Structure and variability of magnetically dominated jets from accreting black holes

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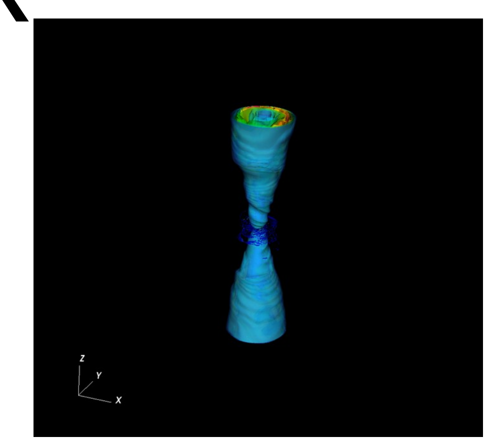
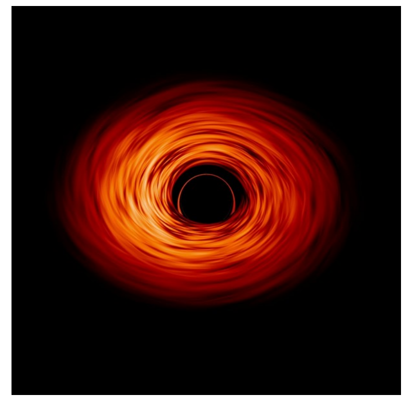
Growing black holes, accretion and mergers
Kathmandu, 17.05.2022

Content of the talk

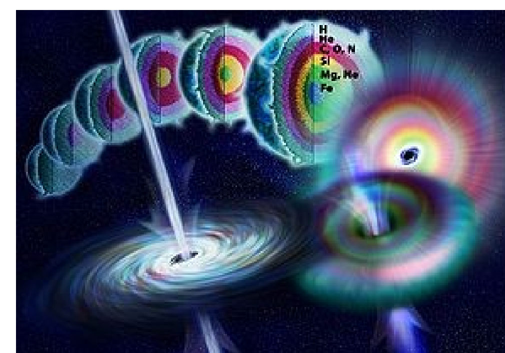


1. Introduction, short and long GRBs, and blazar jets

2. Black hole – jet accretion disk central engine, numerical simulations



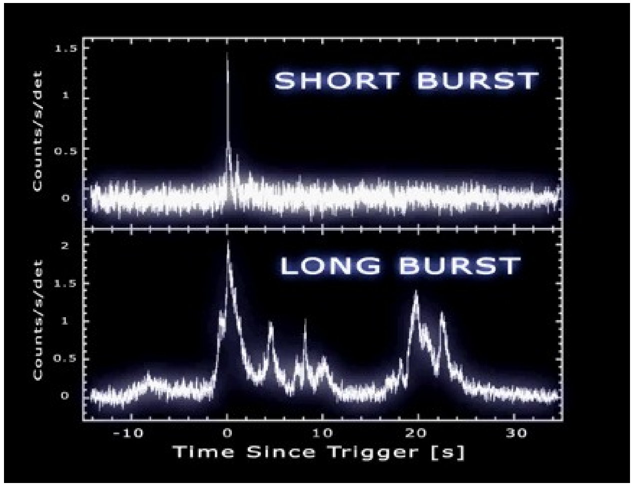
3. Observed correlations in jets and their variability



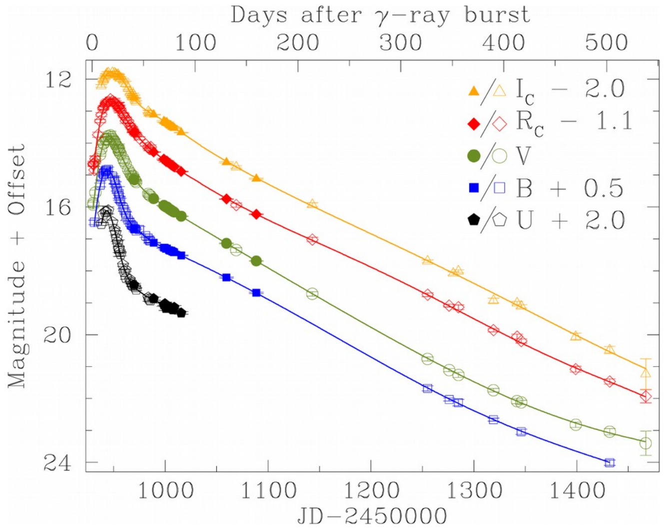
4. Jet-wind interaction in short GRBs and kilonova emission

Gamma Ray bursts

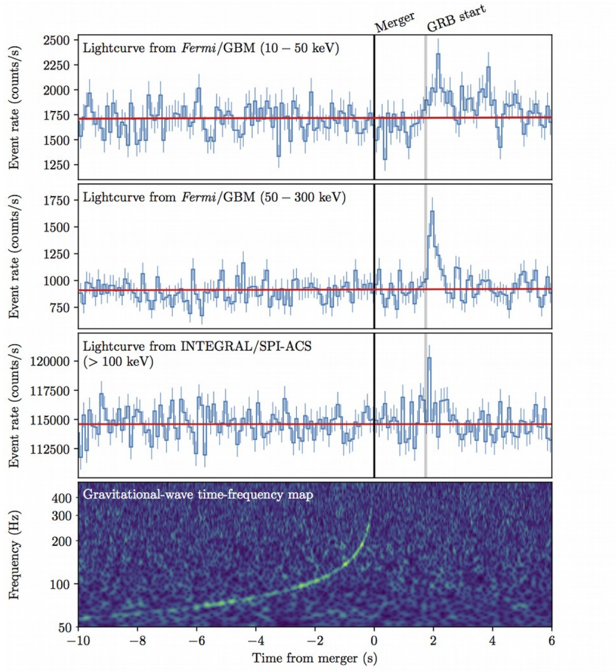
Rapid, bright flashes of radiation peaking in the gamma-ray band



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

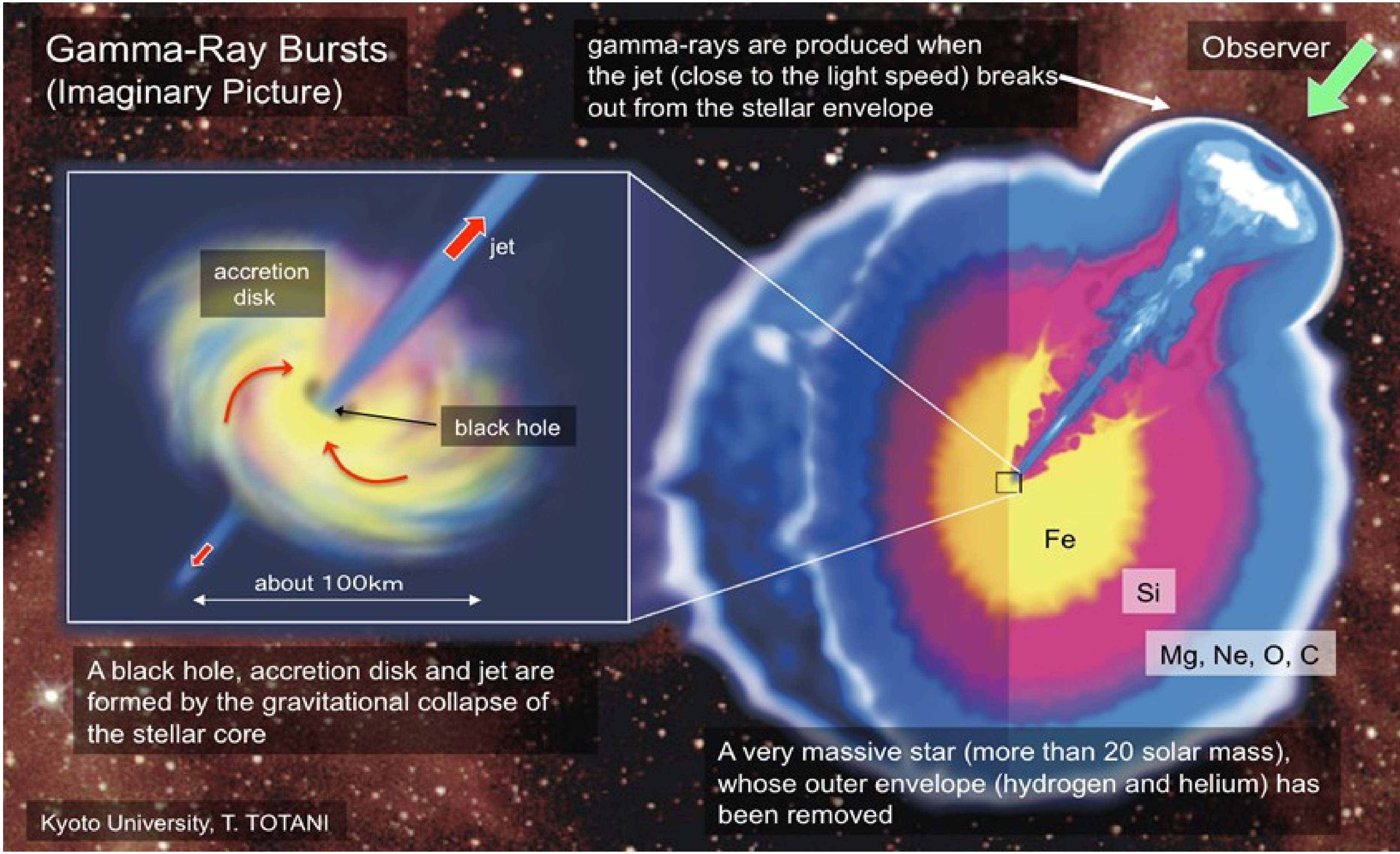


Confirmed source of short GRB: GW170817 (Abbott et al. 2017)

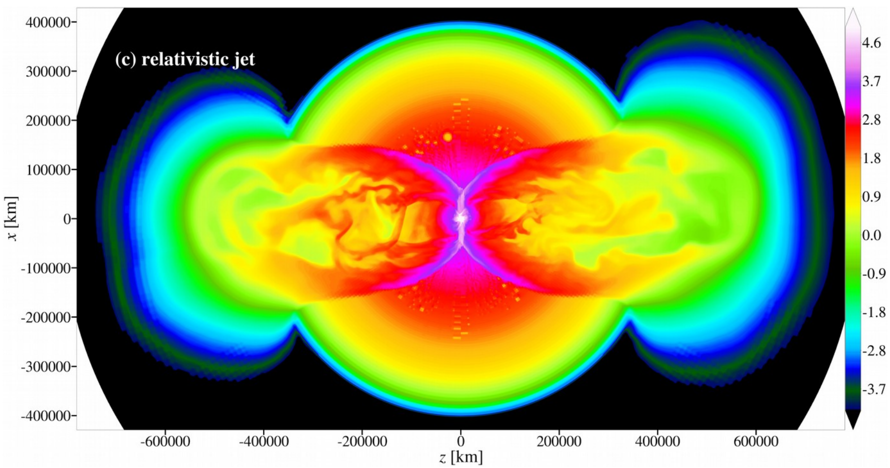


Complete lightcurve from Clochiatti et al. (2011)

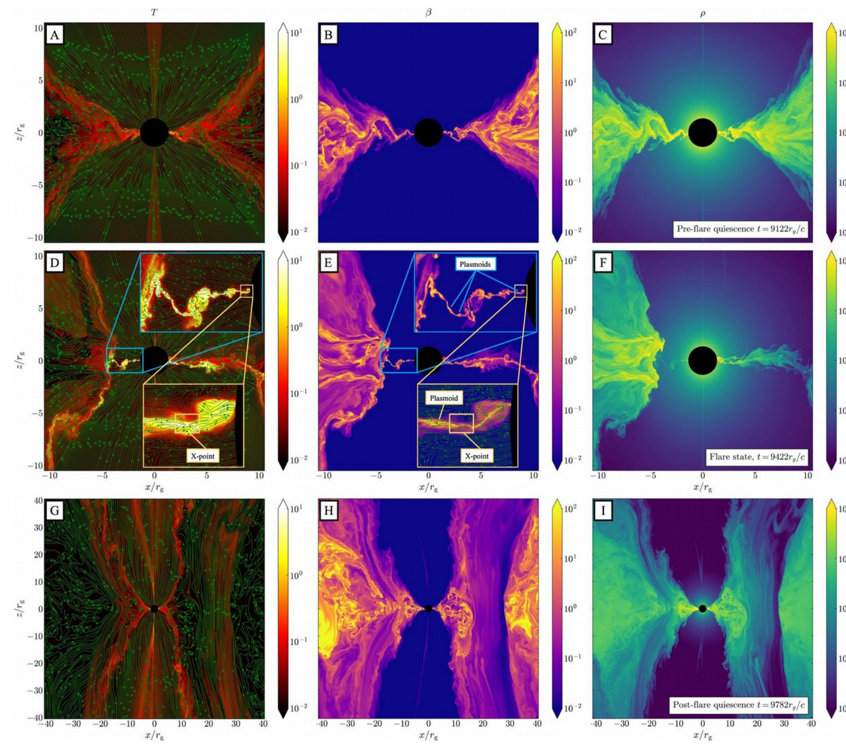
Long GRBs: collapsing massive stars



Collapsar simulation challenges

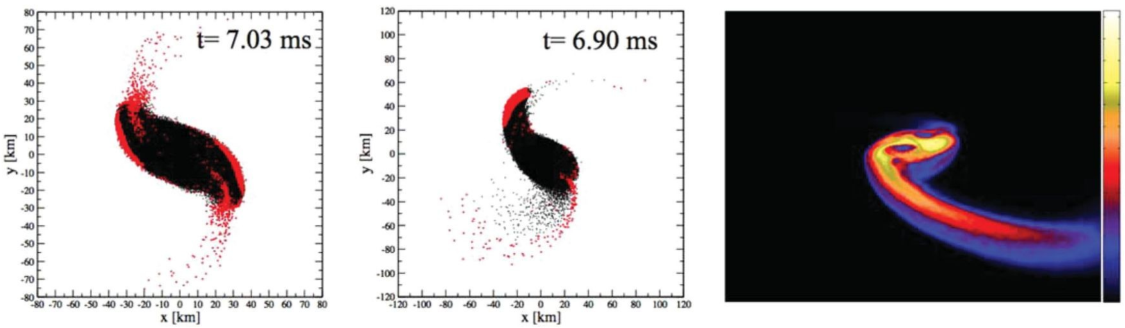


Jet breakout process difficult to model due to multi-scale problem and computational complexity (Gottlieb et al. 2022).

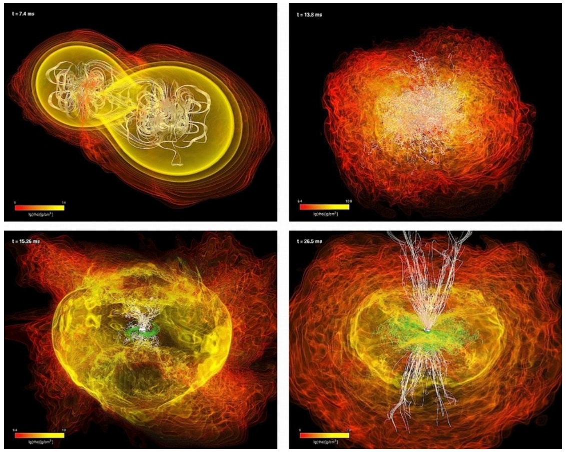


Very high resolution 3D simulations show also importance of plasmoid reconnection
(Ripperda et al. 2022)

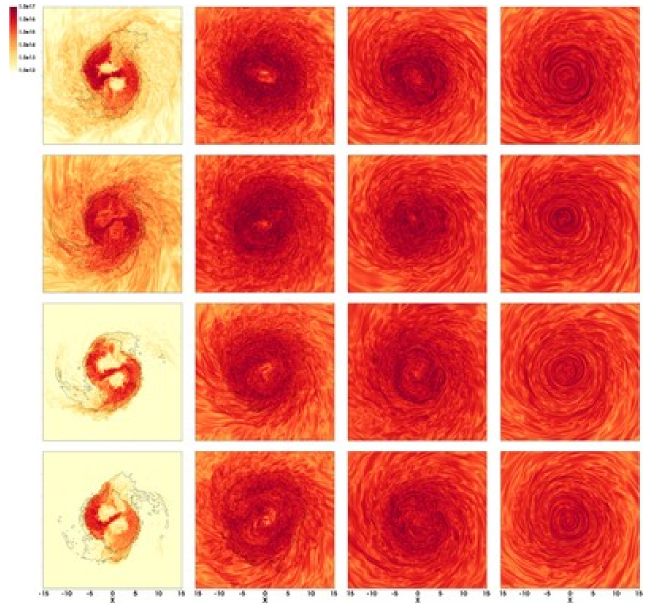
Short GRBs: Compact binary mergers



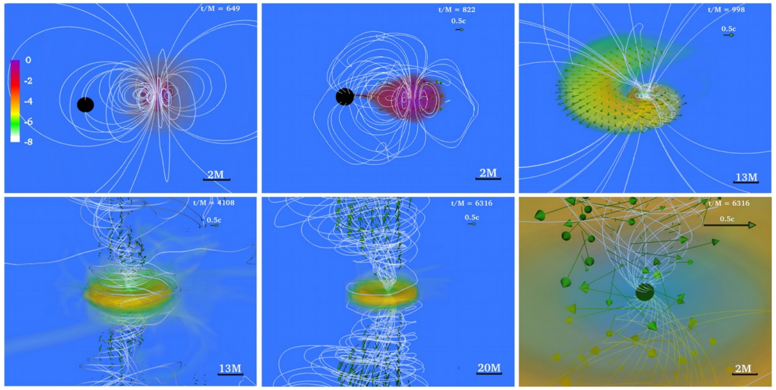
Korobkin et al. 2012



Rezzolla et al. 2014

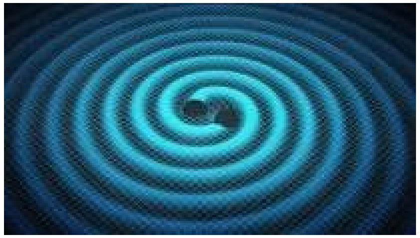


Aguilera-Miret, Vigano & Palenzuela, 2021

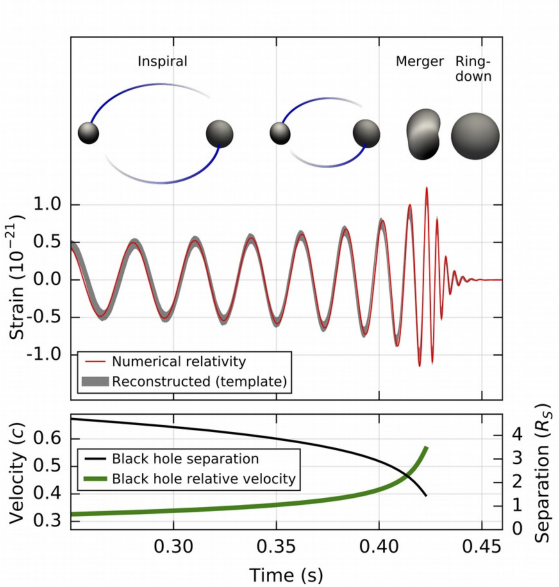


Paschalidis et al. 2015

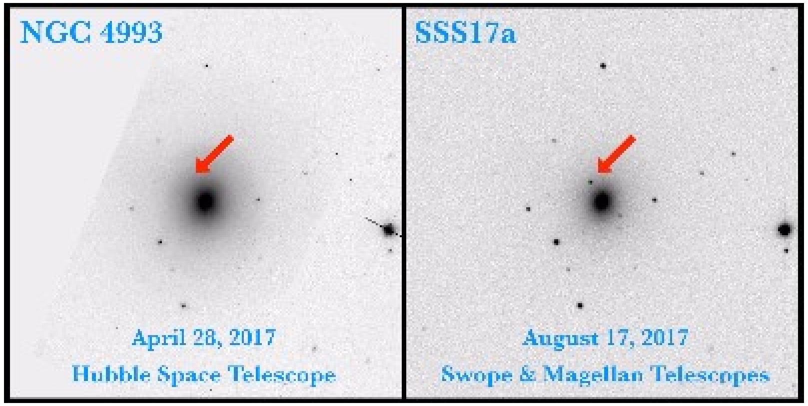
GW 170817



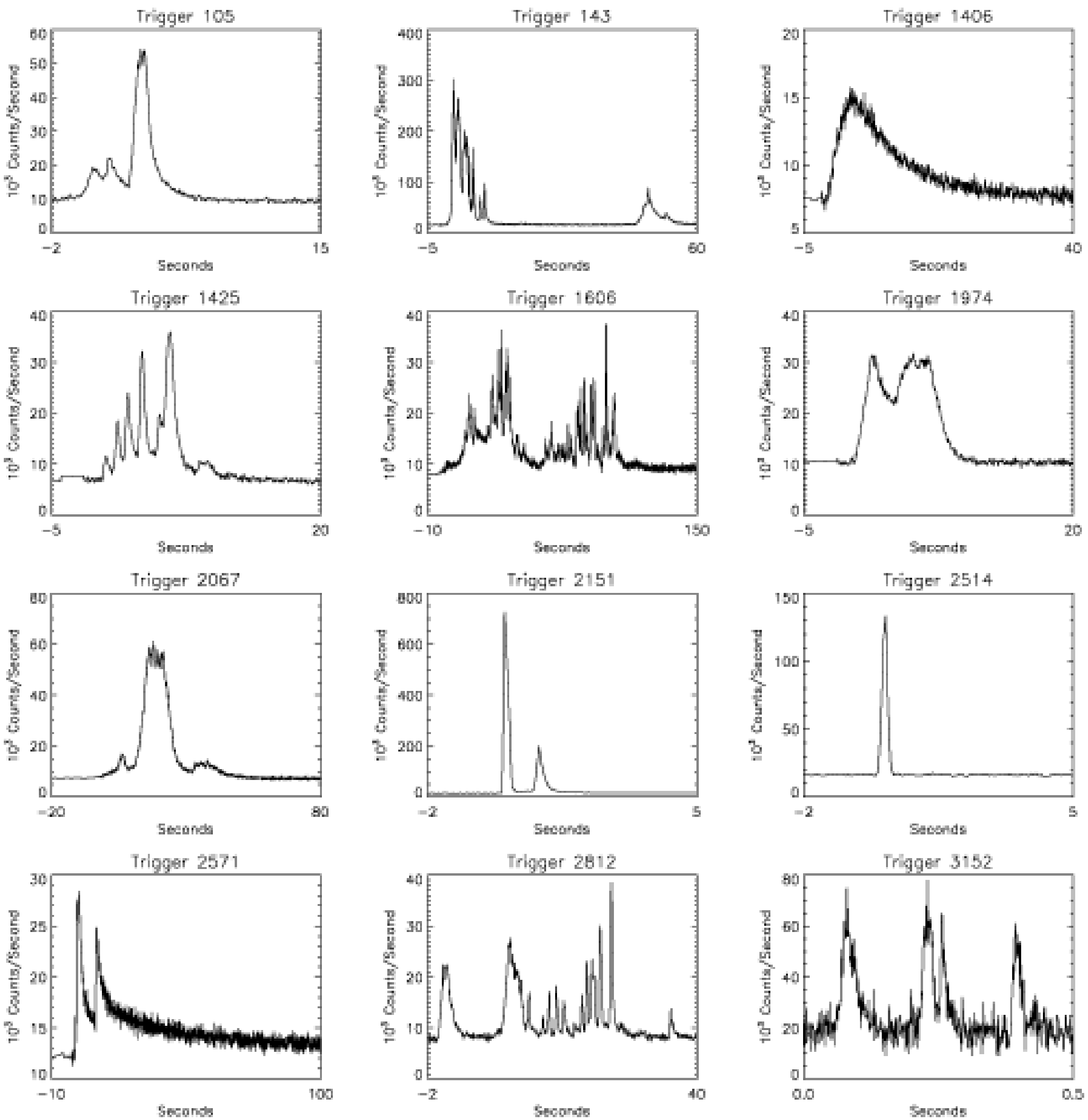
Double neutron stars formed a black hole after their merger.
During the inspiral phase, **gravitational waves** were produced
After the merger, gamma-ray telescopes observed a **burst** of energy.
The time delay of 1.7 s may be associated with formation of HMNS



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)



GRB variability

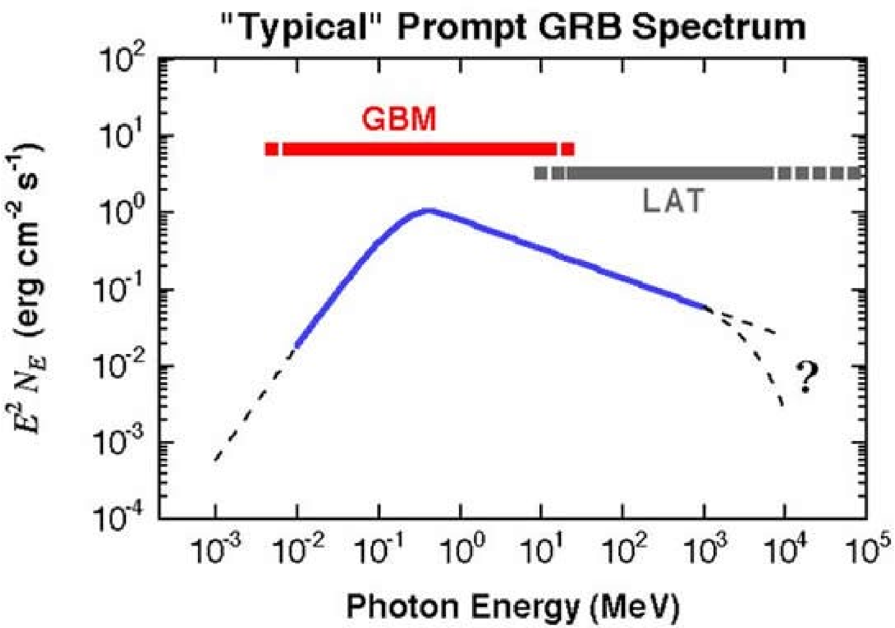


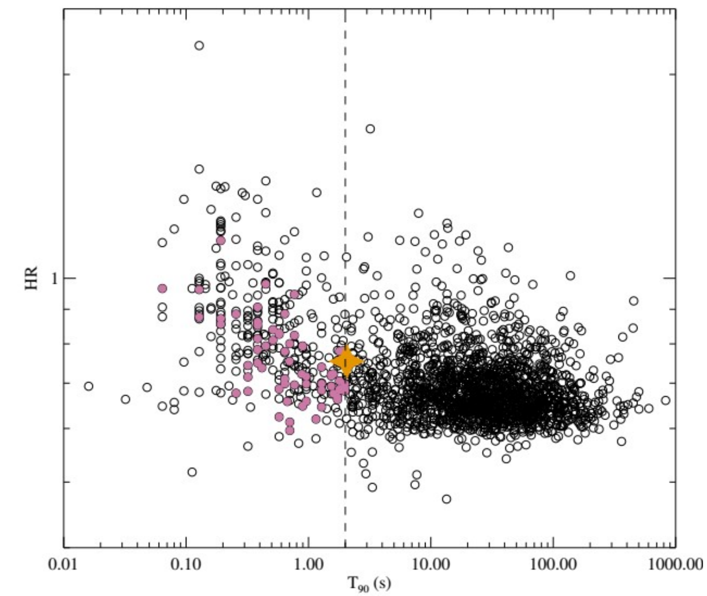
No two gamma-ray bursts are the same, as can be seen from this sample of a dozen light curves.

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

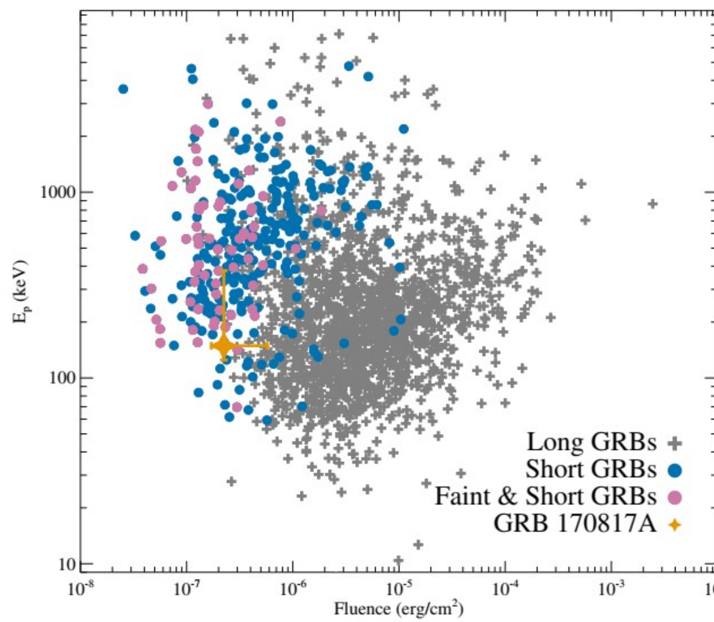
Credit: NASA

Spectra of GRBs





The hardness ratio (HR): ratio of the observed counts in the 50–100 keV band to the counts in the 25–50 keV band within the T90 region.



Outlier: GRB 170817A in the fluence vs. Ep diagram against other sGRBs (Zhang et al. 2018)

Relativistic jets

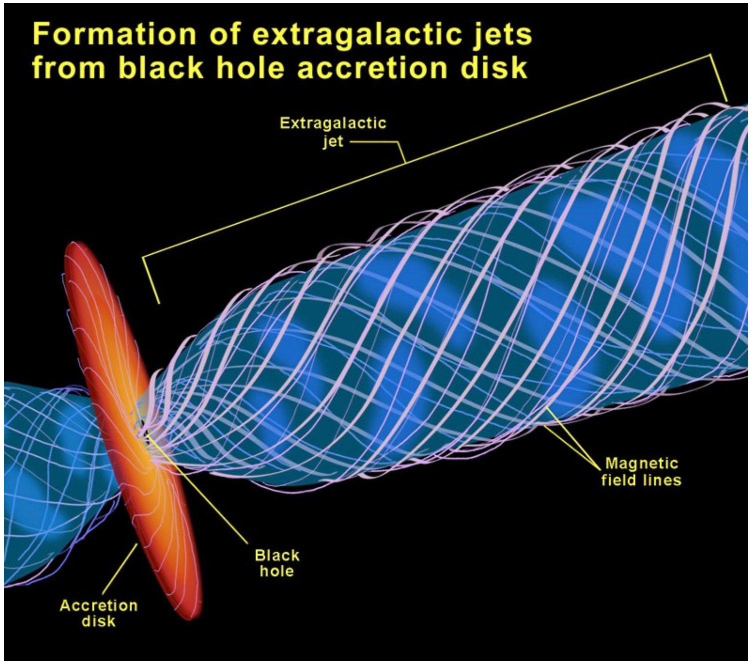
Jets are common in the Universe

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

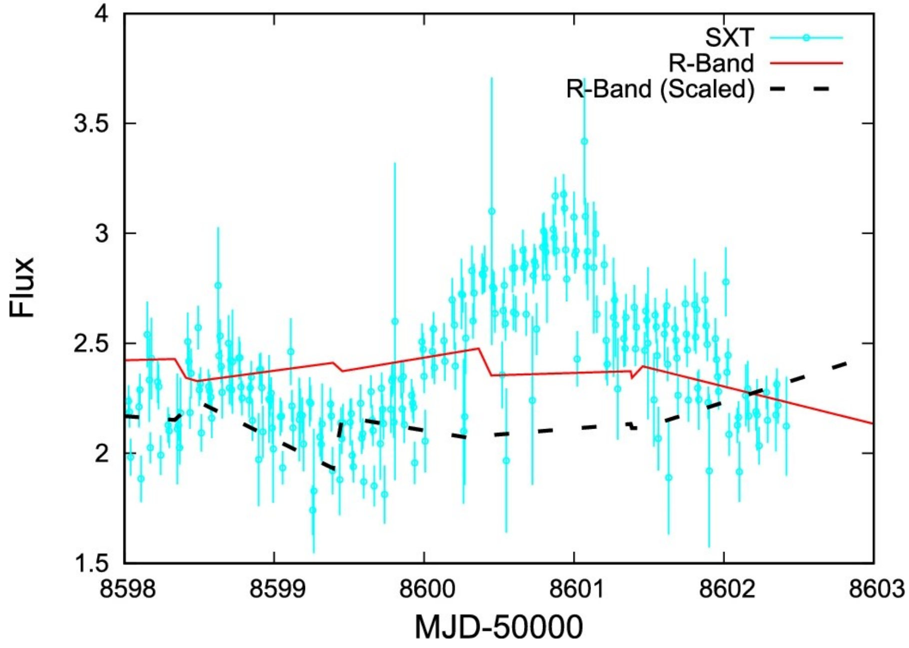
Spinning black hole twists open field lines, helping the jet collimation



Blazars

Type of active galaxies where non-thermal radiation produced in relativistic jet points into our line of sight

X-ray lightcurves show rapid variability of count rate, down into intra-day (minute) time scales and up to 4 magnitude amplitudes



Mrk 501 observed by Astosat (Apil 2019); Chatterjee et al. 2021

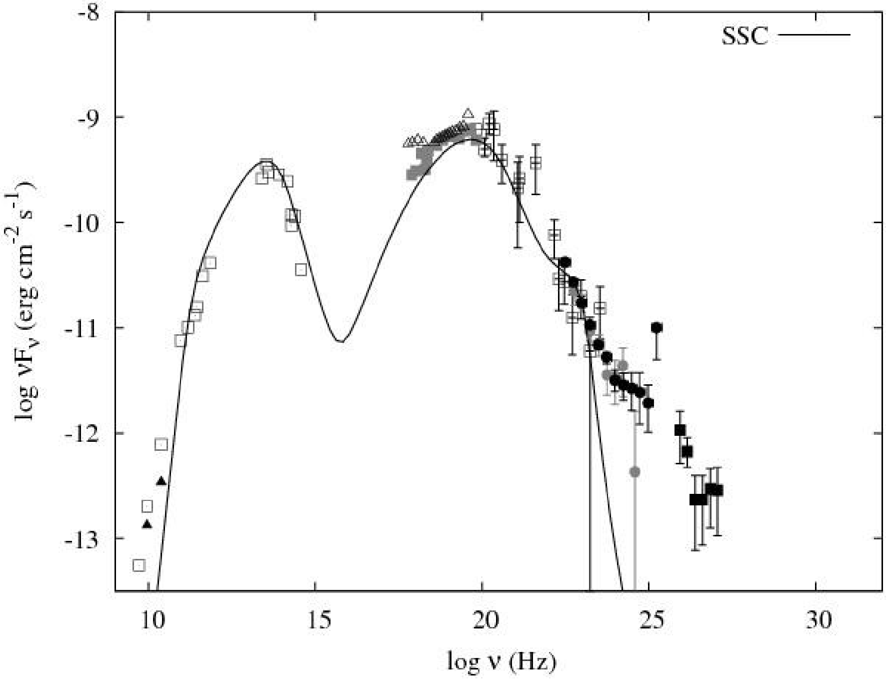
Gopal Bhatta talk

Blazar emission spectra

SSC is an Inverse-Comptom radiation produced when synchrotron radiation is upscattered by their own emitting particles

The one-zone SSC model is popular emission model due to simplicity and small number of free parameters (Mastichiadis & Kirk 1997; Ghisellini et al. 1998)

Some features of high energy spectra, at few GeV, are not explained by this model, and photo-hadronic interactions are proposed



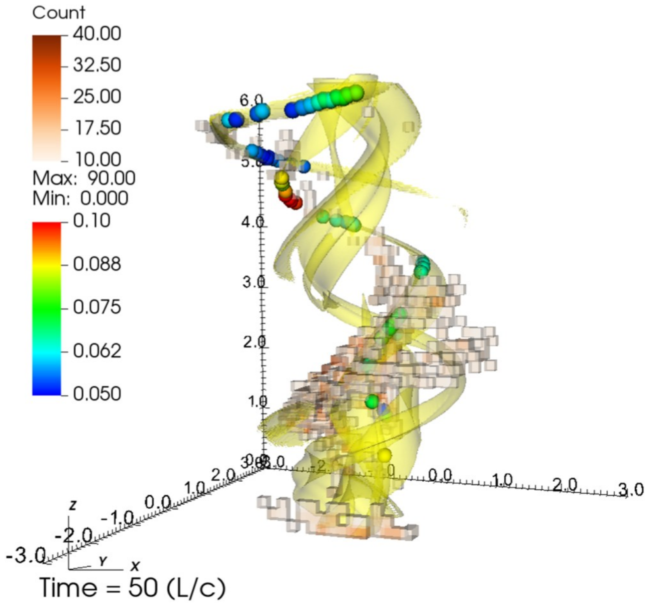
Spectrum of Centaurus-A, and SSC model fit;

(Petropoulou et al., 2014)

K.Nalewajko talk

Blazar variability

Variability time-scales seen in PKS 2155-304 and Mrk 501 are much shorter than inferred light-crossing times at the black hole horizon, suggesting that the variability involves enhanced emission in a small region within an outflowing jet.



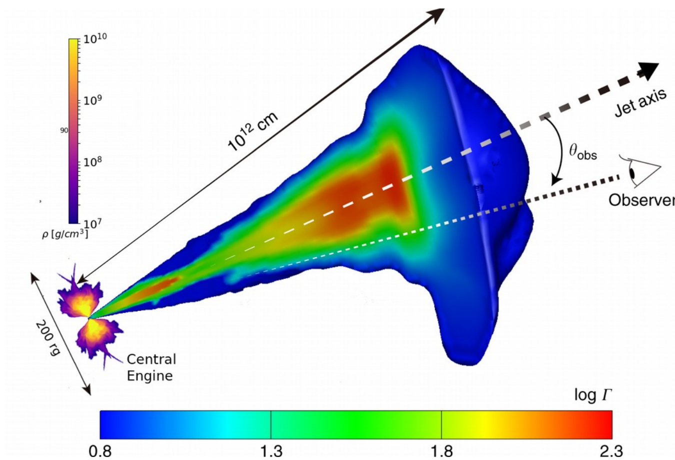
Lorentz factors must be at least

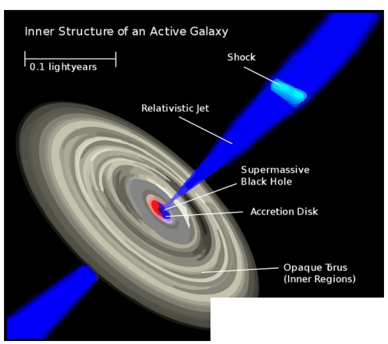
Γ ~ 50, to prevent re-absorption of gamma rays by electron-positron pair creation (Begelman et al. 2008)

Particle acceleration occurs at sub-pc scales in magnetic reconnection sites

Accelerated particles interact with ambient photons and produce pions, then decay to γ's and ν's (Medina-Torrejon et al. 2021)

GRB and AGN Central engine





Gamma ray emission comes from the photosphere of a collimated relativistic outflow pushing through the interstellar medium.

Jet launching mechanism similar in GRB and AGN jets, across the mass scale.

Quantitative differences:
- mass and density of disk
- magnetic flux
- Lorentz factors
- power of jet

Source	M_{BH} ($M_\odot$)	M_{disk}^{unit} ($M_\odot$)	Time^{unit}	$\dot{M}^{unit}$	$\dot{E}^{unit}$ (erg s^{-1})	D^{unit} (g cm^{-3})	B^{unit} (G)	Φ_B^{unit}
Short GRB	3	$1.5 \cdot 10^{-5}$	1.5×10^{-5} s	1 $M_\odot$s^{-1}	$1.8 \cdot 10^{54}$	$3.4 \cdot 10^{11}$	$6.2 \cdot 10^{16}$	$1.2 \cdot 10^{28}$ G cm^2
Long GRB	10	$1.5 \cdot 10^{-4}$	4.9×10^{-5} s	3 $M_\odot$s^{-1}	$5.5 \cdot 10^{54}$	$9.5 \cdot 10^{10}$	$3.2 \cdot 10^{16}$	$7.0 \cdot 10^{28}$ G cm^2
Sgr A$\star$	$4 \cdot 10^6$	$6.2 \cdot 10^{-10}$	6.2×10^{-7} yr	10^{-3} $M_\odot$yr^{-1}	$5.6 \cdot 10^{43}$	$6.0 \cdot 10^{-12}$	$2.6 \cdot 10^5$	$9.0 \cdot 10^{-8}$ G pc^2
M 87	$5 \cdot 10^9$	$7.8 \cdot 10^{-7}$	7.8×10^{-4} yr	10^{-3} $M_\odot$yr^{-1}	$5.6 \cdot 10^{43}$	$3.8 \cdot 10^{-18}$	$2.6 \cdot 10^2$	$1.2 \cdot 10^{-5}$ G pc^2

Table 3. Conversion units for various astrophysical sources

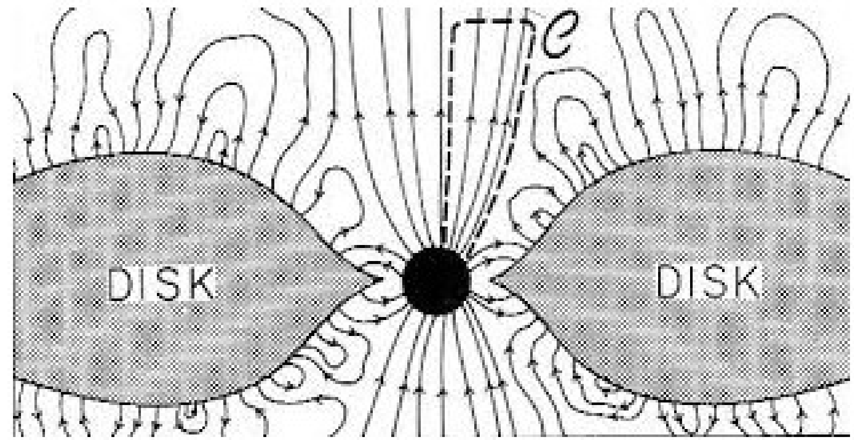
Powering of jets

Extracted power

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

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

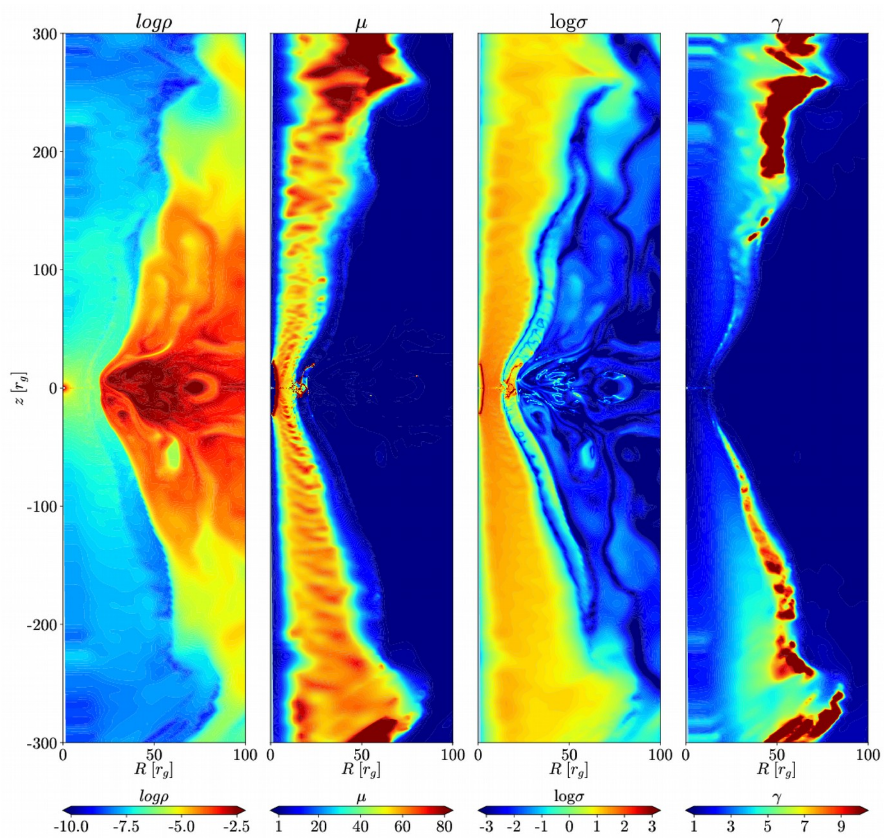
$$a = \frac{c\,J_{\rm BH}}{G\,M_{\rm BH}^2}$$



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)

Jet launching and energetics



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

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

- 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

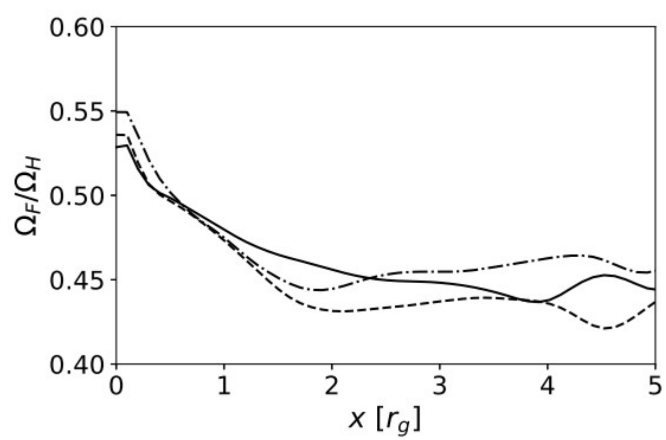
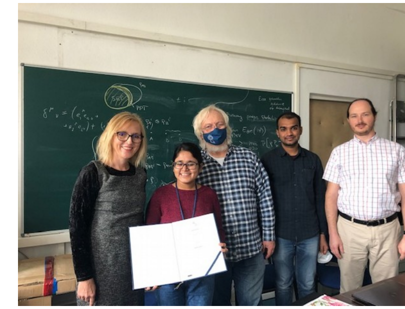
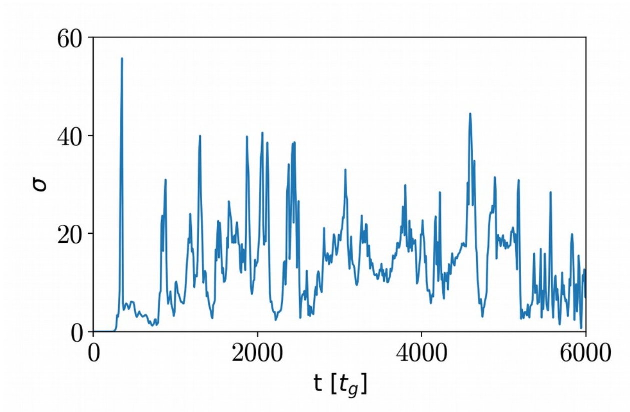
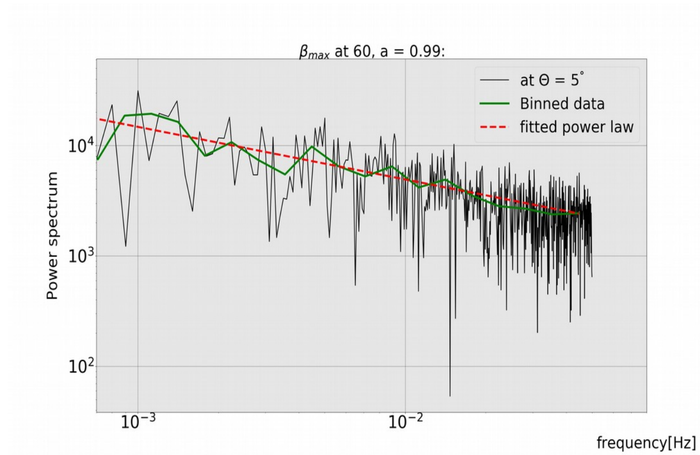


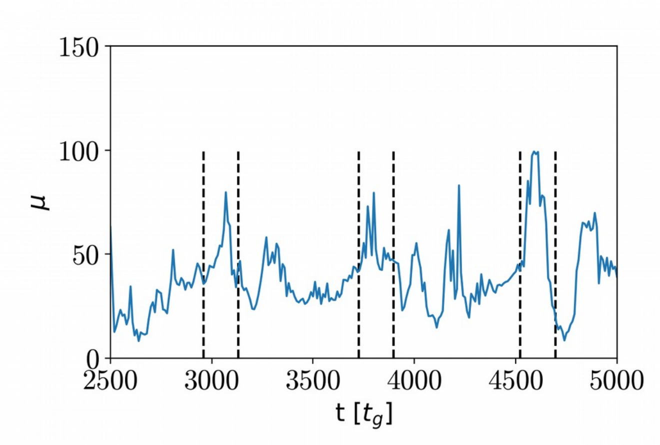
Fig from Sapountzis & Janiuk (2019, ApJ)

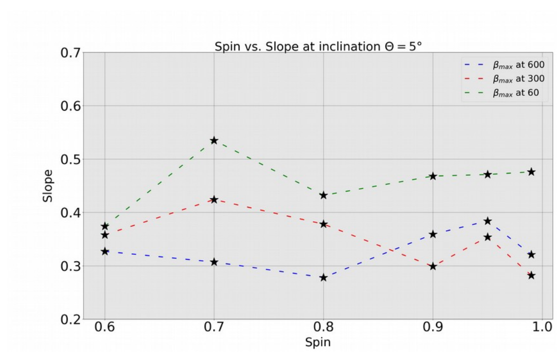
Variability of jets

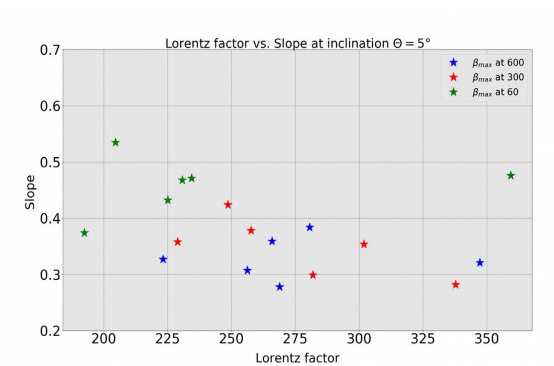












Time variability of σ and μ as measured at inner regions of jet . Variability is correlated with T_{MRI}, timescale of the fastest growing mode of magneto-rotational instability

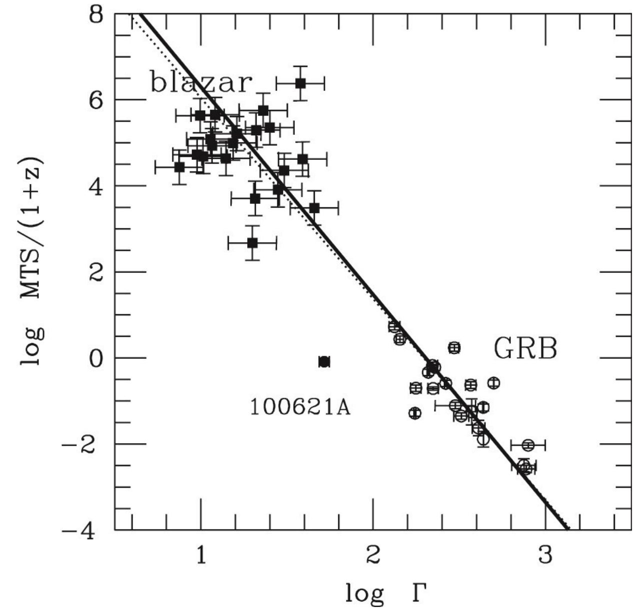
Power spectrum of model lightcurves. Power-law slope weakly depends on the black hole spin, while it seems to depend on jet Lorentz factor.

Variability timescale

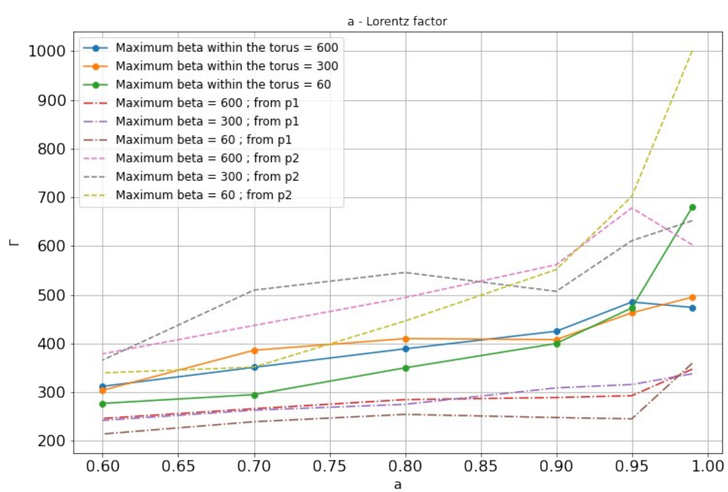
- In our simulation, jet Lorentz factor is calculated as the average of μ in time, $\Gamma = \langle \mu \rangle_t$.

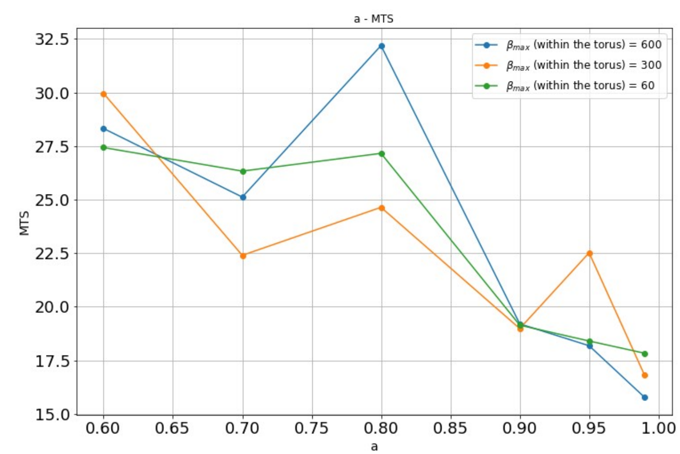
- The Minimum variability Time Scale (MTS) ~ peak widths at their half maximum on the μ – t plot

- 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 ∝ $\Gamma^{-4.7}$±0.3 for blazar and GRB samples (Wu et al. 2016)





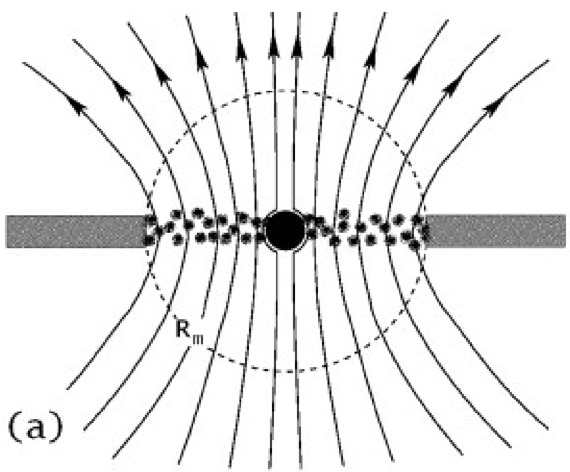
(Janiuk, James & Palit, 2021, ApJ, 917, 102)

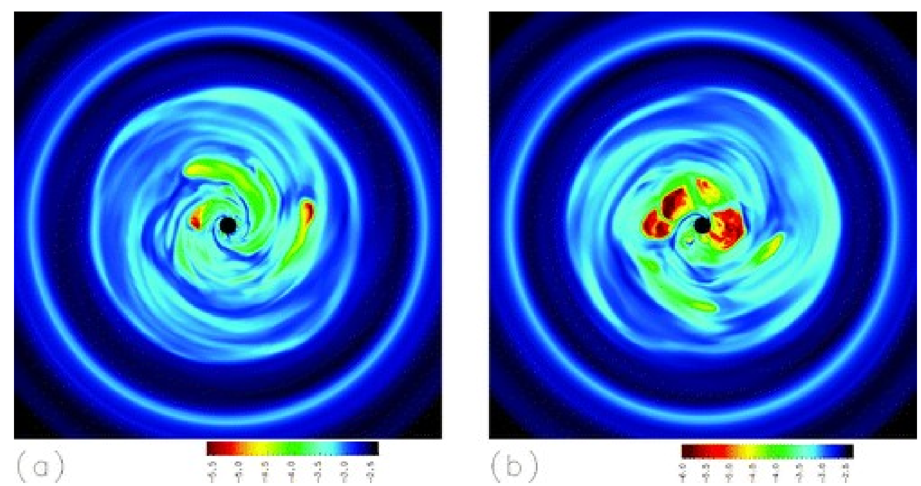
MAD mode of accretion

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 (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).



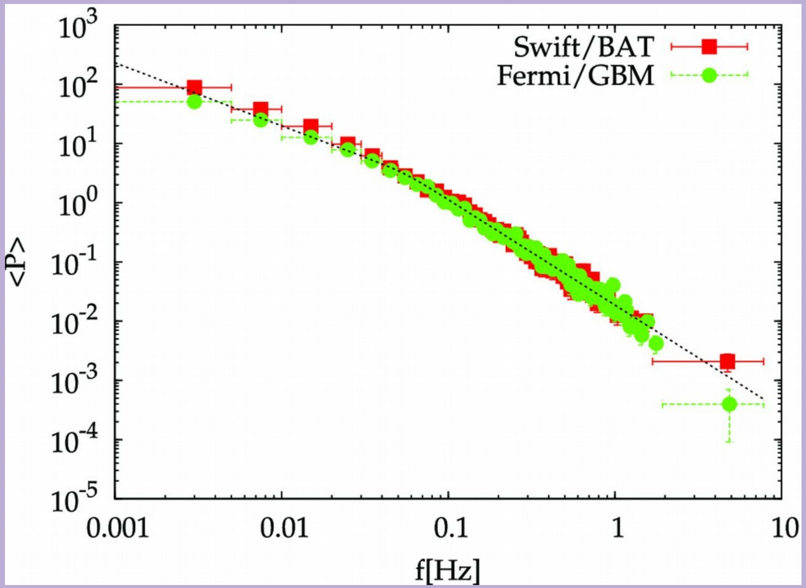


Non-axisymmetric case: gas forms streams which have to find the way towards back hole through magnetic reconnections and interchanges (e.g. Igumenshchev 2008)

Variable energy extraction from MAD disk

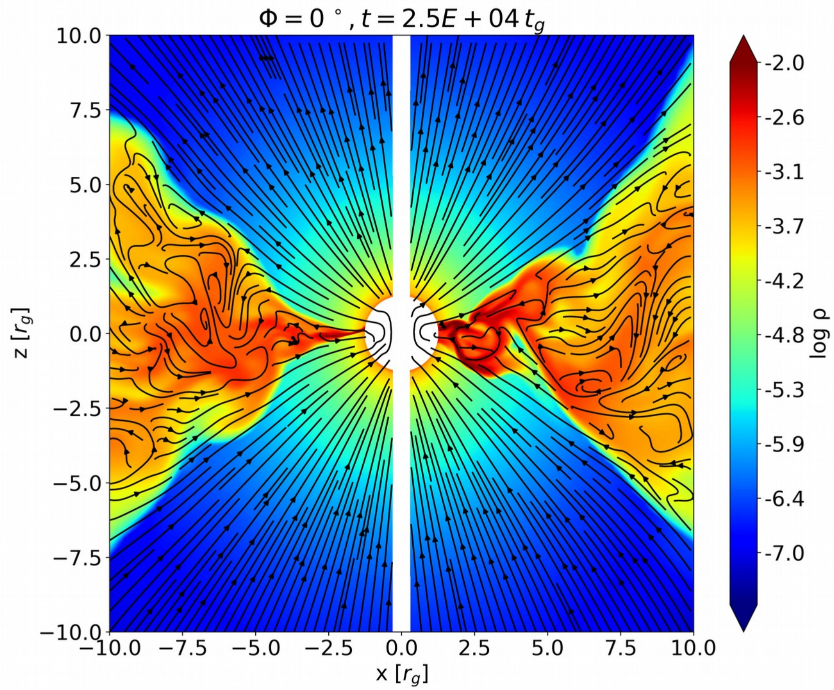
The ratio of total energy reaching infinity (radiative, mechanical, magnetic) to the rest mass energy in the MAD mode is large (cf. Bisnovatyi-Kogan & Ruzmaikin, 1974; 1976).

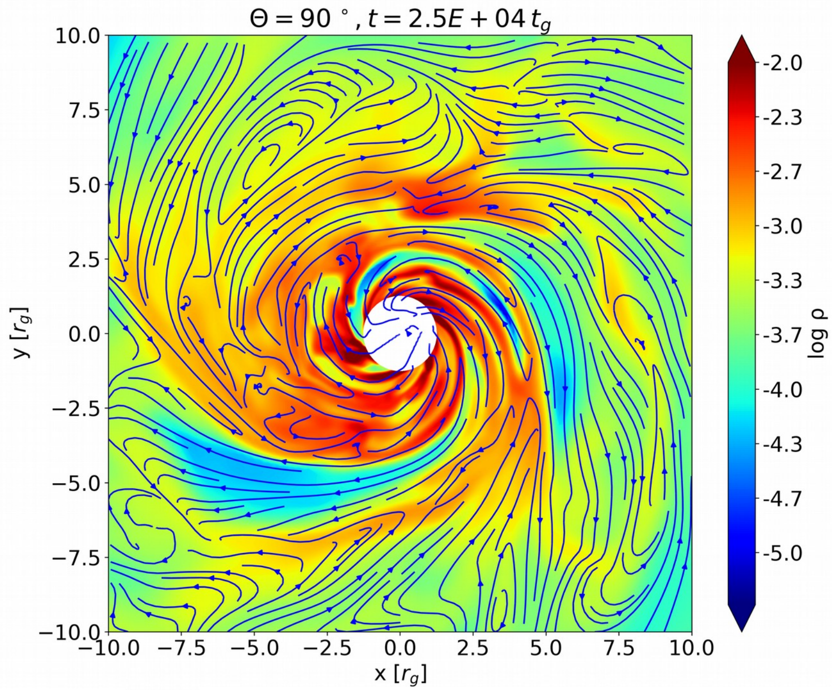
This large efficiency is obtained even for non-rotating black hole.
With a rotating black hole, one can extract in addition its rotational energy (Tschekhovskoy et al. 2011).

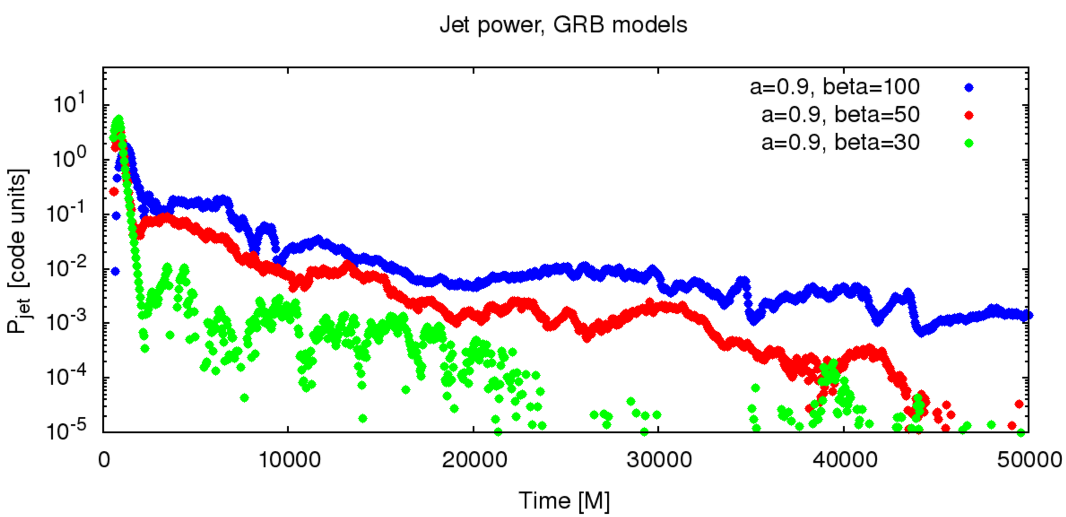


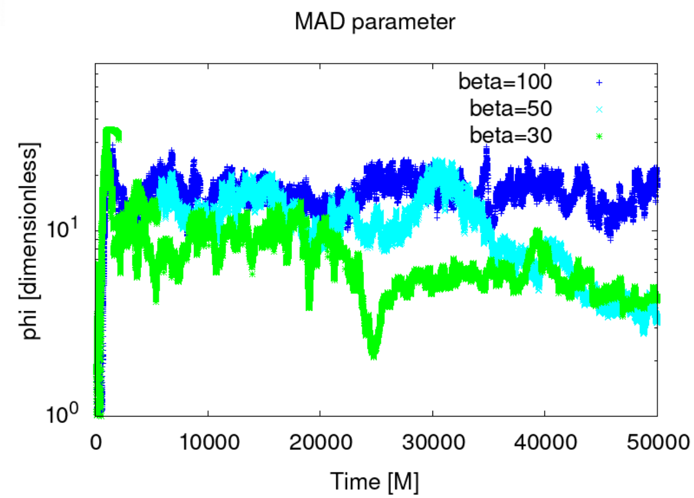
Models for the temporal variability of long gamma-ray bursts (GRBs) during the prompt phase (the highly variable first 100 s or so), were proposed in the context of a MAD around a black hole (see Lloyd-Ronning et al., 2016).

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









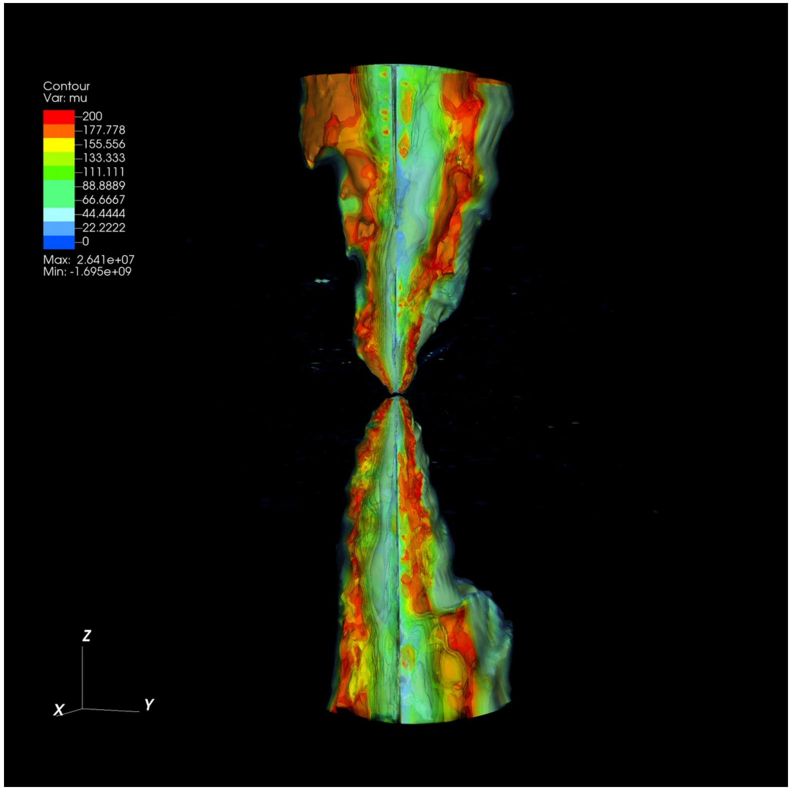
A. Janiuk & B. James (2022, subm.);

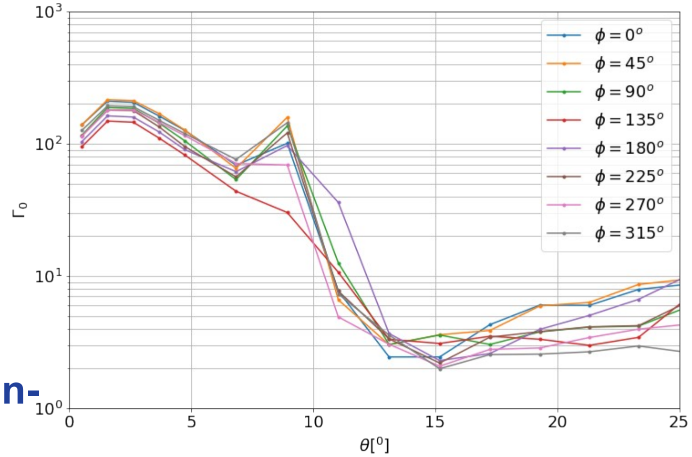
$$\varphi_{BH} = \Phi_{BH} / 5\, (r_g^2 c\, \dot{M})^{1/2}$$

3D simulations of GRB jets from MADs

- We model short and long GRB central engines with different setup for accretion disk and magnetic fields initialisation
- We get the variable jet structure, and study instantaneous and time-averaged jet profiles.
- We determine their opening angles and confront with observed data for short and long GRB samples (e.g. Dichiara et al. 2013; Guidorzi et al. 2016; Fong et al. 2015)

- **See poster presentation by Bestin**





Figs: B. James, A. Janiuk, F. Hossein-Nouri; 2022, ApJ, subm.

Disk wind and jet: two types of outflow in GRBs

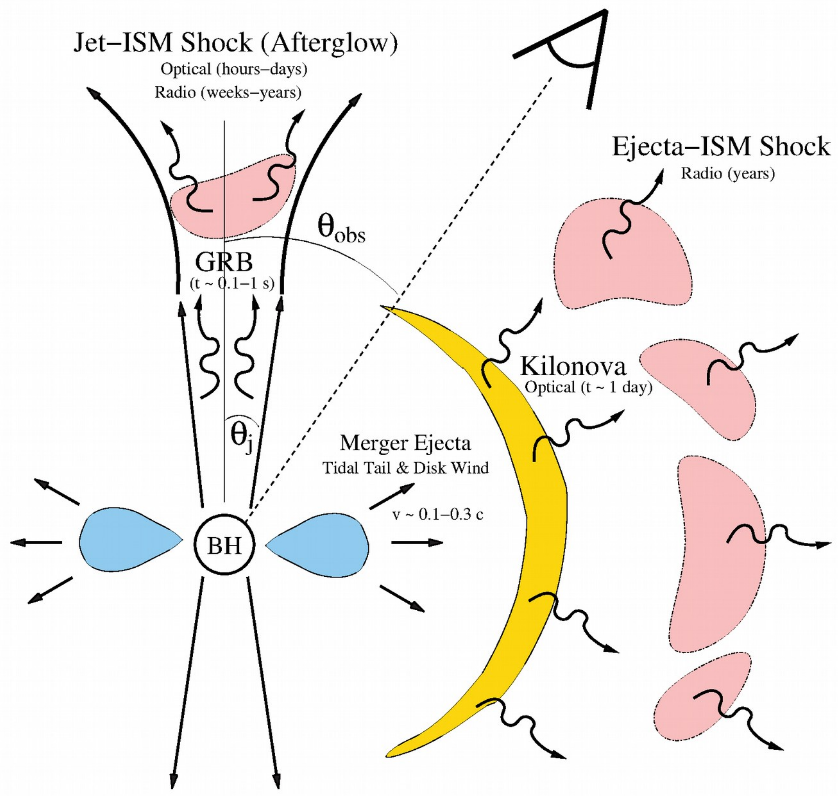


fig. B. Metzger (Living Reviews in Relativity, 2020).

Potential electromagnetic counterparts of compact object binary mergers as a function of the observer viewing angle:

Accretion of a centrifugally supported disk (blue) powers a collimated relativistic jet, which produces a short GRB.

Kilonova is powered by postmerger ejecta, but the disk wind (equatorial outflows) also contributes to lower-energy signal.

Both jet and wind are powered by the Central Engine.

Our GRMHD code with nuclear EOS

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

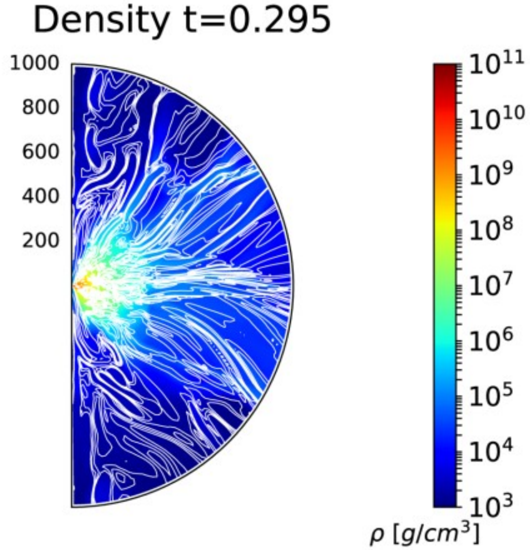
$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$

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

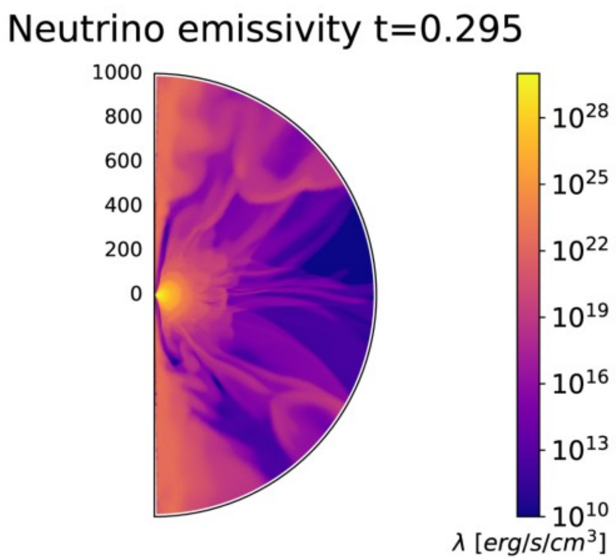
$$(\rho u_\mu)_{;\nu} = 0$$

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

Original scheme:
2D, Gammie et al.(2003)



- Hyperaccretion: rates of 0.01-10 M_S/s
- Plasma composed of free n, p, e+, e− pairs
- Chemical and pressure balance required by nuclear reactions: electron-positron capture on nucleons, and neutron decay (Reddy, Prakash & Lattimer 1998)
- Neutrino absorption & scattering, treated by grey-body approximation

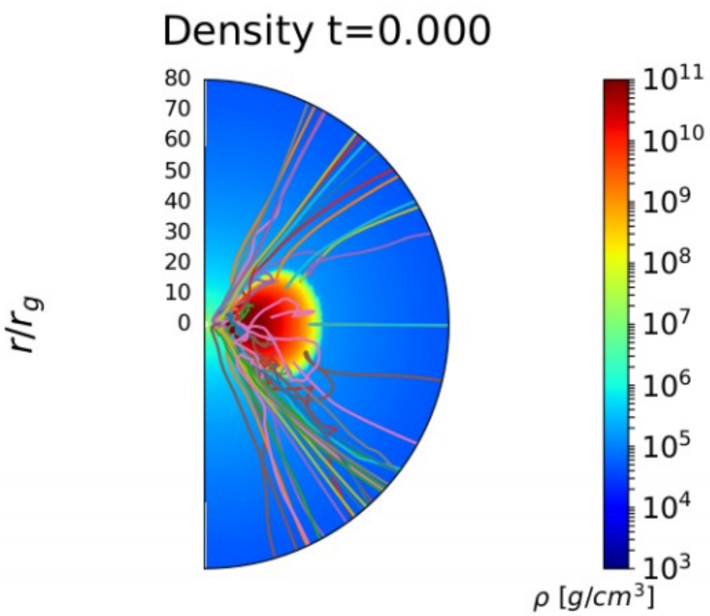


HARM_COOL code is suited for GRB: tabulated Equation of State of Fermi gas is computed numerically by solving the balance of beta reactions. Implemented into HARM scheme in Janiuk et al. (2013) and Janiuk (2017). cf. Fernandez et al. (2018)

Outflow via disk wind

HARM-COOL (Janiuk, 2017, 2019).

- Fermi-gas EOS is implemented as tables, dynamically computed and filled with pressure, and entropy values as function of density and temperature
- Hybrid MPI-Open MP parellelisation; dumps in HDF5/Ascii format



Code 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 store data about density, velocity, and electron fraction in the outflow.

https://github.com/agnieszkajaniuk/HARM_COOL

r-process nucleosynthesis

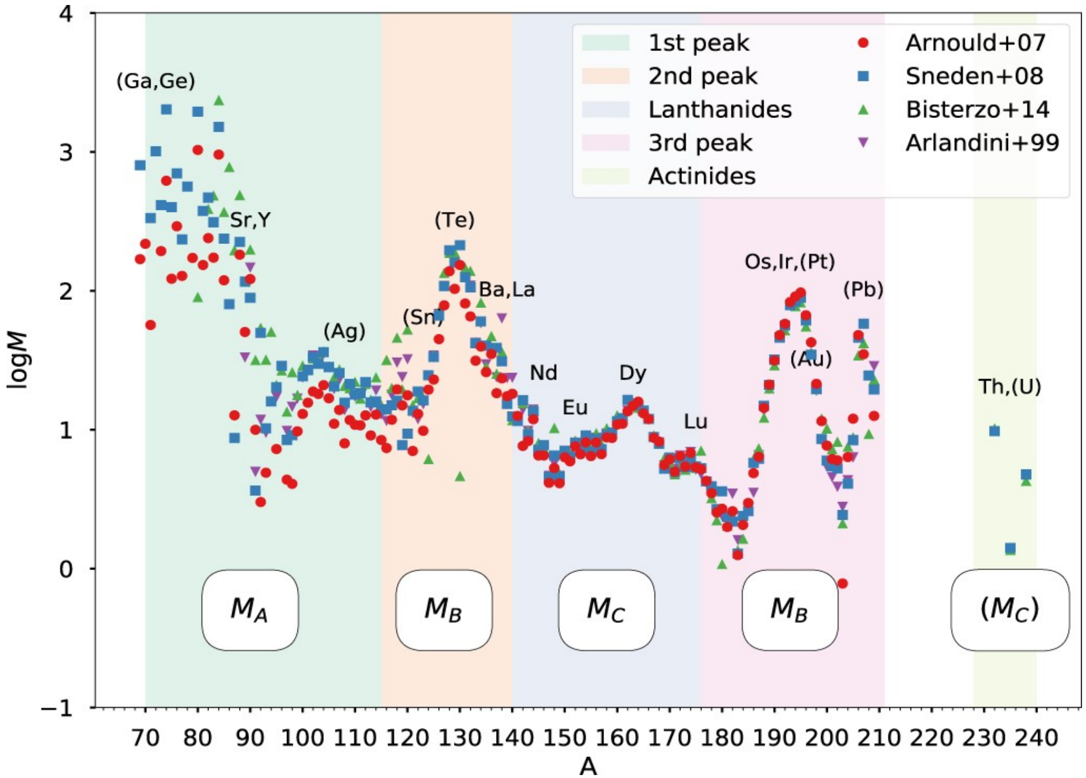
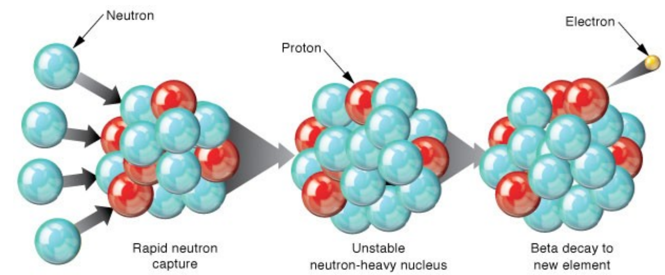


Fig. Form Ji et al. 2019



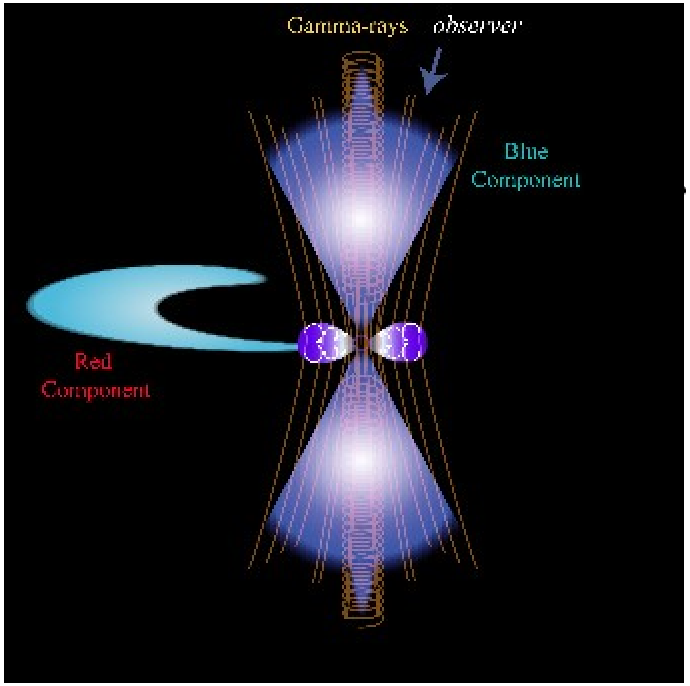
Ye > 0.25: 1st peak

Ye = 0.15-0.25: 2nd peak, Lanthanides

Ye < 0.15: 3rd peak, Actinides

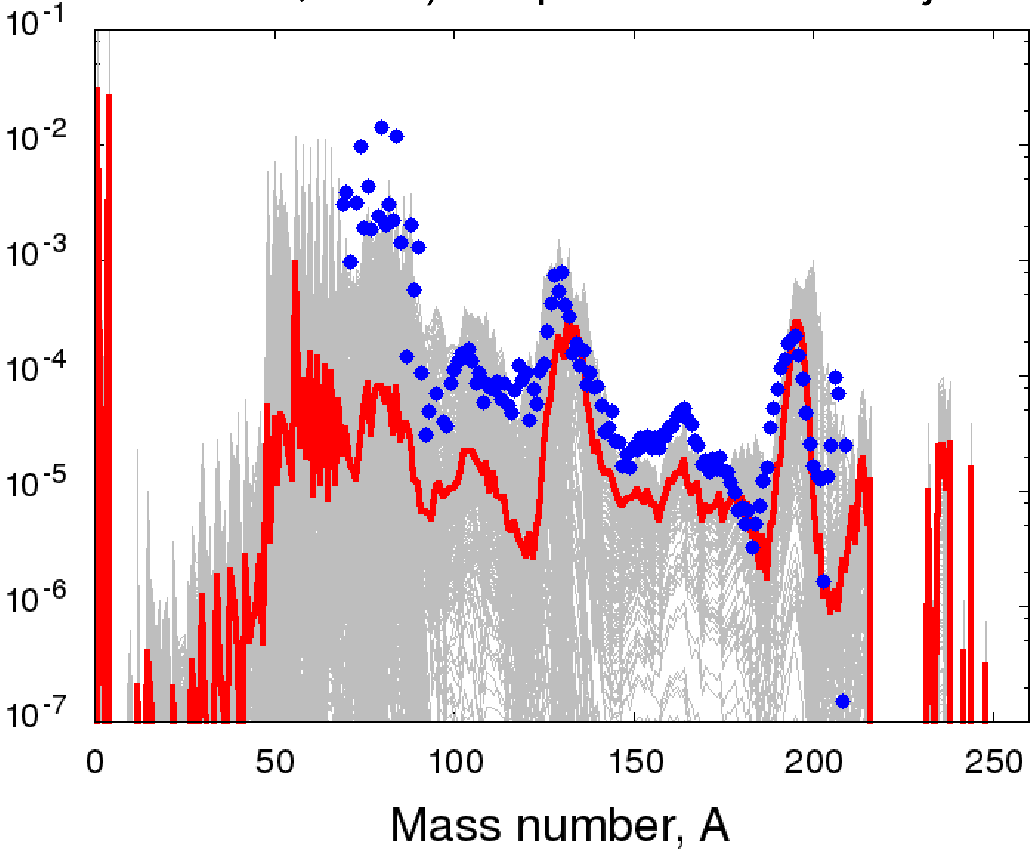
Kilonova/macronova emission can be powered by radioactive decay of massive neutron-rich nuclei (Eichler et al. 1989; Li & Paczynski 1998; Tanvir et al. 2013; Cowperthwaite et al. 2017)

Nucleosynthesis in disk wind



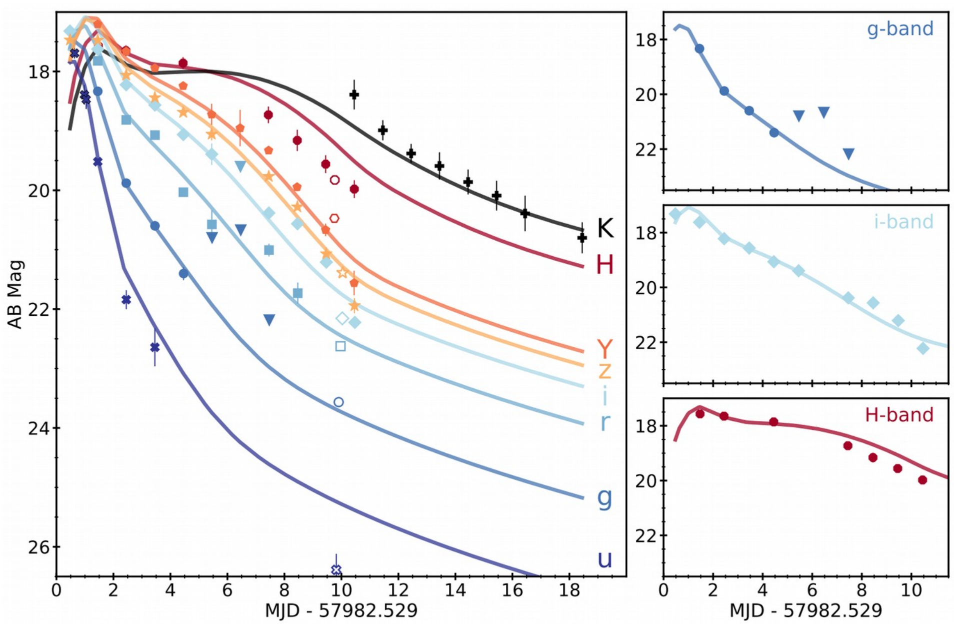
Schematic viev of post-merger system and short GRB jet in GW 170817 (Murguia-Berthier et al., 2018)

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

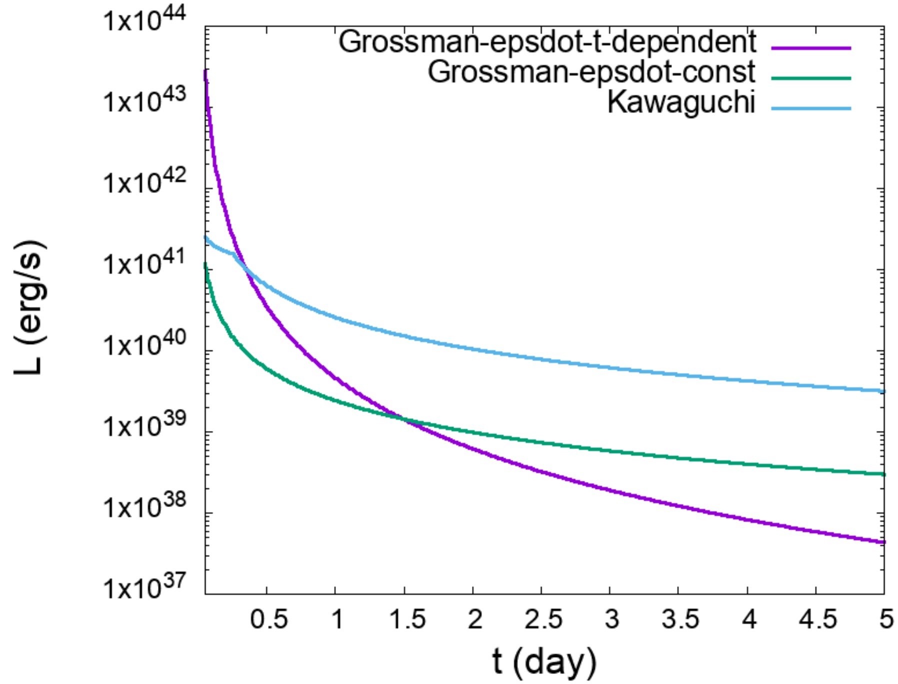


Results of simulation: nucleosynthesis in accretion disk wind (Janiuk, 2019, ApJ, 882, 163)

Kilonova lightcurve



GW 170817 observation
(Cowperthwaite et al. 2017)



Theoretical lightcurve for M_{disk}/M_{BH}=0.13, a=0.9, grey-body atmosphere

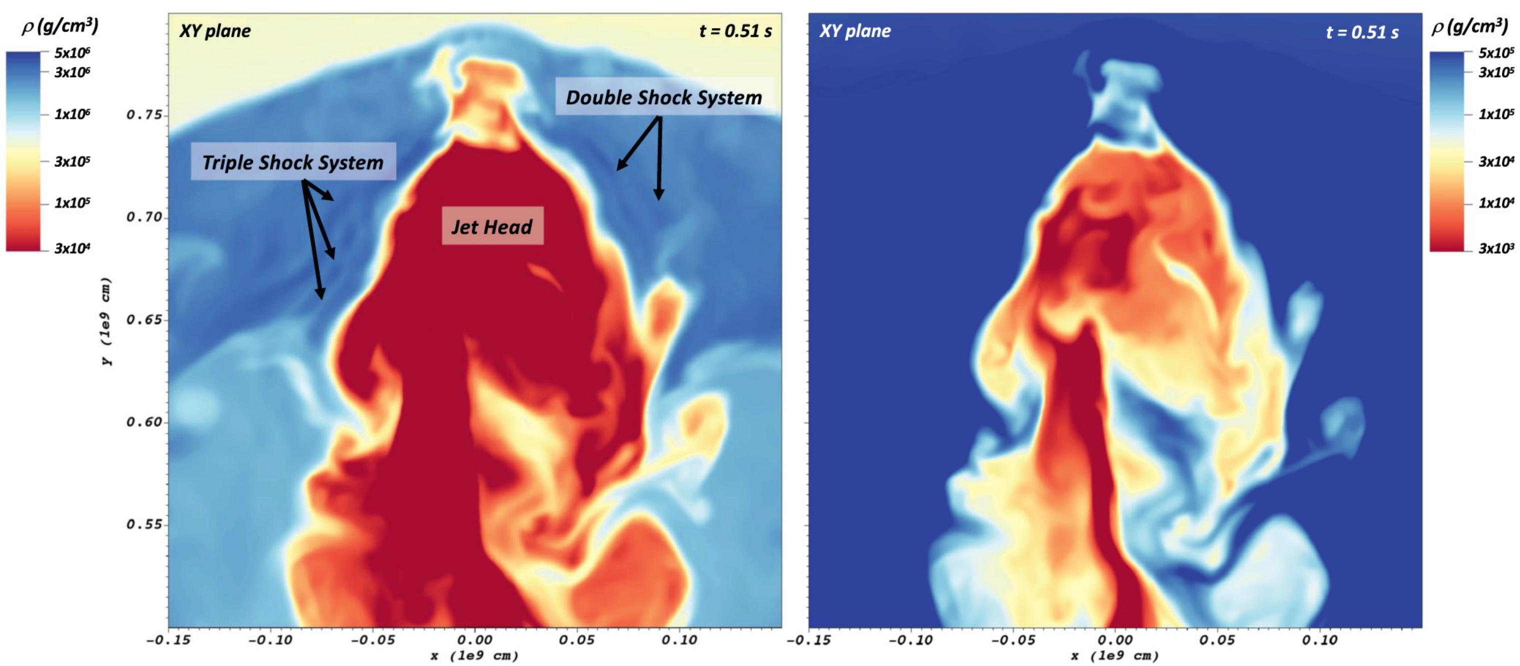
(Hossein-Nouri & AJ, in prep.)

Jet interactions with BNS ejecta

In BNS merger, the interaction of a relativistic jet with the binary ejecta shapes the structure of outflow and its radiation properties.

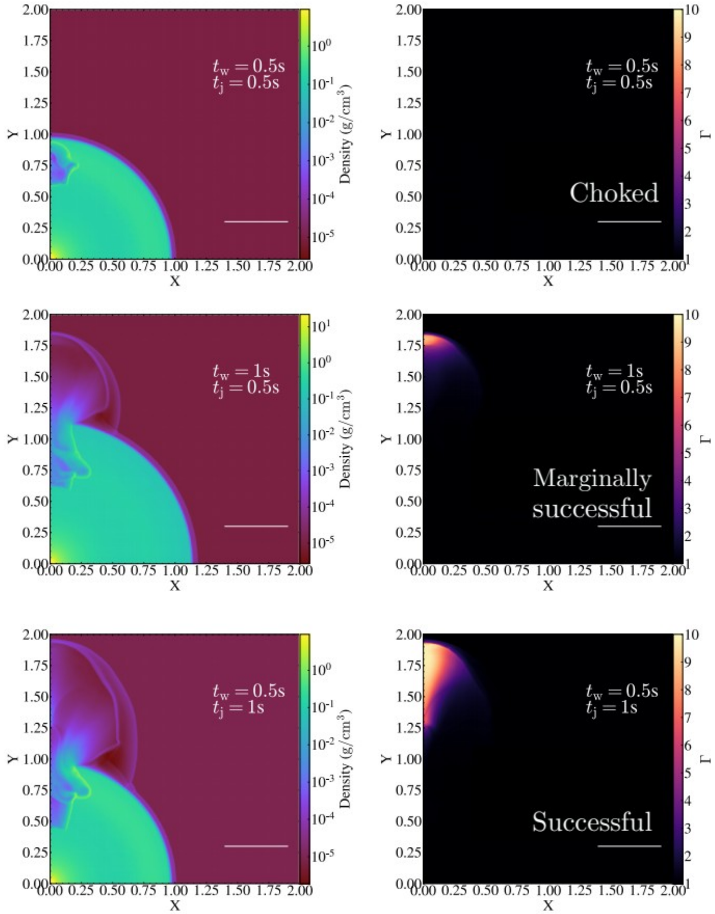
3D simulations show that jet centroid oscillates around the axis due to inhomogeneities encountered in the propagation

The breakout time is comparable to the central engine duration

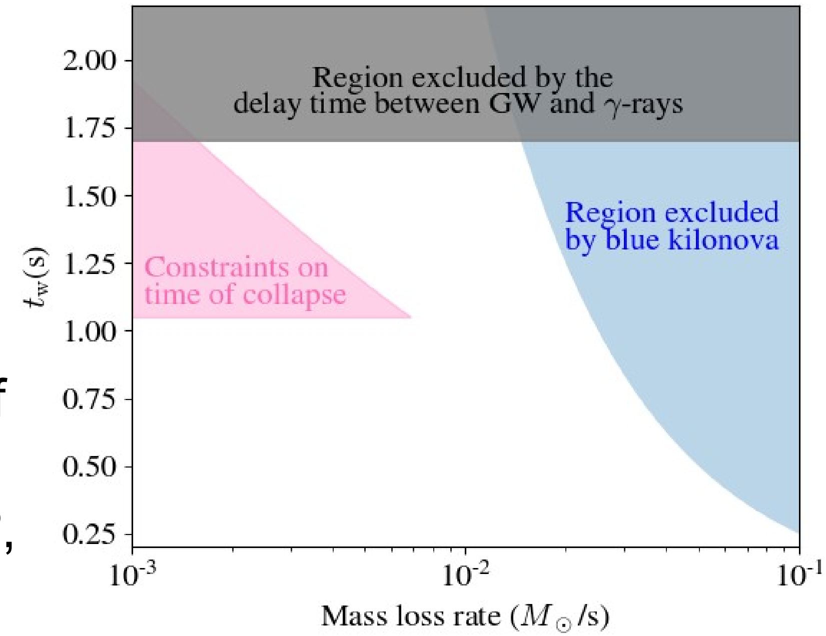


Lazzati et al., 2021

Chocked jet in GW 170817



- Expansion of the jet is affected by the properties of the wind through which it propagates
- Various models of accretion disk wind: neutrino-driven, magnetically driven



Constraints for wind time t_w as a function of mass loss. **GW 170817:** jet energy of 5×10^{48}-10^{50} erg, initial opening angle: 9-20º, Lorentz factor Γ=100-1000

(A. Murguia-Berthier, E. Ramirez-Ruiz, AJ, S. Rosswog, et al., 2021, ApJ)

Summary

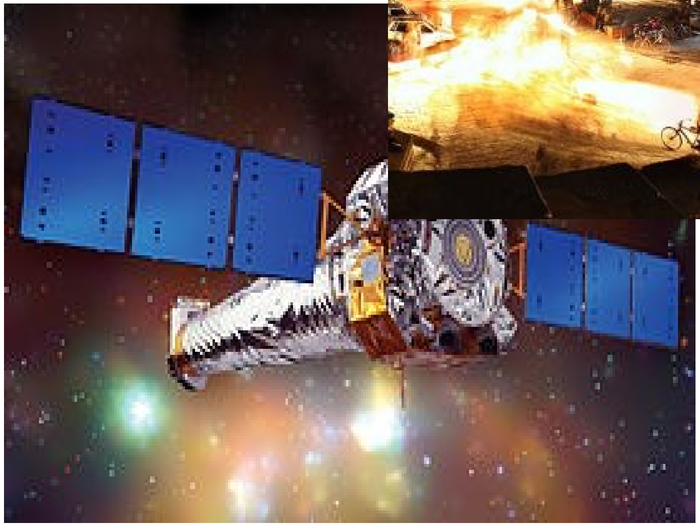
- **Jets from MAD disks are highly variable. And correspond to the variability of emission from GRB jets, quantified by PDS spectra**

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

- **The r − process nucleosynthesis in the magnetically driven accretion disk outflows can provide additional contribution to the kilonova emission, apart from the BNS merger ejecta**

- **The MHD simulations show that rotational instabilities have imprint on the variability of the jet. The same MHD mechanism drives the disk-wind.**

- **Jet interactions with wind shape its radiative properties and together with pre-merger dynamical ejecta may explain time-delay between GW and GRB signals**



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