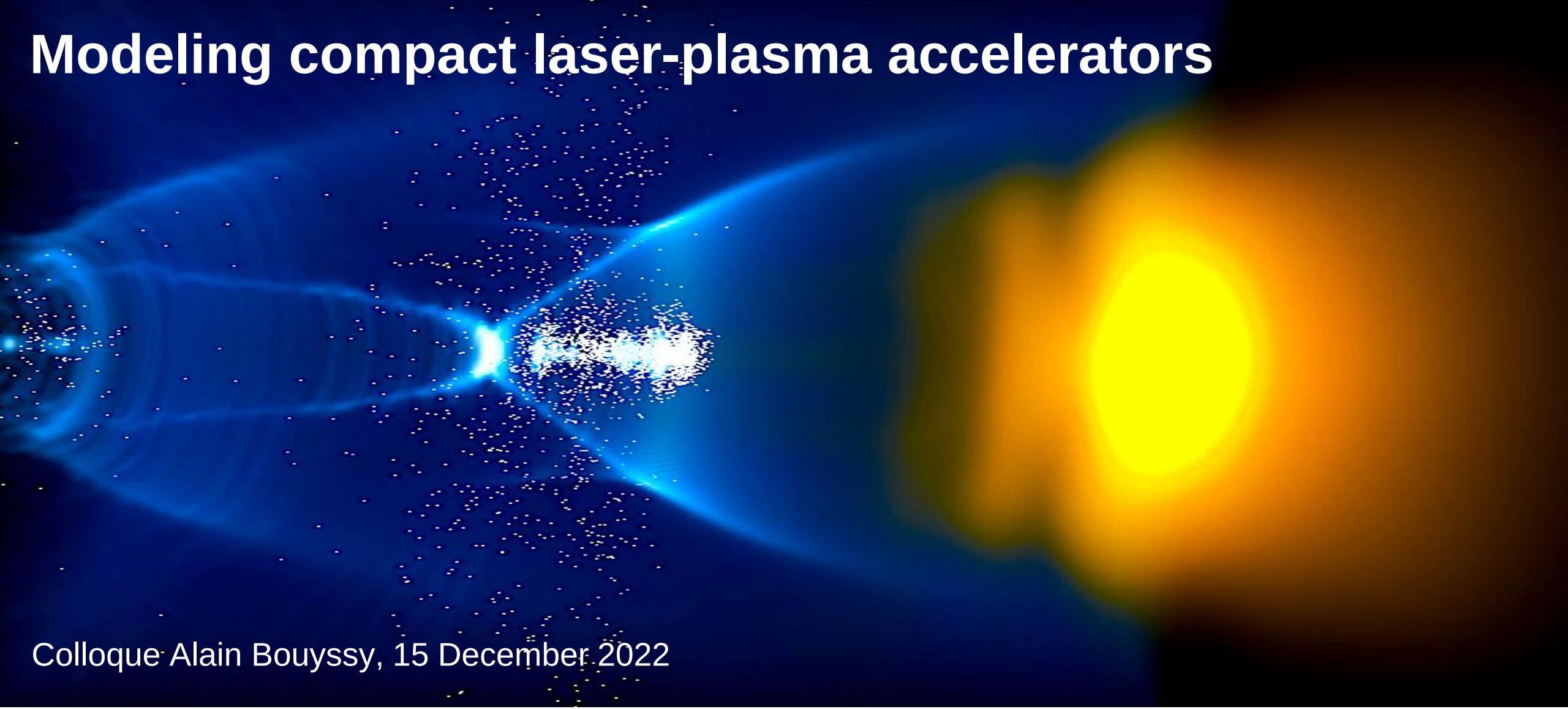
Modeling compact laser-plasma accelerators



Colloque Alain Bouyssy, 15 December 2022

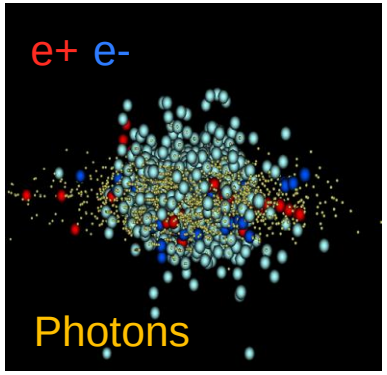
Francesco Massimo, Chargé de Recherche CNRS
Laboratoire de Physique des Gaz et des Plasmas

Electron accelerators have many applications

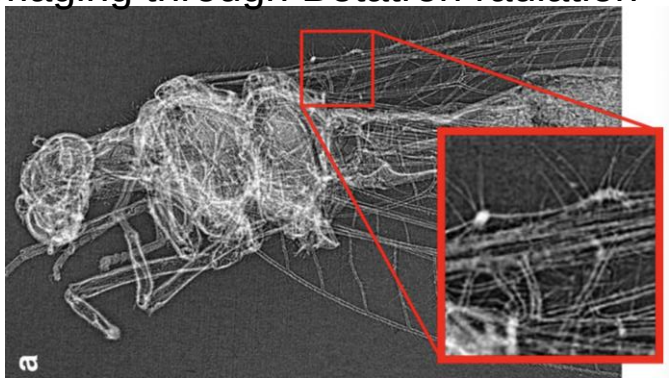
Fundamental Research:

- QED, Particle physics
- Matter Physics
- Biology

Smilei Simulation
of QED e+e- pairs creation
from photons



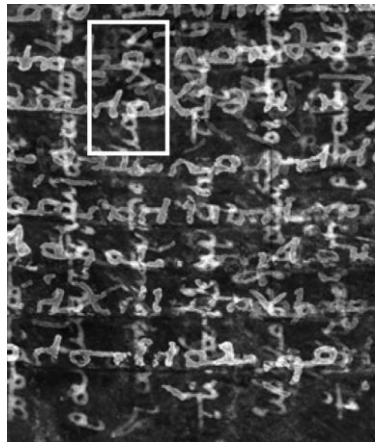
J. Wenz et al., Nat Comm 2014
Imaging through Betatron radiation



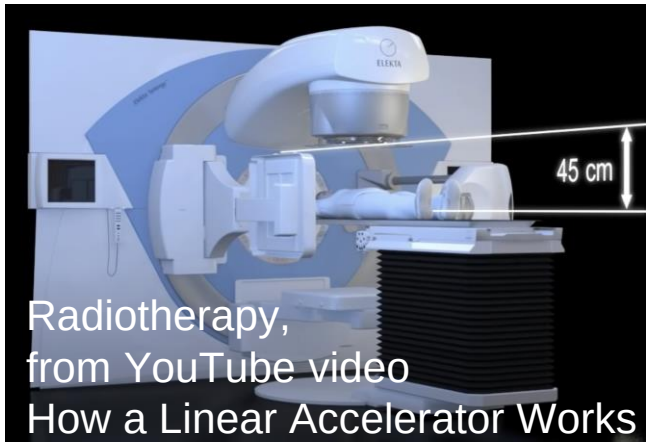
Medicine, Industry, Heritage, …:

- Cancer treatment, medical imaging,
- Electronic industry, study of materials
- Authentication of artwork,
- …

**Can we have
more compact, cheaper
electron accelerators
in the future?**

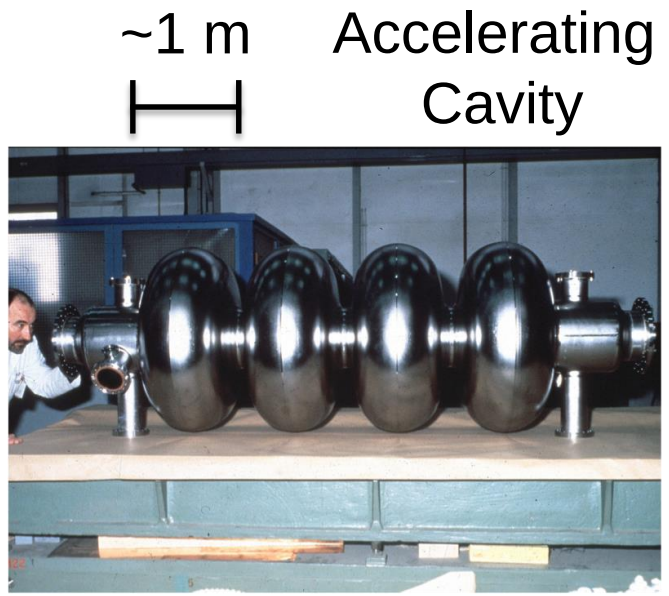


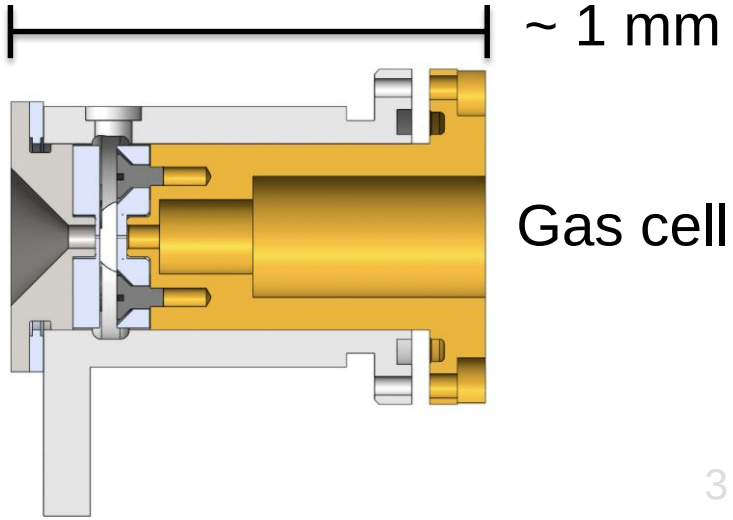
Hidden Archimede's Palimpsest,
revealed by SLAC's synchrotron radiation
in 2005 (U. Bergmann)



Laser-plasma accelerators: a compact alternative to conventional accelerators

Accelerator technology	Peak Accelerating Field	Acceleration length to gain 100 MeV
Radiofrequency metallic cavities	~10^2 MV/m	1 m
Laser Wakefield Acceleration*	~10^4 MV/m	10 mm

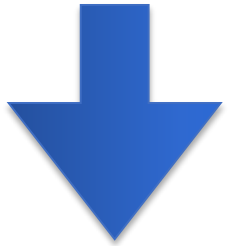




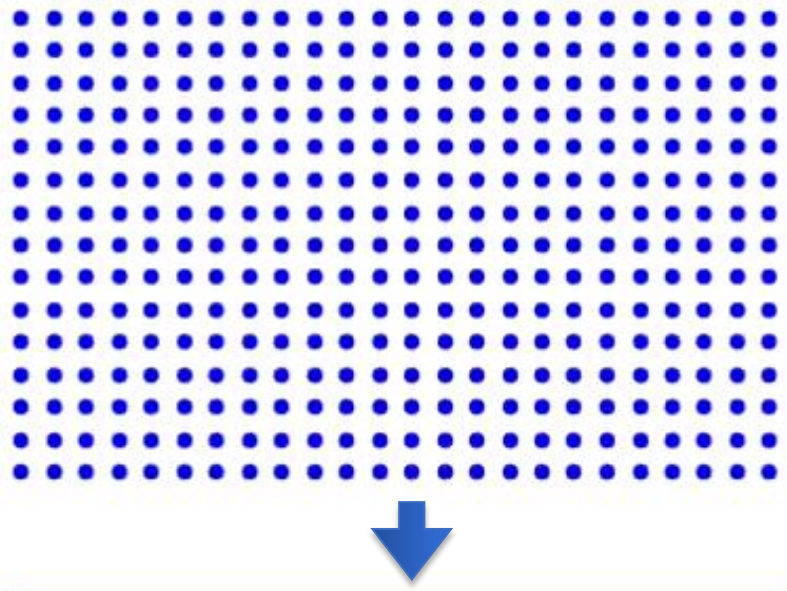
***Open challenge: improve performances of Laser Wakefield Acceleration. Numerical modeling is necessary!**

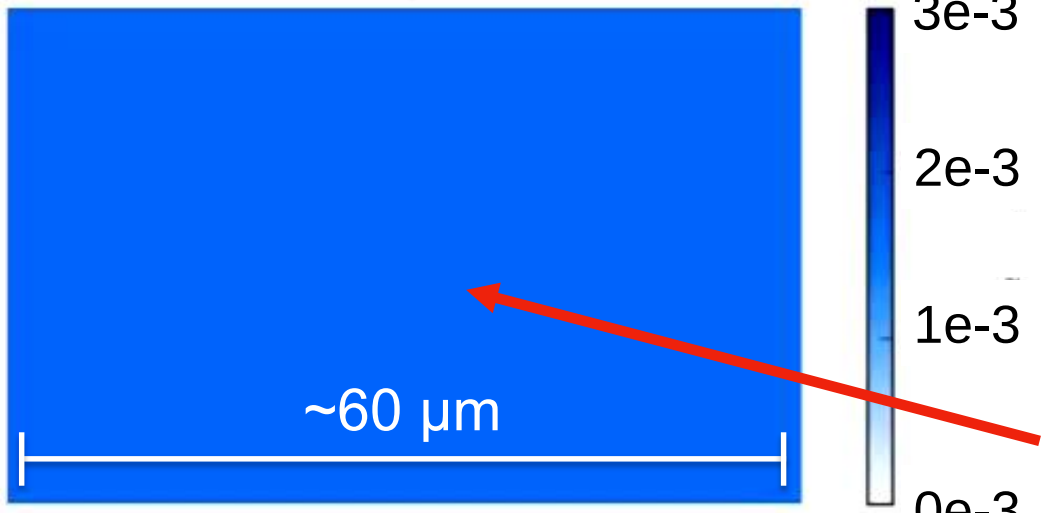
Electron Laser Wakefield Acceleration (LWFA): how it works

Sampling of plasma particles from simulation



Electron Charge Density (A.U.)





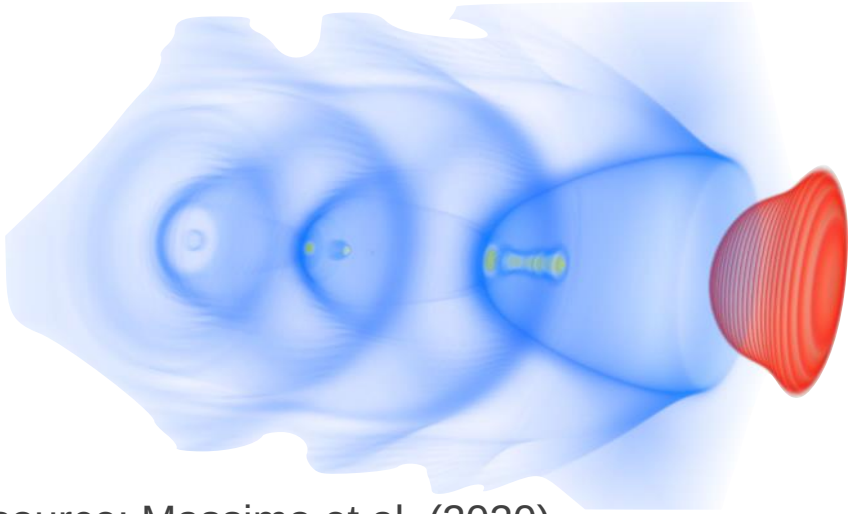
High intensity laser pulse,
Duration: 28 fs

- Electrons
- Heavy ions remain immobile

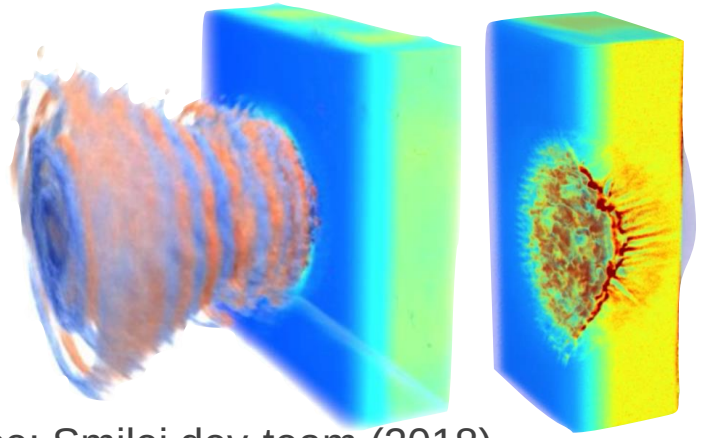
Relativistic electrons injected in this plasma wave can be accelerated

Extreme, nonlinear plasma physics requires advanced numerical modelling

Laser Plasma Interaction

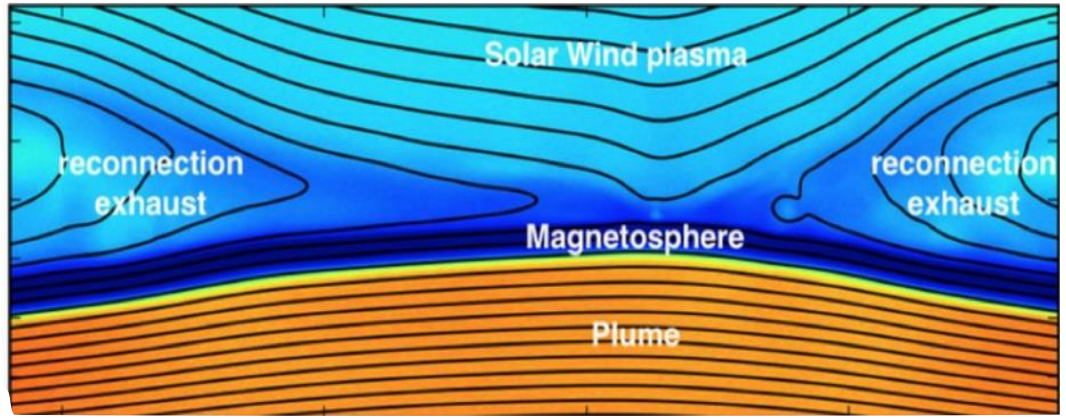


source: Massimo et al. (2020)



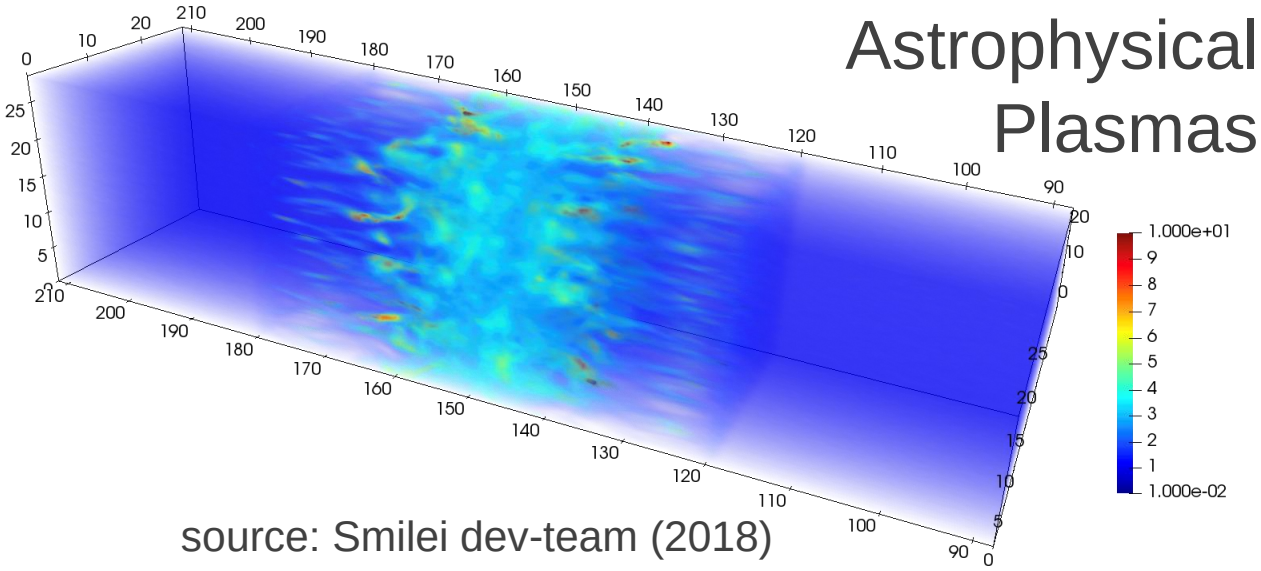
source: Smilei dev-team (2018)

Space Plasmas



source: Dargent et al. (2017)

Astrophysical Plasmas



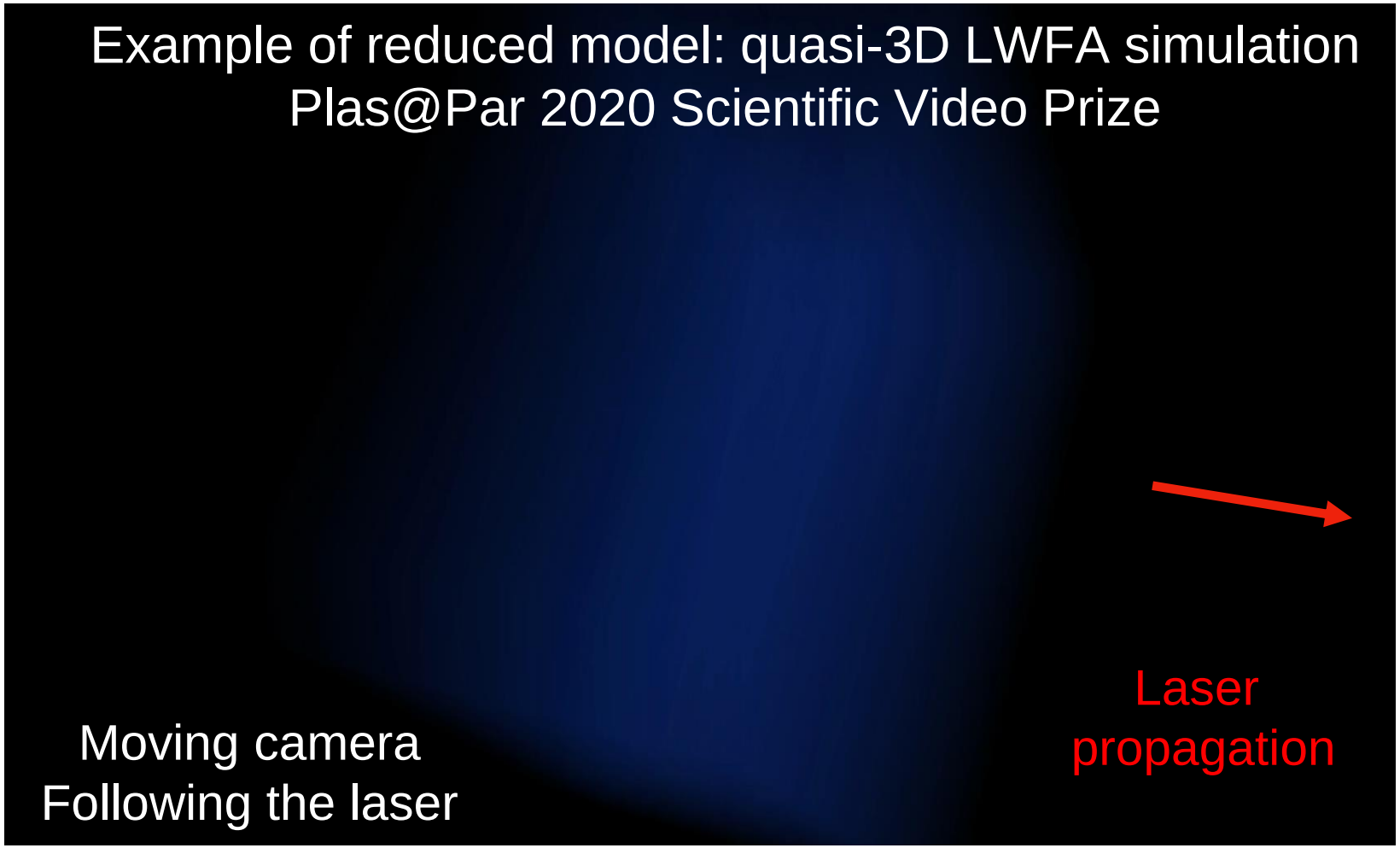
source: Smilei dev-team (2018)

But: advanced numerical modelling is expensive!

3D LWFA simulations:
1 mm plasma ~ 320 kcpu-hours ~ 10.2 k€

→ Quick but accurate models (i.e. reduced models) are needed

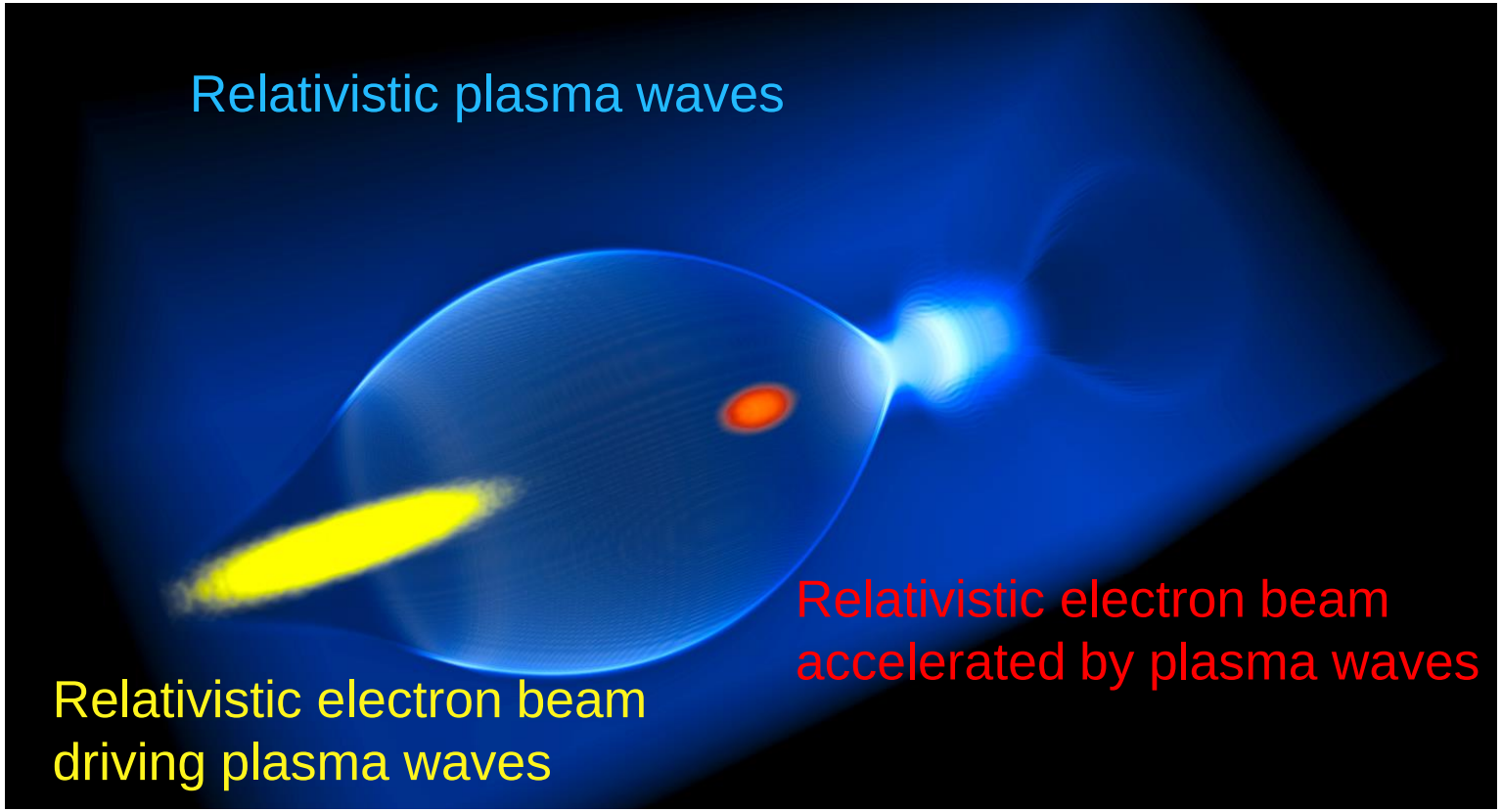
Example of reduced model: quasi-3D LWFA simulation
Plas@Par 2020 Scientific Video Prize



PhD thesis: Modeling High Brightness Electron Beam Acceleration by Plasma Wakefields

2012-2016
INFN PhD Program in Accelerator Physics,
Sapienza University, Rome

Scientific Challenge: how can we significantly speed-up simulations of beam driven plasma acceleration?



PhD thesis result: cylindrical, hybrid particle-fluid model
Speed-ups by orders of magnitude were measured

First Postdoctoral experience: Laser-plasma acceleration studies in a European Project

2012-2016
PhD Program in Accelerator Physics,
Sapienza University, Rome

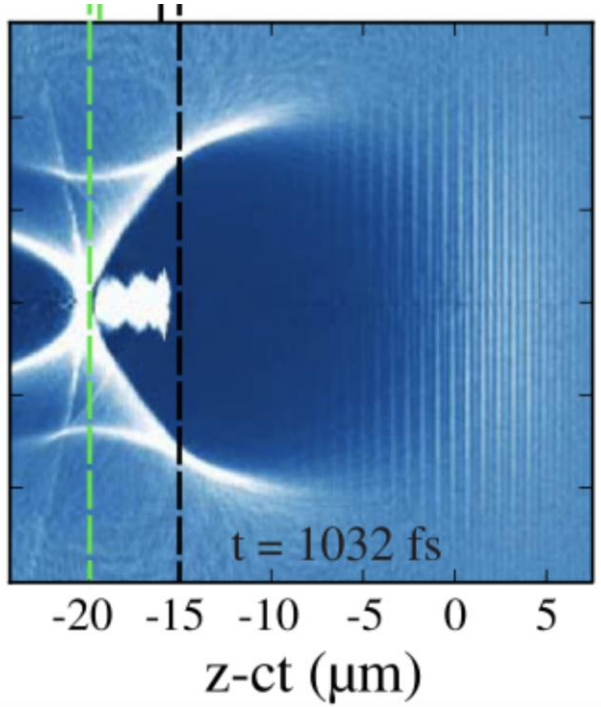
2016-2017
CNRS Researcher,
Laboratoire d'Optique Appliquée, Palaiseau

loa

ÉCOLE POLYTECHNIQUE

INSTITUT POLYTECHNIQUE DE PARIS

Scientific challenge: build a European, large scale, distributed plasma acceleration facility for users



EuPRAXIA

http://www.eupraxia-project.eu

European Strategy Forum on Research Infrastructures (ESFRI) 2021

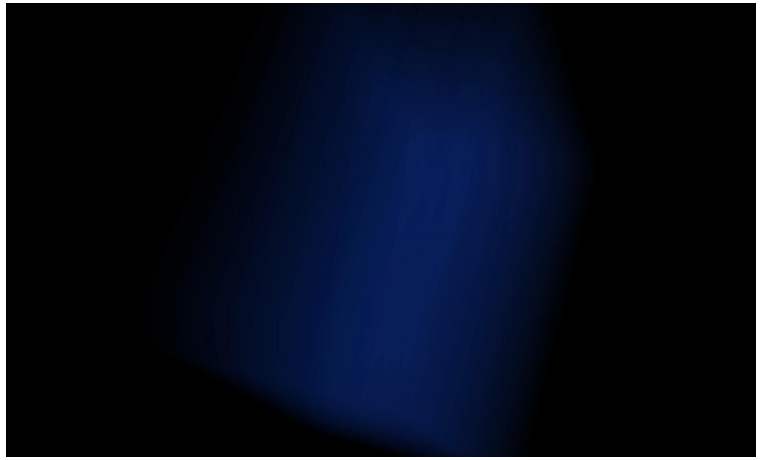
Main results: investigation of electron injection and acceleration using a sharp plasma density transition to improve beam quality

Second Postdoctoral experience: joining the Particle in Cell code Smilei's development team

Co-developing a research simulation code with physicists & HPC specialists

MAISON DE LA SIMULATION

Numerically **investigating** laser-plasma interaction



Using the code to **teach** plasma physics in the national and international community

Second Postdoctoral experience: Developing a quick laser-plasma acceleration model in Smilei

2012-2016
PhD Program in Accelerator Physics,
Sapienza University, Rome

2016-2017
CNRS Researcher,
Laboratoire d'Optique Appliquée, Palaiseau

2017-2020
CNRS Researcher,
Laboratoire Leprince-Ringuet, Palaiseau

Main results: development of a quick envelope model and related ionisation module to speed-up simulations by orders of magnitude

Relativistic plasma waves

Nitrogen electrons

Laser Pulse driving waves and ionising nitrogen

Third Postdoctoral experience:
Improving the execution of simulations using many cpu-cores

2012-2016
PhD Program in Accelerator Physics,
Sapienza University, Rome

2016-2017
CNRS Researcher,
Laboratoire d'Optique Appliquée, Palaiseau

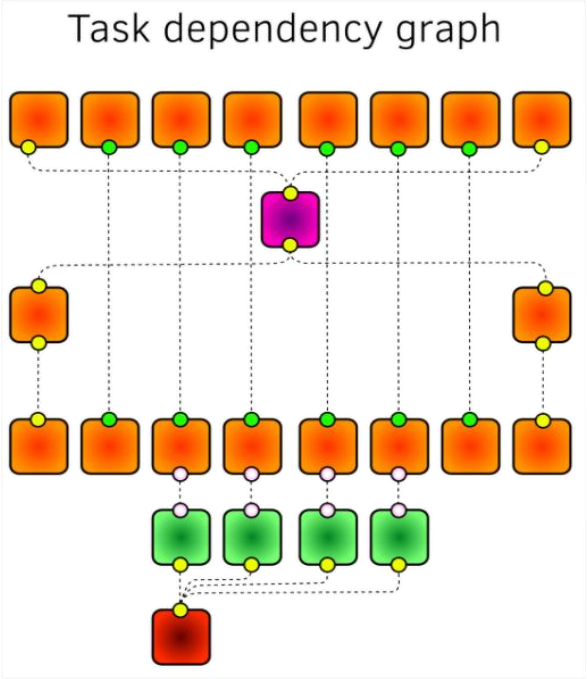
2017-2020
CNRS Researcher,
Laboratoire Leprince-Ringuet, Palaiseau

2020-2022
CEA Researcher Engineer
Maison de la Simulation, Gif-sur-Yvette

Scientific challenge:
how can we improve scalability of large plasma simulations?

Main result:
Task Parallelization of Smilei

The work is divided in small operations (tasks) that are completed asynchronously, improving the scaling of large simulations.



The Present and the Future: many advanced projects at LPGP

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PhD Program in Accelerator Physics,
Sapienza University, Rome

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CNRS Researcher,
Laboratoire d'Optique Appliquée, Palaiseau

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CNRS Researcher,
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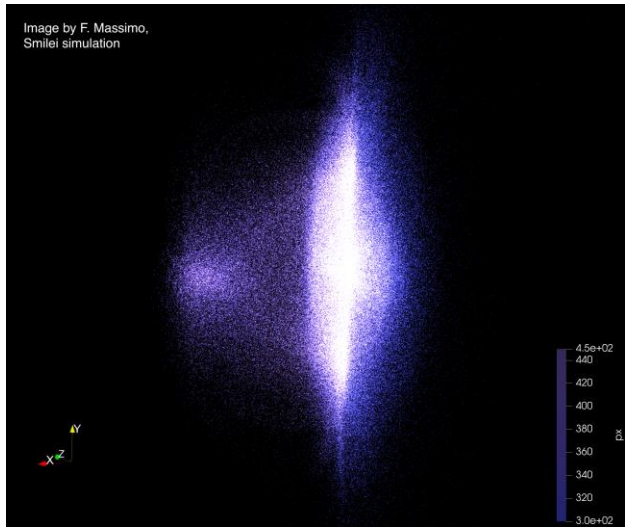
November 2022—> Future
CNRS Researcher
Laboratoire de Physique des Gaz et des Plasmas
Université Paris-Saclay

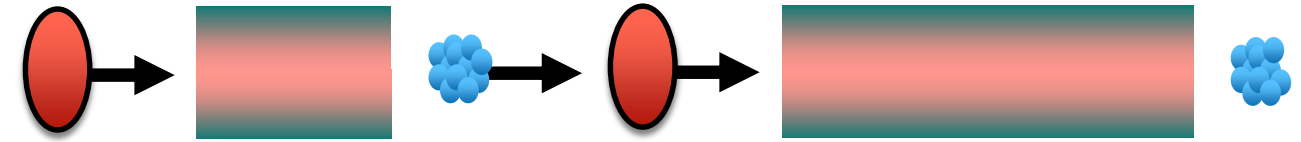


Simulated electron bunch from EARLI Project, Collaboration with CERN

Objective: build a LWFA to inject an electron beam in proton-driven waves propagating in a 10 m plasma

Future multi-stage experiments at Apollon

~100 MeV electrons



The Present and the Future: many advanced projects at LPGP

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CEA Researcher Engineer
Maison de la Simulation, Gif-sur-Yvette

November 2022—> Future
CNRS Researcher
Laboratoire de Physique des Gaz et des Plasmas
Université Paris-Saclay

Co-developing Smilei with several teams

Contributing to the European Project EuPRAXIA

Investigating the application of Artificial Intelligence to LWFA simulations with La Maison de la Simulation

Additional slides

Laser-plasma accelerators: a compact alternative to conventional accelerators

R. Assmann, European Project EuPRAXIA Preparatory Phase kick-off meeting (Nov 2022)

Conventional Acceleration (Max ~100 MV/m)

Plasma Acceleration (Max ~100 GV/m)

Scientific challenge: Obtain beam qualities suited for applications