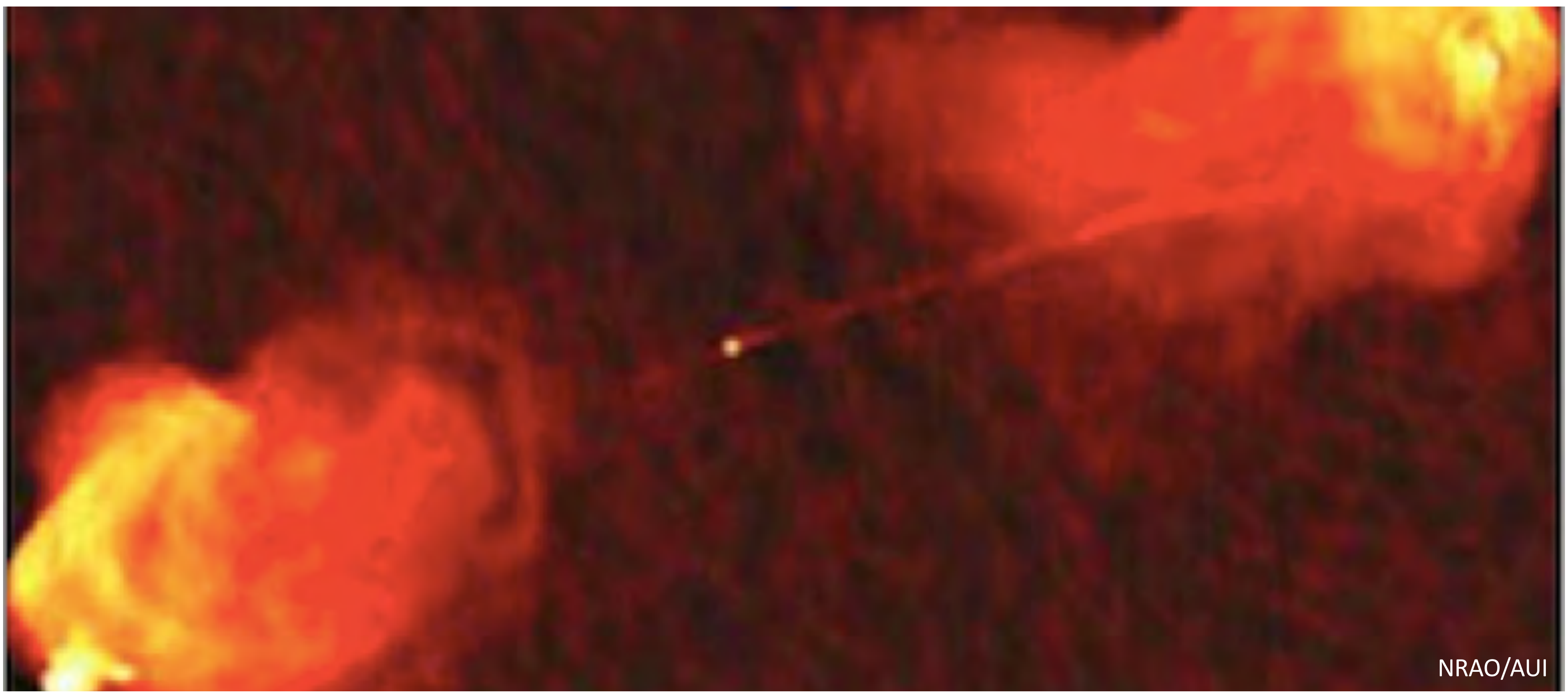
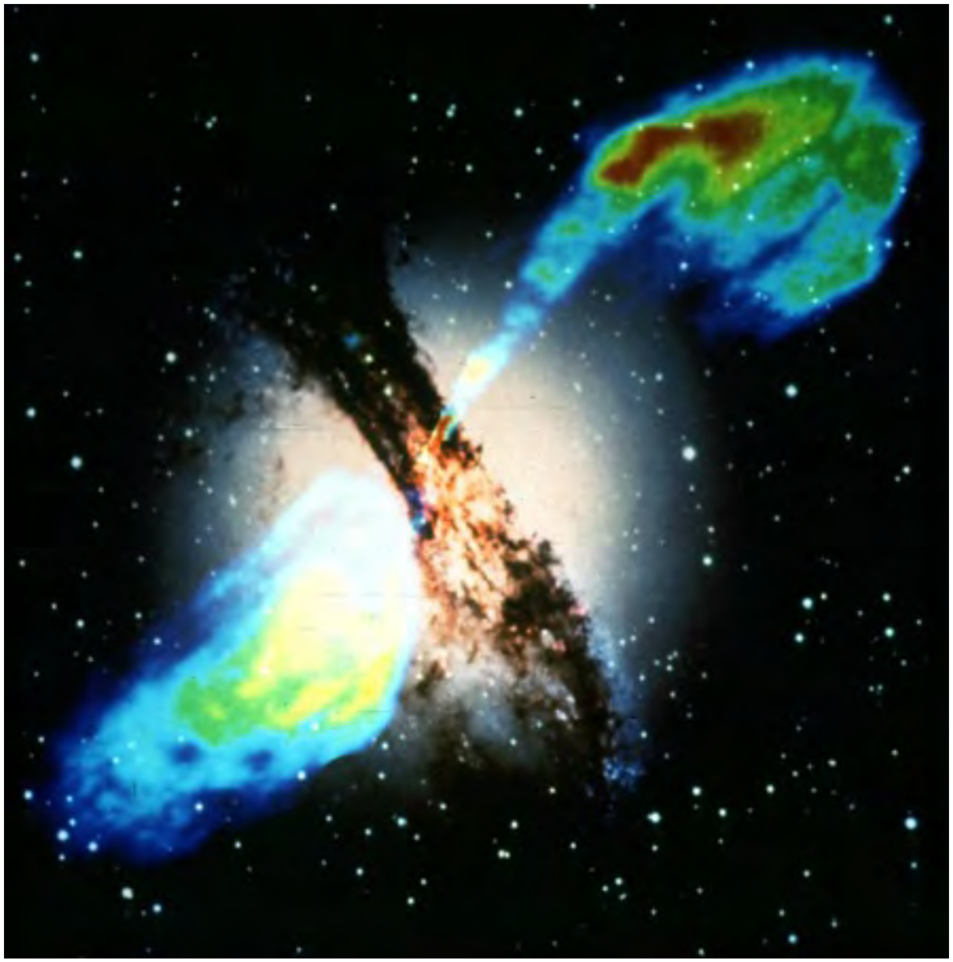
Plasma Accelerator Physics

Toshiki Tajima, Norman Rostoker Chair Professor, UCI

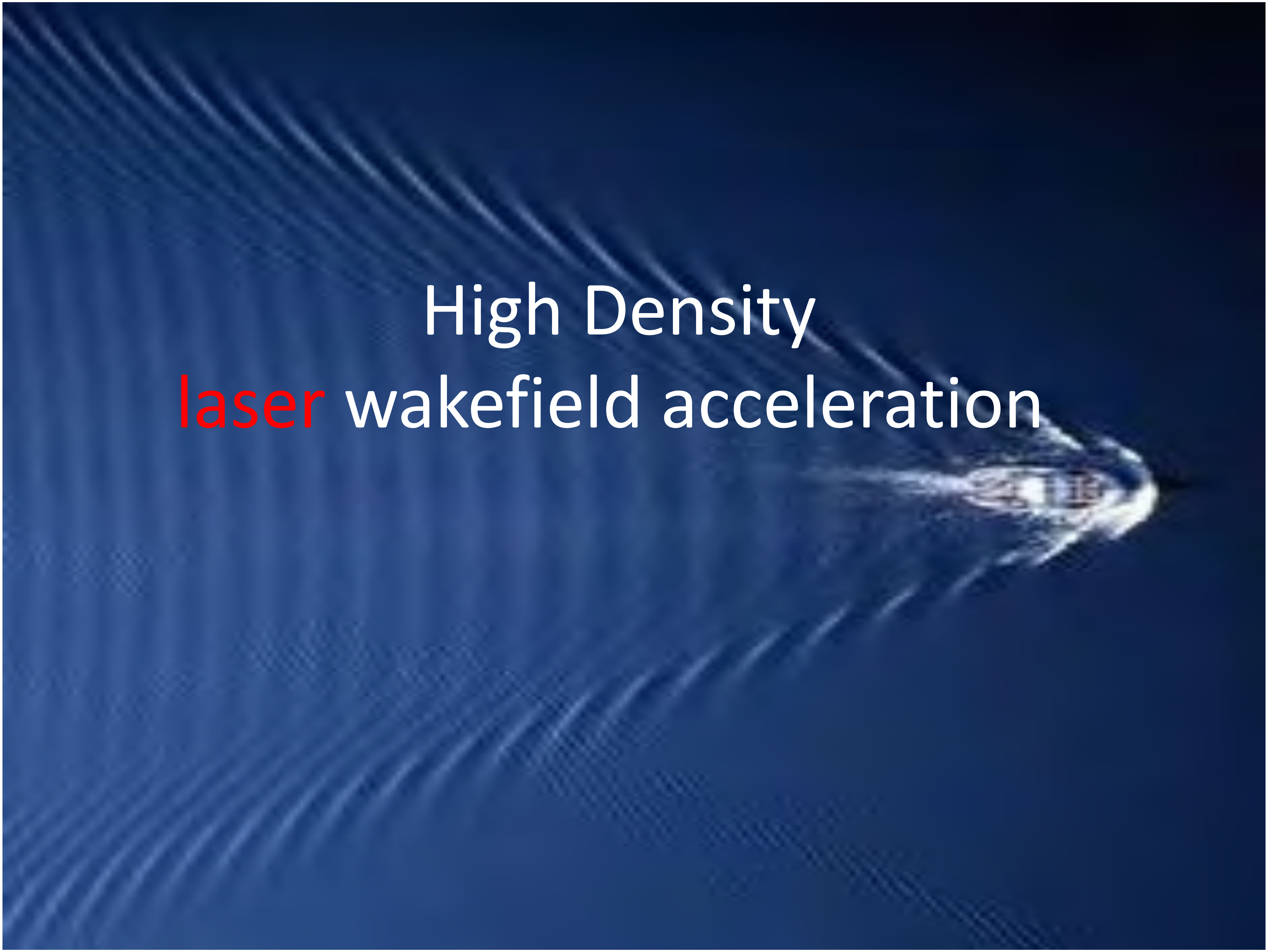
Class 3:PHY249 (2021Fall)



Cen A



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


High Density
laser wakefield acceleration

Exploration of LWFA dependences on a_0, n_e

- Some exploratory attempts in raw theory
- Needs to check by asking the mother nature (or some PIC simulation) → a good test in this Term Project?

High Density LWFA

Trapping width and the phase velocity of plasma wave: v_{tr} ~ *sqrt (E),* v_{ph}

Recall Homework 2

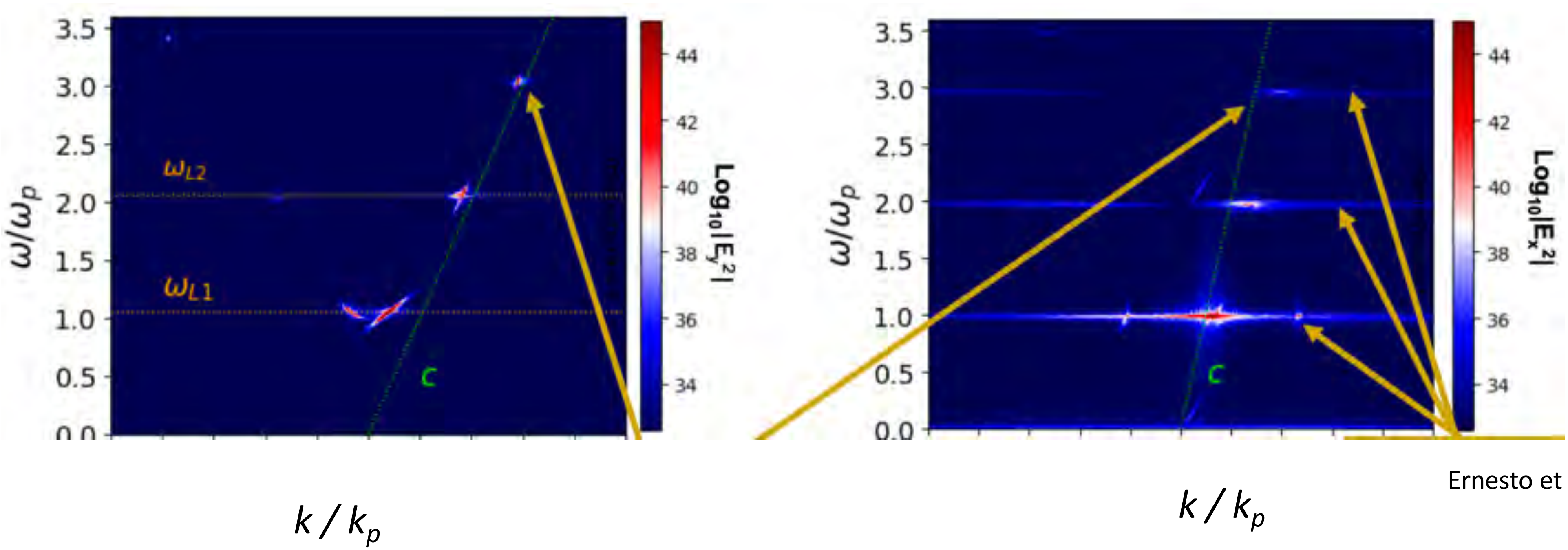
A.

Argue why higher the (longitudinal) plasma wave phase velocity v_{ph} is, it is more robust. Show which plasma electrons are trapped [ref. T. O'Neil, Phys. Plasma **8**, 2255 (1965)] by such a wave whose trapping width is $v_{tr.}$.Then, derive the Tajima-Dawson field $E_{TD} = m\,\omega\_p\, c\,/\,e$ when you set v_{tr} is the ultimate phase velocity of $v_{ph} = c$.

B.

Show that if you set the wakefield phase velocity lower than the speed of light c, say at v_{ph}, then we obtain the saturation field E_{ph} of wakefield as $E_{ph} = E_{TD}\,(v_{ph}\,/\,c)$.

Photon group velocity vs. plasmon phase velocity



Ernesto et al

$v_{gr} = d\,\omega / dk$

→ $v_{ph} = \omega / k = v_{gr}$ (laser driven wakefield)

$= v_{tr}$ (wakefield saturation condition)

HW#2 B

$$v_{ph} = v_{tr} = \sqrt{\frac{eE}{mk}}$$

$$\frac{eE_{ph}}{mk} = v_{ph}^2 \qquad k = \frac{\omega_p}{v_{ph}}$$

$$\rightarrow E_{ph} = \frac{m v_{ph} \omega_p}{e} = \left(\frac{m c \omega_p}{e}\right)\left(\frac{v_{ph}}{c}\right)$$

---

when $v_{ph} \rightarrow v_{th}$

$$v_{th} = \lambda_D \omega_p$$

$$E_{th(ph)} = \frac{m \omega_p}{e v_{th}} v_{th}^2 = 4\pi n e \lambda_D.$$

[TT 11/23/21]

$$F_w = eE_w = m v_{ph} \omega_p a_0^2$$

$$L \sim \frac{\pi c}{\omega_p} \frac{n_{cr}}{n_e} \quad (v_{ph})$$

$$\Delta \mathcal{E} \sim m (v_{ph}\, c) a_0^2 \frac{n_{cr}}{n_e} \rightarrow m c^2 a_0^2 \left(\frac{\Delta n_e}{n_e}\right) \quad (v_{ph})$$

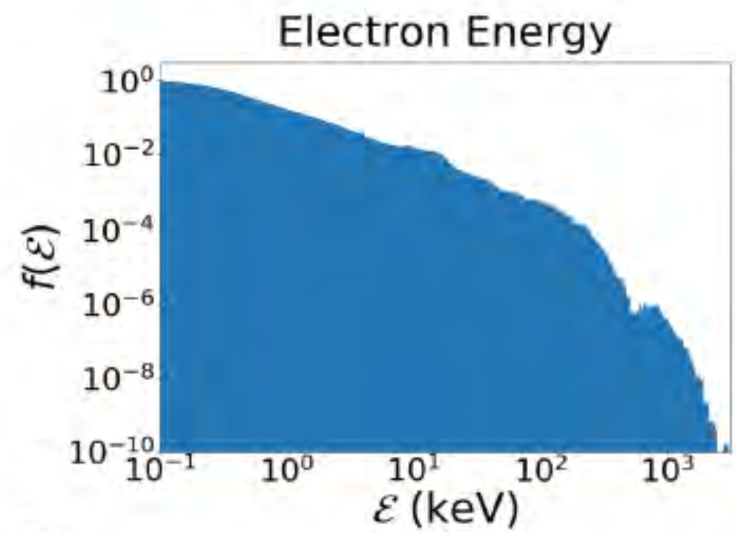
$$v_{ph} \sim c\sqrt{1 - \frac{n_e}{n_{cr}}} \sim c\sqrt{\frac{\Delta n_e}{n_{cr}}}$$

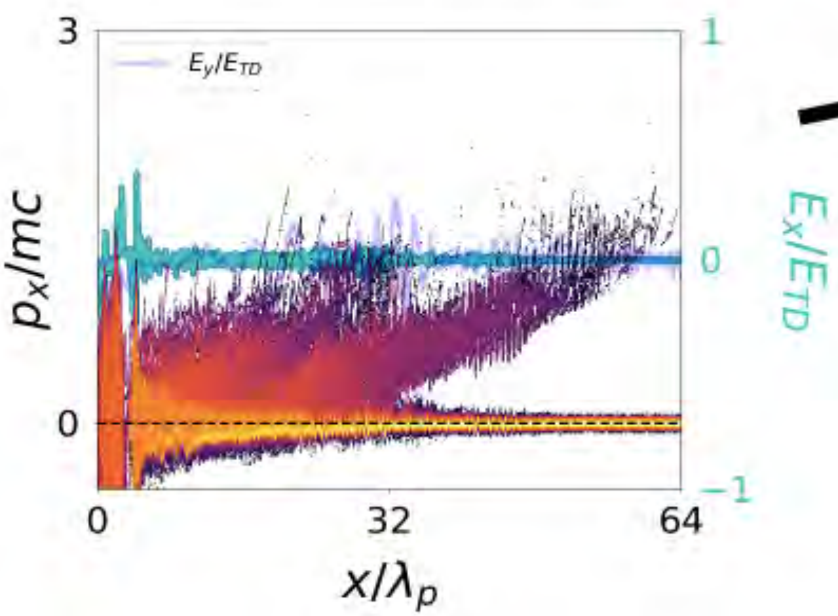
$$= \begin{cases} m c^2 a_0^2 \left(\dfrac{\Delta n_e}{n_e}\right) & (\text{when } n_e \rightarrow n_{cr}) \\ m c^2 a_0^2 \left(\dfrac{n_{cr}}{n_e}\right) & (\text{when } n_e \ll n_{cr}) \end{cases}$$

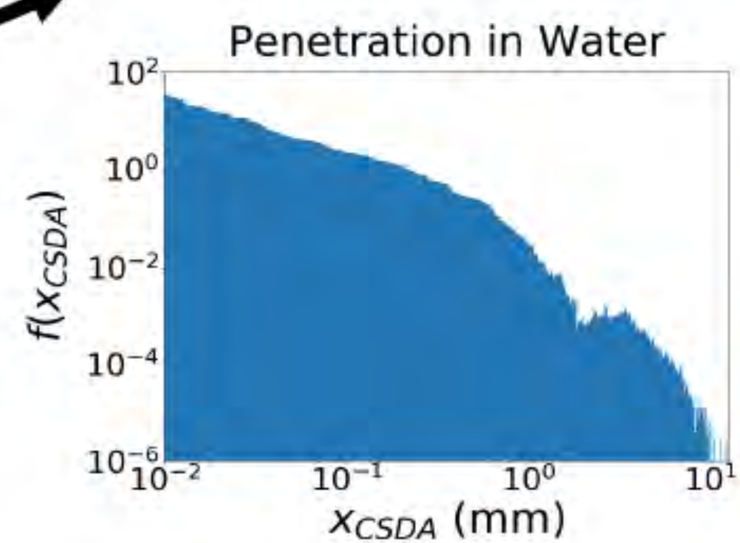
5. Accelerator and X-ray sources in your stomach?

Electron Tissue Penetration

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







S. Nicks et al. (2019)

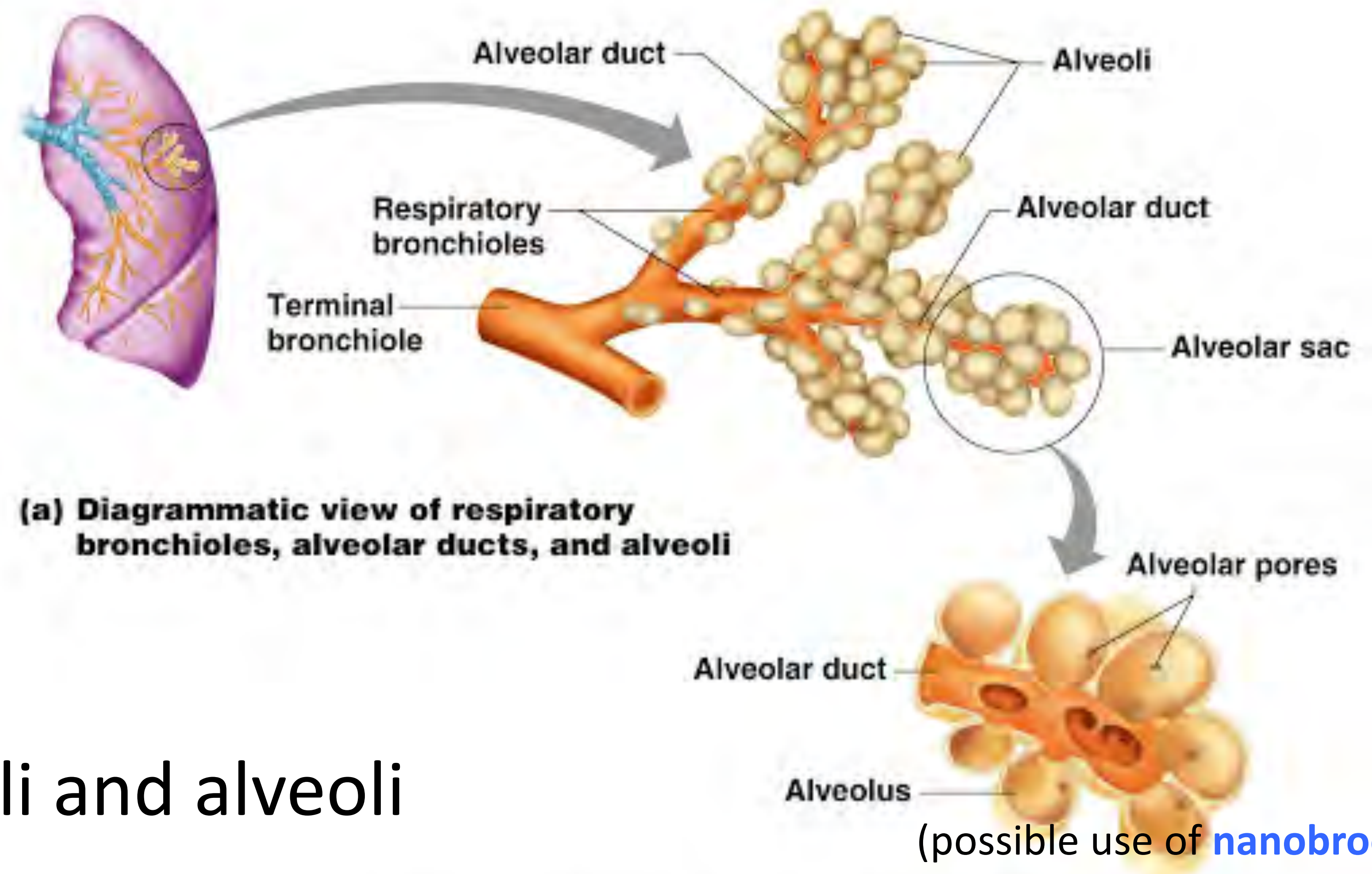
6. Nano vector medicine

Nanometric vector medicine: See Matsumoto et al. Sci. Rpt. (2019)

High-Z nanoparticles can stop electrons right there

(to target Cancer cells)

Now also → inhale (or conduct via the capillary effect) gold nanoparticles toward alveoli.



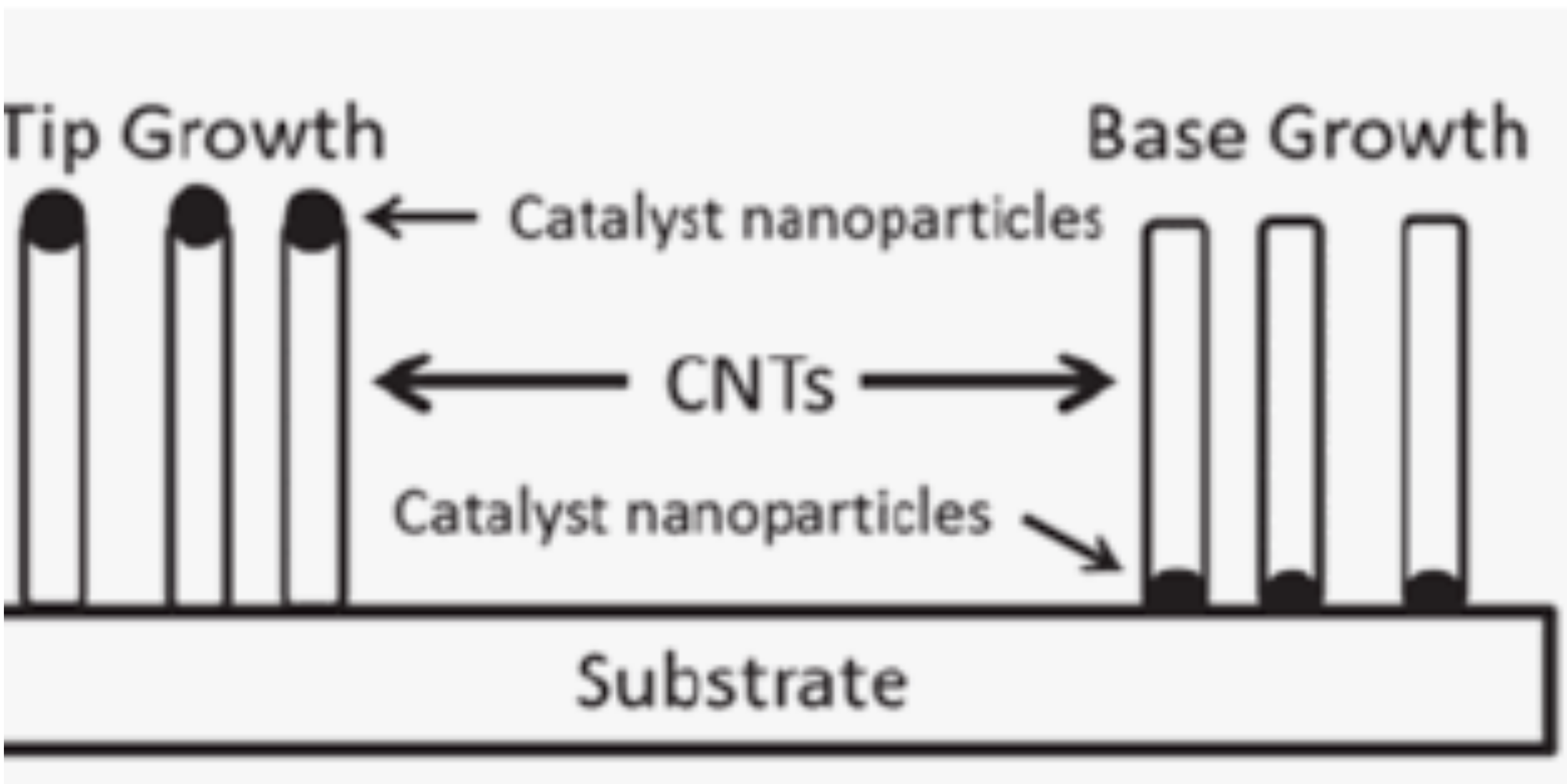
Bronchioli and alveoli

(possible use of **nanobroom**)

Compact laser-driven electron accelerator
Nanotubes organized with the substrate (2019)

CNT: large conductivity along the CNT tube axis, while insulating perpendicular

← Laser propagation

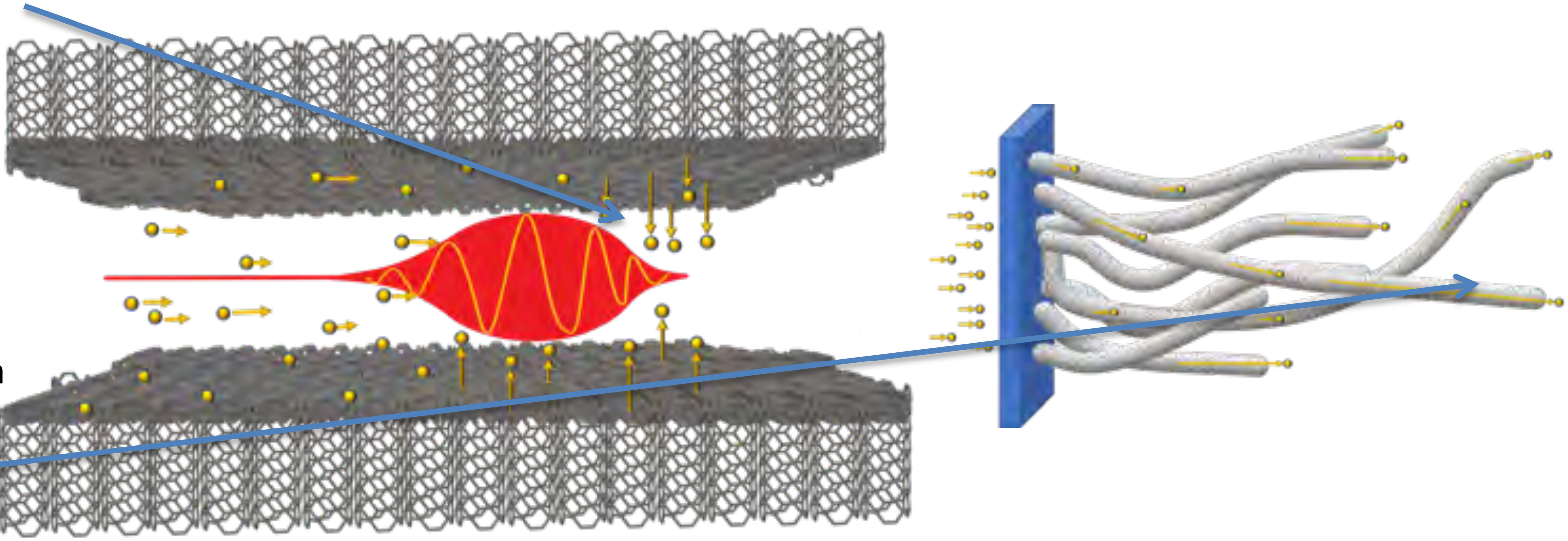


Microaccelerator and Nanobroom at the tip of LWFA

(a future possibility)

“bamboo forest” of nanotubes **“Nanobroom”**

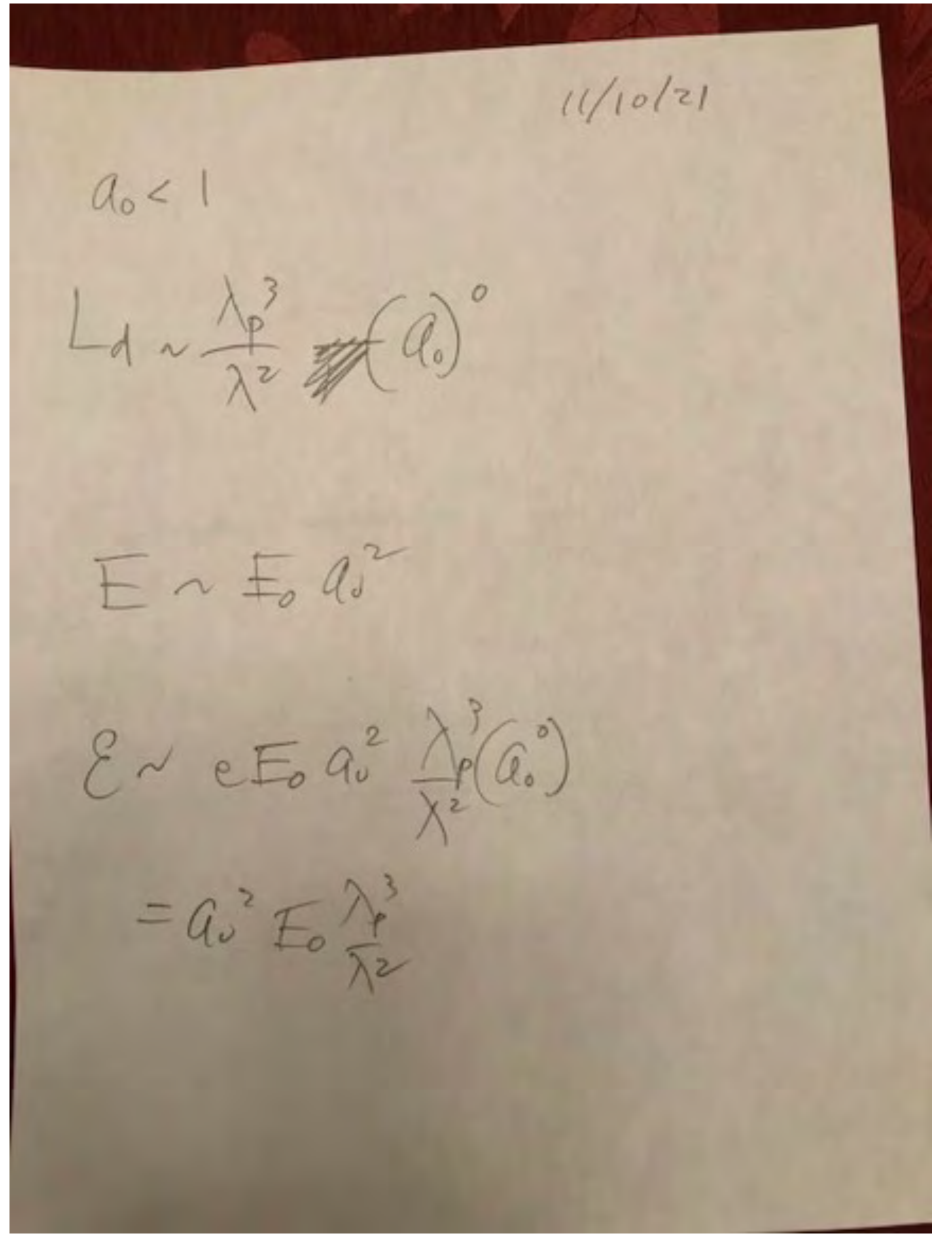
Electrons locally into the
  bronchus (till where
the
  laser fiber reaches)



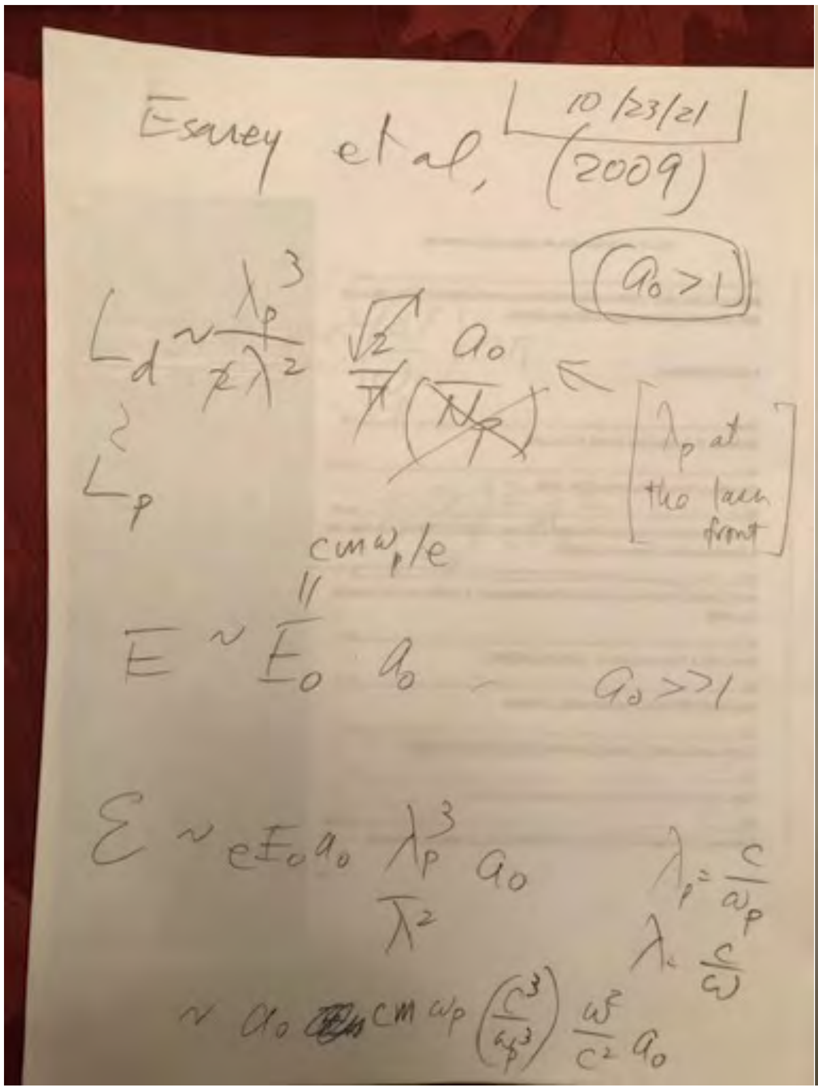
Through **bronchioles** (via
  self-focusing through
  “boom“ nanotubes)
  and reach **alveoli**

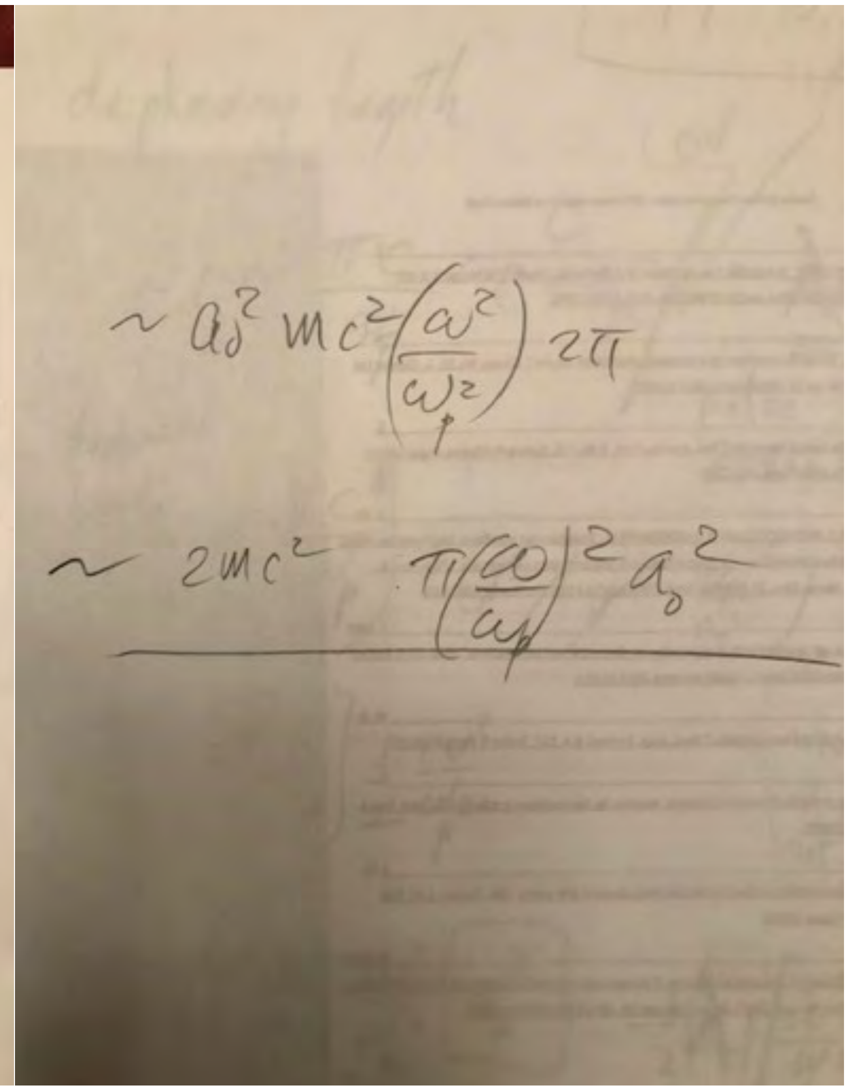
bronchi ← **→ bronchioli** **alveoli**

Simple cases for small a_0 (< 1) dependence

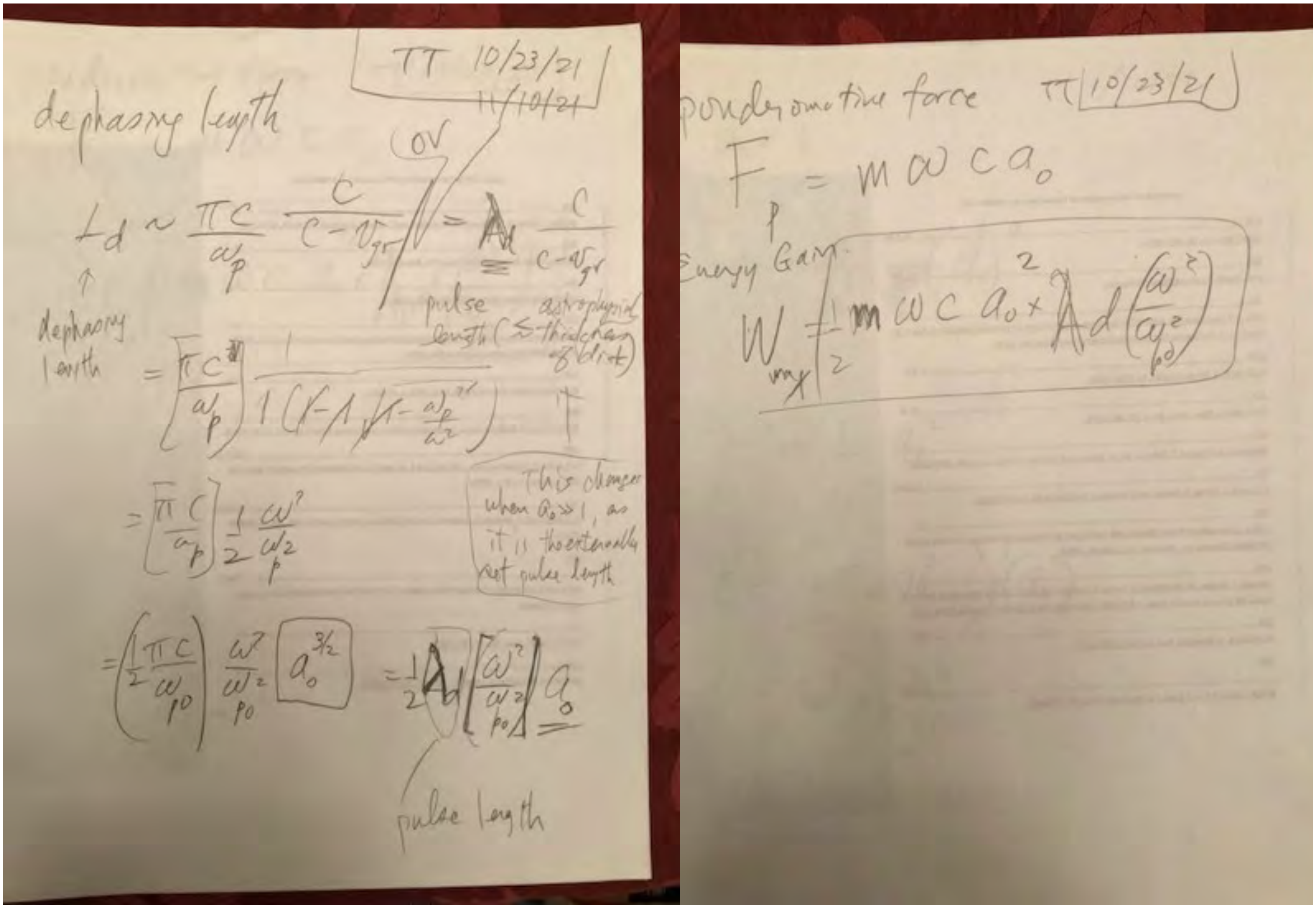


Some scaling exploration in $a_0 > 1$





Some consideration on the pulse length

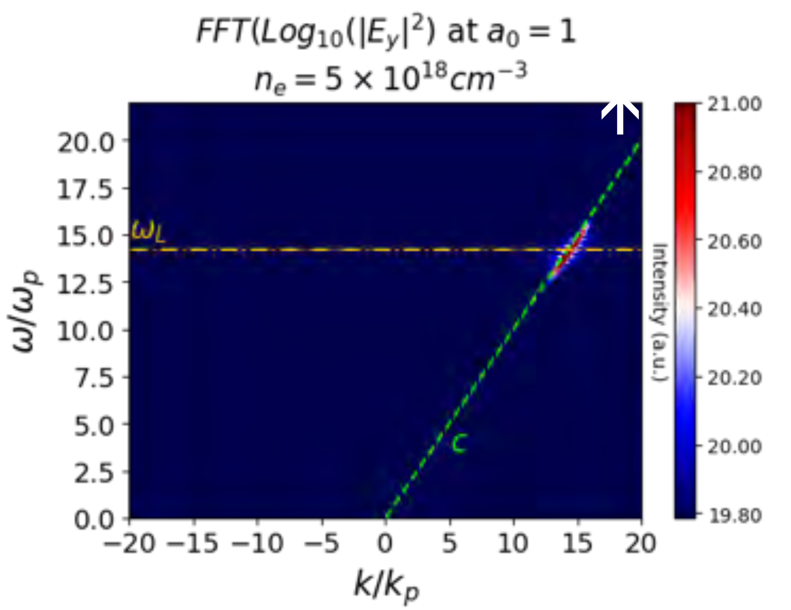


PHY249(fall2021)LWFA (E. Barraza et al.):

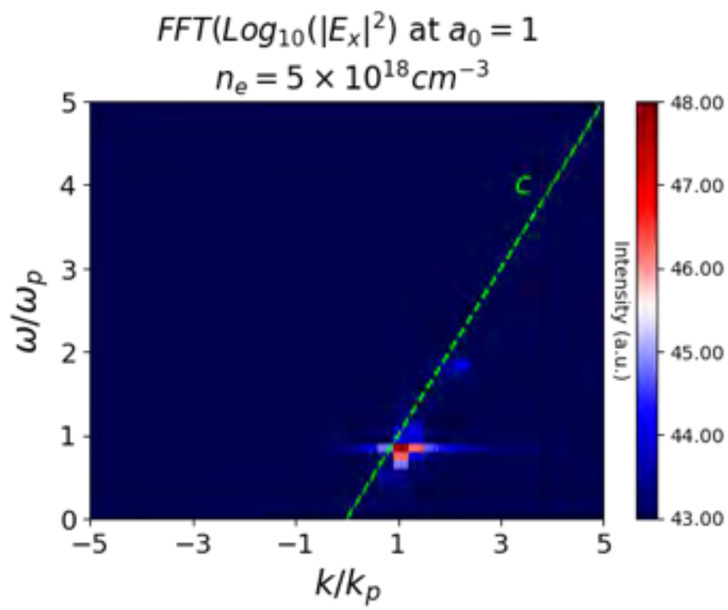
$$\lambda_{laser} = 1.05\ \mu m$$
$$n_e = 5{\times}10^{18} cm^{-3}$$

Group velocity of photons

Phase velocity of plasma wave (wake)



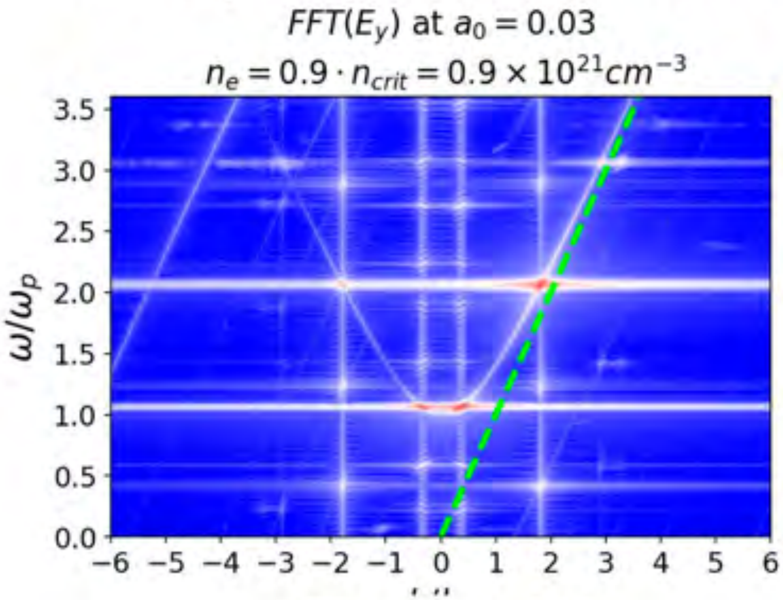
The pulse of laser appears just below the light cone obeying the dispersion relation *w^2 = w_p^2 + k^2 c^2,* where the group velocity of light is *v_gr = c sqrt(1 – w_p^2 / w^2)*

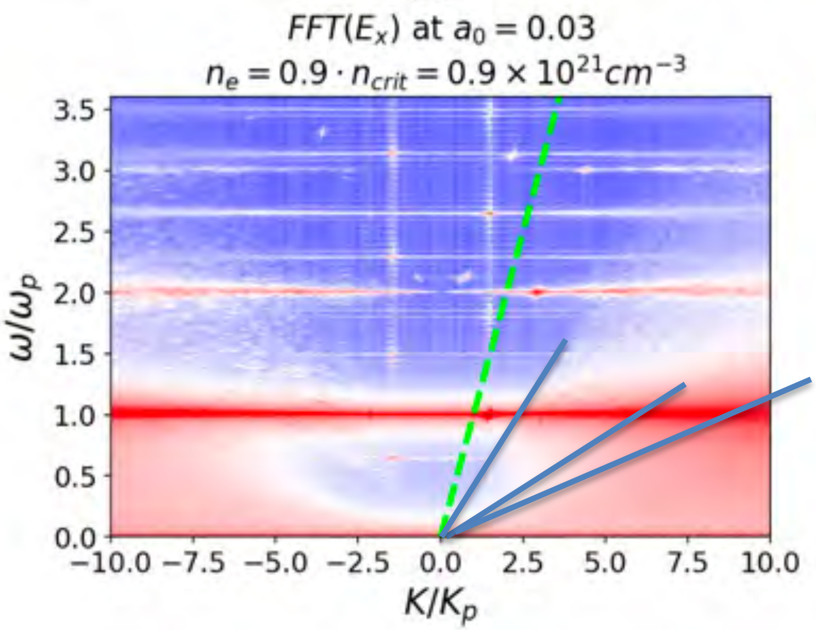


The excited wake behind the laser pulse also sits right below the light cone where the phase velocity of the plasma wave obeys *v_ph = w_p / k_p = v_gr*

In high densities, we get broad v_{ph} from small to large

Dispersion Relations

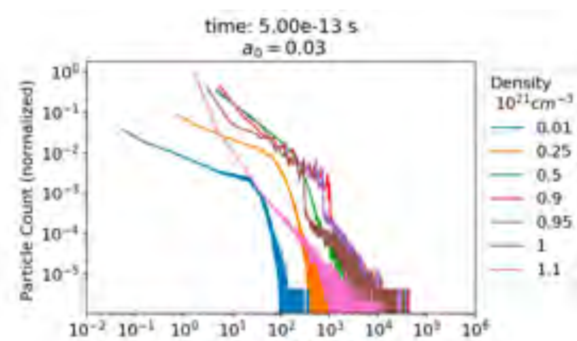


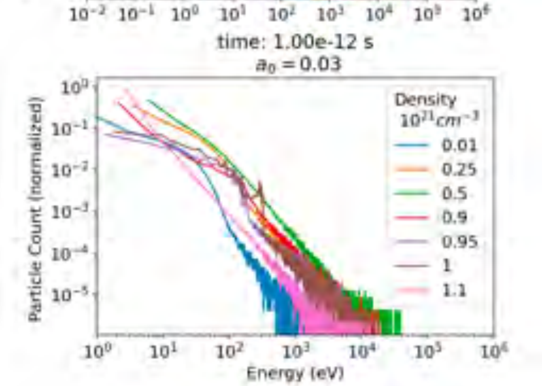


Smaller v_{ph} → smaller v_{tr} → smaller saturated E
→ Less energetic electrons accelerated

Larger v_{ph} can trap electrons to greater energies

Broader trapping ranges → higher efficiency, non-monoenergy





HD LWFA

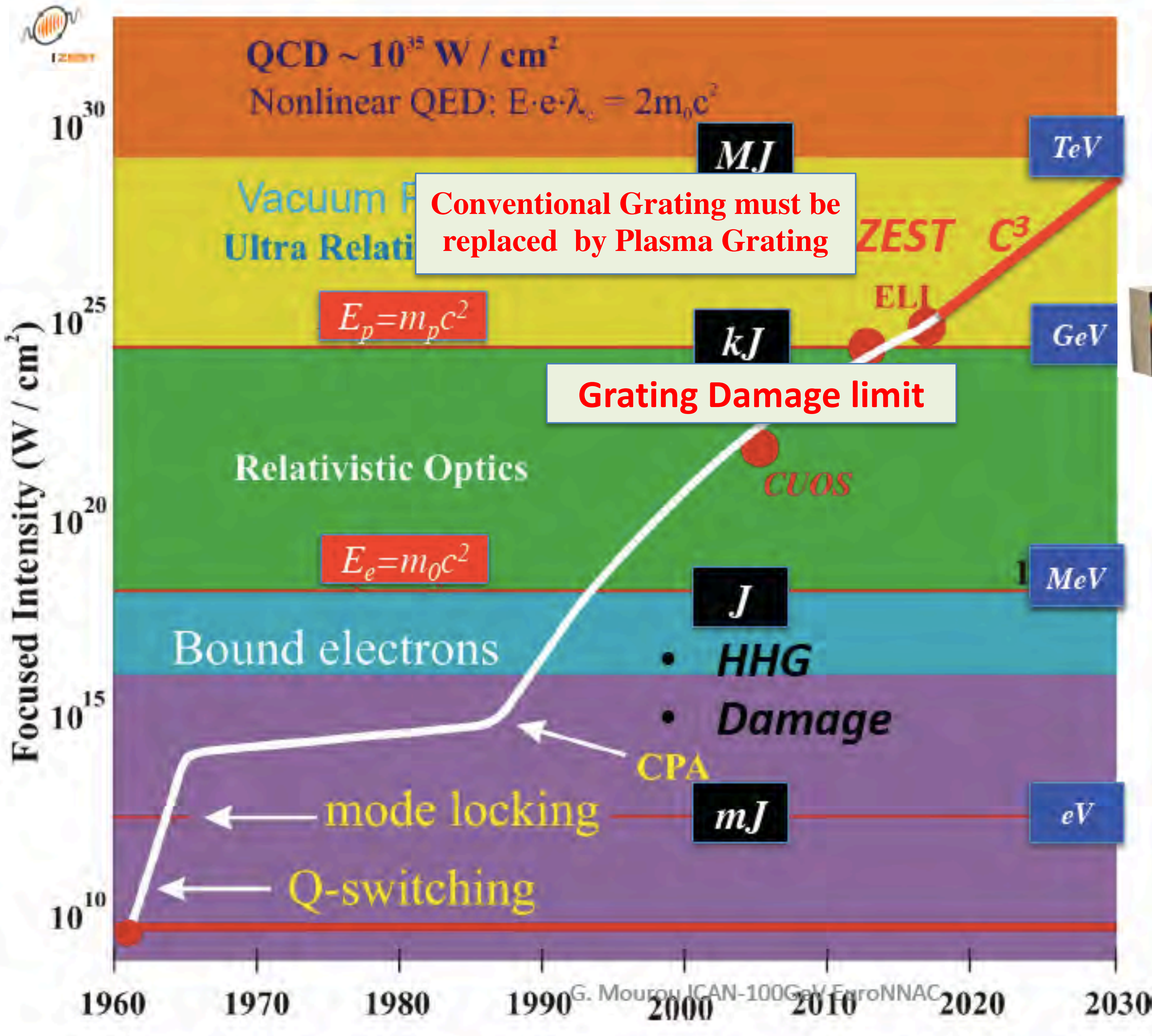
- Low energy acceleration $\sim n_{cr} / n_e$
- Tiny acceleration length ~ micron

$$L_d \sim (c / \omega_p)(n_{cr} / n_e)$$

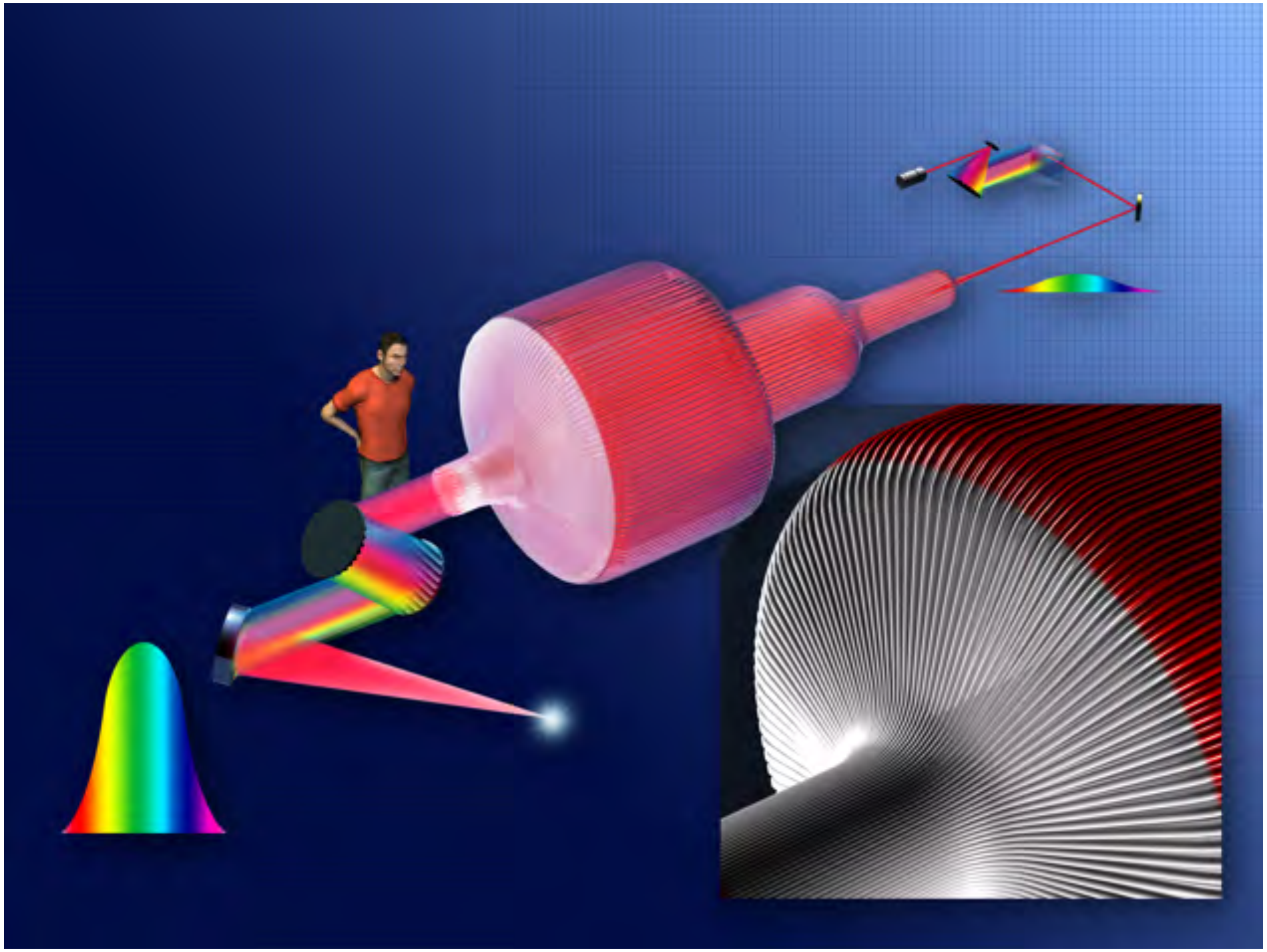
- Higher efficiency
- Less mono-energetic

(we need to further check a_0 *and* n_{cr} / n_e dependences)

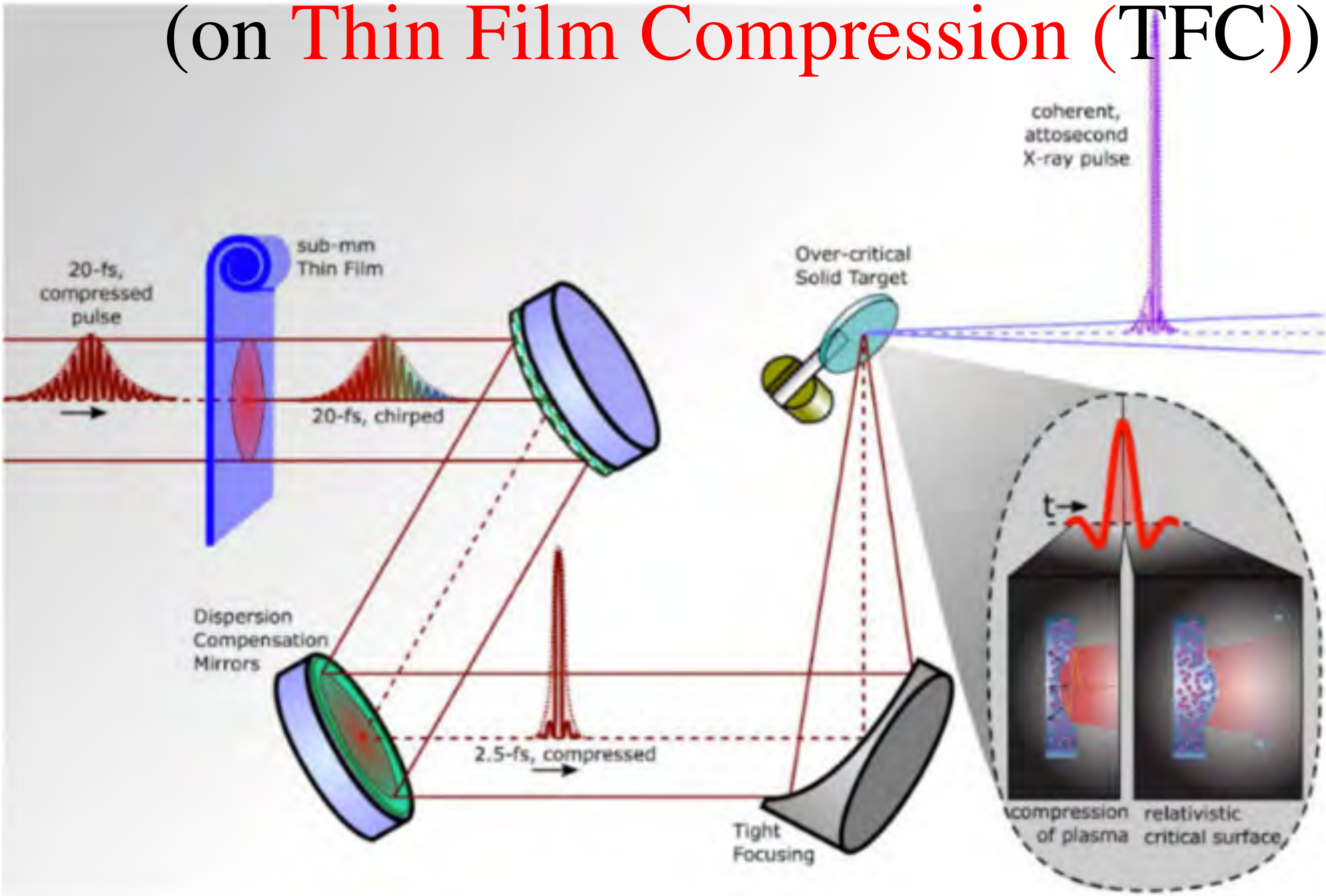
Single-cycled laser and “TeV on a chip”



G. Mourou ICAN-100GeV EuroNNAC



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



Wheeler J, Mourou G, Tajima T. 2016

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

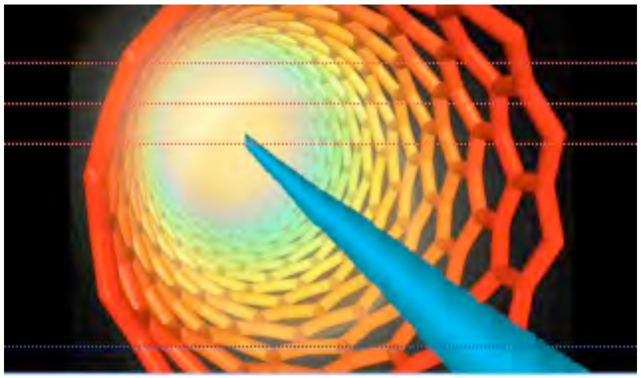
2. X-ray frequency exceeds the nanomaterial's plasma frequency ω_{pe}

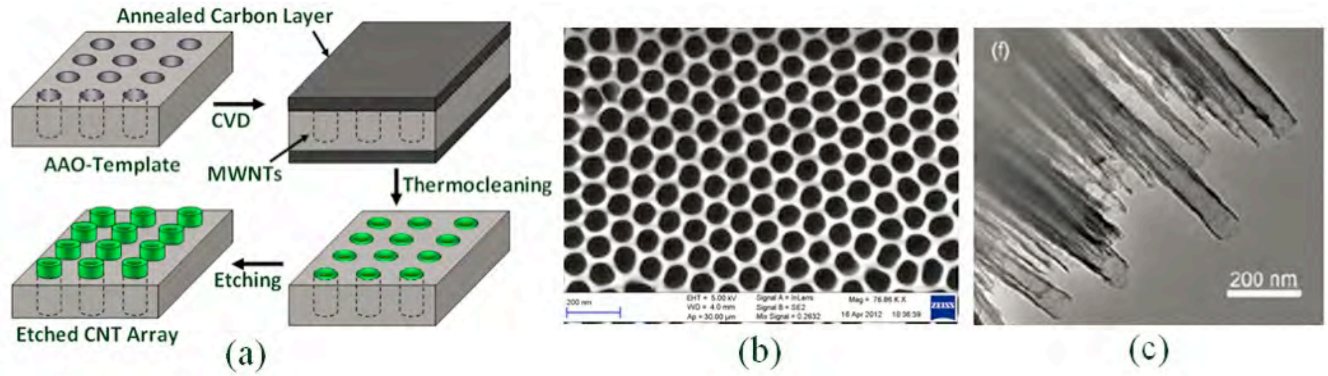
→ **carbon-nanotubes**

higher than 10TV/m wakefield (2014)

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

Why Nanotubes



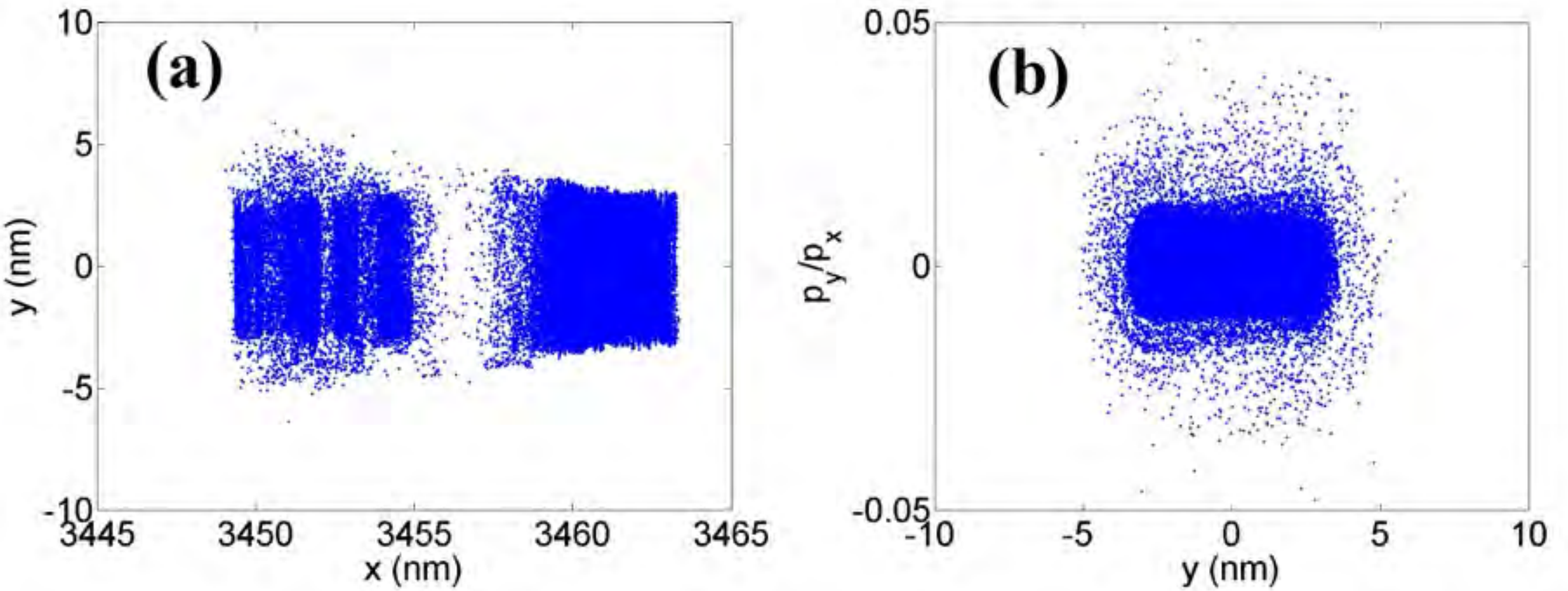


- High density ↔ Higher acceleration gradient (~ TeV / cm)
- Provides external structure to guide laser and electron beam
- No slowdown of electrons by collisions
- Intact for time of ionization (fs)
- More coherent electrons and betatron radiation

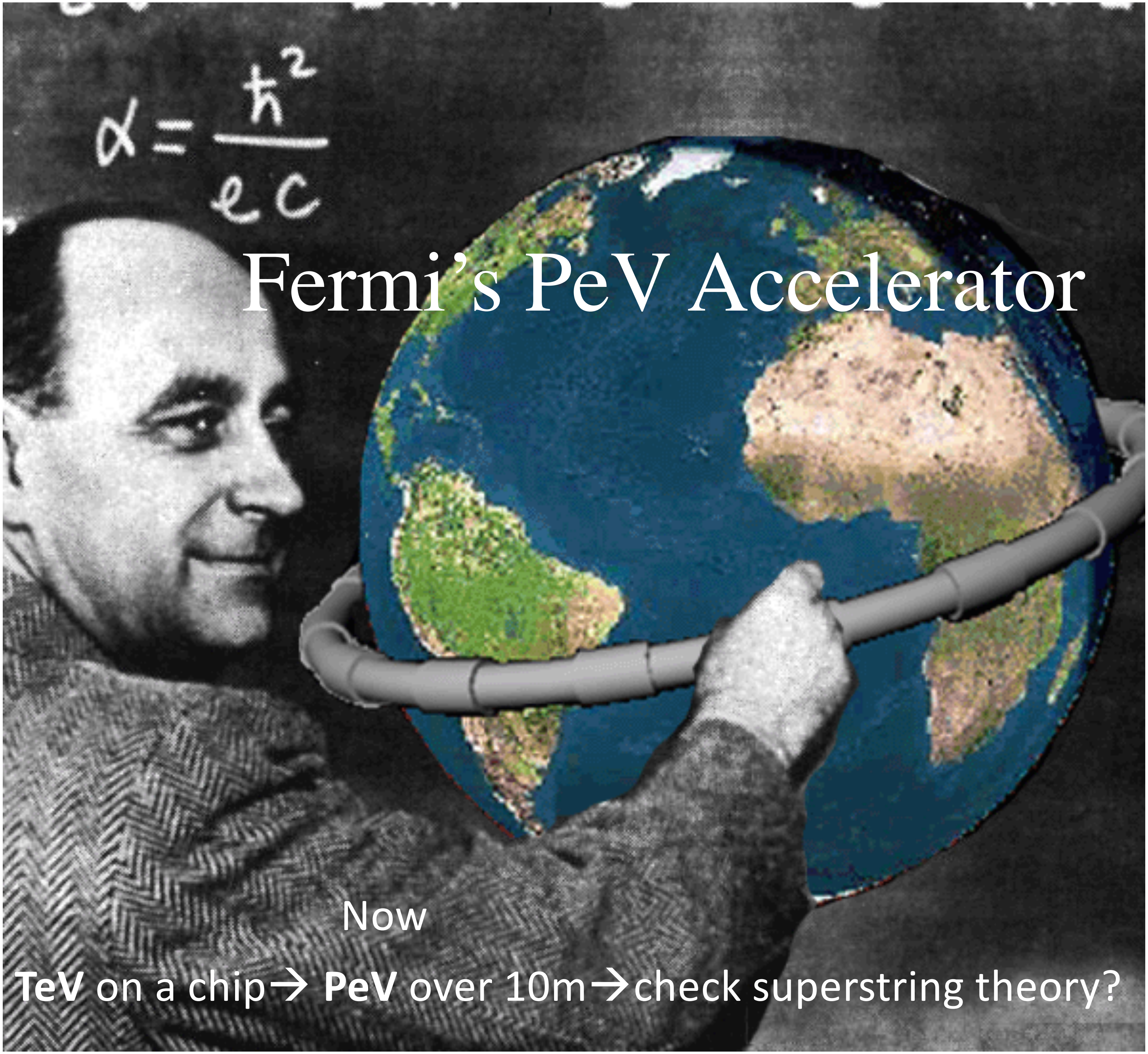
（b）Lazarowich RJ, Taborek P, Yoo BY, Myung NV. 2007

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)


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

1. Background

- New invention toward ulrashort-pulsed higher frequency photon: **Thin Film Compression (TFC)** [Mourou et al. 2014] and its demonstration [Farinella et al., 2019]
- Its use toward X-ray laser driven nanotube accelerator-
  "**TeV on a chip**": [Tajima, 2014], [Zhang et al. 2016]
- SIOM launched SEL (Station for Extreme Light): marriage between PW lasers and XFEL [2017]
- →Need of higher energy, higher intensity X-ray lasers
- SIOM: Center of materials science (nanotechnology)
  emergence of nanomaterials

2. Compact laser-driven electron accelerator

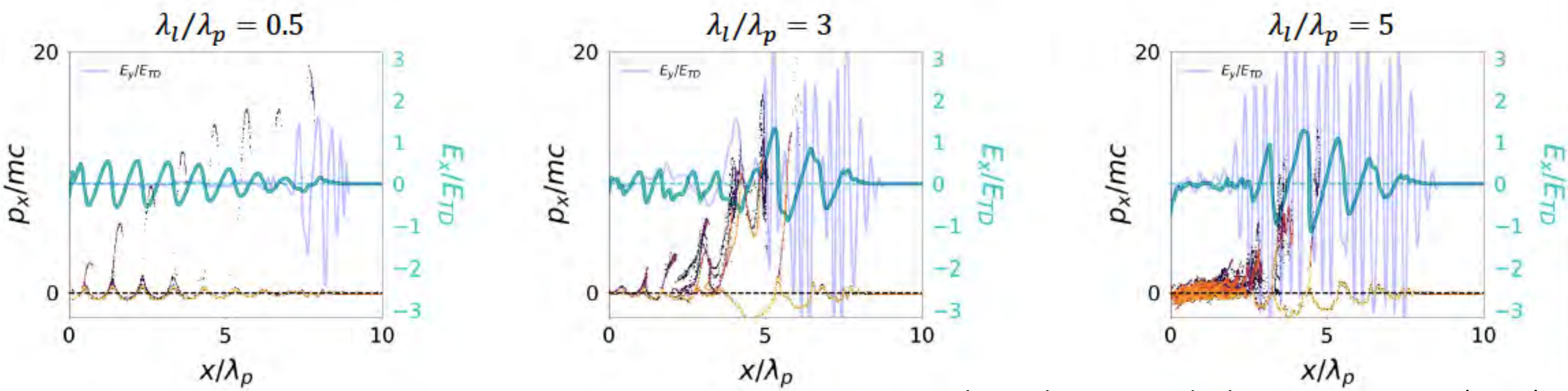
Laser accelerator (invented: Tajima-Dawson, 1979)

First expt (Nakajima et al., 1994);100s of realizations

↓

Nanotube version of laser-driven electrons (2019)

- 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



S. Nicks et al. Int. J. Mod. Phys. A**34**, 1934019 (2019).

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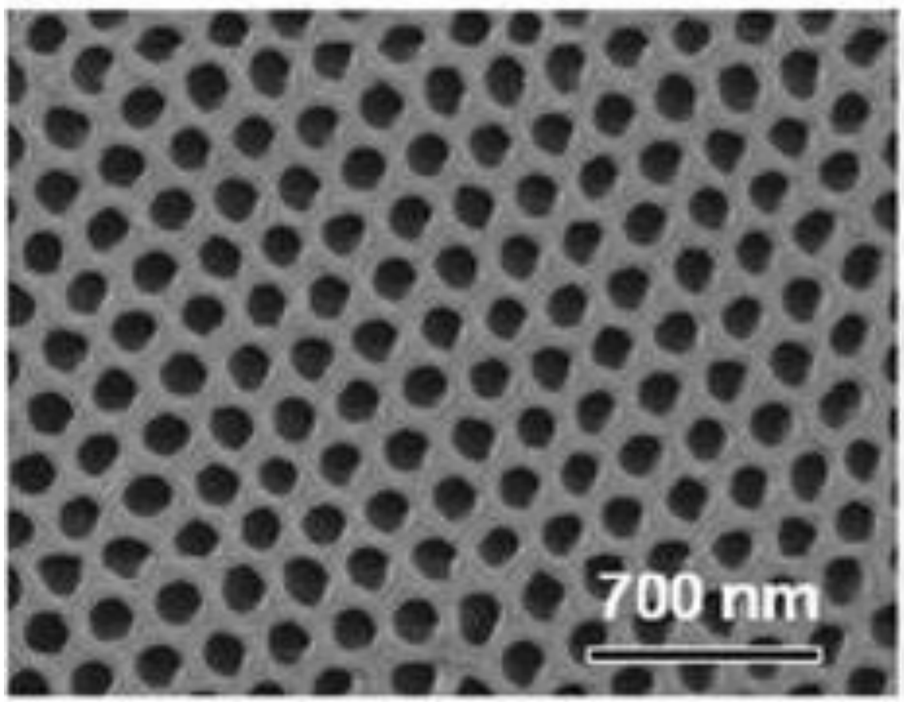
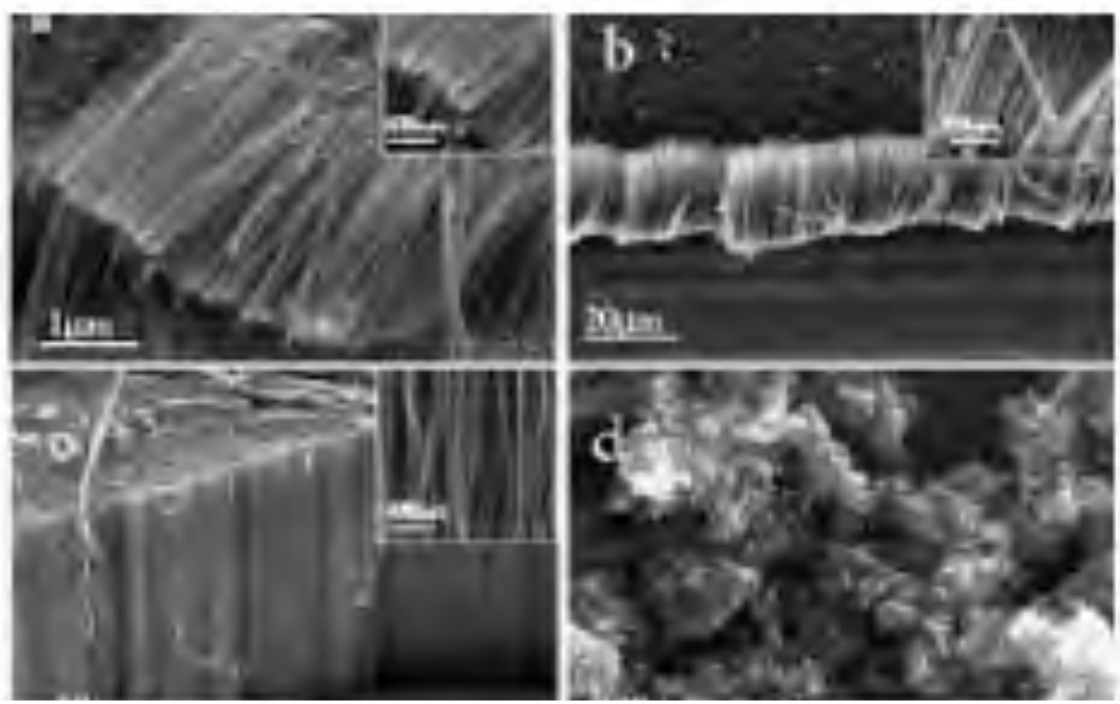
3. Nanotubes

- Emergence of nanotubes and nanotechnology
  --discovery of CNT by Iijima (1991)
- Taborek et al. (2000’s):

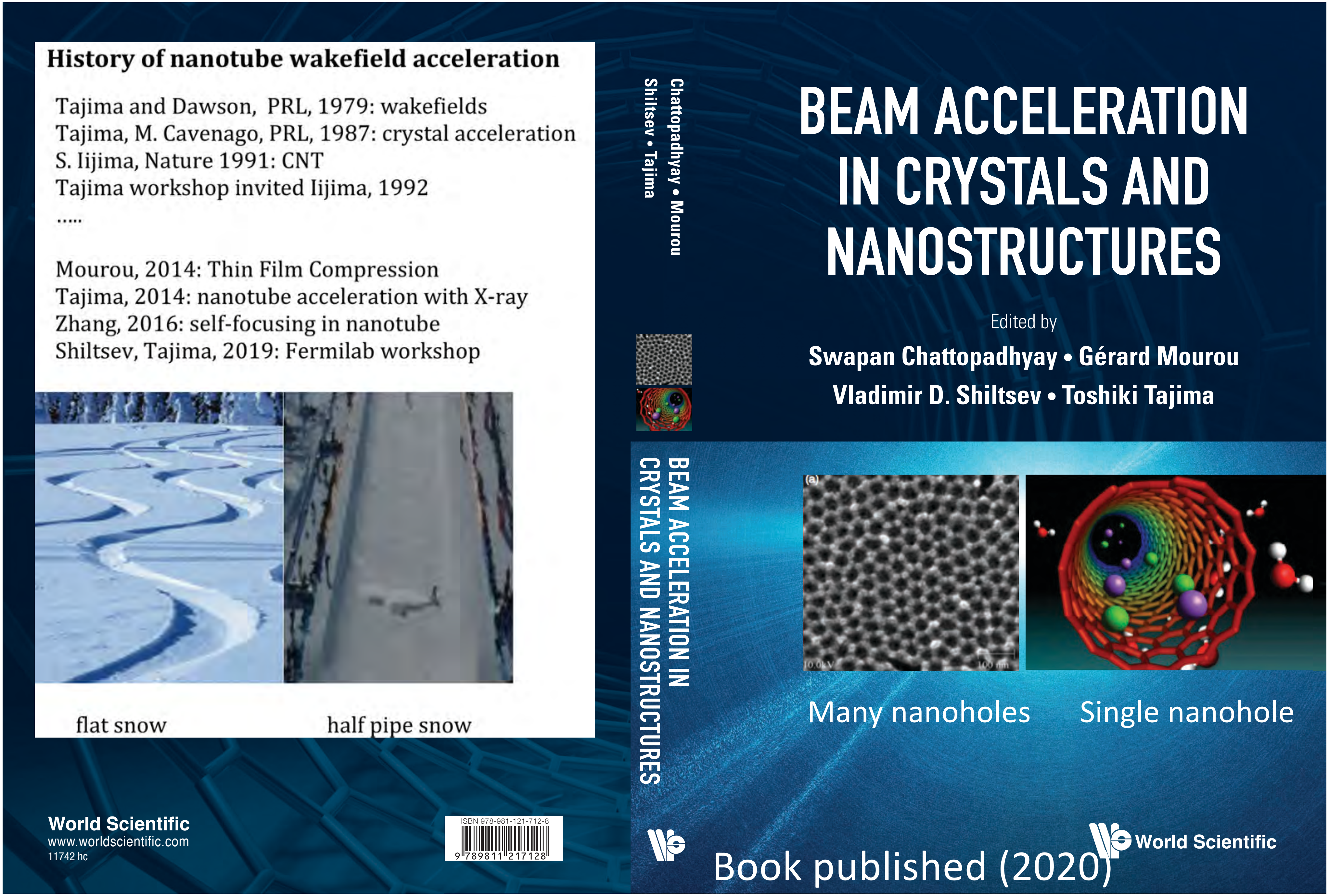
nanotube arrays ; nanoforest





4. Marriage of Intense Lasers and Nanotechnology

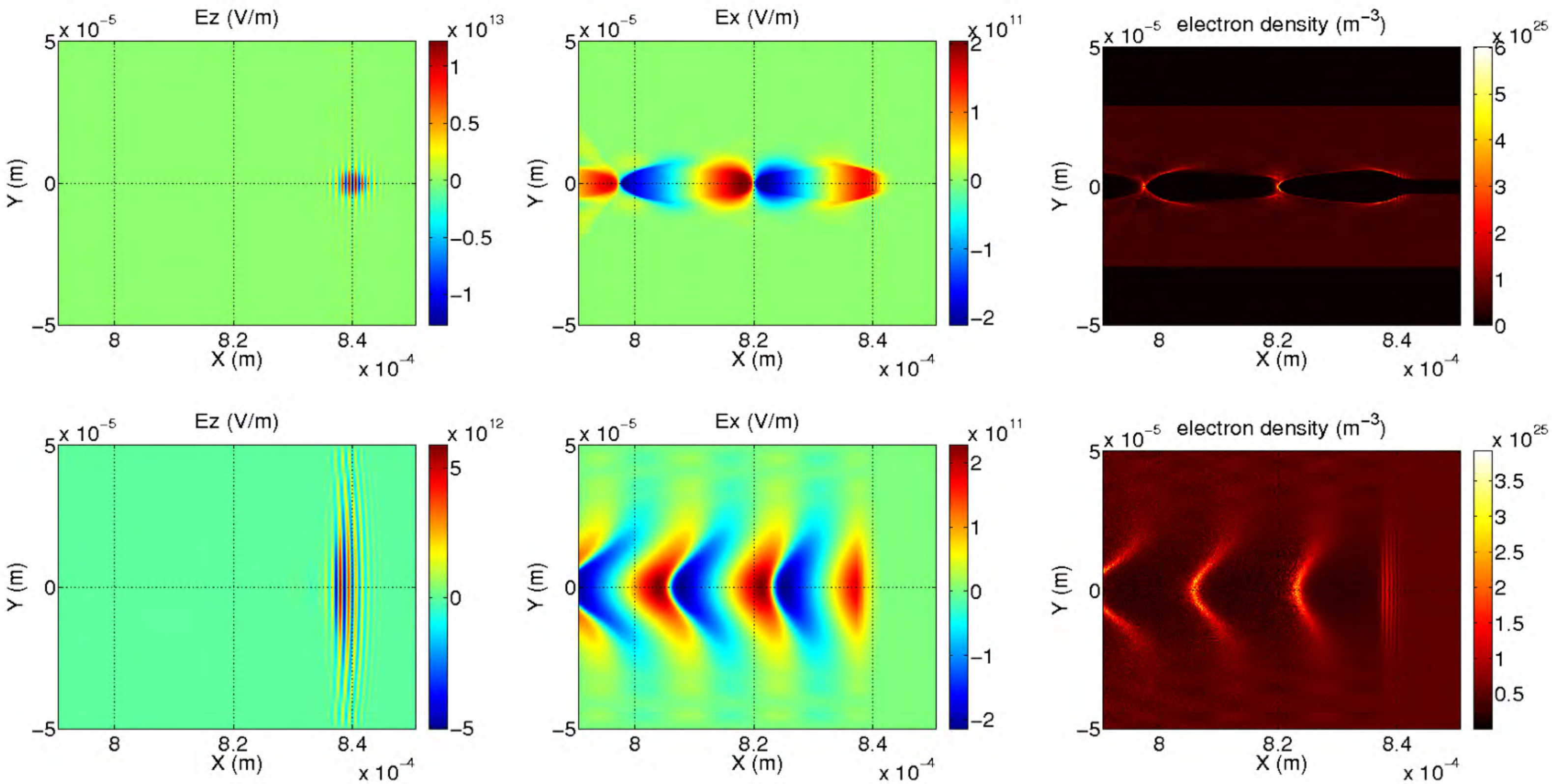
- **Laser wakefield accelerators (LWFA)**: more compactified with nanotubes
- LWFA: with higher frequency photons (e.g. X-rays) → TeV on a chip
- Betatron oscillations in nanotubes → more coherent, high frequency, shorter pulsed X-rays
- Accelerators and X-rays in your stomach; cope with COVID etc.



Gathered for **nanotube wakefield acceleration** (Fermilab, 2019)

X-ray LWFA in nanotube vs. uniform

X. Zhang (PRAB 19, 101004 , 2016)



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

CNT diameter: 10s-100s nm, singular or bundle of nanotubes

drivers: lasers (higher harmonic, TFC X-ray) or ultra-dense *e*- bunch

Already workingh: Zhang, L. M. Chen, Mourou, Shiltsev, P. Chen, Corde, Taborek,R. X. Li, possibly Bulanov, ELI-ALPS, Kawachi (QST), Sone (JST), Iijima, …. (open armed)