Smilei)

PIC simulation ecosystem

Arnaud Beck, LLR

ASN 2025 | Grenoble | December 2025

The Particle-In-Cell simulation of extreme plasmas

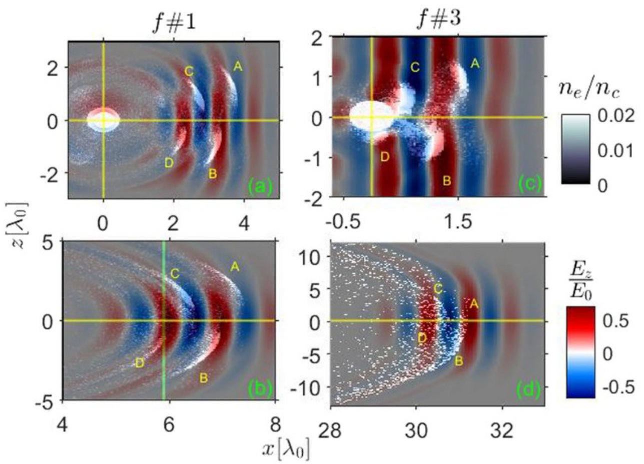
Far From Equilibrium
Kinetic scales

Near Equilibrium
Hydrodynamic scales

Physical scales

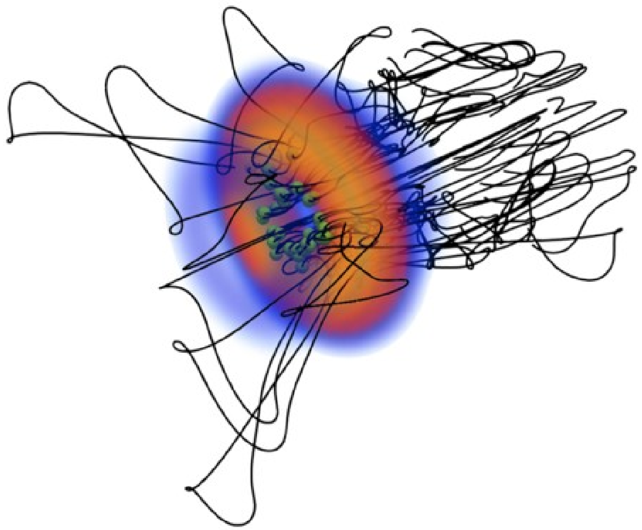
From Laboratory Plasmas...

Vaccum Laser Acceleration



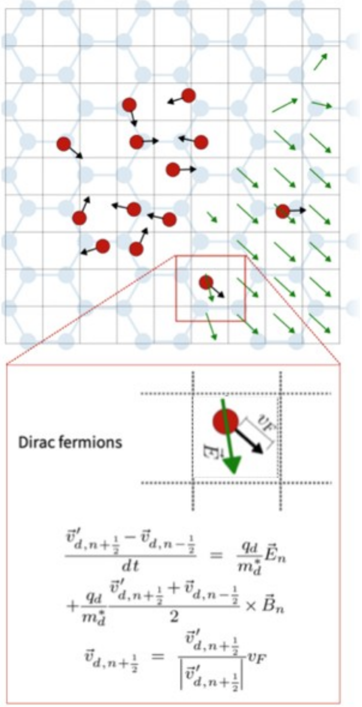
De Andres, Bhadoria et al.
Comm. Phys. **7**, 293 (2025)

Strong-Field QED Cascades



Jirka & Bulanov
Phys. Rev. Lett. **133**, 125001 (2025)

Strongly-Correlated Plasmas



Ngirmang, Do, et al.
arXiv:2501.07465 (2025)

The Particle-In-Cell simulation of extreme plasmas

... to Space & Astrophysical Plasmas

Solar Wind Radio Emissions

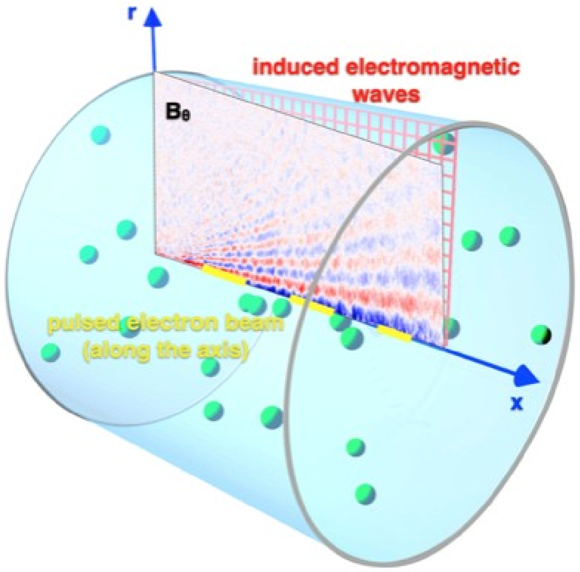
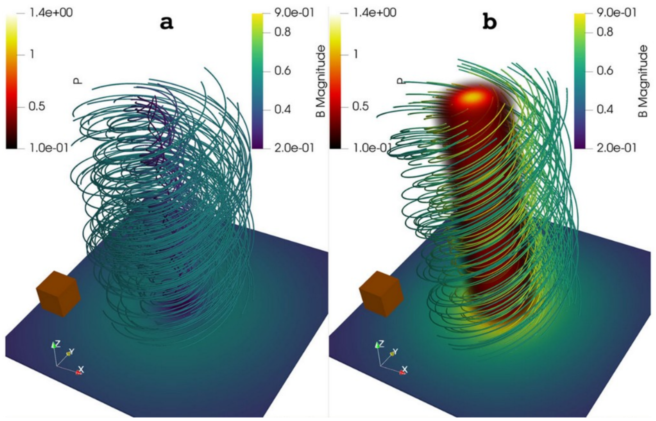


Illustration by J. Dargent

Magnetic Flux Ropes



Yoon et al.
Comm. Phys. **7**, 297 (2024)

What does an explicit electromagnetic PIC code do ?

Maxwell Eqs - Electromagnetic Fields

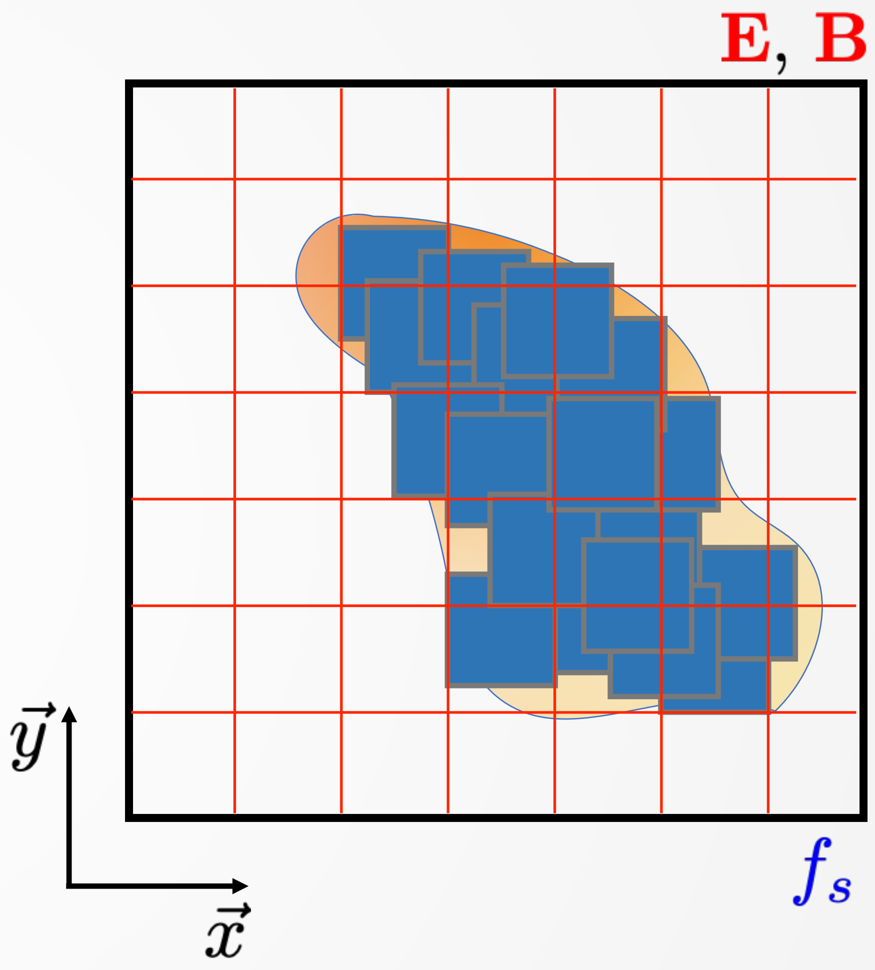
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \qquad \partial_t \mathbf{E} = -\frac{1}{\epsilon_0}\mathbf{J} + c^2 \nabla \times \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

$\rho, \mathbf{J}$ Δt $\mathbf{F}_L$

Vlasov Eq - Species of the plasma

$$\partial_t f_s + \frac{\mathbf{p}}{m_s \gamma} \cdot \nabla f_s + \mathbf{F}_L \cdot \nabla_p f_s = 0$$



SMILEI History and Guidelines

2013
Start of the project

2014
Gitlab repo
Co-dev starts

2016
1st physics studies &
large scale simulations
Public release : Github

2018
Reference paper
Derouillat et. Al

Objective: develop the first open-source PIC code harnessing the latest high-performance computing capabilities

Open-source & Community-Oriented

documentation • chat • online tutorials • post processing & visualization
training workshops • summer school & master trainings • issue reporting

Multi-Physics & Multi-Purpose

advanced physics modules and numerical methods
broad range of applications: from laser-plasma interaction to astrophysics

High-performance

C++/Python • MPI/OpenMP/OpenACC/CUDA/HIP • SIMD • HDF5
Benefit from the latest architectures

An extensive documentation, tutorials and a community

Smilei) Overview **Understand** Use More

Sections

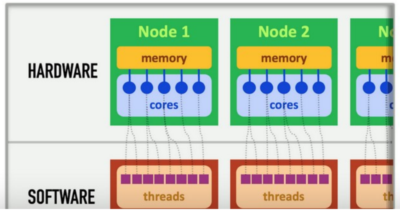
Parallelization basics

For high performances, **Smilei** uses parallel computing, and it is important to understand the basics of this technology. Parallel simply means that many processors can run the simulation at the same time, but there is much more than that.

Nodes, cores, processes and threads

Warning:
The terminology of *nodes, cores, processes and threads* is not universal. Depending on the computer, software (etc.), they can have various meanings. Typical examples: *socket* instead of *node*; *cpu* instead of *core*; *task* instead of *process*.

Supercomputers have complex architectures, mainly due to their processors capability to **work together on the same memory space**. More precisely, the smallest computing units, called *cores*, are grouped in *nodes*. All the cores in one node share the same memory space. In other terms, the cores of the same node can operate on the same data, at the same time; no need for sending the data back and forth. This hardware architecture is summarized in Fig. 2.



i) tutorials **PIC basics** Performances Advanced

Sections

Physical configuration

Download the two input files weibel_1d.py and two_stream_1d.py.

In both simulations, a plasma with density n_0 is initialized ($n_0 = 1$). This makes code units equal to plasma units, i.e. times are normalized to the inverse of the electron plasma frequency $\omega_{p0} = \sqrt{e^2 n_0/(\epsilon_0 m_e)}$, distances to the electron skin-depth c/ω_{p0}, etc...

Ions are frozen during the whole simulation and just provide a neutralizing background. Two electron species are initialized with density $n_0/2$ and a mean velocity $\pm\mathbf{v_0}$.

Check input file and run the simulation

The first step is to check that your *input files* are correct. To do so, you will run (locally) **Smilei** in test mode:

```
./smilei_test weibel_1d.py
./smilei_test two_stream_1d.py
```

If your simulation *input files* are correct, you can run the simulations.

Before going to the analysis, check your *logs*.

Weibel instability: analysis

In an **ipython** terminal, open the simulation:

```
S = happi.Open('/path/to/your/simulation/weibel_1d')
```

The `streak` function of **happi** can plot any 1D diagnostic as a function of time. Let's look at the time evolution of the total the current density J_z and the magnetic field B_y:

and a brilliant collaborative community !

Github
sources, issues

Element
chat

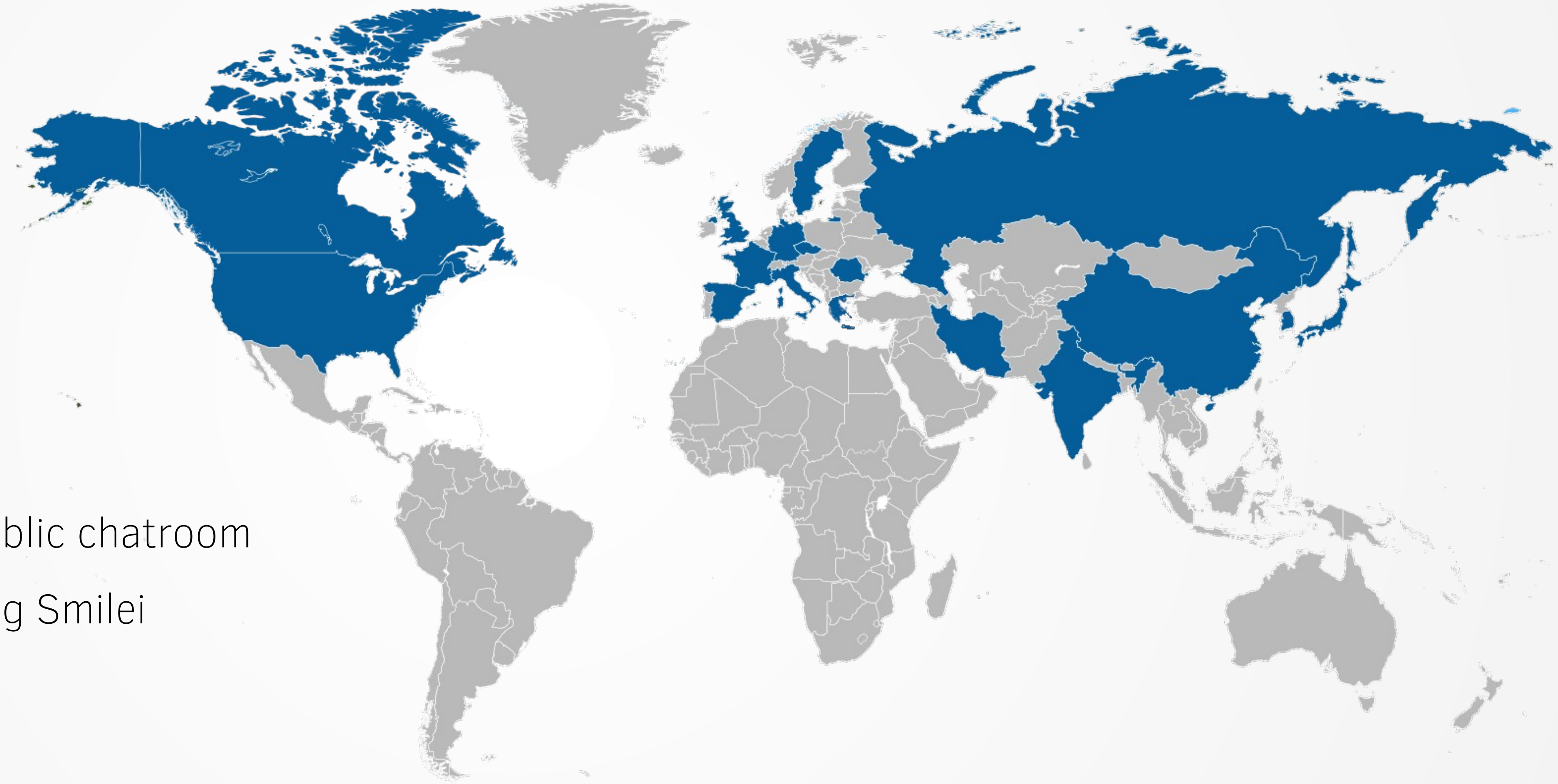
The Smilei Workshops

~ Every 18 months

~ 35 participants « Hands-on »

« Smilers »: a growing international community

1st authors' affiliations



~ 100 messages/week in the public chatroom

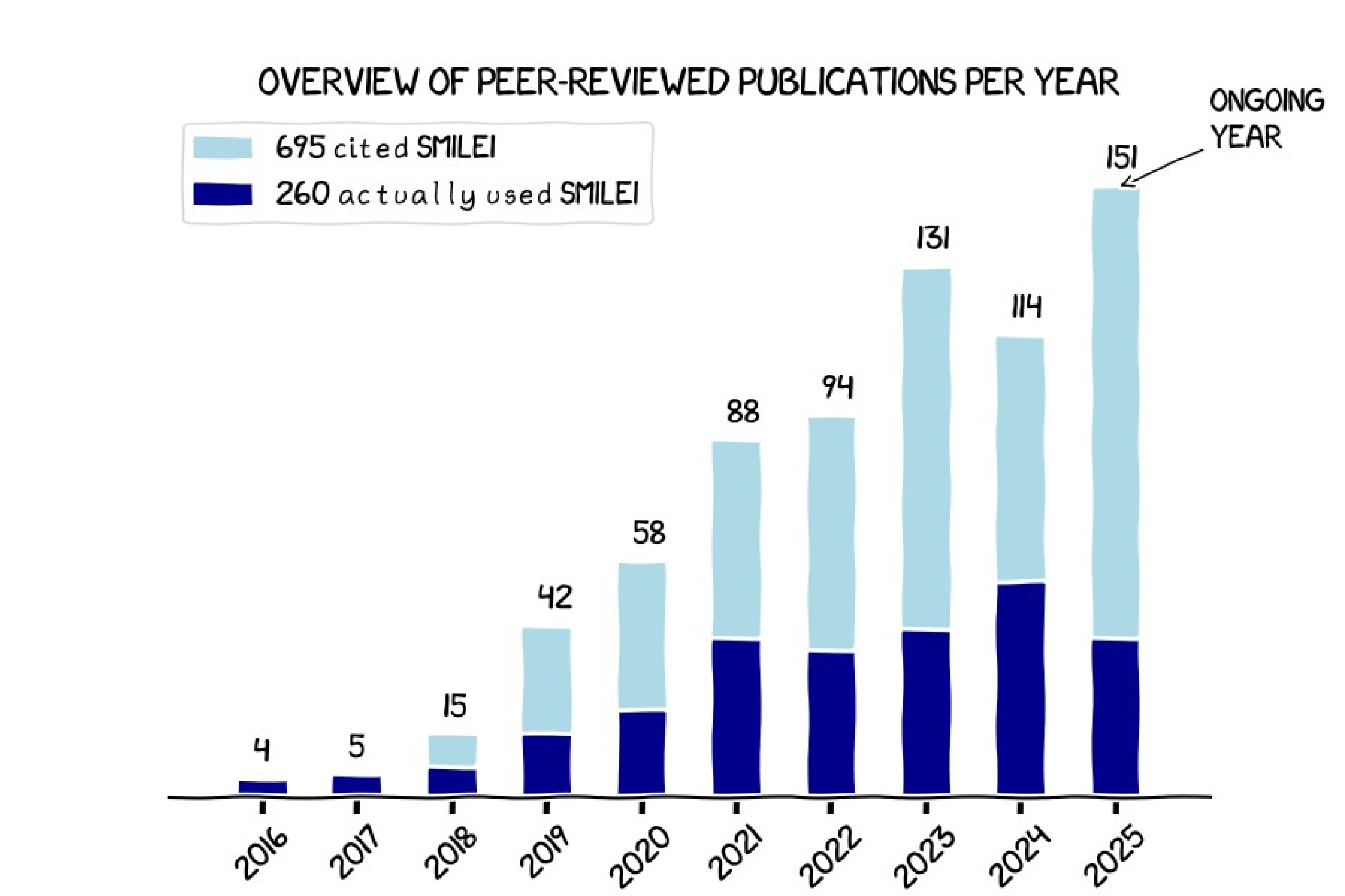
290+ peer reviewed papers using Smilei

(December 2025)

Tens of PhD defended

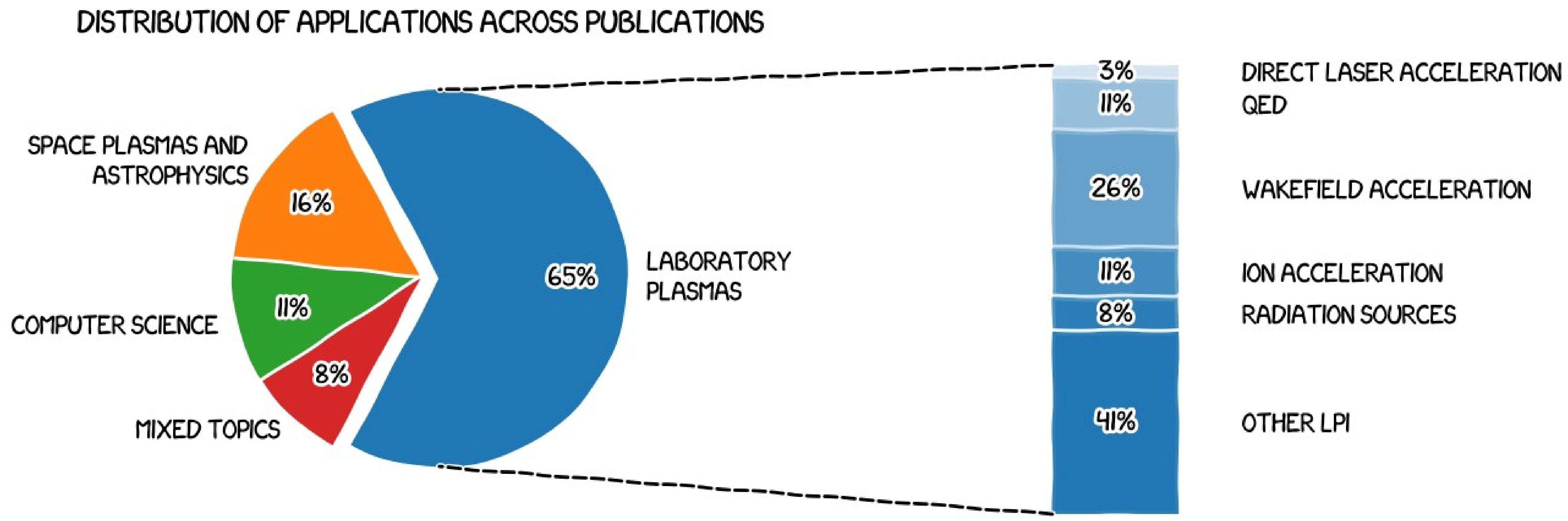
700+ citations

« Smilers » scientific production



Derouillat et. al. Comput. Phys. Commun. 222, 351-373 (2018)

« Smilers » scientific production



Clearly, our expertise does not cover the range of applications Smilei is used for !

Smilei wins a free software prize in 2023

French ministry of higher education
and research

PRIZE
OPEN SCIENCE
OF FREE
SOFTWARE
FOR RESEARCH

CATEGORY
SCIENTIFIC AND
TECHNICAL

The « core » team

MAISON DE LA SIMULATION

- Charles Prouveur
- Juan Jose Silva Cuevas
- Mathieu Lobet

CNRS SCIENCES INFORMATIQUES

- Arnaud Beck

CNRS NUCLÉAIRE & PARTICULES

- Francesco Massimo

CNRS INGÉNIERIE

- Frederic Perez
- Mickael Grech
- Tommaso Vinci

CNRS PHYSIQUE

- Guillaume Bouchard

Co-development between physics and HPC labs.

Integration in the HPC landscape

3 National French Supercomputing Centers

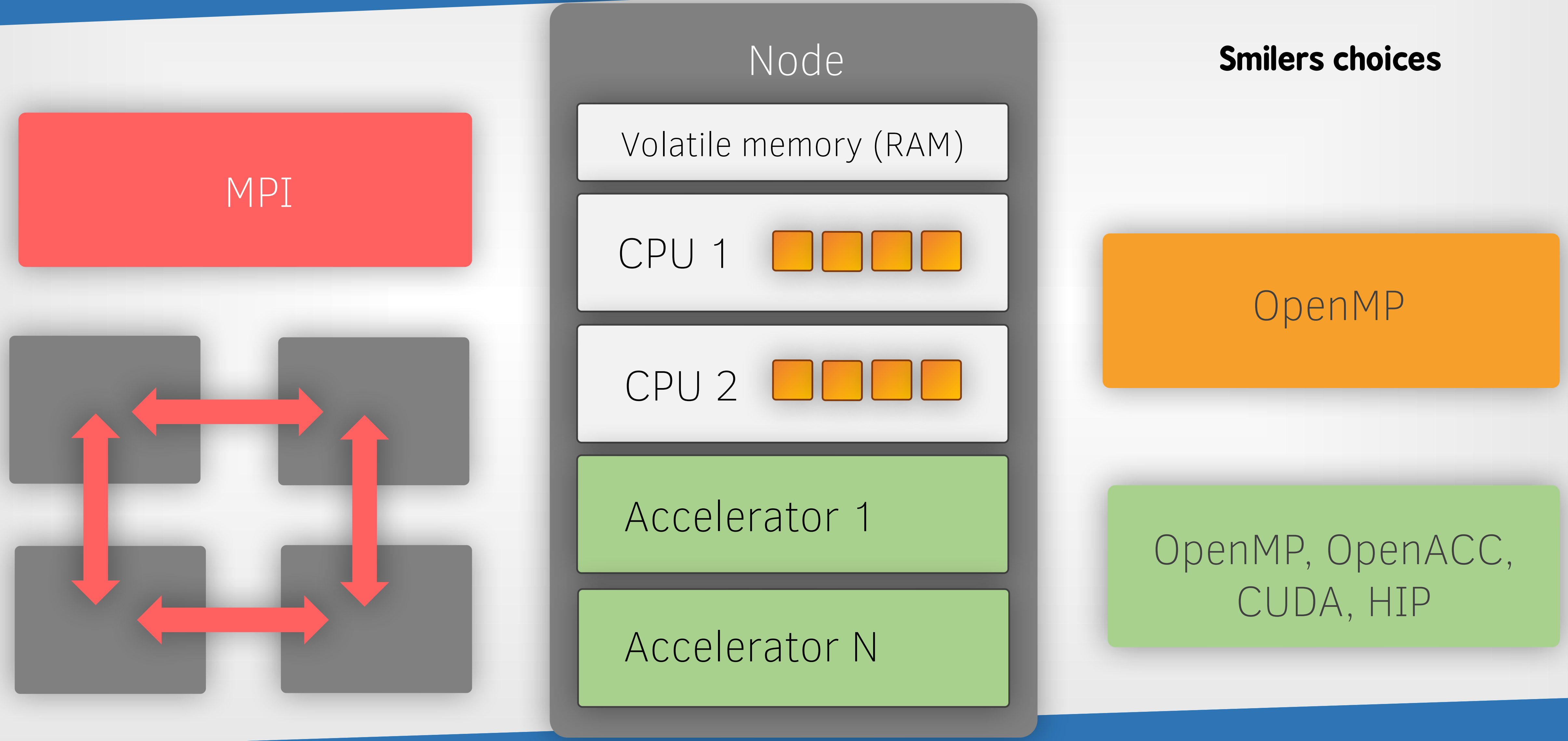
TGCC
Très Grand Centre de calcul du CEA

- Early access to a variety of architectures
- Support and optimization
- Representative of the global HPC landscape
- Reach more systems via euroHPC
  and the users community

GENCI

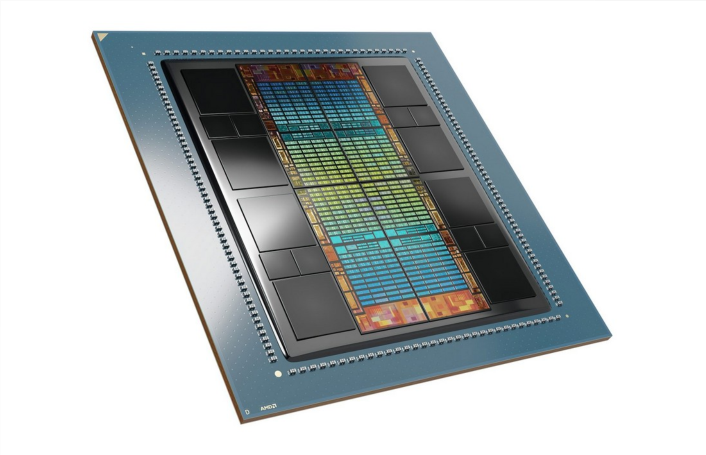
Virtual Laplace project
=> Specific access for Smilei development

Many software technologies adapted to each level of parallelism



GPU lesson learned 1 : multiple manufacturers

openACC



openMP

Effectively doubles the work (developing, integrating, testing, optimizing ...)

Use **software engineering** solutions like Alpaka or Kokkos.

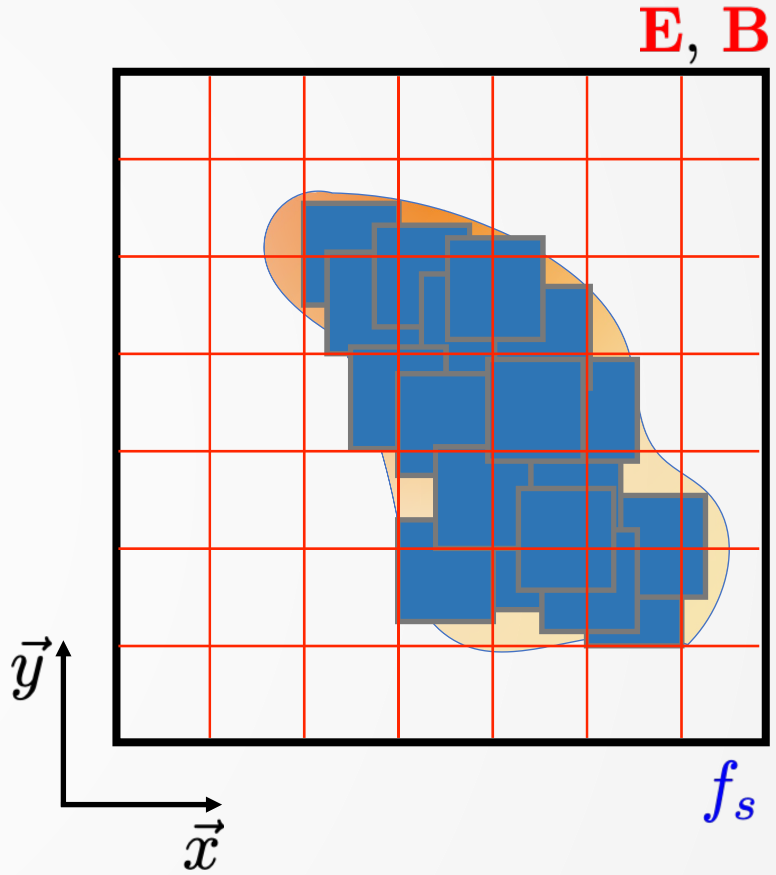
GPU lesson learned 2 : GPU-averse kernels

GPU are not naturally good at everything.

Particles evolve freely in the domain and trigger random access to memory to deposit current.

The projector is a reduction which is difficult to port because of :
- atomic add operation
- on shared memory
- with random access
- hot spot requiring high performance

That can be met with :
- Low level **CUDA-HIP operations.**
- **Algorithmic changes.**



GPU lesson learned 3 : domain decomposition granularity

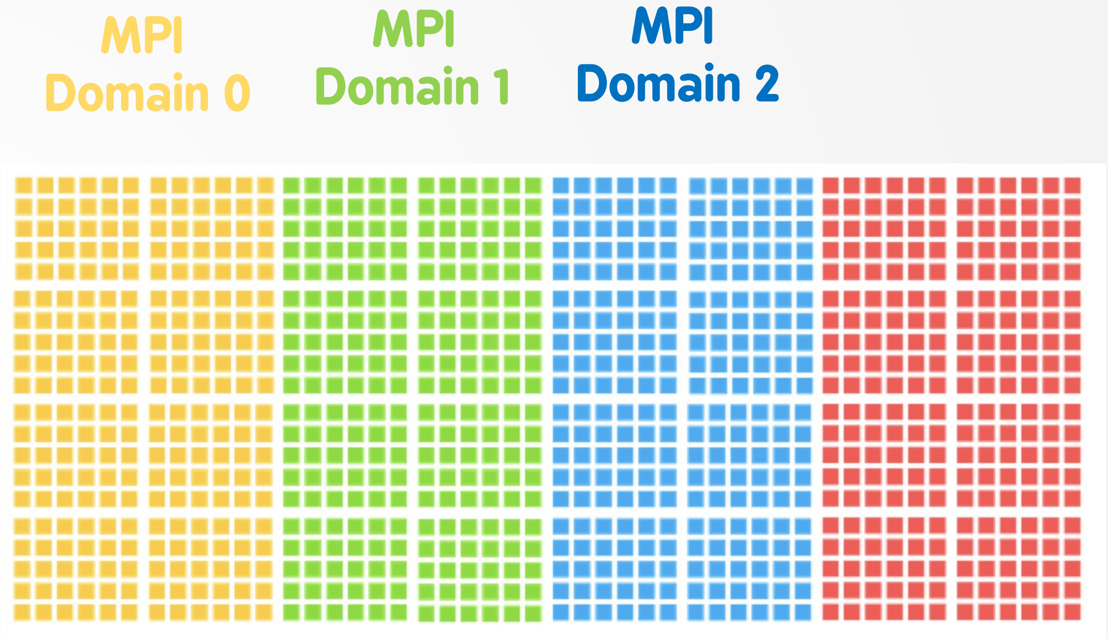
The **domain decomposition** must be adapted to the hierarchy of the GPU.

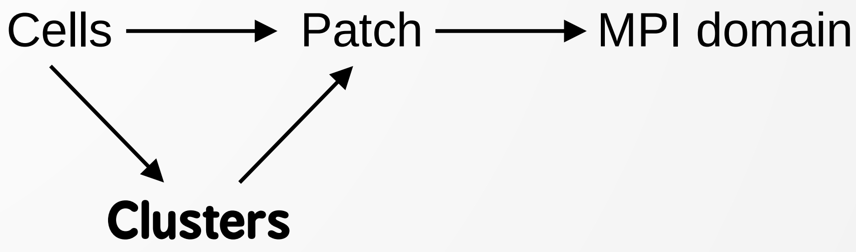
GPU requires large chunks of data whereas multi-core CPU favor independent chunks.

Sorting is required to mitigate randomness.

Fine granularity sorting triggers **bank conflicts**.

Addition of intermediate “clusters” of size 4 cells per dimension.



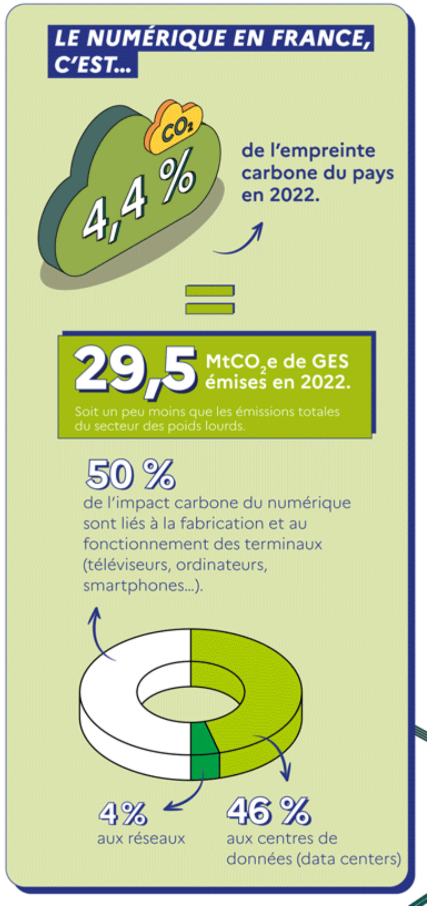


The environmental challenge

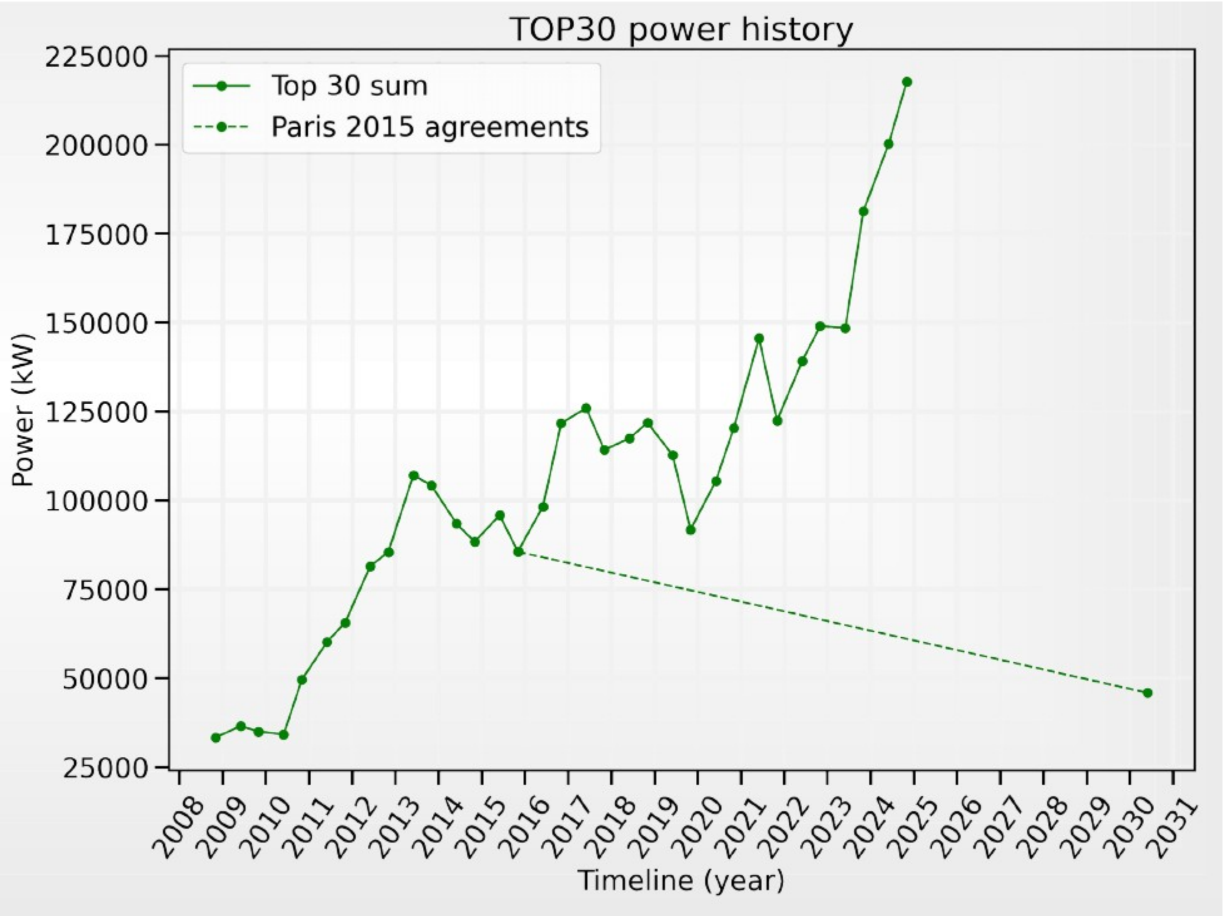
En 16 ans :

- la **performance par W** a été multipliée par **113**
- la **puissance crête** a été multipliée par **905**
- la **consommation** électrique totale a été multipliée par **8**

IDRIS
P.-F. Lavalée

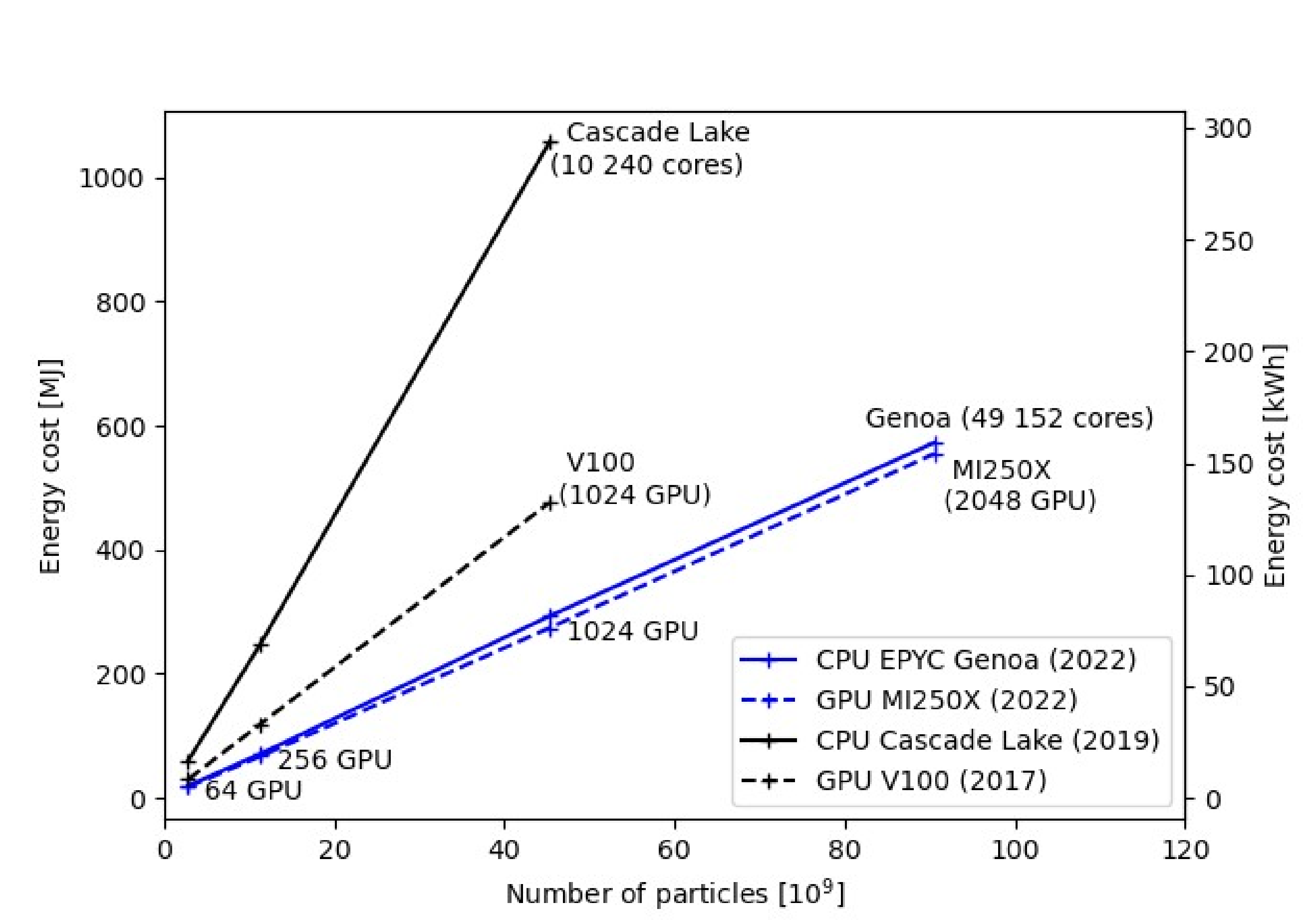


ADEME, Electronic device environmental impact in France.



TOP 500
Power history of the top 30 supercomputers

Energy: the real metric for software performance

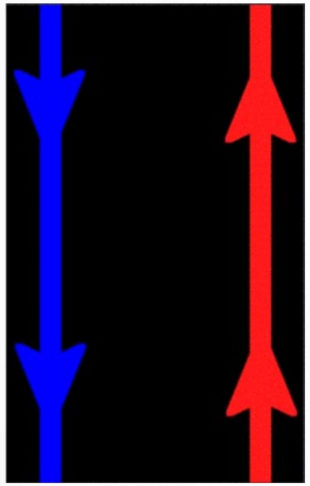


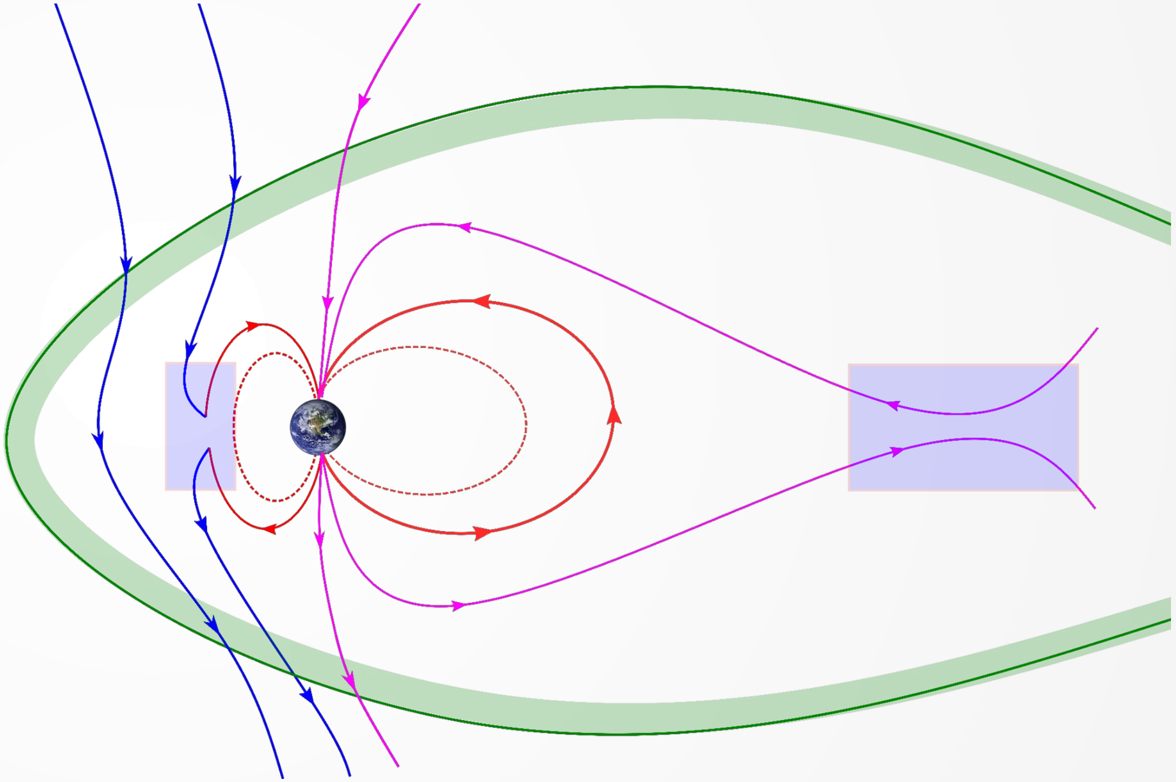
- ▶ Weak scaling: the resources scale with the problem size.
- ▶ The configuration is optimized for each system.
- ▶ Results may differ with another physical case.
- ▶ The energy cost depends linearly on the size.
- ▶ Be aware of the “Rebound effect”.

Magnetic Reconnection and the MMS mission

<u>Mission objective</u>

Dive into details of microphysics of **magnetic reconnection** at earth’s magnetosphere.



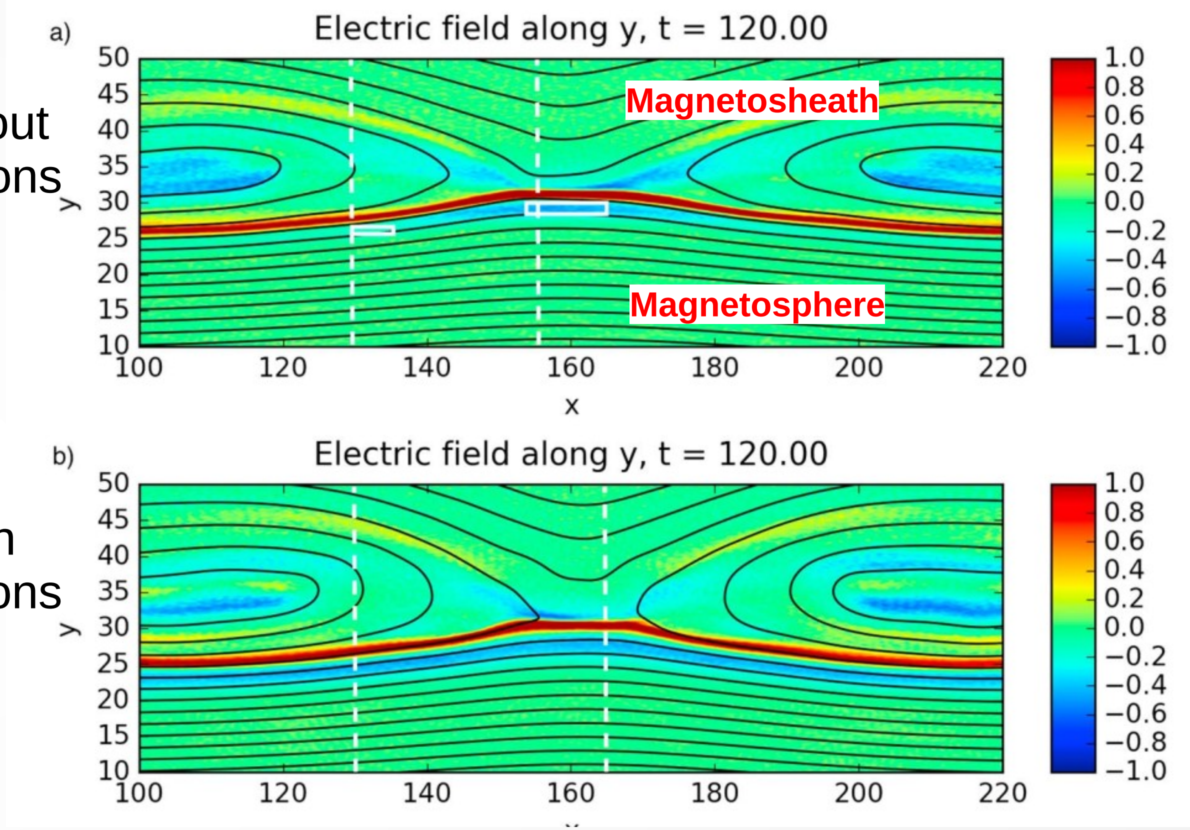


Magnetic Reconnection

The presence of cold ions influences the transition between the magnetosphere and magnetosheath far from the diffusion region.

Without cold ions

With cold ions



Dargent et al. (2017)

~ a millions CPU core hours

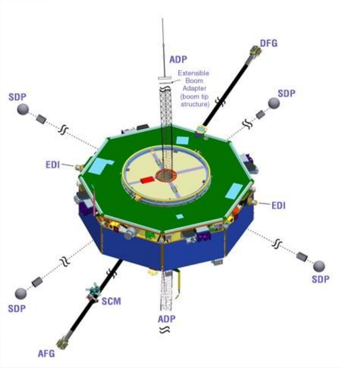
3 day SMILEI simulation

Magnetic Reconnection

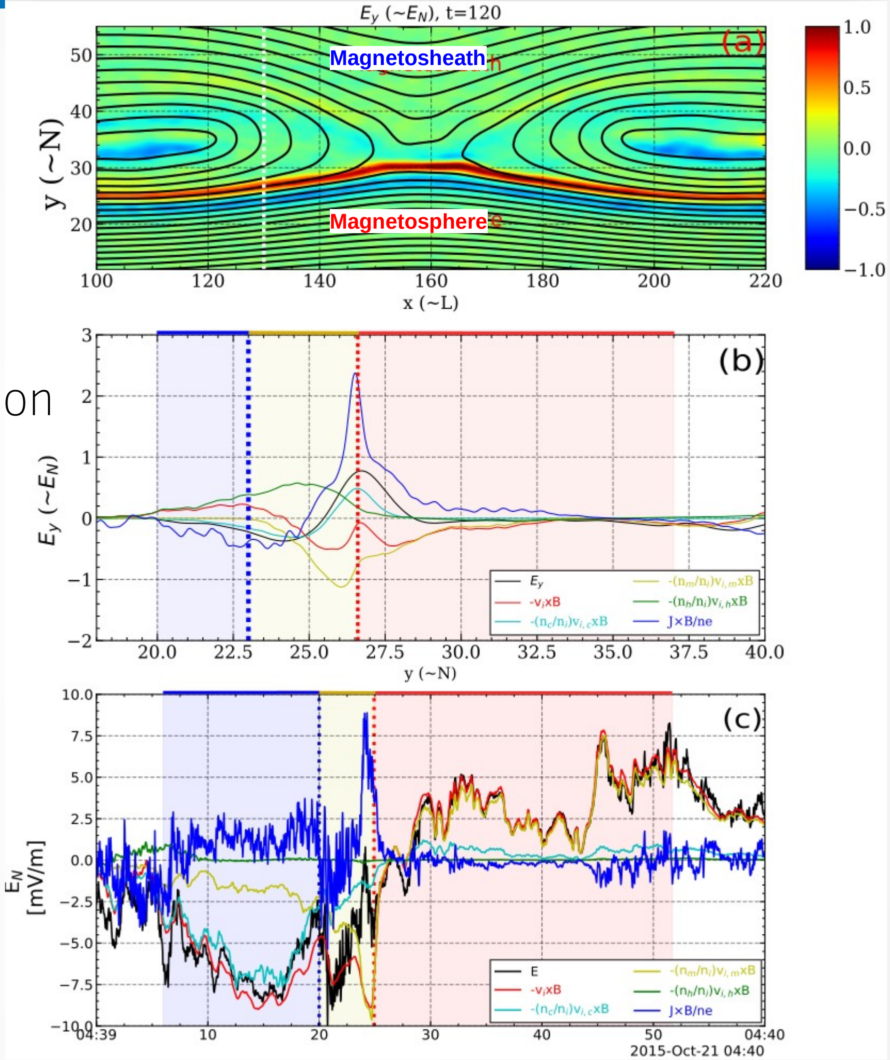
Sharp electric transition and its extension far from the diffusion region in the presence of cold ions **confirmed by MMS**.

Simulations were able to **reproduce** and further **investigate** the contribution of the cold ions.

Baraka et al. (2025)
~ 700 GPU hours
3 hours SMILEI simulation



MMS in situ measures



First PhD defended with Smilei results on GPU !

Baraka, M., et al. (2025). Journal of Geophysical Research: Space Physics, 130.

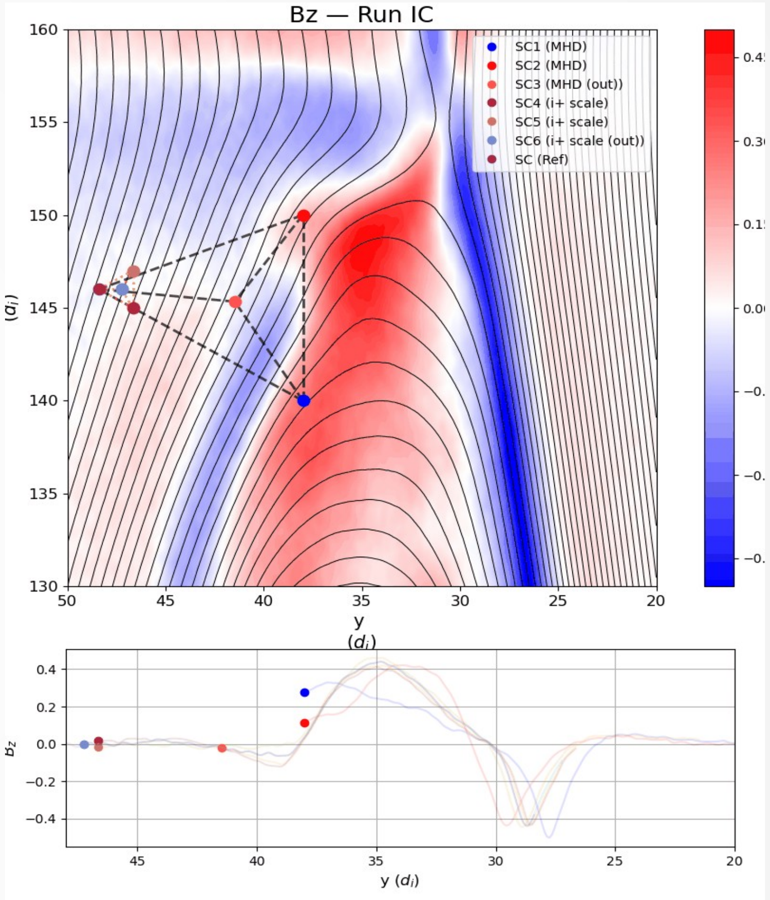
Plasma Observatory mission

Simultaneous measures of ion and fluid scales.

M7 ESA Program.
Final selection in June 2026.
Launch in 2037.

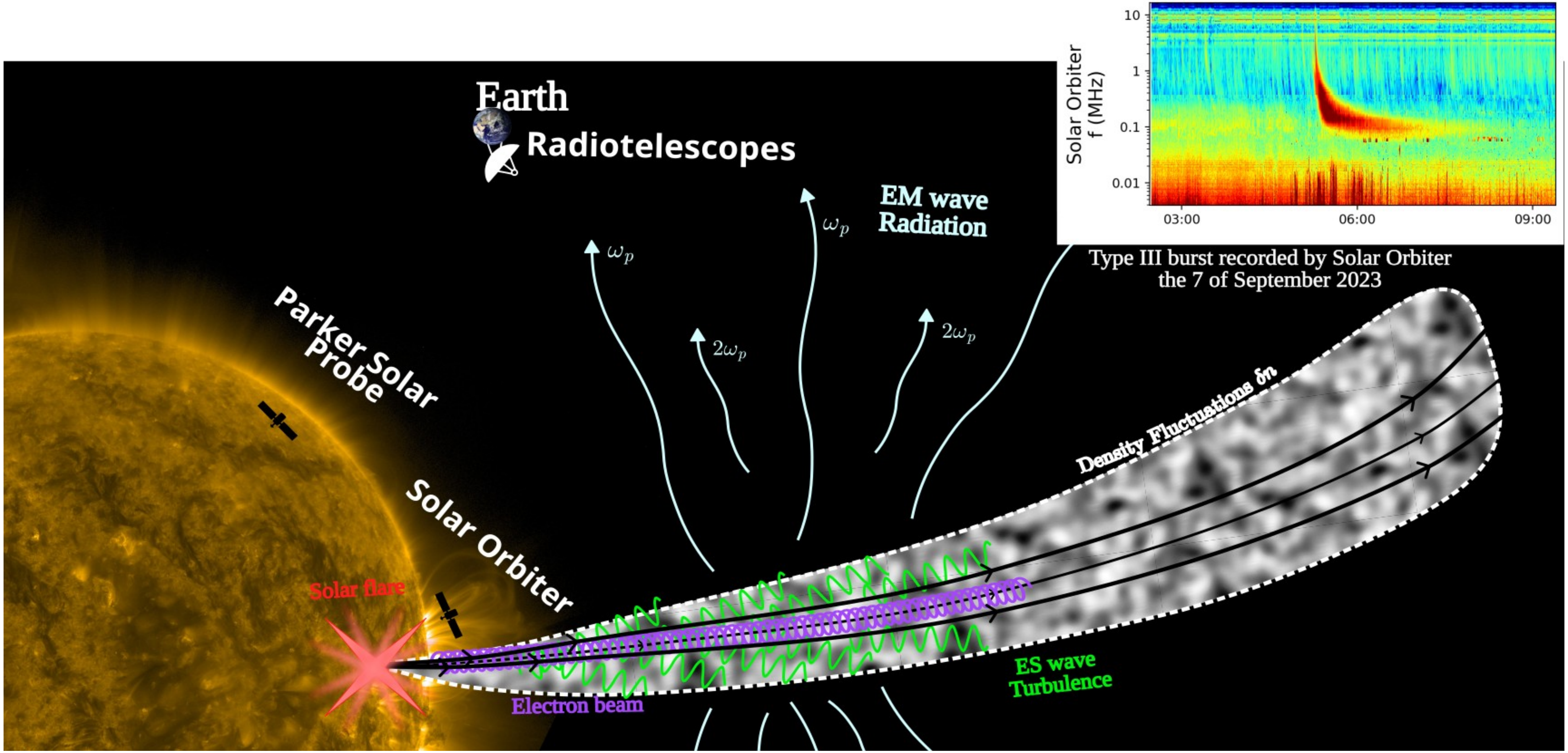
These findings contribute to the preparation of the PMO mission and aim at improving its science return.

More simulations are required to account for realistic mass ratio.



M. Baraka
Joint Cluster – Plasma Observatory workshop
« Towards a new multi-Scale Era for the Magnetospheric System »

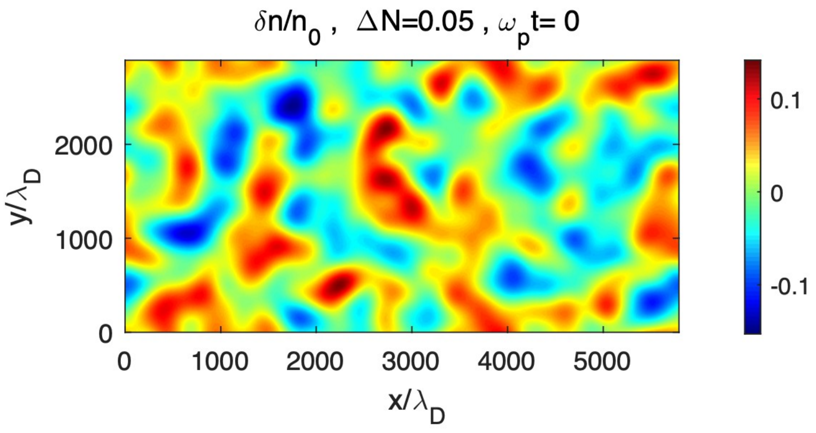
Type III solar radio bursts



Objectives

Understand the properties and the location of the source from radio EM wave measurements (in situ or on Earth)

- What are the dominant processes of EM wave radiation ?
- What are the radiation rates and energies of EM waves in the modes O, X and Z ?
- What is the impact of **density fluctuations** and **magnetization** on EM radiation ?



Critical points

- Time scales from low to high frequencies => 3 orders of magnitudes
- Space scales from electrostatic to electromagnetic => 2 orders of magnitude
- Very low beam density, slow conversion => Long simulation of ~ 1M iterations
- Very low statistical noise required => Up to 50 B macro-particles
- Explore various regions and density fluctuations => Tens of simulations required

~ 1 PB of data accumulated for the whole campaign

Ran mostly on the Adastra GPU partition at CINES

Results of PIC simulations

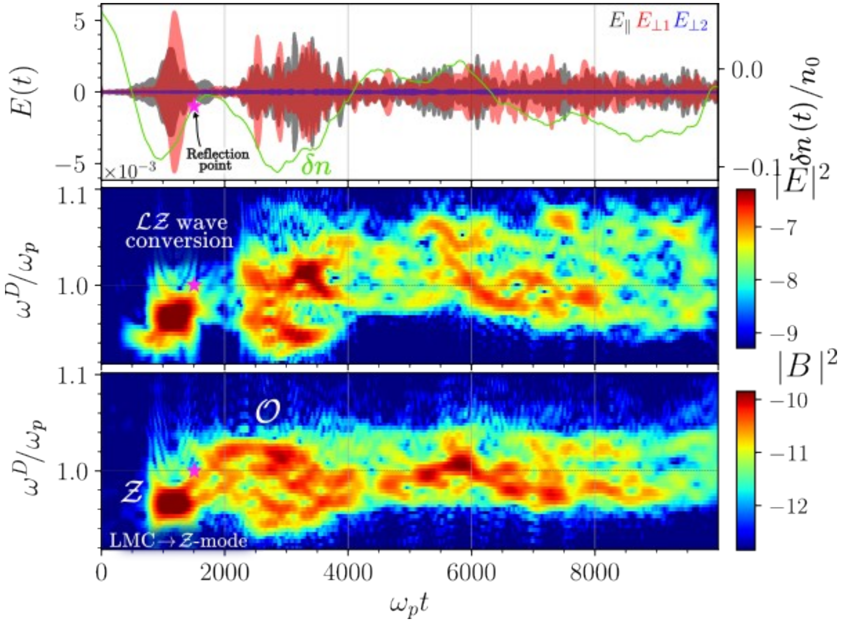
Radiation efficiency of electromagnetic wave modes from beam-generated solar radio sources
C. Krafft et al., Nature astronomy 9 (2025).

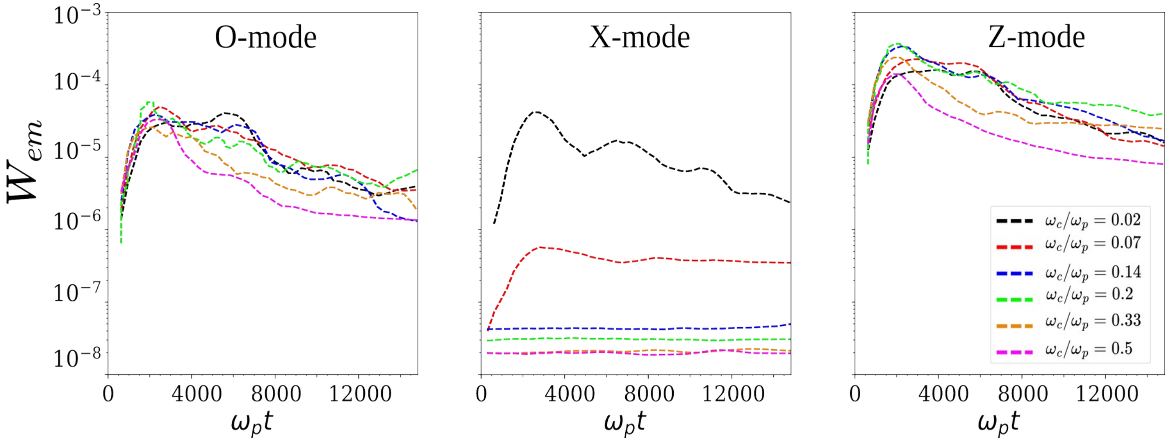
LZ wave turbulence

- Spectral broadening of LZ waves: $\Delta\omega \approx \omega_p \Delta N$ due to density fluctuations.
- LZ waves follow dispersion curves but are shifted to lower frequencies due to their trapping in depletions.

EM waves radiated by LMC process at constant frequency

- Z modes are excited down to the cutoff frequency (100% left handed polarization)
- Z modes have the largest energies and radiation rates for any $\omega_c/\omega_p \leq 0.5$
- O modes are emitted with energies ~10 times smaller than those of Z
- X modes are not excited for $\omega_c/\omega_p > 0.07$
  - significantly excited for $\omega_c/\omega_p = 0.02$
- in agreement with the analytical result, i.e. X-mode is emitted only if $\omega_c/\omega_p \lesssim \alpha\Delta N$





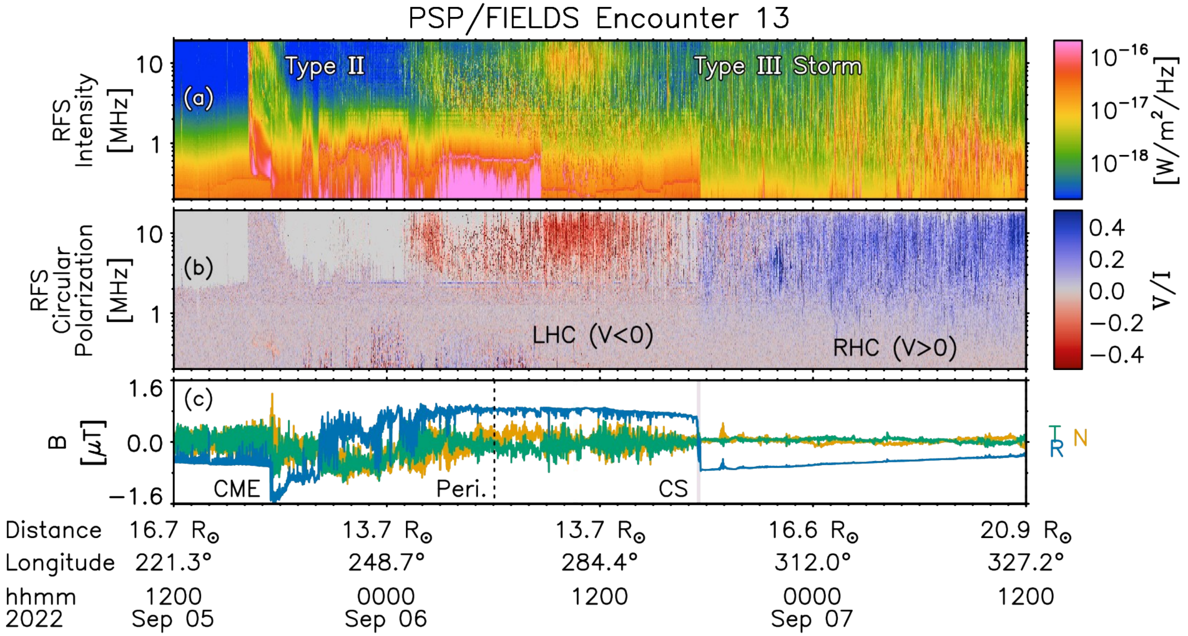
Physics explained at all scales with unprecedented accuracy.

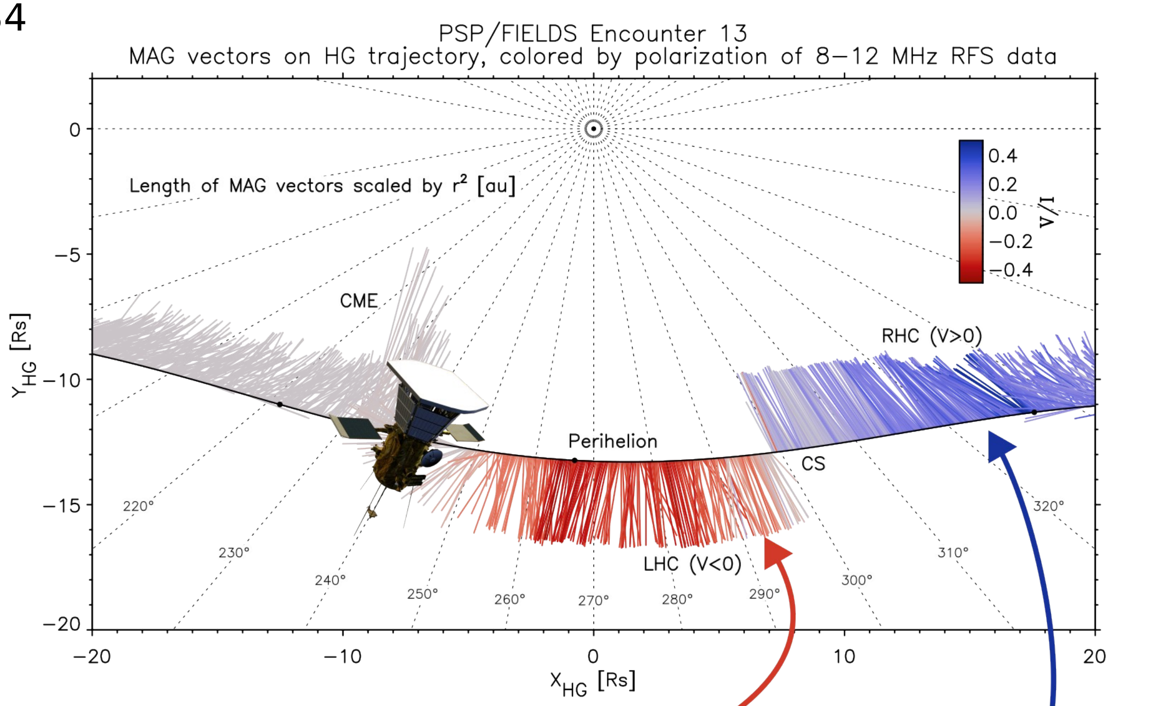
Virtual diagnostics looks extremely realistic…

… and matches measurements !

Agreement with Parker Solar Probe

Marc Pulupa et al. (2025) The astrophysical Journal Letters, 987:L34



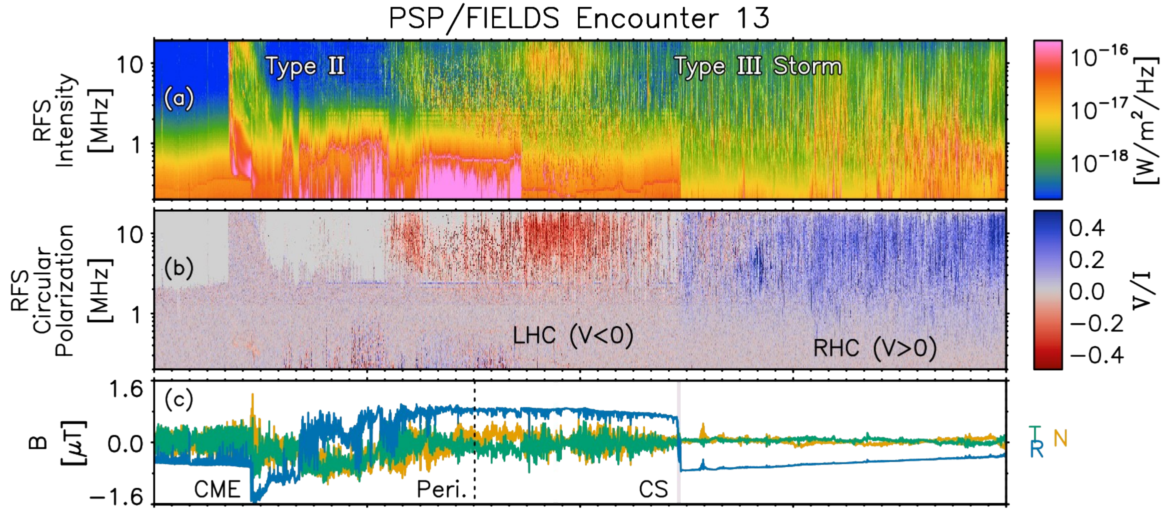


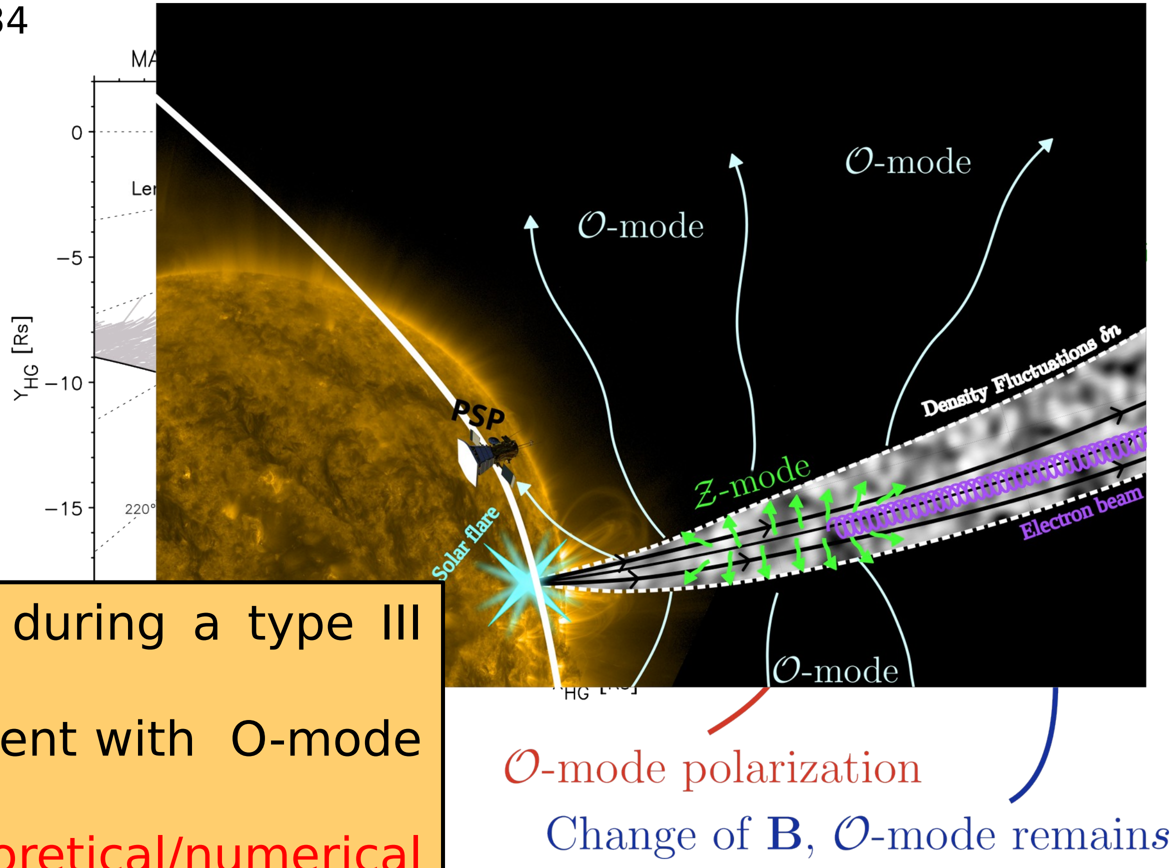
$\mathcal{O}$-mode polarization

Change of $\mathbf{B}$, $\mathcal{O}$-mode remains

Agreement with Parker Solar Probe

Marc Pulupa et al. (2025) The astrophysical Journal Letters, 987:L34





- Inversion of the magnetic field direction observed during a type III storm
- The polarization is also inversed but remains consistent with O-mode radiation
  - ➢ Observations are in agreement with our theoretical/numerical results : Z- and O-mode waves are predominantly generated; only O-mode waves can escape from the radio source and be observed (no X-mode waves observed).

C. Krafft et al., Nature astronomy 9 (2025).

What's next for Smilei ?

- Finalizing the GPU porting – focus on the most popular features.
- Deliver a code performing well on the GPU based exascale European systems.
- Moving to C++ 17/20 and focus on a more portable paradigm (Alpaka, Kokkos …).Rewriting of the code starts in 2026.
- Massive work !!!
  CNRS Physics, Nuclear and Particles, Computer Science, Engineering and CEA DRF are involved.
  We're looking for more contributors !

  Come talk to us : https://smileipic.github.io/Smilei/

Thank you for your attention

Thanks to LPP for obtaining and sharing awesome results

Mohamed Baraka
Olivier Le Contel

Philippe Savoini
Catherine Krafft
Francisco-Javier Polanco Rodriguez

Thanks to current active and contributing labs, institutions and universities

MAISON DE LA SIMULATION

Lpgp
LABORATOIRE DE PHYSIQUE DES GAZ ET DES PLASMAS

cea

cnrs

SORBONNE UNIVERSITÉ

université PARIS-SACLAY

l'X ÉCOLE POLYTECHNIQUE

INSTITUT POLYTECHNIQUE DE PARIS

... and a special thanks to all former contributors.