Scalings for multi-GeV laser-plasma accelerators and recent progresses in numerical modeling

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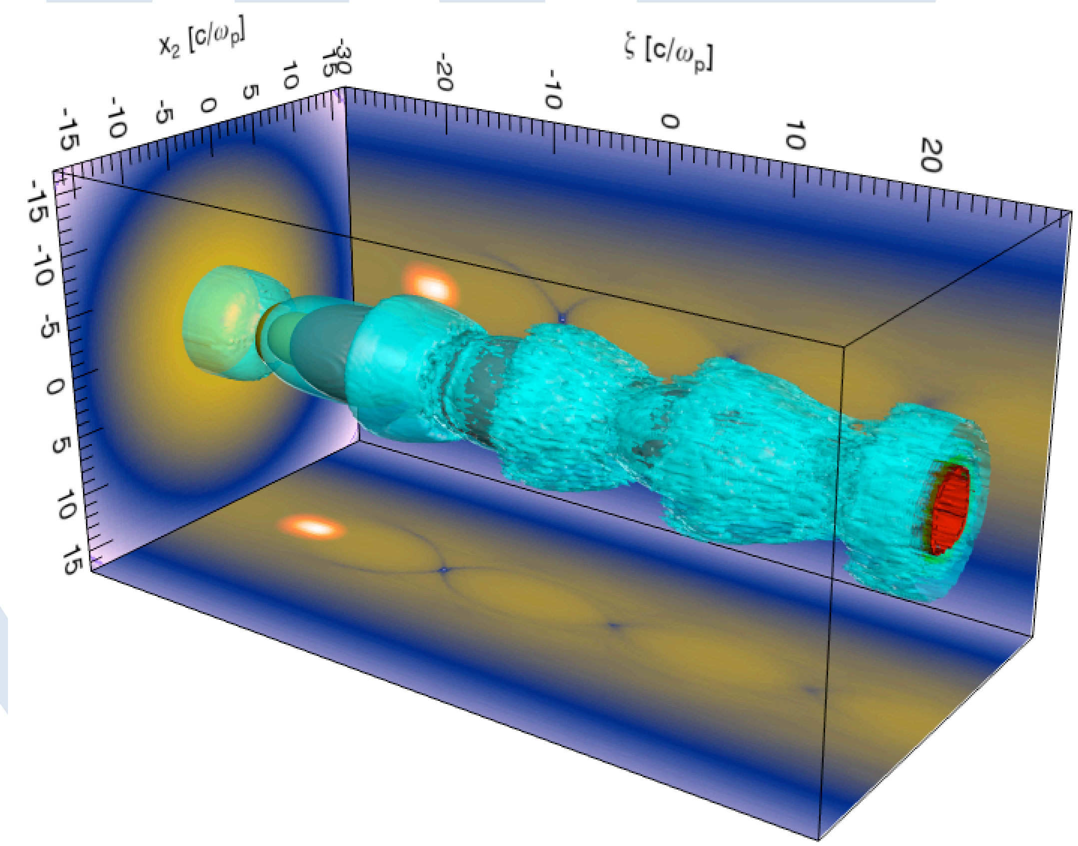
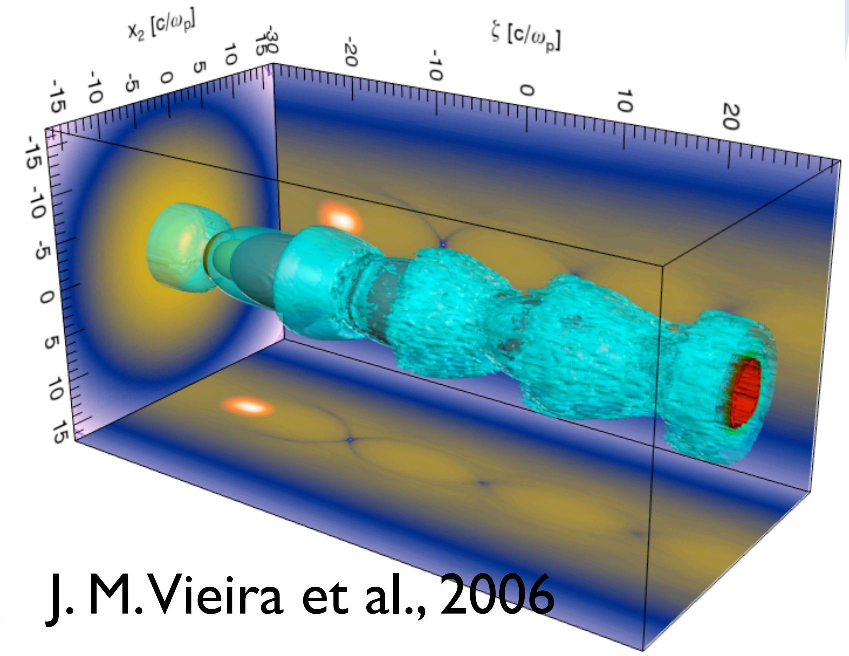
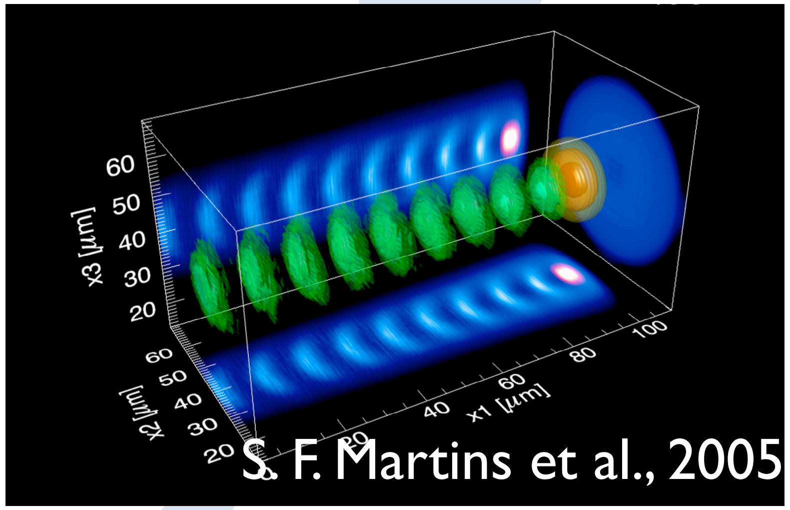


Outline

- Particle-in-cell simulations
- Full scale PIC modeling of Nature experiments
- QuickPIC: a 3D reduced model for intense beam-plasma interactions
    - Benchmarking with full PIC simulations
- Scalings for multi-GeV laser-plasma accelerators
    - blow-out regime



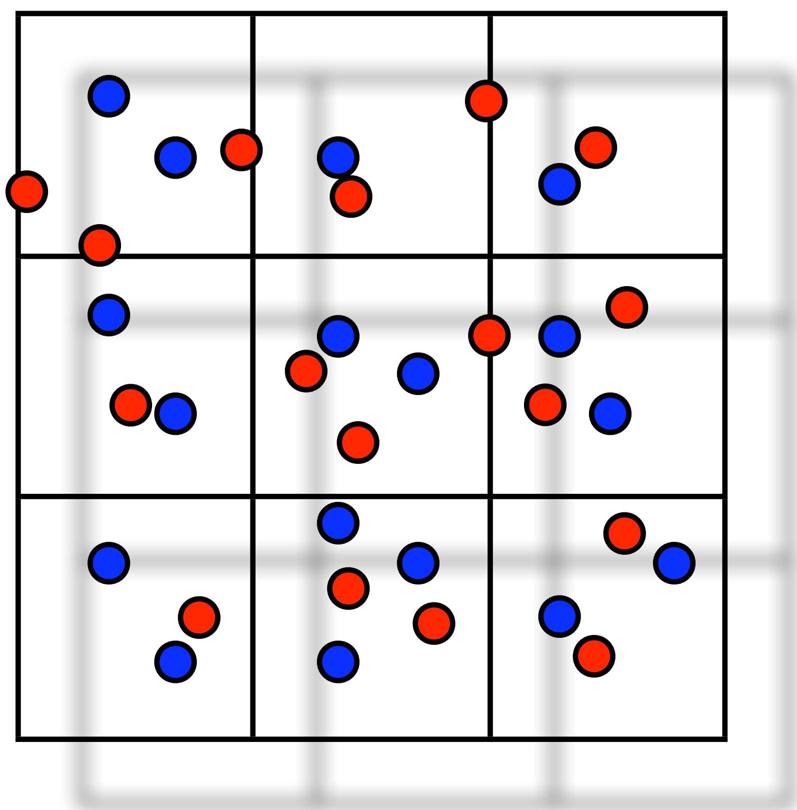
J. M. Vieira et al., 2006



S. F. Martins et al., 2005

Particle-in-cell simulations

Solving Maxwell's equations on a grid with self-consistent charges and currents due to charged particle dynamics



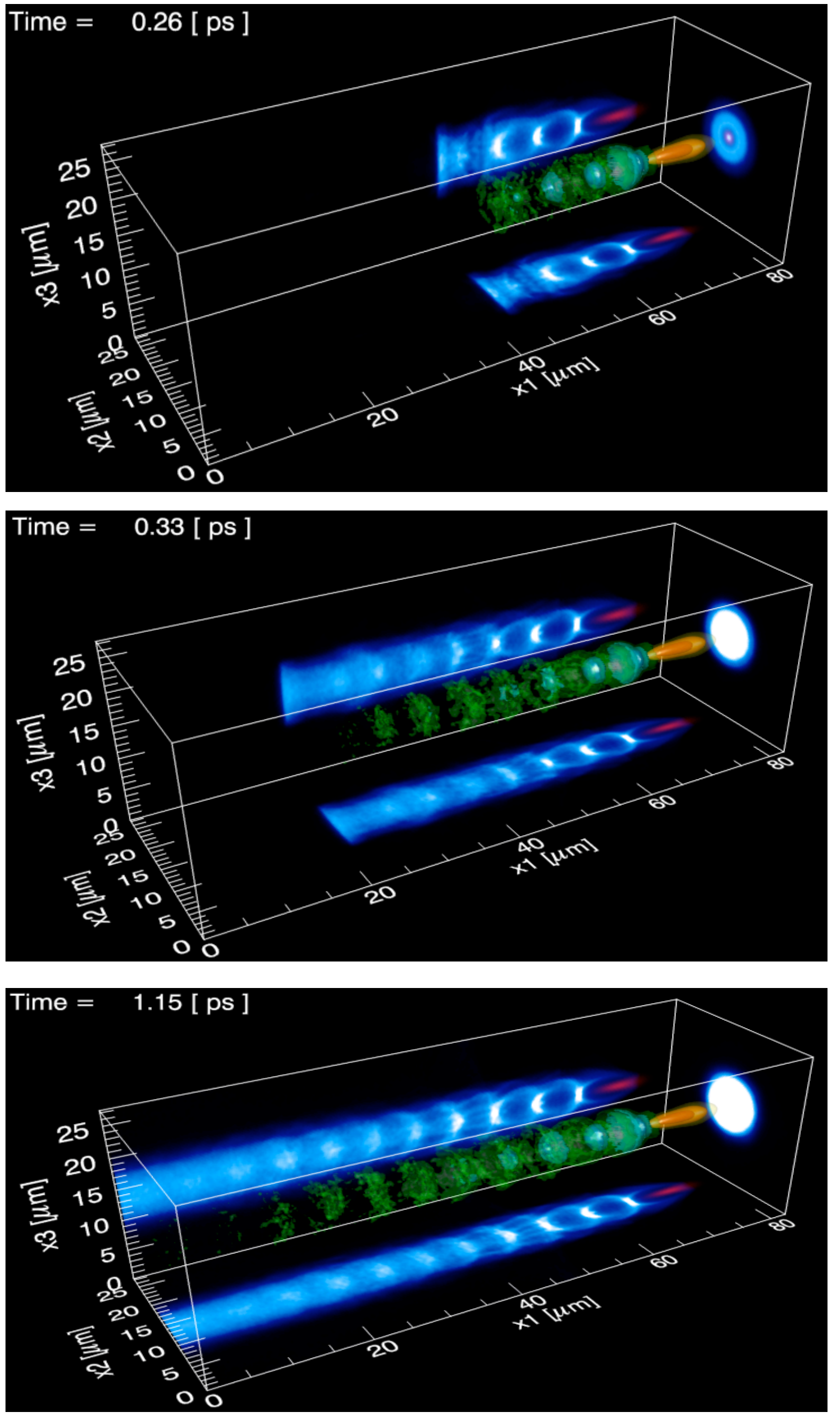
State-of-the-art

~ 10^9 particles

~ $(500)^3$ cells

RAM ~ 0.5 TByte
Run time: hours to months
Data/run ~ 1 TByte

One-to-one simulations of plasma based accelerators & cluster dynamics
Weibel/two stream instability in fast igniton, astrophysics

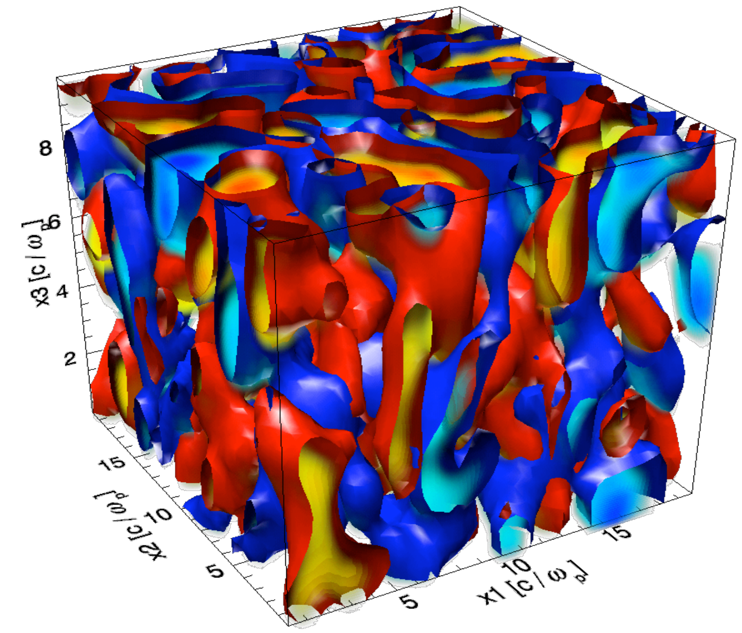


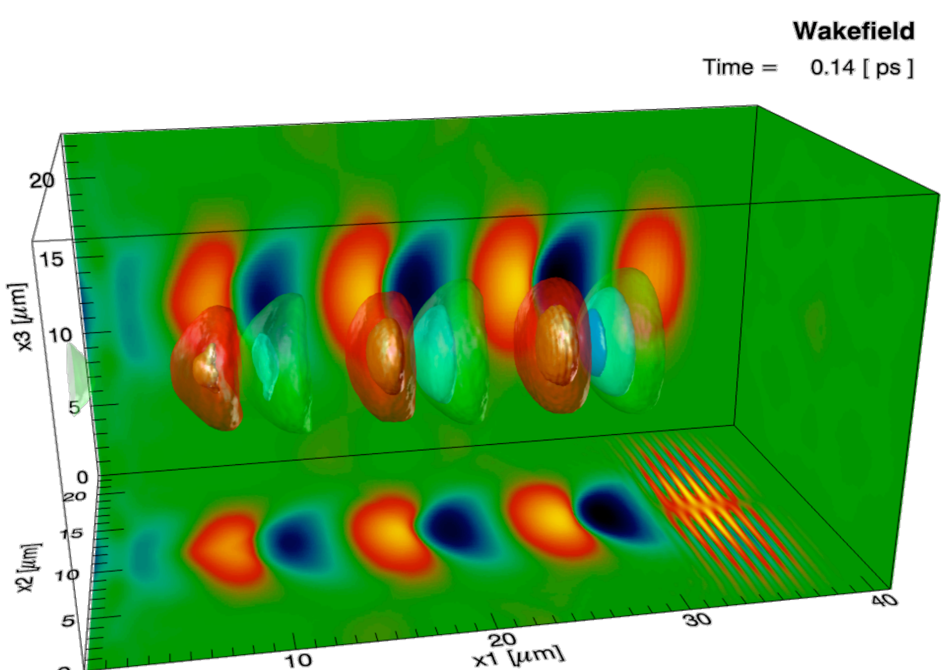
Particle-in-cell (PIC) - (Dawson, Buneman, 1960's)
Maxwell's equation solved on simulation grid
Particles pushed with Lorentz force

osiris 2.0

osiris.framework

- Massivelly parallel particle-in-cell code
- Visualization and data analysis infrastructure
- Developed by the *osiris.consortium*
  - ⇒ UCLA + IST + USC

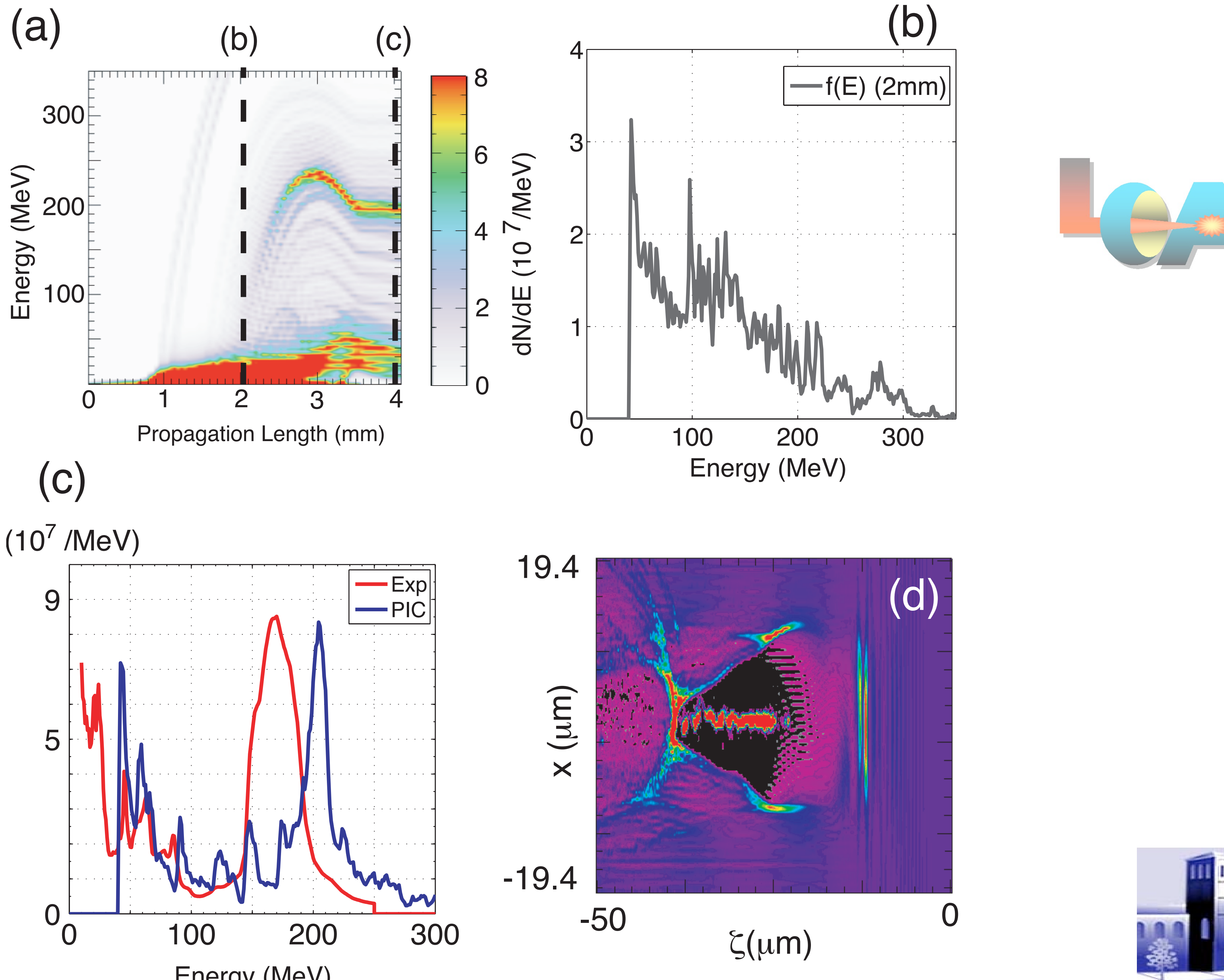




New in version 2.0

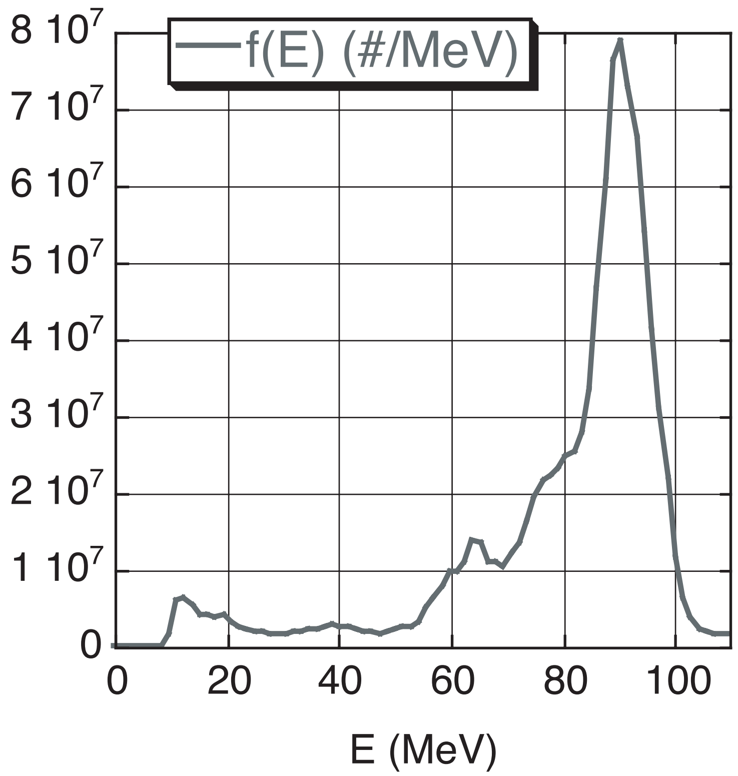
- Bessel beams
- Binary collisions module
- Impact and tunnel ionization (ADK model)
- Dynamic load balancing
- Parallel I/O

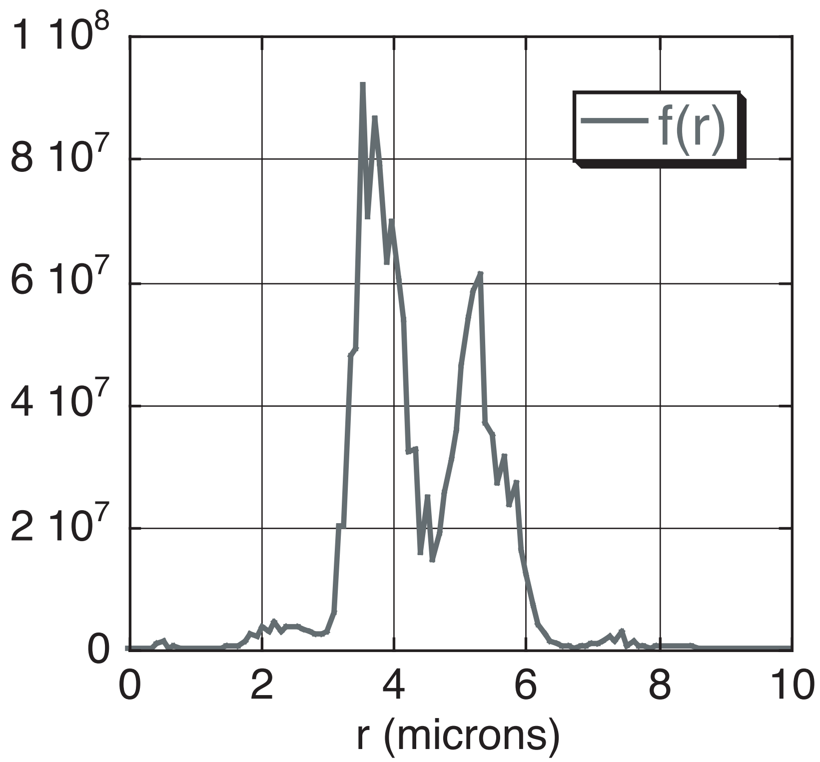
Full scale PIC modeling of Nature experiments I*

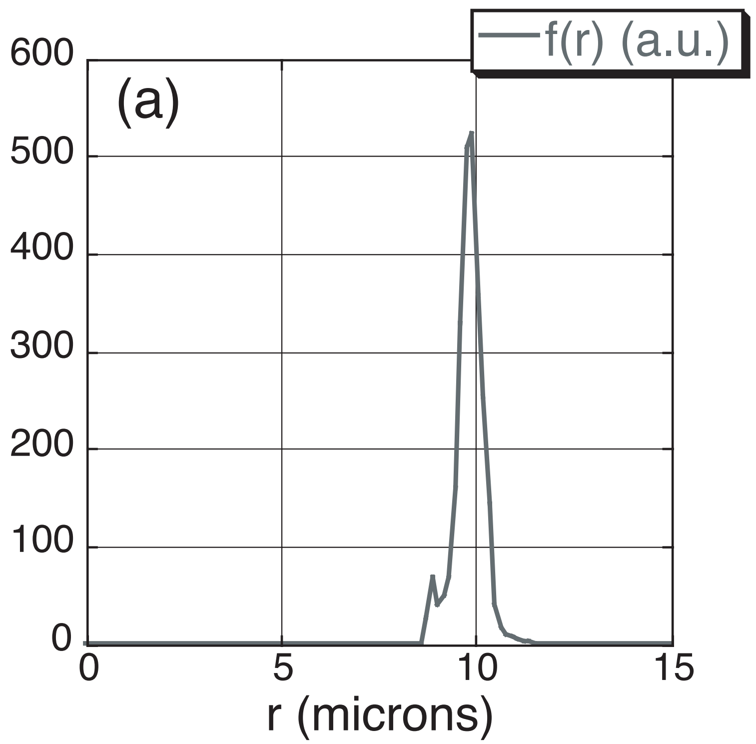


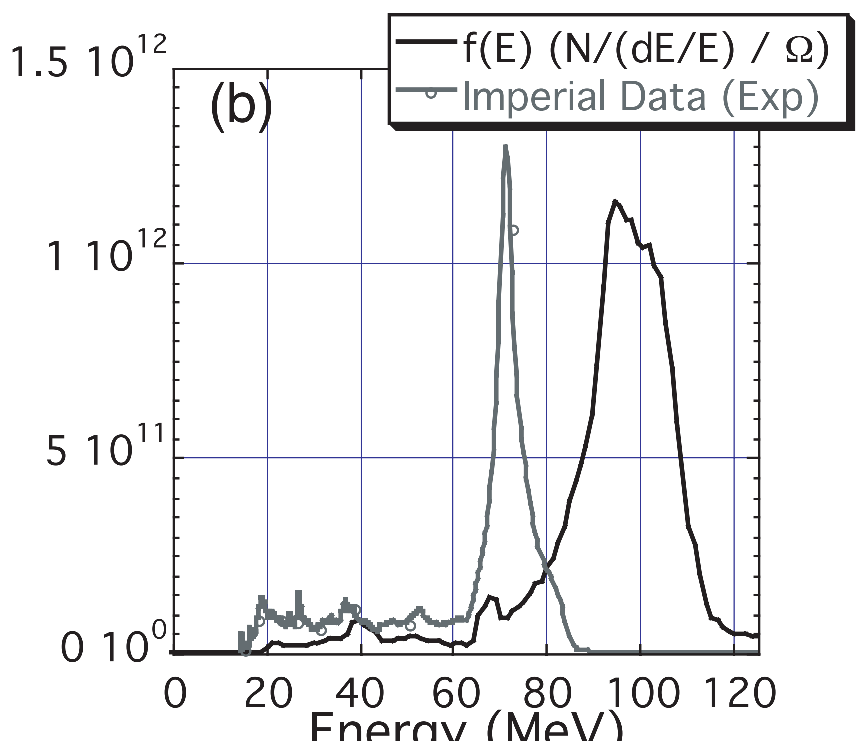
F Tsung et al., to appear in Physics of Plasmas, 2006

Full scale PIC modeling of Nature experiments II*









BERKELEY LAB

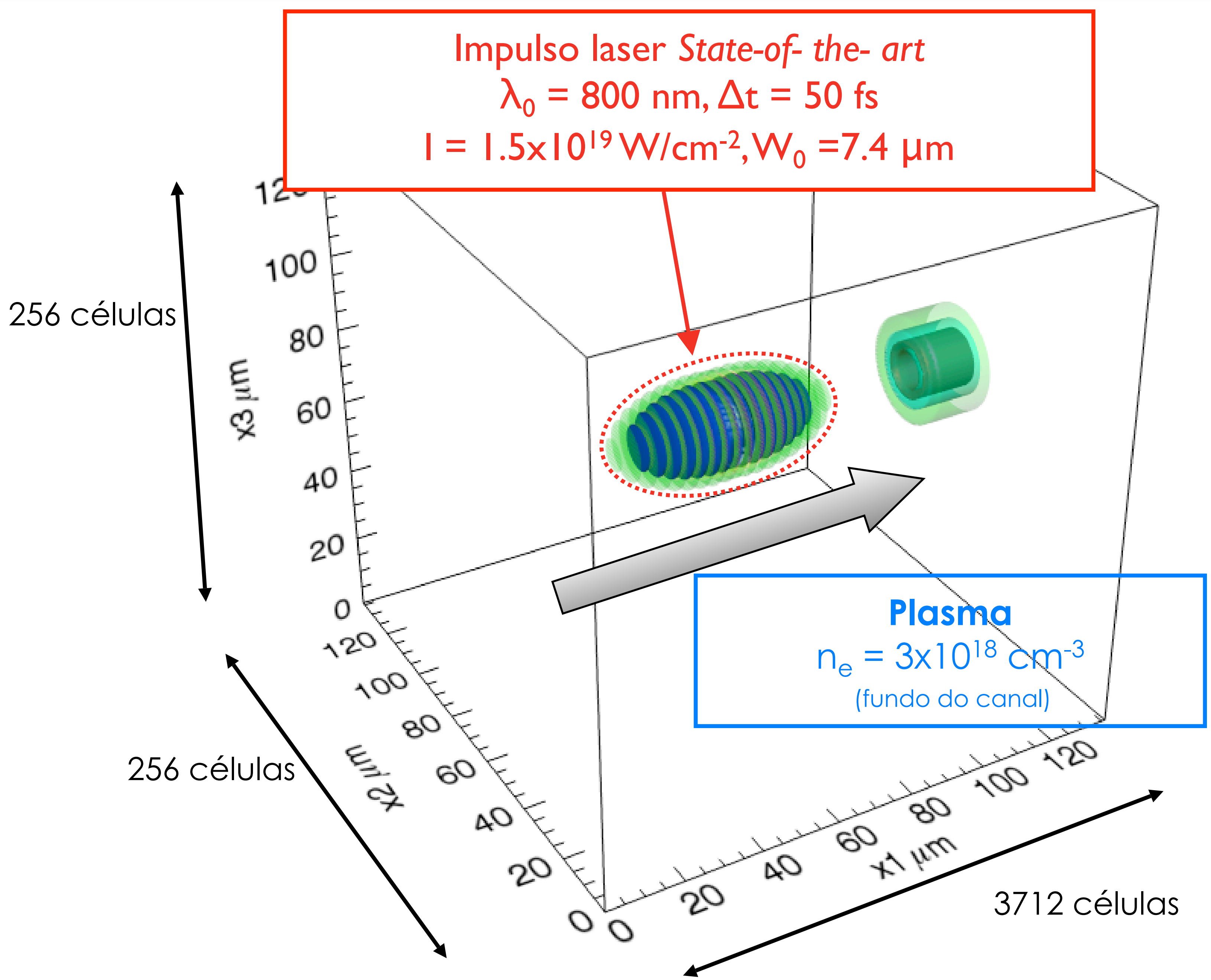
Imperial College London

CCLRC

UCLA

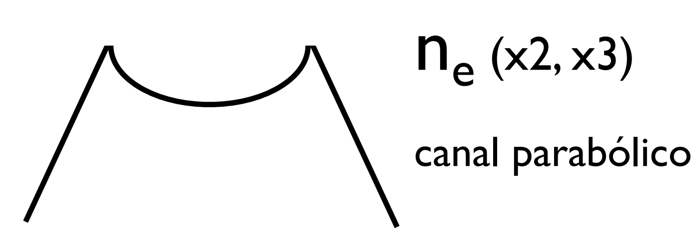
F Tsung et al., to appear in Physics of Plasmas, 2006

Simulações 3D de LWFA num canal



Parâmetros

- Laser:
  - a_0 = 3
  - W_0=9.25 λ_0=7.4 µm
  - ω_l/ω_p = 22.5
- Partículas
  - 1x2x2 partículas/célula
  - 240 milhões
- Comprimento Canal
  - L = .828cm
  - 300,000 passos temporais



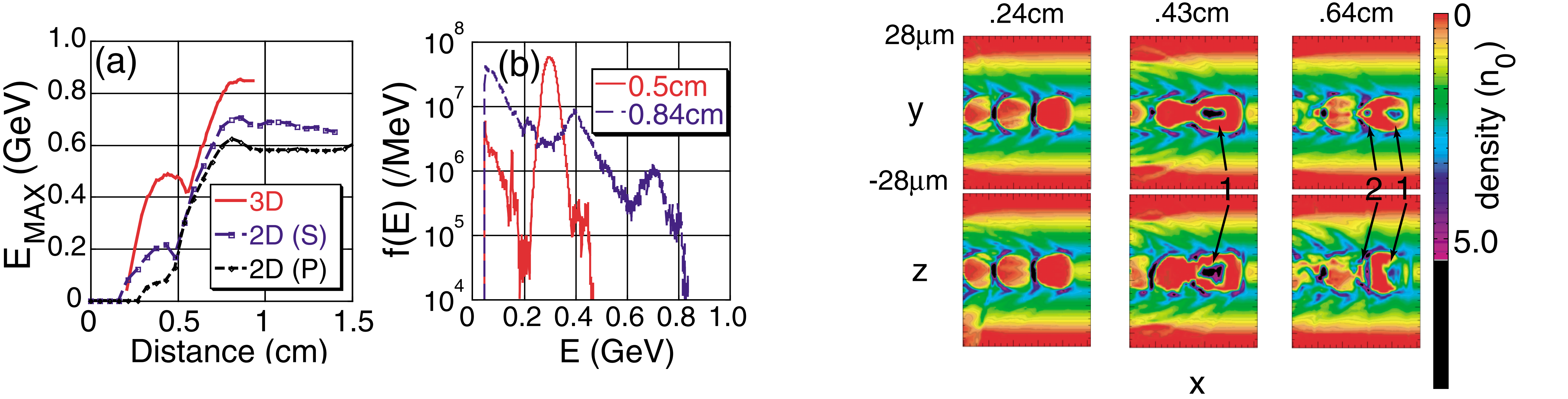
Simulações executadas
para 300,000 passos temporais
(~40 Comprimentos de Rayleigh)

Parâmetros semelhantes aos disponíveis no LOA e LBNL

Near GeV e- beams in a channel

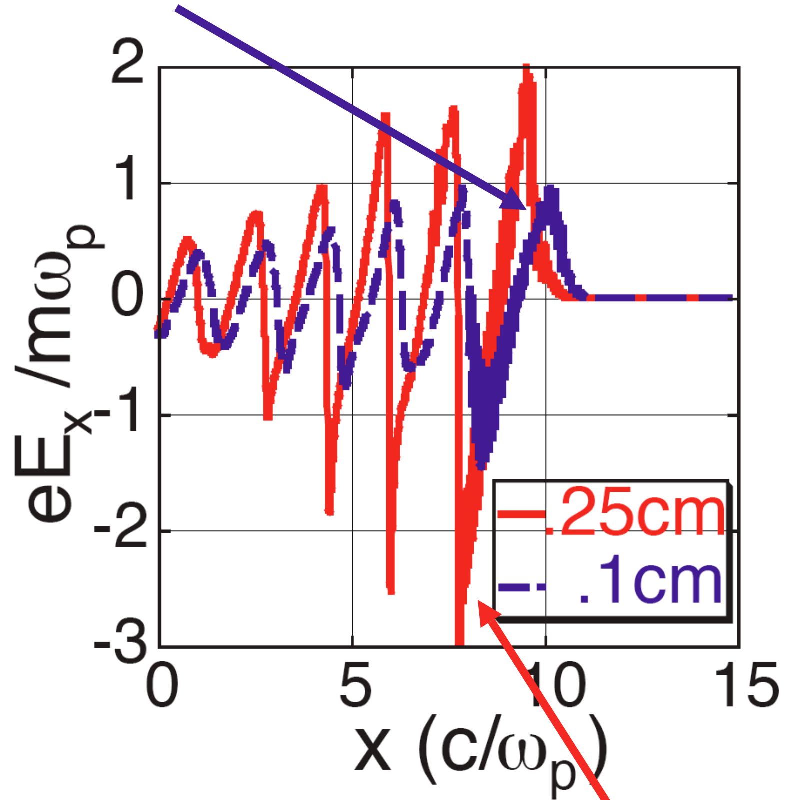
VOLUME 93, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 29 OCTOBER 2004

Near-GeV-Energy Laser-Wakefield Acceleration of Self-Injected Electrons in a Centimeter-Scale Plasma Channel



Nonlinear laser evolution - a_0 amplifier

Initially, no self-injection

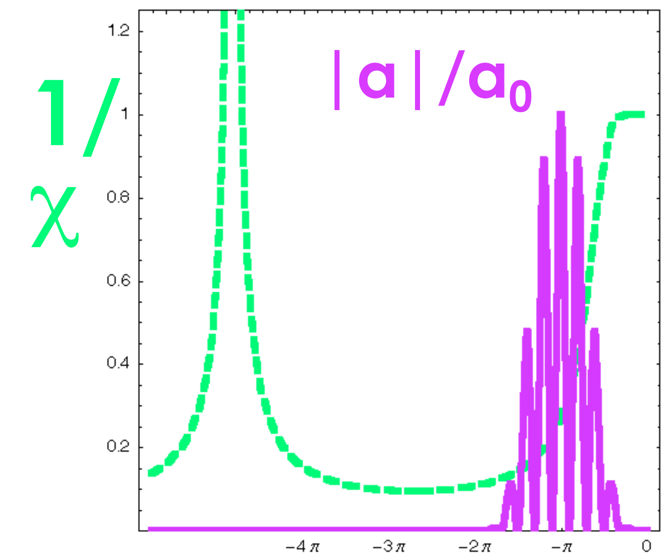


higher a_0 leads to wavebreaking

Conservation of the number of photons

classical wave action

$$\mathcal{N}_{\text{photons}} \approx \omega a_0^2 = \text{const.}$$



$a_0 = 3$

$c\tau_L/\lambda_{p0} = 1/2$

Photon deceleration/ frequency downshift

$$\downarrow \omega \Rightarrow a_0 \uparrow$$

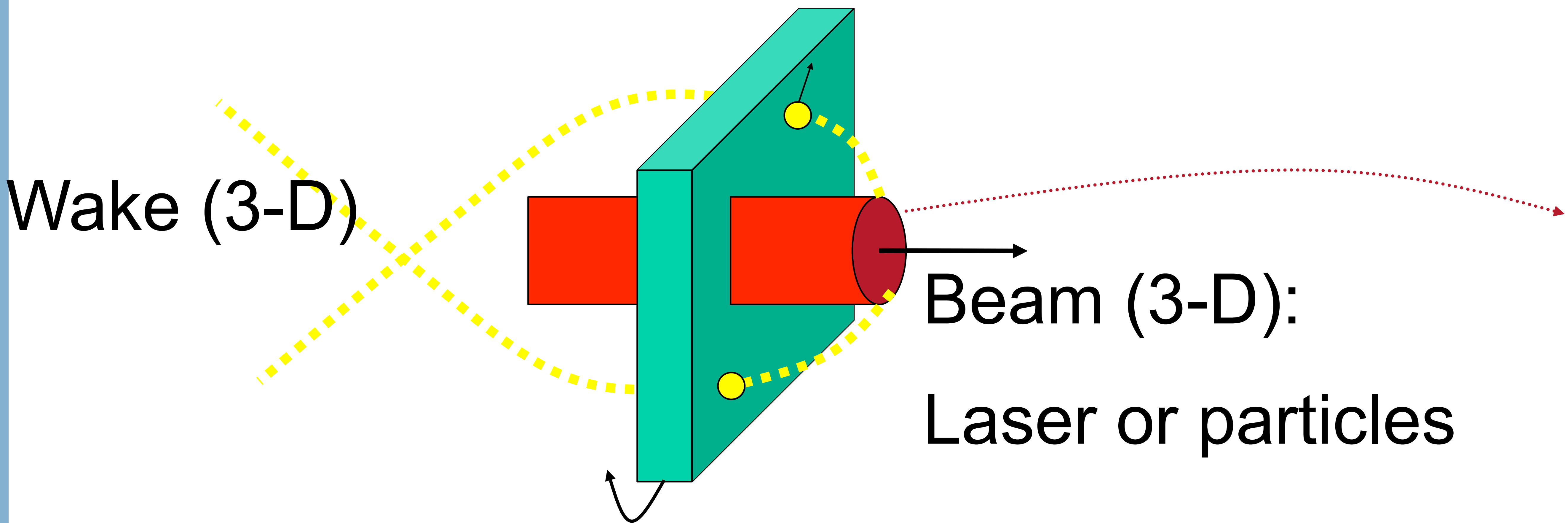
Nonlinear [relativistic] evolution of laser pulse, for long distances, leads to the formation and amplification of single cycle pulses

F. Tsung et al, Proc. Natl. Acad. Sci. 99, 29 (2002)

J. Faure et al, Phys. Rev. Lett. 95, 205003 (2005)

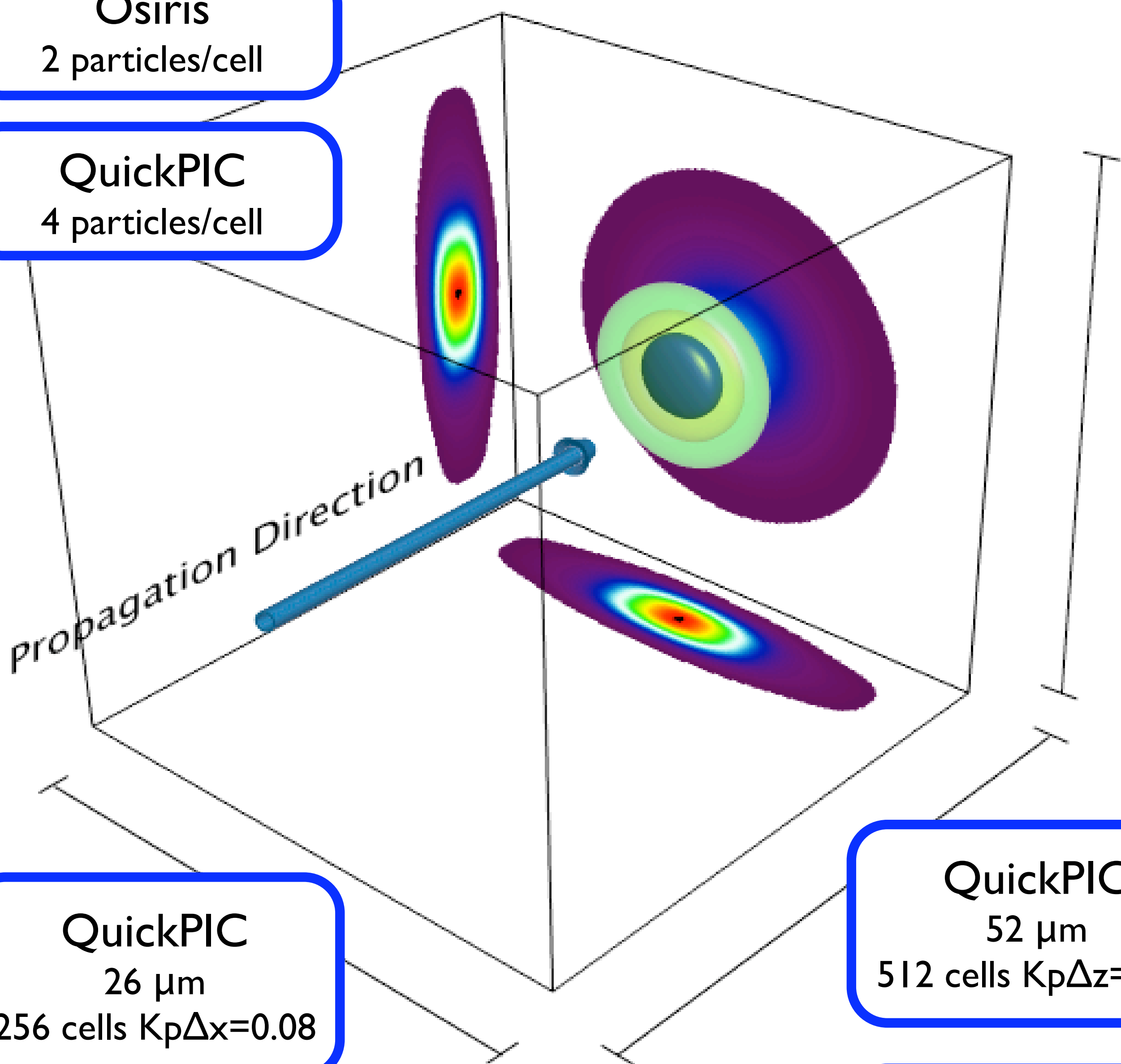
QuickPIC loop:

2-D plasma slab



1. *initialize beam*
2. *solve* $\nabla_\perp^2 \varphi = \rho, \nabla_\perp^2 \psi = \rho_e \Rightarrow F_p, \psi$
3. *push plasma, store* ψ
4. *step slab and repeat 2.*
5. *use* ψ *to giant step beam*

Benchmarking laser drivers in QuickPIC with osiris 2.0 I



Osiris
2 particles/cell

QuickPIC
4 particles/cell

QuickPIC
26 μm
256 cells KpΔy=0.08

Osiris
50 μm
200 cells KpΔy=0.2

QuickPIC
26 μm
256 cells KpΔx=0.08

Osiris
50 μm
200 cells KpΔx=0.2

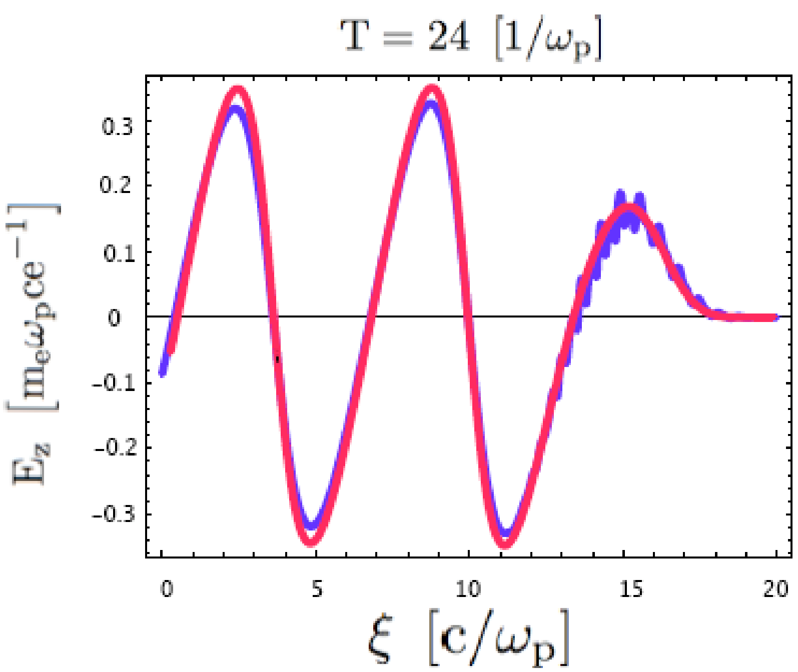
QuickPIC
52 μm
512 cells KpΔz=0.08

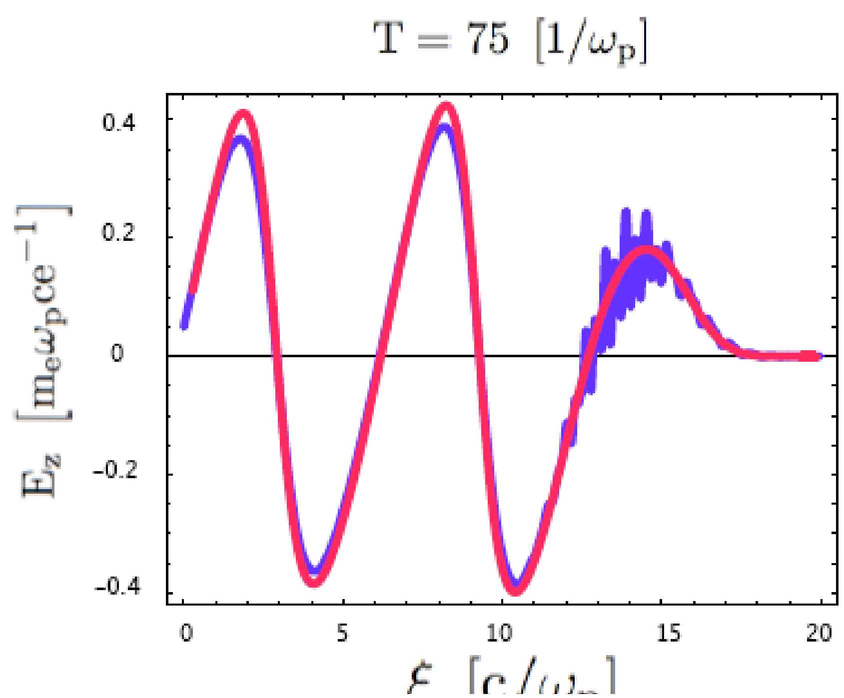
Osiris
50 μm
1000 cells $K_0\Delta z$=0.2

a_0 = 1.0
τ_l = 20 fs
w_0 = 6 μm
n_0 = 1.7×10^{19} cm^{-3}

a_0 = 2.0
τ_l = 20 fs
w_0 = 8.2 μm
n_0 = 1.38×10^{19}cm^{-3}

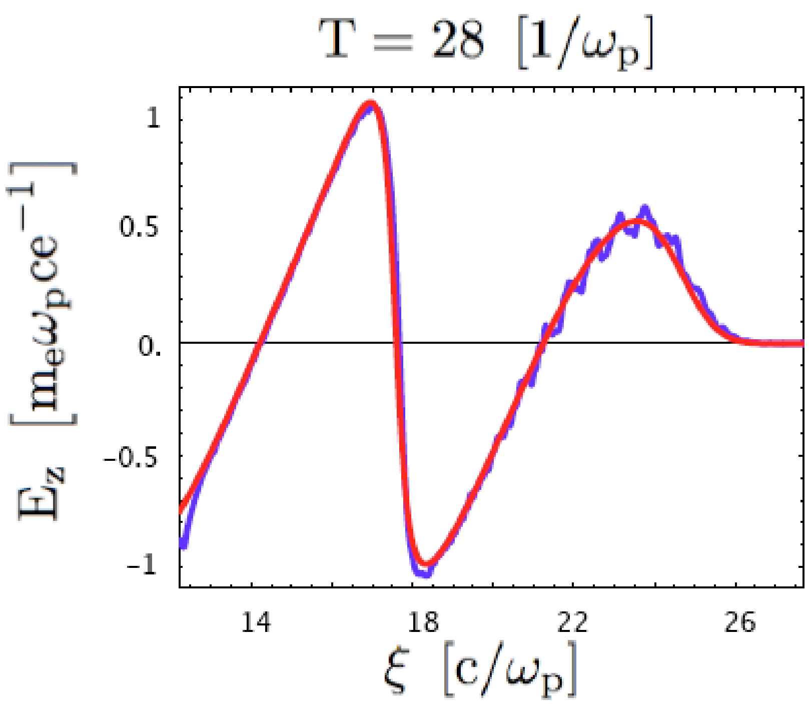
Benchmarking laser drivers in QuickPIC with osiris 2.0 II

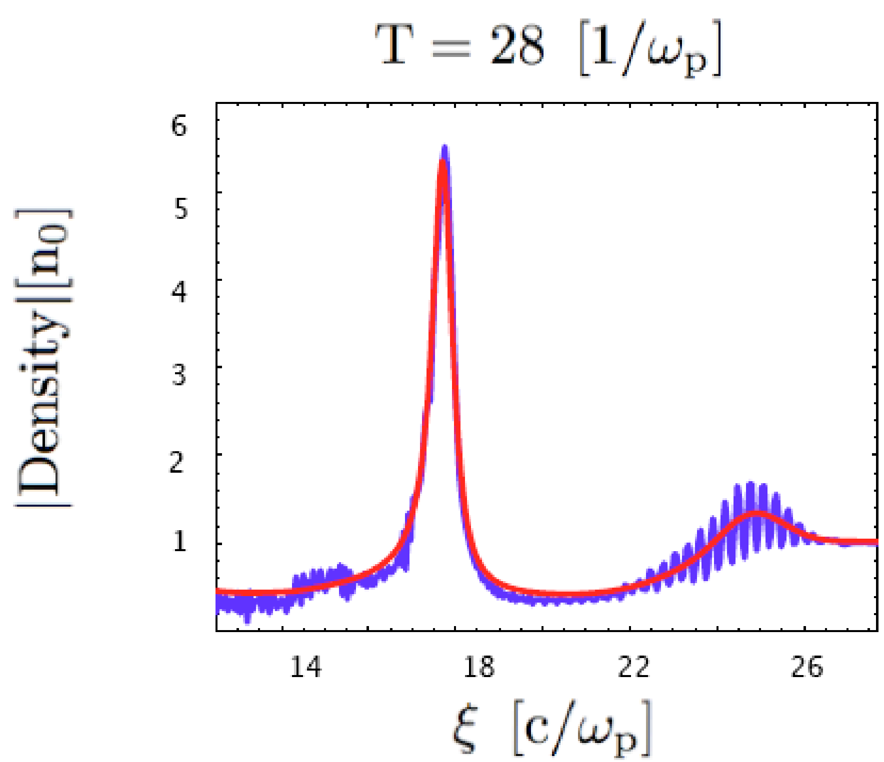




QuickPIC
OSIRIS

a0 = 1

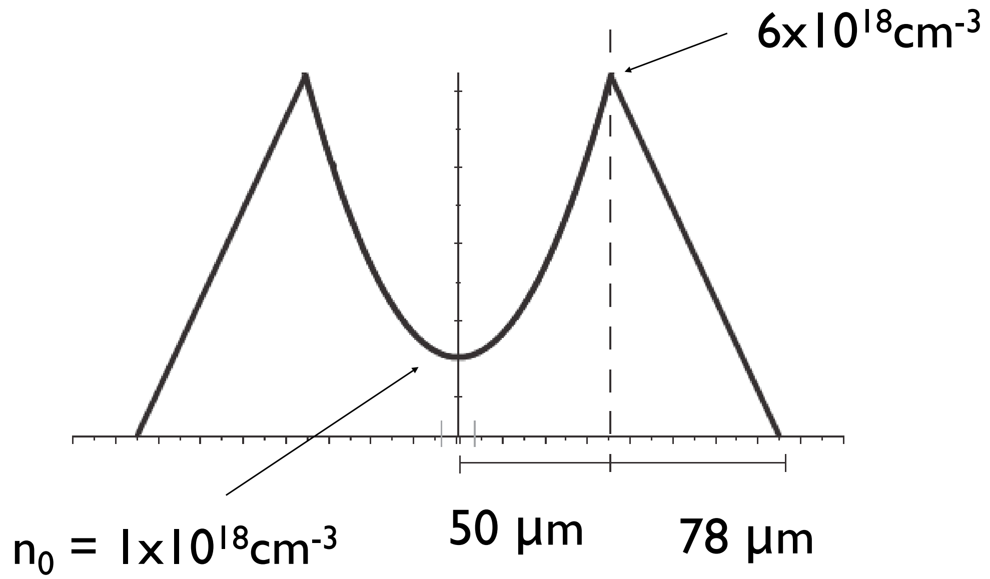




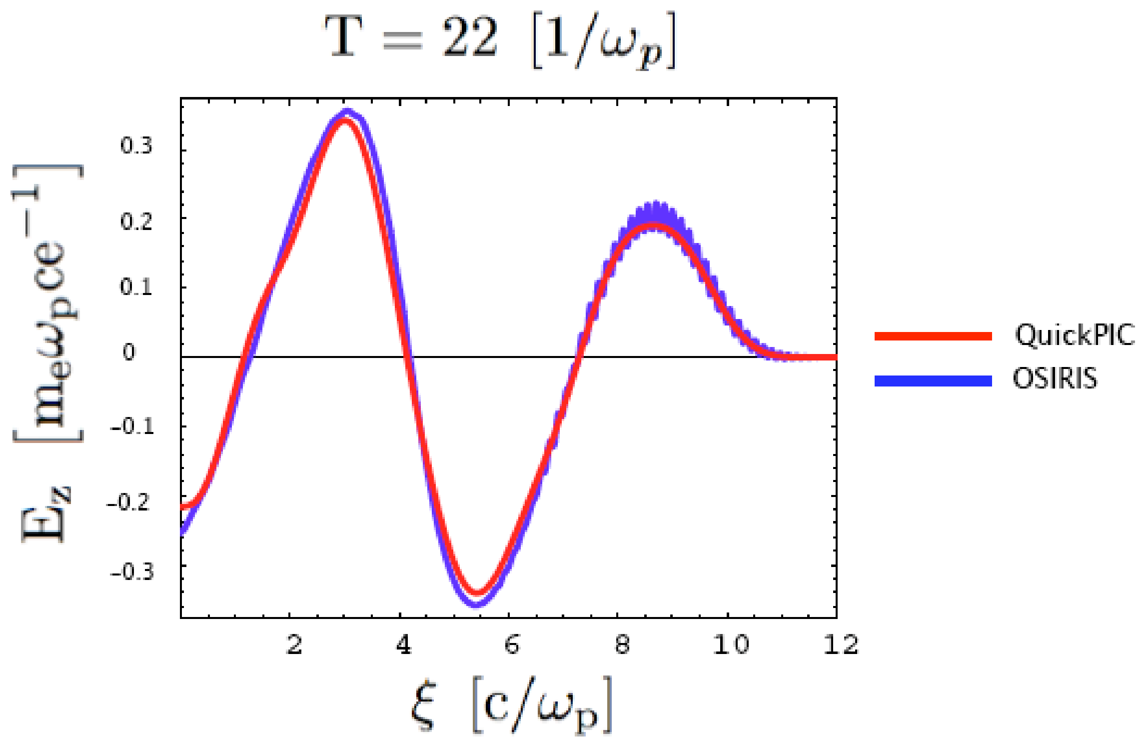
QuickPIC
OSIRIS

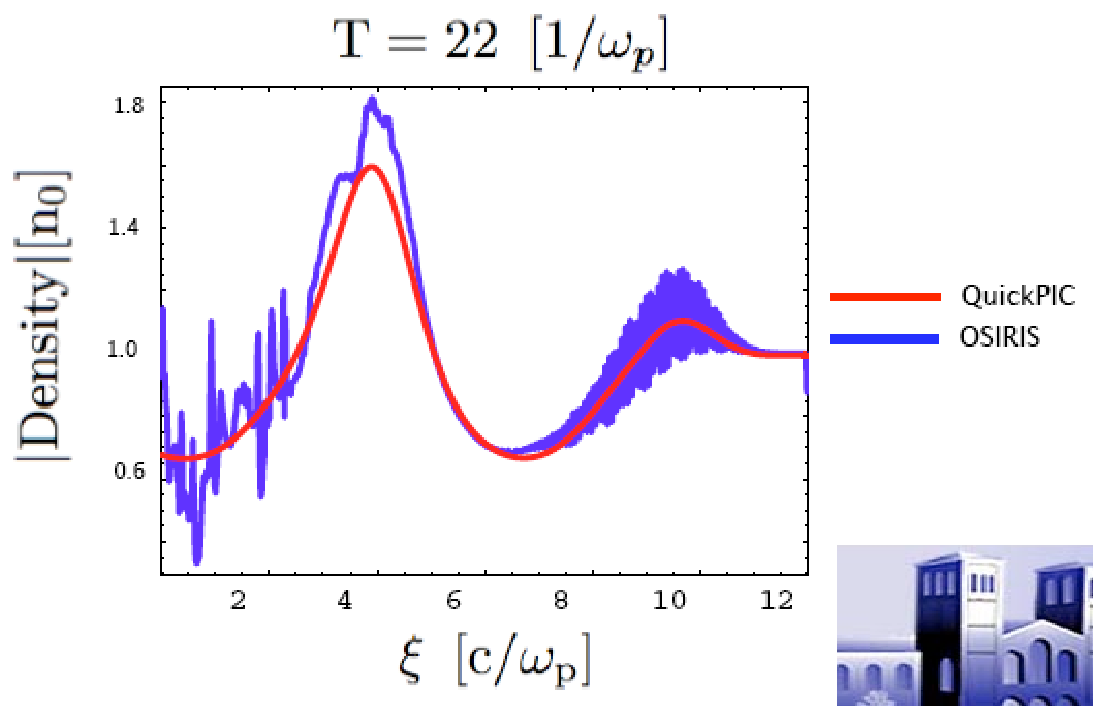
a0 = 2

Benchmarking laser drivers in QuickPIC with osiris 2.0 III



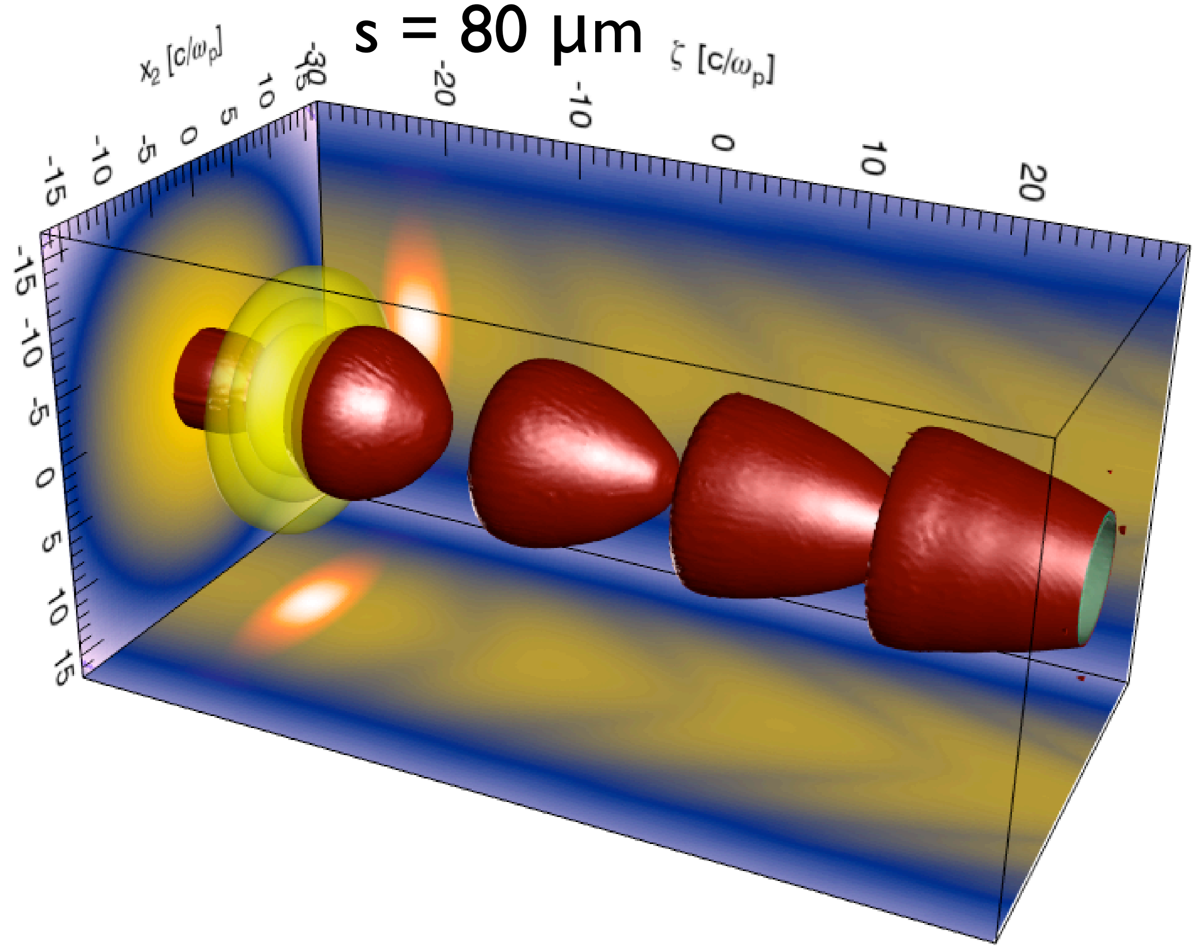
a_0 = 1.0
τ_l = 55 fs
w0 = 25 µm
63 µm × 265 µm × 265 µm



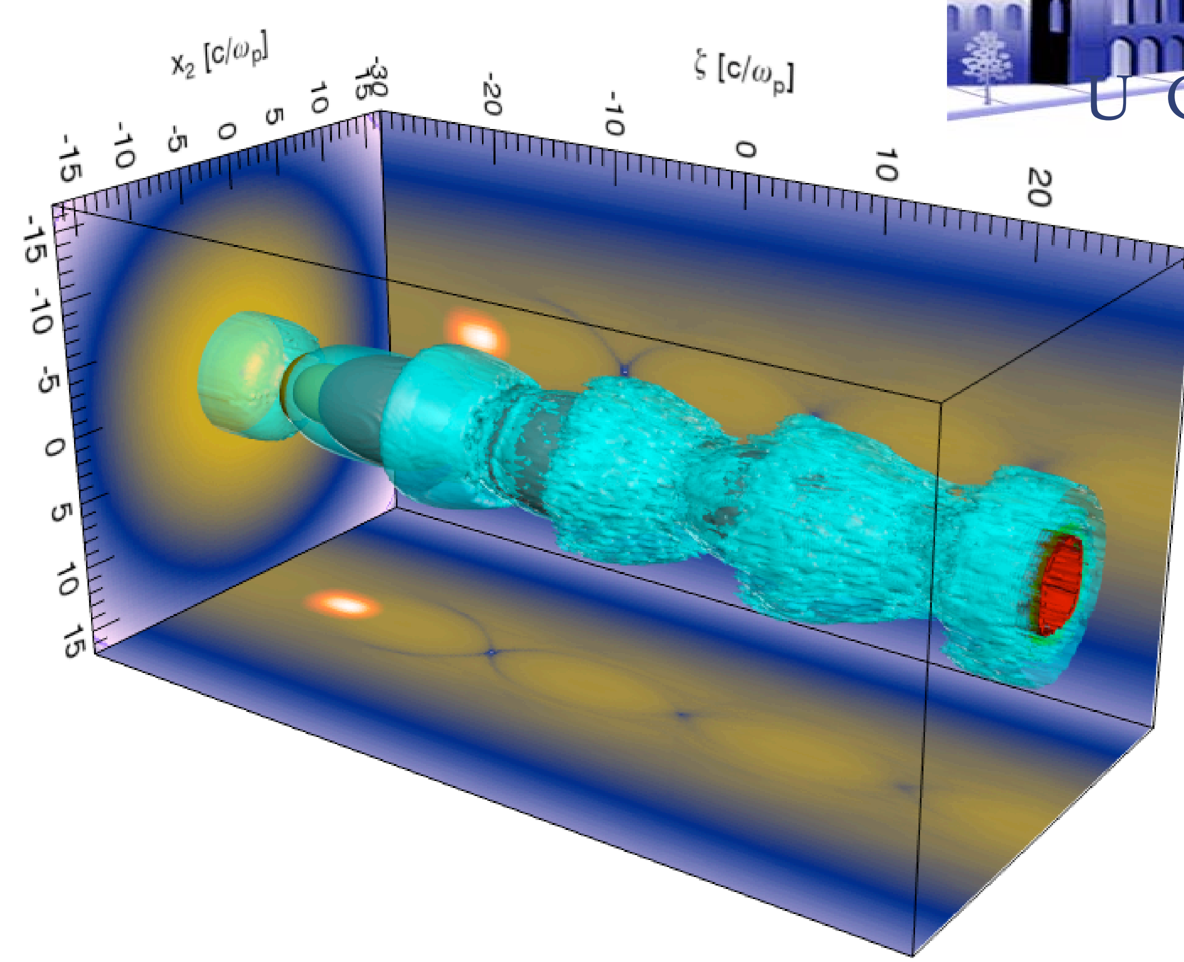


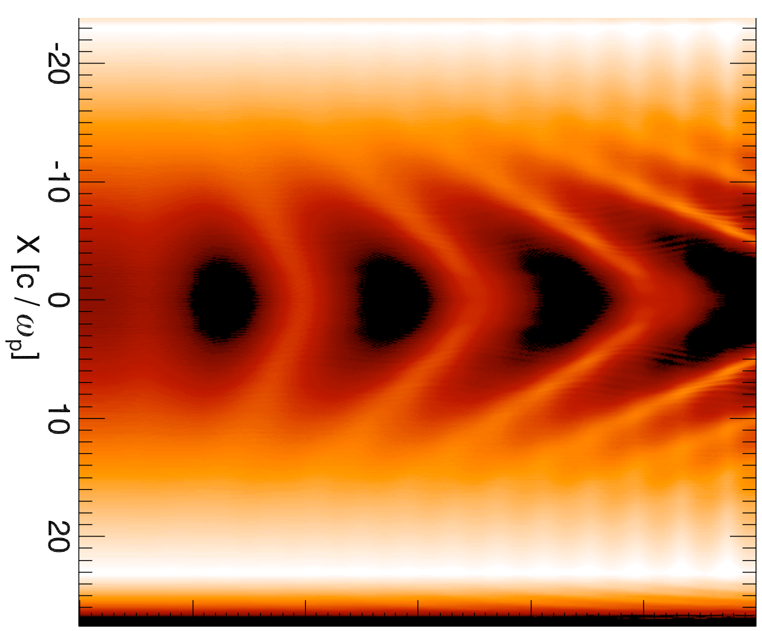
Benchmarking laser drivers in QuickPIC with osiris 2.0 IV

s = 80 µm



s = 840 µm





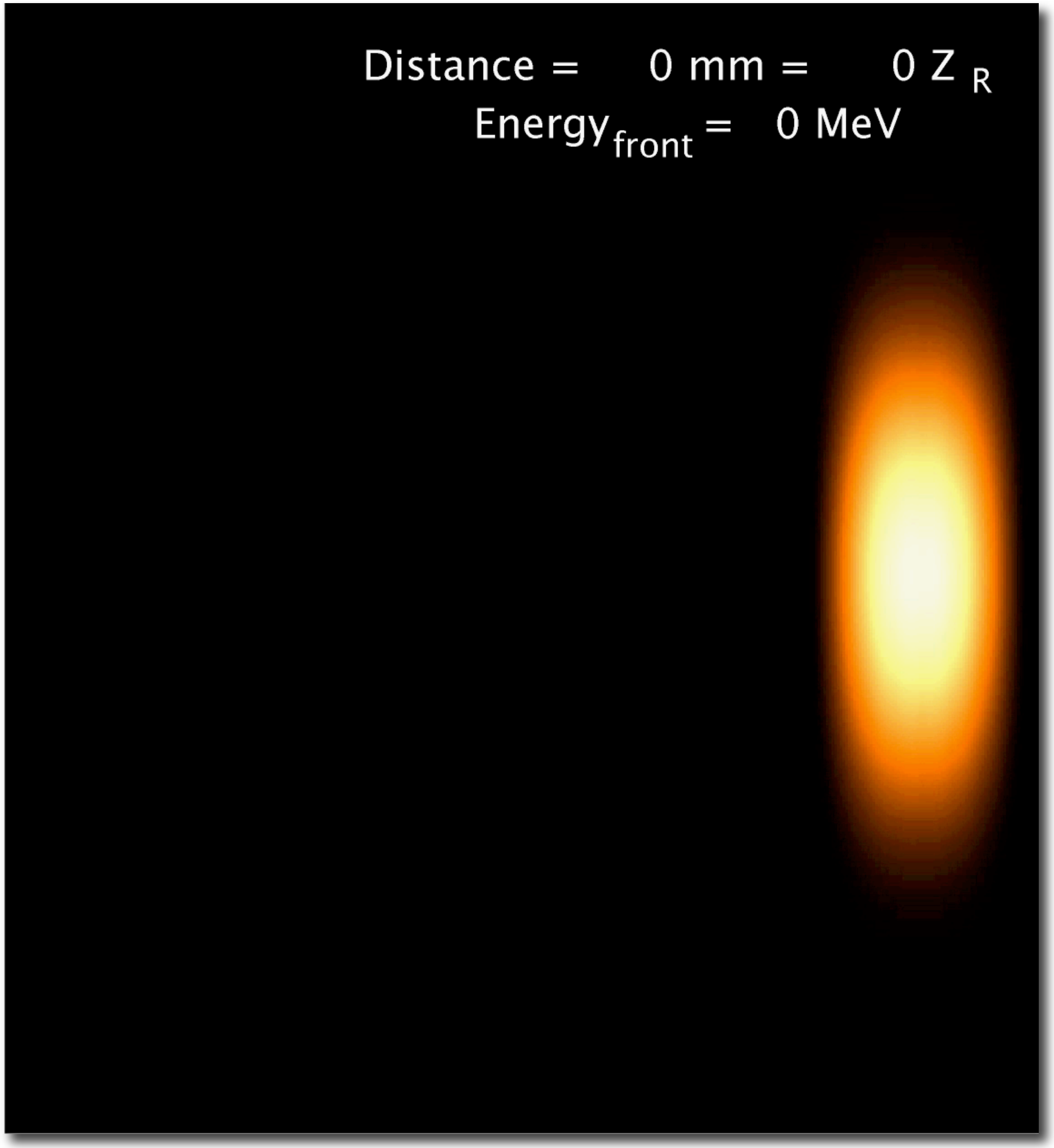
Nonlinear [relativistic] evolution of laser pulse, for long distances, leads to conditions for self-injection

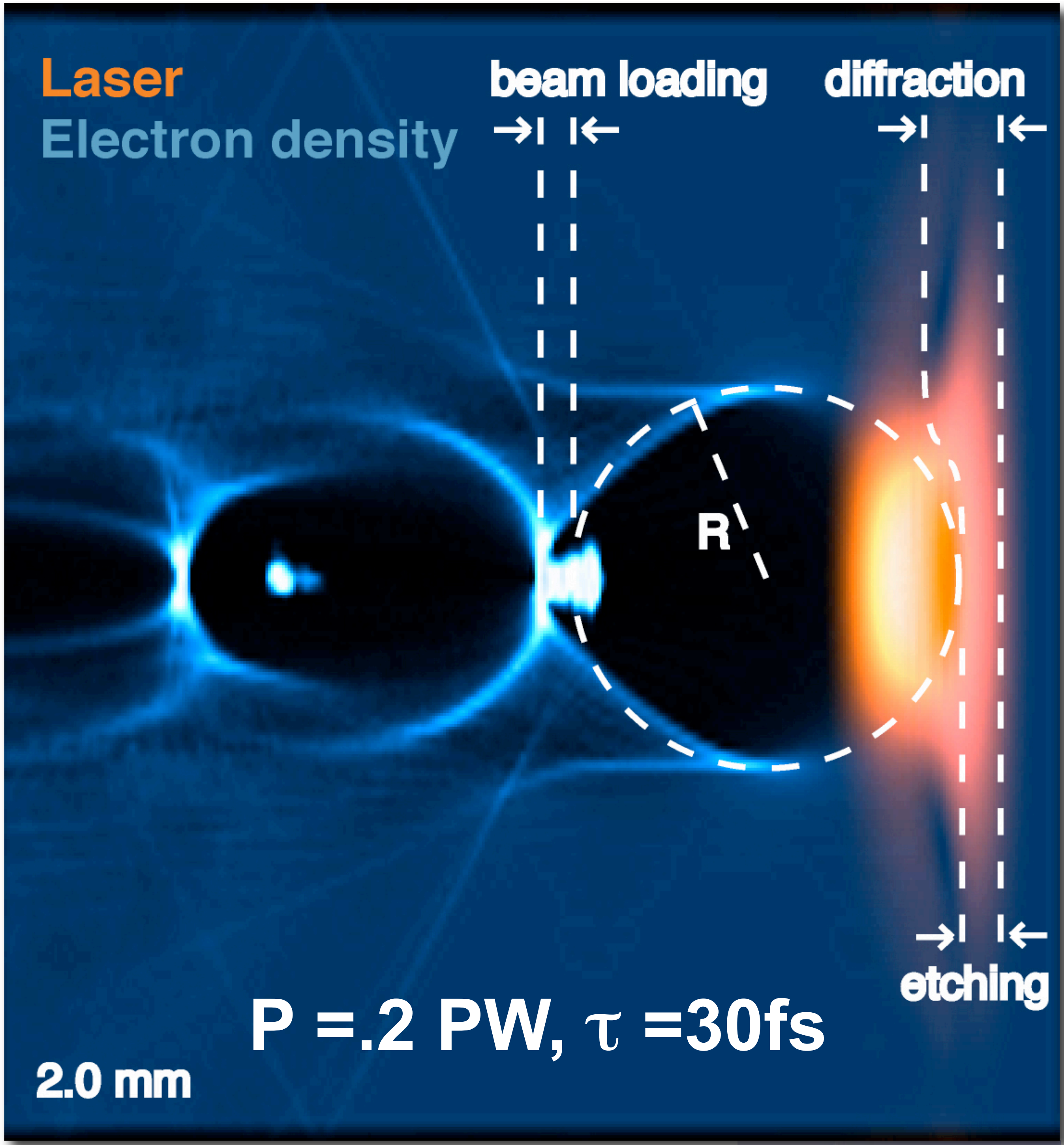
[Work in progress]

How to include self-injection in QuickPIC

3D LWFA simulations for 1.5 GeV e- beam

experiments are very close to this robust regime





W. Lu, M. Tzoufras et al., submitted for Nature Physics, 2006

High quality electron beam
$\epsilon_N \sim r\ \theta \sim$ 1µm x 1 rad=1 mm-mrad
100's pC from "cathode" with 1 µm radius

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Scaling laws for the monoenergetic blow-out regime I

Matched propagation (in the regime $P/P_c >> 1$) *:
Balance of the transverse ponderomotive force by the force of the ion channel

Laser spot size

$$k_p R \simeq k_p w_0 = 2\sqrt{a_0}$$

Blow-out radius

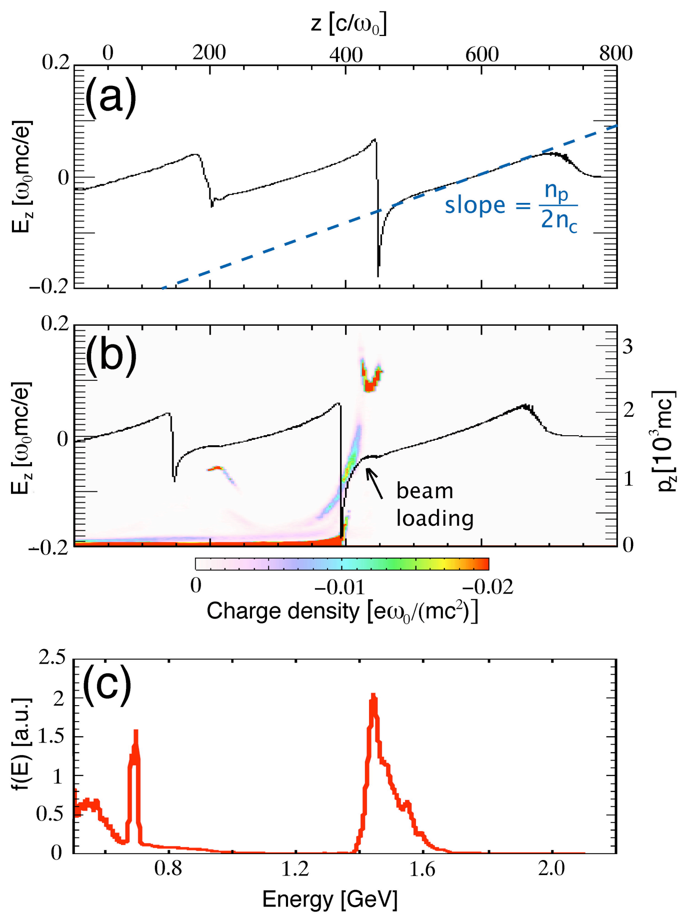
density for matched propagation

Laser pulse energy

Laser pulse length

Electric field in the axis of the ion channel:

$$E \propto \frac{\xi}{2}$$



*When P/Pc >> 1 a degree of self- guiding for short pulses is possible because the leading edge of the laser locally pump depletes before it diffracts and the back of the pulse is still guided in the ion column region (Decker et al. PoP 3, 2091 (1996)).

Scaling laws for the monoenergetic blow-out regime II

Laser pulse etching velocity *

$$v_{etch} \simeq c\,\omega_p^2/\omega_0^2$$

Phase velocity of the bubble

$$v_\phi \approx v_g - v_{etch} \simeq c\left[1 - 3\omega_p^2/(2\omega_0^2)\right]$$

Pump depletion length

$$L_{etch} \simeq \frac{c}{v_{etch}} c\tau_{FWHM} \simeq \frac{\omega_p^2}{\omega_0^2} c\tau_{FWHM}$$

Dephasing length

$$L_\phi \simeq \frac{c}{c - v_\phi} R \simeq \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R$$

>

$$c\tau_{FHWM} > 2R/3$$

Maximum energy gain

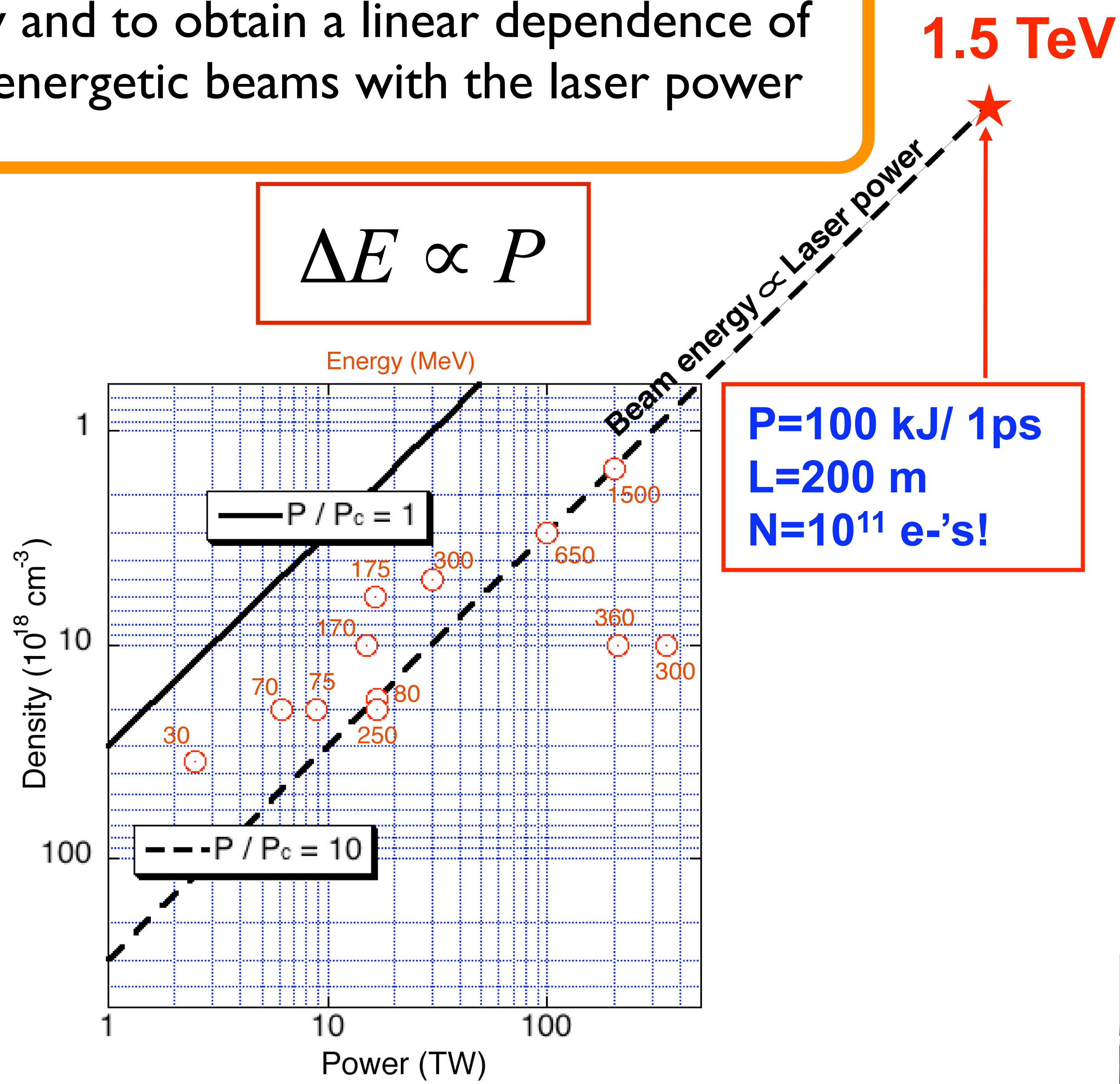
$$\Delta E[\mathrm{GeV}] \simeq 3.8 \left(\frac{P}{P_c}\right)^{-2/3} \frac{P[\mathrm{TW}]}{100}$$

* Decker *et al.* PoP 3, 2091 (1996).

Scaling laws for the monoenergetic blow-out regime III

By self-guiding laser it is possible to increase the laser power, to lower the plasma density and to obtain a linear dependence of the energy of the monoenergetic beams with the laser power

$$\Delta E \propto P$$



P=100 kJ/ 1ps
L=200 m
N=10^{11} e-'s!

W. Lu et al., submitted for publication in Nature Physics, 2006

Summary

- A combined hierarchy of massivelly parallel simulation codes can now perform detailed modeling of multi-GeV plasma based accelerators
  - optimization of features of accelerated beams
  - possibility to examine novel configurations/regimes
- Scaling laws for multi-GeV self-injected beams indicate multi-GeV beams within reach with state-of-the-art laser technology:
  - in the blow-out regime:
    - lower densities
    - wider spot sizes while keeping the intensity relatively constant in order to increase the output electron beam energy and keep the efficiency high

$$\Gamma \sim \mathcal{E}_b/\mathcal{E}_T \sim 1/a_0$$