Nucleosynthesis in the magnetized winds from GRB engines

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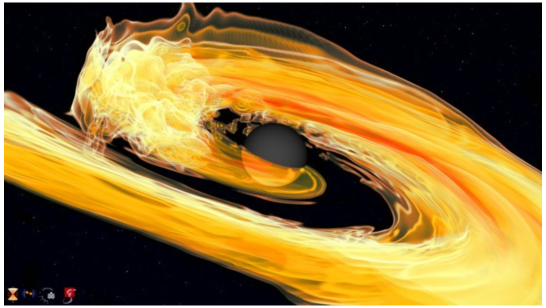
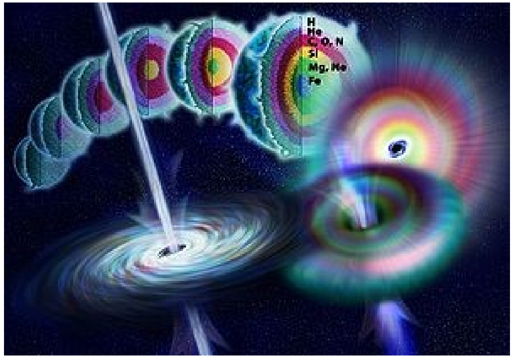
Outline

- Observational challenges for GRBs: powering, collimation, variability, breakout, kilonovae, supernovae, gravitational wave progenitors
- Mergers, accretion and outflow simulations, EOS, nucleosynthesis, neutrinos, ...





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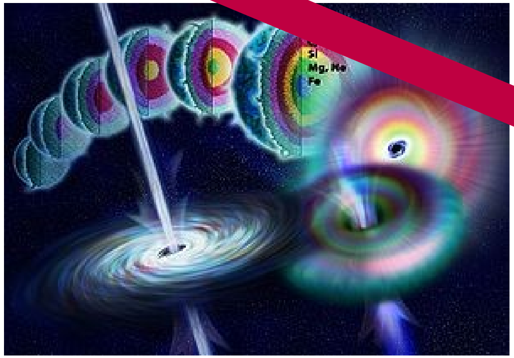
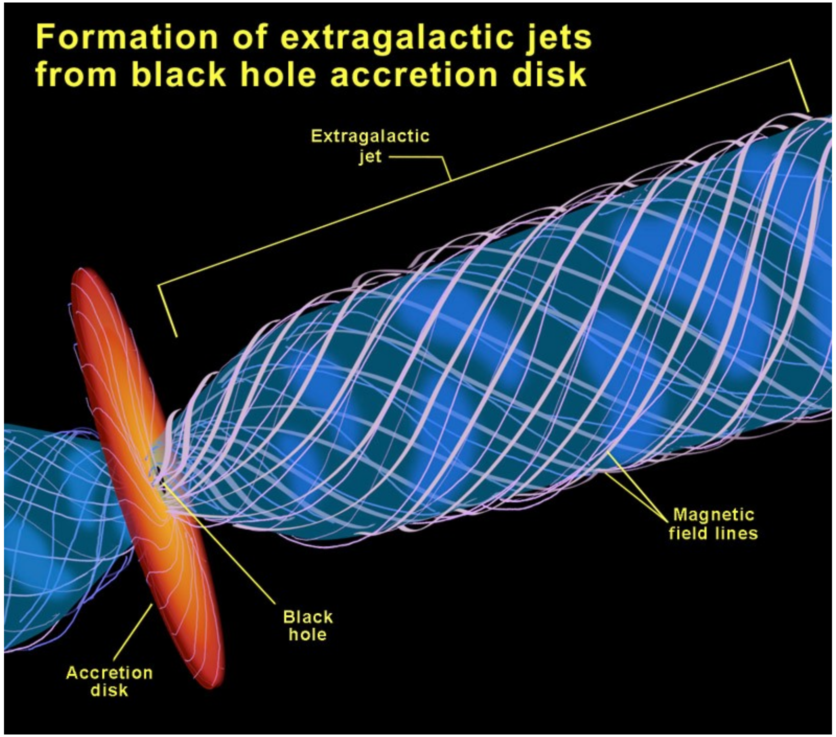


The jet paradigm

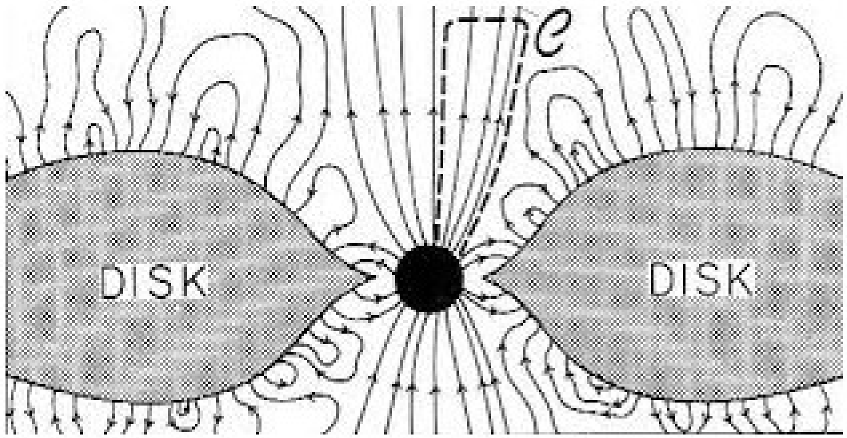
- Jets are common in the Universe
- Observed at different mass scales from accreting black holes
- Need a central engine
- Magnetic fields anchored in the accretion disk penetrate

  black hole’s ergosphere and mediate energy extraction



Power of jets

- By analogy to pulsar's magnetosphere, the field lines accelerate charged particles (Godreich & Julian 1969; Blandford & Znajek 1977)
- Black hole magnetosphere develops from seed magnetic field by differential rotation of the disk (Thorne 1986)



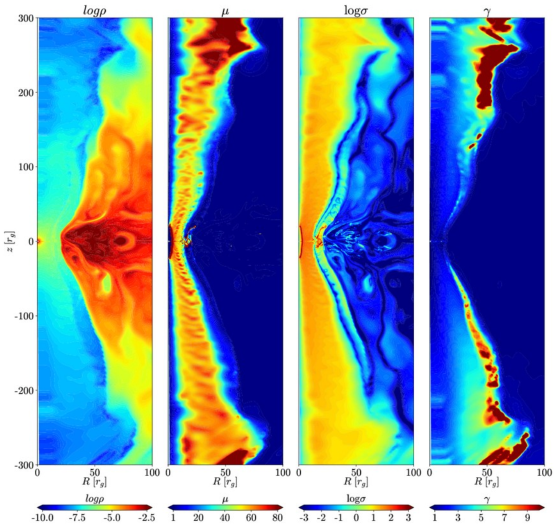
$$\dot{E}_{\rm BZ} = \frac{\kappa}{4\pi}\Phi_{\rm BH}^2 \frac{a^2\, c}{16 r_{\rm g}^2}$$

$$\Phi_{\rm BH} = \frac{1}{2}\int |B^r|\, {\rm d}A_{\theta\phi}$$

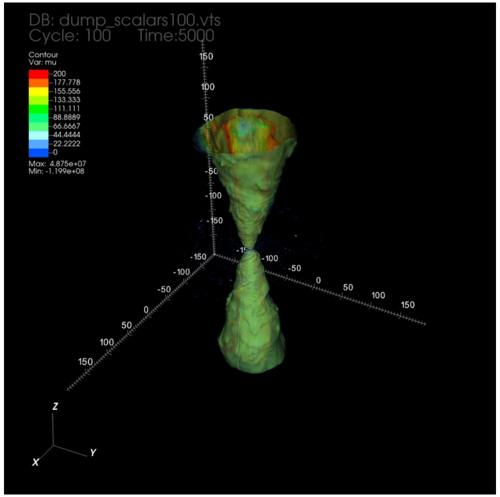
$$a = \frac{c\, J_{\rm BH}}{G\, M_{\rm BH}^2}$$

Structure of jets

- Jet launched when rotational frequency of magnetic field is large wtr. to BH angular velocity
- Energy in the simulated jet non-uniformly distributed



K. Sapountzis & A. Janiuk (2019, ApJ)



B. James, A. Janiuk & F. Nouri (2022, ApJ)

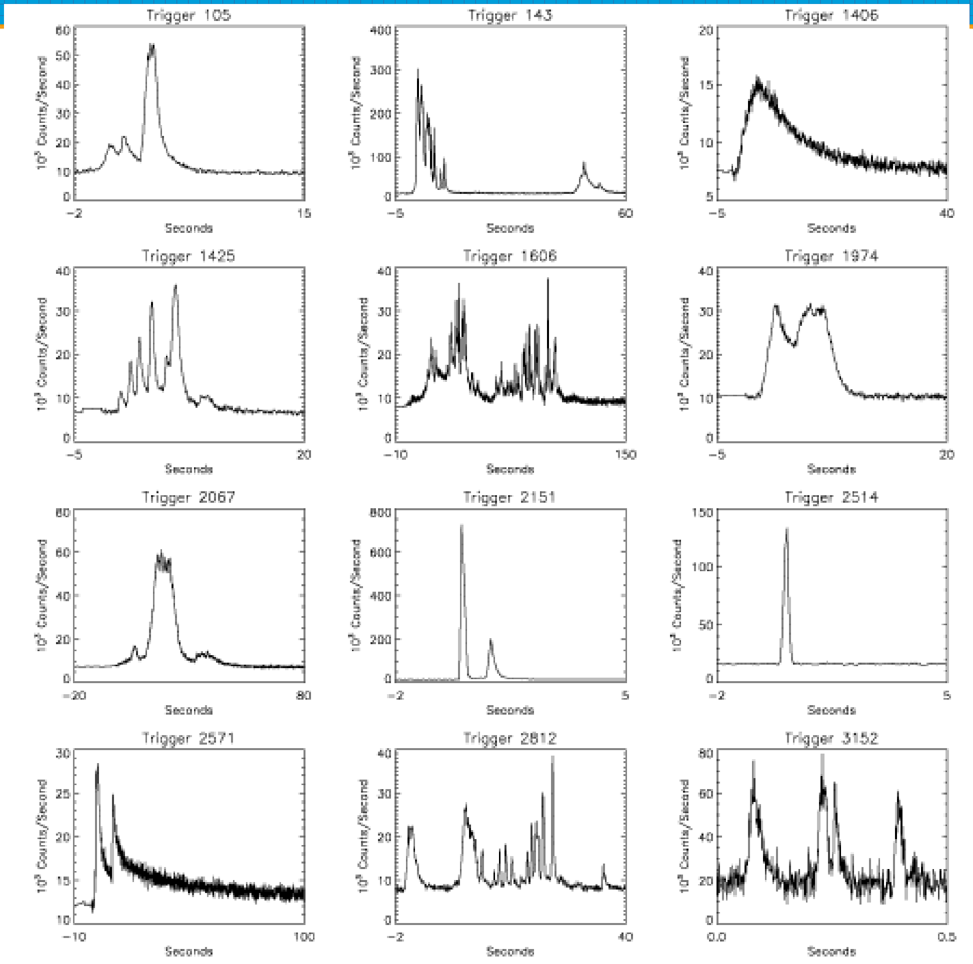
$$\sigma = \frac{\left(T_{EM}\right)^r_t}{\left(T^r_t\right)_{gas}}$$

$$\mu = \frac{-T^r_t}{\rho u^r}$$

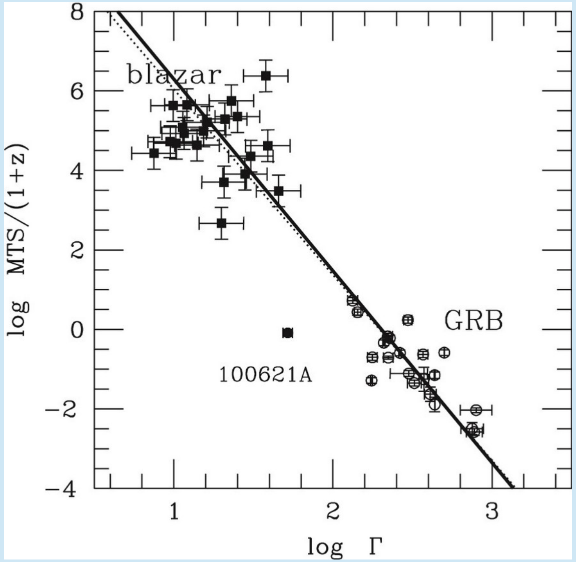
Variability of GRBs

Temporal variability of long GRBs during the prompt phase (the highly variable first ~100 s)

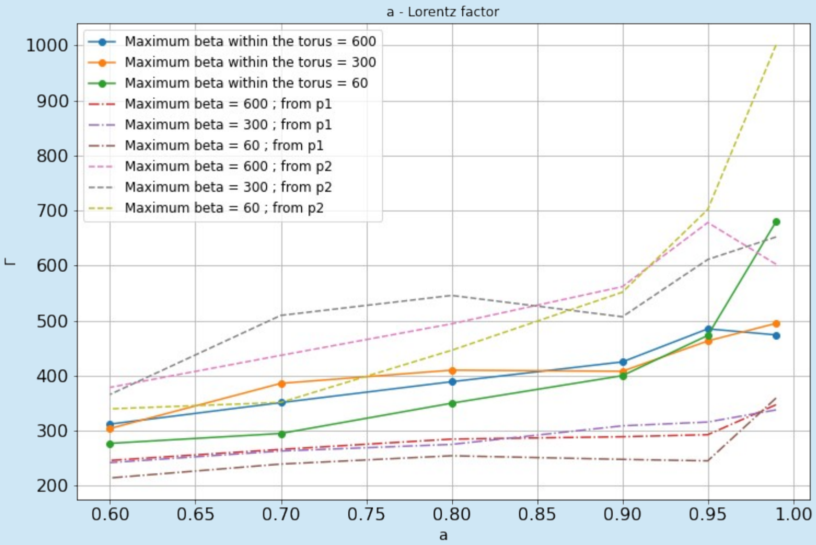
Explained in the context of MAD accretion (e.g. Lloyd-Ronning, Dolence, Fryer, 2016).



Minimum timescale of variability



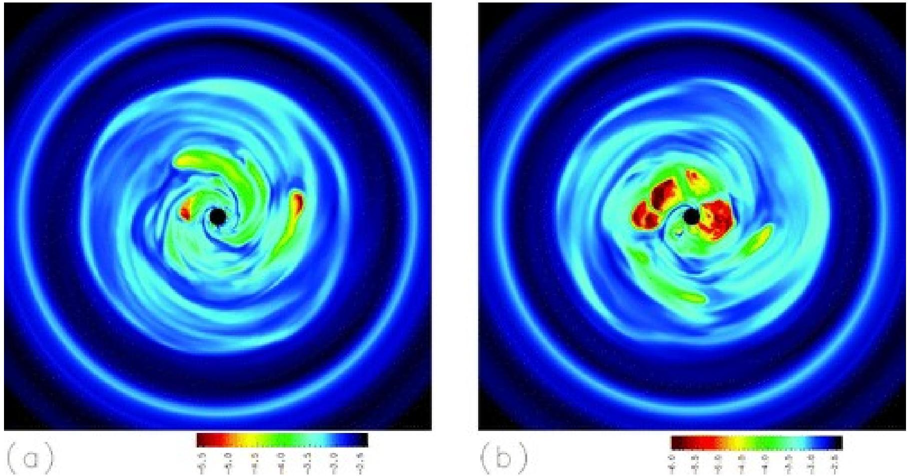
Joint correlation of MTS $\propto \Gamma^{-4.7 \pm 0.3}$ for blazar and GRB samples (Wu et al. 2016)

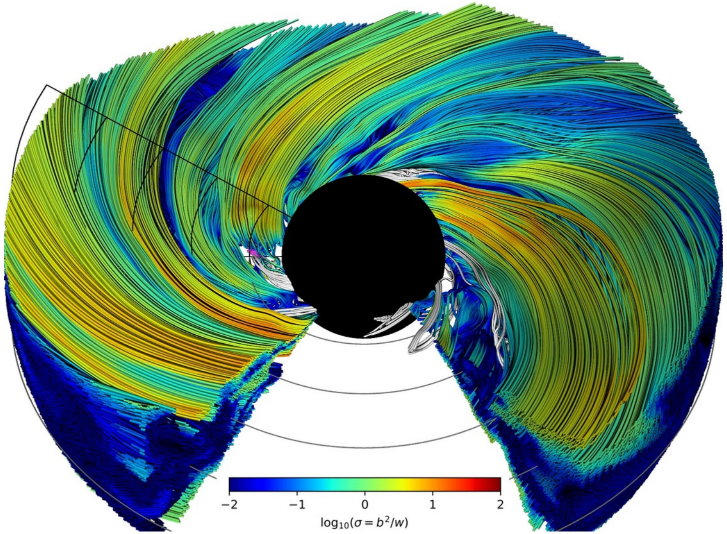


- Numerical models reveal correlations Γ-a and a-MTS (Janiuk, James, & Palit, 2021)
- Results scale with black hole mass:
  $MTS_s = MTS_{MBH} \times GM_{BH}/c^3$

Magnetically arrested or channeled?

- In the MAD mode, poloidal magnetic field is accumulating close to BH horizon, due to accretion (*Bisnovatyi-Kogan & Ruzmaikin, 1974; 1976).*
- Axisymmetric: magnetically confined blobs inside Rm (*Narayan, Igumenschev, Abramowicz, 2003*).
- Non-axisymmetric: gas forms streams towards BH, reconnections and interchanges (e.g. *Igumenshchev 2008; Tchekhovskoy et al. 2011*)

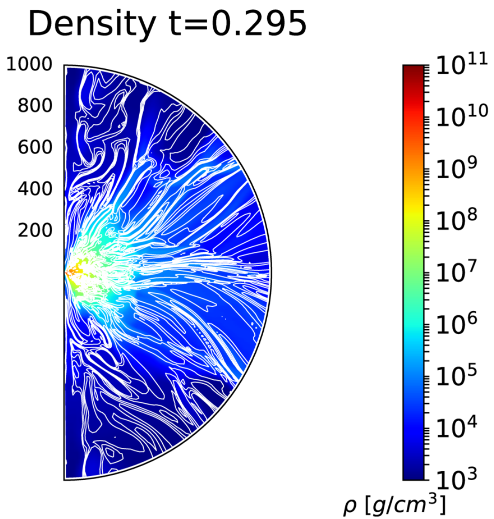




BH magnetic flux is subject to a saturation mechanism by flux eruptions involving reconnection.
Accretion flow is effectively **channeled** along the disconnected lines towards the **current layer**, and further towards the BH by **turbulent cross-field diffusion**.
(Nalewajko, Kapusta &Janiuk, 2024, A&A, in press)

Magnetically driven outflows

- The disk launches fast onbound wind outflows (v=c ∼ 0.11 − 0.23)
- Details are sensitive to engine parameters: BH spin and magnetisation of the disk
- More magnetized disk produce faster winds



Plan to organize a 3-day workshop on BH magnetospeheres / outflows / jets

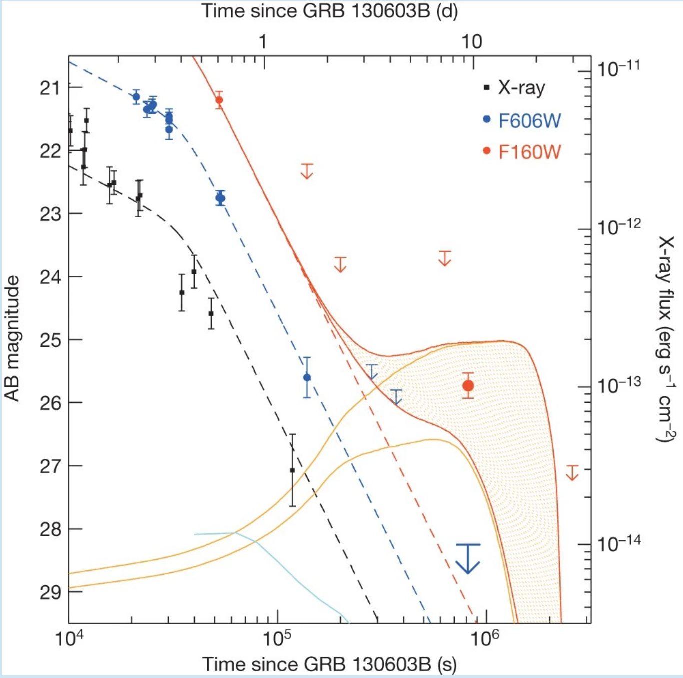
Warsaw, ~ April 2025
Co-Chairs: AJ & Krzysiek Nalewajko

Stay tuned!

(A. Janiuk, 2019, ApJ)

Kilonova

- NS-NS eject material rich in heavy radioactive isotopes.
- Can power an electromagnetic signal called a kilonova (e.g. Li & Paczynski 1998)
- 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)

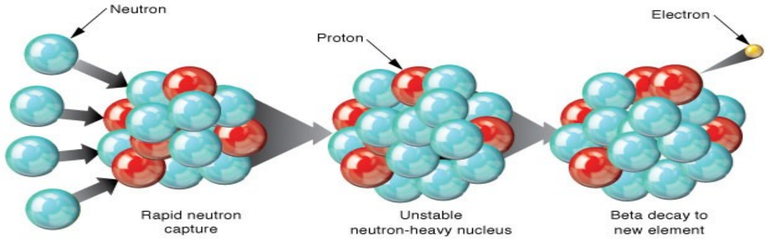


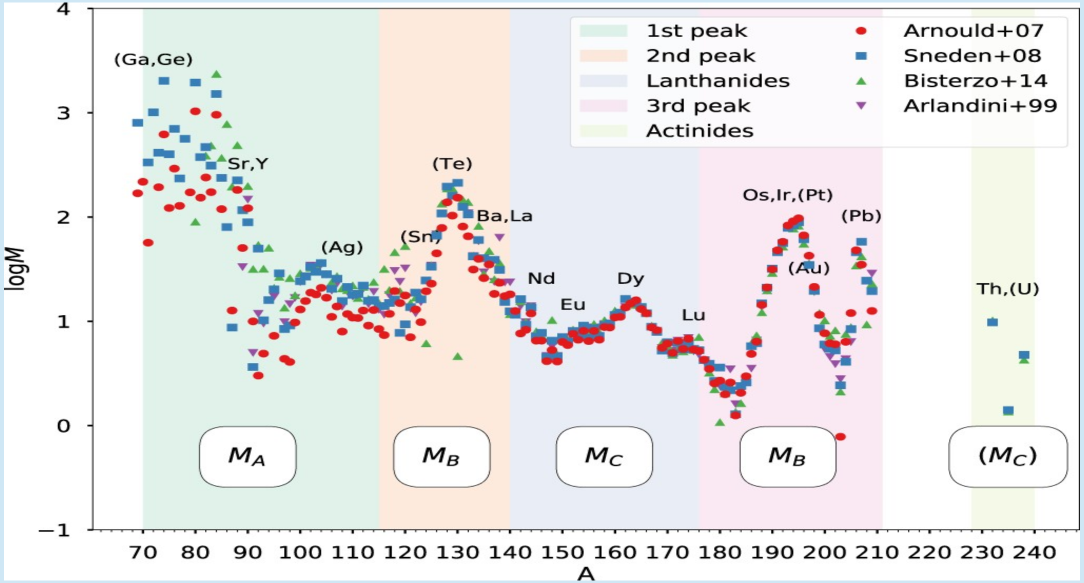
"Kilonova" associated with short GRB, Tanvir et al. 2013, Nature

R-process nucleosynthesis

Matter is neutronized,

$Y_e = n_p/(n_p + n_n) < 0.5$.

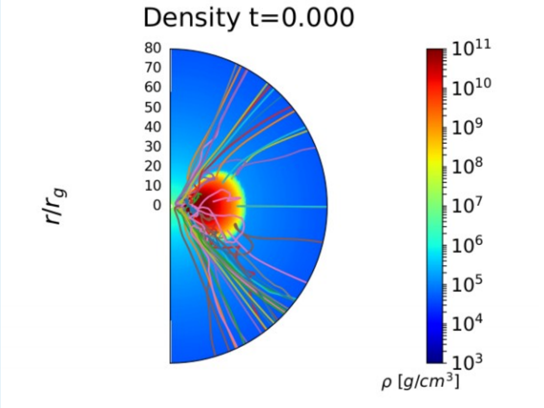


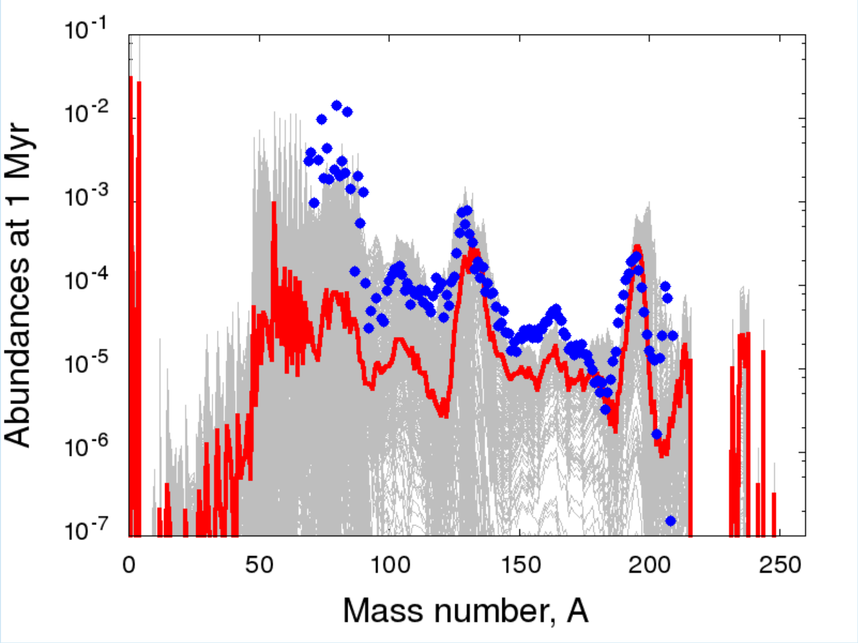


Ji et al. 2019

- $Y_e > 0.25$: 1st peak
- $Y_e = 0.15\text{-}0.25$: 2nd peak, Lanthanides
- $Y_e < 0.15$: 3rd peak, Actinides

Nucleosynthesis in disk wind

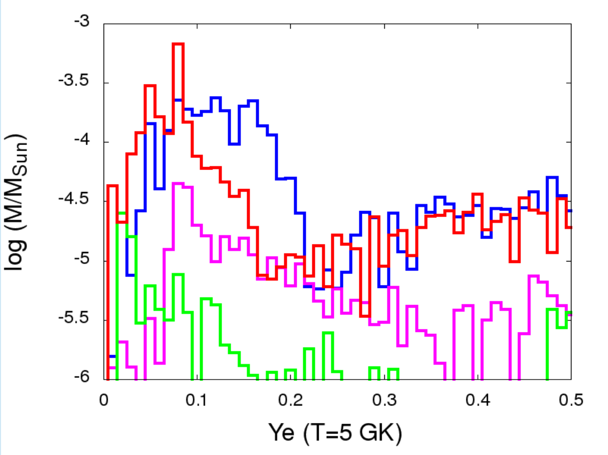


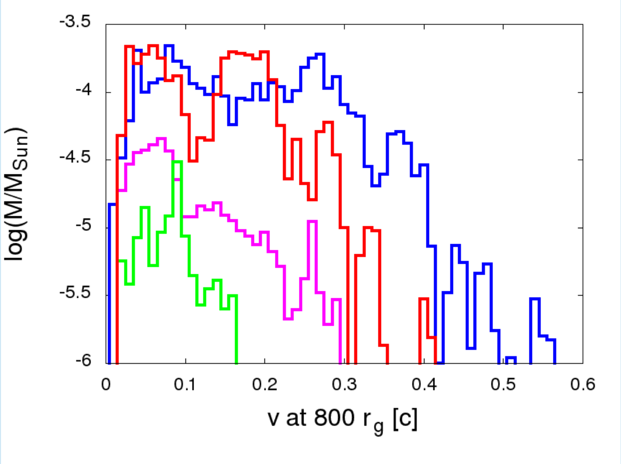


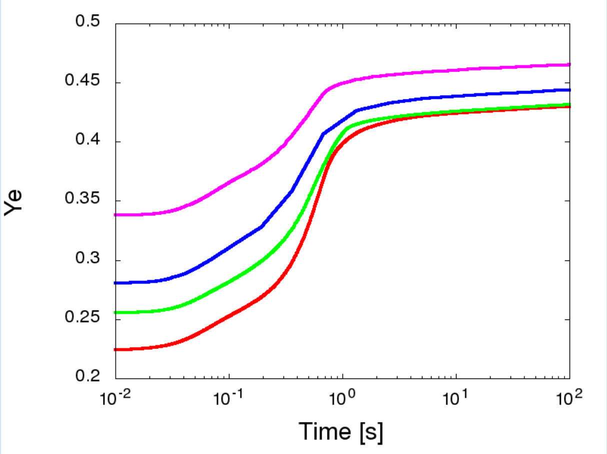
- We trace accretion disk winds by sampling the density, velocity, and composition over outflow trajectories
- Nucleosynthesis is computed by post-processing of results
- Heavy elements up to A ~ 200 (incl. Platinum, Gold) are produced in disk ejecta.

R-process abundance pattern in disk wind (A. Janiuk, 2019)

Composition of disk winds



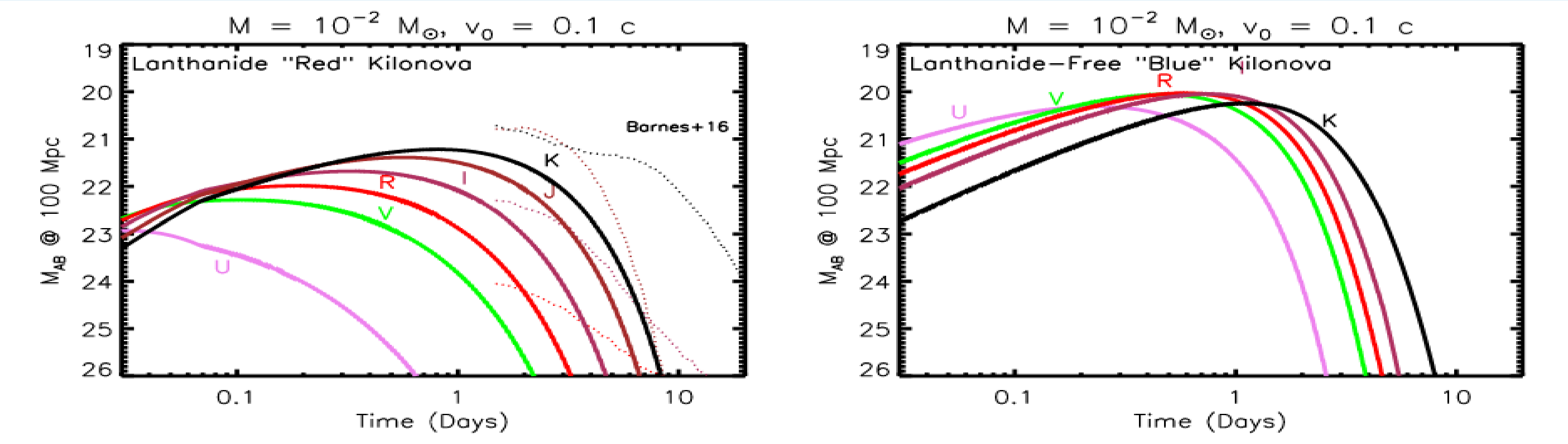




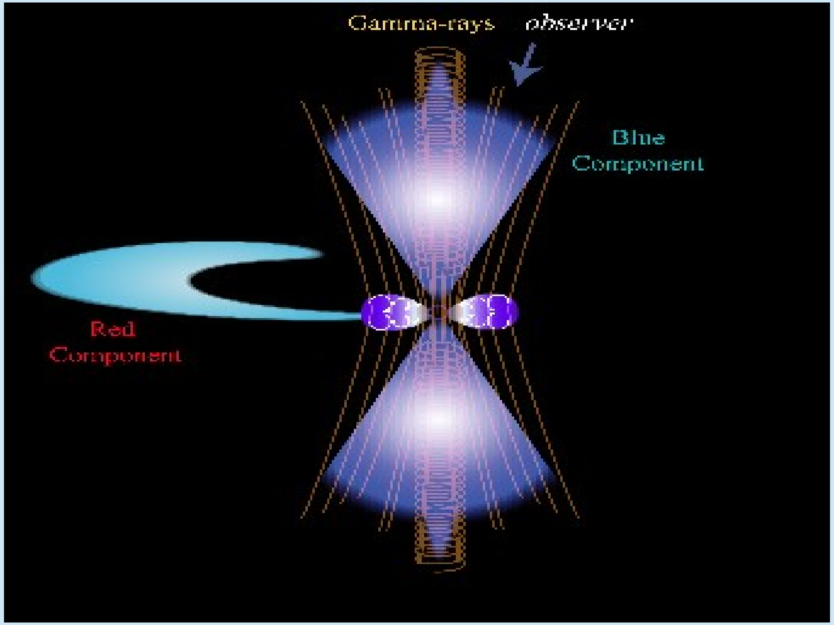
(A. Janiuk, 2019, ApJ)

- Broad range of electron fraction Ye ~ 0.1 – 0.4.
- Mass loss via unbound outflows is estimated at 2.3×10^{-3} – 1.8×10^{-2} Solar mass.
- It is between 2% and 17% of the initial disk mass.

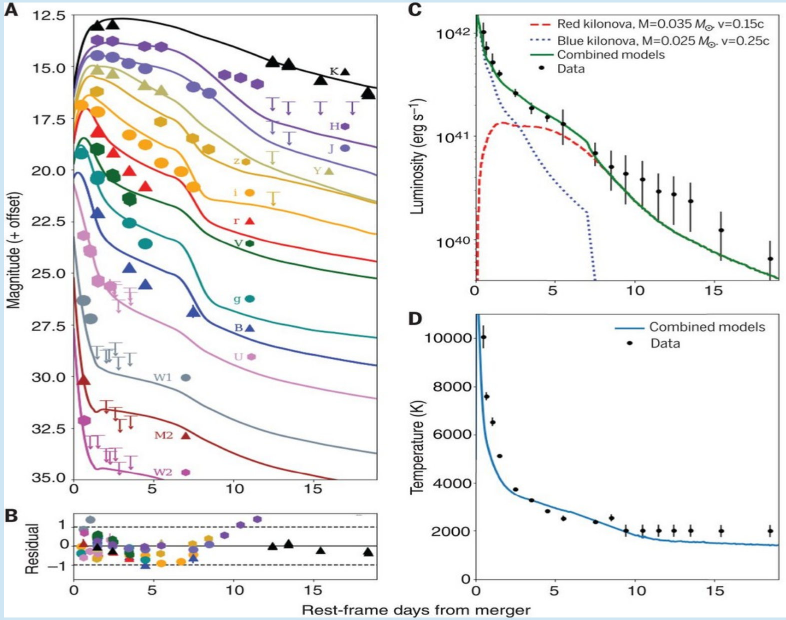
Kilonova colors



Blue and red components



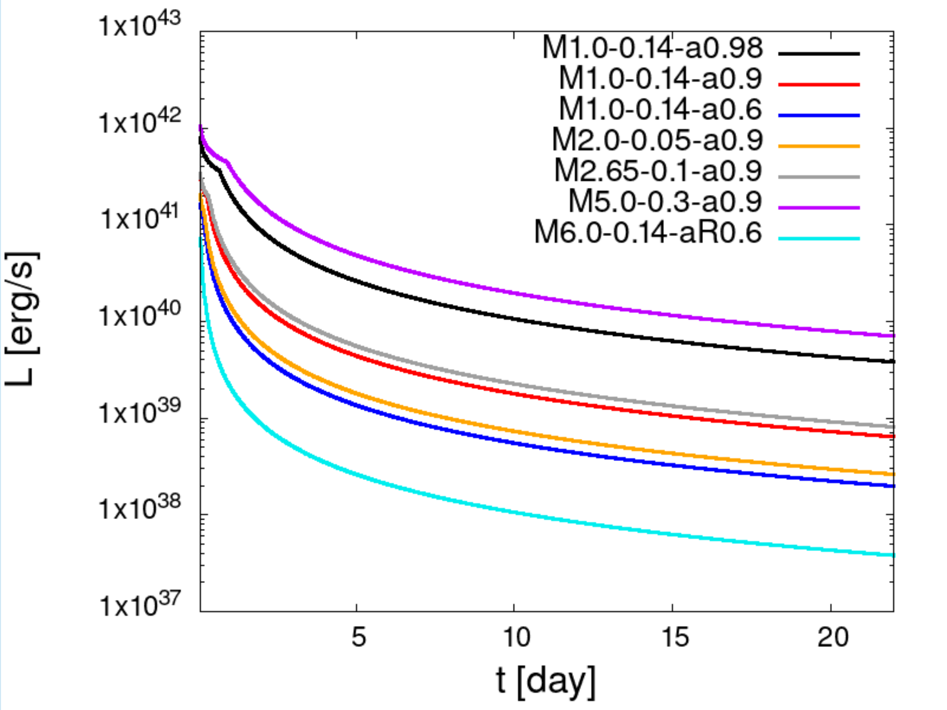
Schematic idea of the GW170817 system in the post-merger phase (Murguia-Berthier et al. 2017).



Blue and the red light from a kilonova, compared to observations of transient SSS17a, associated with GW170817 (Kilpatrick et al. 2017).

Synthetic kilonova lightcurves

- Synthetic kilonova ligtcurves for a range of BH-disk mass ratios and range of black hole spin parameters.
- We use method by Kawaguchi et al. (2016)
- Our models aim to **distinguish between BH-NS and NS-NS** progenitors, eg. by measuring LC slopes (Kasen et al. 2015).



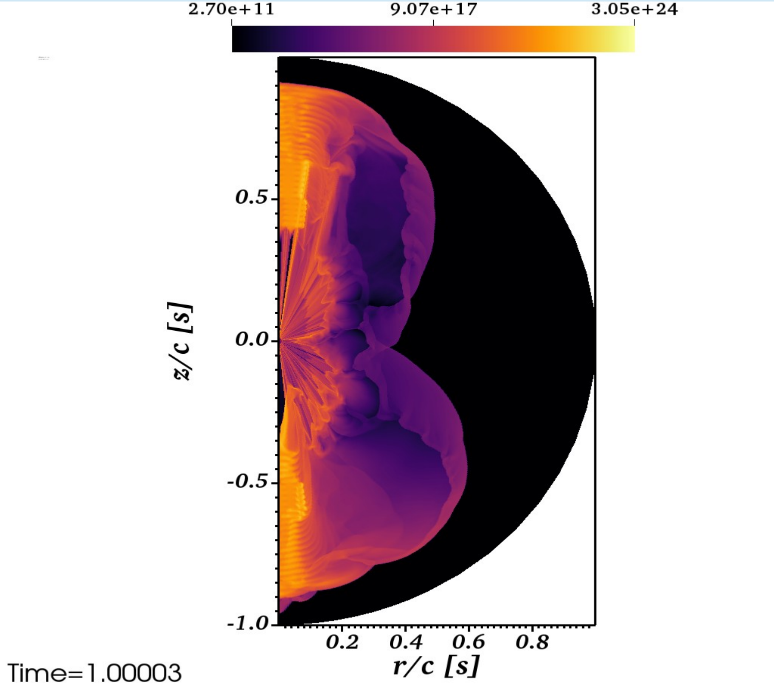
Nouri, Janiuk & Przerwa (2023, ApJ, 944, 220)

Short GRB progenitors

- Our simulations show a correlation between the black hole's spin and ejected mass (Nouri et al. 2023)
- Only a fraction (∼20%) of BHNS binaries gain a high BH spin (Drozda et al. 2022), so majority of these GRBs will not contribute to KN signals
- Low mass Bhs considered as result of PBHs collisions (Abranowicz et al. 2022)

Jet collimation by winds

- In BNS merger, the interaction of a relativistic jet with the ejecta shapes the structure of outflow and its radiation properties.
- We study this with larger scale, AMR-based simulations.
- This 2D simulation is utilizing neutrino-cooled wind and r-process nucleosynthesis.

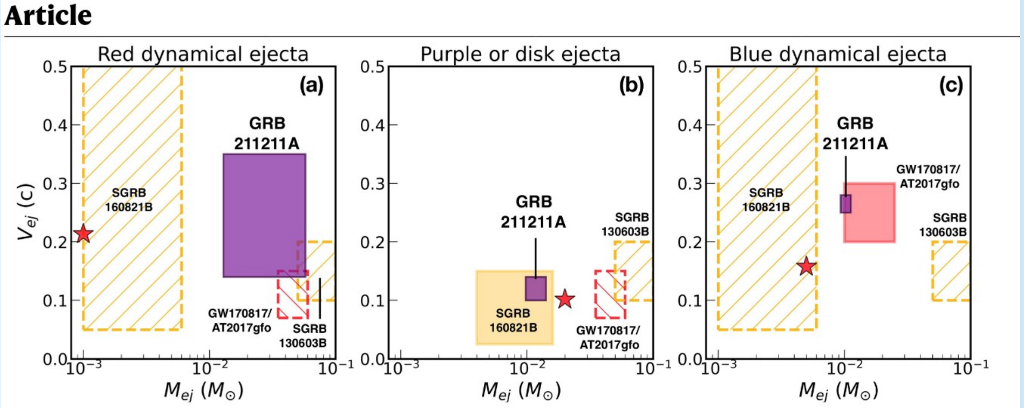


Urrutia, Janiuk, Nouri (submitted, 2024)

Constraints for ejecta

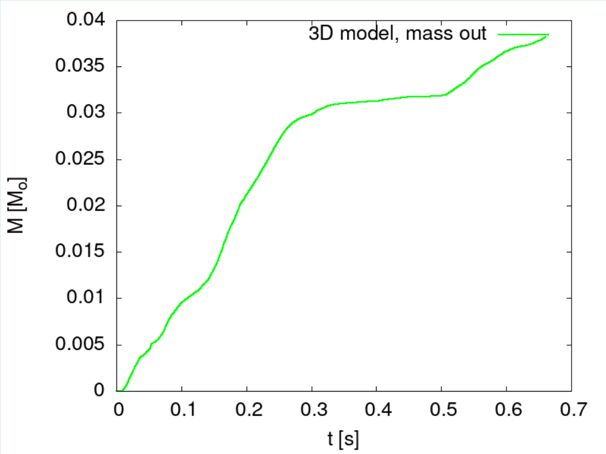
Ejecta Type	Ye	Velocity (v)	Mass ($M_\odot$)	Dominant Timescale	Spectrum Contribution	Source
Red Ejecta	$Y_e \lesssim 0.2$	$0.1c - 0.3c$	~ 0.02	$\sim 5-10$ days	Infrared (high-opacity, lanthanides)	**Tidal ejecta** (from neutron star disruption) or **disk winds** with low neutrino irradiation
Purple Ejecta	$Y_e \sim 0.25$	$\sim 0.1c$	~ 0.01	$\sim 2-5$ days	Optical/near-IR (moderate opacity)	**Disk winds** with moderate neutrino irradiation
Blue Ejecta	$Y_e \gtrsim 0.3$	$0.2c - 0.3c$	~ 0.01	~ 1 day	Optical (low-opacity, lanthanide-free)	**Dynamical ejecta** (from shock-heated material during merger) or **disk winds** with high neutrino irradiation

Ejecta components mix up contributions from disk wind and dynamic ejecta (credit: Joseph Saji, in prep.)

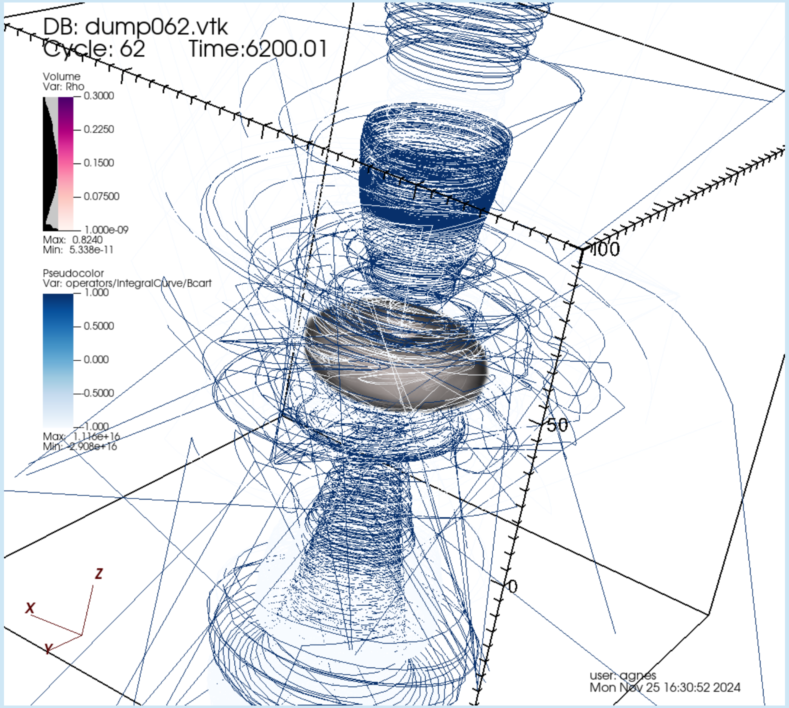


Mass estimates and plot from Rastinejad et al. (2022)
Ye estimates from Villar et al. (2017)

3D simulations

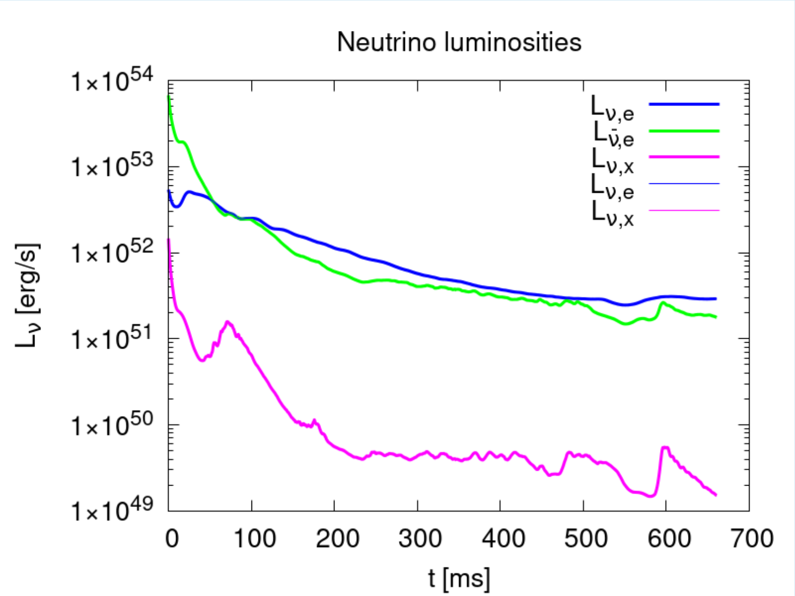


Preliminary estimate for wind ejecta mass



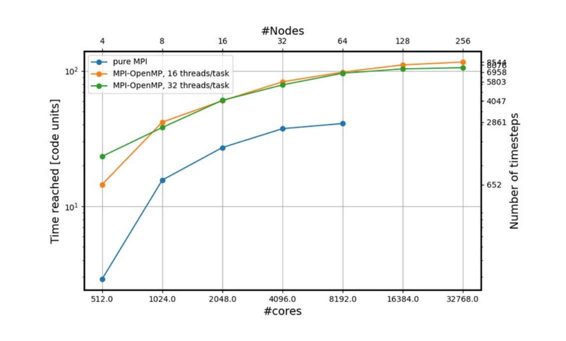
Janiuk et al. (2024, in prep)

Neutrino luminosity



3D-kn - 256x128x64

Parameters:
Rin = 4.0
Rmax = 12.6
Beta= 50
a = 0.6
MBH = 8.2
Mdisk = 0.792
Sdisk = 10

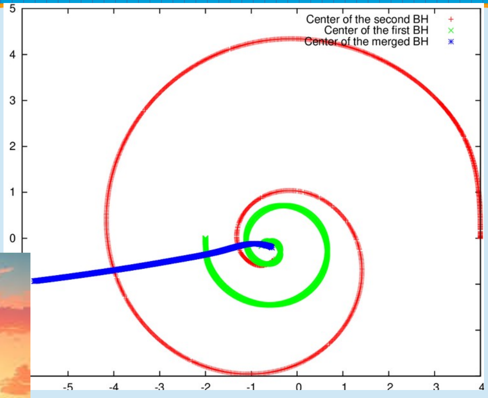


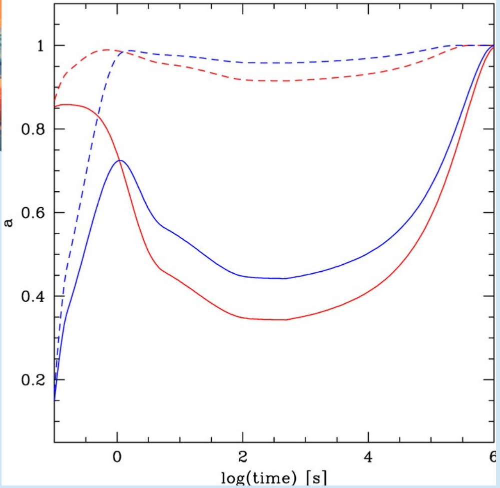
Simulation cost:
2231739/1920000
(116.2%) core/hours

Code optimizing and testing, plus some physics improved in the meantime (neutrino scheme, 3-parameter EOS, additional source terms for energy equation → slave's work

Kilonovae with long GRBs?

- Kilonova from collapsars? Controversial topic… Mergers might be able to explain all phenomena (cf. O. Gottileb talk)
- Sources 211211A and 230507: several explanations proposed, inlc. Accretion-induced collapse of WD, and WD-NS mergers …
- Collapsars might still produce some kilonova emission (e.g. Barnes & Metzger, 2023)
- In past, we considered a scenario for the long GRBs, from the collapse of a massive rotating star in a close binary system with a companion black hole. Tidally induced core collapse forms a binary BH system, embedded in collapsar's envelope (cf. E. Moreno-Mendez talk)
- The BH can be spun down, due to accretion of mass through poles (cf. D. Giannios talk)

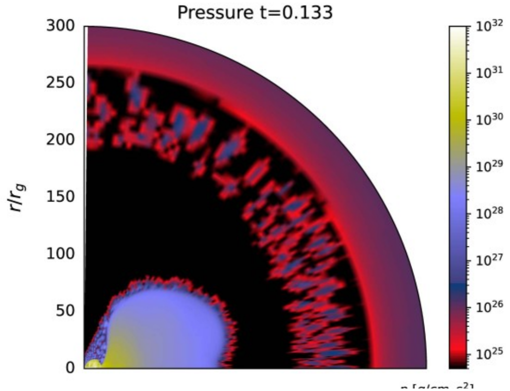


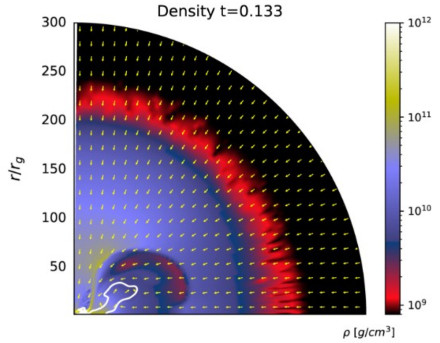


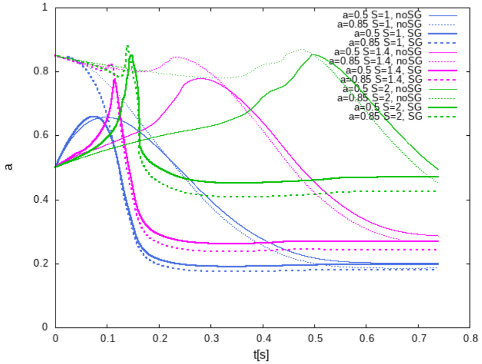
Janiuk, Charzyński & Bejger (2013, A&A)

Instabilities in the collapsing core

- Inhomogeneities and accretion shocks form due to SGI-interfacial instability
- Smear out as accretion rate fluctuations disapppear
- Self-gravity affects the black hole spin evolution





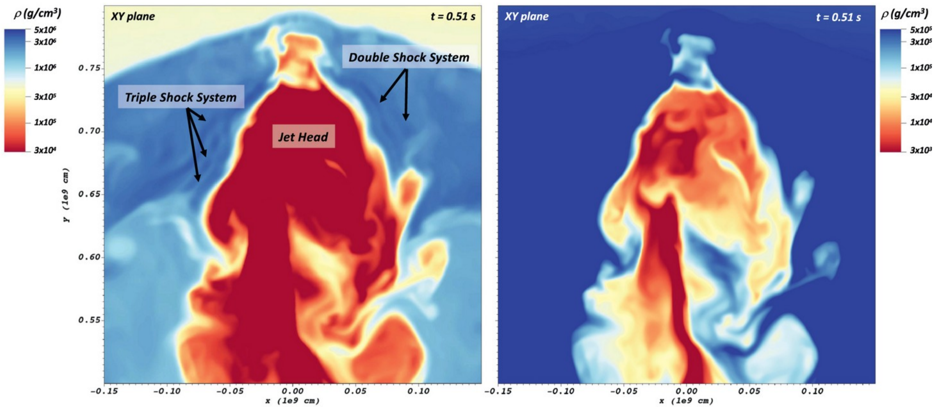


Janiuk, Shahamat, Król (2023, A&A, 677, 19)

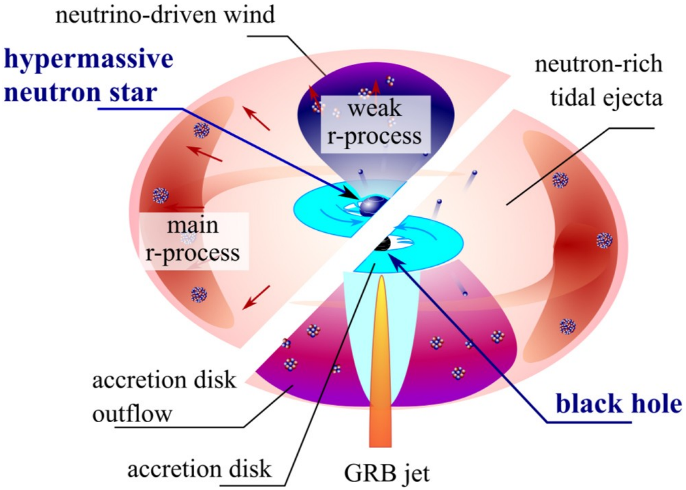
Summary

- **In short GRBs, the r − process nucleosynthesis in magnetically driven accretion disk outflows can provide additional contribution to the kilonova emission, additionally to the BNS post-merger ejecta.**
  - **Jet interactions with wind should shape its properties and together with pre merger dynamical ejecta. Collimation of jet and cocoon possible due to MHD driven winds.**
  - **In long GRBs, process of collapse may be affected by changes of BH mass/spin, the self-gravity of a massive star and by magnetic fields.**
  - **Long GRBs from mergers are puzzle.**

3D hydrodynamic simulations shown that jet centroid oscillates around the axis of the system, due to inhomogeneities encountered in the propagation (Lazzati et al., 2021)

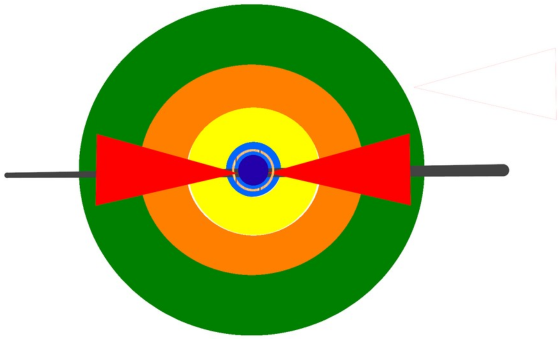


In the two-component model (SPH simulation, Korobkin et al. 2021), day-timescale emission comes at optical wavelengths from lanthanide-free components of the ejecta, and is followed by week-long emission with a spectral peak in the near-infrared (NIR).



Collapse onto growing black hole

- We use GR MHD scheme, presented in Janiuk et al. (2018, 2023) and Król & Janiuk (2021).
- Space-time Kerr metric is evolving due to changing mass and spin of newly formed black hole in collapsar.
- We also account for perturbative terms due to self gravity of collapsing core.
- The core is squeezed C-O core of WR or pre-SN star, into a volume of ~$[10^9 \text{ cm}]^3$.
- Core rotation leads to formation of mini-disk at equatorial plane.



$$\dot{M}_{BH} = \int d\theta d\phi \, \sqrt{-g} \, T^{r}{}_{t},$$

and

$$\dot{J} = \int d\theta d\phi \, \sqrt{-g} \, T^{r}{}_{\phi},$$

$$\delta M_{BH}(t, r) = 2\pi \int_{r_{hor}}^{r} T^{r}_{t} \sqrt{-g} d\theta,$$

$$\delta J(t, r) = 2\pi \int_{r_{hor}}^{r} T^{r}_{\phi} \sqrt{-g} d\theta.$$