CERN ATS Seminar
Geneva, Feb. 13, 2020

"TeV on a Chip":
A New Perspective of Wakefield Acceleration

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1. New compression of laser

2. Nanometric wakefield accelerator driven by X-ray laser = **“TeV on a Chip”**

3. Nanotube driven by e-beam

4. e-beam modulation and **XFEL in nanotube**

5. Astrophysical wakefields

6. Nanotube wakefield **cancer therapy**

Motivation:

1. Invention of **Thin Film Compression** (TFC, 2013) opened up
Laser Wakefield Acceleration (LWFA, 1979)
in X-ray regime,

$$E_{TD} = m\omega_{pe}\, c / e; \qquad \Delta\varepsilon = 2mc^2 a_0^2 (n_{cr} / n)$$

compactifying further by 10^3 over the gas plasma LWFA

2. X-ray frequency exceeds the nanomaterial's plasma frequency ω_{pe}

→ **carbon-nanotubes**

higher than 10TV/m wakefield (2014)

→ Explore X-ray wakefield accelerator in nanotube = "TeV on a Chip"

Plasma (nanomaterial) accelerator driven by beam/pulse

<u>Collective</u> force ~$\boldsymbol{N^2}$ (nonlinear ← linear force ~N)

<u>Coherent and smooth</u> structure (not stochastic)

Plasma (nanomatter) accelerator driven by laser (coherent photons)

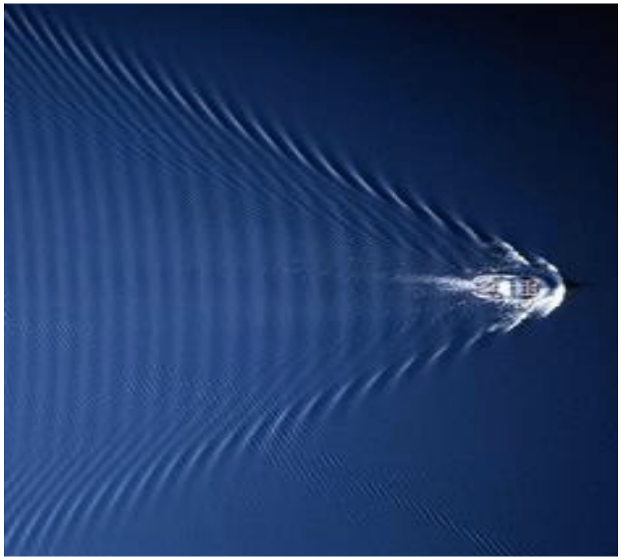
<u>compactification</u> by $10^3 – 10^4$ (now even by $\mathbf{10^6}$) >> conventional accelerators

enabled by laser technology (<u>laser compression</u> (Mourou et al.1985))

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0, causes **wavebreak** and **turbulence**

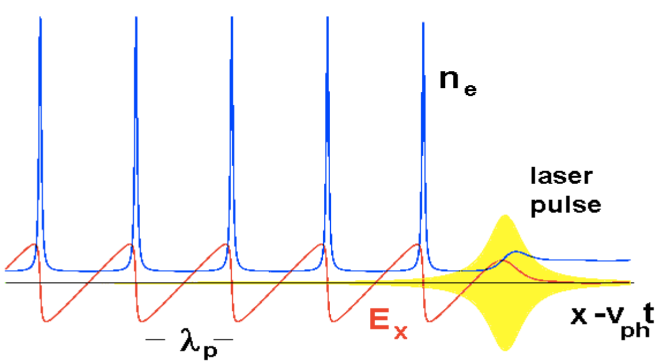


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph} / e$

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at v<c



← relativity regularizes (*relativistic coherence*)

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c / e$ (~ GeV/cm)

The late Prof. Abdus Salam

At ICTP Summer School (1981),
Prof. Salam summoned me and discussed
about laser wakefield acceleration.

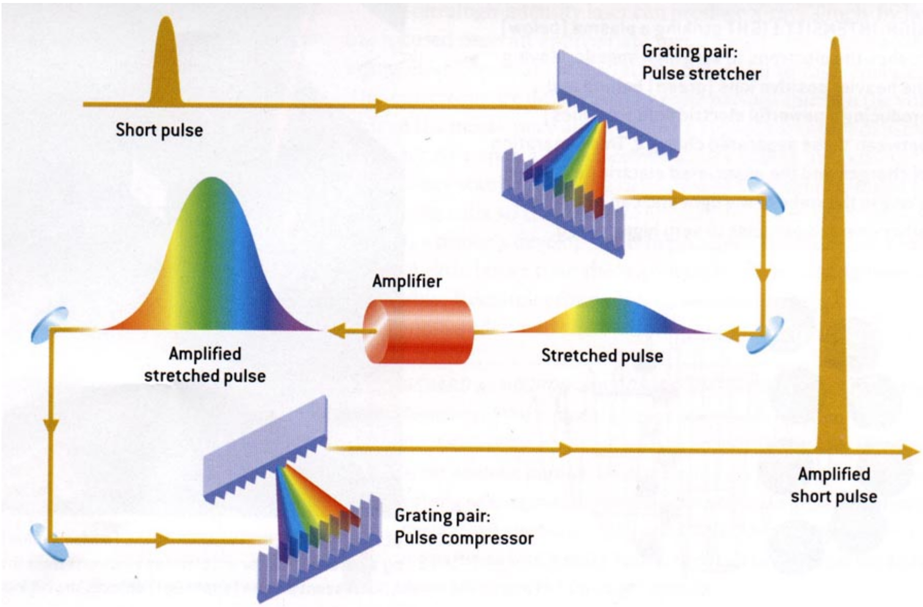
Salam: *'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'*. (1981)

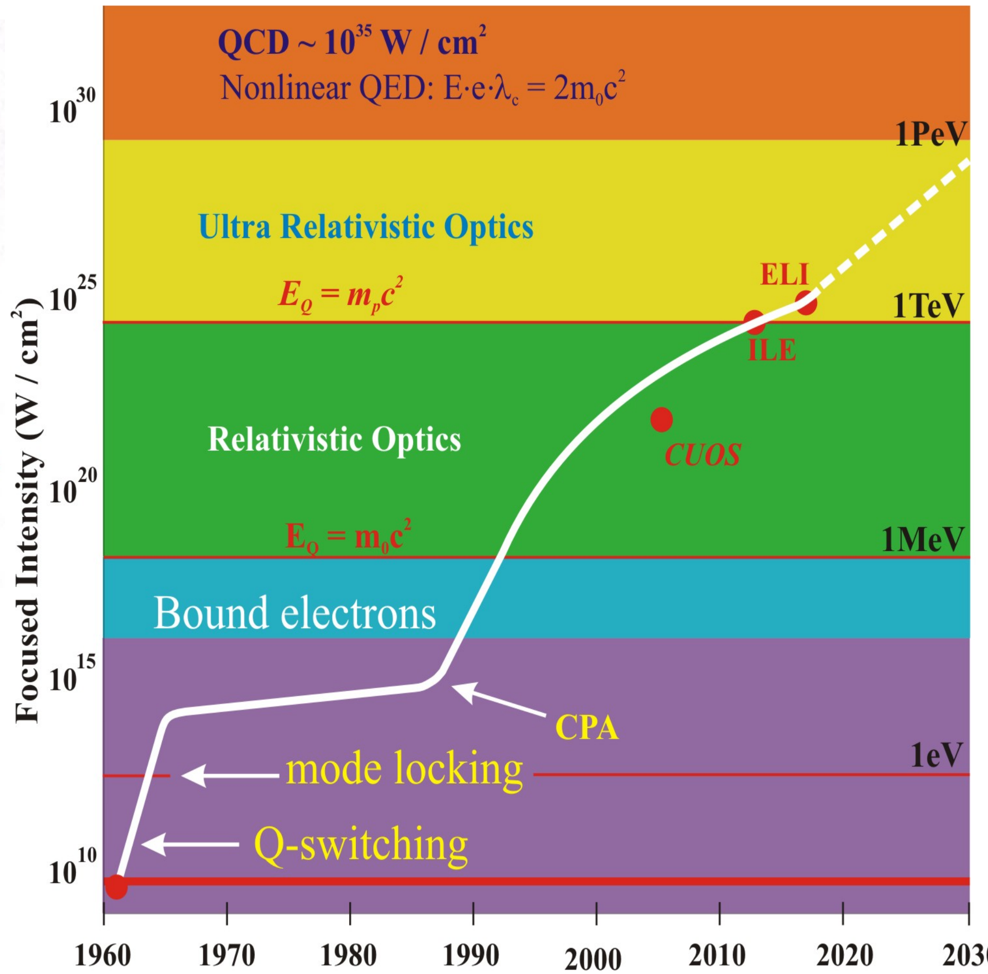
He organized the Oxford Workshop
on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

(NB: Prof. C. Rubbia et al.
discovered his bosons at CERN, 1983)

Enabling technology: laser revolution



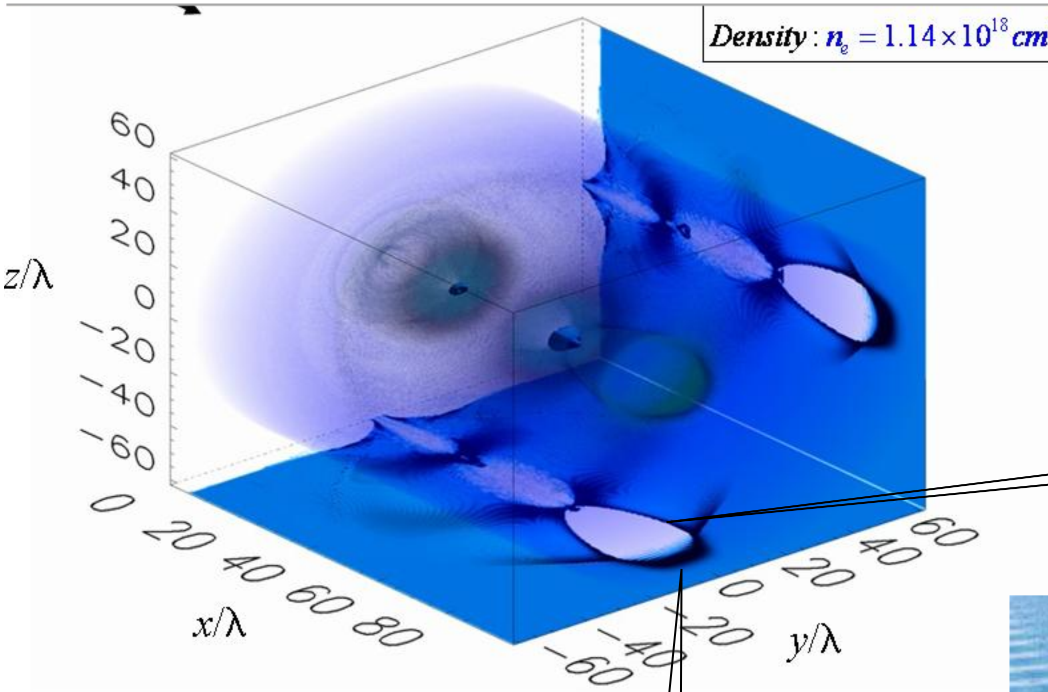


G. Mourou invented Chirped Pulse Amplification (1985)

Laser intensity exponentiated since,

to match the required intensity for Tajima-Dawson's LWFA (1979)

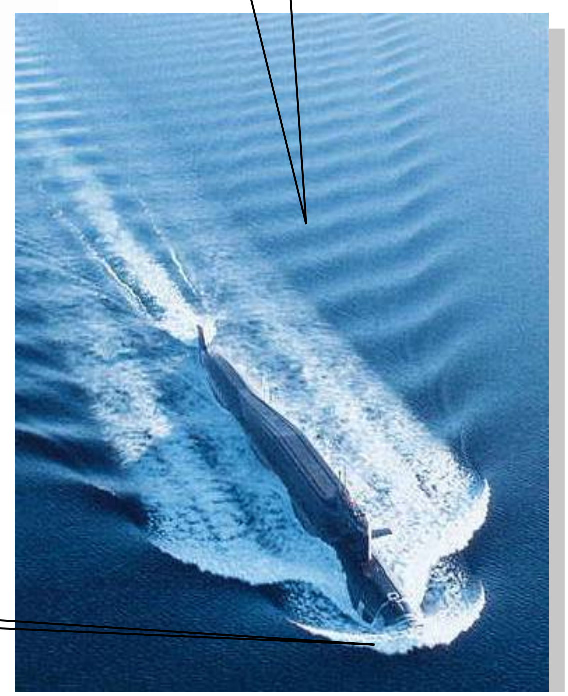
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave

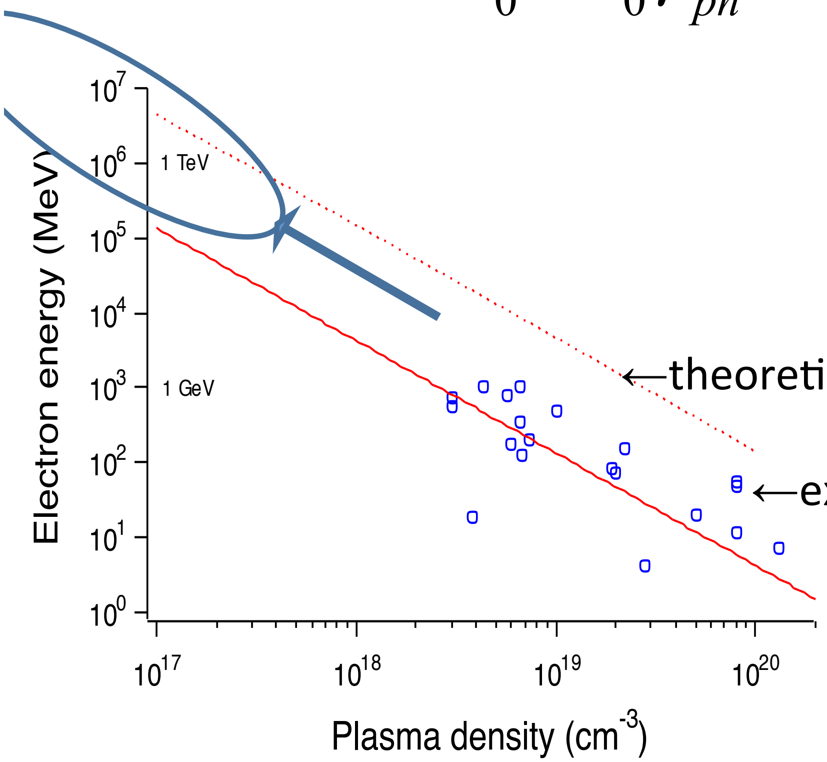


Bow Wave

Ponderomotive acceleration

Theory of wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = [n_{cr}(\omega) / n_e]^{1/2}$$

n_{cr} =10^{21}/cc (1eV photon)

→ 10^{29} (10keV photon)

n_e = 10^{16} (gas) → 10^{23} /cc(solid)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right), \qquad L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

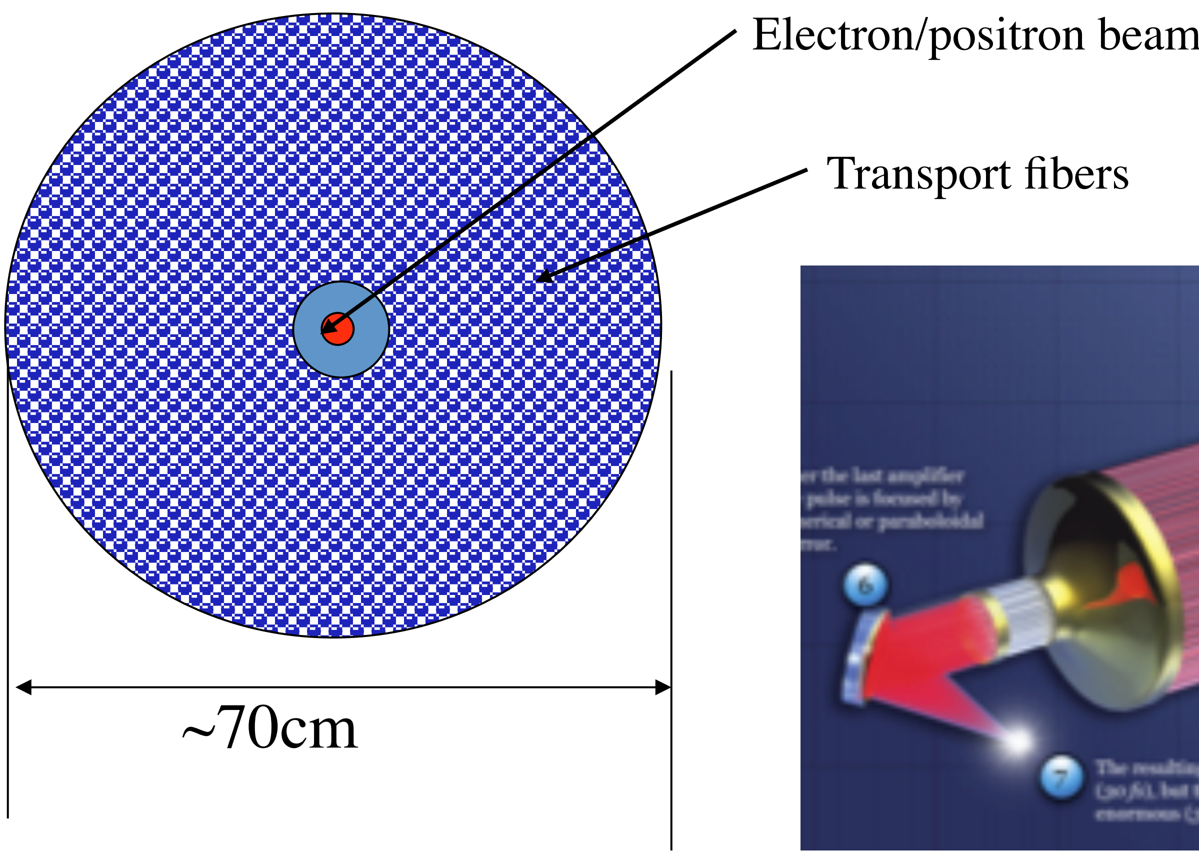
dephasing length

pump depletion length

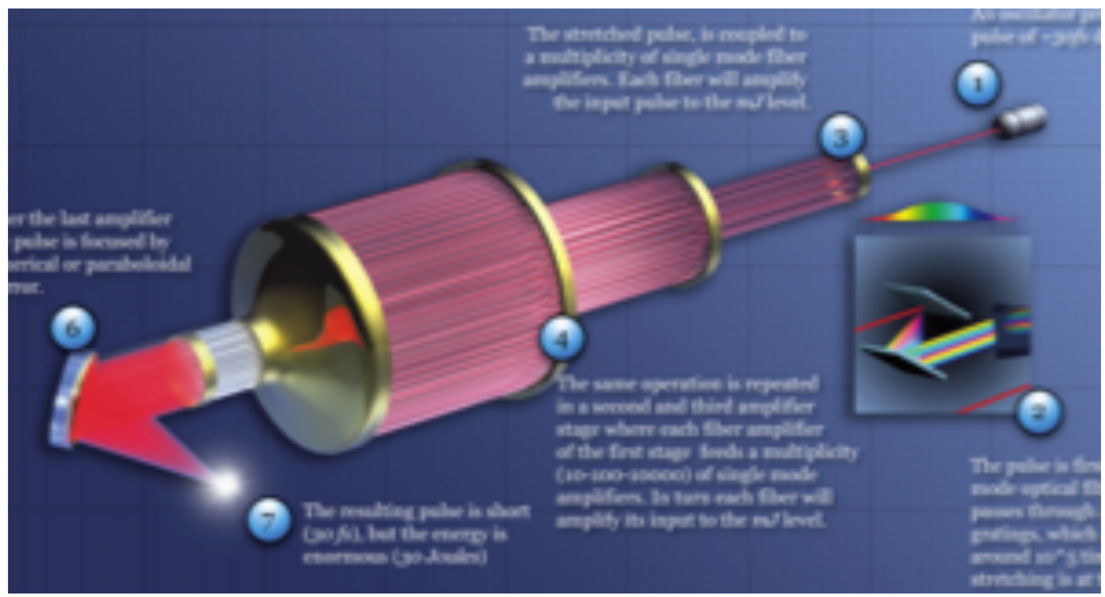
CAN Laser:

Need to Phase

32 J/1mJ/fiber~ 3×10^4 Phased Fibers!

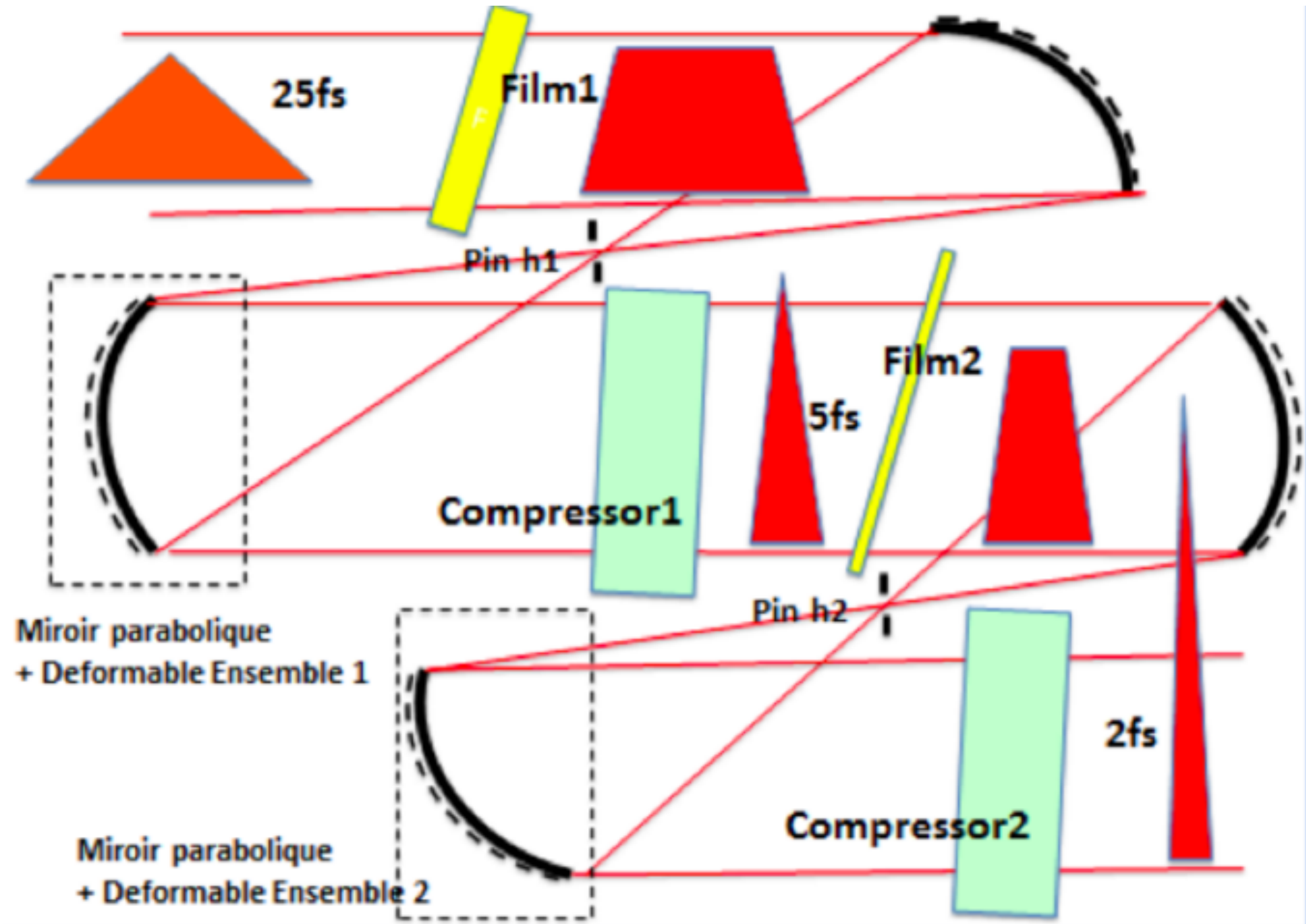


Mourou, Brockesby, Tajima, Limpert (2013)



Length of a fiber ~2m   Total fiber length~ 5 10^4km

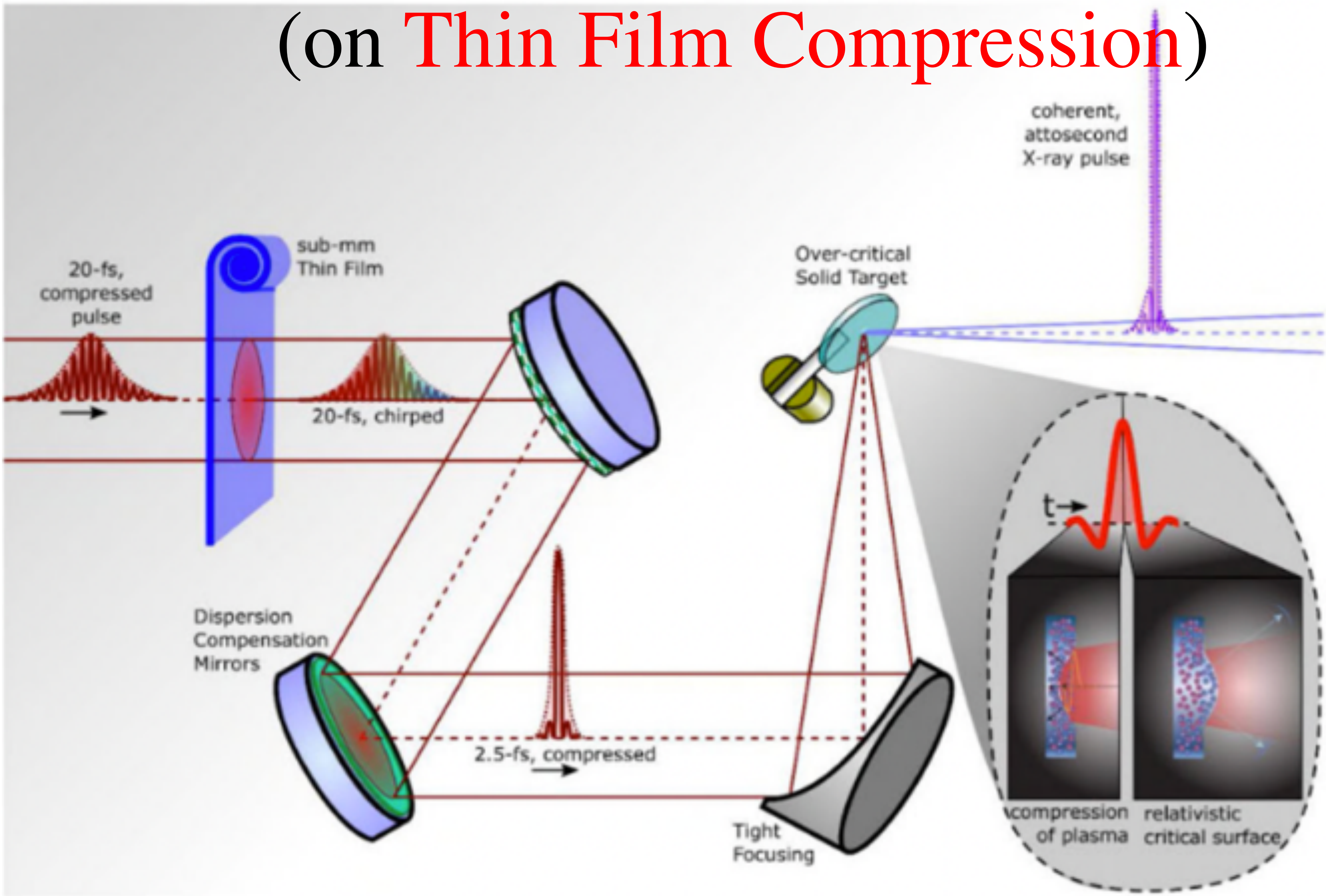
Thin Film Compression



Mourou G, et al., 2014

Single-cycled laser and “TeV on a chip”

Next Generation X-ray Lasers
(on Thin Film Compression)



Wheeler J, Mourou G, Tajima T. 2016

Earlier works of X-ray crystal acceleration

-X-ray optics and fields (Tajima et al. ,1987)

-**Nanocrystal hole** for particle propagation (Newberger, Tajima, et al. 1989)

-particle transport in the crystal (Tajima et al. 1990)

APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

B. Newberger, T. Tajima, The University of Texas at Austin, Austin, Texas 78712
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; which incorporate regular macroscopic features on the underlying crystal lattice are of potential ie application to crystal accelerators and coherent irces. We have recently begun an investigation of iterial, porous Si, in which pores of radii up to a attice spacings are etched through finite volumes rystal. The potential reduction of losses to parti-anneled along the pores makes this a very inter-ial in crystal accelerators for relativistic, positively icles. Our results on material properties which are this context will be presented. The consequences ransport will be discussed.

and $k = v_0/m_I c^2$, v_0, is the "spring constant of th channel well. Its specific form depends on the mo construct the continuum potential of a string of aton purposes it suffices to take a typical value of 2×10^1 is the multiple scattering velocity space "diffusion" We have used[10]

$$D = z\pi r_e^2 N Z_{\rm val} \left(\frac{m_e}{m_I}\right)^2 L_R,$$

where r_E is the classical electron radius, $Z_{\rm val}$ is t of valence electrons, and N is the number density of tal. Logarithmic dependencies on particle energy neglected throughout; L_R is a constant with a ty

Particle Accelerators, 1990, Vol. 32, pp. 235–240
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BEAM TRANSPORT IN THE CRYSTAL X-RAY ACCELERATOR

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Abstract A Fokker-Planck model of charged particle transport in crystal channels which includes the effect of strong accelerating gradients has been developed[1] for application to

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Crystal X-Ray Accelerator

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(Received 18 November 1986)

An ultimate linac structure is realized by an appropriate crystal lattice (superlattice) that serves as a "soft" irised waveguide for x rays. High-energy ($\simeq$40 keV) x rays are injected into the crystal at the Bragg angle to cause Bormann anomalous transmission, yielding slow-wave accelerating fields. Particles (e.g., muons) are channeled along the crystal axis.

PACS numbers: 52.75.Di, 41.80.−y, 61.80.Mk

An approach to the attainment of ever higher energies by extrapolating the linac to higher accelerating fields, higher frequencies, and finer structures is prompted by several considerations, including the luminosity requirement which demands the radius of the colliding-beam spot be proportionately small at high energies: $a_0 = \pi^{-1/2}\hbar c(f\mathcal{N})^{-1/2}P\epsilon^{-2}$, where f, $\mathcal{N}$, P, and ϵ are the duty cycle, total number of events, beam power, and beam energy, respectively. This approach, however, encounters a physical barrier when the photon energy becomes of the order $\hbar\omega \simeq \hbar\omega_p \simeq mc^2\alpha^2 \simeq 30$ eV (α = the fine-structure constant), corresponding to wavelength (scale length) $\lambda \simeq 500$ Å: The metallic wall begins to absorb the photon strongly, where ω_p is the plasma frequency corresponding to the crystal electron density. In addition, since the wall becomes not perfectly conducting for $\hbar\omega \gtrsim mc^2\alpha^2$, the longitudinal component of fields becomes small and the photon goes almost straight into the wall (a soft-wall regime). As the photon energy $\hbar\omega$ much exceeds $mc^2\alpha^2$ and becomes $\gtrsim mc^2\alpha$, however, the metal now ceases to be opaque. The mean free path of the photon is given by Bethe-Bloch theory as $l_i = (3/2^8\pi) \times a_B^{-2}\alpha^{-1}n^{-1}(\hbar\omega/Z_{\rm eff}^2\mathcal{R})^{7/2}$, where a_B is the Bohr radius, n the electron density, $Z_{\rm eff}$ the effective charge of the lattice ion, and $\mathcal{R}$ the Rydberg energy.

In the present concept the photon energy is taken at the hard x-ray range of $\hbar\omega \simeq mc^2\alpha$ and the linac structure is replaced by a crystal structure, e.g., silicon or GaAs-AlAs. (A similar bold endeavor was apparently undertaken by Hofstadter already in 1968.[1]) Here the crystal axis provides the channel through which accelerated particles propagate with minimum scattering (channeling[2]) and the x rays are transmitted via the Bormann effect (anomalous transmission[3,4]) when the x rays (wavelength λ) are injected in the xz plane with a

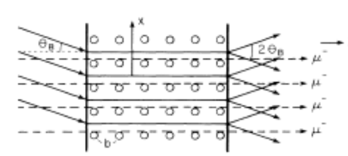
where b is the transverse lattice constant and later a the longitudinal lattice constant ($a \simeq b$) (see Fig. 1). The row of lattice ions (perhaps with inner-shell electrons) constitutes the "waveguide" wall for x rays, while they also act as periodic irises to generate slow waves. A superlattice[5] such as $Ge_cSi_{1-c}S_l$ (in which the relative concentration c ranges from 0 to 1 over 100 Å or longer in the longitudinal z direction) brings in an additional freedom in the crystal structure and provides a small Brillouin wave number $k_s = 2\pi/s$ with s being the periodicity length. We demand that the x-ray light in the crystal channel walls becomes a slow wave and satisfies the high-energy acceleration condition

$$\omega/(k_z + k_s) = c, \tag{2}$$

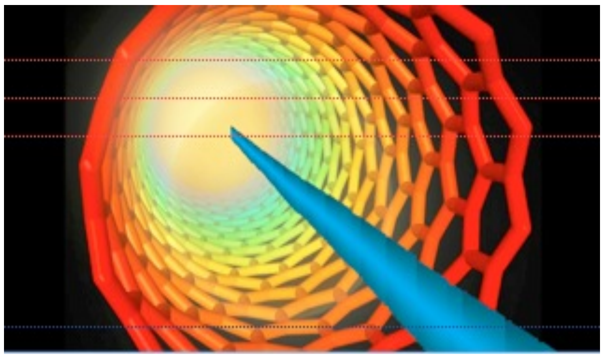
where ω and k_z are the light frequency and longitudinal wave number.

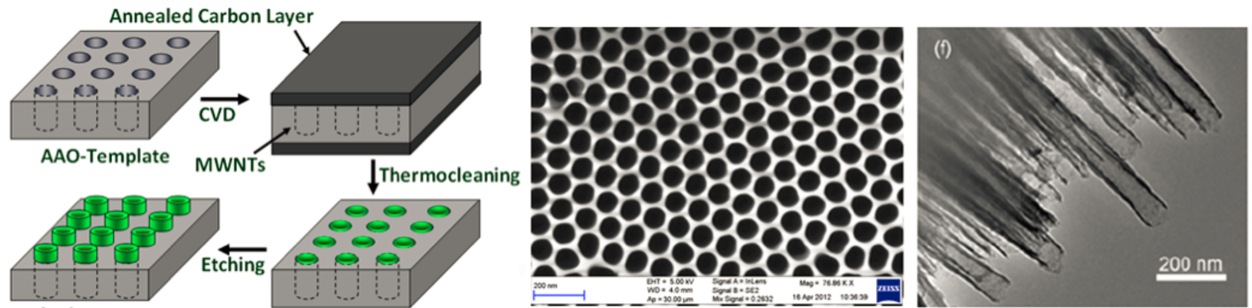
The energy loss of moving particles in matter is due to ionization, bremsstrahlung, and nuclear collisions. We can show[6] that a channeled high-energy particle moving fast in the z direction oscillates in the xy plane according to the Hamiltonian

$$H = \frac{1}{2m}(p_x^2 + p_y^2) + V(x,y), \tag{3}$$



Why Nanotubes



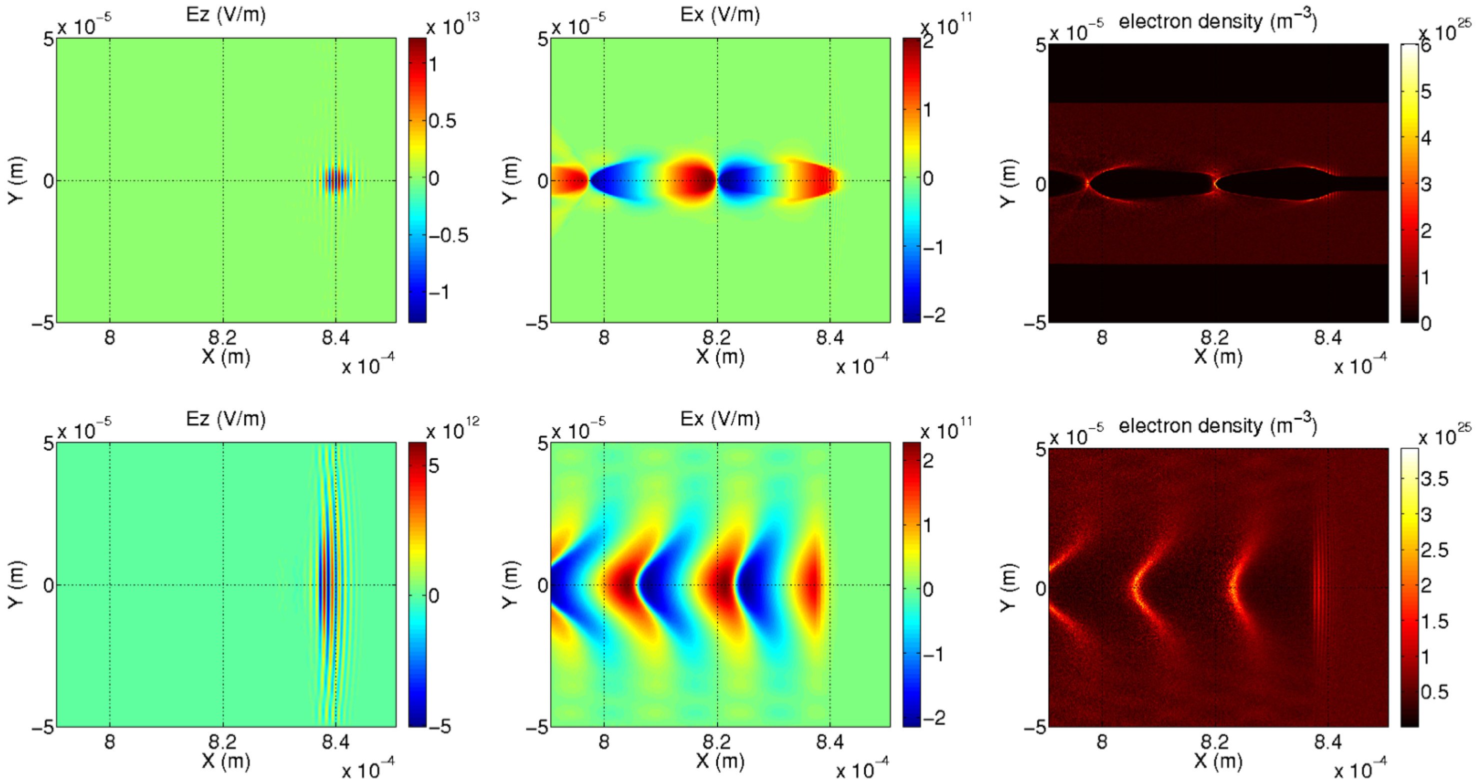


(a) (b) (c)

- High density ↔ Higher acceleration gradient (~ TeV / cm)
- Provides external structure to guide laser and electron beam
- No slowdown of electrons by collisions
- Intact for time of ionization (fs)

(b) Lazarowich RJ, Taborek P, Yoo BY, Myung NV. 2007

X-ray LWFA in a tube vs. uniform solid



in nanotube

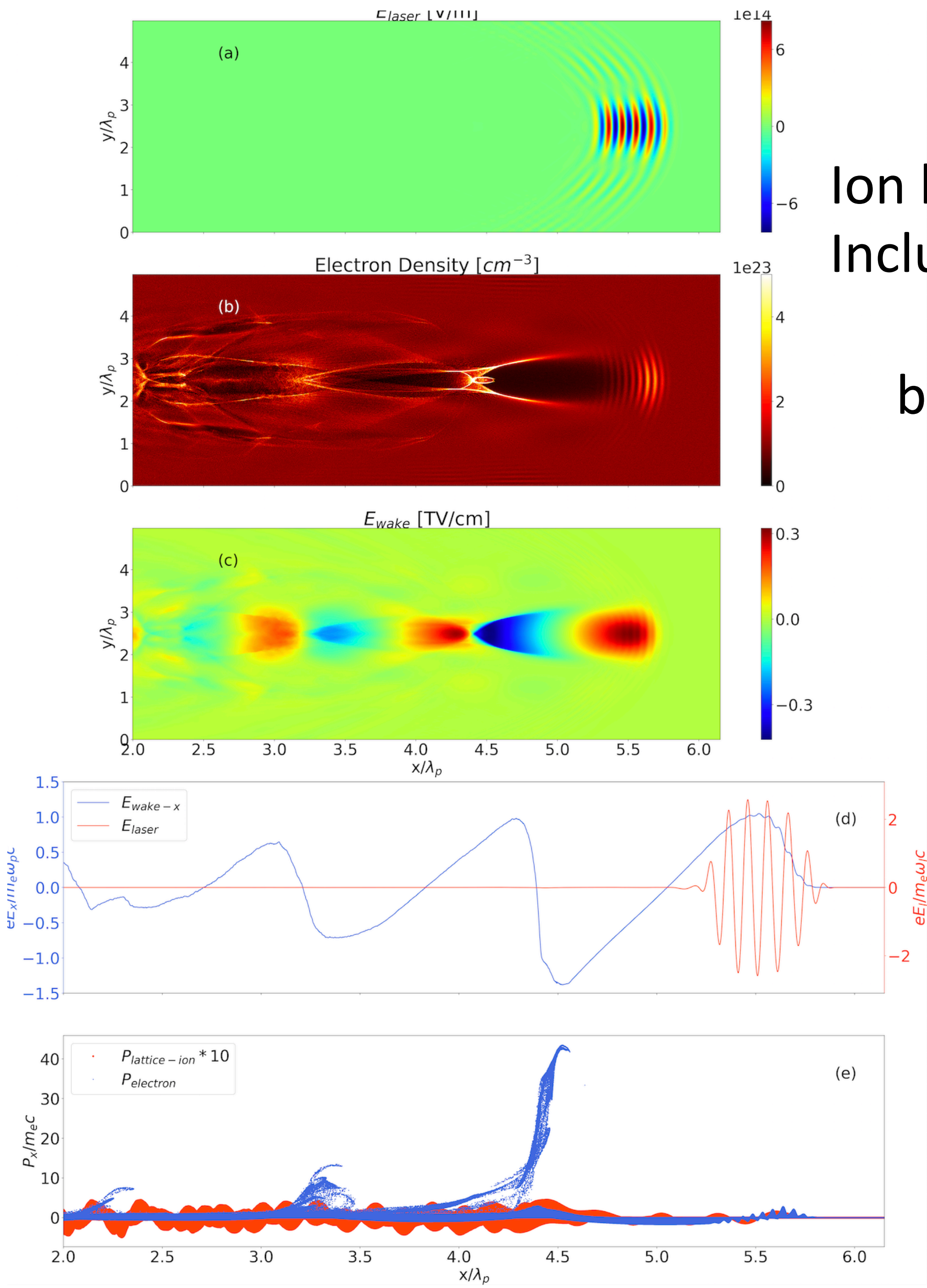
in uniform solid

A few-cycled 1keV X-ray pulse (a_0 ~ O(1)), causing 10TeV/m wakefield in the tube

more strongly confined in the tube

cf: uniform solid

X. Zhang (2016)



Ion lattice modes (s.a. polaritons) Included*) :

basically all actions via plasmons

(S. Hakimi et al. , 2019)

*)

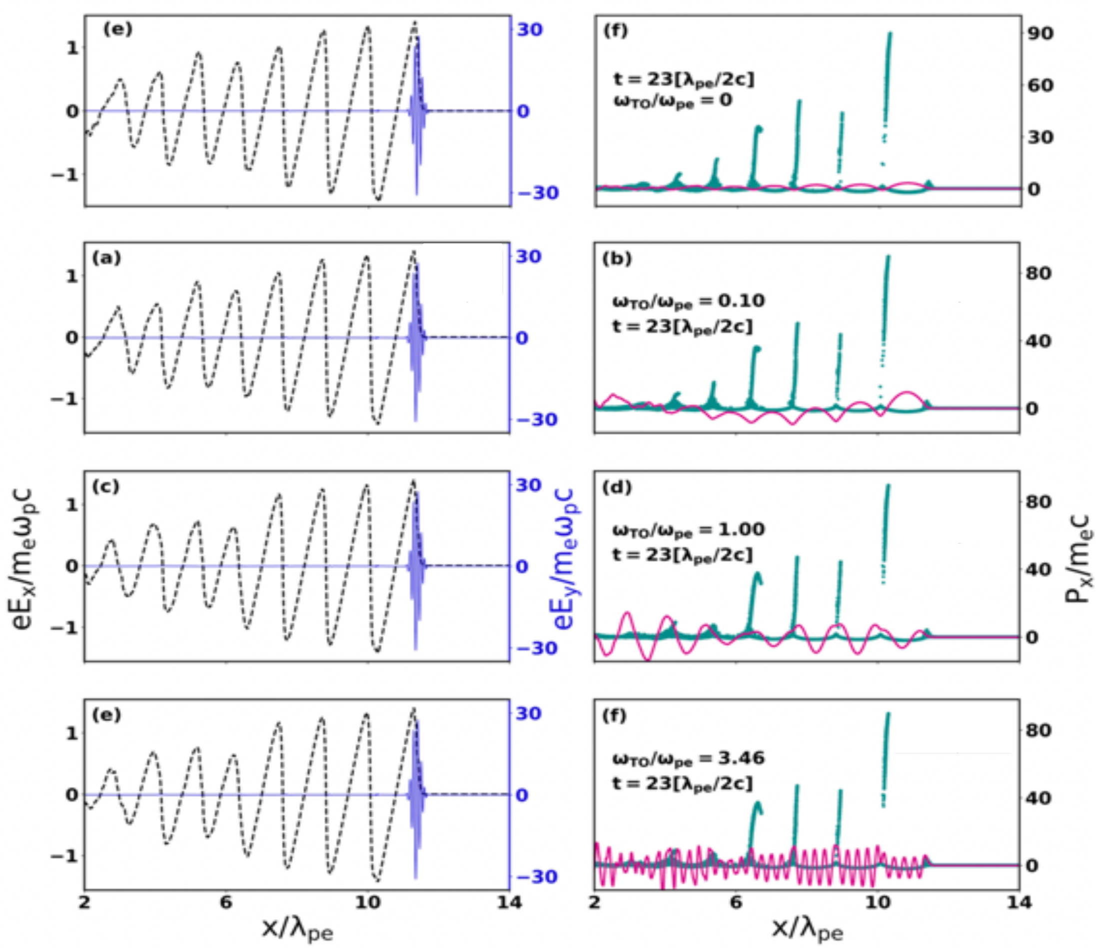
$$\epsilon(k,\omega) = 1 - \frac{\omega_{pi}^2}{\omega^2 - \omega_{TO}^2} - \frac{\omega_{pe}^2}{\omega^2 - k_x^2 v_e^2}.$$

(Tajima and Ushioda, 1978)

Effects of Optical Phonons

without
optical phonon

with
optical phonon



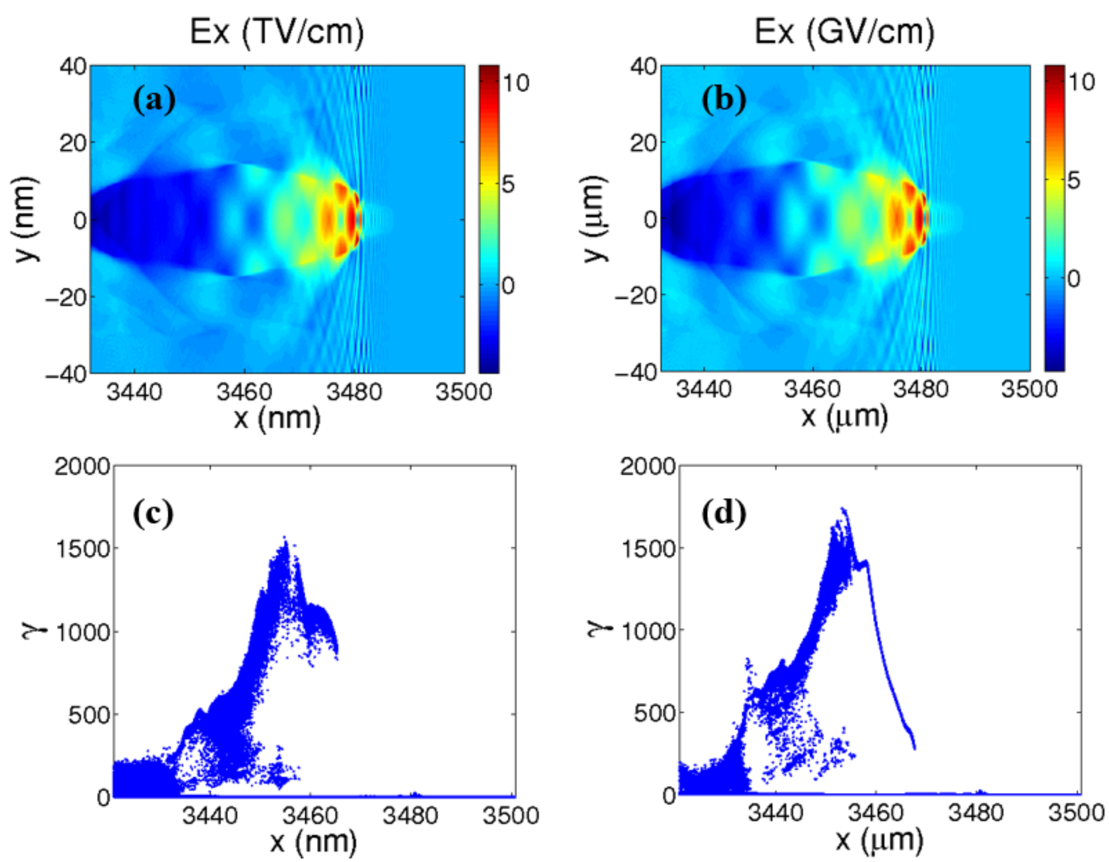
Hakimi S, et al. . 2018

X-ray in **nanotube** ←→ optical laser in **mm plasma guide**

Acceleration process are **self-similar:**
Xray in **micron (short)**, while optical laser in **mm (longer)**

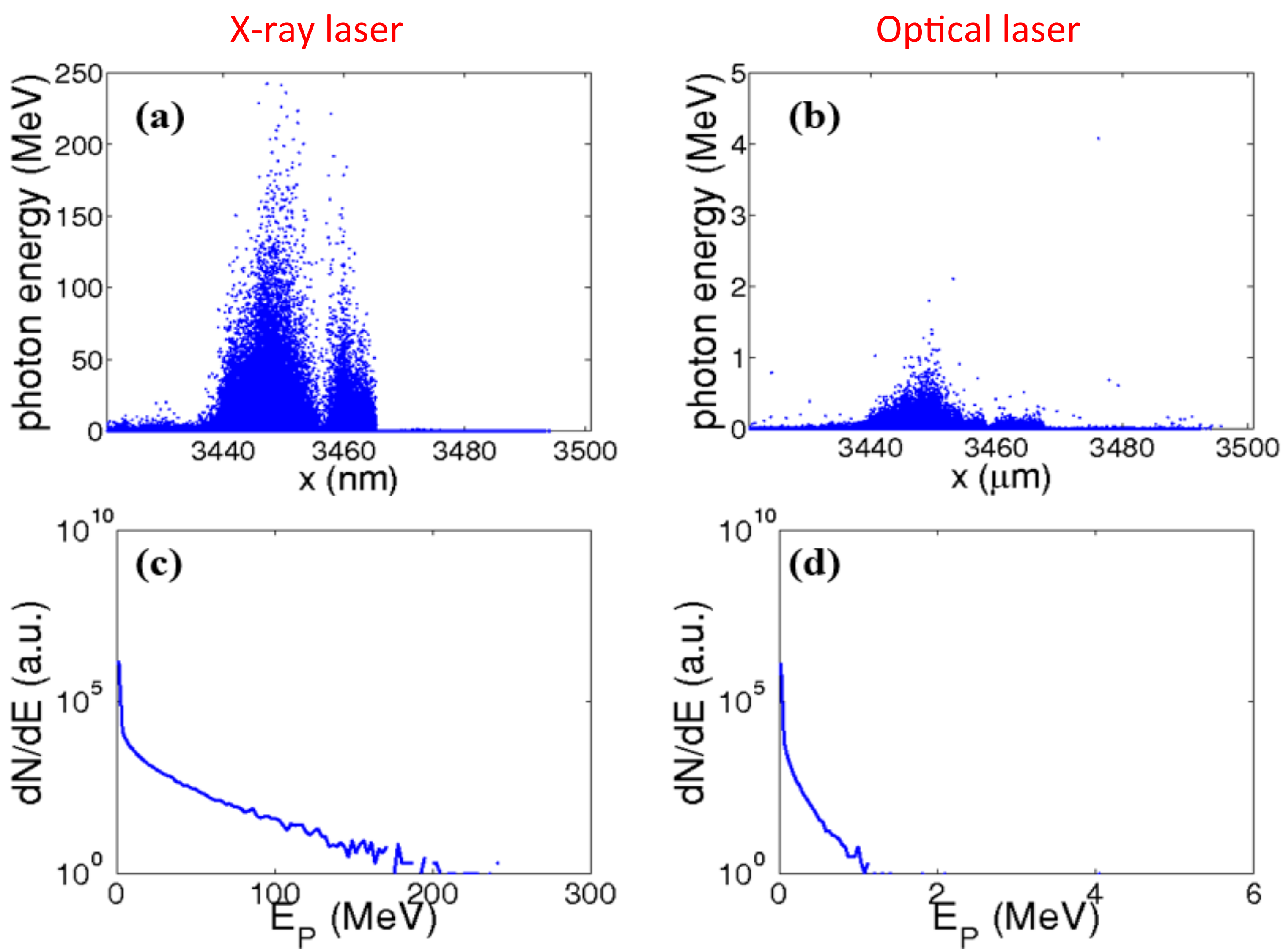
But **beam emittance** and **betatron radiation:** quite different (not self-similar)

X-ray laser Optical laser



Distributions of (a)(b) **wakefield** and (c)(d) electron energy induced by (a)(c) the X-ray laser pulse and (b)(d) optical laser in a tube when a_0=10

Betatron radiation

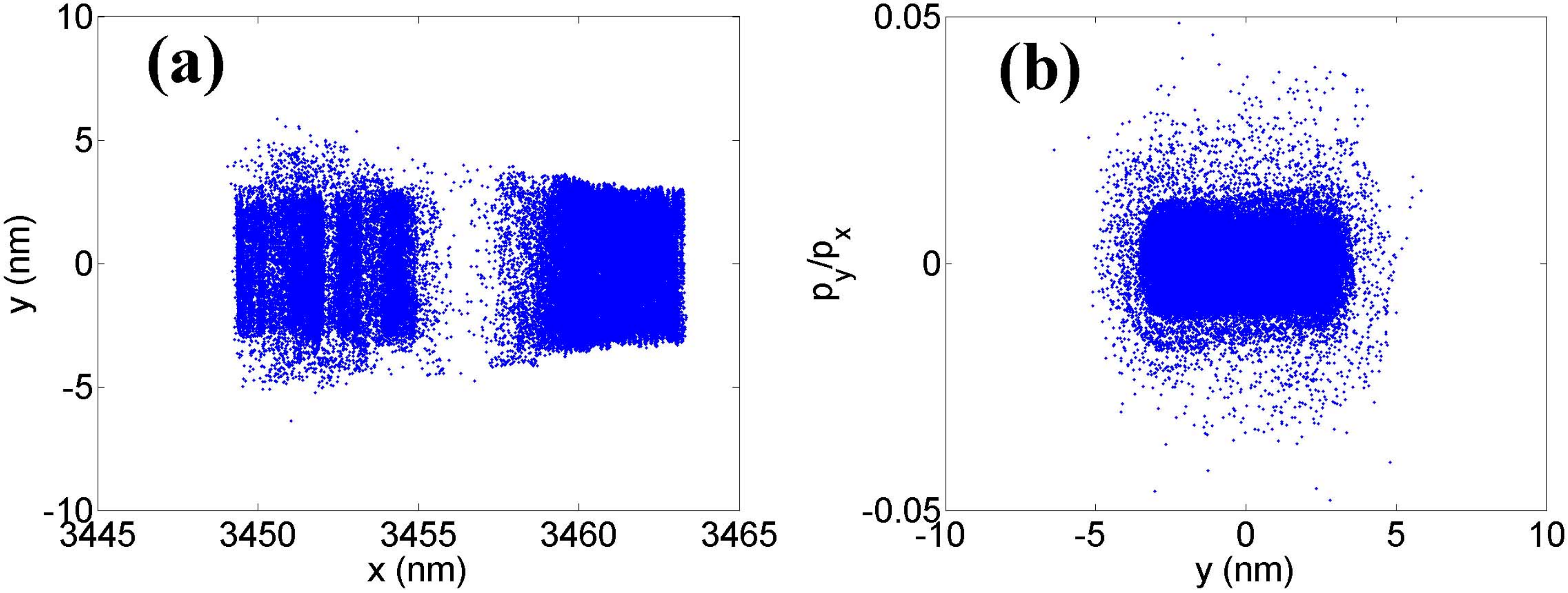


(a)(b) Photon energy distributions and (c)(d) photon energy spectrum in the (a)(c)X-ray driven case and (b)(d) 1eV optical laser driven case in a tube.

Beam emittance reduction

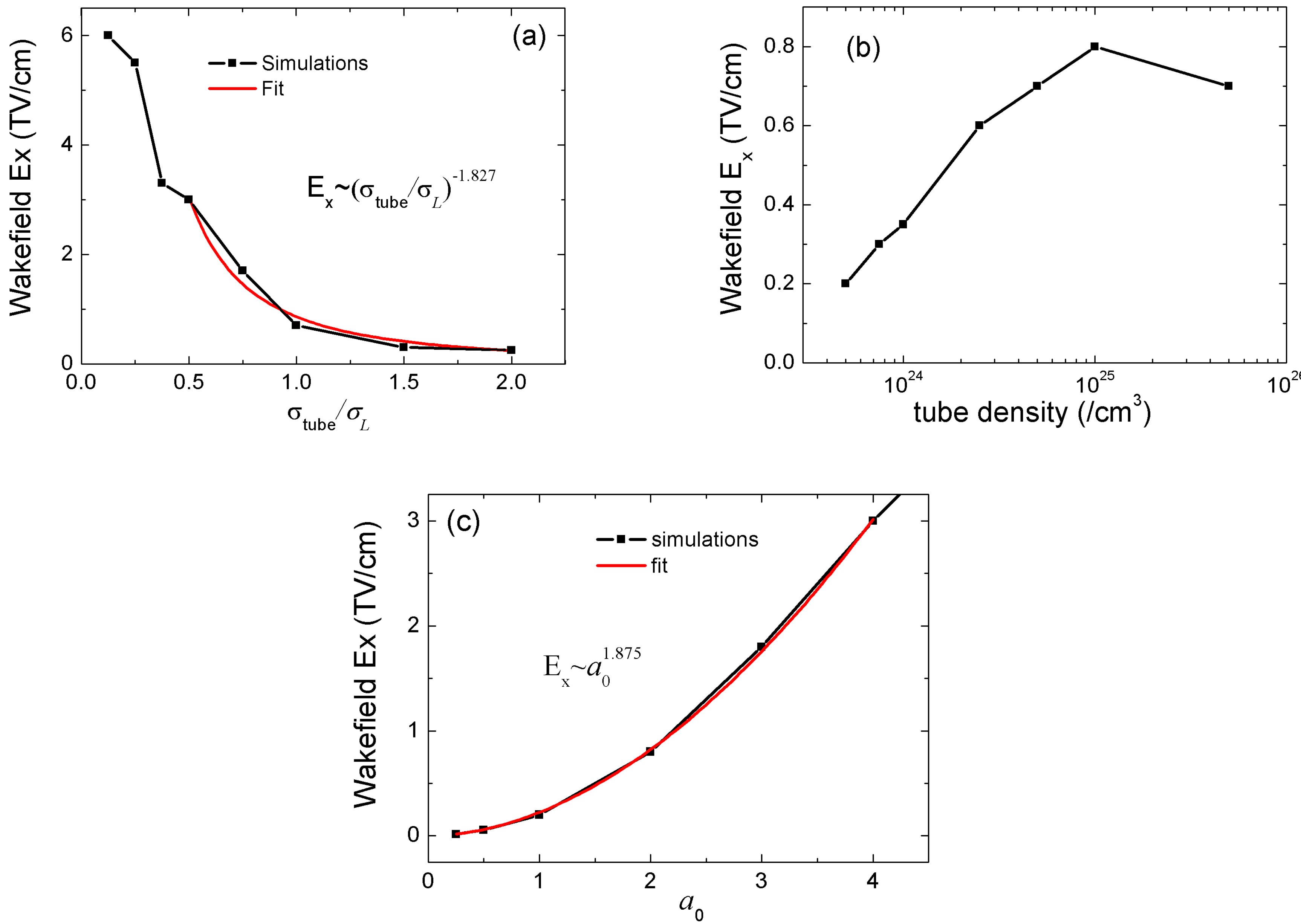
X-ray laser driven wakefield

emittance reduction (much smaller transverse dimension)

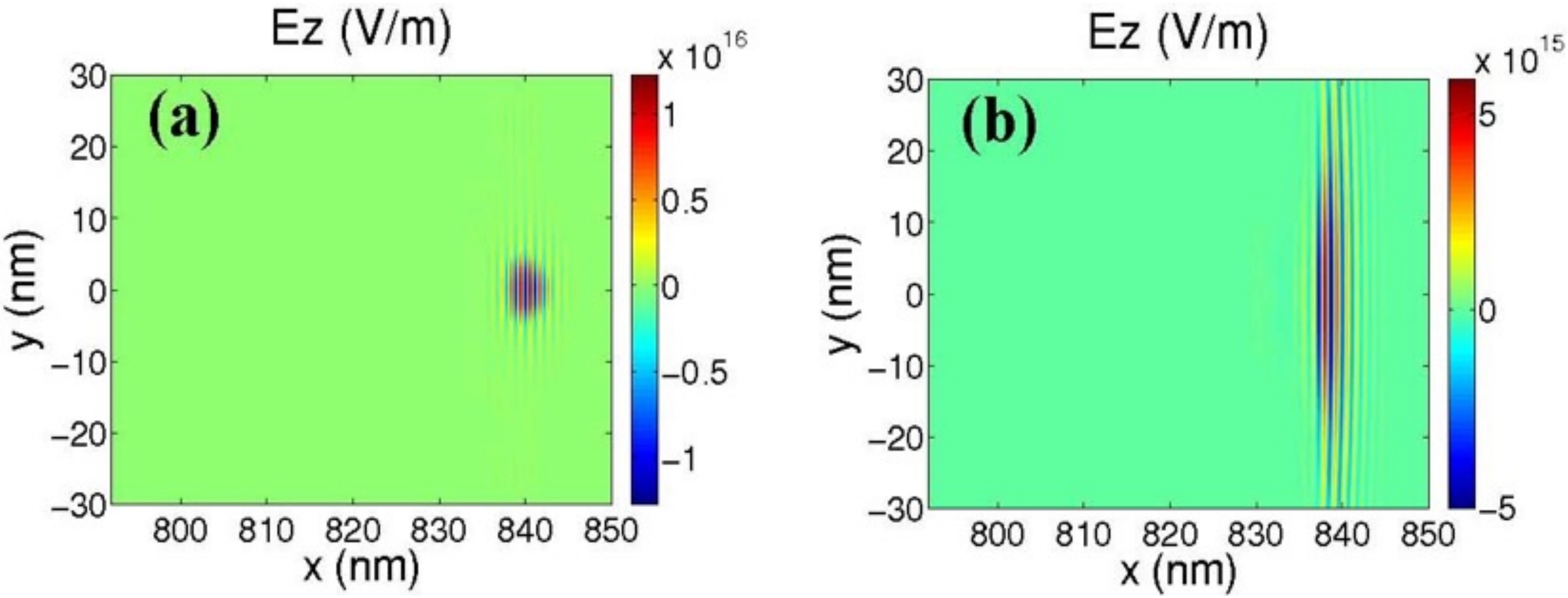


(a) The space distribution (x, y) and (b) the transverse phase space (y, p_y/p_x)

Wakefield strength: tube size, wall density, laser intensity



Nanotube ←→ no hole

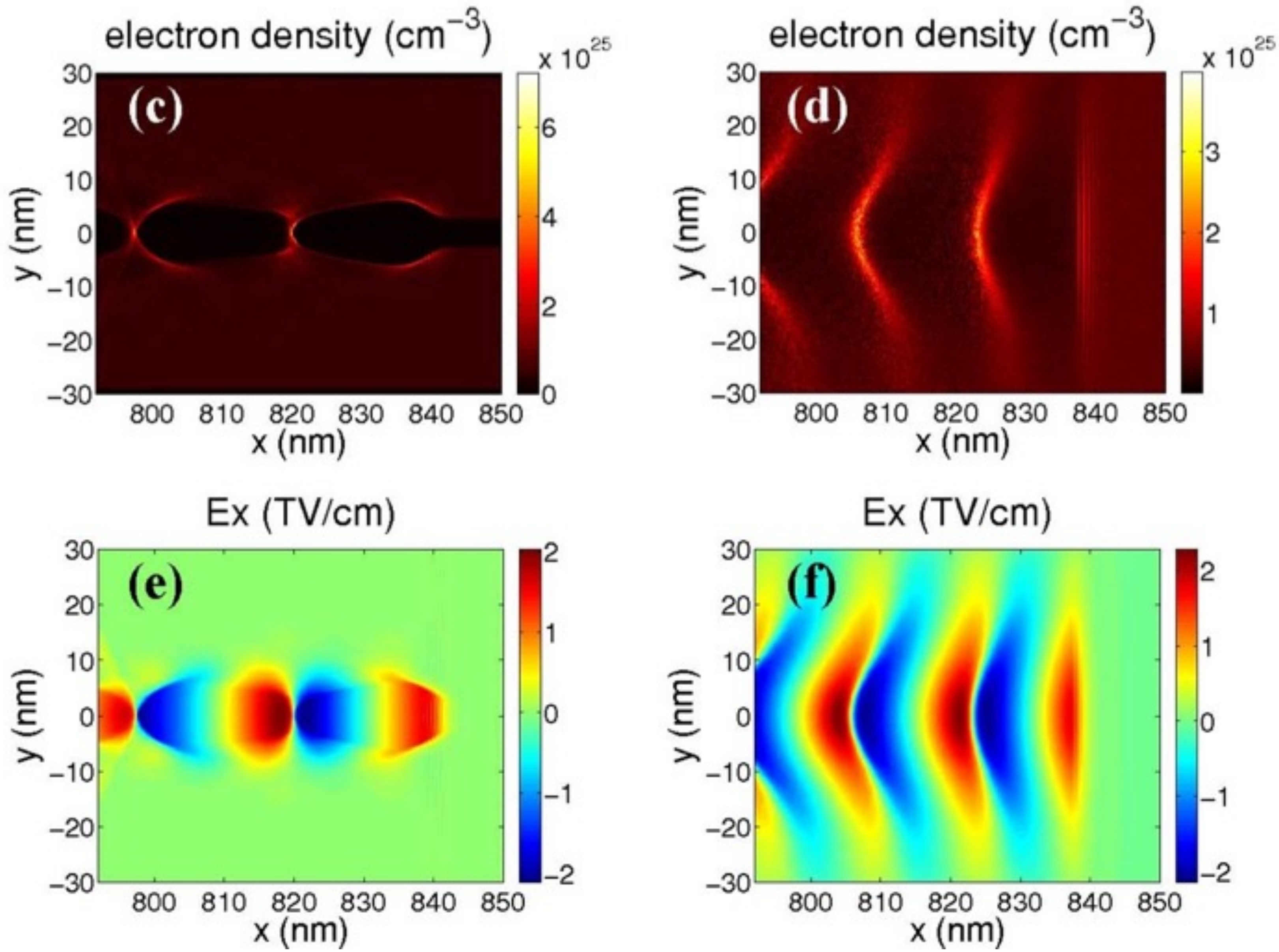


Nanotube (5 nm radius)

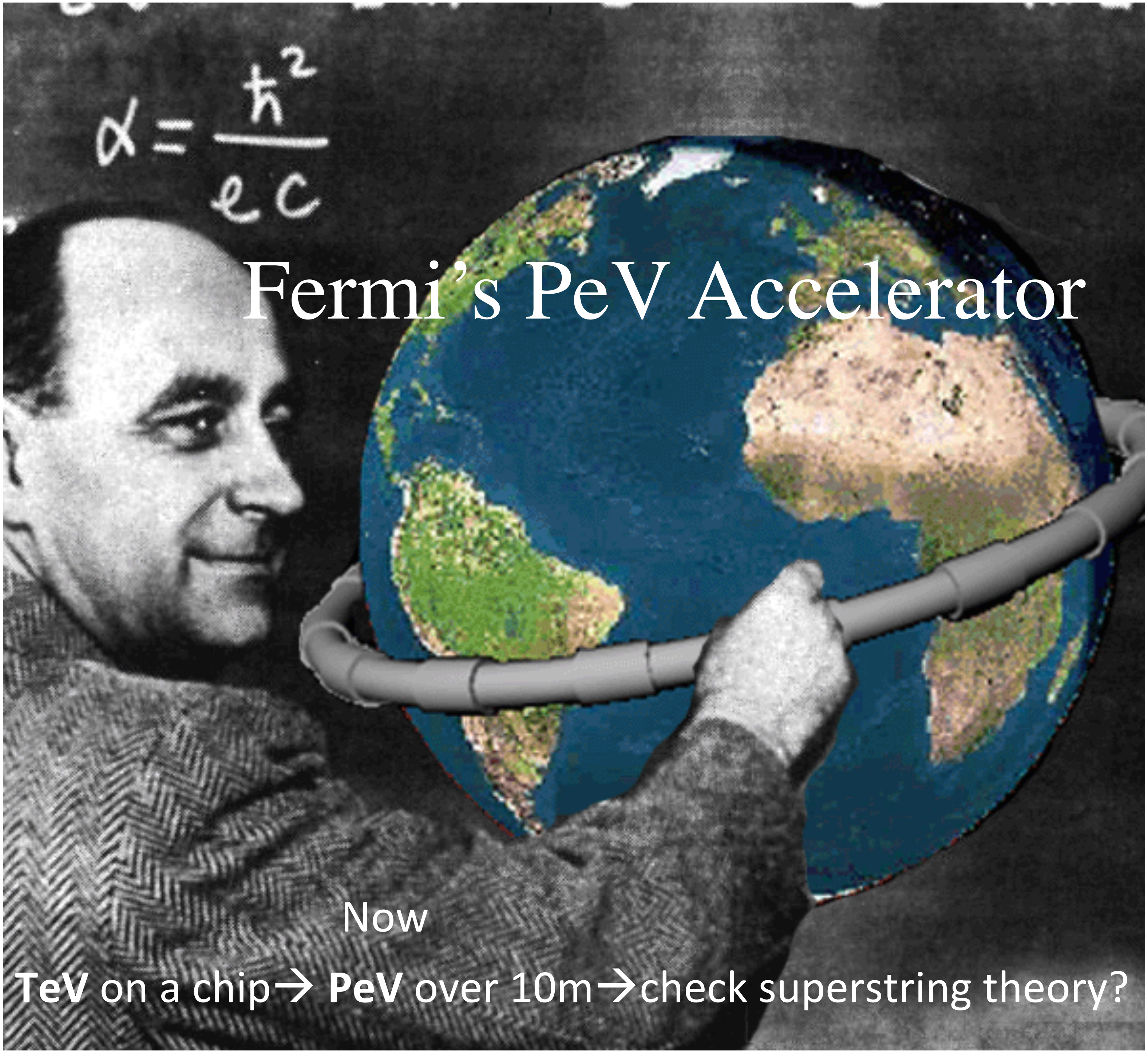
No nanotube

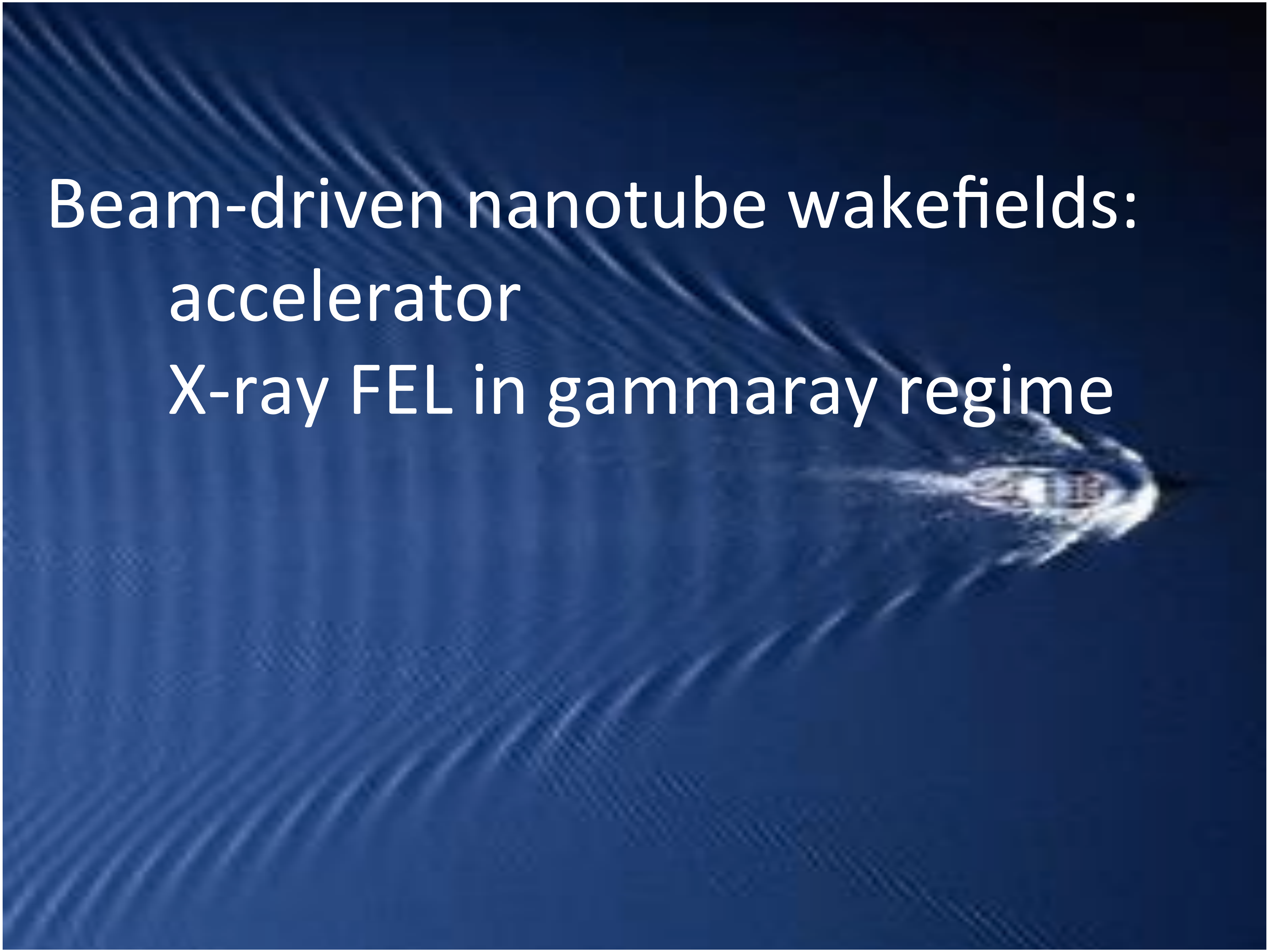
Zhang X, Tajima T, Farinella et al., PRAB. 2016

Nanotube ←→ No tube

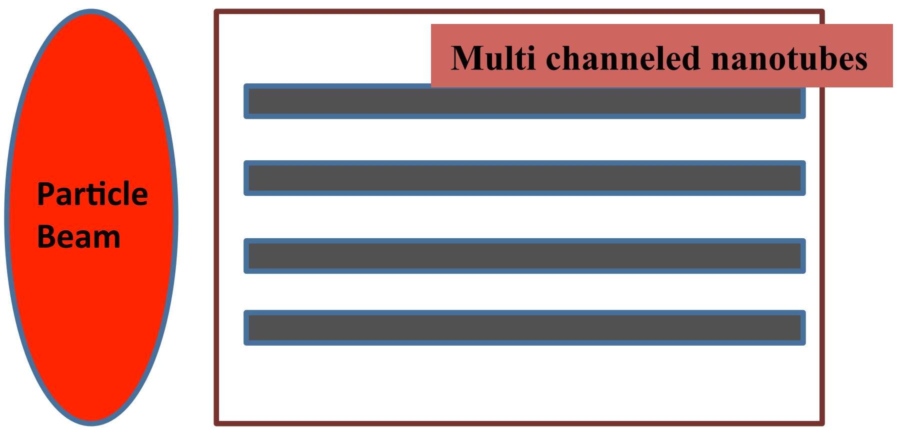


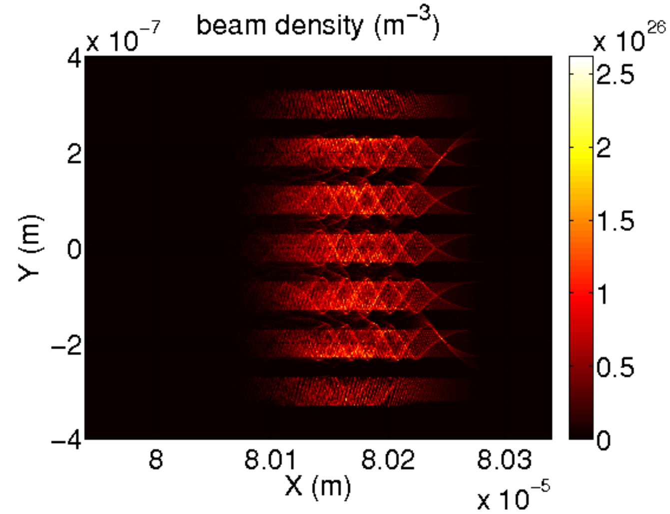
Zhang X, 2016


$\alpha = \frac{\hbar^2}{ec}$
Fermi's PeV Accelerator
Now
TeV on a chip→ **PeV** over 10m→check superstring theory?

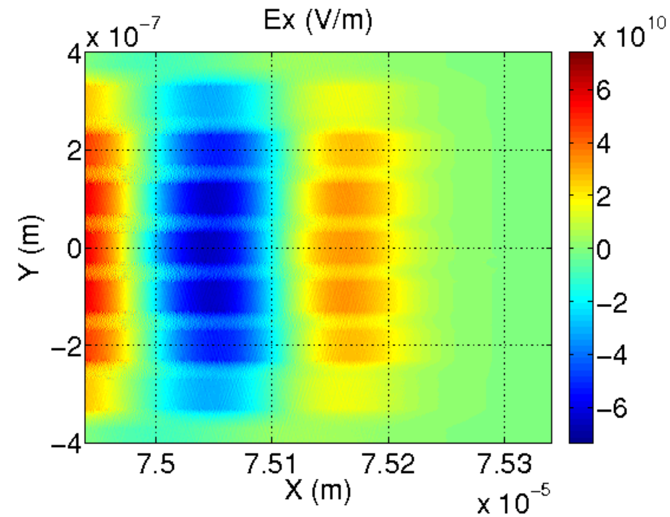

Beam-driven nanotube wakefields:
accelerator
X-ray FEL in gammaray regime

E-Beam driven case





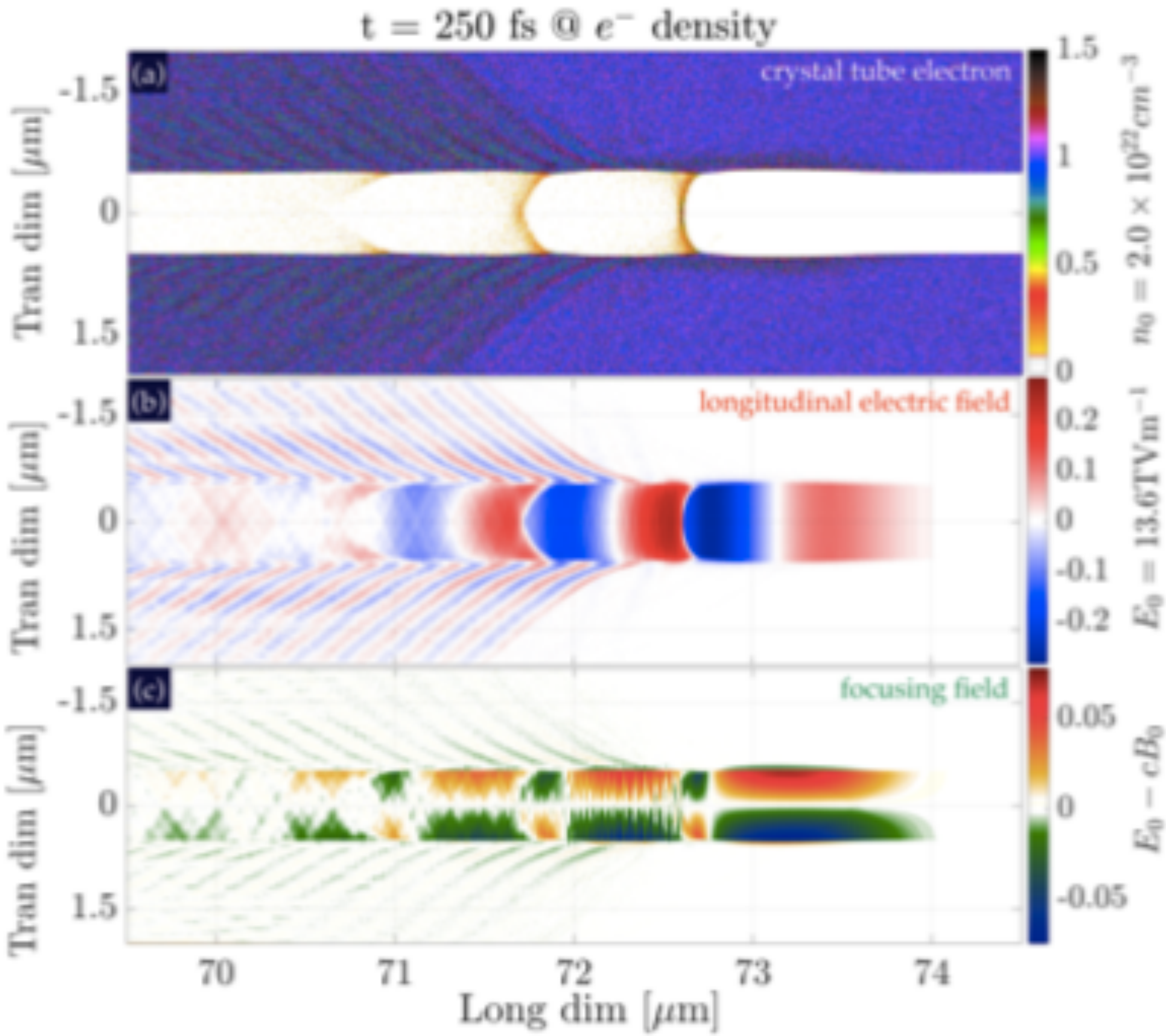
Beams in the tube



(A. Sahai, 2020)

Beam-driven wakefield

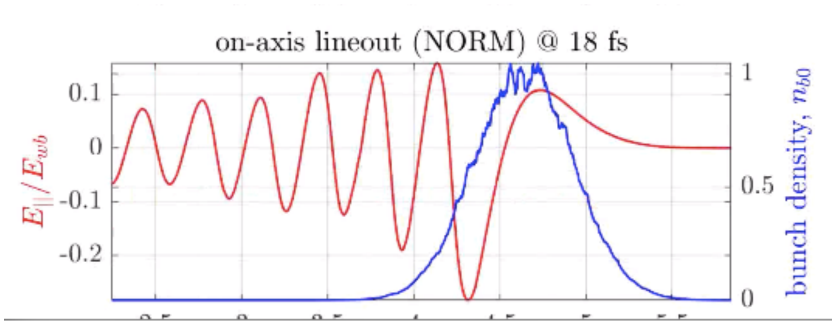
E-beam driven wakefield in nanotube

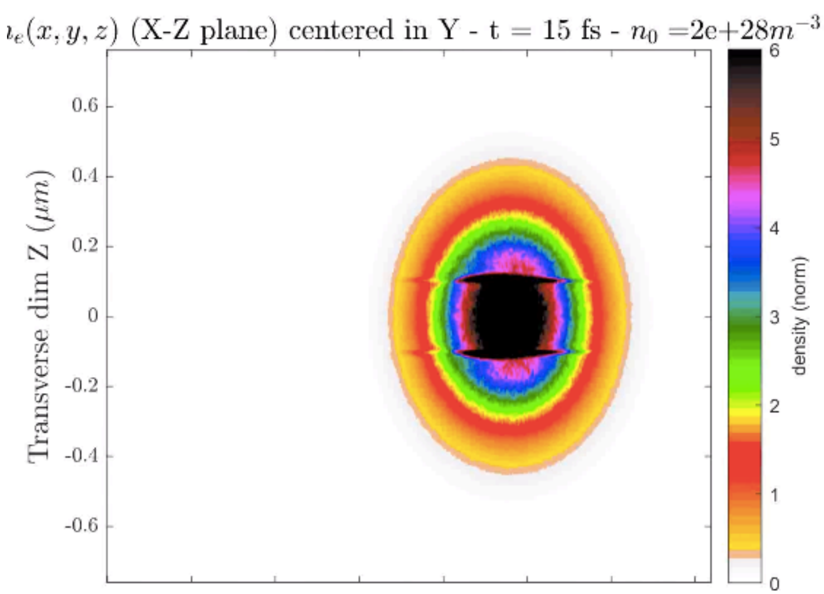


A. Sahai, (2020) supported by U. Colorado at Denver, Boulder RMACC

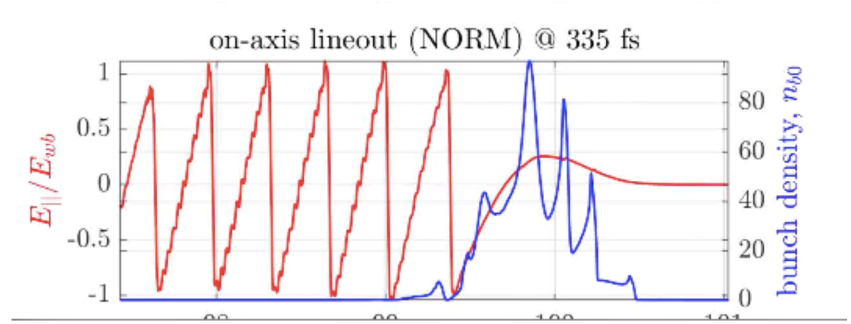
Strong self-focus and self-modulation of electron beam in **nanotube**

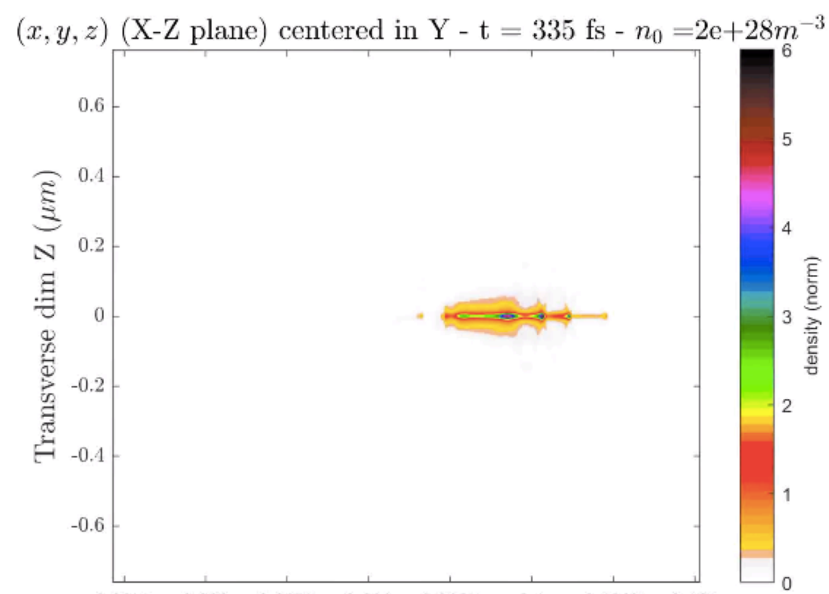
early





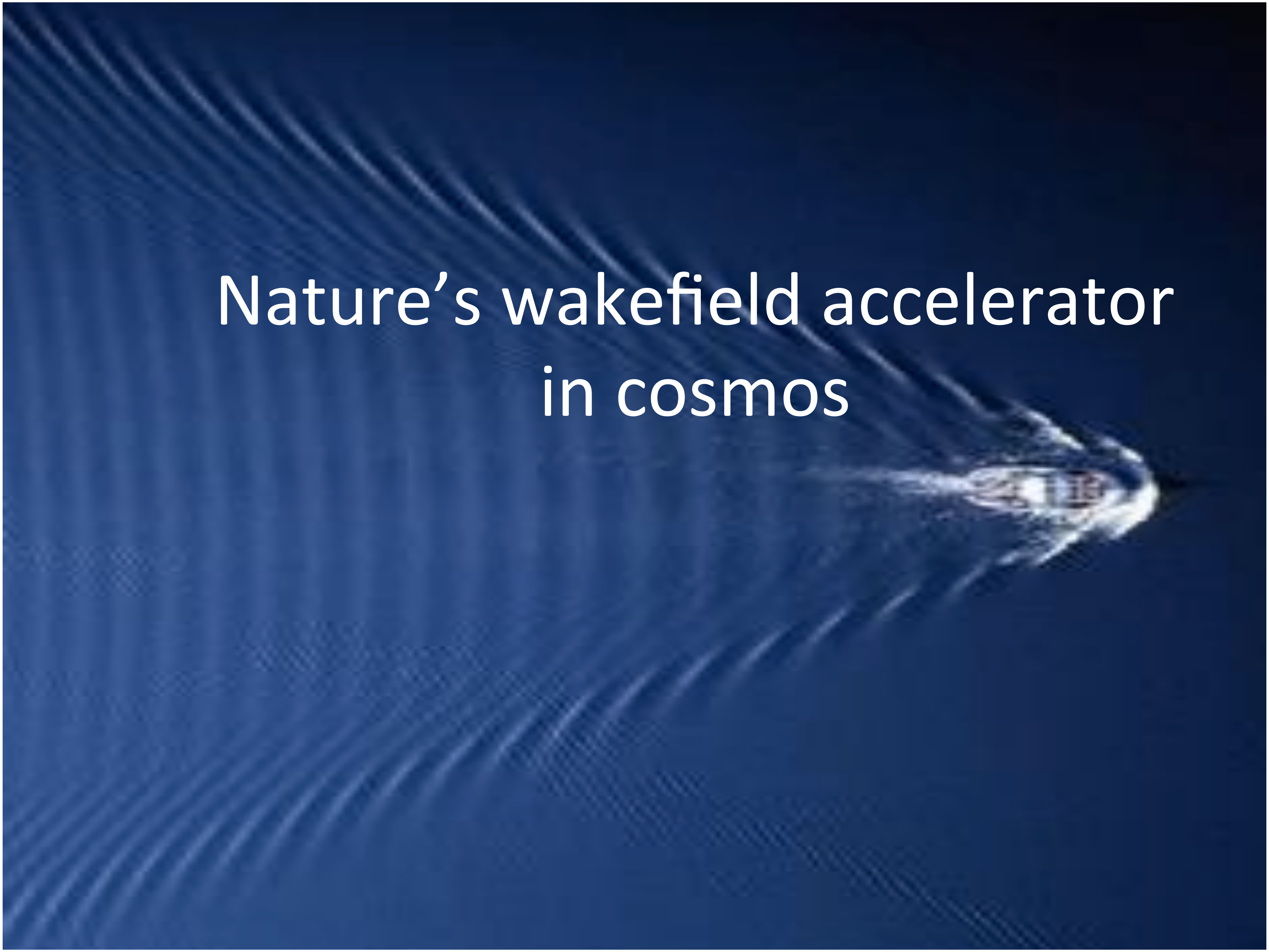
later





Highly compressed

A. Sahai, 2020 (supported by UC Denver, Boulder RMACC)


Nature’s wakefield accelerator
in cosmos

Ultrahigh Energy Cosmic Rays (UHECR)

<u>Fermi mechanism</u> runs out of steam

beyond 10^{19} eV

due to *synchrotron radiation*

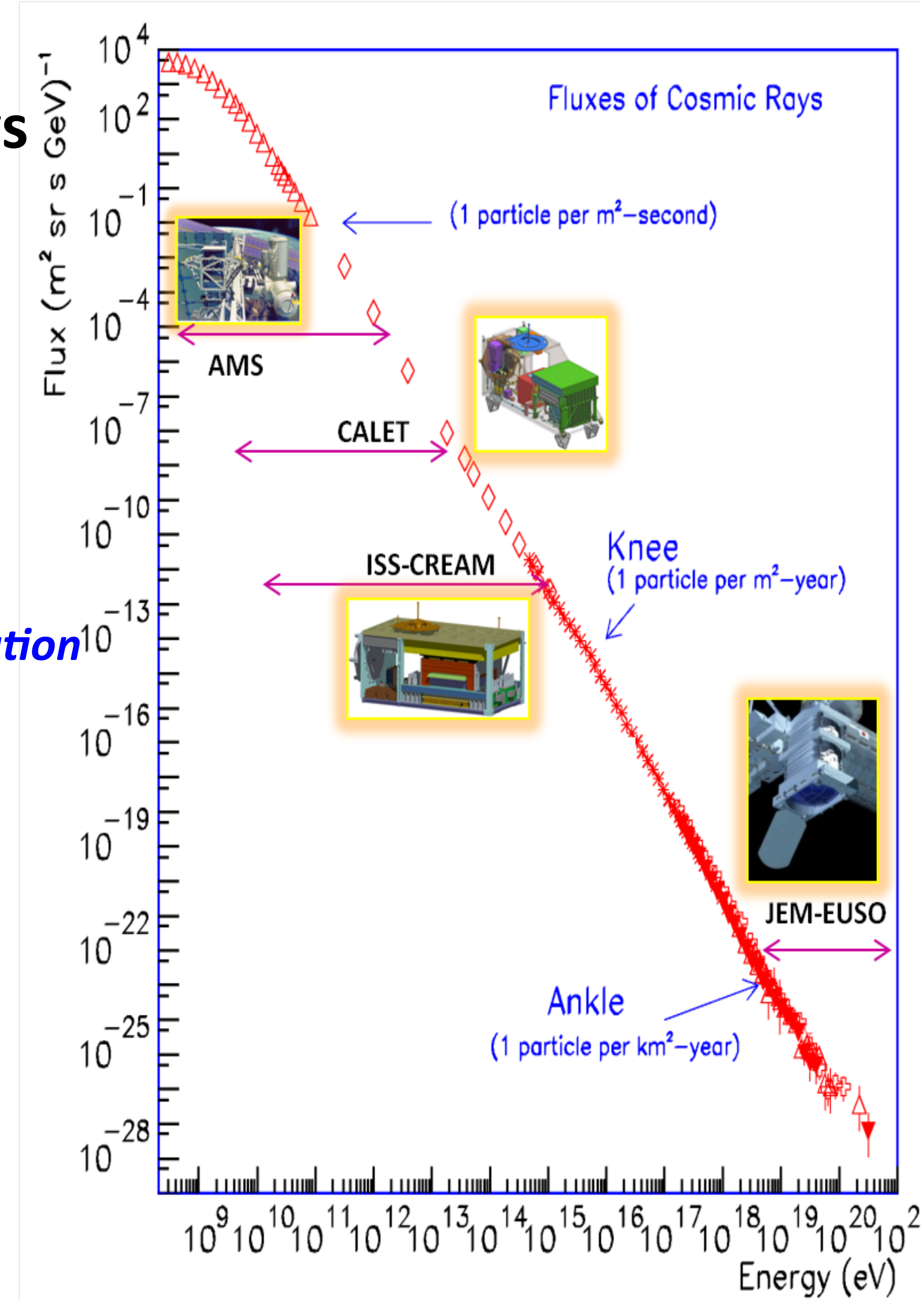
<u>Wakefield acceleration</u>

comes in rescue

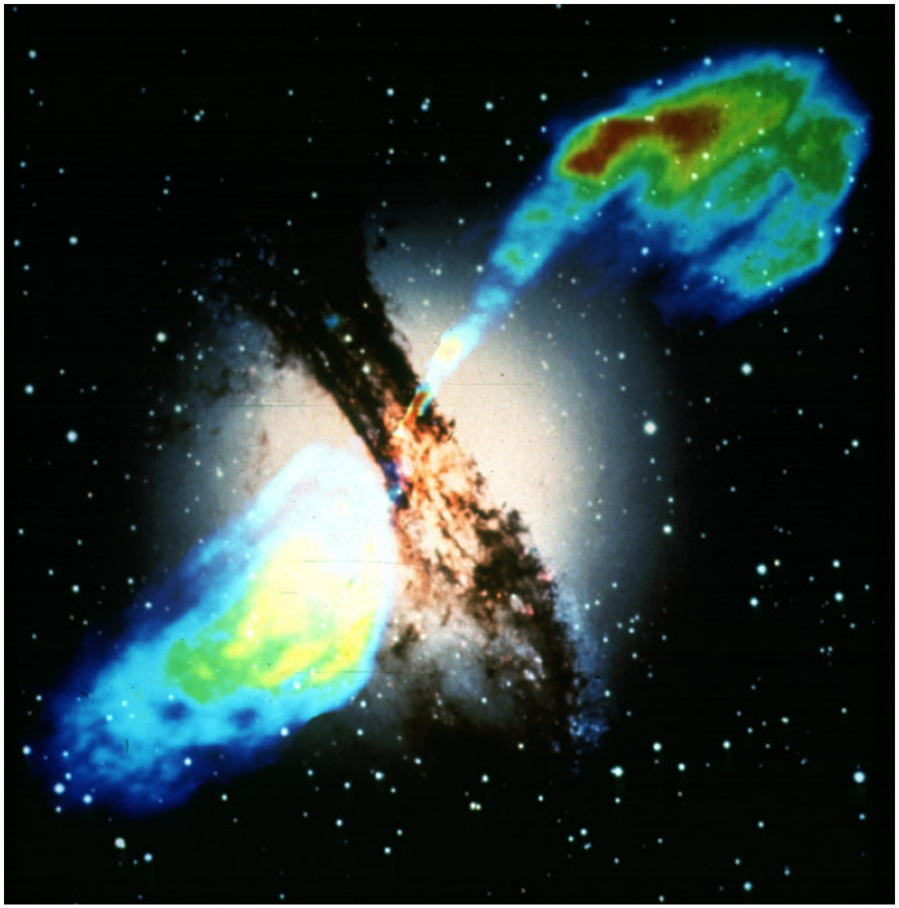
prompt, intense, *linear acceleration*

small synchrotron radiation

radiation damping effects?



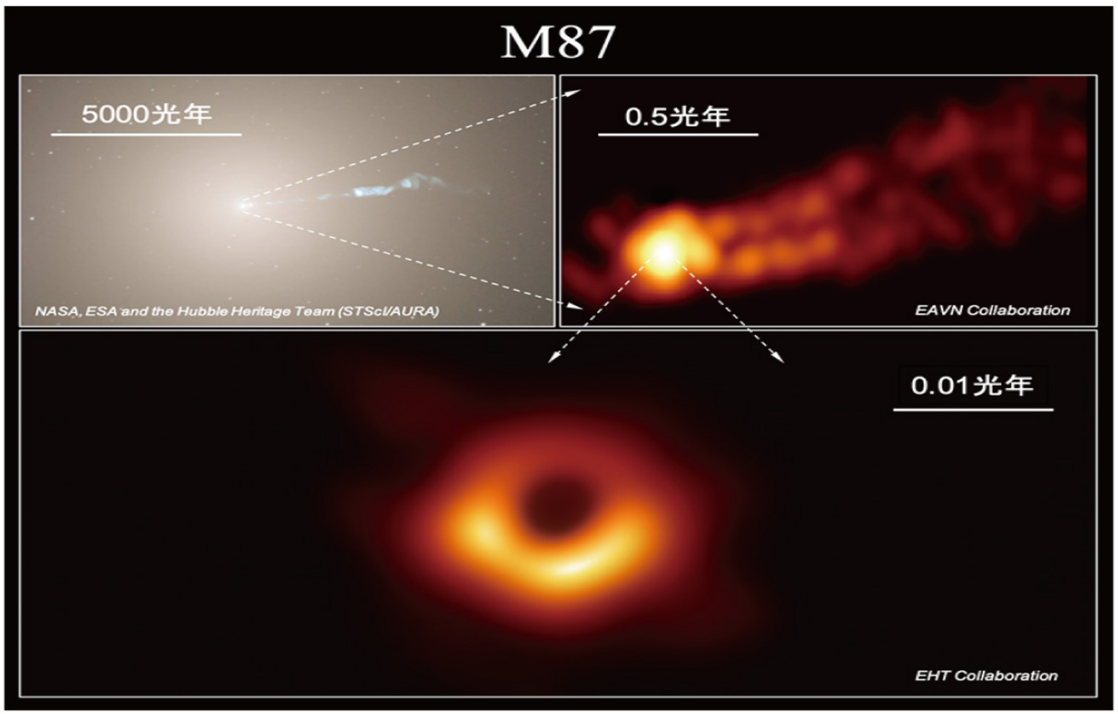
Cen A



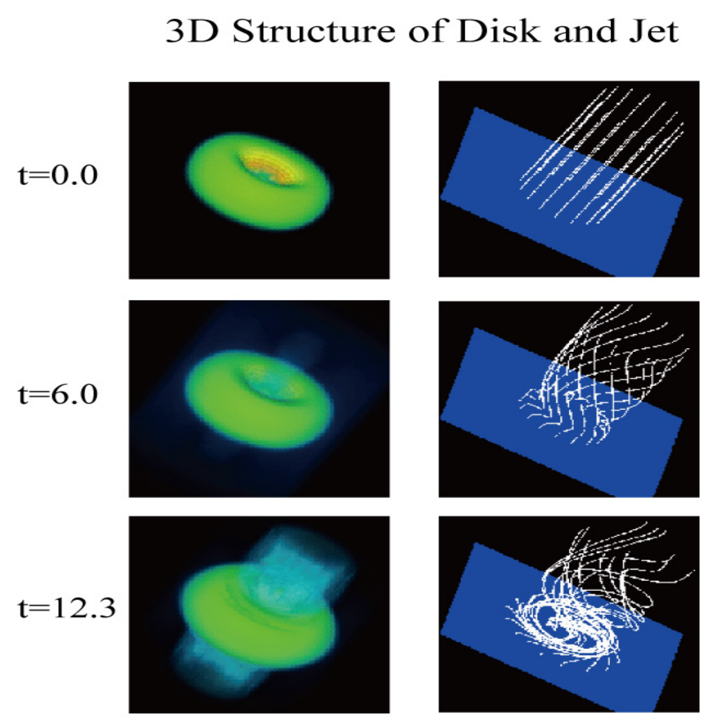
- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets

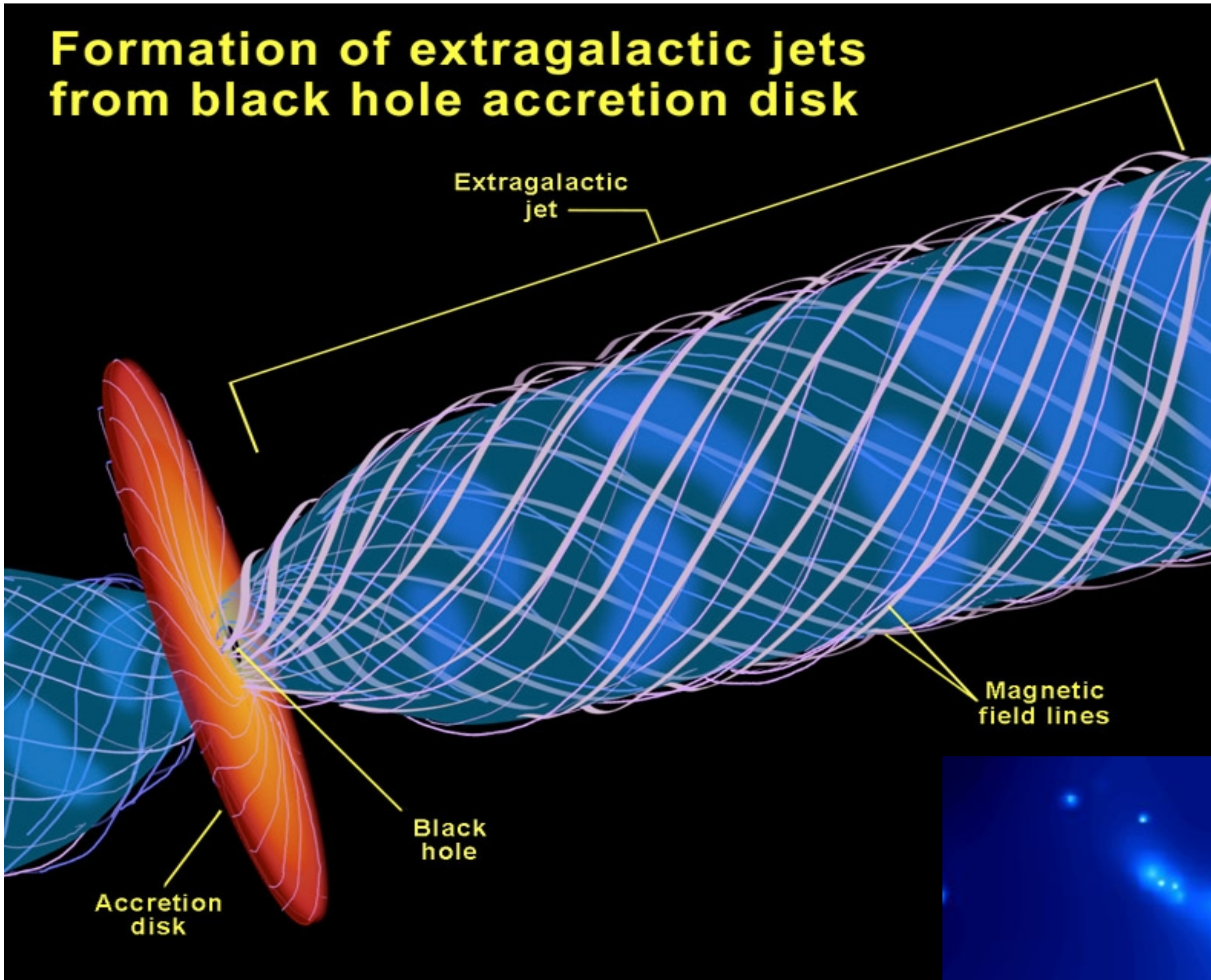
Discovery of Blackhole and Prediction

M87 blackhole: by Event Horizon Telescope (2019)



Prediction: Tajima and Shibata "Plasma Astrophysics" (1997)

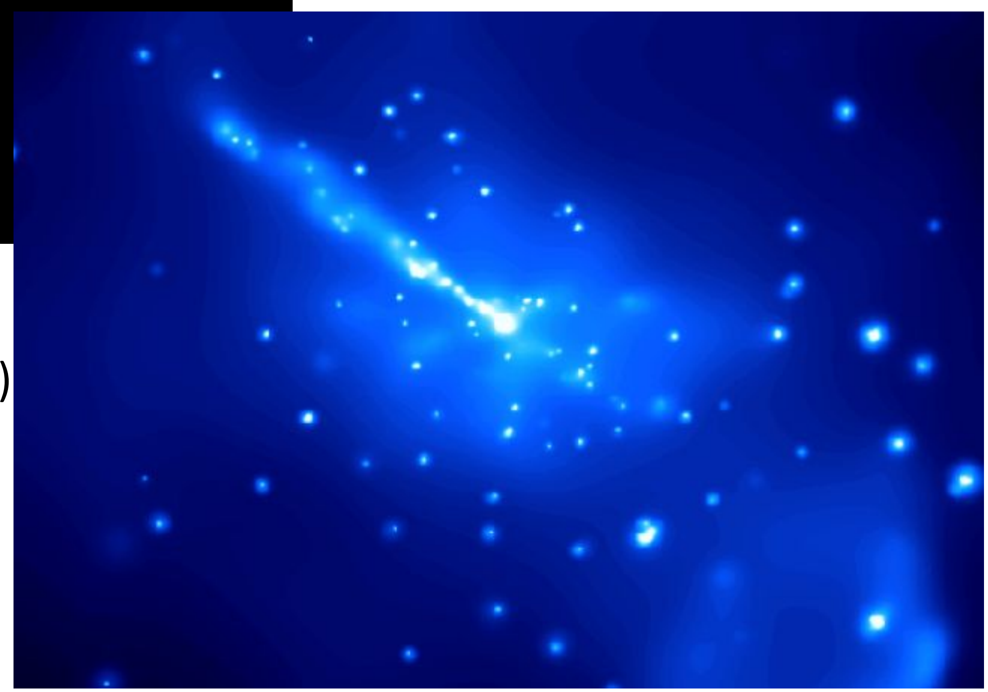




Fermi's '**Stochastic Acceleration**'
(large synchrotron radiation loss)

↓

Coherent wakefield acceleration
(no limitation of the energy)



Nature's LWFA : Blazar jets

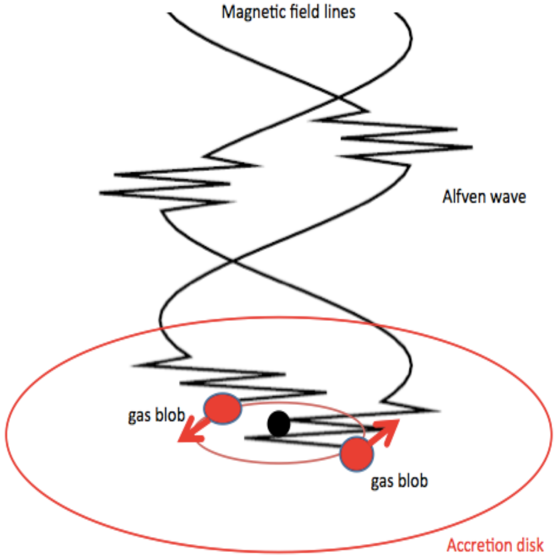
extreme high energy cosmic rays (~10^{21} eV)

episodic γ-ray bursts observed

consistent with LWFA theory

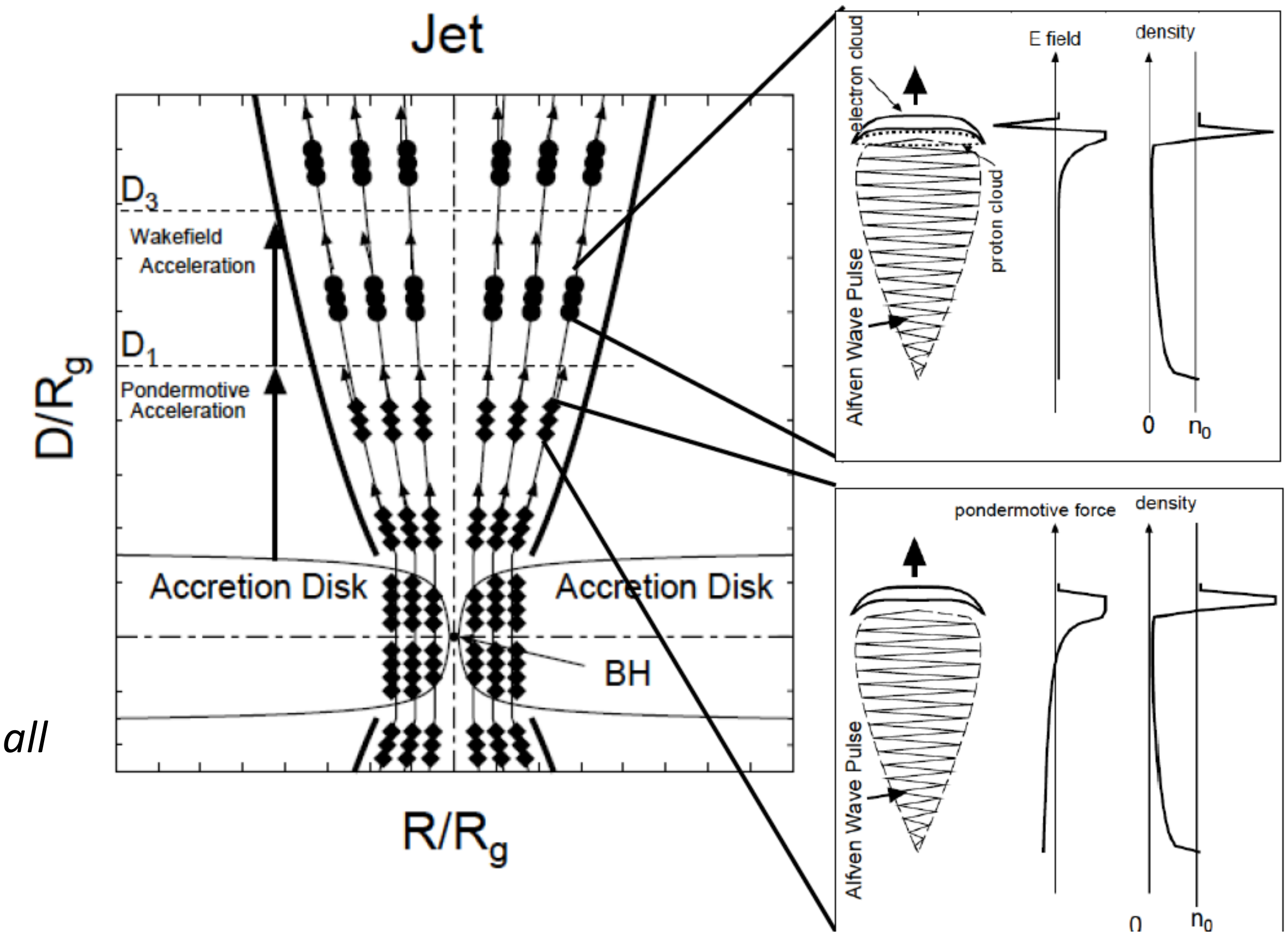
Ebisuzaki-Tajima (2014)

Astrophysical wakefield acceleration:
Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays ($a_0 \sim 10^6$ - 10^{10}, large spatial scale)



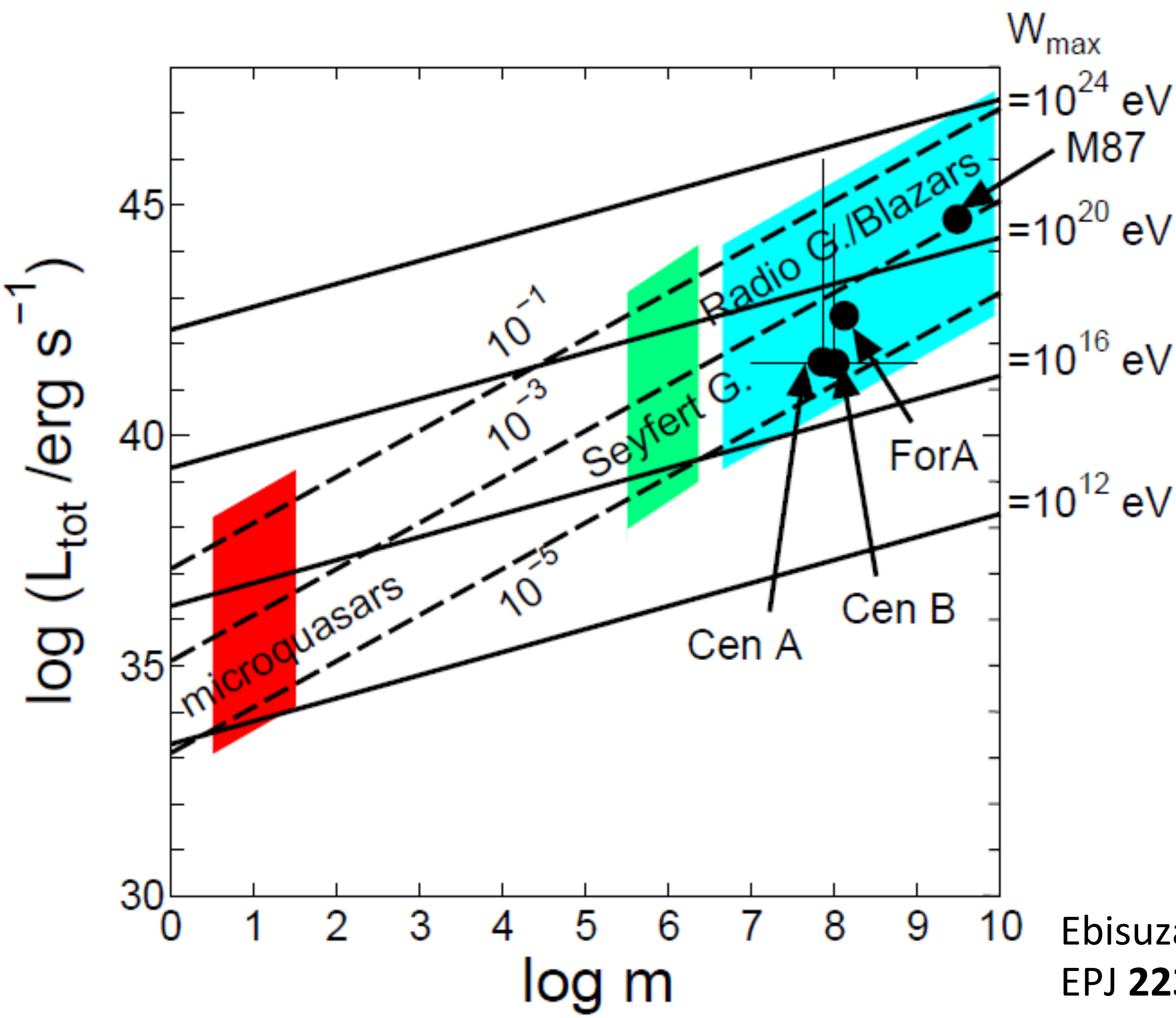
$a_0 = eE_0 / mc\omega_0 >> 1$

E_0: modest
ω_0: extremely small



Ebisuzaki and Tajima, Astropart. Phys.(2014)

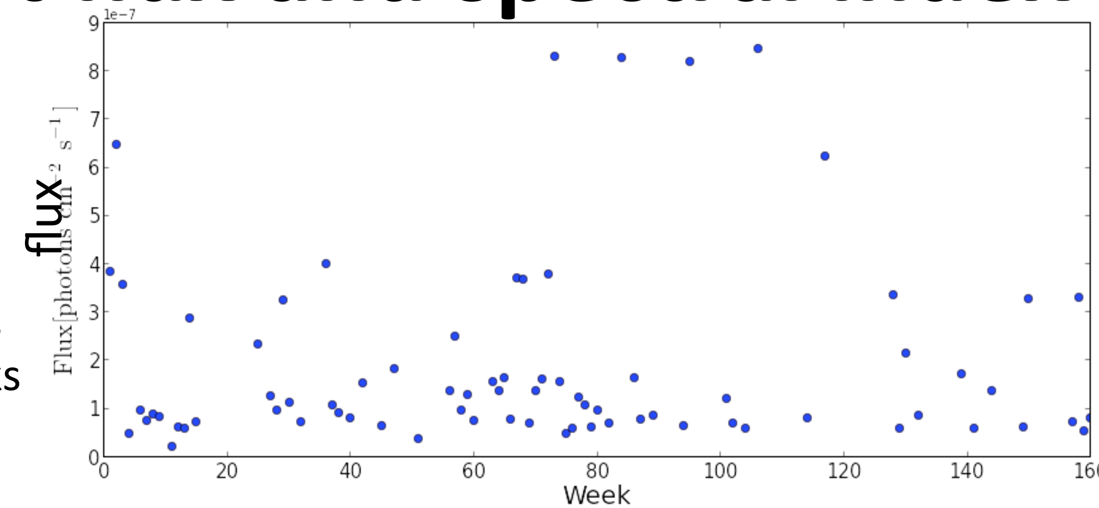
Comic ray acceleration and γ-ray emission: Summary



Ebisuzaki, Tajima
EPJ **223**, 1113(2014)

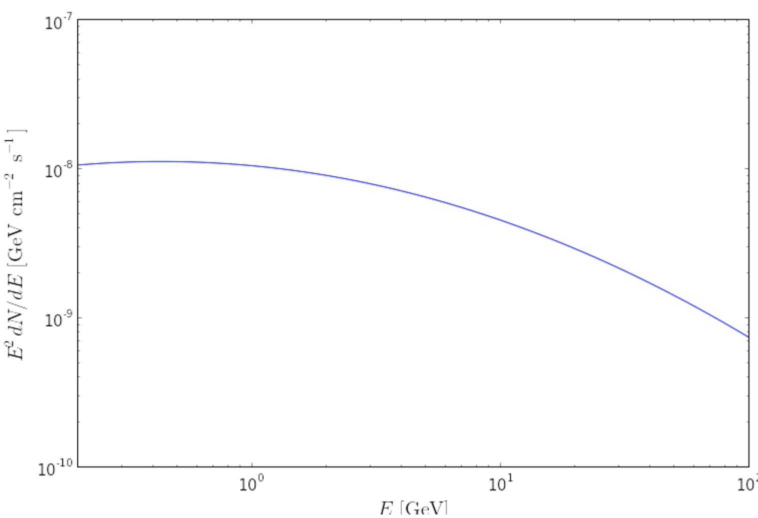
Blazar shows anti-correlation between γ burst flux and spectral index

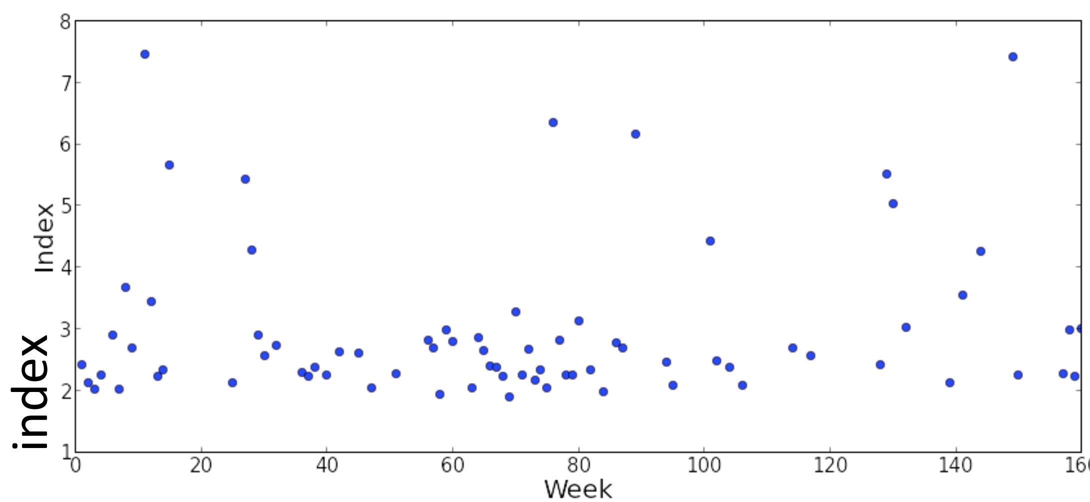
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



Rise time < week (less than a unit),
Period between bursts ~> 10 weeks
Spectral index => 2
(~ Ebisuzaki/Tajima theory)

→ all quantitatively consistent with Wakefield theory





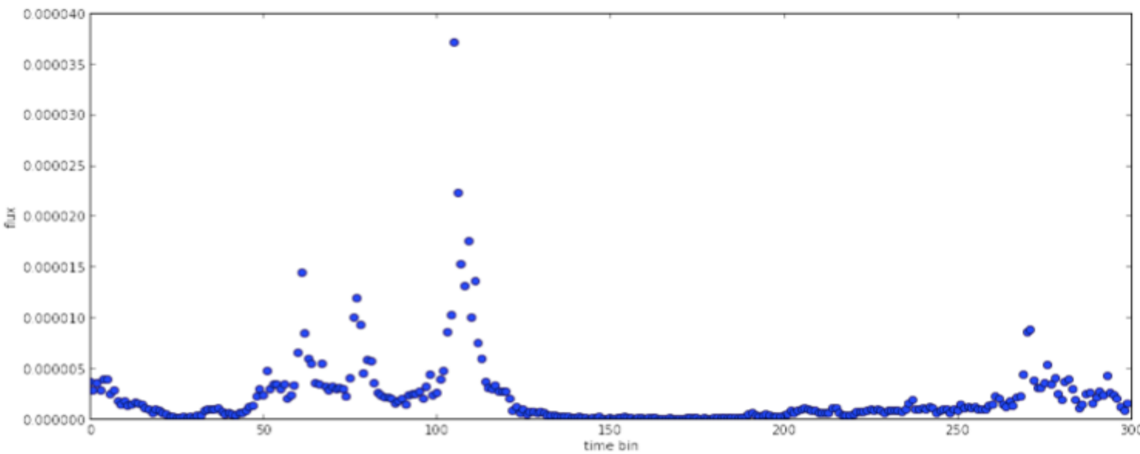
time

N. Canac, K. Abazajian (2019)

Again, Anti-correlation even in a bigger blazar

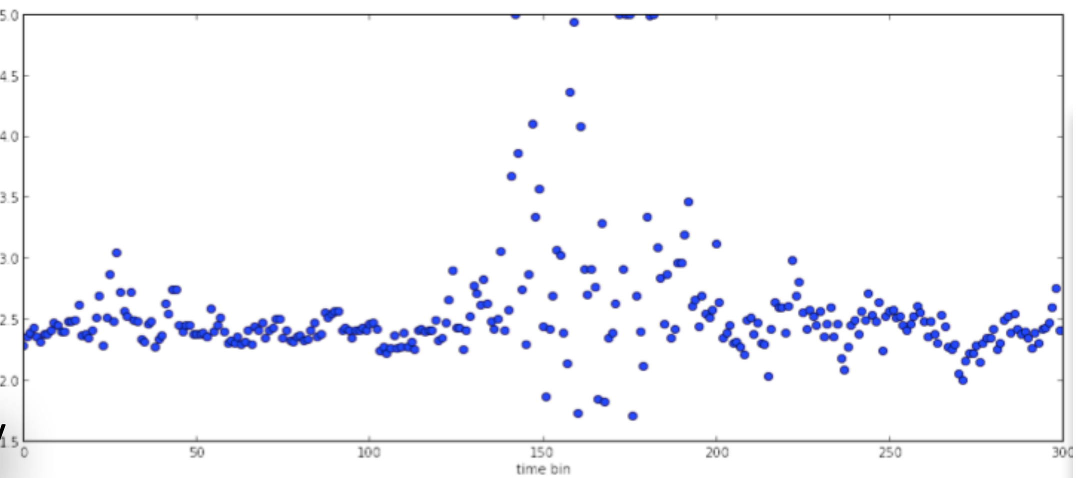
Blazar: 3C454.3

M ~ 10^9 M_{Sun}



Same anti-correlation as
AO0235+164

The rise time and burst periods
a lot longer (by an order of
magnitude)



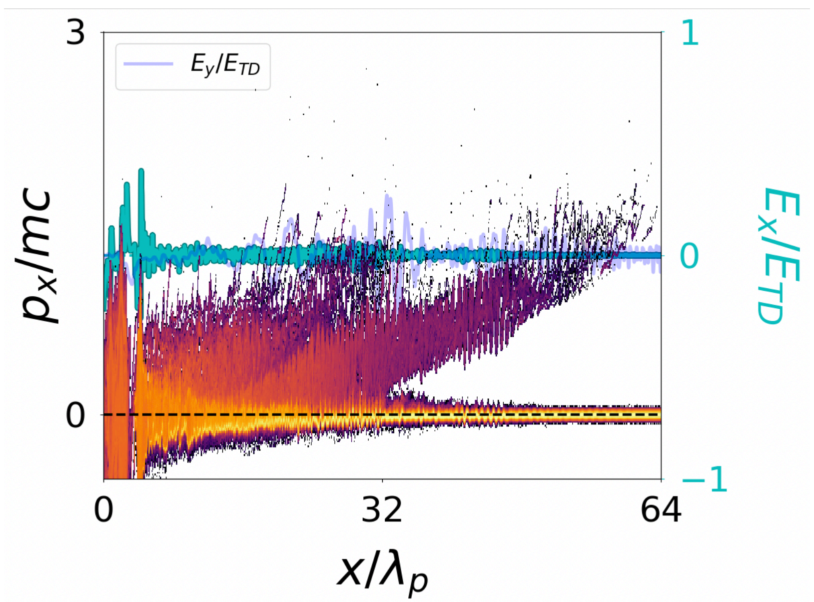
Quantitative agreement and
<u>correct scaling</u> with Blazar mass
with (broader sense of) Wakefield theory
(Ebisuzaki/Tajima)
period ~ *M* ; luminosity ~*M*

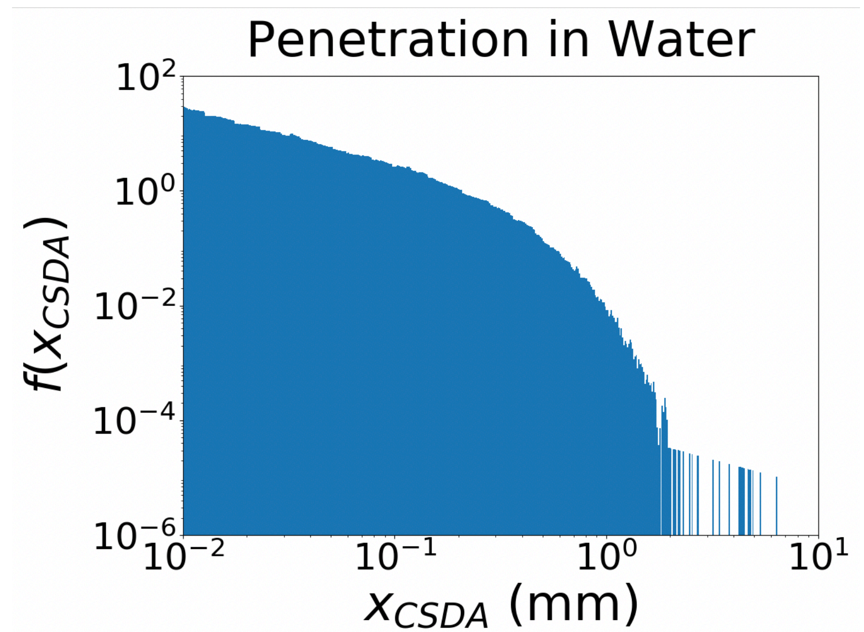
N. Canac, K. Abazajian (2019)

Nanotube cancer therapy

High density wakefields for medicine

- **Micron** accelerator (in body?) by optical laser
- **Nanomaterials** target: density ~ 10^{21} cm^{-3}





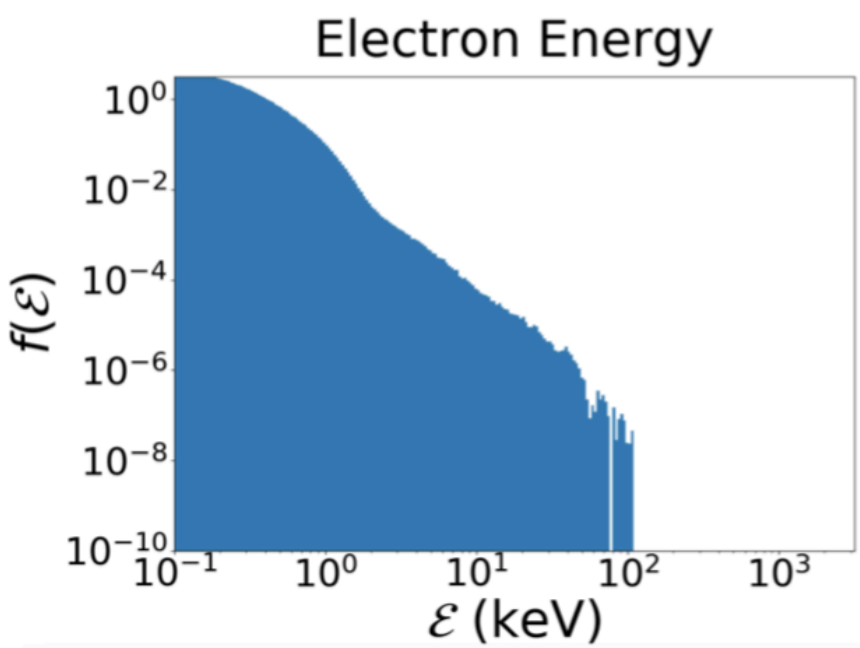
Critical density wakefield acceleration (< MeV) : e.g. skin cancer

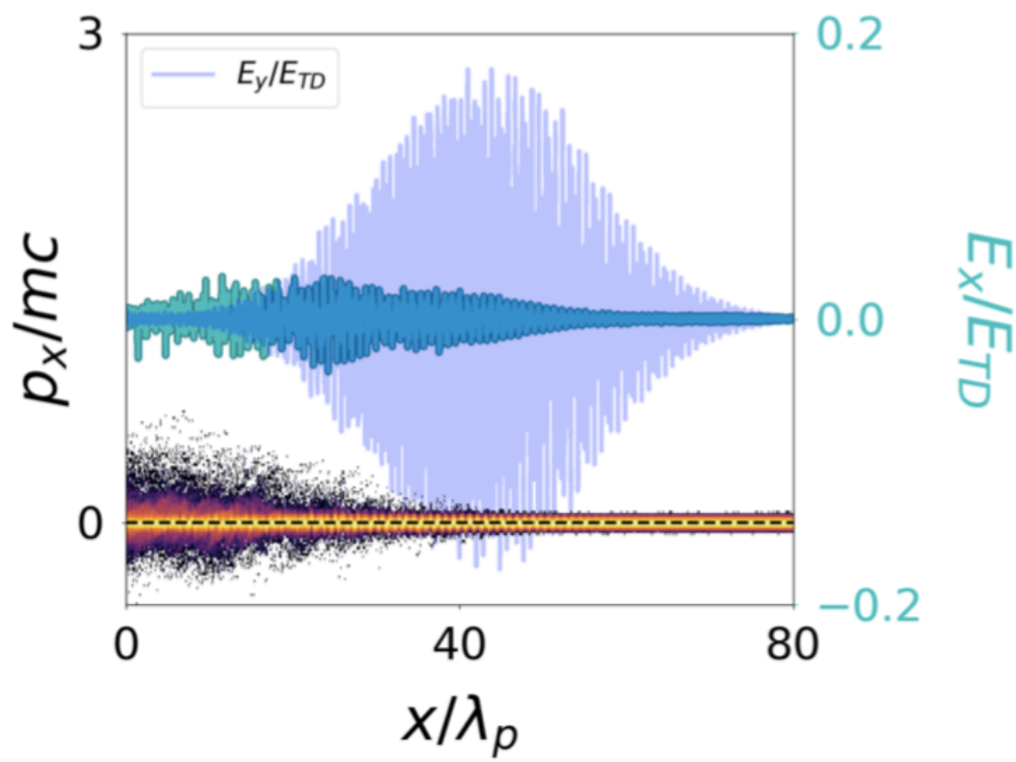
Nicks et al. (2019)

Beatwave wakefield acceleration of electron acceleration in low intensity laser

- Two laser pulses, each @ $a_0 = 0.03$
- $a_0 = 0.03 \rightarrow 1.2 \times 10^{15}\ \mathrm{W/cm^2}$
- Wavelength: $\lambda_0 = 1\ \mu\mathrm{m}$
- $\omega_1 = \omega_0 + \omega_p/2$, $\omega_2 = \omega_0 - \omega_p/2$
- Pulse length: ≈300 fs

← Tajima-Dawson (1979)





Very low intensity laser with **nanotubes** → no vacuum necessary

S. Nicks, et al. (2020)

Conclusions

- 1994-LWFA Demonstrated: ultrafast pulses, coherent collective (robust) intense (GeV/cm) accelerators.
- TFC →Single-cycled laser → single-cycled X-ray laser (also high density e-bunch)
- **Wakefield in nanostructure (TeV/cm):**

TeV on a chip accessible*

- Toward PeV (~10-100m)
- Wakefields: Nature's favored acceleration for UHECR, gamma ray bursts from Blazars
- Applications: tiny LWFA radiotherapy of cancer

* Book: "Beam Acceleration in Crystals and Nanostructures" (WSP, 2020)

Recent advancements in generation of intense X-ray laser ultrashort pulses open opportunities for particle acceleration in solid-state plasmas. Wakefield acceleration in crystals or carbon nanotubes shows promise of unmatched ultra-high accelerating gradients and possibility to shape the future of high energy physics colliders. This book summarizes the discussions of the “Workshop on Beam Acceleration in Crystals and Nanostructures” (Fermilab, June 24–25, 2019), presents next steps in theory and modeling and outlines major physics and technology challenges toward proof-of-principle demonstration experiments.

Thank you!

“Accelerator
Unprecedented and huge
Curious baby
Embraced by Mother Mountain
Where’s her beautiful white coat?”
(Toshiki, Geneva, Feb. 13, 2020)

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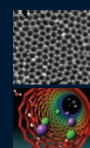
Shiltsev • Tajima



BEAM ACCELERATION IN CRYSTALS AND NANOSTRUCTURES

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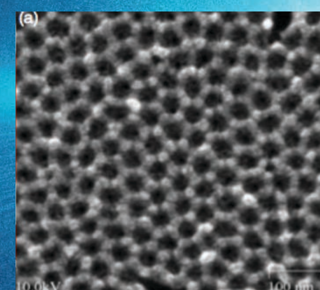

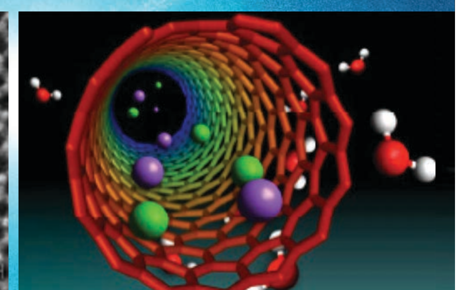

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