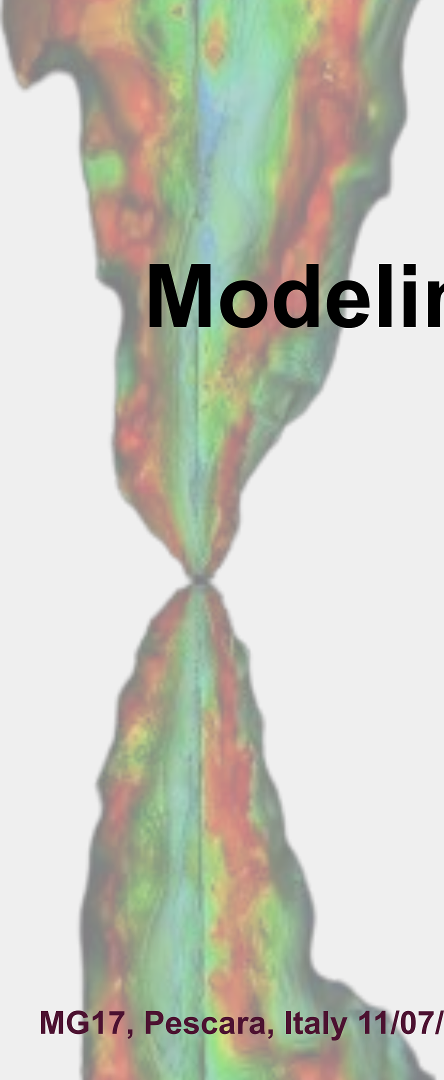

Modeling and Simulating GRB Engines; Short GRB 090510

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MG17, Pescara, Italy 11/07/2024

Origin of Short Gamma ray burst

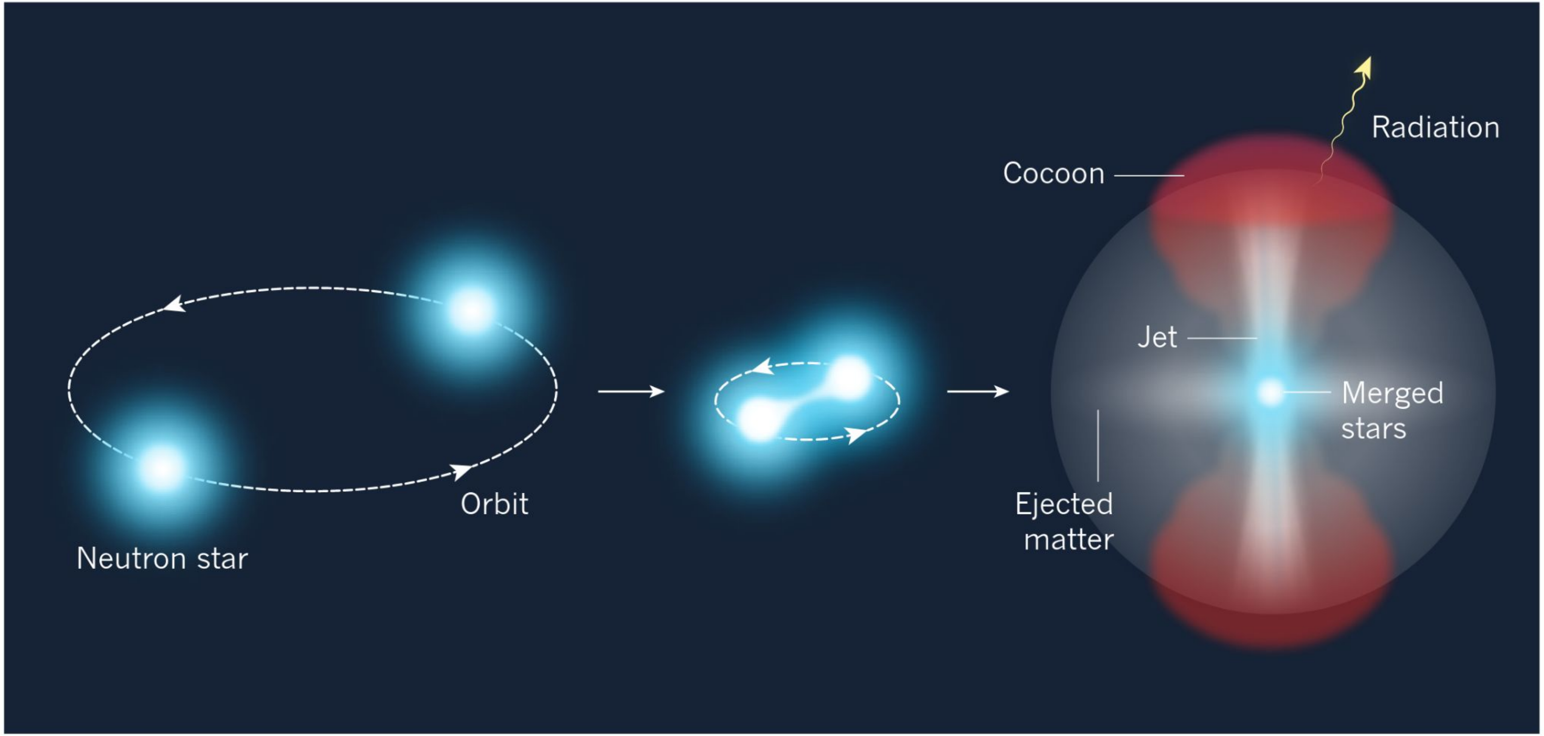


Image credit: Nature 554, 178-179 (2018)

Modeling GRBs using GRMHD Simulations

GRBs are observed as relativistic jets pointing towards our line of sight.

We explore the properties of relativistic jets produced by an accreting system around a Kerr-black → 3D General Relativistic Magnetohydrodynamic (GRMHD) simulations.

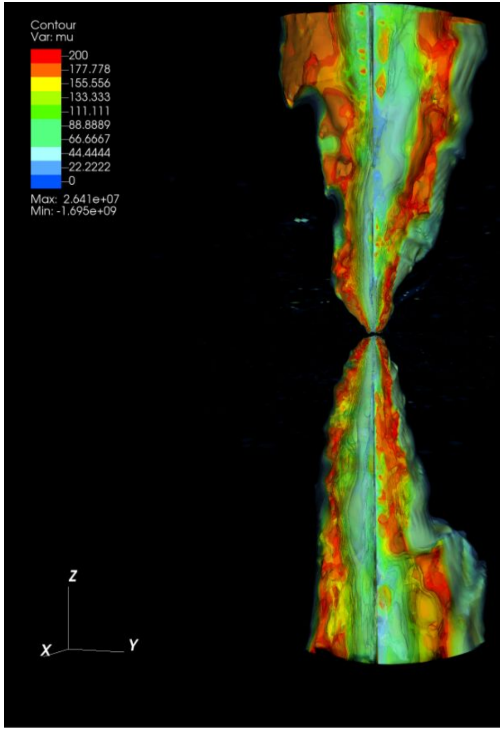
Jets of magnetized, Poynting-dominated plasma are launched from the engine on the cost of rotational energy of the black hole. (Blandford-Znajek mechanism) --> mediated by large scale magnetic fields.

Code: **HARM** *[Gammie et al. 2003, Janiuk et al., 2017; 2019]*
Kerr-schild metric, 3D, Magnetohydrodynamic

The code follows the flow evolution by numerically solving the continuity, energy momentum conservation, and induction equations in the GRMHD scheme

GR code works with c=G=M = 1 units, results scale with BH mass,

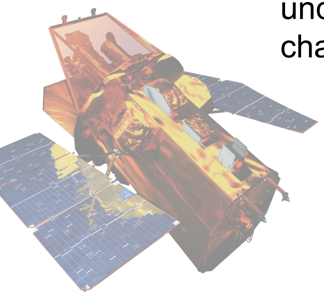
Small simulation length scales - 10^3-10^4 Rg; ~ 10^8 - 10^9 cm



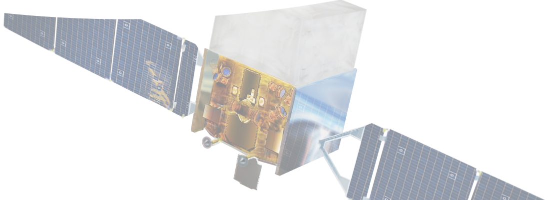
3D jet structure from HARM simulations.
Credit: Bestin James et al 2022 ApJ 935 176

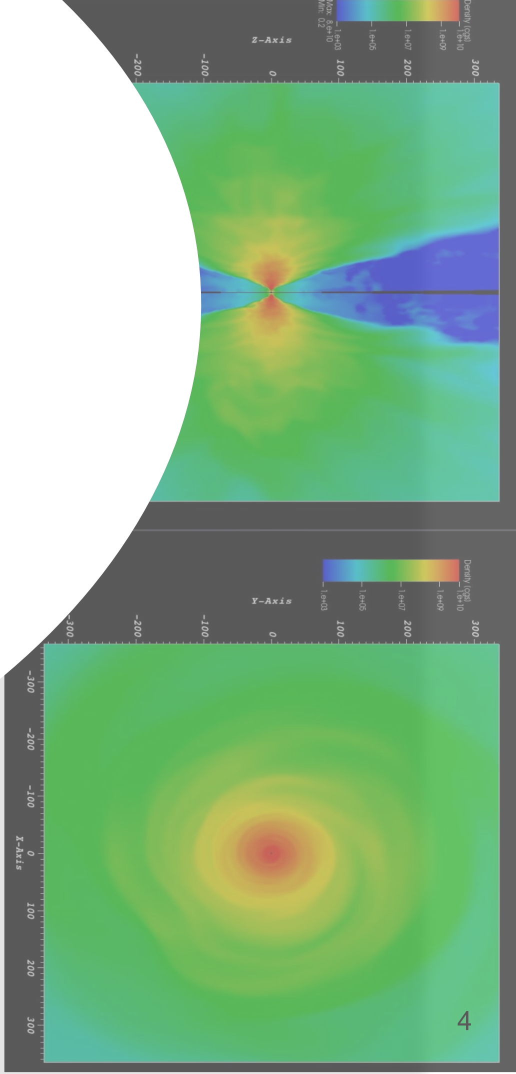
Enhancing GRB Analysis
Merging Observations & Simulations

- Understanding jet properties such as jet opening angle, Lorentz factor and variability is vital for uncovering the mechanisms behind GRB emissions and their role in the universe.
- Reliance on direct observations for these properties faces challenges due to the limited number and scope of multi-wavelength observational campaigns.
- Simulations provide a complementary approach, enabling us to explore jet dynamics beyond the constraints of observational data and develop a comprehensive model of GRB behavior.
- By integrating simulations with observations, we can achieve a more nuanced understanding of GRB jets, enhancing both the accuracy of jet characterizations and the predictions for unobserved bursts.



Fermi
Gamma-ray
Space Telescope





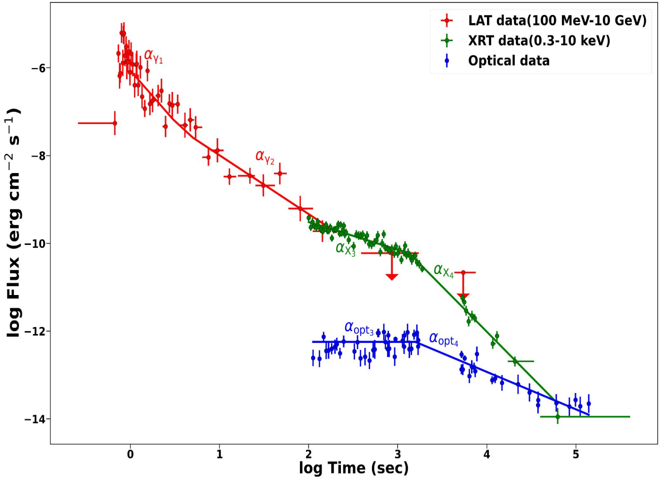
GRB 090510 - overview

Short GRB; Duration (T90): ~0.6s *(50-300 KeV) {GBM NaI3}*
With major LAT emission falling between 0.5-1s

Redshift: **0.903**

Spectral analysis; Fermi Lat collaboration (Ackermann et al 2010)
Time Interval: T0 + 0.5s to T0 + 1.0s
Best Fit Model: Band + power law component

Total bolometric luminosity
Fermi GBM+LAT [10 to 30 GeV] + Swift XRT [0.3-10] = 4×10^{53} erg/s



flux light curve of GRB 090510 observed in γ-rays, X-rays, and optical.

GRB 090510 - opening angle & Variability

Detailed multiwavelength observations required to accurately determine opening angle ((Ghirlanda et al. 2004; Lu et al. 2012; Fong et al. 2015; Goldstein et al. 2016))

But most of the times, these are difficult to attain

We employed an analytical estimate of the jet opening angle
Derivation based on $E_{peak} - E_{\gamma}$ relation (Ghirlanda et al. 2004) & Epeak − Eiso relation (Amati et al. 2002, 2009);
Described in Pescalli et al. (2015)

$$\cos\theta_j \approx 1 - \frac{5.078 \times 10^{11}}{E_{\rm iso}^{0.263}}.$$

Lloyd-Ronning et al. (2019), gives an expression for opening angle - redshift evolution. we correct for the highly statistically significant (≈ 5σ) anti-correlation between jet opening angle and redshift, The correction for redshift evolution using the functional form is a valid approach to account for the observed anti-correlation between jet opening angle and redshift.

$$\theta_{\rm jet} \approx (1+z)^{-0.75\pm0.2}$$

For the Eiso and redshift values; this results in an opening angle of **10-12** degrees for GRB 090510

GRB 090510 - Variability timescale

090510 light curve exhibit strong temporal variability.

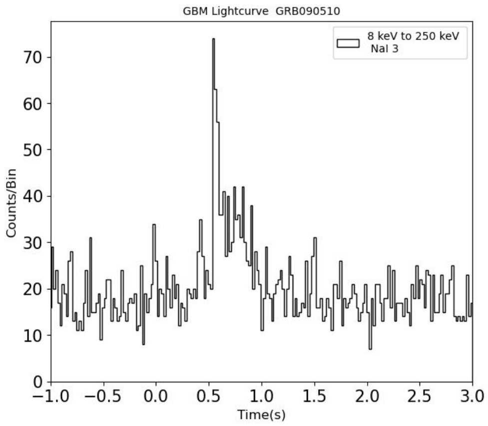
The Bayesian Block (BB) method detailed in Scargle et al. (2013) is employed in the light curve of the GRB to calculate minimum timescale variability (MTS).

BB →Divide lightcurve into various time intervals of dynamic time widths
→The width of the least longer time bin is considered as MTS

→Counts rate lightcurve from brightest NaI detector of Fermi GBM [10 KeV to 250 KeV] for 090510 used to calculate MTS

→GBM MTS; GRB 090510; BB Method= **28 ms.**

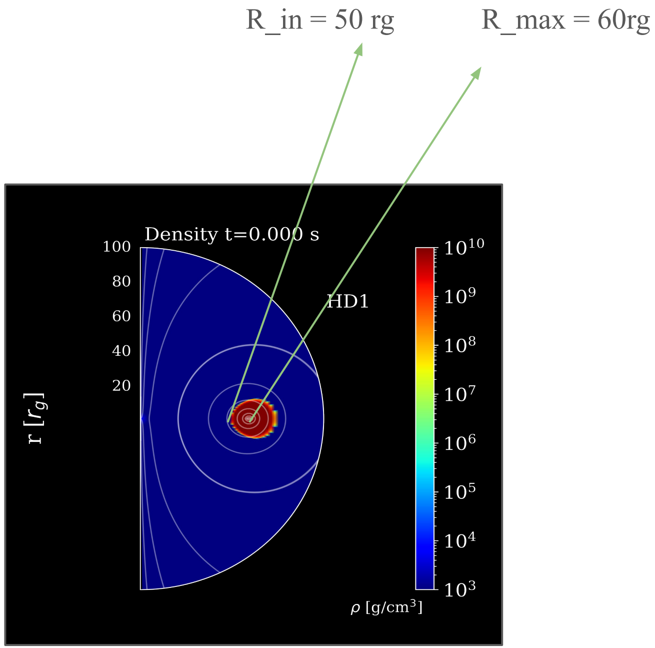
Fermi Lat collaboration (Ackermann et al 2010) : 090510 minimum variability estimates
LAT MTS: **20 ms**
GBM MTS: 06-0.8s - **14 ms**
[full-width at half-maximum of the shortest pulse measured in any of the detectors for a given time interval]



Counts lightcurve of brightest detector for Fermi-GBM observations of GRB 090510

Simulations setup - Accretion Disk and Magnetic Field

- Accretion disk configuration → Fishbone-Moncrief (FM) torus
- Fishbone & Moncrief (1976) torus : An equilibrium solution for a rotating torus of fluid in the gravitational field of a black hole.
- Embedded with poloidal magnetic field
- In the FM torus, position of the material reservoir is determined by the radial distance of the innermost cusp of the torus, r_in, and the distance where the maximum pressure occurs, r_max.
- Kerr BH with a given spin will accrete matter onto it due to the development of the magnetorotational instability (MRI) in the disk, which will, in turn, affect the evolution of the disk and magnetic field.
- The accretion process drives the formation of bi-polar relativistic jets of plasma that are dominated by the Poynting flux.



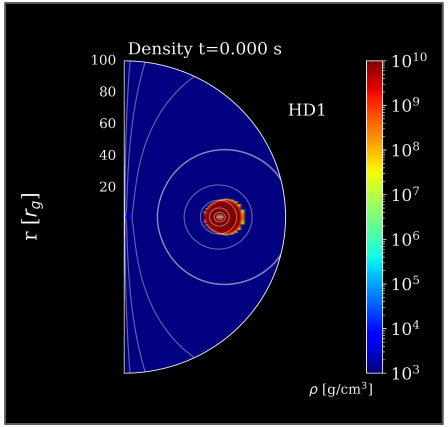
Field Configuration

- Type: Poloidal magnetic field.
- Form → magnetic field produced by a circular current. The only non-vanishing component of the vector potential in such a configuration is given by

$$A_\phi(r,\theta) = A_0 \frac{\left(2-k^2\right) K\left(k^2\right) - 2E\left(k^2\right)}{k\sqrt{4Rr\sin\theta}}$$

$$k = \sqrt{\frac{4Rr\sin\theta}{r^2+R^2+2rR\sin\theta}}$$

- A0 → constant to scale the magnetic field and the β-parameter across the initial torus, E, K → complete elliptic functions



- **σ** → magnetization parameter.
  → quantifies the degree to which a flow is influenced by magnetic fields.
  (ratio of the Poynting flux to the matter energy flux)

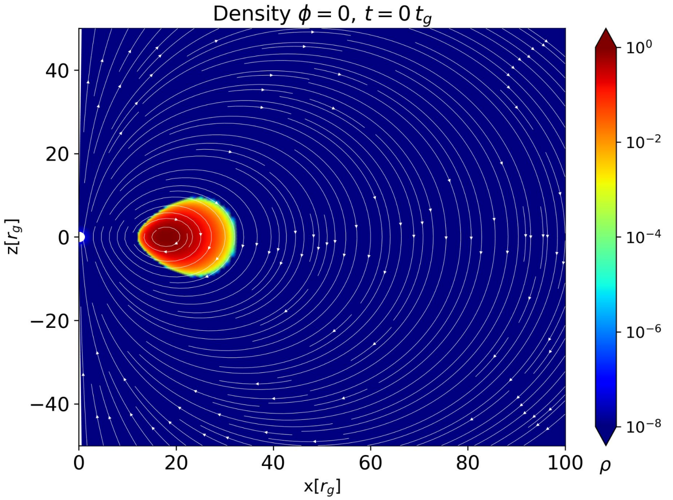
- **μ** → The jet energetics parameter
  → ratio of the total energy flux to the mass flux.
  [T^r_t is the radial energy component of the energy-momentum tensor, ρ is the gas density and u^r is the radial velocity].

$$\sigma = \frac{(T_{em})^r_t}{(T_m)^r_t} \quad \mu = -\frac{T^r_t}{\rho u^r}.$$

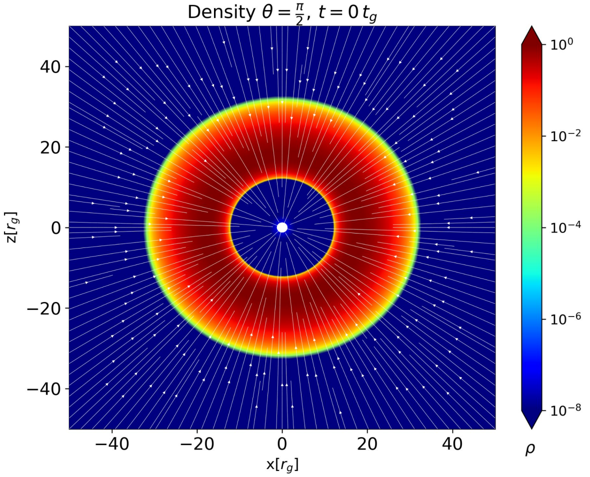
Model: HD-0.1-200-3D

Model Description	
Accretion disk	Fishbone Moncrief
Rin, Rmax	12,18 (rg)
BH Spin	0.95
beta	200
M_disk	0.10 M_{sun}

Density Profile with Magnetic Field
3D Model



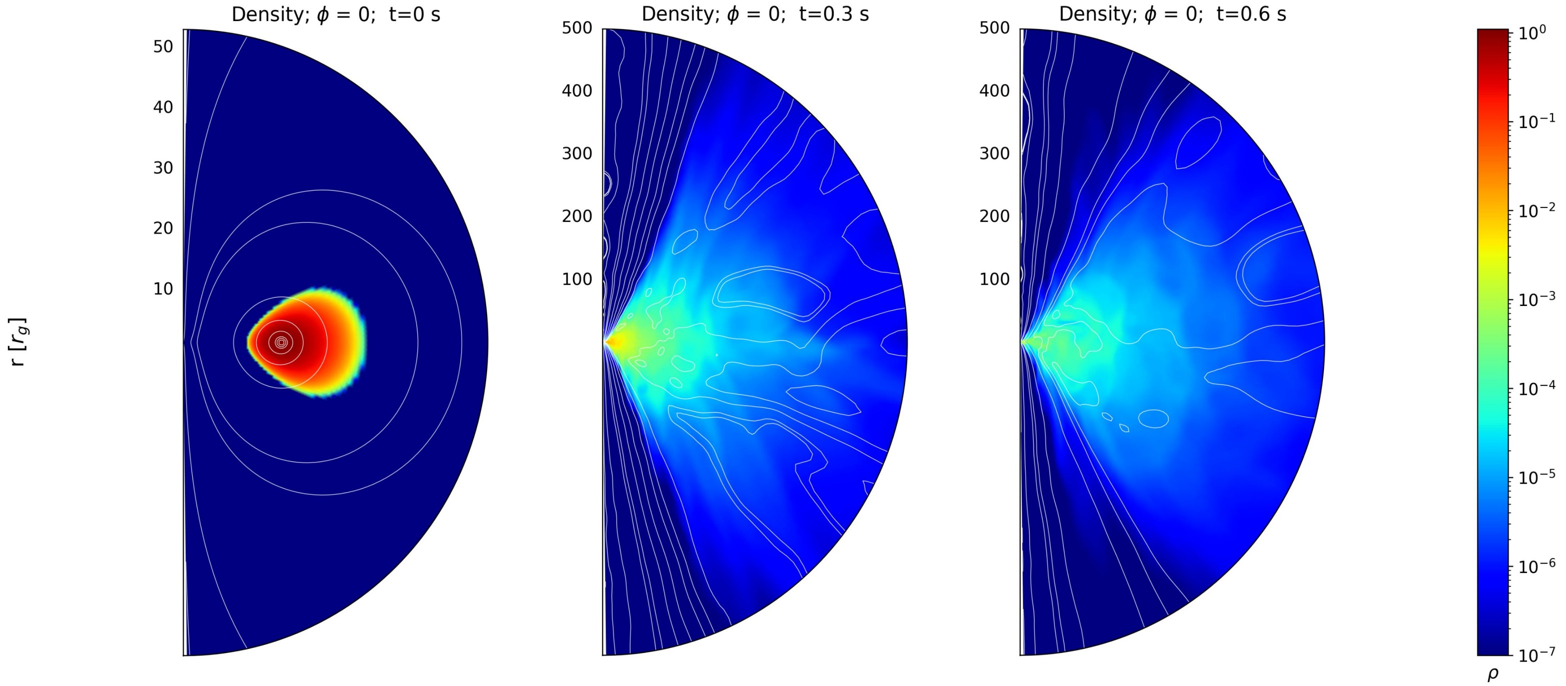
Cross section view



Top down view

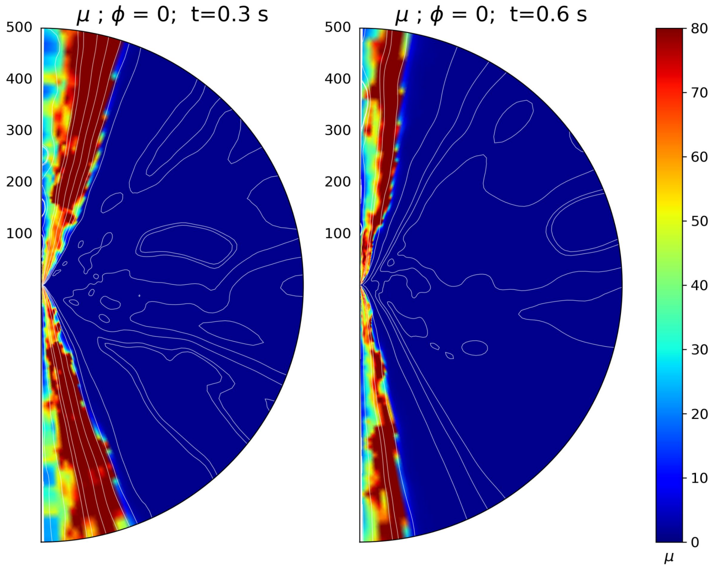
Simulation is run for the duration of 0.6s
Resolution:256x128x64

Density Profile with Magnetic flux contours
3D Model (ϕ = 0 slice)

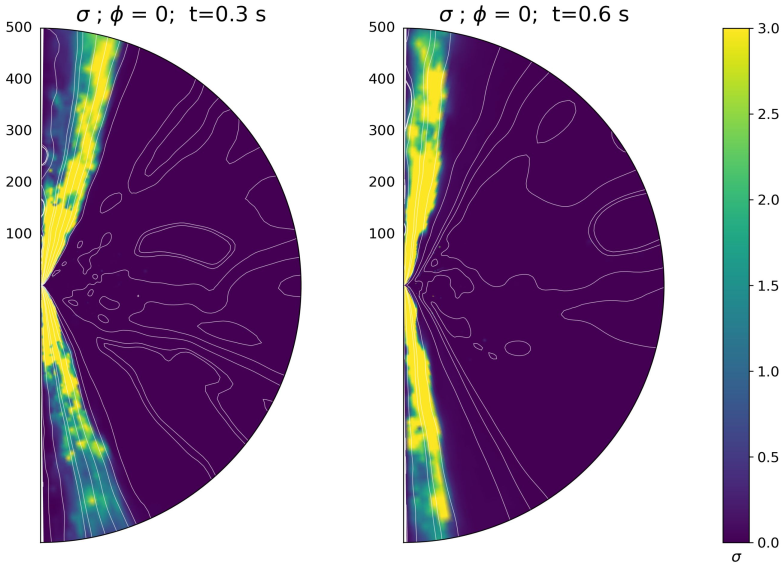


Model: HD-0.1-200-3D; Time evolution of jet structure

Jet energetics parameter; μ



Jet magnetisation parameter; σ

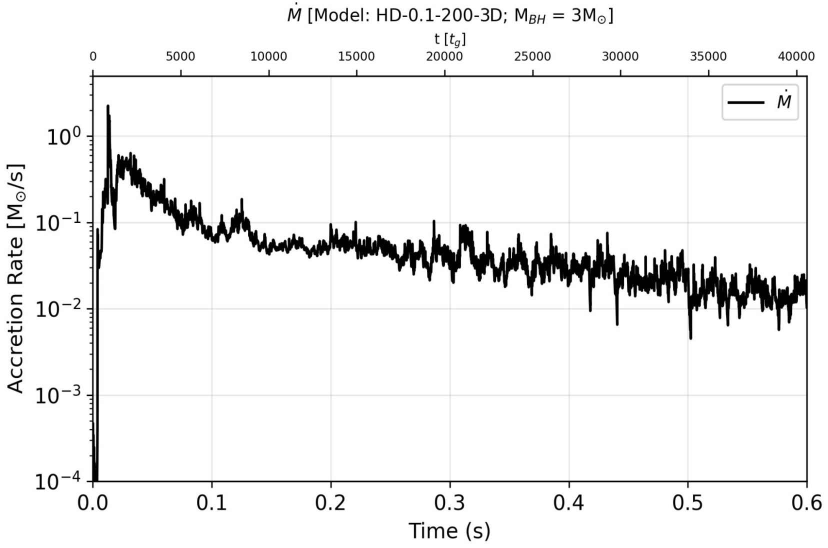


μ → Represents the total specific energy in the jet, including contributions from kinetic, thermal, and electromagnetic energies.

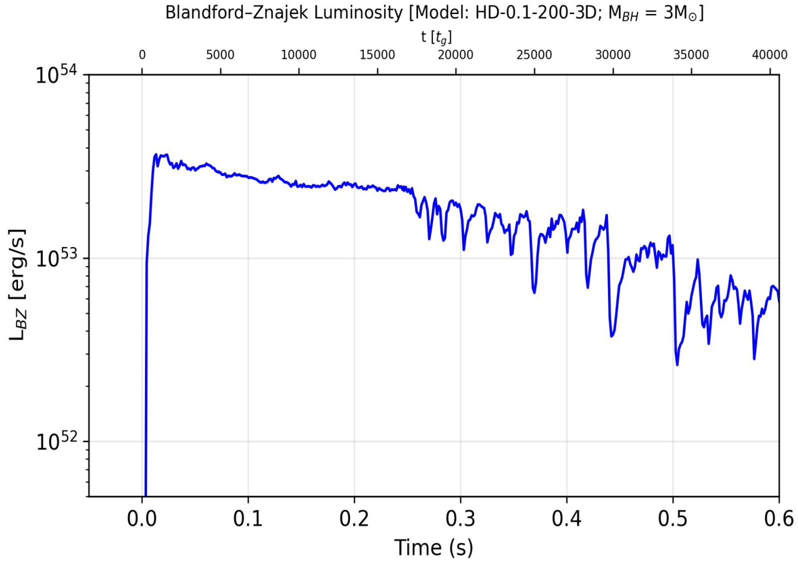
σ → a measure of the ratio of electromagnetic energy density to matter energy density; σ≫1 region indicates a magnetically dominated jet region

High values of both σ and μ lead to more efficient acceleration of the jet, achieving higher Lorentz factors and resulting in more energetic GRBs. These parameters better represent a poynting dominated jets as in our case

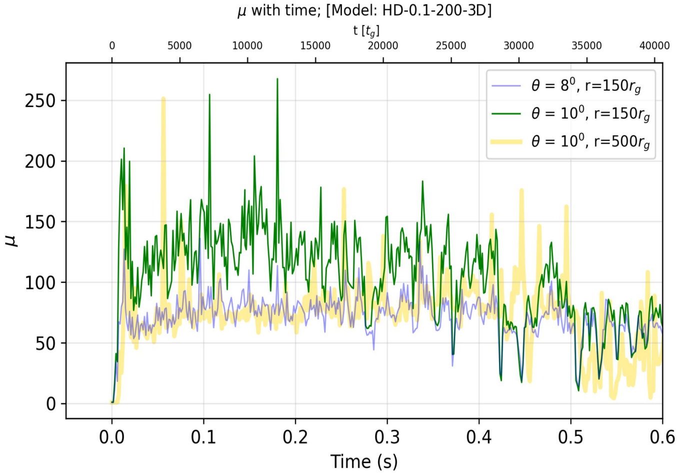
Mass accretion Rate



Luminosity

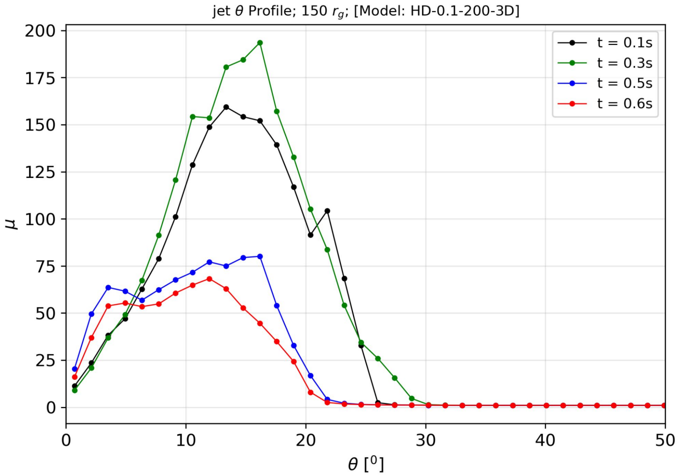


$$L_{BZ} = \int_0^{2\pi} \int_0^{\pi} d\theta d\phi \sqrt{g} T_t^r$$



Lorentz Factor (0.1s to 0.6s)		
r	θ	Lorentz factor
150	8	70.7
150	10	100
150	12	110

Lorentz factor of jet is considered to be the time average of mu at different chosen locations in the jet

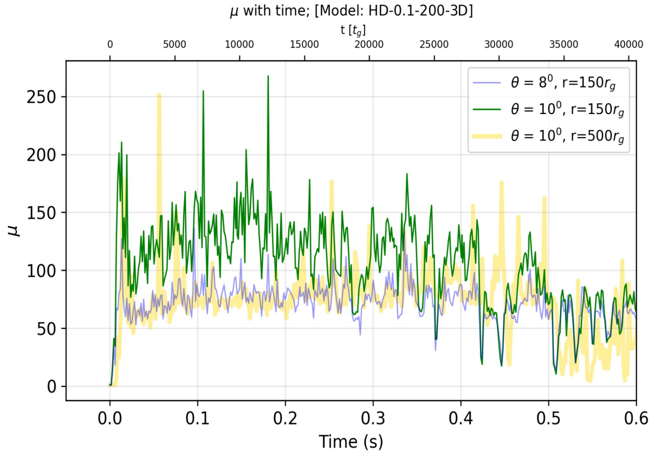


Jet Opening angle		
r	Time	Opening angle
150 500	0.1s to 0.6s	19.43 16.54
150 500	0.3s to 0.6s	17.12 15.06
150 500	0.5s to 0.6s	16.49 11.80

The opening angle of the jet is determined by calculating the value of θ that encompasses 75% of the total energy of the jet.
Involves measurement of the angular distribution of the jet's energy,

Jet Variability Analysis from HARM Simulation

- The high inhomogeneity of the outflow is present in all the quantities but its implication is better illustrated in the μ and σ.
- Variability in a jet can be influenced by fluctuations in the energy distribution along the jet or changes in the jet's acceleration and speed. Since μ represents the total energy available to the jet, variations in μ could reflect changes in these dynamics, potentially causing observable variability in the jet's emission.
- We choose multiple points in jet outflow, and study the time resolved variability of jet energetics parameter. [150 rg, 8^0 & 10^0]
- These points are chosen close enough so that the logarithmic scale of our grid is dense enough to describe the outflow reliably.
- Employing the methodology used by (Ackermann et al 2010) for 090510 MTS estimation; [FWHM of the shortest pulse] in the time evolution of μ
- We calculate an average MTS estimate of 2.5 ms. This falls to the lower limit of MTS of short GRB from observations.
- [Golkhou et al. (2015) median minimum timescale for short GRBs : 10 ms.]

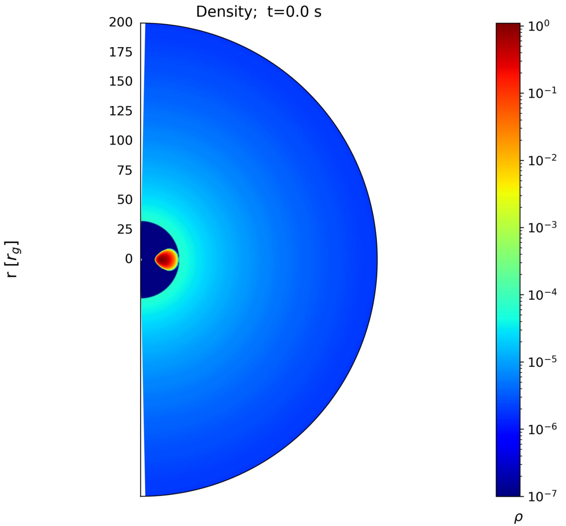


3D Model Summary

Model	R_{in},R_{max} (rg)	a	β	M_disk (M☉) (t=0s)	M_disk (M☉) (t=0.6s)	Resolution	L_BZ max (erg/s)	Final jet angle	Lorentz Factor	Liso (1-10% η) (erg/s)
HD-0.1-200-3D	12,18	0.95	200	0.10	0.040	256*128*64	3.5×10^{53}	12	110	1.6-16 x 10^{53}

Collimation of Jets in GRMHD Simulations

- Collimating jets produced from GRMHD simulations to narrower angles presents significant challenges
- observational analysis have calculated opening angles as small as 1^0 to 10^0
- **Density Profiles**: Utilizing density profiles with varying distributions that simulate post-merger environments is a proven method for effective jet collimation. *[Gottlib et al. (2022), Valeriia Rohoza et al. (2024)]*
- **Simulation Parameters**: Our approach involved a series of 2D simulations, incorporating maximum densities of 10^{-4} and 10^{-5} in code units, along with power-law distribution indices of 2 and 5.
- **Results:** The incorporation of these density profiles successfully collimated the jets, reducing the opening angles to a range of 1^0-2^0.
- Further investigations and simulations are currently underway to refine our understanding and enhance the precision of jet collimation techniques.



Conclusions

- We implement a 3D GRMHD simulation to simulate a central engine that give GRB-090510 energetics and opening angle.
- The simulation results give a detailed information about the jet structure, variability and behaviour in context of short GRB.
- The simulated jet is capable of producing an L_{iso} of $3x10^{53}$ erg/s in an opening angle of 12^0
- We have studied how different models of ambient density medium will affect the opening angles for these jets. 2D simulations with an added radial power law density profiles is found to collimate the opening angle of the jet by 1^0-2^0

THANK YOU