Laser wakefields in plasma, nanostructures, and blackhole vicinities

OSA FiO Visionary Talk
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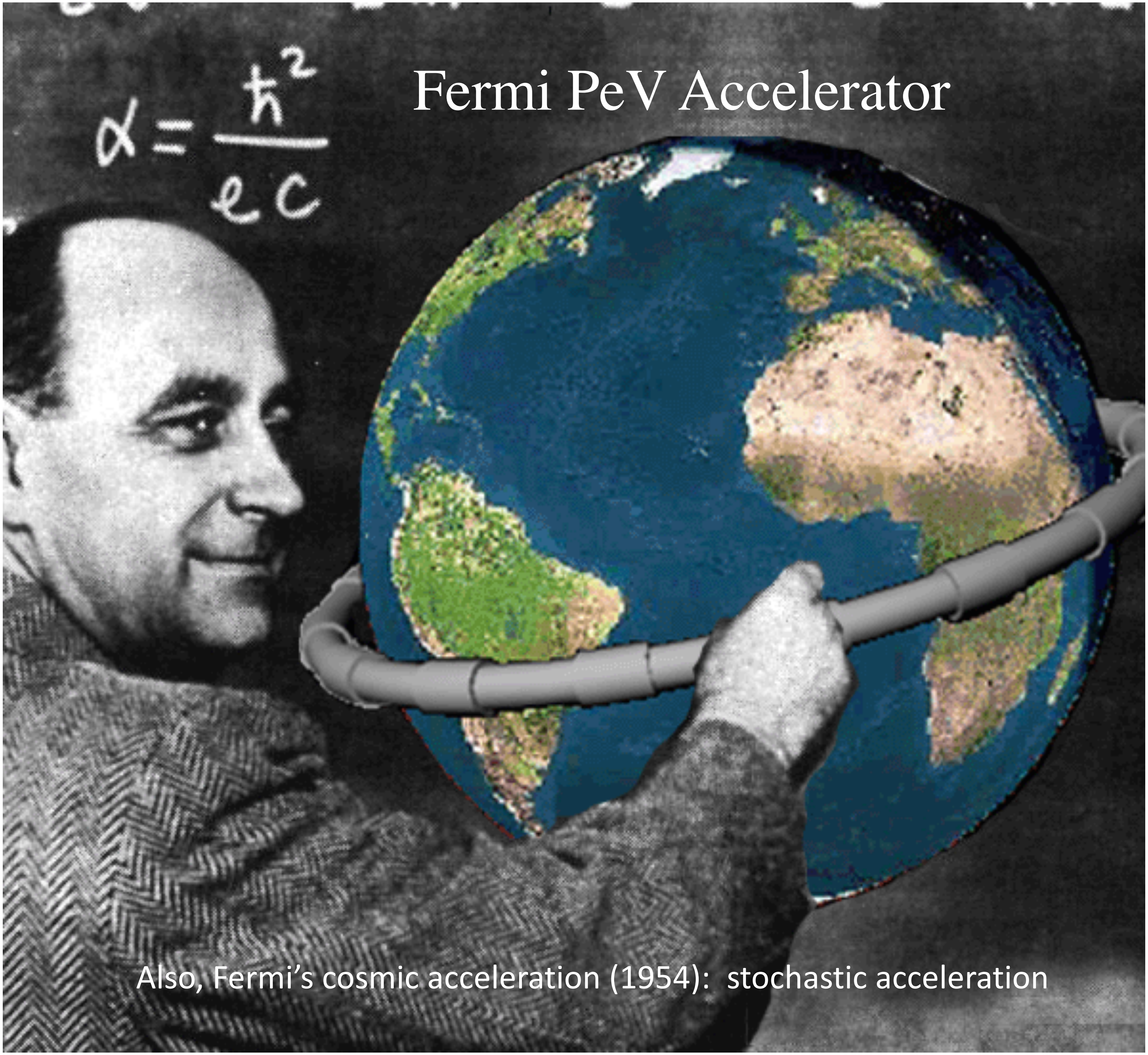
Collaboration: G. Mourou, K. Nakajima, S. Hakimi, S. Bulanov, T. Ebisuzaki, X. Yan, M. Zhou, A. Chao, K. Abazajian, S. Barwick, X. M. Zhang, D. Farinella, P. Taborek, F. Dollar, J. Wheeler, Y.M. Shin, V. Shiltsev, N. Naumova, W. J. Sha, J. C. Chanteloup, S. Nicks, D. Roa, A. Necas, C. Barty, D. Strickland, A. Sahai

- Introduction
- Fiber laser and ascent toward 100GeV and collider (and a tiny laser) by wakefields
- Single-cycled laser and “ TeV on a chip”
- Nature’s favorite acceleration: cosmic wakefield from blackholes
- Laser accelerator inside our body

Fermi PeV Accelerator

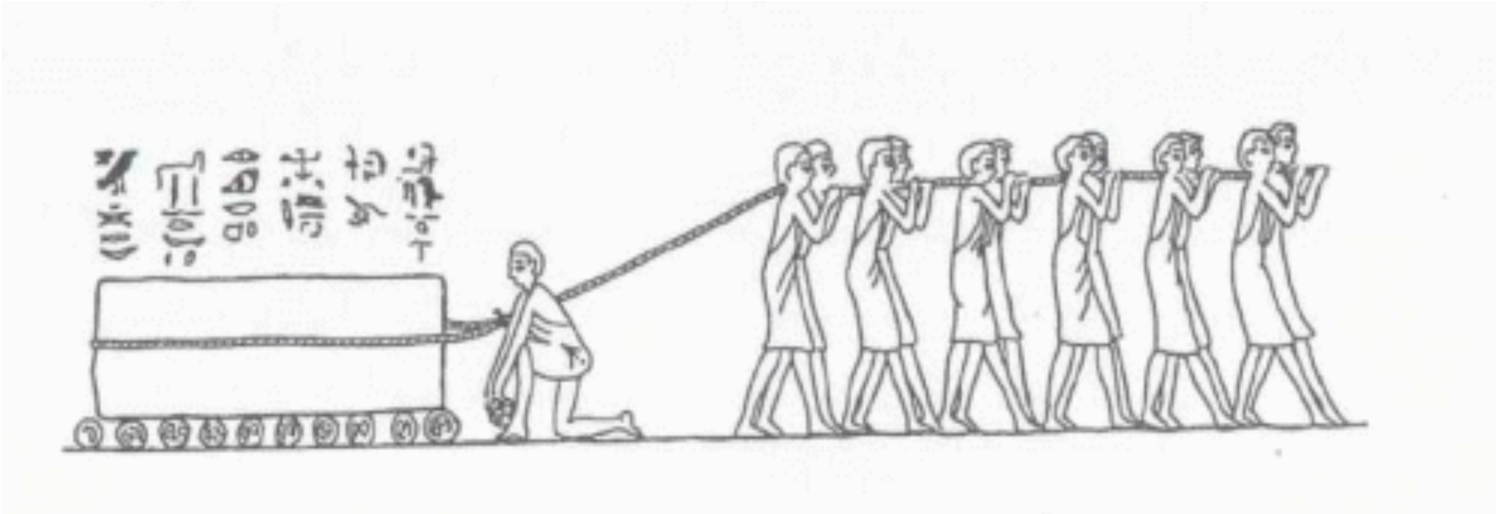


Also, Fermi’s cosmic acceleration (1954): stochastic acceleration

Plasma accelerator driven by beam/pulse

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

Coherent and smooth structure (not stochastic)



Plasma accelerator driven by laser (coherent photons)

←[***Fermi***'s challenge for PeV accelerator]

compactification by $10^3 - 10^4$ (even by 10^6) >> conventional accelerators

enabled by laser technology (intense ultrafast laser compression (Mourou et al.1985. 2013))

[particle beam-driven case: similar (if a bit lower)]

Acceleration by plasma wake waves: History

V. Veksler

Collective acceleration suggested:
Veksler (1956, CERN)
Driven by electron beam
(ion energy)~ (M/m)(electron energy)

N. Rostoker

Many experimental attempts of plasma acceleration (~60's -'70s, Rostoker's lab UCI included)
led to no such amplification
(ion energy)~ (2α+1)x(electron)

Mako-Tajima (UCI) analysis (1978;1984)
sudden acceleration, ions untrapped,
electrons return, while some run away
→ #1 **gradual acceleration necessary**

J. Dawson

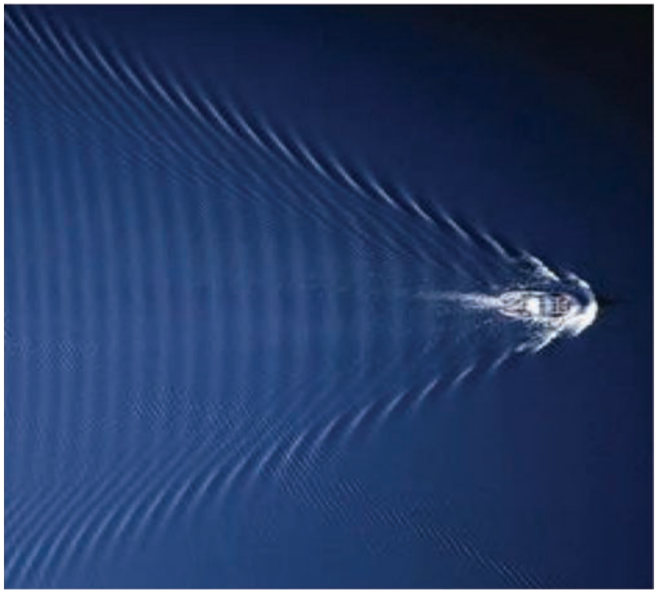
→ **Tajima-Dawson (1979, UCLA) wakefield**
#2 **electron acceleration** possible
with **trapping** **(with the Tajima-Dawson field)** with laser, more tolerant for sudden process

Target Normal Sheath Acceleration
laser-driven ion acceleration (LLNL,2000)
sudden acceleration, ions untrapped

Laser Wakefield (LWFA):

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

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

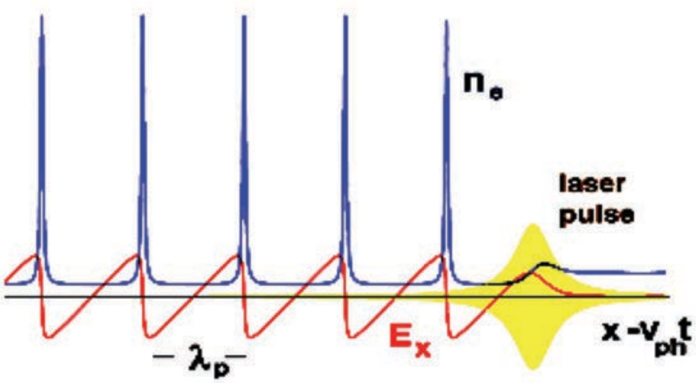


vs

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



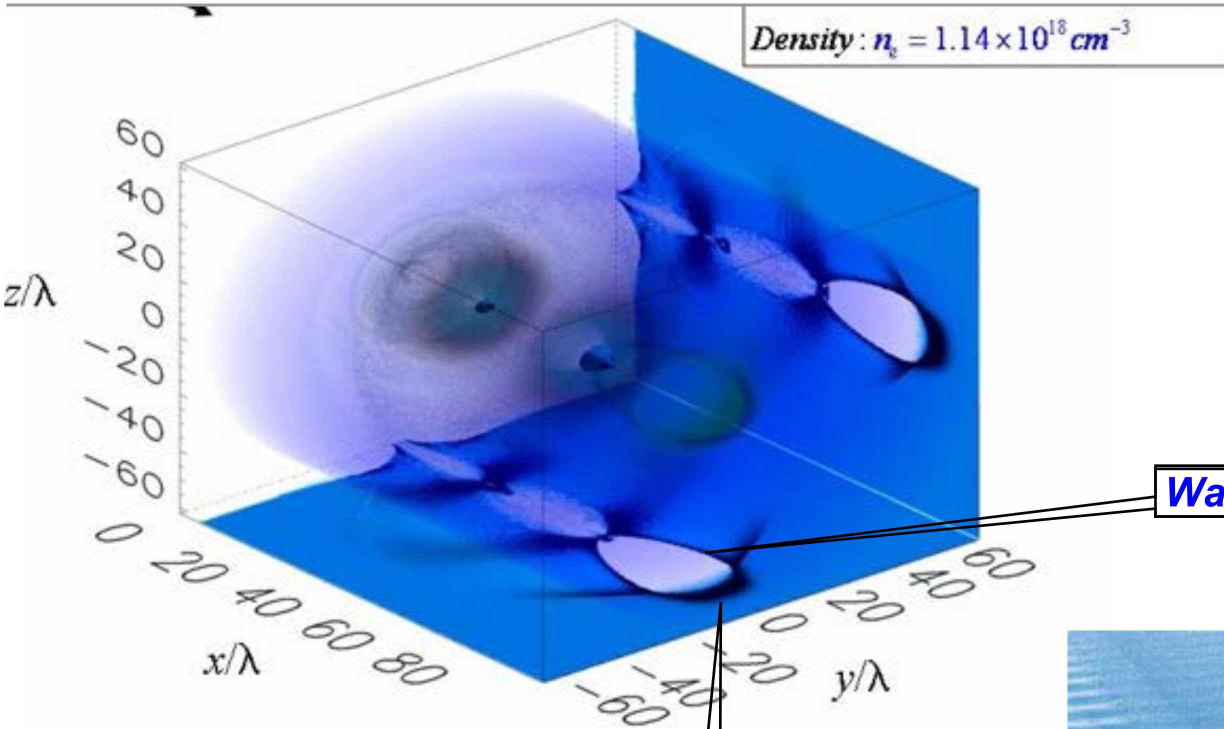
← relativity regularizes (*relativistic coherence*)

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

High phase velocity paradigm

Low phase velocity	High phase velocity
Plasma tends to be unstable	Stable state exists (Landau-Ginzburg state)
$v_{ph} \sim v_{th}$	$v_{ph} \gg v_{th}$
Mode interacts with bulk plasma (Landau resonance)	Mode insulated from bulk plasma
Mode-mode coupling ➔ More modes ➔ More turbulence	Mode maintains coherence
Strongly nonlinear regime (large Reynolds' number) → strong turbulence	Strongly nonlinear regime → strongly coherent Relativistic effects further strengthen coherence
Plasma fragile → anomalous transport, structure disintegration	Plasma cannot be destroyed, structures are formed. Violence tolerated
Trapping: $v_{tr} \lesssim v_{th} \sim v_{ph}$ $x_{tr} = \sqrt{\frac{cE}{B} \frac{L_s}{k_y v_\parallel}}$ [22]	Trapping: $v_{tr} = \sqrt{qE/mk}$ [13] If wave pumped, v_{tr} increases until $v_{tr} \sim v_{ph} \gg v_{th}$ → acceleration or injection Tajima-Dawson saturation: $E_{TD} = \frac{m\omega_p c}{e}$
Characteristic structure: Sheath	Characteristic structure: Wake
Energy gain: by coherent accumulation of electron charges of the sheath (energy amplification of sheath charge accumulation $2\alpha + 1$ (coherence parameter α) [18]	Energy gain: by energy amplification over the trapping width $v_{tr} \sim v_{ph}$ (Lorentz transform factor $2\gamma^2 = 2\, n_{cr}/n_e$)

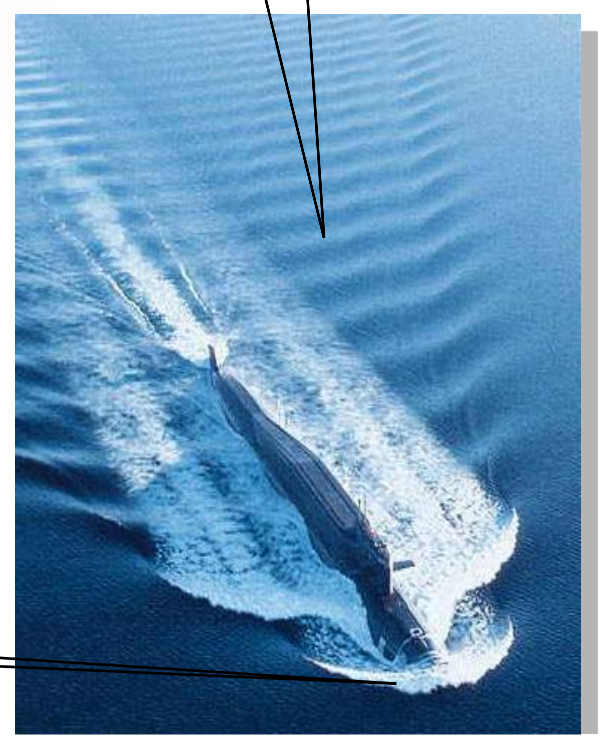
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

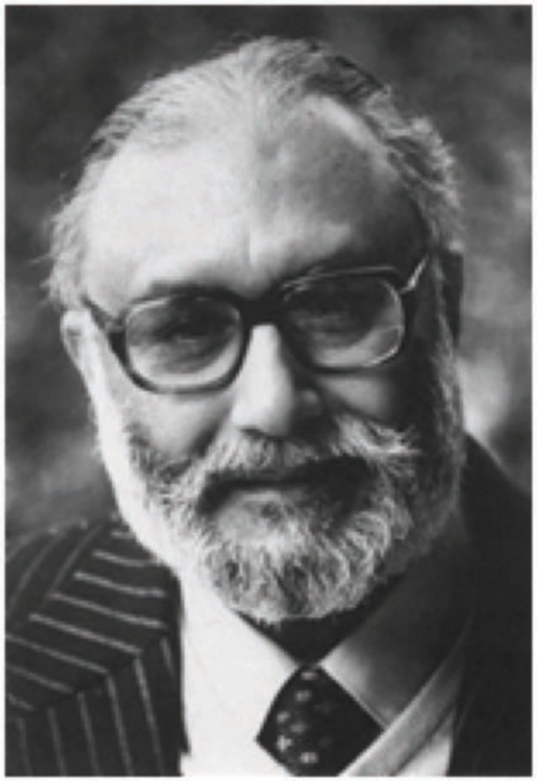
Wake Wave



Bow Wave

Ponderomotive acceleration

The late Prof. Abdus Salam



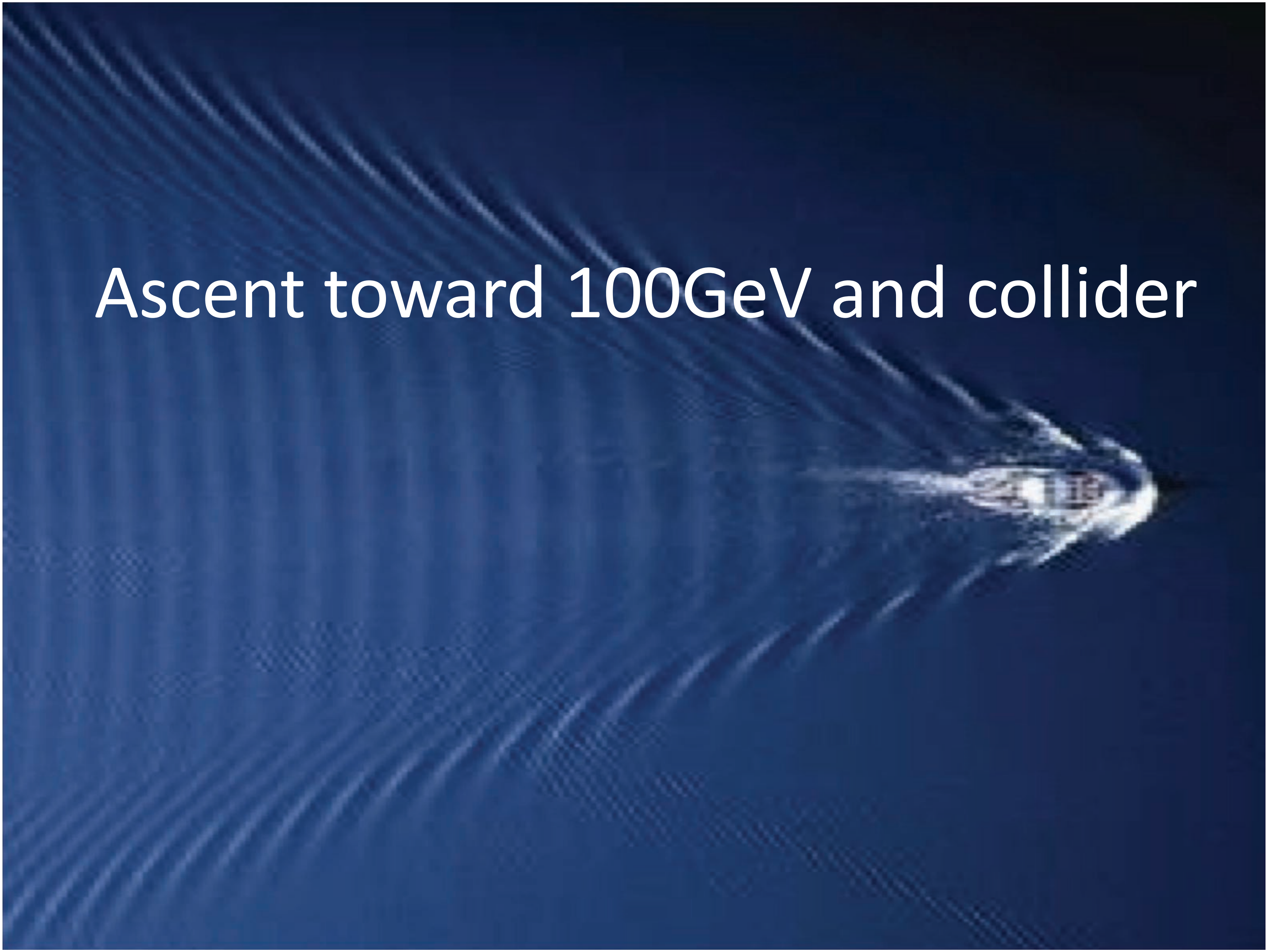
At ICTP Summer School (Trieste,1981),
Prof. Abdus Salam summoned me and discussed about laser wakefield acceleration.

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

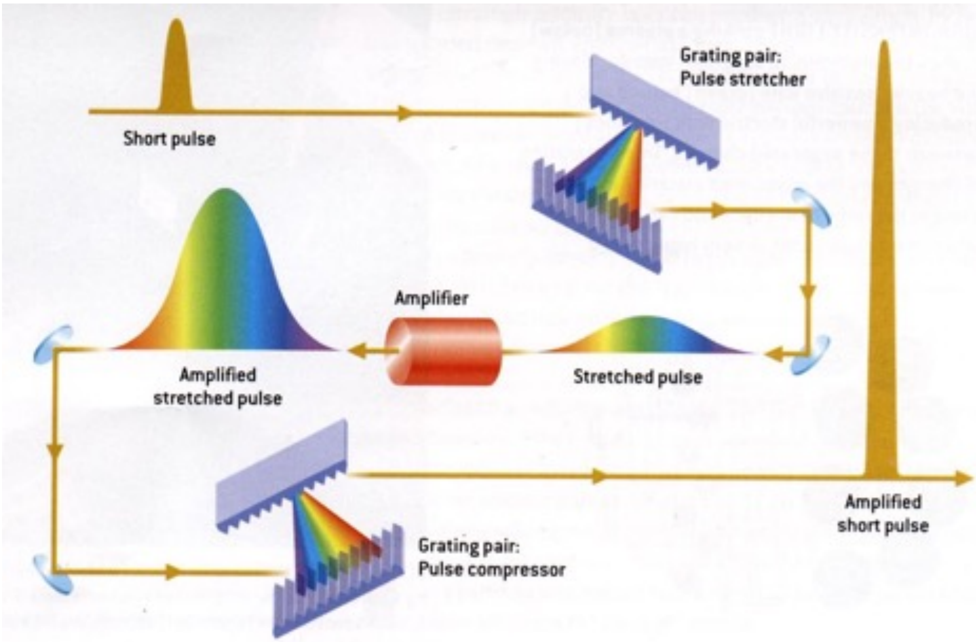
He organized the Oxford Workshop on laser wakefield accelerator in 1982.

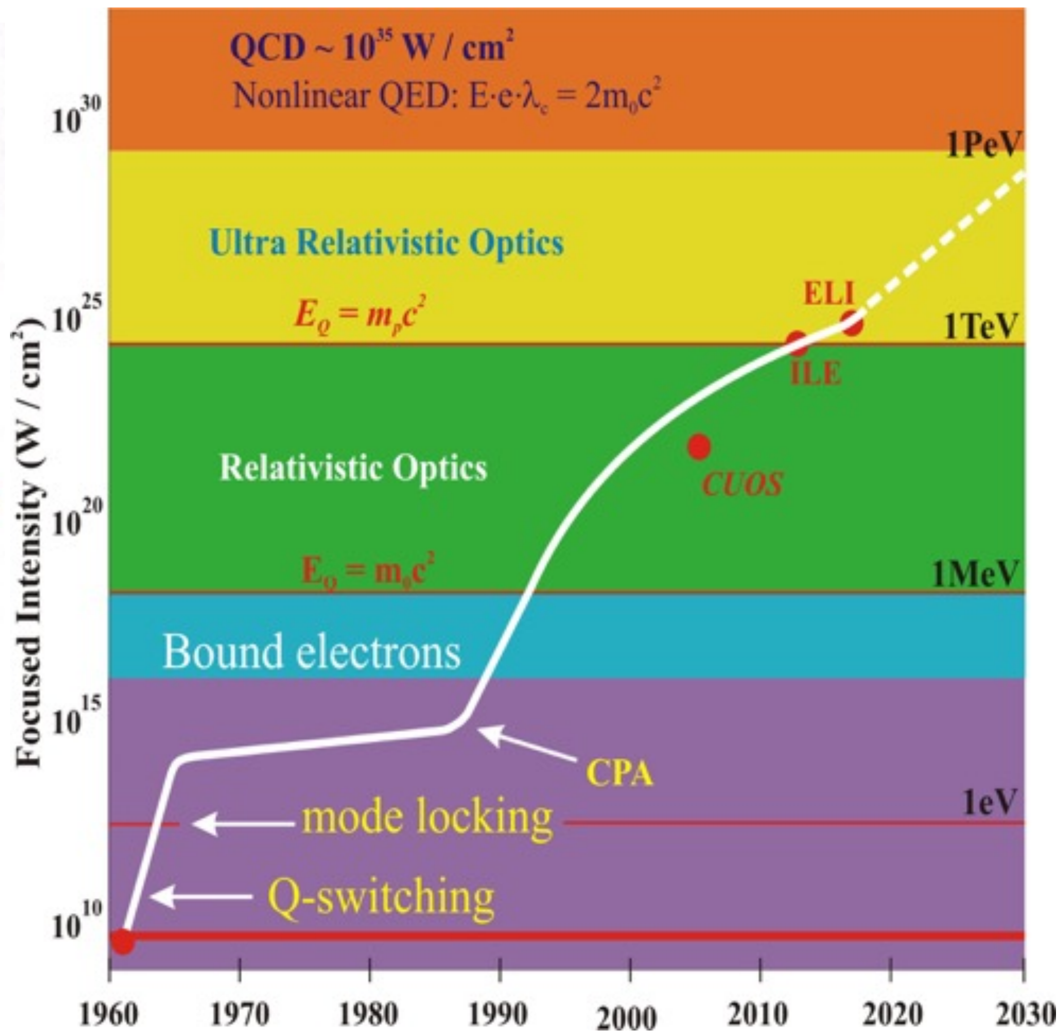
Effort: many scientists over many years to realize his vision / dream
High field science: spawned

Ascent toward 100GeV and collider



Enabling technology: laser revolution



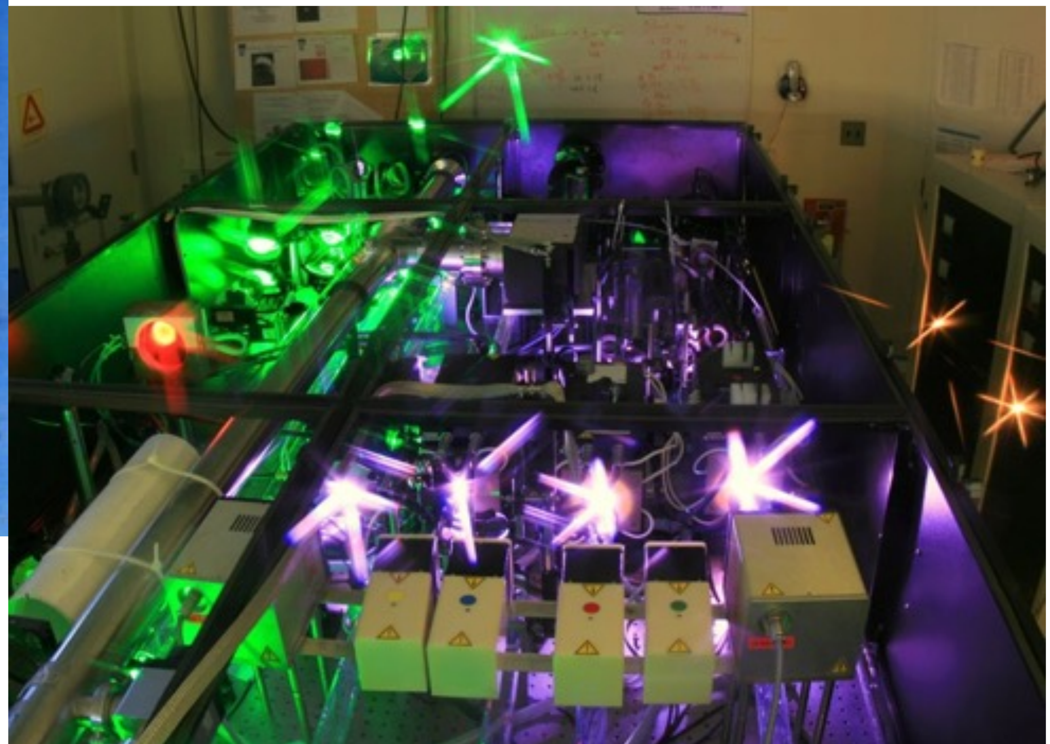


G. Mourou-D. Strickland invented Chirped Pulse Amplification (1985)

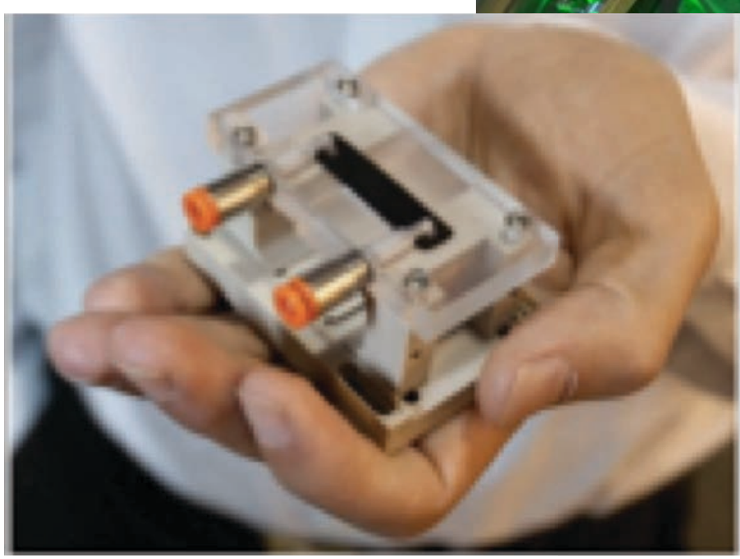
Laser intensity exponentiated since,

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

Demonstration, realization, and applications of laser wakefield accelerators



(Michigan)

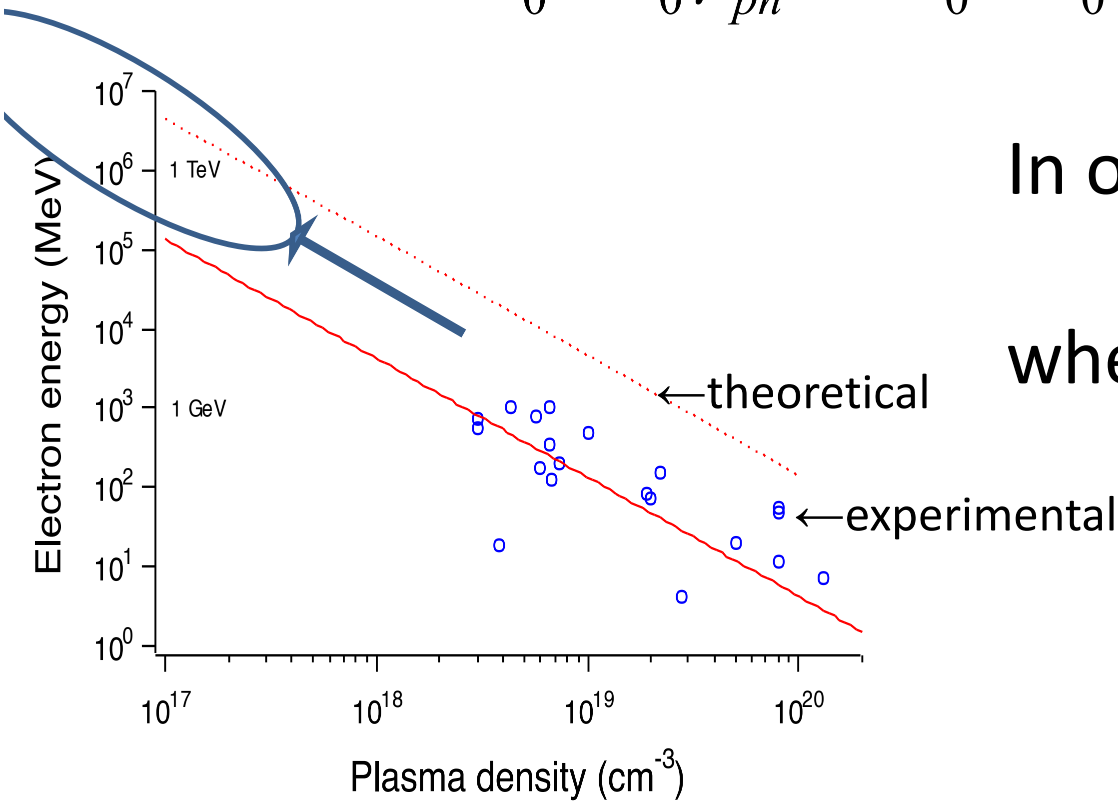


4 GeV laser accelerator LBL

3GeV Synchrotron SOLEIL

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

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

$n_{cr} = 10^{21}$ (1eV photon) → 10^{29} (10keV photon)

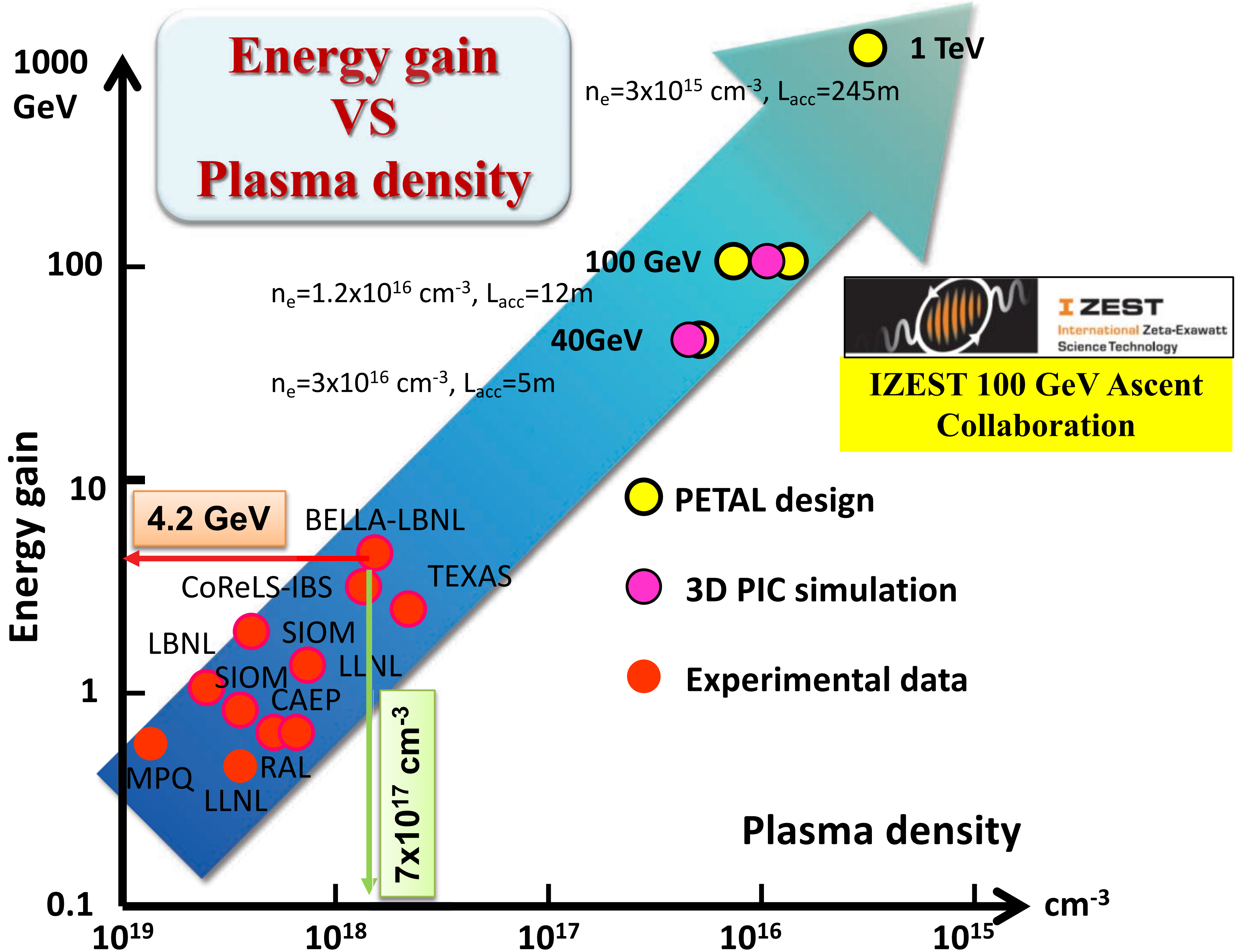
$n_e = 10^{16}$ (gas) → 10^{23} (solid)

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

dephasing length

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

pump depletion length

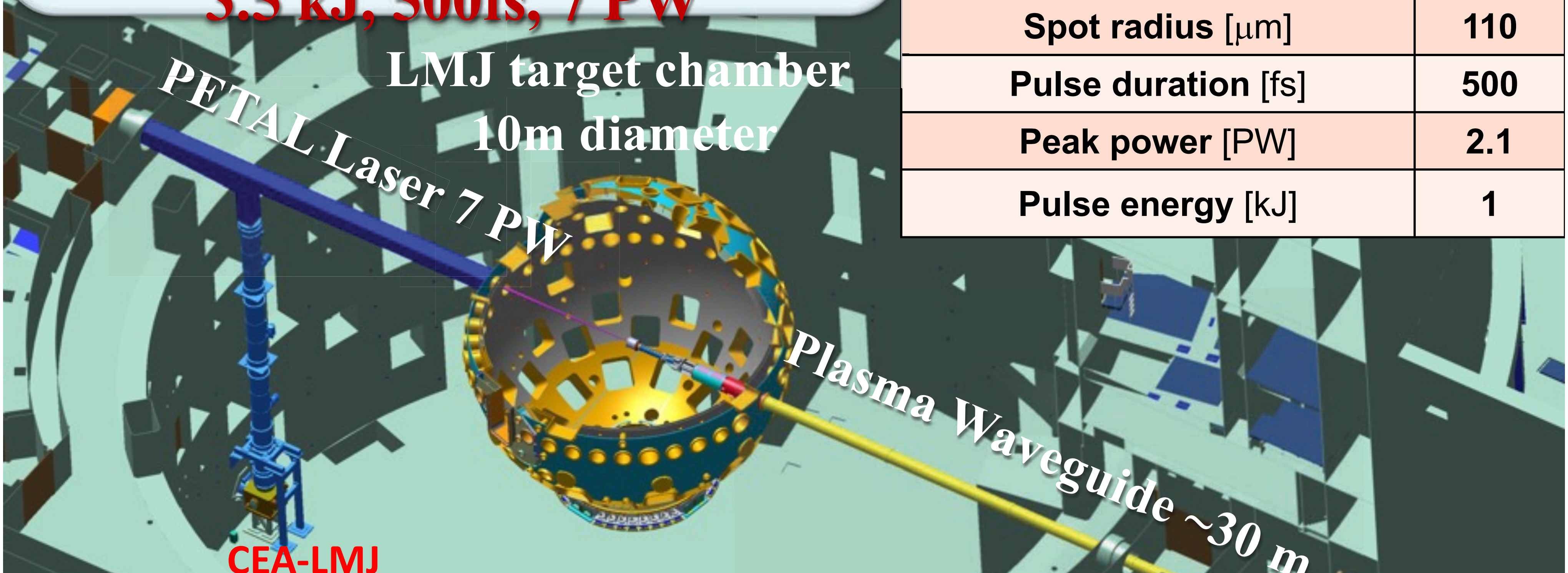


Energy gain
VS
Plasma density
1000
GeV
100
10
1
0.1
Energy gain
1 TeV
$n_e=3x10^{15}$ cm^{-3}, L_{acc}=245m
100 GeV
$n_e=1.2x10^{16}$ cm^{-3}, L_{acc}=12m
40GeV
$n_e=3x10^{16}$ cm^{-3}, L_{acc}=5m
IZEST
International Zeta-Exawatt Science Technology
IZEST 100 GeV Ascent Collaboration
4.2 GeV
BELLA-LBNL
CoReLS-IBS
TEXAS
LBNL
SIOM
SIOM
LLNL
CAEP
MPQ
RAL
LLNL
$7x10^{17}$ cm^{-3}
PETAL design
3D PIC simulation
Experimental data
Plasma density
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
cm^{-3}

K. Nakajima

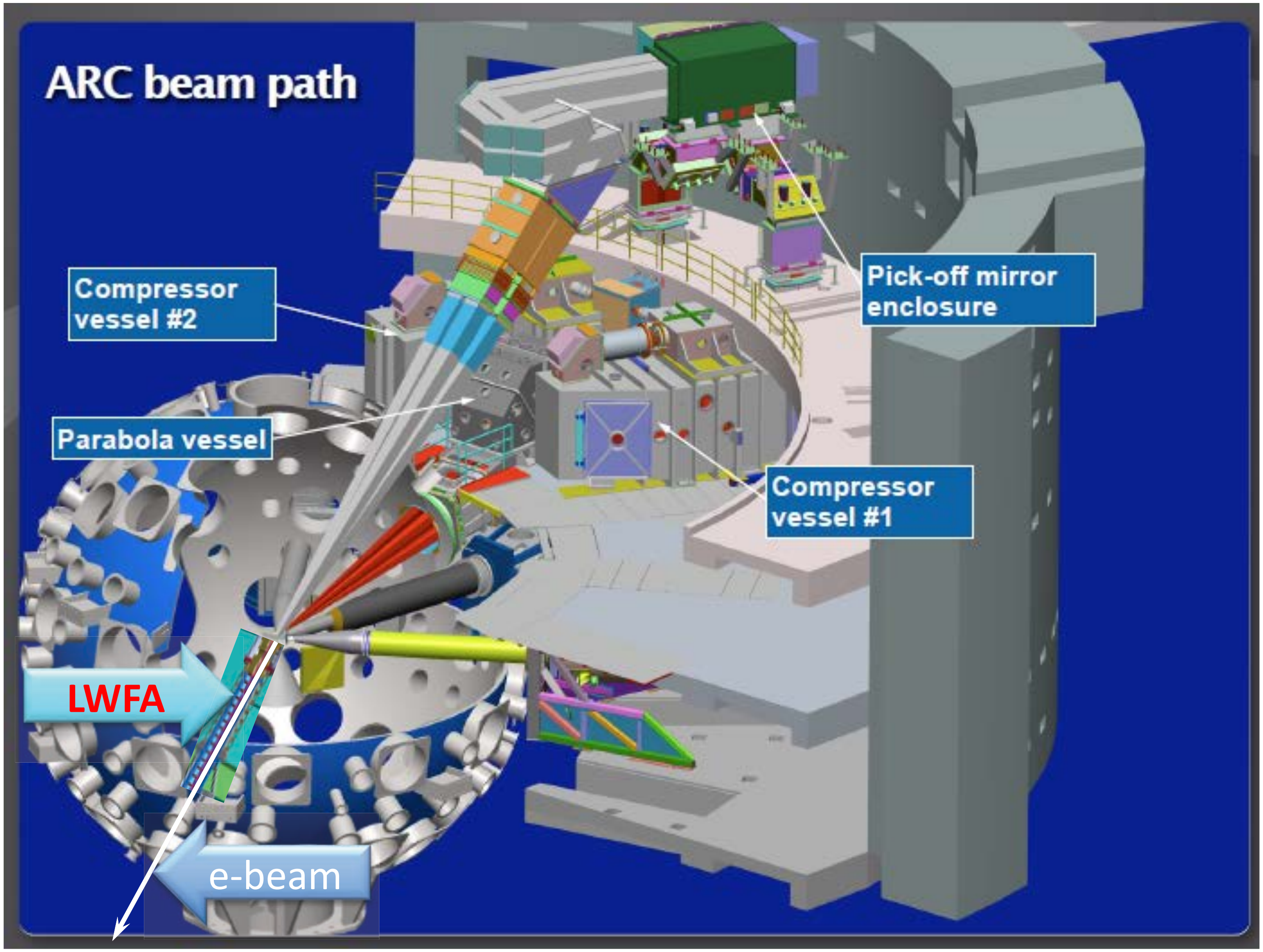
IZEST 100 GeV Ascent Plan
K. Nakajima
at CEA-Bordeaux
PETAL laser
3.5 kJ, 500fs, 7 PW

Experiment parameters	
Energy gain [GeV]	**100**
Plasma density [10^{15} cm^{-3}]	**12**
Accelerator length [m]	**12**
Normalized field a_0	**3**
Spot radius [μm]	**110**
Pulse duration [fs]	**500**
Peak power [PW]	**2.1**
Pulse energy [kJ]	**1**



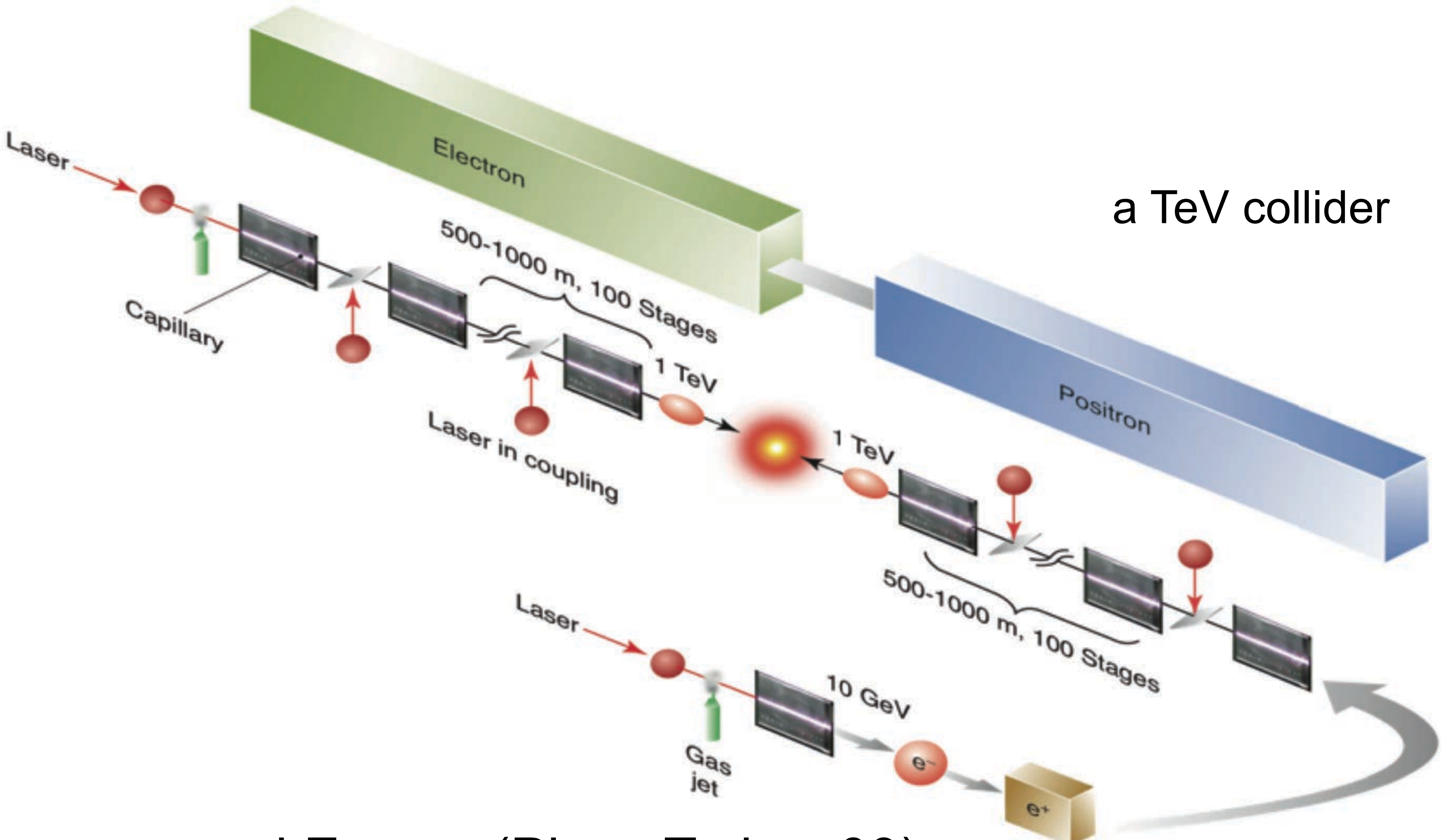
IZEST 100 GeV Ascent Collaboration

100 GeV UV LWFA experiment at LLNL ARC



by courtesy of C.P.J. Barty

Laser driven collider concept



a TeV collider

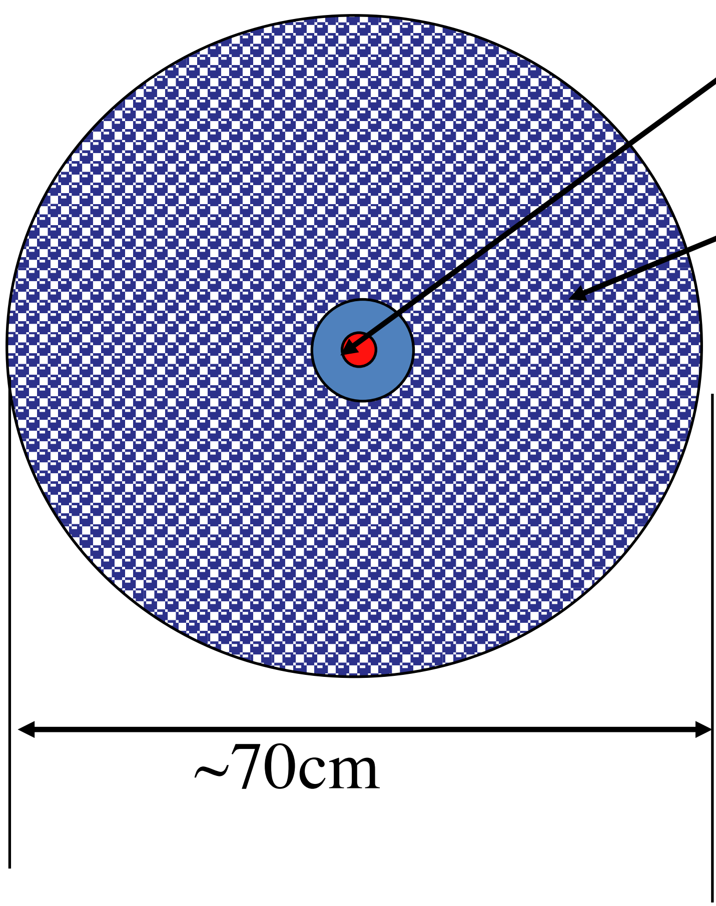
Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

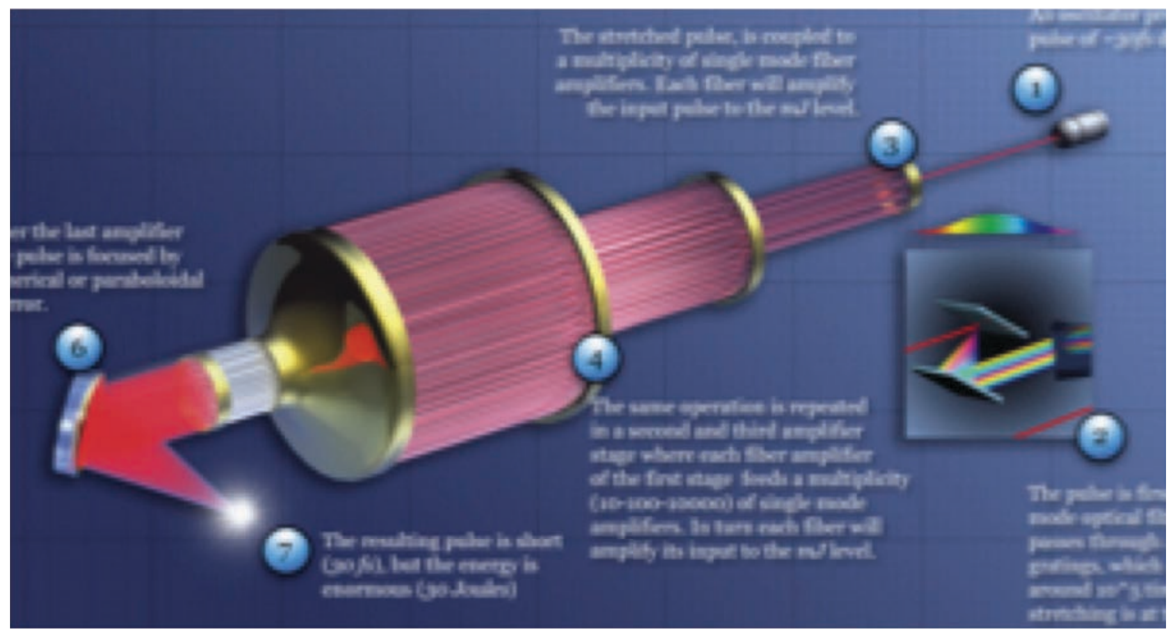
CAN Laser:

Need to Phase

32 J/1mJ/fiber~ 3×10^4 Phased Fibers!

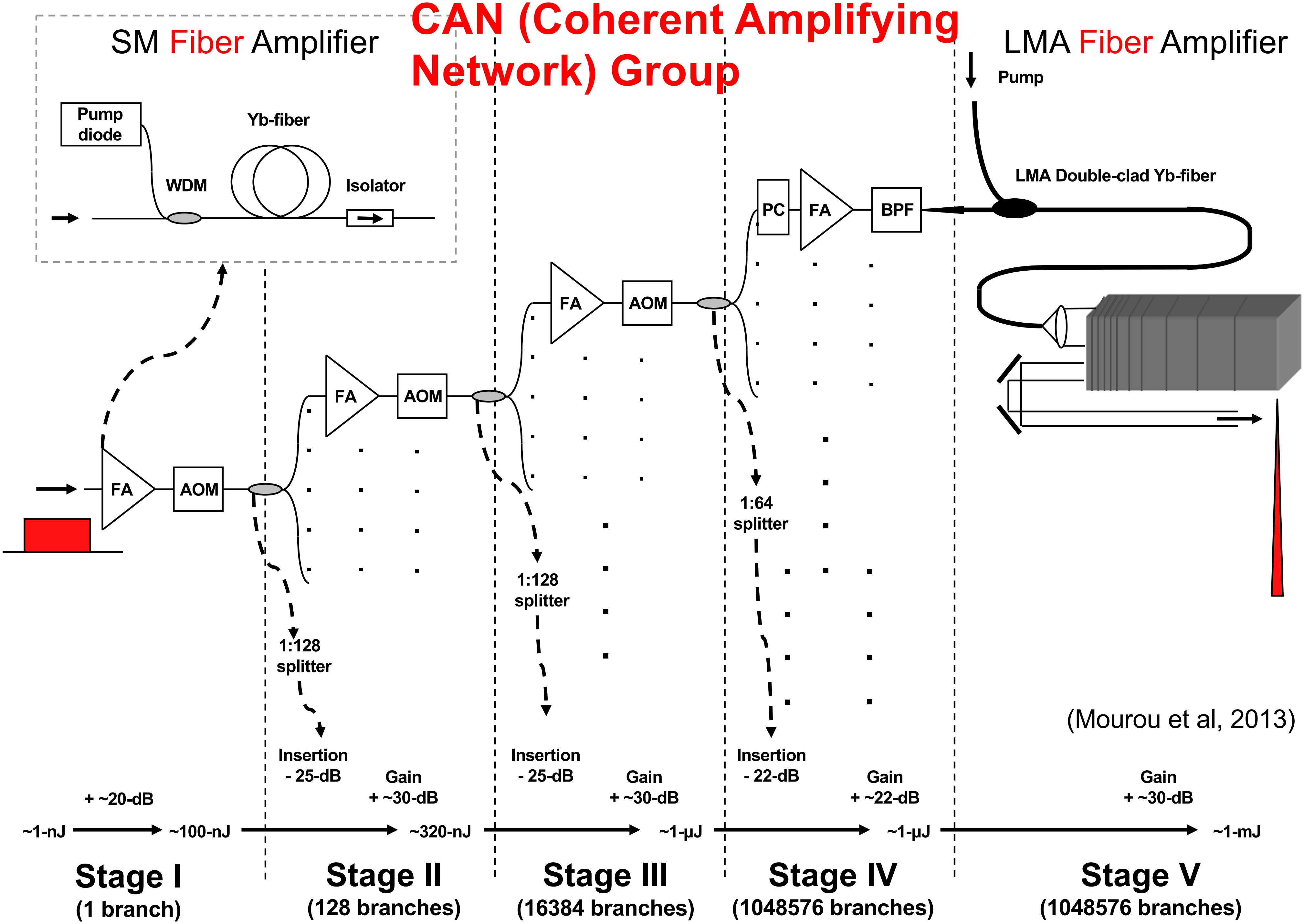


G. Mourou: patent (2009)
Mourou, Brockesby, Tajima, Limpert (2013)



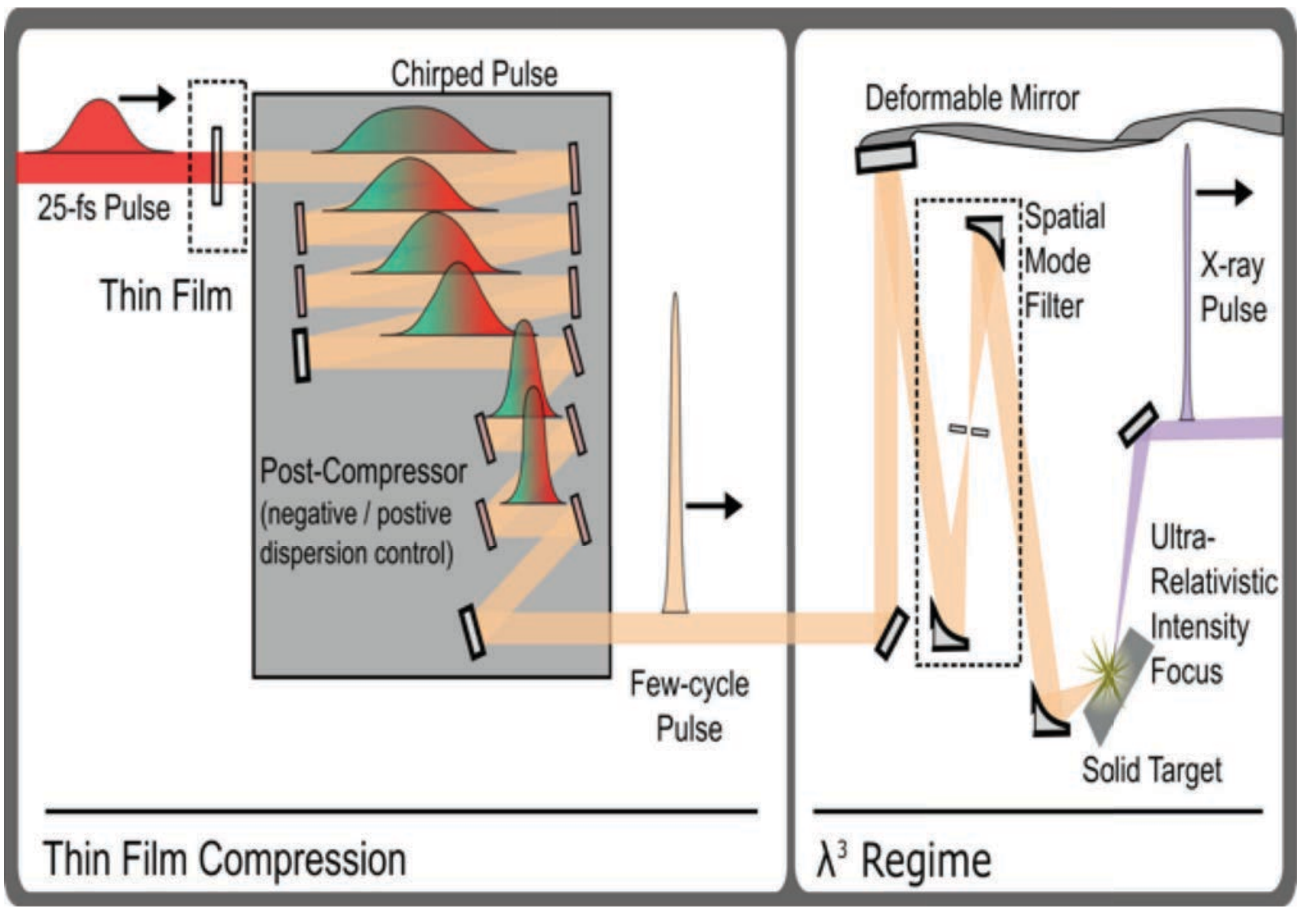
Length of a fiber ~2m   Total fiber length~ 5 10^4km

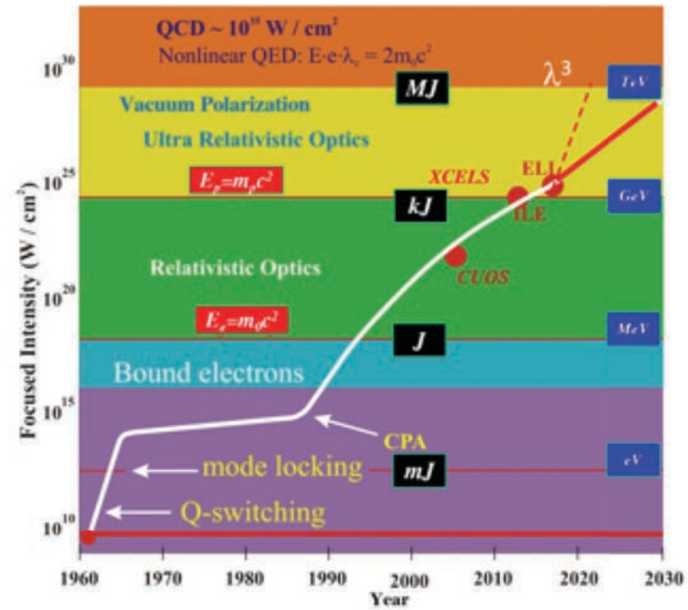
CAN (Coherent Amplifying Network) Group



Single-cycled laser and “TeV on a chip”

Thin film compression and single-cycle optical and X-ray lasers





G. Mourou et al. (2013)

X-ray LWFA in crystal suggested

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

$$L_{acc} \sim a_X\, (c/\omega_p)\, (\omega_X/\omega_p)^2, \qquad (a_X = eE_X/mc\omega_X)$$

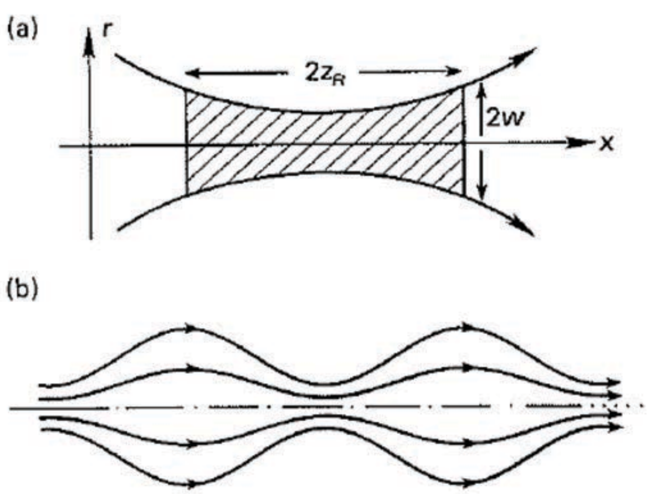
LWFA energy gain

$$\varepsilon_X = 2a_X^2\, mc^2 (n_{cr}/n_e),$$

Here, $n_{cr} = 10^{29}$, $n_e = 10^{23}$, $a_X \sim 30$ (pancake laser pulse with the Schwinger intensity, with focal radius assumed the same as optical laser radius. Could be greater if we further focus by optics, or nonlinearity, or if we not limit the intensity at Schwinger. see below)

The vacuum self-focus power threshold

$$P_{cr} = (45/14)\, c\, E_S^2\, \lambda^2\, \alpha^{-1}, \qquad (E_S: \text{Schwinger field})$$



Schwinger fiber acceleration in vacuum:

(no surface, no breakdown)

Vacuum photon dispersion relation with focus

$$\omega = c\sqrt{(k_z^2 + \langle k_{perp}^2 \rangle)},$$

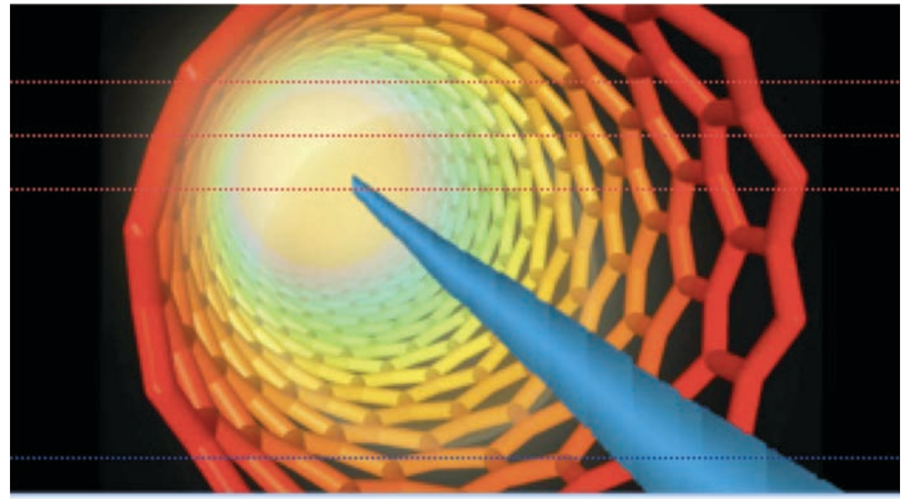
The vacuum dispersion relation with fiber self-modulation

$$\omega / (k_z + k_s) = c, \qquad (k_s = 2\pi / s)$$

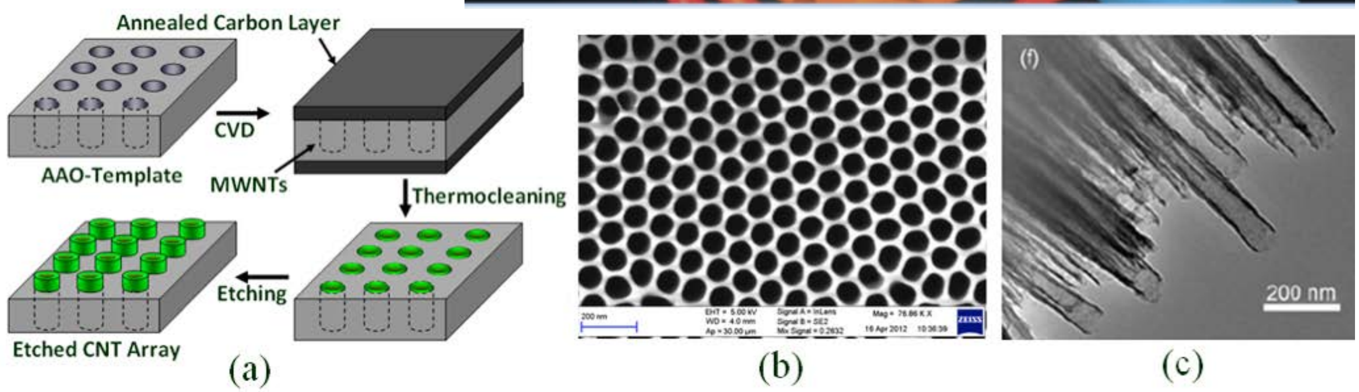
(Tajima and Cavenago, PRL, 1987)

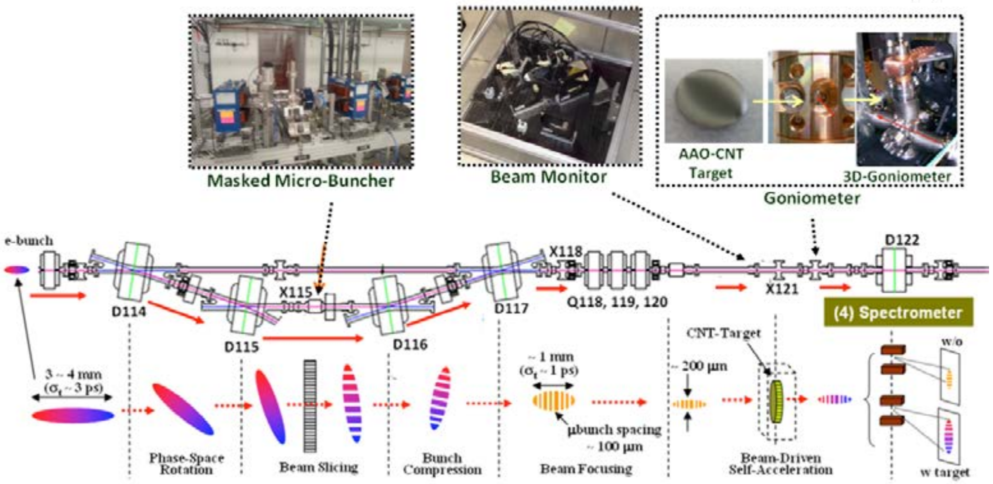
Wakefield acceleration in porous nanomaterials

Carbon nanotube with
Particle beam / X-ray pulse



Porous nanomaterial





Collaboration (2015) with Fermilab / NIU
Y. Shin et al.

Earlier works of X-ray crystal acceleration

-X-ray optics and fields (Tajima et al. PRL,1987)
-**Nanocrystal hole** for particle propagation (Newberger, Tajima, et al. 1989, AAC; PR,..)
-particle transport in the crystal (Tajima et al. 1990, PA)

APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

B. Newberger, T. Tajima, The University of Texas at Austin, Austin, Texas 78712
F. R. Huson, W. Mackay, Texas Accelerator Center, The Woodlands, Texas
B. C. Covington, J. R. Payne, Z. G. Zou, Sam Houston State University, Huntsville, Texas
N. K. Mahale, S. Ohnuma, University of Houston, Houston, Texas 77004

; 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 tal. Logarithmic dependencies on particle energy neglected throughout; L_R is a constant with a tv

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 (≃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: $a_0 = \pi^{-1/2}\hbar c (fN)^{-1/2} P\epsilon^{-2}$, where f, 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 $\hbar\omega \geq mc^2\alpha^2$, 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 $l_t = (3/2^8\pi) \times a_B^{-2}\alpha^{-1}n^{-1}(\hbar\omega/Z_{\rm eff}^2\mathcal{R})^{7/2}$, 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

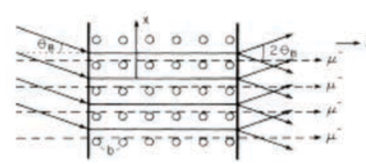
where b is the transverse lattice constant and later a the longitudinal lattice constant ($a \simeq b$) (see Fig. 1). The row of lattice ions (perhaps with inner-shell electrons) constitutes the "waveguide" wall for x rays, while they also act as periodic irises to generate slow waves. A superlattice[5] such as $Ge_cSi_{1-c}S_i$ (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

$$\omega/(k_z + k_s) = c, \qquad (2)$$

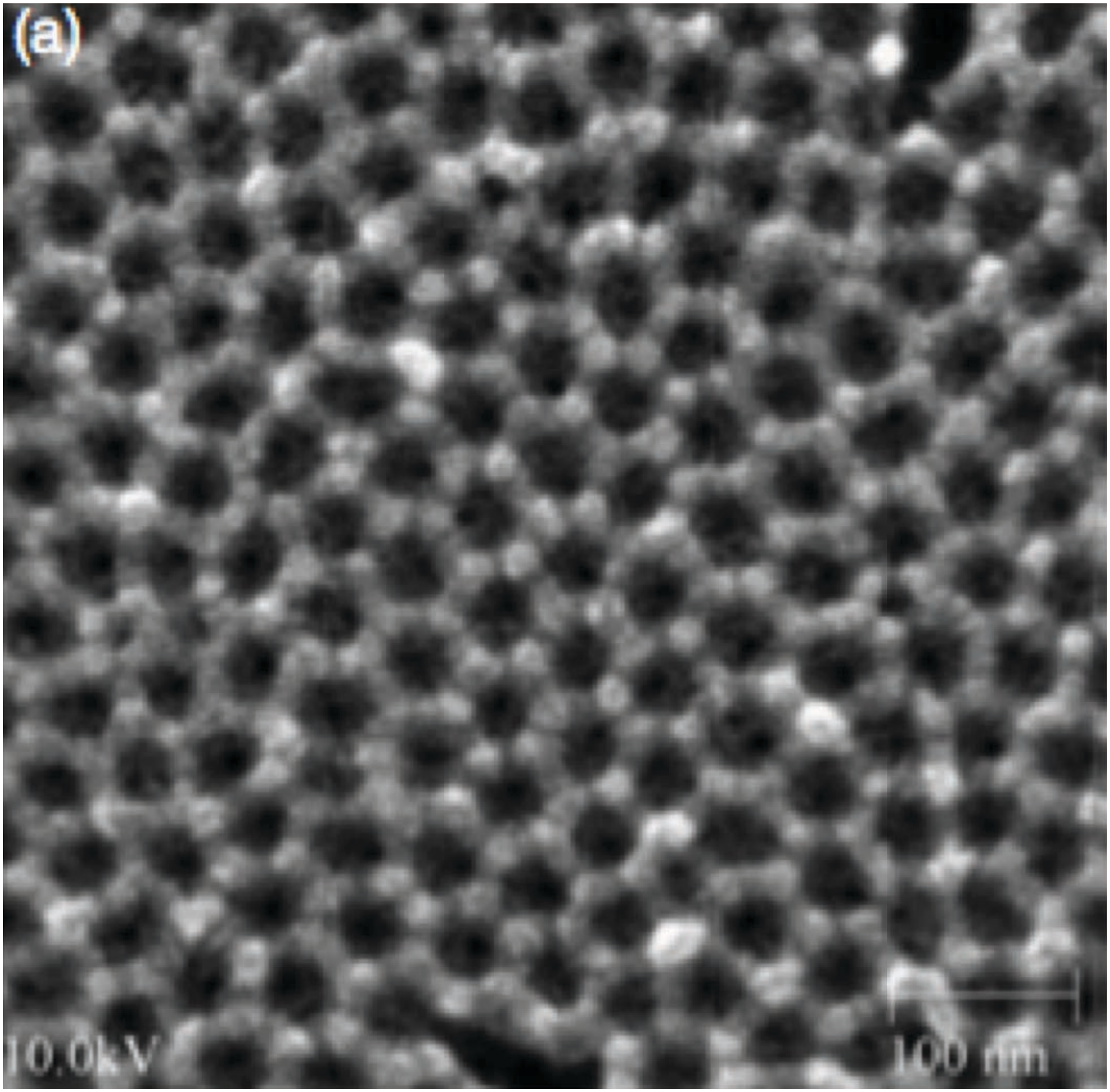
where ω and k_z are the light frequency and longitudinal wave number.

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

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

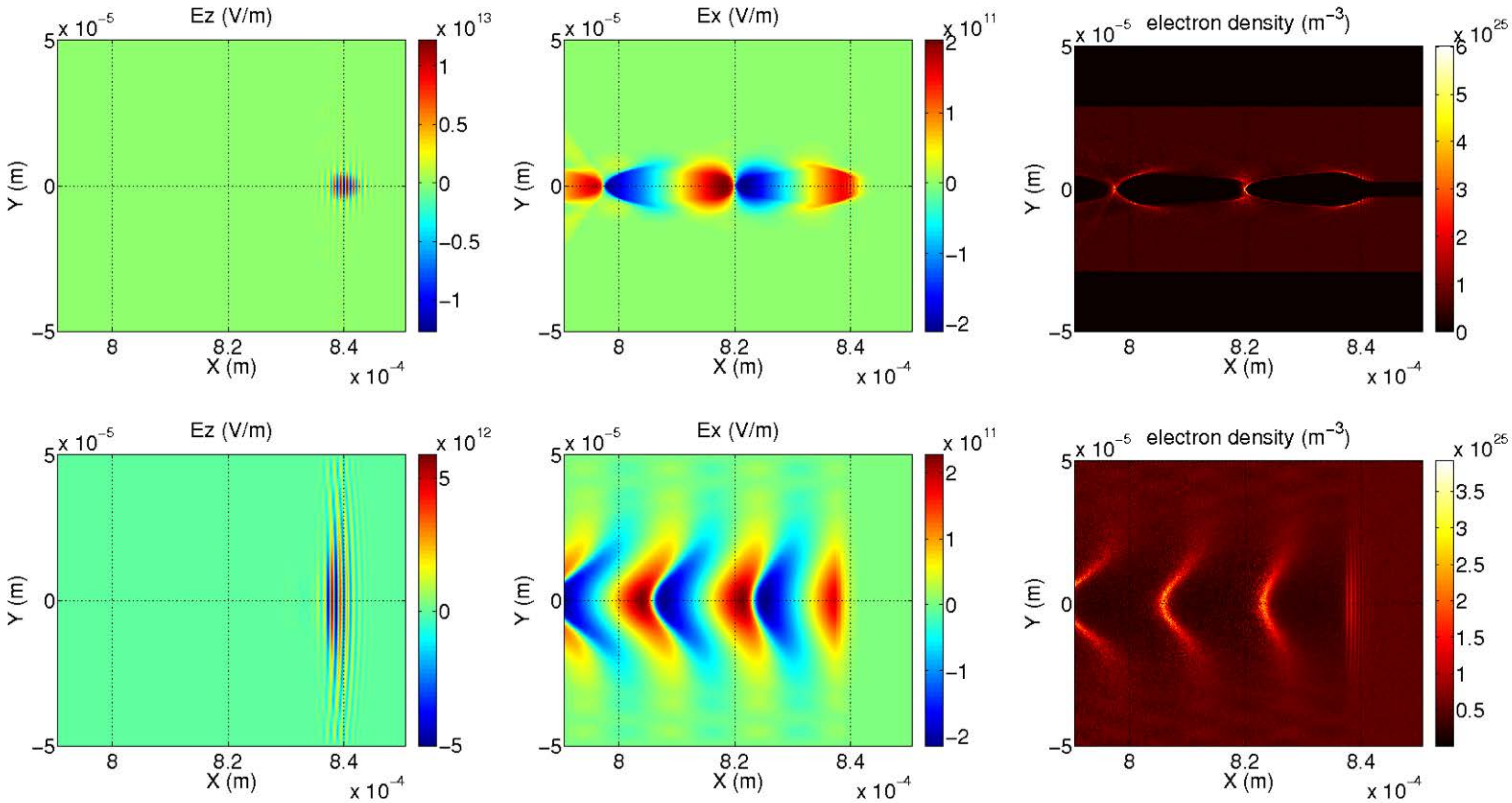


Porous Nanomaterial



Porous alimina on Si substrate
Nanotech. **15**, 833 (2004)

X-ray LWFA in a tube vs. uniform solid



in nanotube

in uniform solid

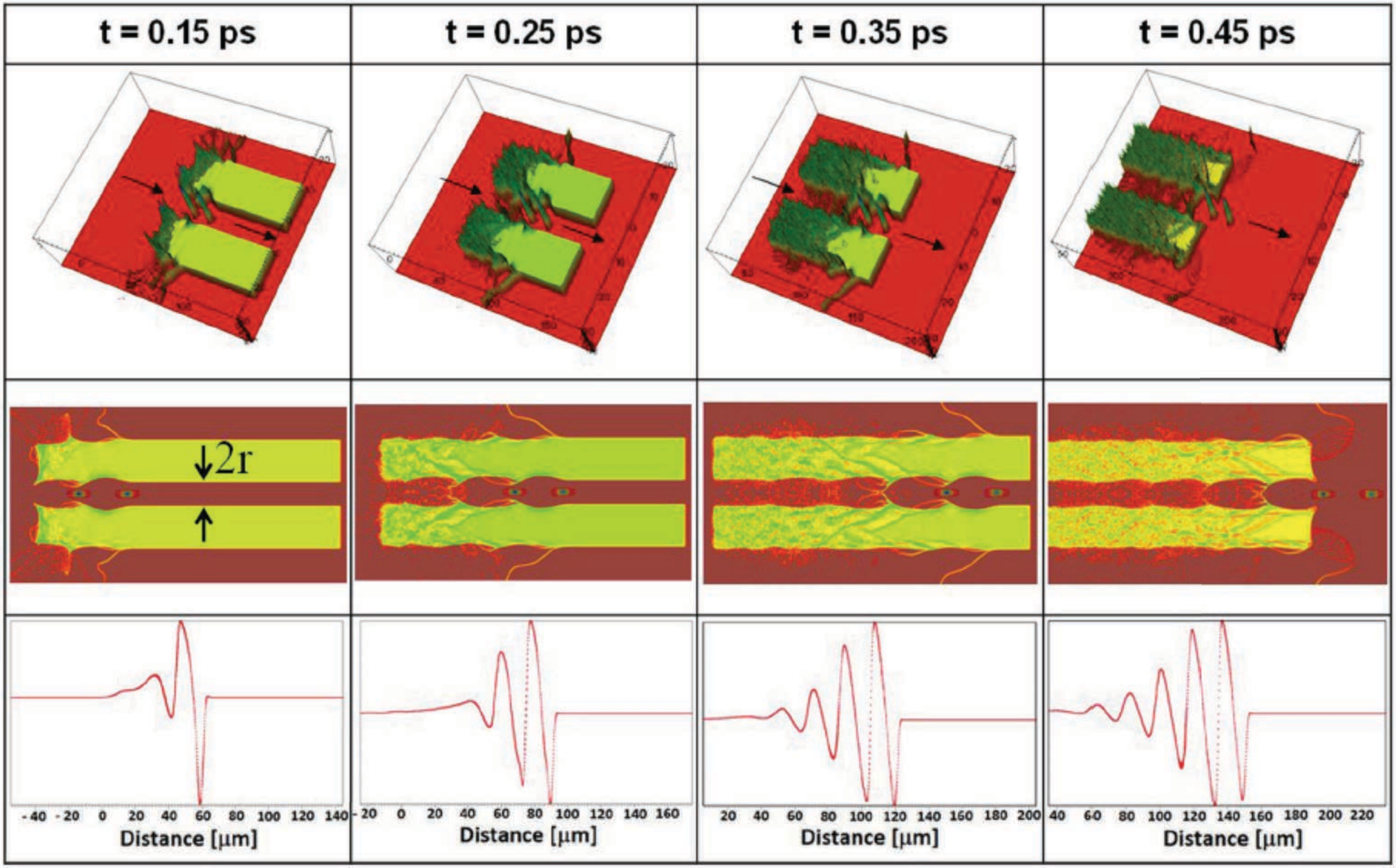
A few-cycled 1keV X-ray pulse (a_0 ~ O(1)), causing 10TeV/m wakefield in the tube

more strongly confined in the tube

cf: uniform solid

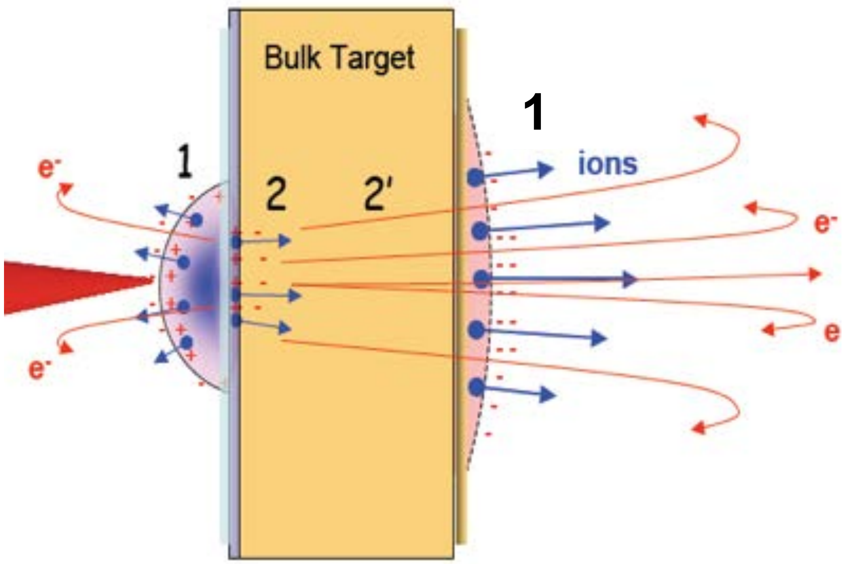
X. Zhang (2016)

Beam-driven wakefield on a chip



Y. Shin (2014)

Laser-driven ion acceleration mechanisms

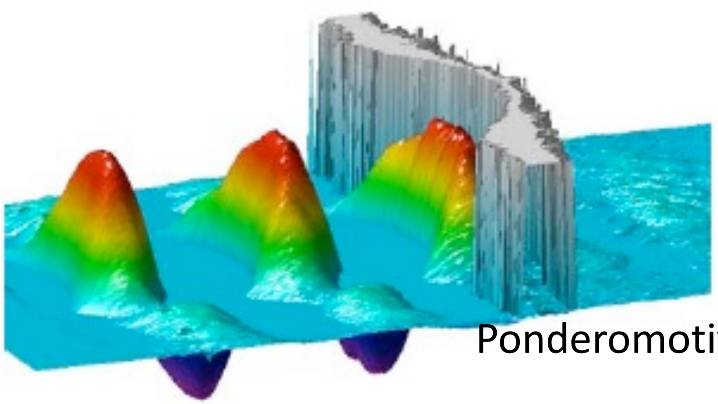


E~TV/m

1)TNSA

micron thick targets

incoherent process



Ponderomotive acceleration

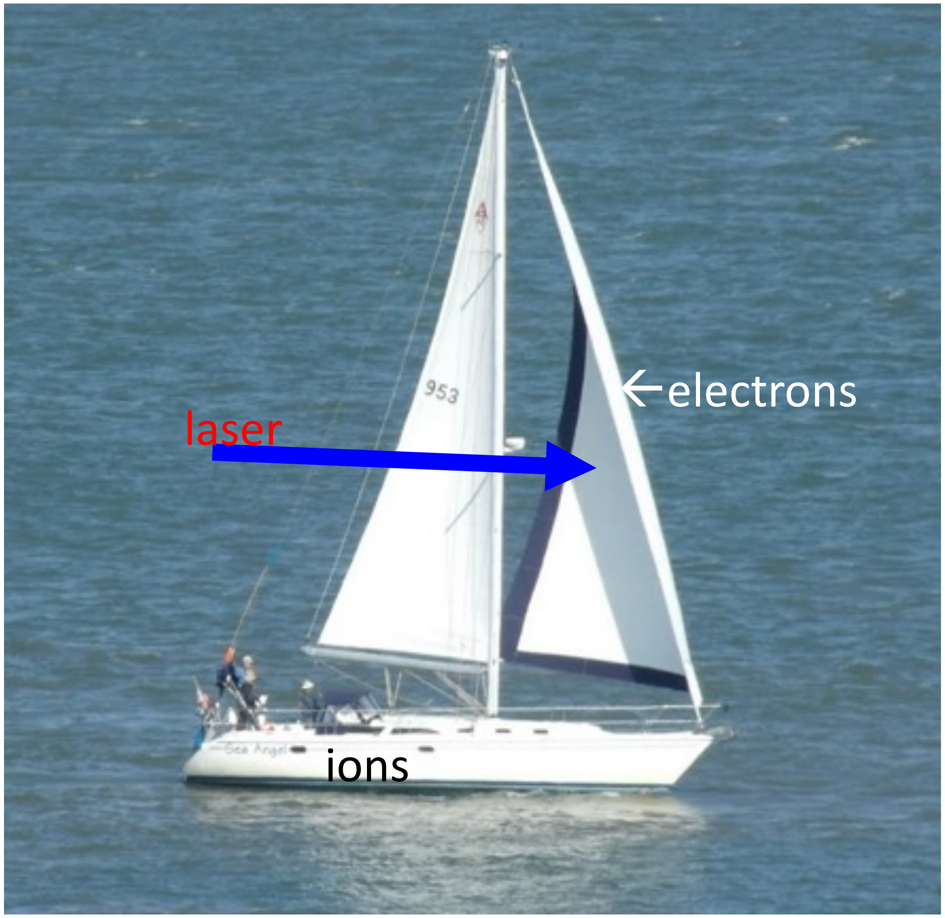
2)**RPA**

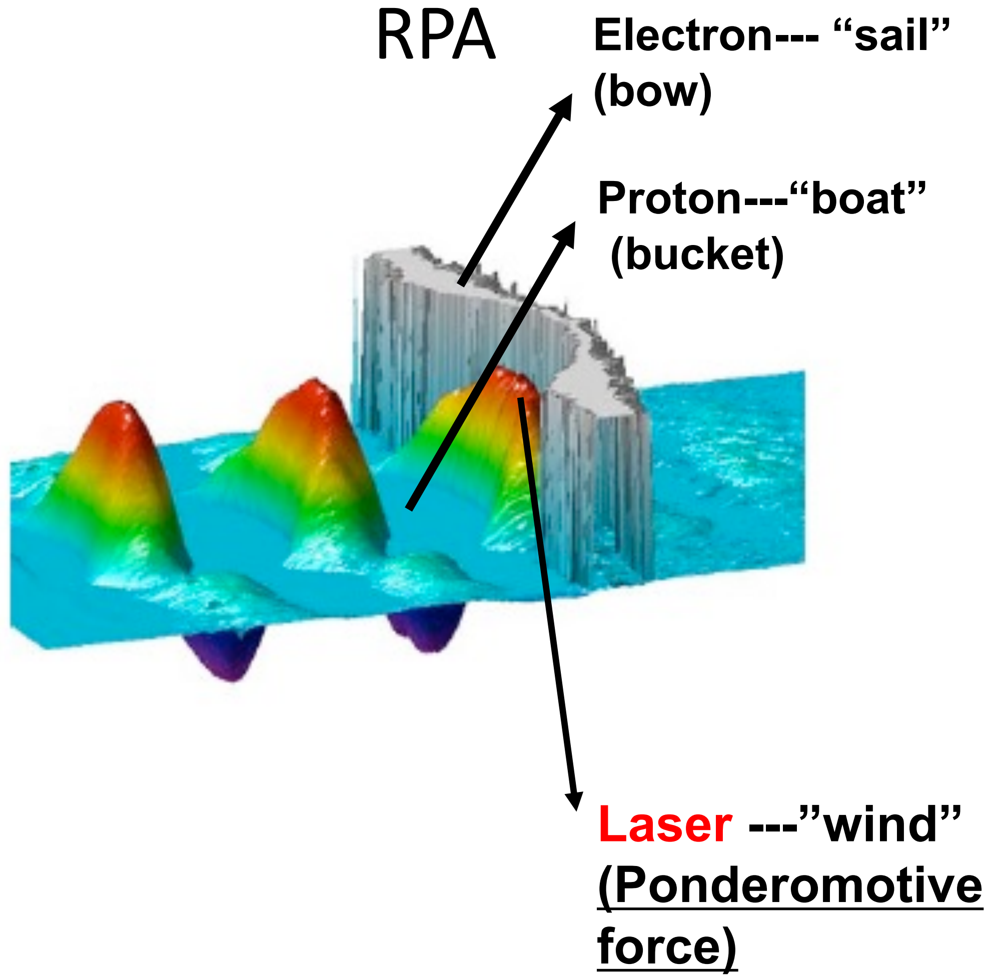
nanotargets

can be coherent

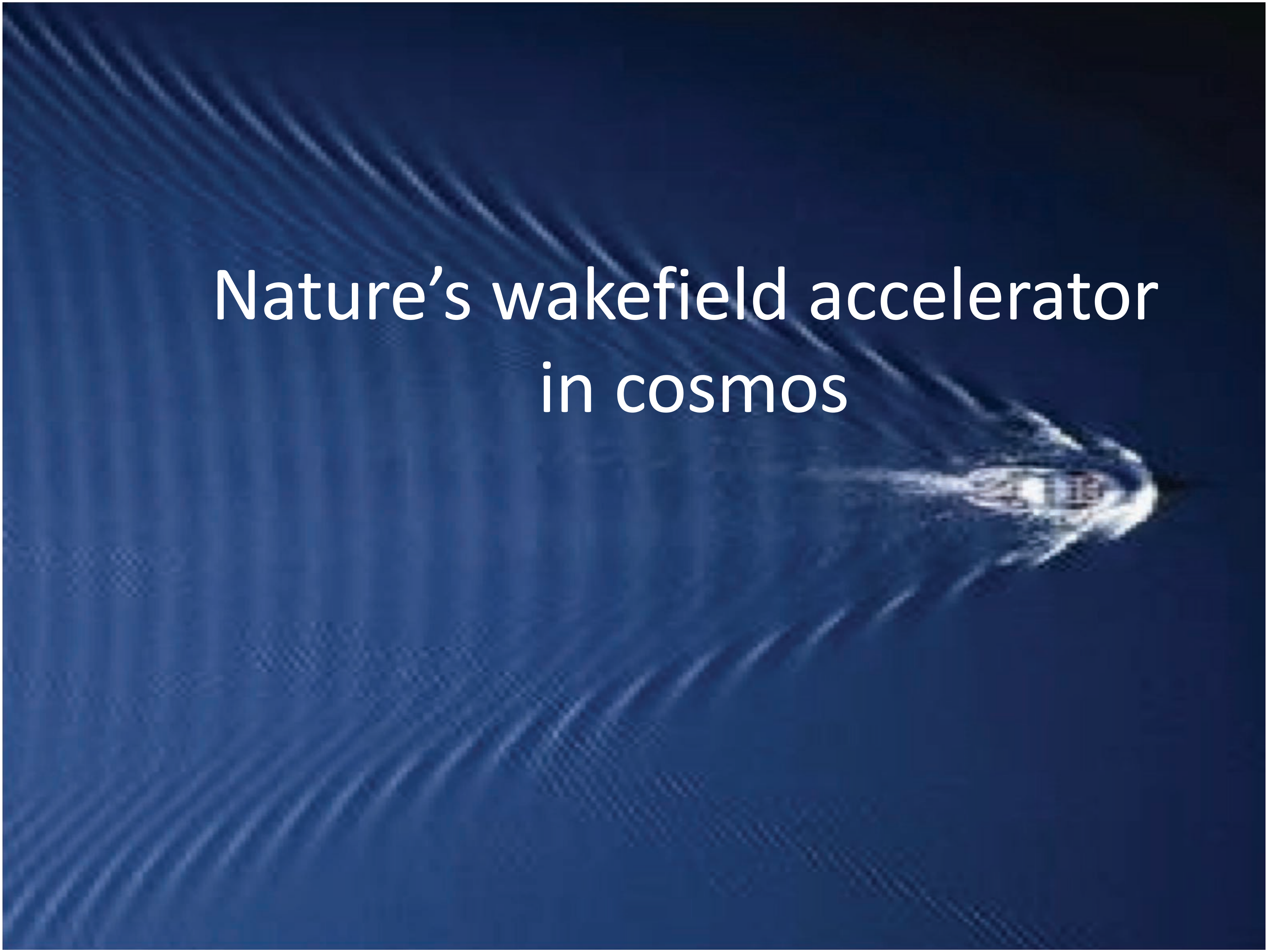
X. Q. Yan (2010)

RPA (Radiation Pressure Acceleration)

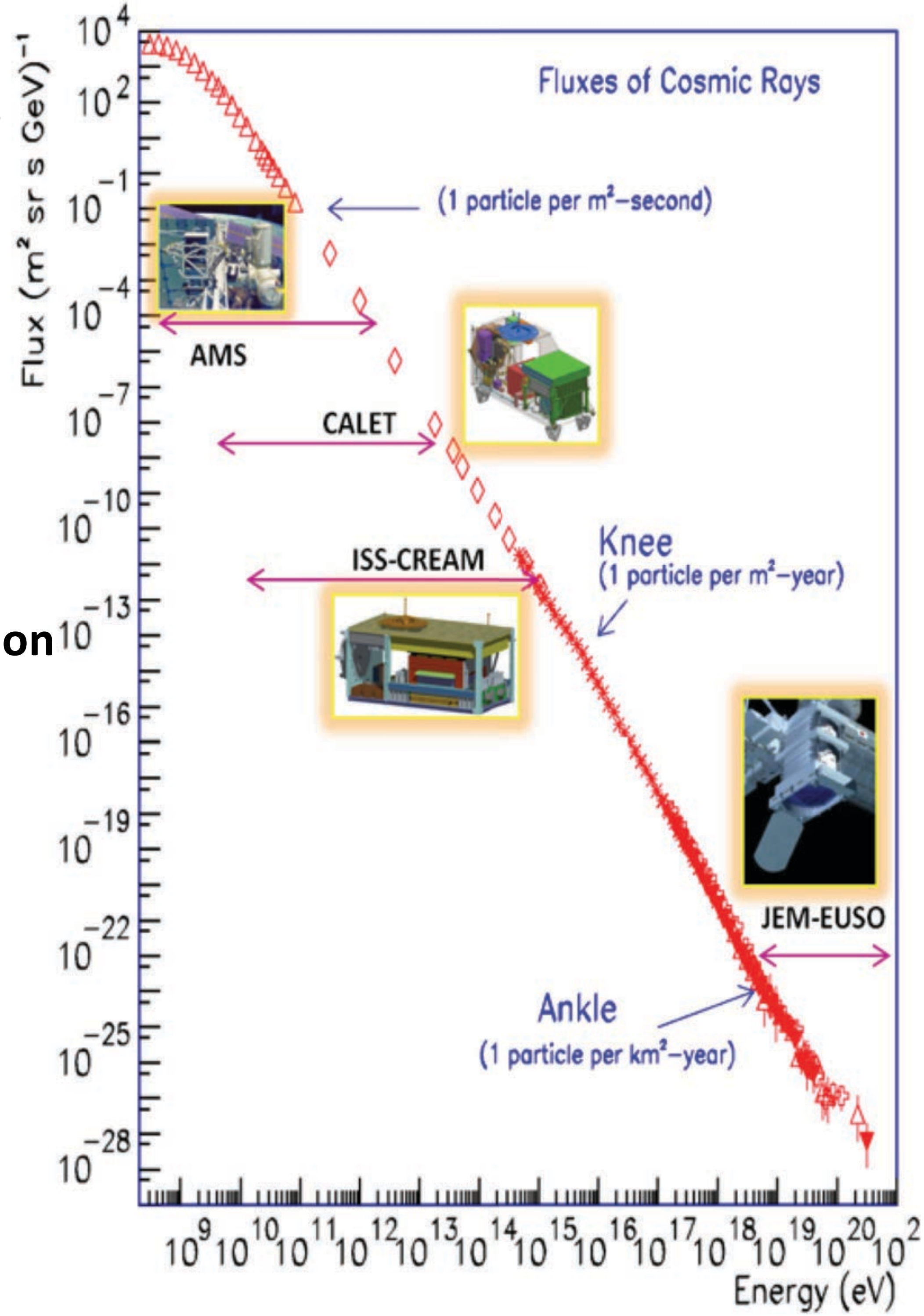




Esirkepov et al. (2004)
X. Yan (2010)


Nature's wakefield accelerator
in cosmos

Ultrahigh Energy Cosmic Rays (UHECR)



Fermi mechanism runs out of steam
    beyond 10^{19} eV
    due to synchrotron radiation

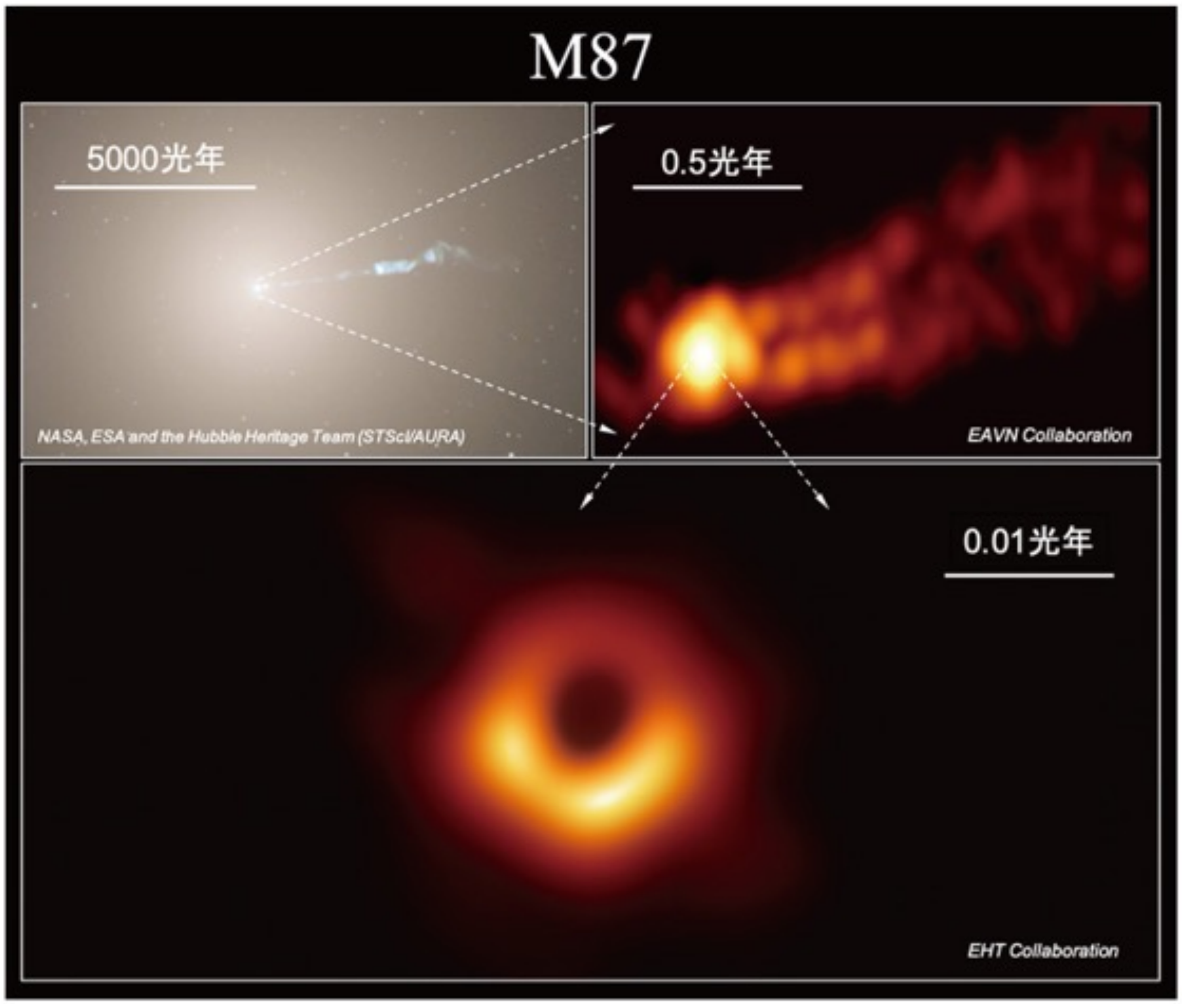
Wakefield acceleration
    comes in rescue
    prompt, intense, linear acceleration
    small synchrotron radiation
    radiation damping effects?

Cen A

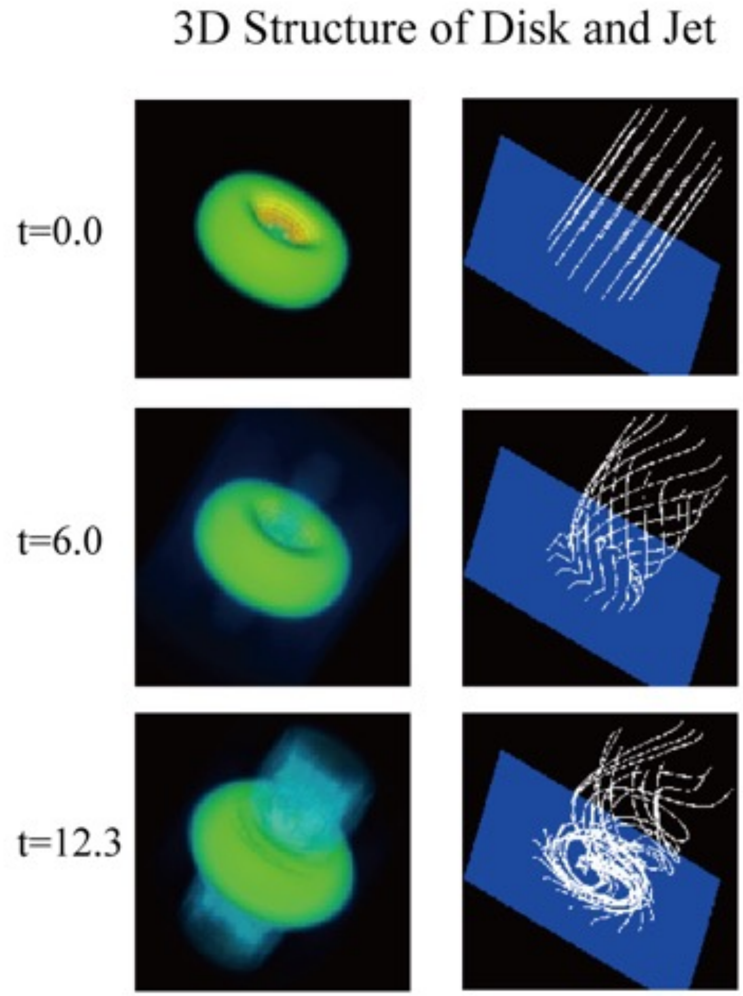
- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets

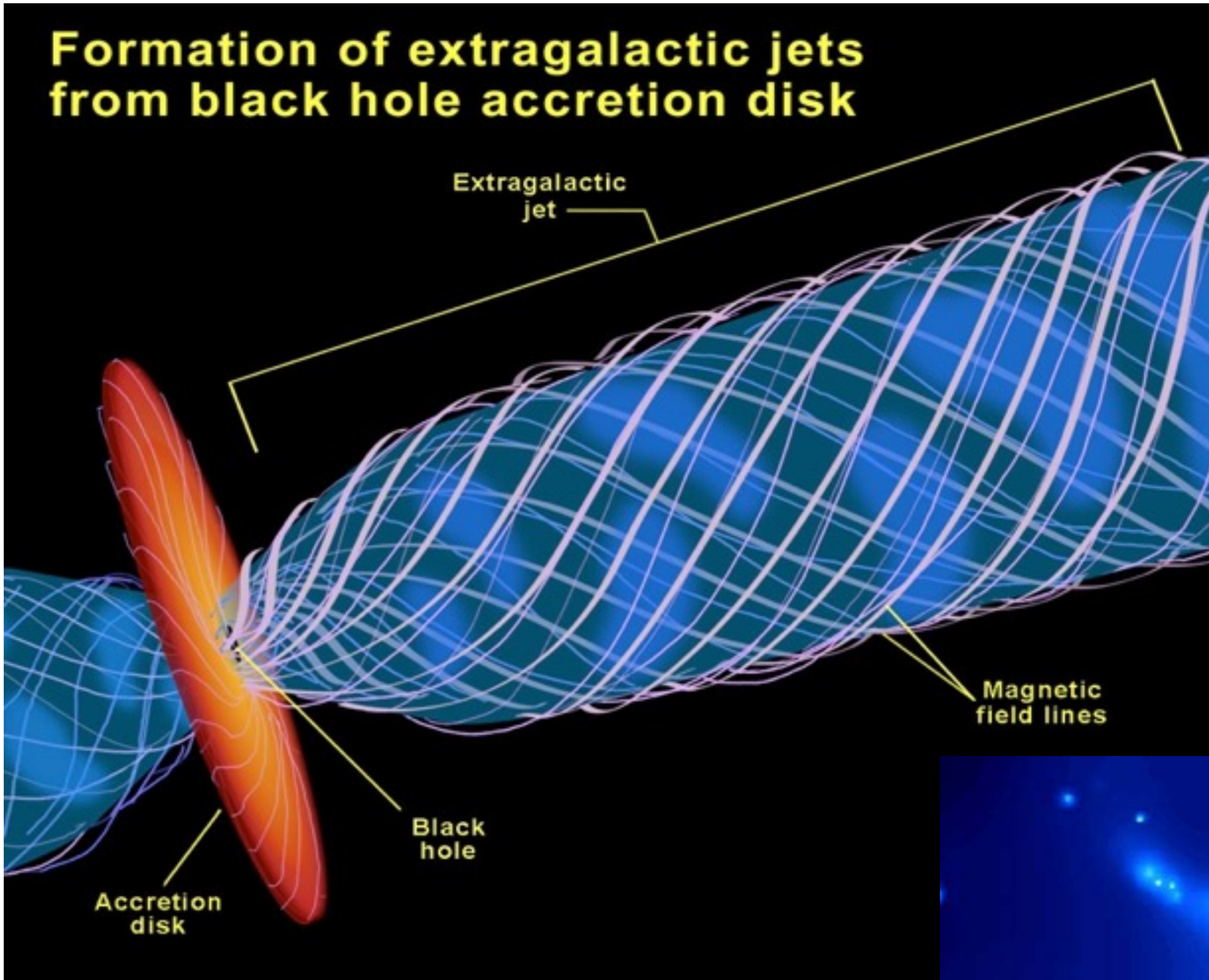
Discovery of Blackhole and Prediction

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

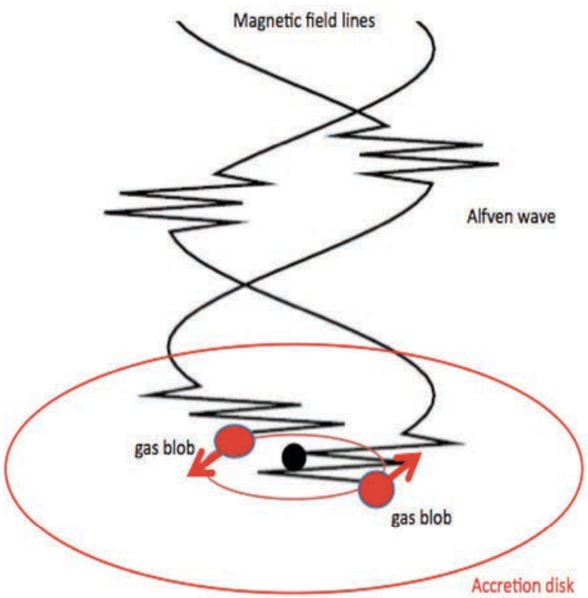
extreme high energy cosmic rays (~10^{21} eV)

episodic γ-ray bursts observed

consistent with LWFA theory

Ebisuzaki-Tajima (2014)

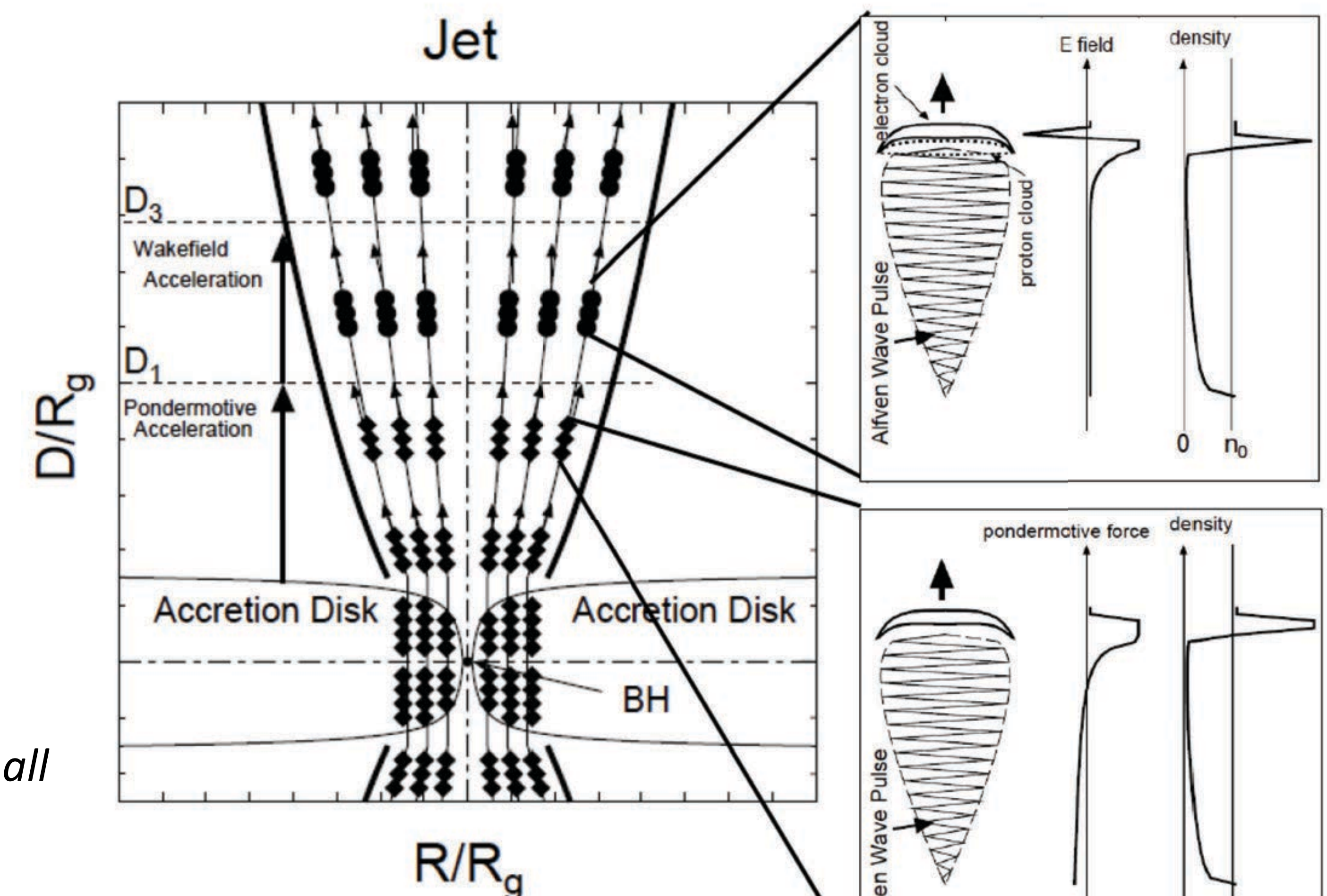
Astrophysical wakefield acceleration: Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays (a_0 ~ 10^6 -10^{10}, large spatial scale)



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

E_0: modest

ω_0 : extremely small



Ebisuzaki and Tajima, Astropart. Phys.(2014)

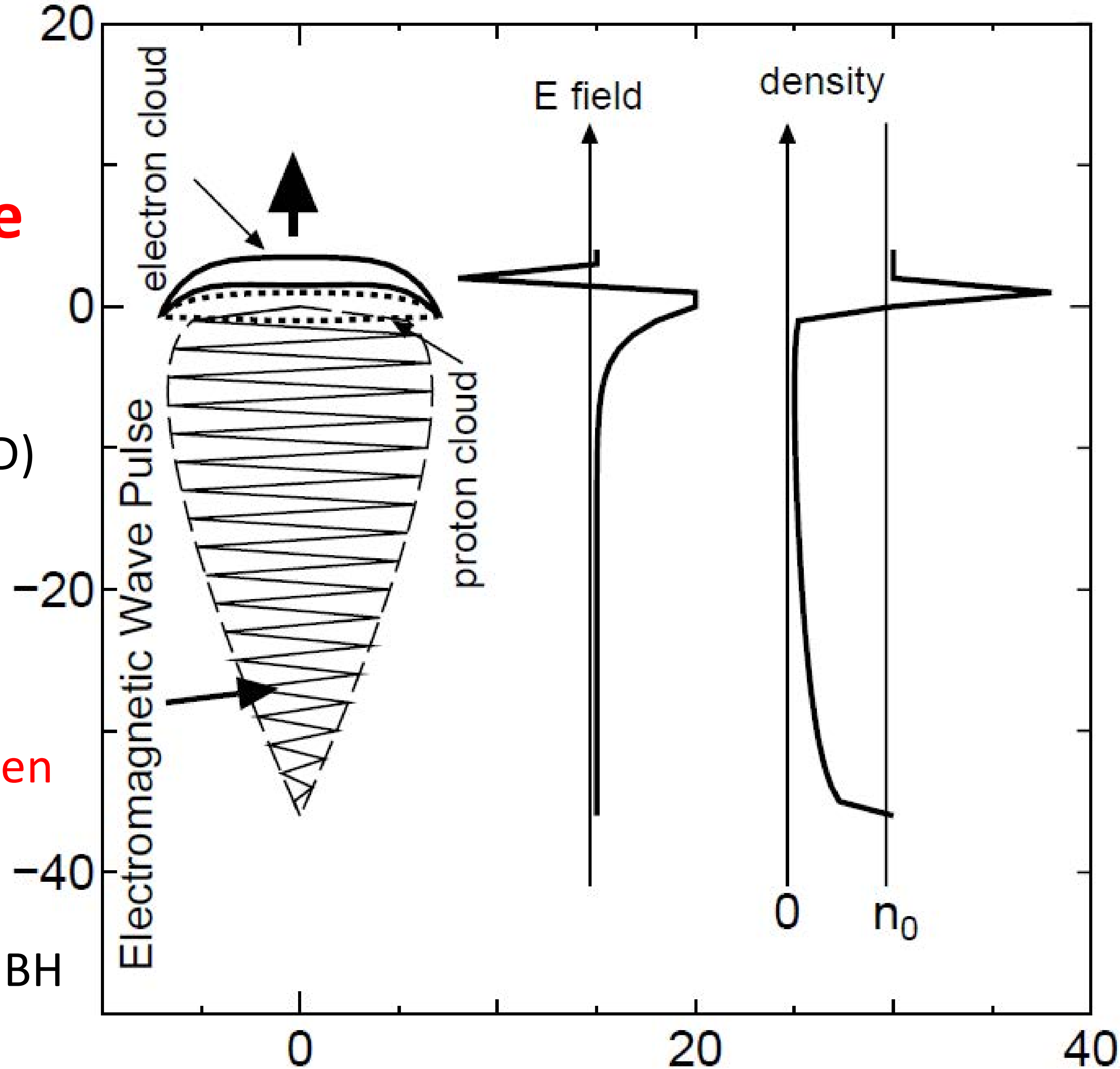
Phys.Rev. STAB, **18**, 024401 (2015).

Wakefield vs. Ponderomotive Acceleration

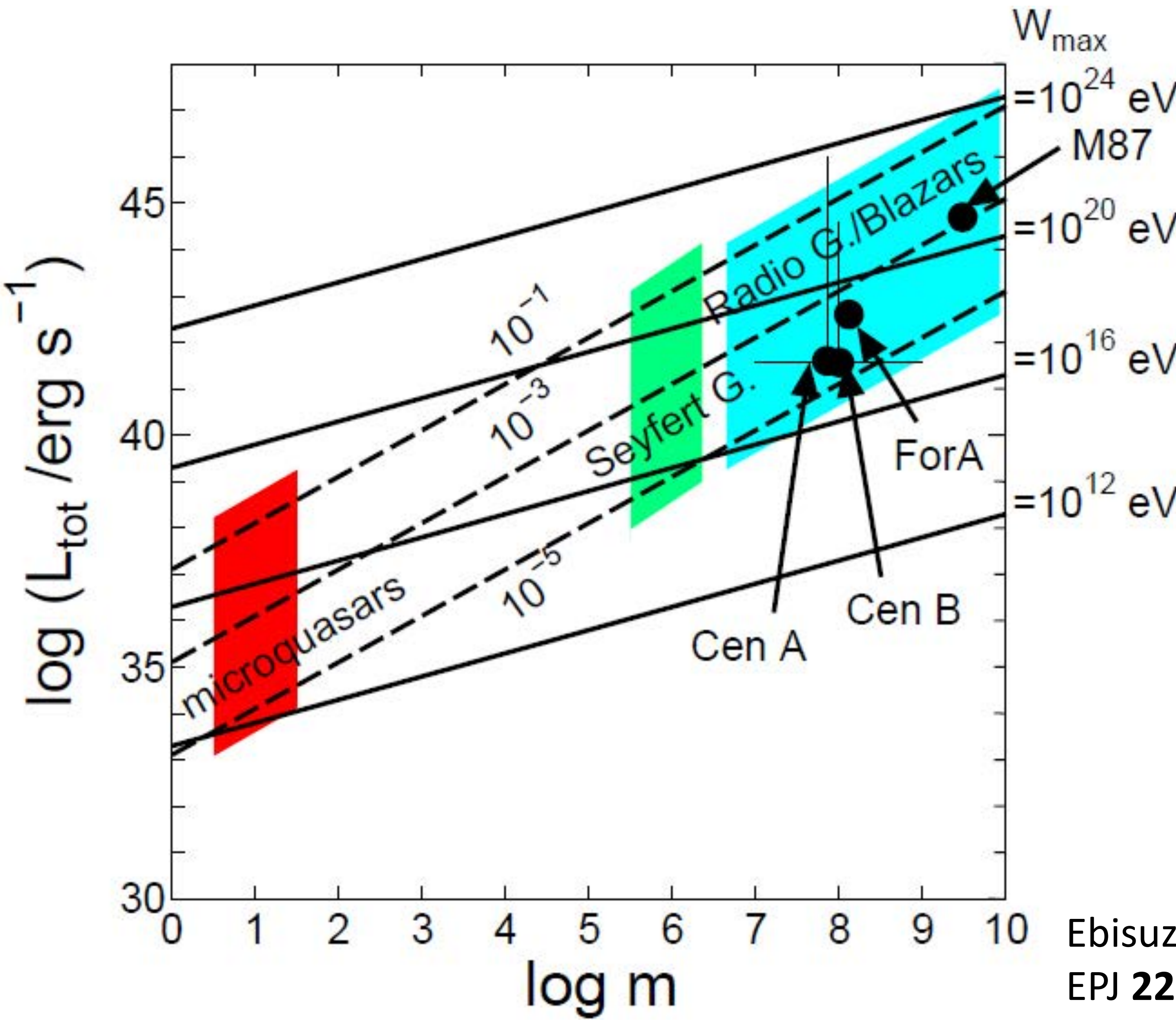
wavebreak (1D or 2D) in higher a_0 → wakefield less important

Ponderomotive-driven Acceleration more robust ($a_0 >> 1$)

$a_0 \sim 10^{6\text{-}10}$ in AGN BH



Comic ray acceleration and γ-ray emission: Summary



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

General Relativistic MHD simulation of accretion disk + jets

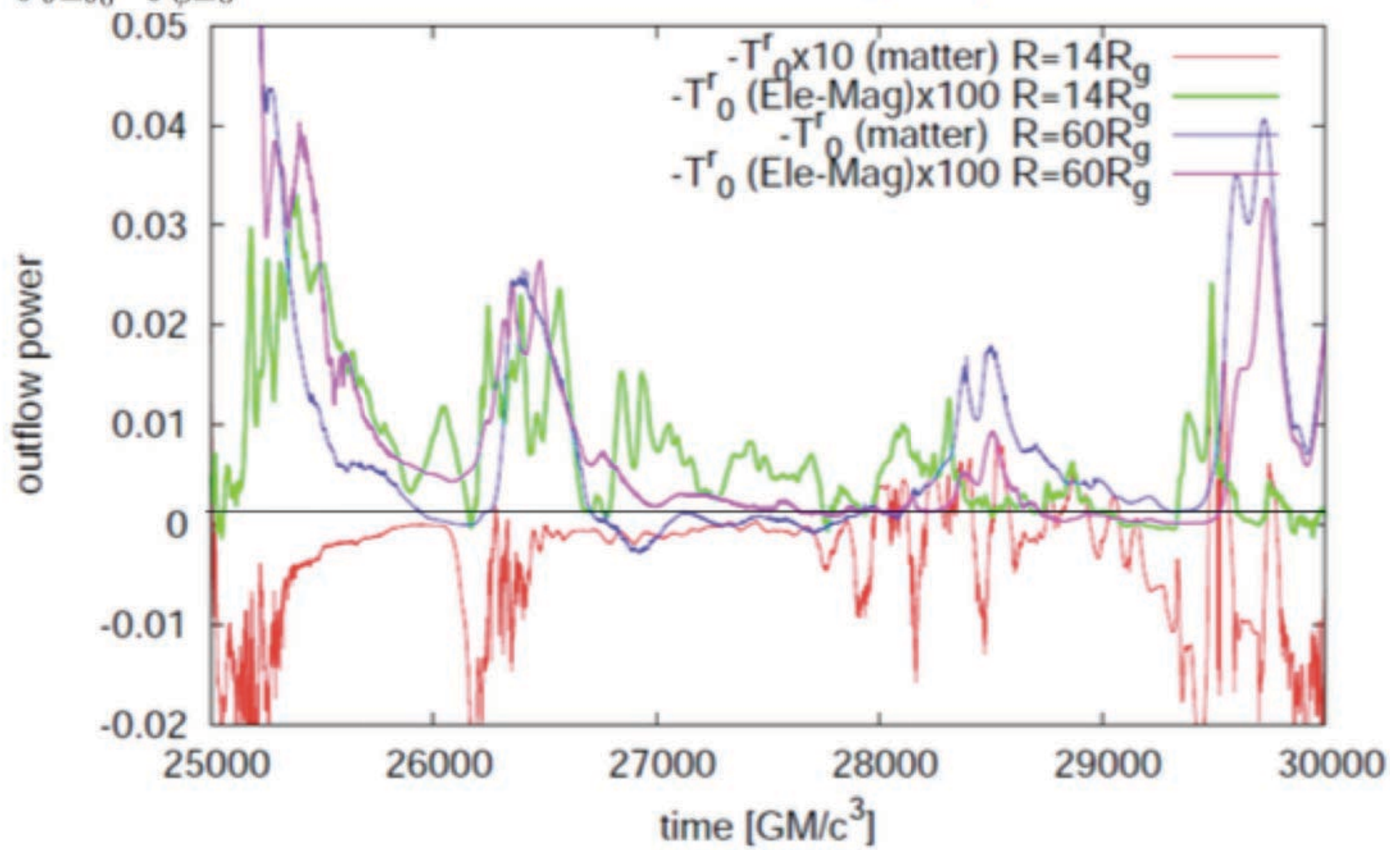
Outflow luminosity (0<θ<10°)

$$E_{\rm dot} = - \int_{\theta=\theta_0}^{\theta=\theta_1} \int_{\phi=0}^{\phi=2\pi} \sqrt{-g}T^r_t \, dA$$

outflow power $14R_g$, $60R_g$

$\theta_0=0$

$\theta_1=10$



Short time variavilitry (Δt~a few tensGM/c³) in electromagnetic components (green and pink) : Good agreement with Ebisuzaki & Tajima(2014) $t_{var} \sim M$

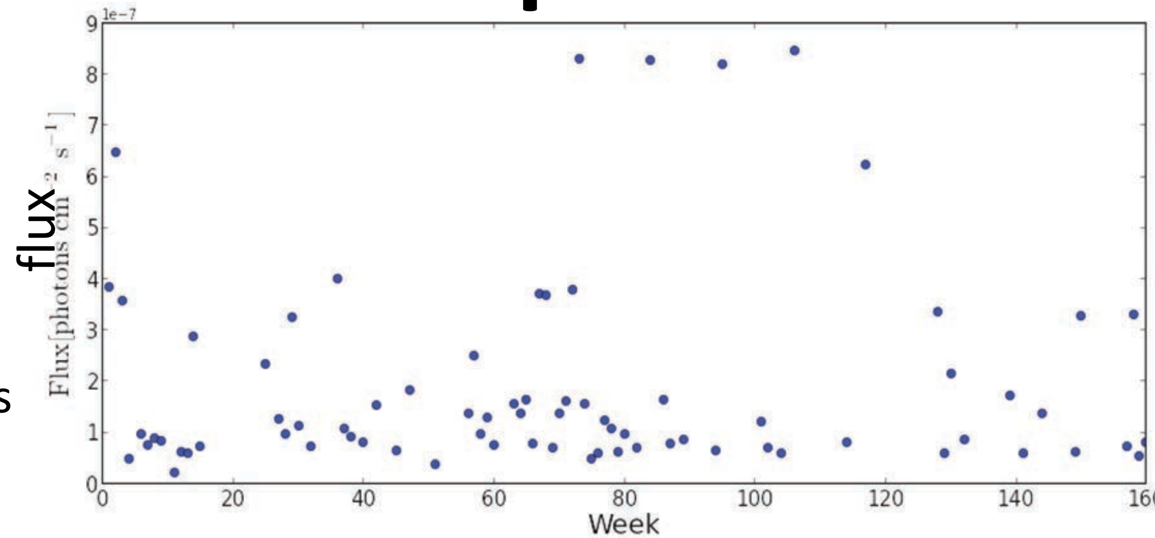
=> possible origine for flares in blazars,

strong Alfven wave mode => Application t wake field acc. for UHECRs

A. Mizuta, T. Ebisuzaki (2018)

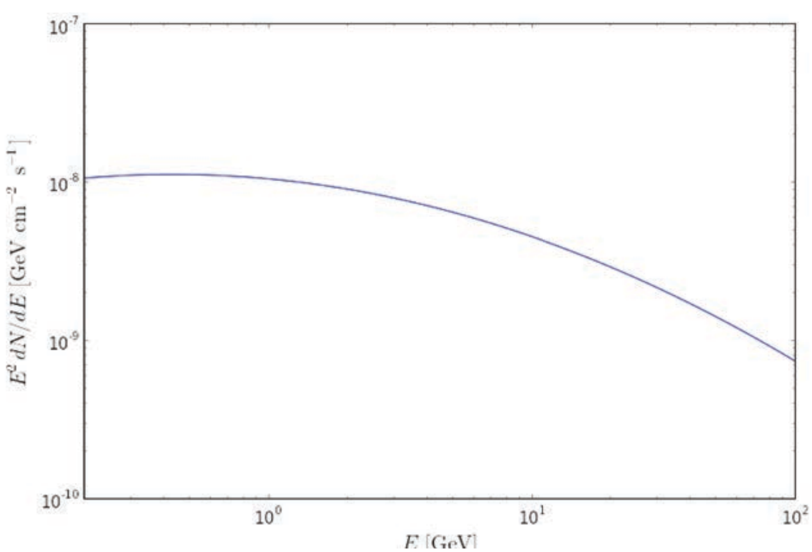
Blazar shows anti-correlation between γ burst flux and spectral index

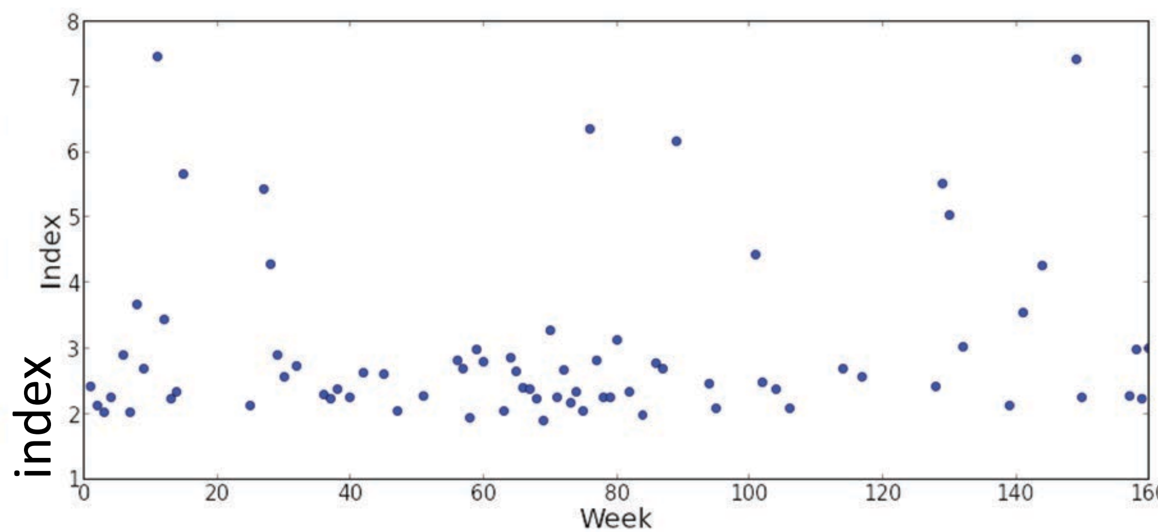
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



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

→ all quantitatively consistent with Wakefield theory



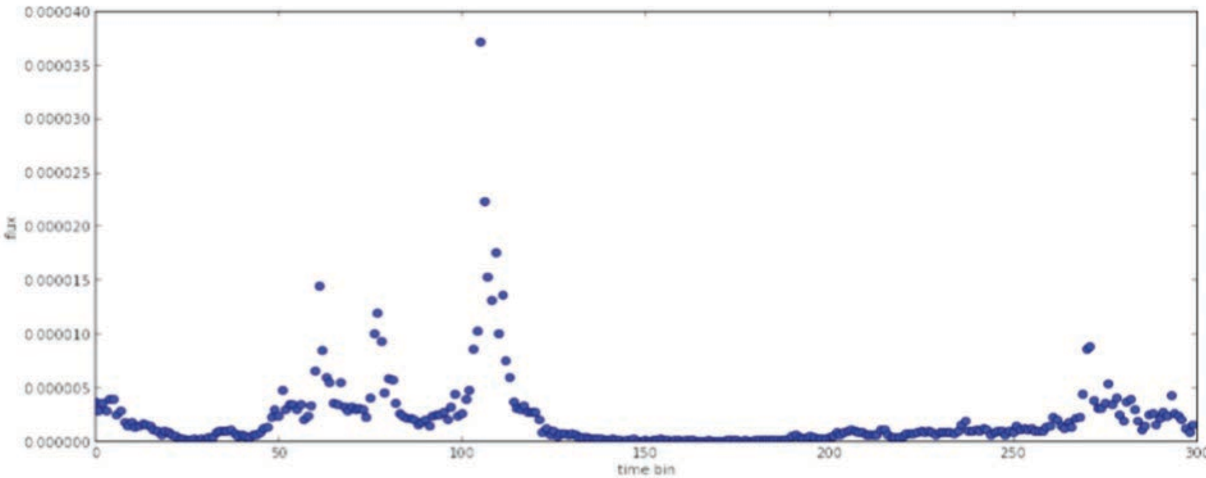


N. Canac, K. Abazajian (2019)

Again, Anti-correlation even in a bigger blazar

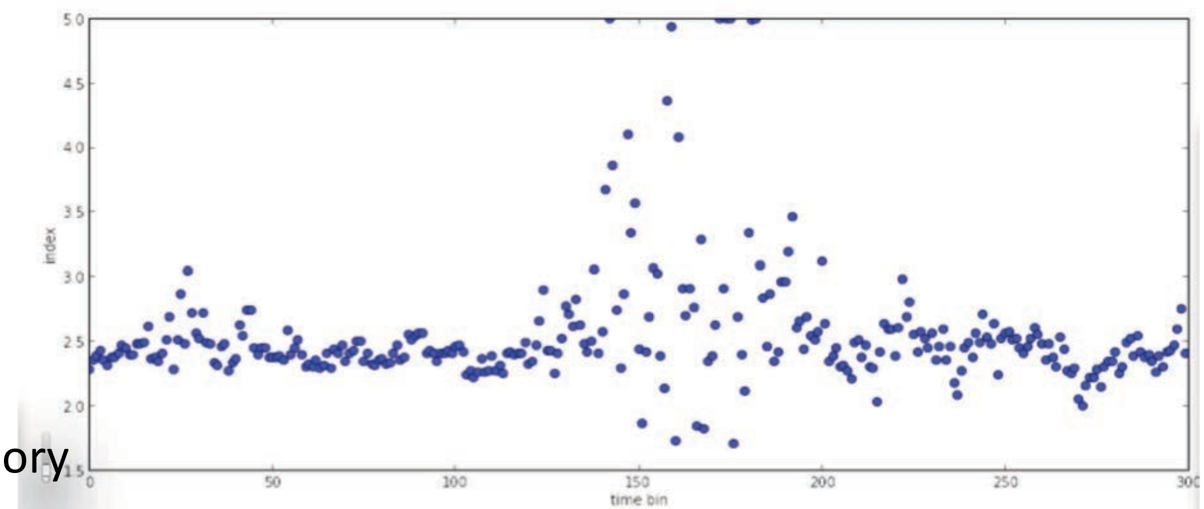
Blazar: 3C454.3

$M \sim 10^9 M_{Sun}$



Same anti-correlation as AO0235+164

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



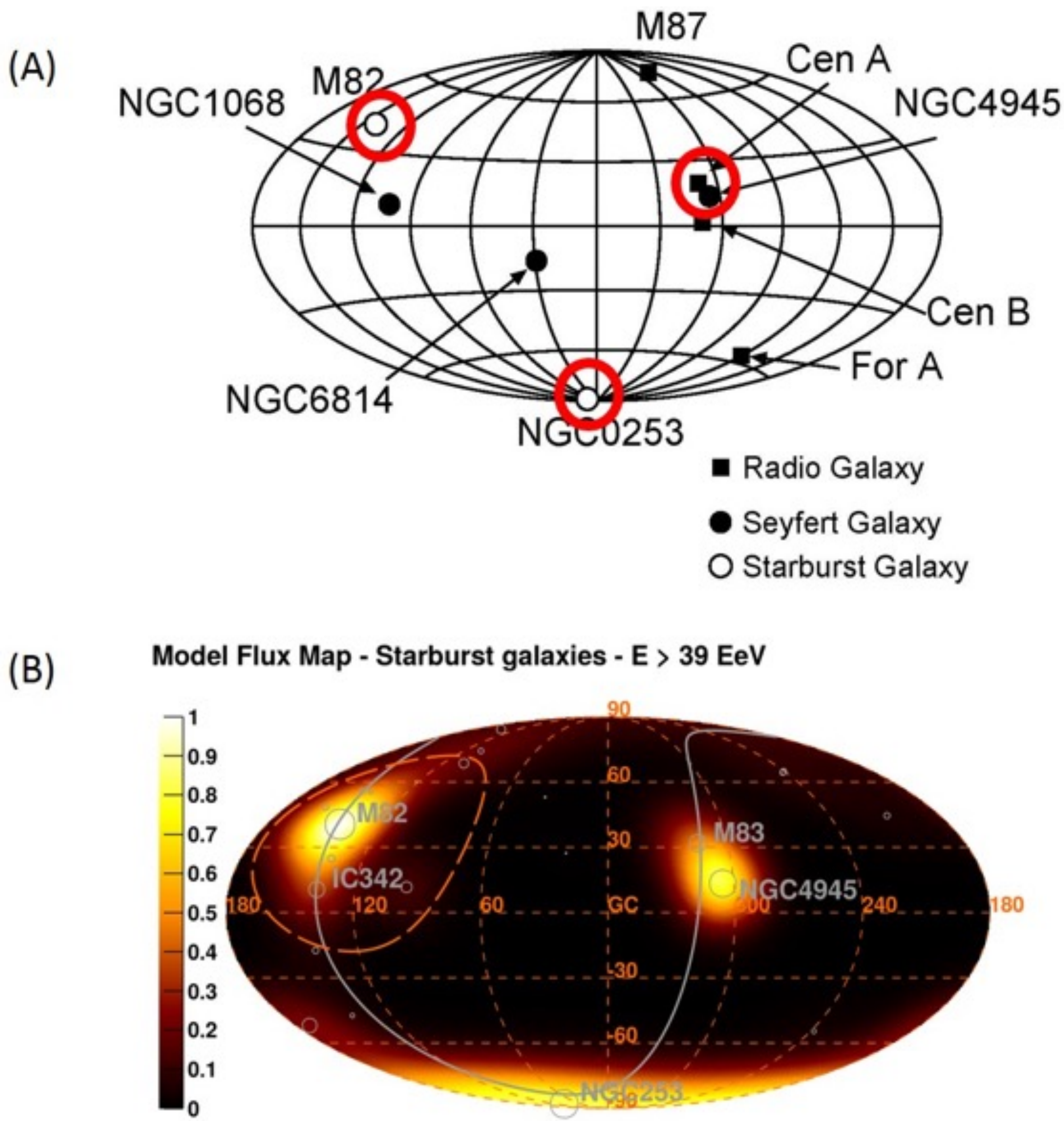
Quantitative agreement and **<u>correct scaling</u>** with Blazar mass with (broader sense of) Wakefield theory (Ebisuzaki/Tajima)

period ~ *M* ; luminosity ~*M*

time

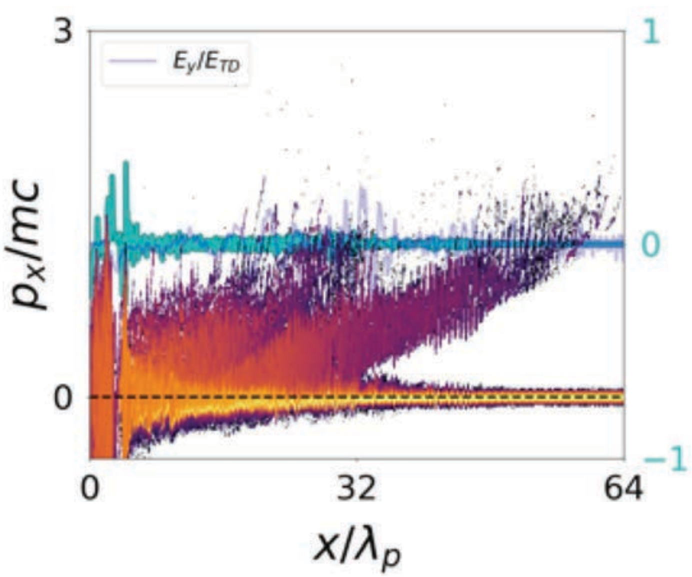
N. Canac, K. Abazajian (2019)

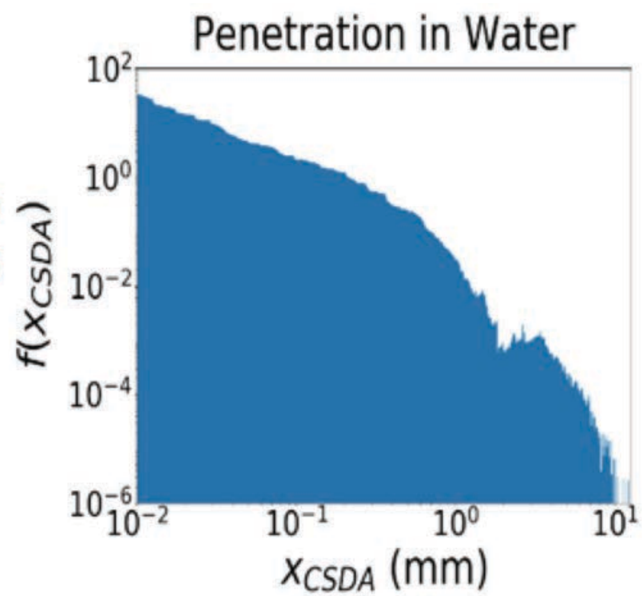
Brightest cosmic rays by wakefields



Low phase velocity wakefields for medicine

- Low energy (lower phase velocity) wake
- High density ~ 10^{21} cm^{-3} nanomaterials target
- **Micron** accelerator in **endoscope** by fiber laser
- Theranostics





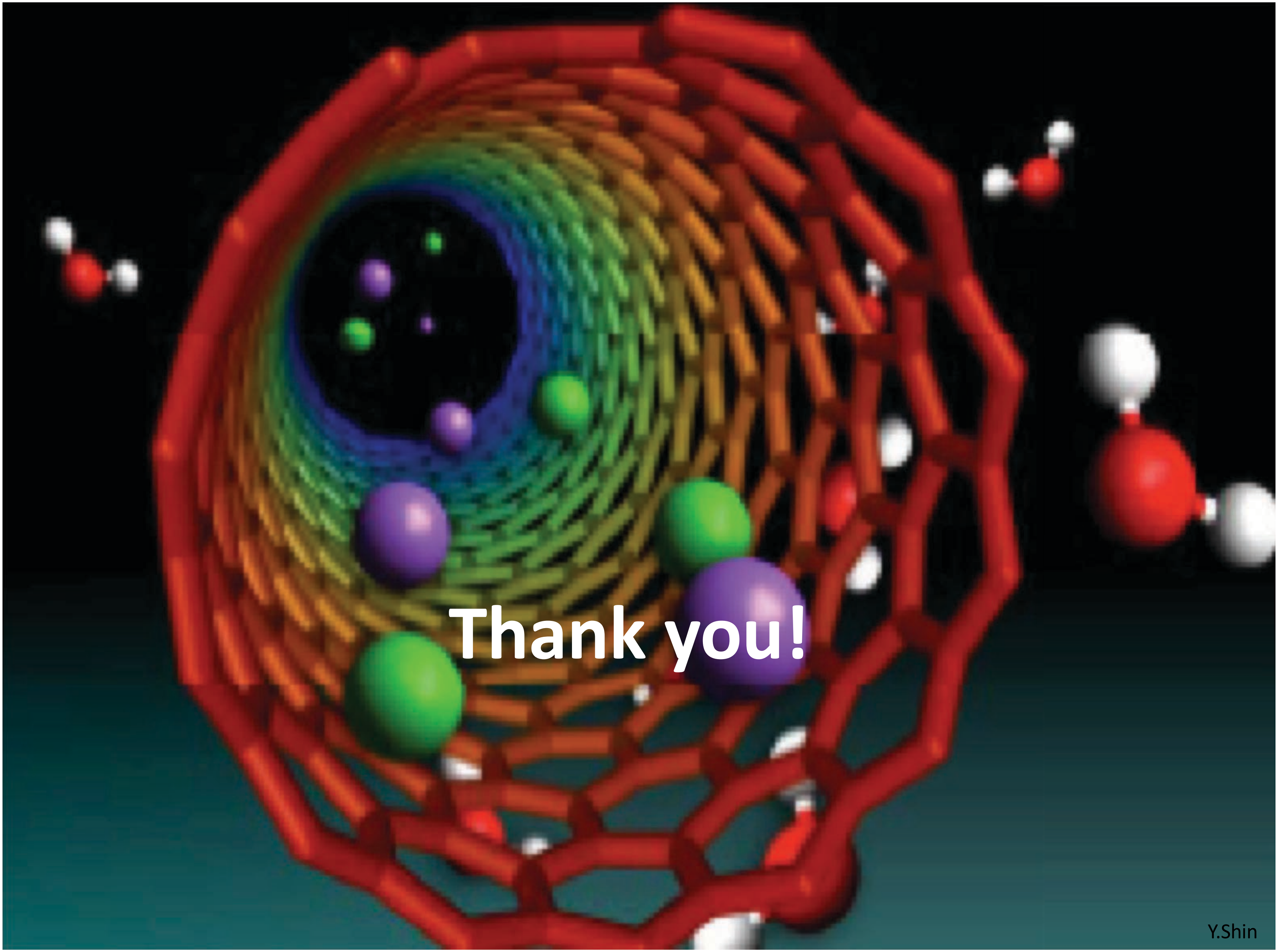
Critical density wakefield acceleration with low phase velocity

Low phase velocity tsunami

Nicks et al. (2019)

Conclusions

- **Demonstrated**: ultrafast pulses, coherent collective (robust) wakefield (GeV/cm) excitable.
- Thin-Film Compression (TFC) (since 2014)
- Single-cycled laser → single-cycled X-ray laser
- Wakefield in **nanostructure** (TeV/cm): accessible
- Wakefield acceleration: Nature's accelerators favored for cosmic rays, gamma ray bursts from Blazars
- Applications: wakfield radiation therapy inside body ← **μm** accelerator ← **fiber laser**


Thank you!
Y.Shin