the relative production of light & heavy r-process elements, lanthanides, and actinides.

- **Temperature–density history, T(t) and ρ(t)**

Governs seed-nucleus formation, nuclear reaction rates, and the transition from equilibrium to neutron-capture evolution.

- **Expansion timescale and velocity**

Determine how rapidly the ejecta cools and dilutes, controlling the duration of neutron exposure before reactions cease.

- **Neutrino processes and magnetic turbulence**

Modify Ye and shape the thermodynamic trajectory of the escaping disk wind.

Weak interactions set Y_e

$$\frac{dY_e}{d\tau} = (\lambda_{\nu_e n} + \lambda_{e^+ n})\, X_n - (\lambda_{\bar{\nu}_e p} + \lambda_{e^- p})\, X_p$$

Ye evolves through electron/positron capture and neutrino/antineutrino absorption

How does the central engine, the black hole and disk, shape these wind conditions?

A simulation suite spanning the black-hole engine's parameter space

Nine 2D/3D ν-GRMHD models, spanning BNS-like and NS–BH-like post-merger remnants.

CODE & PHYSICS

HARM_EOS: GRMHD in a fixed Kerr metric, SANE mode

Tabulated Helmholtz EOS $P(\rho, T, Y_e)$; neutrino leakage

~0.6 & 0.9

black hole spin, a
control the BZ jet power

$10^{-3} – 10^{-1}\, M_\odot$

Initial disk mass (Ye =0.1)

7 – 10 k_B

disk entropy per baryon

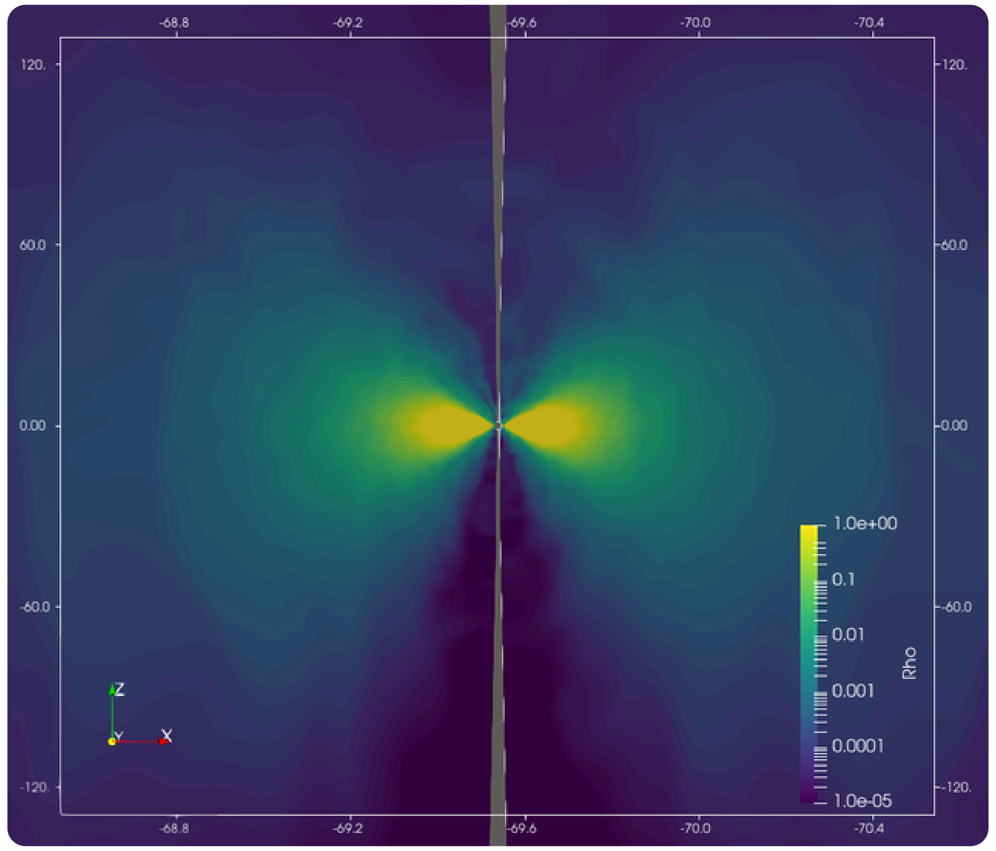
50 -100

Plasma beta

Initial field strength → MRI growth, magnetic stresses, outflow speed

Initial field: poloidal loops that follow the torus density normalised to the target β

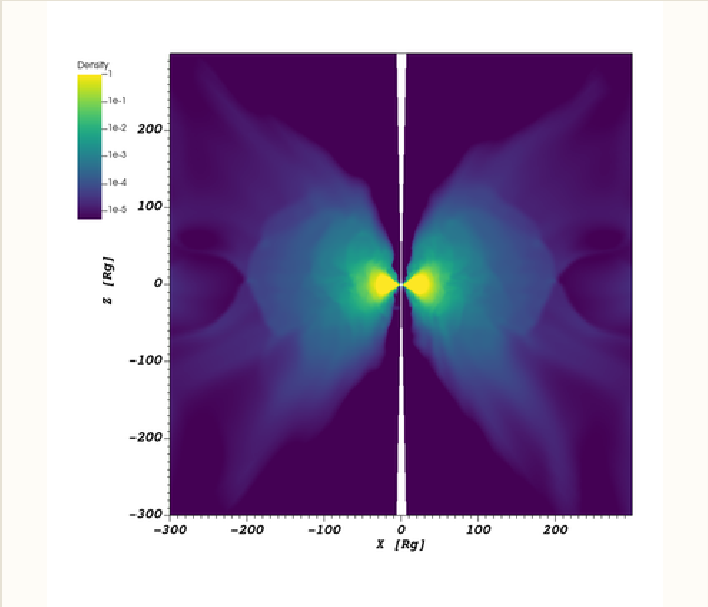
$$A_\varphi = \max\left(\frac{\bar{\rho}}{\rho_{\max}} - \rho_0,\ 0\right)$$



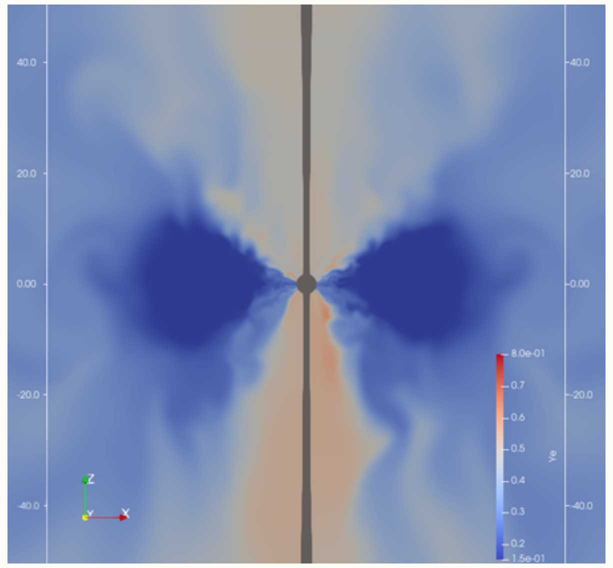
The engine sets the shape of the wind & its neutron-richness

Massive, strongly magnetised disk

density

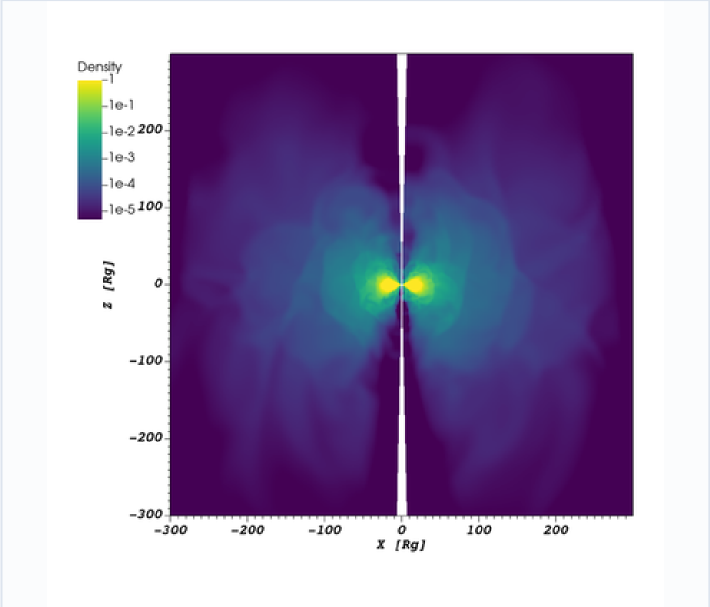


neutron-richness, Y_e

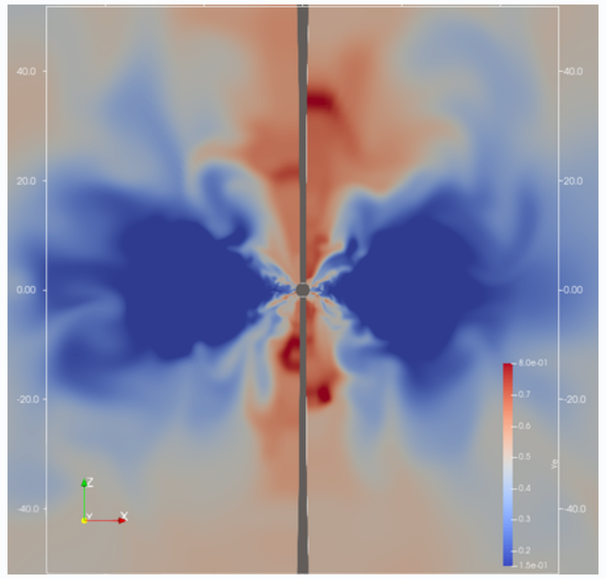


small, less magnetised disk

density



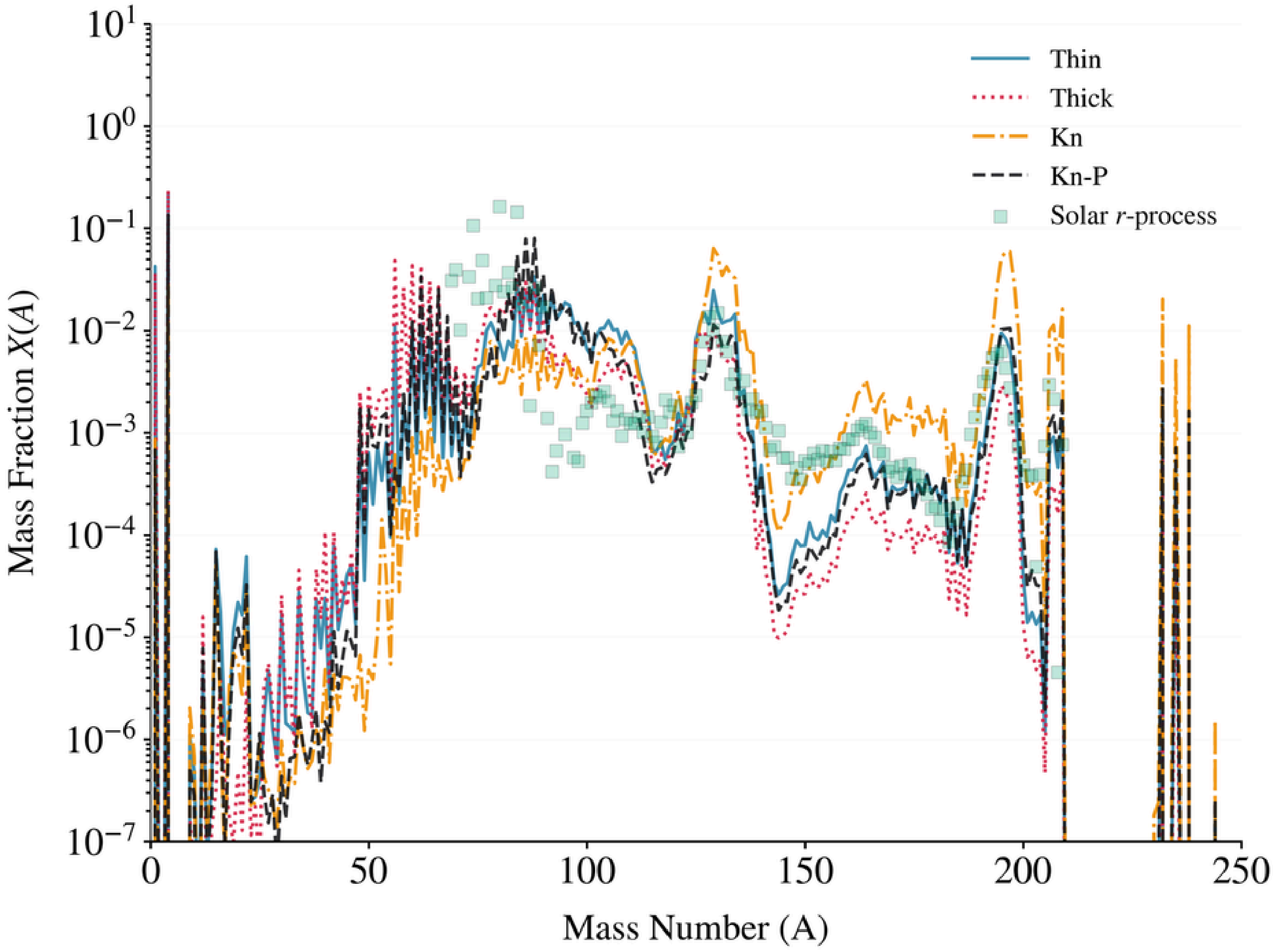
neutron-richness, Y_e



> The massive-magnetised disk pushes neutron-rich material far out along the equator; the smaller, weakly magnetised disk has a more even density distribution.

All models produce r-process elements

- but with different heavy-to-light element ratios



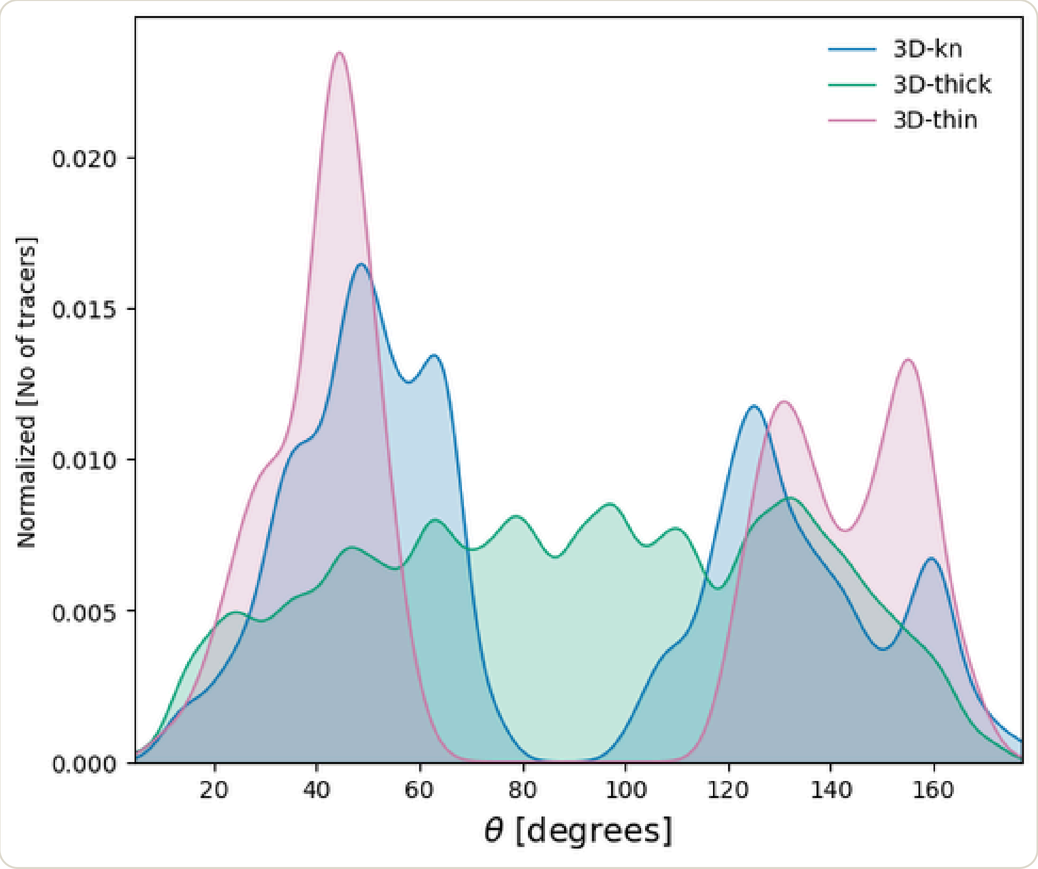
Wind composition of each model vs. the solar pattern (squares)

Model	M_{ej} ($M_\odot$)	$\langle Y_e \rangle$ at 10 GK	v/c at 500 rg	X_lan
3D-Thick	1.6×10^{-2}	0.42	0.13	3×10^{-4}
3D-Thin	1.9×10^{-3}	0.37	0.10	8×10^{-4}
3D-kn	9.8×10^{-2}	0.19	0.07	2×10^{-2}
3D-kn-P	1.8×10^{-3}	0.37	0.19	2×10^{-3}

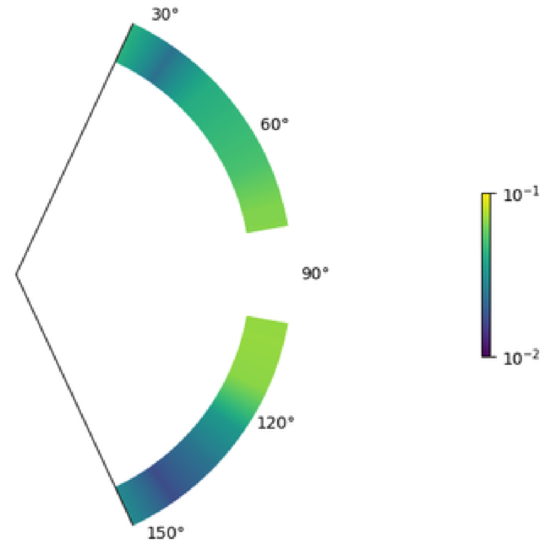
- Every model recovers the three r-process peaks ($A \approx 80, 130, 195$).
- **3D-kn** $\langle Y_e \rangle$ (0.19): most massive ejecta give the strongest third peak and actinide yield;
- **3D-Thick** ($\langle Y_e \rangle = 0.42$) stays light-r-process dominated.

Peak positions are robust. Peak heights depend on the engine

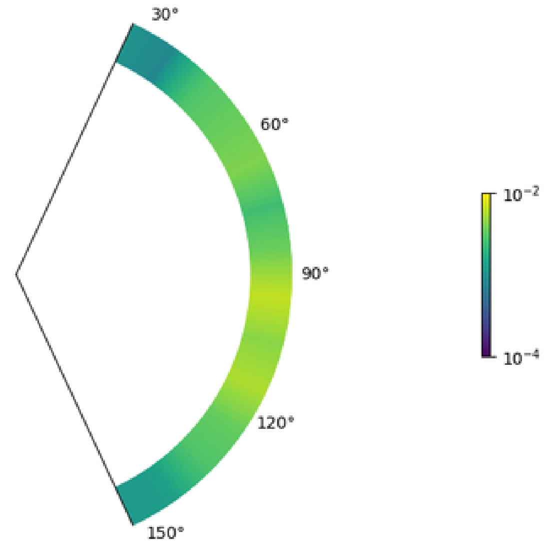
Composition depends on viewing angle



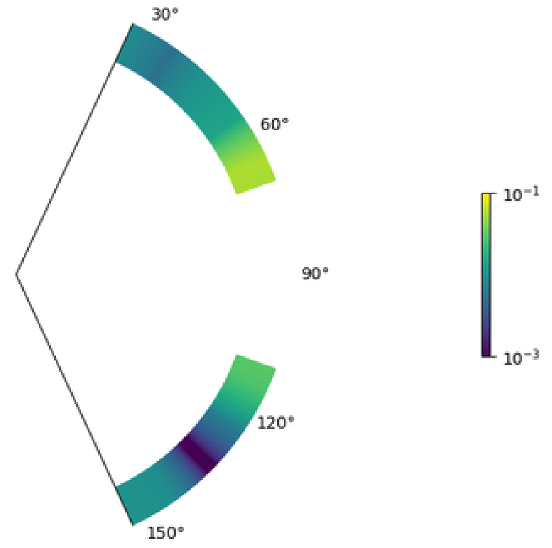
Angular distribution of lanthanide-carrying tracers



3D-kn



3D-Thin



3D-Thick

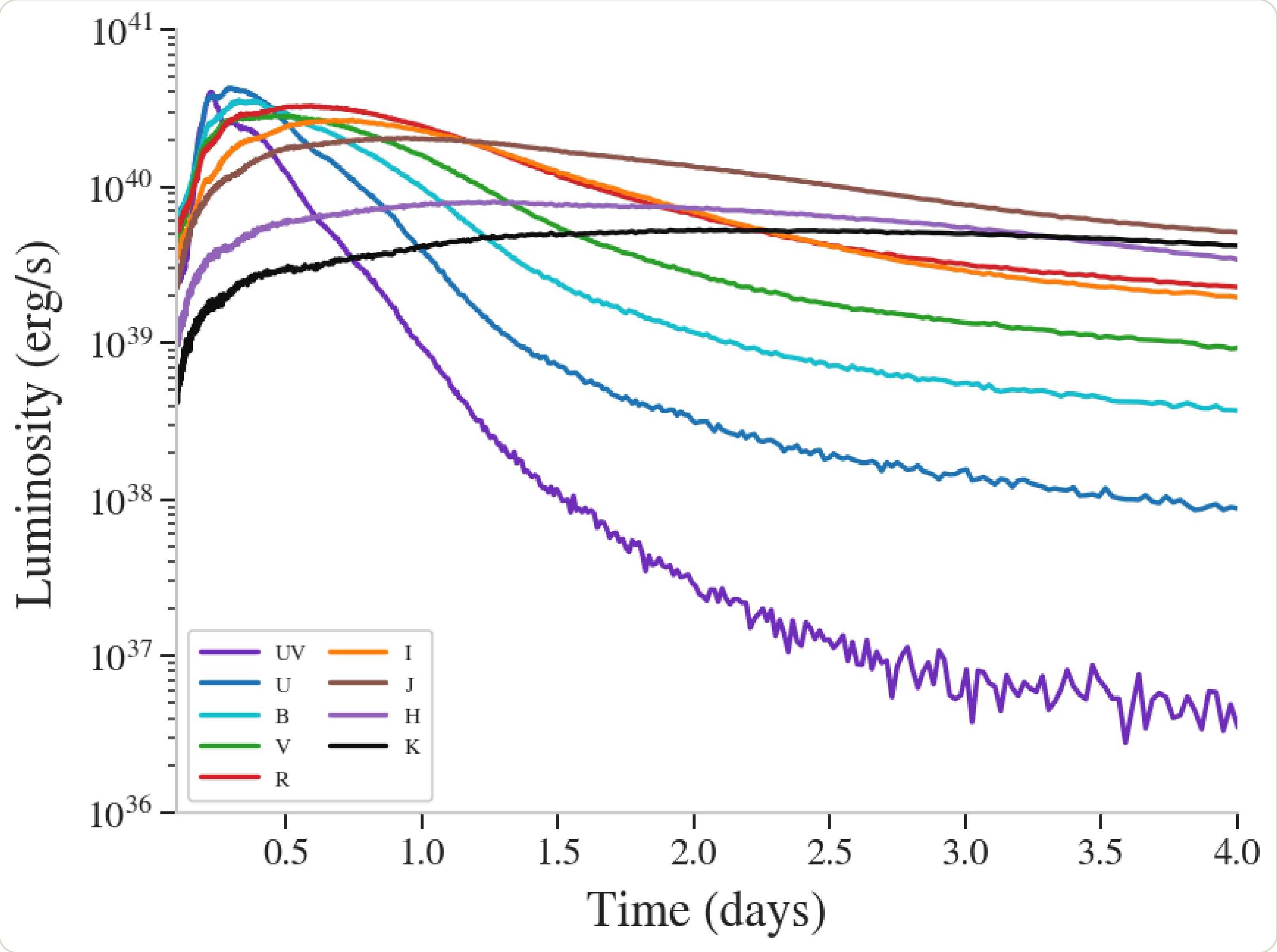
The polar-angle lanthanide fraction is strongly model-dependent – composition, & therefore opacity, varies with direction from the BH spin axis.

Expected: sight-lines through lanthanide-rich material see higher $\kappa \rightarrow$ a later, redder, dimmer peak; lanthanide-poor directions see an earlier, bluer one.

Anisotropic composition → direction-dependent opacity → viewing-angle-dependent kilonova emission

From r-process ejecta to synthetic kilonova light curves

Radiative transfer is complex here: millions of heavy-element lines give composition-, temperature- and wavelength-dependent opacities, & anisotropic ejecta make the emission angle-dependent.



An early blue/UV peak, progressive reddening, and a broad near-infrared tail — the signature of a mixed blue–purple disk-wind kilonova.

Model shown: 3D-Thick disk wind · preliminary · angle-averaged

SuperNu *(Wollaeger et al. 2013, 2014)*

Time-dependent multigroup Monte Carlo radiative transfer in homologously expanding 1D/2D/3D ejecta;
LTE line-binned opacities from LANL/NIST atomic data *(Fontes et al. 2020, 2023).*

$$\kappa = \kappa(E_\gamma,\, \rho,\, T_e,\, Z) \qquad [\mathrm{cm}^2\,\mathrm{g}^{-1}]$$

Summary

- **Disk winds are a robust r-process site.** Every engine produces all three peaks ($A \approx 80, 130, 195$);
- **The engine sets the neutron-richness.** $\langle Y_e \rangle$ at 10 GK spans 0.19–0.42; a massive torus around a slowly spinning BH (3D-kn) gives the lowest Y_e and ~0.1 $M_\odot$ of ejecta.
- **Lanthanide yields differ ~100×** ($X\_lan \approx 3 \times 10^{-4}$ in 3D-Thick to 2.7×10^{-2} in 3D-kn)
- **Composition is anisotropic**, so opacity and kilonova colour should depend on the viewing angle.
- **Engine regime:** All models remain SANE, with limited magnetic-flux accumulation and BZ power.

Kilonova light curves could help constrain the post-merger engine.

Thank you

Questions welcome.

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