Numerical Simulations of Gamma-Ray Burst Afterglows: Dynamics to Emission

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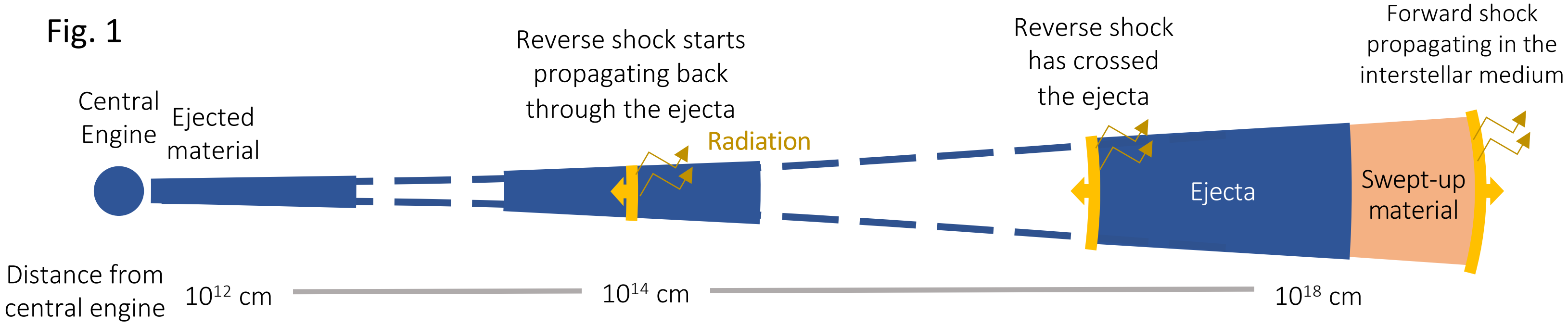
Gamma-ray bursts (GRBs) are the most powerful explosions in the Universe (slide 1). Analytical descriptions of such events fail to capture the overall complexity of these relativistic flows. However, numerical simulations remain challenging. We present a **new approach to numerically modelling the dynamics of GRB afterglow blast waves using a moving mesh**, that allows to **locally trace the particle population responsible for emission** downstream of the shocks (slide 2). We present a first application in one dimension to the problem of **flares in the X-ray afterglow** (slide 3) and the **first preliminary tests in two dimensions** (slide 4).

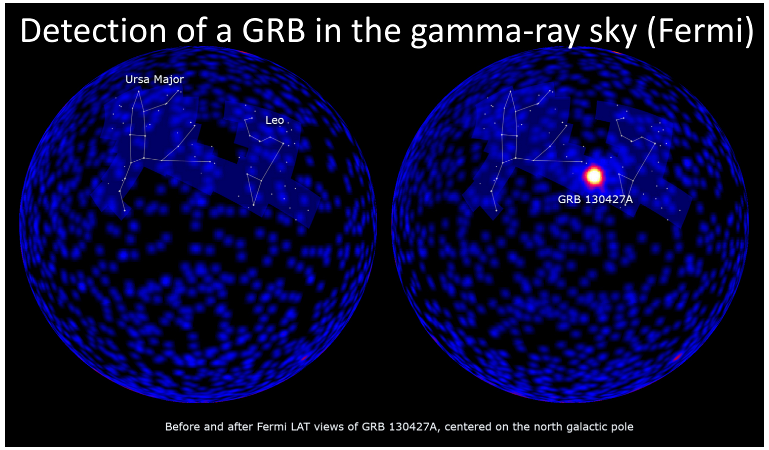
What are Gamma-Ray Burst afterglows?

Fig. 1

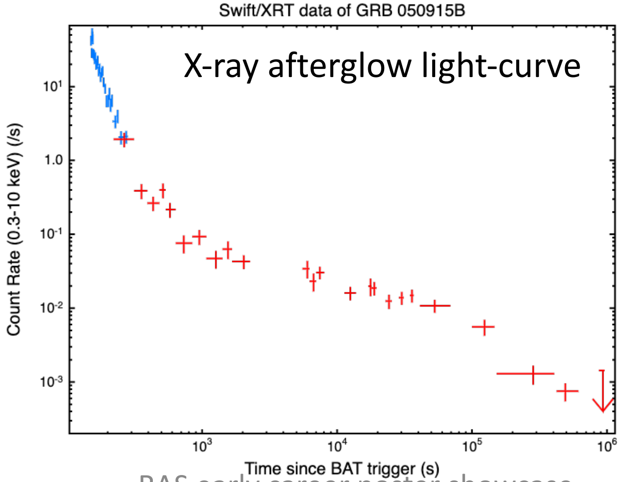


Central Engine
Ejected material
Reverse shock starts propagating back through the ejecta
Radiation
Reverse shock has crossed the ejecta
Ejecta
Forward shock propagating in the interstellar medium
Swept-up material
Distance from central engine
10^{12} cm
10^{14} cm
10^{18} cm

Gamma-ray bursts are the signature of the death of massive stars or the merger of neutron stars. The explosion powers an ultra-relativistic collimated jet that travels over several orders of magnitude in space before it decelerates as it sweeps up material ahead.



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole



As the ejecta collides with the interstellar medium, synchrotron emission is produced at the shock fronts (yellow lines, fig.1), creating an **afterglow** visible from X-ray to radio with fading brightness over time (light curve). Understanding the diverse features of afterglow light curves gives valuable insight on the nature and behaviour of the central engine (the mechanism powering the jet) and the emission mechanisms in the relativistic shocks.

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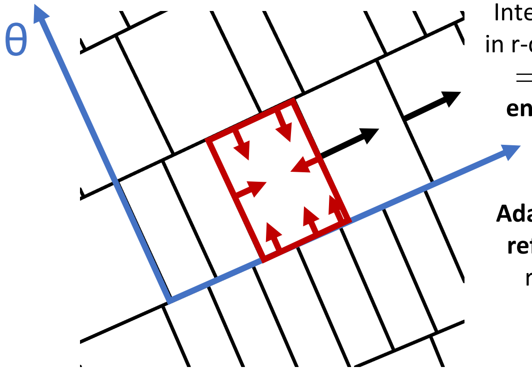
Accurately modelling the afterglow light curve means **precisely modelling the dynamics of the ejecta around shock fronts**. We develop a **numerical relativistic hydrodynamics code**, that operates on a **moving mesh** with arbitrary velocity.

Relativistic hydrodynamics on a moving mesh

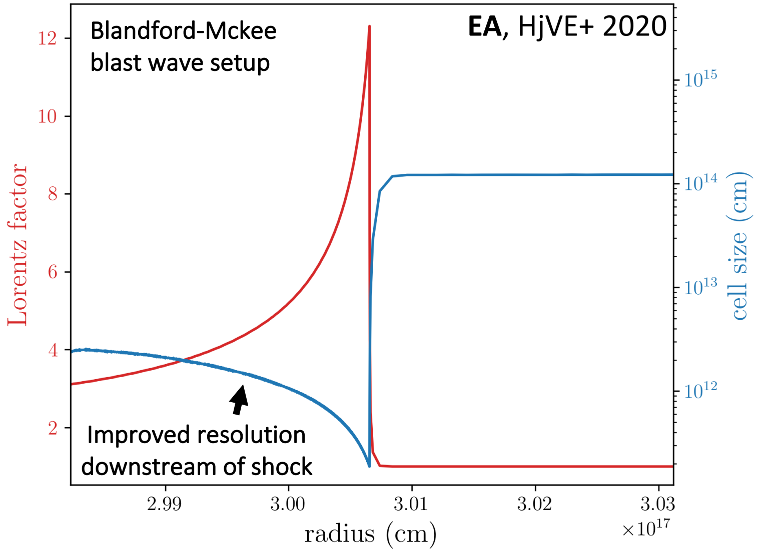
Finite-volume Godunov scheme



Interfaces move in r-direction only ⇒ **no mesh entanglement**

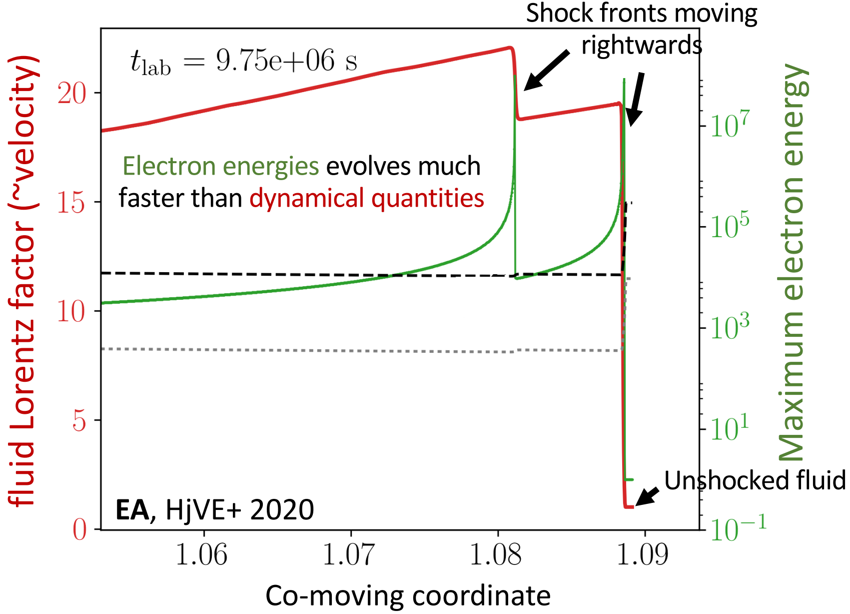
Adaptive mesh refinement in r-direction

➔ Inter-cell fluxes: same solver in all directions.
The mesh can move in any ONE dimension.



Fixed meshes are particularly ill-suited to GRB dynamics as the region of interest is very narrow and moves over great distances and thus cannot be resolved. **A mesh that moves along with the fluid** can use a smaller grid and optimises quantity conservation in each cell allowing for longer time-steps, making it more efficient for highly directional flows. Allowing the mesh to **move only in one direction** circumvents computationally expensive re-gridding operations in multi-dimensions.

Local synchrotron cooling



Shock fronts **accelerate electrons that radiate synchrotron light**. Downstream of shocks the electrons cool down very quickly. High resolution is needed around shocks for (i) accurate detection and (ii) calculation of electron cooling. The moving-mesh provides this resolution and ensures de-coupling of the dynamical (gentle red slope) and cooling (steep green slope) time scales.

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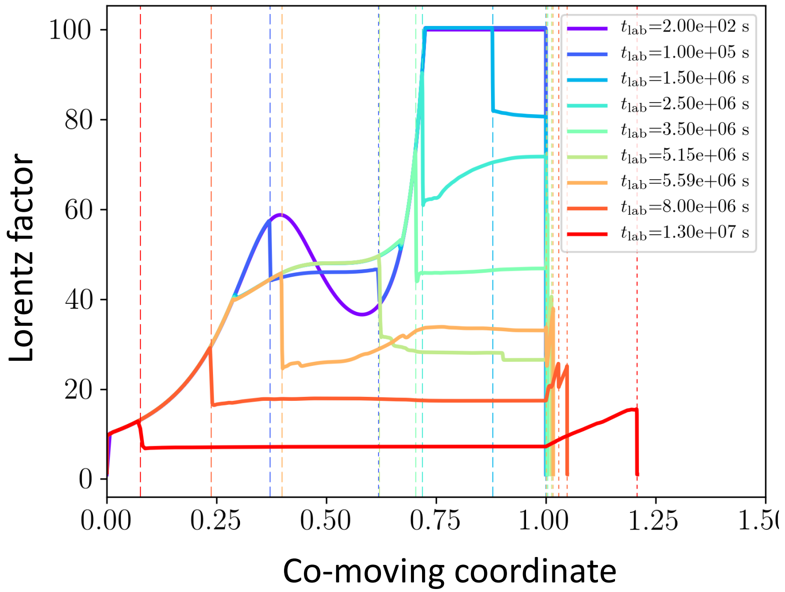
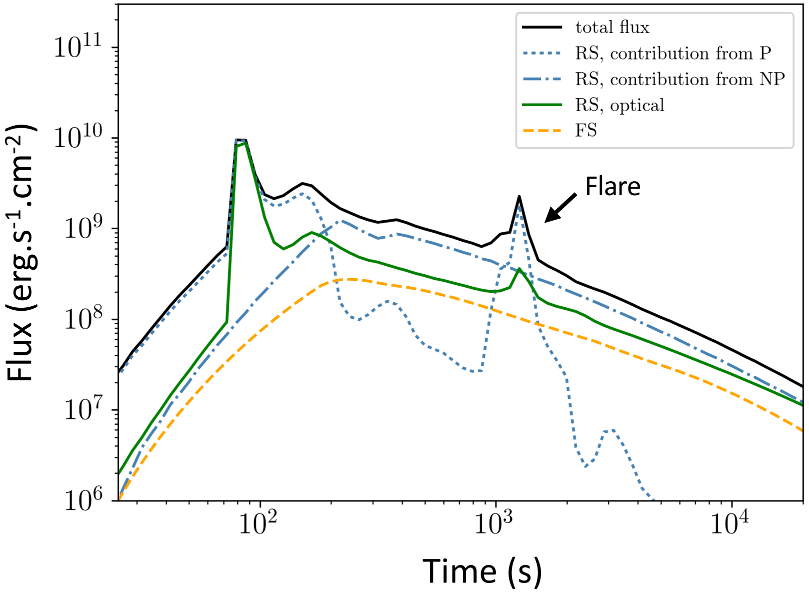
We apply the code in **one dimension** to the problem of the often observed **flares in the early X-ray afterglow**: the moving mesh allows the local calculation of the evolution of the particle population downstream of shocks. We can compute synthetic light curves across the electromagnetic spectrum and show that flares can be the result of an initial perturbation at the back of the ejected material.

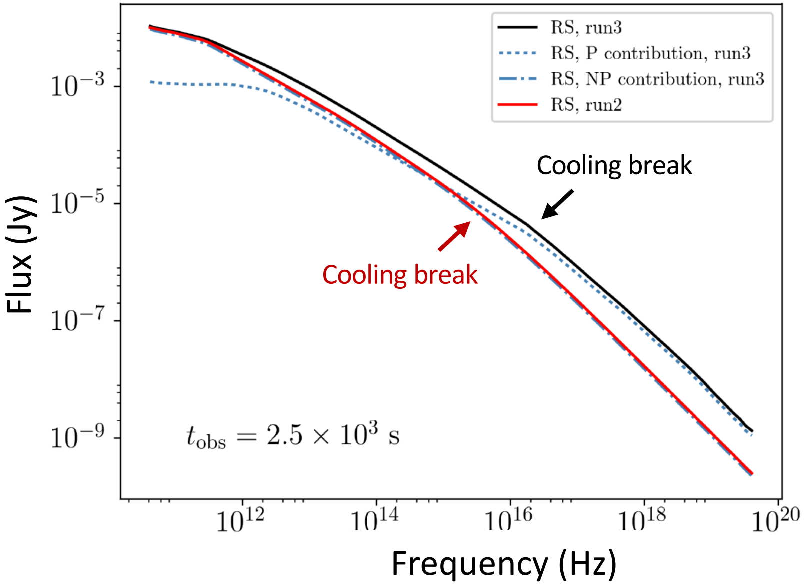
Flares in the X-ray light curve (**Ayache, E. H.**, Van Eerten, H. J., Daigne, F. (2020), MNRAS, 495, 2979-2993)



Velocity profile (Lorentz factor) of the ejecta as a function of time (indigo->red) in our simulations. The vertical lines show detected shock fronts where synchrotron radiation is emitted. One such shock interacts with the perturbation increasing its contribution to emission and producing a flare.



Corresponding synthetic light curve in X-ray and optical, showing a flare at 1000 seconds (black solid line).



Synchrotron spectrum of the afterglow at the time of the flare (black) vs with no flare (red). The spectra show a difference in cooling break. Accurately calculating the cooling break position can only be done by locally tracing the particle population, which is thus crucial to understand the flaring behaviour.

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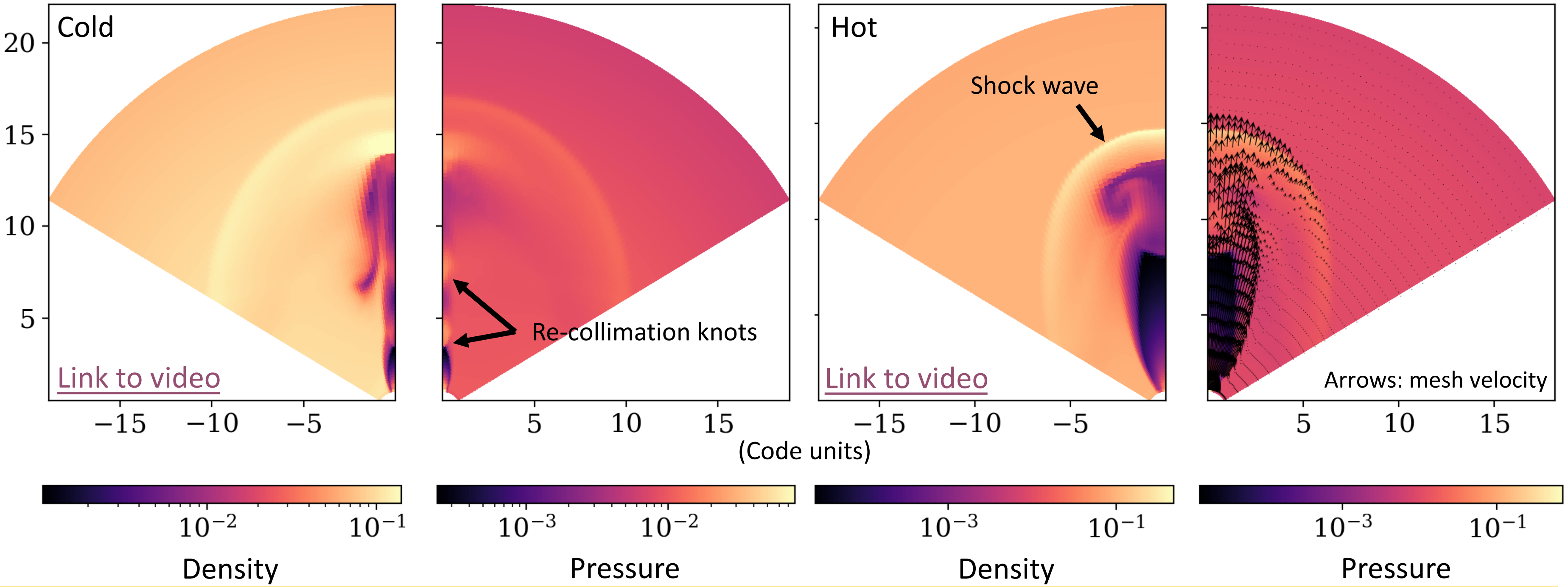
Recent observations (e.g. GRB170817A) have revealed the importance of lateral structure in these jets, both at early and late times of their evolution. Multi-dimensional simulations are thus required to explain the whole range of behaviours observed for GRB afterglows.

Multi-dimensional dynamical simulations (preliminary)



Left: As a first sanity check we run two coarse simulations of the early propagation of a **relativistic jet** in a diffuse surrounding medium.

For a **cold jet** (left), the outflow is strongly collimated onto the jet axis by the higher external pressure. We can observe re-collimation knots typically detected in the jets of galaxies with an active central black hole.

In the **hot jet** case (right), the first rarefaction (low pressure) region is much bigger, and here the actual jet has not yet had time to form. The (potentially radiating) shock wave propagating ahead of the swept up material is well visible here.

Intended applications: Our code can be used to study the **influence of the jet-launching parameters on the radiation**. Moreover, we can better understand **the interplay between large scale jet dynamics and local particle shock acceleration.** From this we can derive better constraints from observations across the electromagnetic spectrum on the fundamental plasma physics of particle acceleration and magnetic field generation in relativistic shocks.