Solar and stellar physics with the PLUTO code

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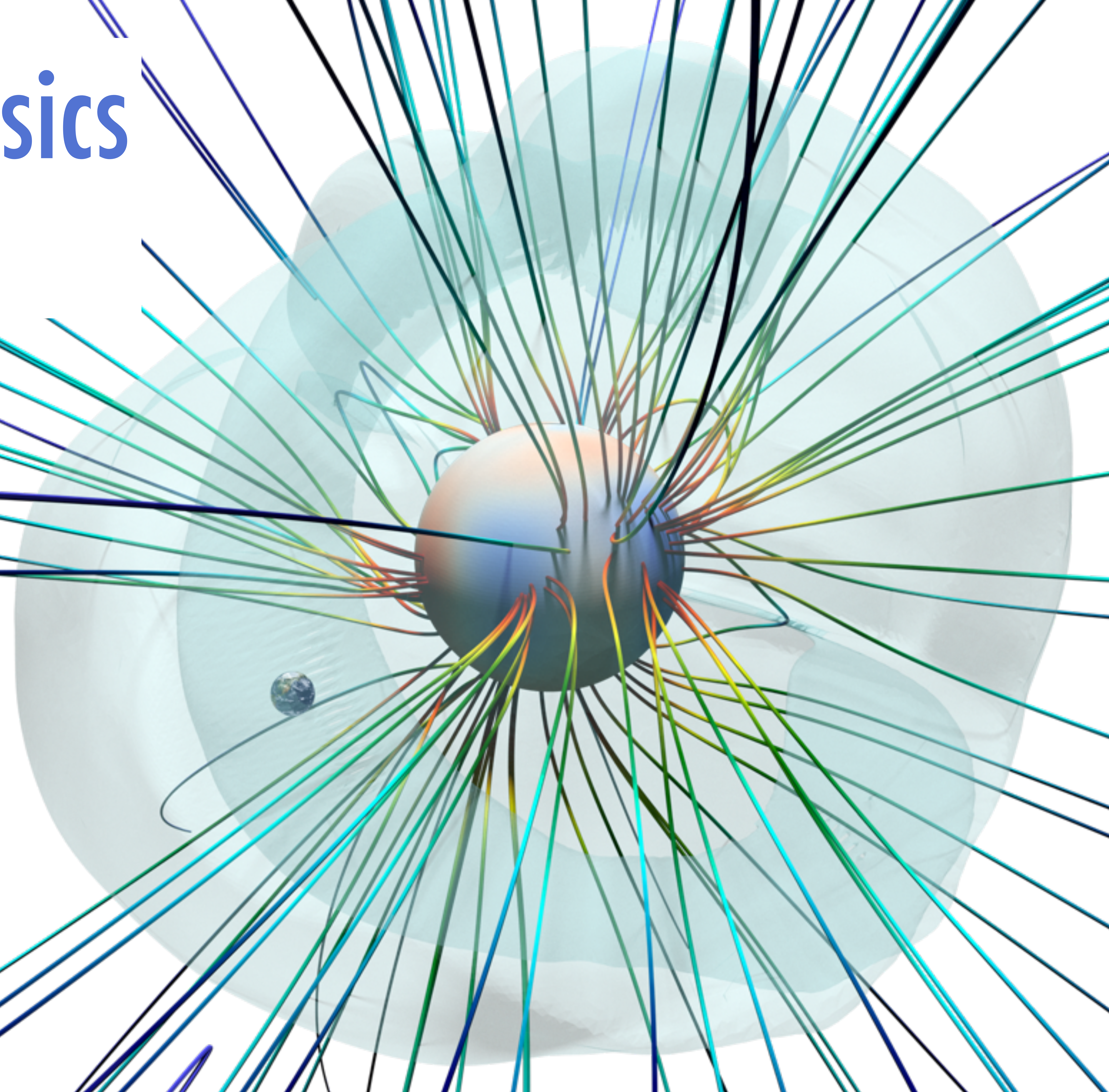
With **V. Réville,** A.S. Brun, S. Hazra, R. Pinto, B. Perri, F. Regnault, A. Gillet

Special thanks: A. Mignone, G. Lesur



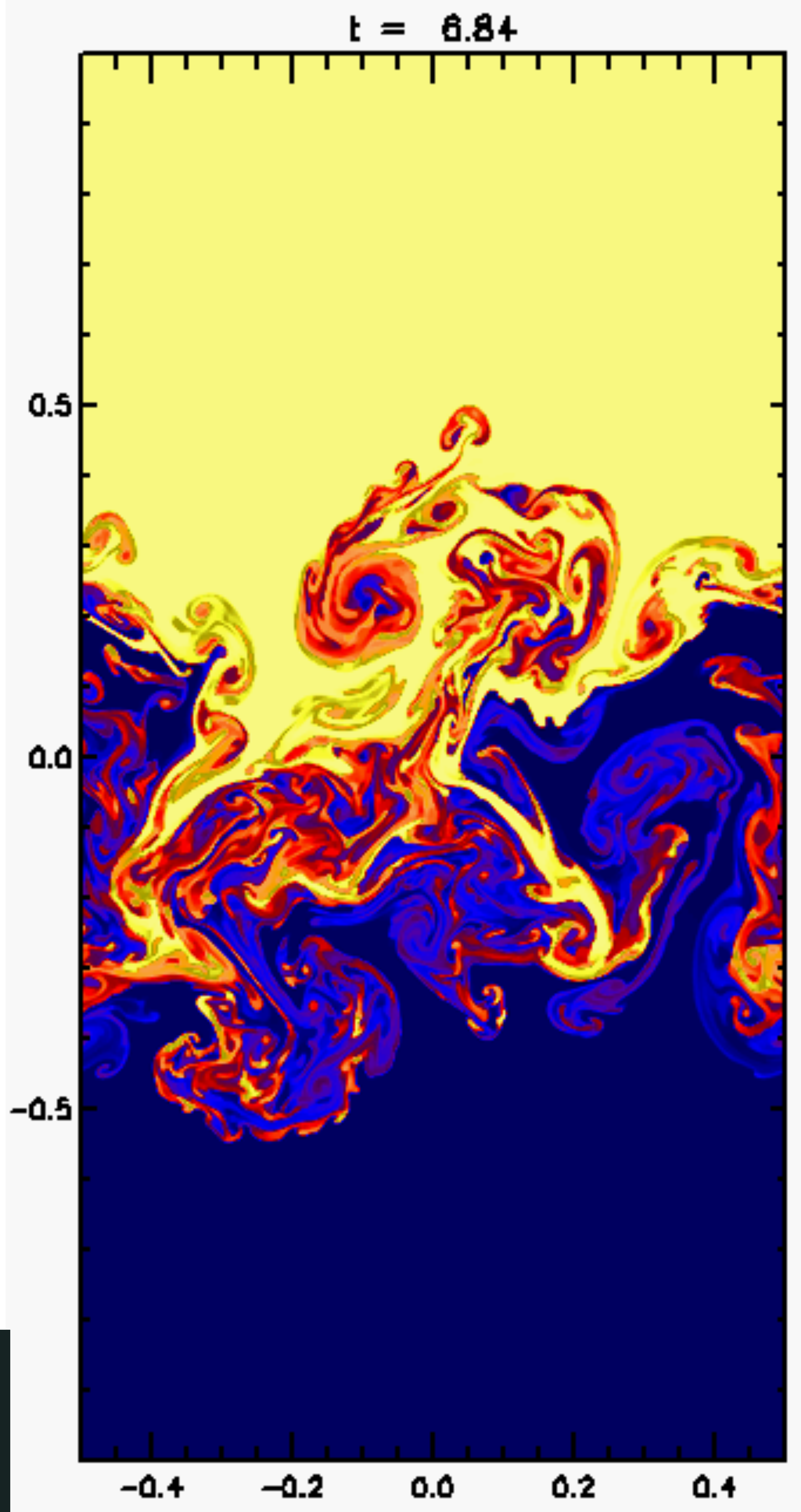
What is PLUTO?

PLUTO is a modular parallel code with a multi-physics, multi-algorithm framework for solving gas and plasma dynamics

It is designed for multi-D compressible plasma with high Mach numbers:

- Compressible Euler/Navier-Stokes
- Ideal/Resistive MHD
- Relativistic extensions
- Heating/colling processes with chemical network
- Hybrid treatments of kinetic physics

Mignone+ 2007



PLUTO webpage

Home Code Overview Gallery Download Documentation Meetings

The PLUTO Code for Astrophysical GasDynamics

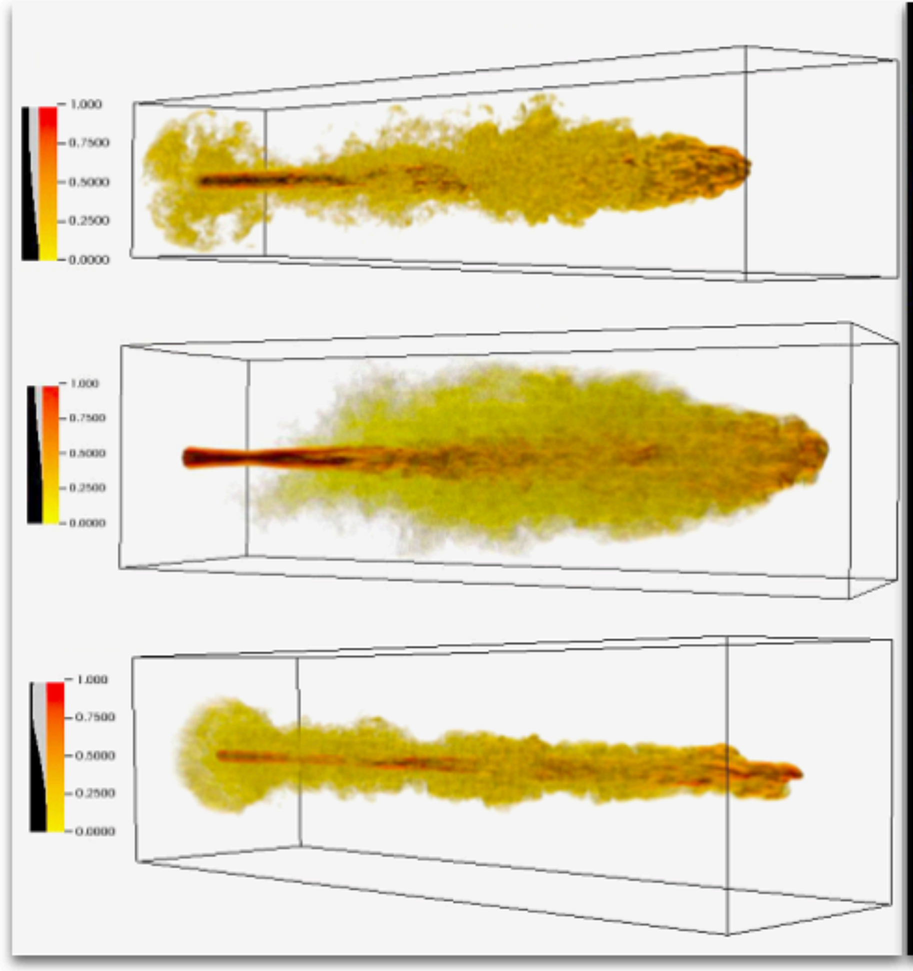
UNIVERSITÀ DEGLI STUDI DI TORINO

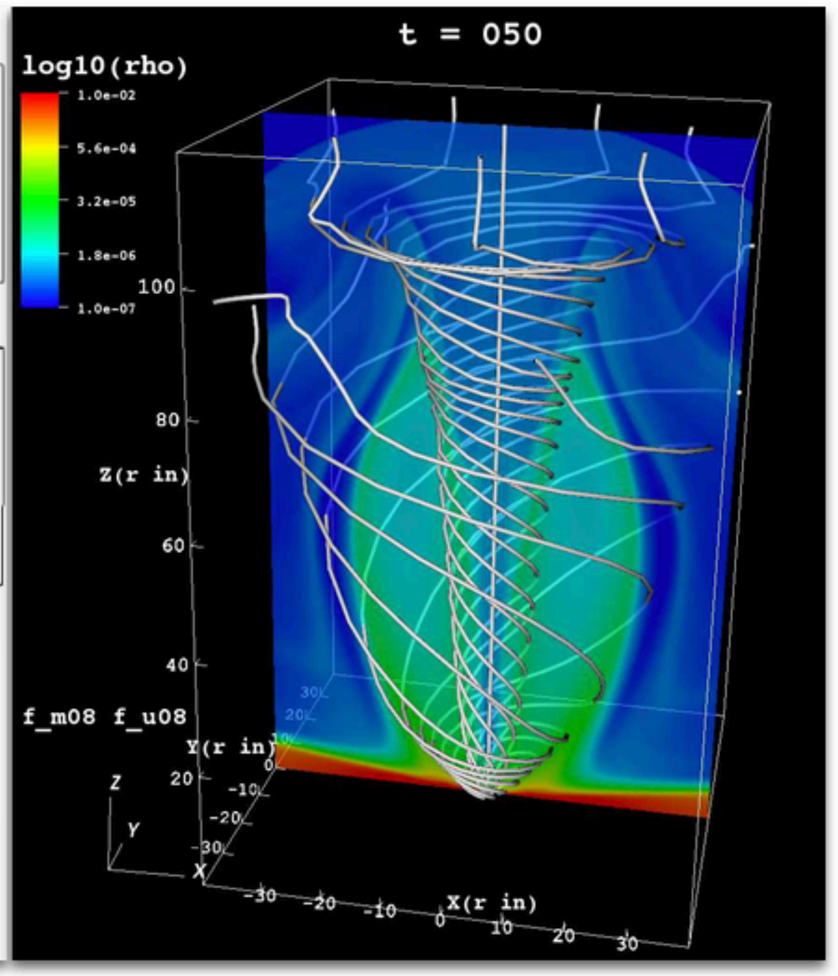
Mignone+ 2007

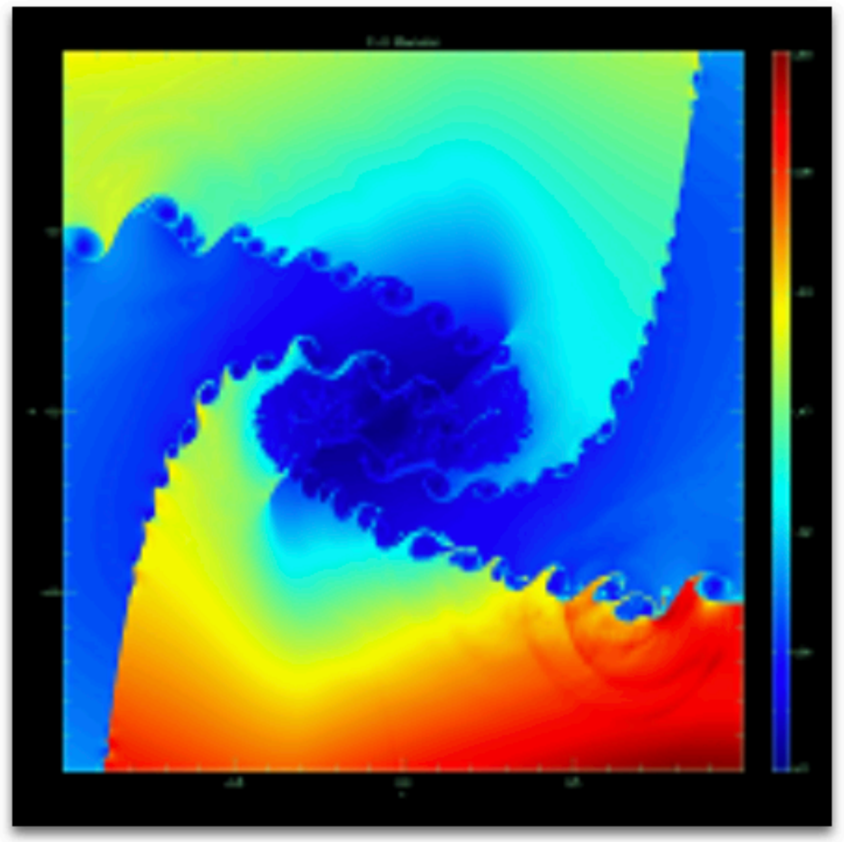
http://plutocode.ph.unito.it

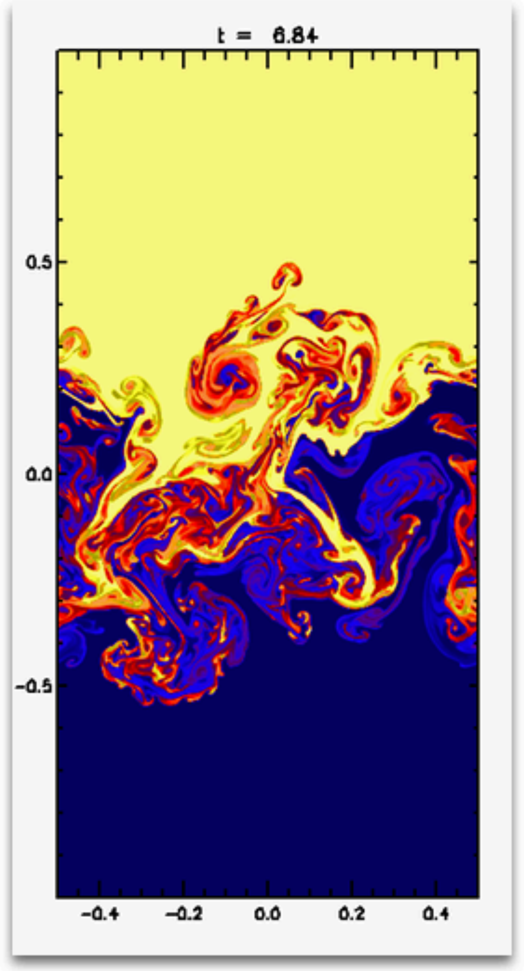
The PLUTO Code

https://groups.google.com/g/pluto_users









Code Version: 4.4-patch2 (Jun 2021)

PLUTO is a freely-distributed software for the numerical solution of mixed hyperbolic/parabolic systems of partial differential equations (conservation laws) targeting high Mach number flows in astrophysical fluid dynamics. The code is designed with a modular and flexible structure whereby different numerical algorithms can be separately combined to solve systems of conservation laws using the finite volume or finite difference approach based on Godunov-type schemes.

Active development (mainly in Italy)

2002: First relativistic hydro version (RHD)

2004: Modular inception: MHD, HD modules

2005: Relativistic MHD

2006: 1st official release: *PLUTO 2.0*

2010: *PLUTO 3.0*

2010: High-order Finite Difference Schemes

2012: Adaptive Mesh Refinement

2012: FARGO Scheme

2012: *PLUTO 4.0*

2014: *PLUTO 4.1*

2015: *PLUTO 4.2*

2018: *PLUTO 4.3*

Particle-Fluid hybrid Implementation

Resistive Relativistic MHD

2020: *PLUTO 4.4*

2021: *PLUTO 4.4-patch2*

Main equations solved in PLUTO

- Suited for a system of conservation laws:

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathsf{F} = \mathbf{S}$$

- F is a tensor, accounting for hyperbolic and parabolic terms:

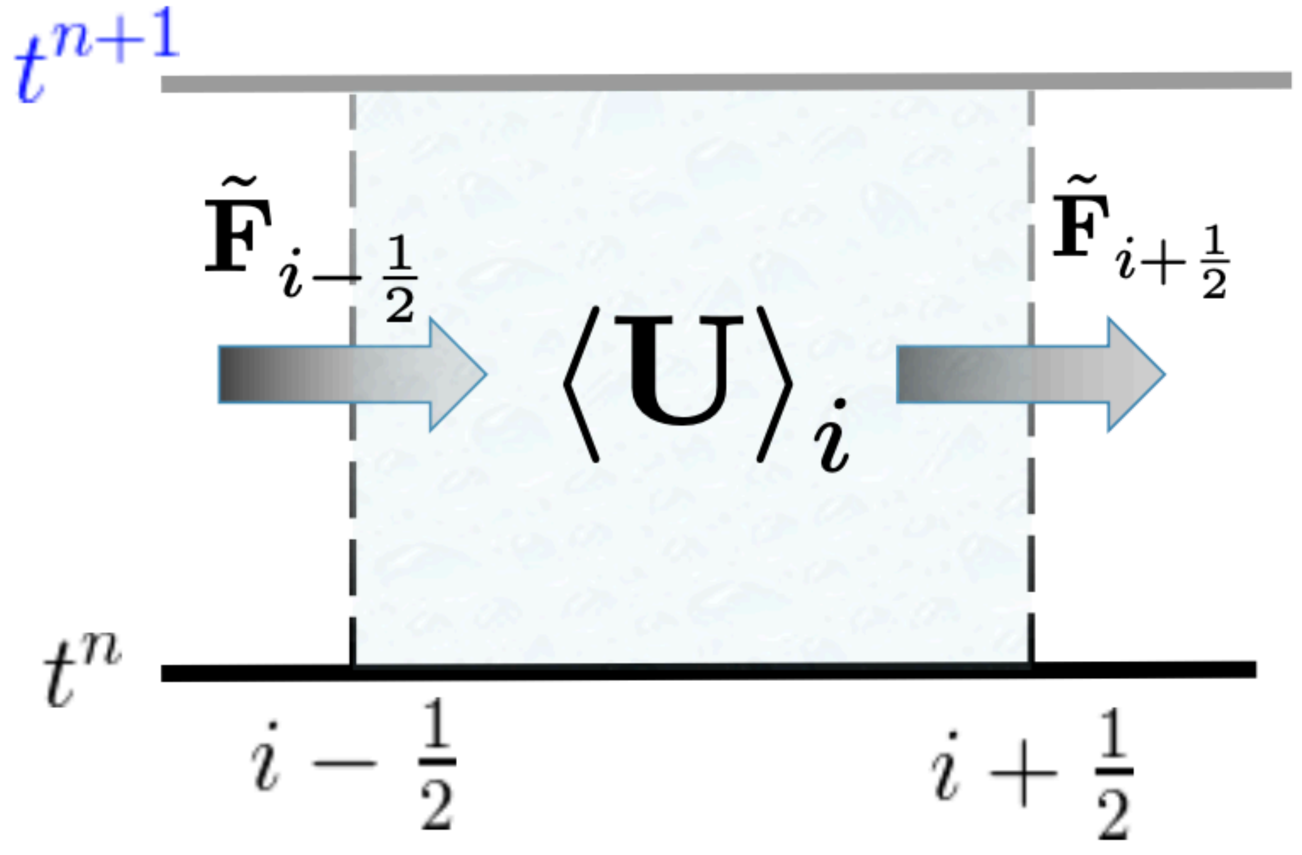
$$F = F_{\text{hyp}} + F_{\text{par}}$$

Hyperbolic Flux
→ *wave propagation*

Parabolic (or diffusive) Flux,
→ *Dissipation physics*

- Grid-based, finite-volume code; building block

$$\langle U \rangle_i^{n+1} = \langle U \rangle_i^n - \frac{\Delta t}{\Delta x}\left(\tilde{F}_{i+\frac{1}{2}}^{n+\frac{1}{2}} - \tilde{F}_{i-\frac{1}{2}}^{n+\frac{1}{2}}\right)$$



Physical modules in PLUTO

Advection Physics (Hyperbolic PDE)
- Hydrodynamics (HD)
- Magnetohydrodynamics (MHD)
- Relativistic Hydrodynamics (RHD)
- Relativistic ideal and nonideal MHD (RMHD)

Thermodynamics
- Isothermal
- Ideal
- Non-constant gamma
- Synge Gas (relativistic)

Dissipation Physics (Parabolic PDE)
- Viscosity (Navier-Stokes)
- Thermal conduction (hydro and MHD)
- Hall MHD, Ambipolar diffusion, Magnetic resistivity
- Radiation Hydrodynamics (FLD, 2 temp)

Geometry
- Cartesian (1D, 2D, 3D)
- Cylindrical (1D, 2D, 3D)
- Spherical (1D, 2D, 3D)

Source Terms
- Gravity / Body forces
- Heating / optically thin cooling
- Chemical networks

Particle Physics
- Lagrangian particles
- Cosmic Rays → MHD-PIC
- Dust^2

Algorithms in PLUTO

Time Stepping

- RK2, RK3
- MUSCL-Hancock
- Characteristic Tracing

Dimensionally split or fully unsplit methods.

Interpolation

- Piecewise Linear
- Piecewise Parabolic
- WENO 3rd – 5th order

Primitive or characteristic fields

Riemann Solvers

- Two-shock
- AUSM
- Roe
- HLL / HLLC / HLLD
- GFORCE
- TVDLF
- MUSTA

Parabolic Solver

- Explicit
- Super-Time-Stepping
- Runge-Kutta-Legendre

$\nabla\cdot$Bcontrol

- 8-wave
- Constrained Transport
- Hyperbolic Divergence Cleaning

Modules and references

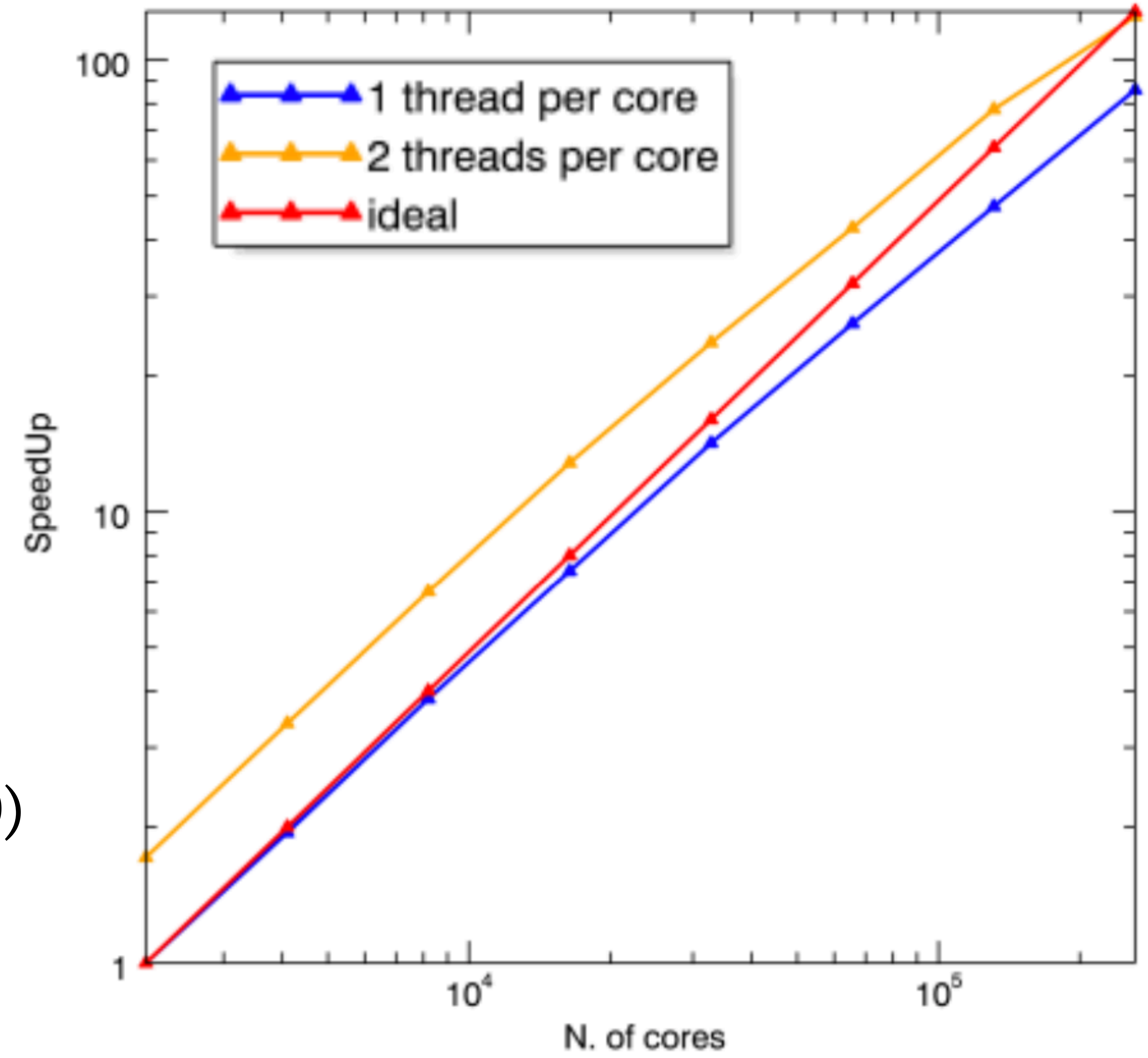
- PLUTO → *Mignone et al.*, 2007ApJS..170..228M
- Cooling → *Tesileanu et al.*, 2008A&A...488..429T
- FARGO Orbital scheme → *Mignone et al.*, 2012A&A...545A.152M
- PLUTO + AMR → *Mignone et al.*, 2012ApJS..198....7M
- Relativistic HLLx solvers:
  - Isothermal HLLD → *Mignone et al.*, 2006MNRAS.368.1040M
  - Relativistic HLLC → *Mignone et al.*, 2005MNRAS.364..126M
  - Relativistic HLLD → *Mignone et al.*, 2009MNRAS.393.1141M
- Divergence Cleaning → *Mignone & Tzeferacos*, 2010JCoPh.229.2117M
- Finite Difference Method → *Mignone et al.*, 2010JCoPh.229.5896M
- Radiation Hydrodynamics → *Melon Fuksman & Mignone*, 2019ApJS..242...20M
- Resistive Relativistic MHD → *Mignone et al.*, 2019MNRAS.486.4252M
- Particles (MHD – PIC) → *Mignone et al.*, 2018ApJ...859...13M
- Particles (Lagrangian formalism) → *Vaidya et al.*, 2018ApJ...865..144V
- Particles (Dust) → *Mignone et al.*, 2019ApJS..244...38M

Parallelisation of the PLUTO code

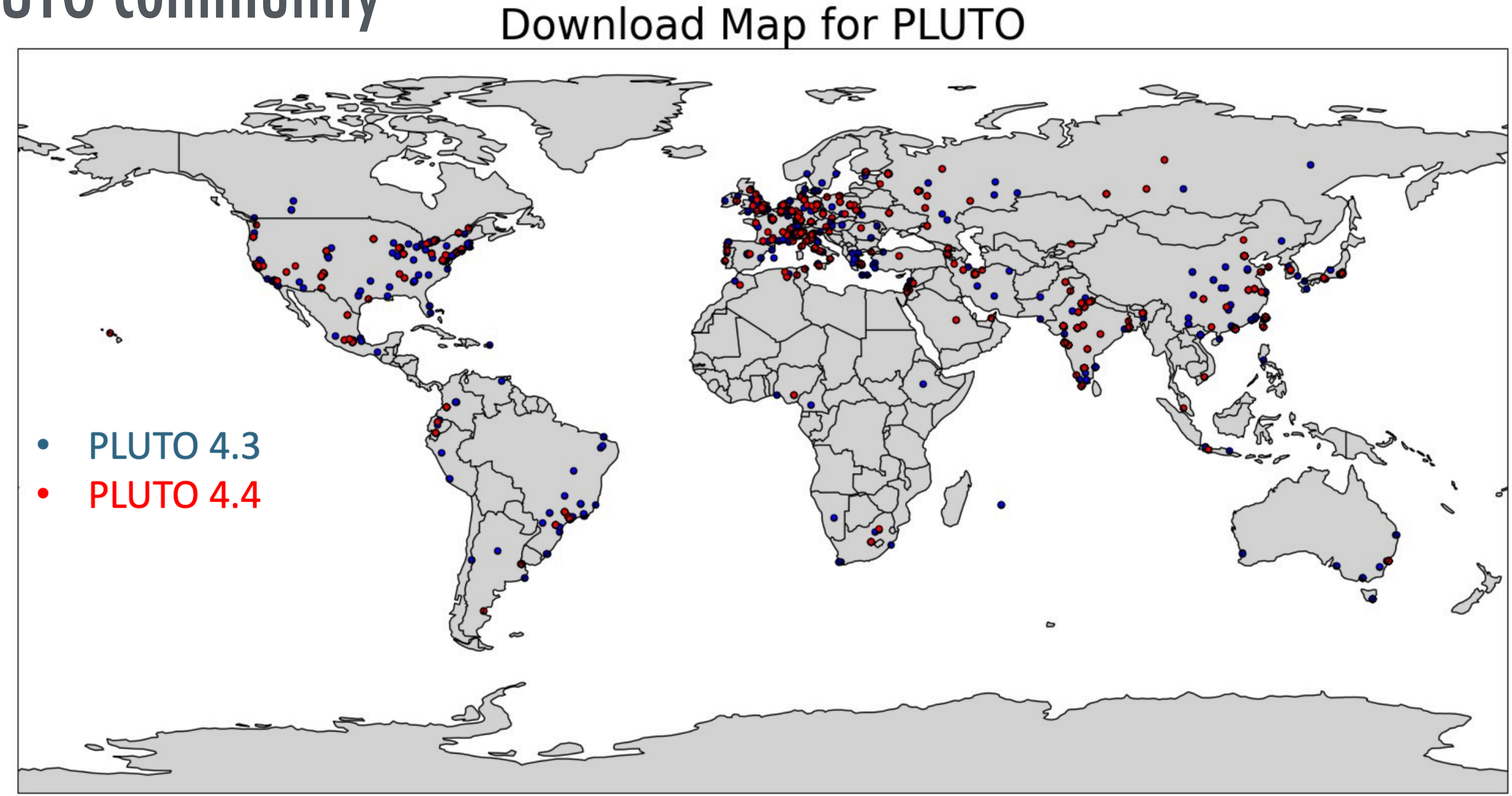
PLUTO is written in C (~ 110,000 lines) and C++ (~6,000 lines)

Parallelisation is handled with MPI (tested up to 262,144 cores), using domain-decomposition

Tested on all-Tier platforms (from laptop to Tier0)



PLUTO community



A few examples of use in France

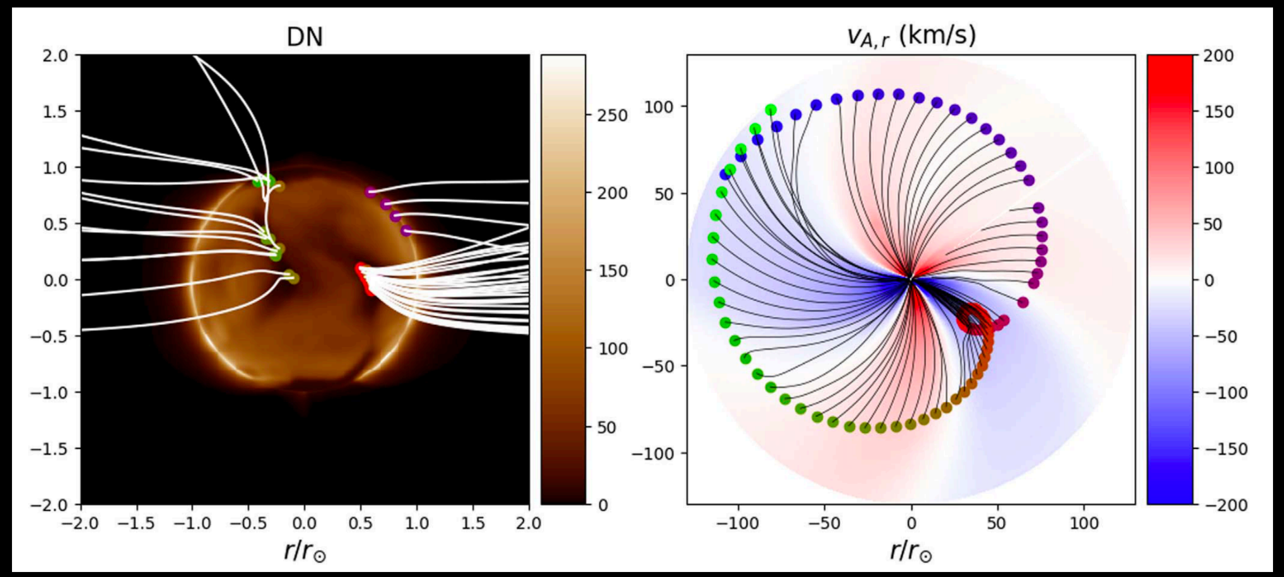
The WindPredict team

WindPredict

Core physics: **PLUTO** code

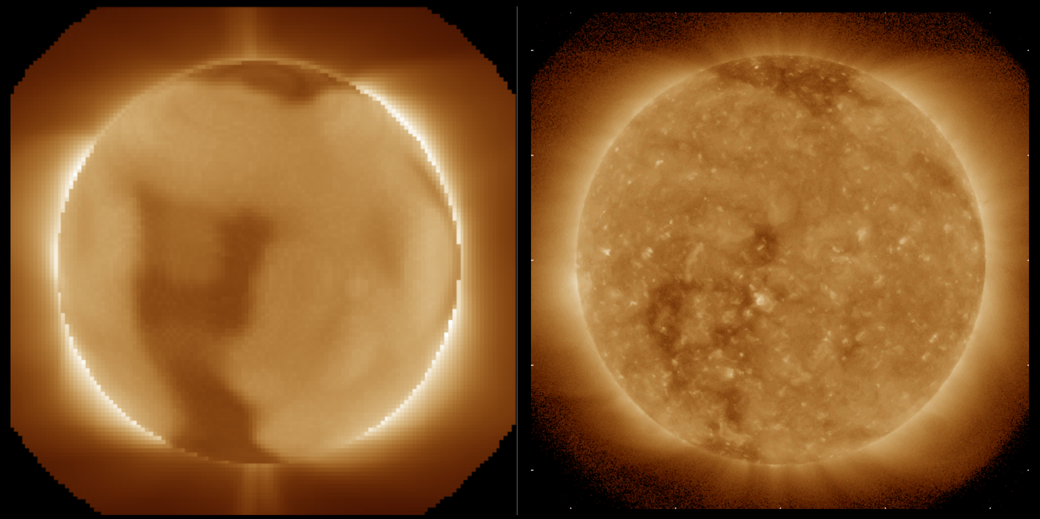
Mignone et al. 2007

Strugarek *Brun* *Réville*



In-situ validation

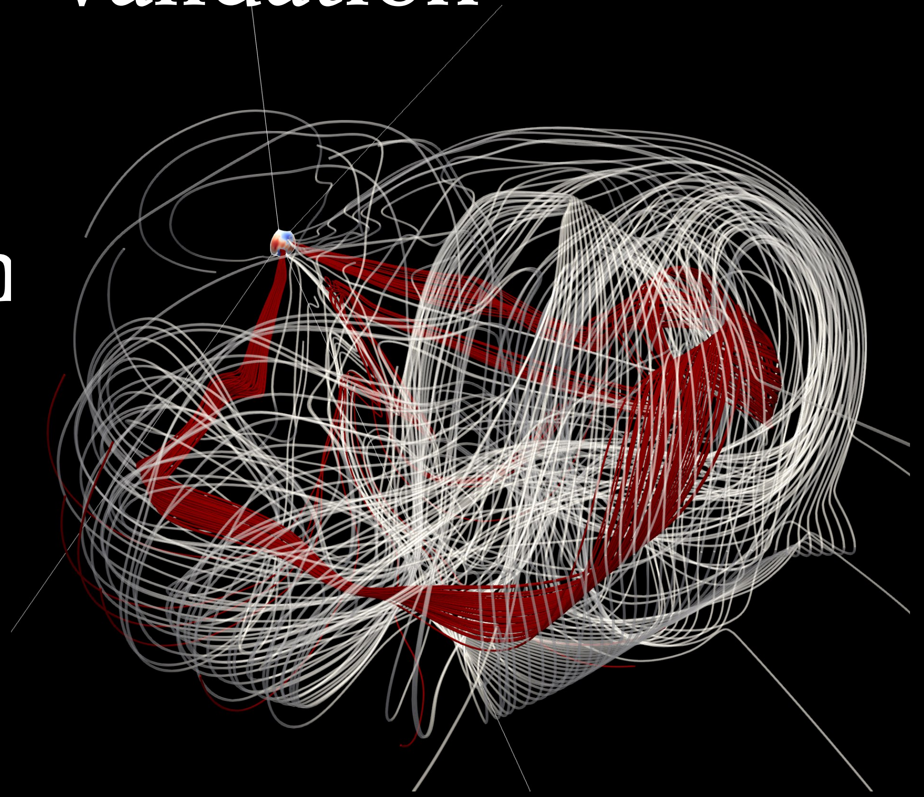
Réville



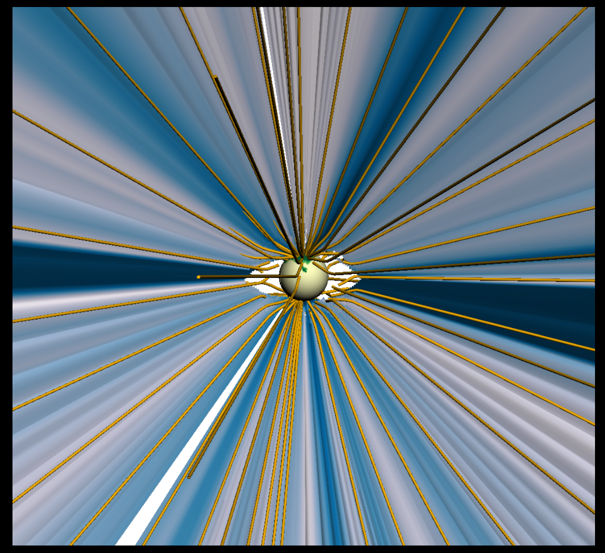
UV+White Light validation

Parenti

CME propagation with AMR

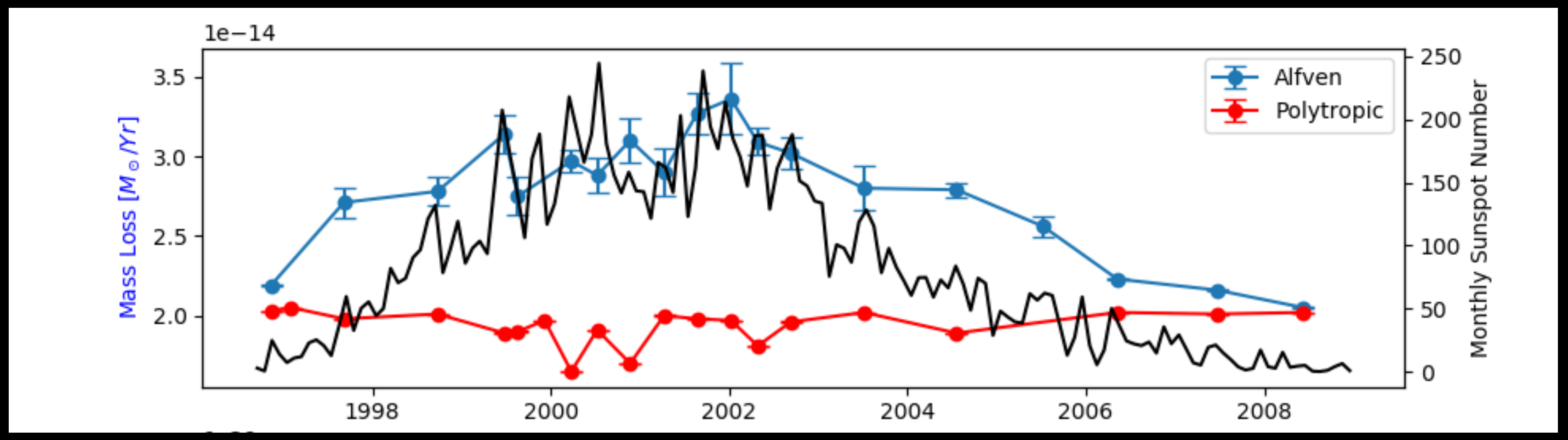


Regnault



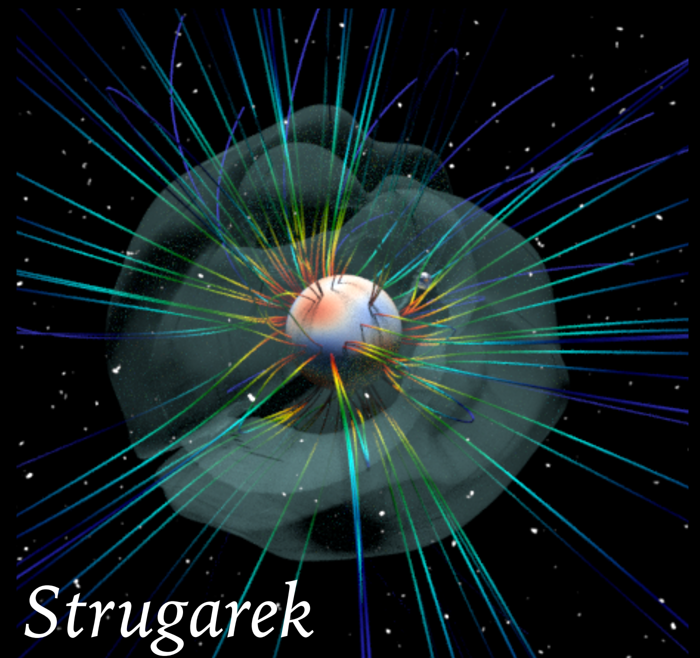
Comparisons WindPredict-MULTI-VP

Pinto



Hazra

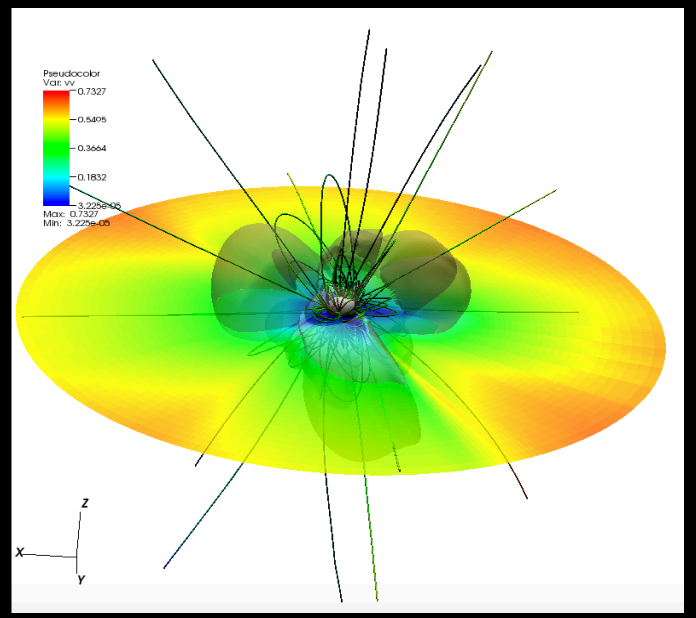
Polytropic/AW-driven comparisons



Strugarek

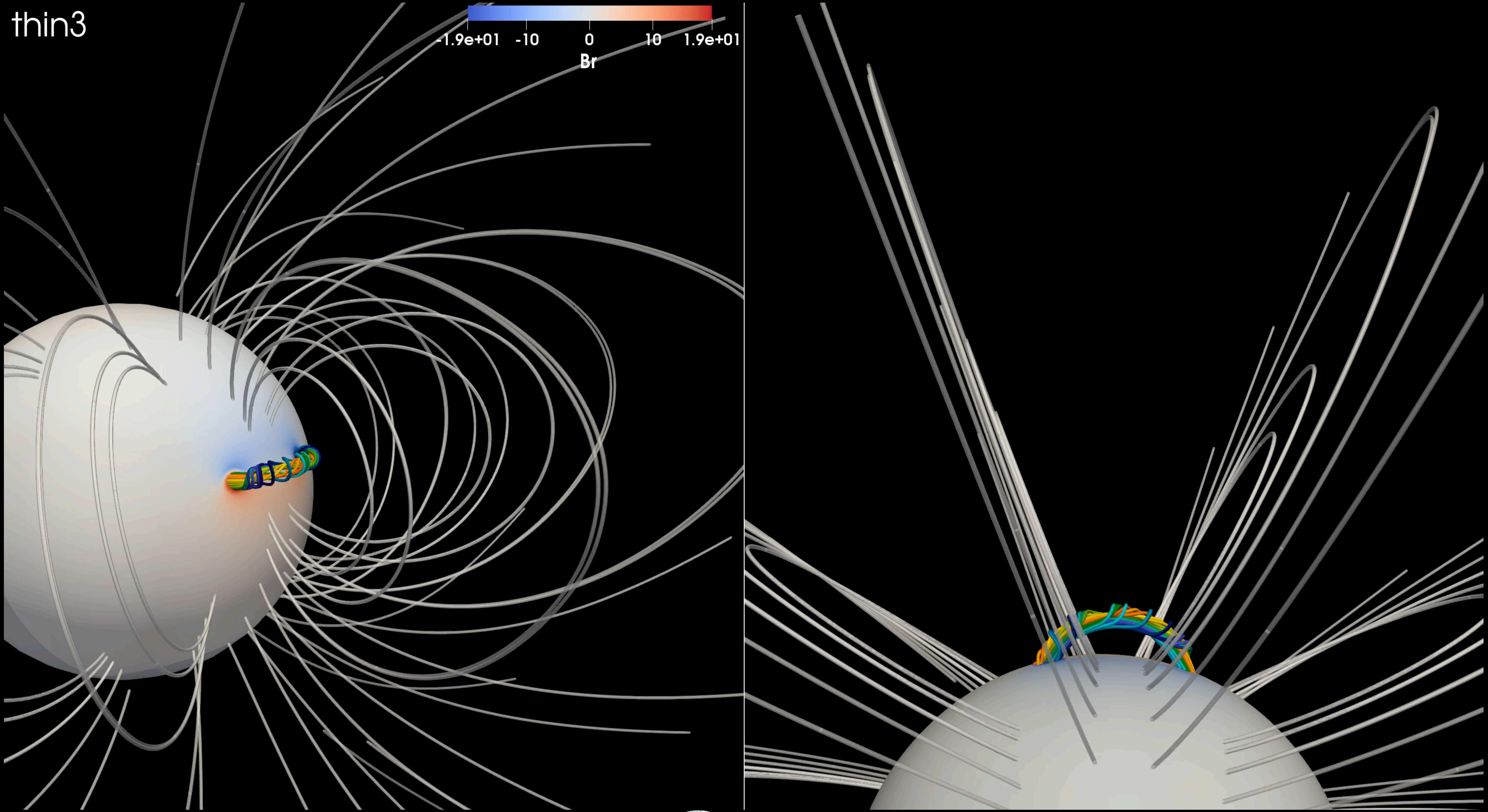
Star-planet interactions

VSWMC integration



Perri

Towards the global modelling of CMEs with AMR



[Thesis of F. Regnault, in collaboration with M. Janvier and F. Auchère]

Effect of the alfvénic turbulence in the solar wind

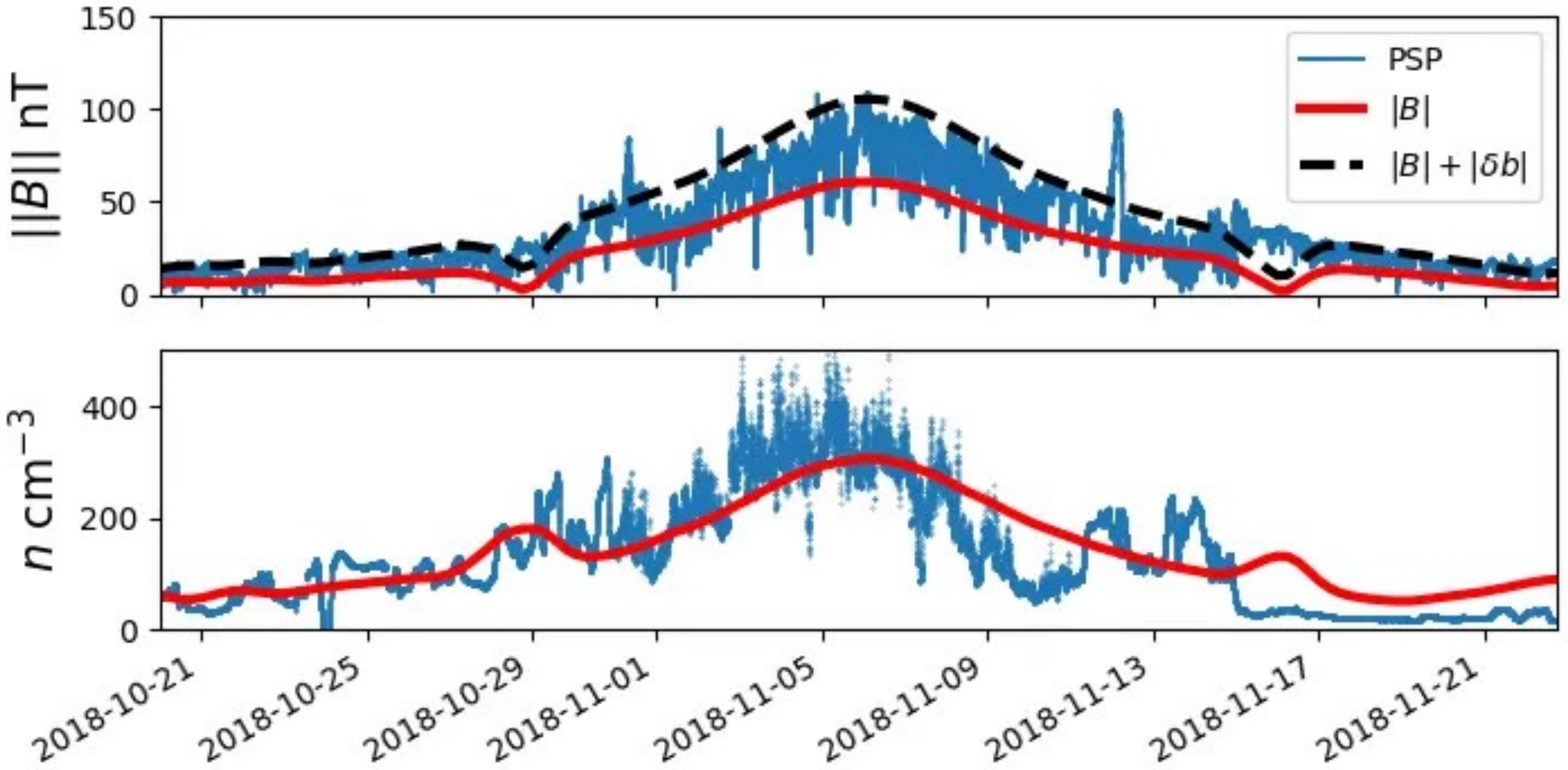
- *WindPredict + 'sub-grid scale model'*

$$\mathcal{E}^{\pm} = \rho \frac{|z^{\pm}|^2}{4}$$

$$\partial_t \mathcal{E}^{\pm} + \underbrace{\nabla \cdot \left[(\mathbf{v} \pm \mathbf{v_A}) \mathcal{E}^{\pm} \right]}_{\text{Transport}} = \overbrace{-\frac{\mathcal{E}^{\pm}}{2} \nabla \cdot \mathbf{v}}^{\text{Wave pressure}} \underbrace{- Q_w^{\pm}}_{\text{Dissipation}},$$

- ***Good*** *agreement with* ***in-situ data***
- ***Thermal structure of the corona ~ ok***

Measures during PSP first perihelion



[Réville, Velli et al. 2020, ApJS]

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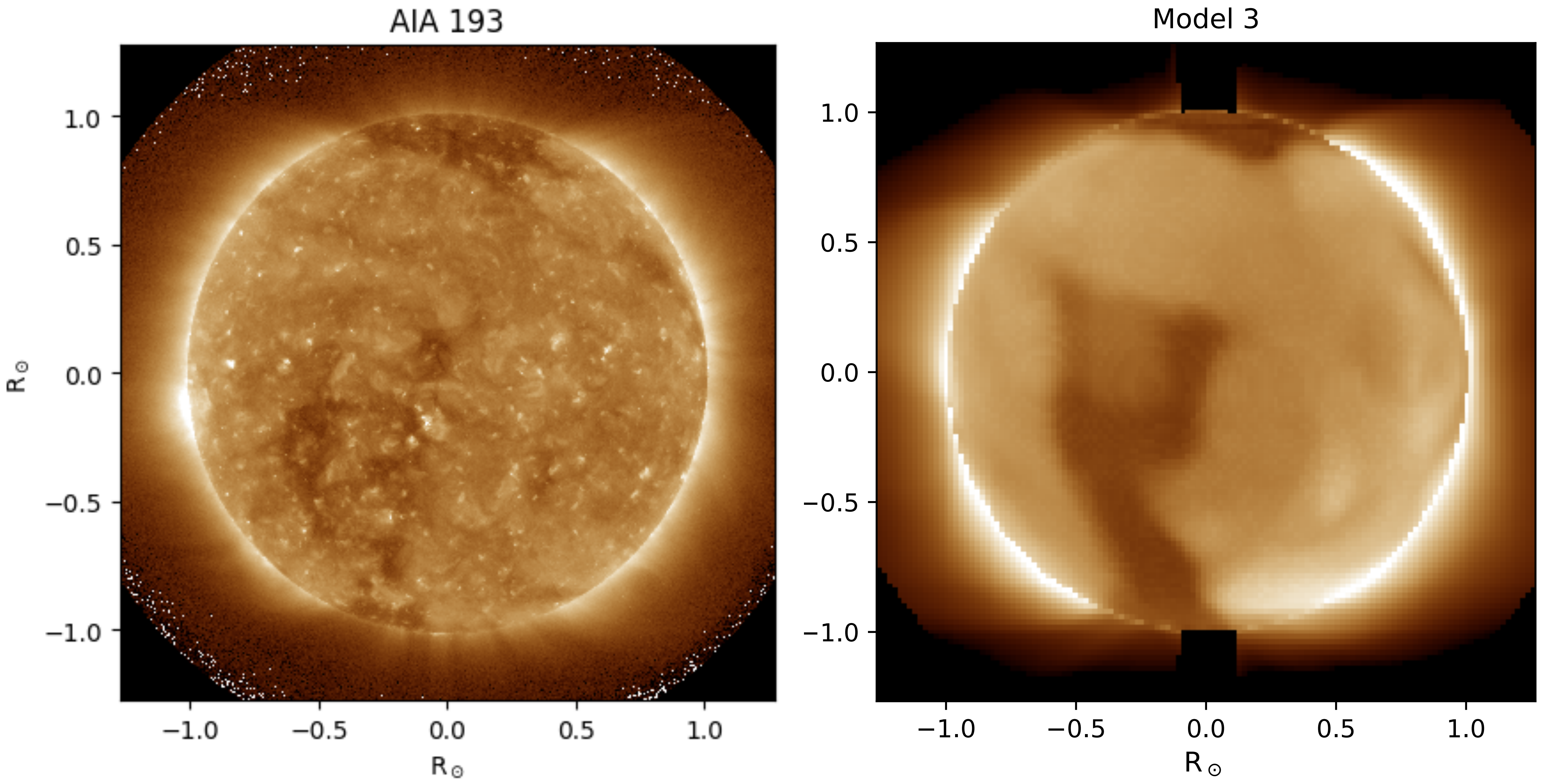
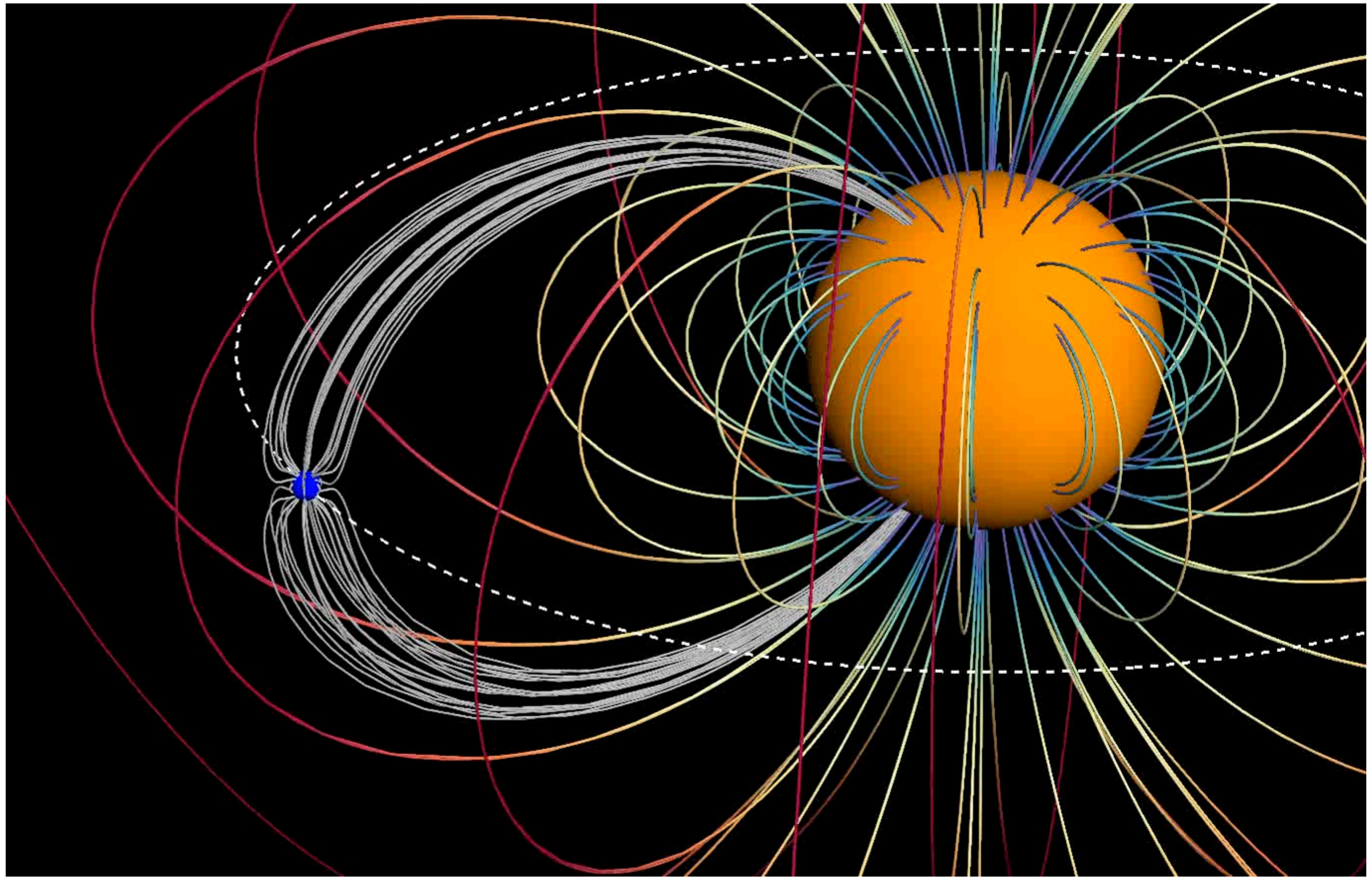
SDO/AIA 193 A



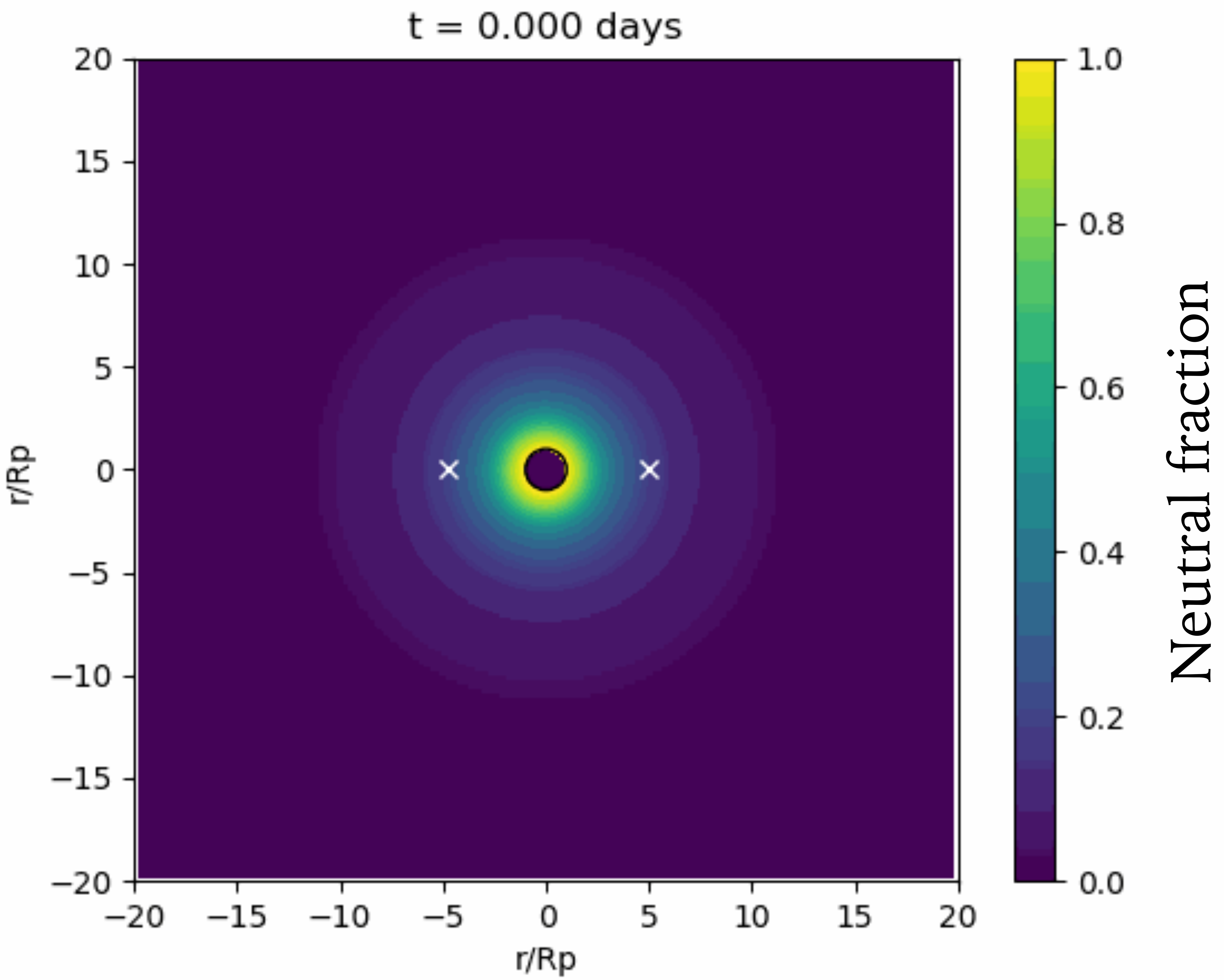
[Parenti, Réville et al. 2022, ApJ]

Star-planet interactions with embedded boundary conditions



Ideal and Resistive MHD global simulations

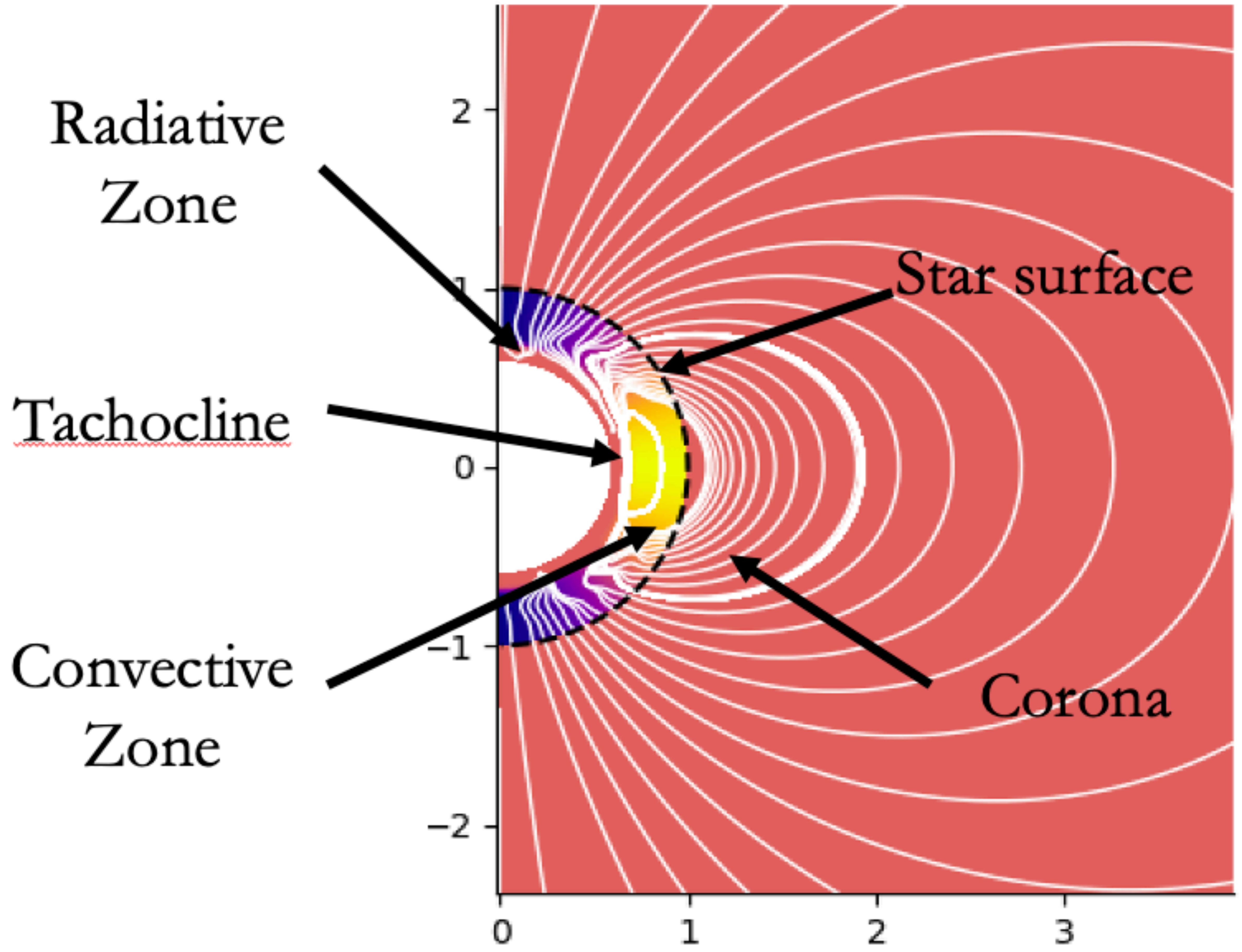
[Strugarek+ 14,15,16,19,22]

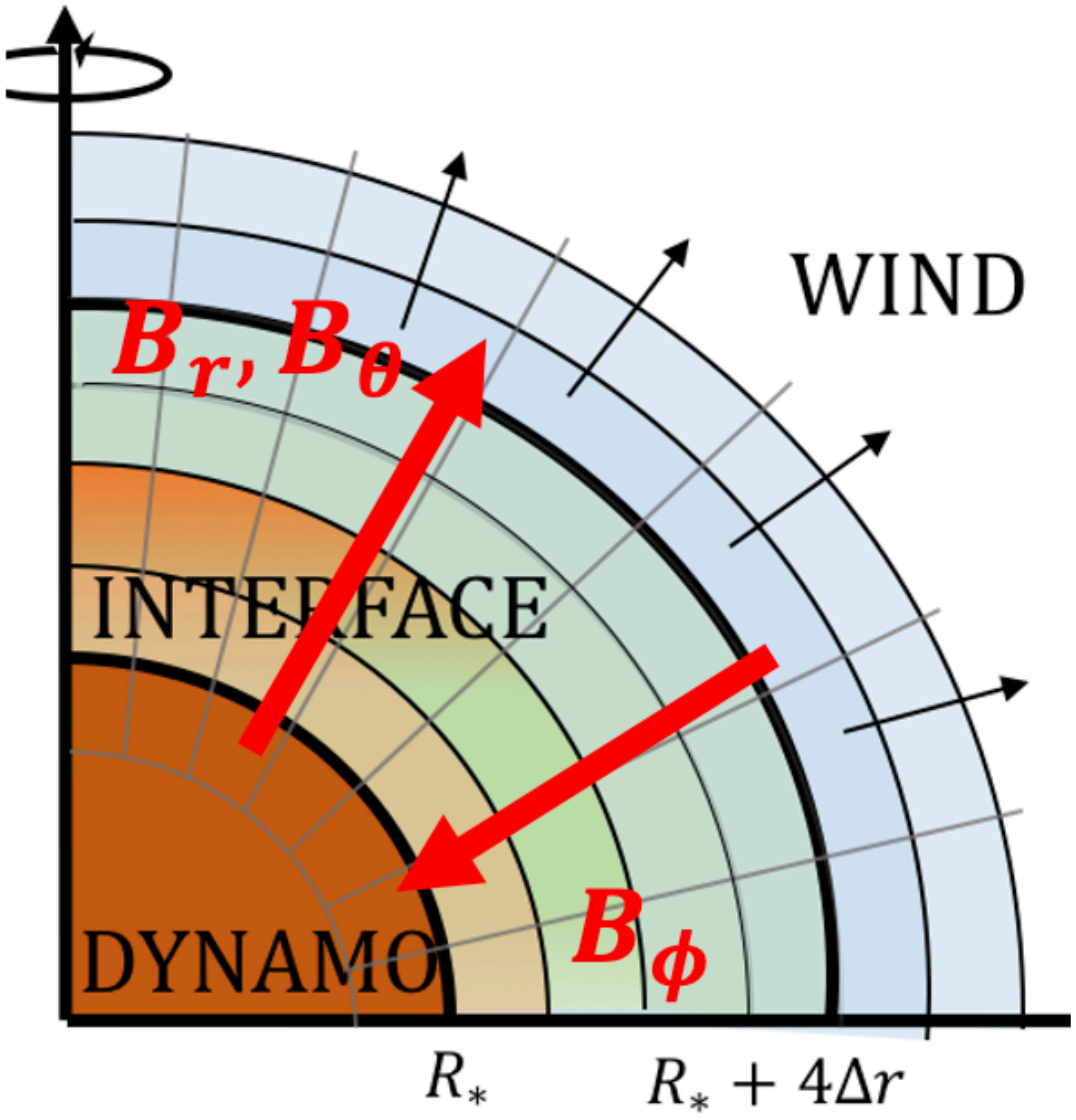


Planetary atmospheric escape with self-consistent photo-chemical heating

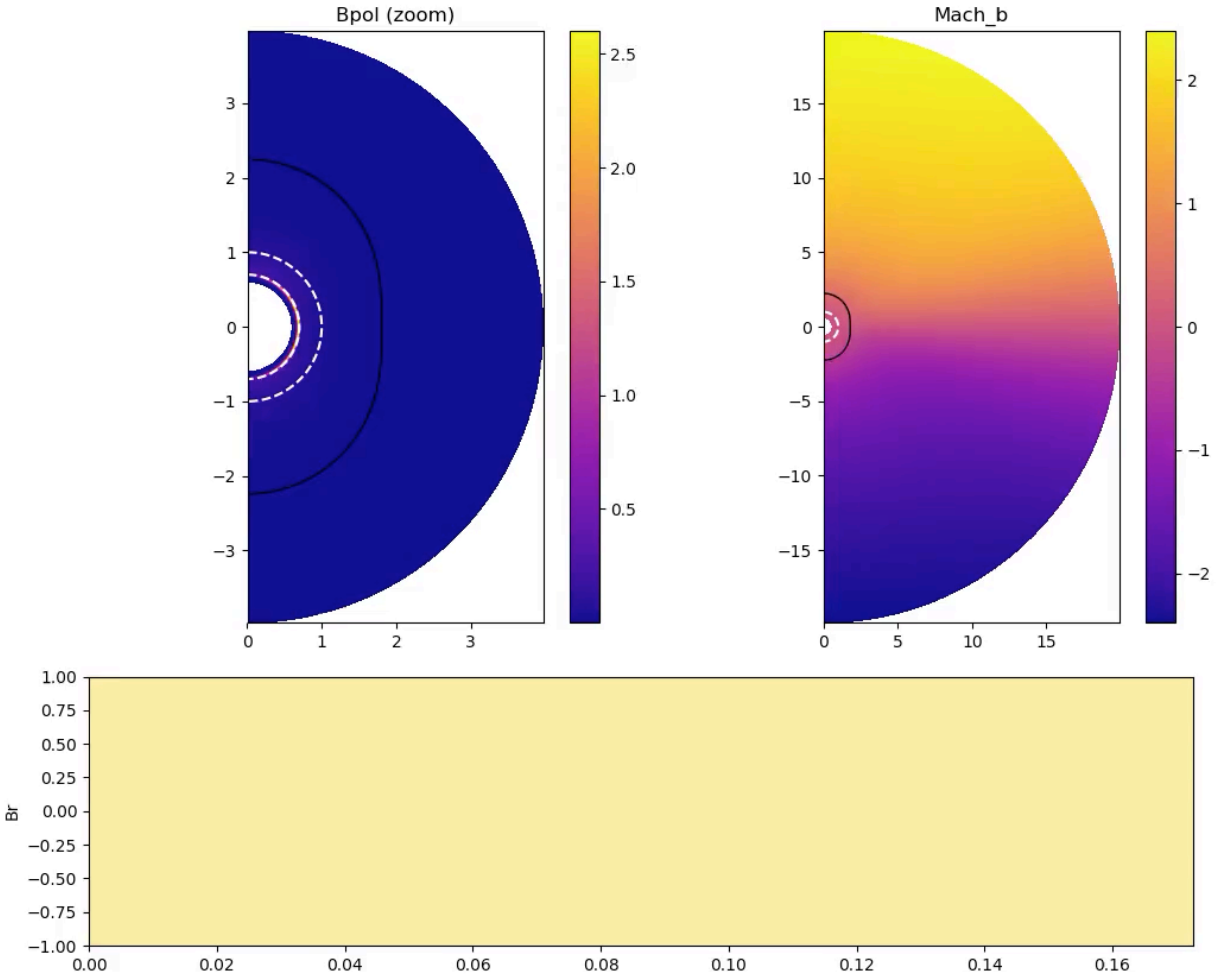
Strugarek, Garcia-Muñoz, Gillet

Coupling dynamos and corona: an novel approach



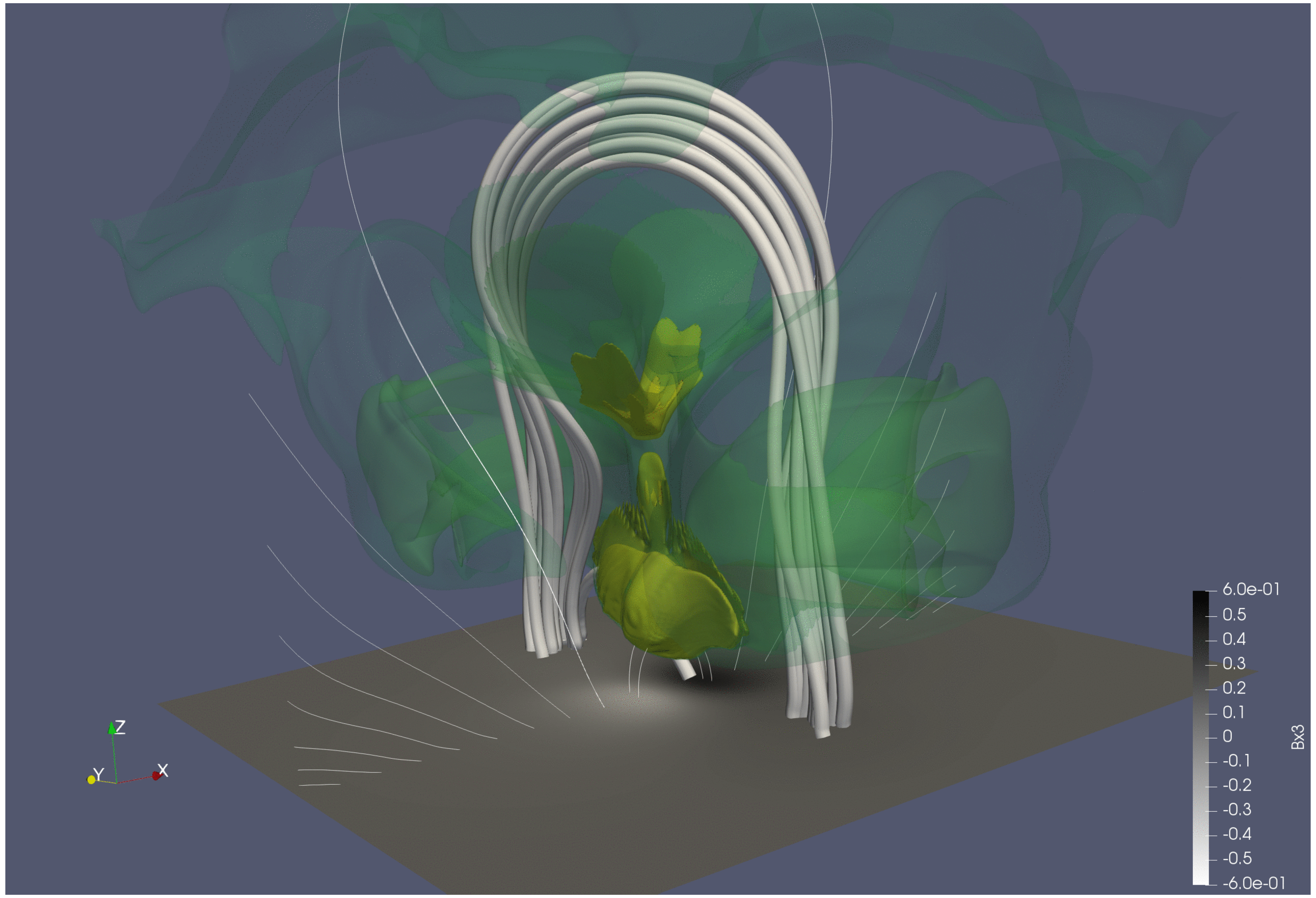


Coupling dynamos and corona: first results



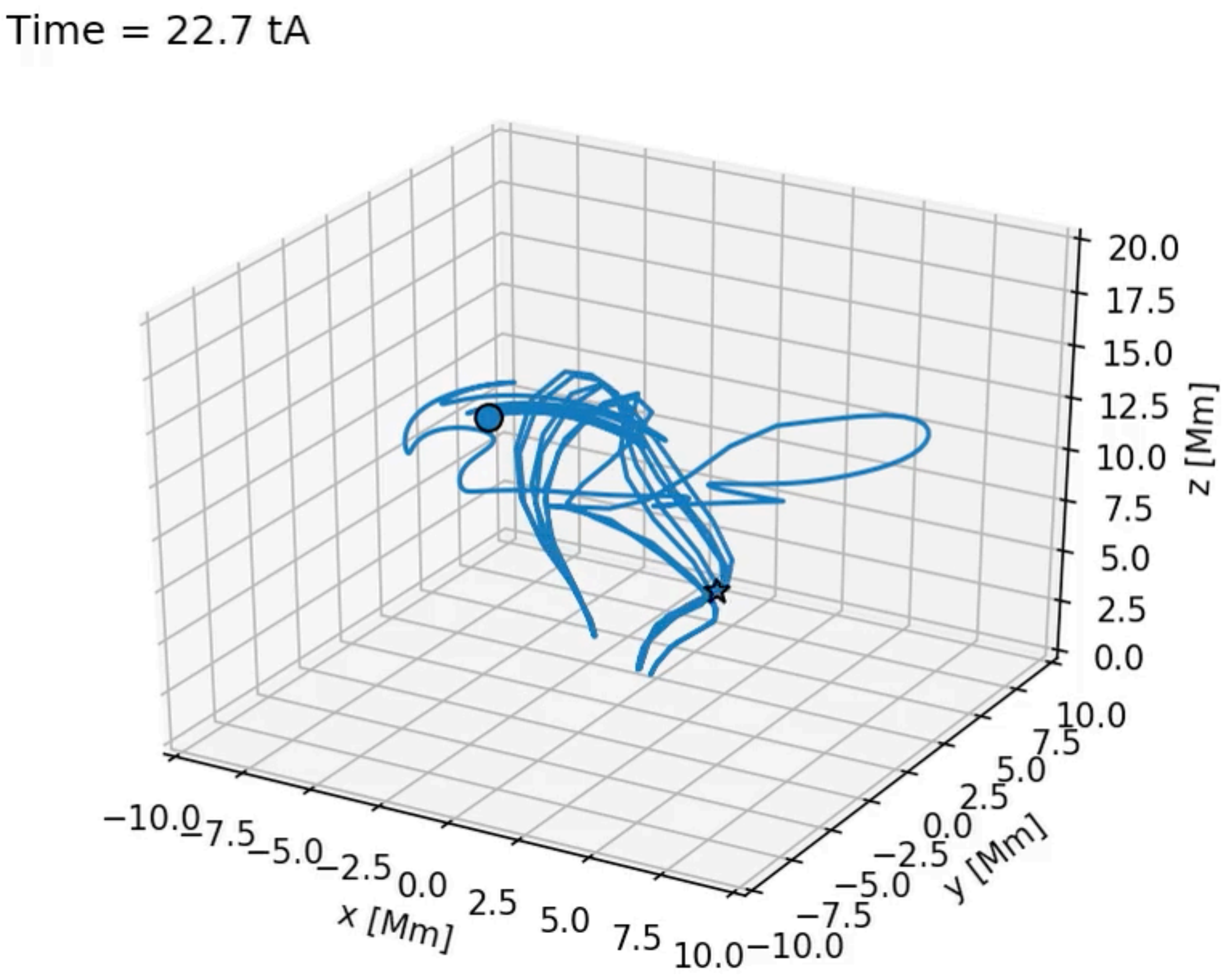
[Perri+ 21]

Understanding multi-wavelengths flares with an hybrid approach



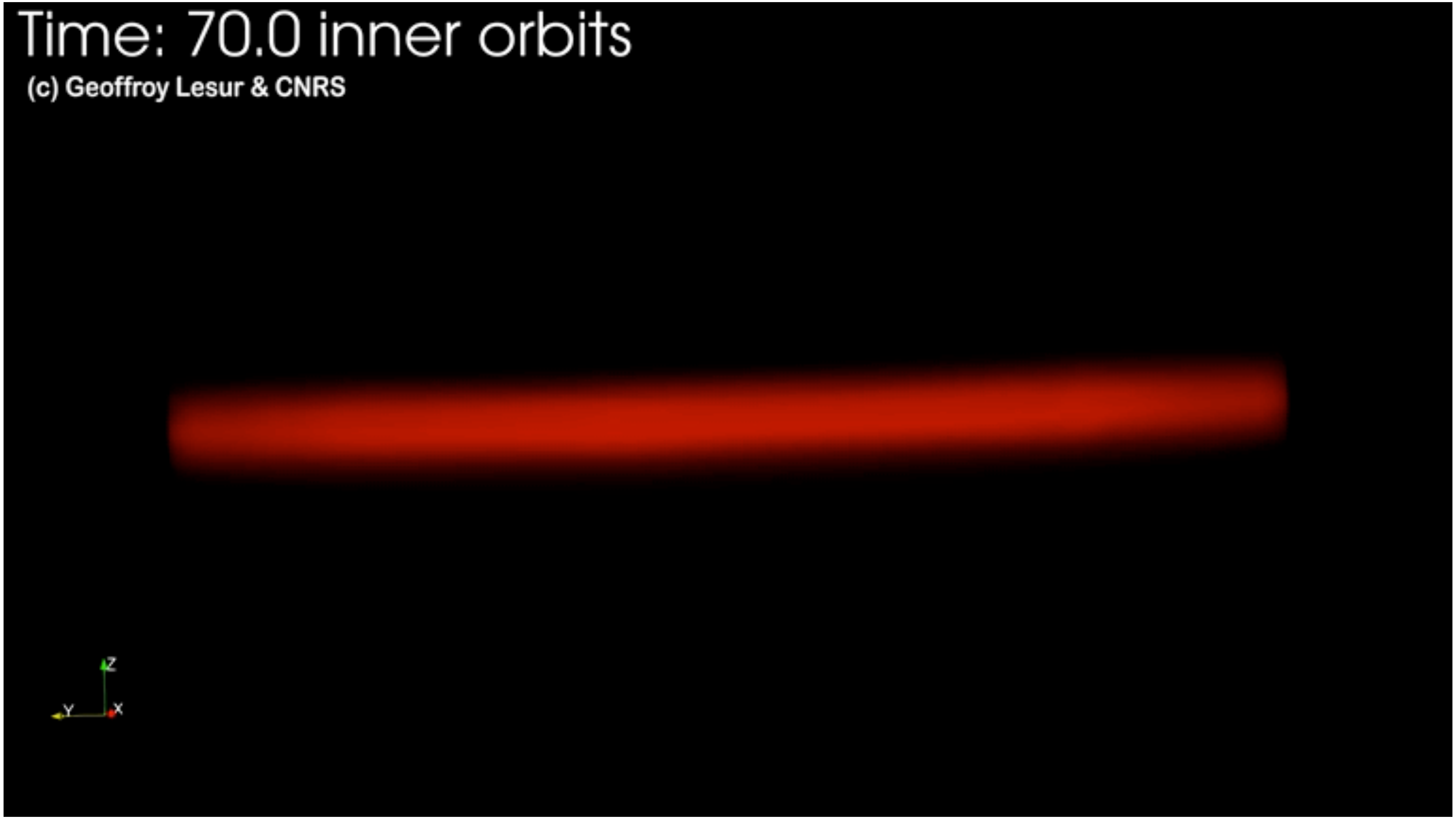
Thermal emission
(MHD, Solar Orbiter/STIX bands)

[Pinto, Strugarek, Gannouni]



Non-thermal (hard X-ray with STIX)
with self-consistent particle acceleration
under guiding-centre approximation

Simulation of protoplanetary disc with non-ideal MHD effects



[Béthune, Lesur & Ferreira 2017]

Future of PLUTO

Genuine 4th-order schemes with Finite Volume

Mapped grids (more flexibility than what exists now)

Lagrangian particles with with feedback and *synthetic observation* capabilities

Particles under the guiding-center approximation (not officially released yet)

GPU Porting

GPU Porting and multi-architecture portability

PLUTO has been recently ported by M. Rossazza on GPUs with openACC

Marconi100 (Teslav100)					
gPLUTO - 3D Orszag-Tang					
64^3 grid points			96^3 grid points		
Procs number	CPU	GPU (OpenACC)	Procs number	CPU	GPU (OpenACC)
1	x1	x15.0	1	x1	x16.6
4	x4.8	x52.0	4	x4.5	x45.8
128^3 grid points			256^3 grid points		
Procs number	CPU	GPU (OpenACC)	Procs number	CPU	GPU (OpenACC)
1	x1	x18.3	1	x1	-
4	x4.3	x53.0	4	x3.9	x57.4
368^3 grid points					
Procs number	CPU	GPU (OpenACC)			
1	x1	-			
4	x4.9	x74.1			

This 'gPLUTO' version is not openly available yet.

BUT

How to ensure long-term portability on future machines and architectures?

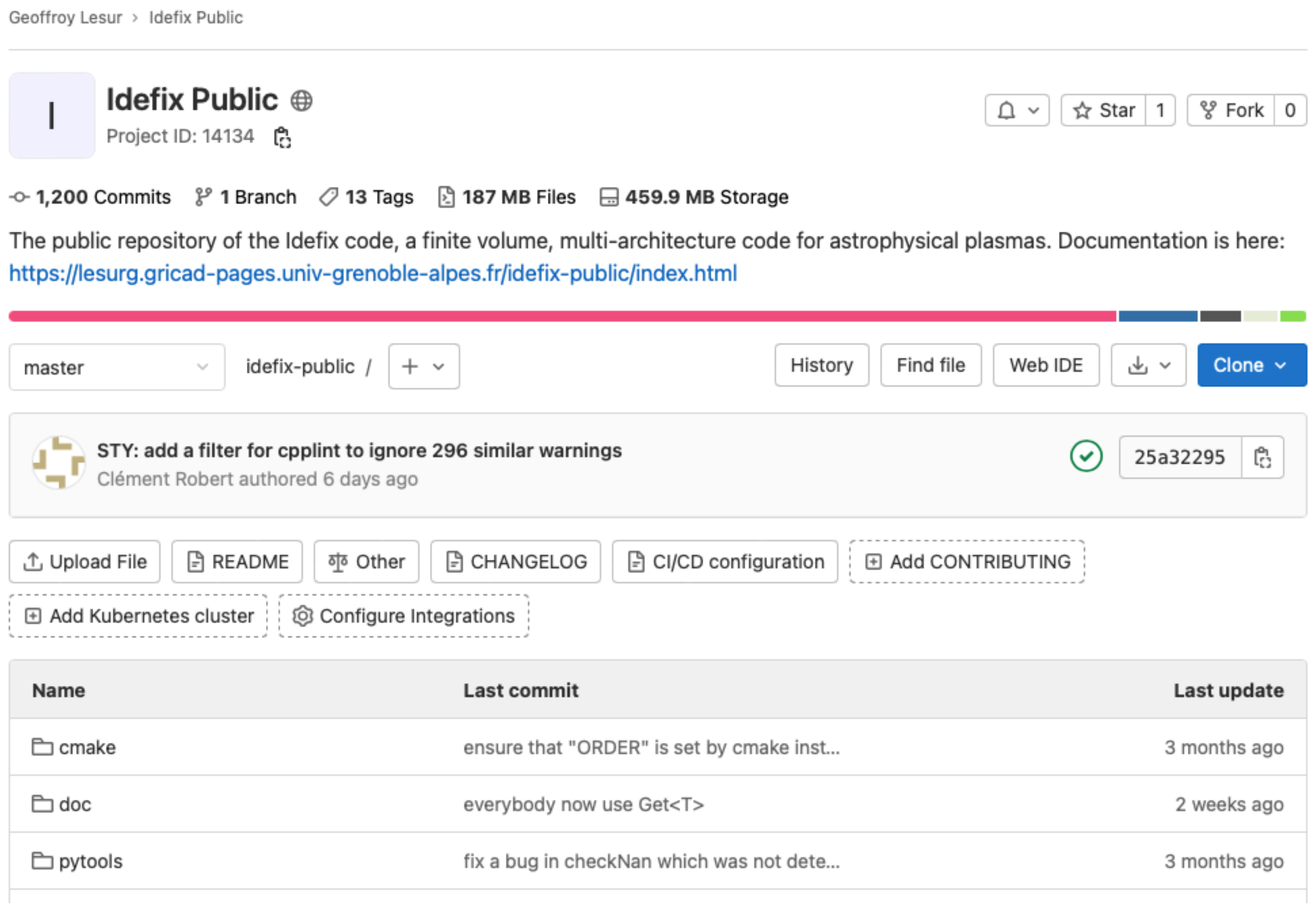
Standard CPUs, GPUs, ARM (…)

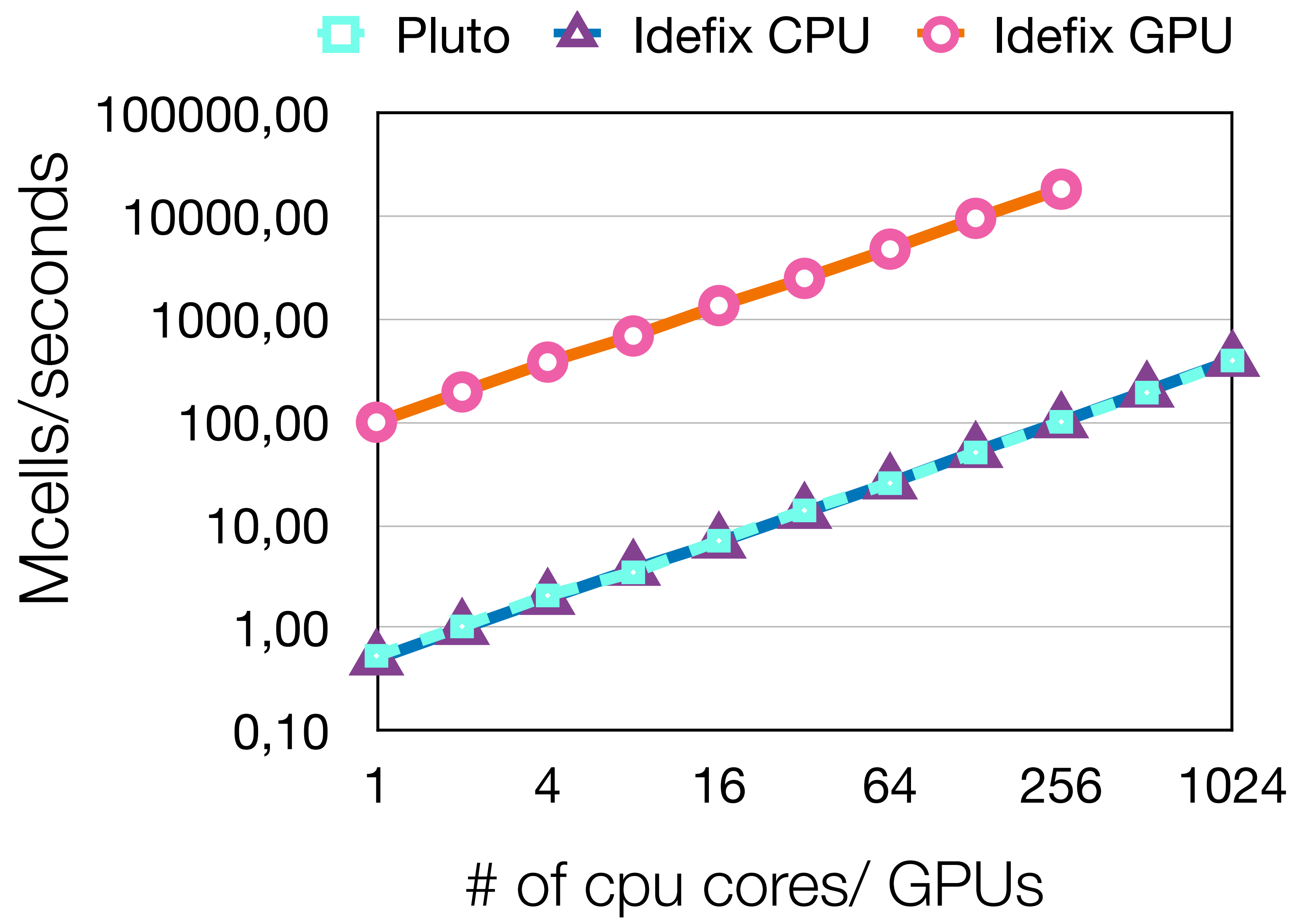
IDEFIX

[Lesur *et al.* 2022, *in prep*]

- Idefix is a new Godunov, exascale-ready code, (written from scratch), solving the (M)HD equation in arbitrary geometry. Written in C++ 14, relying on Kokkos meta-programming library
- Can run with almost no effort on laptop CPUs, GPU systems, ARM, etc…
- Inputs, outputs and data structures are similar to Pluto [Mignone+ 2007]. Simplified portability.
- Speedup compared to Pluto on Nvidia V100: x150
- Available through UGA Gitlab (public version under CECILL license available https://gricad-gitlab.univ-grenoble-alpes.fr/lesurg/idefix-public)

Courtesy G. Lesur

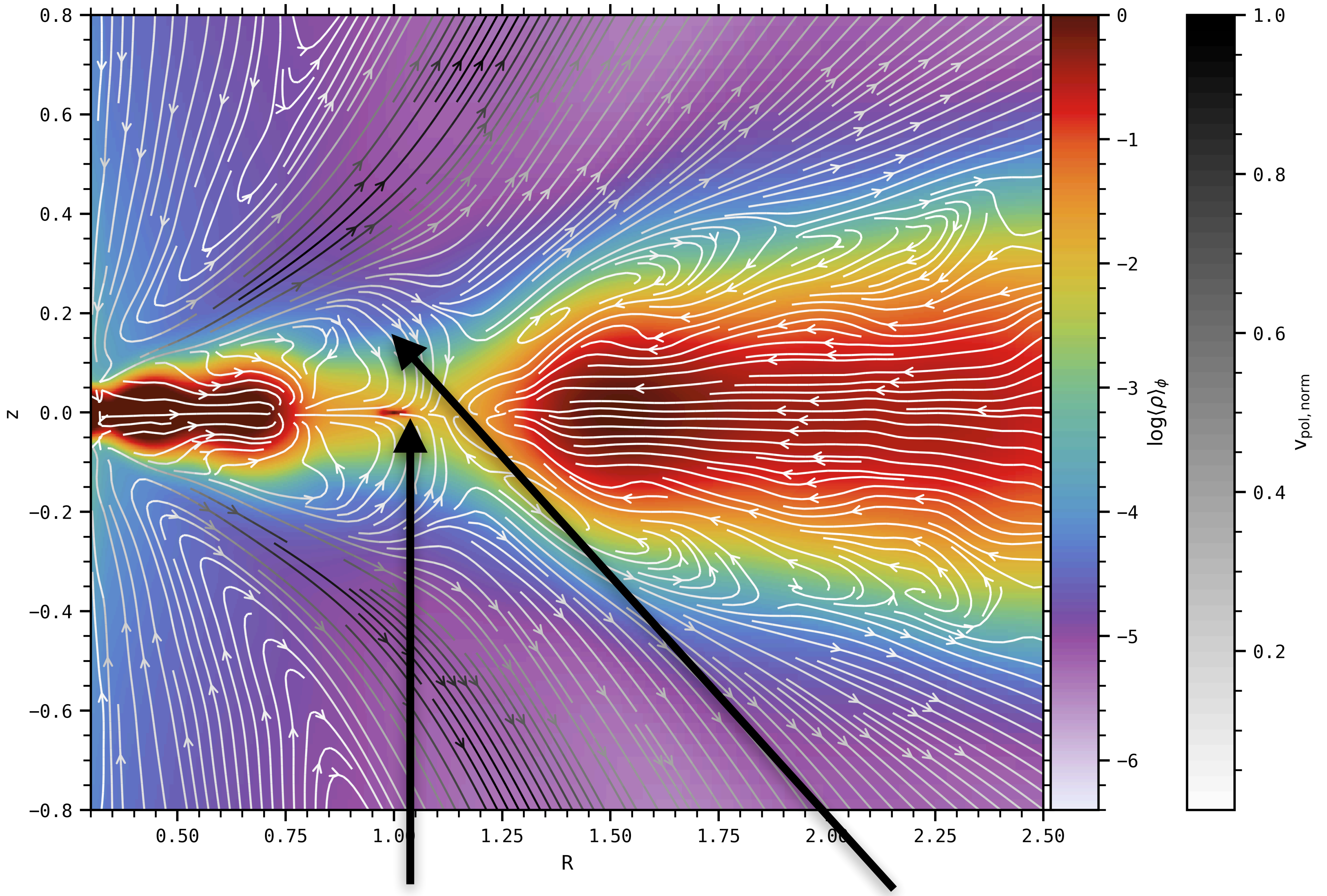




Some applications with IDEFIX

Courtesy
G. Lesur

Planet-disc-wind interaction
[G. Wafflard-Fernandez @IPAG]
Average streamlines



Planet location
(circumplanetary disc)

wind material falling
back in the gap

Core collapse calculations
[J. Mauxion @IPAG]