PIC simulations in the French community: current status & perspectives

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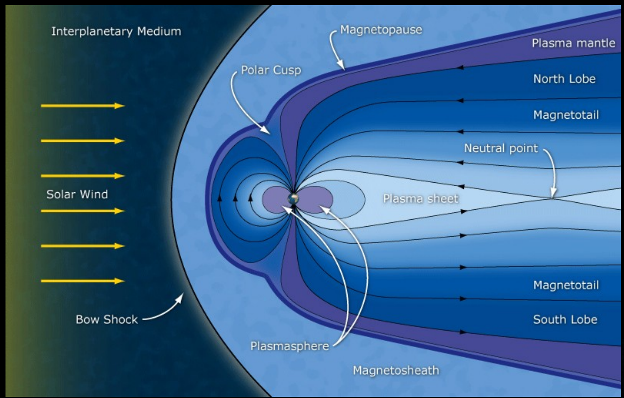
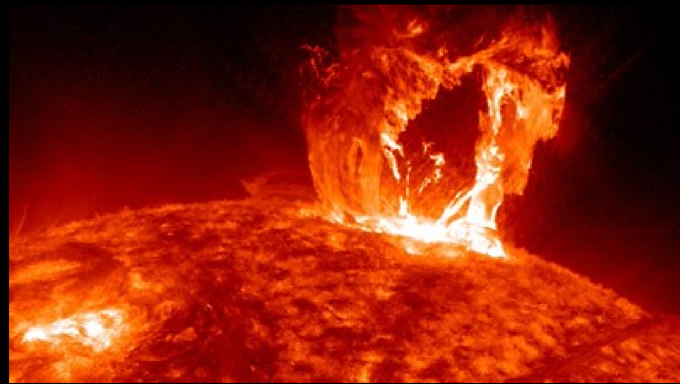
Astrophysical relevance & applications

Planetary magnetospheres

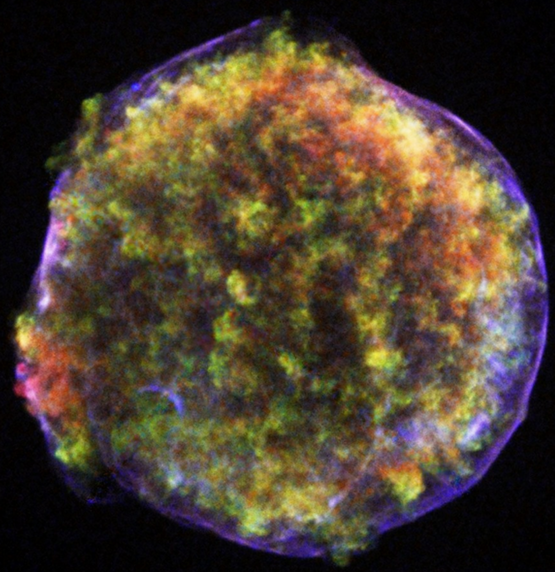


Relativistic magnetospheres

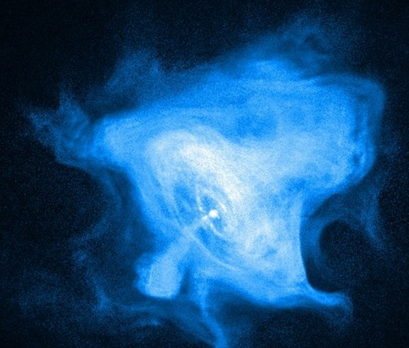
Solar corona & wind, heliosphere



Supernova Remnants

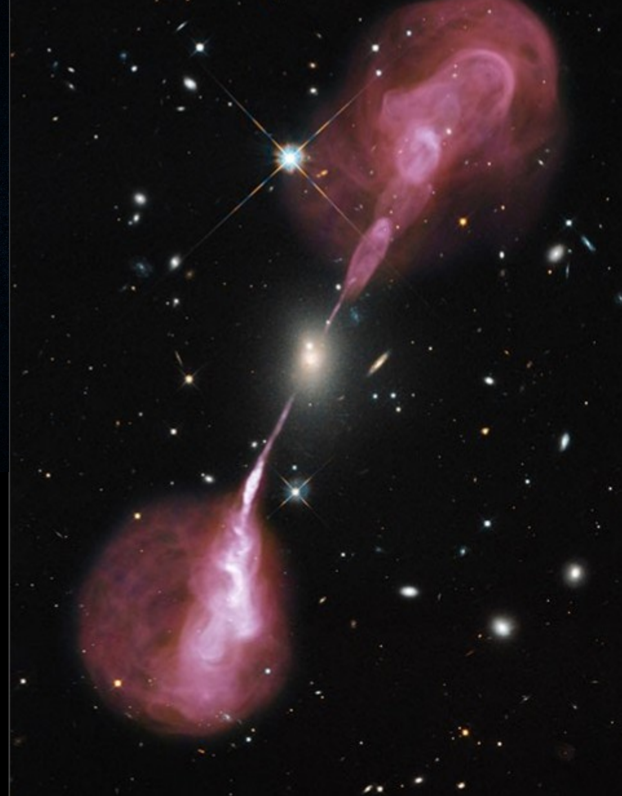


Pulsar Wind Nebulae



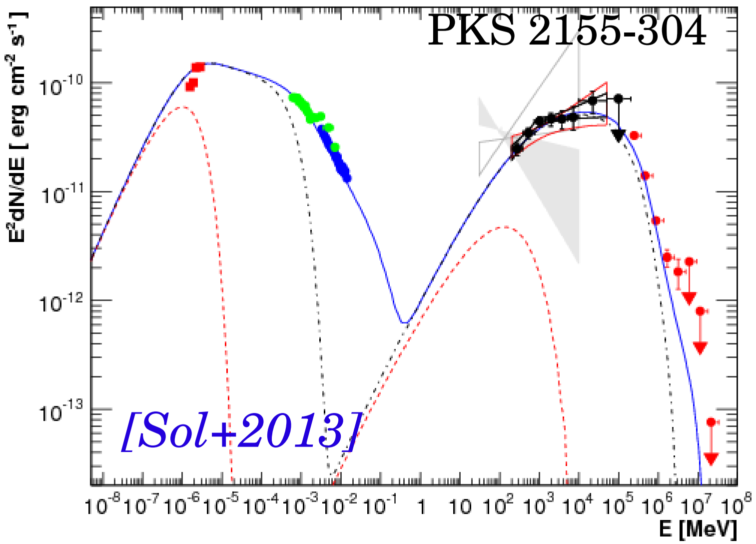
Gamma-ray bursts
Fast radio bursts

Jets

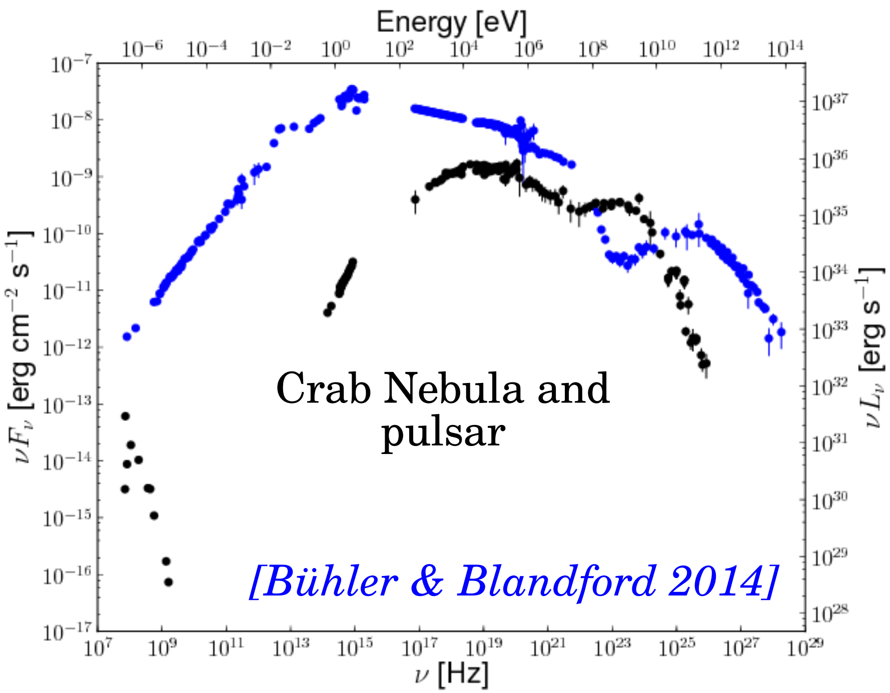


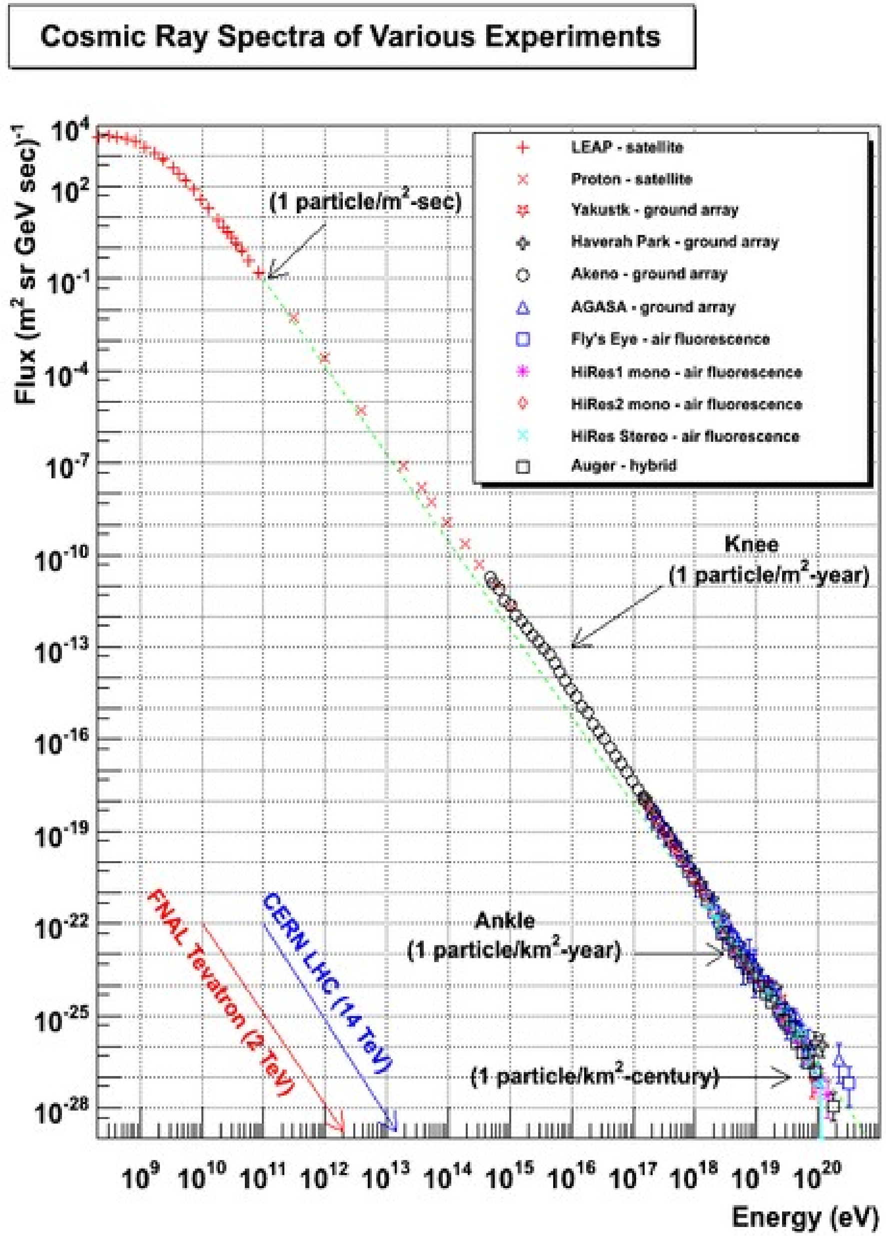
Broad non-thermal distributions

Blazars



Pulsars & Pulsar Wind Nebulae



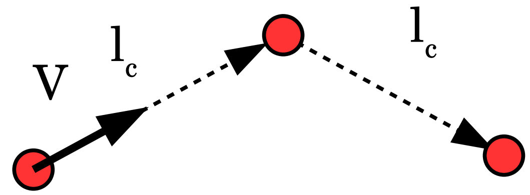


[http://www.physics.utah.edu/~whanlon/spectrum.html]

Collisionless plasmas

Collisions thermalizes efficiently the particle distribution, **not good for non-thermal** distributions. In most astrophysical environments, plasmas are **very dilute** so that they are effectively "**collisionless**".

Coulomb collisions **mean free path**: $l_C = \frac{1}{n\sigma_C}$



Frequency of collisions $\nu = \frac{V}{l_C}$

Collisionless plasma if the plasma frequency $\boxed{\omega_{pe} \gg \nu}$

It also implies that there is a large number of particles per **Debye sphere**:

$$N_D = n\lambda_D^3 \gg 1$$

Particles sensitive to **collective** **plasma phenomena** over binary collisions, particularly important on the **sub-Debye length** and **plasma frequency scales** (plasma frequency and gyroradius).

These microscopic scales are involved in particle acceleration process**.** **Need to resolve kinetic scales** (≠MHD approach), and system size $L \gg \lambda_D$

Two numerical approaches to solve Vlasov

$$\boxed{\frac{\partial f}{\partial t}+\frac{\boldsymbol{p}}{\gamma m}\cdot\frac{\partial f}{\partial \boldsymbol{r}}+q\left(\boldsymbol{E}+\frac{\boldsymbol{v}\times\boldsymbol{B}}{c}\right)\cdot\frac{\partial f}{\partial \boldsymbol{p}}=0}$$

Ab-initio model, no approximations

Directly with a Vlasov-code

Treat phase space as a continuum fluid

Advantages:

- **No noise**, good if tail of f is important dynamically (steep power-law).
- No issue if plasma very **inhomogeneous**.
- **Weak** phenomena can be captured

Limitations:

- Problem **(6+1)D**, hard to fit in the memory, limited resolution.
- Filamentation of the phase space
  But becoming more competitive, new development to come, stay tuned!

Indirectctly with a PIC code

Sample phase space with particles

Advantages:

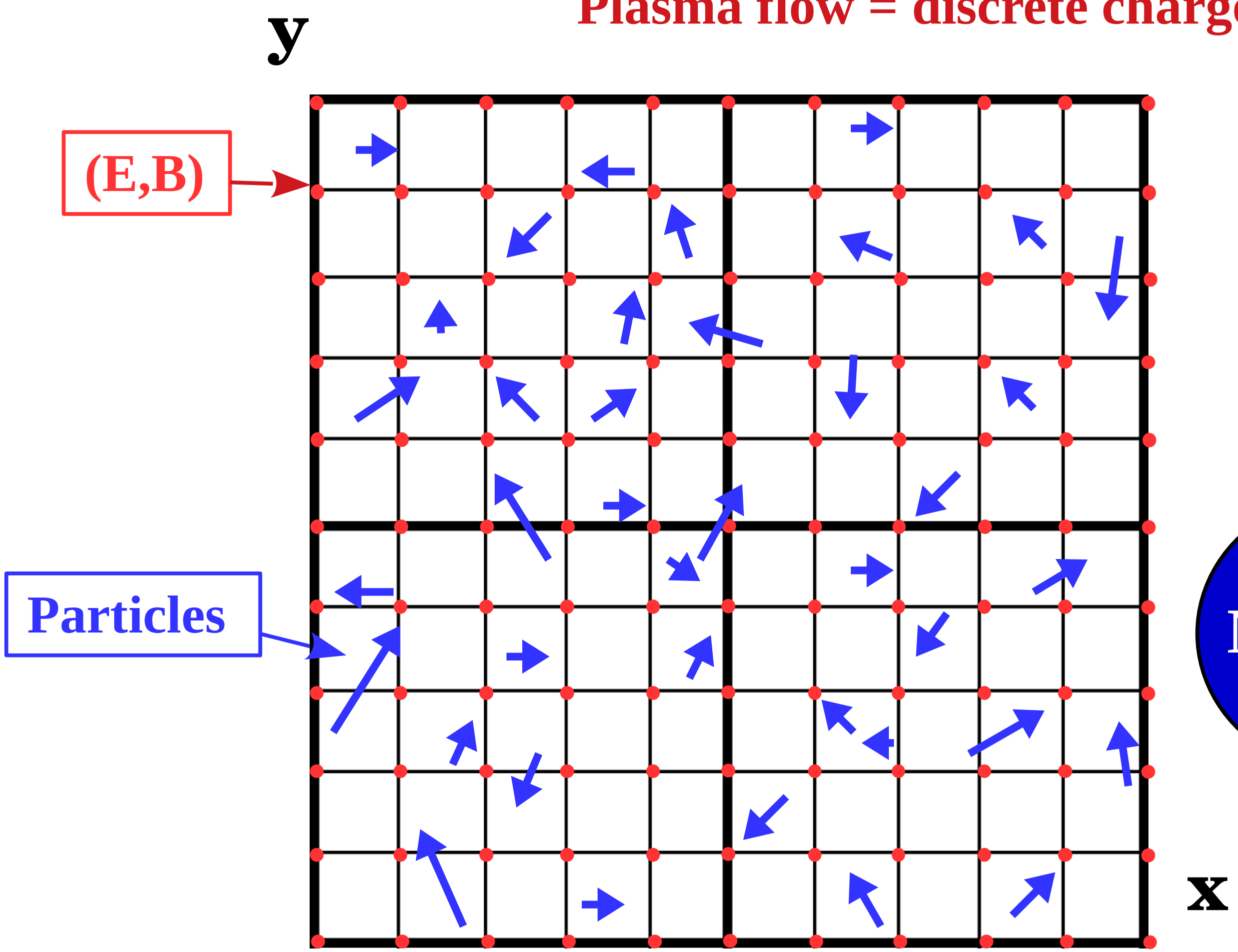
- Conceptually **simple**
- **Robust** and **easy to implement.**
- Easily **scalable** to large number of cores

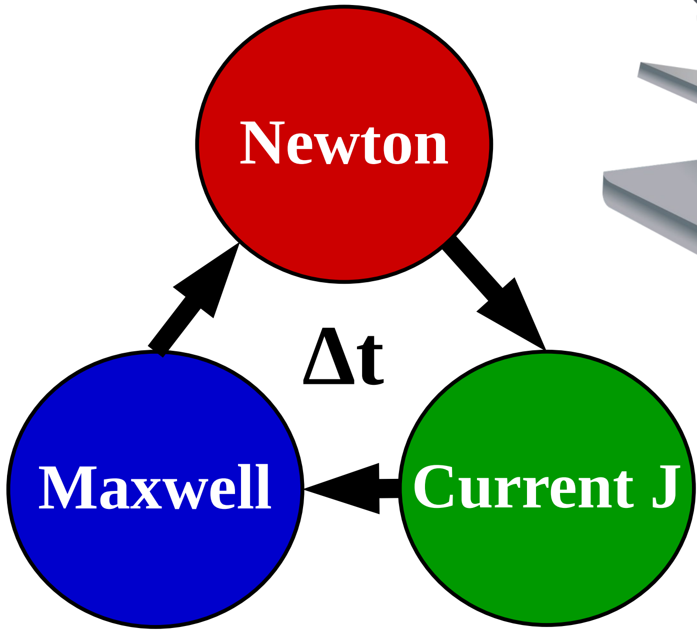
Limitations:

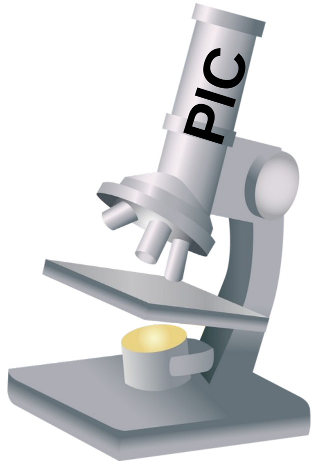
- **Shot noise**, difficult to sample uniformly f
- Artificial collisions, requires many particles
- Hard to capture weak/subtle phenomenas
- Load-balancing issues

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>!

The astrophysical PIC community in France

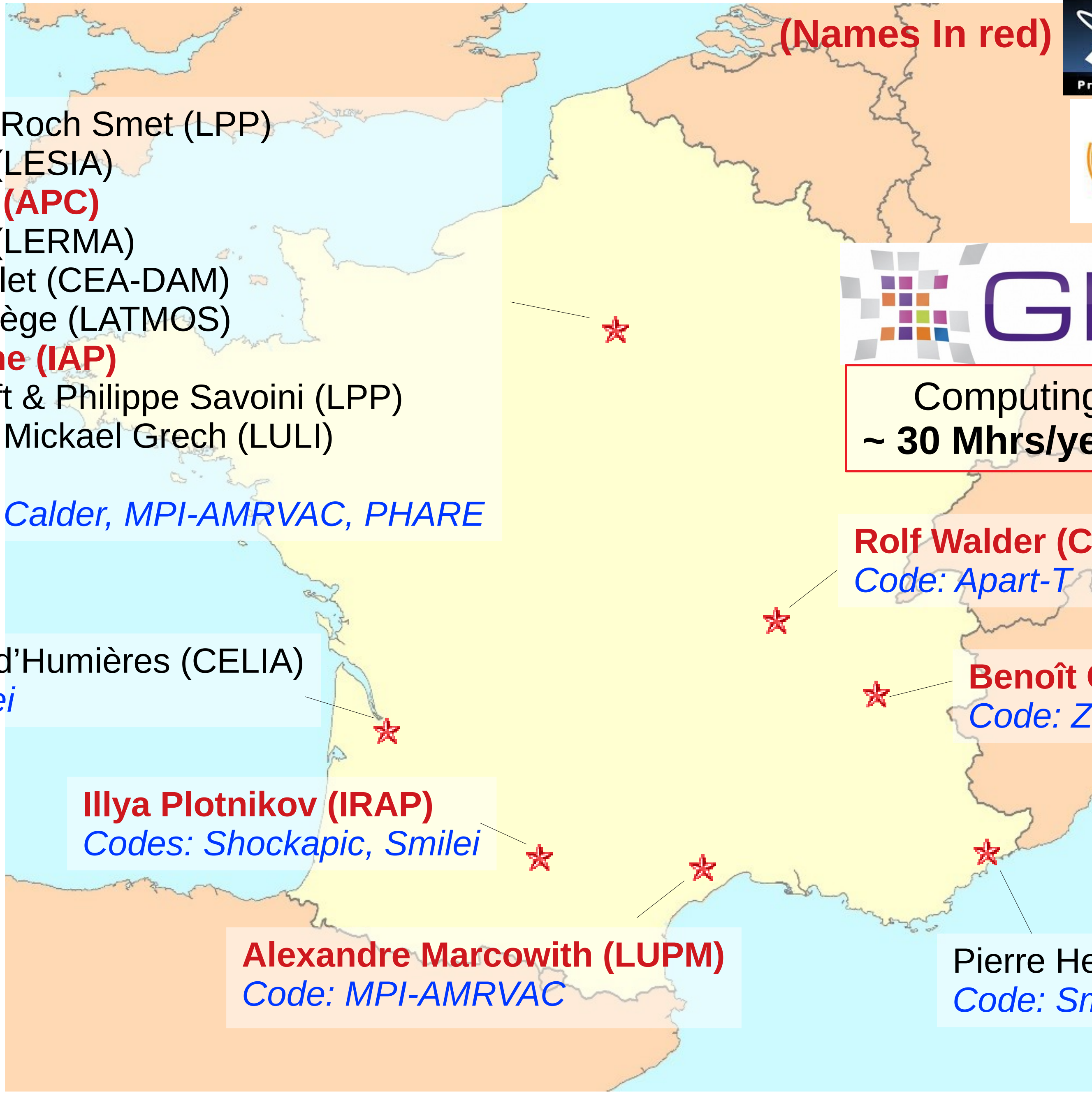
(Names In red)

PNHE Programme national hautes énergies

PNST Programme National Soleil-Terre

GENCI

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



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

Rolf Walder (CRAL)
Code: Apart-T

Emmanuel d'Humières (CELIA)
Code: Smilei

Benoît Cerutti (IPAG)
Code: Zeltron

Illya Plotnikov (IRAP)
Codes: Shockapic, Smilei

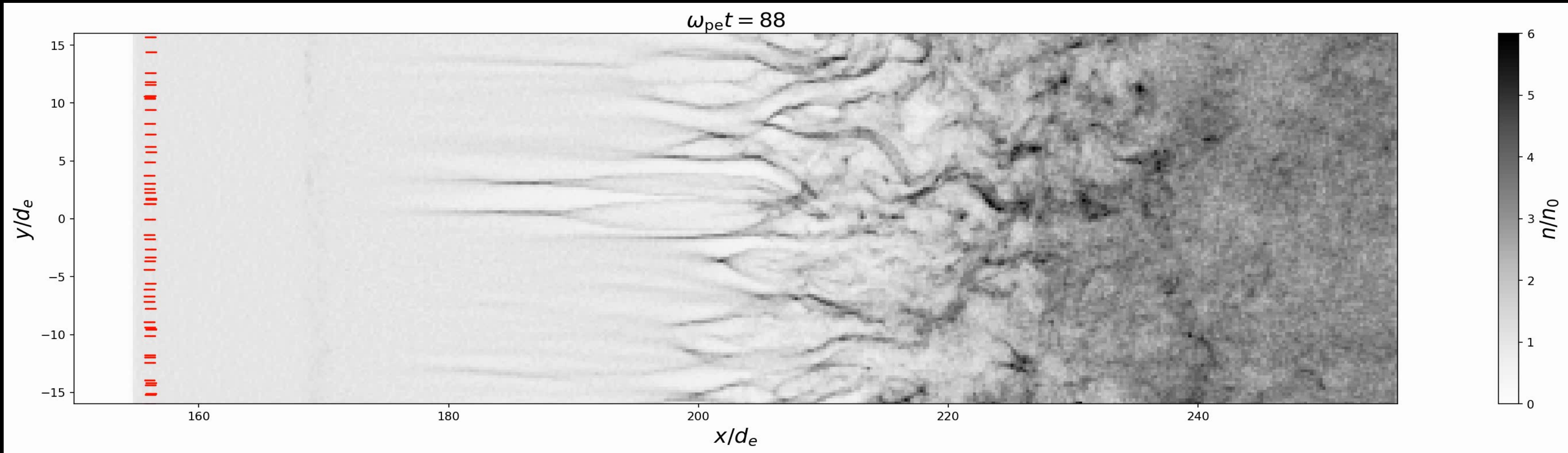
Alexandre Marcowith (LUPM)
Code: MPI-AMRVAC

Pierre Henri (OCA-LPC2E)
Code: Smilei

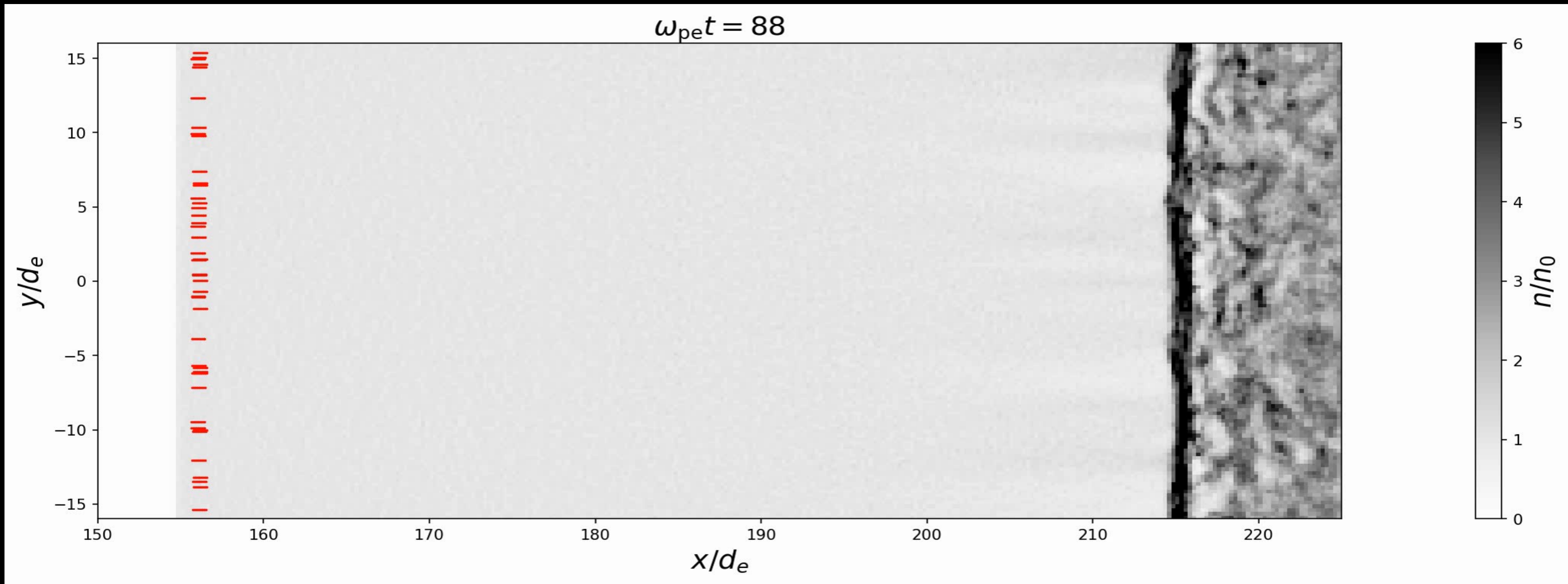
HE astro application: relativistic shocks

See Arno's and Virginia's talks

Unmagnetized



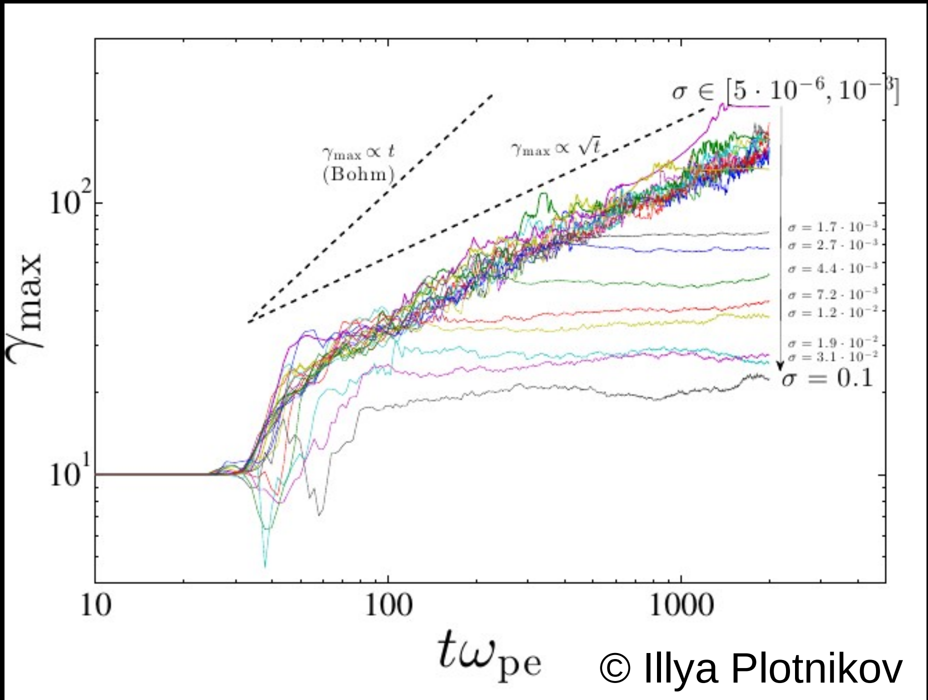
Magnetized



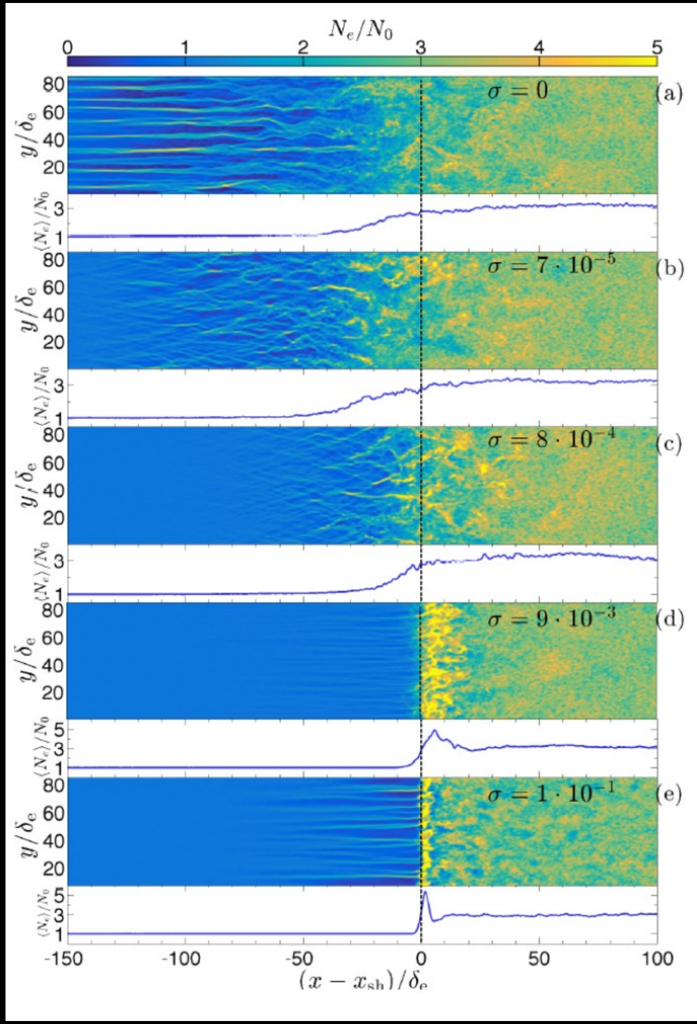
HE astro application: relativistic shocks

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

Particle acceleration

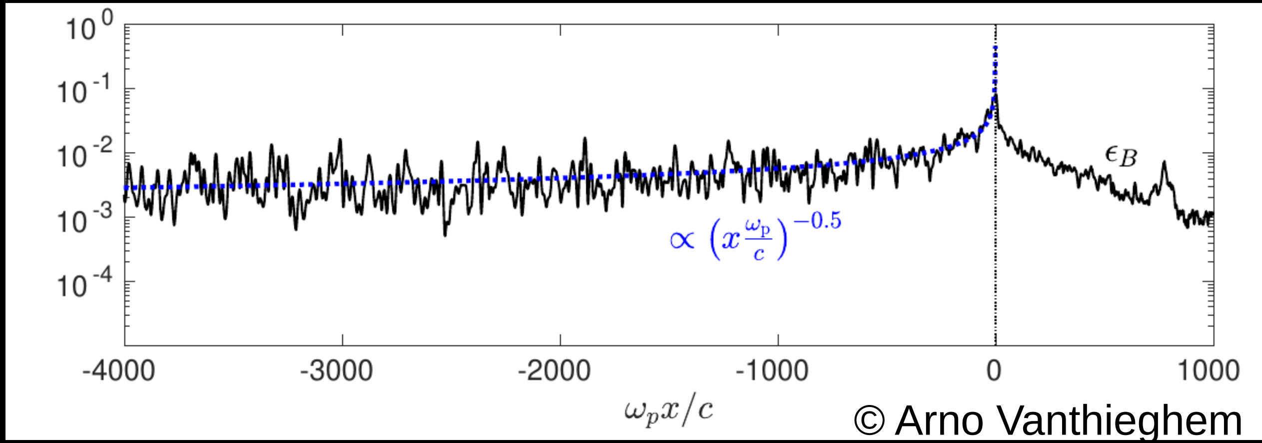


Shock structure

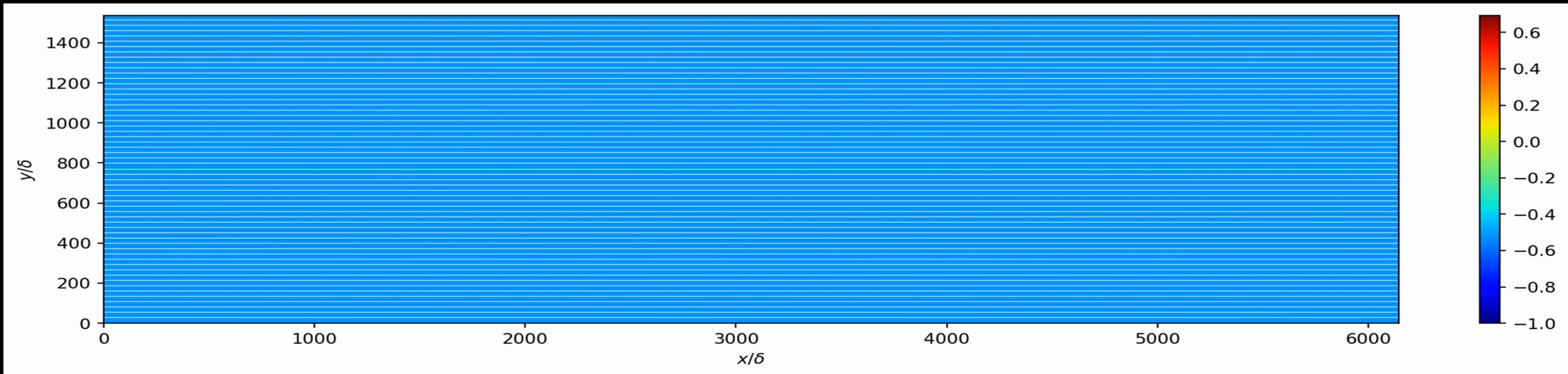


© Illya Plotnikov

Microturbulence



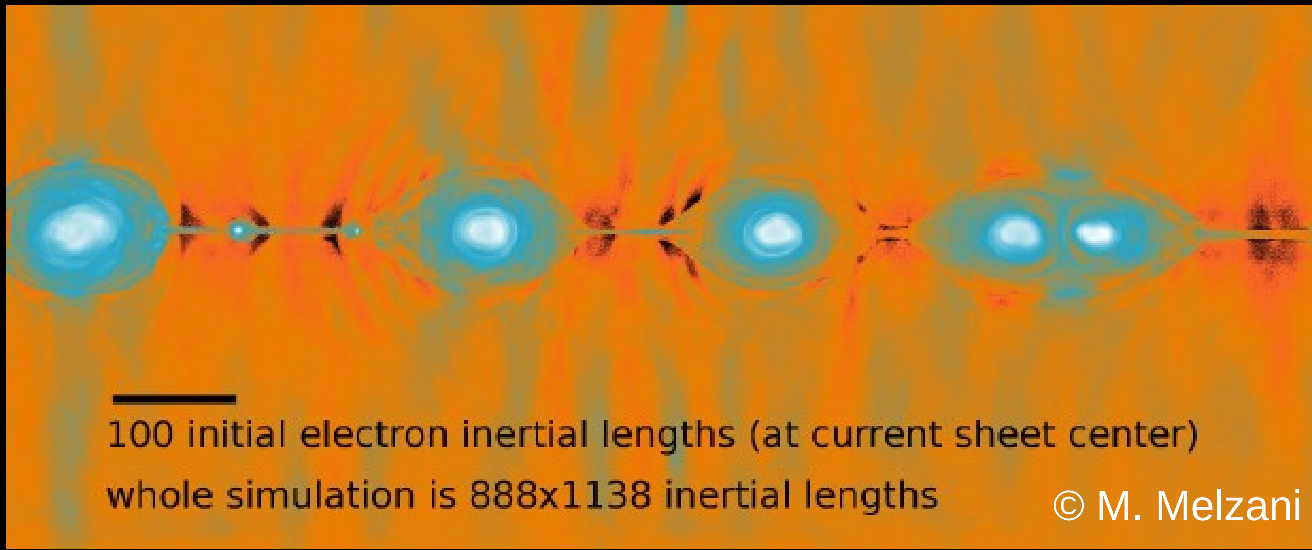
HE astro application: relativistic reconnection



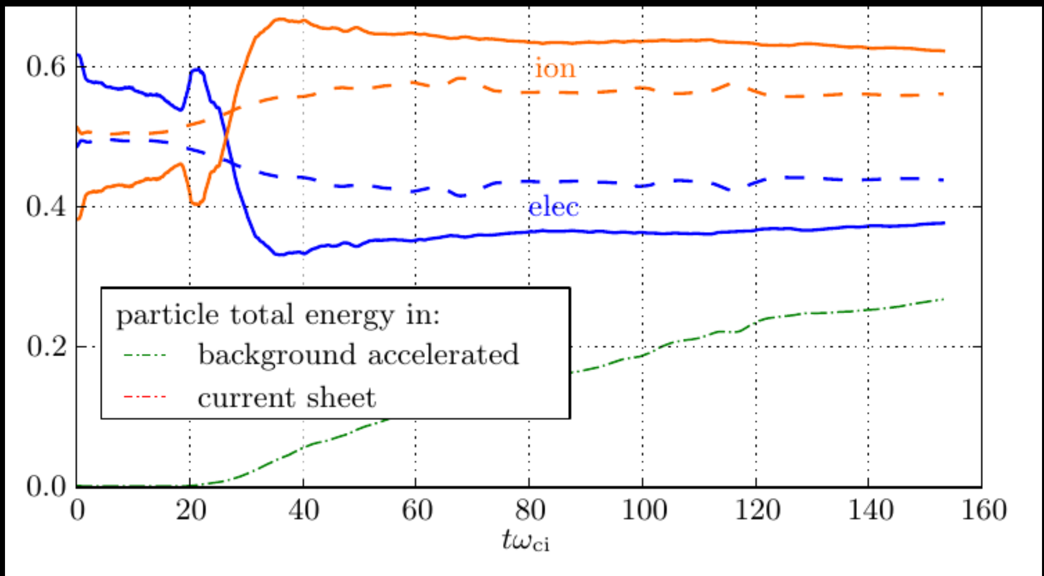
HE astro application: relativistic reconnection

e.g., Cerutti et al. 2013, Melzani et al. 2014

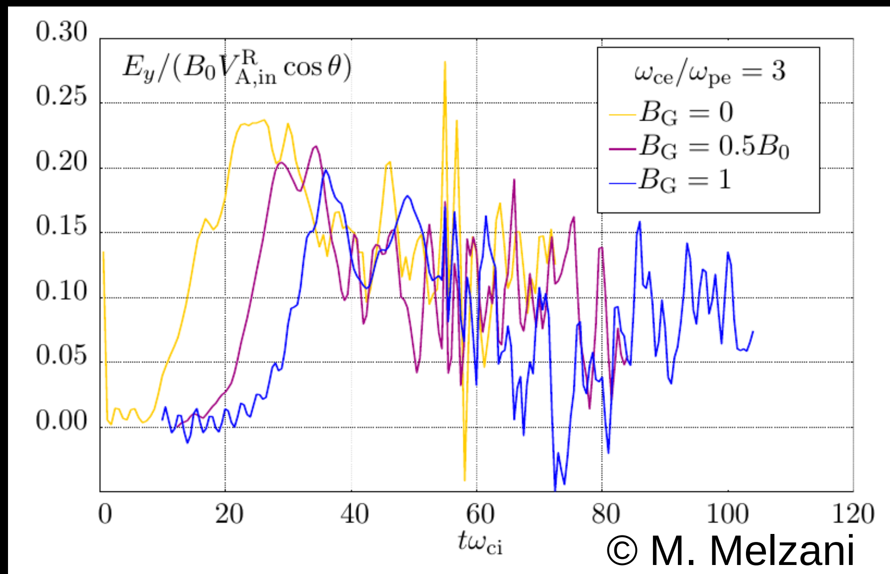
Plasmoid-dominated reconnection



Energy partition ions/electrons



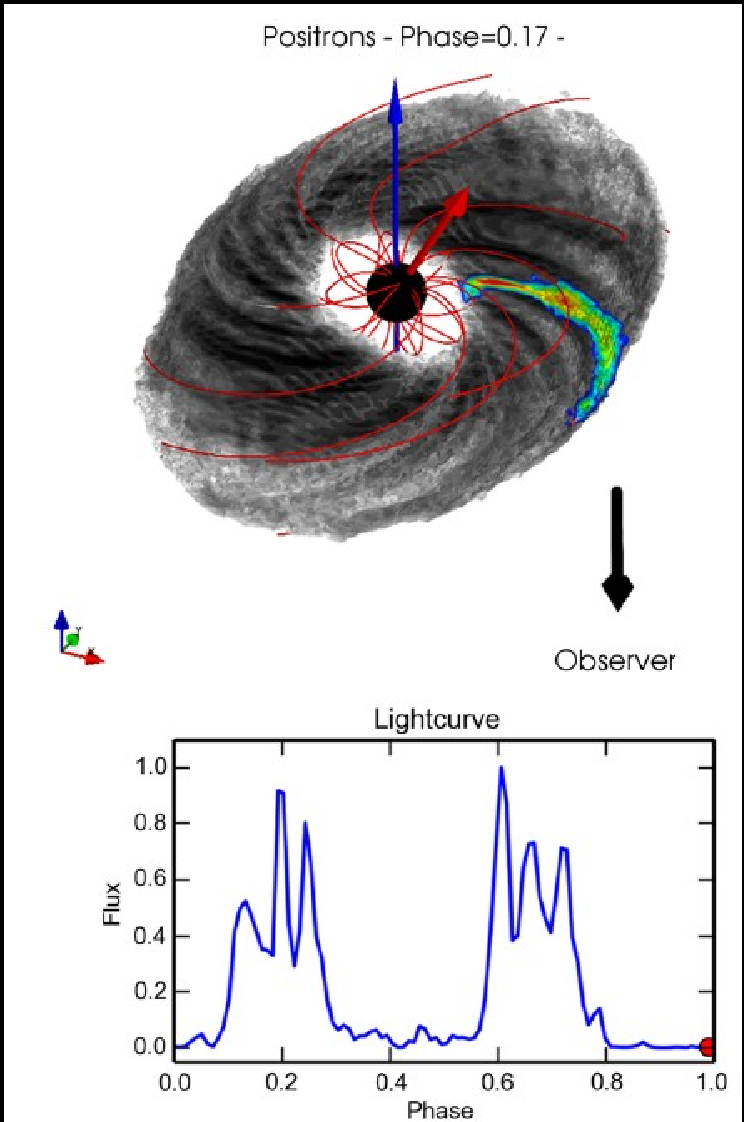
Reconnection rate



HE astro application: relativistic magnetospheres

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

Pulsar magnetospheres, pulse-profiles



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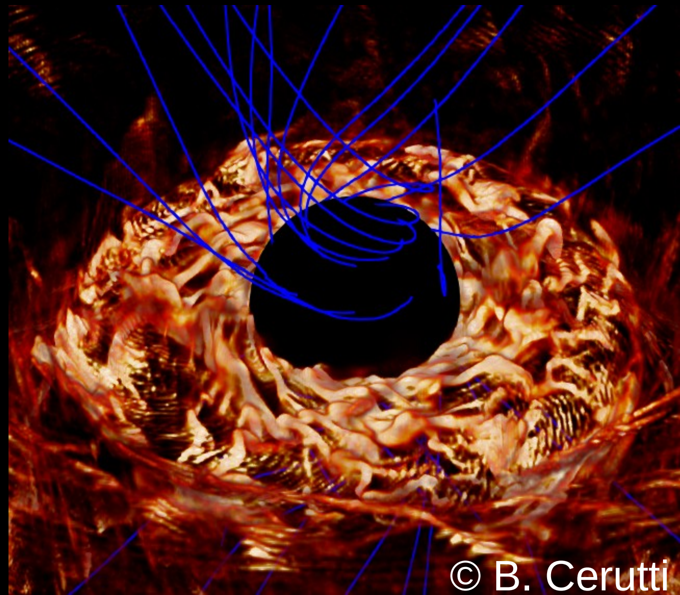
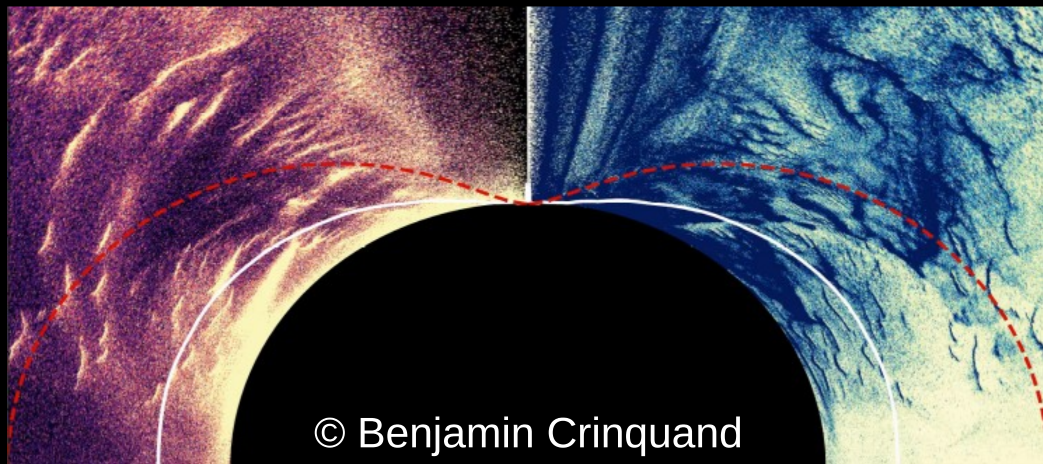
Spinning black-hole magnetospheres



Spark-gap, pair cascades (GR+QED)



The multi-challenges

Multi-architecture

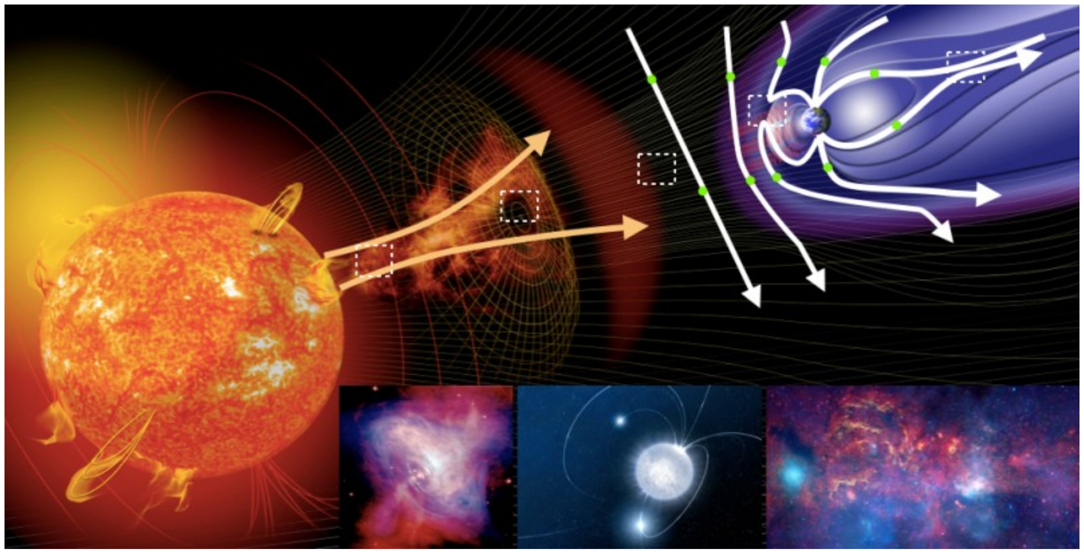
CPU, GPU, ARM
MPI, OpenMP,
Vectorization

Multi-physics

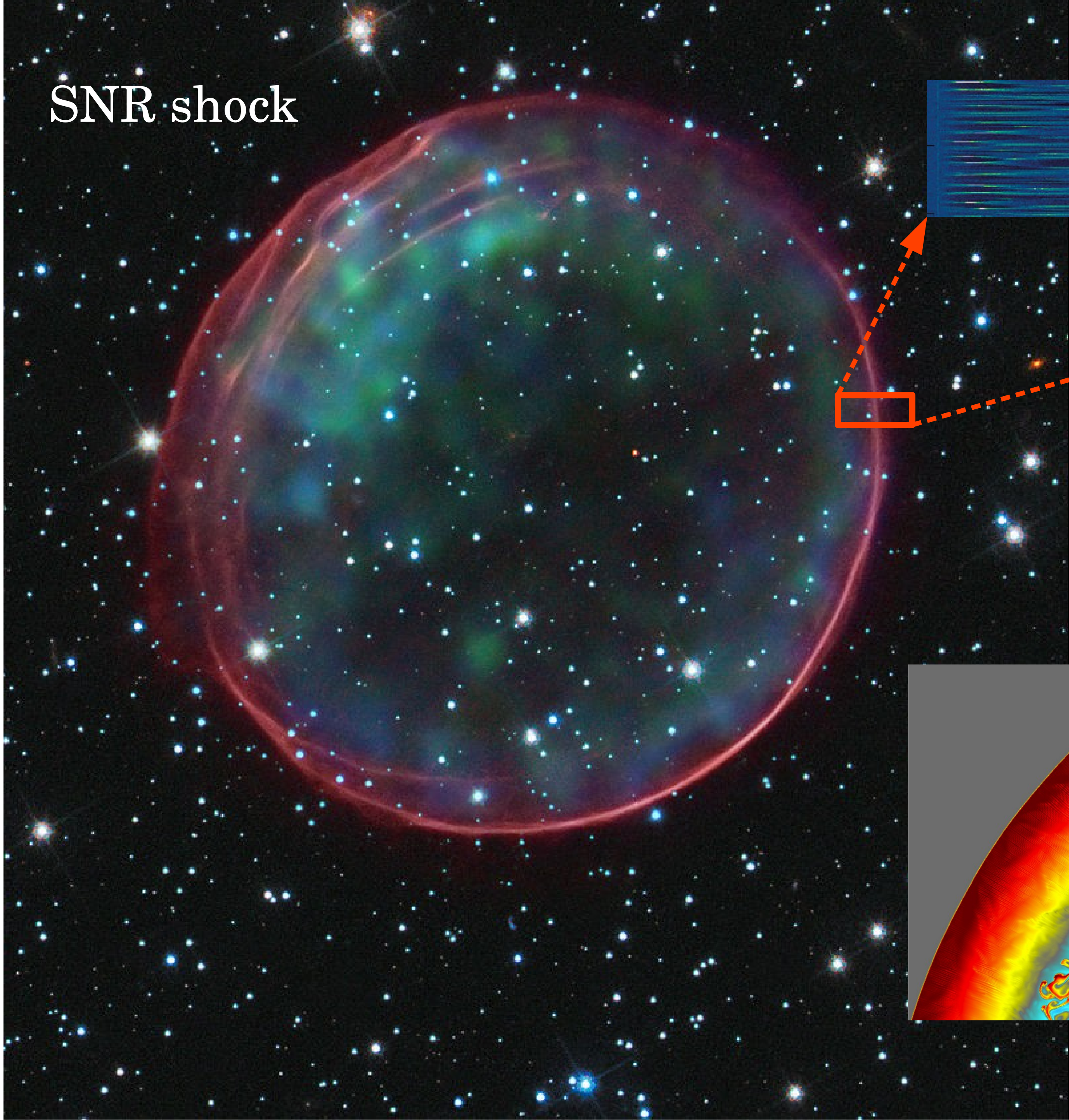
QED, GR, neutrinos

Multi-scales

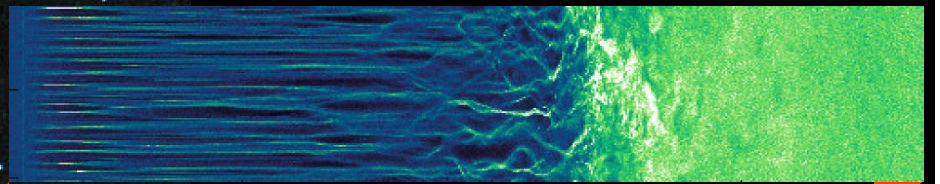
Kinetic <-> global
Long integration
Hybrid codes



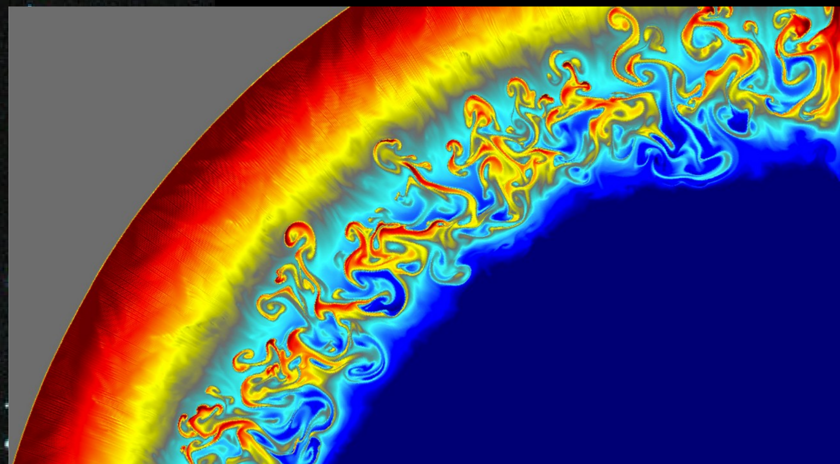
Coupling PIC with MHD: Astro exemple 1



Local => PIC

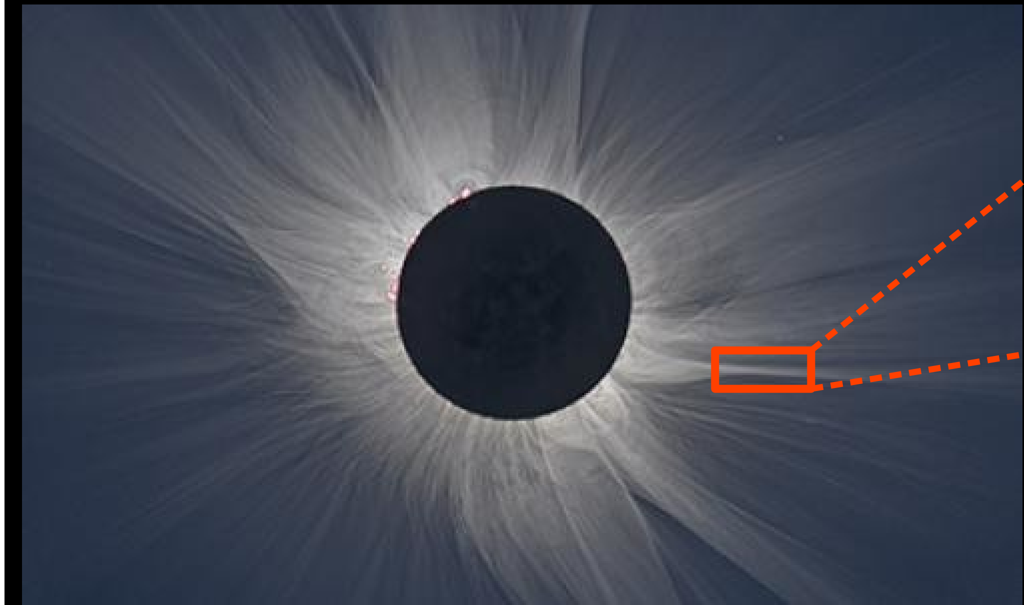


Global => MHD

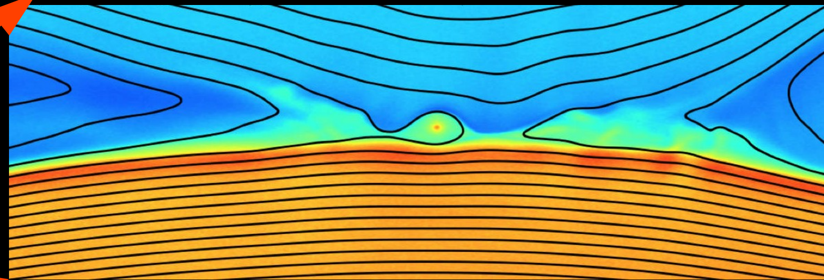


Coupling PIC with MHD: Astro exemple 2

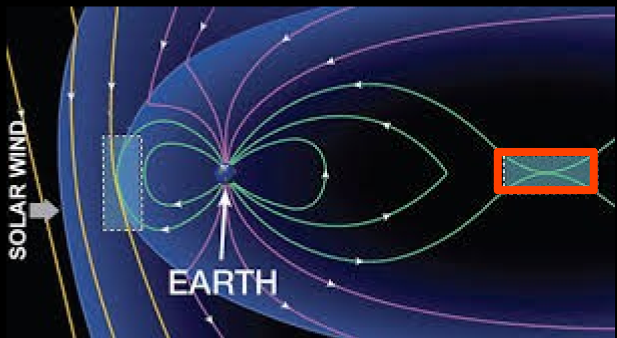
Reconnection

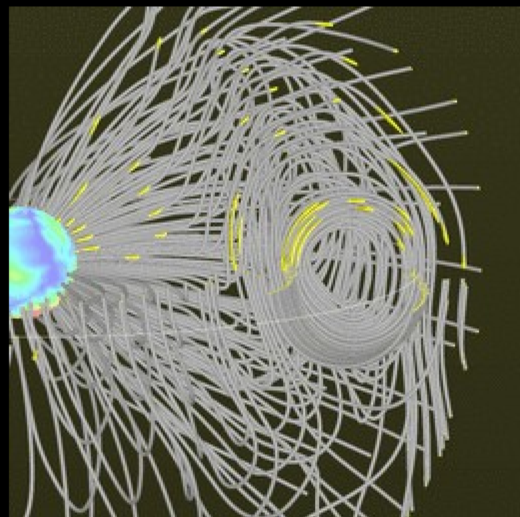


Local => PIC



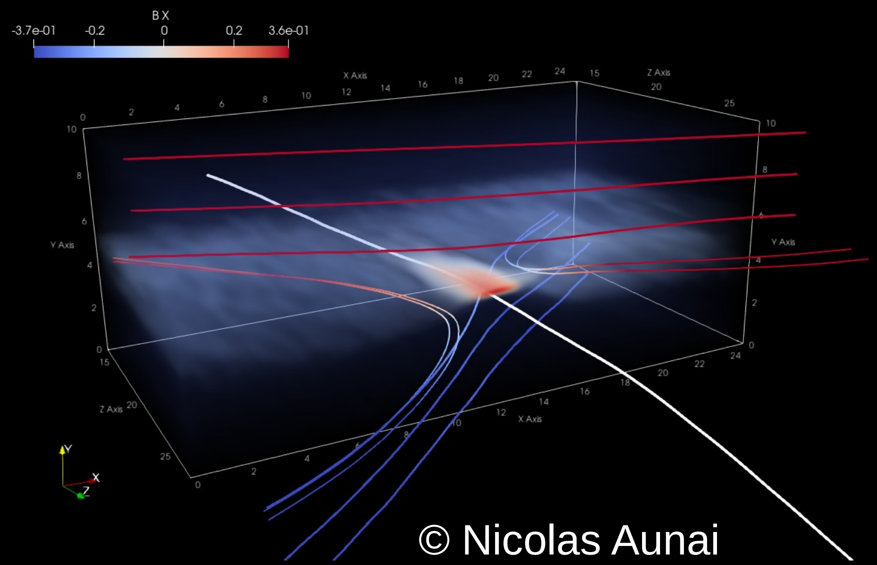
Global => MHD



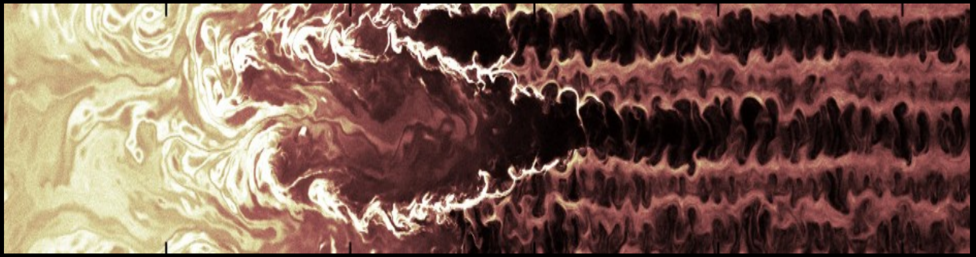


Beyond the “full” PIC approach: hybrid schemes

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



© Nicolas Aunai



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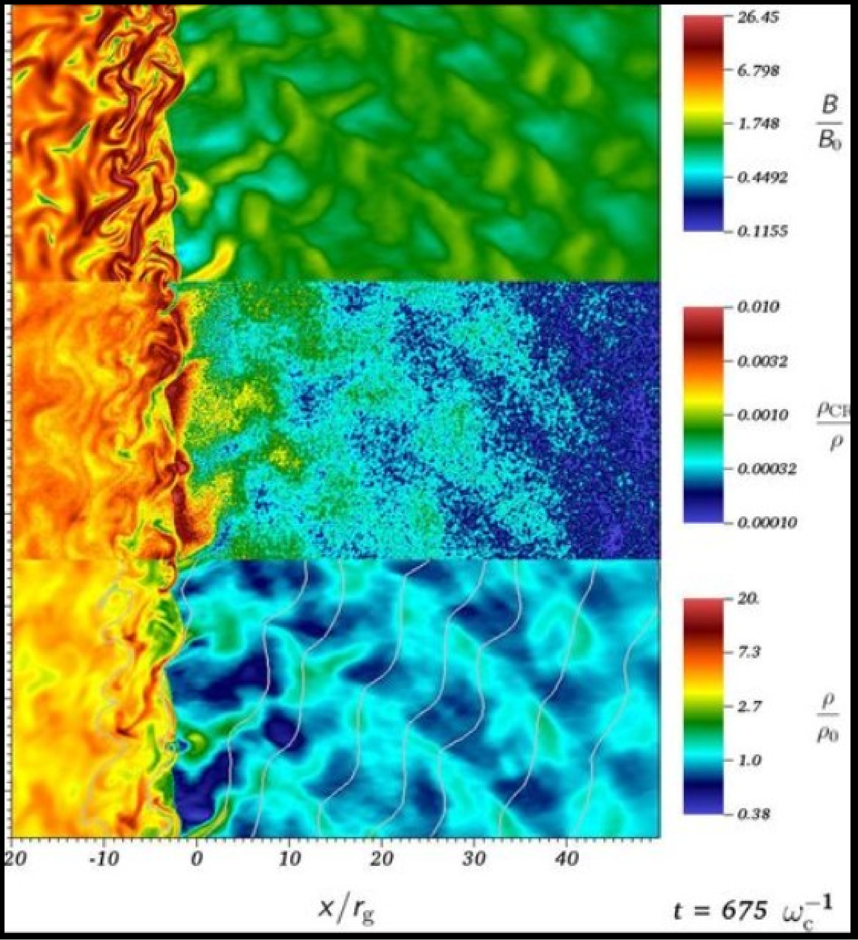
See Alexis Marret’s talk

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



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The need of the community for the coming decade

- Expertise in **Exascale computing**, HPC and GPU specialists. What is the good level: National, OSU, laboratory? Difficulty in being attractive and competitive (high-level expertise required but low salary).

- 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). Self-consistent and versatile coupling, AMR.

- **Physical processes/effects**: pair creation, radiative transfer, GR, neutrinos.

- Pursue the **training of students** in numerical techniques (e.g., Astrosim school).