Laser-Wakefield Acceleration Application to Endoscopic Oncology

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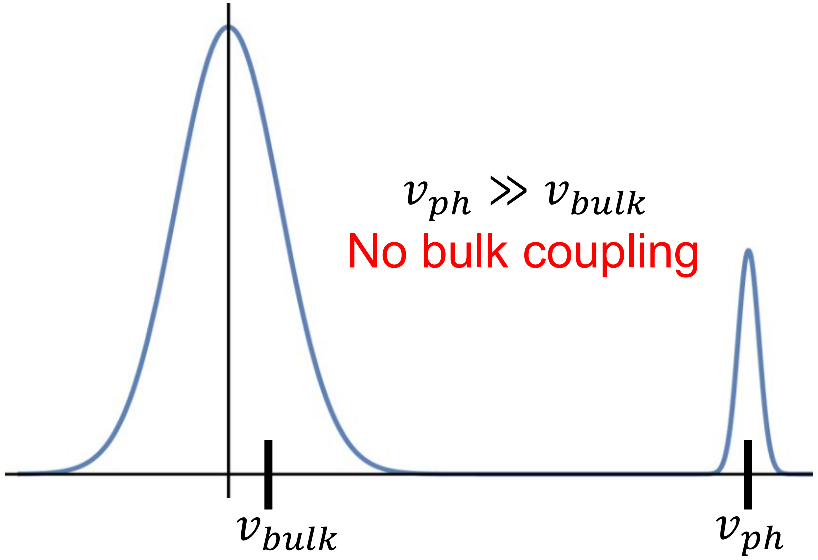
Workshop on Beam Acceleration in Crystals and Nanostructures

June 25, 2019

THE UNIVERSITY OF CALIFORNIA IRVINE

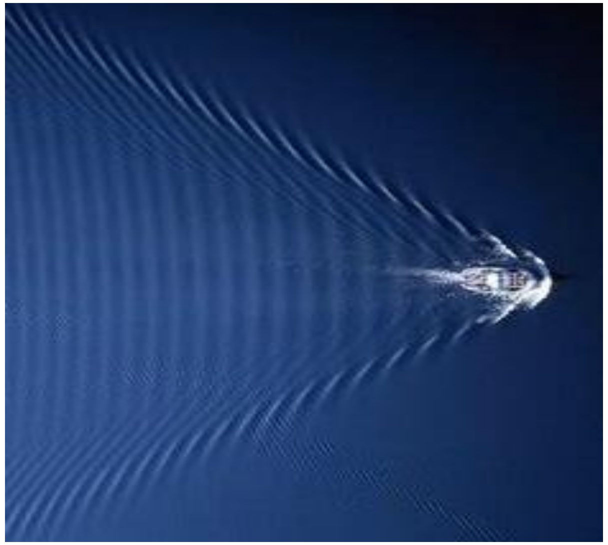
Laser Wakefield Acceleration (LWFA)

- Collective force $(\sim N^2)$
- Coherent, smooth, robust (not stochastic)
- Driven by laser or beams
- High acceleration gradient: ~ GeV/cm
- Wake phase velocity $(v_{ph}) \gg$ bulk velocity (v_{bulk})



$\boldsymbol{v_{ph} \gg v_{bulk}}$

- Coherent, robust
- No turbulence
- Deep-ocean tsunami



$\boldsymbol{v_{ph} \sim v_{bulk}}$

- Wavebreak
- Turbulence
- Near-shore tsunami

T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. **81**, 1229 (2009)

Laser Wakefield Theory

- Laser group velocity: $v_g = c\sqrt{1 - n_e/n_c}$

Laser critical density

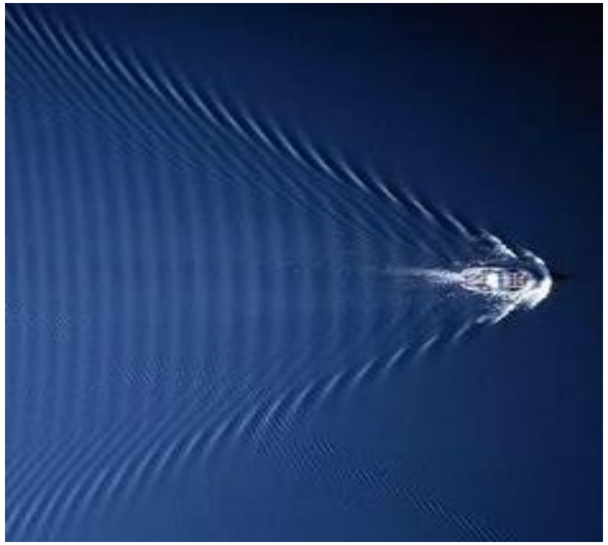
Plasma density

- Wake phase velocity $v_{ph} = v_g$
- Low-density regime → $v_{ph} \gg v_{bulk}$
- High-density regime → $v_{ph} \sim v_{bulk}$
- Electron energy gain: $\Delta\mathcal{E} = 2m_e c^2 (n_c/n_e)$
- Robust wave saturation → Tajima-Dawson field:

$$E_{TD} = \frac{m\omega v_{ph}}{e}$$

$$\boldsymbol{v_{ph} \gg v_{bulk}}$$

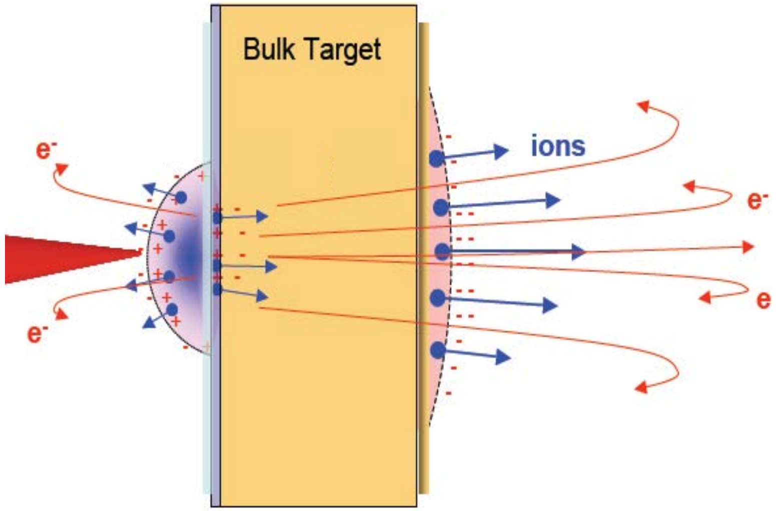
$$\Delta\mathcal{E} \gg m_e c^2$$



$$\boldsymbol{v_{ph} \sim v_{bulk}}$$

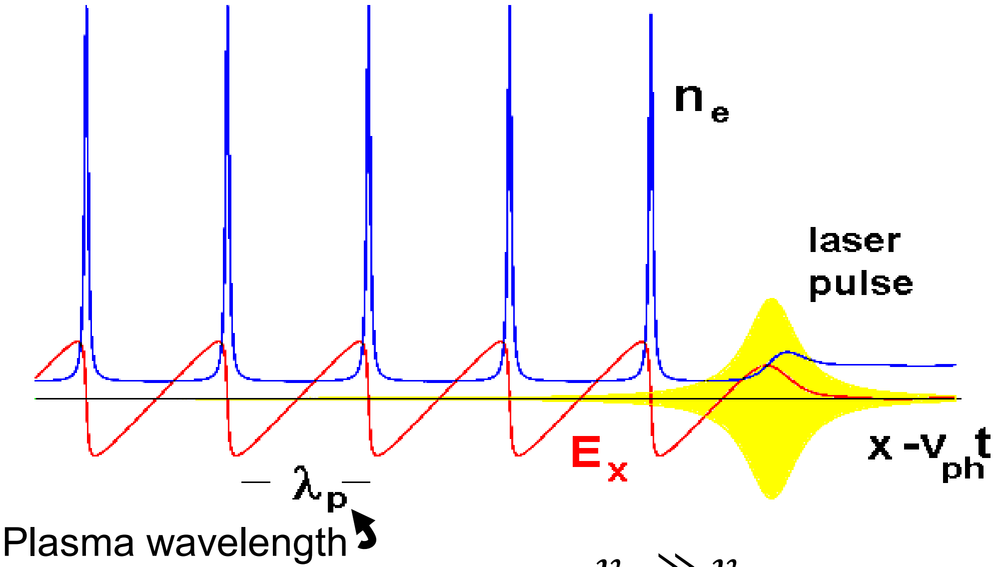
$$\Delta\mathcal{E} \lesssim m_e c^2$$

Wakefields as Tsunamis



Pristine wakefield

Bulk solid-target interaction (TNSA)[1]



$v_g \approx 0$
Black wave

$v_g \gg v_{bulk}$
Blue wave

ProtoThema.gr

Clean, no dredging

Extensive sediment dredging, mass transport

SurferToday.com

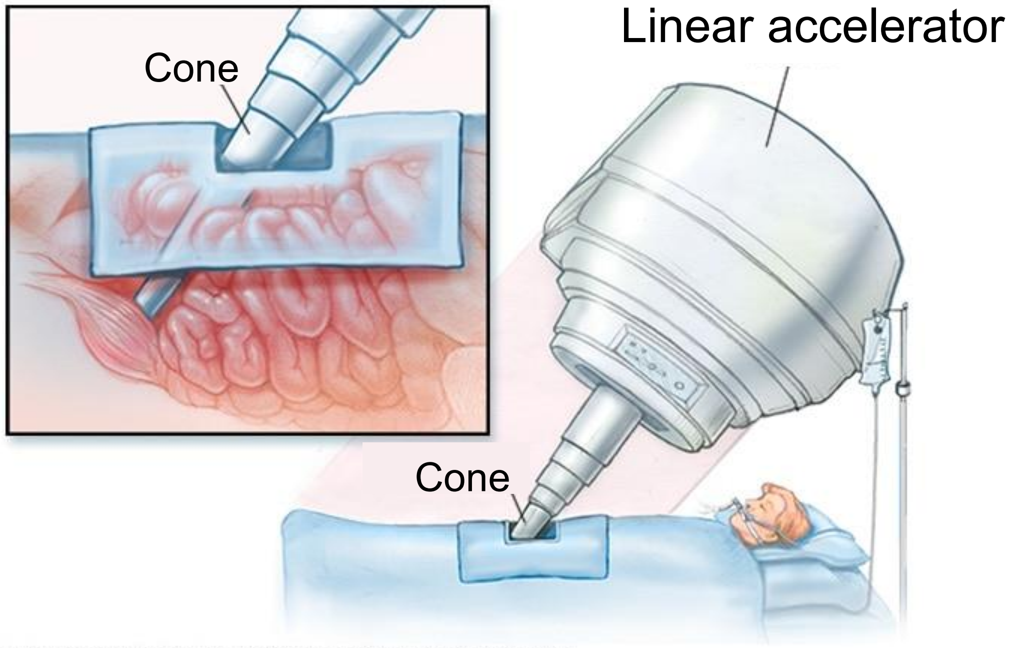
[1] B. M. Hegelich et al., Nature **439**, 441-444 (2006)

Endoscopic Oncology

- Bring radiation directly to tissue
- Endoscopic or intra-operative
- No collateral tissue damage
- Low-energy particles
- **LWFA → LINAC alternative**

Professor Dante Roa,
Radiation Oncology, UCI

A. Giulietti, ed., *Laser-Driven Particle Acceleration Towards Radiobiology and Medicine*, 2016
A. S. Beddar et al. Med. Phys. **33**, 1476 (2006)



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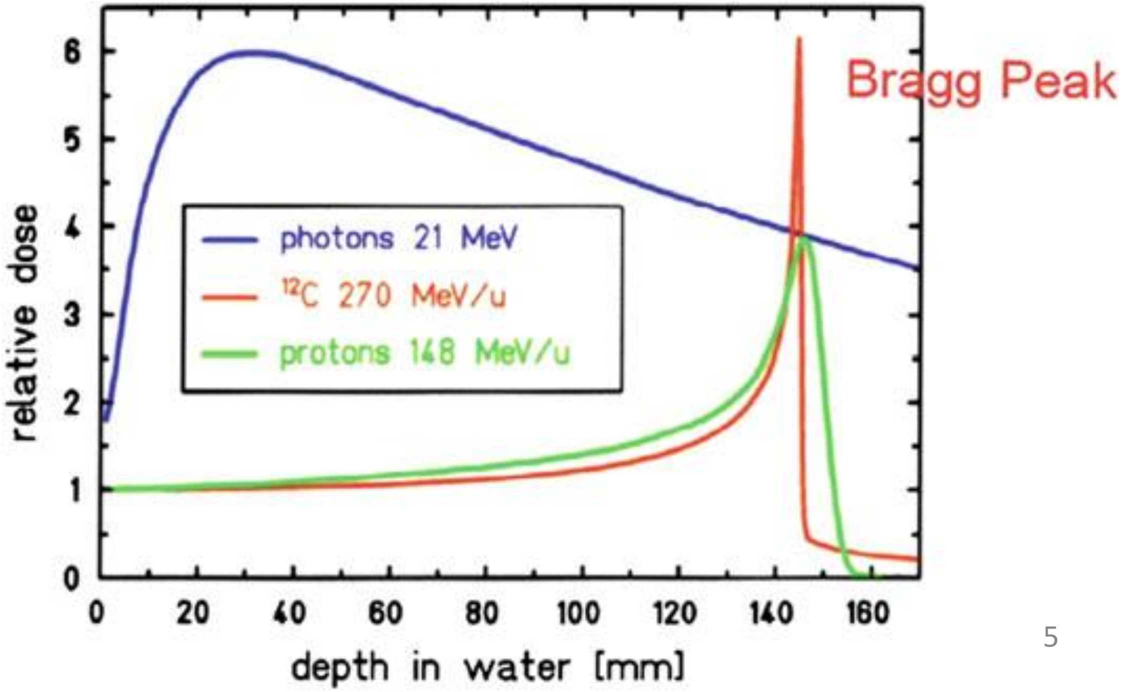
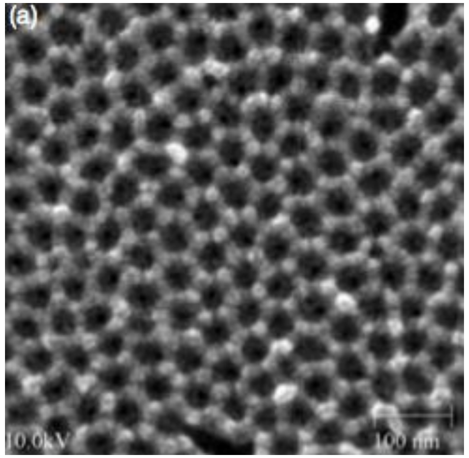


Fiber lasers for LWFA

- Coherent Amplification Network (CAN)
- Optical lasers
- Many lasers together
- Technology reached critical stage
- Fiber laser for endoscopic LWFA

G. Mourou, W. Brocklesby, T. Tajima, and J. Limpert, Nat. Photonics **7**, 258 (2013)

Nanomaterials for LWFA

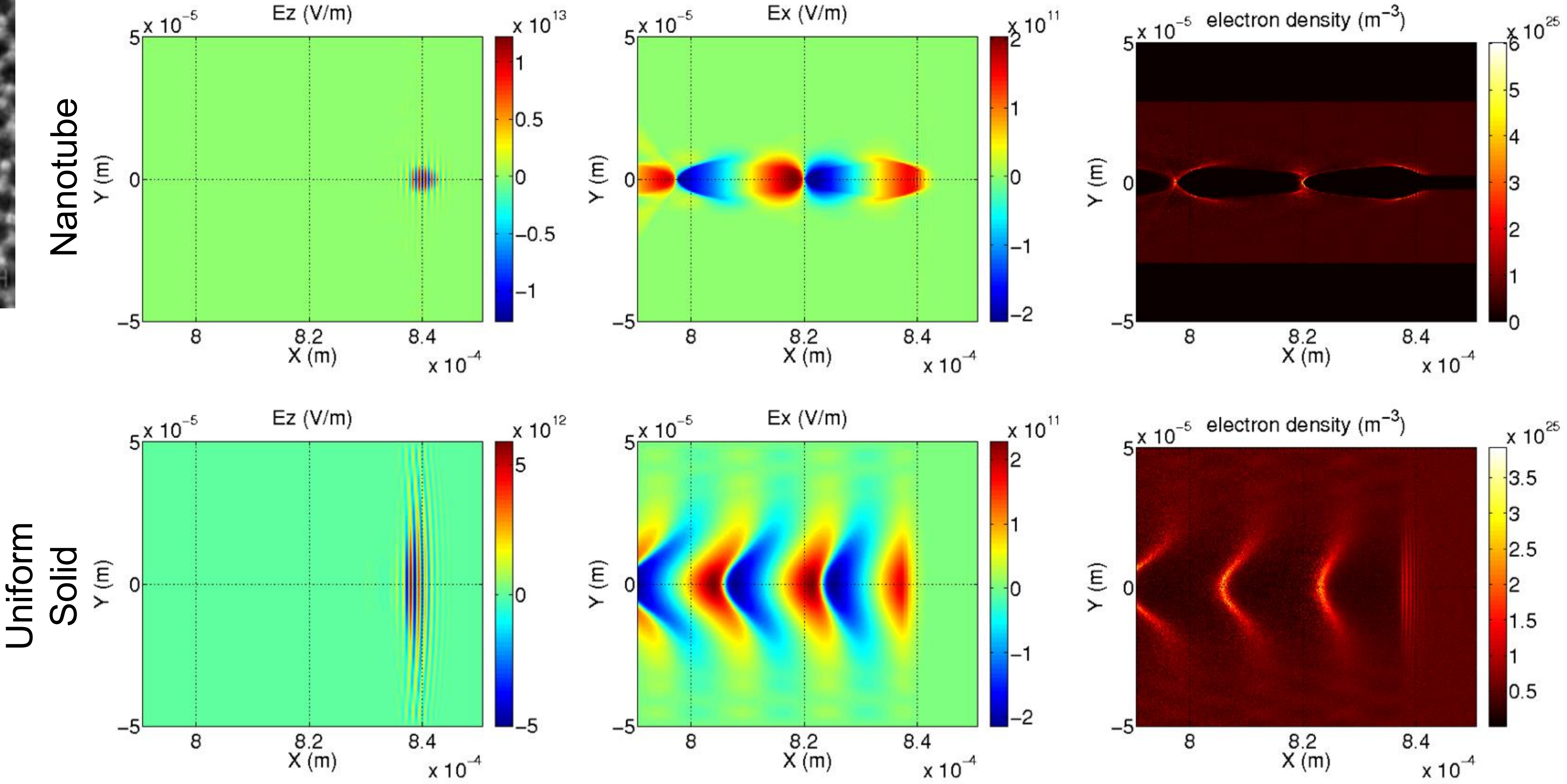


Porous alumina
on SI substrate

Nanomaterials:

→ Wakefield guide

→ Optical laser n_c



N. V. Myung, J. Lim, J-P Fleurial, M. Yun, W. West, and D. Choi, Nanotech. **15**, 833 (2004)
X. Zhang et al., Phys. Rev. Accel. Beams **19**, 101004 (2016)
T. Tajima, Eur. Phys. J. Spec. Top. **223**, 1037 (2014)

LWFA for Endoscopic Oncology

- Putting the pieces together

→ low-energy electrons

→ near-critical density LWFA

→ Nanomaterial provides density/guide

→ CAN laser (optical) for endoscopy

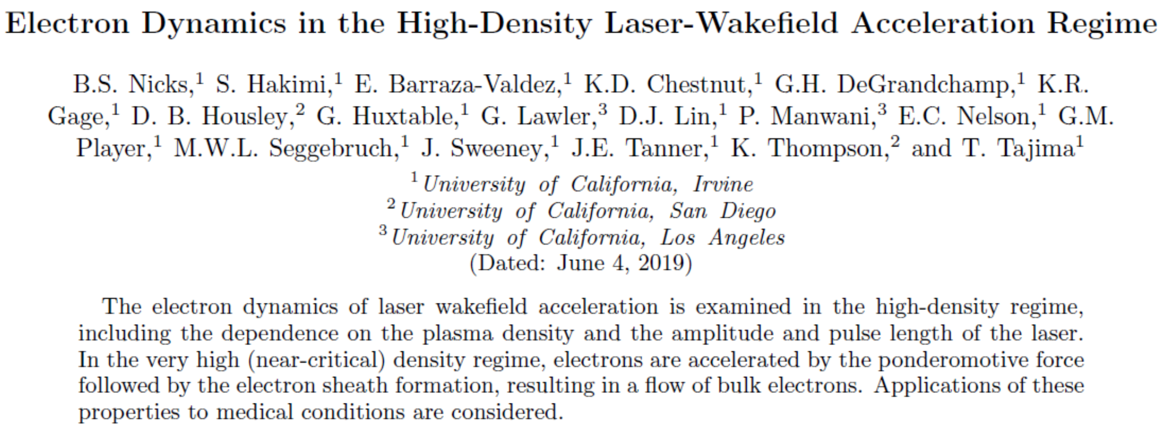
- **Next steps**

→ Wakefield physics at $n_e/n_c \approx 1$

→ Scaling: density, intensity

→ Self-modulation

Paper and Collaborators



Electron Dynamics in the High-Density Laser-Wakefield Acceleration Regime

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[3] *University of California, Los Angeles*

(Dated: June 4, 2019)

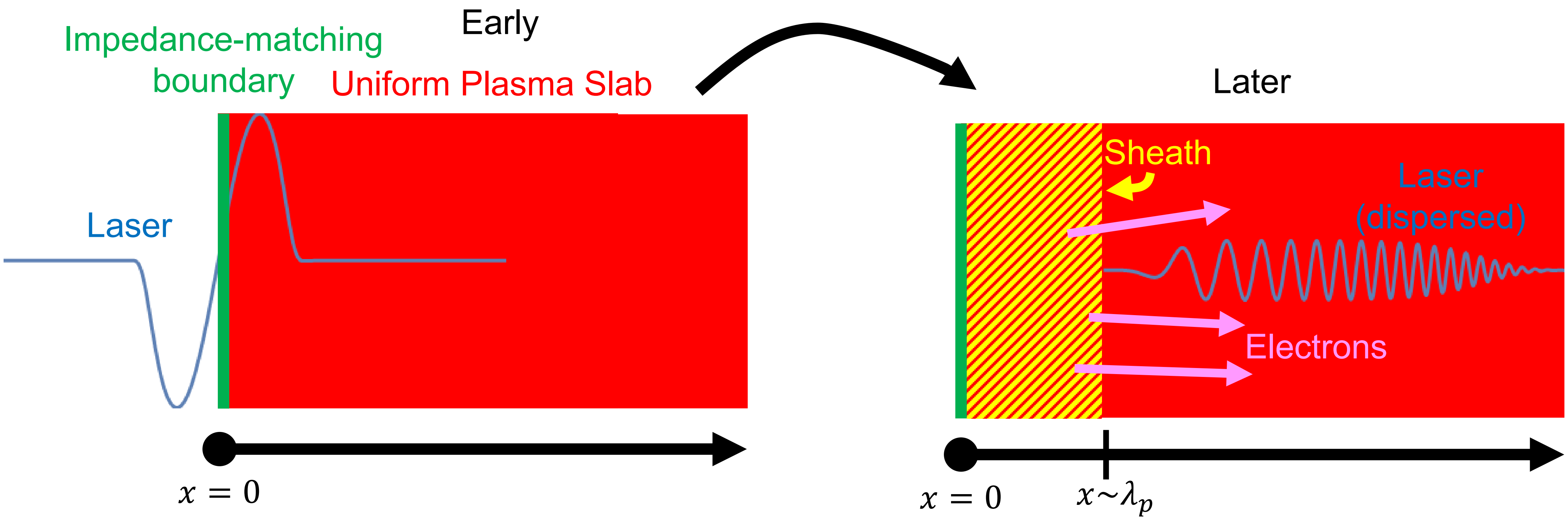
The electron dynamics of laser wakefield acceleration is examined in the high-density regime, including the dependence on the plasma density and the amplitude and pulse length of the laser. In the very high (near-critical) density regime, electrons are accelerated by the ponderomotive force followed by the electron sheath formation, resulting in a flow of bulk electrons. Applications of these properties to medical conditions are considered.

Submitted, Phys. Rev. Accel. Beams (2019)

Modeling Critical-Density Wakefields

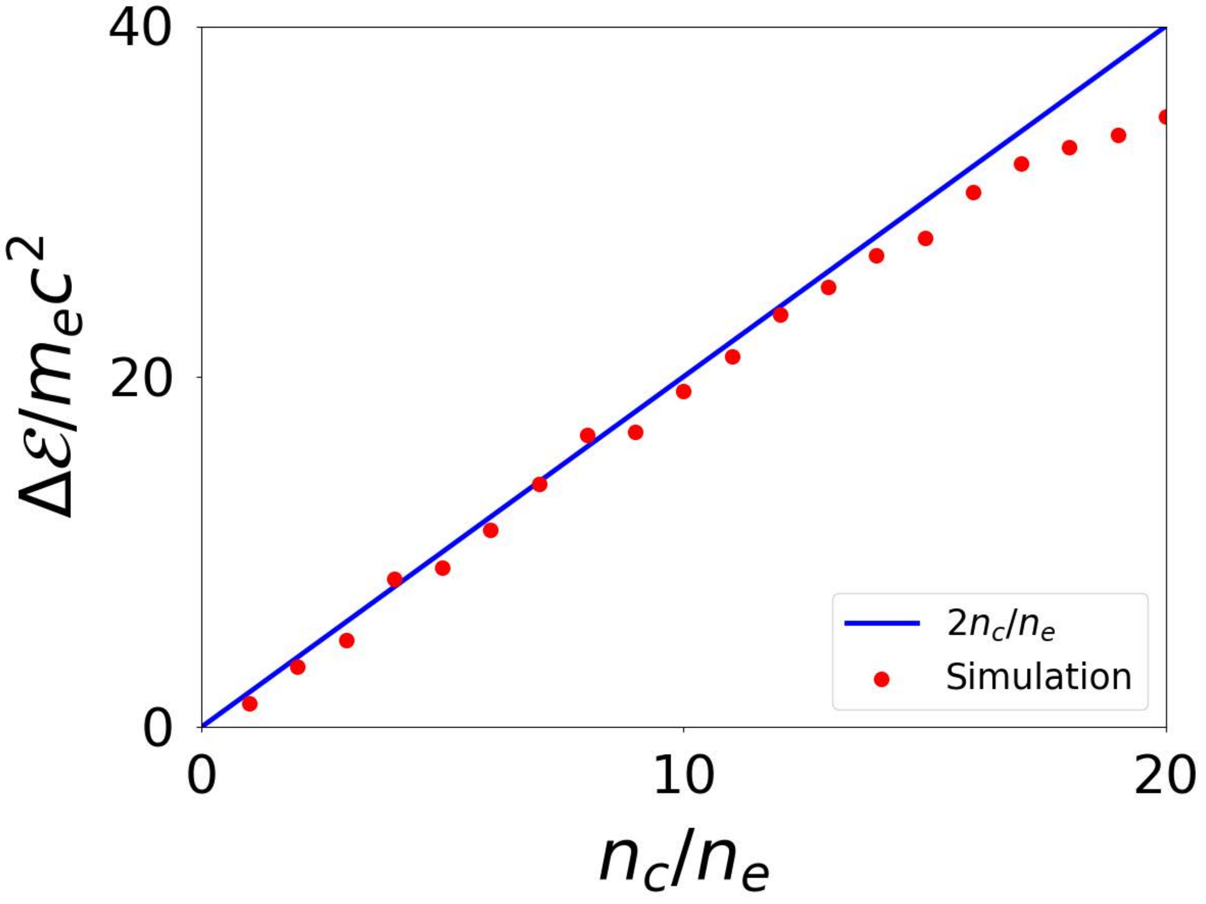
- Critical density → $v_g = 0$
- Laser enters plasma → sheath formation
- Sheath accelerates electrons
- Simulation → laser injected from vacuum

- 1D 3V Particle-in-cell (PIC) code
- Ti:Sapphire laser, $\lambda = 1\ \mu\mathrm{m}$
- Laser $E_y = E_0 \sin(kx - \omega t - \phi)\, h(x,t)$
- $h(x,t)$ → flat-top, resonant profile



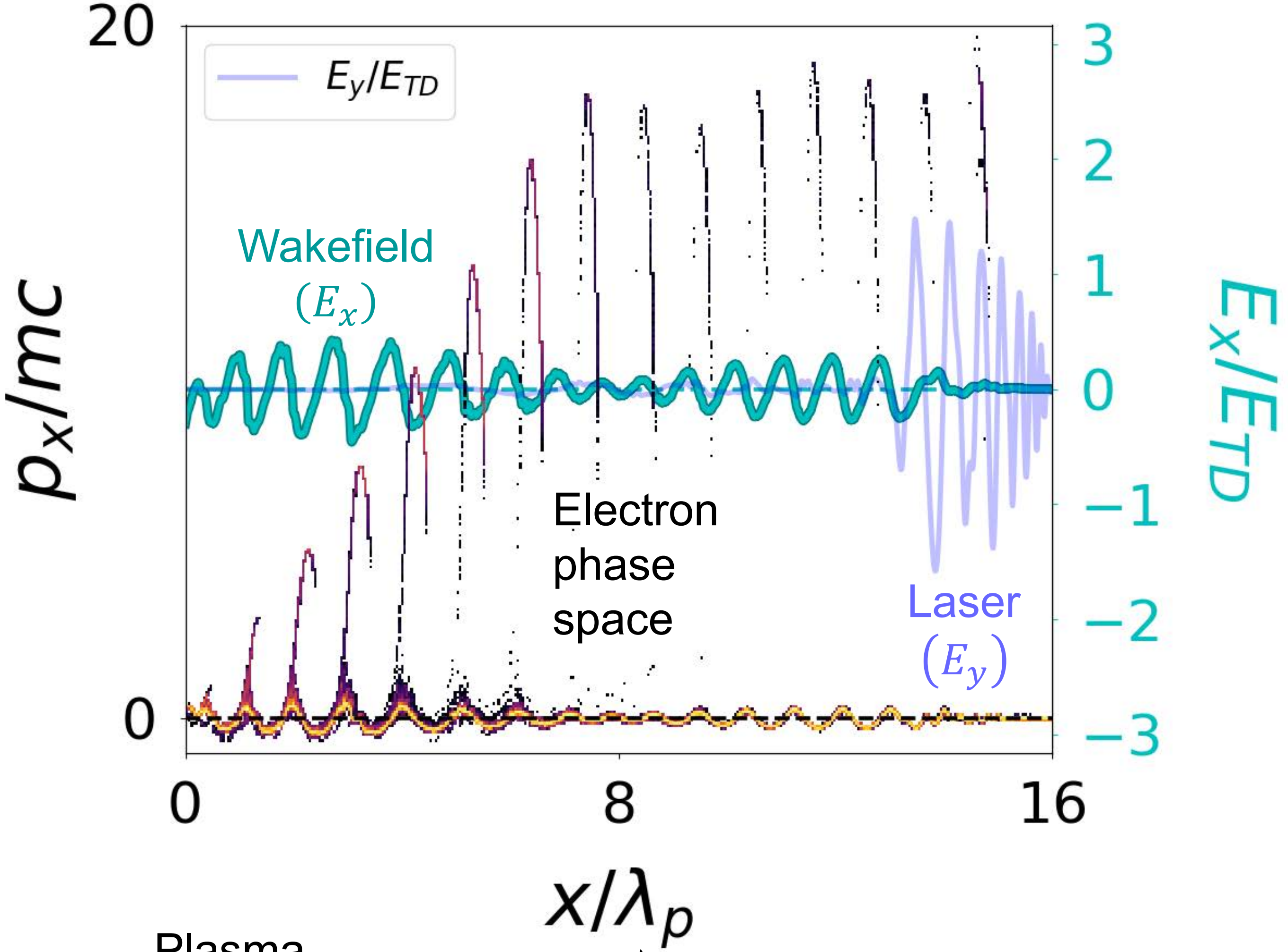
Density Scaling of Electron Energy

- Electron energy gain: $\Delta\mathcal{E} = 2m_e c^2 (n_c/n_e)$
- Linear dependence on n_c/n_e
- Scan over n_c/n_e → linear $\Delta\mathcal{E}$ trend agrees
- Low density → wakefield not constant → deviation from linearity



Low-Density Regime

- Typical wakefield regime, $n_c/n_e = 10$
- Clear, robust wakefield
- Wakefield → train of trapped electrons
- "Blue" wave → no bulk coupling/turbulence

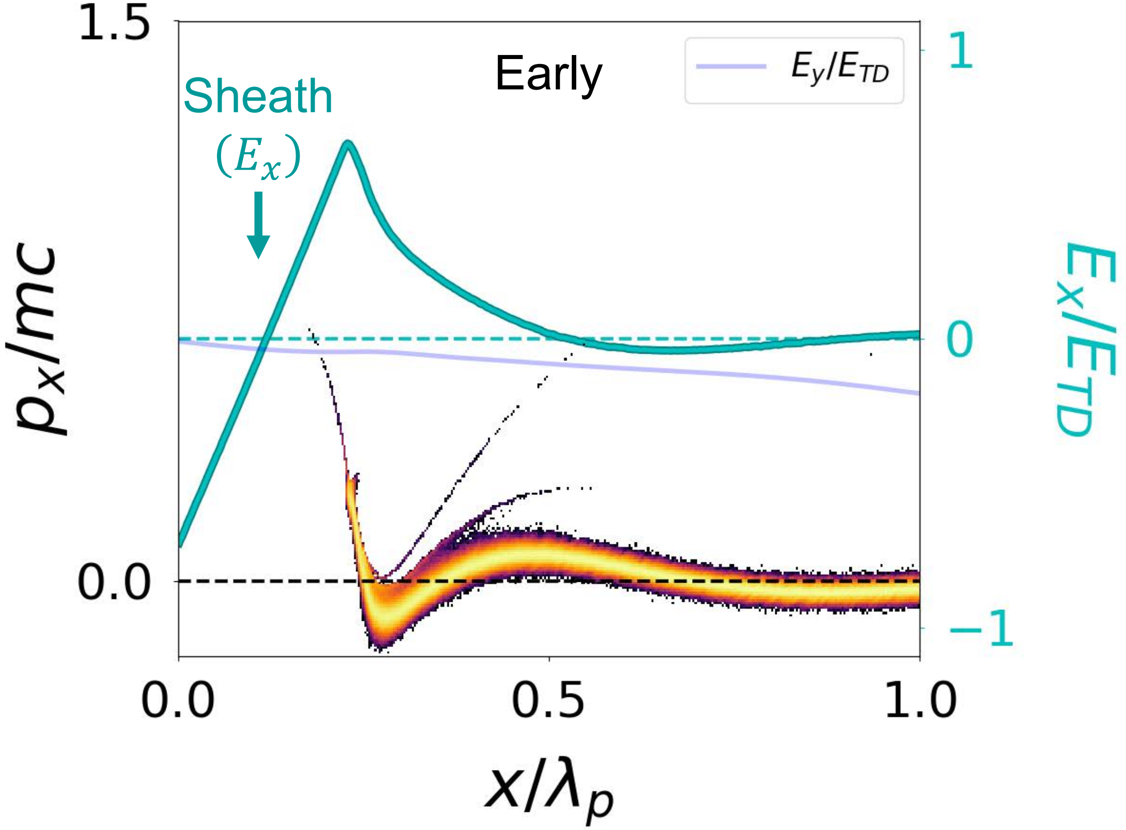


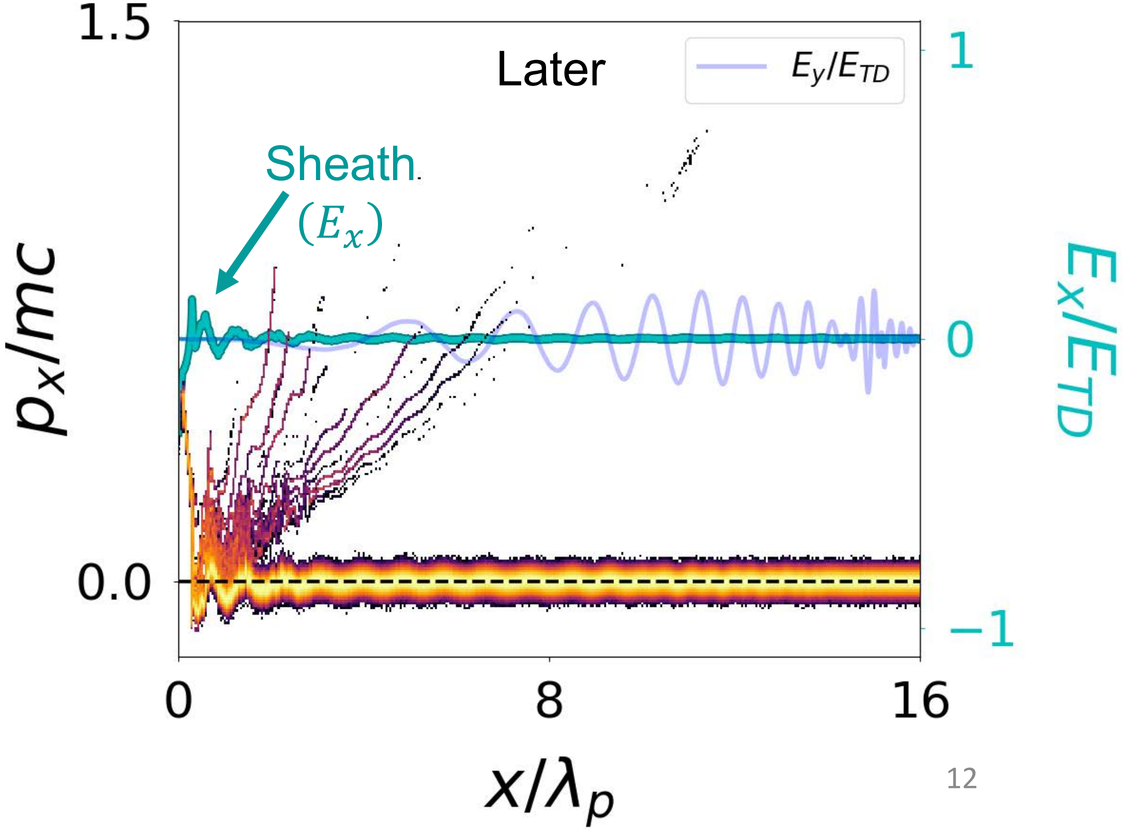
Plasma wavelength

$$\lambda_p = \frac{2\pi c}{\omega_p}$$

High-Density Regime

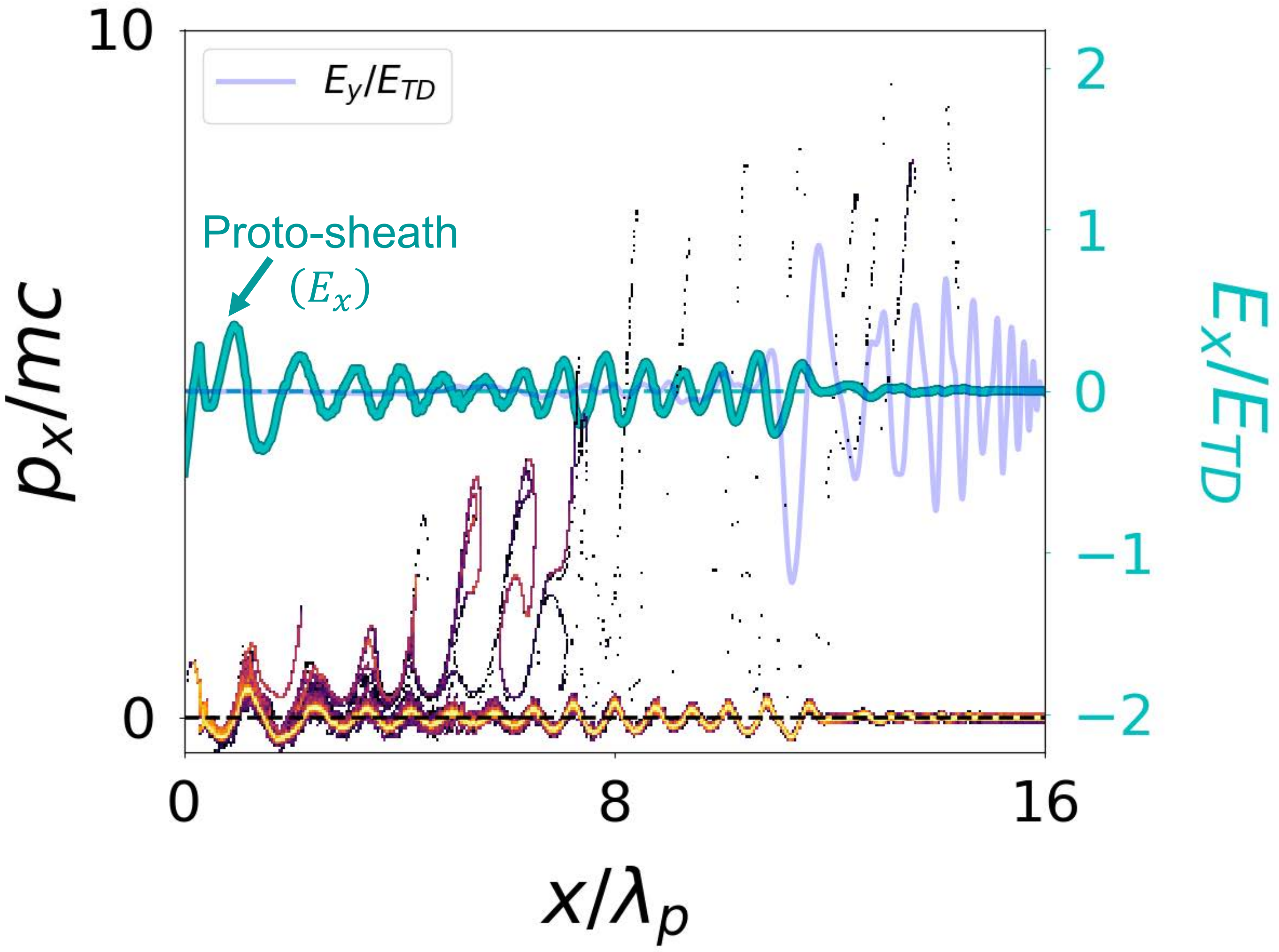
- Critical density regime, $n_c/n_e = 1$
- $v_g = 0$ → sheath oscillation
- Sheath → low-energy electron streams
- Streams build up → sheath exhausted
- Novel regime
- “Black” wave → bulk coupling





Transition Regime

- Intermediate regime, $n_c/n_e = 5$
- Modest electron trapping
- Transition → sheath physics beginning
- “Grey” wave

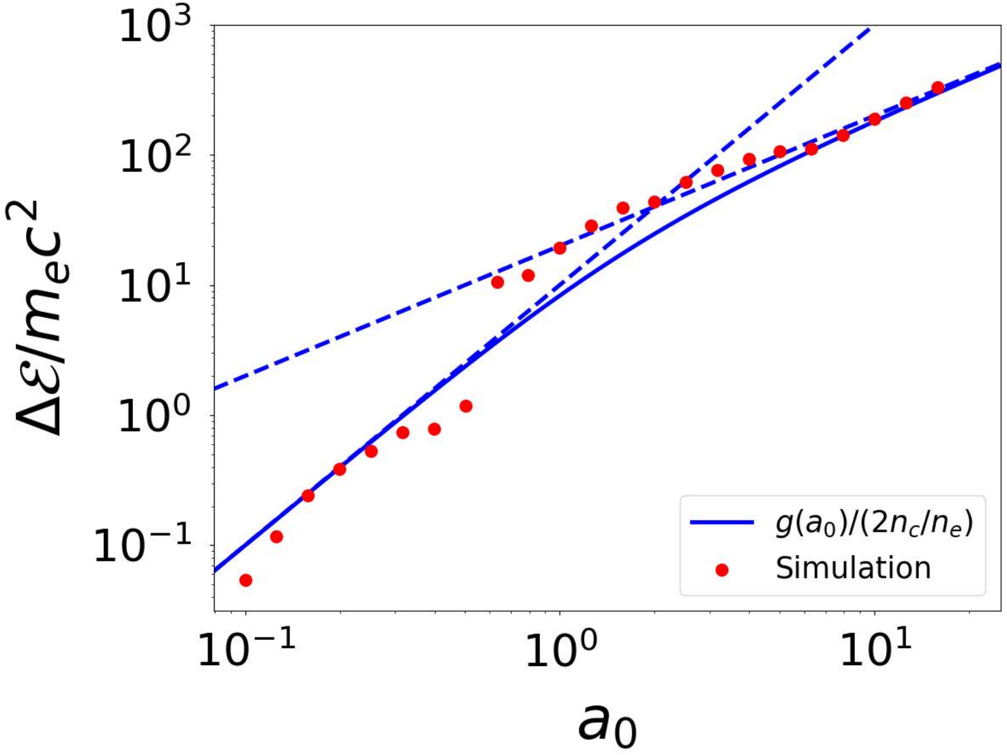


Intensity Scaling of Electron Energy

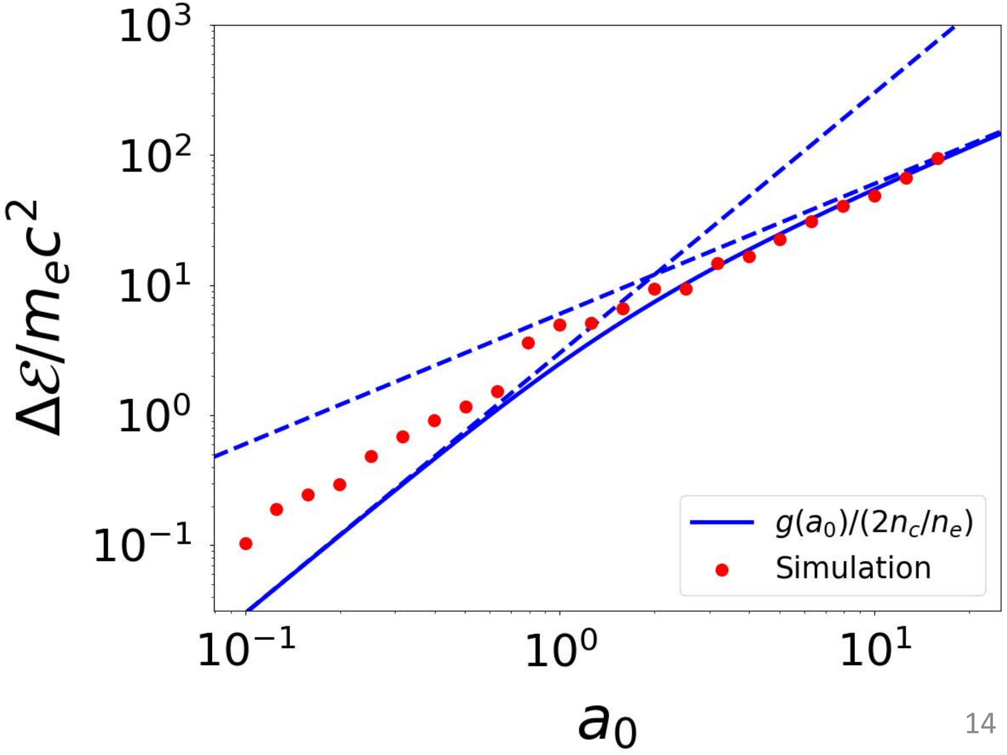
- Electron energy gain in high-density regime
- a_0 → Normalized laser intensity
- Energy gain a_0 dependence: $\Delta\mathcal{E} \propto g(a_0)$

- Ponderomotive potential $g(a_0) = (1 + a_0^2)^{1/2} - 1$
- Density fixed, $\Delta\mathcal{E}$ scanned over a_0
- $\Delta\mathcal{E}$ compared → $g(a_0)$

$n_c/n_e = 10$



$n_c/n_e = 3$

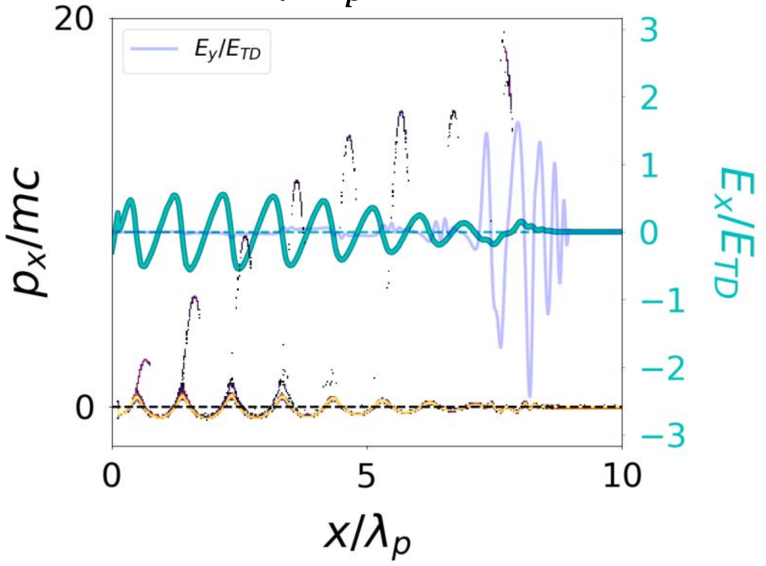


Self-Modulation

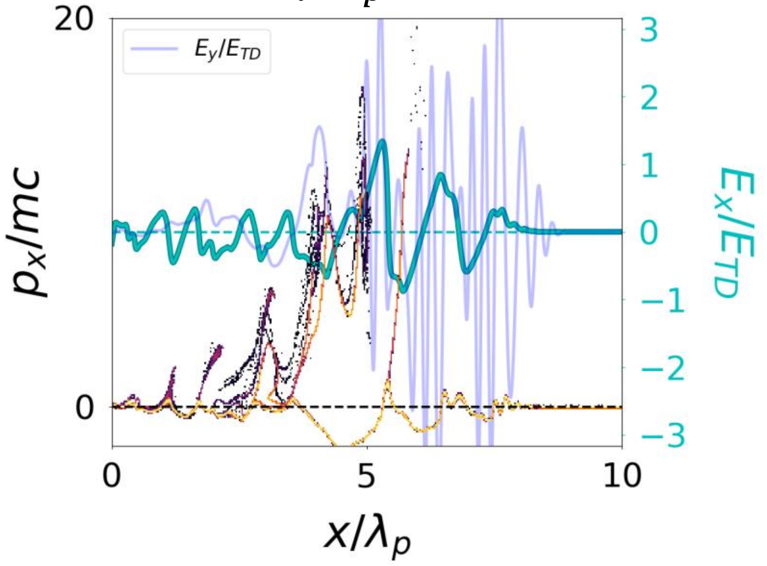
- Fiber lasers → long pulse better
- Self-modulation: long pulse breaks → small pulses

- Pulse length λ_l/λ_p scanned, $n_c/n_e = 10$, $a_0 = 1$
- Long pulses → Laser/wakefield modulated

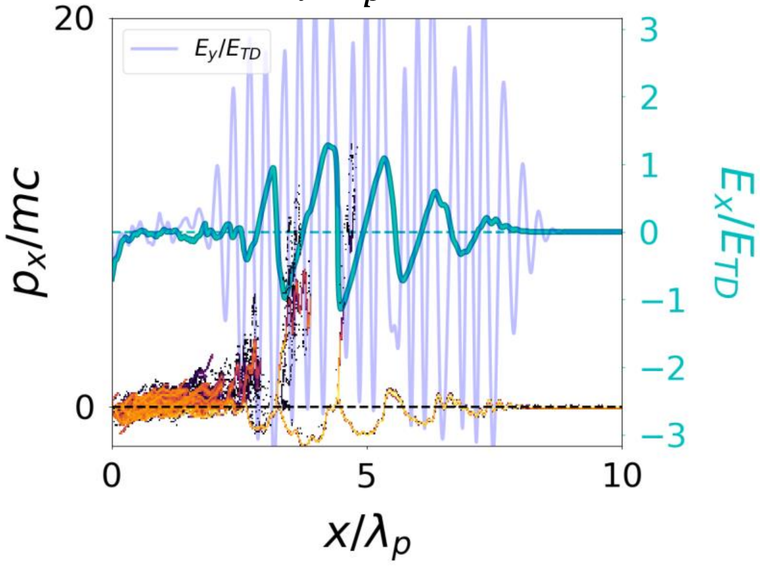
$\lambda_l/\lambda_p = 0.5$



$\lambda_l/\lambda_p = 3$



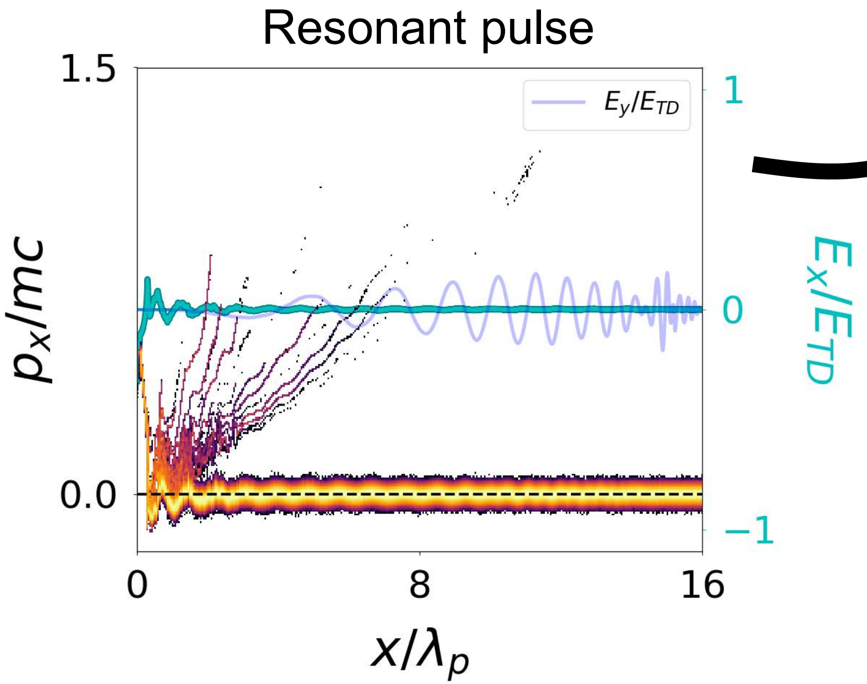
$\lambda_l/\lambda_p = 5$

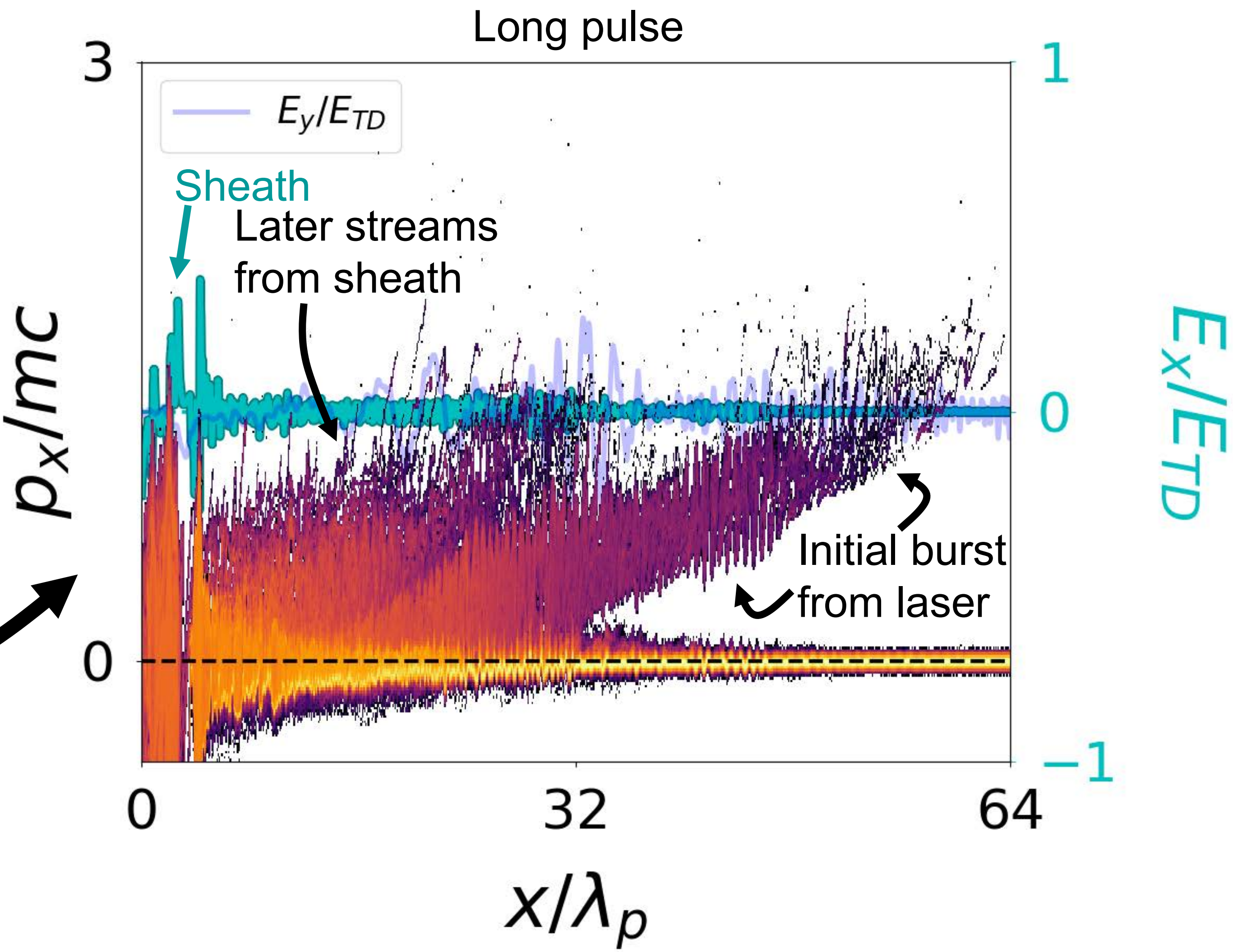


J. Krall, A. Ting, E. Esarey, and P. Sprangle, in *Proceedings of the 1993 Particle Accelerator Conference*, Vol. 4
E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. **81**, 1229 (2009)

Self-Modulation at the Critical Density

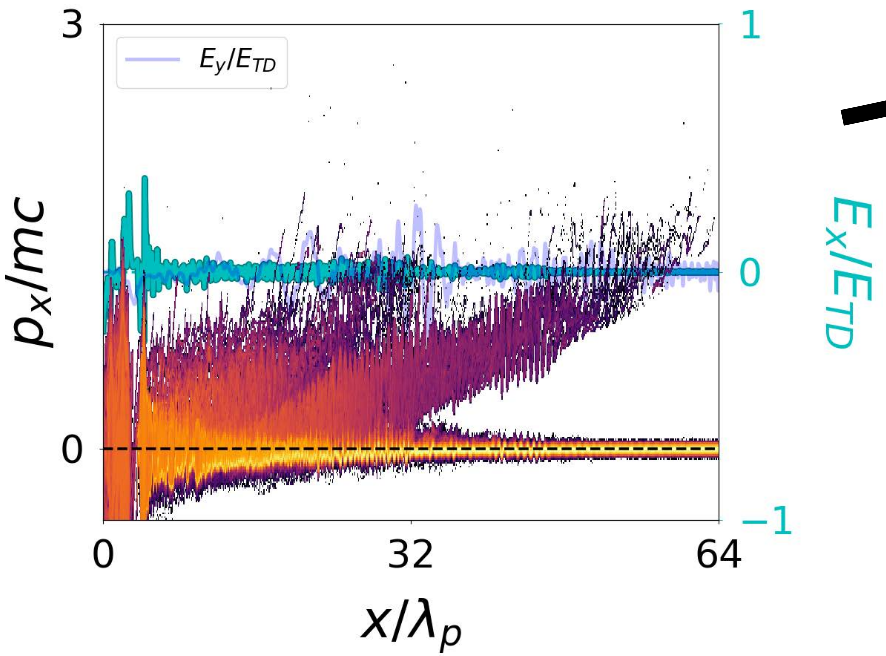
- Critical plasma + long laser pulse $\left(\lambda_l = 8\lambda_p\right)$
- $v_g = 0$ → huge sheath oscillation
- Violent sheath → huge electron acceleration
- Laser → initial burst
- Sheath → later streams


Resonant pulse

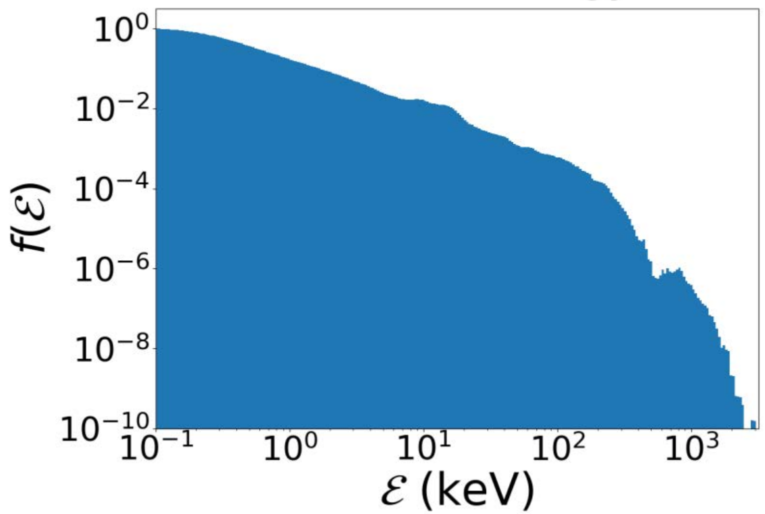

Long pulse

Electron Tissue Penetration

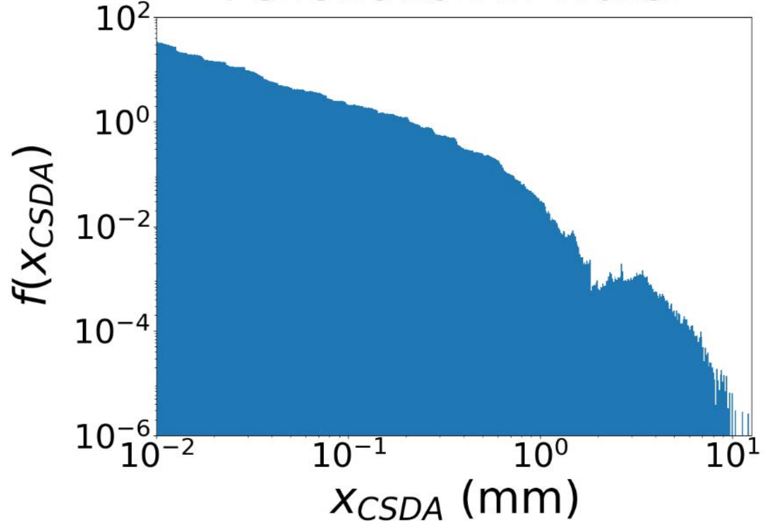
- Critical plasma + long laser pulse $\left(\lambda_l = 8\lambda_p\right)$
- Electron energy spectrum → tissue penetration
- Continuous slowing-down approximation (CSDA)
- Penetration → tuned by n_c/n_e, a_0



Electron Energy

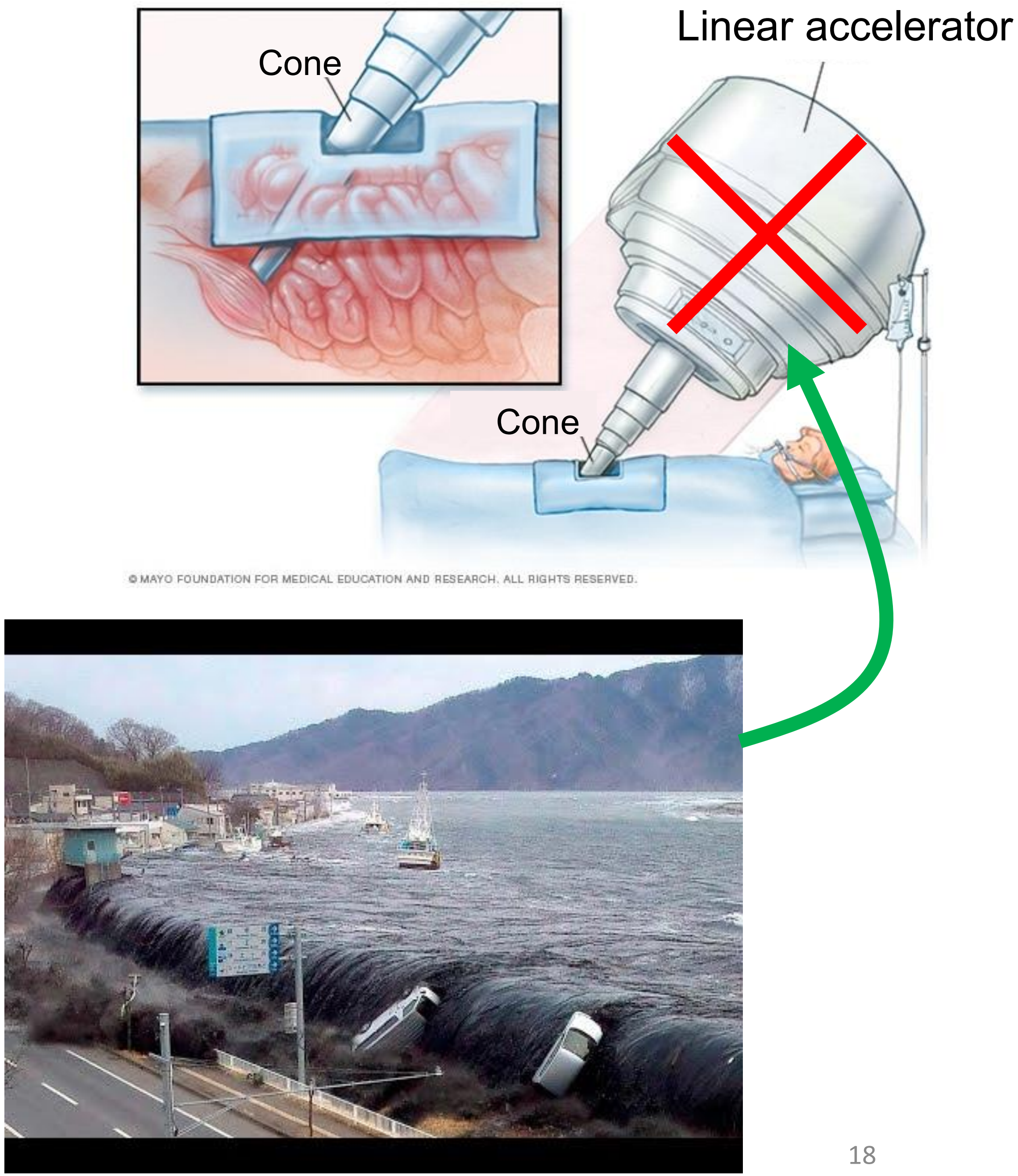


Penetration in Water



Summary

- Laser evolution → CPA to fiber
- Endoscopic therapy → keV electrons
- Fiber → tiny keV accelerator
- Technology exists → quick deployment
- Low-hanging fruit for large medical benefit
- Critical-density wakefield → Novel physics regime



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