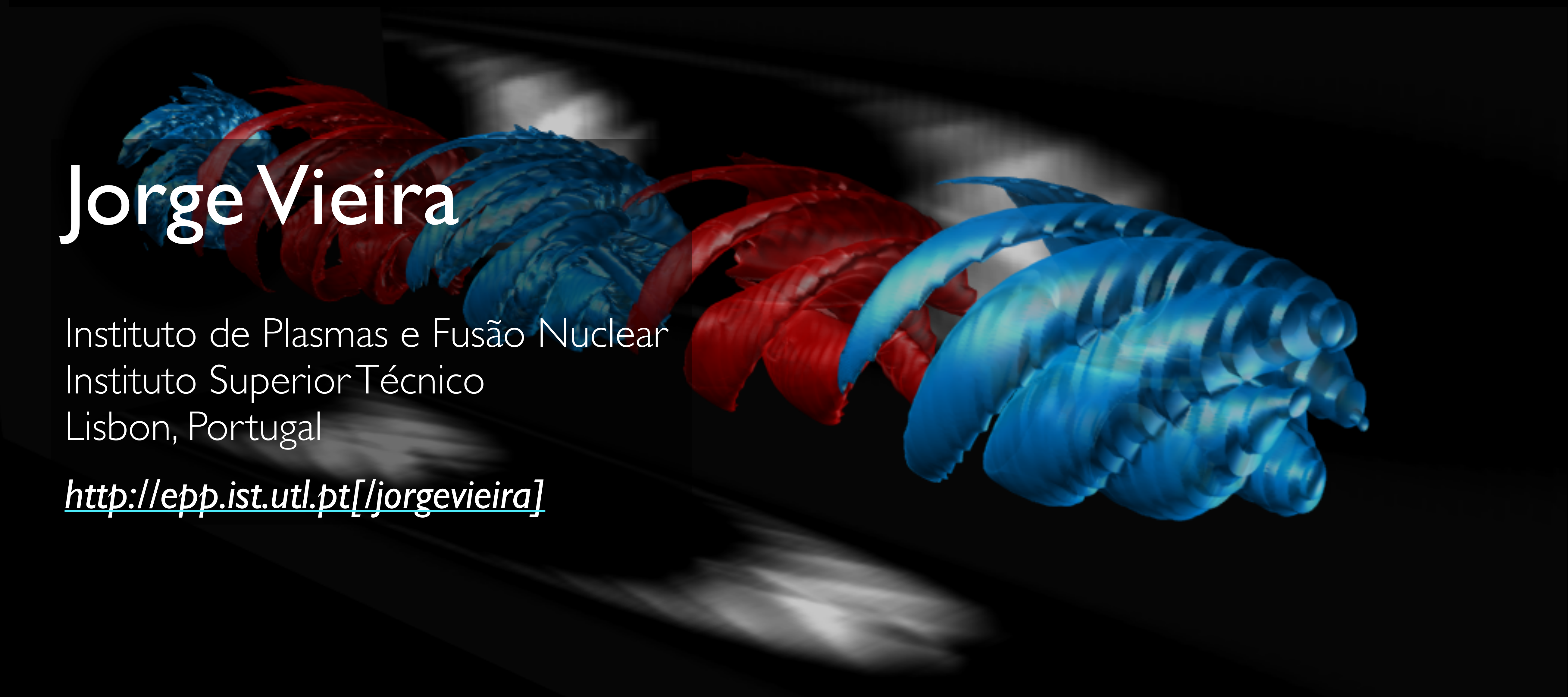
# High quality electron beams from plasma: overview of beam dynamics issues




## Jorge Vieira

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GoLP/IPFN Instituto Superior Técnico

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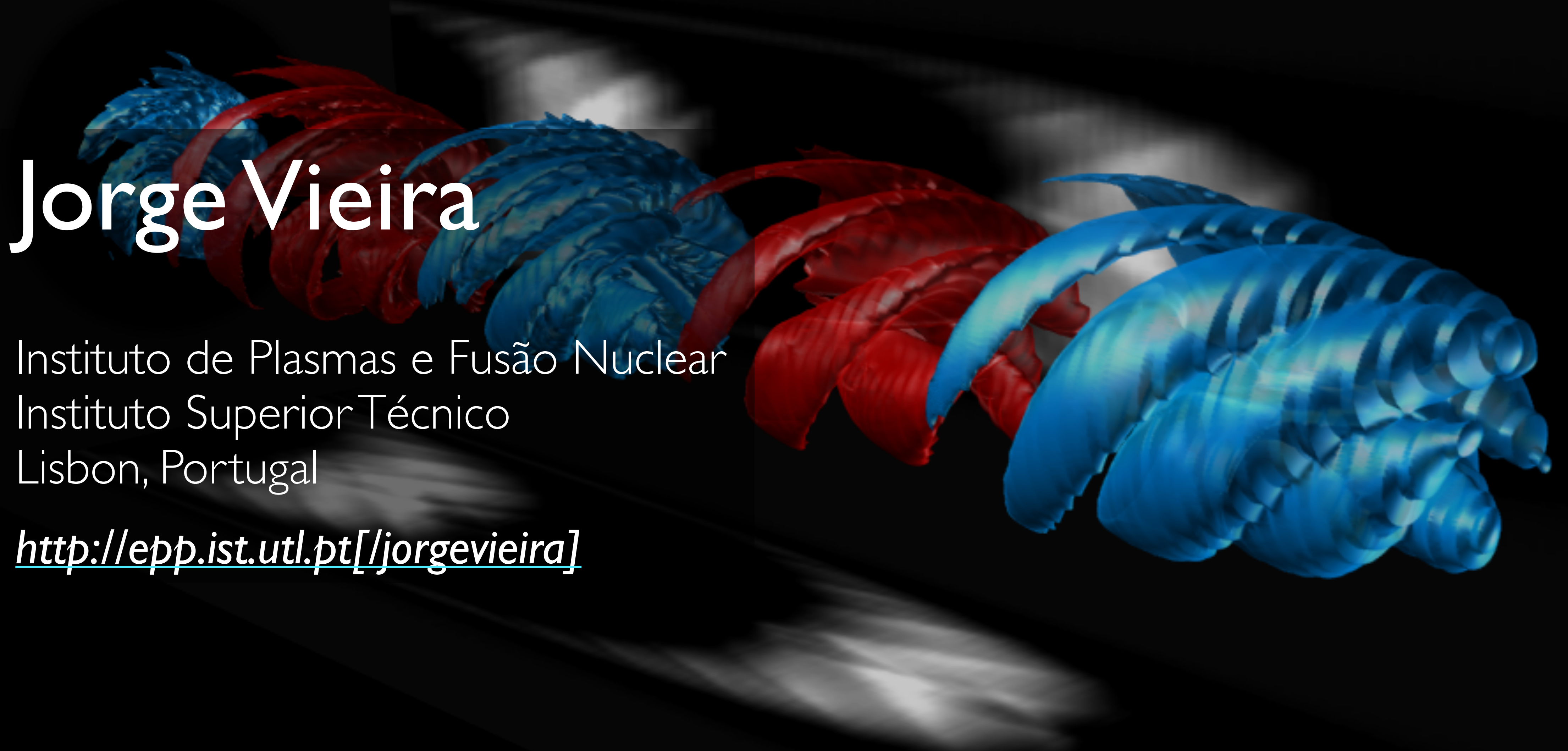


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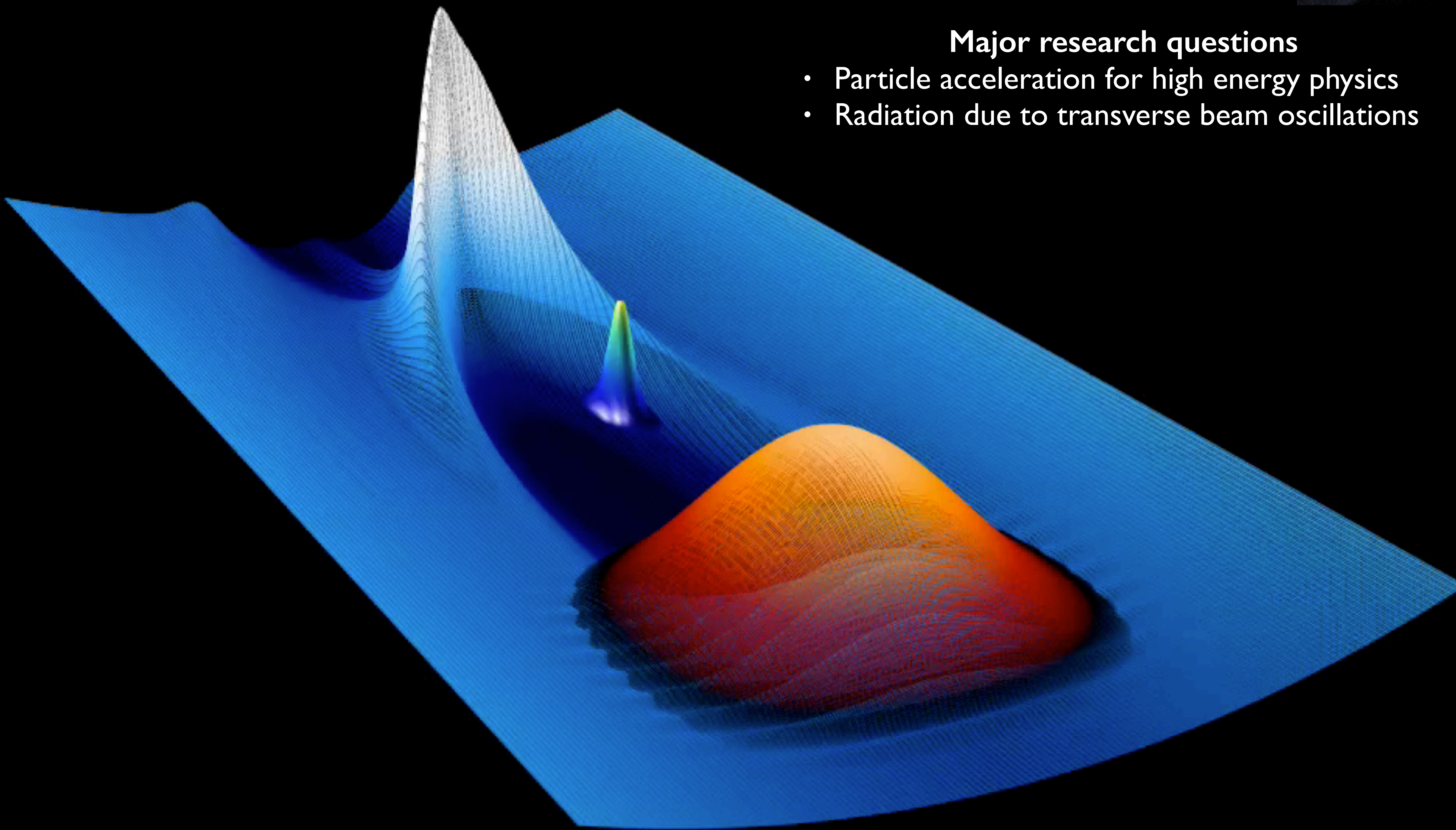
# Plasma accelerators for **High Energy Physics and radiation**

**Major research questions**

- Particle acceleration for high energy physics
- Radiation due to transverse beam oscillations

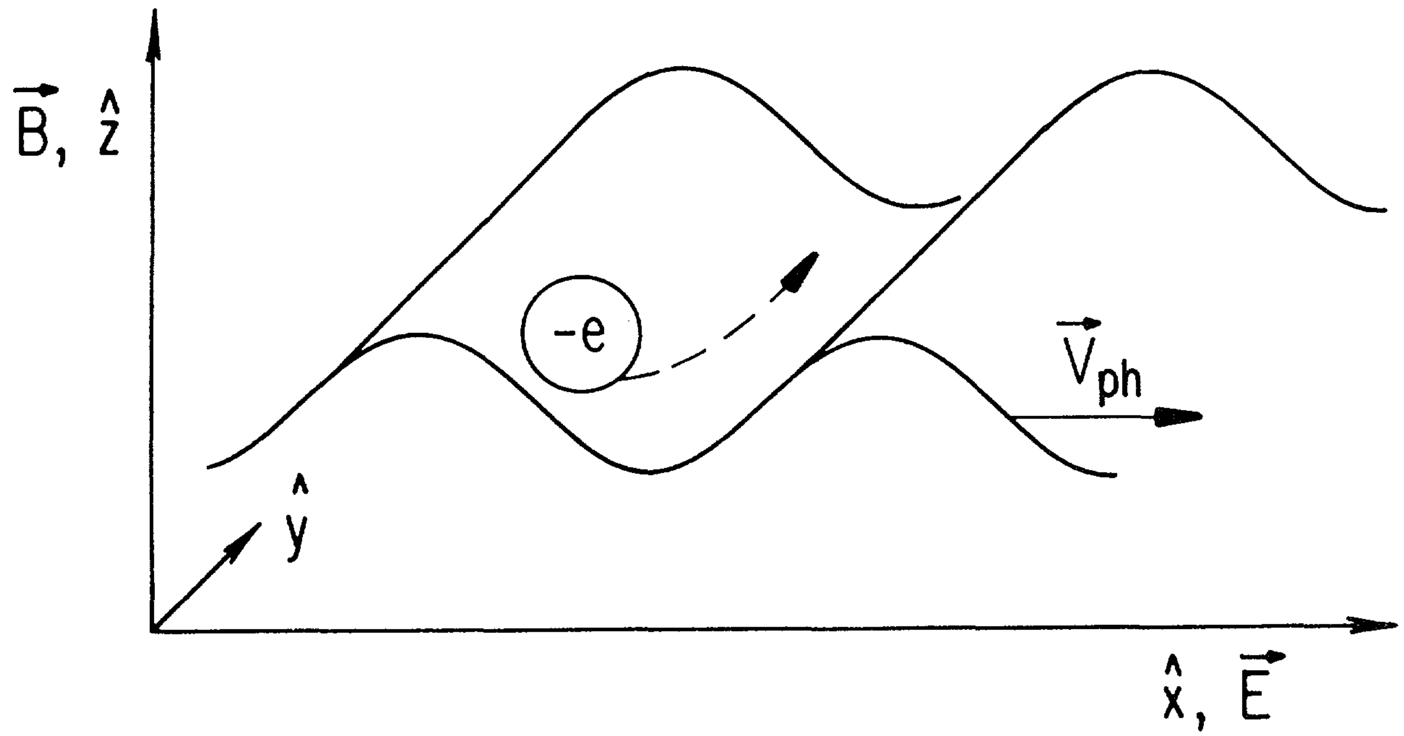


**Movie in a frame that travels at c**

# Magnetised plasma acceleration can be important in astrophysics

**Surfatron acceleration, Katsouleas and Dawson 1983**

unlimited acceleration of particles in the presence of a magnetic field



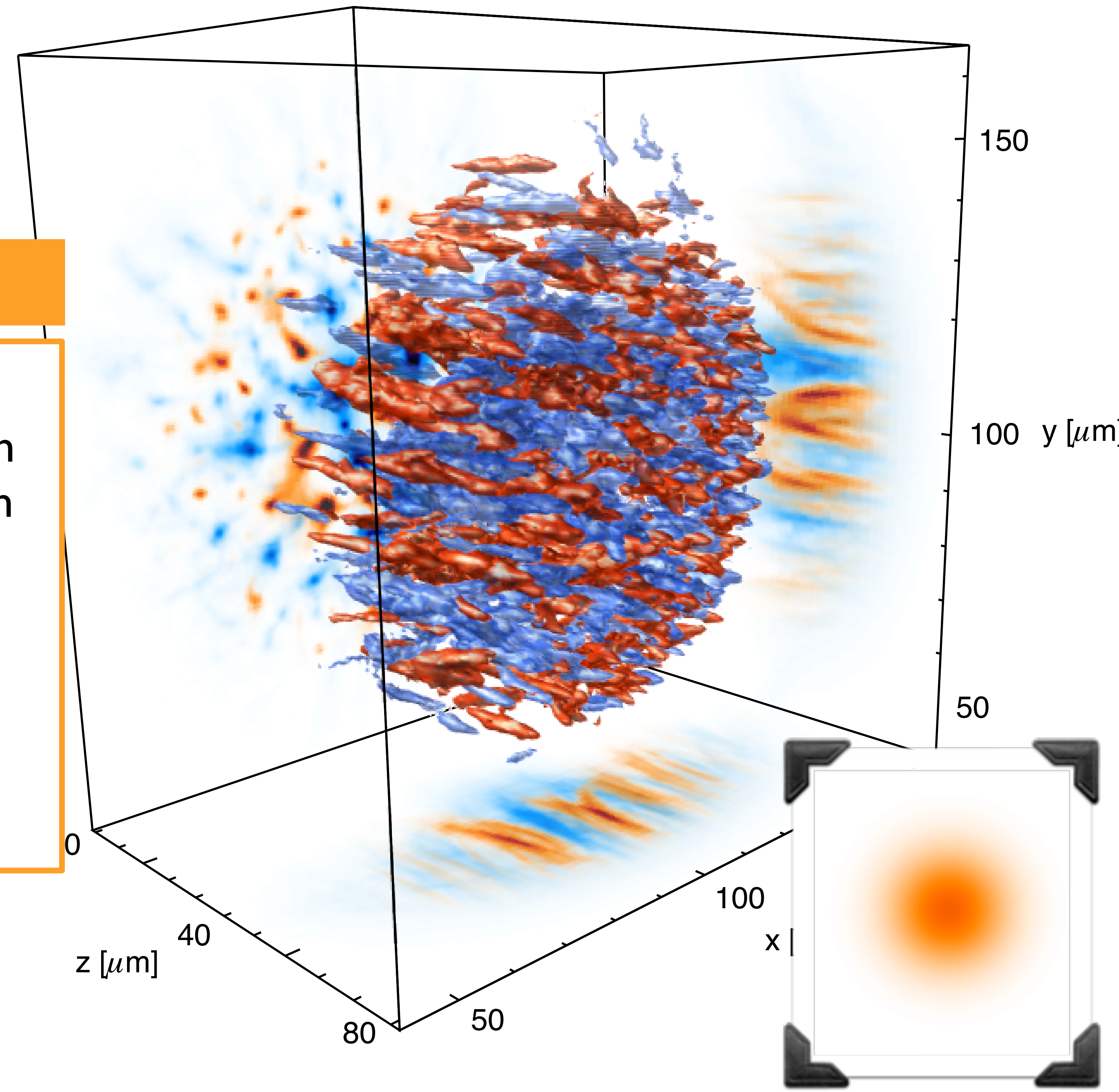

**Can provide a way to accelerate heavy particles like**

**protons or cosmic rays**

# Plasma accelerators for astrophysics in the lab

**Major questions/challenges**

- Magnetic fields can lead to radiation generation and particle acceleration in astrophysics
- Generation and amplification of magnetic fields
- Cosmic ray acceleration



# Puzzle on the origin of magnetic fields in astrophysics

**Faraday's Law**

**Electric field for massless electrons**

$$\mathbf{E} = \eta \mathbf{J} - \frac{\mathbf{v} \times \mathbf{B}}{c}$$

$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

Need magnetic fields to produce electric fields

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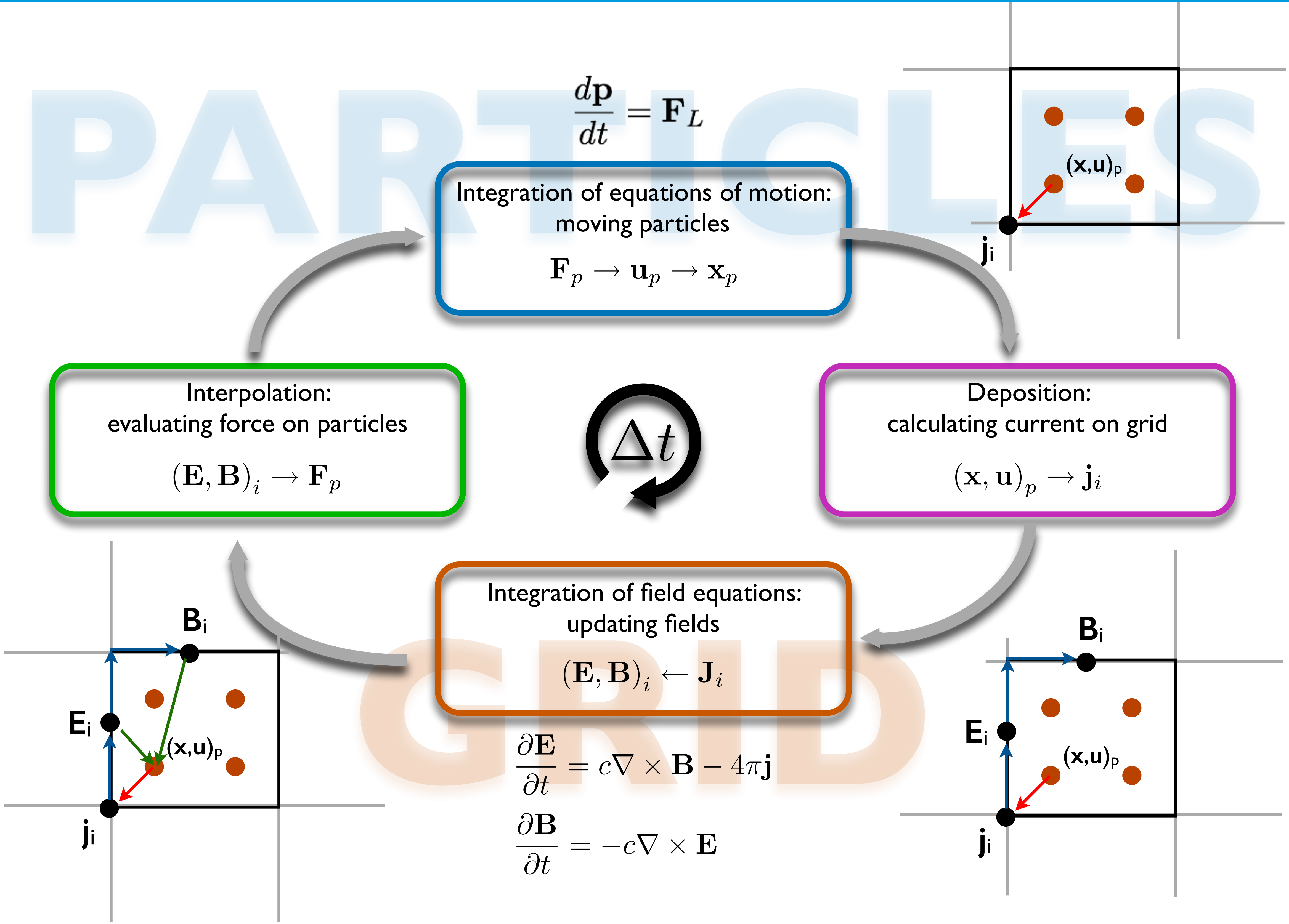
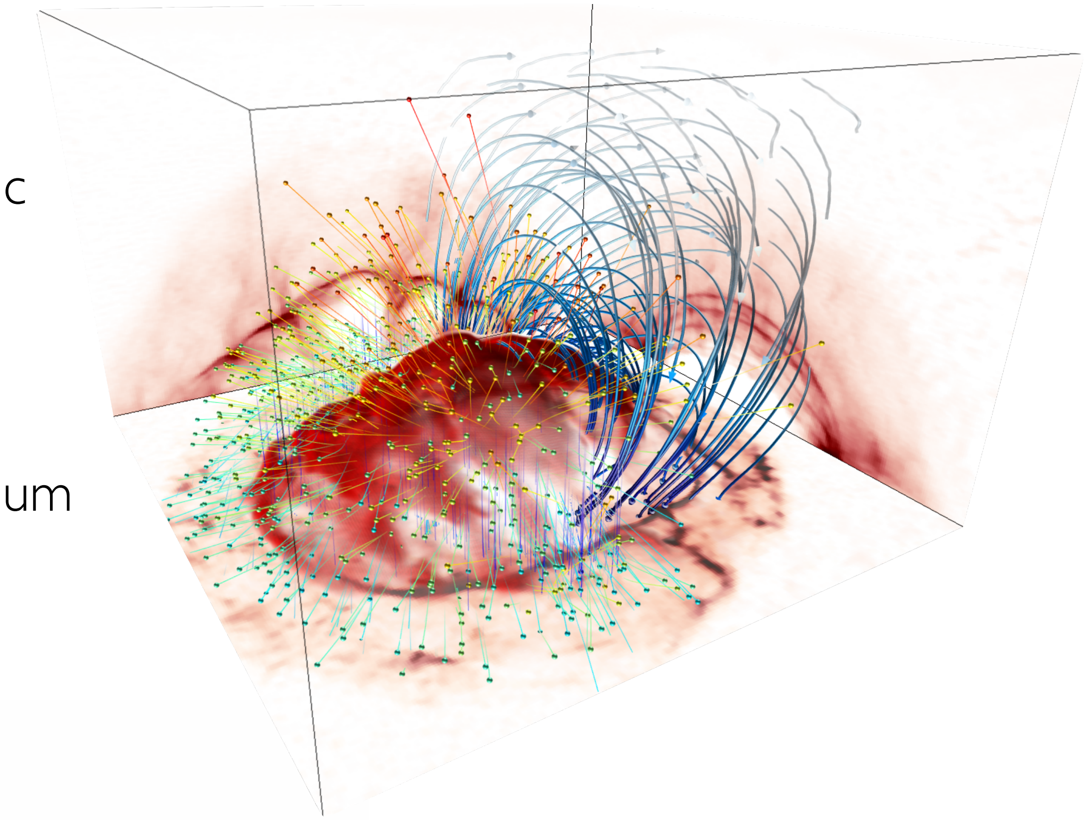
# To assist analytical modelling and experimental design in these topics we use particle-in-cell simulations



# OSIRIS 3.0

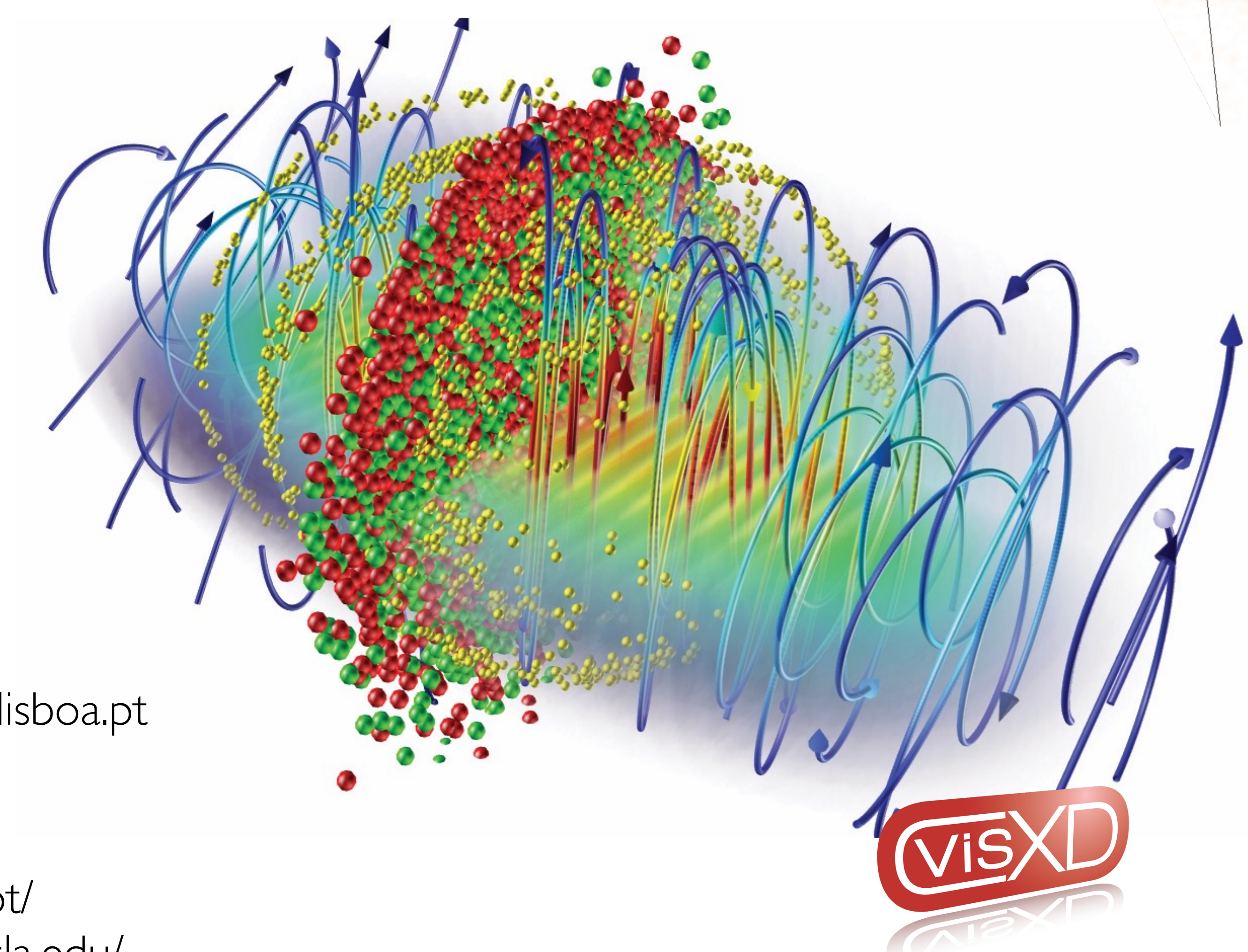
## osiris framework

- 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

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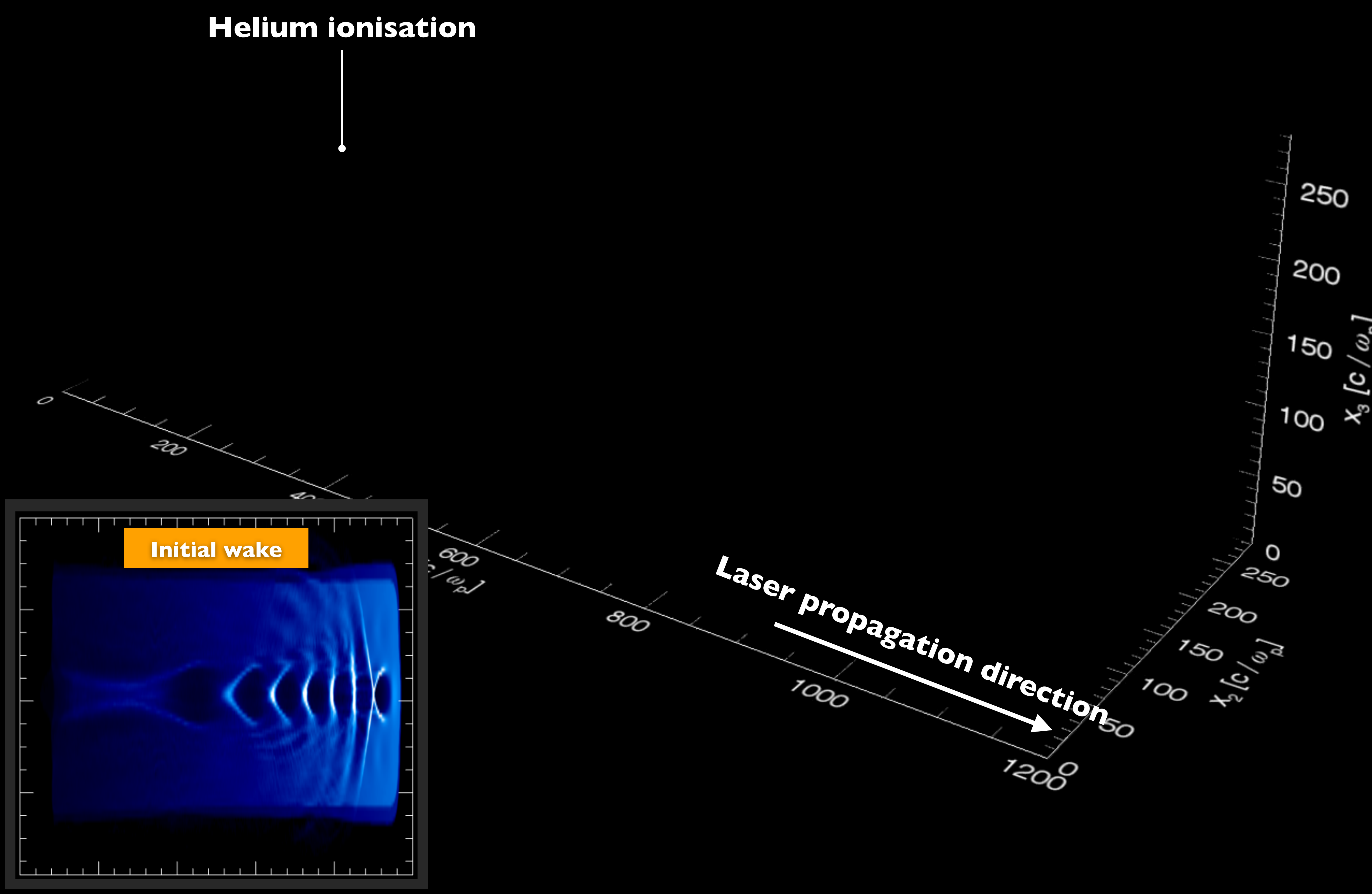
http://plasmasim.physics.ucla.edu/

# Full scale simulation of an entire >1 mm long gas jet without moving window

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



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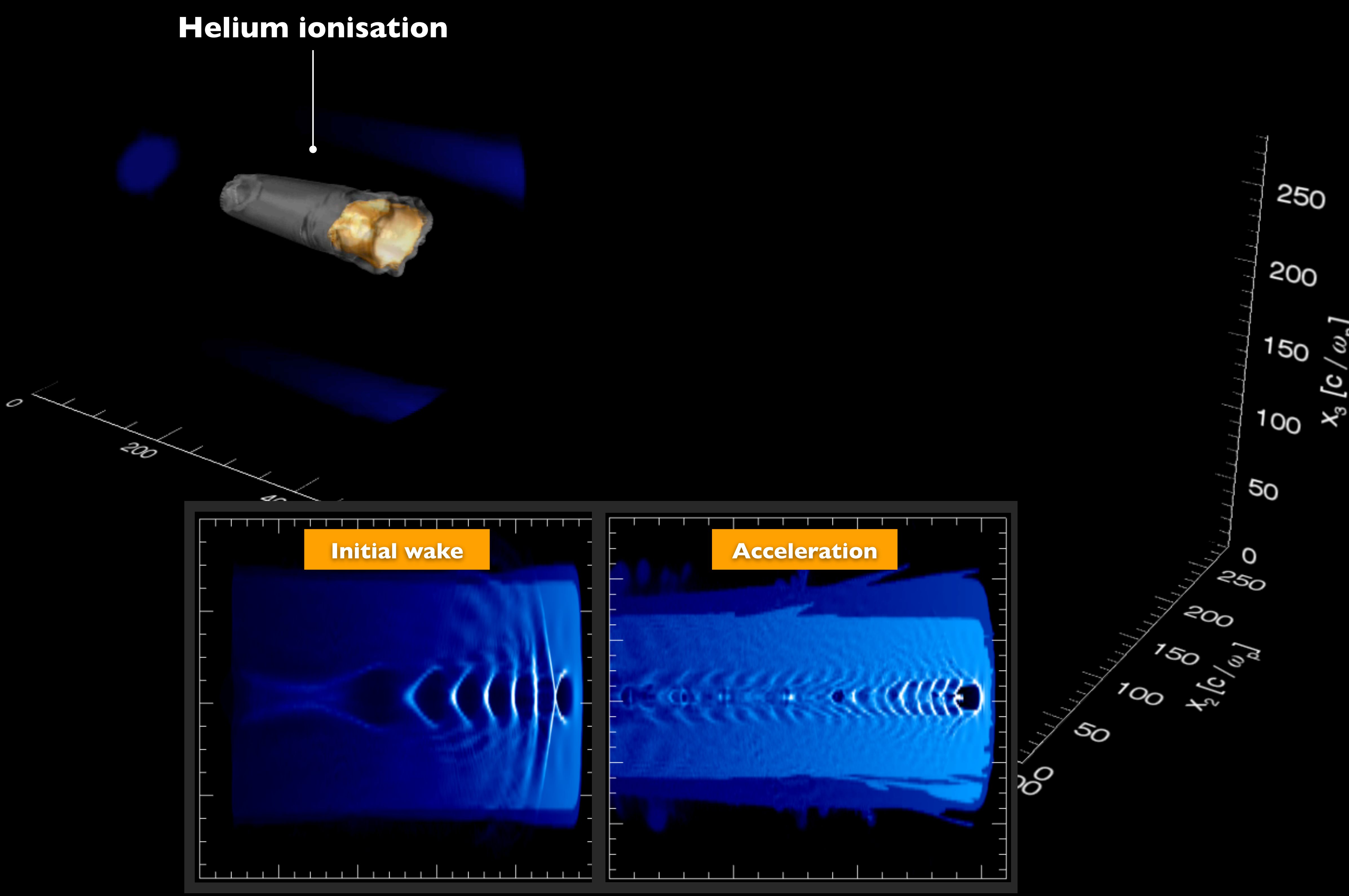
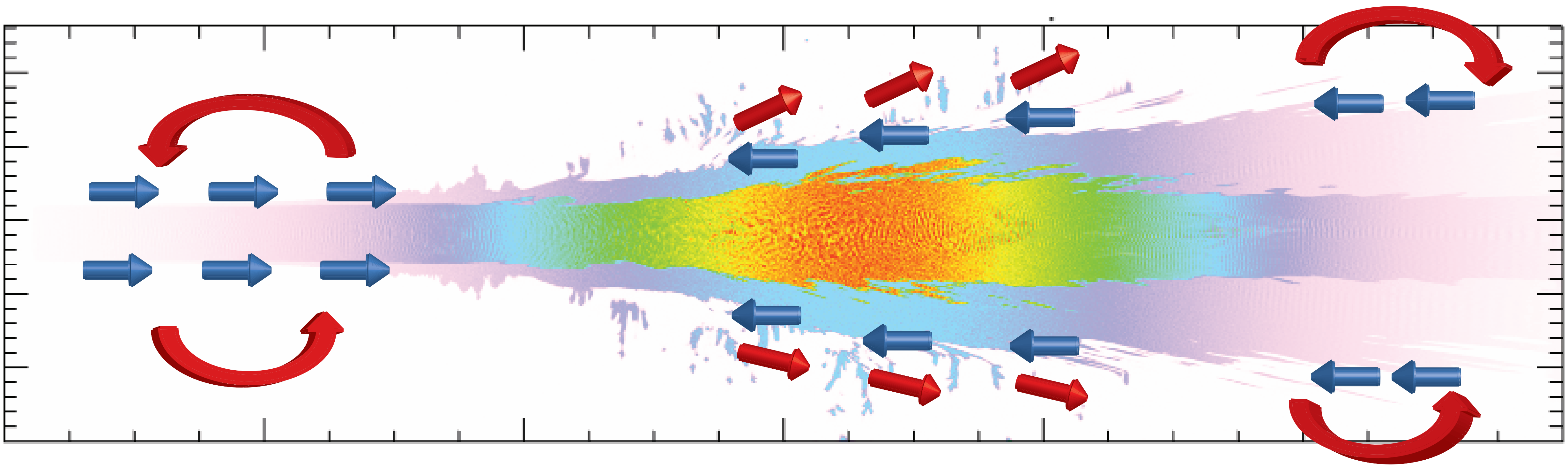


# Onset of magnetic field generation during wavebreaking/electron acceleration in a LWFA

**Plasma electron density map**

**shielding: no currents inside the plasma**

**Wave breaking: hot electrons stream out of the plasma**

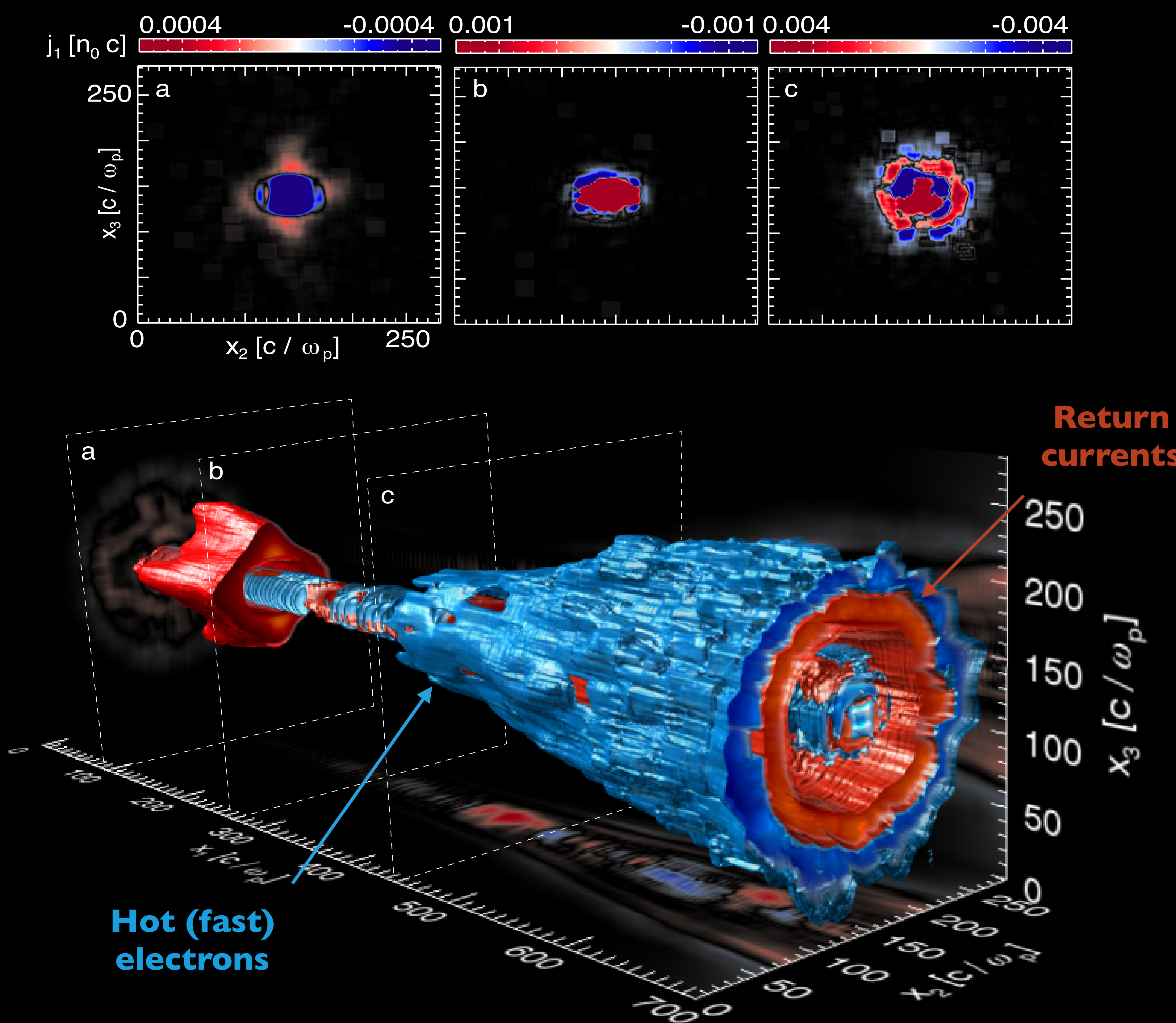


**Electron recirculation at plasma entrance/exit**

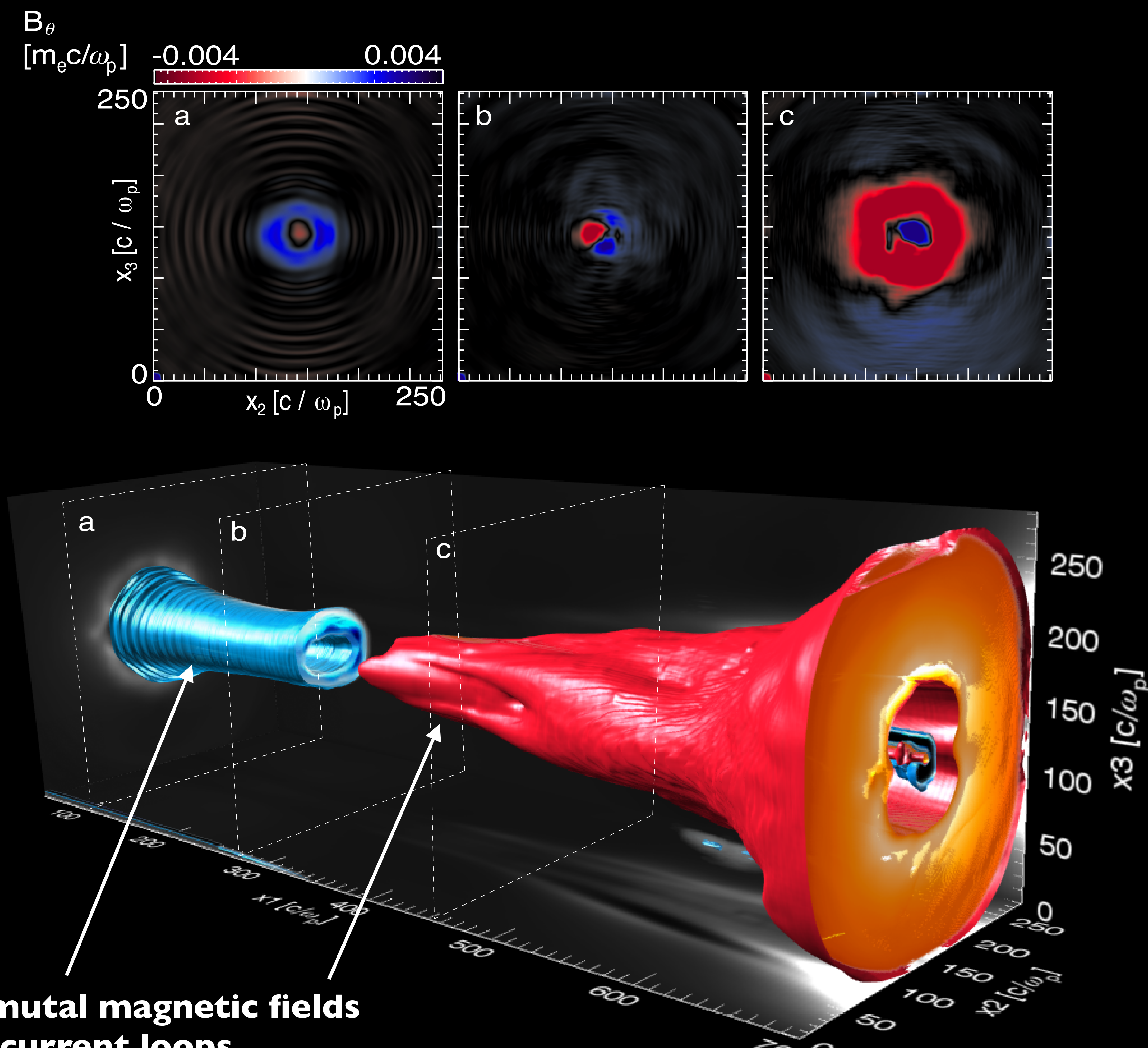
**Cold electron currents form at vacuum-plasma interface**

**Laser propagation direction**

# Current loops surrounding the plasma



# Currents loop driven by the expansion of hot electrons lead to azimutal large scale and persistent magnetic fields




**Direction of azimutal magnetic fields given by current loops**

# Scaling laws for the magnetic fields compatible with astrophysical scenarios

**B fields compatible with astro scenarios**

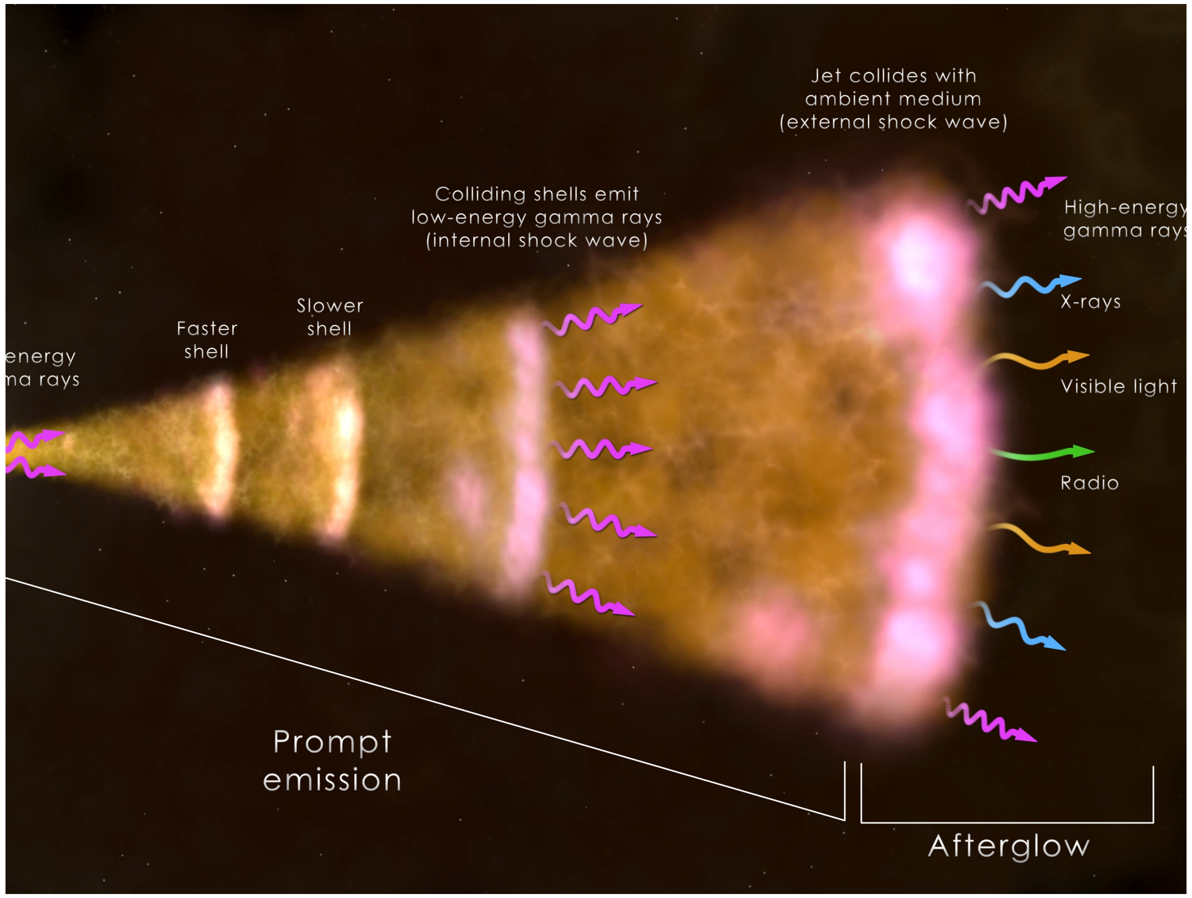
$$\mathbf{B}_\theta[\mathrm{nT}] \simeq 320\eta_{hot}\sqrt{n_0\ [\mathrm{cm}^{-3}]}$$

**Interstellar medium**

Wide range of densities
$n_0 \sim 10^{-2}$ - $1\,\mathrm{cm}^{-3}$, $\eta_{hot}$=0.01-1

**$B_\theta$~0.1-10 nT**

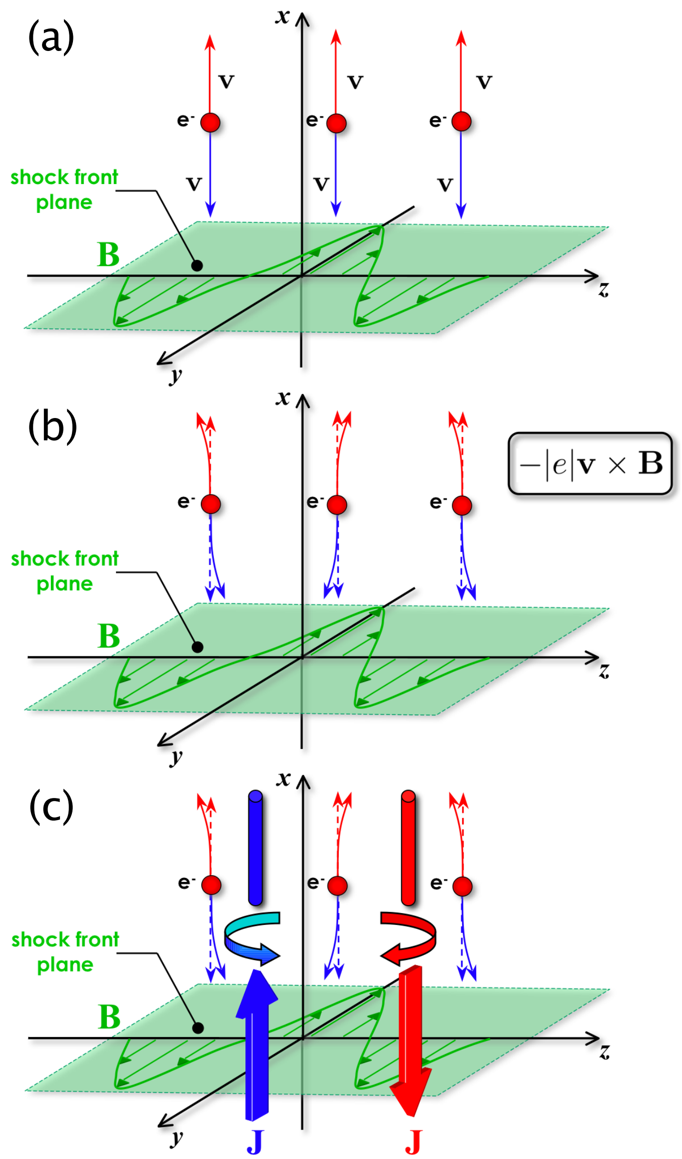
**B-field amplification**




http://regmedia.co.uk/2013/11/21/gamma_ray_burst_shell.jpg

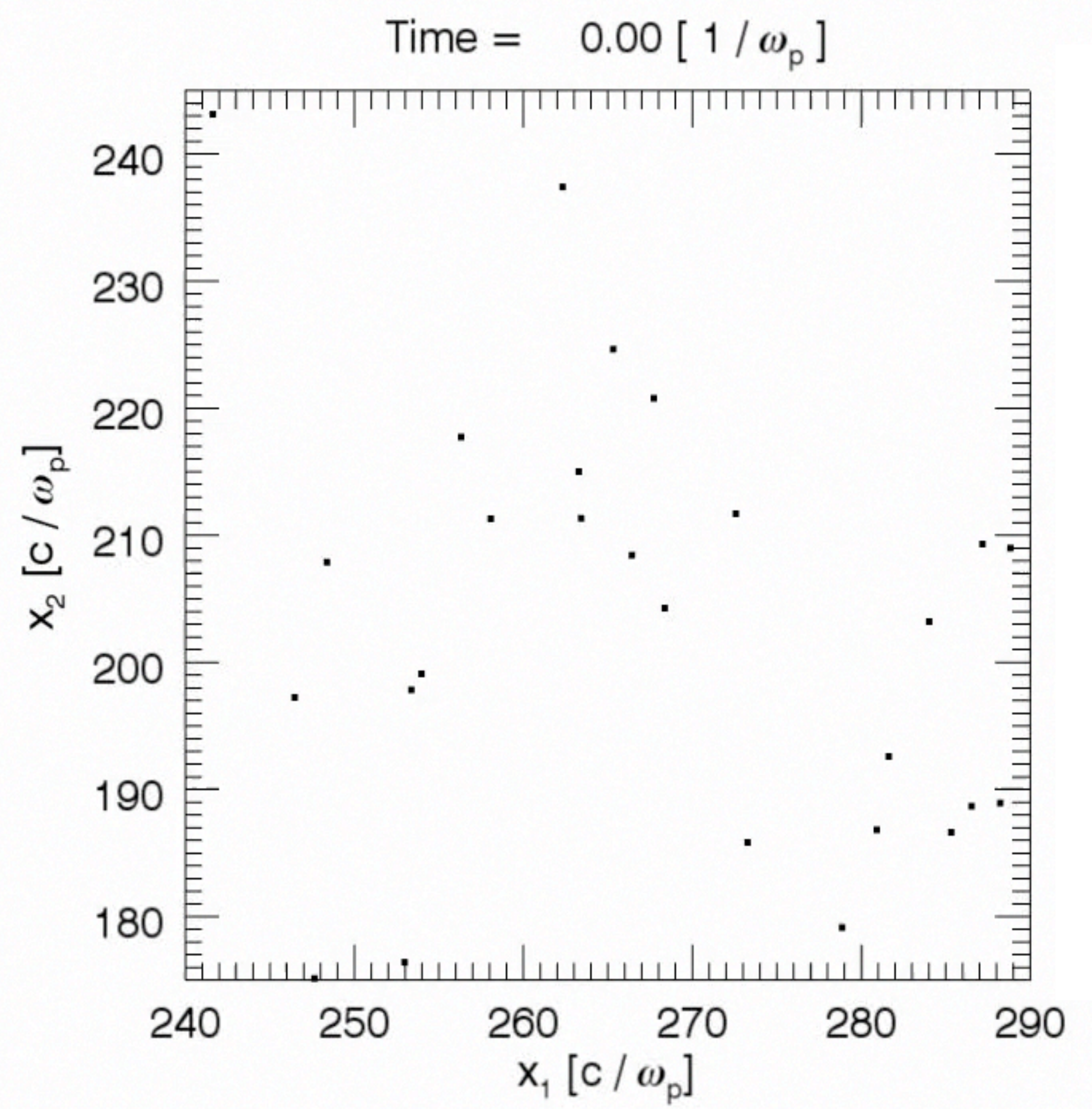
# Amplification of magnetic fields through the Weibel/Current filamentation instability

## Current filamentation instability




M. Fiore, PhD Thesis IST 2008

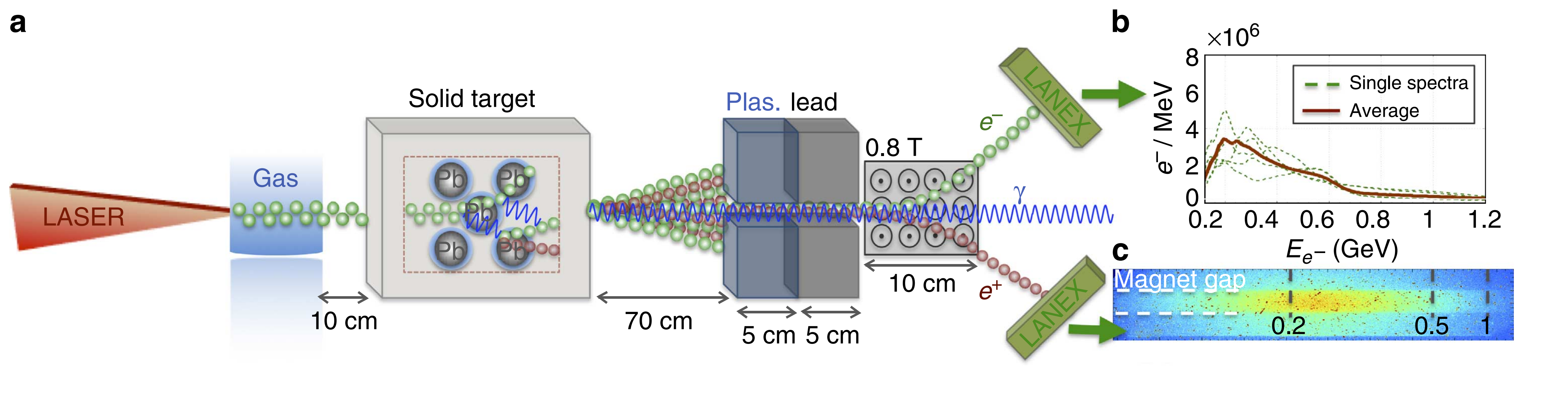
## Filament formation



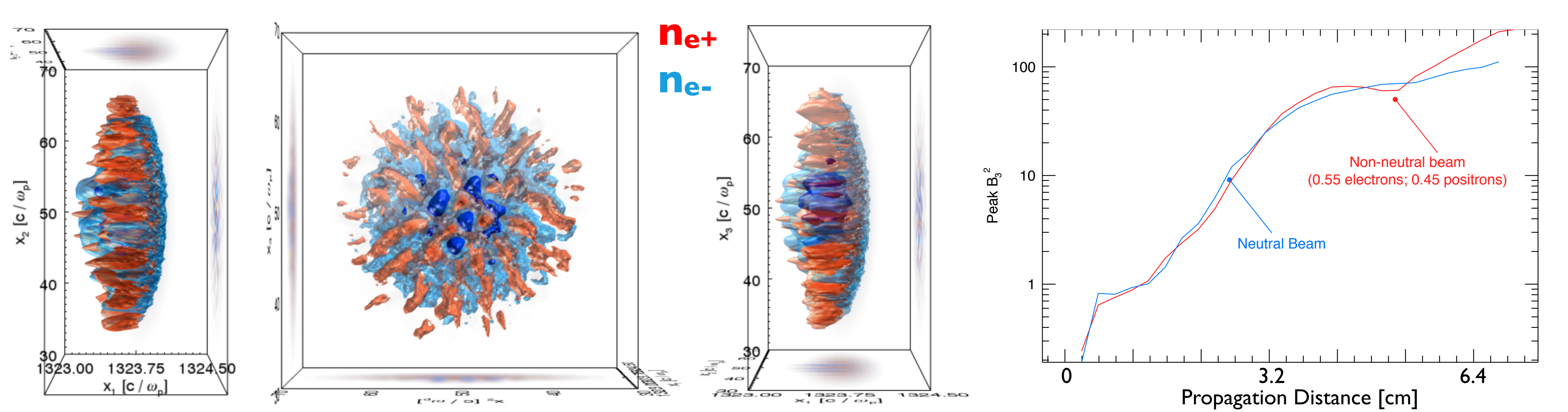

U. Sinha *et al.* (2016)

# Current filamentation instability in neutral fireballs could amplify seed magnetic fields

## Experiments demonstrated e-e+ fireball production



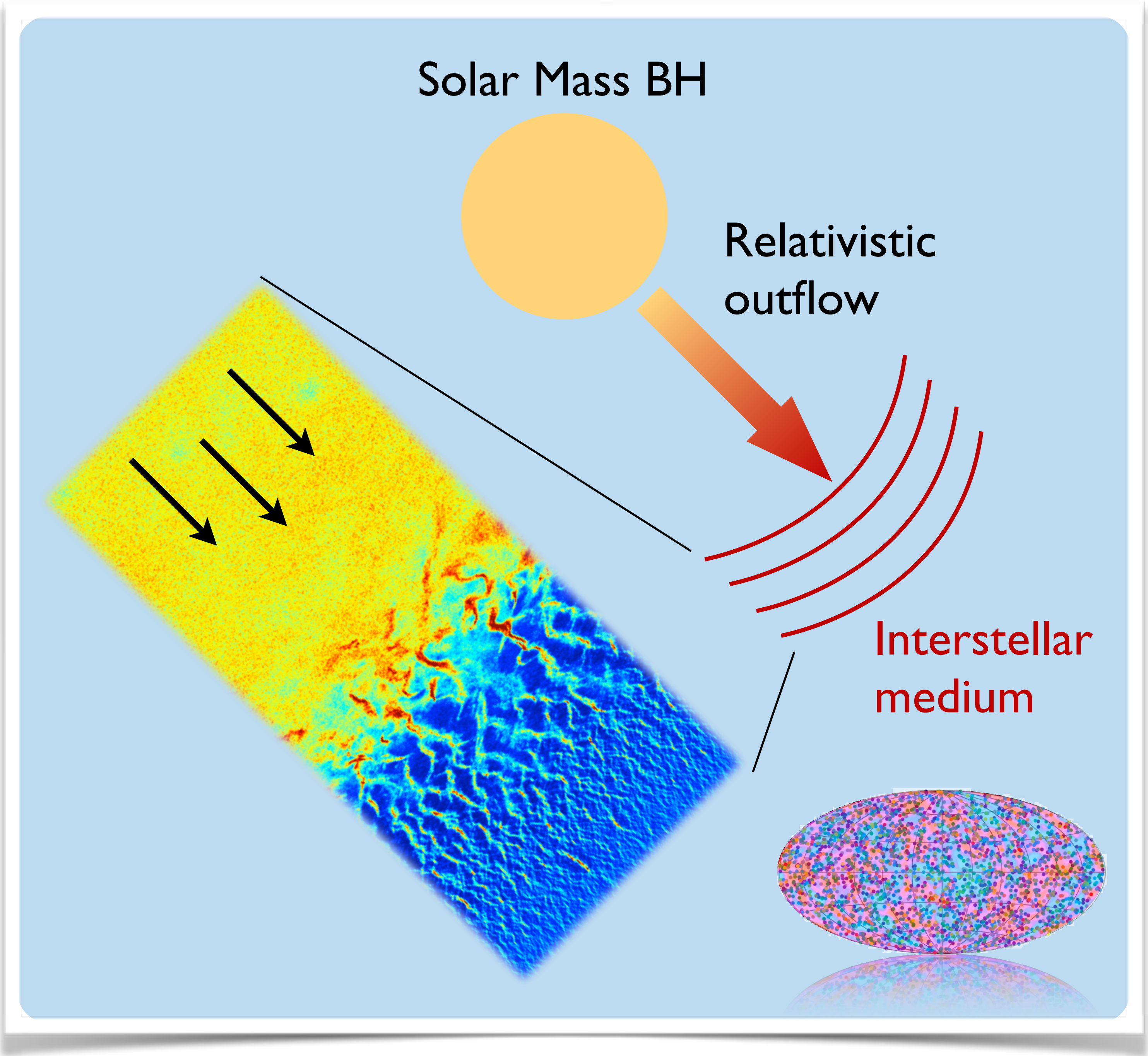

## e-e+ beam filamentation leads to magnetic field amplification




G. Sarri *et al.* Nature Communications 6, 6747 (2015)

# Particle acceleration, shocks and Gamma ray bursts (in the lab with plasma accelerators?)

## Fireball model




**Collisionless shock**

- Particle mean-free-path much larger than system size
- Scattering mediated by collective plasma instabilities

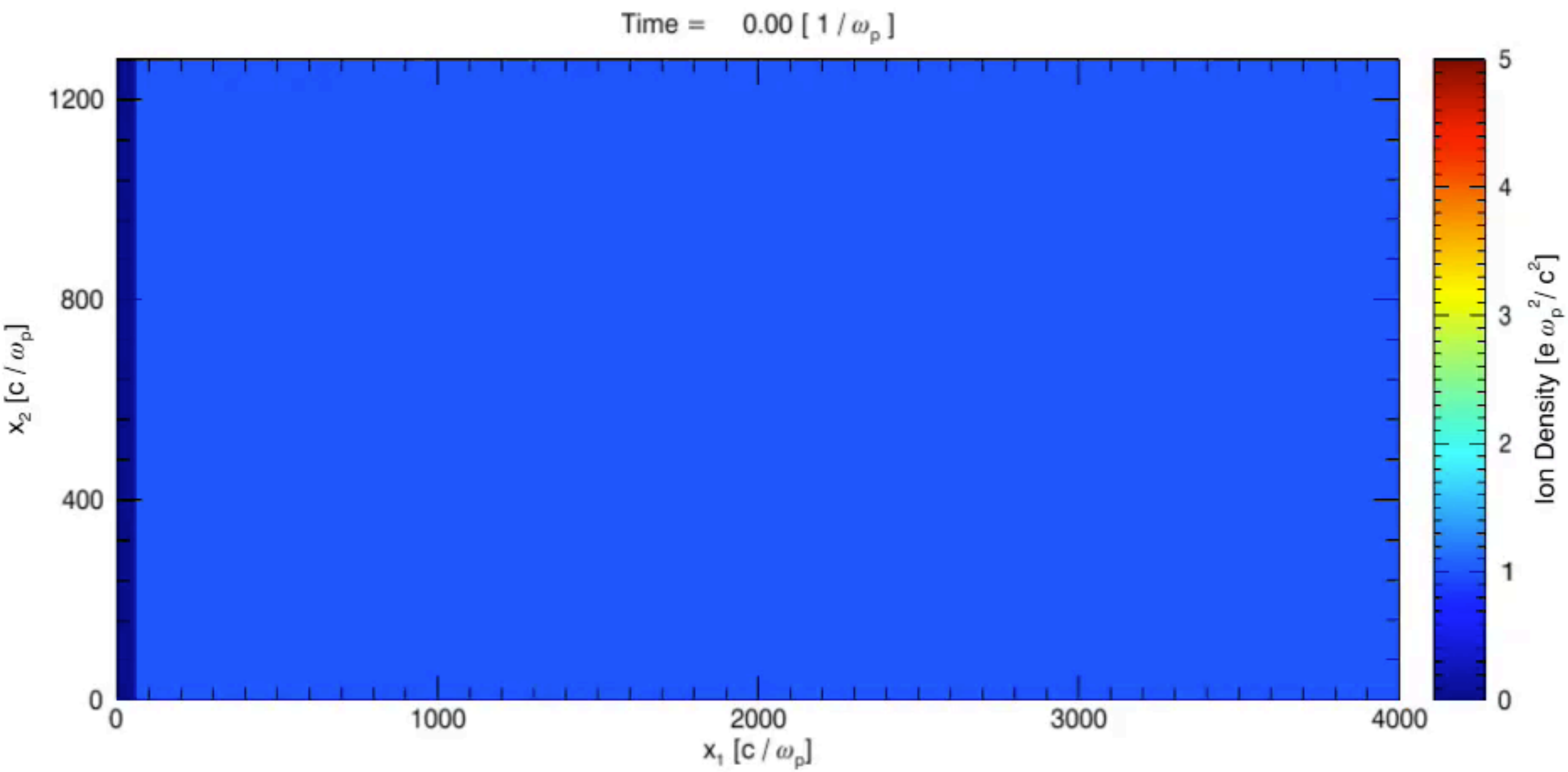
**Main challenges**

- ✦ Particle Heating and scattering
- ✦ Shock formation
- ✦ Particle Acceleration/ cosmic rays
- ✦ Radiation emission

Courtesy of S.F. Martins

# Shock formation and evolution

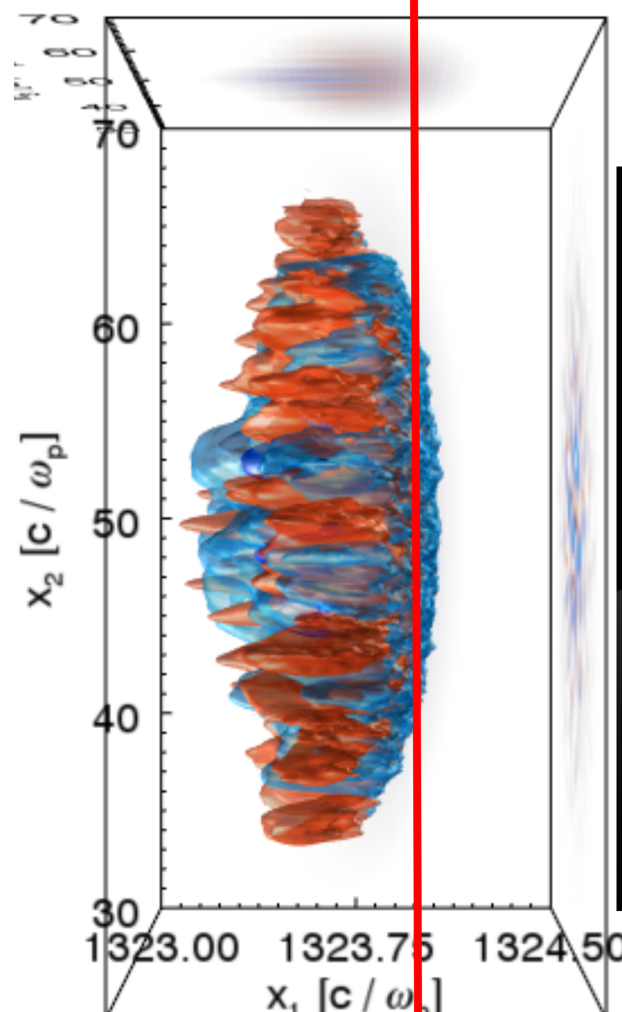
**Ion density**

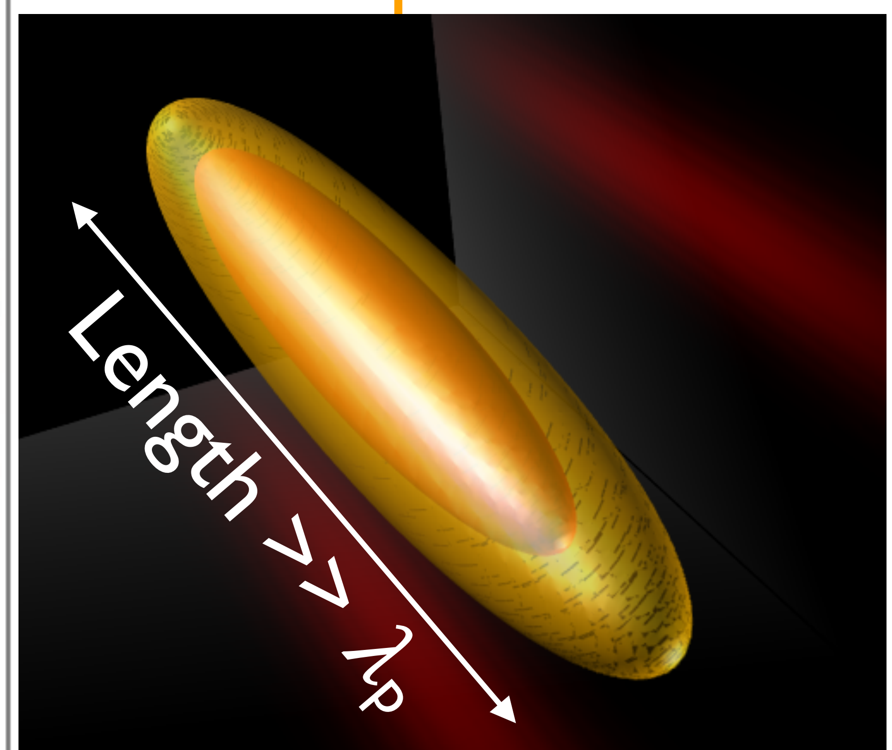


# Generation of plasma waves for particle acceleration using long beams

**Current filamenta**

**Self-modulation instability**




$\mathbf{k}_{CFI} \perp \mathbf{v}_b$

$\mathbf{k}_{SMI} \parallel \mathbf{v}_b$

**Particle acceleratio**

**Particle acceleration in the laboratory**

# Contents

Magnetic field generation in a LWFA

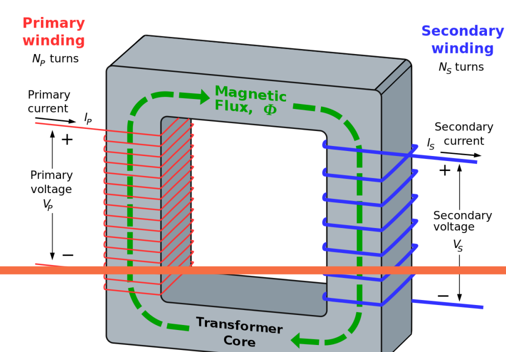
Magnetic field amplification using electron-positron beams accelerated in a LWFA

**Accelerating high quality electrons with small energy spreads in self-modulated scenarios**

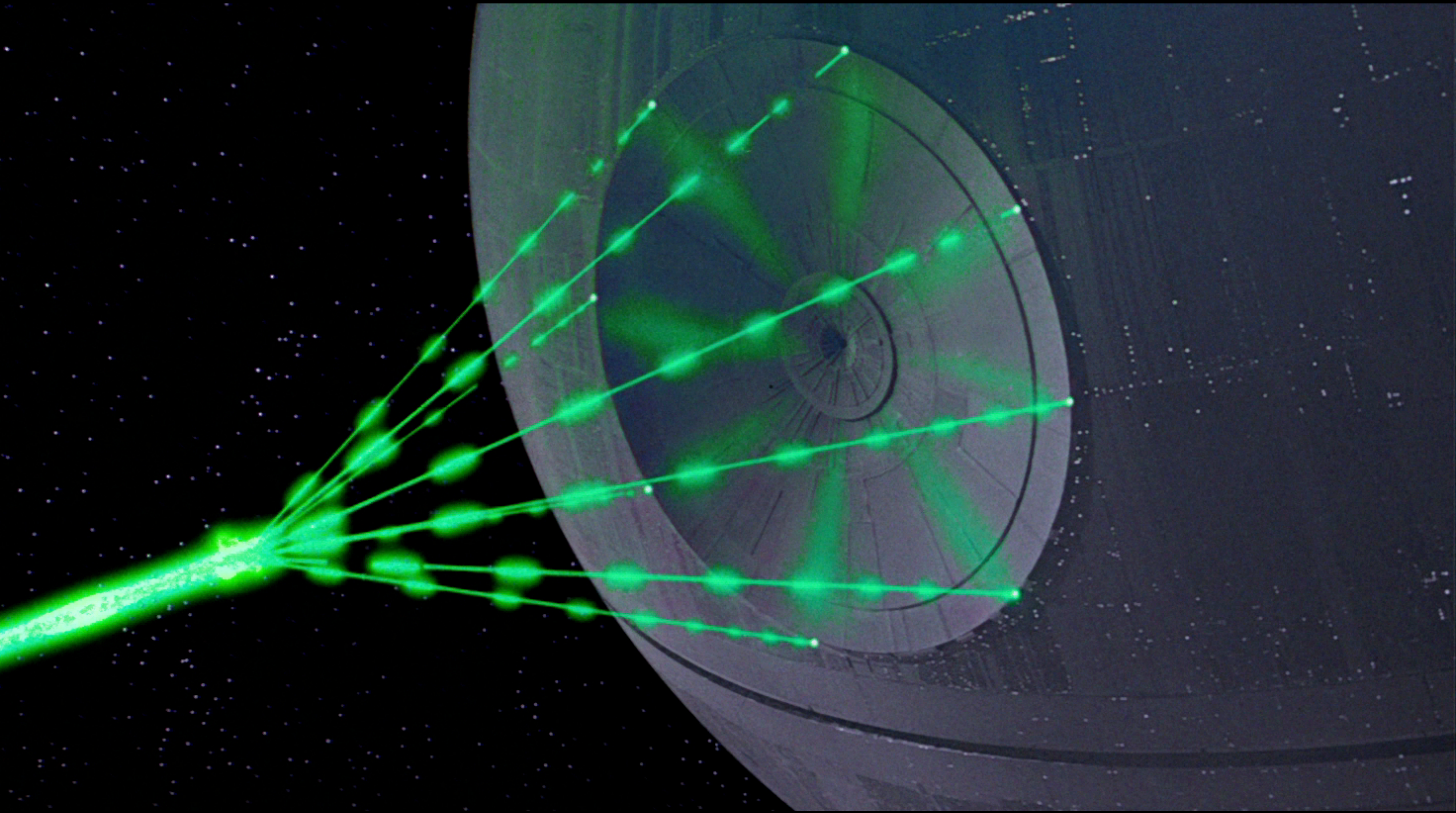
Stabilising the wakefields: hosing instability

Conclusions

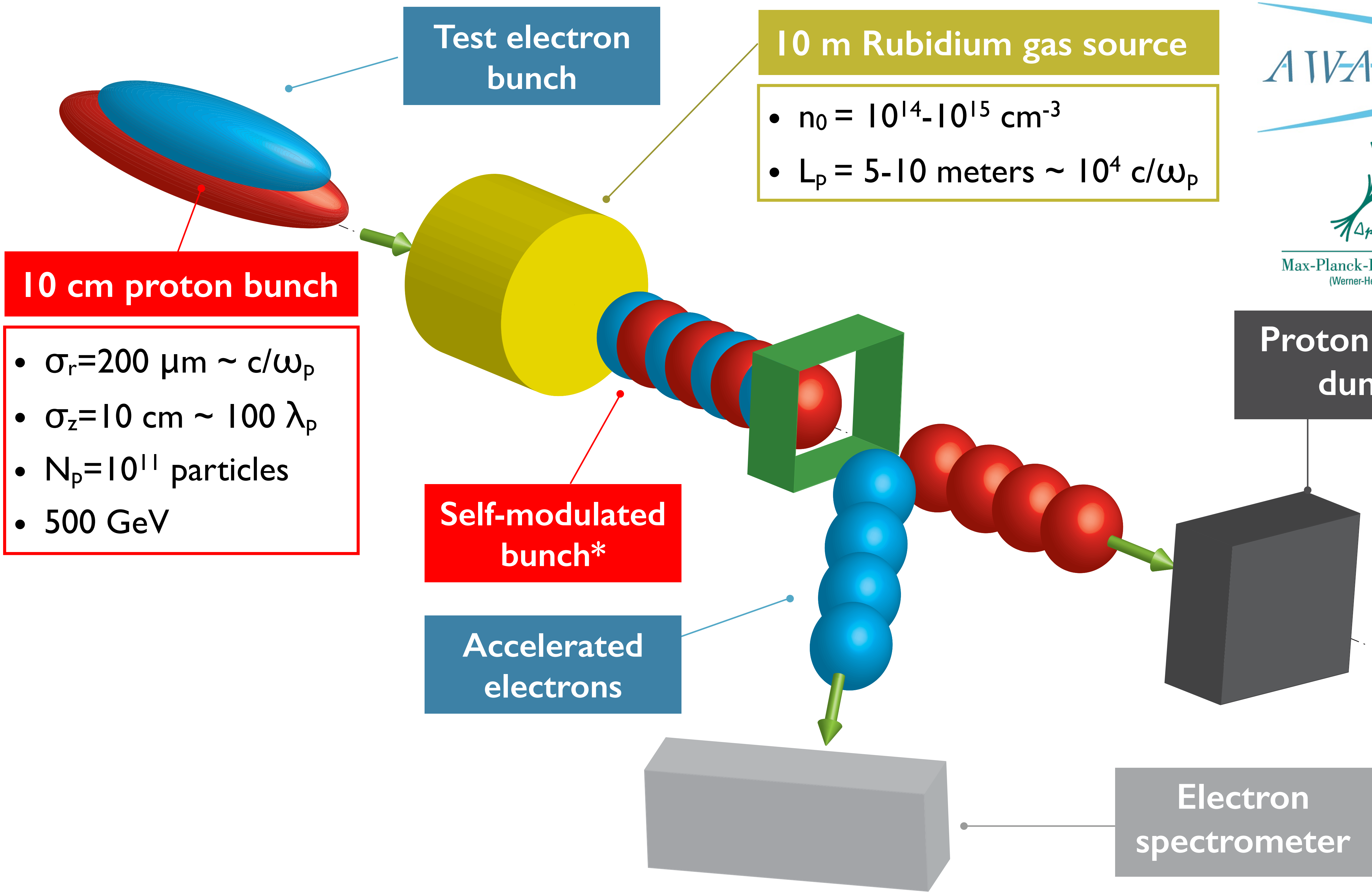
# A driver with more than 100 kJ would be required to achieve 10 TeV electron acceleration in a single stage.

| | Laser / Particle beam | Plasma | Accelerated e-/e+ |
|---|---|---|---|
| **Today** | **1-10 J lasers**<br>**100 J e-/e+ (SLAC)** | **20 % Efficiency**<br> | **0.2-20 J**<br>**1 nC ~ 6x10$^9$ particles** |
| **1000 stages** | **100 drivers , < 10 fs synchronisation precision** | **1000 + (10 cm + 10 m spacing/stage) = 10 km** | **0.1 GeV - 10 GeV**<br>**10 TeV / particle** |
| **Single stage** | **100 kJ driver** | **1-10 Km (depends on acceleration gradient)** | **10 TeV/particle** |

# Going beyond the energy frontier require very energetic beams



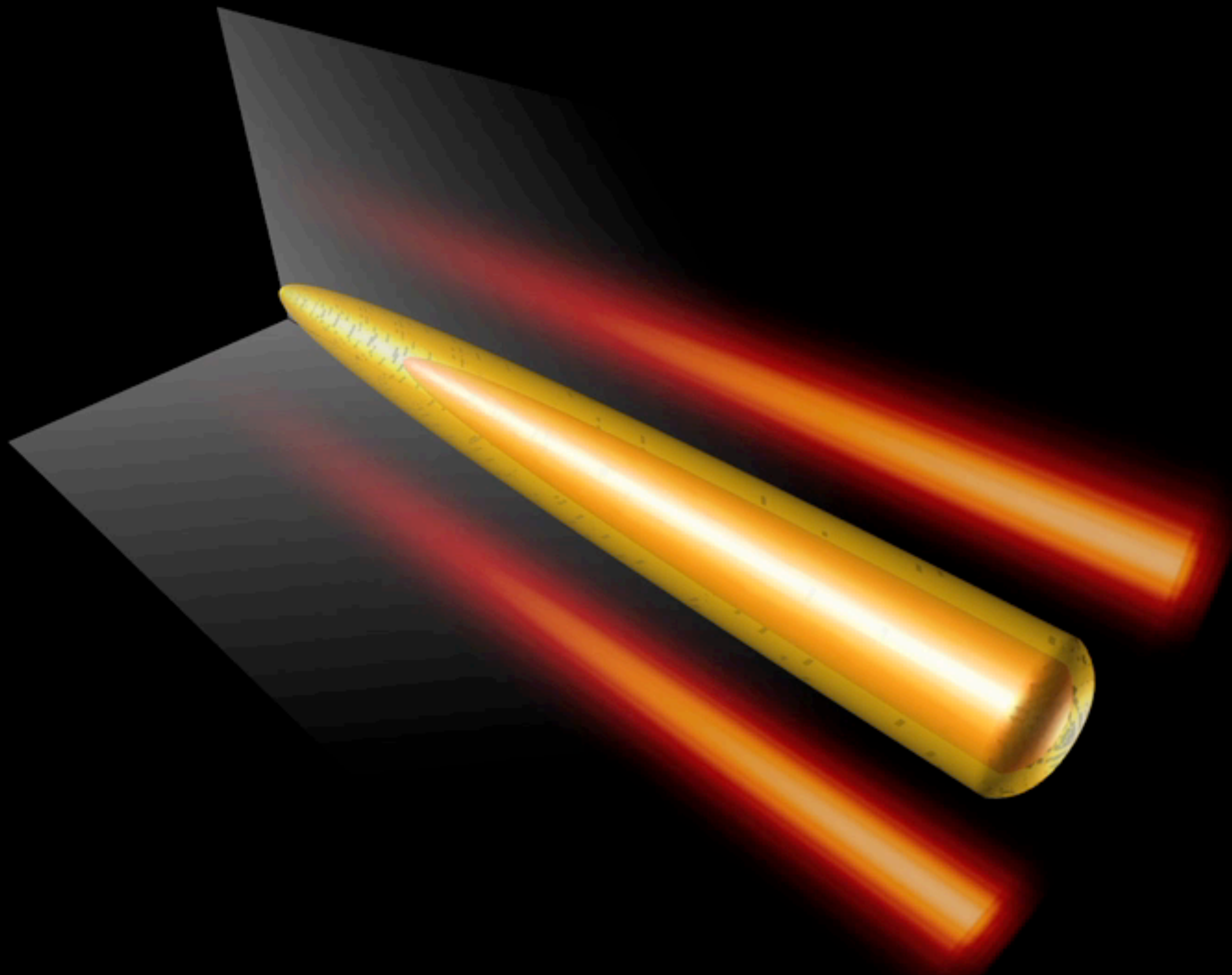
# Self-modulated proton driven plasma wakefield accelerator





- N. Kumar *et al.* PRL 104 255003 (2010)
- C. Schroeder *et al.* PRL 107 145002 (2011)

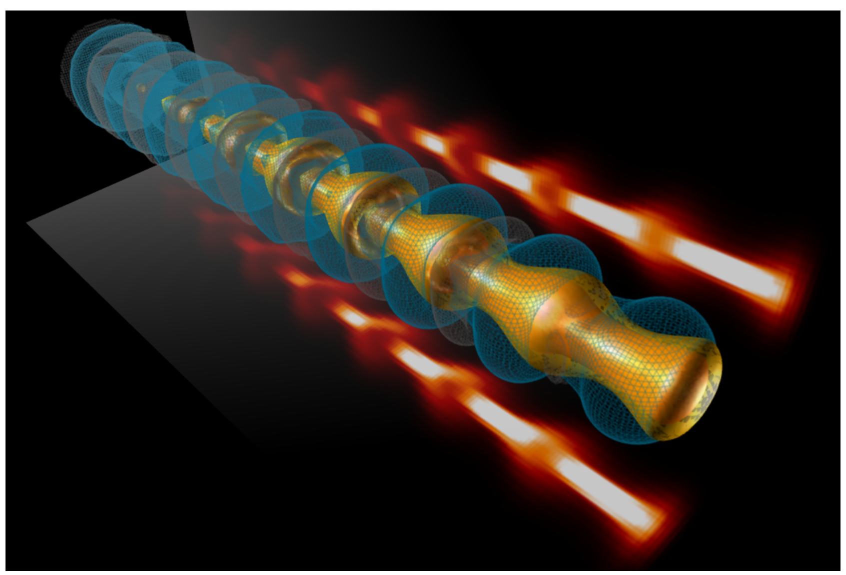
# Self-modulation instability



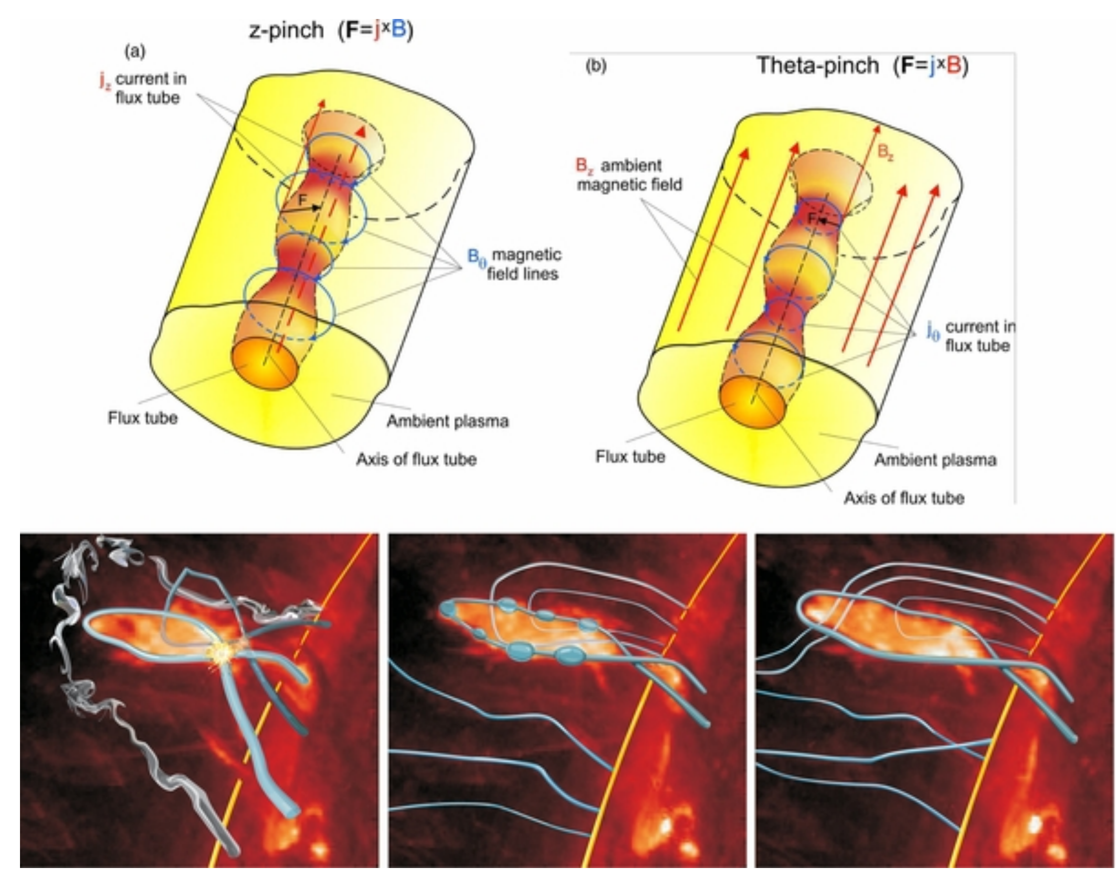
**Movie in a frame that travels at c**

# Similar structures can be found in astrophysical scenarios

**Self-modulation**



**Sausage instability**




A.K. Srivastava *et al.* ApJL 2013

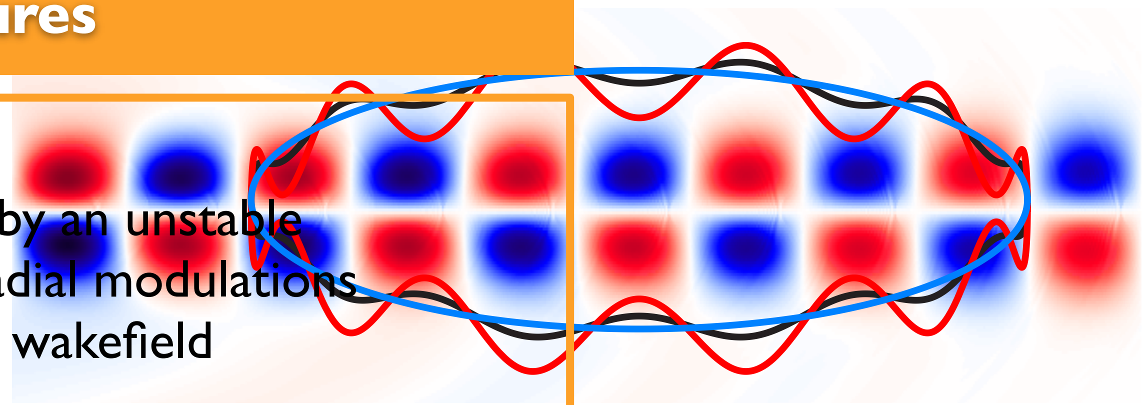
# Self-modulation instability physical picture

## Key features

- Self-modulation is caused by an unstable coupling between beam radial modulations and the transverse plasma wakefield
- It grows from the initial wakefields or plasma/plasma radial perturbations
- It leads to very large wakefield amplitudes that grow along the beam and with propagation distance
- Self-modulation provides a mechanism to create large amplitude wakefields using tenuous beams

## Physical picture

…sing fields $E_r$-$B_\theta$



Blue focuses protons

Red defocuses protons

- Initial wakefield contains focusing and defocusing regions
- Beam radius **increases in defocusing fields**
- Beam radius decreases in focusing fields
- Beam modulations at $k_p\xi$ enhance the wakefields

# Self-modulation instability physical picture

## Analytical model

**Plasma density perturbation**

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right)\frac{\delta n}{n_0} = \mp k_p^2 \frac{n_b}{n_0}$$

↓

**Plasma focusing fields**

$$\left(\nabla_\perp^2 - k_p^2\right)\frac{E_r - B_\theta}{E_0} = -k_p \frac{\partial(\delta n/n_0)}{\partial r}$$

↓

**Beam radius envelope equation**

$$\frac{\mathrm{d}^2\sigma_r}{\mathrm{d}z^2} - \frac{\epsilon_n^2}{4\gamma^2\sigma_r^3} = \mp\frac{1}{\gamma\sigma_r}\frac{m_e}{m_b}\langle k_p r \frac{E_r - B_\theta}{E_0}\rangle$$

# Self-modulation instability physical picture

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**Plasma density perturbation**

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right)\frac{\delta n}{n_0} = \mp k_p^2 \frac{n_b}{n_0}$$

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C. Schroeder *et al.* PRL (2016)

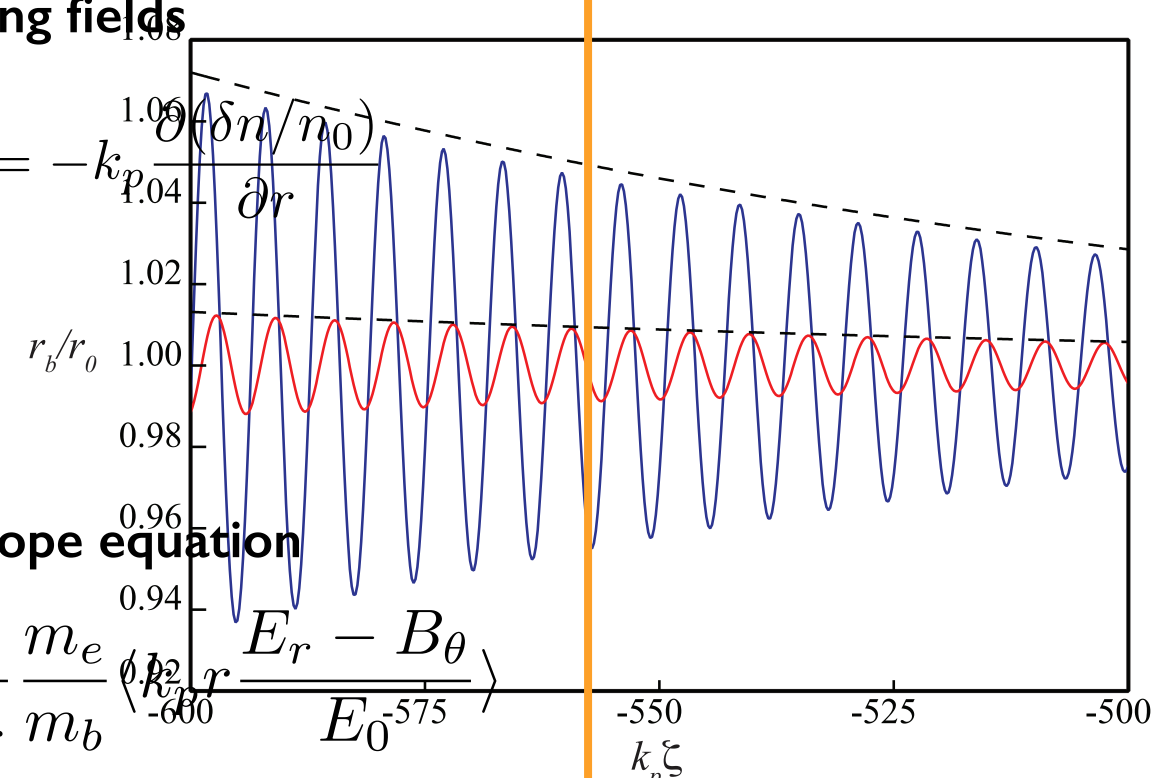
## th rate

**Evolution of beam radius**

$$\delta\sigma_r \propto \exp(N)\cos\left(k_p\xi + \frac{N}{\sqrt{3}} - \frac{\pi}{12}\right)$$

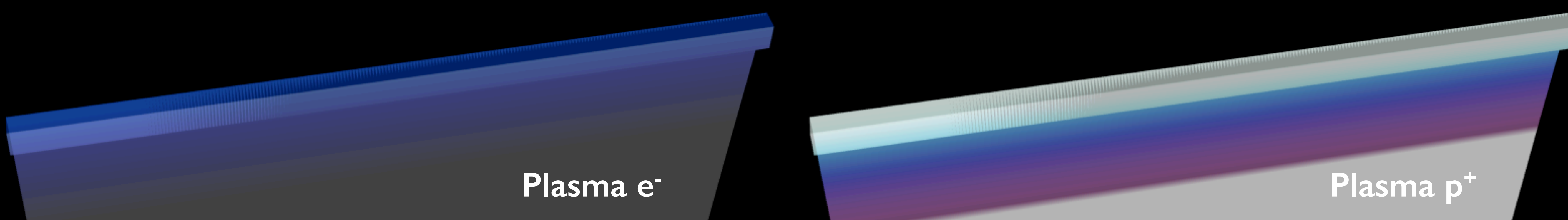
**Number of e-foldings**

$$N \simeq \frac{3^{3/2}}{4}\left[\frac{n_b}{n_0}\frac{m_e}{\gamma m_b}(k_p\xi)(k_p z)^2\right]^{1/3}$$



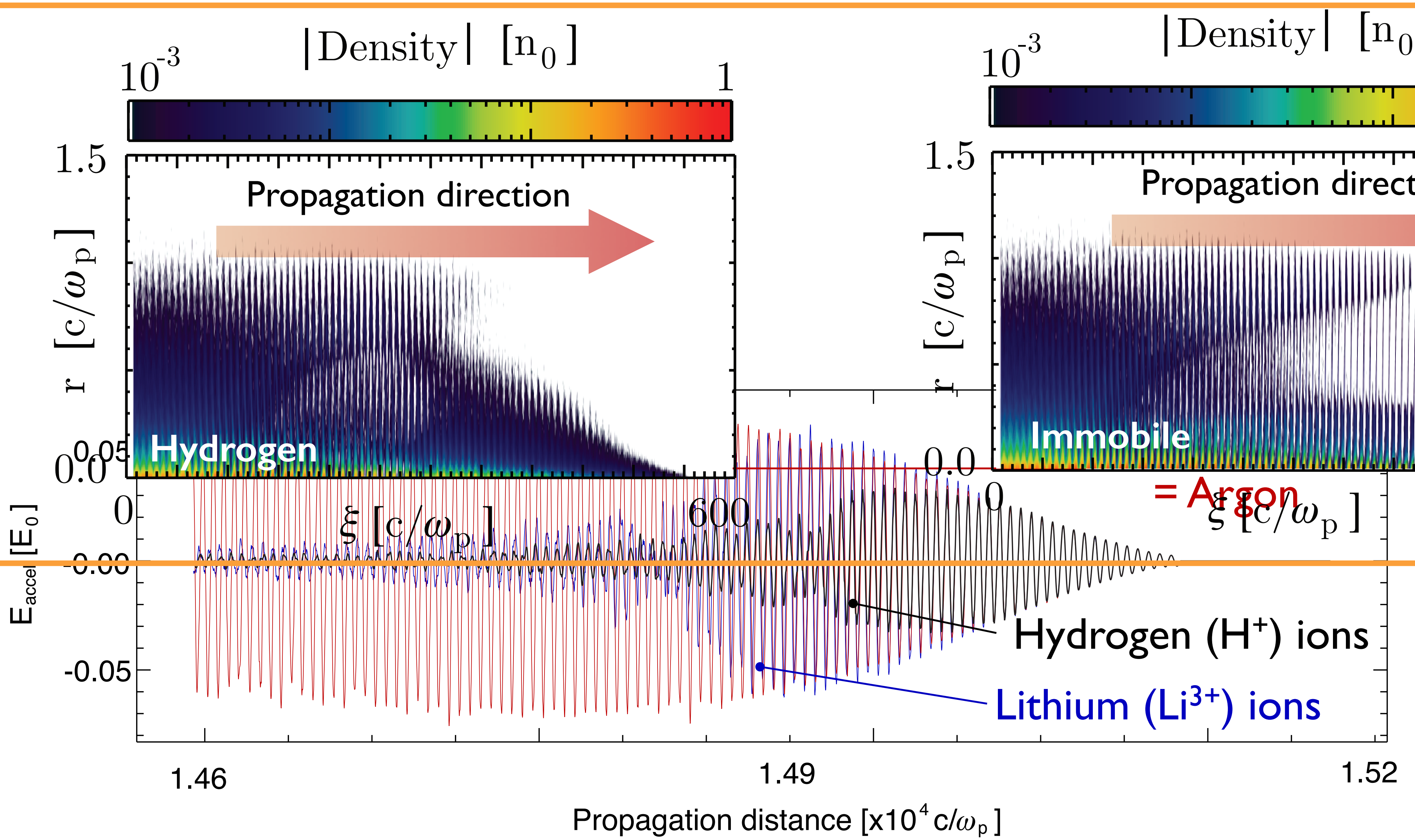

A. Pukhov *et al.* PRL 107 145003 (2011); C. Schroeder *et al.* PRL 107 145002 (2011).

# Ion motion can occur in self-modulated regimes when the length of the driver is comparable to the plasma ion wavelength



# Ion motion can be mitigated by using heavier plasma ions

**SMI shutdown in Hydrogen plasma**

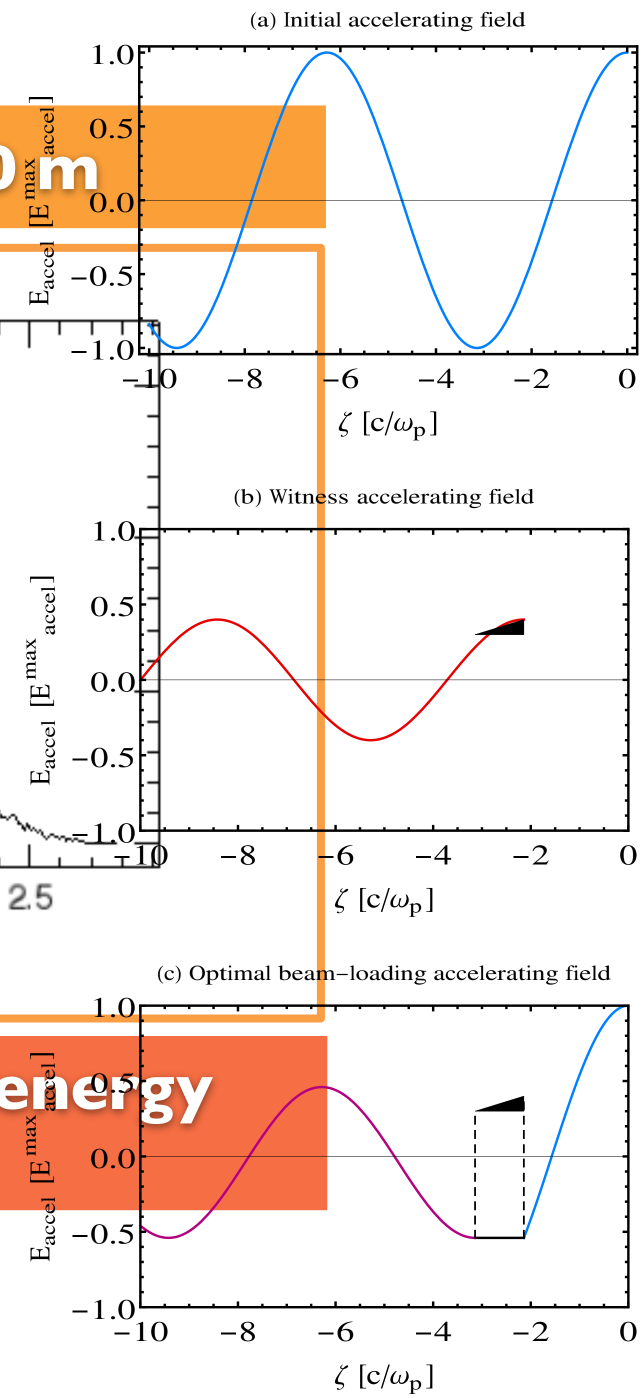



Simulations showed that **Ar/Rb plasmas** suppress the ion dynamics

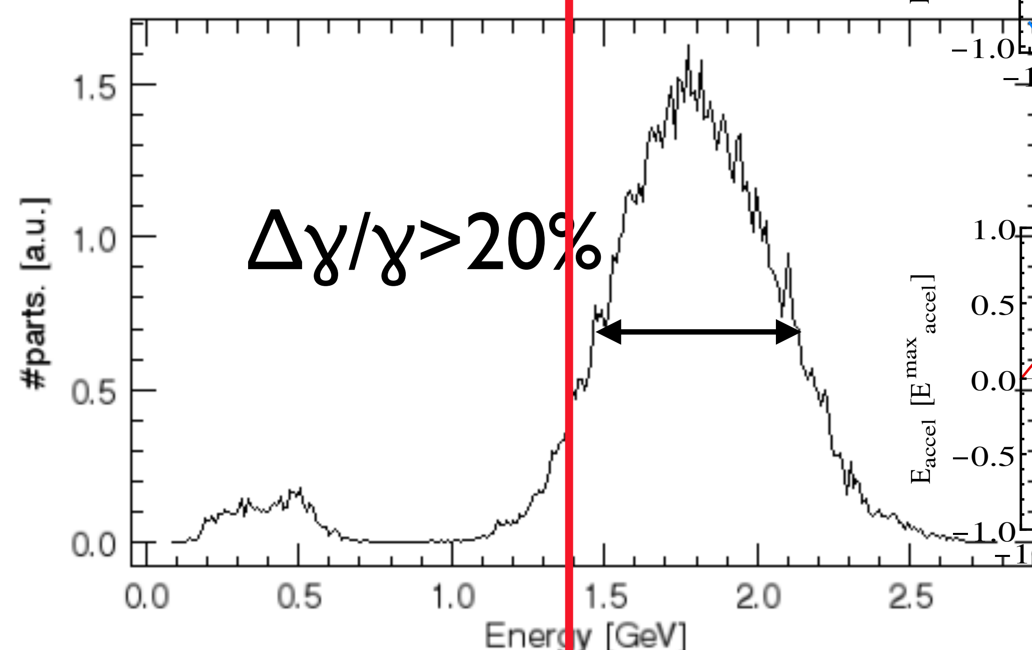
J.Vieira et al, Phys. Rev. Lett. **109** 145005 (2012)

# Beam loading plasma wakefields to minimize the energy spread

**Tailored profiles flatten $E_{accel}$**



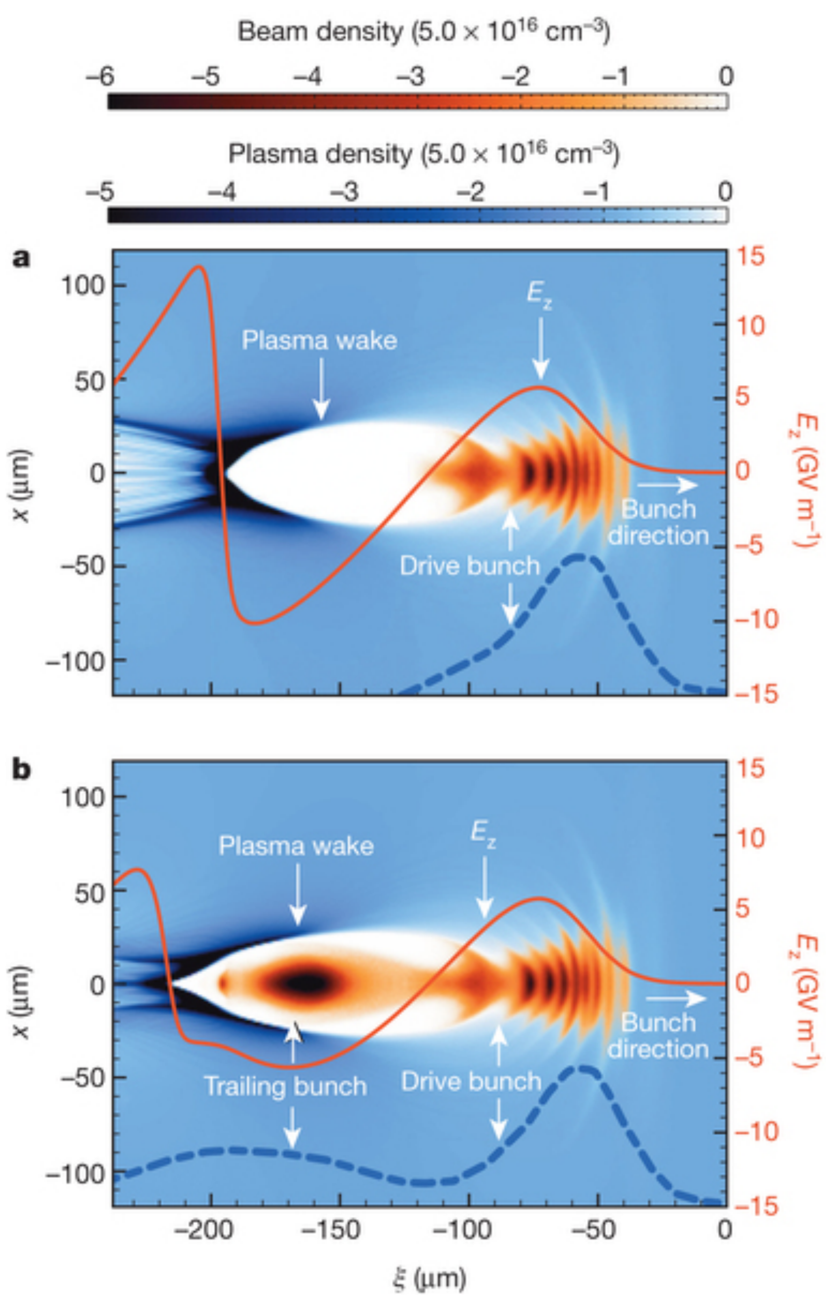

**Energy spectra after 10 m**



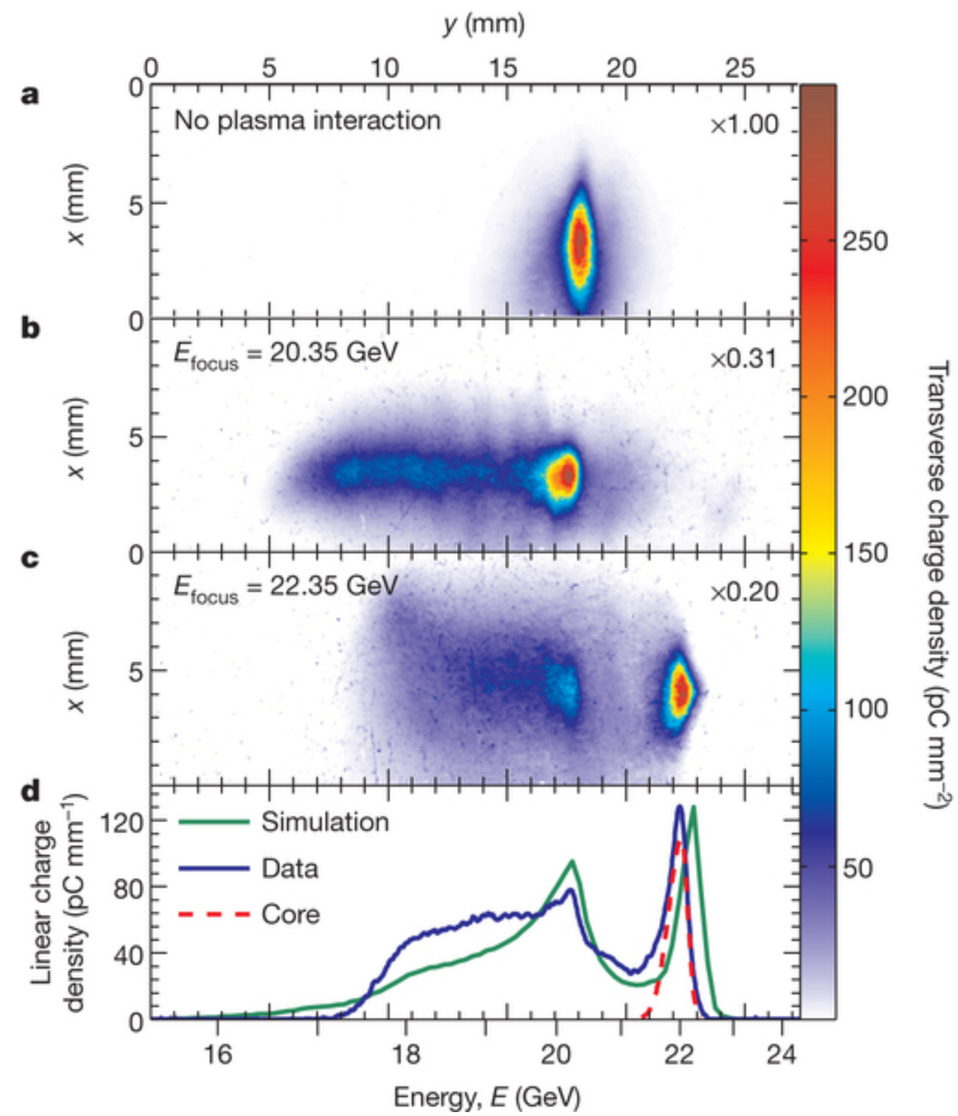

**Most applications require energy spreads below 1%**

# Recent experiments using short beam drivers demonstrated sub-percent energy spreads

## Nearly optimal beam loading




## Efficiency above 20 %

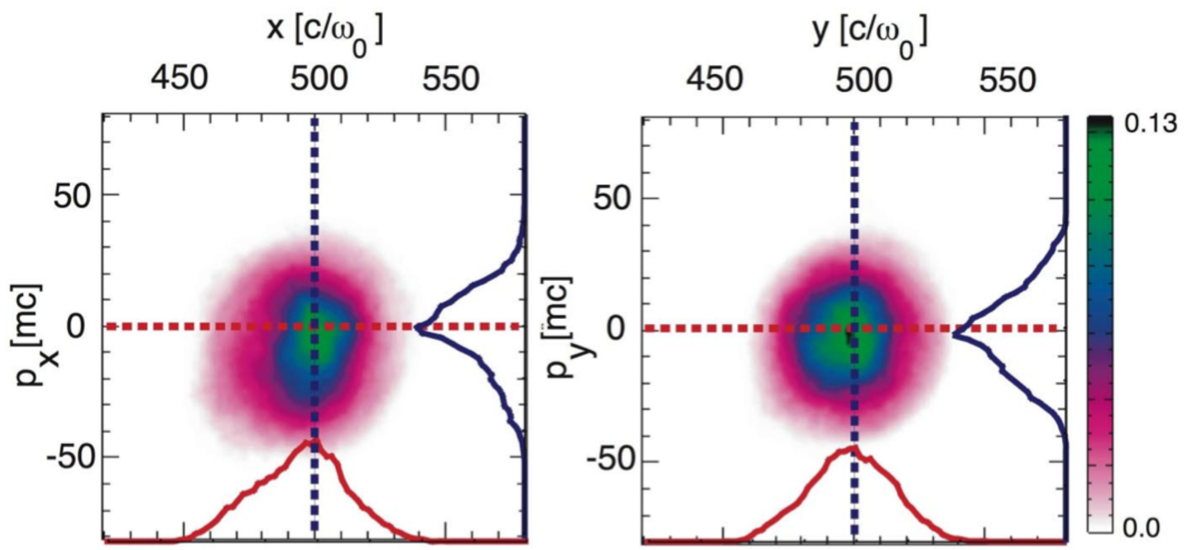



**M. Litos *et al*, Nature 2015**

# Optimal beam loading is also important to preserve beam emittance

## Emittance

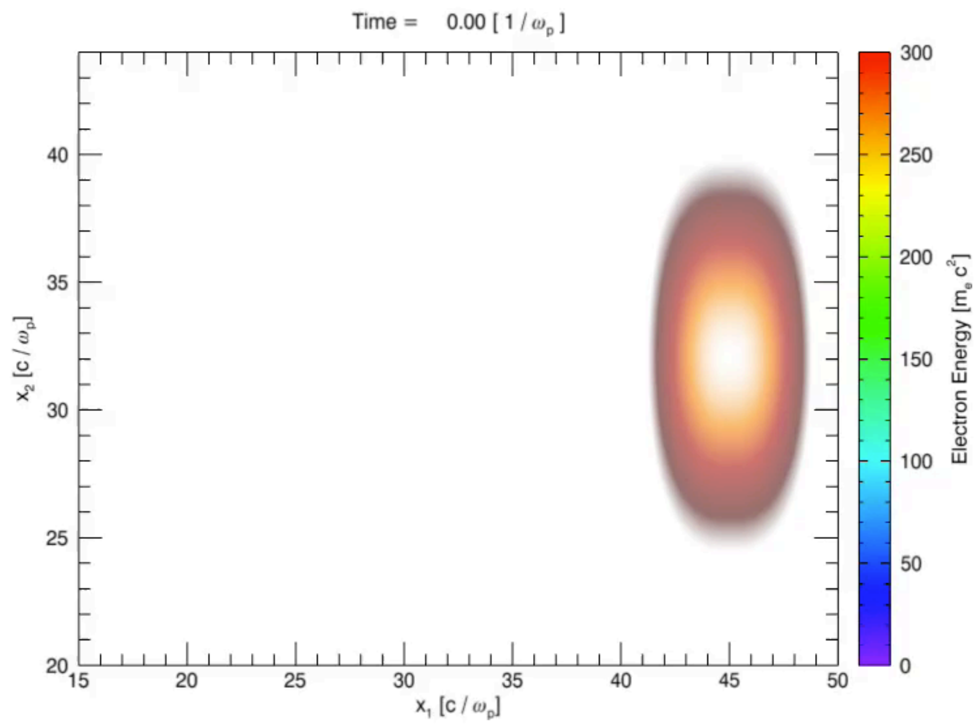
Emittance is the area enclosed by the transverse beam phase space




$$\epsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2} p_z/(m_e c)$$

prime denotes temporal derivative

## Transverse betatron trajectories

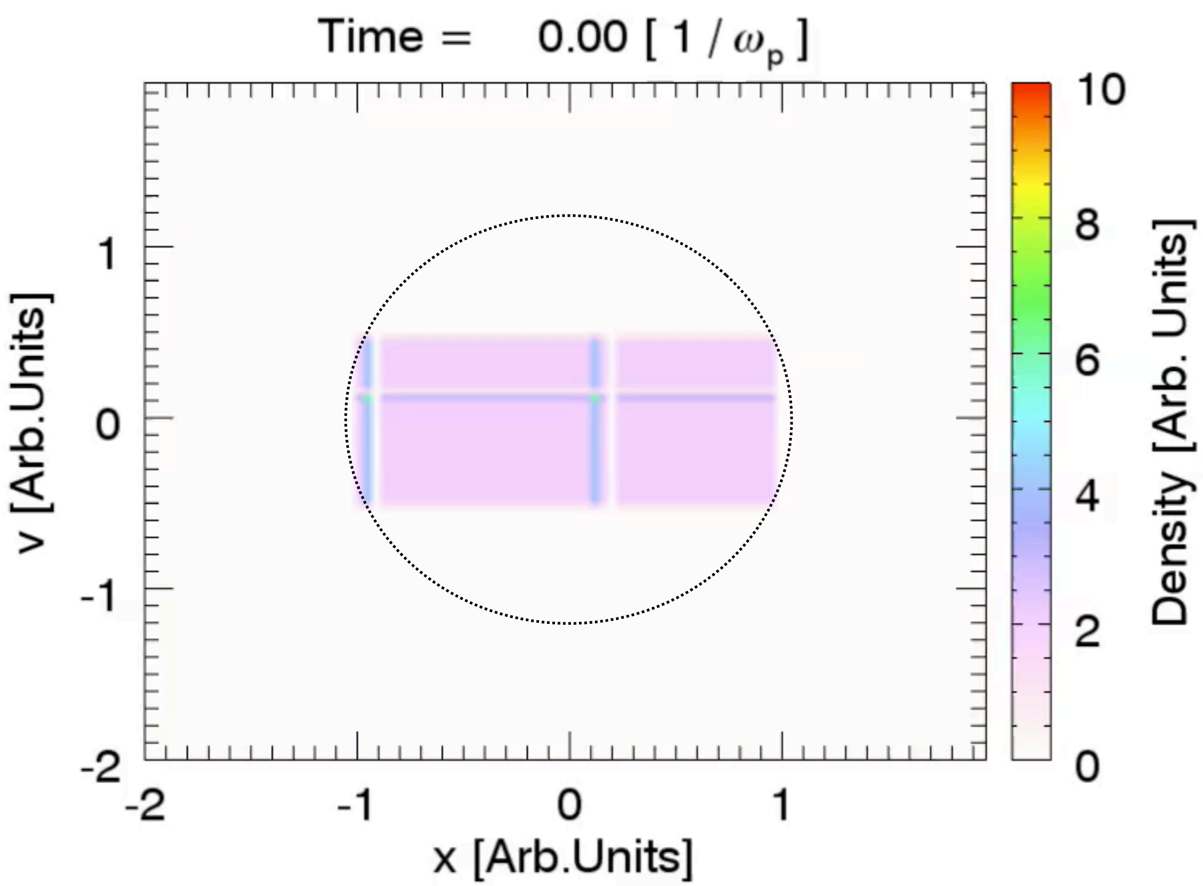


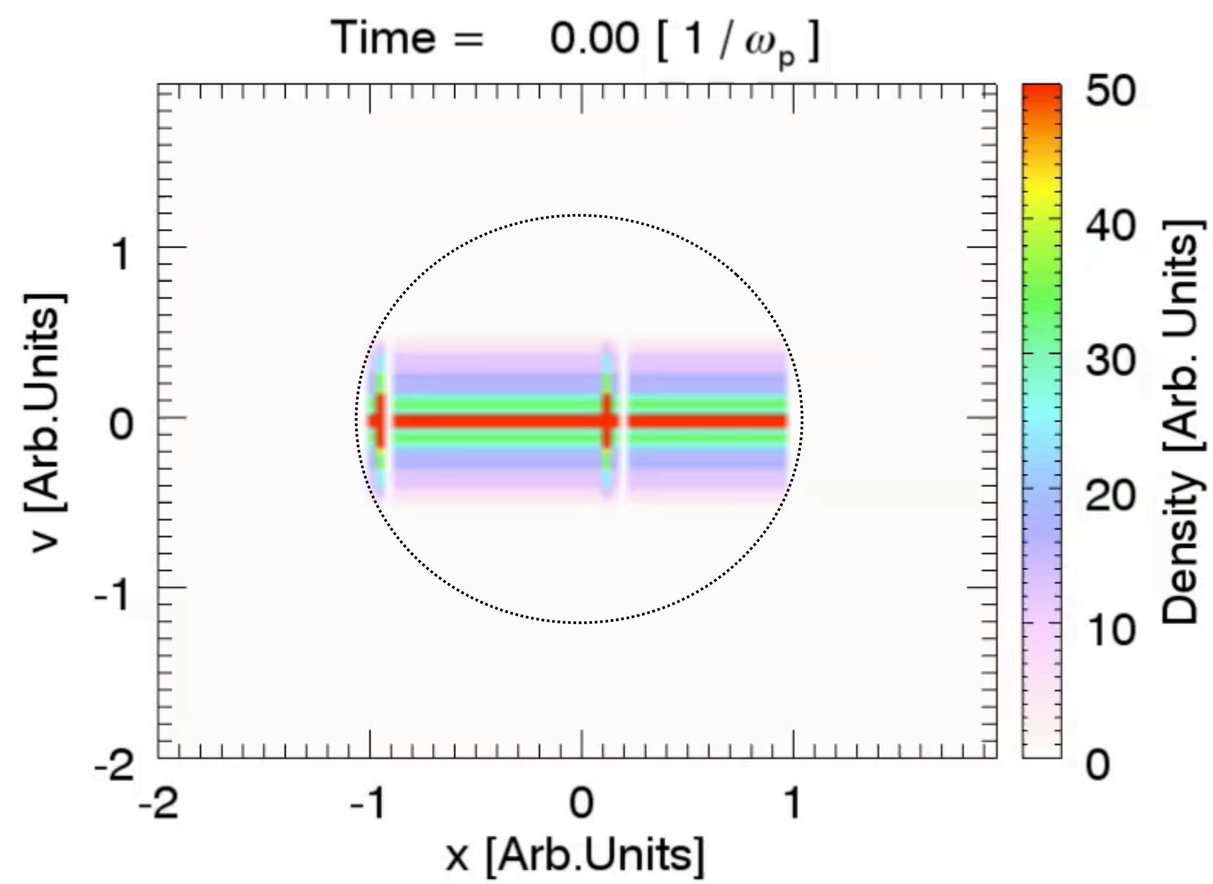

$$\mathbf{x}_\perp \propto \mathbf{x}_{\perp 0}\cos(\omega_\beta t + \phi)$$

$$\mathbf{v}_\perp \propto -\mathbf{x}_{\perp 0}\omega_\beta \sin(\omega_\beta t + \phi)$$

# Beam emittance evolution in a plasma accelerator

| Beam emittance stays constant | Beam emittance increases |
|---|---|
| Beam electrons oscillate with the same betatron frequency | Beam electrons oscillate with different betatron frequencies |




| **Phase space area is preserved** | **Phase space area increases** |
|---|---|

# Conditions for emittance preservation

## Betatron frequency

$$\omega_\beta \propto \left(\frac{\alpha}{\gamma}\right)^{1/2} \omega_p$$

**γ** is the relativistic factor

**α** is related to the focusing force

**Emittance preserved if**

- **α** and **γ** are the same for every beam particle
- Harmonic (sinusoidal) betatron trajectories

**Requirements**

- Small energy spreads
- Linear focusing force (harmonic oscillations)

## Beam emittance increases

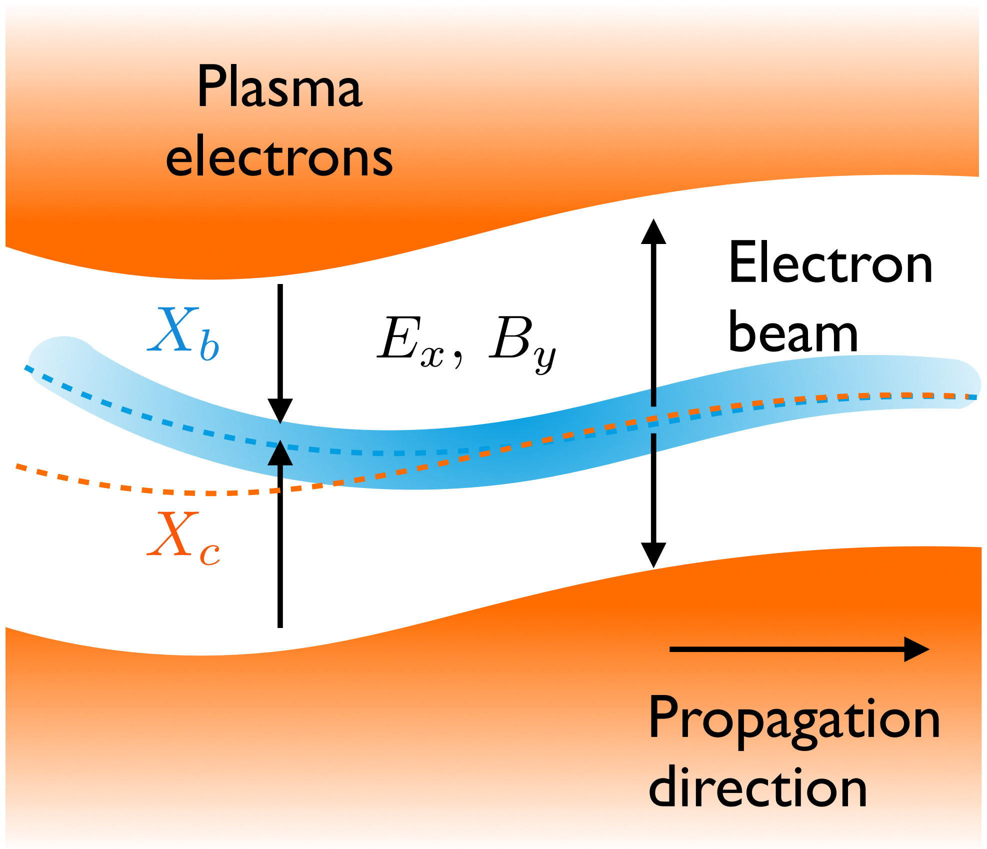
**Non-linear regime**

- Optimal beam loading can be reached with tailored beam density profiles
- Focusing force is linear everywhere
- Focusing force is the same along the beam

# Contents

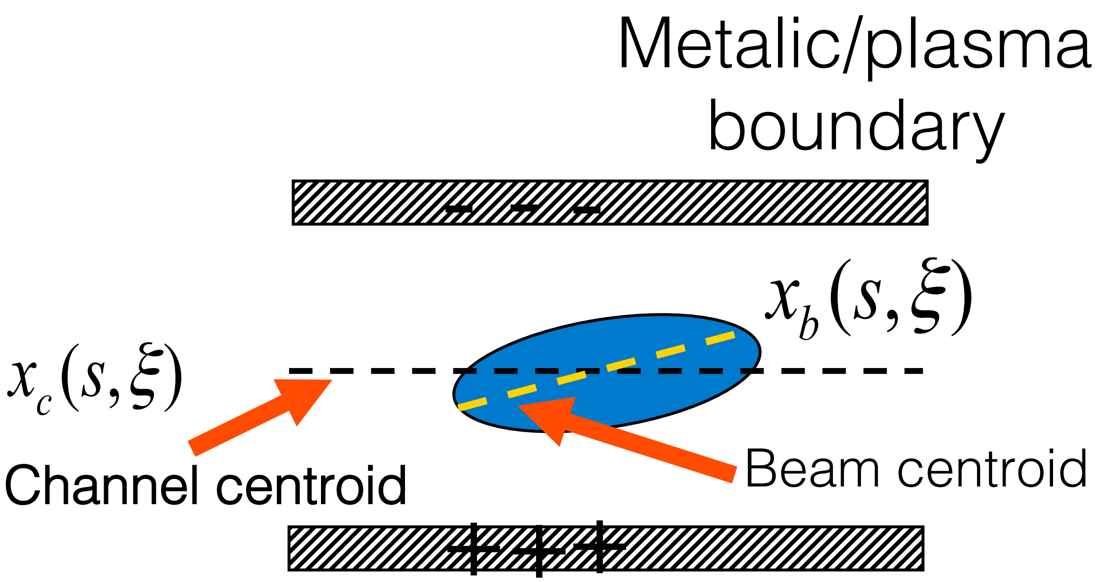
# Hosing instability/beam breakup instability (BBU) in a nutshell

## Hosing in plasma




- Beam expels plasma electrons
- Beam centroid deviation $X_b$ drives deviation in evolution of $X_c$
- Channel centroid $X_c$ feeds back into temporal evolution of $X_b$ at beam-tail

## BBU in accelerating cavity

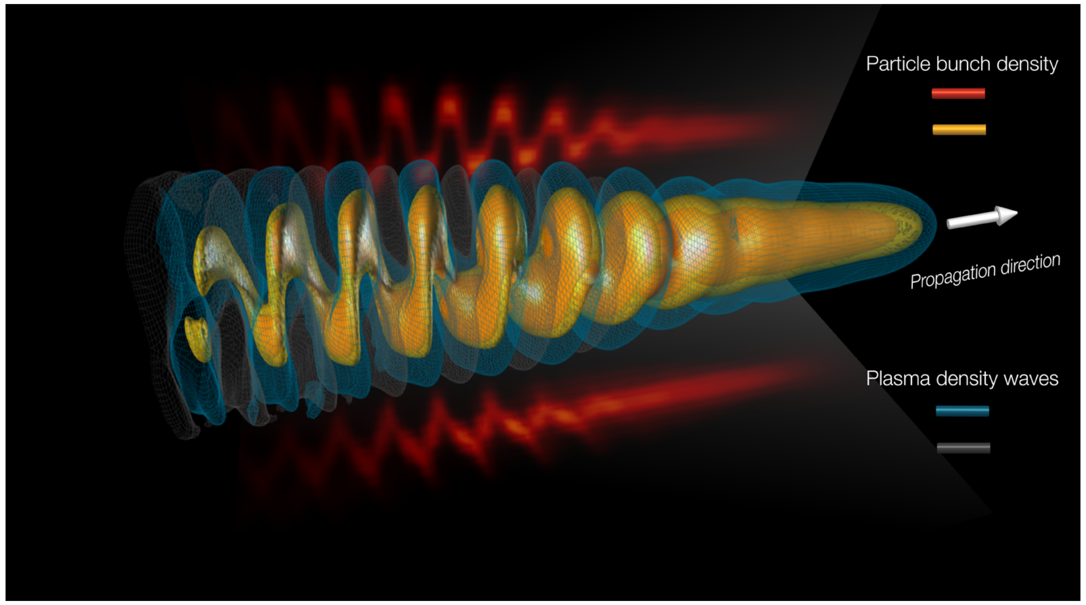



- Initial beam centroid deviation causes charges to accumulate in the metallic plates.
- Wakefields created in the cavity enhance the initial perturbation

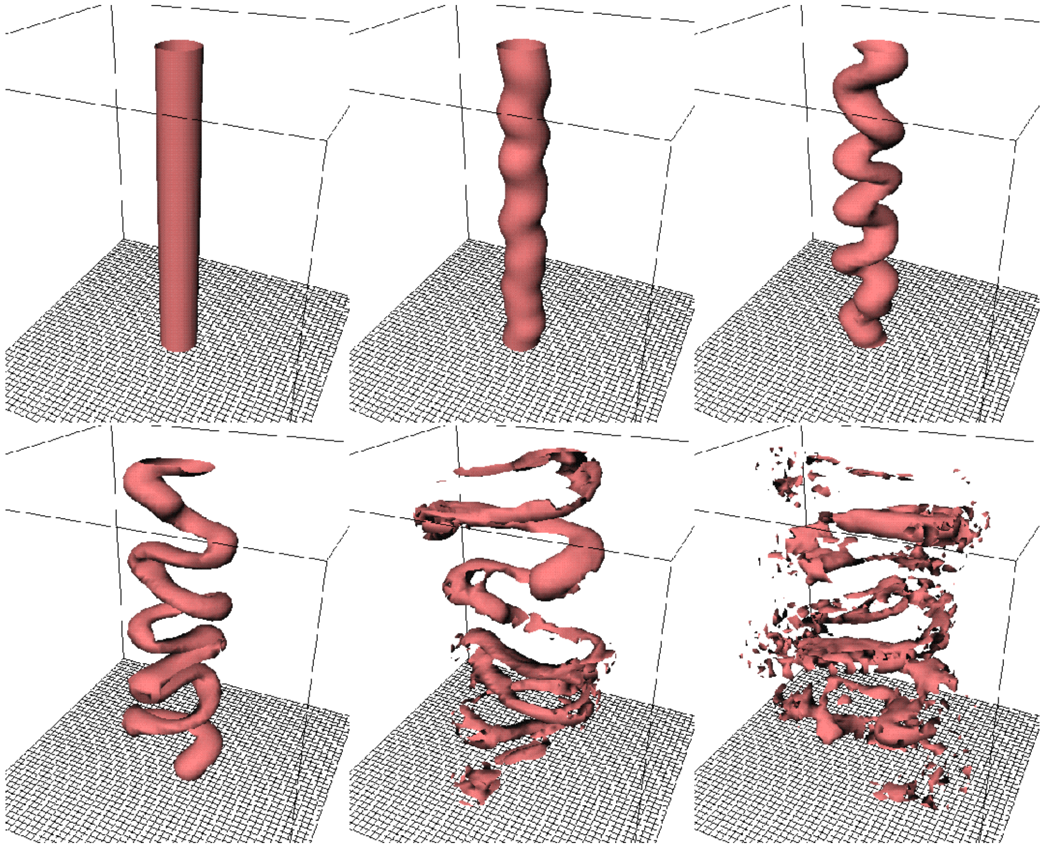
Adapted from T. Mehrling and C. Huang (2016)

# Kink instability: same modes in totally different physical contexts

## Hosing instability




## Kink instability



Astronomy & Astrophysics (2006)

# Different regimes unified by a similar set of equations

## Regimes

### Beam driver

- Long beam/short beam limits
- Multi bunch instability (long range wakefields)
  - Important for long drivers
  - Competition with self-modulation can be important
- Single bunch instability (short range wakefield)
  - Drivers shorter than the plasma wavelength

### Plasma response (properties of the cavity boundary)

- Adiabatic (preformed, straight channel) /non-adiabatic (nonlinear, relativistic regime)
- Self-generated curved channel (i.e. blowout regime)
- Relativistic/non-relativistic boundary
- Magnetic field effect

## Particles probe different wakefields

**Beam centroid evolution in time**

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 X_b = \omega_\beta^2 X_c$$

**Channel centroid evolution in co-moving coordinate** $\xi = ct - z$

$$\frac{\partial^2 X_c}{\partial \xi^2} + k^2 c_\psi c_r X_c = k^2 c_\psi c_r X_b$$

$$k = k_p/\sqrt{2}$$

Adapted from T. Mehrling and C. Huang (2016)

# 2-particle model:
# Intuitive mathematical approach to understand hosing

## Physical picture

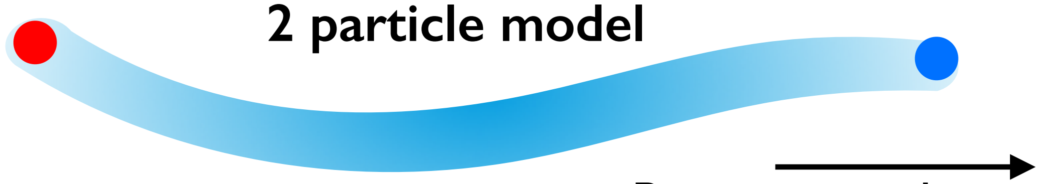
**Beam centroid evolution in time**

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 X_b = \omega_\beta^2 X_c$$

**Channel centroid formal solution**

$$X_c \sim \int \mathrm{d}\xi' \frac{n_b(\xi')}{n_0} X_b \sin\left[k_p(\xi - \xi')\right]$$

**2 particle model**




$$n_b = n_{b0}\delta(\xi) + n_{b1}\delta(\xi - \xi_1) + \ldots$$

## Particles probe different wakefields

**1st particle ($X_c$=0):**

$$X_b \sim X_{b0} \cos\left(\omega_\beta t\right)$$

**2nd particle**

Channel centroid oscillates at $k_p\xi$ and at $\omega_\beta t$

$$X_c \sim X_{b0} \cos\left(\omega_\beta t\right) \sin\left(k_p \xi\right)$$

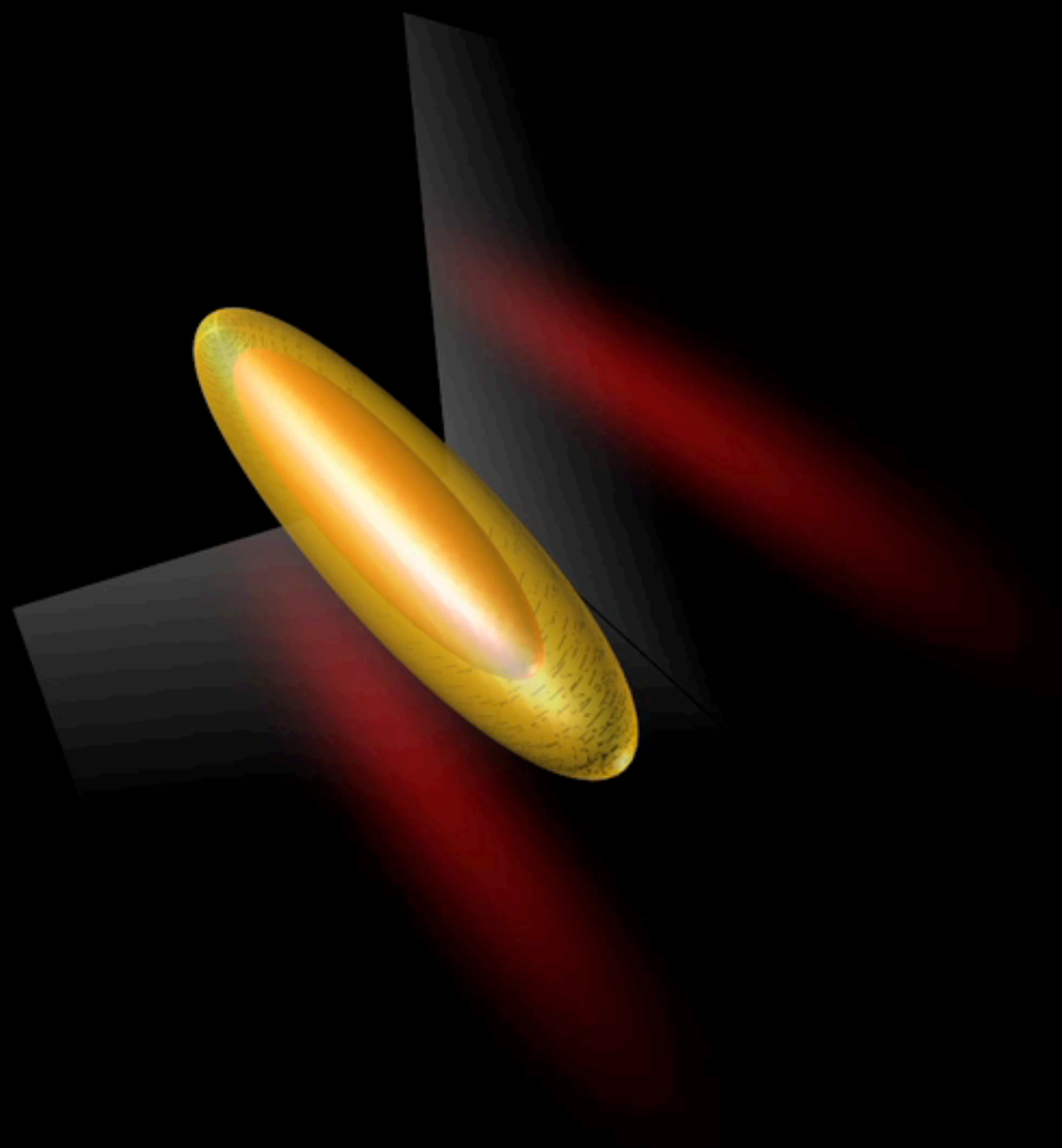
Beam centroid is resonantly driven:

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 X_b \sim \omega_\beta^2 X_{c0} \sin(k_p\xi)\cos(\omega_\beta t)$$

**Beam centroid oscillations grow secularly with t**

$$X_{b1} \sim t \cos(\omega_\beta t)$$

# Long beam limit
## Competing self-modulation and hosing instabilities



# Long beam limit
# Competing self-modulation and hosing instabilities

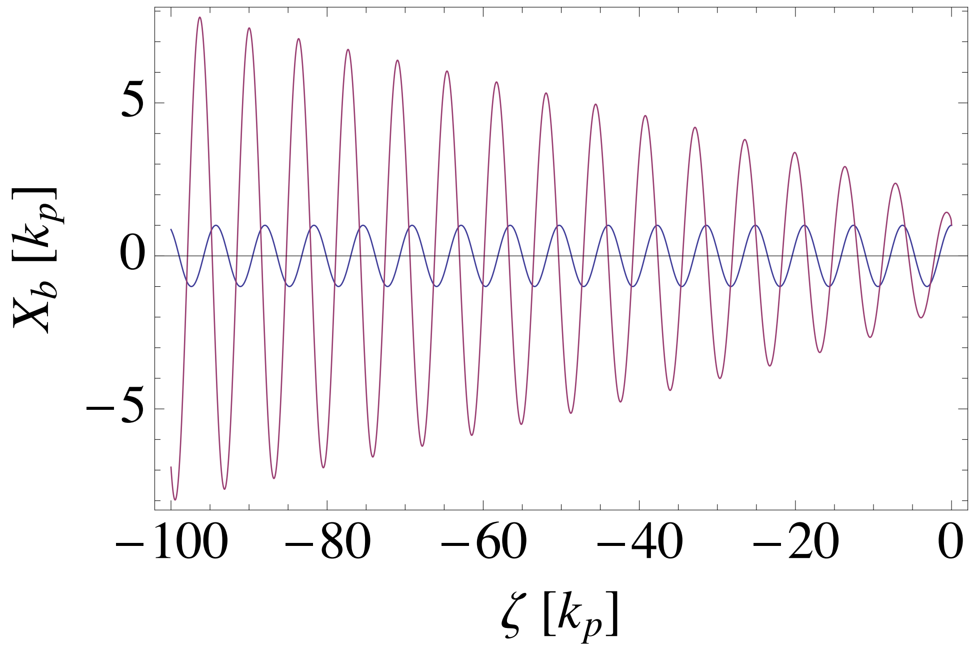
## Growth rate

**Evolution of beam centroid**

$$X_b \sim X_{b0} \exp\left(N\right) \cos(k_p \xi + \eta N + \phi)$$

**Number of e-foldings**

$$N \sim \left(\omega_\beta^2 t^2 k_p \xi\right)^{1/3}$$




**Centroid oscillations grow with t and with ξ**

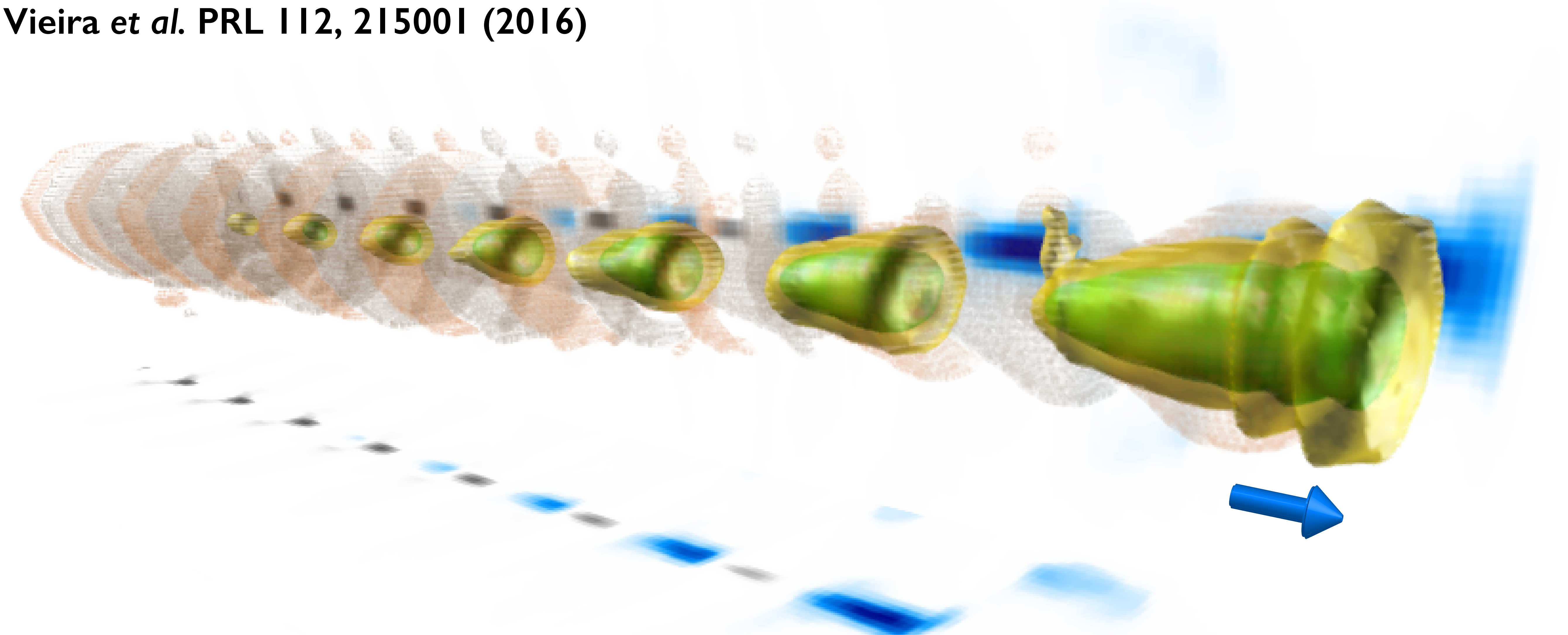
## Hosing could destroy self-modulation

**Growth rate for the hosing instability is remarkably similar to self-modulation**

**Beam break up could occur in experiments**

# Multi-bunch limit: Already self-modulated wakes can suppress hosing

J. Vieira *et al.* PRL 112, 215001 (2016)



**Centroid of each beamlet**

$$\frac{\partial^2 x_c^{(n)}}{\partial z^2} + \frac{\delta n}{n_0} x_c^{(n)} = \sum_{i<n} x_c^{(i)} w^{(i)}$$

**δn grows along the beam. Betatron oscillations of each beamlet are different.**

**Suppression mechanism**

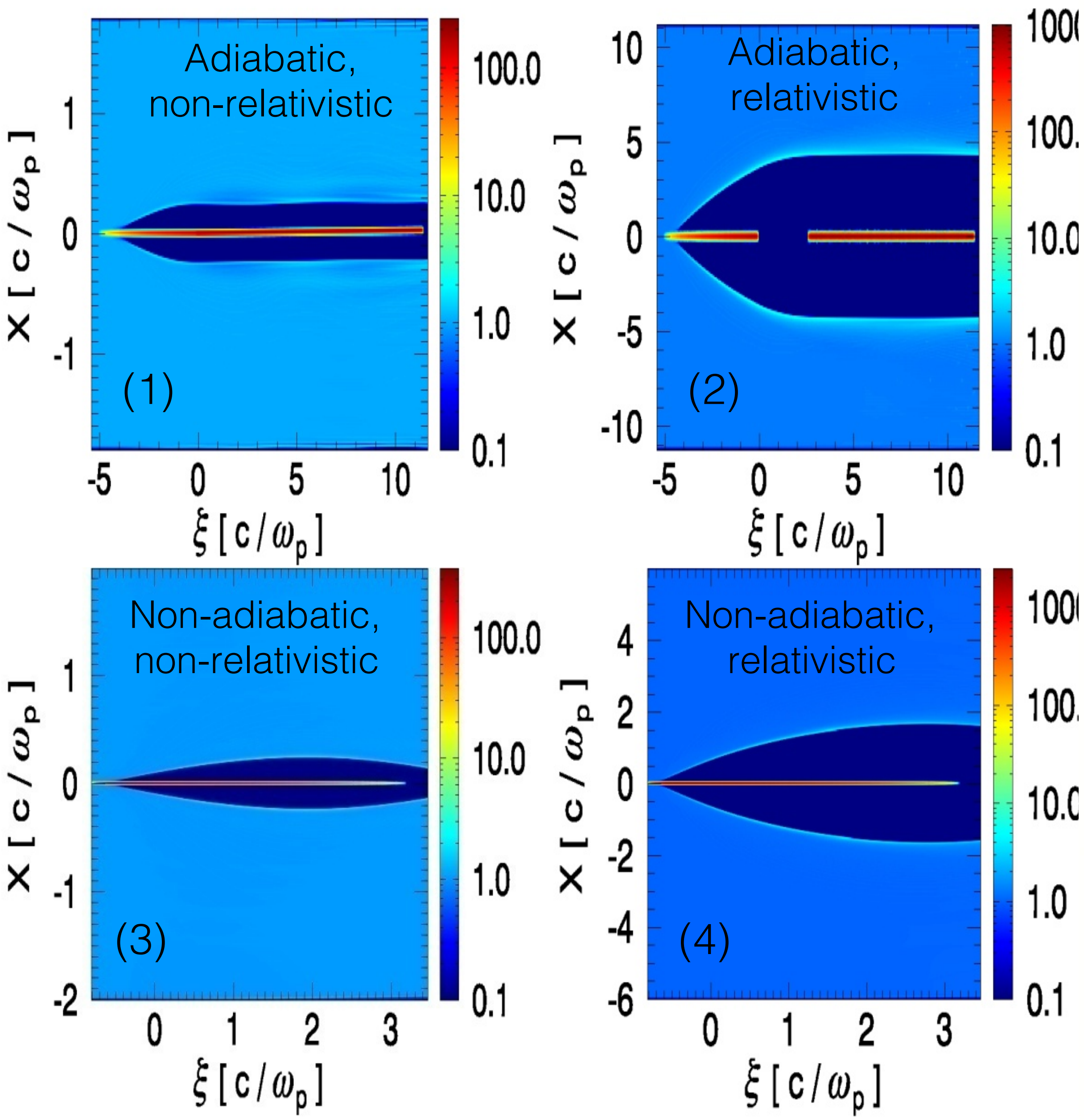
- Secular wakefield growth prevents resonant centroid oscillations
- Betatron frequency detuning due to resonant wakefield excitation
- Analogous to BNS damping!

# Theory including relativistic effects is in very good agreement with simulations

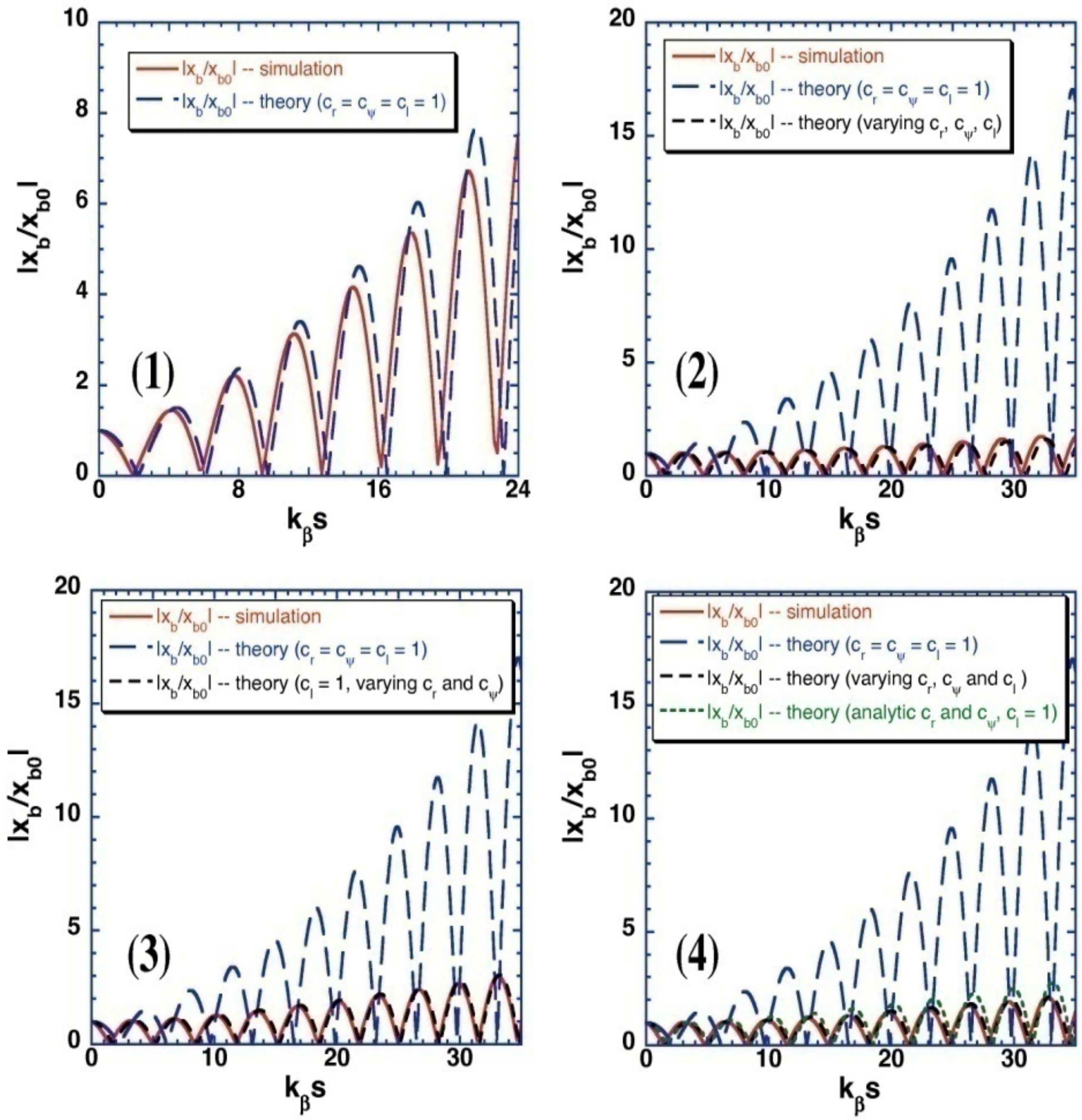
**Asymptotic solution:**

$$x_b / x_{b0} = 0.341 \cdot \alpha^{-3/2} e^{\alpha} \cos(k_\beta s - \alpha/\sqrt{3} + \pi/4)$$

$$\alpha = 1.3\left[c(\xi)(k_\beta s)(\omega_0 \xi)^2\right]^{1/3}$$




Excellent agreement between simulation and theory




D. H. Whittum, PRL 67, 991 (1991)

C. K. Huang et al. PRL 99, 255001 (2007)

# Recent progresses indicate that hosing of the driver beam can be suppressed

## Hosing mitigation mechanisms

**BNS damping**

- Detuning the betatron frequency of each beam slice (energy chirp)
- Doable for drive beam, but not for witness beam (e.g. misalimgnent in staging)

**External quadupole focusing?**

Should be much larger than focusing from wakefield

**Introduce ion motion?**

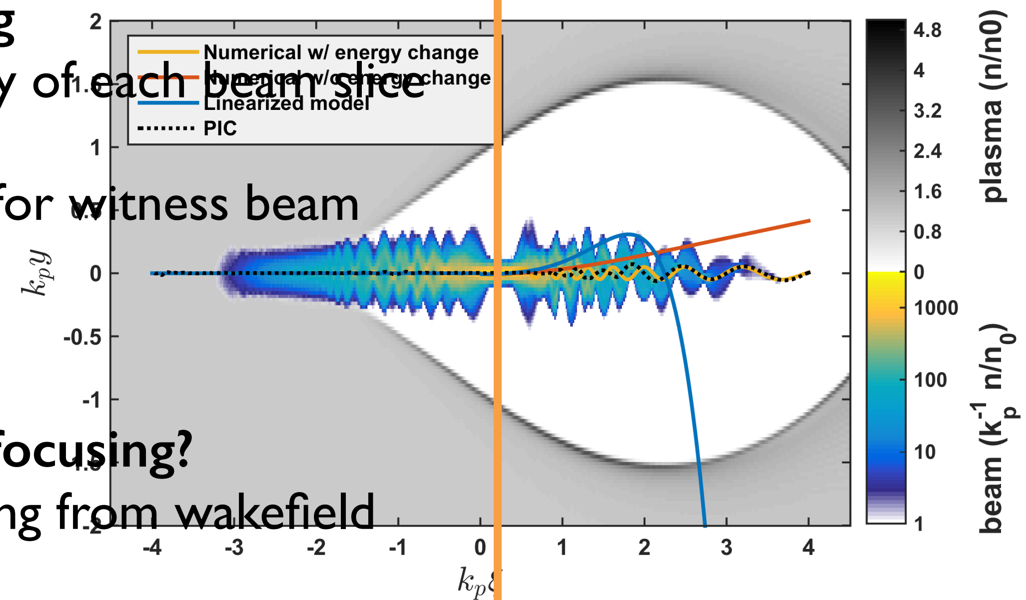
Ion collapse causes localized nonlinear focusing force

Could be a problem for emittance conservation

**Common understanding of transverse instabilities in high gradient accelerators (e.g. Plasma, Dielectric)?**

**Adapted from C. Huang (LANL)**

## s and simulations




**Hosing mitigation and damping**

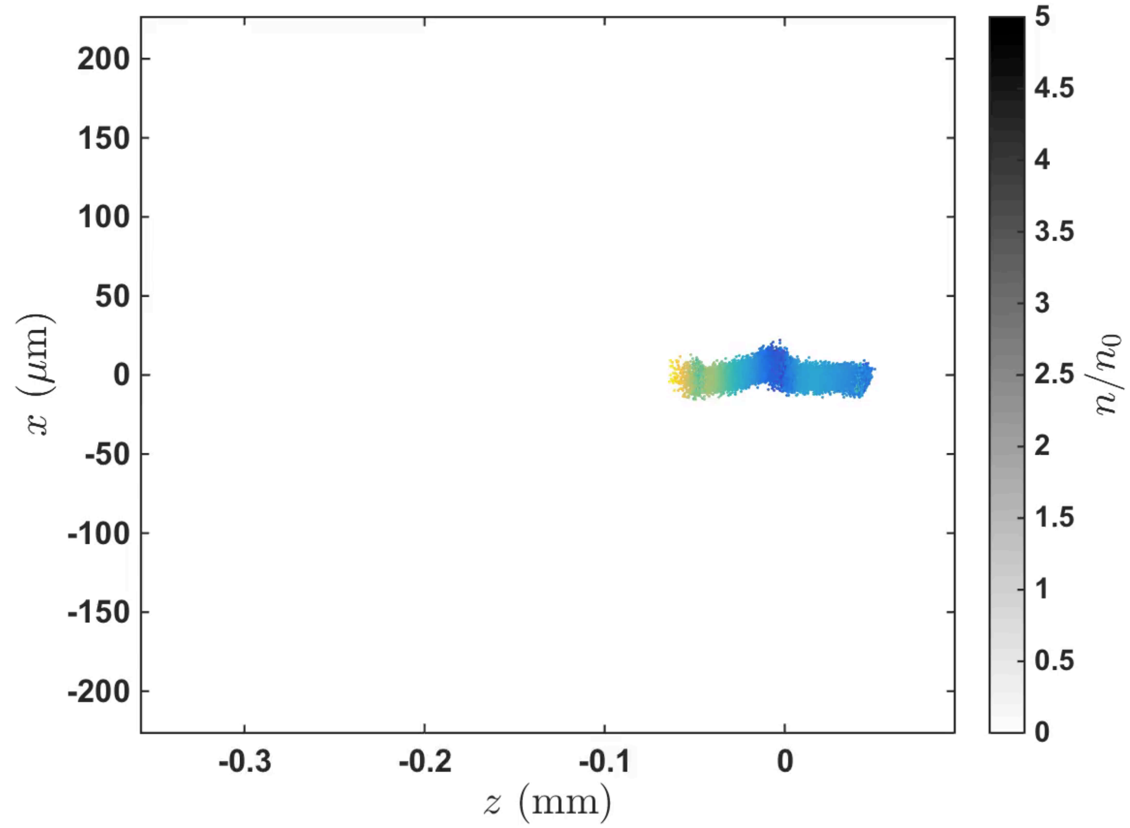
- New model incorporates energy change and energy spread
- Energy change detunes betatron frequencies in time and space
- Energy spread decouples oscillations

**T. Mehrling *et al.* in preparation (2016)**

# Hosing in the short beam limit for a single bunch

**Hosing can still be an issue**

**Large enough initial seeds can cause the hosing instability to grow and destroy the driver beam**




**T. Mehrling *et al.* in preparation (2016)**

# Hosing in the short beam limit for a single bunch

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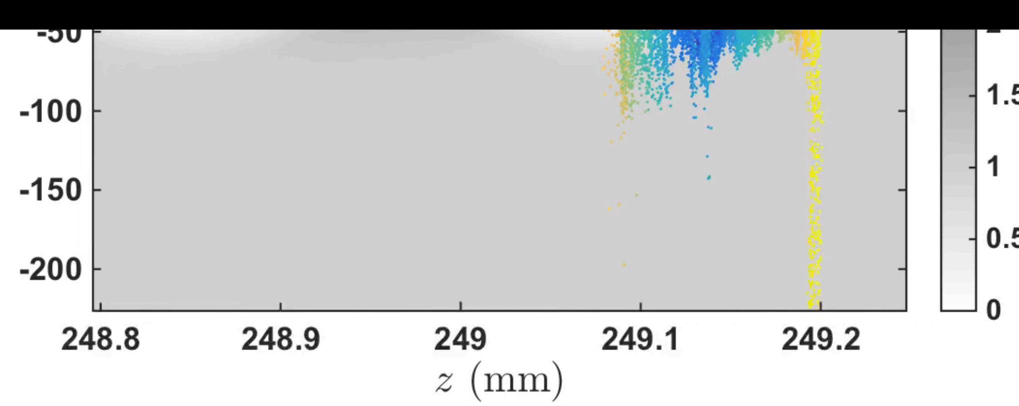
Large enough initial seeds can cause the hosing instability to grow and destroy the driver beam

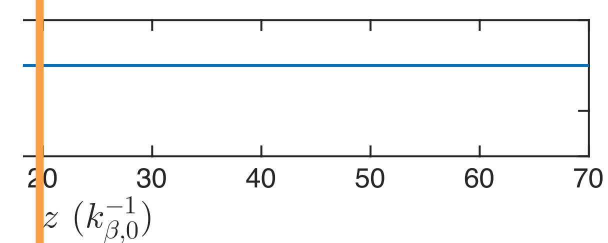



## ng initial seed

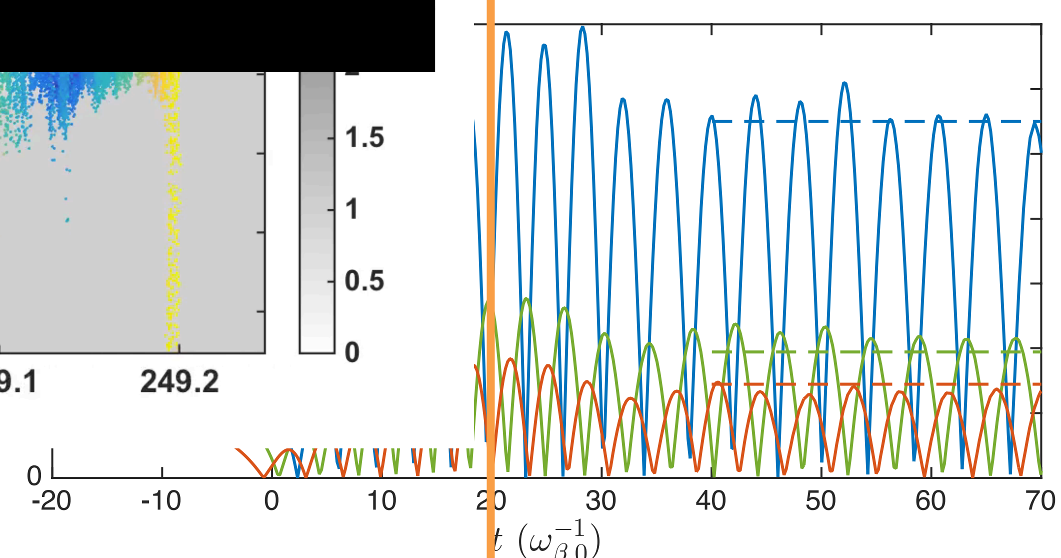
**Key idea:**

Plasma taper such that beam particles perform roughly 1/4 betatron oscillation

**Tappered plasma profile**




**of centroid oscillations**




**These schemes have not been applied to witness beam hosing**

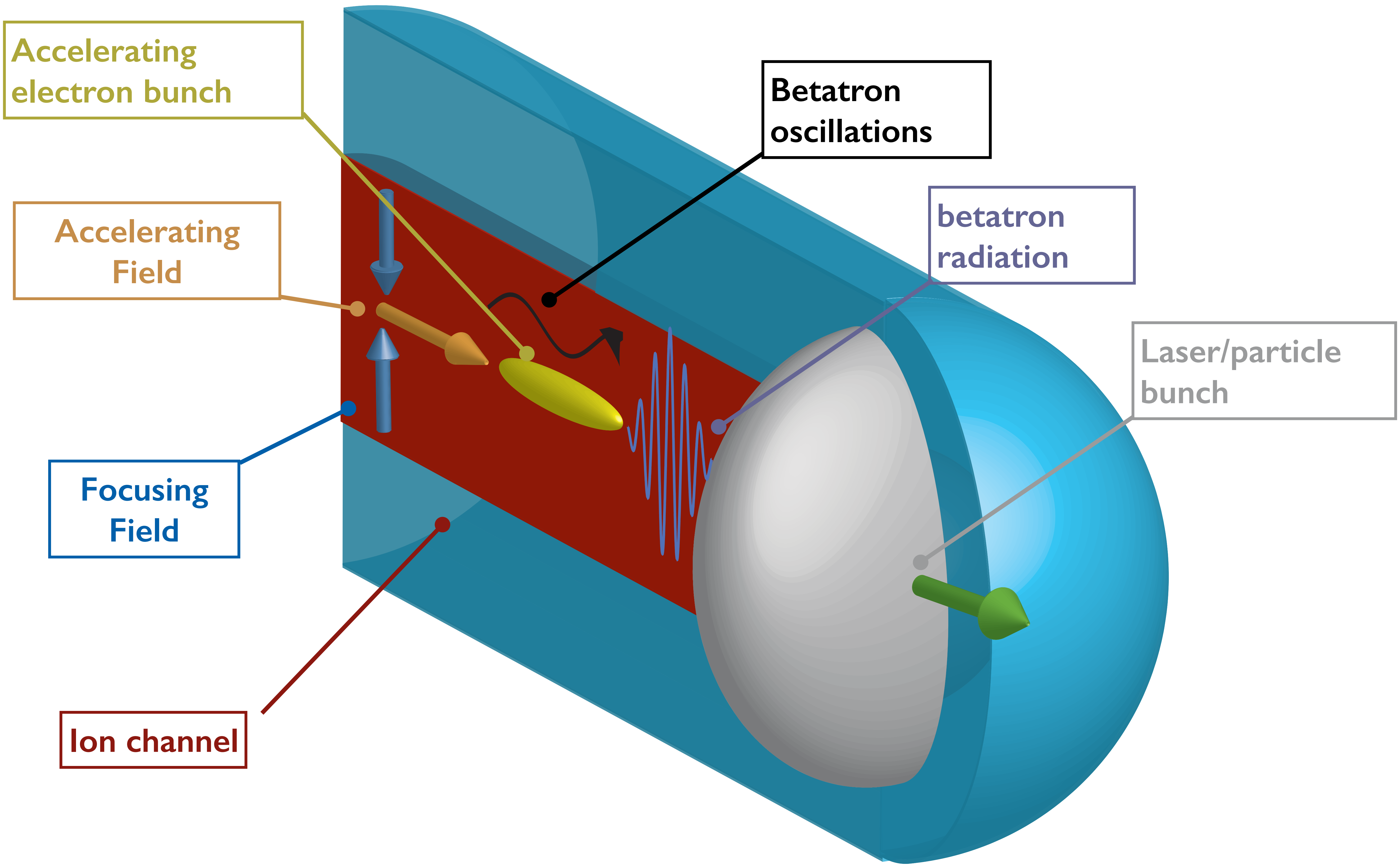
**Hosing of the witness beam is still an open question**

T. Mehrling *et al.* in preparation (2016)

**Hidden topic**

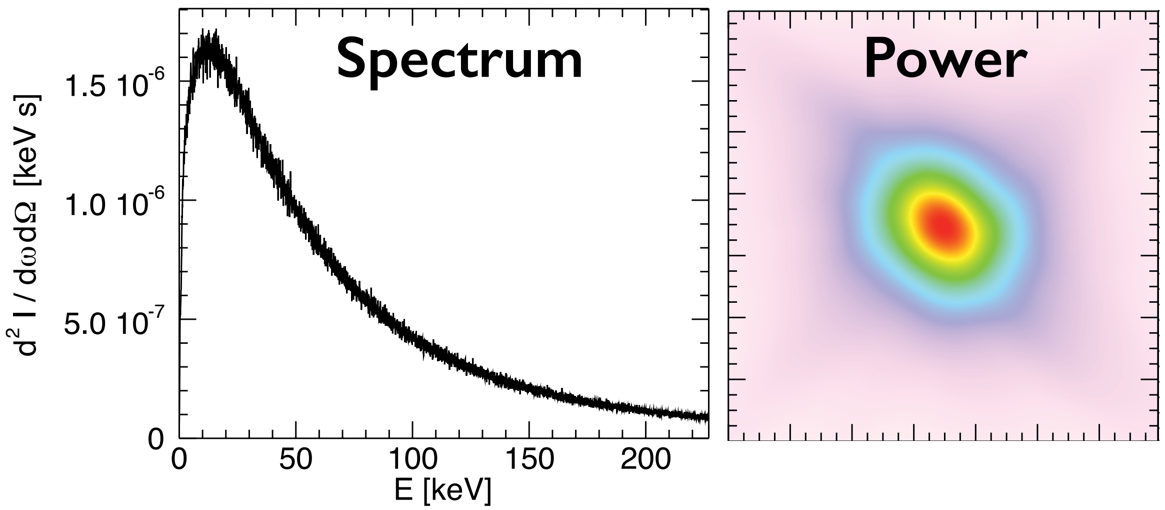
Can we produce a plasma-based FEL?

# A novel plasma based radiation source can be explored at ELI: Transverse electron oscillations produce betatron radiation



# Achieving temporal coherence is important to enhance the output energy of x-rays.

## Betatron radiation



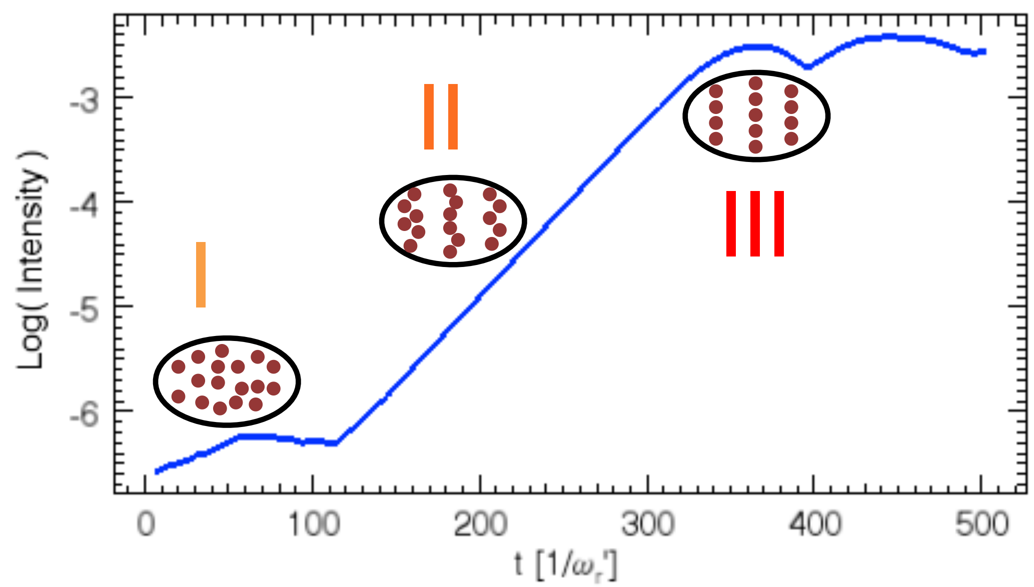

### Main features

- Broad spectrum
- Collimated source (few mrads)
- Multi-keV source

### Applications (so far)

- Warm dense matter
- High resolution imaging

## Self-guiding in nonlinear wakes




I - Random interference $E \sim N_{particles}$

II - Electron bunching (FEL instability) by the emitted radiation and amplification

III - Coherent radiation emission $E \sim N_{particles}^2$

Adapted from X. Davoine

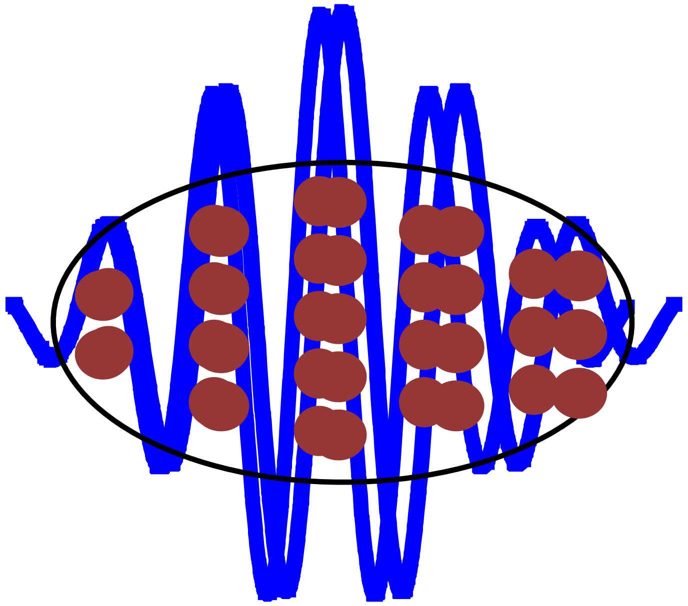
# Conditions for betatron radiation amplification

## A small $\Delta\lambda_r$ is needed

**Spectral width must be sufficiently small**

$\Delta\lambda_r/\lambda_r \ll \rho$

$\rho \ll 1$ is the FEL parameter for the betatron



**If not the amplification is reduced, can be stopped or even completely absent**

## Small $\Delta\gamma$ and $\Delta r_0$ is needed

$$\lambda_r = \frac{2+K^2}{4\gamma_0^2}\lambda_\beta$$

$$\lambda_\beta = 2\pi c\frac{\sqrt{2\gamma_0}}{\omega_p}$$

$$K = r_0 k_p\sqrt{\gamma/2}$$

**Very small energy spreads and narrow beams**

$\Delta\gamma/\gamma \ll \rho$

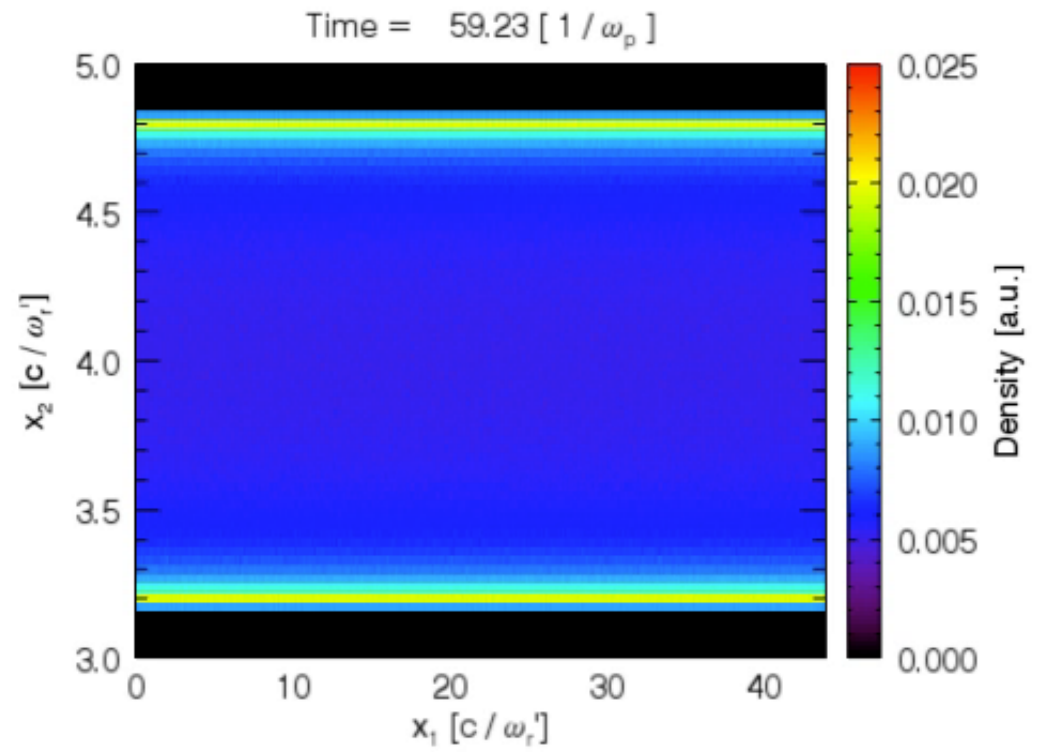
$\Delta r_0/r_0 \ll \rho$

**X. Davoine *et al***

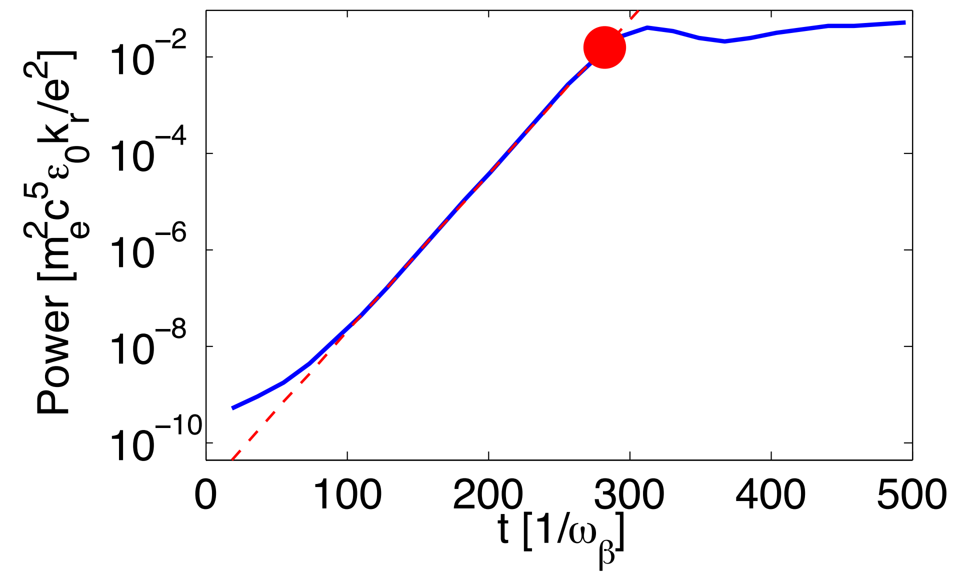
# Two dimensional simulations show that amplification is possible

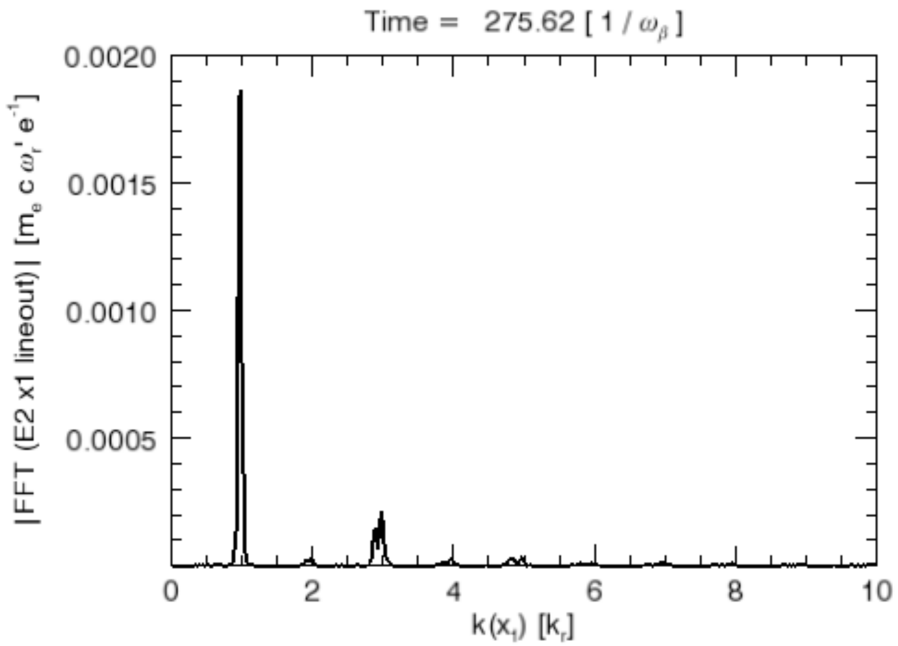
## Initial simulation parameters

- $\gamma_0 = 50$
- $K = 1$
- $I = 0.8$ kA
- $\rho = 4.7\times10^{-2}$




## Power and spectrum

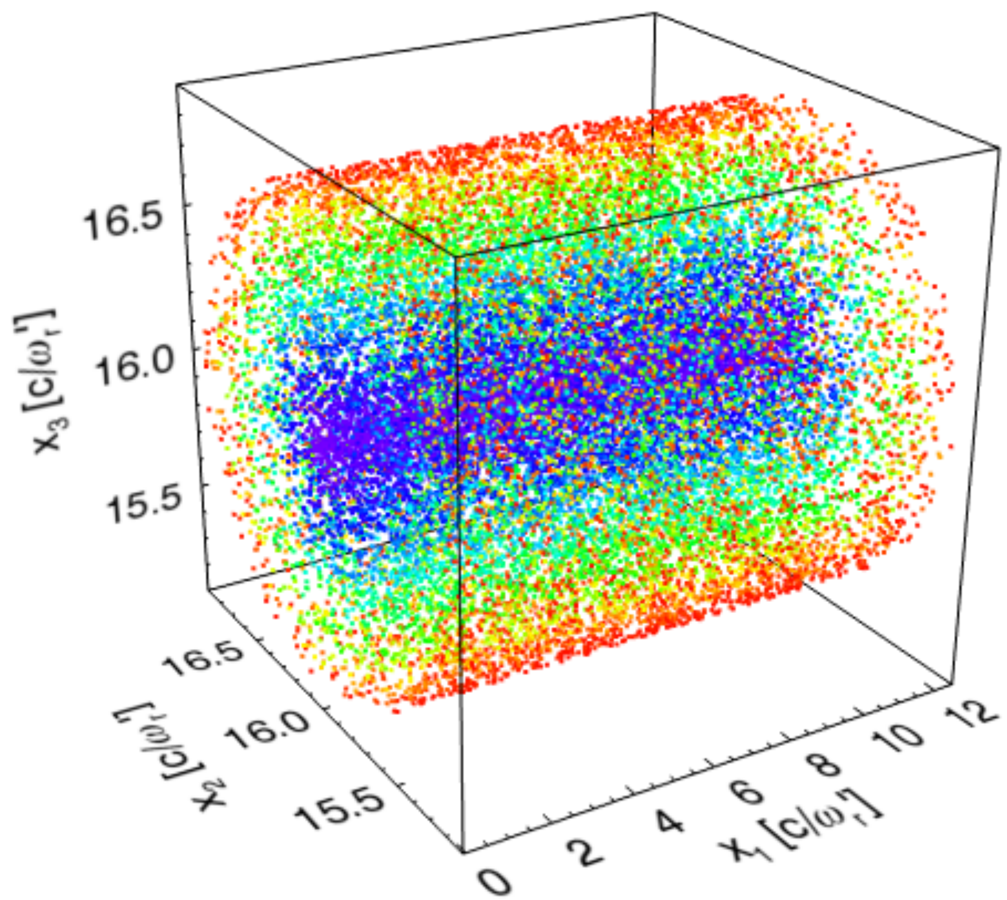


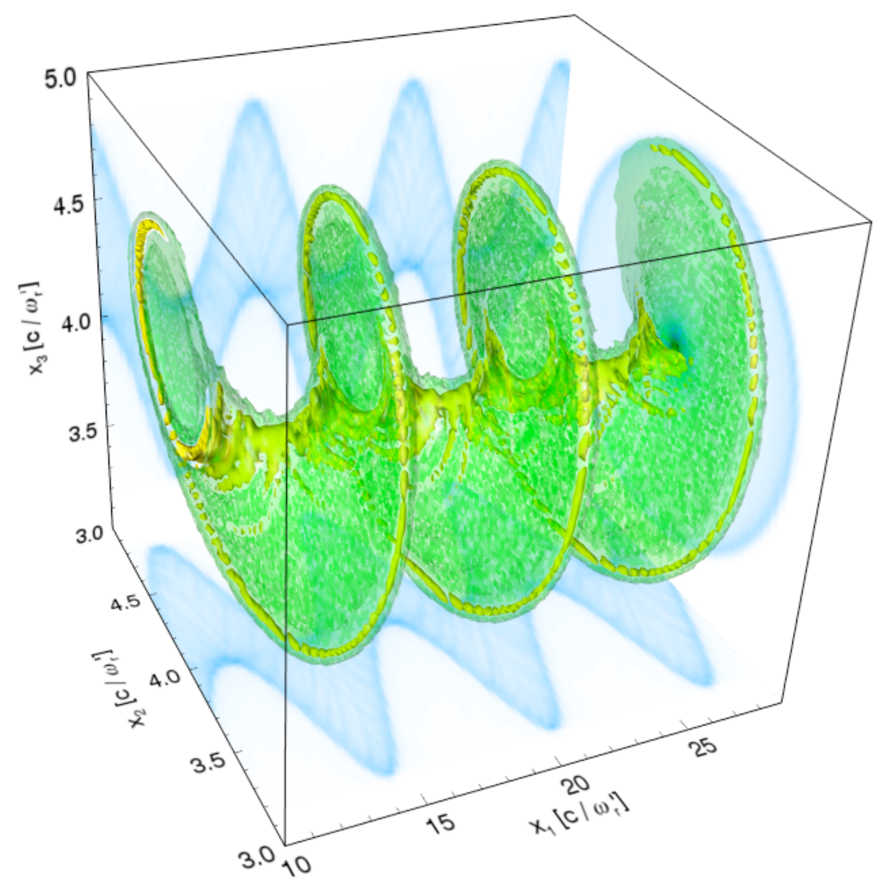

**X. Davoine *et al***

# 3D simulation results also show bunching and coherent betatron emission

## Bunching




## Final bunch density profile

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# Contents

# Conclusions

**Laboratory astrophysics**

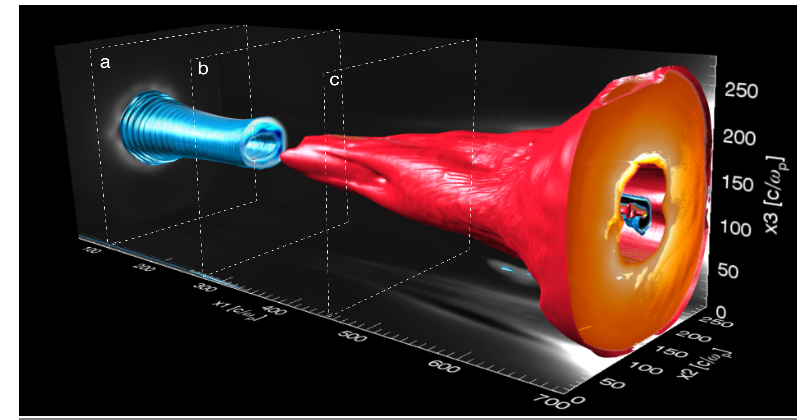
- Plasma accelerators could produce electron (and positron) beams to test instabilities relevant for astrophysics.
- Can we observe shocks in the lab and cosmic ray acceleration analogues?

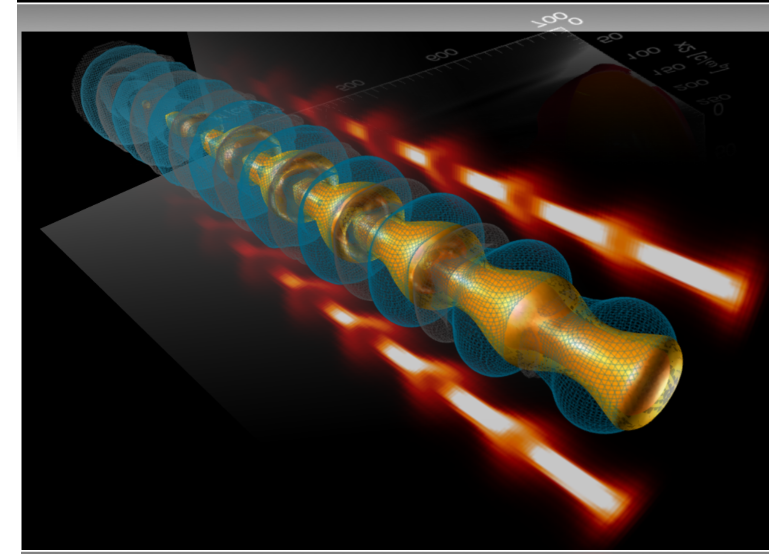
**Low energy spread electron beams**

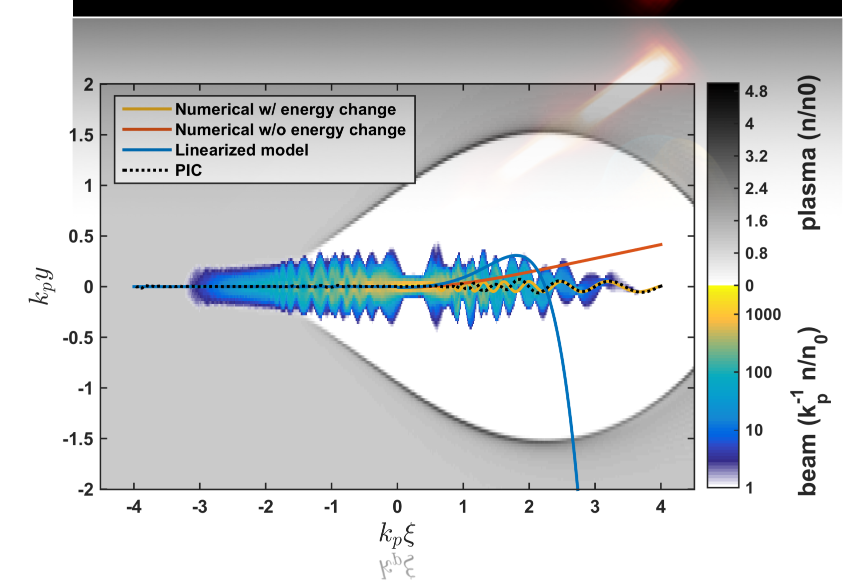
- Energy spreads can be minimised and beam emittance preserved through optimal beam loading
- Can we use current electron beams from plasma accelerators to drive an FEL?

**Hosing and beam break-up**

- Plasma fields can mitigate and damp hosing of the driver
- How can we damp hosing of the witness beam?





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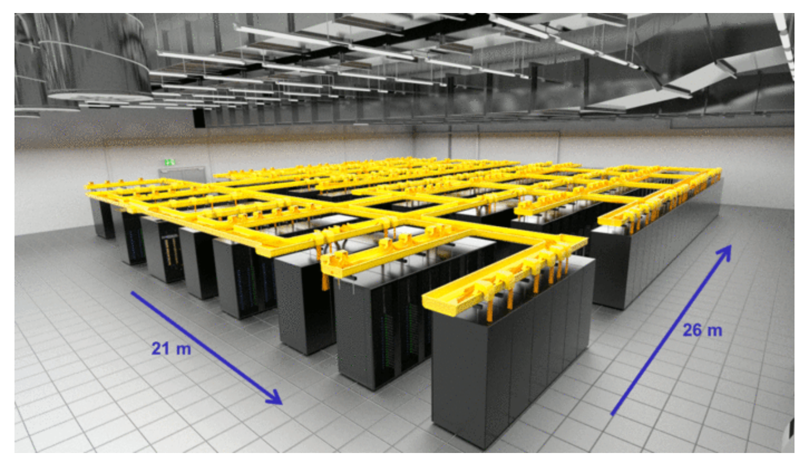


golp grupo de lasers e plasmas

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR