Turbulence everywhere: atmosphere, heliosphere, cosmos

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Spoke 2, WP3, Università della Calabria

Kick-off meeting Spoke 2, October 13th 2022

Topics treated by the WP3 at Università della Calabria (Unical):

- Numerical simulations of Fluid, Magnetohydrodynamics (MHD) and General Relativity MHD (GRMHD)
- Artificial Intelligence techniques for the analysis of numerical simulations and space data
- Numerical simulation of black holes dynamics and gravitational waves

Main requirements for the advancement of the project:

- HPC simulations
- GPU computing

Fluid simulations of atmospheric turbulence

Navier-Stokes equations in Boussinesq approximation:

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho_0}\nabla p - N\theta\hat{z} - 2\Omega\hat{z} \times \mathbf{u} + \nu\nabla^2\mathbf{u}$$

$$\partial_t \theta + (\mathbf{u} \cdot \nabla)\theta = Nw + k\nabla^2\theta$$

Different characteristic time and length scales:

$$N = \left[-g\frac{\partial_z\bar{\theta}}{\theta_0}\right]^{1/2} \qquad f = 2\Omega\cos\phi \qquad \ell_{Oz} = \sqrt{\frac{\epsilon_V}{N^3}} \qquad \ell_\Omega = \sqrt{\frac{\epsilon_V}{f^3}}$$

Brunt-Vaisala frequency — Coriolis frequency — Ozmidov length — Zeman length

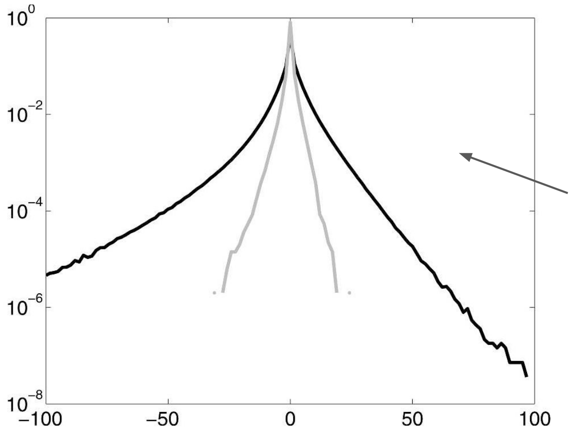
and corresponding characteristic dimensionless numbers:

$$Fr = \frac{\tau_{gw}}{\tau_{nl}} = \frac{U}{NL} \qquad Ro = \frac{\tau_{iw}}{\tau_{nl}} = \frac{U}{\Omega L} \qquad R_B = ReFr^2$$

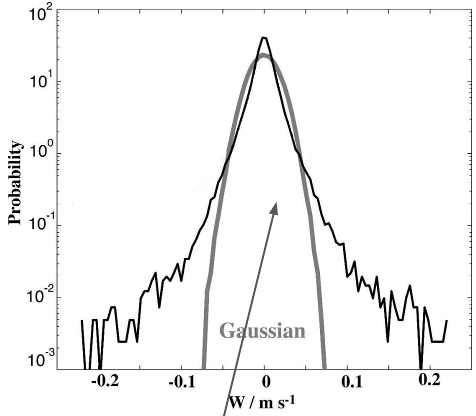
Froude number — Rossby number — Buoyancy Reynolds

Large scale intermittency in the atmosphere

Intermittency: sudden release of energy followed by relatively long quiescent states
Intermittency is well-known to be present at small scales in turbulent fluids
In geophysical flows, intermittency is observed also at large scales!

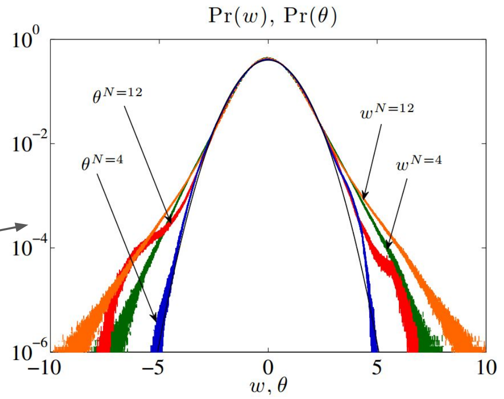


Capet et al. , J. Phys. Oceanogr. (2008): vertical velocity in the ocean



D'Asaro et al., J. Phys. Oceanogr. (2006): PDF of vertical velocity (days 212-245) on the Oregon shelf.

Numerical simulations: Rorai et al. PRE (2014). PDFs of vertical velocity and temperature for two values of the Froude number



Numerical resources

The tool for our numerical simulations: Geophysical High-Order Suite for Turbulence (GHOST):

- 3D pseudo-spectral (fully periodic) parallel code, GPU ready
- Solves the Navier-Stokes equations in Boussinesq approximation
- The code scales almost linearly up to 130,000 cores
- The code ran on several different supercomputers

International collaboration, several groups involved:

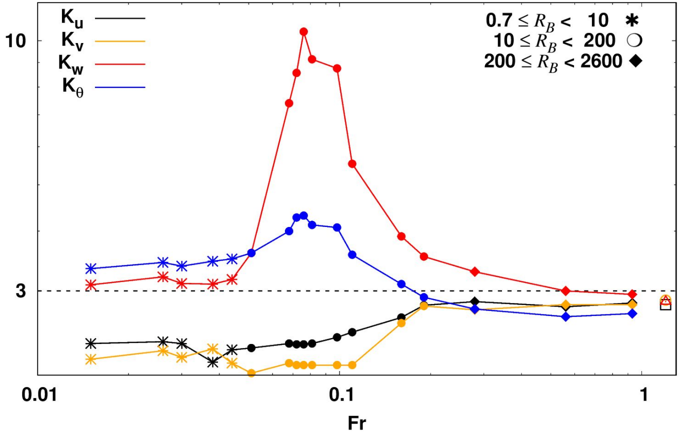
- Raffaele Marino, Ecole Centrale Lyon
- Alain Pumir, Ecole Normale Superieure, Lyon
- Annick Pouquet, NCAR + Duane Rosenberg (NOOA), Boulder (USA)
- Pablo Mininni, University of Buenos-Aires (AG)

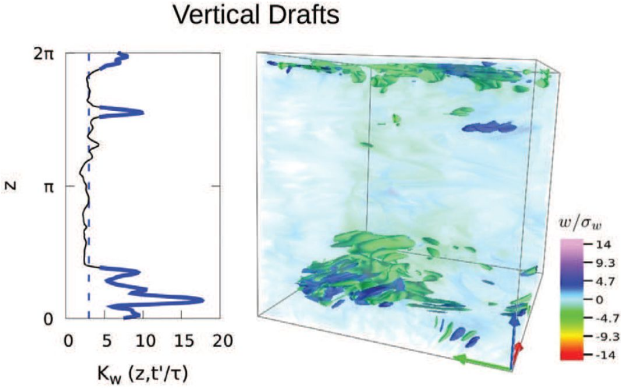
Problems:

- Turbulence requires high numerical resolutions and long simulation times
- Huge dimension of the parameter space

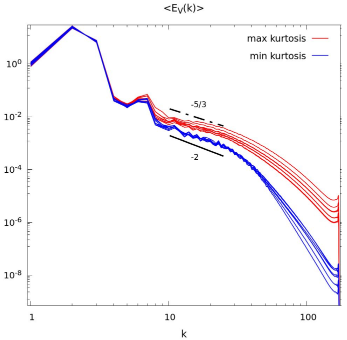
Summary of the work done

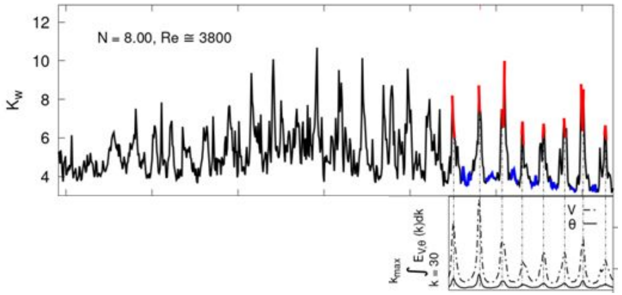
Quite large database of cases, purely stratified (no rotation!) with low resolution (512^3) and long total simulation time (~400 non-linear times).

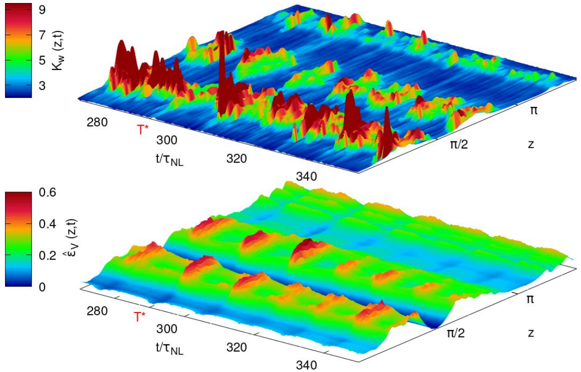




Large-scale intermittency reveals itself as large vertical drafts in the vertical velocity component and in the temperature







They strongly influence the small scales and the dissipative properties of the fluid!

Outlooks inside the project

Plan:

- Explore the space parameters (inclusion of rotation and stratification) for both atmosphere and oceans
- Enhance the numerical resolution of the simulations (that is fundamental for understanding the turbulence behavior)
- Developing of ML algorithms for a smart identification of the intermittent events.

Bibliography:

- F. Feraco, R. Marino, L. Primavera, A. Pumir, P.D. Mininni, D. Rosenberg, A. Pouquet, R. Foldes, E. Lévêque, E. Camporeale, S. Cerri, H. Charuvil Asokan, J.L. Chau, J.P. Bertoglio, P. Salizzoni, M. Marro, “Connecting Large-Scale Velocity and Temperature Bursts with Small-Scale Intermittency in Stratified Turbulence”, Europhysics Letters Vol. 135(1), September 2021.
- R. Marino, F. Feraco, L. Primavera, A. Pumir, A. Pouquet, D. Rosenberg, P. Mininni, “Turbulence Generation by Large-Scale Extreme Vertical Drafts and the Modulation of Local Energy Dissipation in Stably Stratified Geophysical Flows”, Physical Review Fluids, Vol. 7(3), p.033801, February 2022.
- D. Buaria, A. Pumir, F. Feraco , R. Marino, A. Pouquet, D. Rosenberg, L. Primavera, “Single-particle Lagrangian statistics from direct numerical simulations of rotating-stratified turbulence”, Physical Review Fluids, Vol. 5(6), p. 064801, 2020.
- Fabio Feraco, Raffaele Marino, Alain Pumir, Leonardo Primavera, Pablo Daniel Mininni, Annick Pouquet, Duane Rosenberg, “Vertical drafts and mixing in stratified turbulence: Sharp transition with Froude number”, Europhysics Letters, Vol. 123(4), p. 44002, 2018.

Comparison between numerical simulations of solar wind turbulence and real data

The astrophysics and geophysics group of Unical has developed, in collaboration with the University of Pisa and the Observatoire de Meudon-Paris a very big parallel numerical code to simulate the Vlasov-Maxwell system of equations (a system of differential equations in 7D!).

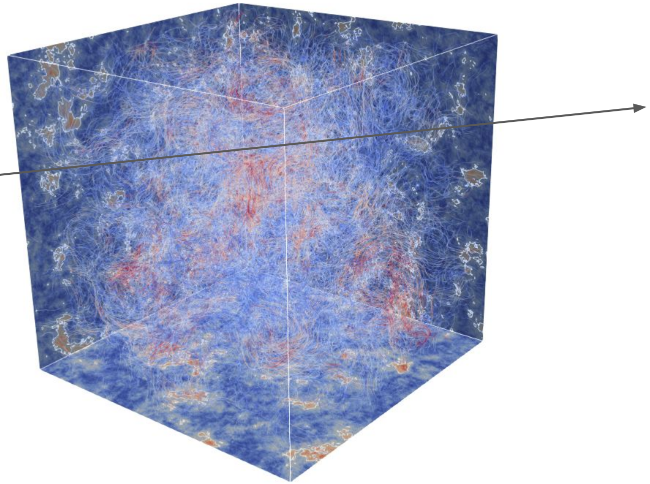
The main objective of the code is to study the development and evolution of turbulent states in the solar wind and plasma laboratory devices.

New space missions allow to measure different quantities (magnetic field, density and velocity field) and their gradients thanks to swarm-missions (missions involving simultaneous measures made by several spacecrafts in order to allow the computation of gradients).

A big problem is represented by the comparison between the numerical and observational data.

Simulating the measurements of a spacecraft inside a 7D code

Basic principles problem



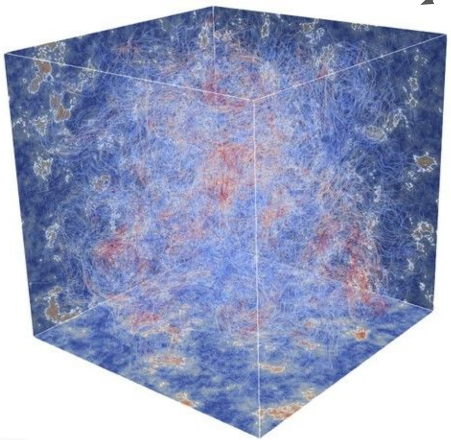
High-resolution numerical simulations in 7D.

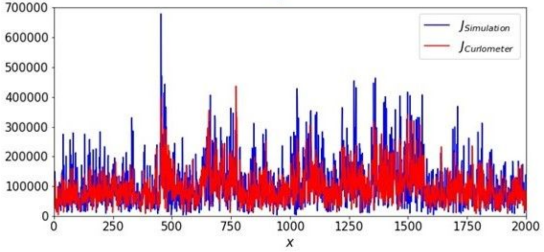
Interpolation of the data outside the gridpoints to simulate the passage of a satellite inside the computational domain.

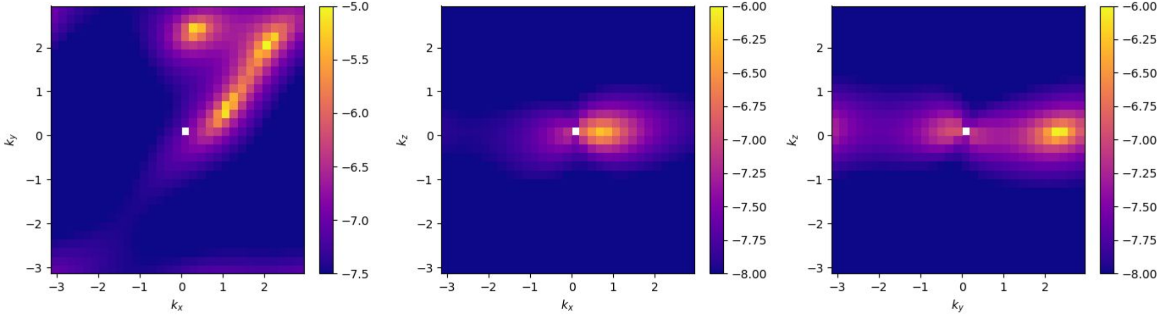
Establish a pool of tools to compare the numerical results with the observational ones. All this involves very long computational times!

Comparison techniques

Several techniques developed in the past, for instance the curlometer technique, to estimate the current density from one-dimensional signals arranged in a tetrahedral geometry:







or the k-filtering technique to identify waves in multi-spacecraft measurements

Outlooks for the project

- Carry out the numerical simulations with high-resolution (very long computational times) for values of the parameters similar to the one of the solar wind

- Interpolate the data in 4D (3 spatial coordinates and time) by building up a 4D interpolator to compare with the spacecraft results (a 3D interpolator has been already realized, but it already requires far too large computational times for the clusters available at Unical.

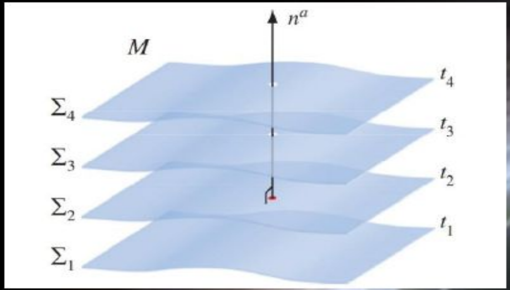
- The Vlasov code is currently being ported to GPU (collaboration with CINECA), although many problems come from the high-dimensionality of the model, compared to the very limited RAM of the GPUs.

Numerical simulations of compact objects

- The Group has developed, in the past years, a numerical code to solve the Einstein field equations, named Spectral-FIltered Numerical Gravity codE (SFINGE)
- The solves the equations on a 3+1 formalism, according to the Baumgarte-Shibata-Shapiro-Nakamura (BSSN) approach
- The algorithm is based on the use of pseudospectral techniques
- The code has been tested via all the classical general relativisit testbeds
- The numerical tool has been optimized to work on large supercomputers and makes use of MPI directives

The model

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$



$\mu, \nu = (0,1,2,3)$
$i, j = (1,2,3)$

$$\begin{cases}
\partial_0 \tilde{\gamma}_{ij} = -2\alpha \tilde{A}_{ij} \\
\partial_t \chi = \frac{2}{3}\chi(\alpha K - \partial_a \beta^a) + \beta^i \partial_i \chi \\
\partial_0 \tilde{A}_{ij} = \chi(-D_i D_j \alpha + \alpha R_{ij})^{TF} + \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{A}^k{}_j) \\
\partial_0 K = -D^i D_i \alpha + \alpha\left(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}K^2\right) \\
\partial_t \tilde{\Gamma}^i = \tilde{\gamma}^{jk}\partial_j\partial_k\beta^i + \frac{1}{3}\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\partial_j\tilde{\Gamma}^i - \tilde{\Gamma}^j\partial_j\beta^i + \\
\qquad +2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} + 6\tilde{A}^{ij}\partial_j\varphi - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right) + \\
\qquad + \frac{2}{3}\tilde{\Gamma}^i\partial_j\beta^j - 2\tilde{A}^{ij}\partial_j\alpha
\end{cases}$$

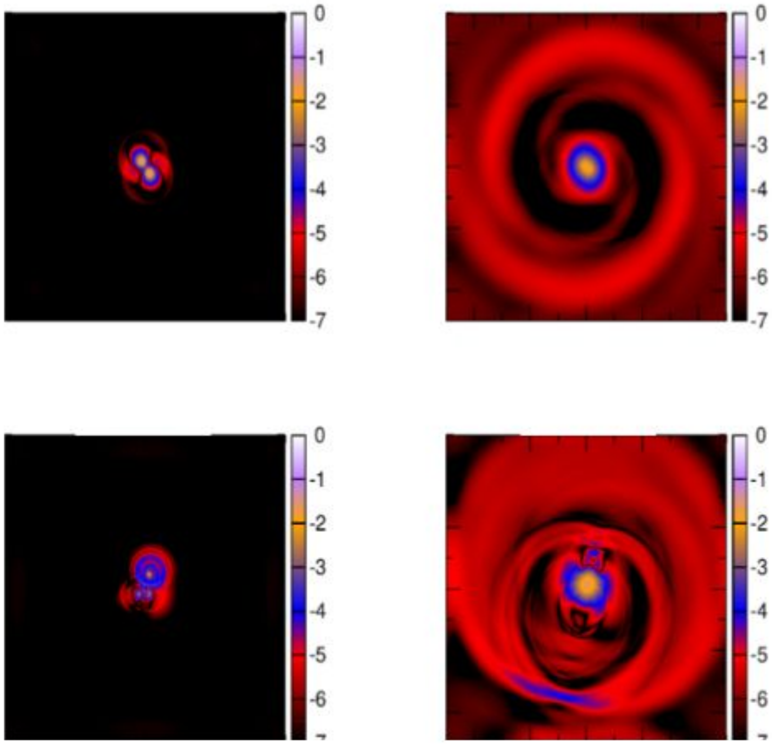
BSSN

17 equations and 4 constraints

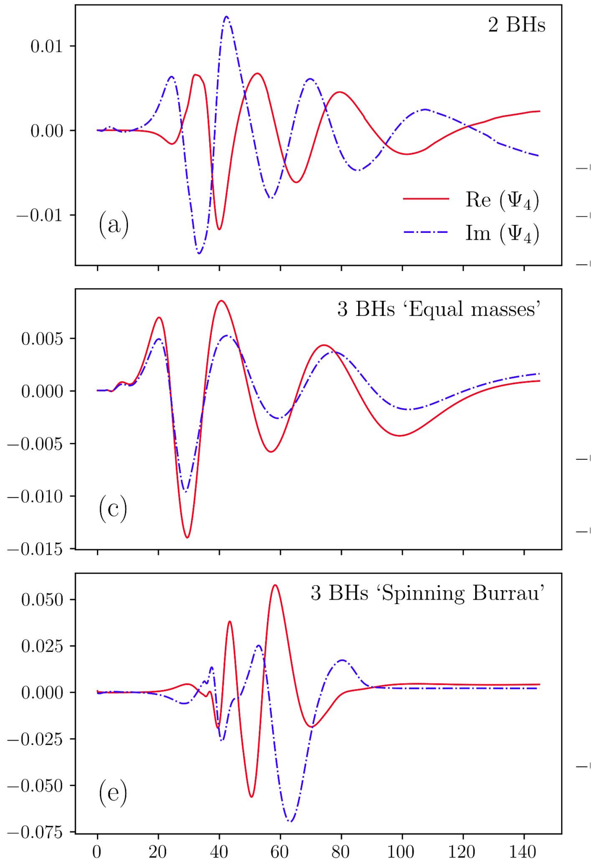
Black holes simulations

2 black holes

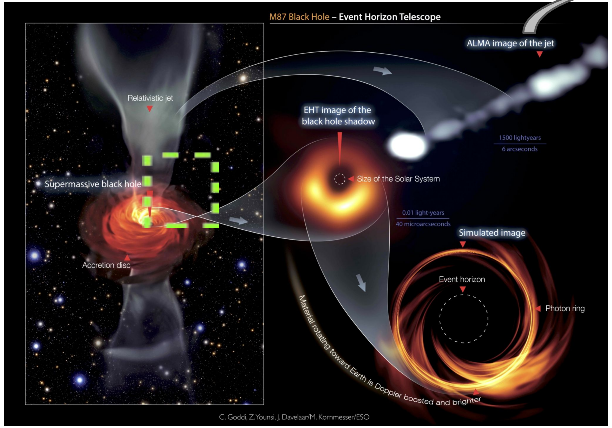
3 black holes

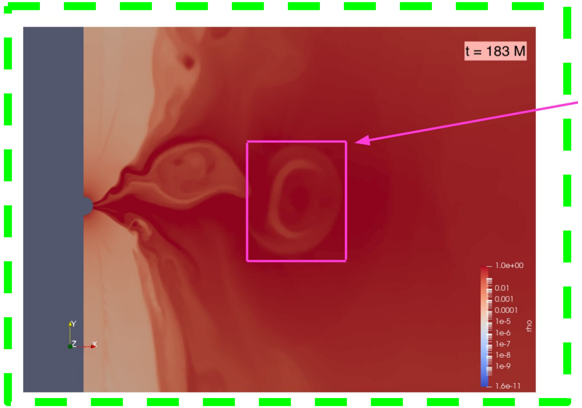


Some examples of waveforms

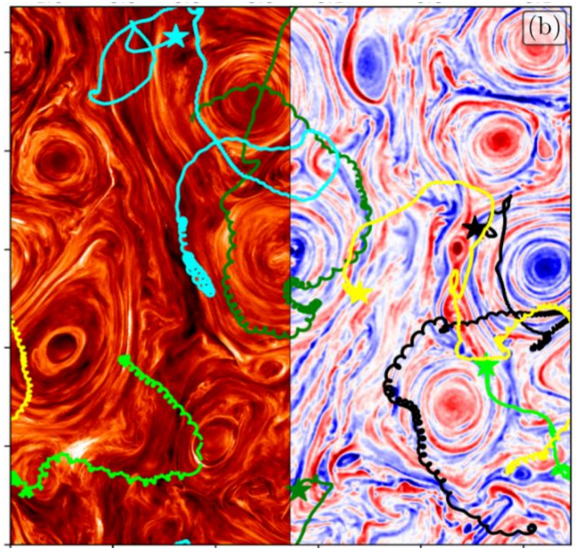


GRMHD and beyond

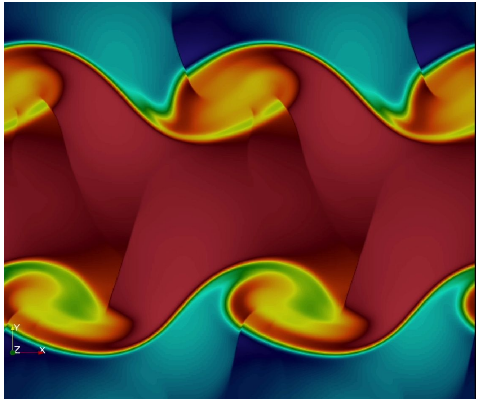




Kinetic simulations of relativistic plasma turbulence with the pic-code ZELTRON



The group makes use also of commercial GRMHD codes such as the Black Hole Accretion Code (BHAC)



Tasks of the GR-subtopic

- High-resolution simulations of binary systems and multiple black holes in the inspiraling phase
- Simulations with high mass aspect ratios
- Use the BHAC code to understand strong general relativistic MHD turbulence in the accretion disks
- Campaign of kinetic simulations, in different parametric regimes, by using ZELTRON, to understand the turbulence in the jet
- Upgrade of the existing SFINGE code to cosmological models, by including a module for the general relativistic hydrodynamics equations

C. Meringolo, S. Servidio, and P. Veltri, "A spectral method algorithm for numerical simulations of gravitational fields", Classical and Quantum Gravity 38 (7), 075027 (2021)

C. Meringolo and S. Servidio, "Aliasing instabilities in the numerical evolution of the Einstein field equations", General Relativity and Gravitation 53 (10), 1-21 (2022)

C. Meringolo and S. Servidio, "A pseudo-spectral numerical approach to solve the Einstein field equations", Il nuovo cimento C 45 (5), 1-4 (2022)

M. Imbrogno, C. Meringolo, and S Servidio, "Strong Interactions in the Three Black Holes Problem", submitted (2022)