Uncovering the secrets of extreme physics with large scale numerical plasma simulations (and lasers)

Luís O. Silva

GoLP
Instituto de Plasmas e Fusão Nuclear
TÉCNICO LISBOA

http://web.ist.utl.pt/luis.silva/
http://golp.ist.utl.pt/

grupo de lasers e plasmas

Accelerates ERC-2010-AdG 267841

GoLP/IFPN Técnico Lisboa

Acknowledgments

- Everyone at golp — grupo de lasers e plasmas
- Work in collaboration with:
  - W. B. Mori, C. Joshi (UCLA)
- Simulation results obtained at the epp and IST Clusters (IST), Dawson Cluster (UCLA), Franklin (NERSC), Intrepid (Argonne), Jugene (FZ Jülich), and Jaguar (ORNL)

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

erc

Distributed European Infrastructure for Supercomputing Applications

PRACE

SEVENTH FRAMEWORK PROGRAMME

Laserlab Europe

euro LEAP

SciDAC
Scientific Discovery through Advanced Computing

eli

HiPER

NVIDIA

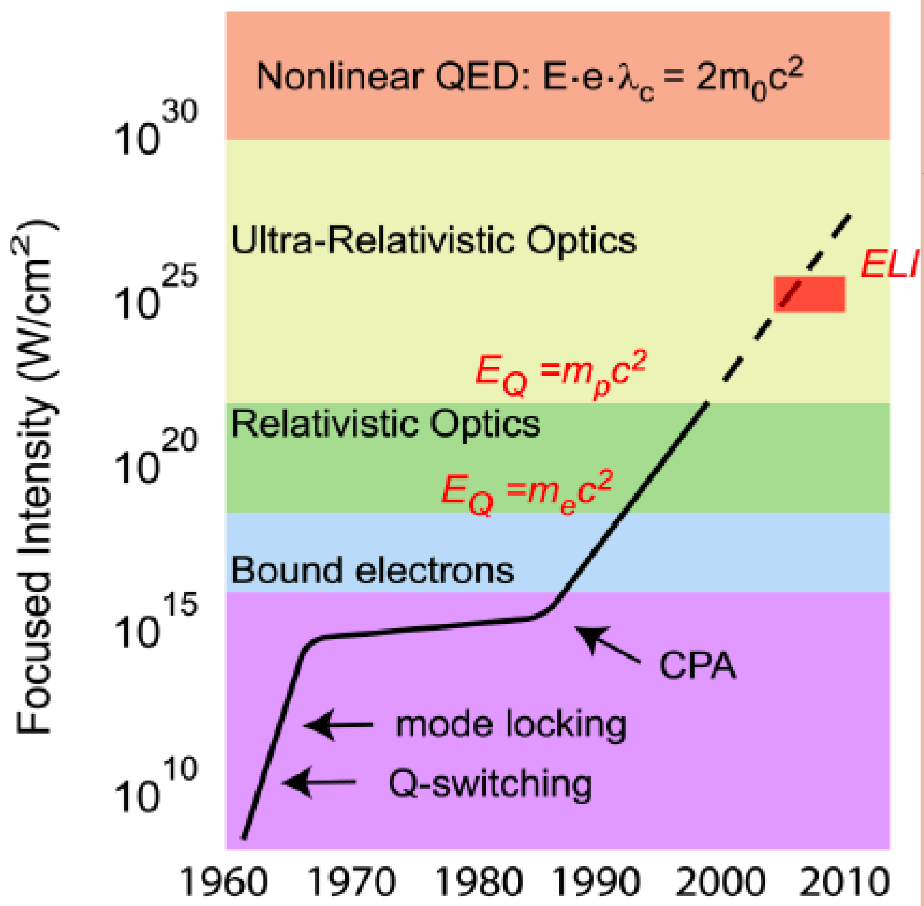
U.S. DEPARTMENT OF ENERGY

Office of Science

Tech developments have triggered a revolution

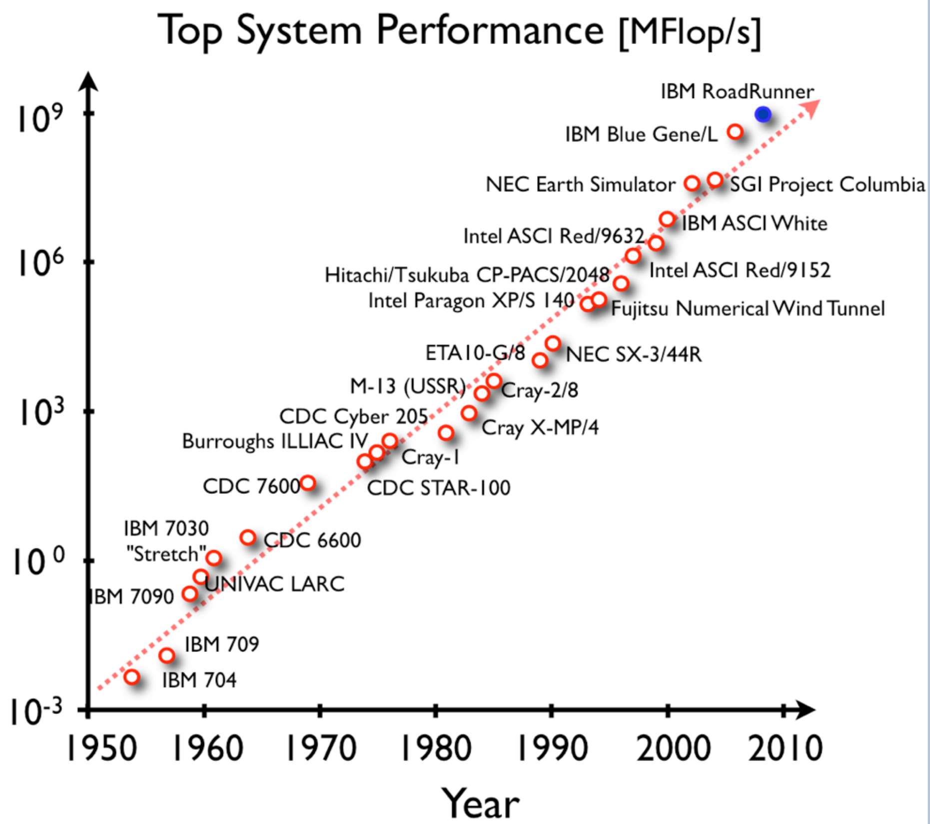
Lasers and supercomputers

’11 Peak laser intensity ~ 10^{23} W/cm²

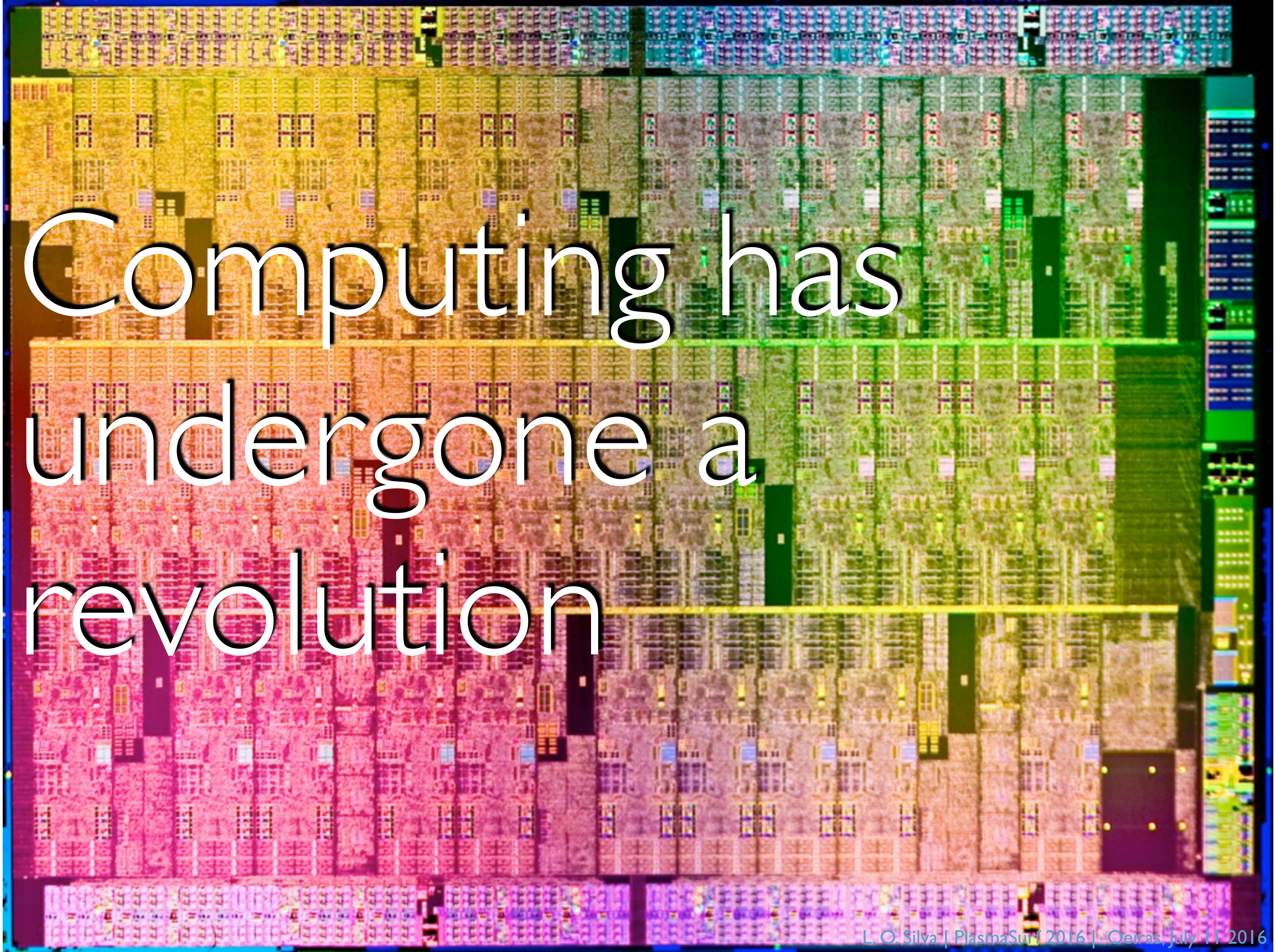


Mourou, Tajima, Bulanov (2006)

’12 Peak computing power > 10 Pflop/s



Source: top500.org



Computing has undergone a revolution

In the project Manhathan (c. 1940) the cost of one floating point operation was ~ 10^{-3}€

Operations performed in mechanical calculators.
Cost of labour ~ 4 €/hour, assuming one operation per second.
Total number of operation corresponding to 4 € = 1 flop/s 60 x 60 s

Today, in a graphics processor unit each floating point operation costs $\sim 10^{-18}$ €

GPU performs 0.5 Tflop/s and costs ~ 2000 euros.
We assume a 3 year lifetime. Neglect the cost of electricity.
Total number of operation for 2000 euros = 0.5×10^{12} flop/s $\times 3 \times 365 \times 24 \times 60 \times 60$ s

How can we describe the plasma physics?

Hierarchy of descriptions (ignoring quantum effects)

- Klimontovich equation ("exact").

- Ensemble average the Klimontovich equation
  - Leads to Vlasov Fokker Planck equation (approximate)

- Take the limit that N_D is very very large
  - Vlasov equation

- Take moments of the Vlasov or Vlasov Fokker Planck equation
  - "Two" fluid (transport) equations

- Ignore electron inertia
  - Single fluid or MHD equations

What is the particle-in-cell model?

Is it an efficient way of modeling the Vlasov equation?
No, it is a Klimontovich description for finite size (macro-particles)

Klimontovich eq. of macro-particles

$$\frac{D}{Dt}F = 0$$

$$F(\vec{x}, \vec{v}; t) = \sum_{i}^{N} S_p(\vec{x} - \vec{x}_i(t))\delta(\vec{v} - \vec{v}_i(t))$$

$$\left[\frac{D}{Dt} \equiv \partial_t + \vec{v} \cdot \nabla_x + \vec{a} \cdot \nabla_v\right]$$

$$\vec{a} \equiv \frac{d}{dt}\vec{v} = \frac{q}{m}\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

Maxwell's equations

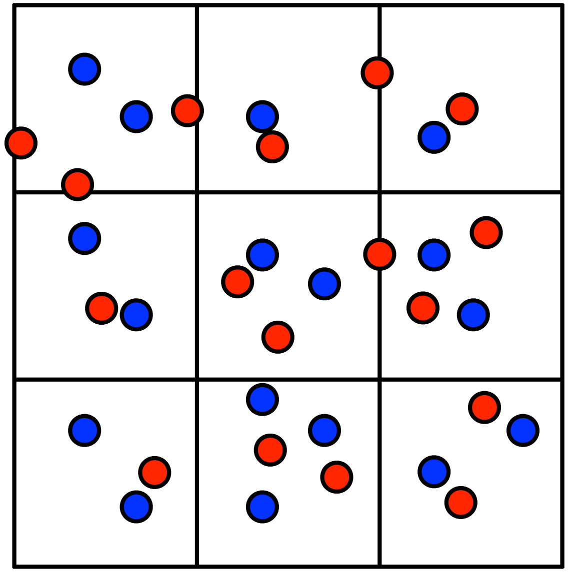
$$\frac{\partial}{\partial t}\vec{E} = \nabla \times \vec{B} - \frac{4\pi}{c}\vec{J}$$

$$\frac{\partial}{\partial t}\vec{B} = -\nabla \times \vec{E}$$

$$\vec{J}(\vec{x}, t) = \int d\vec{v}\; q\vec{v}\; F(\vec{x}, \vec{v}, t)$$

Particle-in-cell simulations

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



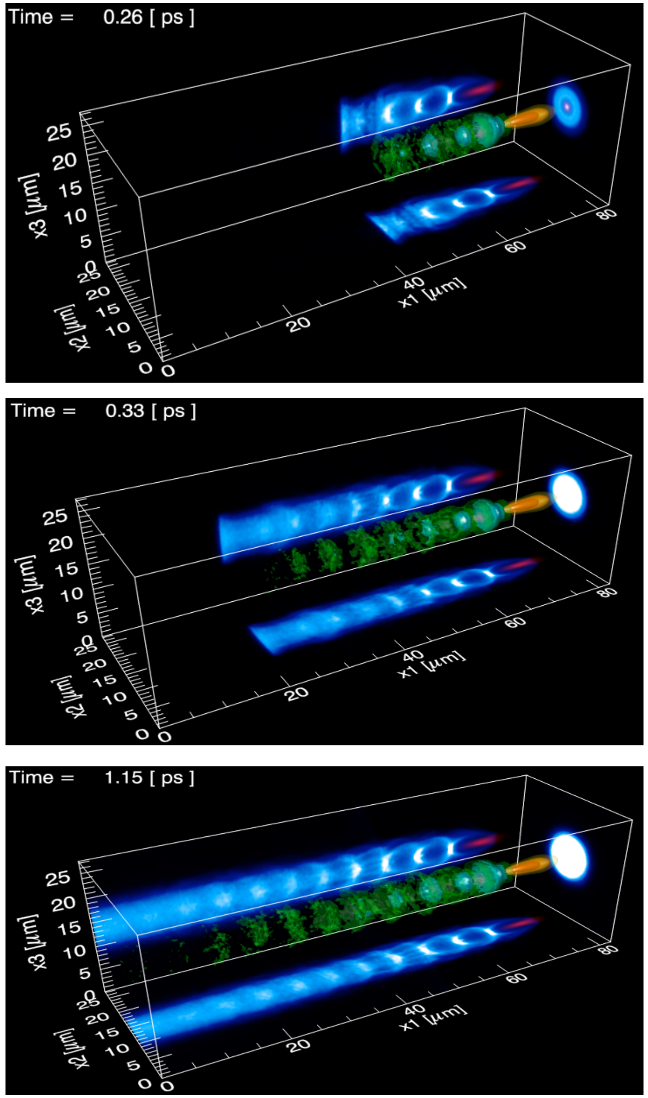
State-of-the-art

~ 10^{10} particles

~ $(1000)^3$ cells

RAM ~ 1 Gbyte - 5 TByte
Run time: hours to months
Data/run ~ few MB - 10s TByte

One-to-one simulations of plasma based accelerators & cluster dynamics
Weibel/two stream instability in astrophysics, relativistic shocks, fast igniton/inertial fusion energy, low temperature plasmas



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

The particle-in-cell methodology

Modeling kinetic physics

- Particle simulations

  (# operations ∝ N^2)

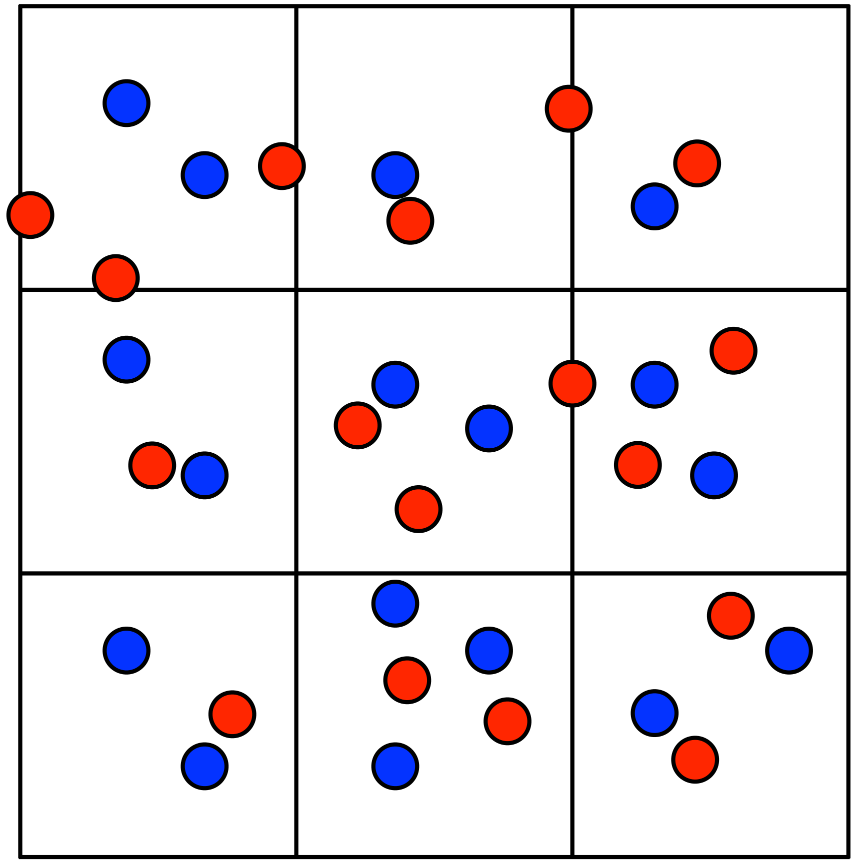
- Particle-Mesh simulations

  (# operations ∝ N)

  - Fields + densities
  - Long range interactions

- Additional MC binary Coulomb collision module can model short range interactions

Particle-in-cell methodology*



* Dawson, Buneman, 1960's; Birdsall and Langdon, *Plasma Phys. via Comp. Simulation* (1985)

The particle-in-cell methodology

Modeling kinetic physics

- Particle simulations

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  (# operations ∝ N)

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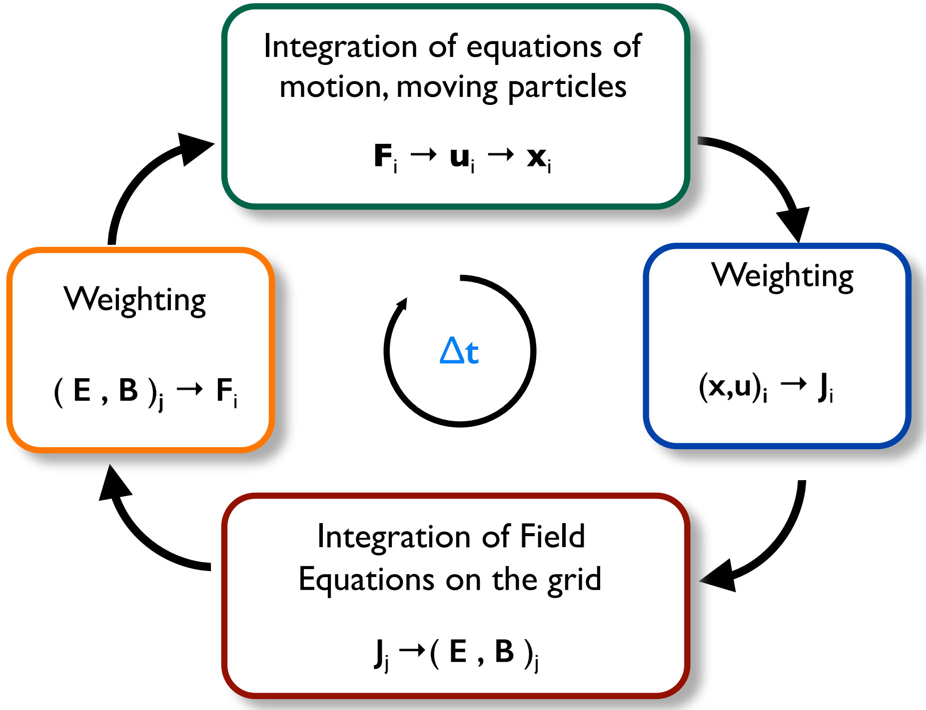
Particle-in-cell methodology*

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{gc}\mathbf{u}\times\mathbf{B}\right)$$



$$\frac{\partial \mathbf{E}}{\partial t} = c\vec{\nabla}\times\mathbf{B} - 4\pi\mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\vec{\nabla}\times\mathbf{E}$$

* Dawson, Buneman, 1960's; Birdsall and Langdon, *Plasma Phys. via Comp. Simulation* (1985)

The particle-in-cell methodology

Modeling kinetic physics

- Particle simulations

  (# operations $\propto$ N^2)

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  - Fields + densities
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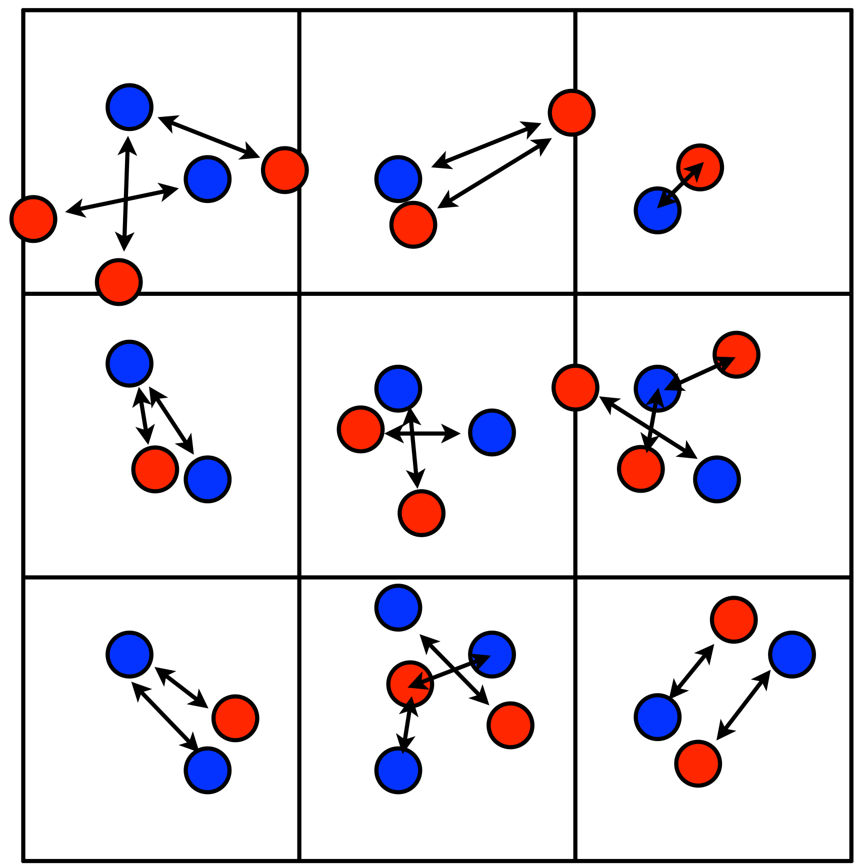
MC binary Coulomb collisions*

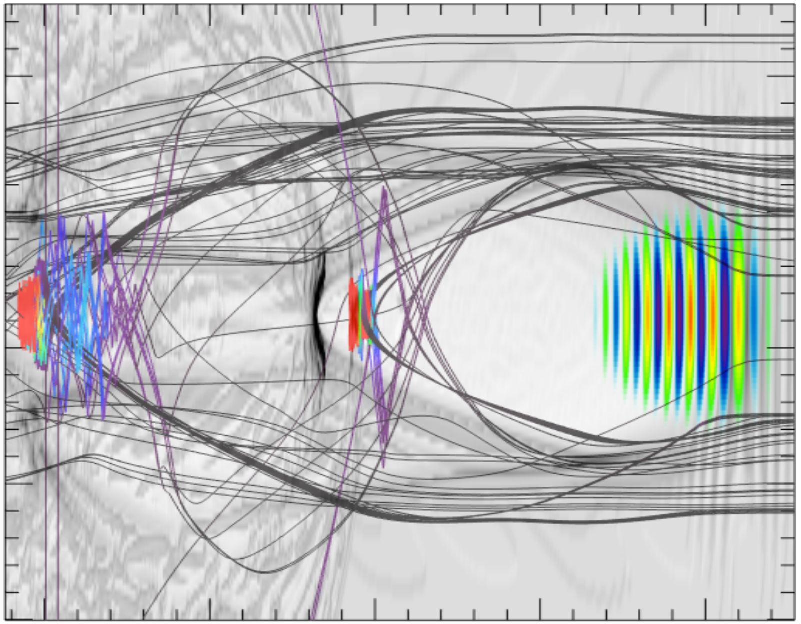


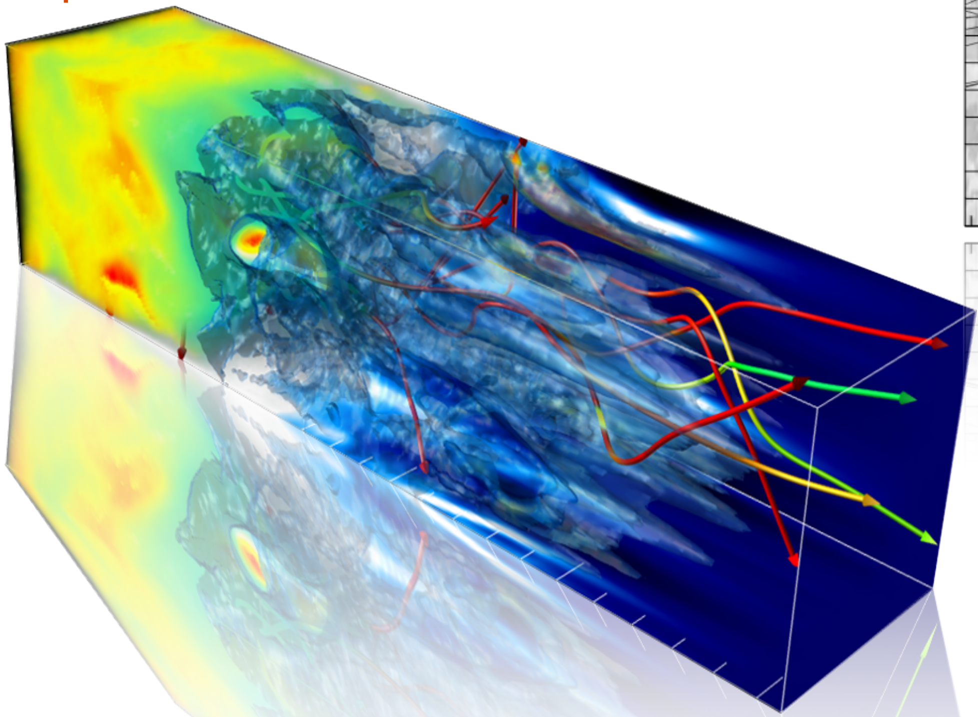
* Takizuka & Abe JCP 1977

OSIRIS 2.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

Particle-in-cell loop in osiris 2.0

osiris
v2.0

INSTITUTO SUPERIOR TÉCNICO

UCLA

PARTICLES

$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$$

Integration of equations of motion: moving particles

$$\mathbf{F}_p \rightarrow \mathbf{u}_p \rightarrow \mathbf{x}_p$$

Deposition: calculating current on grid

$$(\mathbf{x}, \mathbf{u})_p \rightarrow \mathbf{j}_i$$

$$\Delta t$$

Integration of field equations: updating fields

$$(\mathbf{E}, \mathbf{B})_i \leftarrow \mathbf{J}_i$$

Interpolation: evaluating force on particles

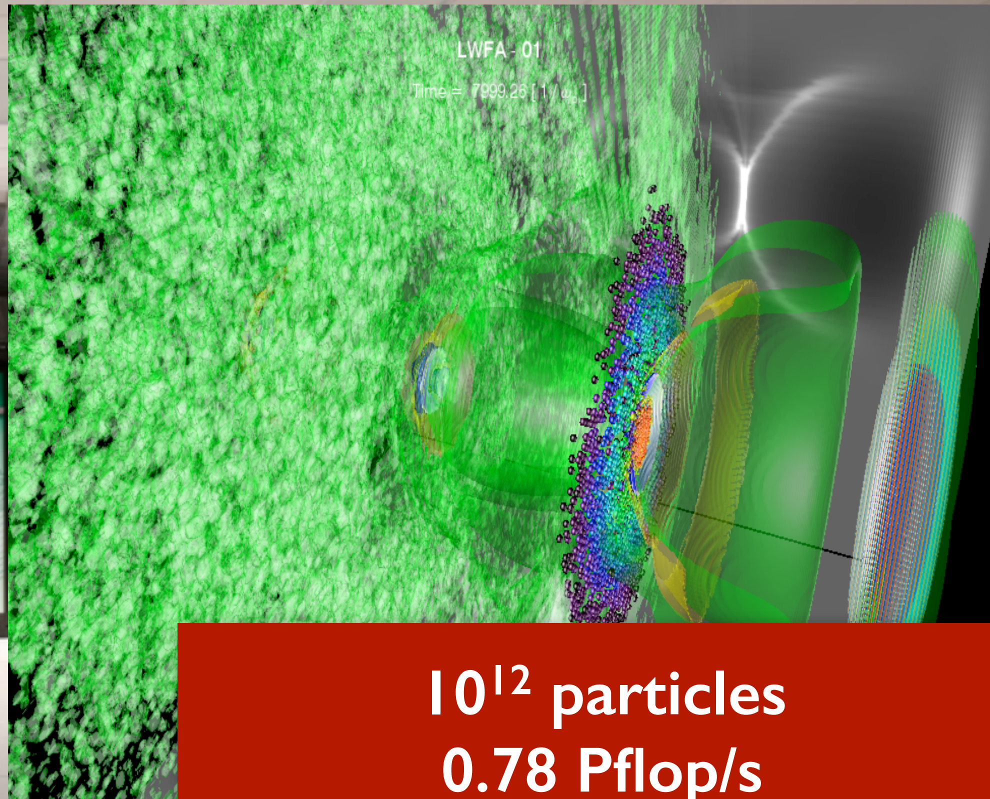
$$(\mathbf{E}, \mathbf{B})_i \rightarrow \mathbf{F}_p$$

GRID

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

Taking advantage of the largest machines in the World



10^{12} particles
0.78 Pflop/s
33% peak performance

- Jaguar (jaguarpf)
  - 18688 compute nodes
  - dedicated service/login nodes
  - SeaStar2+ network

- XT5 Compute node
  - Dual hex-core AMD Opteron 2435 (Istanbul) at 2.6 GHz
  - 16GB DDR2-800 memory

- Complete system
  224256 processing cores
  300 TB of memory
  Peak performance **2.3 PFlop/s**

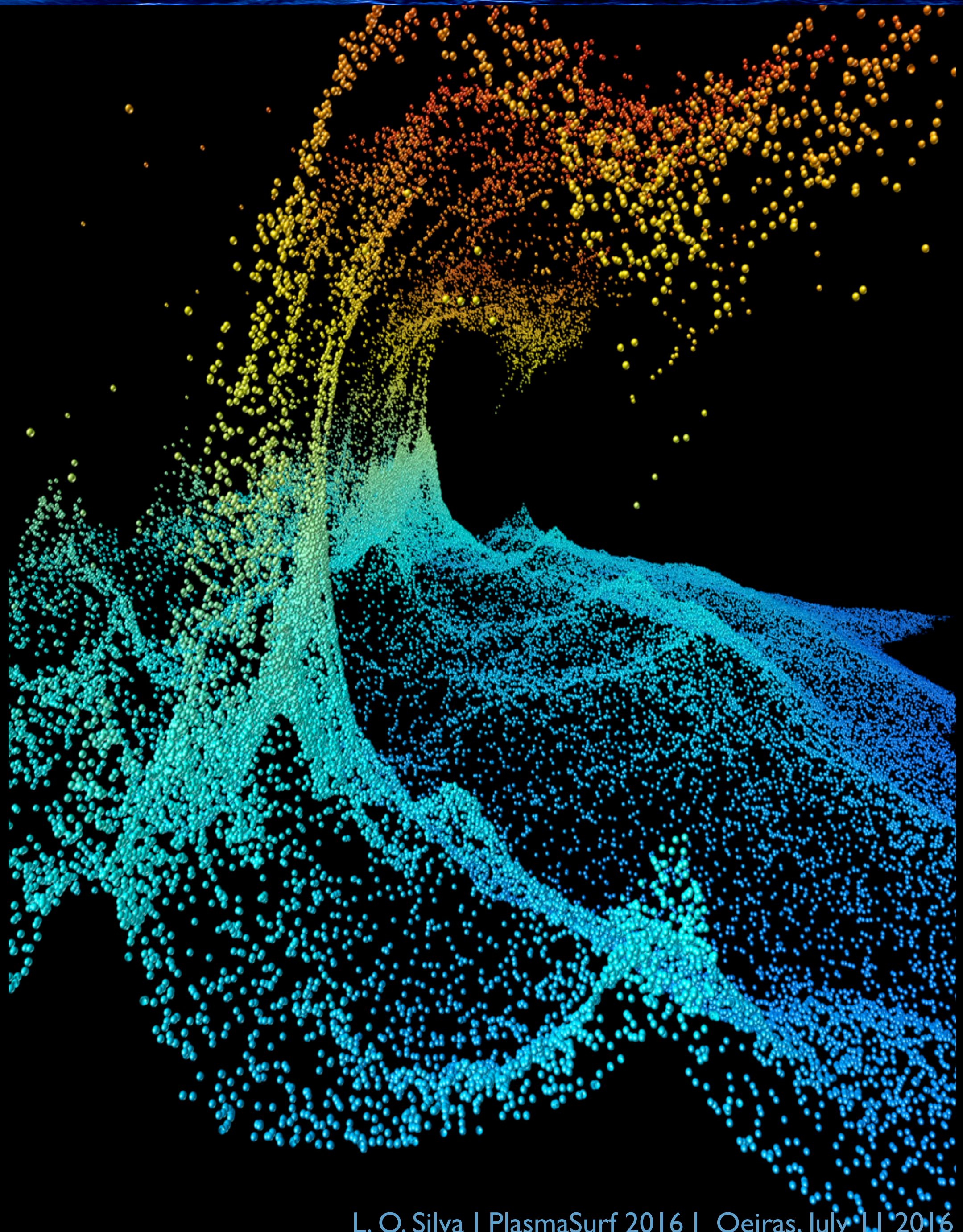
What challenges lie ahead?

Demonstrate 10s GeV e- and 200 MeV protons with lasers

Make nuclear fusion (with lasers) a viable alternative for energy production

Determine the conditions & observe Fermi acceleration in the laboratory

“Boil the vacuum”



Contents

Particle accelerators: rich science and applications

From compact to country size

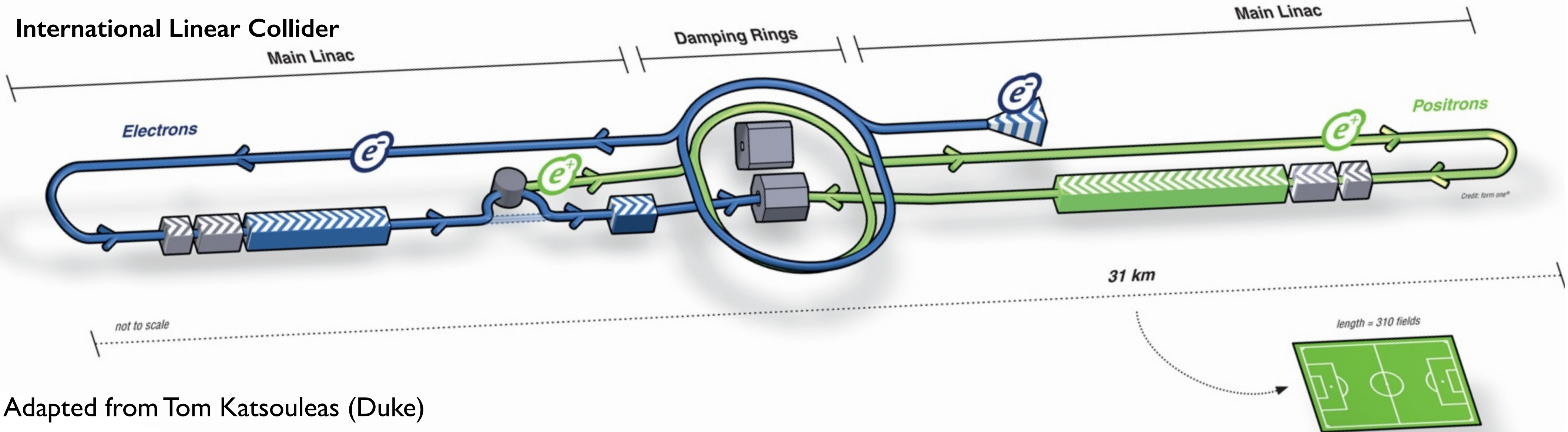
Large

- Verified Standard Model of Particle Physics
- W, Z bosons
- Quarks, gluons and quark-gluon plasma
- Asymmetry of matter and anti-matter
- In pursuit of the Higgs boson

Compact

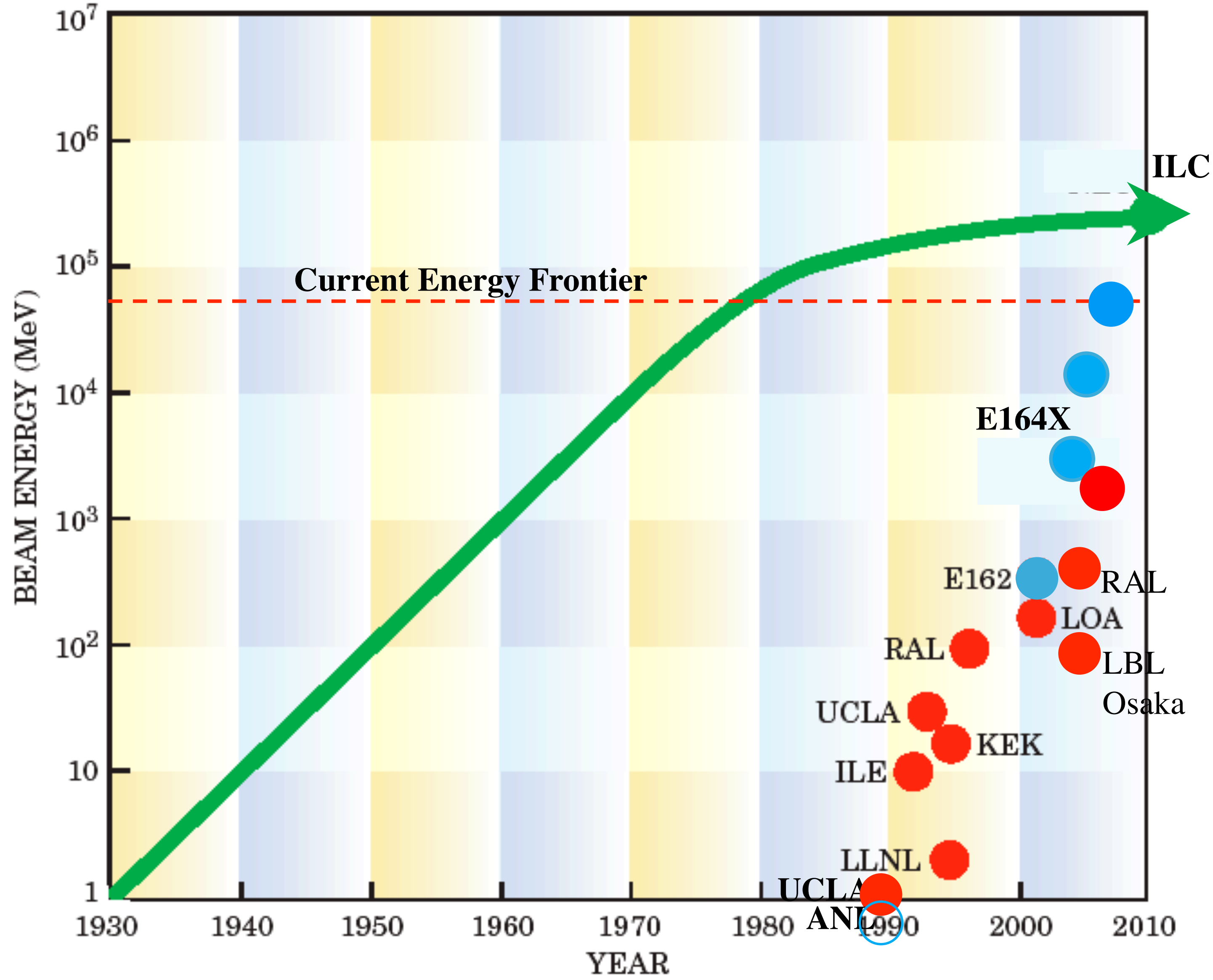
- Medicine
  - cancer therapy, imaging
- Industry
  - lithography
- Light sources (synchrotrons)
  - bio imaging
  - condensed matter science

International Linear Collider

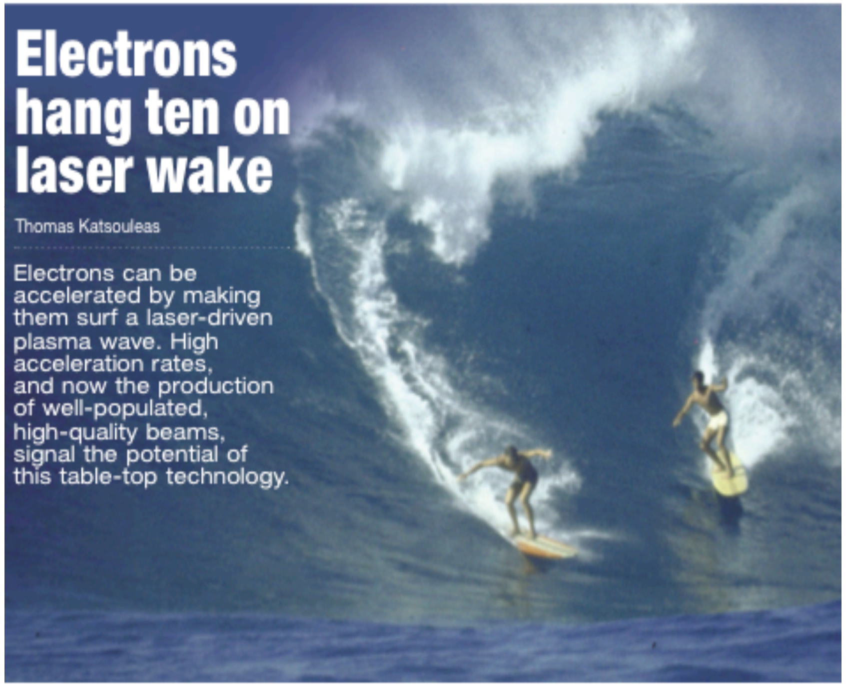


Adapted from Tom Katsouleas (Duke)

Plasma Accelerator Progress and the *"Accelerator Moore's Law"*



Courtesy: Tom Katsouleas (Duke) / Physics Today 2004



CHIP SIMONS

PLASMA ACCELERATORS

A new method of particle acceleration in which the particles "surf" on a wave of plasma promises to unleash a wealth of applications

By Chandrashekhar Joshi

www.sciam.com

SCIENTIFIC AMERICAN 41

Accelerating particles in plasma wakes

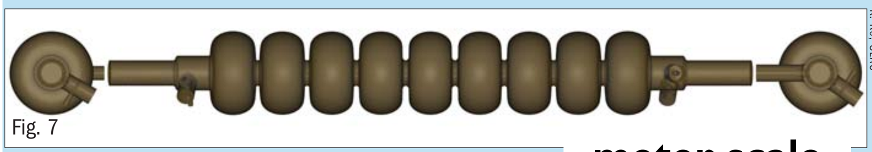
Recent progress has put plasma acceleration at the forefront of Science

Simulations + lasers + sources directly impacted this progress

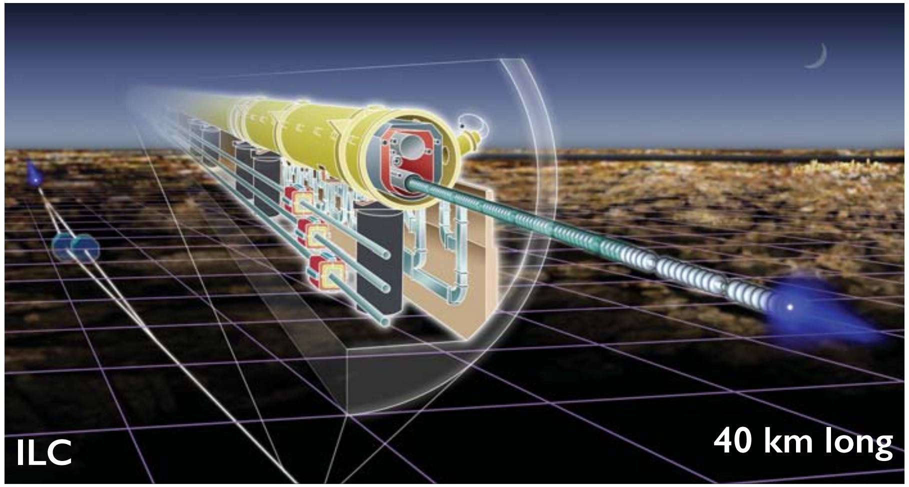
Why plasmas?

Plasmas do not "break" under very large electric fields

RF cavities sustain 50 MeV/m

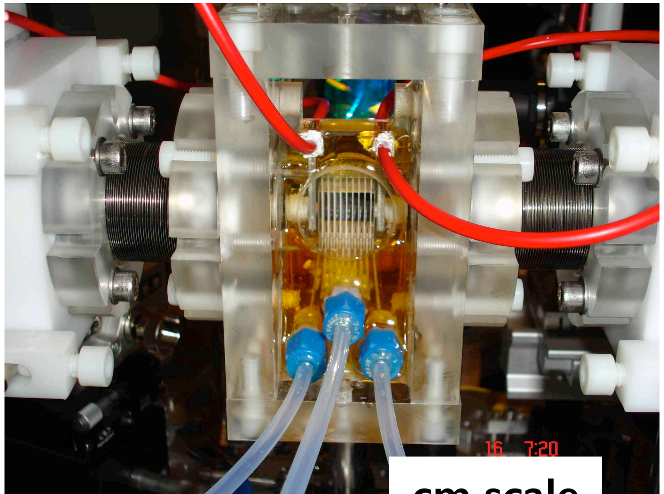


x 20 000 for ILC



Maximum accelerating electric field determined by disruption of RF cavity walls

Plasmas can sustain 10's GeV/m



$$E_0[\text{V/cm}] \approx 0.96\, n_0^{1/2}\, [\text{cm}^{-3}]$$

$$n_0 = 10^{18}\ \text{cm}^{-3} \rightarrow \boldsymbol{E_0 \approx 1\ \text{GV/cm}}$$

Plasmas can sustain waves with very large electric fields with relativistic phase velocities

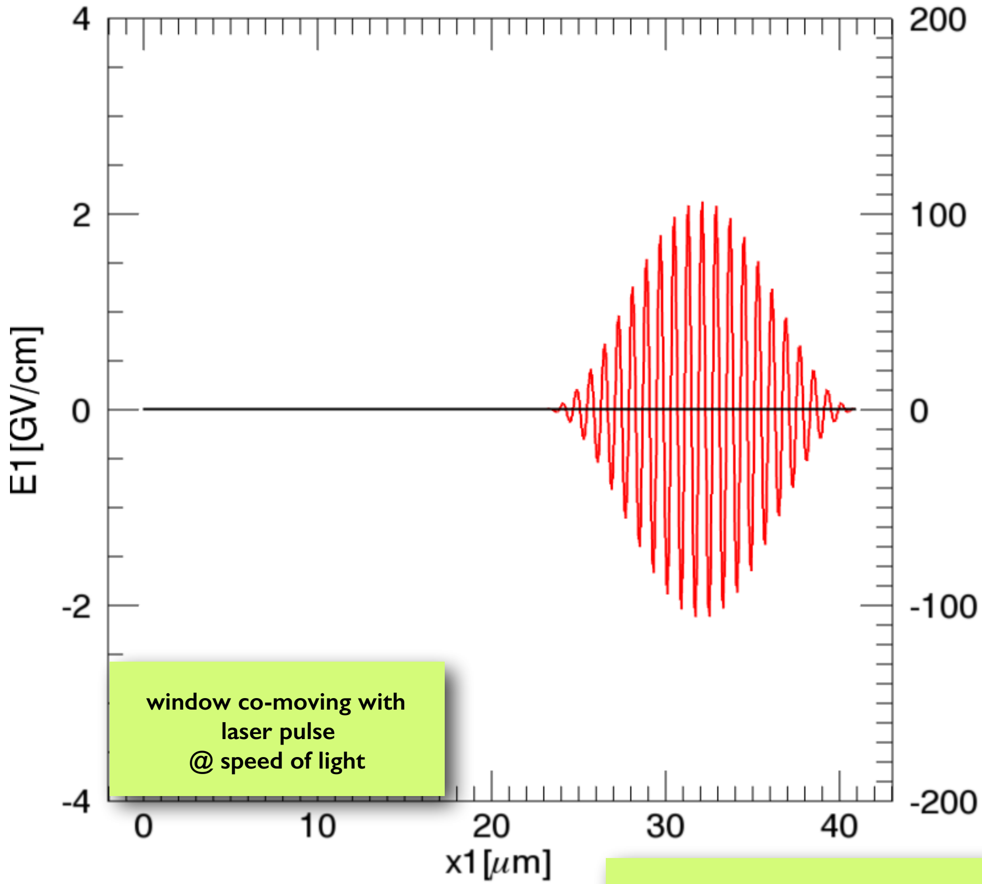
Pioneering work in 70s - 80s opened a brand new field

Plasma based accelerators

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

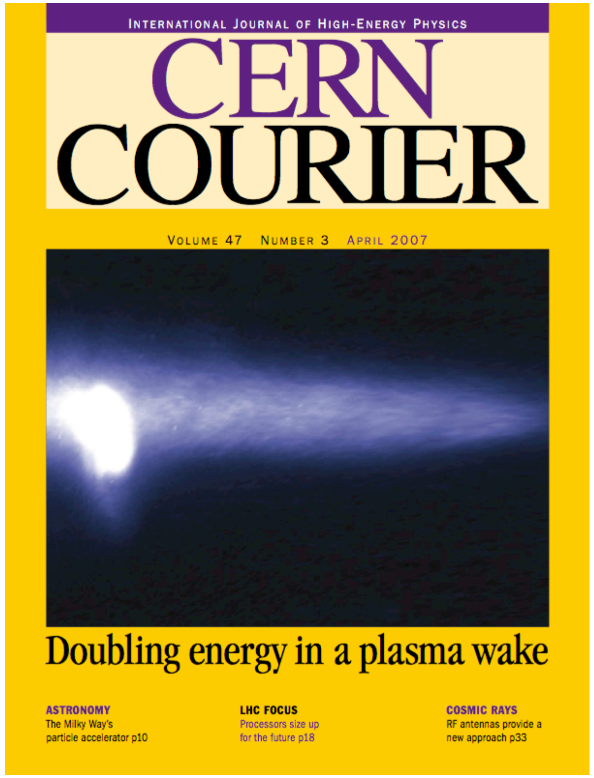
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)



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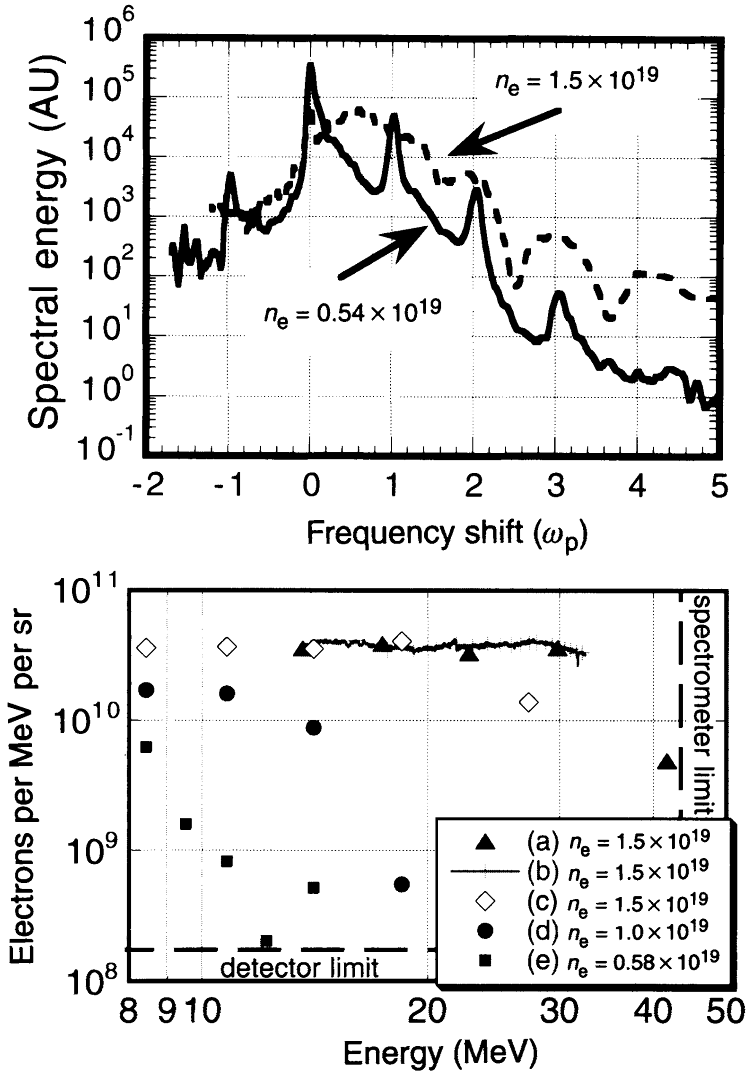
Pre-2004 results demonstrated relativistic plasma wave excitation

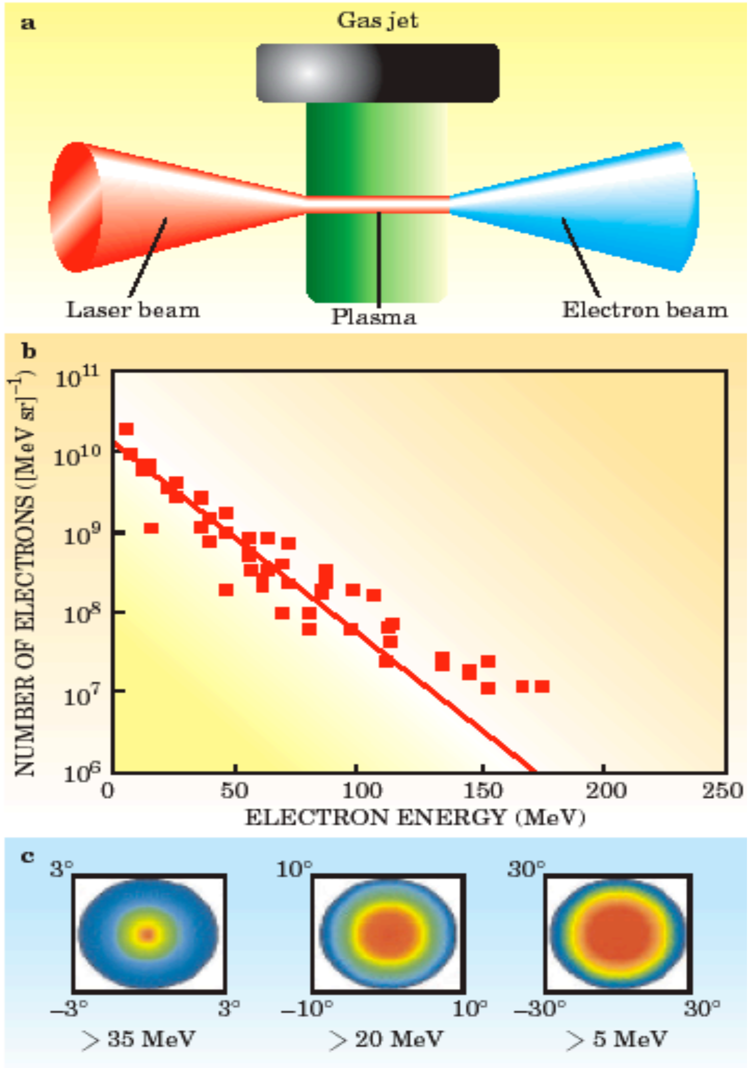
Electron acceleration up to ~ 200 MeV

Relativistic plasma waves



A. Modena *et al*, Nature (1995)

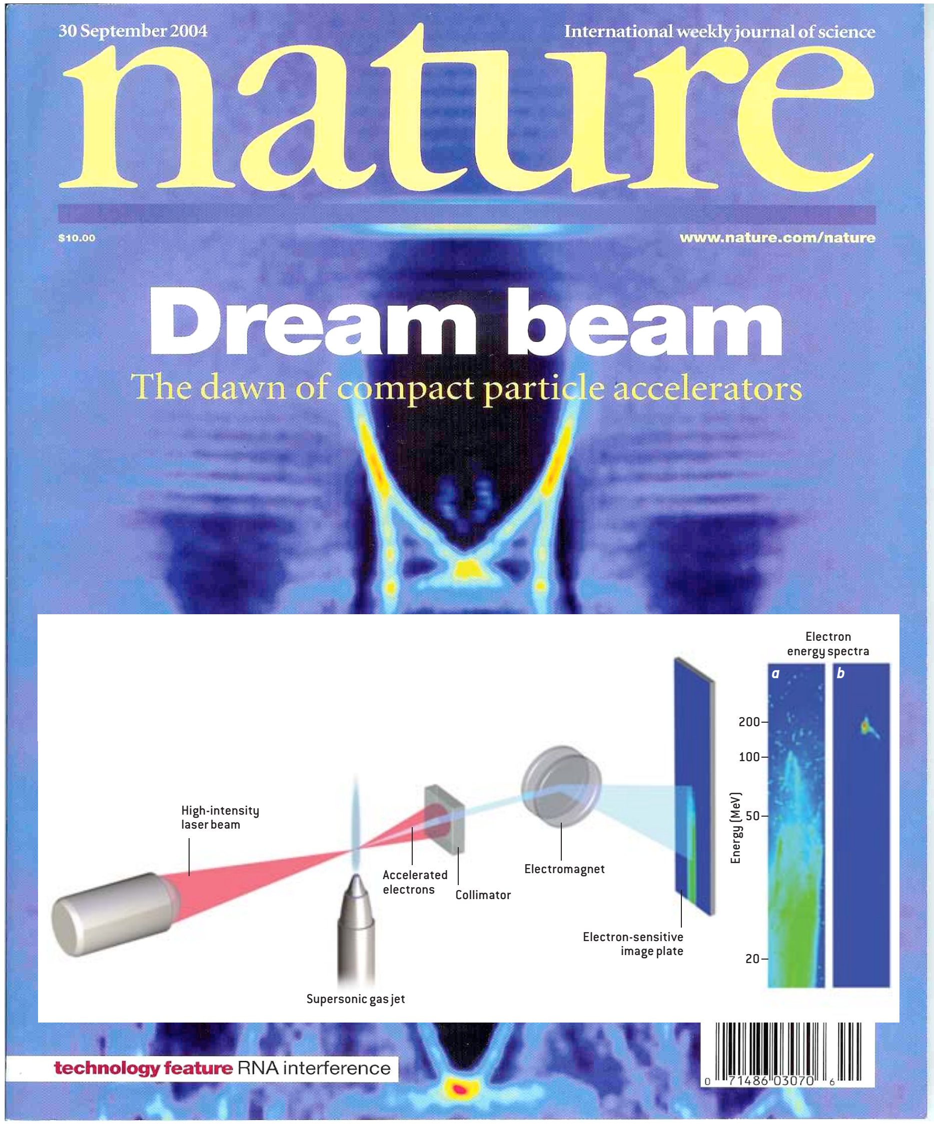
Thermal-like spectrum up to 200 MeV



V. Malka *et al*, Science (2002)

2004 results confirm potential of laser-plasma accelerators

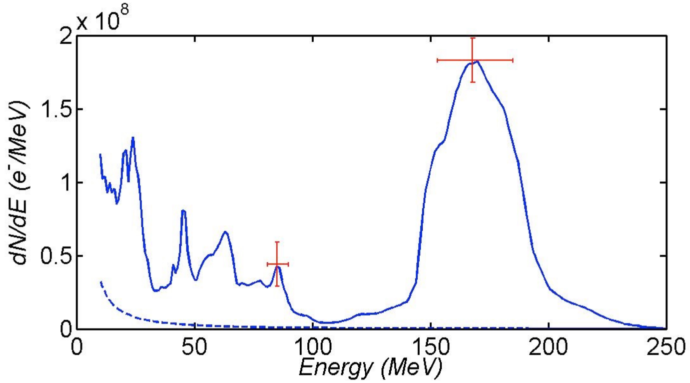
Monoenergetic beams of self-injected electrons

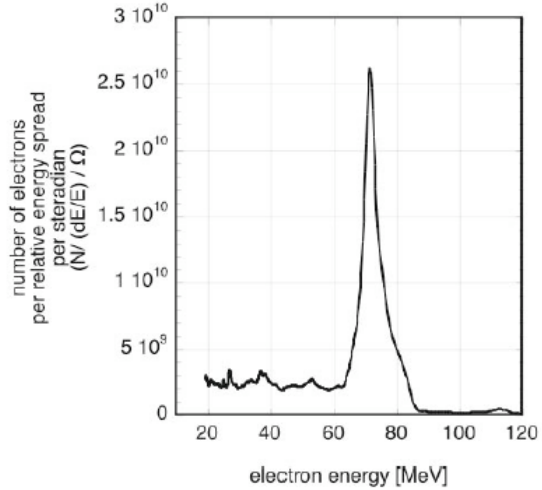


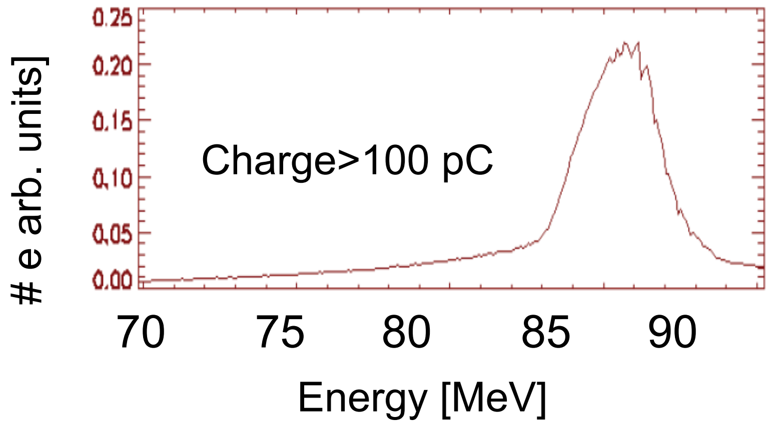
Imperial College London

CCLRC

Berkeley Lab



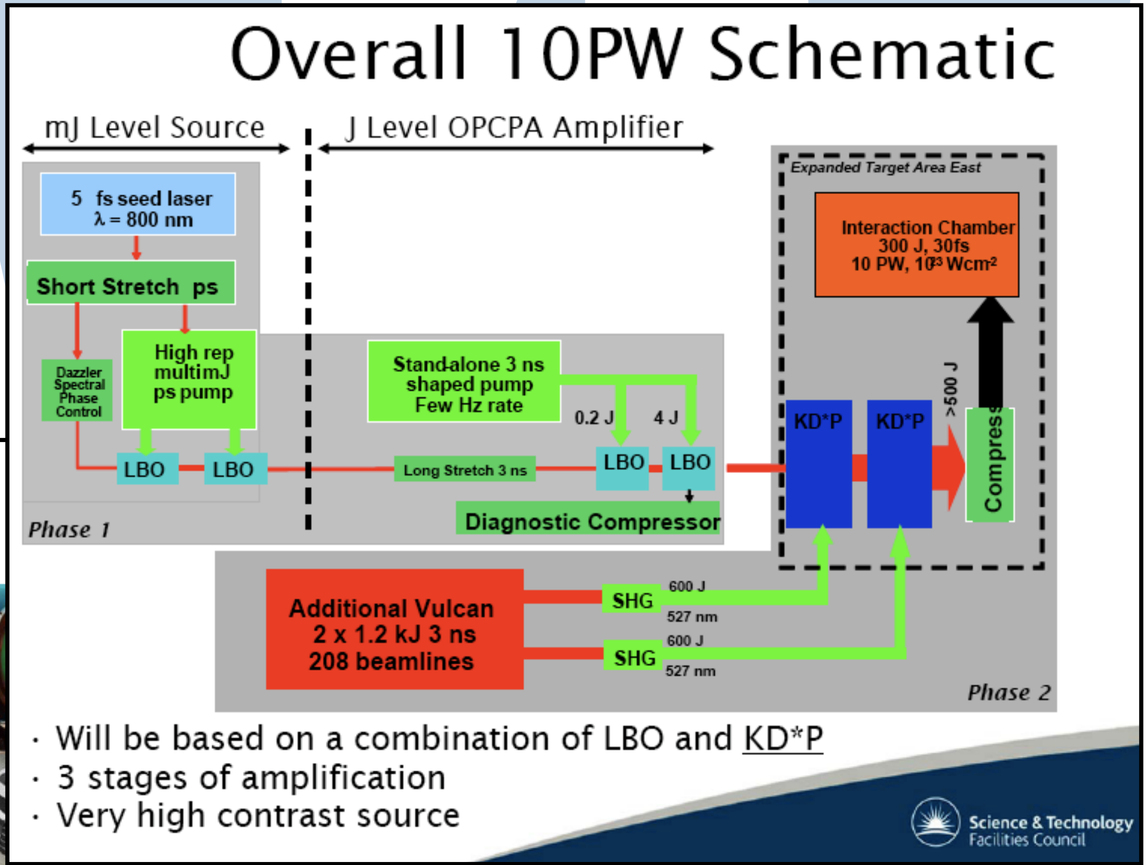




Courtesy: V. Malka (LOA), K. Krushelnick (IC/RAL), W. Leemans (LBL)

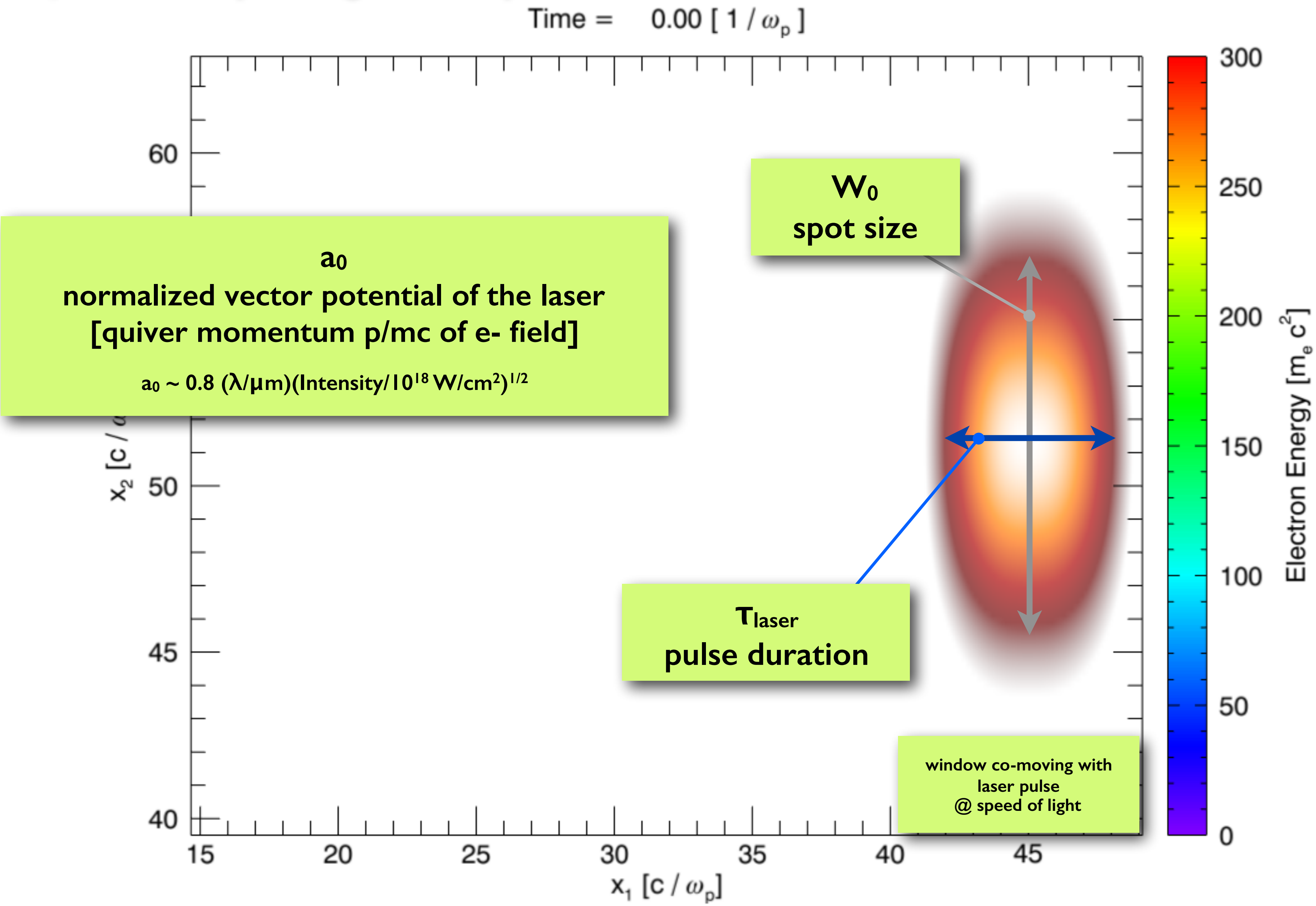
Can LWFA reach the energy frontier with the next generation of lasers?

Next generation of lasers @ 10 PW

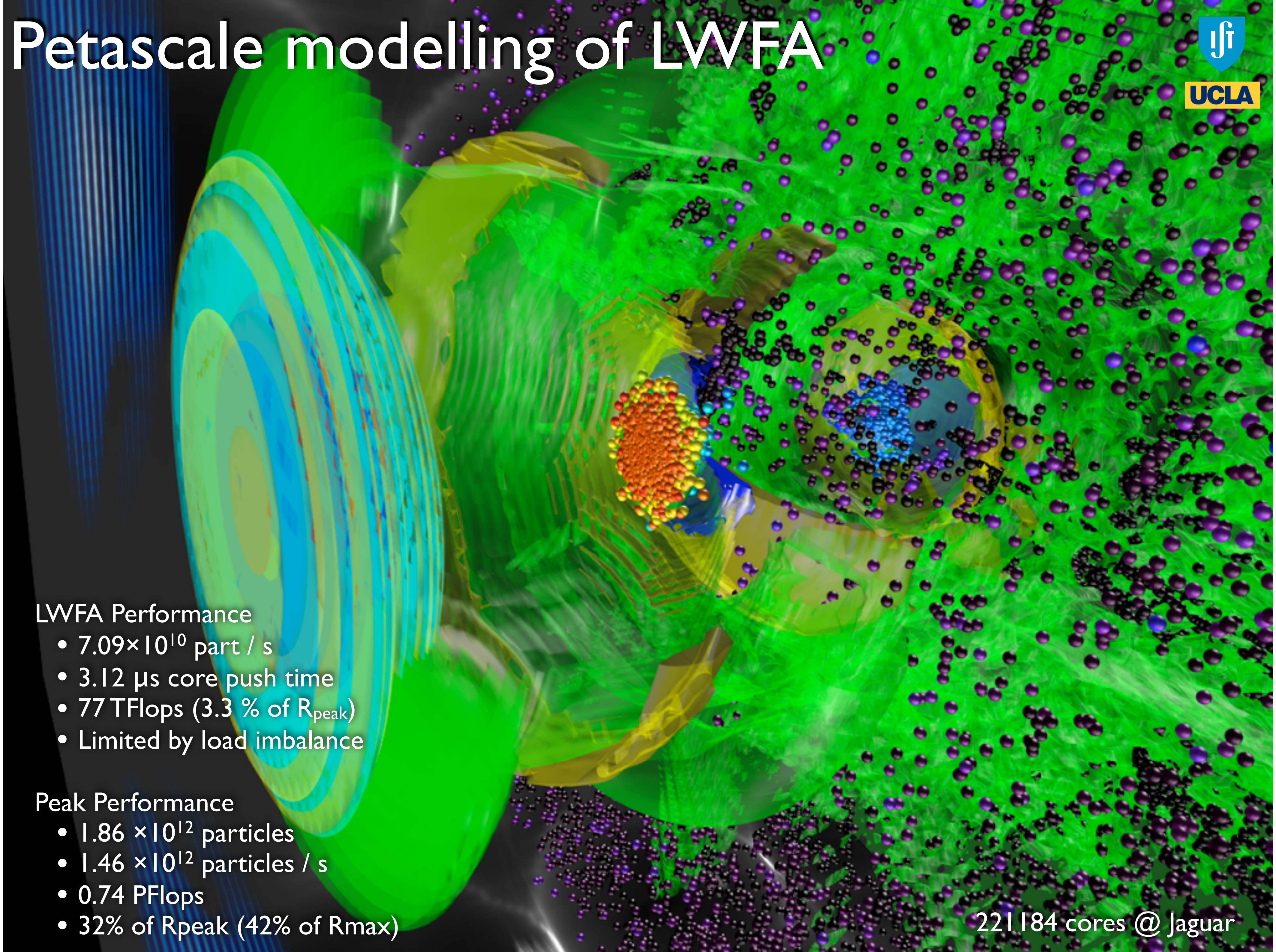


Blow-out regime of laser wakefield acceleration

Self-injection, Dephasing, and Depletion



Petascale modelling of LWFA



LWFA Performance

- 7.09×10^{10} part / s
- 3.12 µs core push time
- 77 TFlops (3.3 % of R_{peak})
- Limited by load imbalance

Peak Performance

- 1.86×10^{12} particles
- 1.46×10^{12} particles / s
- 0.74 PFlops
- 32% of Rpeak (42% of Rmax)

221184 cores @ Jaguar

Challenge: Parameter range for a 300J laser

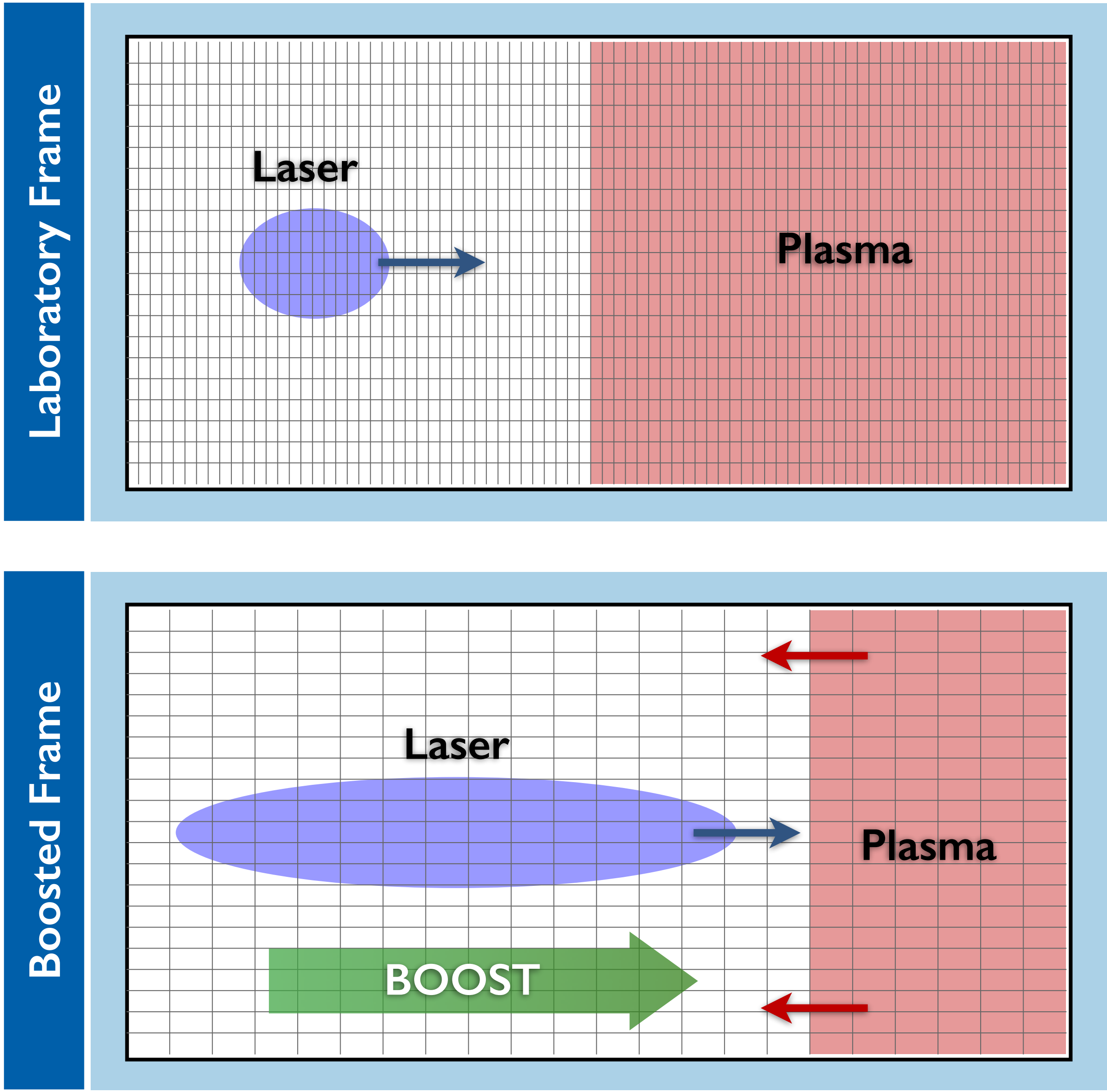
		Self-guiding		External-guiding	
		Self Injection I*	Self Injection II**	Self Injection**	External Injection**
Laser	a0	43	5.8	3.5	2
	Spot [μm]	9	50	70	101
	Duration [fs]	30	110	155	224
Plasma	Density [cm^{-3}]	1.5×10^{19}	2.7×10^{17}	8.2×10^{16}	2.2×10^{16}
	Length [cm]	0.25	22	100	500
e- Bunch	Energy [GeV]	**4**	**13**	**25**	**53**
	Charge [nC]	14	2	1.8	1.5
Simulation time [days in 512CPUs]		**1**	**400**	**2,500**	**12,000**

* S. Gordienko and A. Pukhov PoP (2005)

** W. Lu *et al*. PR-STAB (2007)

Boosted Frames in LWFA simulations

Grid resolution in Laboratory and Boosted frame



Resolution gains

Particles

- Resolutio… — …$\beta)$
- Plas… cont…ion — γ

Moving window in Lab Frame

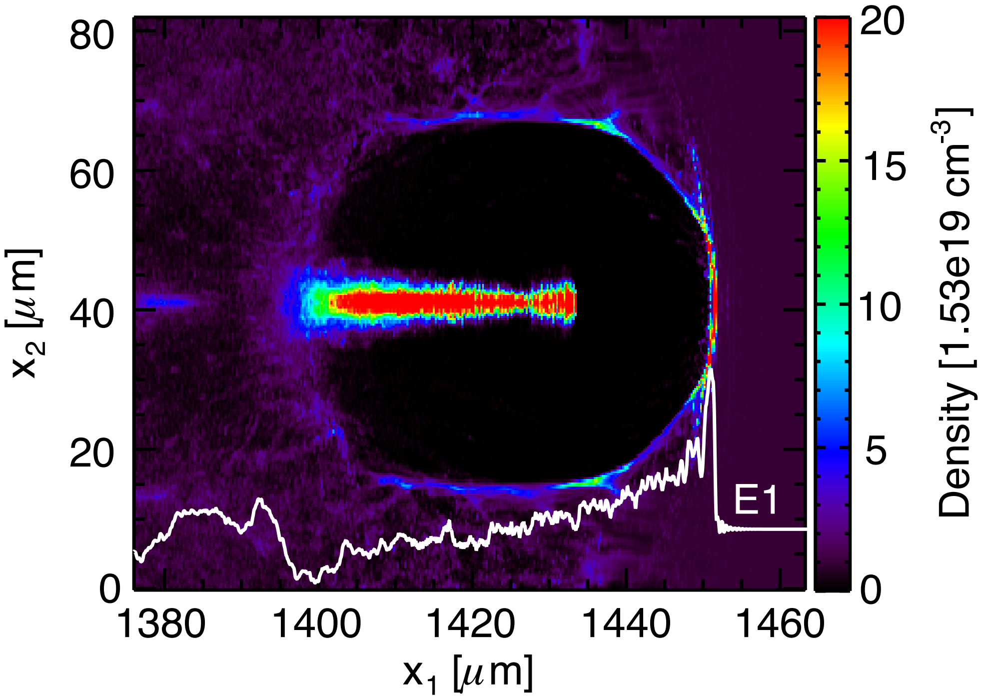
Time steps

- Time step — $\gamma(1+\beta)$
- Total time — $\gamma(1+\beta)$

Total — $\gamma^2(1+\beta)^2$

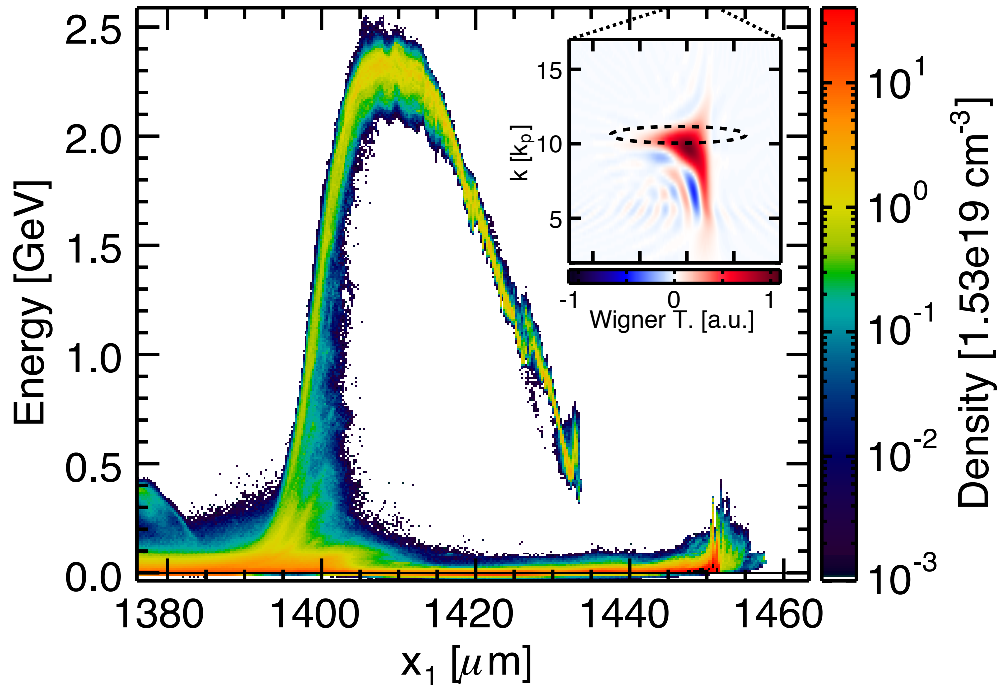
~2GeV self-injection in strongly nonlinear regime

Charge density



18nC above 2GeV
Total 42nC injected

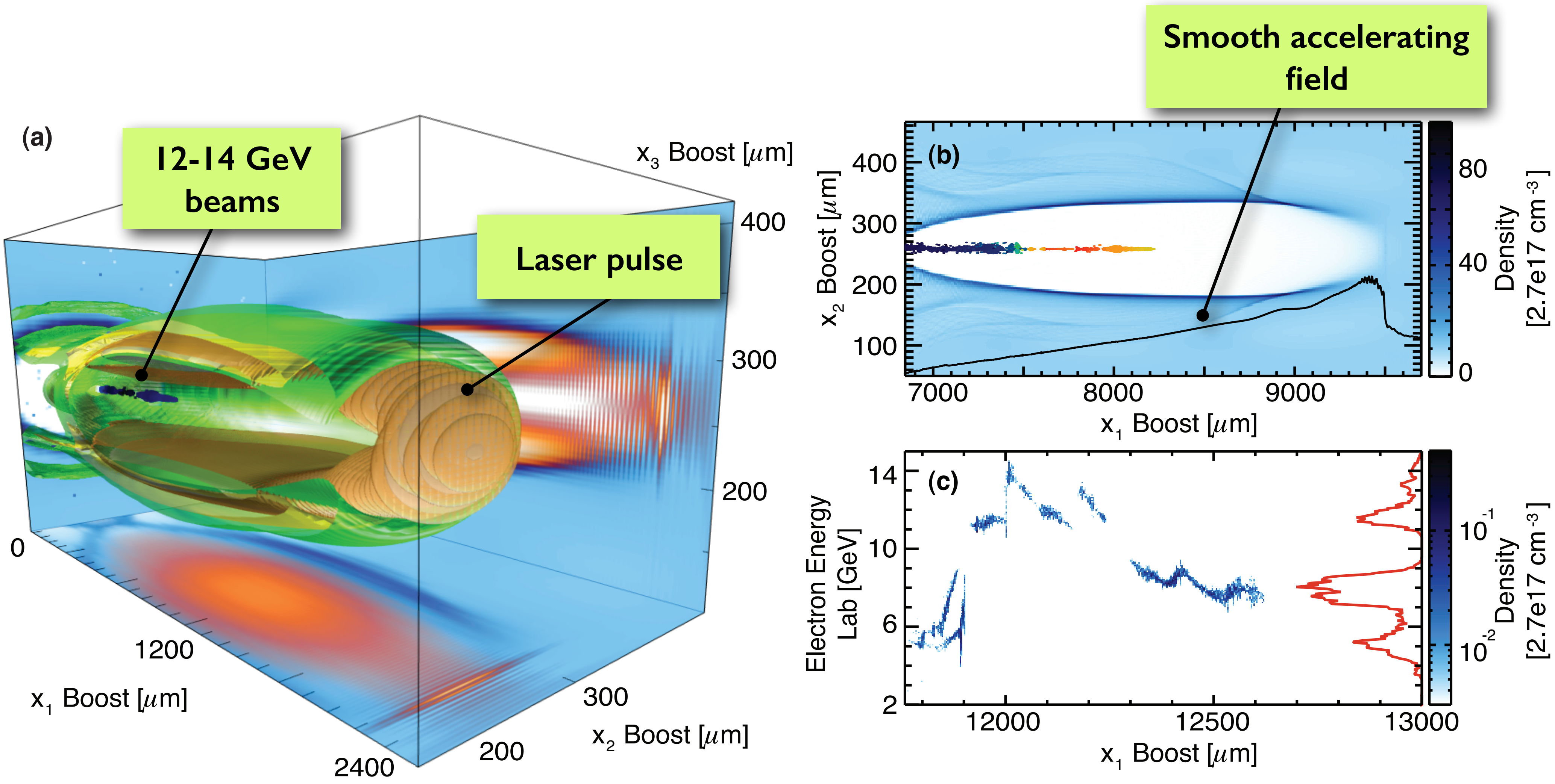
Longitudinal momentum & Wigner transf.



2.3GeV electrons
Pulse redshift

S.F. Martins *et al.*, Nat Phys (2010)

+10GeV self-injection in nonlinear regime

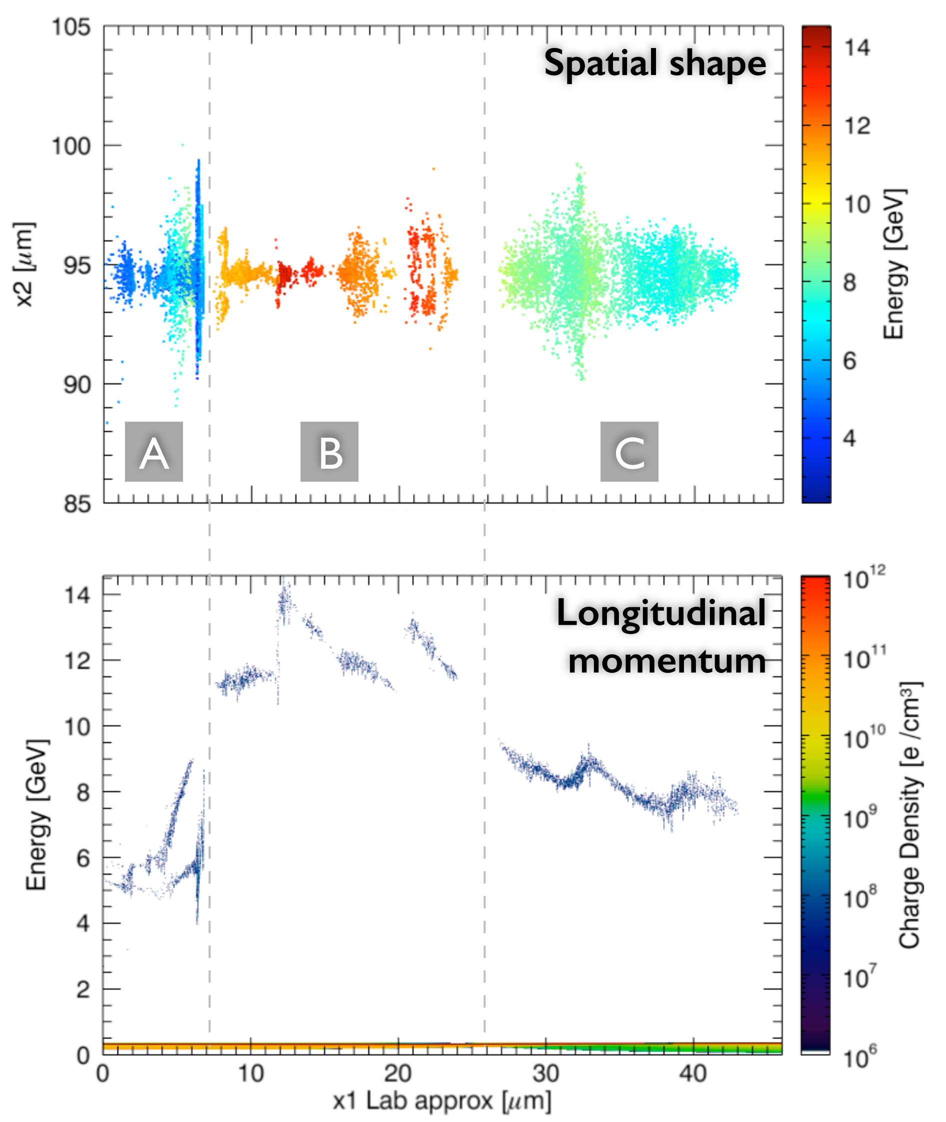


S.F. Martins *et al.*, Nat Phys (2010)

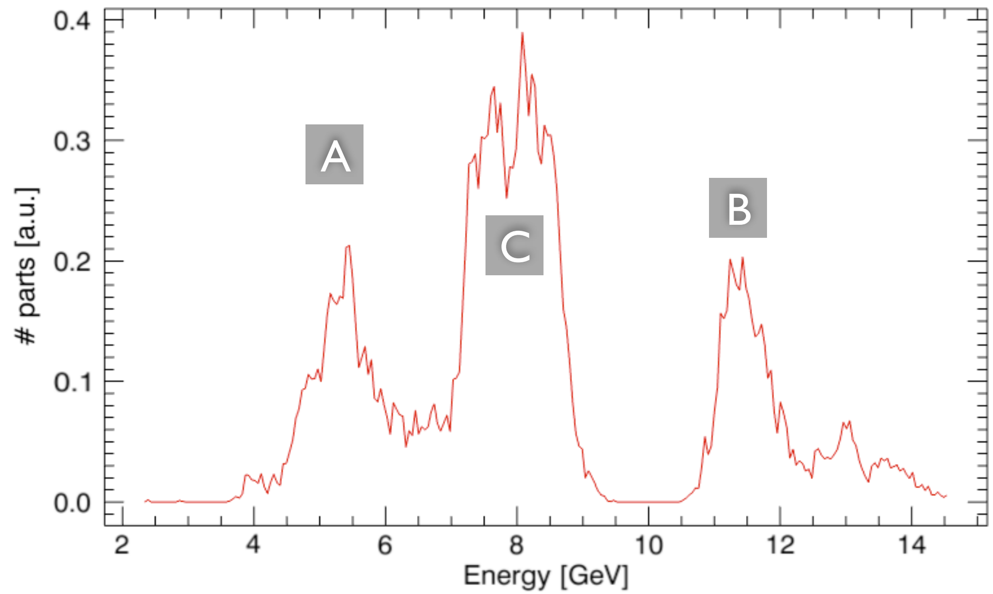
>10GeV simulation for next generation lasers

Injected bunches properties

Bunch shape and momentum



Energy spectrum & Emittance



				Total
Injected charge (nC)	1.4	2.2	1.1	4.7
Energy (J)	7.0	17.6	12.7	37.3
Emittance (μm)				SLAC beam
x2	16.6	10.6	4.5	10
x3	25.4	9.9	10.2	50

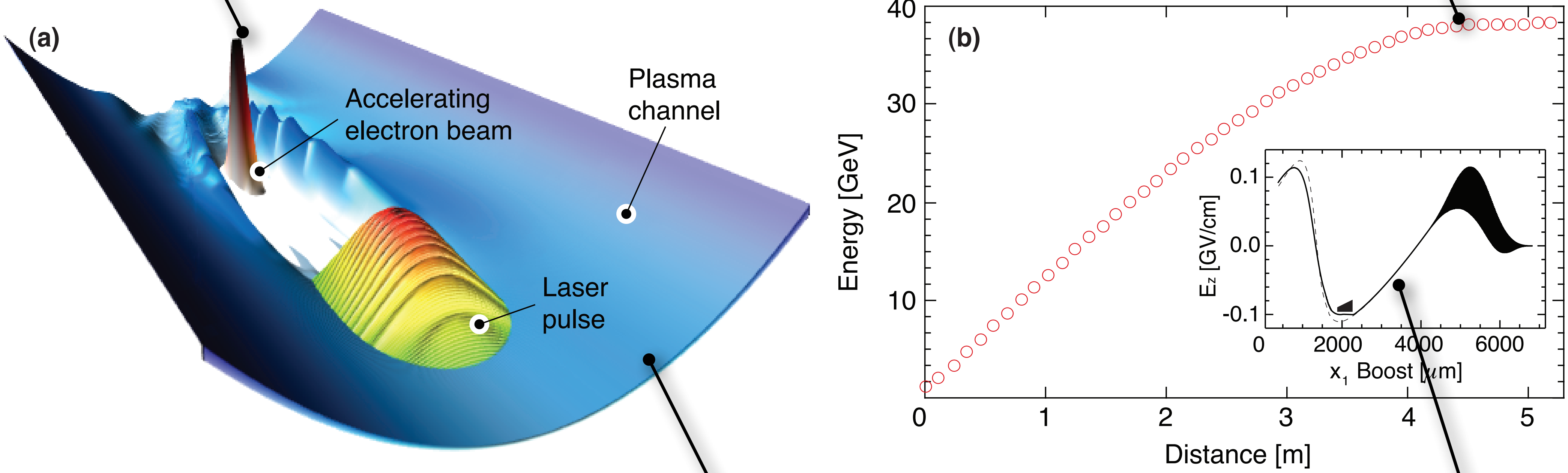
12.4% efficiency

*Norm. Emitt. $= \gamma[\langle x^2\rangle\langle \dot{x}^2\rangle - \langle x\dot{x}\rangle^2]^{\frac{1}{2}}$ $\quad \dot{x} = p_x/p_z$

+40GeV with externally injected beams

Tailored injected beam to minimize final energy spread

40GeV beam



Guiding channel
Length: 5.28 m
Density: 2.2 10^{16} cm^{-3}

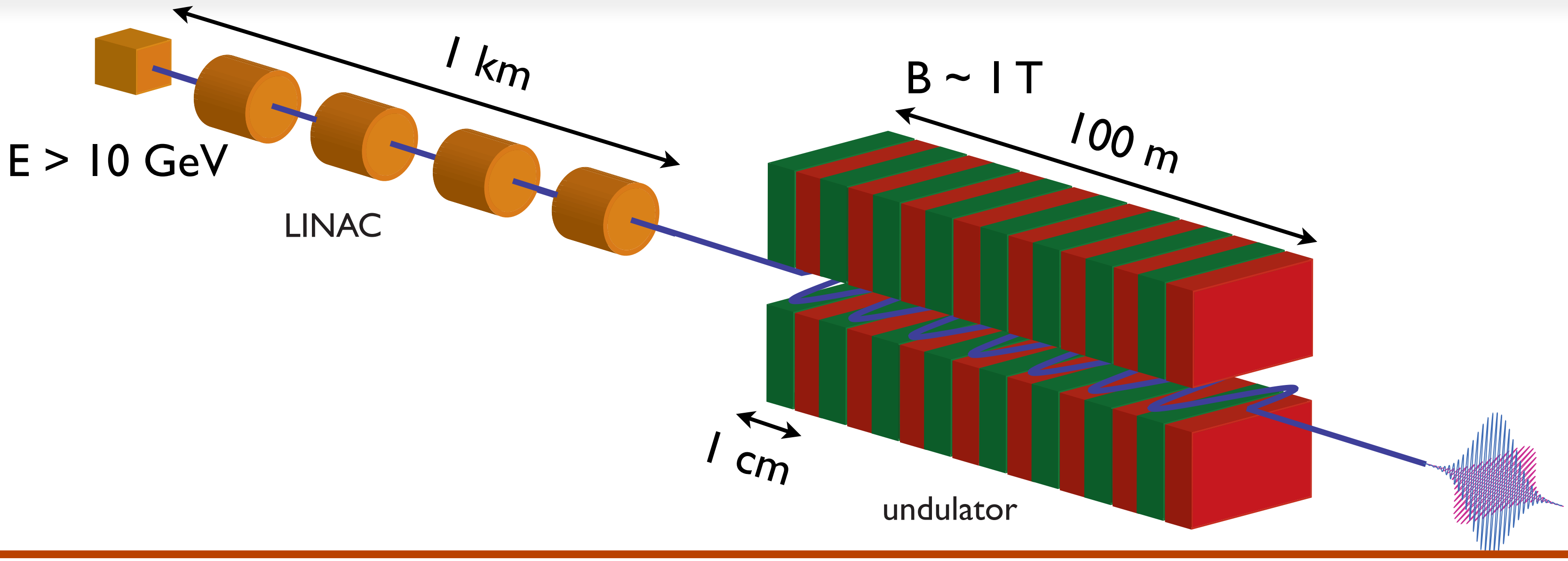
Stable accelerating field for over 5 meters

S.F. Martins *et al*, Nat Phys (2010)

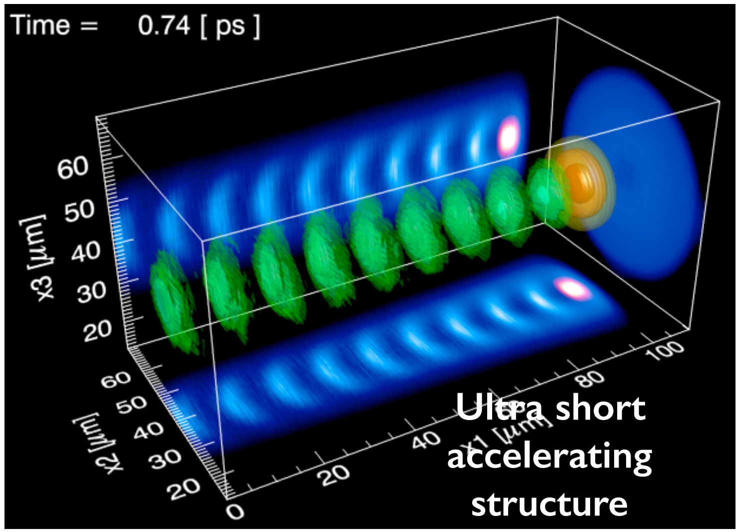
Applications for LWFA beams

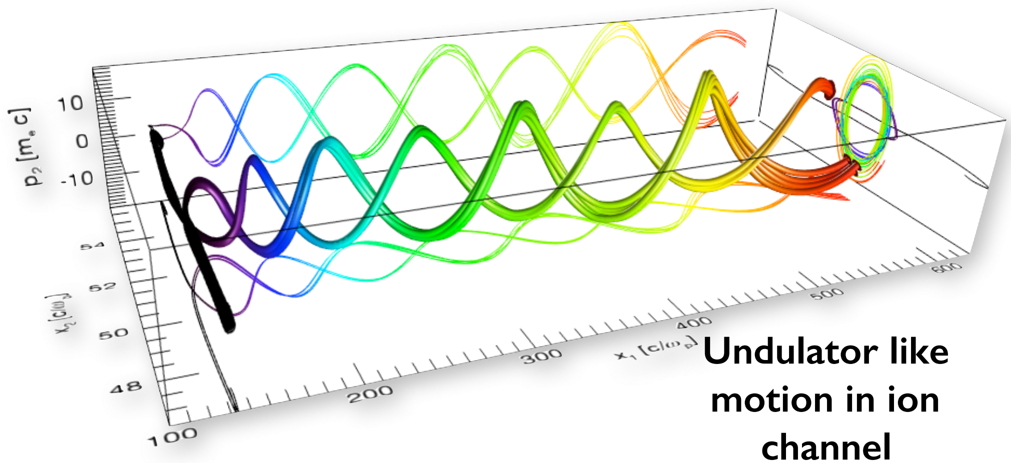
HEP Collider & radiation

Light Sources (FEL)



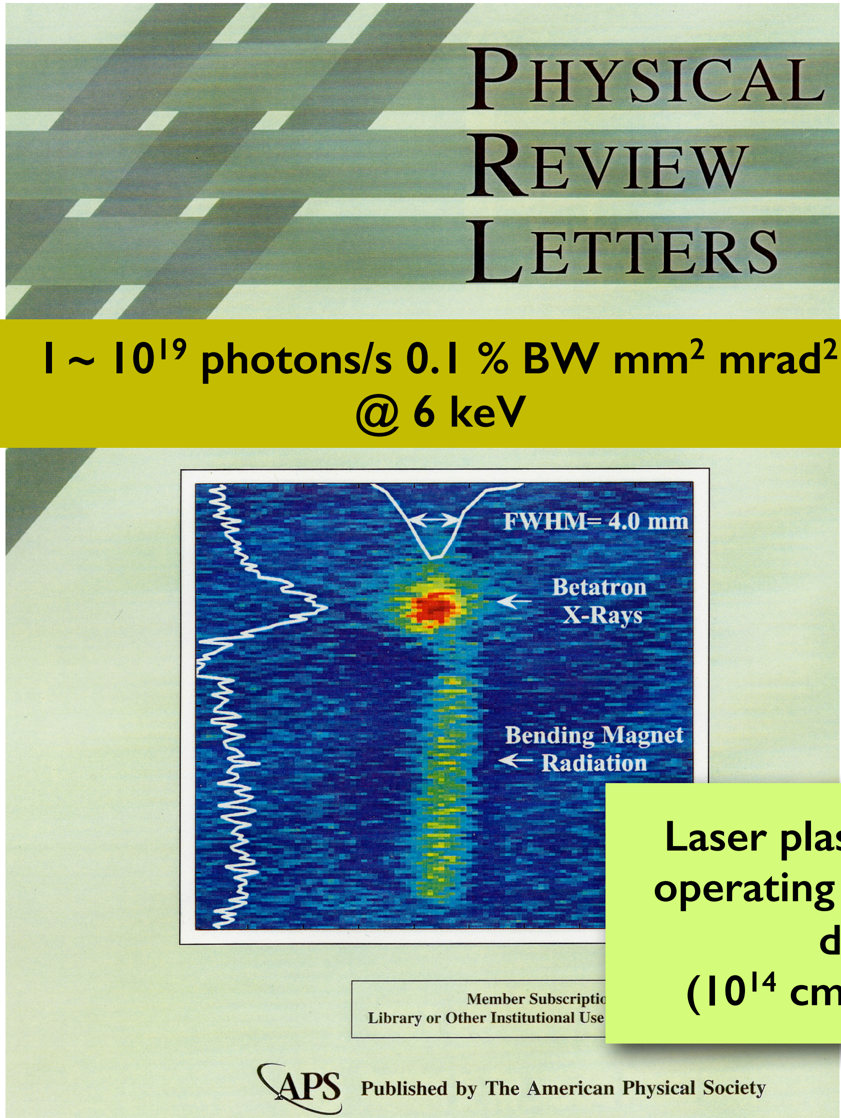
Plasma based





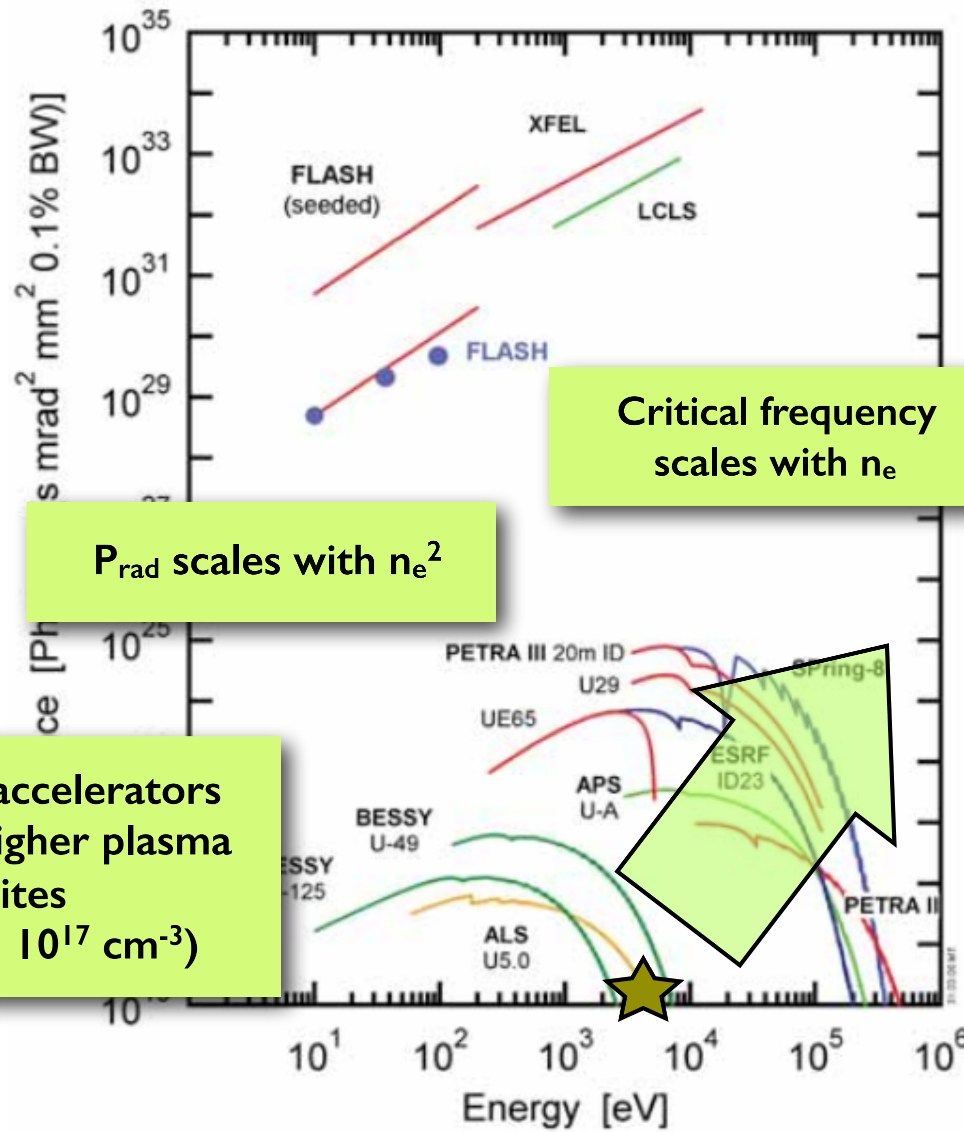
Betatron radiation in plasma wakefield acceleration

UCLA/SLAC/USC have demonstrated x-ray betatron radiation with SLAC beam (28 GeV)



I ~ 10^{19} photons/s 0.1 % BW mm^2 mrad^2 @ 6 keV

S. Wang et al, PRL (April 2002)



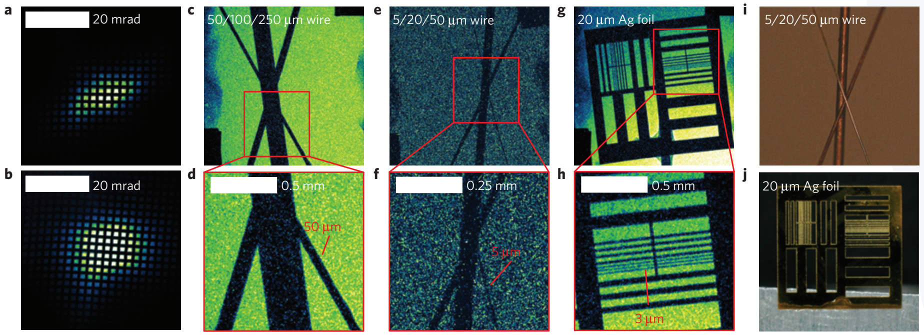
Critical frequency scales with n_e

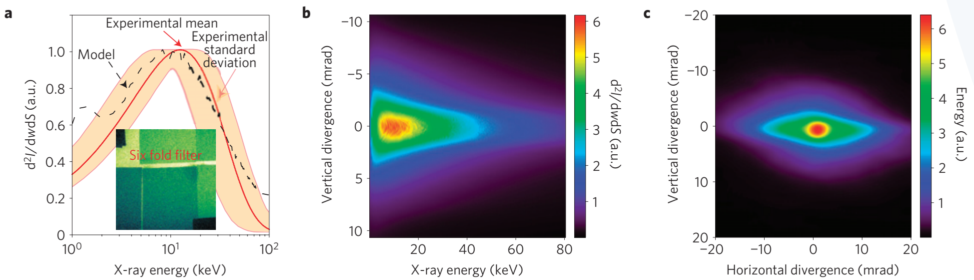
P_{rad} scales with n_e^2

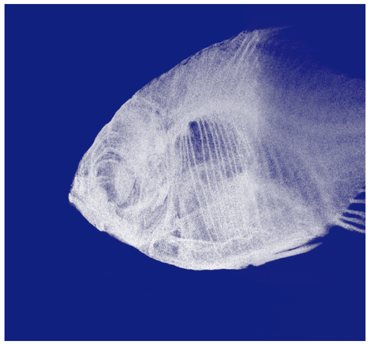
Laser plasma accelerators operating @ higher plasma densitites (10^{14} cm^{-3} → 10^{17} cm^{-3})

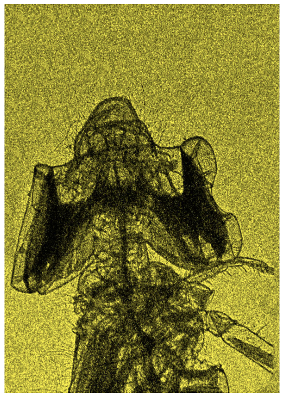
Betatron sources & table top synchrotrons

Spatially coherent x-ray radiation



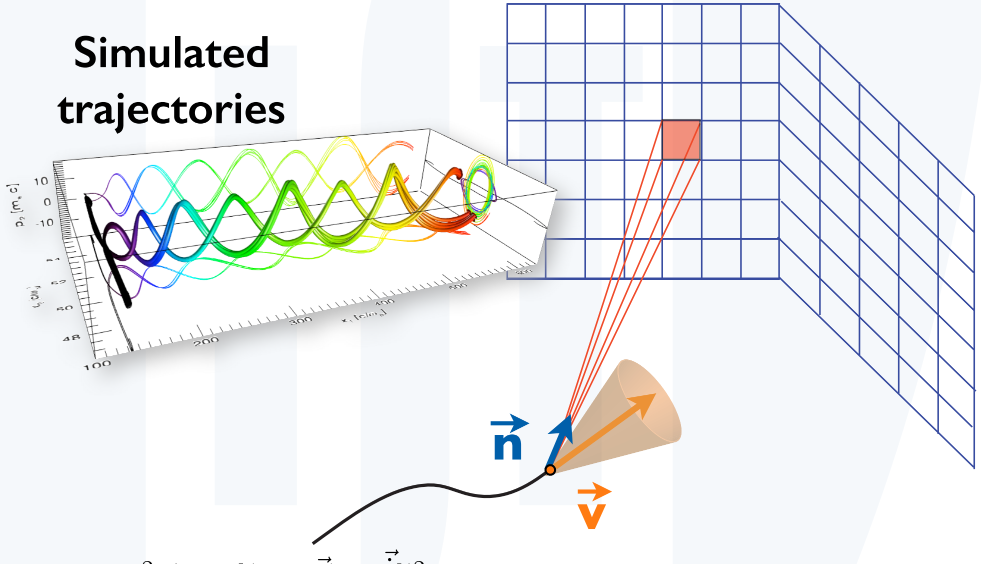






Advanced radiation diagnostic

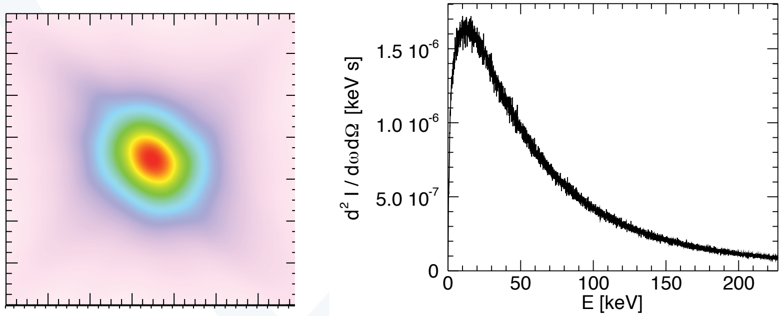
Simulated trajectories



$$\frac{dP}{dS} = \frac{e^2}{4\pi c}\frac{|\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]|^2}{(1-\vec{\beta}.\vec{n})^5 R(t')^2}$$

$$\frac{d^2I}{d\omega dS} = \frac{e^2}{4\pi c}\left|\int_{-\infty}^{-\infty}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{n}\cdot\vec{\beta})^2 R(t')^2}e^{i\omega(t'+R(t')/c)}dt\right|^2$$

Radiated power & spectrum

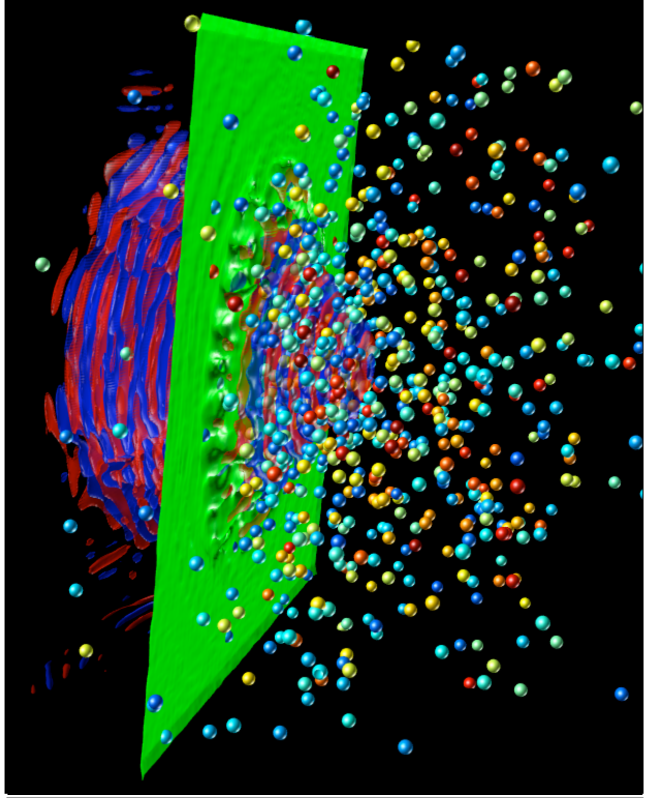


S. Kneip, C. McGuffey, J. L, Martins et al., Nature Phys., 2010

Contents

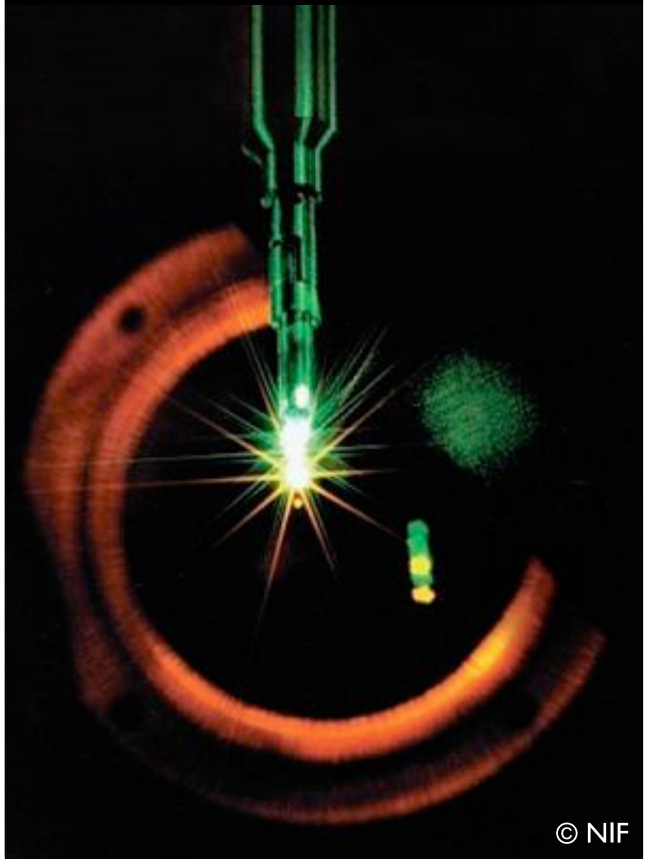
Laser driven ion beams hold promising applications

Laser-plasma accelerators



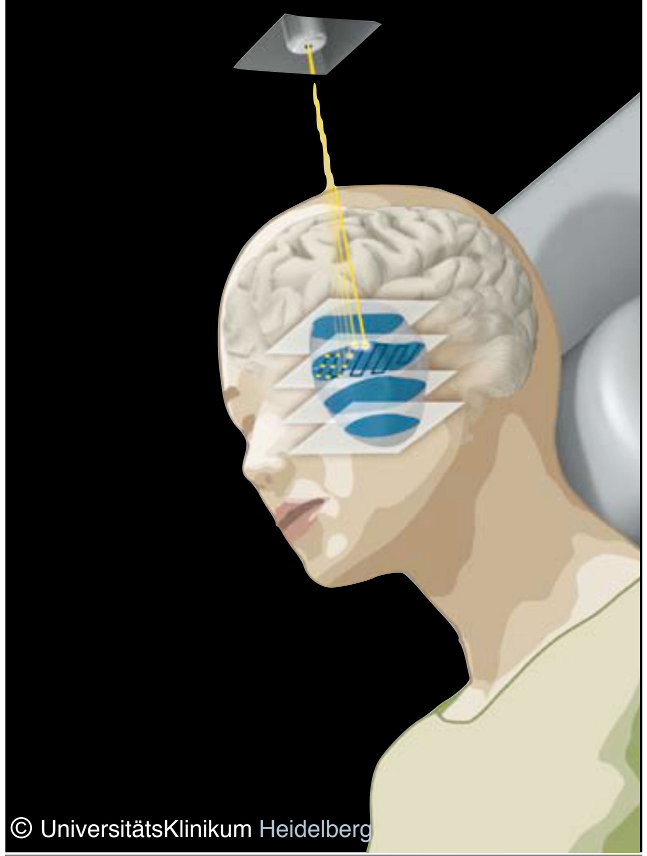
Compact sources

Fusion energy



Ion beam driven inertial fusion

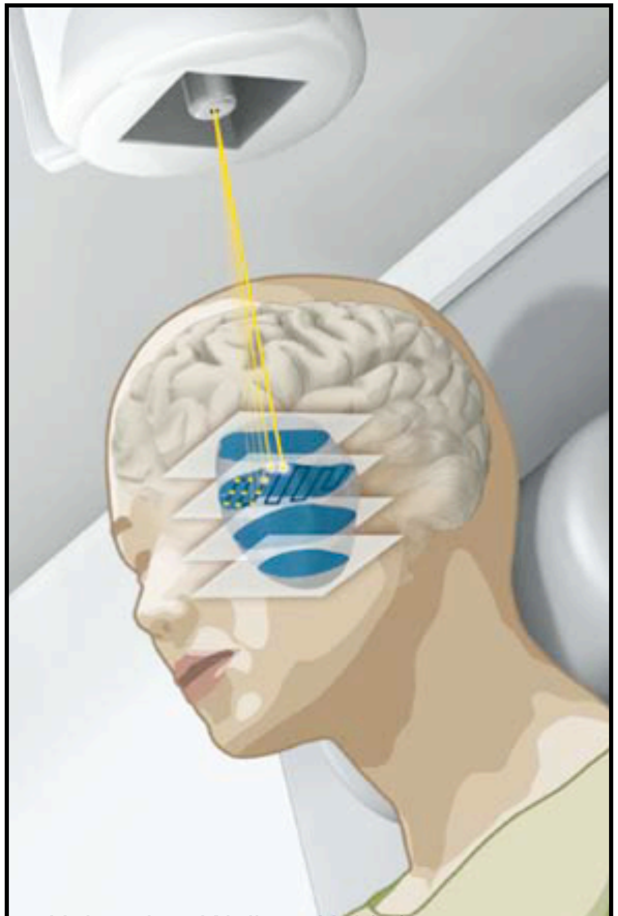
Medical applications



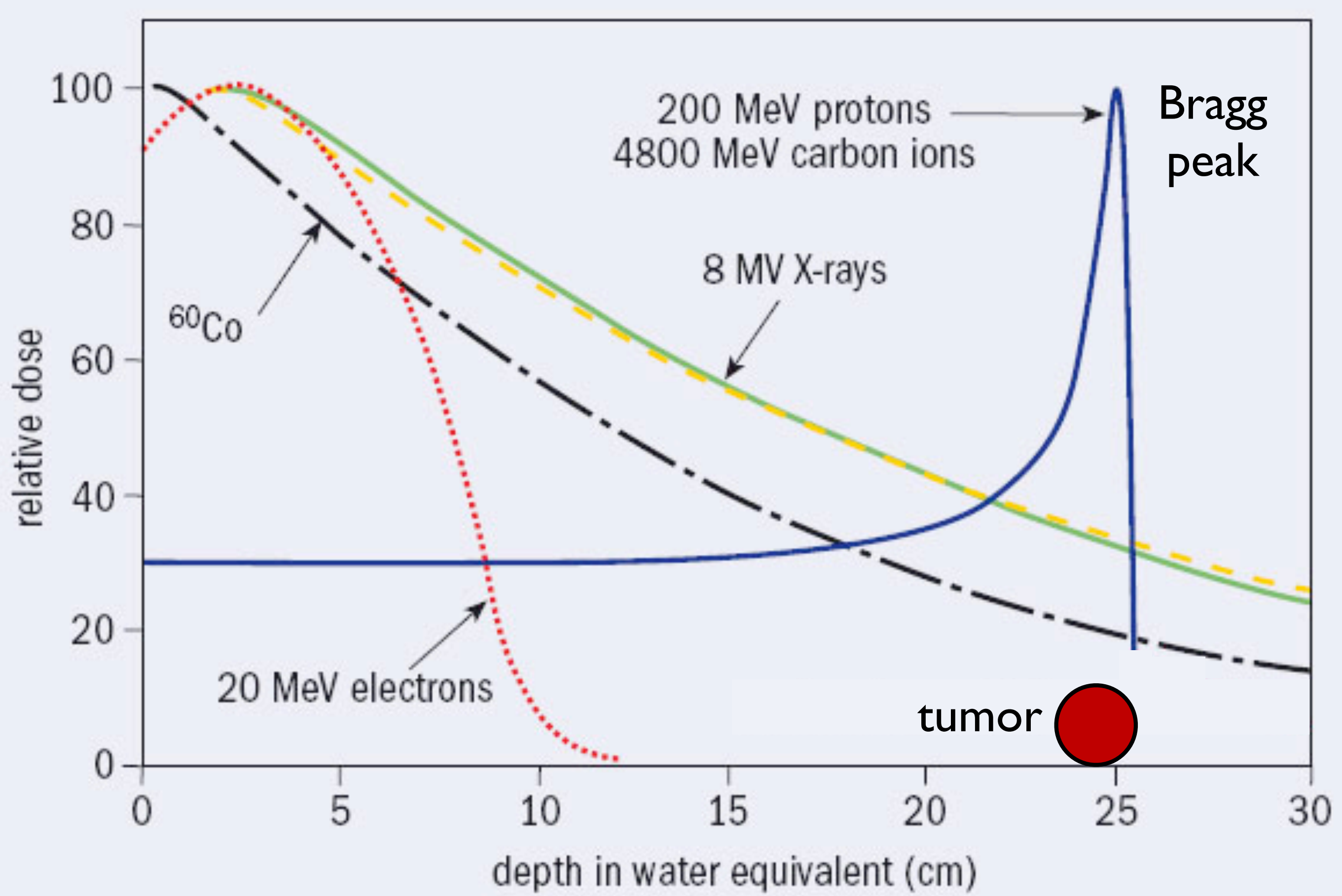
Tumor therapy

Quest is driven by medical applications

Ion beams can have a localized energy deposition in deep-seated tumors

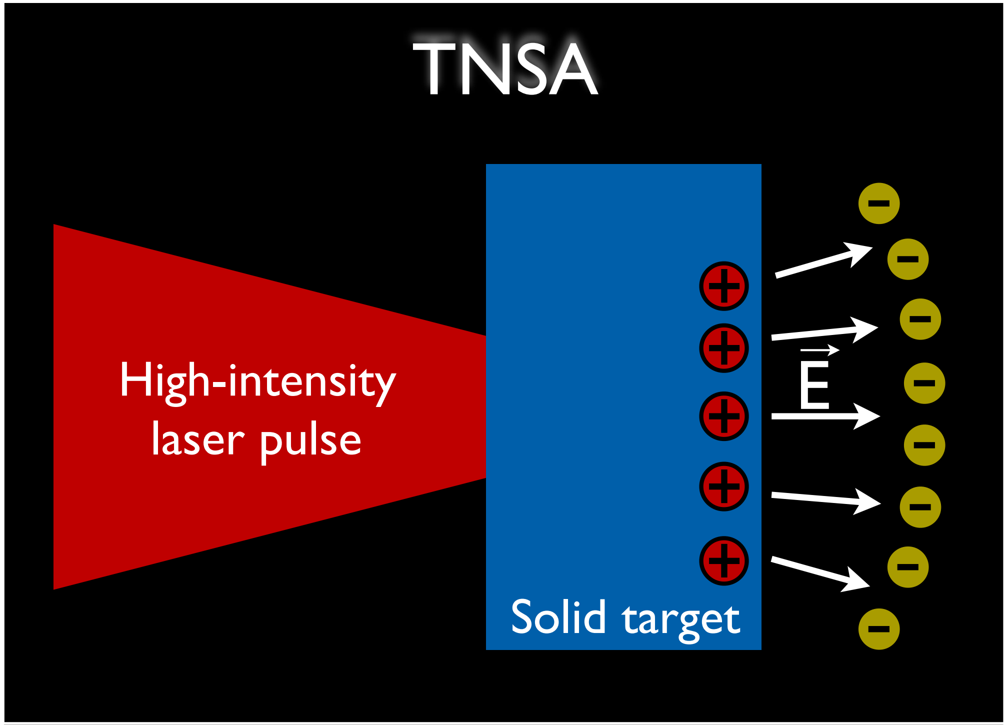


© UniversitätsKlinikum Heidelberg



© CERN Courier, 2006

The quest for high-quality mono-energetic proton beams

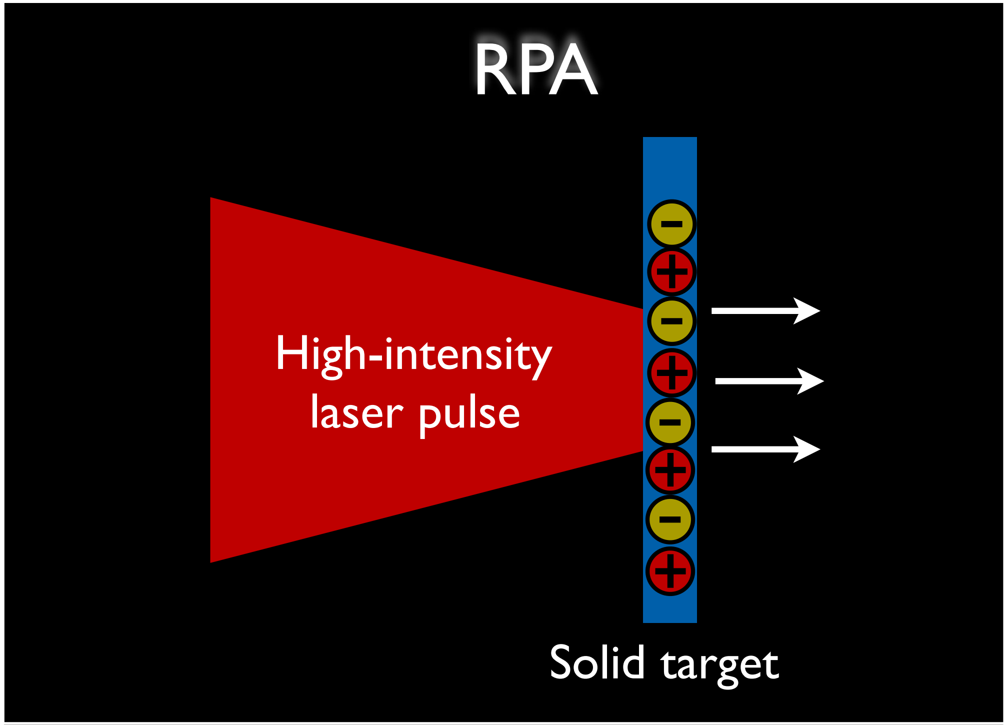


Cold solid target

Linear polarization

Continuum spectrum

Max. proton energy ~ 60 MeV



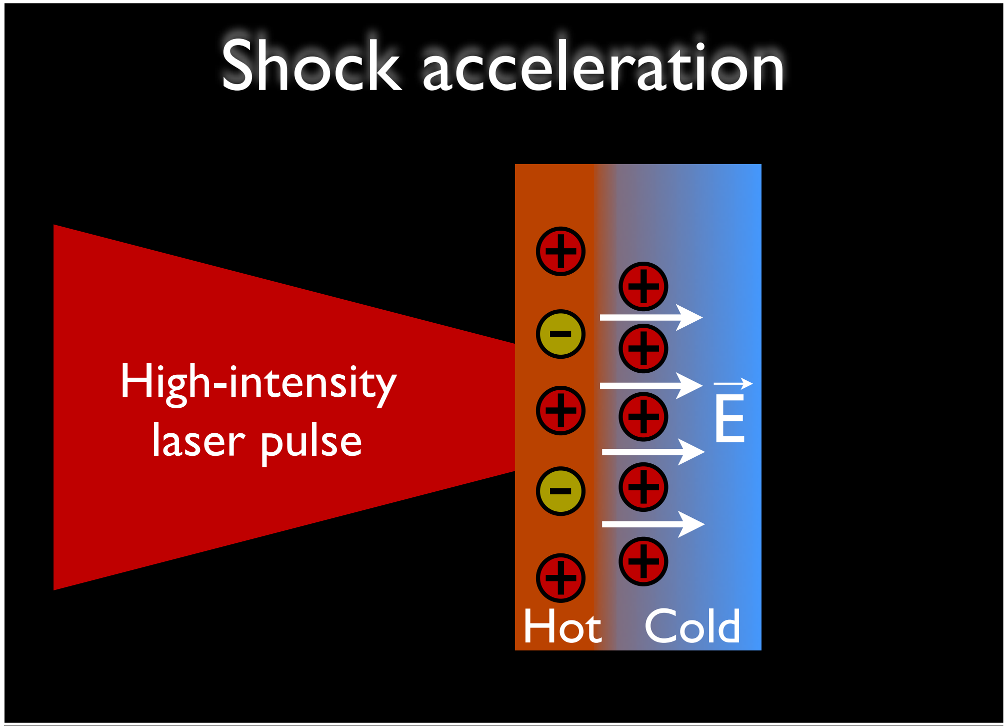
Cold solid target

Circular polarization

High contrast ratio

Mono-energetic spectrum

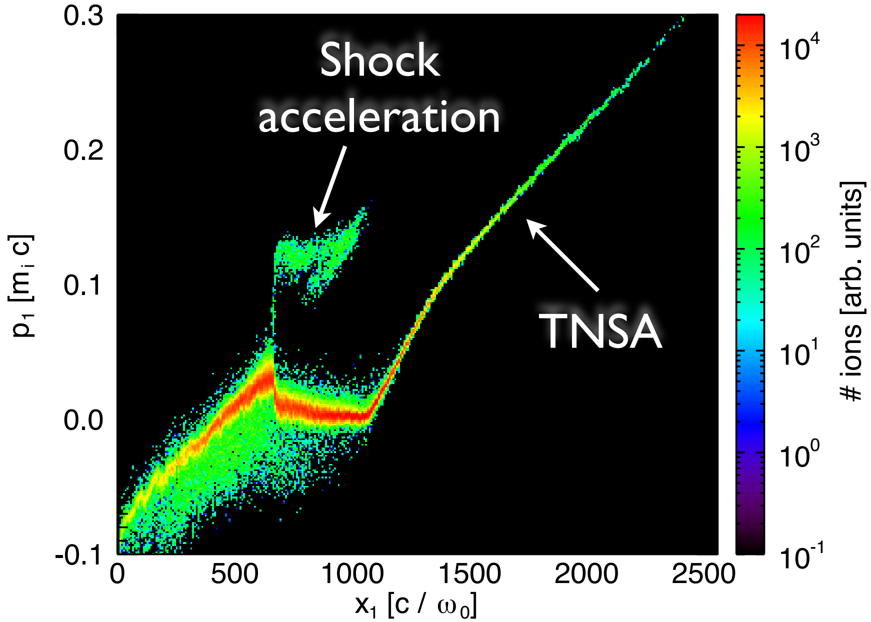
Shock acceleration can potentially lead to mono-energetic beams

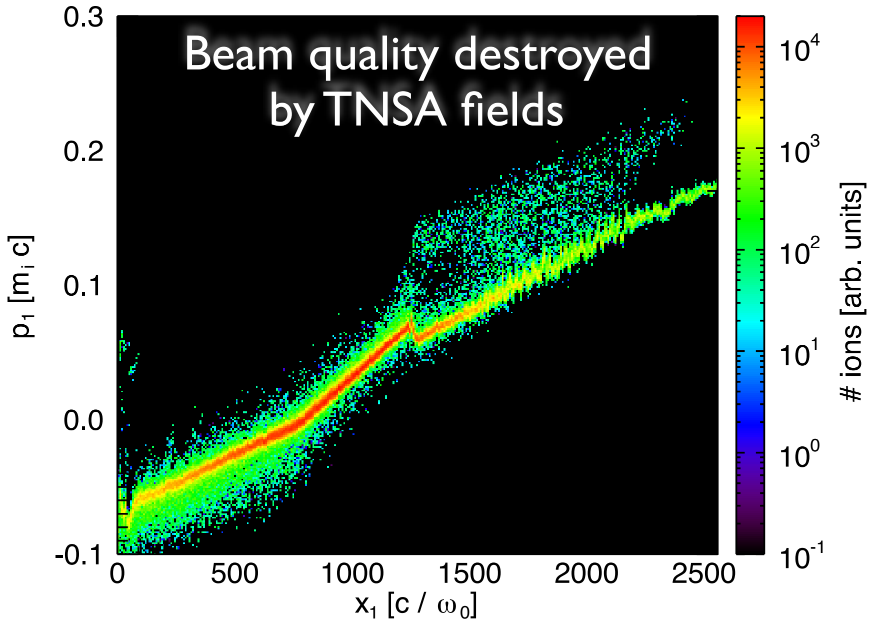


Linear polarization

Strong heating

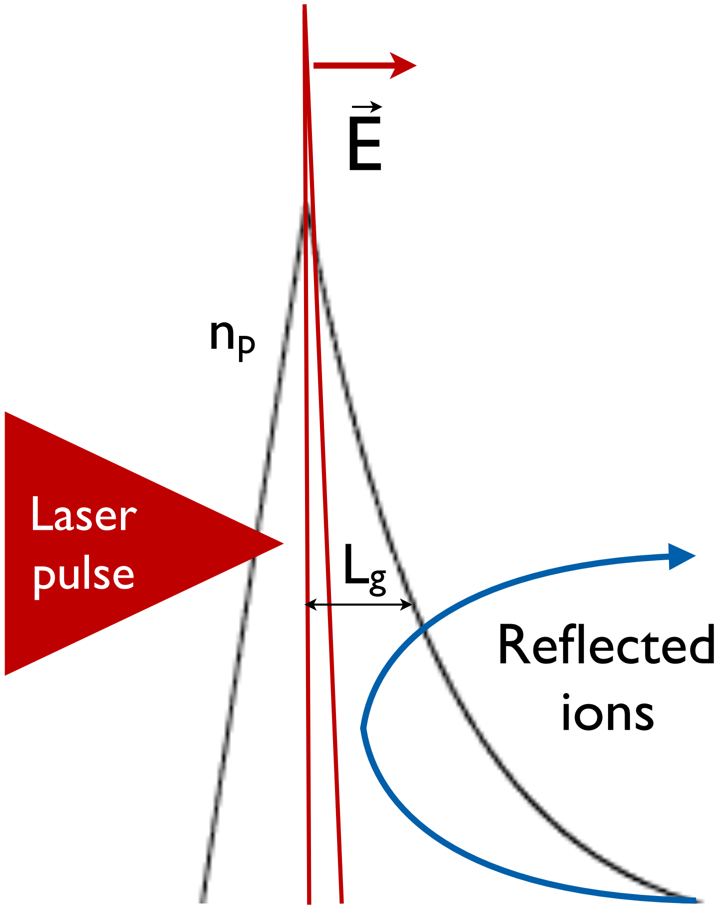
Mono-energetic spectrum?





J. Denavit PRL 69, 3052 (1992)
L. O. Silva et al. PRL 102, 015002 (2004)

n_{cr} targets allow for high-quality shock accelerated beams



Plasma profile

Requirements for high-quality shock acceleration

- High Mach number shocks in different density/temperature plasmas*
- Shock acceleration must dominate over TNSA fields**
- When shock is formed:***

$$v_{sh} > v_{ions} \Rightarrow \quad L_g > \frac{20\pi}{\omega_{pi}} \frac{C_{s0}^2}{v_{sh}}$$

- When shock crosses back of target:

$$v_{sh} > v_{ions} \Rightarrow \quad L_g \ll \frac{v_{sh}}{\omega_{pi}} \left(e^{\frac{v_{sh}}{2C_{s0}}} - 20\pi \right)$$

- For optimal absorption ($n_p \sim n_c$), optimal thickness $L_g \sim 20\ l_0$

Near n_{cr} targets are optimal

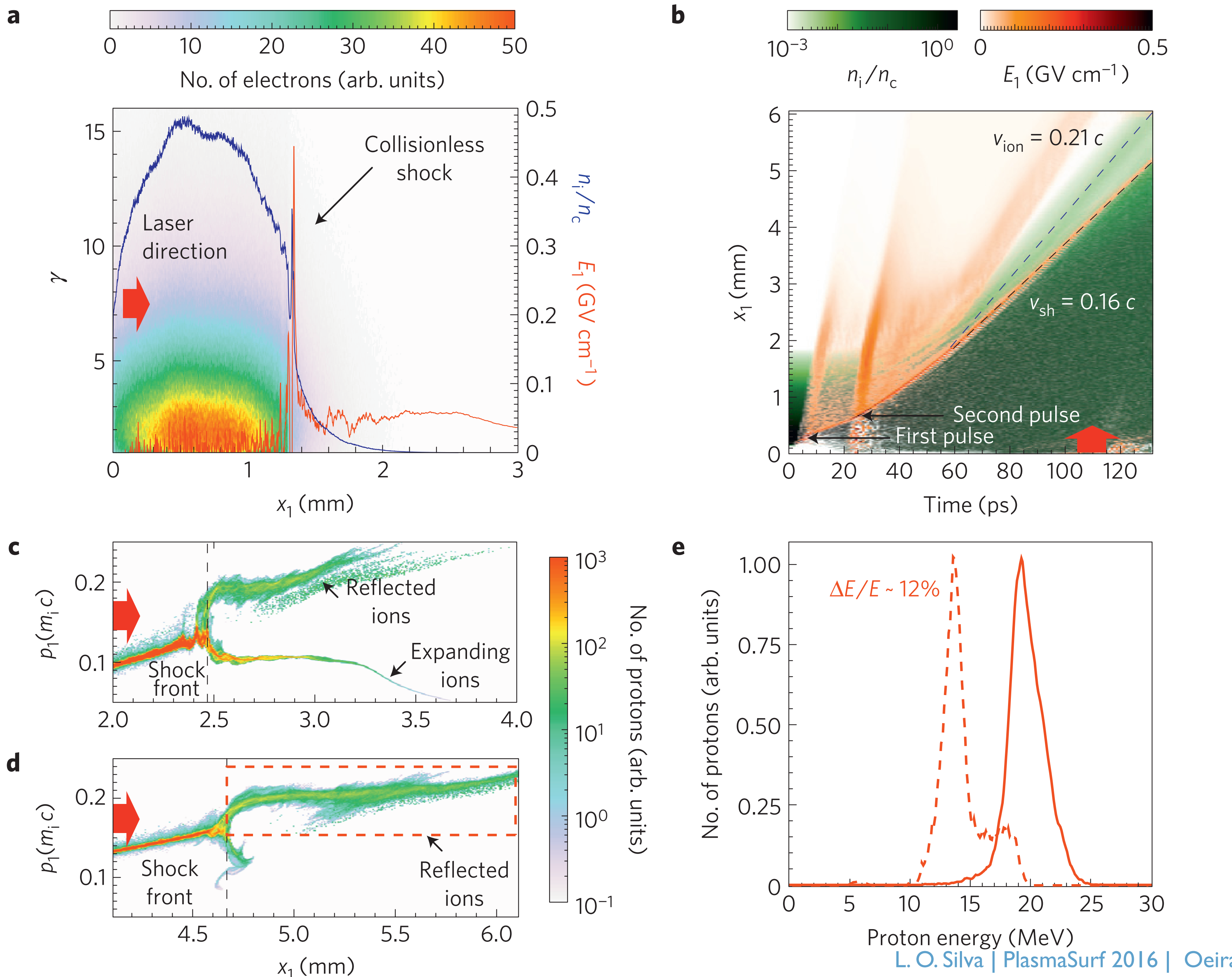
CO_2 lasers in mm scale gas jet targets (n_c) at high repetition rates

* G. Sorasio et al. PRL 2006

** T. Grismayer & P. Mora Phys. Plasmas 2006

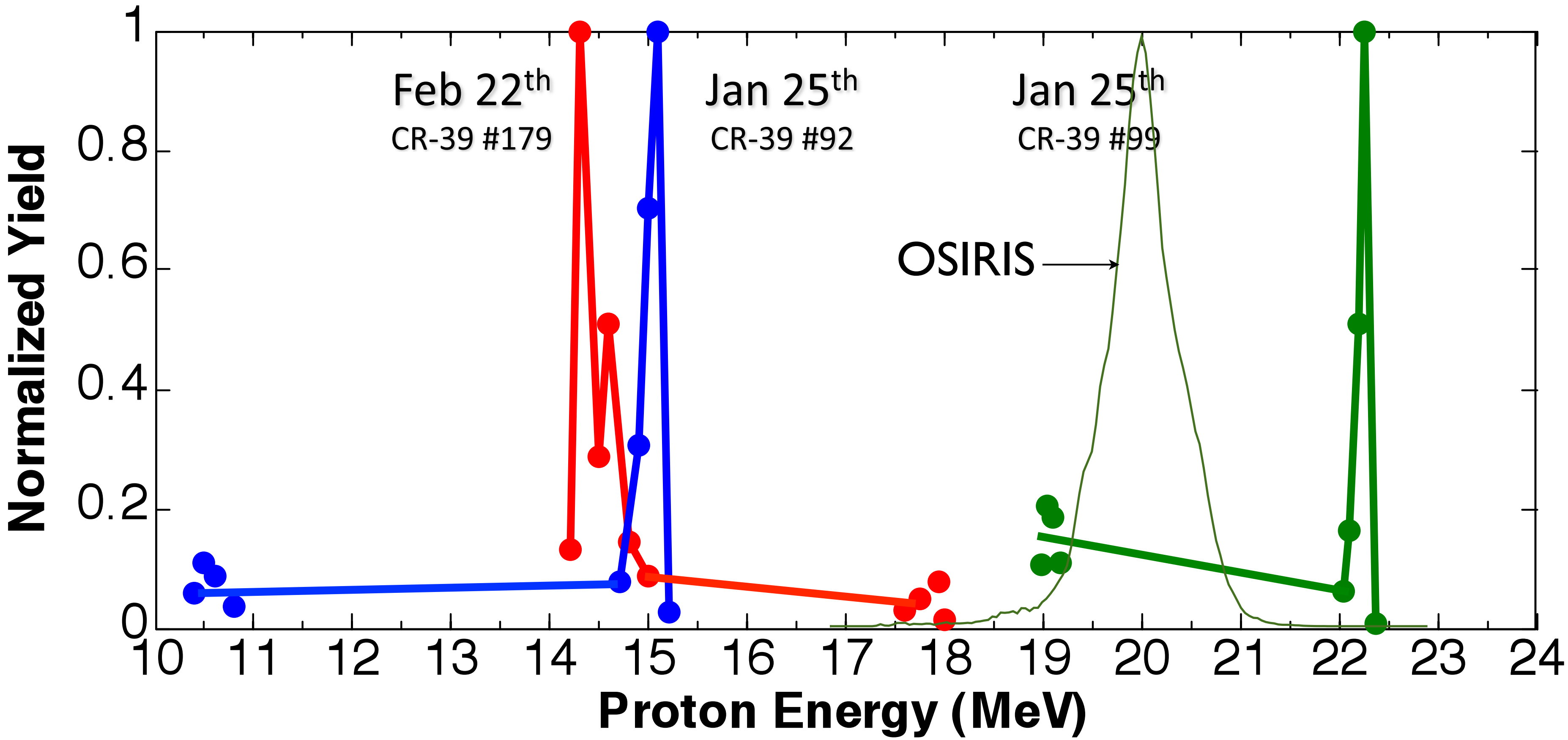
*** shock formation time ~ 20p w_{pi}^{-1} (D.W. Forslund & C. R. Shonk PRL 1970)

Interplay between shock acceleration and TNSA is critical



Monoenergetic proton beams with unprecedented energies

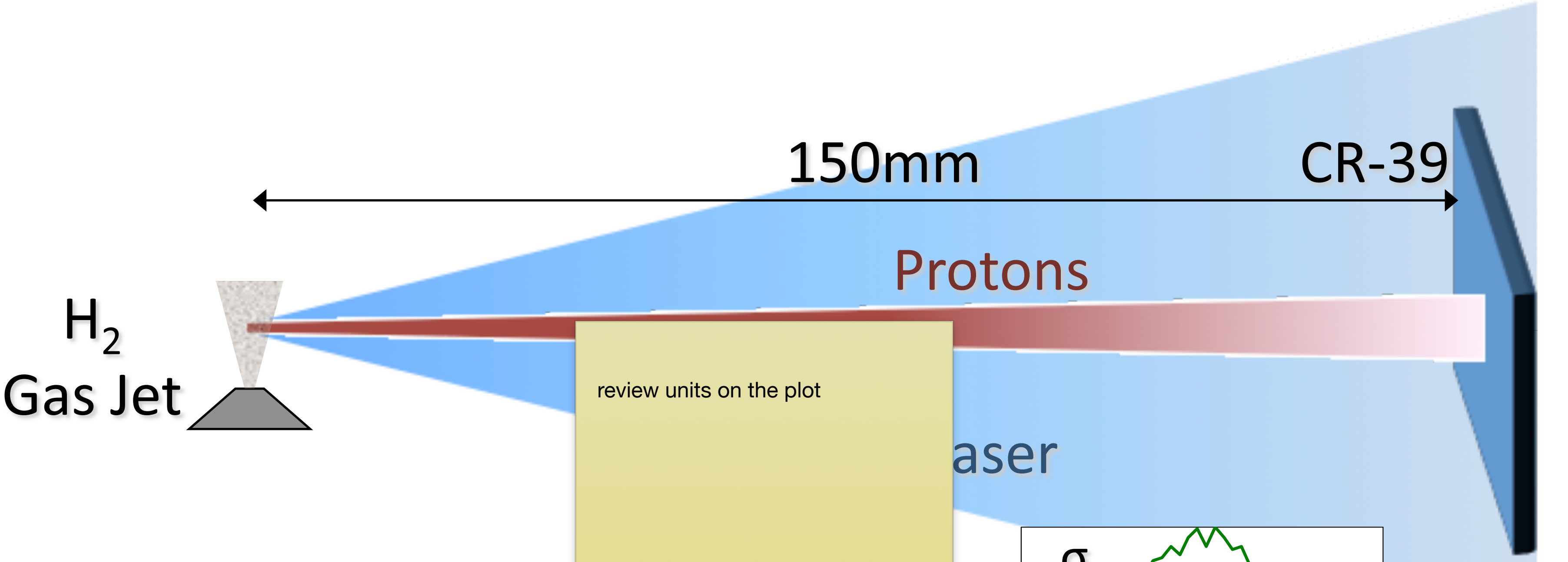
Energy spreads measured to be FWHM ΔE/E ~1%

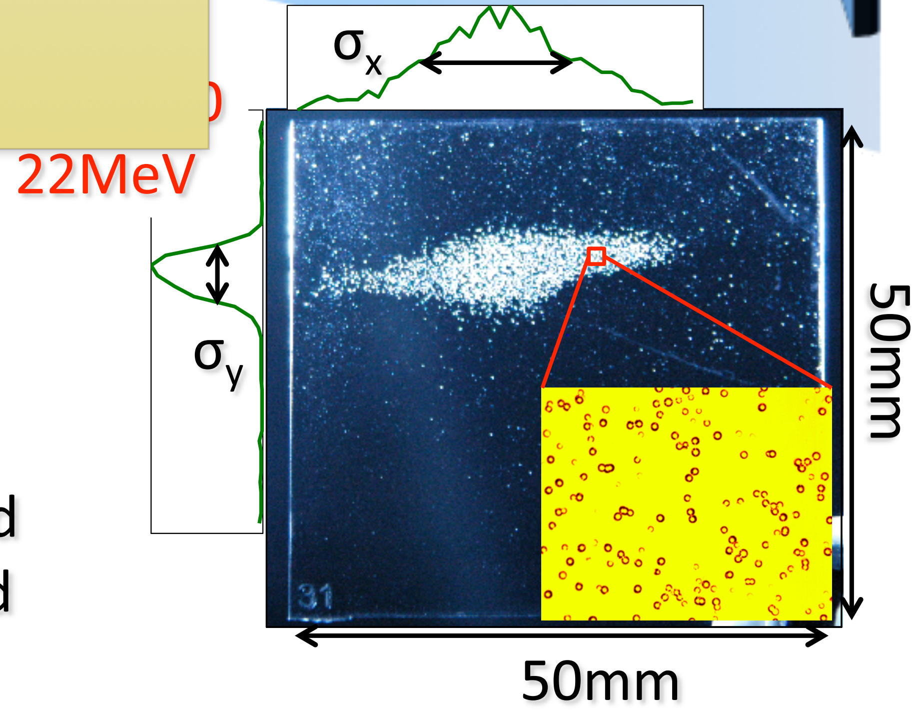


Previously 1 MeV, rms ΔE/E ~ 4% had been measured (C. Palmer PRL 2011)

D. Haberberger et al., Nature Physics, January 2012

Low beam emittance has been measured





Source Size : d = 120µm

Beam Size (RMS) : σ_x ~ 5.7mm

σ_y ~ 2.2mm

Divergence : θ_x ~ 37mrad

θ_y ~ 14mrad

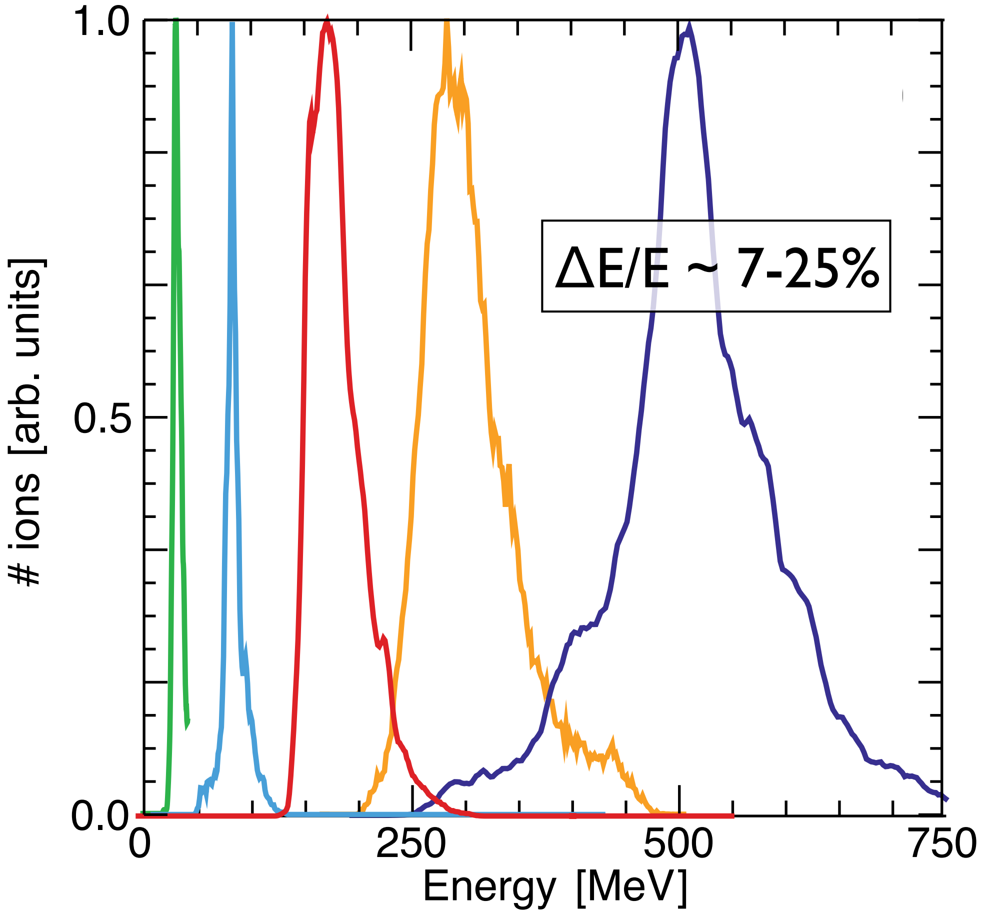
Emittance : $\varepsilon_x = d \cdot \theta_x$ = 4.6mm·mrad

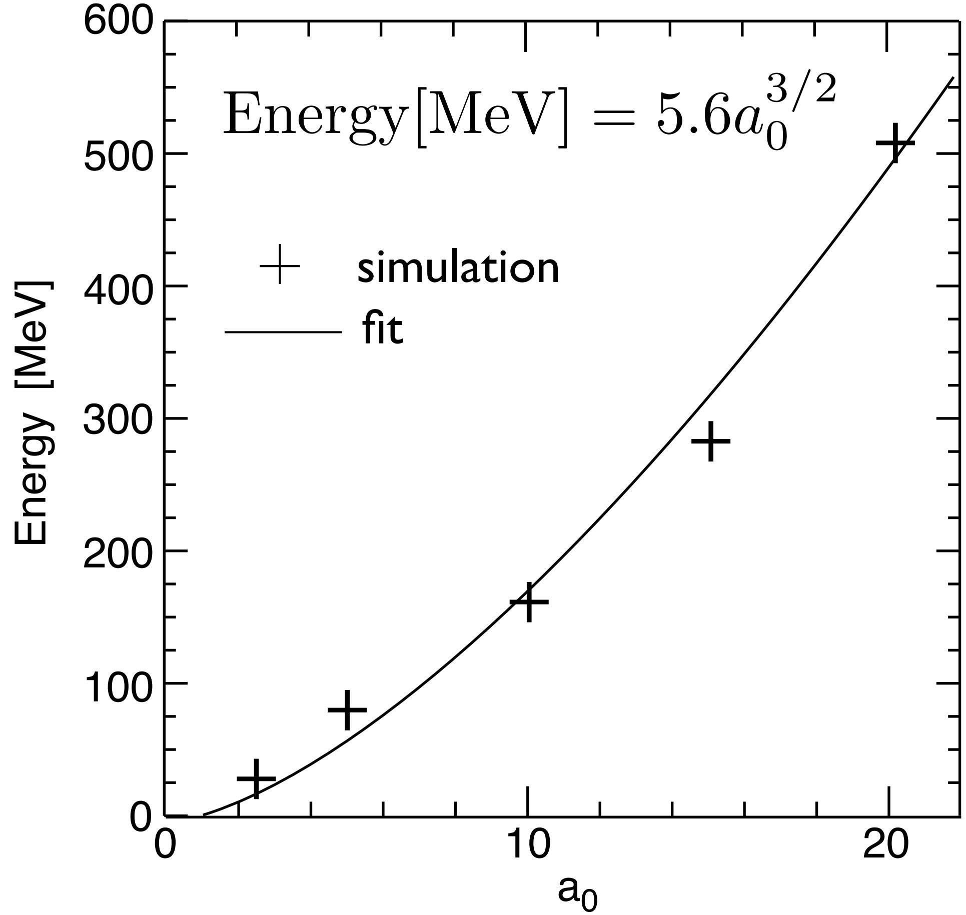
$\varepsilon_y = d \cdot \theta_y$ = 1.7mm·mrad

D. Haberberger et al., Nature Physics, January 2012

Shock acceleration is extensible to ultrahigh energies

Favorable scaling provides proton beams for medical applications (200 MeV) with readily available lasers (a0 ~ 10)





F. Fiuza et al., to appear PRL (2012); arXiv:1206.2903

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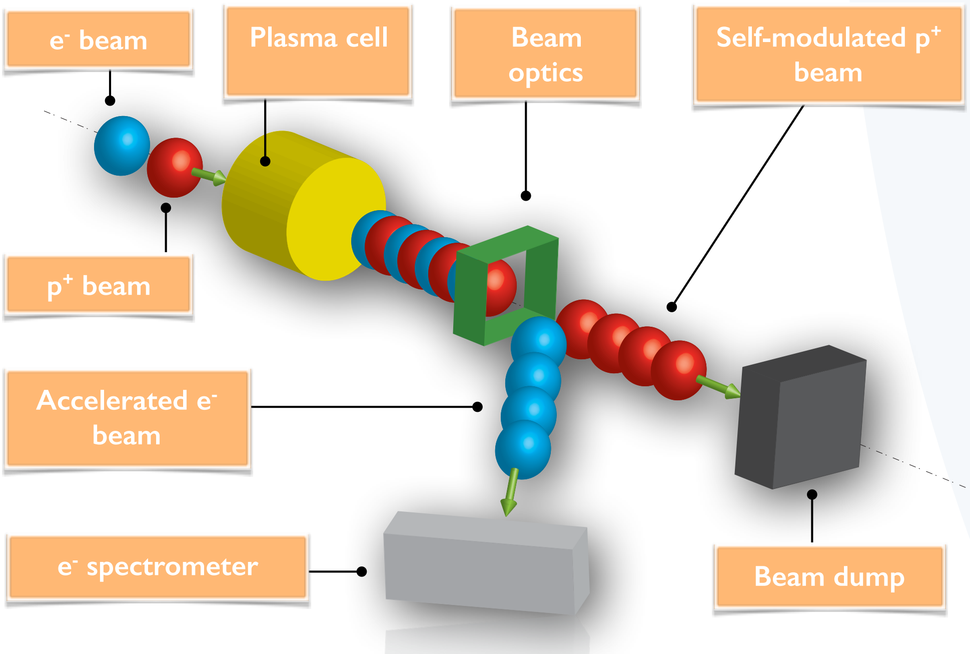
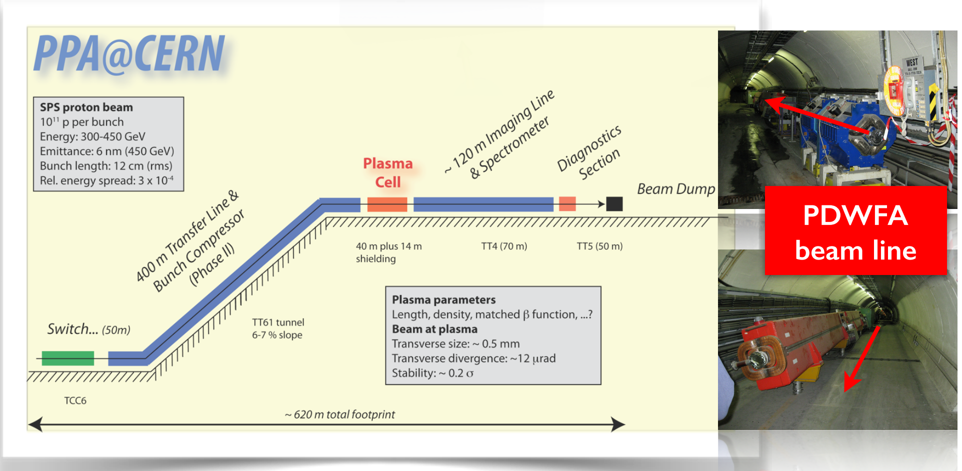
Proton driven wakefield accelerator @ CERN

AWAKE

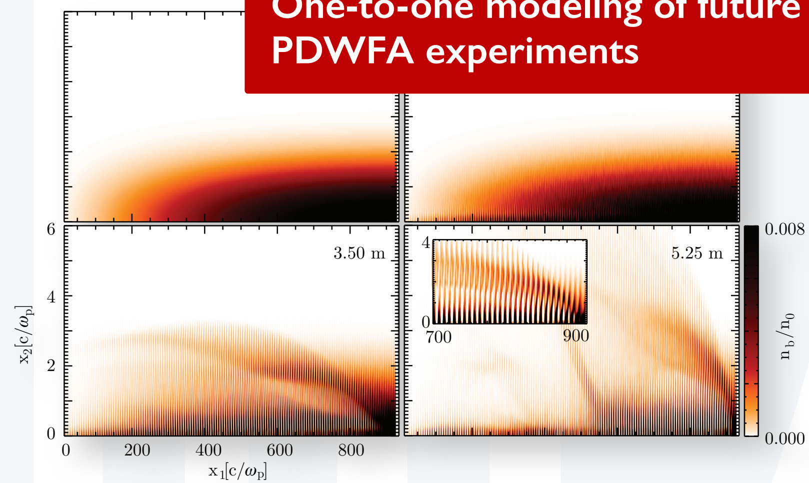
Experimental concept

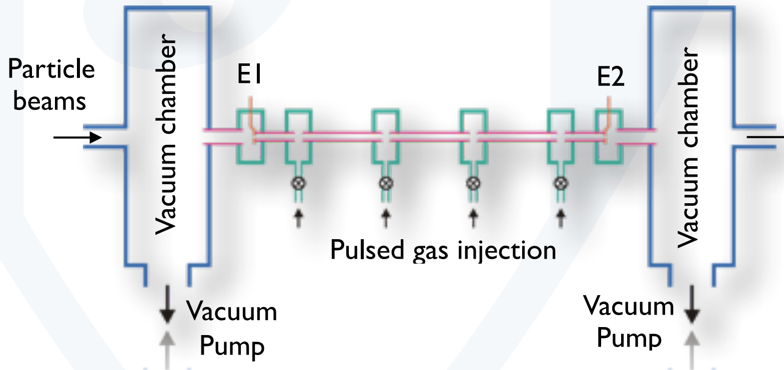




IST participation

One-to-one modeling of future PDWFA experiments





High voltage tunable density 10 m long plasma discharge

CERN, DESY, MPI, UCLA, USC, BNL, TH, D, IST, UCL, IC, IPP, RAL

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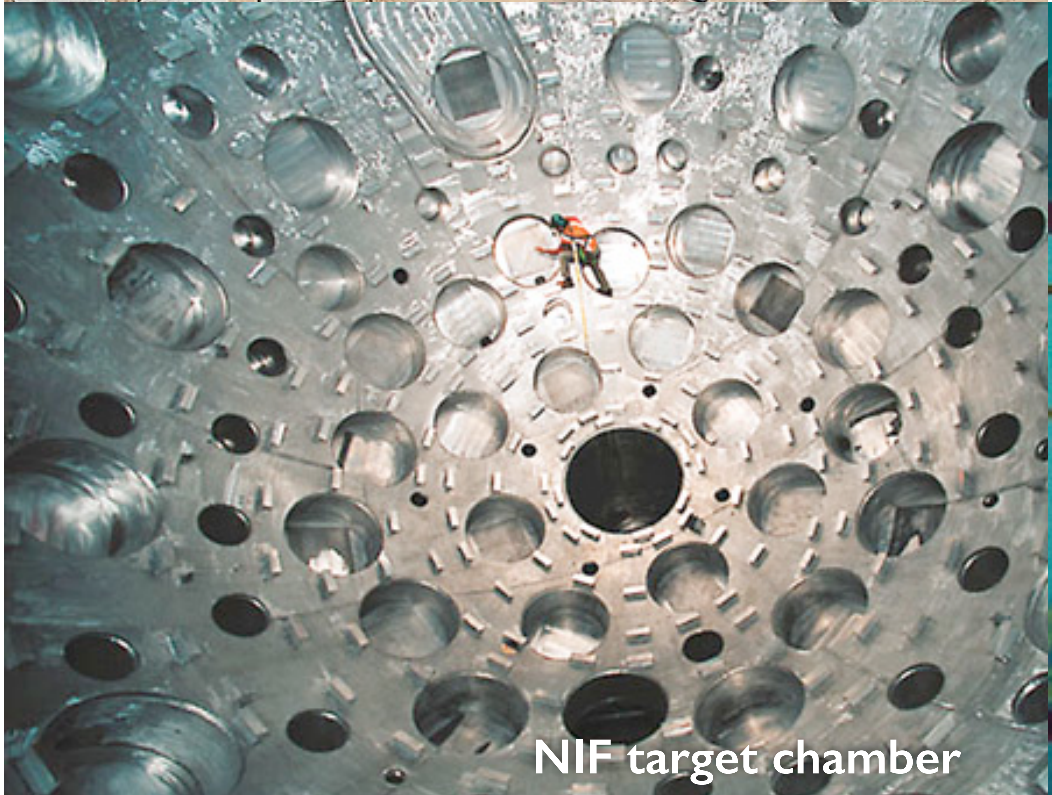
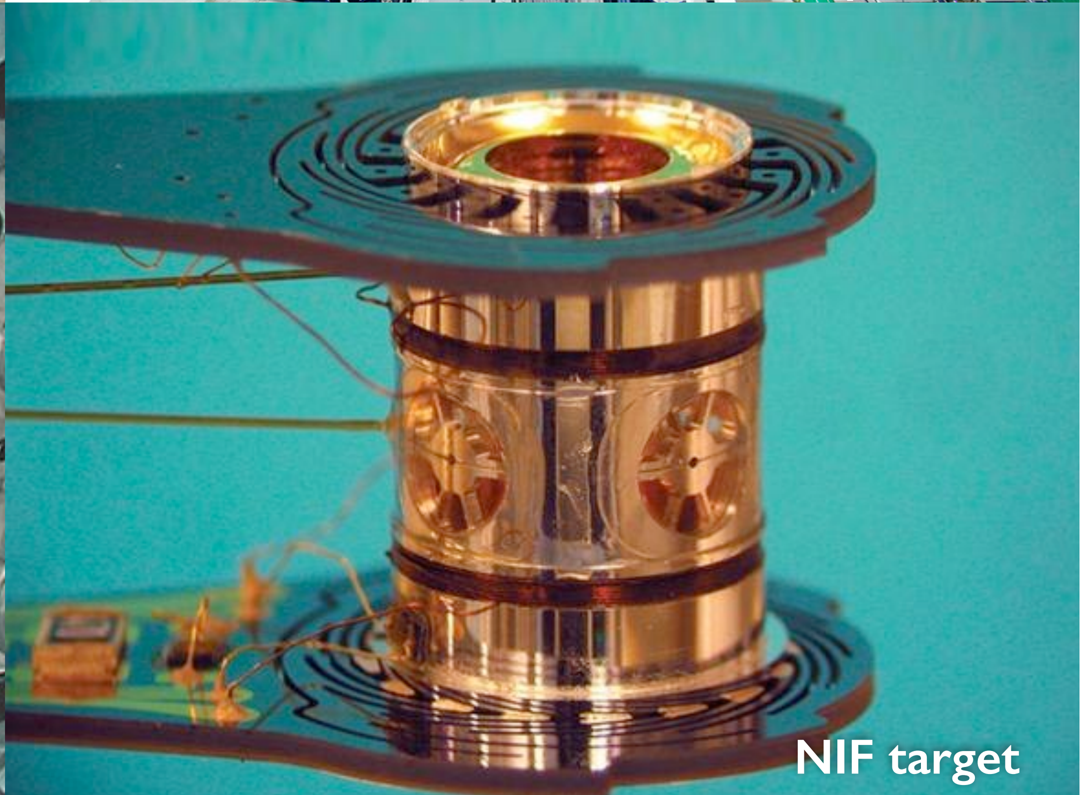
Nuclear fusion with lasers @ NIF

NIF building @ LLNL

NIF laser amplifiers

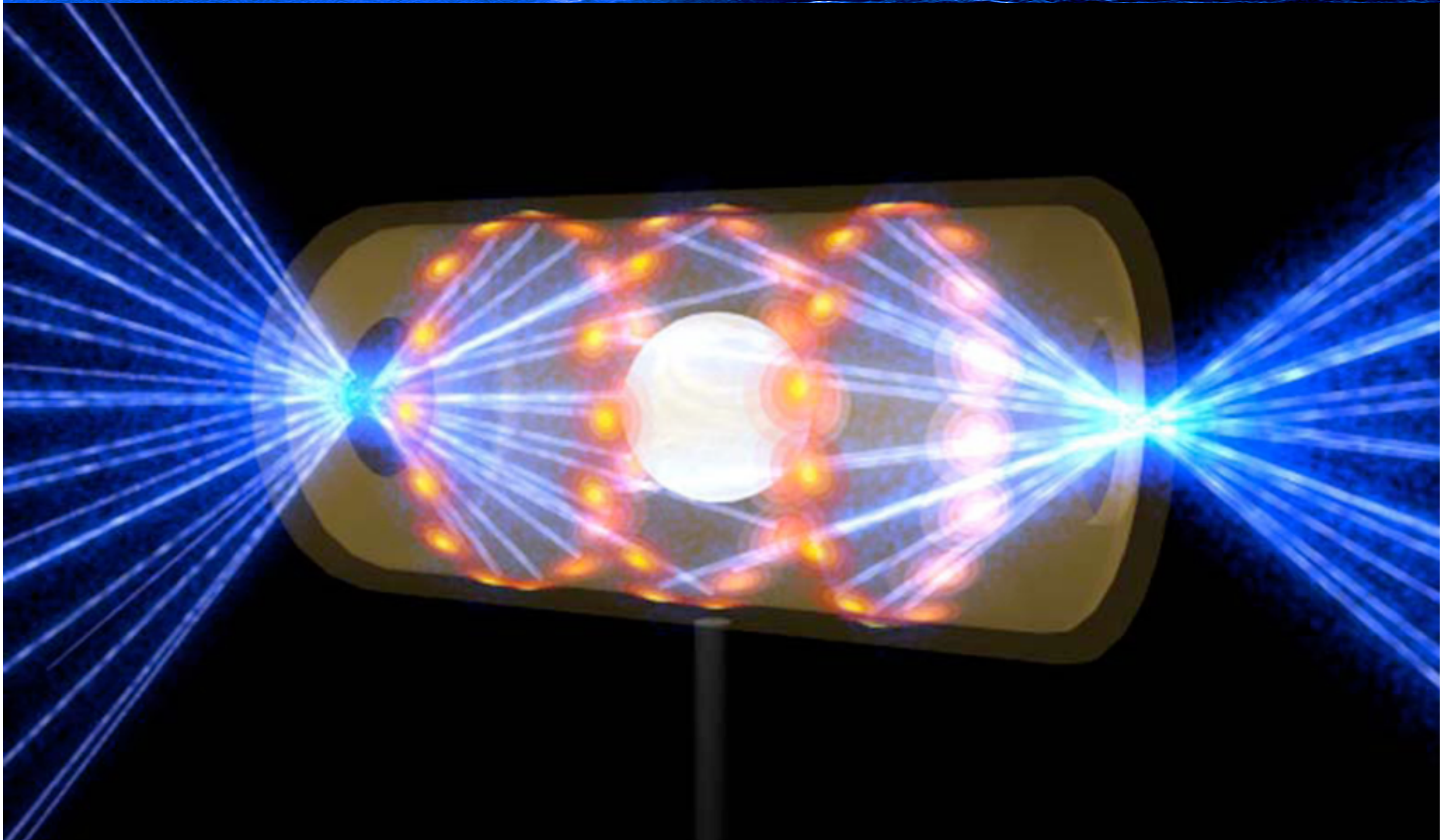


NIF target chamber



NIF target

Indirect drive nuclear fusion

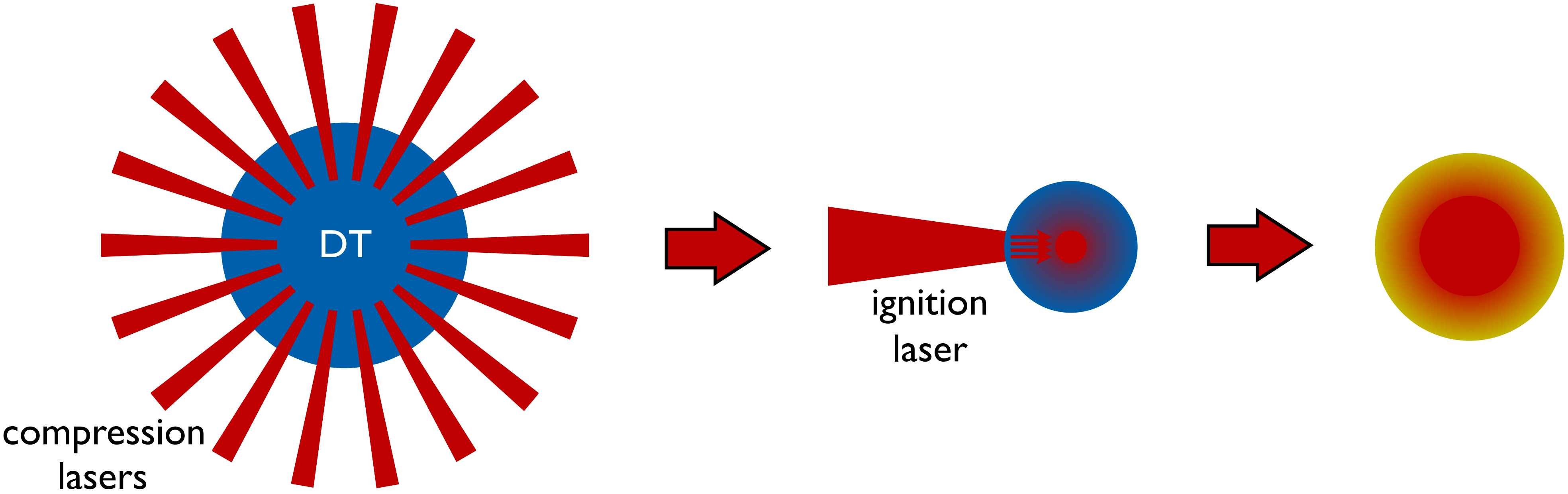


National Ignition Facility
Target (~ 1 cm long)

Advanced concepts: fast ignition concept*

Compression

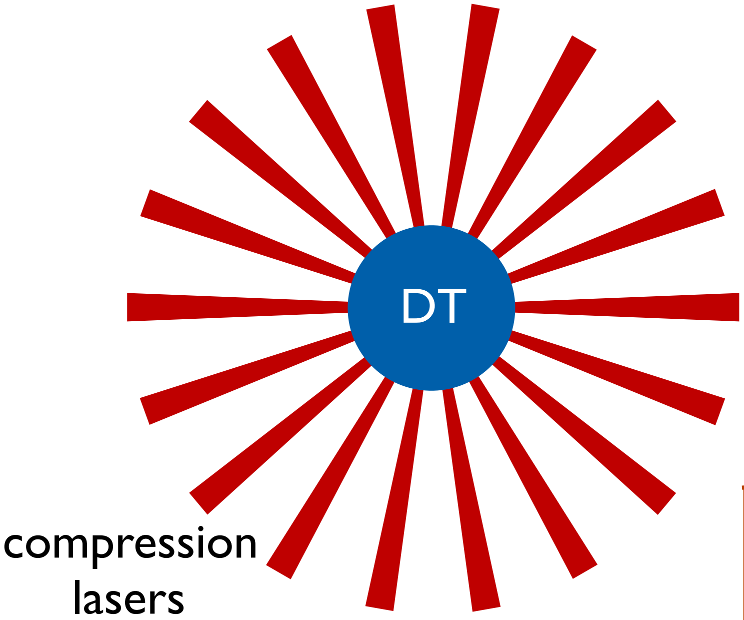
Ignition

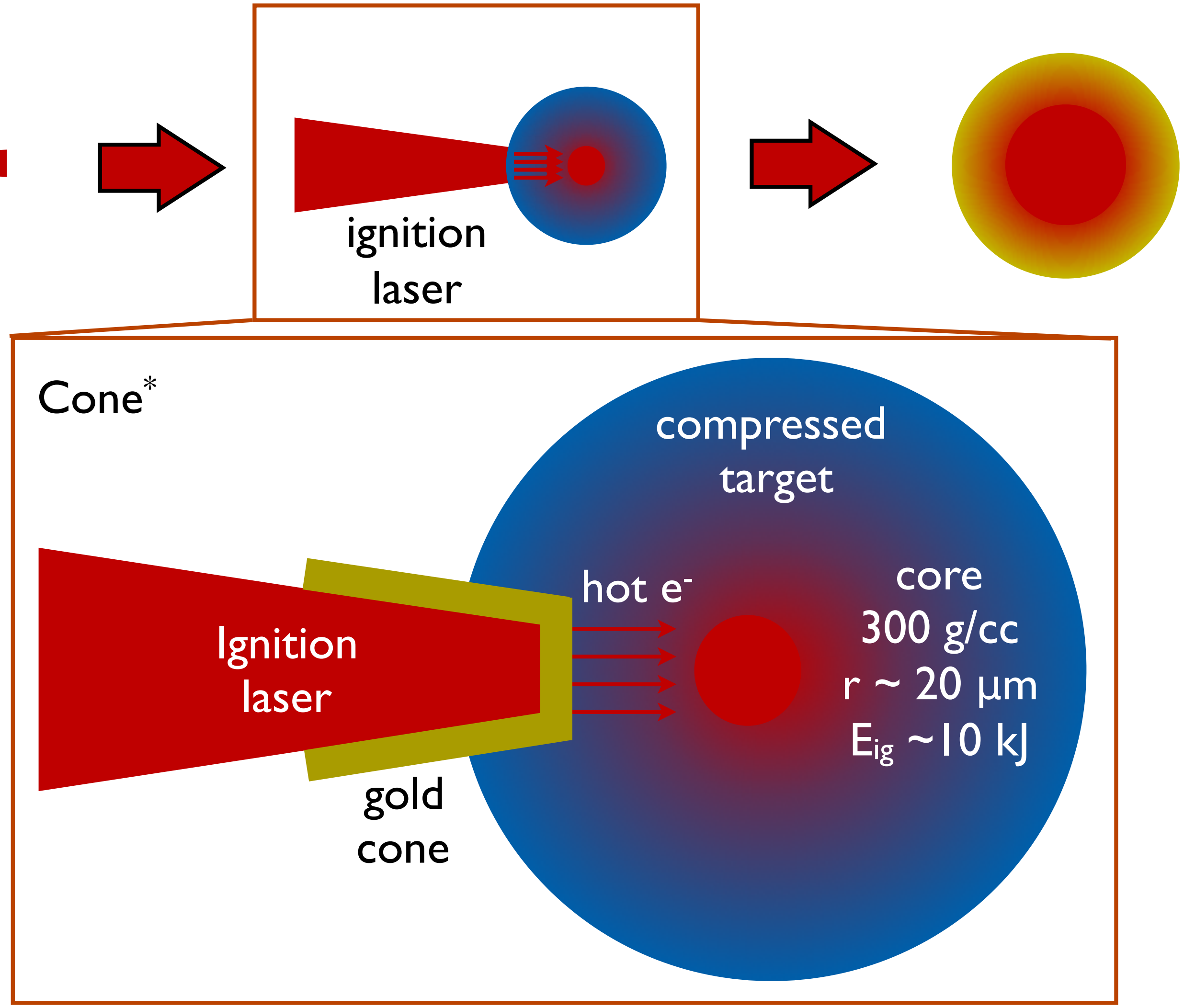


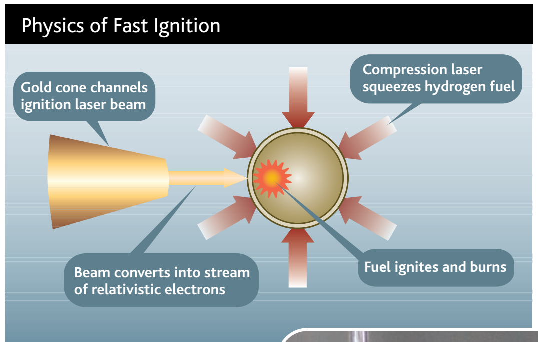
* M. Tabak et al., Phys. Plasmas **1**, 1626 (1994)

The fast ignition concept

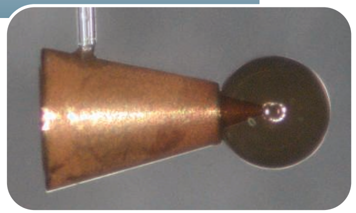
Ignition





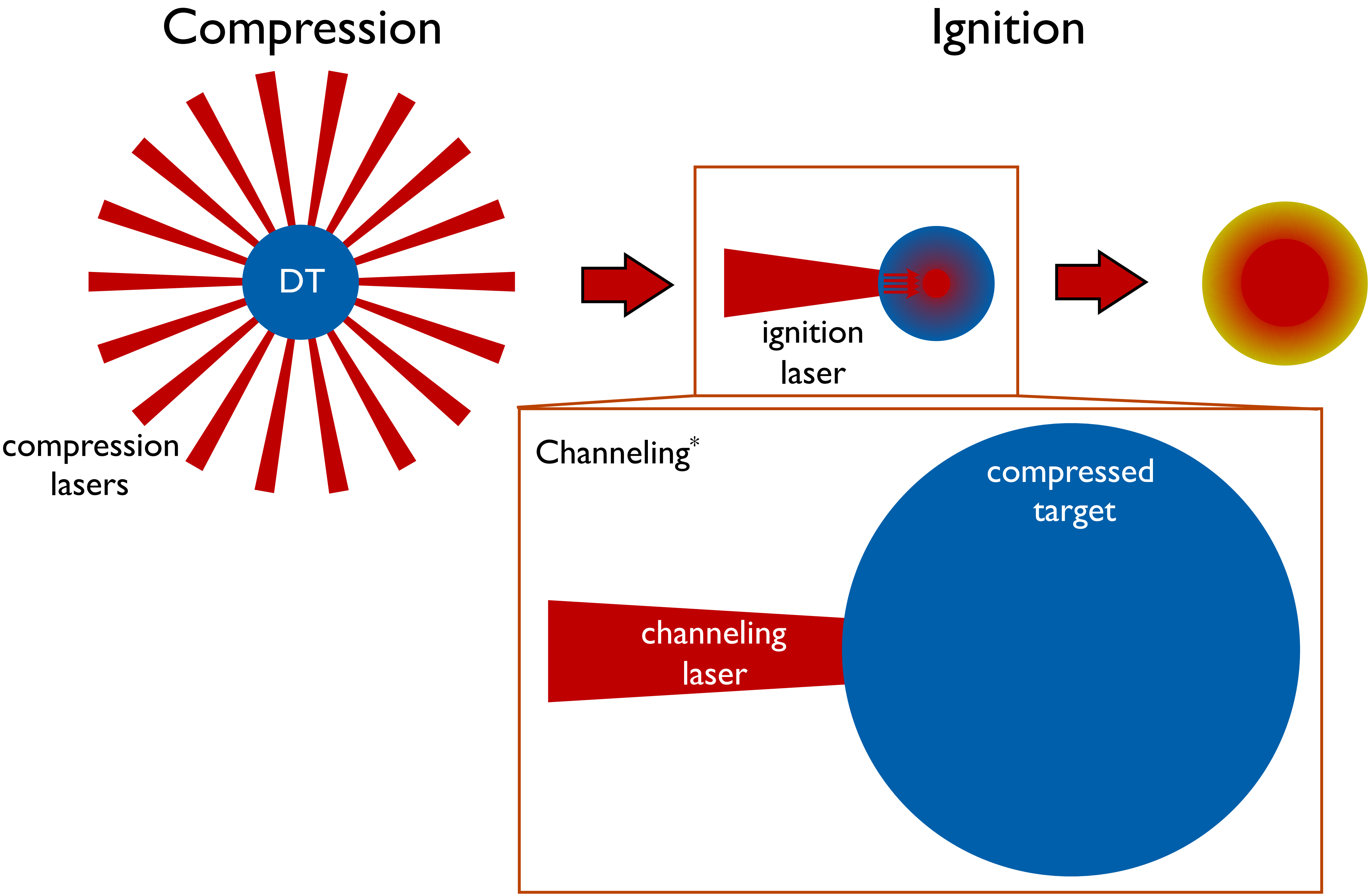


"Foolish" geometry. A gold cone is key in getting sufficient laser power into the capsule of hydrogen and igniting fusion.



* R. Kodama et al., Nature **412**, 798 (2001); R. Kodama et al., Nature **432**, 1005 (2004)

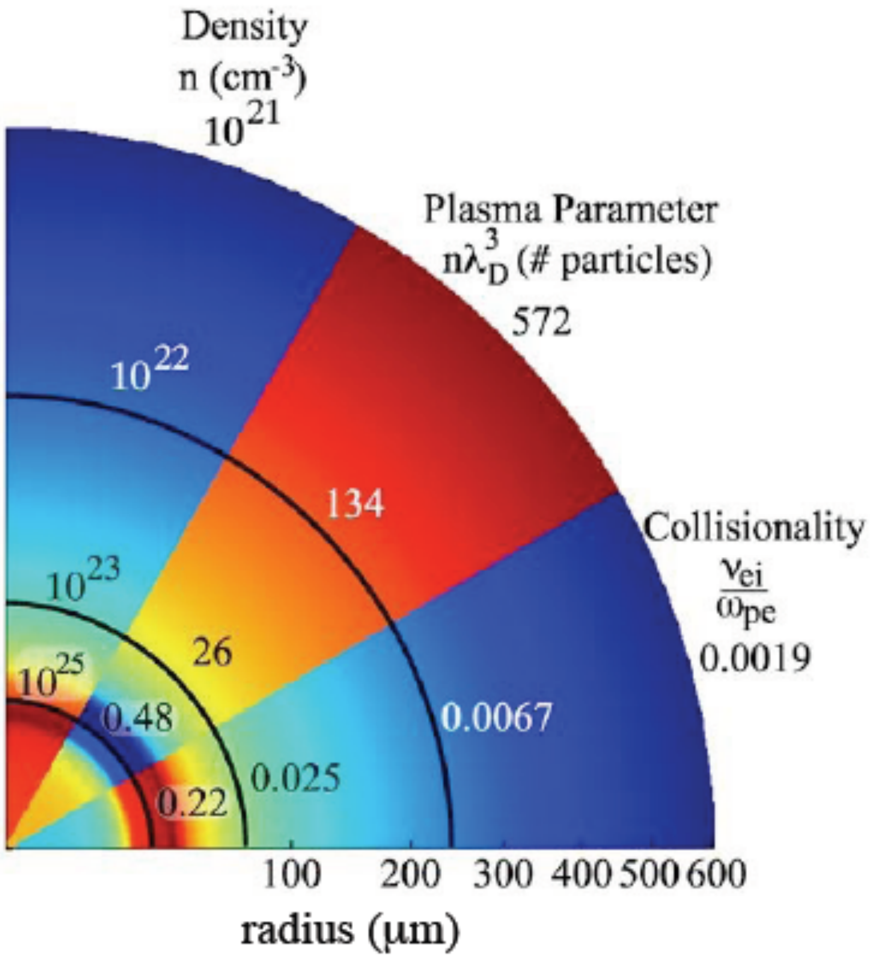
The fast ignition concept

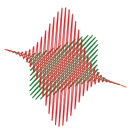


* G. Li et al., Phys. Rev. Lett. **100**, 125002 (2008)

Modeling is extremely demanding due to different scales involved

Typical HED compressed target





Laser duration = 10 ps - 10 ns

Computational requirements for PIC

Physical size

Box size: 1 mm
Cell size: 5 Å
Duration: 10 ps
Time step: 1 as (10^{-18} s)

Numerical size

\# cells/dim: 2×10^6
\# particles/cell: 100 (1D); 10 (2D); 1 (3D)
\# time steps: 10^6

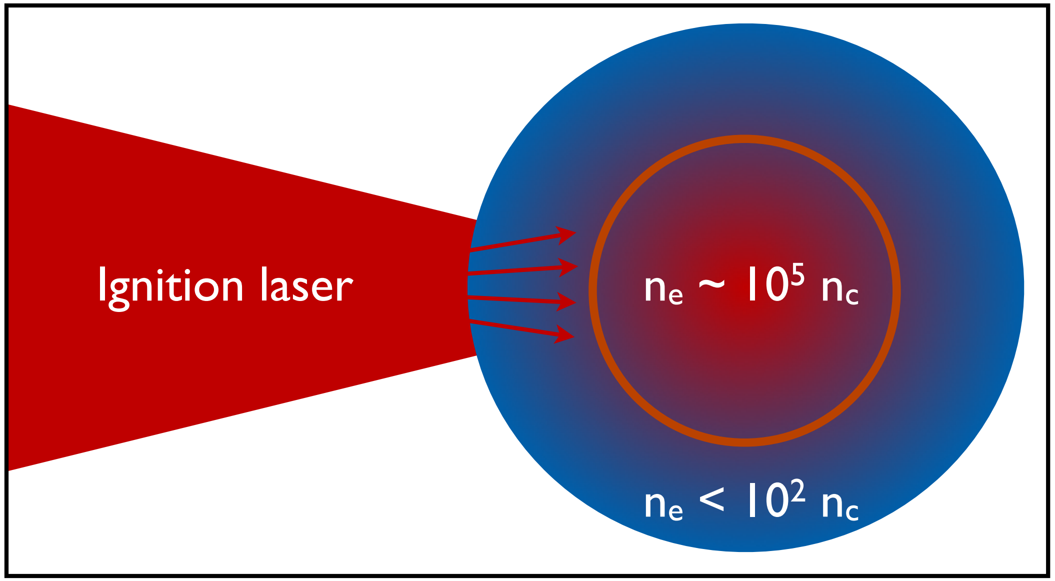
Particle push time: 1 ms

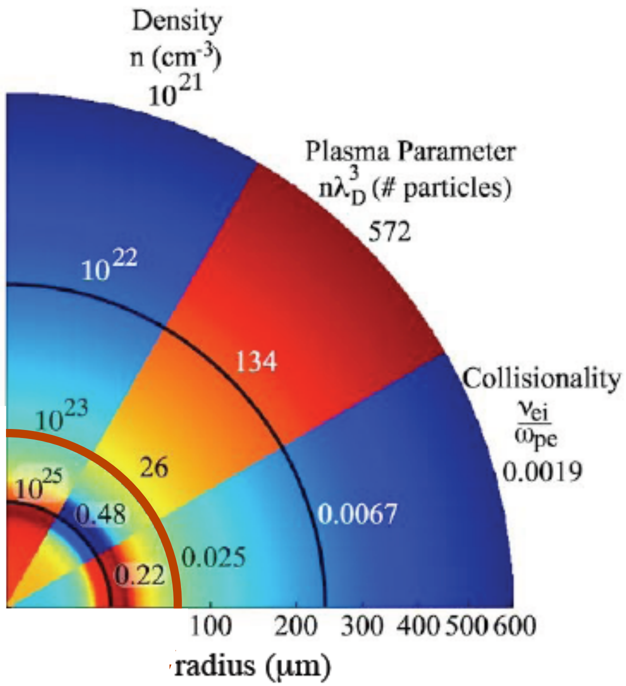
Computational time

1D - 2×10^3 CPU days
2D - 5×10^8 CPU days ~ 10^6 CPU years
3D - 2×10^{11} CPU days ~ 7×10^8 CPU years

F. Fiúza *et al*

New hybrid-PIC algorithm for HEDP modeling*





Full-PIC code
• Full Maxwell's equations
• Kinetic species
• $n_0 < 10^{23}$ cm^{-3}
• $\omega_p \Delta t < O(1)$
• $\Delta x \omega_p / c < O(1)$
• $c\Delta t/\Delta x < 1$

If resistivity (Ohm's law) matches collisional model transition is natural and self-consistent

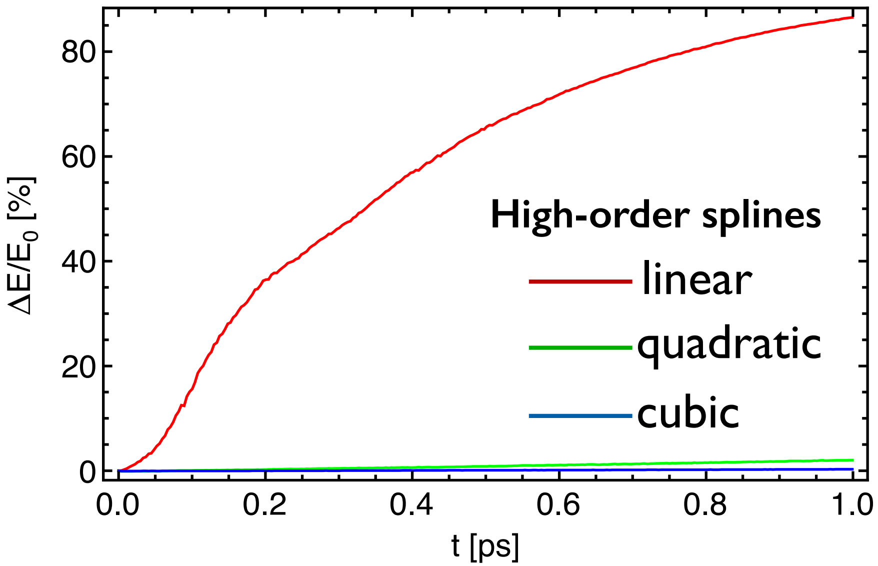
Hybrid-PIC code
• Maxwell's equations + Ohm's law (inertialess)
• Kinetic species
• $n_0 > 10^{23}$ cm^{-3}
• $\nu_{ei} \Delta t < O(1)$
• $c\Delta t/\Delta x < 1$

* B. Cohen, A. Kemp, L. Divol, JCP 229, 4591 (2010)

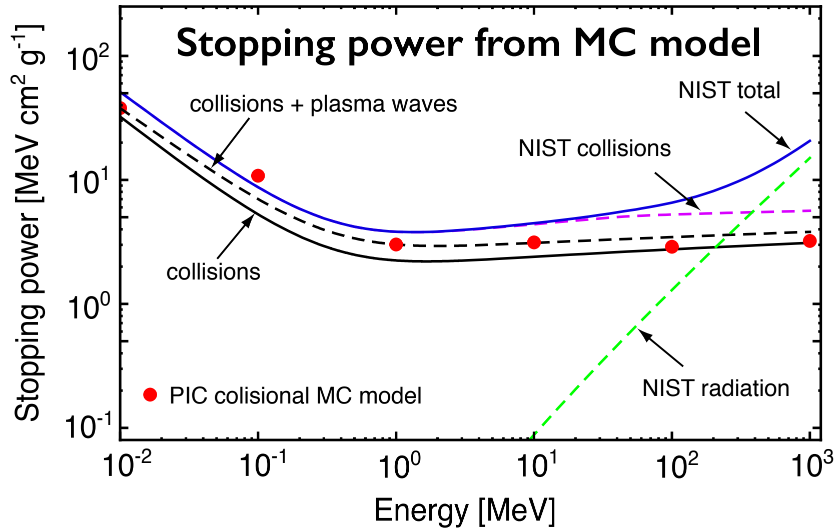
Accurate hybrid-PIC transition requires careful numerics

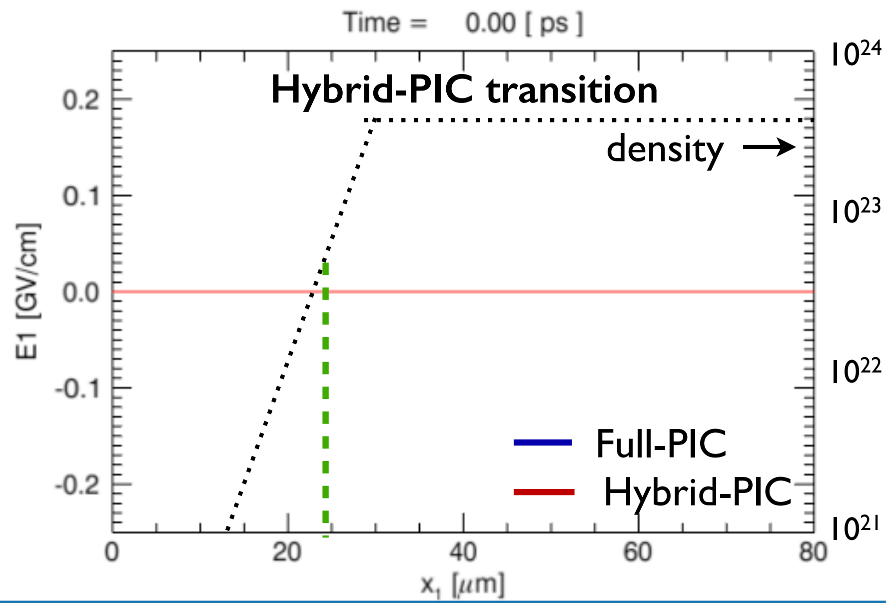
Advanced numerical techniques

- High-order splines
- MC binary Coulomb collisions
- Advanced smoothing
- PML boundary conditions



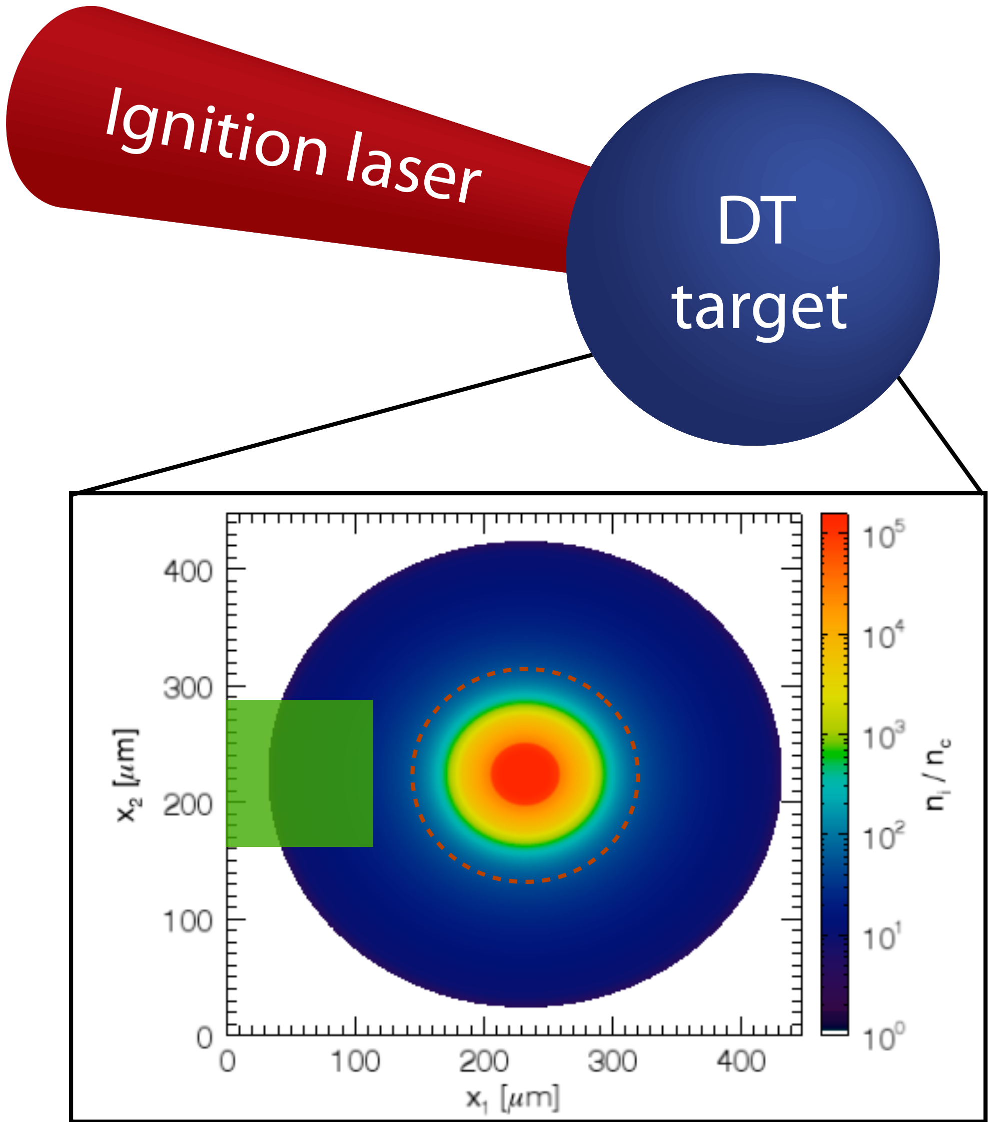
Stable and accurate transition





F. Fiuza *et al.* PPCF 53, 074004 (2011)

First full-scale FI modeling with realistic densities



Previous largest PIC simulations used a 5 kJ 2 ps laser and a 100 μm 100 n_c plasma

Physical Parameters

Laser

- λ_0 = 1 μm
- $I_0 = 2\times10^{20}$ Wcm^{-2} (100 kJ)
- W_0 = 30 μm
- **τ_0 = 15 ps**

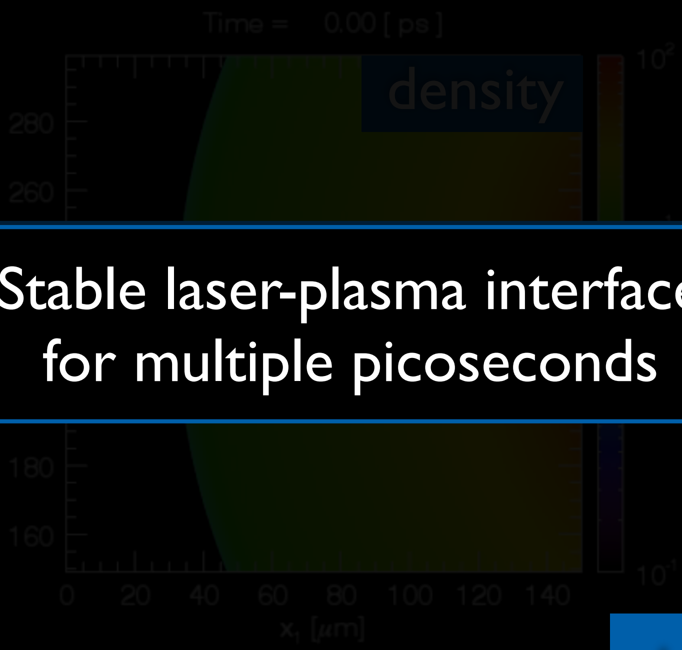
Plasma

- **L = 450 x 450 μm^2**
- **n_{e0} = 1 n_c - 2×10^5 n_c**
- m_i/m_e = 3672

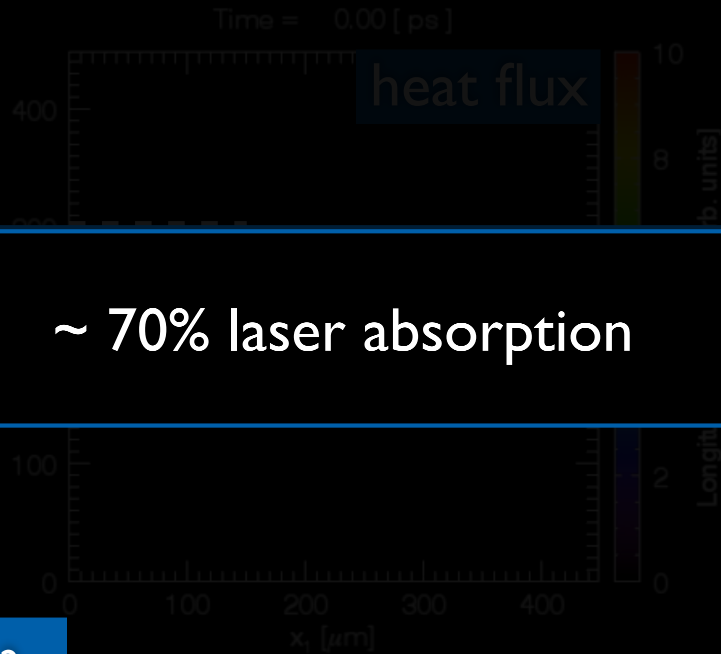
Numerical Parameters

- 42 cells/μm
- hybrid/full-PIC transition = 100 n_c
- Particles per cell = 64
- # time steps = 10^5
- cubic interpolation

First full-scale FI modeling with realistic densities

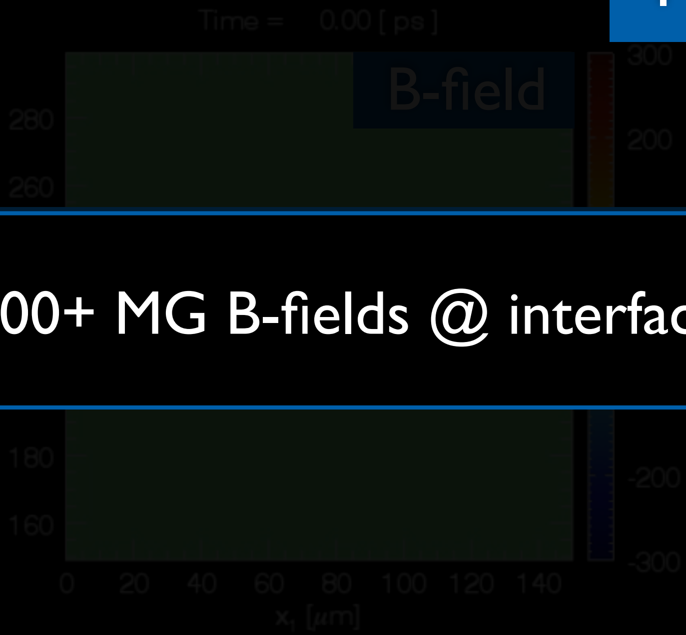


Stable laser-plasma interface for multiple picoseconds

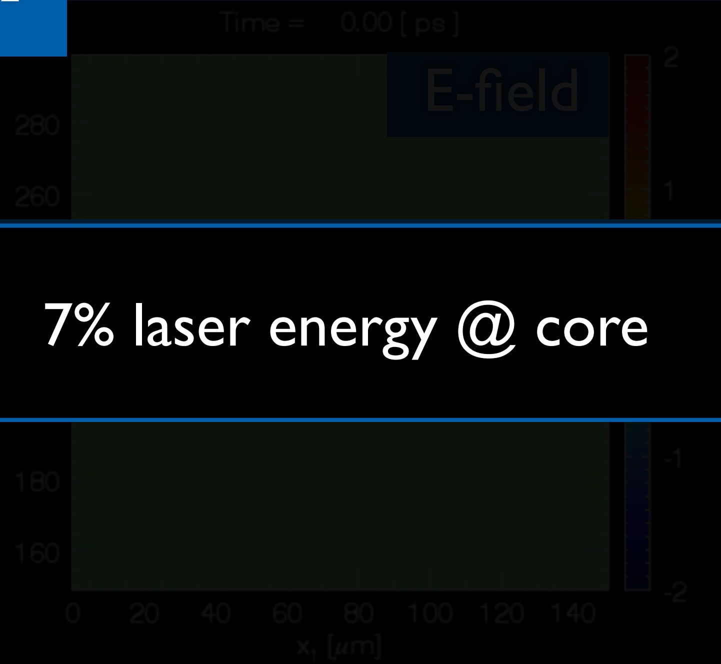


~ 70% laser absorption

I = 2x10^{20} Wcm^{-2}



300+ MG B-fields @ interface



7% laser energy @ core

Contents

Fundamental questions on quantum electrodynamics

The quantum vacuum and pair production with intense fields

QED at ultra high intensities is almost unexplored*

Intensities required to start to probe the quantum vacuum are within reach

Strong debate about this transition:
10^{24} W/cm^2 or 10^{26} W/cm^2

Work done by the electric field over a Compton wavelength > electron rest mass determines the Schwinger field

*Physicists like perturbation theory around small quantities...

Adding radiation reaction force to the PIC loop

osiris v2.0

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L \boxed{+ \mathbf{F}_{rad}}$$ Continuous drag

PARTICLES

Integration of equations of motion: moving particles

$$\mathbf{F}_p \rightarrow \mathbf{u}_p \rightarrow \mathbf{x}_p$$

Deposition: calculating current on grid

$$(\mathbf{x}, \mathbf{u})_p \rightarrow \mathbf{j}_i$$

$$\Delta t$$

Integration of field equations: updating fields

$$(\mathbf{E}, \mathbf{B})_i \leftarrow \mathbf{J}_i$$

Interpolation: evaluating force on particles

$$(\mathbf{E}, \mathbf{B})_i \rightarrow \mathbf{F}_p$$

GRID

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

INSTITUTO SUPERIOR TÉCNICO

UCLA

Adding radiation reaction force to the PIC loop

osiris v2.0

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \boxed{\frac{d\mathcal{P}_\gamma}{dtd\chi}}$$ Probabilistic

PARTICLES

Integration of equations of motion: moving particles

$\mathbf{F}_p \rightarrow \mathbf{u}_p \rightarrow \mathbf{x}_p$

Emission of photons

Probability of pair creation

➡ new particles

Δt

Interpolation: evaluating force on particles

$(\mathbf{E},\mathbf{B})_i \rightarrow \mathbf{F}_p$

Deposition: calculating current on grid

$(\mathbf{x},\mathbf{u})_p \rightarrow \mathbf{j}_i$

GRID

Integration of field equations: updating fields

$(\mathbf{E},\mathbf{B})_i \leftarrow \mathbf{J}_i$

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi\mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

INSTITUTO SUPERIOR TÉCNICO

UCLA

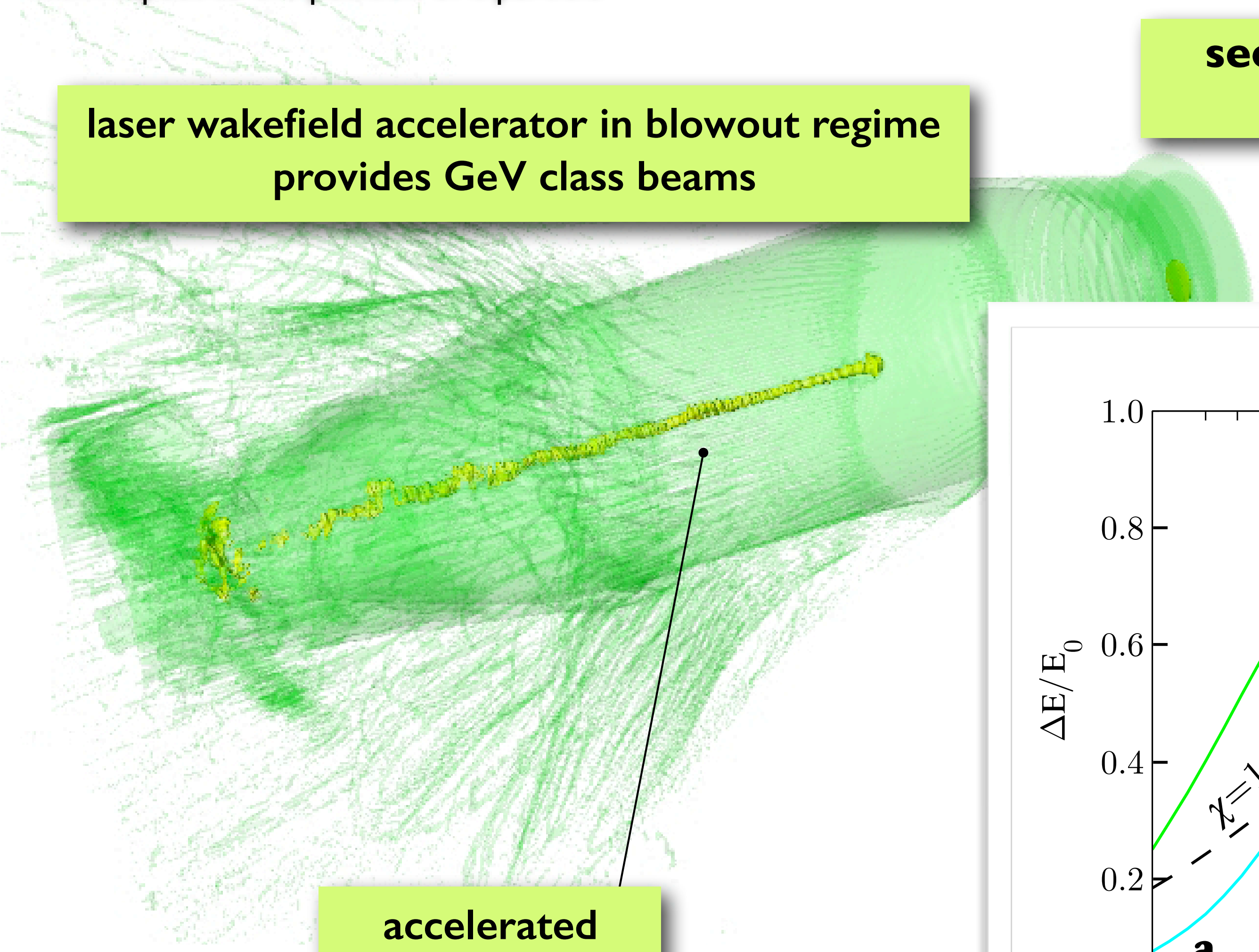
Unravelling the nature of radiation reaction

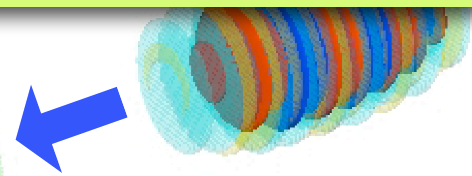
Understanding one of the oddest equations in physics

Lorentz-Abraham-Dirac equation has a third order derivative
with respect to the position of a particle

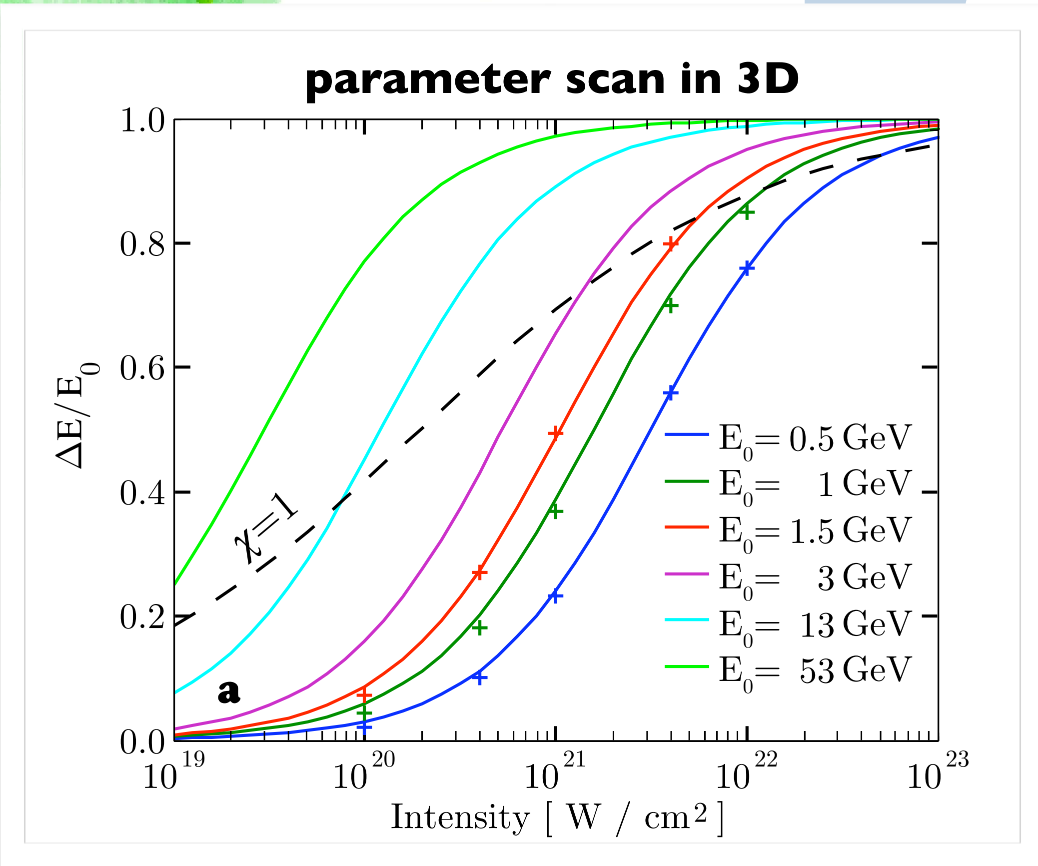
second laser scatters on e- beam
I ~ 10^{21} W/cm^2

laser wakefield accelerator in blowout regime provides GeV class beams



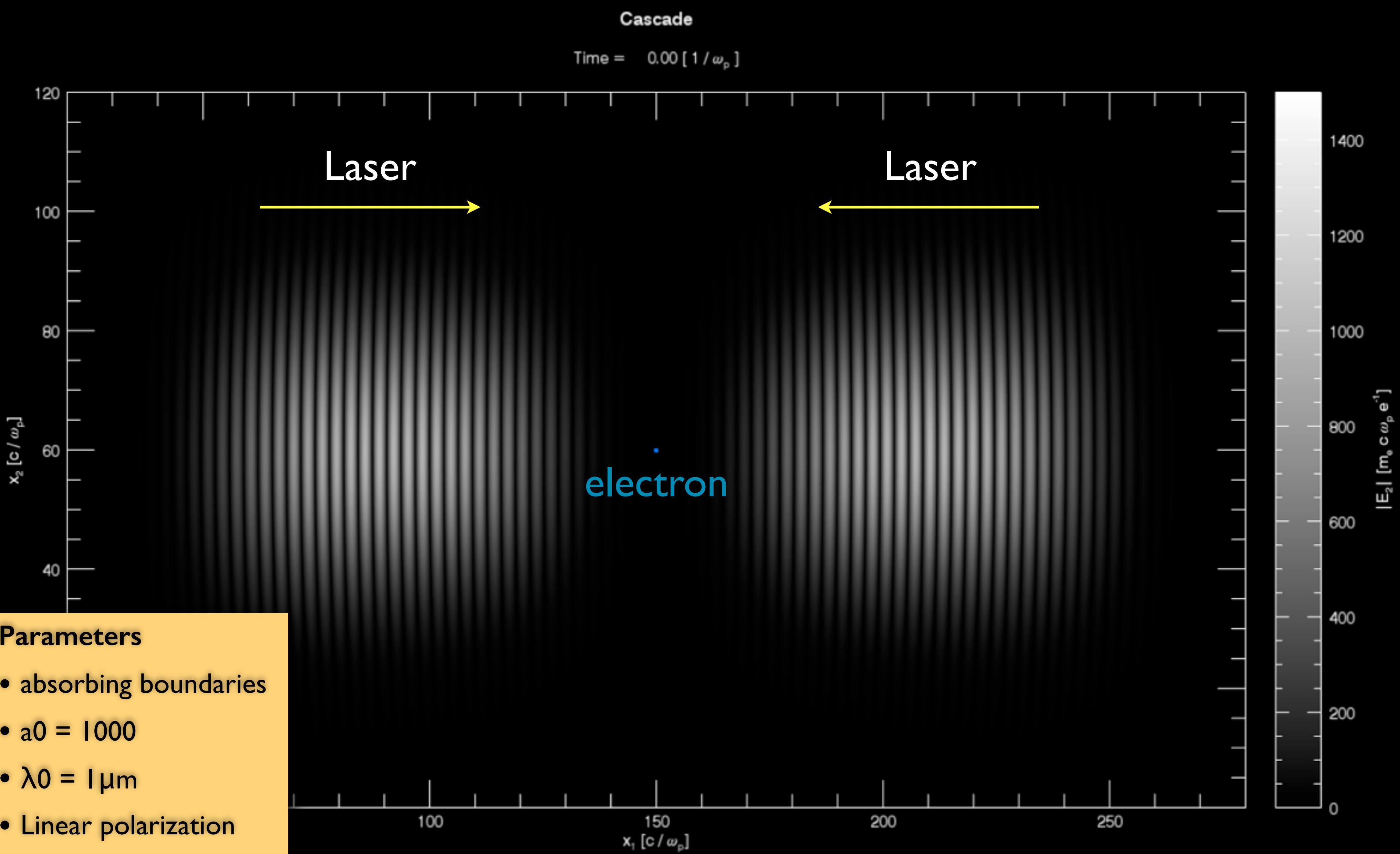


accelerated electrons



M. Vranic, J. L. Martins *et al.*, arXiv:1306.0766 (2013)

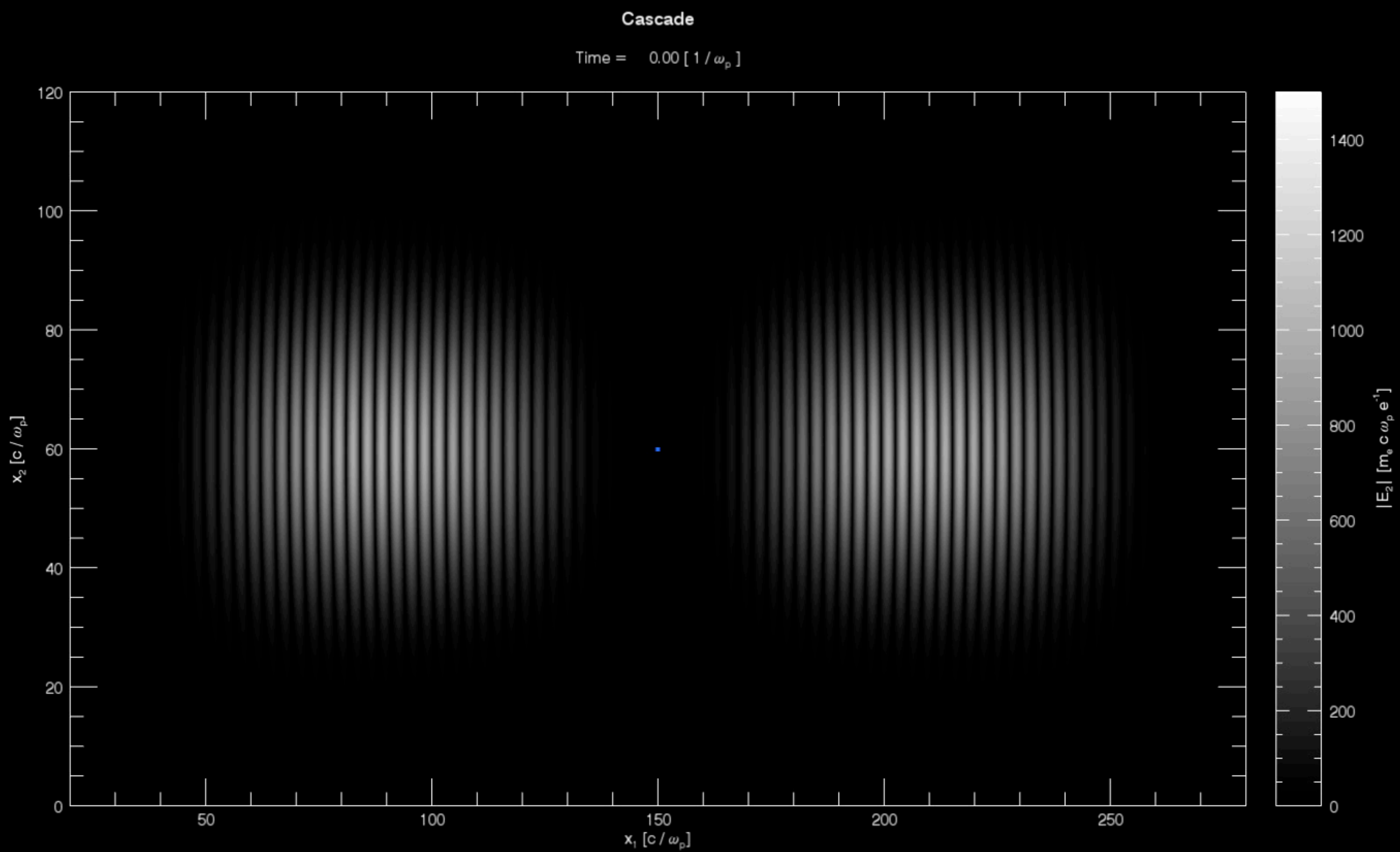
QED cascades in counter propagating lasers



Parameters

- absorbing boundaries
- a0 = 1000
- λ0 = 1 μm
- Linear polarization
- W0 = 5 μm
- τ = 30 fs

QED cascades in counter propagating lasers



photons positron electron

Parameter range for QED cascade

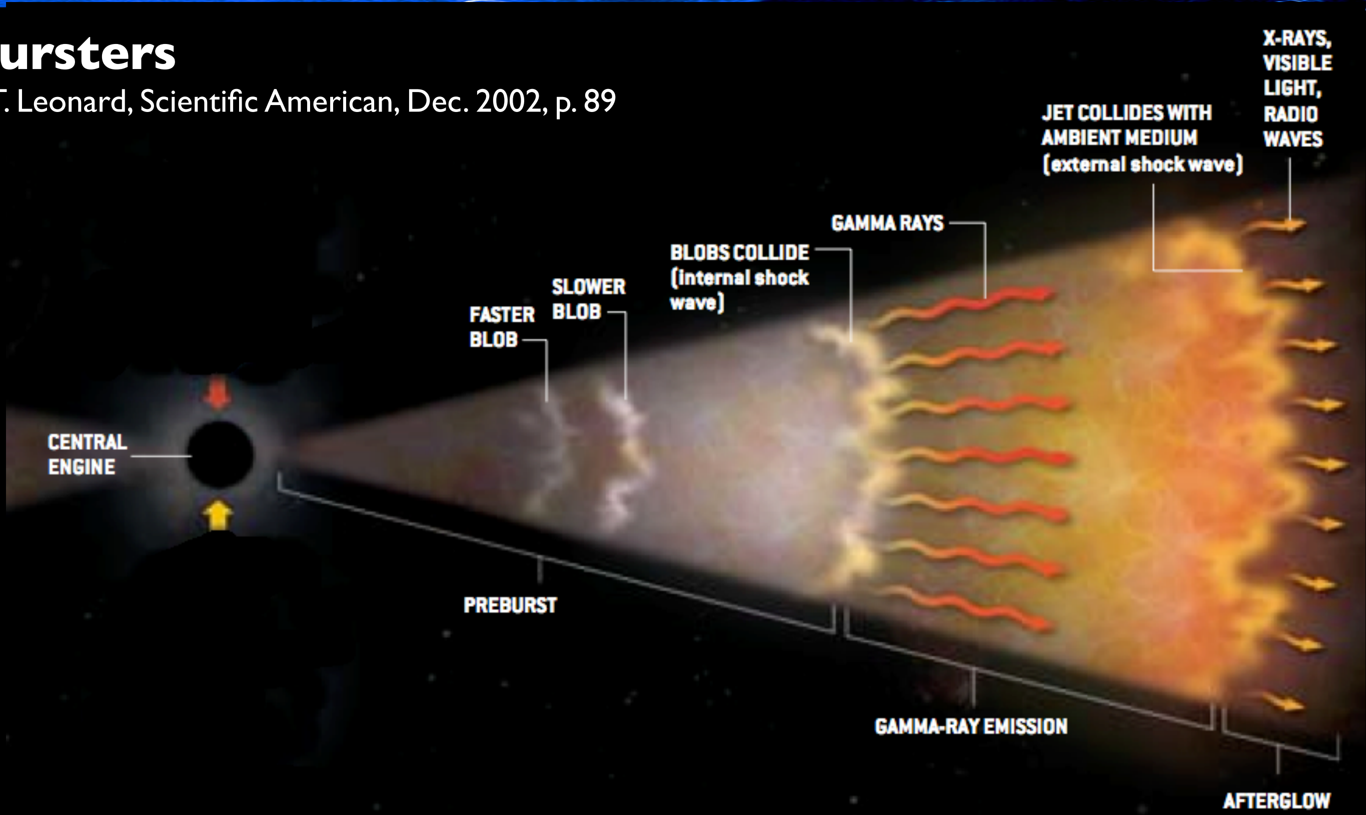
Polarization	Linear				Circular
Laser					
a0	1000		1500	3000	1000
Spot [μm]	8	∞ (plane)	5	5	8
Duration [fs]	30	30	30	30	30
Intensity	10^{24}	10^{24}	4.10^{24}	9.10^{24}	10^{24}
Pairs					
Number	3.10^{3}	3.10^{4}	$\sim 10^{7}$	$\sim 10^{15}$	3.10^{3}
Growth rate	0.21	0.24	0.44	0.62	0.21

T. Grismayer, *et al.*, in preparation (2013)

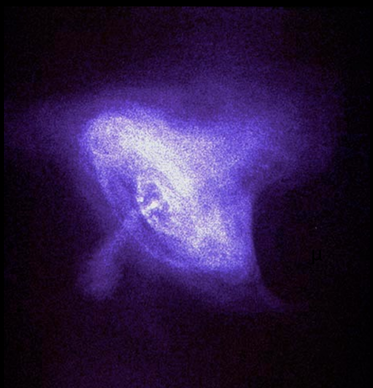
Colliding flows of plasmas are pervasive in astrophysics

Gamma Ray Bursters

N. Gehrels, L. Piro and P. J. T. Leonard, Scientific American, Dec. 2002, p. 89



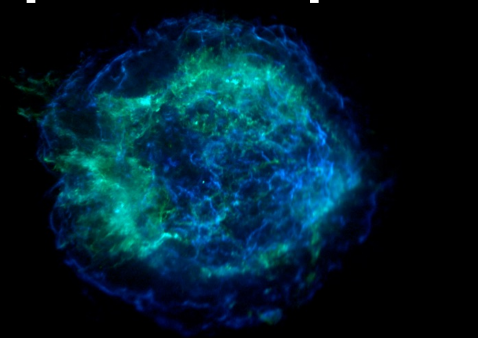
Pulsar Wind Nebulae

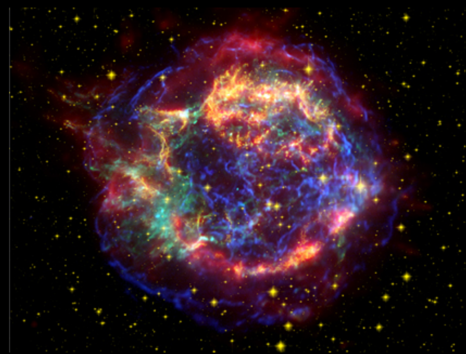


Crab nebula

NASA/CXC/SAO

Supernova Explosion



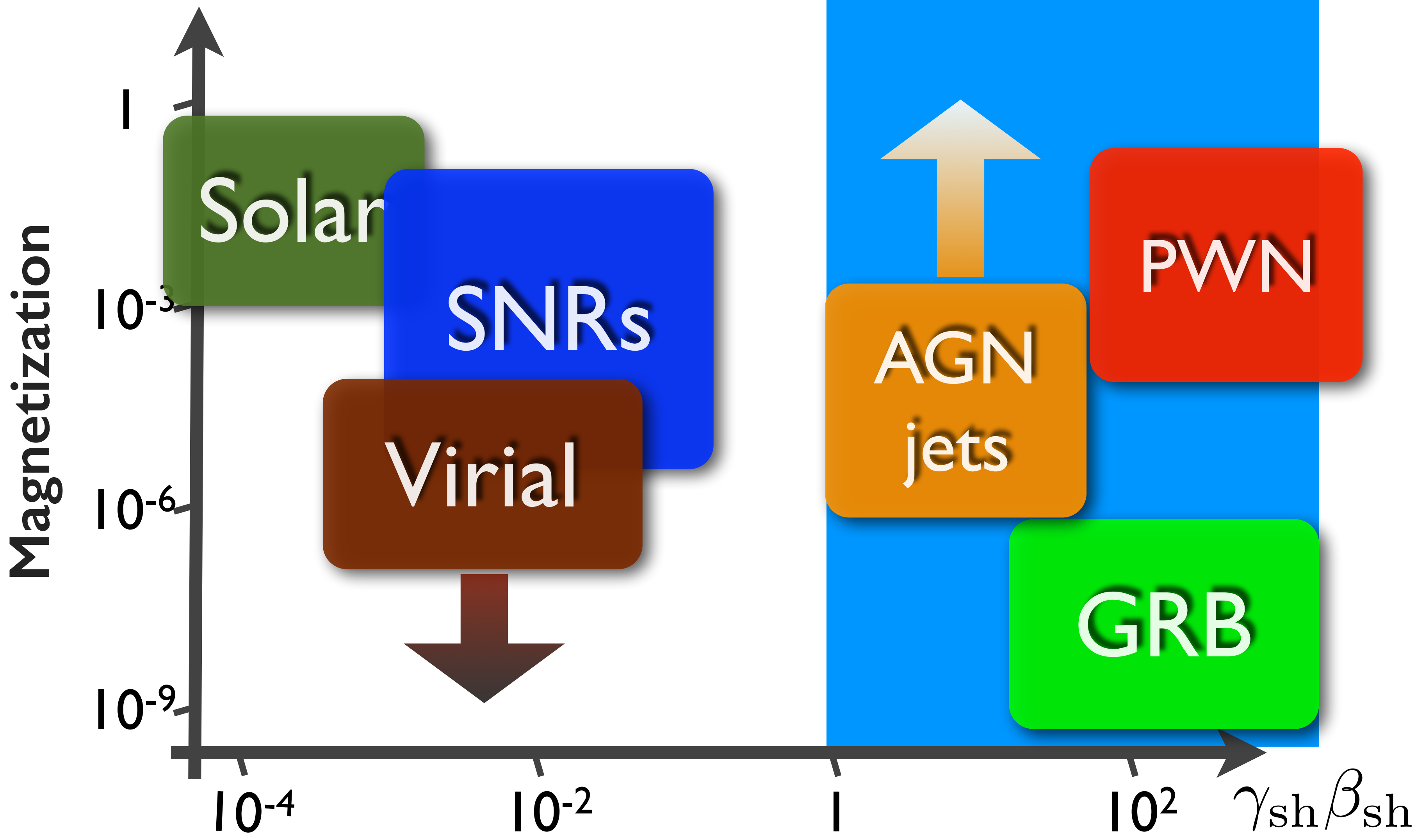


Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech

The landscape of collisionless astro/space shocks

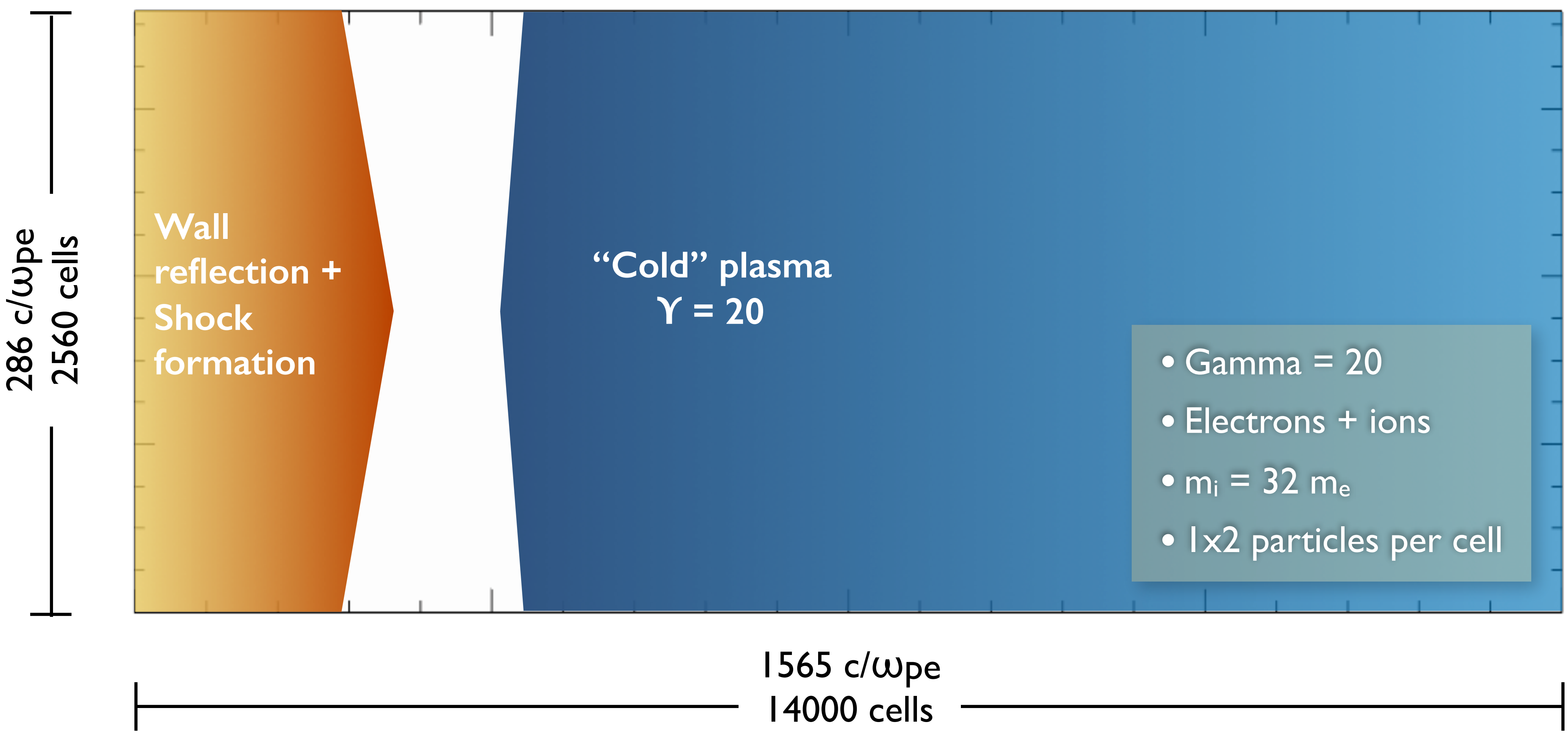
$$\sigma \equiv \frac{B^2}{4\pi(\gamma - 1)nmc^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2$$



Adapted from A. Spitkovsky

Collision of two relativistic plasma slabs

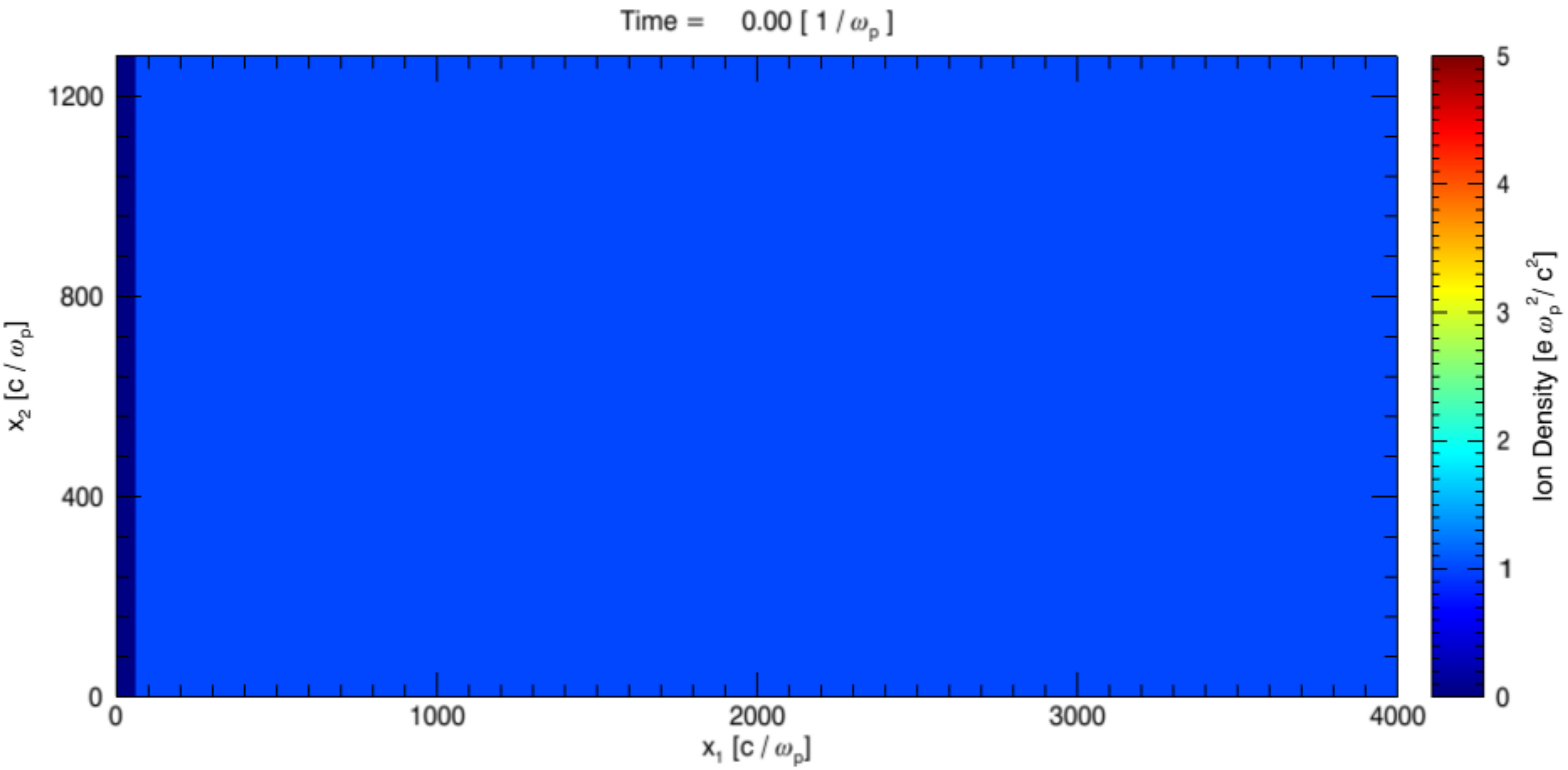
Simulation apparatus



S. F. Martins *et al.*, ApJ Lett (2009)

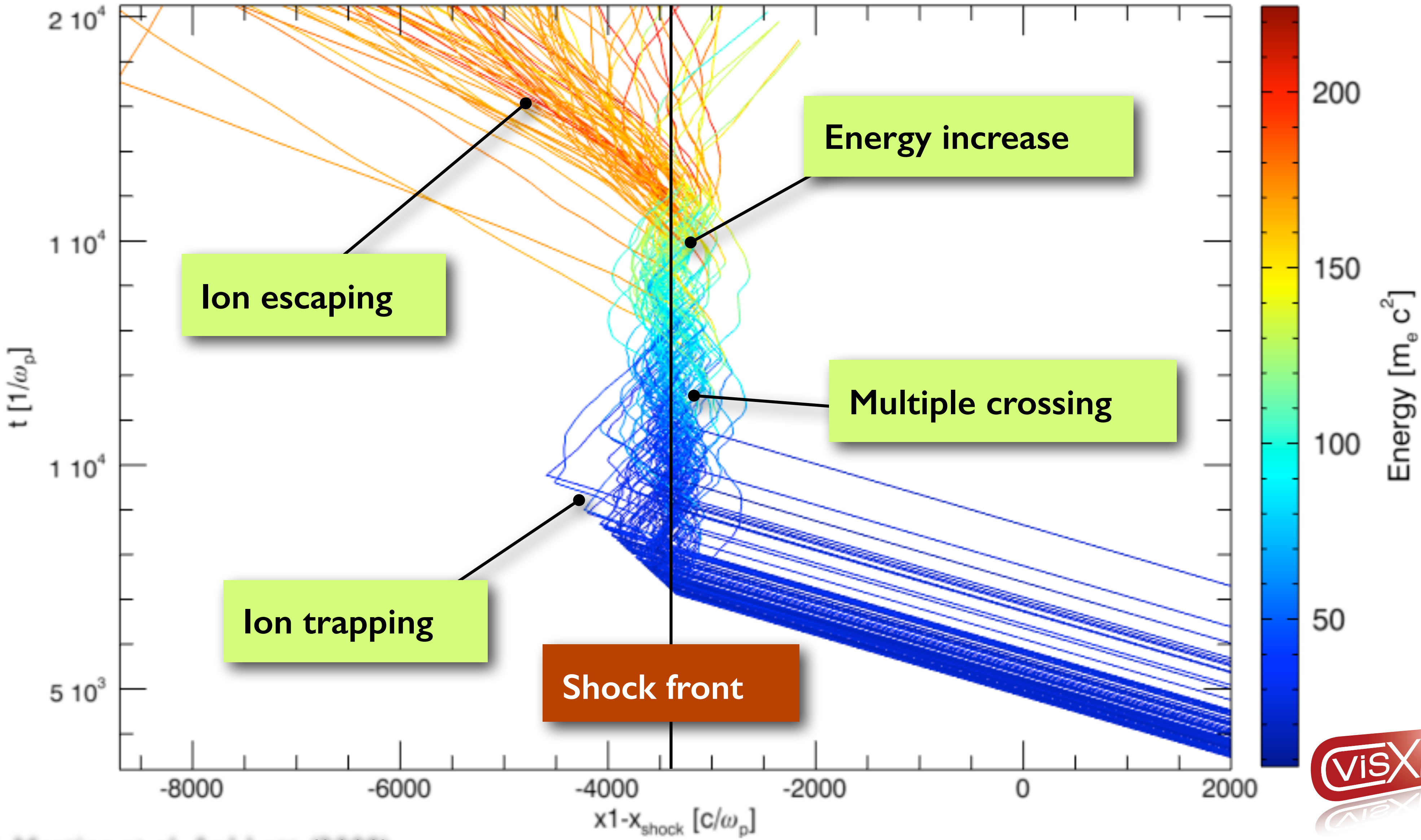
Ab initio shock formation and evolution

Ion density



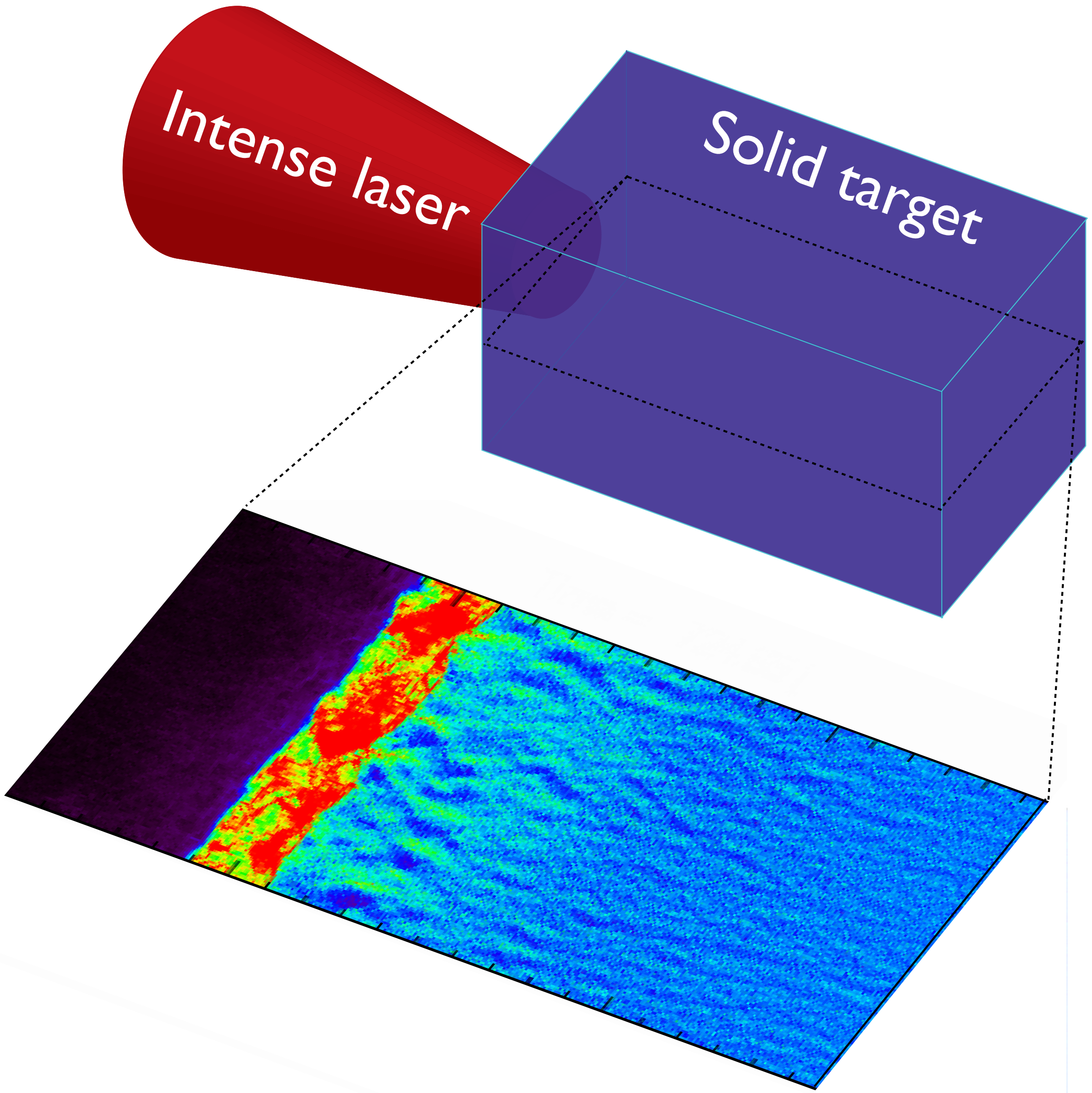
Ab initio Fermi acceleration

Trapped particle trajectories in the shock front - x1 vs time



S. F. Martins et al, ApJ Lett (2009)

OSIRIS simulation setup: shock generation in lab



Physical Parameters

Laser

- λ_0 = 1 μm
- $I_0 = 10^{20}$-10^{22} Wcm^{-2}
- τ_0 = 1 ps

Plasma

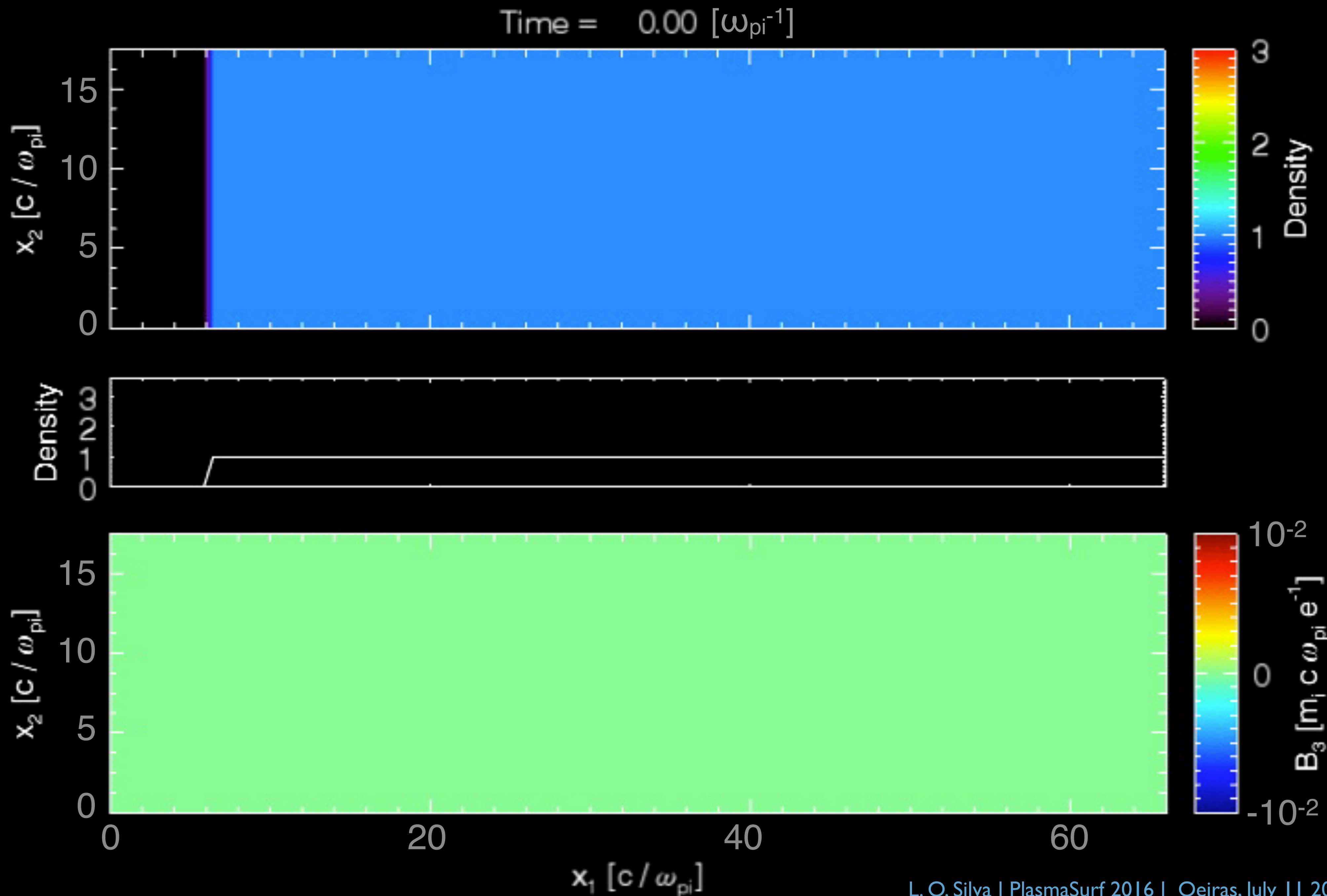
- L = 20 x 100 μm^2 (w_{pi}^2)
- n_{e0} = 10 n_c - 100 n_c
- m_i/m_e = 1836

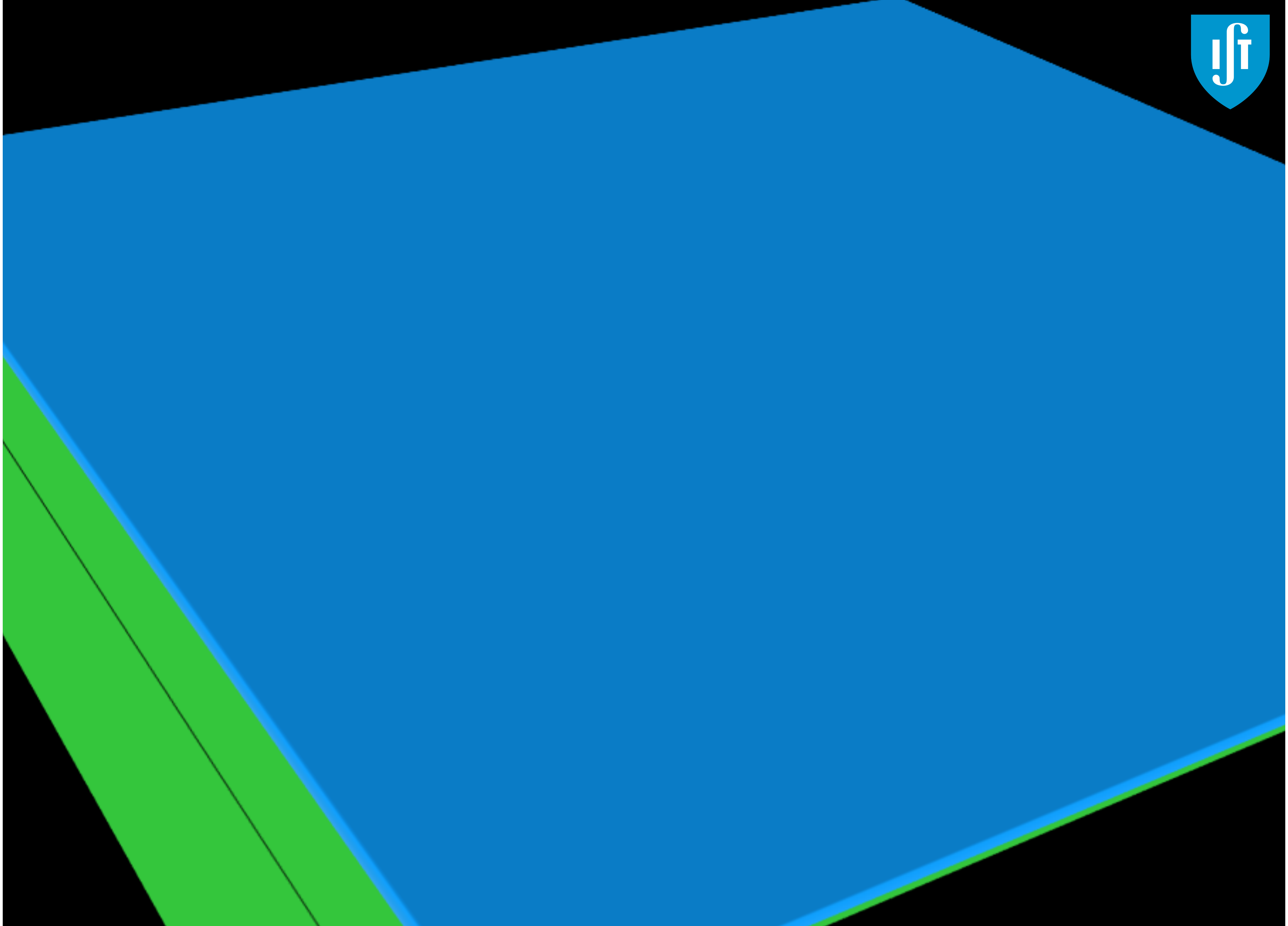
Numerical Parameters

- Dx = Dy = 0.25 c/w_{pe}
- 64 particles per cell
- 10^9 particles
- cubic interpolation

F. Fiúza *et al.*, PRL, 2012

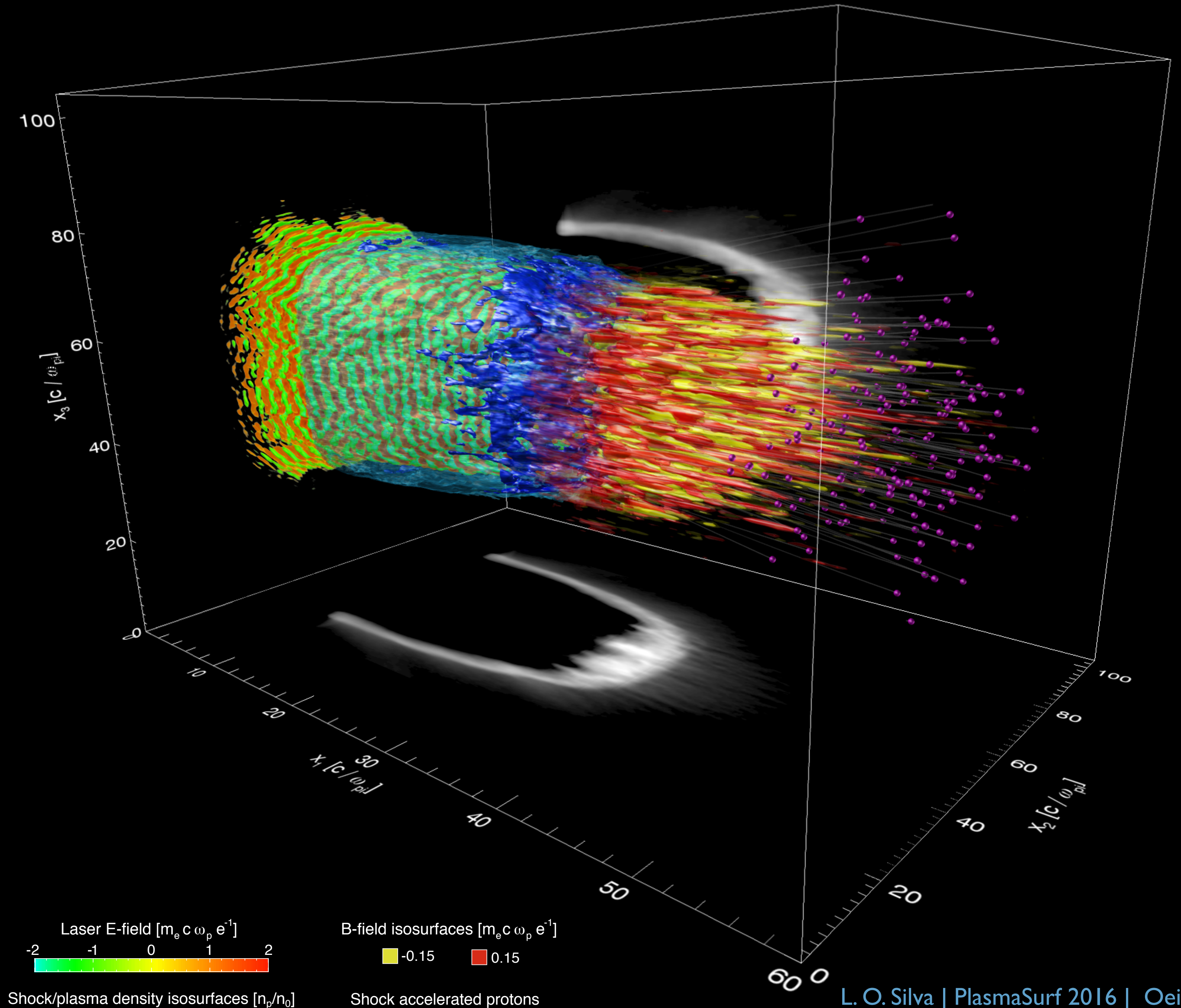
Collisionless shock launched with ultraintense laser





F. Fiúza et al, PRL (2012)

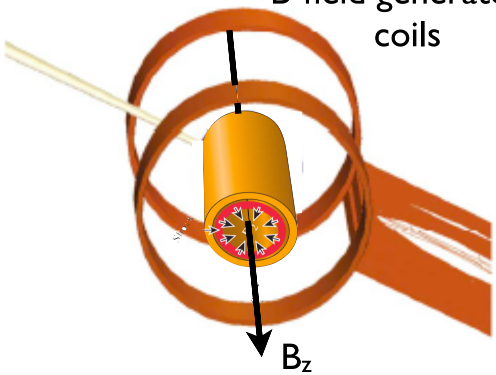
Similar underlying physics/results in 3D

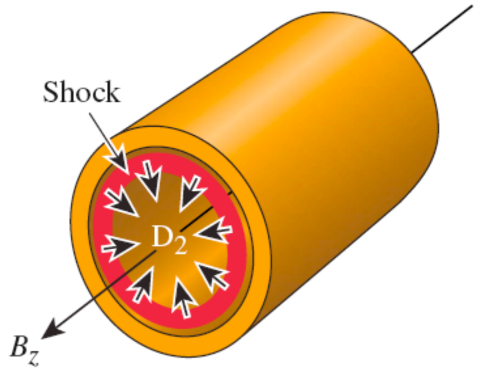


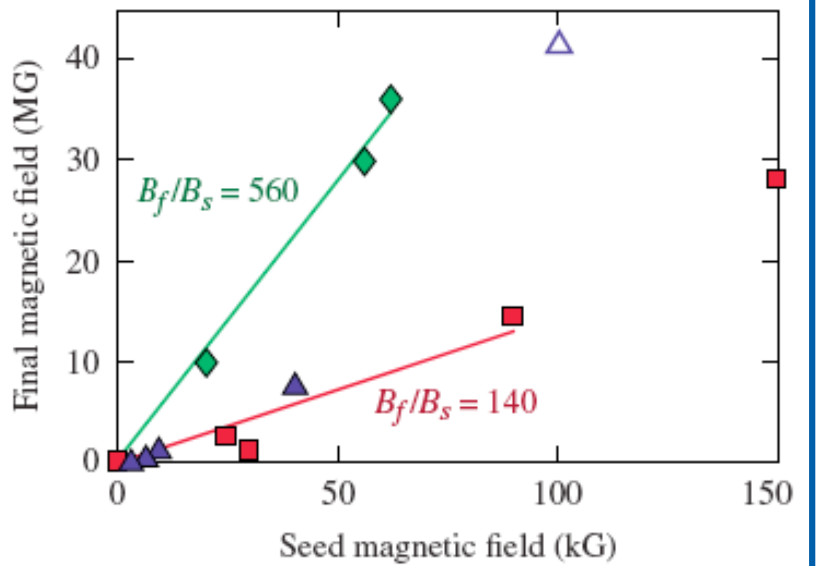
How about magnetized shocks?

10s MG axial B-fields have been generated in the lab

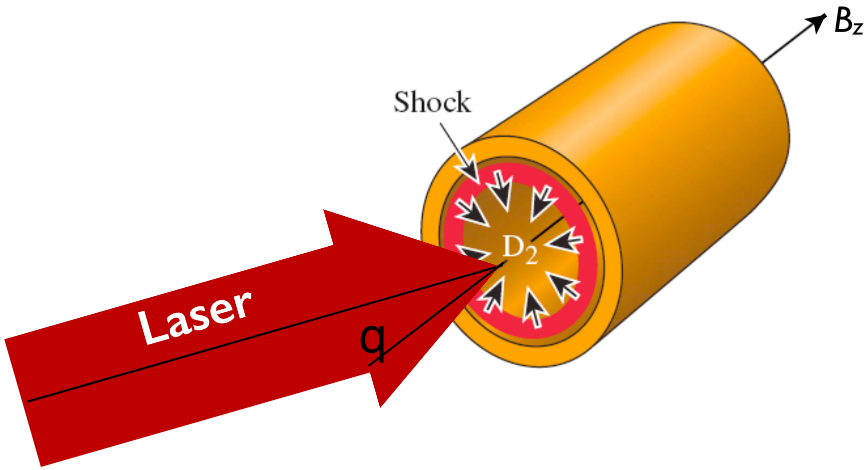
Laser driven magnetic flux compression*

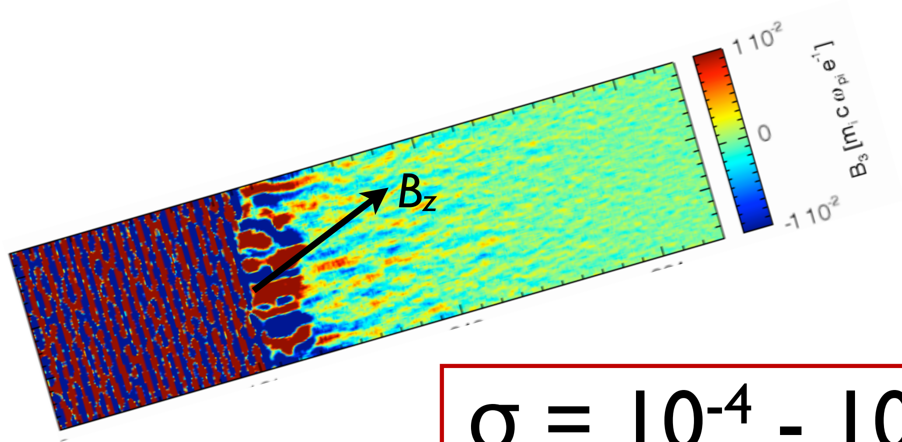






Possibility to probe different B-field configurations experimentally





$$\boxed{\sigma = 10^{-4} - 10^{-1}}$$

* J. P. Knauer et al., Phys. Plasmas 17, 056318 (2010)

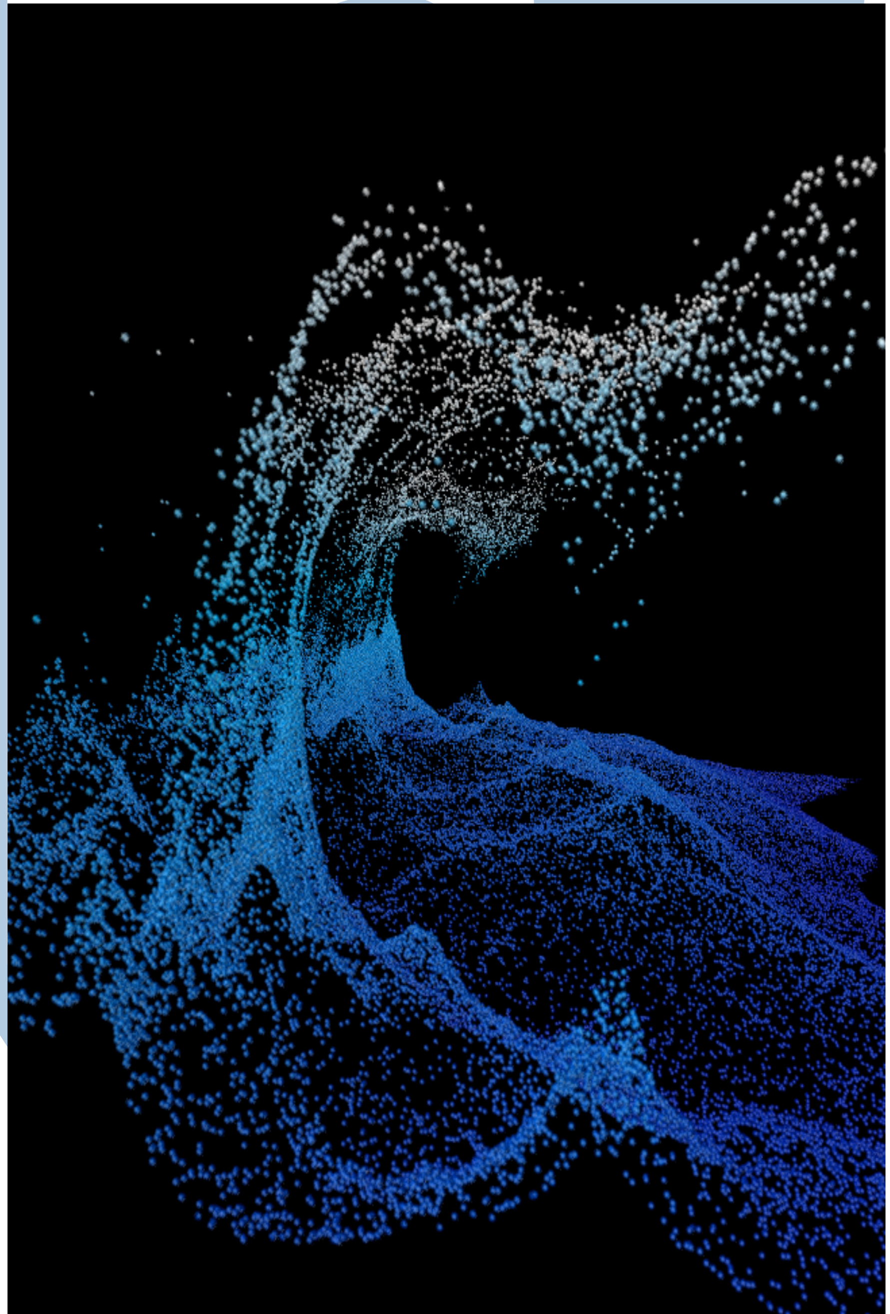
Contents

Summary

The quest for ultra intense beams is driving technological advances in lasers and particle beams and computer simulations are opening these directions

Significant potential impact in many relevant societal questions

Potential to address fundamental questions in physics is also outstanding in regimes far from equilibrium



What challenges lie ahead?

Demonstrate 10s GeV e- and 200 MeV protons with lasers

Make nuclear fusion (with lasers) a viable alternative for energy production

Determine the conditions & observe Fermi acceleration in the laboratory

“Boil the vacuum”