# Transverse evolution of e$^+$ beams accelerating in hollow plasma channel non-linear wakefields


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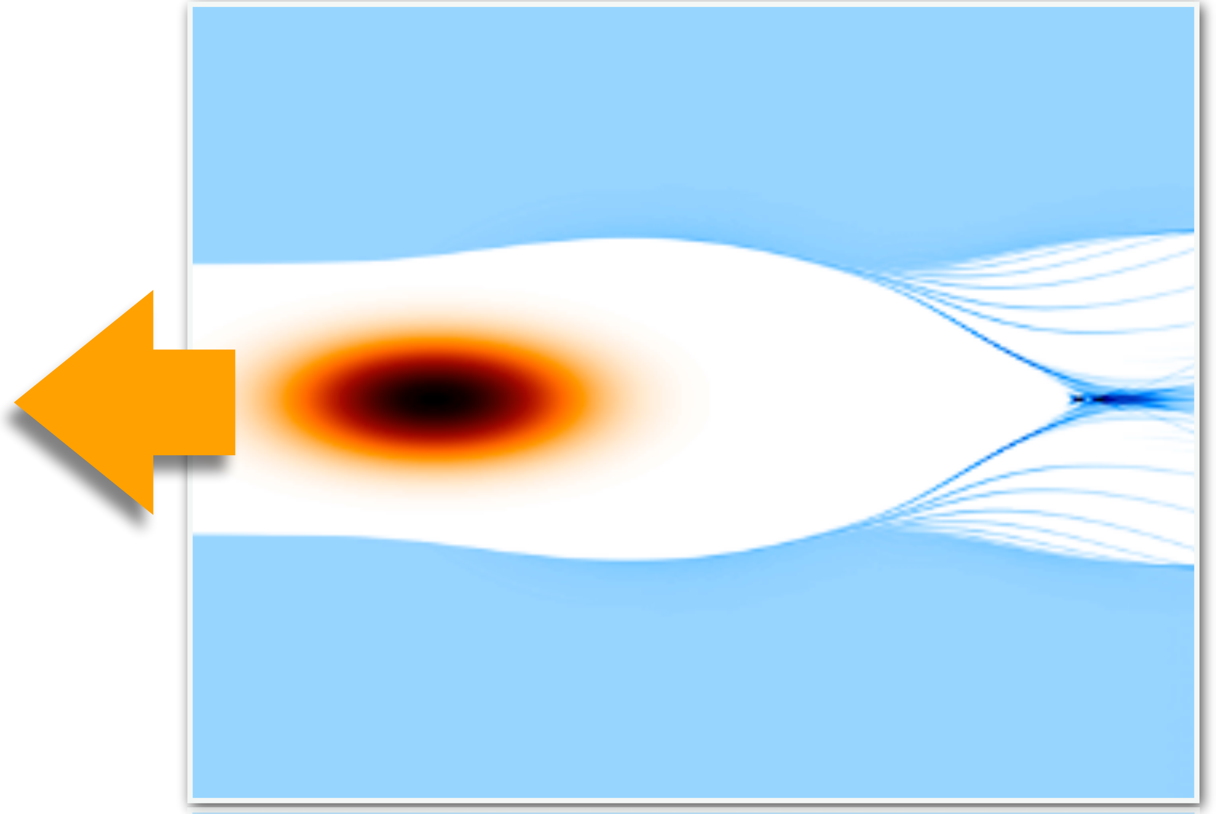


# Outline of the work

## Main motivations

Advantages of hollow plasma channels for wakefield accelerators

## Limits of linear theory for hollow plasma channels

Simulations show limits of wakefield theory for both $e^-$ and $e^+$ beams

Non linear case shows interesting co-moving plasma $e^-$ structure

Analysing validity of beam loading theory for e+ beams

## Asymmetrical beams propagation in hollow channels

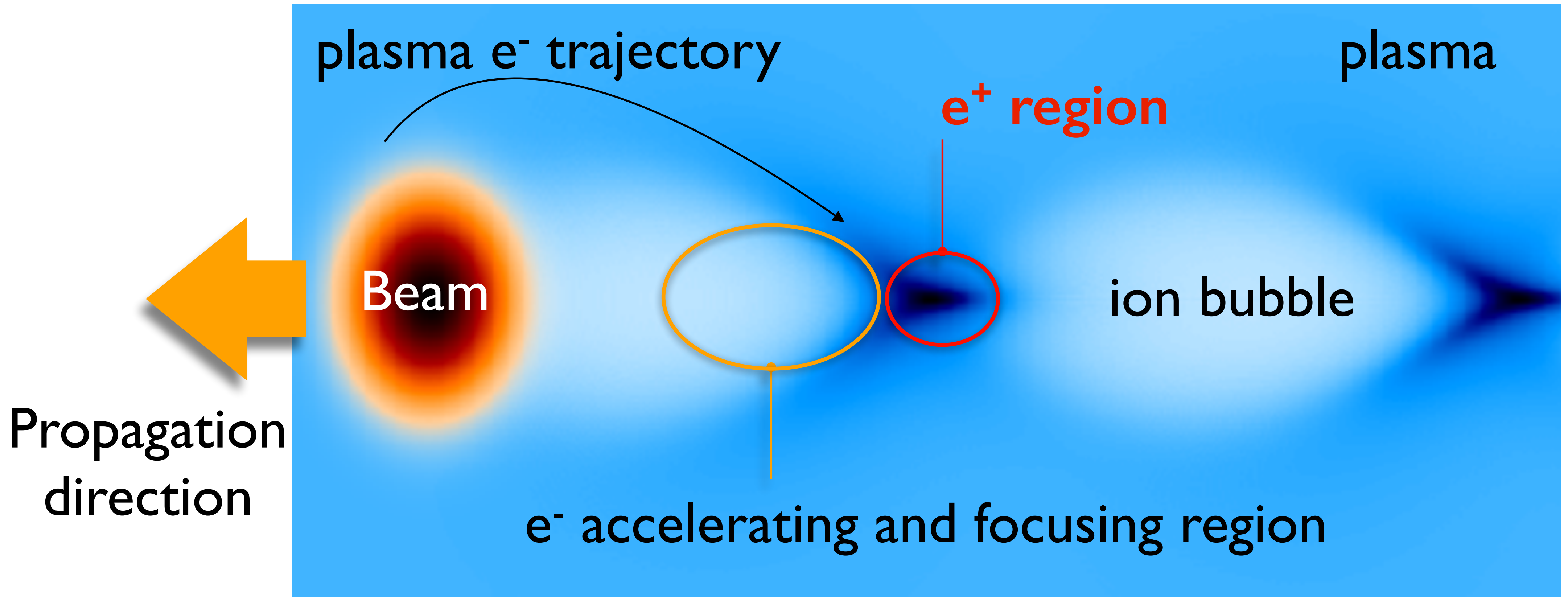
Beam azimuthal mode 0 and 1 components separate analysis shows how asymmetries in realistic scenario can excite higher order wakefield modes

Beam break up instability in hollow plasma channels

# Plasma hollow channels provide an alternative to standard blowout regime for $e^+$ acceleration

- ➡ Developing accelerator technologies is vital to explore physics at the energy frontier
- ➡ Plasma based accelerators can overcome breakdown constraint

## Ideal e- acceleration in beam driven plasma wakefield blowout (bubble) regime

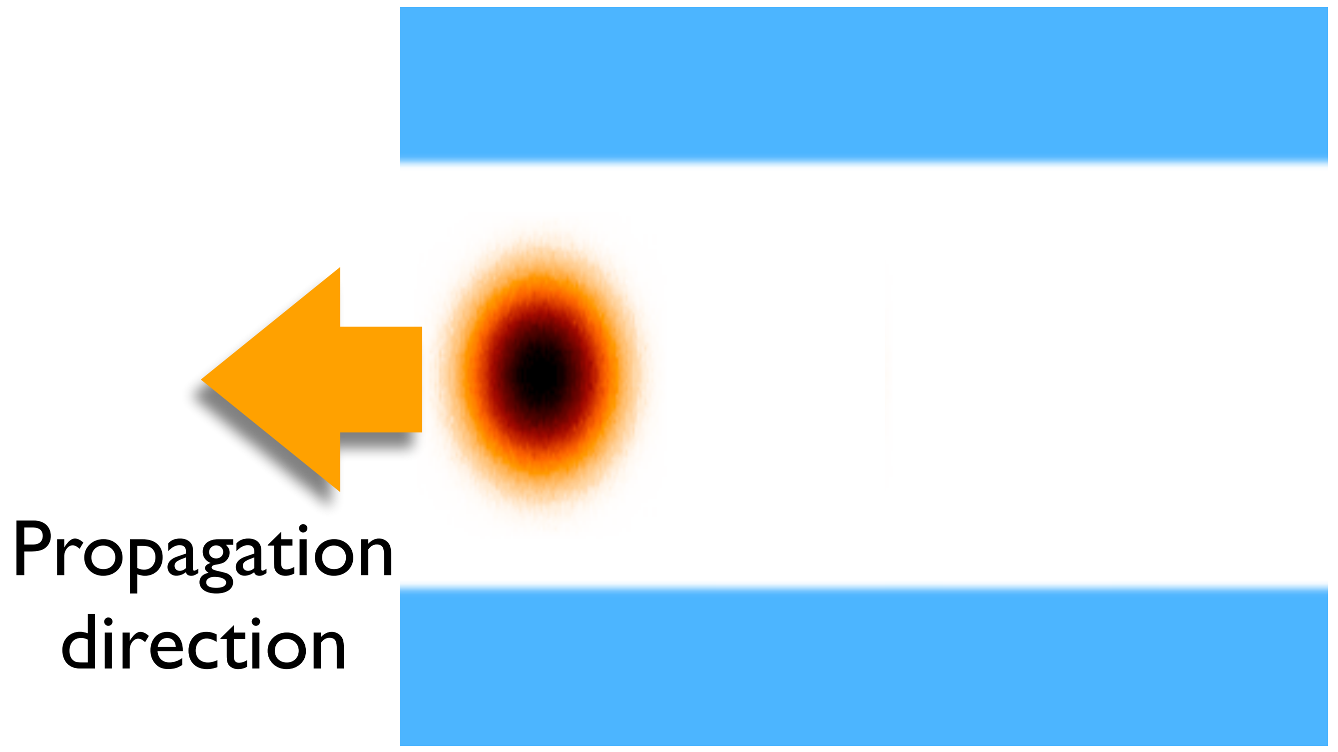



Plasma $e^-$s are repelled by the $e^-$ (or laser) drive beam forming bubble with immobile ions that attract $e^-$s

**Ideal scheme setup for $e^-$ acceleration**

**Not efficient for $e^+$ acceleration!**

## Hollow plasma channel is an alternative configuration where $e^+$s are not defocused




In plasma **hollow channels** $e^+$s are accelerated without being defocused by ions

Recent experiments corroborated this advantage

T.Chiou et al., PoP 2 (1995), PRL **81** (1998)
L.D.Amorim et al., (to be submitted)
S.Gessner et al., Nat Com (2016)
K.A. Marsh et al., Proc. PAC (2003)

C. B.Schroeder et al., PRL **82,** 6 (1999)
C.B.Schroeder et al., PoP **20**, 080701 (2013)

W. Lu et al., PoP **13,** 056709 (2006)
J.Thomas et al., PoP **23**, 053108 (2016)
Talk by Aakash SAHAI in this AAC
A.A.Golovanov et al., QE **46**, 295 (2016)

# Longitudinal peak field value decreases for increasing plasma hollow channel radius

## Linear theory for azimuthally symmetrical (Gaussian) particle beams in hollow channels

Longitudinal accelerating field behind the drive beam follows[1,2]:

$$E_z = \Omega^{-2} \int_{\infty}^{\xi} d\xi' \cos[\Omega(\xi - \xi')] W_0 \frac{I(\xi')}{I_A}$$

Beam current

co-moving longitudinal position

Alfvén current

Oscillating at the frequency:

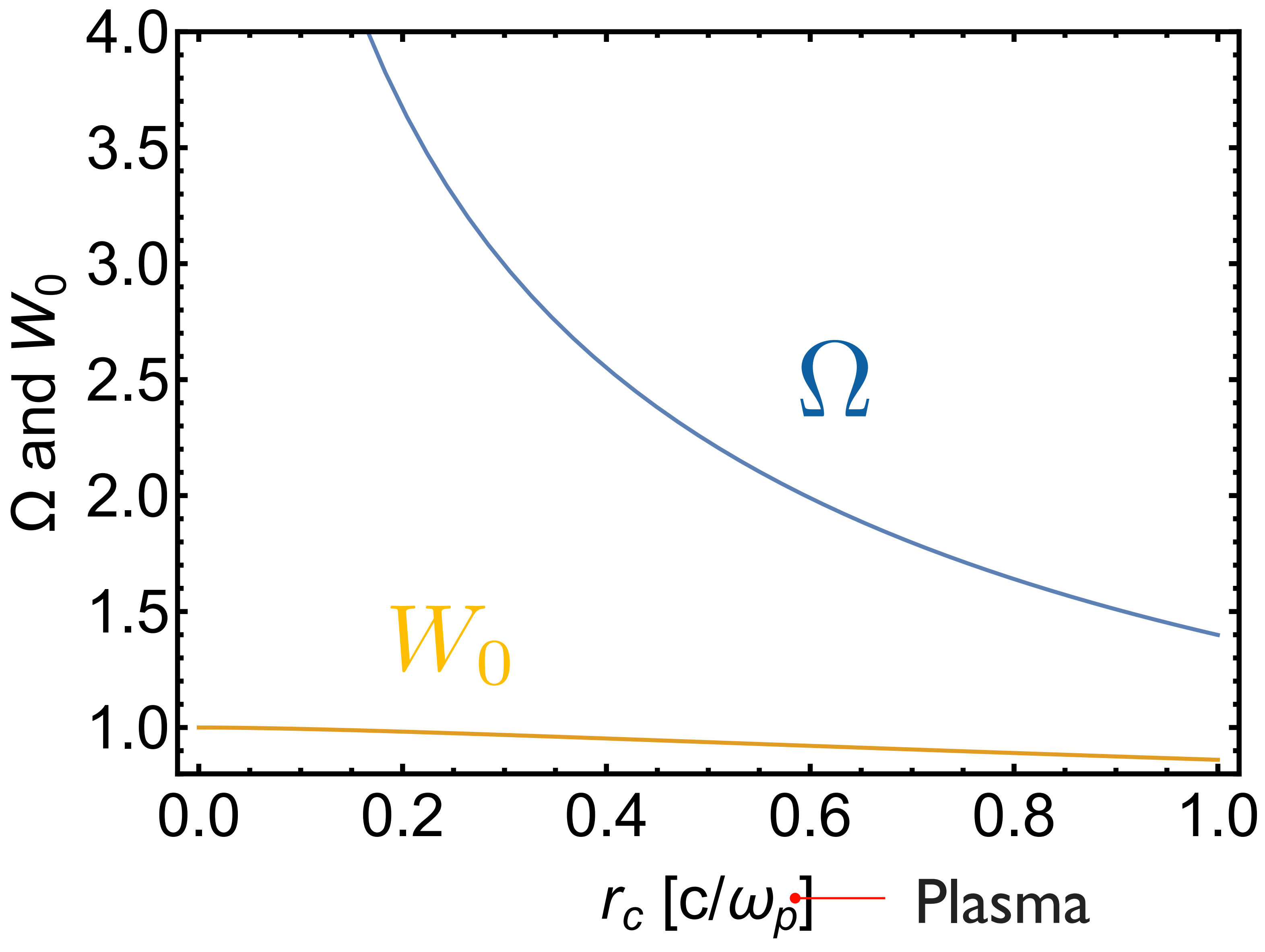
$$\frac{\omega}{\omega_p} = \Omega = \left[1 + \frac{r_c K_0(r_c)}{2K_1(r_c)}\right]^{-1/2}$$

2nd kind Modified Bessel functions

Plasma frequency

Where: $$W_0 = \frac{2K_0(r_c)}{r_c K_1(r_c)}$$

Normalised channel radius




Plasma skin depth

➡ This plot shows that the peak field ($E_z$) decreases with higher channel radius ($r_c$)


[1]C.B.Schroeder et al., PoP **20**, 080701 (2013)
[2]T.Chiou et al., PoP 2, 1 (1995)

# Non linear regime is reached for lower beam current for $e^+$ beam than for $e^-$ beam

**Simulations with OSIRIS-3D, Quasi-3D and QuickPIC agreed with linear theory**

**Linear theory validity scan over $I_b/I_A \in$ [.0001 to 2] for both e- and e+ drive beam**

- Theory breaks when space charge of drive beam overcomes restoring force from ions outside of the channel and makes plasma $e^-$s cross the axis
- For channel radius, $r_c$=2.4c/$\omega_p$ plasma $e^-$s reach the axis of propagation for a $e^+$ drive beam with $I_b/I_A > 0.1$ and an $e^-$ beam with $I_b/I_A > 0.2$

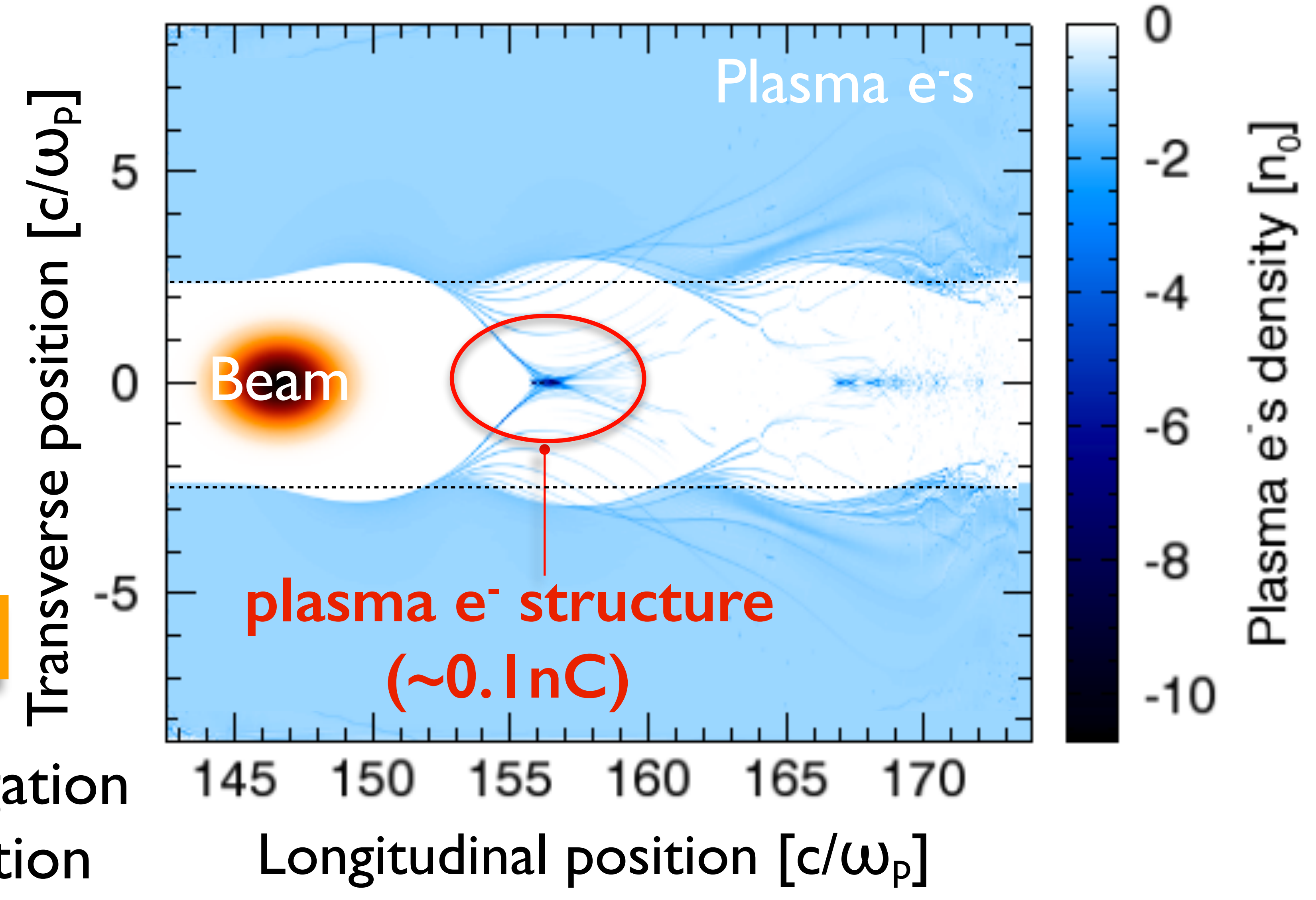
**Reducing channel radius didn't recover homogeneous plasma wakefield linear theory**

**Decreasing channel radius and beam spot size to 75% (keeping $\Lambda = n_b/n_0\sigma_r^2$ constant)**

- The range of $I_b/I_A$ for which linear theory was valid, for both the $e^-$ and $e^+$ driver, also decreased by a similar factor - the threshold for the linear regime varies with channel radius

# Plasma channel $e^-$s that cross the axis form a co-moving structure that loads the wake

Plasma e-s form a “beam-like”

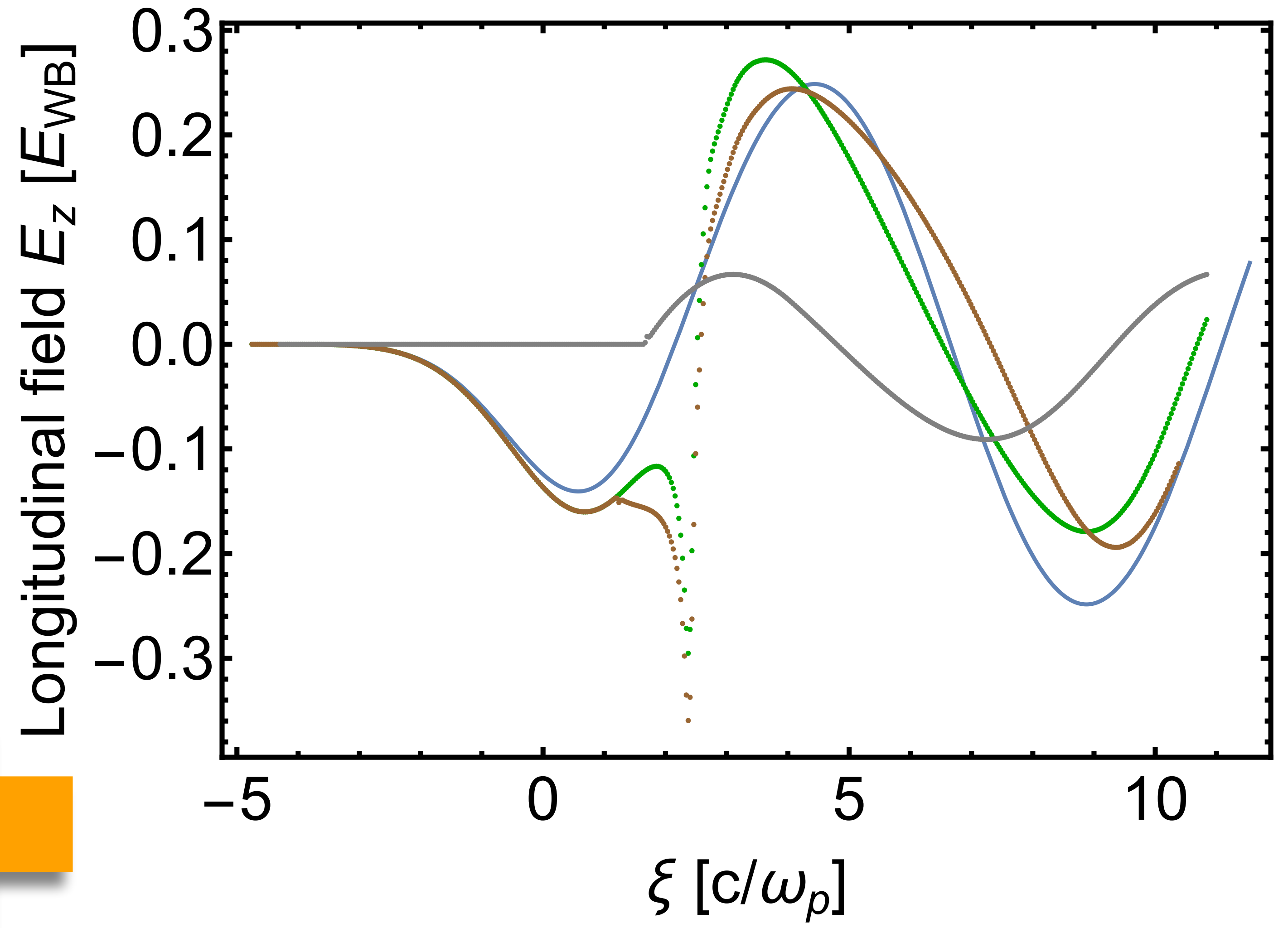



Propagation direction

Plasma $e^-$s are repelled by an e- beam and then pushed in the direction of the axis by the plasma ions

Forming a structure with high e- density that co-moves with the drive beam and contributes to the wakefields

Wakefields form structure




$e^-$ beam reproducing plasma $e^-$s structure space charge and current excites significant fields

It makes the wakefields diverge from theory

The structure model allows to beam load with $e^+$s

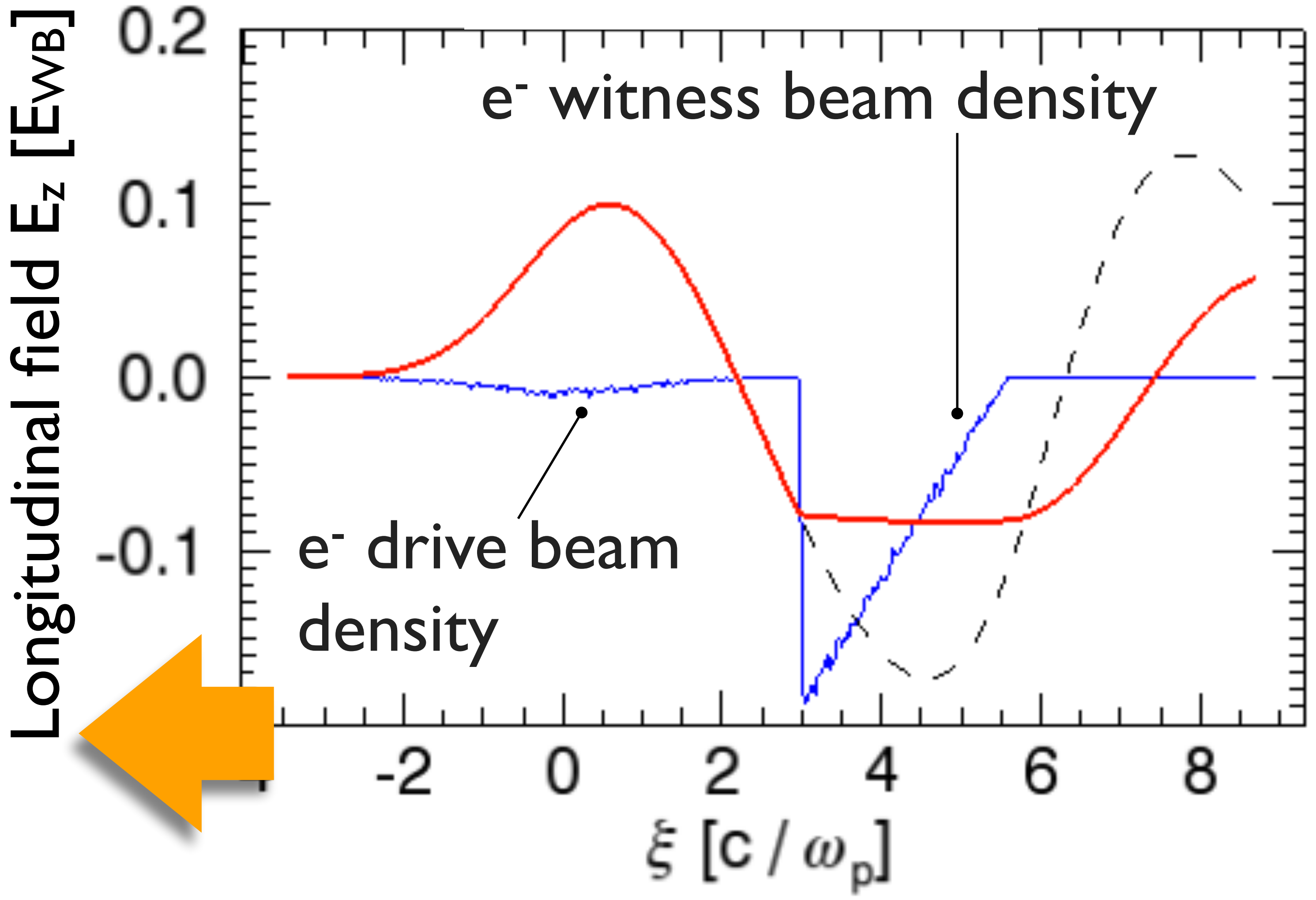
- $e^+$ drive beam wakefield
- $e^-$ structure wakefield
- subtraction of both
- HC theory

Plasma: $n_0=10^{17}cm^{-3}$, rc = 40μm (2.4 $c/\omega_p$), $E_{WB}$=30GV/m

Beam: $N_b=6x10^9$, $\sigma_r$=10μm, $\sigma_z$=20μm, $I_b/I_A$=3.3, $n_b/n_0$=1.9

# Beam loading charge limit is lower for $e^+$ beam than for $e^-$ beam due to that structure

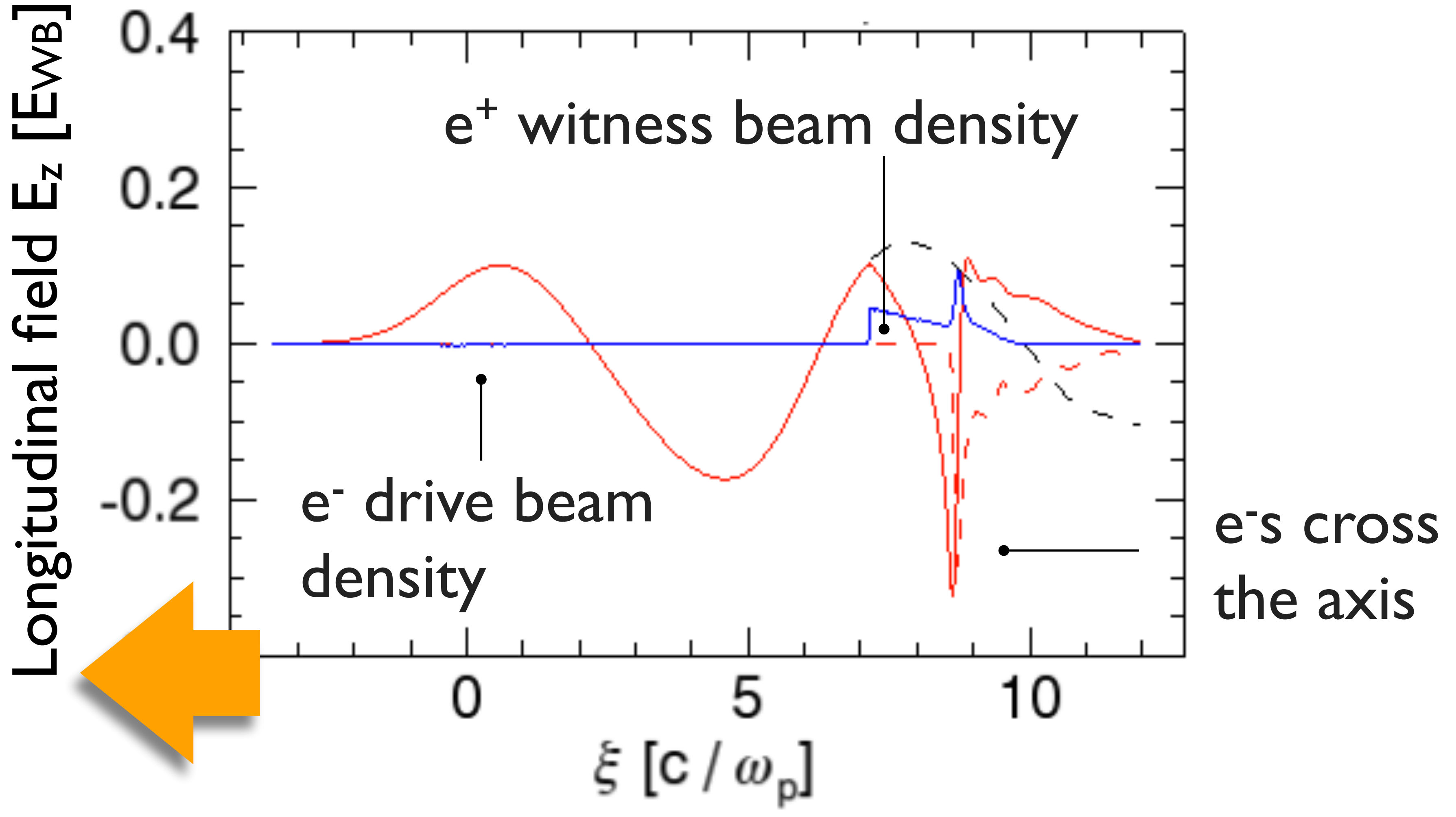
## Loading hollow channel wake with $e^-$ beam




Drive and trailing beams positions
Loaded Wakefield
Unloaded wakefield

➡ Loaded wake allows for uniform acceleration of witness beam

## Loading hollow channel wake with $e^+$ beam




Drive and trailing beams positions
Loaded Wakefield
Unloaded wakefield
Plasma electron density

➡ e+ witness beam already reaches non linear regime thus charge needs to be lowered

Plasma: $n_0=10^{17}cm^{-3}$, rc = 25µm (2.4 c/$\omega_p$), $E_{WB}$=30GV/m
Beam: $N_b=2.8\times10^9$, $\sigma_r$=20µm, $\sigma_z$=17µm, $I_b/I_A$=0.35, $n_b/n_0$=0.53
Witness: $N_b=1.4\times10^9$, $\sigma_r$=4.2µm, $L_z$=44µm, $I_b/I_A$=5.5, $n_b/n_0$=8.25

C.B.Schroeder et al., PoP **20**, 080701 (2013)

# Conclusions

**Hollow channel wakefield linear and non linear regime for $e^-$ and $e^+$ beams**

- Beam current and space charge, channel radius determine validity region for linear theory
- If beam space charge is enough for plasma e-s to cross the axis they will form nonlinear wakefields with different structure than those in uniform plasmas
- Non-linear regime is achieved for lower beam current for $e^+$ beams
- Such structure can be an interesting region for $e^+$ acceleration and beam loading

**In linear regimes wakefield asymmetries are of the order of beam asymmetries**

- Each beam azimuthal mode component excites the respective mode in the fields
- This is not the case for the non-linear regime
- In the non-linear regime m=1 beam asymmetries can excite m=0 as well as m=1 wakefield modes. This will modify the analysis of the beam breakup instability (hosing)

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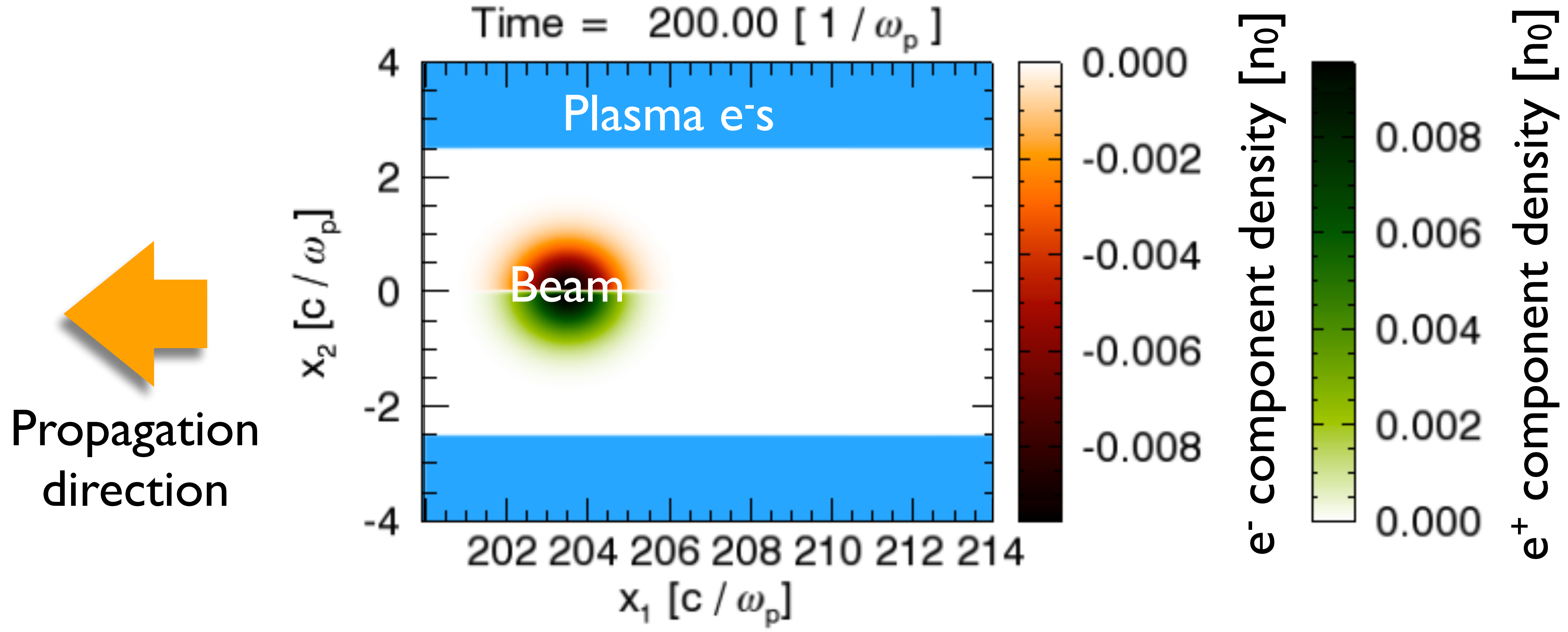
Thank you for your attention

# Realistic beam with more than 1 azimuthal mode can lead to transverse instabilities

## Non linear contribution of each beam azimuthal mode excited higher order modes

- In the linear regime a cylindrically symmetrical beam (mode 0) propagating in the in the hollow plasma channel will lead to the excitation of mode 0 fields
- Also in the linear regime a mode 1 beam (as in the plot below) will excite only mode 1 wakefields

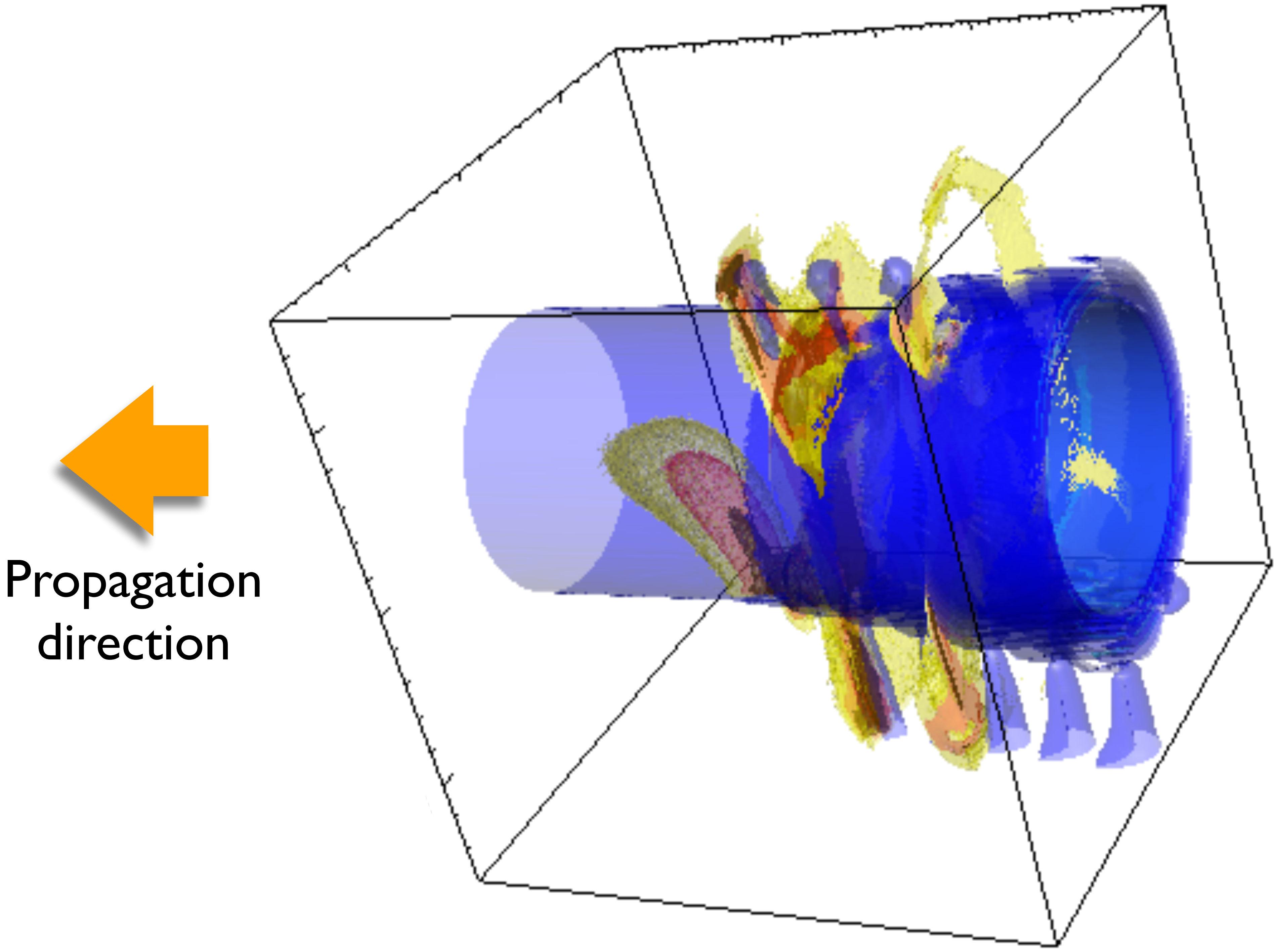



- In the non linear regime, however, a mode 0 and a mode 1 beam will lead to higher order wakefields in the channel (that can couple to transverse instabilities)
- In the homogeneous plasma a mode 1 beam will excite higher order modes also in the linear regime

# Beam break up instability in the linear hollow channel is main consearn

➡ Beam propagation in the hollow channel is prone to misalignments and asymmetries in both beam and plasma density profile (higher order modes)

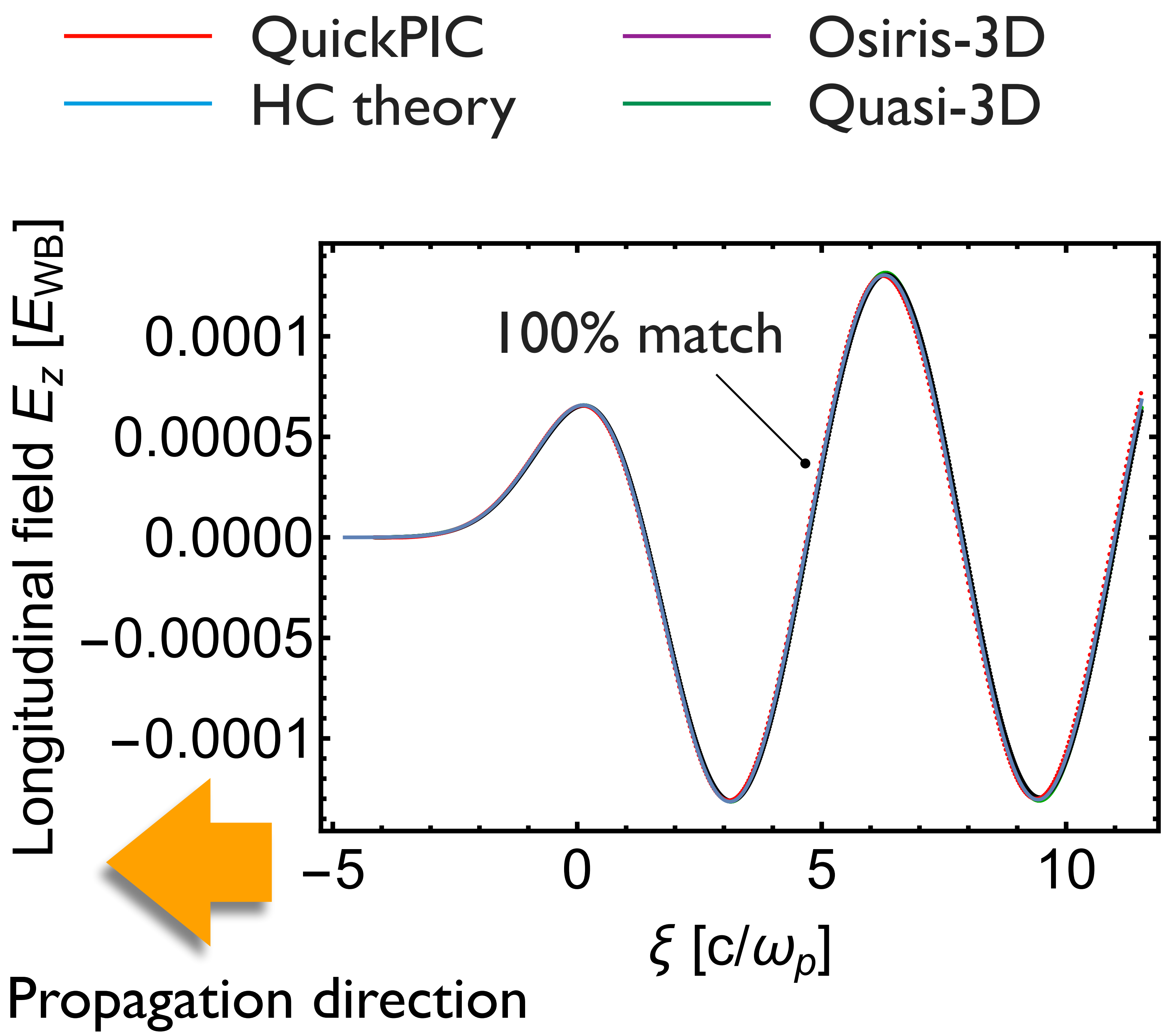
➡ We are interested in investigating the beam break up from the linear regime of the hollow channel to the non linear (where higher order wakefield modes will be excited)




[5]C. B.Schroeder et al., PRL **82,** 6 (1999)

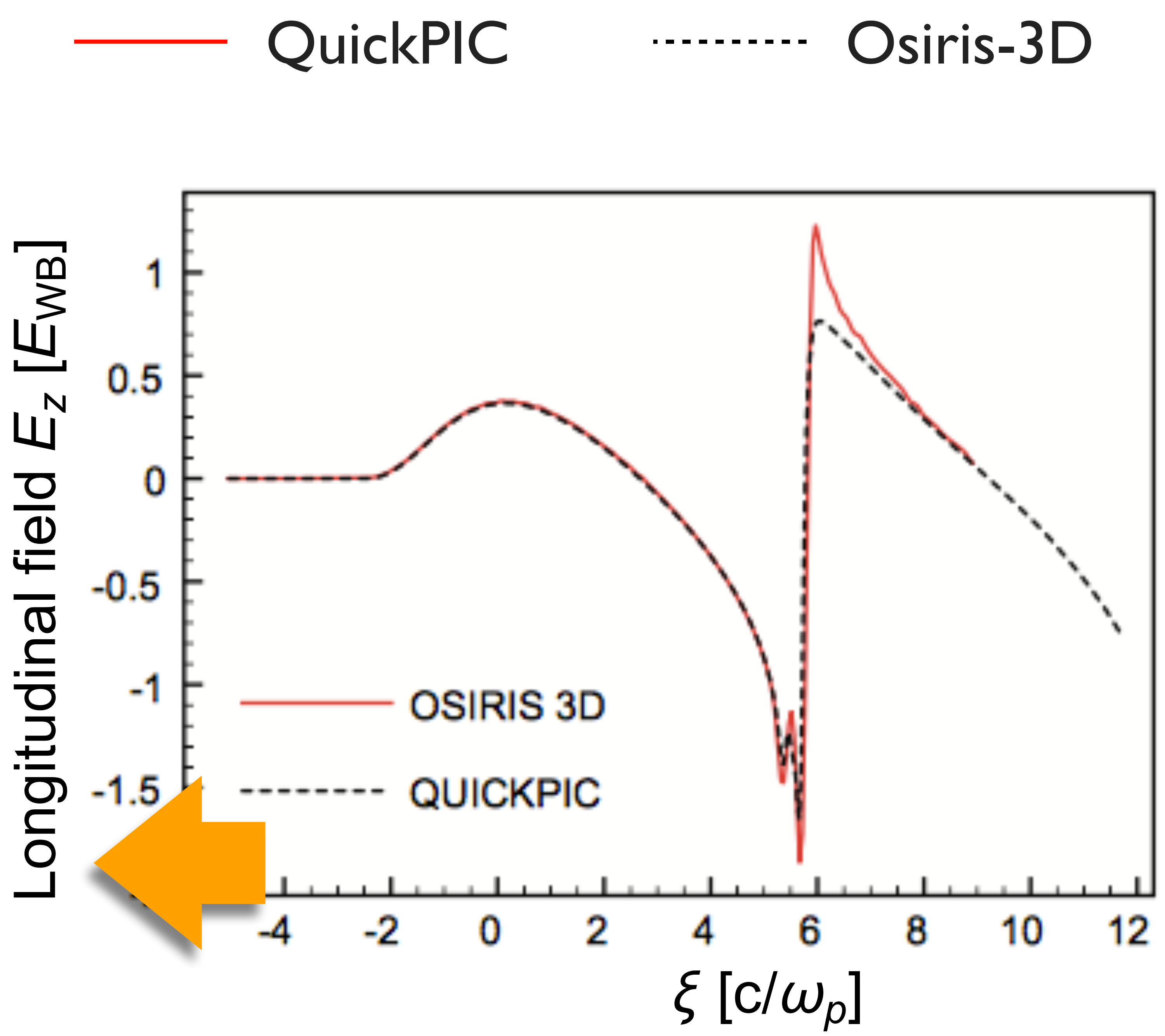
# QuickPIC and OSIRIS PIC codes agree even in the non linear blowout regime

## Linear homogeneous plasma field




➡ All codes agree perfectly with the linear theory for beam wakefield excitation in homogeneous plasmas

## Non-linear homogeneous plasma on-axis field




➡ Even in non linear blowout regime QuickPIC reproduces same results as Osiris

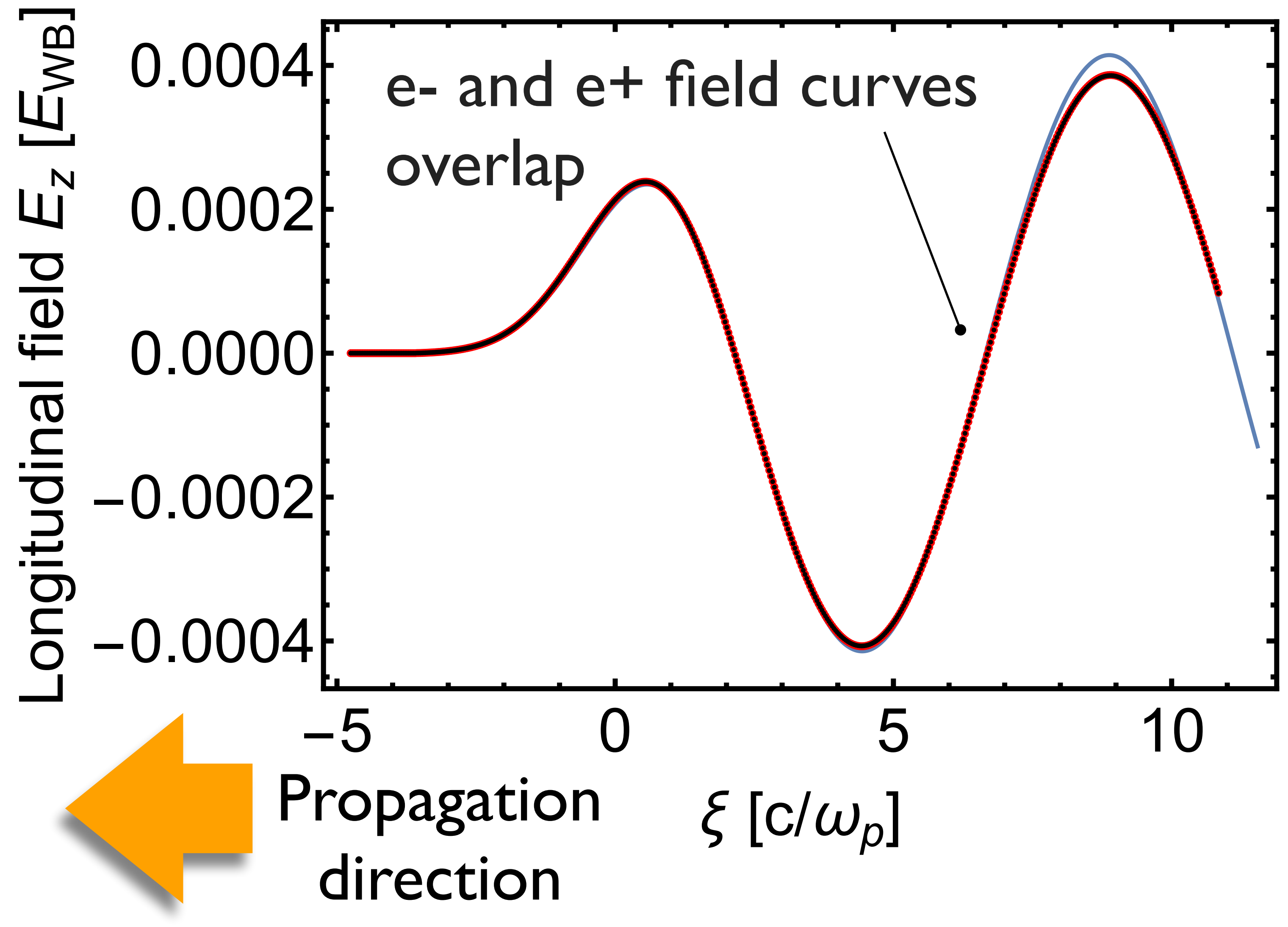

[1]W.An et al., JCP **250**, 156 (2013)
[2]C.Huang et al., JCP **217**, 658 (2006)


Plasma: $n_0=10^{17}cm^{-3}$, rc = 40μm (2.4 c/$\omega_p$), $E_{WB}$=30GV/m
Beam: $N_b=10^7$, $\sigma_r$=10μm, $\sigma_z$=20μm, $I_b/I_A$=0.0006, $n_b/n_0$=0.003

$\xi$ - co-moving longitudinal position

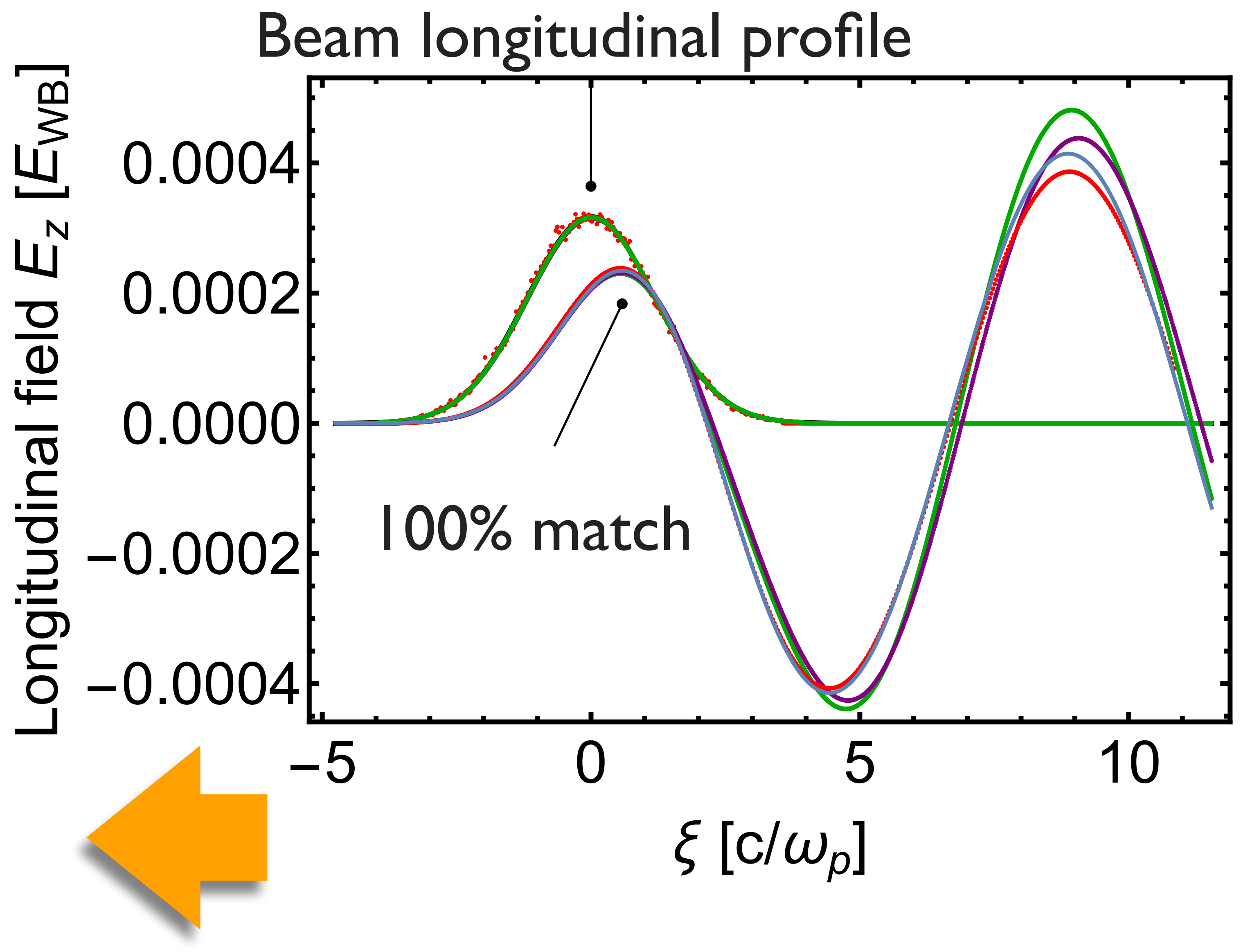
# Codes model accelerating hollow channel field in linear regime with errors <15%

## Linear hollow channel field for e⁻s and e⁺s




➡ As expected in the linear regime the field only has a phase difference for $e^-$ and $e^+$ beams

## Linear hollow channel field for all codes



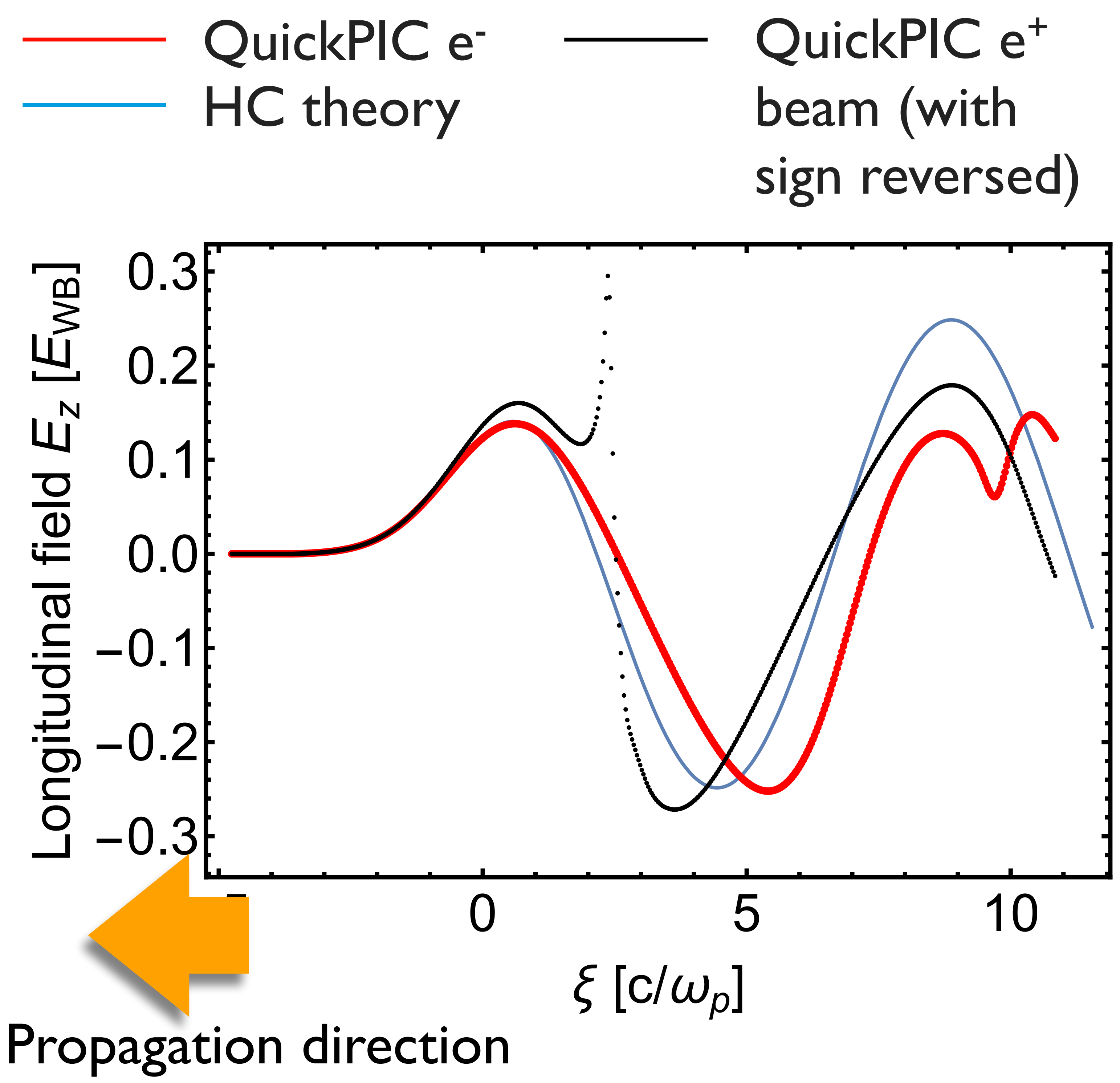

➡ Quasi-3D code version of Osiris produces similar results to the other codes and theory (up to 15%)

Plasma: $n_0=10^{17}$cm$^{-3}$, rc = 40μm (2.4 c/$\omega_p$), $E_{WB}$=30GV/m

Beam: $N_b=10^7$, $\sigma_r$=10μm, $\sigma_z$=20μm, $I_b/I_A$=0.0006, $n_b/n_0$=0.003

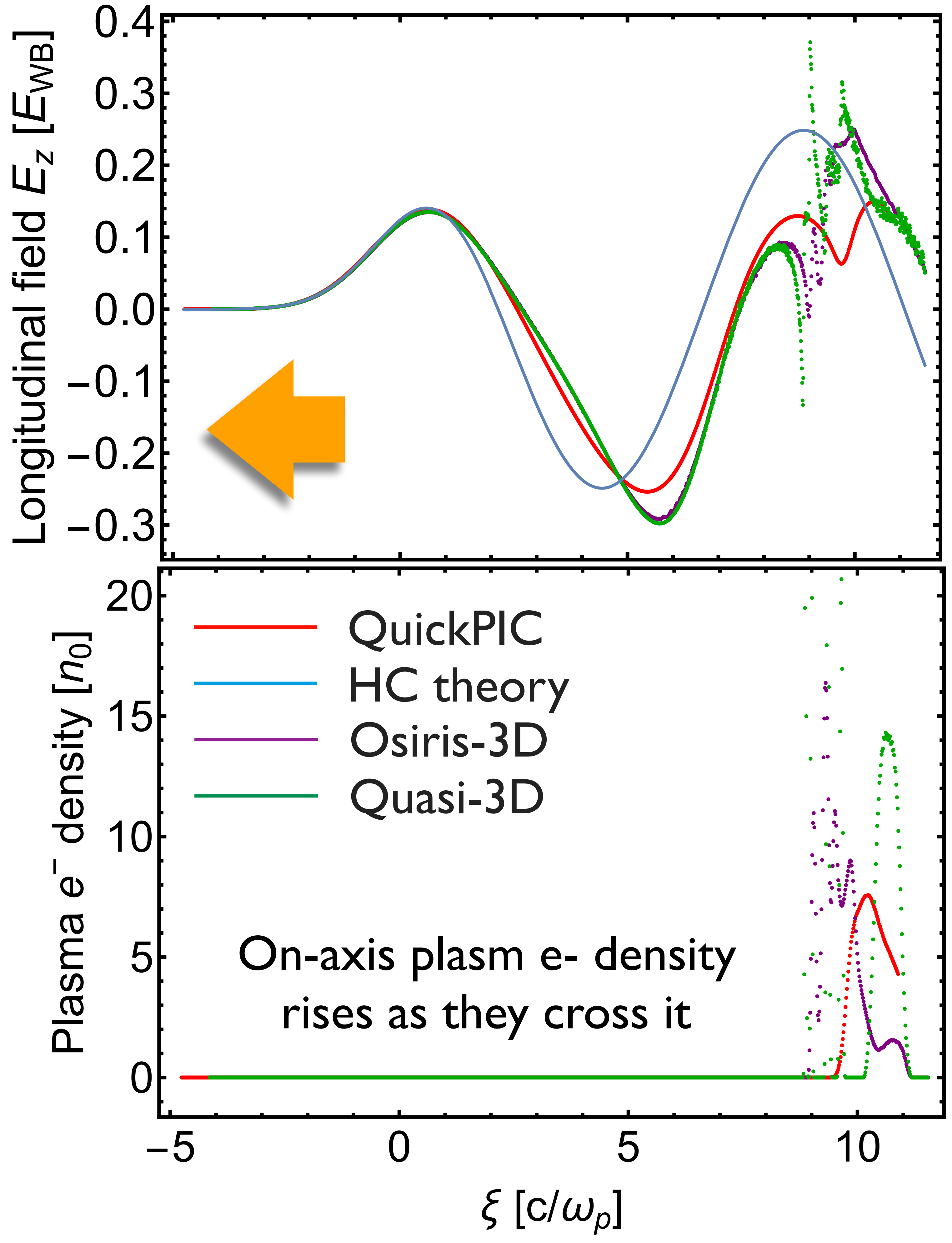
# Non linear $e^-$ and $e^+$ driven wakefields differ in both amplitude and wavelength

## Non-linear hollow channel field for $e^-$s and $e^+$s




➡ The peak field amplitude is similar but the wavelength differs significantly for $e^-$ and $e^+$ drive beams

## QuickPIC yield different results from Osiris




➡ Codes no longer agree with linear theory

Plasma: $n_0=10^{17}\text{cm}^{-3}$, rc = 40μm (2.4 c/$\omega_p$), $E_{WB}$=30GV/m

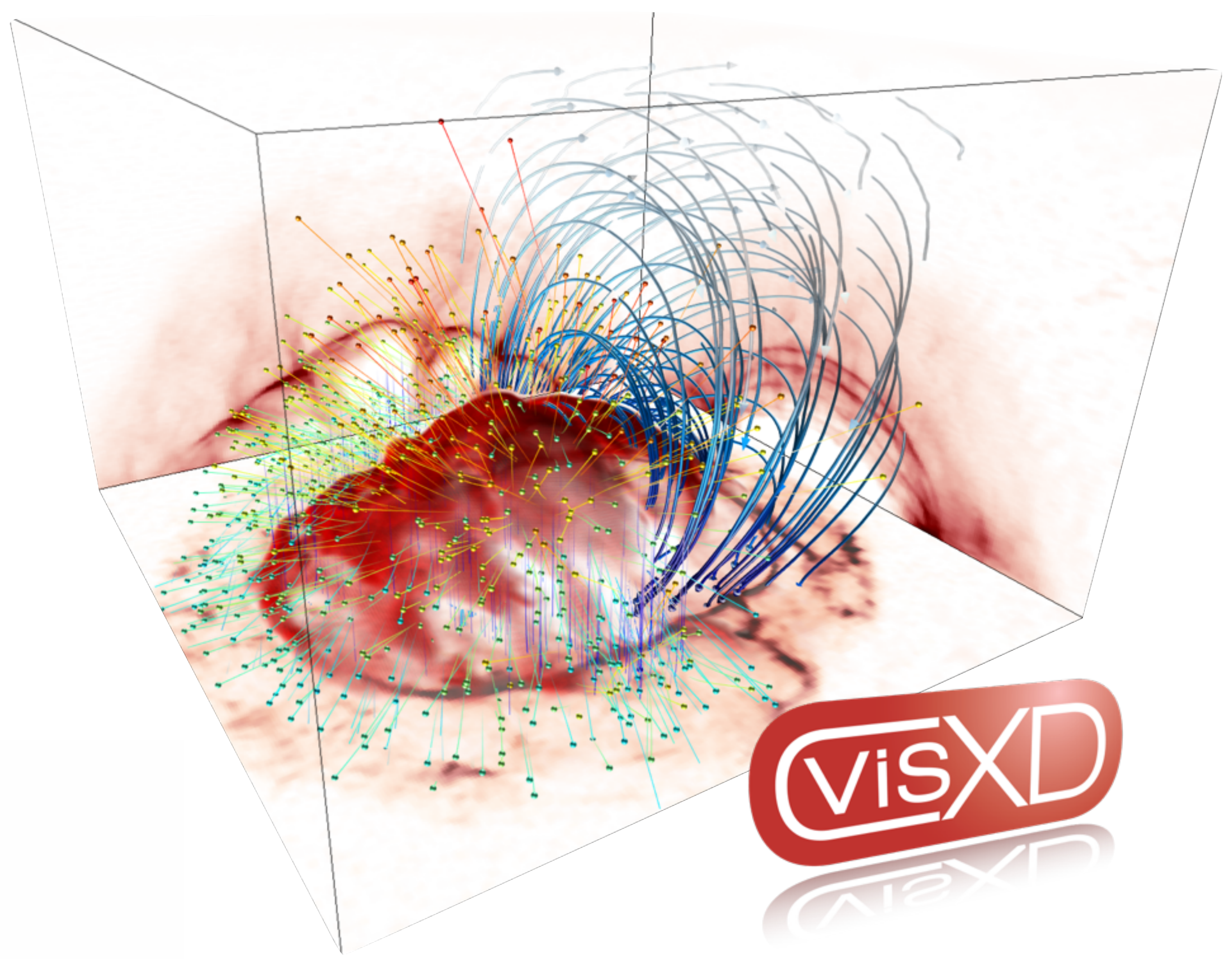
Beam: $N_b=6\times10^9$, $\sigma r$=10μm, $\sigma_z$=20μm, $I_b/I_A$=3.3, $n_b/n_0$=1.9

# Simulations were done using Osiris 3D and Quasi-3D (fields decomposed azimuthally)

**Osiris 3.0**

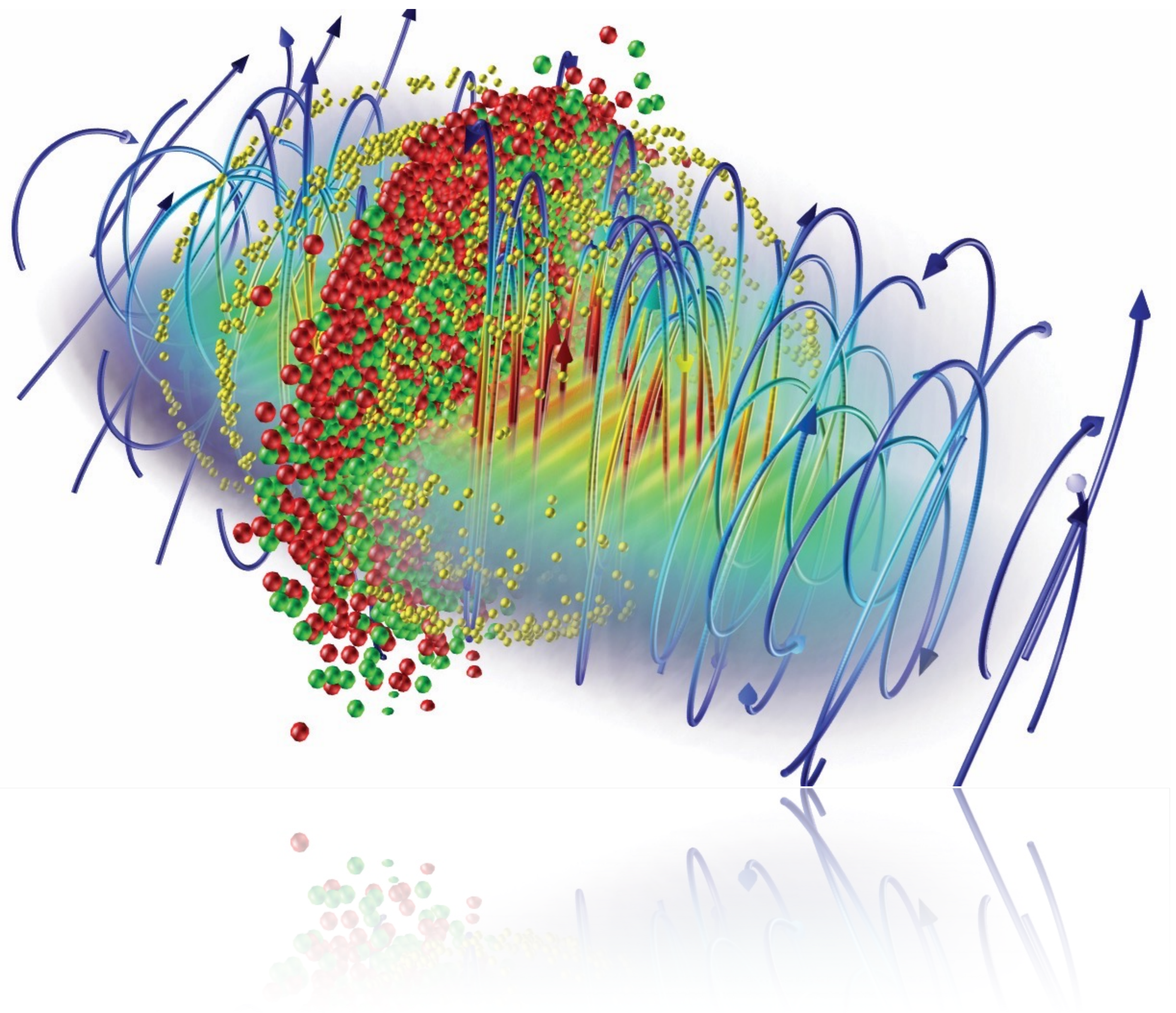
osiris framework

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




TÉCNICO LISBOA

UCLA



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
- **Quasi-3D**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# And with the QuickPIC numerical code

QuickPIC is a 3D parallel Quasi-Static PIC code, which is developed based on the framework UPIC.

Quasi-Static Approximation

(x, y, z; t)

↓

(x, y, ξ=ct-z, s=z)

↓

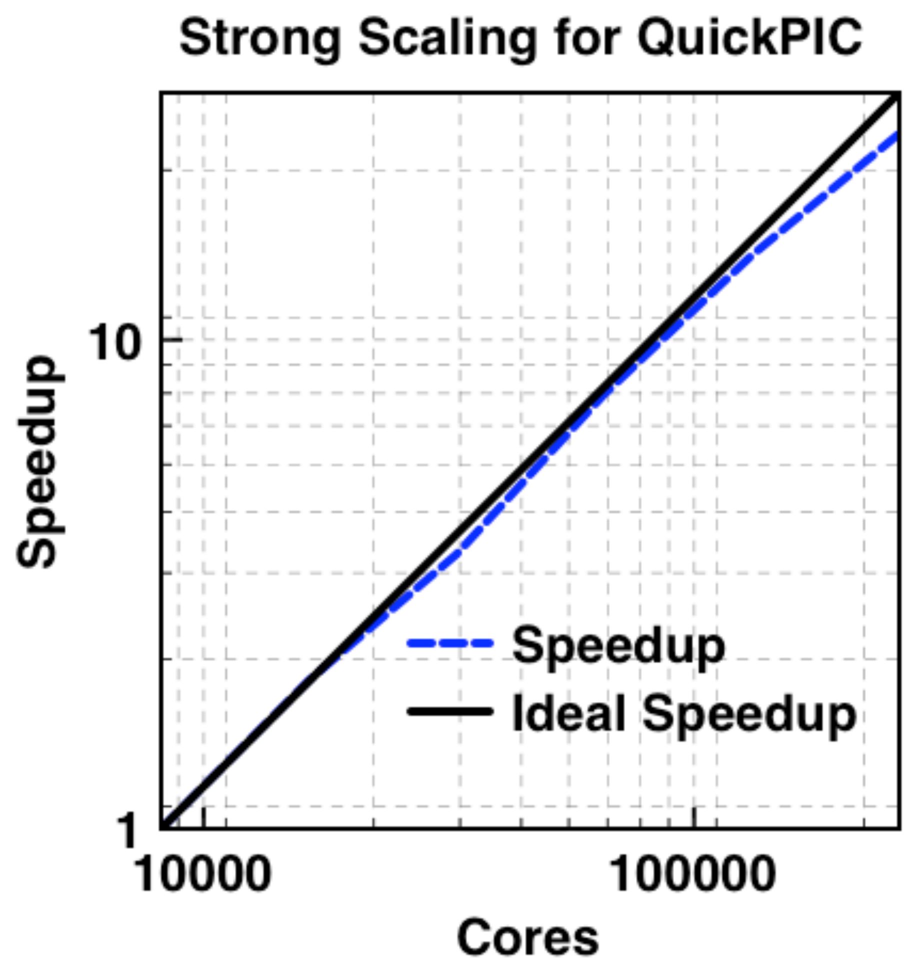
$\partial_s << \partial_\xi$

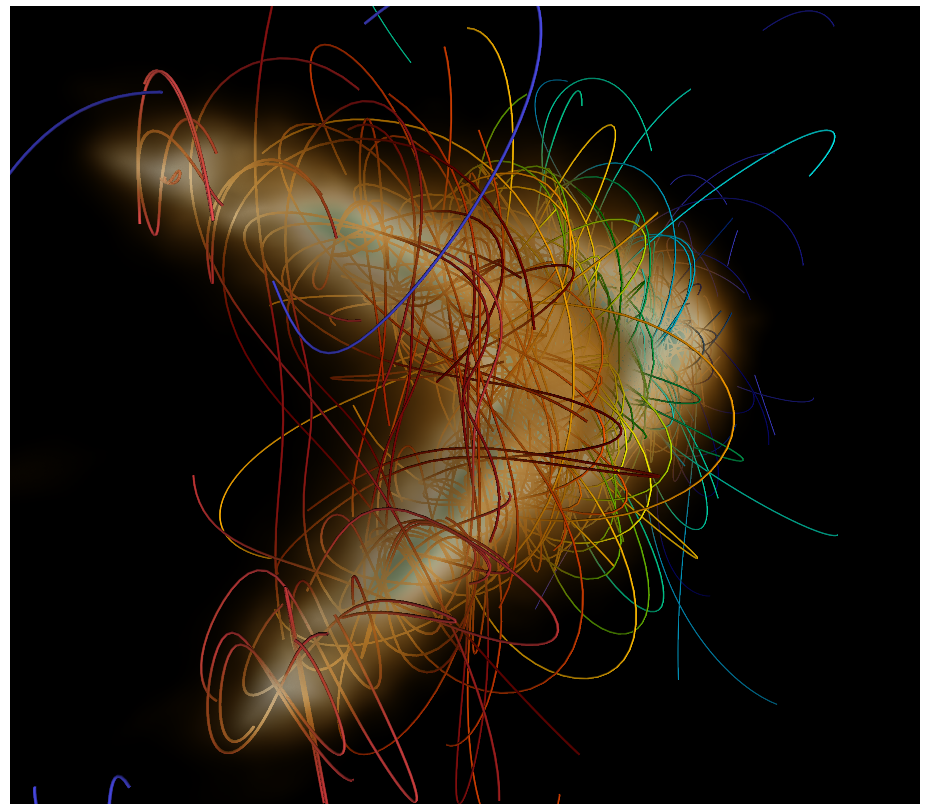
↓

Plasma: (x, y; ξ)

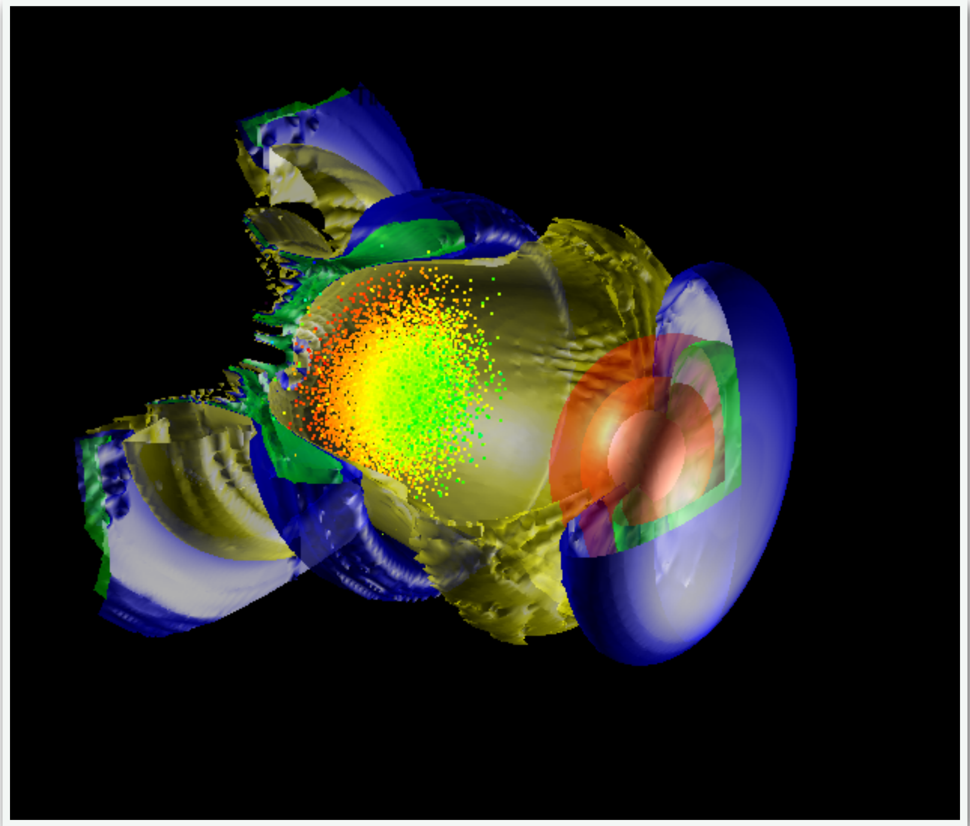
↓

Beam: (x, y, ξ, s)



QuickPIC simulation of positron-driven PWFA.



QuickPIC simulation of LWFA with a beam load


QuickPIC simulation of two-bunch electron-driven PWFA experiment at FACET shown on the Nature cover.