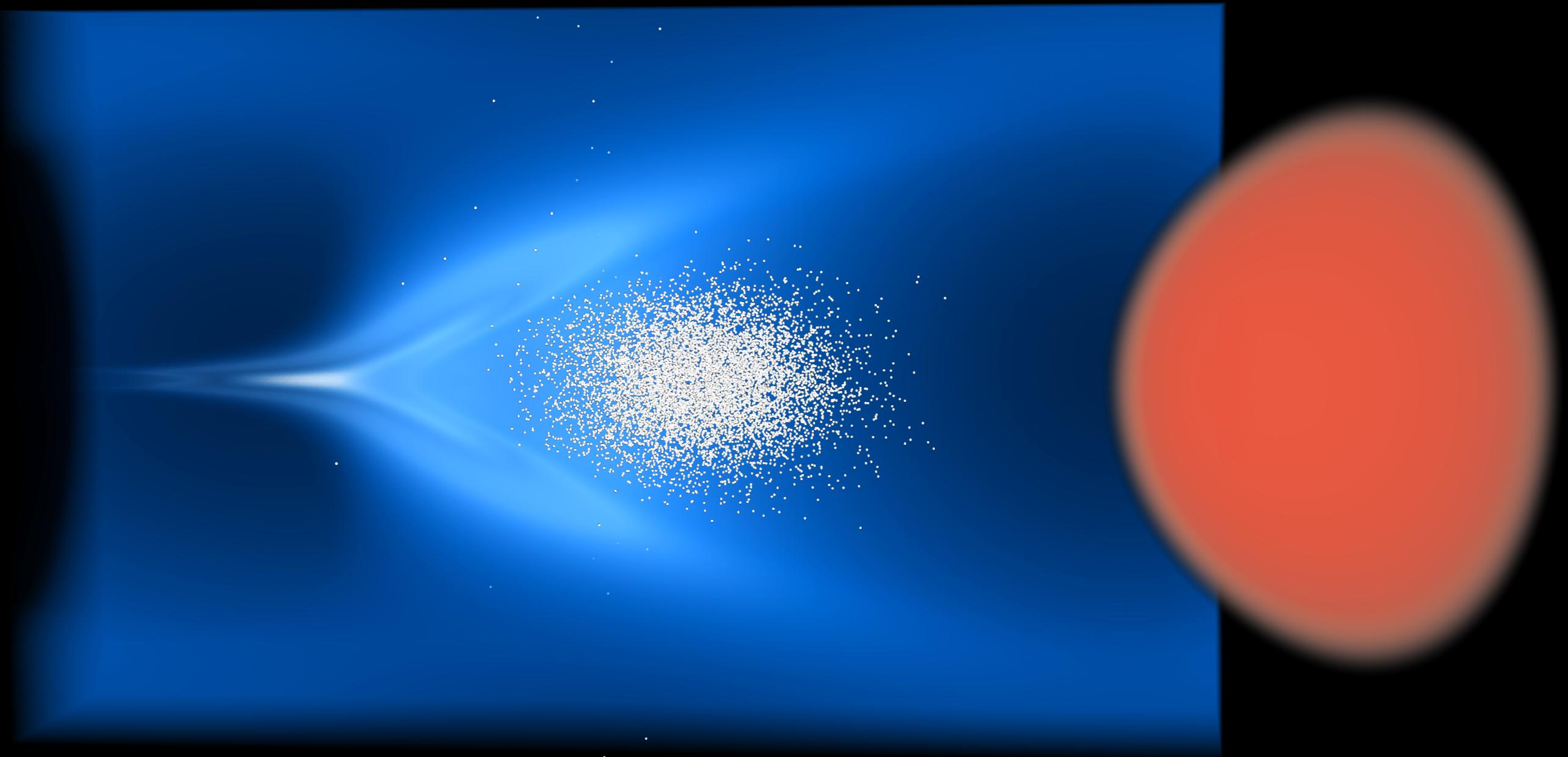


# Simulation of Laser Wakefield Acceleration



Francesco Massimo, LPGP

1-4 Dec 2023



# Outline

- Why plasma accelerators?
- Basics of plasma acceleration
- Numerical simulation of plasma acceleration: PIC codes
- The PIC code Smilei
- Introduction to the case study and the practical

# Outline

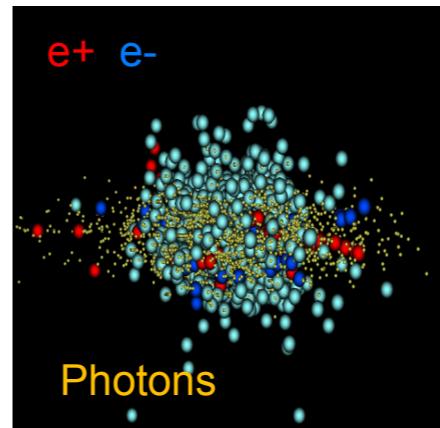
- Why plasma accelerators?
- Basics of plasma acceleration
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- The PIC code Smilei
- Introduction to the case study and the practical

# Applications of high energy electrons (just a few )

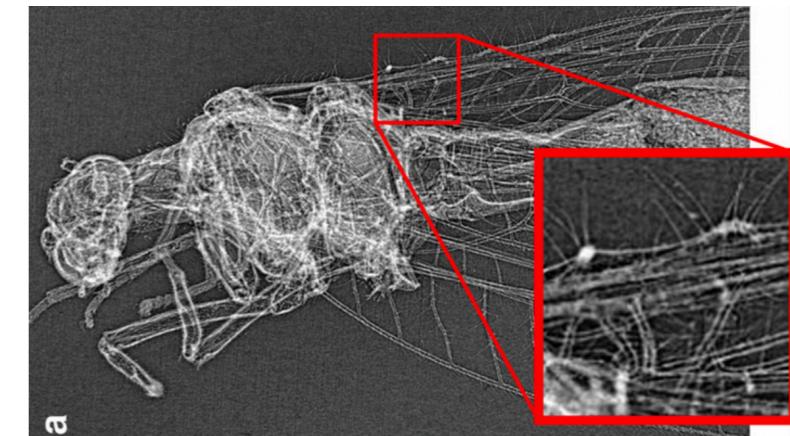
## Fundamental Research:

- 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
- ...



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



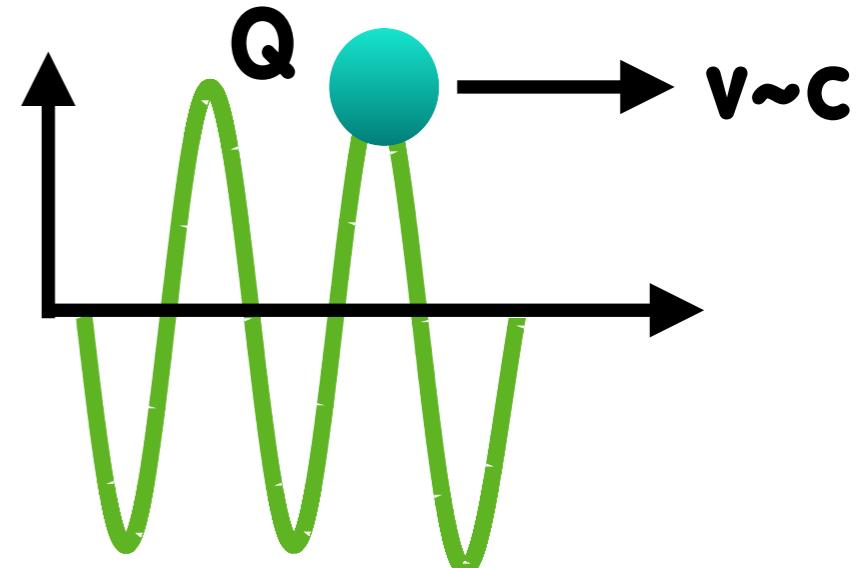
# Particle accelerators size and cost

Relativistic charge **Q**

In an accelerating cavity of length **L**

With peak accelerating field **E**

**Electric  
Field**



$$\text{Maximum energy gain} = Q E L$$

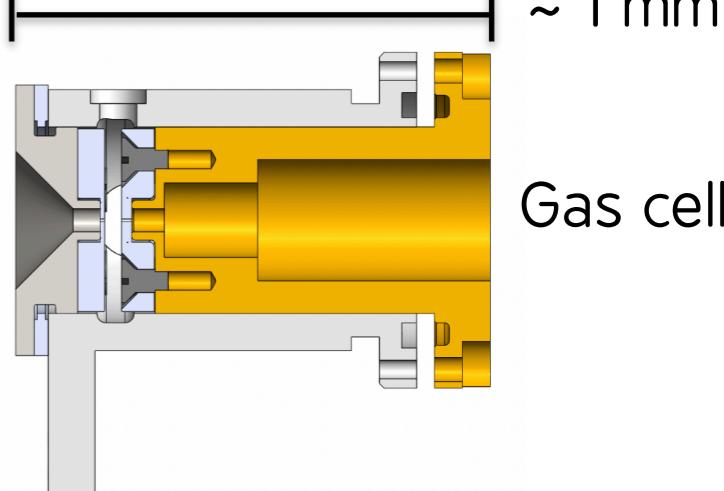
Given a target energy,

if **E** is limited by technology, **L** increases

→ need more metallic cavities

→ the accelerator size and cost increase

# Particle accelerators size and cost

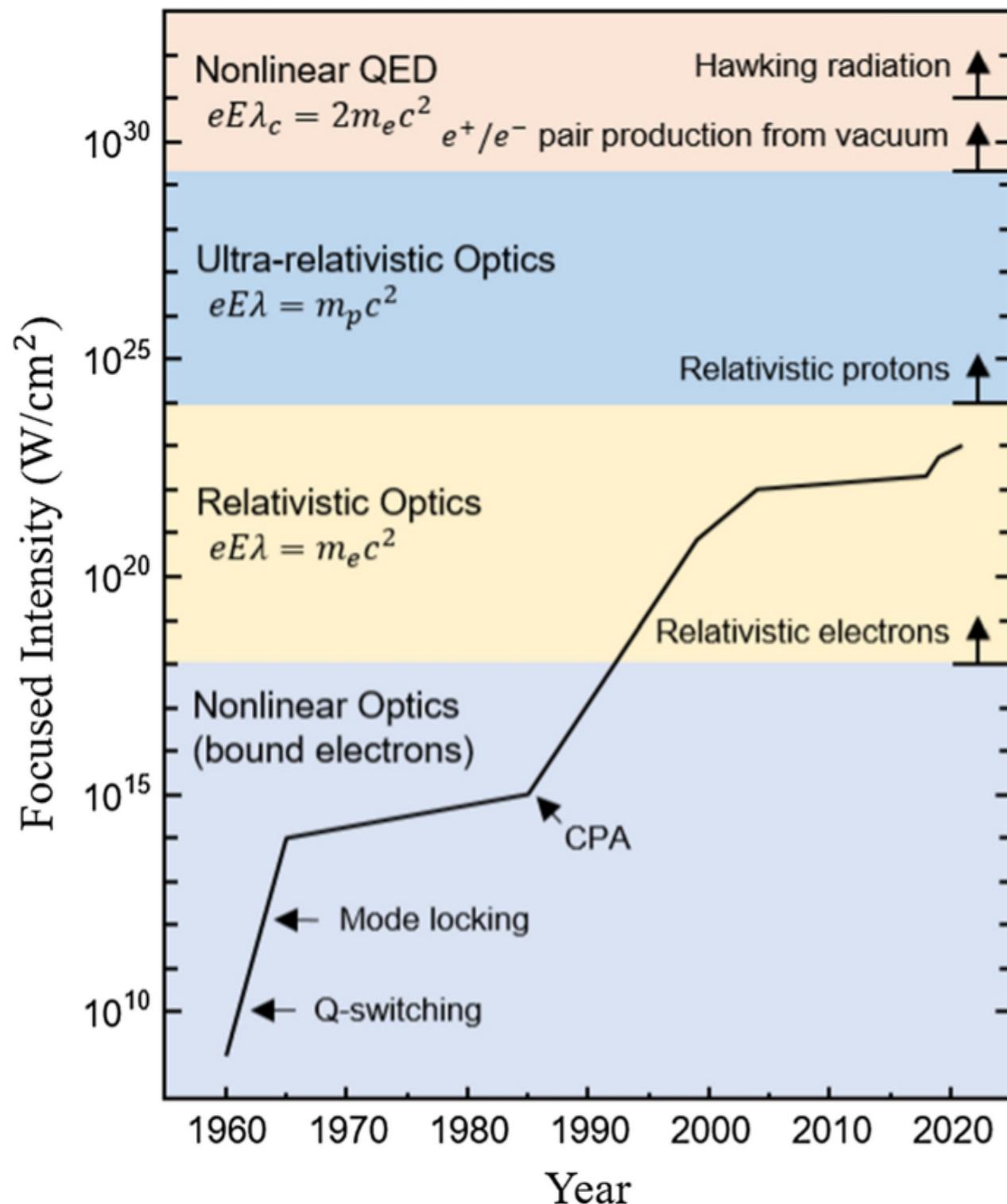
Accelerator technology	Peak Accelerating Field	Acceleration length to gain 100 MeV	~1 m H Accelerating Cavity
Radiofrequency metallic cavities	$\sim 10^2$ MV/m	1 m	
Laser Wakefield Acceleration (LWFA)*	$\sim 10^4$ MV/m	0.01 mm	

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

# Outline

- Why plasma accelerators?
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# High Intensity Lasers and their interaction with matter



## Techniques:

- Chirped Pulse Amplification
- Femtosecond Lasers
- Nonlinear Optics
- ...

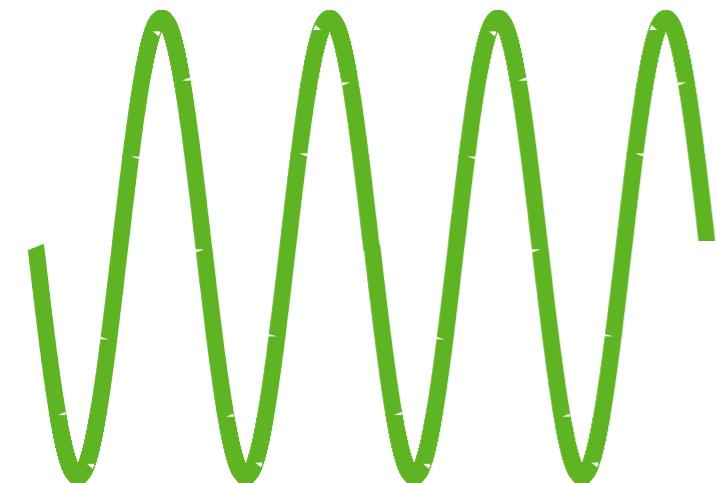
## Physics Domains:

- Relativistic Fluids
- Physics of Relativistic Plasmas
- Relativistic Optics
- Laboratory Astrophysics

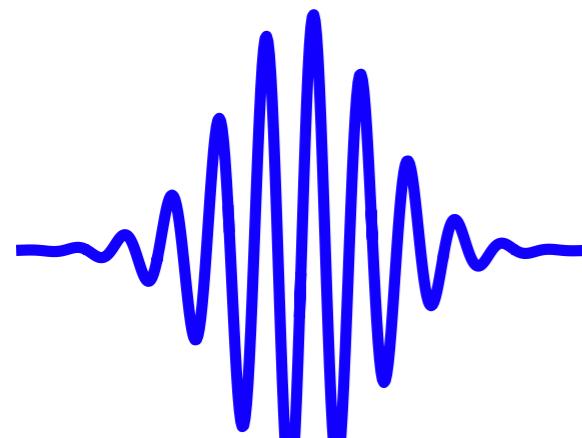
## Applications:

- Electron and ion sources
- Acceleration of particles
- Radiation sources (UV, X,  $\gamma$ )
- Novel, high resolution diagnostics
- Pump-probe measurements

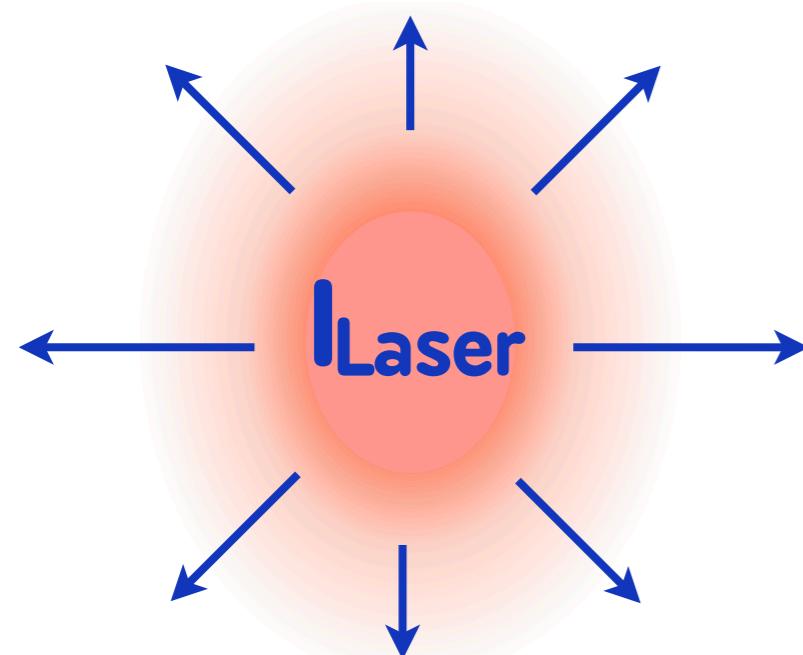
# Ponderomotive Force: the trigger for laser wakefield excitation in plasmas



Electron in infinite plane wave:  
Oscillating Force



Electron in finite laser pulse:  
Oscillating Force + Ponderomotive Force



$$F_{\text{pond}} \propto -\nabla I_{\text{Laser}} \quad (\text{a.k.a. radiation pressure})$$

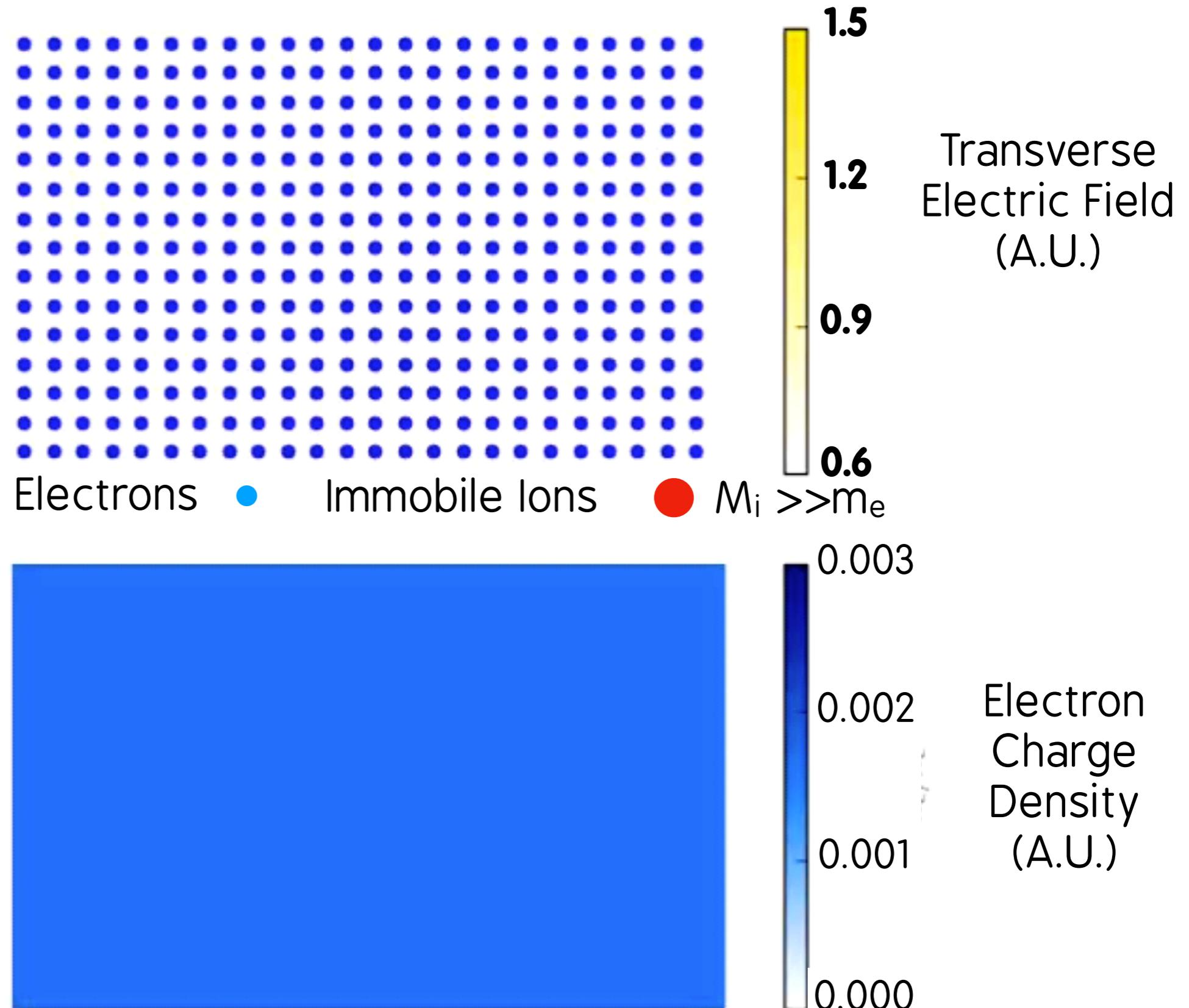
# Laser Wakefield Acceleration (LWFA): plasma wave excitation by the laser ponderomotive force

Laser Beam  
Duration: 28 fs

Ponderomotive  
Force:  
 $F = -\nabla I_{\text{Laser}}$

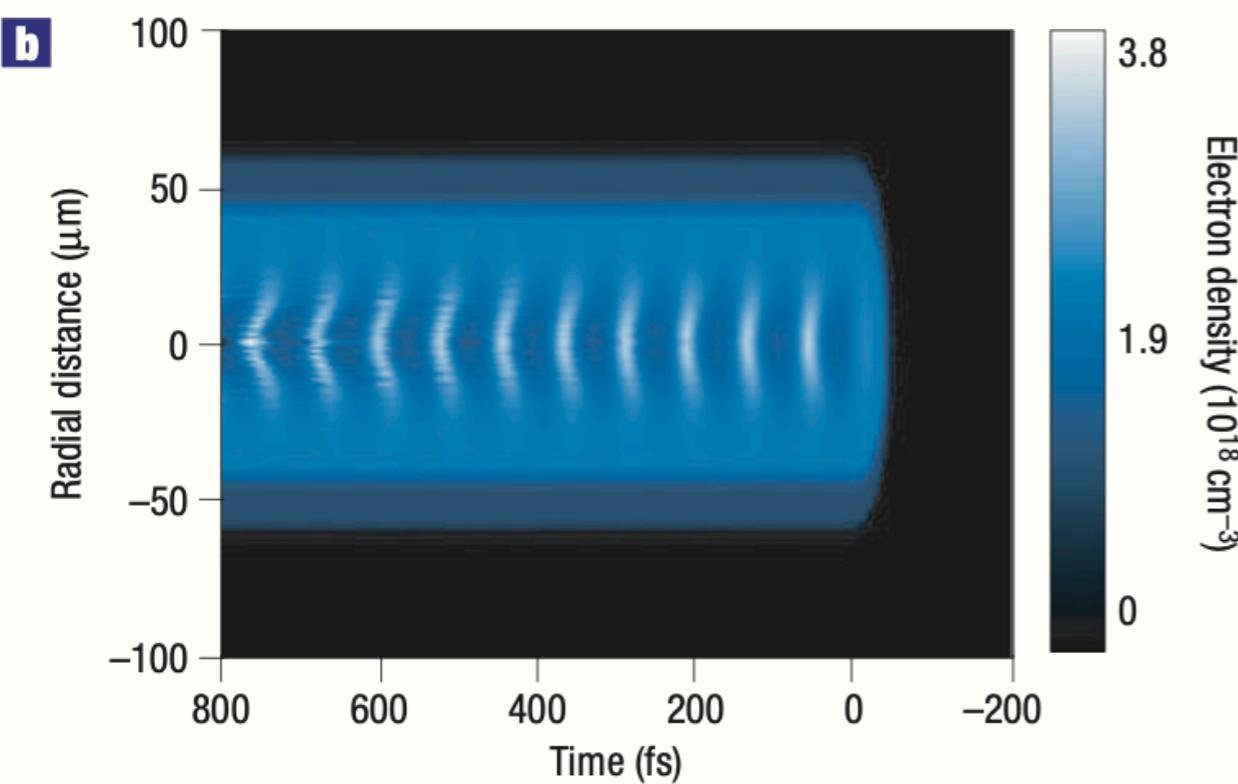
Plasma density:  
 $3 \cdot 10^{18} \text{ cm}^{-3}$

Plasma  
wavelength:  
 $\sim 20 \mu\text{m}$

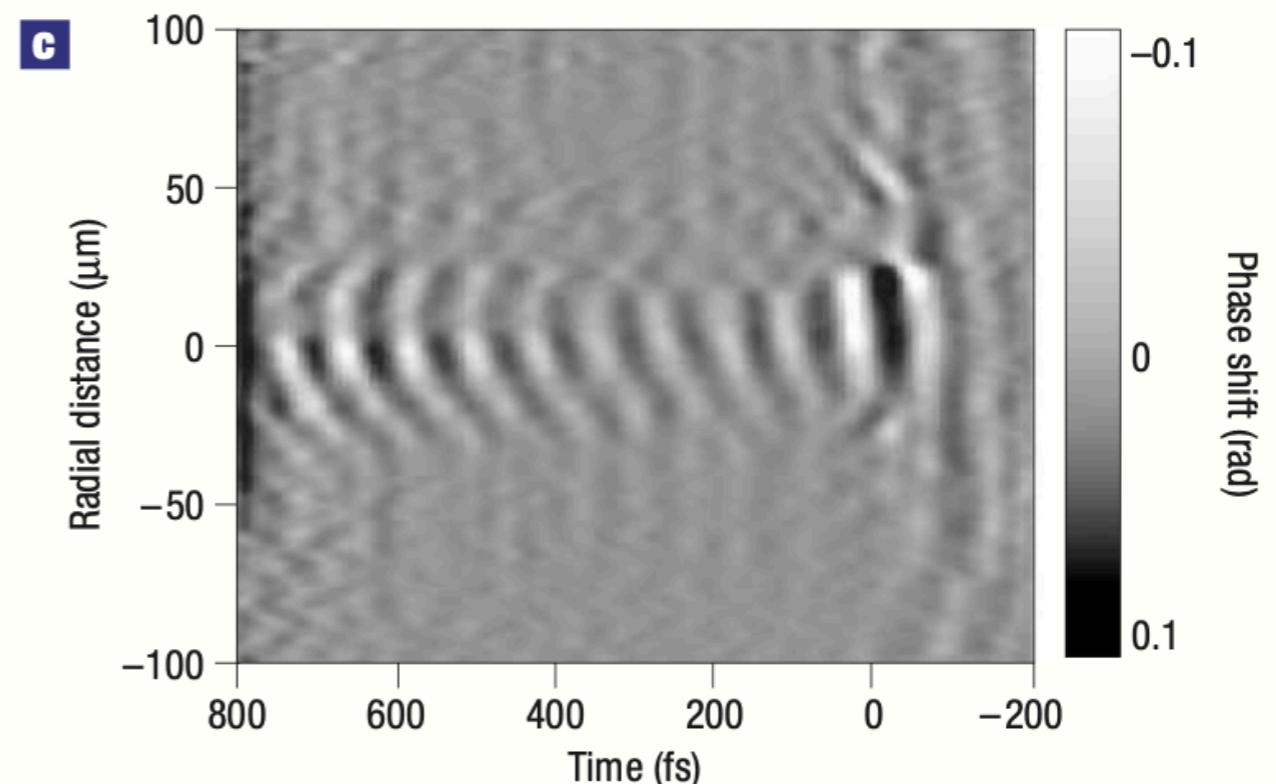


# Laser Wakefield Acceleration (LWFA): visualising the plasma waves

Simulation



Experiment

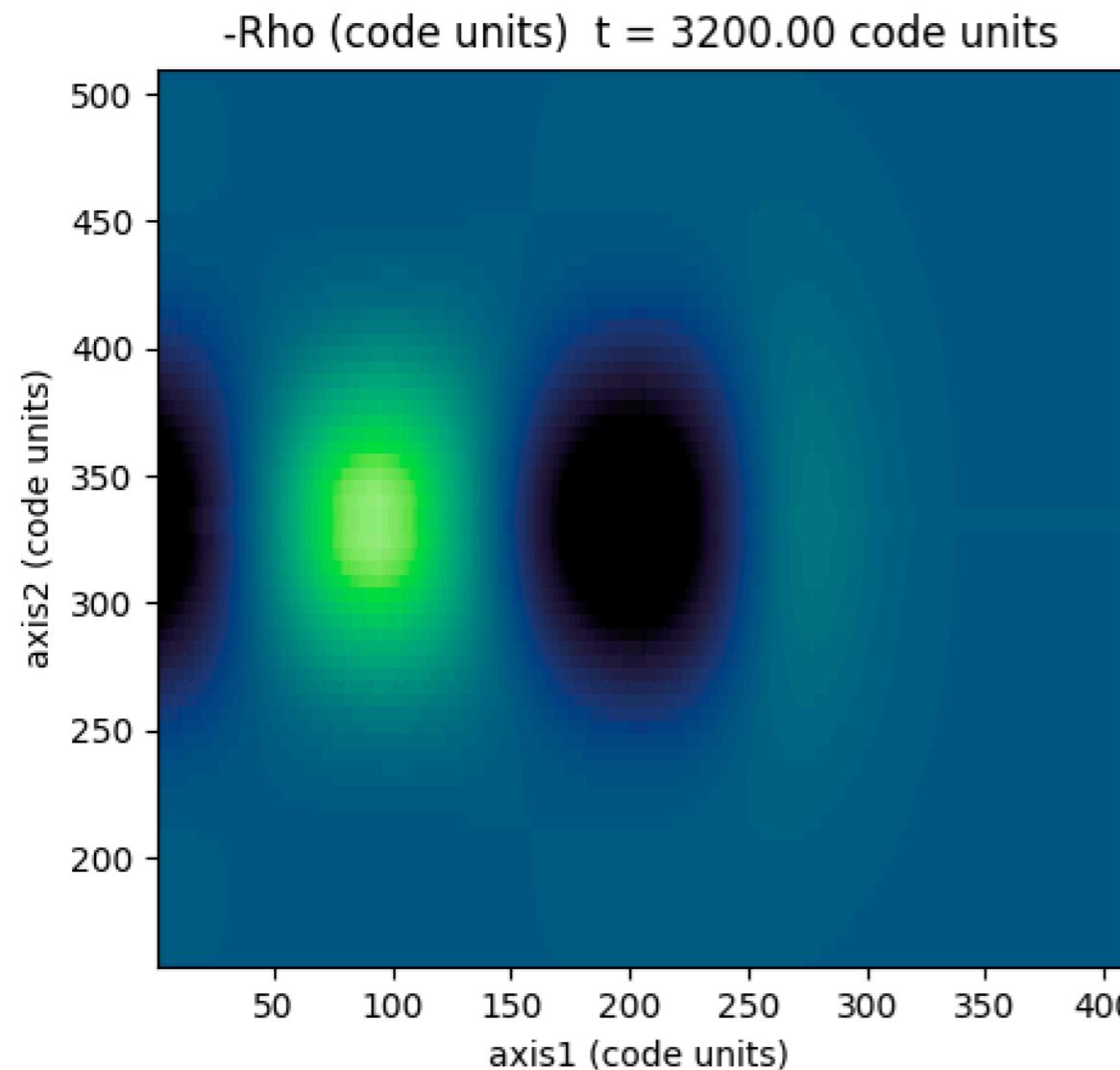


N. Matlis et al., Snapshots of laser wakefields, Nature Physics (2006)

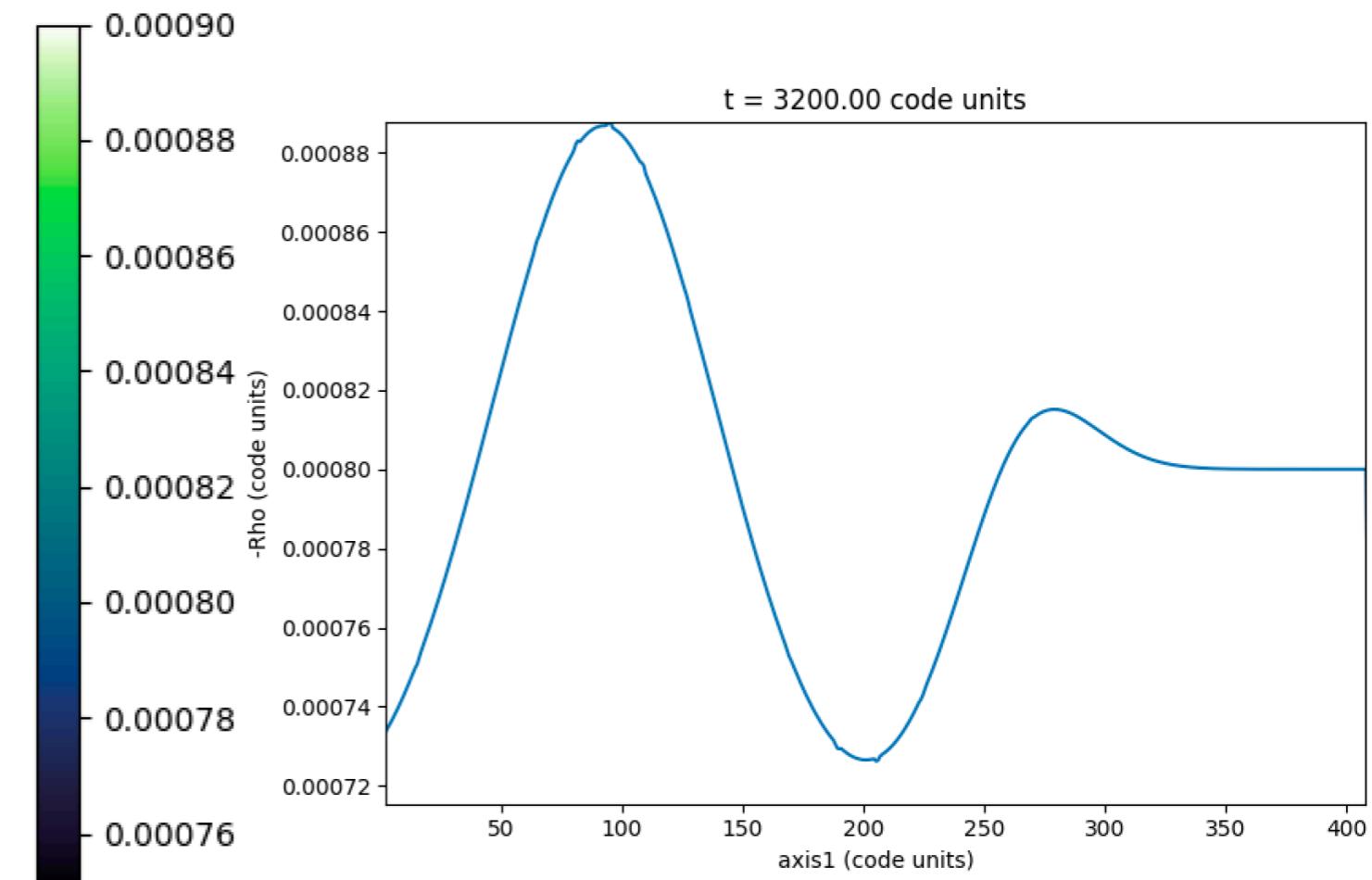
# Laser wakefield excitation: linear regime

$a_0$  = normalized laser peak field =  $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

**$a_0 \ll 1$ : Linear regime**  
**Sinusoidal plasma waves at the plasma frequency**



2D charge density

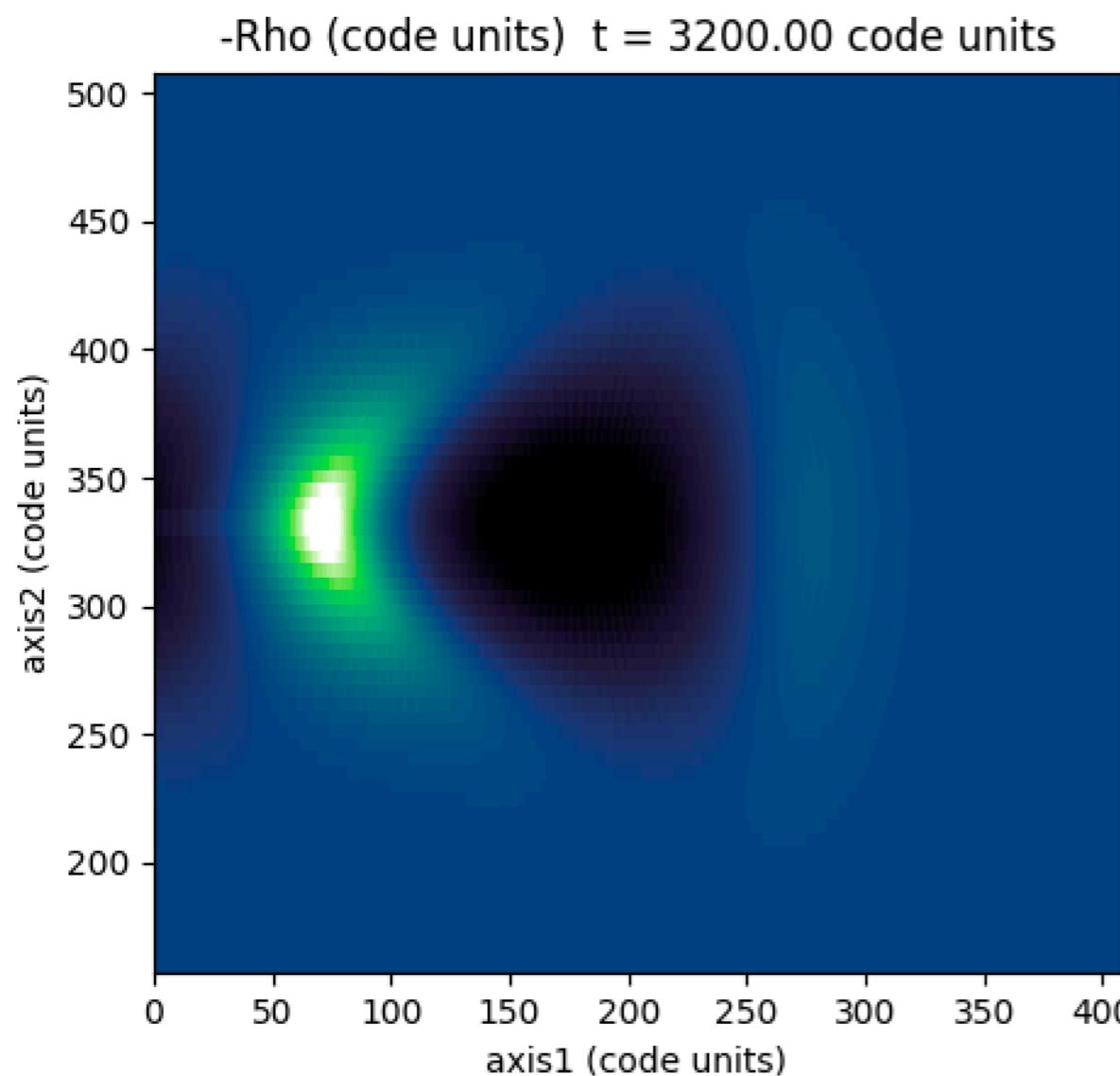


1D charge density  
on propagation axis

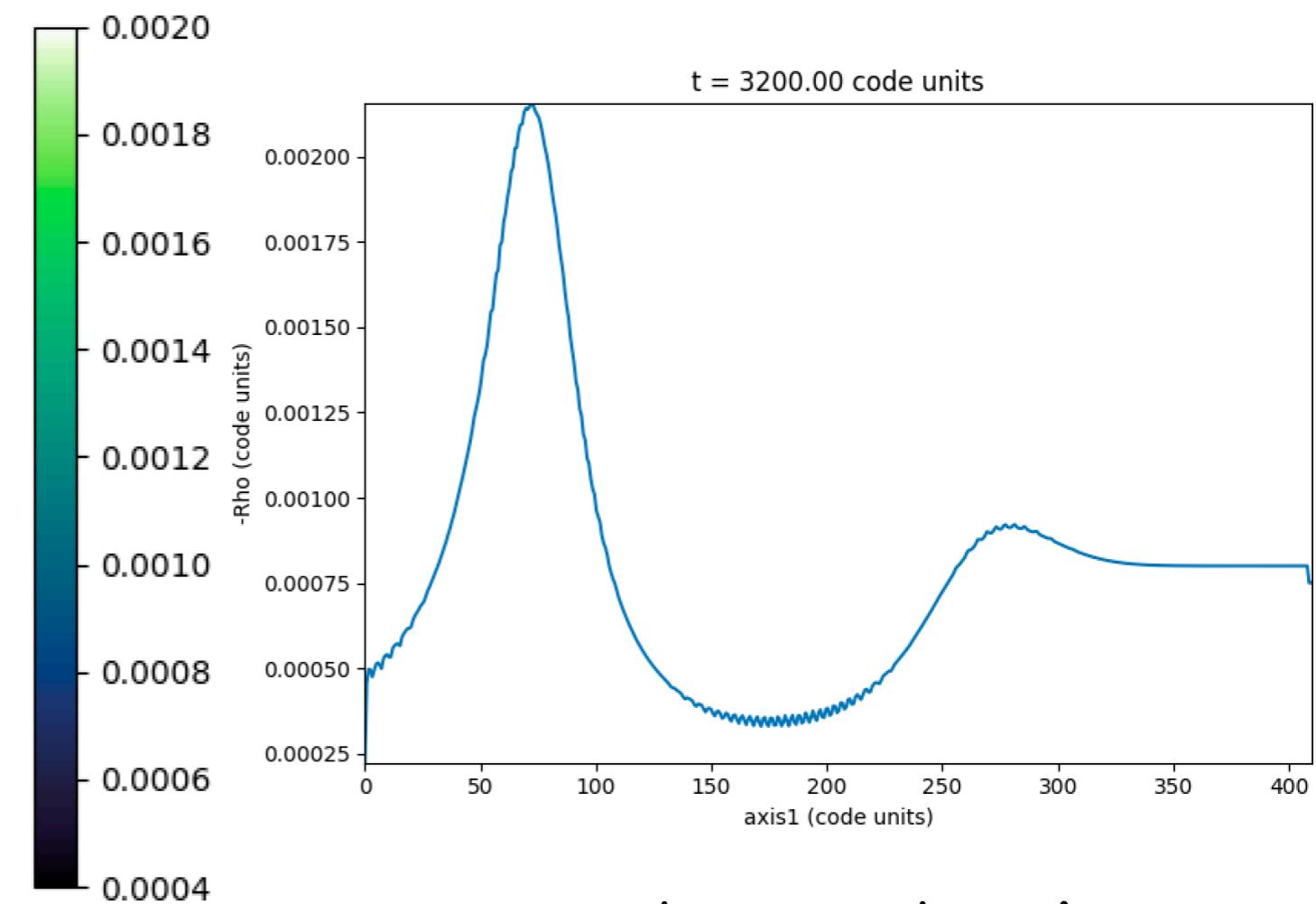
# Laser wakefield excitation: weakly linear regime

$a_0$  = normalized laser peak field =  $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

$a_0 \lesssim 1$  : Weakly nonlinear regime



2D charge density

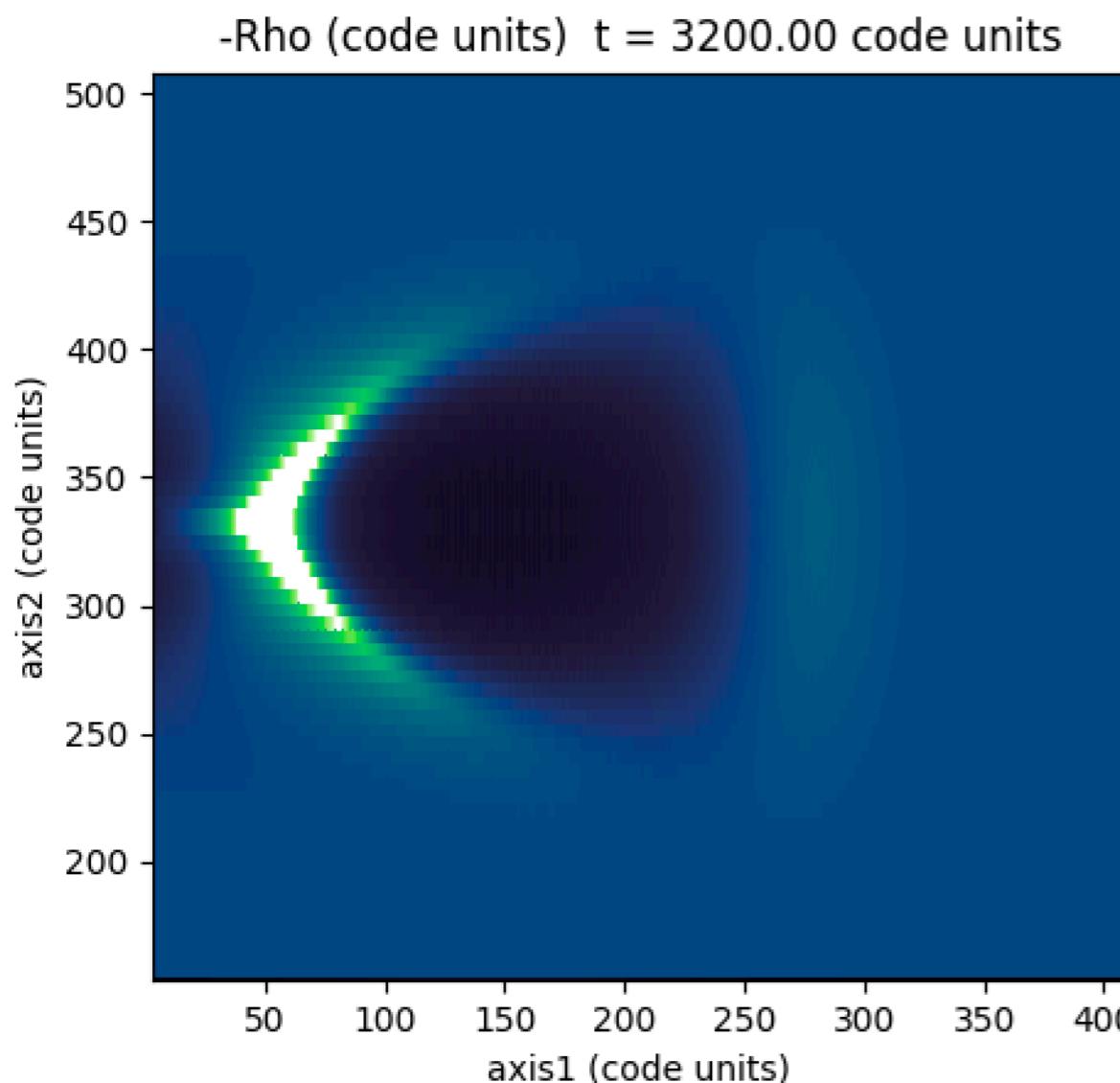


1D charge density  
on propagation axis

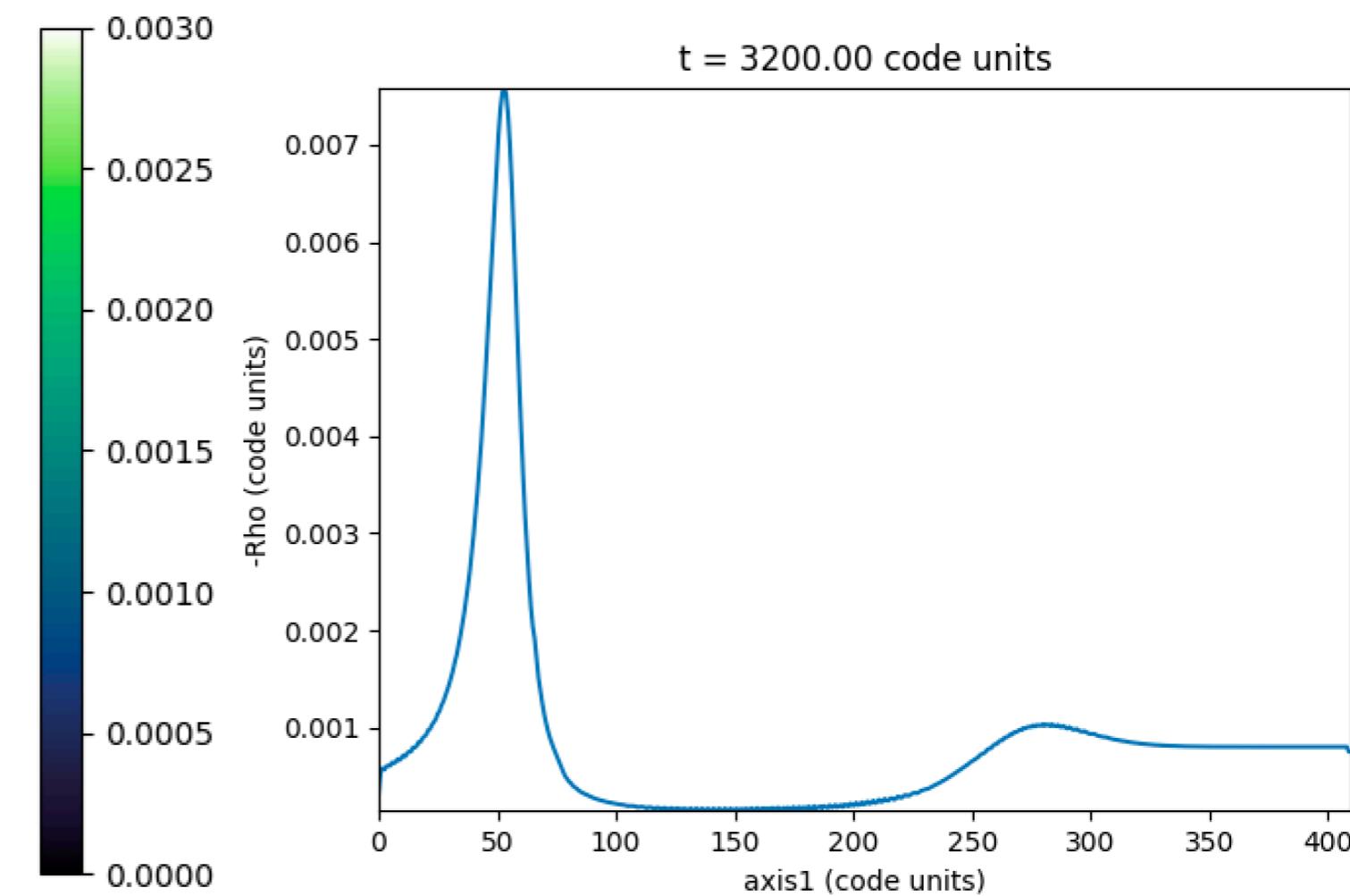
# Laser wakefield excitation: nonlinear regime

$a_0$  = normalized laser peak field =  $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

**$a_0 > 1$ : Nonlinear regime**  
**“Bubble”-like waves**



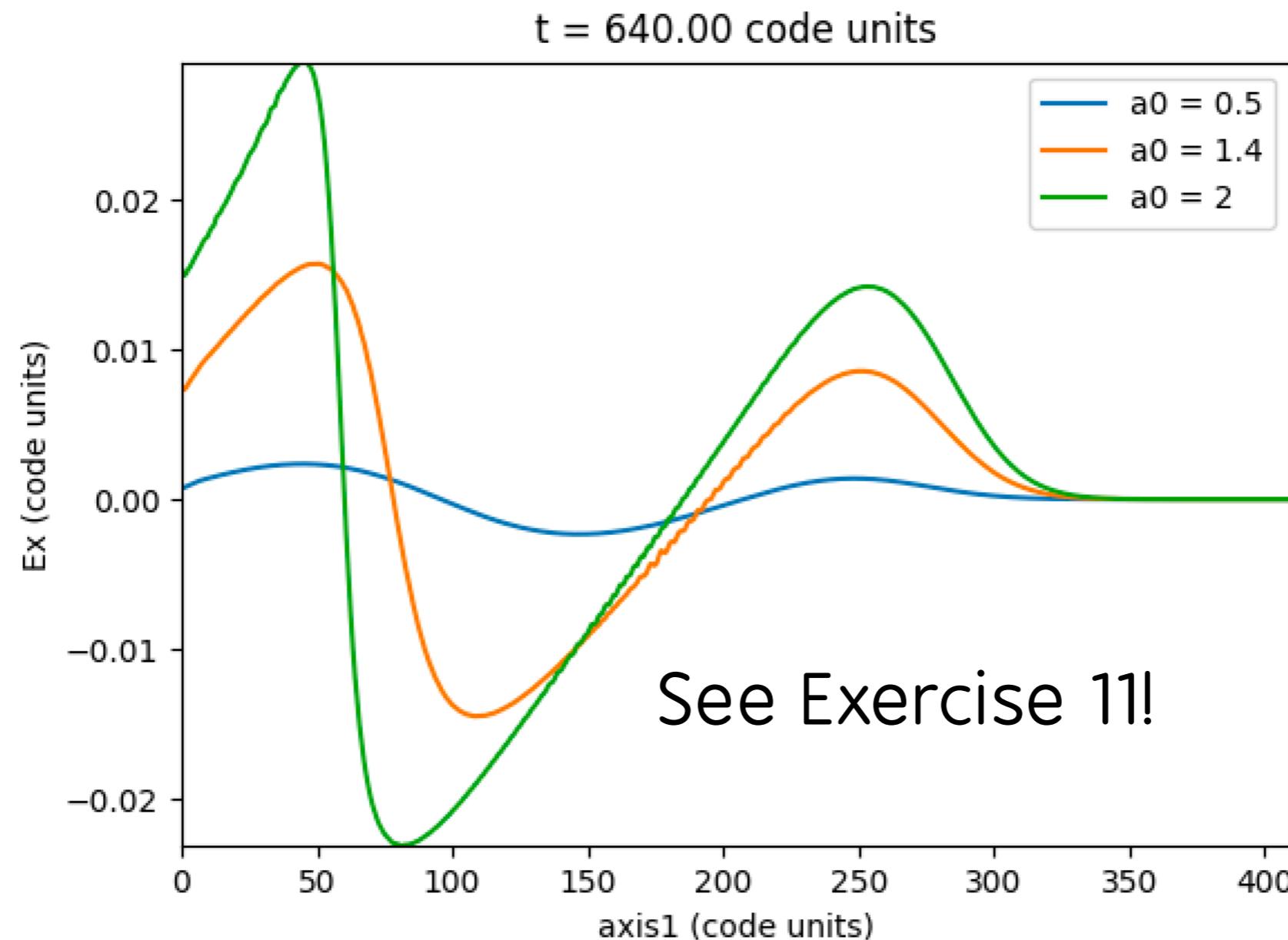
2D charge density



1D charge density  
on propagation axis

# Laser wakefield excitation regimes: Ex on axis

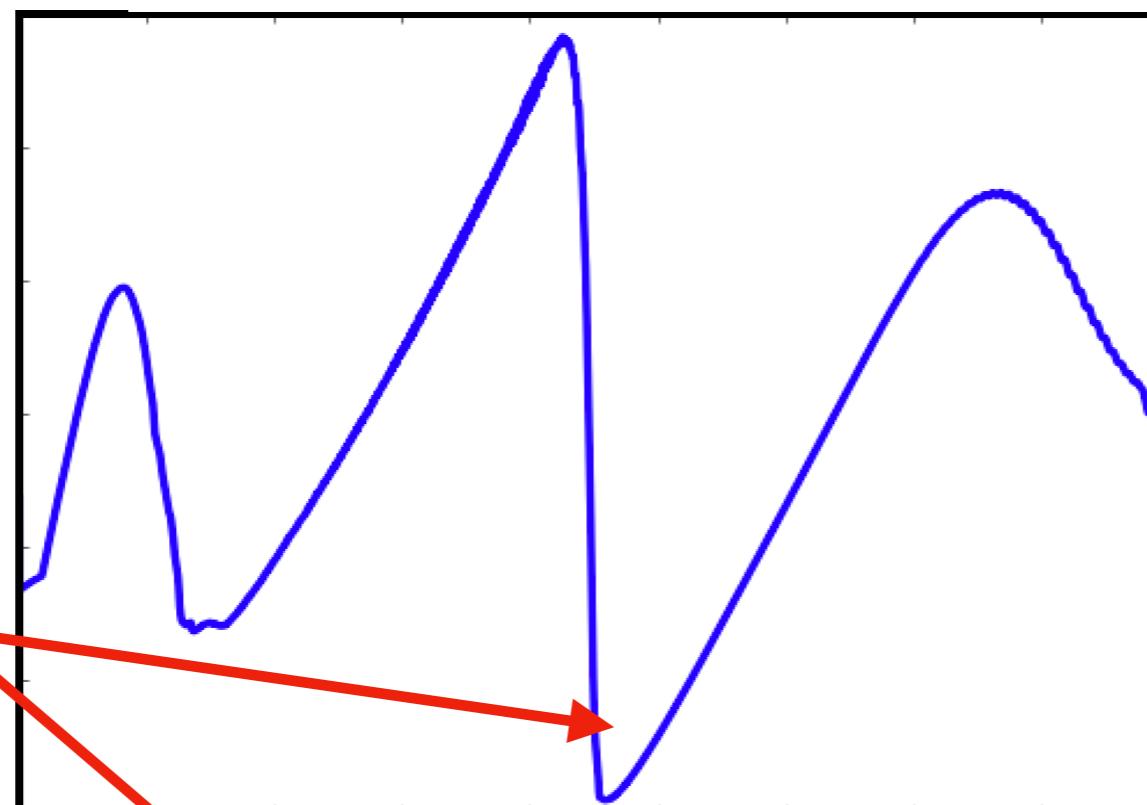
```
import happy
S1 = happy.Open("path/to/sim1"); Ex1 = S1.Probe.Probe0("Ex",timesteps=1000)
S2 = happy.Open("path/to/sim2"); Ex2 = S2.Probe.Probe0("Ex",timesteps=1000)
S3 = happy.Open("path/to/sim3"); Ex3 = S3.Probe.Probe0("Ex",timesteps=1000)
happy.multiPlot(Ex1,Ex2,Ex3,figure=3)
```



# Laser Wakefield Acceleration (LWFA): accelerating electric field

$E > 100 \text{ GV/m}$

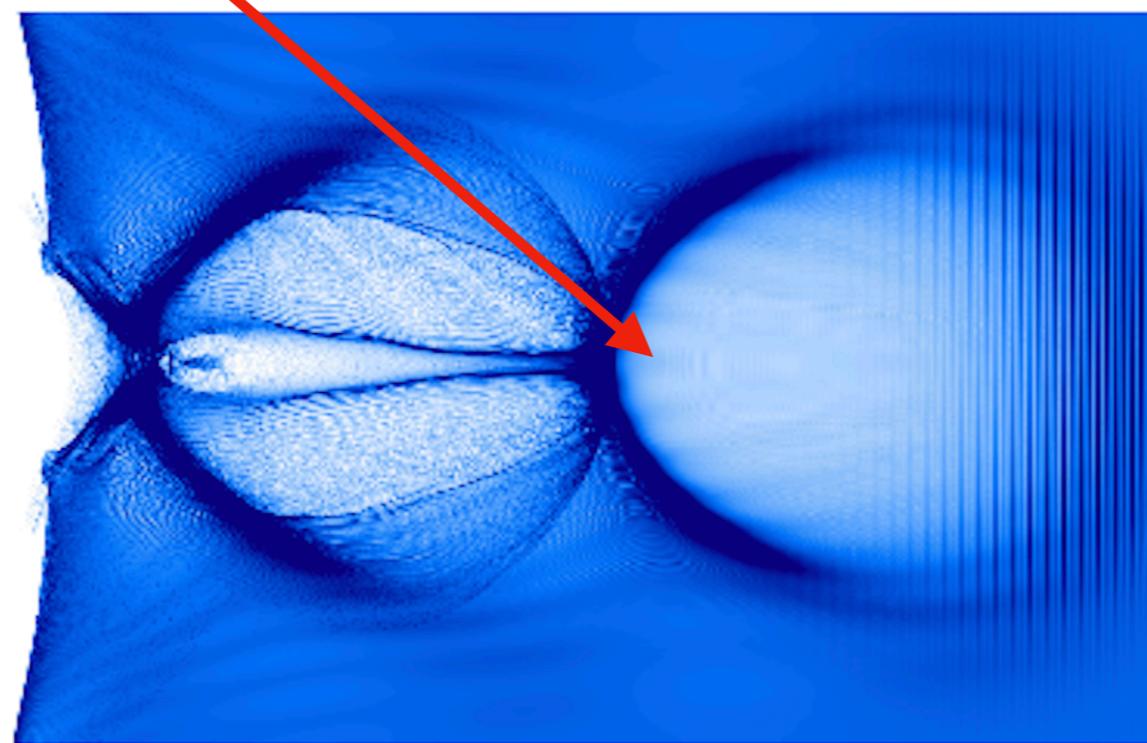
Relativistic  
electrons  
injected here  
are accelerated  
towards the right



0.04  
0.00  
-0.04

Longitudinal  
Electric Field  
(A.U.)  
on propagation axis

Nonlinear  
regime here

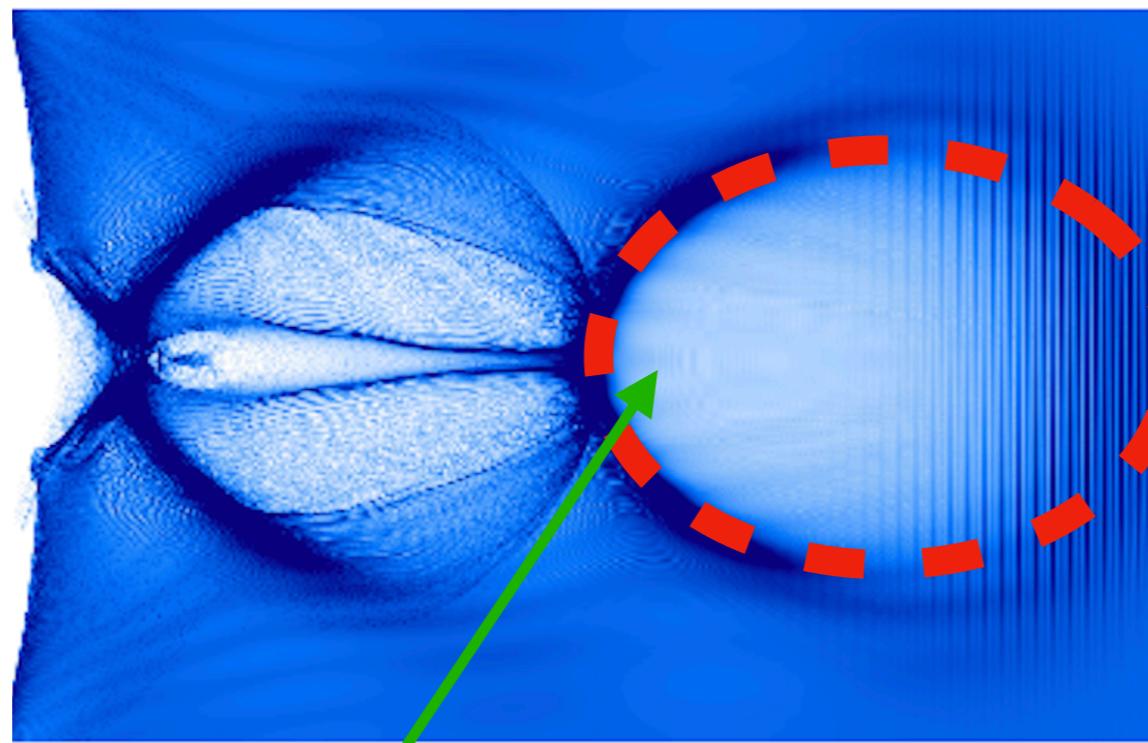


0.003  
0.002  
0.001  
0.000

Electron  
Charge  
Density  
(A.U.)

# LWFA: Electric fields inside the “bubble”

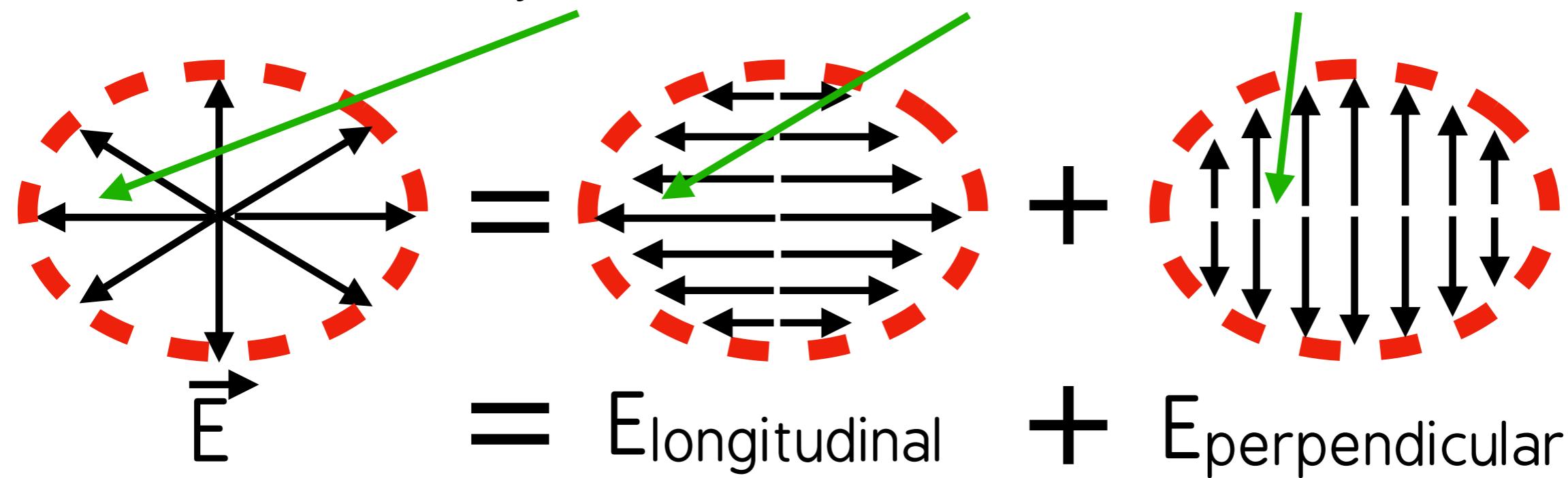
Plasma wavelength:  
~20  $\mu\text{m}$



0.003  
0.002  
0.001  
0.000

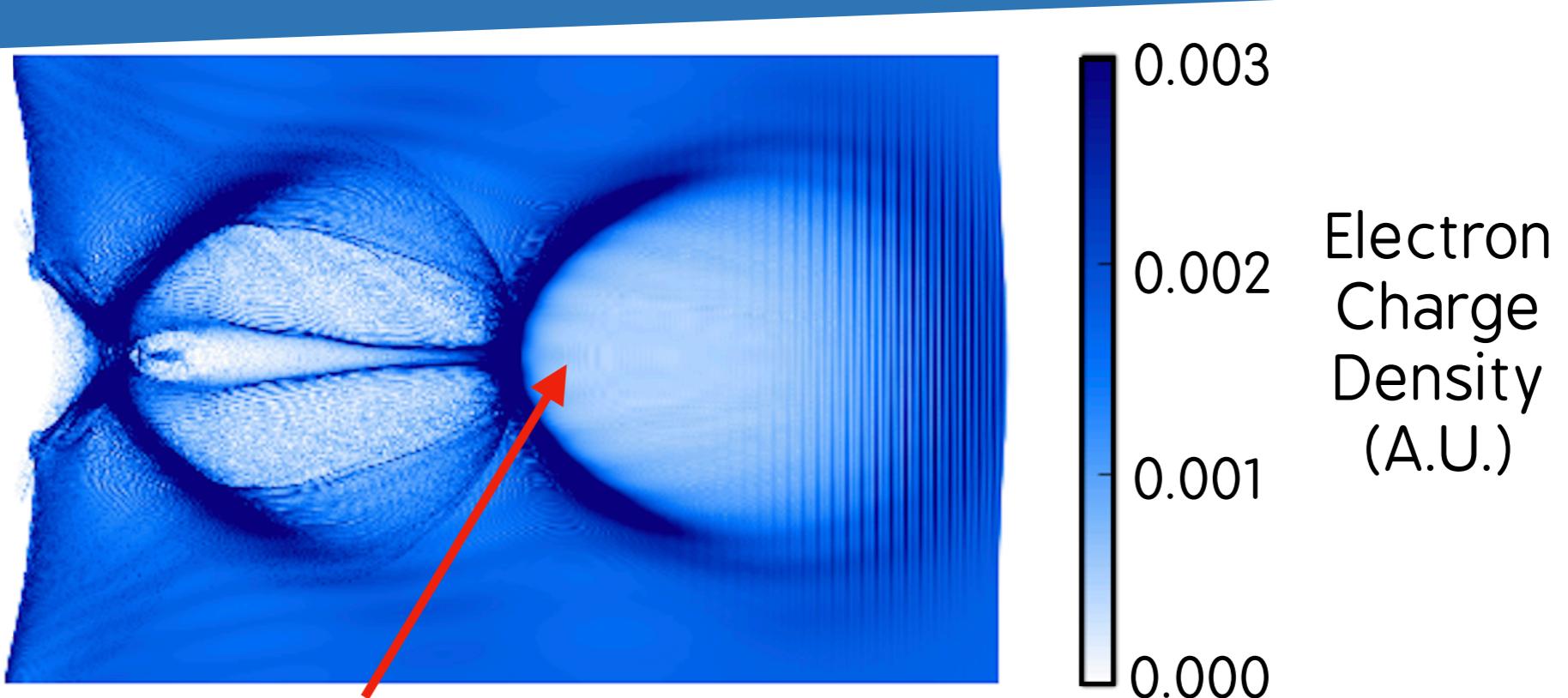
Electron Charge Density (A.U.)

Relativistic electrons injected here are both accelerated and focused

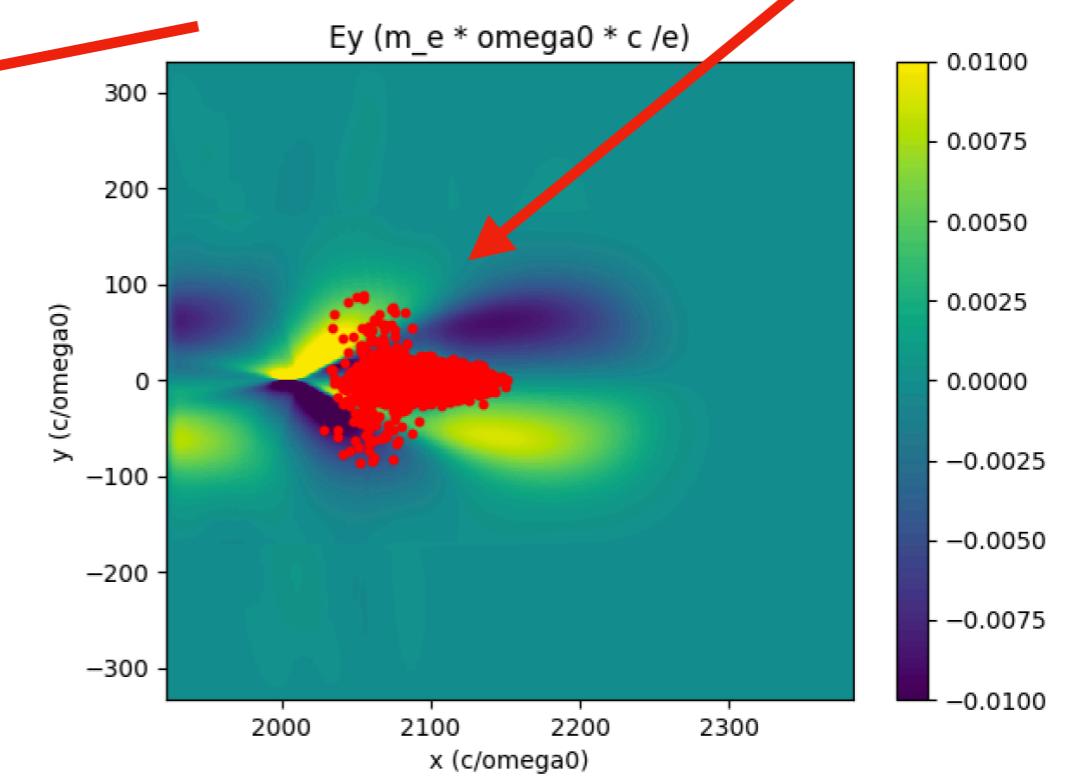
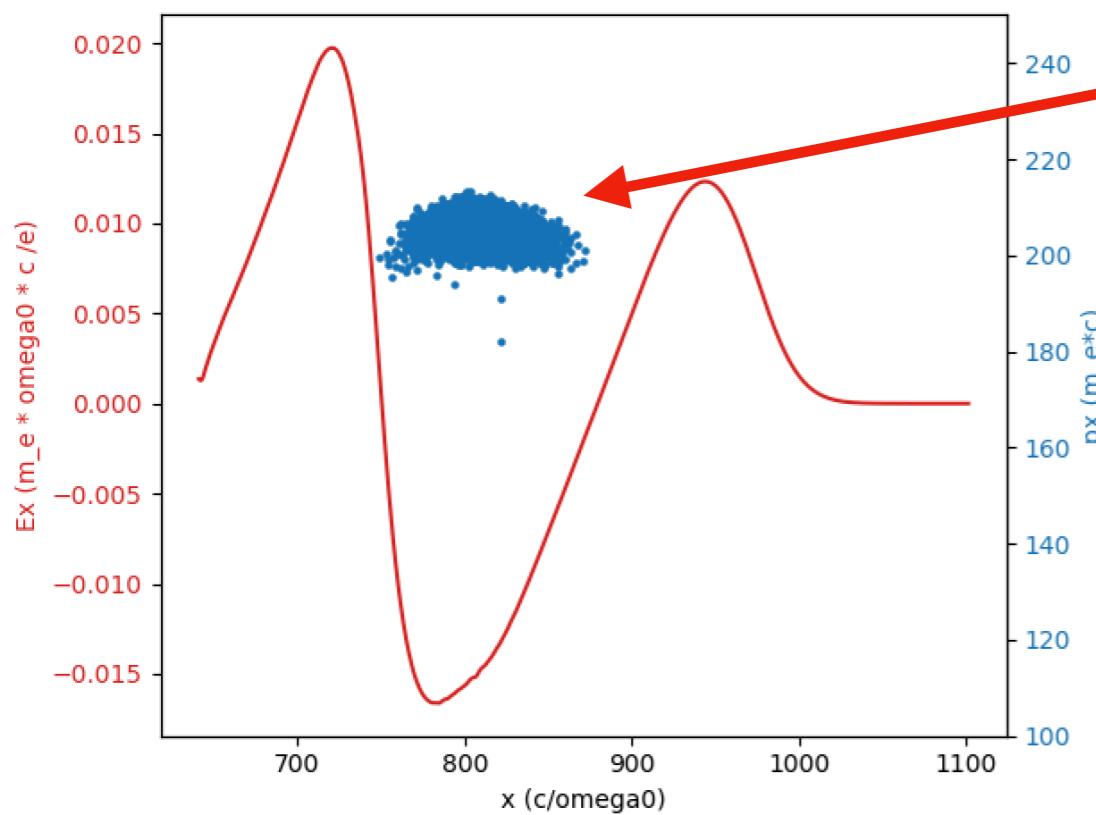


# Fields inside the “bubble”: effects on an electron beam

Plasma wavelength:  
 $\sim 20 \mu\text{m}$



Relativistic electrons injected **here** are both **accelerated** and **focused**

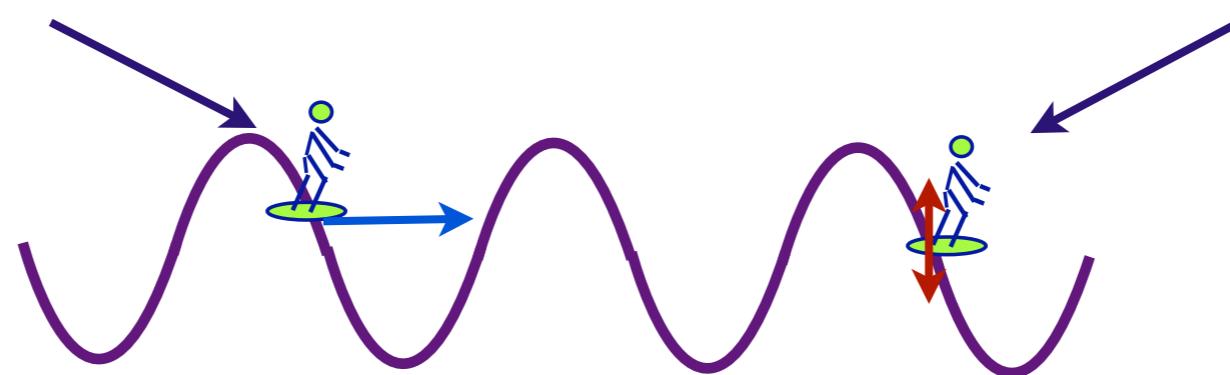


# Laser Wakefield Acceleration (LWFA) challenges: injection

## Surfer with

- sufficient initial speed,
- injected in the proper phase

## Surfer with Zero initial speed



**Surfer: electron**

**wave: electric field of the plasma wave in the wake of the laser**

Plasma wavelength  $< 100 \mu\text{m}$ , Duration of the electron beam  $< 10 \text{ fs} \sim 3 \mu\text{m}$

# Laser Wakefield Acceleration with ionization injection

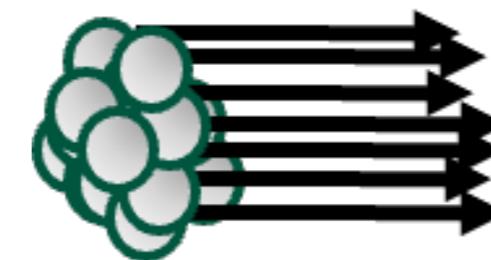
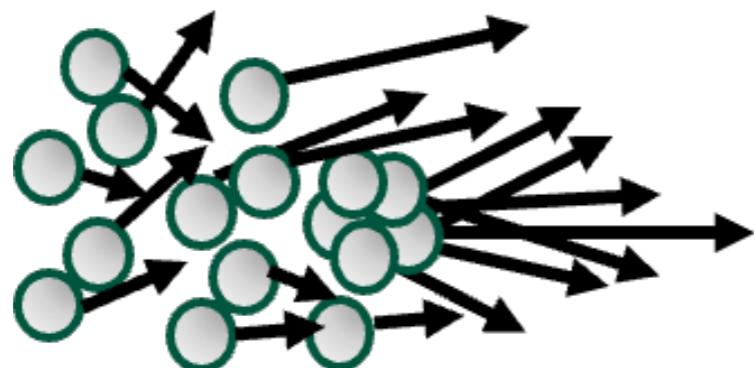


Smilei<sup>®</sup>



Plasma wave  
Intense Laser Pulse  
High energy electrons

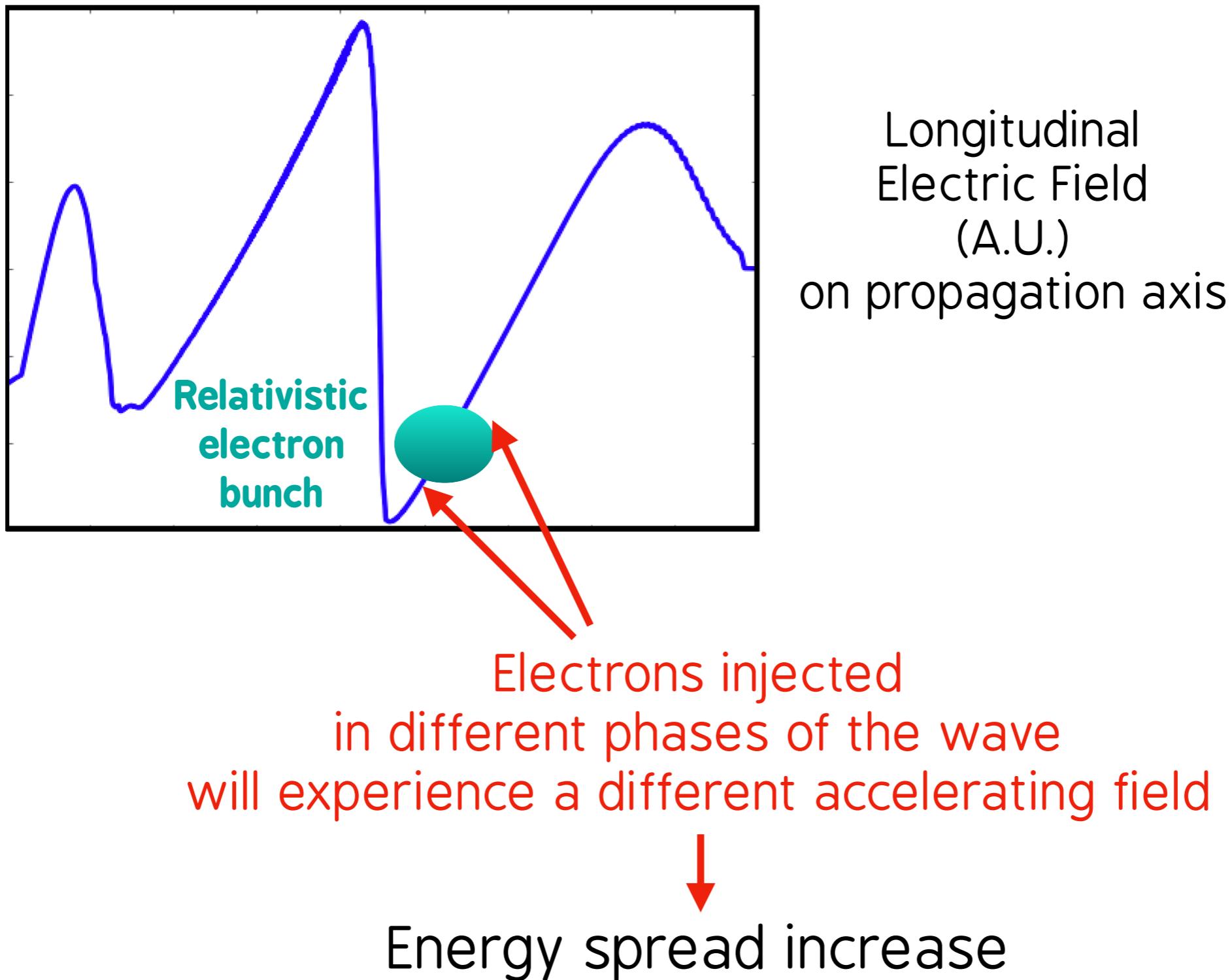
# LWFA objective (not the only one): realize compact electron accelerators for applications



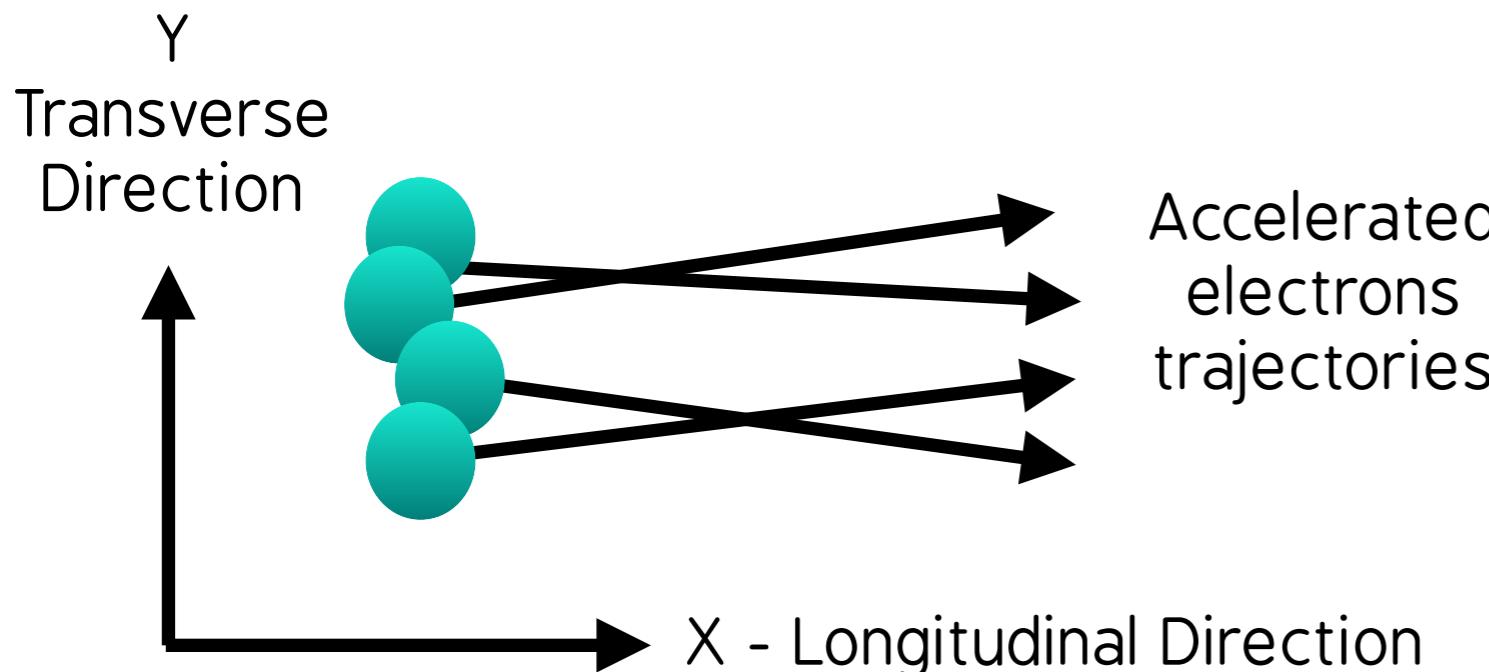
- Few electrons or many dispersed in space
- High divergence
- Different Energies (high energy spread)
- Many electrons in a small volume
- Low divergence
- Similar Energies (low energy spread)



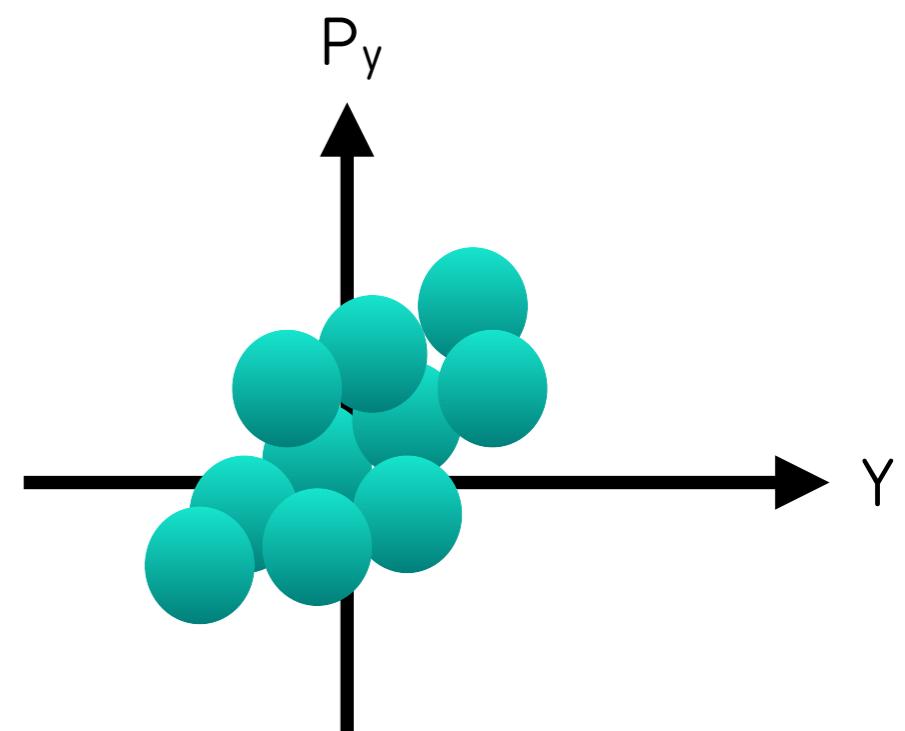
# LWFA challenges: reduce the energy spread



# LWFA challenges: lowering the emittance



Bunch distribution  
in the transverse phase space



Most applications of accelerated beams require:

- Small transverse size (i.e. small  $\sigma_y$ )
- Small divergence (i.e. small  $\sigma_{p_y}/\text{Energy}$ )



**Minimize  
Transverse Emittance**

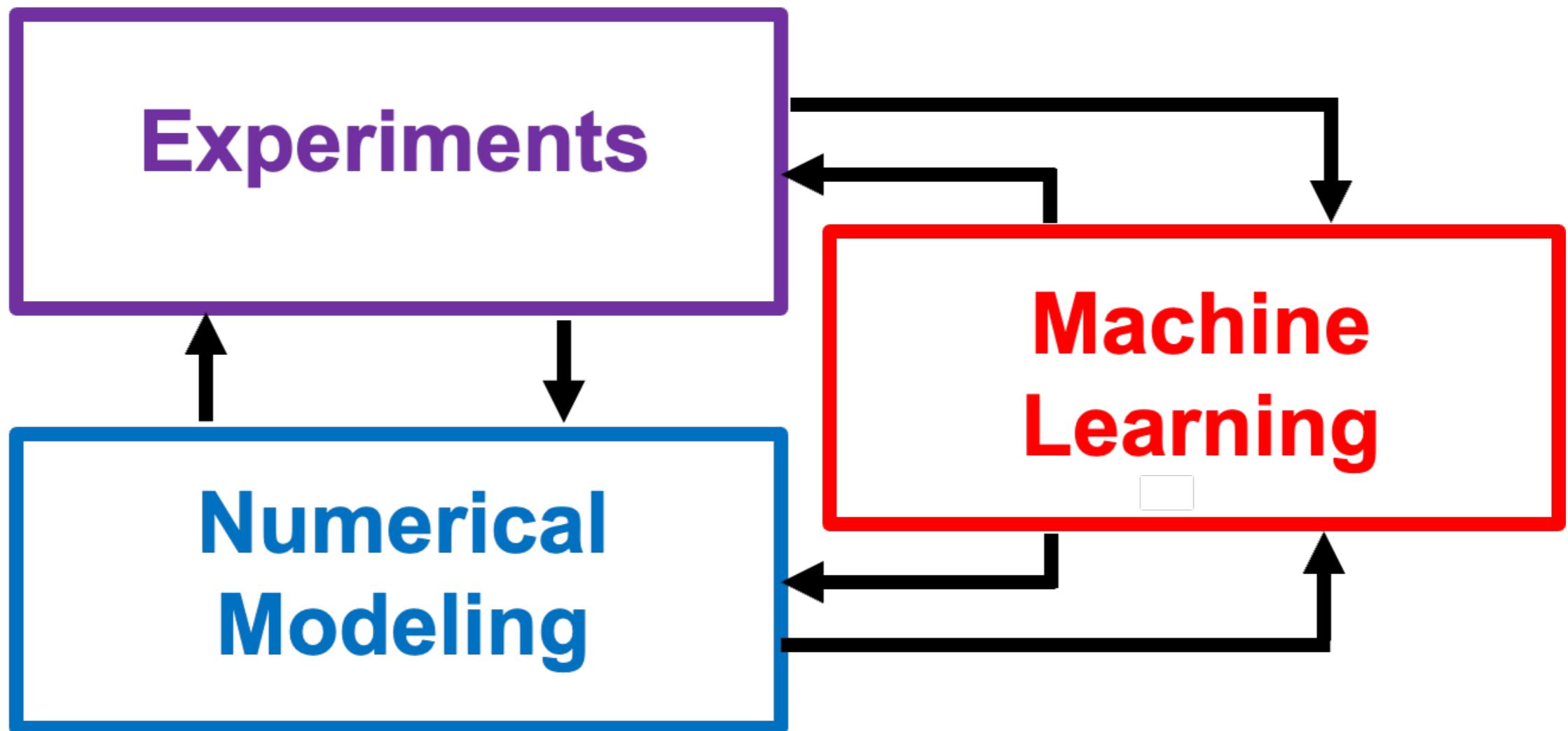
**Transverse  
Normalized  
Emittance**

$$\epsilon_{ny} = \frac{1}{m_e c^2} \sqrt{\sigma_y^2 \sigma_{p_y}^2 - \sigma_{y p_y}^2}$$

# Outline

- Why plasma accelerators?
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# LWFA investigation techniques



# Why numerical simulation is necessary for LWFA?

- **No general analytical solutions are available**
- **You cannot measure everything simultaneously**
- **Before the experiment:**
  - Study new physical phenomena
  - Conceive new kind of experiments
  - Design experiments (also using Machine Learning)
- **After the experiment:**
  - Analyze the data (also using Machine Learning)
  - Understand the physics

# Model for Laser-Plasma Interaction in LWFA

## Complete Maxwell-Vlasov system

Plasma distribution function

$f(x, y, z, p_x, p_y, p_z, t) \longrightarrow \text{6 dimensions + time!}$

Coupled to the electromagnetic fields  $\longrightarrow$  **Non-linearity**

$$\frac{\partial f}{\partial t} + \beta c \cdot \nabla_x f - e(E + \beta c \times B) \cdot \nabla_p f = 0 \leftarrow \text{Collisions neglected}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \begin{matrix} \text{Current density} \\ J \text{ of the plasma} \end{matrix}$$

$$\nabla \times B = -\mu_0 ec \left( \int \beta f d^3 p \right) + \frac{1}{c^2} \frac{\partial E}{\partial t}$$

Explorable Physics:

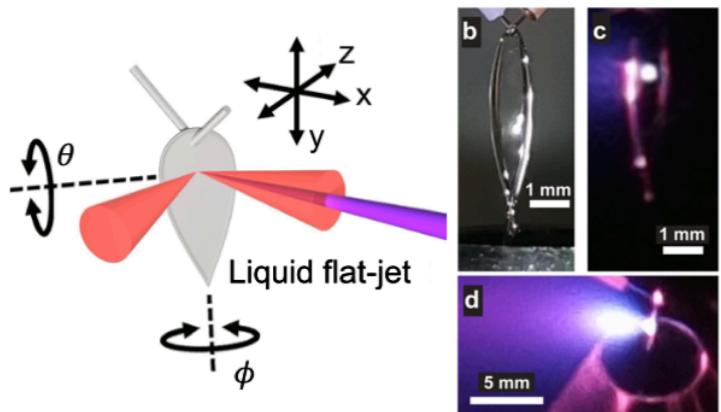
- Relativistic optics (laser self-focusing, ...)
- Nonlinear phenomena
- Wave-breaking
- Injection and acceleration of particles

## Approximate solution: Particle in Cell method

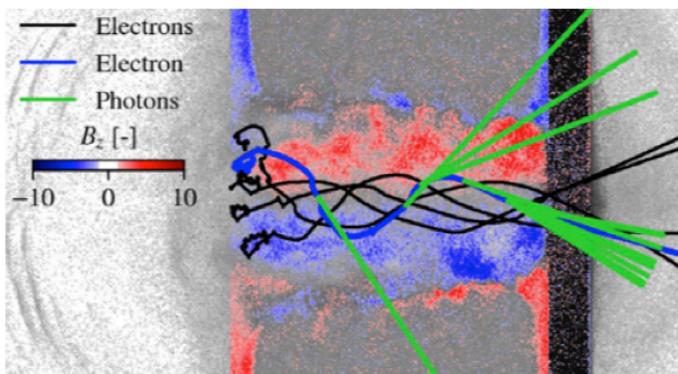
# Particle in Cell (PIC) method : essential kinetic plasma investigation technique

## Applications From Laboratory plasmas to Space and Astrophysical plasmas

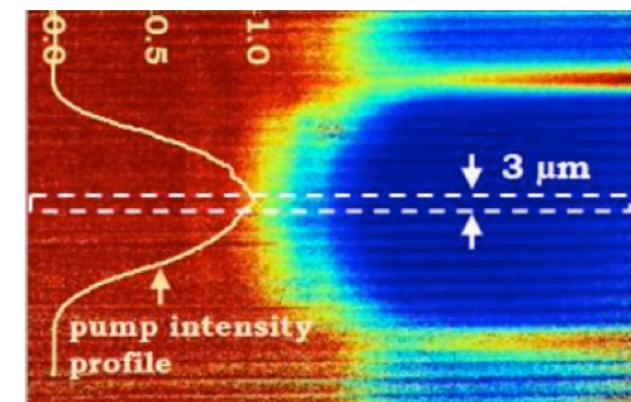
High-Harmonic Generation



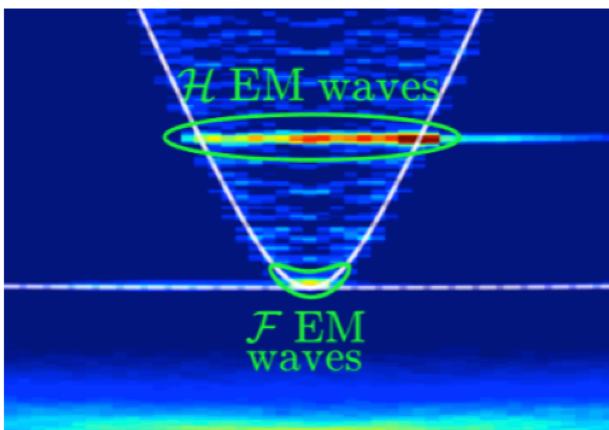
Radiation sources from DLT



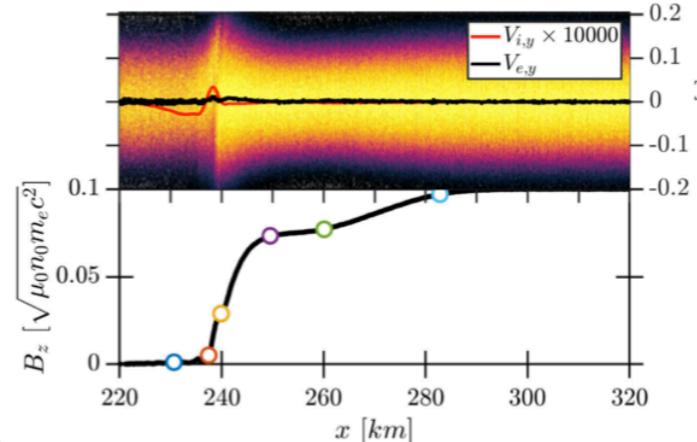
Solid to plasma transition



Solar radio-burst



Comet boundaries



Collisionless shocks & Dark Matter



- Wide range of physics applications
- Conceptually simple
- Efficiently implemented on small or massively parallel supercomputers

Some studies performed with **Smilei**)

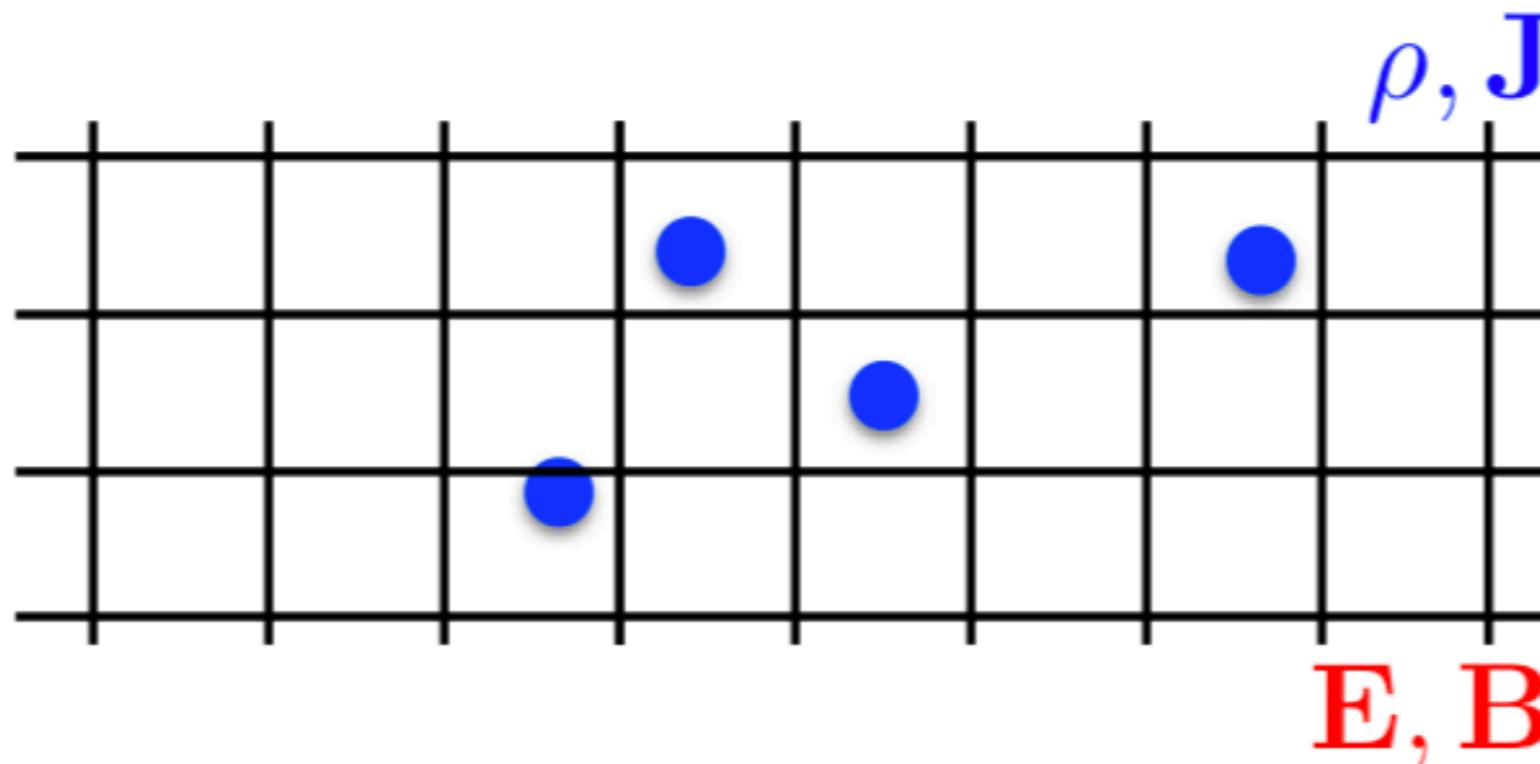
# Particle in Cell concept

Sample Plasma with Macro-Particles  
(1 Macroparticle = position, momentum, charge, ...)

+

Discretize space with computational grid

Define  $E, B, \rho, J$  on the grid cells



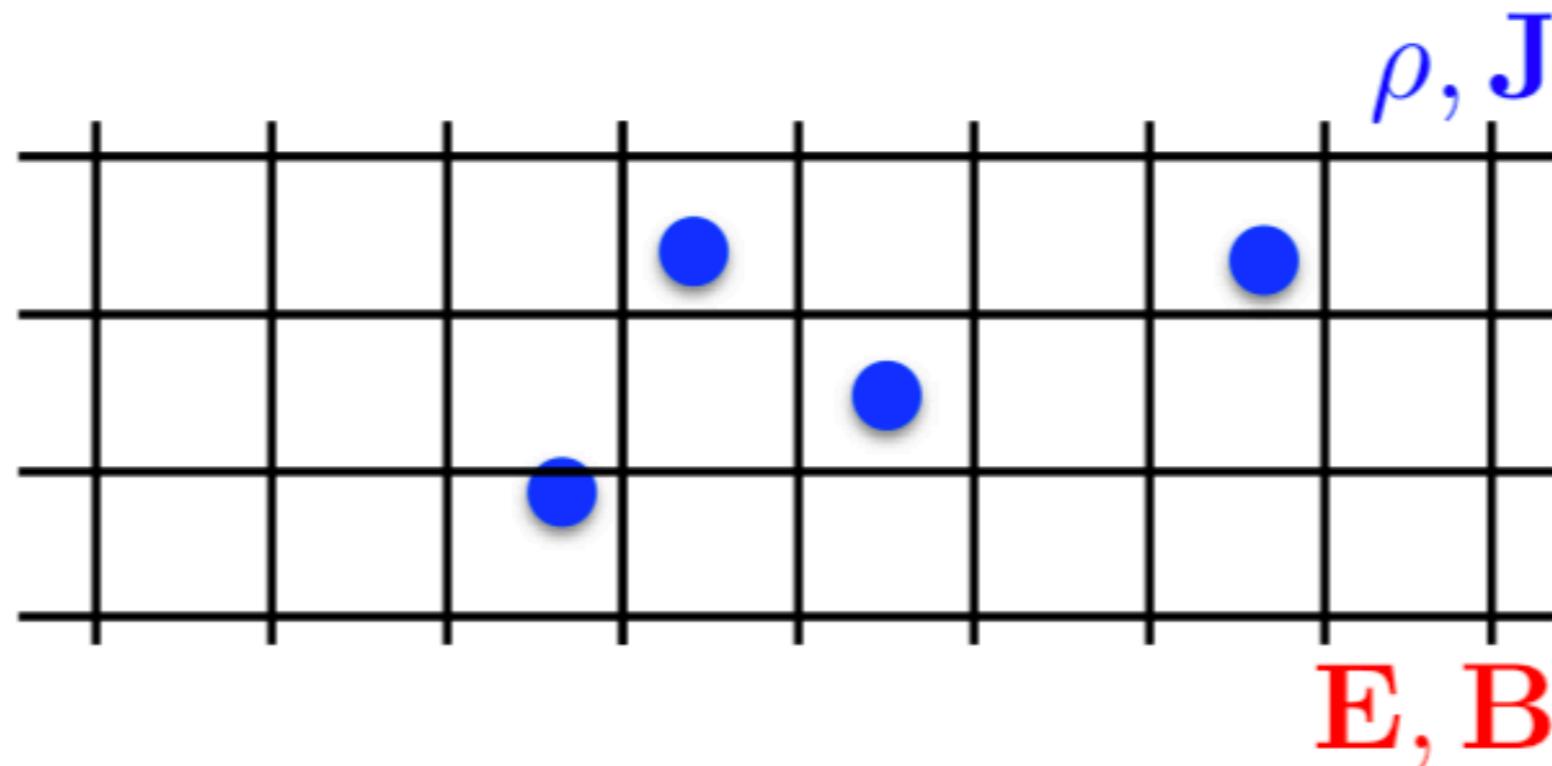
# Particle in Cell concept

## **Macro-Particles:**

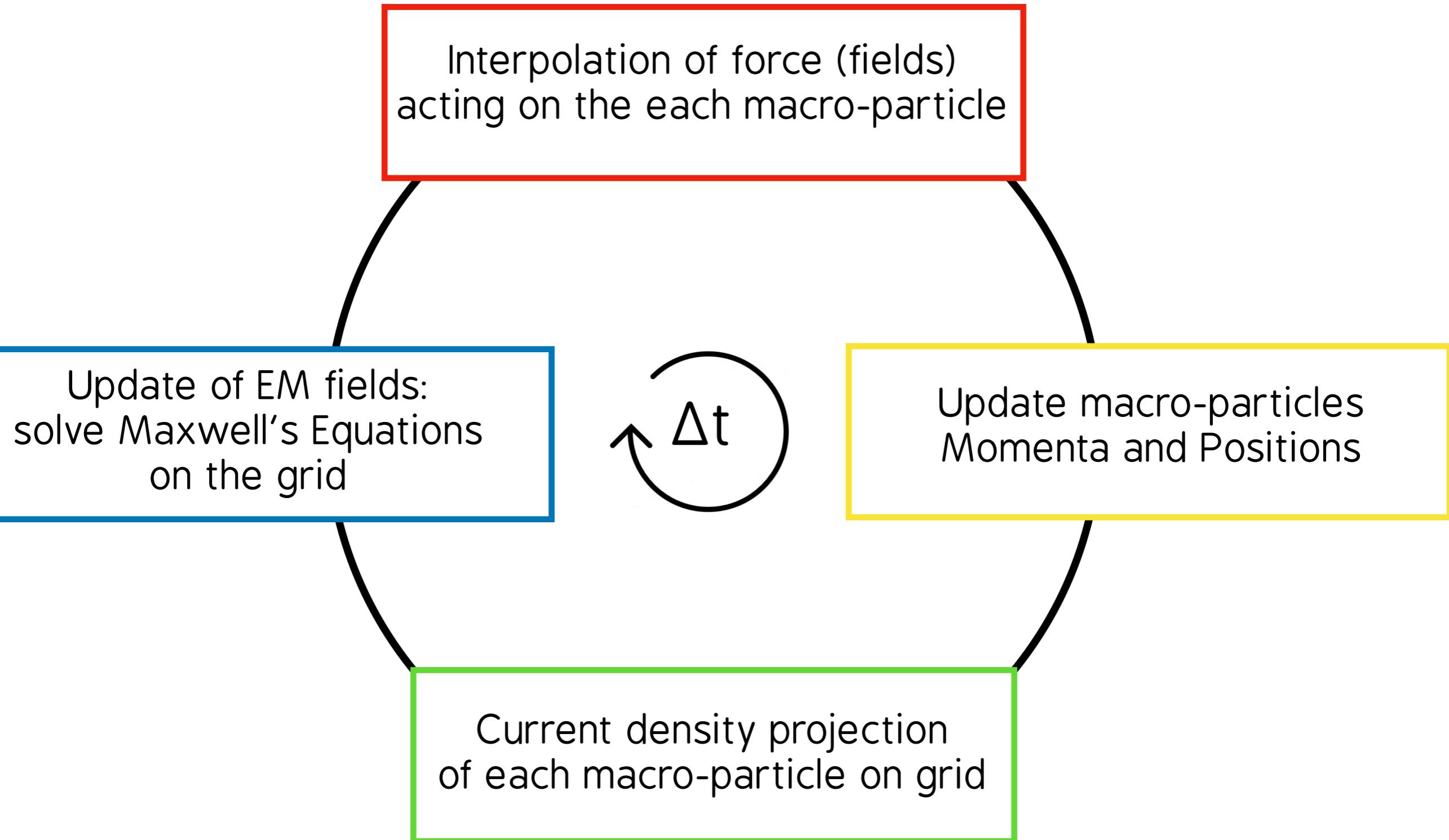
evolve following the characteristics of Vlasov Equation  
(In the PIC method they look like equations of motion)

+

**Electromagnetic Fields:** evolve following Maxwell's Equations



# Particle in Cell modelling is self-consistent



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# Smilei)

## User-friendly

- online: documentation, tutorials
- Python input / output
- quick visualisation library
- teaching platform
- bi-annual training workshop
- Element chat with the developers

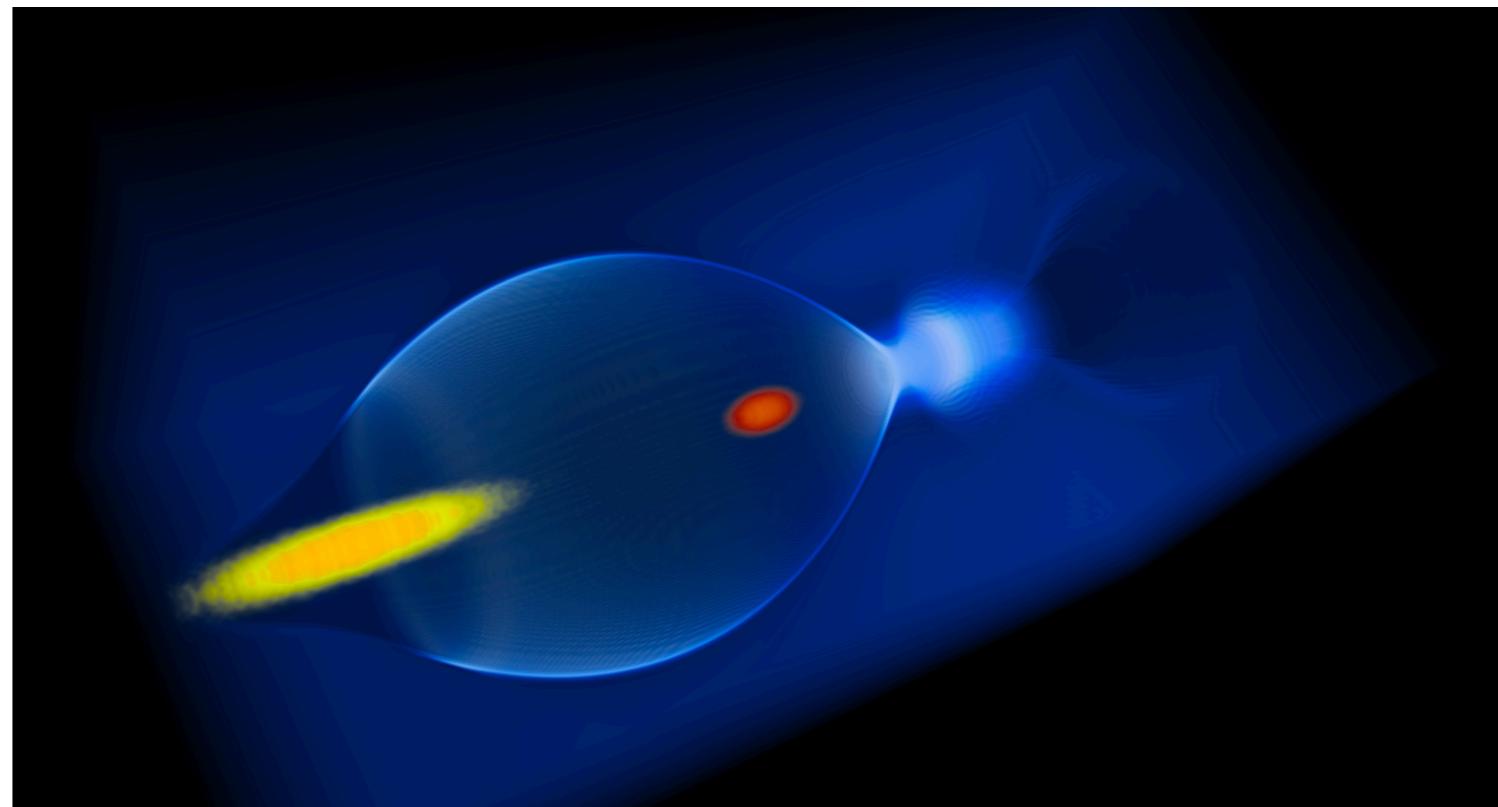
## High Performance

- MPI + OpenMP parallelization
- dynamic load balancing
- adaptive vectorization
- GPU computing on both NVIDIA and AMD architectures

## Multi-physics

- 1D, 2D, 3D, quasi-3D geometries
- ionization, collisions, strong-field QED
- laser envelope model
- relativistic beam field initialization

A collaborative, open source  
multi-purpose Particle in Cell code  
<https://smileipic.github.io/Smilei/index.html>



## High quality

- developers: experts of physics and HPC
- continuously benchmarked
- GitHub bug reporting
- OpenPMD standard
- >130 publications using the code up to 2023

## Additional material

# Extensive Documentation ( Installation, Use, Postprocessing, ... )

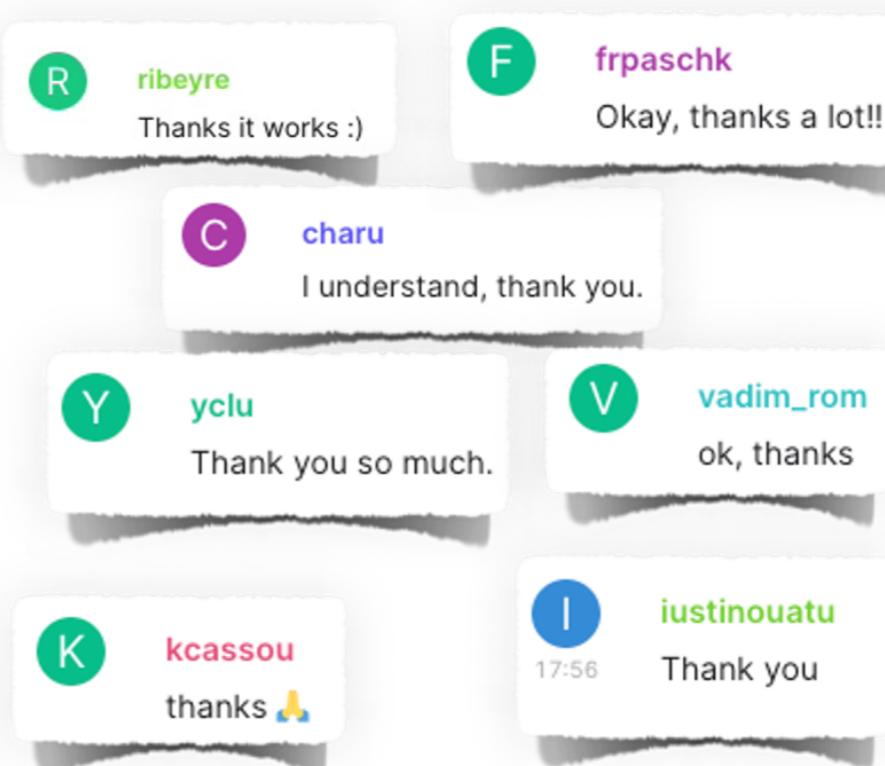
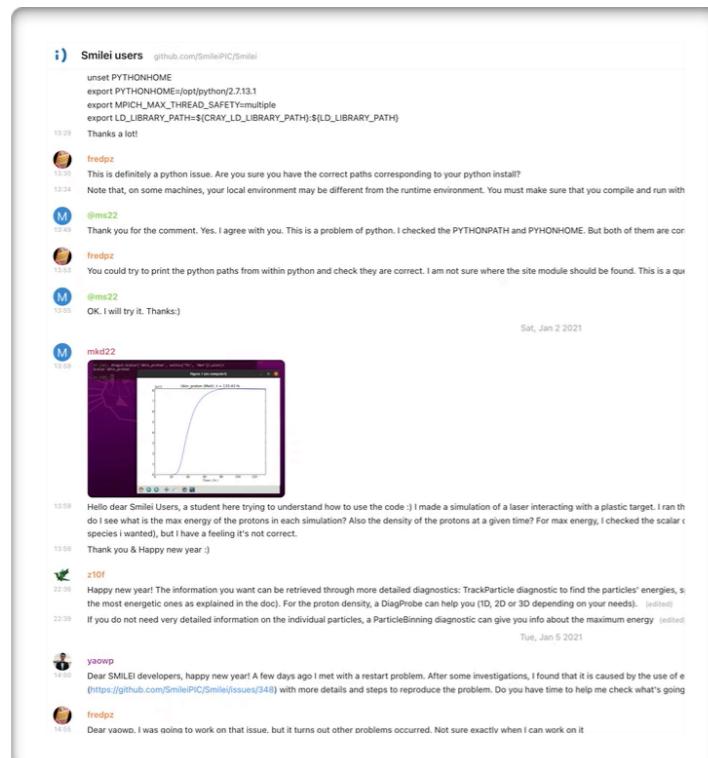
<https://smileipic.github.io/Smilei/index.html>



<https://smileipic.github.io/tutorials/>

**Presentations from the 4th Training Workshop** <https://indico.math.cnrs.fr/event/9577/>

# Questions? We answer on the Element chat



1600 messages  
in 2021

# Outline

- Why plasma accelerators?
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# Example of input file

```
Main(  
    geometry      = "1Dcartesian",  
    timestep      = 0.009,  
    cell_length   = [0.01],  
    ...  
)
```

```
x_center_plasma = 200.
```

```
def my_density_profile(x):  
    return exp(-(x-x_center_plasma)**2)
```

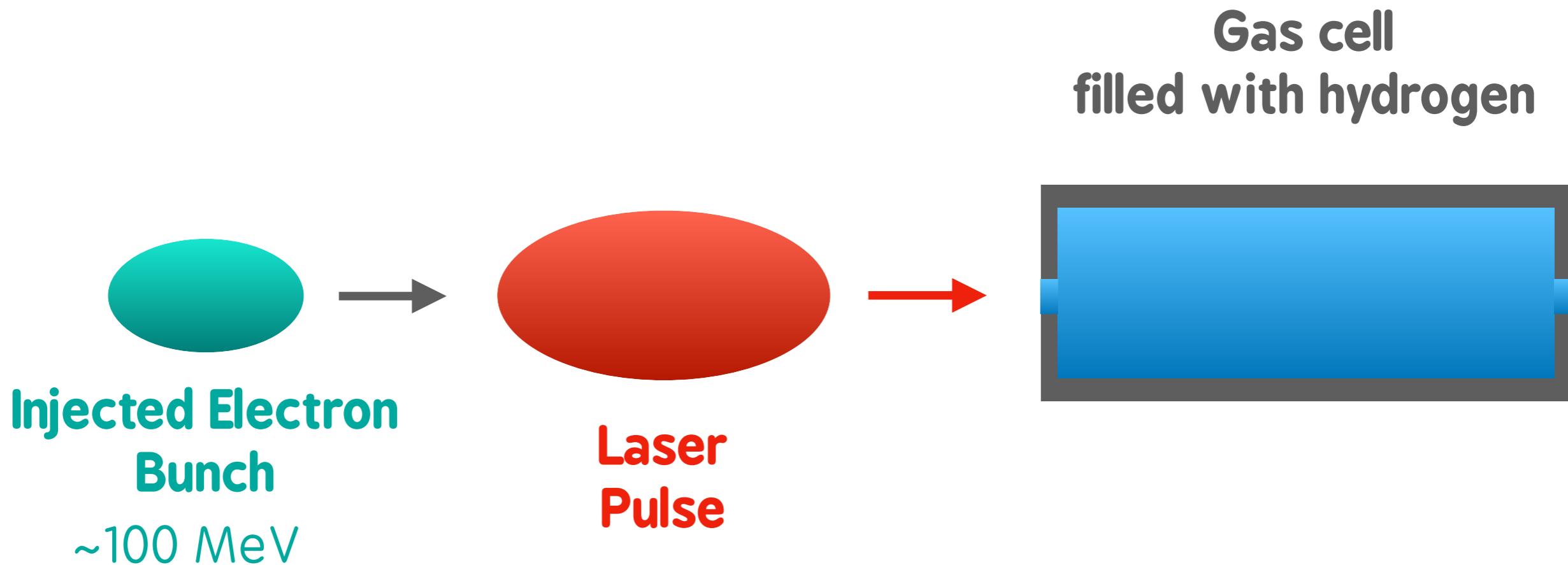
```
Species(  
    name          = "electron",  
    charge        = -1.,  
    mass          = 1.,  
    particles_per_cell = 100,  
    number_density = my_density_profile  
    ...  
)
```

- Normalised units
- Quantities can be computed at runtime

Laser /Plasma profiles = Functions  
(also user-defined)

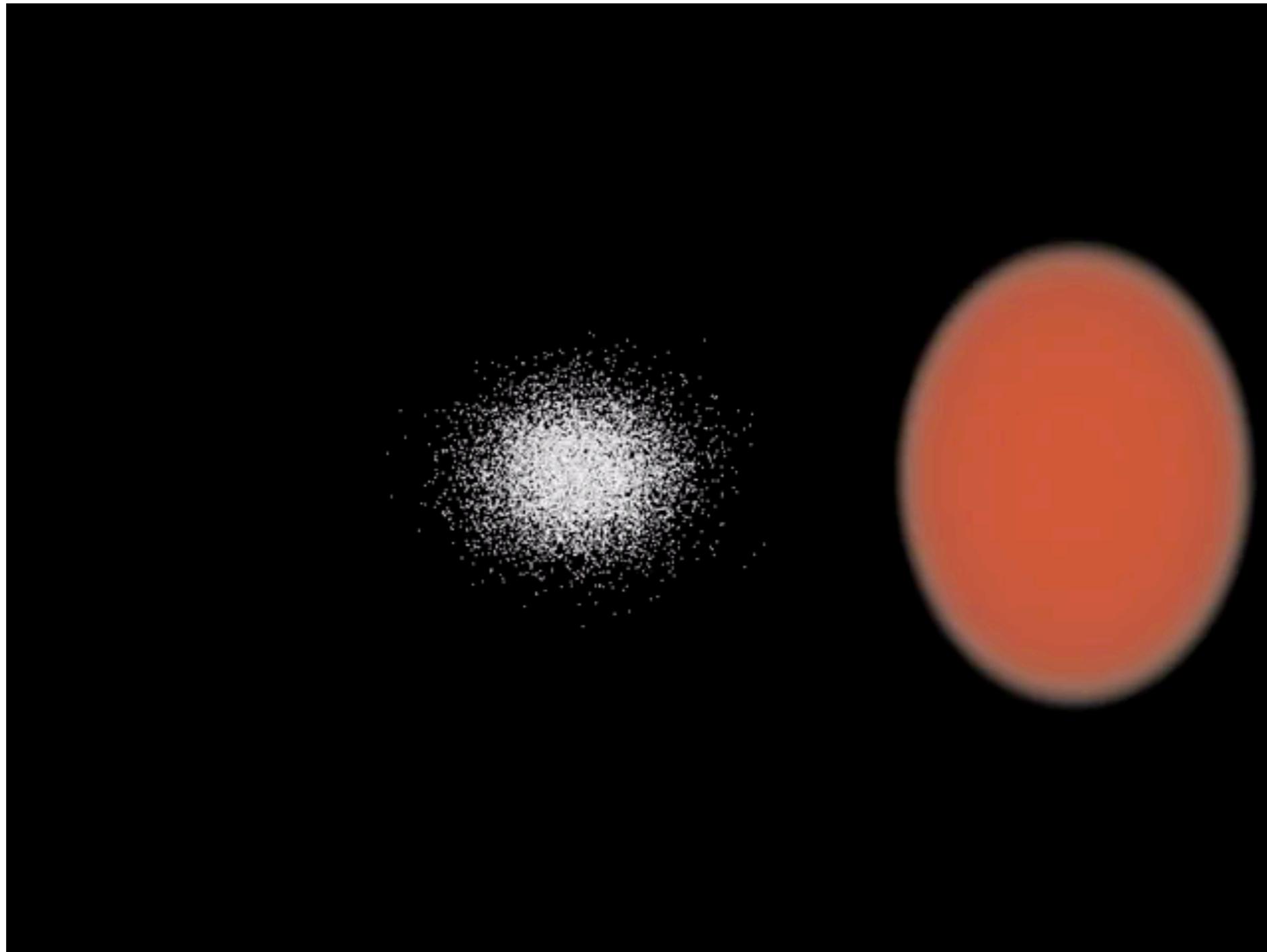
If Python can read it, SMILEI can read it

# Case study: LWFA with external injection



Assumption: plasma already created in the gas cell  
(the laser's repulse ionises the gas in its path)

# 3D rendering of LWFA with external injection



# Practical material

<https://github.com/SmileiPIC/TP-M2-GI/tree/main>

**Answer Form for the Exercises   Link to TP documentation and Exercises**

The screenshot shows a GitHub repository page for 'TP-M2-GI'. The repository has 2 branches and 0 tags. It contains several files and folders:

- .github/workflows
- Answers\_Form
- Postprocessing\_Scripts
- doc
- InputNamelist.py
- LICENSE
- Presentation\_TP.pdf
- README.md
- submission\_script.sh

Recent commits:

- Francesco Massimo and Francesco Massimo change environment (c5cf6d1, 15 hours ago)
- Update sphinx.yml (10 months ago)
- update TP (5 days ago)
- update namelist (16 hours ago)
- correction (5 days ago)
- update namelist (16 hours ago)
- Create LICENSE (2 years ago)
- update presentation (last year)
- Update README.md (10 months ago)
- change environment (15 hours ago)

Repository details:

- About: Numerical practical for the students of the M2 - Grands Instruments.
- smileipic.github.io/TP-M2-GI/ (highlighted with a red box)
- Readme
- GPL-3.0 license
- Activity
- 2 stars
- 7 watching
- 2 forks
- Report repository

Annotations:

- A purple arrow points from 'submission\_script.sh' to the text 'Simulation submission file'.
- A blue arrow points from 'Presentation\_TP.pdf' to the text 'These slides'.
- A green arrow points from 'InputNamelist.py' to the text 'Input Namelist file to run simulations'.
- A red arrow points from 'smileipic.github.io/TP-M2-GI/' to the text 'Postprocessing Scripts'.

Text labels:

- Simulation submission file
- These slides
- Input Namelist file to run simulations
- Postprocessing Scripts

# Practical exercises

- Read **in detail** the **TP documentation**  
<https://smileipic.github.io/TP-M2-GI/index.html>
- Solve the exercises in the **TP documentation** progressively, e.g.

## Exercise 1:

Assuming  $\lambda_0 = 0.8\mu m$  (a Ti:Sa laser system), what is the value of the critical density  $n_c$ ?

What is the value of the reference electric field  $E_0 = (2\pi m_e c^2)/(e\lambda_0)$ ?

This choice of  $\lambda_0$  will be used throughout all subsequent exercises.

**Hint:** Some lines at the start of the `InputNamelist.py` file can help you in the calculations.

## Exercise 5:

In the next exercise we will check that the Gaussian laser pulse diffracts following the theory for a Gaussian beam [Siegman]:  $w(x) = w_0 \sqrt{1 + x^2/x_R^2}$ , where  $w_0$  is the laser waist size at the focal plane position,  $w(x)$  the laser waist size at propagation distance  $x$ ,  $x_R$  is the Rayleigh length  $x_R = \pi w_0^2/\lambda_0$ .

What is the theoretical Rayleigh length  $x_R$ ?

## Exercise 10:

Launch a new simulation with  $a_0=1.8$ . This simulation will be in the nonlinear regime ( $a_0 > 1$ ), so the plasma wave will not be sinusoidal. You can visualize both the normalized absolute value of the envelope of the laser field and the electron number density by defining a transparency for the parts where the latter field is lower than a threshold  $v_{min}$ :

```
Env_E = S.Probe.Probe1("Env_E_abs",units=["um"],cmap="hot",vmin=0.8,transparent="unde  
Rho = S.Probe.Probe1("-Rho/e",units=["fs","um","1/cm^3"],cmap="Blues_r",vmin=0.,vma  
happi.multiSlide(Rho,Env_E,xmin=0,figure=10, xlabel="x [um]",ylabel="y [um]")
```

Using `timestep=2500` in the definition of `Env_E` and `Rho`, and then using `multiPlot` instead of `multiSlide`, you should have a plot of the data at half of the propagation length.

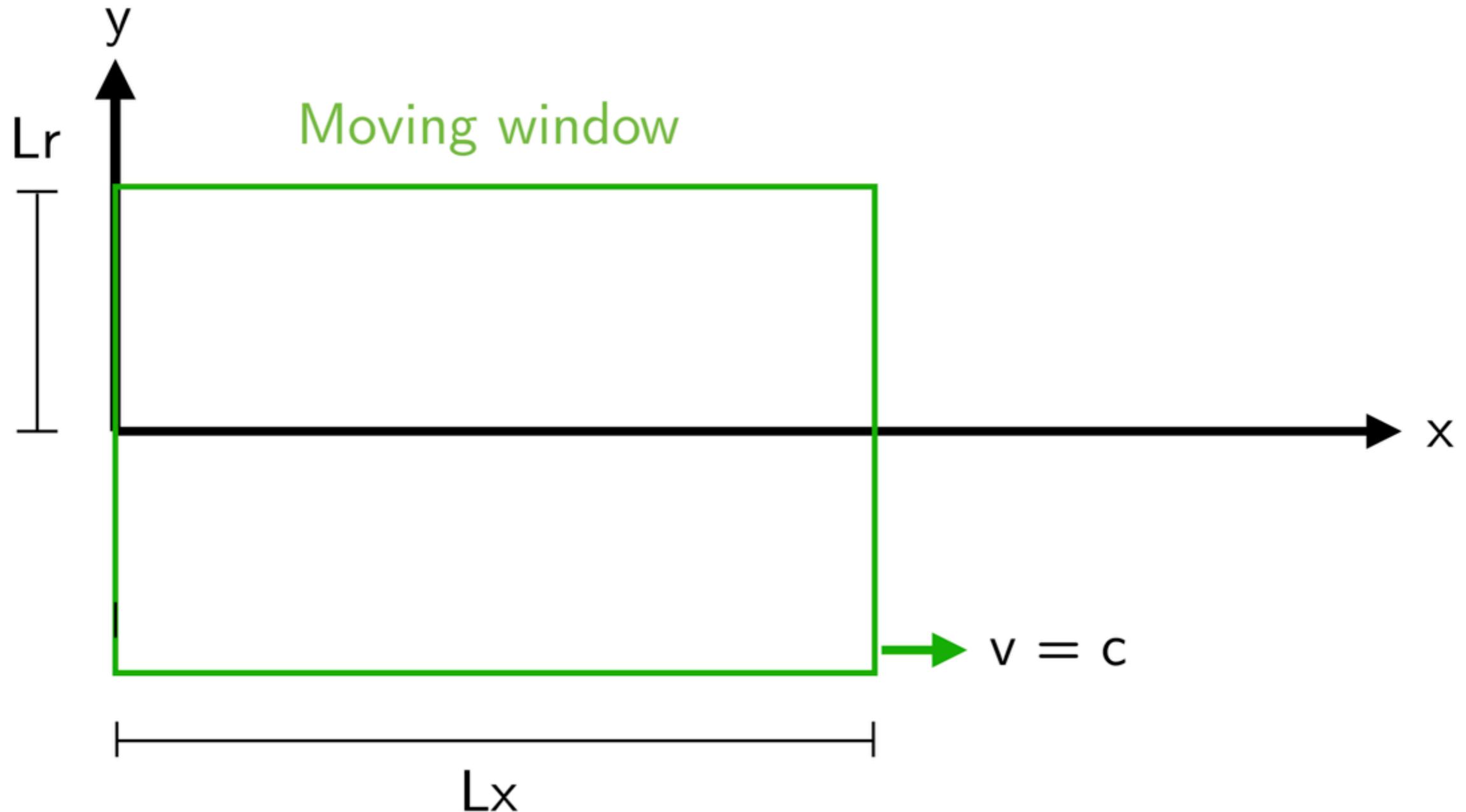
Include this image in your answers.

- Run simulations when necessary, following the instructions in the **TP documentation**
- Fill the answers report **Answers\_Form.docx**  
(You can download it from GitHub  
<https://github.com/SmileiPIC/TP-M2-GI/tree/main>)

# Suggestions

- Again read **in detail** the **TP documentation**
- **Understand** the physical set-up
- **Any doubts? Ask the instructor**
- Solve the exercises **progressively**
- Create one folder for each simulation asked by the exercises  
(to **avoid losing data**)
- Feel free to adapt the commands in the **TP documentation**
- When an image is asked for the report, save it or make a screenshot
- **Better do few exercises but understand them at 100%**

# Part 1: Exploring the Input Namelist (Exercises 1-2)



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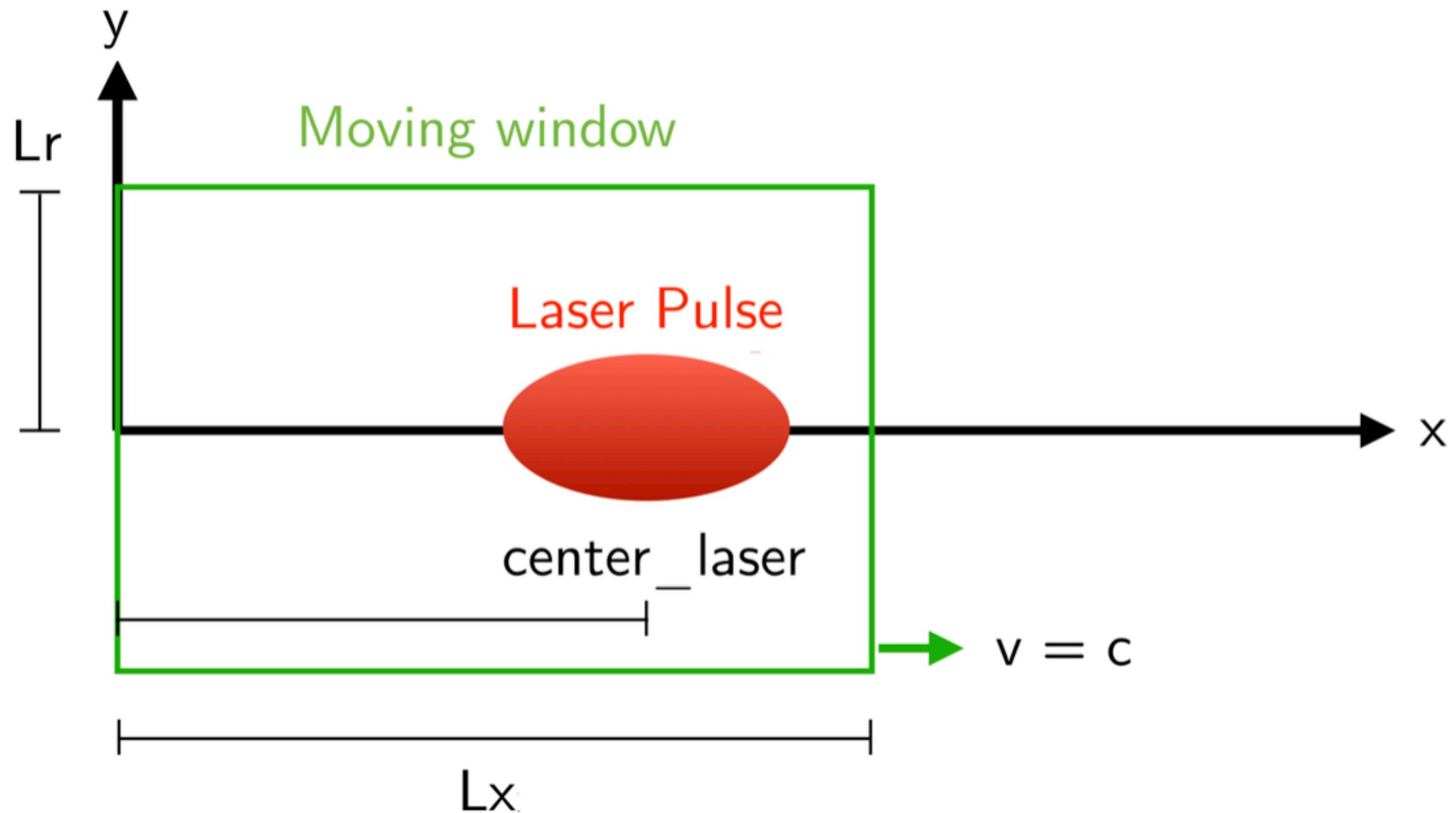
## Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

## Part 2: Laser pulse in vacuum (Exercises 4-6)



## Part 2: Laser pulse in vacuum (Exercises 4-6)

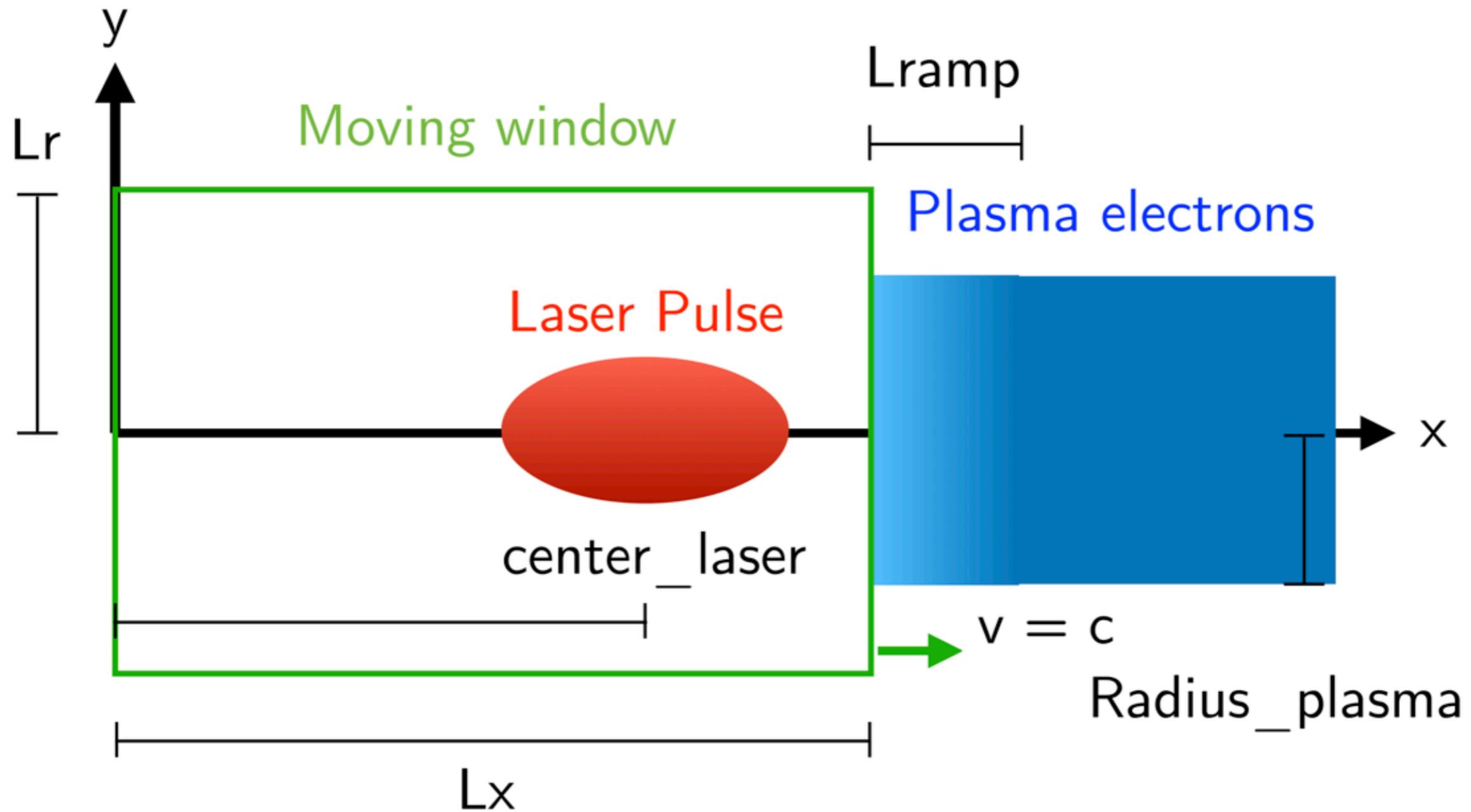
### Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

# Part 3: Laser Wakefield Excitation (Exercises 7-11)



# Part 3: Laser Wakefield Excitation (Exercises 7-11)

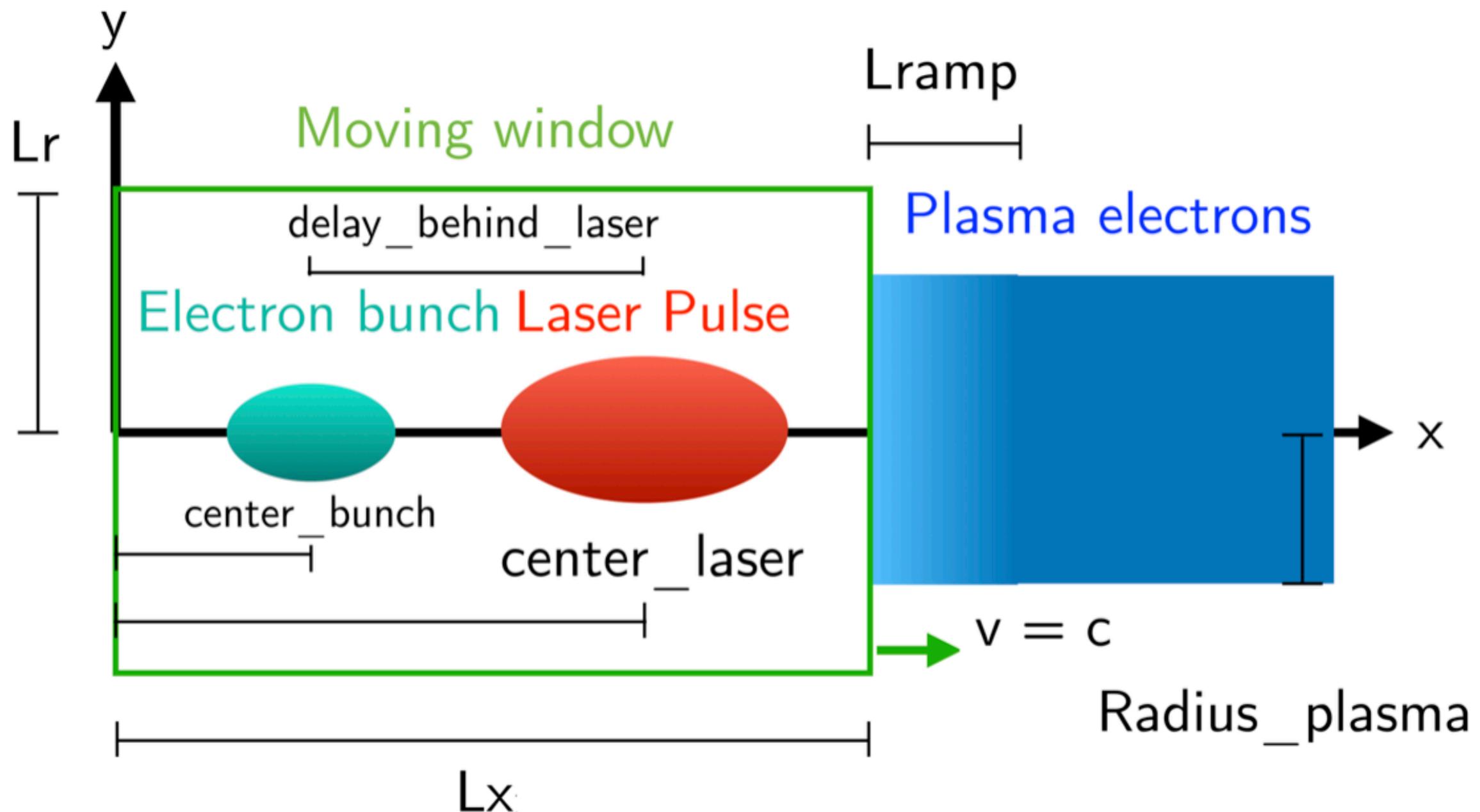
## Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

## Part 4: Laser Wakefield Acceleration of an electron bunch (Exercises 12-20)



## Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

# Postprocessing for the practical

Included in the code: the Python postprocessing library **happi**

```
$ ipython  
In [1]: import happi
```

## Diagnostics available for this practical:

- 1D Probe on the x axis (electromagnetic fields, density)
- 2D Probe on the xy plane (electromagnetic fields, density)
- DiagTrackParticles for the bunch electrons (phase space data)

## Tips:

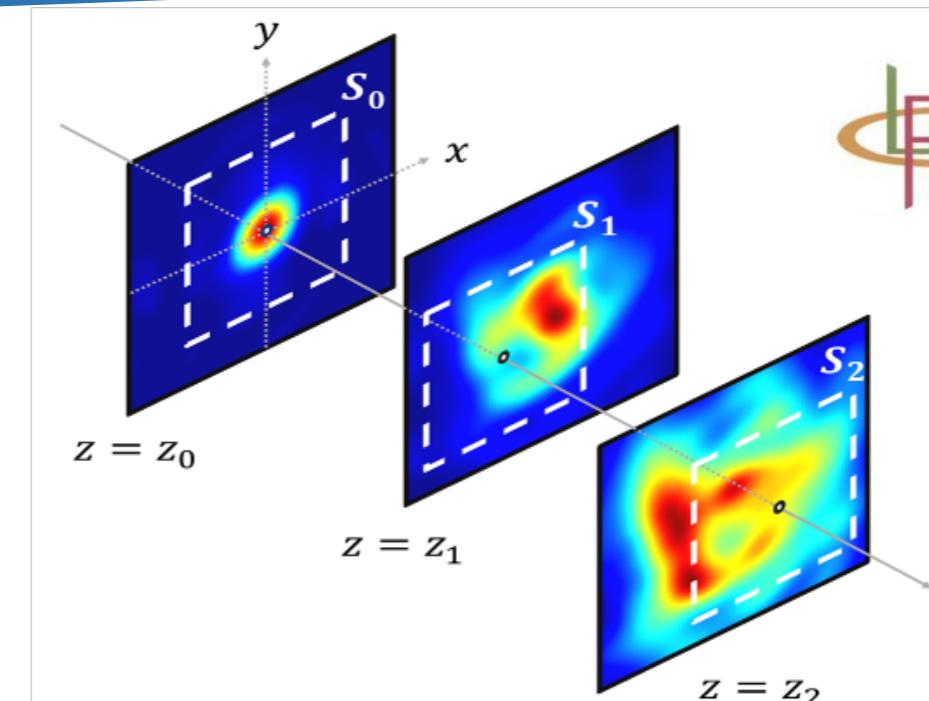
- Open the **Ipython** interface (command **ipython** in the terminal)
- Copy and paste the happi commands from the handouts
- Adapt them for your purposes
- Use the post processing scripts available (see handouts)

# Questions?

# Additional Slides

# Some current LWFA research themes (1)

Realistic laser pulses in PIC simulations yield  
Accurate reconstructions of experimental data



I. Moulanier et al.,  
Physics of Plasmas (2023)

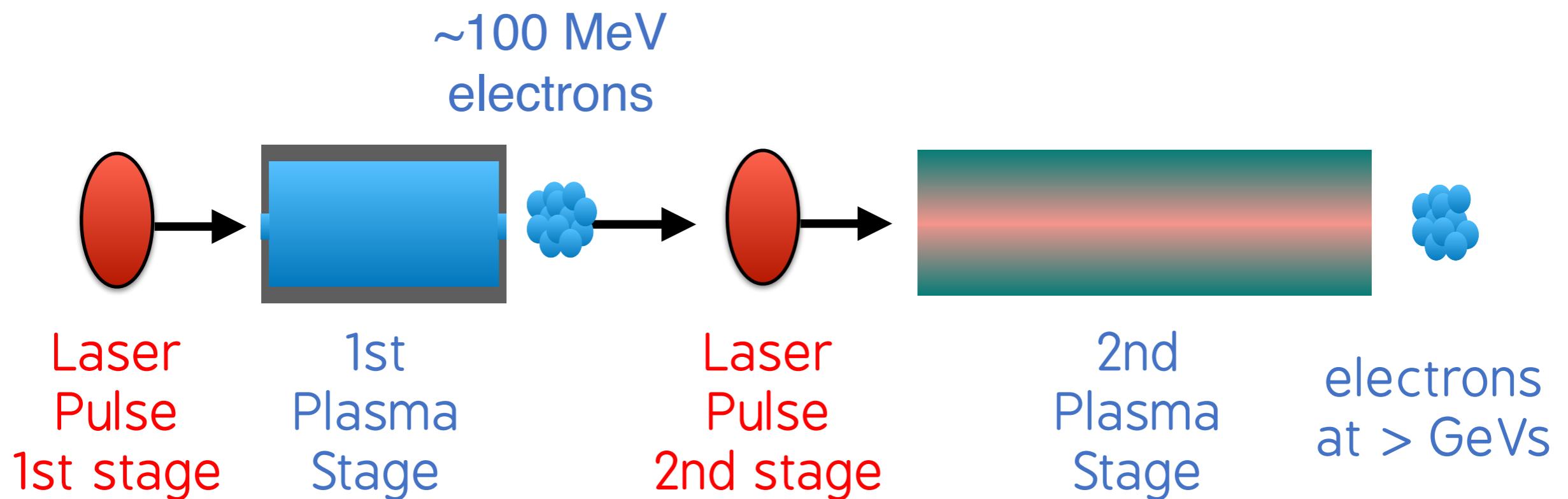
I. Moulanier et al.,  
J. Opt. Soc. Am. B **40**(9), 2450-2461 (2023)

## **Internship at LPGP: Advanced electric field reconstruction analysis**

Use advanced phase reconstruction algorithm to reconstruct laser field

# Some current LWFA research themes (2)

## Making LWFA scalable: Multi-stage experiments

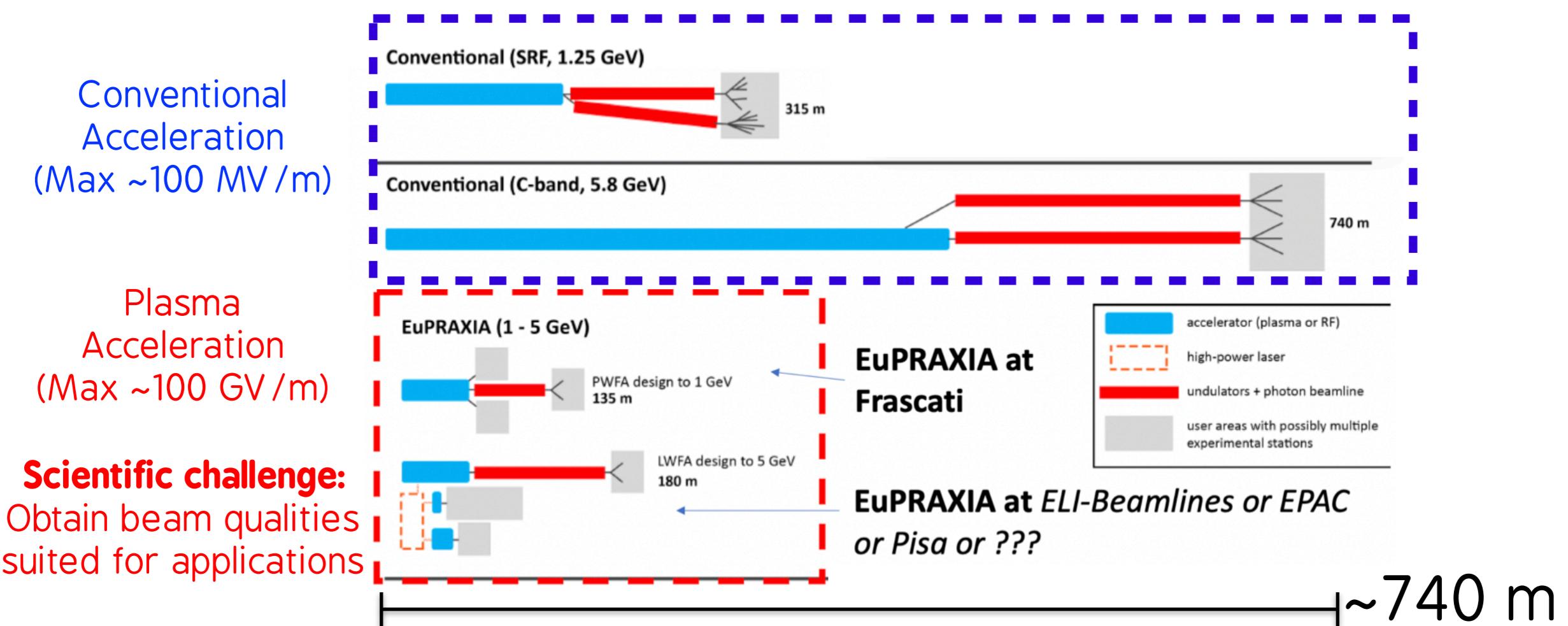


# Some current LWFA research themes (3)



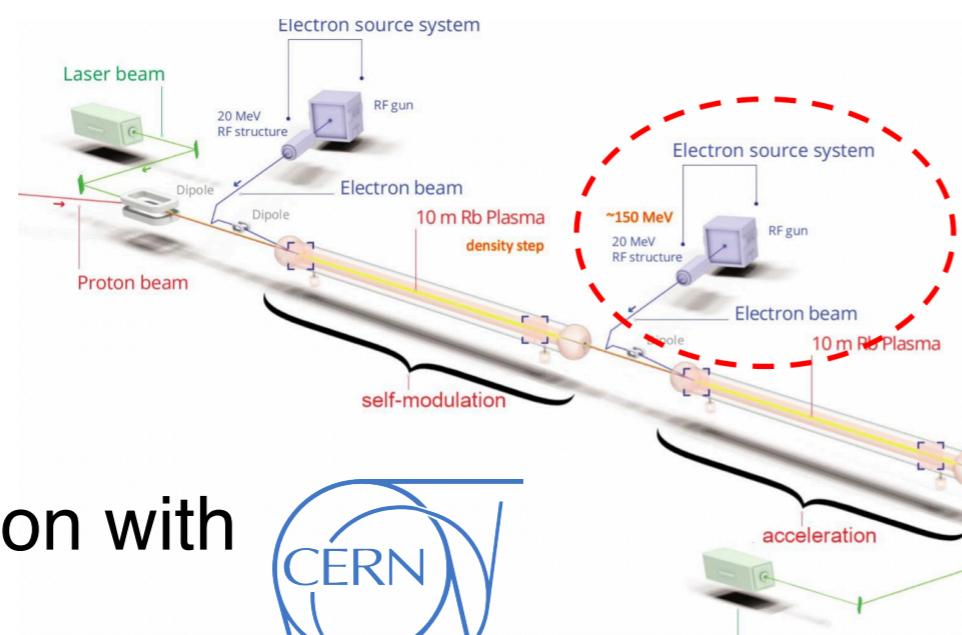
**Objective:** build a European, large scale, distributed plasma acceleration facility for users

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



# Some current LWFA research themes (4)

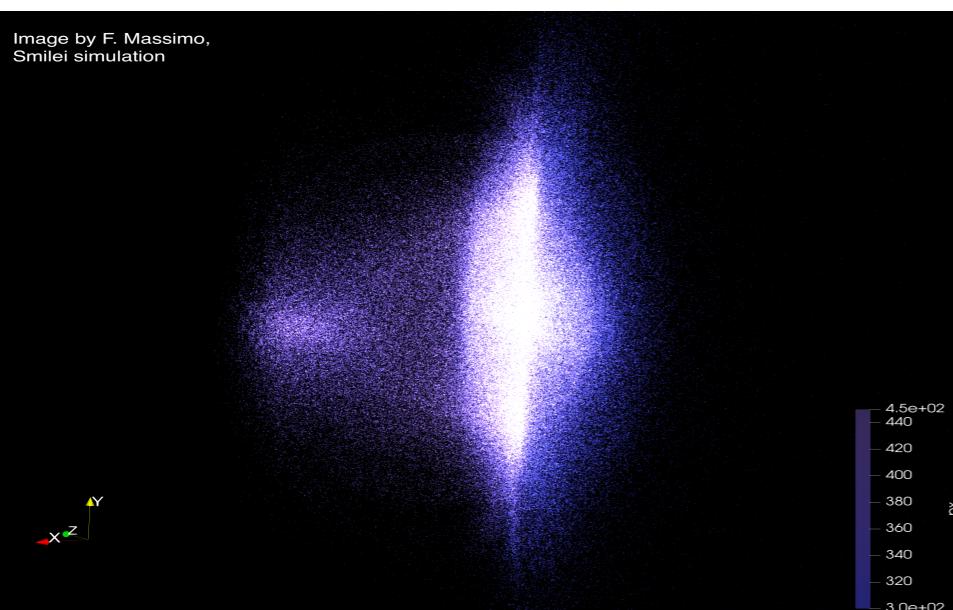
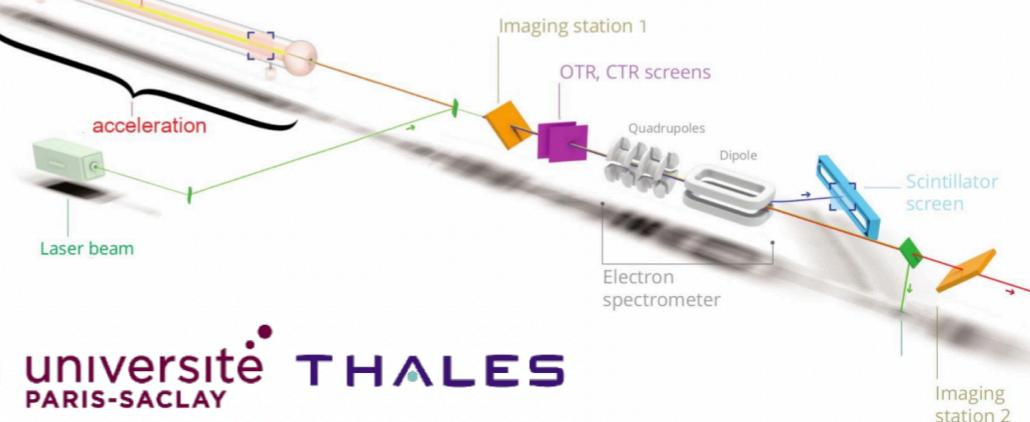
## Electron Accelerator driven by a Reliable Laser for Industrial uses (EARLI)



Can we use  
a laser Wakefield accelerator  
as electron injector in project



Collaboration with

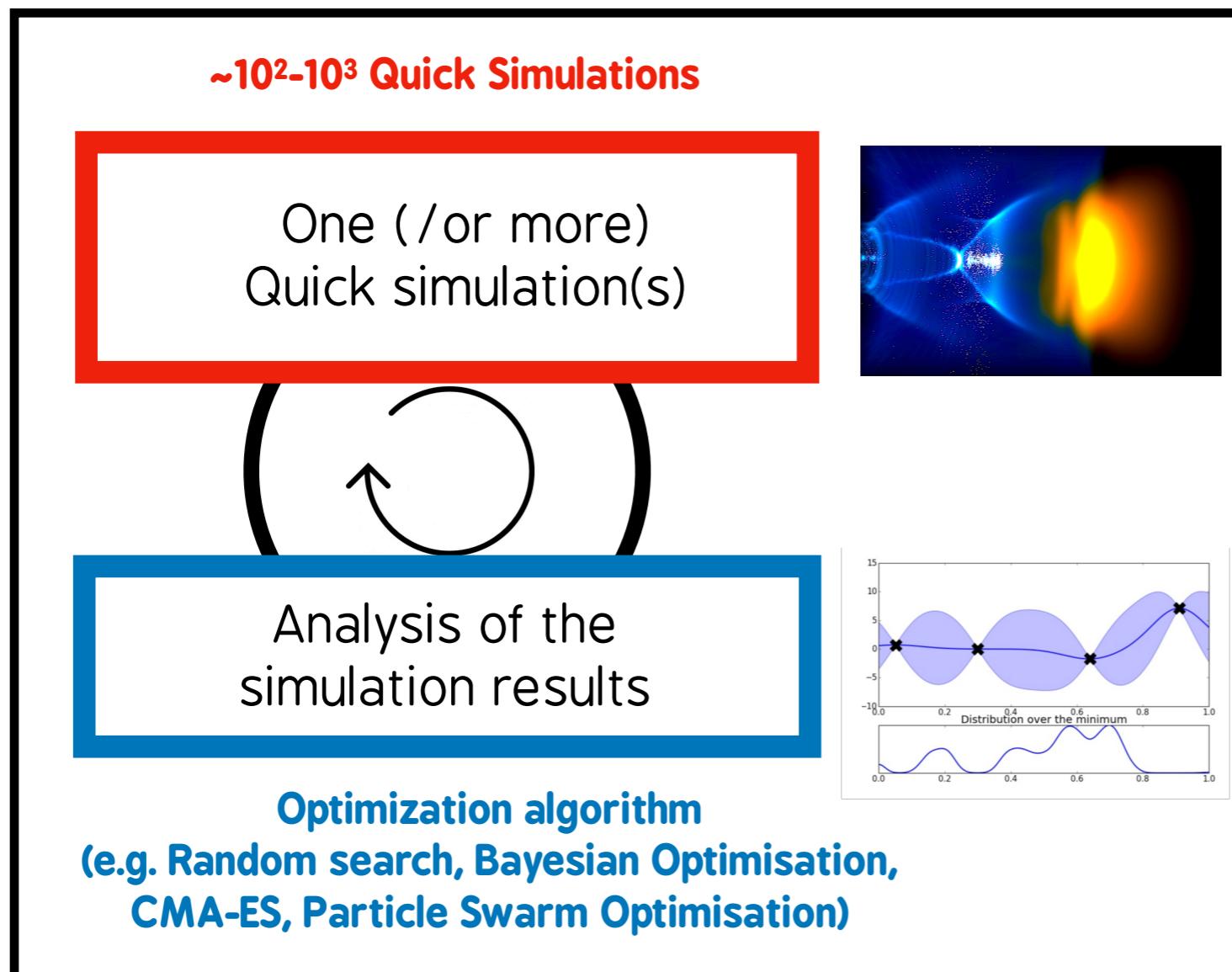


Objective: build a LWFA  
to inject an electron beam  
in proton-driven waves  
propagating in a 10 m plasma

Electron beam at plasma exit, Smilei simulation

# Some current LWFA research themes (5)

## Machine Learning and AI for LWFA



P. Drobniak and IJClab,  
2021