Plasma Wakefield Acceleration of Positron Bunches

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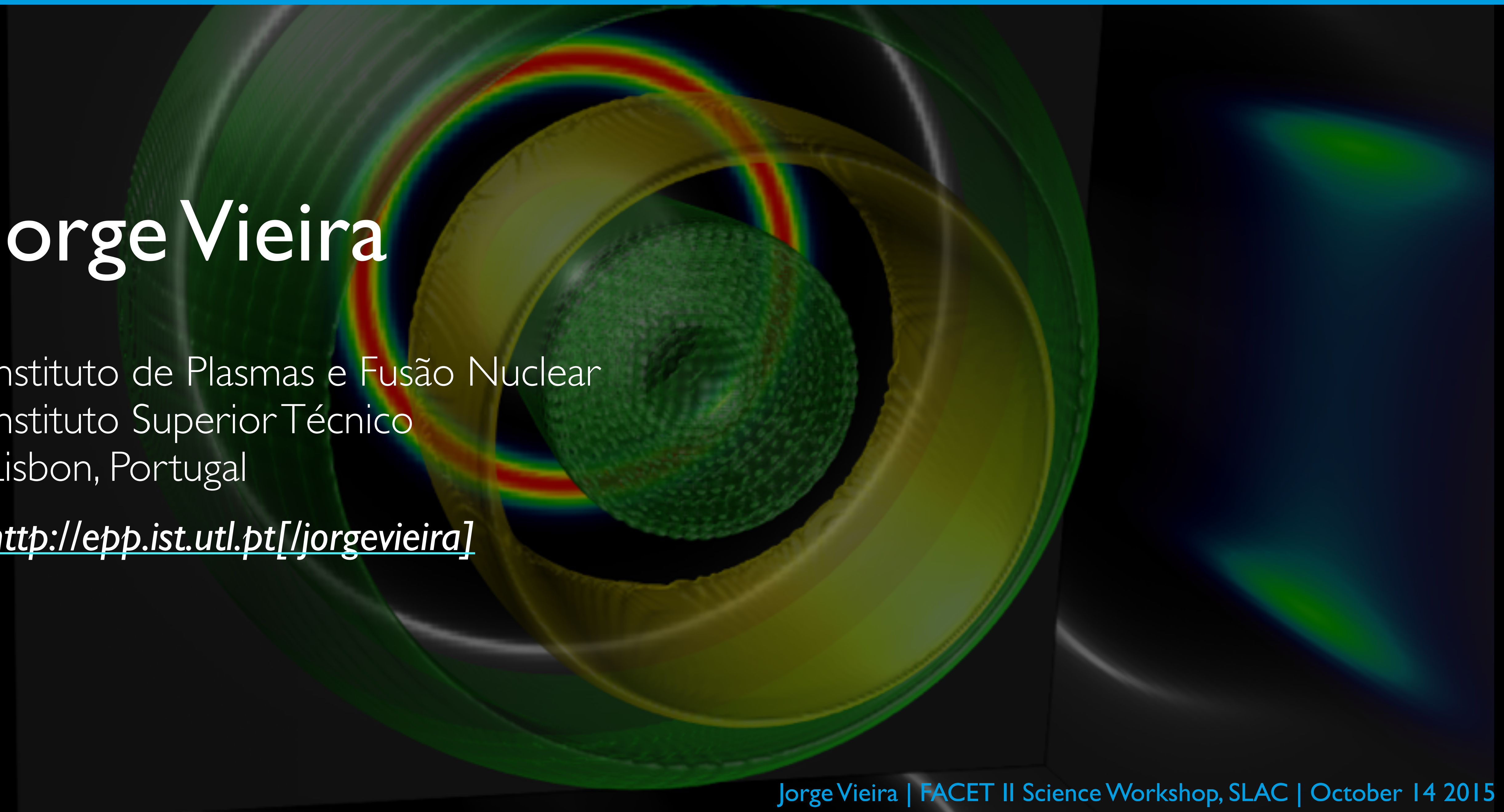

GoLP/IPFN Instituto Superior Técnico

Acknowledgments

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  - **L.D. Amorim, 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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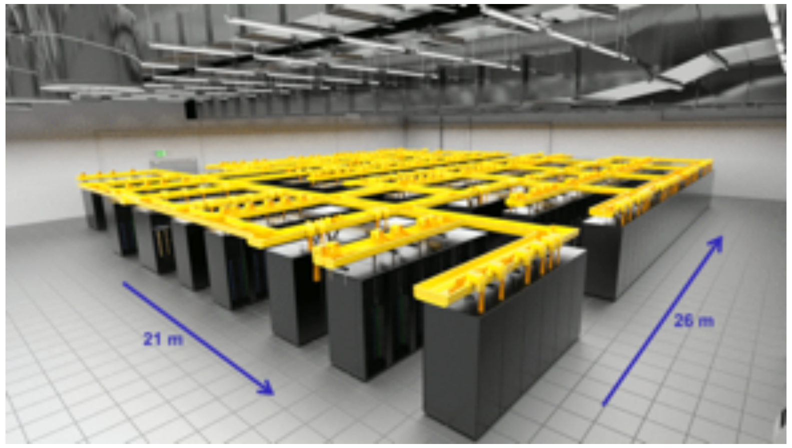


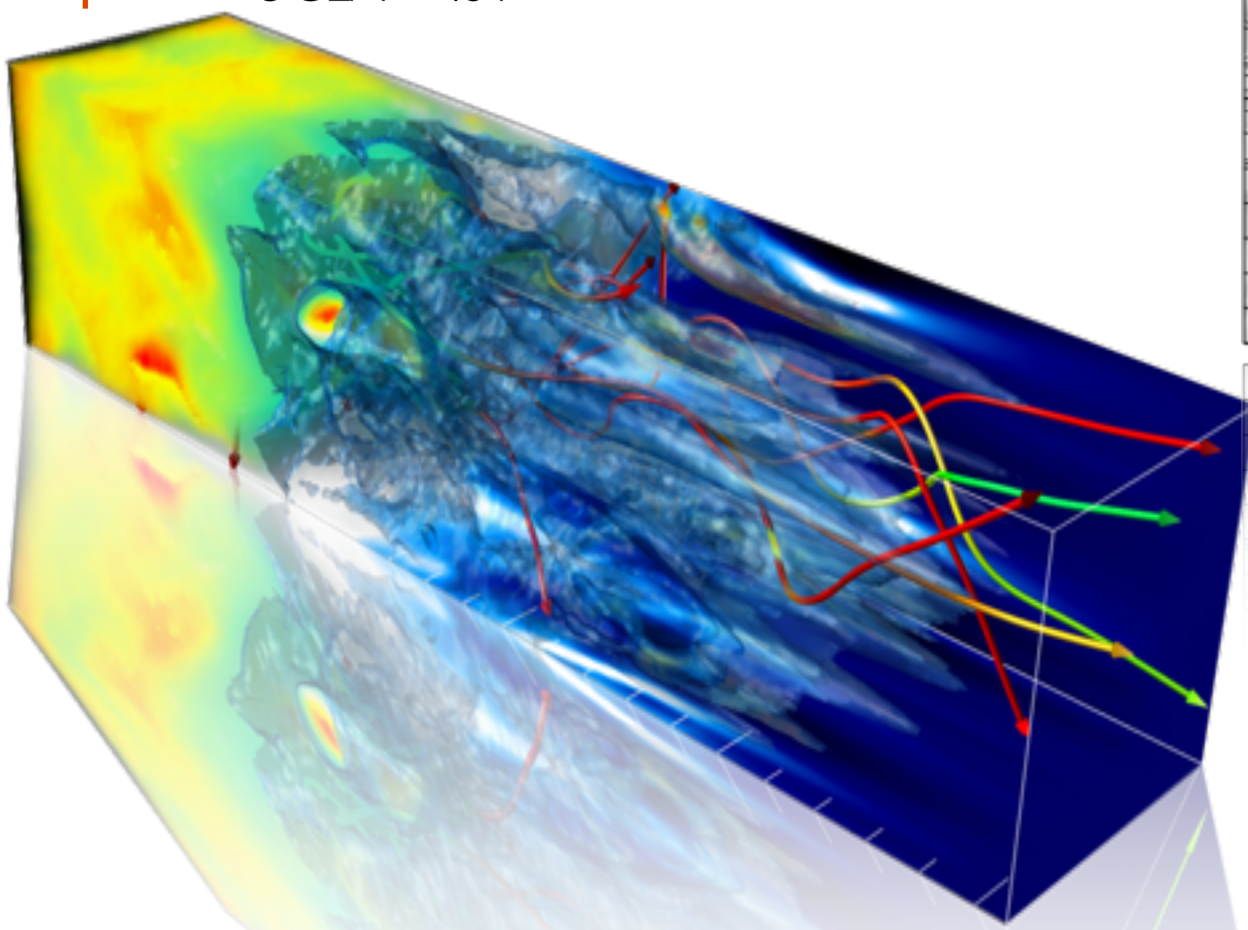
golp grupo de lasers e plasmas

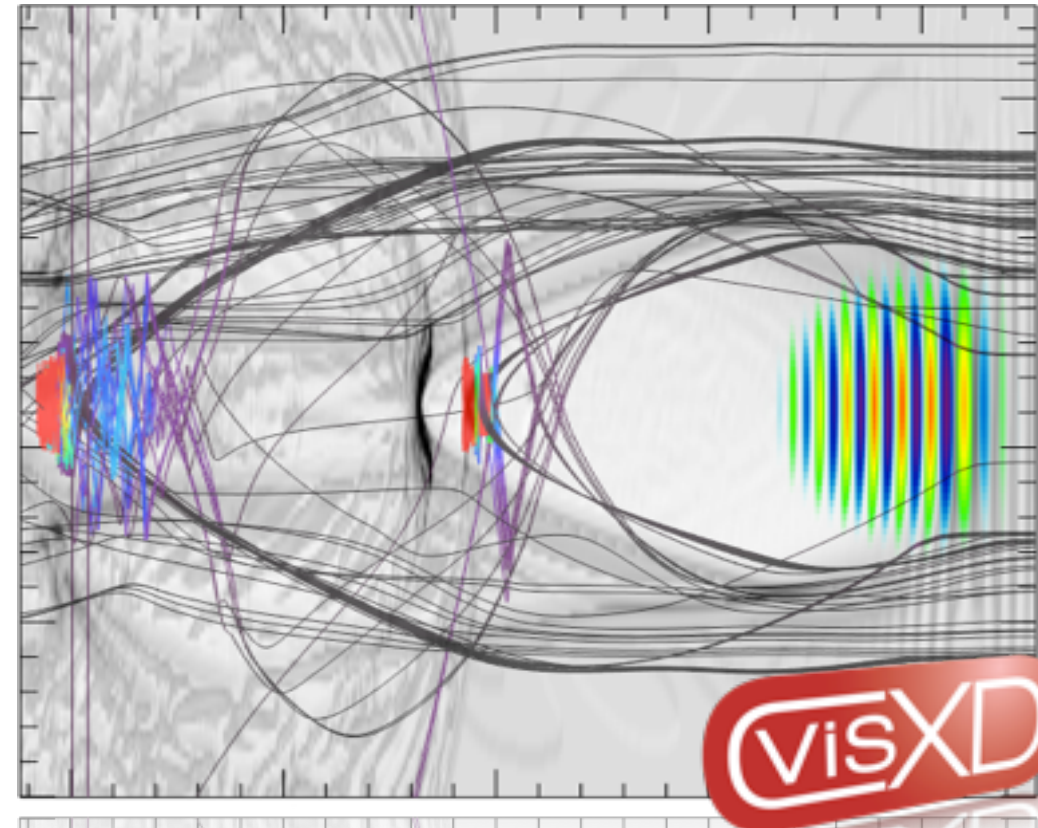
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Osiris/dev 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 ~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
- QED, meta-materials

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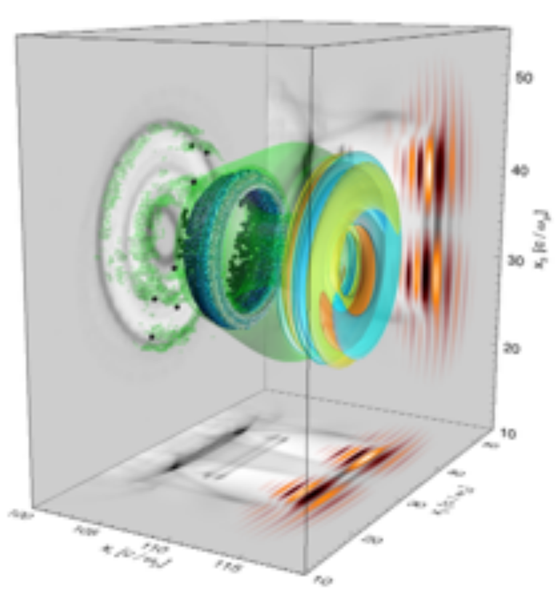
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

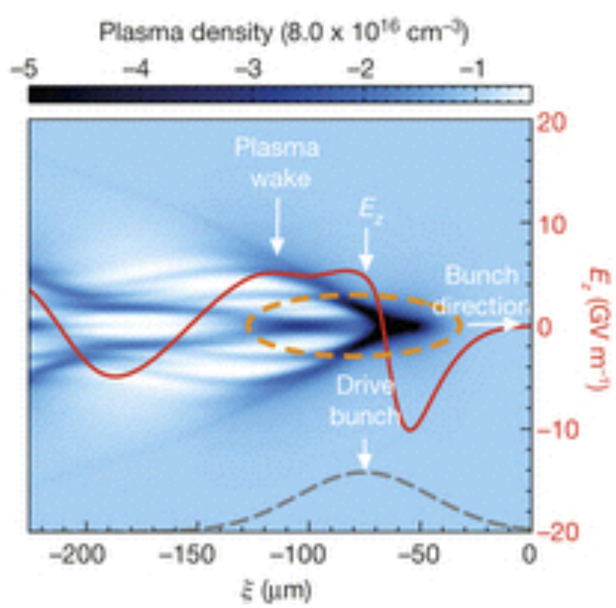
Two paths for positron acceleration in plasmas: **enhance electron density** or **create a hollow plasma channel**

On-axis electron filament

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



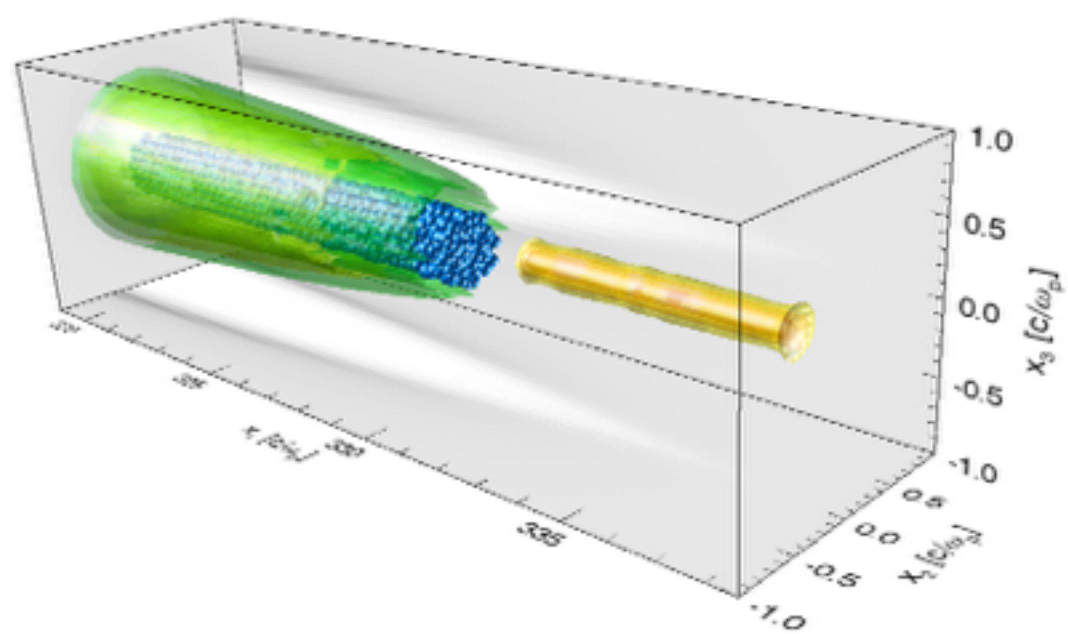
from J. Vieira *et al* PRL (2014)



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)

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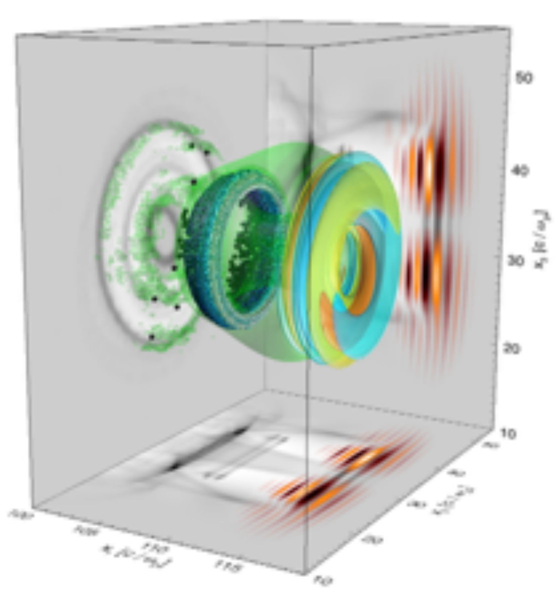

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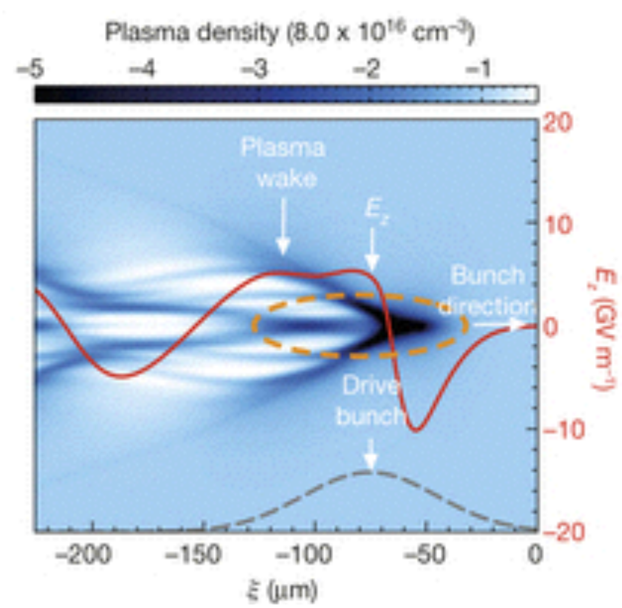

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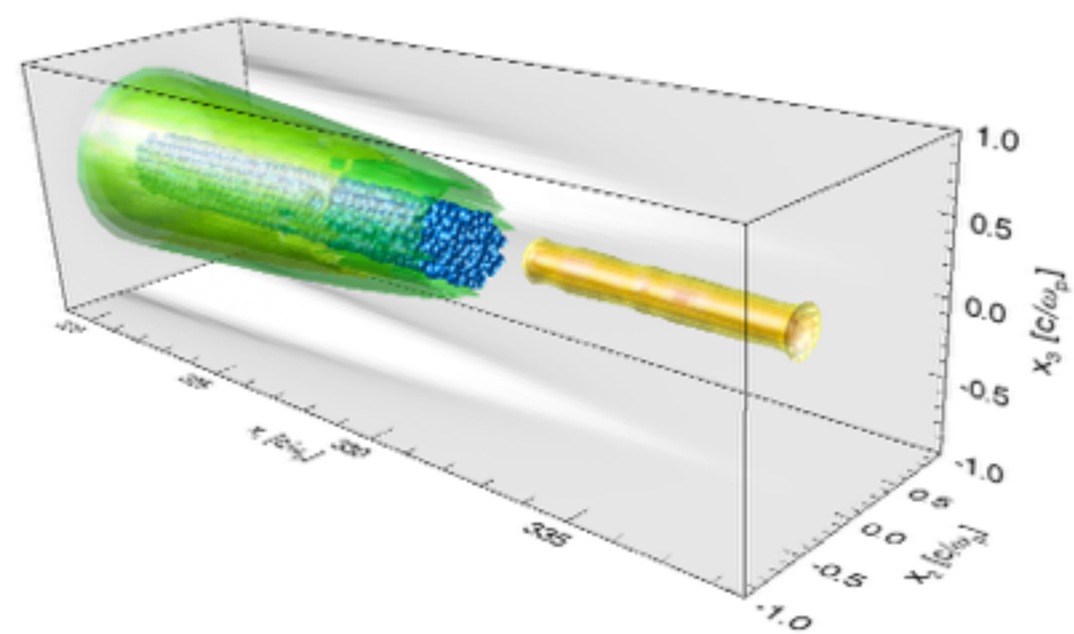
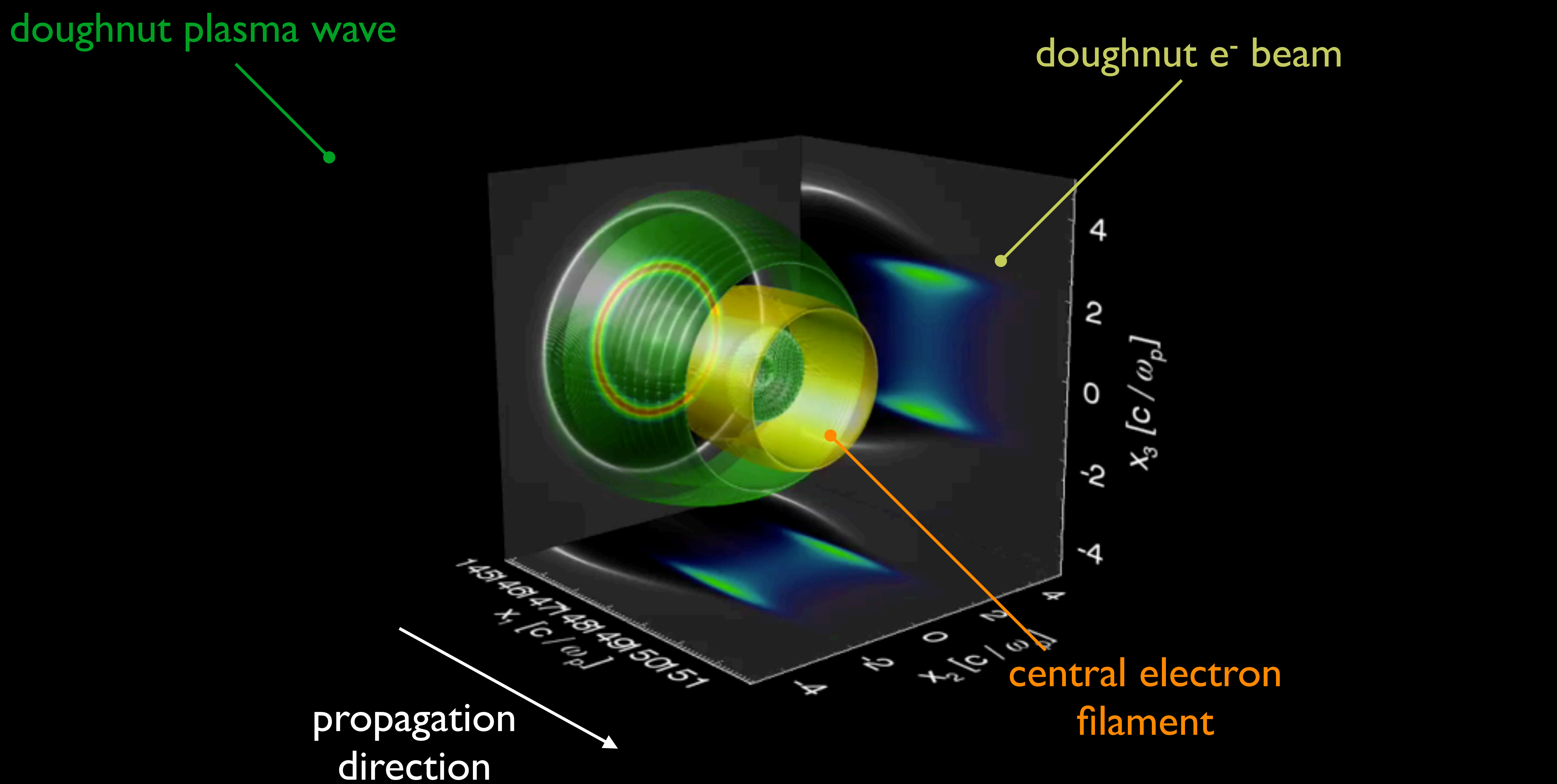


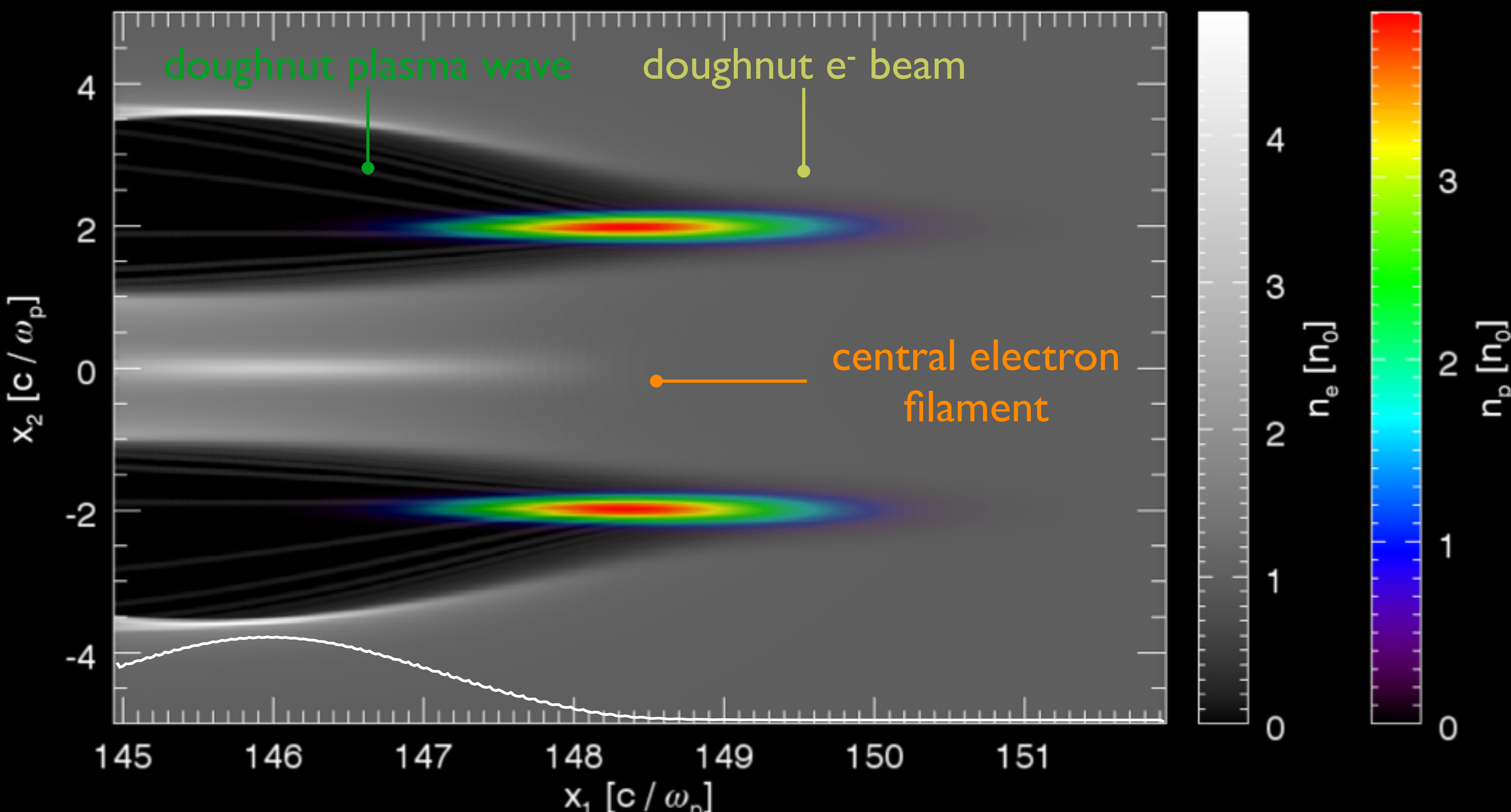
L.D. Amorim et al (2015)

Plasma wakefield accelerator driven by a doughnut electron beam



Doughnut plasma wave in the blowout regime

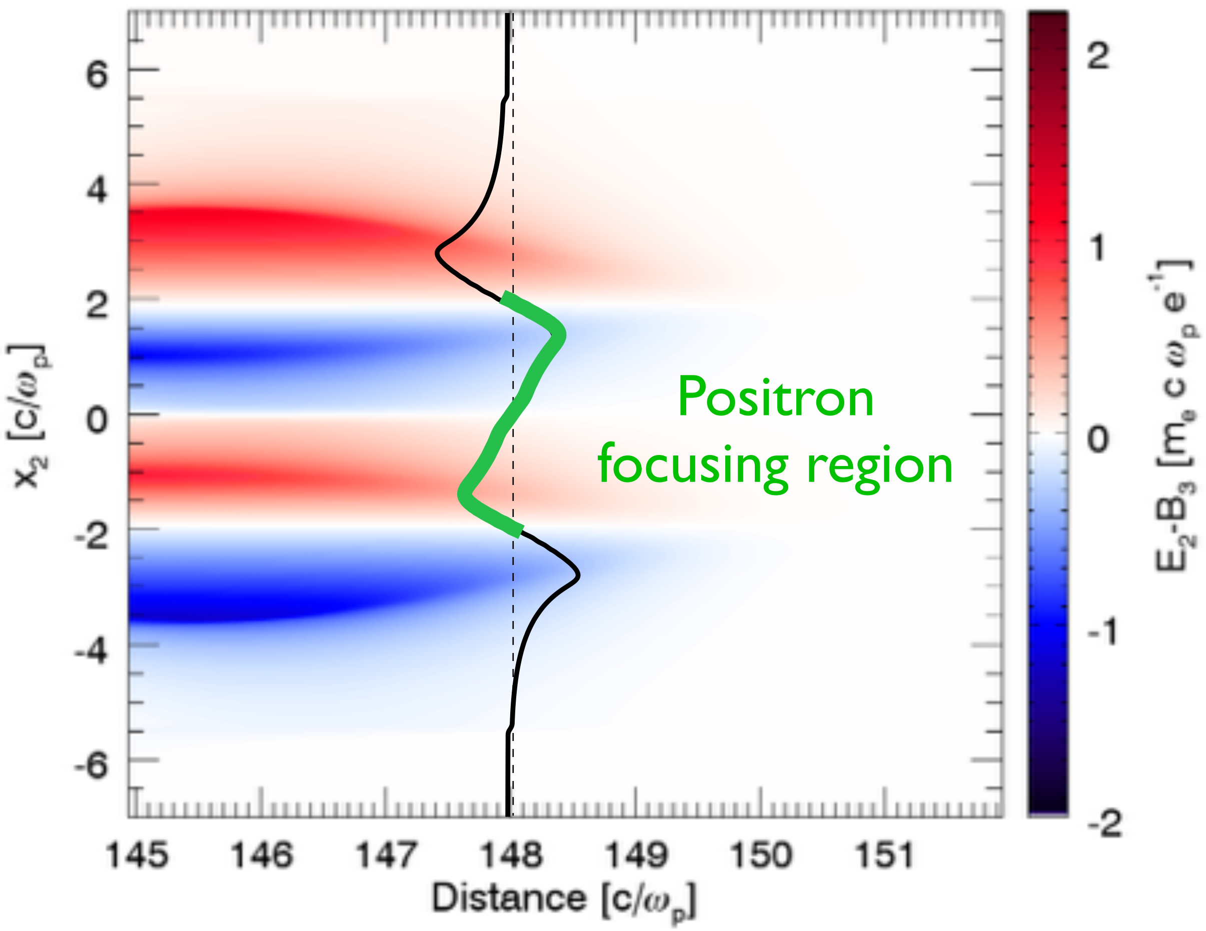
propagation direction



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

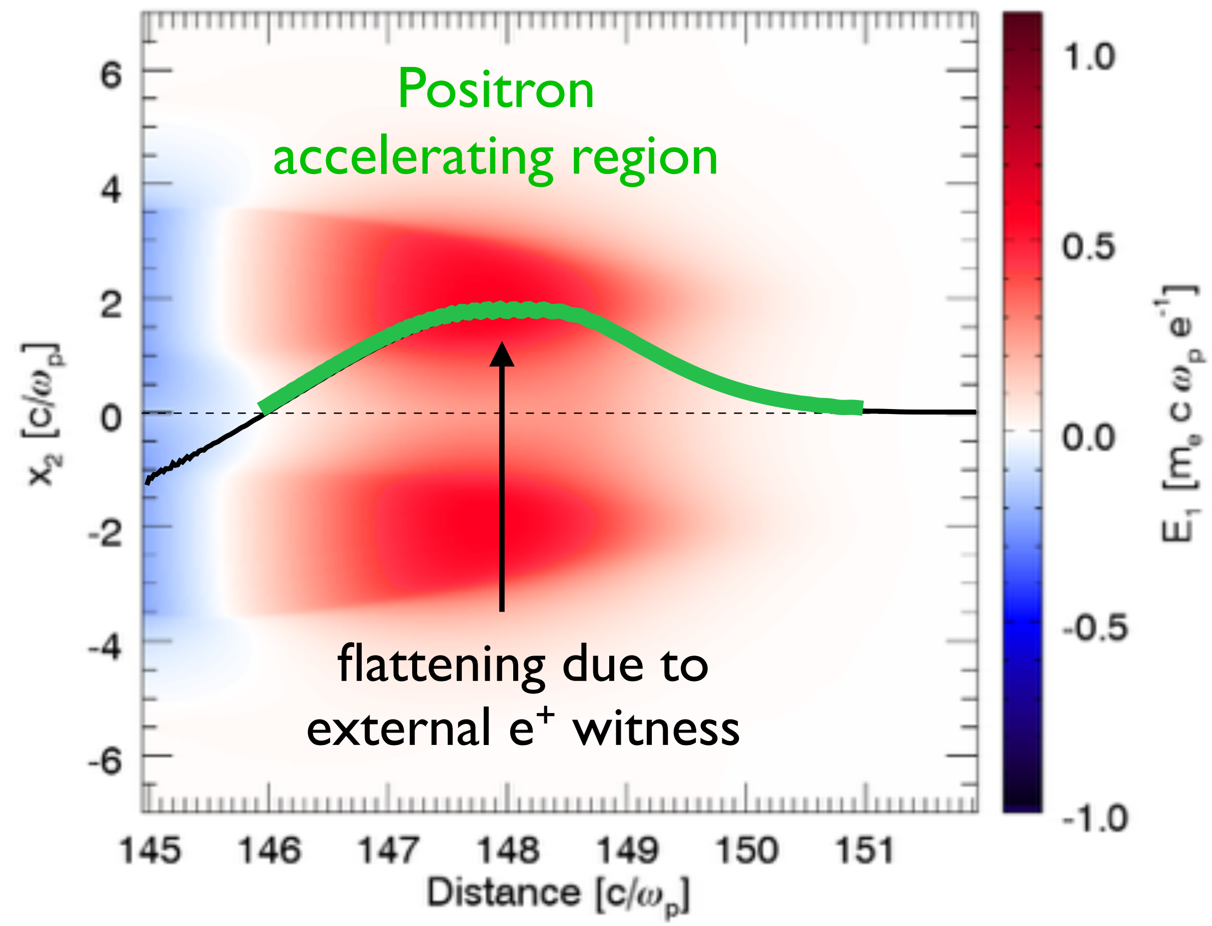
Wakefield structure shows positron focusing and accelerating regions.

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

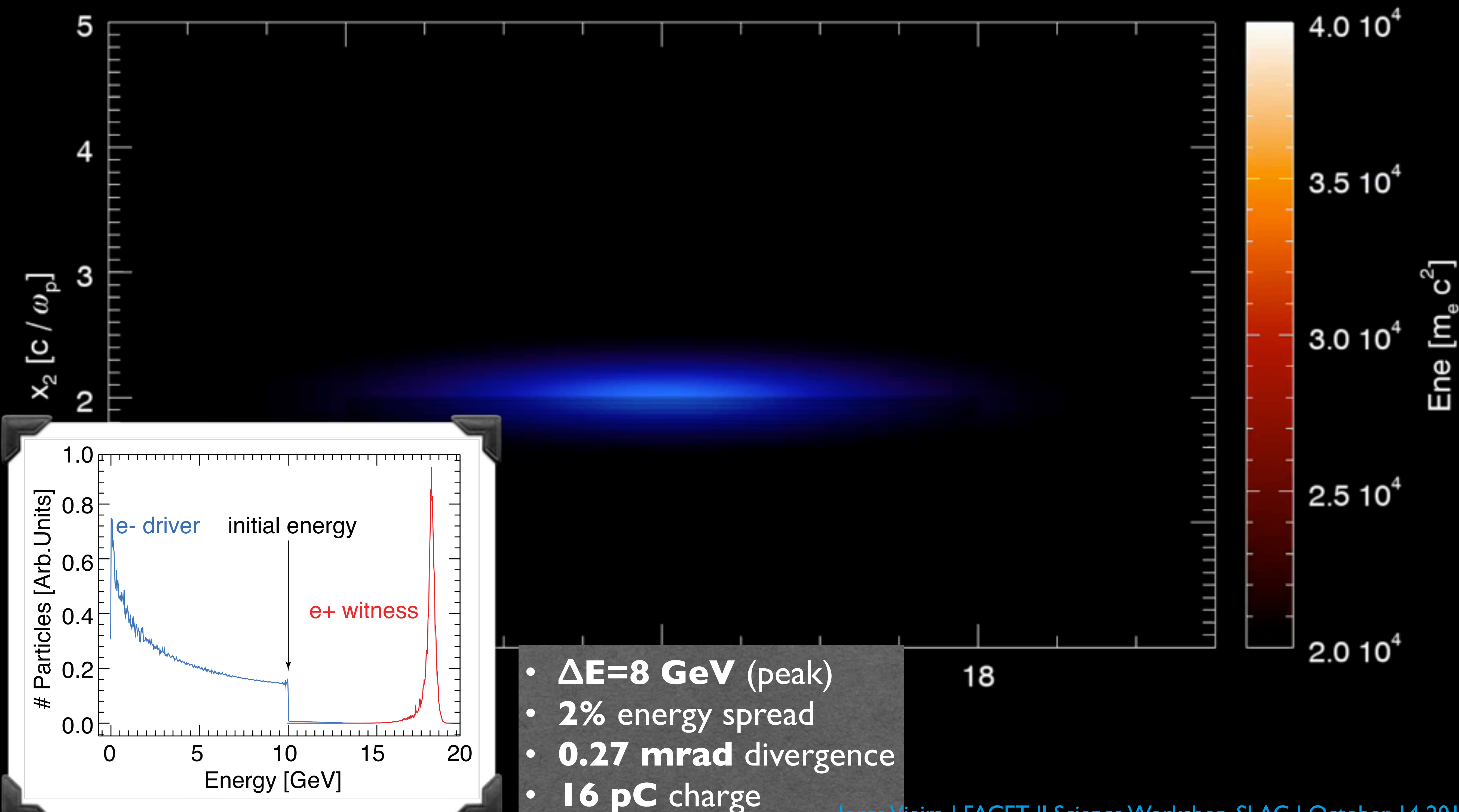


- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

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

Driver:

10 GeV; 3.4 nC; σ_z=23 µm; no emittance

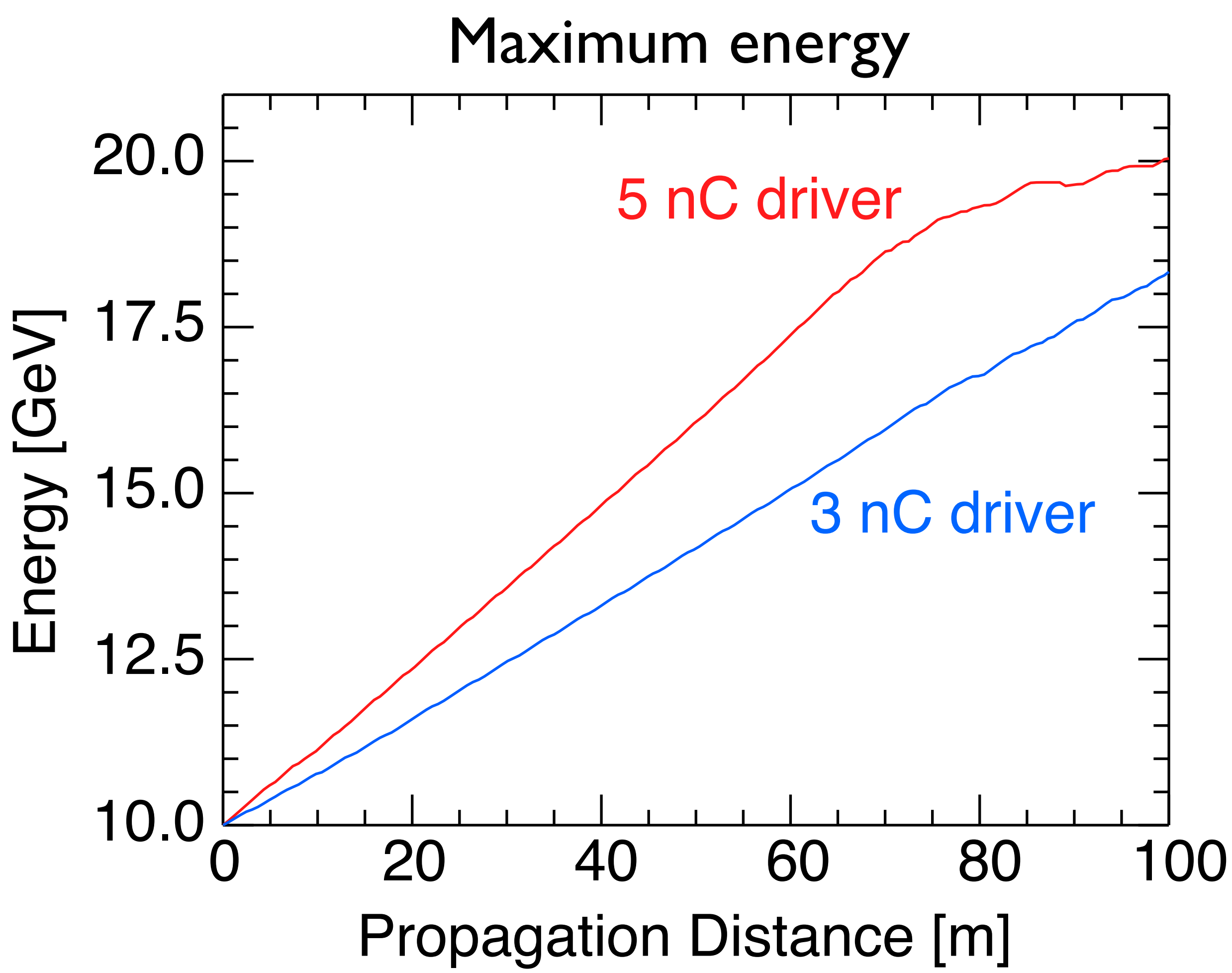


- **ΔE=8 GeV** (peak)
- **2%** energy spread
- **0.27 mrad** divergence
- **16 pC** charge

Positron acceleration/focusing is limited by the driver slowdown.

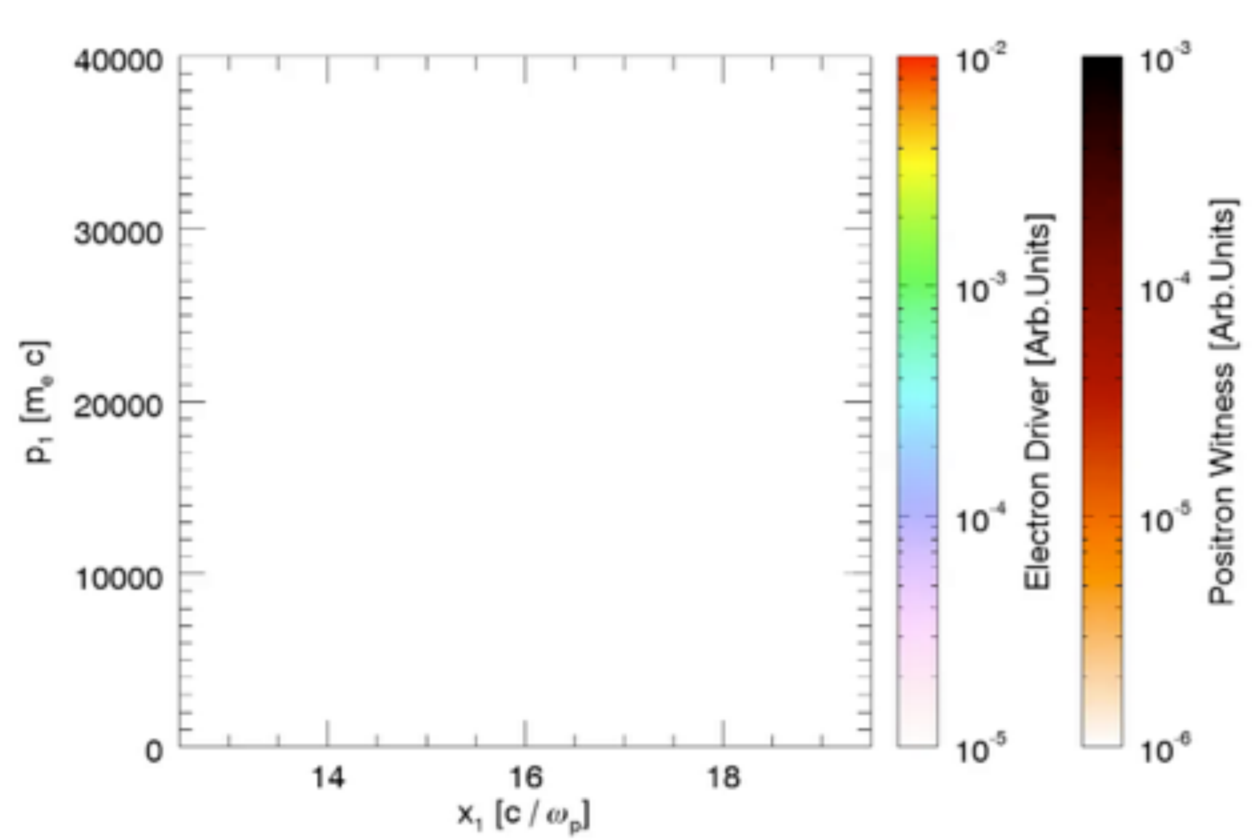
Drivers with higher charges may not lead to higher final energies considering the same density.

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

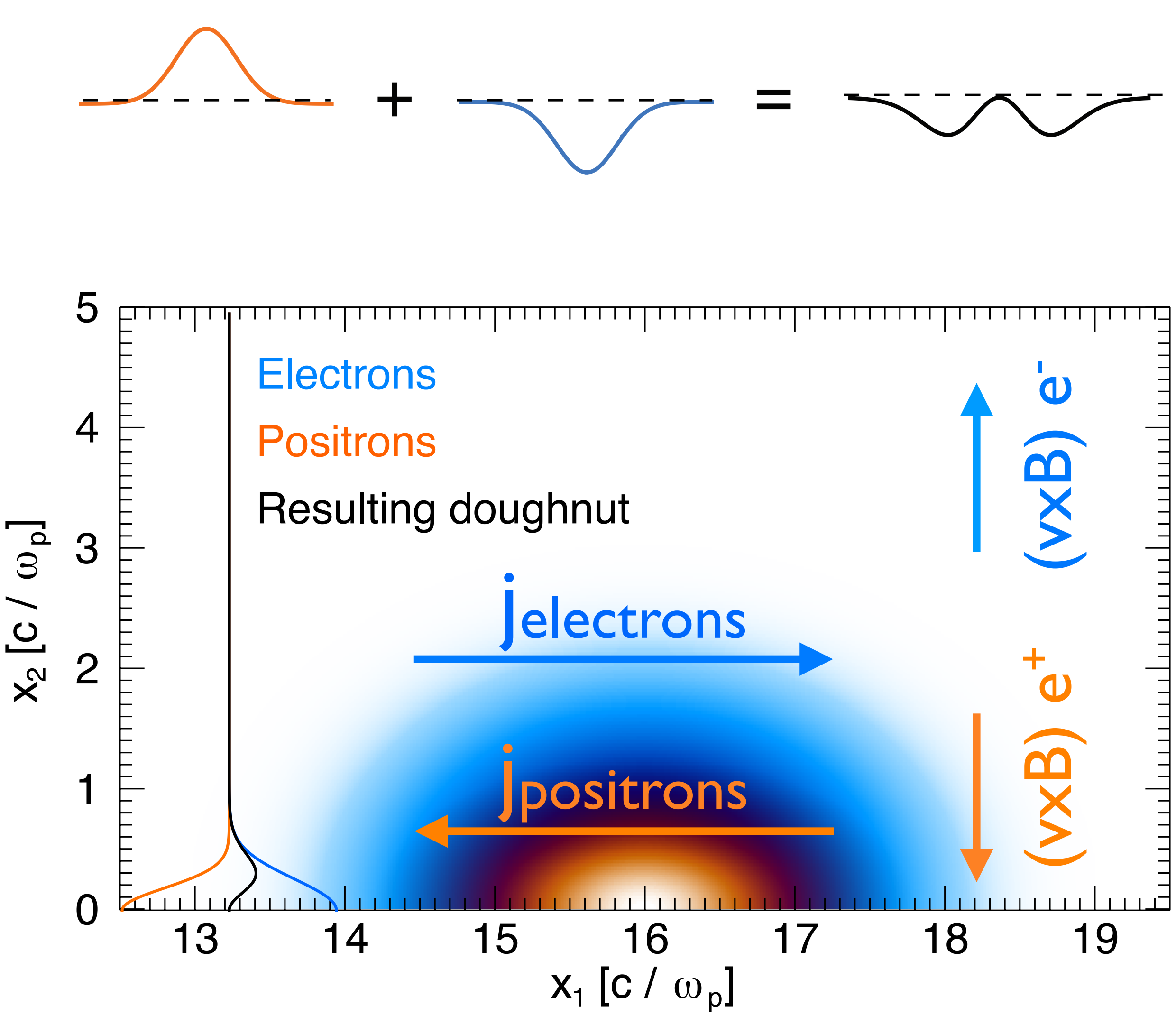


- Doughnut e^- beam focuses on-axis
- Positrons defocus shortly after
- Max. acceleration distance $L_{accel} < \gamma/E_{accel}$

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

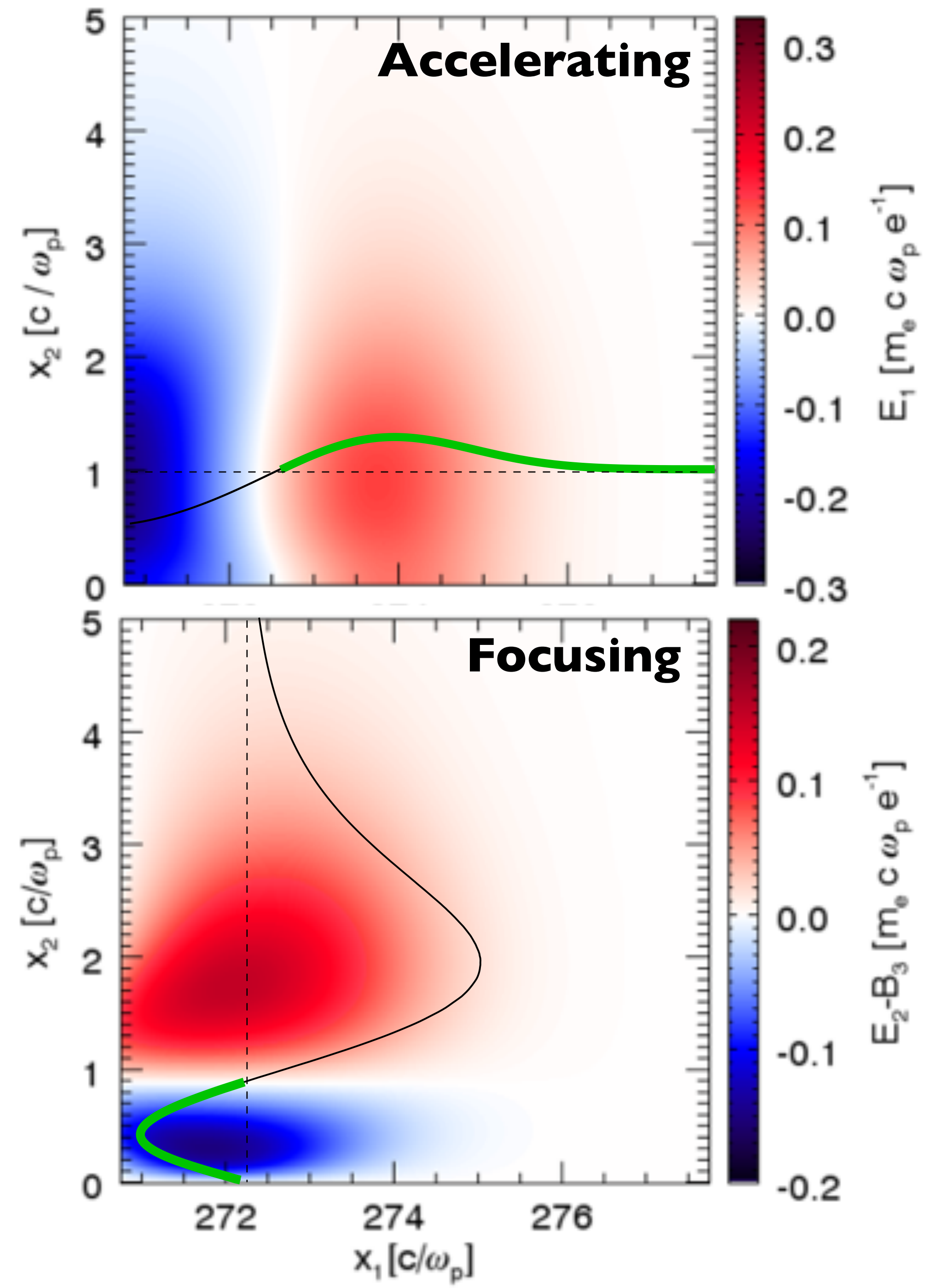
Scheme could be realised superimposing Gaussian e- driver with e+ witness

Self-generated doughnut e⁻ bunch



Connection to astrophysics:
Neutral fireballs and σ_r>>c/ω_p leads to Weibel Instability

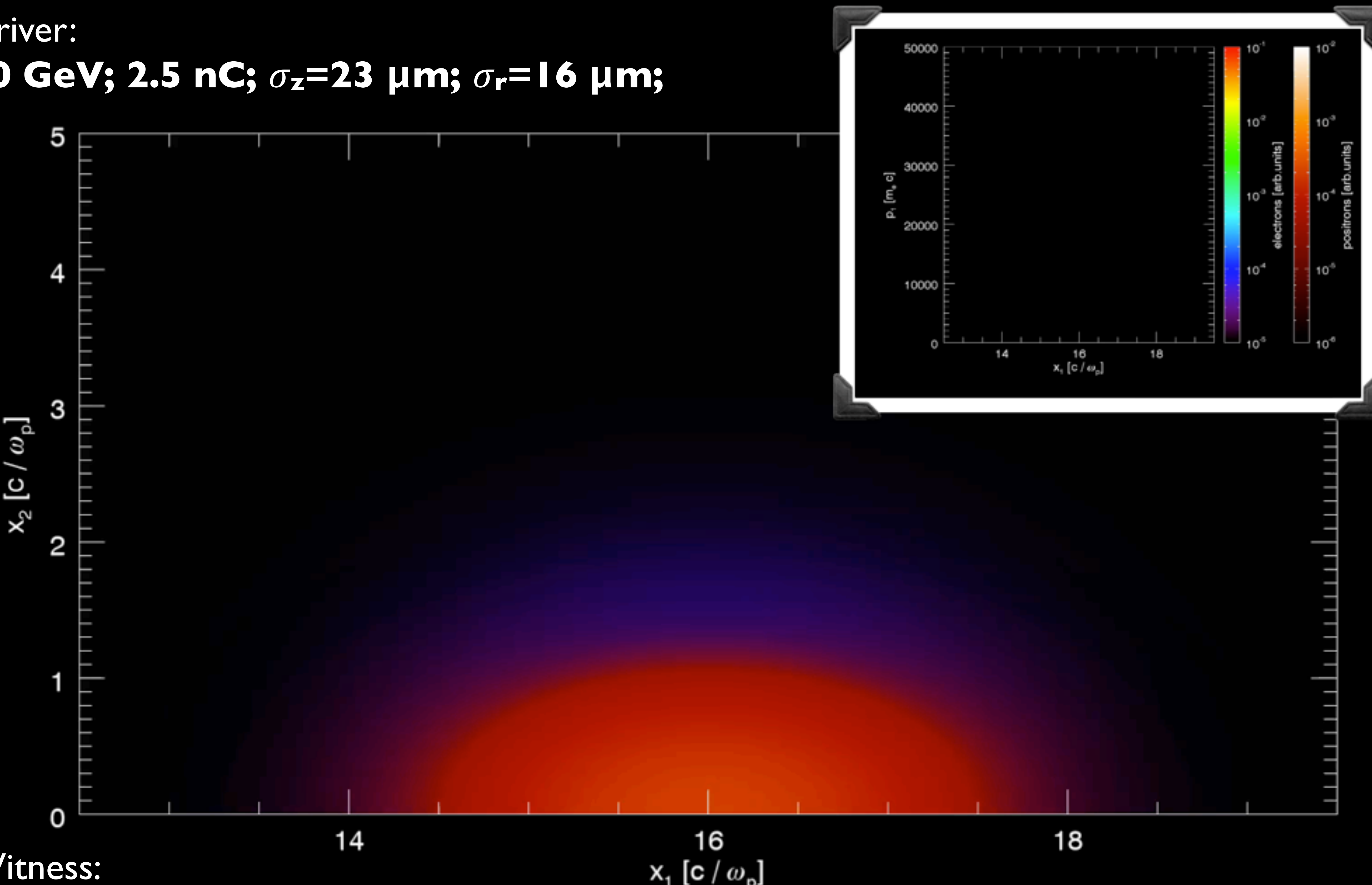
Wakefields are similar to doughnut



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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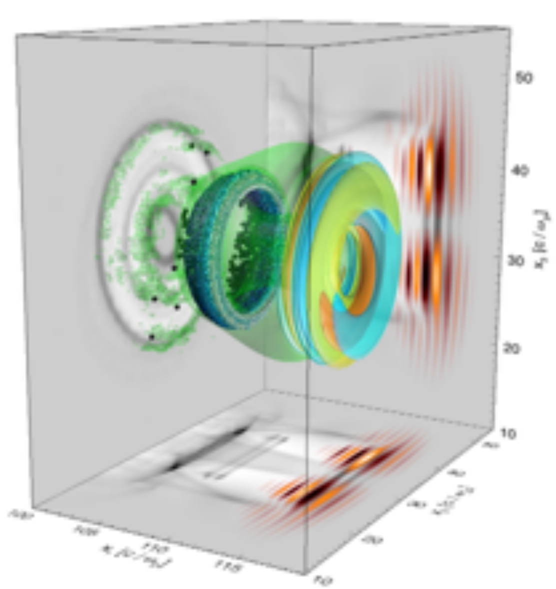

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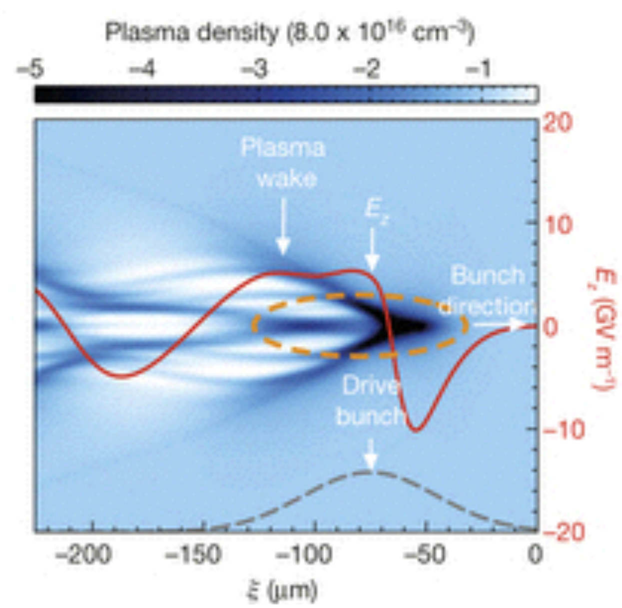

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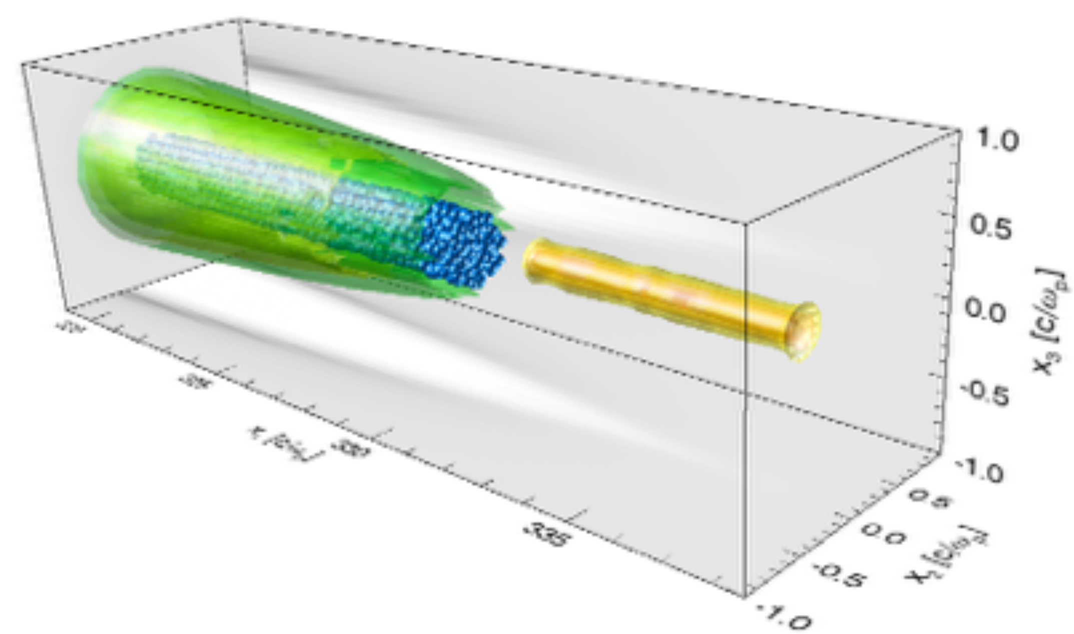
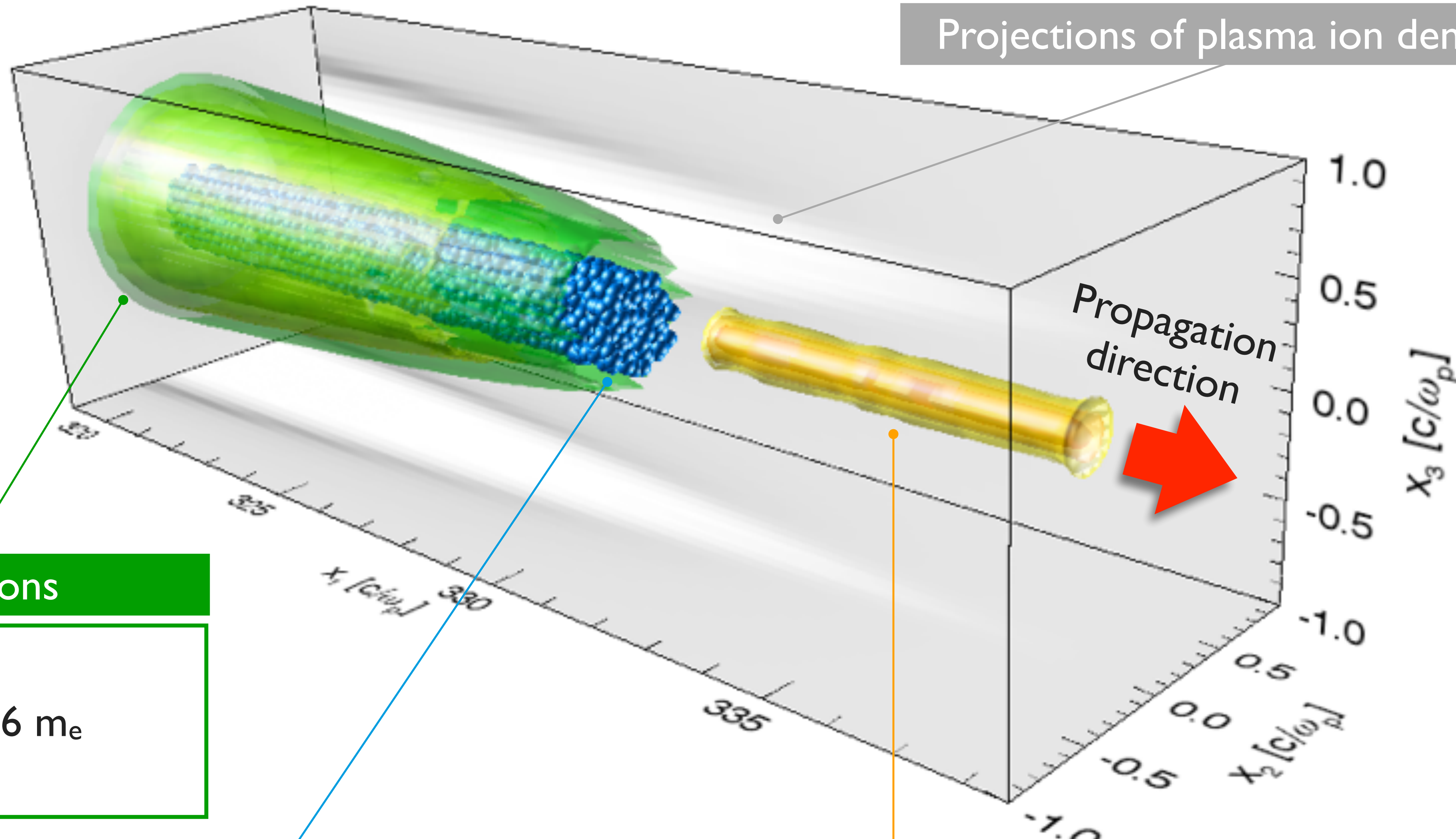


L.D. Amorim et al (2015)

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

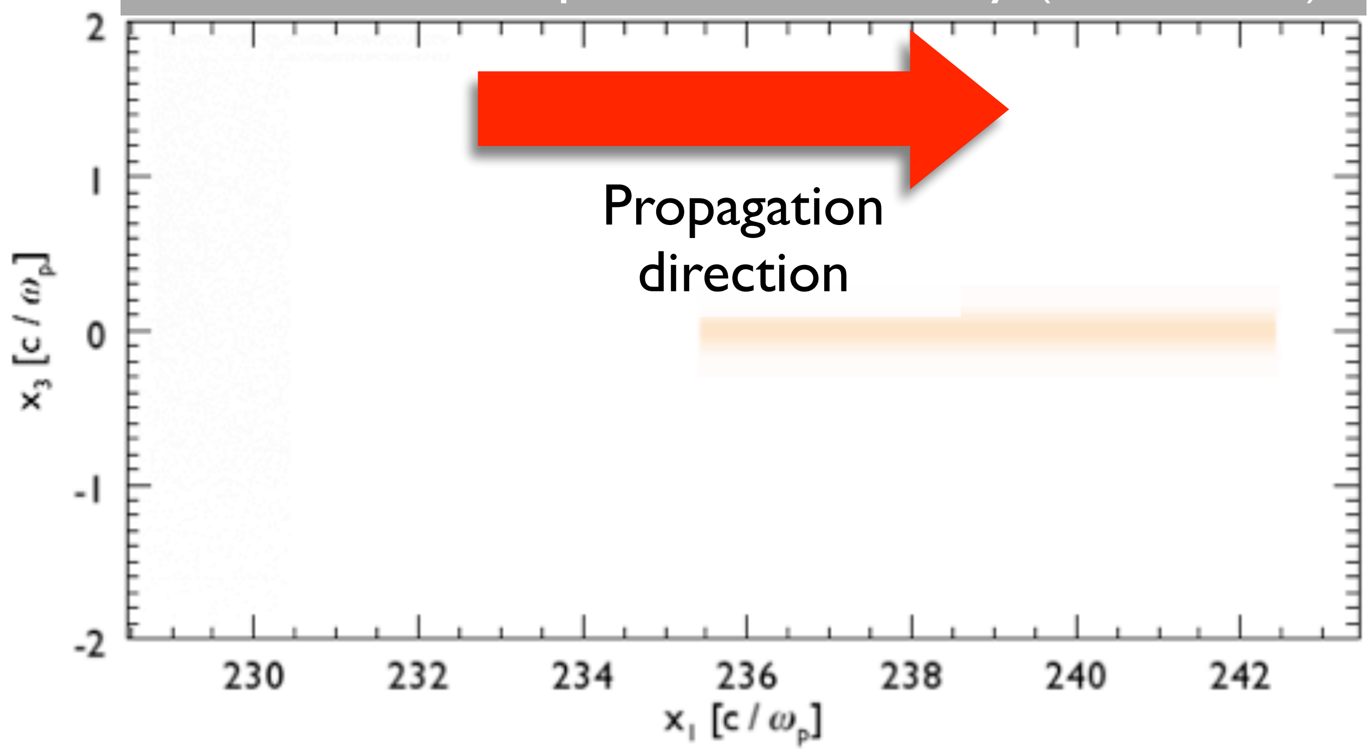
Width σ_r = 0.12 c/ω_p

e+ drive beam

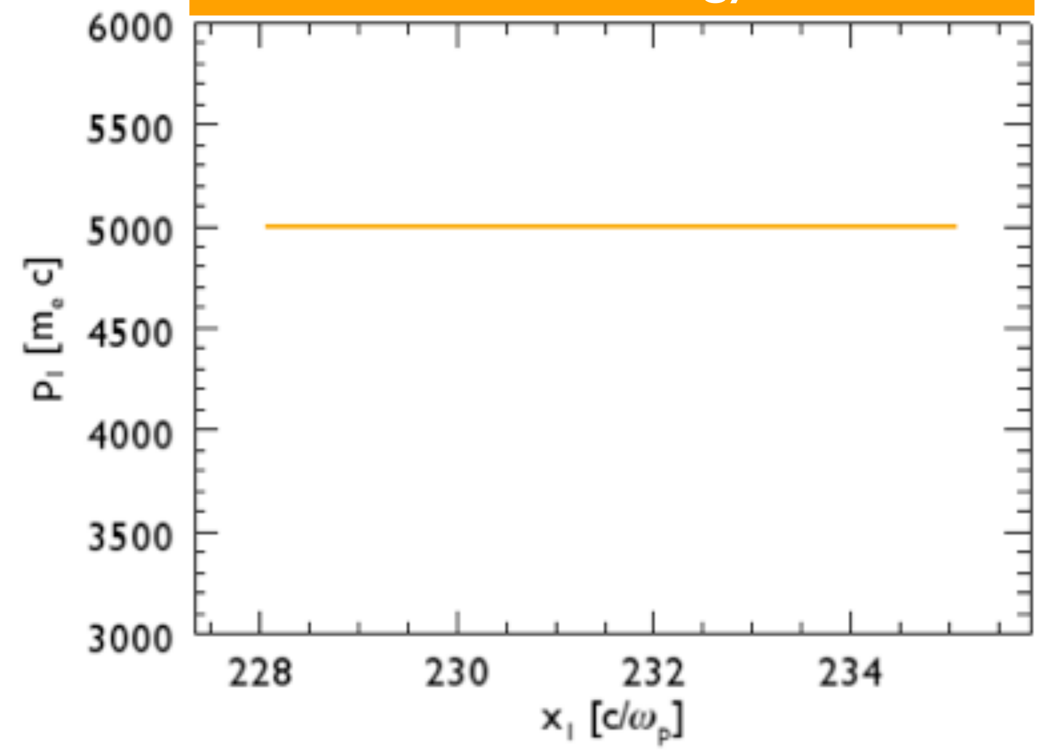
Density n_b = 200 n_0	**can be relaxed for longer beams**
Length σ_z = 6 c/ω_p	**close to the plasma wavelength**
Width σ_r = 0.12 c/ω_p	**tightly focused**
Energy = 2.5 GeV	**ultra relativistic**

Simulations show hollow channel formation and positron bunch energy gain inside the hollow channel

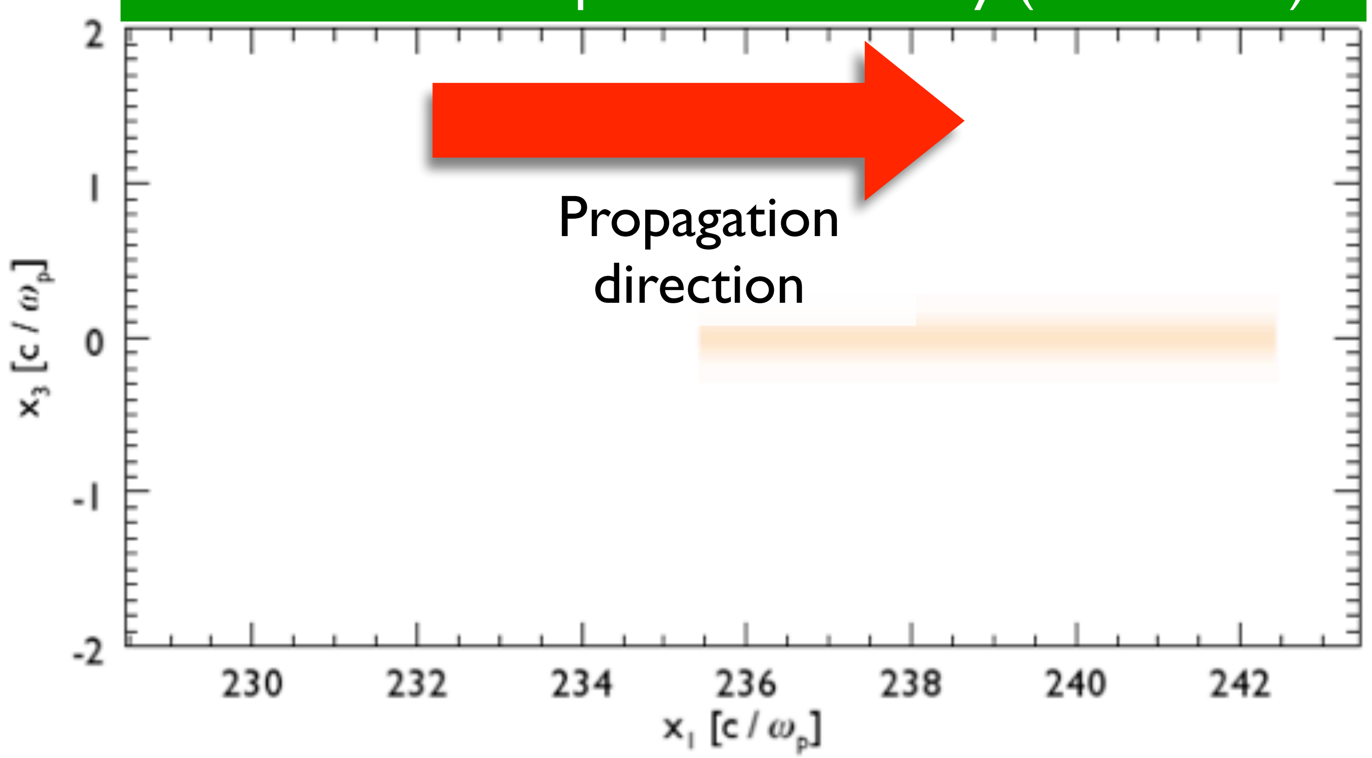
Evolution of the plasma ions density (slice of 3D)



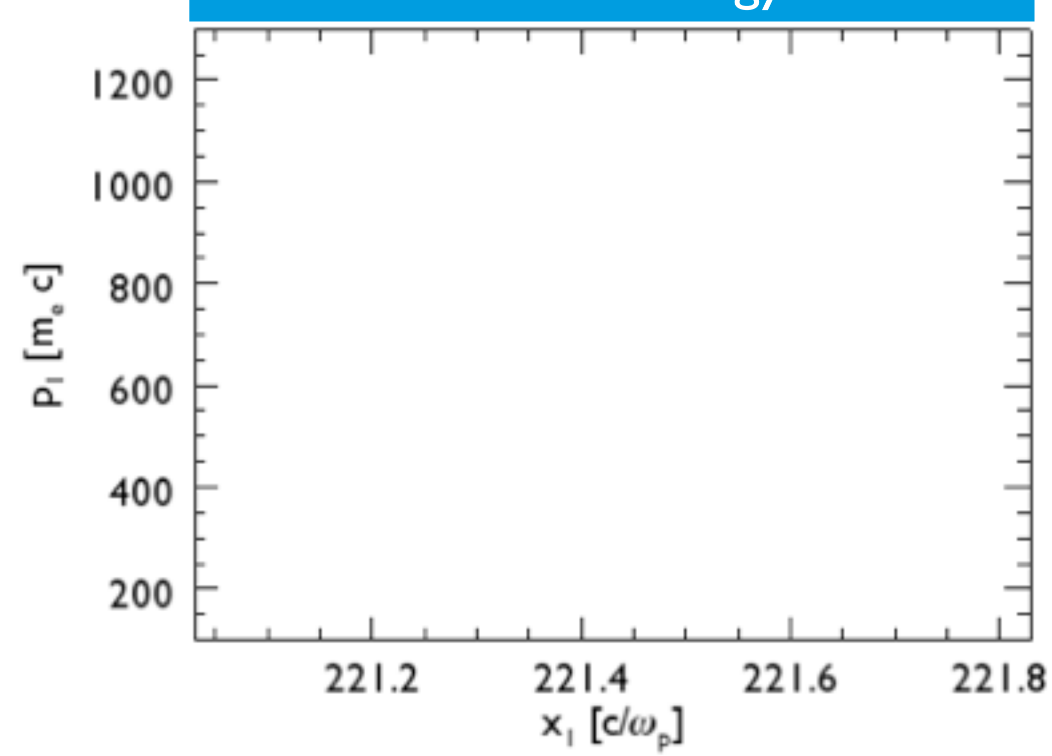
Drive e$^+$ beam energy evolution



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



Witness e$^+$ beam energy evolution



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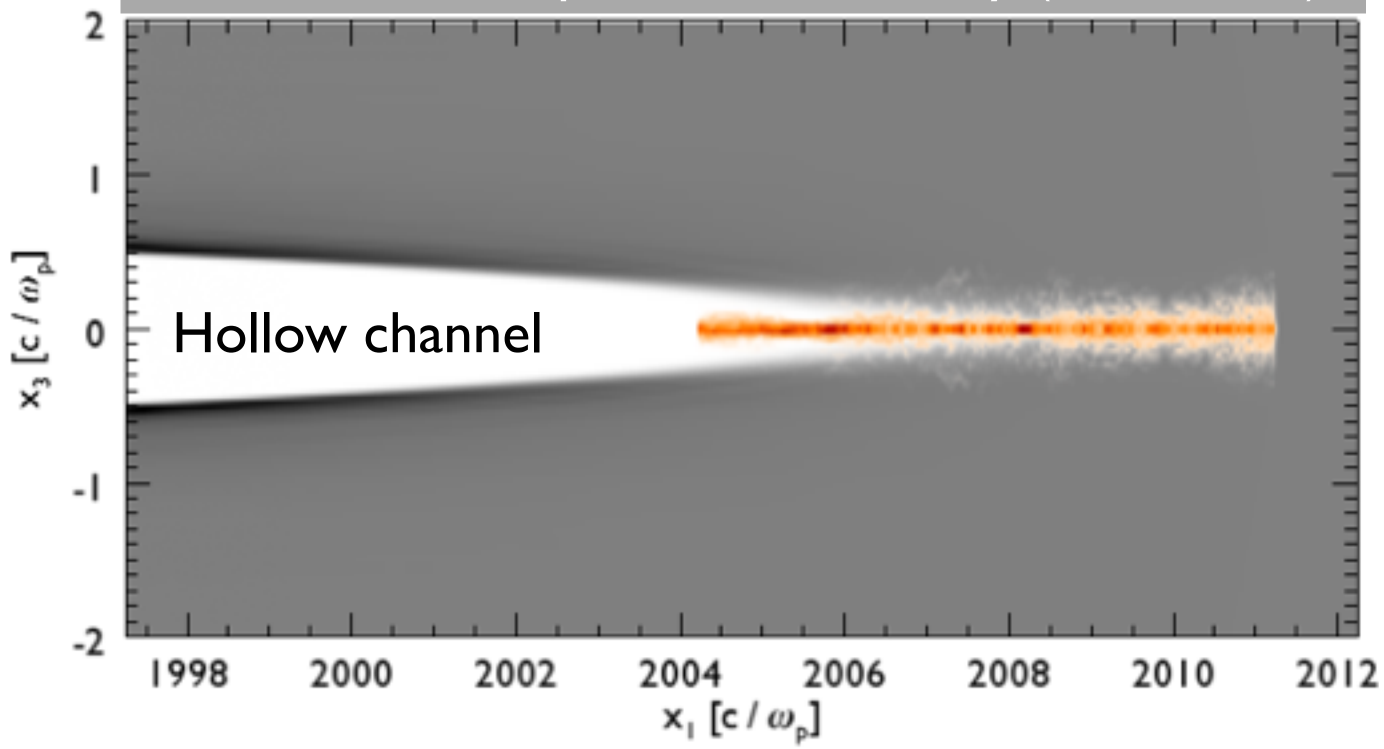

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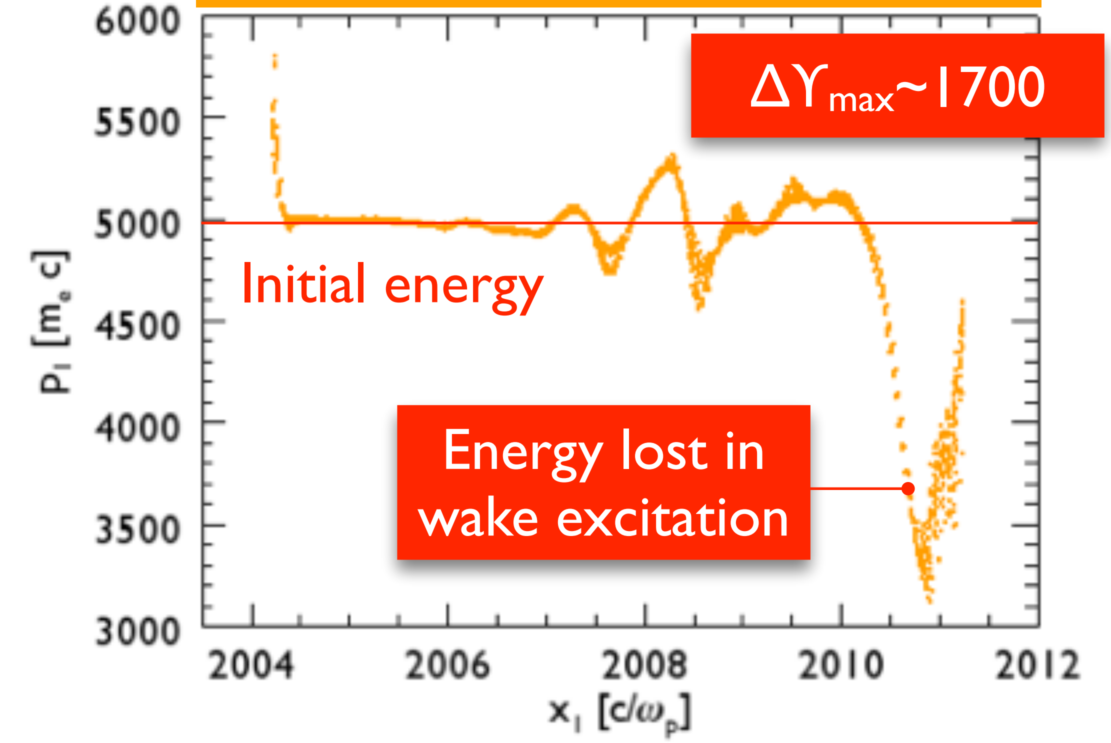

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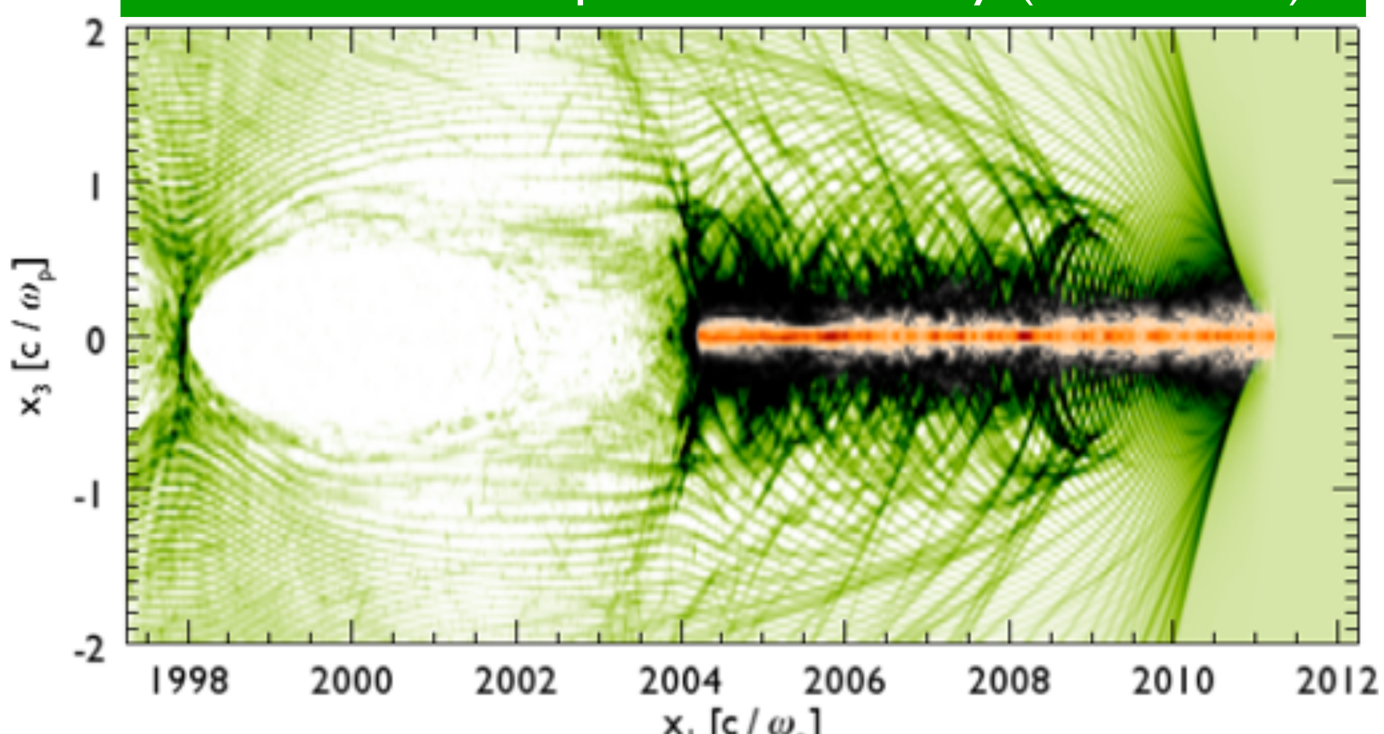

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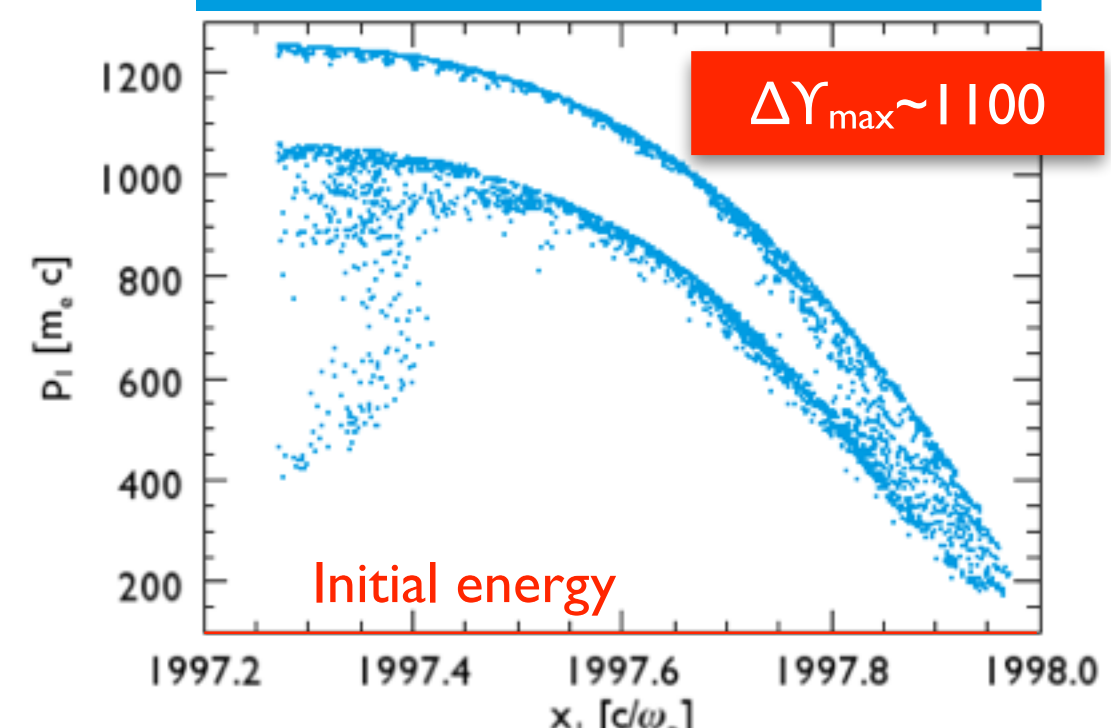
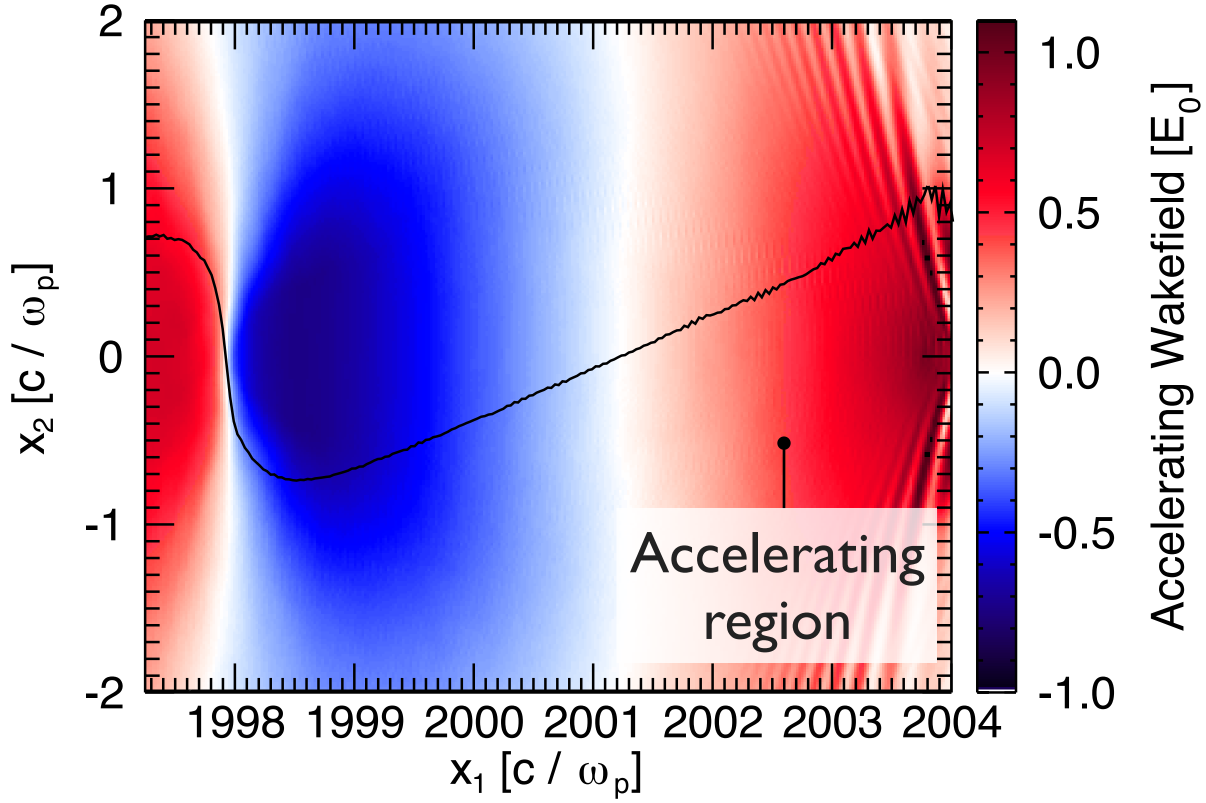


L.D. Amorim et al (2015)

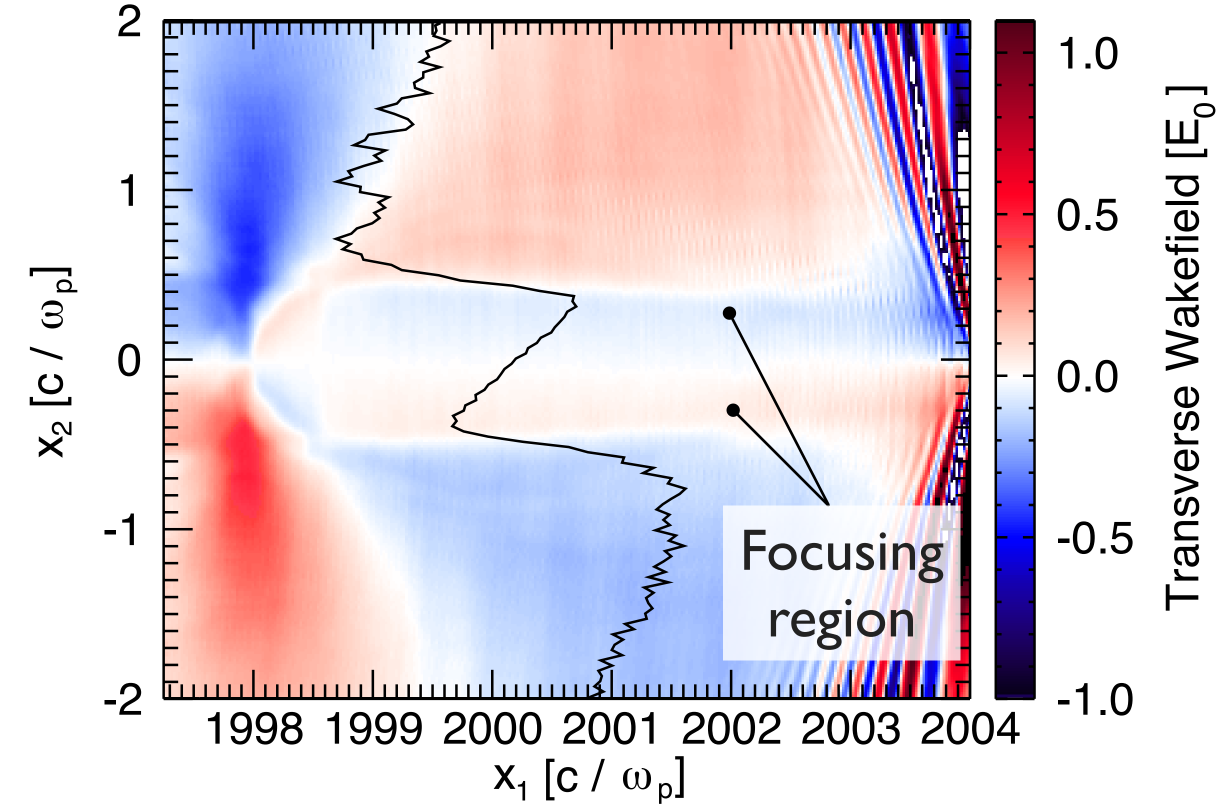
Positron focusing and accelerating fields in hollow channel created by narrow drivers

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

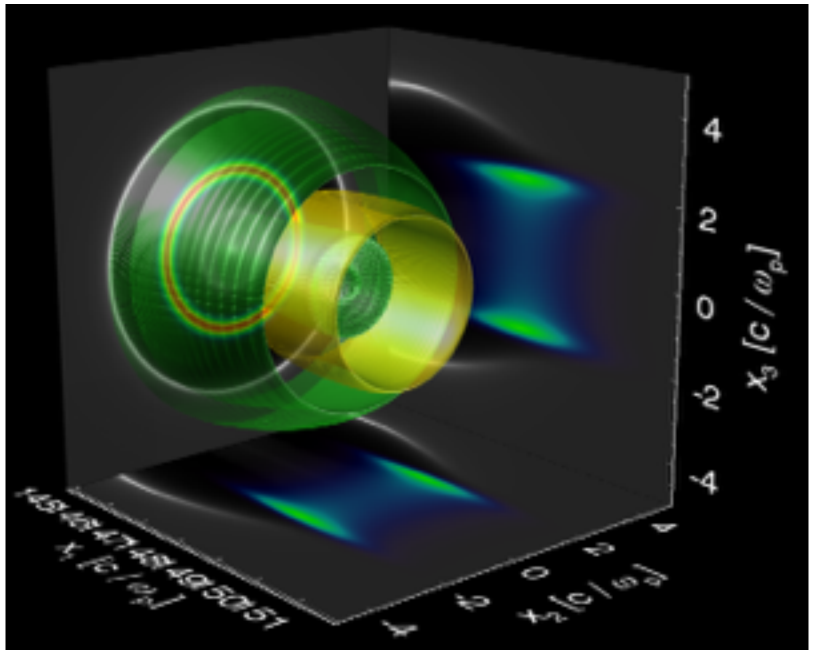
L.D. Amorim et al (2015)

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.