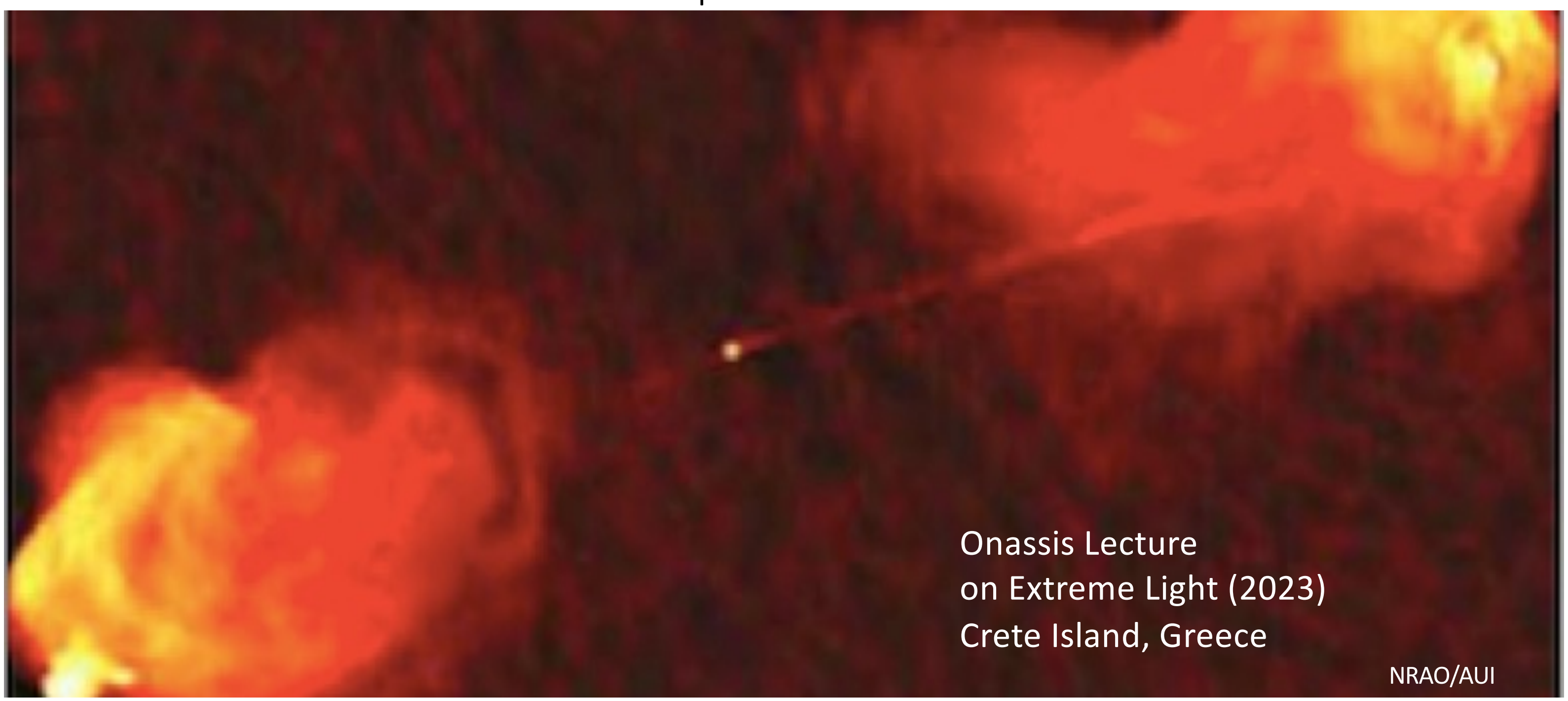
(7/4/23)

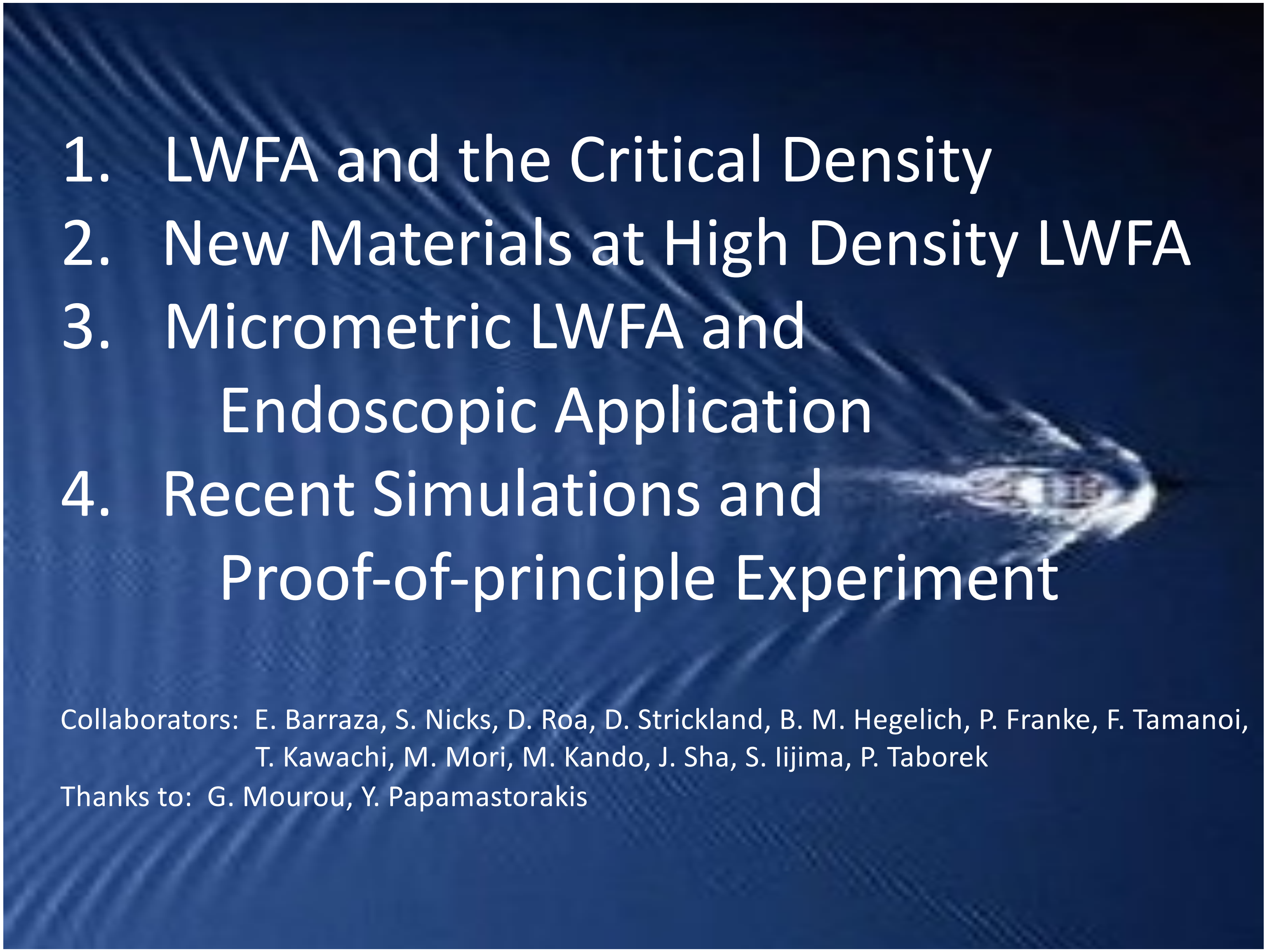
High Density LWFA:

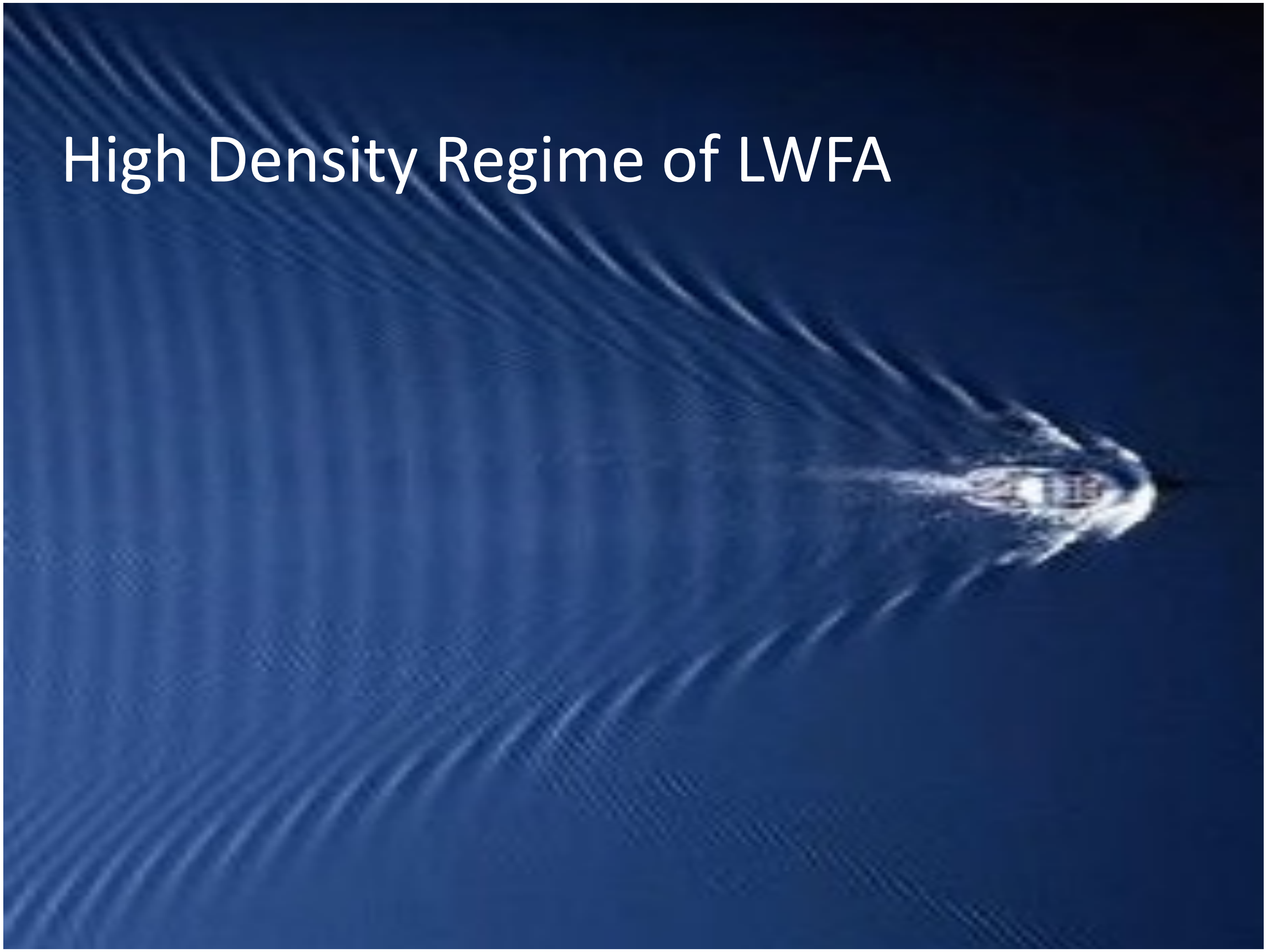
Micrometric Accelerator and Endoscopic Application

Toshiki Tajima, Norman Rostoker Chair Professor, UCI, USA

part 2:



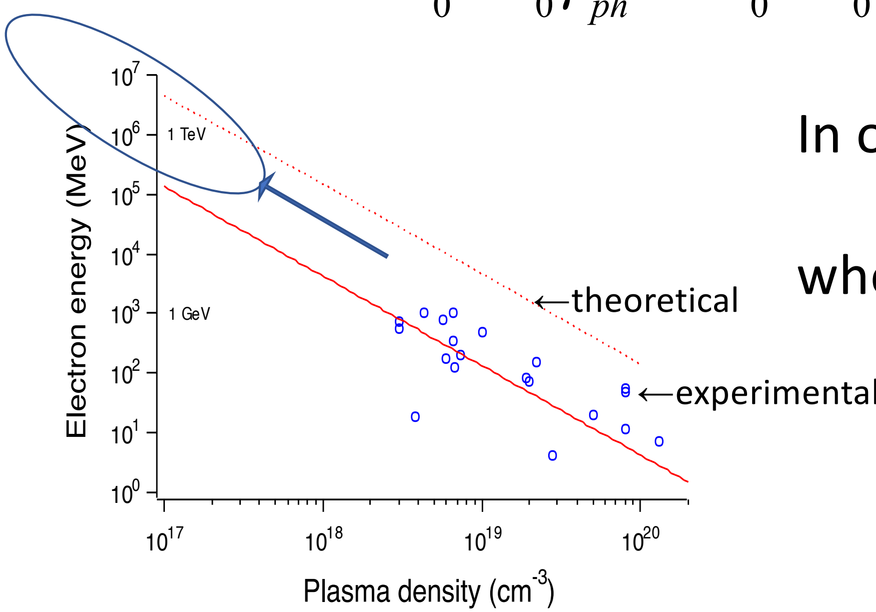

1. LWFA and the Critical Density
2. New Materials at High Density LWFA
3. Micrometric LWFA and
Endoscopic Application
4. Recent Simulations and
Proof-of-principle Experiment
Collaborators: E. Barraza, S. Nicks, D. Roa, D. Strickland, B. M. Hegelich, P. Franke, F. Tamanoi,
T. Kawachi, M. Mori, M. Kando, J. Sha, S. Iijima, P. Taborek
Thanks to: G. Mourou, Y. Papamastorakis


High Density Regime of LWFA

Theory of wakefield : scaling laws

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

(when 1D theory applies Tajima / Dawson, 1979)



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)

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

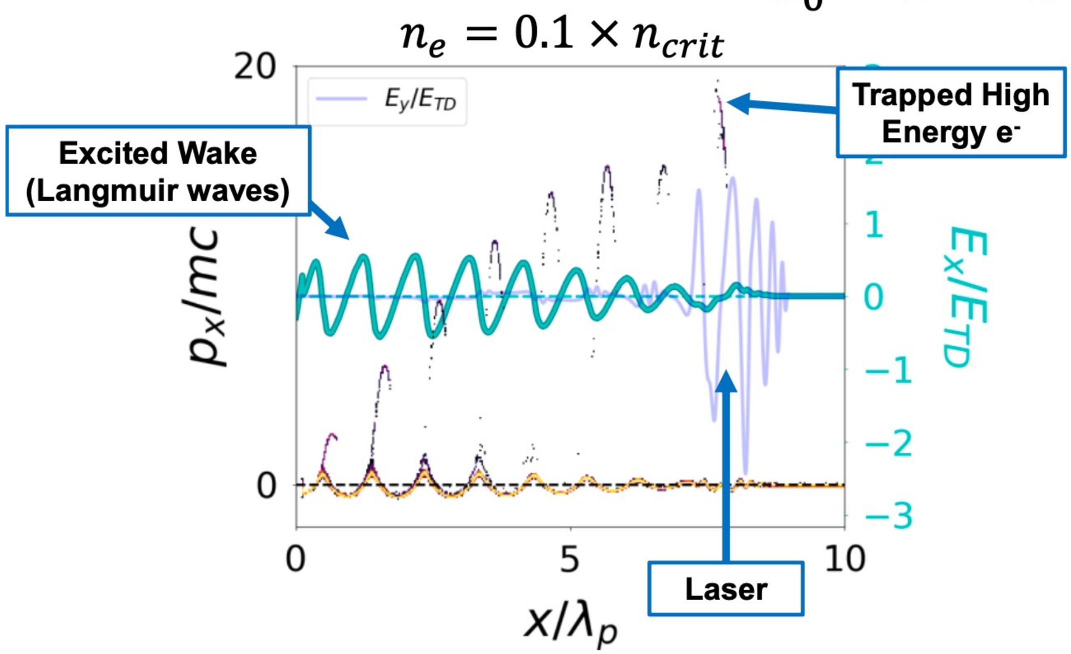
dephasing length

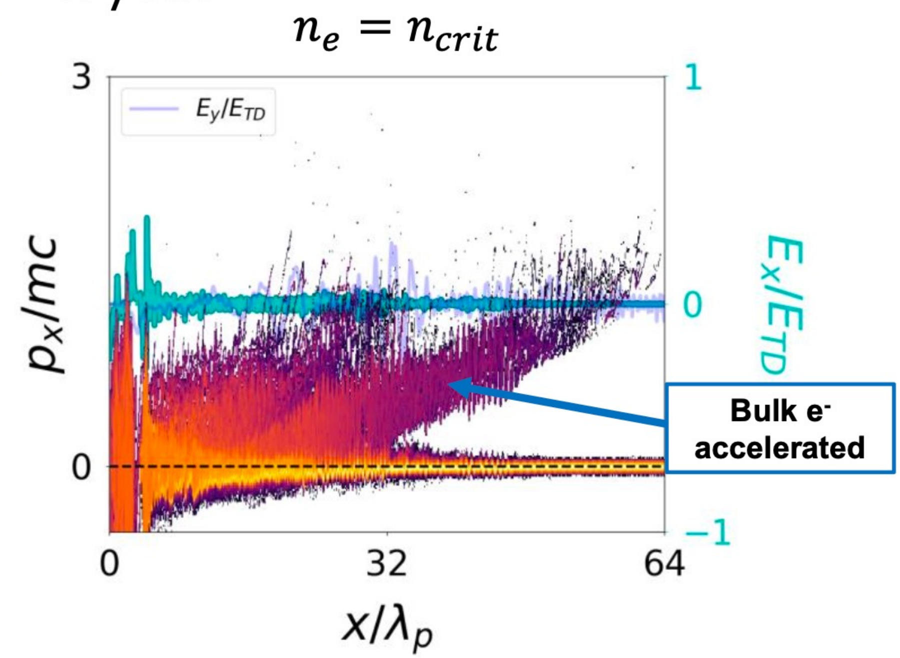
$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length

LWFA: Conventional Underdense vs Near Critical Density

$a_0 = 1 \rightarrow 10^{18}\ W/cm^2$



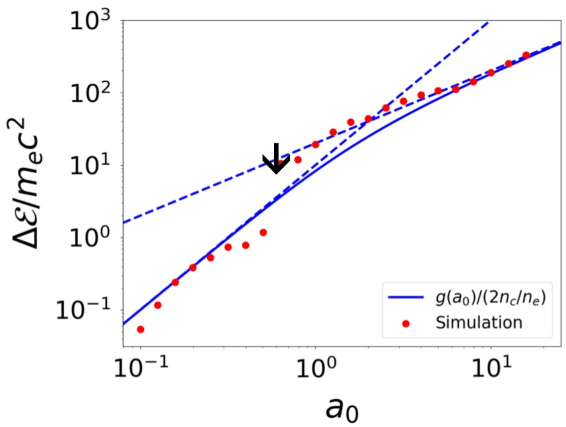


Intensity scan to $a_0 < 1$ regime
Transition to near-critical density $n_e \sim n_{cr}$

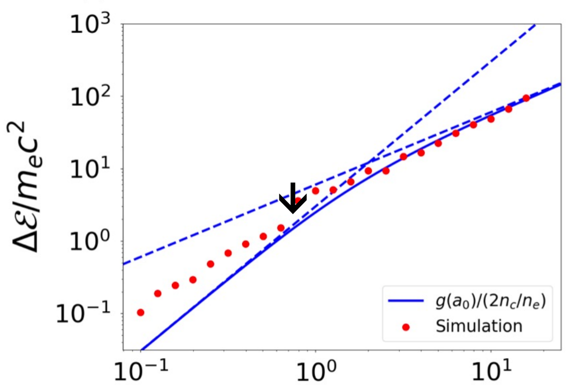
v_g (group velocity of photon) = v_p (phase velocity of plasma wave) << c

(S. Nicks, 2019)

Energy gain

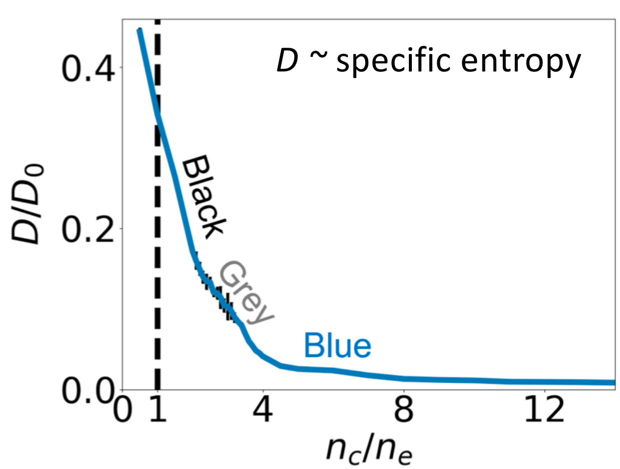


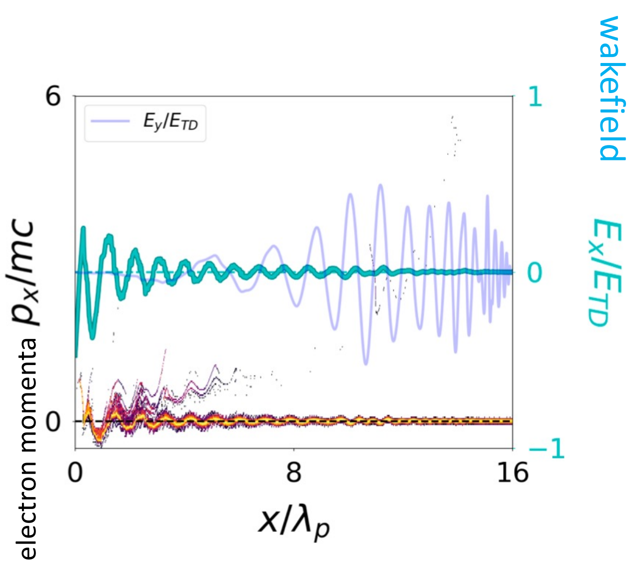
(a) E_{max} vs a_0 for fixed density ratio of 10



$n_{cr} / n_e = 3$

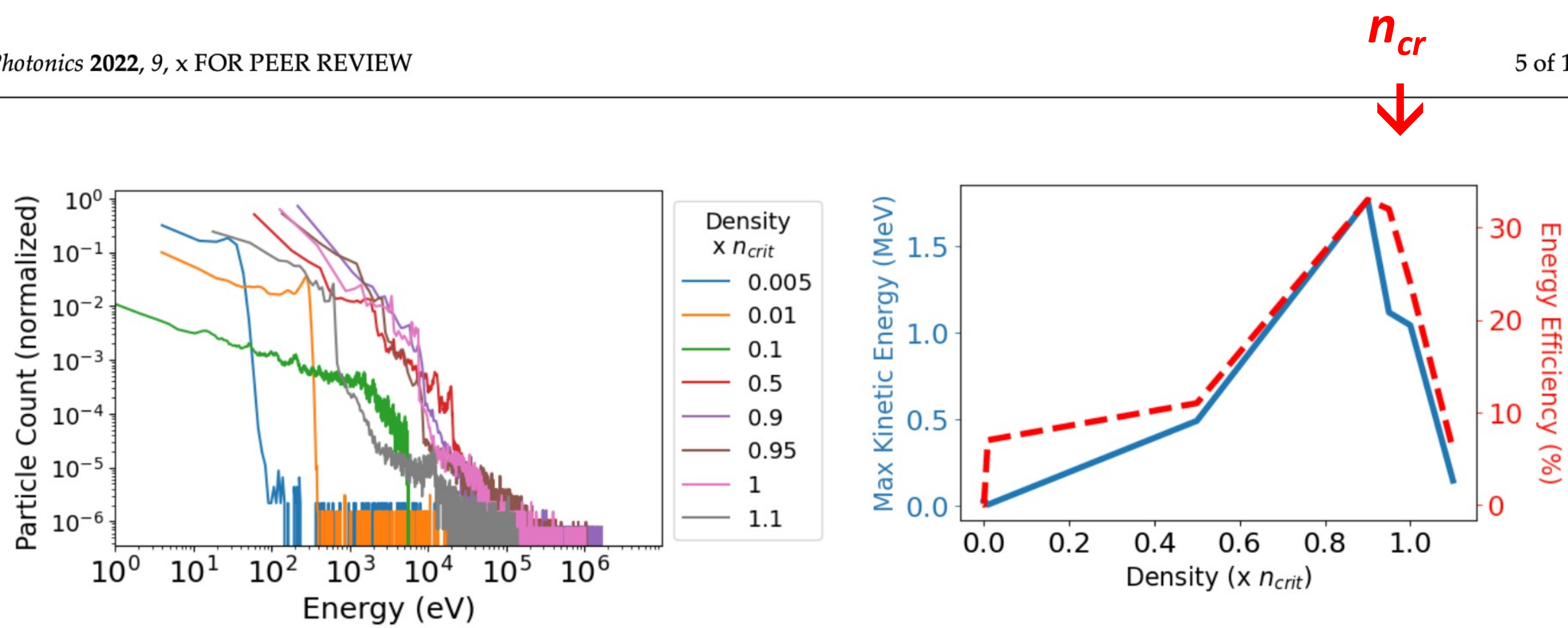
$n_e \sim n_{cr}$





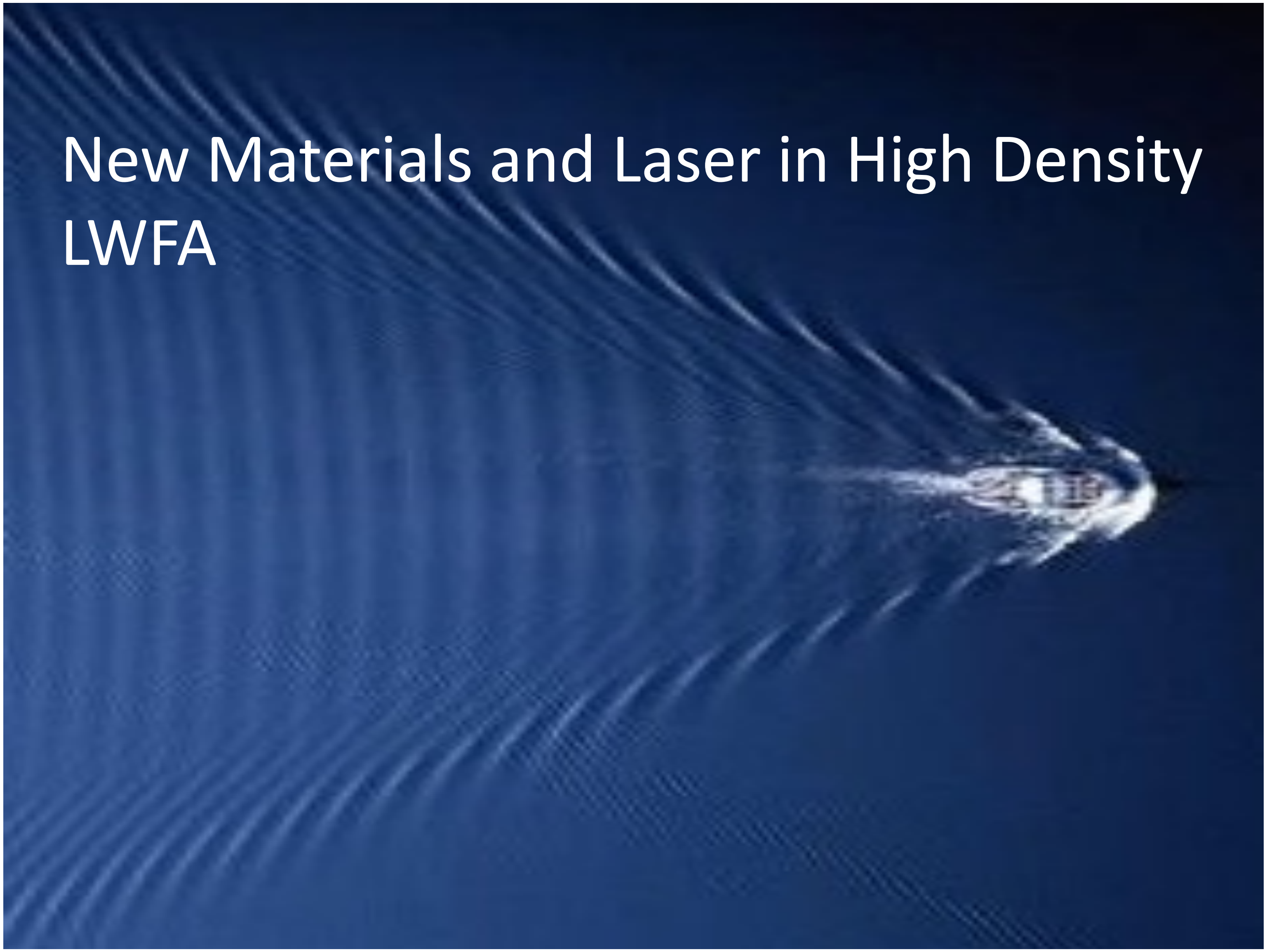
Density scan: Near Critical Density (in low intensity)

Barraza, Tajima, Strickland, Roa (Photonics, 2022)

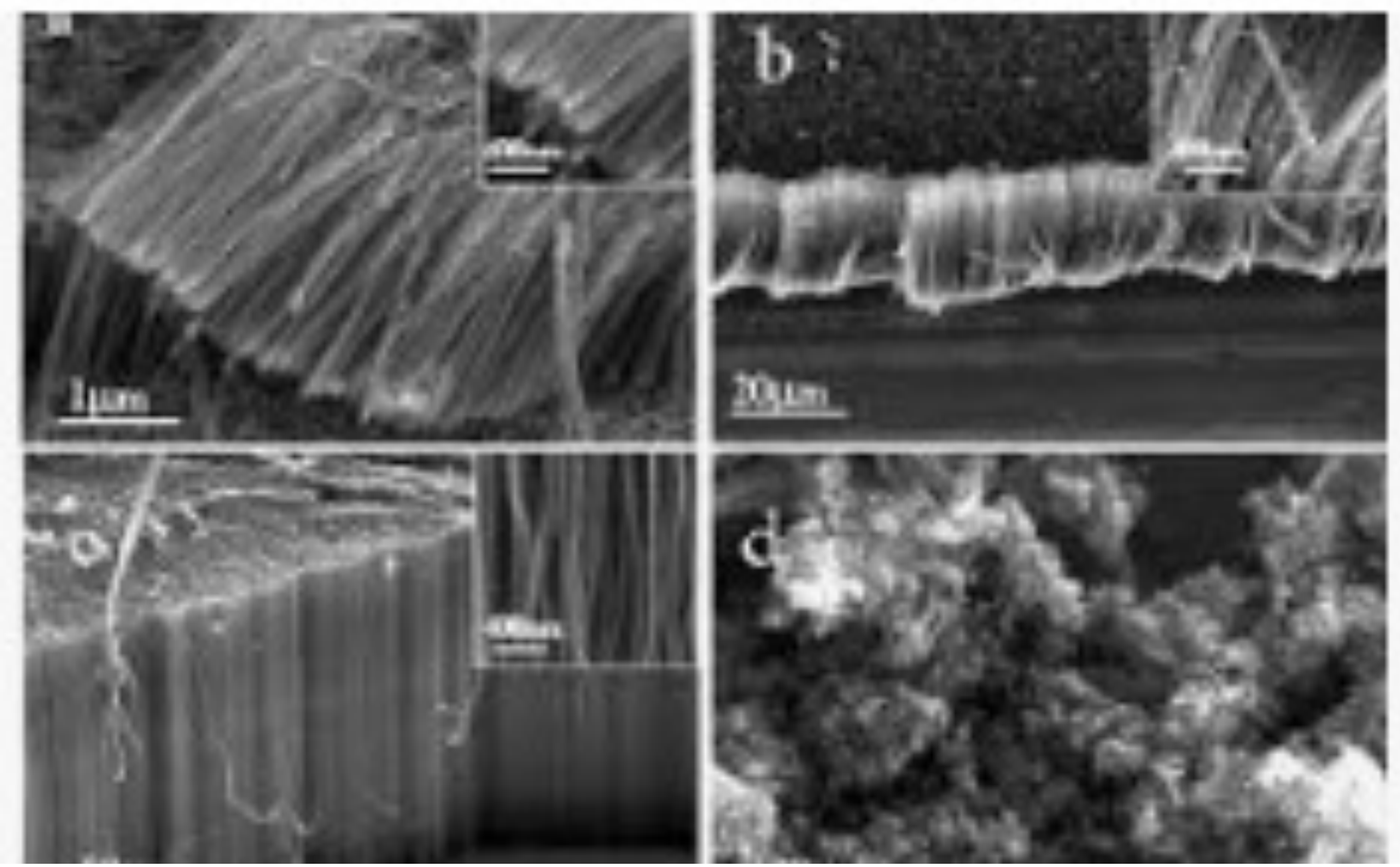


(a) **(b)**

Figure 3. Energy distributions, maximum kinetic energies, and laser to total particle energy efficiency with respect to plasma density for BWA simulations after 1 ps using gaussian lasers with intensities of $a_0 = a_1 = 0.1$, and pulsewidth of 100 fs. The seed laser wavelength was held at λ =1 μm


New Materials and Laser in High Density
LWFA

Carbon nanotubes on a substrate:
→ toward Carbon Nanoforest (instead of plasma w/vacuum)

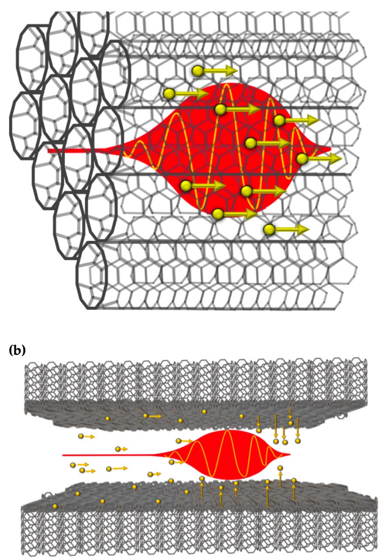


Laser Wakefield Acceleration near critical density

Near critical density ~ $n_e = 10^{21}$ /cc

gaseous plasma → solid nanotube

no vacuum necessary!



(laser size and nanotubes do not scale in these cartoons)

Excitation of electron acceleration possible with $I \sim 10^{14}$ W / cm^3

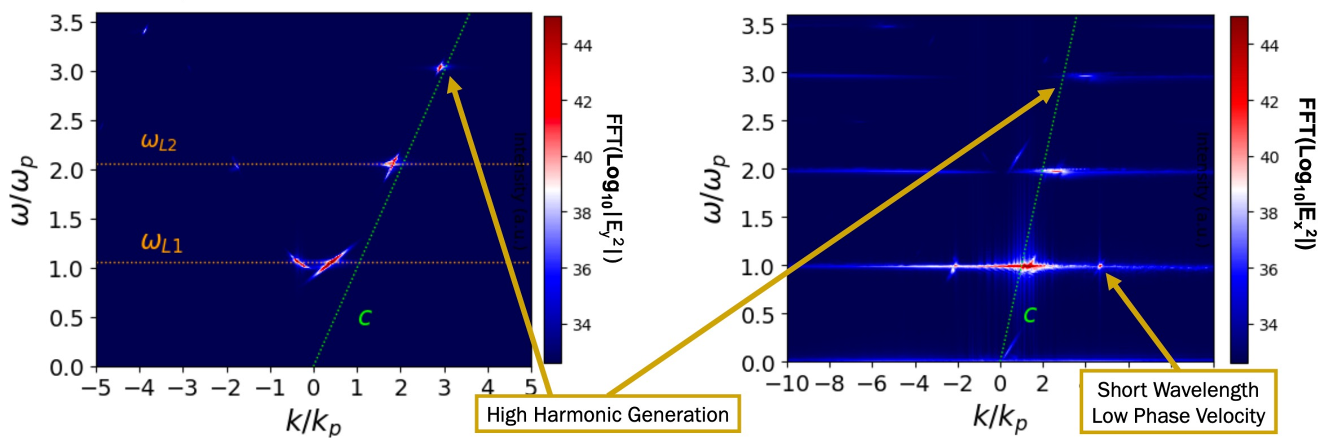
Coupling gets stronger near $n_e = 10^{21}$ /cc

← overlap of plasma waves with different v_p

← curved laser $\omega(k)$, varied v_g

Dispersion Relation: FFT($Log_{10}E$)

- High Harmonic Generation
- Short Wavelength and Low Phase Velocity Electrostatic Waves allow for more efficient particle acceleration

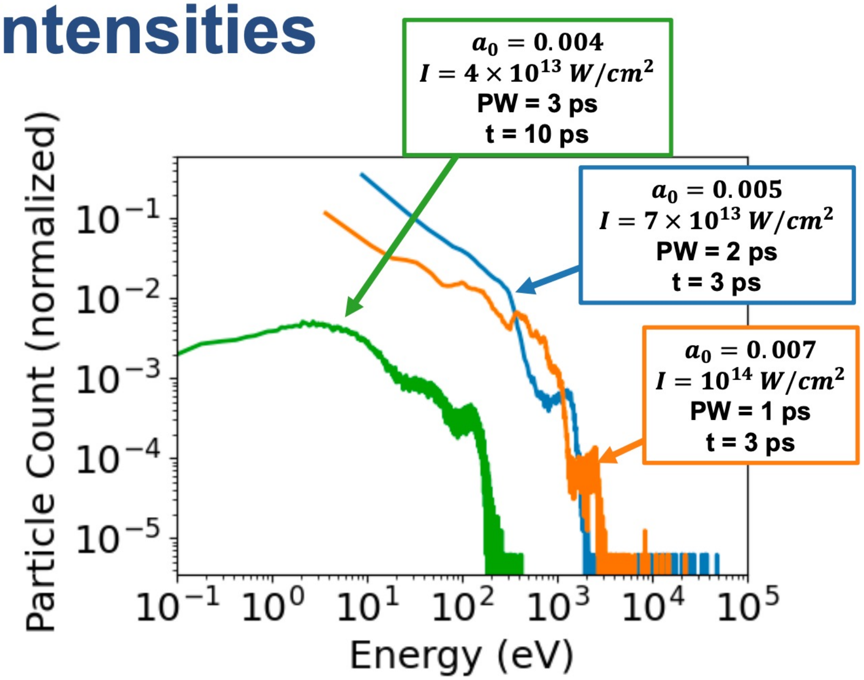


Simulated cases of High Density LWFA with fiber laser (I ~ 10^{14} W/cm^2)

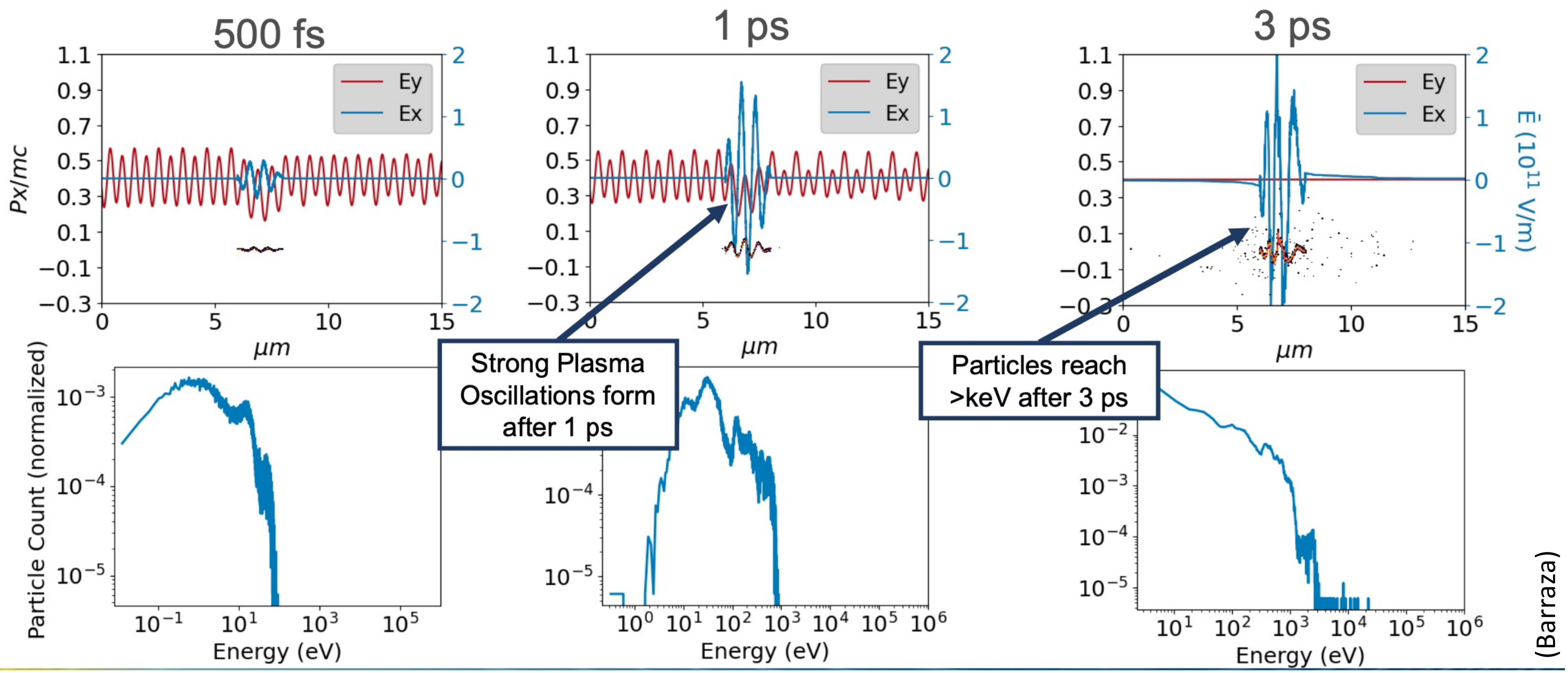
Electron Acceleration vs a_0 and Pulse Width at low Intensities

Pump Intensity (W/cm^2)	Pulse Width (ps)	Time for keV energies (ps)
4×10^{13}	3	NA
7×10^{13}	2	3
1.4×10^{14}	1	3

- Electron Energy has is not strongly correlated to intensity
- Instead electron energy is more a function of total laser energy deposited onto target
- For simulation of a_0=0.004 and 3 ps pulsewidth, strong plasma waves were still developing after 10 ps simulation time.



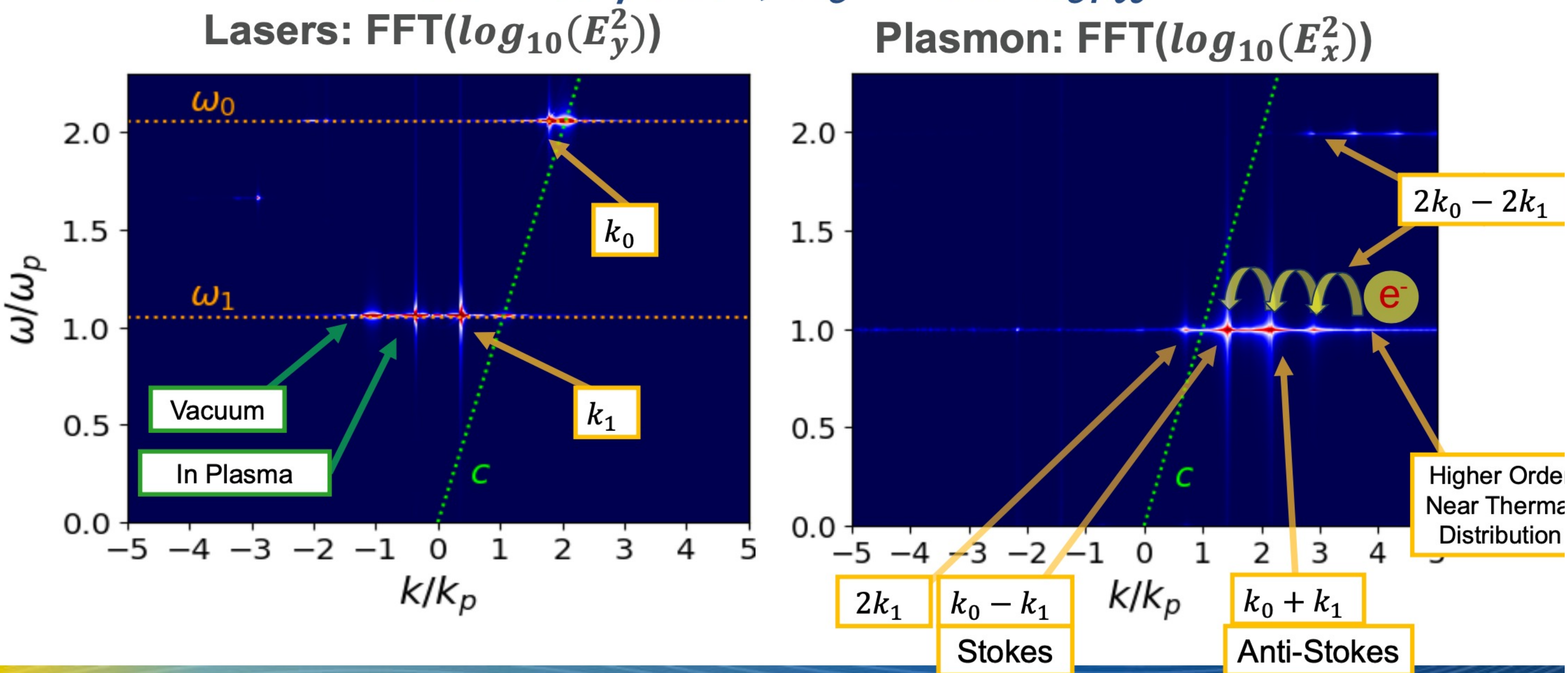
Target Foil Simulations in time: $a_0 = 0.007 \rightarrow 10^{14} W/cm^2$ with 2 μm Target



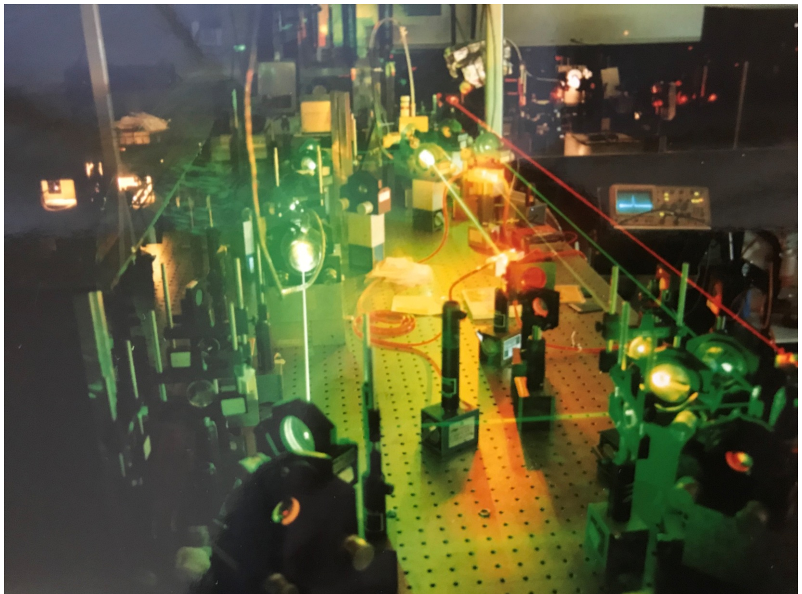
(Barraza)

Four-Wave Raman Cascade Excite Low Phase Velocity

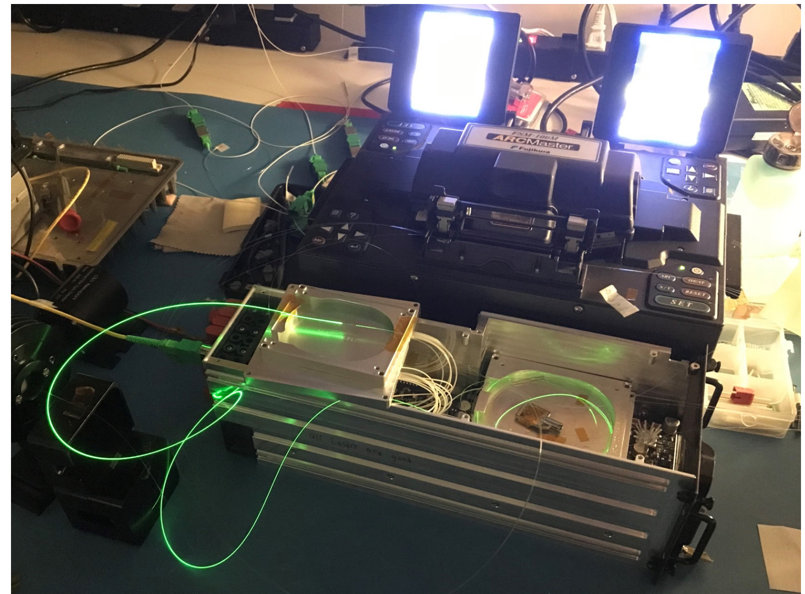
$\approx 10^{14}\ W/cm^2,\ n_e = 0.9\ n_{crit}$



Free-Space Laser vs. Fiber Laser



CPA laser
(invented by Strickland / Mourou)



Fiber laser
(currently we collaborate with
Donna’s fiber laser lab)

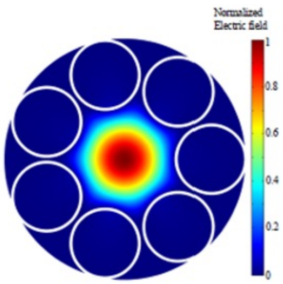
Fiber laser technology

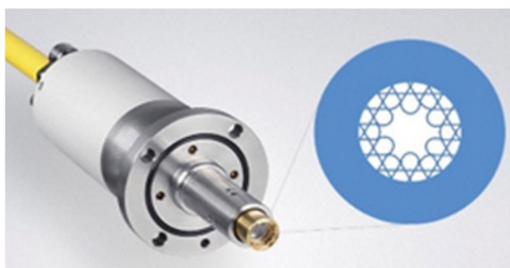
Application	Average Power	Pulse Width	Peak Power	Spatial Mode	Focused Intensity
Metal cutting (heat)	1 to 100 kW	Continous	same as average	MM	10^{7} W/cm^{2} (CW)
Semiconductor Processing	10 to 1000 W	1 to 100 ns	MW (10^{6} W)	MM/SM	10^{9} W/cm^{2} (peak)
Glass cutting (cold ablation)	> 10 W	≤ 0.5 ps	Hundreds of MW	SM	10^{13} W/cm^{2} (peak)
Portable LWFA (>10 keV eletrons)	1 to 10 W	≤ 1 ps	≥ GW (10^{9} W)	SM	≥ 10^{14} W/cm^{2} (peak)

MM: multi-mode (spatial) SM: single mode

Under the collaboration with Dr. Donna Strickland on going

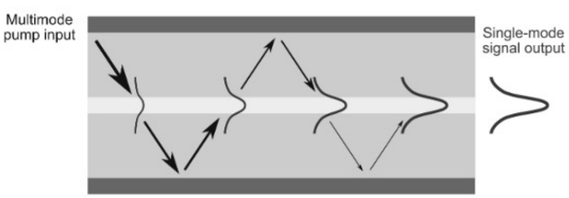
(Dr. W. J. Sha)

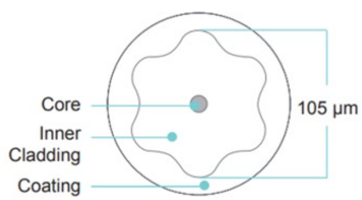


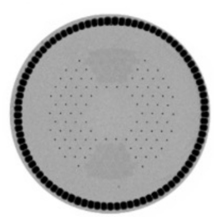


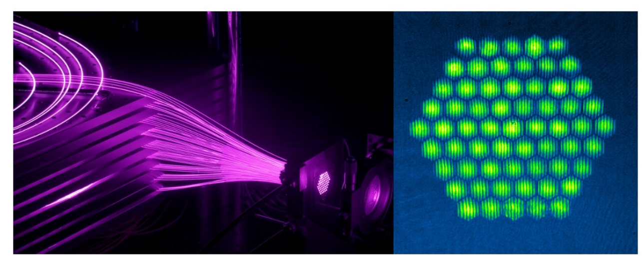
hollow fiber laser

CAN fiber lasers

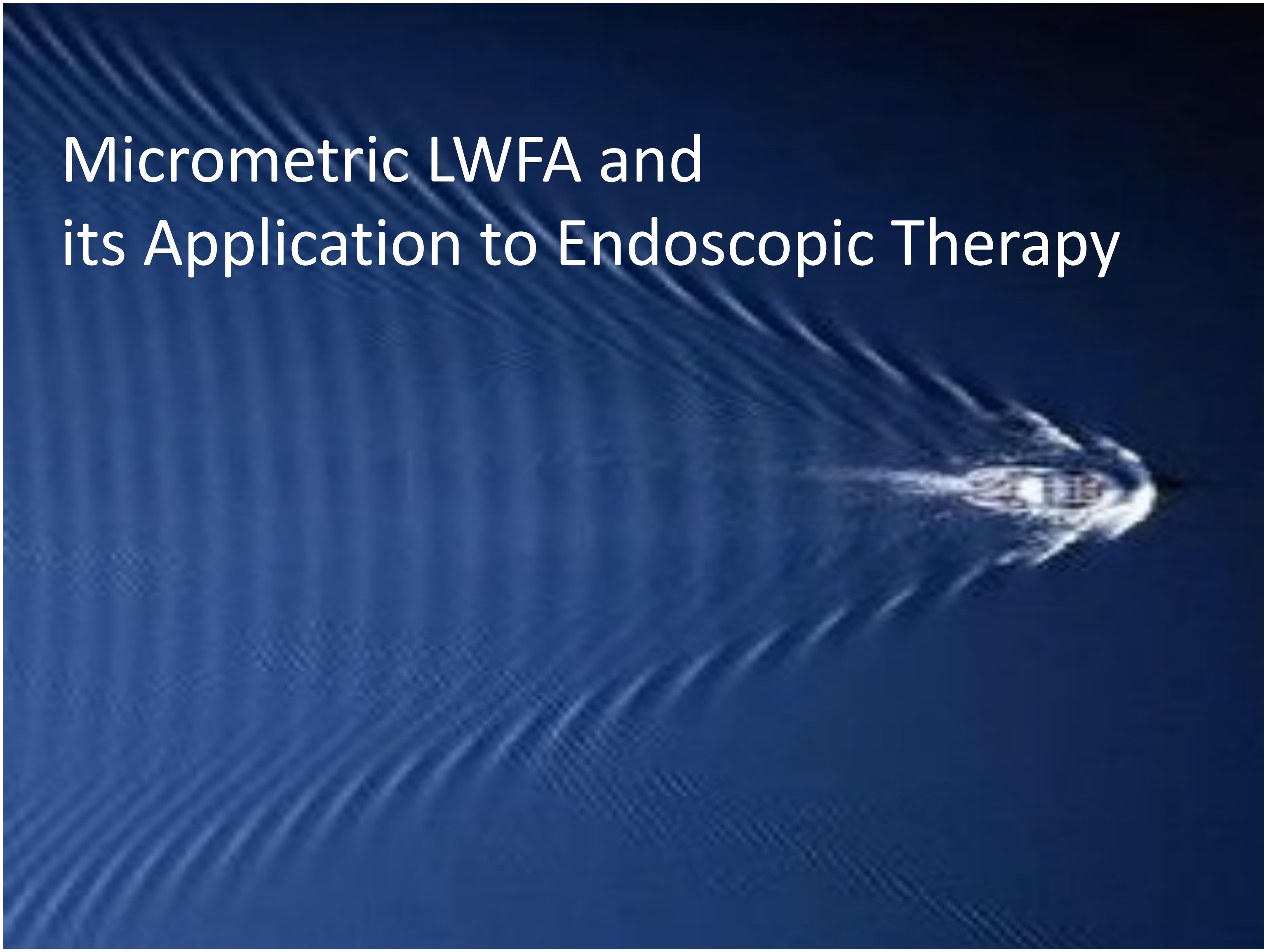








Micrometric LWFA and its Application to Endoscopic Therapy



Conventional electron accelerator (and X-ray) for Therapy

← 5-10m (next room) →

Electron energies by accelerator: 6-20MeV

→ X-rays

(Varian)

LWFA could provide high dose “FLASH” therapy

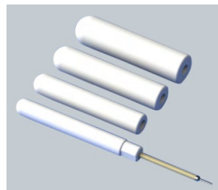
Furthermore, much tinier with **fiber**

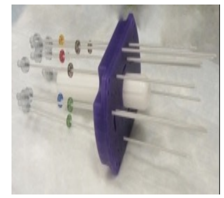
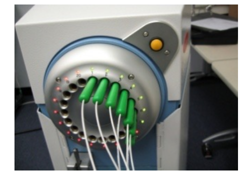
L_e ~ 1 cm / 10MeV → 10 micron / 10keV

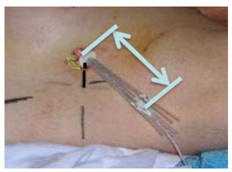
^ Body penetration

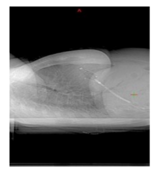
↑ Cancer cell size

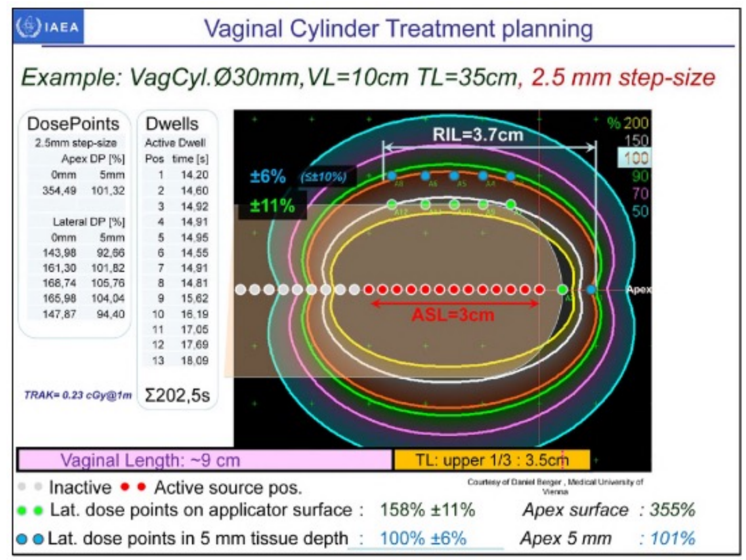
Current radiotherapy applications (from skin, vagina, uterine, breast, etc.)

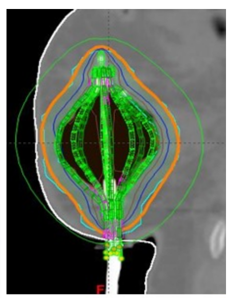







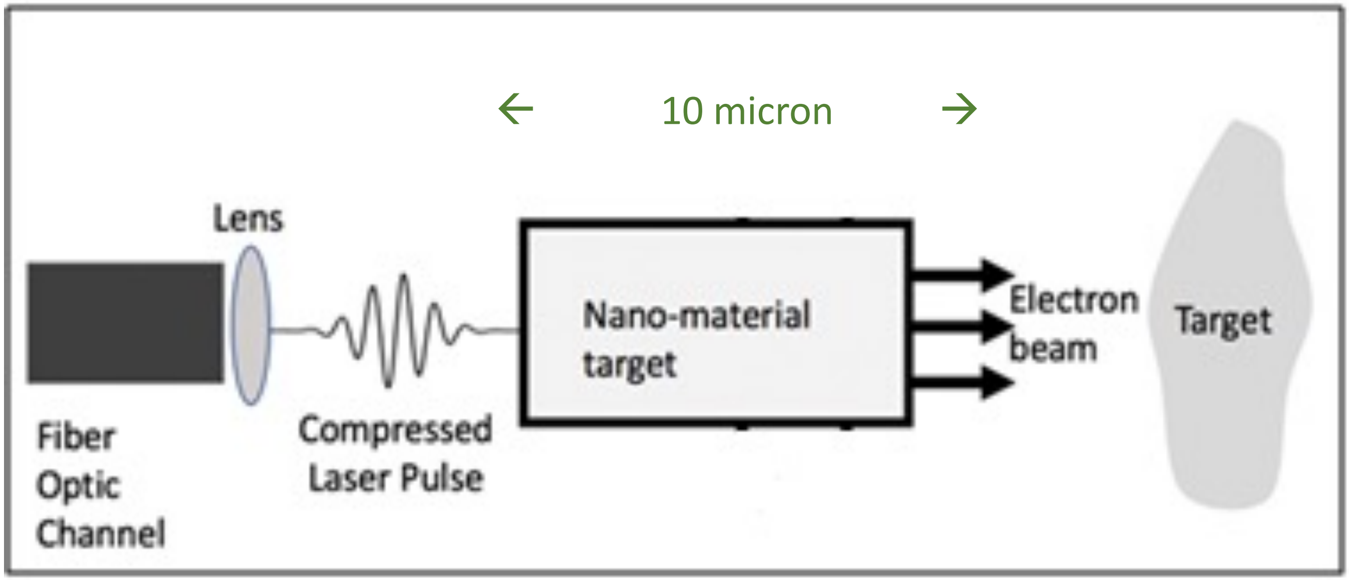


→ Much smaller, endoscopic in ours

(Prof. D. Roa)

In situ / endoscopic fiber delivery of electron radiotherapy of cancer (Roa et al, 2022)



Fiber laser drives *in situ* **nanotube** target in front of **cancer cells**

→ **Compactification**, **accurate** (no collateral damage), and **cheap** (vacuum can be avoided)

Cost estimate comparison with Brachy therapies

↓

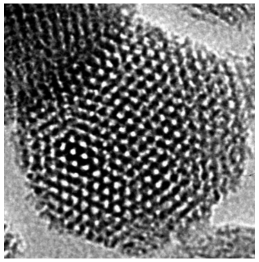
	LWFA – HDR	Iridium-192–HDR	Cobalt-60–HDR
Purchase Estimate	$100K - $300K	$700K - $900K	$700K - $900K
Room Shielding	None	$200K - $500K	$200K - $500K
Source Replacement	None	~$10K every 4-6 months	~130K every 60 months
Downtime due to Source Replacement	None	1-2 days	1-2 days

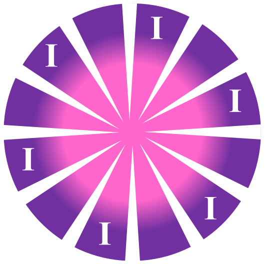
(Prof. D. Roa, preliminary estimate)

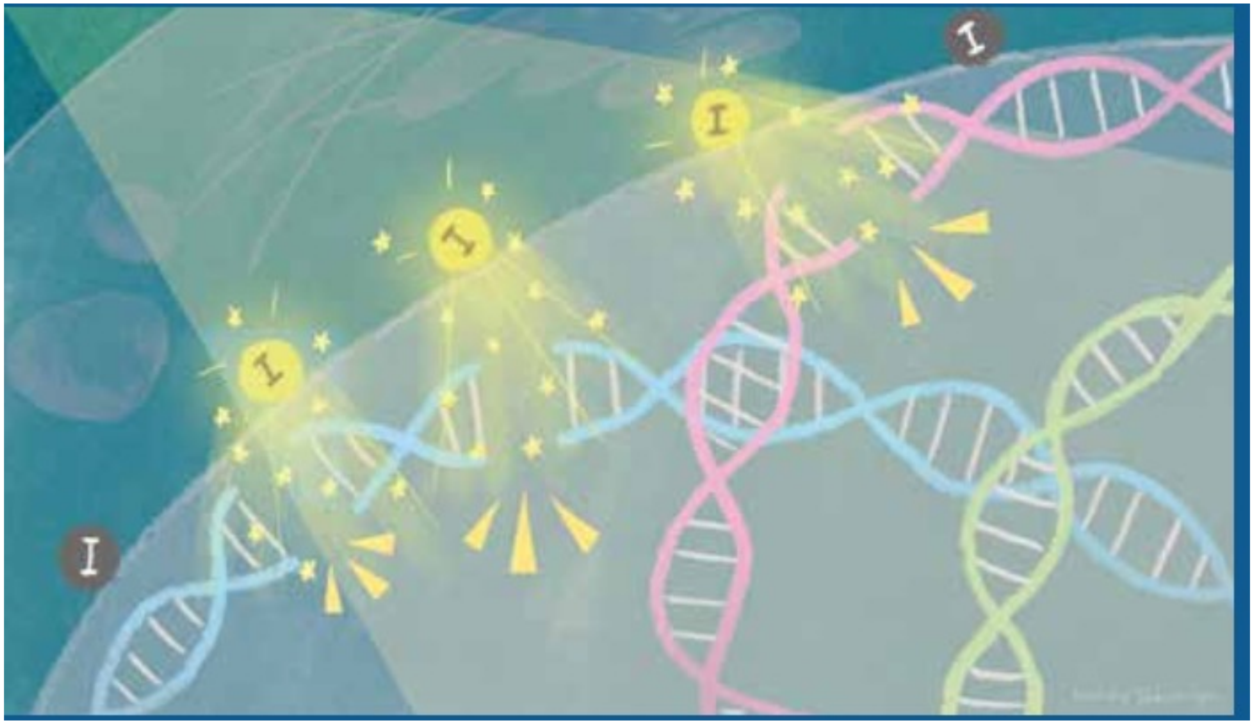
Vector nanomedicine with high-Z metal to target cancer cells for electron radiotherapy

High-Z attached to the vector:
stop **electrons**

Nanoparticle **vector**:
delivered to **cancer cell**







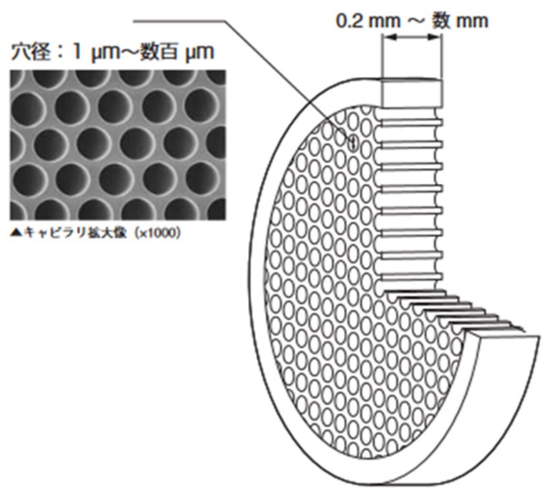
Nanomolecular vector medicine (after Prof. F. Tamanoi, 2022)

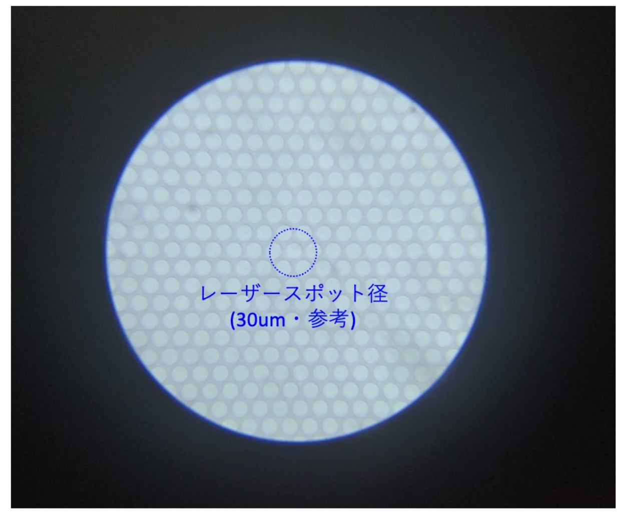

Recent Simulations and
a Proof-of-principle Experiment

Proof-of-principle experiment of High Density regime LWFA

Experiment at KPSI, Japan (Sept-Oct., 2022) (Mori et al.)

キャピラリープレートの概要





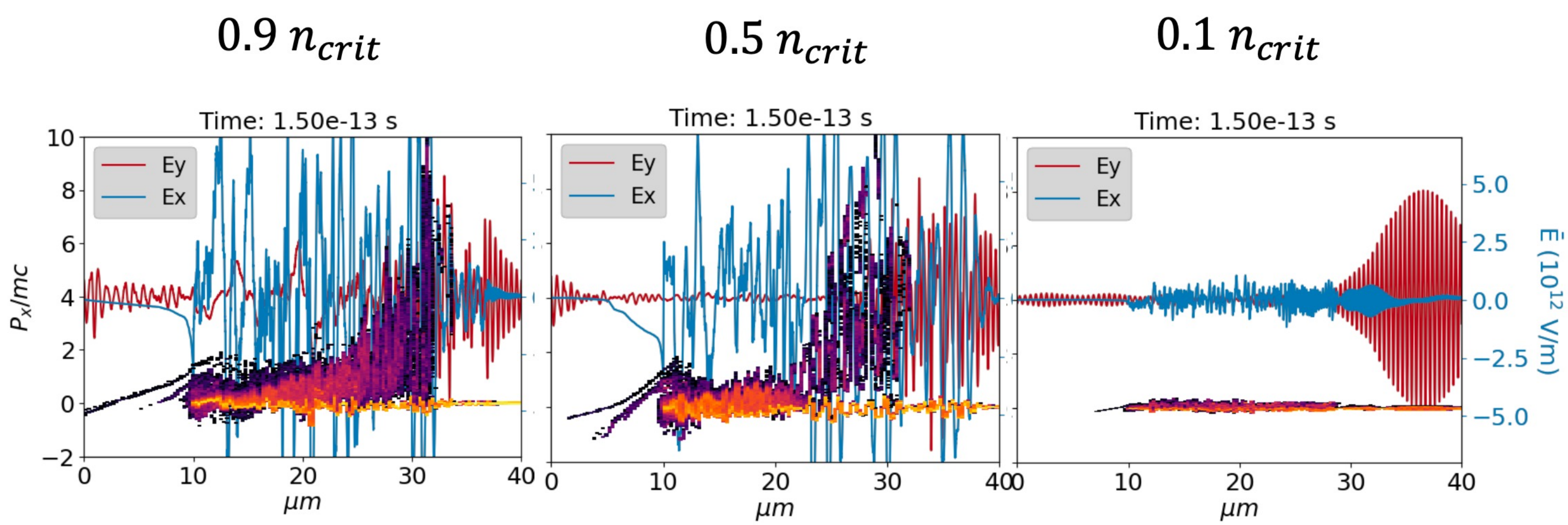
Capillary holed glass target

光学顕微鏡像

材質　重フリントガラス　(鉛含有ガラス)
穴径10um, ピッチ12.5um, 厚み400um, 斜めに穴を加工(角度12度、戻り光防止)

Simulation: density dependence

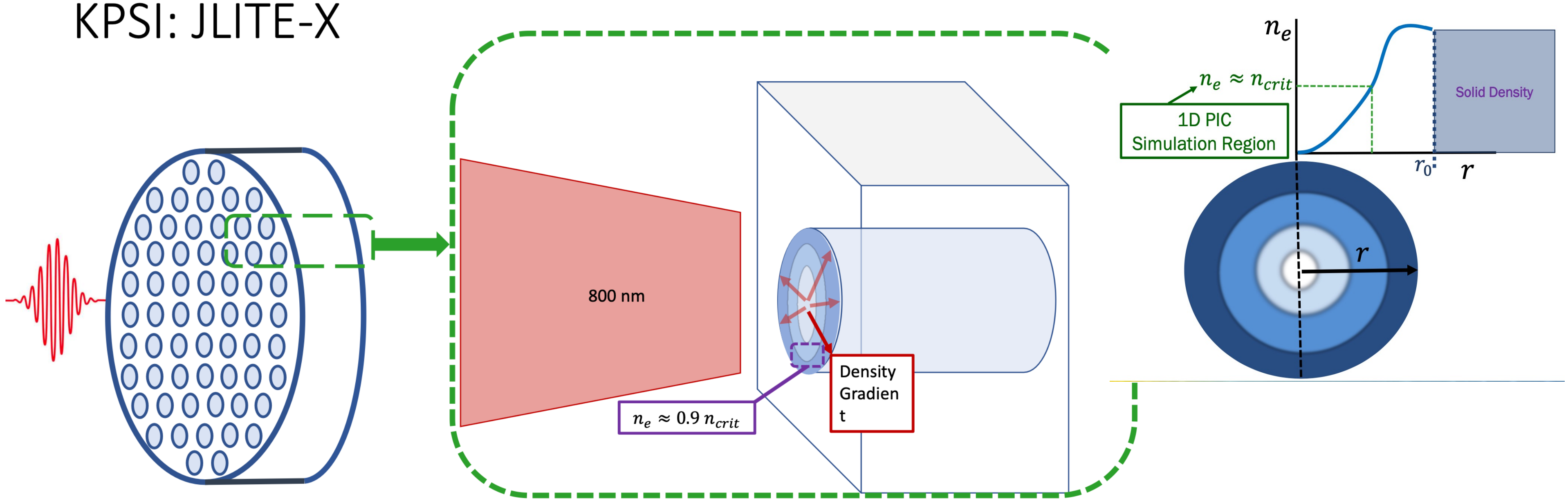
Under Dense



(E. Barraza)

Density Profile in the mm cavity : the channel with near critical density path

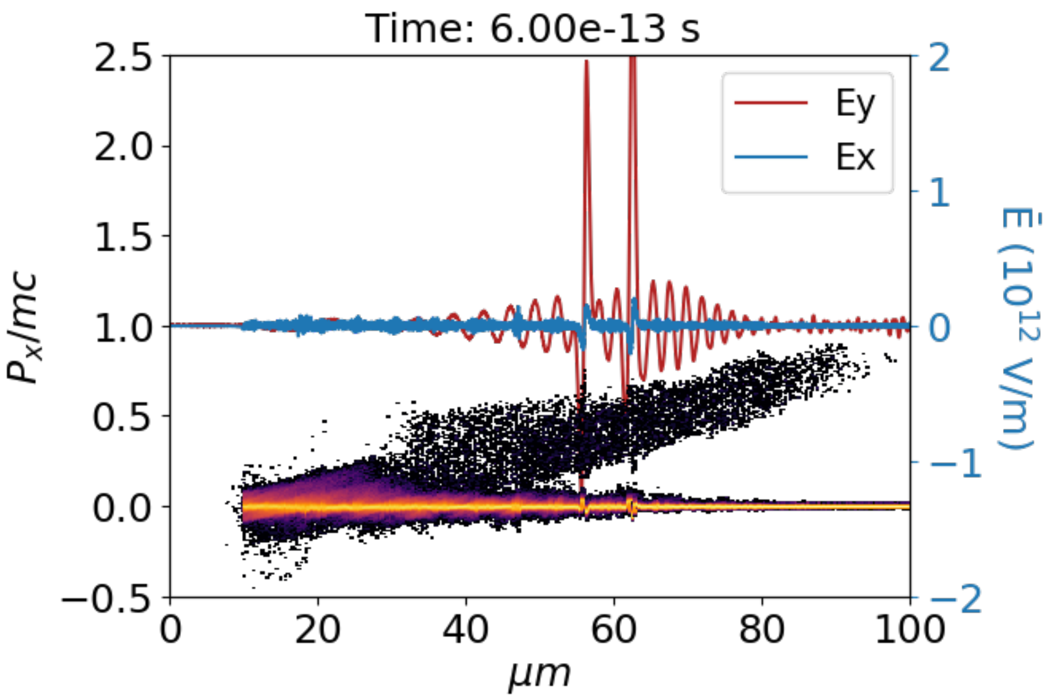
KPSI: JLITE-X

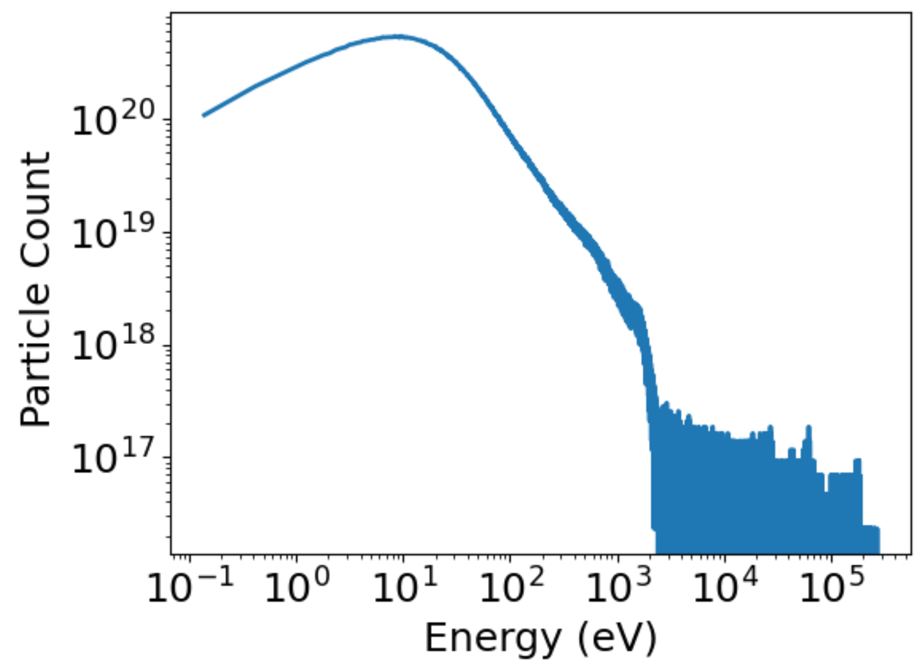


KPSI (Mori et al.2023)

$$n_e = 0.9\, n_{crit}$$
$$a_0 = 0.4\,,\ \tau_{pw} = 40\ fs$$

(simulation of KPSI expt)





(Roughly agreeing with the observed electron energies at KPSI up to 100keV)

(E. Barraza)

Conclusions

1. LWFA acceleration to near the critical density
2. Coupling strongest near the critical density
3. Short pulse → longer pulsed, beat wave
4. Micrometer acceleration, to 10keV electrons
5. Fiber laser possible: intensity ~ 10^{14} W/cm^2
6. At the tip of endoscope
7. Inside of the patient, look and shoot

   no need for vacuum (e.g. carbon nanotube)
8. proof-of-principle experiment