DESY Summer Student School
Hamburg | August 19th, 2019

Plasma Wakefield Acceleration

An introduction to laser- (and beam-)driven concepts

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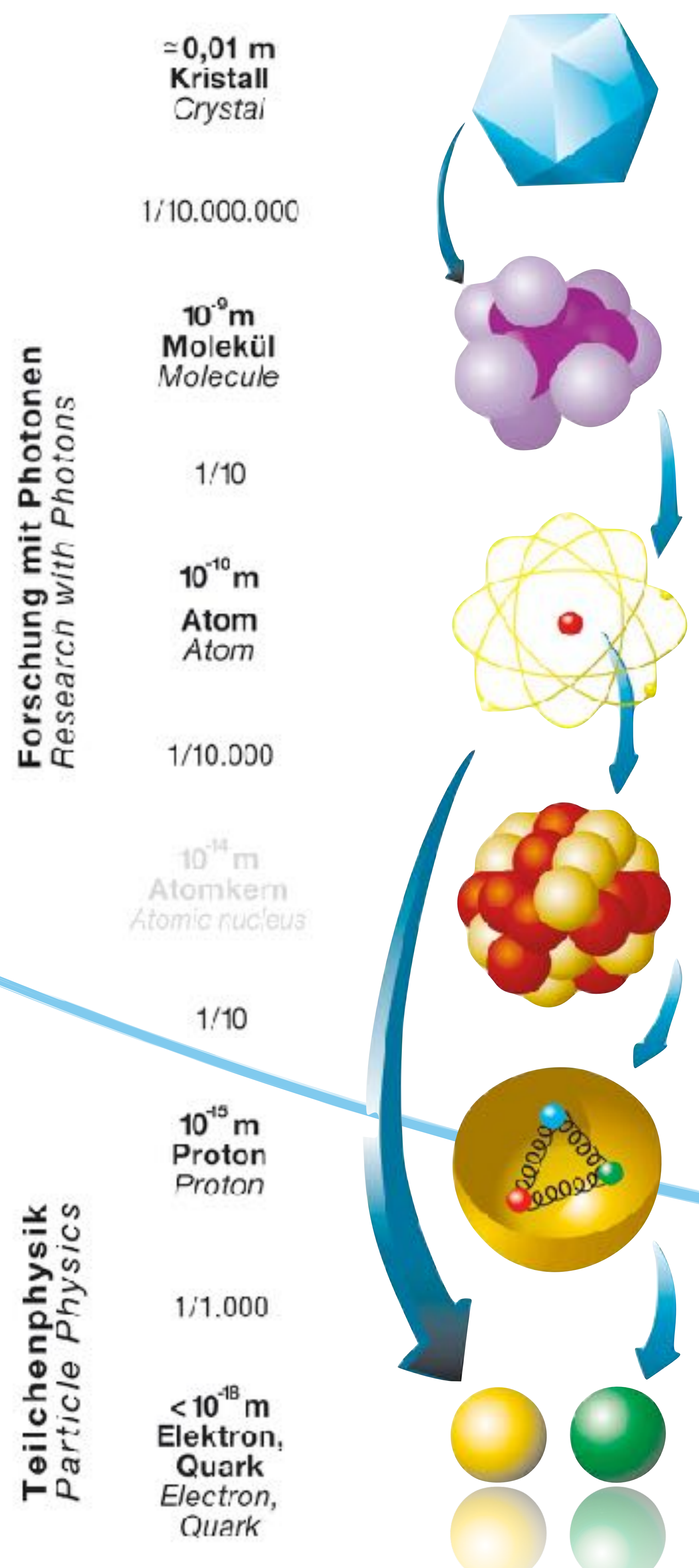
Accelerator Research and Development, Matter and Technology
Helmholtz Association of German Research Centres, Berlin, Germany

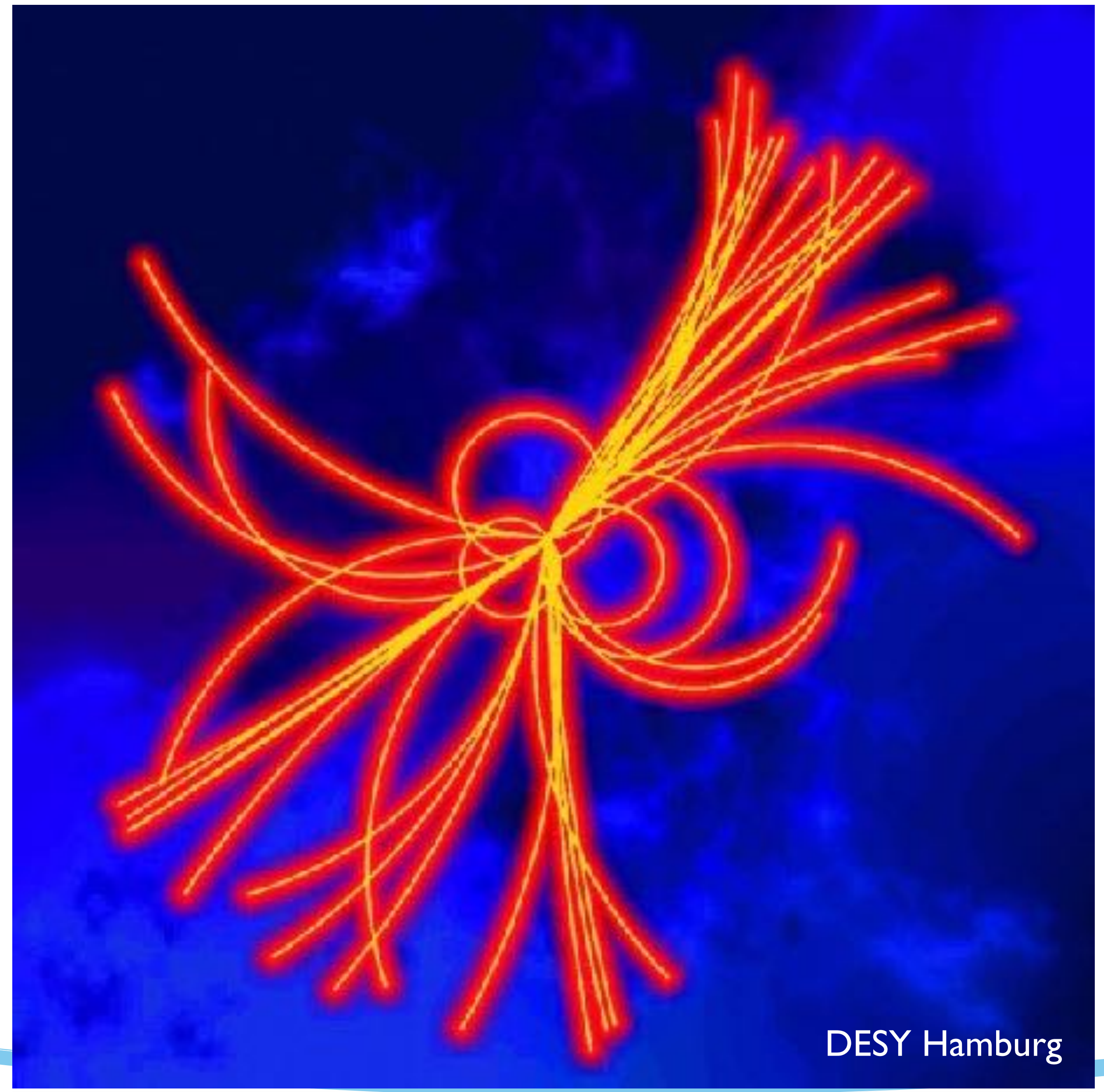
Outline

- Introduction to laser-driven plasma wakefield accelerators: why do we care?
- Properties of plasma wakefields
- (Some) controlled beam injection techniques
- Energy limit of the acceleration process
- *Annex:* beam-driven plasma wakefield acceleration (and the FLASHForward project)

Accelerators are at the heart of high-energy photon sources and particle 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

Accelerators are at the heart of high-energy photon sources and particle colliders

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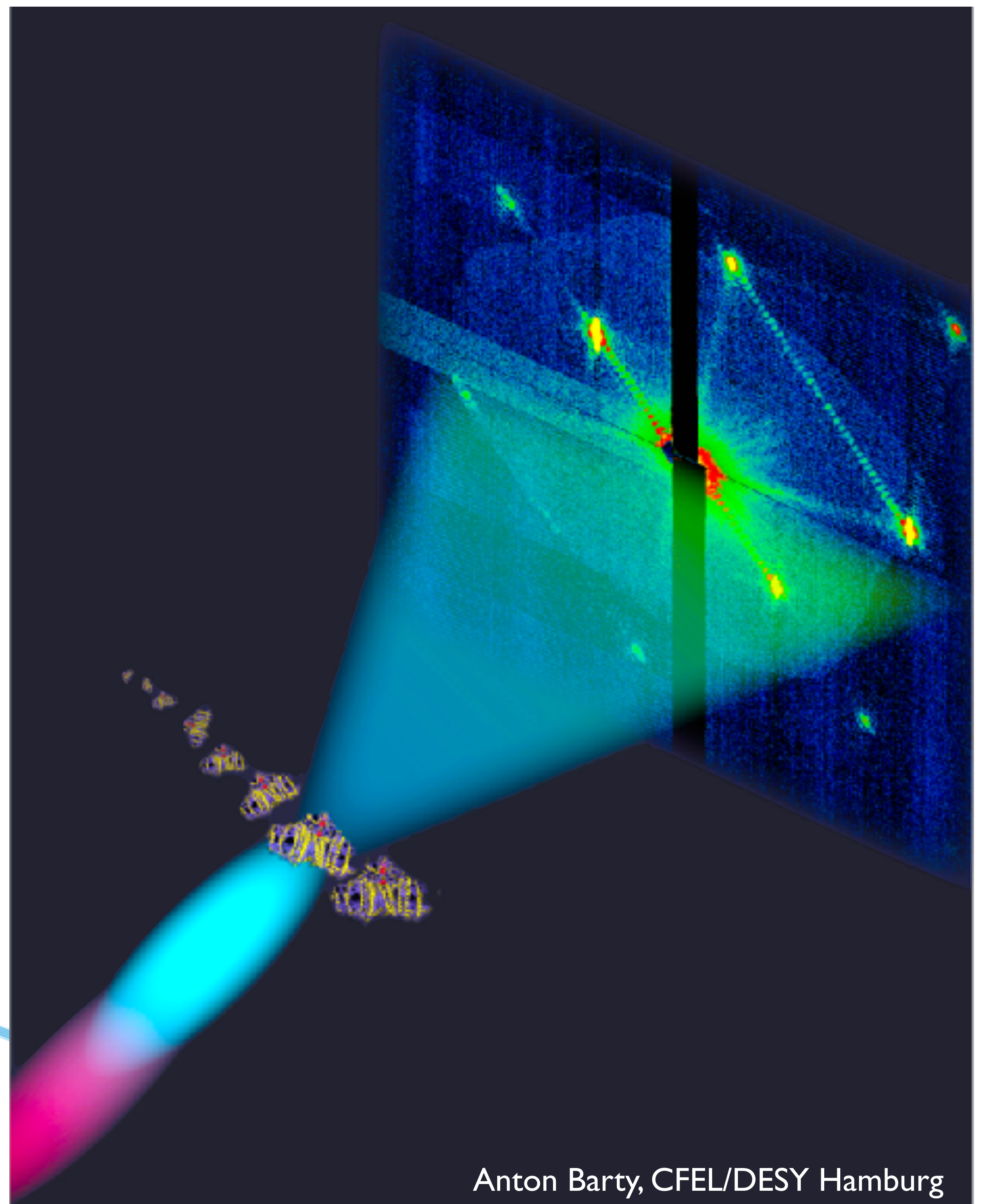
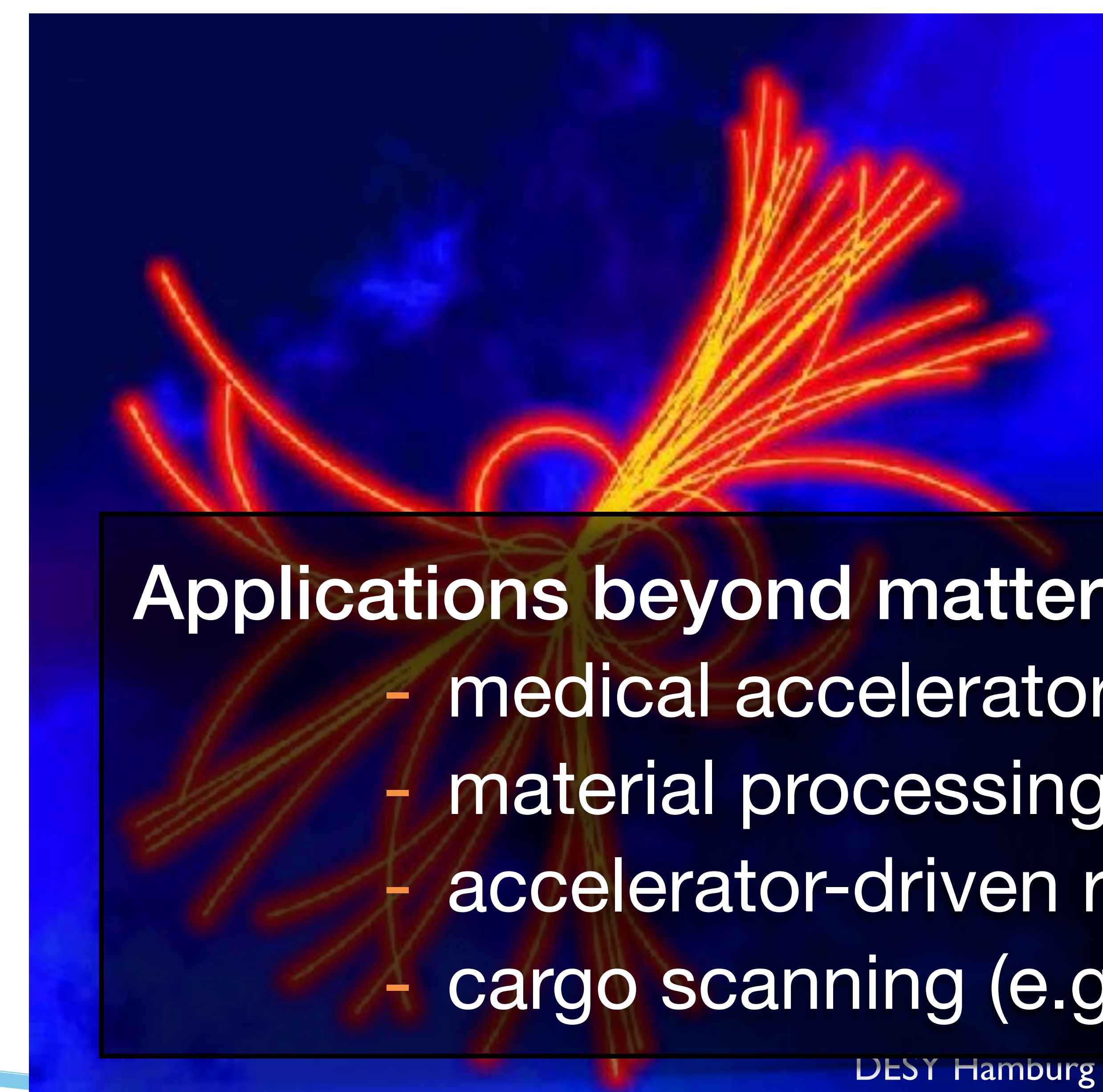


Illustration of an FEL-pulse diffracting off a protein (XFEL, DESY)

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

Particle colliders
investigation of the fundamental forces and constituents of matter

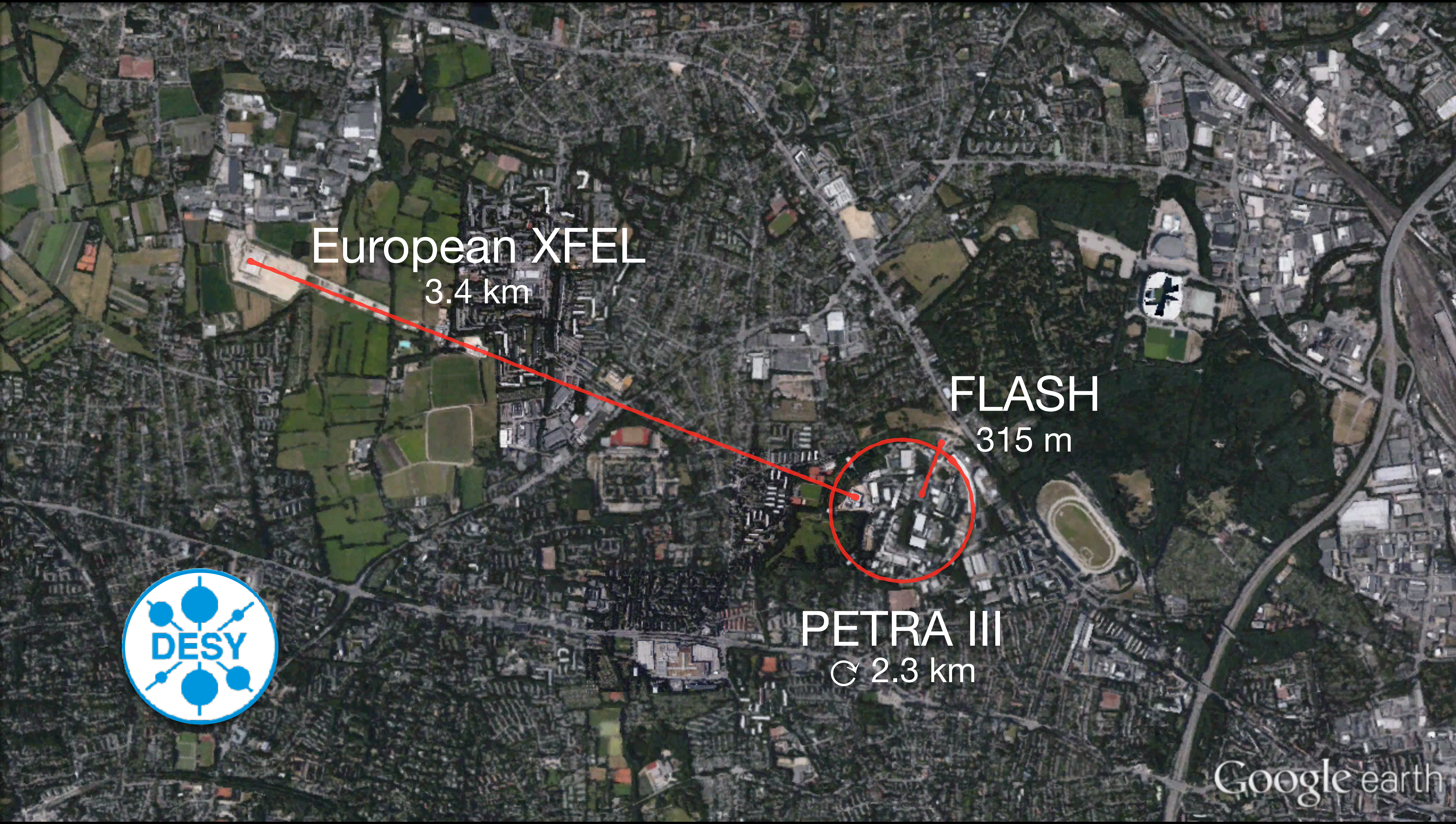


Applications beyond matter

- medical accelerators (e.g. cancer therapy)
- material processing (e.g. food sterilization, welding)
- accelerator-driven reactors
- cargo scanning (e.g. for nuclear fuel)

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


Earth
⌀ 12700 km
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth


European XFEL
3.4 km
FLASH
315 m
PETRA III
2.3 km
DESY
Google earth

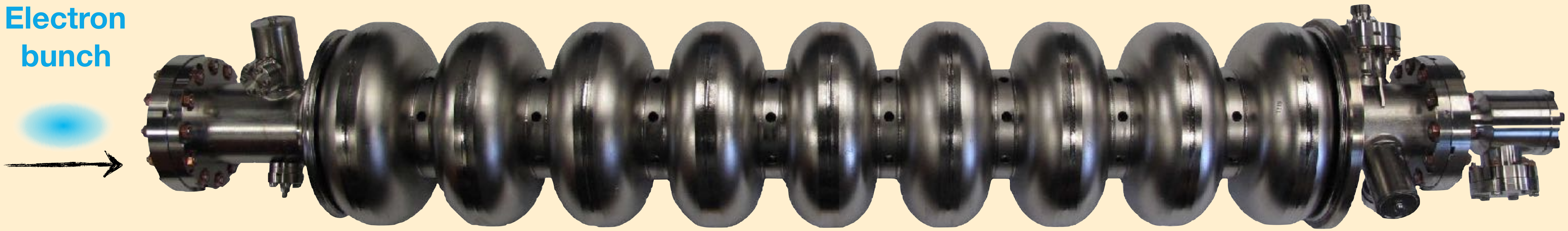

MODUL 6
DESY
FLASH FEL facility
315 m long with ~100 m 1.2 GeV SRF accelerator
Google earth

What defines the scale length of the accelerator?

LIMITS OF CONVENTIONAL TECHNOLOGY

Working principle of an RF-cavity

Electron bunch

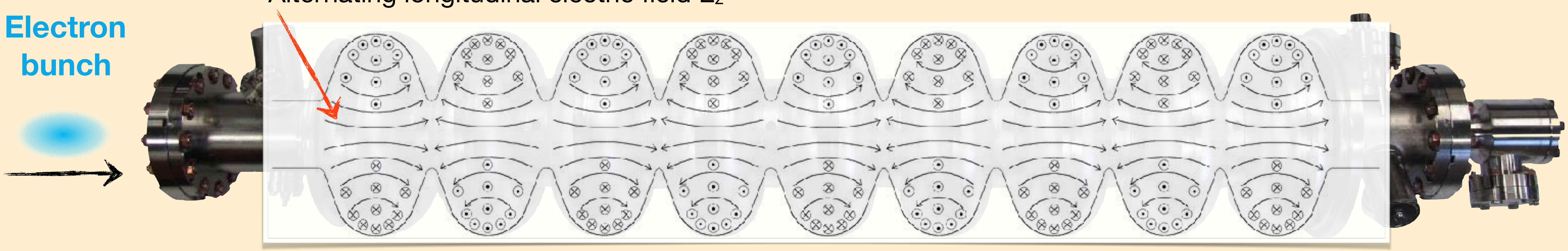


~1 m long TESLA-type superconducting structure

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!

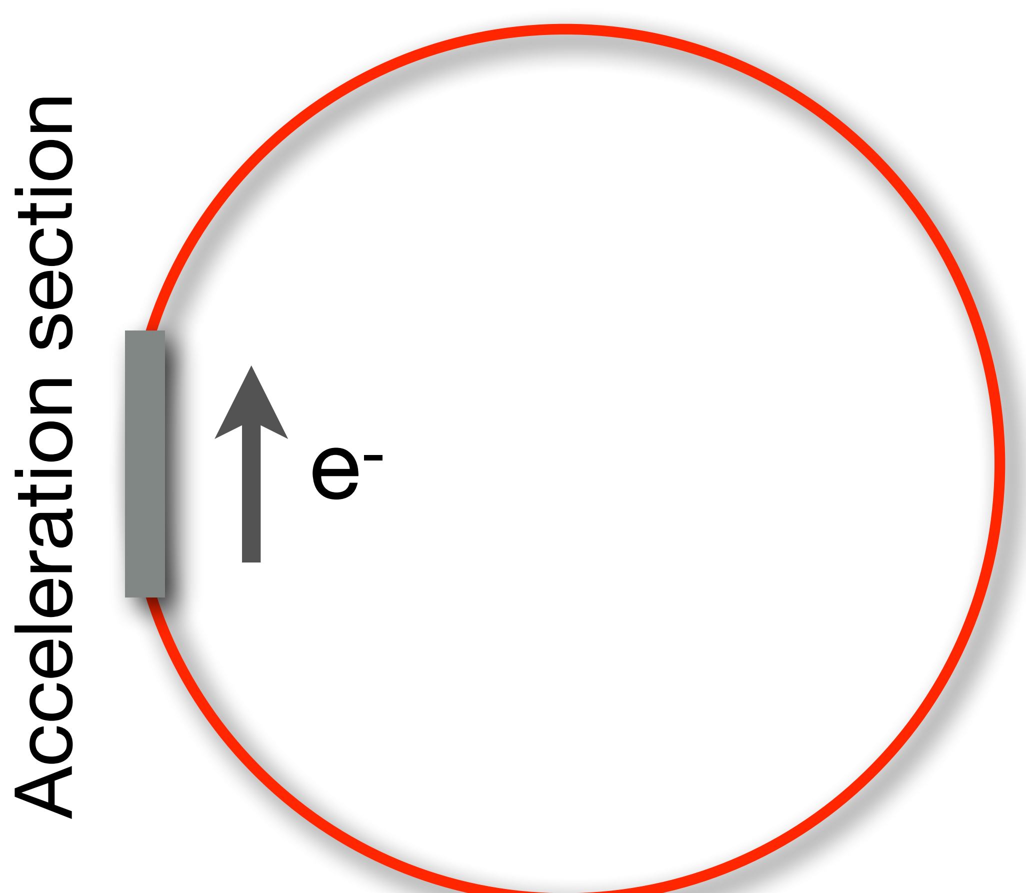
What defines the scale length of the accelerator?

LIMITS OF CONVENTIONAL TECHNOLOGY

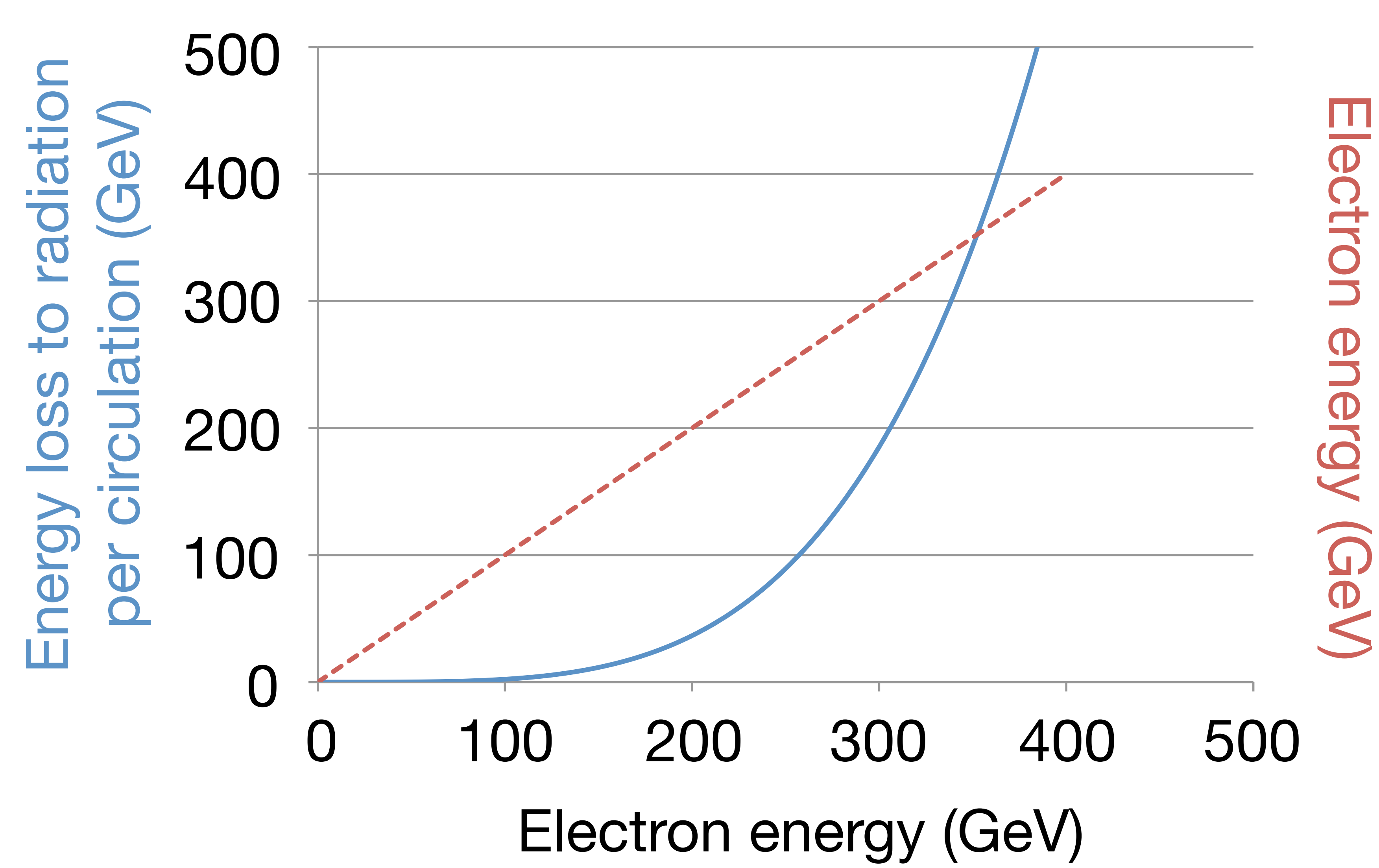
Ring accelerators for electrons?

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



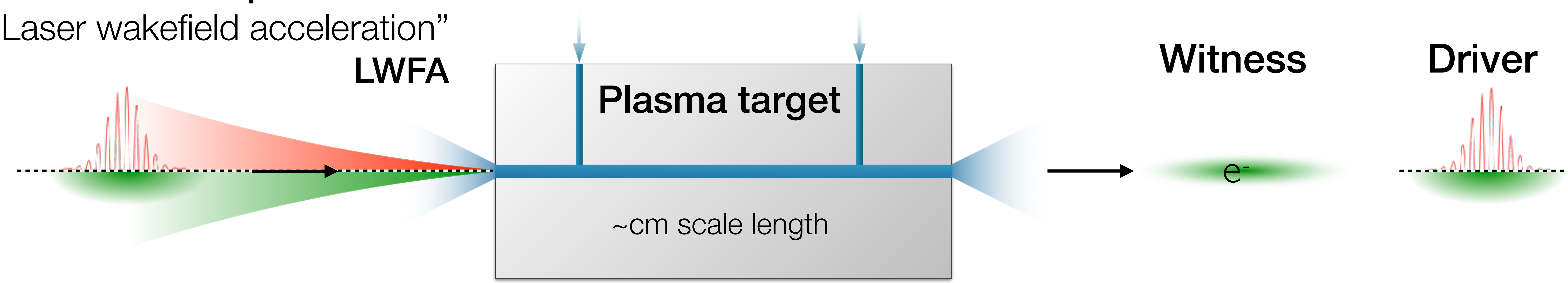
$$\Delta W_{syn} \propto \frac{1}{r^2} \frac{W_{kin}^4}{(m_e c^2)^4}$$


MODUL 6
DESY
FLASH FEL facility
315 m long with ~100 m 1.2 GeV SRF accelerator
Google earth


Plasma wakefield accelerator
0.07 m
delivers ~1 GeV, a similar energy as FLASH
→ Leemans *et al.*, Nature Physics **2**, 696 (2006)

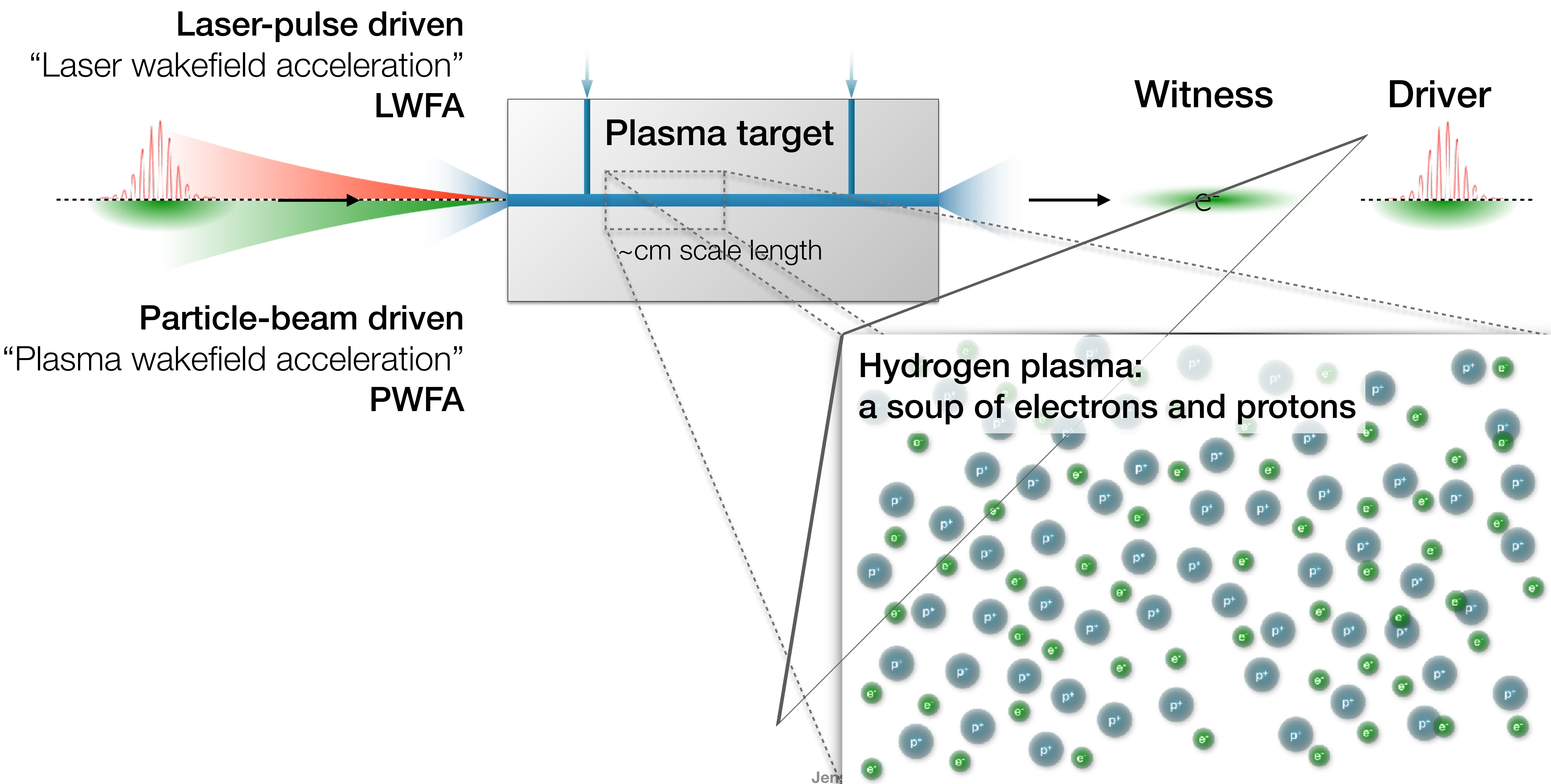
Plasma wakefield acceleration in a nutshell

Laser-pulse driven
"Laser wakefield acceleration"
LWFA



Particle-beam driven
"Plasma wakefield acceleration"
PWFA

Plasma wakefield acceleration in a nutshell



Plasma wakefield acceleration in a nutshell

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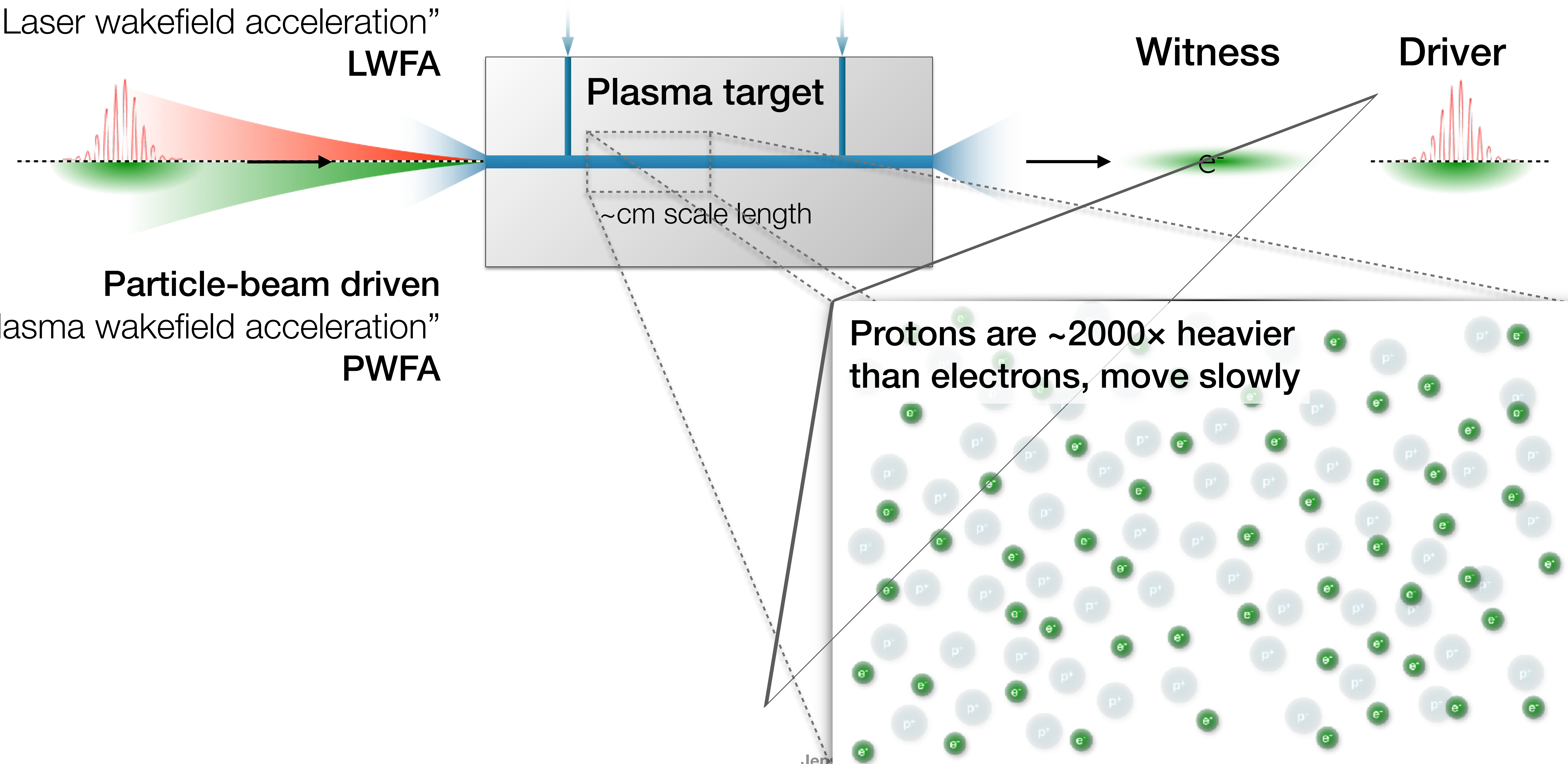

Plasma wakefield acceleration in a nutshell

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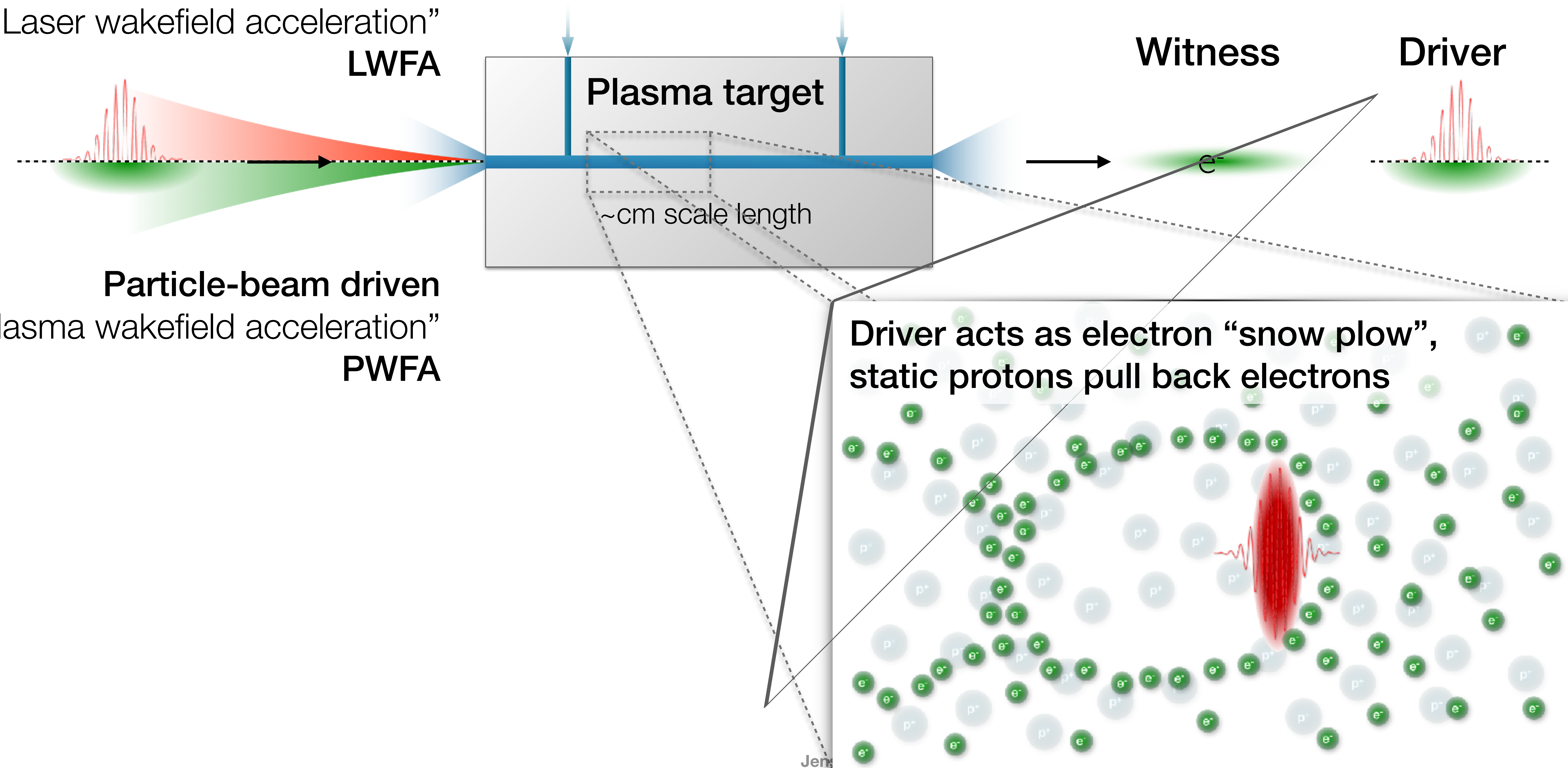

Plasma wakefield acceleration in

Laser-pulse driven
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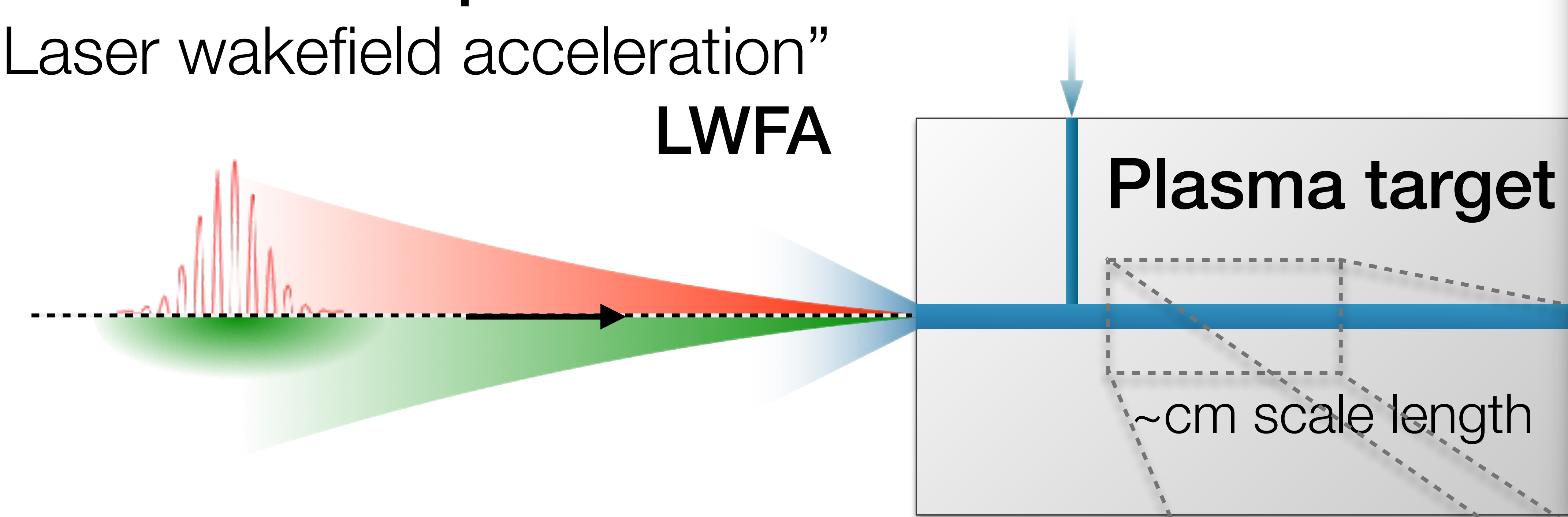

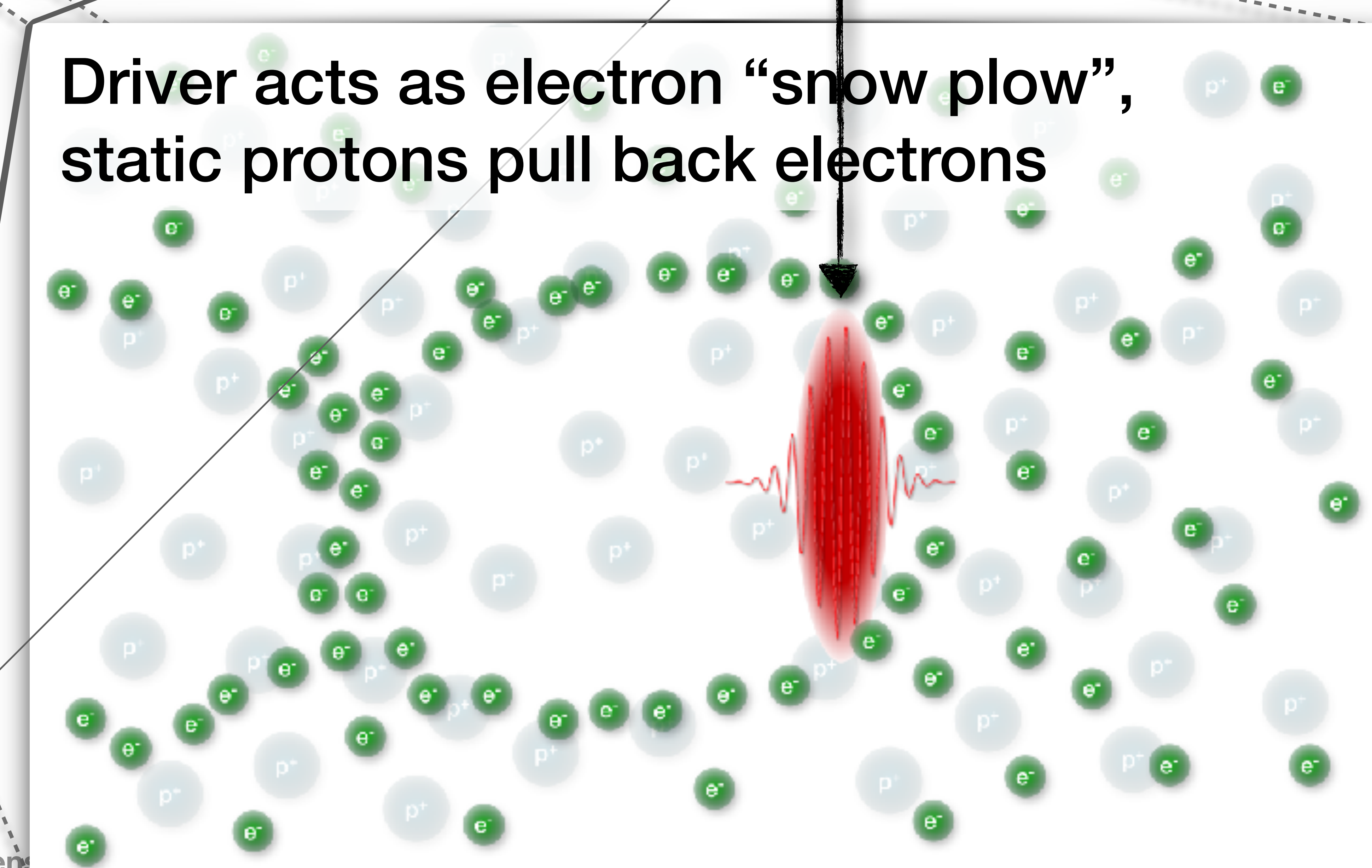

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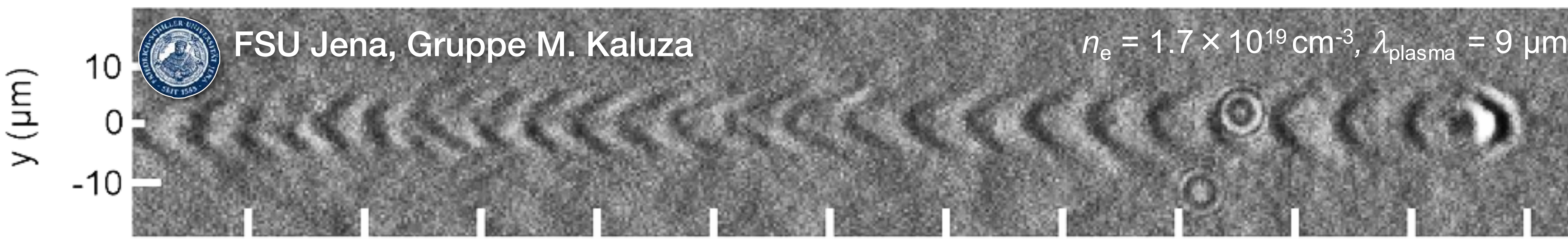

M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

Particle-beam driven
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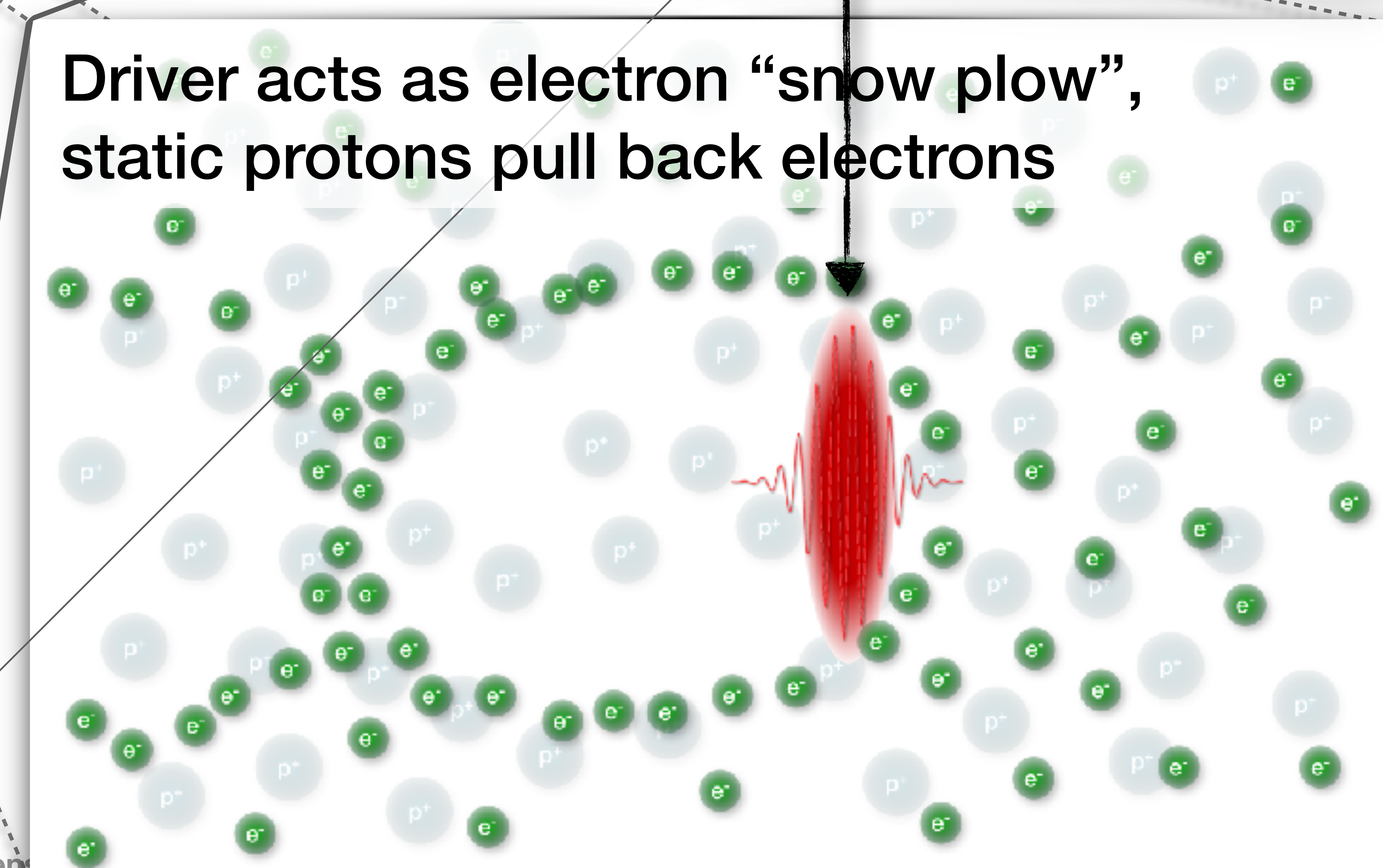


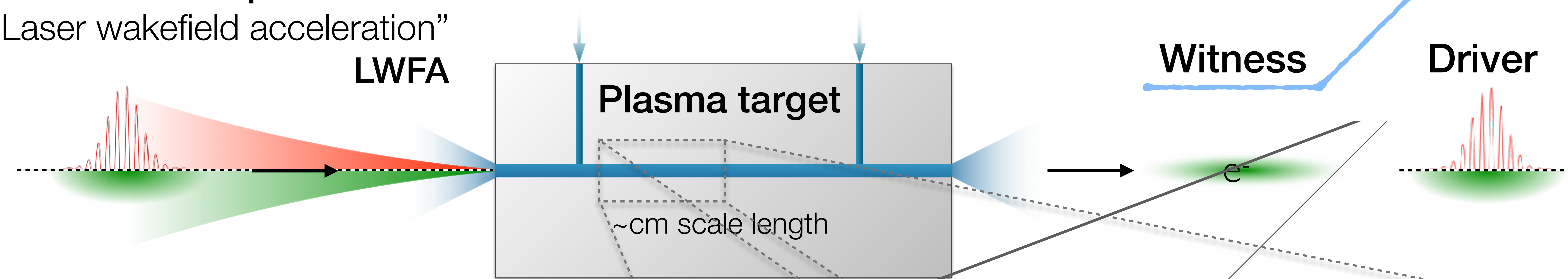
Plasma wakefield acceleration in a nutshell

Interesting for applications

~GeV energy < µm emittance
~fs duration ~kA current

Laser-pulse driven
"Laser wakefield acceleration"
LWFA

Particle-beam driven
"Plasma wakefield acceleration"
PWFA



Bunch duration: fs

→ O. Lundh *et al.*, Nature Physics 7, 219 (2011)
→ A. Buck *et al.*, Nature Physics 7, 543 (2011)

GeV energy gain over cm

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

Size of structure

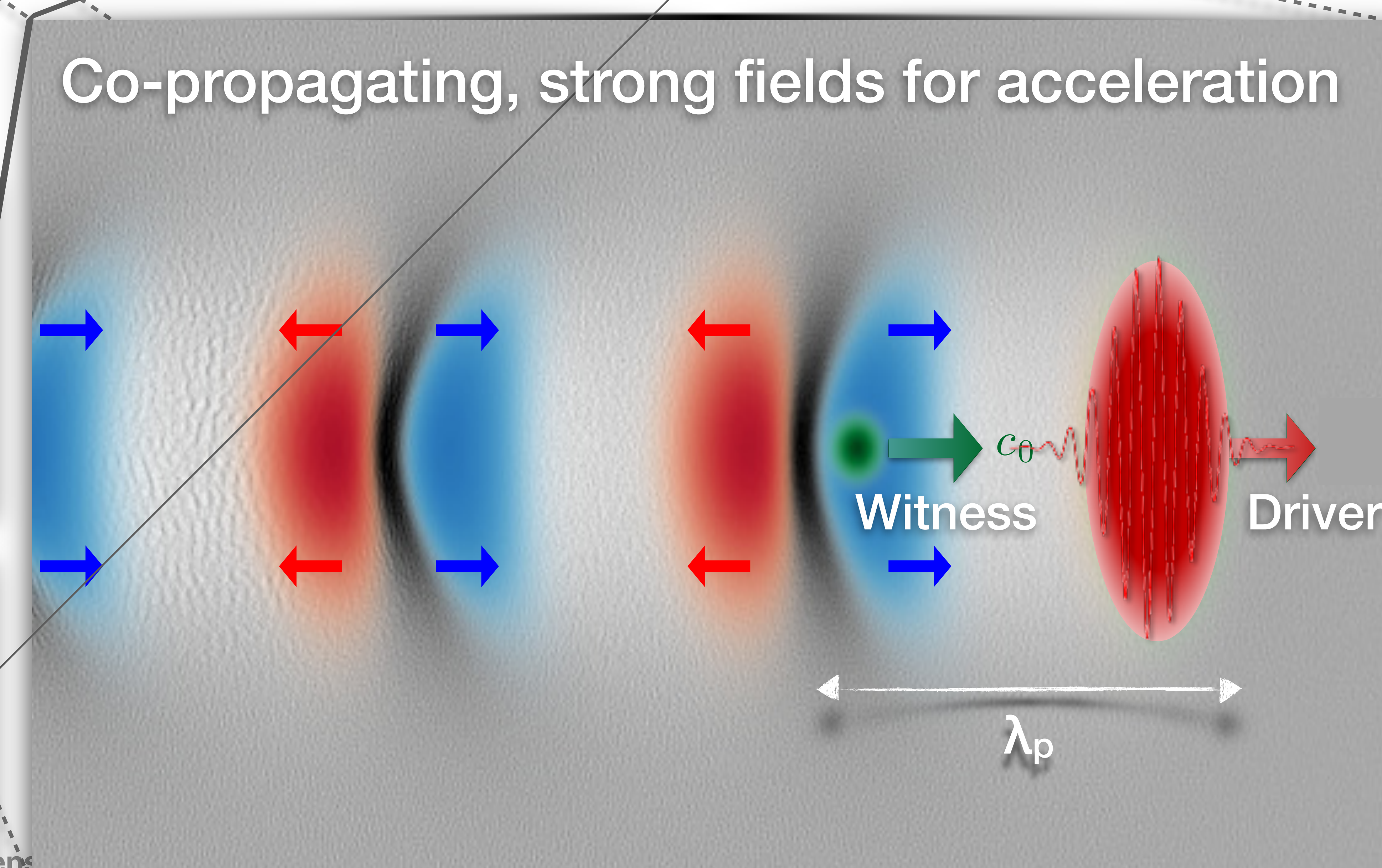
$$\lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33\ \mathrm{km})\sqrt{n_e^{-1}[\mathrm{cm}^{-3}]}$$

typically **$\lambda_p \approx 33$ µm** (for $n_e \approx 10^{18}$ cm^{-3})

Electric field strength

$$E \approx \frac{mc\omega_p}{e} \approx (96\ \mathrm{V/m})\sqrt{n_e[\mathrm{cm}^{-3}]}$$

typically **E ≈ 100 GV/m** (for $n_e \approx 10^{18}$ cm^{-3})



Basics of plasma-based particle acceleration

Wake excitation

Basics of plasma-based particle acceleration

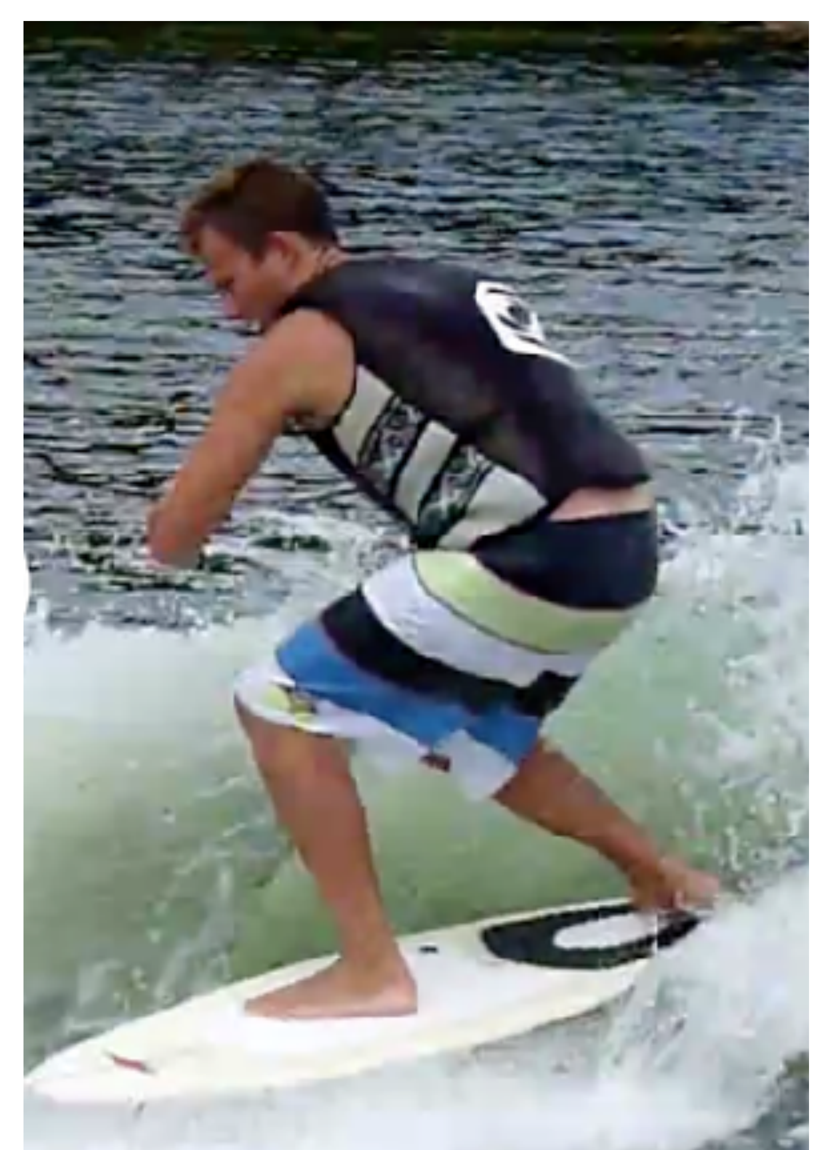
Wake excitation

Particle injection

Basics of plasma-based particle acceleration

Just to make sure, you are paying attention…

What is the color of the surfers pants?



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

$$\frac{\partial^2\phi_0}{\partial\xi^2} = \frac{\omega_{\mathrm{p}}^2}{c^2}(n_0 - 1)$$
$$= \frac{\omega_{\mathrm{p}}^2}{c^2}\gamma_{\mathrm{g}}^2\left[\frac{\beta_{\mathrm{g}}(1+\phi_0)^2}{\sqrt{(1+\phi_0)^2 - \frac{1+a_0^2}{\gamma_{\mathrm{g}}^2}}} - 1\right]$$

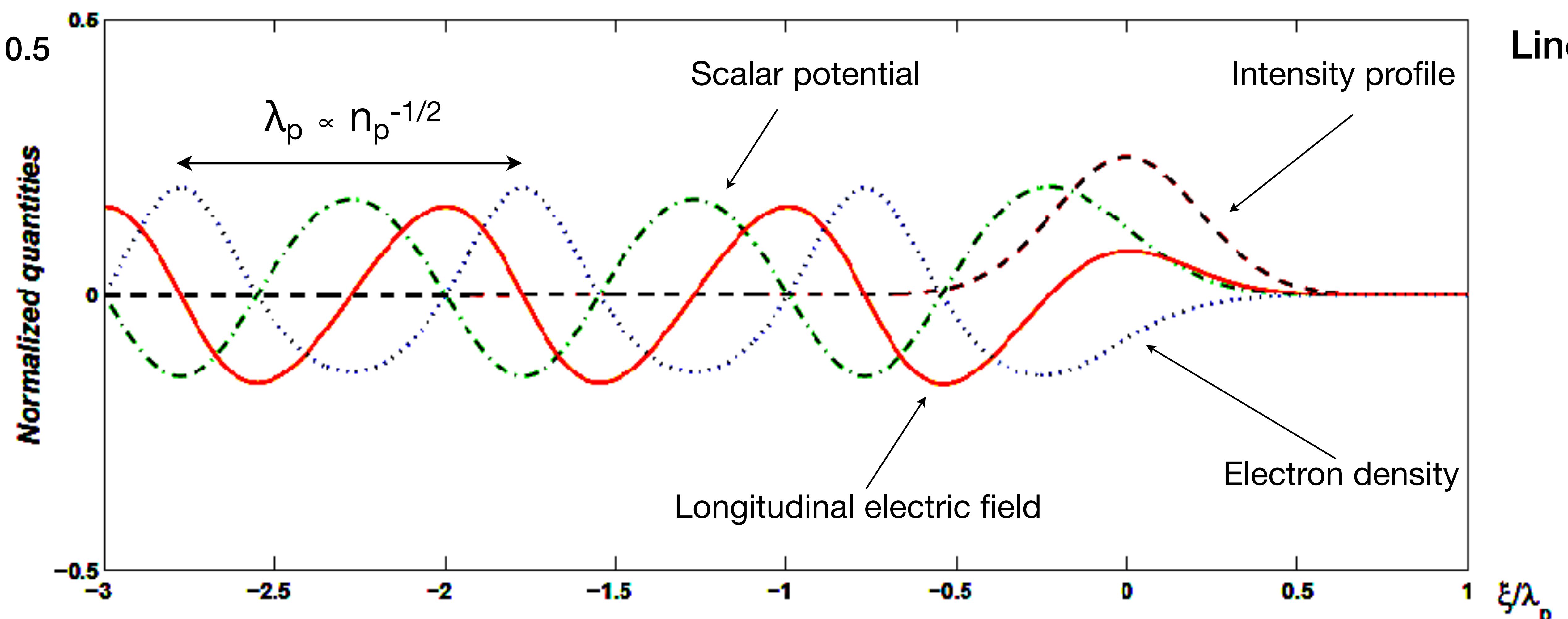
↓ with $\beta_{\mathrm{g}} \to 1$

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

Numerical solution for the scalar wake potential for a Gaussian laser-pulse envelope

1d in space
3d in momentum

$a_0 = 0.5$



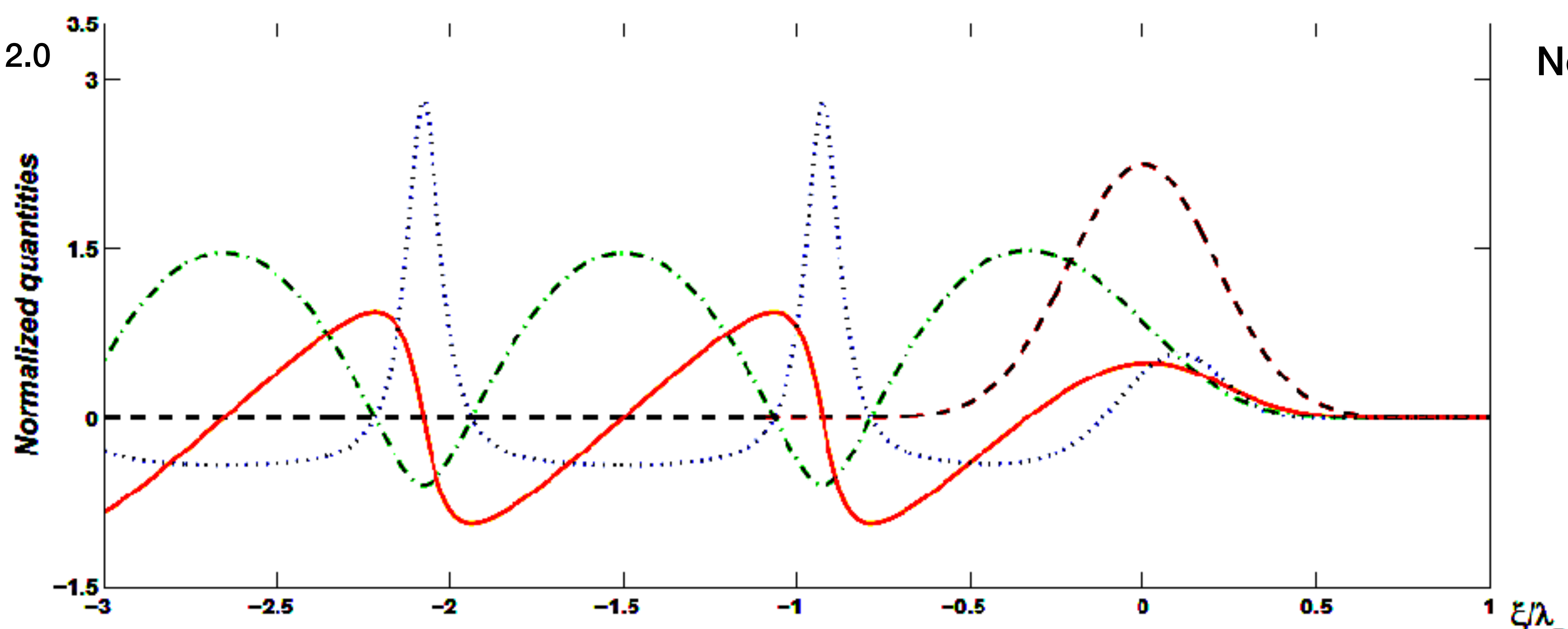
Linear regime

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

Temporal laser-pulse shape in intensity

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

$a_0 = 2.0$



Nonlinear regime

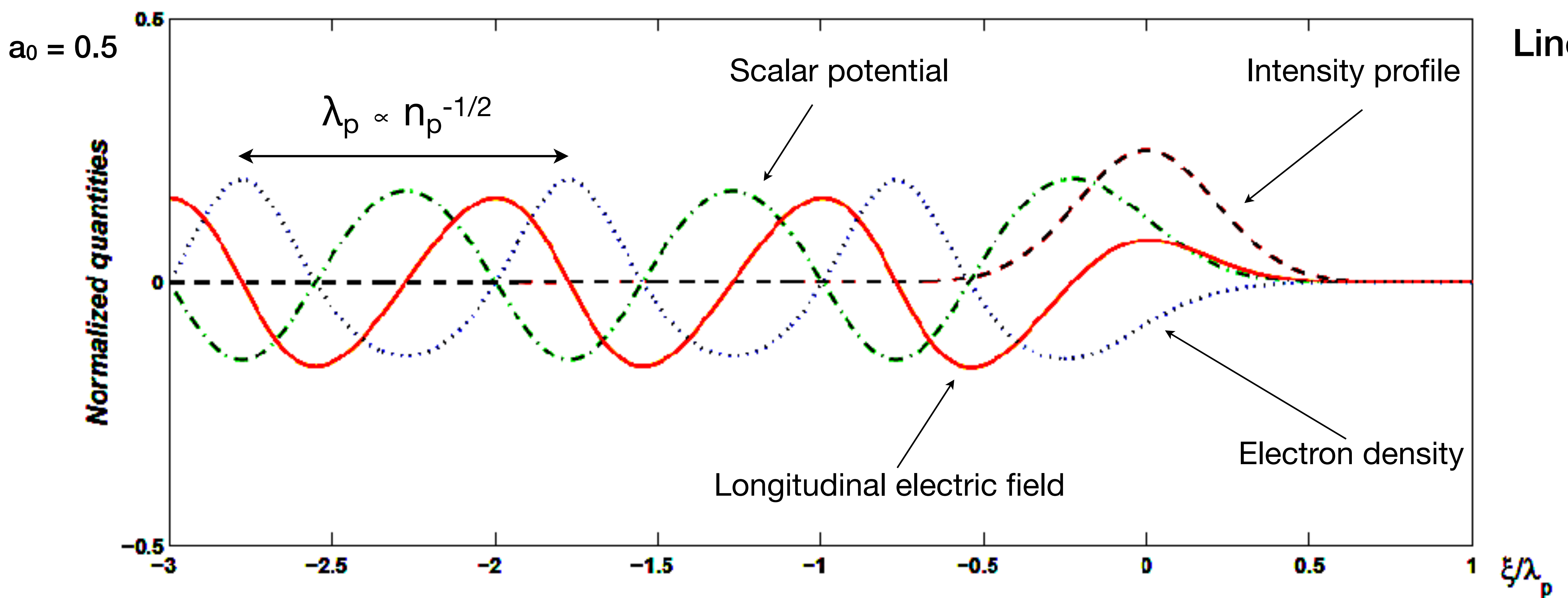
Accelerating field strength

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

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

Numerical solution for the scalar wake potential for a Gaussian laser-pulse envelope

1d in space
3d in momentum



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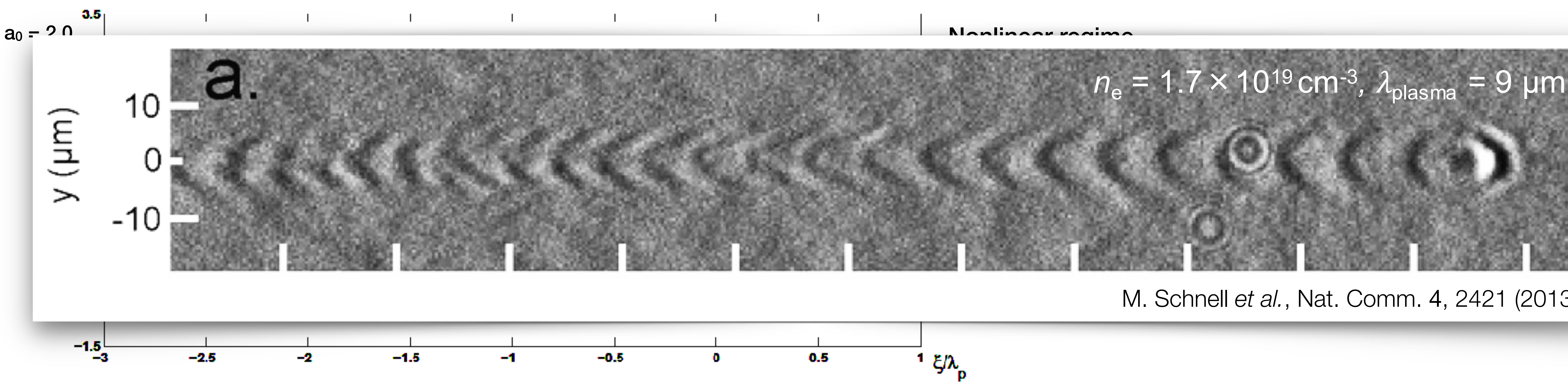
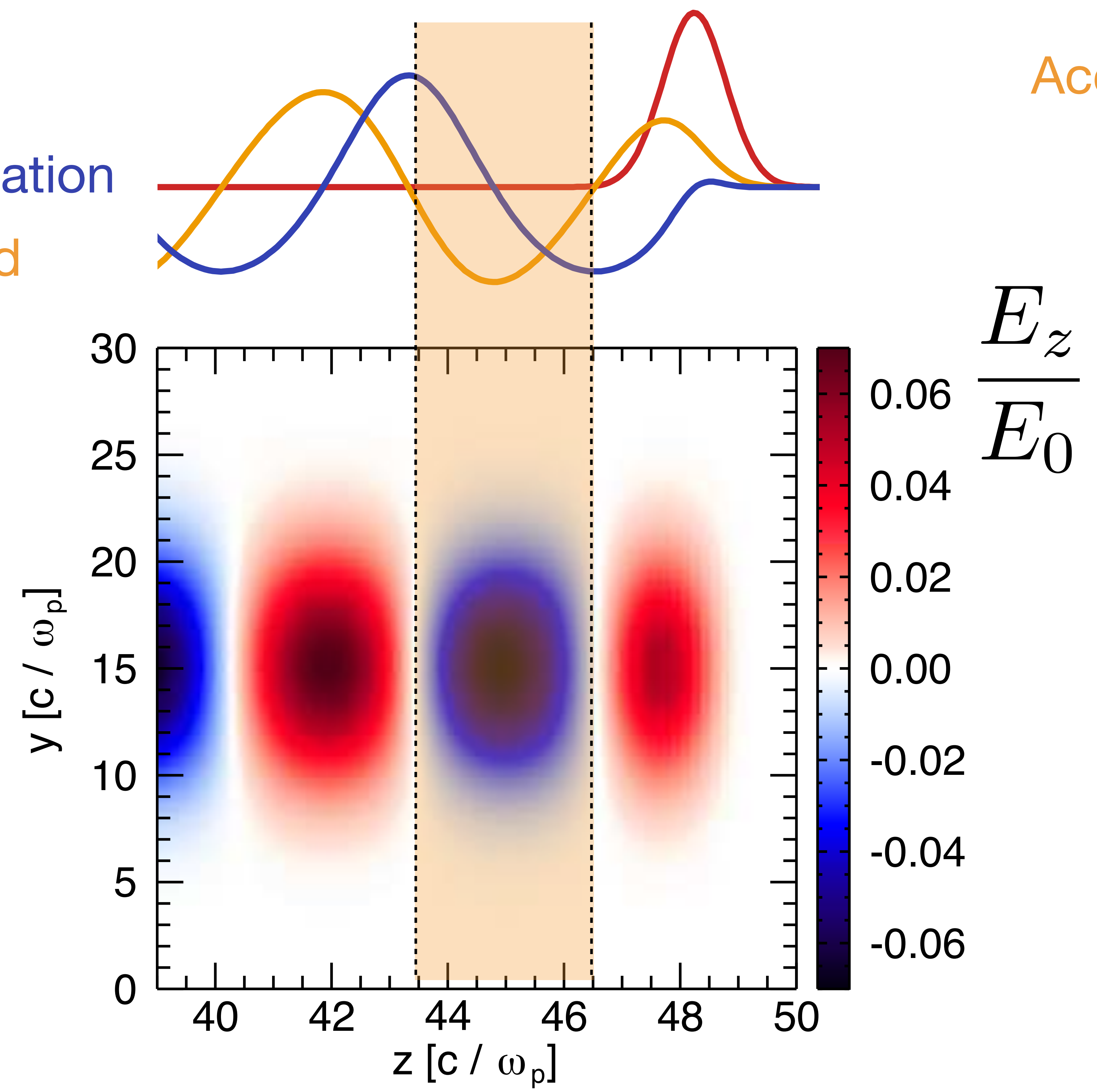


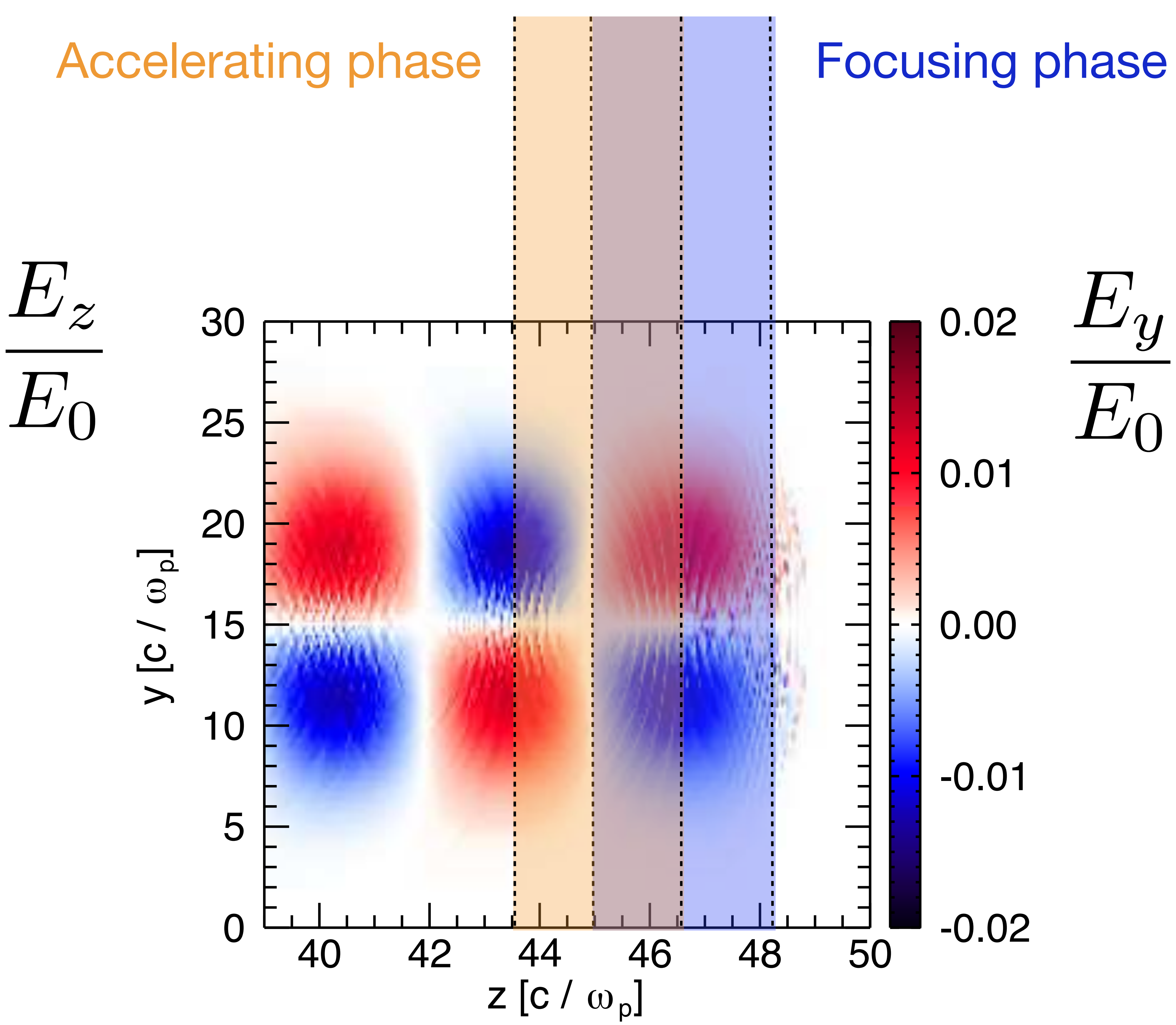
M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

Wakefield properties in transverse dimensions

3d in space
3d in momentum



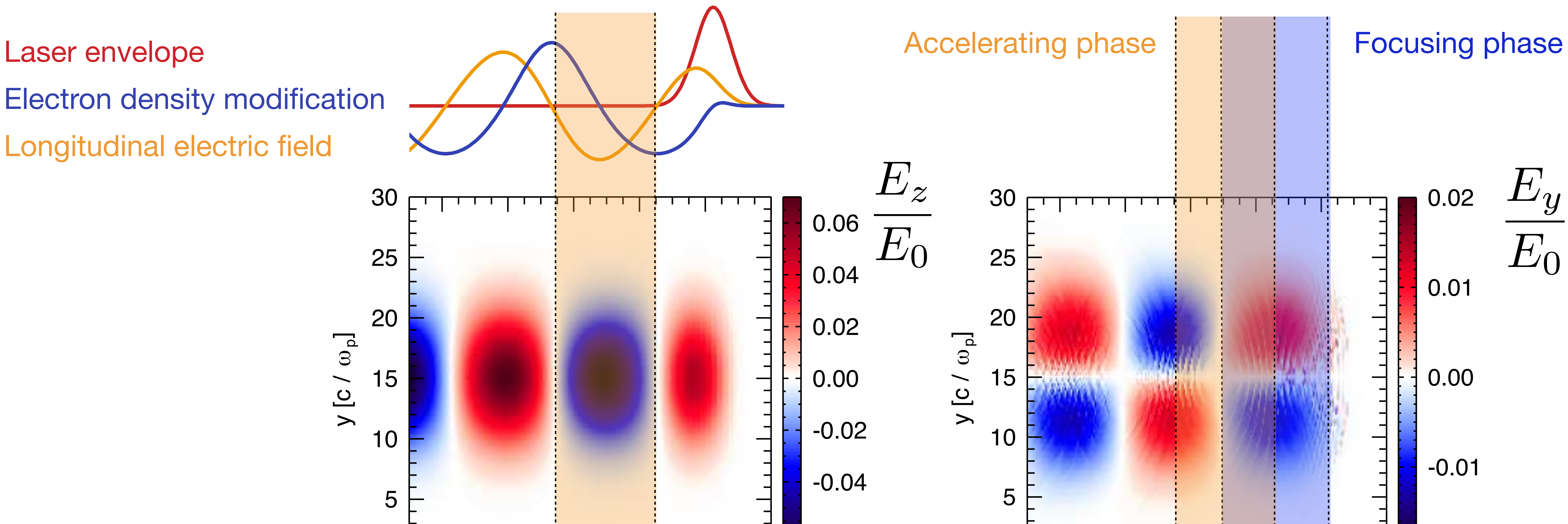
Longitudinal fields
of a quasi-linear plasma wave



Transverse fields
of a quasi-linear plasma wave

Wakefield properties in transverse dimensions

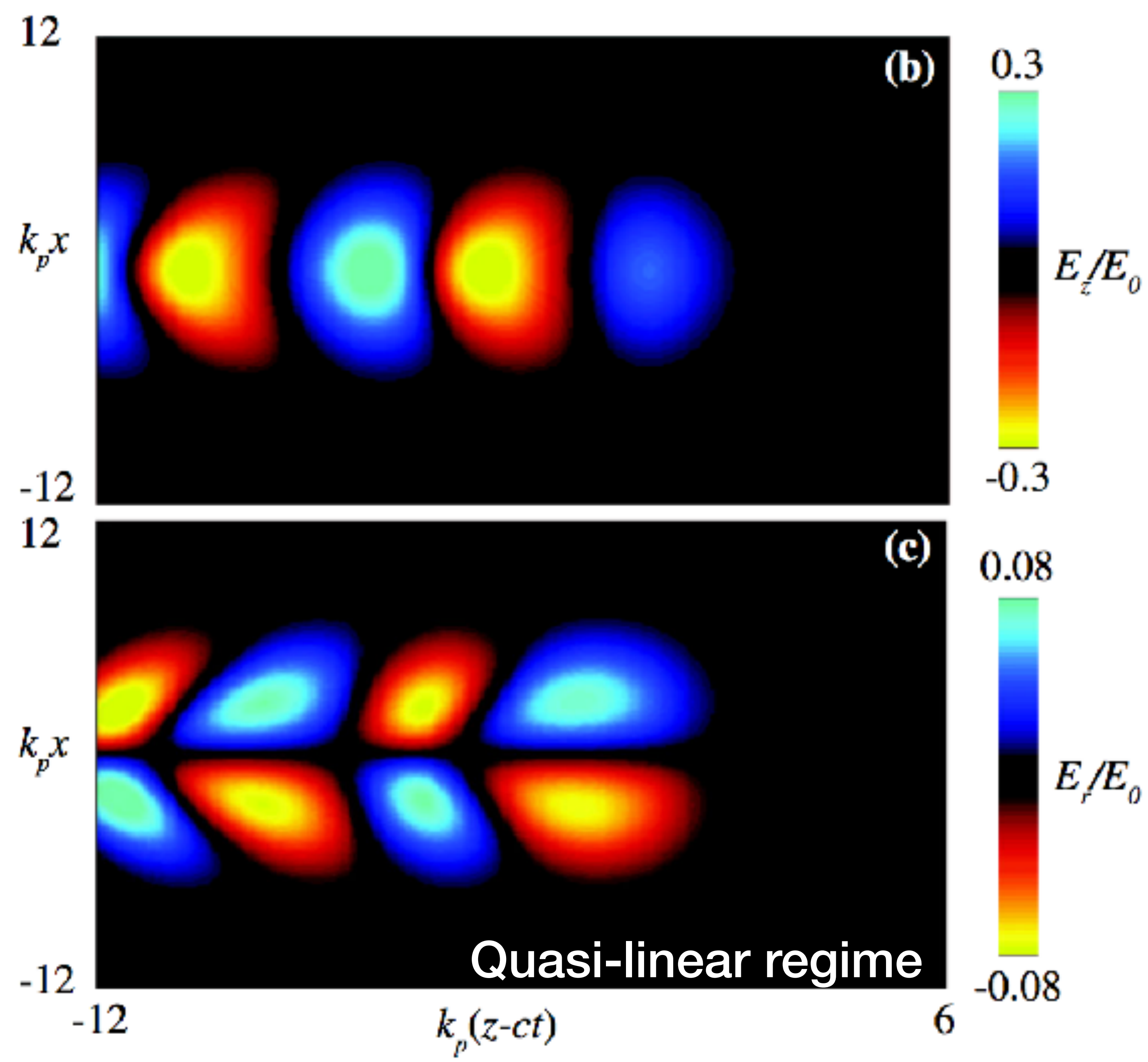
3d in space
3d in momentum

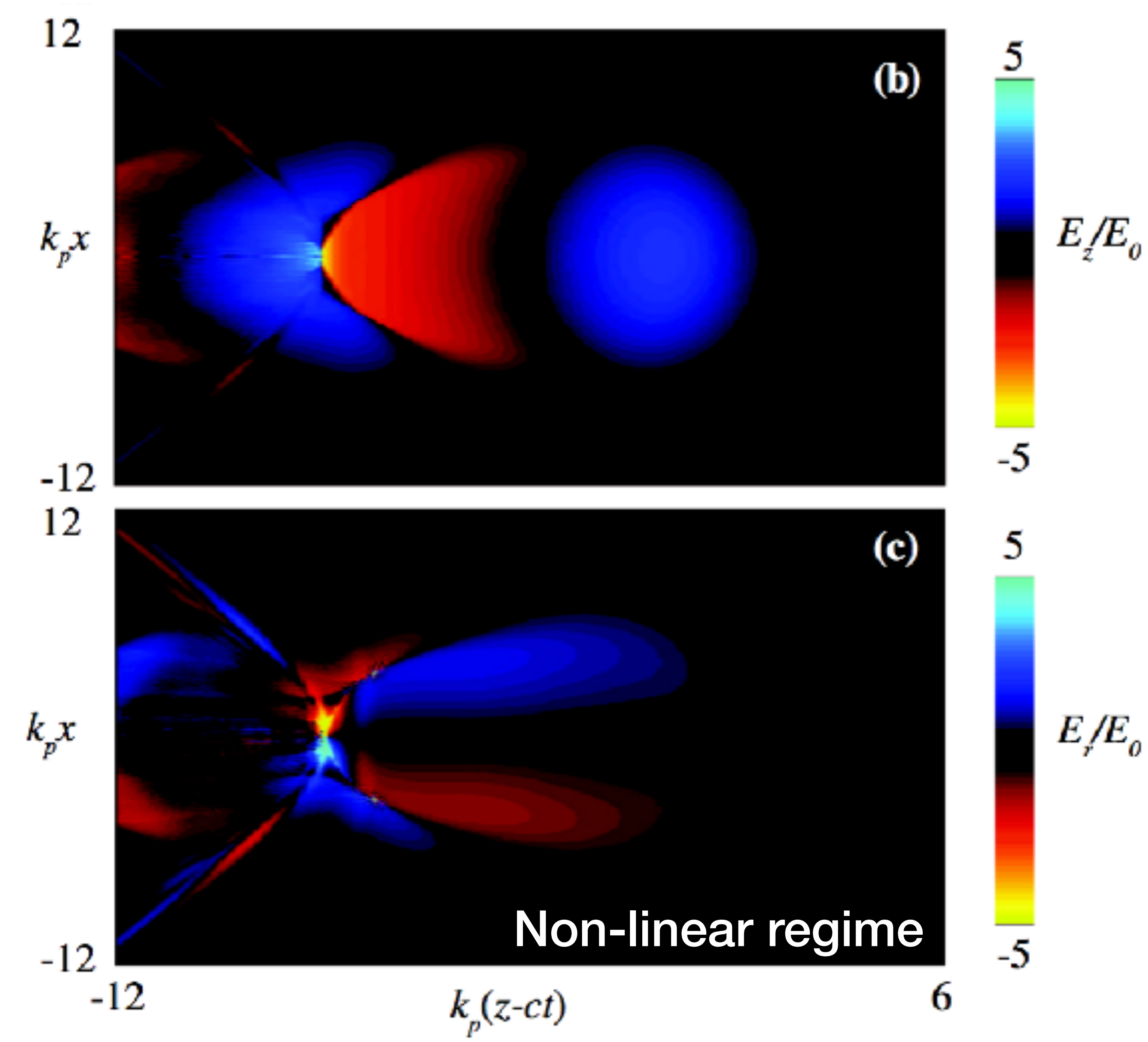


Fraction of plasma wavelength usable for electron acceleration?

Wakefield properties in transverse dimensions

3d in space
3d in momentum





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

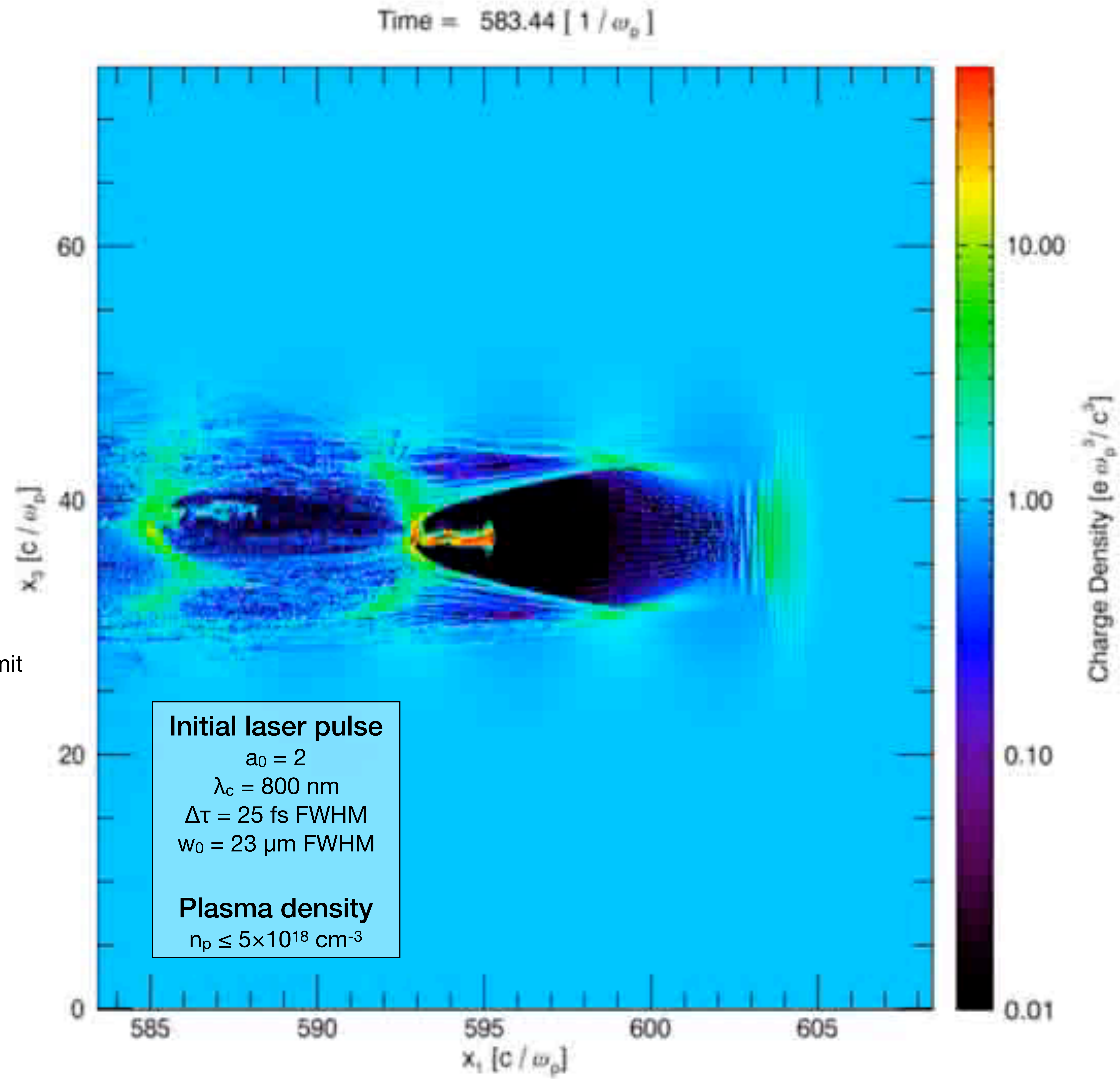
Cold, non-relativistic wave breaking limit

$$E_0 = \frac{c m_e \omega_p}{e}$$

Cold, relativistic wave breaking limit

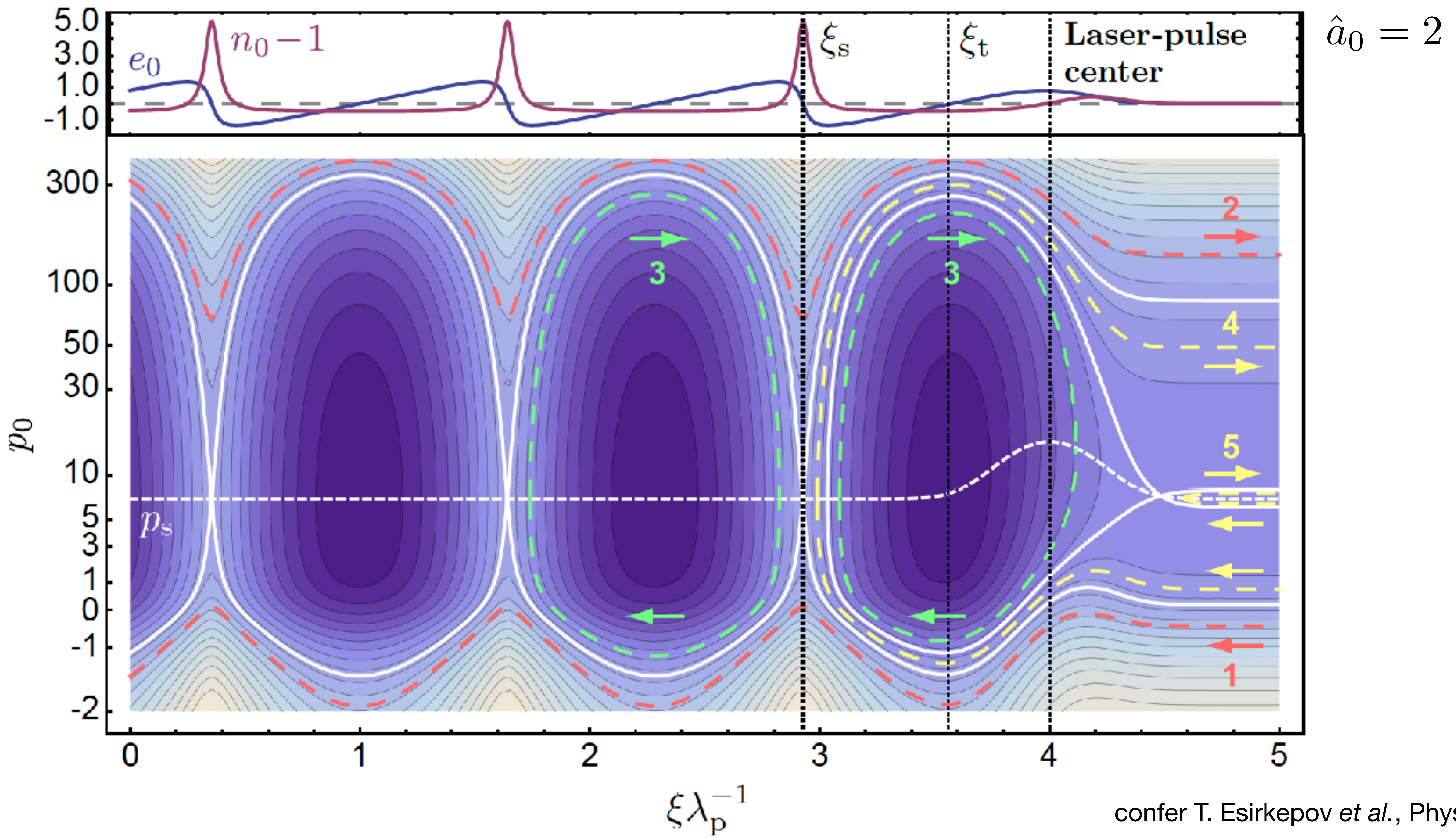
$$E_{wb} = E_0 \sqrt{2(\gamma_\phi - 1)}$$

Temperature and transverse dynamics require further modifications…



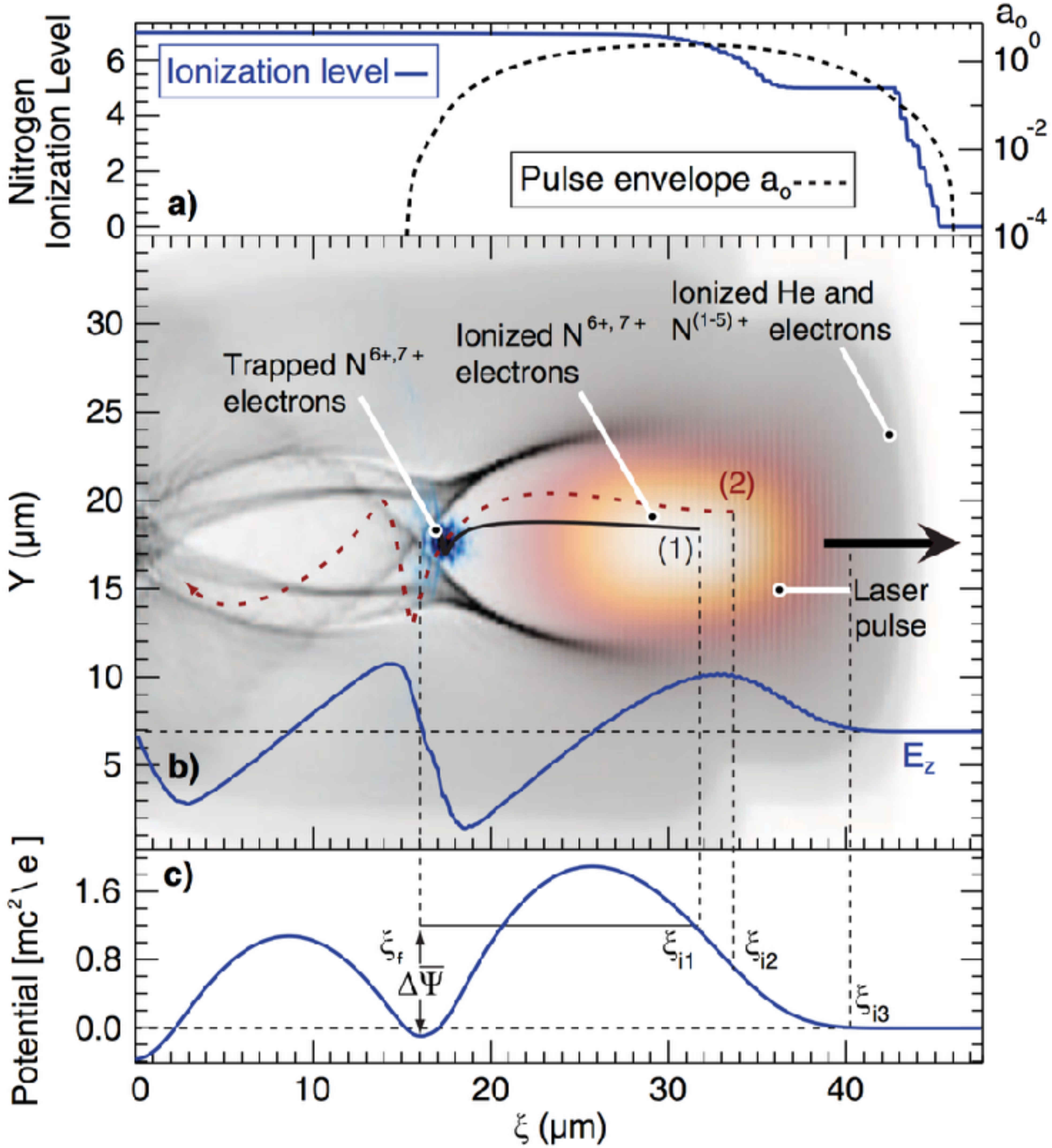
Longitudinal phase space for test particles in wakefield

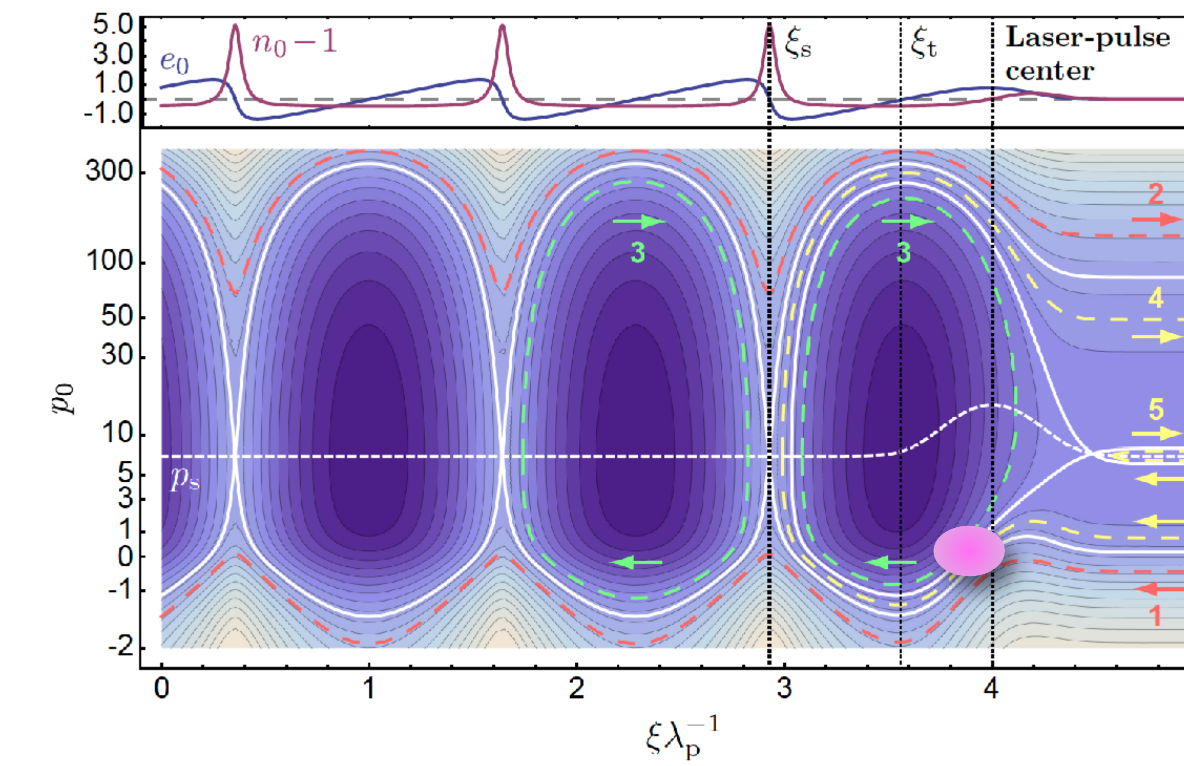
Hamiltonian: $h\left(\xi, p_0\right) = \sqrt{1 + p_0^2 + a_0^2\left(\xi\right)} - \phi_0\left(\xi\right) - \beta_\mathrm{p} p_0 = h_0$



confer T. Esirkepov *et al.*, Phys. Rev. Lett. **96**, 014803 (2006)

Ionization for injection control



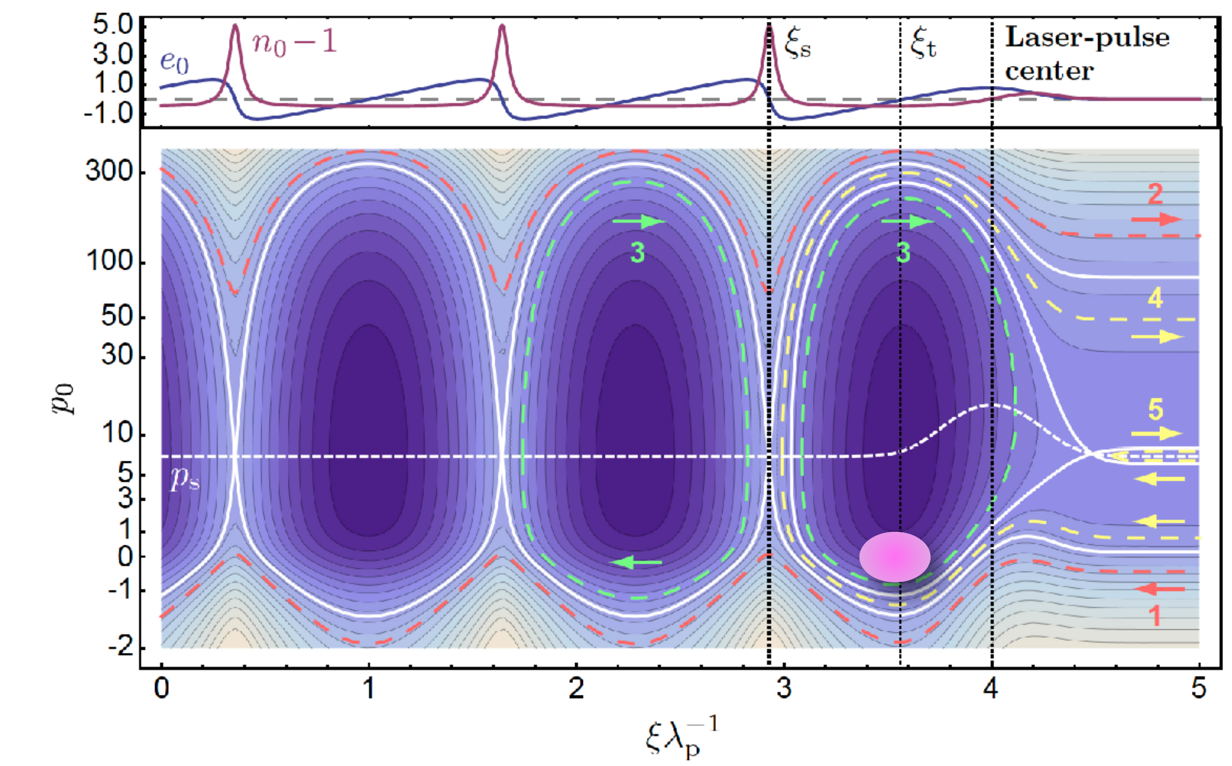


> ionization of dopant gas near laser-pulse peak intensity

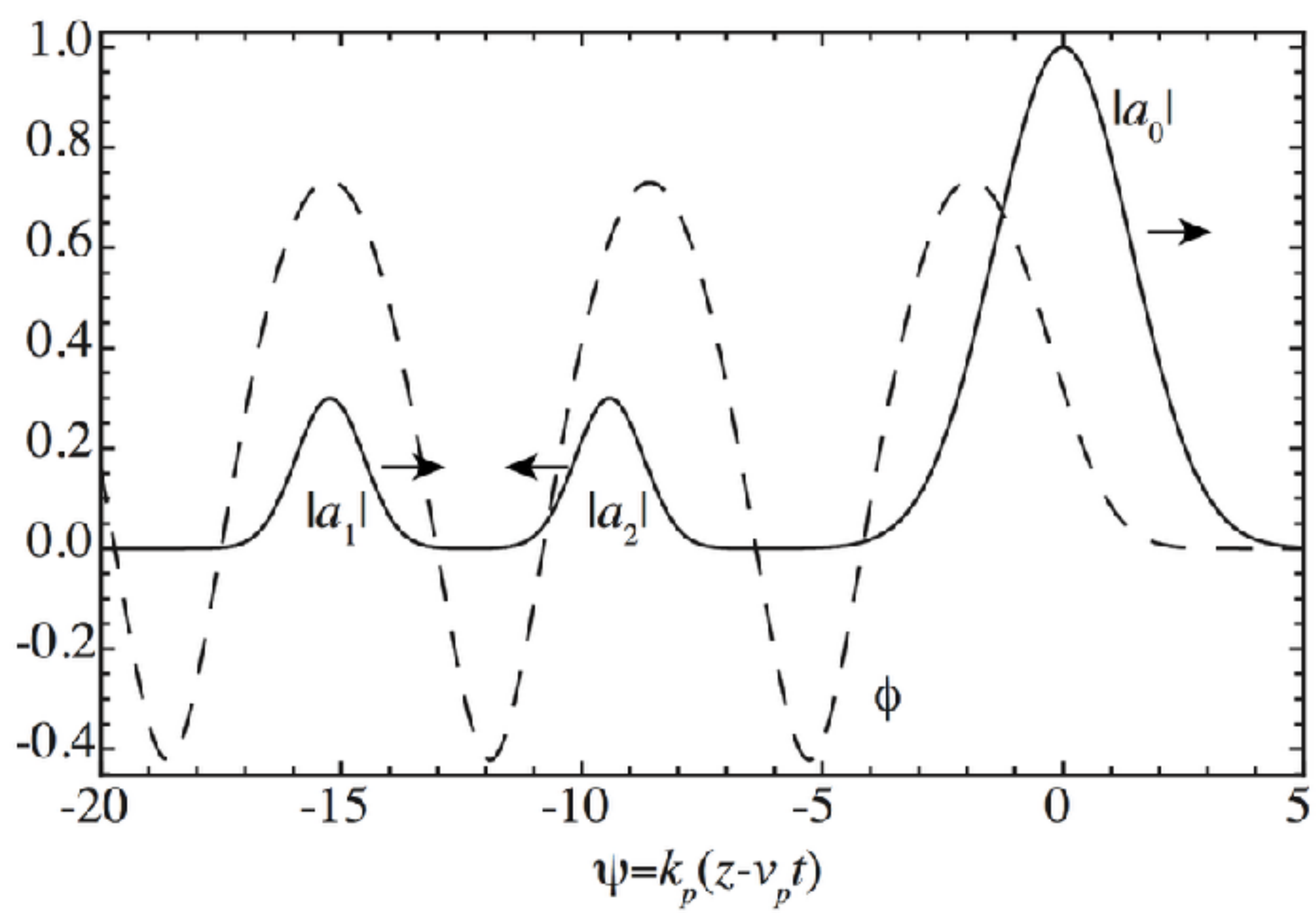
> dopant concentration to tune injected charge and beam loading

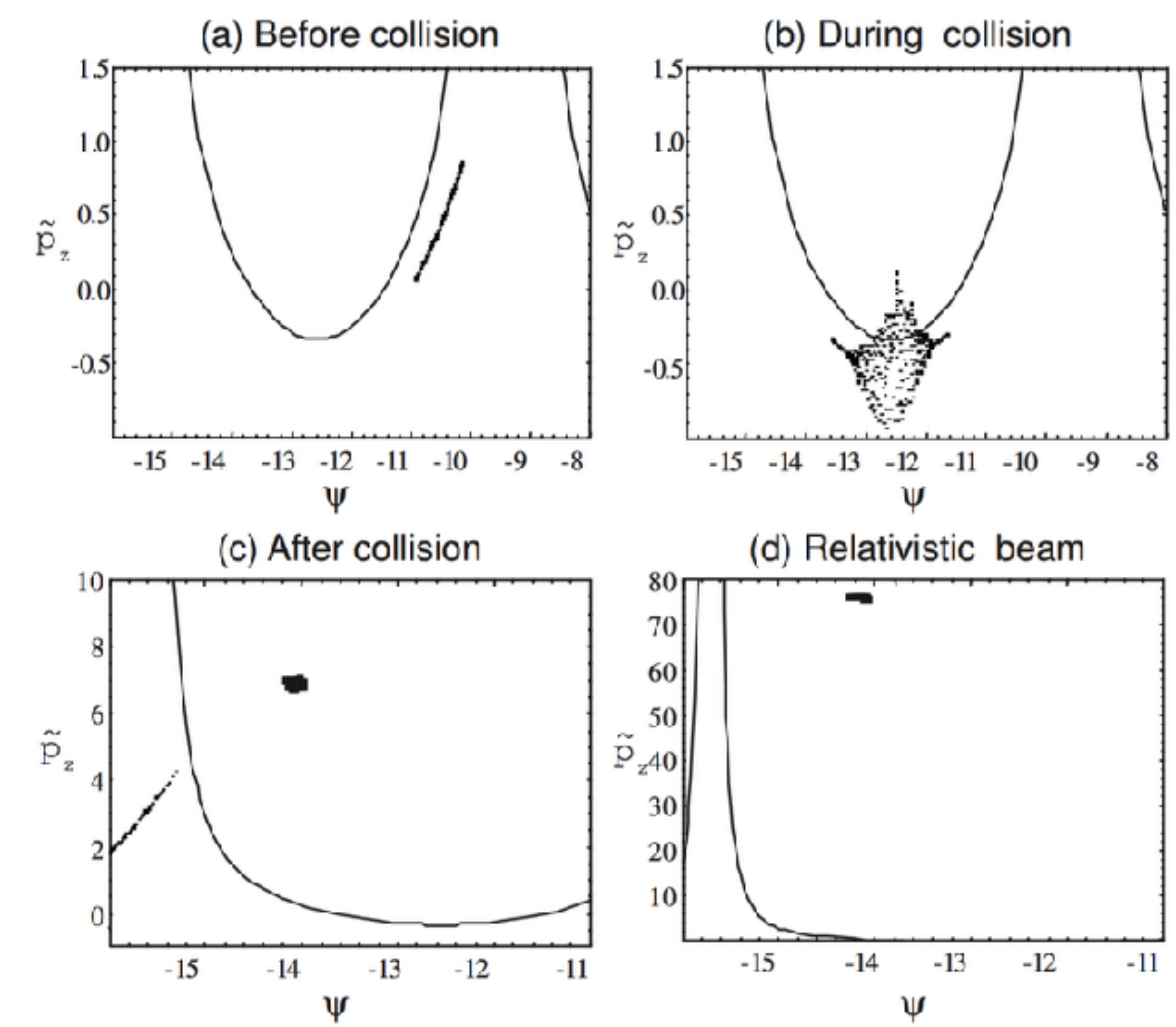
idea:	D.Umstadter *et al.*, Phys. Rev. Lett. **76**, 2073 (1996)
demonstration:	A.Pak *et al.*, Phys. Rev. Lett. **104**, 025003 (2010)
	C.McGuffey *et al.*, Phys. Rev. Lett. **104**, 025004 (2010)

Colliding lasers for injection control



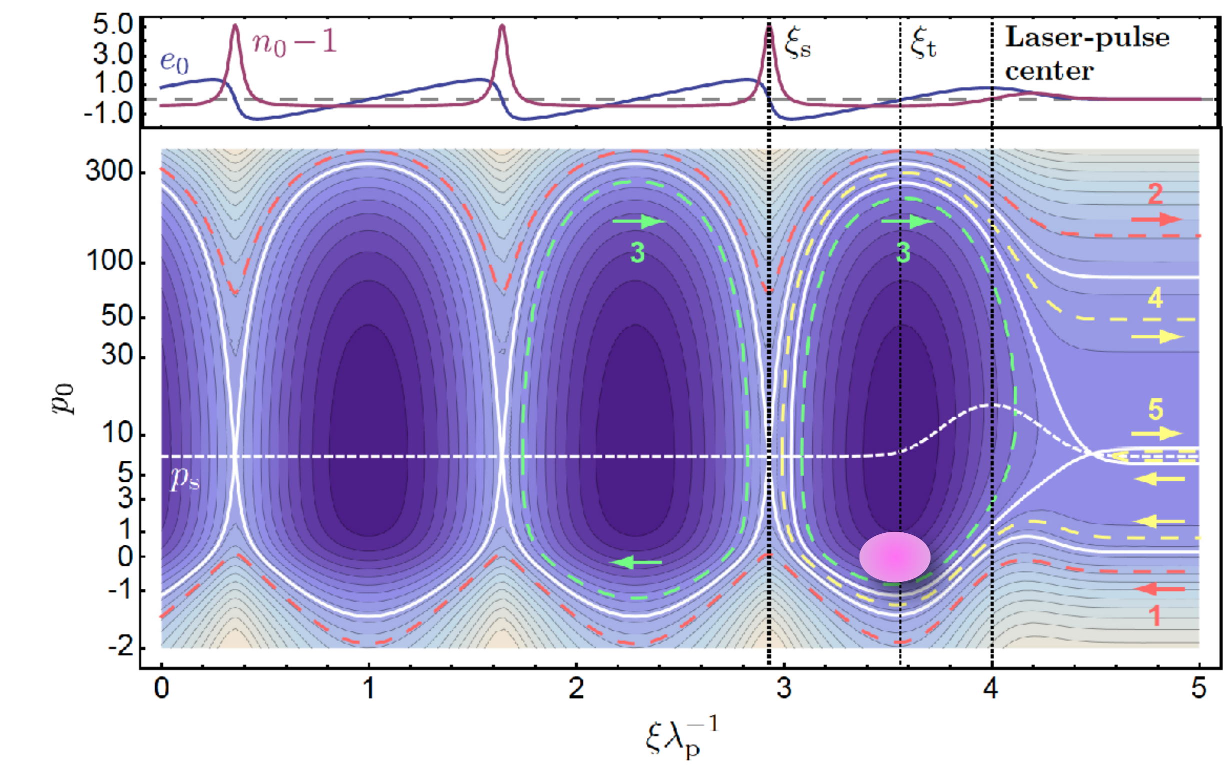
- colliding lasers create strong ponderomotive kick
- control laser parameters (pol., λ, a_0) and overlap position for injection control





idea: E.Esarey *et al.*, Phys. Rev. Lett. **79**, 2682 (1997)
demonstration: J.Faure *et al.*, Nature **444**, 737 (2006)

Colliding lasers for injection control



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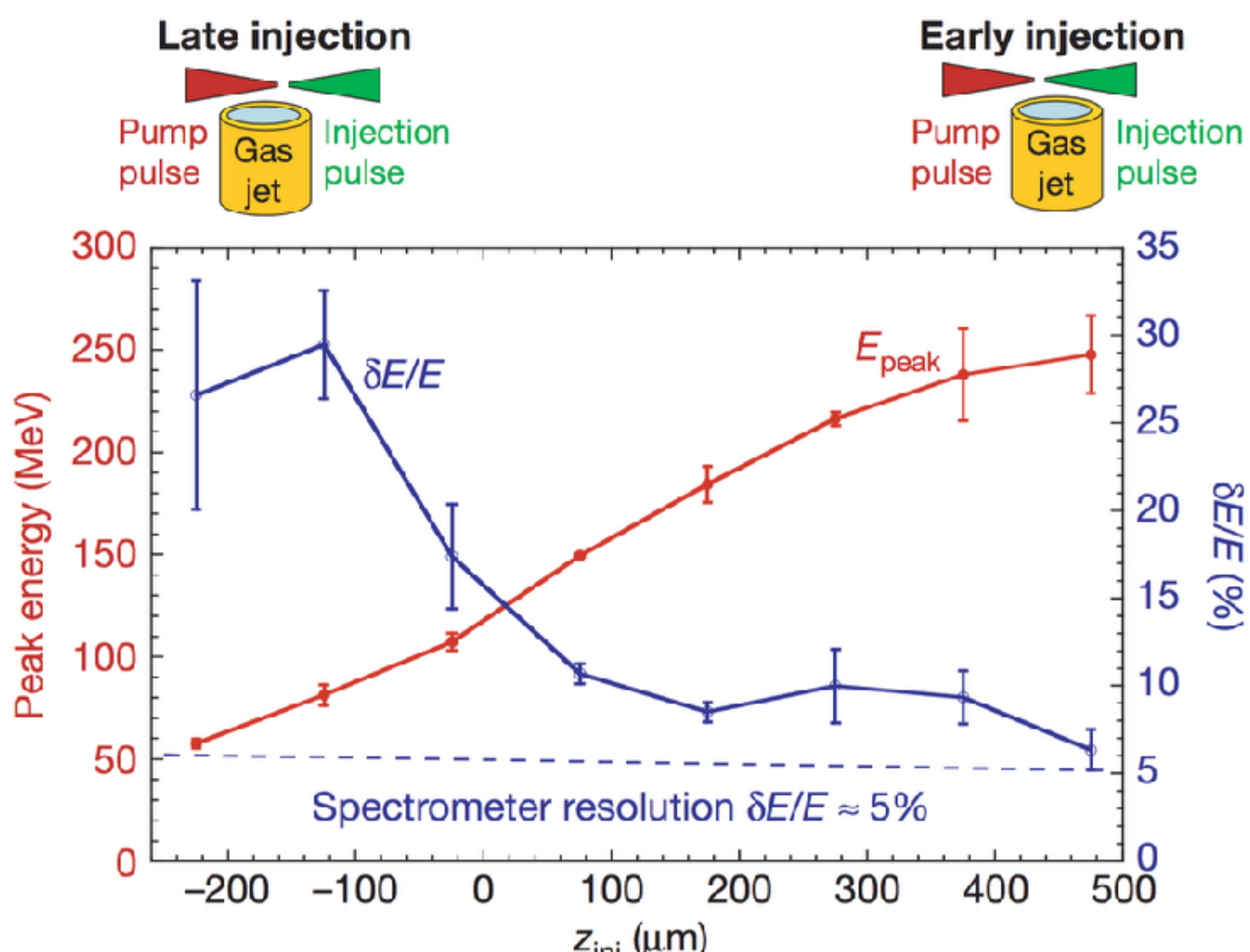

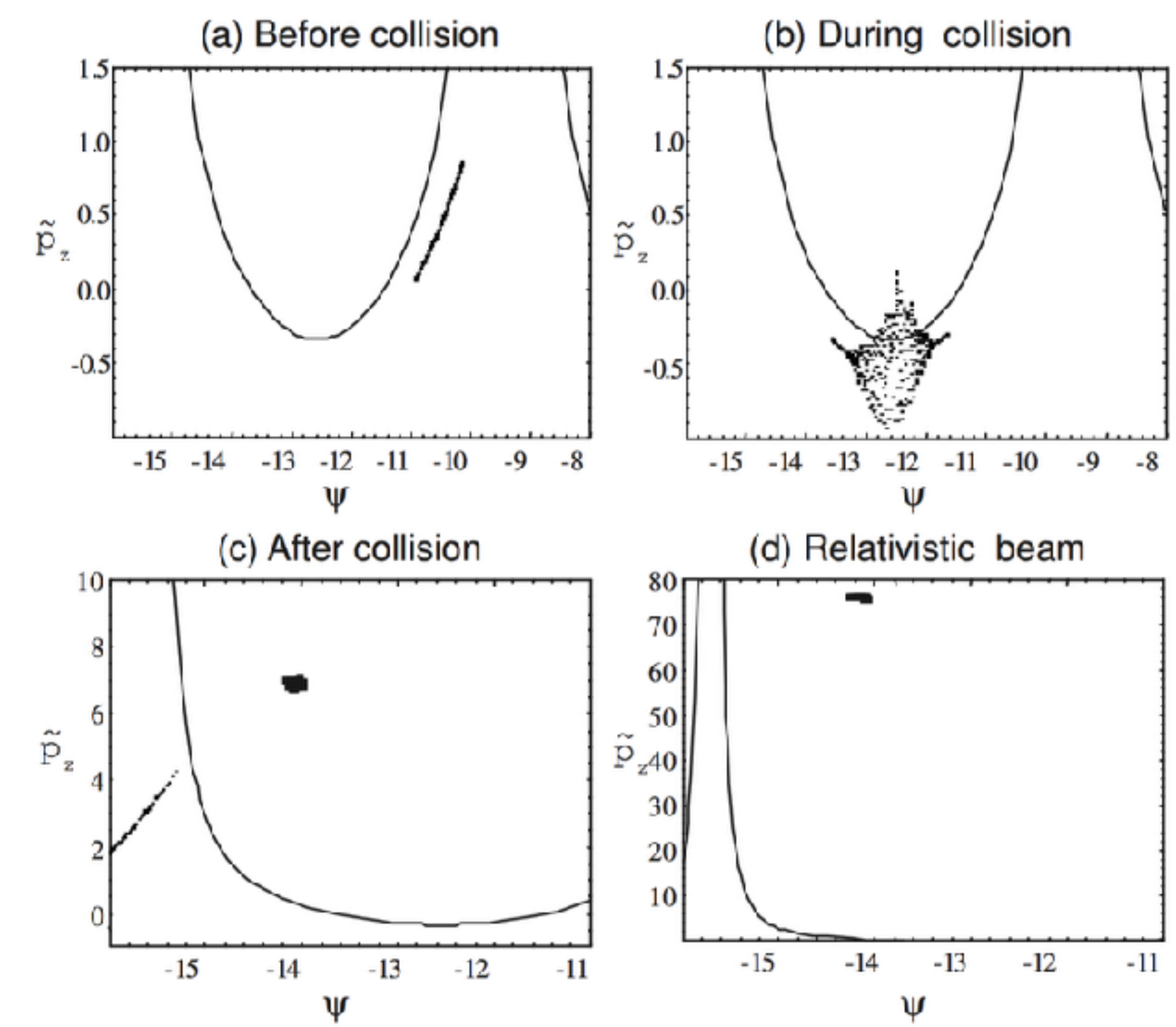

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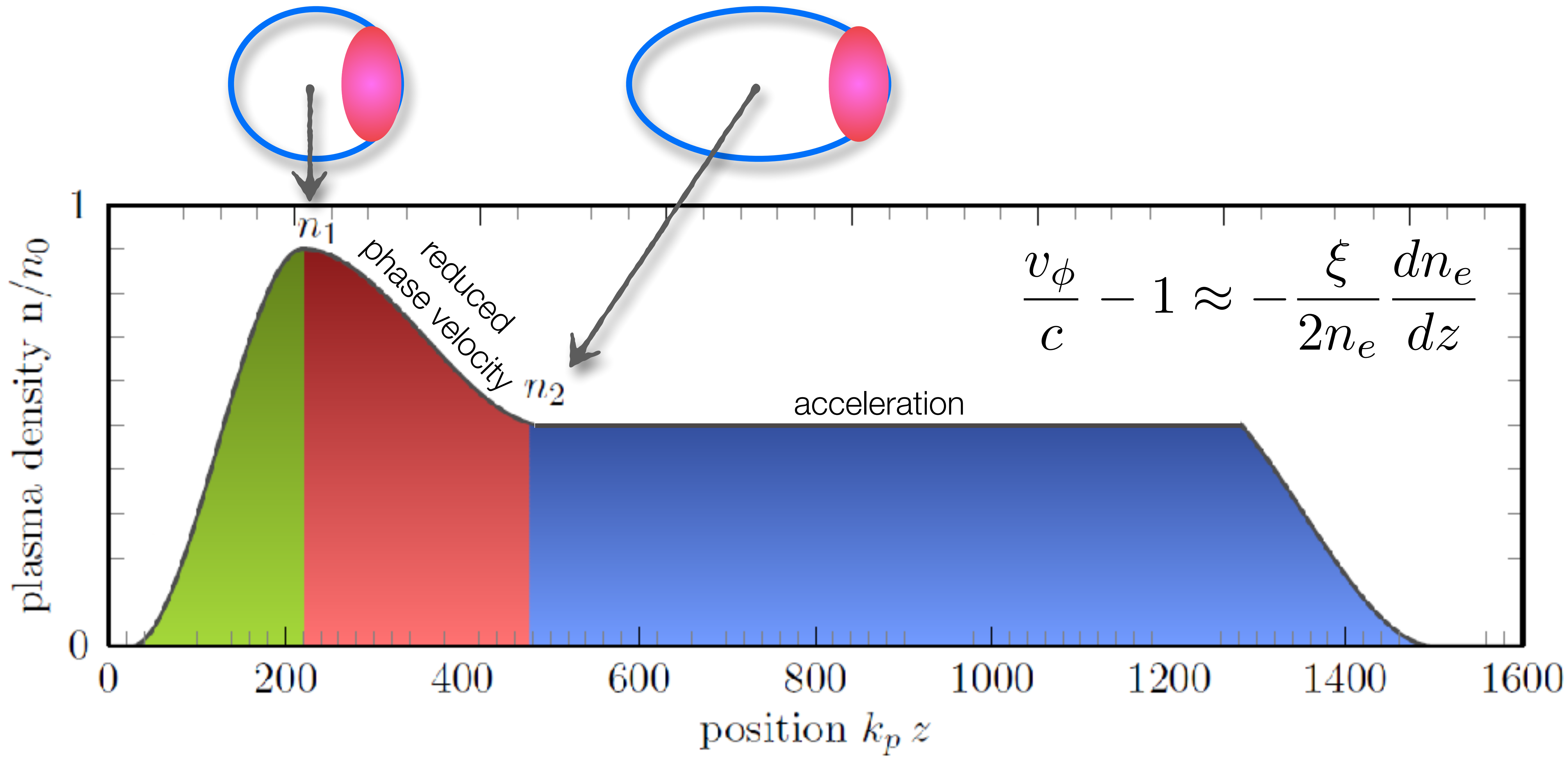
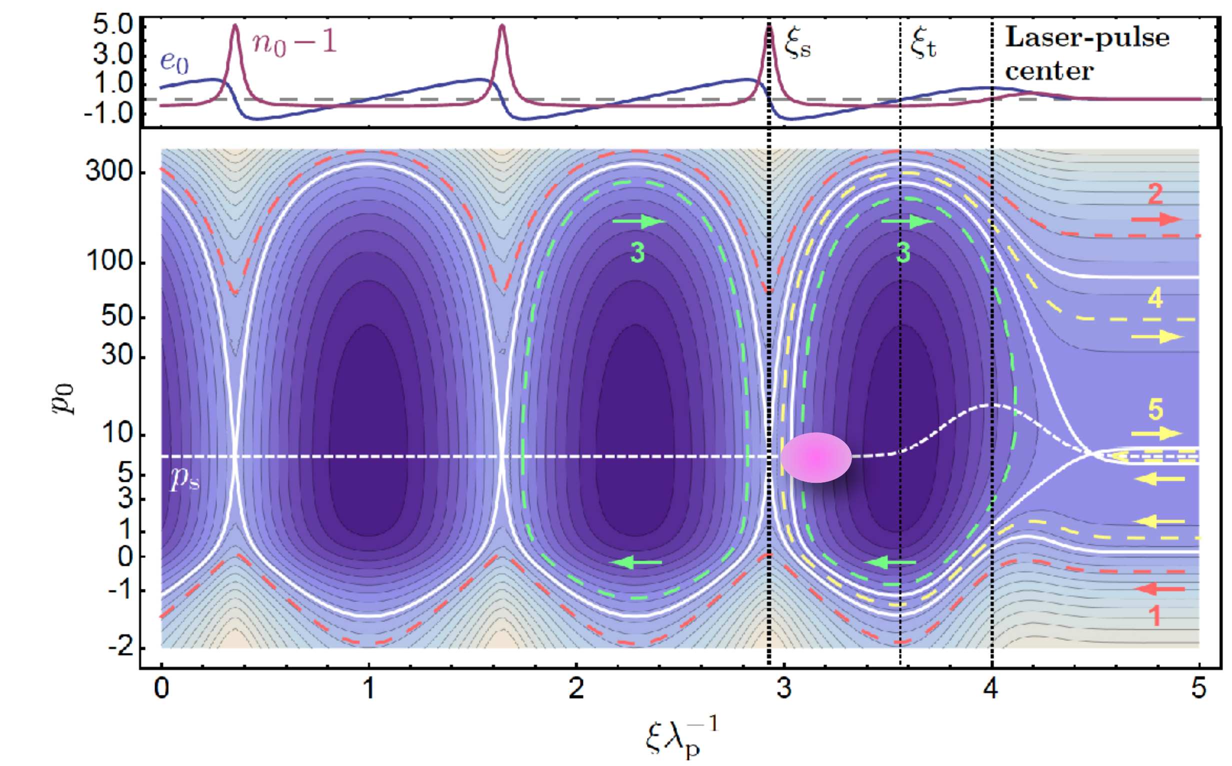
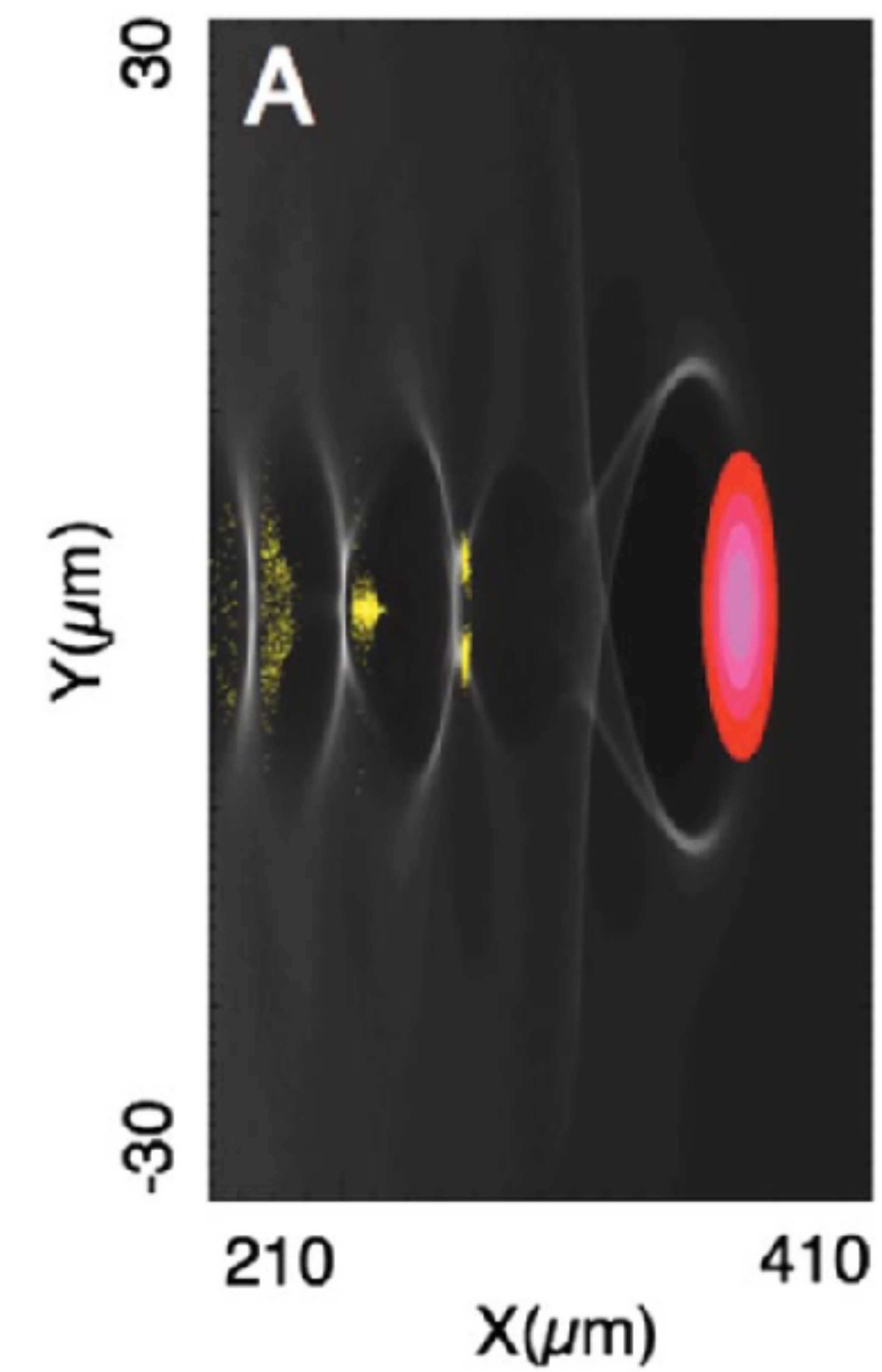
demonstration: J.Faure *et al.*, Nature **444**, 737 (2006)

Density slopes for injection control





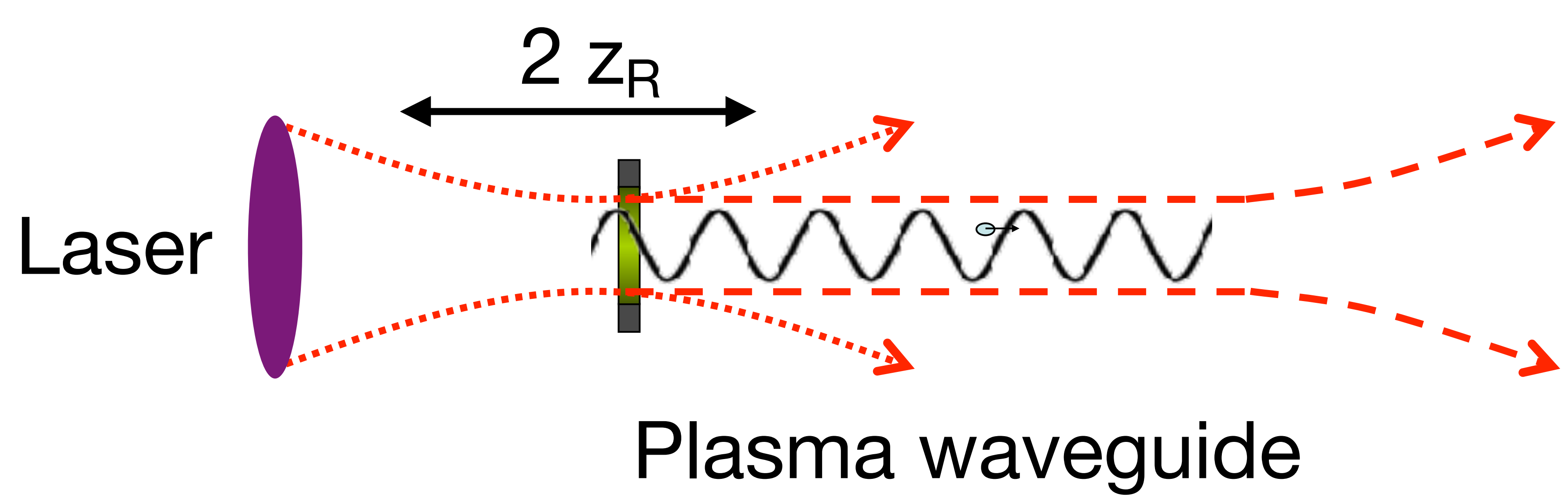


- > phase velocity of plasma wake reduced on density down-slope
- > velocity of electrons may exceed v_Φ, leads to trapping
- > trapping in multiple buckets possible

idea: S.Bulanov *et al.*, Phys. Rev. E **58**, R5257 (1998)
demonstration: C.G.R.Geddes *et al.*, Phys. Rev. Lett. **100**, 215004 (2008)

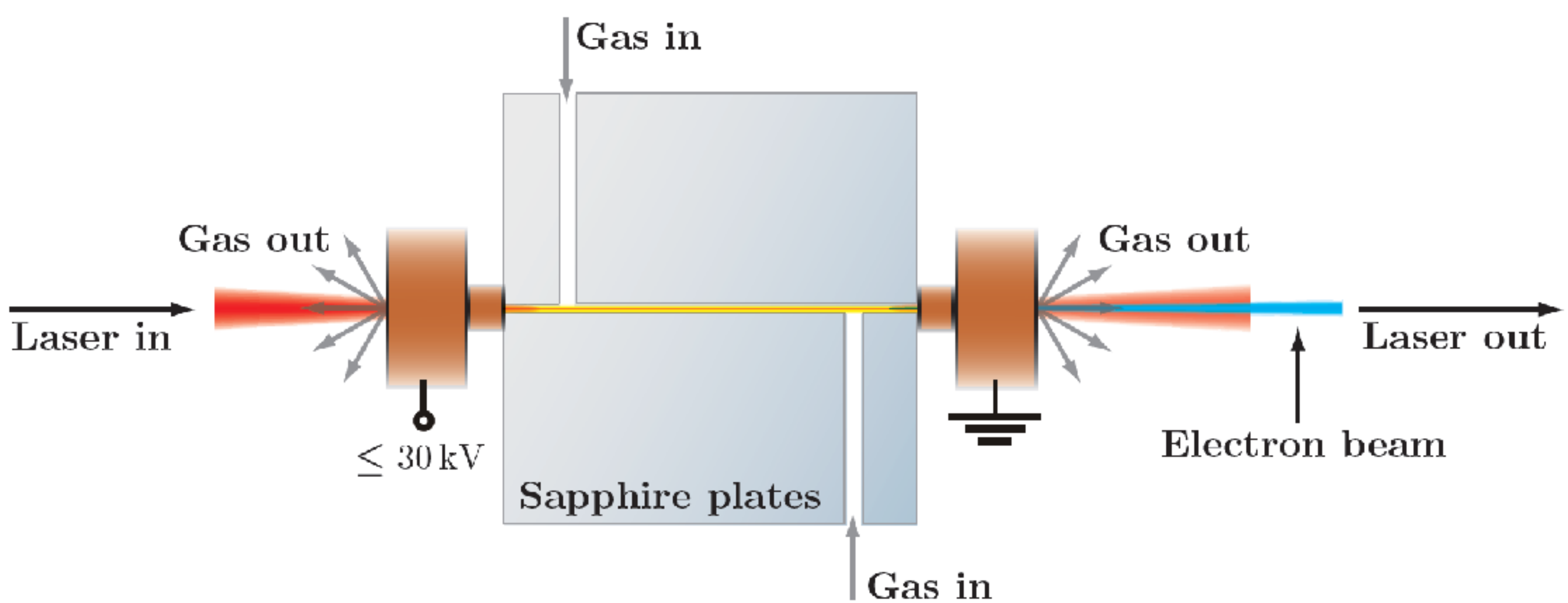
Energy gain scalings and single-stage limitations

Laser diffraction: mitigated by transverse plasma density tailoring (plasma channel)



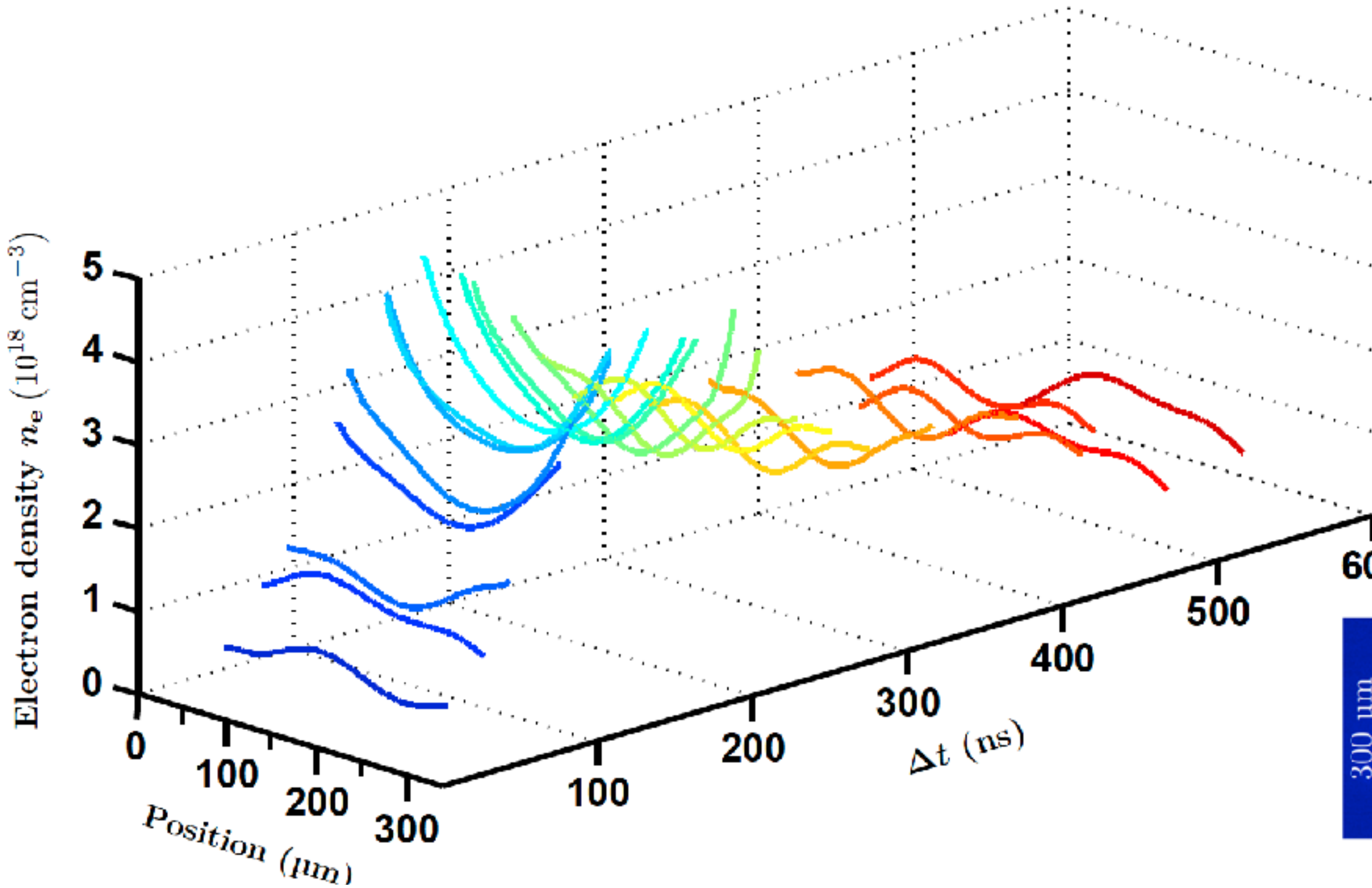
Capillary discharge plasma waveguides

- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for >10^6 shots
- $n_p \approx 10^{17}$ - 10^{19} cm^{-3}



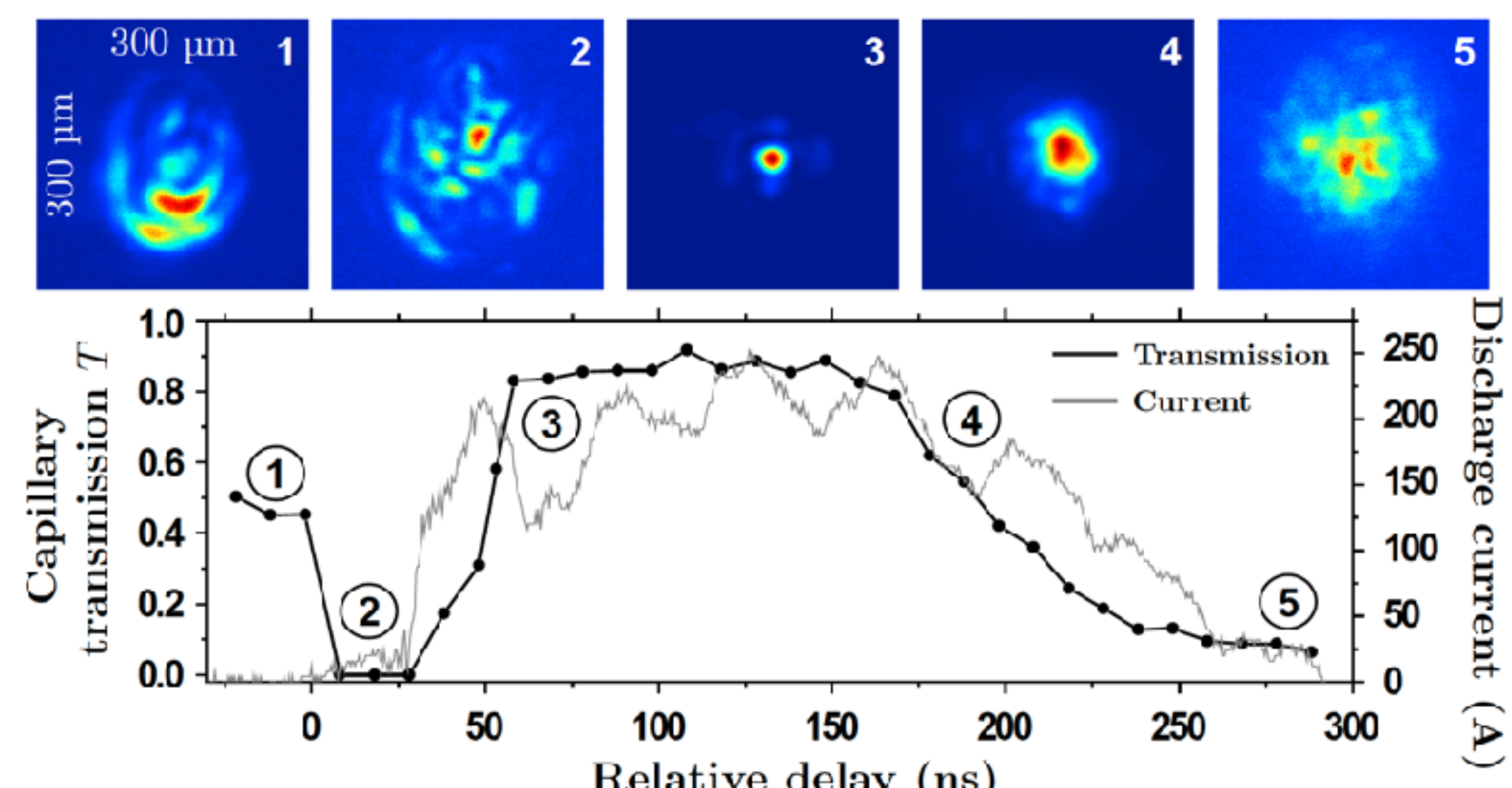
Energy gain scalings and single-stage limitations

LASER DIFFRACTION: MITIGATED BY TRANSVERSE PLASMA DENSITY TAILORING (PLASMA CHANNEL)



Capillary discharge plasma waveguides

- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for >10^6 shots
- $n_p \approx 10^{17}$ - 10^{19} cm^{-3}

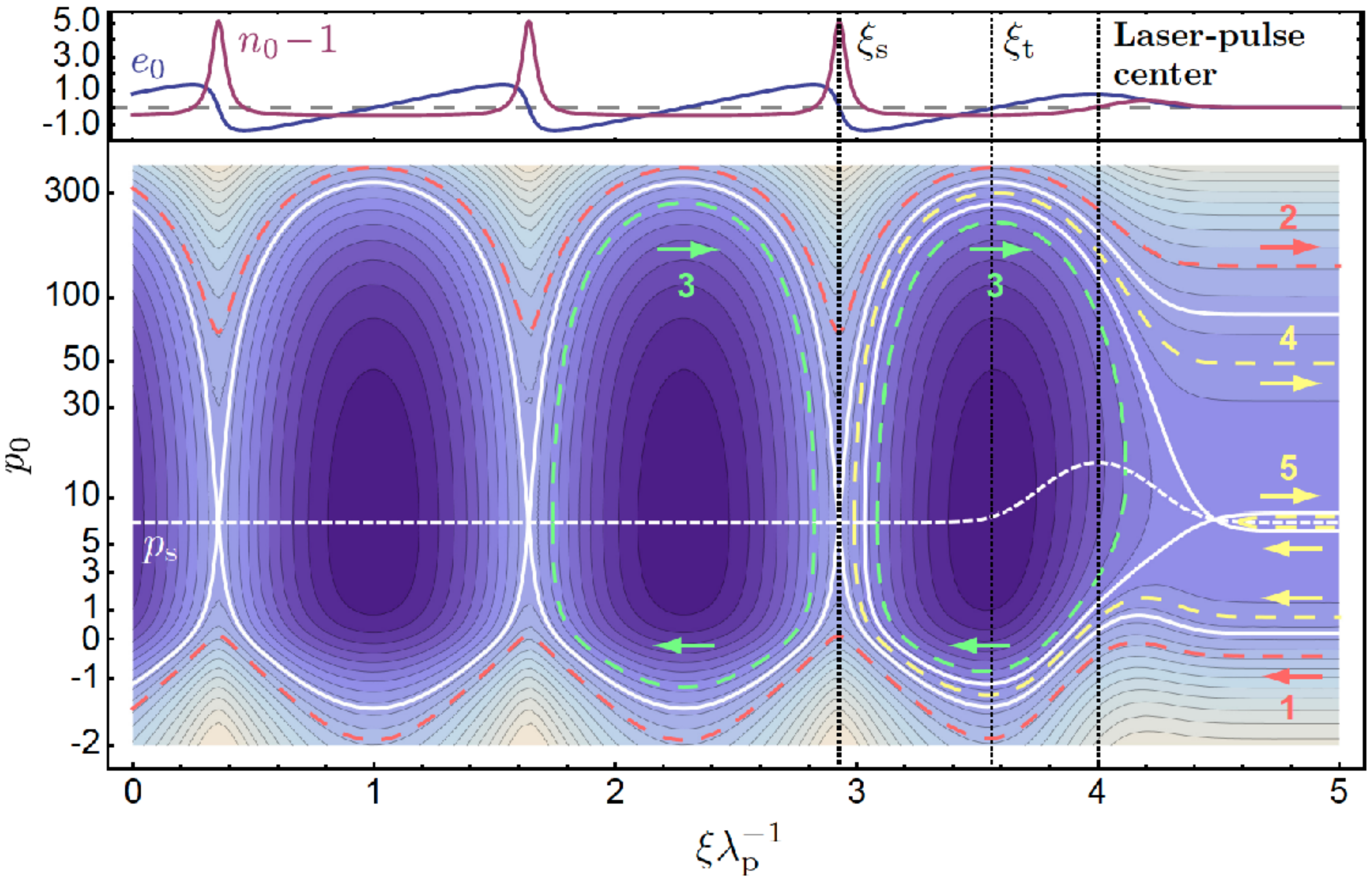


In this example:
Z_R = 2 mm, guiding over 16 mm, guiding efficiency > 90 %

Karsch, Osterhoff *et al.*, New J. Phys. **9**, 415 (2007)
D.J. Spence *et al.*, J. Phys. B **34**, 4103 (2001)

Energy gain scalings and single-stage limitations

ELECTRON-LASER DEPHASING: MITIGATED BY LONGITUDINAL PLASMA DENSITY TAILORING (PLASMA TAPER)



Constant density plasma

Laser pulse, plasma wave travel with $v_\Phi = v_g < c$

Electrons travel with $v_e \approx c > v_\Phi$

⇒ they outrun the accelerating field structure

Energy gain scalings and single-stage limitations

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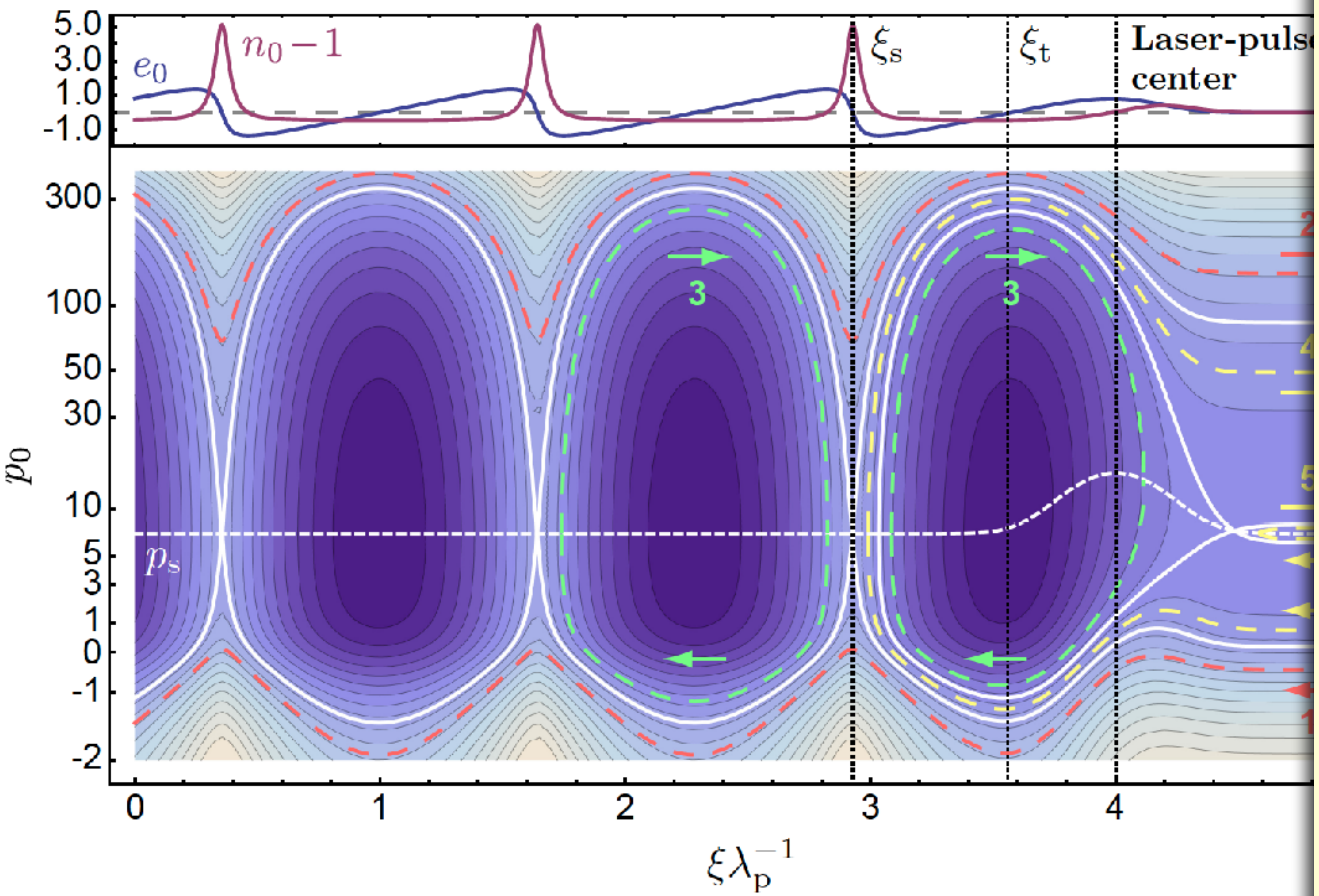

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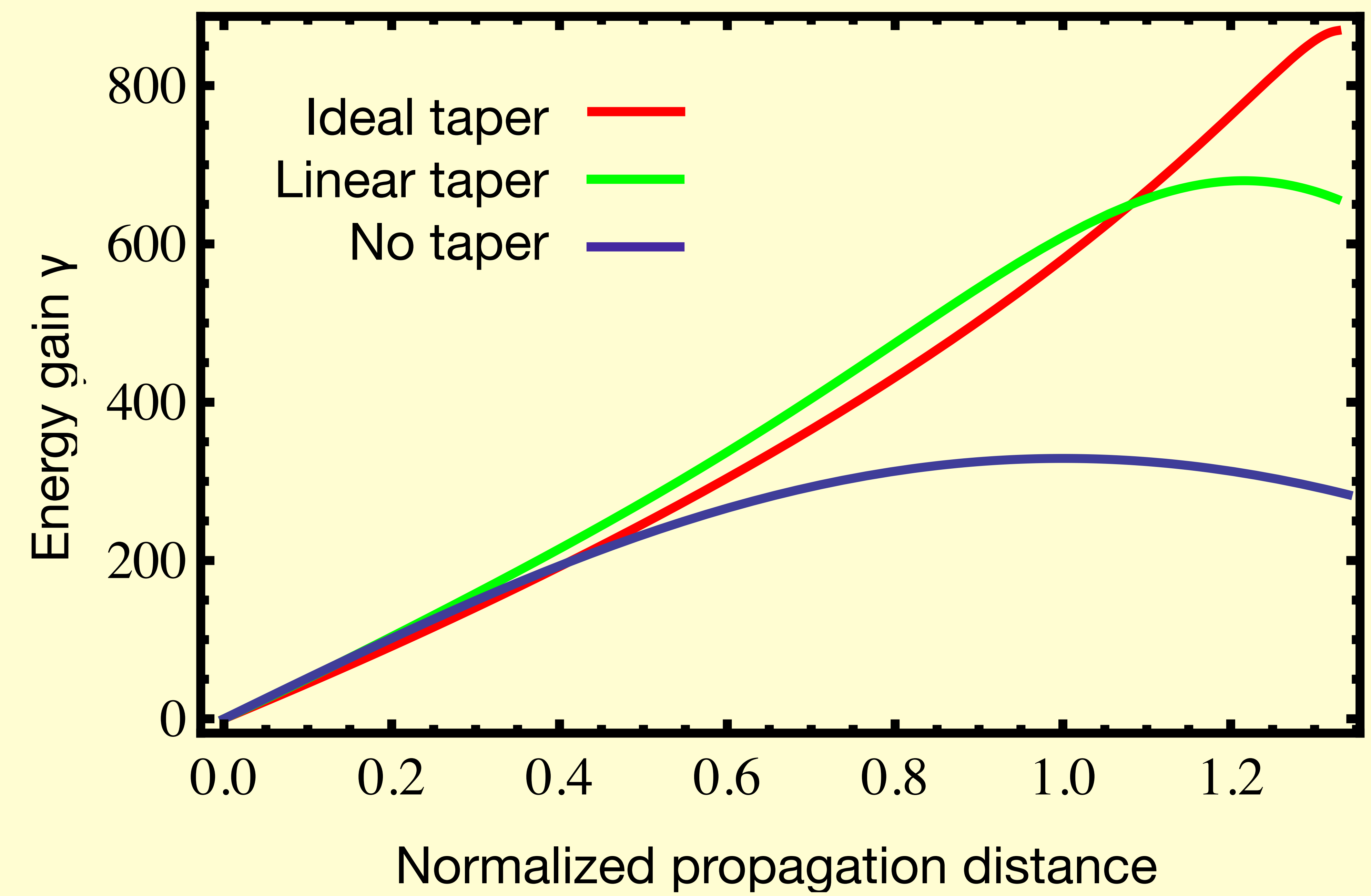


Rising density plasma

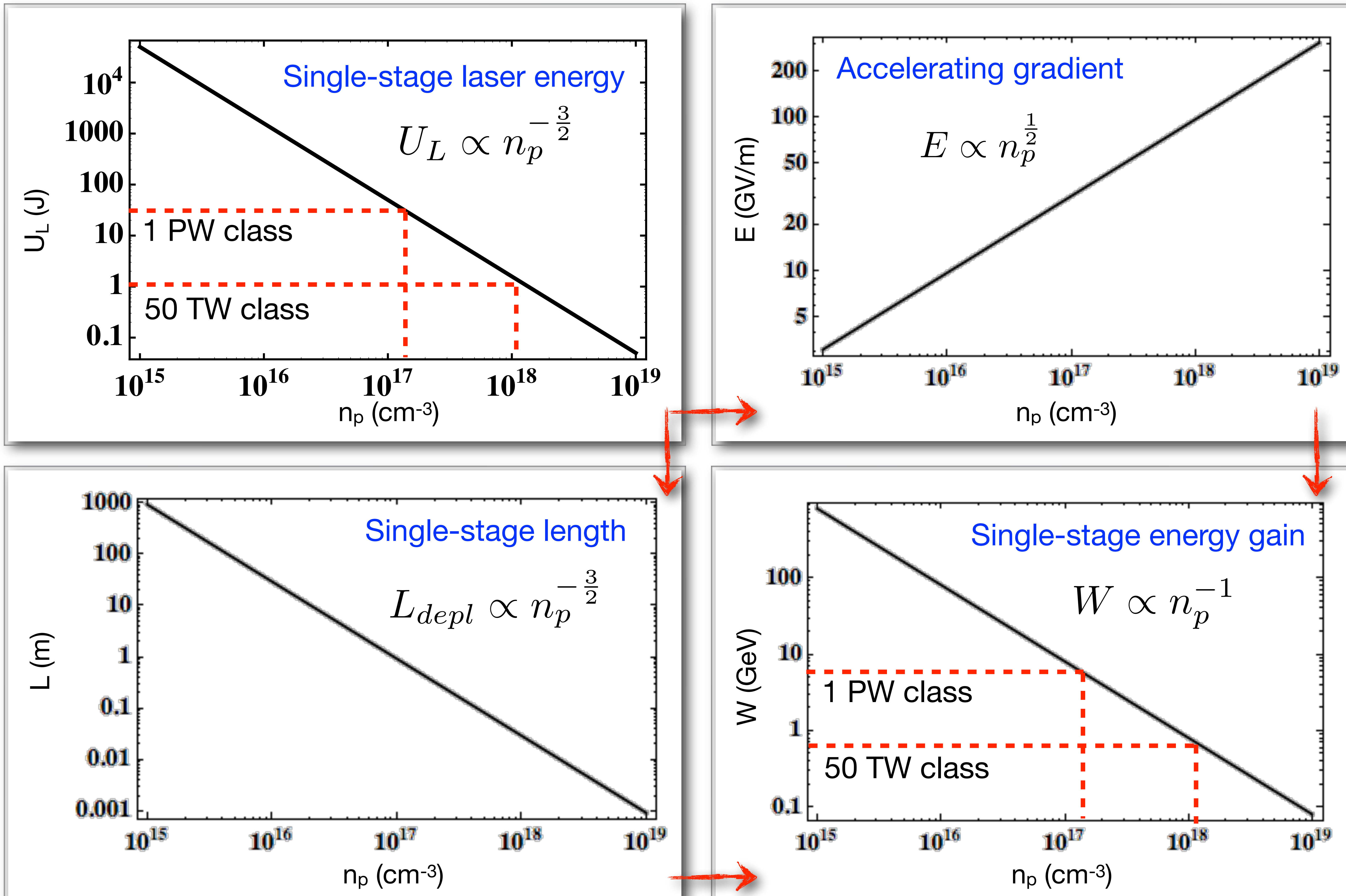
Plasma wave phase velocity v_Φ may be set to v_e

⇒ electrons can be phase locked

→ Rittershofer *et al.*, Phys. Plasmas **17**, 063104 (2010)

Energy gain scalings and single-stage limitations

LASER DEPLETION: ENERGY LOSS INTO PLASMA WAVE EXCITATION



Coefficients determined from PIC simulations in the quasi-linear regime (a_0 = 1.5)

Staging required for higher electron energies

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

Straw-man design of a TeV-class LWFA-based linear collider

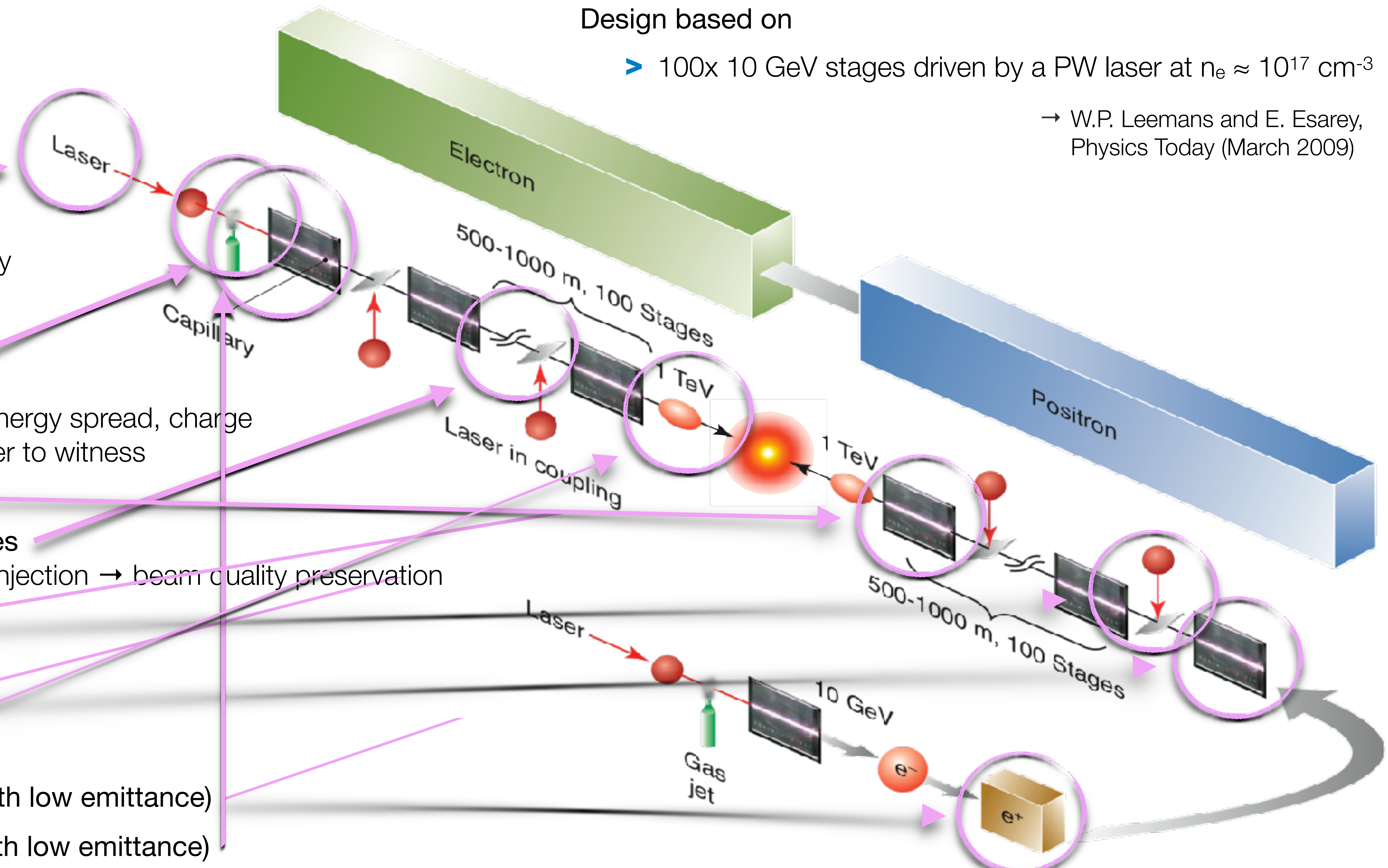
Design based on

> 100x 10 GeV stages driven by a PW laser at $n_e \approx 10^{17}$ cm^{-3}

→ W.P. Leemans and E. Esarey, Physics Today (March 2009)

Challenges / required R&D

- Laser system
  high peak power,
  high average power + efficiency
- Single acceleration module
  deliver consistent beam quality
  → emittance, energy, energy spread, charge
  efficient energy transfer of driver to witness
- Heat management
- Coupling of two plasma stages
  electron beam extraction and injection → beam quality preservation
- Laser in-coupling
  → accelerator length
- Positron acceleration
- Final focus system
- Positron beam generation (with low emittance)
- Electron beam generation (with low emittance)



Efficiency and average-power requirements demand a quantum leap in laser technology

Required power per particle beam $P_b \approx 5$ MW
Maximum power from the grid $P_{AC} \approx 200$ MW

→ Need 5% wallplug efficiency

- Efficiency laser to plasma wave ~50%
- Efficiency plasma wave to beam ~30%

→ Expected laser-to-beam efficiency of 15%

→ Requires wallplug-to-laser efficiency of 33%

confer C.B. Schroeder *et al.*, Phys. Rev. STAB 13, 101301 (2010)

confer B. Shadwick *et al.*, Phys. Plasmas 16, 056704 (2009)

from simulations

With 10 GeV modules ×50 and total energy per beam ~300 J

→ 6 J energy gain per module

→ 40 J laser energy per module at ~17 kHz repetition rate

→ 680 kW average laser power required

Modern 1 PW lasers: ≪ **1%** wallplug efficiency, **~100 W** average power

→ Current roadblock for LWFA colliders.

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confer C.B

confer B. S

from simul

High-peak and high-average power, high-efficiency lasers based on fibers

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What makes beam-driven plasma accelerators attractive?

VS. LASER-BASED WAKEFIELD ACCELERATORS

Considerable disadvantage

> Require a large conventional accelerator to produce driver, therefore cannot be as compact

Advantages

Laser engineering revolution required

> **Particle beams may be produced at high average power** (up to MWs)
  - ~100 W average power of state-of-the-art TW to PW laser technology

> **Particle-beam production is efficient** (~10 % from the wall plug)
  - ≪ 1 % wall-plug efficiency for high-intensity lasers

> **Driver-beam stability** (can be ≪ 1 %)
  - high peak-power lasers fluctuate ~1% in intensity

Plasma target engineering

> **No dephasing** of plasma wakefield and electron beam, wave breaking difficult
  - LWFA: pulse velocity less than *c*, electrons outrun wake, wave breaking can lead to dark current

> **Diffraction lengths longer than energy depletion scales** for beams of µm normalized emittance
  - diffraction length of laser pulse shorter than depletion distances → limits witness beam energy

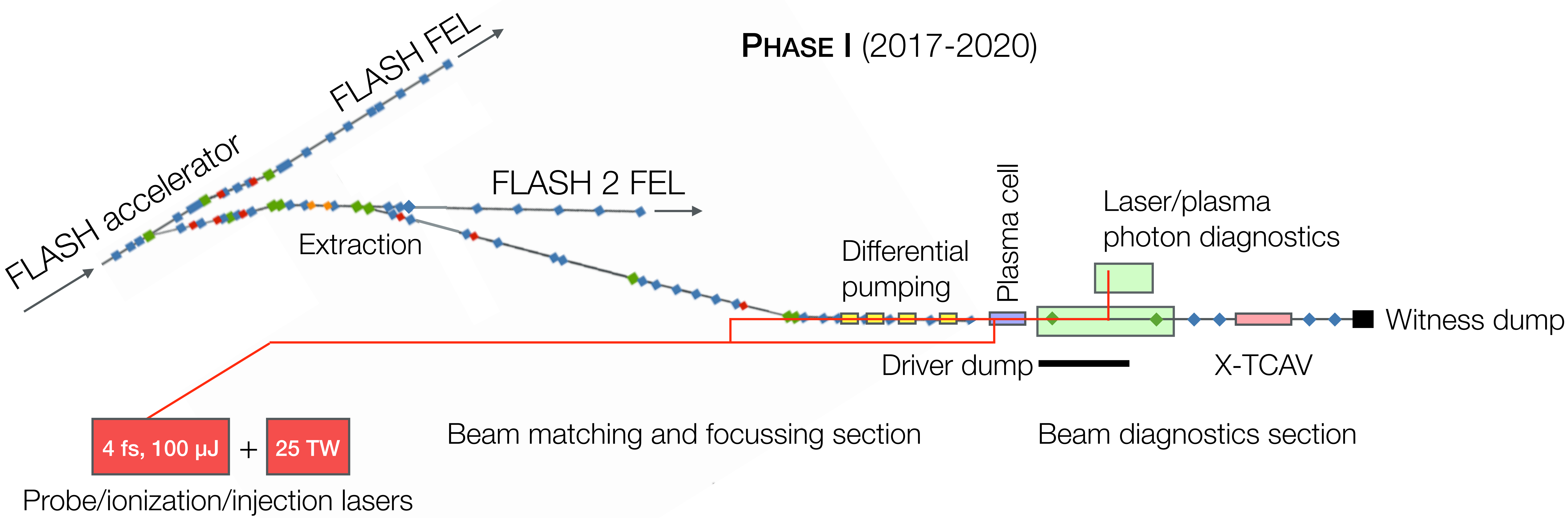
The next-generation plasma wakefield accelerator - FLASHForward▸▸ at DESY

FLASHForward is

- > an extension to the FLASH 1.2 GeV superconducting RF FEL facility
- > a new ***experiment for beam-driven plasma wakefield accelerator research***

Scientific mission

- > to demonstrate beam quality from a plasma-based wakefield accelerator suitable for first ***applications in photon science*** as a stepping stone towards ***high-energy physics*** applications



- boost FLASH to ~2 GeV with high efficiency (30%), **conserve emittance and energy spread**
- generate **usable beams** in plasma with **low emittance** (≤ 100 nm) at > 1.5 GeV

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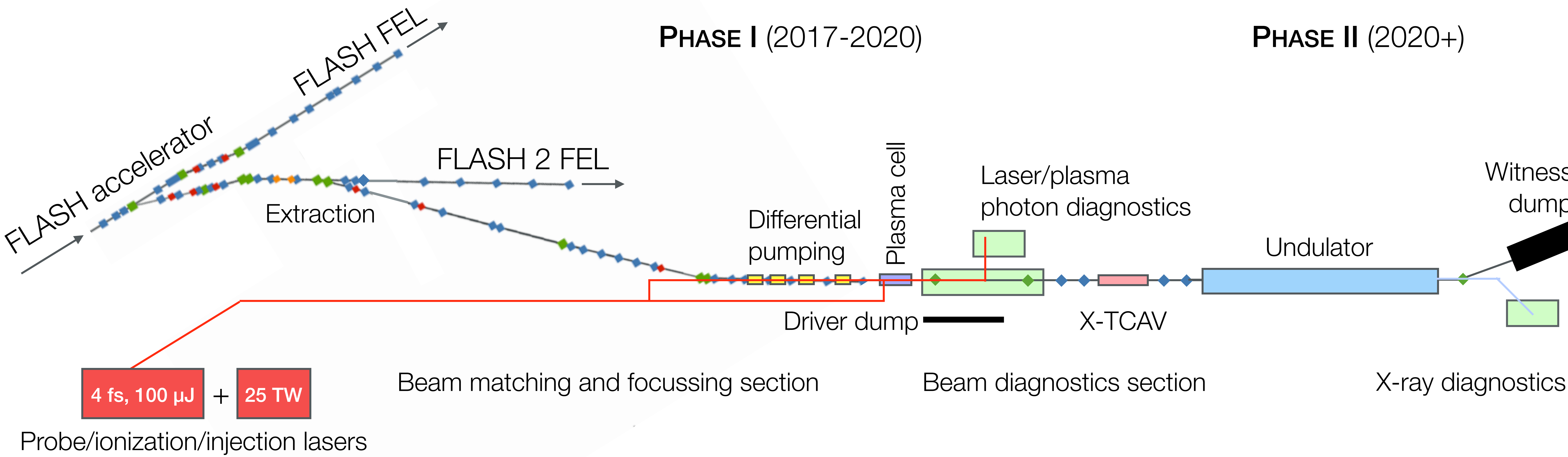

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Summary

- Accelerators are at the heart of most photon science and particle physics experiments, but are large installations
- Plasma wakefield technology offers a promising path to compact accelerators with > 10 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