Relativistic MHD simulations of merging and collapsing stars with GRB transients

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HEPRO IX

Rio de Janeiro, 07.08.2025

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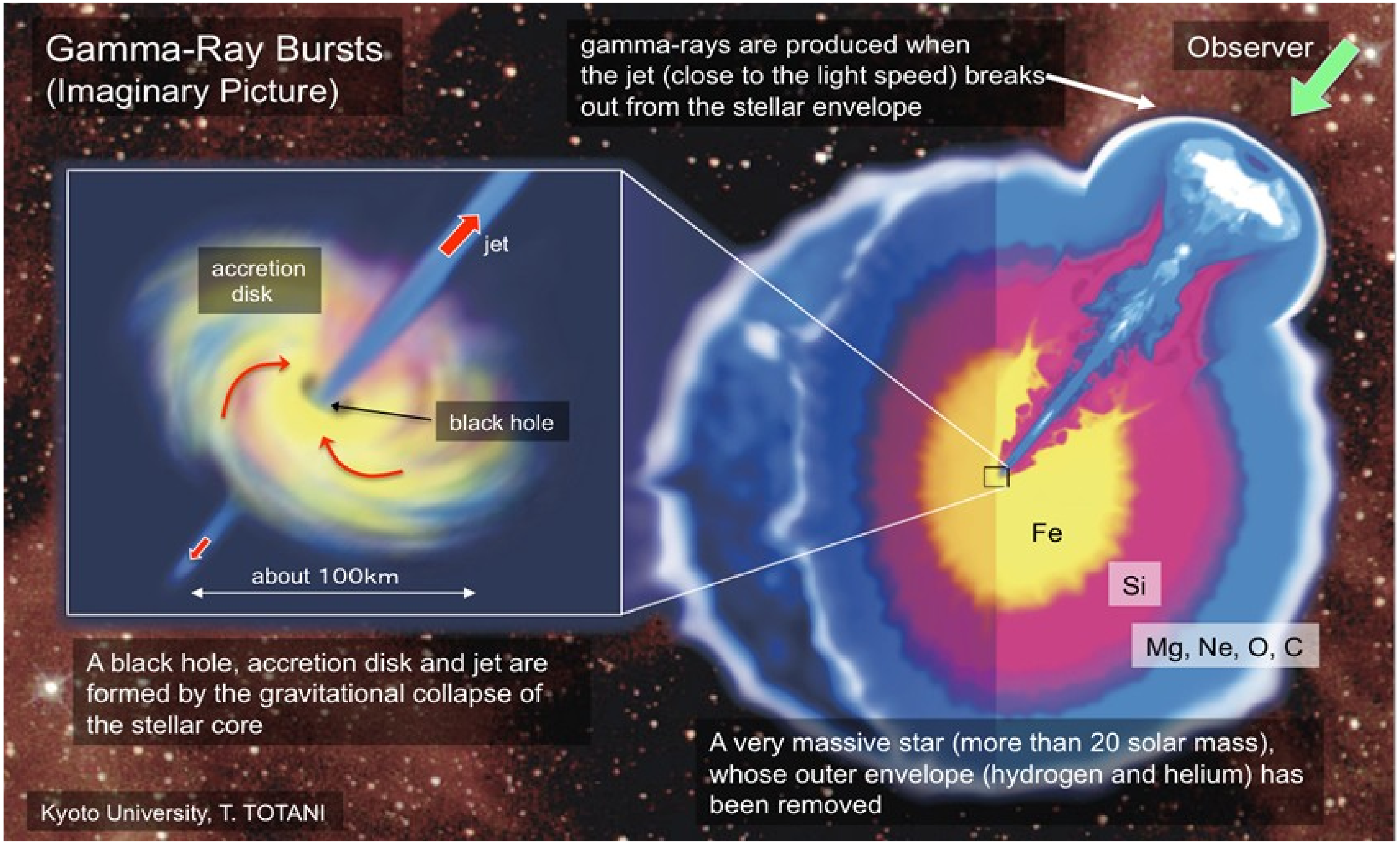
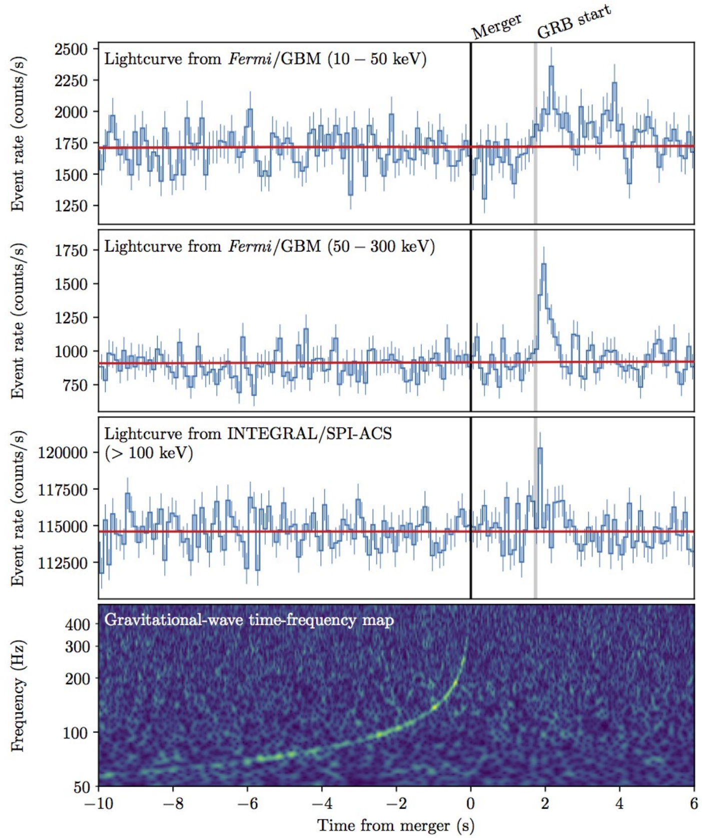
Long GRBs: collapsing massive stars

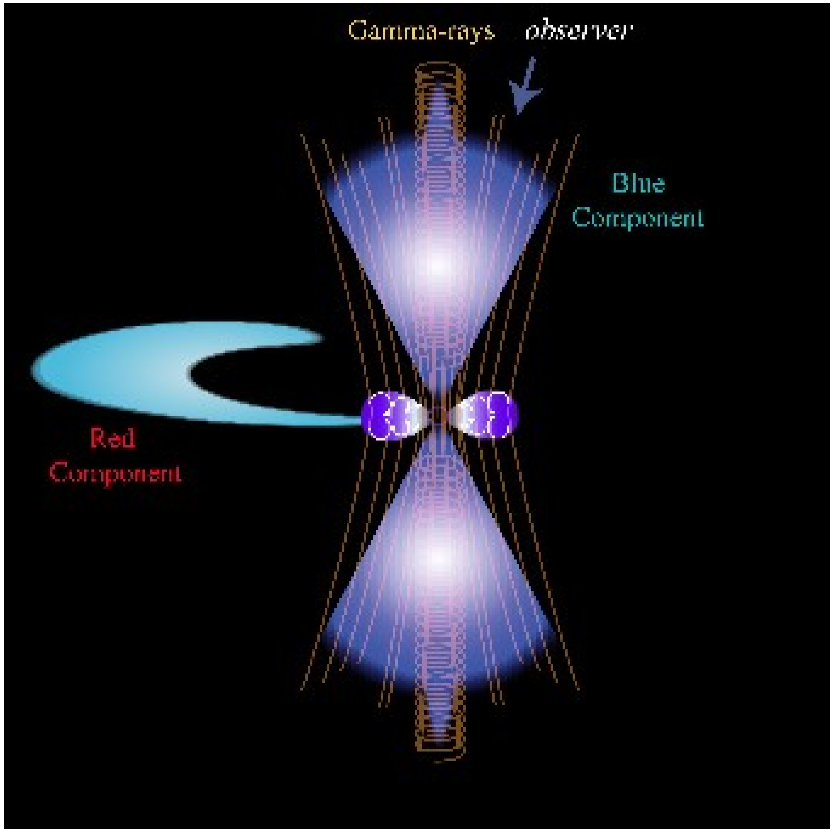


First association of events: GRB 980425 and SN 1998bw (Kuulkarni et al. 1998)

Short GRBs: merging compact binaries



First association of events: GW-GRB 170817 (Abbott et al. 2017)



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

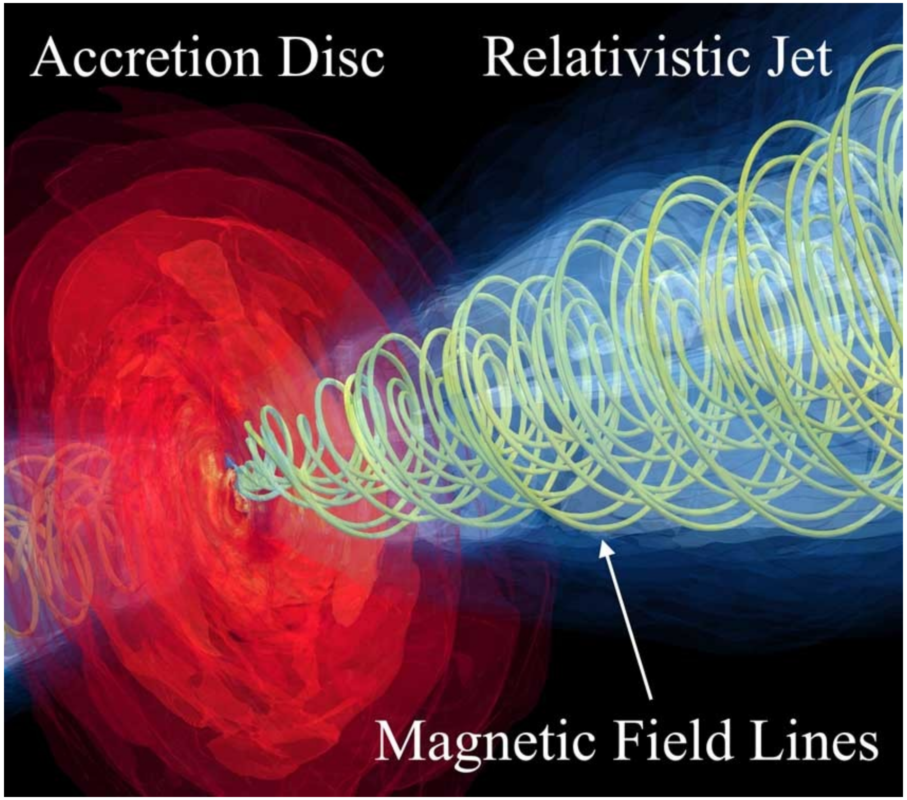
Relativistic jets paradigm

Jets are common in the Universe

Need a central engine: accreting black hole

Magnetic fields anchored in the accretion disk penetrate black hole's ergosphere and mediate extraction of its rotational energy

Spinning black hole twists open field lines, helping the jet collimation

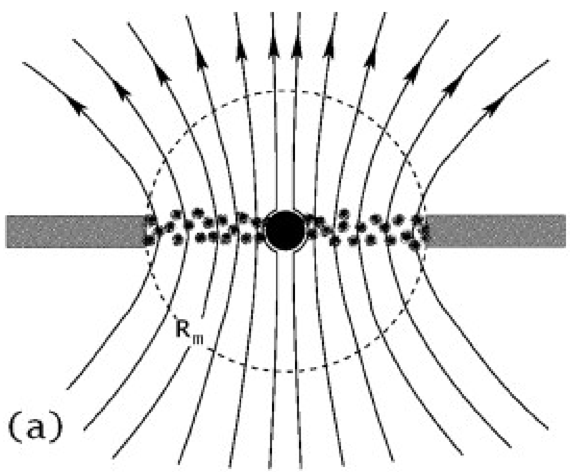


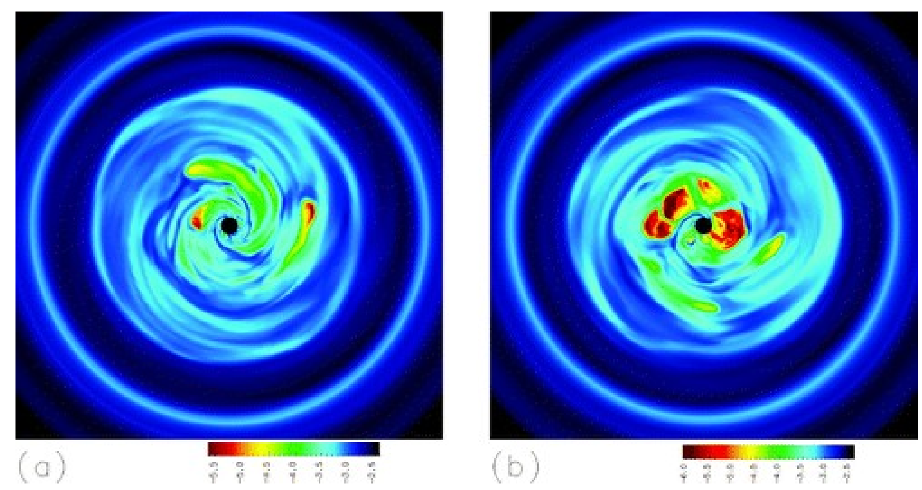
Visualisation from simulation.
courtesy: L. Rezzola's group

MAD mode of accretion

In the MAD mode, poloidal magnetic field is accumulating close to BH horizon, due to accretion

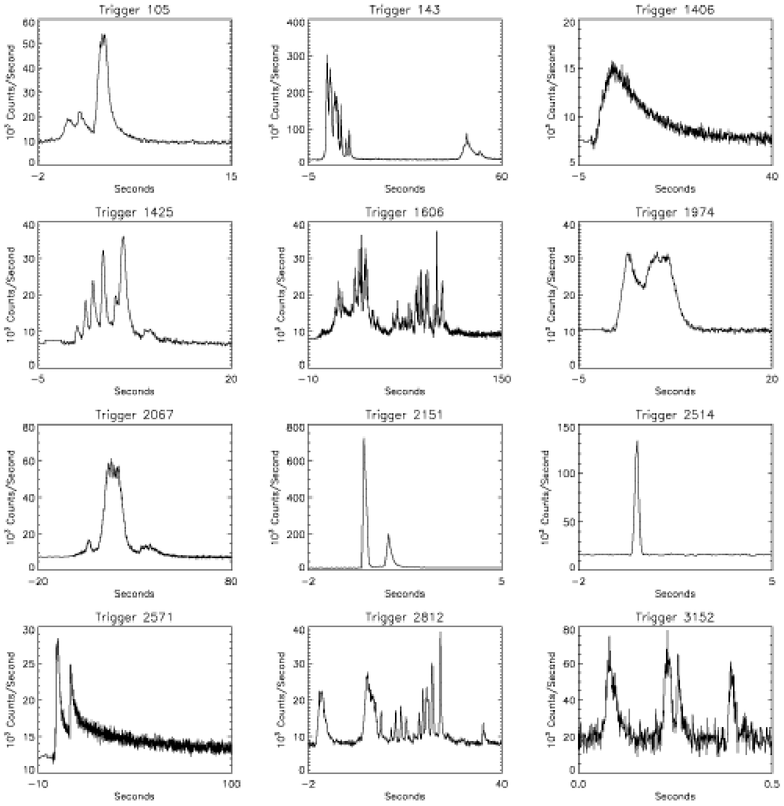
Axisymmetric case: inside magnetospheric radius, R_m, gas accretes as magnetically confined blobs (Narayan, Igumenschev, Abramowicz, 2003).





Non-axisymmetric case: gas forms streams which have to find the way towards back hole through magnetic reconnections and interchanges
(e.g. Igumenshchev 2008; Tchekhovskoy et al. 2011)

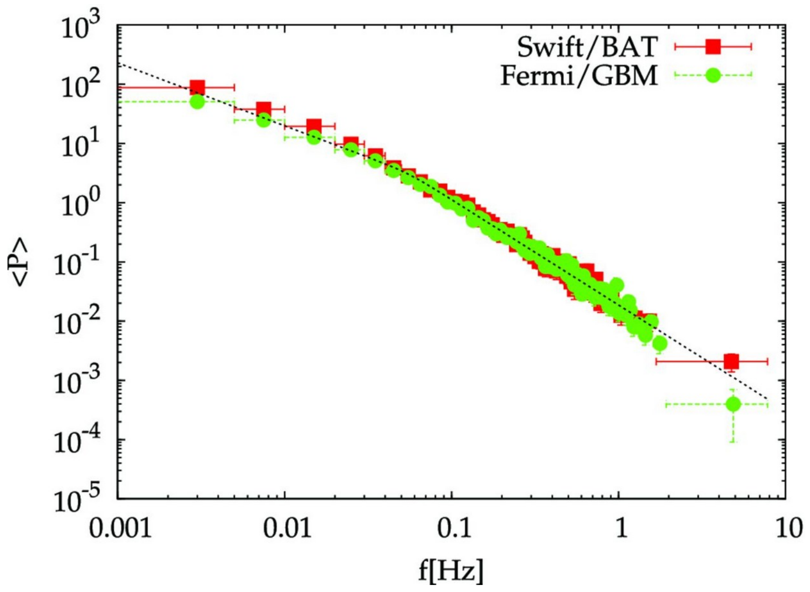
Time variability of GRBs



PDS spectra show power-law slopes between 1.49-1.65

(Dichiara et al. 2013)

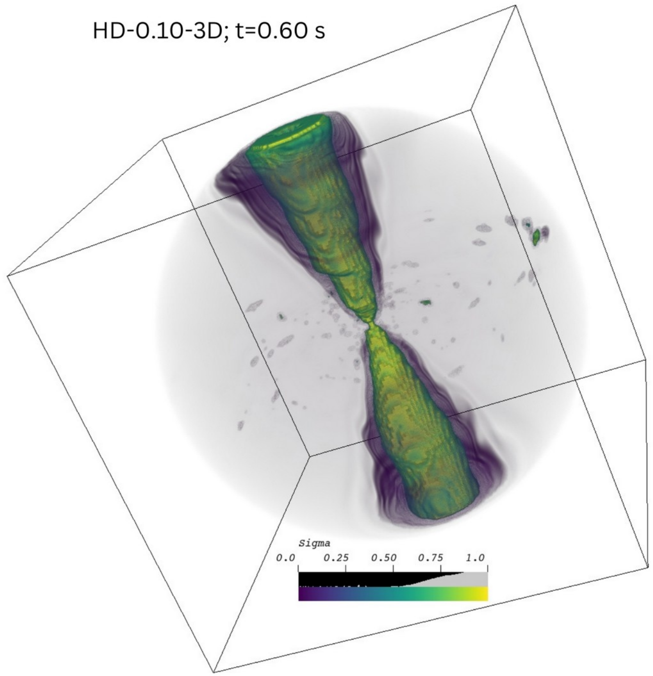
Prompt phase (the highly variable first ~ 100 s), explained by the MAD accretion onto a black hole
(Lloyd-Ronning et al., 2016).



Variability of accretion inflow rate translates into jet variability

Variability in the jet translates into changes in emitted radiation

Jet launching and energetics



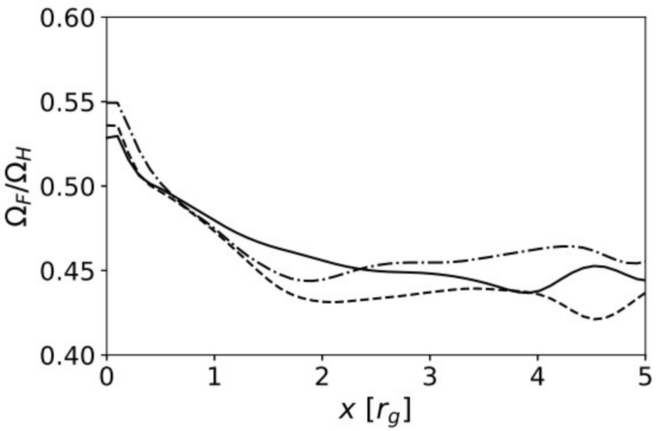
Jet structure

$$\sigma = \frac{\left(T_{EM}\right)^t_r}{\left(T^t_t\right)_{gas}} \qquad \mu = \frac{-T^r_t}{\rho u^r}$$

$$\mu = \gamma h \left(1 + \sigma\right)$$

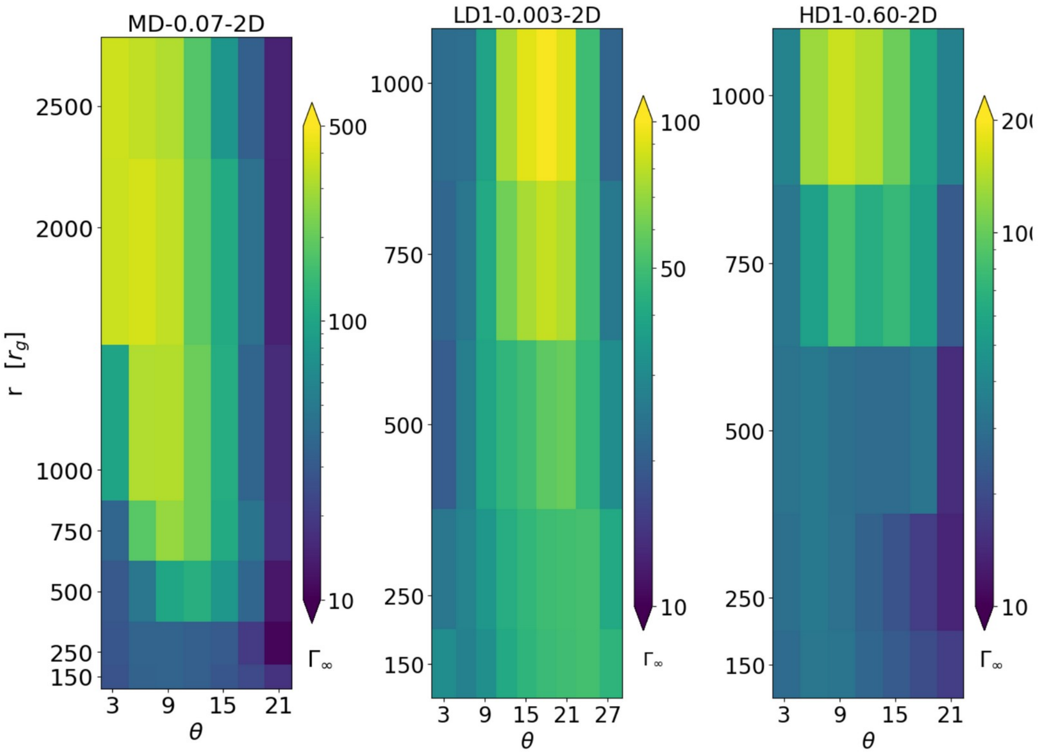
- Variability is correlated with T_{MRI} (timescale of the fastest growing mode of magneto-rotational instability)

- Blandford-Znajek process, efficient as the rotational frequency of magnetic field is large wtr. to angular velocity of the black hole



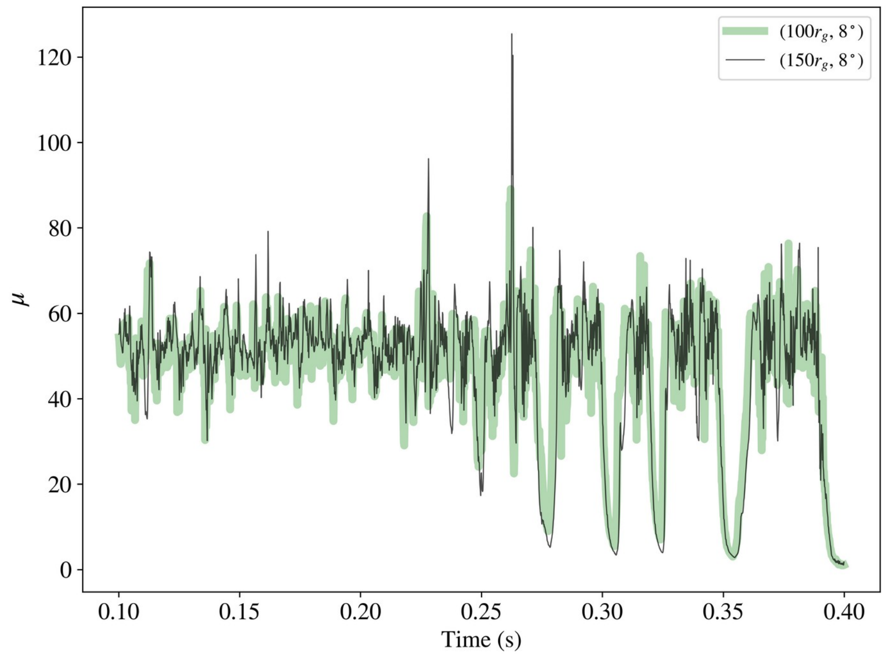
Rotational frequency ratio;
Sapountzis & Janiuk (2019, ApJ, 873, 12)

Jet profiles and variability



Maps of jet energetics (app. terminate Lorentz factor).

(Saji, Dainotti, Bhardwaj, *Janiuk, 2025, A&A, arXiV:2507.14938)*



Time evolution of jet

PDS slope depends on jet Lorentz factor
(A. Janiuk, B. James & I. Palit; 2021, ApJ, 917, 102).

Comparison to observed GRBs

GRB	z	E_{iso} [erg]	θ_{jet} [deg]	Model
090510	0.90	9.97e52	10	MD-0.07
1501101B	0.13	4.2e48	25.7	LD1-0.03
100117A	0.92	9.75e50	18.6	MD1-0.06
090927	1.37	1.21e51	21.1	MD2-0.06
120804A	1.3	3.4e52	>13	HD1-0.60

Observational application to several short GRBs, including 'target' GRB 0905010.

Opening angles extimated from Pescalli et al. (2021) relation, accounting for redshift evolution (Efron & Petrosian 1992). Fermi-LAT and GBM data were used to constrain energy (Dainotti et al. 2021; Pollakil et al. 2021)

Saji, Dainotti, Bhardwaj, Janiuk (2025, arXiV:*2507.14938*)

MHD disk wind and r-process

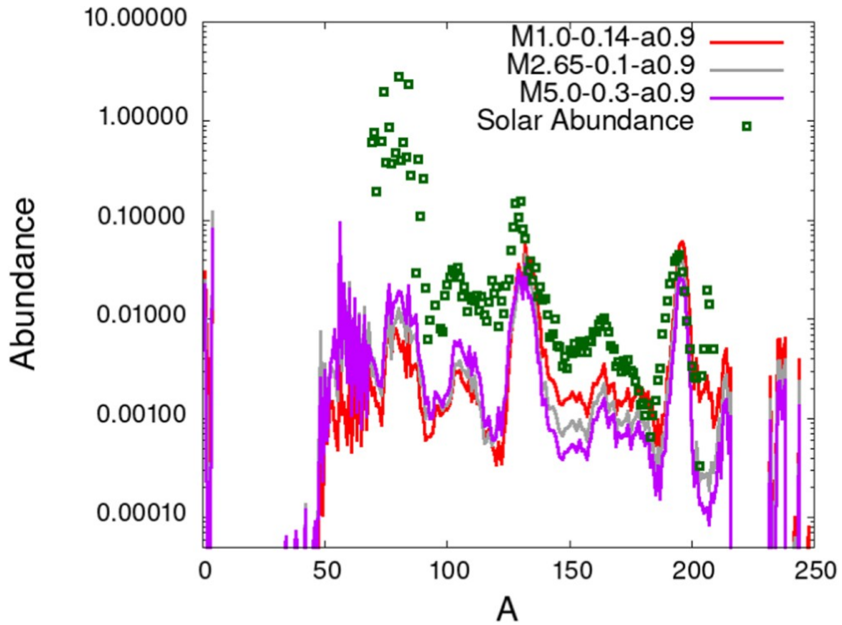
Neutronisation

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

$Y_e > 0.25$: 1st peak

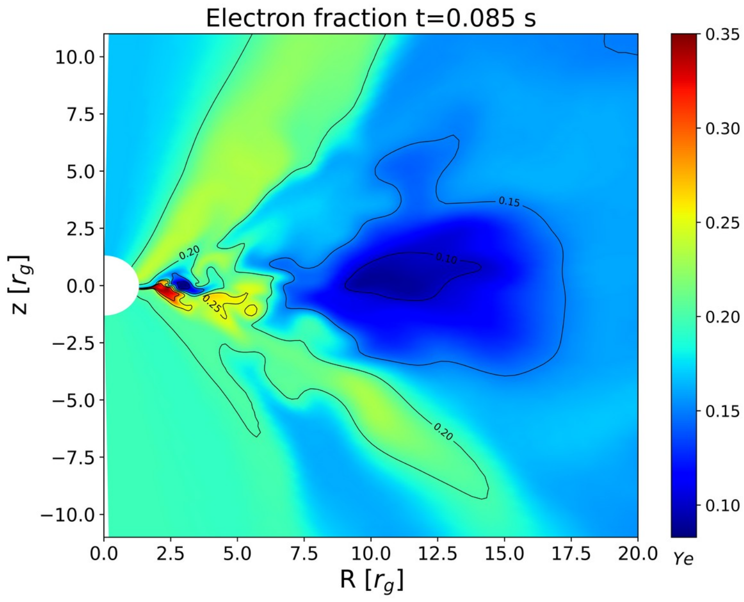
$Y_e = 0.15$-0.25: 2nd peak, Lanthanides

$Y_e < 0.15$: 3rd peak, Actinides



Nucleosynthesis pattern computed on outflows, from **set of 2D** GR MHD simulations

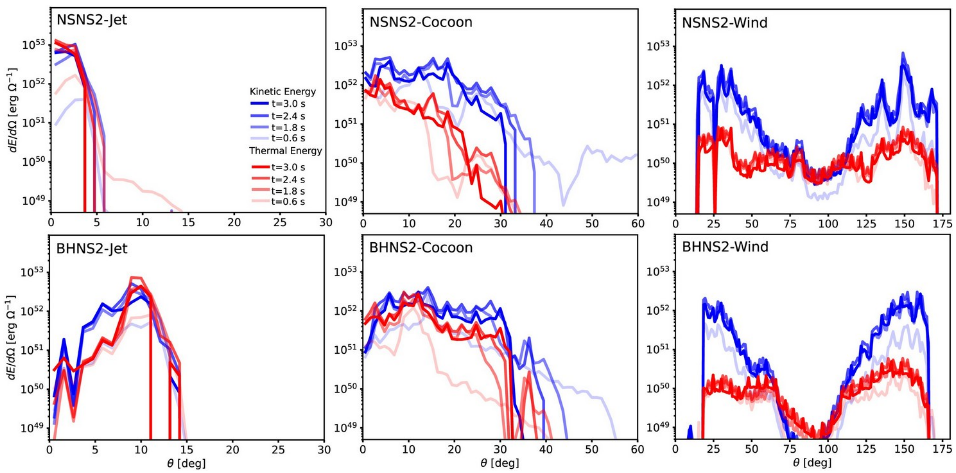
(Nouri, Janiuk & Przerwa, 2023, ApJ, 944, 220)



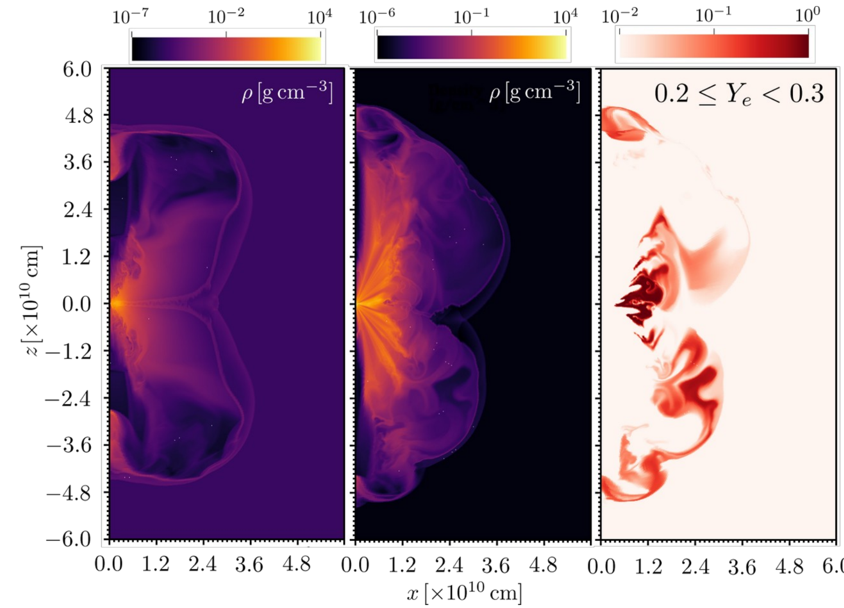
→ Accretion disk launches not only jet but also uncollimated winds

→ Disk wind is the site of r-process nucleosynthesis and gives contribution to ‘red’ or ‘purple’ kilonova emission

Collimation by disk wind

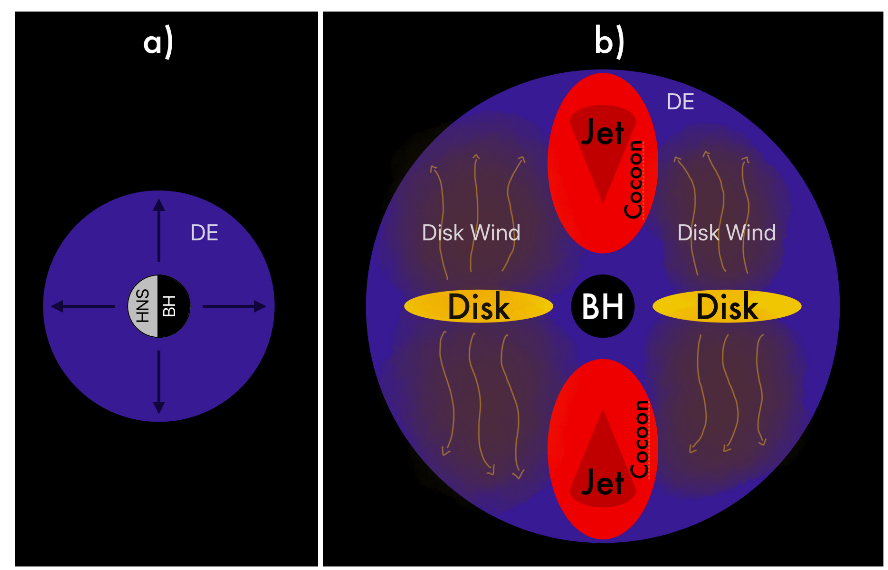


Urrutia, Janiuk, Nouri (2025, MNRAS, 538, 124)

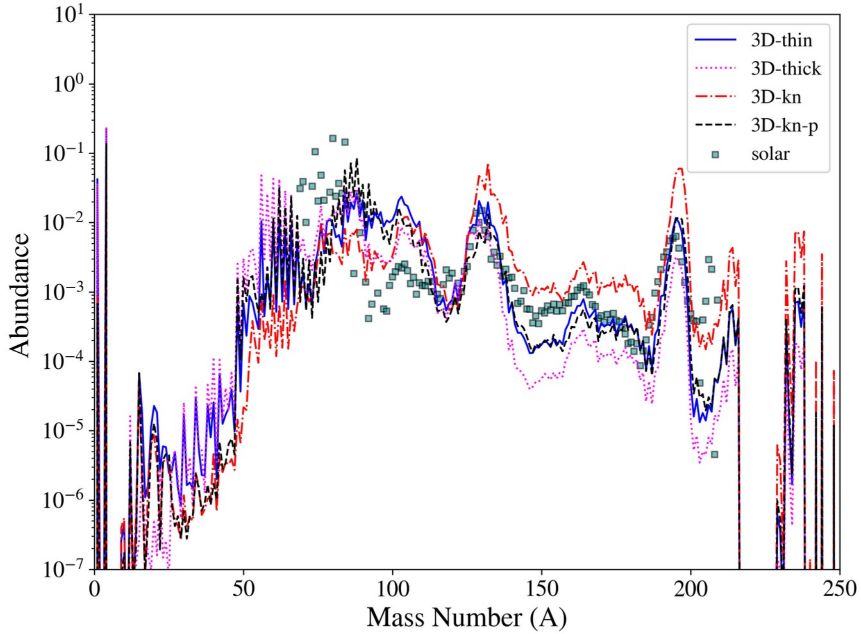


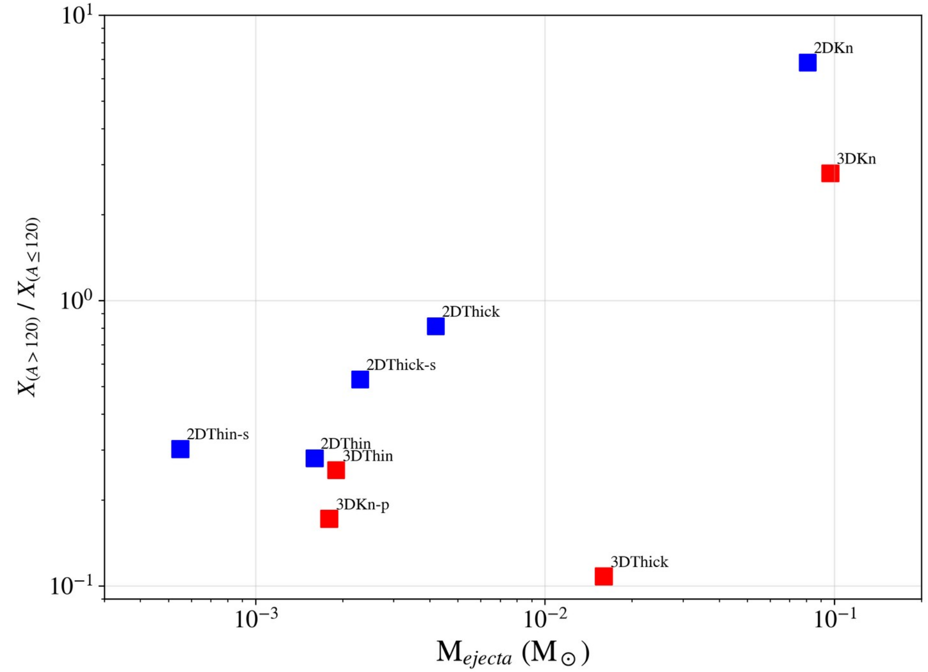
→ Disk wind from GR MHD simulation remapped to large scale jet propagation model. Wind injection rate is between $4\mathrm{x}10^{-4}$ and $4\mathrm{x}10^{-2}$ M_{sun}/s

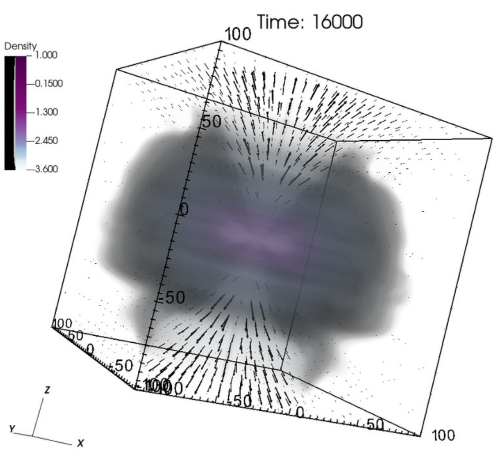
→ Jet & cocoon collimation due to disk wind, in addition to post-merger dynamical ejecta.



Probing wind nucleosynthesis







→ r-process patterns and heavy-to-light element ratios for set of **2D and 3D** simulations show correlation of heavy-to light element ratio with ejecta mass

→ disk winds can produce enough Lanthanides to explain red/purple kilonovae

Janiuk, Saji, Urrutia (2025, in prep)

Simple collapse scenario & gravity self-force

- Space-time Kerr metric is evolving due to changing mass and spin of newly born black hole in collapsar.
- Perturbative terms due to self gravity of the core (Teukolsky 1972; van Meent 2017).
- Core rotation leads to formation of mini-disk at equatorial plane.

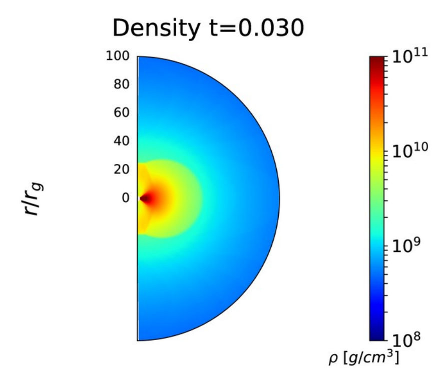
$$\dot{M}_{BH} = \int d\theta d\phi \, \sqrt{-g} \, T^{r}{}_{t},$$

and

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

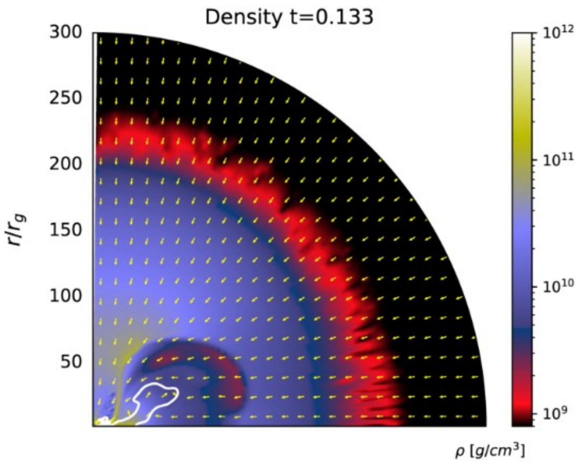
$$\delta J(t,r) = 2\pi \int_{r_{hor}}^{r} T^{r}_{\phi} \sqrt{-g} d\theta.$$

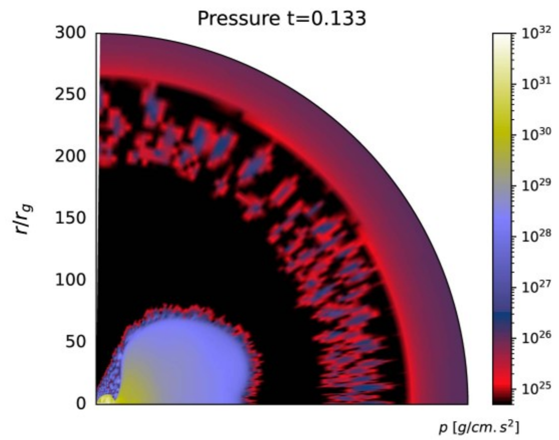
$$\delta M_{BH}(t,r) = 2\pi \int_{r_{hor}}^{r} T^{r}_{t} \sqrt{-g} d\theta,$$



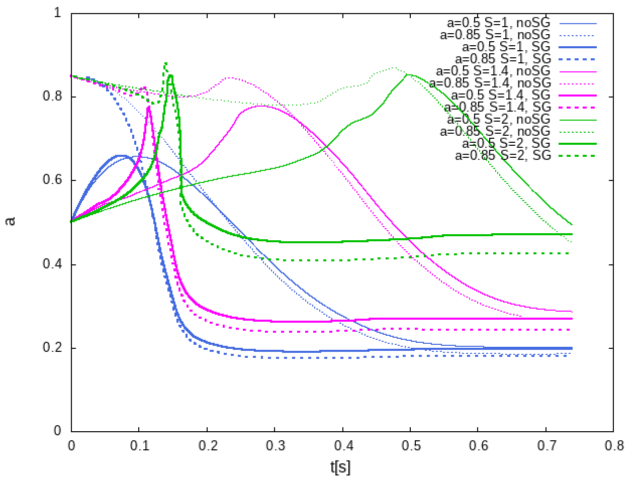
Janiuk, Sukova & Palit (2018);
Król & Janiuk (2021);
Janiuk, Shahamat & Król (2023);
Płonka, Janiuk, Shahamat (2025; in prep.)

Collapsing star simulation





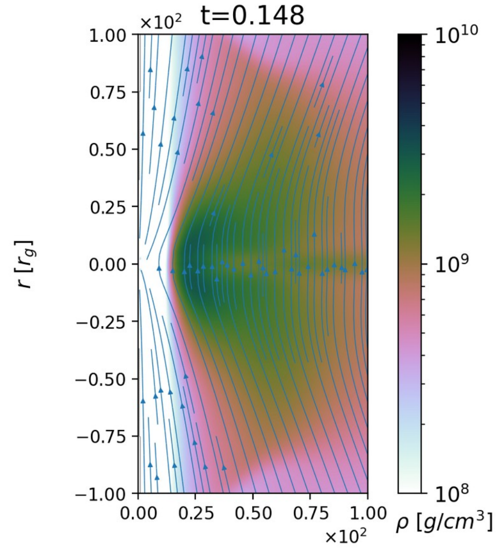
- Black hole spin-down to a ~ 0.2
- Self-gravity additionally affects the black hole spin evolution
- Density and pressure inhomogeneities; expanding accretion shocks

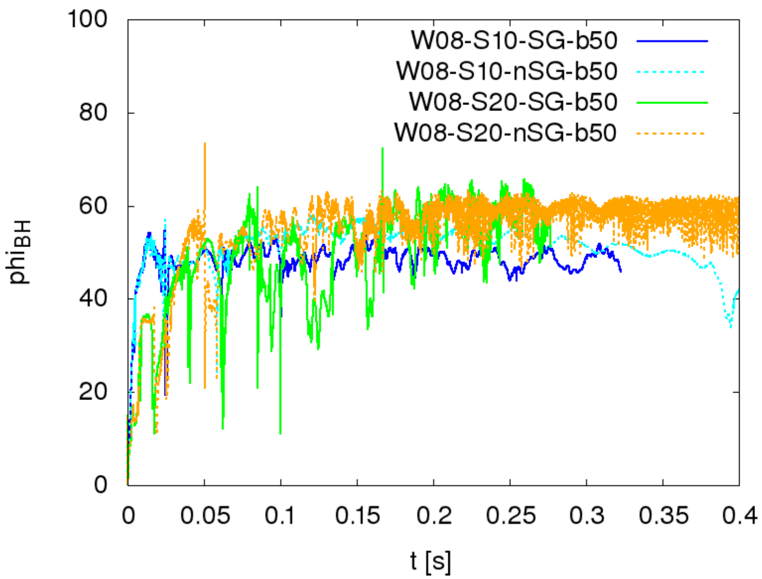


A. Janiuk, N. Shahamat Dehsorkh & D. Król (2023, A&A, 677, 19)

Effects of magnetic field

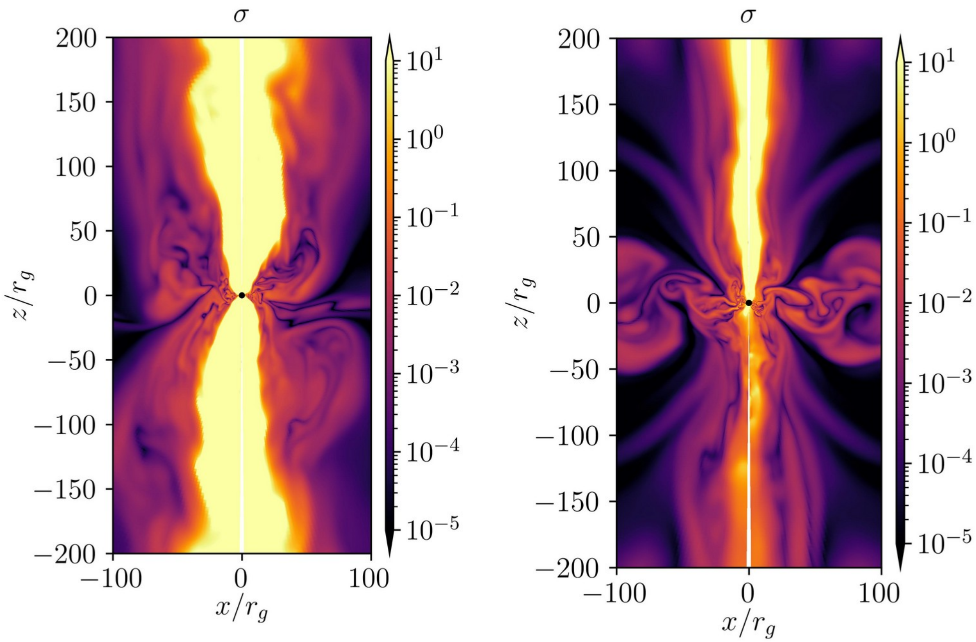
- We adopt weak poloidal magnetic field: uniform, or dipole
- For uniform field the rotating Kerr black hole magnetosphere has a repulsive effect (Wald 1974).
- A magnetically arrested state develops and facilitates bi-polar jet-like outflows.
- In 2D simulation, the jets were not able to break out.

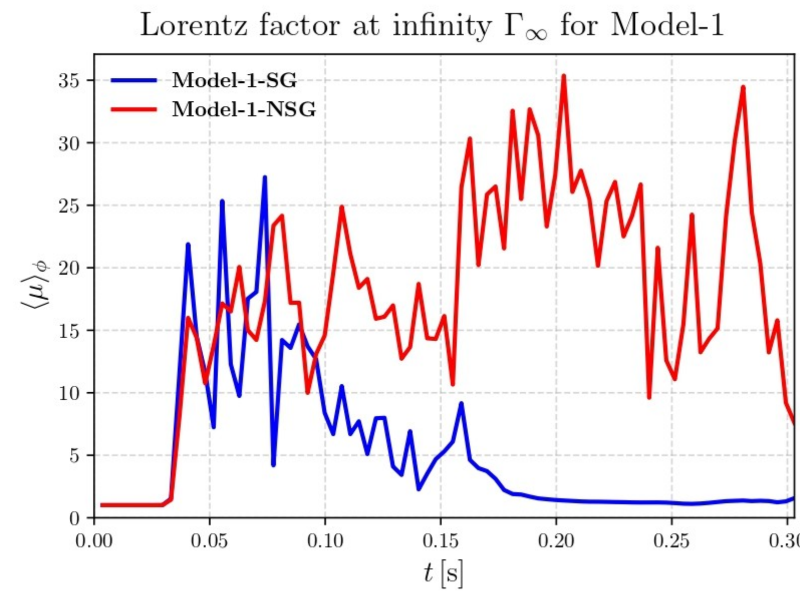


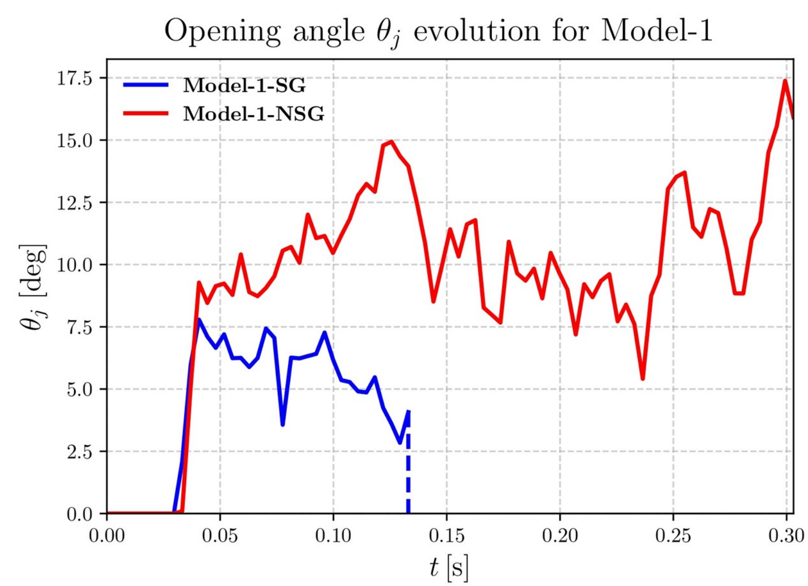


Janiuk, Sahahamat & Król 2023, A&A, 677, 19

Jet launching from self-gravitating collapsars







→ In 3D simulation, for some models the jet launching was successful

→ SG affects jet quenching

→ differences in energetics and opening angle

(Piotr Plonka, MSc thesis)

GR MHD simulations with HARM

$$(\rho u_\mu)_{;\nu} = 0$$
$$T^\mu_{\nu;\mu} = 0.$$

Continuity & Energy-momentum

$$F^{*\mu\nu}{}_{;\nu} = 0 .$$

Maxwell eqs.

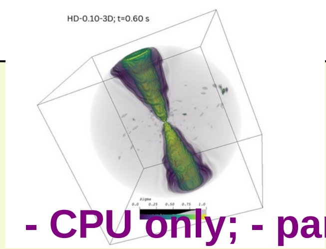
EM field tensor (GR)

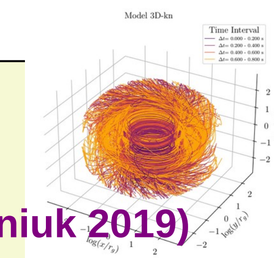
$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$
$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$
$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

Stress energy tensor (GR)

$$F^{*\mu\nu} = b^\mu u^\nu - b^\nu u^\mu$$

HARM = Conserved scheme for High Accuracy Relativistic MHD
(Gammie et al. 2003)





Version developed at CTP PAS

- CPU only; - parallelized with MPI or OpenMP (Janiuk et al. 2017; Sapountzis & Janiuk 2019)
- outputs in ASCII or HDF5 or VTK
- analytic or tabulated EOS (HARM_COOL; 2-parameter; Janiuk 2019; HARM_EOS; 3-parameter; Janiuk et al. 2022; 2025); neutrino leakage scheme
- tracer particles implemented to follow outflows and composition
- module for Kerr metric evolution self-gravity (HARM_METRIC; Janiuk, Sukova & Palit 2018; HARM_SELFG; Janiuk, Shahamat & Król 2023)
- Integrated HARM_COMBO with cmake-based parser scripts prepared and tested, results on next HEPRO X

PL GRID

Relativistic Astrophysics group at CTP PAS

- please visit our website.
https://ra.cft.edu.pl/

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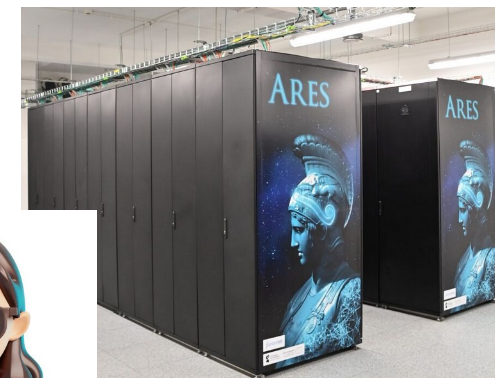

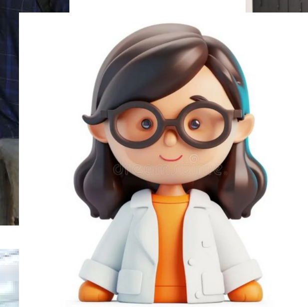

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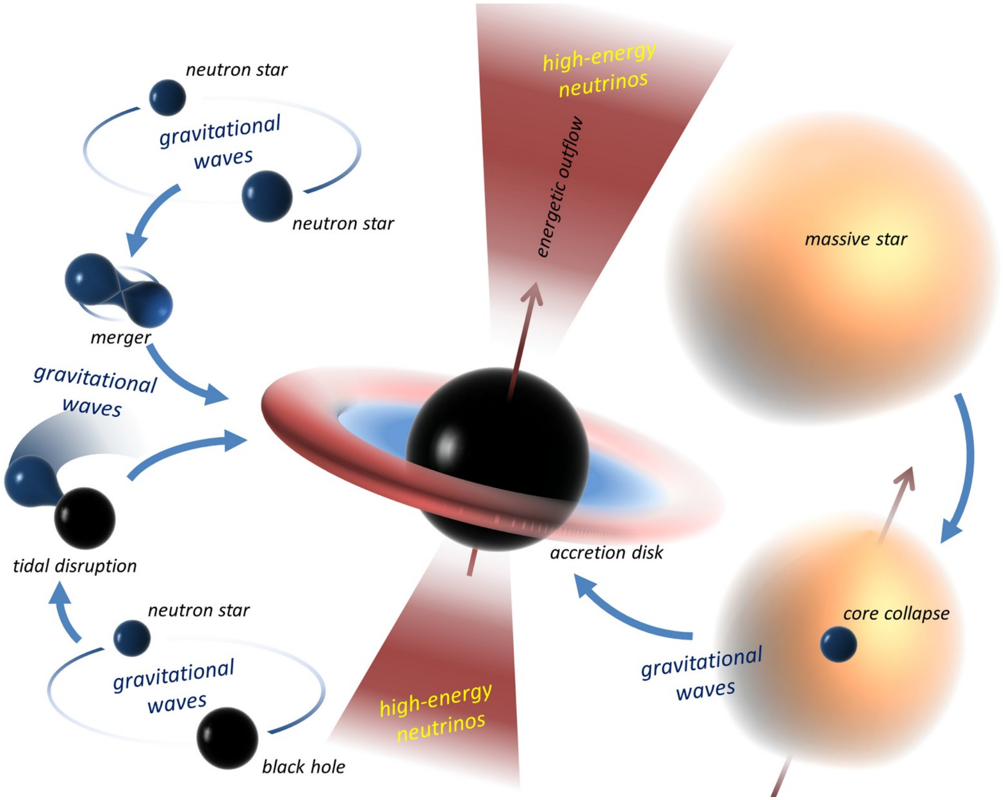
CTP Astro group: mergers and collapsars

Follow up projects planned on Relativistic Outflows

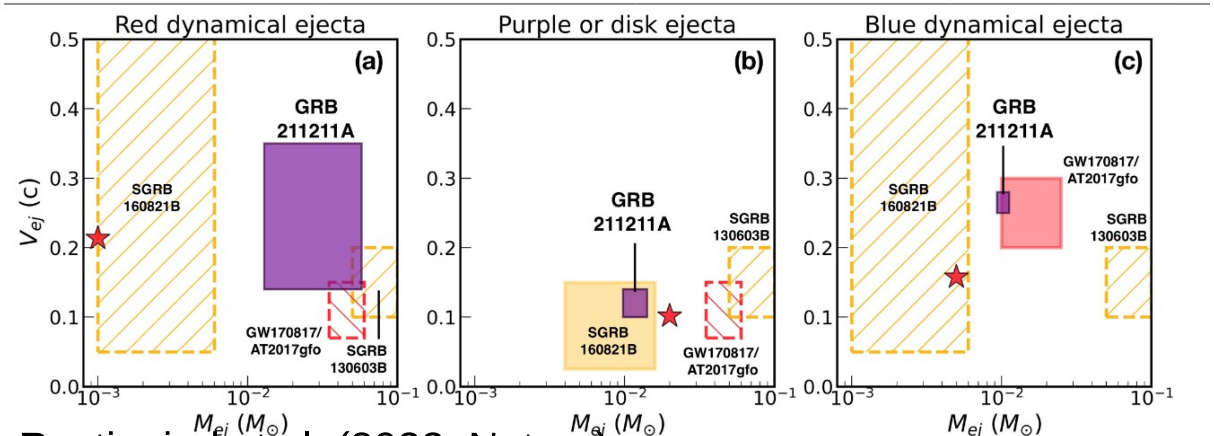
- ***GWs from accretion disks / jets;***
- ***disappearing stars;***
- ***collapsar-related KNe ?***
- ***role of ejecta in jet collimation***

Potential new post-doc opening...



Kilonova from long GRB?

Article



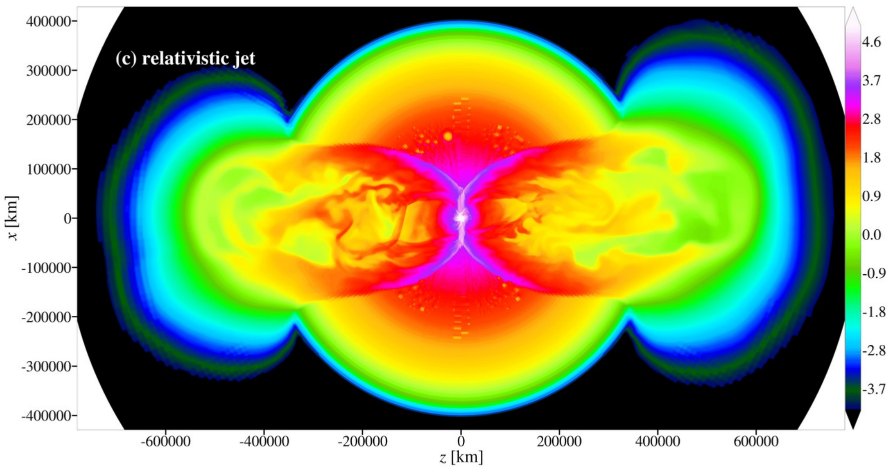
Rastinejad et al. (2022, Nature)

Scenarios for long GRB 211211A

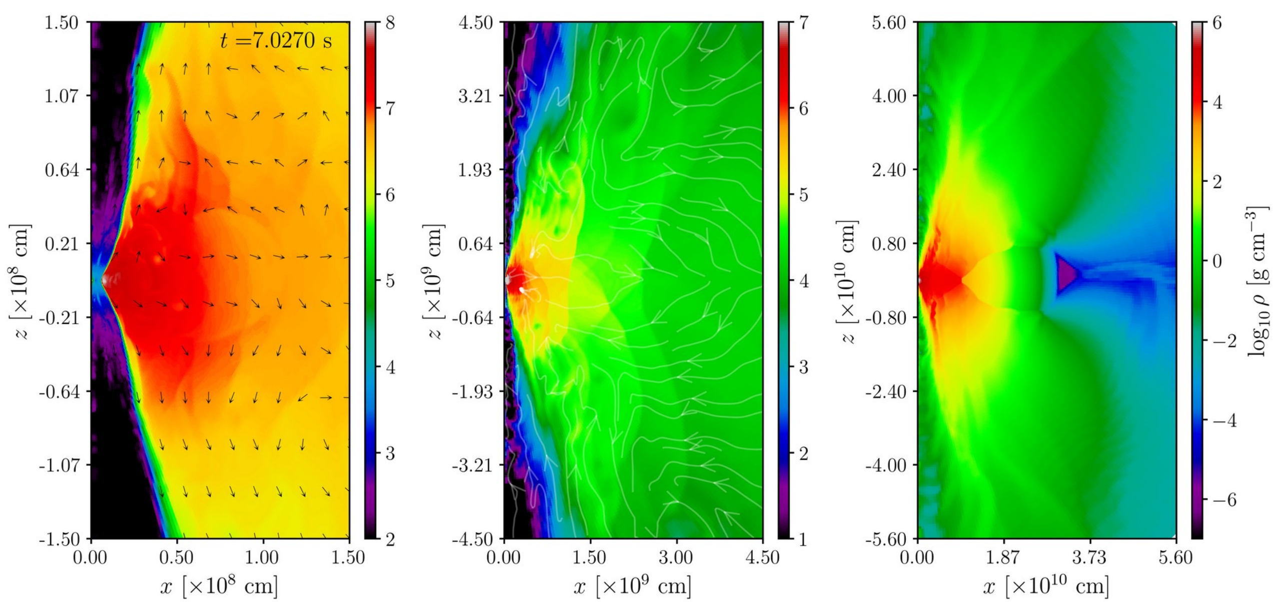
- accretion induced collapse of white dwarf (Batziou et al. 2025)
- WD-NS merger (Yang et al. 2022)
- NS-NS merger (Gottlieb et al. 2025)
- collapsar (Barnes & Metzger 2023)

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

Collapsar simulation challenges



Jet breakout process difficult to model due to multi-scale problem and computational complexity (fig from Gottlieb et al. 2022).



→ Simulation with AMR based BHAC code; multiscale setup (Porth & Olivares, 2020)
→ various stellar evolution models implemented (from the MESA & Kepler codes)

(G. Urrutia, A. Janiuk & H. Olivares; arXiV:2507.10231)