# Plasma Wakefield Acceleration

## An introduction to laser- and beam-driven concepts


**Jens Osterhoff**

Head of Plasma Accelerator R&D

DESY. Accelerator Division


DESY Summer School

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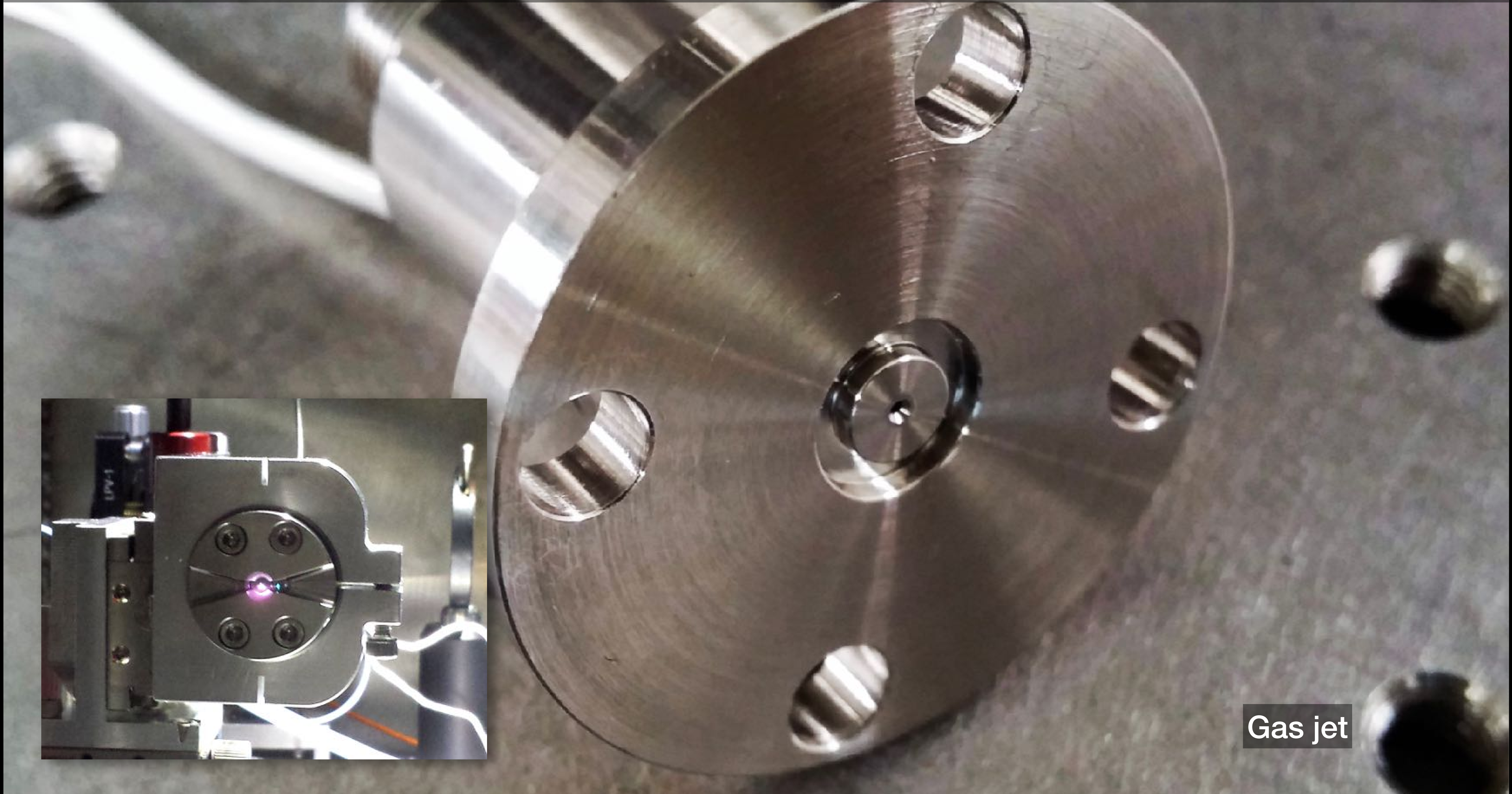
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# Plasmas for accelerators come in many flavors…



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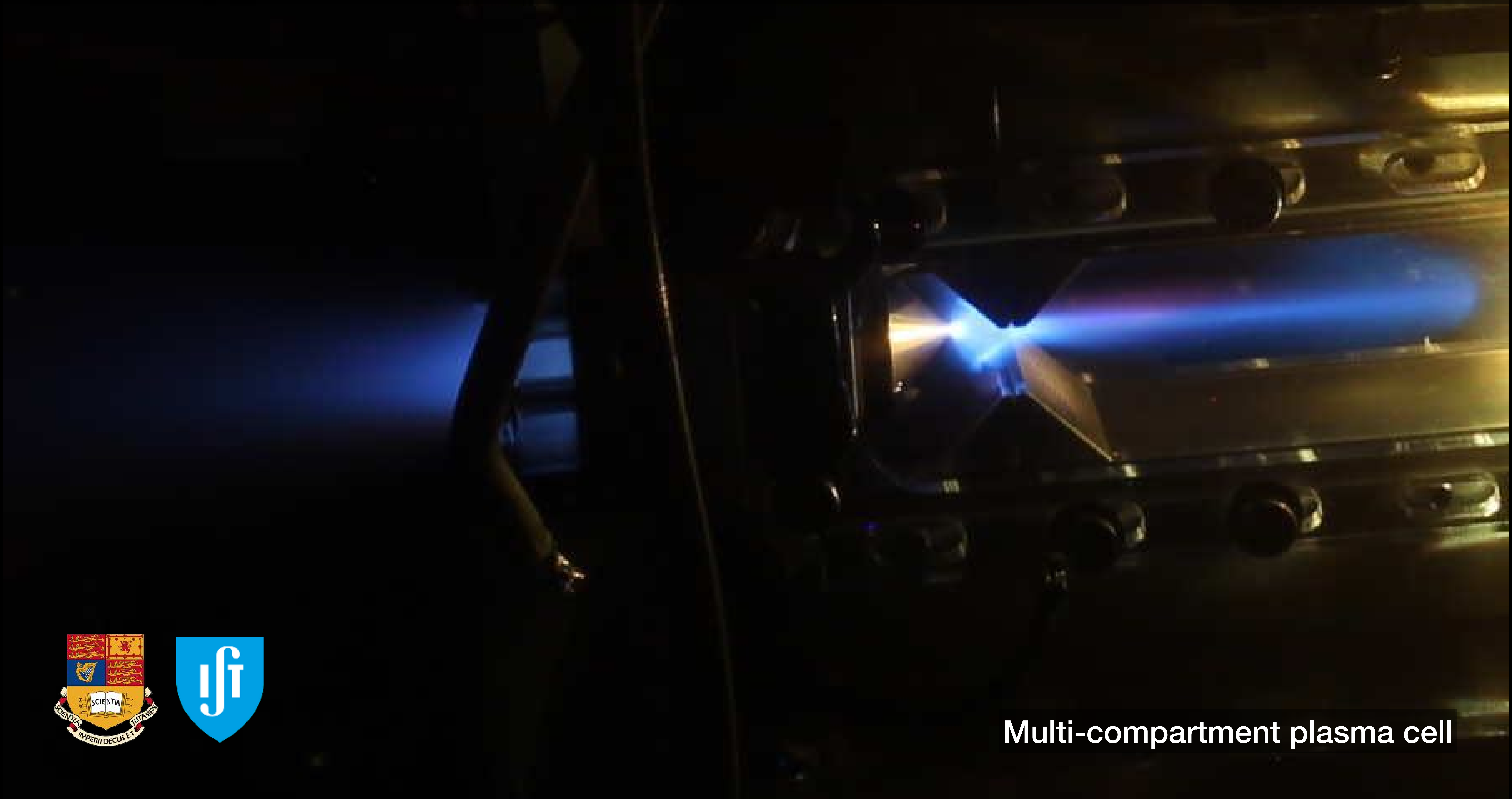
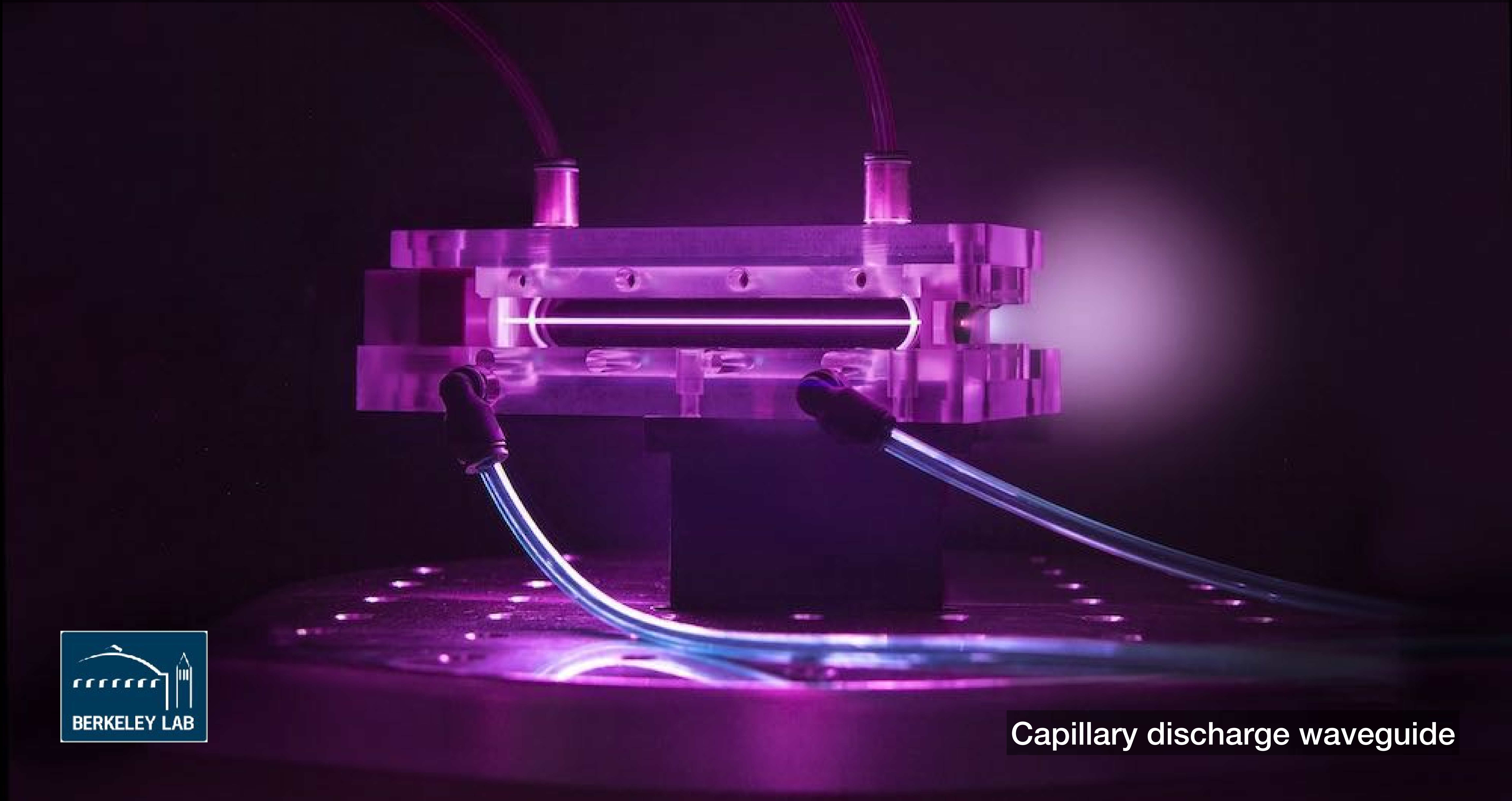


Multi-compartment plasma cell

# Plasmas for accelerators come in many flavors…



Capillary discharge waveguide

# Plasmas for accelerators come in many flavors…

Alkali vapor oven

# Plasmas for accelerators come in many flavors…

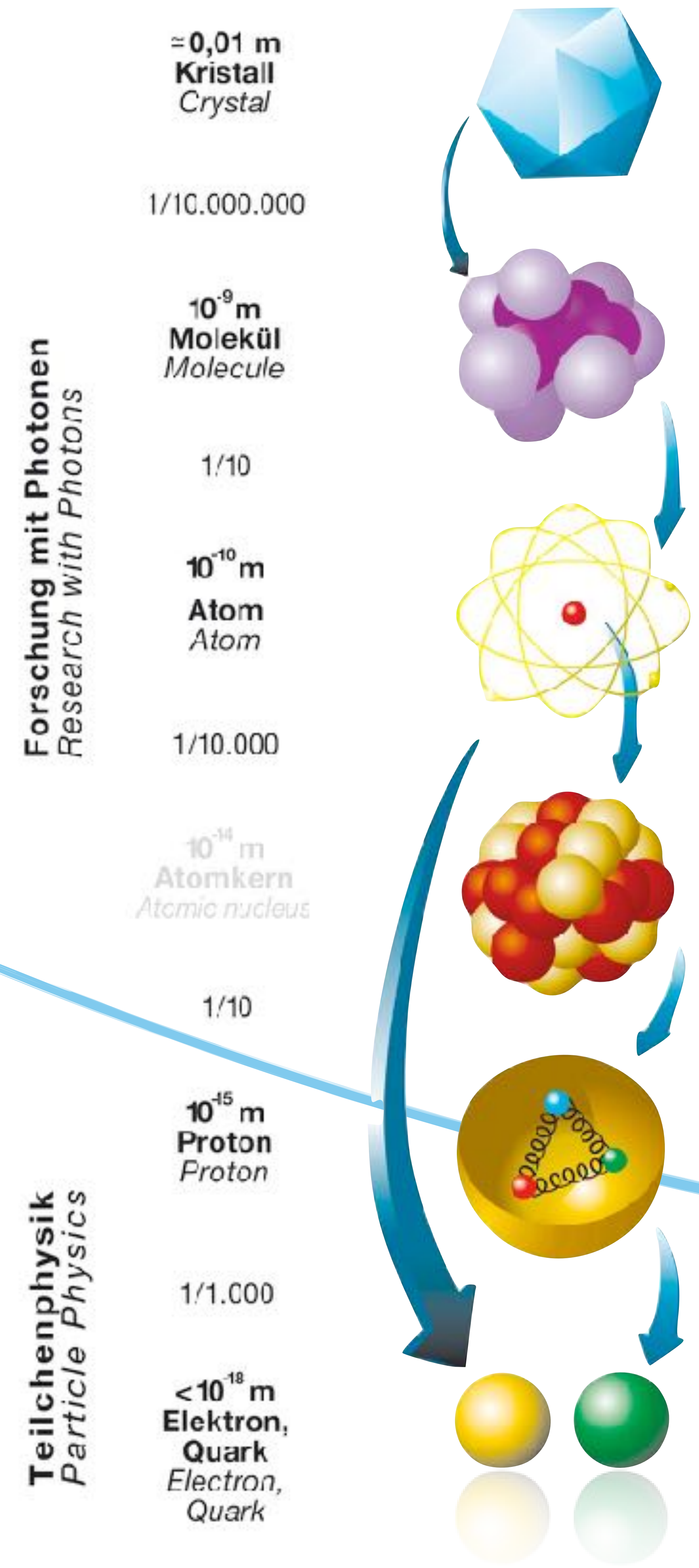
Active plasma lens

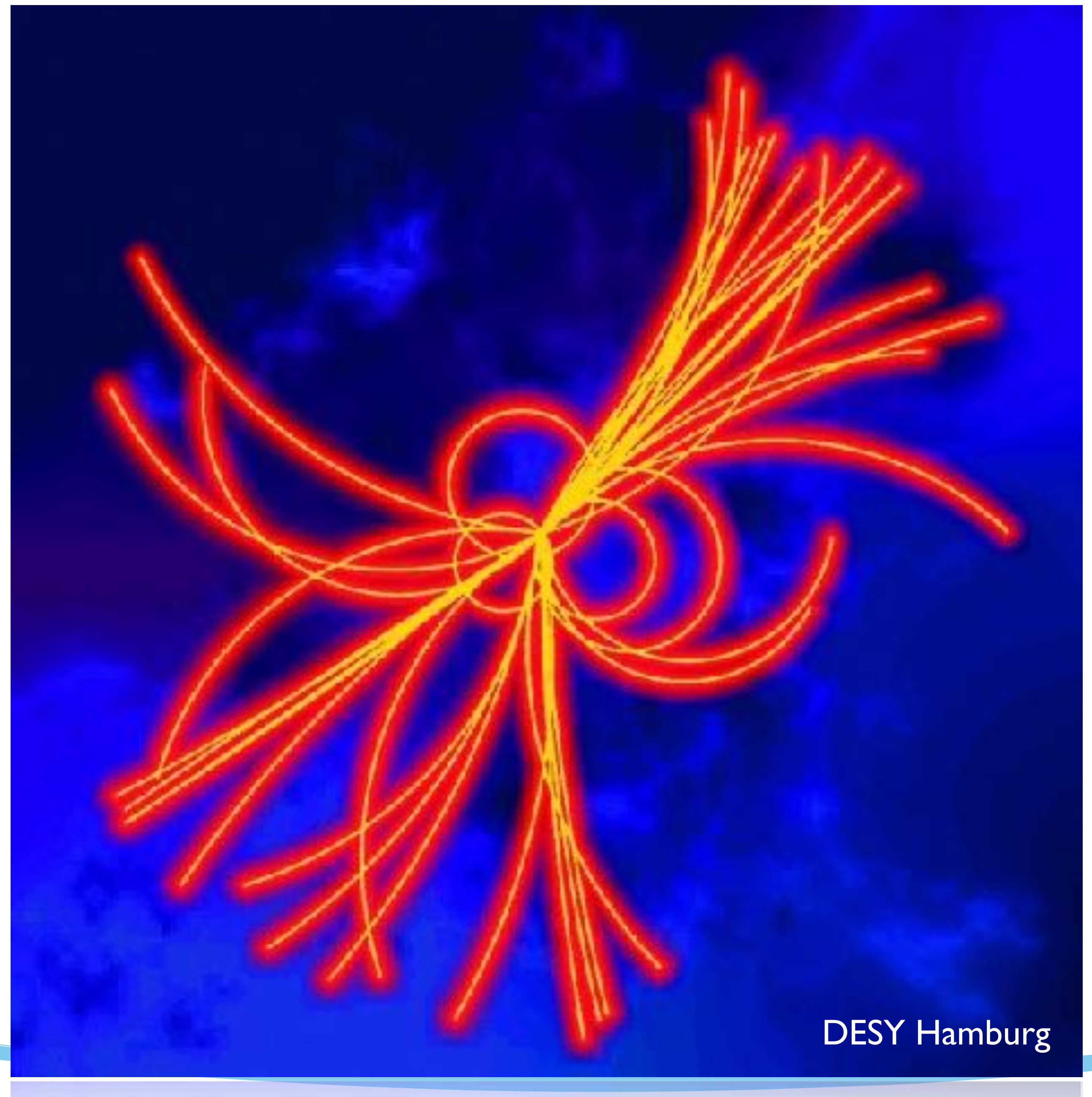
# Outline

- Introduction to laser-driven plasma wakefield accelerators: why do we care?
- Properties of plasma wakefields
- Example of current research: FLASHForward at DESY

# Accelerators are the heart of high-energy photon sources & colliders

## Cutting-edge, high-end slow-motion-cameras and microscopes to study the structure of matter




*Simulation of the decay of a Higgs Boson (LHC, CERN)*

**Particle colliders**
investigation of the fundamental forces and constituents of matter

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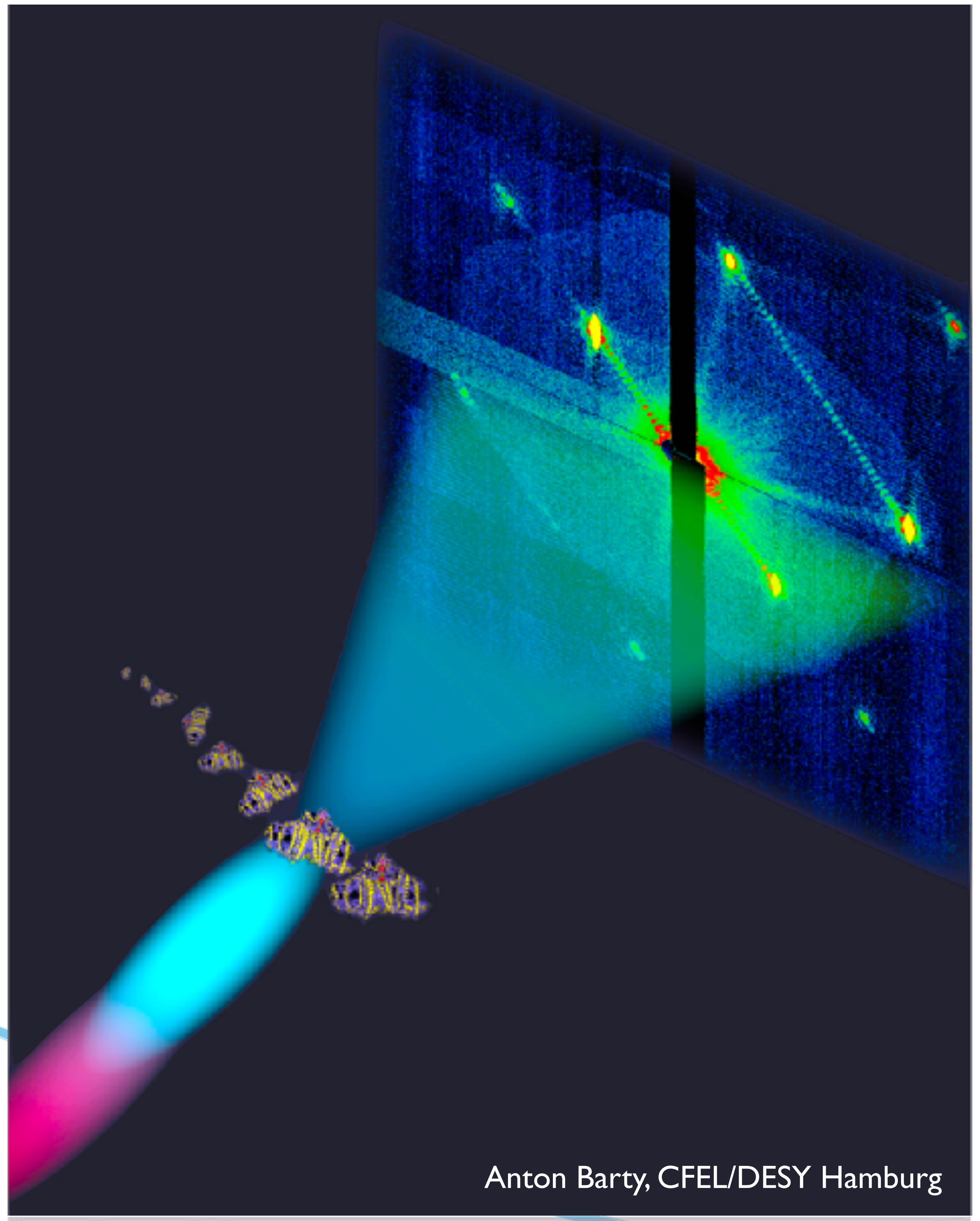
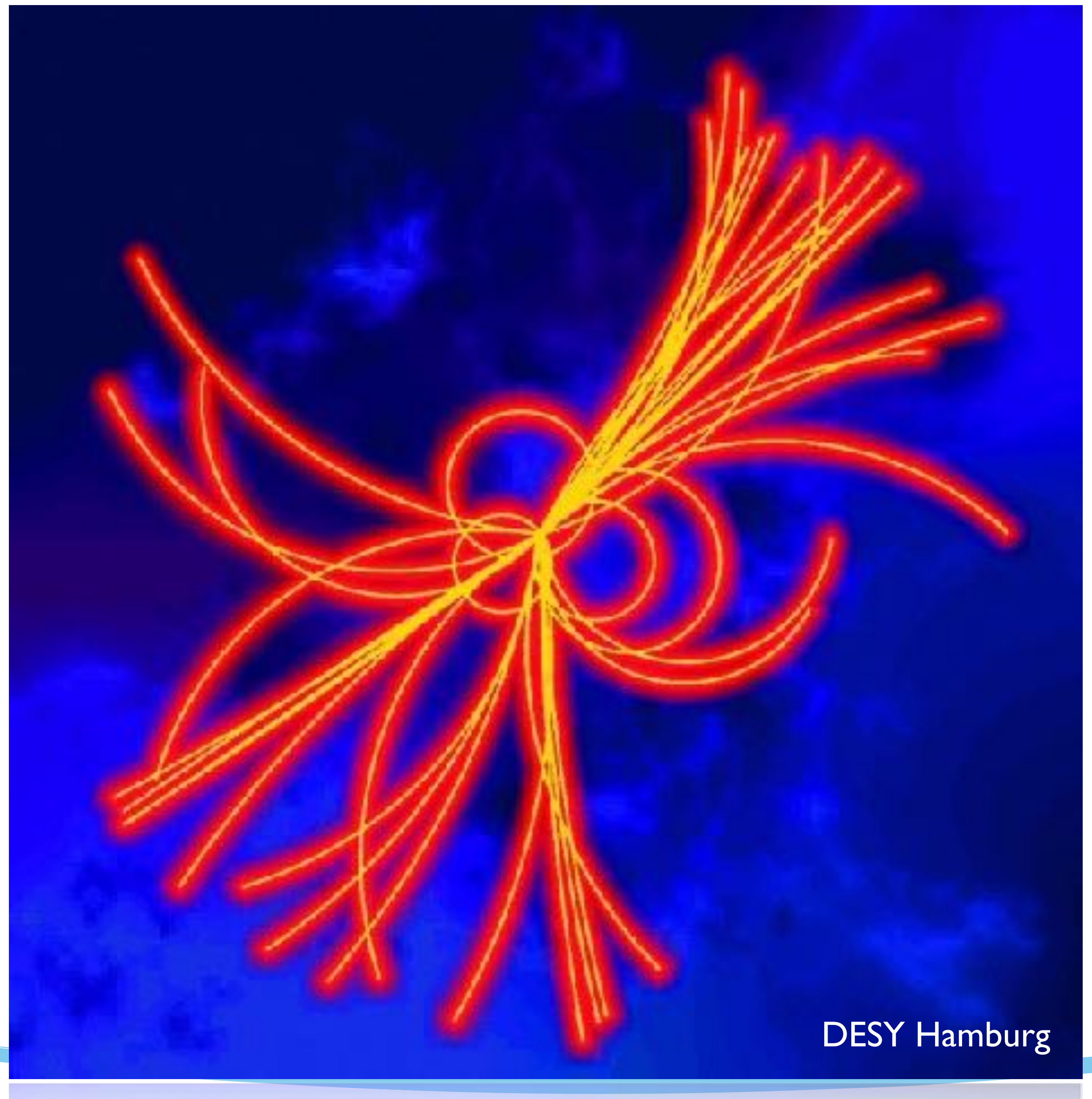



*Illustration of an FEL-pulse diffracting off a protein (XFEL, DESY)*

**Synchrotron photon sources, e.g. Free-Electron Lasers (FELs)**
investigation of processes on atomic and molecular scales

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**Particle colliders**
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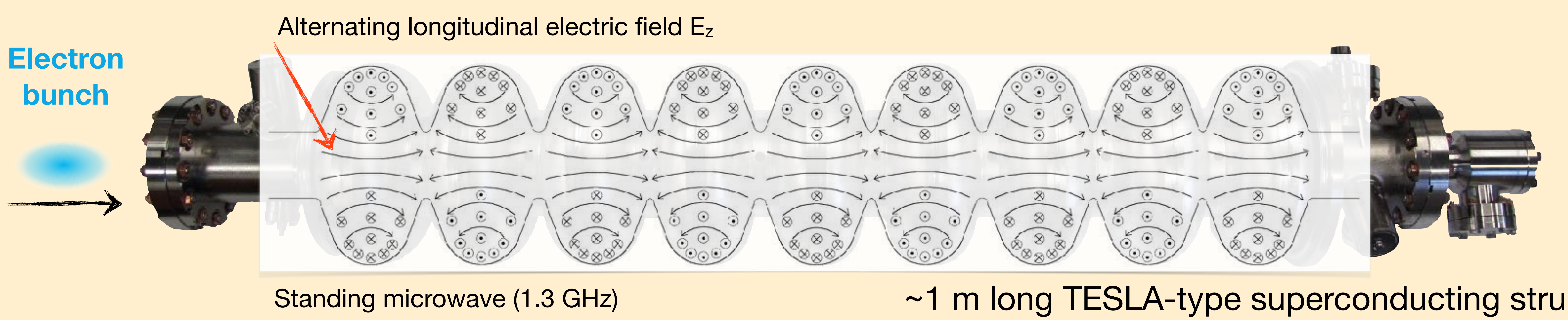
# Accelerators for research are powerful, large scale machines


# What defines the scale length of the accelerator?

## Limits of conventional technology

**Working principle of an RF-cavity**




**The goal:** electrons with well defined energy gain

Kinetic energy gain $\Delta W_{kin} = eE_z d$

Accelerating field strength limited to ~50 MV/m by electrical breakdown

Energy increase can only be achieved by longer acceleration distances!

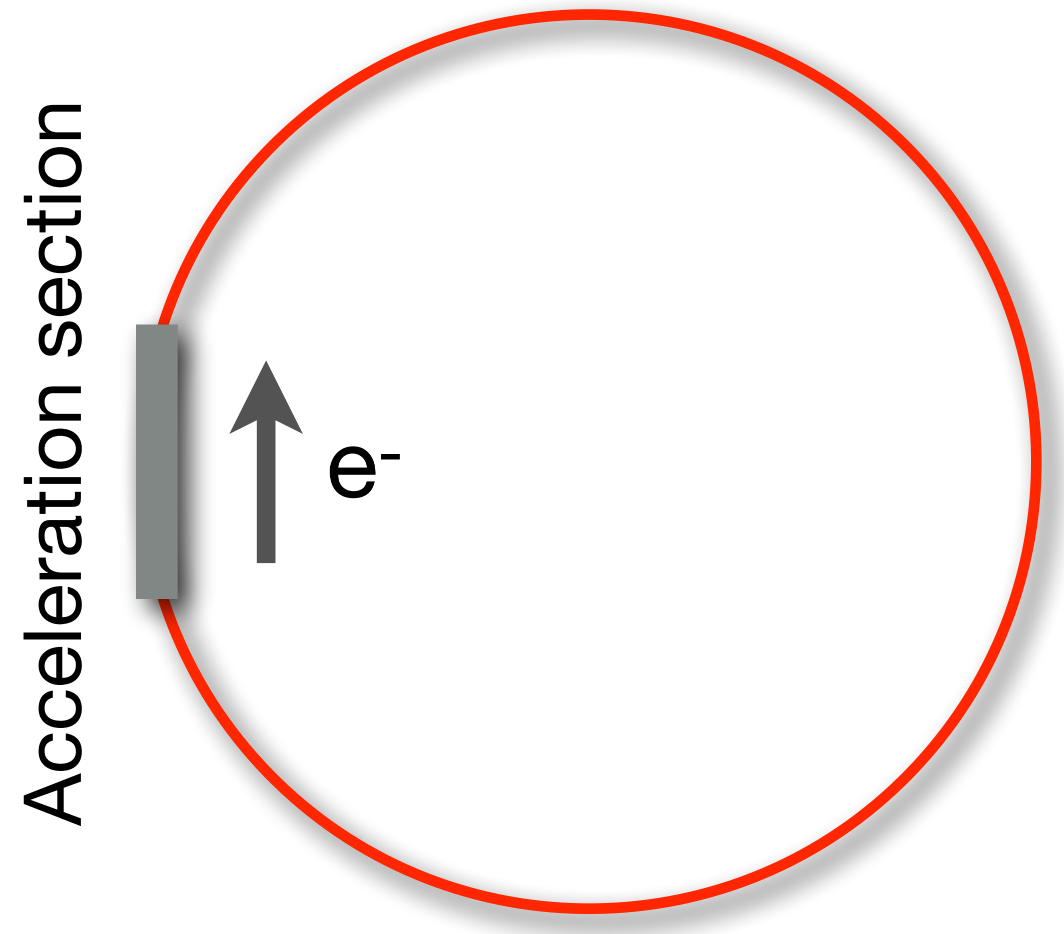
# What defines the scale length of the accelerator?

## Limits of conventional technology

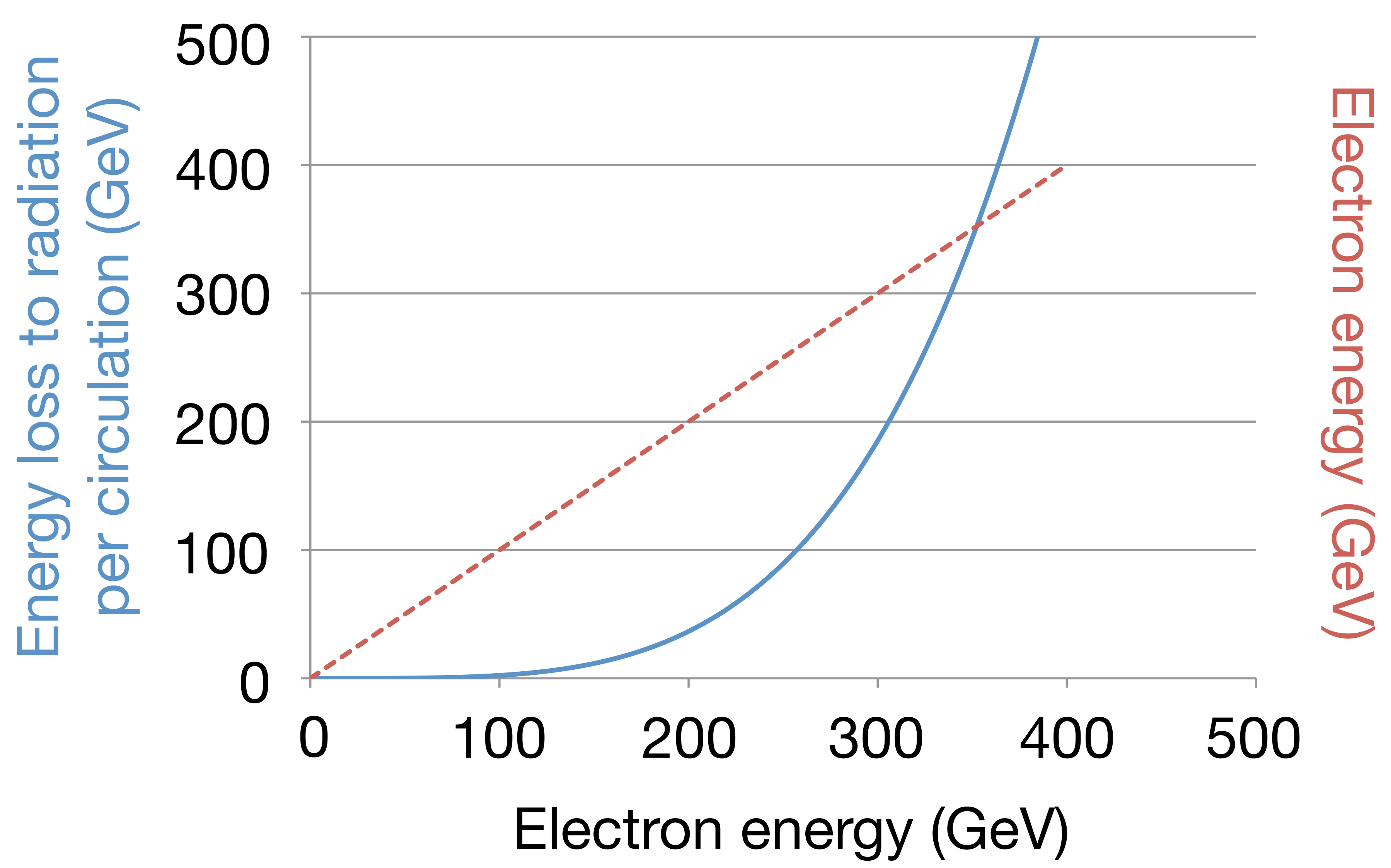
**Ring accelerators for electrons?**

*Advantage:* the same (short) acceleration section may be used multiple times

*Disadvantage:* the energy loss by synchrotron radiation limits the maximum energy (and achievable beam quality: insufficient for X-ray FELs…)




*Example:* utilize the LEP/LHC ring (27 km circumference) for electrons




$$\Delta W_{syn} \propto \frac{1}{r^2} \frac{W_{kin}^4}{(m_e c^2)^4}$$

# Computers shrunk and became super powerful in the past 60 years

**IBM NORC** supercomputer (1954)


Can the same be done with particle accelerators?

What new applications will this enable?

# Plasma is everywhere

## A soup of inoized (broken-down) matter

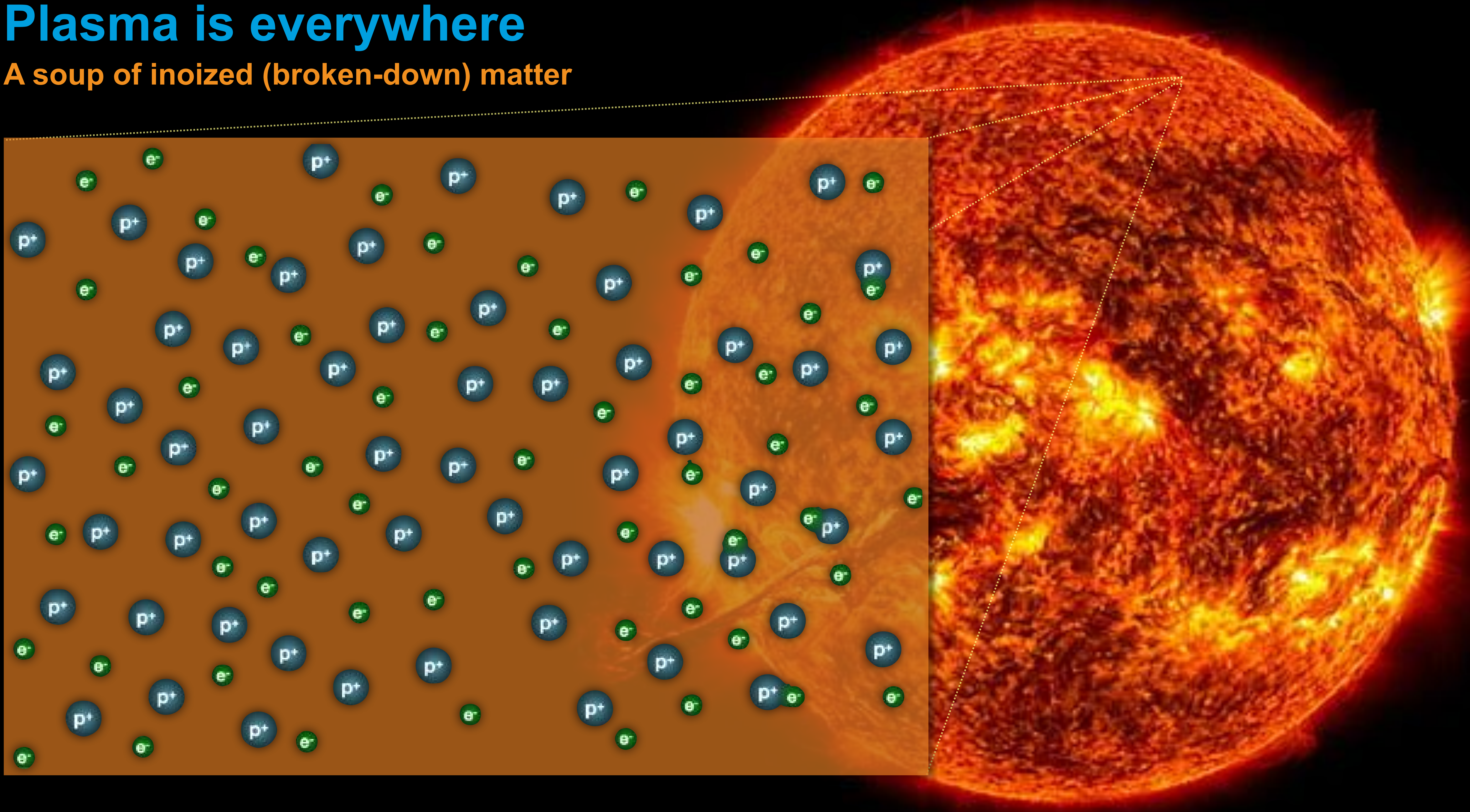
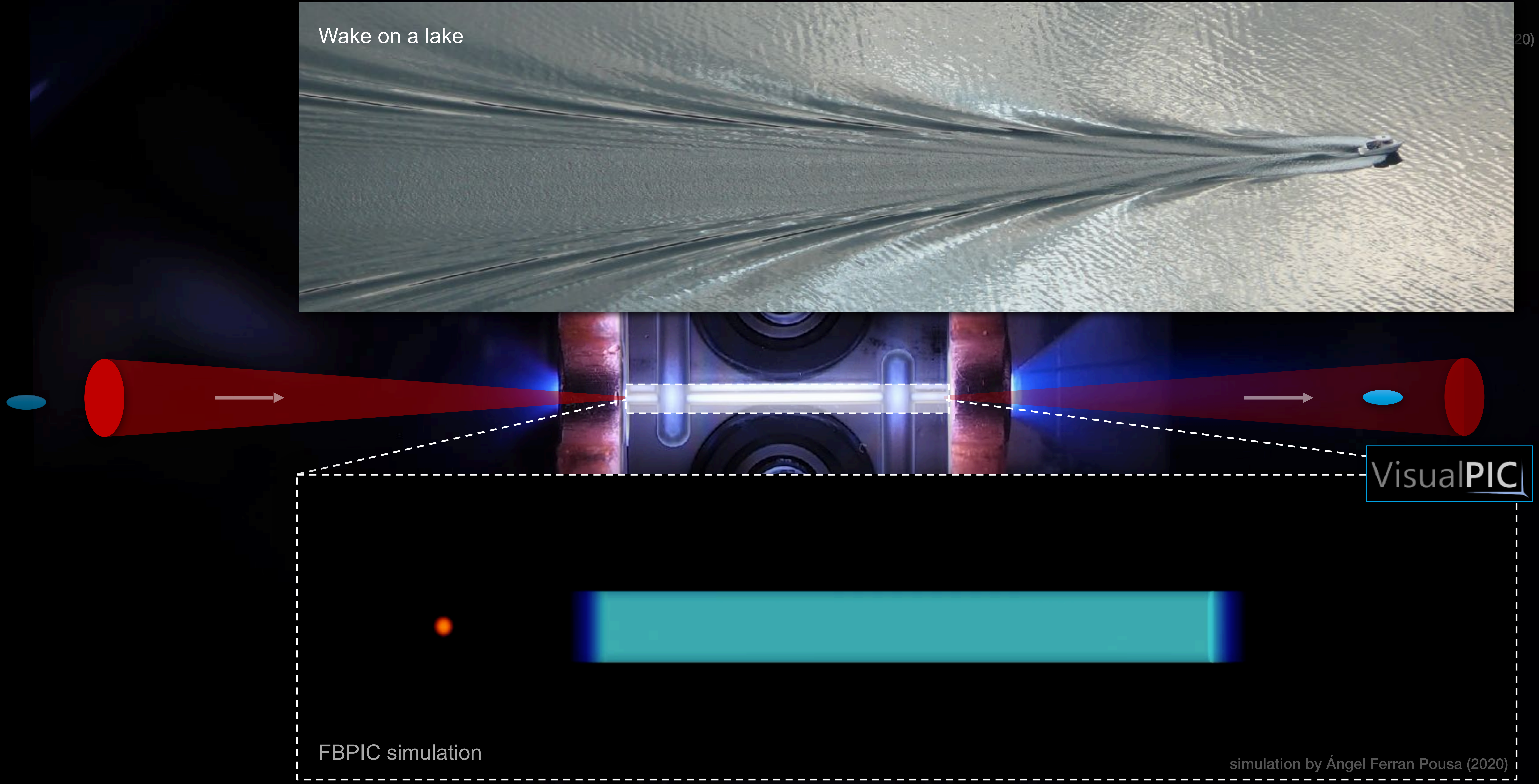
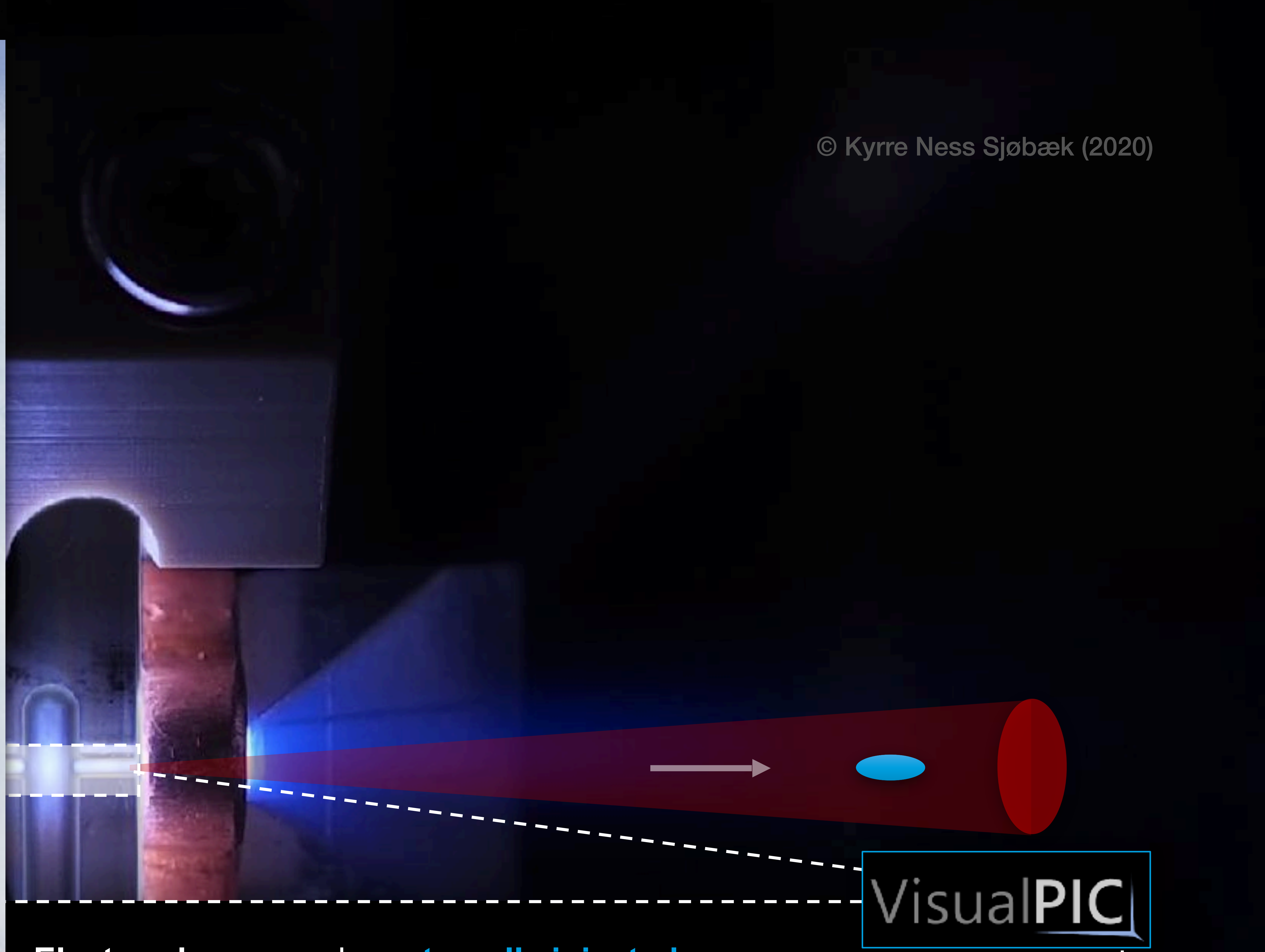


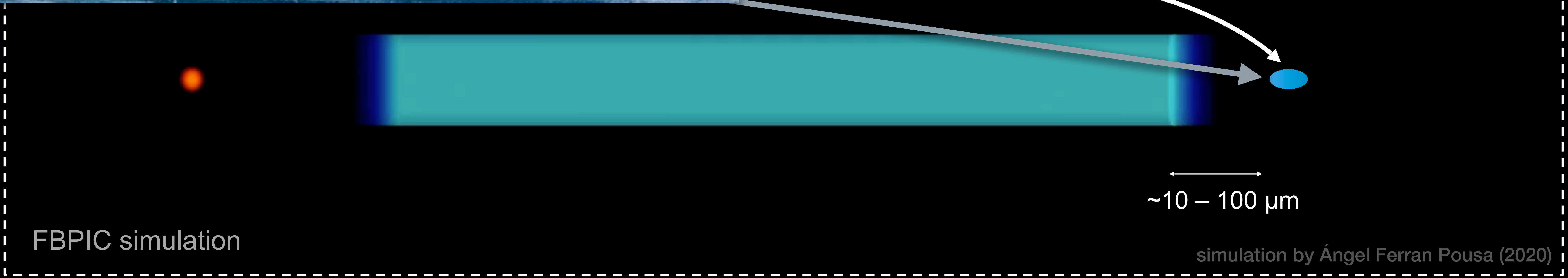

Figure: nasa.gov

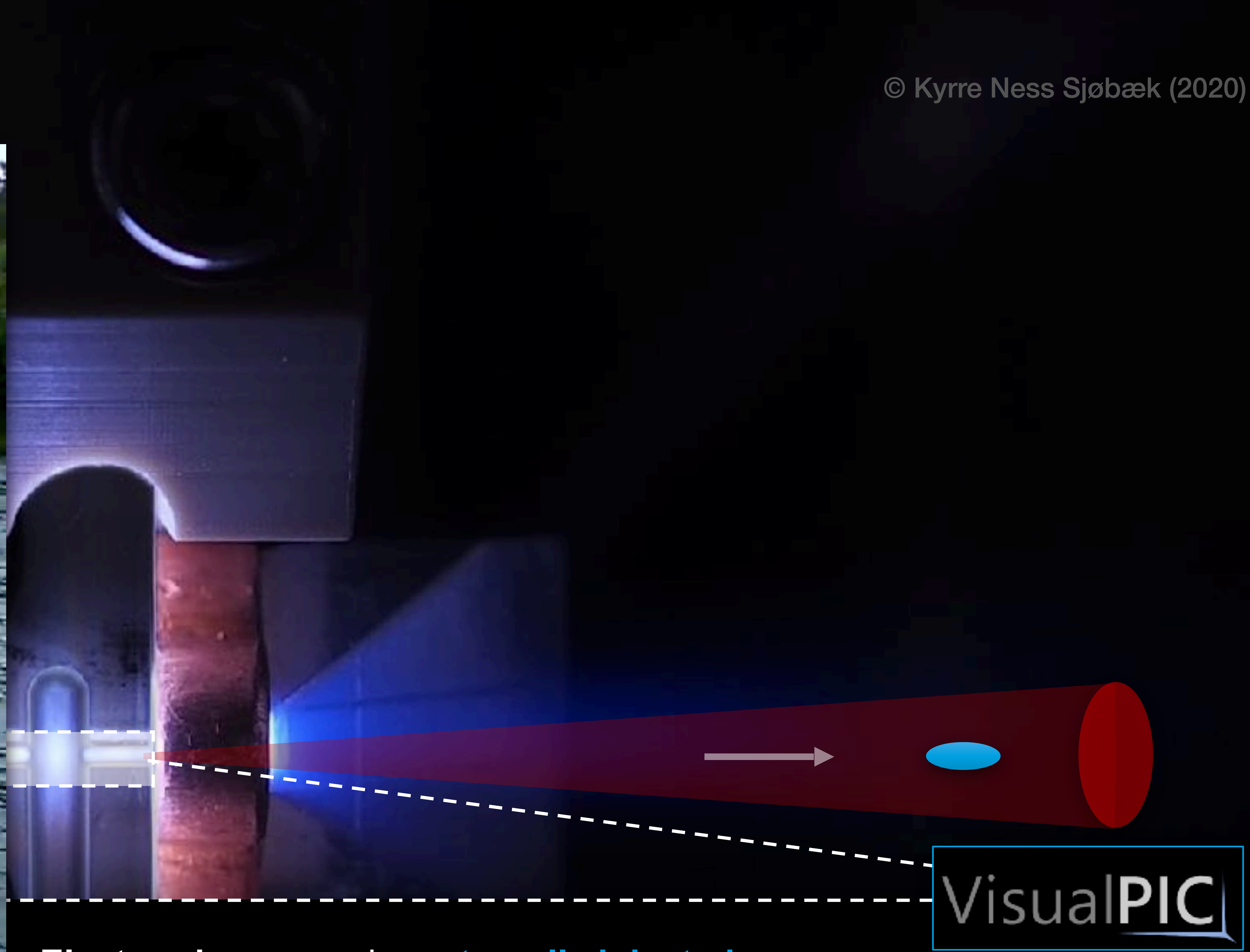

Plasma
source
p+
e-


Wake on a lake
VisualPIC
FBPIC simulation
simulation by Ángel Ferran Pousa (2020)




**Electron beam** can be **externally injected**
or formed from trapped plasma electrons (**internal injection**)



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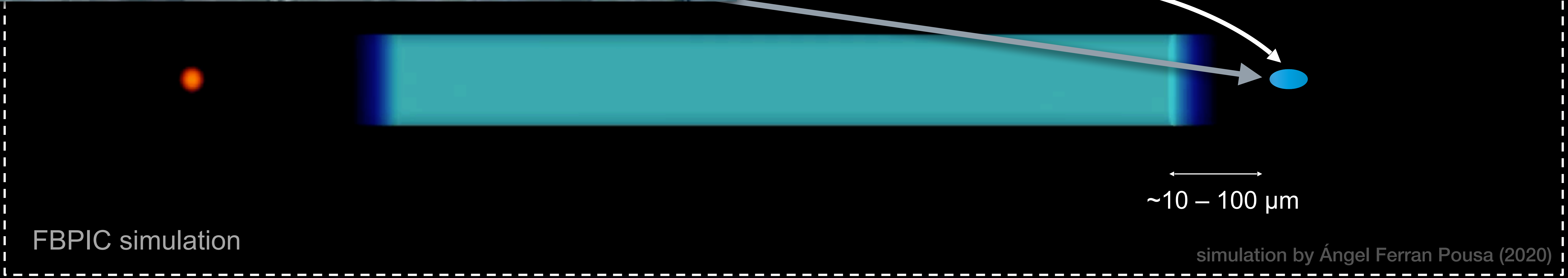
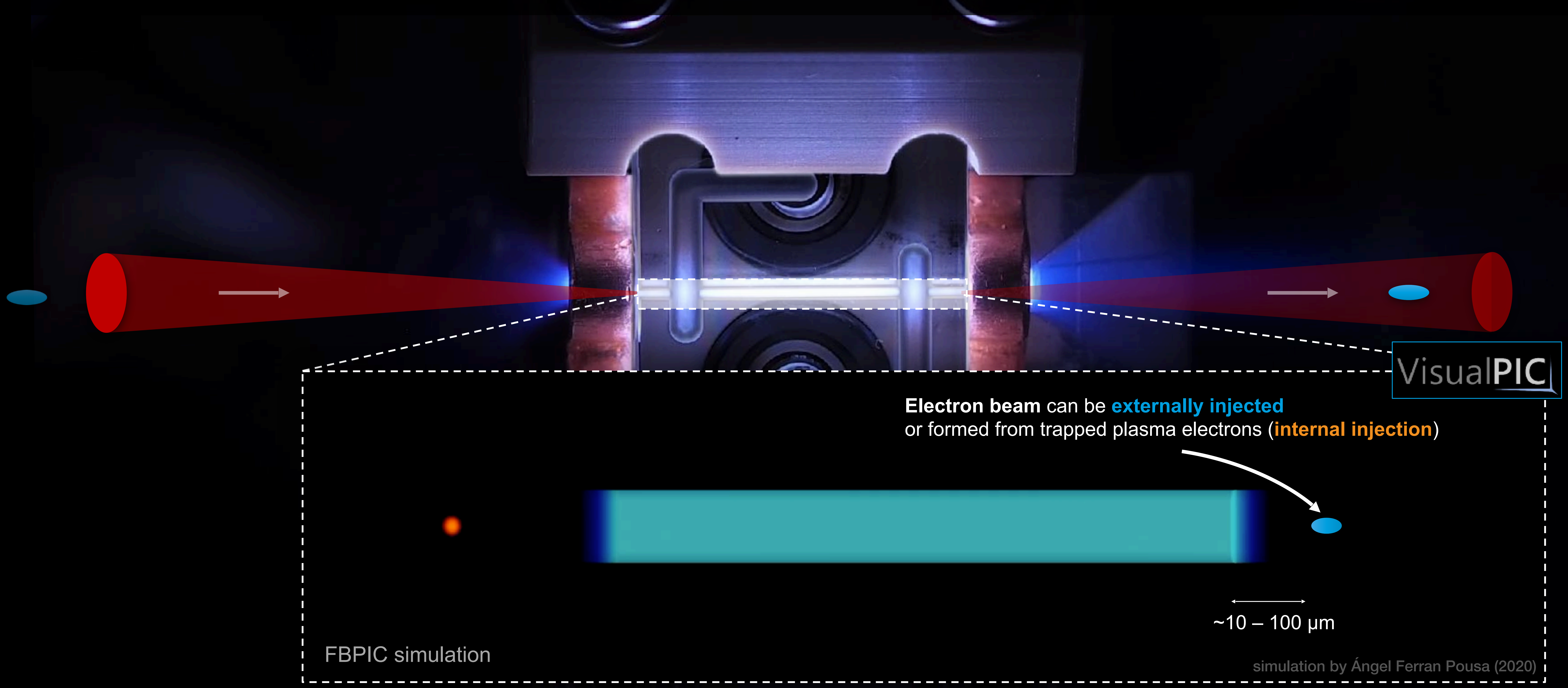


# Plasma accelerators are a centimeter-scale source of GeV beams

→ Leemans *et al.*, Nature Physics **2**, 696 (2006)




**Plasma wakefields** can sustain accelerating fields of up to **~1-100 GV/m** with focusing gradients above **~1 MT/m**

**x1000** more than RF technology

# Simple fluid model for plasma-wave excitation

## 1D in space / 3D in momentum

| | |
|---|---|
| Transverse electron momentum (from equation of motion) | $\gamma\beta_{\mathrm{y}} = a_0$ |
| Longitudinal electron momentum (from equation of motion) | $\frac{d}{dt}(\gamma\beta_{\mathrm{x}}) = c\left(\frac{\partial\phi_0}{\partial x} - \frac{1}{2\gamma}\frac{\partial a_0^2}{\partial x}\right)$ |
| Continuity equation | $\frac{\partial n_{\mathrm{e}}}{\partial t} + c\frac{\partial}{\partial x}(n_{\mathrm{e}}\beta_{\mathrm{x}}) = 0$ |
| Electro-magnetic wave equation | $\frac{\partial^2 a_0}{\partial t^2} - c^2\frac{\partial^2 a_0}{\partial y^2} = -\omega_{\mathrm{p}}^2\frac{n_0 a_0}{\gamma}$ |
| Poisson's equation | $\frac{\partial^2\phi_0}{\partial x^2} = \frac{\omega_{\mathrm{p}}^2}{c^2}(n_0 - 1)$ |

→ Transformation into a co-moving frame with

$\tau = t$ and $\xi = x - v_{\mathrm{g}}t$ and *quasi-static approximation*

↓

Resulting differential equation for scalar potential

$$\frac{\partial^2\phi_0}{\partial\xi^2} = \frac{\omega_{\mathrm{p}}^2}{c^2}(n_0 - 1)$$

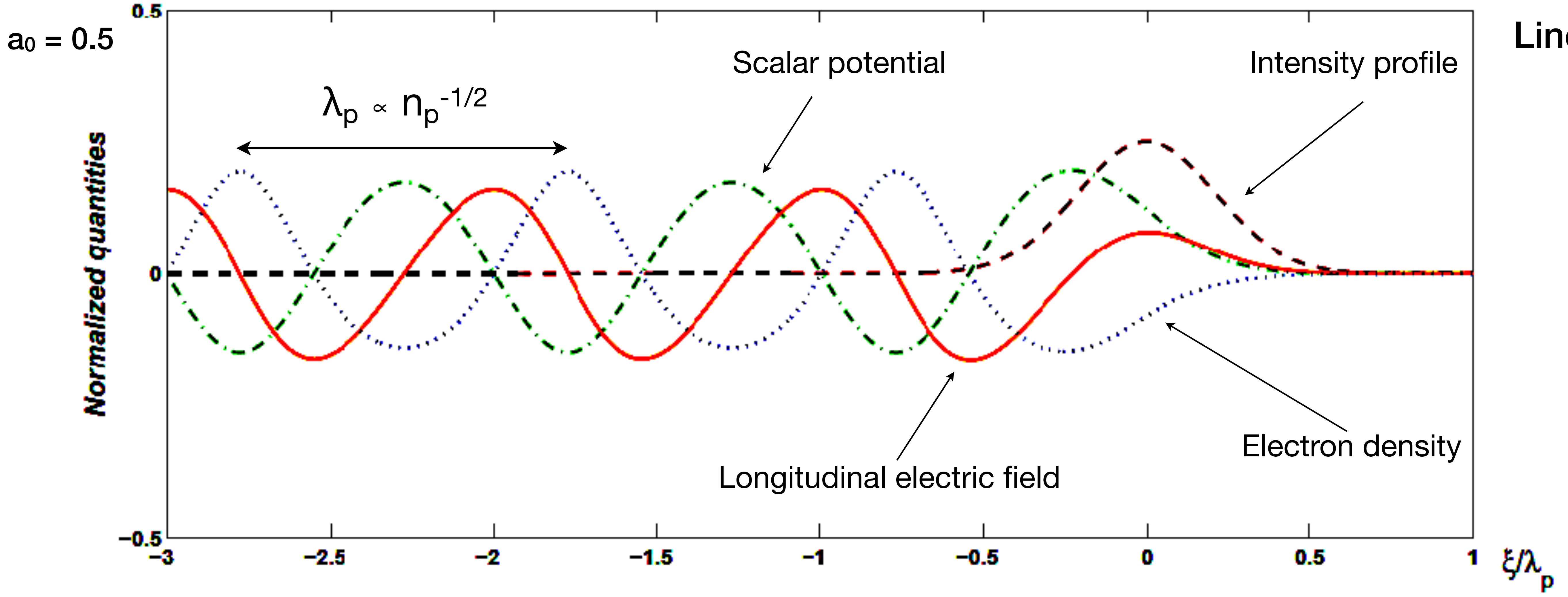
$$= \frac{\omega_{\mathrm{p}}^2}{c^2}\gamma_{\mathrm{g}}^2\left[\frac{\beta_{\mathrm{g}}(1+\phi_0)^2}{\sqrt{(1+\phi_0)^2 - \frac{1+a_0^2}{\gamma_{\mathrm{g}}^2}}} - 1\right]$$

↓ with $\beta_{\mathrm{g}} \to 1$

$$\frac{\partial^2\phi_0}{\partial\xi^2} = \frac{\omega_{\mathrm{p}}^2}{2c^2}\left[\frac{1+a_0^2}{(1+\phi_0)^2} - 1\right]$$

# Solution for the scalar wake potential for a Gaussian laser pulse

## 1D in space / 3D in momentum

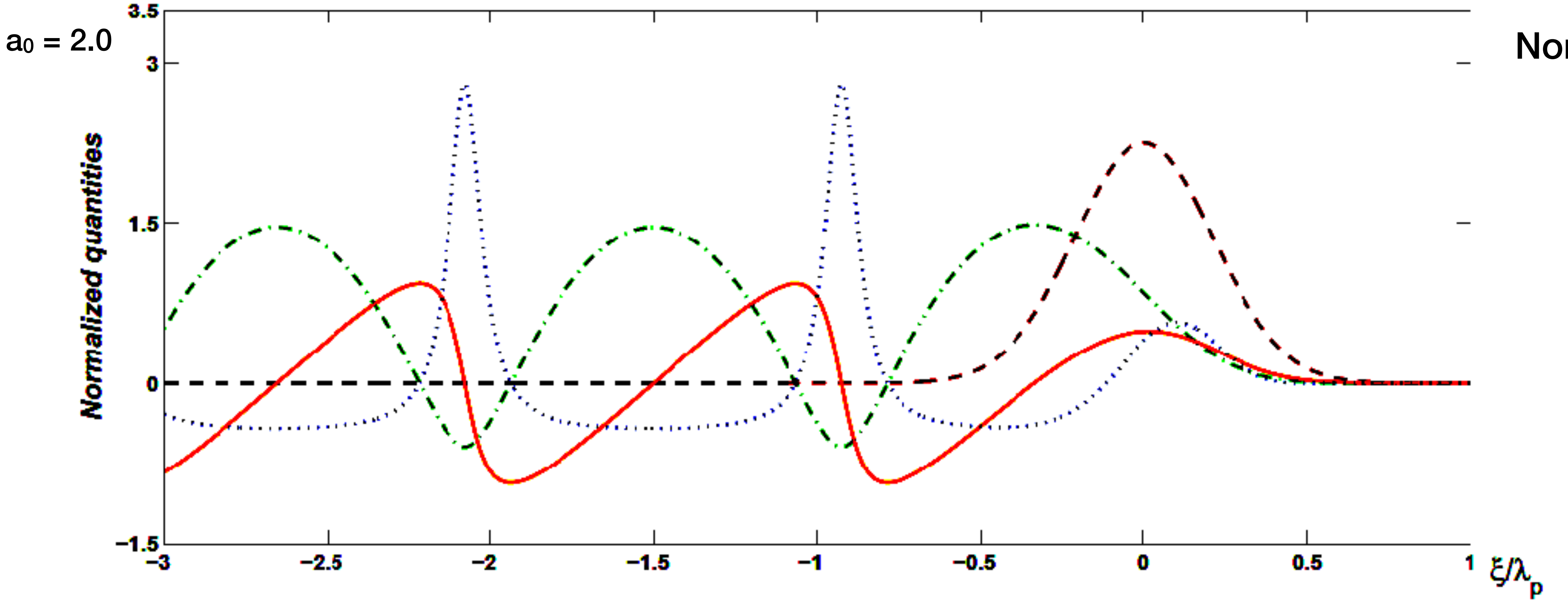



**Linear regime**

$$\frac{\partial^2 \phi_0}{\partial \xi^2} = \frac{\omega_p^2}{2c^2}\left[\frac{1+a_0^2}{(1+\phi_0)^2} - 1\right]$$

Temporal laser-pulse shape in intensity

$$a^2(\xi) = {a_0}^2 \exp\left[-\left(\frac{\xi-\xi_0}{L}\right)^2 4\log(2)\right]$$




**Nonlinear regime**

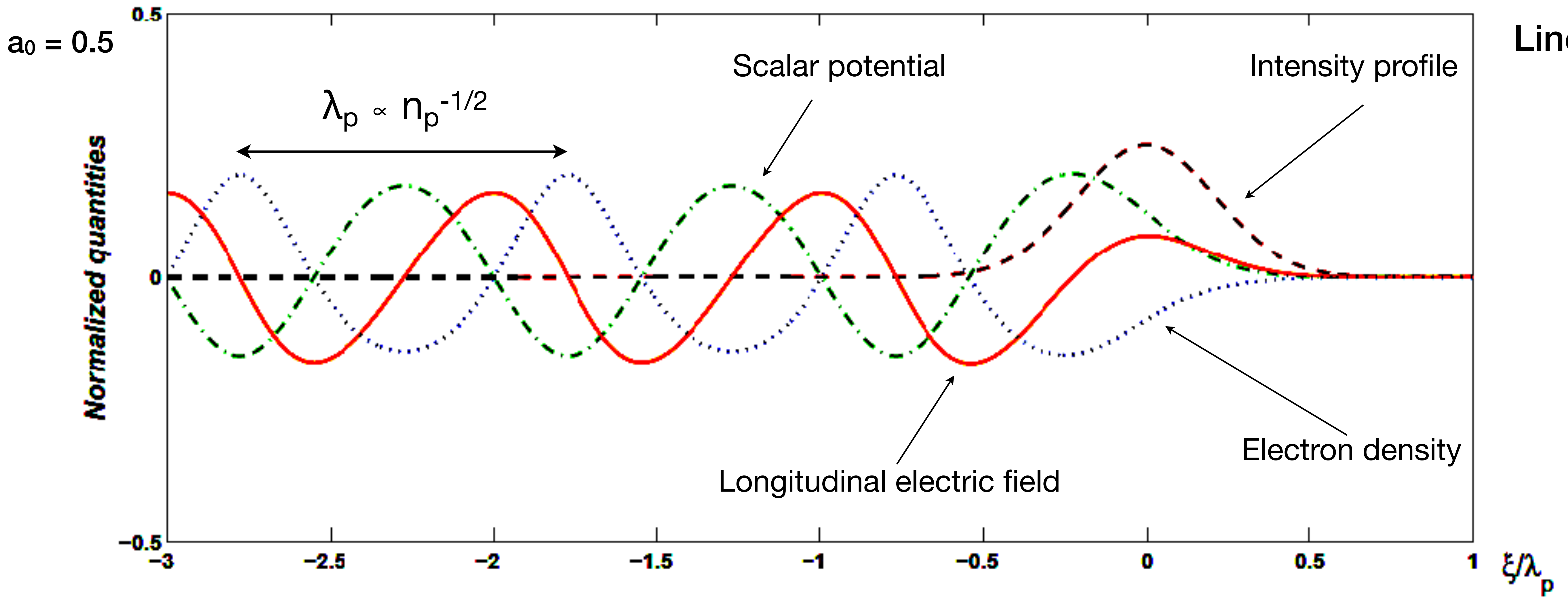
Accelerating field strength

$$E \sim \left(\frac{mc\omega_p}{e}\right)\frac{a^2}{\left(1+a^2/2\right)} \approx (96\mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}\frac{a^2}{\left(1+a^2/2\right)}$$

e.g. E ≈ 100 GV/m (for n ≈ $10^{18}$ cm$^{-3}$, a ≈ 1)

# Solution for the scalar wake potential for a Gaussian laser pulse

## 1D in space / 3D in momentum




**Linear regime**

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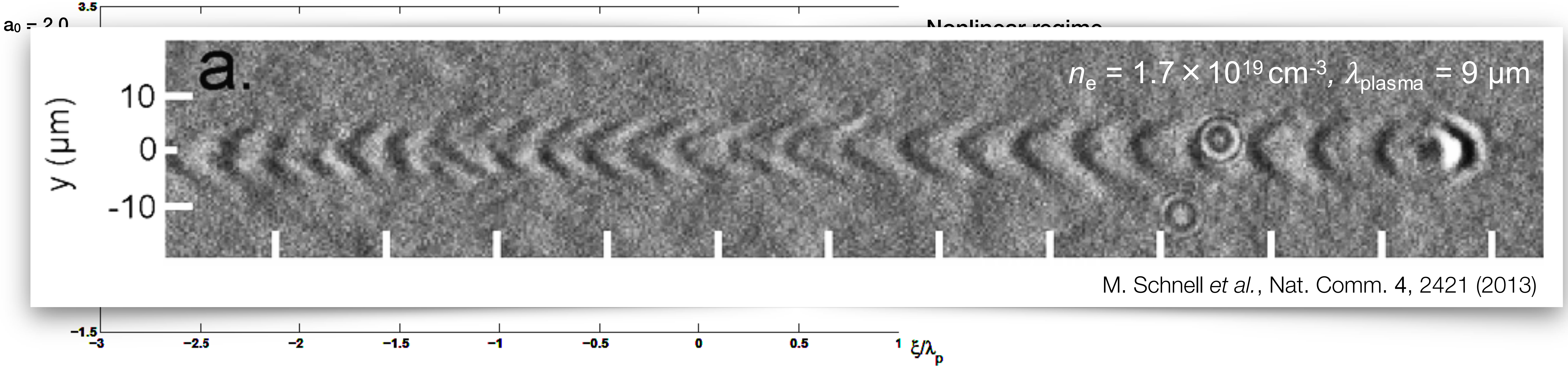
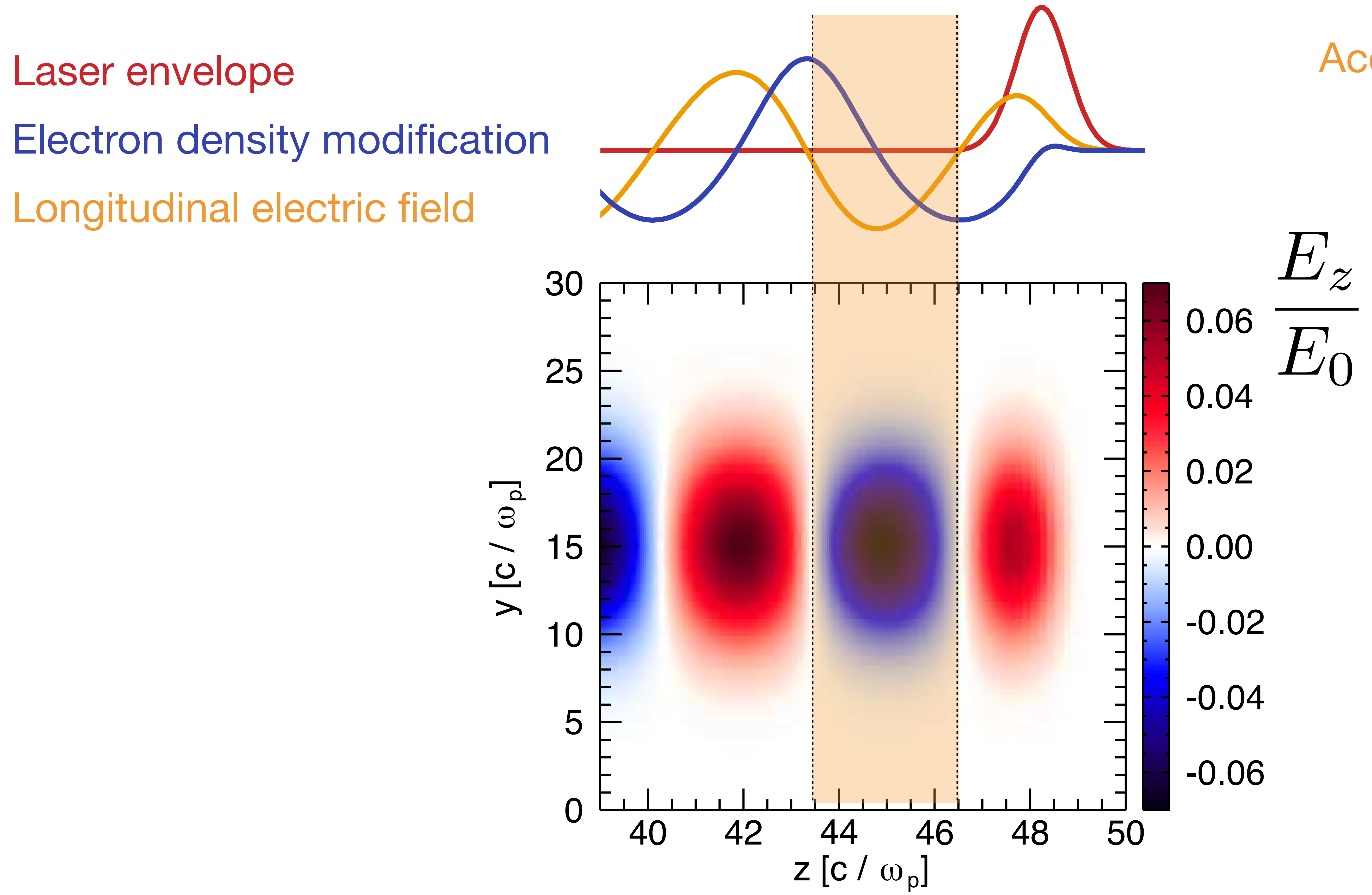


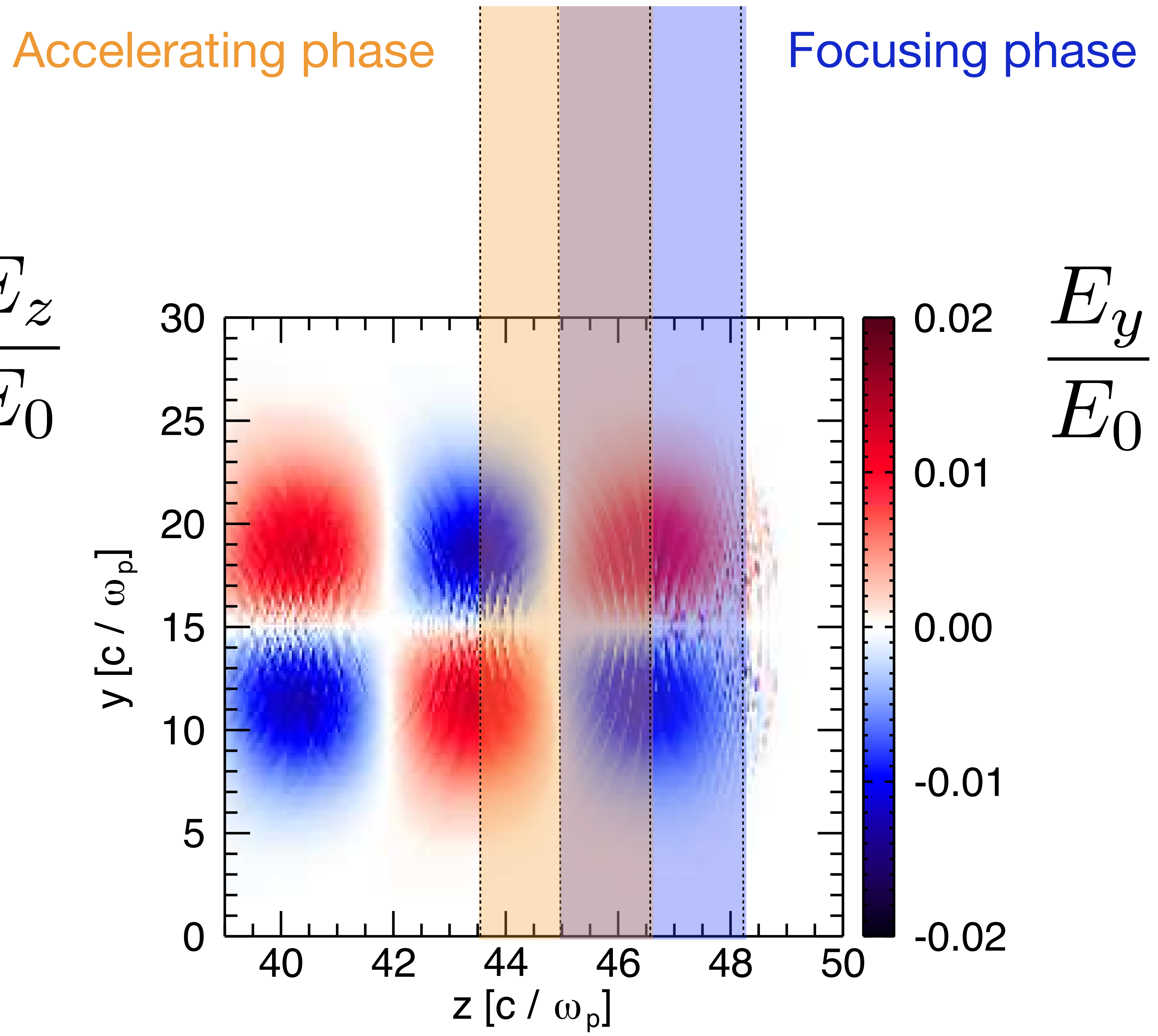

M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

# Wakefield properties in transverse dimensions

## 3D in space / 3D in momentum




Longitudinal fields
of a quasi-linear plasma wave




Transverse fields
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# Wakefield properties in transverse dimensions

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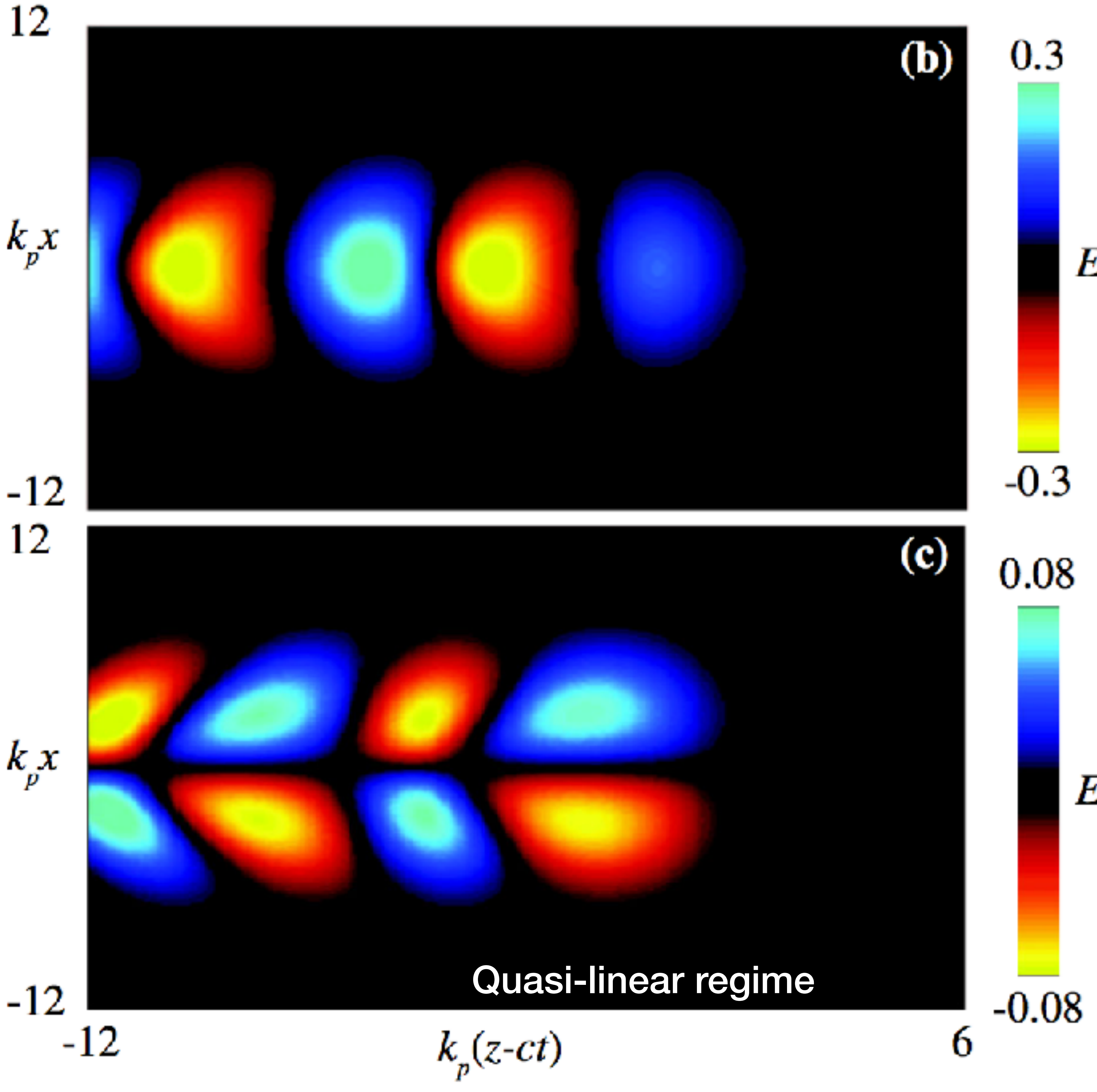
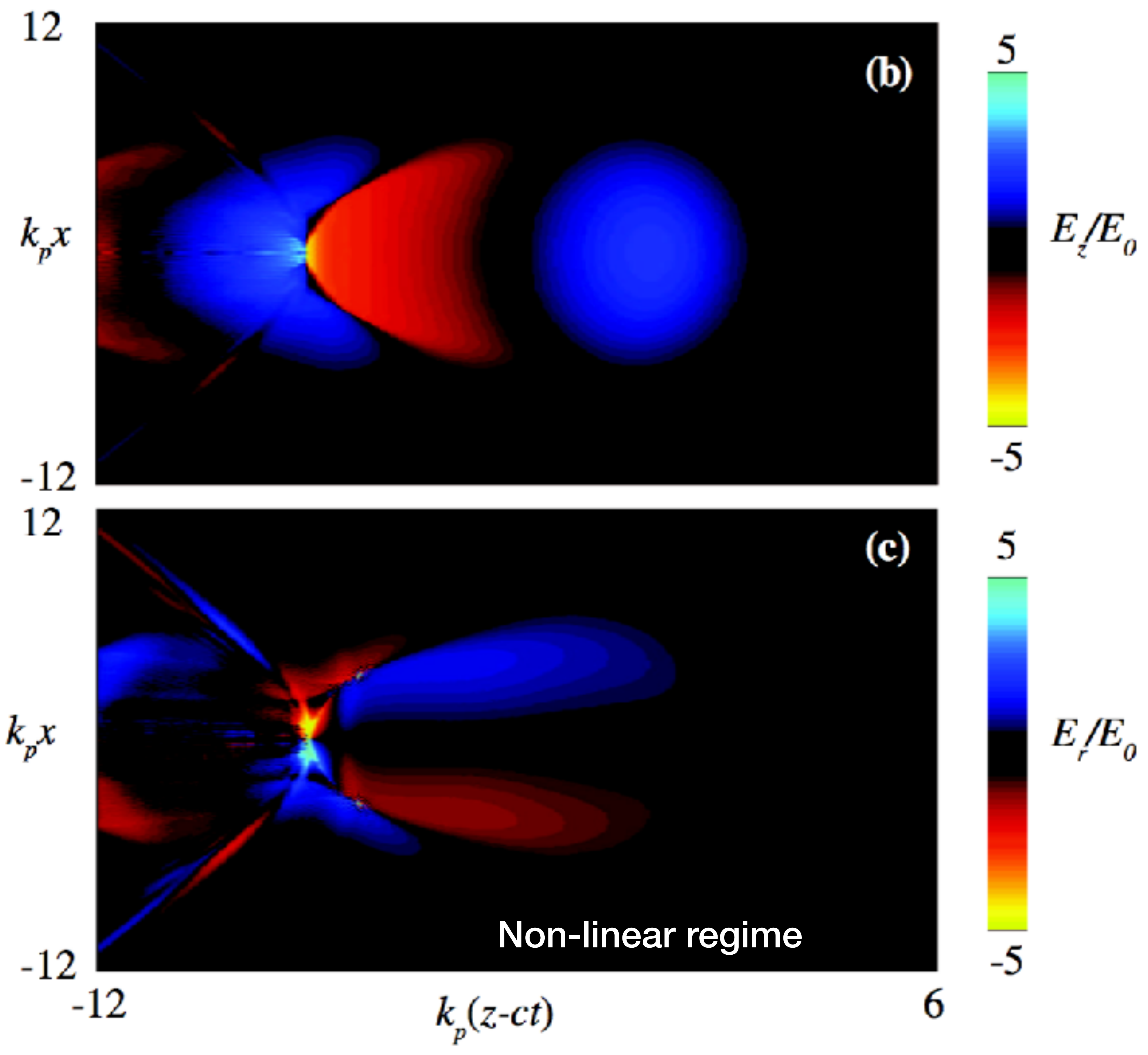


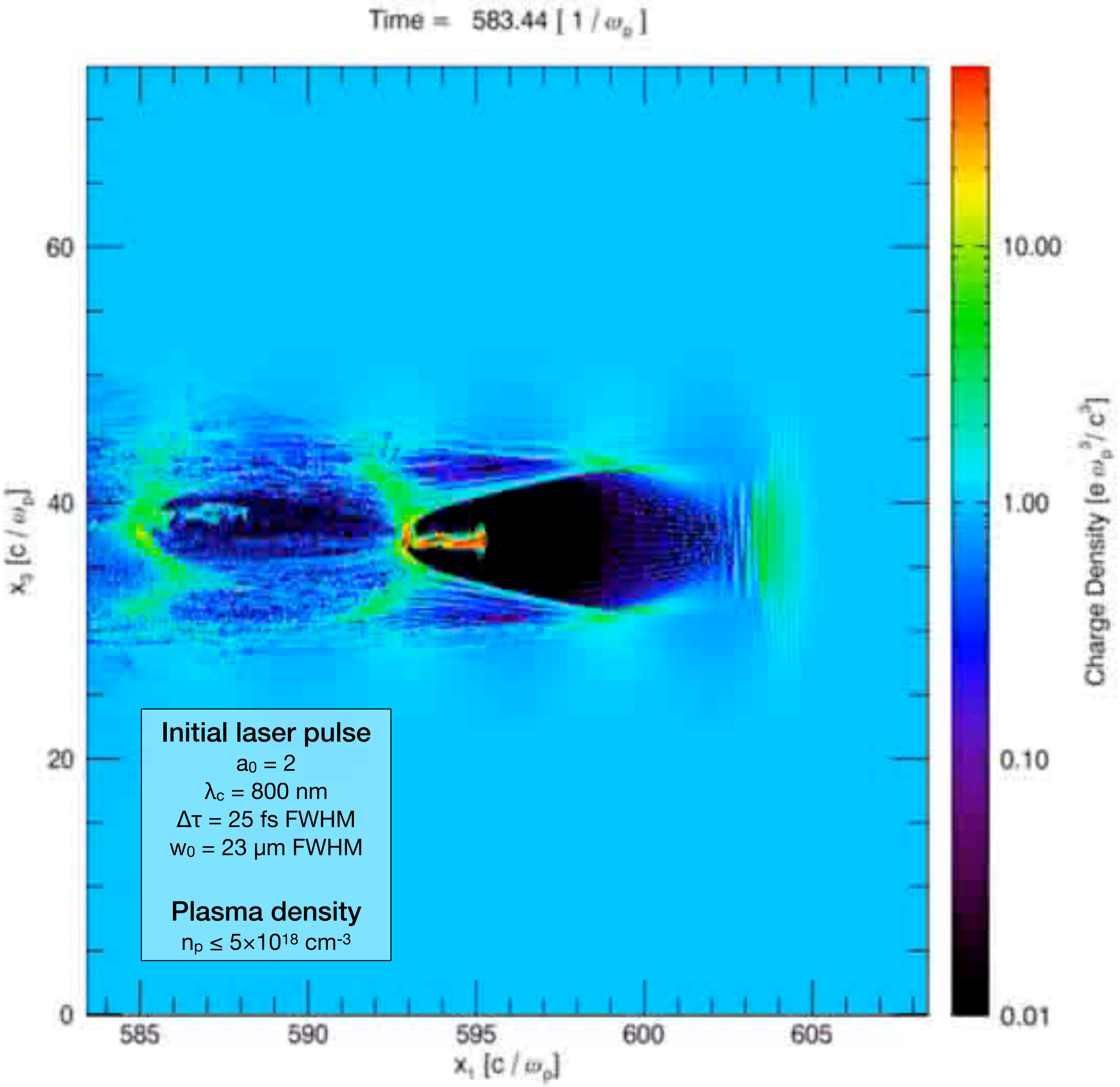




from C.B.Schroeder *et al.*, PRSTAB **13**, 101301 (2010)

# The LWFA process can be complex

- laser self-focussing
- laser self-compression
- **wave breaking**
- beam hosing
- beam loading
- …


*3D particle-in-cell (PIC) simulation*



# Our customers: high-energy physics and photon science

> High-energy physics and photon science demand high(est) energy at low cost.
  > *Solution:* Plasma accelerators — significantly higher acceleration gradients.

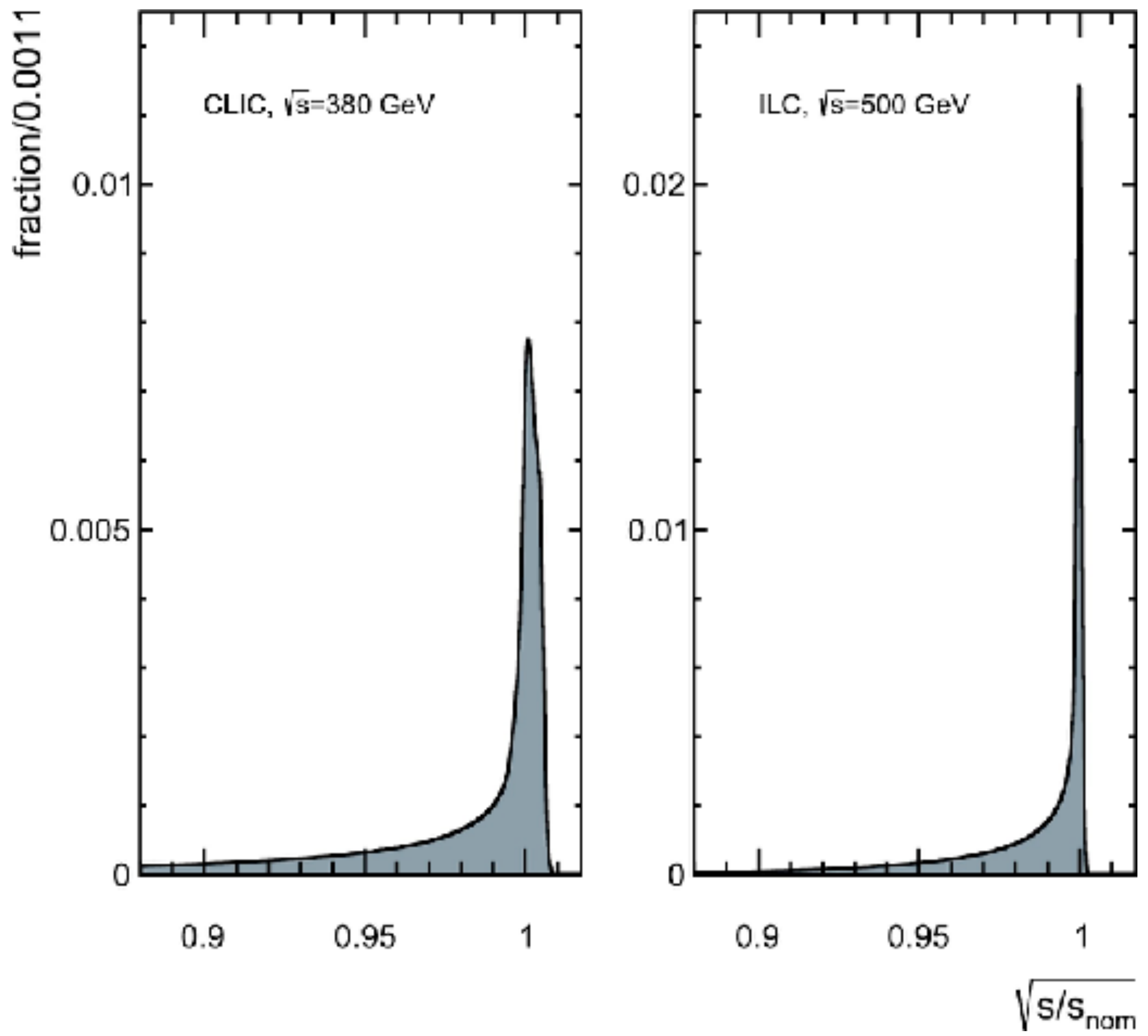
> Simultaneously, particle colliders have strict demands for luminosity: (FELs have similar demands for brightness)

High repetition rate — High energy efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread (luminosity spectrum, final focusing) — Low emittance

> Energy efficiency motivates use of beam-driven plasma acceleration.




**Luminosity distribution across collision energies.**
Source: M. Boronat *et al.*, Phys. Lett. B 804, 135353 (2020).

$$\eta = \eta_{wall\to DB} \times \eta_{DB\to WB}$$

Beam-drivers are orders of magnitude more efficient than laser-drivers (for now)

# Primary goal of FLASHFORWARD▸▸

**Develop a self-consistent plasma-accelerator stage**
with high-efficiency, high-quality, and high-average-power

### High efficiency

Transfer efficiency

Driver depletion

### High beam quality

Energy-spread preservation

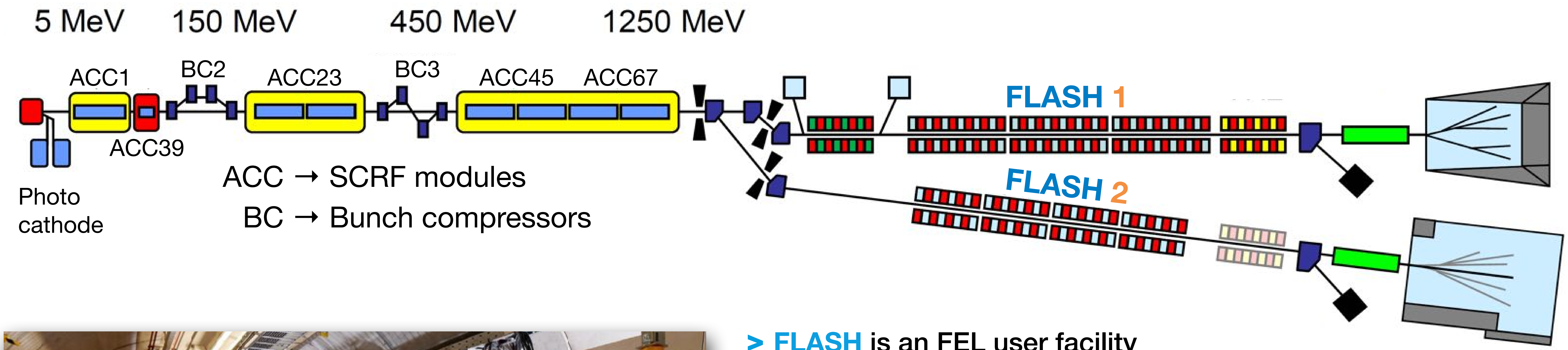
Emittance preservation

### High average power

High repetition rate

# FLASHFORWARD▸▸ utilizes FLASH superconducting accelerator

## Plasma accelerator tightly integrated into facility and benefits from Free-Electron Laser beam quality





- **FLASH is an FEL user facility**
  - 10% of beam time dedicated to generic accelerator research
- **Superconducting accelerator based on ILC/XFEL technology**
  - ≲ 1.25 GeV energy with ~nC charge at few 100 fs bunch duration
  - ~2 µm trans. norm. emittance
  - ~10 kW average beam power, MHz repetition rate in 10 Hz bursts
  - exquisite stability by advanced feedback/feedforward systems
- **Unique opportunities for plasma accelerator science**

# FLASHFORWARD▸▸ utilizes FLASH superconducting accelerator

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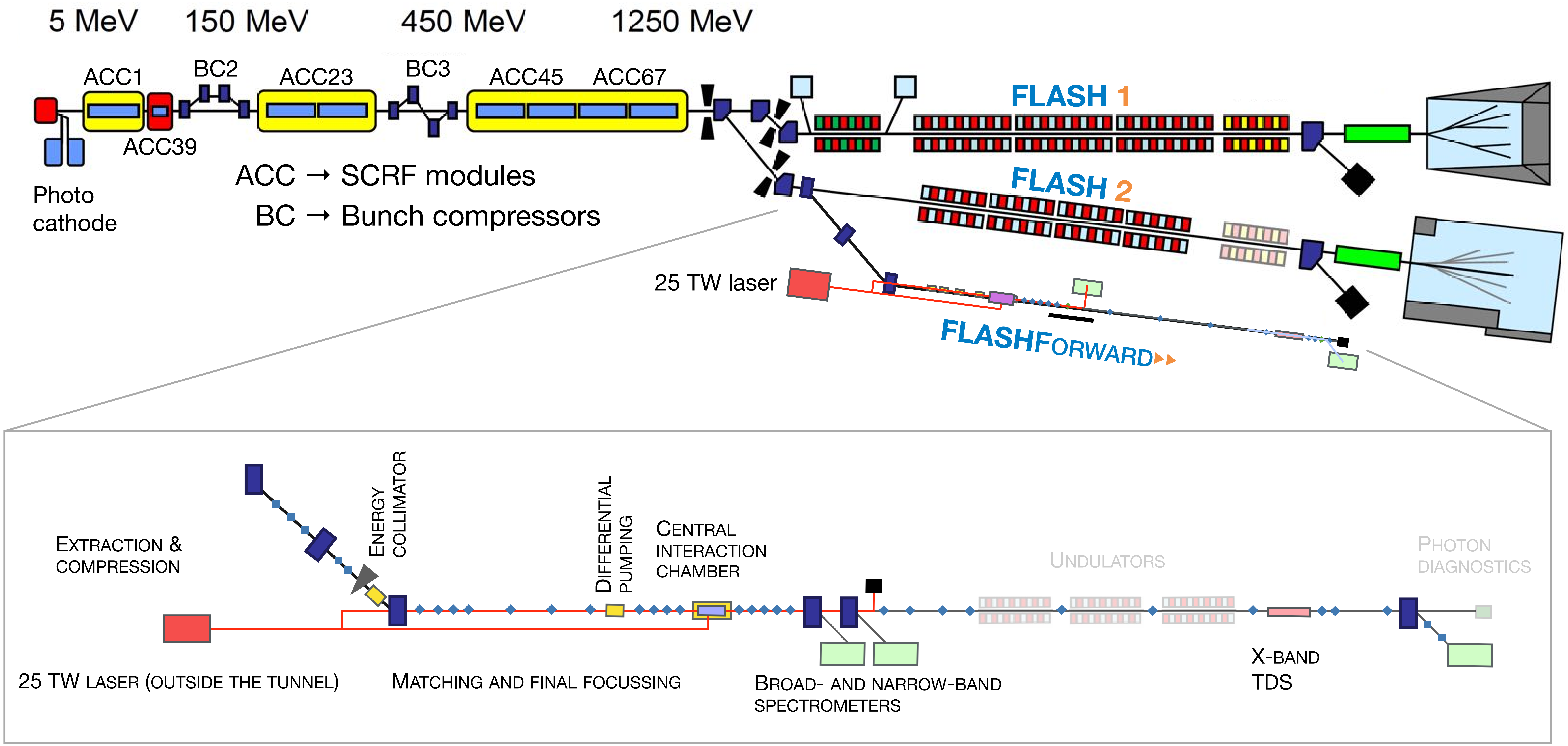
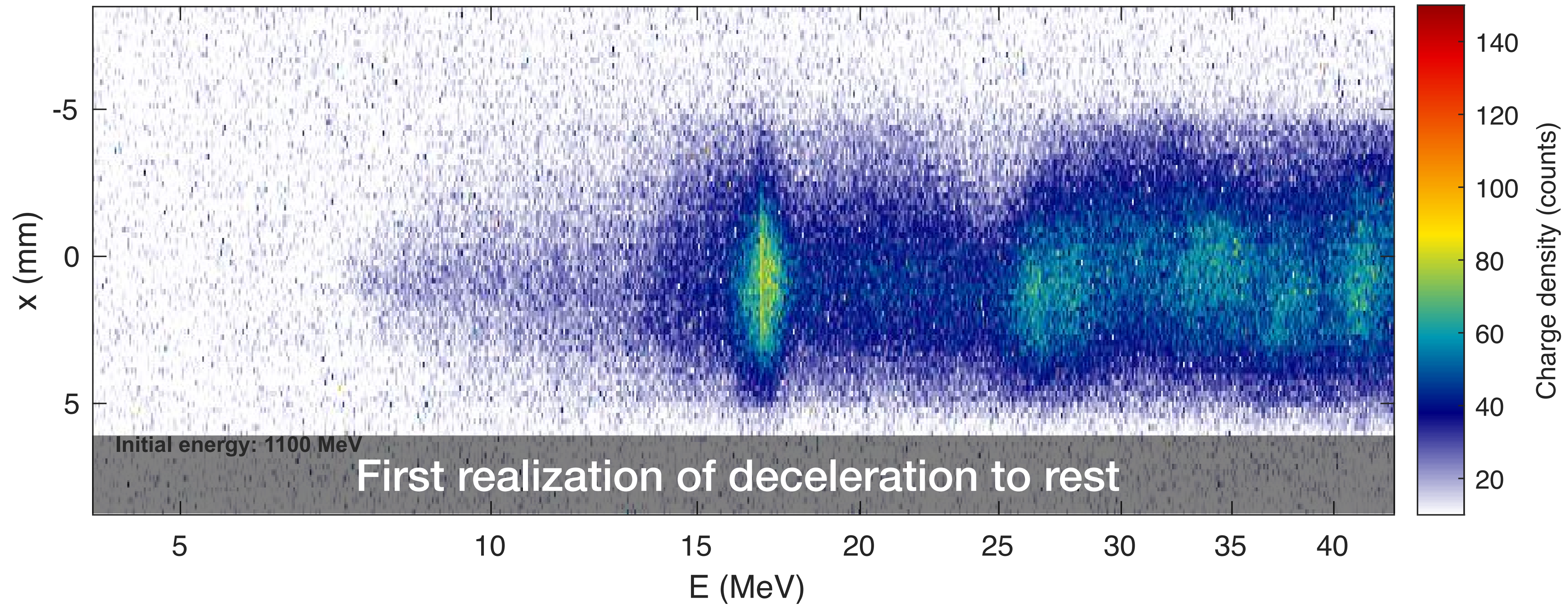



R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

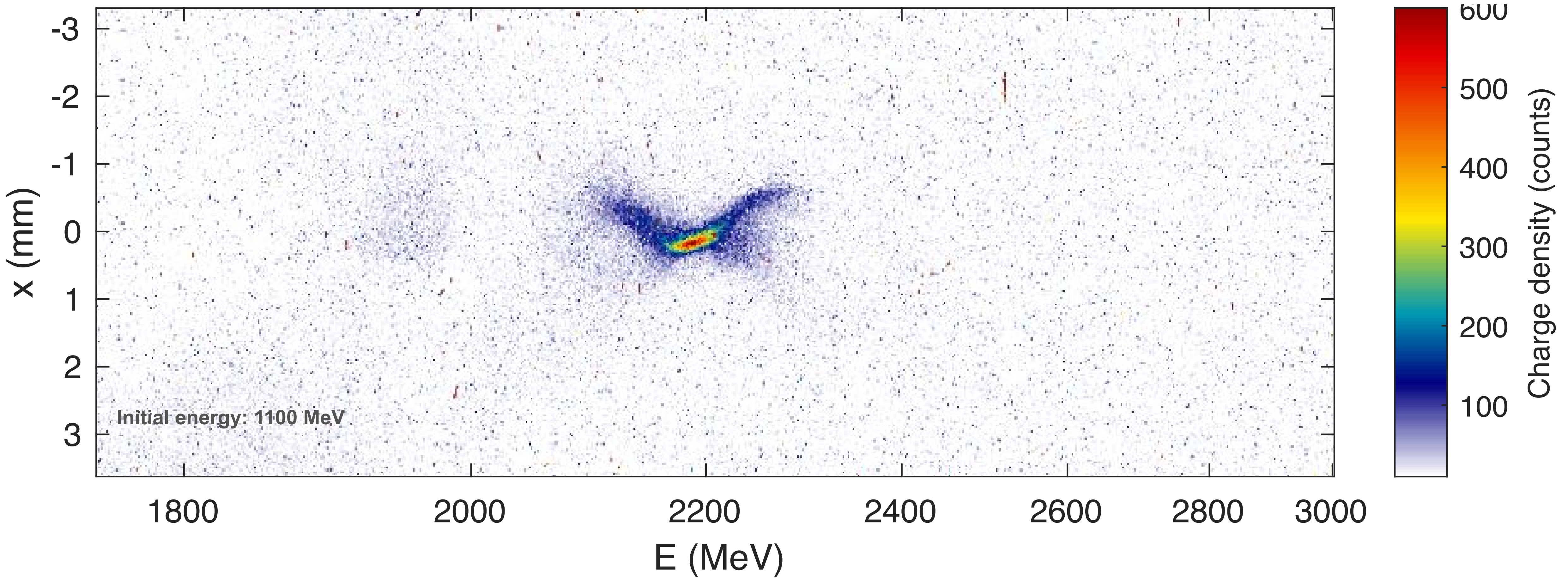
# 1.1 GeV energy gain and loss achieved in a 195 mm plasma module

## Plasma accelerator essentials — demonstrating 6 GV/m field strength

### Energy extraction → plasma beam dump (+ efficiency)




### Energy doubling to 2.2 GeV → plasma booster



# Optimal beam loading enables uniform and efficient acceleration

- *Problem 1:* Compared to RF cavities (Q ~ $10^4$–$10^{10}$), the electric fields in a plasma decay very rapidly (Q ~ 1–10).
  - The energy needs to be extracted very rapidly —ideally within the first oscillation.

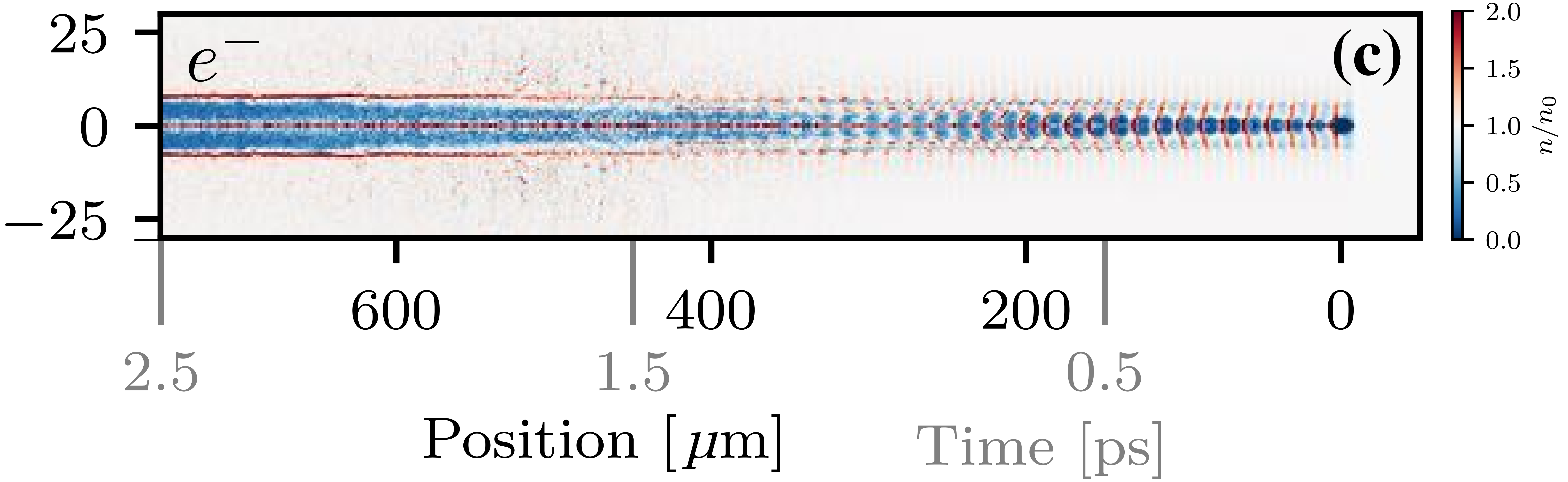



Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

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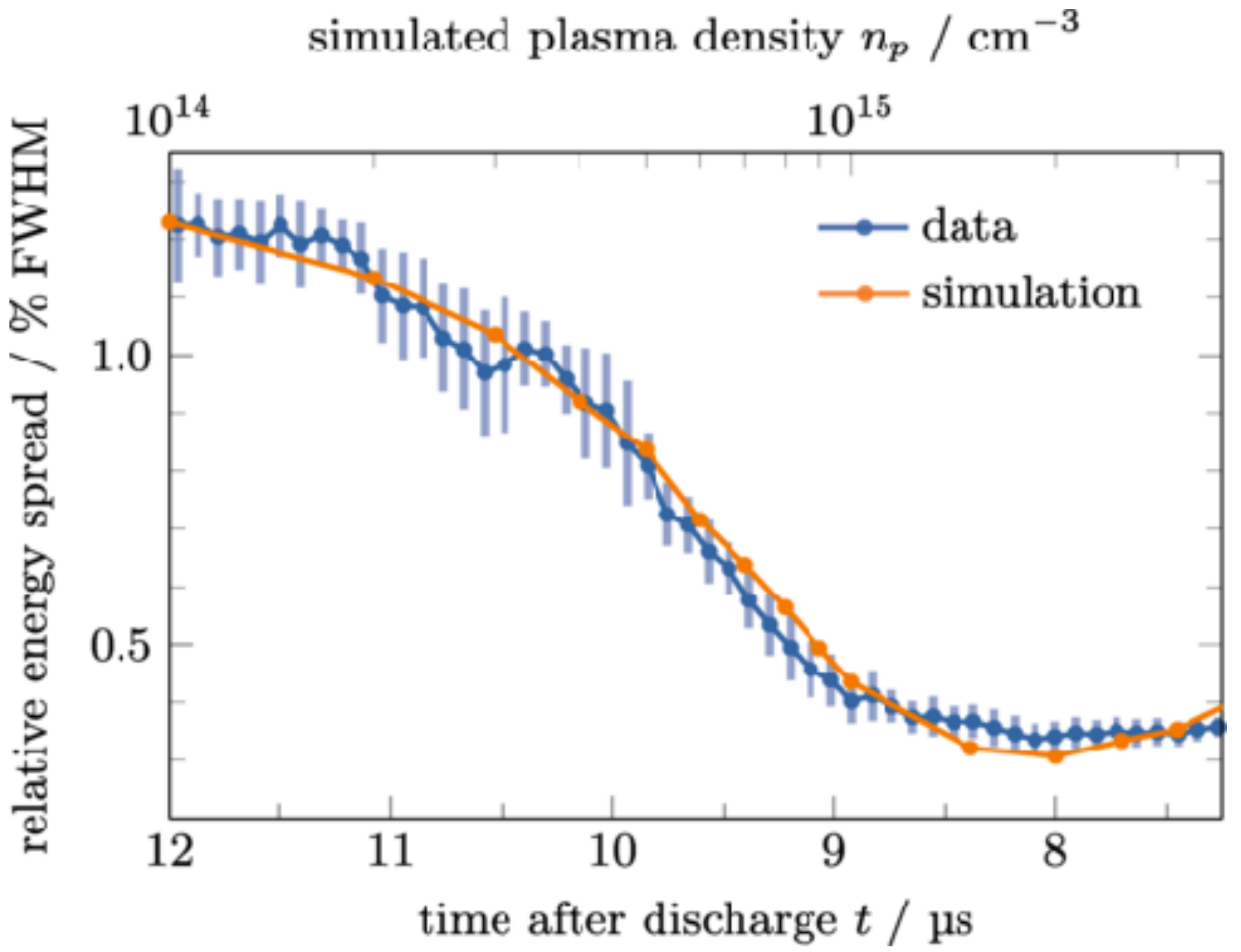
> *Solution:* Beam loading
**The trailing-bunch wakefield "destructively interferes" with the driver wakefield—extracting energy.**

> Problem 2: to extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).

> Large energy spread is induced.

> *Not (easily) possible:* Dechirping




R. D'Arcy *et al.*, PRL **122**, 034801 (2019)

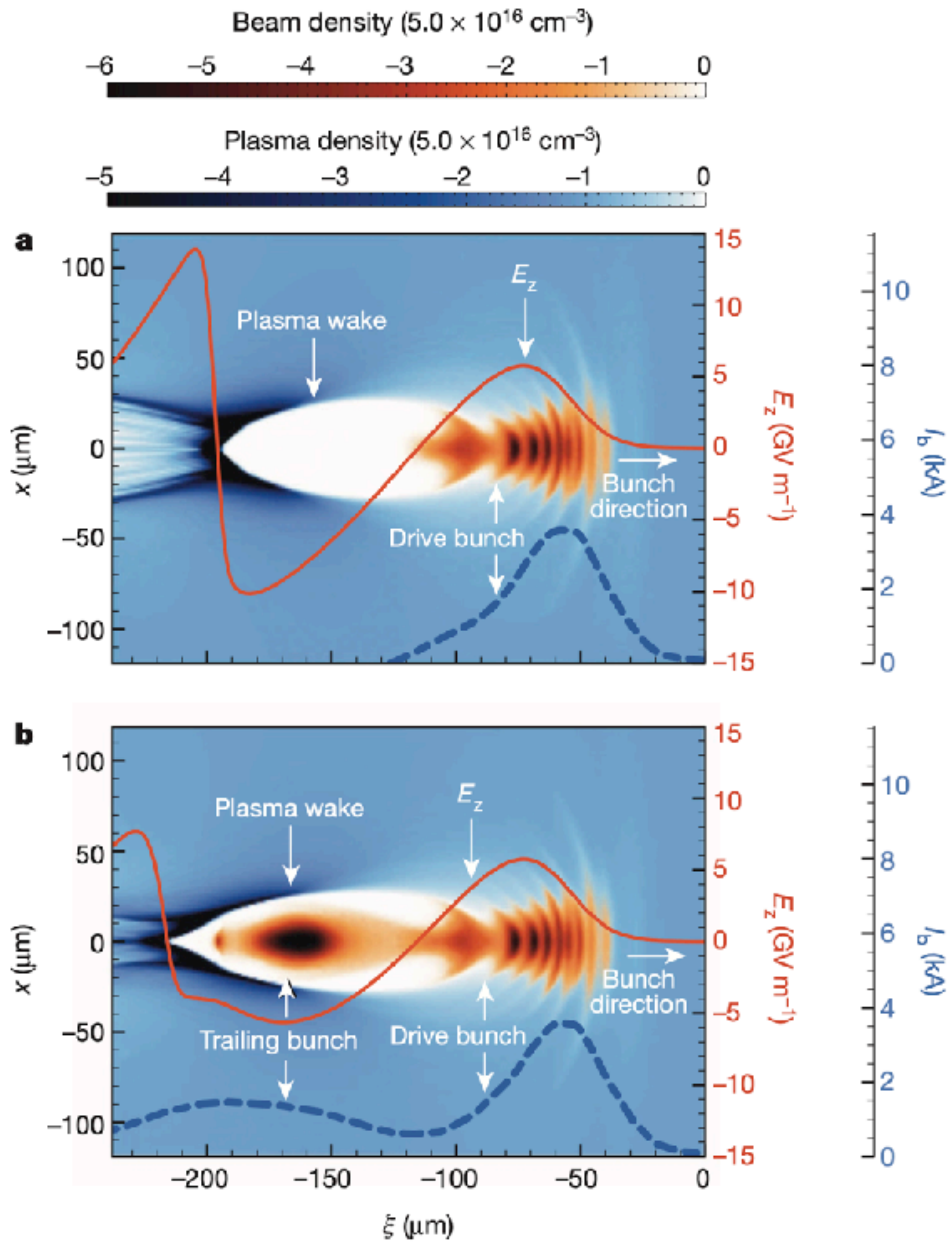



Image credit: M. Litos *et al.*, Nature **515**, 92 (2014)

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> > *Solution:* Optimal beam loading
> > **The current profile of the trailing bunch is *precisely tailored* to exactly flatten the wakefield.**

> This requires extremely precise control of the current profile.

> > **FLASHForward provides the tools to do that.**

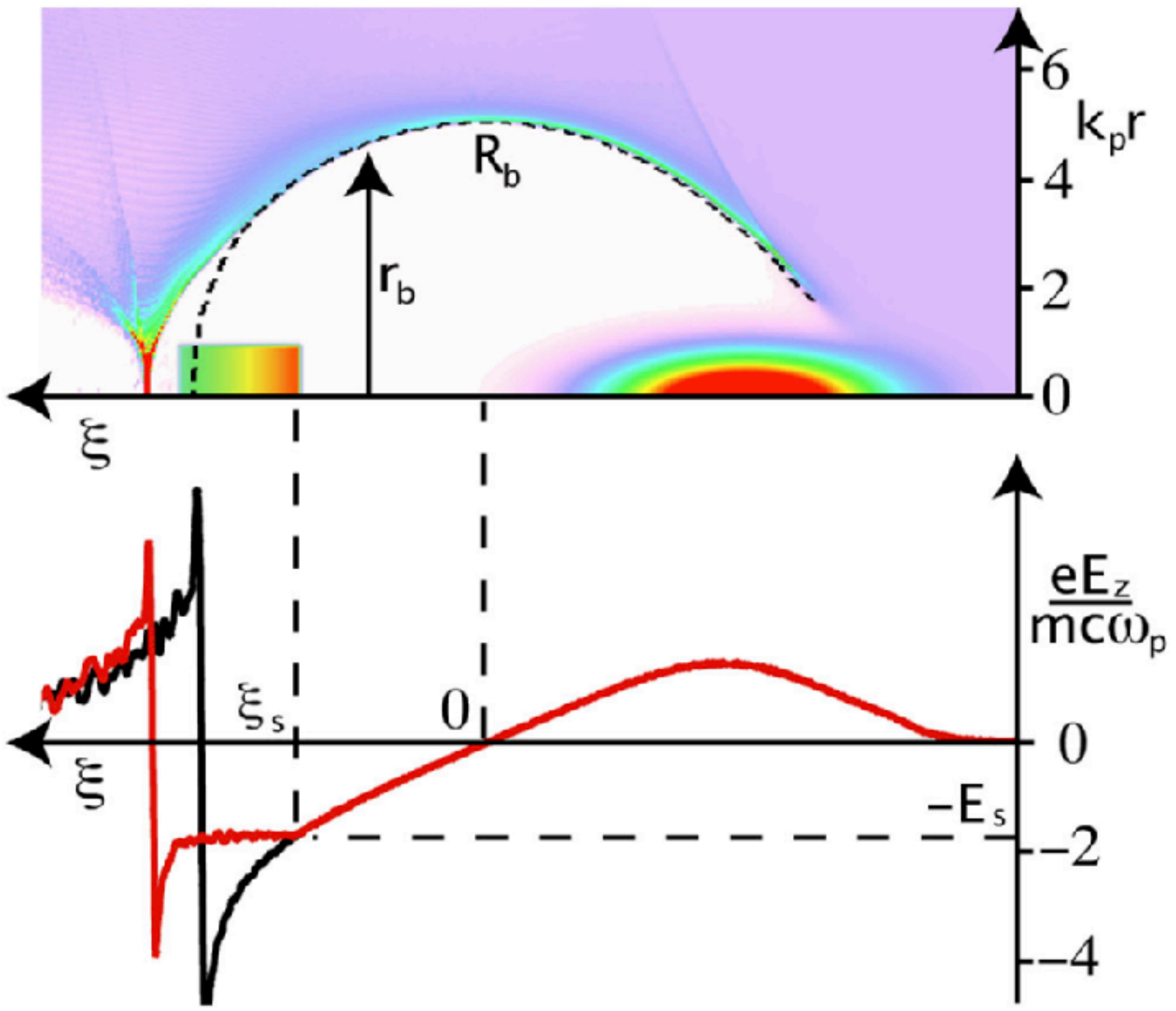
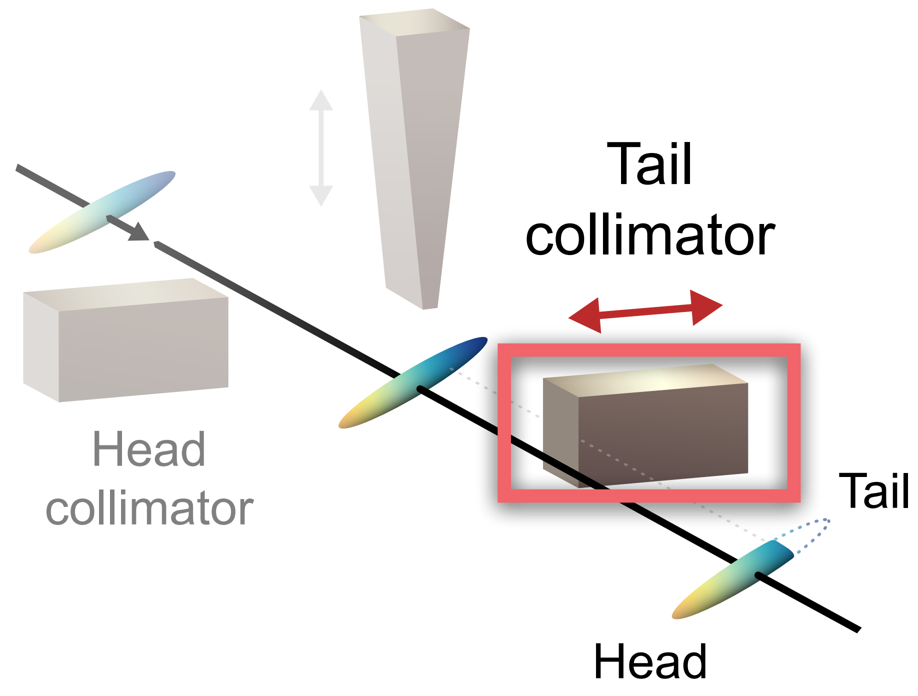


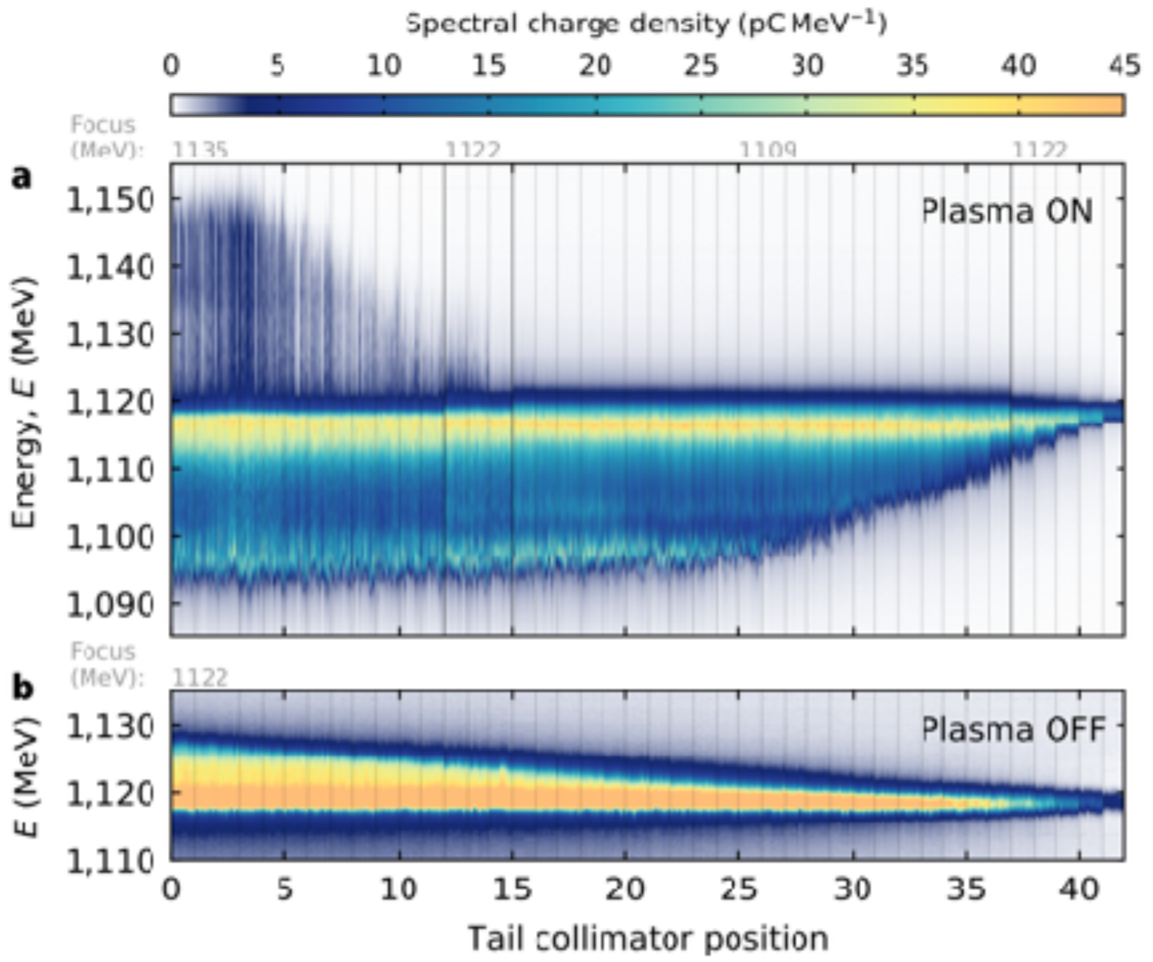

Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

# High-resolution plasma wakefield sampling demonstrated

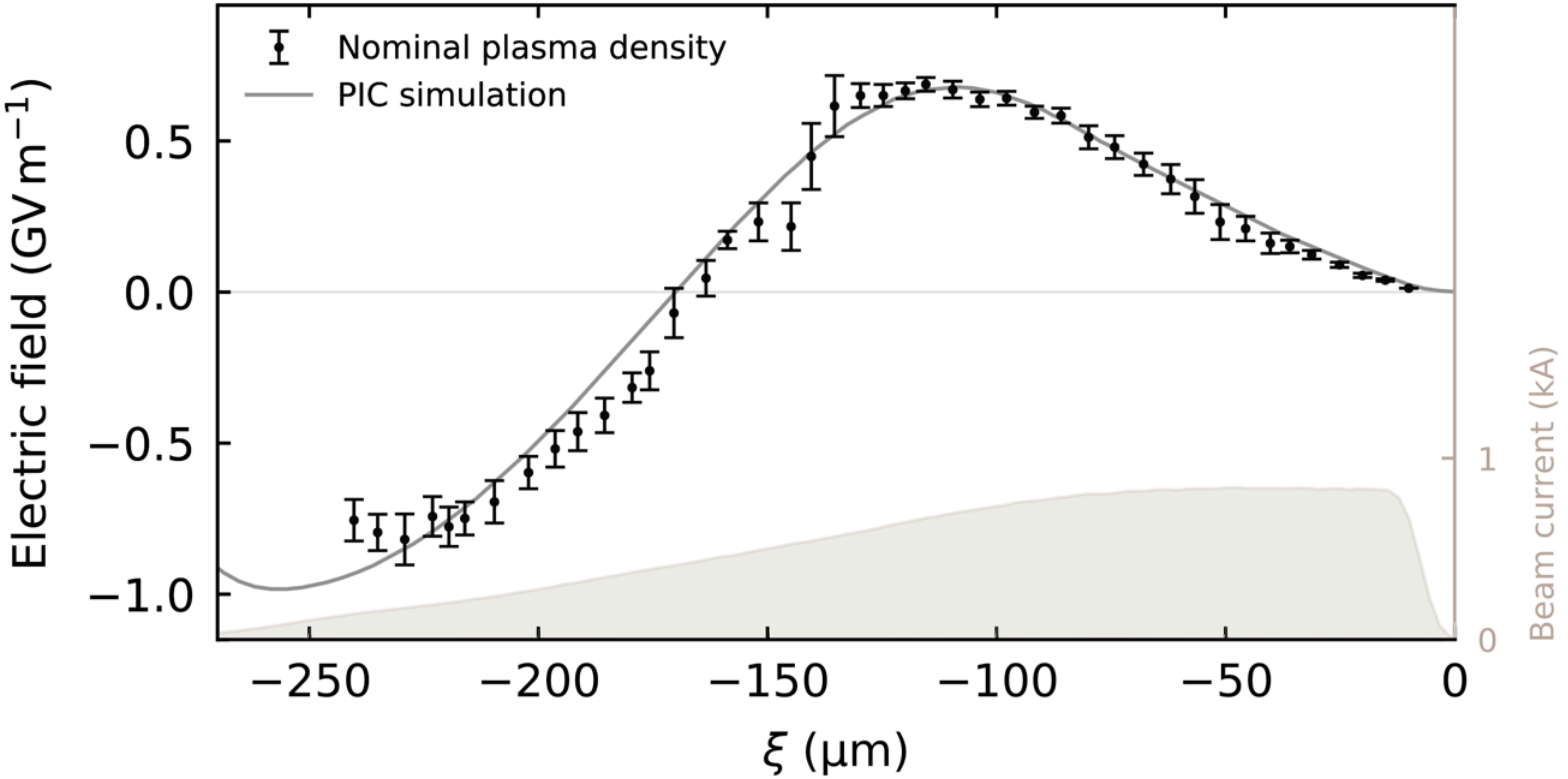
## Opens a pathway to targeted and precise field manipulation

> **Beam itself acts as a probe**
> → measures in-situ (under actual operation conditions) the effective field acting on beam with μm / fs resolution




S. Schröder *et al.*, Nat. Commun. **11**, 5984 (2020)



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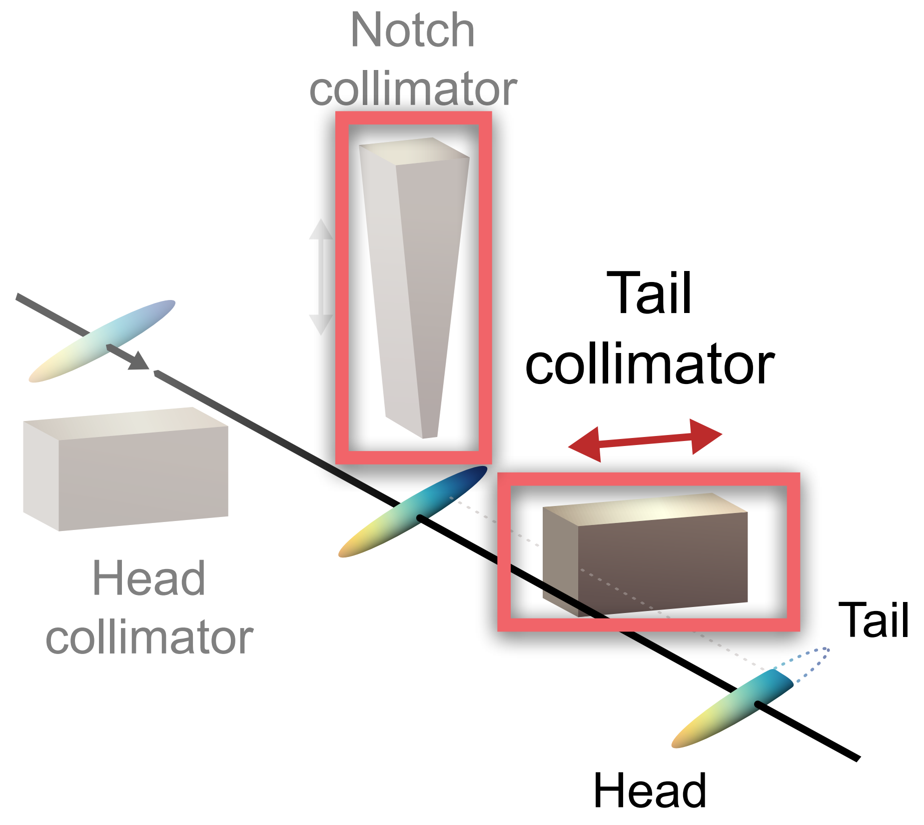


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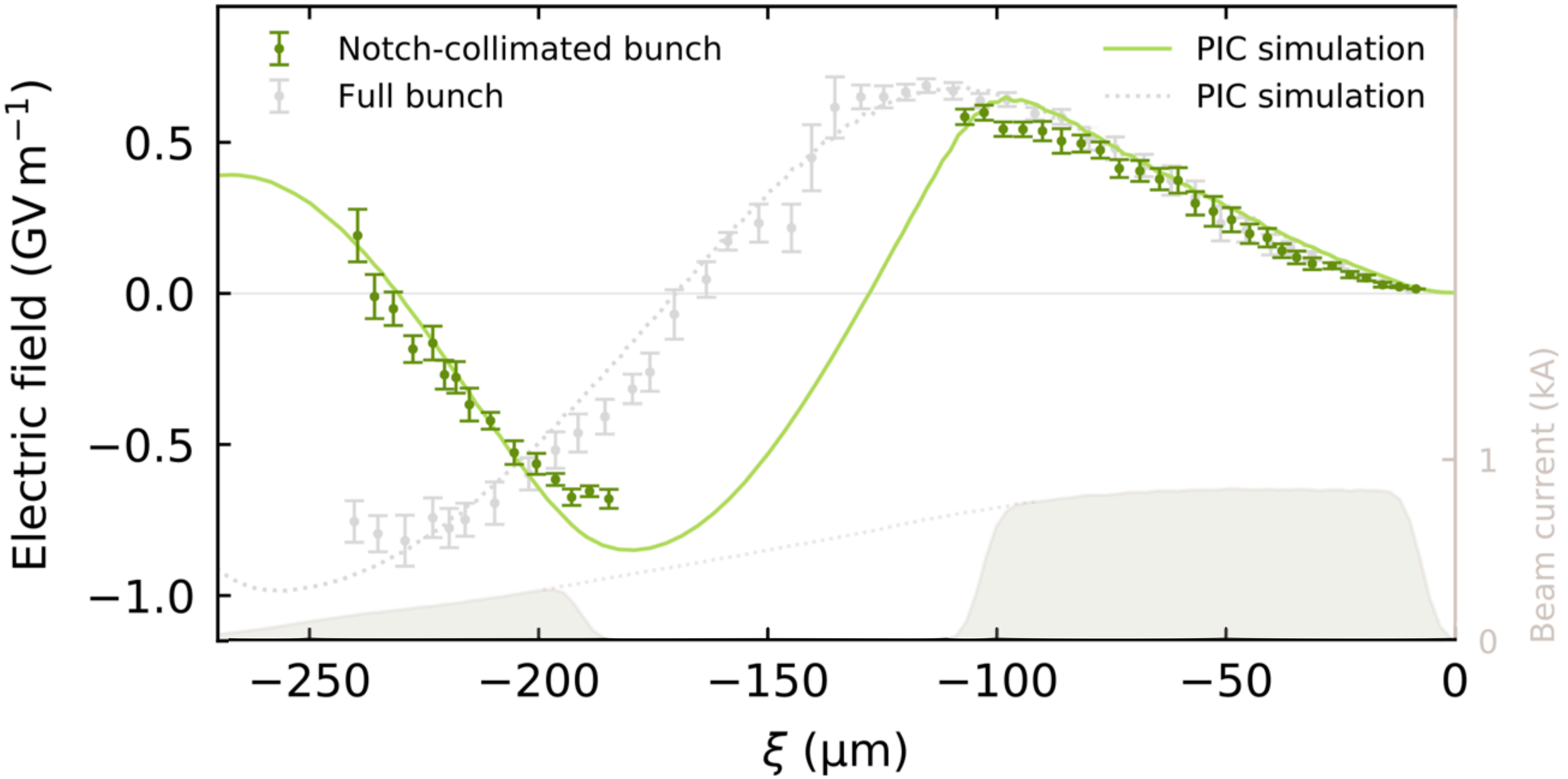
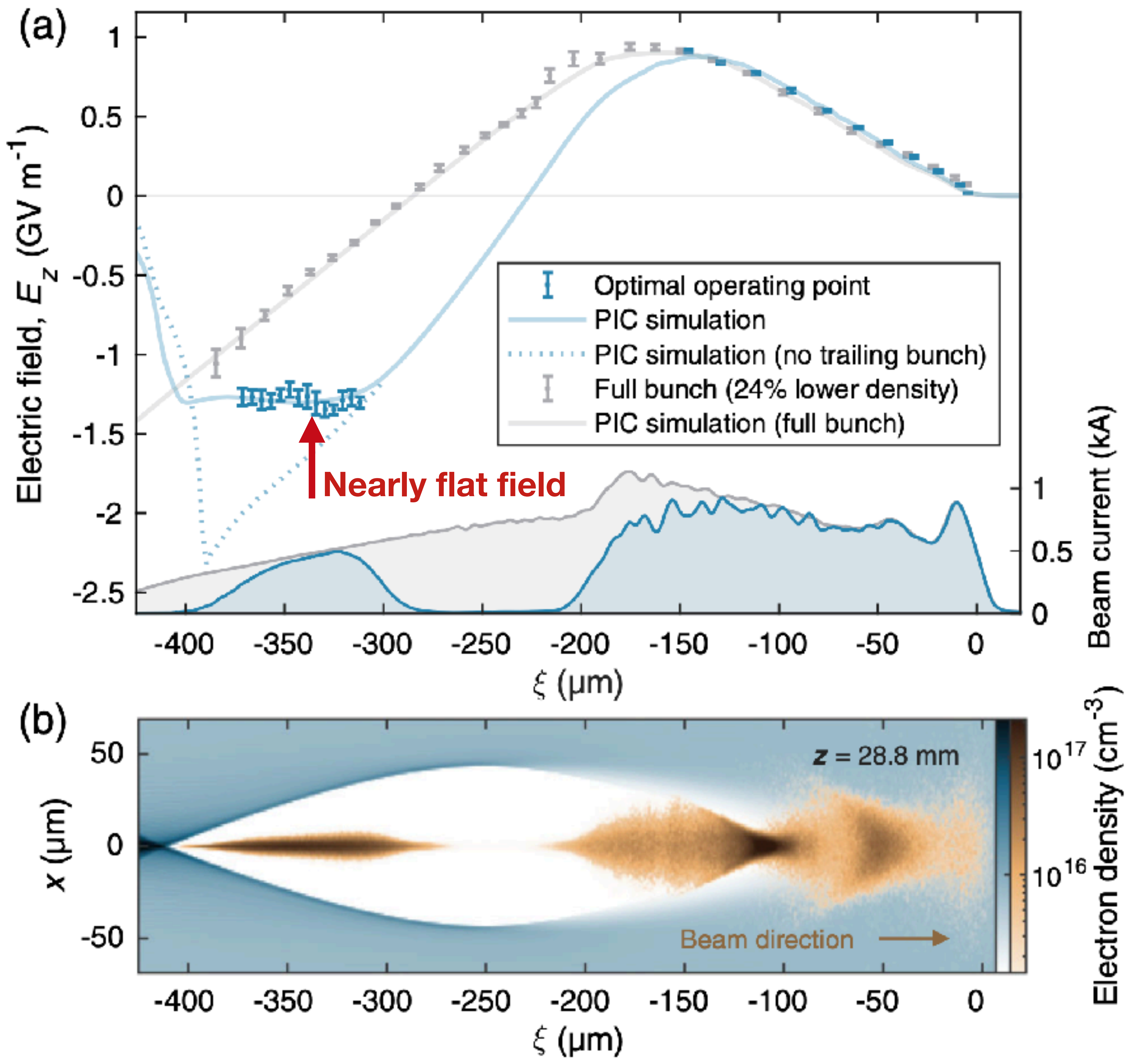
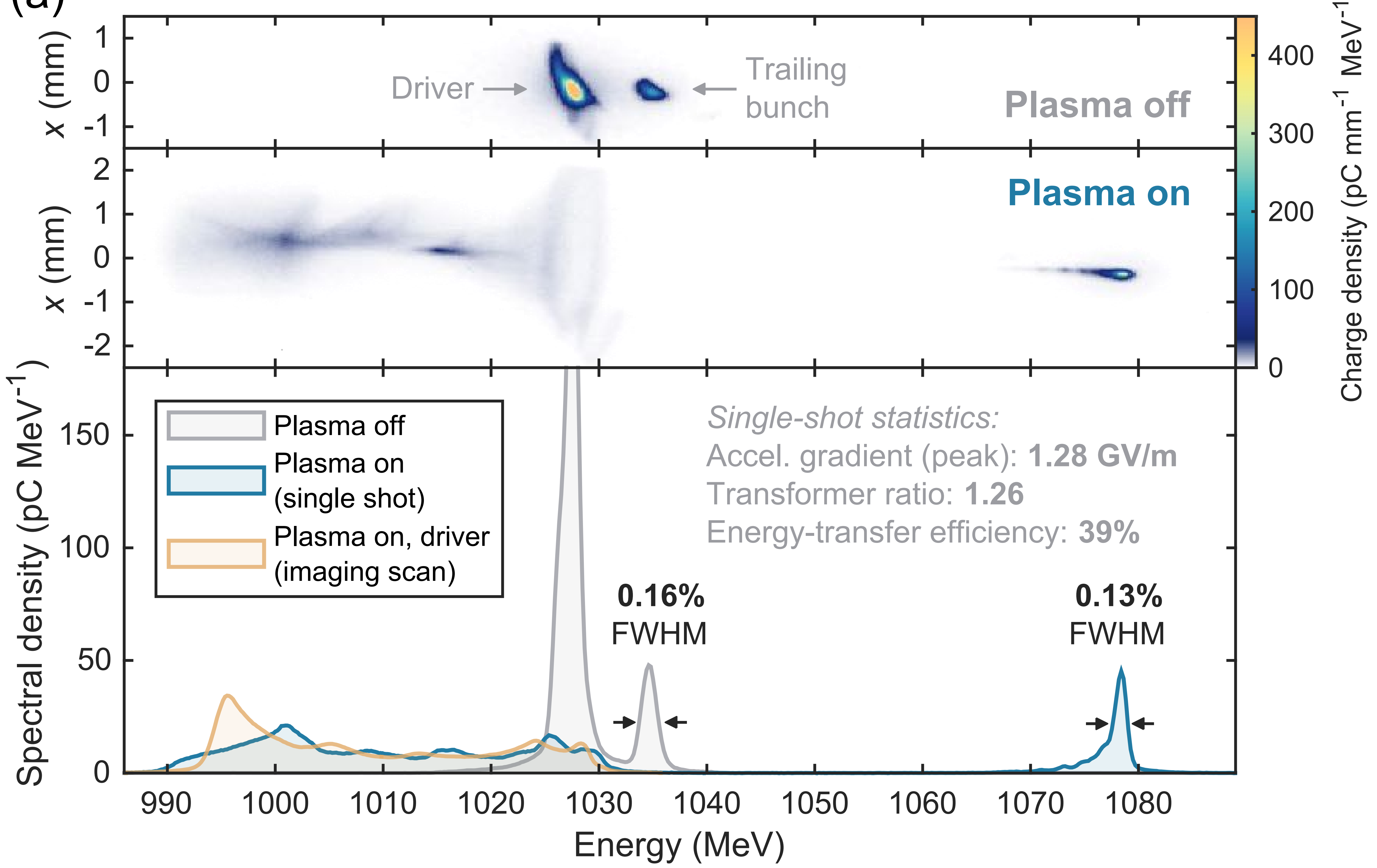


# Loading the wakefield and beam shaping flattens the gradient

## Direct visualization of electric-field control by wakefield sampling




C.A. Lindstrøm *et al.*, PRL **126, 014801** (2021)

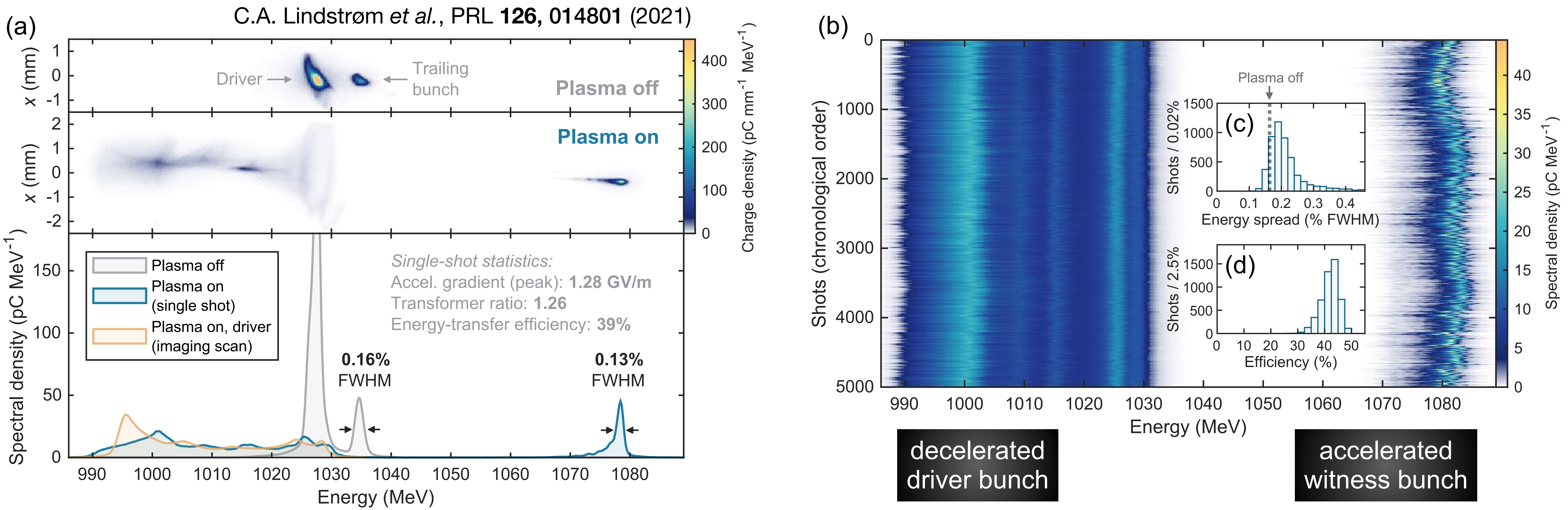



- Accelerating **gradient of 1.3 GV/m**
- Energy gain 45 MeV (over 3.5 cm distance) of 100 pC witness, with energy spread of 1.4 MeV FWHM and **no charge loss**
  - **Few-percent-level wakefield flattening demonstrated**

# High-quality, efficient acceleration for sustainable applications

## Beam-loading facilitates 42% energy-transfer efficiency, 0.2% energy spread with full charge coupling

C.A. Lindstrøm *et al.*, PRL **126, 014801** (2021)

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- Energy gain 45 MeV (over 3.5 cm distance) of 100 pC witness, with energy spread of 1.4 MeV FWHM and **no charge loss**
  - **Few-percent-level wakefield flattening demonstrated**

- **0.2% energy spread (input 0.16%)**
  (improvement by factor 10 over state-of-the-art)
- **(42±4)% energy transfer efficiency**
  (improvement by factor 3 over state-of-the-art)

# FLASHFORWARD▸▸ roadmap aims at 10 kW with high beam quality

## Plan covers major plasma accelerator challenges

**2018** Plasma dechirper
- D'Arcy *et al.*, **PRL** 122, 034801 (2019)

**2019** Energy depletion and energy doubling

Wakefield sampling
- Schröder *et al.*, **Nat. Commun. 11 5984** (2020)

**2020** Energy spread preservation by beam loading control
- Lindstrøm *et al.*, **PRL** 126, **014801** (2021)

Emittance preservation

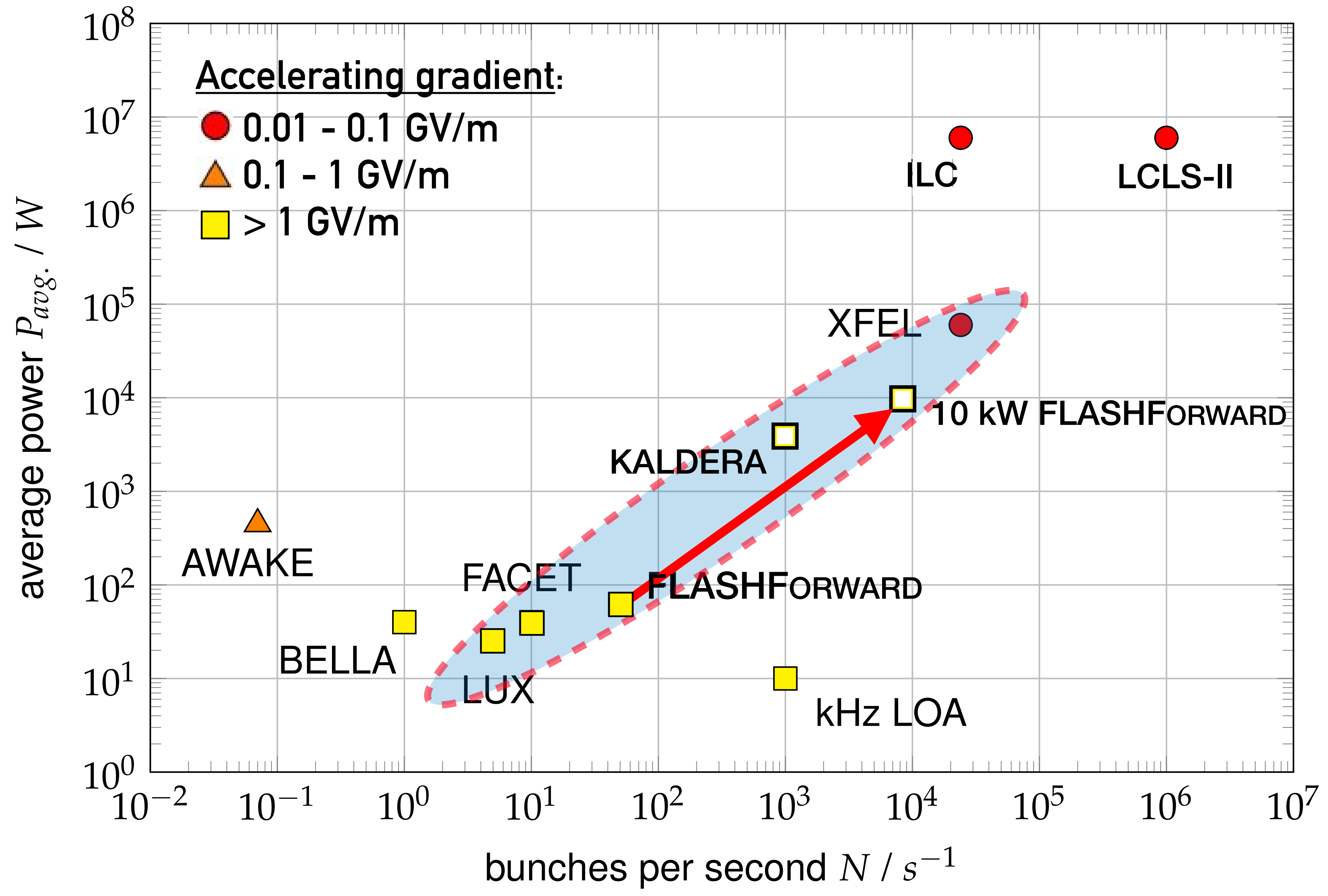
**2022** High gain and overall efficiency for sustainable operation

Detection of slice properties with fs resolution

**2024** kHz-to-GHz plasma response

**2026** 10 kW avg. power operation

**2030**




**10 kW stage with 50% efficiency & beam quality conservation**

→ **FLASH:** increase FEL energies, access oxygen K-edge at 2.33 nm wavelength

# FLASHFORWARD▸▸ roadmap aims at 10 kW with high beam quality

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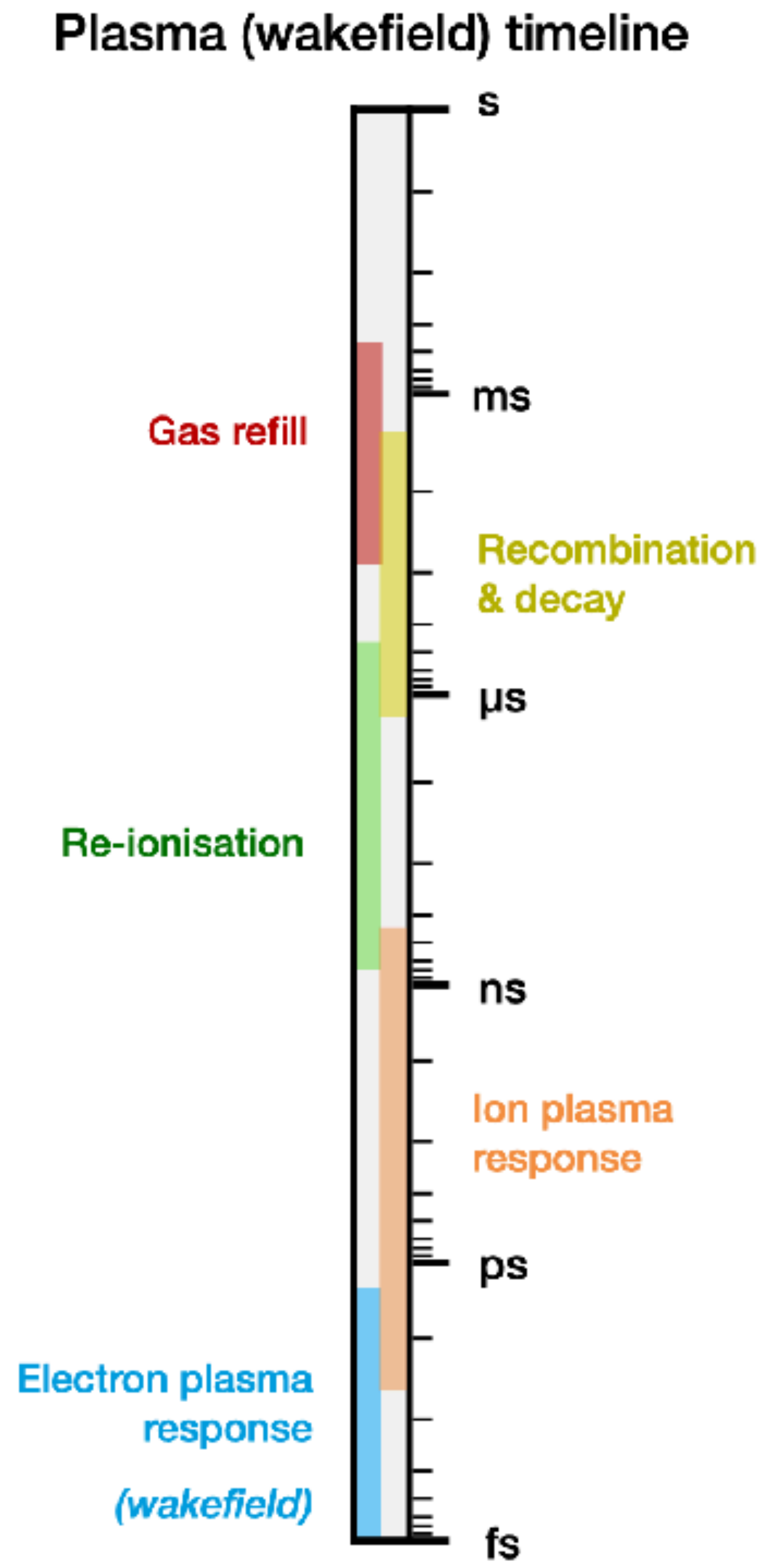
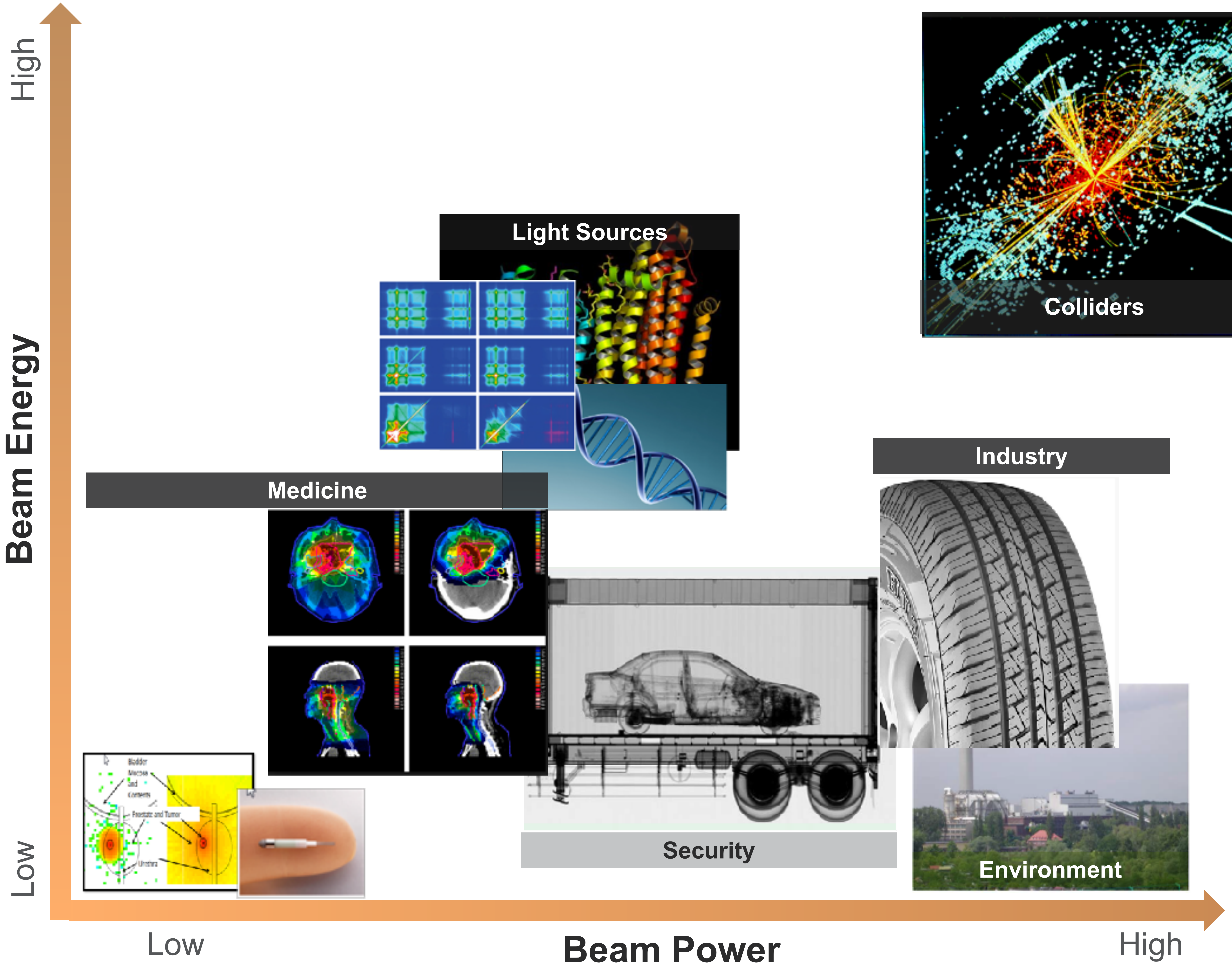


# High-power plasma accelerators unlock new areas of application

## Miniaturize current concepts and change the paradigm: bring the machine to the problem

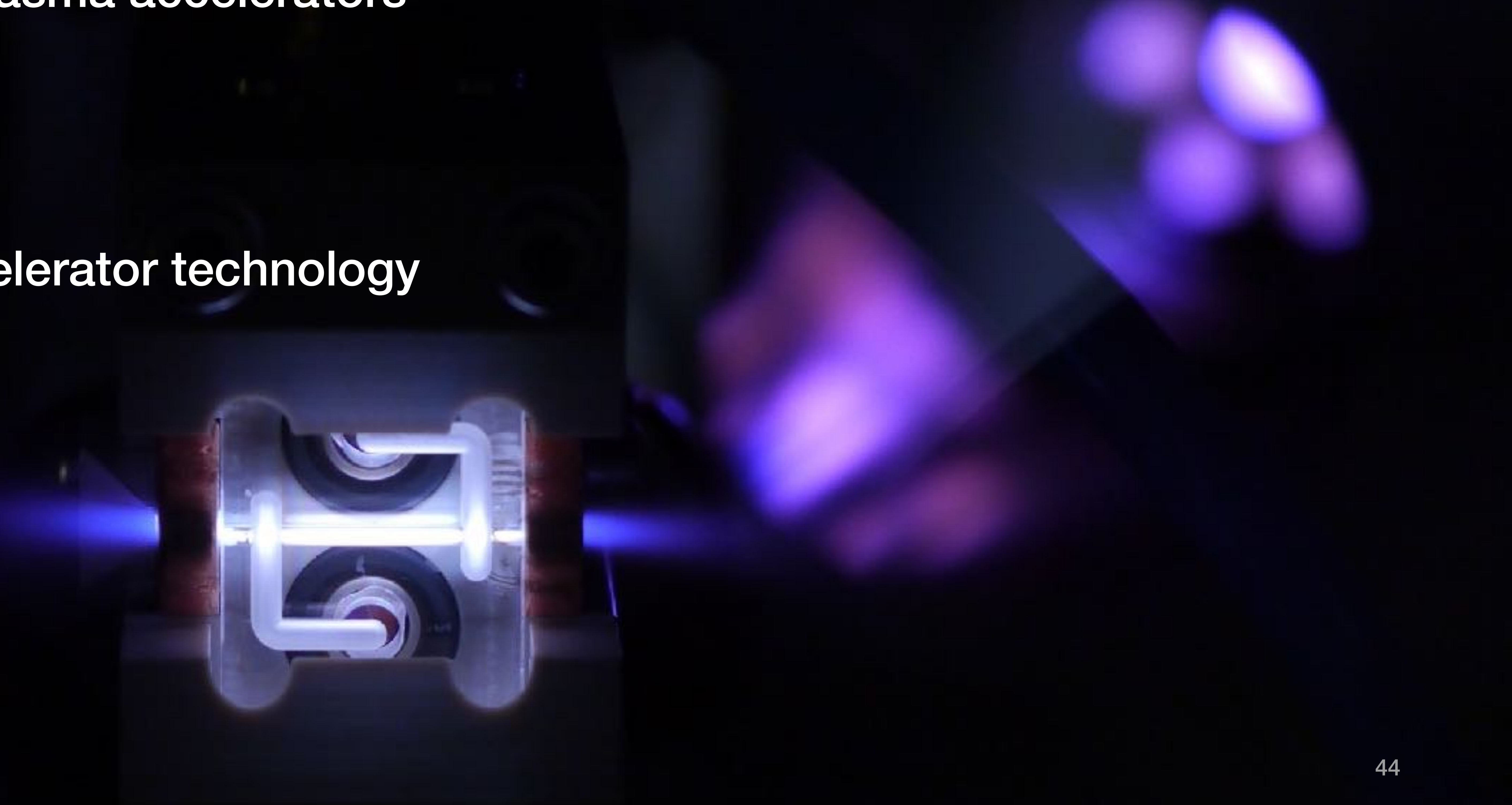
Cole *et al*, PNAS **115** (2018)

Imperial College London
Science & Technology Facilities Council



# Summary

- Accelerators are at the heart of photon science and particle physics experiments, but are large installations
- Plasma wakefield technology offers a promising path to compact accelerators with > 1 GV/m fields
- Two alternative driver technologies: laser- and beam-excited plasma wakes
- **Common goal:**
  - plasma accelerator research → usable plasma accelerators
- **Hope:** miniaturization of accelerators leads to
  - significant cost reduction
  - widespread proliferation of compact accelerator technology
  - beams with new and extreme properties
- Plasmas may have a revolutionary influence on accelerator applications and society



Thank you for your attention!