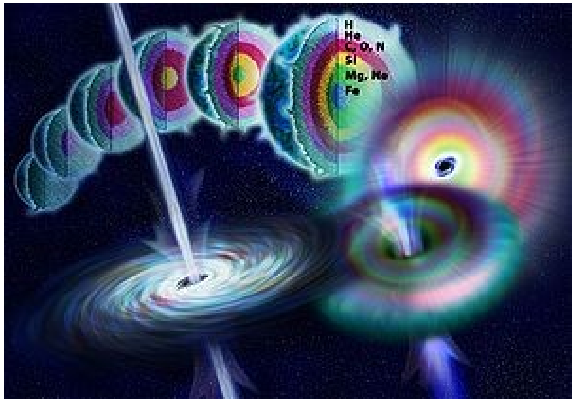
Collapsing massive stars and their possible electromagnetic transients



Agnieszka Janiuk

Center for Theoretical Physics PAS, Warsaw

SN2025gw Conference

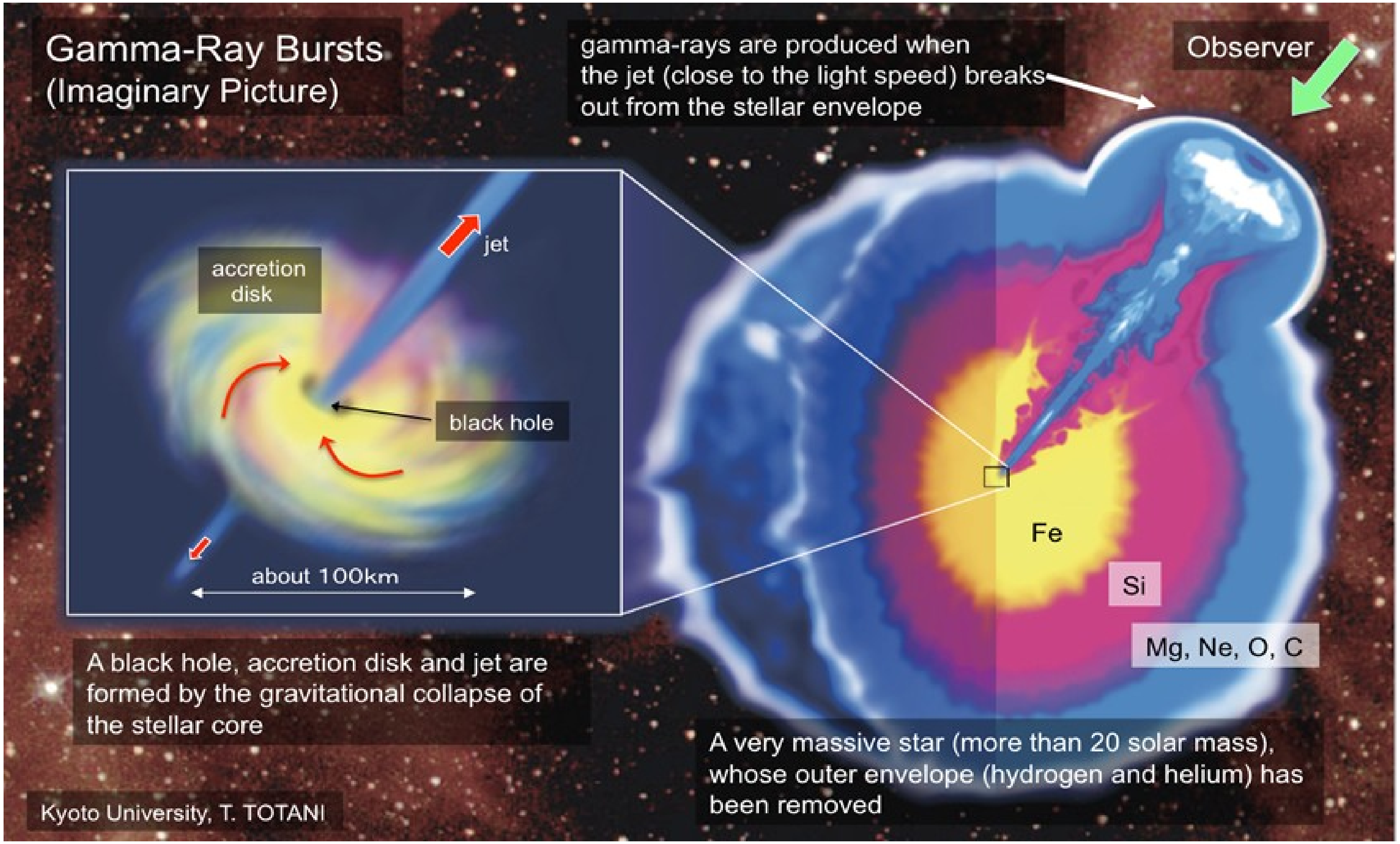
Warsaw, 24.07.2025

PL GRID

Narodowe Centrum Nauki

dxdx dxdxdx dxdxdxdx dxdxpandx dxdxdxdx dxdxdx dx dx dx dx cft

Long GRBs: collapsing massive stars



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

Relativistic jets paradigm

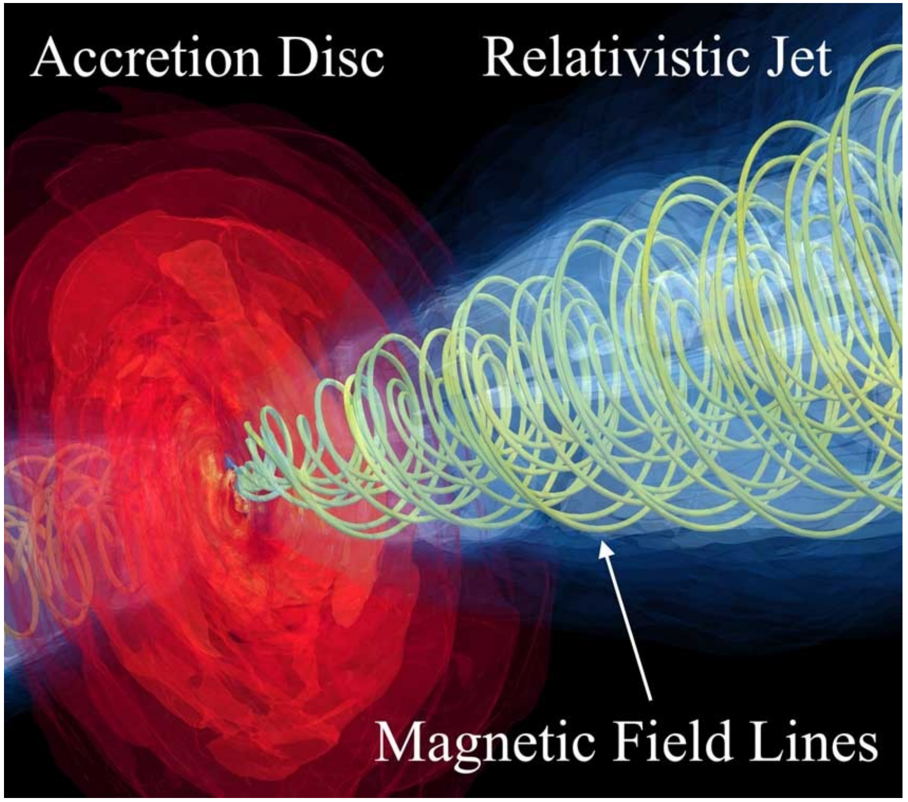
Jets are common in the Universe

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 extraction of its rotational energy

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



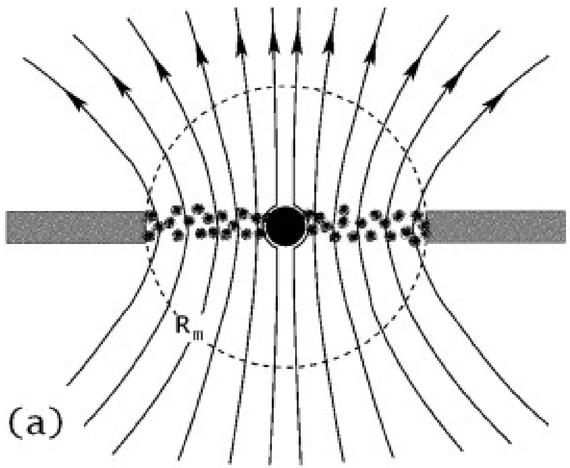
Visualisation from simulation.
courtesy: L. Rezzola's group

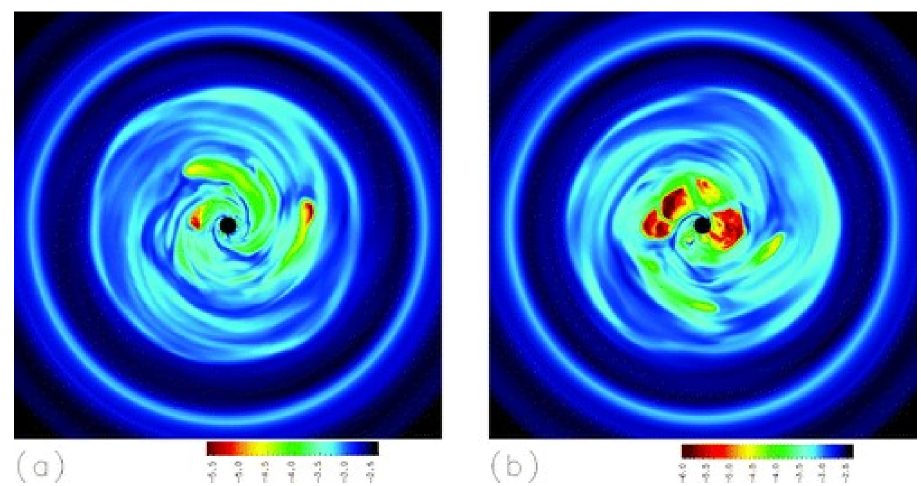
MAD mode of accretion

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

Field is prevented from escape as a result of inward pressure. It cannot fall into black hole either, while only the matter can fall in. The velocity of gas in this region is much smaller than free-fall.

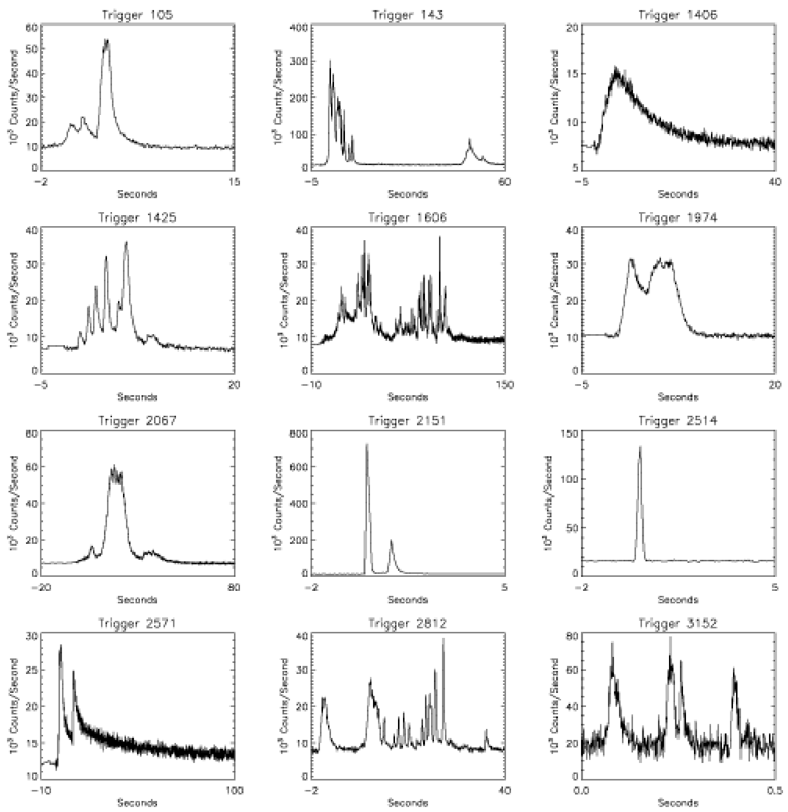
Axisymmetric case: inside magnetospheric radius, R_m, gas accretes as magnetically confined blobs (Narayan, Igumenschev, Abramowicz, 2003).





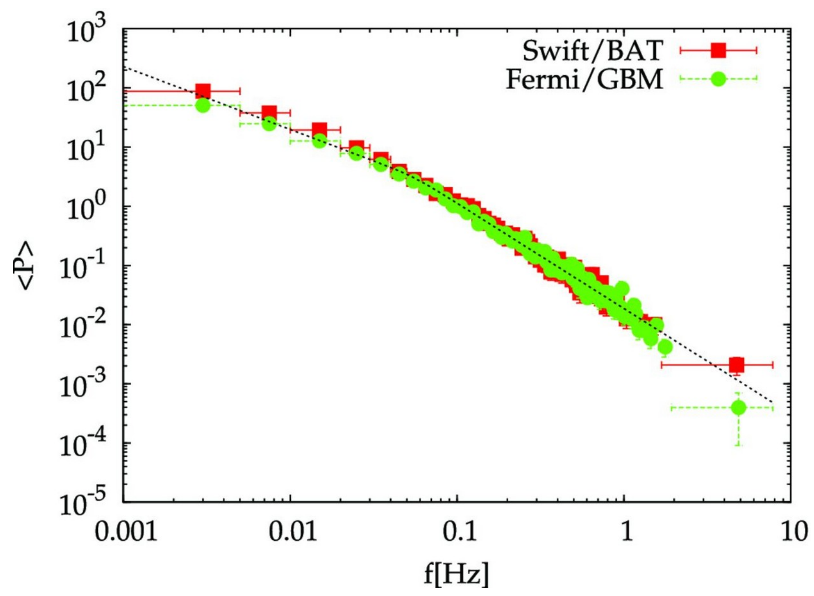
Non-axisymmetric case: gas forms streams which have to find the way towards back hole through magnetic reconnections and interchanges (e.g. Igumenshchev 2008)

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 inflow rate translates into jet variability

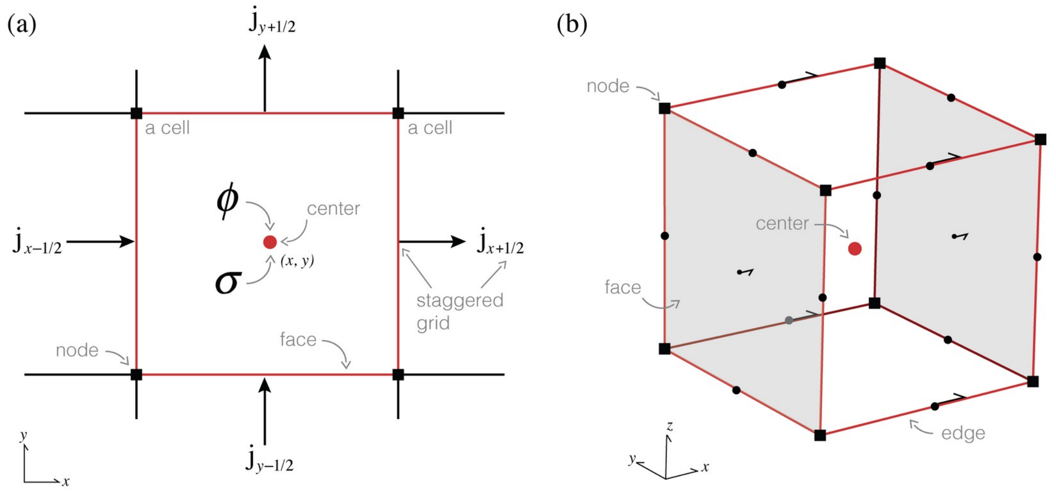
Variability in the jet translates into changes in emitted radiation

Seconds/Days/weeks/months to observe various counterparts

Multiwavelength observations

MHD numerical simulations

$$\partial_t \mathbf{U(P)} = -\partial_i \mathbf{F^i (P)} + \mathbf{S(P)}$$



- Equations discretized on the grid
- Finite Volume methods
- Scheme advances conserved variables in time, via the fluxes and source terms
- Inversion schemes used to recover primitive variables
- In GR, set of 5 nonlinear eqs. to be solved

P(U) needed by the equation of state

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.

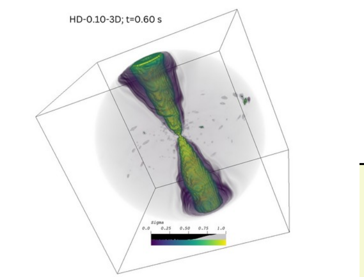
EM field tensor (GR)

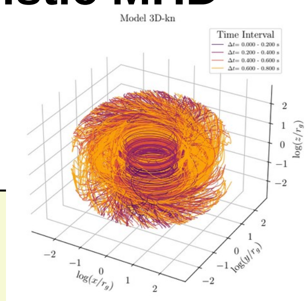
$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$
$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$
$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

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

Stress energy tensor (GR)

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

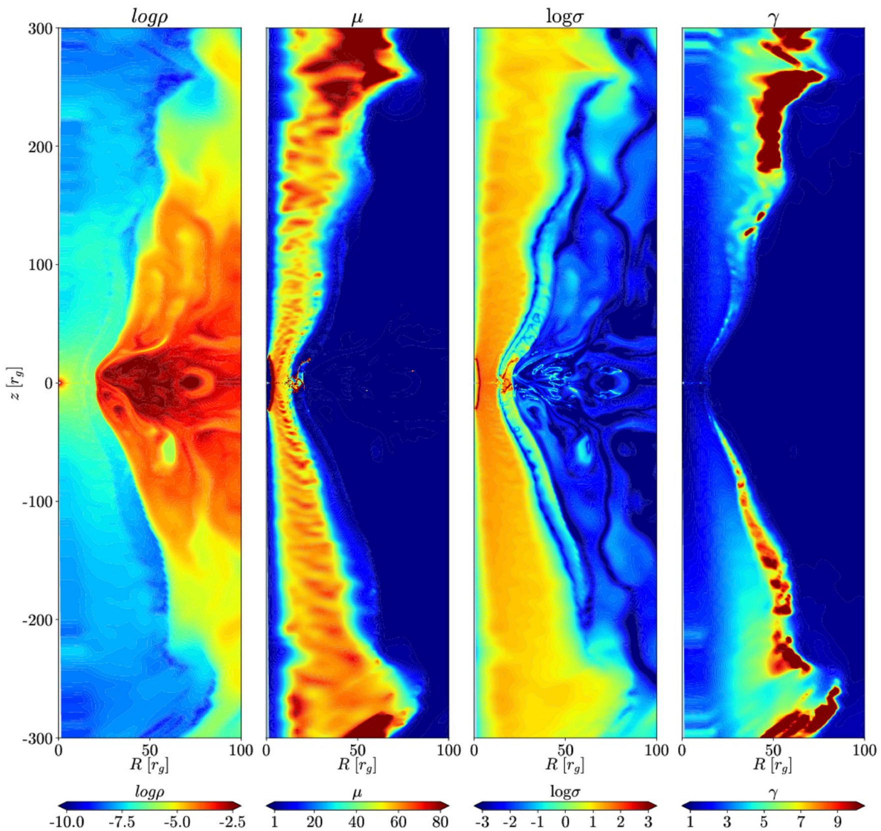




Version developed at CTP PAS

- 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)
- 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)

Jet launching and energetics



$$\mu = \frac{-T^r_{\ t}}{\rho u^r} \qquad \sigma = \frac{\left(T_{EM}\right)^t_{\ r}}{\left(T^t_{\ t}\right)_{gas}}$$

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

- The presence of magnetic fields and black hole rotation powers the jet acceleration

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

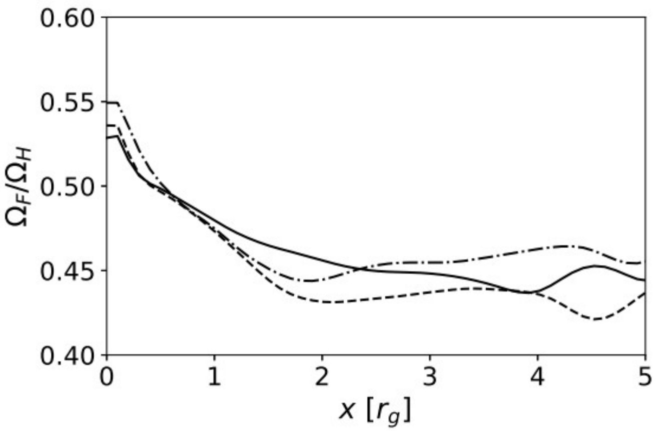
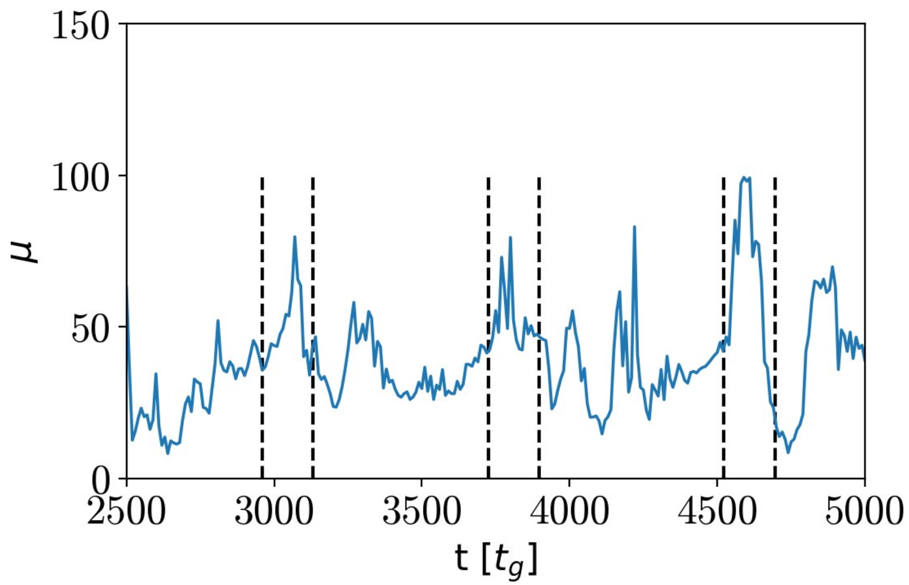


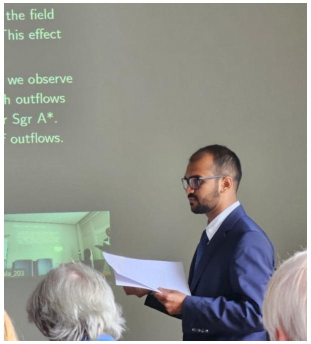
Fig from Sapountzis & Janiuk (2019, ApJ)

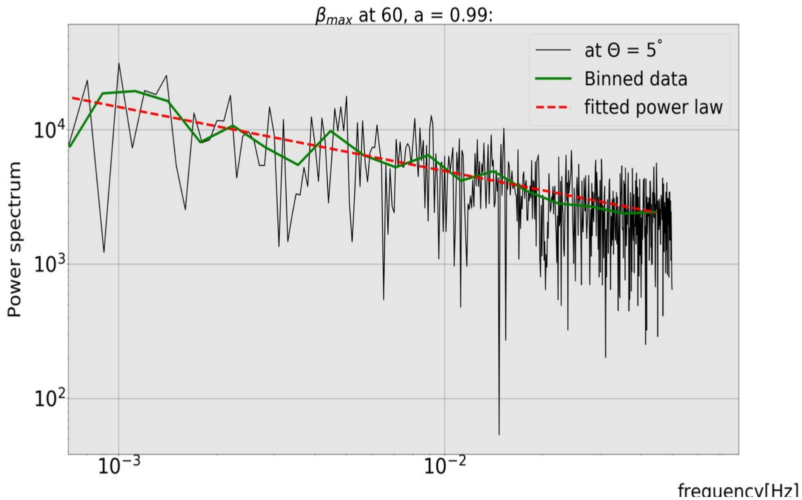
Variability of jets

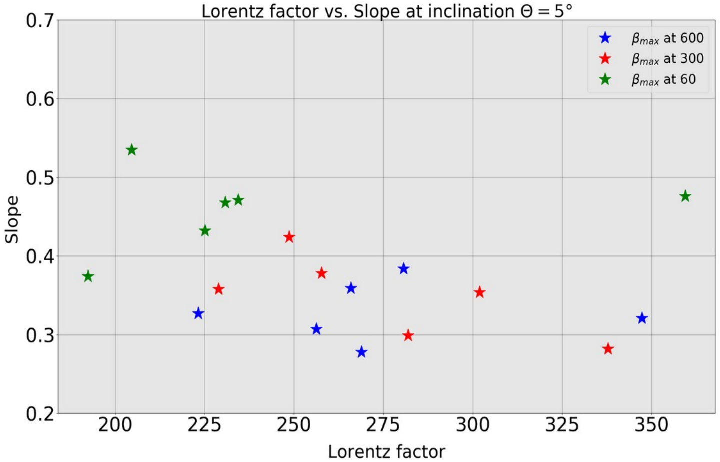


Time variability of jet energetics.

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





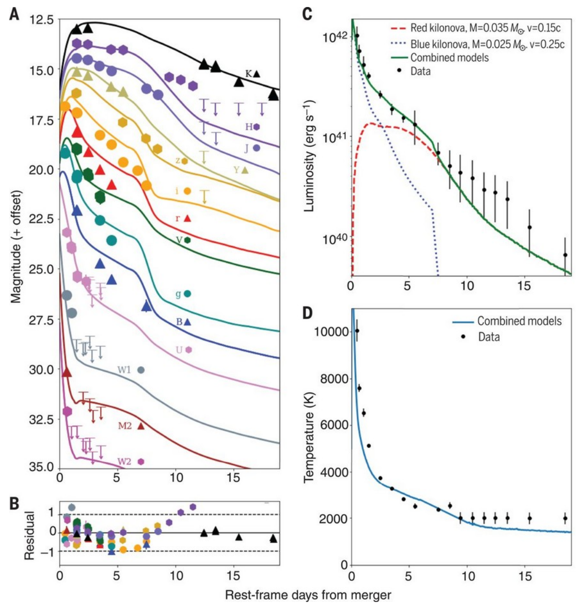


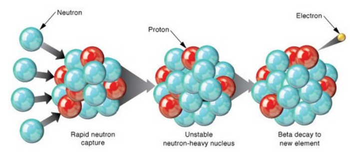
Power spectrum of model lightcurves.

Power-law slope weakly depends on the black hole spin, while it seems to depend on jet Lorentz factor.

(Janiuk, James & Palit, 2021, ApJ, 917, 102)

Heavy elements from r-process





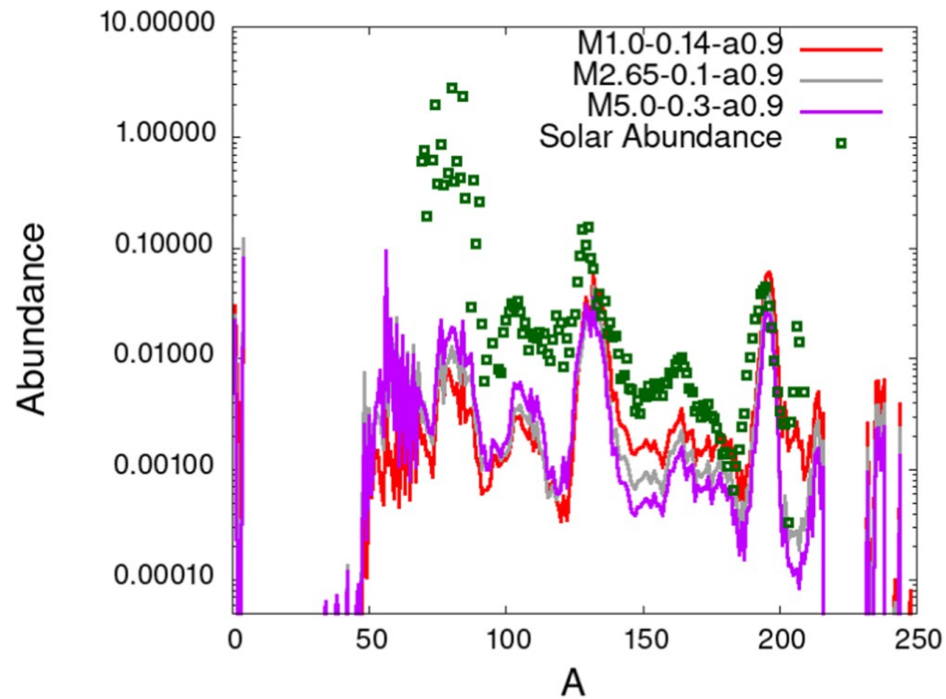
Neutronisation

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

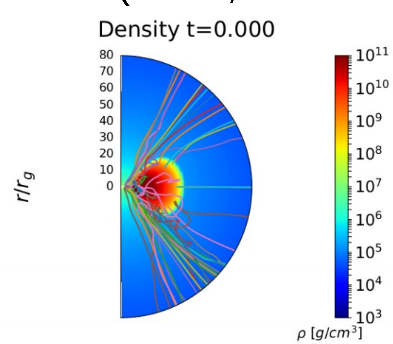
$Y_e > 0.25$: 1st peak

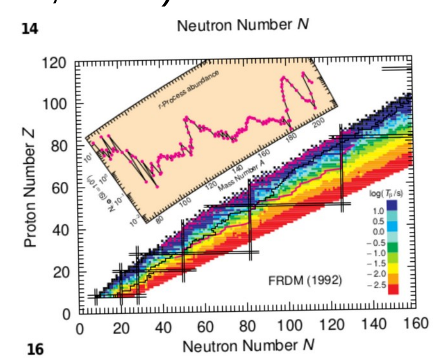
$Y_e = 0.15\text{-}0.25$: 2nd peak, Lanthanides

$Y_e < 0.15$: 3rd peak, Actinides



Nucleosynthesis pattern computed on outflows, from set of GR MHD simulations of post-merger accretion disks (Nouri, Janiuk & Przerwa, 2023)

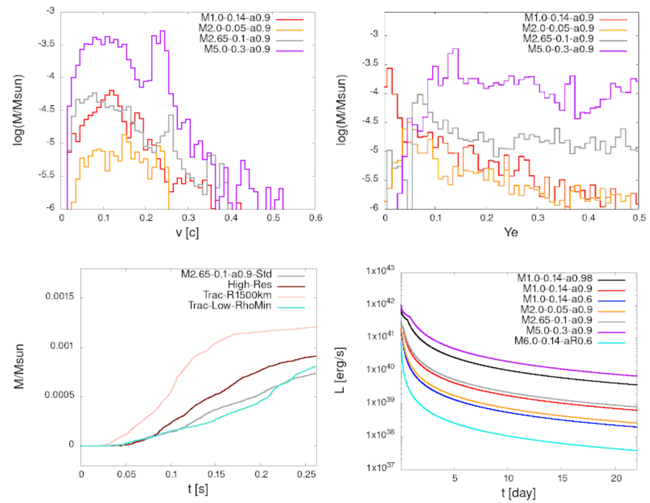




GRB jet collimation by disk wind

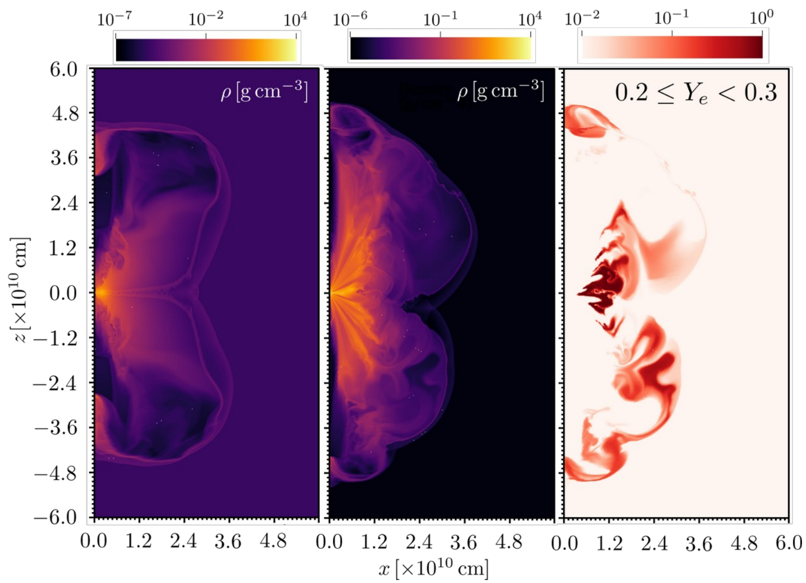
→ From 2D simulation, disk wind mass estimated by various methods between 4×10^{-4} and 4×10^{-2} M_{Sun}

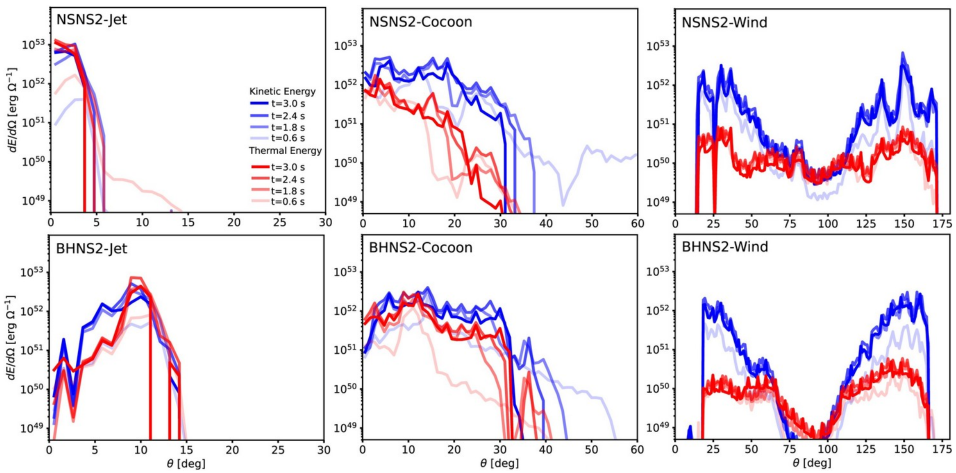
- simulations show a correlation between the black hole's spin and ejected mass (Nouri et al. 2023)



→ Disk wind contribution to 'purple' kilonova emission

→ Jet collimation due to dynamical ejecta, and disk wind.



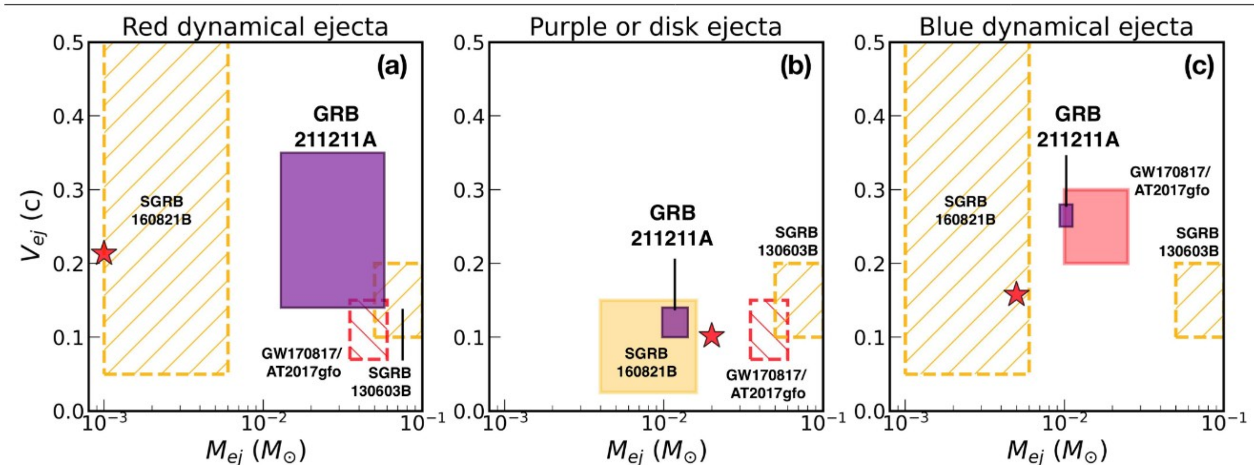


Urrutia, Janiuk, Nouri (2025, MNRAS)

Kilonovae components

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

Article



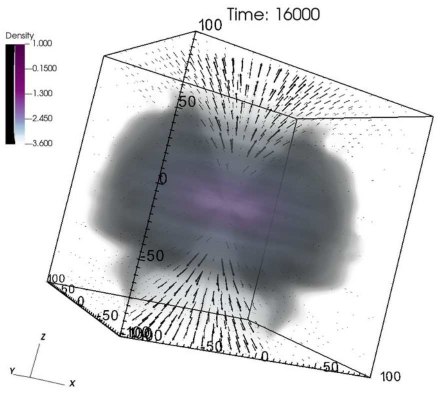
Disk winds produced in a post-merger system can contribute to powering all kilonova components

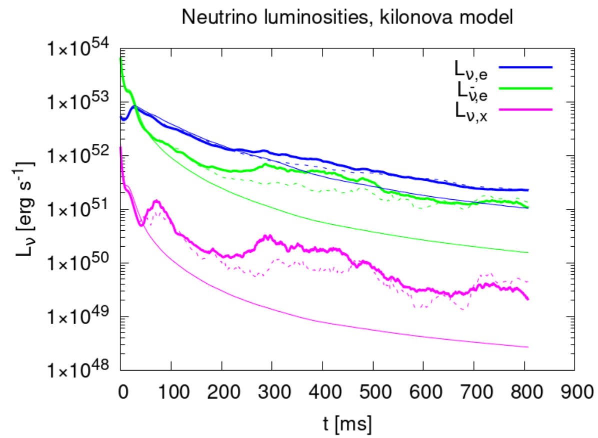
Long GRB engine scenarios for 211211:

- accretion induced collapse of white dwarf (see T. Janka's talk)
- WD-NS merger (Yang et al. 2022)
- NS-NS merger (Gottlieb et al. 2025)
- collapsar (Barnes & Metzger 2023)

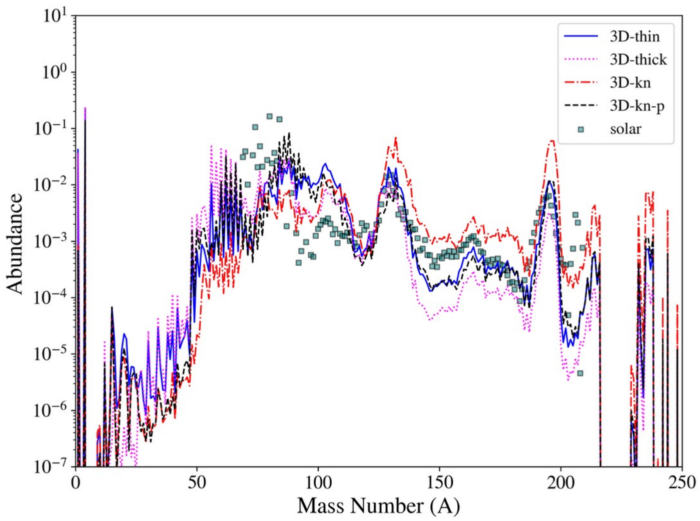
Rastinejad et al. (2022, Nature)

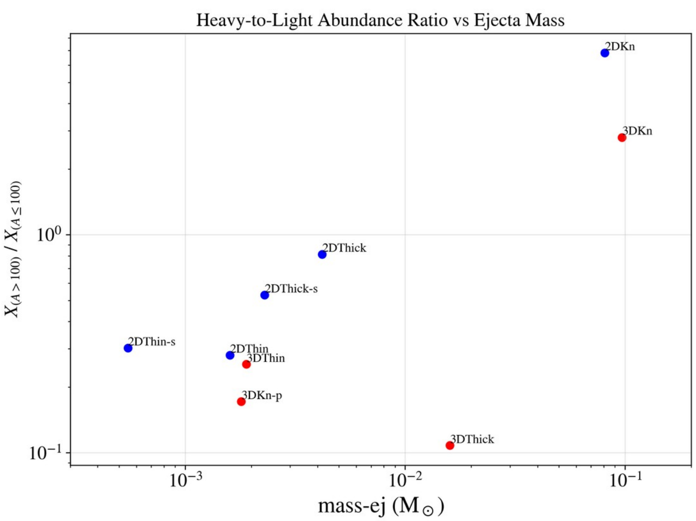
Nucleosynthesis in neutrino-driven MHD disk wind





Neutrino lightcurves for set of 2D and 3D simulations

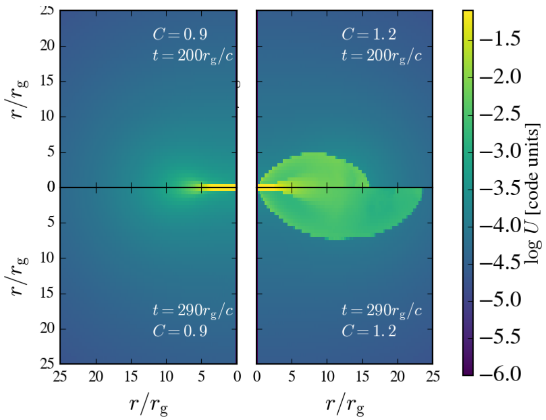




R-process patterns and heavy-to-light element ratios for set of 2D and 3D simulations

Janiuk, Saji, Urrutia (2025, in prep)

Collapsing stars

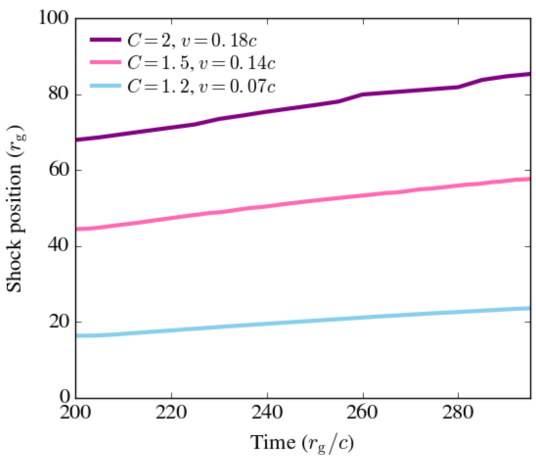


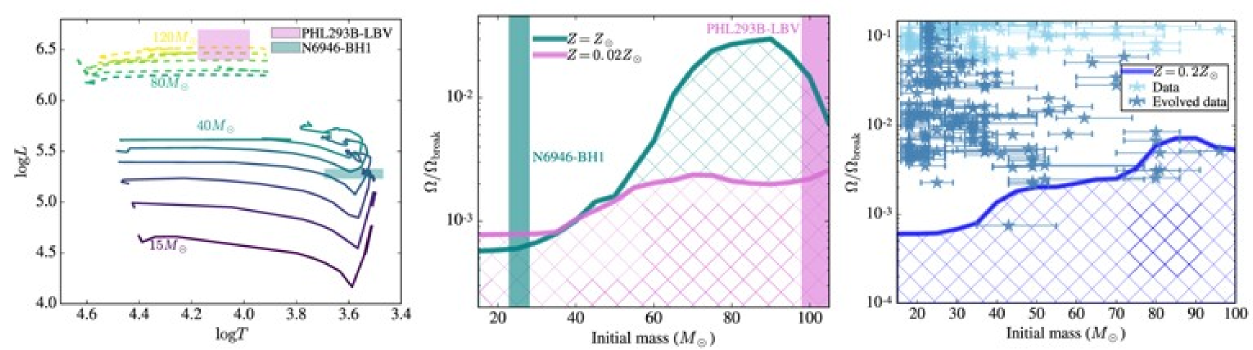
We studied maximum stellar rotation to form a black hole without an accompanying luminous transient

Collapse of cloud with low angular momentum

No magnetic fields, no jets

Centrifulally suported disk exists and energetic feedback possible, if stellar rotation is high enough





Murguia-Berthier, Batta, Janiuk et al. (2020, ApJL)

Copenhagen, summer school 2017

Simple collapse scenario, with gravity self-force

- Space-time Kerr metric is evolving due to changing mass and spin of newly born black hole in collapsar.

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

and

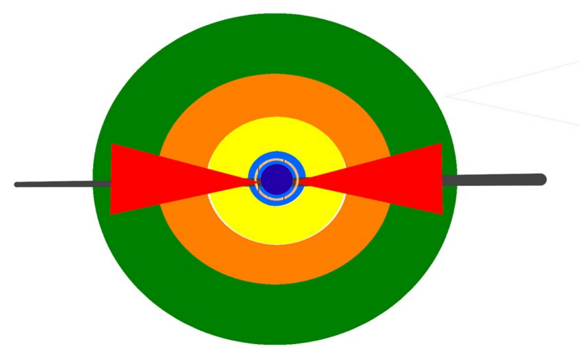
$$\dot{J} = \int d\theta d\phi \sqrt{-g}\, T^r{}_\phi,$$

- Perturbative terms due to self gravity of collapsing core.

$$\delta J(t,r) = 2\pi \int^{r'} T^r_\phi \sqrt{-g} d\theta.$$

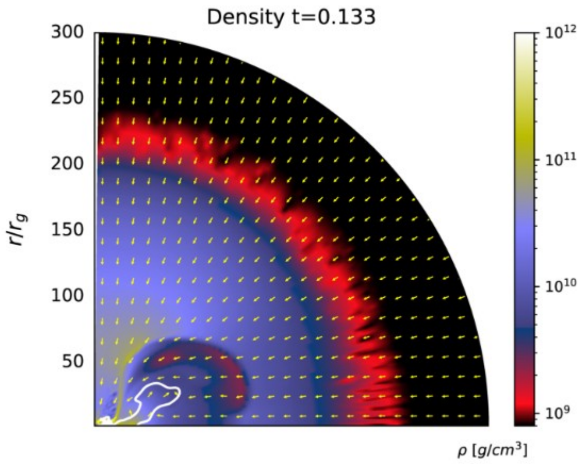
$$\delta M_{BH}(t,r) = 2\pi \int_{r_{hor}}^{r'} T^r_t \sqrt{-g} d\theta,$$

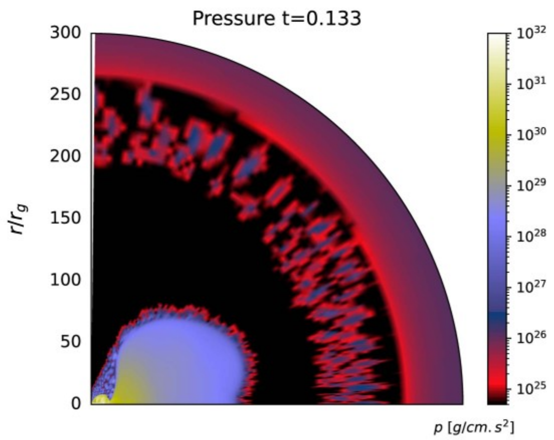
- Core rotation leads to formation of mini-disk at equatorial plane.



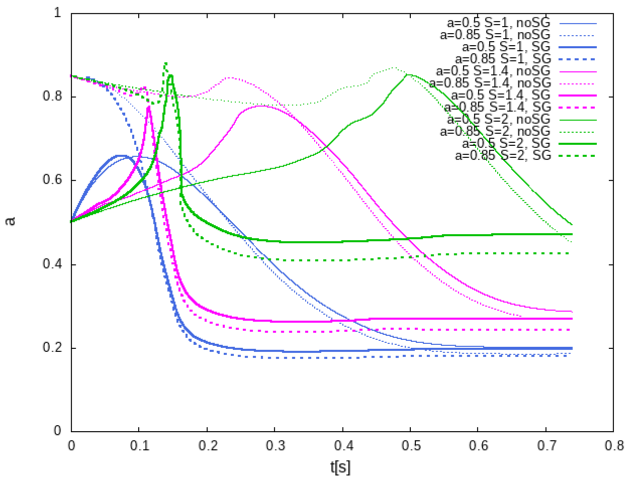
Janiuk et al. (2018, 2023); Król & Janiuk (2021)

Collapsing star simulation





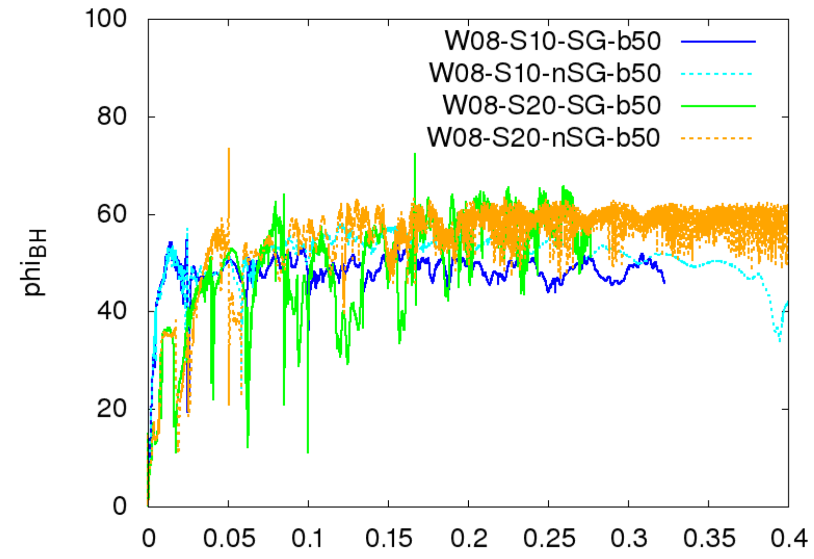
- Black hole changes its mass and spin → Kerr metric evolves
- Self-gravity additionally affects the black hole spin evolution
- Density and pressure inhomogeneities; expanding accretion shocks

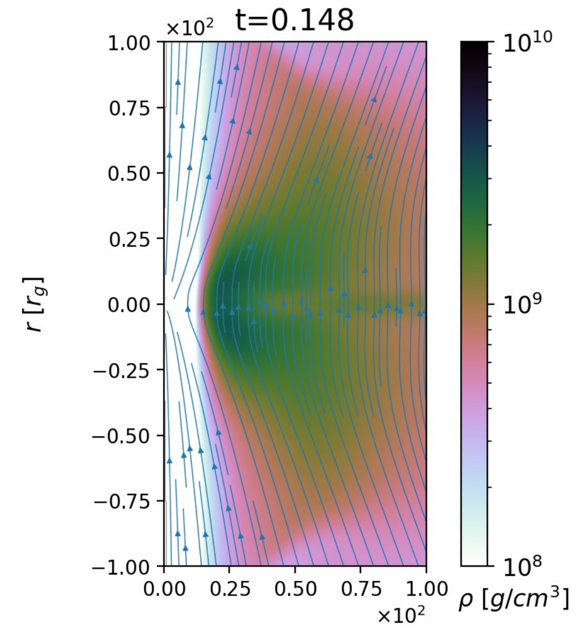


A. Janiuk,N.S. Dehsorkh & D. Król (2023, A&A)

Effects of magnetic field

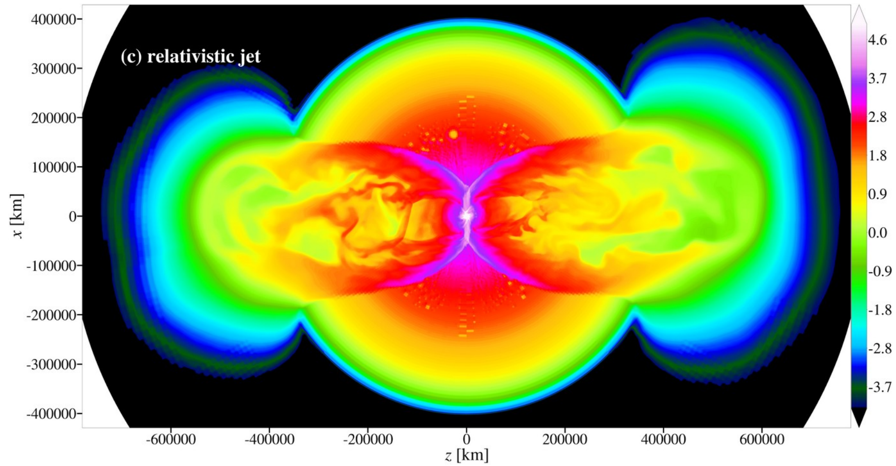
- We adopt weak poloidal magnetic field: uniform, or dipole
- For uniform field the rotating Kerr black hole magnetosphere has a repulsive effect (Wald 1974).
- A magnetically arrested state of accretion develops in the core and facilitates bi-polar jet-like outflows.
- In 2D simulation, the jets were not able to break out from envelope.
- BH spin drops below a=0.5 at the end of simulations (for a_0=0.8 and rotation with S=2.0).
- Density contrast of transonic shocks in SG models is weakened by B field
- In 3D simulation, for some models the jest breakout from self-gravitating collapsars was successful (see poster by P. Płonka)



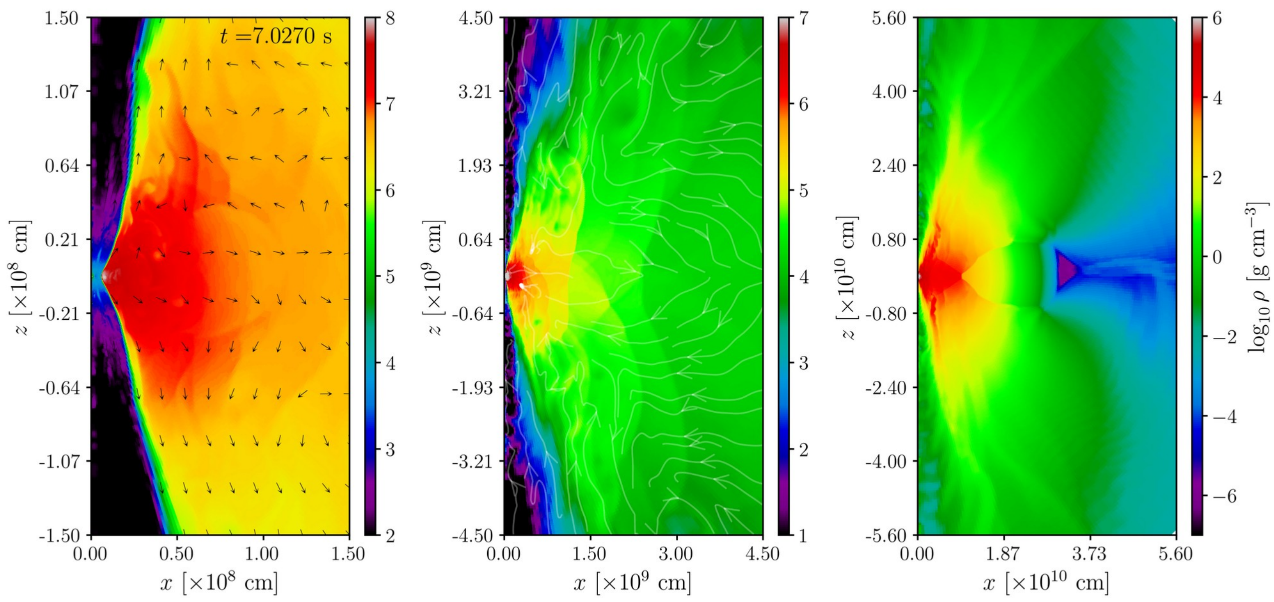


Janiuk, Sahahamat & Król 2023, A&A

Collapsar simulation challenges



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



Simulation with AMR on multiscale setup, stellar model implemented

(Urrutia, Janiuk & Olivares. 2025)

[See next talk by Gerardo Urrutia]

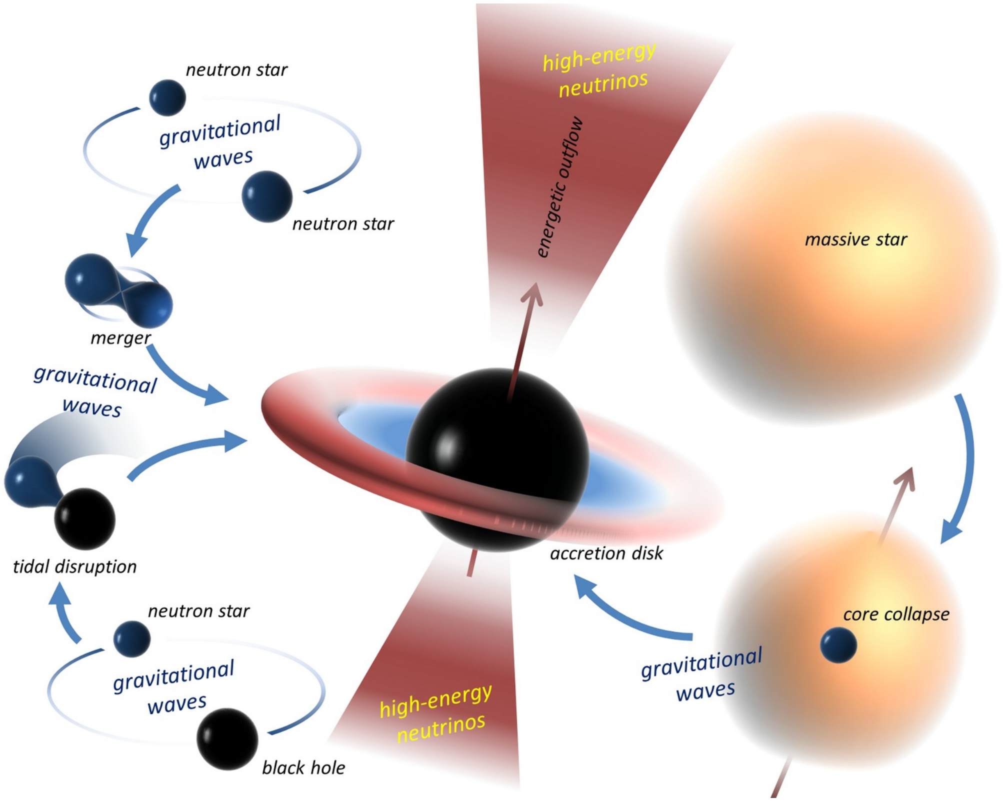
CFT Astro group: mergers and collapsars

See posters by:

Joseph Saji
(about heavy-element nucleosynthesis in BH-disk systems)

Piotr Płonka (about self-gravitating collapsars and jet launching)

Follow up projects planned
- GWs from accretion disks / jets;
- disappearing stars;
- collapsar-related KNe ?
- role of ejecta in jet collimation
(cf. Saji et al. Paper on opening angle in GRB 050910;
ArXiV: 2507.14948)



Potential new post-doc opening...

PL GRID

Relativistic Astrophysics group at CTP PAS

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

dxdx dxdxdx dxdxdxdx dxdxpandx dxdxdxdx dxdxdx dx dx dx dx cft

WYDZIAŁ FIZYKI
UNIWERSYTET WARSZAWSKI

NARODOWE CENTRUM NAUKI