Magnetic dissipation in astrophysical jets: application to short gamma-ray bursts

G. Mattia (INFN - Sezione di Firenze)

L. Del Zanna, A. Pavan, R. Ciolfi, M. Bugli, A. Mignone

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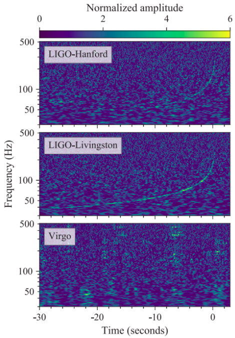
Short Gamma-ray bursts (Short GRBs)

Gamma-ray bursts: energetic explosions observed outside of our galaxy.
Described by NASA as "the most powerful class of explosions in the universe" (they release in few seconds the same energy of the Sun in its lifetime).

Short gamma-ray bursts:

- 30% of the gamma-ray bursts observed
- duration from 10^{-2} s to 2 s
- likely generated by binary neutron star mergers

August 2017: first joint detection of gravitational waves from the coalescence of two neutron stars and a short gamma-ray burst (GW170817 & GRB 170817A)

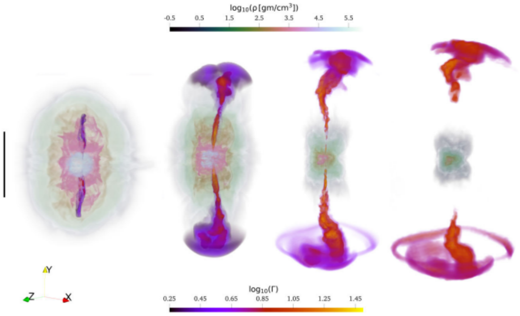


Paczynski 1986, Kouveliotou et al. 1993, Sari et al. 1999, Dai et al. 2017, Abbott et al. 2017 a, b, c, d, Margutti & Chornock 2021, Reddy 2023

The magnetic field

Some key ingredients:

- realistic vs analytical environment
- unmagnetized vs magnetized jet



Nathanail et al. 2020, Gottlieb et al. 2020, Ciolfi & Kalinani 2020, Ciolfi 2020, Pavan et al. 2021, Gottlieb et al. 2022, Pavan et al. 2023, Gottlieb et al. 2023

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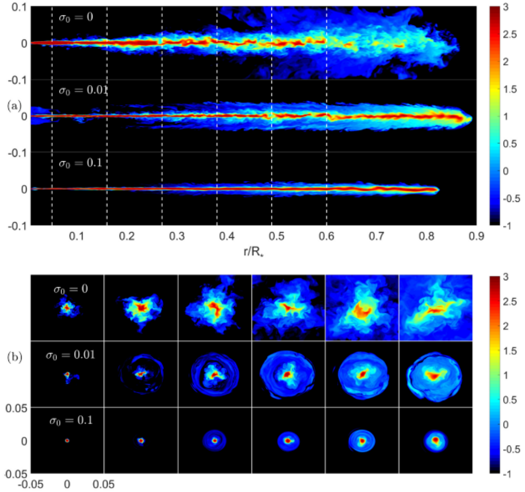
Impact on:

- environment structure and evolution
- opening angle
- magnetic field structure
- angular structure
- propagation and dynamics
- long term evolution



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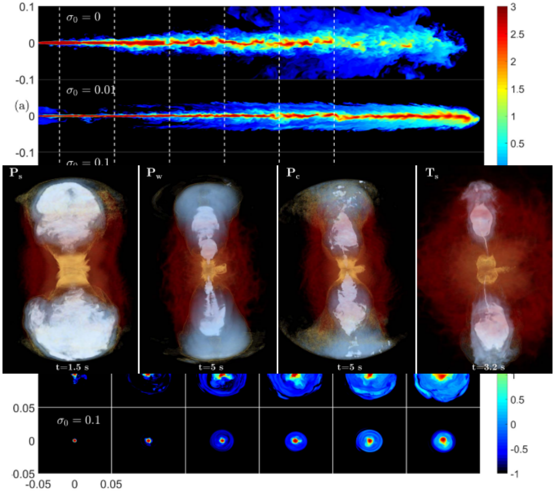
> Different parameters and configurations can lead to very different outputs!



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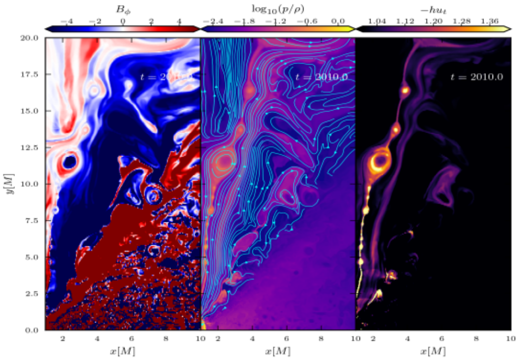
Magnetic reconnection in jets

Magnetic reconnection and dissipation play a role in the formation and evolution of astrophysical jets!

Impact:

- formation of plasmoids and current sheets
- power dissipated and Ohmic heating
- intermittent features
- large scale jet dynamics



Sheikhnezami et al. 2012, Vourellis et al 2020, Nathanail et al. 2022, Mattia & Fendt 2022

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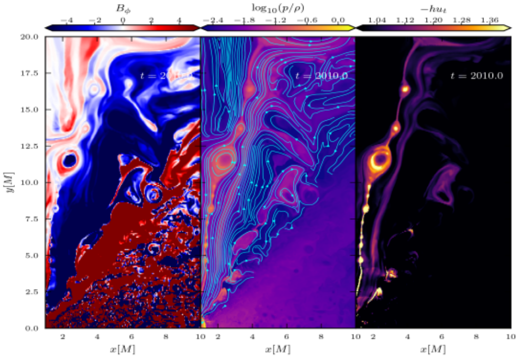
Open questions:

- Do GRB propagate under the assumption of infinite conductivity?
- Do magnetic dissipation and reconnection impact the jet shape and dynamics?



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Resistive Relativistic MHD equations

(Almost) full set of relativistic MHD equations:

$$
\begin{aligned}
&\partial_t D + \nabla \cdot (\rho\gamma \mathrm{v}) = 0 \\
&\partial_t \mathrm{m} + \nabla \cdot (\rho h \gamma^2 \mathrm{vv} - \mathrm{EE} - \mathrm{BB} + p_t \mathrm{I}) = 0 \\
&\partial_t \mathcal{E} + \nabla \cdot \mathrm{m} = 0 \\
&\partial_t \mathrm{B} + \nabla \times \mathrm{E} = 0 \\
&\partial_t \mathrm{E} - \nabla \times \mathrm{B} = -\mathrm{J}
\end{aligned}
$$

Ideal case

$$F_{\nu\mu} u^{\mu} = 0$$

$$\mathrm{E} + \mathrm{v} \times \mathrm{B} = 0$$

Electric field:

- always a function of v and B
- always perpendicular to B

Anile 1989, Komissarov 1999, 2007, Del Zanna 2007

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Resistive case

$$\mathrm{F}_{\nu\mu} u^\mu = \eta I_\nu + \eta I_\mu u^\mu u_\nu$$

$$\mathrm{J} = \gamma \eta^{-1} [\mathrm{E} + \mathrm{v} \times \mathrm{B} - (\mathrm{E} \cdot \mathrm{v})\mathrm{v}] + q\mathrm{v}$$

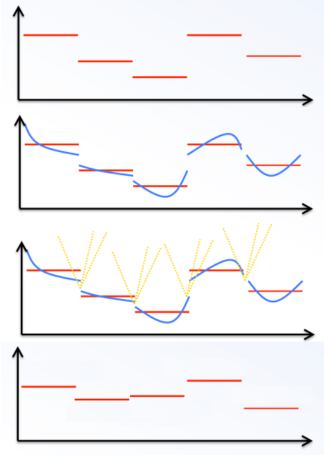
Electric field:

- independent variable of the physical system

The PLUTO code

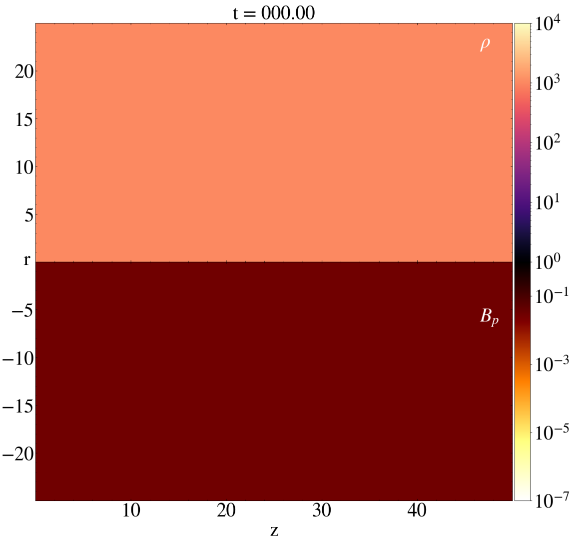
PLUTO is a finite-volume code designed to integrate and solve a set of conservation laws in the following steps:

- Starts from volume averages
- Reconstruct interface values from zone averages
- Solve Riemann problems between adjacent, discontinuous states to compute the interface flux
- Update conserved variables with time stepping algorithm



Mignone et al. 2007, 2012, 2019

Resistive Jets (Mattia et al. 2023)



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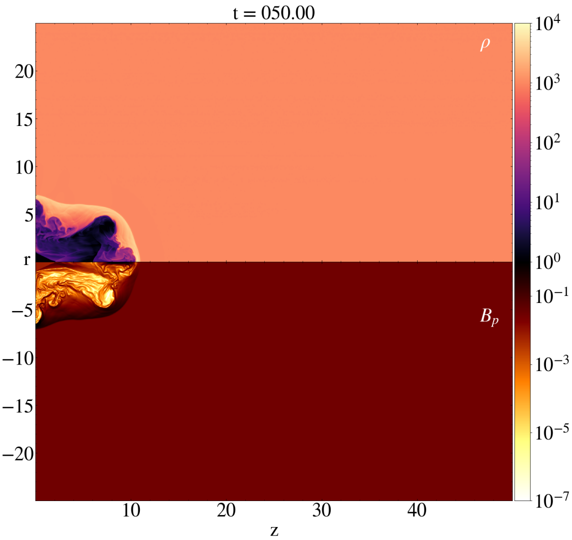

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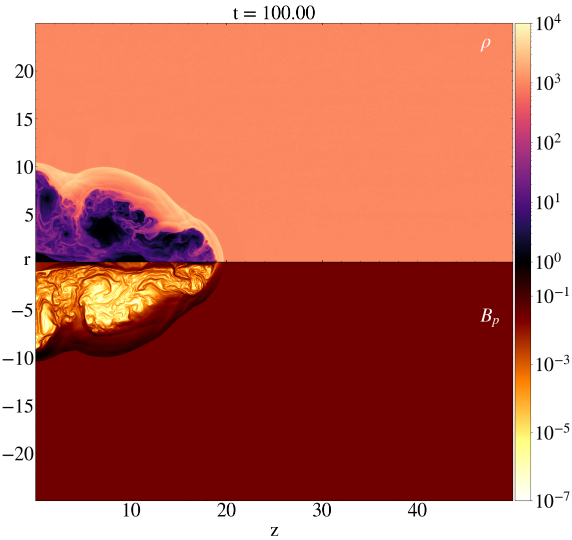

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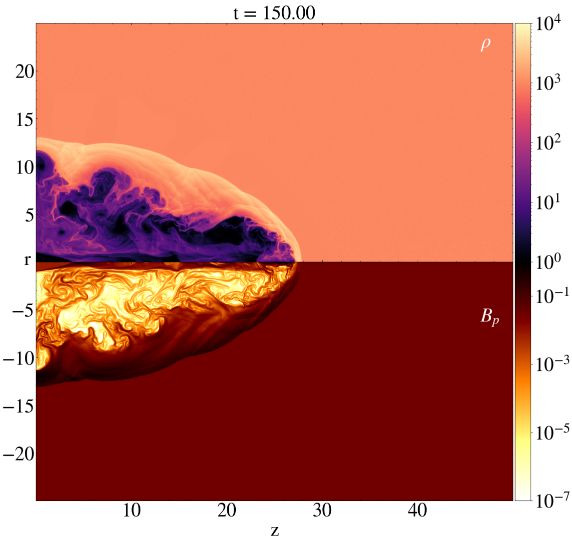

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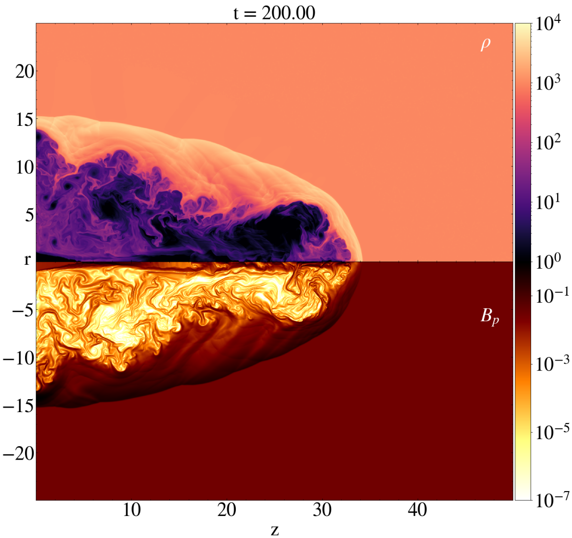

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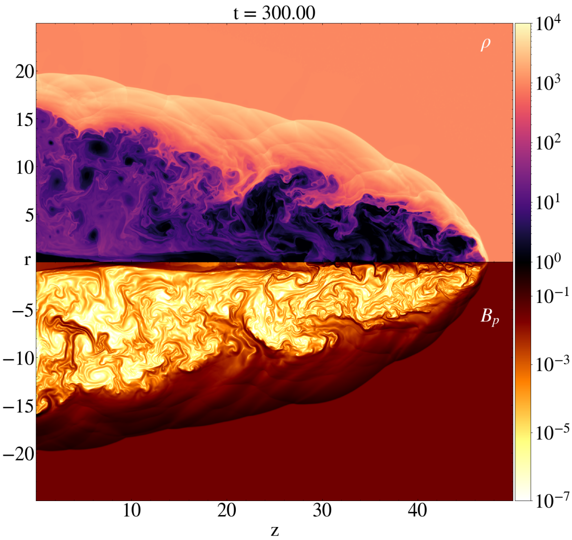

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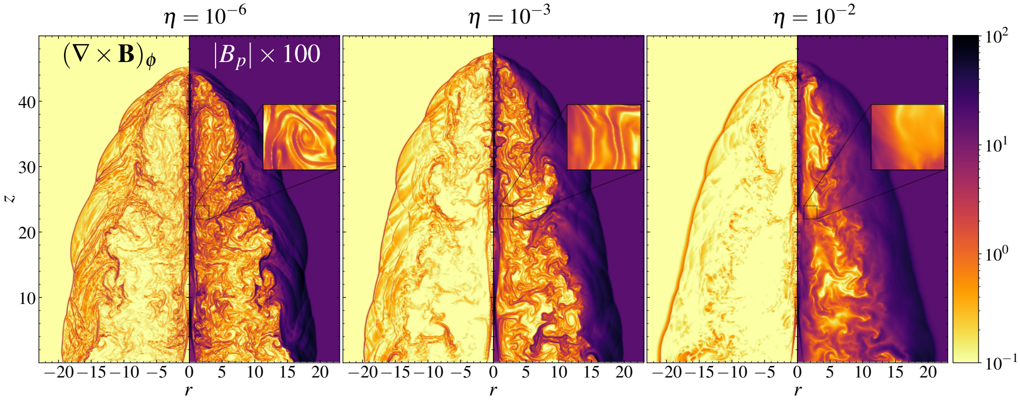

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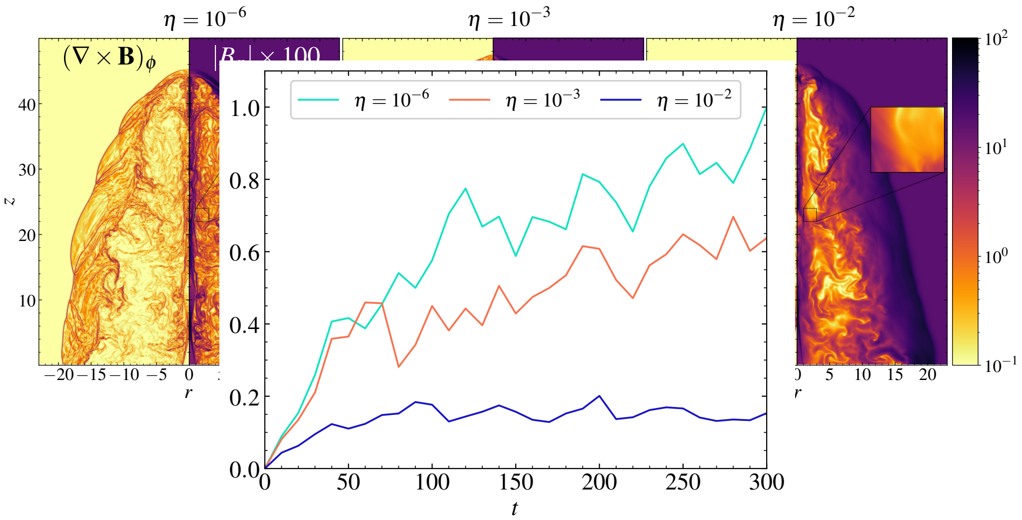
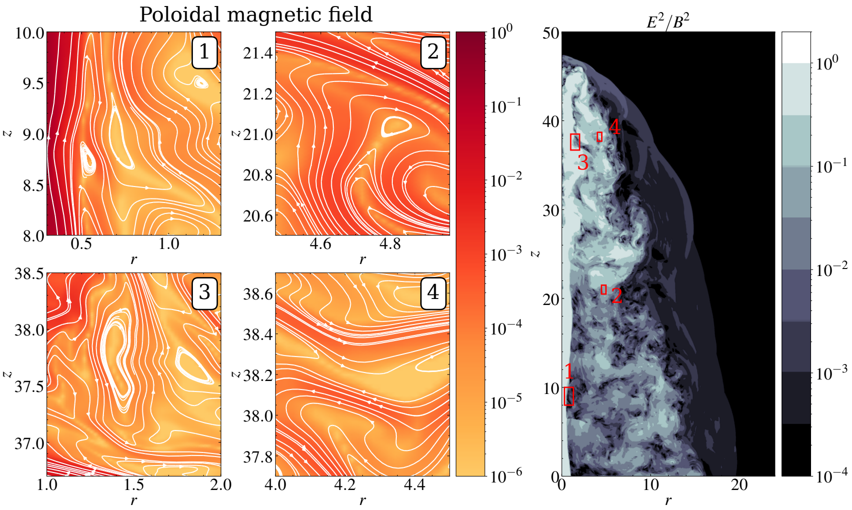


Formation of current sheets (Mattia et al. 2023)



GRB Jet setup (Mattia et al., accepted in A&A)

- PLUTO code, ResRMHD Module
- 2D spherical axisymmetric simulation (4 runs) + 3D spherical simulation (1 run)
- radial extension: $[562.6, 95439.3]$ km
- analytical environment + analytical jet
- expanding post-merger wind, static atmosphere
- magnetic dipole from the compact object, unmagnetized atmosphere
- jet injected at the inner radial boundary

Mignone et al. 2007, 2012, 2019, Pavan et al. 2021, 2023

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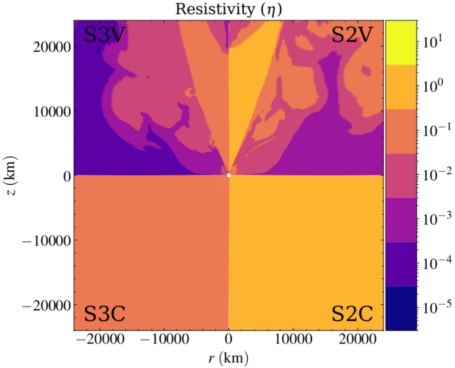
$$S = \frac{r_{min} v_a}{\eta}$$



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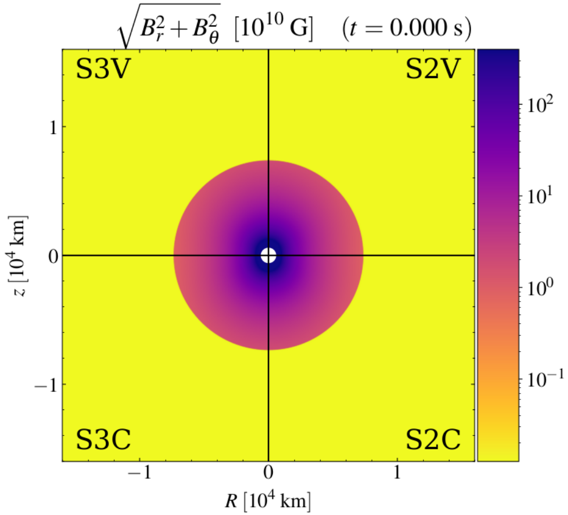

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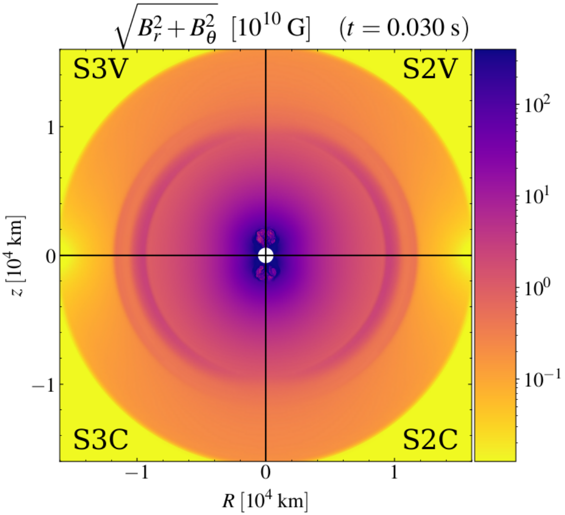

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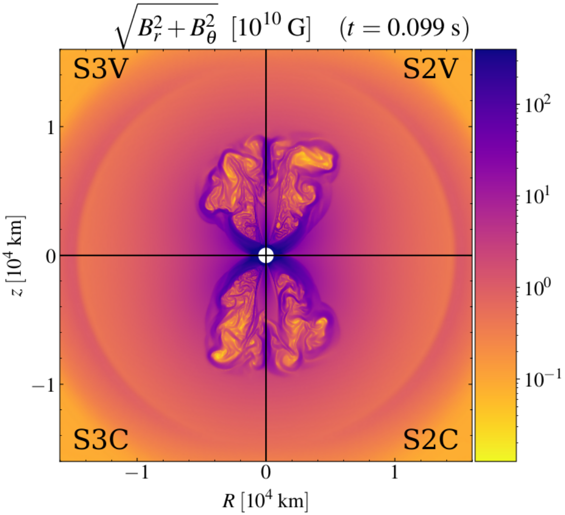

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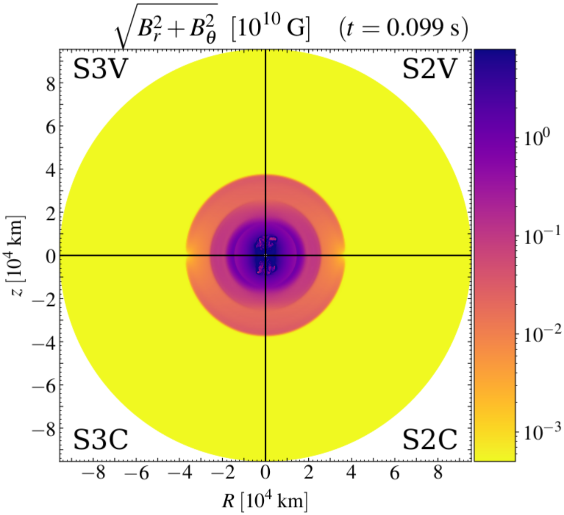

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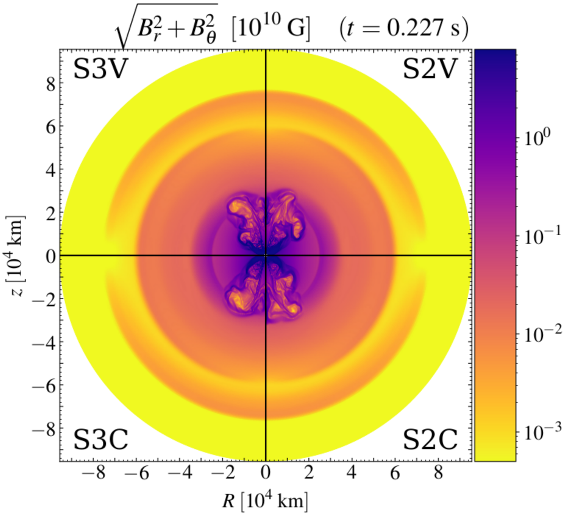

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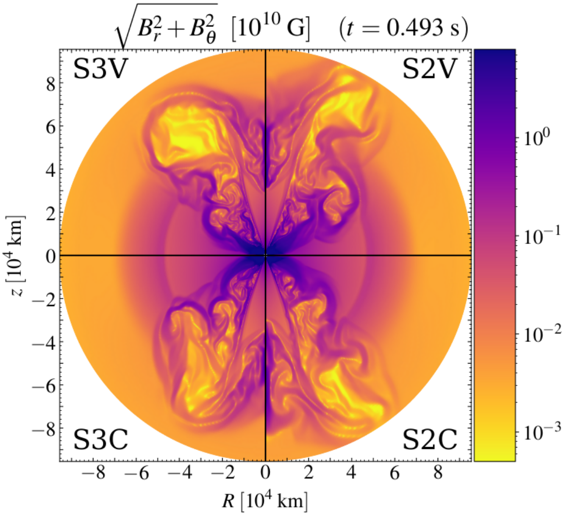
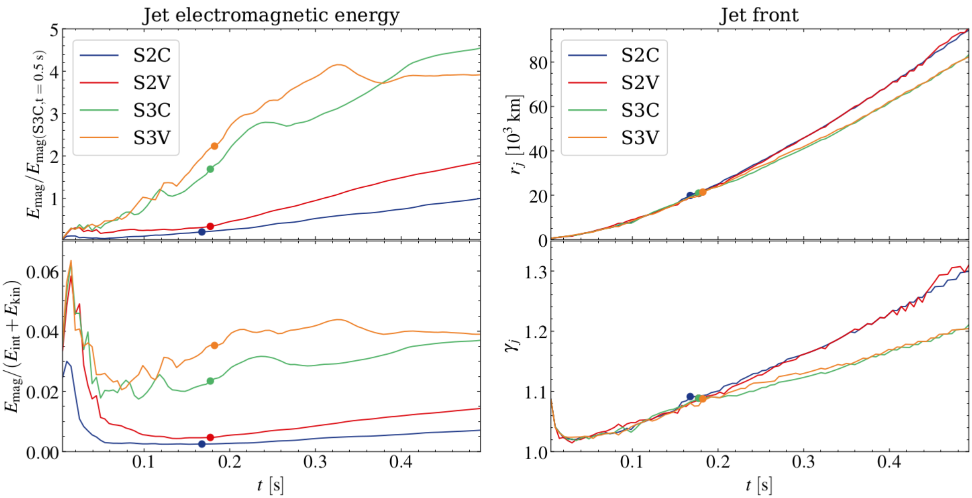
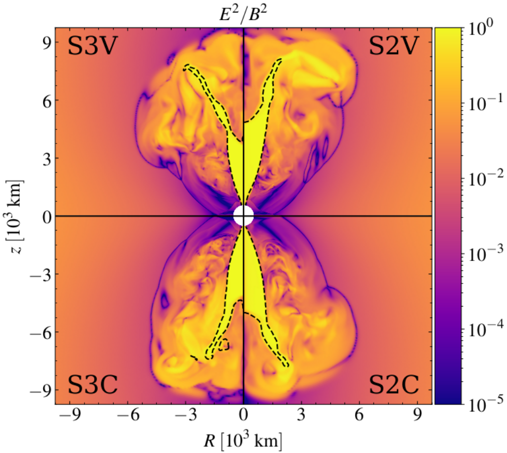
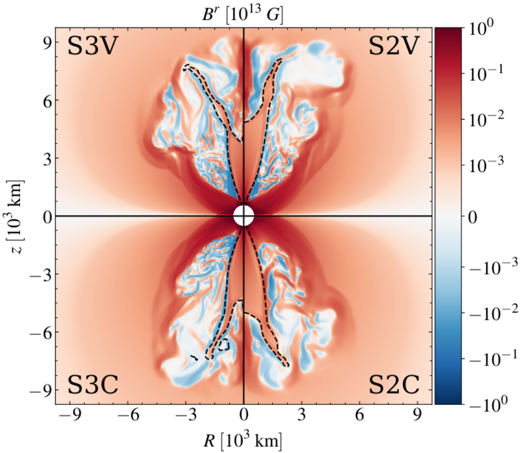


Energy and dynamics (Mattia et al., accepted in A&A)

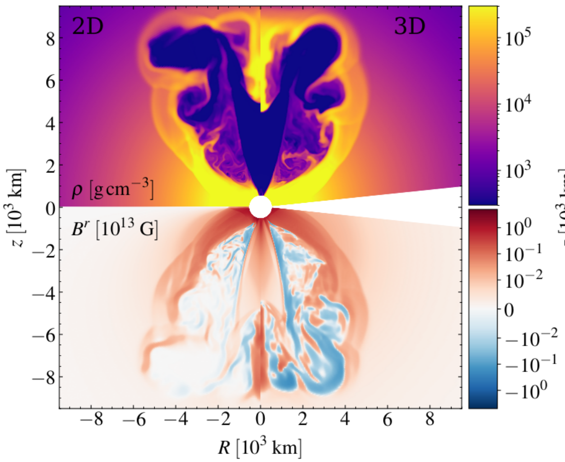


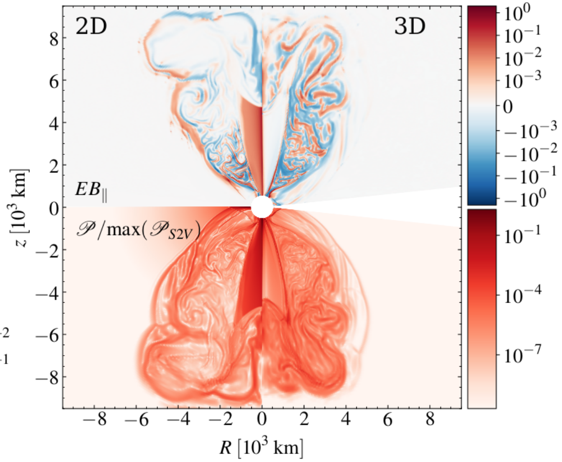
The resistive electric field (Mattia et al., accepted in A&A)





A fully 3D simulation (Mattia et al., accepted in A&A)





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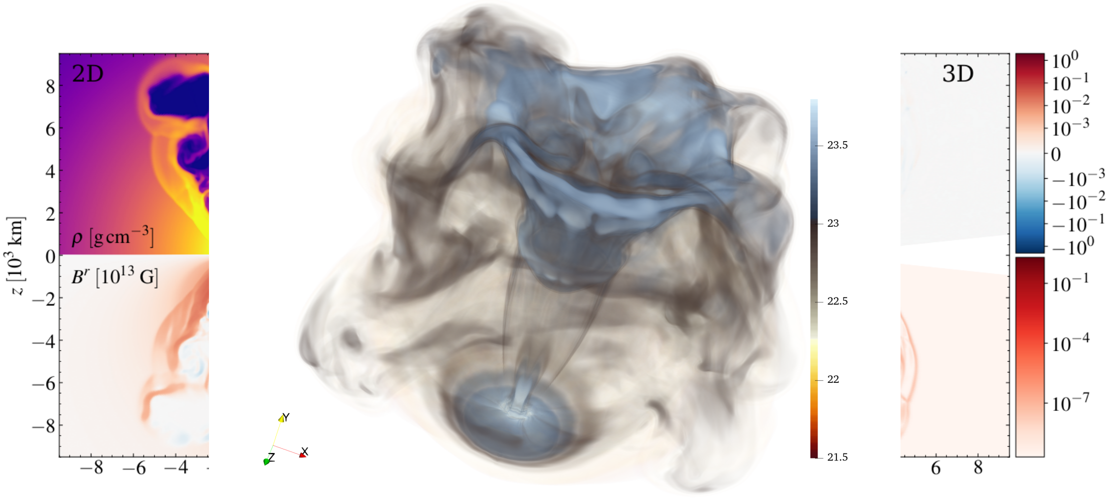

Conclusions

In summary:

- non-ideal processes may play a strong role on jets evolution
- the dynamics and the energy budget of the jet is related to the magnetic resistivity
- magnetic resistivity impacts also the interaction and the turbulence with jet and the post-merger medium in short GRB jets
- 3D simulations are necessary to fully investigate the jet dynamics

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Next step:

- 3D resistive simulations with realistic environment

THANK YOU