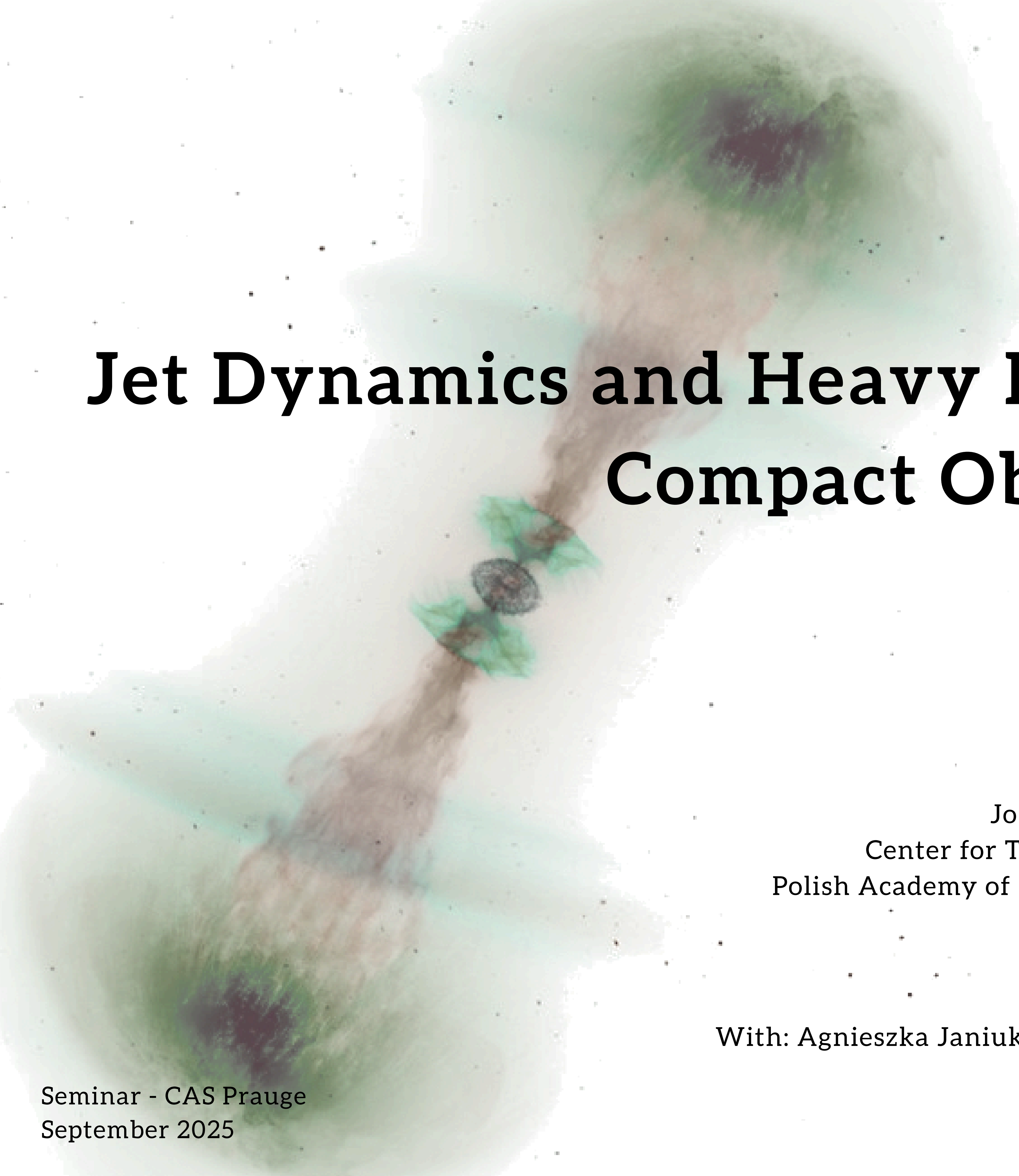


Jet Dynamics and Heavy Element Nucleosynthesis in Compact Object Mergers

Joseph Saji
Center for Theoretical Physics
Polish Academy of Sciences, Warsaw, Poland

With: Agnieszka Janiuk & Gerardo Urrutia (CFT-PAN)

Narodowe Centrum Nauki

Seminar - CAS Prauge
September 2025

Short Gamma Ray Bursts (SGRBs)

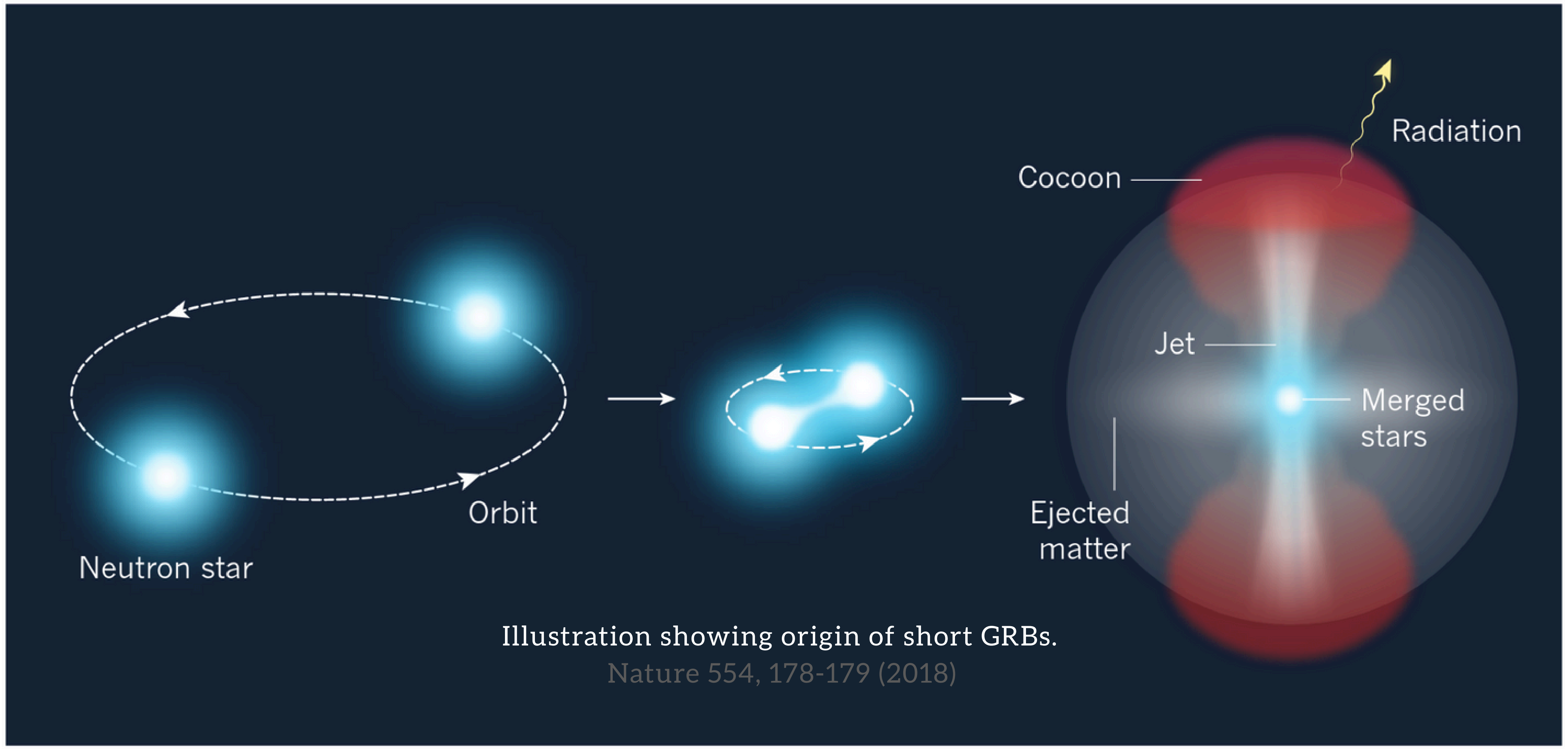


Illustration showing origin of short GRBs.
Nature 554, 178-179 (2018)

Transient event that originates from the merger of compact objects; NS-NS; NS-BH (<2s)

<u>Post-merger environment</u>
Black-Hole + Accretion Disk + Disk Wind + Dynamic Ejecta + ultra relativistic jet (GRB)

Outline of the Talk: A Tale of Two Outflows

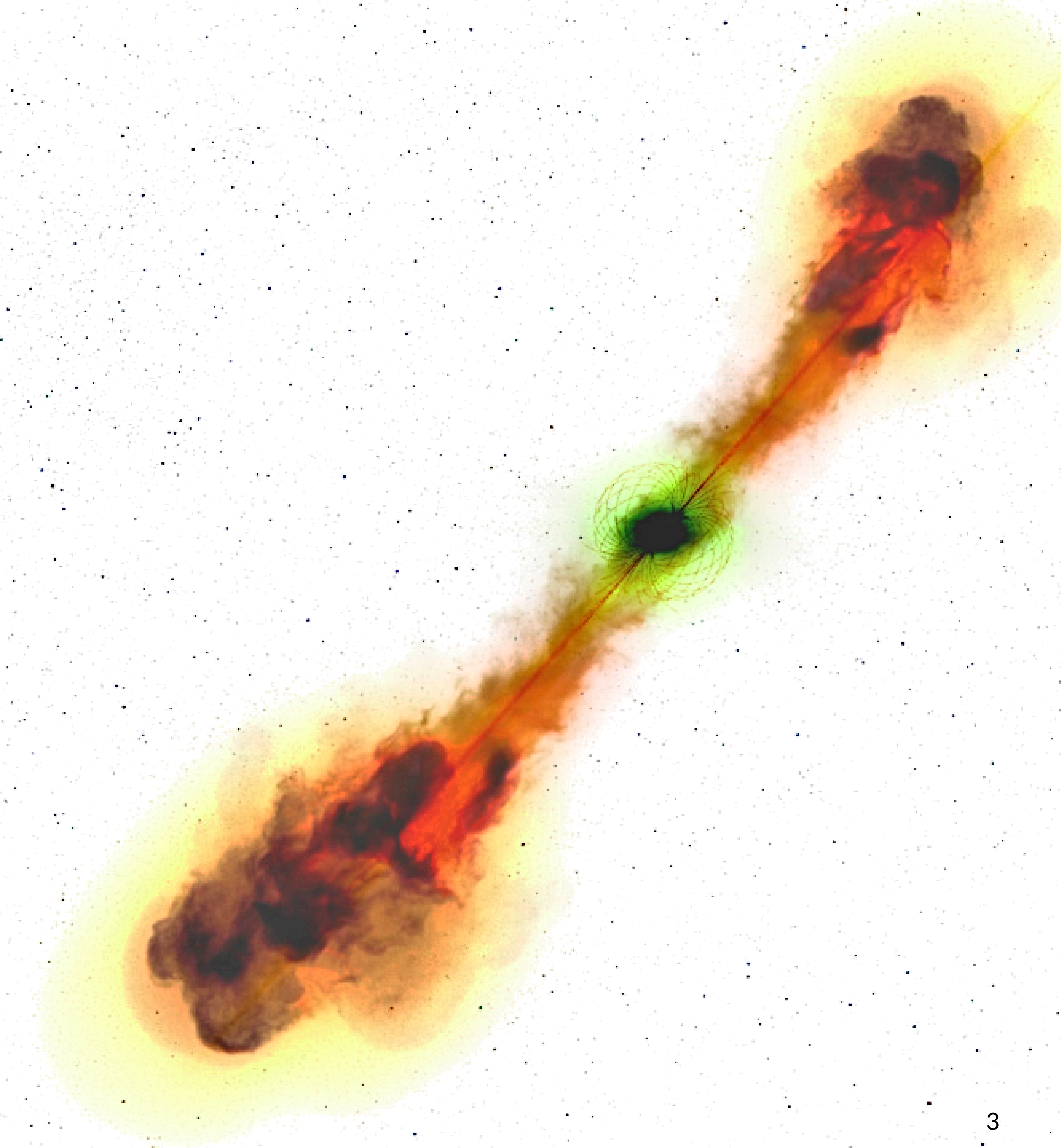
The Central Engine:
Aftermath of a compact object merger

Part I: The Jet — Decoding a Gamma-Ray Burst

- Explain the structure, energetics, and variability of the relativistic jets we observe as short GRBs
- Method - GRMHD Simulations
- Targeted Study on GRB 090510

Part II: The Wind — Forging the Heavy Elements

- Role of multiple ejecta in the aftermath of a merger in shaping the elemental abundance of the universe
- Method - GRMHD simulations (Composition dependent EOS + Neutrino treatment) & Nuclear Reaction network postprocessing



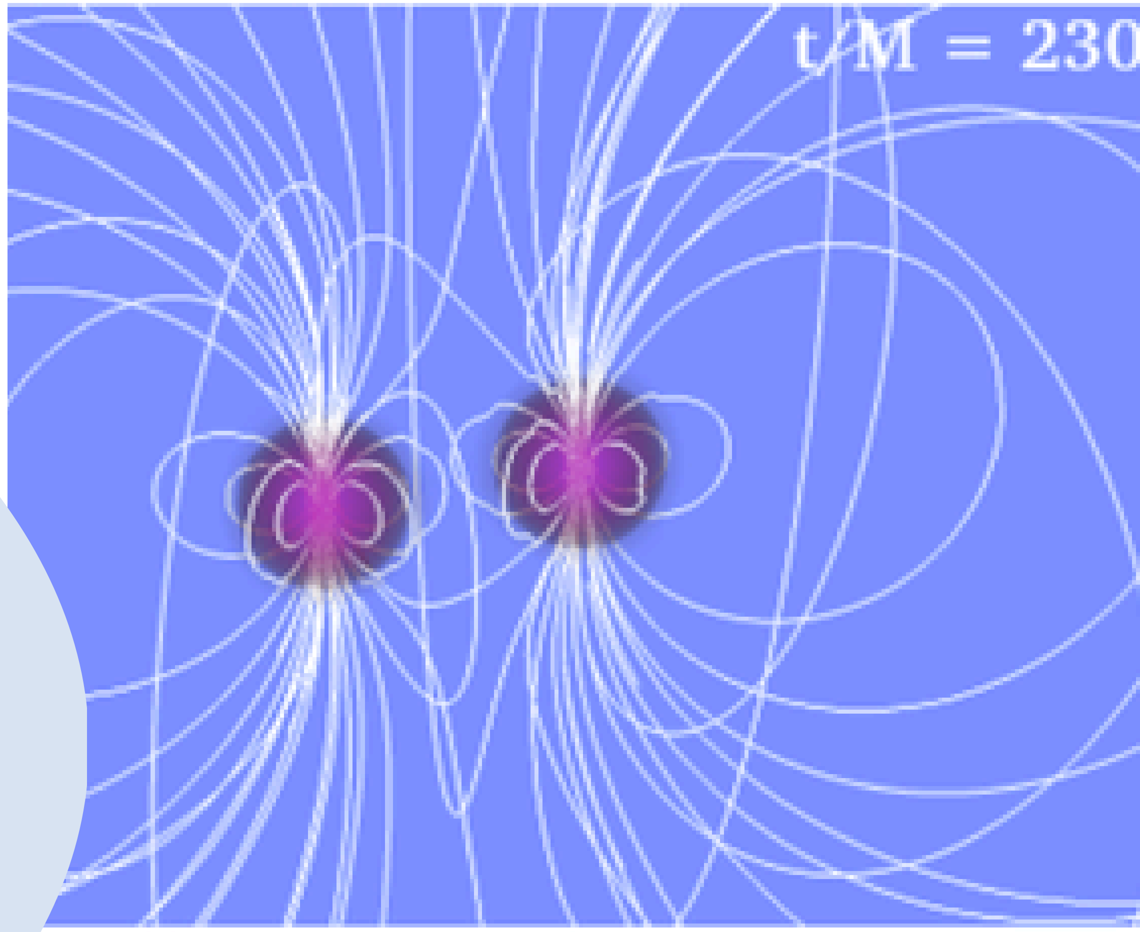
Gamma Ray Bursts
Combining Observations & Simulations

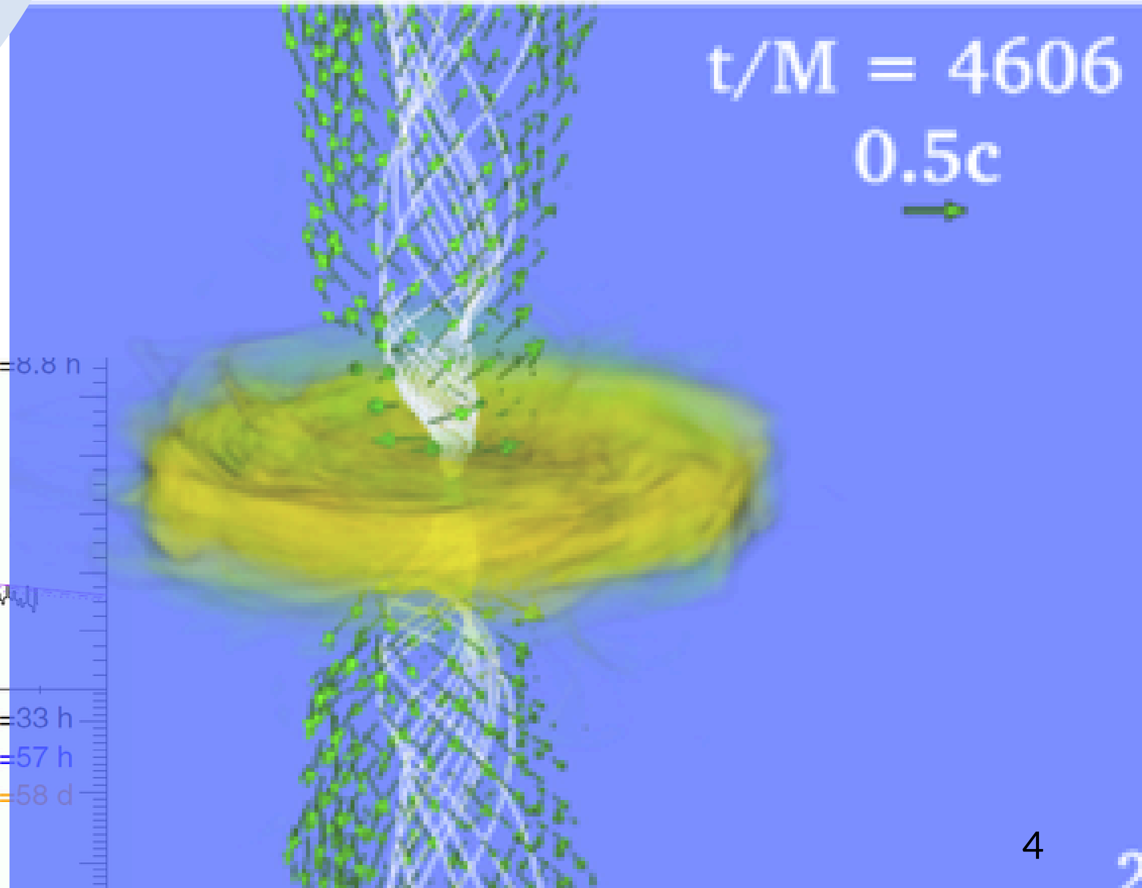
Decades of Observations (1970s → ; Batse, Swift, Fermi etc)
- Despite vast data, key questions in jet physics remain unanswered.

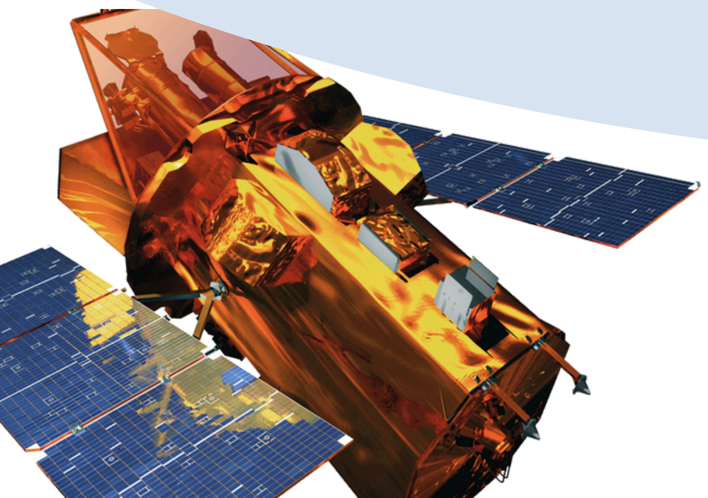
Physical Jet Properties
- Lorentz factor, opening angle, & variability timescales are crucial to understanding GRB engines.

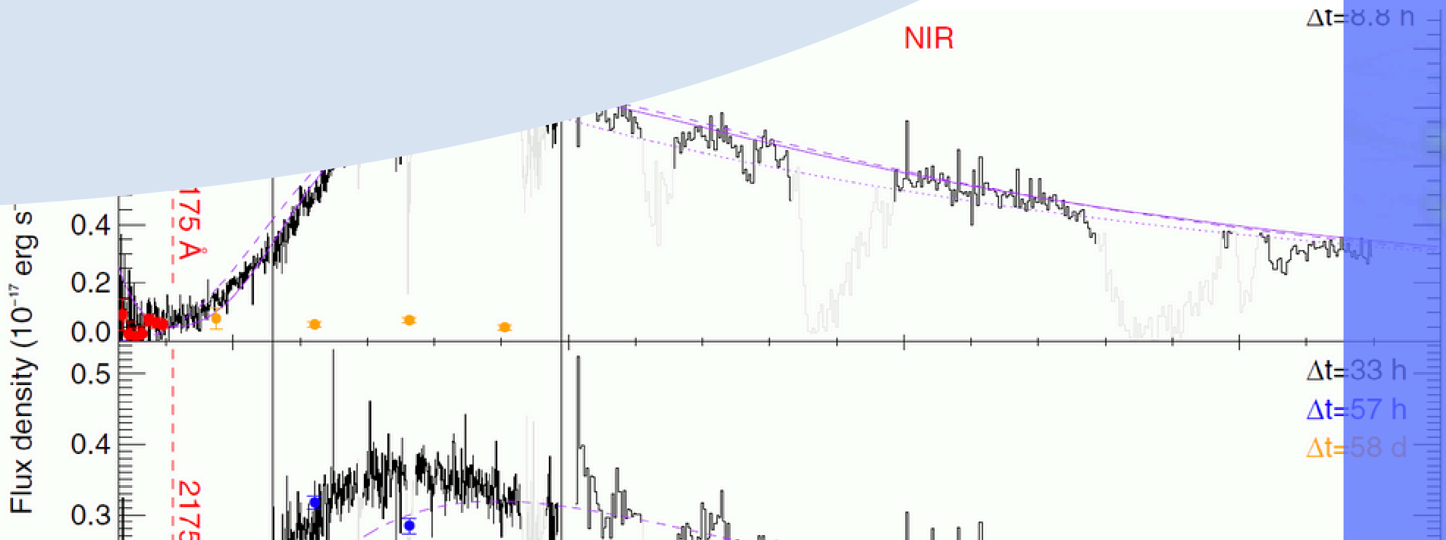
Observational Challenges
- Limited multi-wavelength coverage and opaque central engine

Role of Simulations
- Extend beyond observational limits, exploring jet formation and evolution under extreme conditions.
- Provide “controlled experiments,” enabling systematic parameter studies and insight into unobservable regimes.





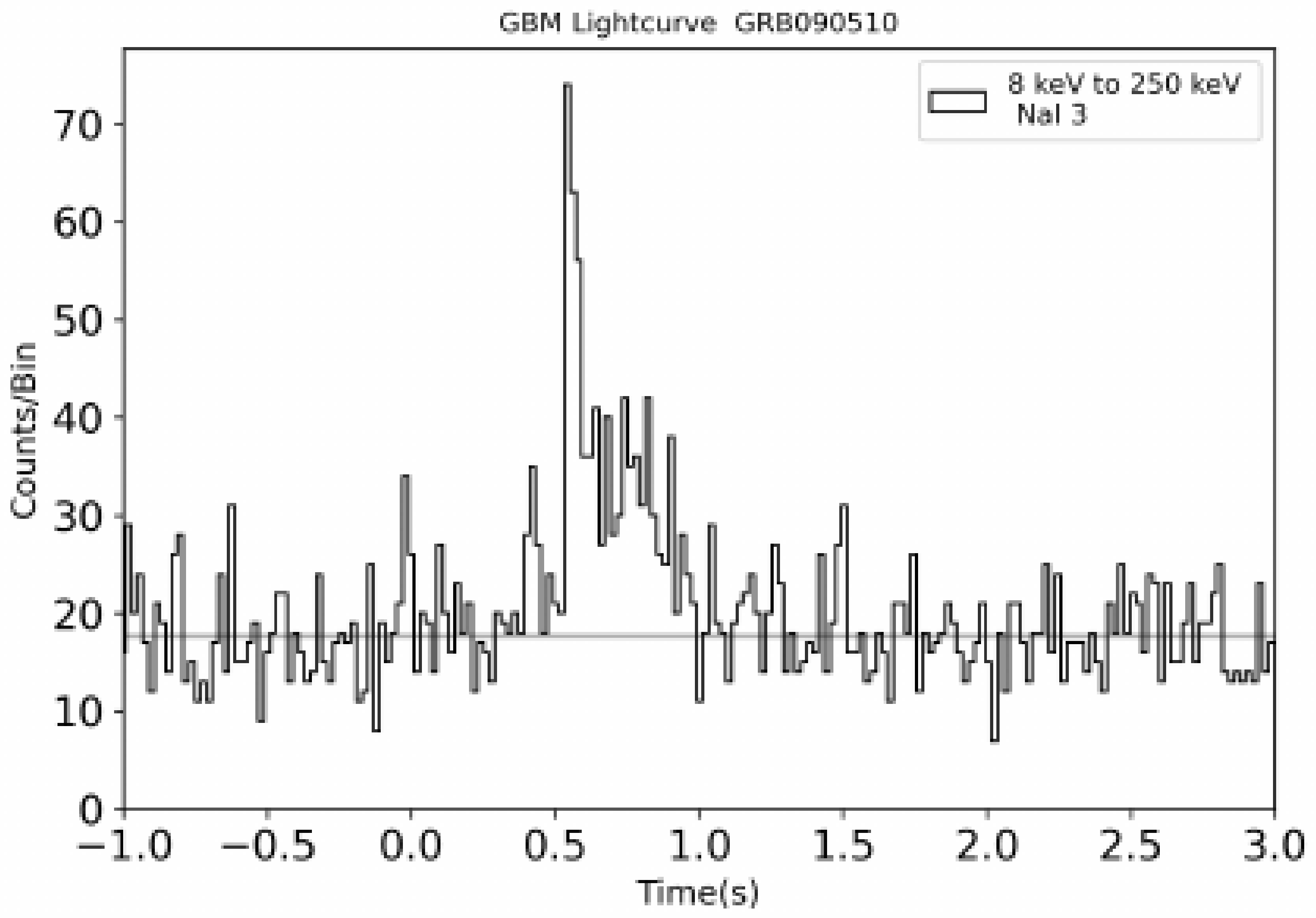




The Jet - A Case Study of GRB 090510

GRB 090510

- Duration (T90): ~0.6s (50-300 KeV) {GBM NaI3}
- Redshift: 0.903;
- Spectral analysis; Fermi Lat collaboration (Ackermann et al 2010)
- Total bolometric luminosity = 4×10^{53} erg/s
- Total isotropic energy, Eiso : 1×10^{53} ergs
- Opening angle from observation: 10.04°
  (Analytical estimate using Eiso, based on GRB correlations)
- Minimum variability timescales = 4.5 ms
  (wavelet analysis on light curves)



Prompt emission light curve of GRB 090510 observed in γ-rays

AIM – Use GRMHD simulations to produce a GRB jet comparable to the target short GRB and quantify how its dynamics depend on key physical drivers.

The Simulation Tool & Setup

GRMHD Framework : *HARM*

A NUMERICAL SCHEME FOR GRMHD
numerical code to simulate astrophysical flows in strong gravitational fields

- Solves GRMHD equations in conservative form with finite-volume methods.

Core evolution equations:
- (continuity, energy - momentum conservation, induction equations)

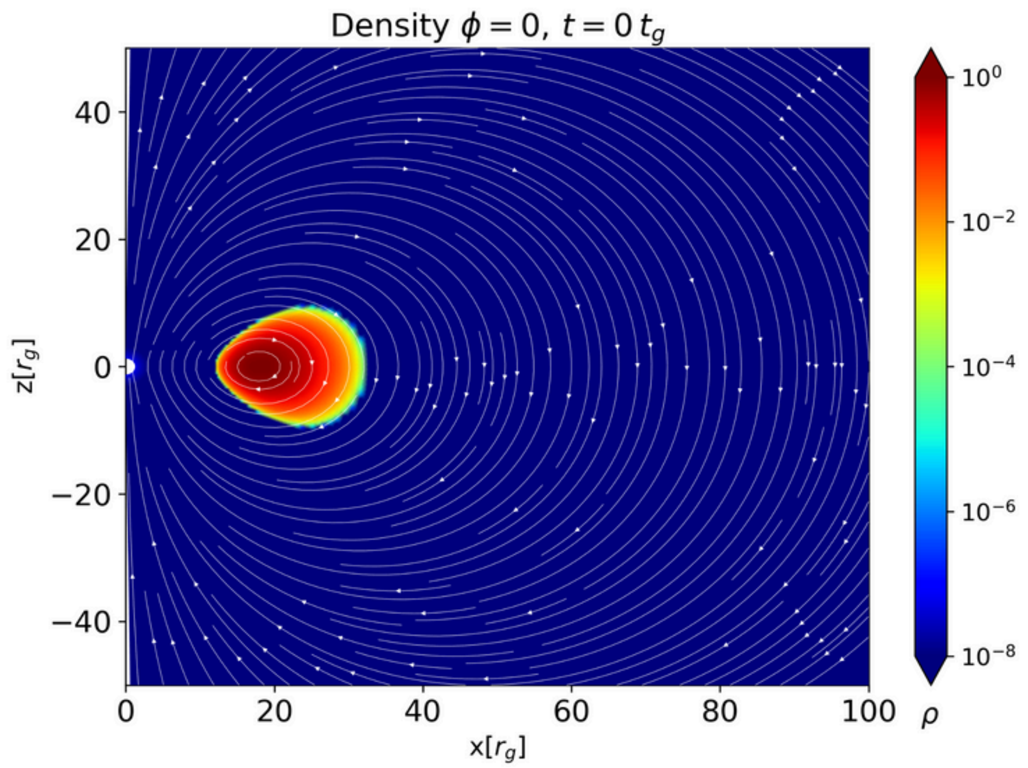
Polytropic - EOS

Dynamic Ejecta (DE - Models):
Origin: Ejecta stripped off from the neutron stars (NSs) during the merger;
Density distribution:

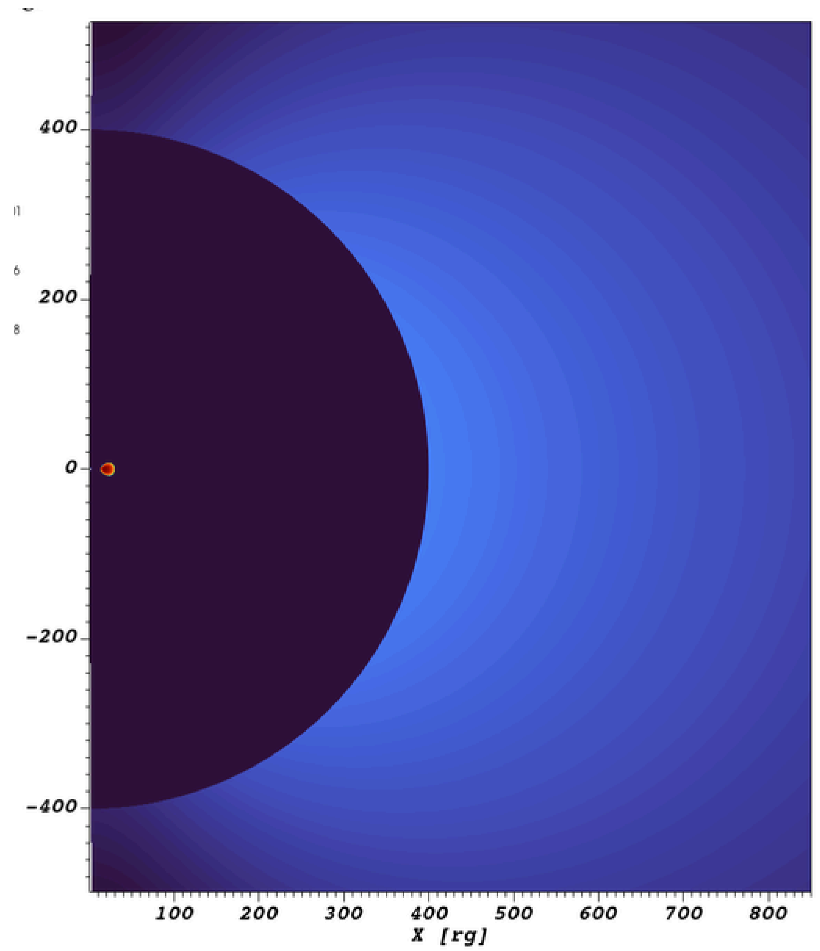
$$\rho(r,\theta) = \rho_0 r^{-\alpha}\left(0.1 + \sin^2\theta\right)^{\delta}$$

Ejecta --> unmagnetized & Mass = 0.006 & 0.012 M⊙, expands homologously with v = 0.15c

Initial Setup - Rotating kerr BH + Accretion Disk (Poloidal B)



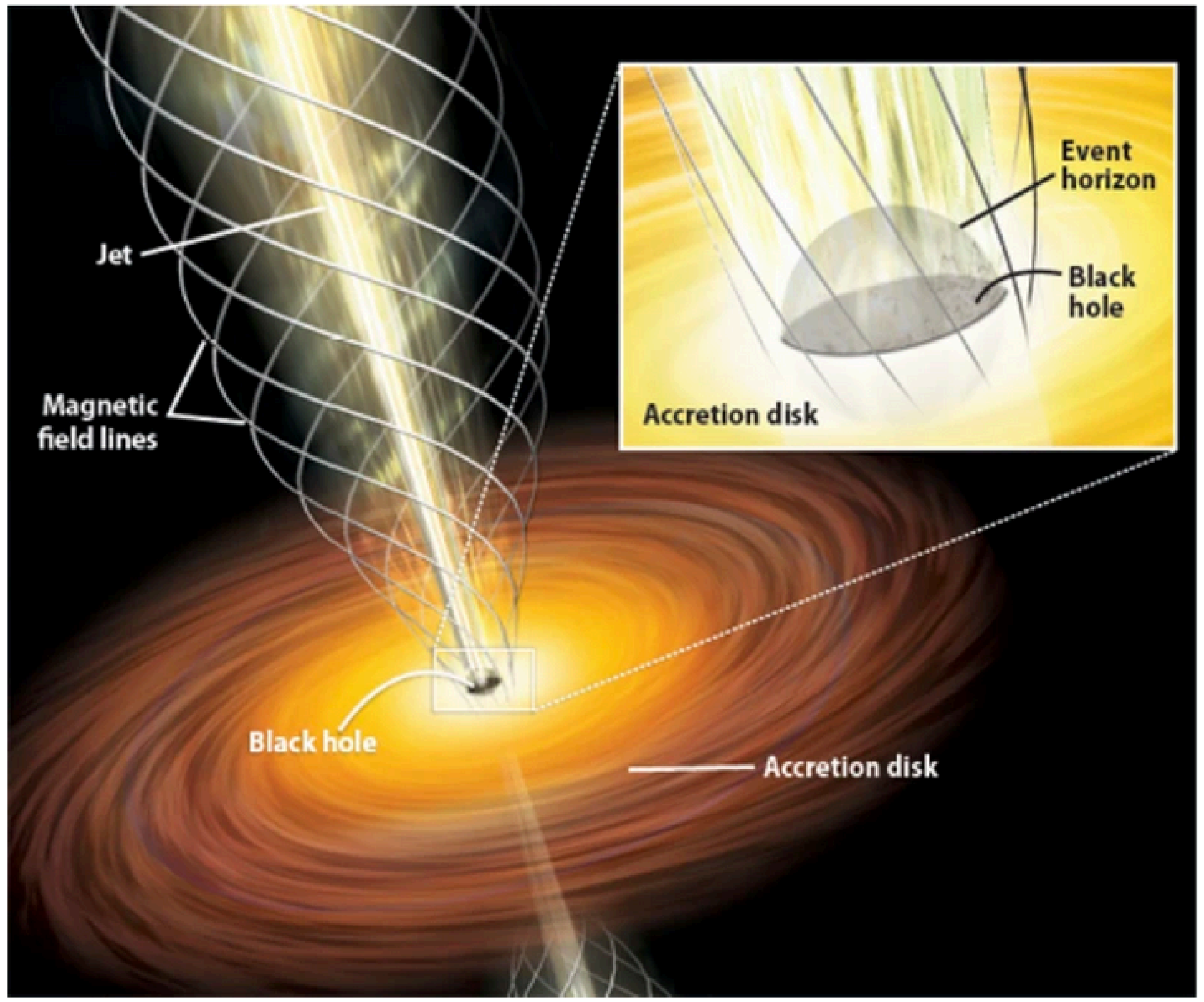
Accretion disk density profile with Magnetic field streamlines at time=0;



Density profile for model with an expanding dynamic ejecta

Models

- Accretion Disk Mass – > LD (10^{-3} M$_\odot$) , MD (10^{-2} M$_\odot$), HD (10^{-1} M$_\odot$)
- BH Spin: 0.6 - 0.95
- plasma β : 1 - 10^4
- 2D Models: 10
- 3D Model: 1
- Jets are produced via Blandford Znajek Process



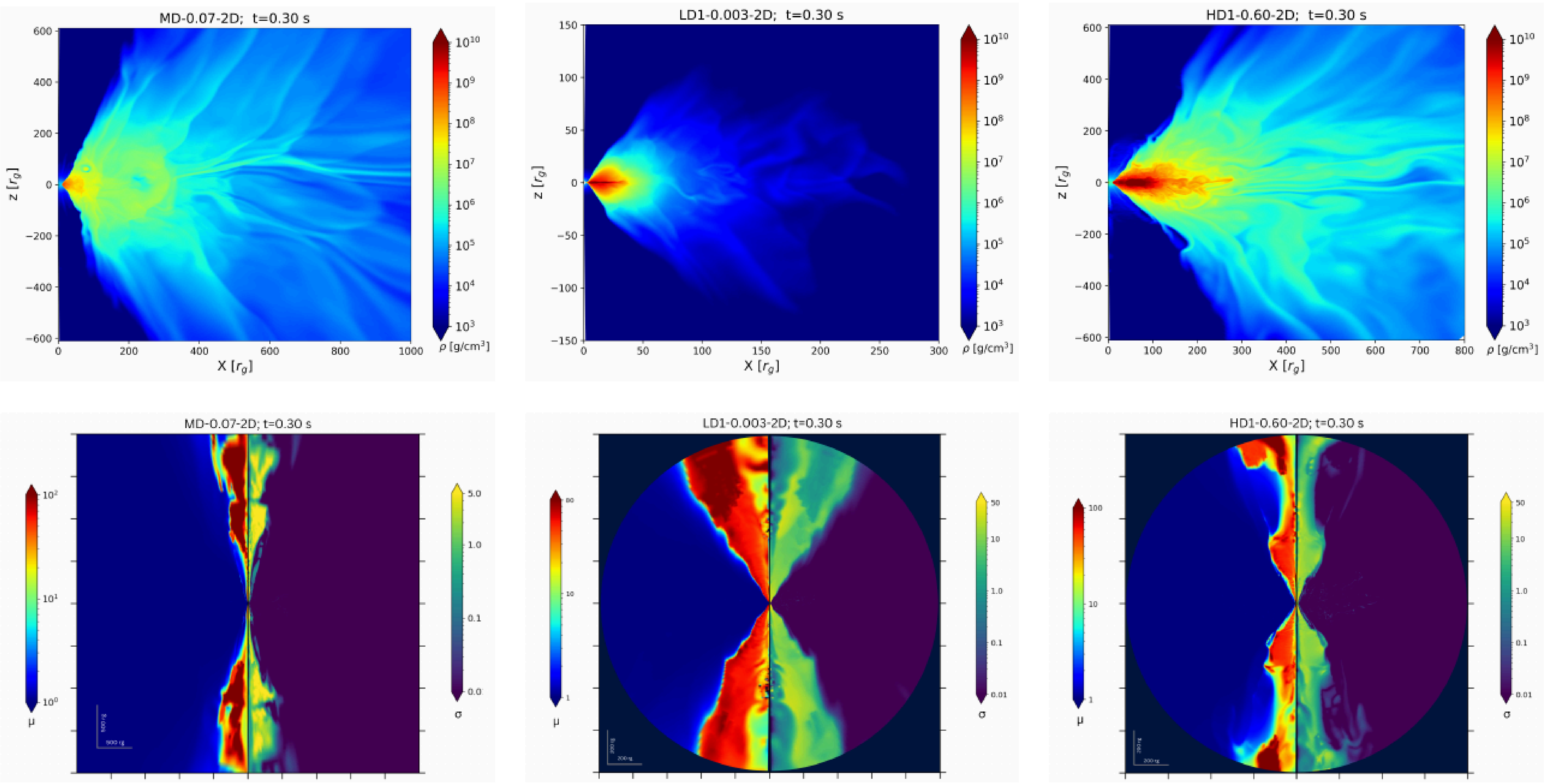
<u>Quantifying Jet Properties</u>

→ Jet energetics parameter (μ) ; Ratio of total energy flux to mass flux, used in methodologies involving the calculation of jet opening angle, Lorentz factor, and minimum timescale variability.

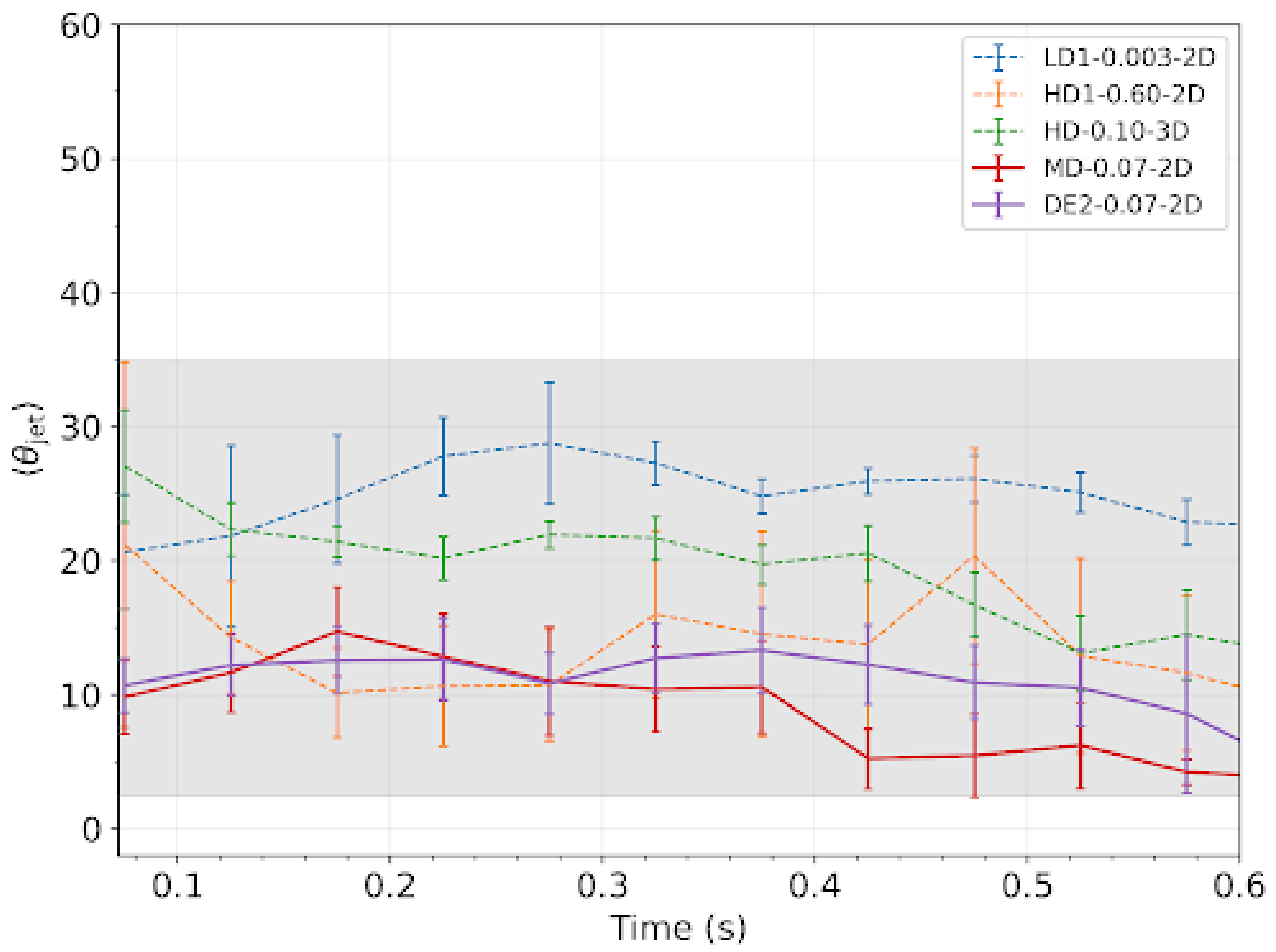
→ Jet magnetisation parameter (σ) ; The ratio of the electromagnetic energy flux to the gas energy flux.

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

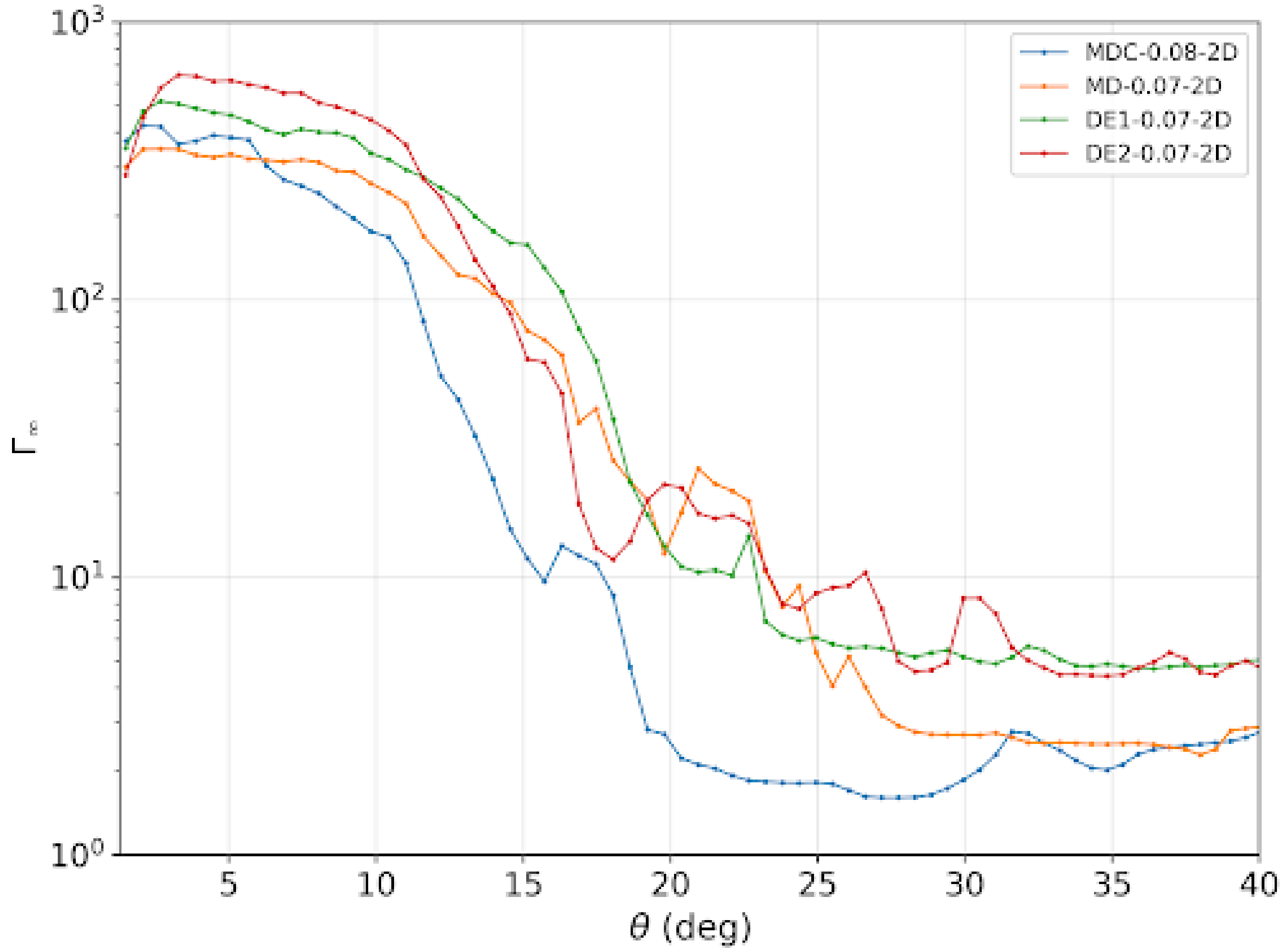
Accretion Disk & Jet for MD,LD,HD models



Opening angle & Lorentz Factor
– selected models –



Opening angle evolution over time



Radial profile of lorentz factor

Results - Jet simulations

- 3 Models in sample produce jets of duration ~0.6s, with Energy, Luminosity, opening angle and MTS similar to GRB 090510
- MTS from simulations (Two locations)
- (150,8) - 4.75 ms & (100,8) - 4.98 ms

Model	Disk Mass ($M_\odot$)	BH spin	β_{max}	E_{jet} (erg)	θ_{jet} (deg)	Resolution ($N_r \times N_\theta \times N_\phi$)	R_{out} (r_g)	t_f (t_g)
LD1-0.003-2D	3×10^{-3}	0.60	1000	1.87×10^{47}	25.5	512×256×1	1000	100k
MD1-0.06-2D	6×10^{-2}	0.60	1600	3.5×10^{50}	19.1	512×256×1	1000	100k
HD-0.10-3D	1×10^{-1}	0.95	200	1.10×10^{53}	18.1	256×128×64	1000	45k
HD2-0.60-2D	6×10^{-1}	0.90	3.5	1.70×10^{53}	14.9	512×256×1	1000	50k
MD-0.07-2D	7×10^{-2}	0.80	150	1.11×10^{52}	9.2	700×512×1	3500	50k
DE2-0.07-2D	8×10^{-2}	0.80	150	1.60×10^{52}	10.0	700×512×1	3500	50k

GRB	z	$E_{\rm iso}$ [erg]	$\theta_{\rm jet}$ [deg]	Model
150101B	0.13	4.2×10^{48}	25.7	LD1-0.003-2D
090927	1.37	1.21×10^{51}	21.1	MD2-0.06-2D
100117A	0.92	9.75×10^{50}	18.60	MD1-0.06-2D
120804A*	1.3	3.4×10^{52}	≥ 13	HD1-0.60-2D

- 3 Models reproduce observed properties simiar to that of GRB090510
- Few other short GRBs were also taken for comparison and their properties explained via simulations
- Accretion Disk Winds were major source of jet collimation
- Dynamic Ejecta profile didn’t add considerable change in jet profile - an appreciable collimating contribution from the DE is expected only at a larger radii.

Part - II

From GRB Jets → to Ejecta, Nucleosynthesis & Kilonovae

Short Gamma Ray Bursts (SGRBs)

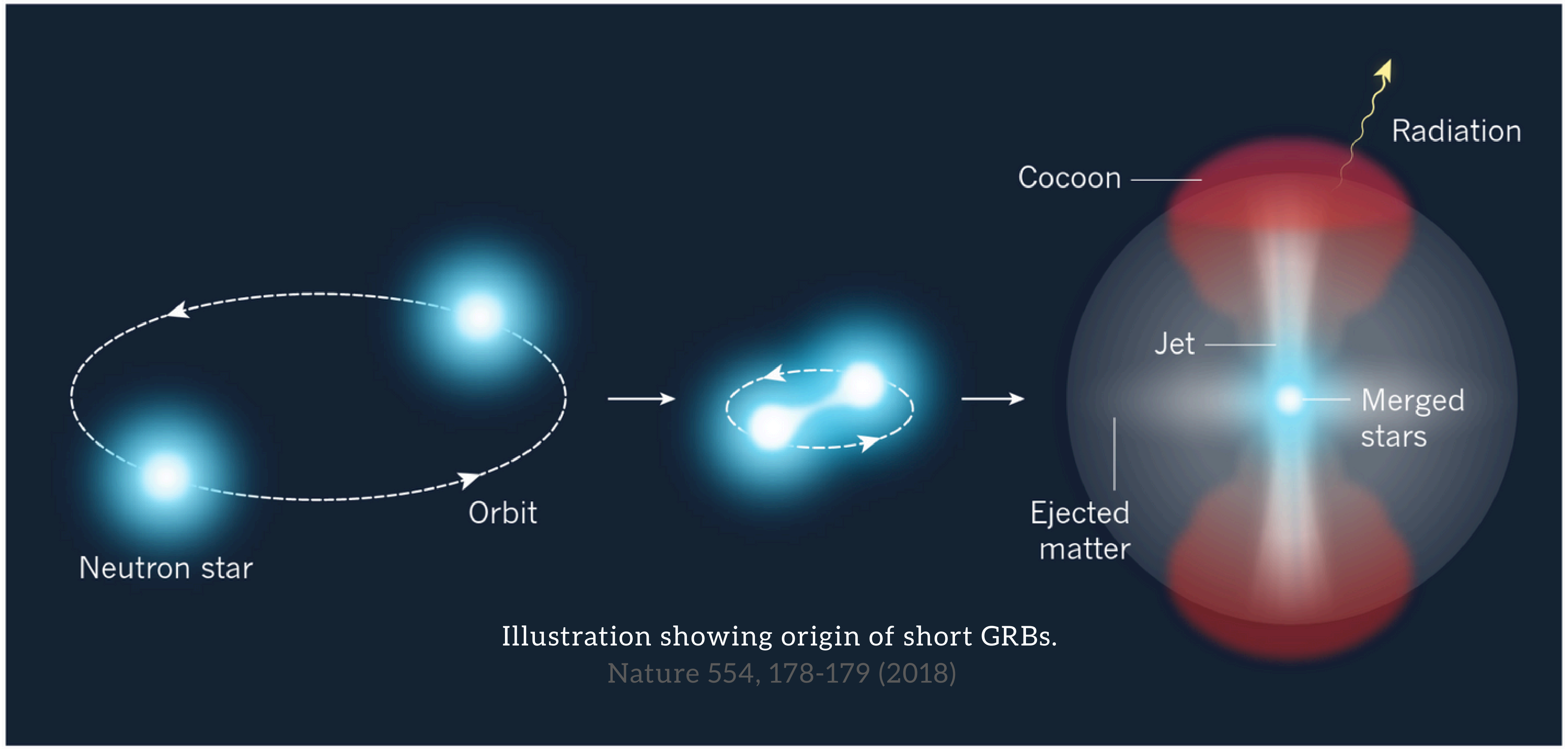


Illustration showing origin of short GRBs.
Nature 554, 178-179 (2018)

<u>Post-merger environment</u>
Black-Hole + Accretion Disk + Disk Wind + Dynamic Ejecta + ultra relativistic jet (GRB)

R-PROCESS NUCLEOSYNTHESIS

Merger Ejecta

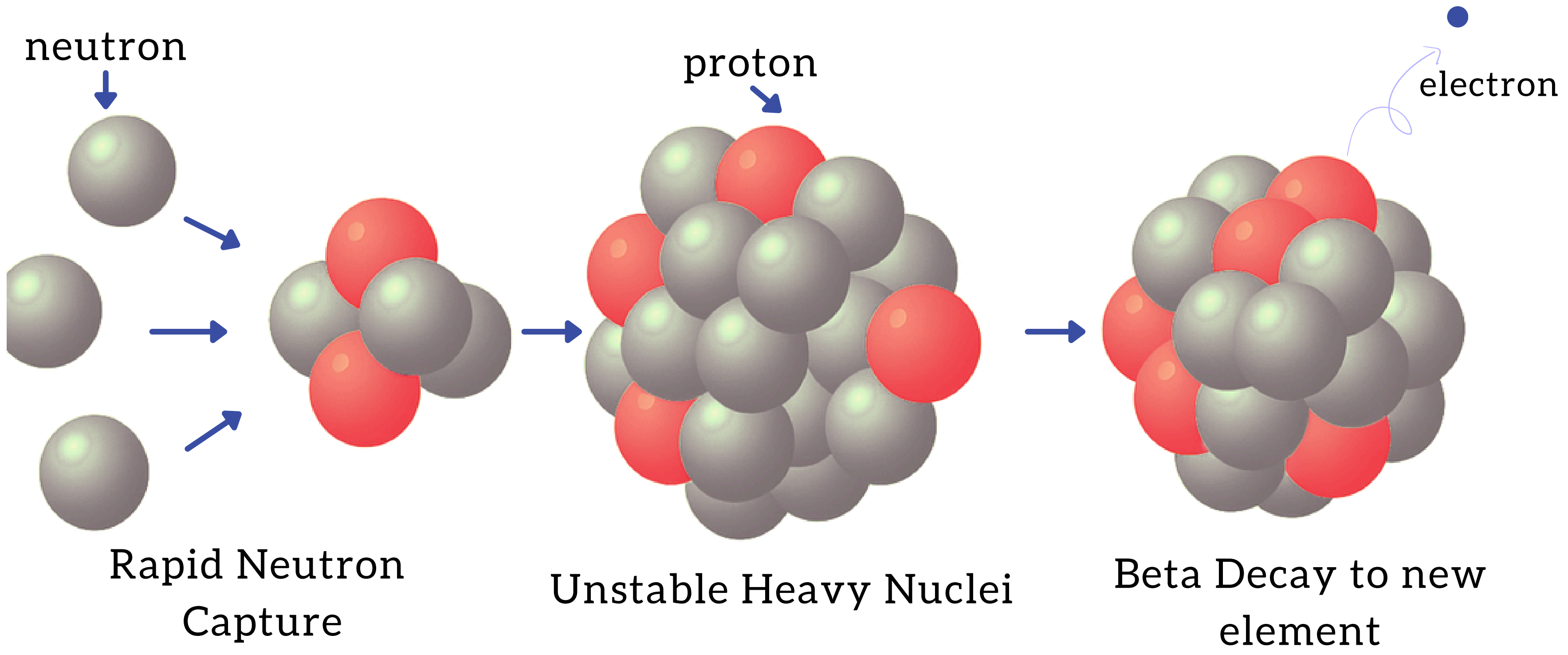
Dynamic Ejecta + Accretion Disk Winds

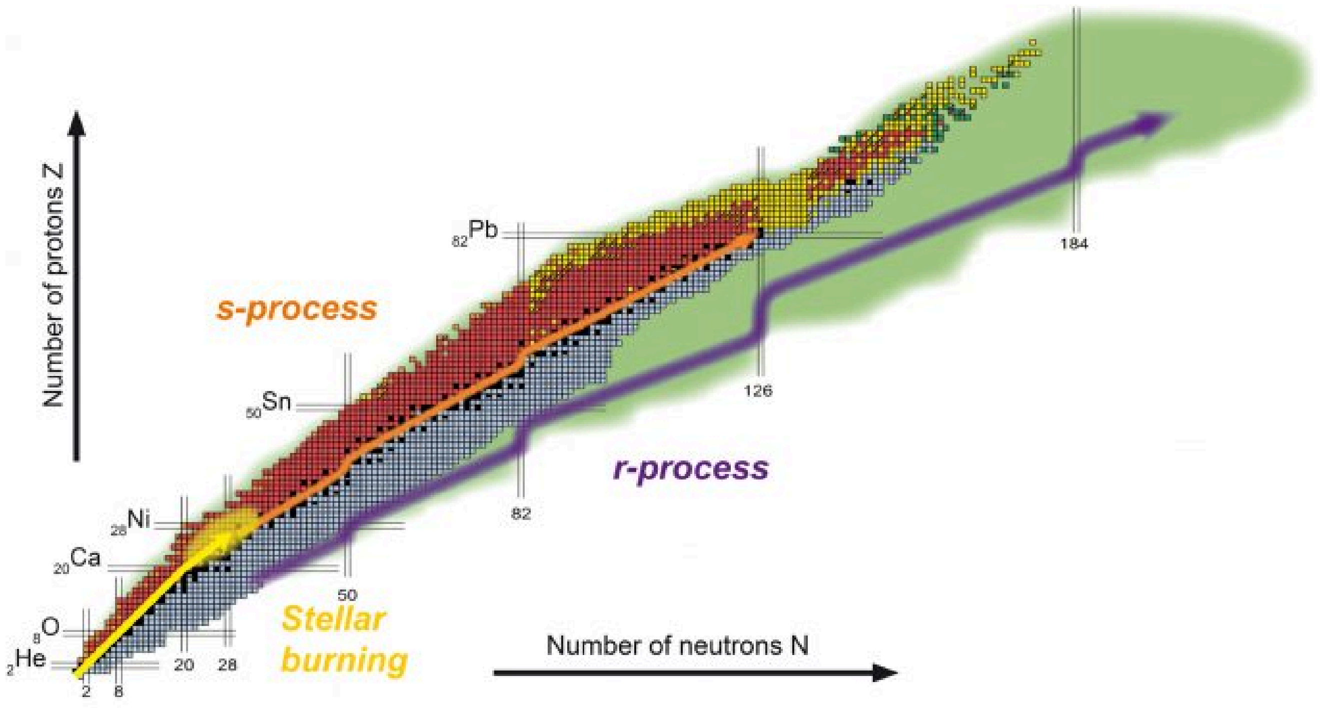
Highly neutron-rich (Ye ~0.1 - 0.3)

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}.$$

What is R-process

- In neutron-rich ejecta, seed nuclei rapidly capture neutrons, building very heavy, neutron-rich nuclei.
- Followed by β^--decay, converting neutrons to protons and stabilizing nuclei into heavy elements.



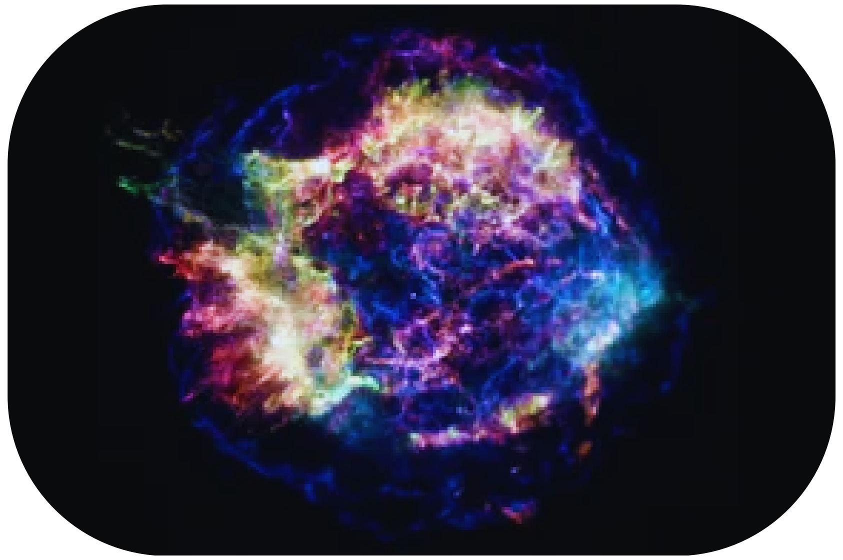


credit: EMMI, GSI/Different Arts)

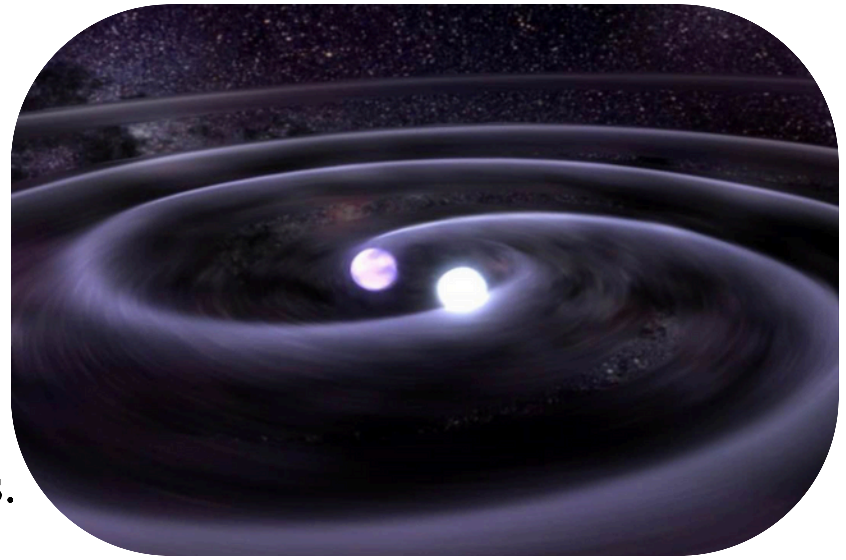
WHY THE R-PROCESS IS IMPORTANT

- Cosmic inventory: $\gtrsim$50% of all nuclei heavier than Fe are r-process products; they dominate galactic heavy-element budgets.
- Multi-messenger link: GW events → kilonovae powered by r-process radioactivity; ties gravity, neutrinos, MHD, and nuclear physics.

🌌 Astrophysical Sites of the r-Process



- ***Binary Neutron Star Mergers***: Robust site; confirmed by GW170817 + kilonova (AT2017gfo).
- ***NS-WD Mergers*** - proposed sites but possibly low enrichment
- ***Core-Collapse Supernovae***: Neutrino-driven winds are often too proton-rich; role still debated.
    - ***Collapsars & Magnetorotational SNe***: BH + disk systems with strong magnetic fields; potential site for early-universe enrichment.



Conditions for a successful r-process

- Neutron-rich: $Y_e \lesssim 0.25$ for lanthanides/actinides; higher Y_e → light-r only (Sr–Ag).
- Fast expansion: ms–s freeze-out (capture - decay competes); sets nuclear abundance peak widths/positions.

How do we study these conditions ?..

The Simulation Challenge

A Multi-Stage Approach

Studying nucleosynthesis from mergers is a multi-physics, multi-scale problem (GR, MHD, Neutrino, Nuclear reactions.....)

GRMHD Framework : *HARM-EOS*

Neutrino Cooling:

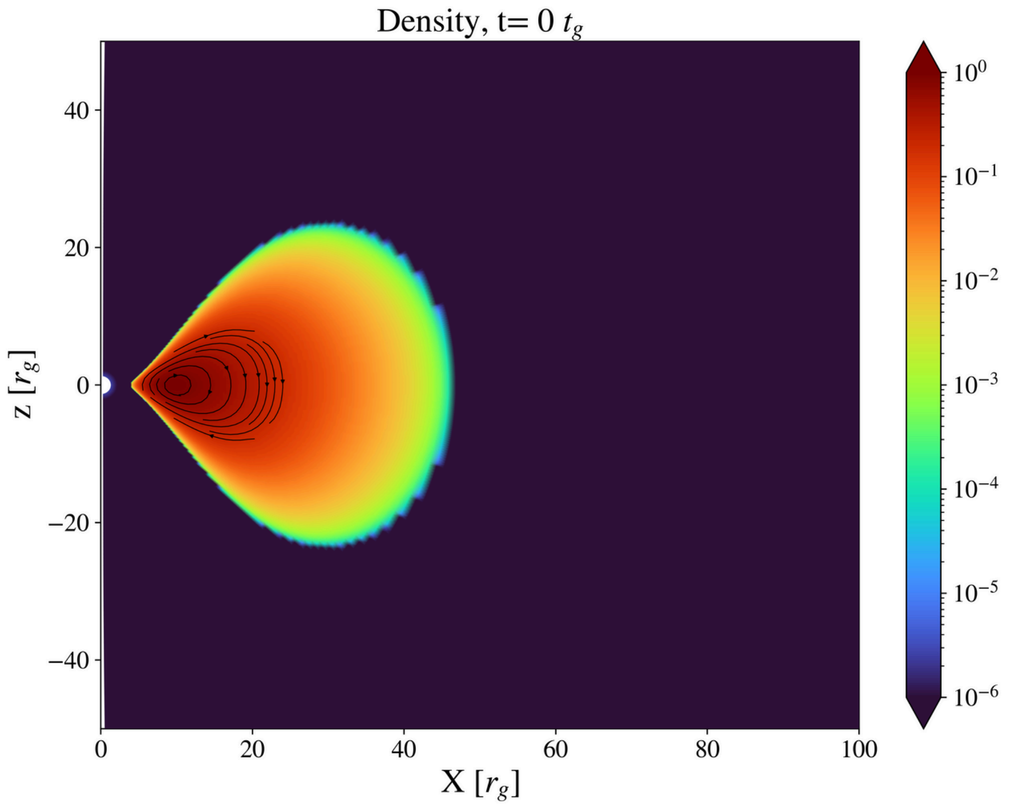
- Leakage scheme computes a gray optical depths for neutrinos (ν_e,ν_e,ν_x)

Equation of State (EOS)

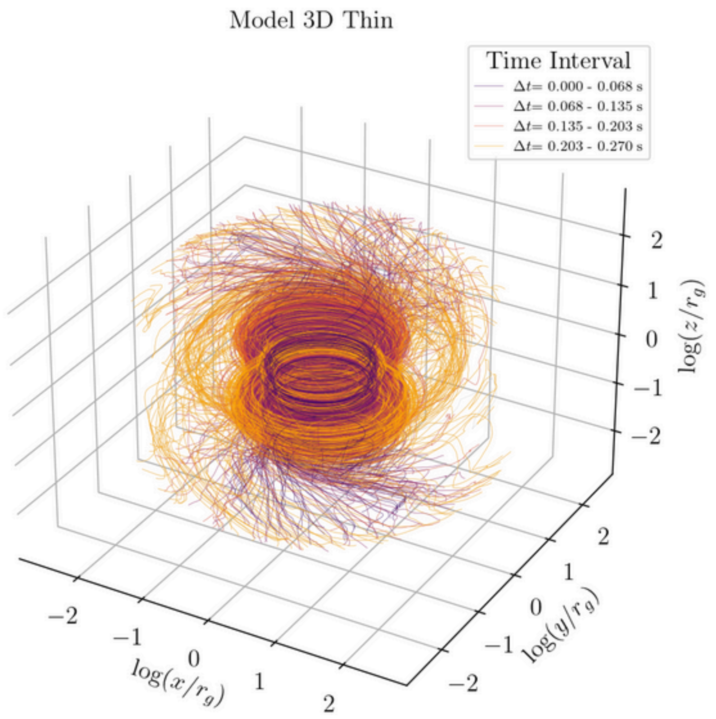
- Tabulated 3-parameter EOS: ε(ρ,T,Ye) P(ρ,T,Ye)
- Additional modules are available with self-gravity implementations

-

Initial Setup - Rotating kerr BH + Accretion Disk (Poloidal B)



Accretion disk density profile with Magnetic field streamlines at time=0; (Model 3D-Kn)

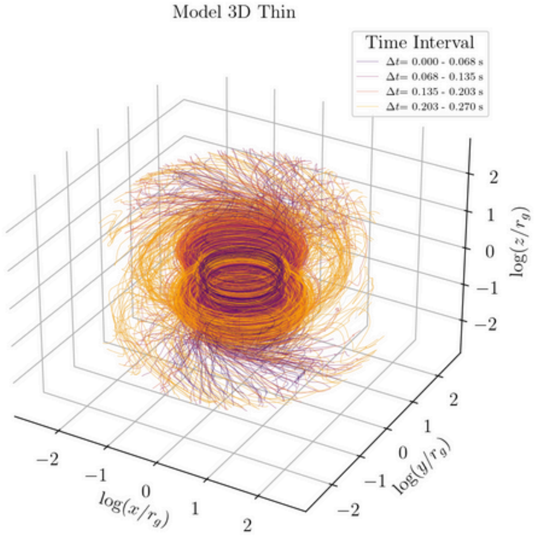


Tracer particle - records properties like density, temperature, electron fraction, coordinates & time to track the disk winds and used in Skynet to calculate nuclear abundance

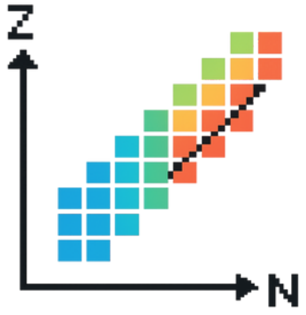
Nuclear Reaction Network
Code : SKYNET

(Post processing of GRMHD results to calculate abundance profiles)

HARM-EOS



bitbucket.org/jlippuner/skynet



EM Signals (Kilonova)
(spectrum & lightcurves)

- General-purpose nuclear reaction network
- Tracks >7 000 nuclides, ~140 000 reactions
- Accepts tracer histories ρ(t), T(t), Ye(t) from HARM-EOS
- Returns time-resolved abundances, heating rates
- Supports coulomb screening, self-heating & ν-driven Ye evolution

SkyNet - compute the nucleosynthesis evolution in all astrophysical scenarios where nucleosynthesis occurs.

Proper elemental abundance combined with nuclear opacities is crucial for detailed studies of EM signals following this event.

Further radiation transport helps us study the EM emission following these events.

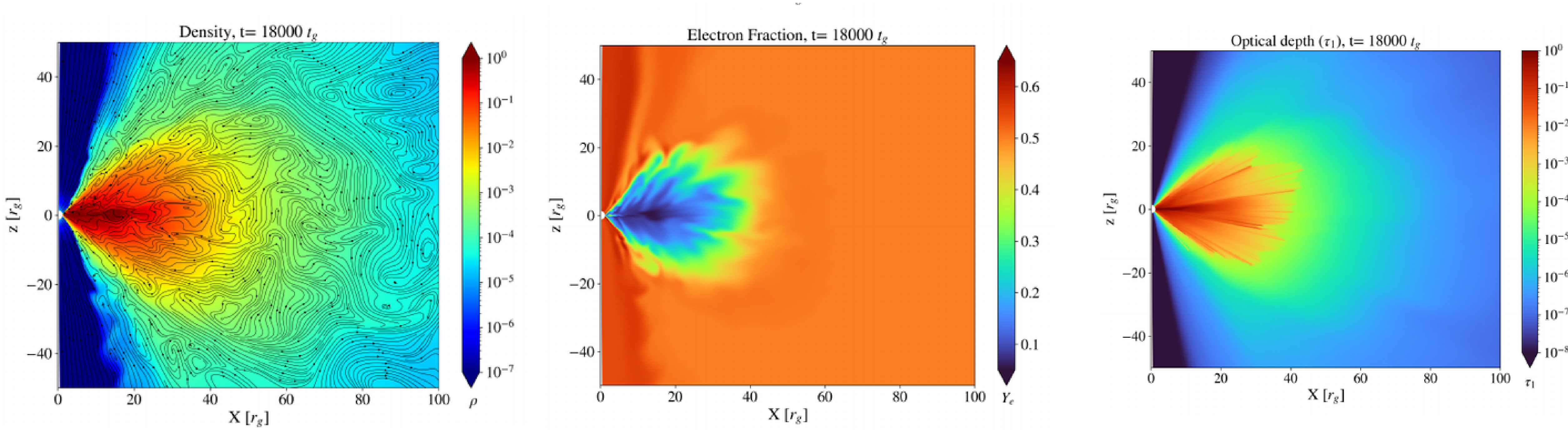
Post-Merger Simulations - Results

- AIM - Study how the Post-merger Accretion disk properties evolve & affect heavy element formation & Resulting EM Transient
- 3-D & 2D ν-GRMHD with HARM-EOS – composition-dependent, 3-parameter EOS + neutrino-leakage; Magnetised jet production, and self-consistent Ye evolution.
- The current simulation properties focus on the BNS and NS-BH merger scenario & some models are fine-tuned to reproduce kilonova emission followed by GRB 211211A.
- ~10^5 tracers are initialised to follow unbound winds; record (ρ, T, Ye); trajectories post-processed with SkyNet.

Simulation Parameters –

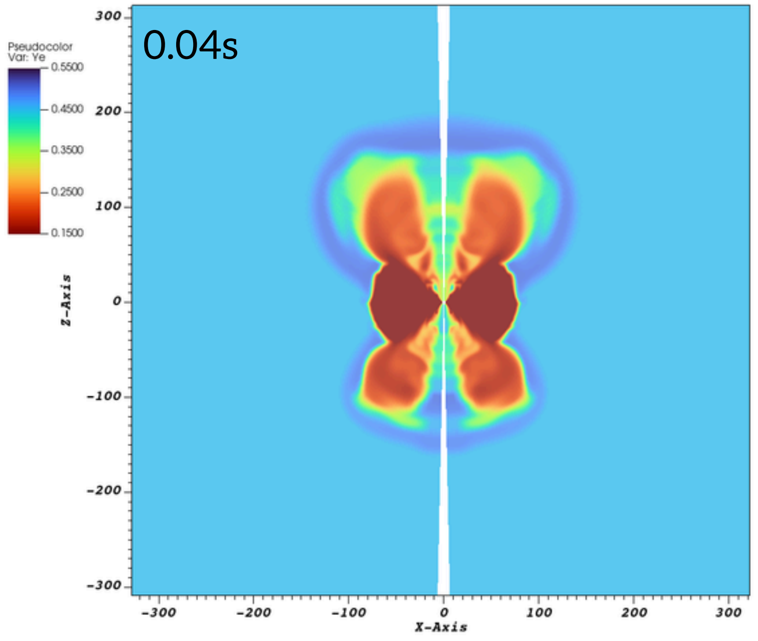
9 Models - 2D & 3D simulations

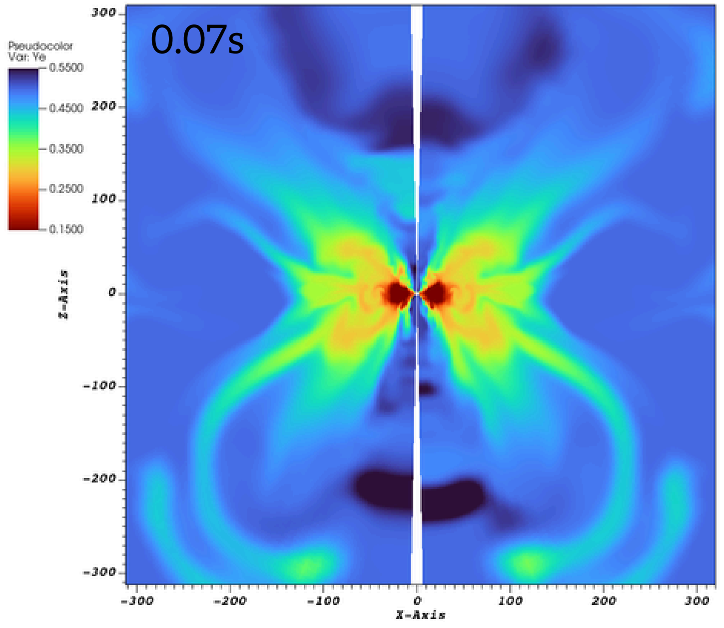
- BH spin, a = 0.6 – 0.9,
- BH mass, 3 – 8 M☉,
- Accretion disk mass ~0.001 – ~0.1 M☉,
- plasma β ~ 50 - 100
- disk entropy 7-10 kB per baryon;

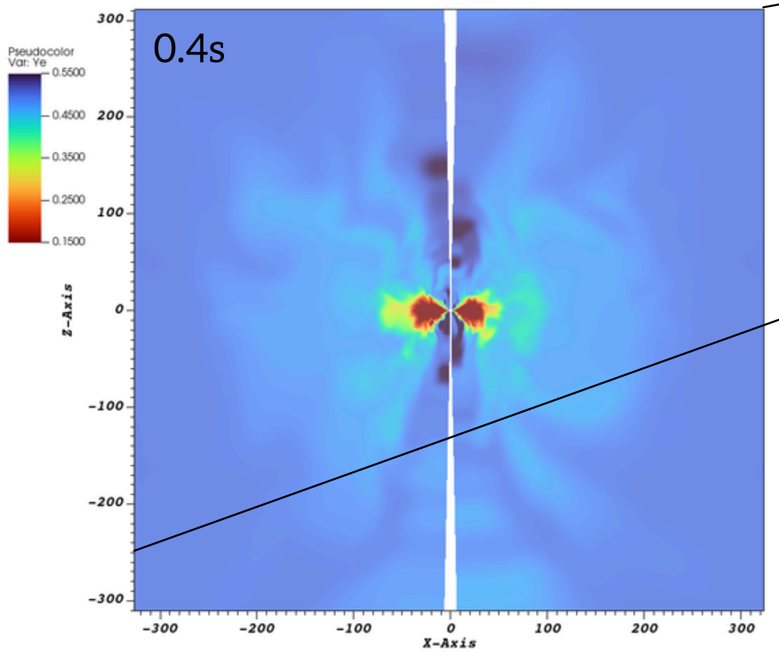


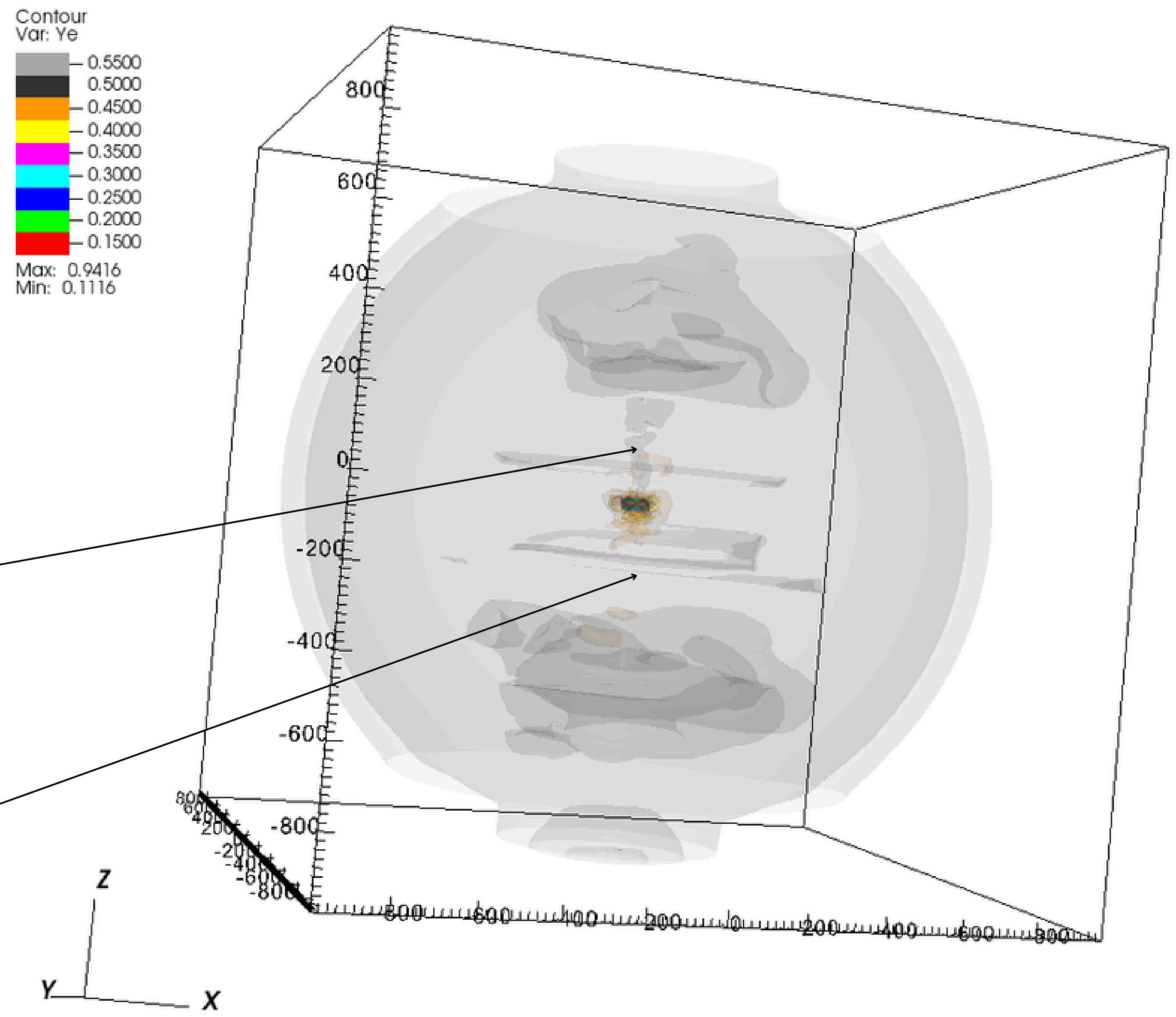
Accretion Disk snapshots at a later time of evolution (Model 2D-Thin) (~0.3s in real time)
Left Panel: Density + Magnetic field lines, Mid Panel- Ye ; Right Panel - Neutrino optical depth

Ye Evolution - Model 3D-Kn





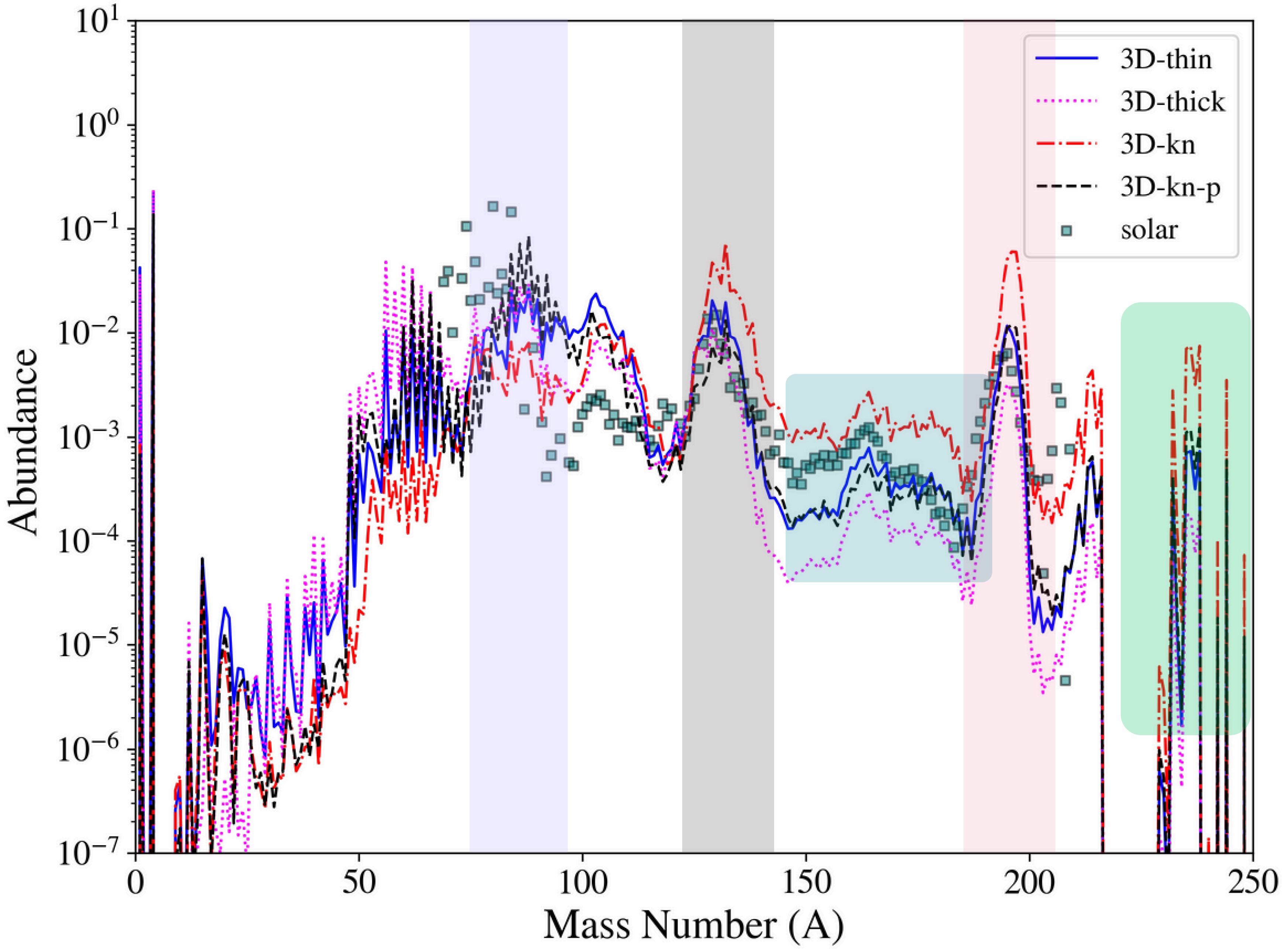




Model 3D KN

- BH spin, a = 0.6
- BH mass, 8 M⊙,
- disk mass ~0.781M⊙,
- plasma β ~ 50

Nuclear Abundance Profiles



Nuclear Abundance profiles of four 3D models in this work.
Models succeed in reproducing solar r-process peaks.

Models reproduce prominent r-process peaks
1st A~95 (Sr,Zr..), 2nd A~130 (Xe,Sn..), 3rd A~195 (Pt, Au..)
lanthanides (Nd, Eu..) & Actinides (Th, U..)

Model	Mass Ejecta (M⊙)	<Ye> (10 GK)	Velocity (1/c) (500 rg)
3D-Thick	2×10^{-2}	0.42	0.13
3D-Thin	2×10^{-3}	0.37	0.10
3D-kn	1×10^{-1}	0.20	0.07
3D-kn-p	2×10^{-3}	0.37	0.19

NS Merger R-Process → Responsible for formation more than 50% of Universes heaviest Elements

R-process & Kilonovae

<u>Merger Scenario - Heavy Element production</u>

- Disk Winds (post merger) + Dynamic Ejecta (pre Merger)

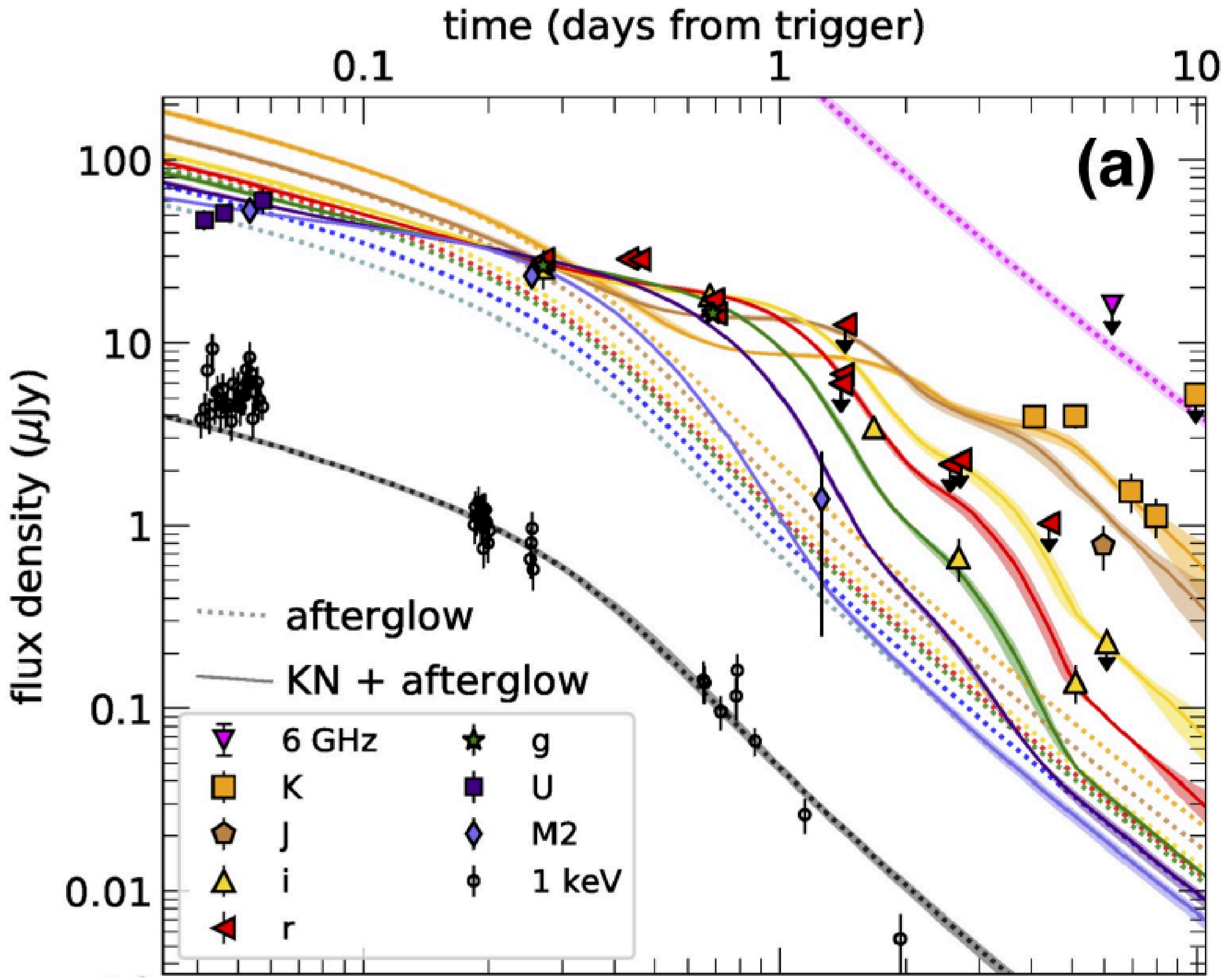
  - Radioactive decay of heavy elements - Power Transient
  - electromagnetic transient from r-process → (Li & Paczy´nsky 1998)
  - GW170817 - Discovery of kilonovae (Overlapping GRB afterglow; Optical - IR; timescale ~days)
  - Modeling Kilonova Emission required a detailed understanding of ejecta properties + Radiation Transport

<u>Two & Three Component Analytical KNe Modelling</u>

✓ Dynamical ejecta → Neutron-rich, heavy r-process elements (lanthanides, actinides, high opacity) **Red Kilonova**

✓ Disk wind ejecta→ Moderately neutron-rich, light/heavy r-process elements **Blue Kilonova**

GW170817 / AT2017gf
Blue - Mej = 0.02, v= 0.25c
Red - Mej = 0.05, v= 0. 15c



Kilonova observation: GRB 211211A
Source: Rastinejad, J.C., et al .(2022).

Our simulation Models produce ----
Total disk M_ejecta ranging 10^{-3} - 10^{-1} ⊙
Velocities: 0.05 - 0.20 c

Ejecta produced have properties in the range sufficient to produce observed kilonovae properties; Detailed Radiation Transport - Planned/ongoing

Summary

- 3D simulations of post-merger accretion disks with multiple initial configurations were carried out using the new HARM-EOS 3D ν-GRMHD code, developed at CTP PAS.
- Post-processing using Skynet nuclear reaction network shows that accretion disk winds robustly produce heavy r-process ($A \gtrsim 100$); yields (10^{-3}–10^{-1} $M_\odot$) of ejecta with velocities (0.1 - 0.2c).
- Post-merger disk properties significantly impact the microphysics of ejecta and, consequently, the production of heavy elements (We found 1-3 orders of difference in heavy element ratios between different models).
- Abundance profiles from simulations match solar abundance, and the velocity/ejecta properties are consistent with powering a GW170817-like kilonova.

Thank You