Non-neutral fireball and possibilities for accelerating positrons with plasma

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GoLP/IPFN Instituto Superior Técnico

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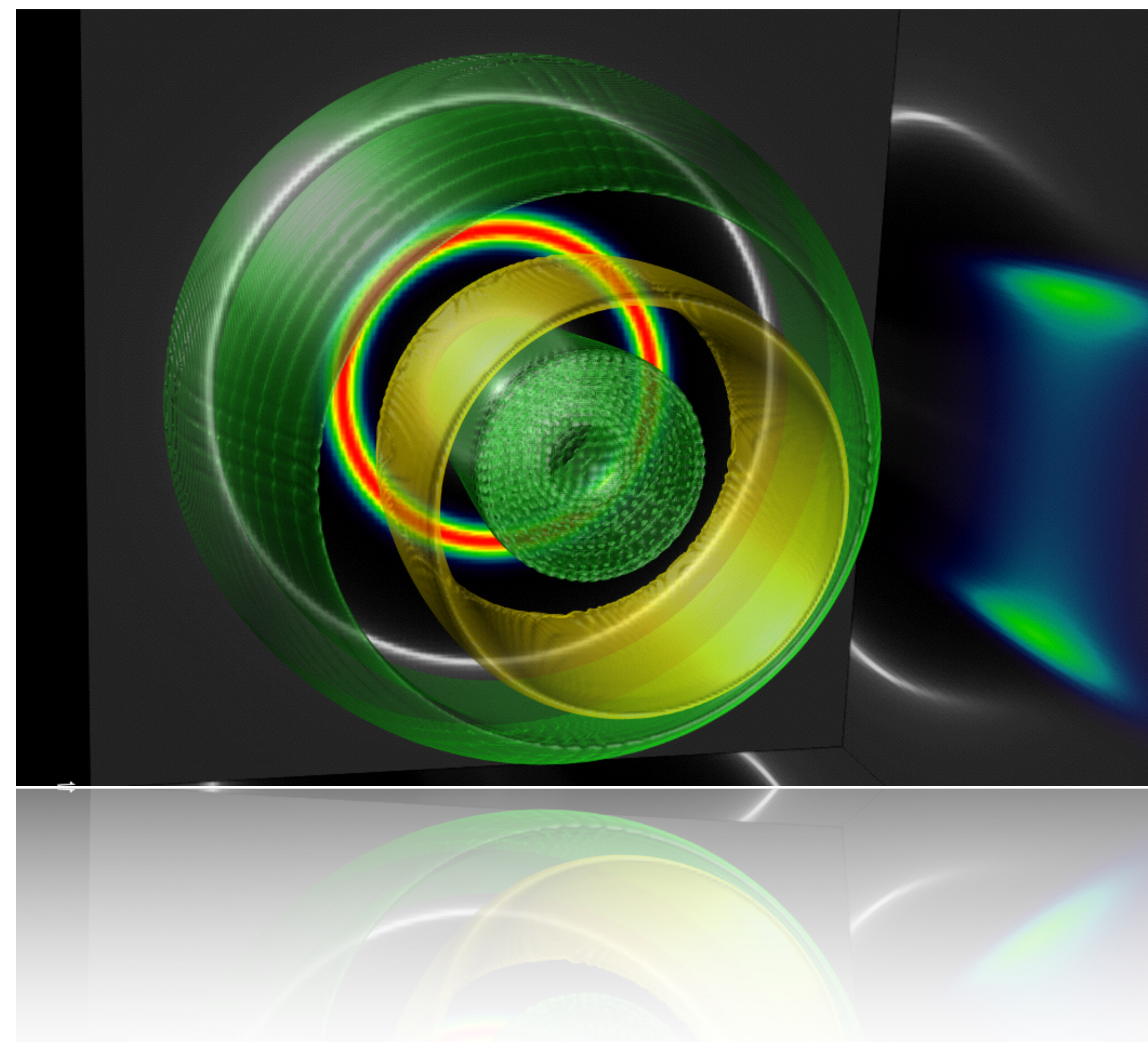
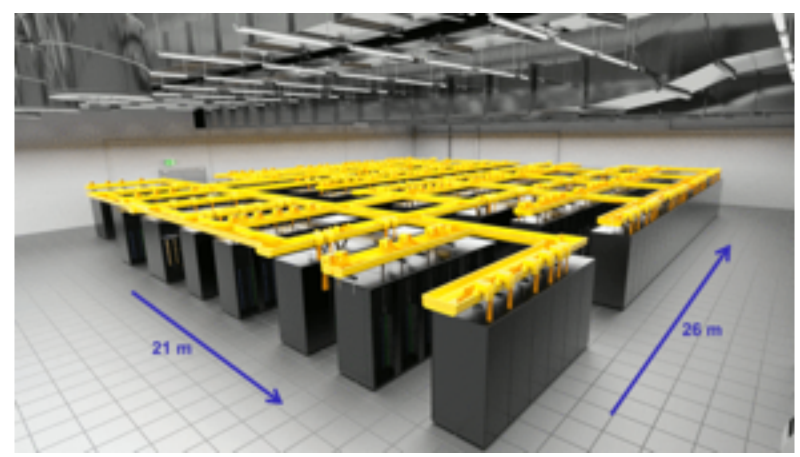


Acknowledgments

- 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

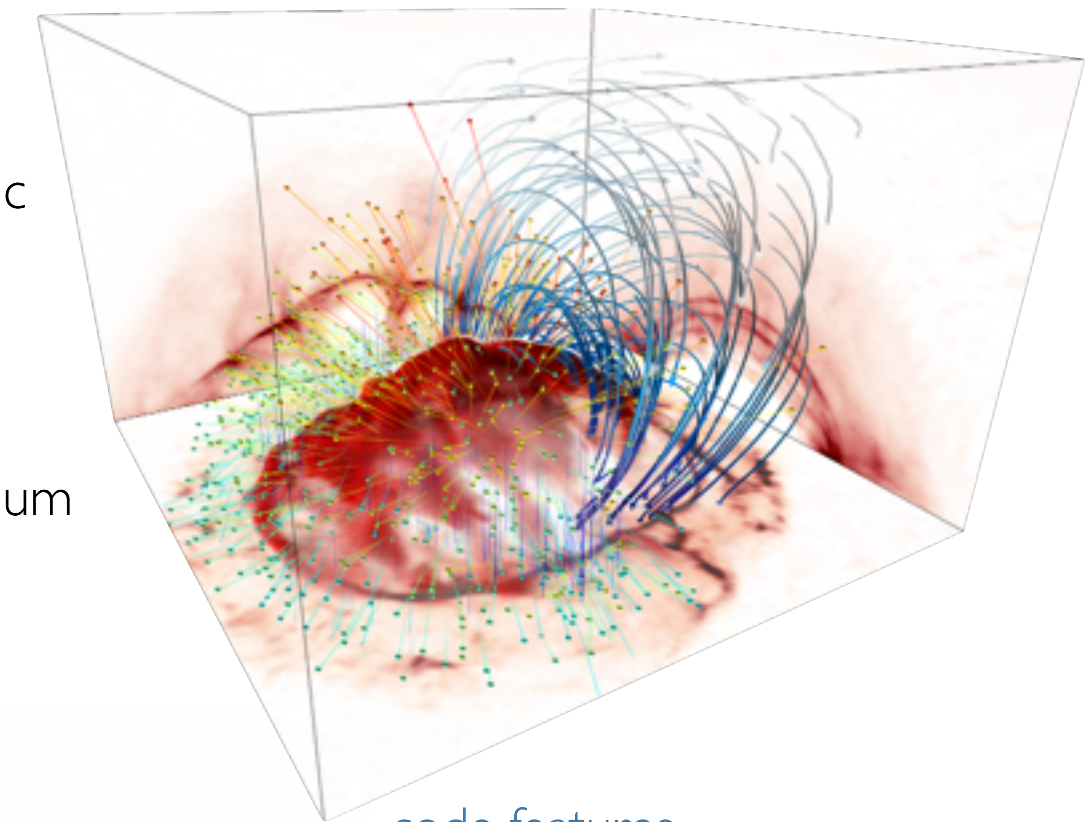
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR



golp grupo de lasers e plasmas

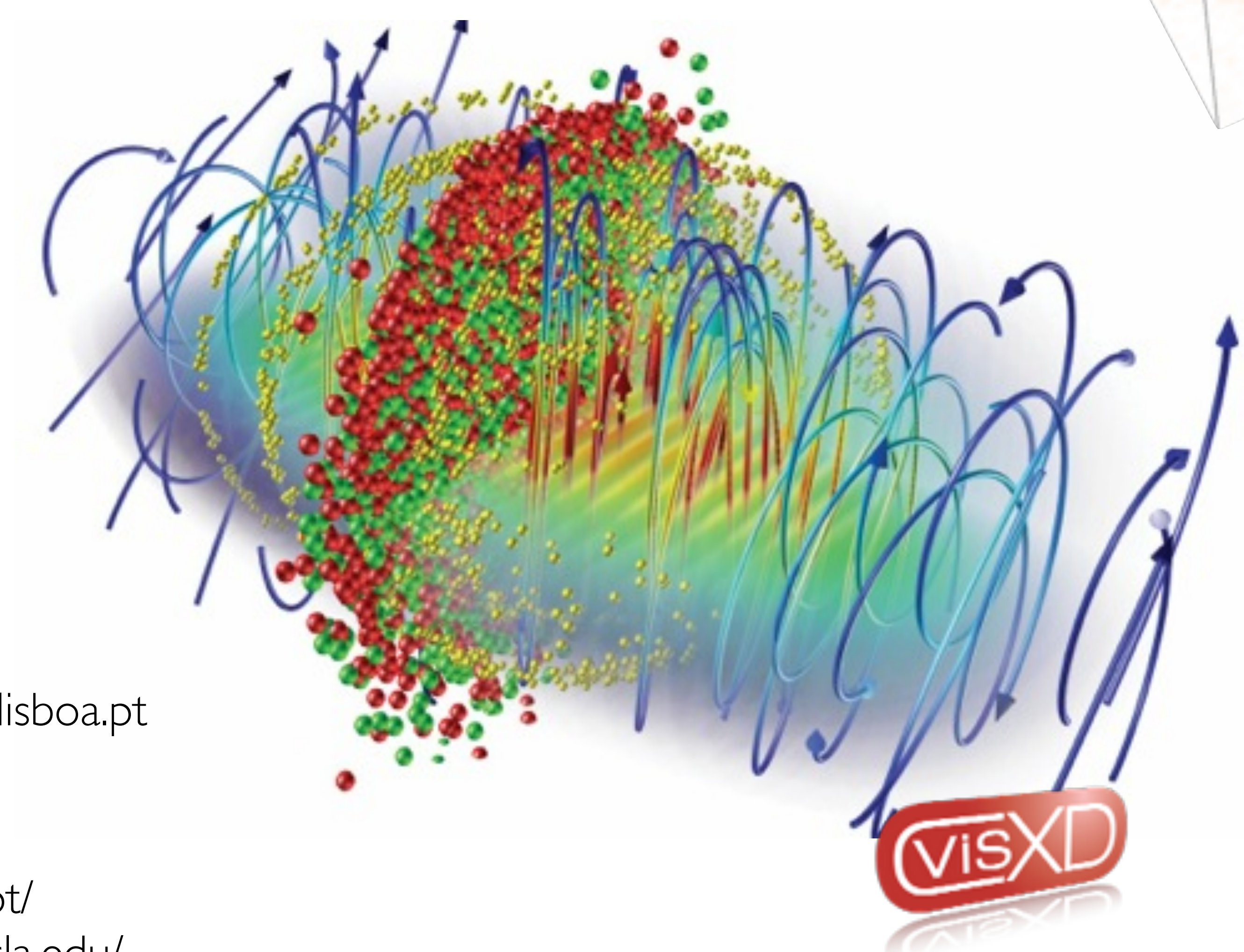
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

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
- 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

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Outline

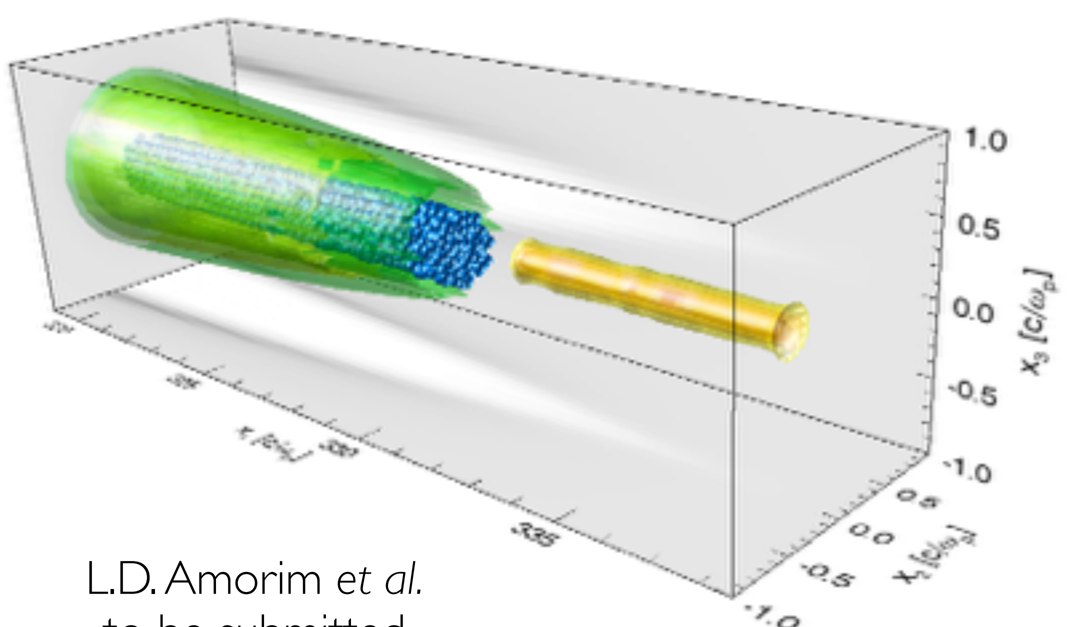
- Positron acceleration in the nonlinear regime using higher order laser drivers
- Positron acceleration in the nonlinear regime with particle beam drivers
- Conclusions & future work

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

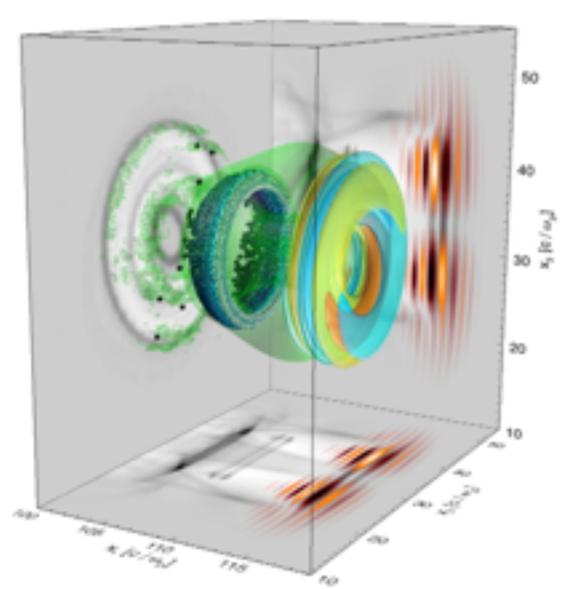
Positron self-driven hollow channel



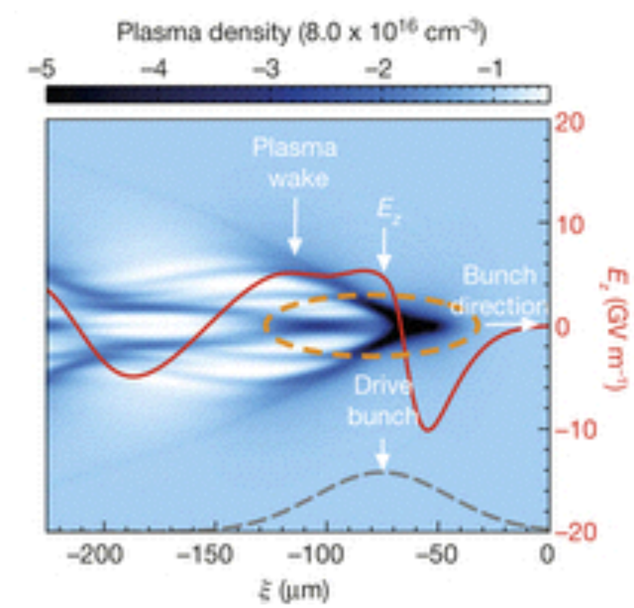
L.D. Amorim *et al.*
to be submitted

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)

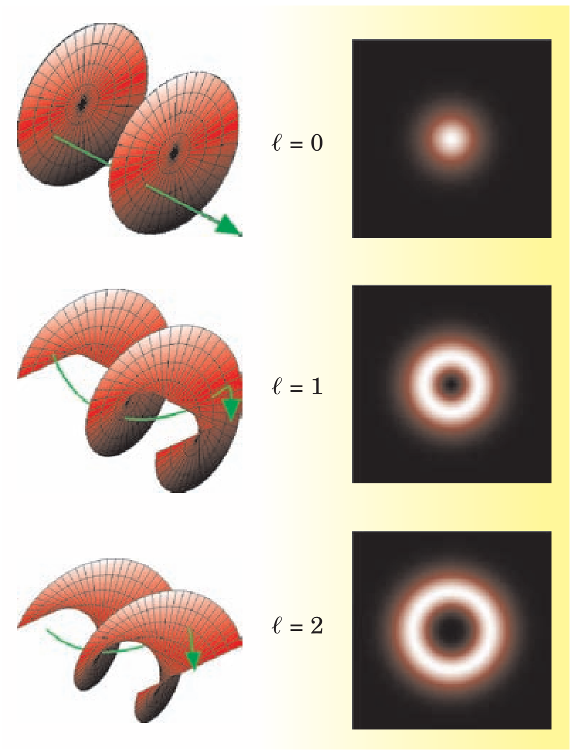


S. Corde *et al.* Nature (2015)

Challenge: controlled regimes may require shaped plasma waves and drivers

The orbital angular momentum of light (OAM)

Orbital angular momentum

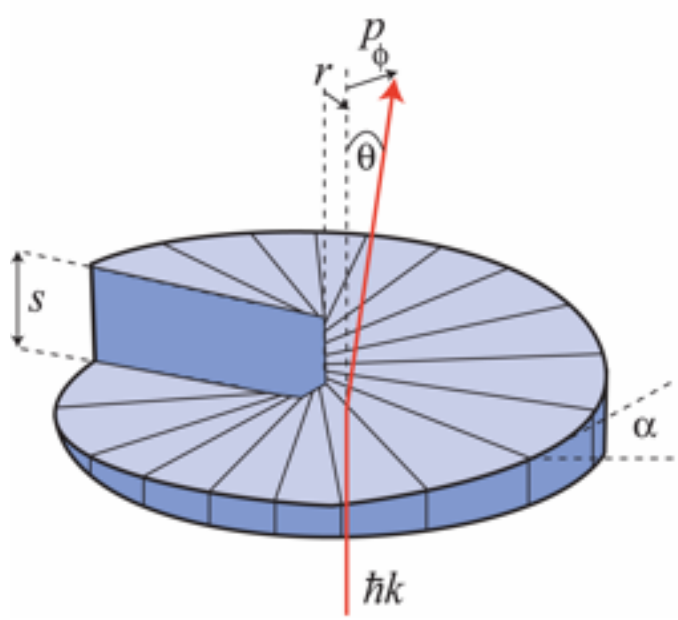


$$E_{\text{laser}} \propto \left(\frac{r}{w_0}\right)^{|\ell|} \mathrm{L}_p^{|\ell|}\left(\frac{r}{w_0}\right) \exp\left(-\frac{r^2}{w_0^2}\right) \times \cos\left(\omega_0 t - k_0 z + \ell\phi\right)$$

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

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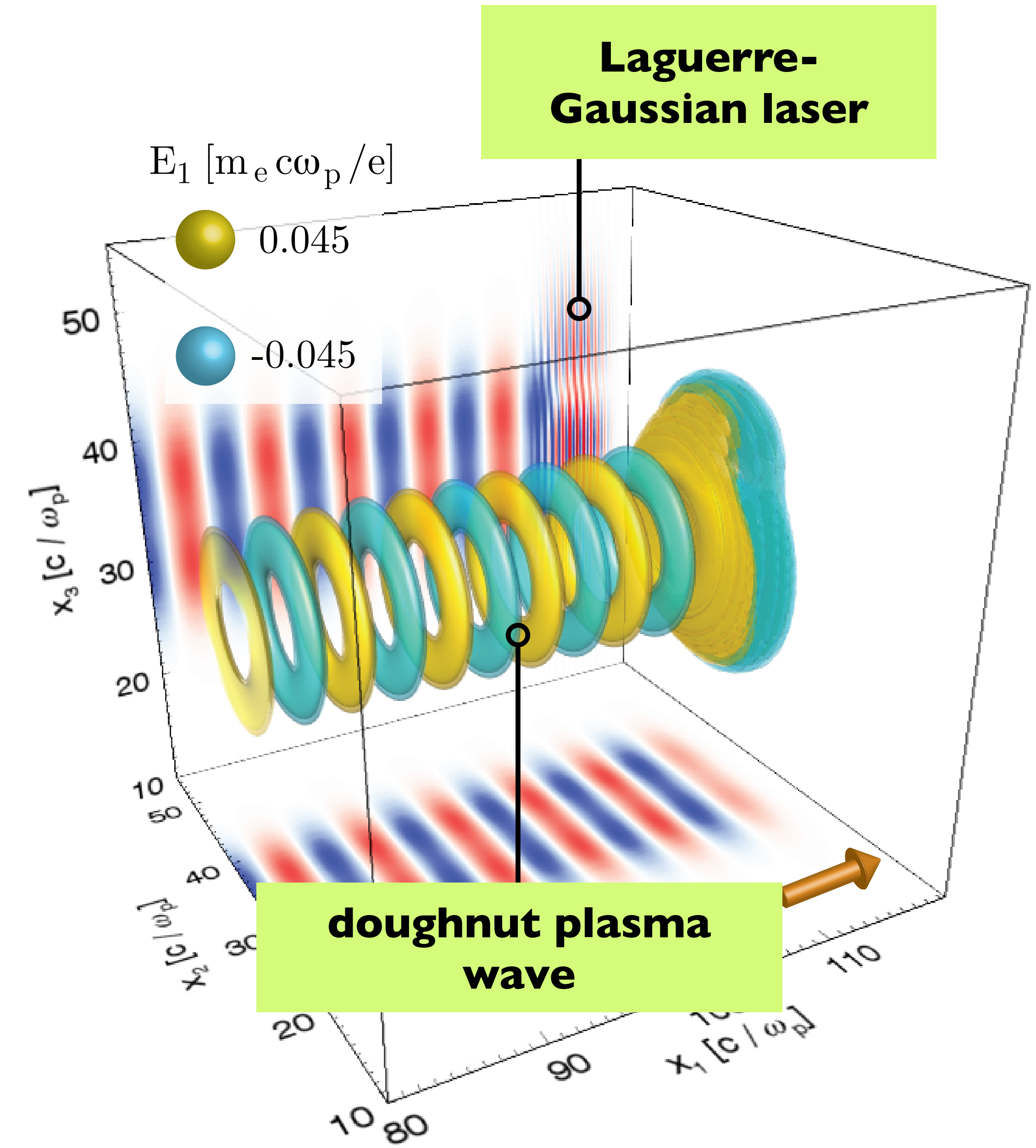
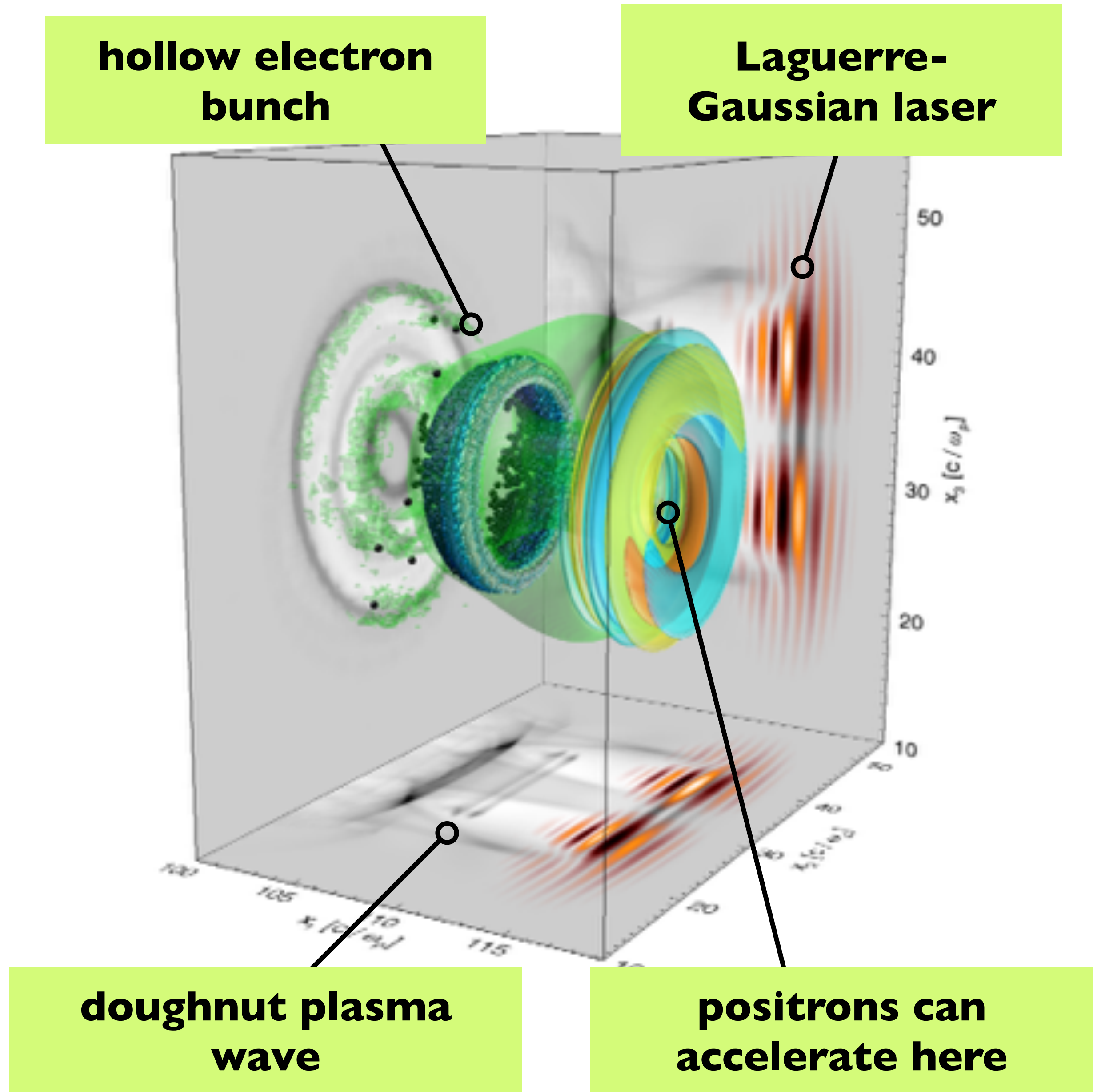
Linear doughnut wakefields



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

Non-linear doughnut blowout

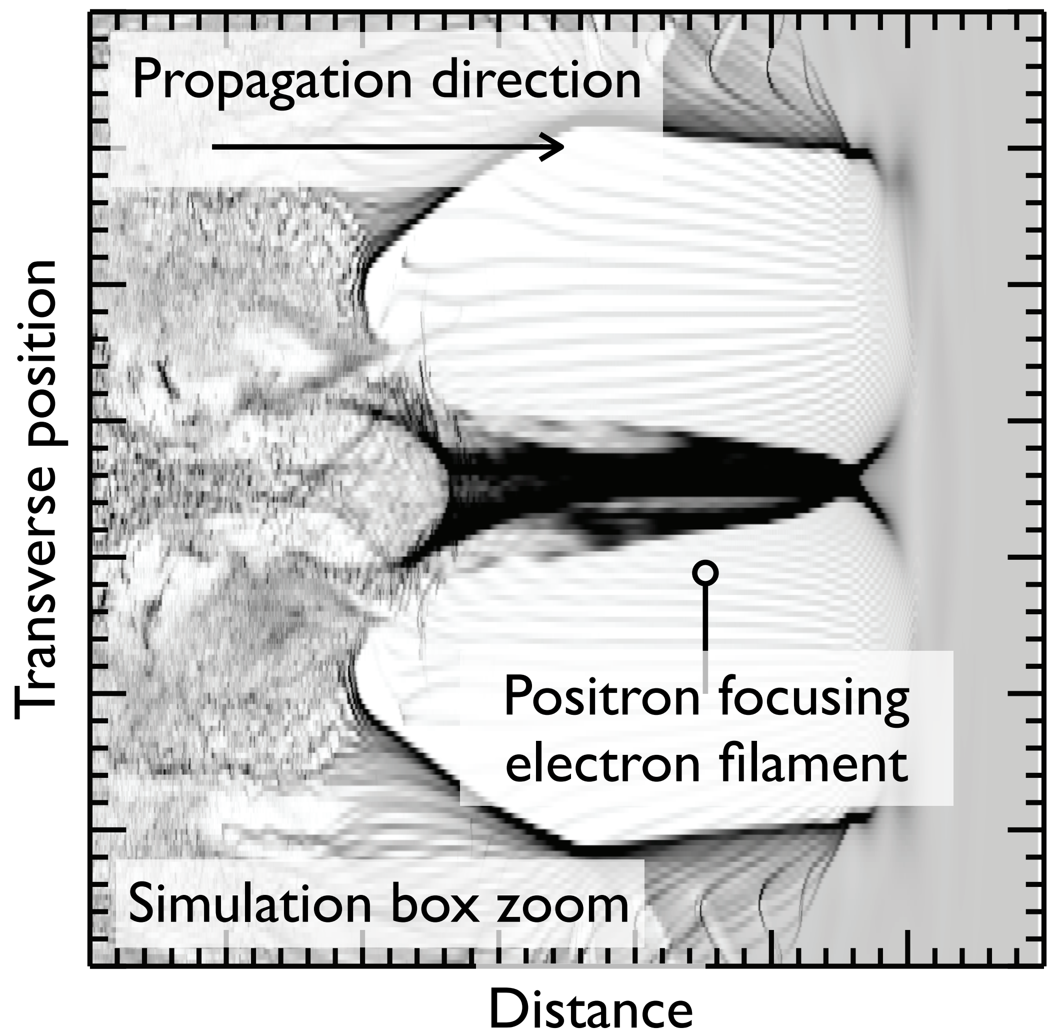


J. Vieira and J.T. Mendonça PRL 112, 215001 (2014)

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

Longitudinal electric field

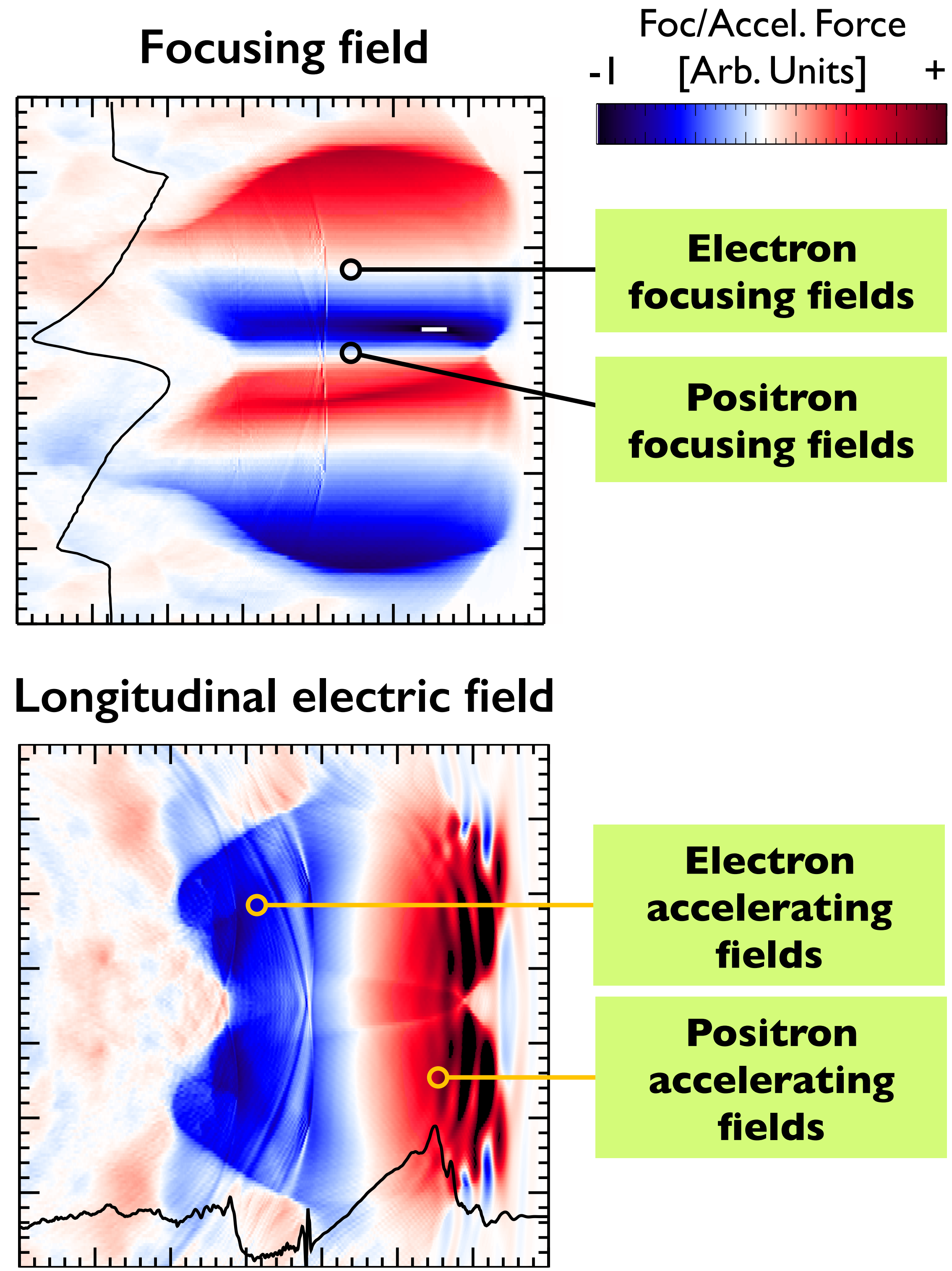
Plasma density: slice from 3D simulation



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

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

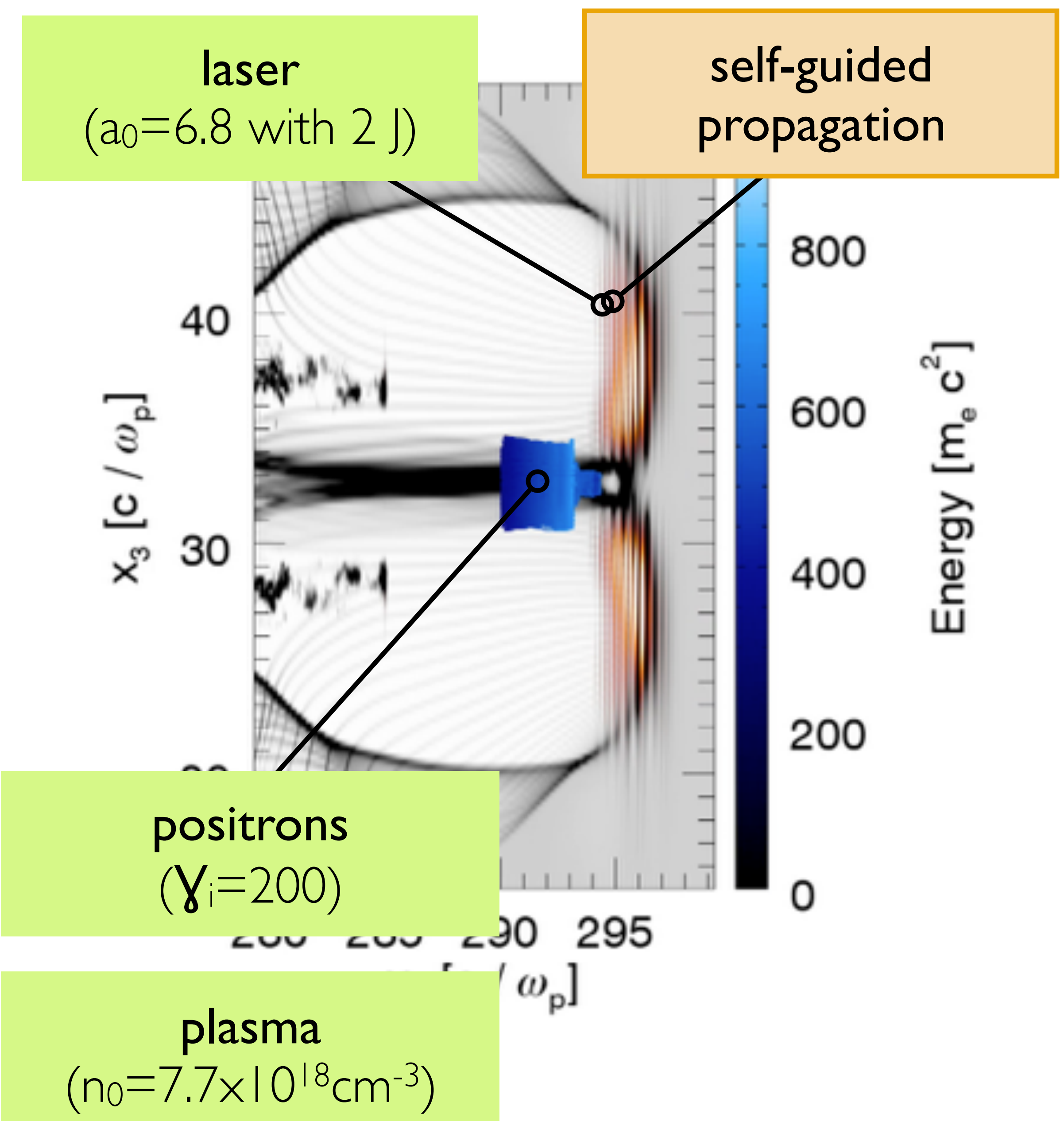
Wakefield structure



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

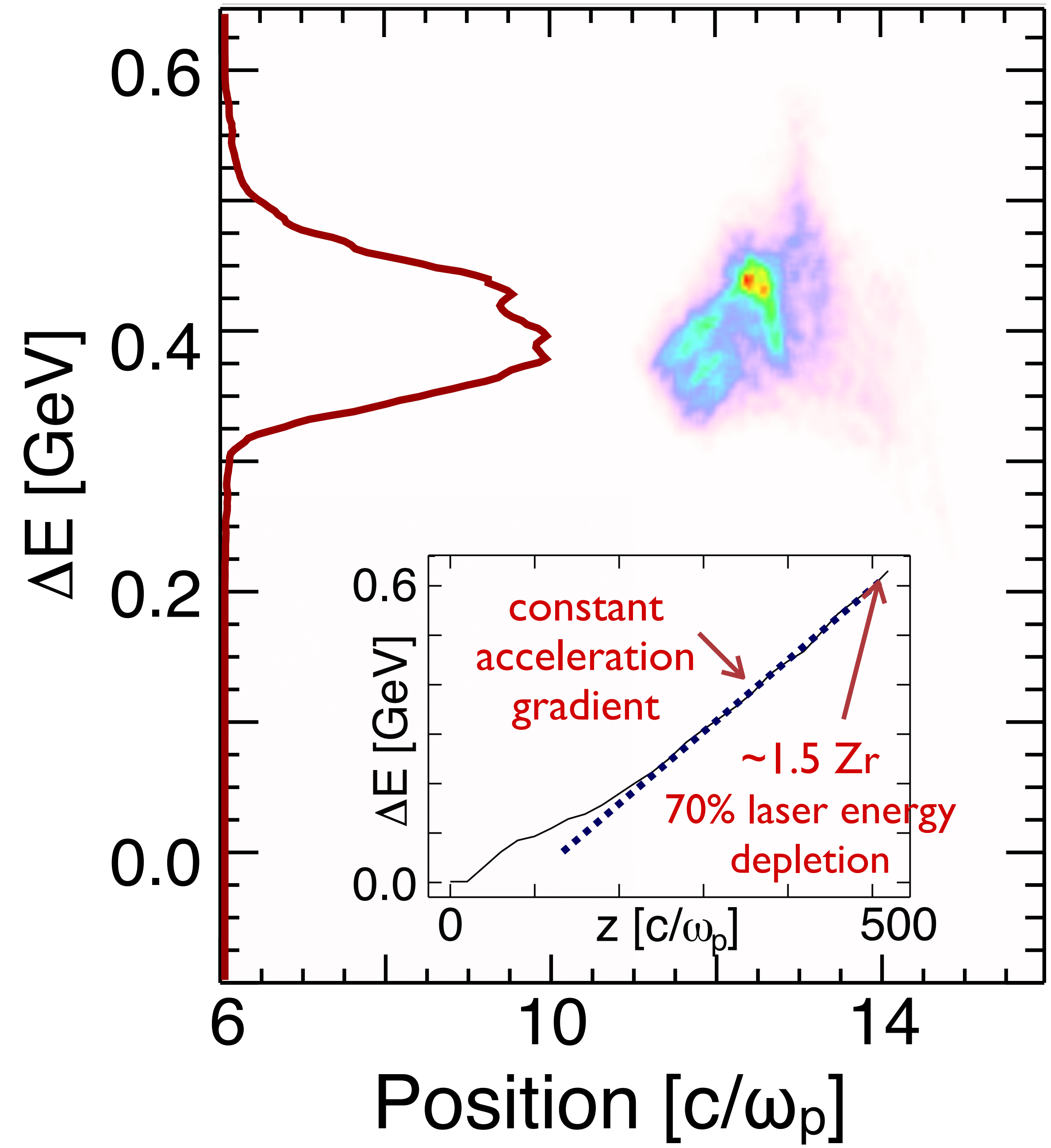
3D simulation of positron acceleration

laser and plasma parameters within experimental reach



simulation box zoom

Positron bunch is quasimonoenergetic



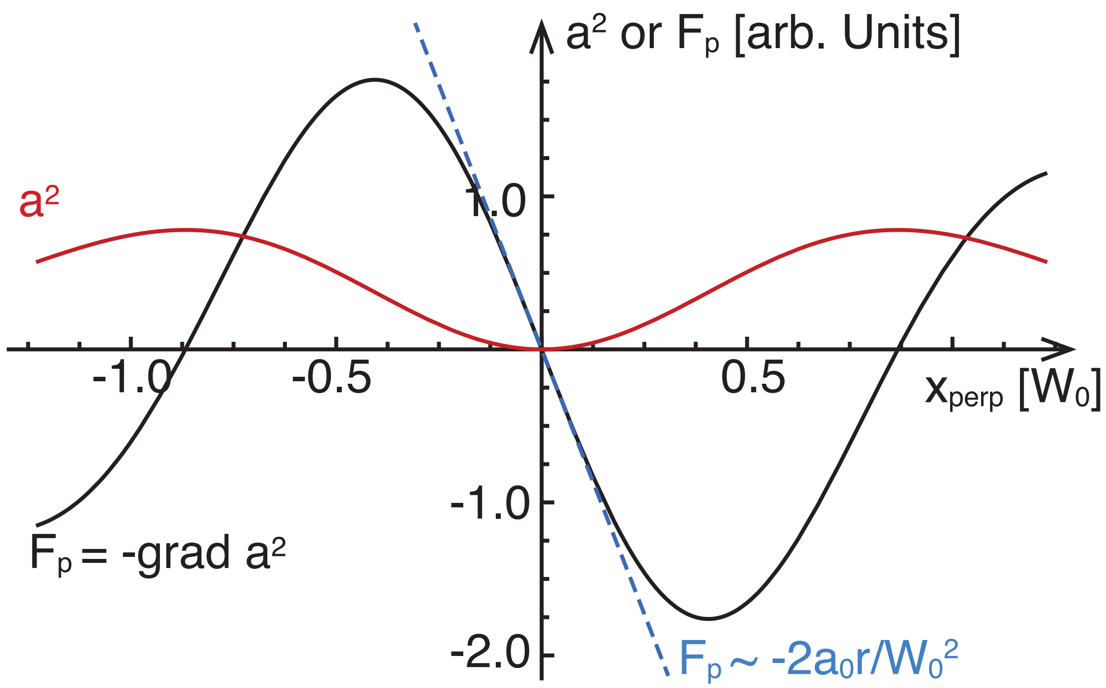
Proof-of-concept using a Gaussian laser pulse as a driver

Laguerre-Gaussian laser driver

on-axis ponderomotive force for
Laguerre-Gaussian pulse

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

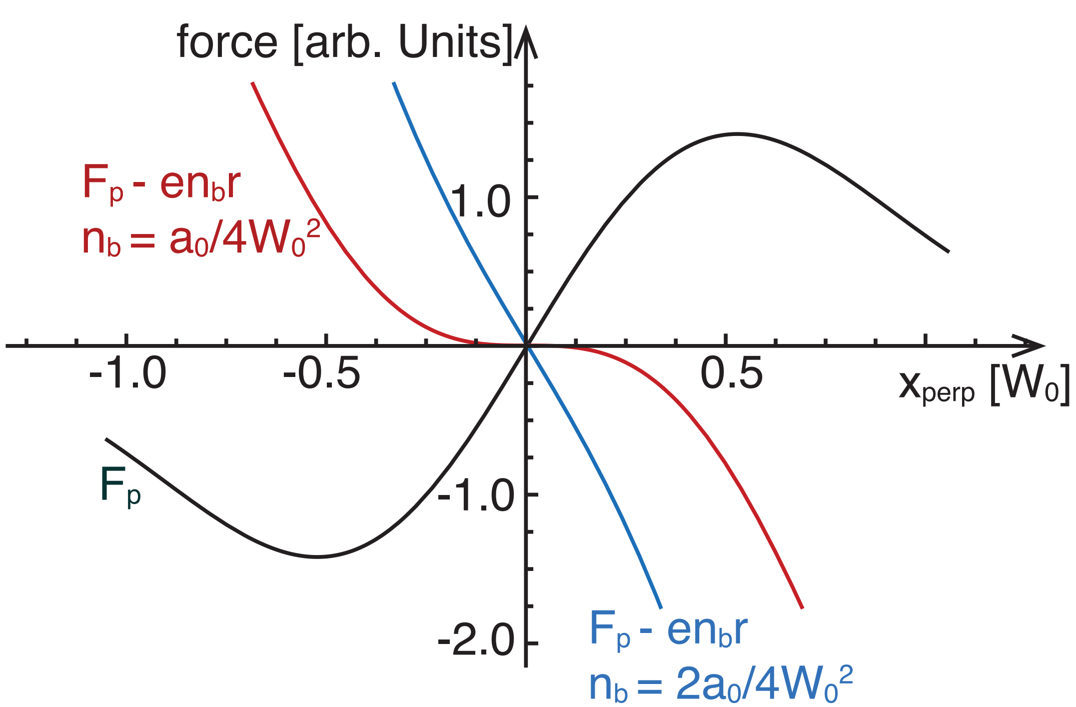
provides on-axis focusing that generates positron focusing electron filament



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

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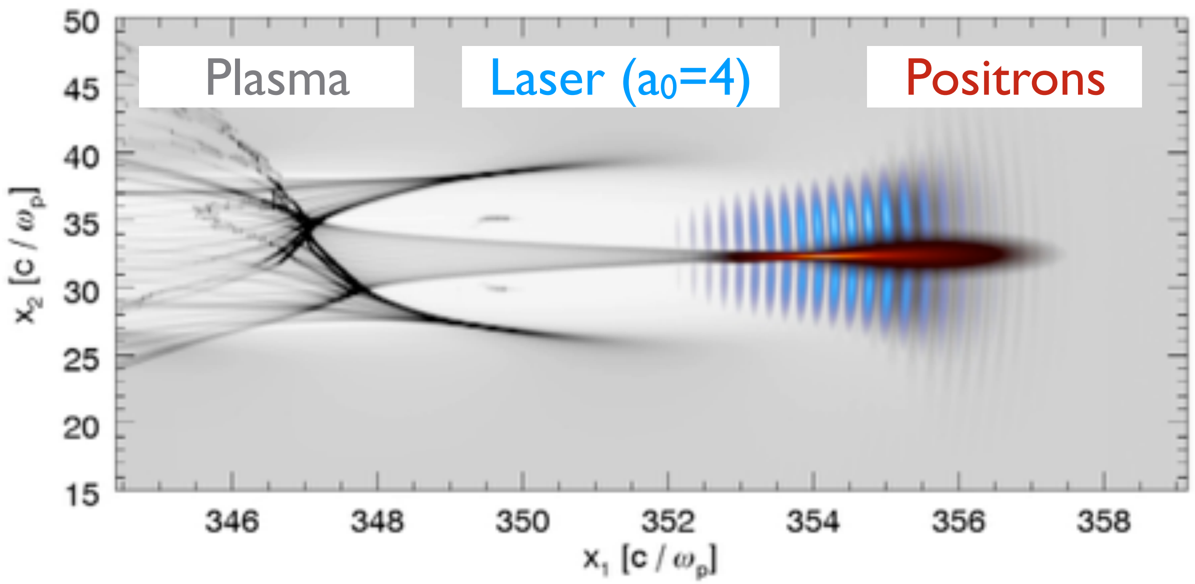
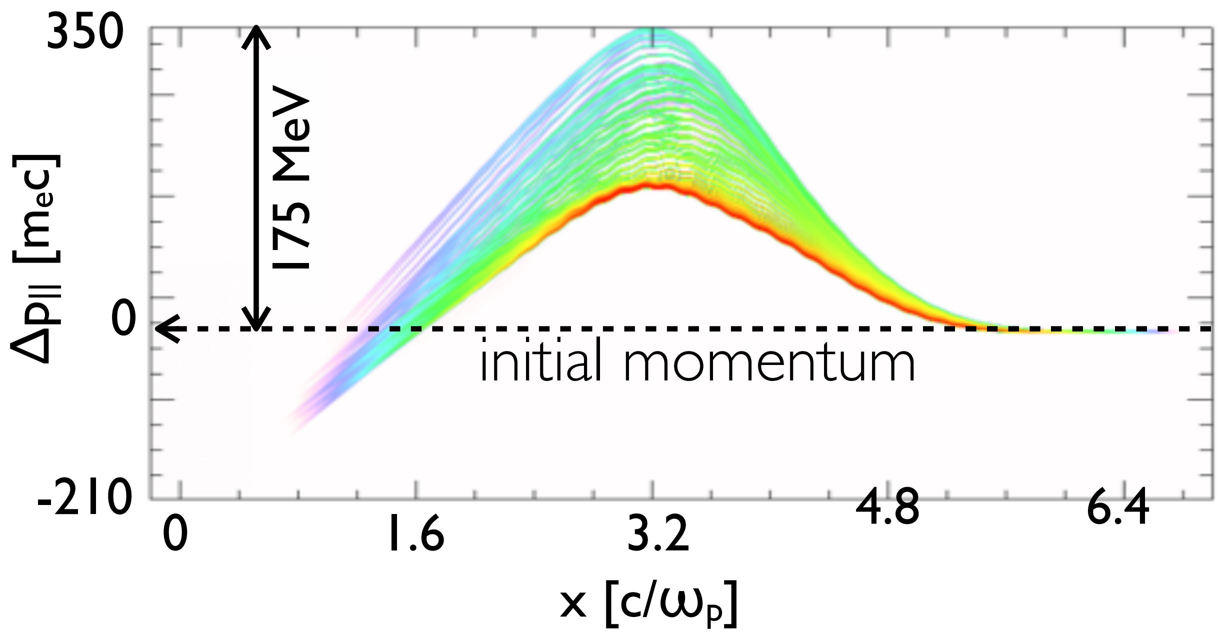
Proof-of-concept simulations

Positron beam loading required



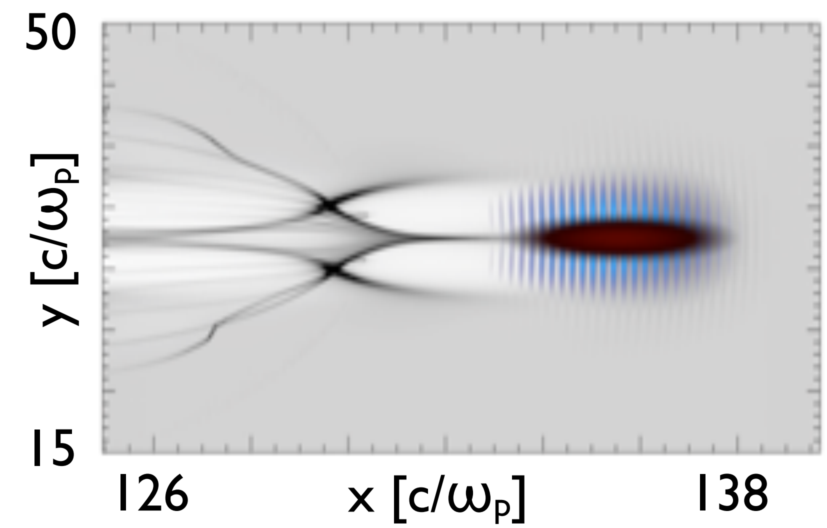
balance laser ponderomotive force with positron attraction

Positrons extract energy from wakefield



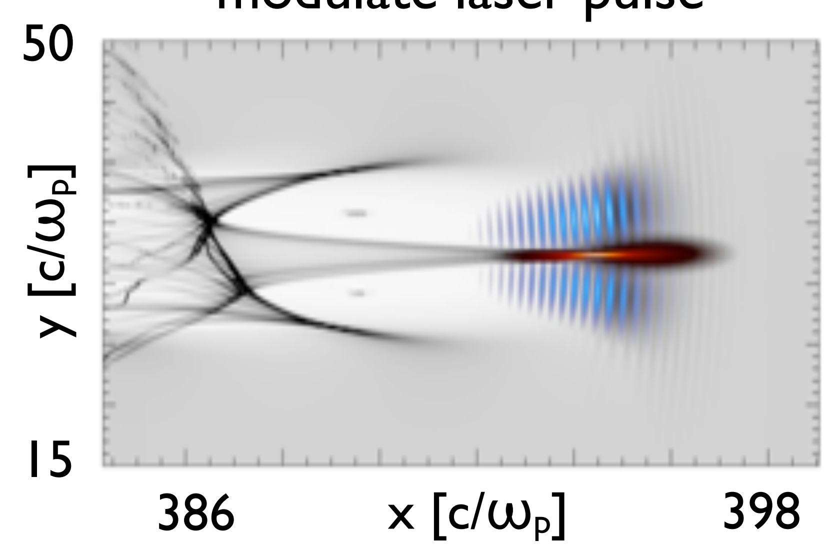
On-axis filament

positrons attract e⁻ towards the axis



Doughnut laser

plasma refractive index gradients modulate laser pulse



Outline

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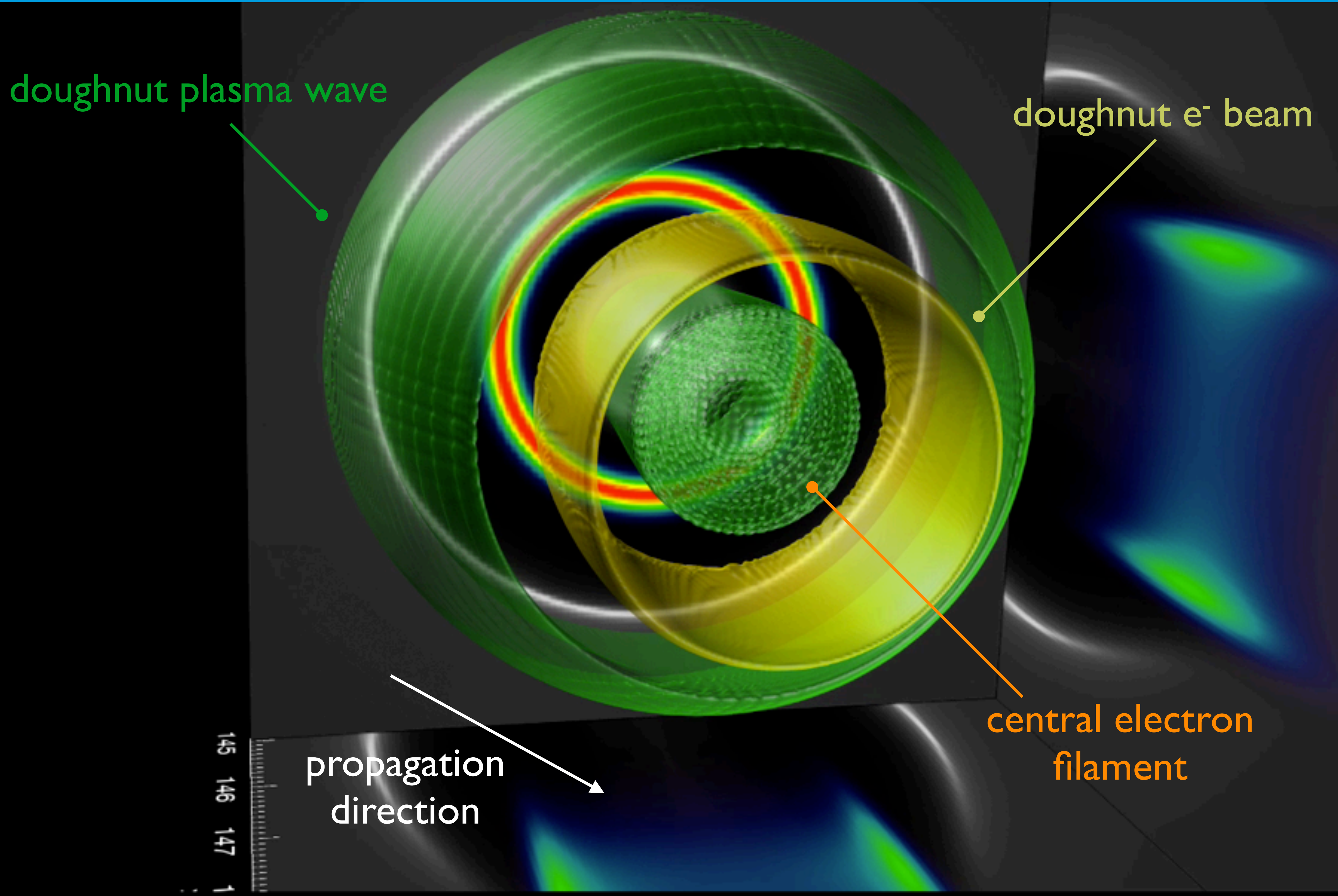
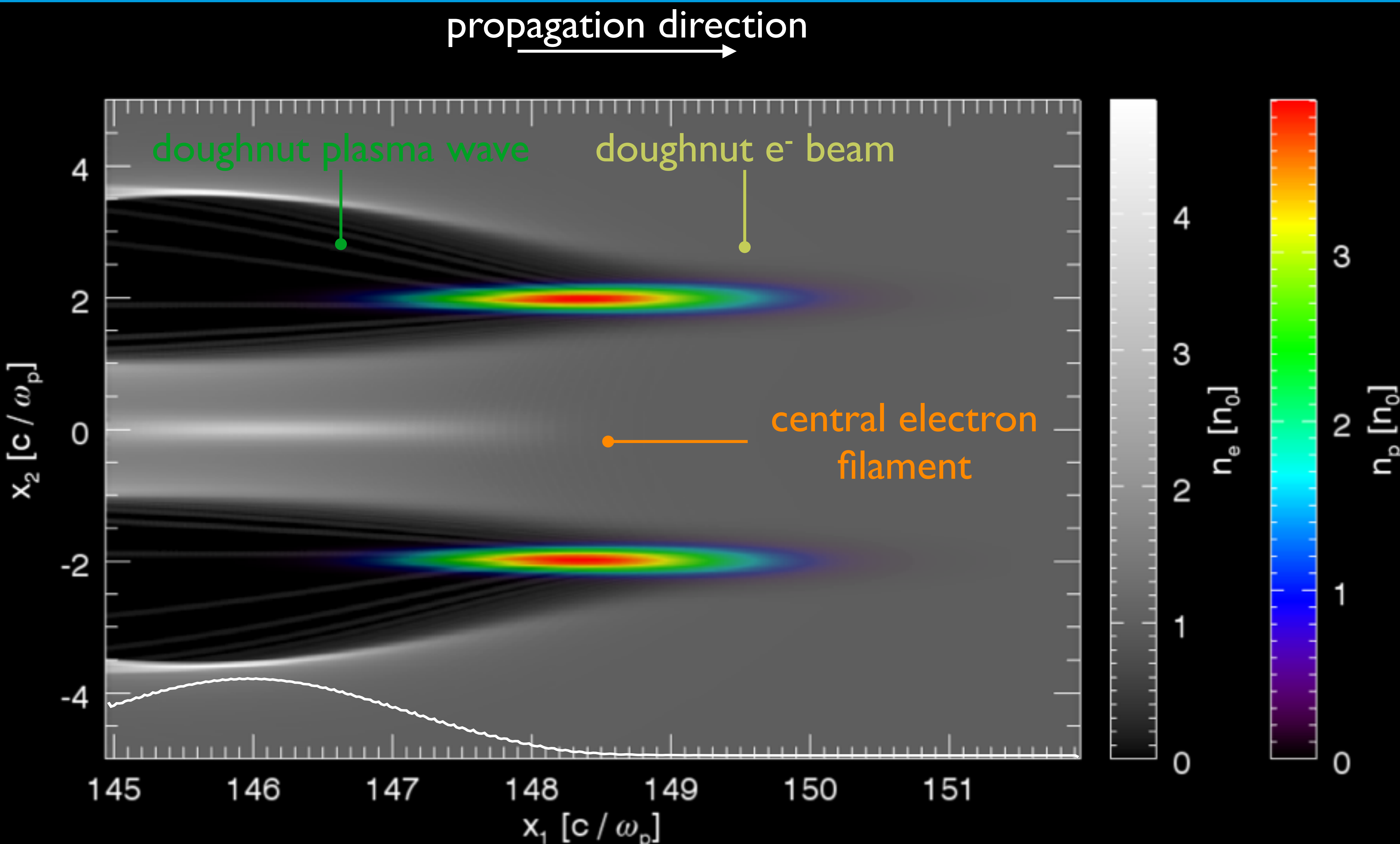
- **Positron acceleration in the nonlinear regime with particle beam drivers**
- Conclusions & future work

Plasma wakefield accelerator driven by a doughnut electron beam



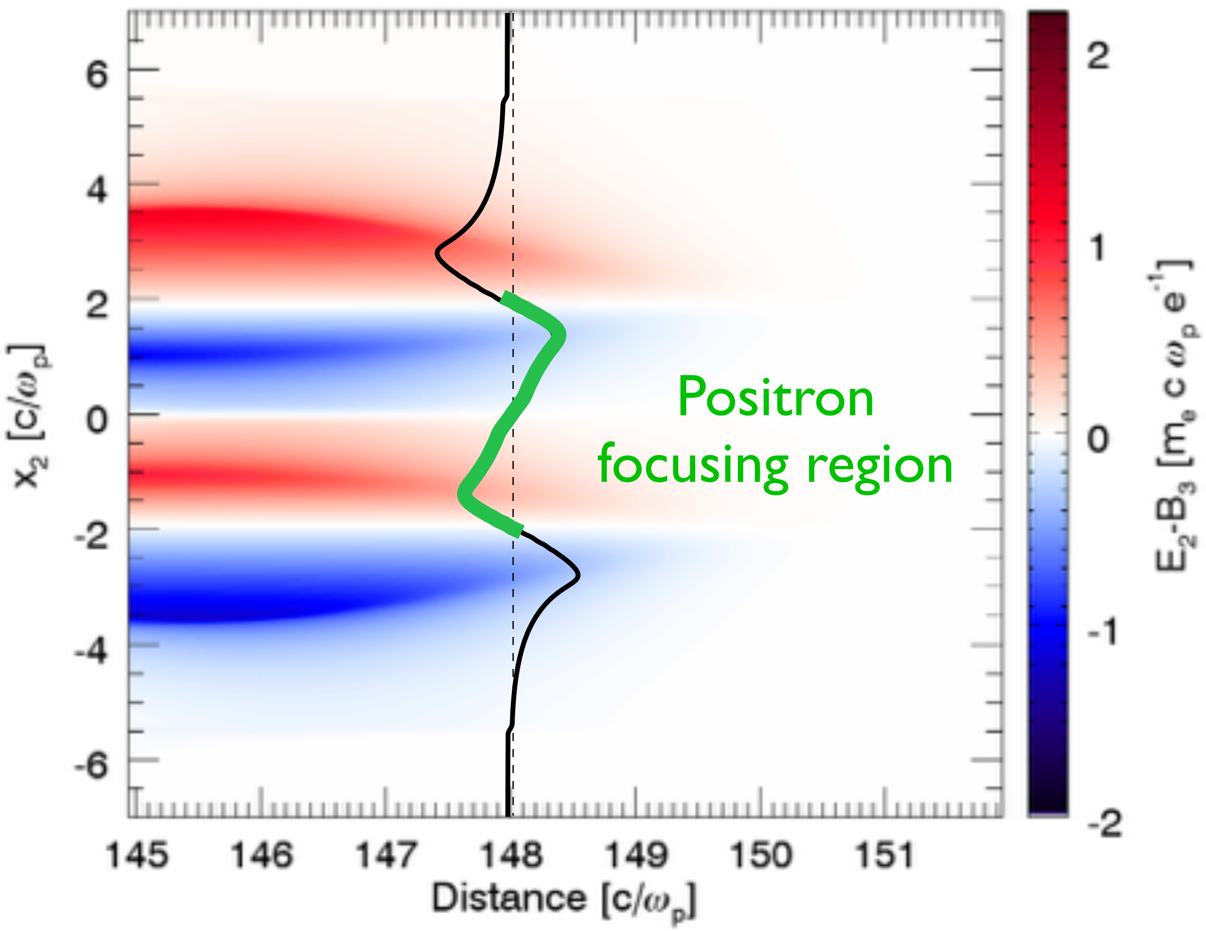
Doughnut plasma wave in the blowout regime



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

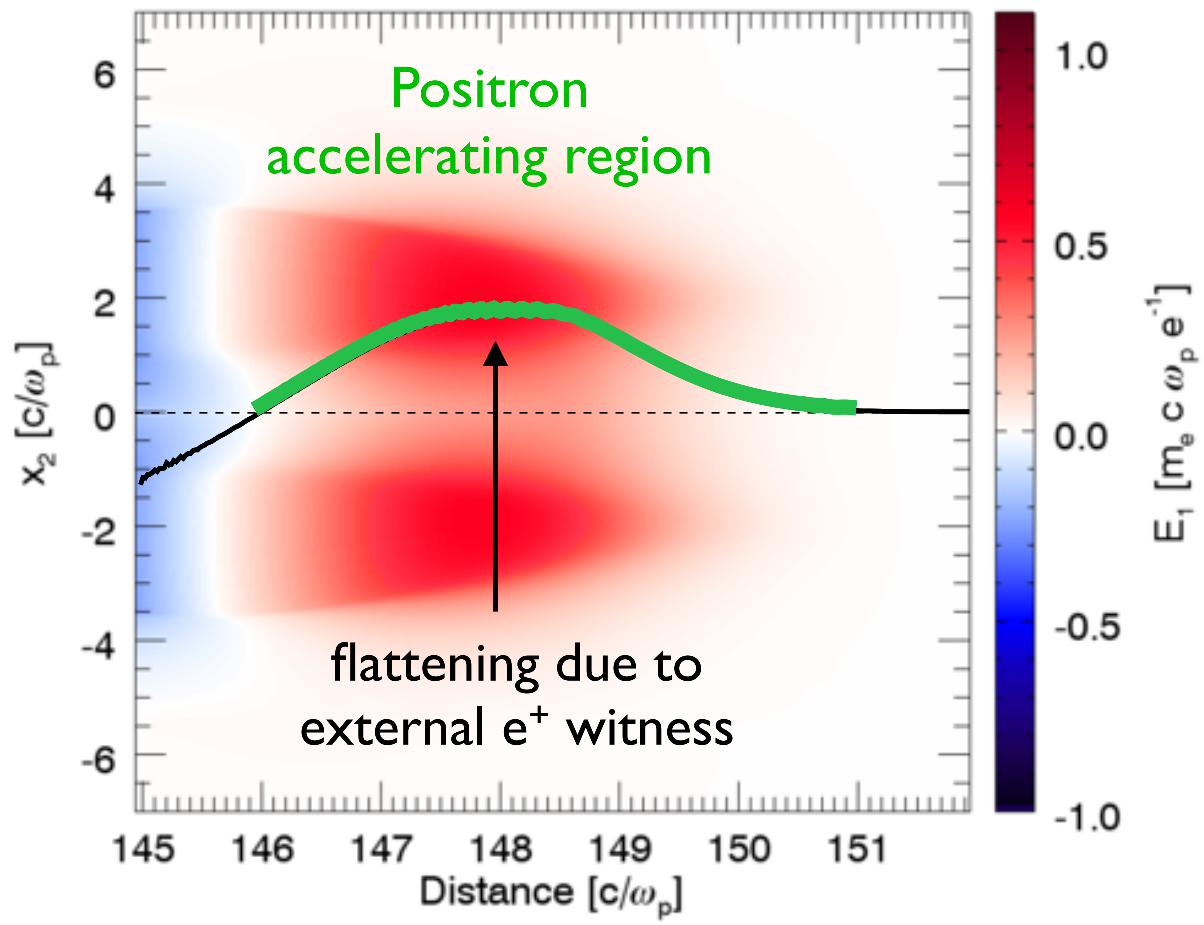
Wakefield structure shows positron focusing and accelerating regions.

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

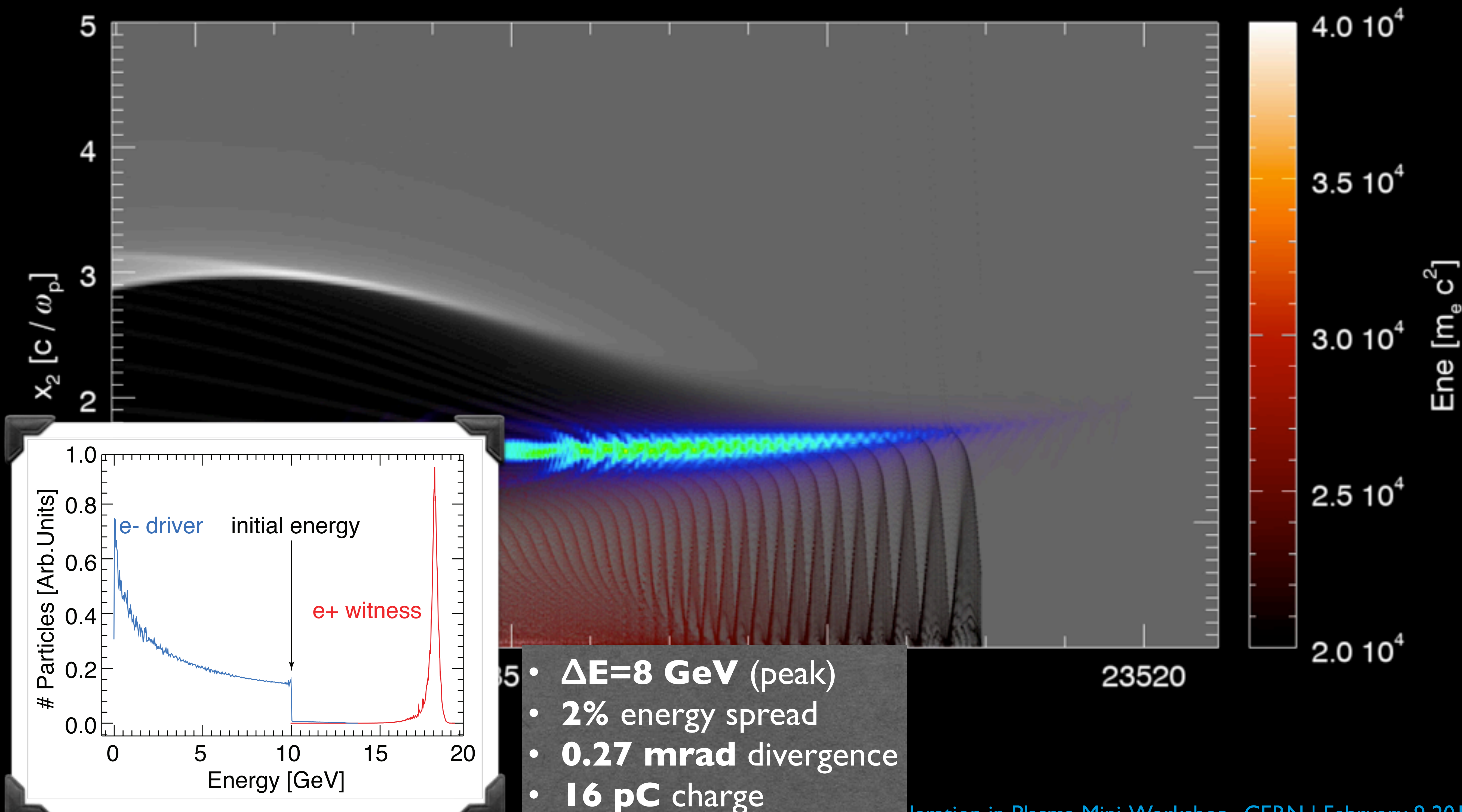


- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

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

Driver:

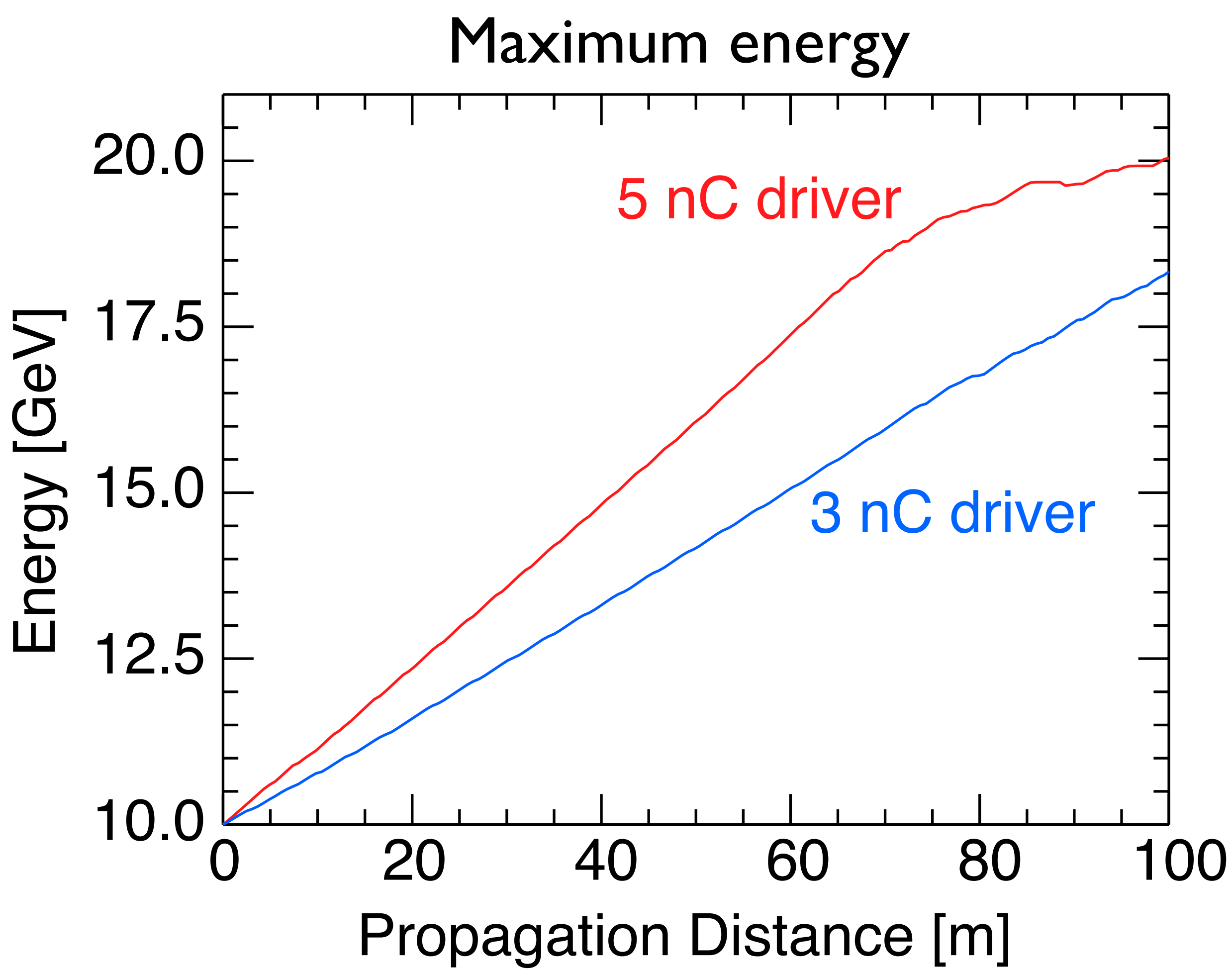
Ring profile, 10 GeV; 3.4 nC; σ_z=23 μm; no emittance



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

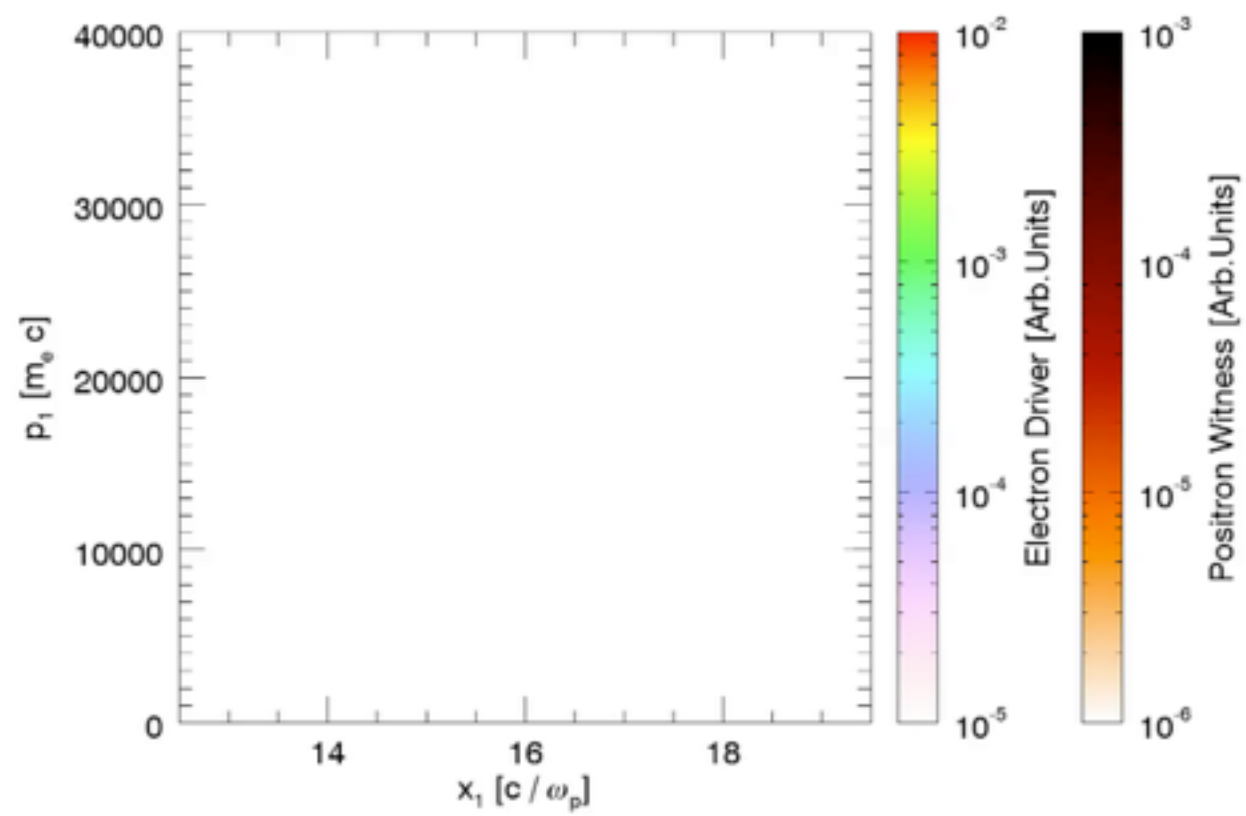
Energy doubling of some of witness positron in 1 meter with 5 nC e- driver

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



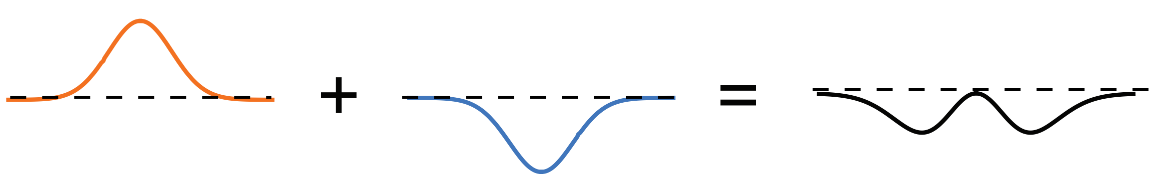
- Doughnut e^- beam focuses on-axis
- Positrons defocus shortly after
- Max. acceleration distance $L_{accel} < \gamma/E_{accel}$

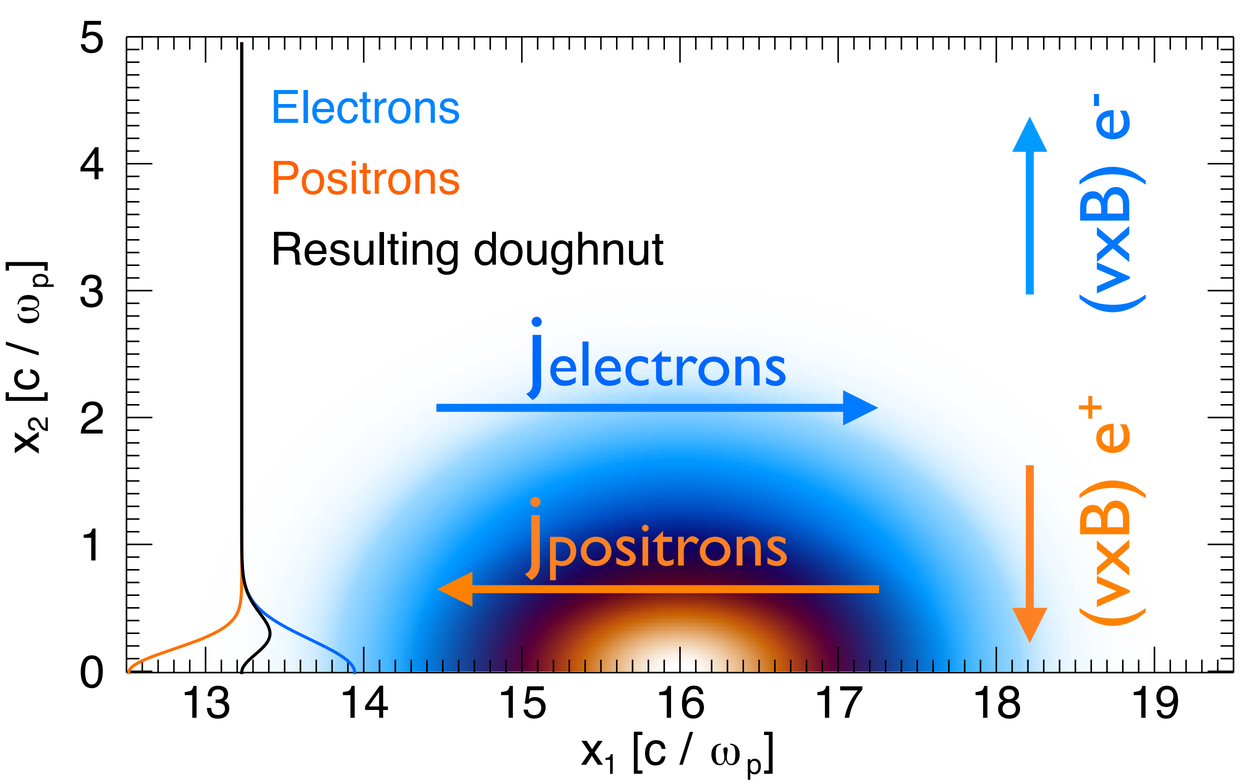
Approach to realise scheme without ring e- drivers:
Nonneutral fireball beam

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

Self-generated doughnut e⁻ bunch

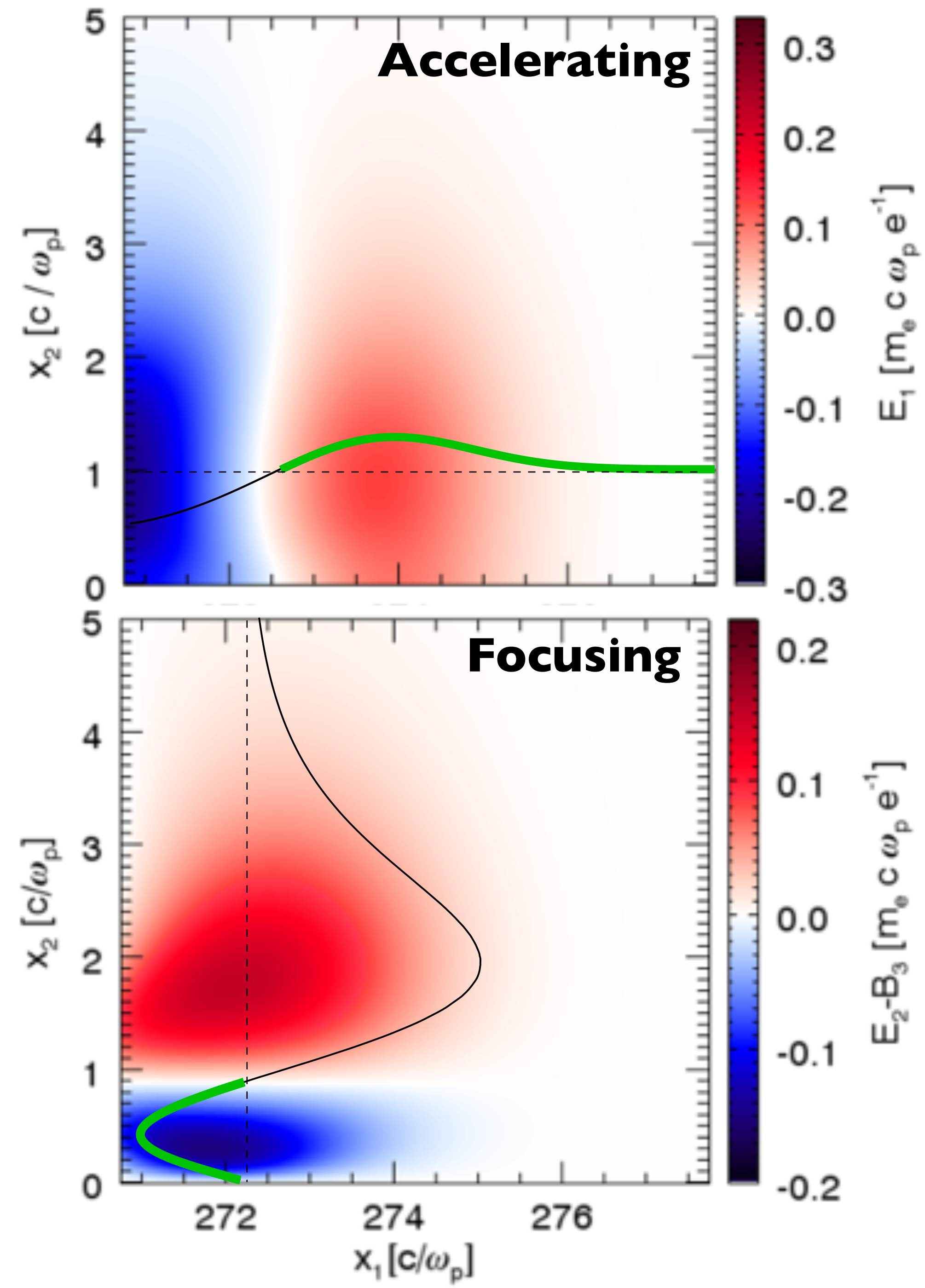
Use positron bunch with smaller transverse size than electron bunch





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

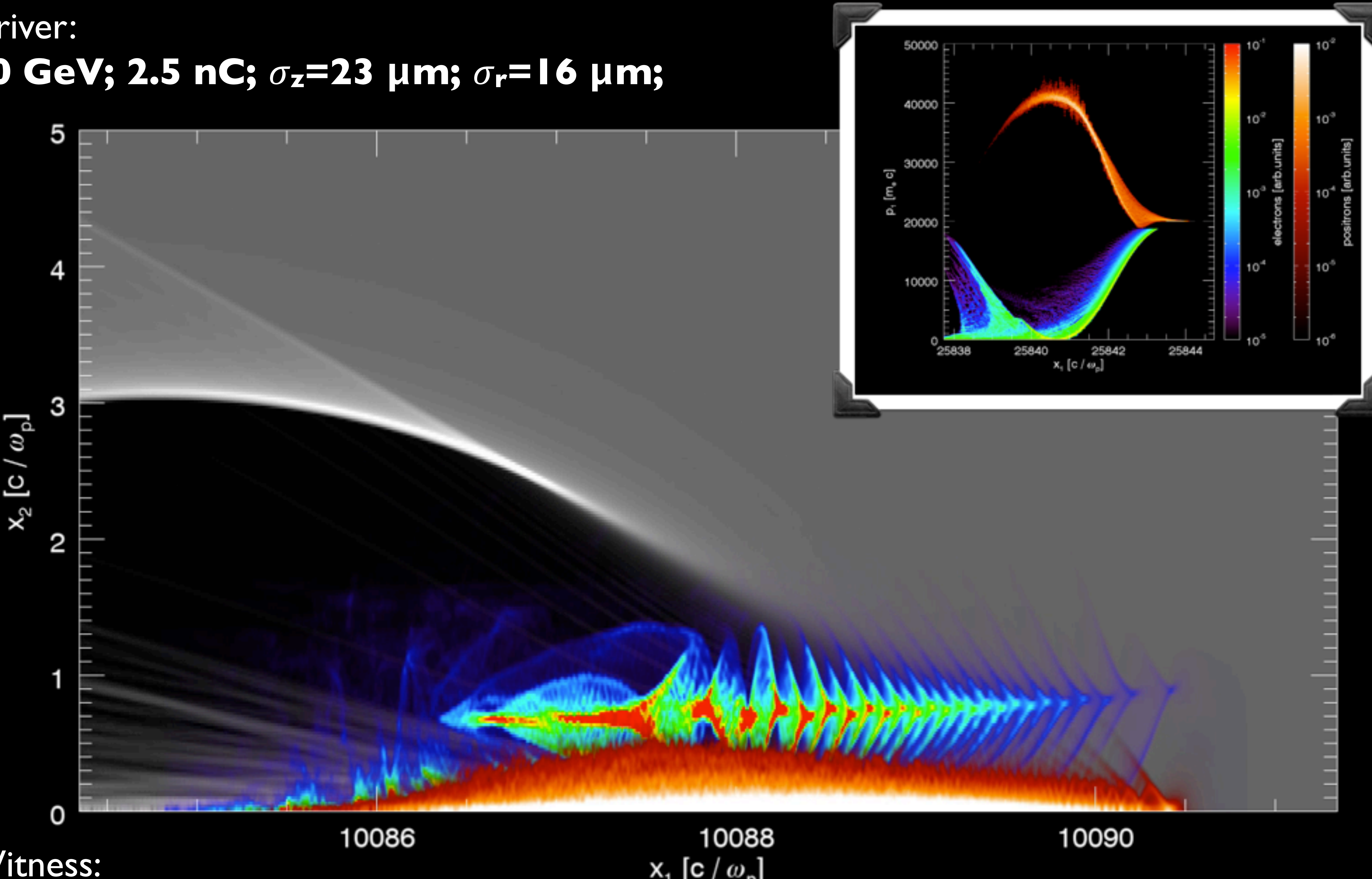
Wakefields are similar to doughnut



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;

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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)