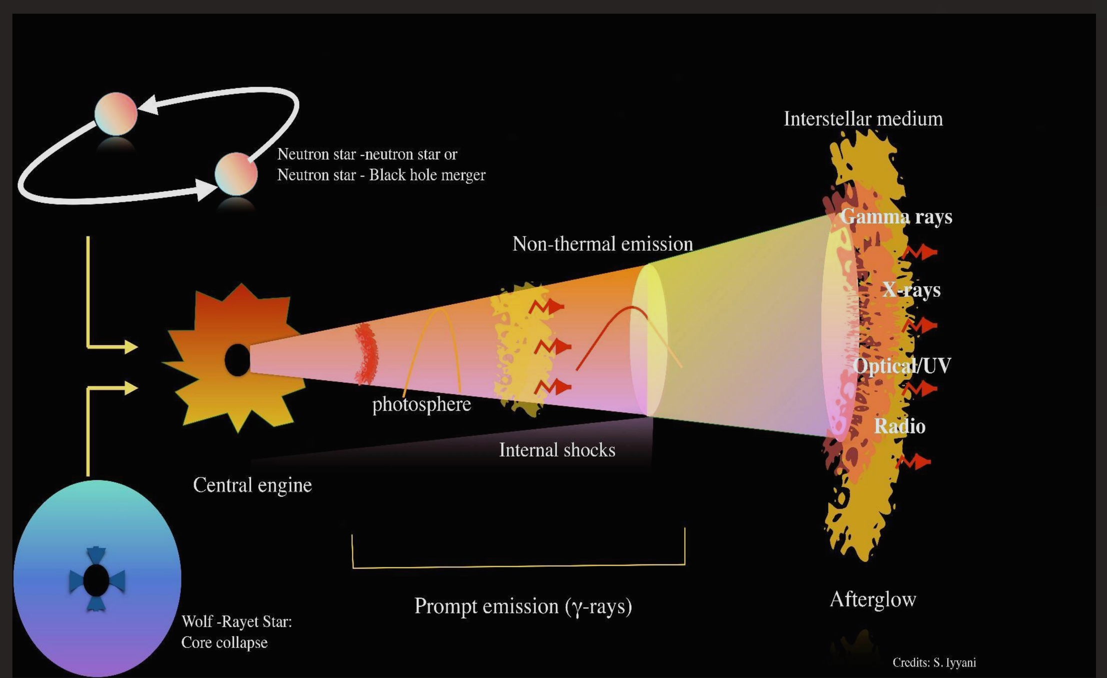
Gamma Ray Bursts and their central engines studied by computational hydrodynamics methods

Agnieszka Janiuk[1], Joseph Saji[1], Gerardo Urrutia[1], Hector Olivares[2]
1.Center for Theoretical Physics, Polish Academy of Sciences
2. University of Aveiro, Portugal

Gamma Ray Bursts

- Short but intense flashes of high energy radiation detected in gamma rays
- Last from milliseconds to hundreds of seconds.
- Typical Radiation energy : $10^{52} - 10^{54}$ ergs
- Explode at cosmological distances and distribution is isotropic.
- Classified into two groups based on duration T_{90}
  Short GRB: Originates from the merger of compact objects
  Long GRB: Progenitors are identified to be massive stars based on their association with a core-collapse supernova

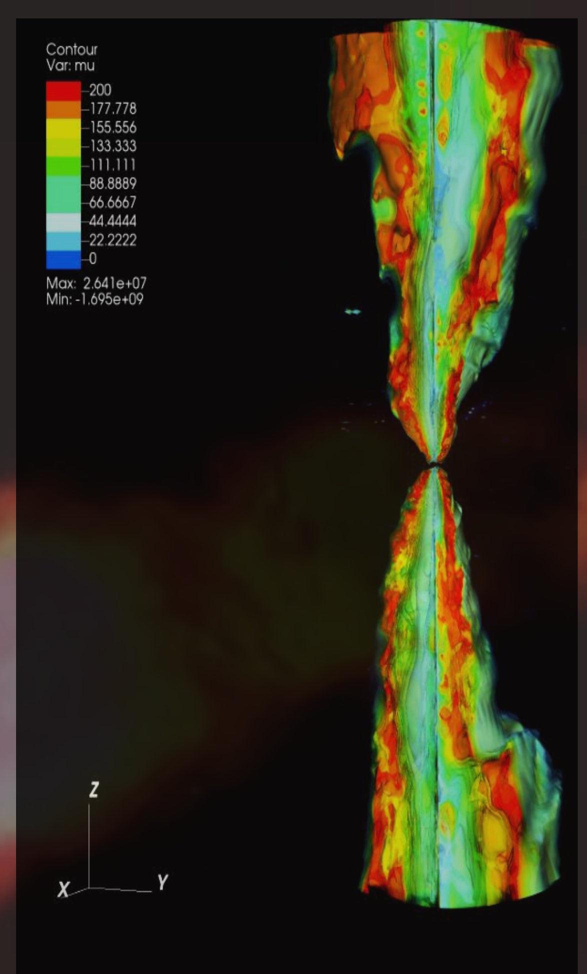


Origin of observed radiation from jet

Modeling GRB jets

Jets of magnetized, Poynting dominated plasma are launched from the engine on the cost of rotational energy of the black hole. This process, called the Blandford-Znajek mechanism, is mediated by large scale magnetic fields, when the significant poloidal component is threading the disk.

We follow the flow evolution by numerically solving the continuity, and energy momentum conservation, and induction equations in the GRMHD (General Relativistic Magneto-Hydrodynamics) scheme. We observe how variable, structured jets are launched from rotating black hole central engine.



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

Abstract

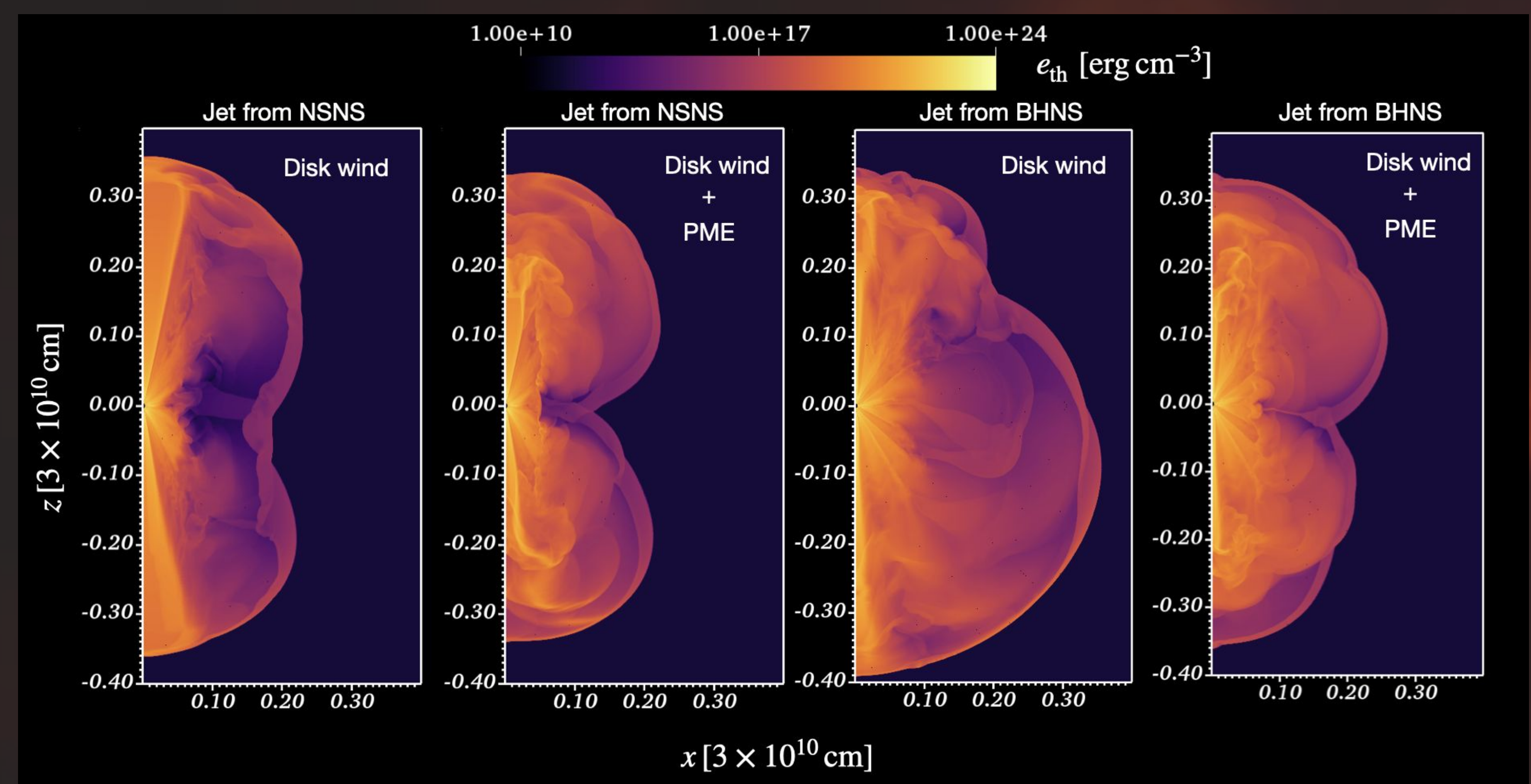
We present a set of 2D and 3D, large scale numerical simulations of the gamma ray burst (GRB) central engines, their jets and outflows. The computational astrophysics group at CTP PAS in Warsaw is using general relativistic MHD codes with advanced microphysics, to address multi-scale evolution and physics of GRBs.

The engine of short GRB engines is modeled with code HARM_COOL. We quantify the interaction between GRB jets and neutrino-driven disk wind, for different types of compact binary progenitors. The central engine simulations consider r-process nucleosynthesis in the ejecta and the kilonova phenomenon, using the Skynet nuclear reaction network. The main properties of GRB: its energy distribution, cocoon expansion, angular structure, and collimation degree, are estimated from our simulations, by mapping the HARM results onto the larger grid with an adaptive mesh refinement (AMR) code MEZCAL.

Long GRB model is the multiscale evolution of collapsing star, and the jet breakout. We study specific configurations of magnetized collapsars, with various topology of magnetic fields and stellar rotation, that allow for the formation of an electromagnetic transient. To accomplish this, we use the GR MHD code BHAC. The capability of this code to read initial and boundary conditions from tabulated data allows us to use as input the realistic stellar models generated by the stellar evolution code MESA. We also benefit from its AMR capabilities, which in combination with the use of logarithmic spherical coordinates allow the treatment of the several-orders-of-magnitude separation in the length-scales.

Modeling uncollimated outflows (winds)

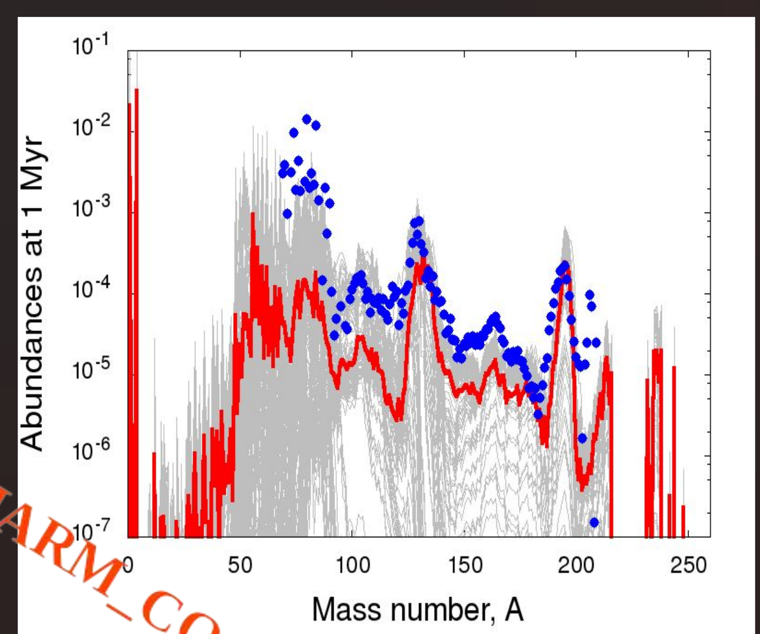
Interaction of large scale jets with winds



2D jet structure from MEZCAL simulations, with winde re-mapped with HARM_COOL. G. Urrutia et al 2024 (A&A, submitted)

Nucleosynthesis in accretion disk wind

HARM-COOL – numerical code developed by the Relativistic Astrophysics Group at CTP PAS, build on top of original GRMHD HARM code by C. Gammie et al. (2003), but extended to 3D and parallelized with MPI/Open-MP.

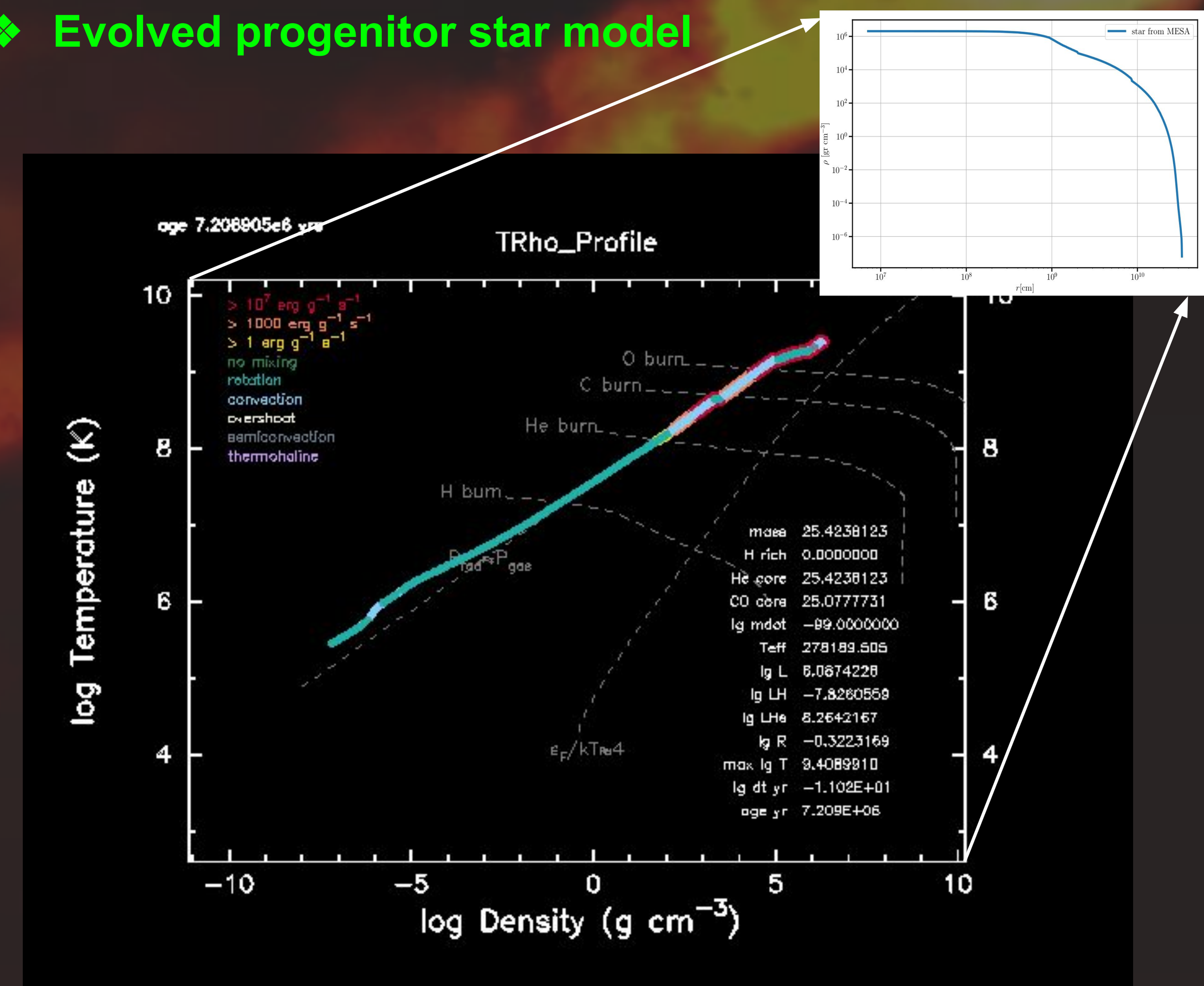


Code is supplemented with optional EOS functions for the Fermi Gas, under arbitrary degeneracy as by Yuan (Yuan Y.-F. 2005, Phys. Rev.D), and interpolates over tables with pressure and energy and neutrino cooling rate in the function of temperature and density. Code makes use of the tracer particles, for the analysis of outflows.

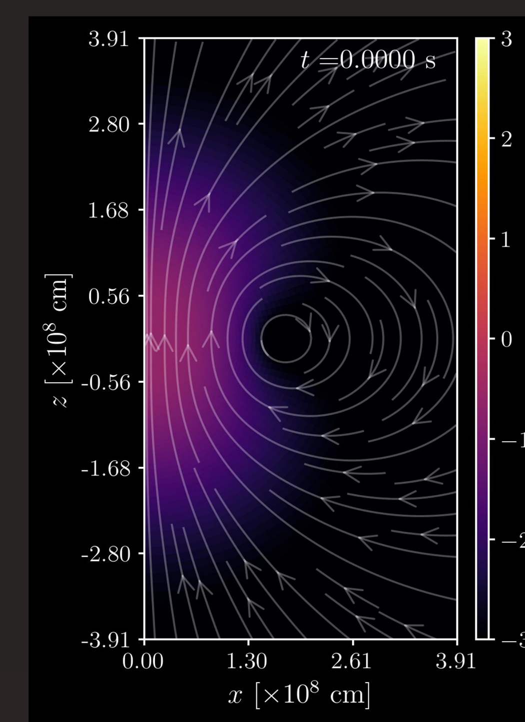
They are sites of r-process nucleosynthesis, evolved by nuclear reaction network. Three characteristic peaks in abundance pattern are produced in our simulations

Modeling collapsing stars

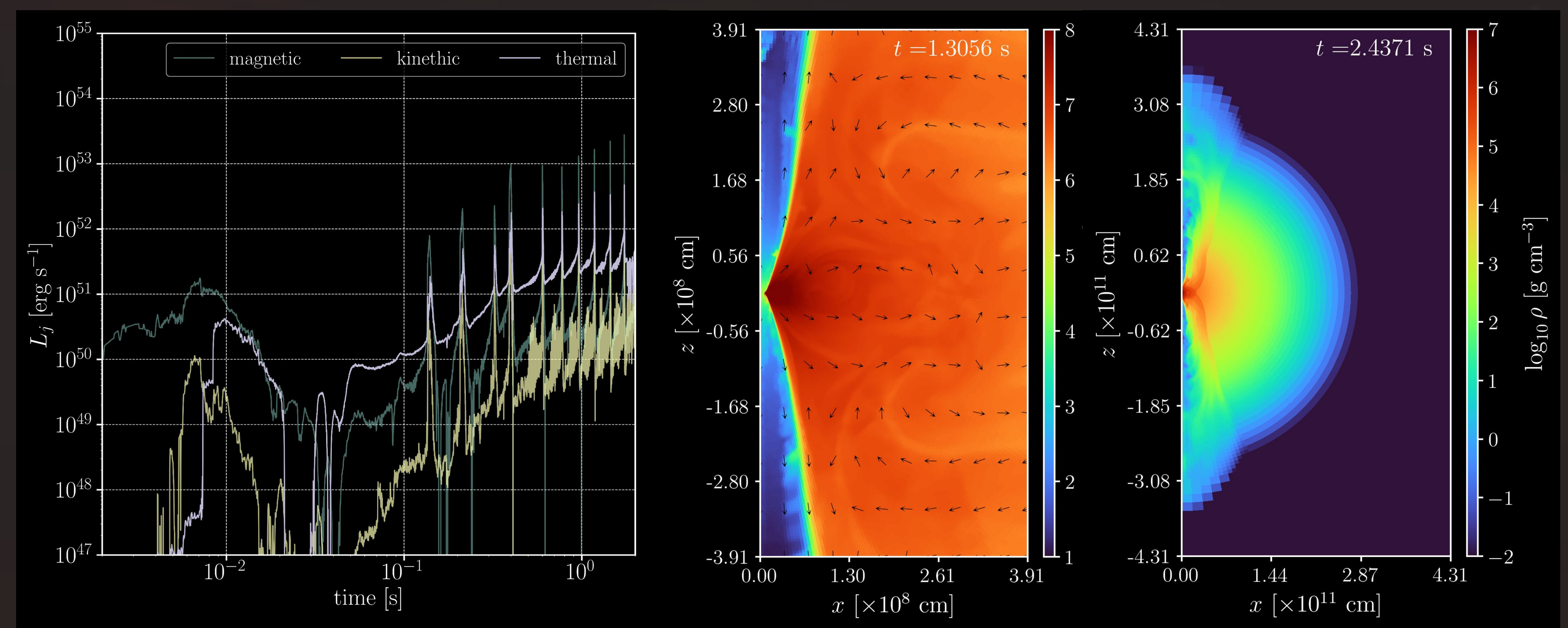
Evolved progenitor star model



Evolved pre-SN star structure from MESA evolutionary code used as initial condition for BHAC. Poloidal magnetic field is imposed to facilitate jets



Jet breakout on large scale



We follow the jet launched from collapsar GRB central engine, until it breaks from the envelope at large distance (*10^{12} cm*). Successful jet is dominated by magnetic energy (over thermal and kinetic) and variable due to MAD (magnetically-arrested) accretion mode.

agnes@cft.edu.pl