Wakefield Acceleration of Positron Bunches in the Blowout Regime

Jorge Vieira

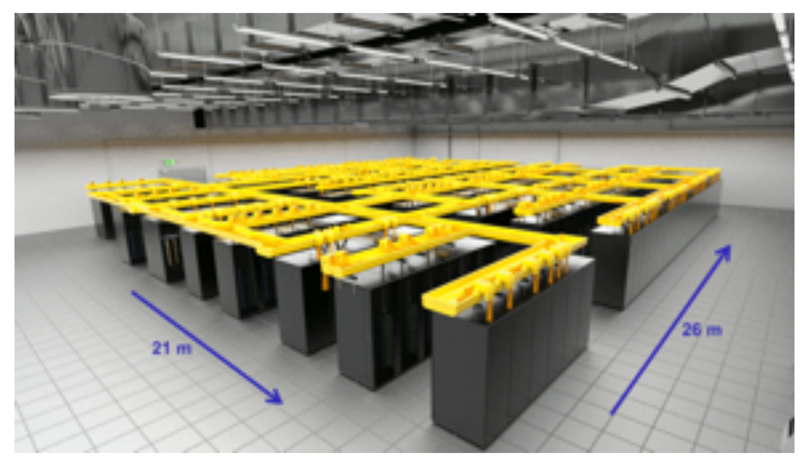
Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Lisbon, Portugal

[http://epp.ist.utl.pt[/jorgevieira]](http://epp.ist.utl.pt[/jorgevieira])

Acknowledgments

- Work in collaboration with:
  - **L. D. Amorim, R. A. Fonseca, J. T. Mendonça, L.O. Silva** (IST); **R.Trines, R. Bingham, P. Norreys** (RAL)
- Simulation results obtained at **SuperMUC** and through **PRACE** awards

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



golp grupo de lasers e plasmas

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

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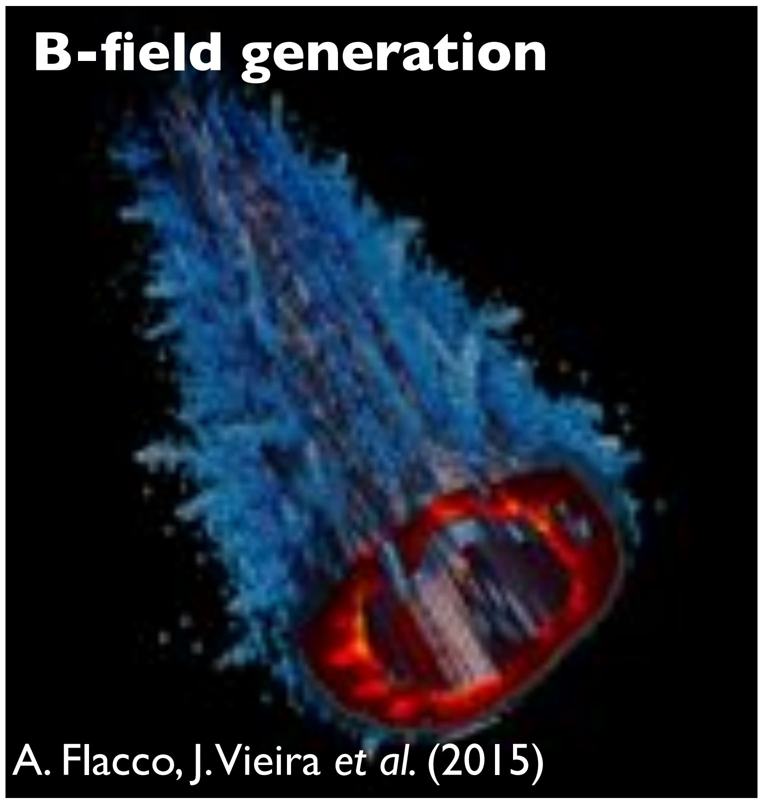
Ultra-intense lasers have a multitude of applications

Achievements reached exploring very few fundamental properties (e.g. intensity)

Astrophysics

B-field generation



A. Flacco, J.Vieira *et al.* (2015)

Collisionless shocks

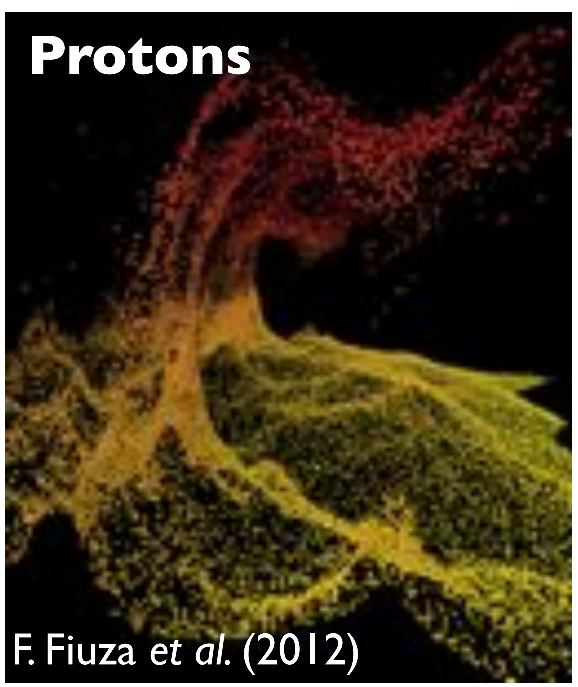
F. Fiuza *et al.* (2012)

Particle acceleration

Electrons

S.F. Martins *et al.* (2010)

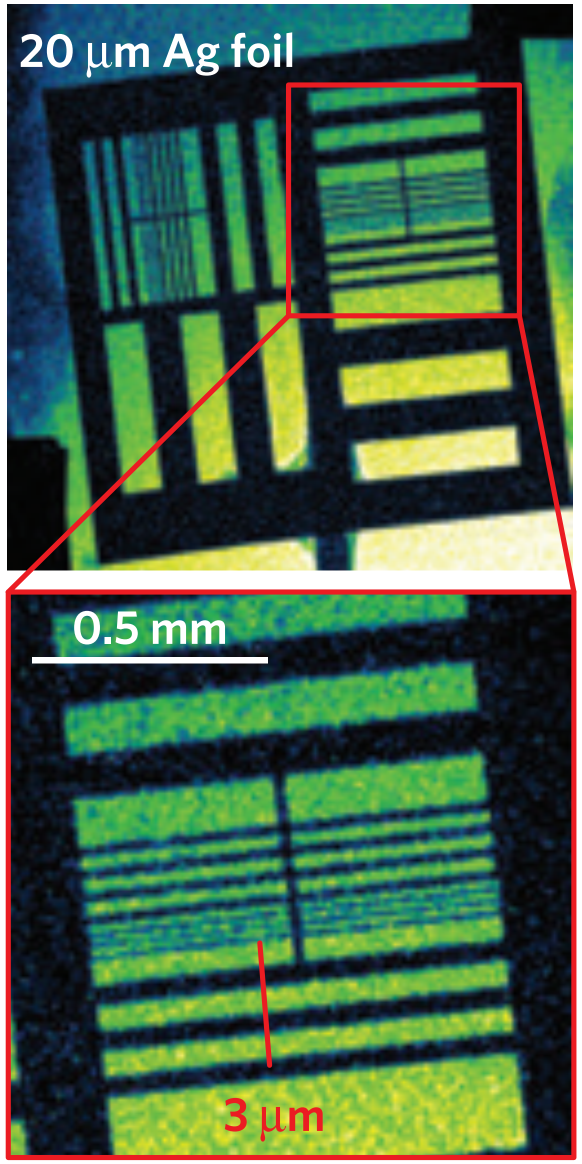
Protons



F. Fiuza *et al.* (2012)

Radiation generation

Betatron radiation

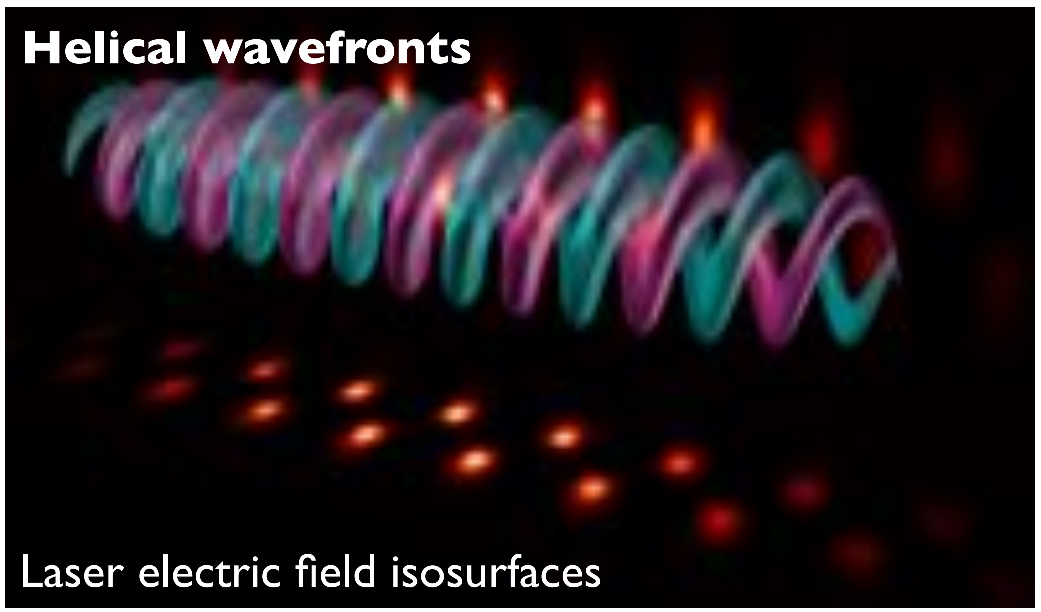


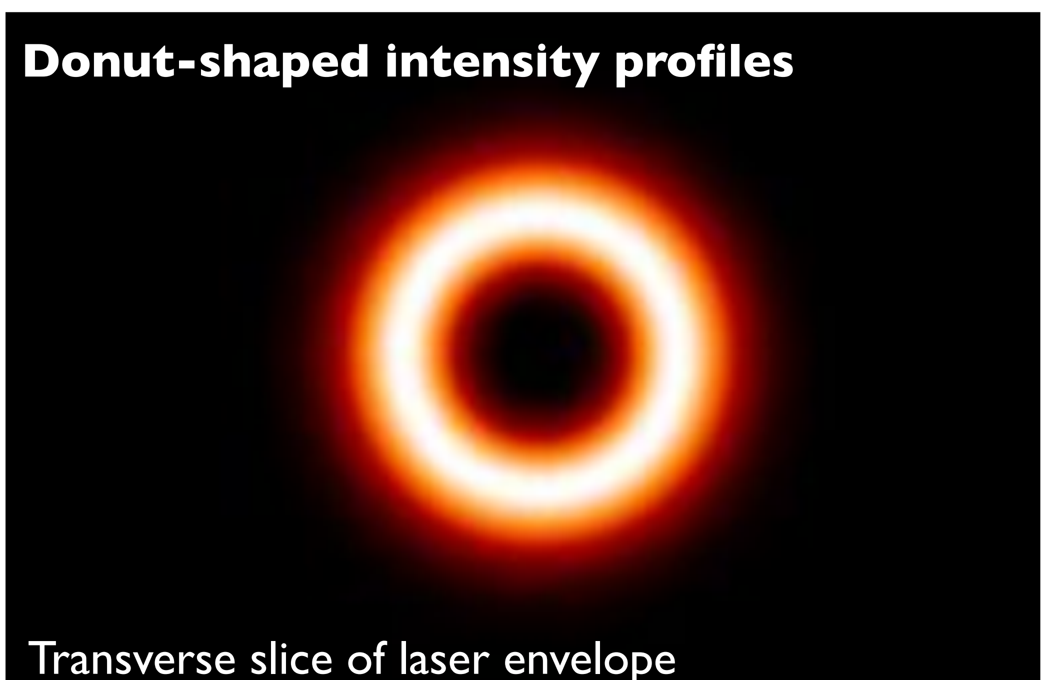
S. Kneip *et al.* (2010)

Exploring new fundamental degrees of freedom in lasers could also give rise to equally exciting achievements

Orbital angular momentum is a fundamental degree of freedom that stands in equal foot to laser intensity and duration

Main properties of OAM





OAM lasers are described by LG modes

Transverse laser profile: Helical phase and doughnut shaped profile

$$a_r(r) = \underbrace{c_{l,p}}_{\text{Normalization}} \left(\frac{r}{w_0}\right)^{|l|} \exp\left(-\frac{r^2}{w_0^2} + \overbrace{il\theta}^{\text{Helical phase}}\right) \underbrace{L_p^{|l|}}_{\text{Generalized Laguerre Polynomial}} \left(\frac{2r^2}{w_0^2}\right)$$

Orbital angular momentum also corresponds to spiralling wavevector

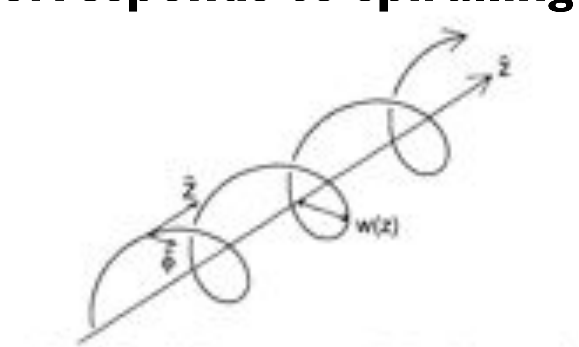


FIG. 2. The spiraling curve represents the Poynting vector of a linearly polarized Laguerre-Gaussian mode of radius w(z).

L. Allen et al, PRA (1992)

laser k has an azimutal component.

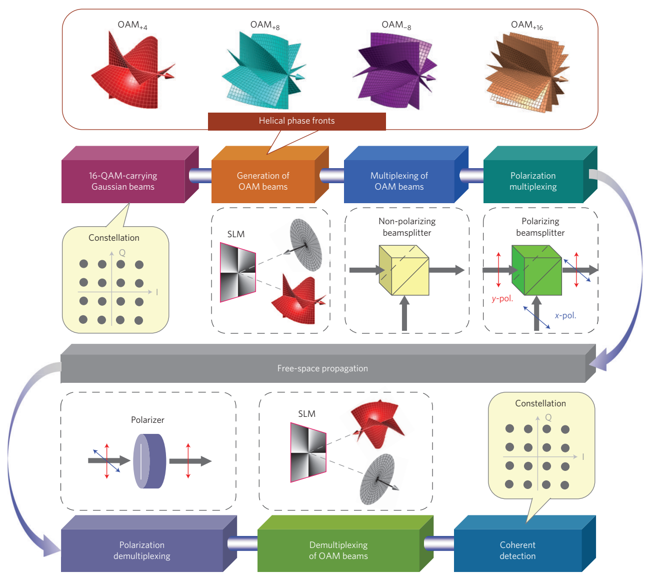
laser k rotates an integer number of turns (l) per laser wavelength.

Revolutionary applications at low intensities below damage thresholds

The role of orbital angular momentum in laser-plasma interactions has been scarcely explored.

Communications

Ultra-fast terabit data transmission

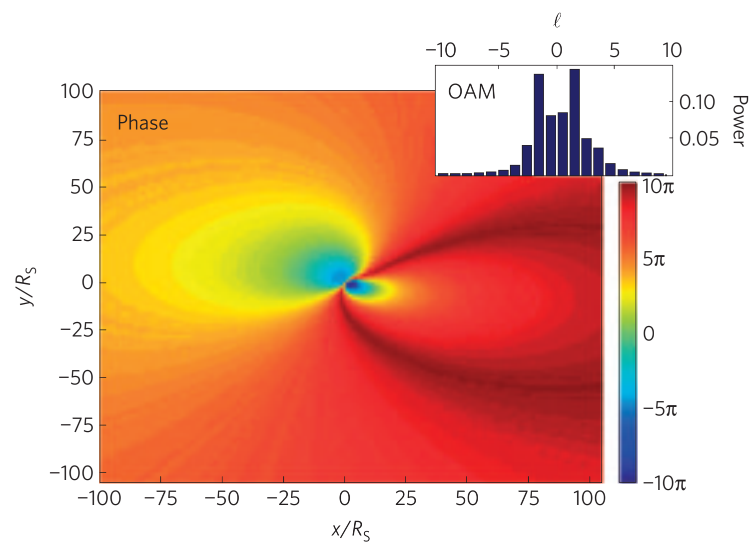


More information encoded for different OAM at each frequency

Wang et al, Nat Photonics 2012

Astrophysics

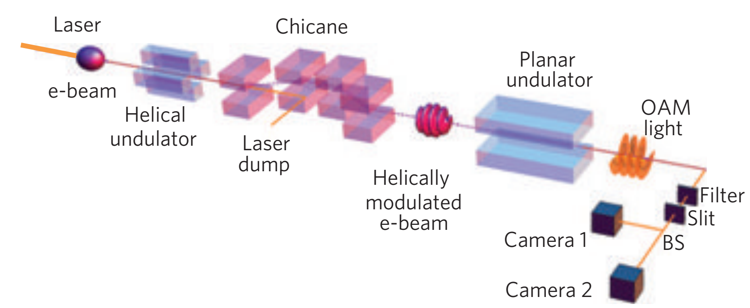
OAM in rotating black holes

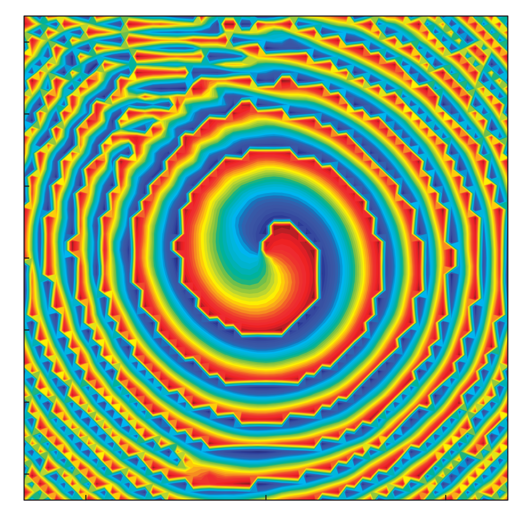


Tamburini et al, Nat Physics 2011

OAM x-rays

Helical e- beams in undulators





E. Hemsing et al, Nat Physics 2014

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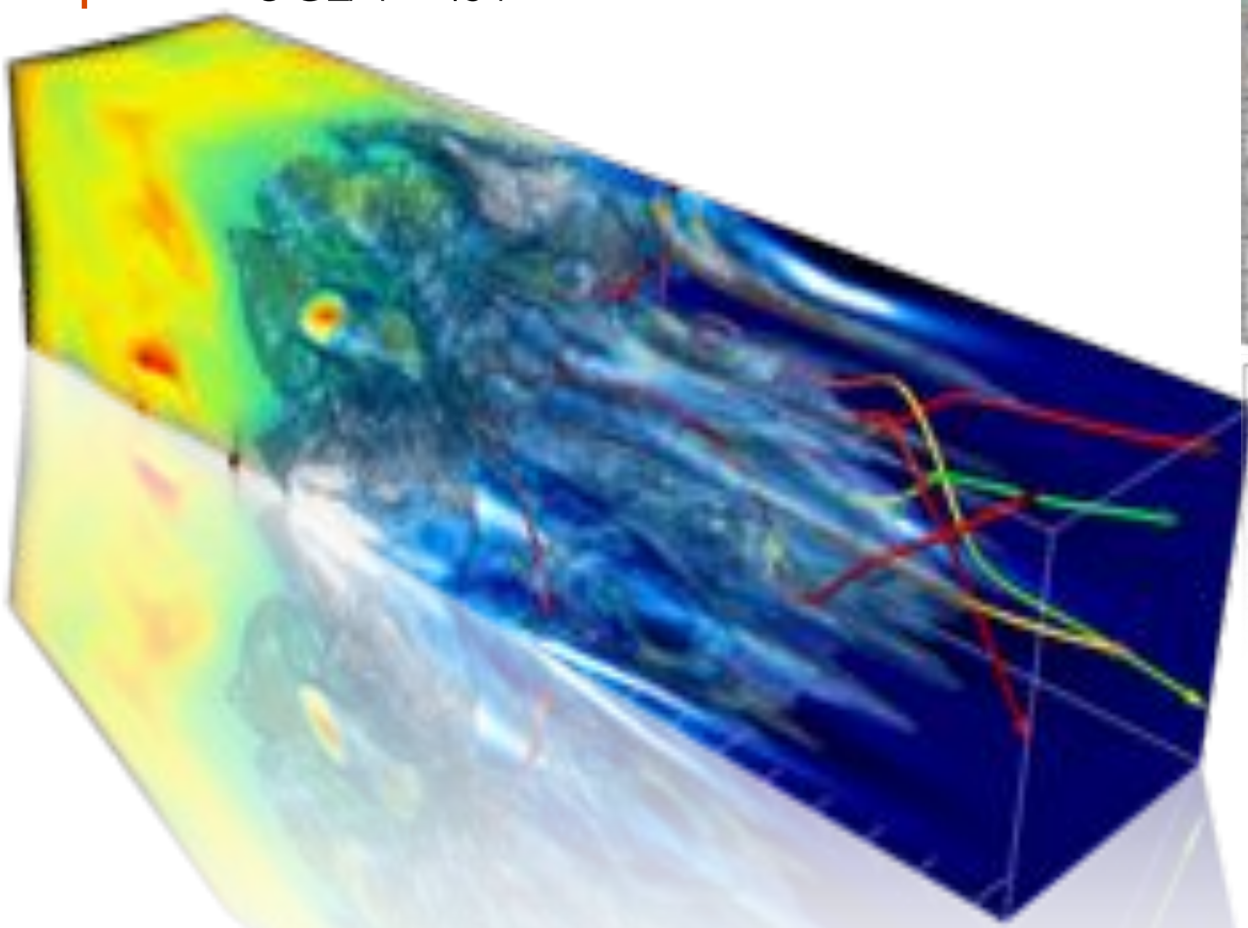
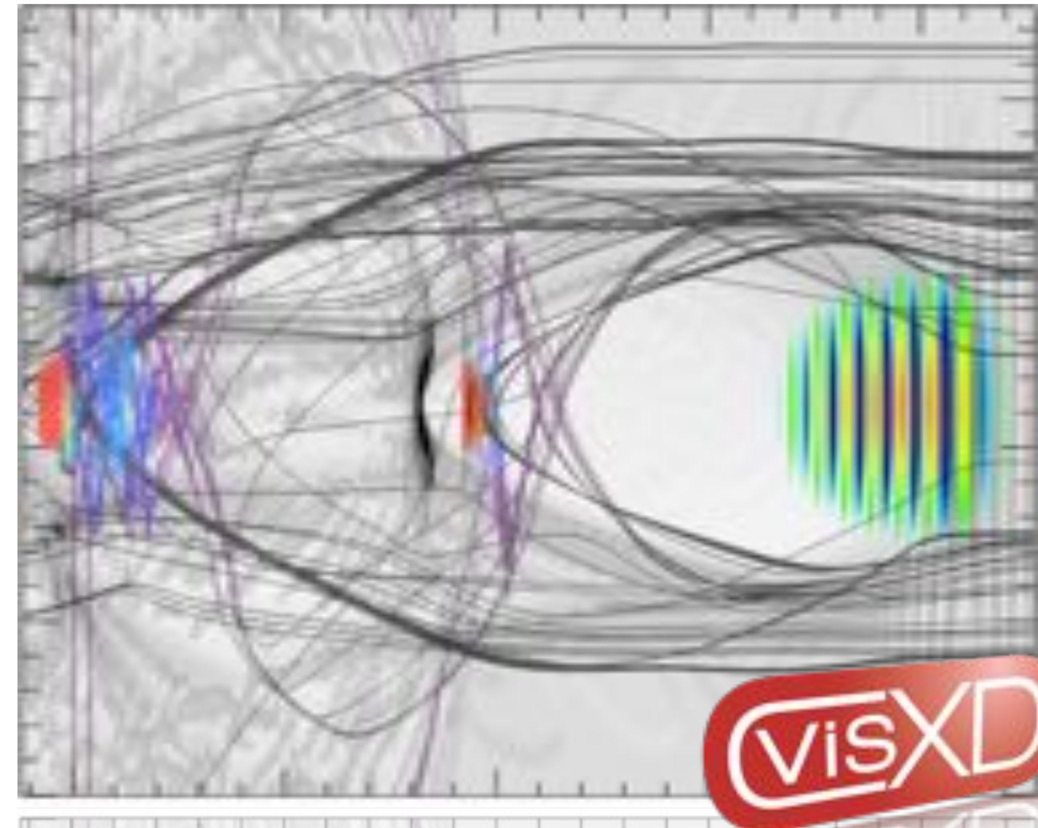
One of the challenges for a plasma based linear collider is high gradient positron acceleration

OSIRIS 2.0 , 3.0 /dev

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

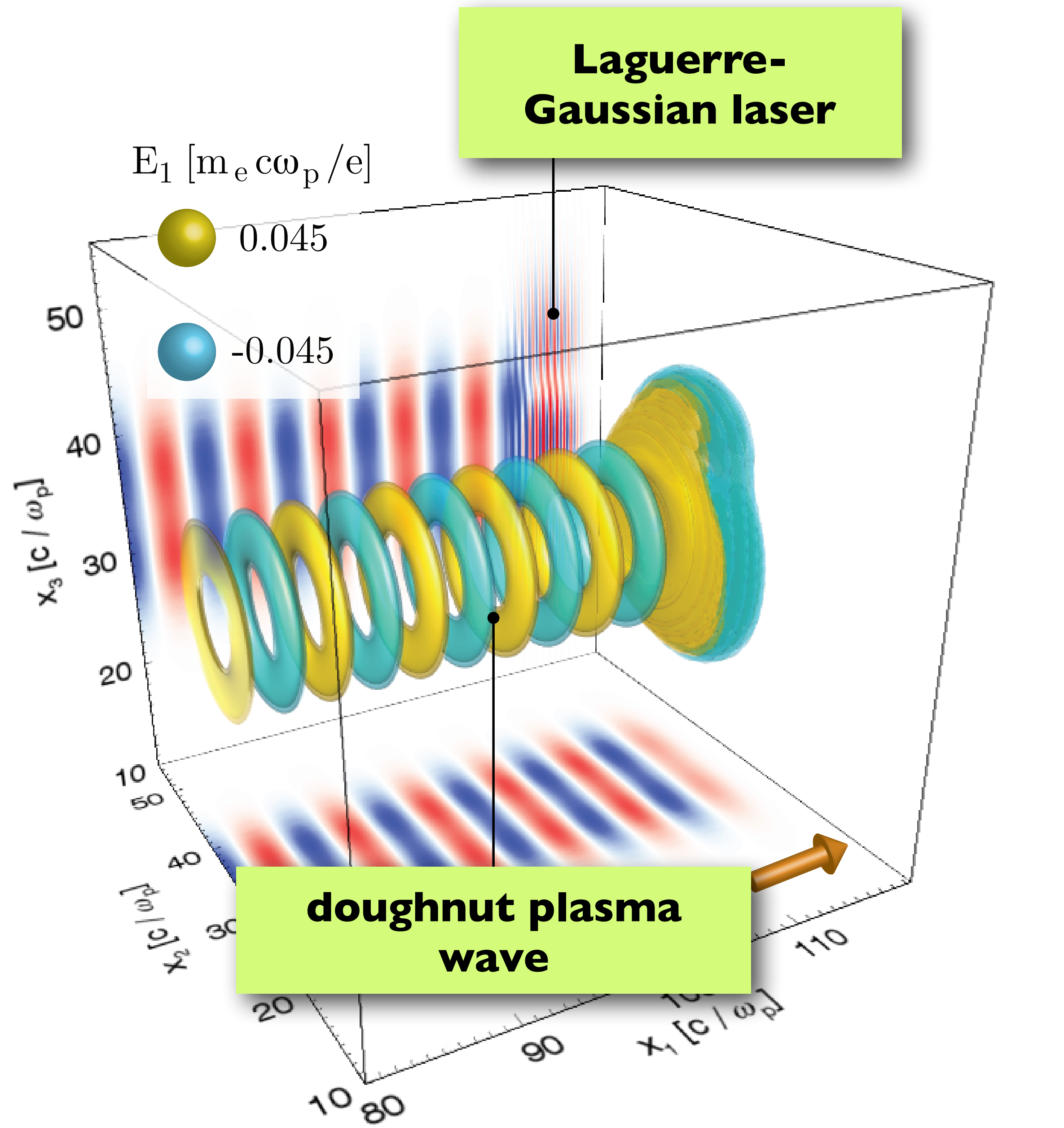
- Scalability to ~300 K cores
- SIMD hardware optimized
- Tunnel (ADK) and Impact Ionization
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D
- Ponderomotive guiding center

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/

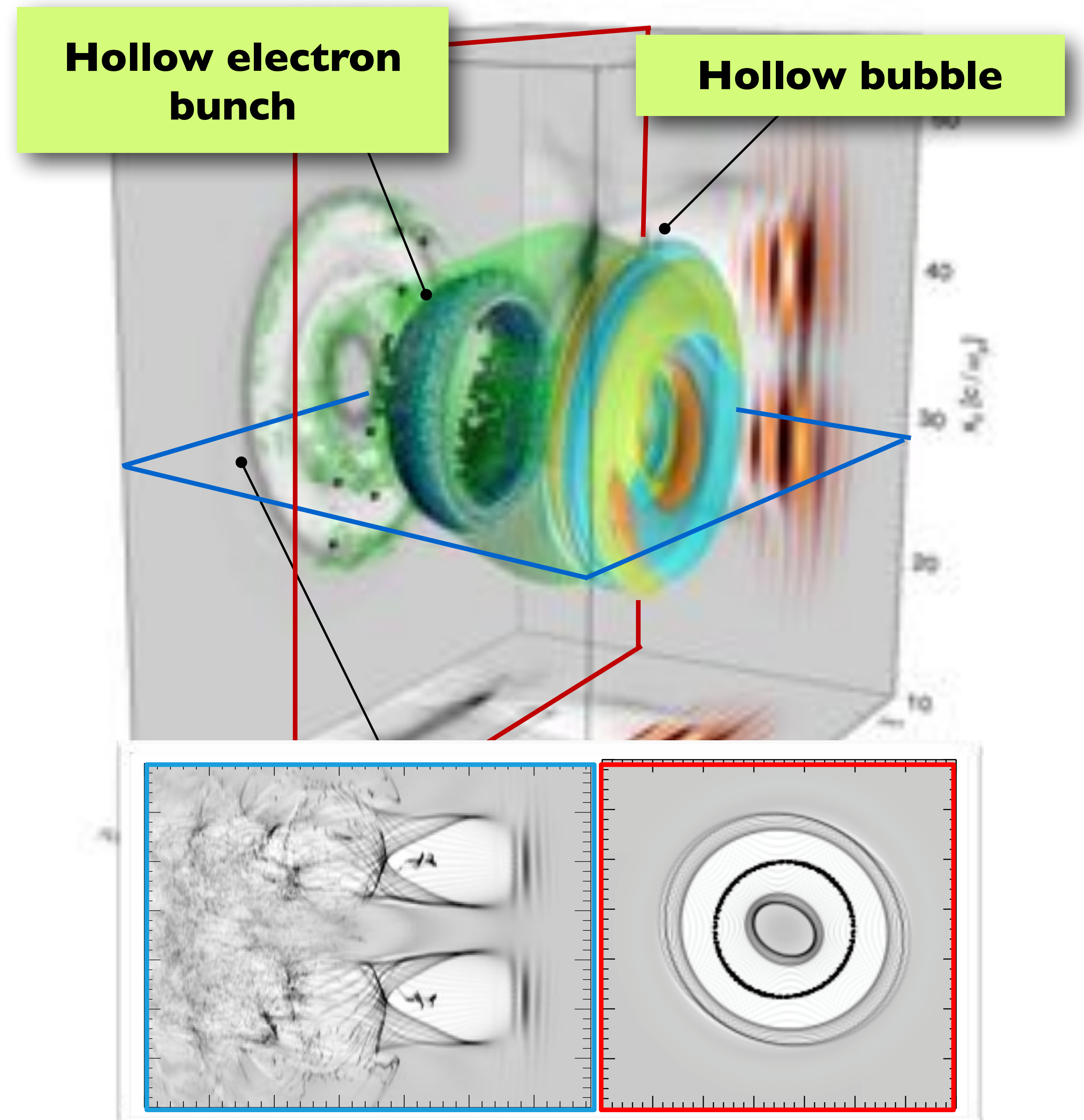
Laguerre-Gaussian lasers can drive doughnut shaped bubbles in strongly non-linear regimes

Linear doughnut wakefields



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

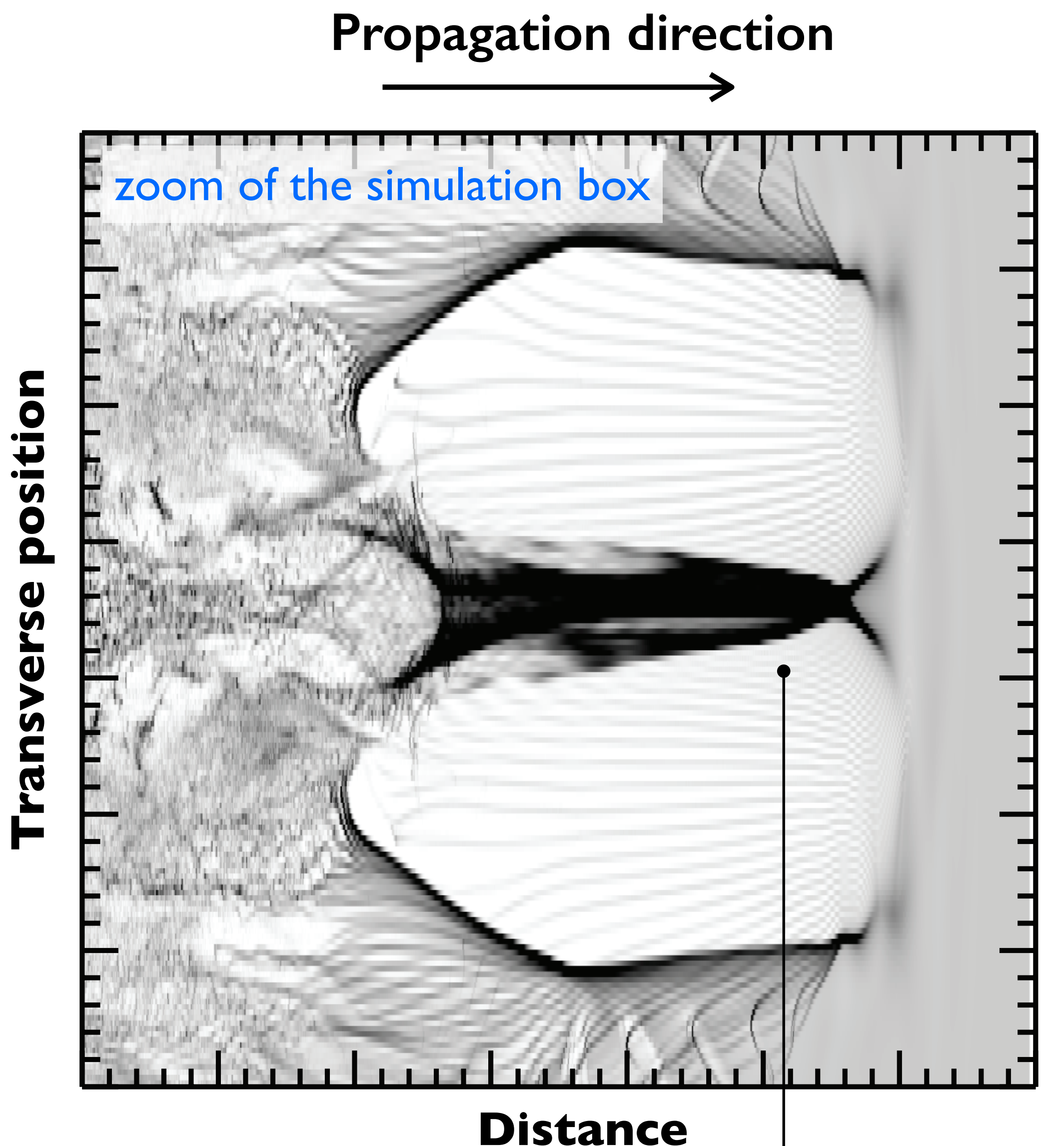
Non-linear doughnut bubbles



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

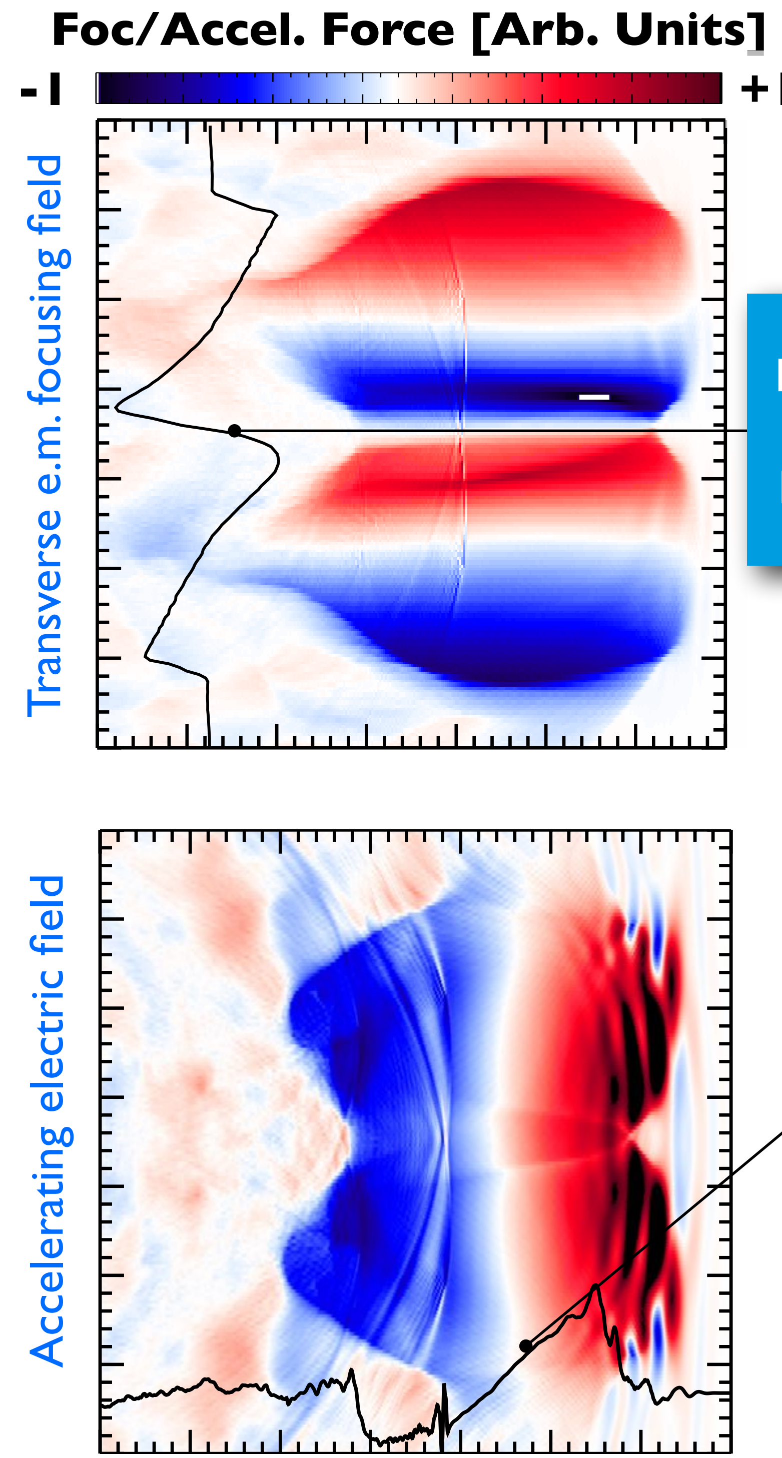
The onset of positron focusing and acceleration occurs when the inner sheath of the doughnut bubble merges on-axis

Onset of positron focusing



electrons merge on-axis providing positron focusing for $a_0 > (8W_0[c/\omega_p])^{1/2}$

e+ can accelerate at doughnut front



Positron focusing fields provided by electron layer

Positron acceleration fields

Doughnut bubbles can have positron focusing fields that are much stronger than pure ion channel

Non-linear theory in the blowout

Large blowout radius

$$\alpha = \frac{\Delta}{R_b} \ll 1$$

Focusing force in electron-focusing regions

$$W_r = \frac{r}{2} - \frac{R_b^2}{8r}$$

Focusing force in positron-focusing regions

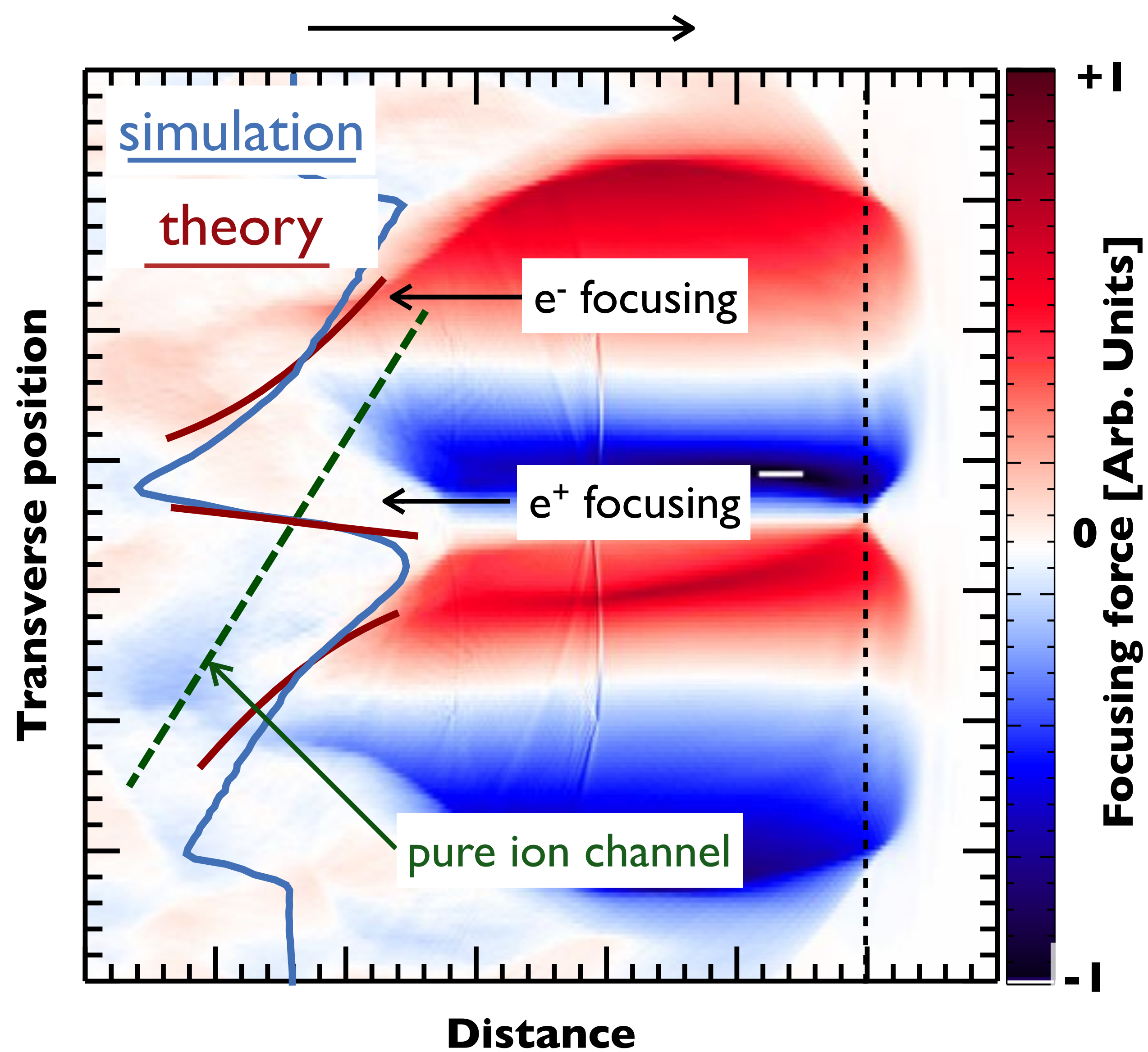
$$W_r = \frac{r}{2}\left[1 - \frac{1}{4\alpha^2}\right] \simeq -\frac{r}{8\alpha^2}$$

Ion column

Electron filament

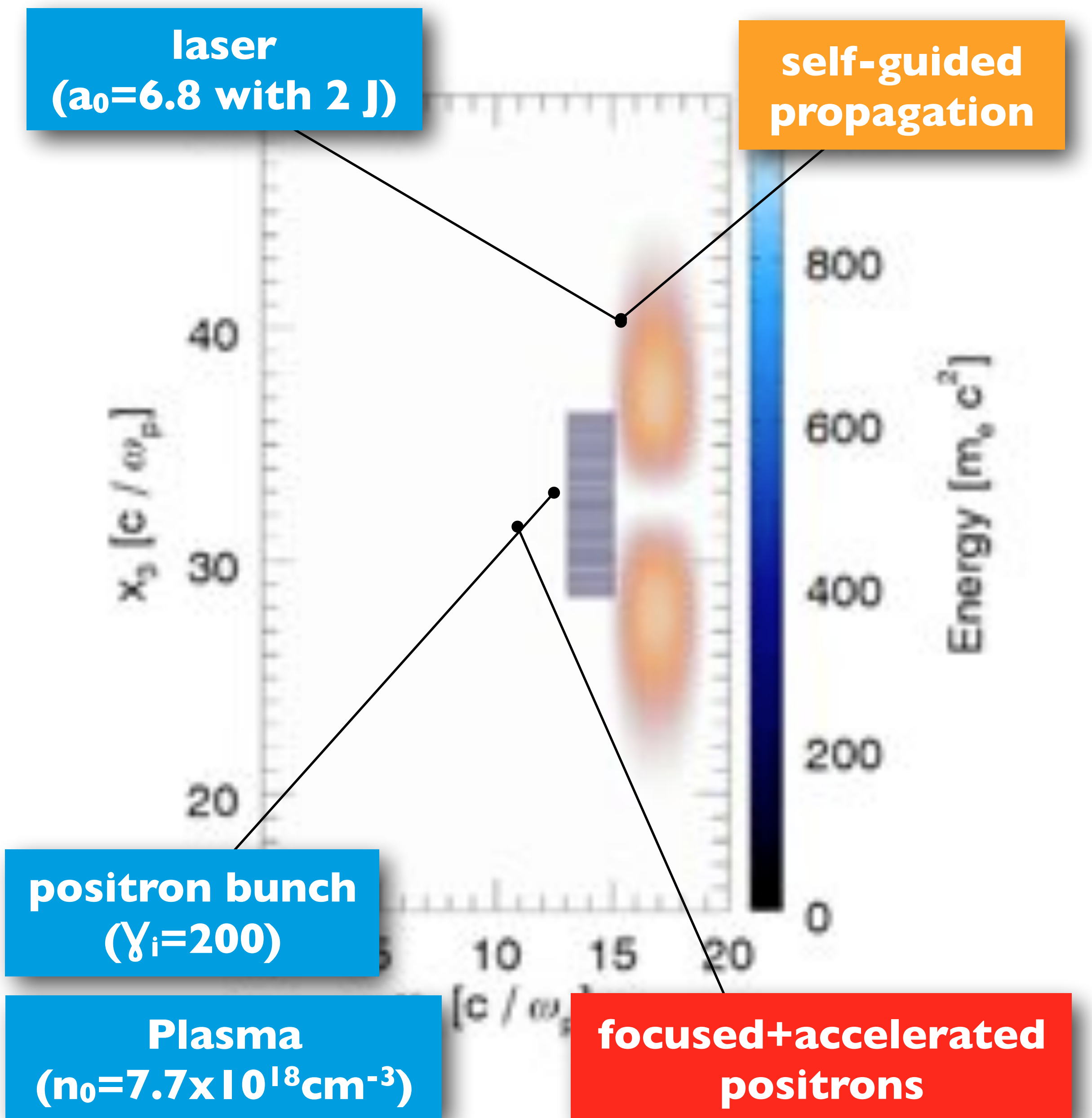
Strong positron focusing!

Focusing force in blowout

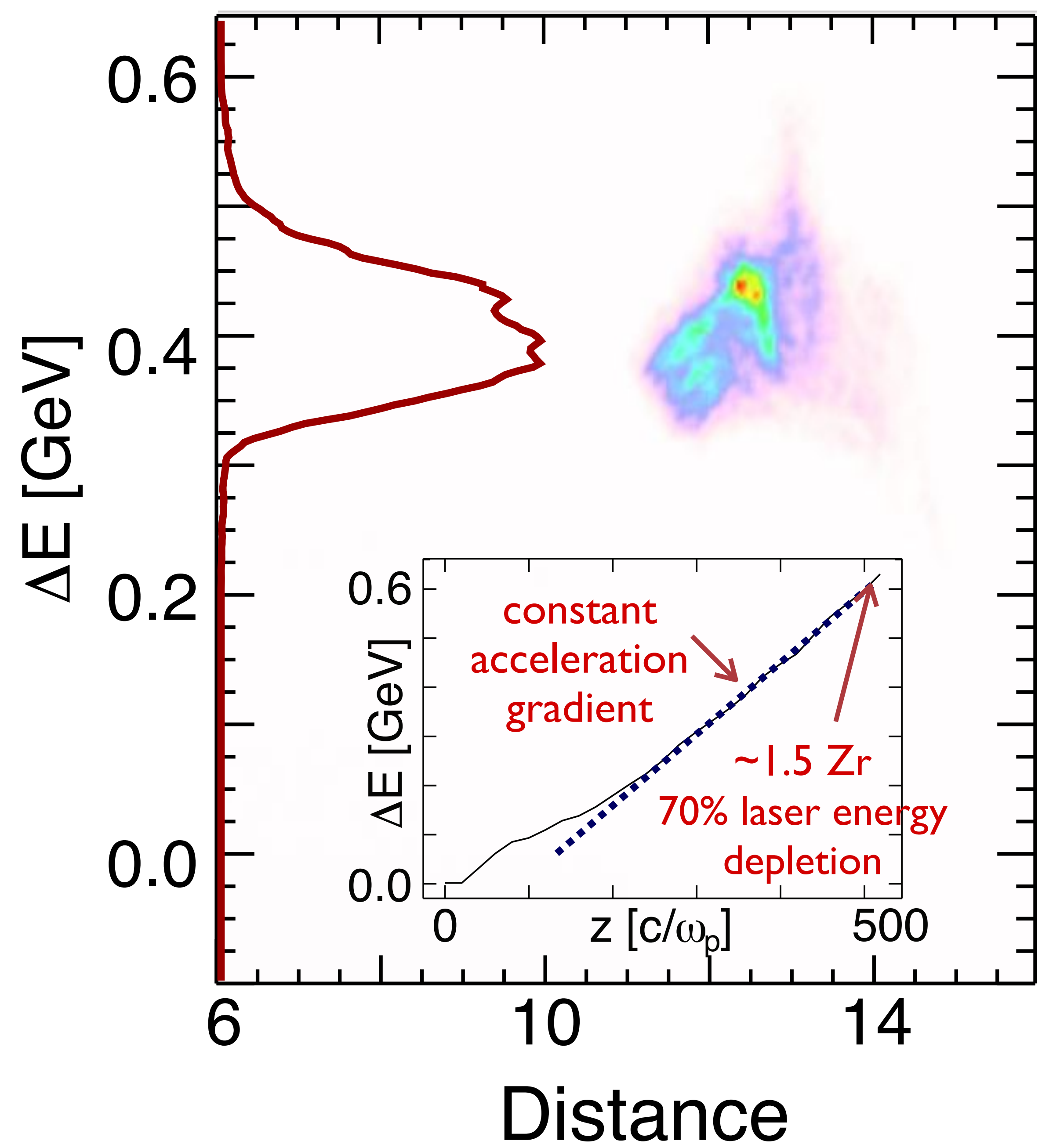


3D simulations show positron acceleration in strongly non-linear regimes

3D simulation of e+ acceleration

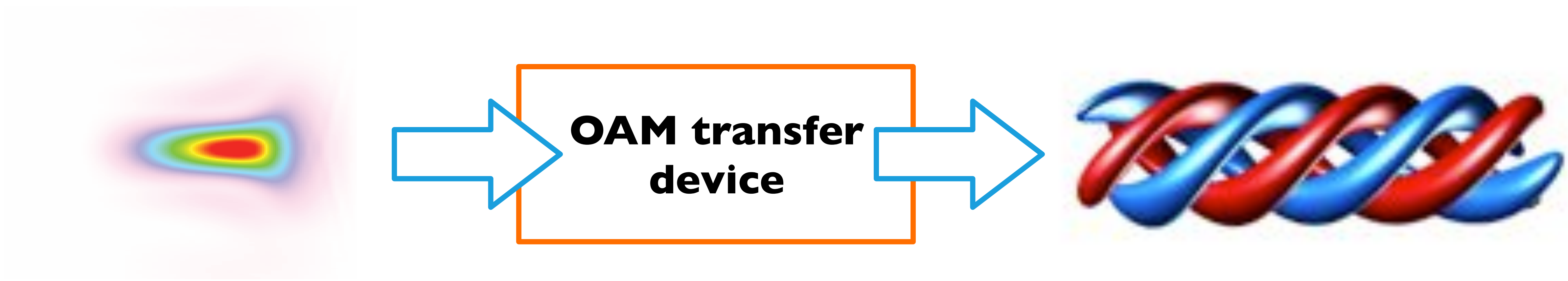


e+ bunch is quasi mono energetic

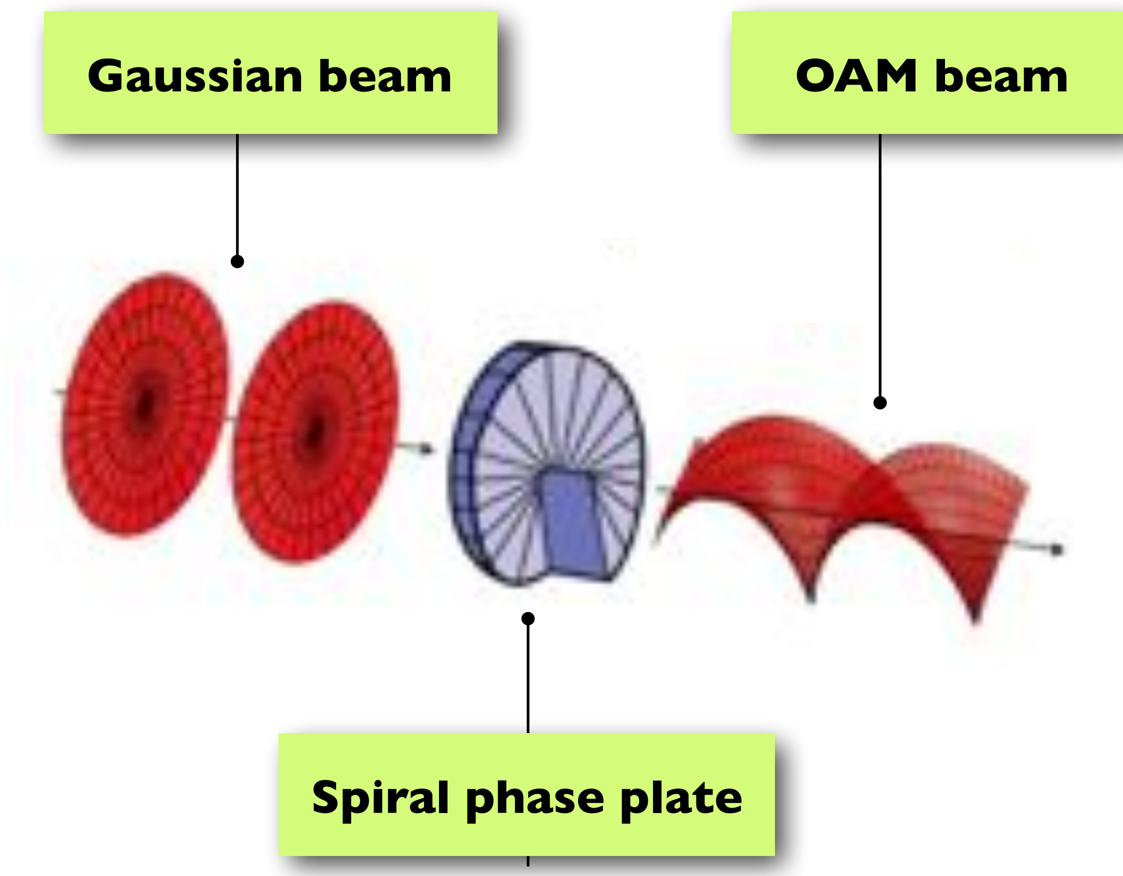


J. Vieira and J.T. Mendonça PRL **112**, 215001 (2014)

There are different ways to produce OAM light at high intensities

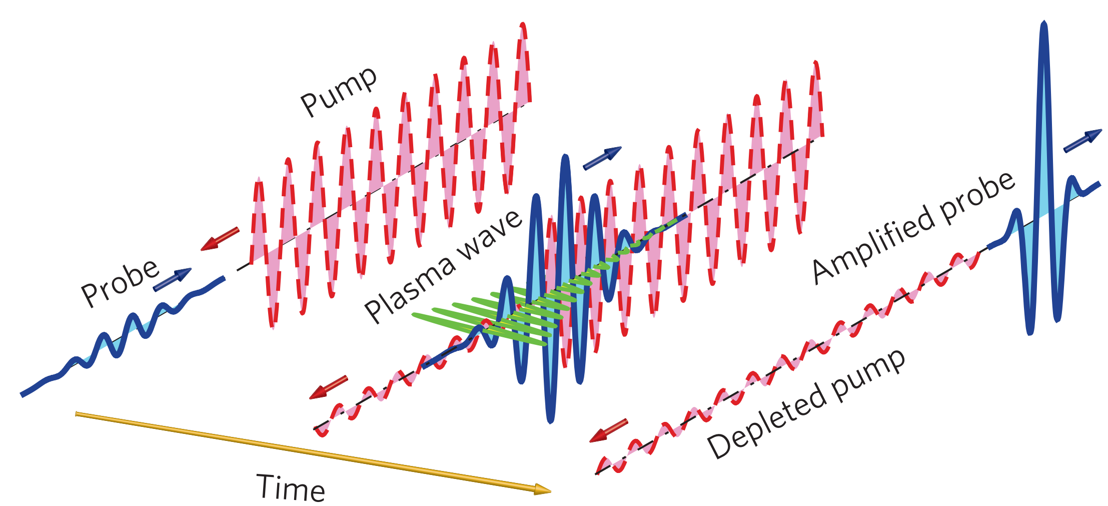


Spiral phase plate



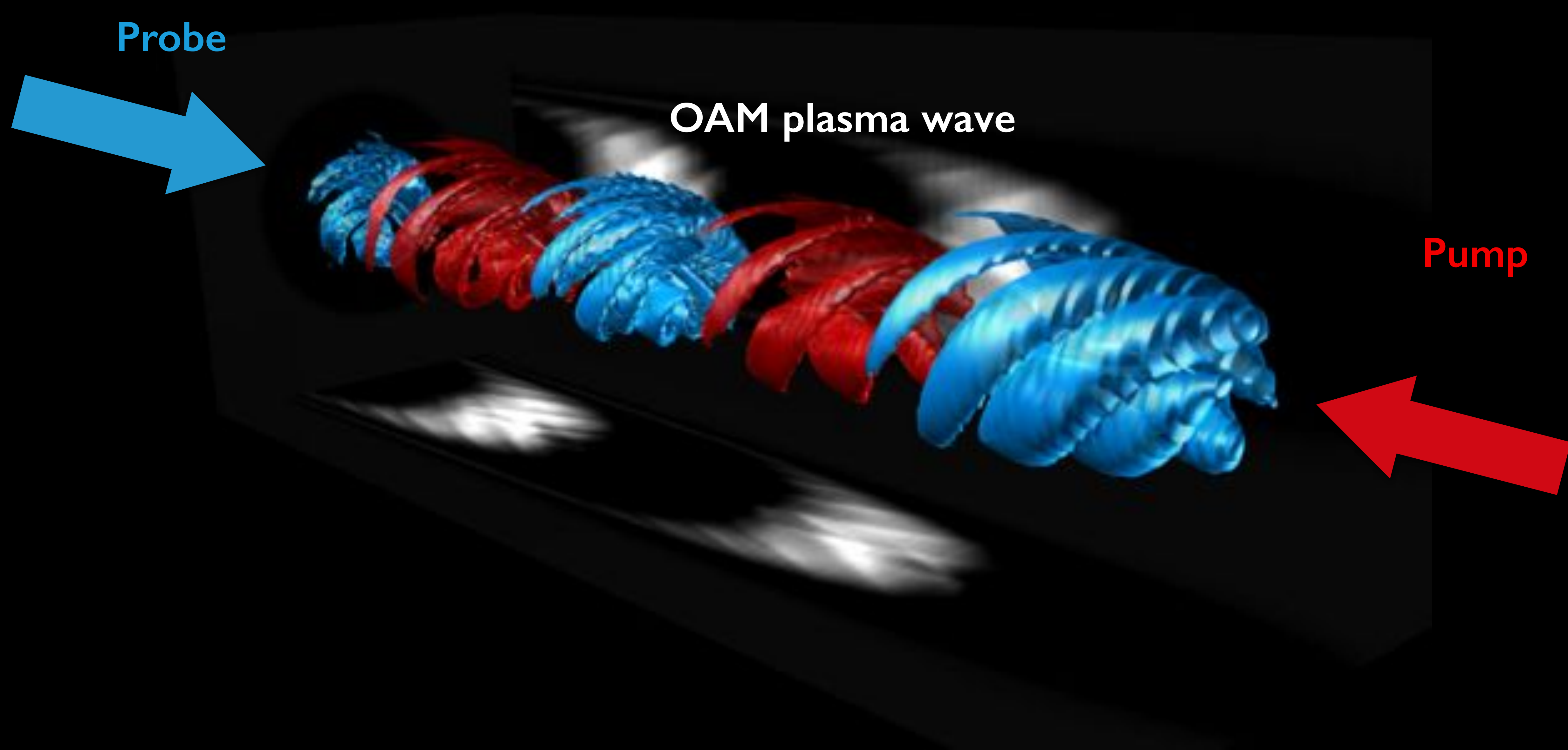
Stimulated Raman scattering

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



Stimulated Raman scattering: energy transfer from a long pump to a short probe leading to efficient pulse compression

Plasma waves can carry orbital angular momentum leading to exotic wakefield structures



Creation and amplification of new OAM modes through stimulated Raman scattering in plasmas

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Production and amplification of
new mode with l = 2

Production and amplification of
new mode with l = 3

J. Vieira, R. Trines et al submitted for publication (2015)

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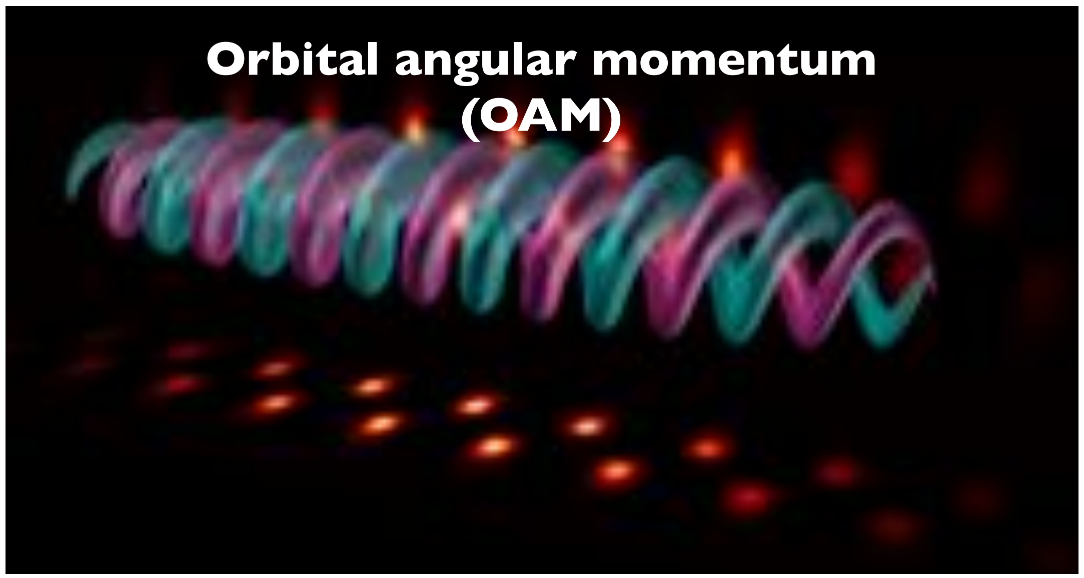
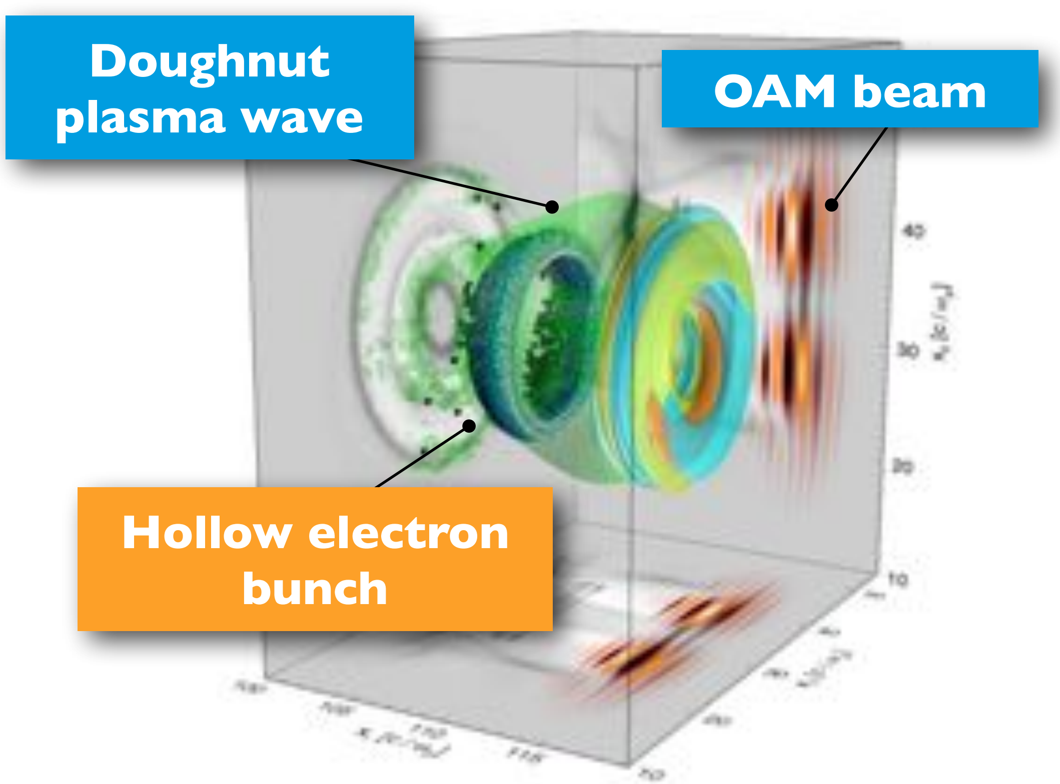
Doughnut wakefields inject ring electron bunches which could then be a driver for a PWFA

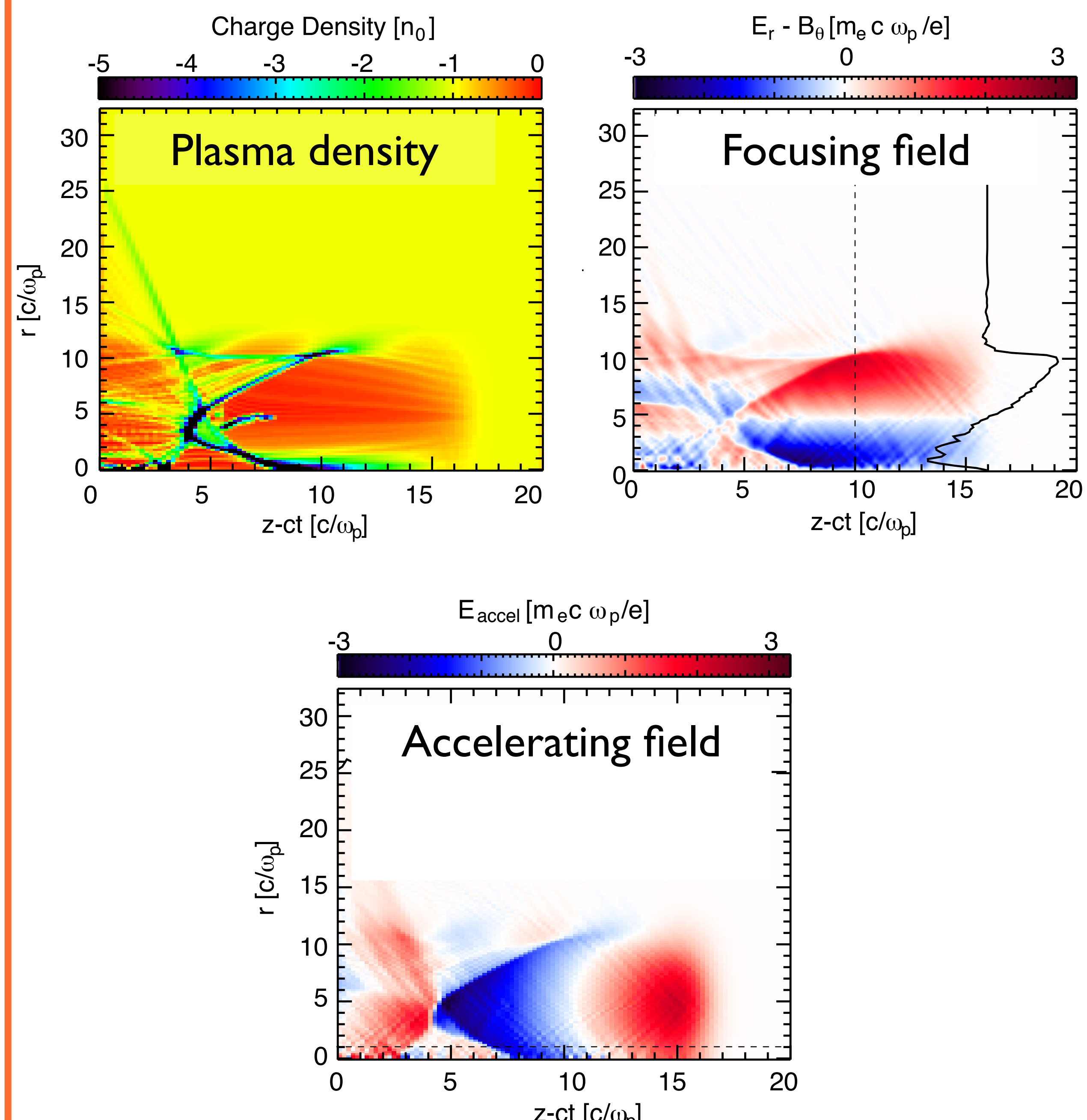
Exotic lasers





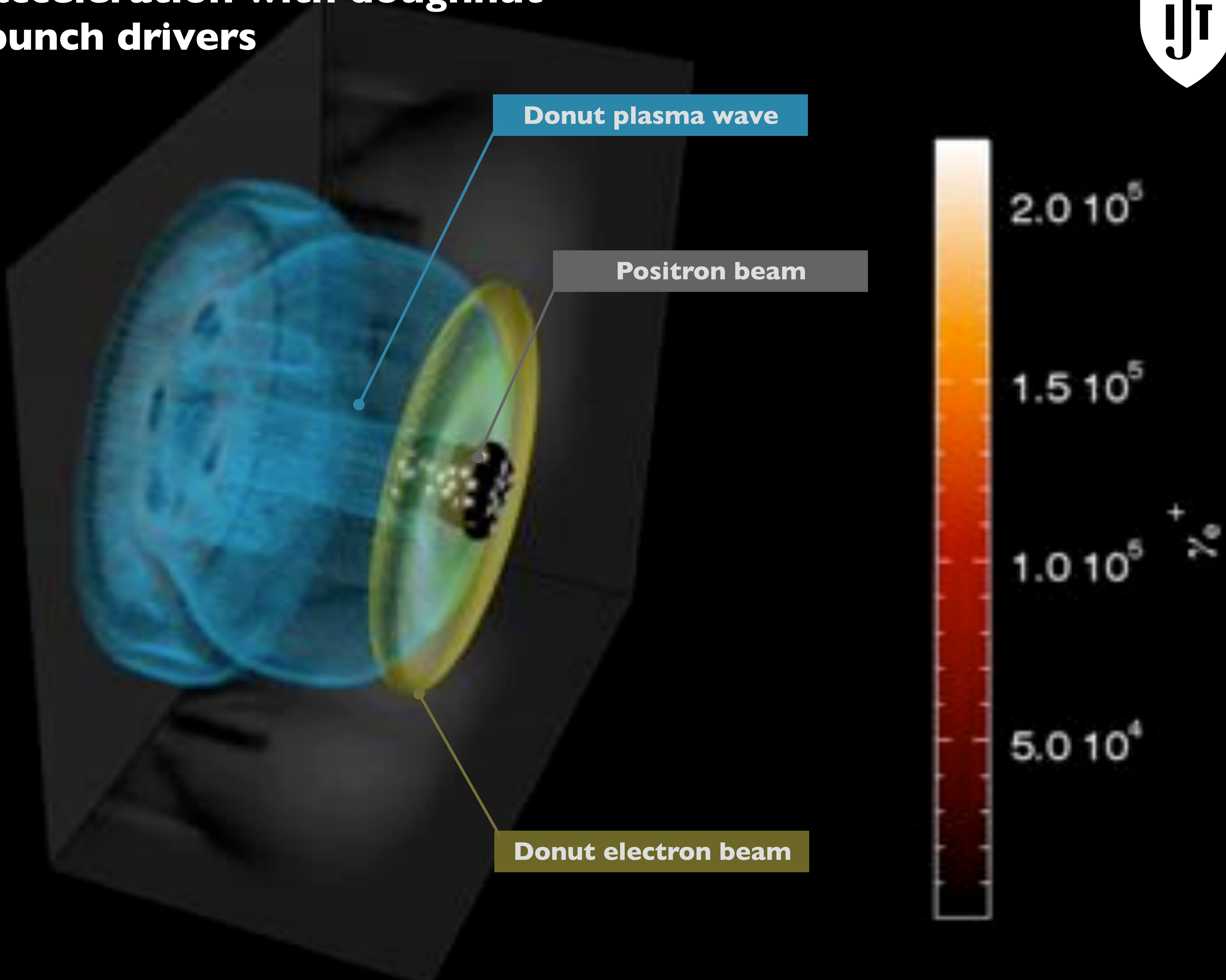
Ring electron beams [B.B. Pollock *et al* PRL (2015)]

Wake from a hollow e-beam driver



J. Vieira *et al* Proc. of AAC (2014); N. Jain *et al* arXiv (2014)

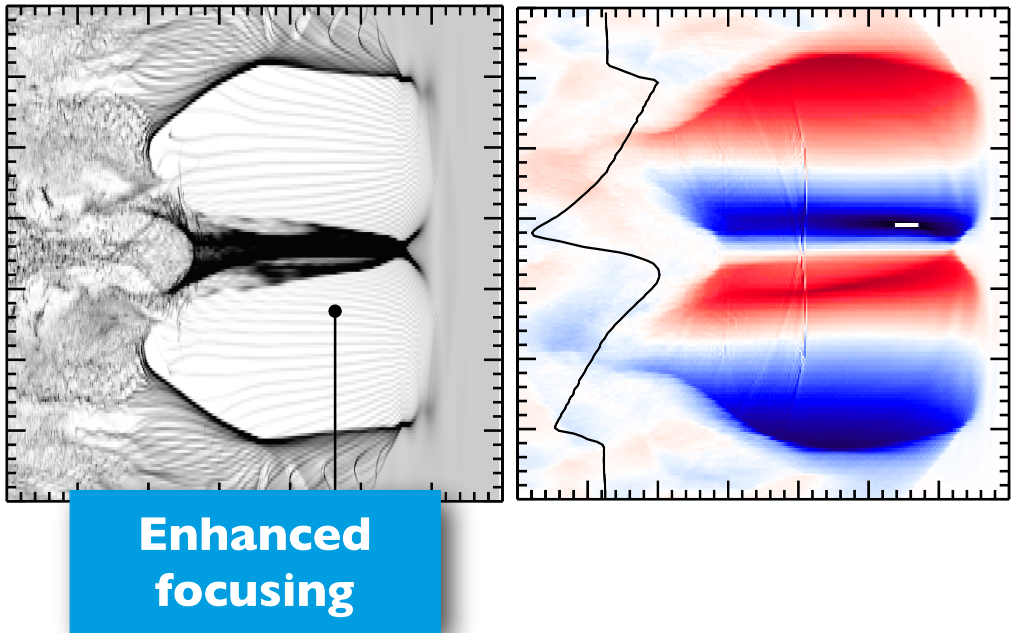
Positron acceleration with doughnut electron bunch drivers



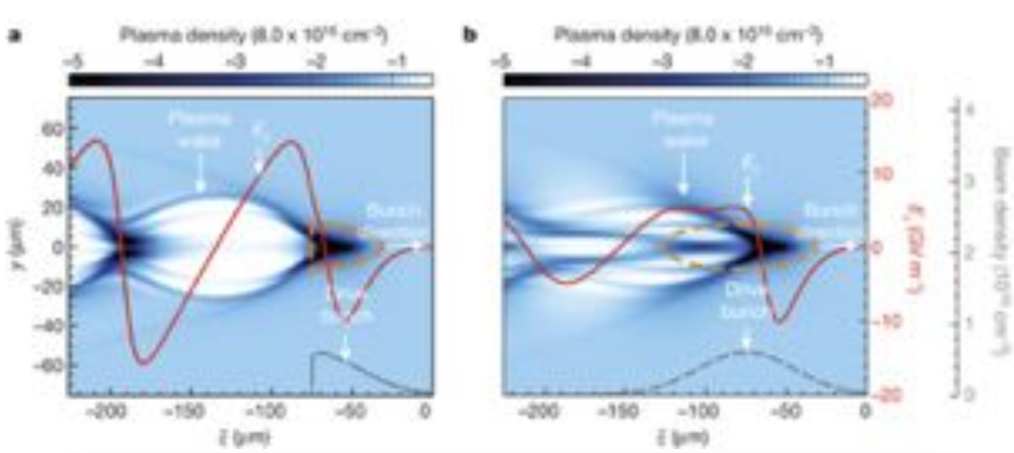
Positron acceleration occurs in regions with high background plasma electron density or in regions without plasma (hollow channels)

High density electron filament

Doughnut blowout regime



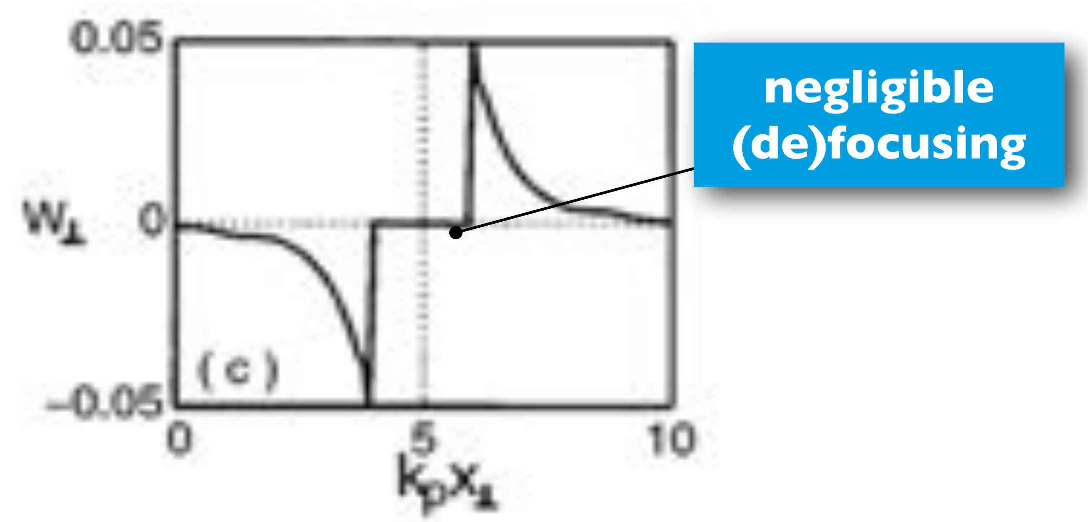
Suck-in regime [S. Lee *et al* PRE (2001)]



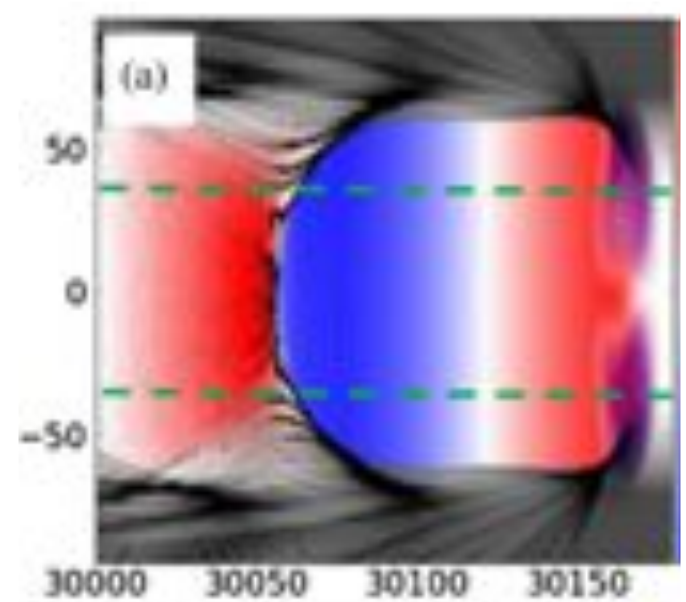
from S. Corde *et al* Nature (2015)

Hollow plasma channel

Linear regime
[T.Chiu *et al* PRL (1998);
C. Schroeder *et al* PoP (2013)]

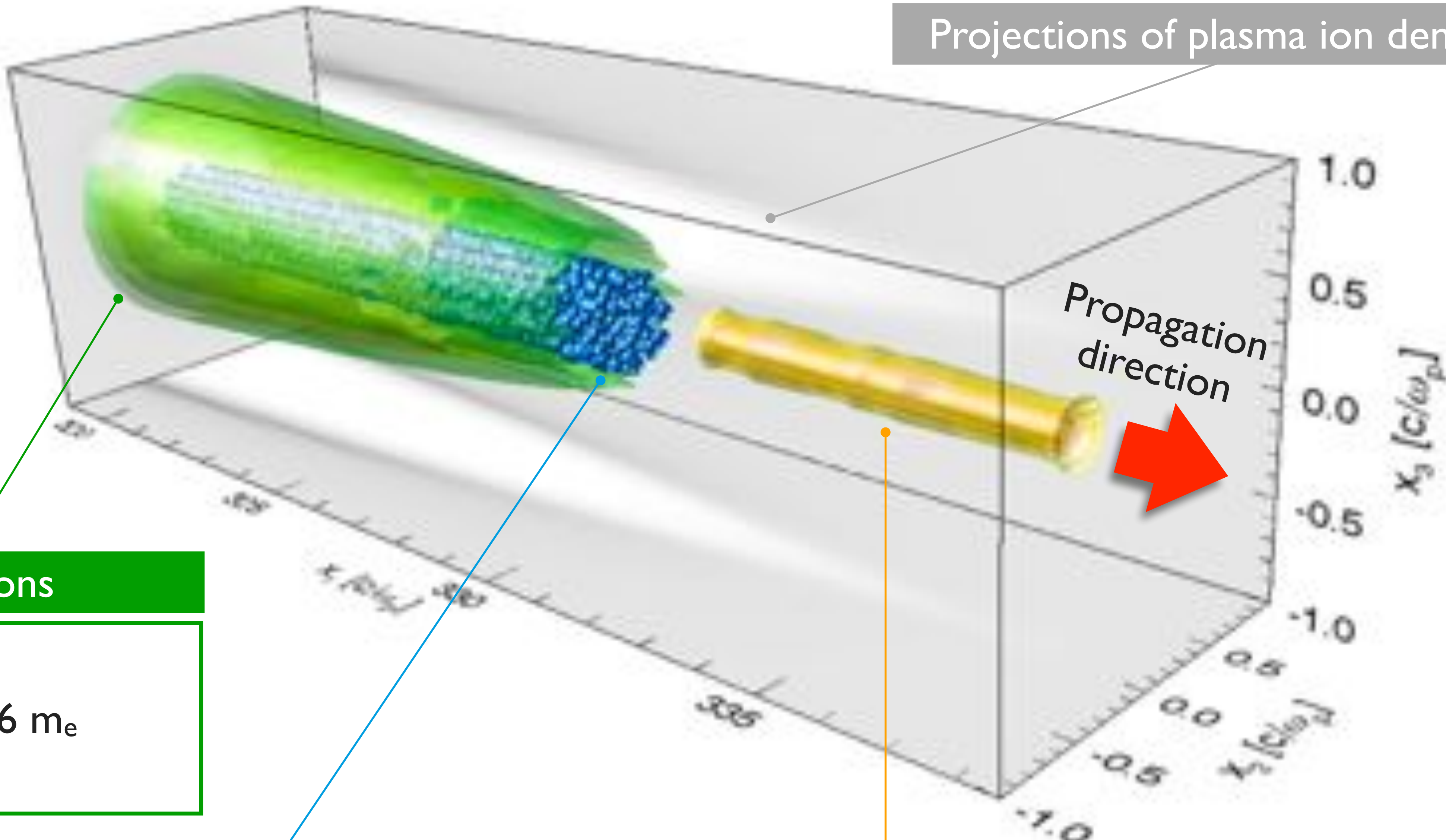


Nonlinear regime [A. Pukhov *et al* PRL 2014]



A positron beam driver can create a self-driven plasma hollow channel for positron acceleration

L.D. Amorim et al (2015)



Plasma ions

Density n_0

Mass m_{ion} ~1836 m_e

Charge q=+e

e+ witness bunch

Test particle regime

Length $\sigma_z = 12\ c/\omega_p$

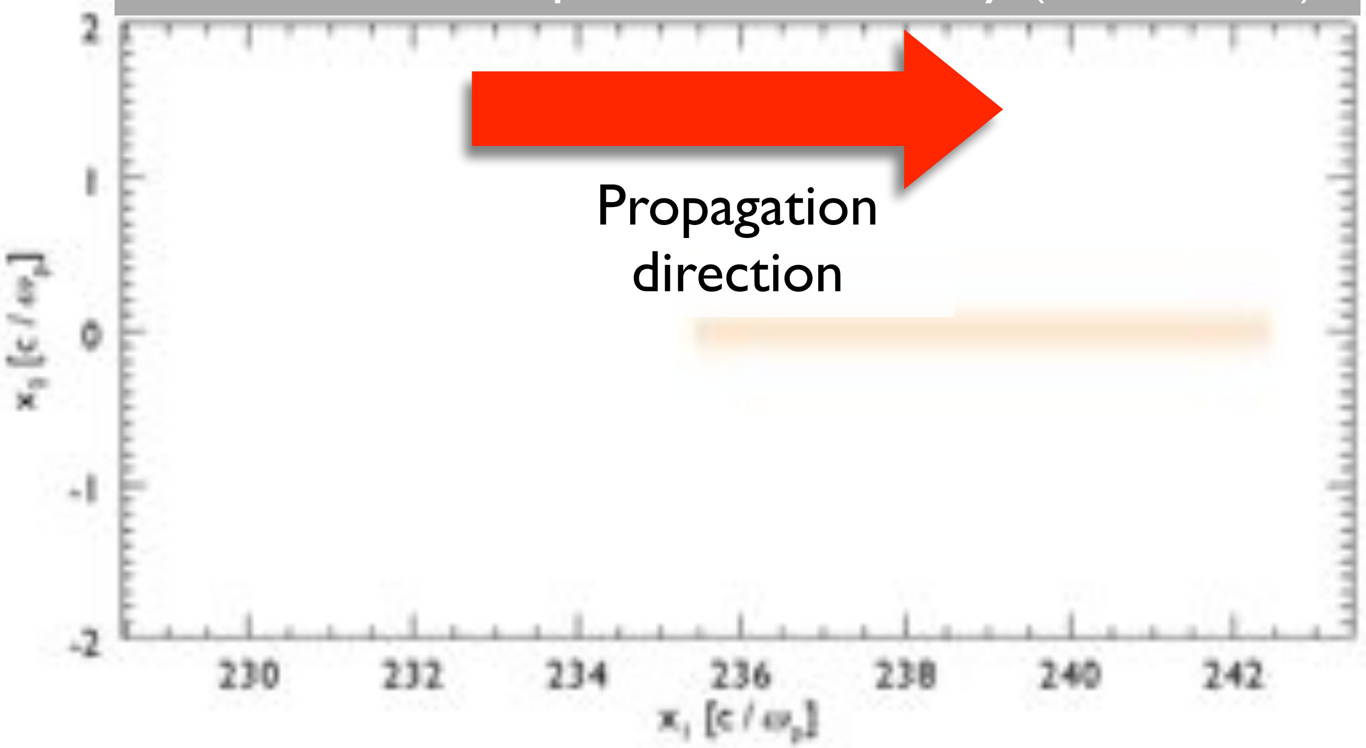
Width $\sigma_r = 0.12\ c/\omega_p$

e+ drive beam

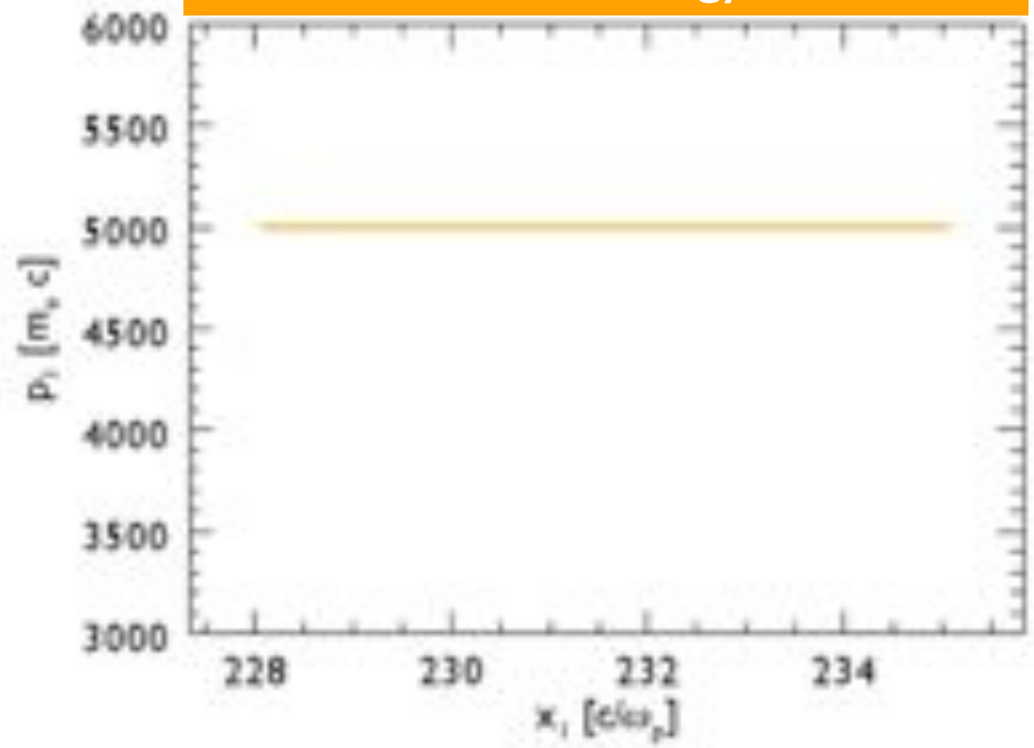
Density $n_b = 200\ n_0$	**can be relaxed for longer beams**
Length $\sigma_z = 6\ c/\omega_p$	**close to the plasma wavelength**
Width $\sigma_r = 0.12\ c/\omega_p$	**tightly focused**
Energy = 2.5 GeV	**ultra relativistic**

Simulations show positron bunch energy gain inside the hollow channel

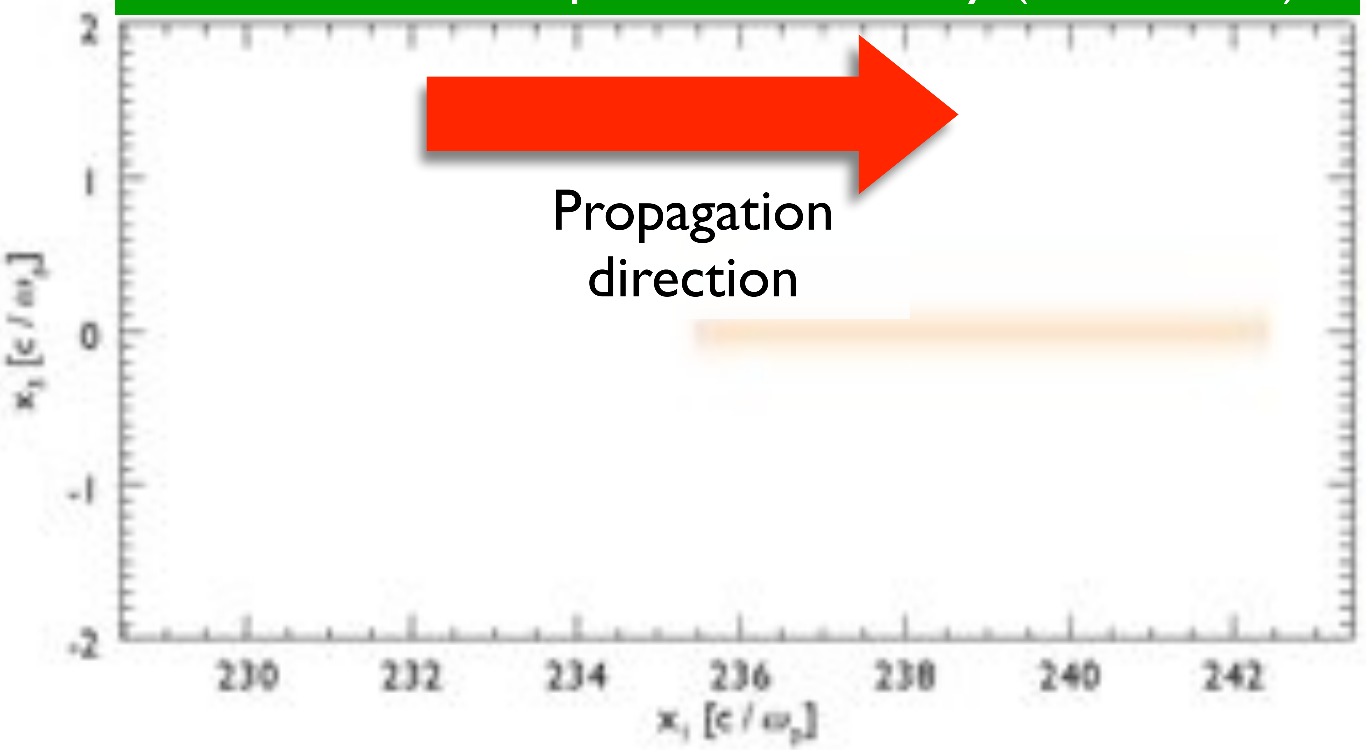
Evolution of the plasma ions density (slice of 3D)



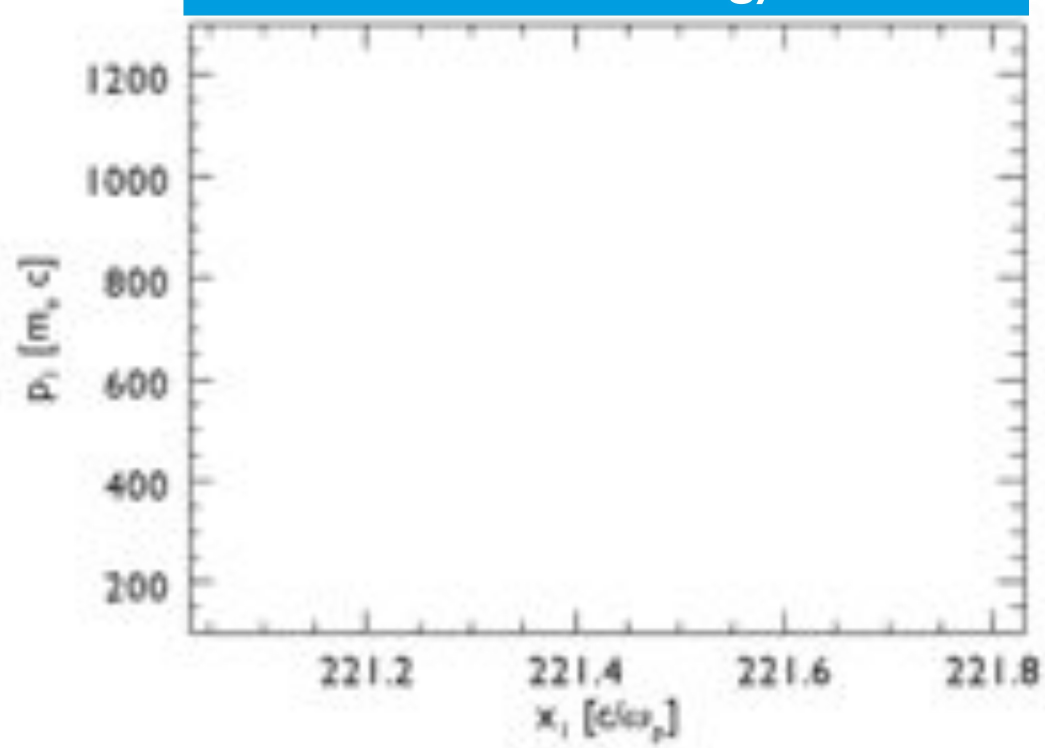
Drive e+ beam energy evolution



Evolution of the plasma e-s density (slice of 3D)



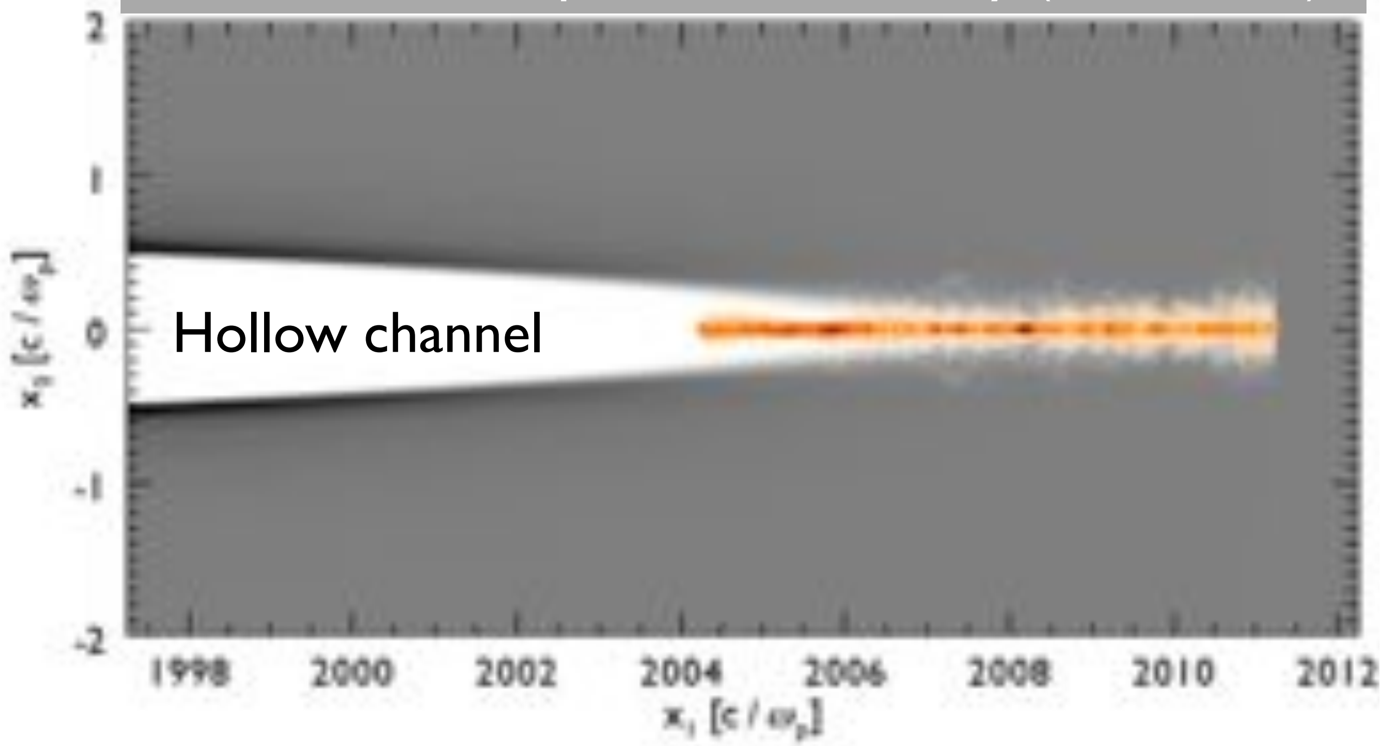
Witness e+ beam energy evolution



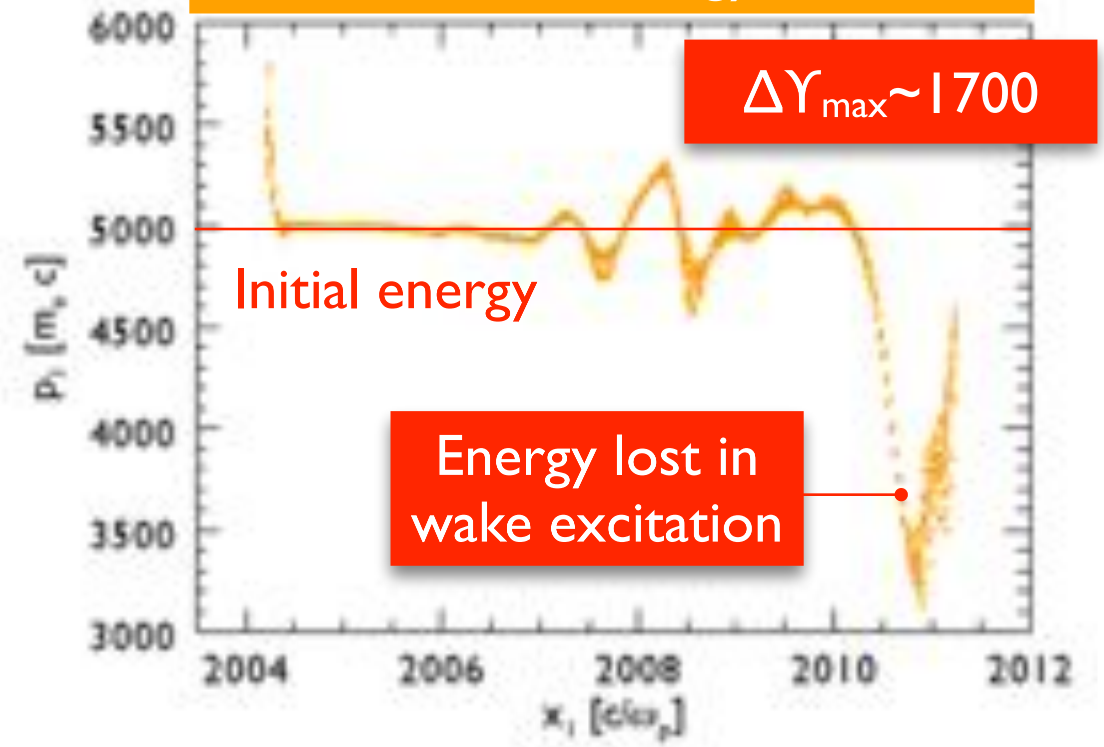
L.D. Amorim et al (2015)

Simulations show positron bunch energy gain inside the hollow channel

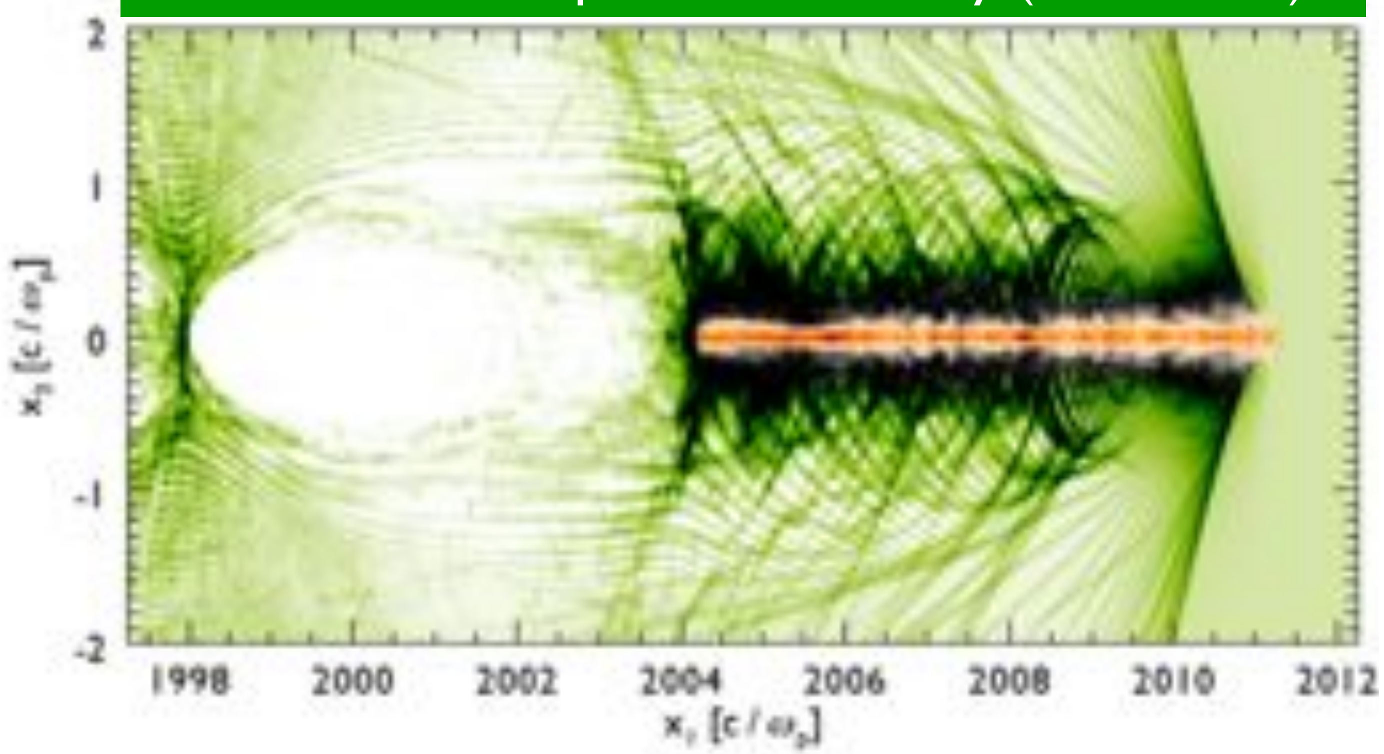
Evolution of the plasma ions density (slice of 3D)



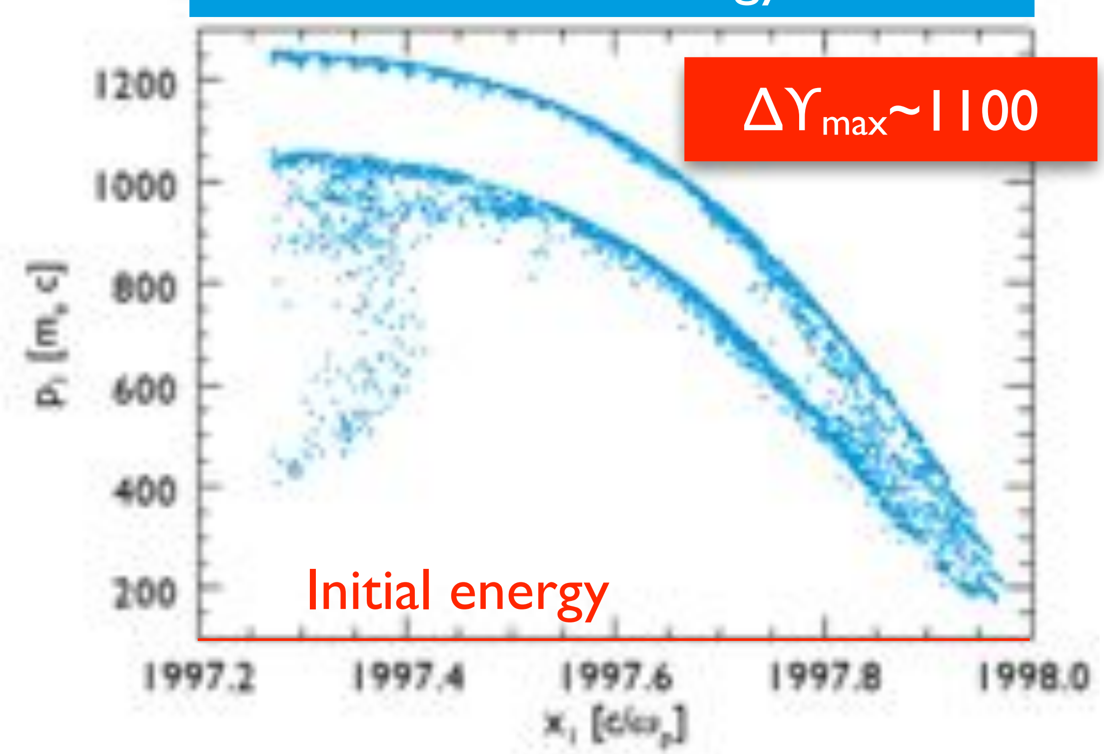
Drive e+ beam energy evolution



Evolution of the plasma e-s density (slice of 3D)



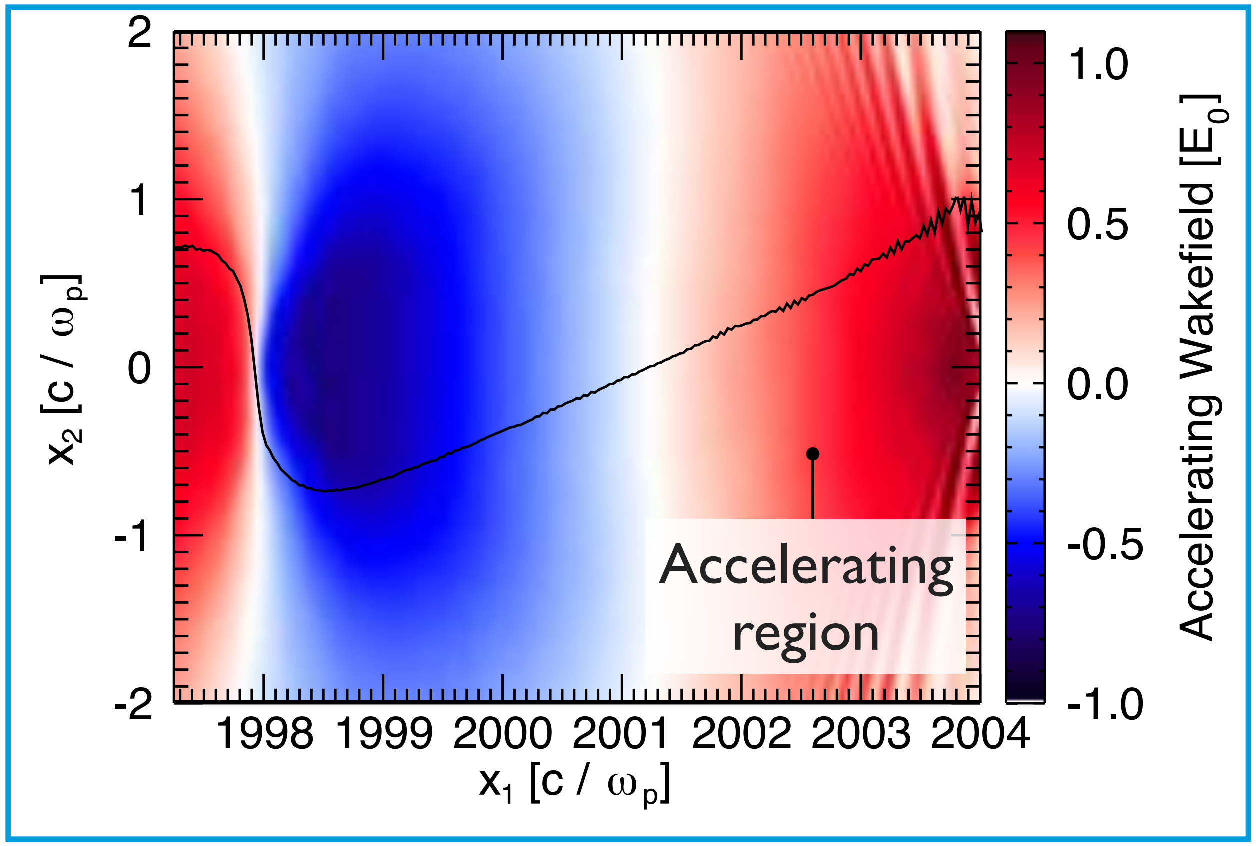
Witness e+ beam energy evolution

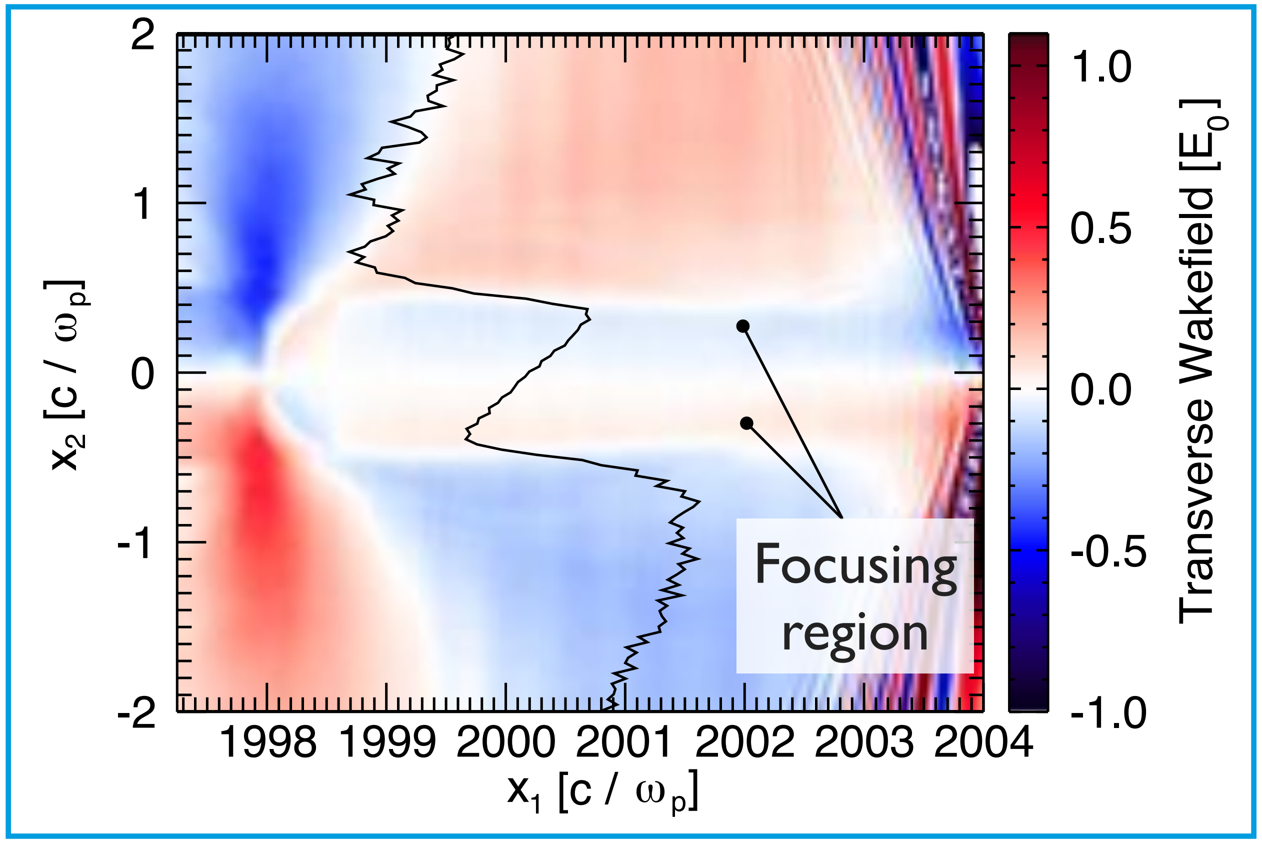


L.D. Amorim et al (2015)

Positron focusing and accelerating fields in hollow channel created by narrow drivers

L.D. Amorim et al (2015)





Non-linear accelerating wakefields:

- ➡ Strong decelerating fields at front of driver ($E_{accel} > E_0 = m_e c\omega_p/e$)
- ➡ Peak field in the hollow channel region ~ $0.7E_0$
- ➡ Sawtooth shape

Positron focusing wakefields:

- ➡ Are highly defocusing in the drive beam region ($E_{focus} > 20\ E_0$)
- ➡ Mainly focusing for lengths of ~ $\lambda_p = 2\pi$ inside the channel
- ➡ Focusing due to plasma e^-s in the channel region

Contents

Conclusions & Future work

Positron accelerations with exotic beams

- Lasers with orbital angular momentum
- Ring electron bunches
- Self-driven hollow channels by tightly focused positron bunches

Exotic beams can be produced experimentally

- Pure OAM lasers are not that different from Bessel beams which can also have orbital angular momentum
- Doughnut electron bunches have been produced in the LWFA and in conventional accelerators
- Tightly focused, overdense positron beam drivers could be achieved at lower plasma densities