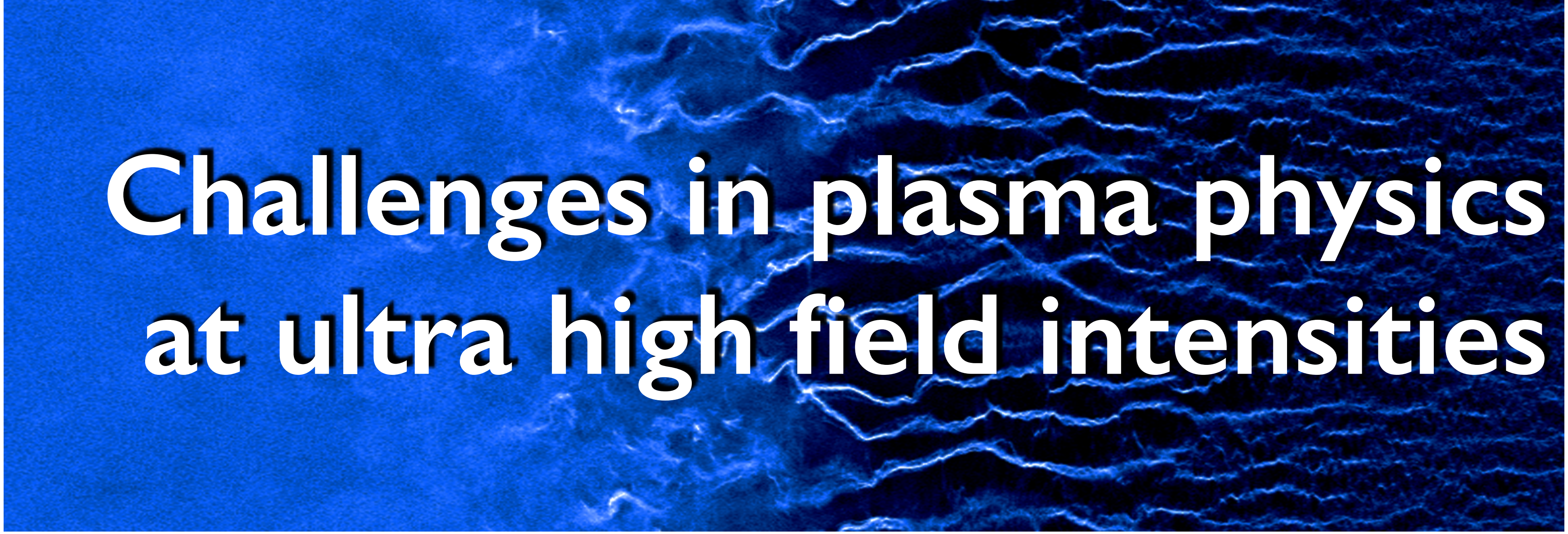
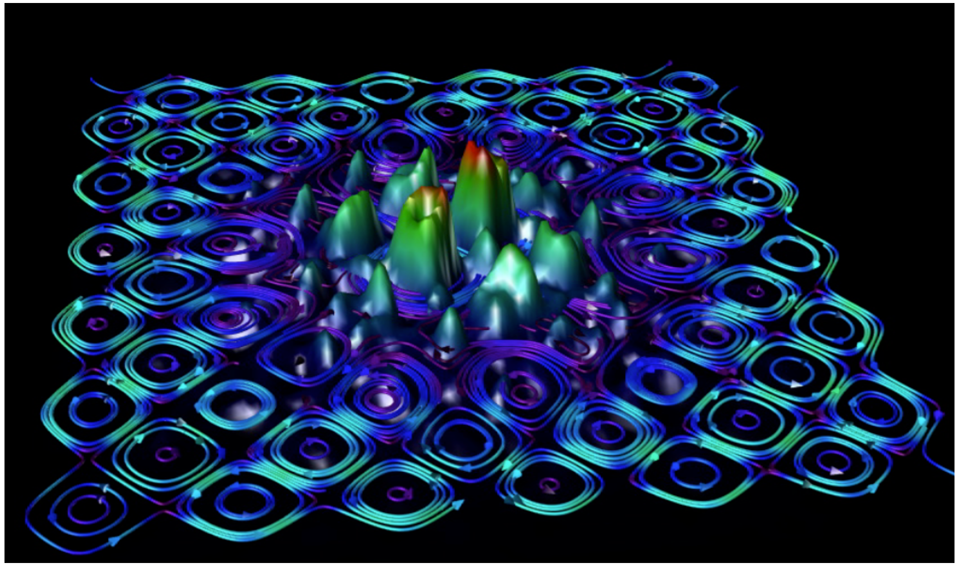


Challenges in plasma physics at ultra high field intensities

Luís O. Silva

GoLP
Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Lisbon, Portugal



GoLP/IPFN Instituto Superior Técnico

TÉCNICO LISBOA

golp grupo de lasers e plasmas

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Acknowledgments

- **R. Fonseca, T. Grismayer, J. Vieira, K. Schoeffler, M. Vranic, N. Shukla, J. L. Martins, S. Martins**
- Work in collaboration with:
  - **W. B. Mori (UCLA), F. Fiúza (SLAC), G. Sarri (QUB), M. Marklund (Chalmers)**
- Simulation results obtained at **the epp and IST Clusters (IST), Dawson2 Cluster (UCLA), Franklin (NERSC), Intrepid (Argonne), Jugene/Juqueen (FZ Jülich), Jaguar (ORNL), SuperMUC (Münich), Sequoia (LLNL)**

PRACE

ACCELERATES

erc 2

INPAIRS

Advanced Grants "Accelerates" (2010) and InPairs (2015)

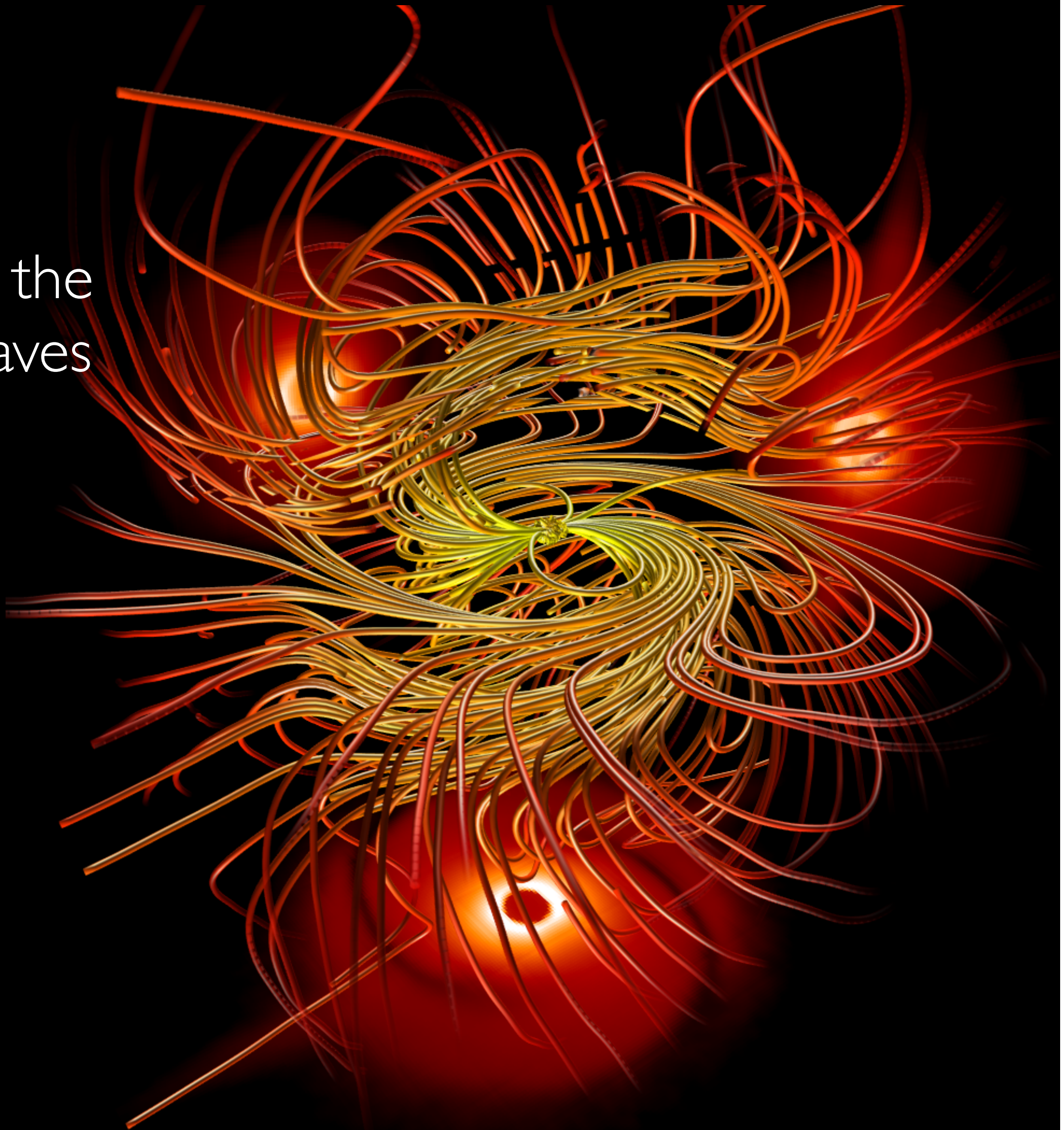
Challenges at ultra high intensities

Particle acceleration towards the energy frontier and exotic waves

From radiation reaction to "boiling" the vacuum

e-e+ plasmas

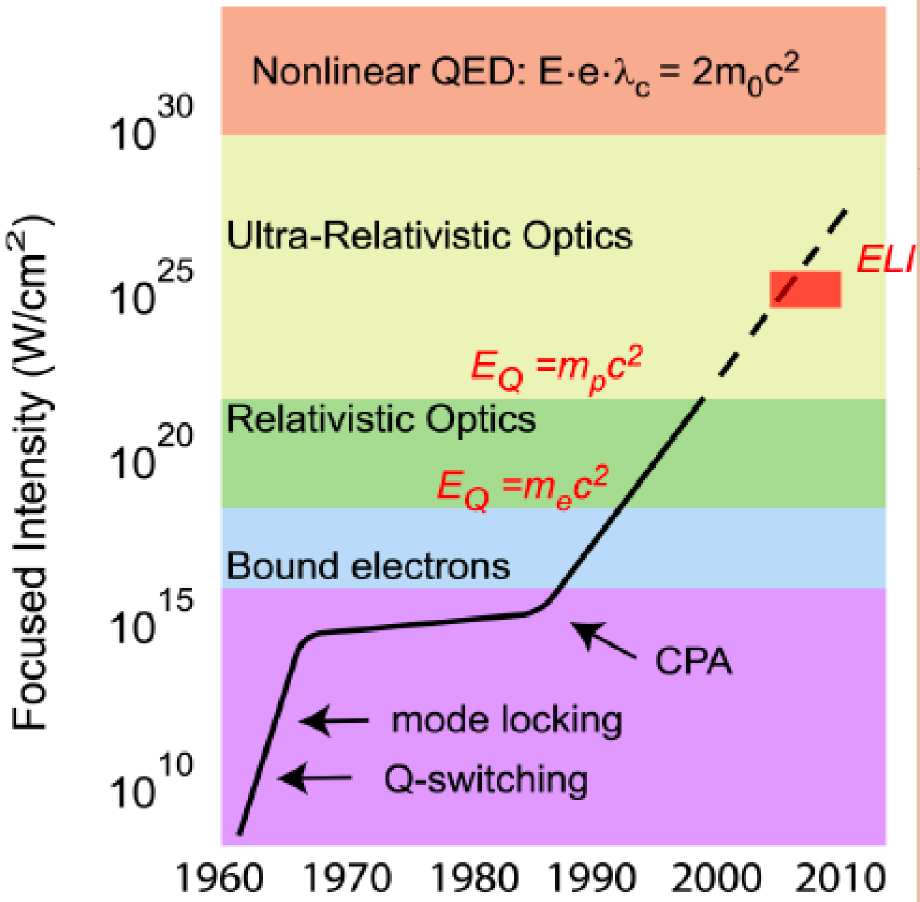
http://epp.ist.utl.pt/



Tremendous progress in lasers is opening new opportunities

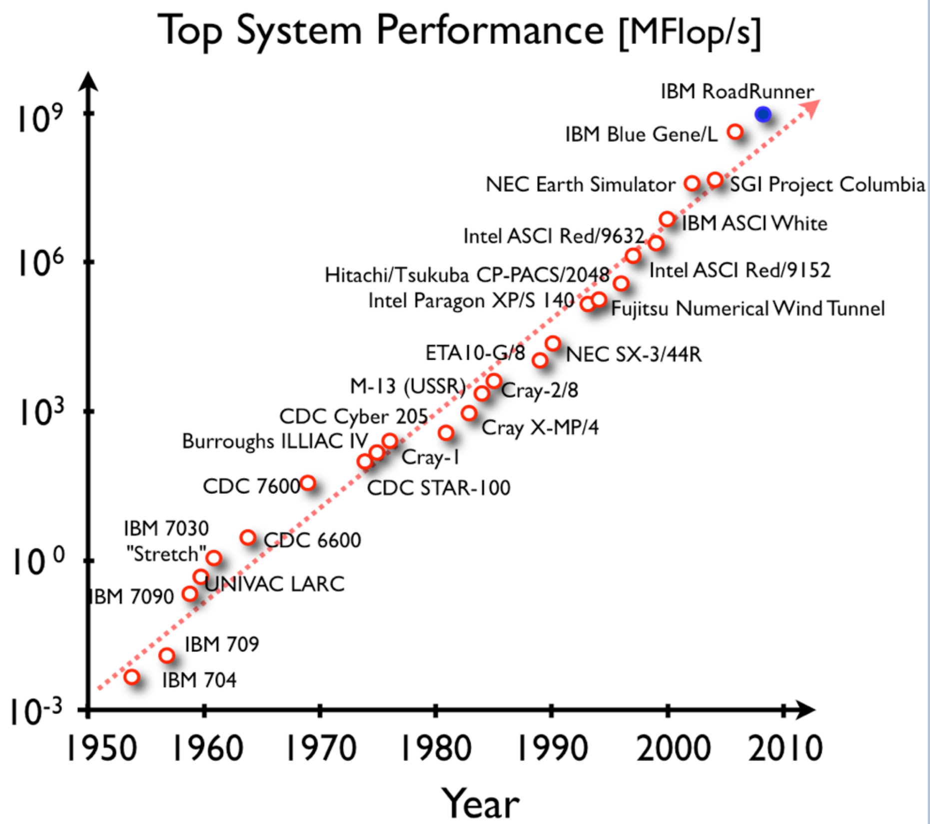
Lasers and supercomputers

’15 Peak laser intensity ~ 10^{23} W/cm^2



Mourou, Tajima, Bulanov (2006)

’15 Peak computing power > 10 Pflop/s



Source: top500.org

Similar intensities are present in particle beams

Existing or planned particle beams

LHC @ CERN I ~ 2.5x10^{19} W/cm^2
100 kJ, 7 TeV per proton, 10^{11} protons per beam; 10 cm long bunch; 200 microns spot

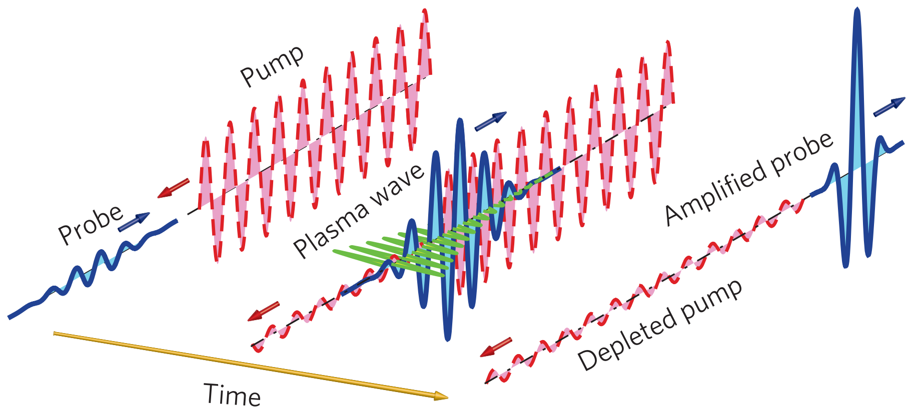
SPS @ CERN I ~ 1.5x10^{18} W/cm^2
~7 kJ, 0.5 TeV per proton, 10^11 protons per beam; 10 cm long bunch; 200 microns spot

ILC I ~ 1.5x10^{24} W/cm^2
1.6 kJ, 0.5 TeV per electron/positron, 2x10^{10} electrons/positrons; < 10 nm width in x; < ~100 nm width in y; 6 mm long

SLAC I ~ 1.2 x10^{19} W/cm^2
160 J, 50 GeV per electron/positron, 2x10^{10} electrons/positrons; ~50 microns long; ~50 microns spot

Stimulated (Raman/Brillouin) amplification promises even higher intensities

Stimulated Raman backscattering

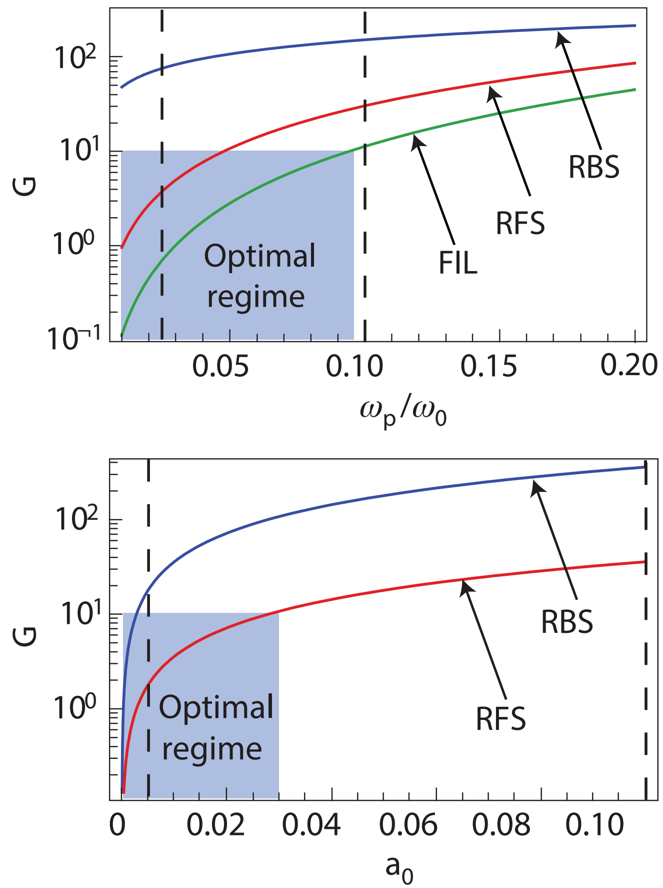


Amplification matching conditions:

$$\omega_l = \omega_0 + \omega_p$$
$$k_l = k_0 + k_p$$

V.M.Malkin et al., PRL 82, 4448 (1999);
G. Shvets, et al., 81, 4879 (1998)

Window for stable amplification



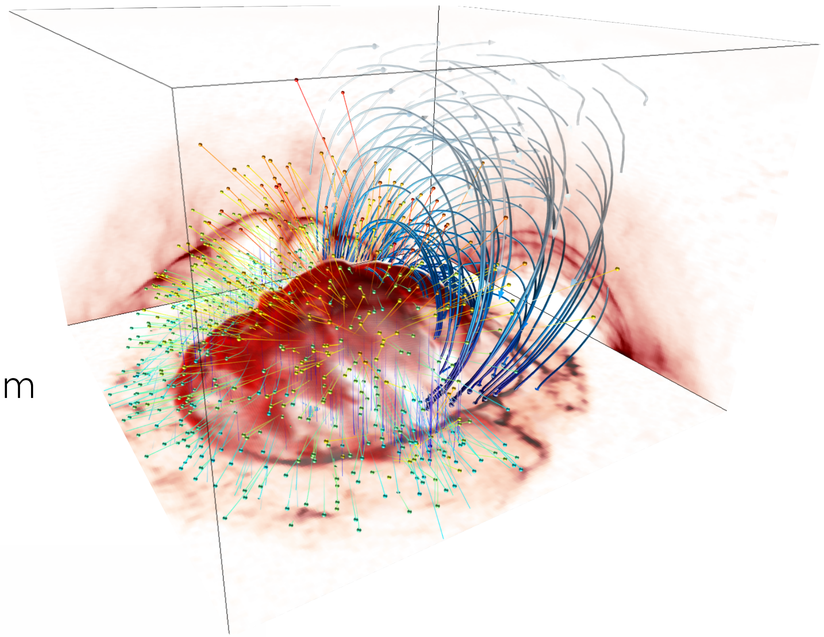
Number of e-foldings (G) < 10 to mitigate role of competing instabilities

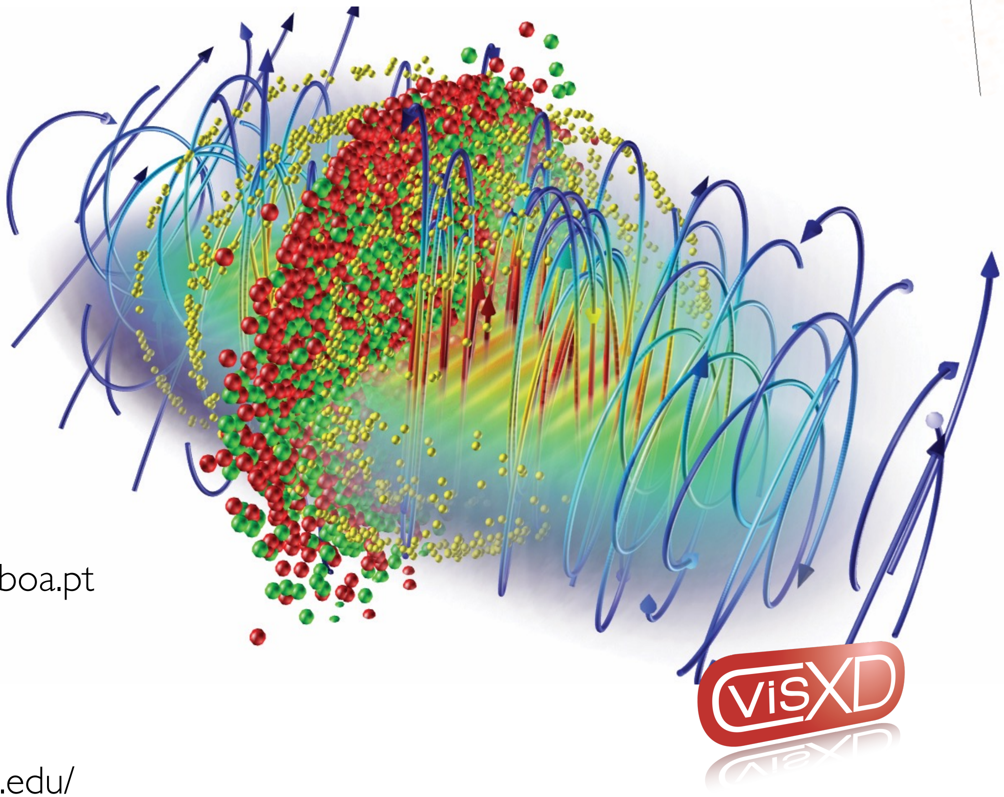
R.Trines et al, Nat.Phys. 7 87 (2011)
R.Trines et al, PRL 107 105002 (2011)

Osiris 3.0

osiris framework

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





code features

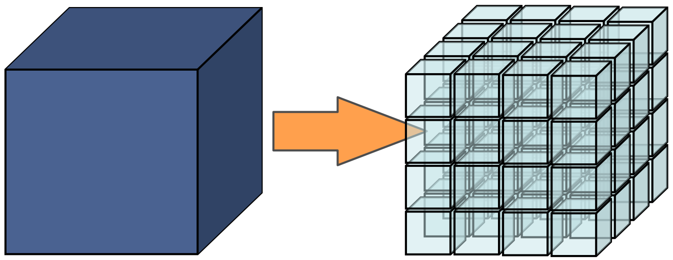
- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

Ricardo Fonseca
ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung
tsung@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

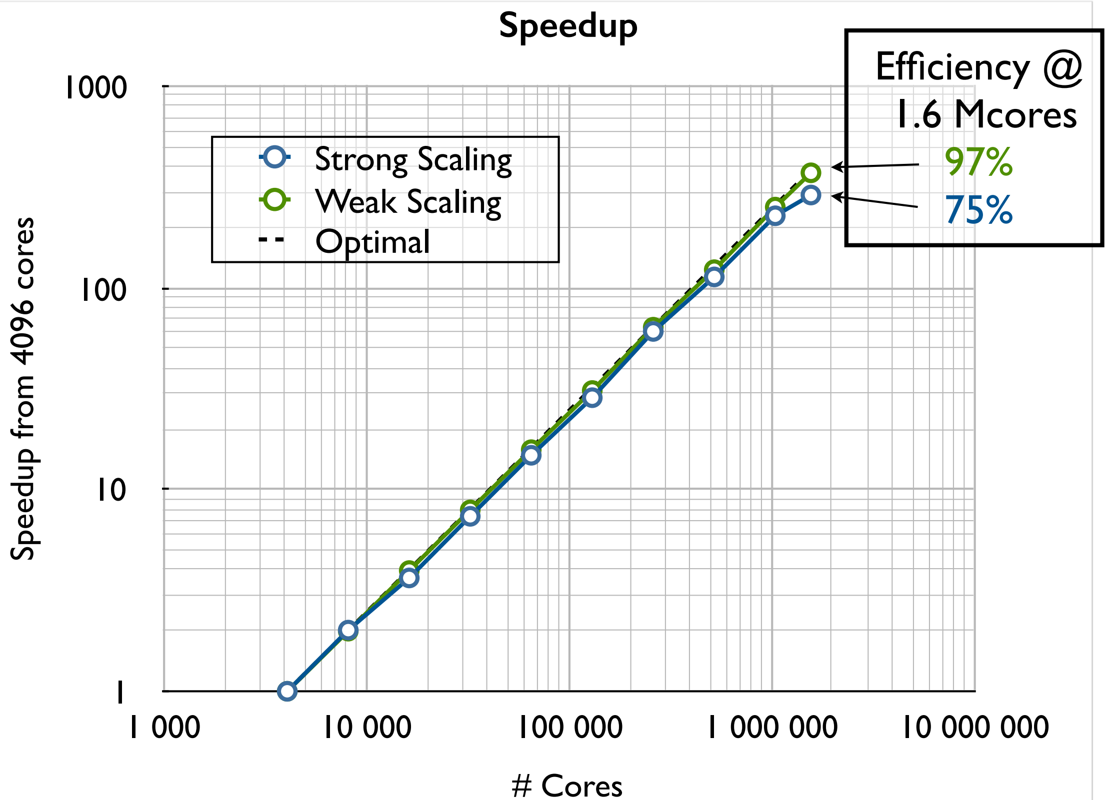
Extreme resources to explore opportunities at ultra high intensities

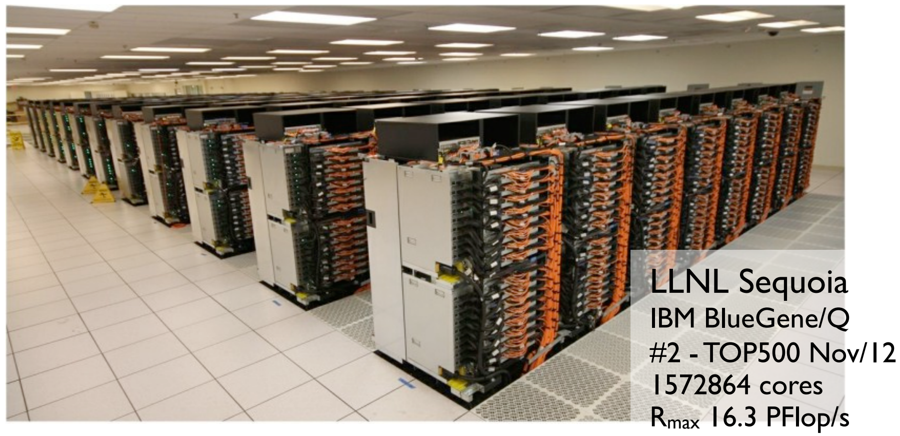
Scaling Tests



- Scaling tests on LLNL Sequoia
  4096 → 1572864 cores (full system)
- Warm plasma tests
  Quadratic interpolation
  $u_{th} = 0.1$ c
- Weak scaling
  Grow problem size
  cells = $256^3 \times (N_{cores} / 4096)$
  2^3 particles/cell
- Strong scaling
  Fixed problem size
  cells = 2048^3
  16 particles / cell

R. A. Fonseca *et al.* PPCF 55, 4011 (2013)





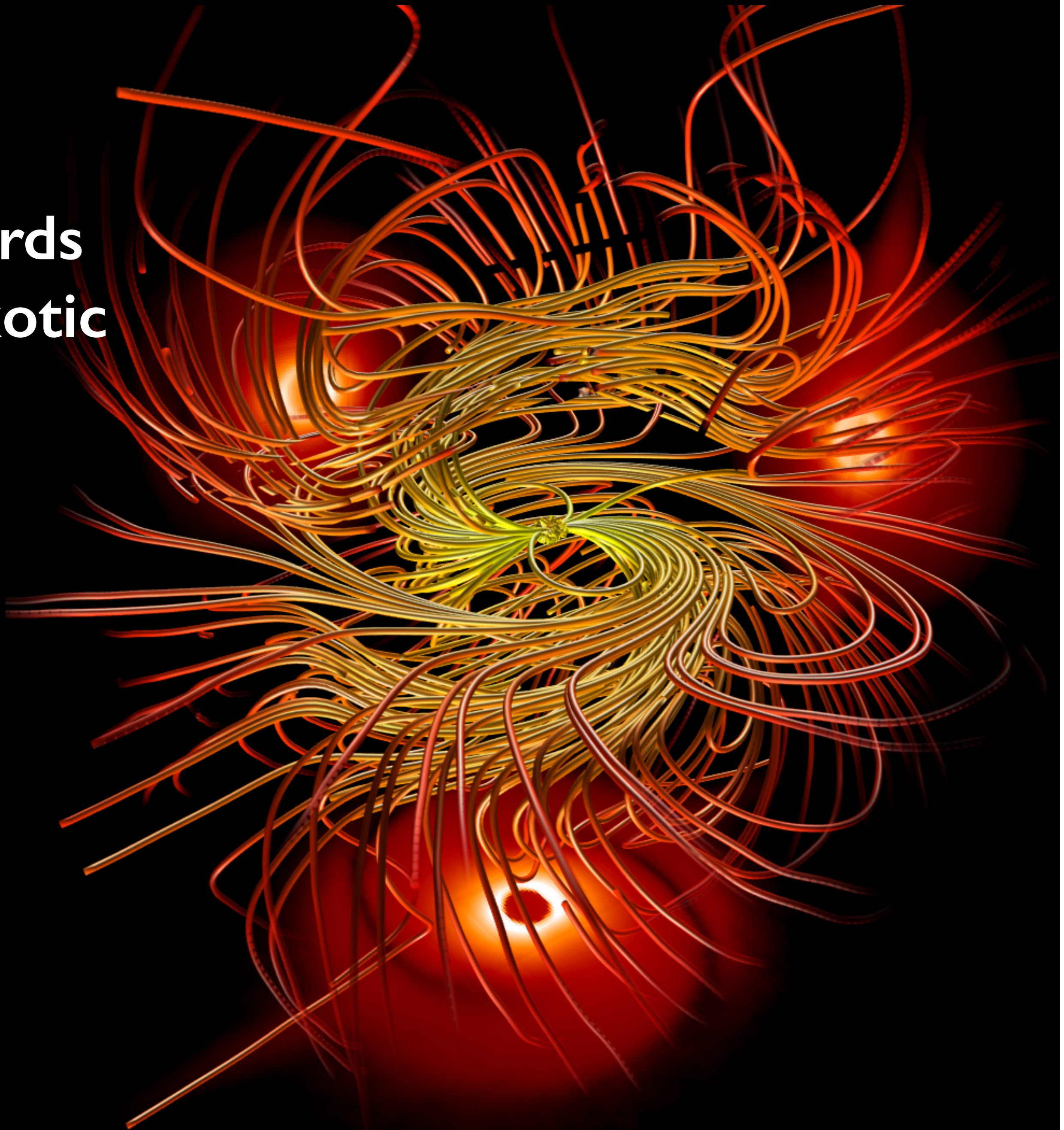
Challenges at ultra high intensities

Particle acceleration towards the energy frontier and exotic waves

From radiation reaction to
"boiling" the vacuum

e-e+ plasmas

http://epp.ist.utl.pt/

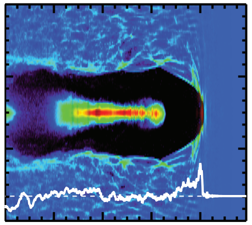


Can (laser) plasma accelerators reach the energy frontier?

Next generation of lasers @ 10+ PW

Energy frontier LWFA @ 250 J

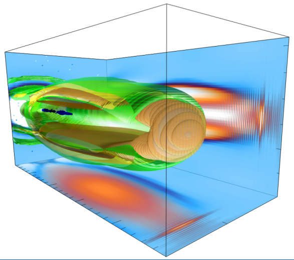
Extreme blowout :: a_0=53



- Very nonlinear and complex physics
- Bubble radius varies with laser propagation
- Electron injection is continuous ⇒ very strong beam loading
- Wakefield is noisy and the bubble sheath is not well defined

few GeV

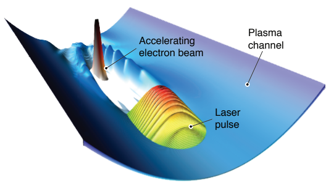
Controlled self-guided :: a_0=5.8



- Lower laser intensity ⇒ cleaner wakefield and sheath
- Loaded wakefield is relatively flat
- Blowout radius remains nearly constant
- Three distinct bunches ⇒ room for tuning the laser parameters

~10-15 GeV

Channel guided :: a_0=2



- Lowest laser intensity ⇒ highest beam energies (less charge)
- External guiding of the laser ⇒ stable wakefield
- Tailored electron beam that initially flattens the wake
- Controlled acceleration of an externally injected beam to very high energies

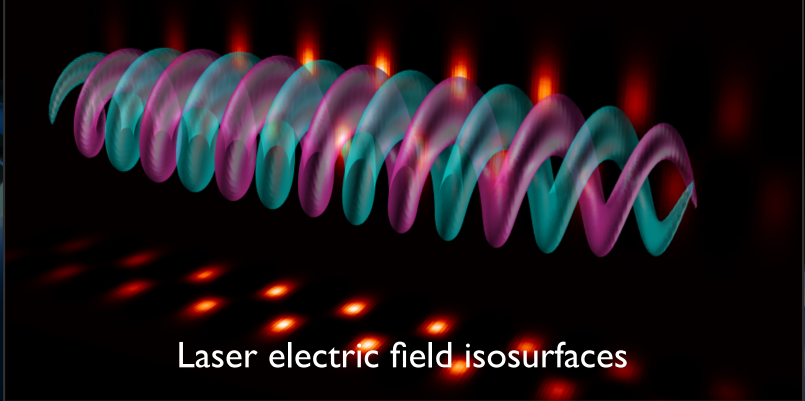
~30-40 GeV

S. Gordienko and A. Pukhov PoP (2005); W. Lu et al. PR-STAB (2007)
S. F. Martins et al., Nature Physics (2009)

The orbital angular momentum of light is an unexplored degree of freedom for laser-plasma interactions

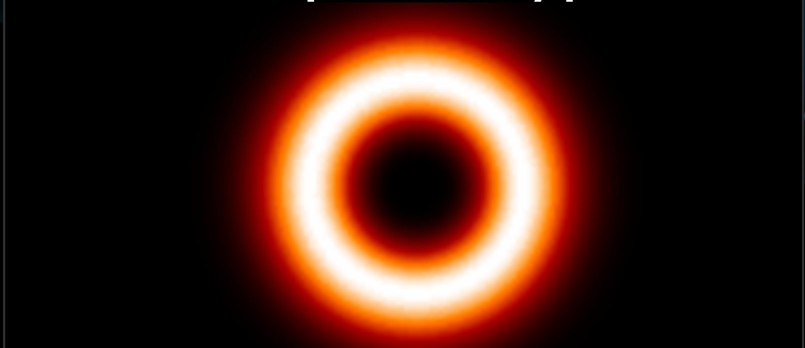
Production/ amplification of OAM lasers via Stimulated Raman Amplification: J.Vieira *et al.*, Nat. Comms (2016)

Helical wavefronts



Laser electric field isosurfaces

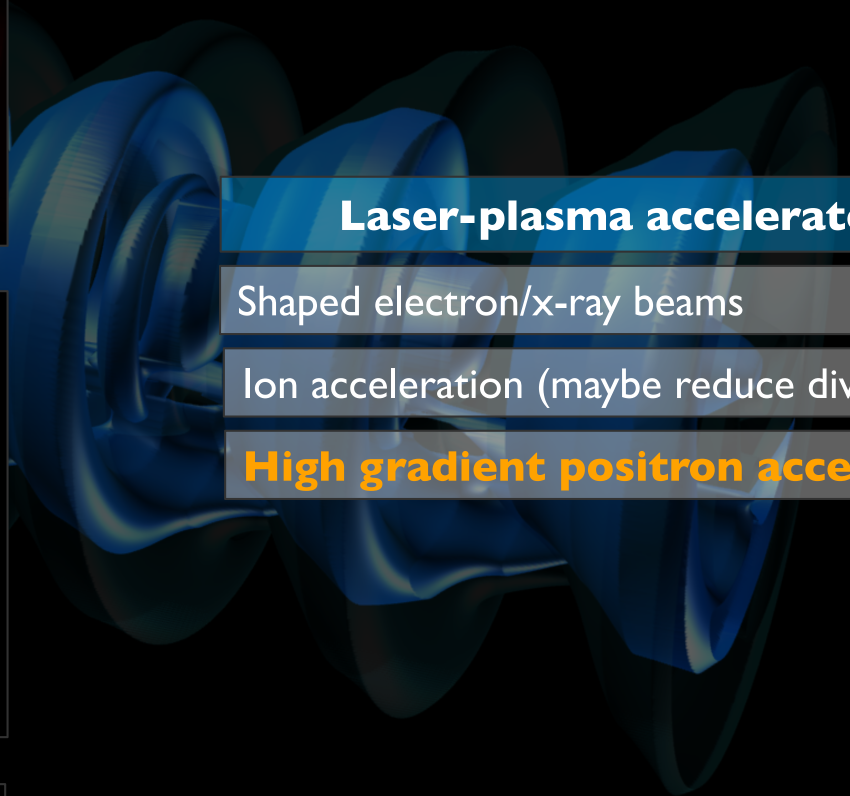
Donut-shaped intensity profiles



Transverse slice of laser envelope

Applications

- Astrophysics
- Ultrafast optical communications
- Nano particle manipulation

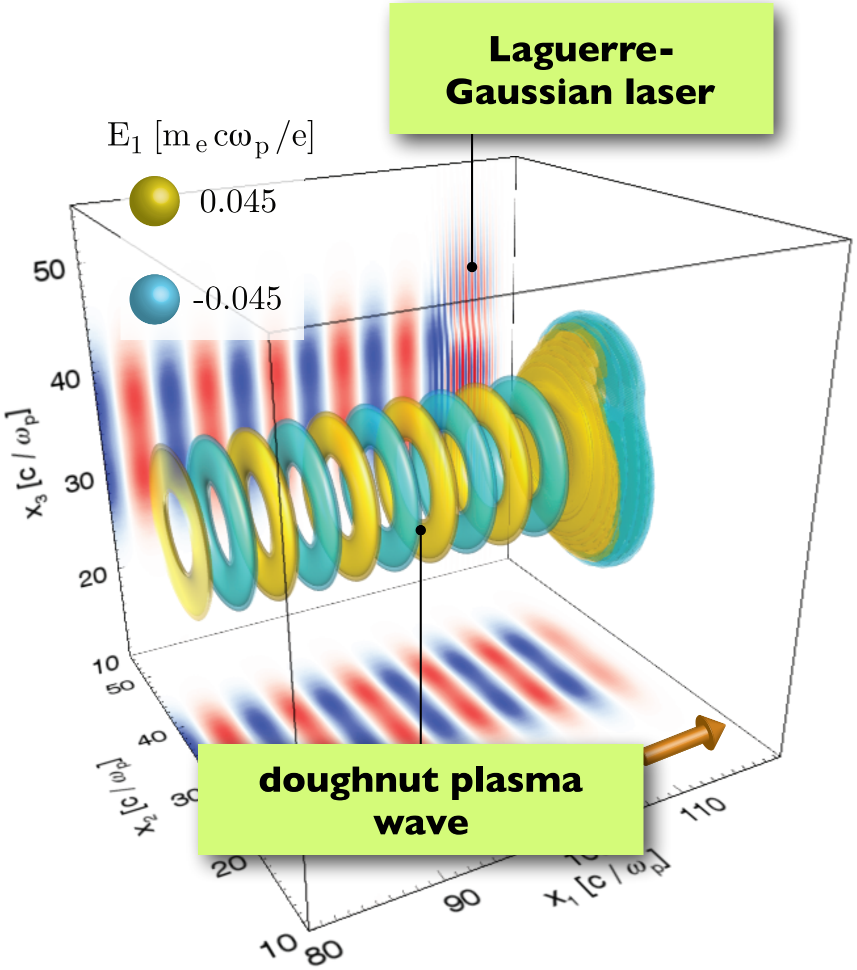


Laser-plasma accelerators

- Shaped electron/x-ray beams
- Ion acceleration (maybe reduce divergence)
- **High gradient positron acceleration**

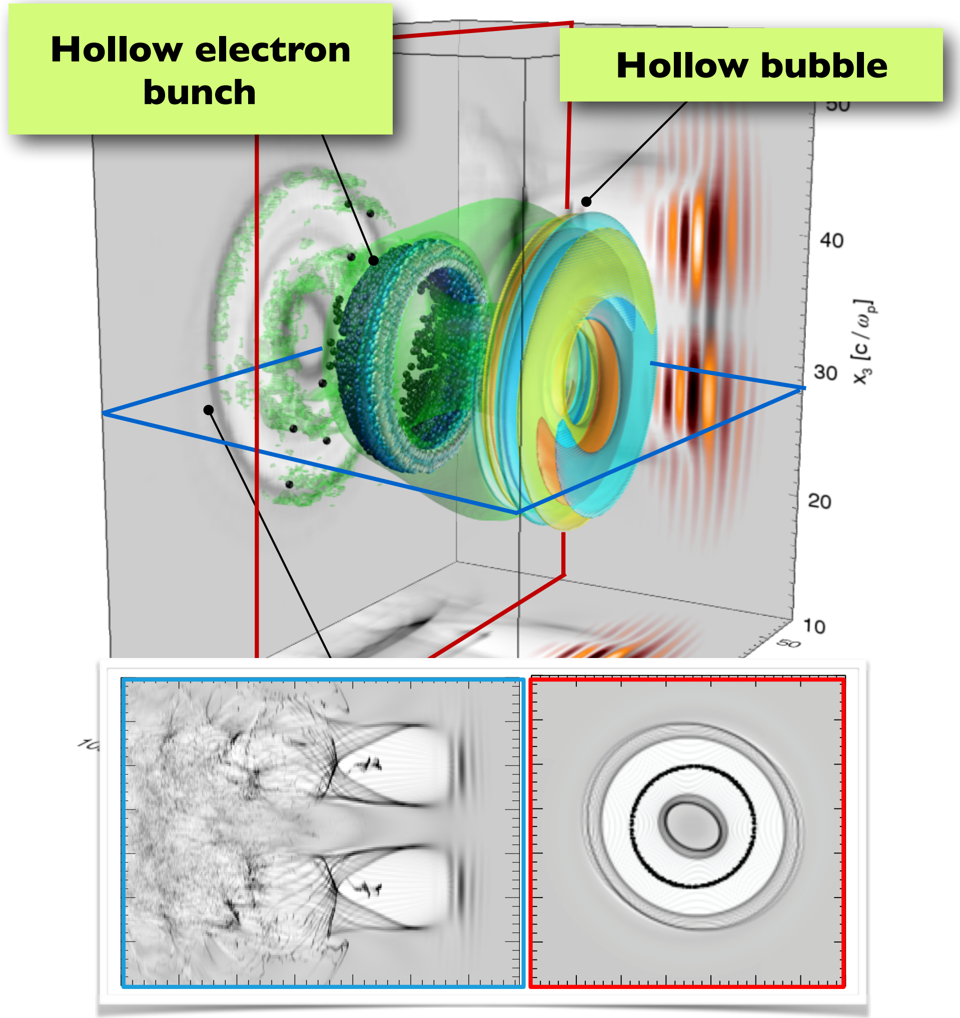
Laguerre-Gaussian lasers drive exotic (e.g. doughnut like) plasma waves in strongly non-linear regimes

Linear doughnut wakefields



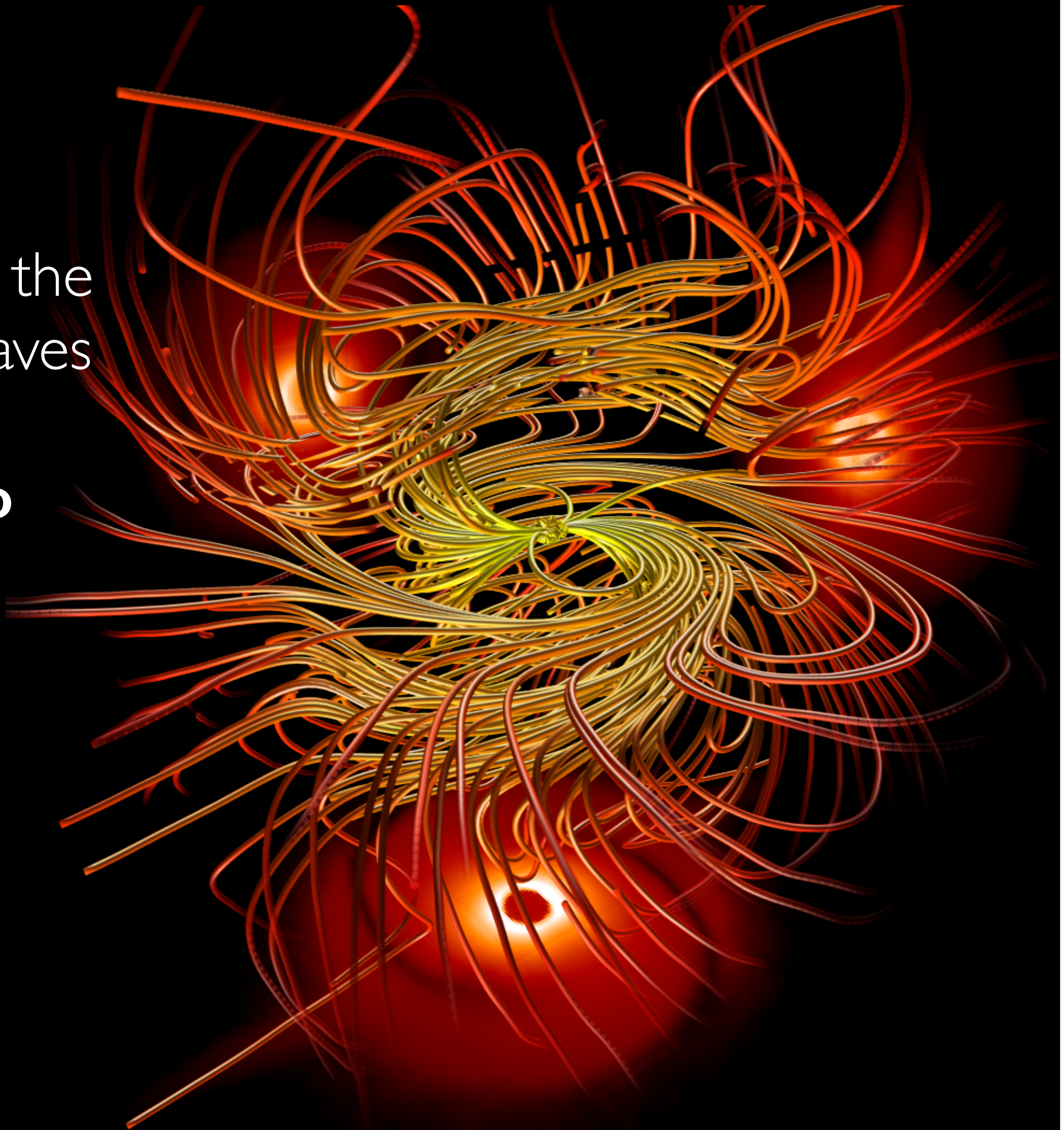
J.T. Mendonça and J.Vieira, PoP **21**, 033107 (2014)

Non-linear doughnut bubbles



J.Vieira and J.T. Mendonça PRL **112**, 215001 (2014)

Challenges at ultra high intensities



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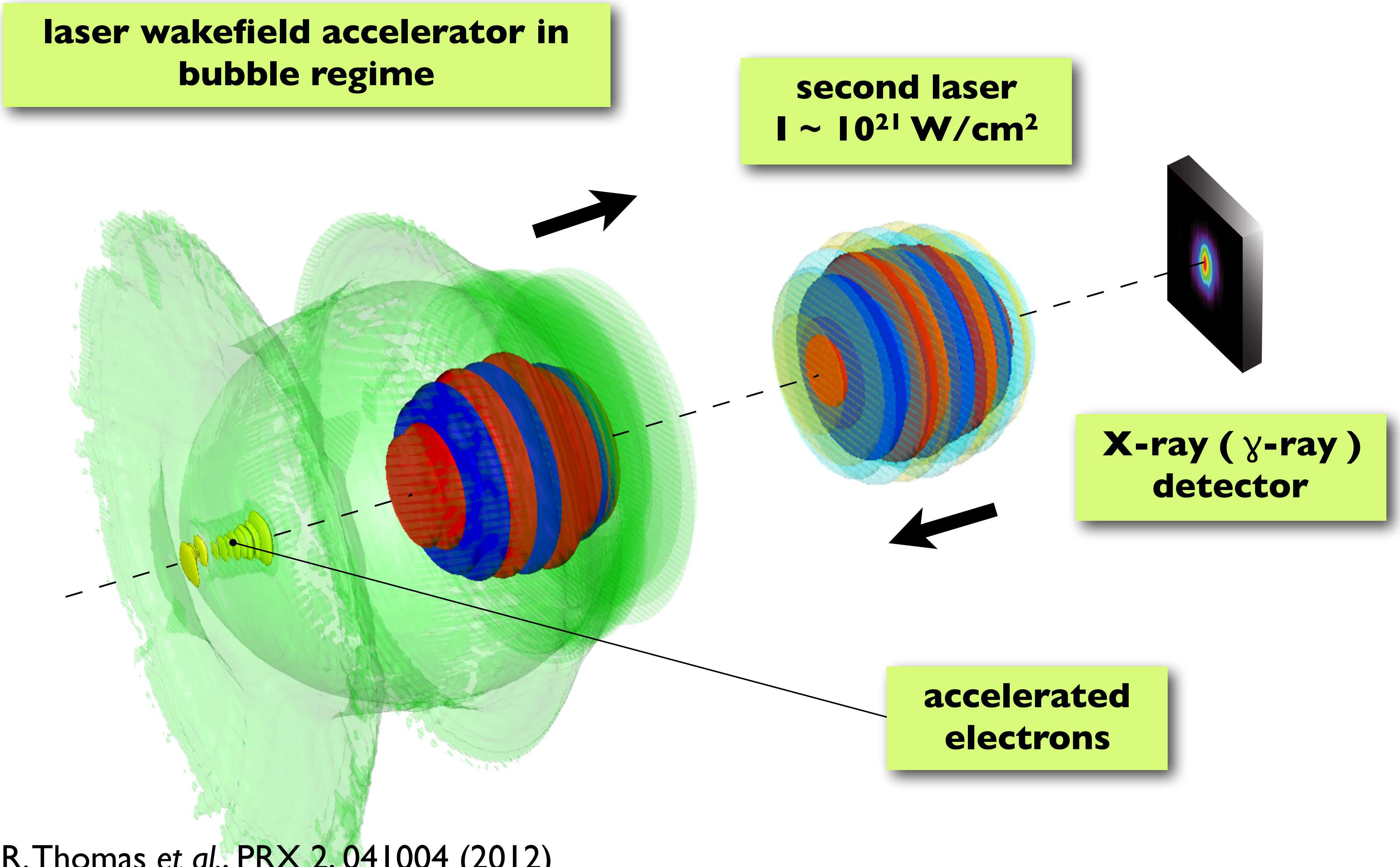
e-e+ plasmas

http://epp.ist.utl.pt/

All-optical radiation reaction configuration

Identifying radiation reaction signatures in electron beam spectrum

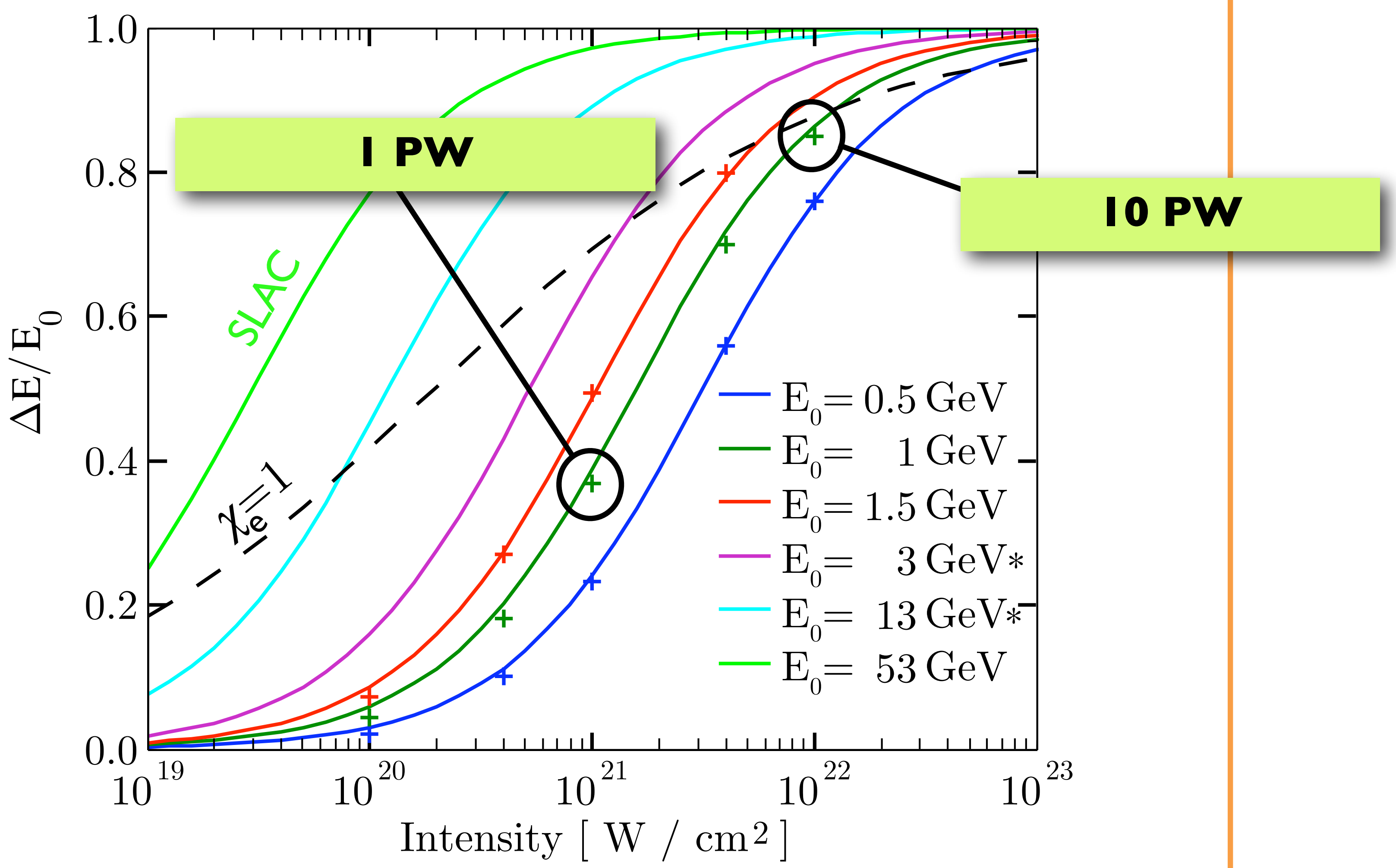


A. G. R. Thomas *et al.*, PRX 2, 041004 (2012)
M. Vranic *et al.*, PRL 113, 1348001(2014)

~40% energy loss for 1 GeV beam at 10^{21} W/cm^2

Radiation reaction can be tested with state-of-the-art lasers in this configuration

3D full-scale parameter scan



M. Vranic *et al.*, PRL 113, 1348001(2014)

Capturing QED in plasma simulations

2009 | 2010 | 2011 | 2012

Monte Carlo simulations showing pair production *via* real photons per electron

J. G. Kirk, A. R. Bell, and I. Arka, PPCF 51, 085008 (2009).

R. Duclous, J.G. Kirk & A.R. Bell, PPCF, 53, 015009 (2010)

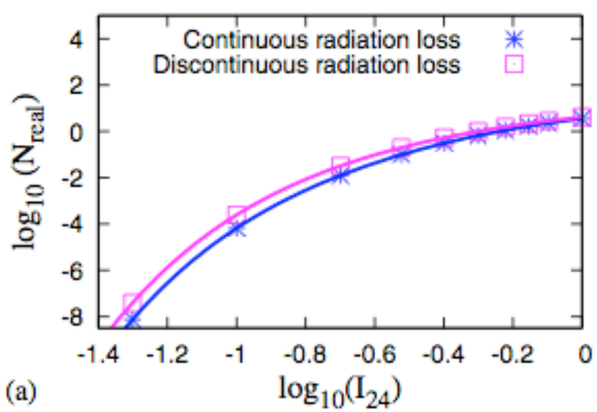
PIC simulations of QED cascade in various configuration (counter propagating laser, rotating field)

N.V. Elkina et al, Phys. Rev. ST. AB., 14, 054401 (2011)

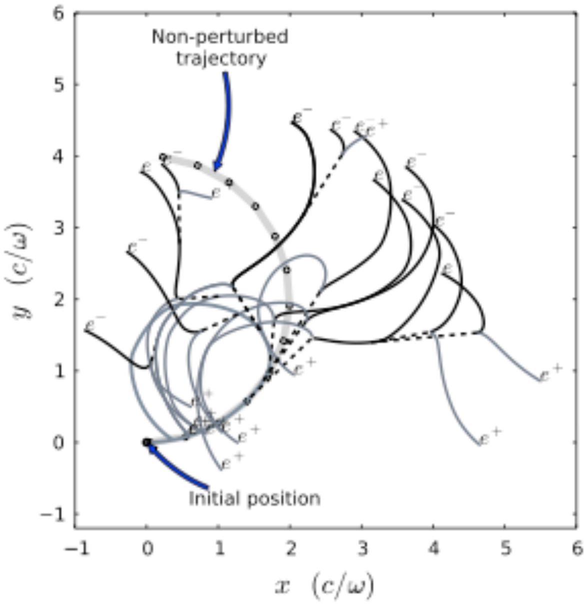
E.N. Nerush, et al, Phys. Rev. Lett., 106, 035001 (2011)

Dense pair Plasmas and Ultra-Intense Bursts of Gamma-Rays from Laser-Irradiated Solids

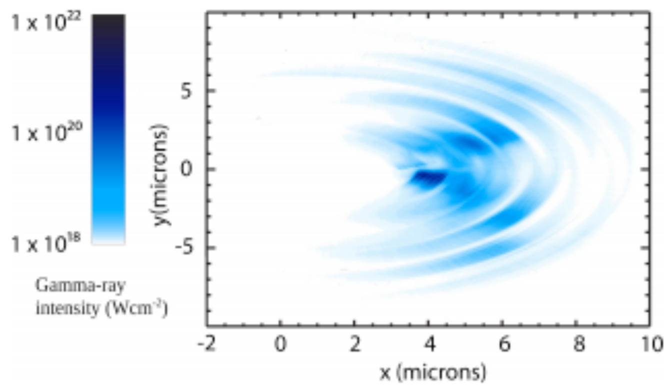
C.P. Ridgers, et al Phys. Rev.Lett., 108, 165006 (2012)



Number of pairs produced

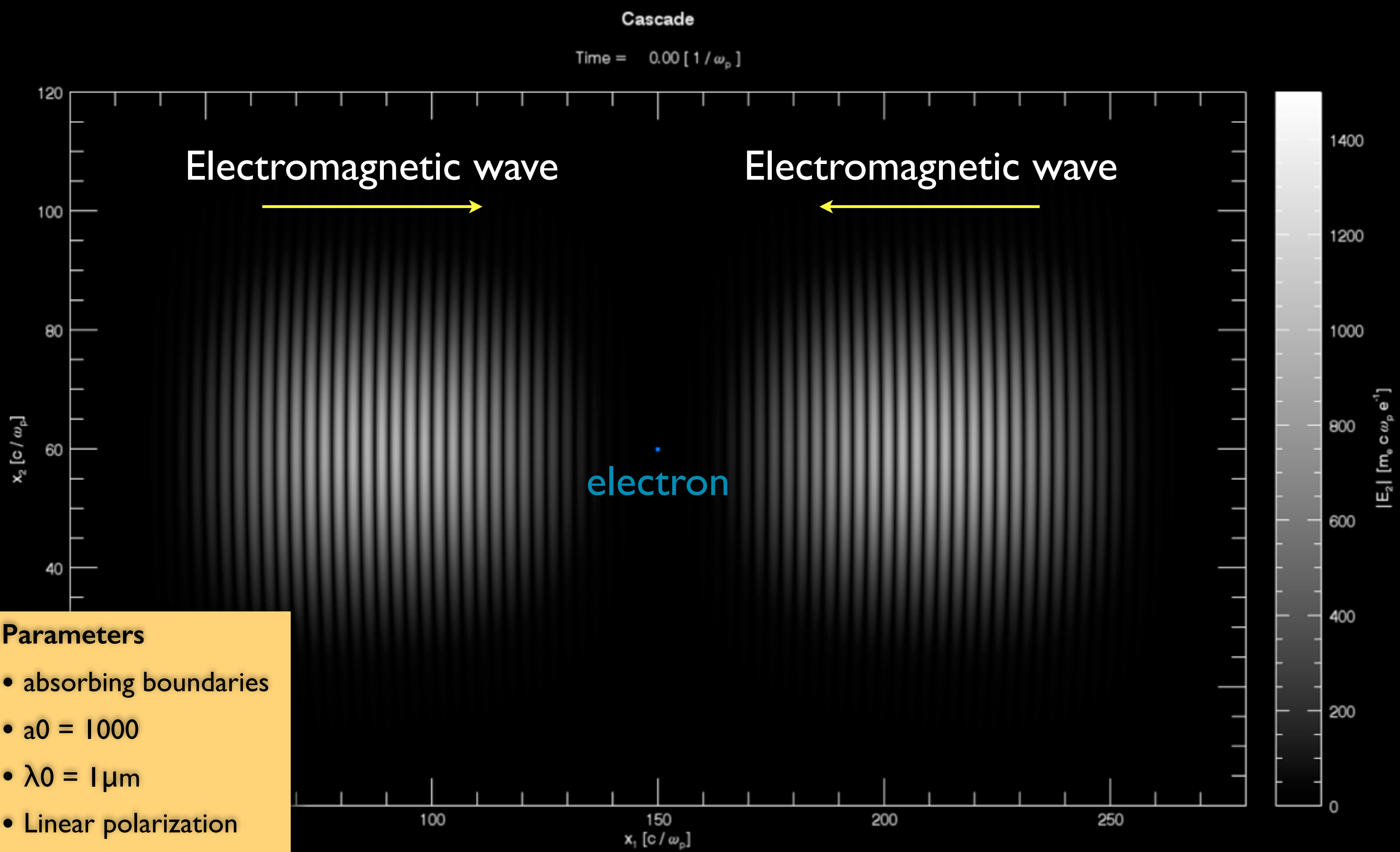


Picture of a cascade in rotating field



Gamma rays from laser-irradiated solid

Modelling of QED cascades (& radiation cooling)

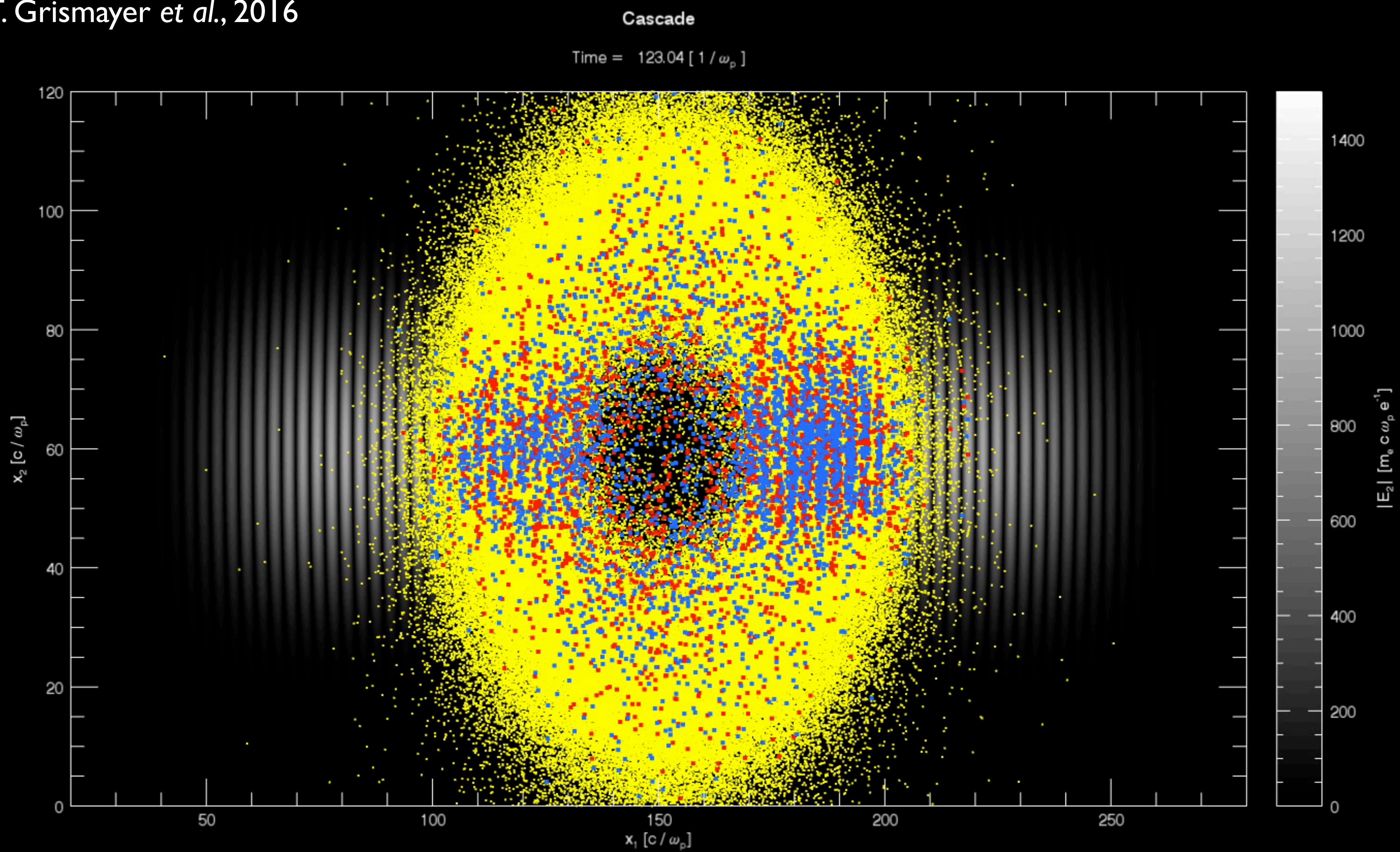


Parameters

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

QED cascades in counter propagating electromagnetic fields

T. Grismayer *et al.*, 2016

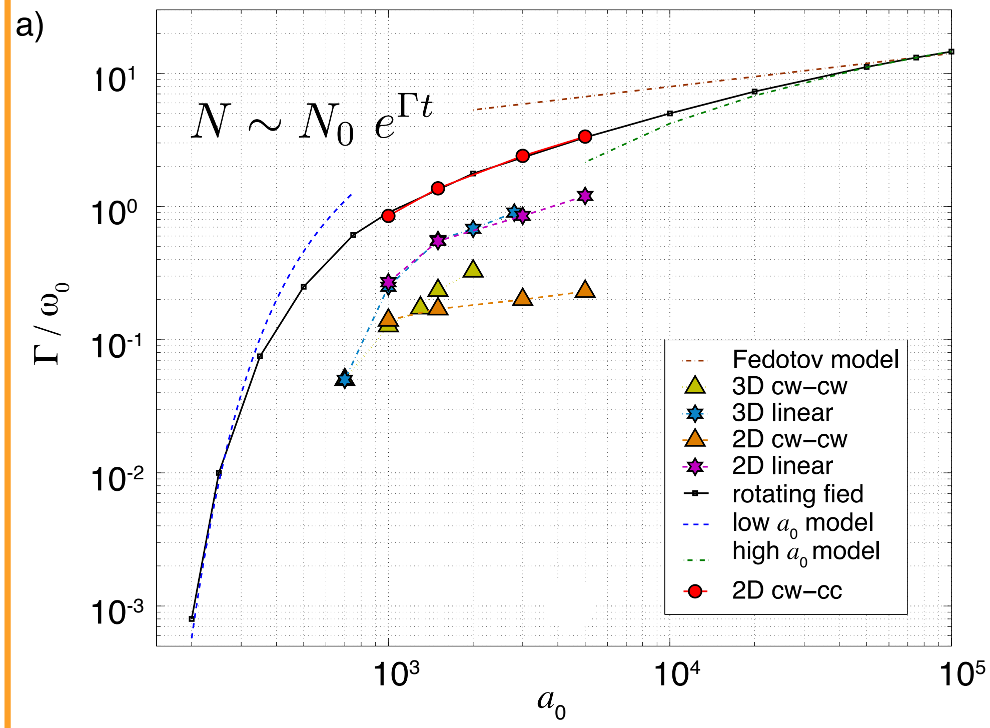


photons positron electron

QED cascades: from the seed to full laser absorption

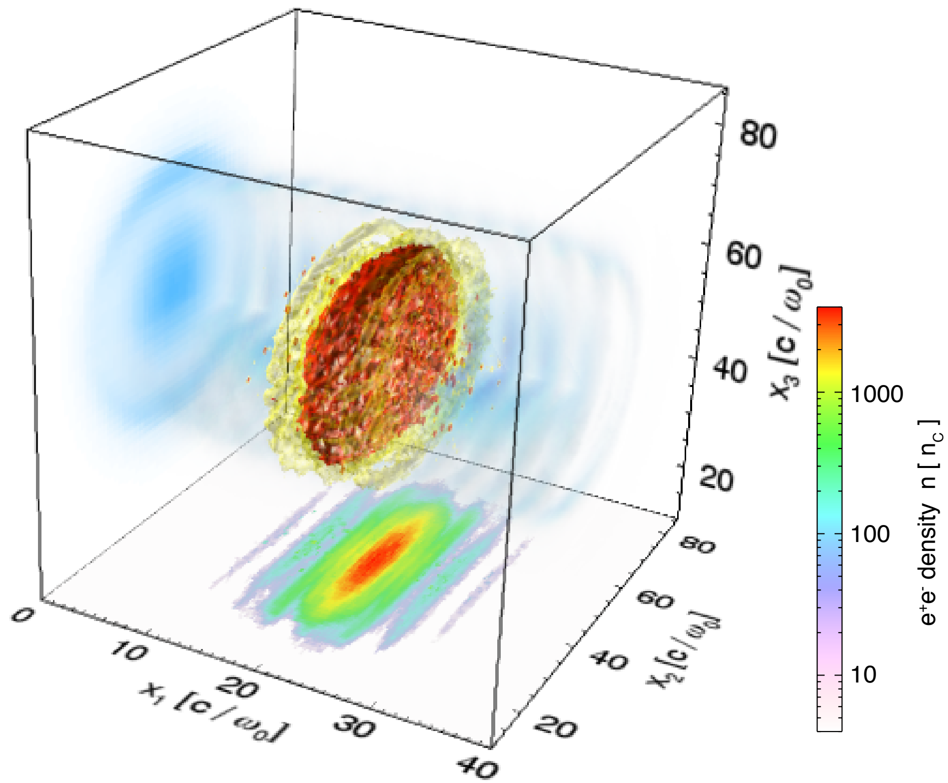
Analytical growth rate model + 3D full scale parameter scan

T. Grismayer, *et al.*, ArXiv: 1511.07503



Laser absorption via QED cascades absorption model + 2D, 3D sim.

T. Grismayer, *et al.*, ArXiv: 1512.05174



Possibility to achieve conditions close to the Goldreich-Julian density e-e+ density ~ n_{cr} ~ Goldreich-Julian density

A. Gruzinov, Arxiv:1404.4615v1 (2014)

Heisenberg-Euler QED corrections

Physics below Schwinger limit

◉ Relevance for extreme astrophysical scenarios?

◉ Effect on laser properties as we reach Schwinger limit?

◉ Extract observable consequences of fundamental QED predictions.

◉ ELI energies will allow us to probe the dynamics of the Quantum Vacuum.

Heisenberg-Euler corrections to Maxwell's Equations*

Electron-positron fluctuations give rise to an effective polarisation and magnetisation of the vacuum which can be treated in an effective form as corrections to Maxwell's equations.

$$\mathcal{L} = \mathcal{L}_{\mathcal{M}} + \mathcal{L}_{HE} + \mathcal{L}_D$$

Valid for static inhomogeneous fields such that

$$E << E_S \qquad \omega << \omega_c$$

$$E_S = \frac{m^2 c^3}{e\hbar} \qquad \omega_c = \frac{mc^2}{2\hbar}$$

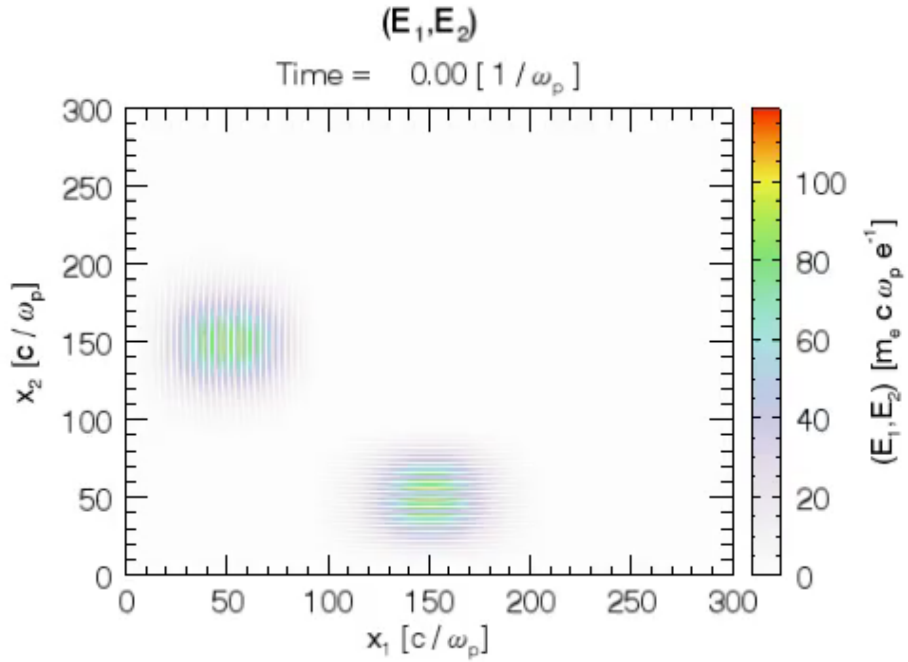
Effectively, we obtain a highly non linear, non dispersive vacuum (e.g. M.Soljačić and M. Segev Phys. Rev. A 62, 043817 (2000))

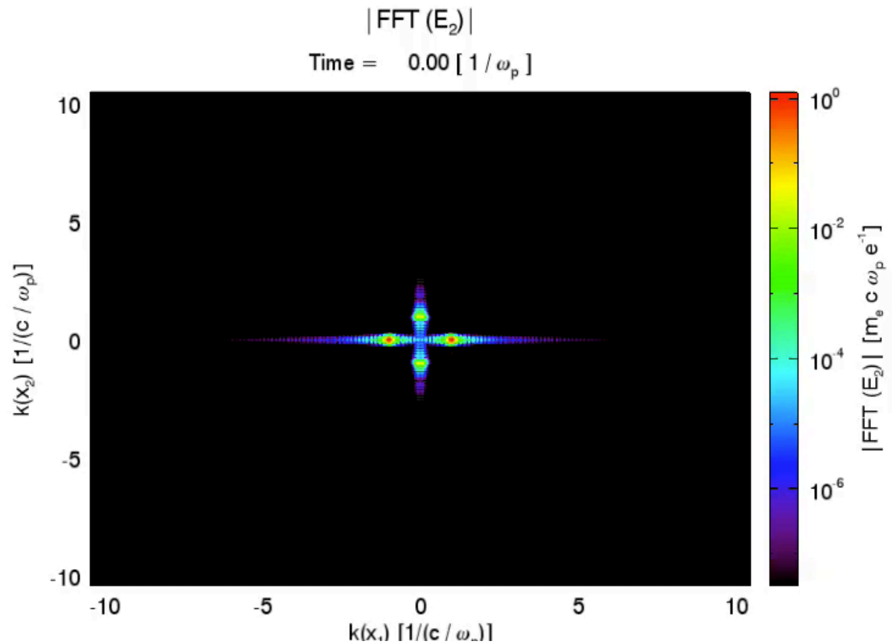
Higher order corrections include spatial and temporal derivatives of these corrections. May be neglected for: $\omega << \omega_c \frac{E}{E_S}$

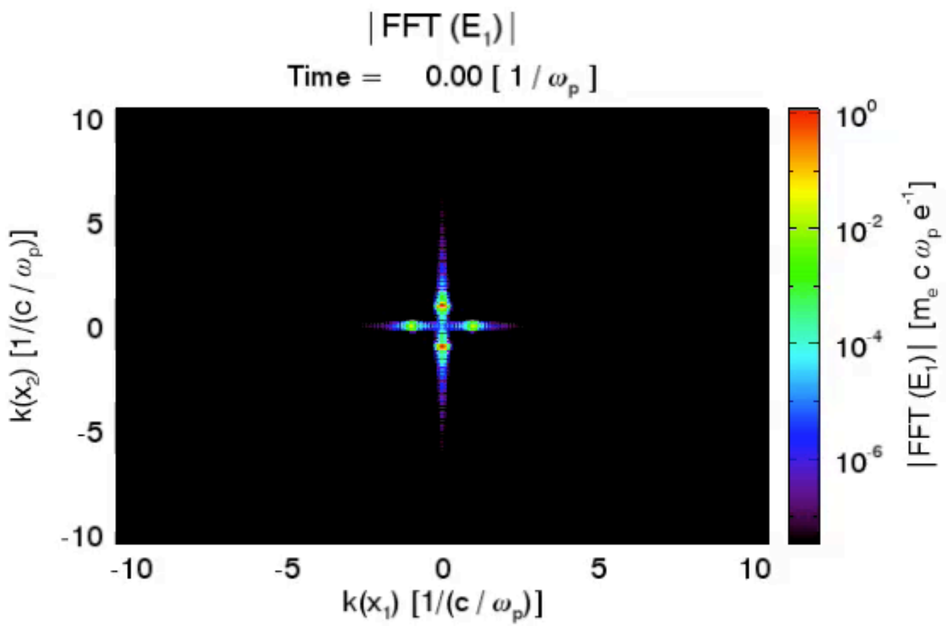
*W. Heisenberg and H. Euler, Z. Physik 98, 714 (1936).

Multi mode mixing due to nonlinear vacuum corrections

To be explored *e.g.* at HIBEF (XFEL + ultra high intensity laser)







Setup with 2 Gaussian pulses propagating in perpendicular directions (a_0 = 100, ξ = 10^{-6}, λ = 1 μm)

Combination of odd and even harmonics is generated; **After interaction**, imprint is left in both pulses as they now freely propagate.

P. Carneiro *et al*,. in preparation (2016)

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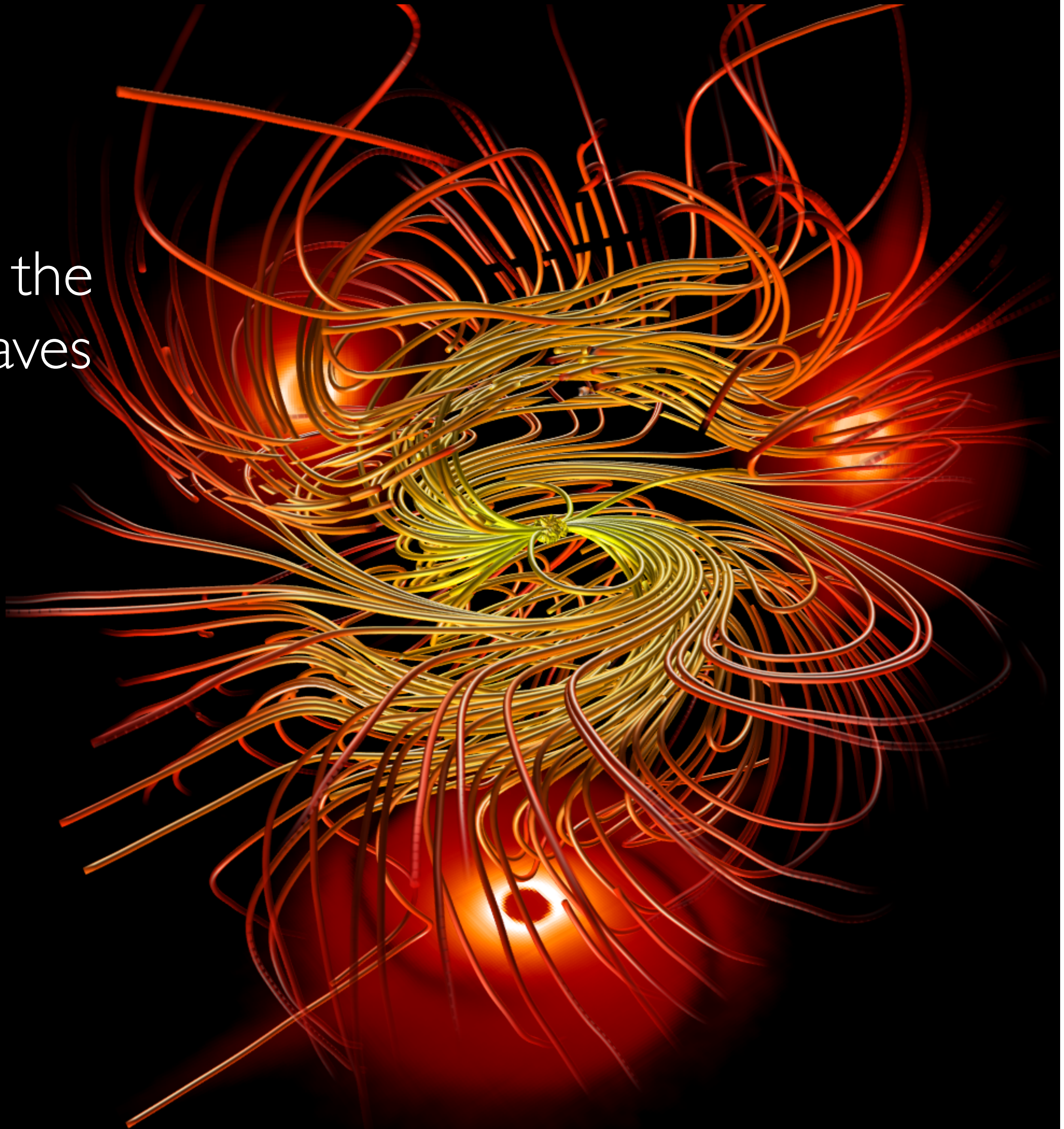
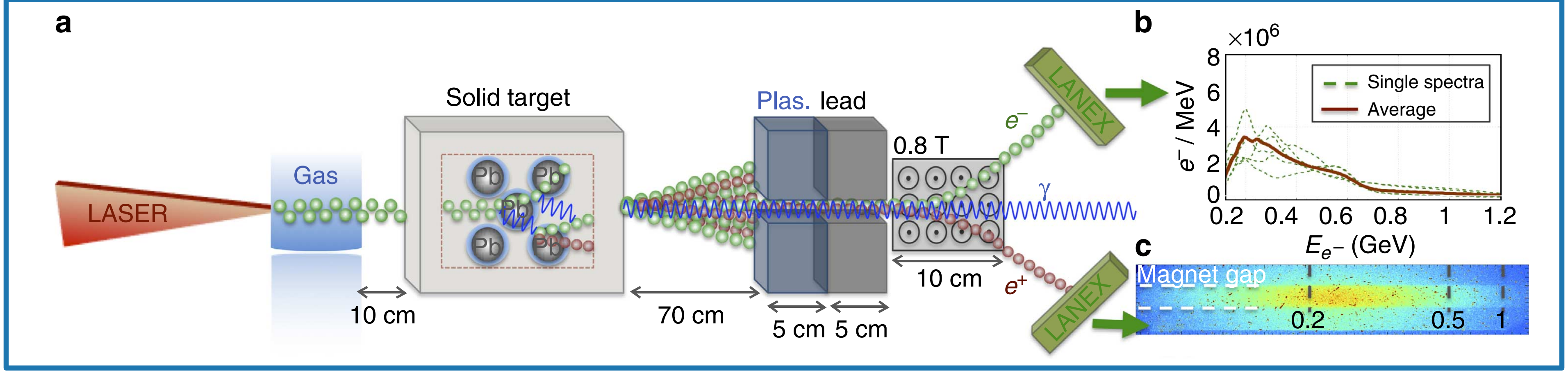
http://epp.ist.utl.pt/

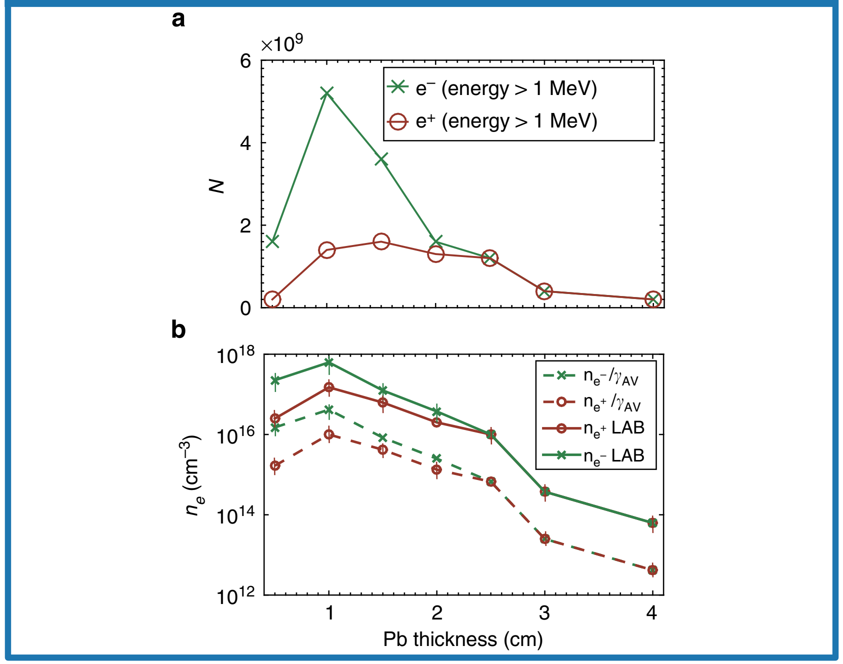


e-e+ fireballs from laser generated beams in solids

Experimental results demonstrate formation of e-e+ fireball



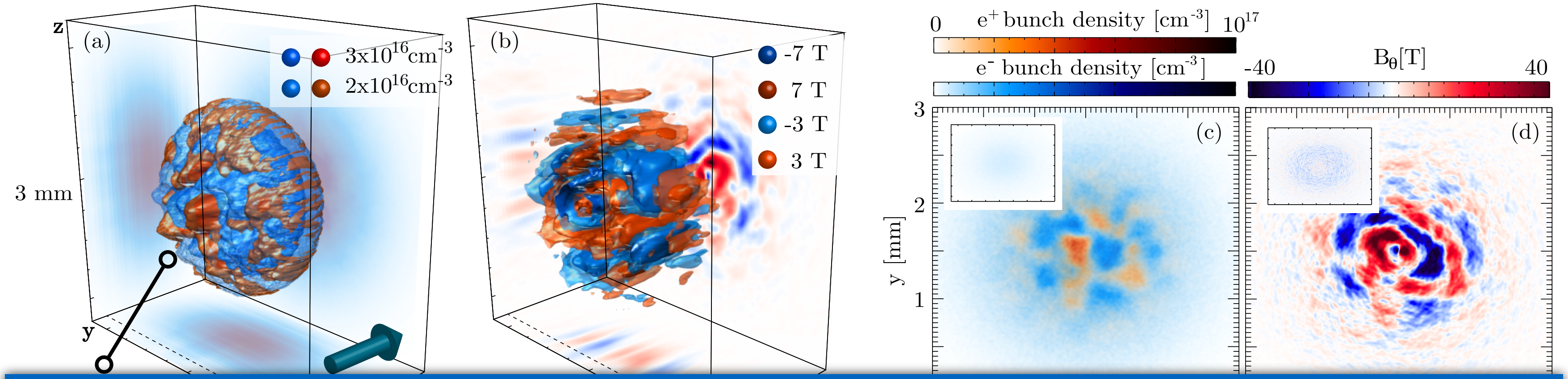
e-e+ fireball is neutral



G. Sarri *et al.*, Nature Communications (2015)

e-e+ fireballs to explore Weibel instability

LWFA fireball beam will undergo current filamentation instability



G. Sa

e-e+ plasma

Additional source of secondary radiation (e.g. gamma rays)

Platform to understand microinstabilities of relevance in astrophysics

"Dark electromagnetism"

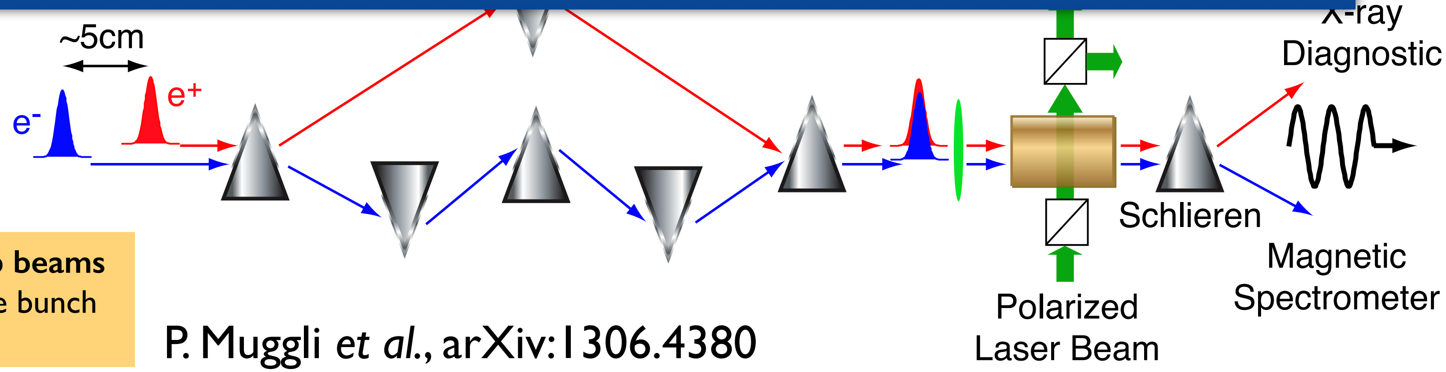
29

$\sigma_x = \sigma_y = 2\sigma_z = 20\ \mu m$

$\mathrm{Emittance} = 10^{-5}\ \mathrm{mrad}$

Dephasing technique to overlap beams

Typically used in PWFA to reduce bunch distance to ~100 microns



P. Muggli *et al.*, arXiv:1306.4380

Scenarios where all this comes together

Pulsar magnetospheres

M.A. Belyaev, MNRAS (2015)

A.A Philippov, A. Spitkovsky, B. Cerruti, ApJ Lett (2015)

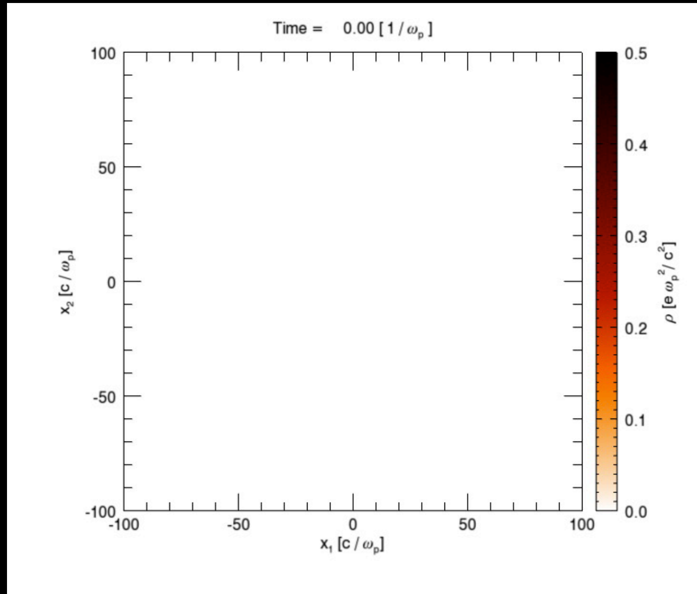
Y. Chen, A. M. Beloborodov, ApJ Lett (2014)

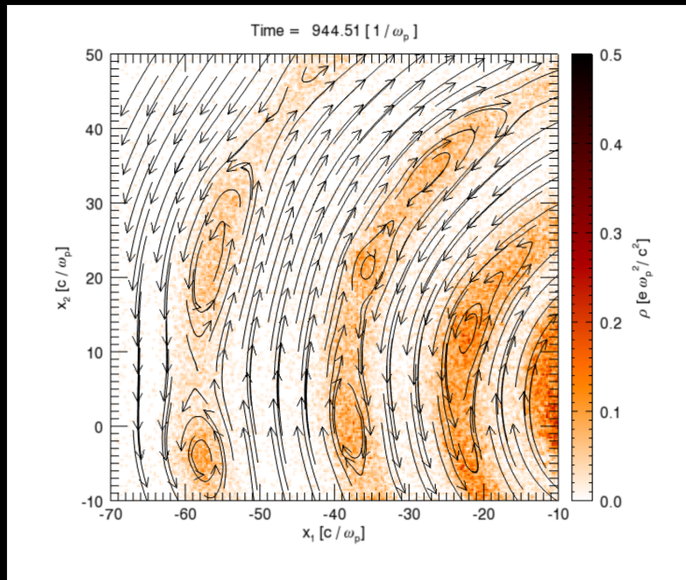
A.A Philippov, A. Spitkovsky, ApJ Lett (2014)

A. N. Timokhin, MNRAS (2010)

JK Daugherty and AK Harding, ApJ (1982)

P. Goldreich and W.H Julian, ApJ (1969)





Summary

A wide range of extreme laboratory and astrophysical scenarios can now be explored and captured by *ab initio* plasma simulations encompassing physics beyond *classical plasma physics*

Upcoming lasers at ultra high intensities (and the prospects provided by Raman/Brillouin amplification & compression) will allow for the exploration of a new range of phenomena

http://epp.ist.utl.pt/