ECLIM - Sep 2022 - Frascati, Italy

# Smilei)


## An open-source PIC code for laser-plasma interaction

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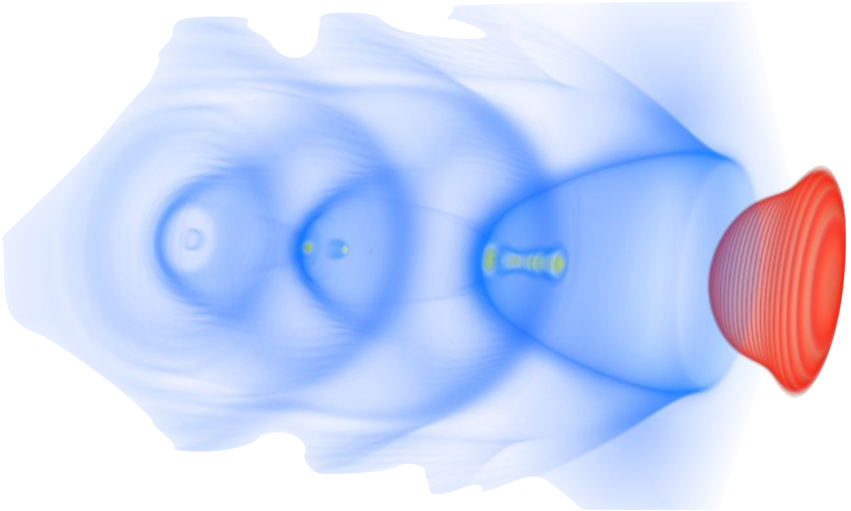
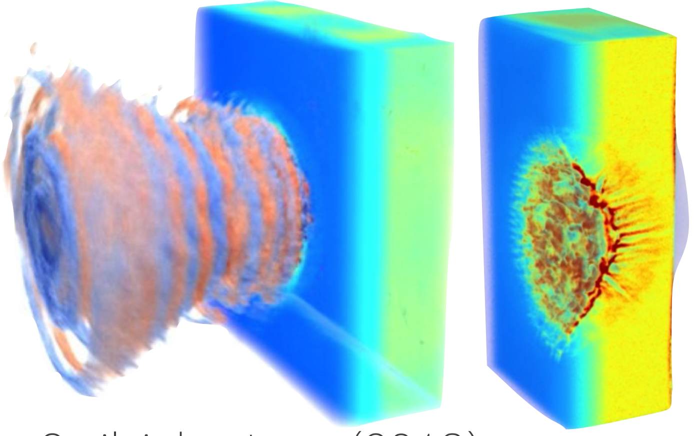
# Smilei is a Particle-In-Cell (PIC) code for the simulation of plasmas

## Laser Plasma Interaction

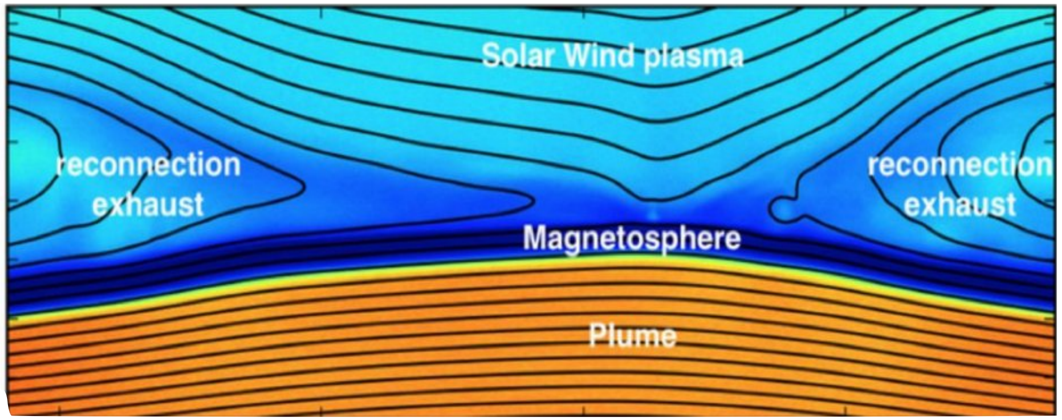


source: Massimo et al. (2020)



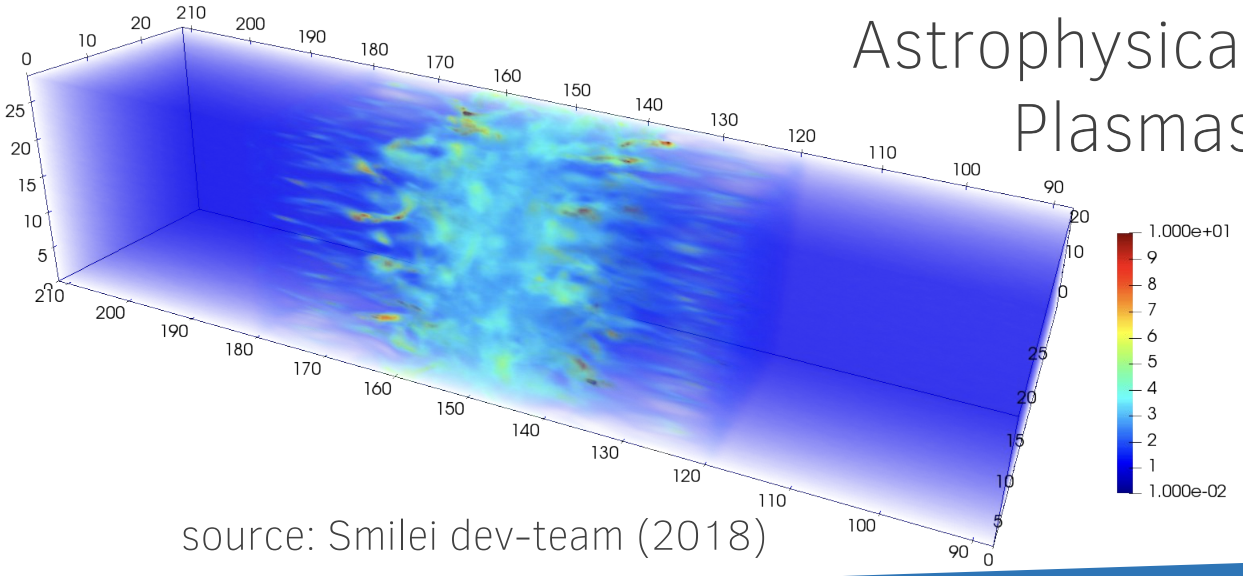
source: Smilei dev-team (2018)

## Space Plasmas




source: Dargent et al. (2017)

## Astrophysical Plasmas



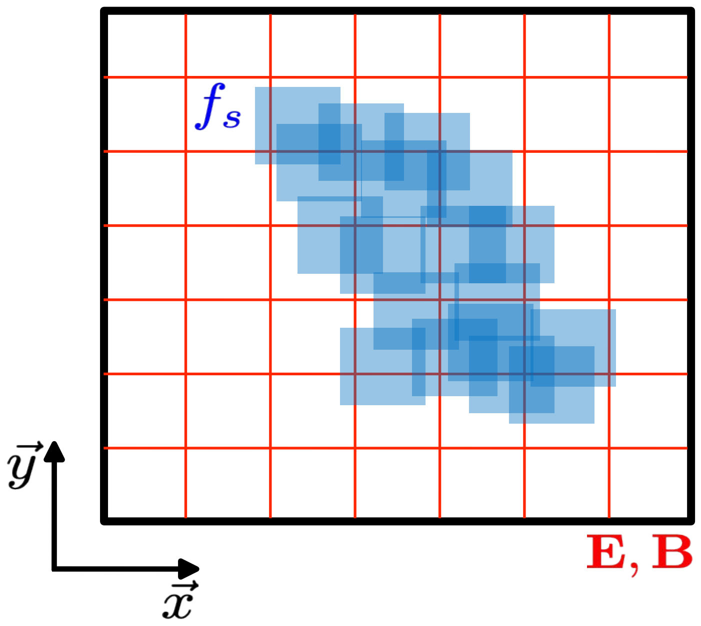

source: Smilei dev-team (2018)

# Smilei is an electromagnetic Particle-In-Cell (PIC) code

## Electromagnetic Fields - Maxwell

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

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




## Particles of the plasma - Vlasov

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

## The code

150 000 lines of code
C++ 85% / Python 15%
300 man.months in dev. only
Open-source (GitHub)

# Outline

Project organisation

High-performance

Scientific production & physics

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# Smilei in a nutshell

2013
Start of the project

2014
release to co-dev

2016
1st physics studies &
large scale simulations
Github

2018
Reference
paper

## Open-source & Community

user-friendly • full doc • bug reporting • chat • tutorials
training • summer school & master trainings

## High-performance

C++/Python • MPI/OpenMP • SIMD • HDF5/OpenPMD • tasks
GPU in a few months

## Multi-Physics & Multi-Purpose

Many geometries, solvers, boundary conditions,
Collisions, ionization, QED, nuclear reactions,
bremsstrahlung, betatron

# The Smilei dev-team

Co-development between physicists & HPC specialists

Mickael Grech*
Frederic Perez*
Tommaso Vinci*

Marco Chiaramello, Anna Grassi

Arnaud Beck*
Guillaume Bouchard
Imène Zemzemi, Ahmed Houebib

Francesco Massimo*

MAISON DE LA SIMULATION

Mathieu Lobet*
Julien Derouillat **
Olga Abramkina **
Haïthem Kallala

*permanent staff **Res. Engineer

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*permanent staff **Res. Engineer

Marie Flé
Olga Abramkina (also at MdlS)

Asma Farjallah

Umesh Seth
Etienne Malaboeuf

Nicolas Aunai
Jérémie Dargent

Clément Caizergues
Emmanuel d'Humières
Philippe Nicolai

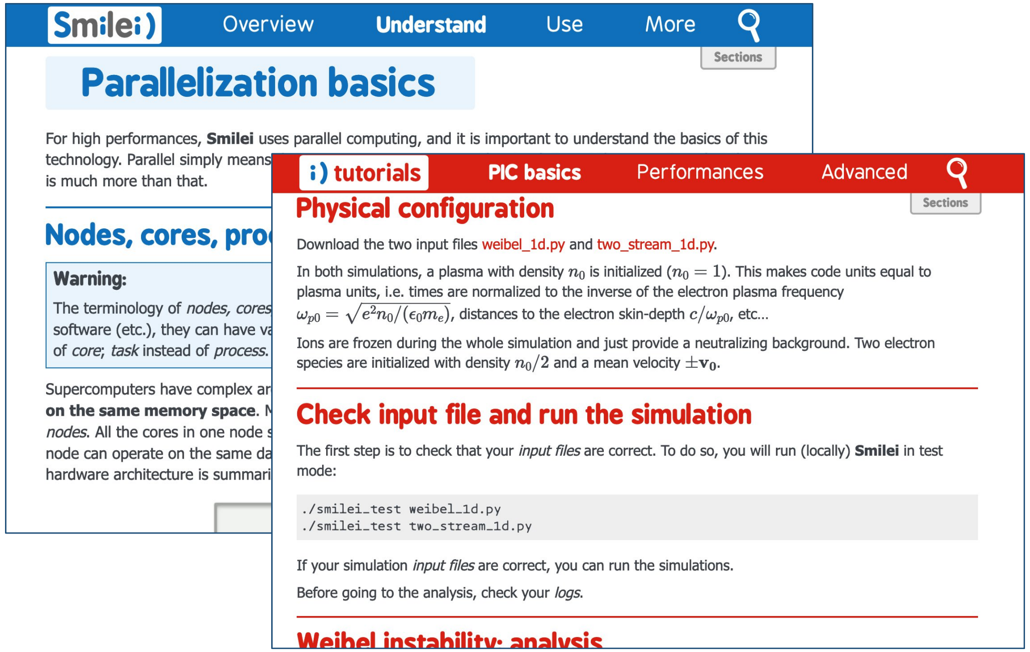
astrophysique & planétologie

Illya Plotnikov

Paula Kleij
Michèle Raynaud

# Tools for the community

## An extensive documentation
with online tutorials

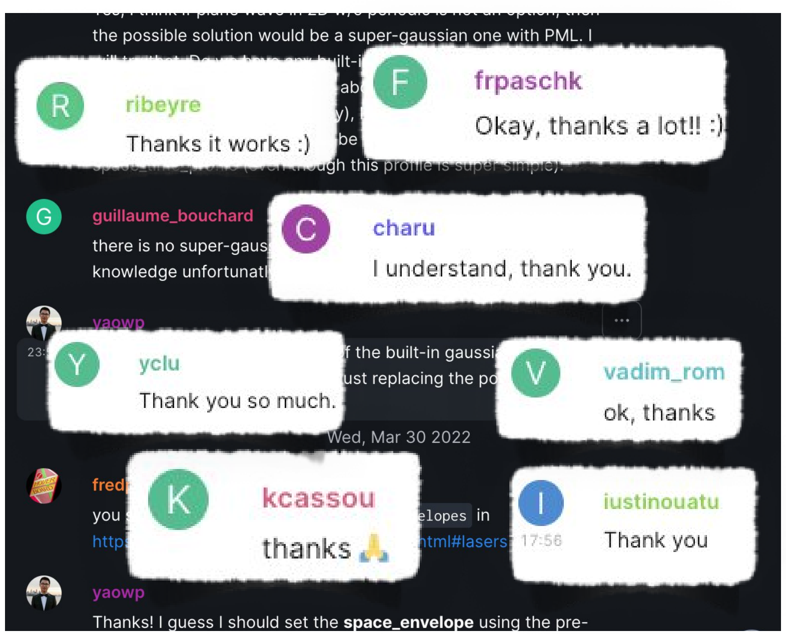



## User-friendly post-processing suite *(happi)*

## and a collaborative community

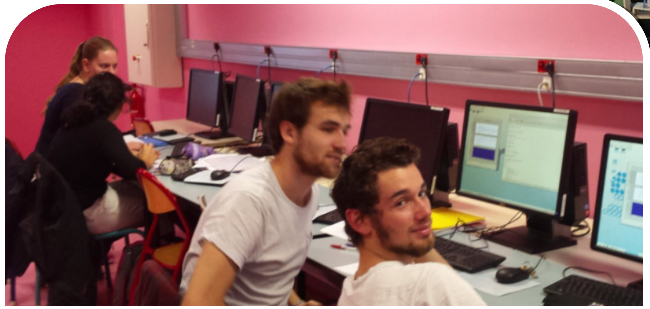
Github
sources, issues

Element
chat



# Teaching helps federate the community around Smilei

- 2016 **First teaching activities:** Practicals at Sorbonne Université
- 2017 1st training workshop
- 2019 2nd training workshop
  **Winter & summer schools:** Vietnam, les Houches ...
- 2020 Teaching activities in 2 Plasma-oriented Masters
- 2022 3rd User & Training Workshop
  at Institut Polytechnique de Paris



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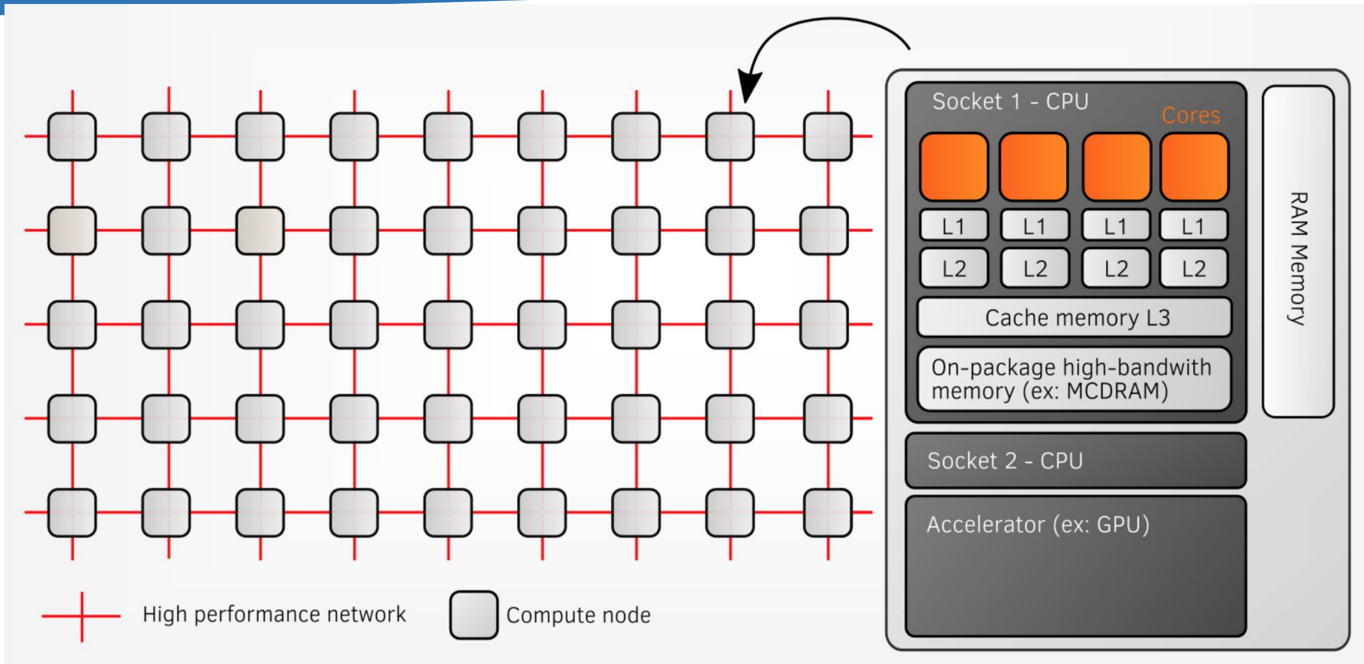
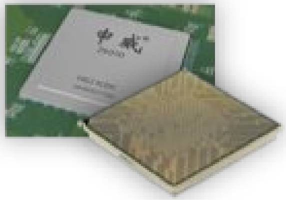
# Supercomputers are more and more complex




x86-based (Intel, AMD)

ARM-based (Fujitsu)

RISC-based (IBM, Sunway)



NVIDIA GPU

AMD GPU

**Parallelization**[1]: inter-node (MPI), intra-node (openMP, tasks[3] )

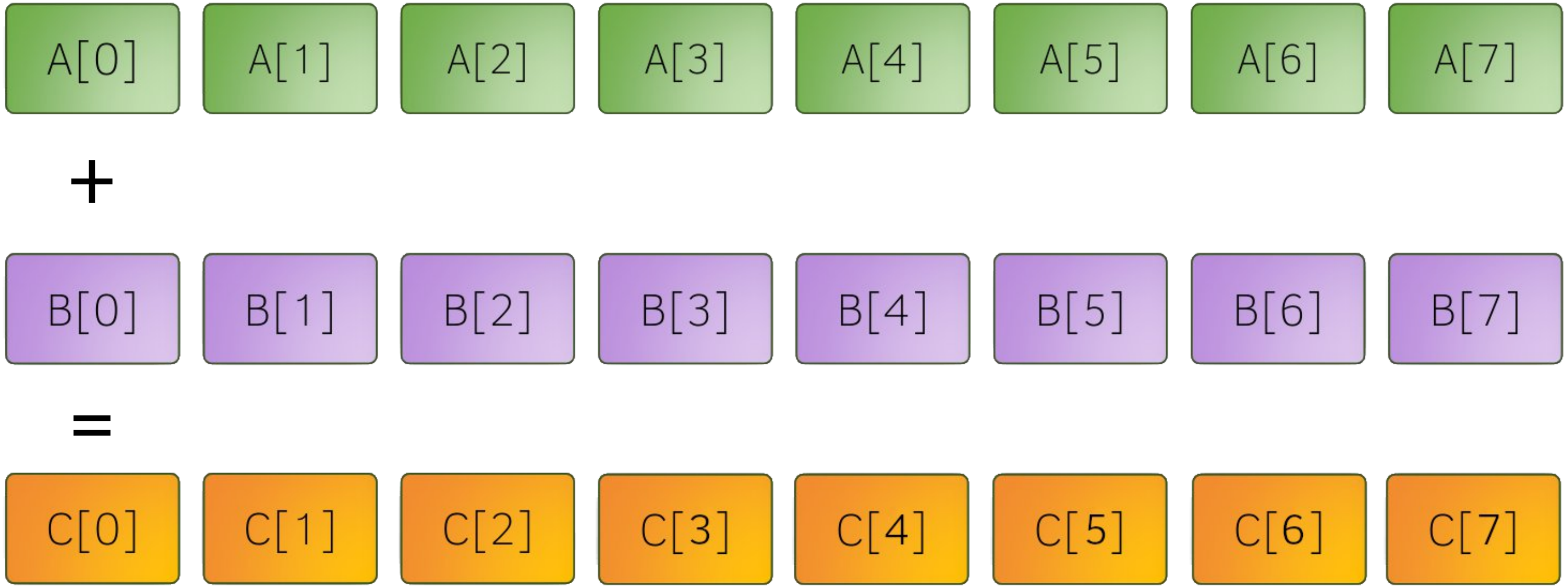
**Core-level optimization:** vectorization[2]

**Hardware optimization** (e.g. ARM[4]) or **porting** (NVIDIA GPU with IDRIS and AMD GPU with CINES)

[1] Derouillat et al. Comp. Phys. Comm. (2018)
[2] Beck et al. Comp. Phys. Comm. (2019)
[3] Massimo et al. arXiv:2204.12837 (2022)
[2] Lobet et al. HPCAsia (2022)

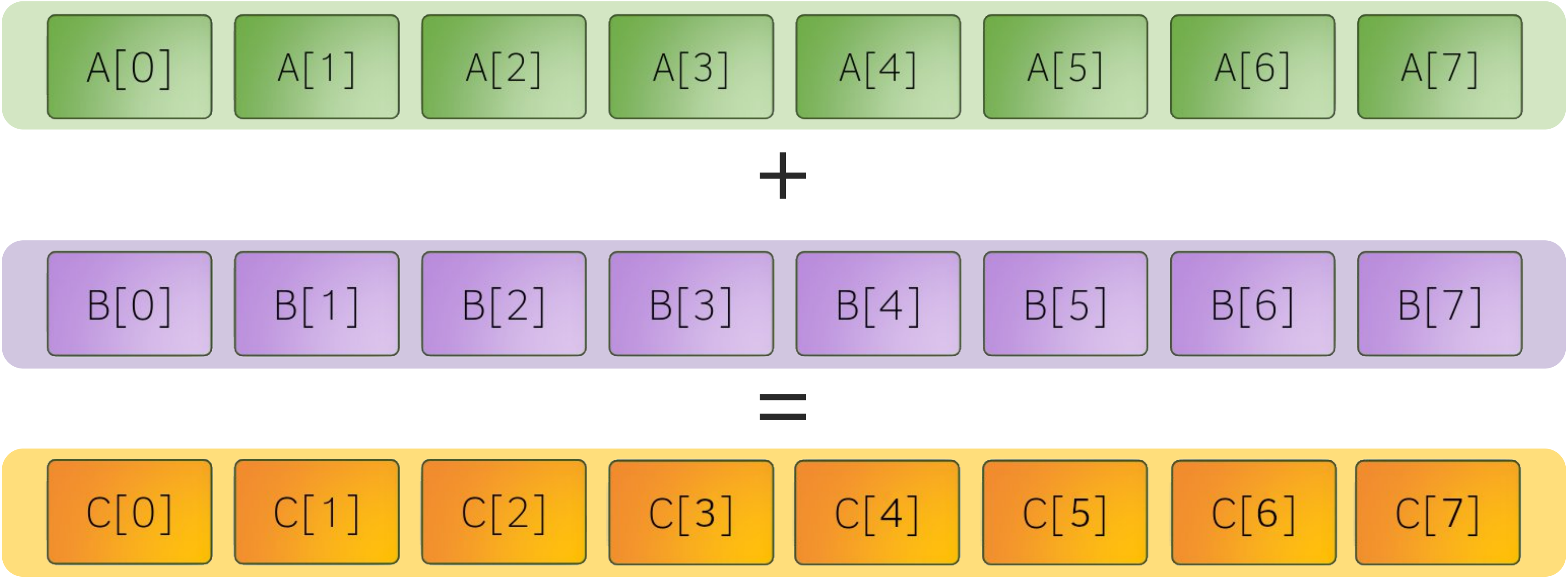
# Vectorization = parallel computation at the core level

In a traditional "scalar" algorithm, operations are done 1 by 1.



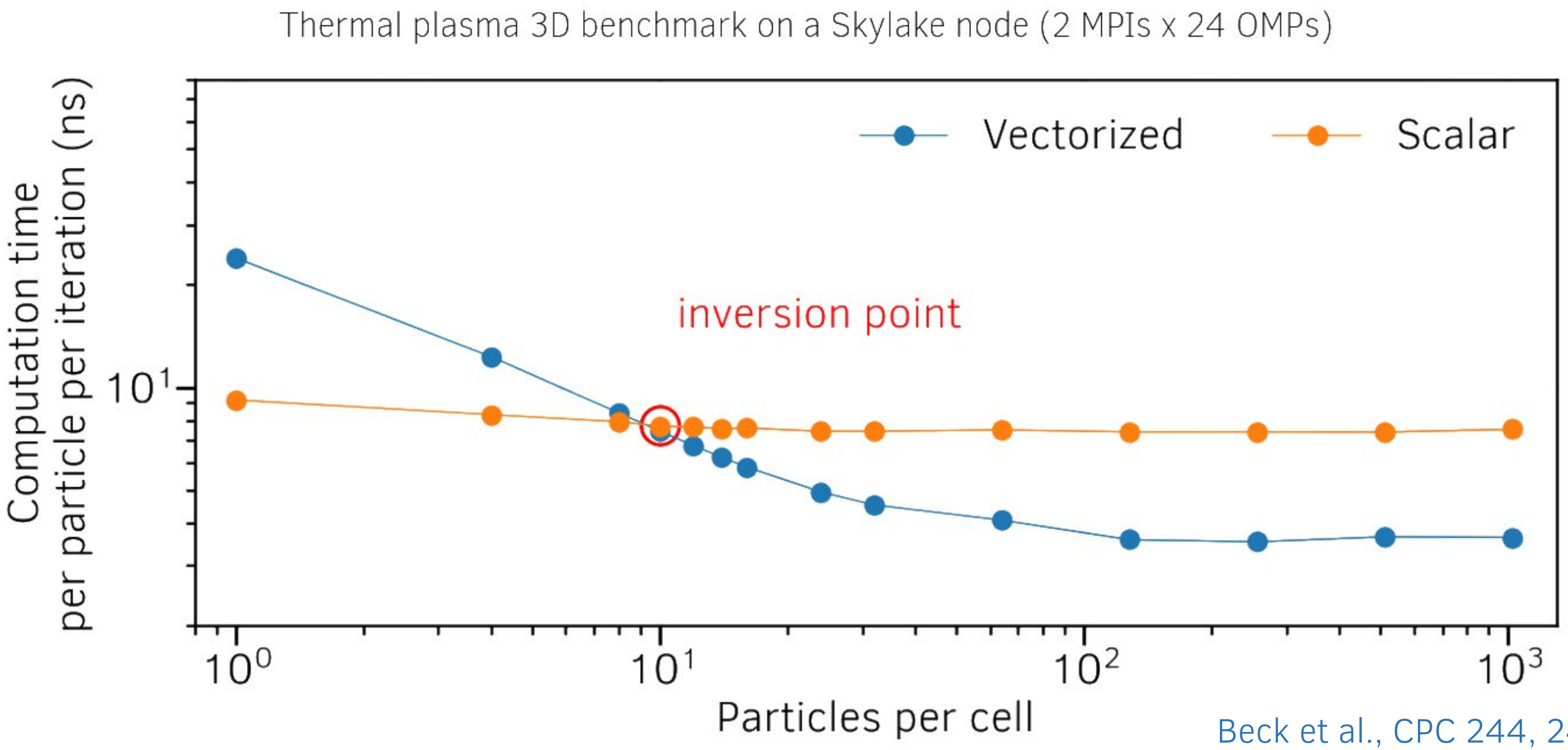
# Vectorization = parallel computation at the core level

SIMD = Single Instruction Multiple Data.
Operations are done at once for 4 or 8 variables.




In Smilei: all main operators are vectorized + QED

# Vectorization works for enough particles in a cell

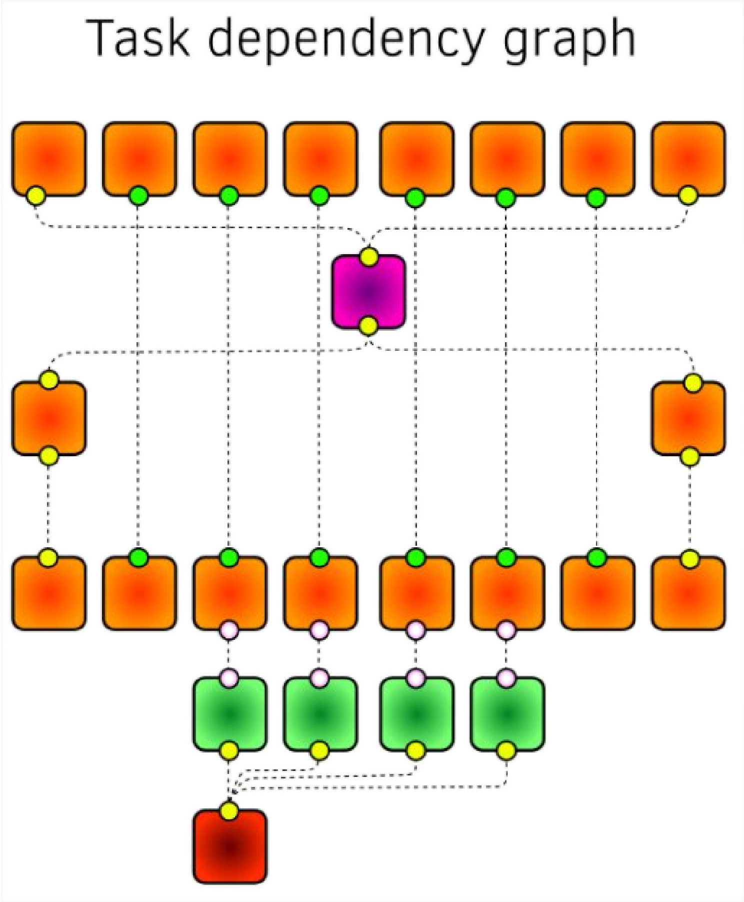



Beck et al., CPC 244, 246 (2019)

Smilei chooses dynamically vectorized or scalar operators

Up to x3 speedup

# Task parallelization allows for more asynchronism



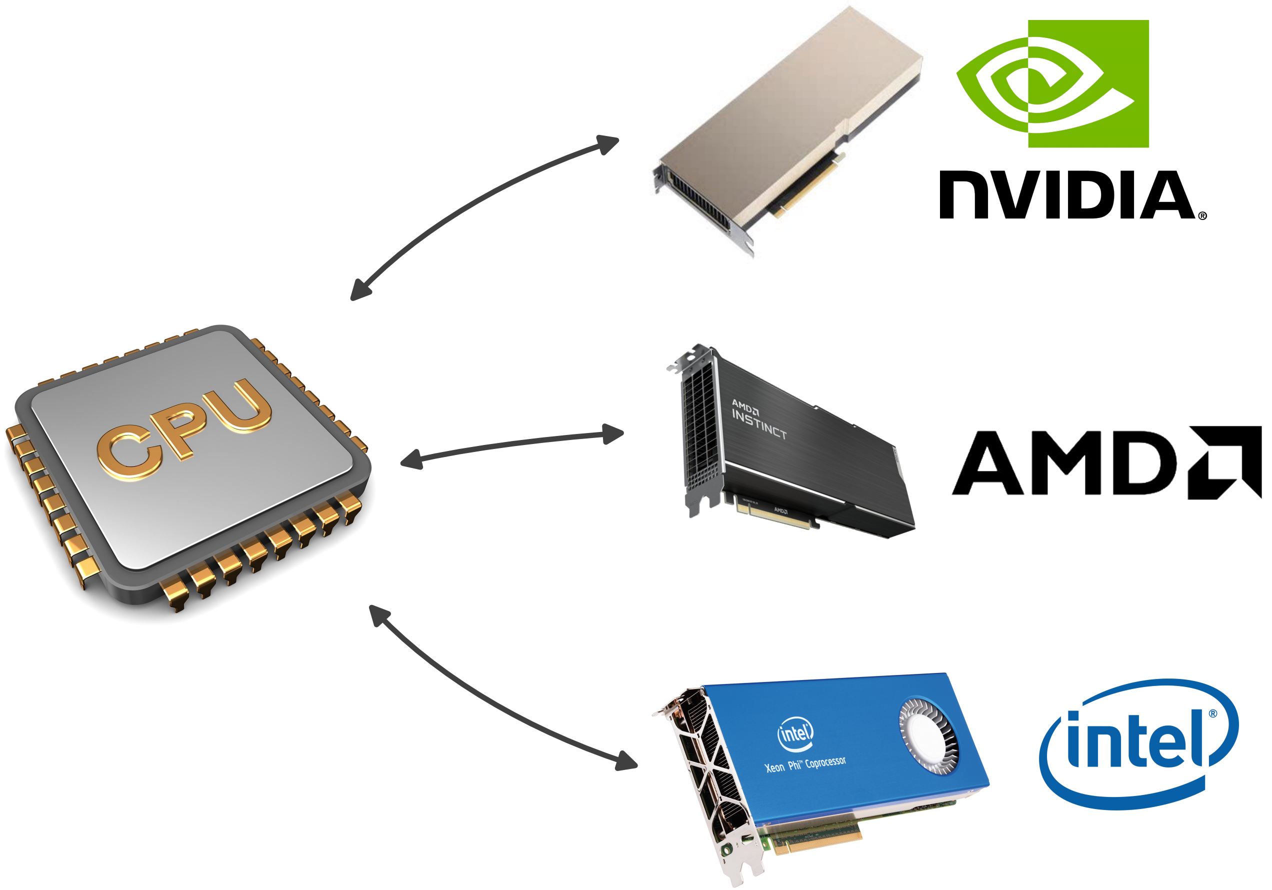

The work is divided is small operations that are achieved asynchronously.

Better strong scaling, especially for simulations with strong imbalance (up to x2 speedup).

In Smilei: all particle operators + QED + ionization

Release ~ November

# GPU are a challenge for programming




CUDA, OpenCL, OpenACC, OpenMP, SYCL, Kokkos, RAJA

HIP, OpenCL, OpenACC, OpenMP, SYCL, Kokkos, RAJA

OneAPI, OpenCL, SYCL

# GPU is coming to Smilei

3 developers for GPU porting

| | AMD | nVidia |
|---|---|---|
| 2D | ✔ | |
| 3D | ✔ | ✔ |
| Moving window | ✔ | ✔ |
| Ionization | soon | |
| Radiation | | ✔ |
| Pair creation | | soon |

Performances / energy consumption are slightly better than CPU at the moment

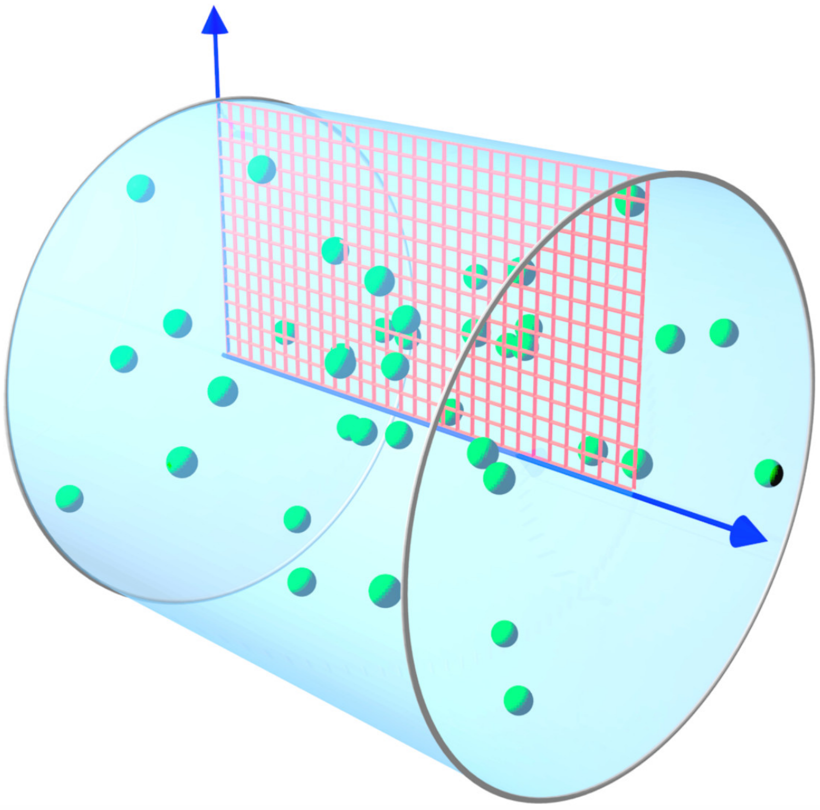
# Advanced models for higher performances

- Quasi-cylindrical geometry
- Envelope solver
- Particle merging
- Pseudo-spectra solver

# Quasi-cylindrical geometry

Fields are 2D, decomposed in θ modes

Particles are 3D



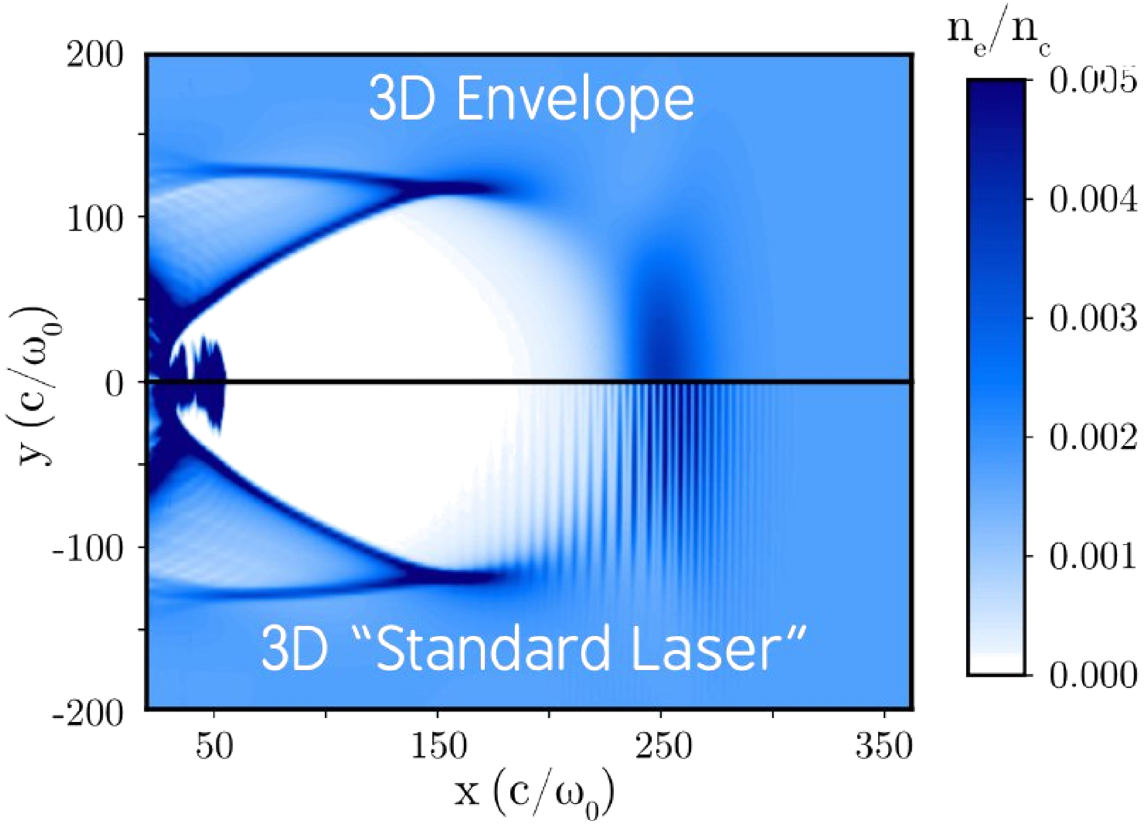
Up to x50 speedup compared to 3D

# Envelope solver

Instead of describing the whole laser pulse, solve an equation for the envelope only.

Particles interact with the envelope via the ponderomotive force.

Speedup x20 compared to full laser

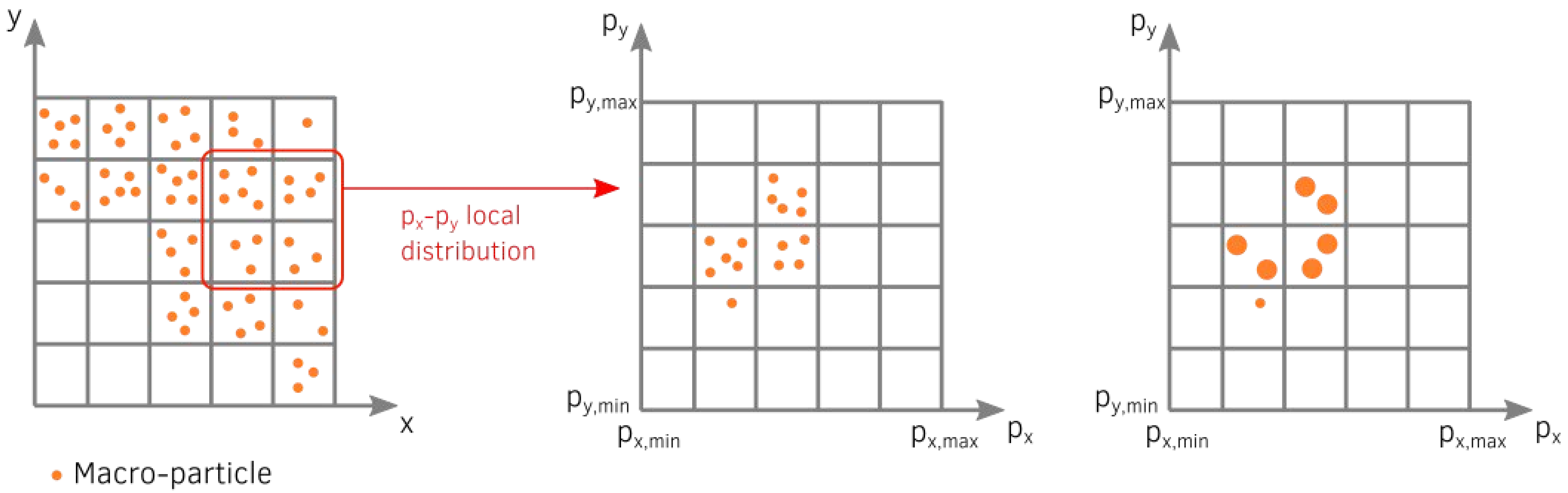


# Particle merging can handle the creation of many new particles

1) Merge cells in the position space (2d)

2) Merge cells in the momentum space (2d)

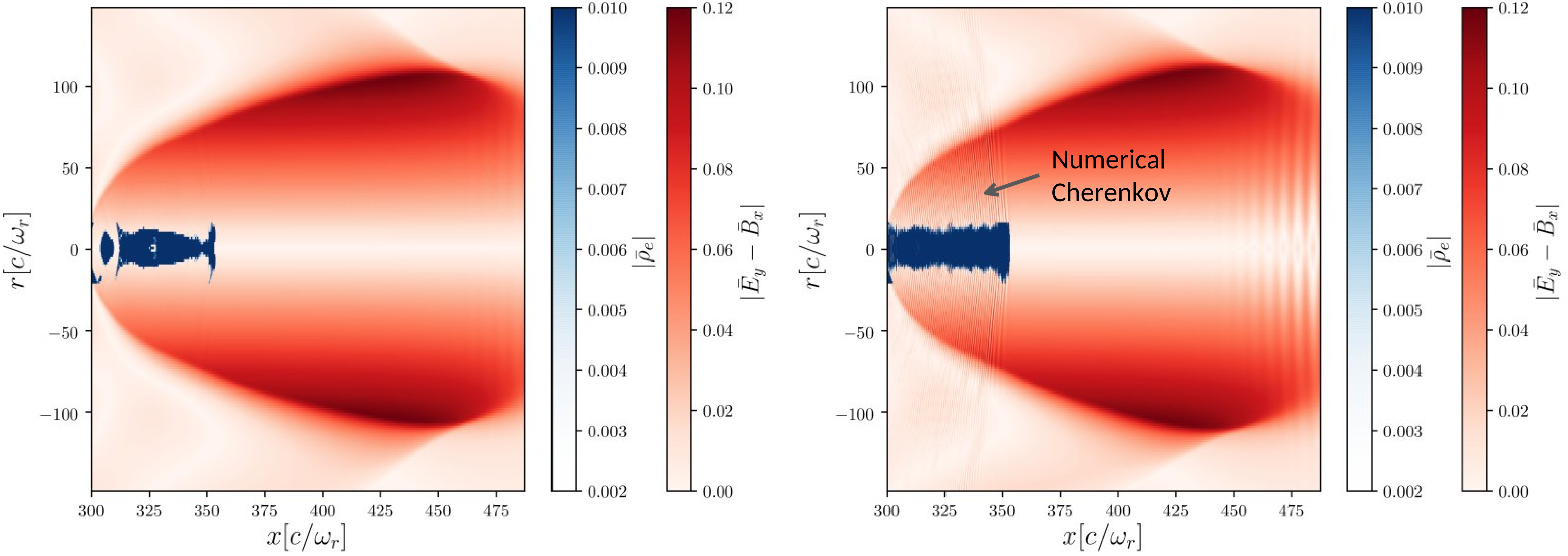
3) macro-particles merged per momentum cells



# Pseudo-spectral solver in cylindrical geometry

Pseudo-spectral

Finite-difference




Released soon

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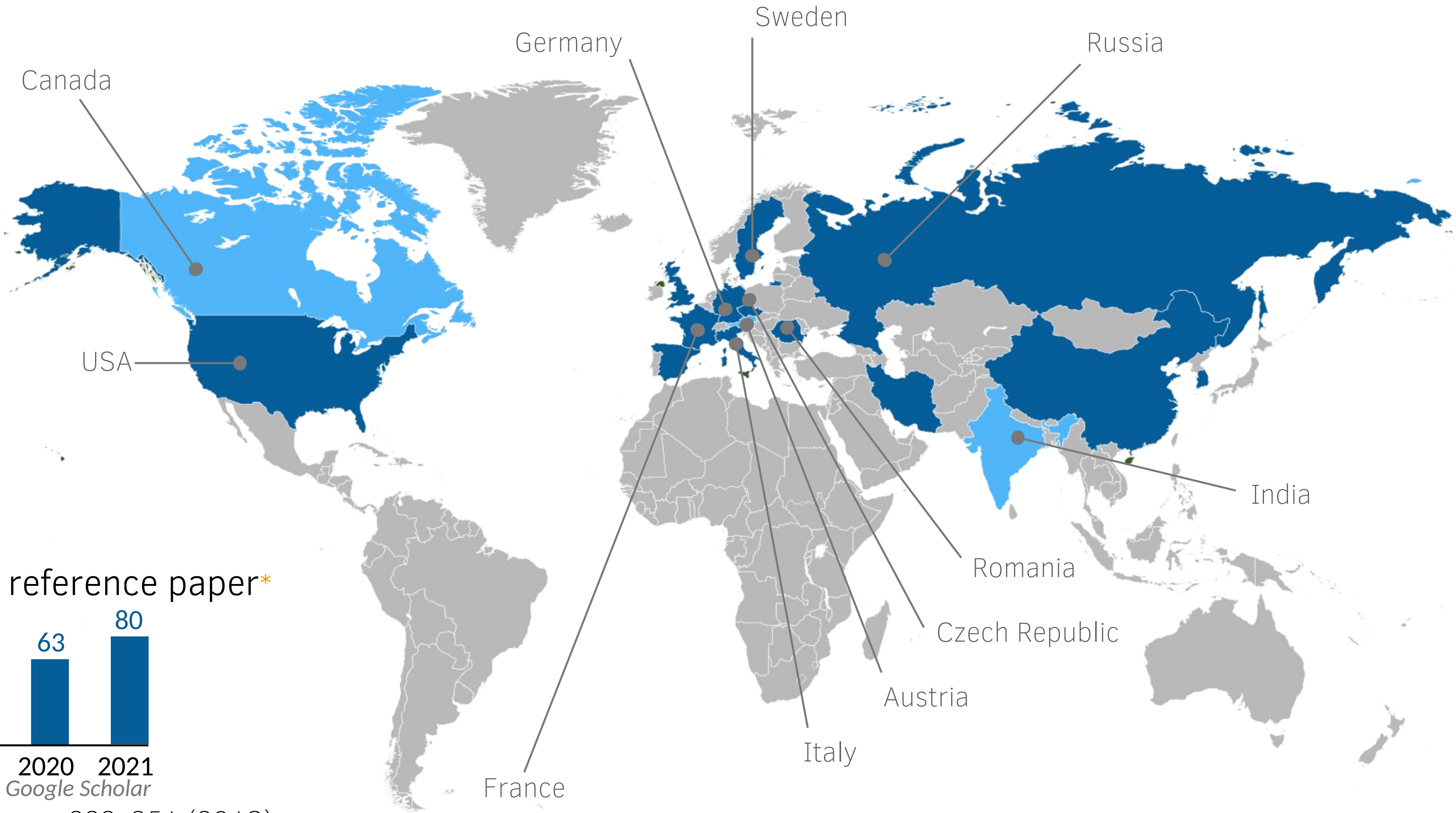
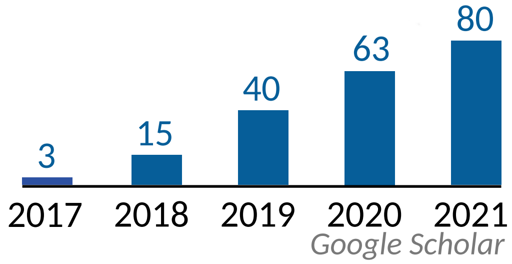
# Smilei's user community is international & steadily growing




200+ citations for Smilei reference paper*




*Dérouillat et al., Comp. Phys. Comm. 222, 351 (2018)

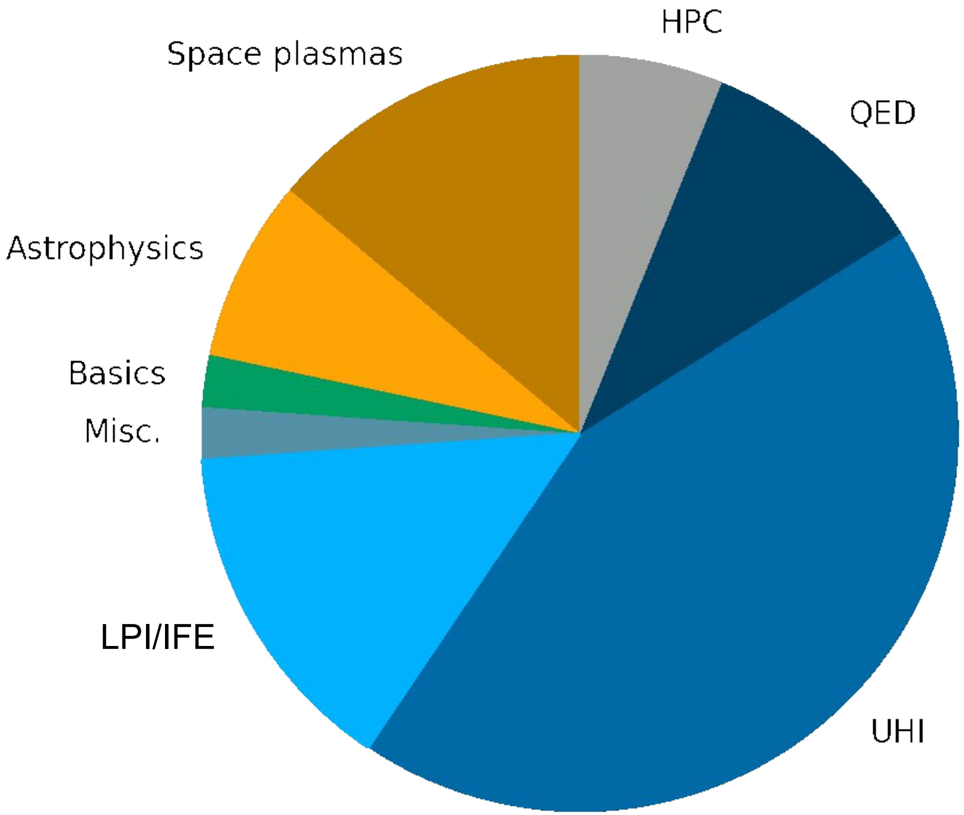
# A broad range of applications

## Scientific production is rich ...

100+ peer-reviewed papers have been published using Smilei
10+ PhD theses in France benefited from Smilei

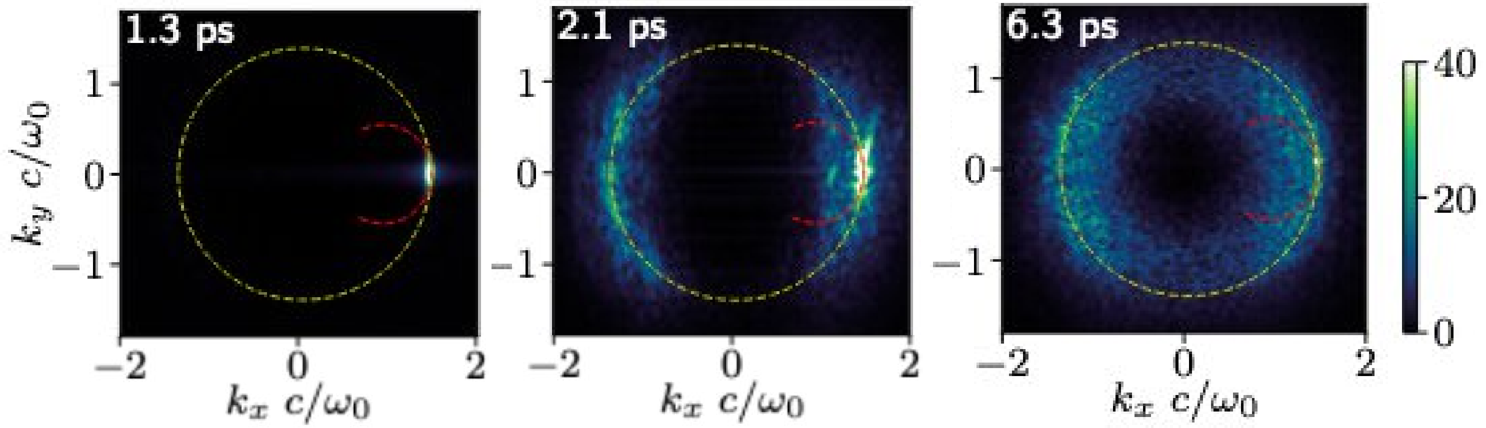
## ... and focuses on various applications

LPI/IFE : laser-plasma interaction / inertial fusion for energy
UHI : Ultra-high intensity
QED : Quantum electrodynamics (extreme light)
HPC : high-performance computing
Space plasmas & astrophysics



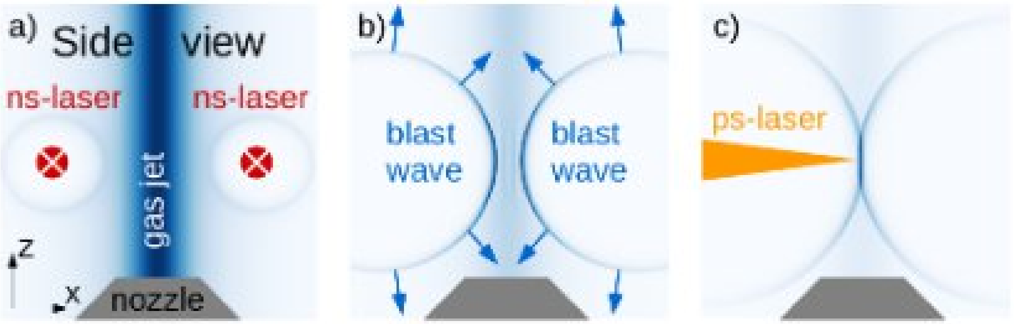
# Examples of recent work with Smilei

A laser-plasma interaction experiment to reproduce type III radio-solarbursts



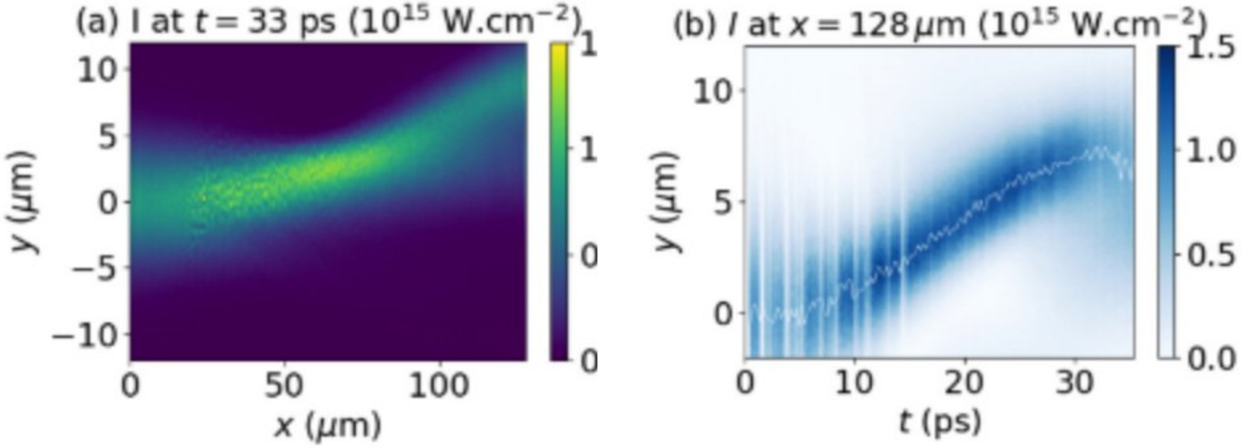

Marques et al. Phys. Rev. Lett. (2020)
Pérez et al. Phys. Plasmas. (2021)

Ion acceleration from laser-shaped near critical targets




Marques et al. Phys. Plasmas (2021)

Laser-plasma interaction for ICF



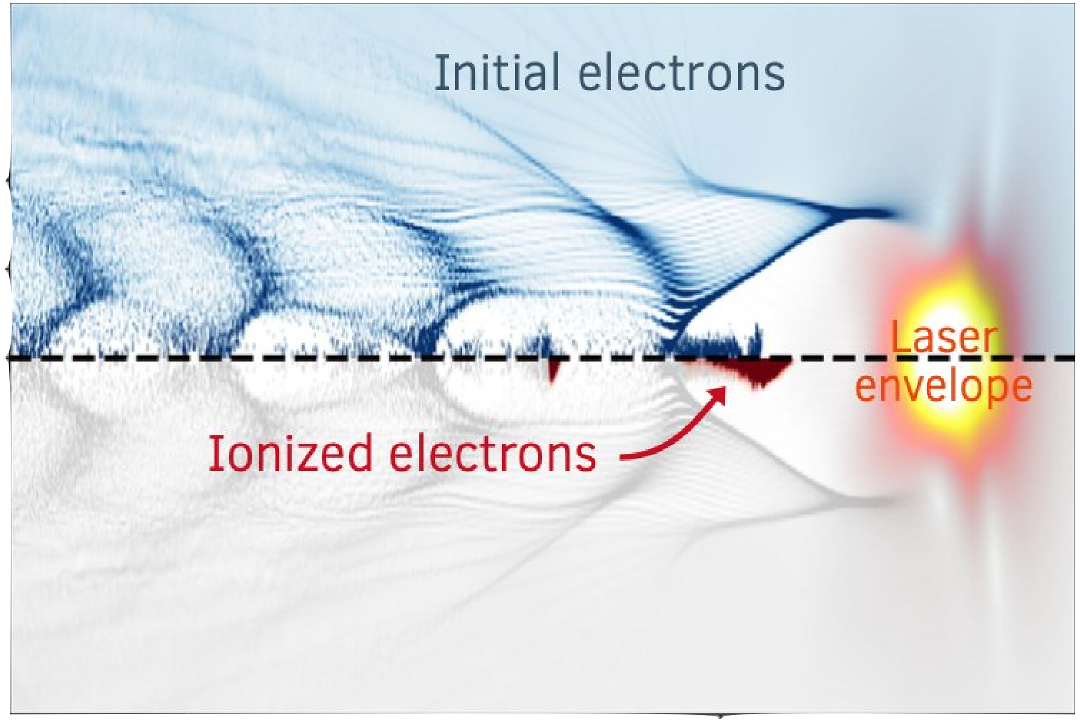

Ruyer et al. Phys. Plasmas. (2020)

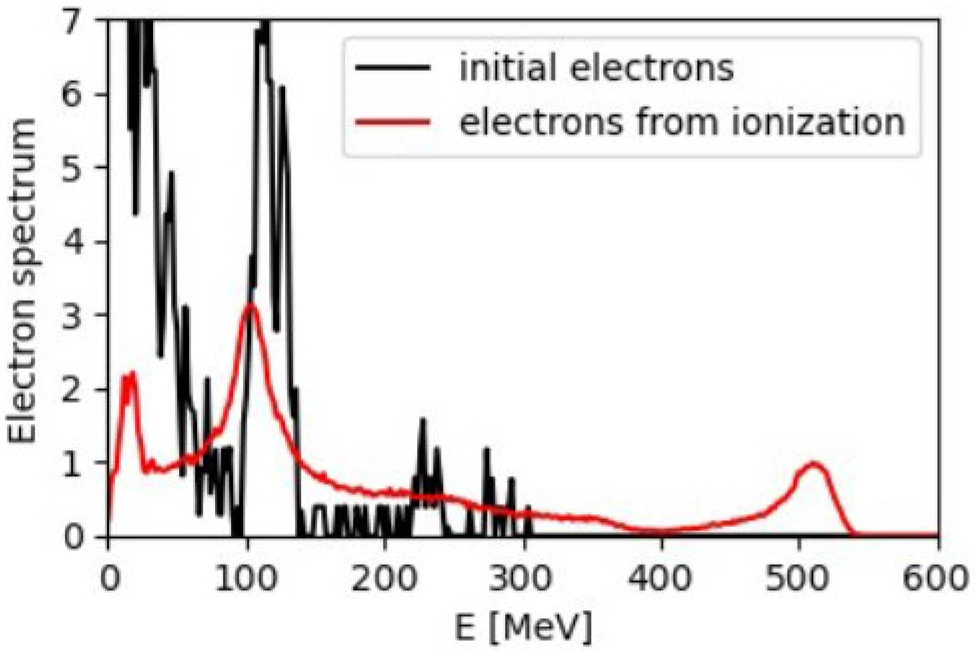
# Physics modules

- Ionization
- Collisions
- Radiation
- $e^+e^-$ pair creation
- Nuclear reaction

# Field ionization

New model for envelope ionization

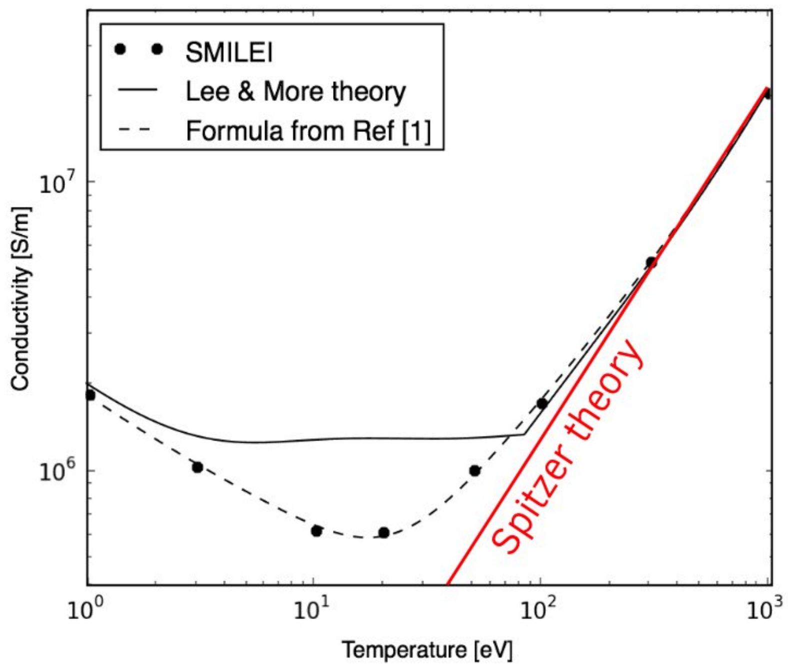


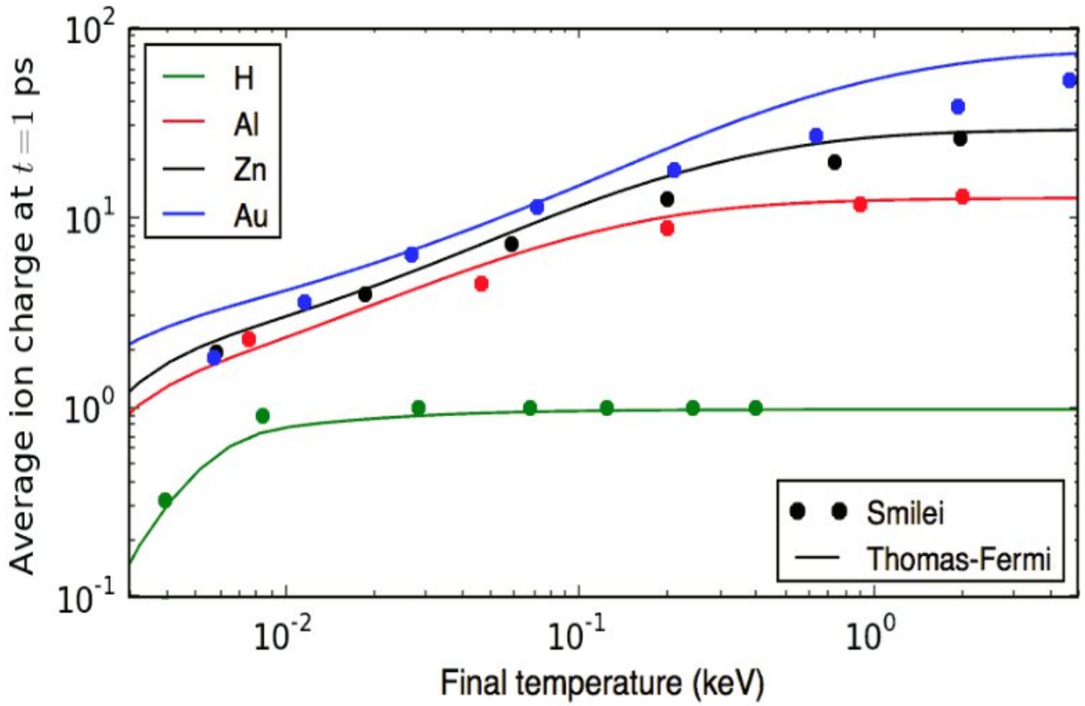




Nuter et al. Phys. Plasmas (2011)
F. Massimo et al., Phys. Rev. E 102, 033204 (2020)

# Collisions, collisional ionization & nuclear reactions

Collisions are critical for simulations of laser-solid interaction



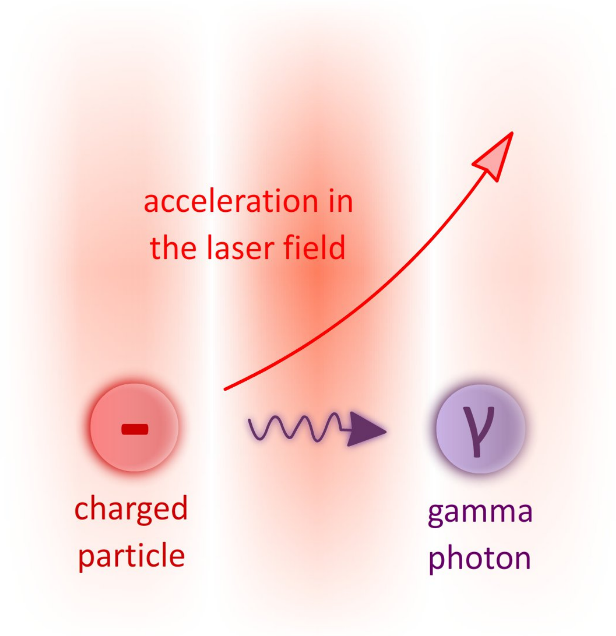




New in Smilei: D-D nuclear fusion

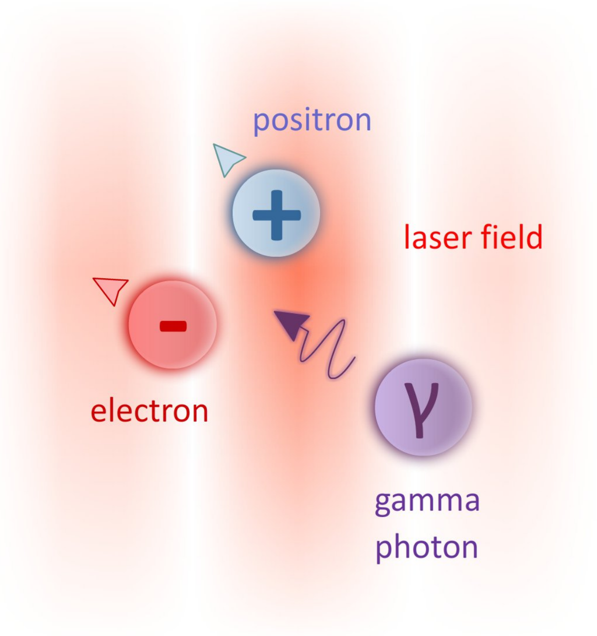
Coming soon: p-B fusion, and collisions with neutral atoms

# Strong-field QED processes

Inverse Compton Scattering




Breit-Wheeler pair creation




Lobet et al. Phys. Plasmas (2011)
Niel et al. Phys. Rev. E (2018); Phys. Plasma Control. Fusion (2018)

Smilei)

# Acknowledgements

## Funding agencies

PLAS@PAR Plasmas à Paris

P2IO Physique des 2 Infinis et des Origines

PALM Laboratoire d'Excellence Physique : Atomes Lumière Matière

Physique des Infinis Une Initiative Sorbonne Université

Institut Polytechnique de Paris | PLASMAScience

AIDAS AI Data Analytics and Scalable Simulations

## Contributing labs & institutions

Maison de la Simulation

LULI

LULI

LPP

irap astrophysique & planétologie

cnrs

École Polytechnique | Institut Polytechnique de Paris

iris

intel

LSI

CELIA

cea

Sorbonne Université

université Paris-Saclay

Thank you for your attention!