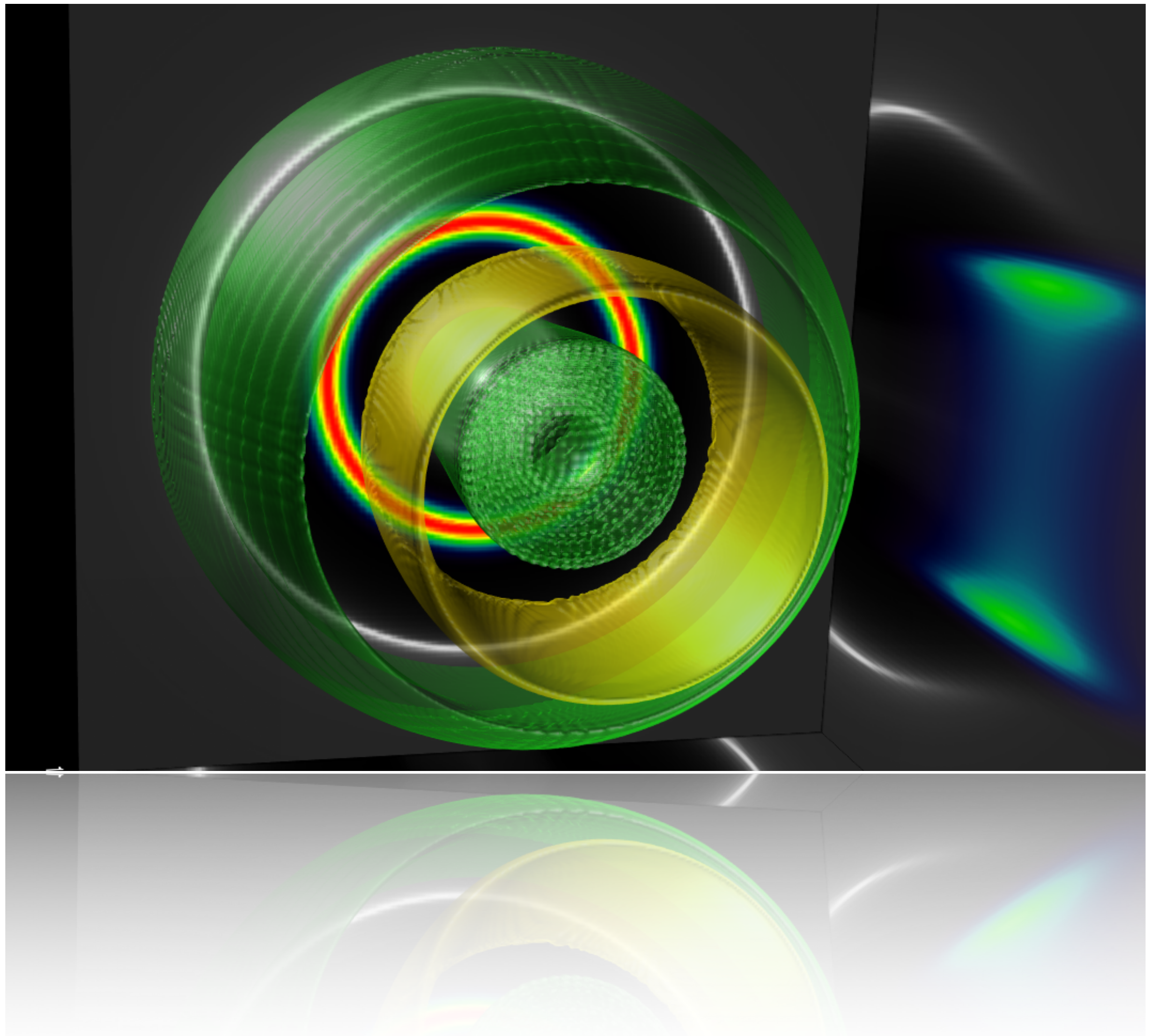
Non-neutral fireball and possibilities for accelerating positrons with plasma

J. Vieira

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

web.ist.utl.pt/**jorge.vieira** || **epp**.tecnico.ulisboa.pt || golp.tecnico.ulisboa.pt



Acknowledgments

- Work in collaboration with:
  - **J.T. Mendonça, R.A. Fonseca, L.O. Silva** (IST); **W. Mori** (UCLA)
- Simulation results obtained at **SuperMUC** through **PRACE** awards

FCT Fundação para a Ciência e a Tecnologia
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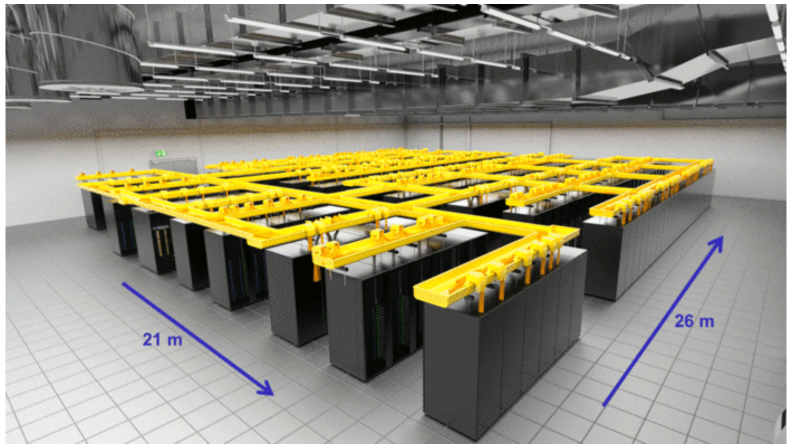

golp grupo de lasers e plasmas

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

OSIRIS 3.0

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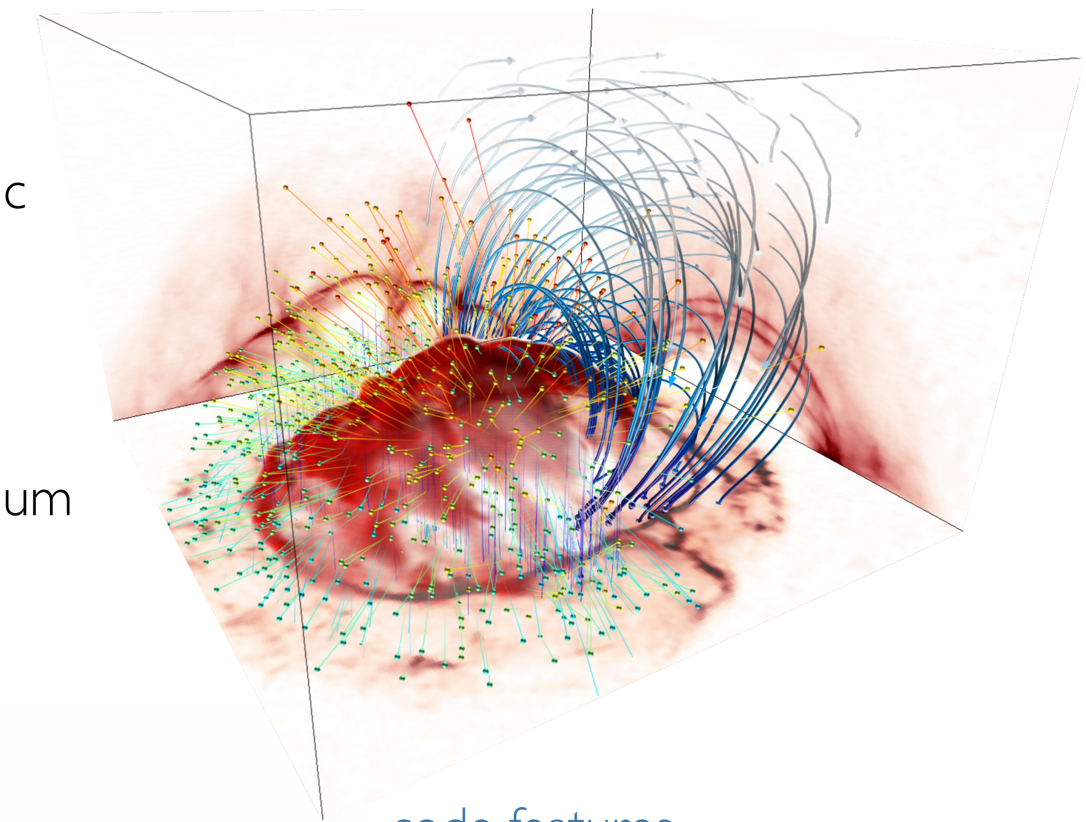
Osiris 3.0

osiris framework

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



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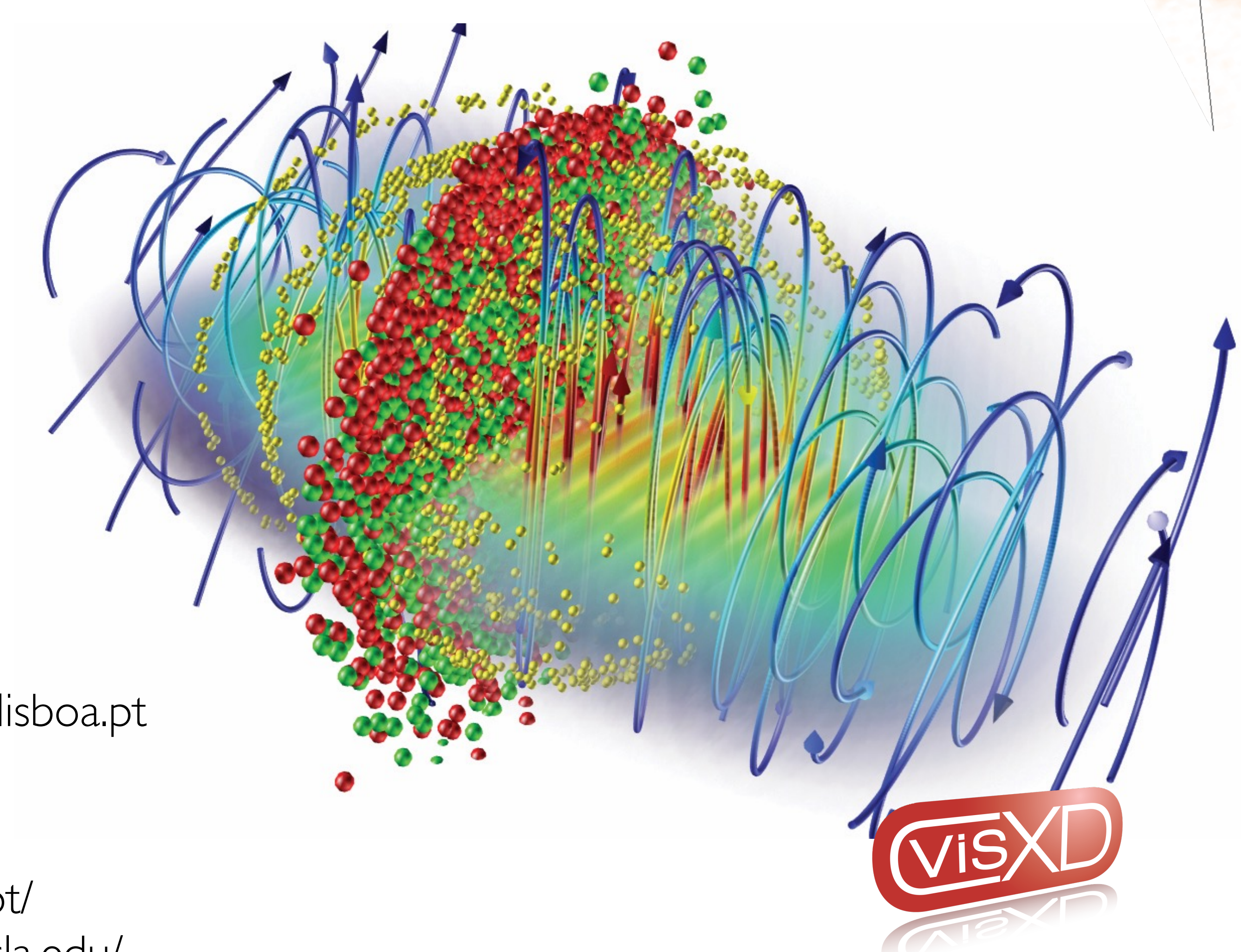
UCLA



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

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

code features

- Scalability to ~ 1.6 M cores
- Dynamic Load Balancing
- GPGPU and Xeon Phi support
- Particle merging
- QED module
- Quasi-3D
- Current deposit for NCI mitigation
- Collisions
- Radiation reaction
- Ponderomotive guiding center

Outline

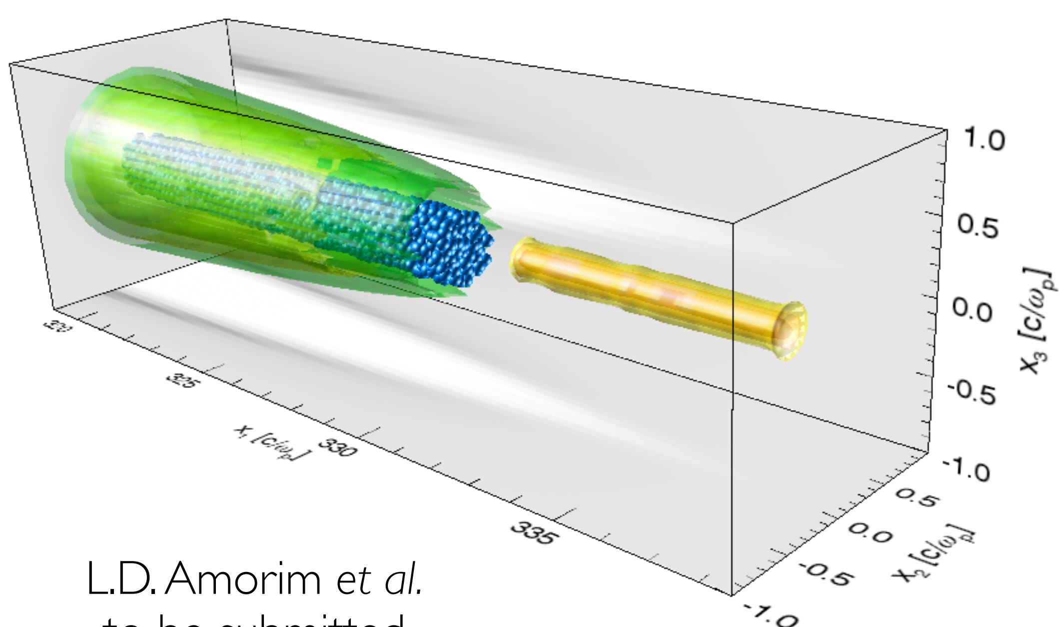
- Positron acceleration in the nonlinear regime using higher order laser drivers
- Positron acceleration in the nonlinear regime with particle beam drivers
- Conclusions & future work

Two paths for positron acceleration in plasmas: **enhance electron density** or **create a hollow plasma channel**

Hollow plasma channel

- Remove plasma electrons and plasma ions to form a hollow channel.
- No focusing force: positrons/electrons still diffract
- Beam breakup may be a challenge

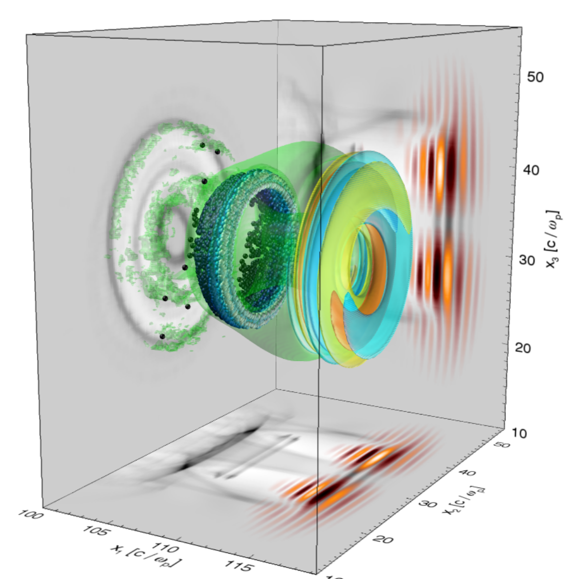
Positron self-driven hollow channel



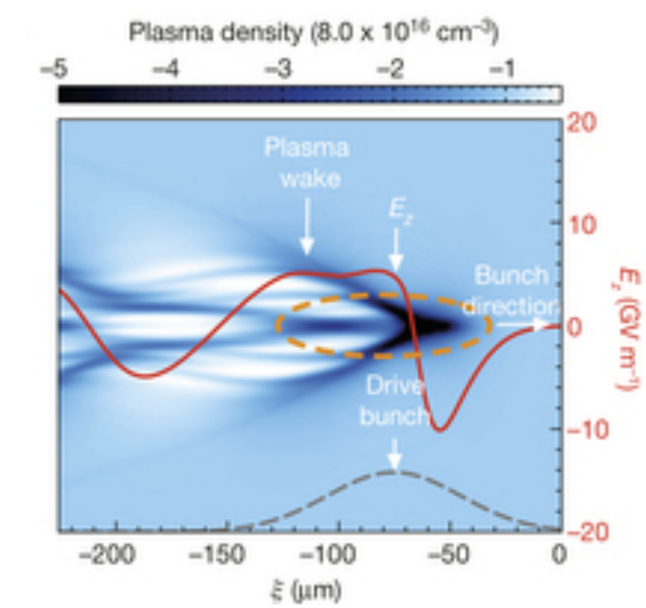
L.D. Amorim *et al.*
to be submitted

On-axis electron concentration

- On-axis, high density plasma e-filament could focus positrons.
- Is it possible to create positron focusing structures in a controllable way?



J. Vieira *et al.* PRL (2014)

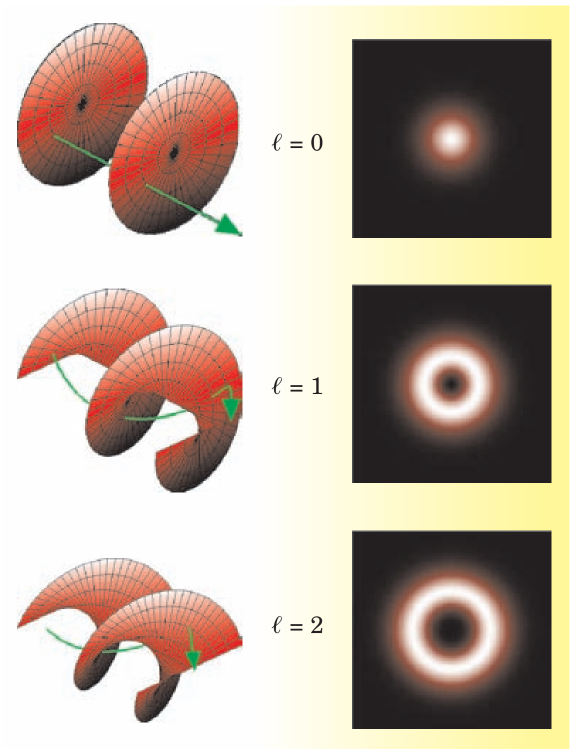


S. Corde *et al.* Nature (2015)

Challenge: controlled regimes may require shaped plasma waves and drivers

The orbital angular momentum of light (OAM)

Orbital angular momentum

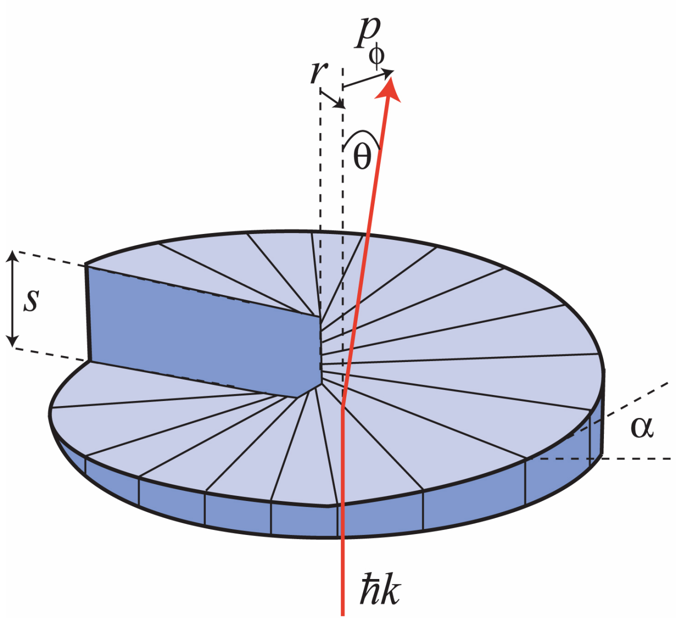


$$E_{\text{laser}} \propto \left(\frac{r}{w_0}\right)^{|\ell|} \mathrm{L}_p^{|\ell|}\left(\frac{r}{w_0}\right) \exp\left(-\frac{r^2}{w_0^2}\right) \times \cos\left(\omega_0 t - k_0 z + \ell\phi\right)$$

M. Padgett et al., Phys. Today 57(5), 35 (2004)

Twisted light in the lab

spiral phase plate

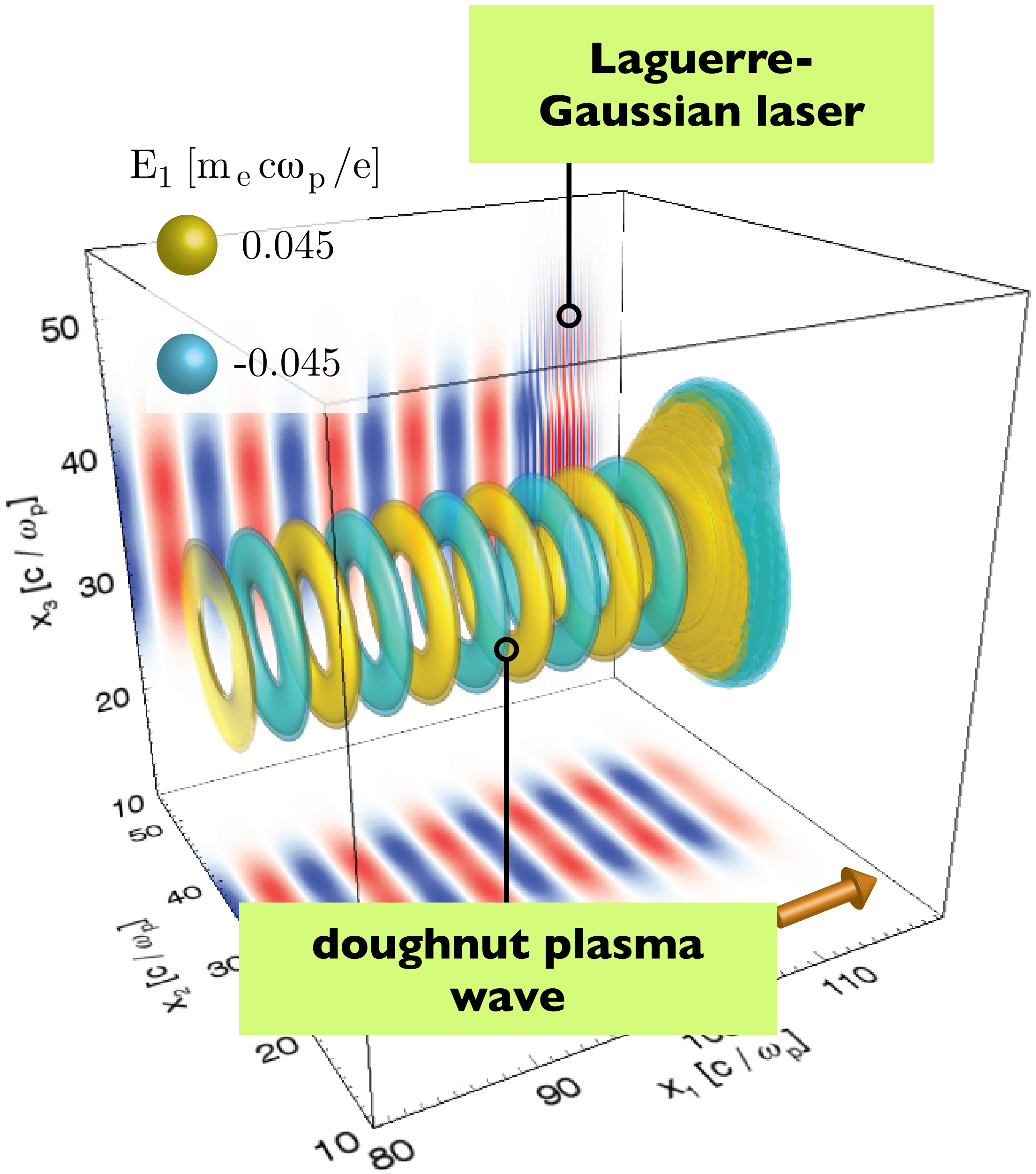


- azimuthally dependent phase delay due to dispersion
- pure OAM level ℓ when phase delay over 2 Pi corresponds to $\ell\, \lambda_0$
- also used to create Bessel beams (to drive a hollow channel)

First experiments to generate twisted light at ultra-high intensities have been done e.g. at GSI [C. Brabetz et al., PoP 22, 013102 (2015)] **and CEA** [Denoeud et al. PRL 118 033902 (2017)]

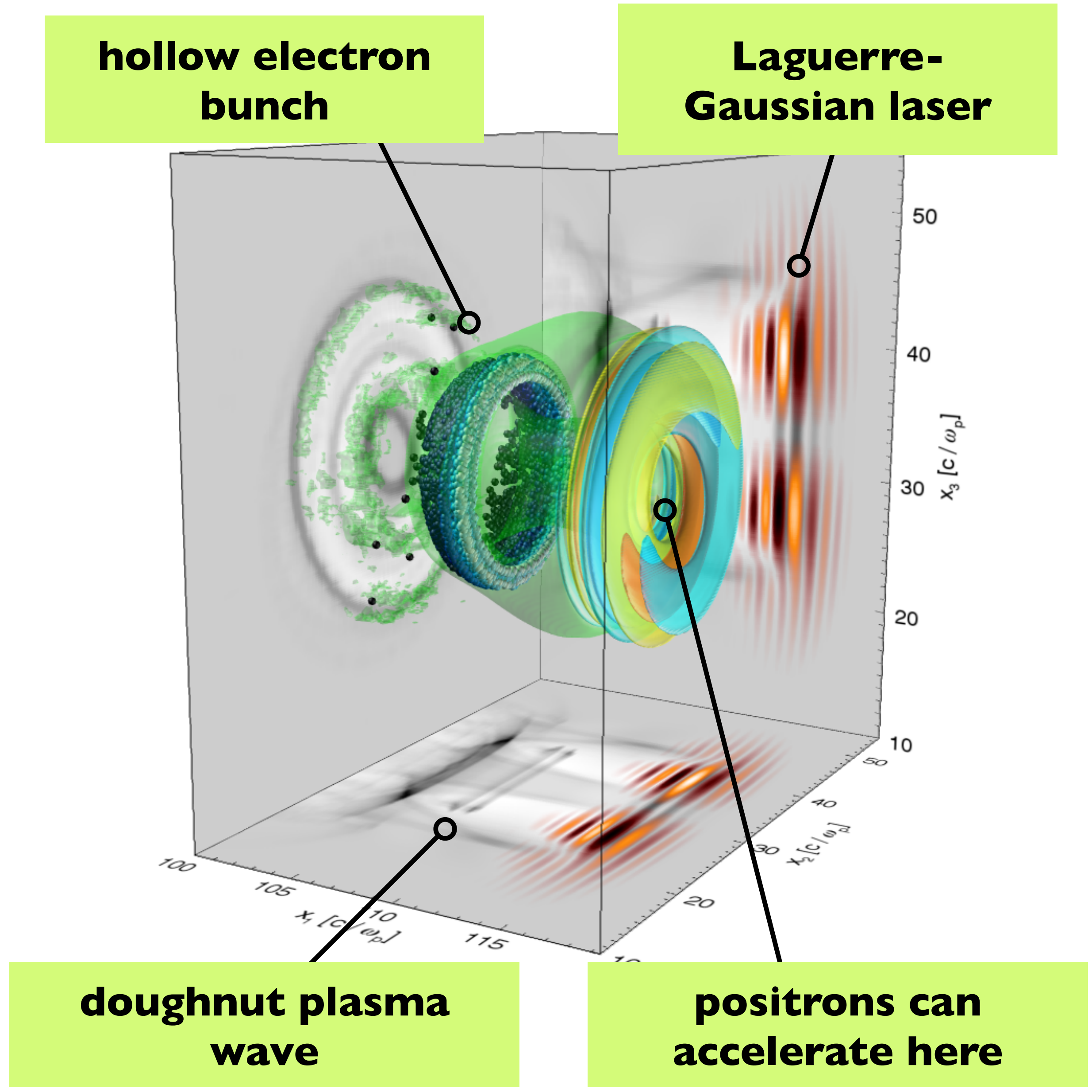
Twisted light drives doughnut plasma waves

Linear doughnut wakefields



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

Non-linear doughnut blowout



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

Doughnut plasma waves have novel focusing properties: positron focusing in strongly non-linear regimes

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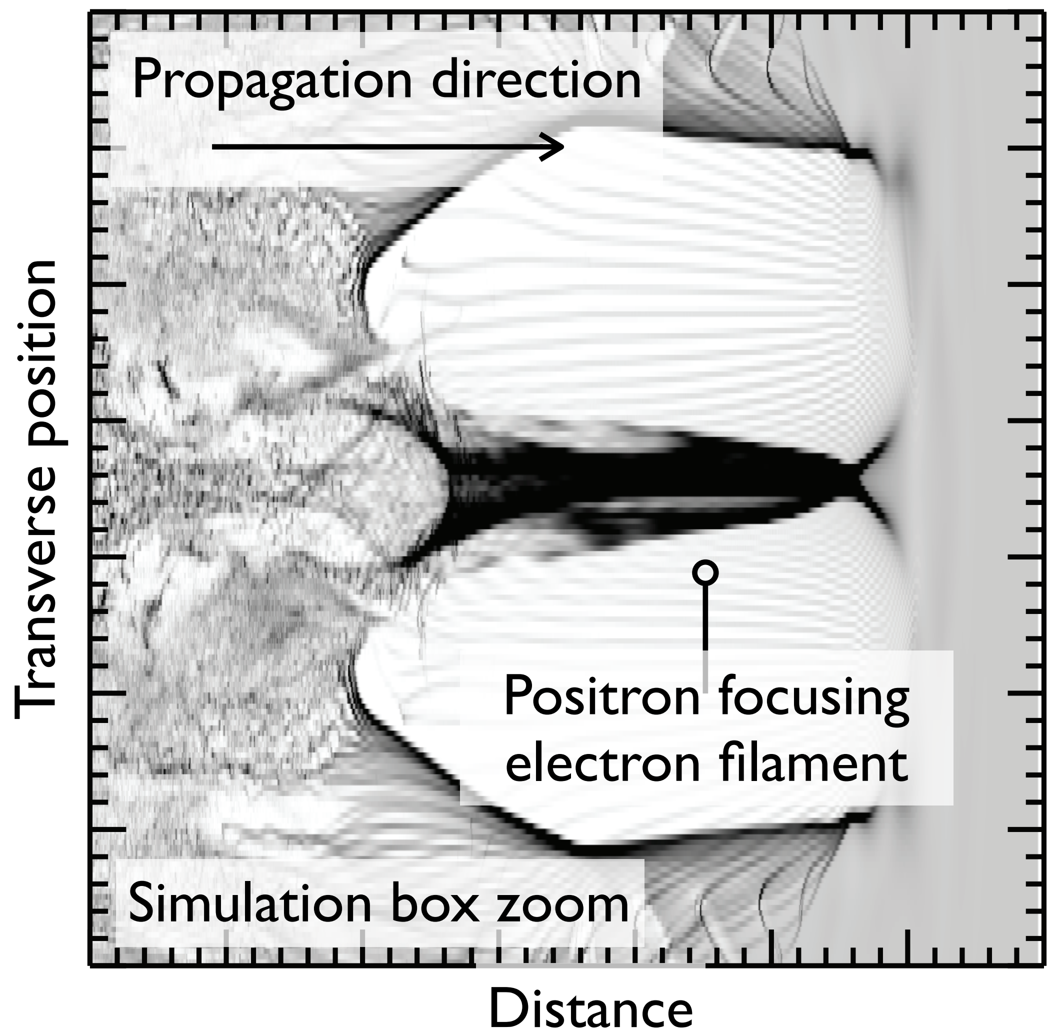
Longitudinal electric field

Plasma density: slice from 3D simulation

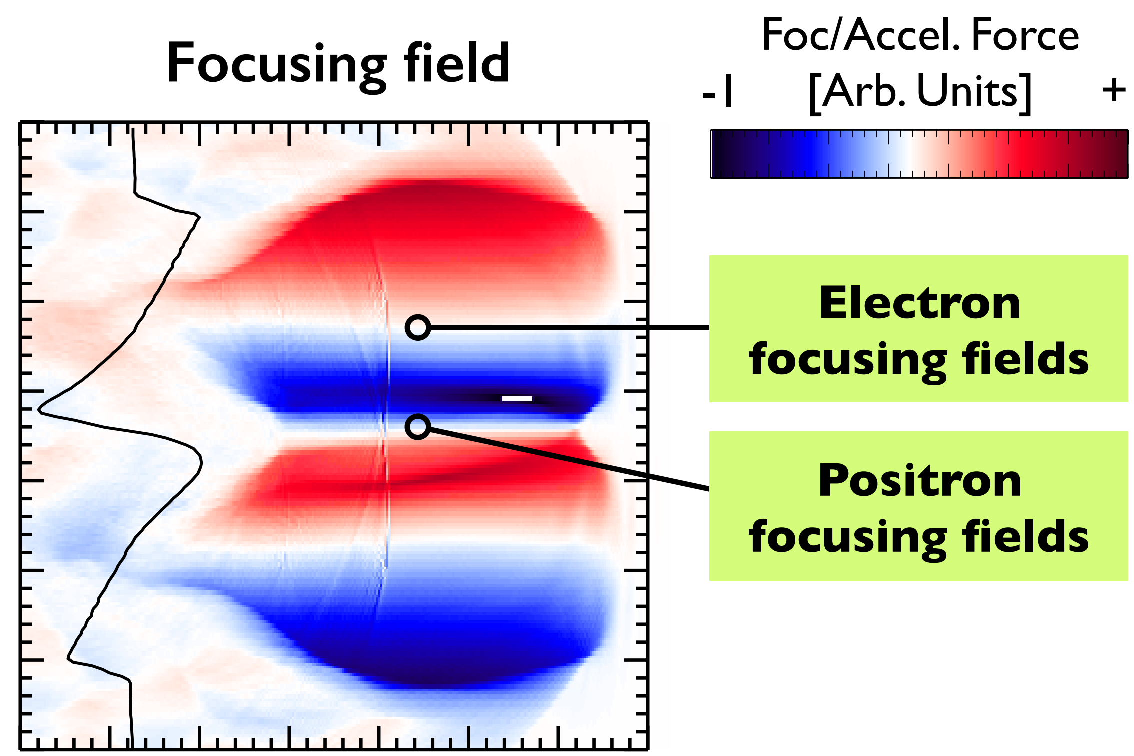


electrons merge on-axis providing positron focusing when $W_0 \approx r_b$:

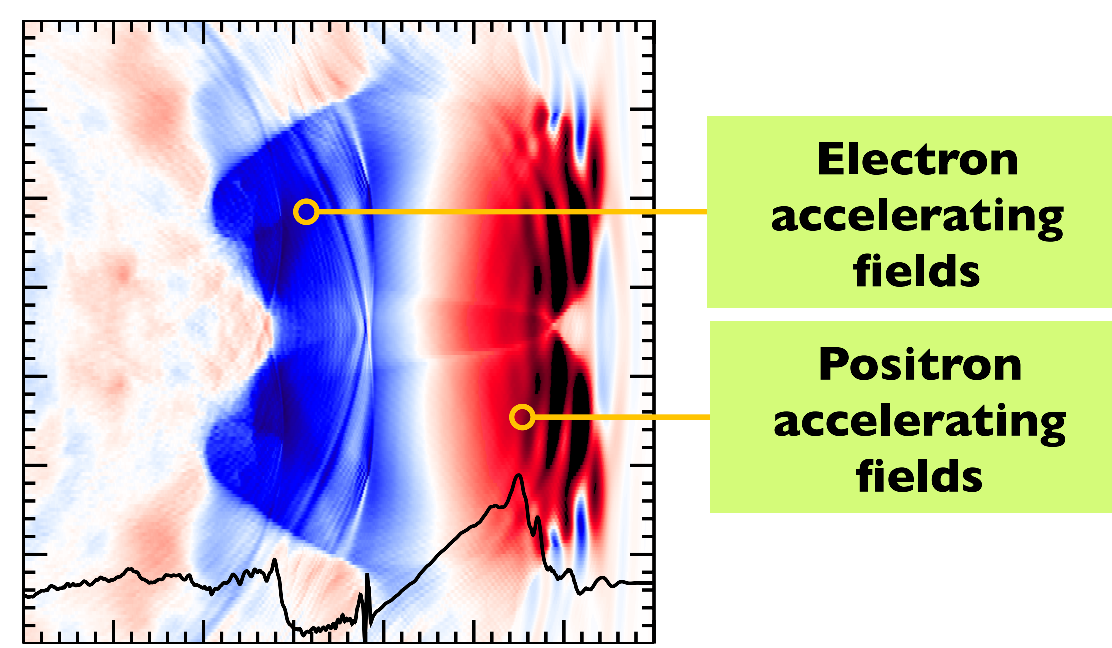
$$a_0 \gtrsim (8W_0[c/\omega_p])^{1/2}$$

Wakefield structure

Focusing field



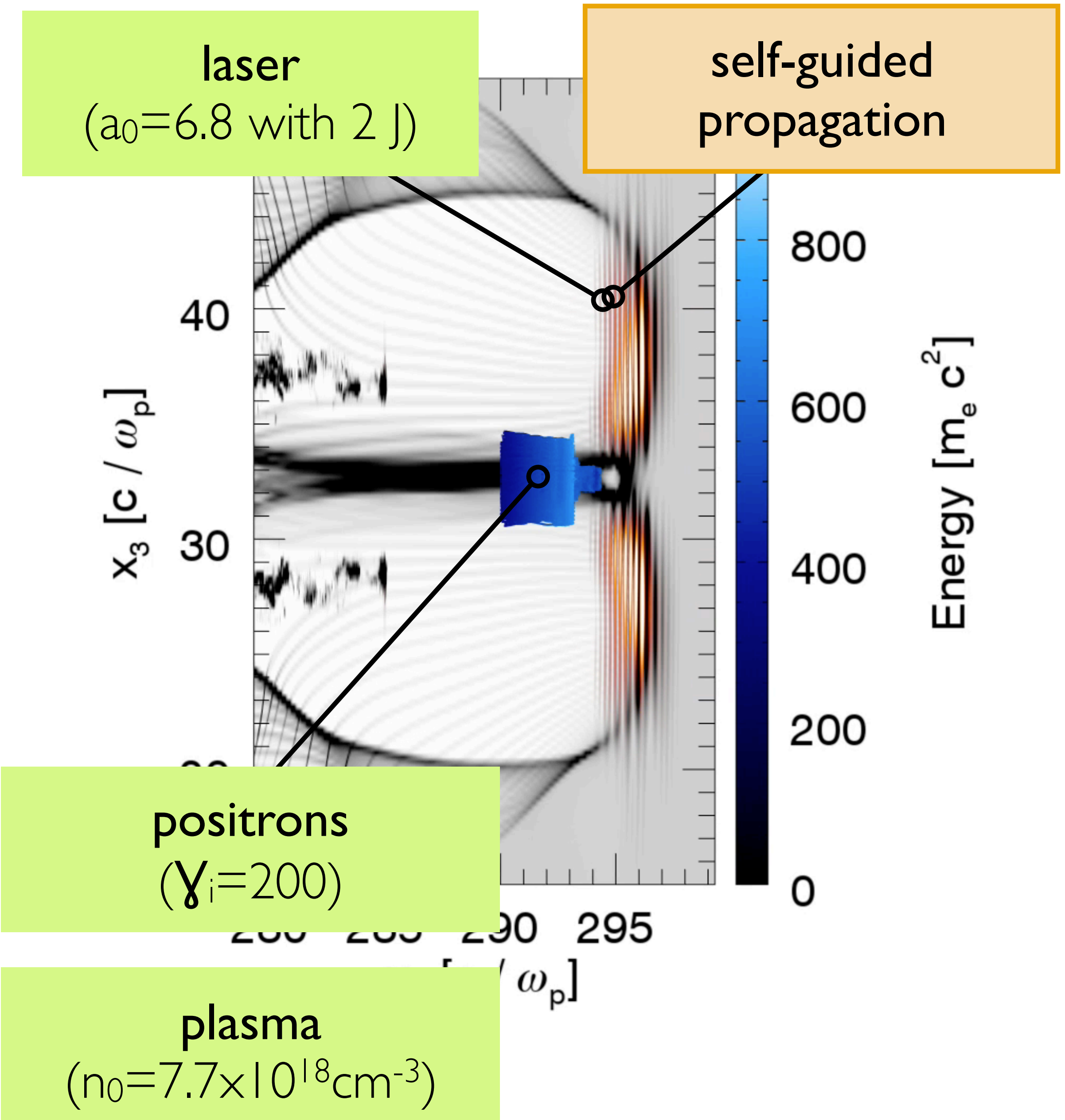
Longitudinal electric field



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

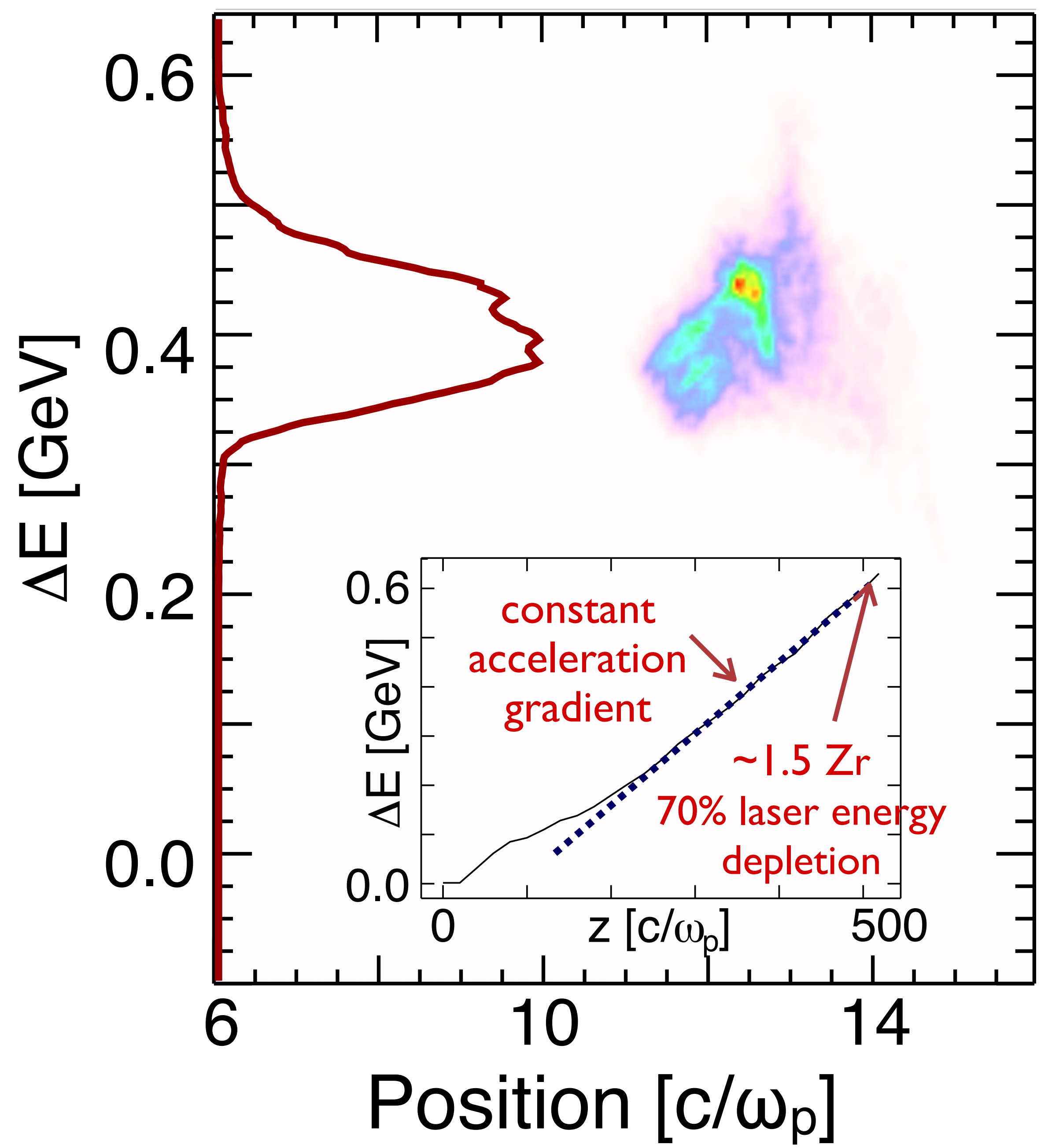
3D simulation of positron acceleration

laser and plasma parameters within experimental reach



simulation box zoom

Positron bunch is quasimonoenergetic



Proof-of-concept using a Gaussian laser pulse as a driver

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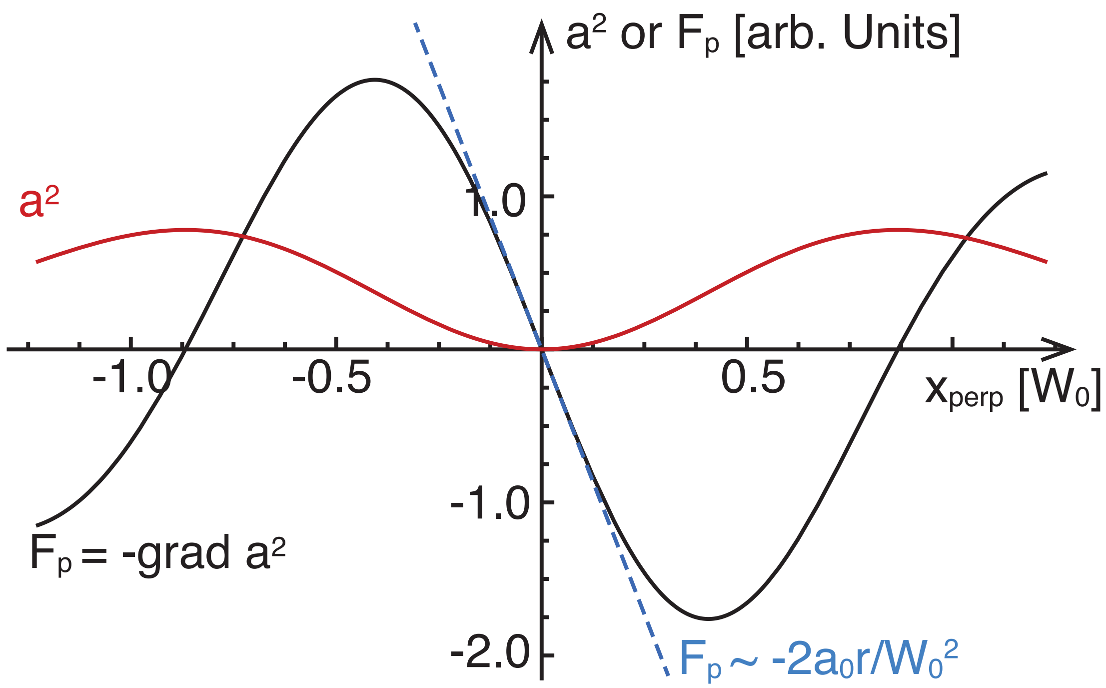
Laguerre-Gaussian laser driver

on-axis ponderomotive force for
Laguerre-Gaussian pulse

$$F_p \propto -\nabla a^2 = -a^2\left(\frac{2}{r} - \frac{4}{r^2}\right) \simeq -\frac{2a_0^2 r}{w_0^2} + \mathcal{O}(r^2)$$

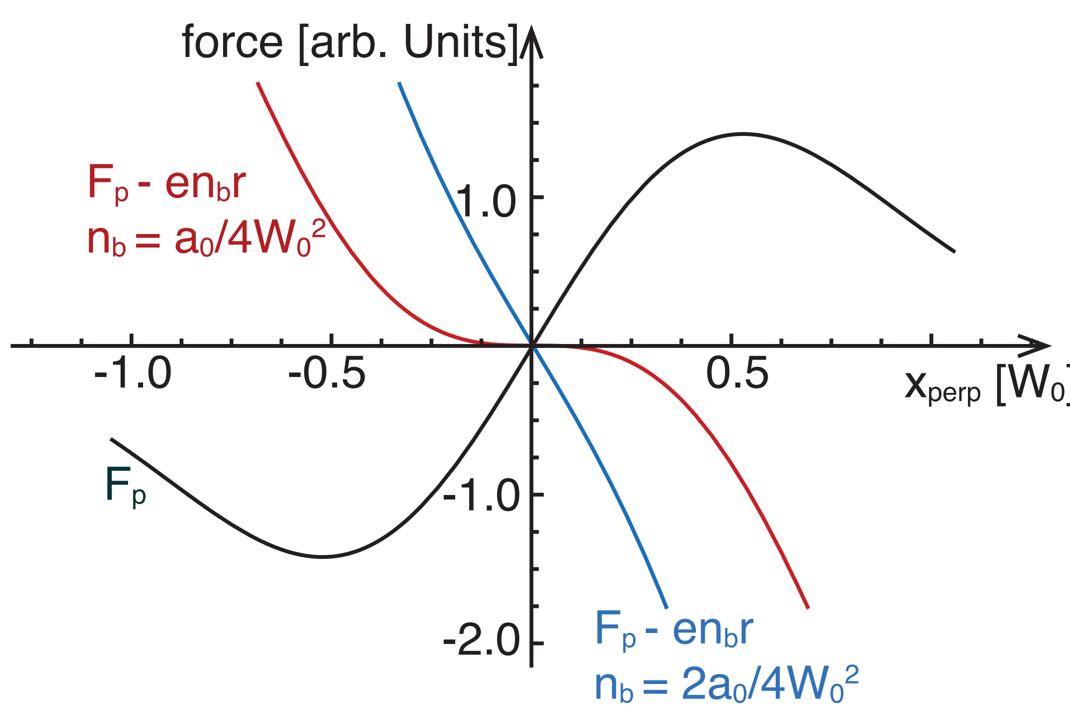
provides on-axis focusing that generates
positron focusing electron filament



Gaussian laser and positron bunch

- Gaussian beam
  electrons **defocused** from the axis
- Gaussian beam + positron bunch
  electrons can be focused on-axis
- Positron focusing requirement ($a_0 \gg 1$)

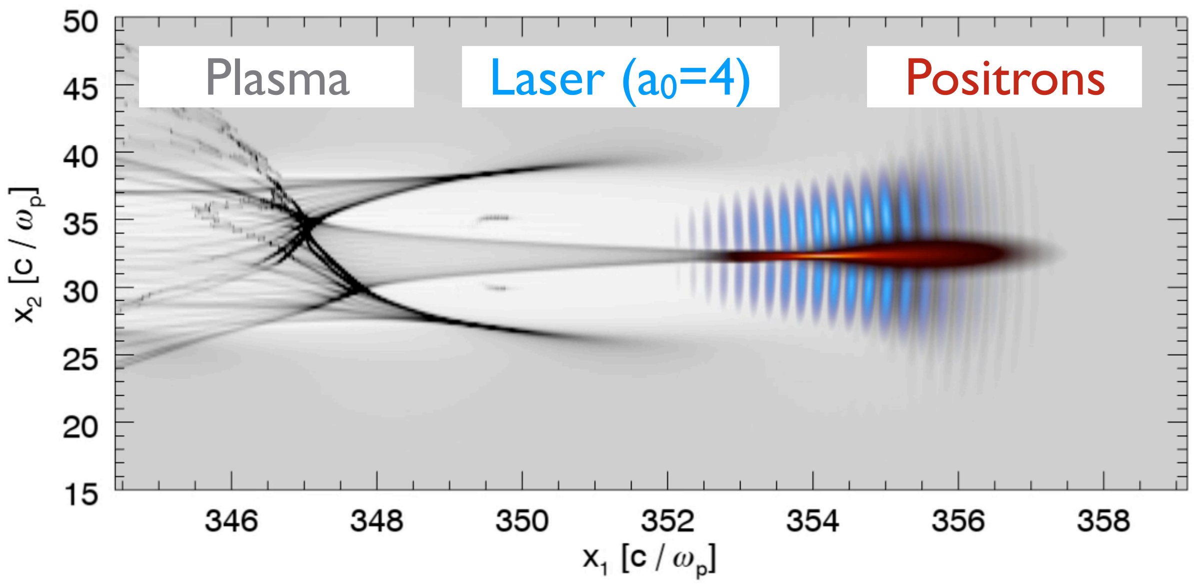
$$\frac{n_b}{n_0} \gtrsim \frac{4a_0}{W_0^2}$$



Related configurations using Gaussian lasers are possible

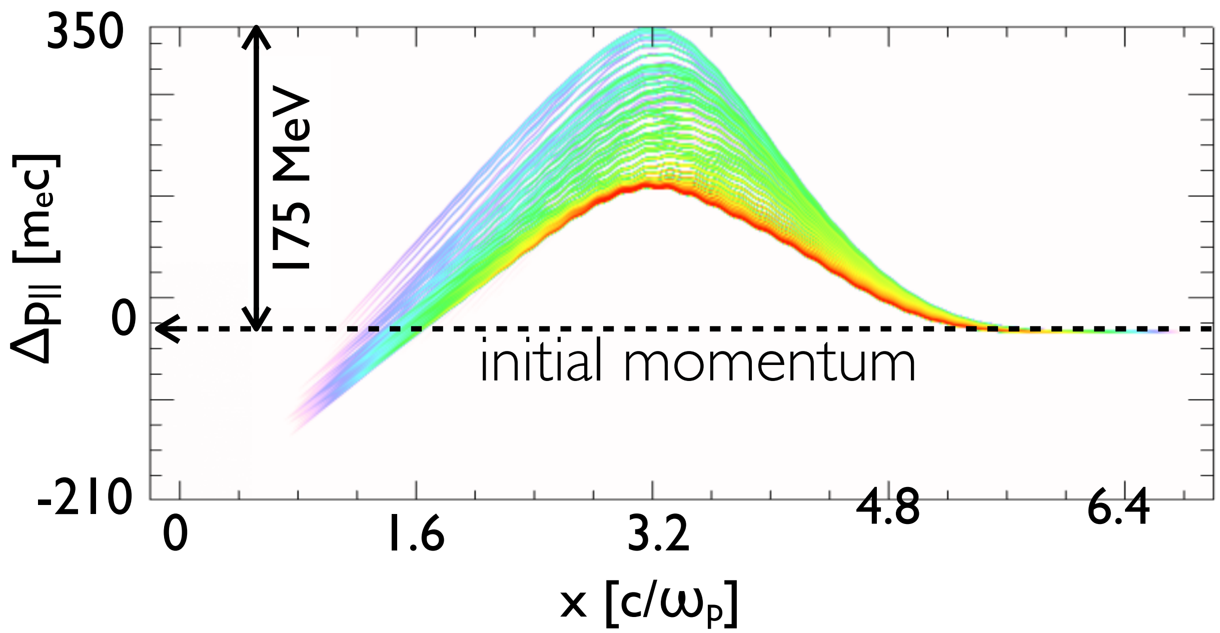
Proof-of-concept simulations

Positron beam loading required



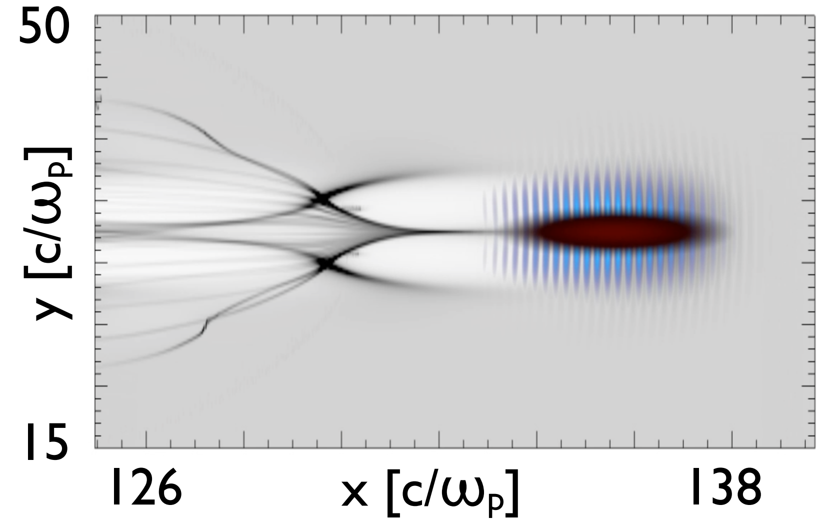
balance laser ponderomotive force with positron attraction

Positrons extract energy from wakefield



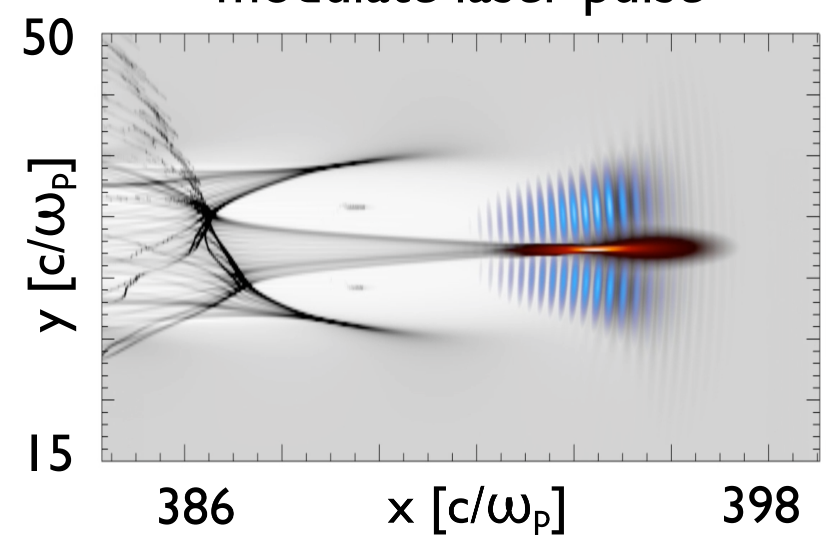
On-axis filament

positrons attract e^- towards the axis



Doughnut laser

plasma refractive index gradients modulate laser pulse



Outline

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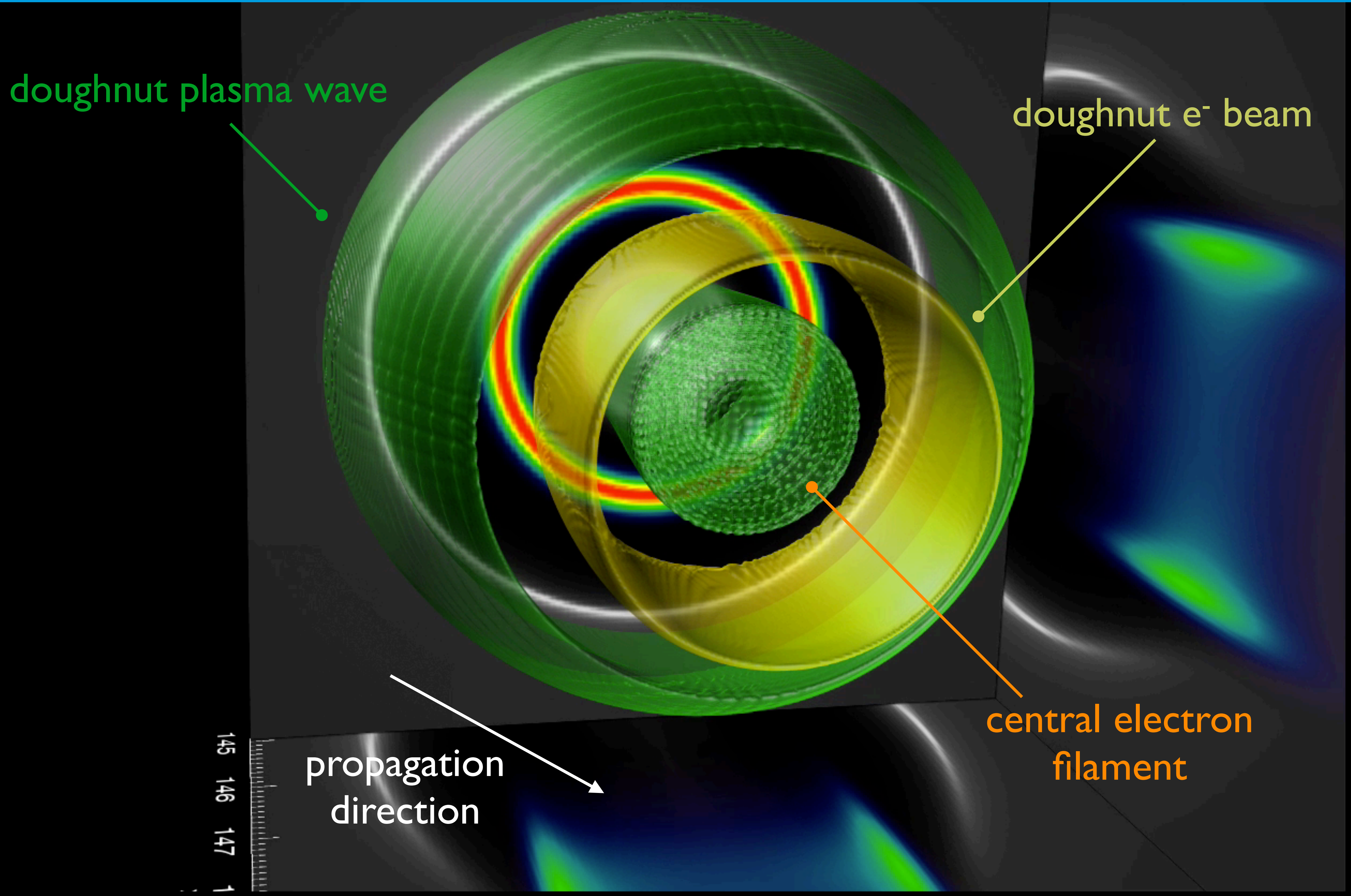
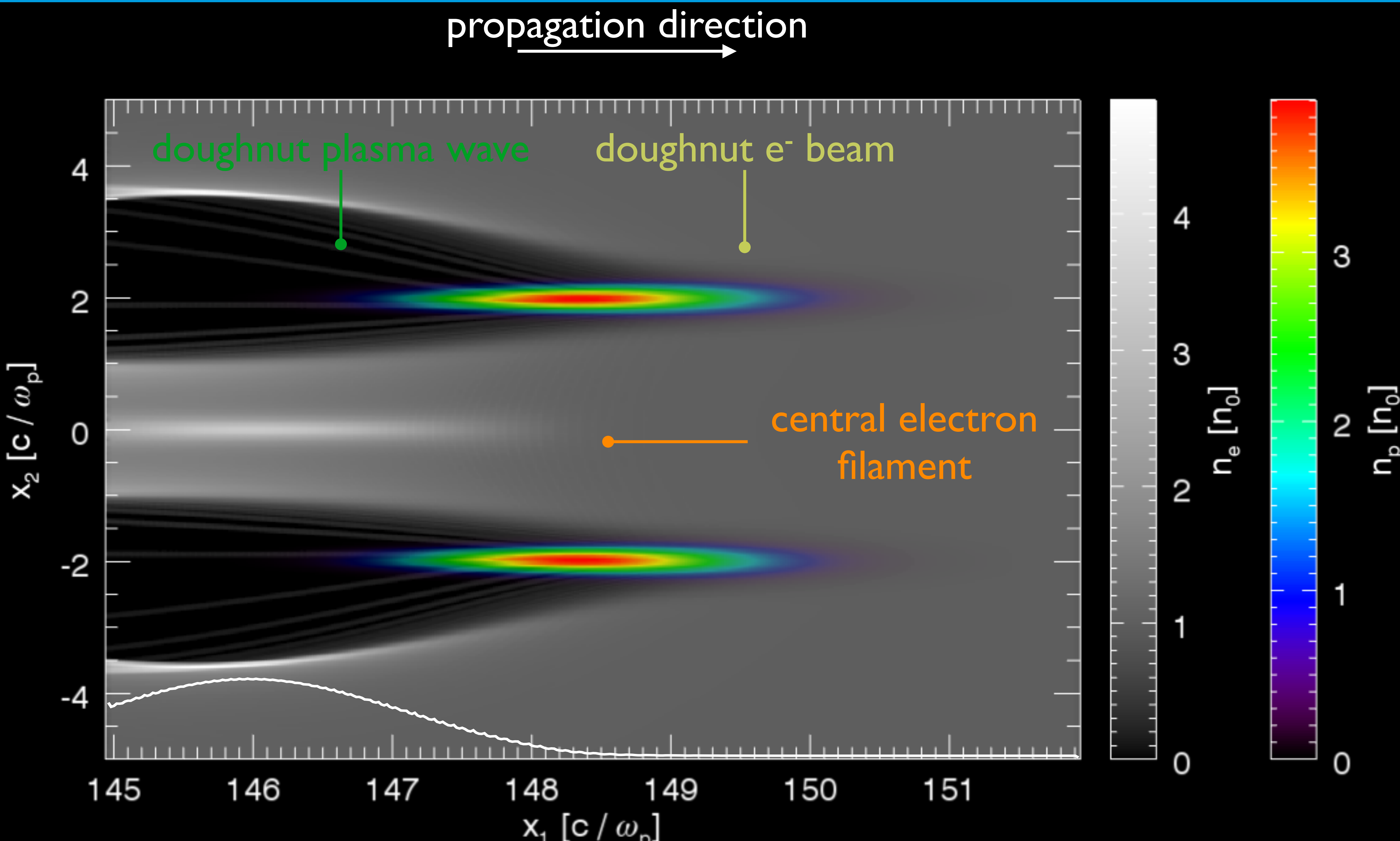
- Positron acceleration in the nonlinear regime using higher order laser drivers
- Positron acceleration in the nonlinear regime with particle beam drivers
- Conclusions & future work

Plasma wakefield accelerator driven by a doughnut electron beam



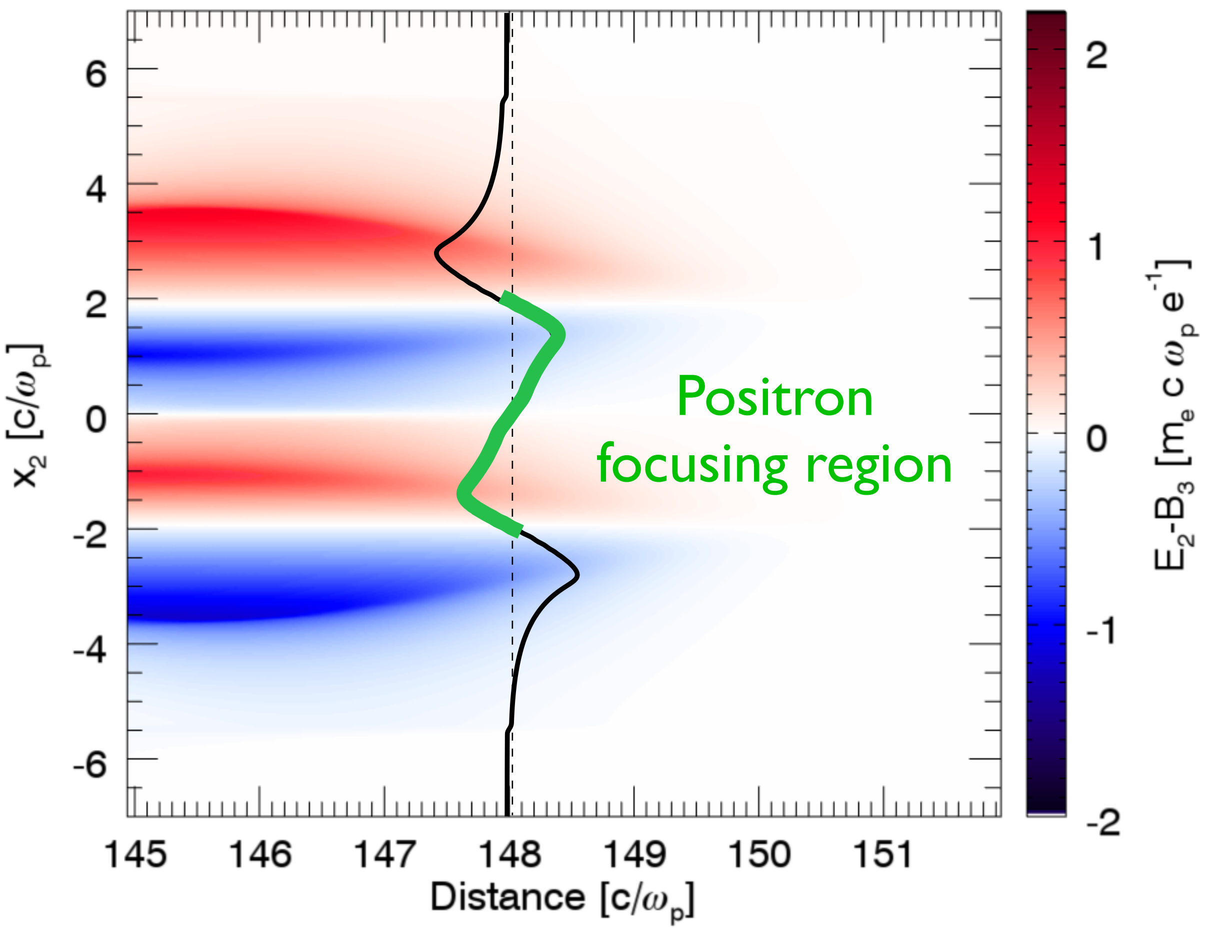
Doughnut plasma wave in the blowout regime



J. Vieira *et al* Proceedings of AAC (2014);
N. Jain *et al* arXiv (2015)

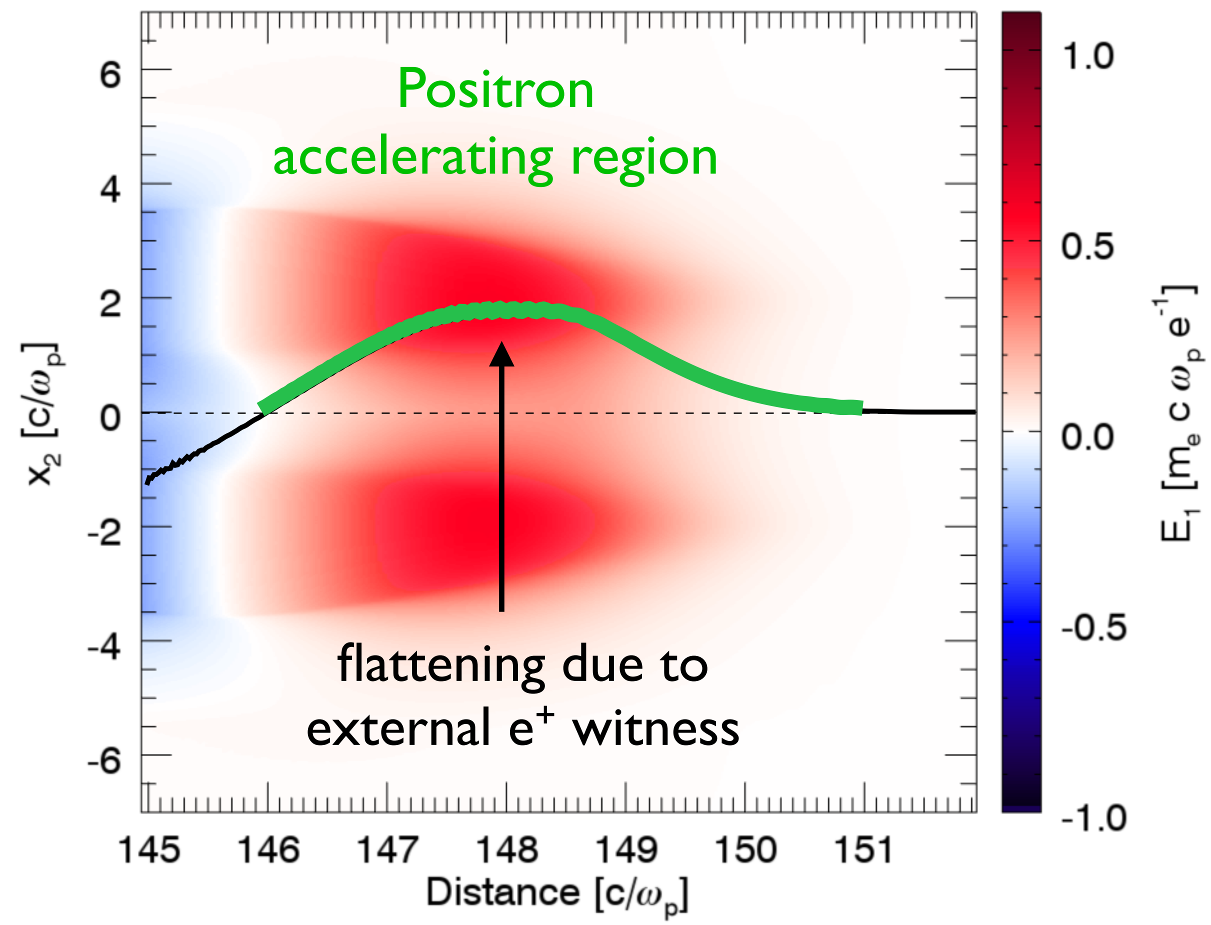
Wakefield structure shows positron focusing and accelerating regions.

Focusing force



- **Linear focusing** force for e^+
- Width of linear focusing region on the order of the skin depth
- Focusing varies but **may not compromise divergence/emittance growth**

Accelerating force

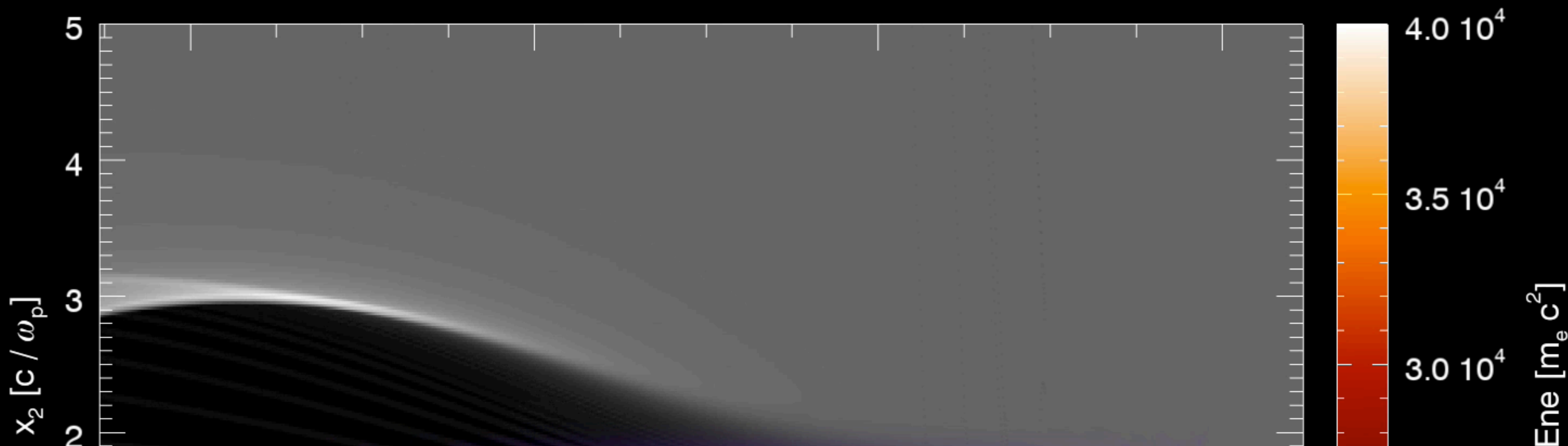


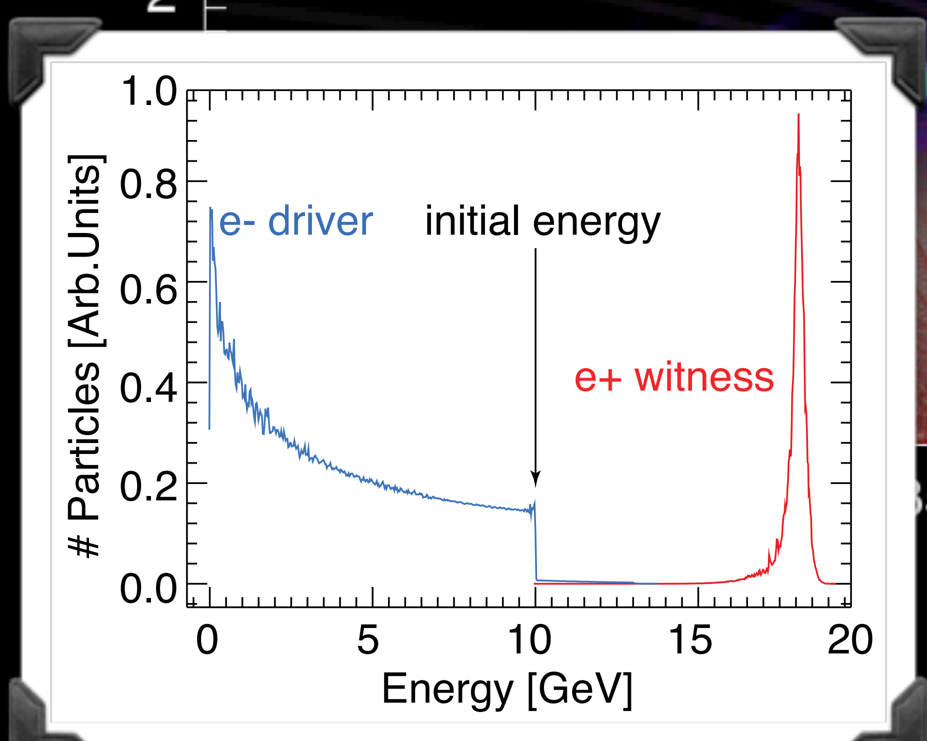
- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

Positrons gain 8 GeVs in 118 cm with low energy spread and low divergence (emittance)

Driver:

Ring profile, 10 GeV; 3.4 nC; σ_z=23 μm; no emittance

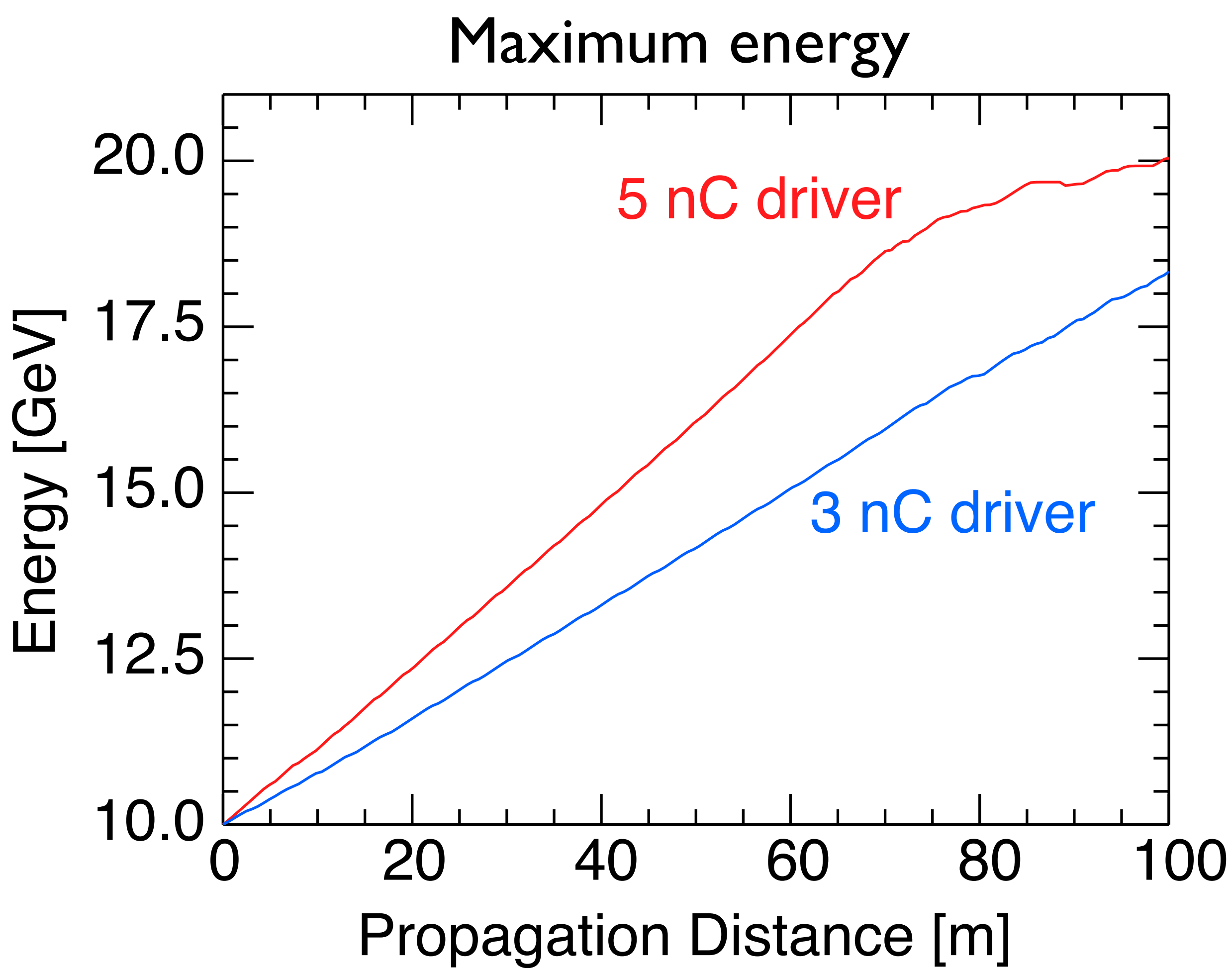




- **ΔE=8 GeV** (peak)
- **2%** energy spread
- **0.27 mrad** divergence
- **16 pC** charge

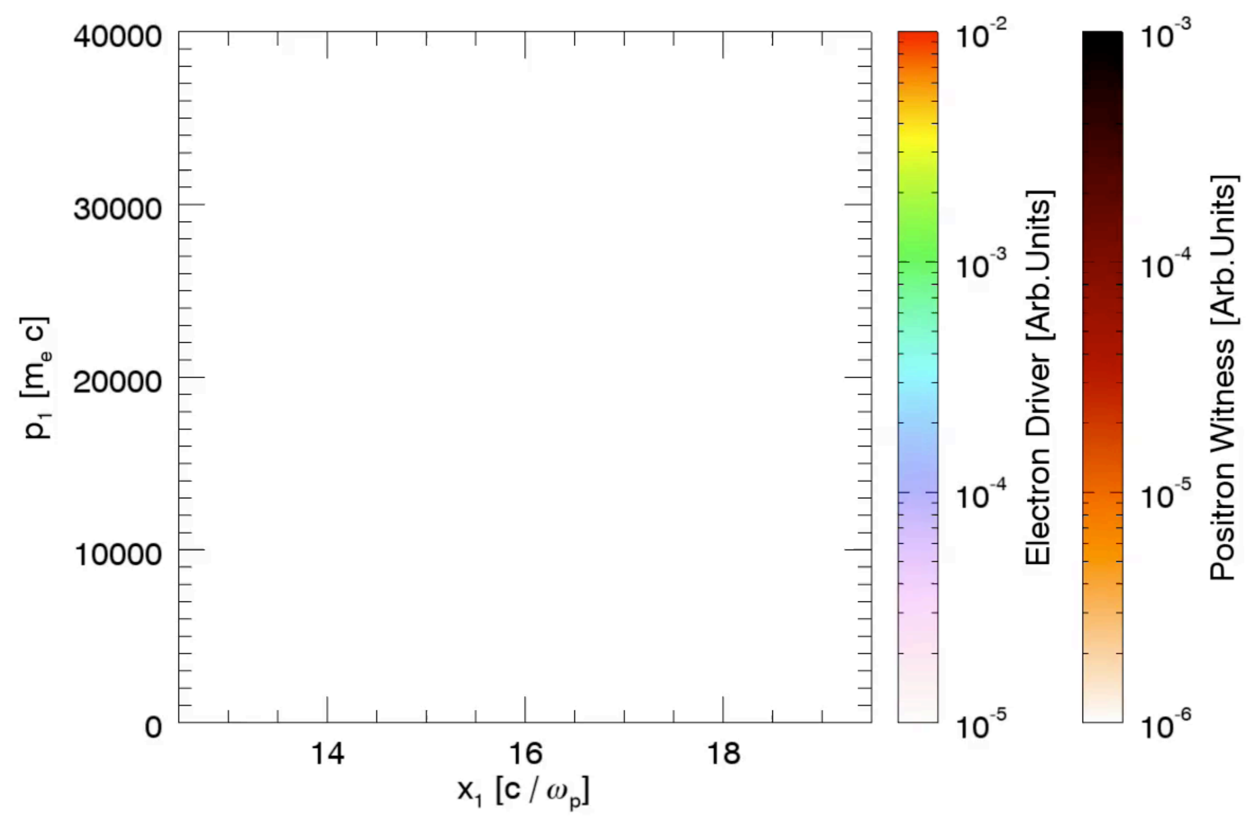
Energy doubling of some of witness positron in 1 meter with 5 nC e- driver

Higher charges and accelerating grads.



- **ΔE=8.5 GeV** energy gain (peak)
- **2%** energy spread
- **0.2 mrads** divergence
- **26 pC**

Energy loss limits acceleration distance



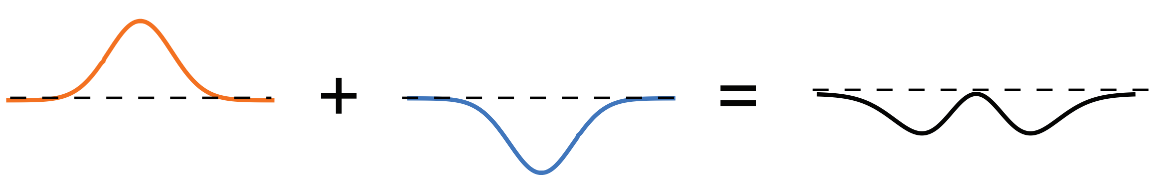
- Doughnut e^- beam focuses on-axis
- Positrons defocus shortly after
- Max. acceleration distance $L_{accel} < \gamma/E_{accel}$

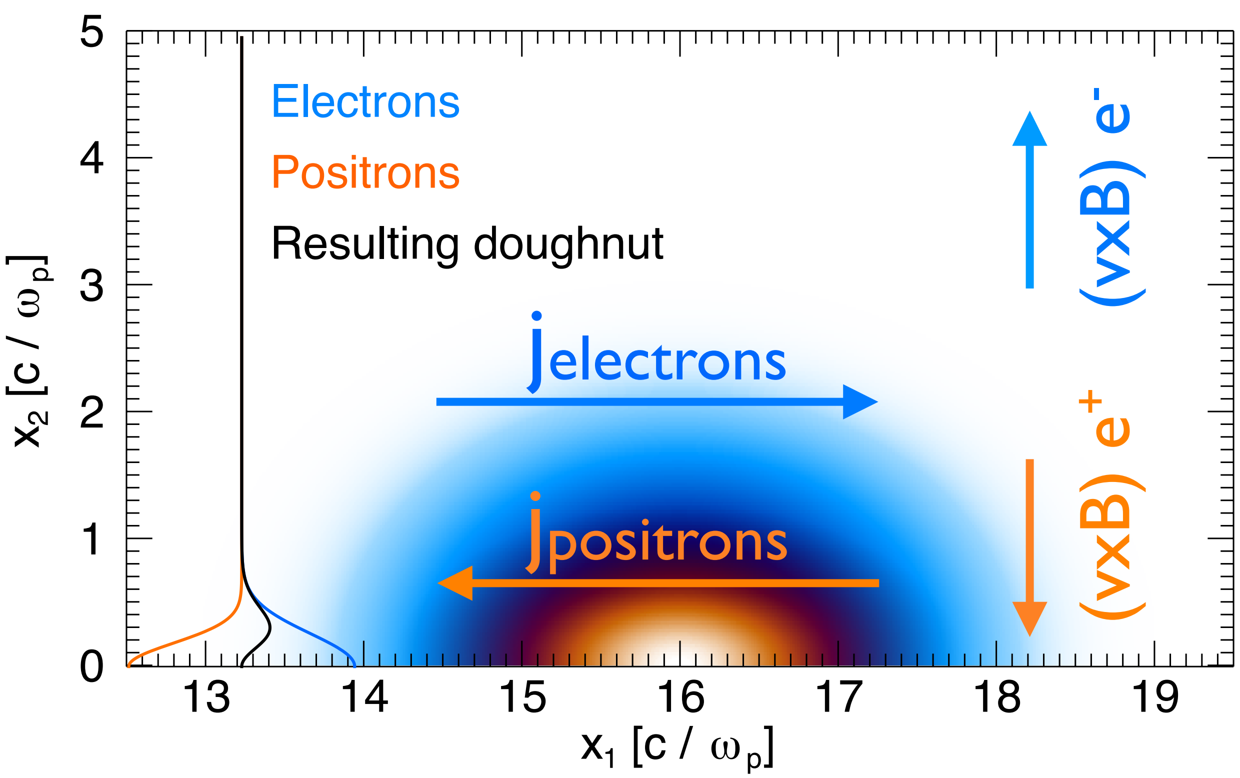
Approach to realise scheme without ring e- drivers:
Nonneutral fireball beam

Scheme could be realised superimposing Gaussian e- driver with e+ witness

Self-generated doughnut e^- bunch

Use positron bunch with smaller transverse size than electron bunch

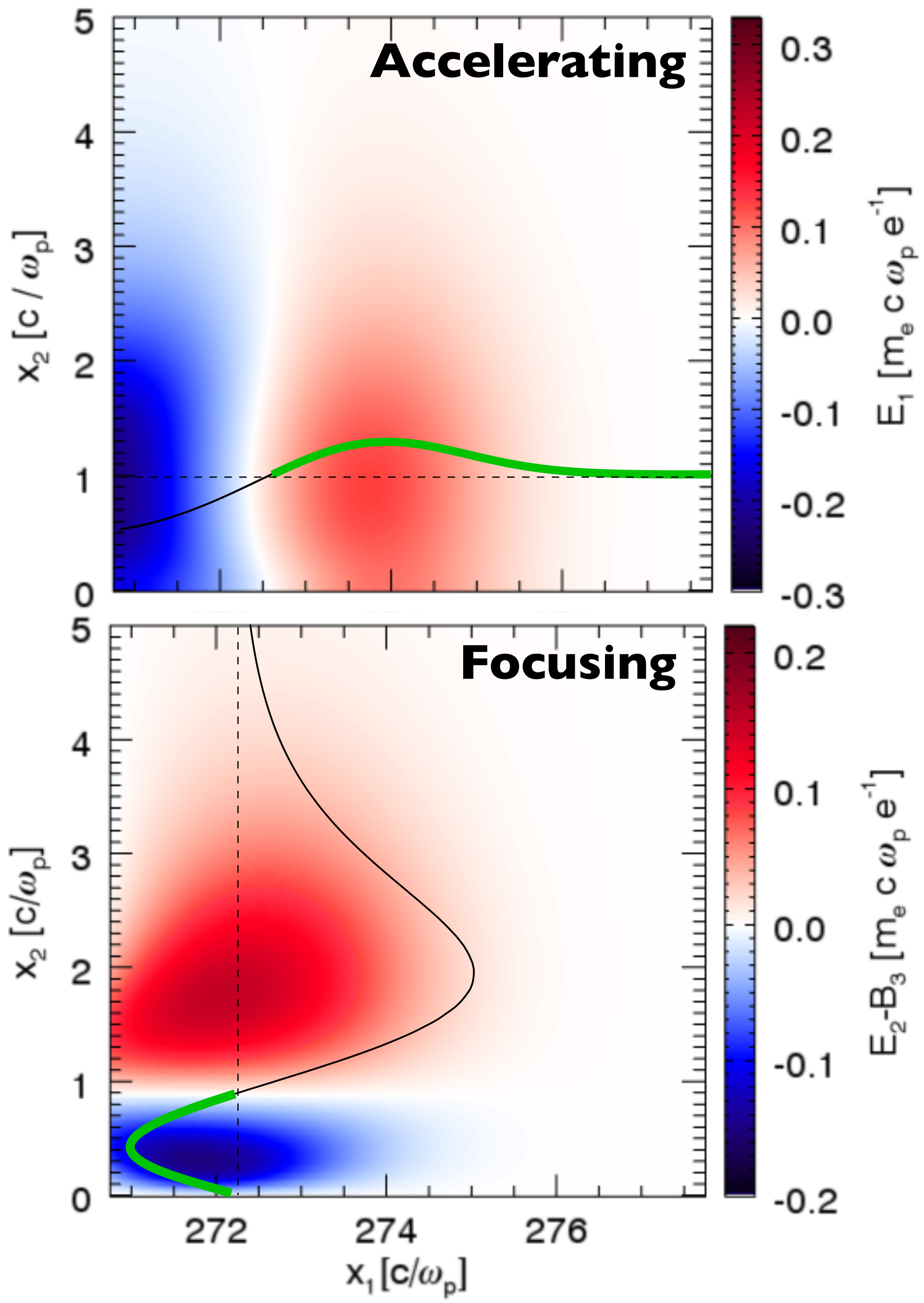




Connection to astrophysics:

Neutral fireballs and $\sigma_r >> c/\omega_p$ leads to Weibel Instability

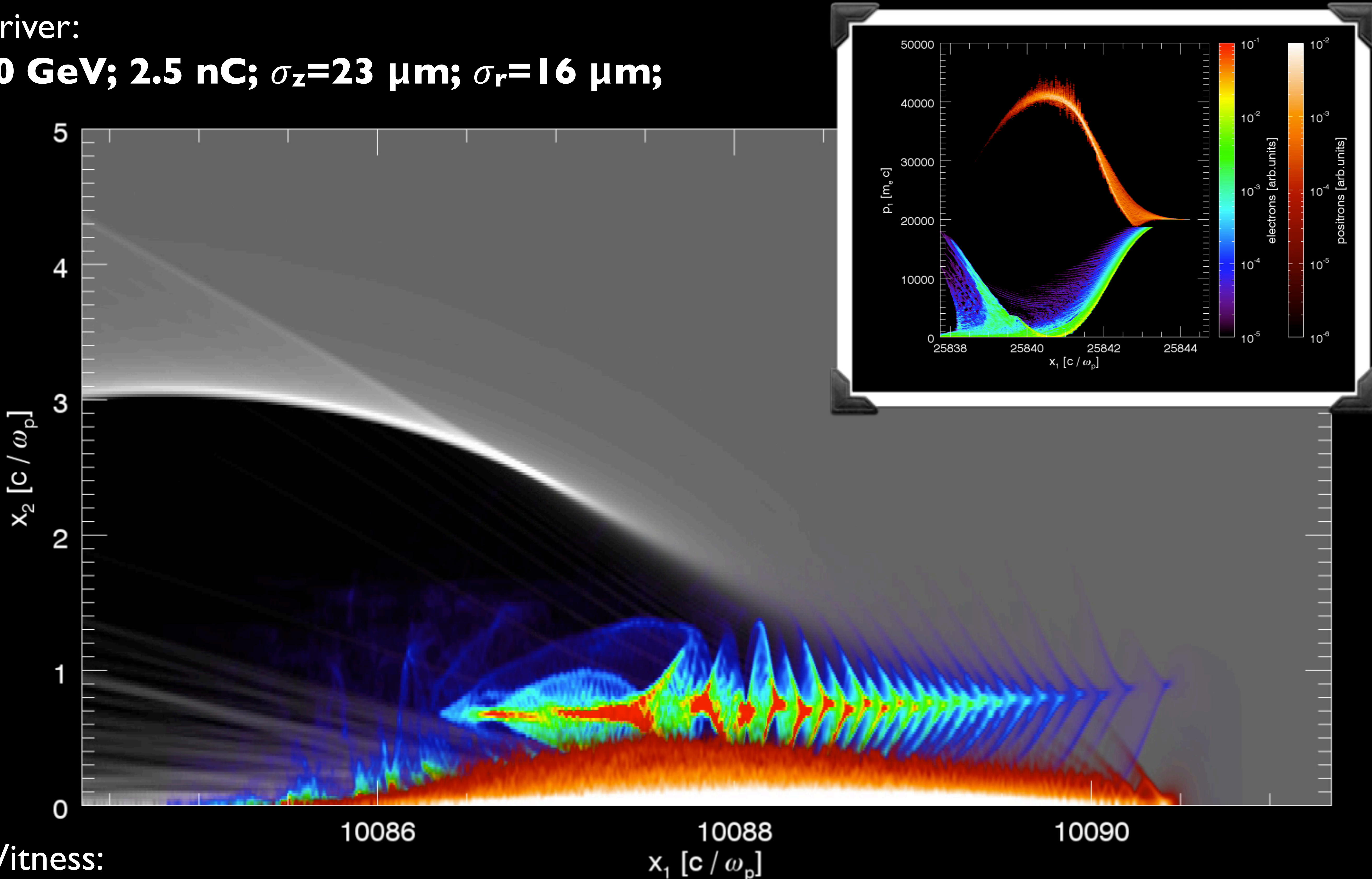
Wakefields are similar to doughnut



Fireball positron acceleration could double the energy of some of the positrons in 85 cm

Driver:

10 GeV; 2.5 nC; σ_z=23 μm; σ_r=16 μm;



Witness:

10 GeV; 1.2 nC; σ_z=23 μm; σ_r=11 μm;

Outline

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Conclusions and future work

Ring shaped lasers or particle bunches could drive nonlinear plasma waves suitable for positron acceleration

A Gaussian particle bunch (or laser) could also be used provided that the positron bunch strongly loads the plasma wave (connection with current filamentation)

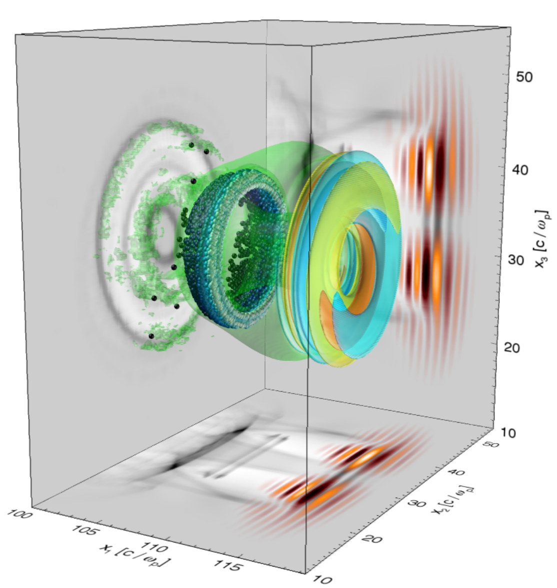
Future work

- Tolerances related to misalignments and overall beam profile
- Explore the role of other instabilities (e.g. hosing)

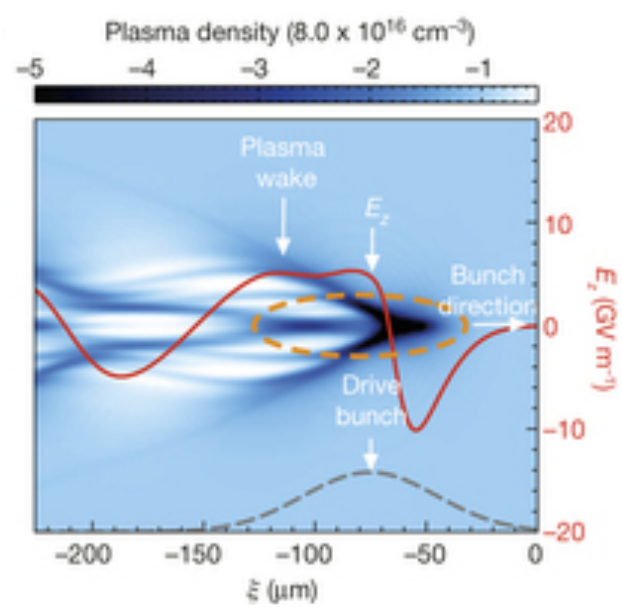
Two paths for positron acceleration in plasmas:
enhance electron density or **create a hollow plasma channel**

On-axis electron filament

- On-axis, high density plasma e-filaments focus positrons.
- Can we create positron focusing structures in a controllable way?



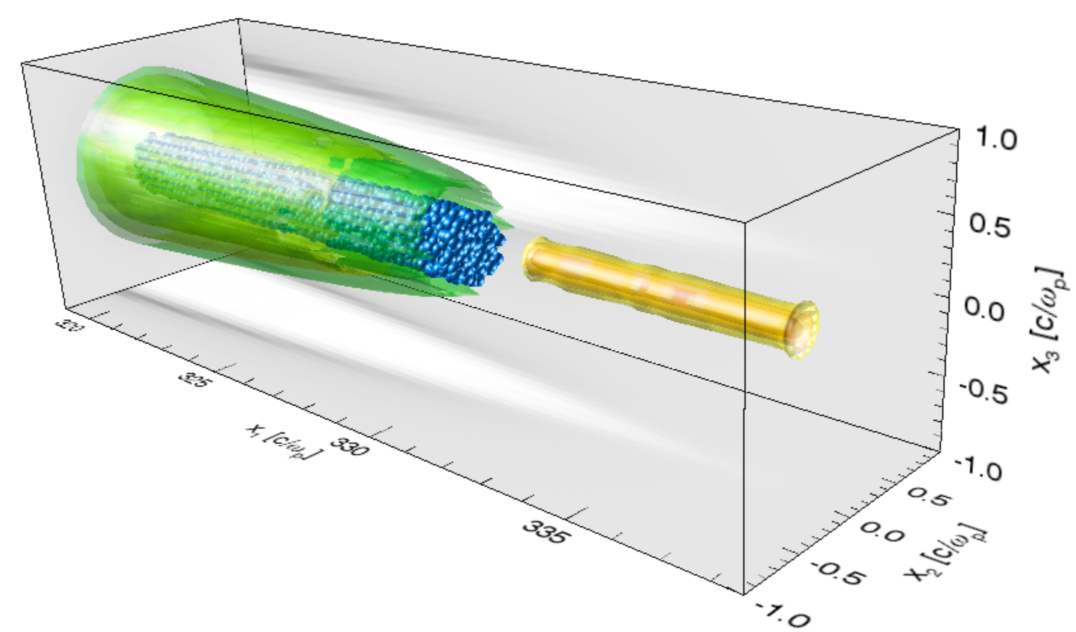
from J. Vieira *et al*
PRL (2014)



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

Hollow plasma channel

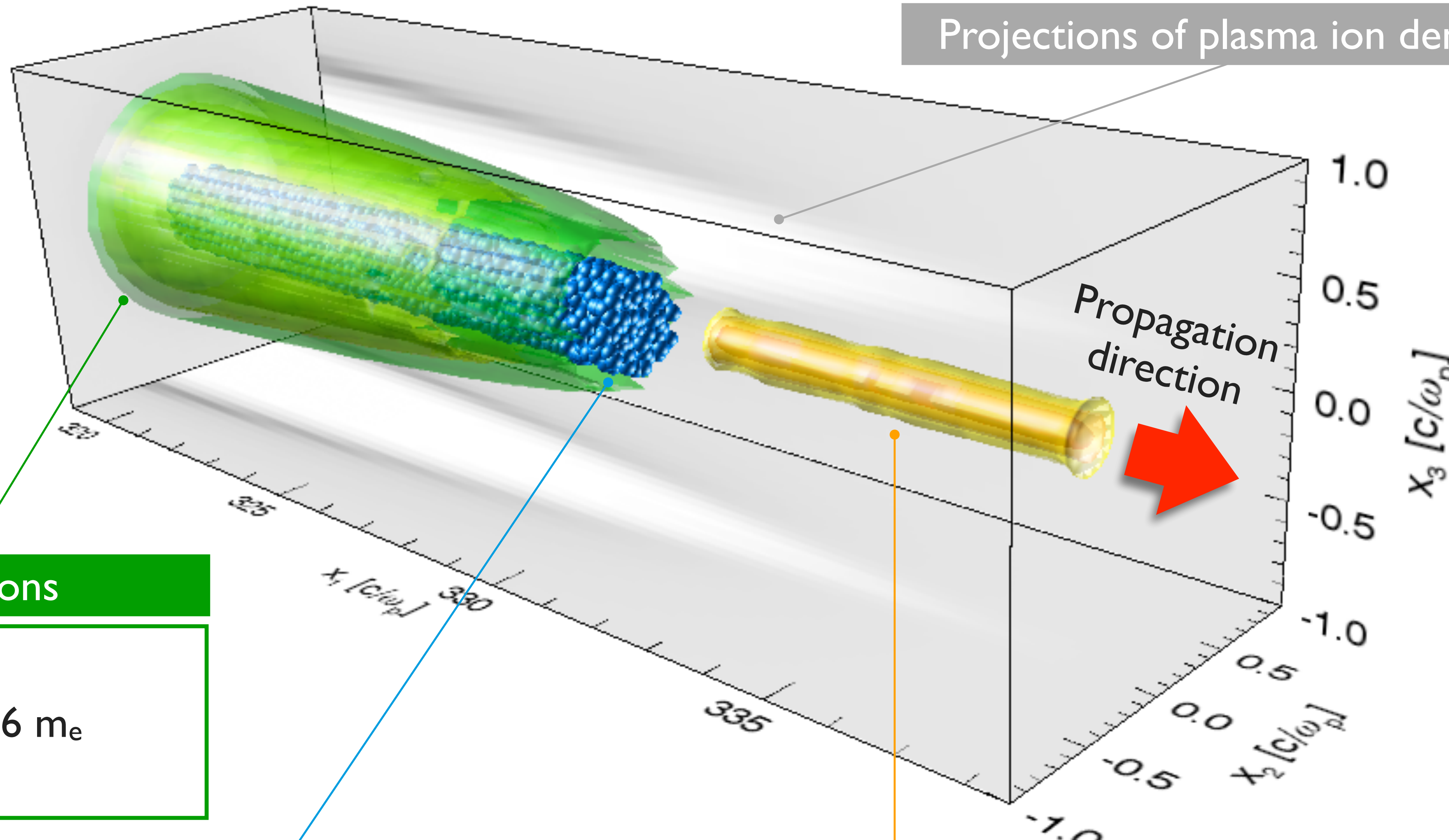
- Remove plasma electrons and plasma ions to form a hollow channel.
- What are the conditions for a driver to create its own hollow channel?



L.D. Amorim et al (2015)

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

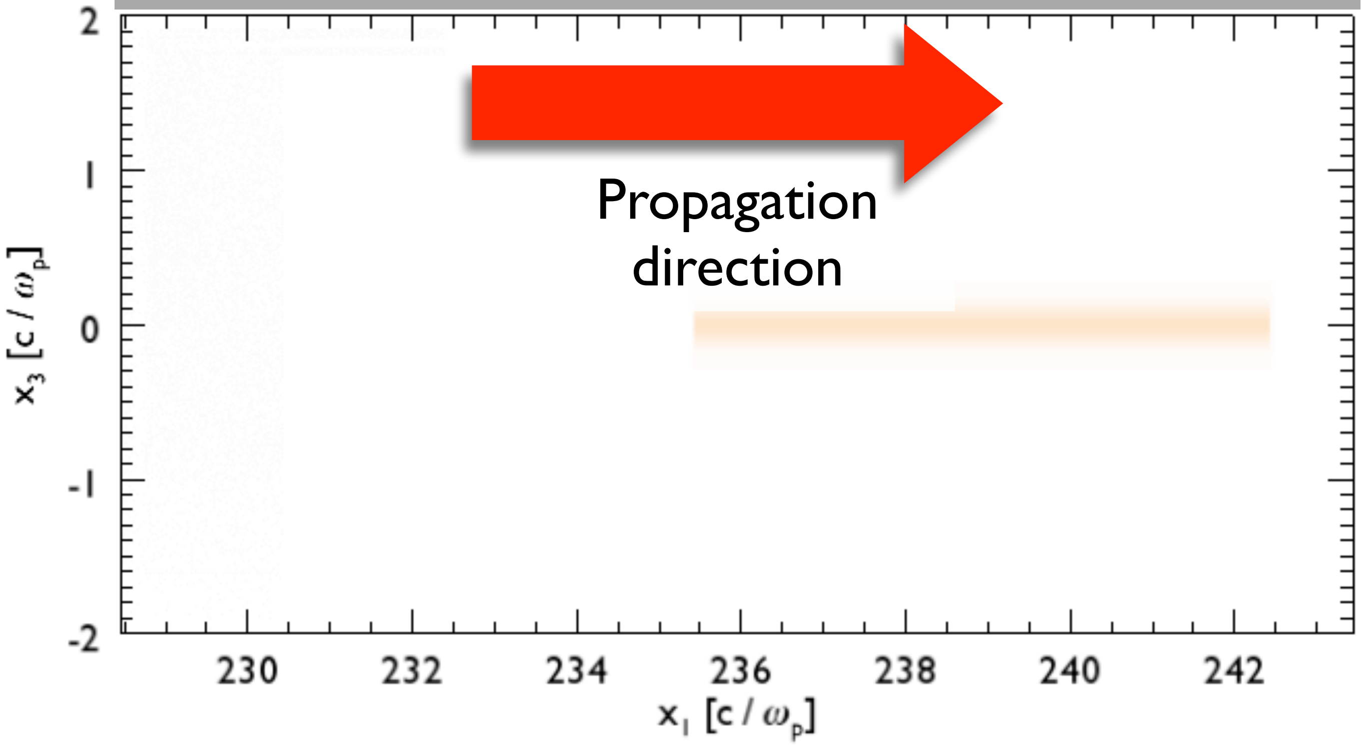
Test particle regime
Length σ_z = 12 c/ω_p
Width σ_r = 0.12 c/ω_p

e+ drive beam

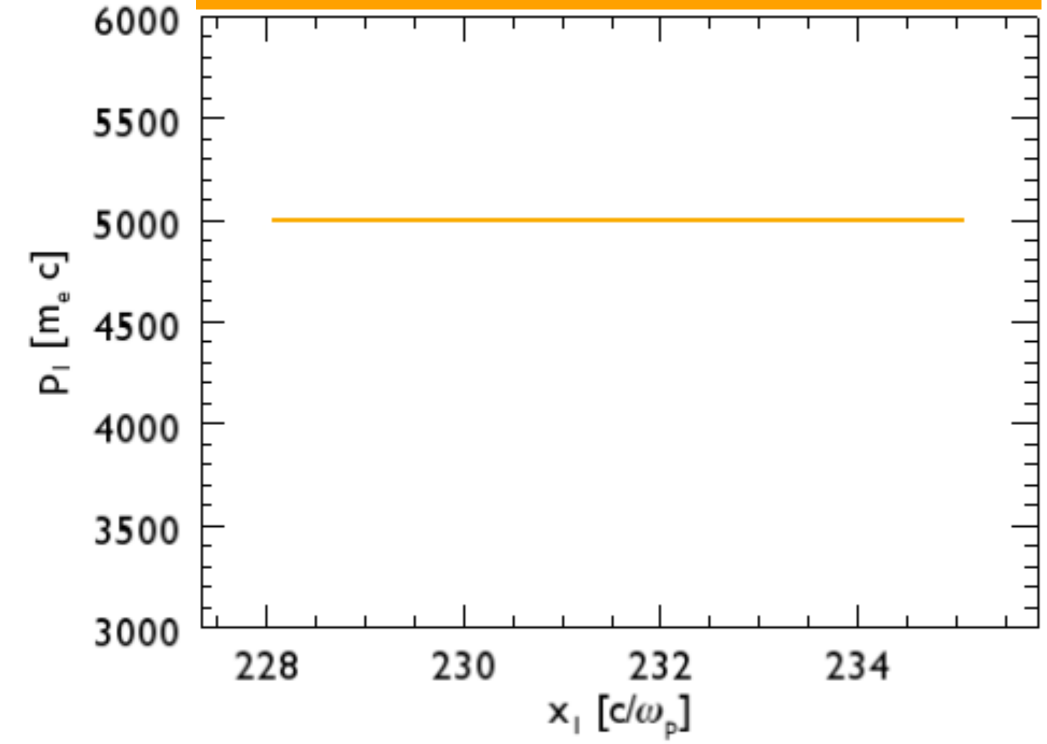
Density n_b = 200 n_0 **can be relaxed for longer beams**
Length σ_z = 6 c/ω_p **close to the plasma wavelength**
Width σ_r = 0.12 c/ω_p **tightly focused**
Energy = 2.5 GeV **ultra relativistic**

Simulations show positron bunch energy gain inside the hollow channel

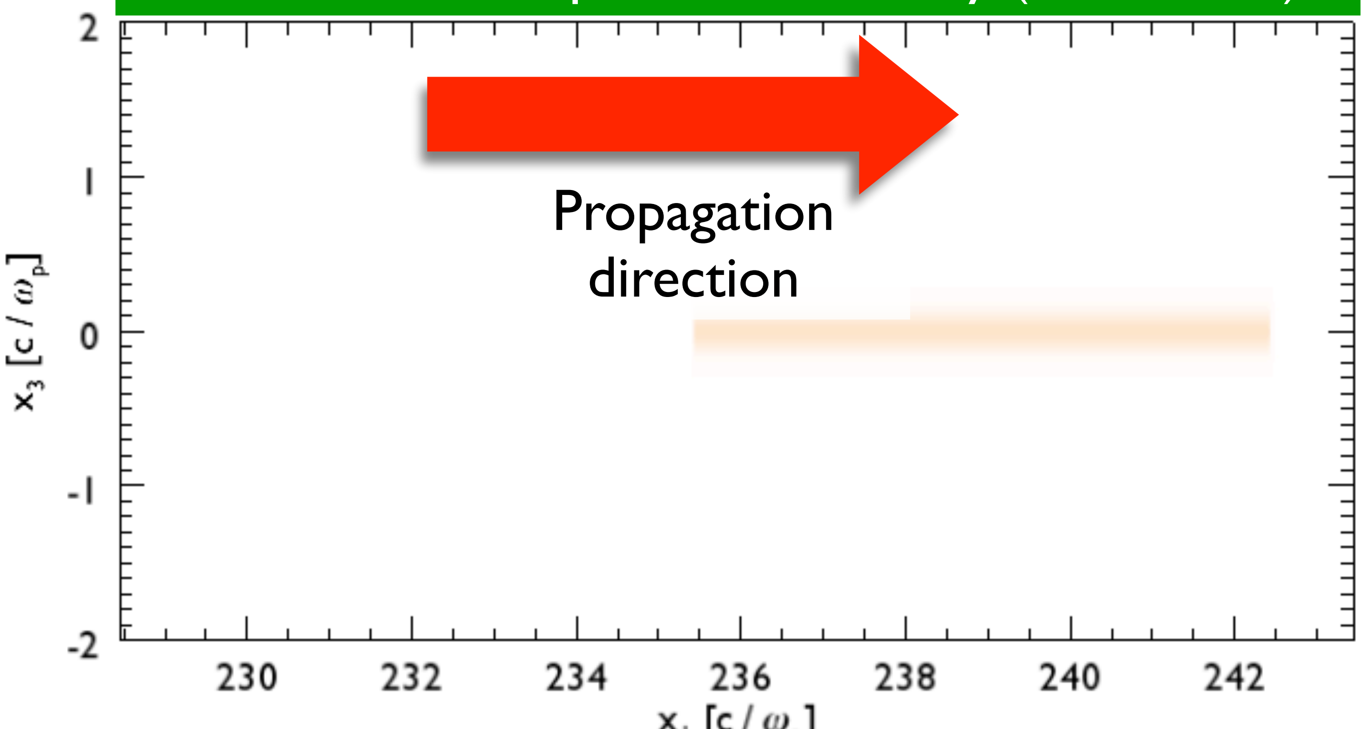
Evolution of the plasma ions density (slice of 3D)



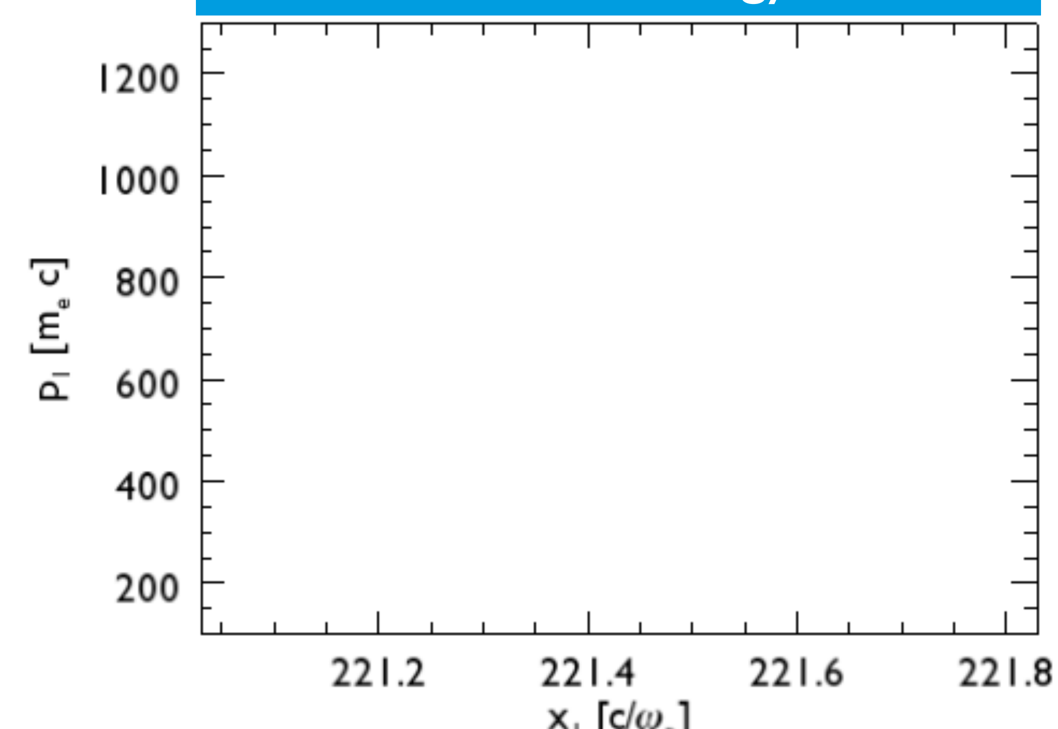
Drive e^+ beam energy evolution



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



Witness e^+ beam energy evolution



L.D. Amorim et al (2015)

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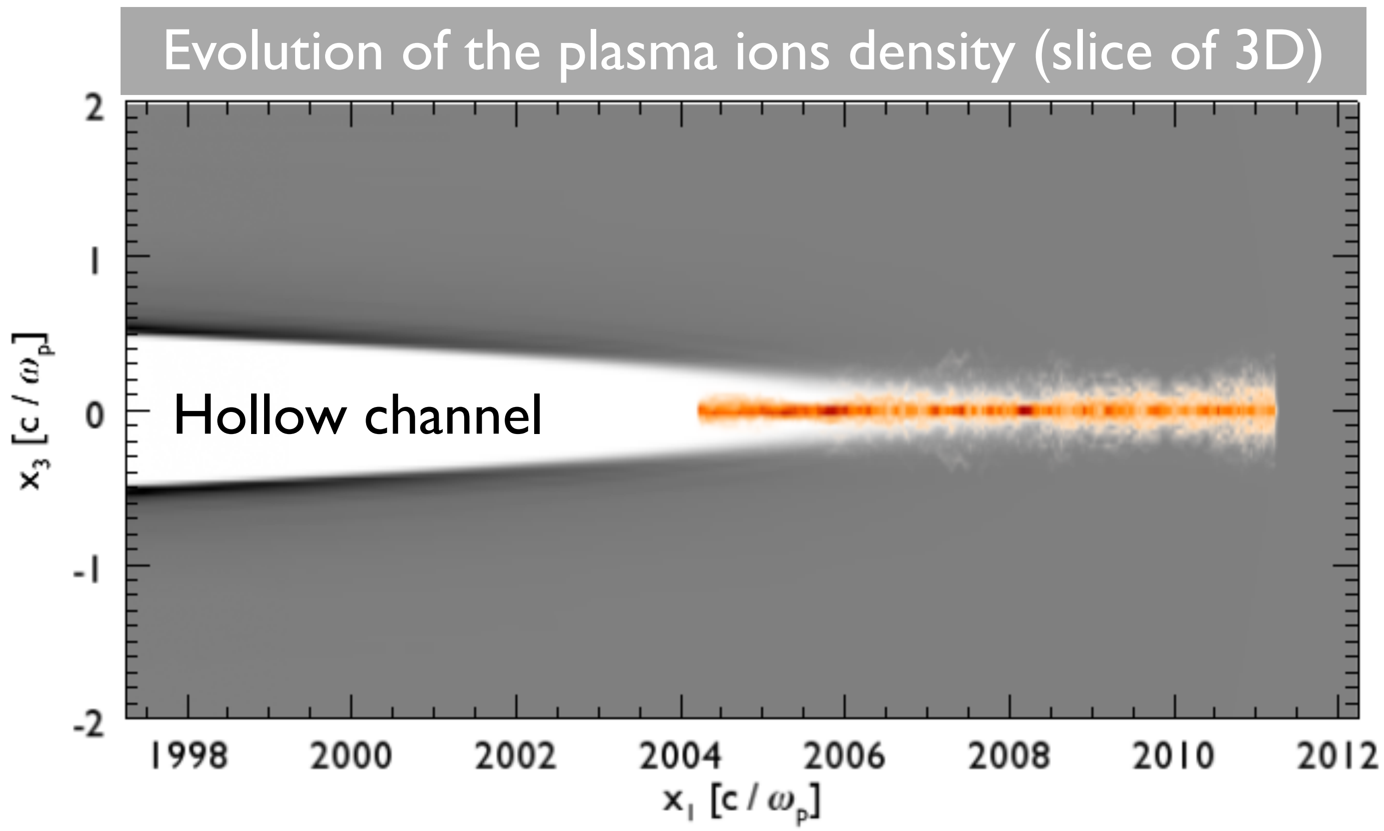
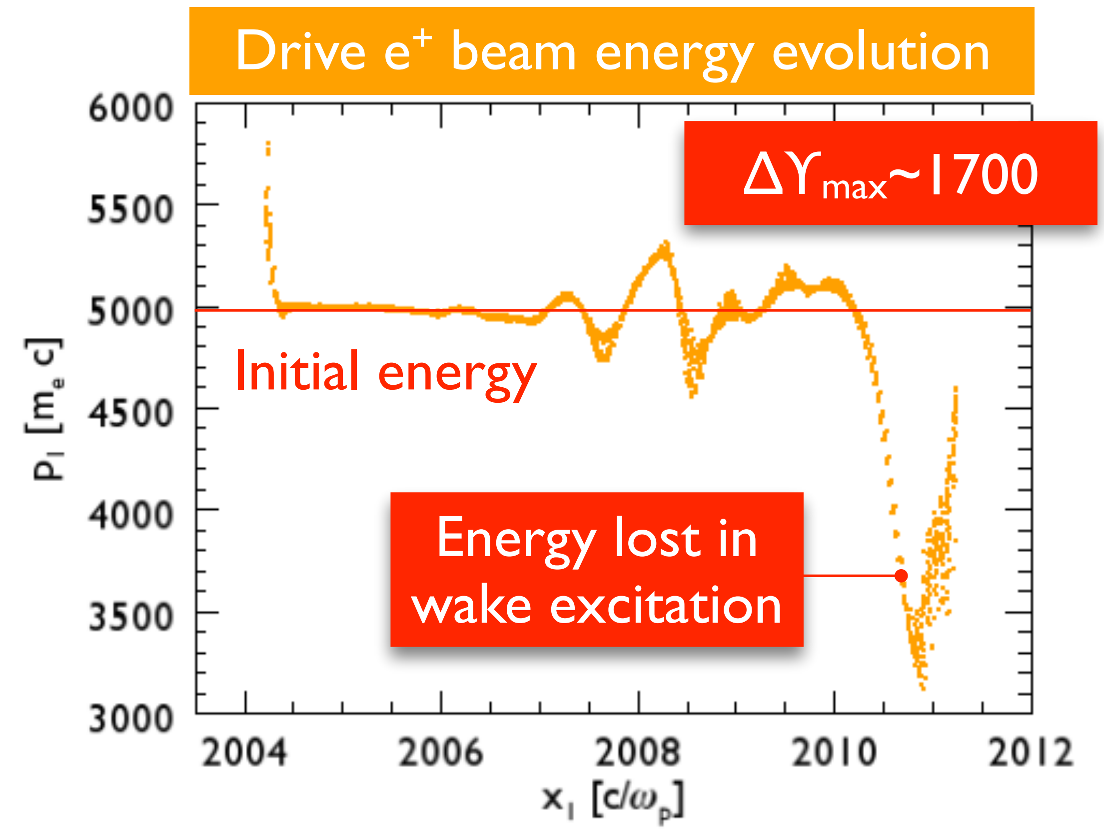
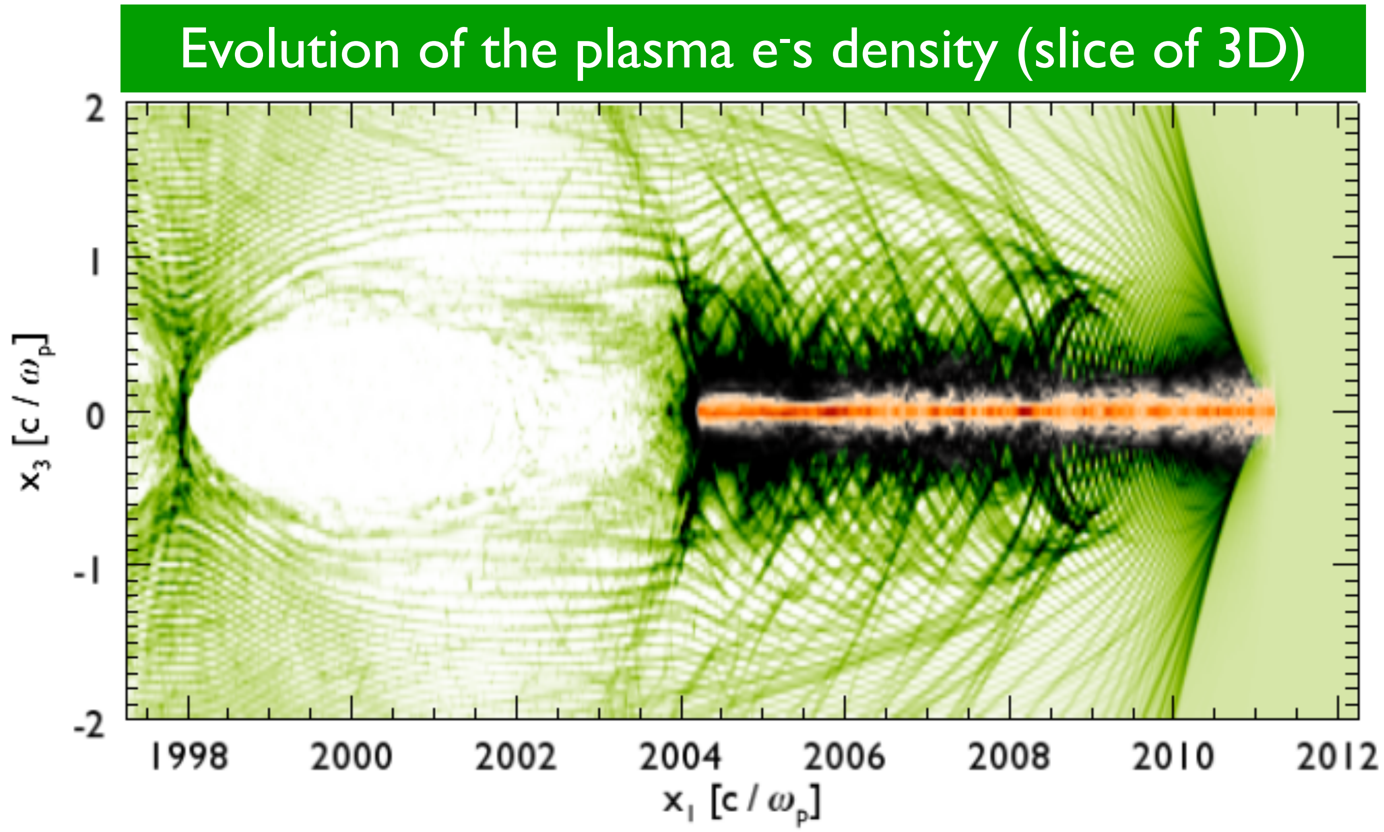
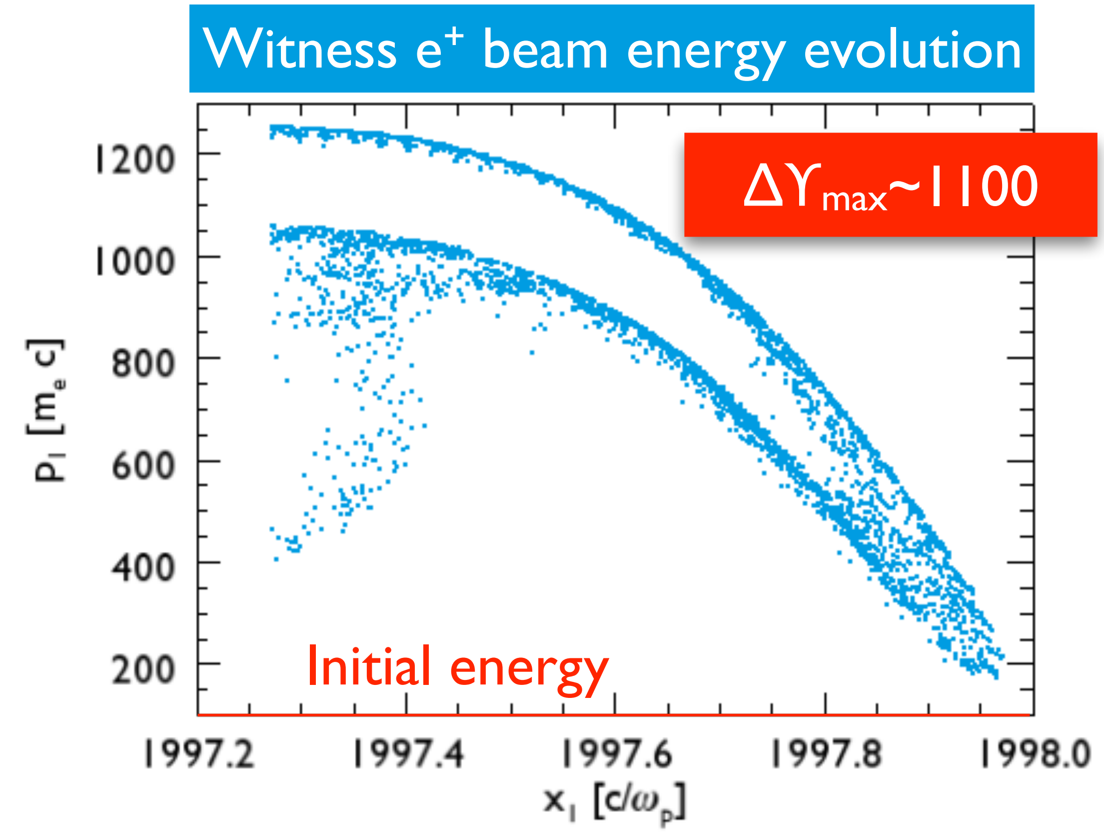






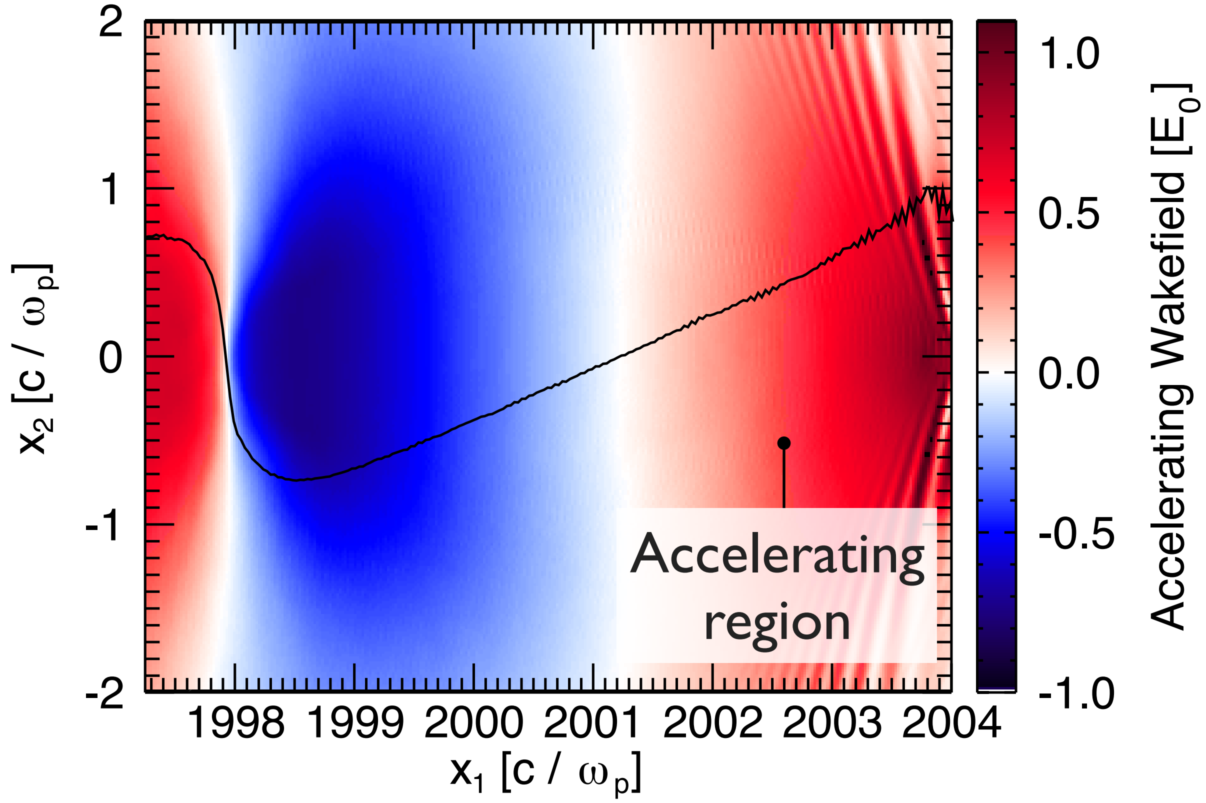


L.D. Amorim et al (2015)

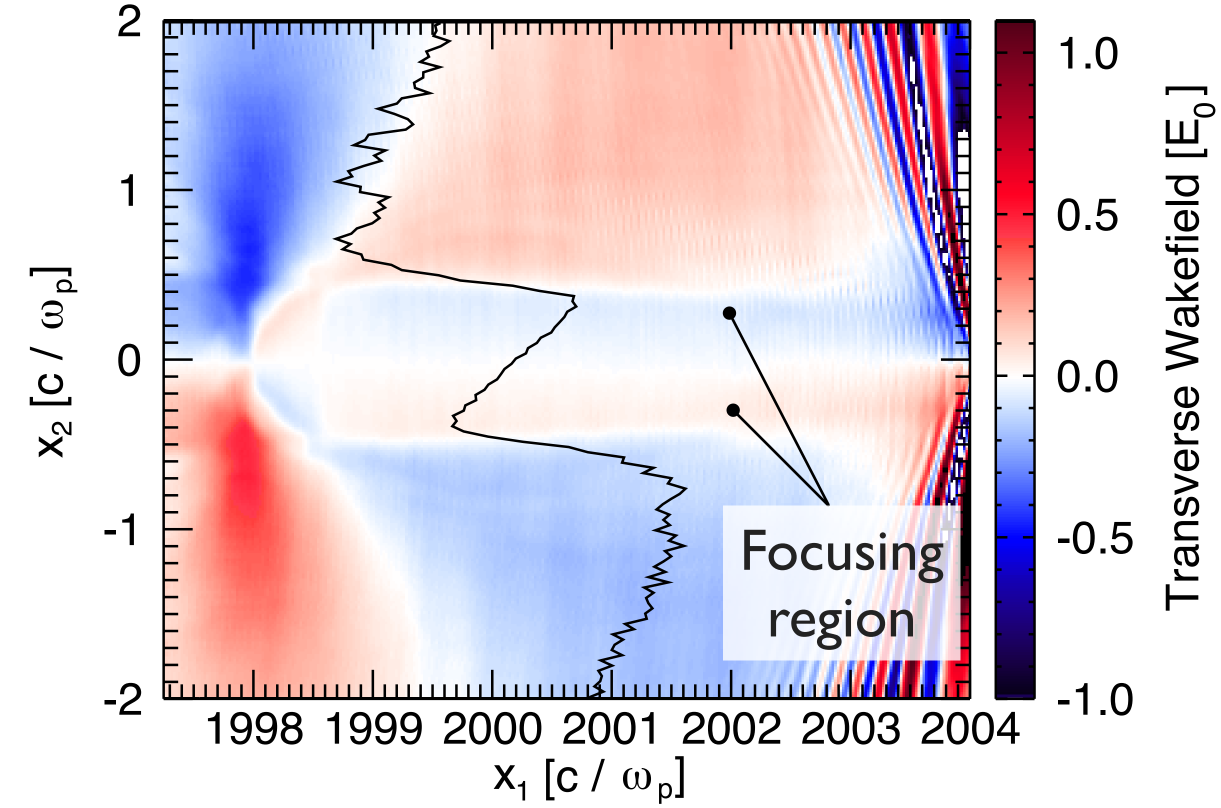
Positron focusing and accelerating fields in hollow channel created by narrow drivers

L.D. Amorim et al (2015)

Accelerating wakefield inside the hollow channel



Focusing wakefields inside the hollow channel



Key wakefield properties

Non-linear accelerating wakefields:

- Peak field in the hollow channel region ~ $0.7E_0$
- Sawtooth shape

Positron focusing forces:

- Mainly focusing for lengths of ~ $\lambda_p = 2\pi$ inside the channel
- Focusing due to plasma e^-s in the channel region

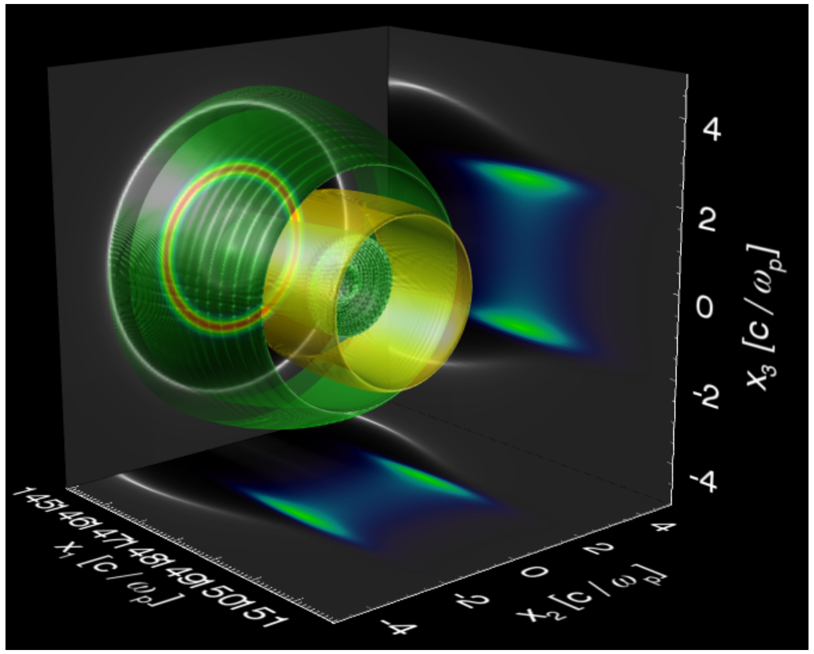
SLAC positron bunches could self-drive a hollow plasma channel and are close to the onset for positron acceleration

Plasma parameters		Beam parameters			
n_0 [cm^{-3}]	k_p^{-1} [μm]	σ_z [μm]	σ_r [μm]	# positrons	Charge [nC]
1,00E+15	167,92	1007,50	20,15	2,57E+11	4,11E+01
2,50E+15	106,20	637,20	12,74	1,63E+11	2,60E+01
5,00E+15	75,09	450,57	9,01	1,15E+11	1,84E+01
7,50E+15	61,31	367,89	7,36	9,39E+10	1,50E+01
1,00E+16	53,10	318,60	6,37	8,13E+10	1,30E+01
2,50E+16	33,58	201,50	4,03	5,14E+10	8,22E+00
5,00E+16	23,75	**142,48**	**2,85**	**3,63E+10**	**5,82E+00**
7,50E+16	19,39	**116,34**	**2,33**	**2,97E+10**	**4,75E+00**
1,00E+17	16,79	**100,75**	**2,02**	**2,57E+10**	**4,11E+00**

Conclusions & Future work

Positron accelerations using doughnut electron beam drivers

- Positron focusing and acceleration on axis
- Co-propagating non-neutral e-e+ fireball results in doughnut e- beam profile
- New types of hosing could appear.
- Beam dynamics with emittance and energy spreads need to be examined



Hollow plasma channels driven by tightly focused positron bunches

- Hollow plasma channel with positron focusing and acceleration regions
- Parameters could be realised at lower plasma densities
- Could also be a first demonstration of background plasma ion motion.