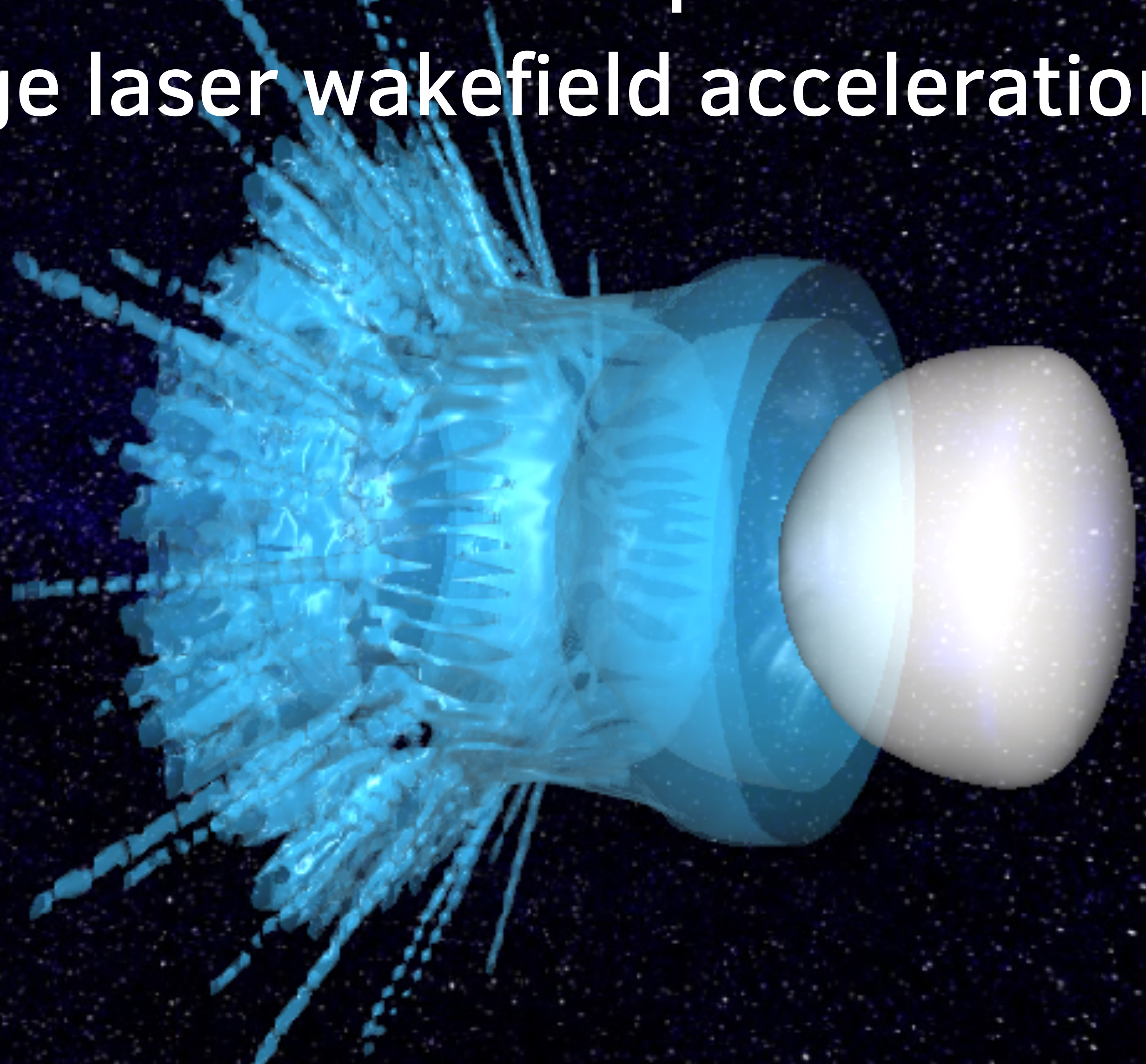
Efficient 3D envelope modelisation for two-stage laser wakefield acceleration experiments



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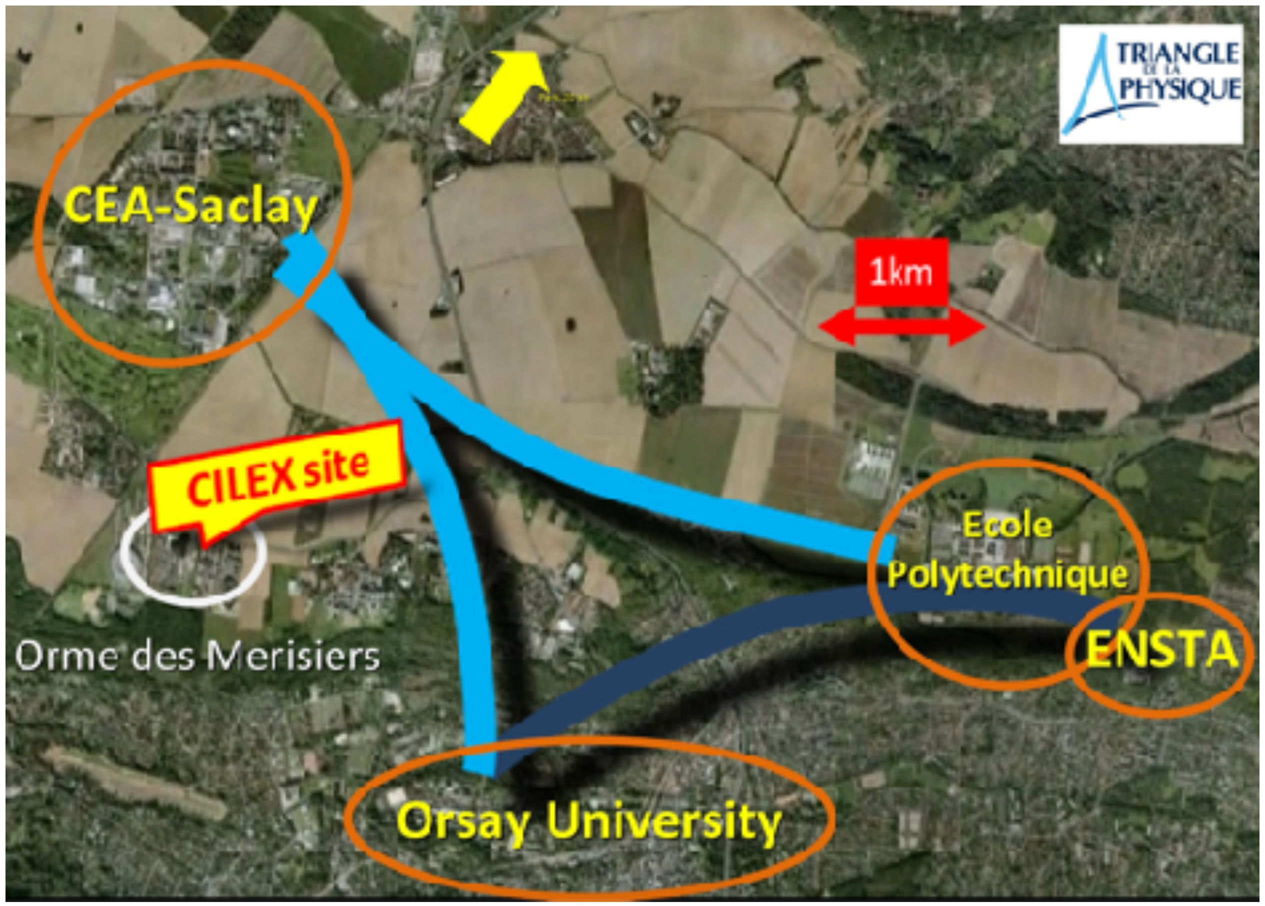
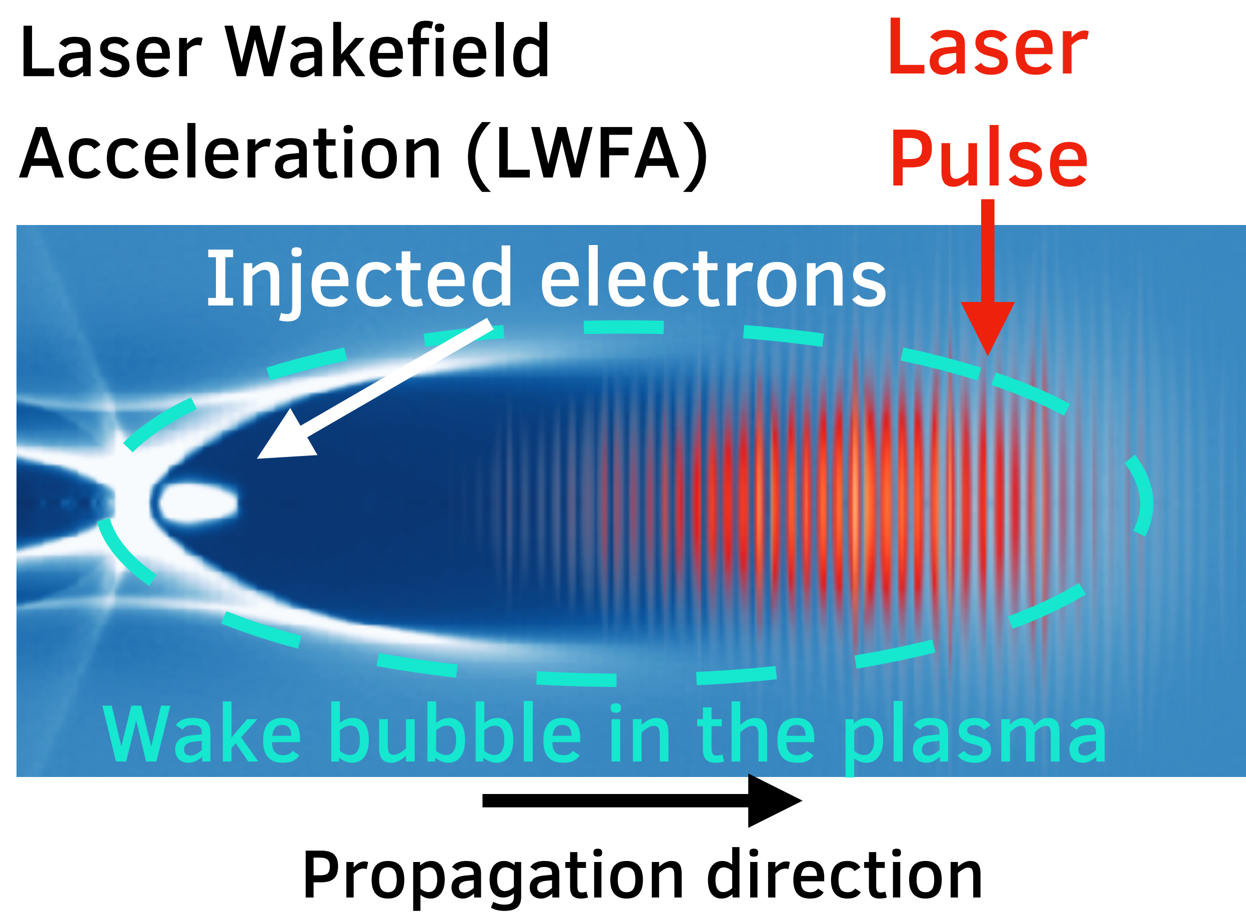
Outline

- Context
- Modeling Laser Wakefield Acceleration with a laser envelope
- First stage simulations
- Second stage simulations: Standard PIC vs Envelope PIC
- Conclusions

Centre Interdisciplinaire de la Lumière Extrême (CILEX)



Laser Wakefield Acceleration (LWFA)

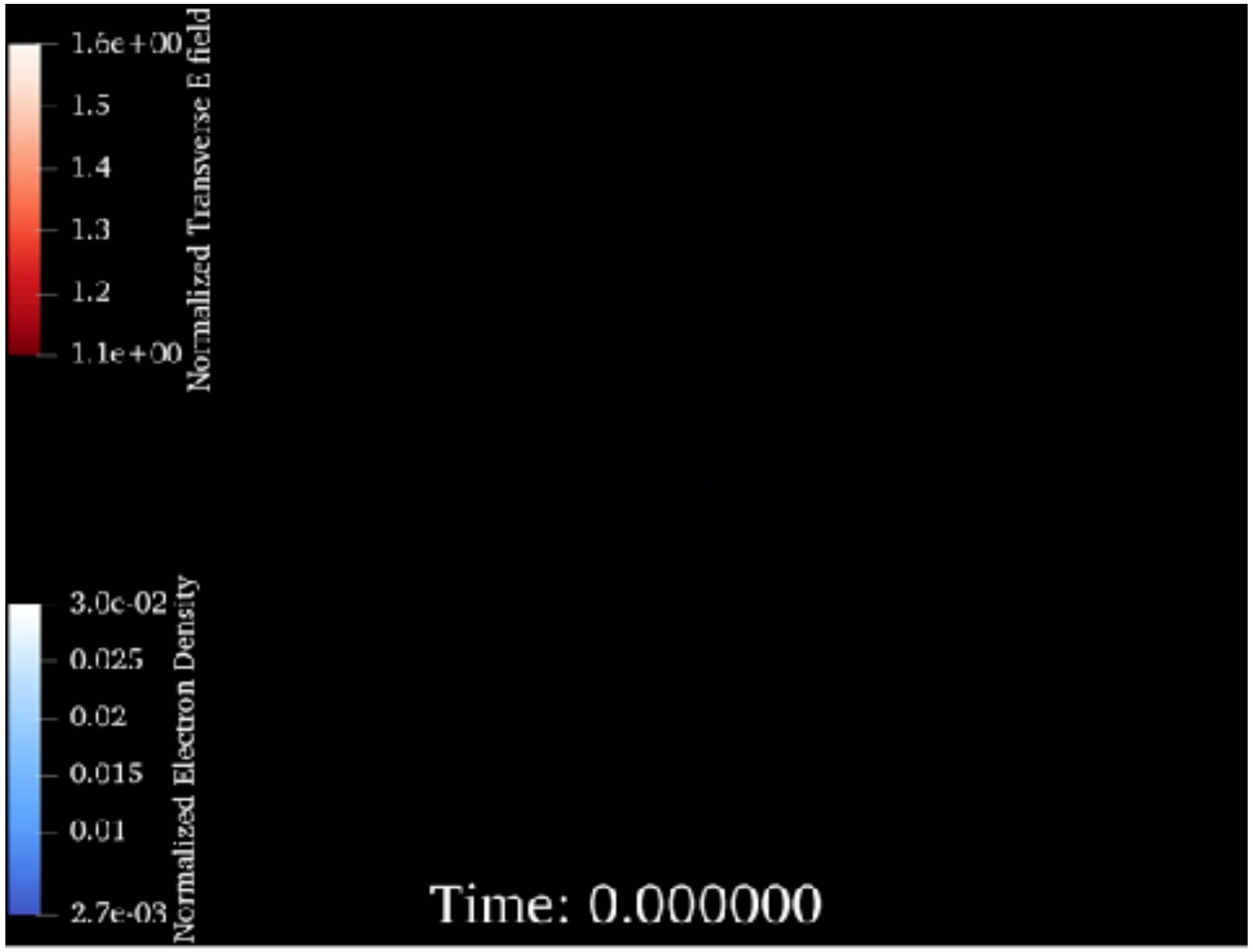


A collaborative open source Particle in Cell code

Smilei)

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

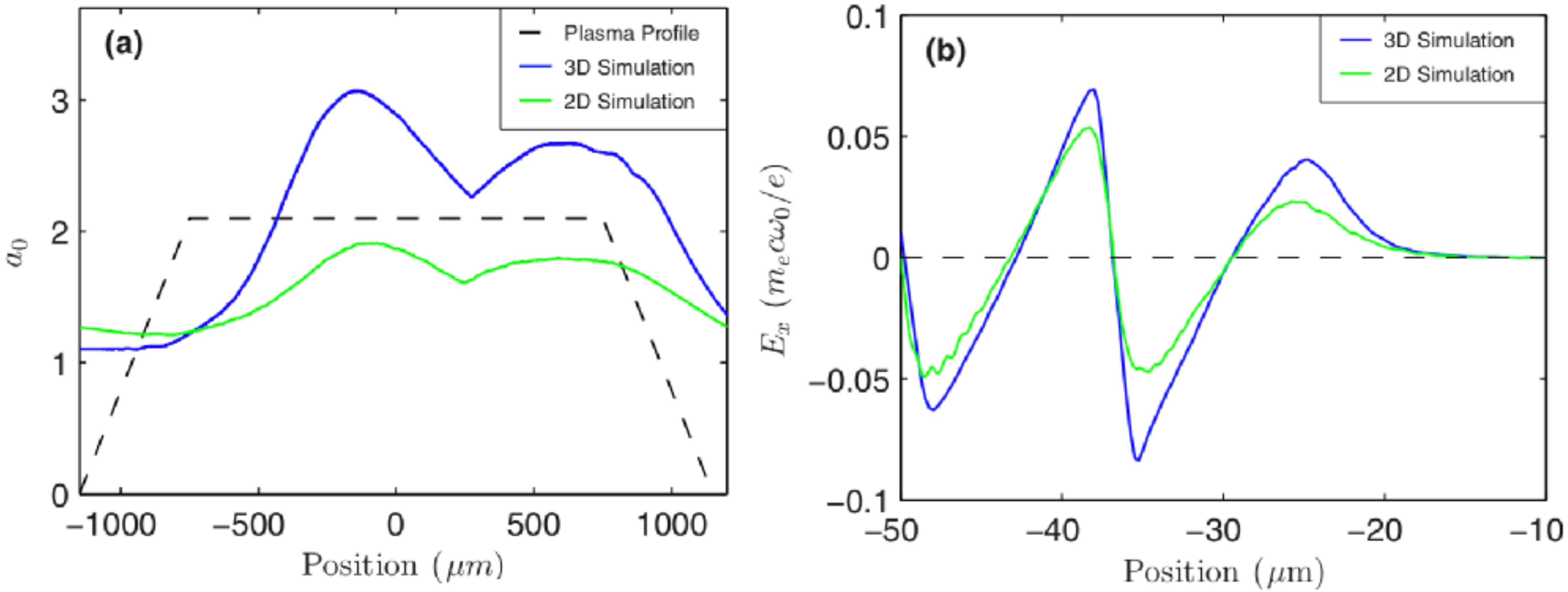
- 1D, 2D, 3D, Quasi-3D Geometry
- Hybrid MPI-OpenMP
- Python Input/Output Interface
- Advanced Dynamic Load Balancing
- Dynamic Adaptive Vectorisation
- Ionisation, Collisions, QED effects
- Envelope Model for the Laser
- Relativistic Beam Field Initialisation



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

LWFA PIC simulations are cumbersome

X. Davoine, Physics of Plasmas 15, 113102 (2008)

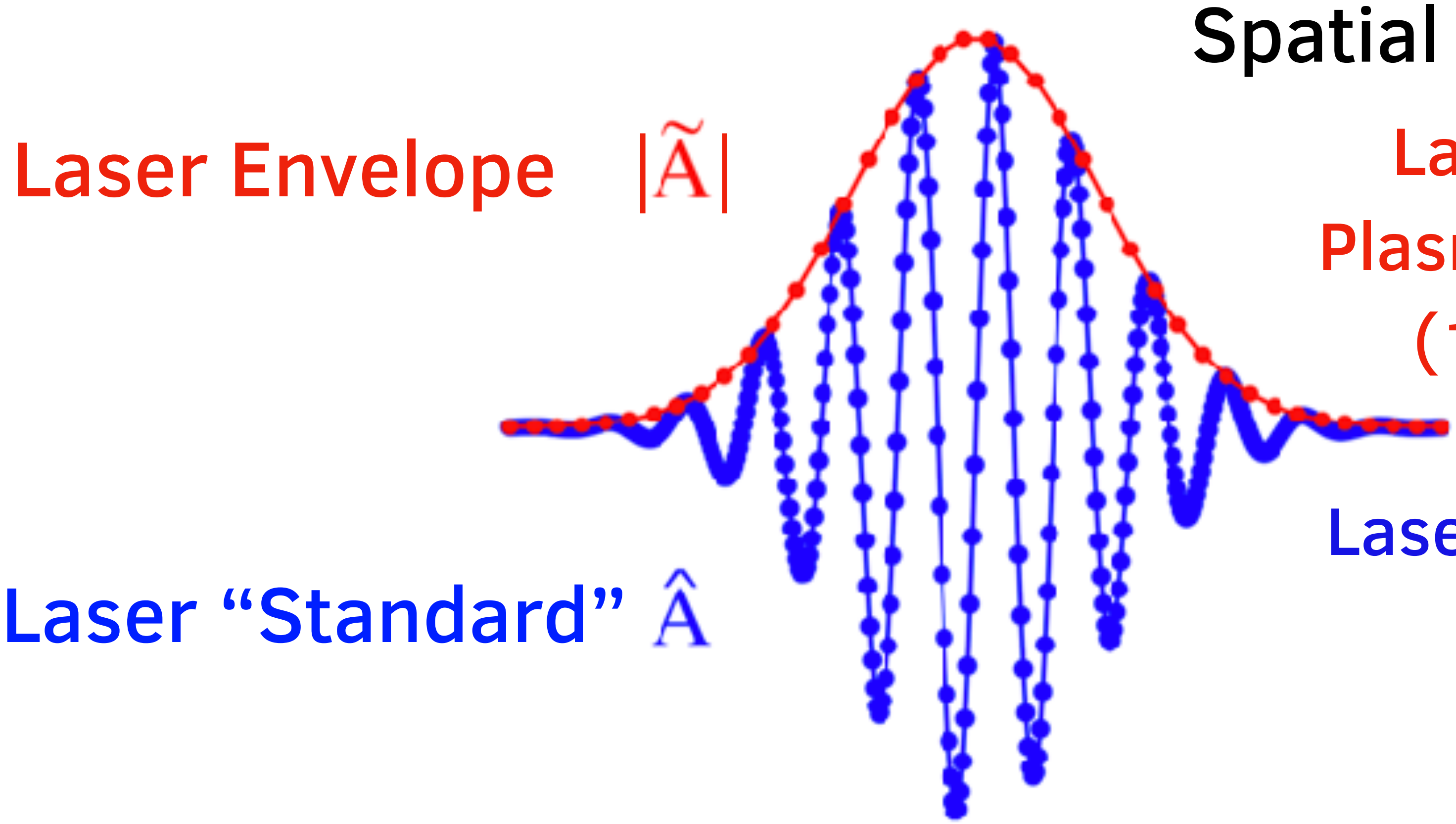


2D cartesian simulations
are not accurate enough for LWFA!

3D LWFA simulations:

1 mm plasma ~ 320 kcpu-hours ~ 10.2 k€

Laser Envelopes need less sampling points



Spatial variation scales:

Laser length ~ Plasma wavelength (10-100 μm)

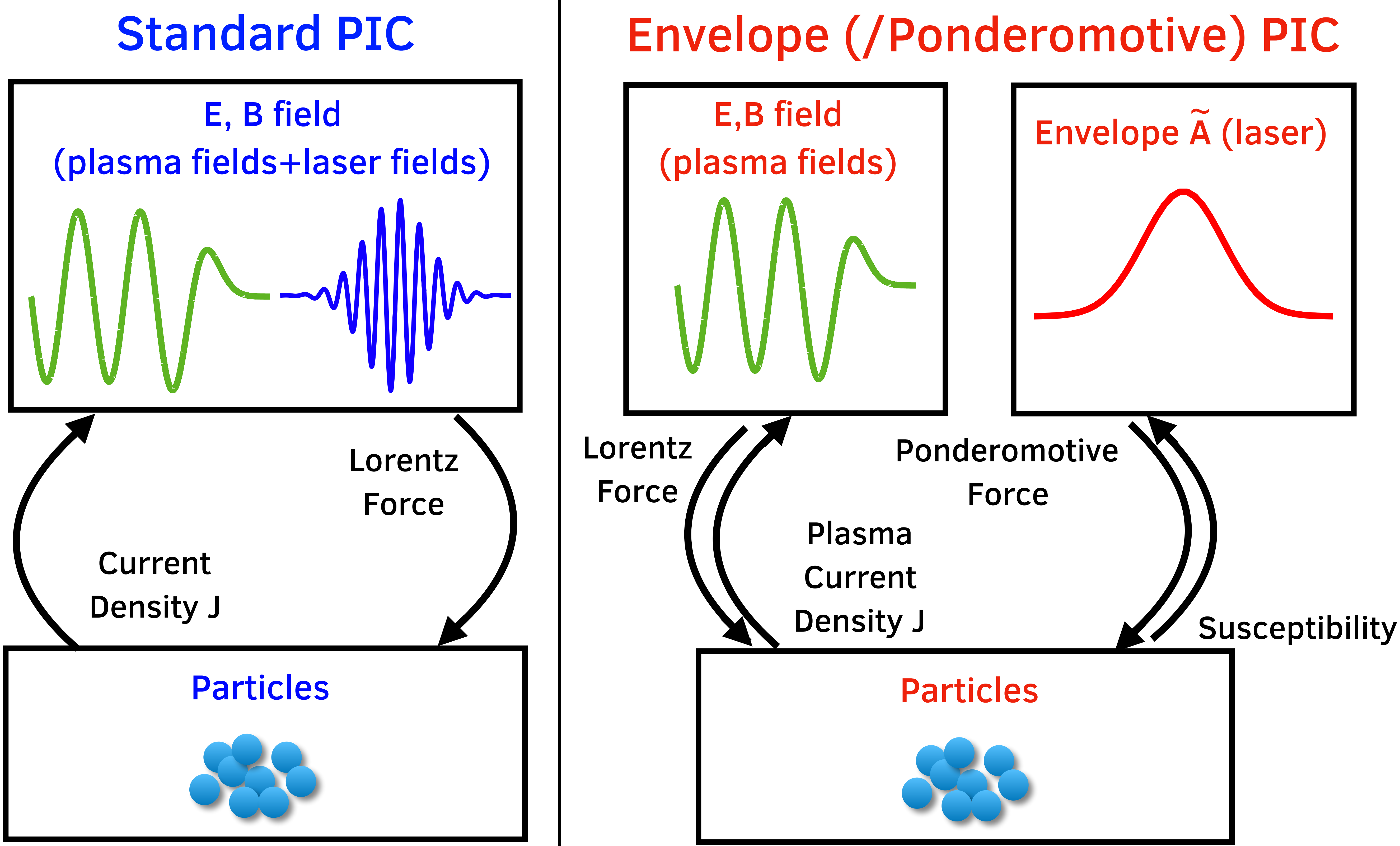
Laser wavelength (~1 μm)

D. Terzani and P. Londrillo, Comput. Phys. Comm. (2019)

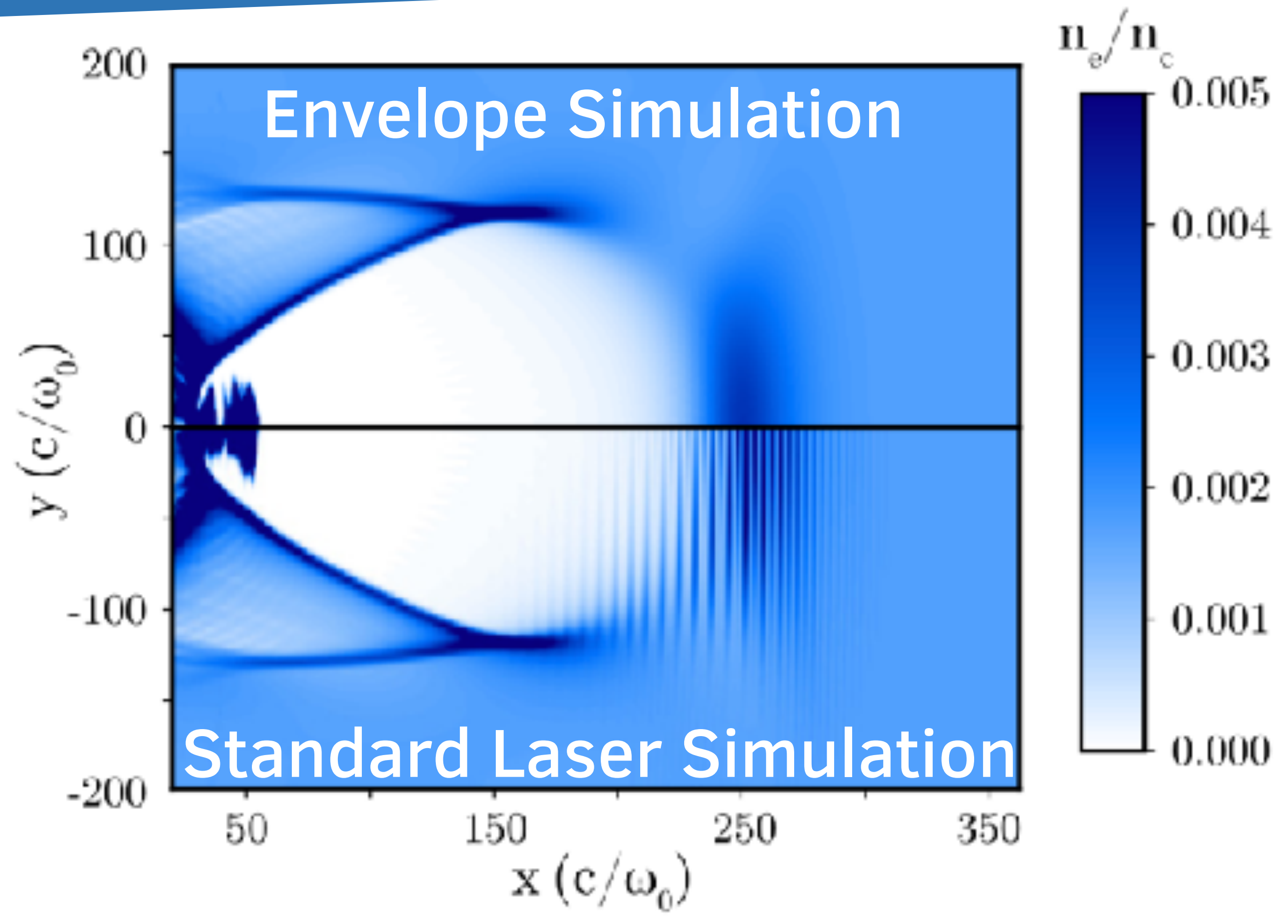
$$\frac{\text{Points sampling Laser "Standard"}}{\text{Points sampling Laser Envelope}} = 10$$

→ Larger Δx and Δt can be used!

Envelope model: separate the laser field



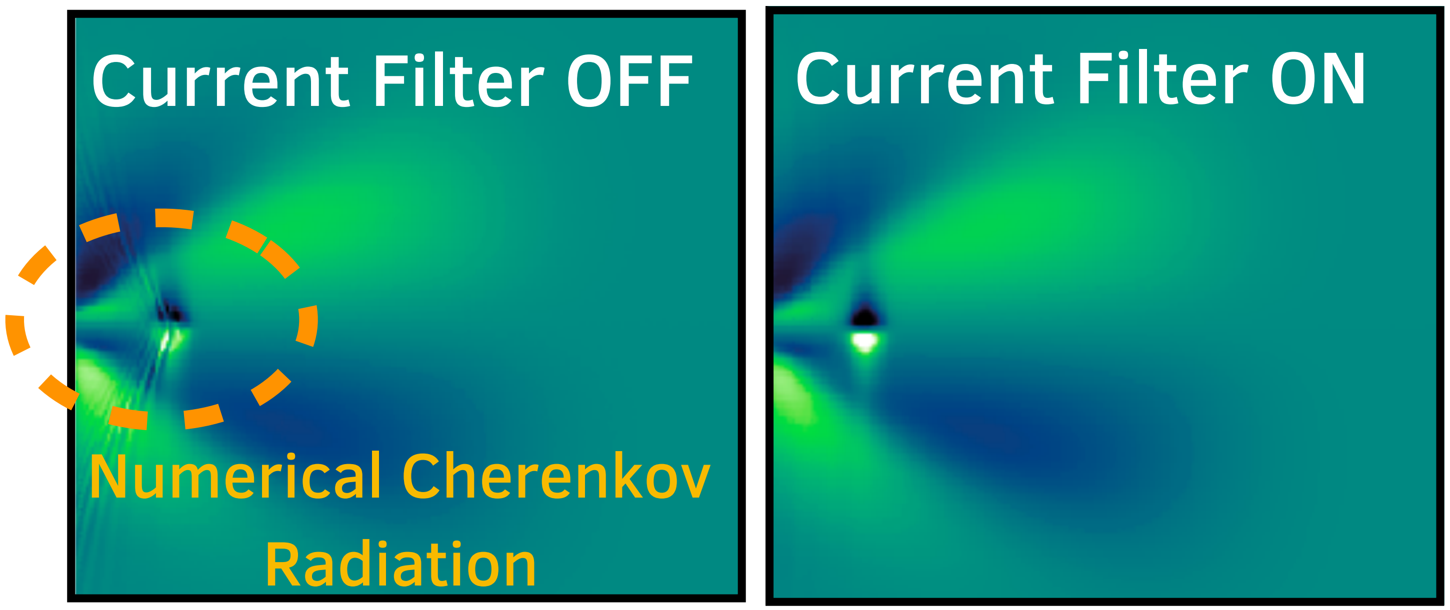
Envelope modeling has multiple advantages



Transverse E field, Apollon Simulations

$T_{\text{Standard PIC}}$ (1 mm of propagation):
~ 320 kcpu-hours
~ 10.2 k€

$$\frac{T_{\text{Standard PIC}}}{T_{\text{Envelope PIC}}} > 20$$



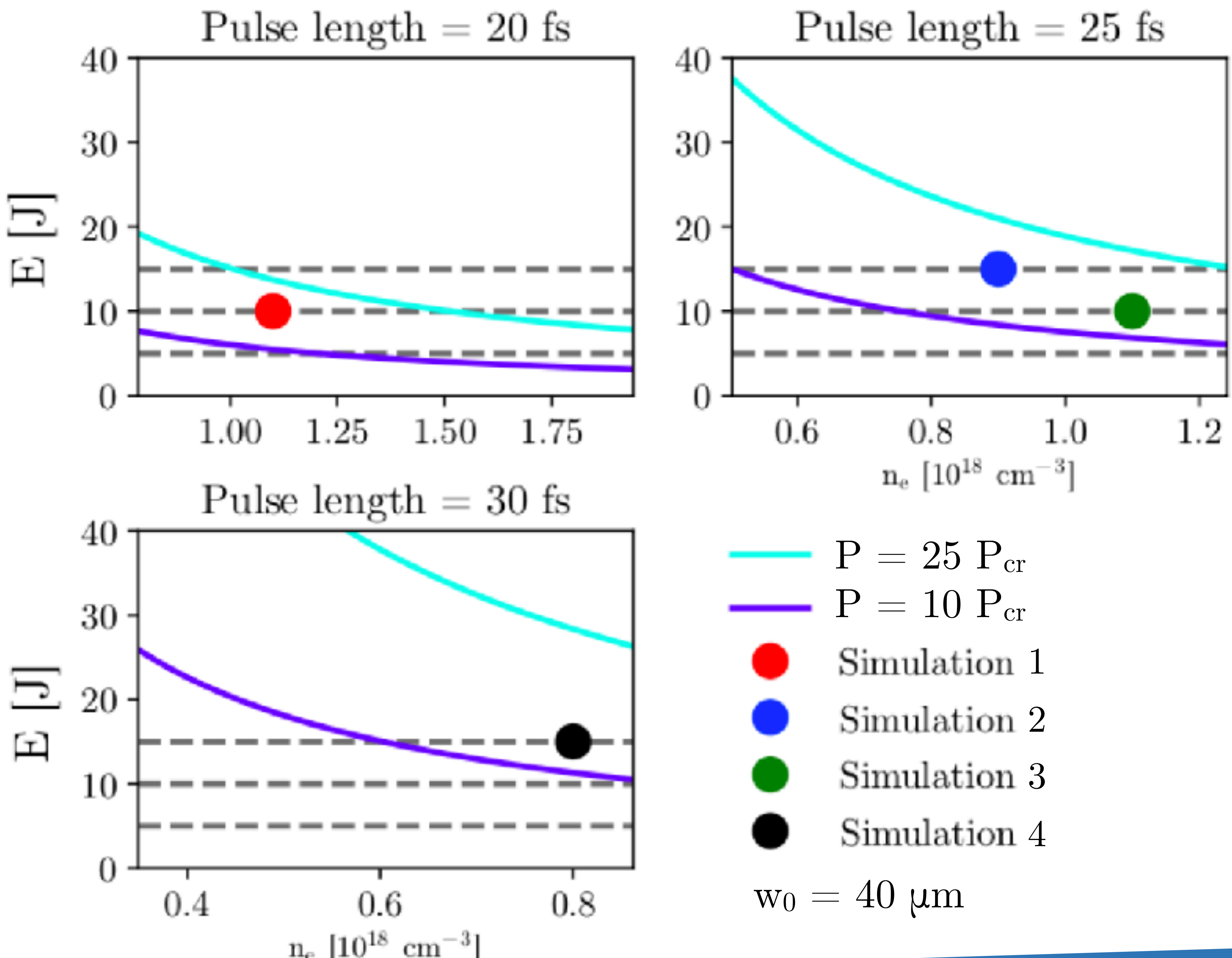
J.-L.Vay, JCP 230 (2011)

Advantages of the envelope:

- Quicker (speedup>20)
- Safe Filtering
- Accurate laser speed

CILEX 1st stage: possible working points

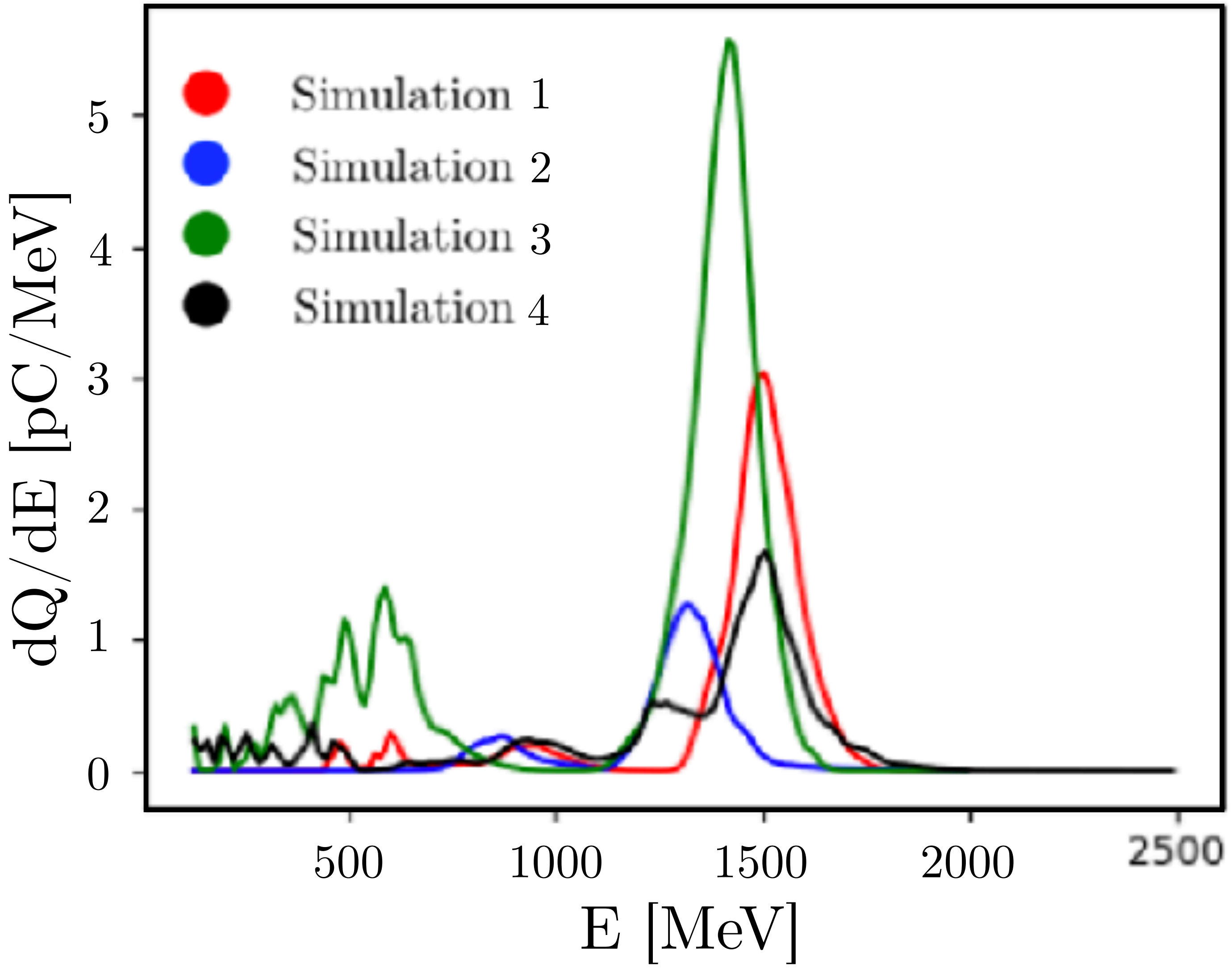
Scalings from A. Beck et al. , NIM A 740 (2014)



CILEX 1st stage: possible working points

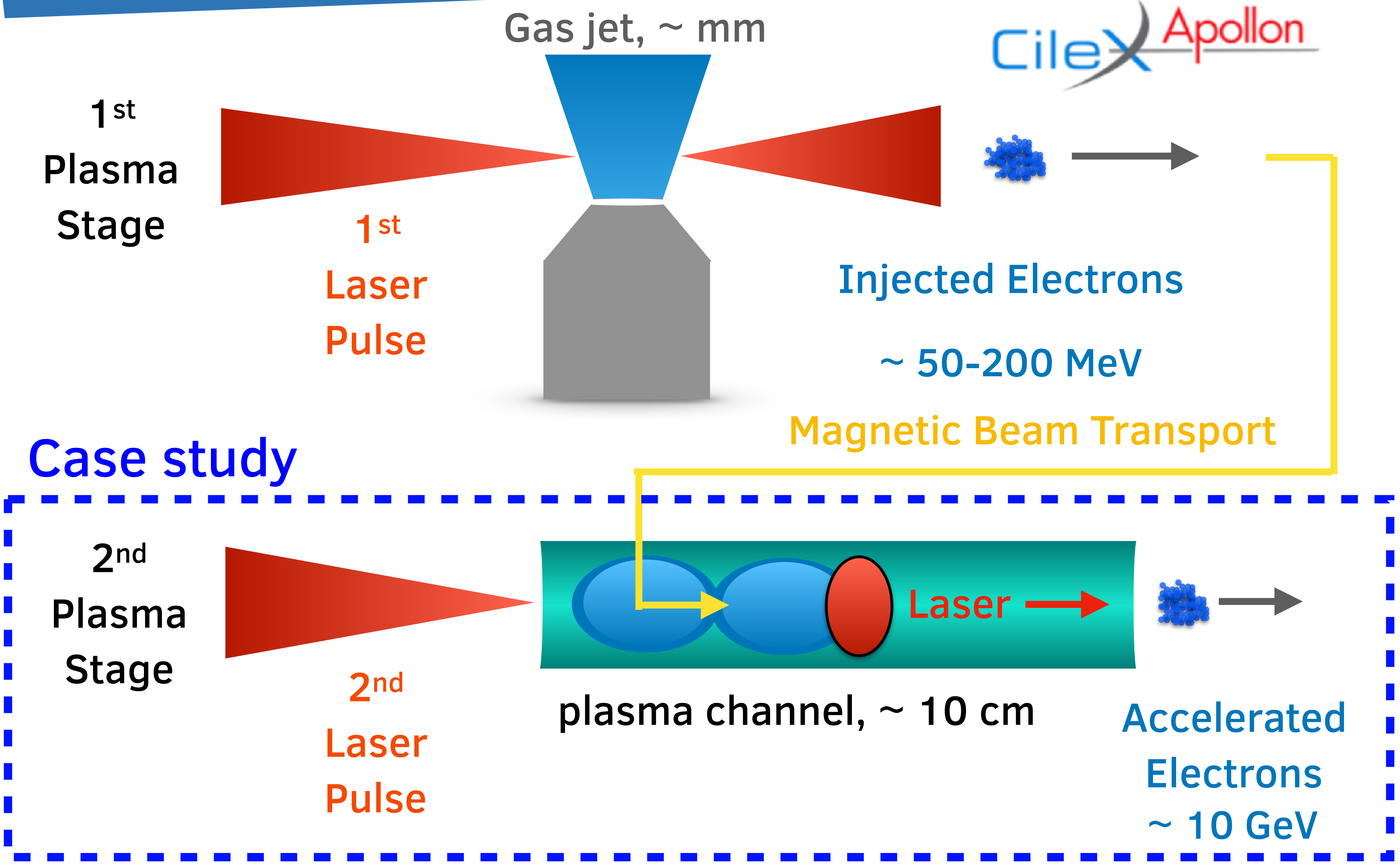
1er Étage d'Apollon, Étude Paramétrique avec le Modèle d'enveloppe

Simulation	1	2	3	4
E_{Laser} [J]	10	15	10	15
P/P_{cr}	18.3	12.0	22.0	13.3
$n_{plasma}[10^{18}cm^{-3}]$	1.1	0.9	1.1	0.8
$L_{FWHM,\ Laser}$ [fs]	20	25	25	30
Q [pC]	535	229	949	317
E_{peak}[GeV]	1.5	1.3	1.4	1.5
ΔE/E (%)	10.8	14.3	11.5	11.6
$E_{e\ beam}$ [J]	0.8	0.3	1.3	0.5
$E_{e\ beam}/E_{Laser}$	8 %	3 %	9 %	3 %



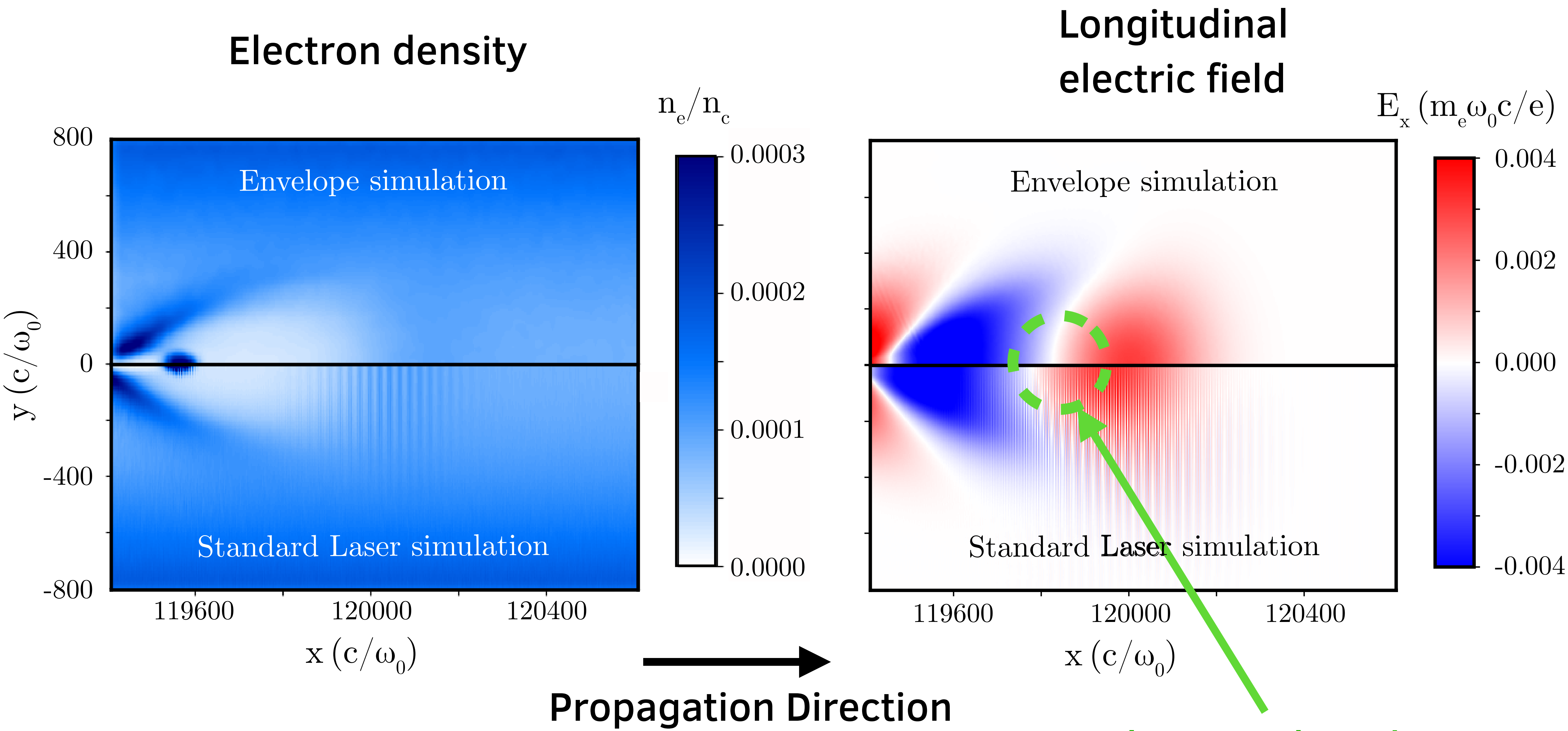
@12 mm de propagation, Résultats Préliminaires

Case Study: Multistage LWFA experiments



Simulation of External injection LWFA

Comparison @15 mm of propagation, Preliminary Results



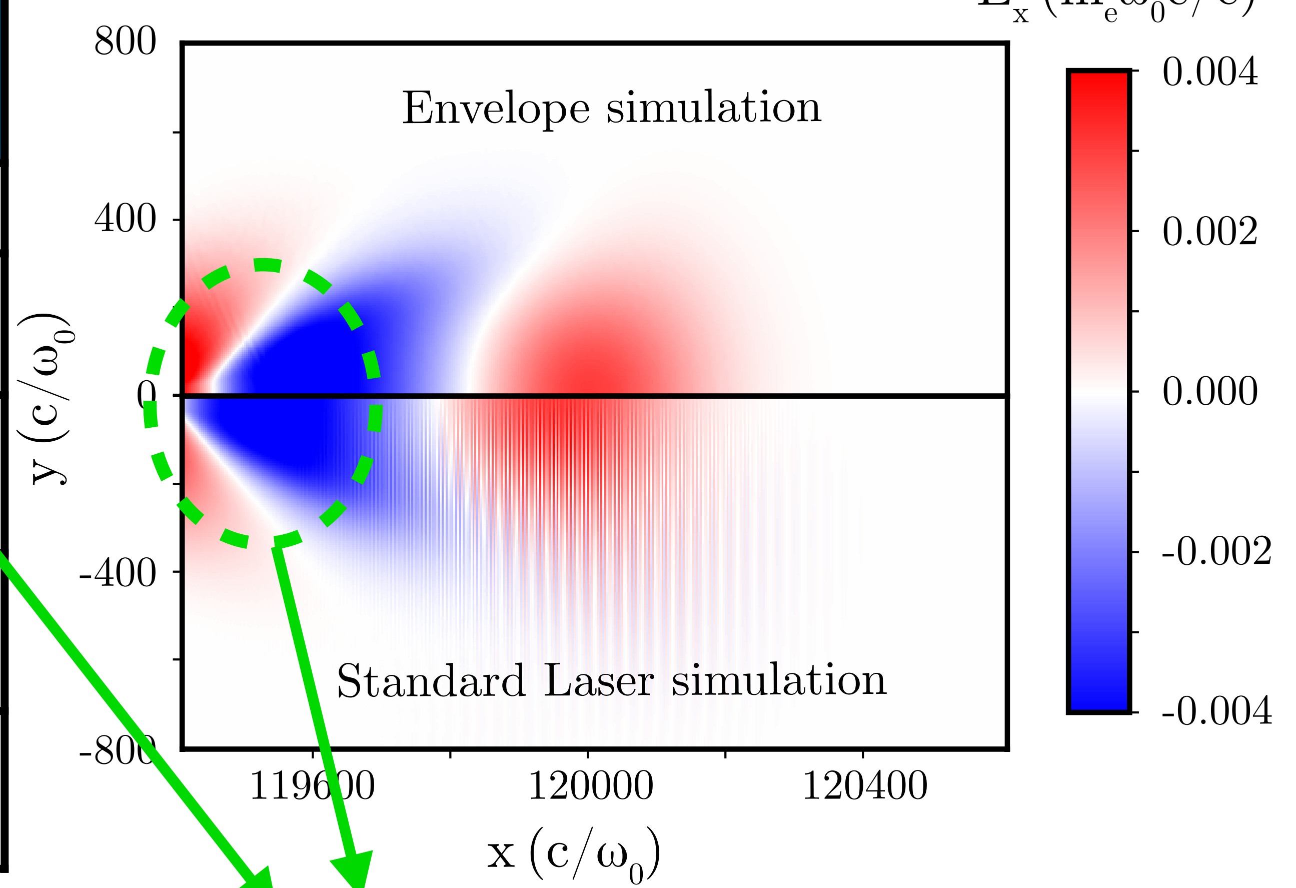
$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20$$

Simulation of External injection LWFA: envelope advantages

2ème Stage of Apollon, Comparison between Standard PIC and Envelope PIC

Electron Beam Parameters	Valeues @Injection	Standard Simulation @15mm	Envelope Simulation @15 mm
Q [pC]	30	29.98	29.94
E [MeV]	150	427	438
ΔE/E [%]	0.5	4.7	6.4
σ_x, σ_y, σ_z [μm]	2.0, 1.3, 1.3	2.0,1.5,1.4	2.0, 1.0, 1.0
$\varepsilon_{n,y}$, $\varepsilon_{n,z}$ [mm-mrad]	1.0, 1.0	2.0, 2.1	1.0, 1.0

Champ E longitudinal



Numerical Cherenkov reduced by filtering:
- Emittance conserved
- Beam stays focused

More accurate laser speed: More accurate phase and Longitudinal phase space evolution

Conclusions and perspectives

- Quick envelope model implemented for 3D LWFA PIC simulations
- More accurate laser propagation speed
- More room to current filtering to reduce numerical Cherenkov radiation
- Model benchmarked in nonlinear regimes and 15mm external injection
- Possible CILEX first stage working points found through parametric scan
- Model suited for multi-stage LWFA simulation
- Future development: envelope model + cylindrical symmetry
- Next steps: simulations with realistic laser beams, realistic particle beams

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- Davide Terzani

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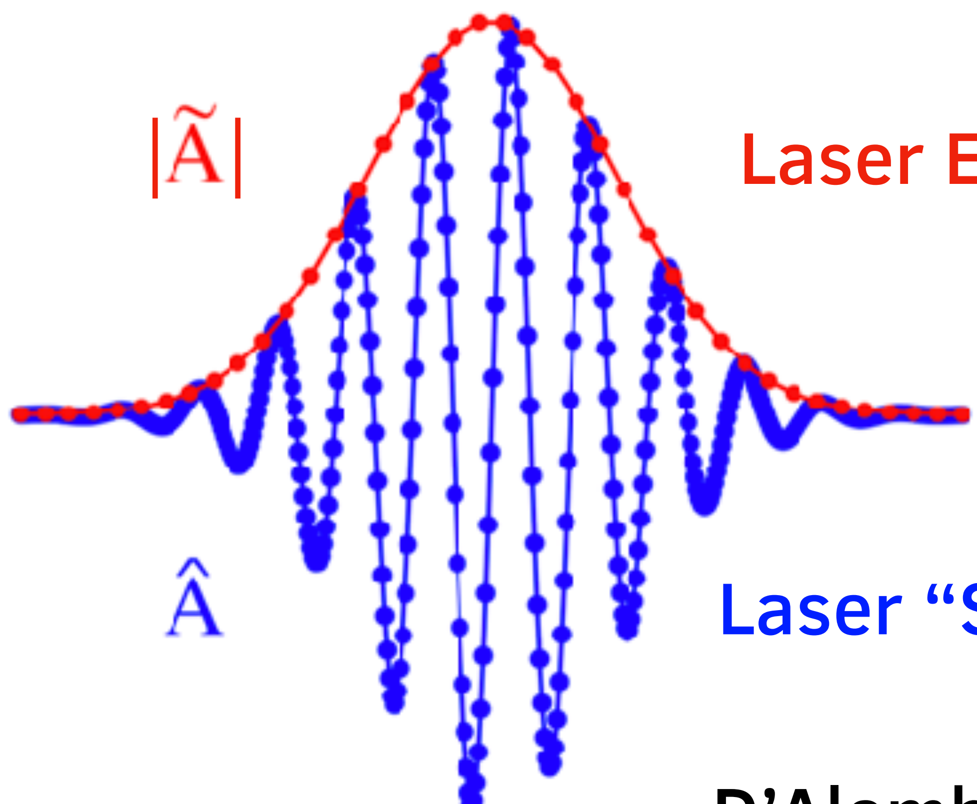
P2IO LabEx (ANR-10-LABX-0038) in the Framework "Investissements d'Avenir" (ANR-11-IDEX-0003-01) managed by Agence Nationale de la Recherche (ANR, France) provided financial support for F. Massimo

Additional slides

The Laser Envelope evolution: wave equation

D. Terzani and P. Londrillo,
Comput. Phys. Comm. (2019)



Hypothesis:

$$\hat{A}(\mathbf{x},t) = Re\left[\tilde{A}(\mathbf{x},t)e^{i(x-ct)}\right]$$

Laser Complex Envelope

+

D'Alembert Equation:

$$\nabla^2\hat{A} - \partial_t^2\hat{A} = -\hat{J}$$

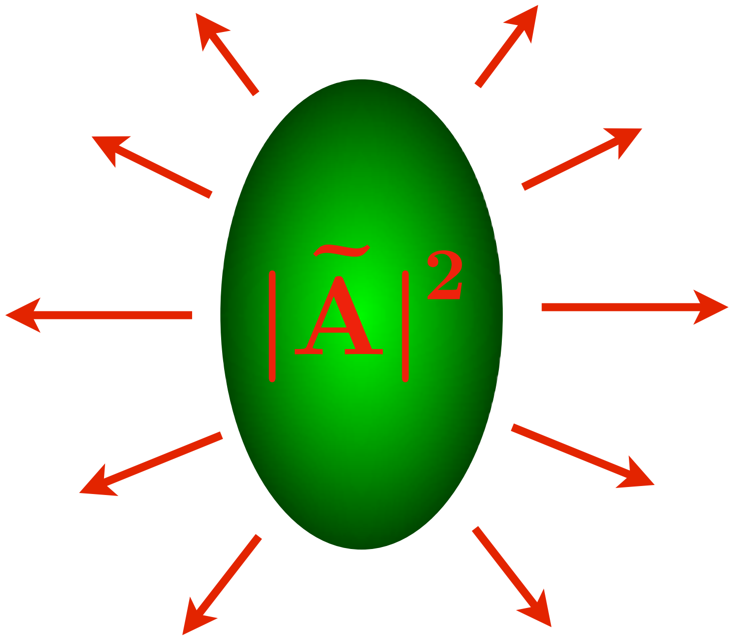
=

Envelope Equation:

$$\nabla^2\tilde{A} + 2i\left(\partial_x\tilde{A} + \partial_t\tilde{A}\right) - \partial_t^2\tilde{A} = \chi\tilde{A}$$

Plasma Susceptibility

Ponderomotive Equations of motion



Ponderomotive force acts as a radiation pressure on charged particles : it expels the electrons from high-intensity zones

$F_{ponderomotive}$

Motion Equations for the macroparticles (here electrons):

$$\frac{d\bar{\mathbf{x}}_p}{dt} = \frac{\bar{\mathbf{u}}_\mathbf{p}}{\bar{\gamma}_p}$$

$$\frac{d\bar{\mathbf{u}}_p}{dt} = \left(\bar{\mathbf{E}}_p + \frac{\bar{\mathbf{u}}_p}{\bar{\gamma}_p} \times \bar{\mathbf{B}}_p\right) - \frac{1}{4\bar{\gamma}_p}\nabla\left(|\tilde{A}_p|^2\right)$$

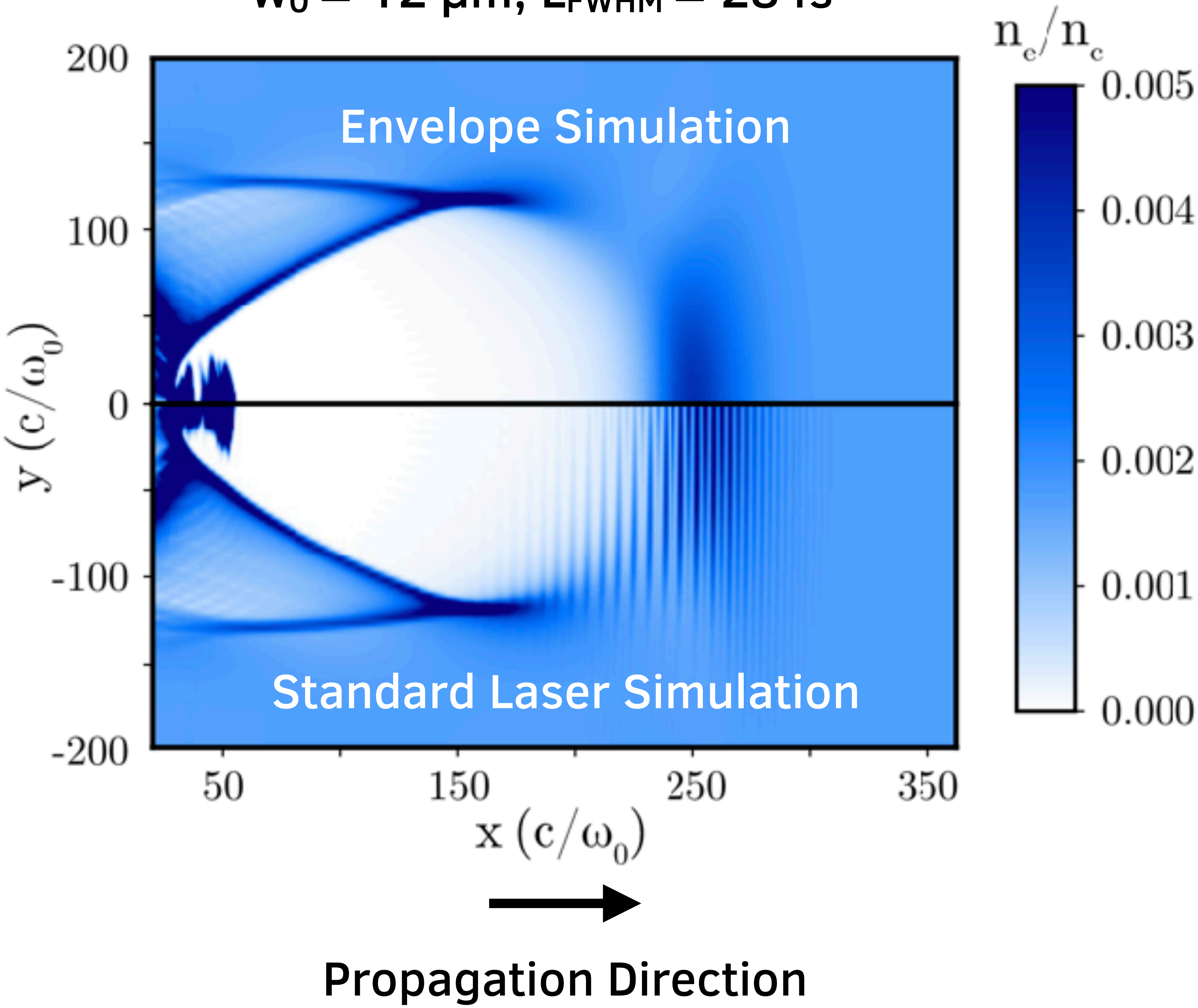
Lorentz Force (plasma fields) + Ponderomotive Force (laser envelope)

B. Quesnel and P. Mora, Physics Review E 58, 3719 (1998)

Validation test: Nonlinear LWFA, Electron density

$a_0 = 5$, $n_0 = 3 \cdot 10^{18}$ cm^{-3},
$w_0 = 12$ µm, $L_{FWHM} = 28$ fs

8 ppc, $\Delta y = \Delta z = 3\ c/\omega_0$



Standard Laser simulation

$\Delta x = 0.125\ c/\omega_0$

$\Delta t = 0.124\ c/\omega_0$

Envelope simulation

$\Delta x = 0.75\ c/\omega_0$

$\Delta t = 0.675\ c/\omega_0$

$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20$$

@1 mm

$T_{\text{Envelope}} = 16$ kh-cpu