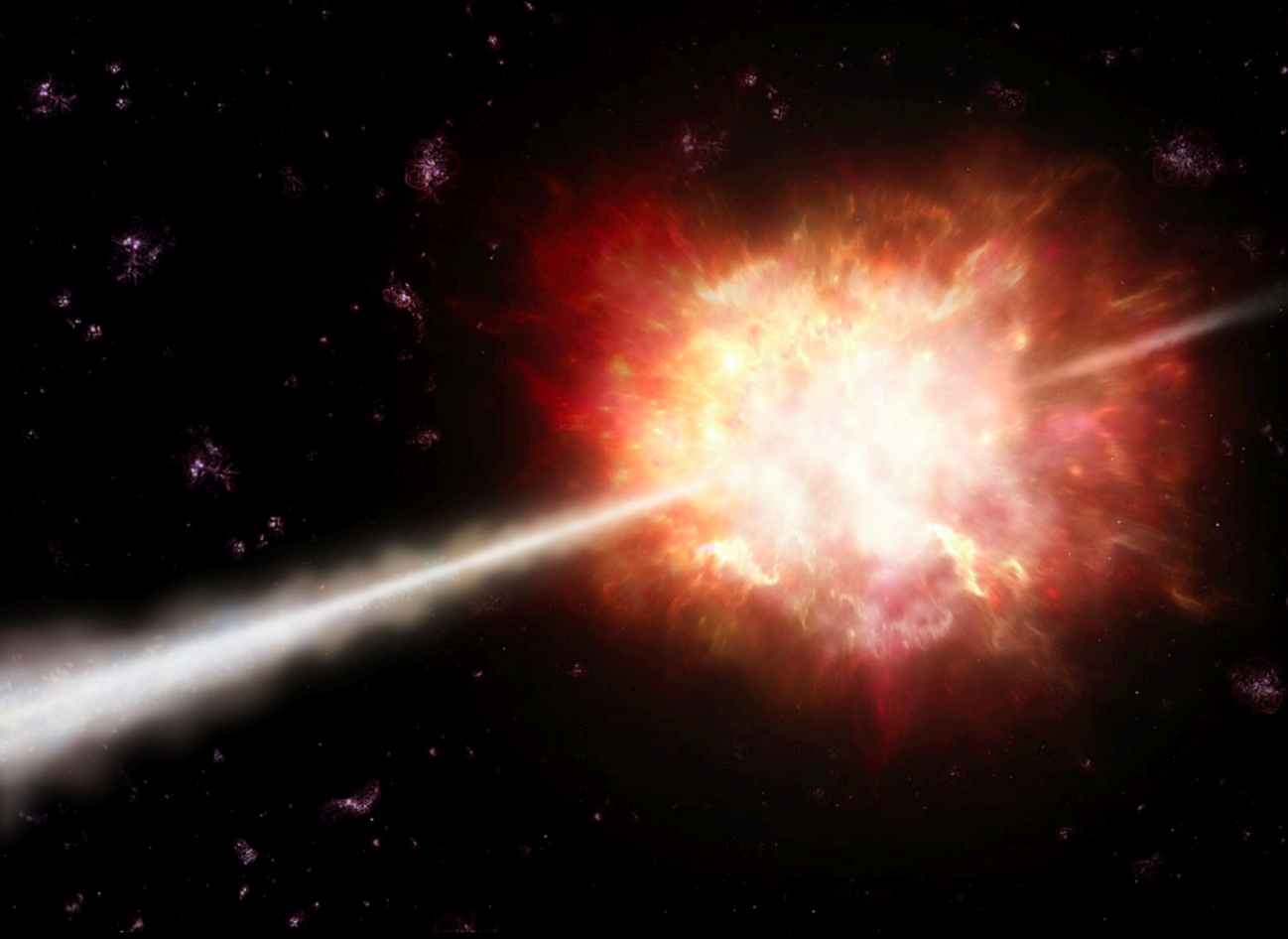

An end-to-end HPC workflow for 3D RMHD jet simulations and GRB afterglow synthesis

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Supervisors and collaborators:

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Riccardo Ciolfi
Om Sharan Salafia
Andrea Pavan

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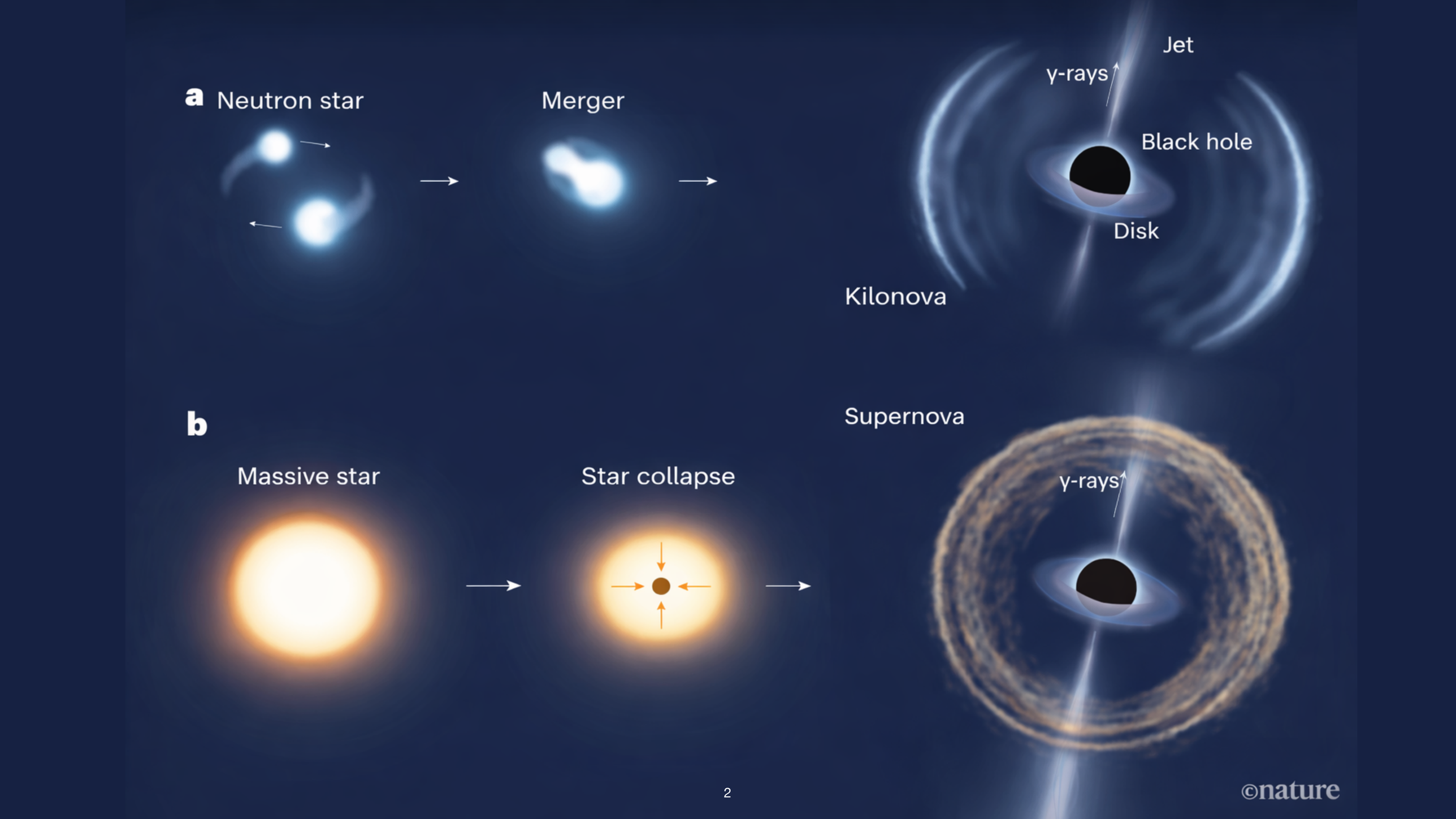
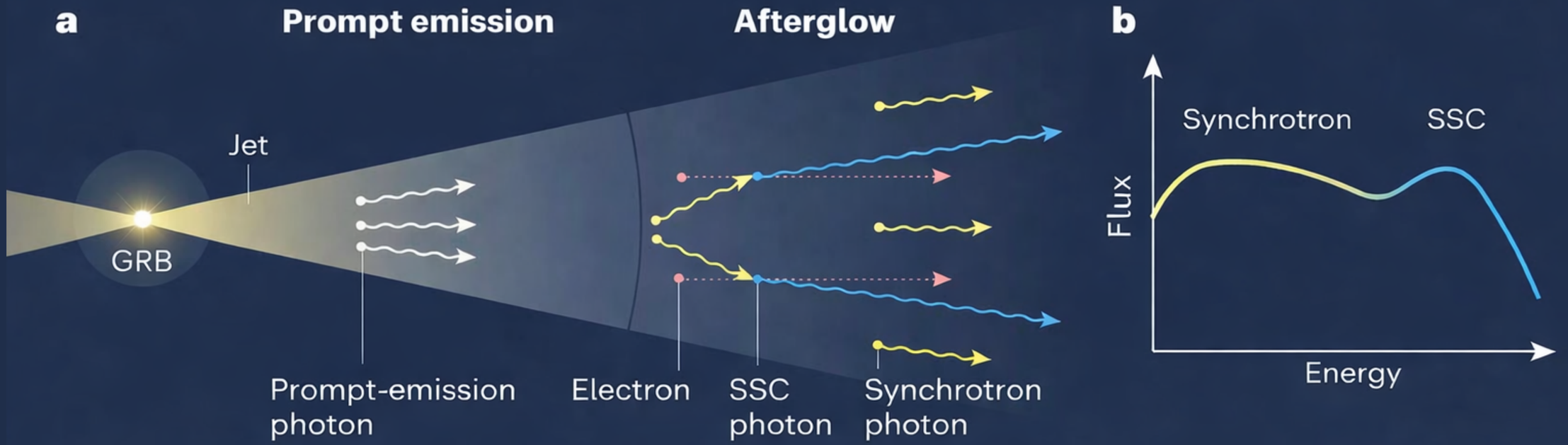
SISSA

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

INAF ISTITUTO NAZIONALE DI ASTROFISICA


a
Neutron star
Merger
Jet
γ-rays
Black hole
Disk
Kilonova
b
Massive star
Star collapse
Supernova
γ-rays
©nature


a
Prompt emission
Afterglow
Jet
GRB
Prompt-emission photon
Electron
SSC photon
Synchrotron photon
b
Synchrotron
SSC
Flux
Energy

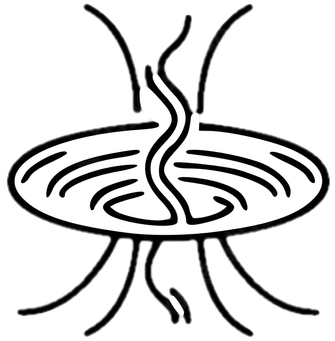
©nature

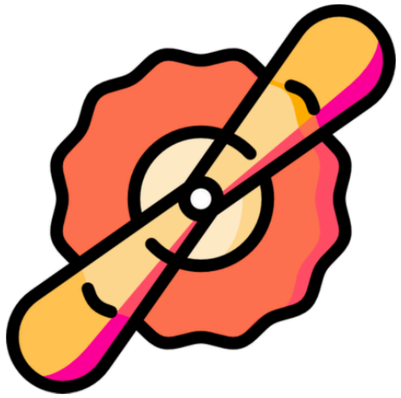
GOAL

Gain information on the progenitors, jet physics and emission mechanisms

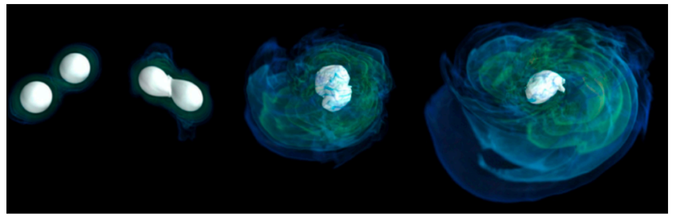
APPROACH

Connect and compare the input/output of numerical simulations with observations



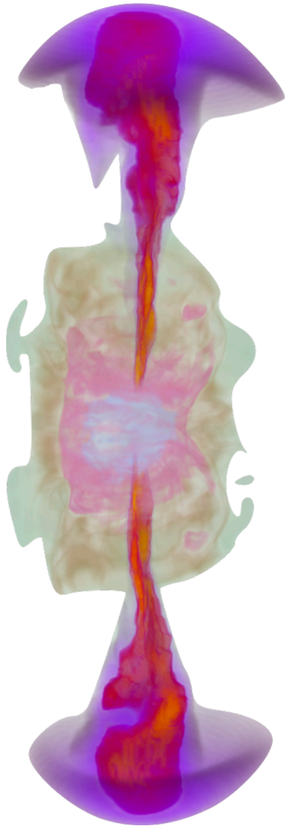


End-to-end description

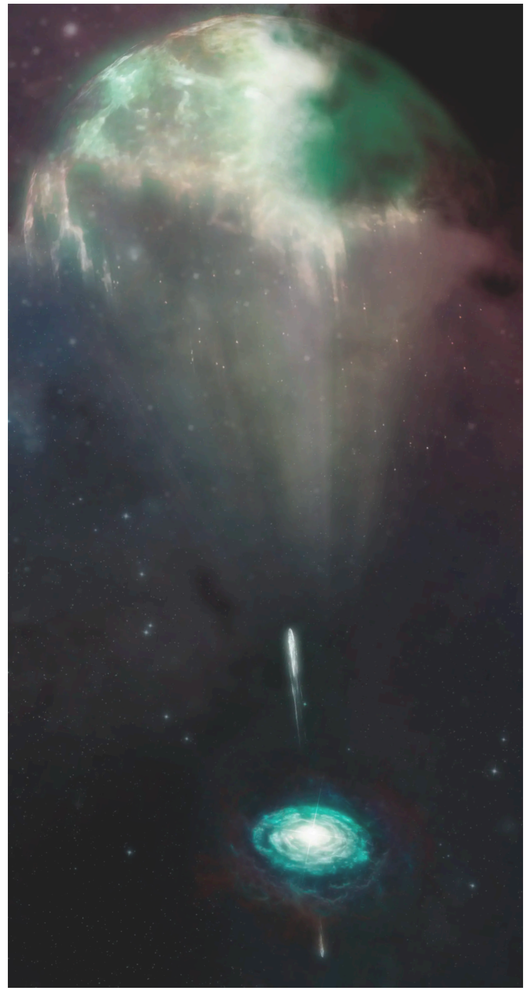


Merger

Jet formation



Jet evolution

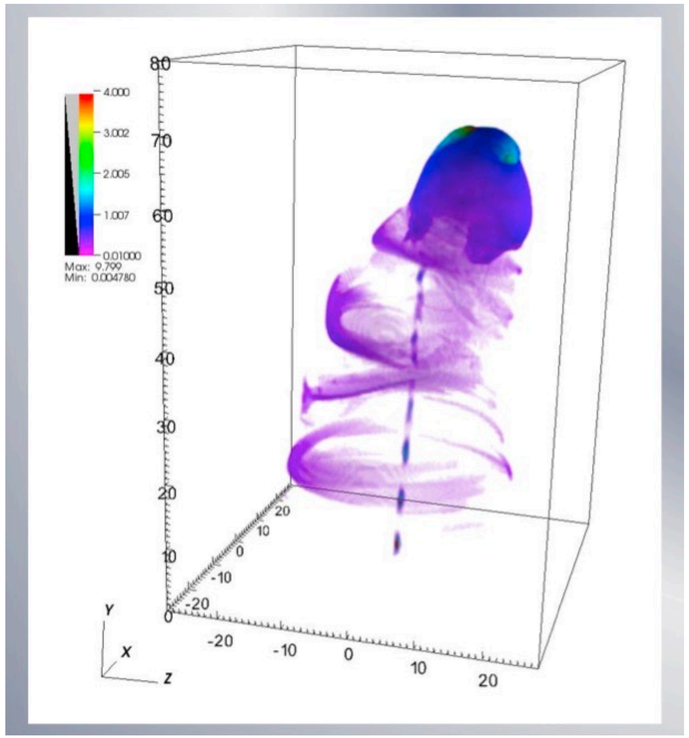


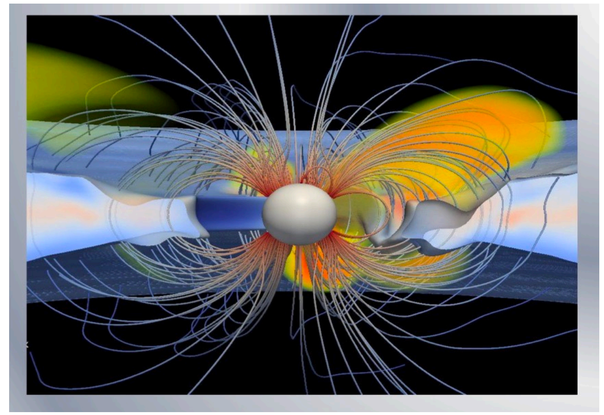
EM emission

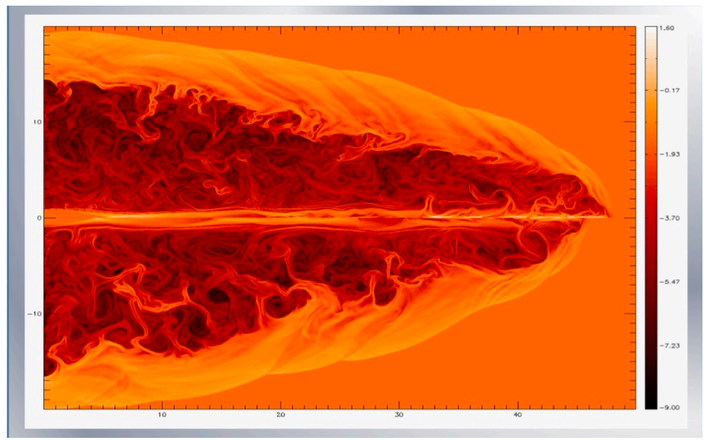
The PLUTO code
For astrophysical gas dynamics

A. Mignone et al.

- Numerical code aimed at solving supersonic/relativistic fluids
- Treatment of astrophysical flows in presence of discontinuities and shocks
- Applications: stellar astrophysics, jet propagation, planetary and atmospheric physics…
- **SRMHD** module
- Different **coordinate systems** in 1-2-**3D**







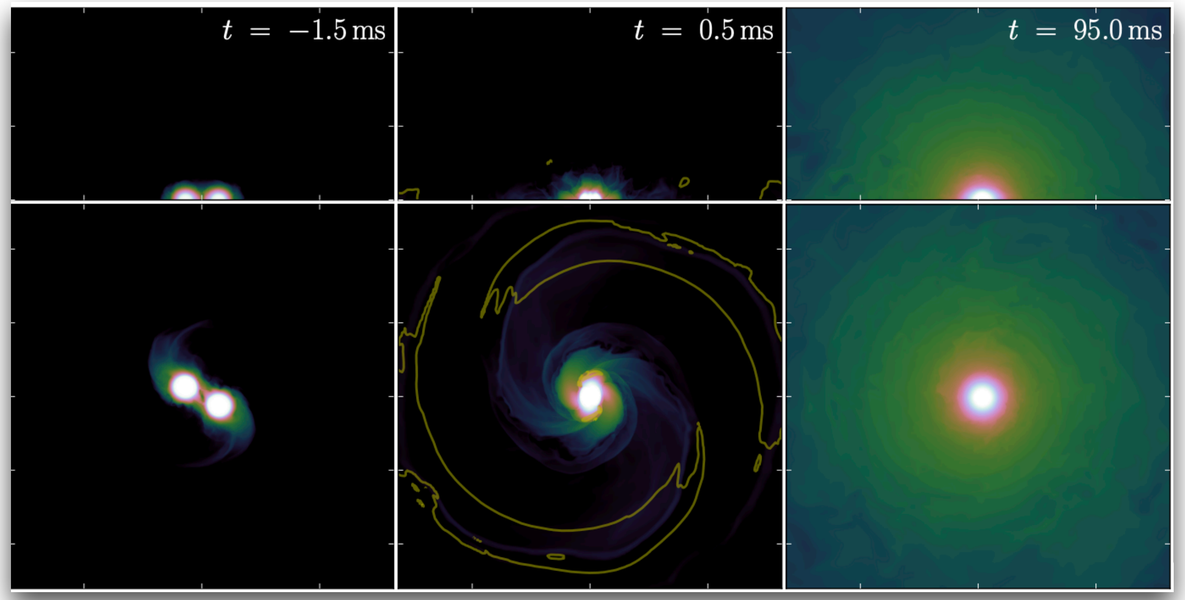
HPC resources

Discoverer HPC cluster, Bulgaria

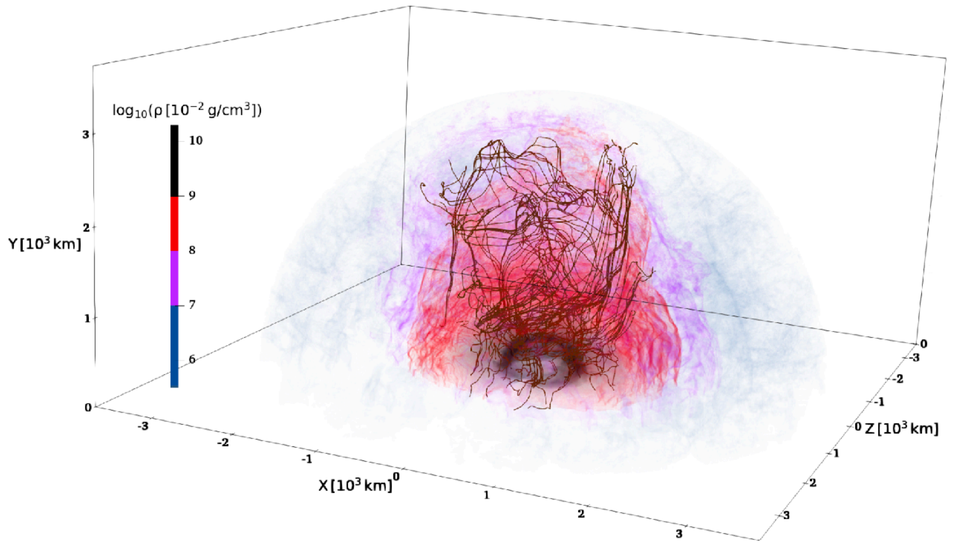
Leonardo HPC cluster, Italy

Ulysses cluster,
SISSA, Italy

Early time jet evolution



First 100 ms of a long-lived magnetized neutron star formed in a binary neutron star merger
Ciolfi et al. 2019

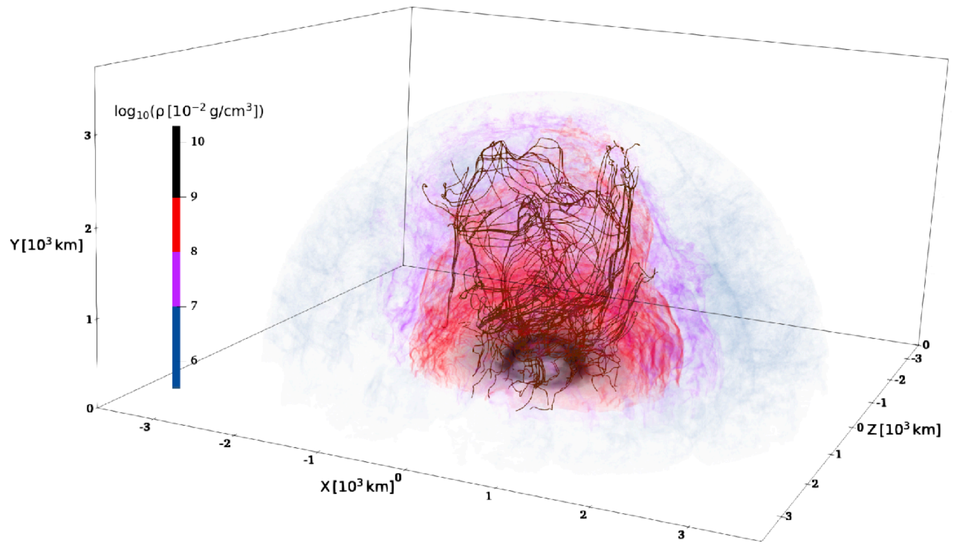


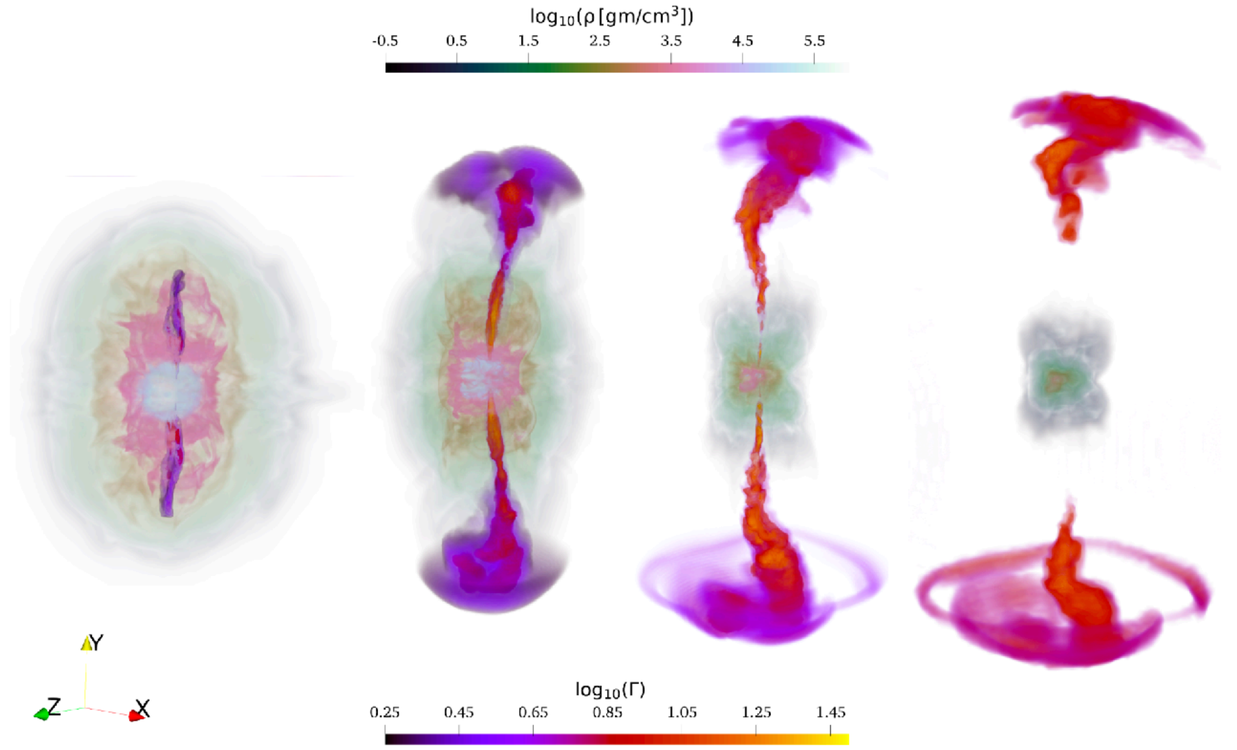
GRMHD Spritz code

Initial conditions:

- **Realistic magnetized environment evolved self-consistently up to 355ms after merger → collapse time**

Early time jet evolution





First three seconds of jet evolution
From Pavan et al. 2023

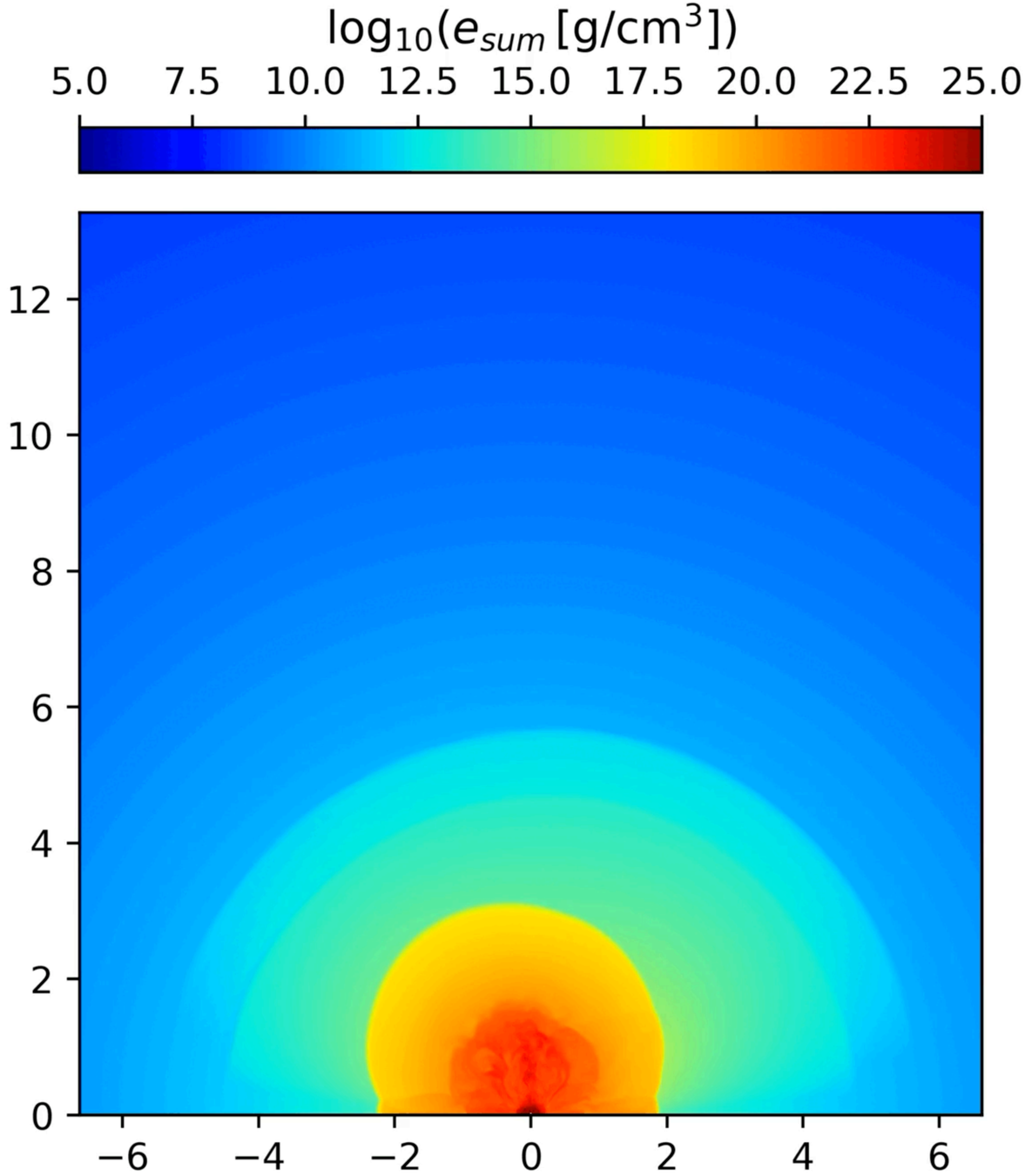
Initial conditions:

- Realistic magnetized environment evolved self-consistently up to 355ms after merger → collapse time
- Jet launch at 385ms after merger

Energy density

3”

Jet evolution

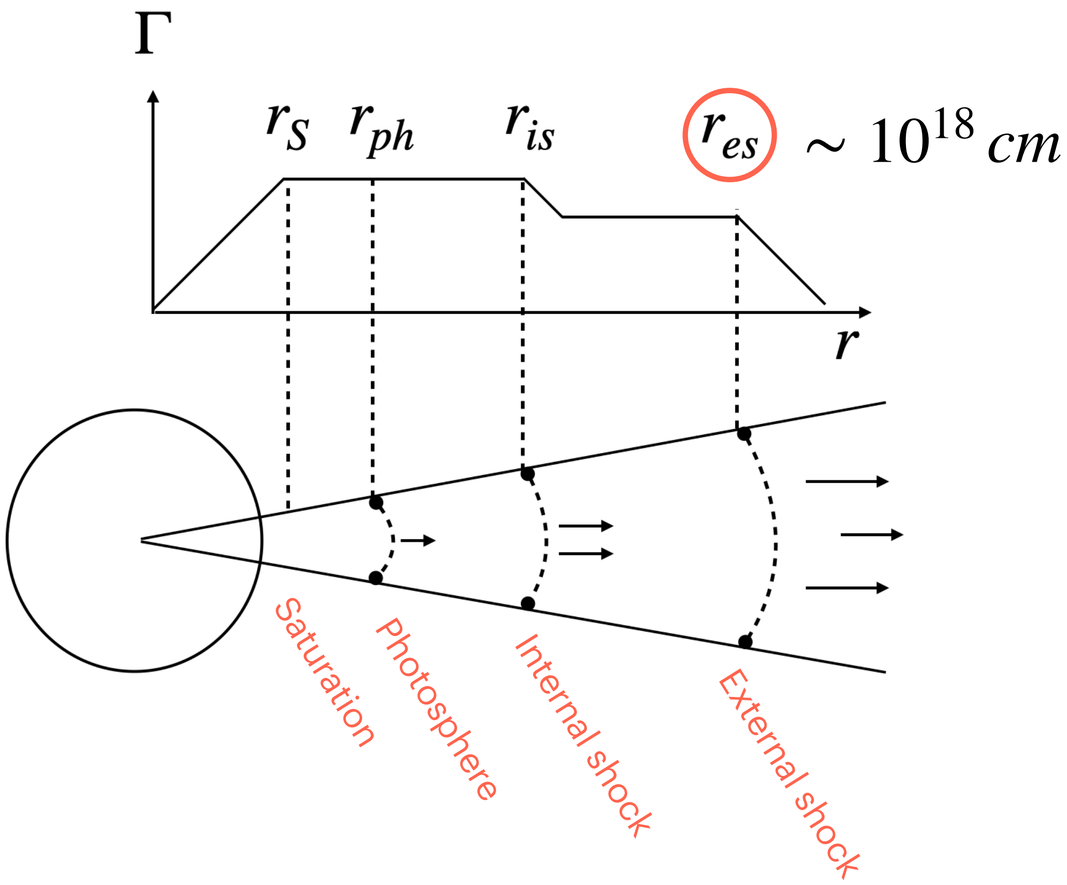


From Pavan et al. 2023

https://drive.google.com/file/d/1IcxSwZ0UzGbzUYfEi6dlumHmFVZd-vXq/view?usp=drive_link

Afterglow

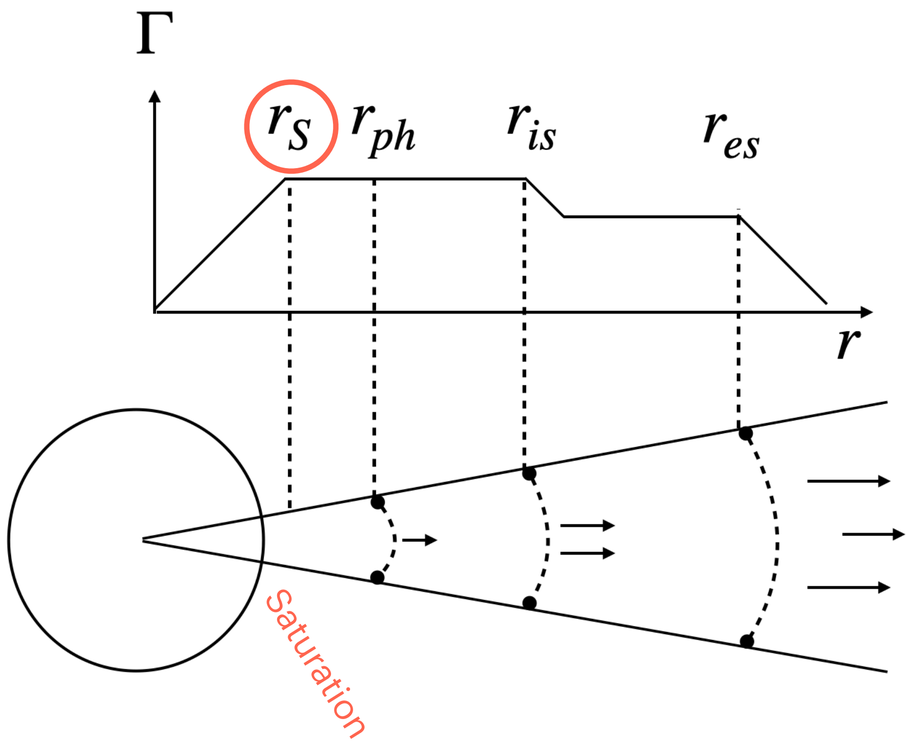
emission scales unreachable in 3D simulations



- Reach jet ballistic expansion

- Compute afterglow emission via semi-analytic models

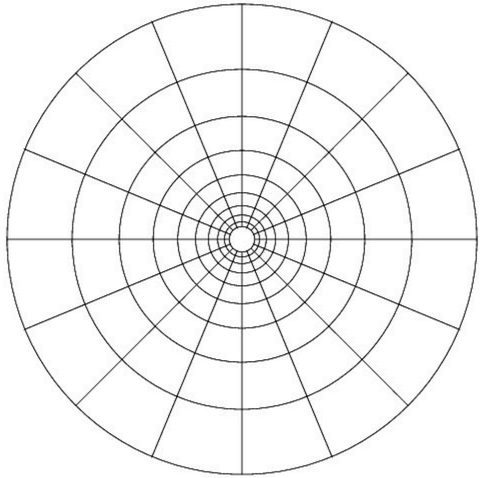
✦ Predictions are reliable if the final jet structure is reached

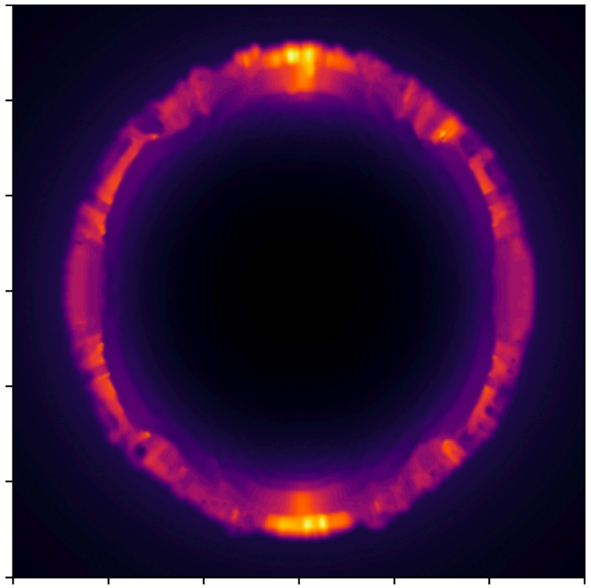


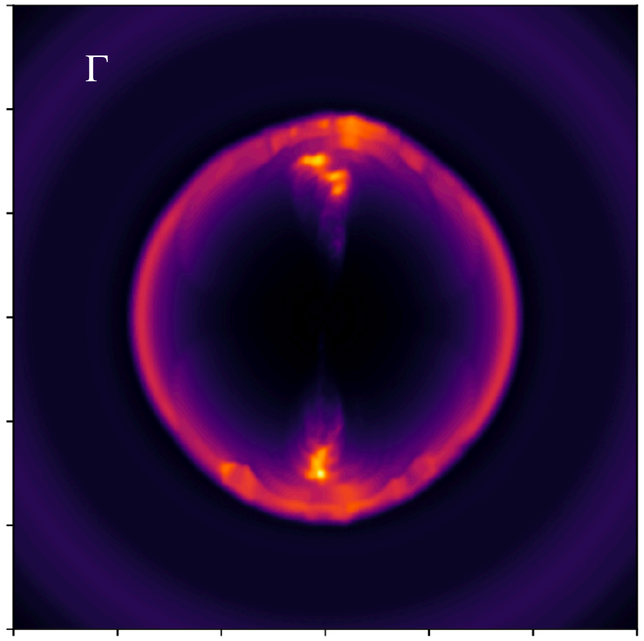
Extended jet evolution

(Dreas et al. 2025, A&A)

Spherical grid at larger scales: huge loss of resolution

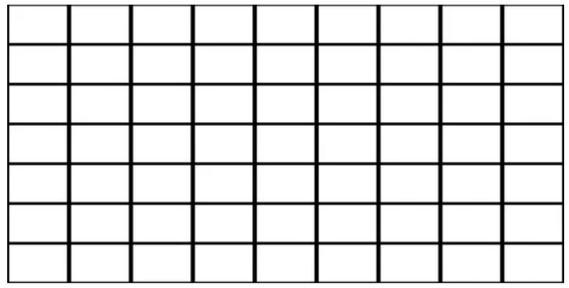






Starting point of extended evolution

~10s of jet evolution in 3D

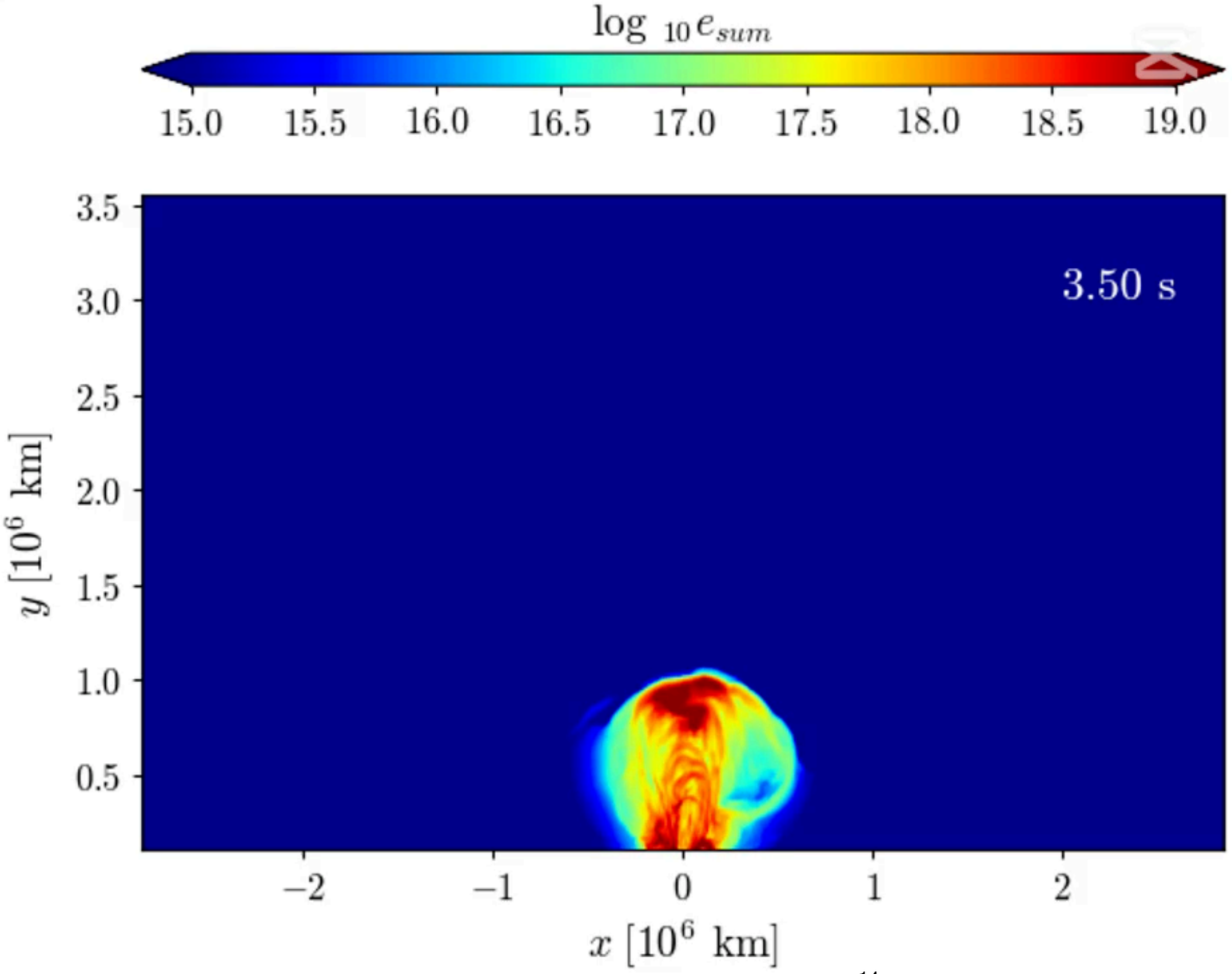


Uniform, no loss of resolution

Possible solution:

Cartesian grid

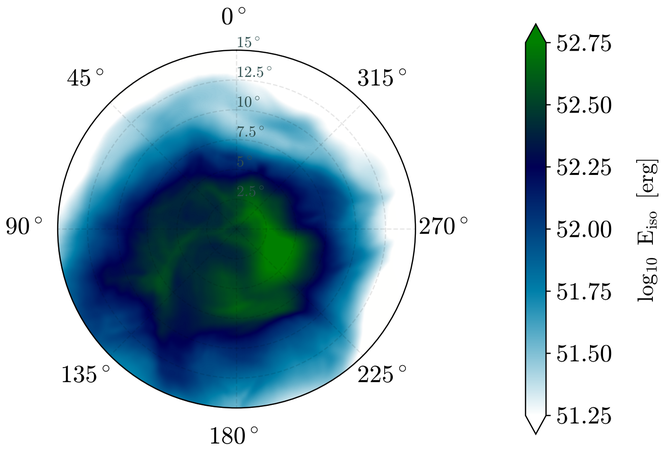
Energy density



Approaching jet ballistic motion
From Dreas et al. 2025

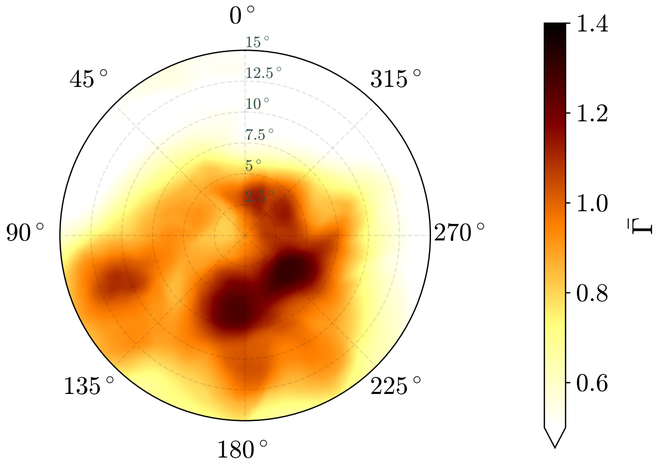
https://drive.google.com/file/d/1hGtjVJC2YQQdafKYGU99qWViM-uWm3ML/view?usp=drive_link

Angular distributions



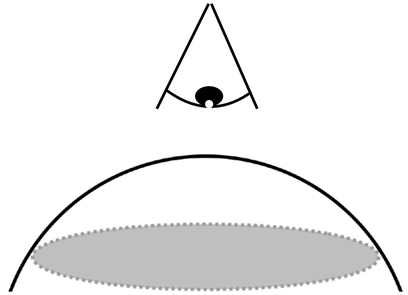
Isotropic equivalent energy

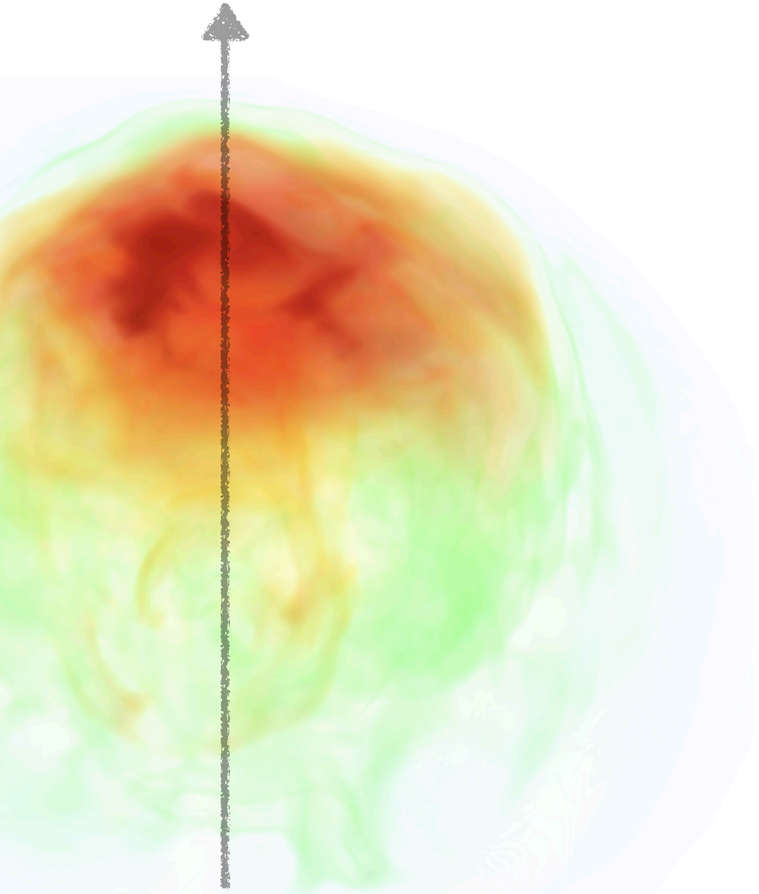
$$E_{\rm iso}(\theta,\phi) = 4\pi \int_{r_{\rm in}}^{r_{\rm out}} r^2 e_{\rm sum}(r,\theta,\phi)\,dr$$

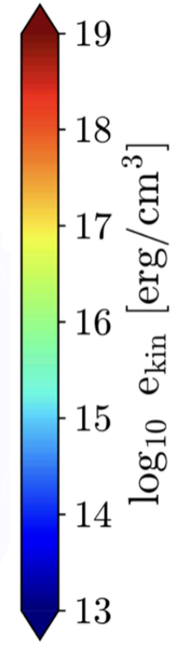


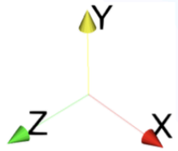
Average Lorentz factor

$$\bar{\Gamma}(\theta,\phi) = \frac{\int_{r_{\rm in}}^{r_{\rm out}} \Gamma(r,\theta,\phi)\, e_{\rm sum}(r,\theta,\phi)\, r^2 dr}{\int_{r_{\rm in}}^{r_{\rm out}} e_{\rm sum}(r,\theta,\phi)\, r^2 dr}$$



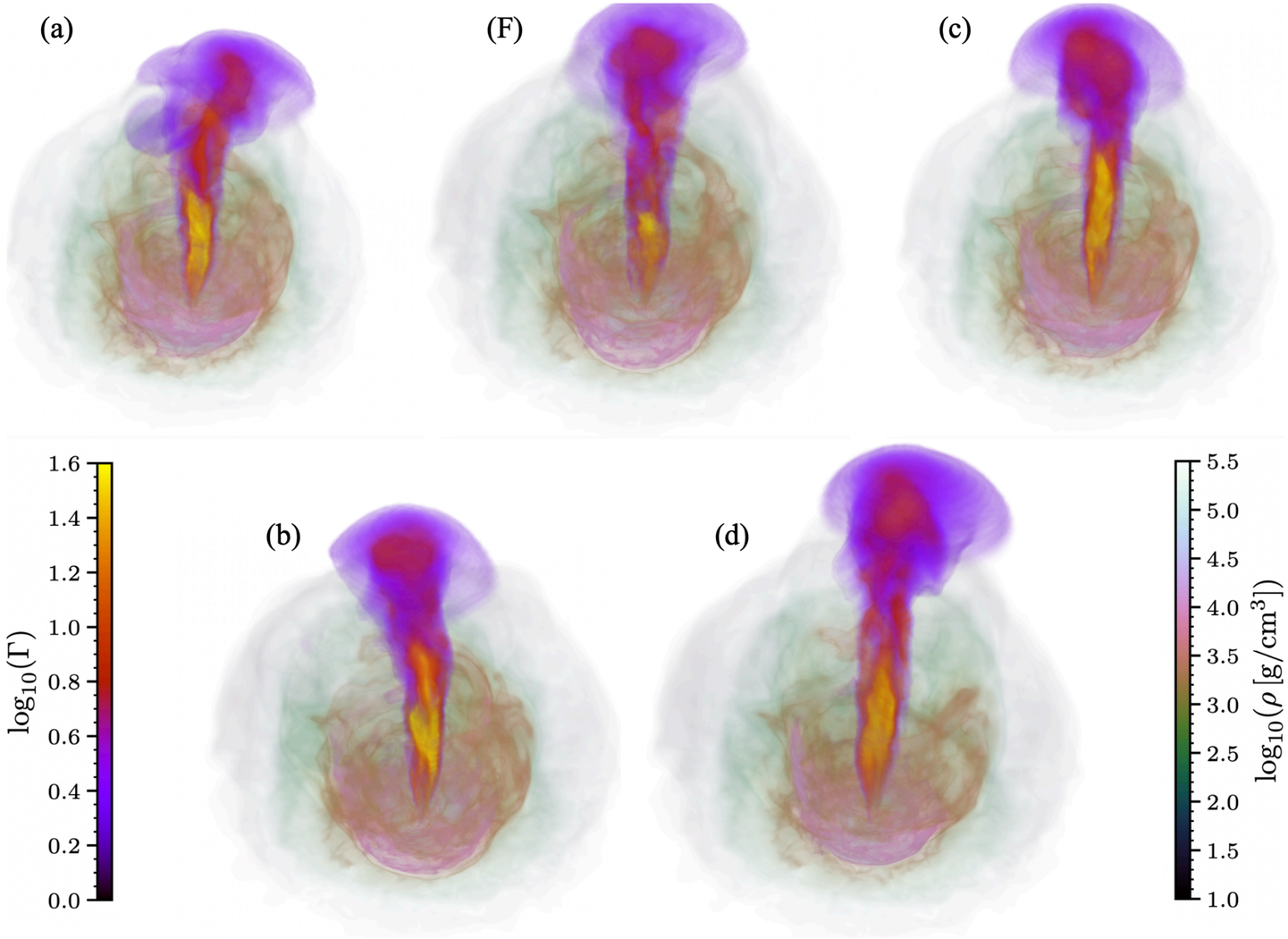






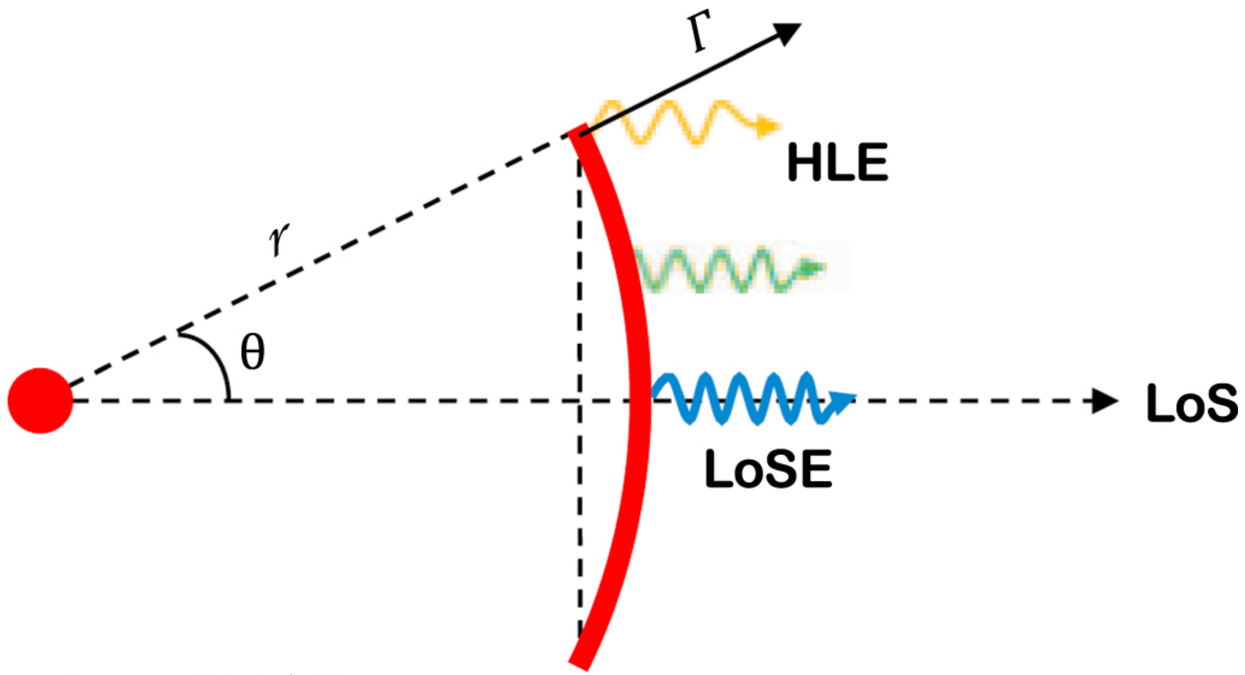
Parameter study

	t_coll [ms]	Lj [erg/s]	t_acc [s]	Mag
(a)	355	9E+51	0.3	1.2%
(b)	355	5E+51	0.5	1.2%
(c)	355	5E+51	0.3	1.6%
(d)	355	4E+51	0.3	1.6%
(F)	355	5E+51	0.3	1.2%
(e1)	355	3E+51	0.3	0.5%
(e2)	155	3E+51	0.3	0.5%



Pavan et al. 2025, MNRAS

Afterglow light curves



Donggeun Tak et al. 2023

Jet structure and energy distribution

↓

Following evolution and deceleration is followed with a semi-analytical code *

↓

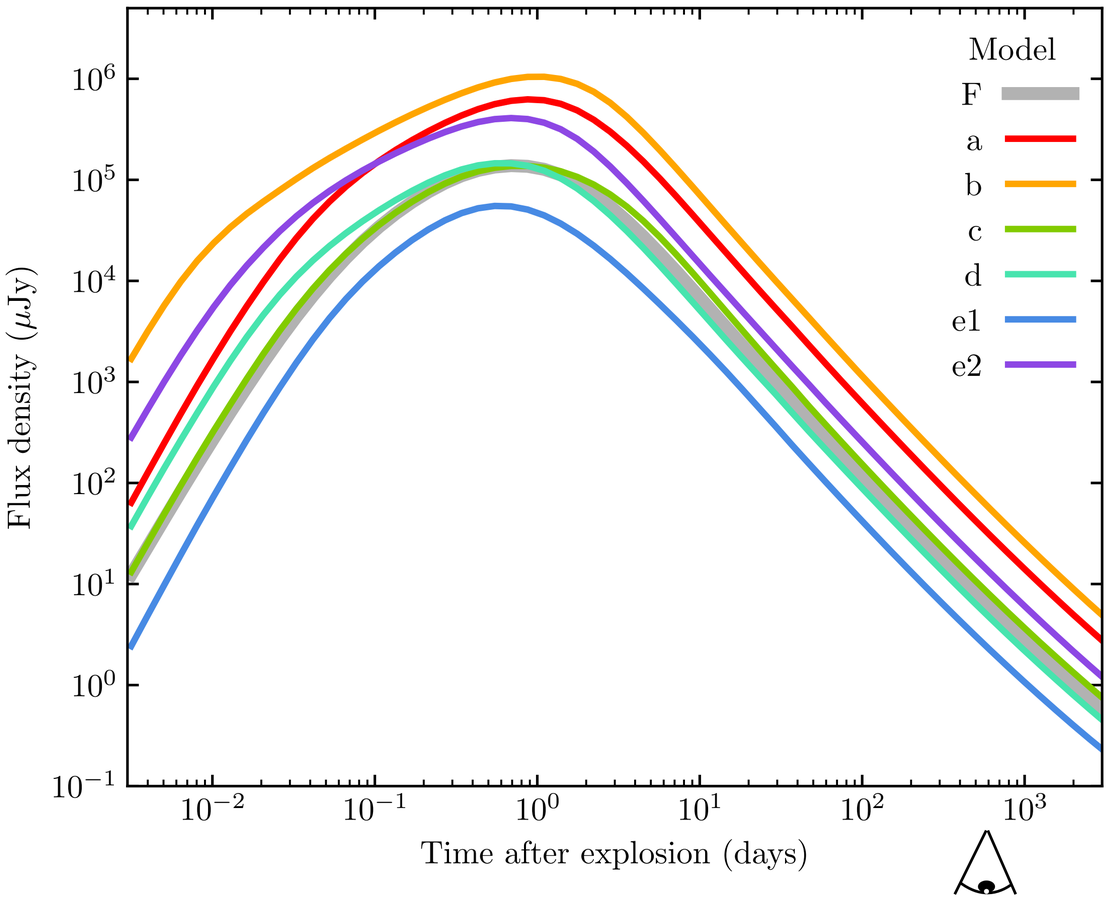
Synchrotron emission from relativistic electrons

↓

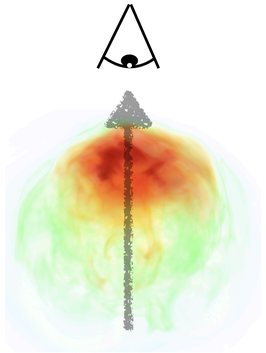
Multi wavelength light curves

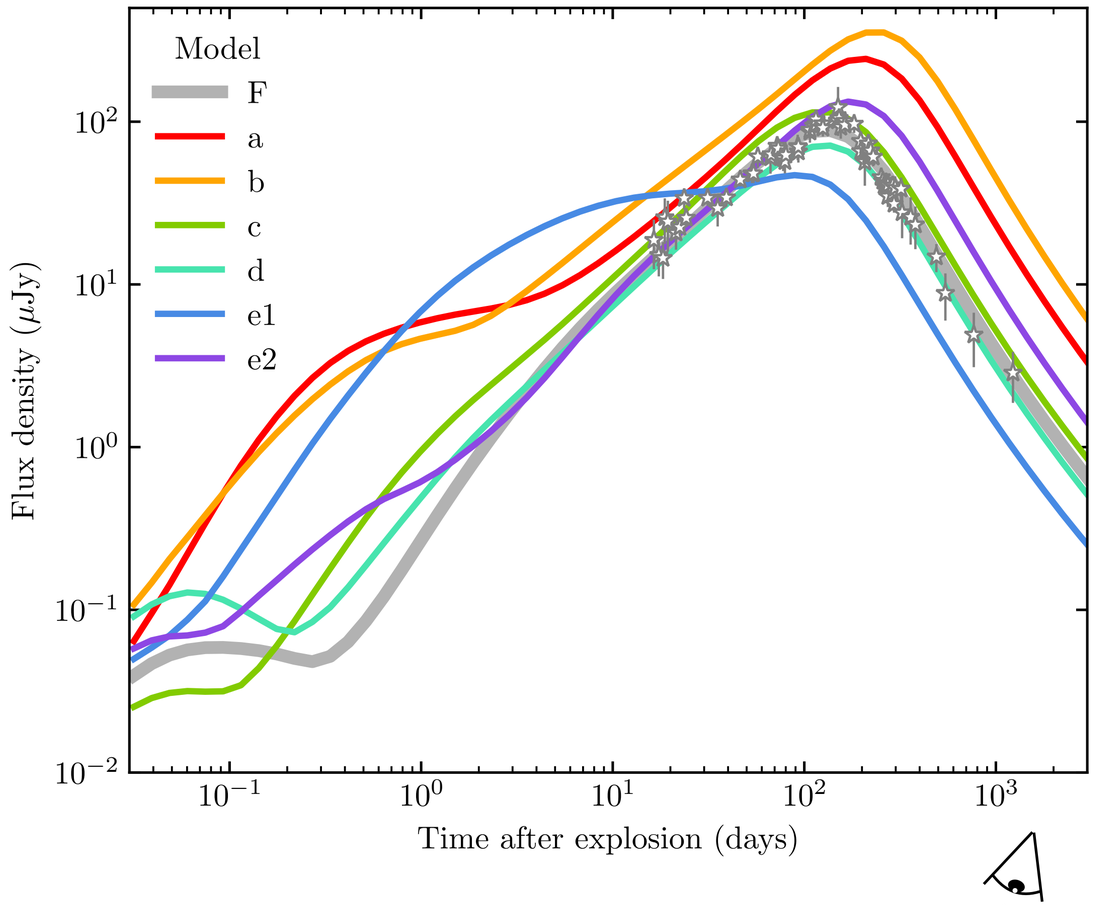
*Salafia et al. 2019

Afterglow light curves

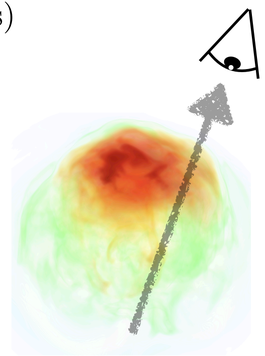


On axis observer





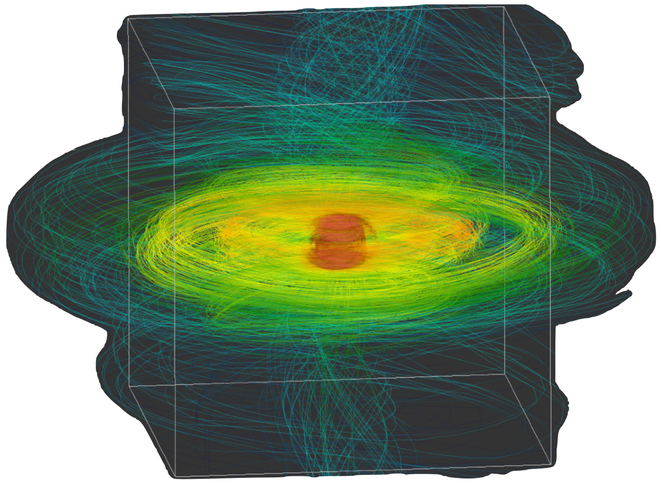
Off axis observer



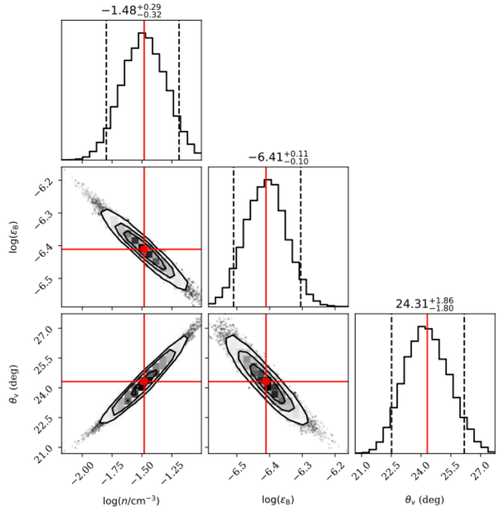
OUTLOOK

gPLUTO

- Increase performance with gPLUTO (GPU version)
- Test with gPLUTO AMR module
- Pipeline applied to other progenitors e.g. collapsar
- machine learning techniques applied to MCMC afterglow parameter estimation for systematic observable-model comparison



Aloy, Obergaulinger et al.



Thank you!