Simulations PIC: Applications astrophysiques et besoins

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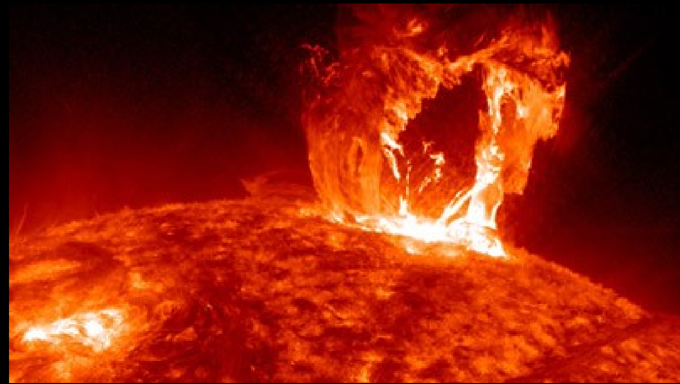
Journées ASOV-ASN 2022, 6-7 octobre 2022

Astrophysical relevance & applications

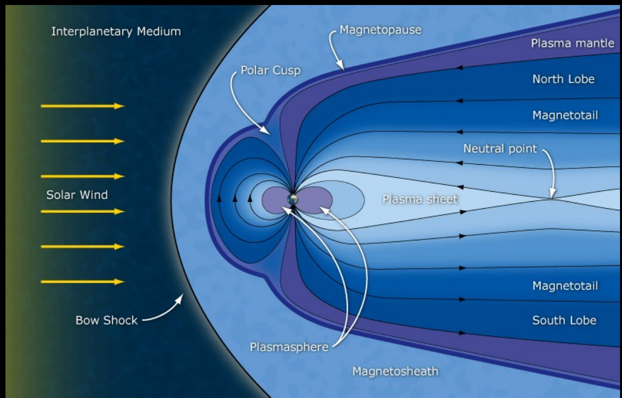
Collisionless environments

Solar corona & wind, heliosphere

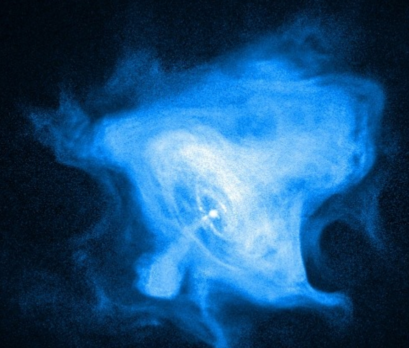


Relativistic magnetospheres

Planetary magnetospheres

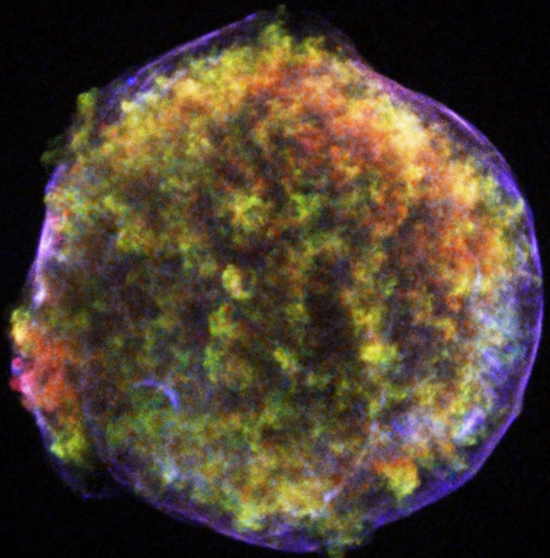


Pulsar Wind Nebulae



Jets

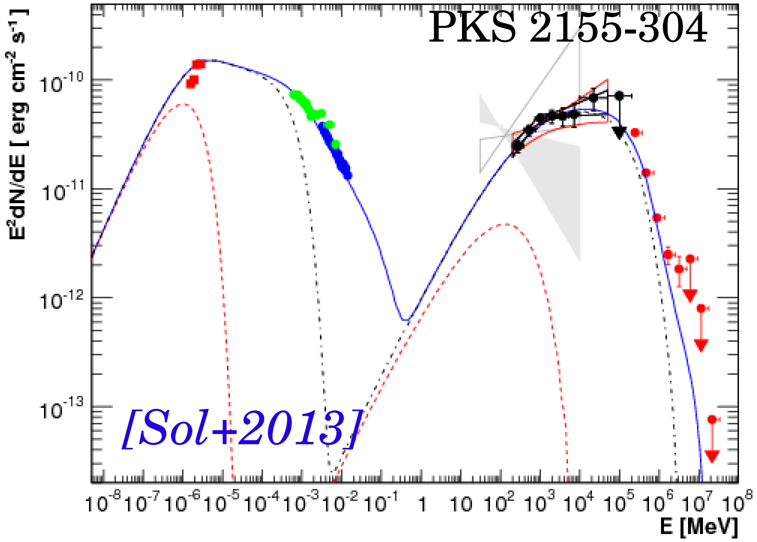
Supernova Remnants



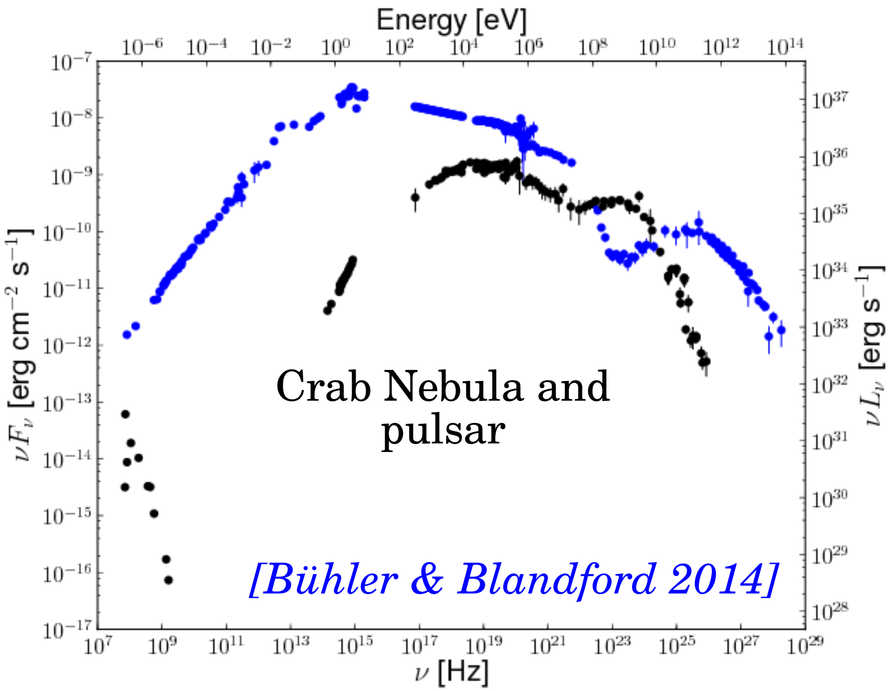
Gamma-ray bursts
Fast radio bursts

Broad non-thermal distributions

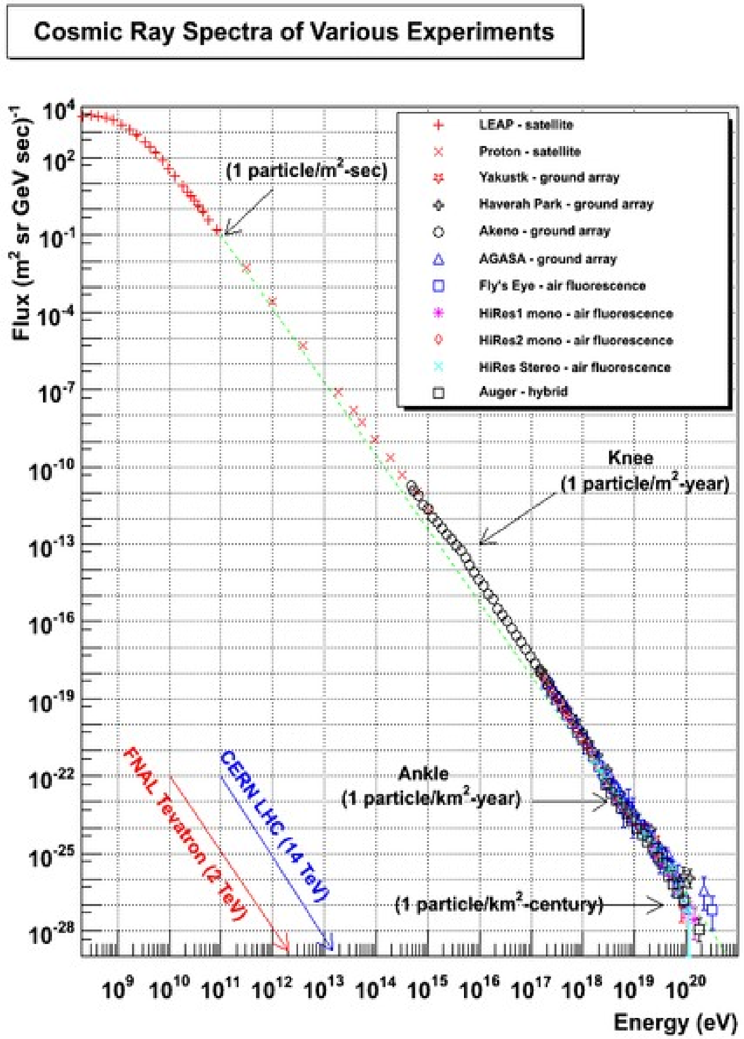
Blazars



Pulsars & Pulsar Wind Nebulae



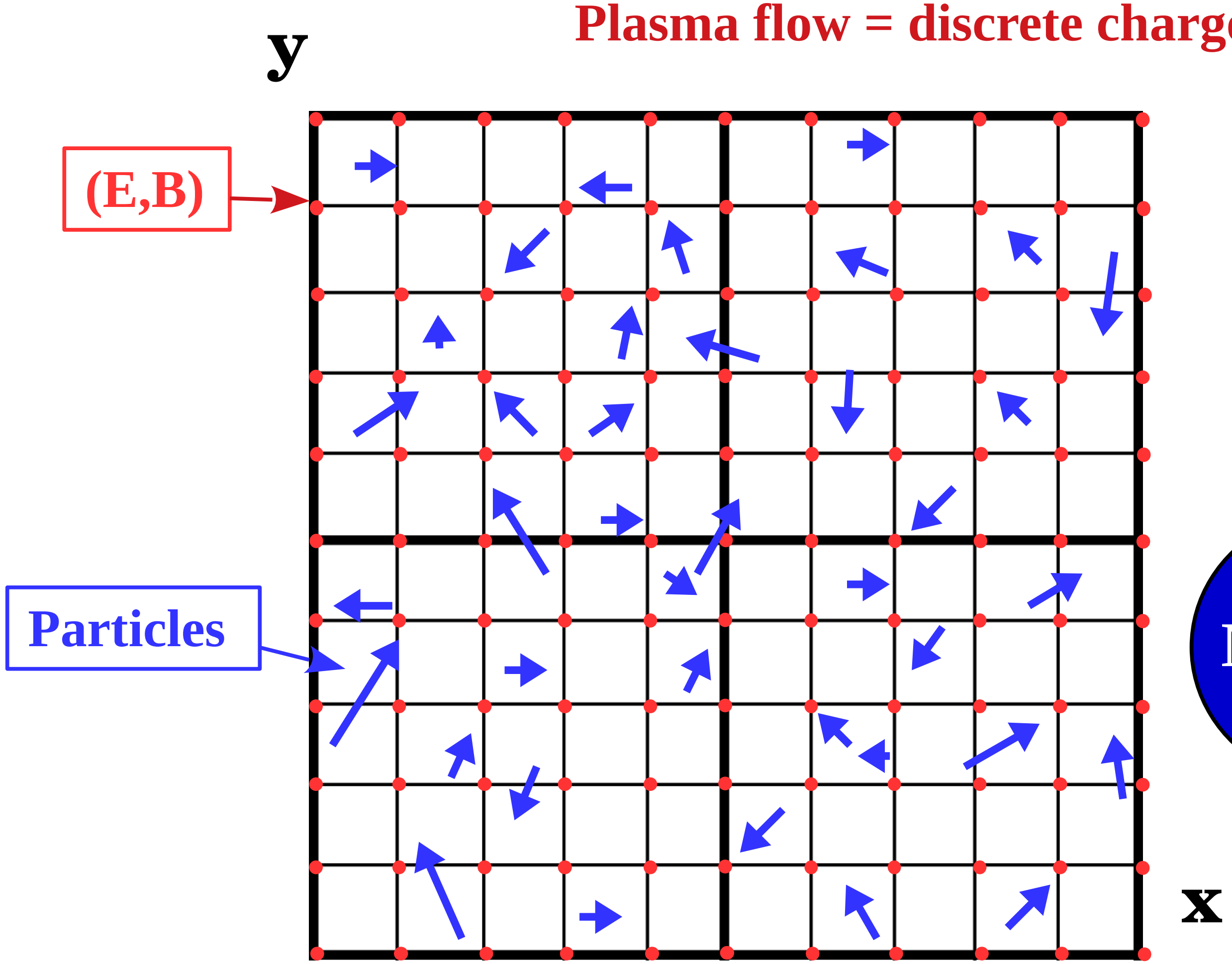
Challenge:
Particle acceleration at microscopic scales << system size

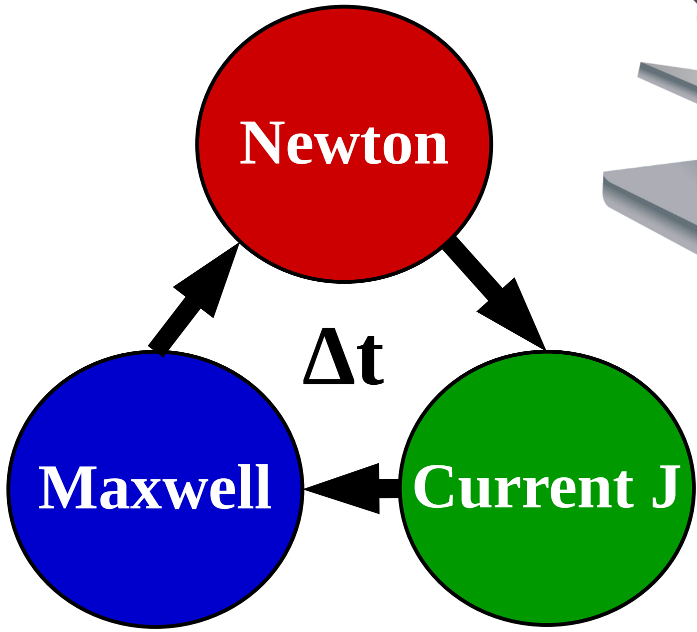


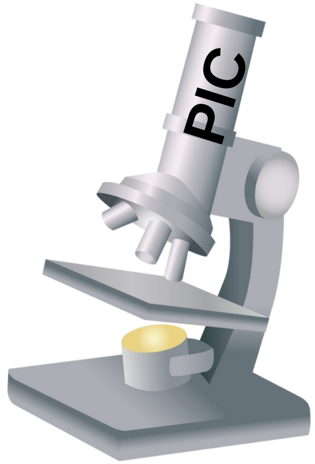
[http://www.physics.utah.edu/~whanlon/spectrum.html]

The spirit of the particle-in-cell approach

Plasma flow = discrete charged particles







- ✔ Ab-initio modeling of plasmas, capture μ-physics
- ✔ Particle acceleration, radiation, pair creation
- ✔ Model observables
- ✘ Computationally expensive strong need of HPC
- ✘ Short-term evolution, small scale-separation

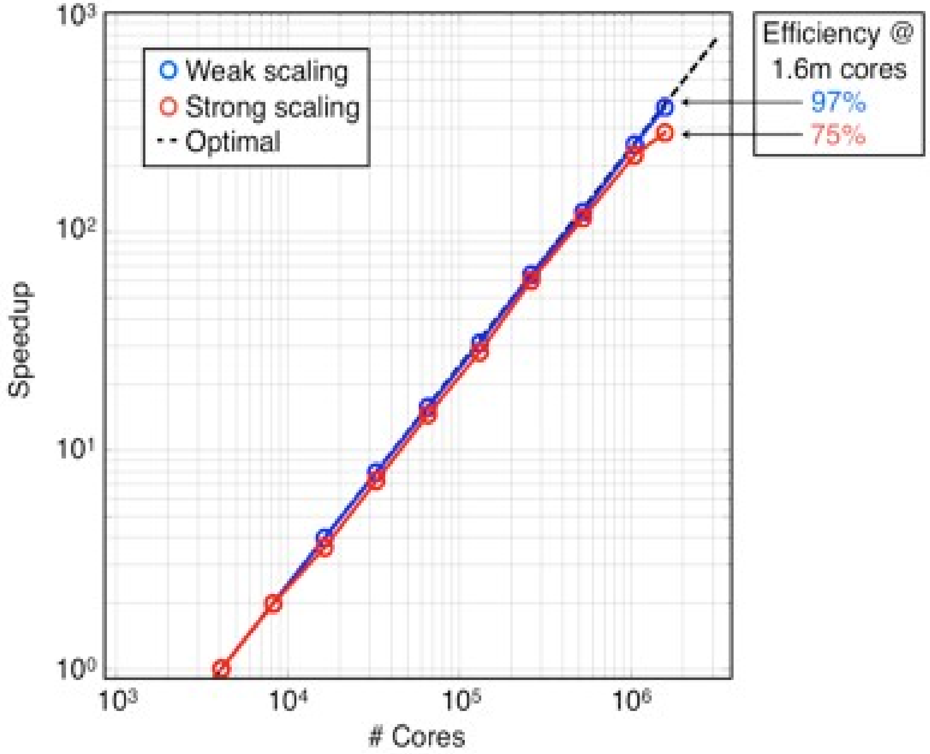
Study non-thermal particle acceleration from <u>first principles</u>

Numerical observatory => PIC simulations has become a real <u>discovery tool</u>!

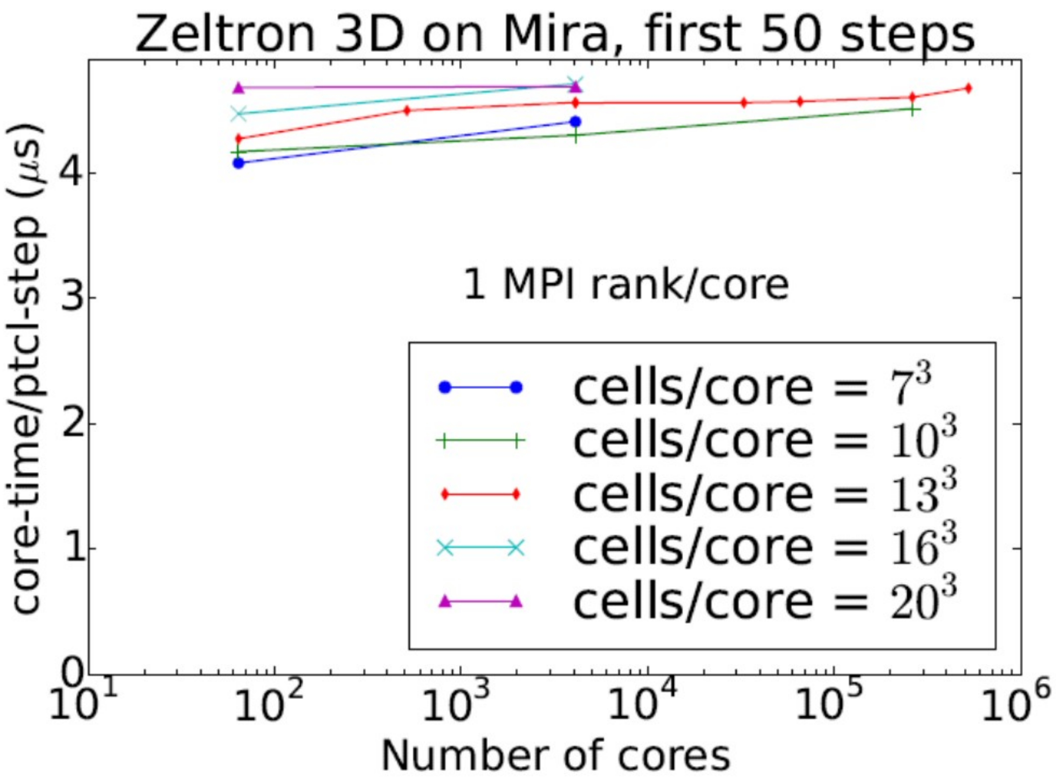
PIC codes usually scale very well

Usually **CPU-limited** rather than **memory-limited**

OSIRIS Code



Zeltron Code



Particle data structure

Global CPU time & memory **dominated by the particles** evolution and data

List of particles

	x	y	z	u_x	u_y	u_z	weight
Part 1							
Part 2							
...							
Part NP							

Memory estimate of a large PIC run: 10^{11}-10^{12} particles: **10-100 To**

In practice, **only a few complete snapshots** are conserved to ensure simulation restoration.

Data reduction is performed on the fly:

- Particle spectra
- Plasma density/ EB fields maps
- Stress-energy tensor
- Particle trajectories of a sub-sample of particles

…

$$\frac{dN}{dV} \approx \frac{1}{\Delta V} \sum_{k=1}^{N_{cell}} w_k$$

$$T^{\mu\nu} = \left(\rho + \frac{P}{c^2}\right) V^{\mu} V^{\nu} - P \eta^{\mu\nu}$$

Manageable/shareable dataset … but you need to know what you are looking for ahead of time

The Zeltron code

URL: http://ipag.osug.fr/~ceruttbe/Zeltron

Created in 2012 and Cartesian version published in 2015.
Includes QED and General Relativistic effects since 2019 (currently private repo @ GRICAD).

The Zeltron code

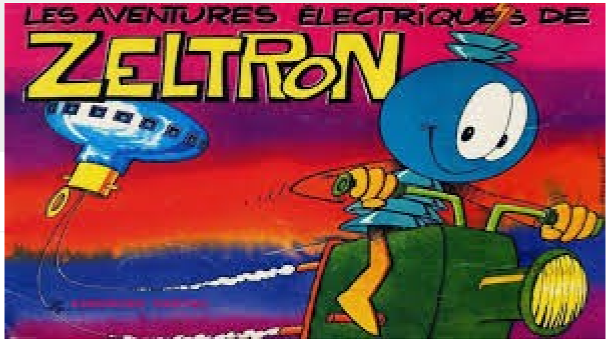
- Home
- Features
- Download
- Quickstart
- User guide
- Gallery
- Publications
- Developers
- Contact

The Zeltron code project

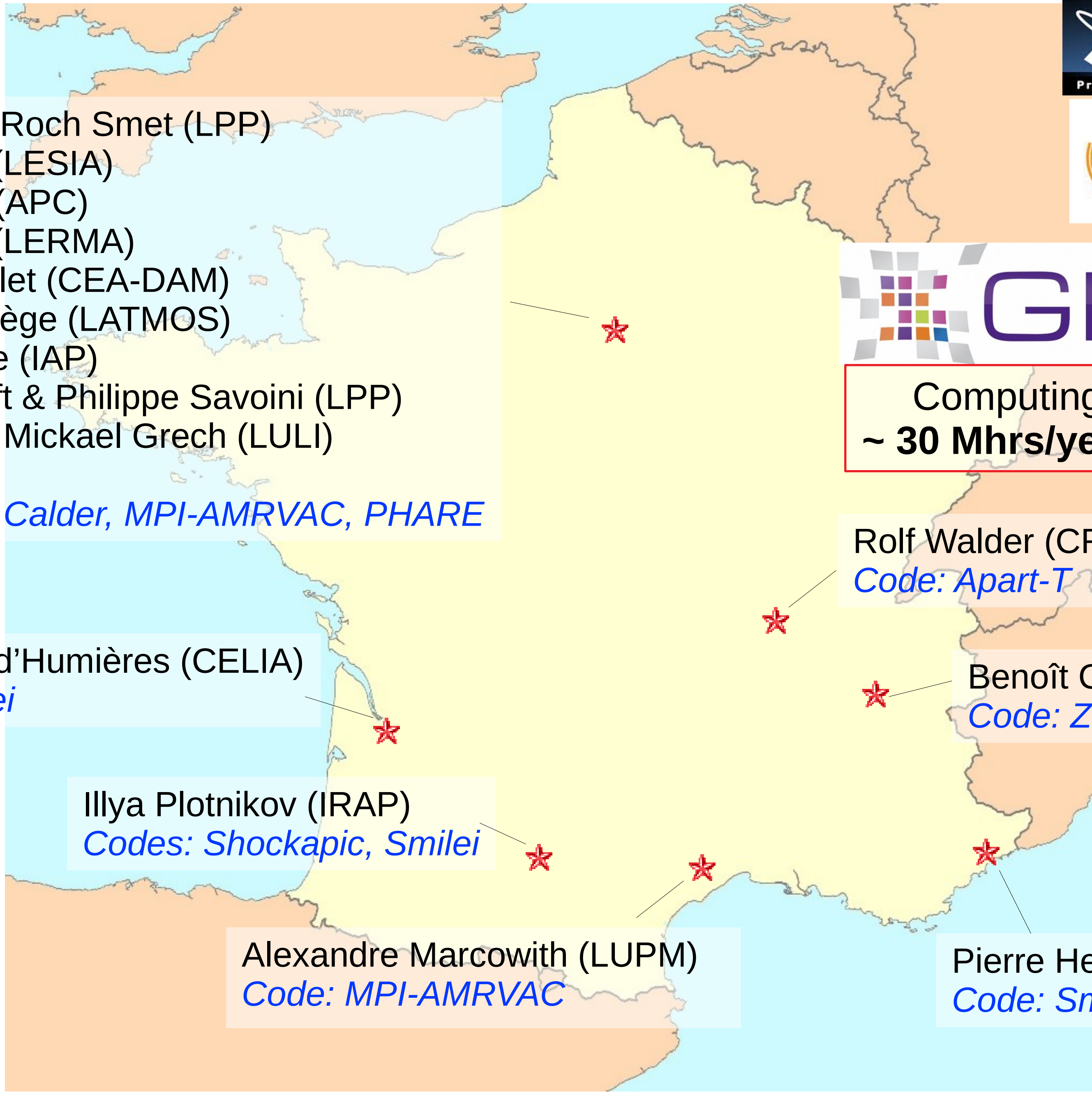
Zeltron is an explicit 3D relativistic electromagnetic Particle-In-Cell code, ideally suited for modeling particle acceleration in astrophysical plasmas. The code is efficiently parallelized with the Message Passing Interface, and can be run on a laptop computer or on multiple cores on current supercomputers.

The Zeltron code is freely available here, and runs on linux and OS X operating systems.

Learn more › Download



The astrophysical PIC community in France



Nicolas Aunai, Roch Smet (LPP)
Carine Briand (LESIA)
Fabien Casse (APC)
Andrea Ciardi (LERMA)
Laurent Gremillet (CEA-DAM)
Bertrand Lembège (LATMOS)
Martin Lemoine (IAP)
Catherine Krafft & Philippe Savoini (LPP)
Anna Grassi & Mickael Grech (LULI)

Codes: Smilei, Calder, MPI-AMRVAC, PHARE

PNHE Programme national hautes énergies

PNST Programme National Soleil-Terre

GENCI

Computing time (CT4)
~ 30 Mhrs/year (~15% CT4)

Rolf Walder (CRAL)
Code: Apart-T

Emmanuel d'Humières (CELIA)
Code: Smilei

Benoît Cerutti (IPAG)
Code: Zeltron

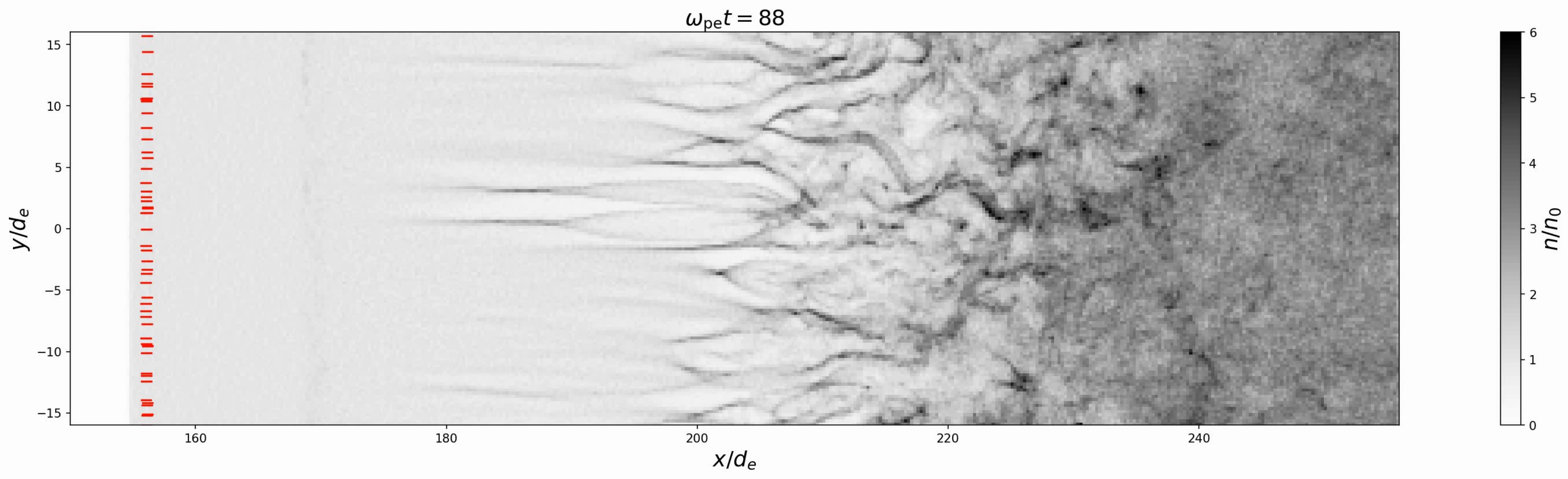
Illya Plotnikov (IRAP)
Codes: Shockapic, Smilei

Alexandre Marcowith (LUPM)
Code: MPI-AMRVAC

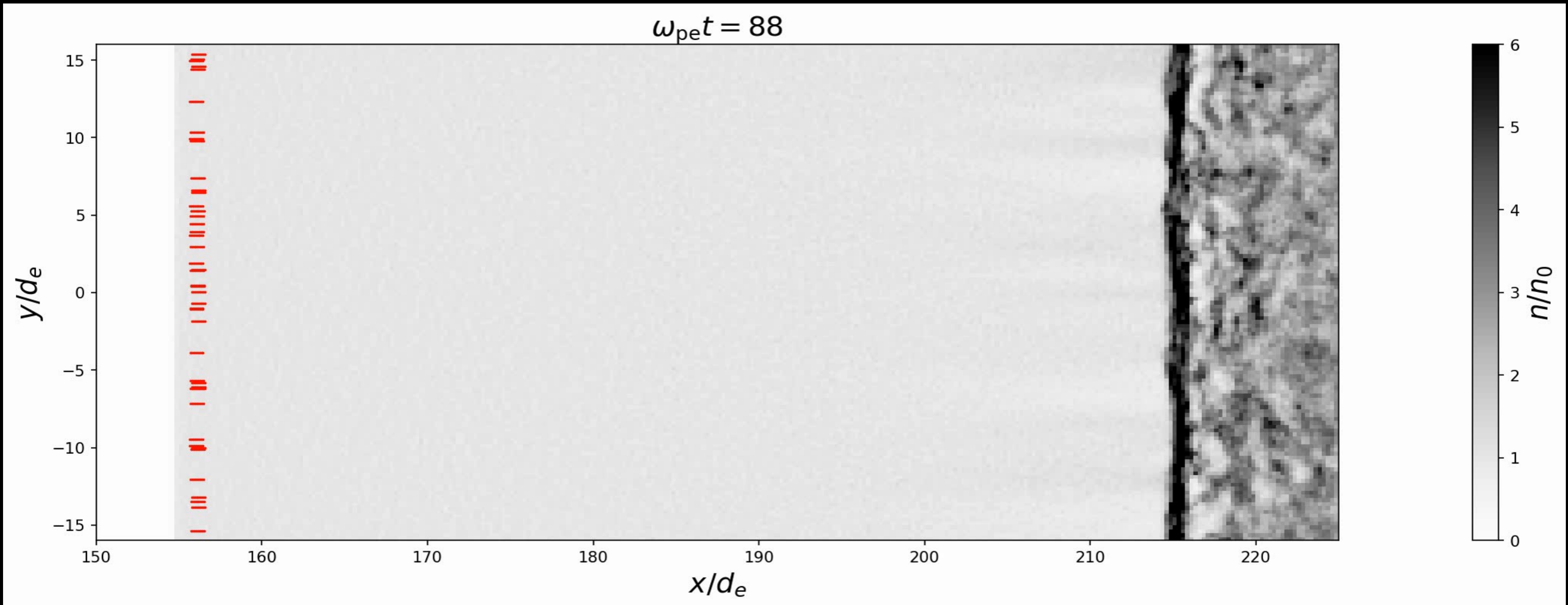
Pierre Henri (OCA-LPC2E)
Code: Smilei

HE astro application: relativistic shocks

Unmagnetized



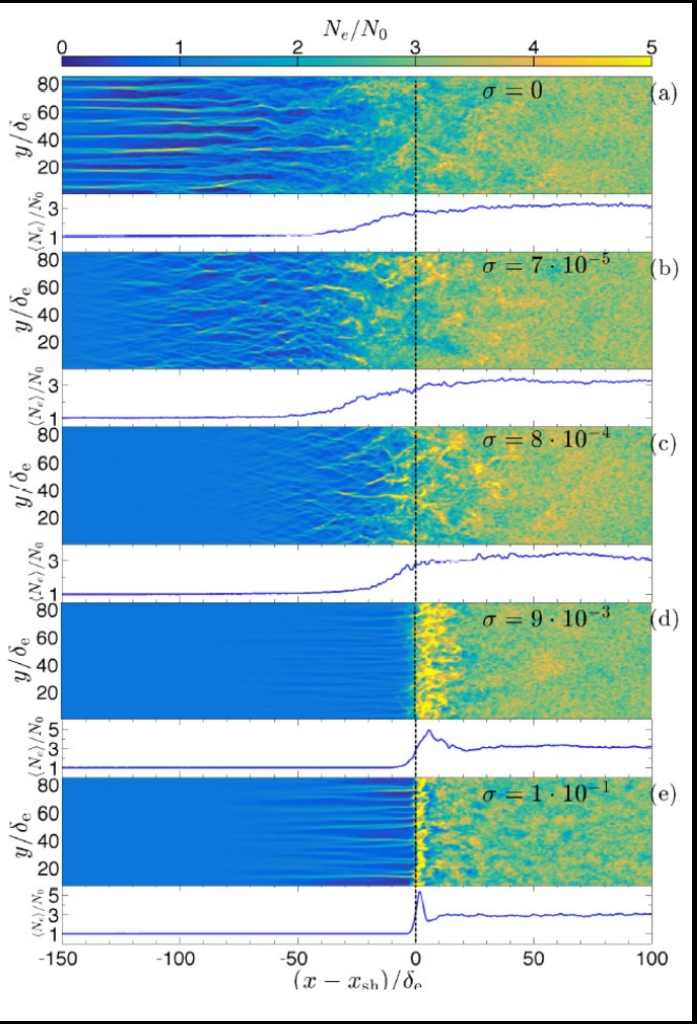
Magnetized



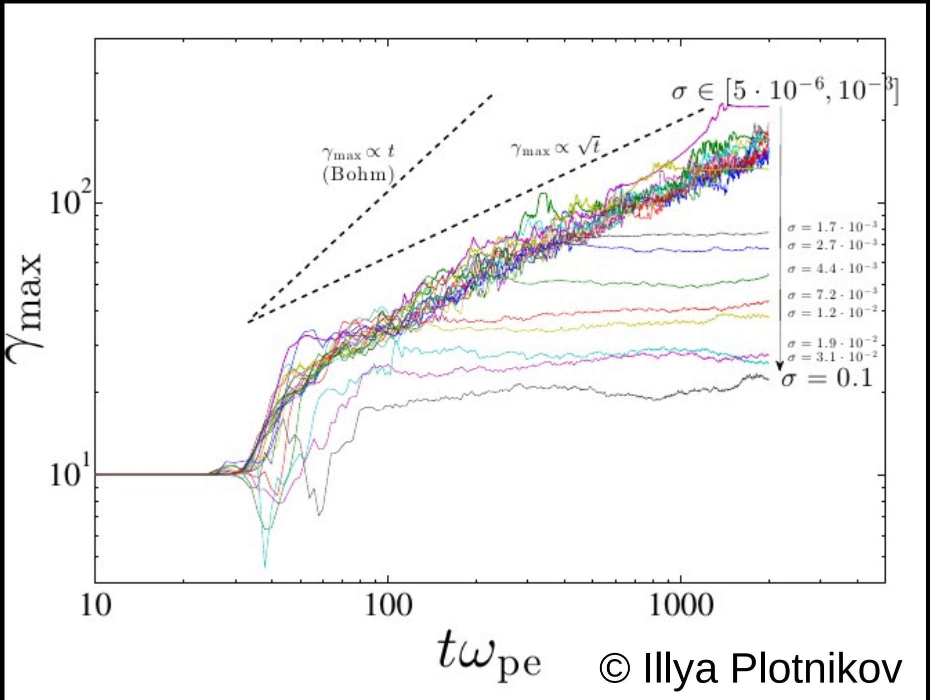
HE astro application: relativistic shocks

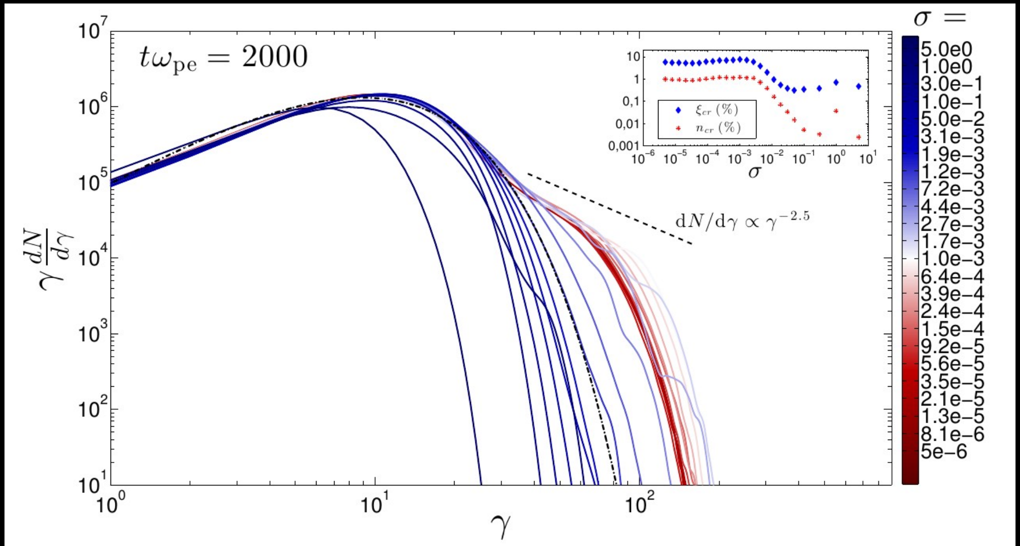
e.g., Plotnikov et al. 2018
Lemoine et al. 2019
Vanthieghem et al. 2020
Cerutti & Giacinti 2020

Shock structure



Particle acceleration

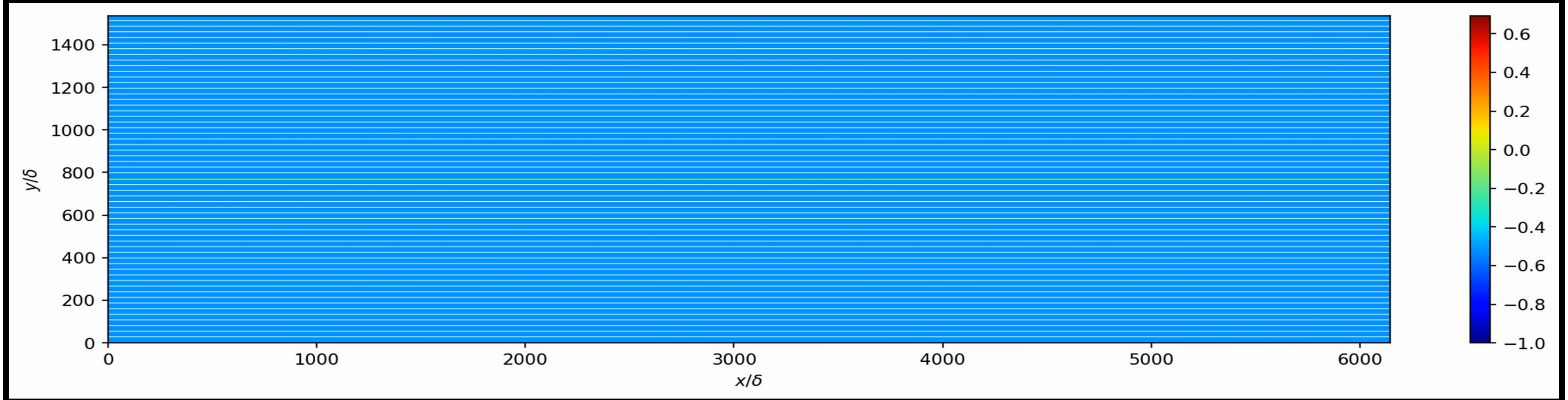


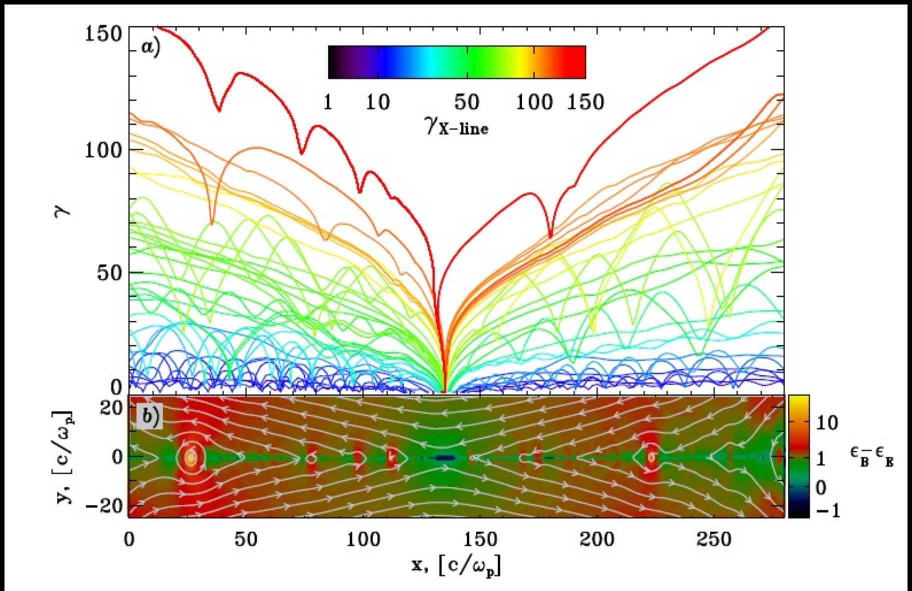


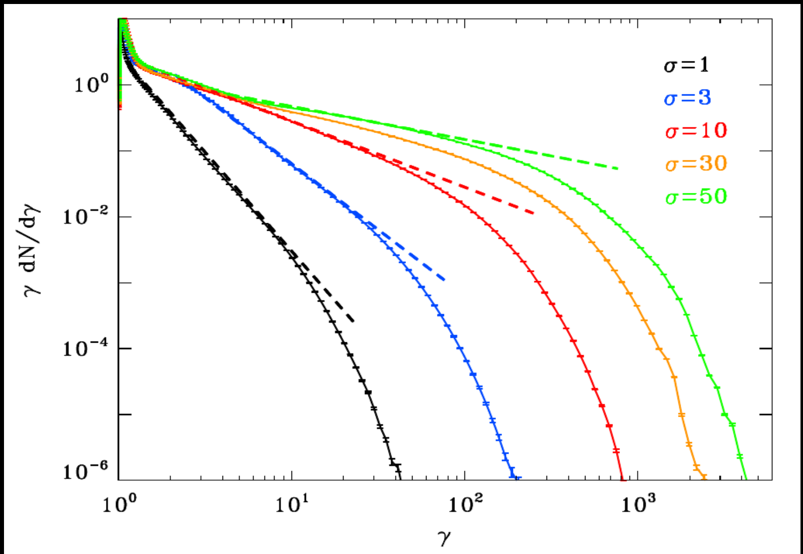
HE astro application: relativistic reconnection

e.g., Cerutti et al. 2013, Melzani et al. 2014, Sironi & Spitkovsky 2014

Plasmoid-dominated reconnection



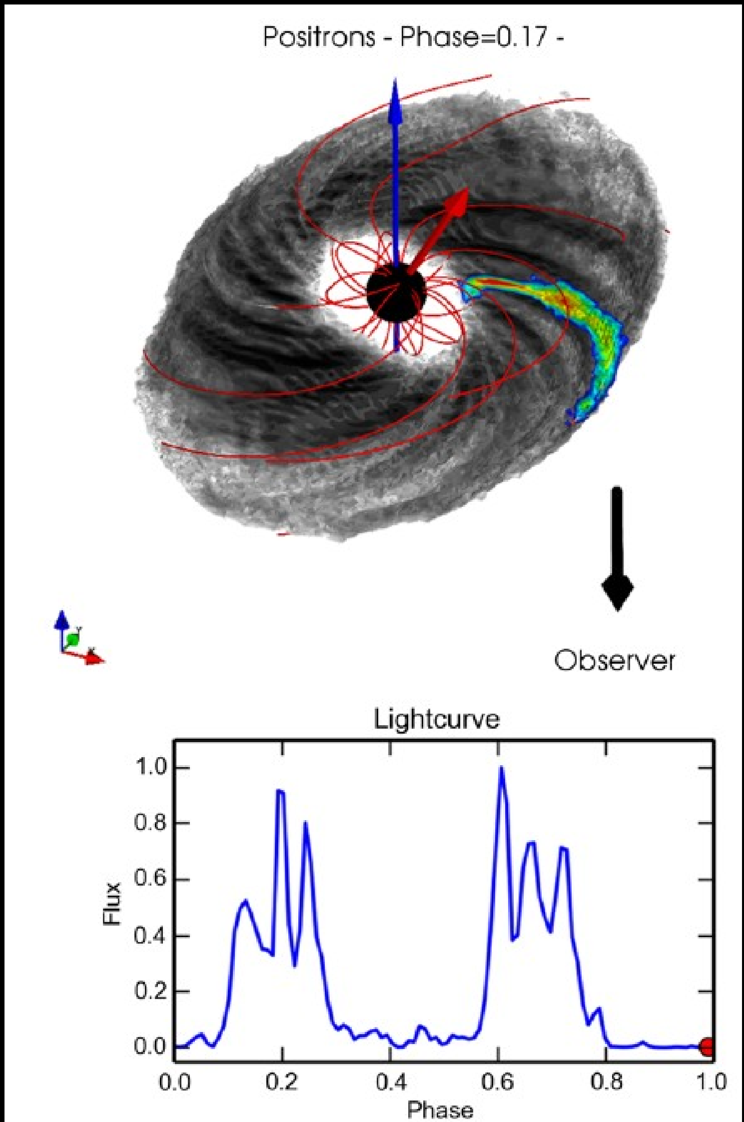




HE astro application: relativistic magnetospheres

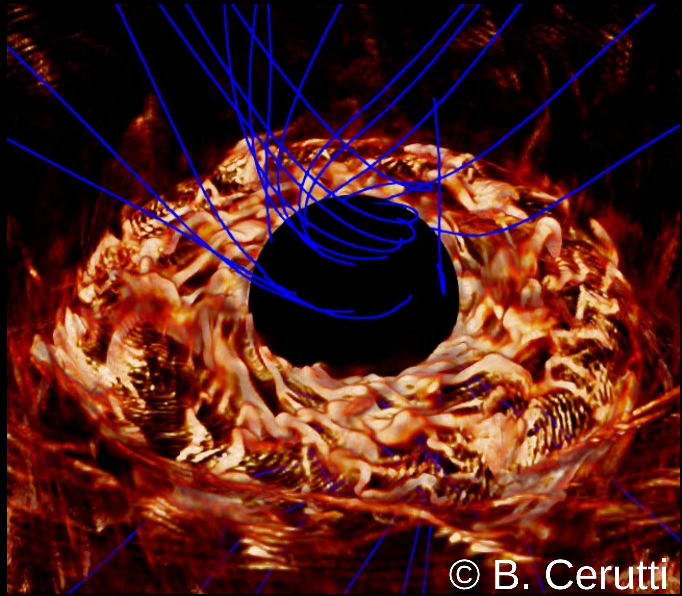
e.g., Cerutti et al. 2016, Guépin et al. 2020, Crinquand et al. 2020

Pulsar magnetospheres, pulse-profiles

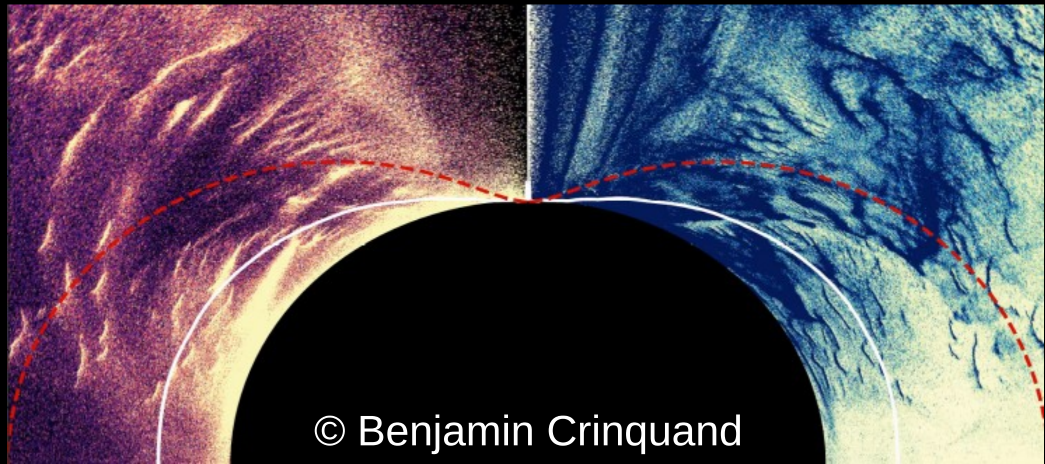


© B. Cerutti

Spinning black-hole magnetospheres



Spark-gap, pair cascades (GR+QED)



The multi-challenges

Multi-architecture

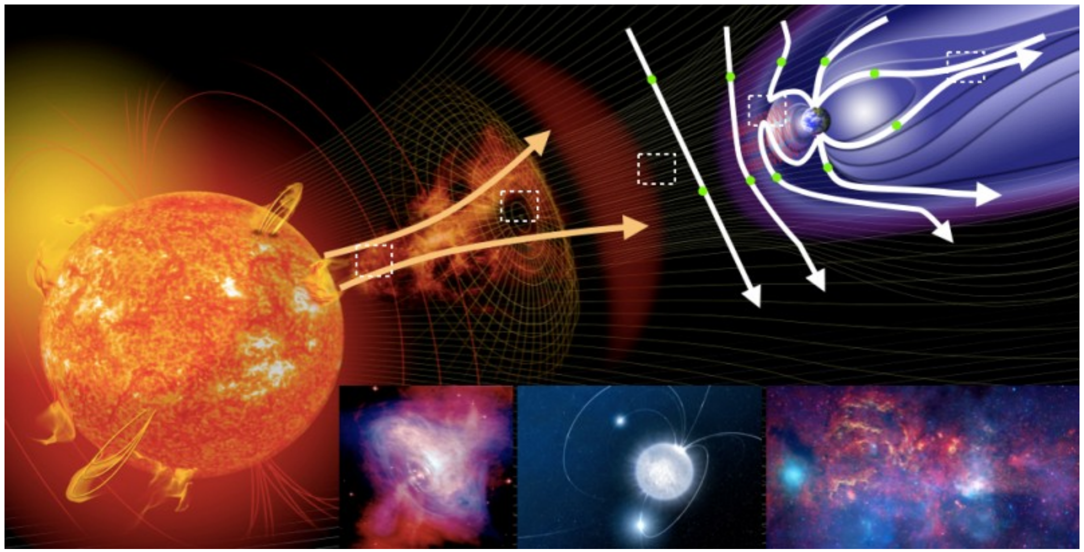
CPU, GPU, ARM
MPI, OpenMP,
Vectorization

Multi-physics

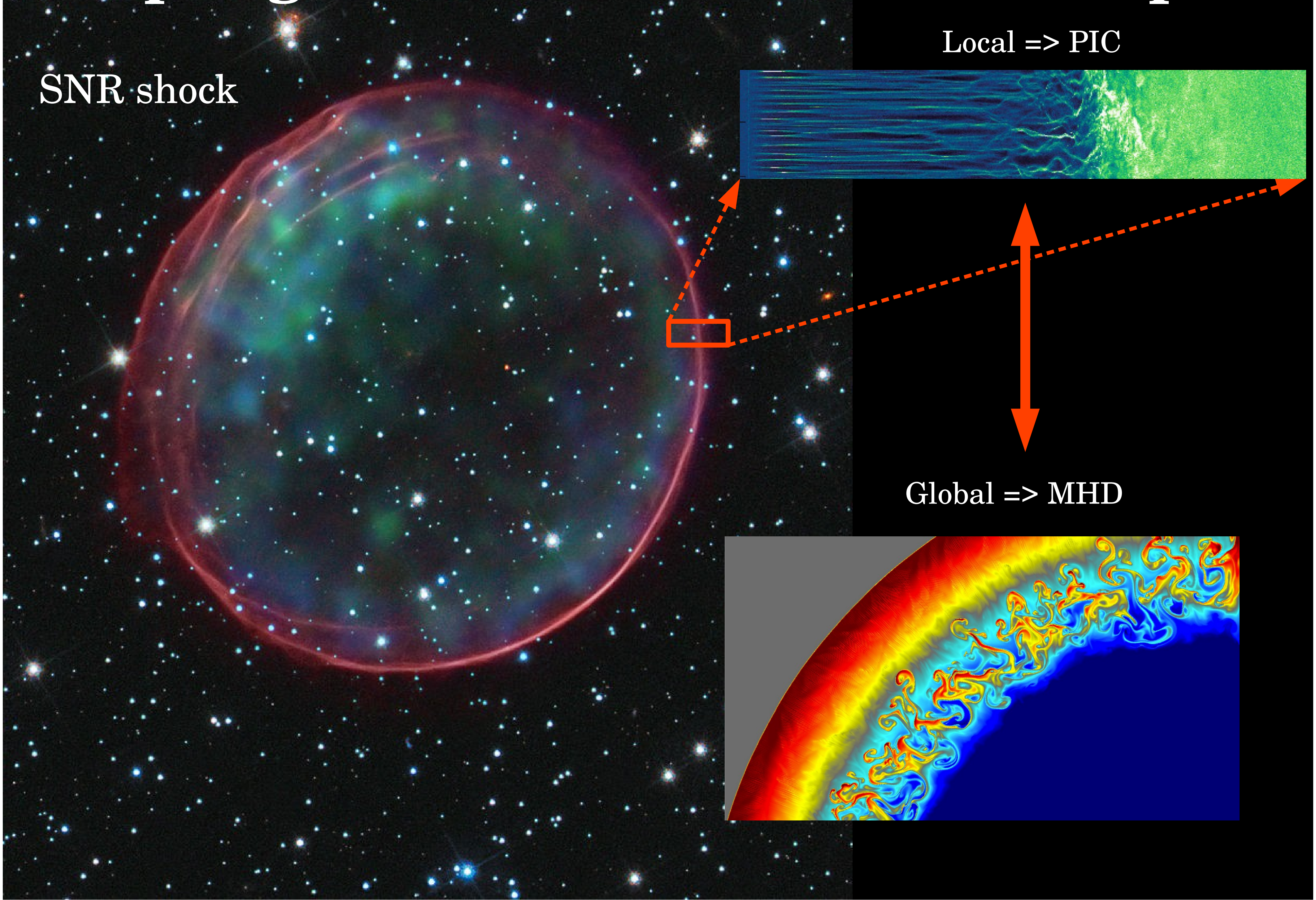
QED, GR, neutrinos

Multi-scales

Kinetic <-> global
Long integration
Hybrid codes

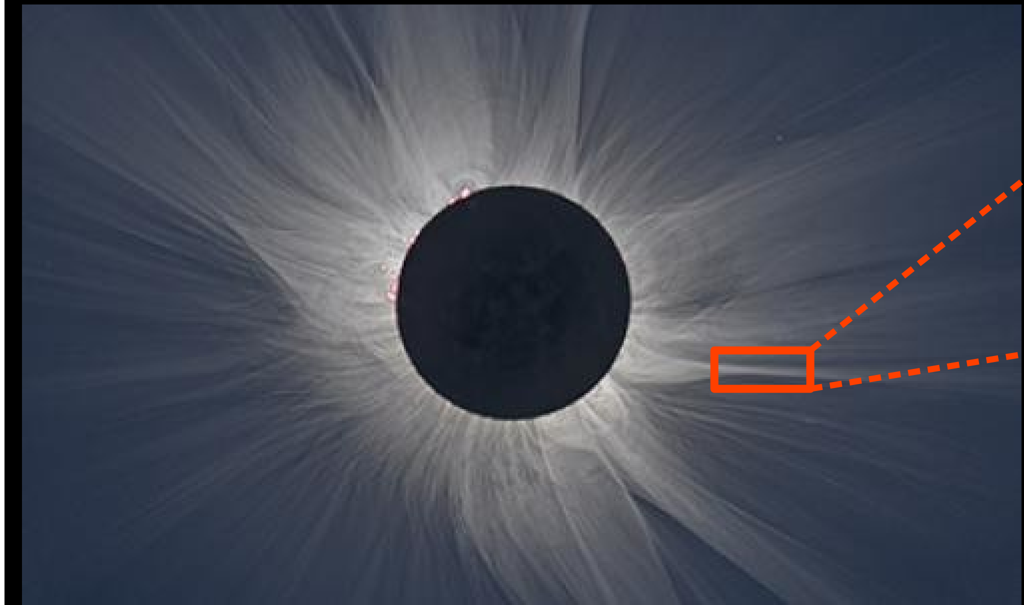


Coupling PIC with MHD: Astro exemple 1

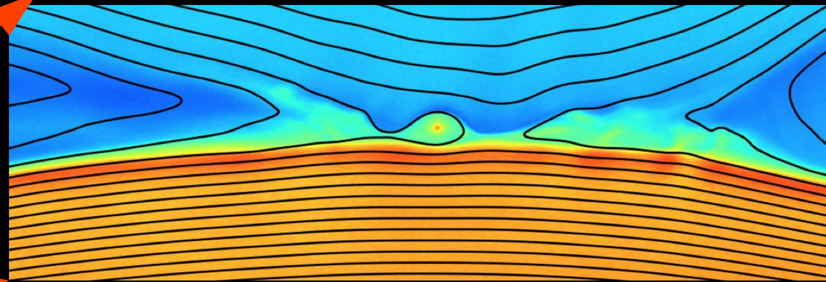


Coupling PIC with MHD: Astro exemple 2

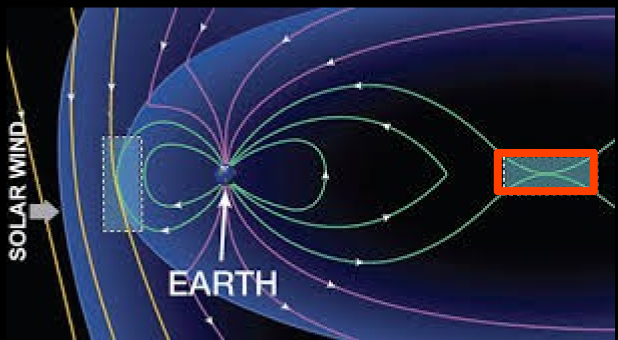
Reconnection

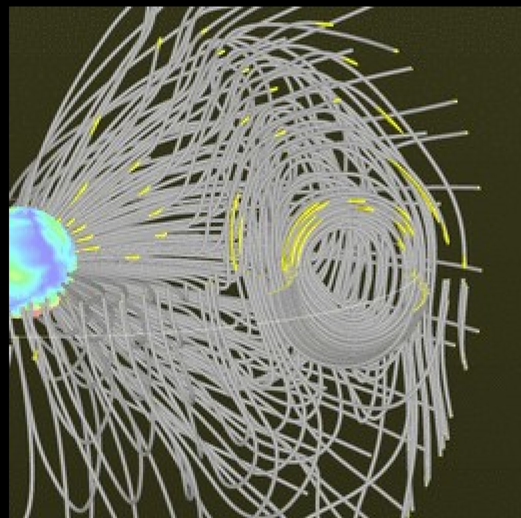


Local => PIC



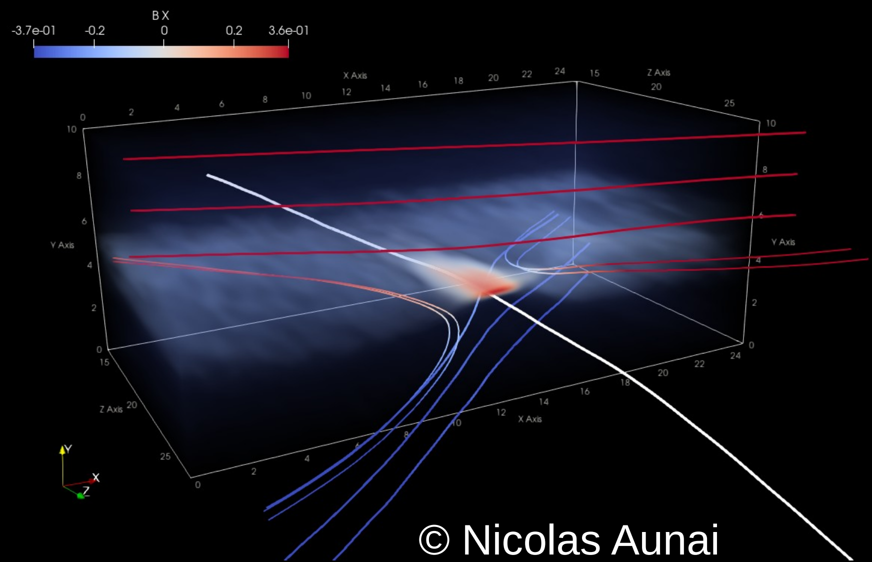
Global => MHD



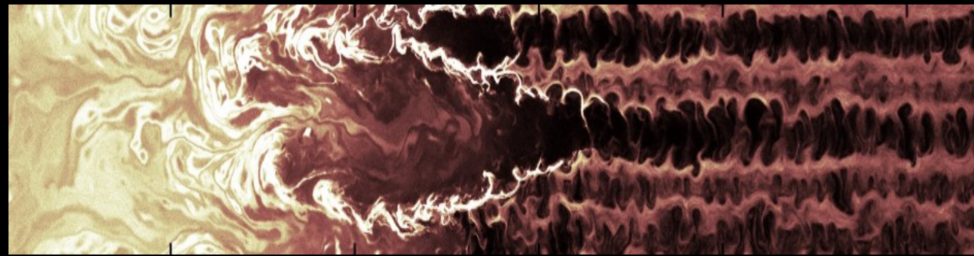


Beyond the “full” PIC approach: hybrid schemes

Hybrid: **Kinetic ions, fluid electrons (code: PHARE with AMR)**



© Nicolas Aunai



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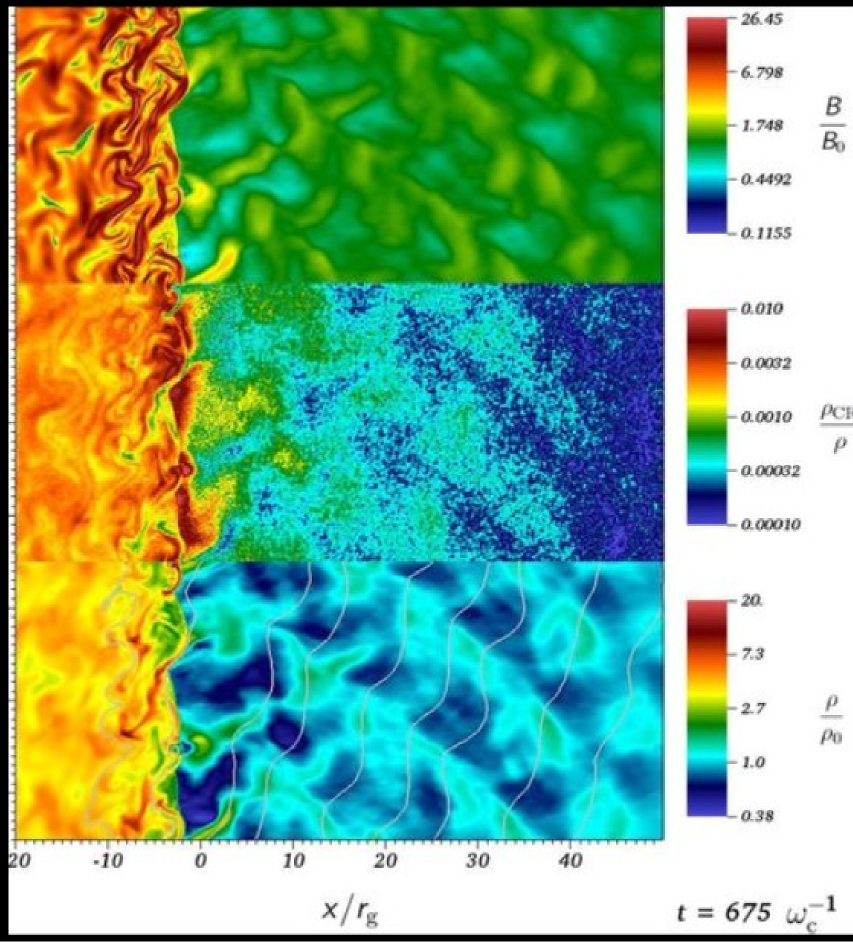
Hybrid: **MHD+cosmic rays**
(code: MPI-AMRVAC with AMR)



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Summary of challenges & needs

- The **raw dataset** (list of particles & fields) usually too large for long-term storage and for an easy open access. Reduced dataset easily shareable (but I've never received any request of this type).

- Address **multi-scale physics**: non-linear feedback between kinetic and the large astrophysical object scales. Numerical stability and convergence at long integration times.

- Develop **hybrid numerical approaches** (MHD, PIC, Vlasov, radiative transfer, Numerical Relativity) & **GPU acceleration**. Self-consistent and versatile coupling, AMR.