Numerical models of GRB central engines and challenges with observations

Agnieszka Janiuk
Center for Theoretical Physics PAS, Warsaw

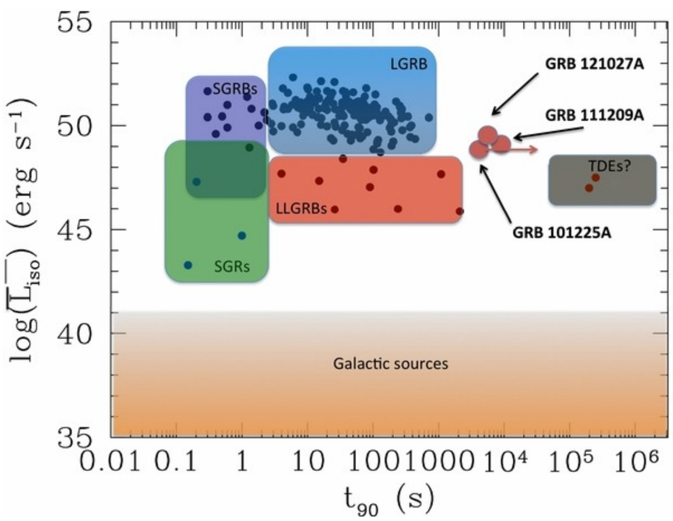
17th Marcel Grossmann meeting
Pescara, 11.07.2024

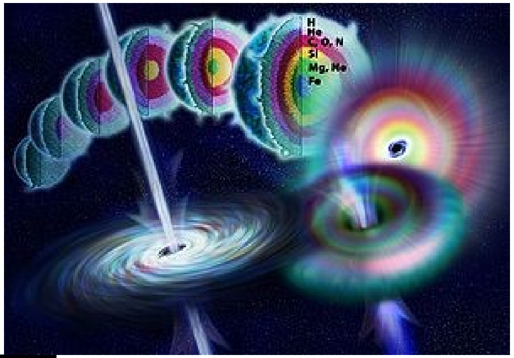
Outline

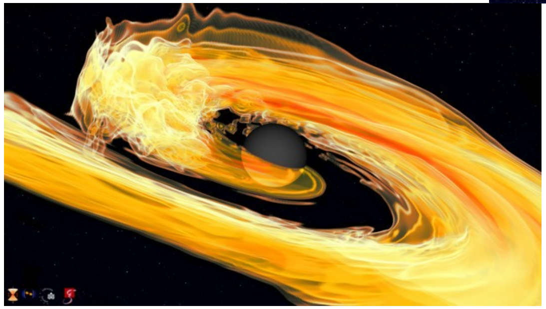
1. Introduction, long and short GRBs,

2. Observational challenges: powering, collimation, variability, breakout, kilonovae, supernovae, gravitational wave progenitors

3. Accretion and outflow simulations, GR MHD models, EOS, nucleosynthesis, neutrinos, ...

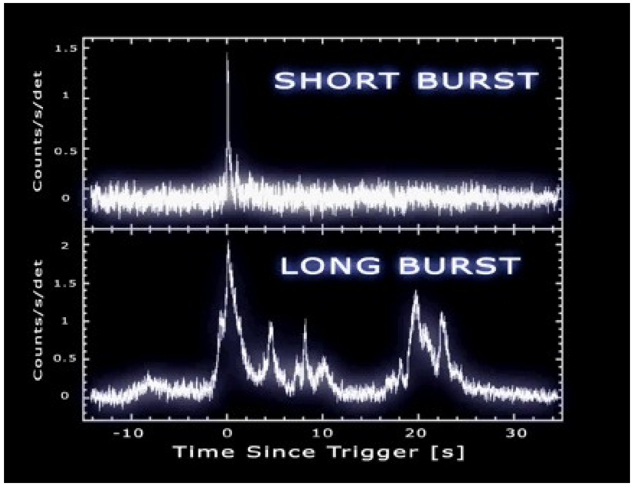




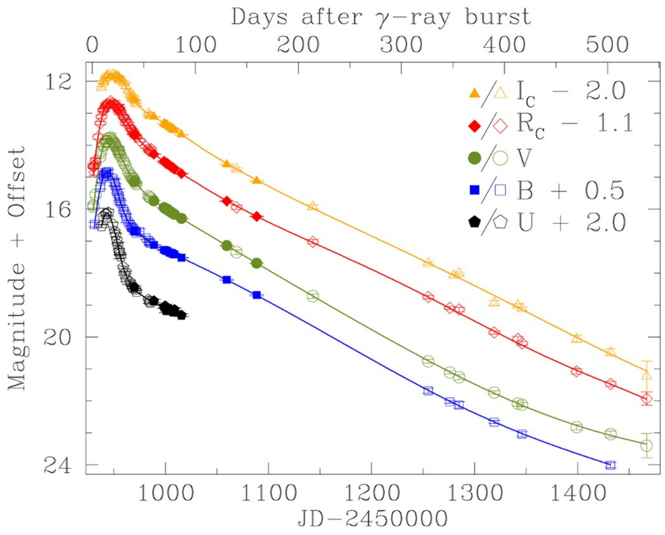


Gamma Ray bursts

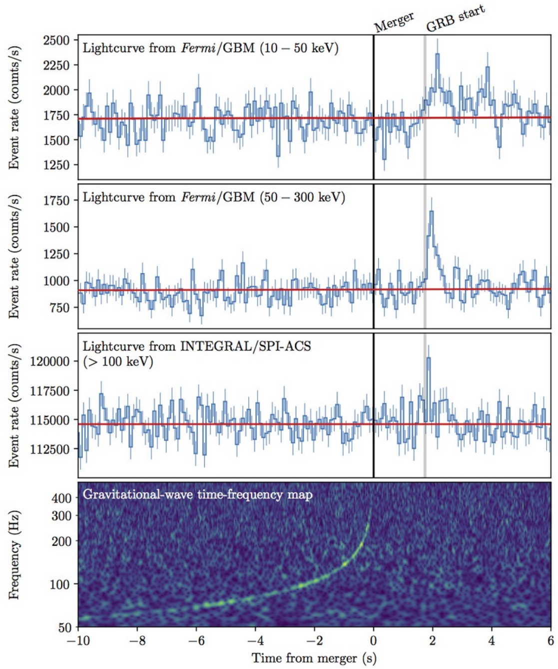
Rapid, bright flashes of radiation peaking in the gamma-ray band



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



Confirmed source of short GRB: GW170817 (Abbott et al. 2017)



Complete lightcurve from Clochiatti et al. (2011)

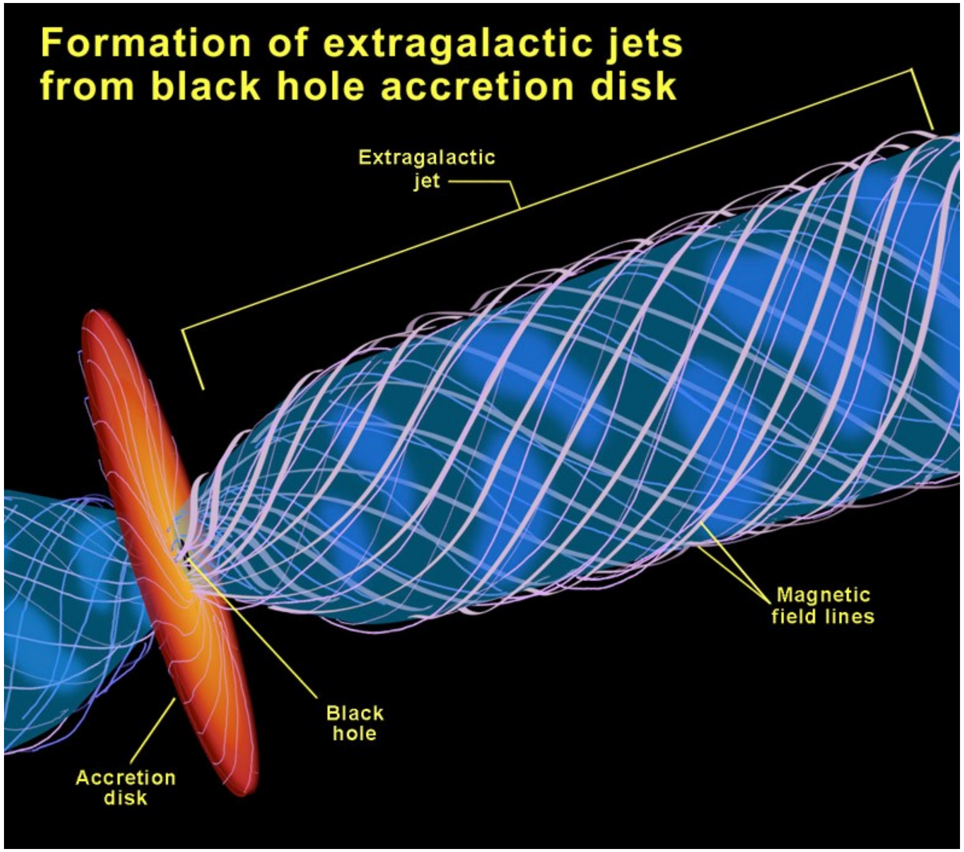
Relativistic jets paradigm

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

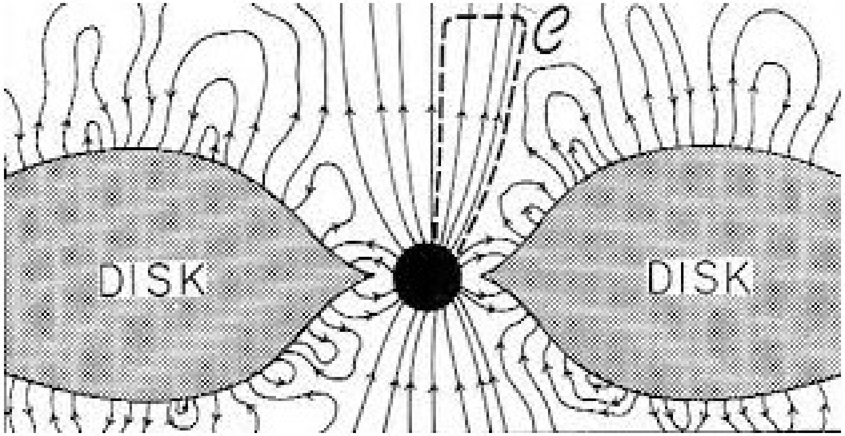
Powering of jets

Extracted power

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

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

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



By analogy to pulsar magnetosphere, the field lines accelerate charged particles (Godreich & Julian 1969; Blandford & Znajek 1977)

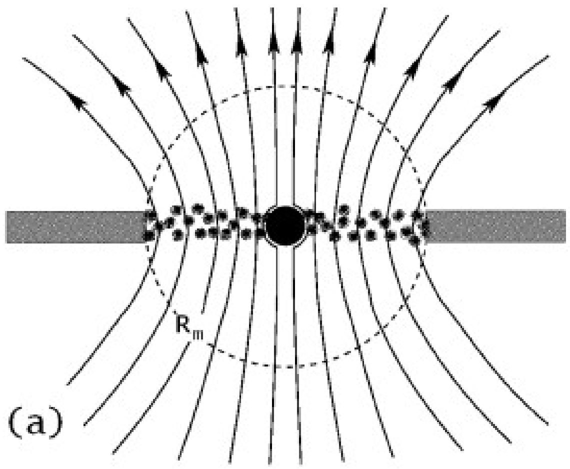
Black hole magnetosphere develops from seed magnetic field by differential rotation of the disk (Thorne 1986)

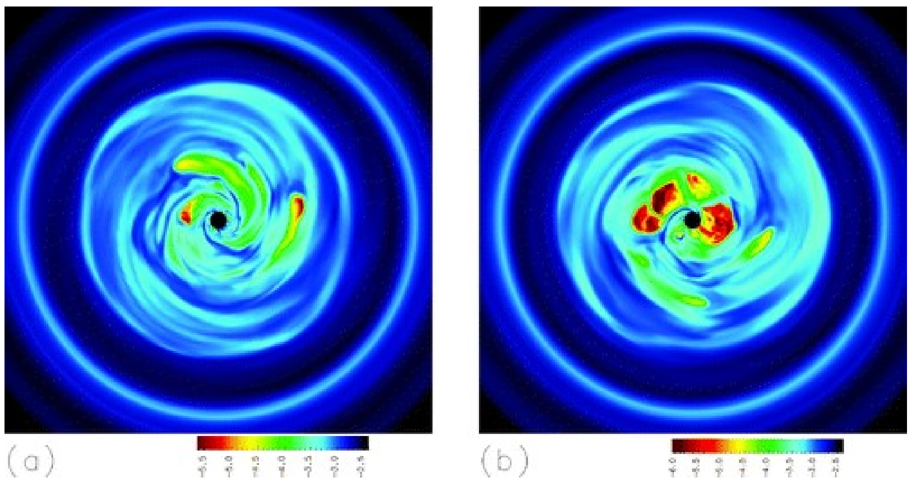
Magnetically arrested accretion

In the MAD mode, poloidal magnetic field is accumulating close to BH horizon, due to accretion (Bisnovatyi-Kogan & Ruzmaikin, 1974; 1976).

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 (Punsly 2001). The velocity of gas in this region is much smaller than free-fall.

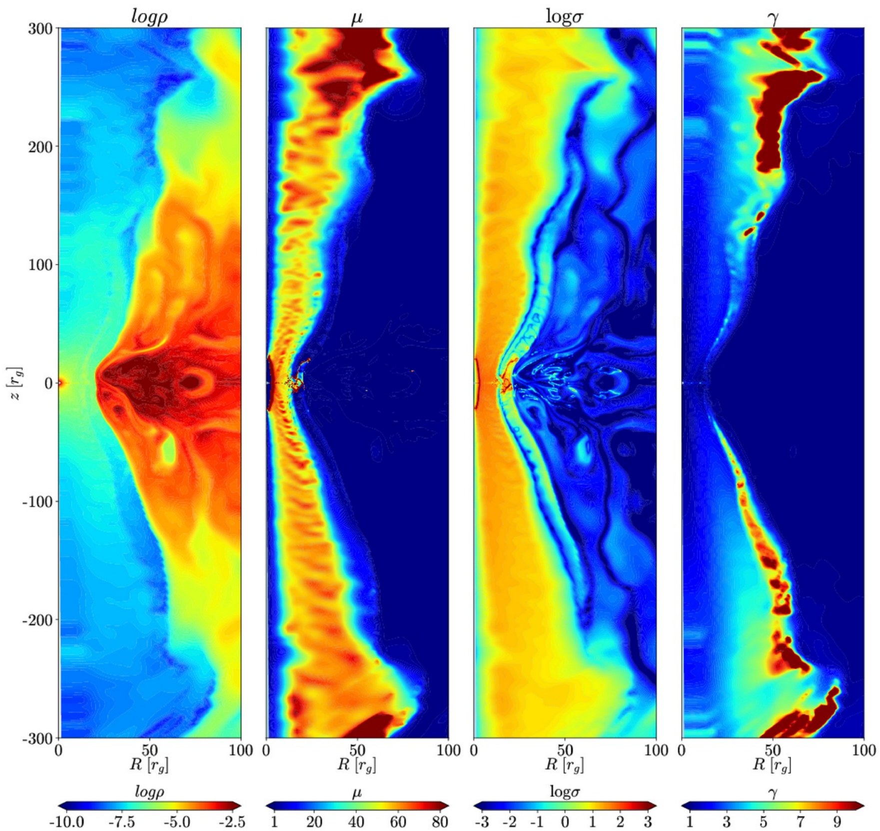
• Axisymmetric case: inside magnetospheric radius, Rm, gas accretes as magnetically confined blobs (Narayan, Igumenschev, Abramowicz, 2003).





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)

Jet launching and structure



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

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

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

- 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

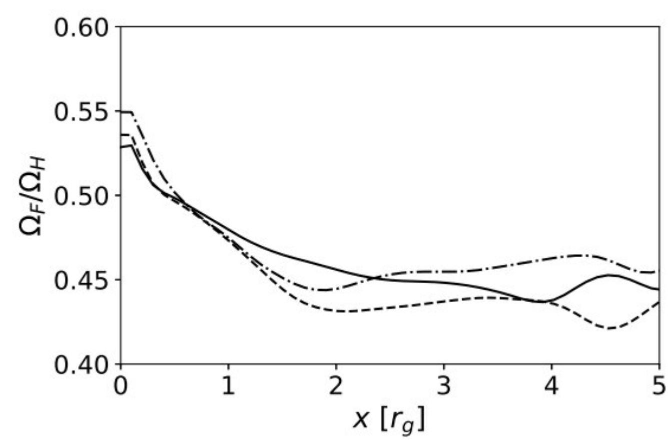
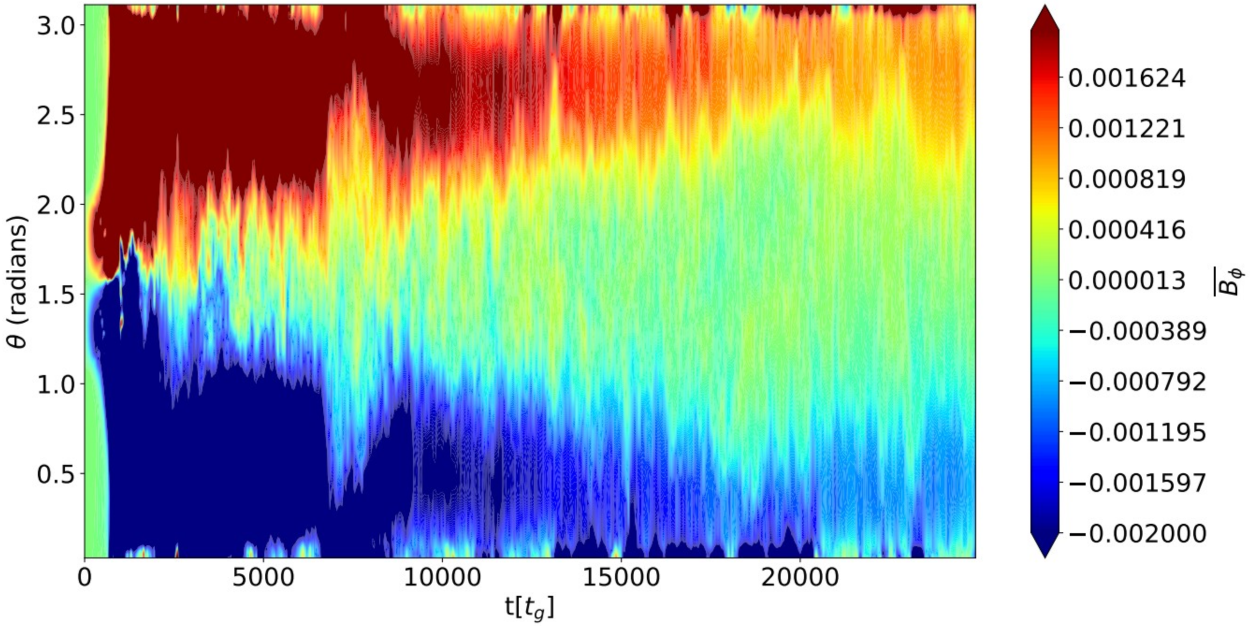
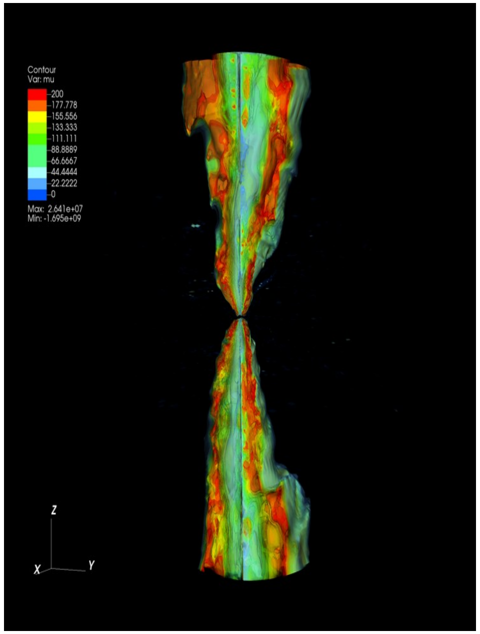


Fig from Sapountzis & Janiuk (2019, ApJ)

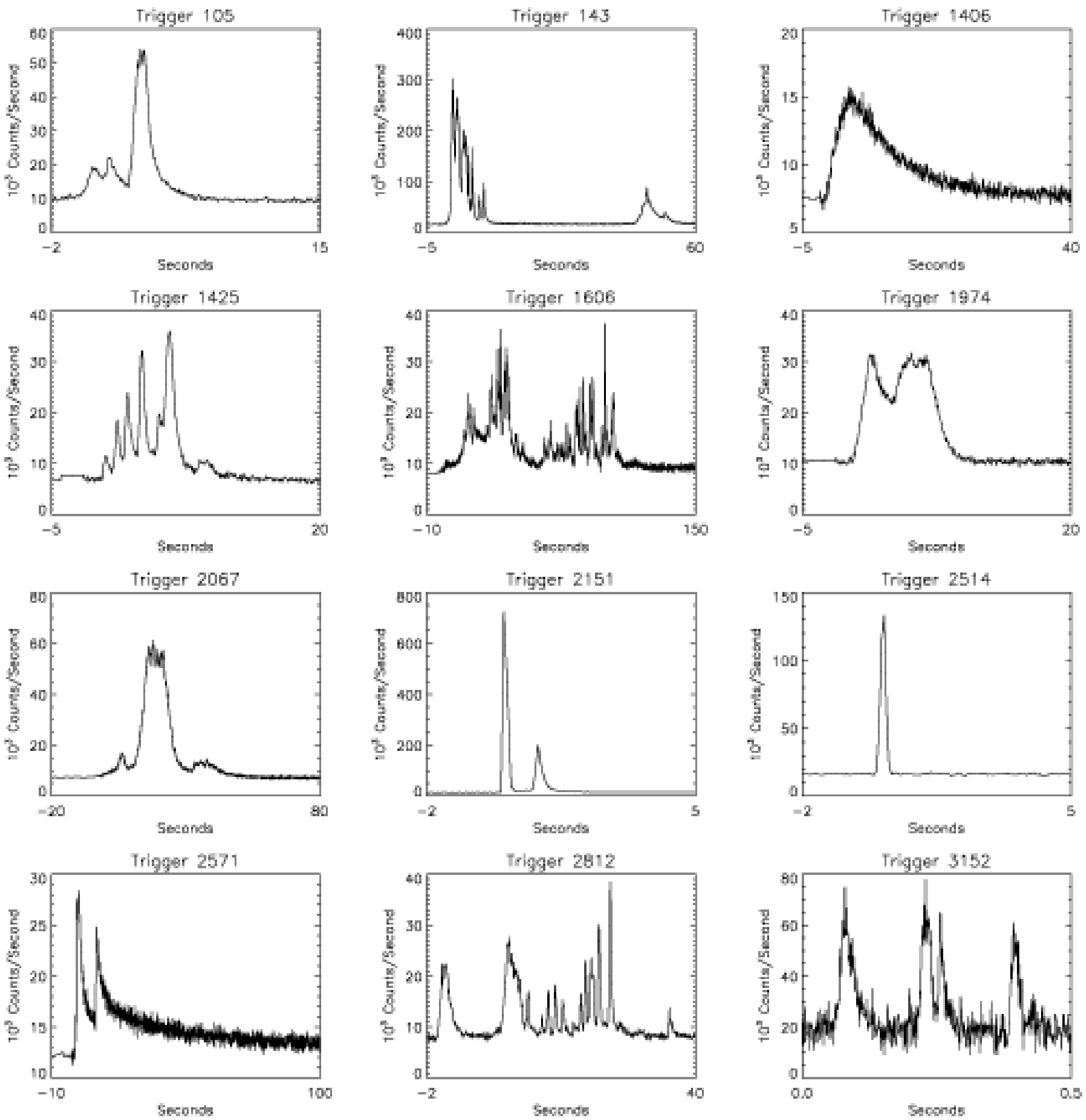
Toroidal magnetic field, and jet collimation, 3-D simulation





B. James, A. Janiuk, F. Hossein-Nouri (2022, ApJ, 935, 176)

GRB variability



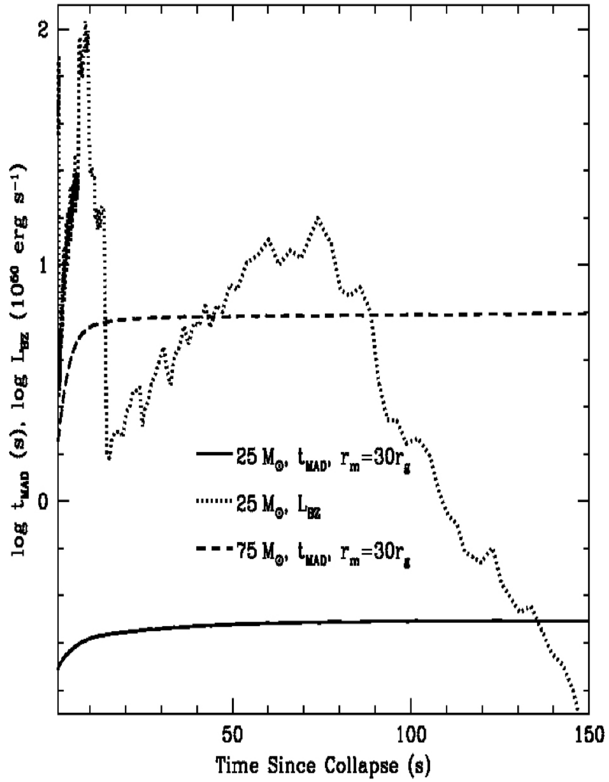
No two gamma-ray bursts are the same, as can be seen from this sample of a dozen light curves.

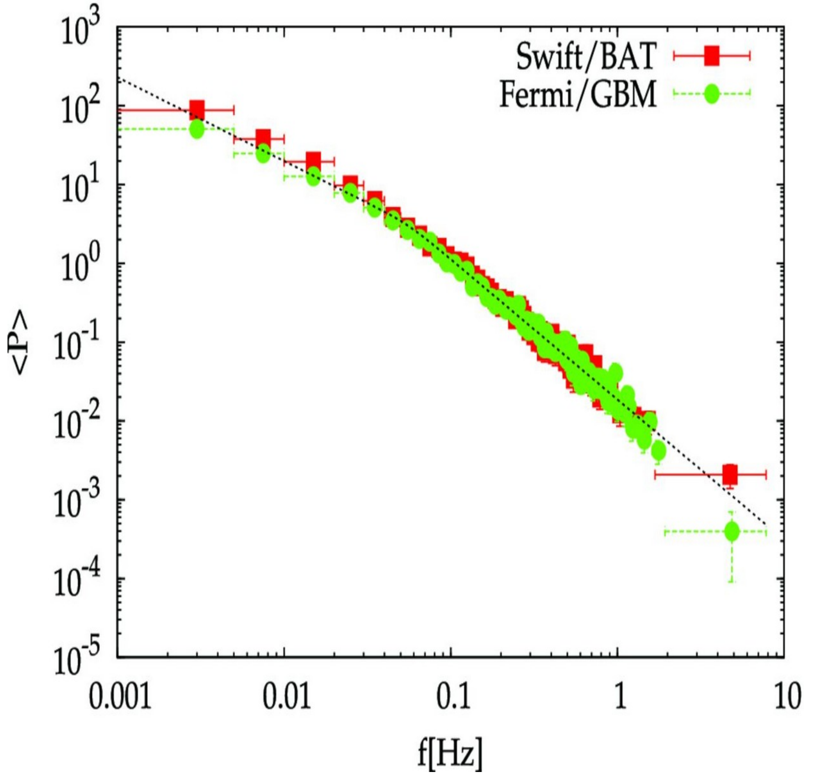
Some are short, some are long, some are weak, some are strong, some have more spikes, some have none, each unlike the other one.

Credit: NASA

Variable energy extraction from MAD disk

Models for the temporal variability of long gamma-ray bursts (GRBs) during the prompt phase (the highly variable first 100 s or so), were proposed in the context of a MAD around a black hole (Lloyd-Ronning, Dolence, Fryer, 2016).





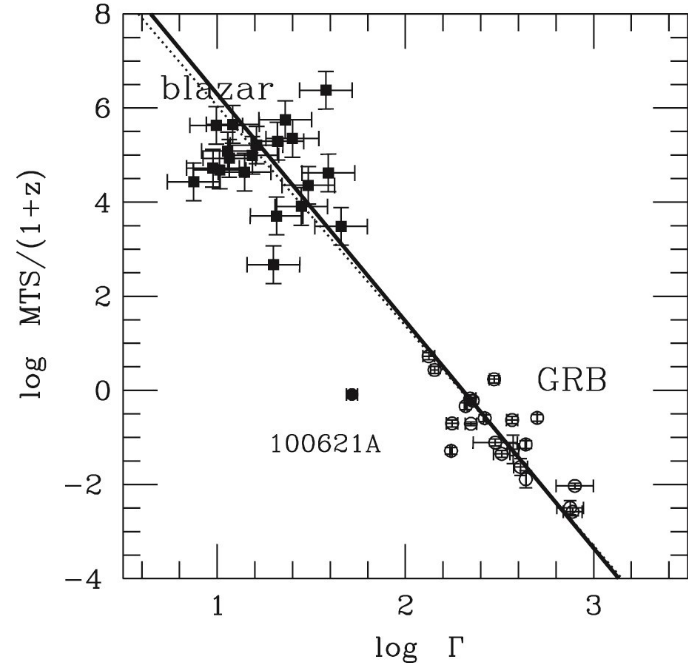
PDS spectra show power-law slopes between 1.49-1.65 (Dichiara et al. 2013)

Variability timescale

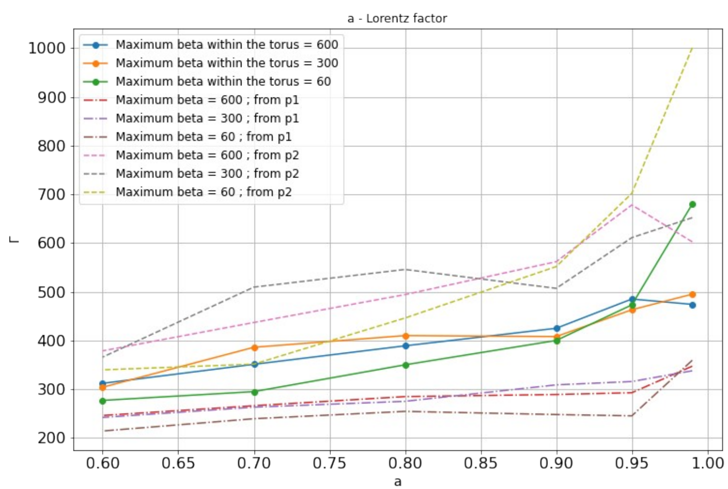
● In our simulations, jet Lorentz factor is calculated as the average of μ in time, $\Gamma = \langle \mu \rangle_t$.

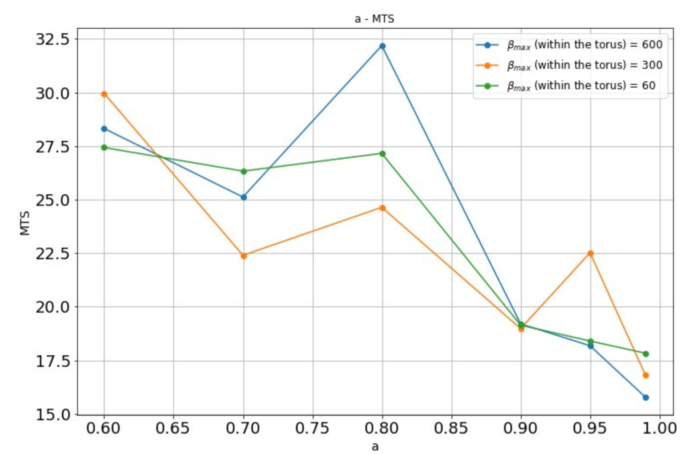
● The Minimum variability Time Scale (MTS) ~ peak widths at their half maximum on the μ – t plot

● Correlations Γ-a and a-MTS are confirmed. Results scale with black hole mass: $MTS_s = MTS_{MBH} \times GM_{BH}/c^3$



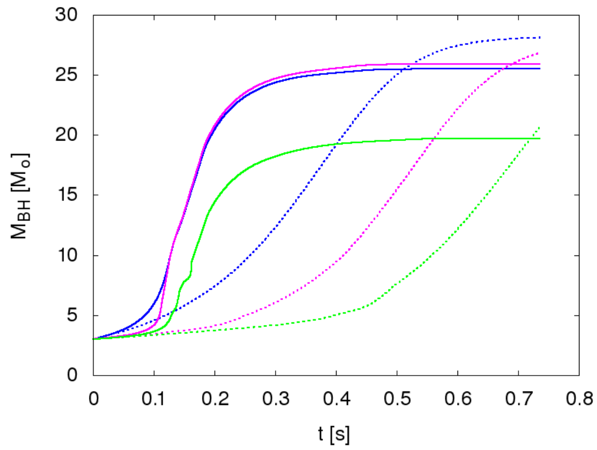
Joint correlation of MTS ∝ $\Gamma^{-4.7} \pm 0.3$ for blazar and GRB samples (Wu et al. 2016)

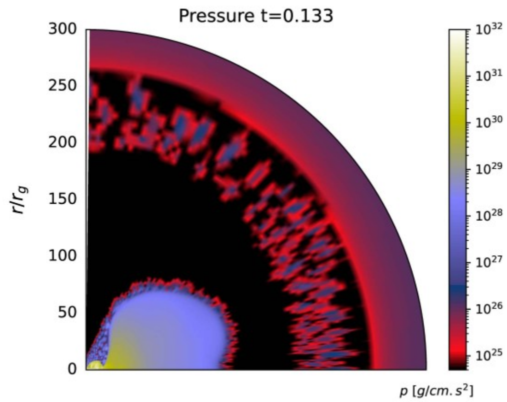


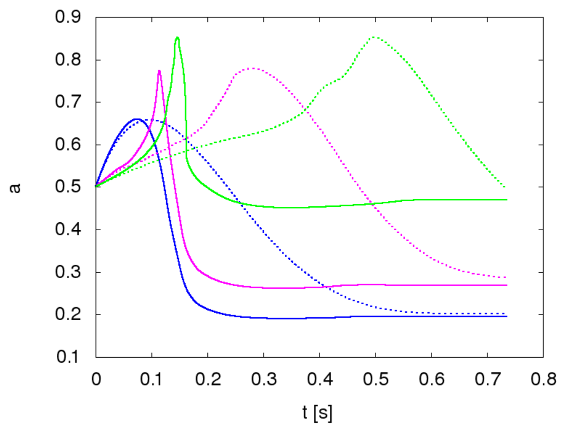


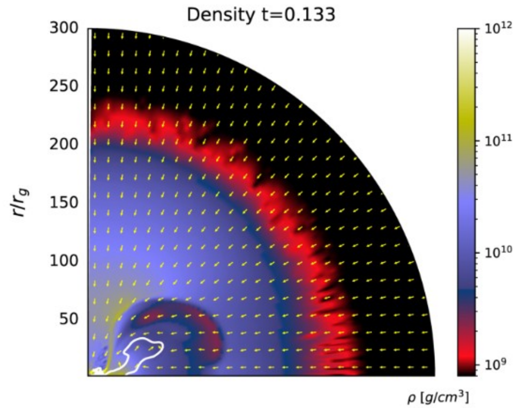
Janiuk, James & Palit, 2021, ApJ, 917, 102

Novel simulations in evolving Kerr metric









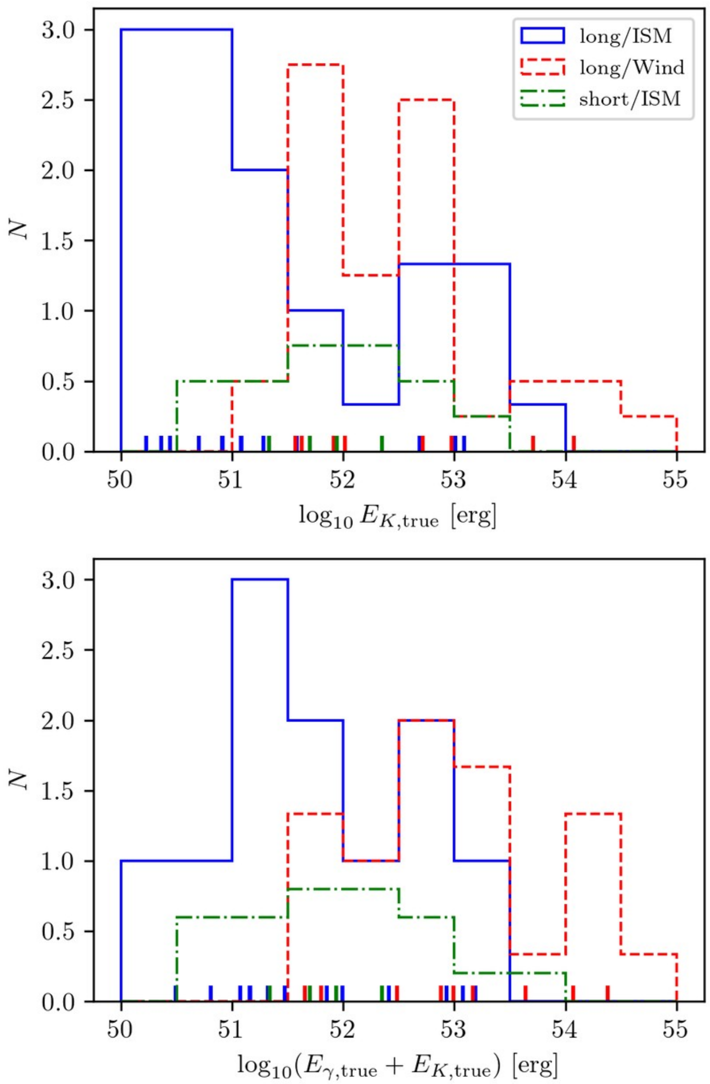
Both black hole **mass and spin evolve** due to accretion of dense mass with various angular momentum content during collapse.

This makes change to the Kerr metric parameters.

The self-gravity of collapsing core is an additional perturbation.
Inhomogeneities found in the **self-gravitating** star may lead to **variability**.
All these effects will manifest in the prompt emission of the GRB

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

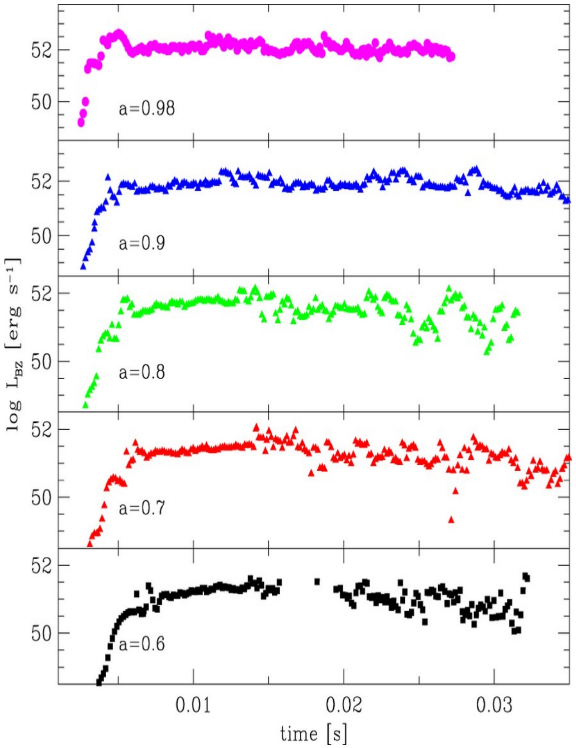
GRB energetics



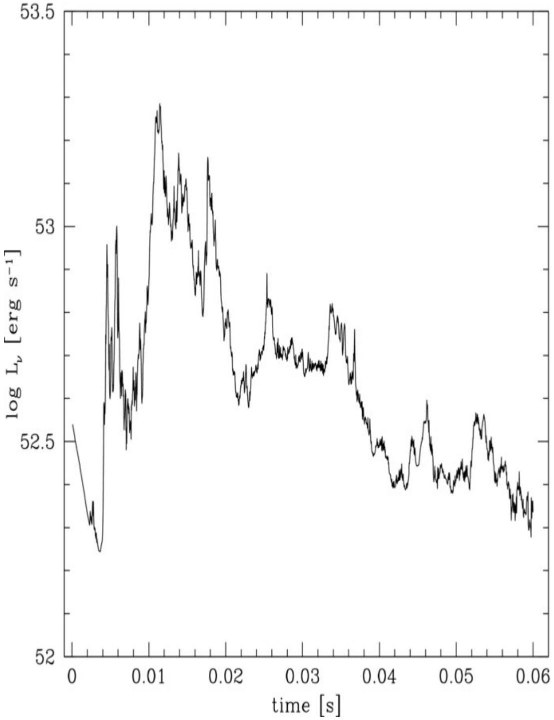
Histogram of the inferred energetics for the GRB sample (Aksulu et al. 2021).

The upper and lower panels show the histograms for the beaming corrected, *EK*-–true and *E*-true, energy distributions, respectively.

Source of power to the jets: BZ process, neutrinos?



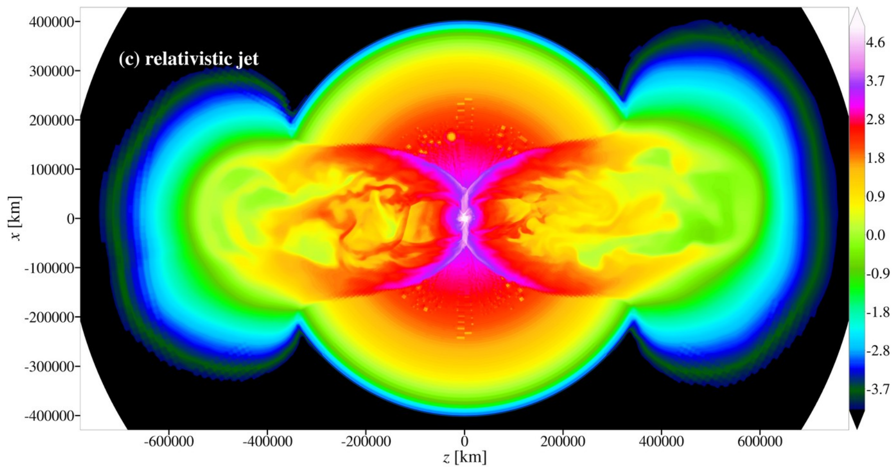
GRB jet luminosity from
Blandford-Znajek
Process (MAD-driven)

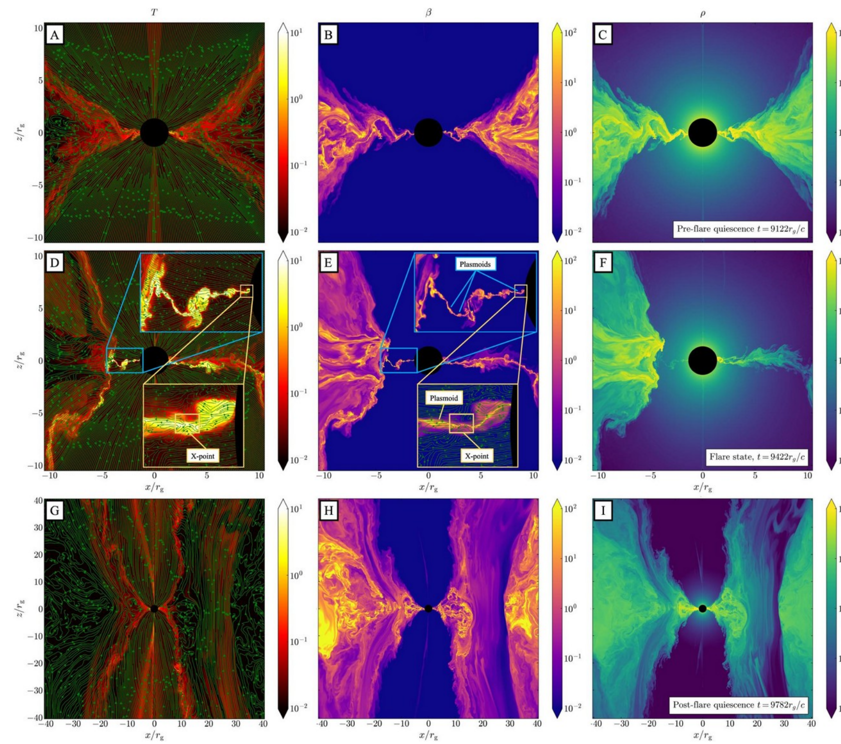


Neutrino luminosity can be at least order of magnitude larger.
A. Janiuk (2019);

Most energetic GRBs hard to be explained with MAD models!

Long GRBs engines: state-of-the-art simulations



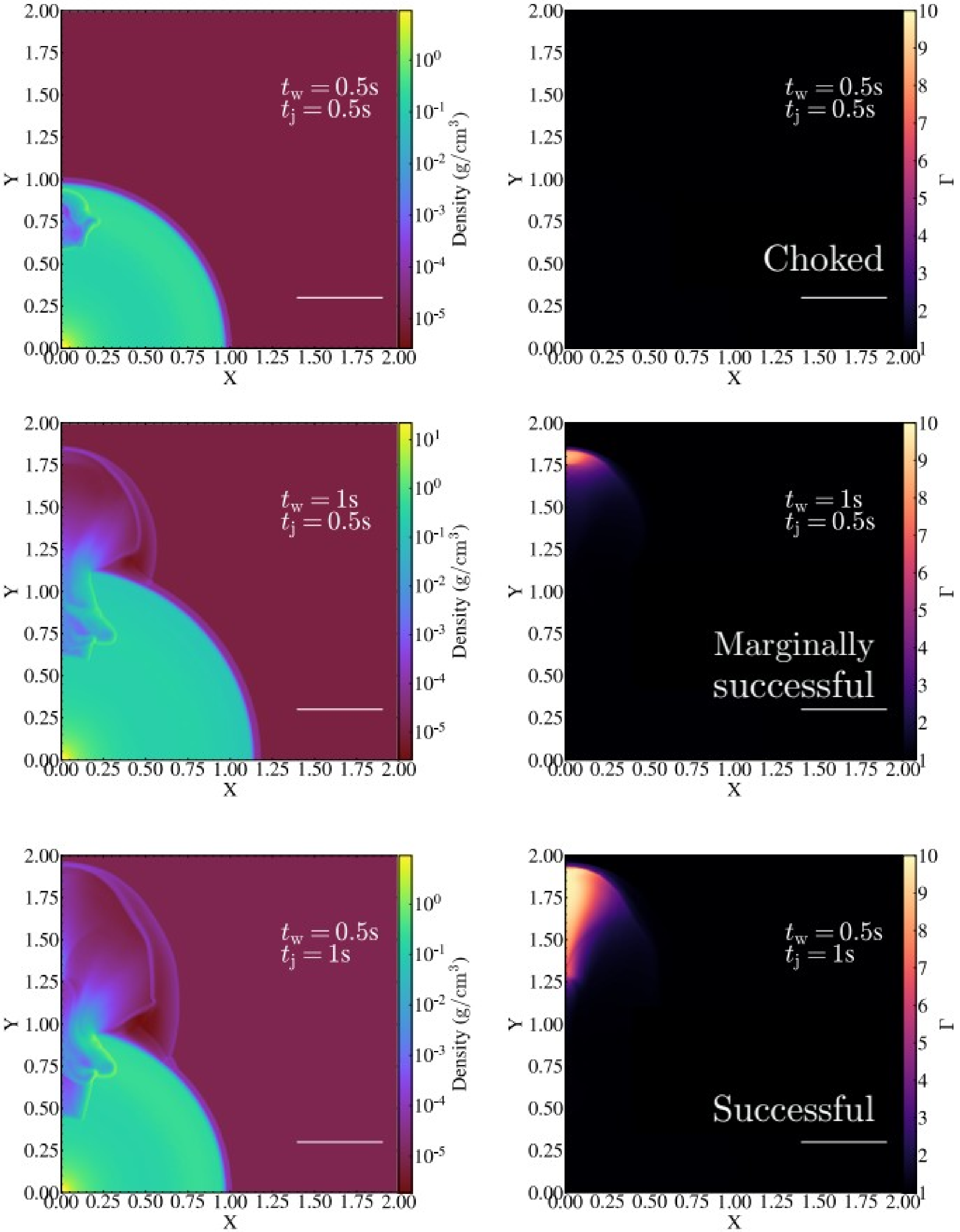


Jet breakout process difficult to model due to multi-scale problem and computational complexity (Gottlieb et al. 2022).

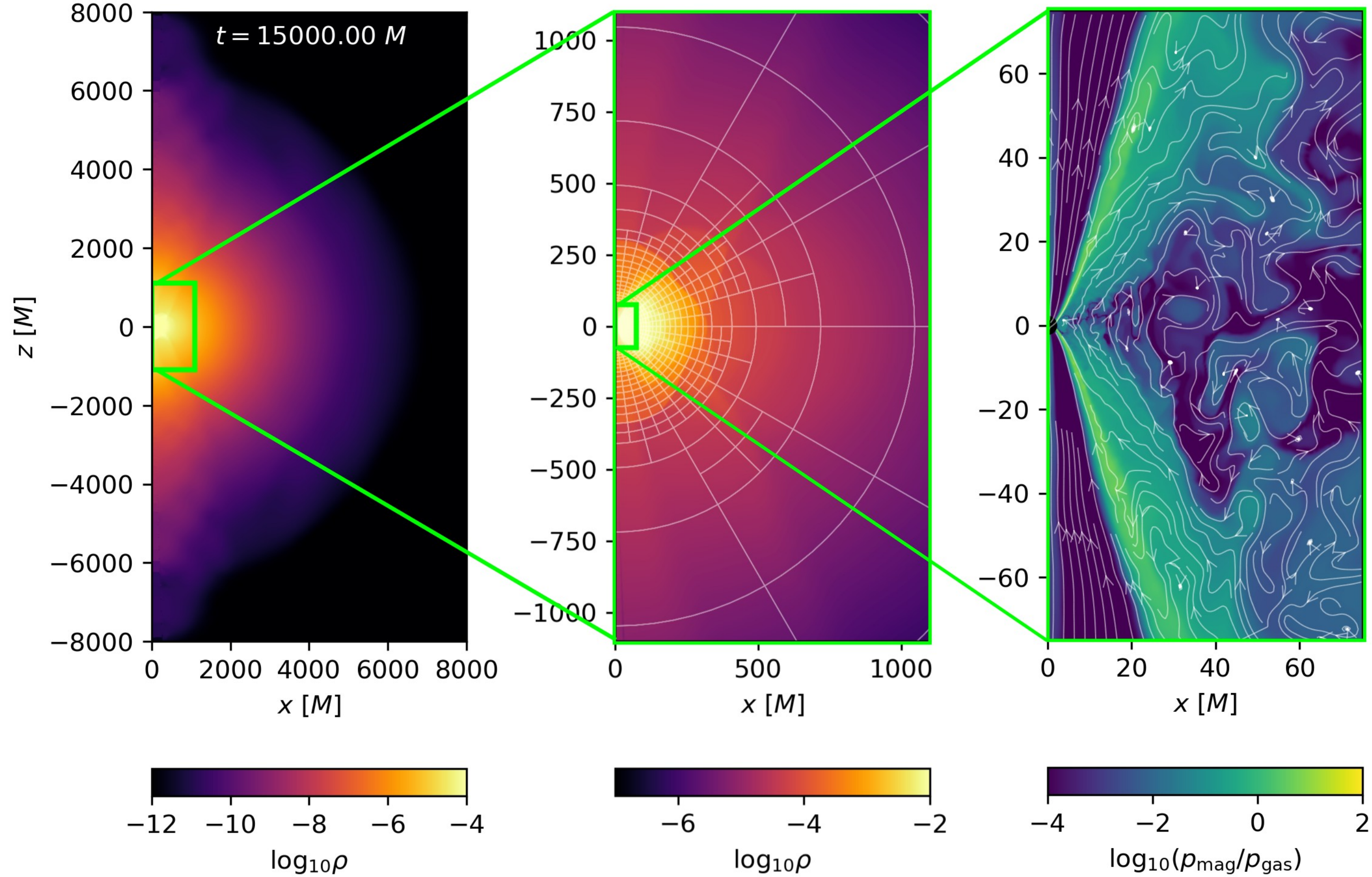
Very high resolution 3D simulations show also importance of plasmoid reconnection
(Ripperda et al. 2022)

The breakout time is comparable to the central engine duration and possibly a non-negligible fraction of the total delay between the gravitational and gamma-ray signals

Murguia-Berthier, Ramirez-Ruiz, De Colle, Janiuk, et al., 2021, ApJL

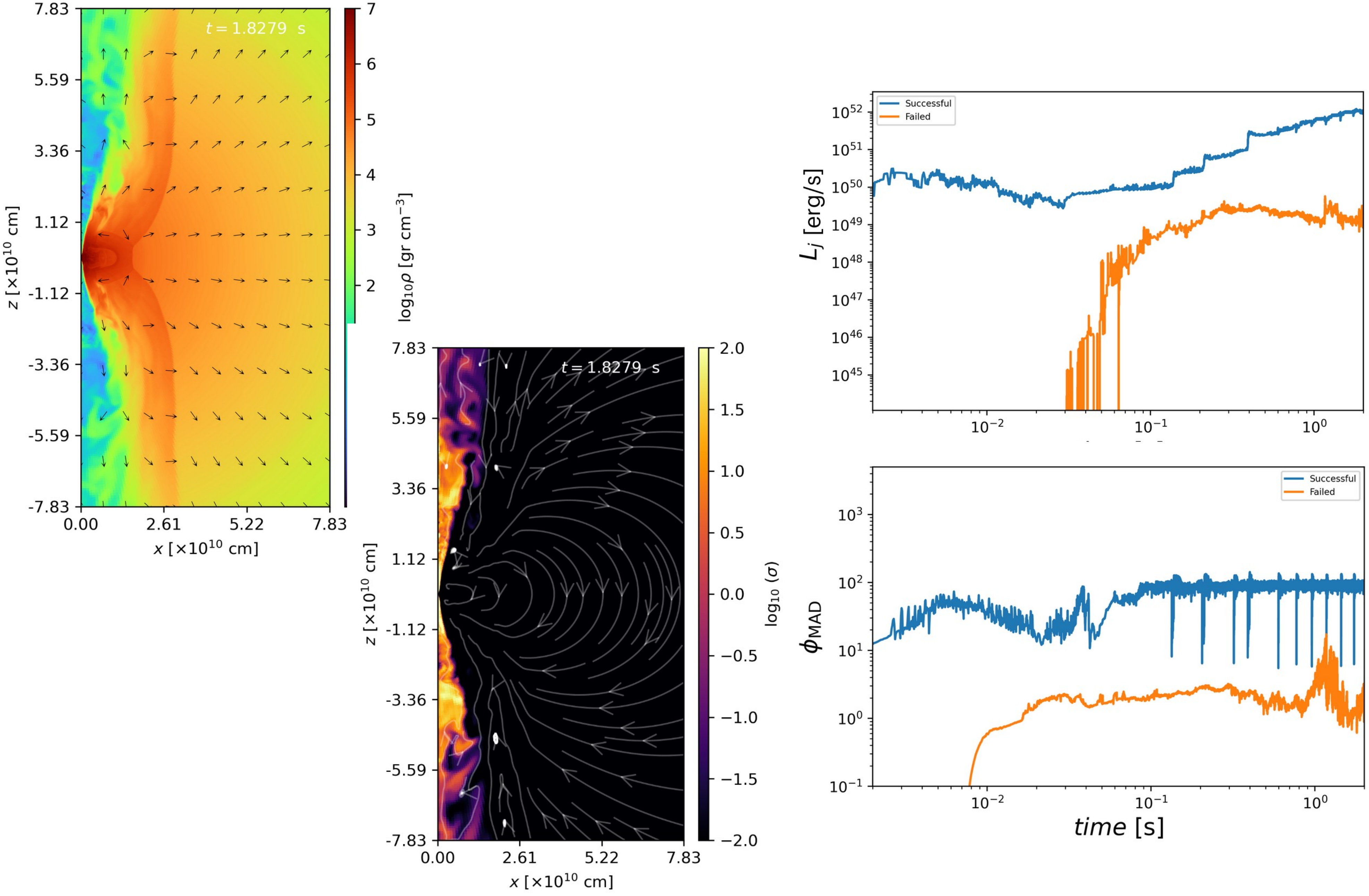


Our new simulations of magnetized collapsar (AMR framework, stationary Kerr metric)



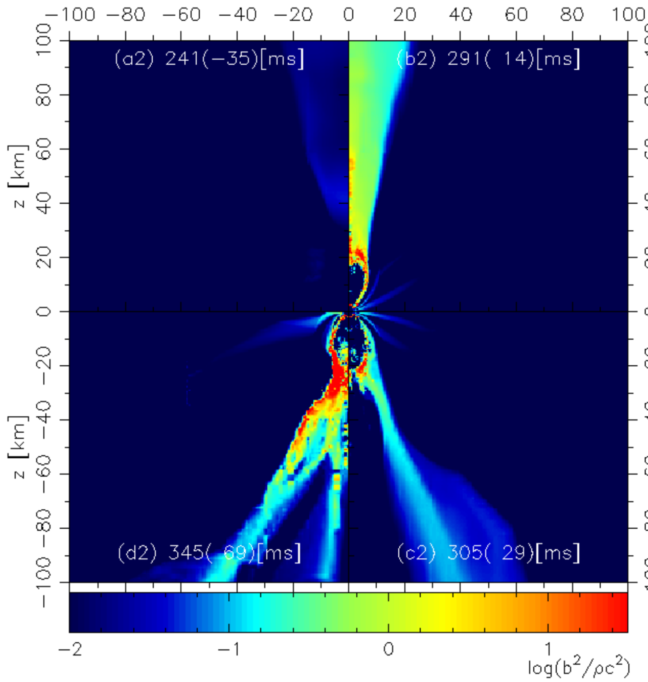
The black hole accretion code BHAC (Porth, Olivares et al. 2017; Olivares, Porth, et al. 2019) now

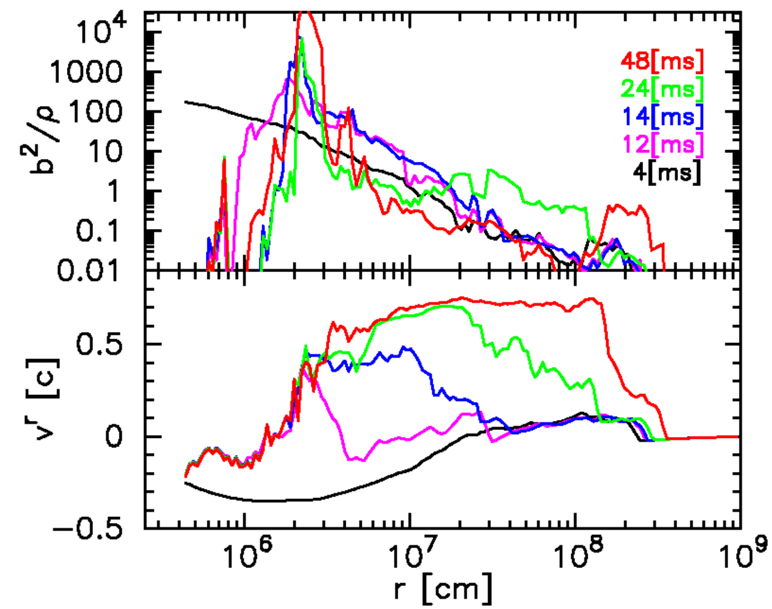
with **realistic initial condition of pre-SN star, and pre-collapse magnetic field** (Urrutia, Olivares, Janiuk, 2024, in prep.)



Formation of collapsar jet and breakout, depends on the adopted magnetic field structure (in the star and in the core). Urrutia, et al., in prep.

Jet launching by BZ process from BH spinned-up during supernova event



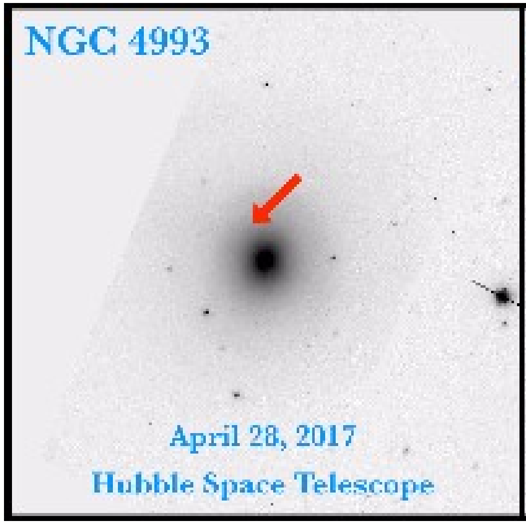


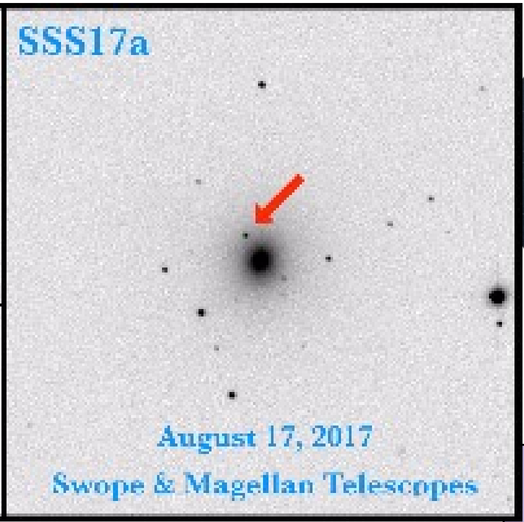
(T. Kuroda & M. Shibata, arXiV: 2404.02792)

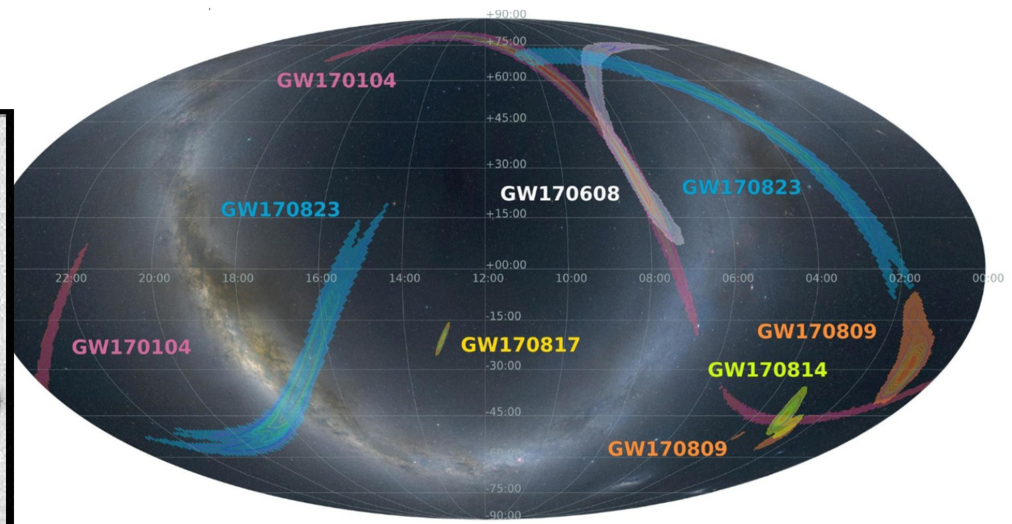
Formation of black hole after proto-neutron star collapse occurs in an exploding supernova. Poloidal magnetic fields induce formation of jets from rotating core (effective spin ~0.5).

The jets decelerate however before they are able to break out from the star.

GW 170817



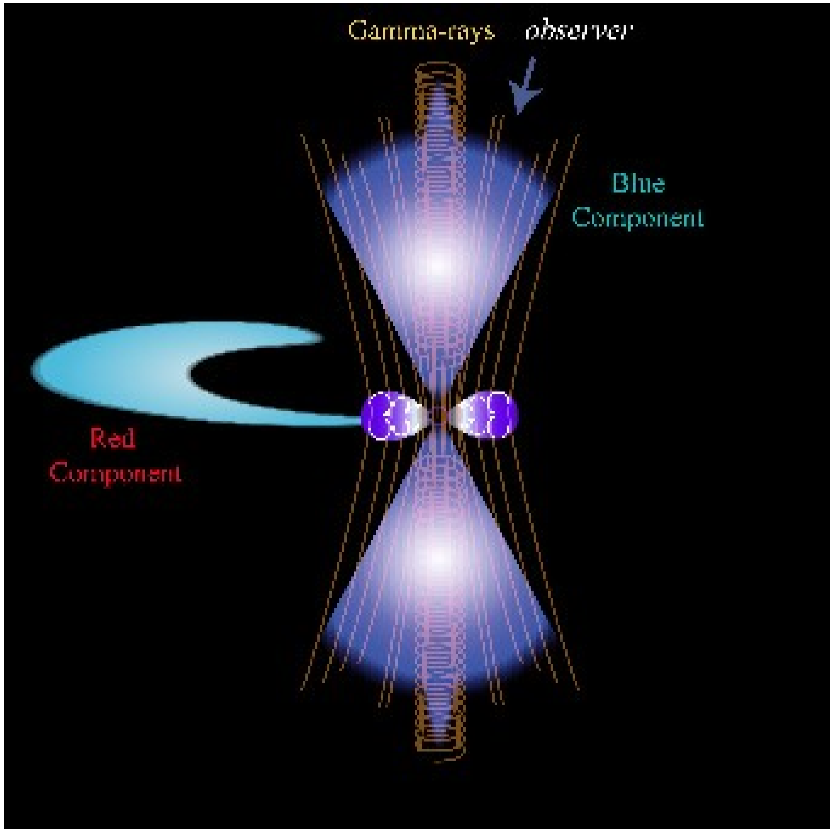




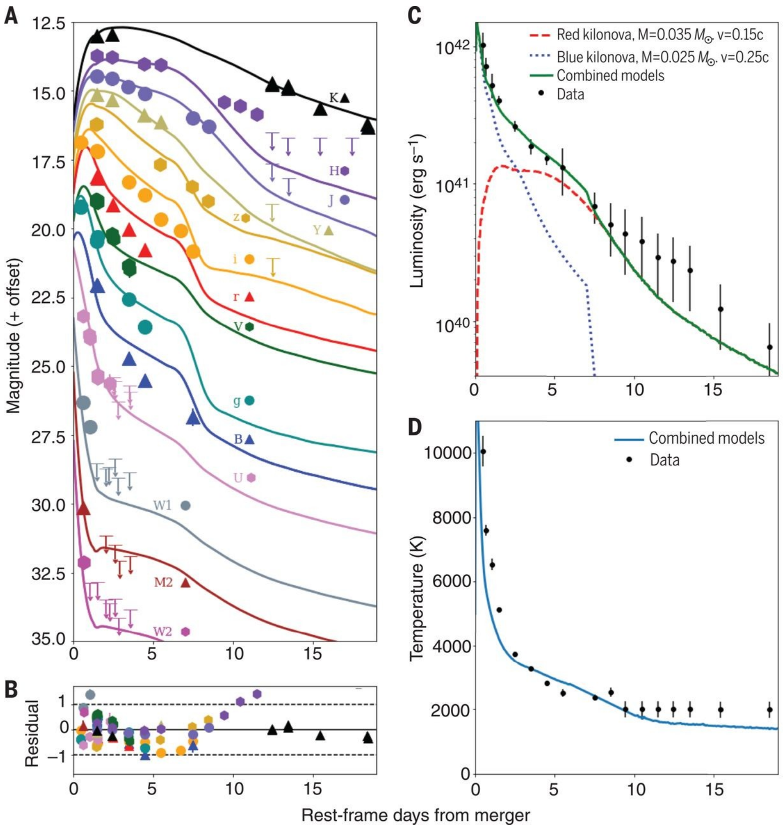
Double neutron stars formed a black hole after their merger.
During the inspiral phase, **gravitational waves** were produced
After the merger, gamma-ray telescopes observed a **burst** of energy.
The time delay of 1.7 s may be associated with formation of HMNS

Rapidly fading electromagnetic transient in the galaxy NGC4993, was spatially coincident with GW170817 and a weak short gamma-ray burst (e.g., Smartt et al. 2017; Zhang et al. 2017, Coulter et al. 2017)

Blue and red kilonova 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 observational data for the transient SSS17a, associated with GW170817

(Kilpatrick et al. 2017).

Short GRB models: Kilonova

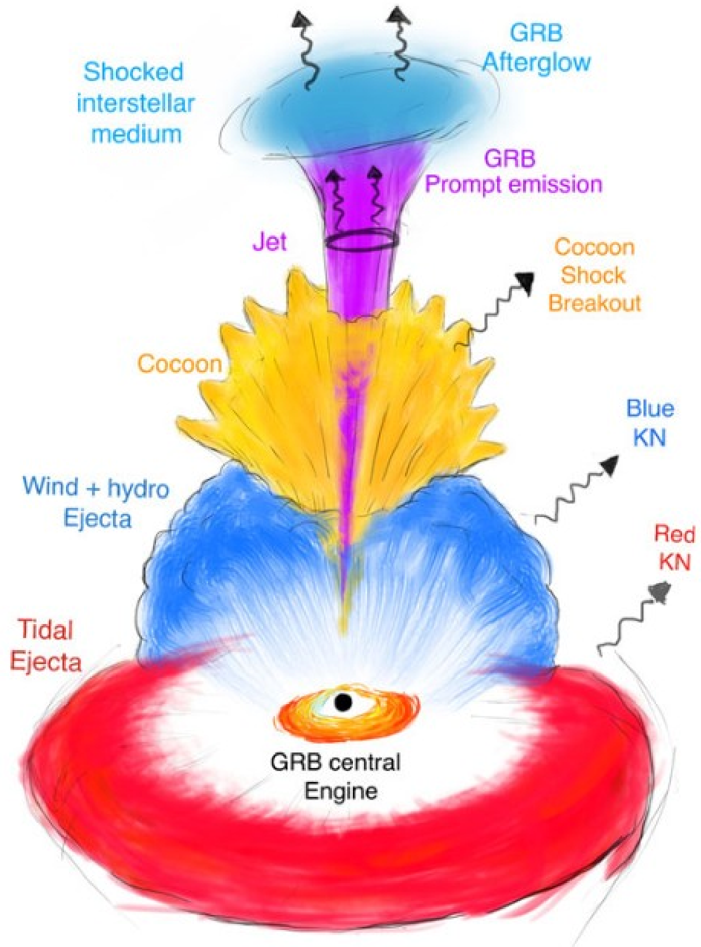
NS-NS eject material rich in heavy radioactive isotopes.

Can power an electromagnetic signal called a kilonova

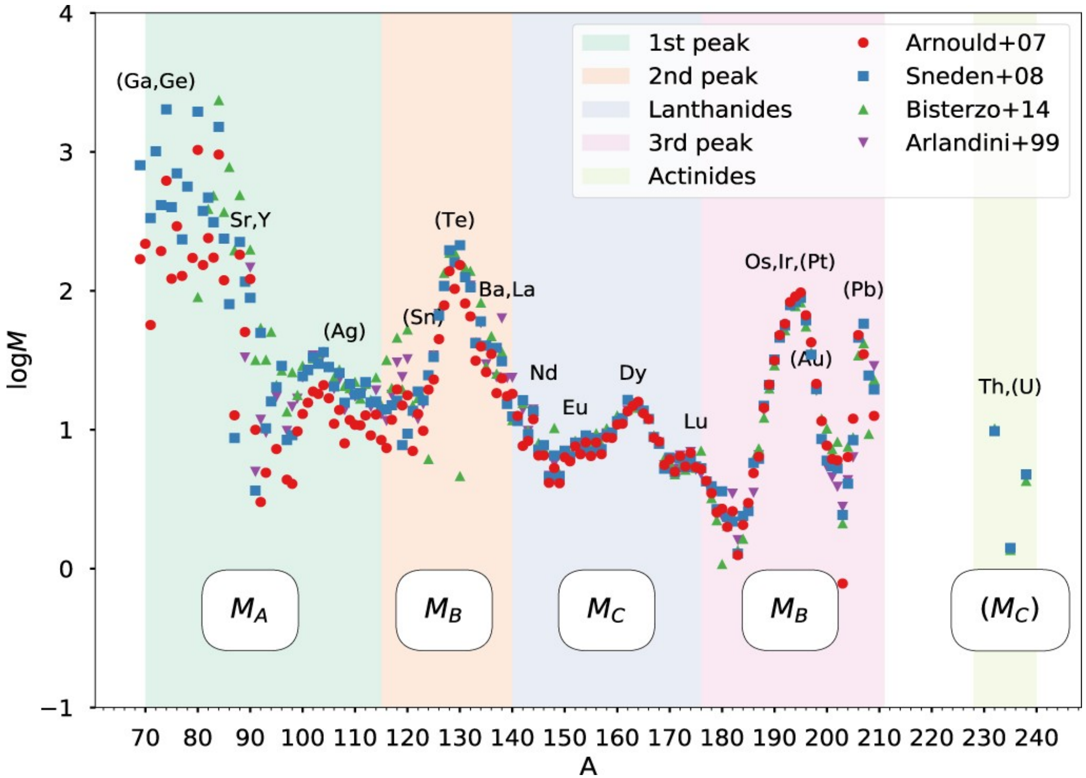
(e.g. Li & Paczynski 1998; Tanvir et al. 2013, Berger 2016)

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

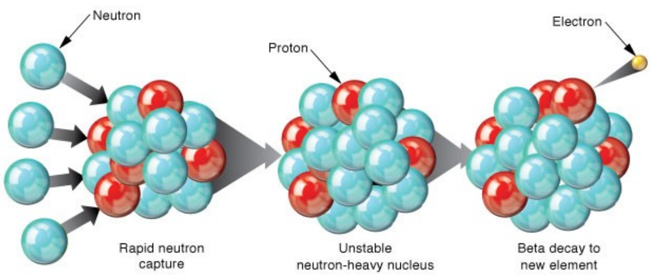
Subsequent accretion can provide bluer emission, if it is not absorbed by precedent ejecta (Tanaka, 2016, Berger 2016, Siegel & Metzger 2017)



r-process nucleosynthesis



Ji et al. 2019



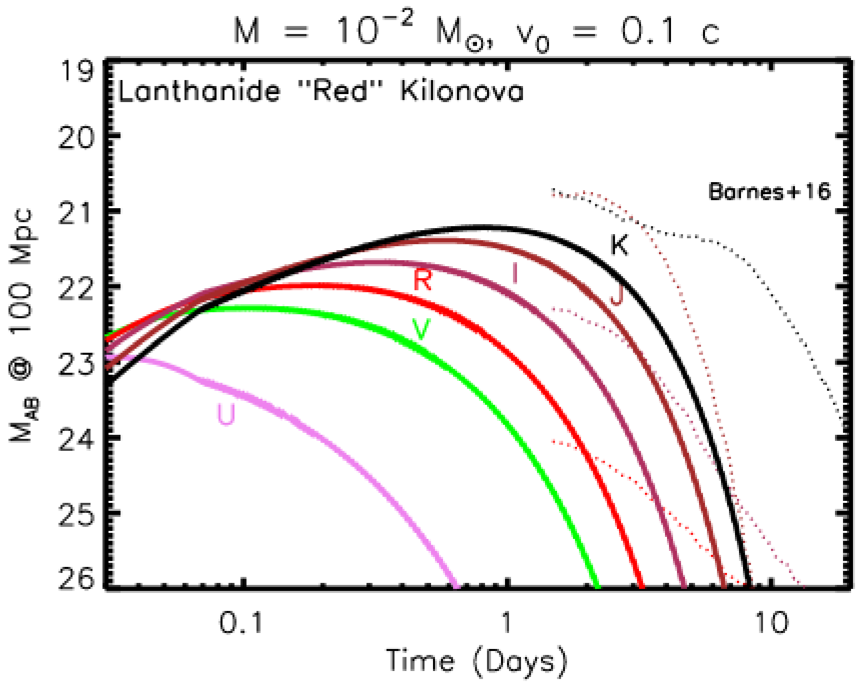
$Y_e > 0.25$: 1st peak

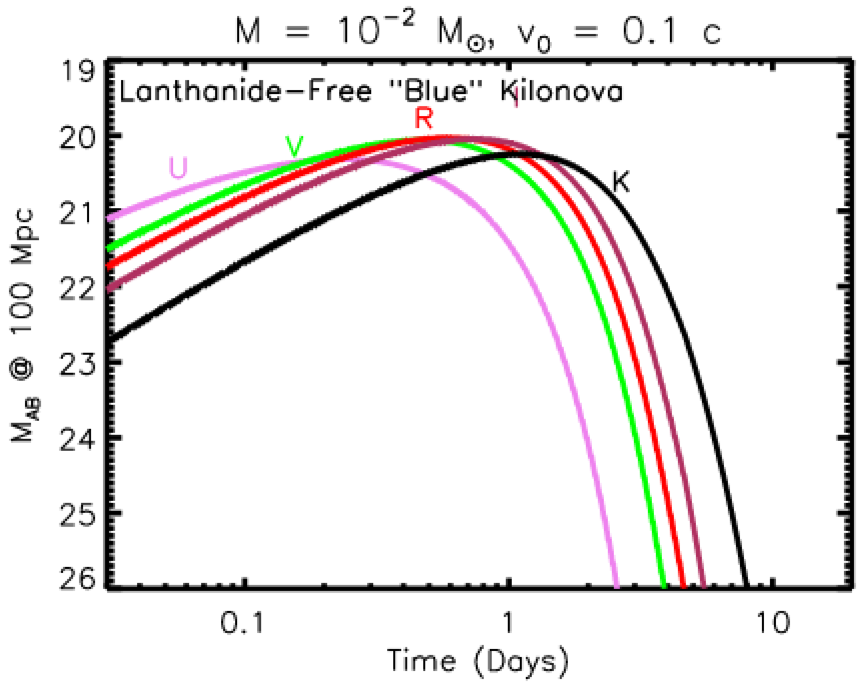
$Y_e = 0.15$-0.25: 2nd peak, Lanthanides

$Y_e < 0.15$: 3rd peak, Actinides

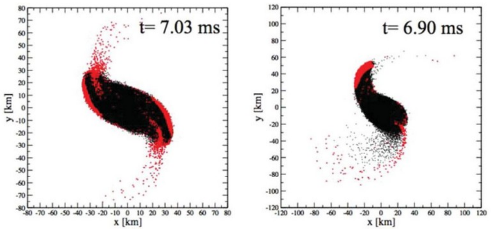
Matter is neutronized, $Ye = n_p/(n_p + n_n) < 0.5$.

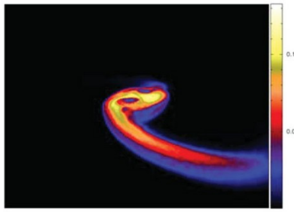
Kilonova colors

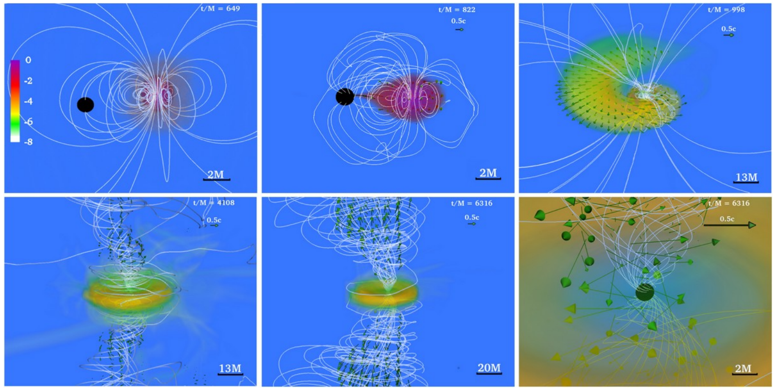


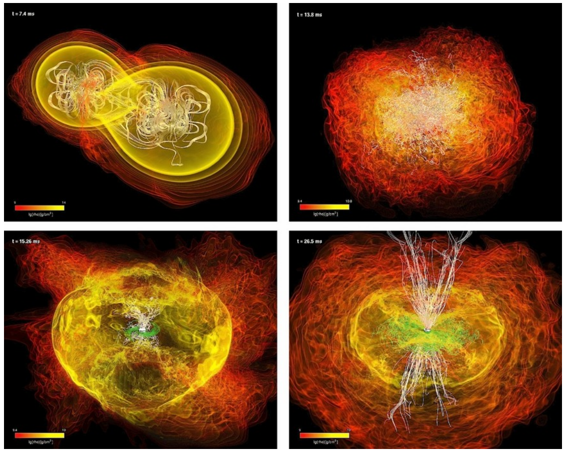


Compact binary mergers: state-of-the-art simulations





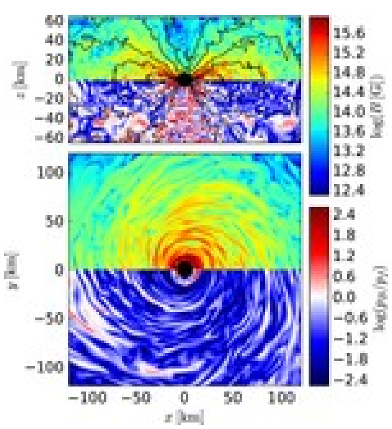


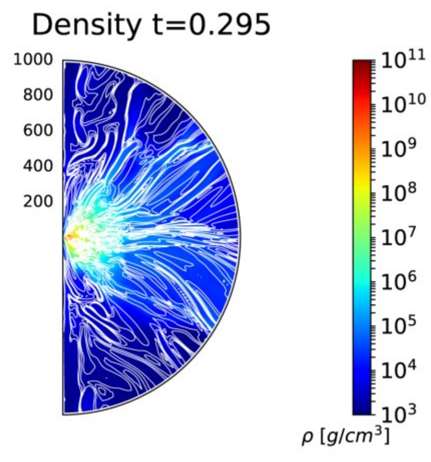


Compact binary mergers

NS-NS and NS-BH (*e.g.Korobkin et al. 2012, Rezzolla et al. 2014, Paschalidis et al. 2015, Shibata, Baumgarte & Shapiro 2000*).

Post-merger systems





Neutrino-cooled BH accretion disk with nuclear EOS (e.g., Janiuk et al. 2017, 2019; Siegel & Metzger. 2018; Fernandez et al. 2019)

Our GR MHD simulations of central engine

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

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

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

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

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

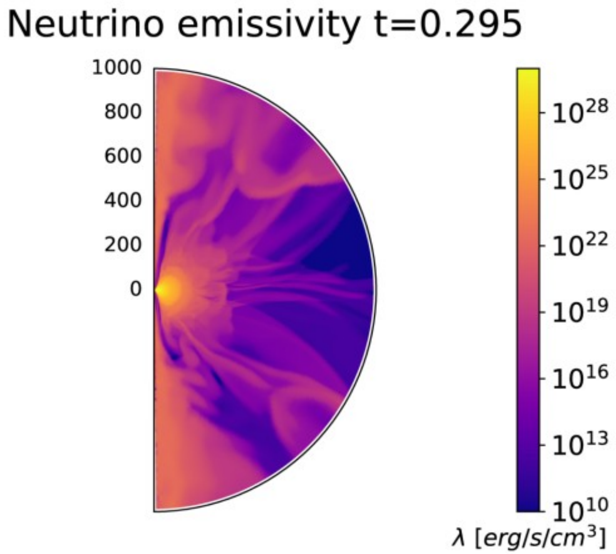
HARM= High Accuracy Relativistic MHD
Equation of State of ideal gas with analytic form was used in the original code (Gammie et al. 2003).
Fermi gas EOS is computed numerically and tabulated during simulation with
P(ρ, T), e(ρ,T) implemented in
Janiuk et al. (2017; 2019).

- **Three paparameter EOS and neutrino leakage: public release soon!**

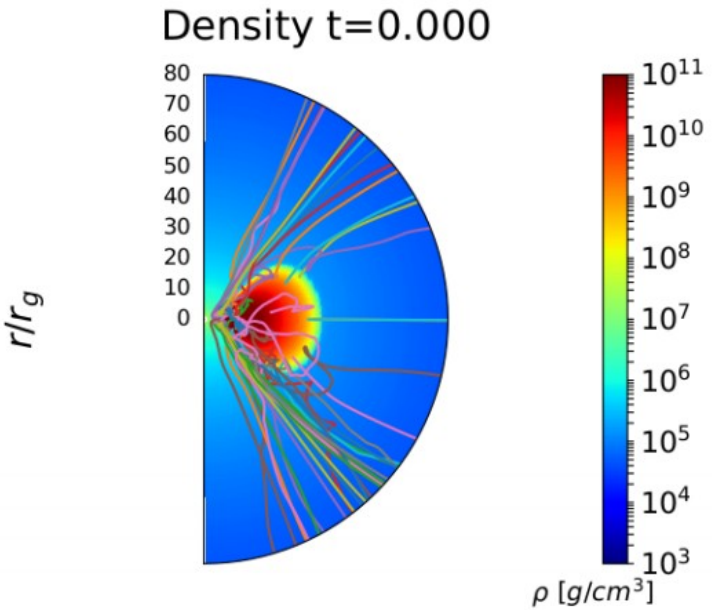
Current publicly available code version

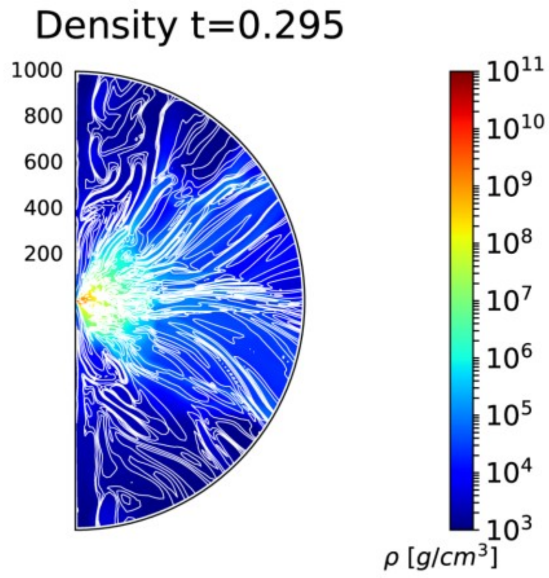
https://github.com/agnieszkajaniuk/HARM_COOL

- Hyperaccretion: rates of 0.01-a few M_{Sun}/s. Nuclear temperatures and densities
- Plasma composed of free n, p, e+, e− pairs, and He nuclei
- Nuclear reactions: electron-positron capture on nucleons, and neutron decay (Reddy, Prakash & Lattimer 1998; Yuan Y.-F. 2005)
- Neutrino absorption & scattering: two-stream approximation (Di Matteo et al. 2002)



Outflow from disk: wind

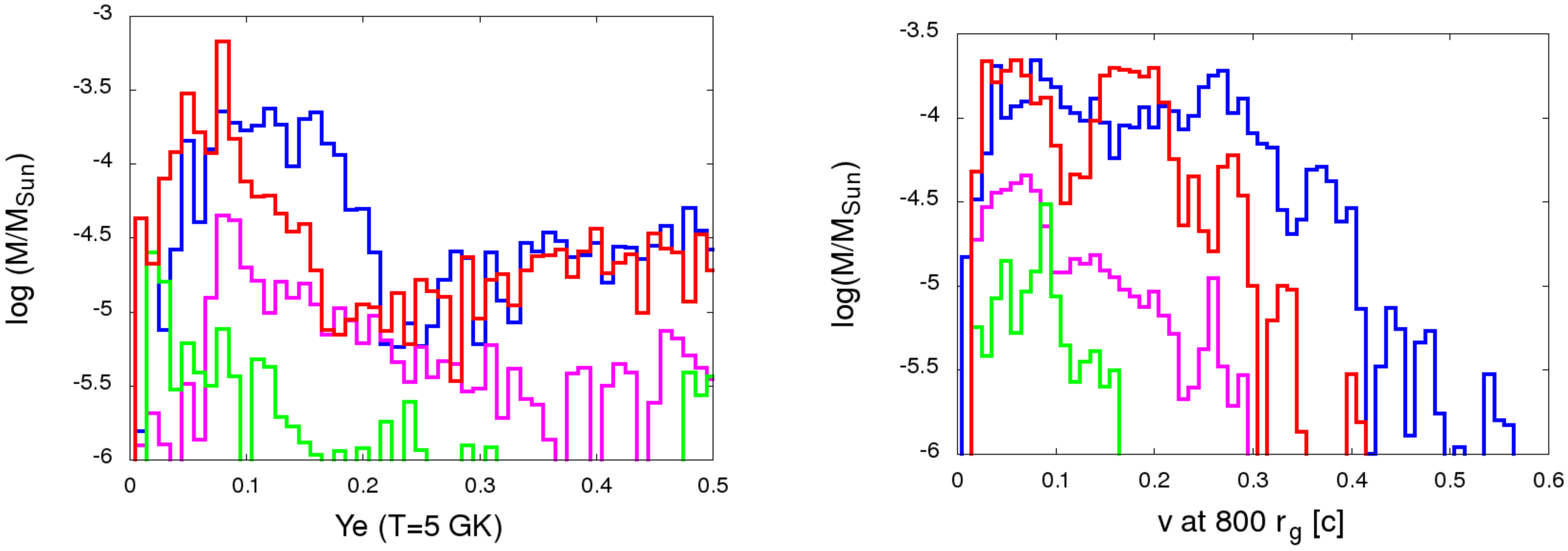




Code **HARM-COOL** **(Janiuk, 2019, ApJ, 882, 163)**
follows the wind outflow, and computes the trajectories, where mass is ejected in sub-relativistic particles. Tracers disributed uniformly in rest-mass density inside initial torus (cf. Wu et al. 2016; Bovard & Rezzola 2017).

Tracers are Lagrangian particles, which store data about density, velocity, and electron fraction in the outflow. The r-process nucleosynthesis is calculated by postprocessing of these data, to obtain chemical evolution of the wind.

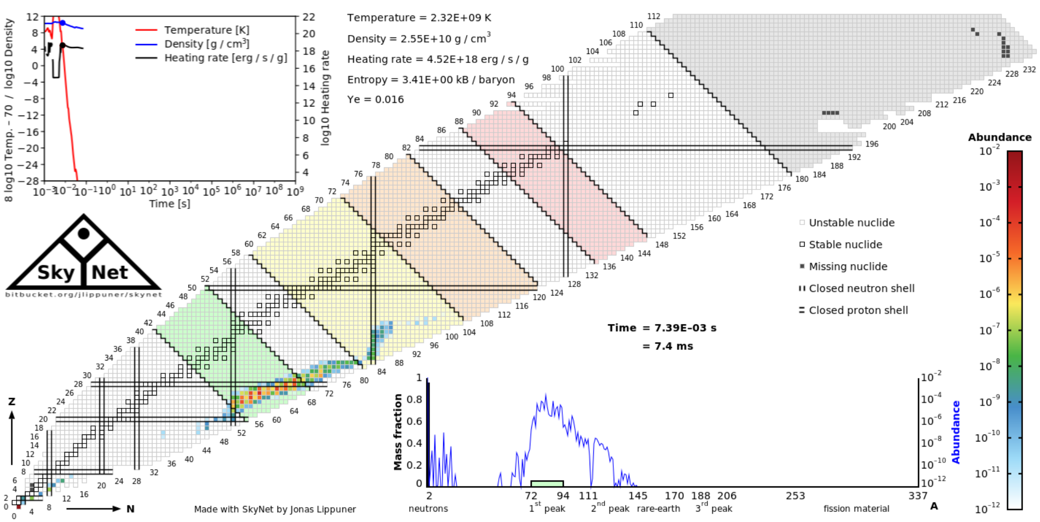
Disk wind properties

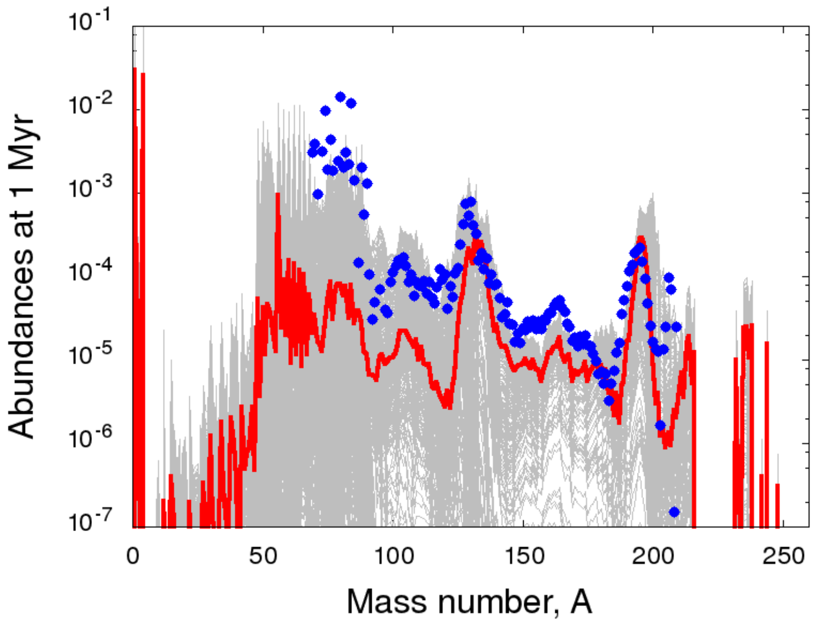


The disk launch fast wind outflows (v=c ∼ 0.11 − 0.23) with a broad range of electron fraction Ye ∼ 0.1 − 0.4. Mass loss via unbound outflows is between 2% and 17% of the initial disk mass. The details are sensitive to engine parameters: BH spin and magnetisation of the disk (a=0.9 and a=0.6, for blue/magenta and red/green histograms). More magnetized disk produce faster outflows. They should contribute to the kilonova signal, due to radioactive decay of r-process formed isotopes

Nucleosynthesis in disk wind

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





Nucleosynthesis in disk wind
(Janiuk, 2019, ApJ)

Code **SkyNet**, provides a nuclear reaction network; Lippuner & Roberts (2017).

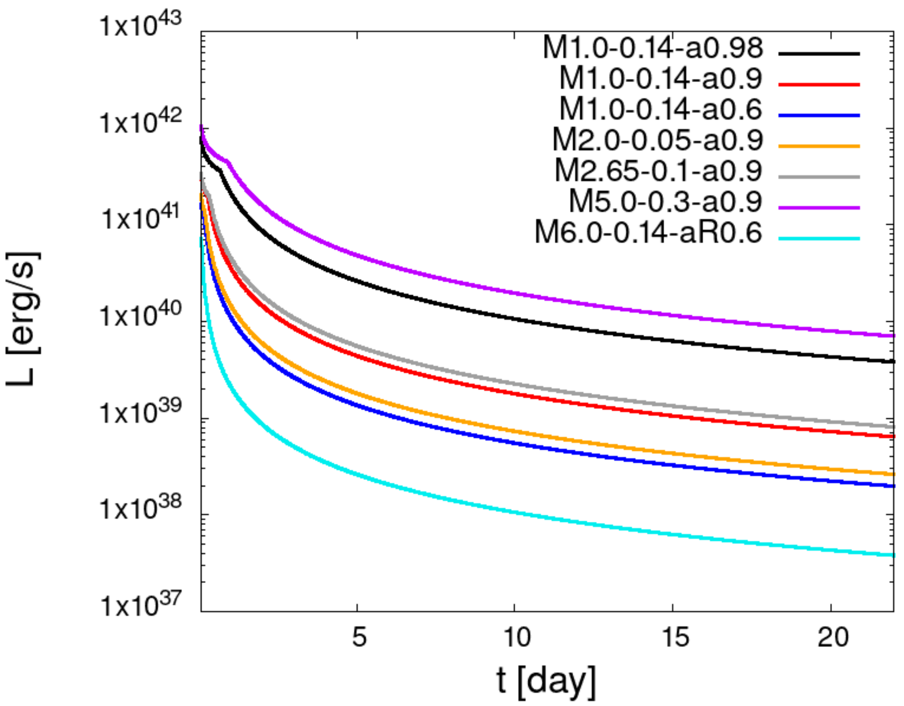
Capable to trace the nucleosynthesis in the rapid neutron capture process, icluding self-heating. Involves large database of over a thousand isotopes. Takes into account the fission reactions and electron screening.

Synthetic kilonova lightcurves

We calculated synthetic kilonova ligtcurves for a range of BH-disk mass ratios and range of black hole spin parameters.

We find strong correlation between the black hole's spin and ejected mass.

Drozda et al. (2022) found that only a fraction (∼20%) of BHNS binaries gain a high BH spin.



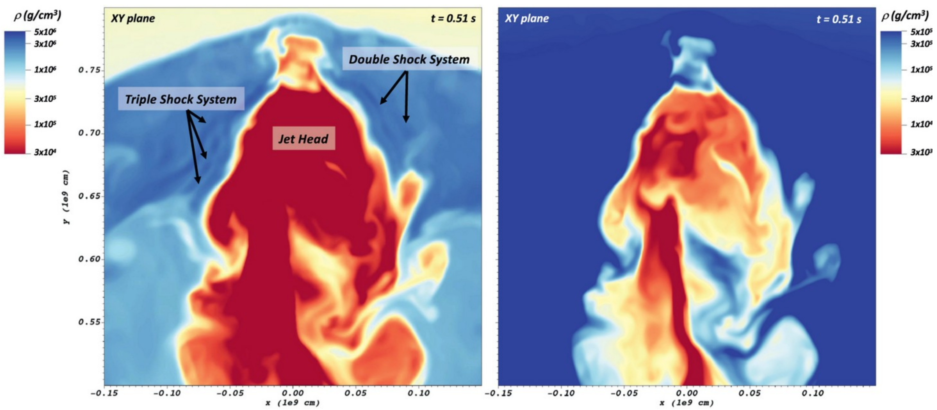
Nouri, Janiuk & Przerwa (2023, ApJ, 944, 220)

Our models address the problem how to **distinguish between BH-NS and NS-NS** progenitors, eg. by measuring LC slopes (see Kasen et al. 2015).

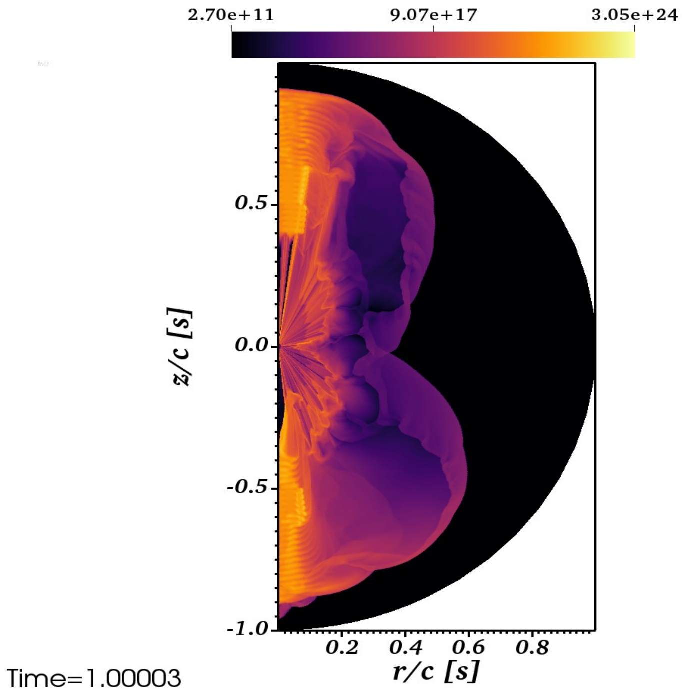
Creation of a magnetized and differentially rotating HMNS with different lifetimes can affect the amount of ejected matter significantly (de Haas et al. 2022).

Jet interactions with pre- and post-merger ejecta

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. Our 2D simulation is utilizing neutrino-cooled wind and r-process nucleosynthesis.

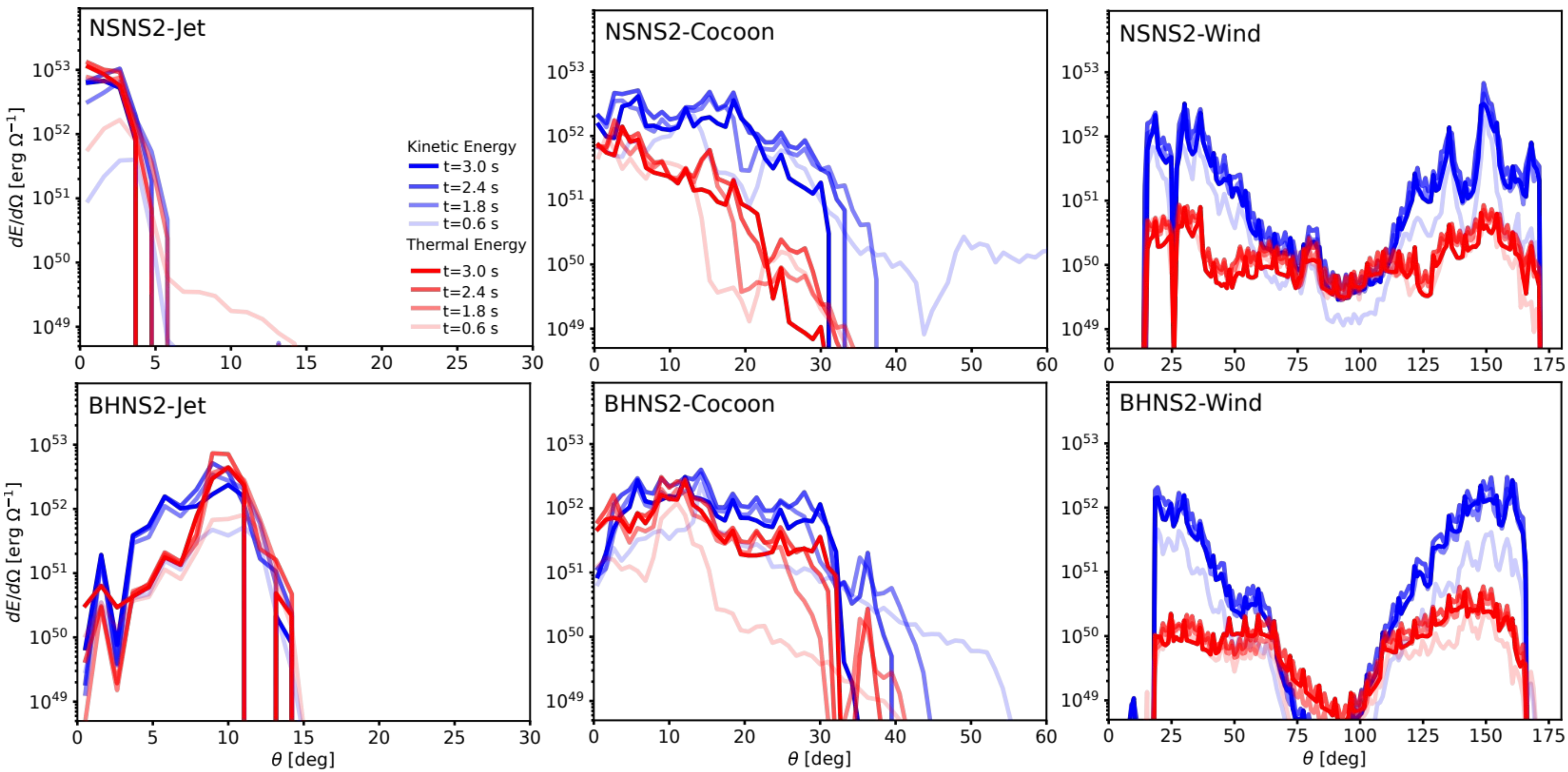


3D simulations show that jet centroid oscillates around the axis of the system, due to inhomogeneities encountered in the propagation (Lazzati et al., 2021)



Urrutia, Janiuk, Nouri, James (2024, arXiV: 2401.10094)

Jet and cocoon recollimation due to interactions with disk wind

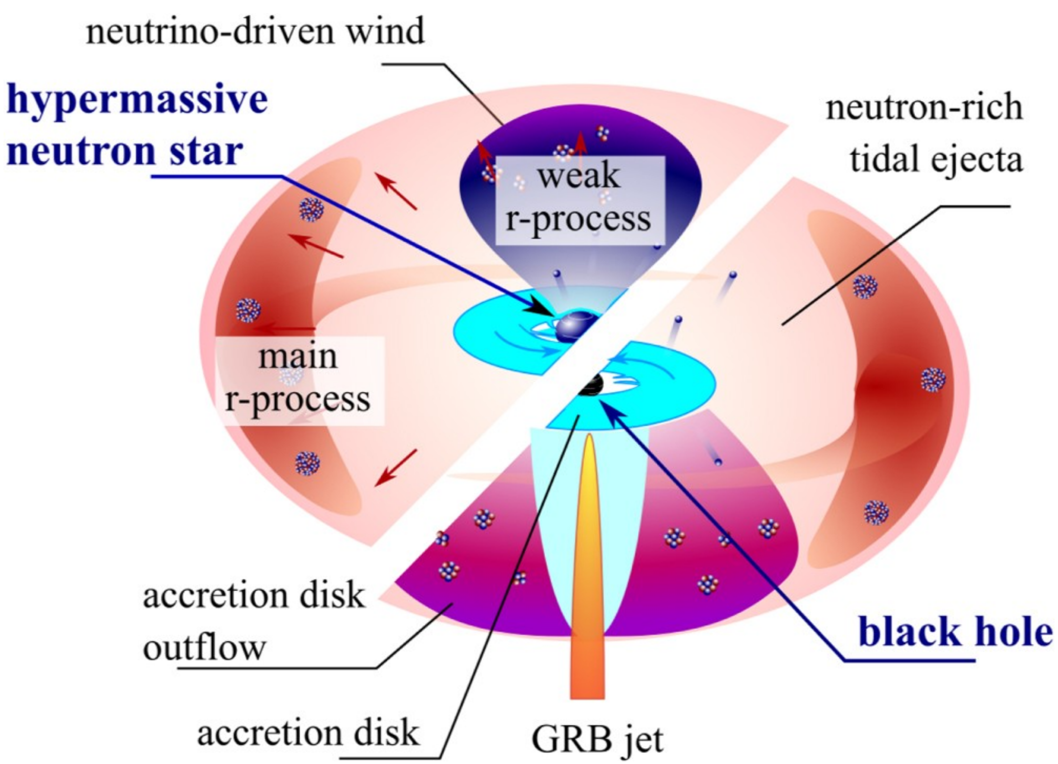


The energy distribution at t = 2 s

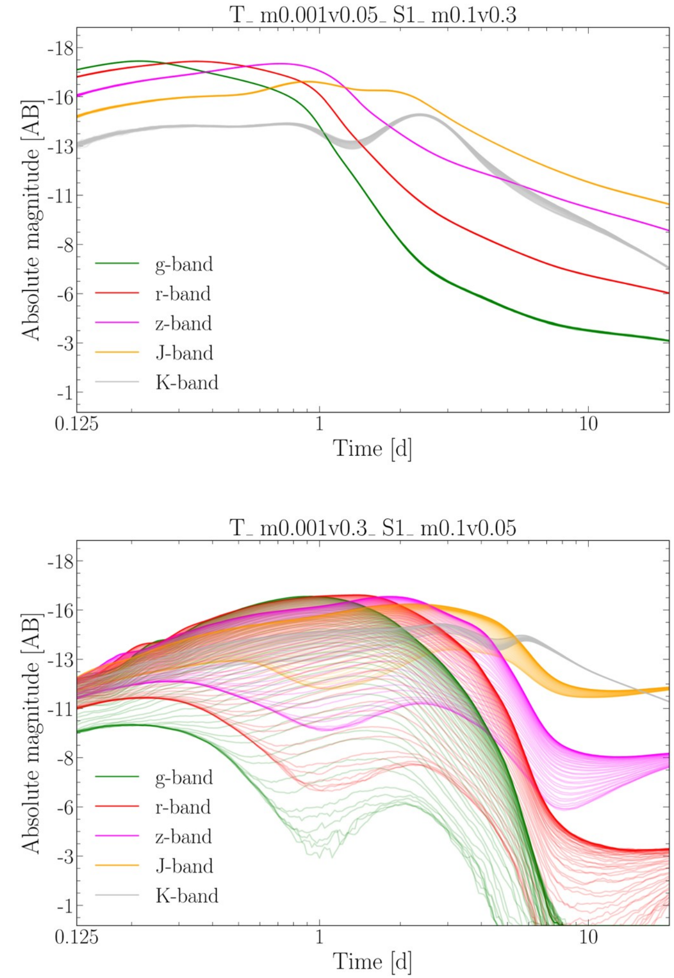
Details in: Urrutia et al. (2024)

Emission simulations

- 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).



Two-component model scheme (Korobkin et al. 2021)



Monte Carlo radiative transfer software SuperNu (Wollaeger & van Rossum 2014) . Two models with 0.001 M⊙ and 0.1 M⊙ in the low-Ye and high-Ye component, respectively. Top: low-Ye and high-Ye ejecta speed of 0.05 c and 0.3 c, respectively. Bottom: low-Ye and high-Ye ejecta speed of 0.3 c and 0.05 c, respectively.

Summary

Jets from MAD disks are highly variable. And correspond to the variability of emission from GRB jets, quantified by PDS spectra

Broad-band correlations between jets Lorentz factors and variability timescales from blazars to GRBs are reproduced by numerical simulations.

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. Jets launched via BZ process, still hardly break out from the stellar mantle.

In short GRBs, the $r-$process nucleosynthesis in magnetically driven accretion disk outflows can provide additional contribution to the kilonova emission, apart from the BNS merger ejecta. Amount of this outflow hard to reconcile with Optical/IR lightcurves.

Jet interactions with wind should shape its properties and together with pre-merger dynamical ejecta may explain time-delay between GW and GRB signals. Collimation of jet and cocoon possible due to MHD driven winds.

Relativistic Astrophysics group at CTP PAS

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

PL GRID

EuroHPC
Joint Undertaking

cft

NARODOWE CENTRUM NAUKI