"TeV on a Chip" : X-ray Wakefield Accelerator in Nanomaterials

Accelerator Physics and Technology Seminar, Fermilab
Batavia, IL,Aug. 6, 2015

Toshiki Tajima, UC Irvine
(also: IZEST and ICUIL)

Acknowledgments for Collaboration: G. Mourou, X. M. Zhang,Y. M. Shin, D. Farinella, T. Saeki, D. Farinella, N. Naumova, K. Nakajima, S. Bulanov, A. Suzuki, T. Ebisuzaki, J. Koga, X. Q. Yan, M. L. Zhang, U. Wienands, U. Uggerhoj, A. Chao, N.V. Zamfir, V. Shiltsev, M. Hogan, P. Taborek, K. Abazajian, G. Yodh, S. Barwick

Eur. Phys. J. Spec. Top. **228**, 1037 (2014)

Content

- **High intensity frontiers of lasers: (1) large energy; (2) high fluence (CAN laser); (3) ultrashort**
- e.g. (1) High energy laser ascent: wakefields toward 100GeV (also, beam-driven wakefileds); (2) CERN collaboration in CAN laser
- **(3) How short? ---- zeptoseconds**
- **New 2-step Laser Conversion**:

  1PW Opt. Laser → 10PW Opt. Laser → 1EW X-ray Laser

  30fs, 40J, 1eV 3fs, 30J, 1eV 0.3as, 0.3J, 10keV
- **LWFA at solid density enabled**

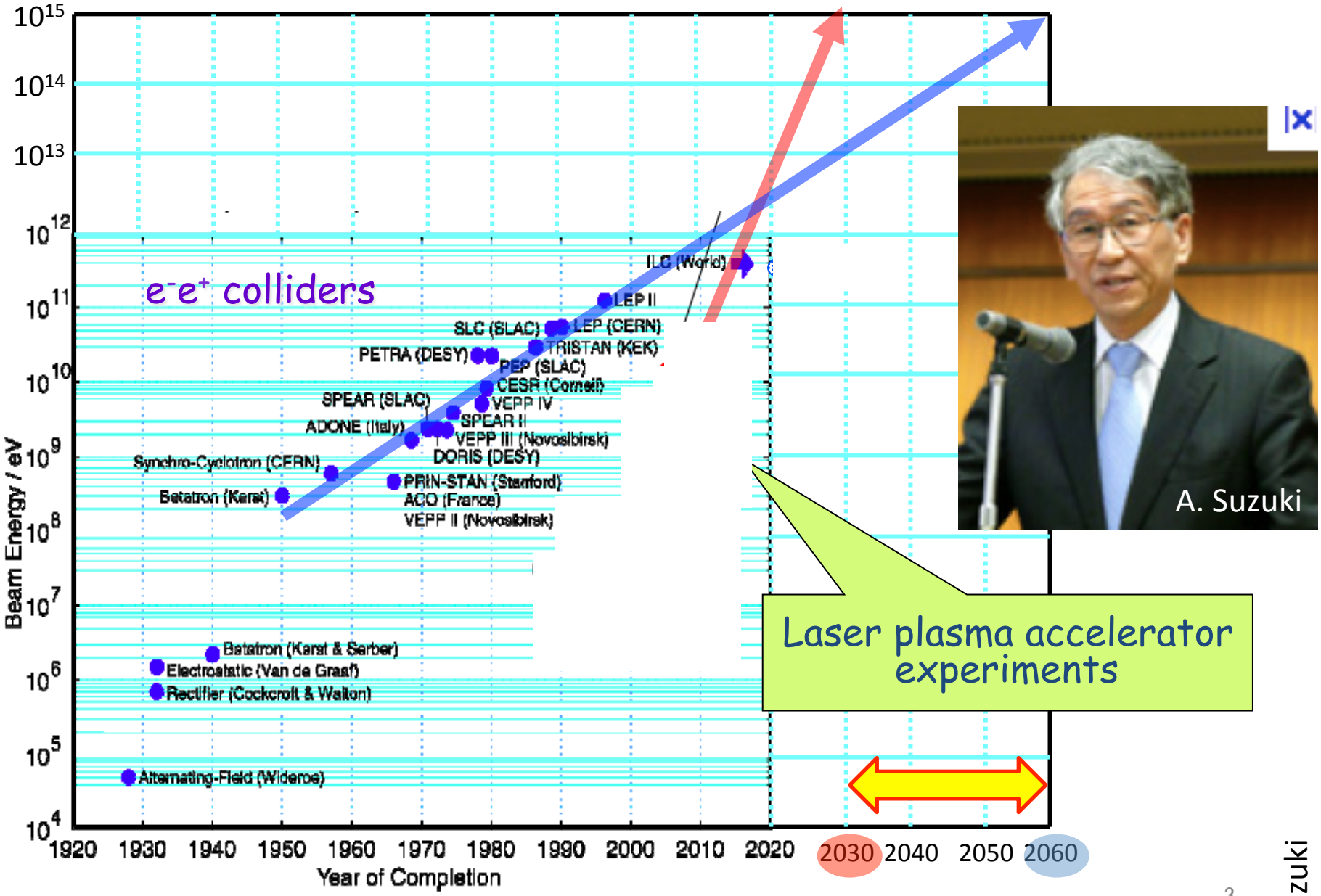
  10keV photon: $n_{cr} = 10^{29}$ /cc---- solid density $n = 10^{23}$/cc

  wakefield energy gain $= 2mc^2 a_0^2 (n_{cr} / n) = a_0^2$ TeV
- **X-ray crystal optics and nanostructure: Simulation study**

  X-ray (γ-ray) intensity scaling, radius, density scalings
- **Nature (Blackhole jets):** creates extremely strong EM pulses

  nature provides robust extreme acceleration (ZeV); gamma bursts

Suzuki's Challenge: "When can we reach 1 PeV ?"



V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

Suzuki

Suzuki's Challenges

suzuki

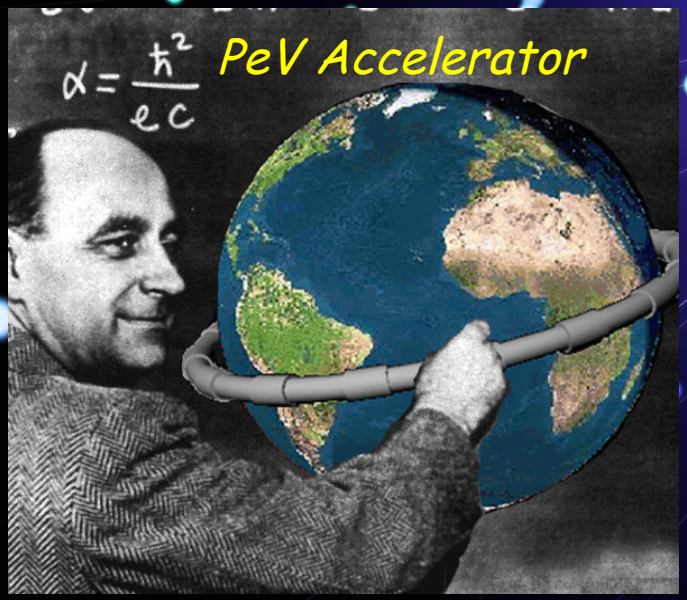
1000 times higher energy

1 PeV=10^{15} eV

" New paradigm"

Leptogenesis

SUSY breaking



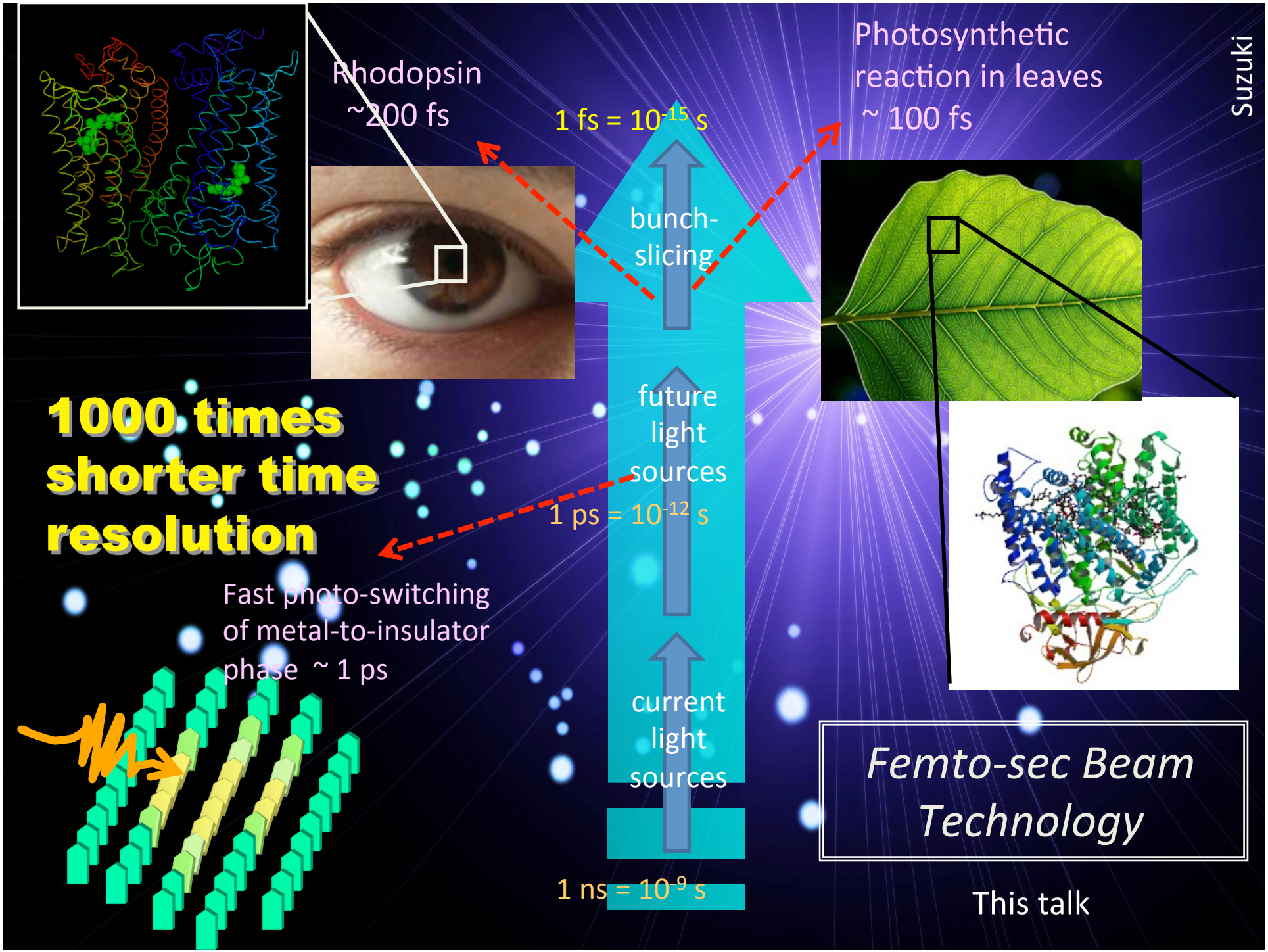
Extra dimension
Dark matter
Supersymmetry

1 TeV=10^{12} eV

"Standard model"
Higgs
Quarks
Leptons

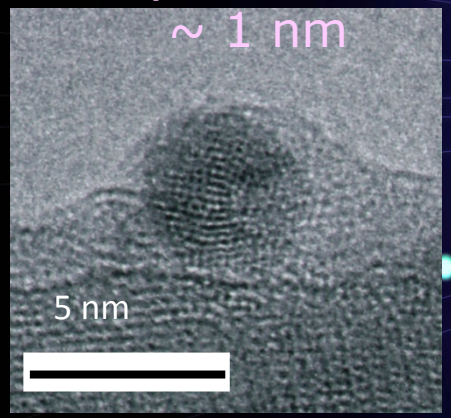
Laser wakefield Acceleration Technology

This talk

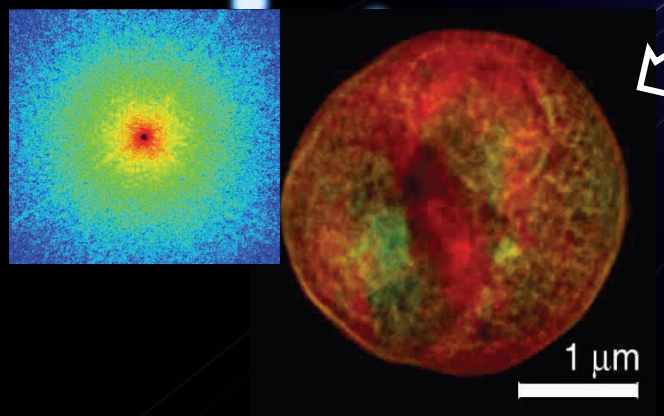

Rhodopsin
~200 fs
1 fs = 10-15 s
Photosynthetic
reaction in leaves
~ 100 fs
Suzuki
bunch-
slicing
future
light
sources
1 ps = 10-12 s
1000 times
shorter time
resolution
Fast photo-switching
of metal-to-insulator
phase ~ 1 ps
current
light
sources
1 ns = 10-9 s
Femto-sec Beam
Technology
This talk

1000 times higher spatial resolution

catalytic chemistry
~ 1 nm



cellular structure
and function ~ (1-10) nm



1 pm

future
light
sources

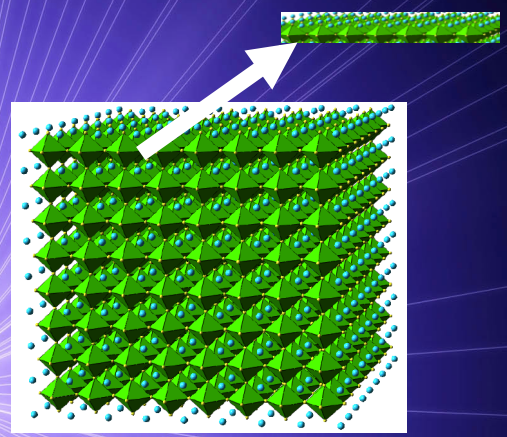
1 nm

10 nm

current
light
sources

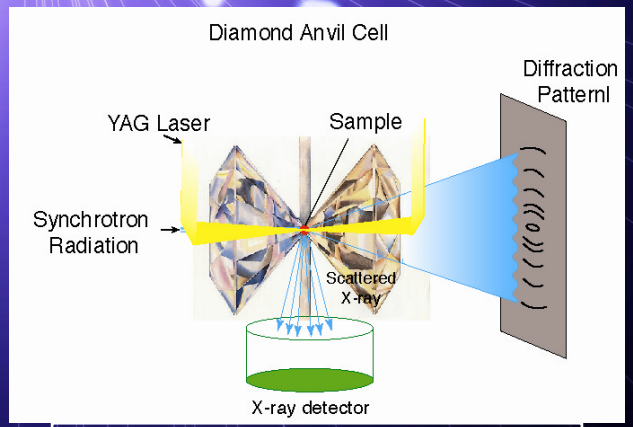
~100 nm

Nano-crystal ~ 1 nm



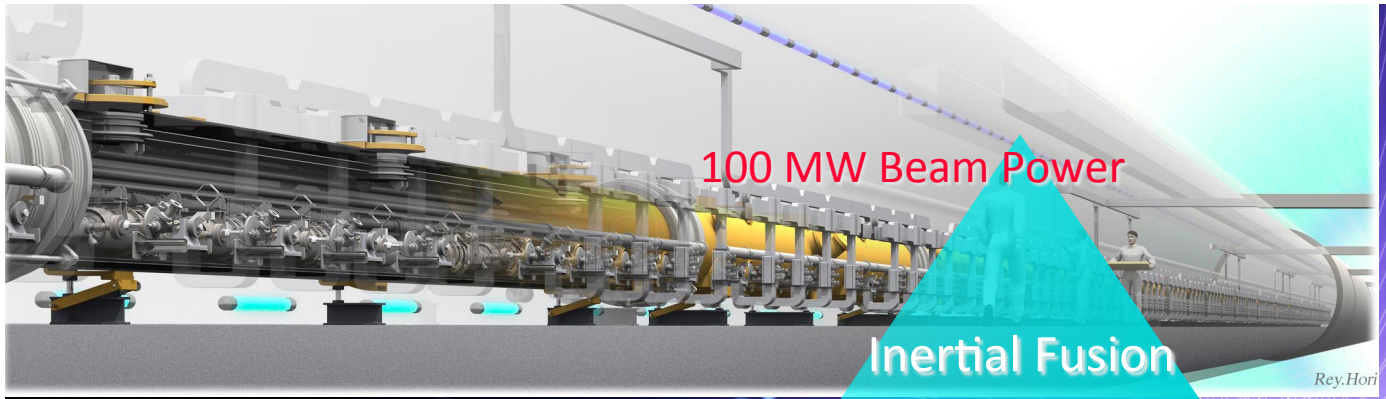
Suzuki

extreme condition
~ (1-10) nm



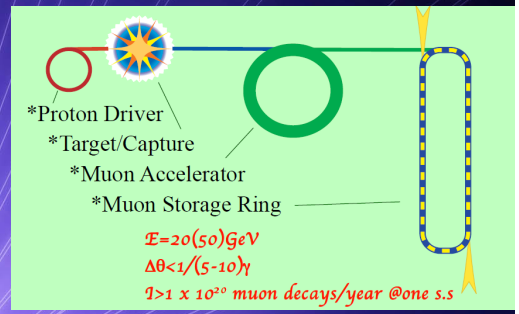
Nano beam Technology

This talk



100 MW Beam Power

Inertial Fusion



Muon-collider

Neutrino factory

1000 times more powerful beam

Nuclear waste processing

Brighter neutron source

Muon Collider

Neutrino Factory

Linear Collider

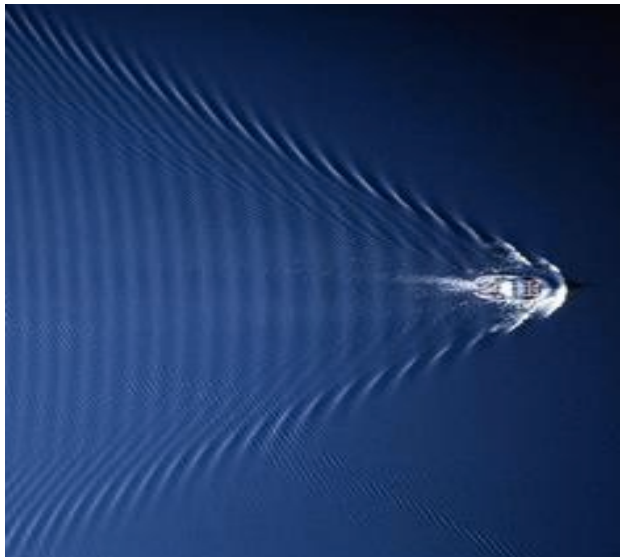
Super-conducting Accelerator Technology

100 kW Beam Power

Suzuki

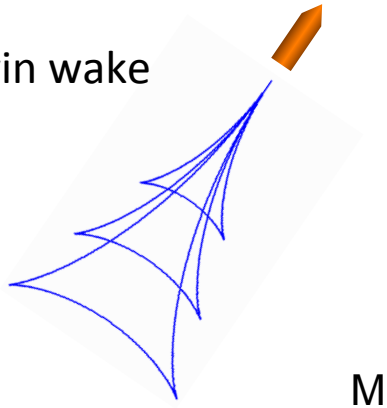
→See CAN laser

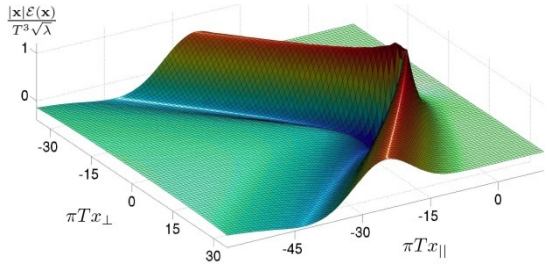
Laser Wakefield (LWFA): nonlinear optics in plasma



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

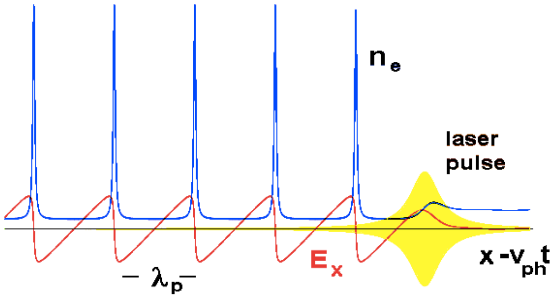
Kelvin wake





Maldacena (string theory) method: ys QCD **wake** (Chesler/Yaffe 2008)

Wave **breaks** at v<c



← relativity regularizes (*relativistic coherence*)

(The density cusps. Cusp singularity)

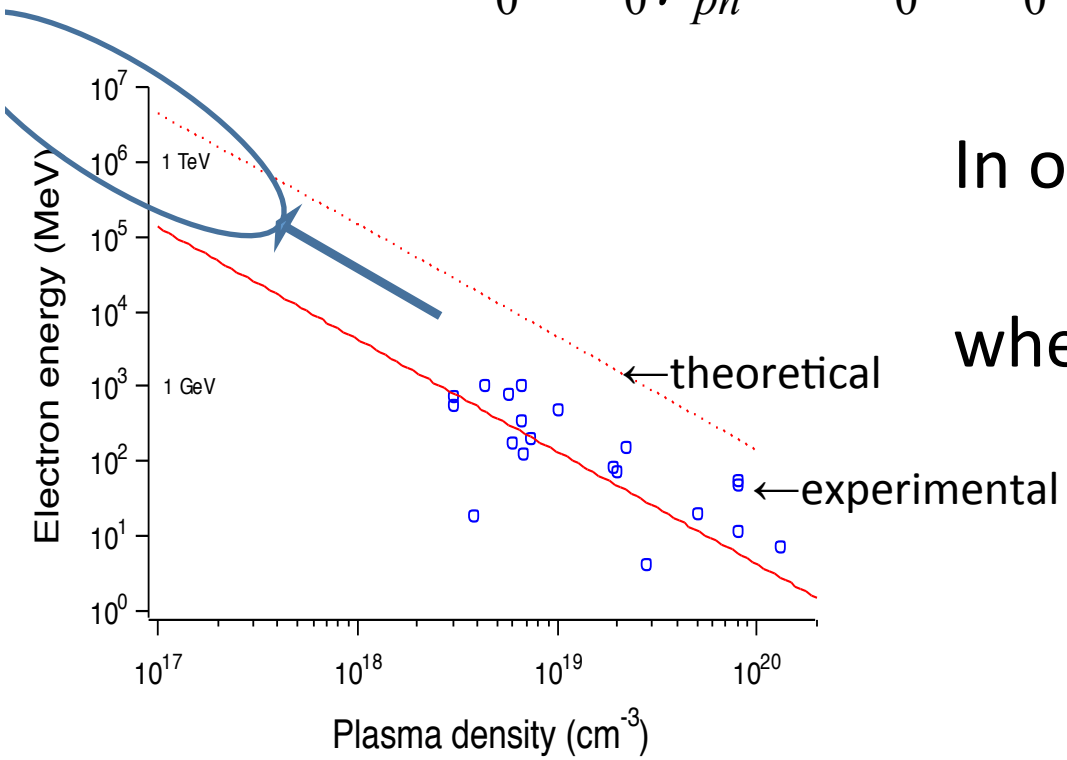
Hokusai

Maldacena

(Plasma physics vs. String theory)

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)

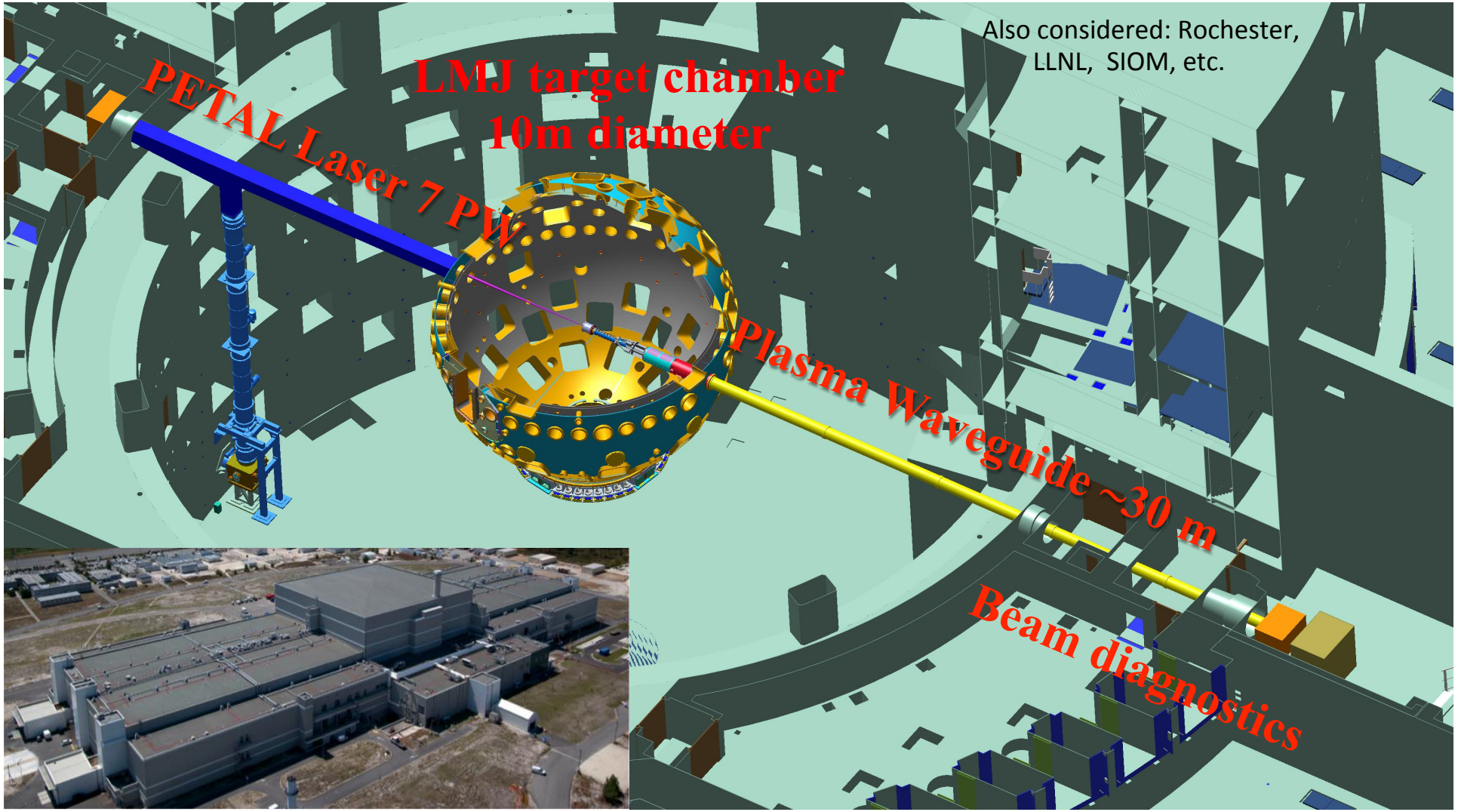
$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right), \qquad L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length pump depletion length

IZEST proposes 100 GeV Ascent Experiment using 3.5 kJ, 500fs, 7 PW PETAL laser

⇧ Large Energy Laser

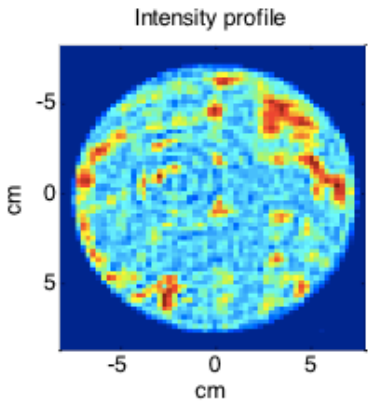
K. Nakajima

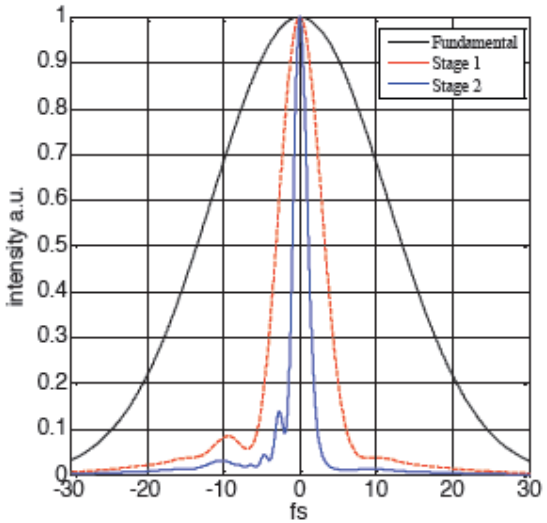


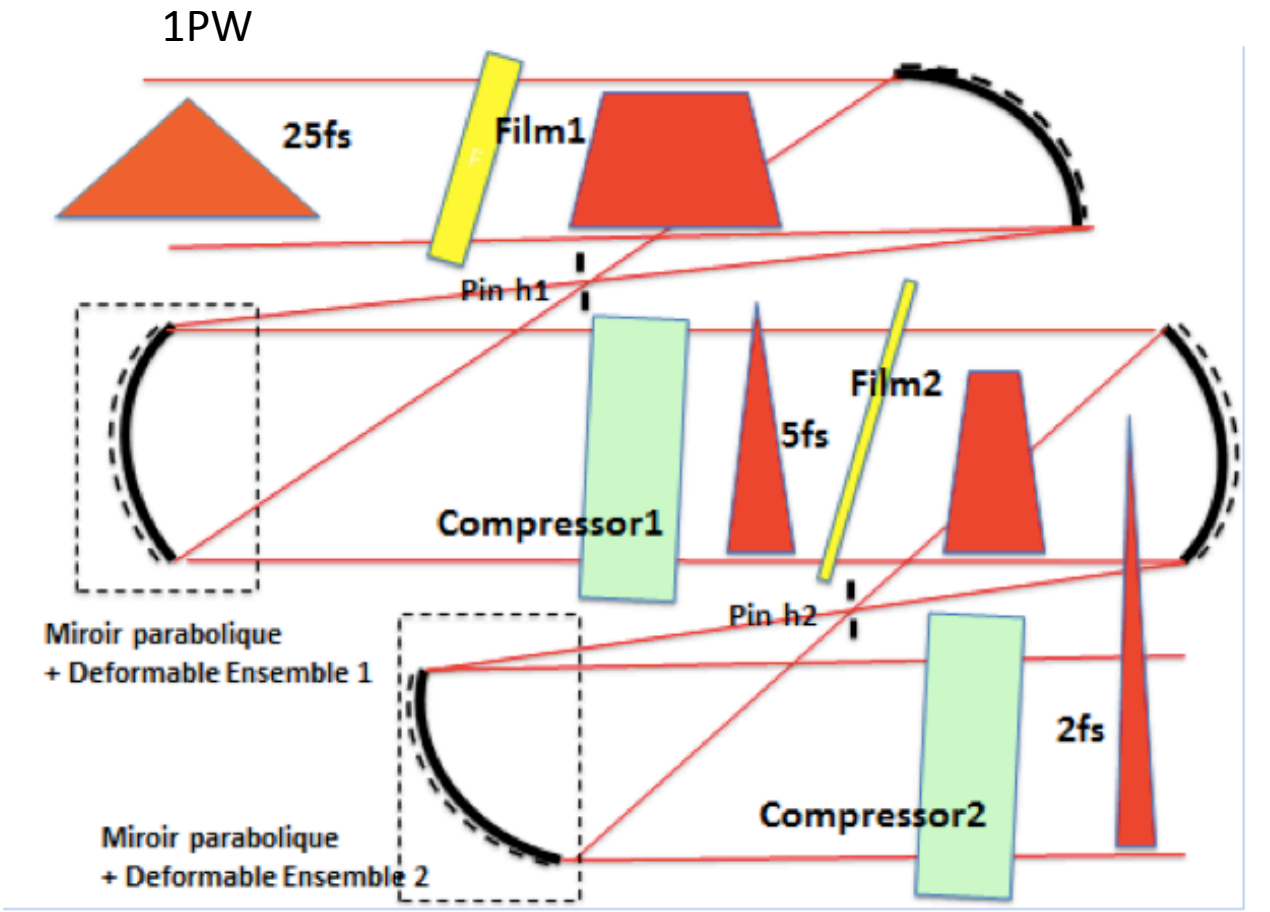
Single-Cycle Laser Compressor w/thin film

(first step)

(G. Mourou)







G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Eur. Phys. J. Special Topics, **223**, 1181(2014)

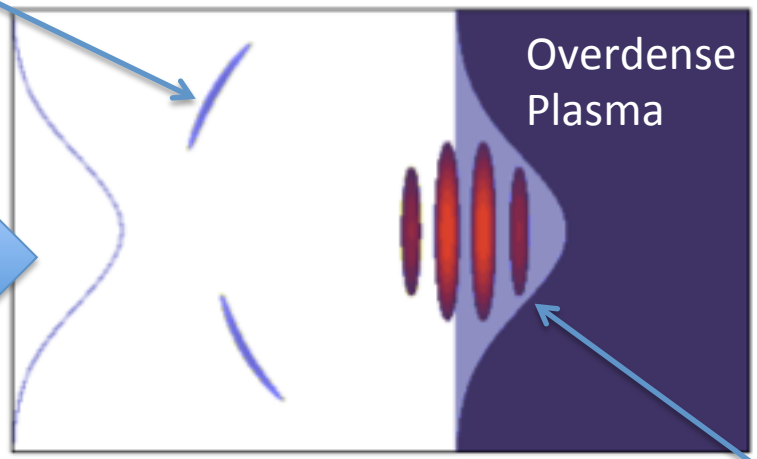
Ultrarelativistic Mirror in the λ^3-laser Regime

(second step)

(G. Mourou)

γ =10^3
τ Pulse ~few zs
Pulse Power ~ EW
Wavelength ~ keV

Single Cycle Thin Film Compressor
10PW, 2fs, 100J, 1μm^2
Intensity ~10^{25}W/cm2

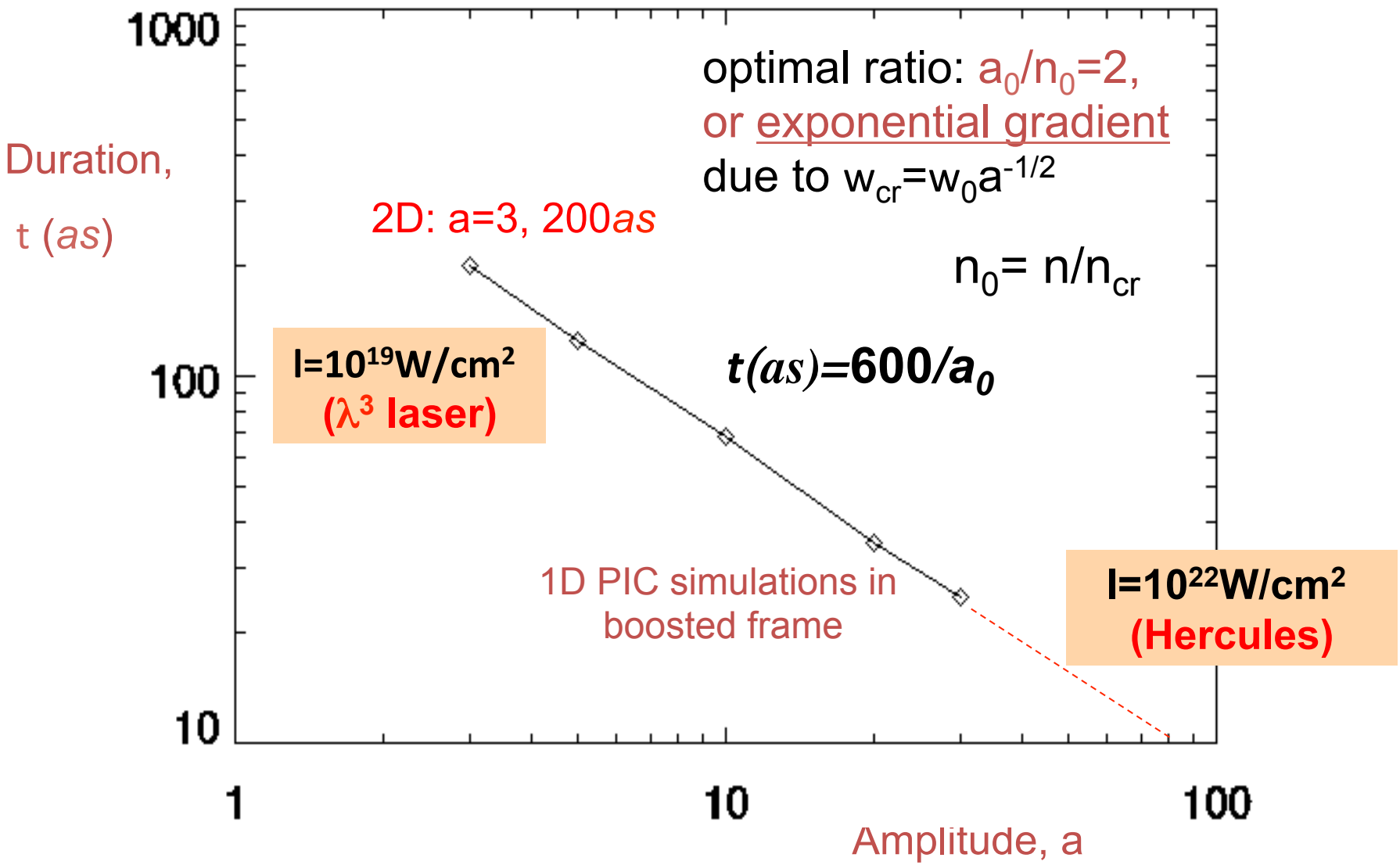


Critical Surface
Moving at v ~c ,
γ =10^3

N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou,
Phys. Rev. Lett. **92**, 063902-1 (2004).

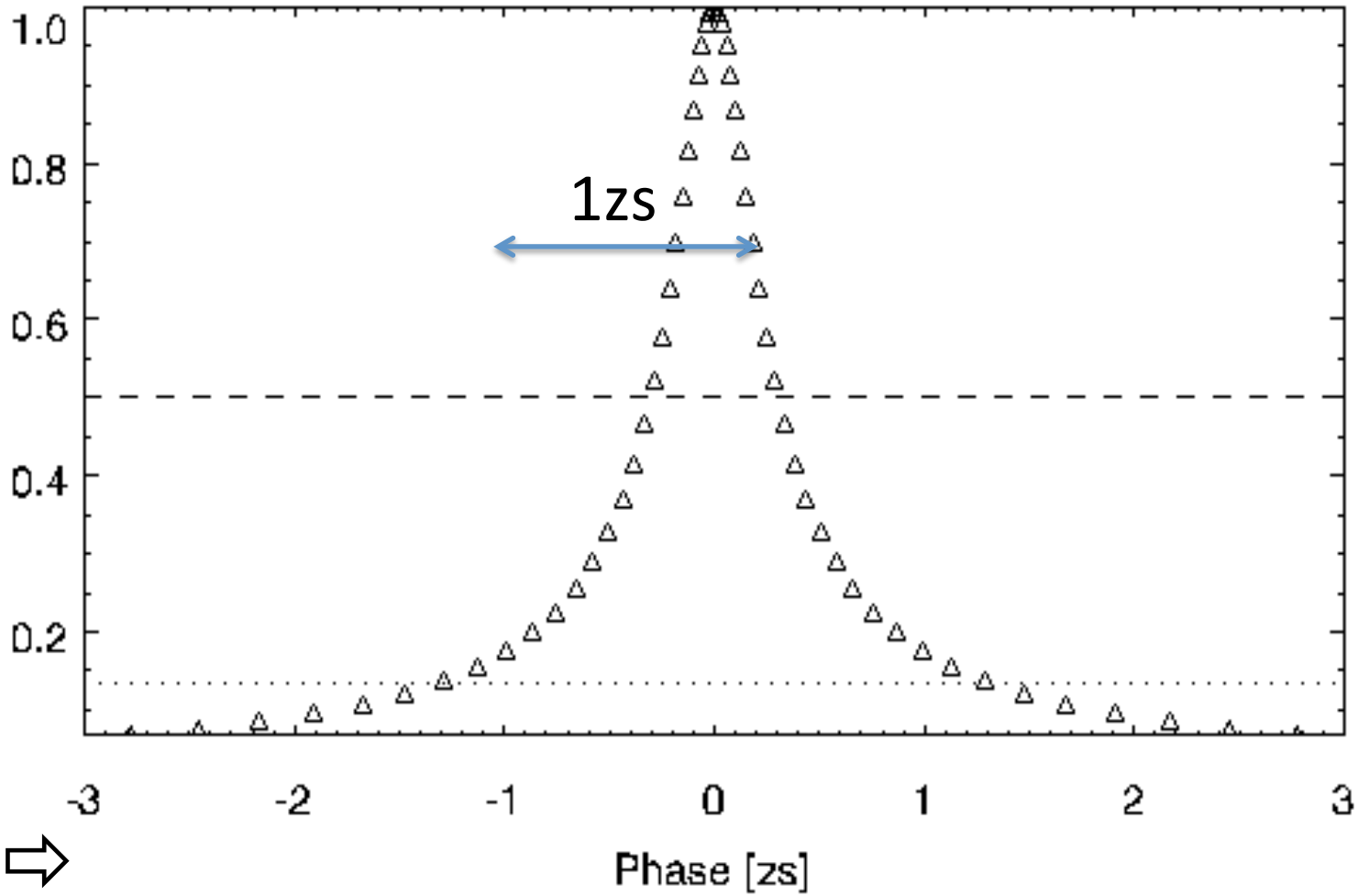
Scalable Isolated Attosecond Laser Pulses

(Naumova et al. PRL, 2004)



Even,isolated zeptosecond X-ray laser pulse possible

(simulation by N. Naumova, I. Sokolov, G. Mourou, 2014)



⇨

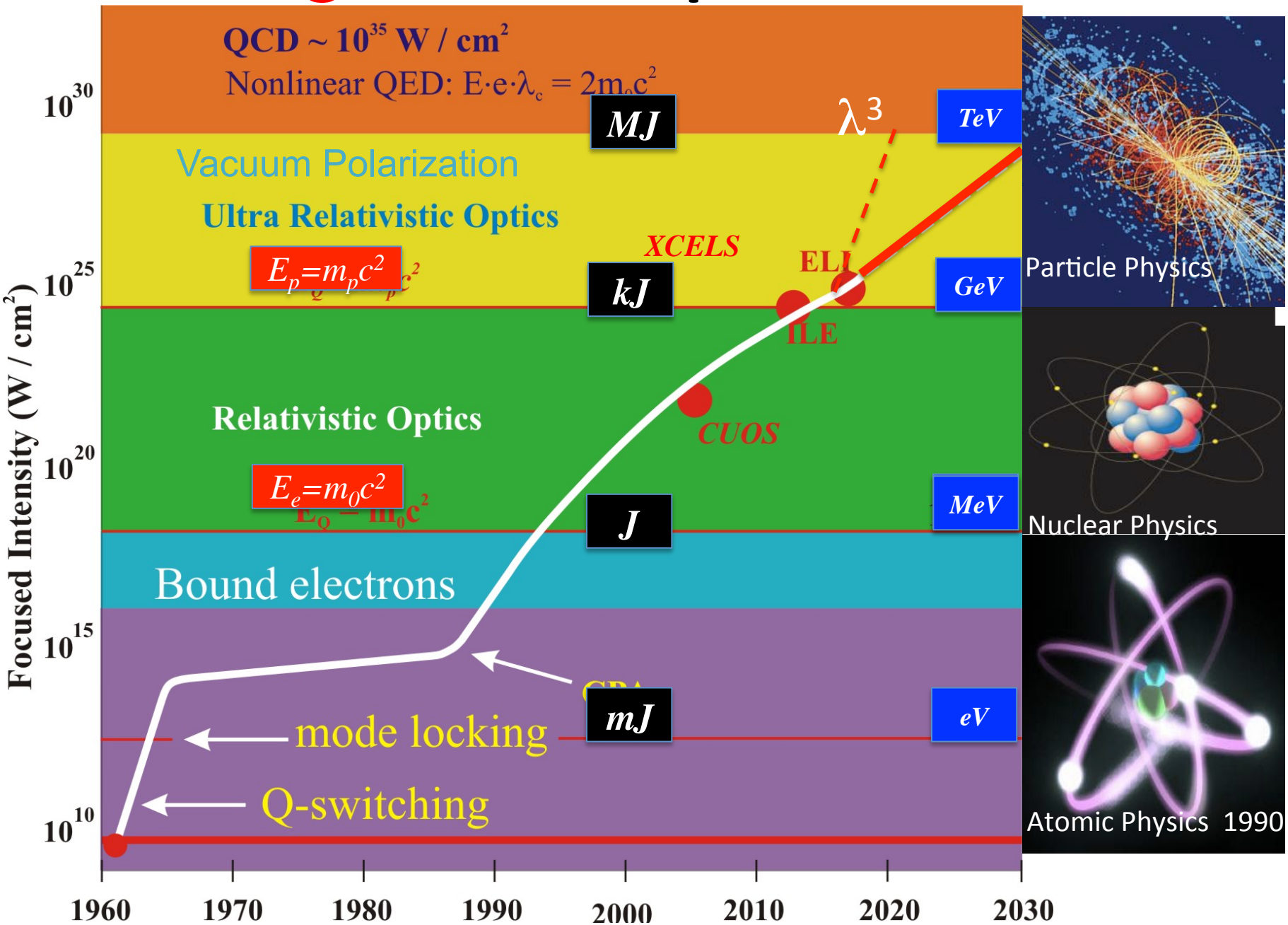
1PW optical laser → 10PW single osc. Optical laser

→ EW single osc. X-ray laser

Consistent with "Intensity-pulse-width Conjecture" (Mourou-Tajima, Science **331** (2011))

Extreme Light Roadmap

(modified from Tajima and Mourou, PR 2002)



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
terial, 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 ty

Particle Accelerators, 1990, Vol. 32, pp. 235–240
Reprints available directly from the publisher
Photocopying permitted by license only

© 1990 Gordon and Breach, Science Publishers, Inc.
Printed in the United States of America

BEAM TRANSPORT IN THE CRYSTAL X-RAY ACCELERATOR

T. TAJIMA, B. S. NEWBERGER
University of Texas-Austin, Austin TX 78712 U.S.A.
F. R. HUSON, W. W. MACKAY
Texas Accelerator Center, The Woodlands, TX 77381 U.S.A.
B. C. COVINGTON, J. PAYNE
Sam Houston State University, Huntsville, TX 77341 U.S.A.
N. K. MAHALE, S. OHNUMA
University of Houston, Houston, TX 77204 U.S.A.

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

VOLUME 59, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1987

Crystal X-Ray Accelerator

T. Tajima
Department of Physics and Institute for Fusion Studies, The University of Texas, Austin, Texas 78712
and
M. Cavenago
Department of Physics, University of California, Irvine, California 92717
(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: $a_0 = \pi^{-1/2}\hbar c(fN)^{-1/2}P\epsilon^{-2}$, 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 $\hbar\omega = \hbar\omega_p \simeq mc^2\alpha^2 \simeq 30$ 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 $\lesssim mc^2\alpha$, however, the metal now ceases to be opaque. The mean free path of the photon is given by Bethe-Bloch theory as $l_i = (3/2^8\pi) \times a_B^{-2}\alpha^{-4}n^{-1}(\hbar\omega/Z_{\rm eff}^2\mathcal{R})^{7/2}$, 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 $\hbar\omega = mc^2\alpha$ 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

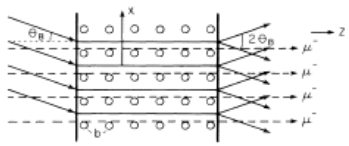
where b is the transverse lattice constant and later a the longitudinal lattice constant ($a \simeq b$) (see Fig. 1). The row of lattice ions (perhaps with inner-shell electrons) constitutes the "waveguide" wall for x rays, while they also act as periodic irises to generate slow waves. A superlattice[5]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

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



X-ray LWFA in crystal suggested

Tajima, Eur. Phys. J. **223** (2014)

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

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

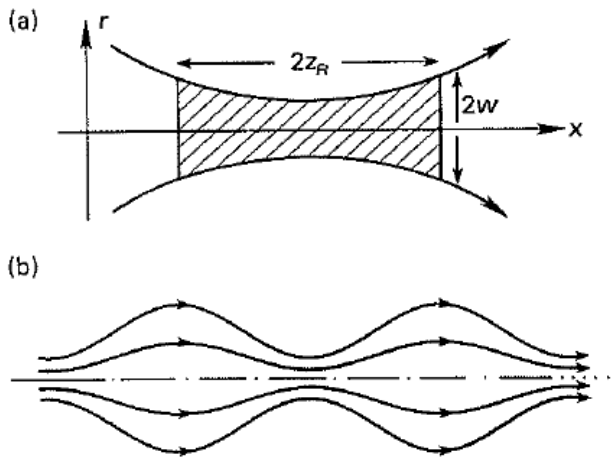
LWFA energy gain

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

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

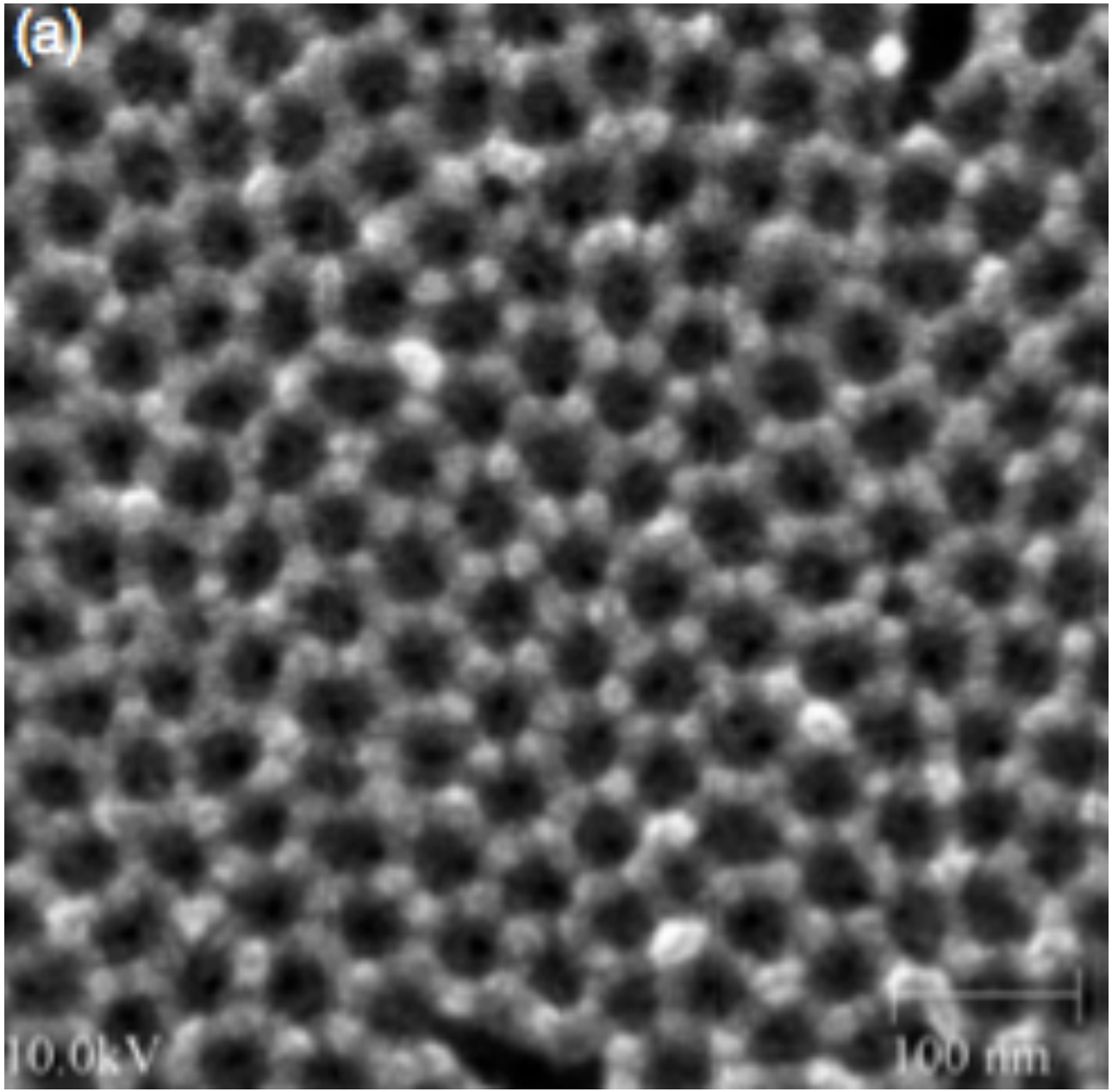
$$\omega = c\sqrt{(k_z^2 + \langle k_{perp}^2 \rangle)},$$

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)

Porous Nanomaterial



Nano holes:
- reduce the stopping power
- keep strong wakefields

➔ Marriage of *nanotech* and *high field science*

Porous alimina on Si substrate
Nanotech. **15**, 833 (2004);
P. Taborek (UCI): porous alumina

UCI/Fermilab efforts on nanostructure wakefield acceleration

16th Advanced Accelerator Concept Workshop (AAC2014)

TeV/m Nano-Accelerator

Current Status of CNT-Channeling Acceleration Experiment

Y. M. Shin[1,2], A. H. Lumpkin[2], J. C. Thangaraj[2], R. M. Thurman-Keup[2], P. Piot[1,2], and V. Shiltsev[2]

Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, and E. Harms

[1]Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University

[2]Fermi National Accelerator Laboratory (FNAL)

Simulation of X-ray wakefield acceleration in nanomaterials tubes

X-ray laser with short length and small spot used according to proposal (G. Mourou)

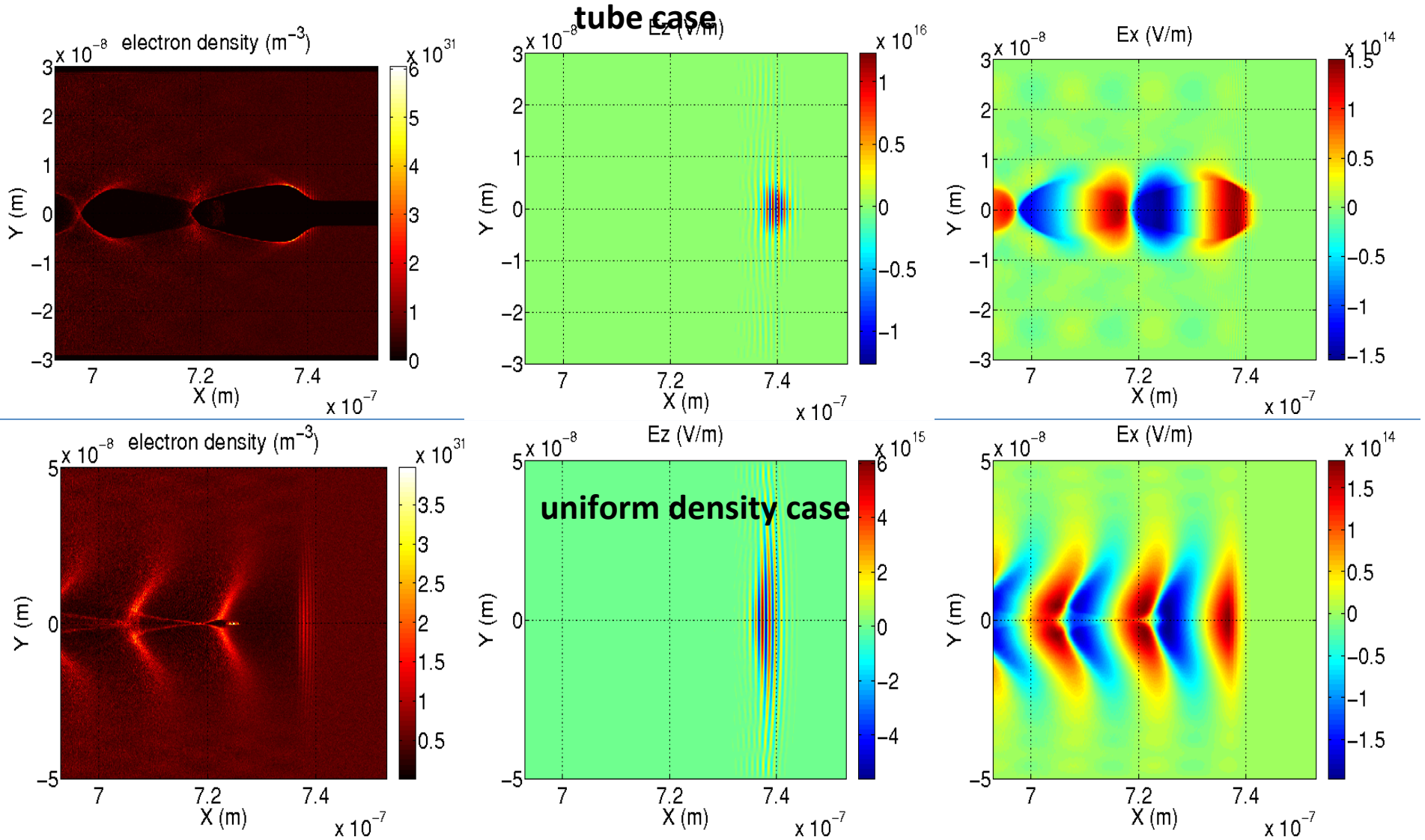
Laser pulse with small spot can be well controlled and guided with a tube. Such structure available e.g. with **carbon nanotube,** or **almumina nanotubes** (typical simulation parameters)

$$\lambda = 1nm, a_0 = 4, \sigma_L = 5nm, \tau_L = 3nm / c$$

$$n_{tube} = 5 \times 10^{24} / cm^3, \sigma_{tube} = 2.5nm$$

X.M. Zhang (2015)

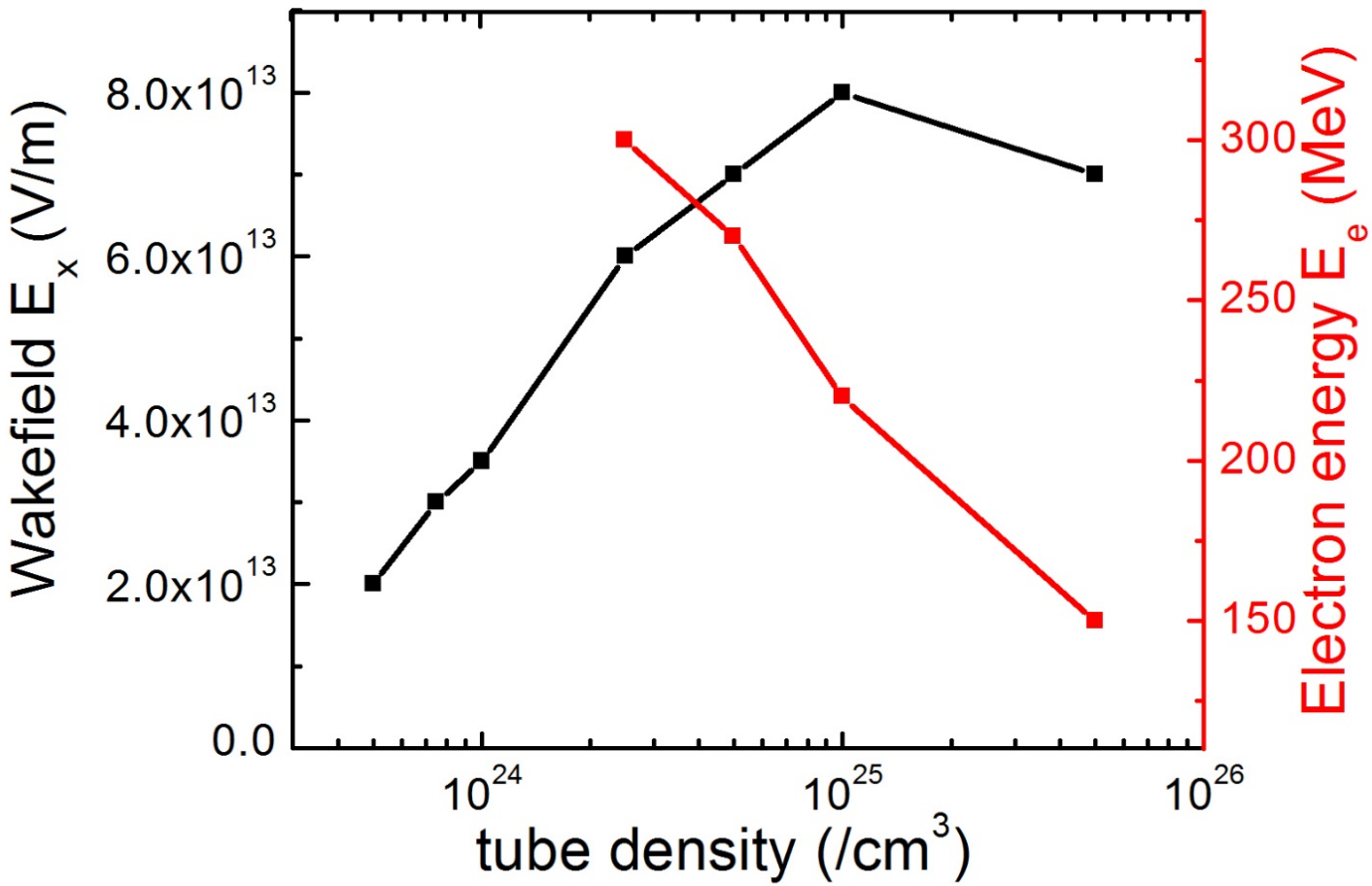
Wakefield comparison between the cases of a tube and a uniform density



X. M. Zhang

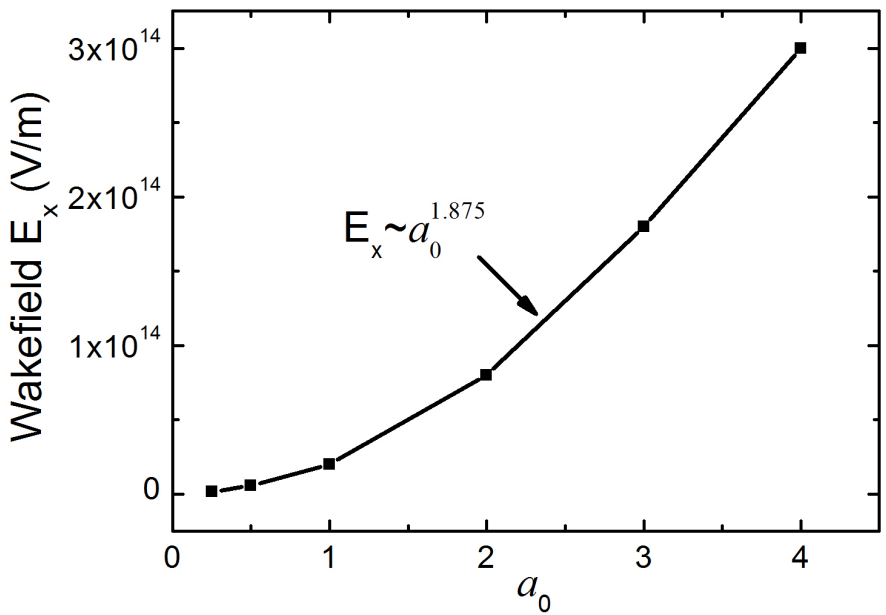
PIC simulation of X-ray wakefields in a nanomaterial tube; Density scaling

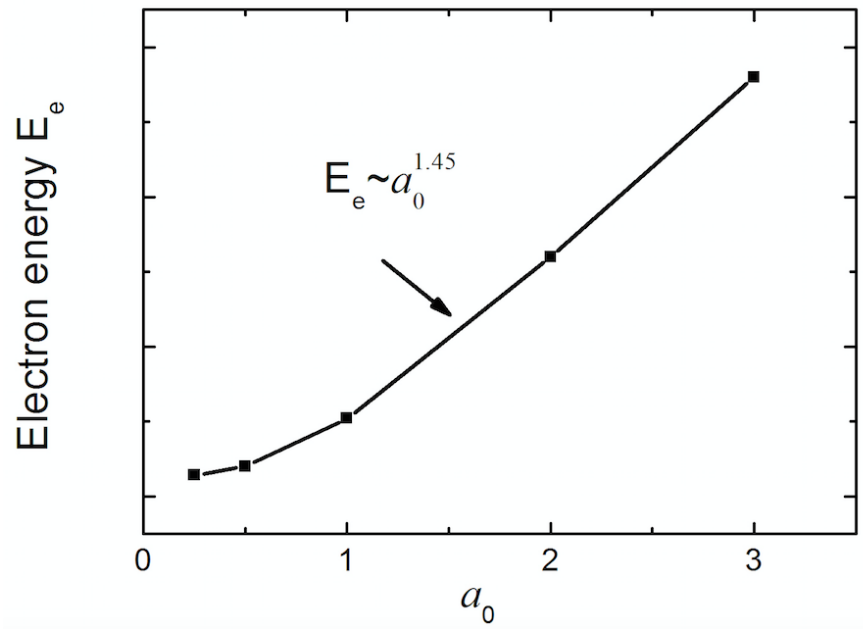
Photon energy = 1keV,tube radius = 5nm, a_0 =4, (n_{cr} / n = around 200) , few-cycled laser



X. M. Zhnag (2015)

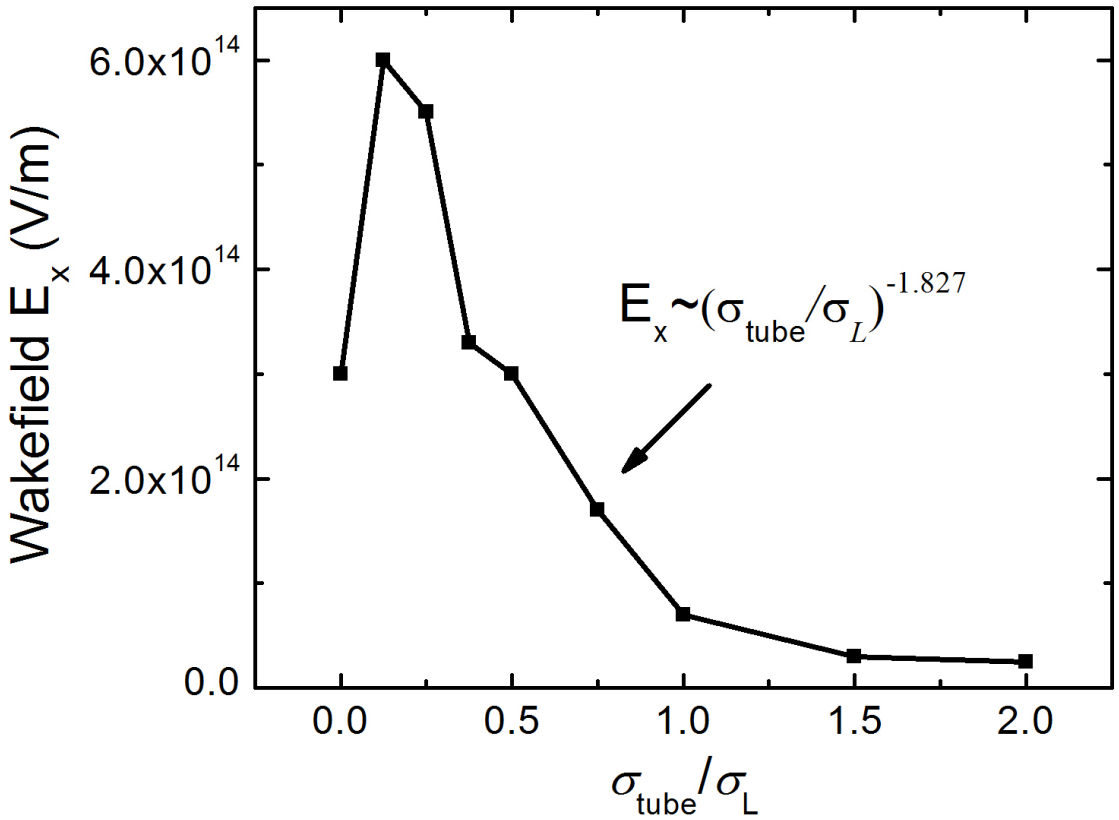
Wakefield scaling to the X-ray laser amplitude





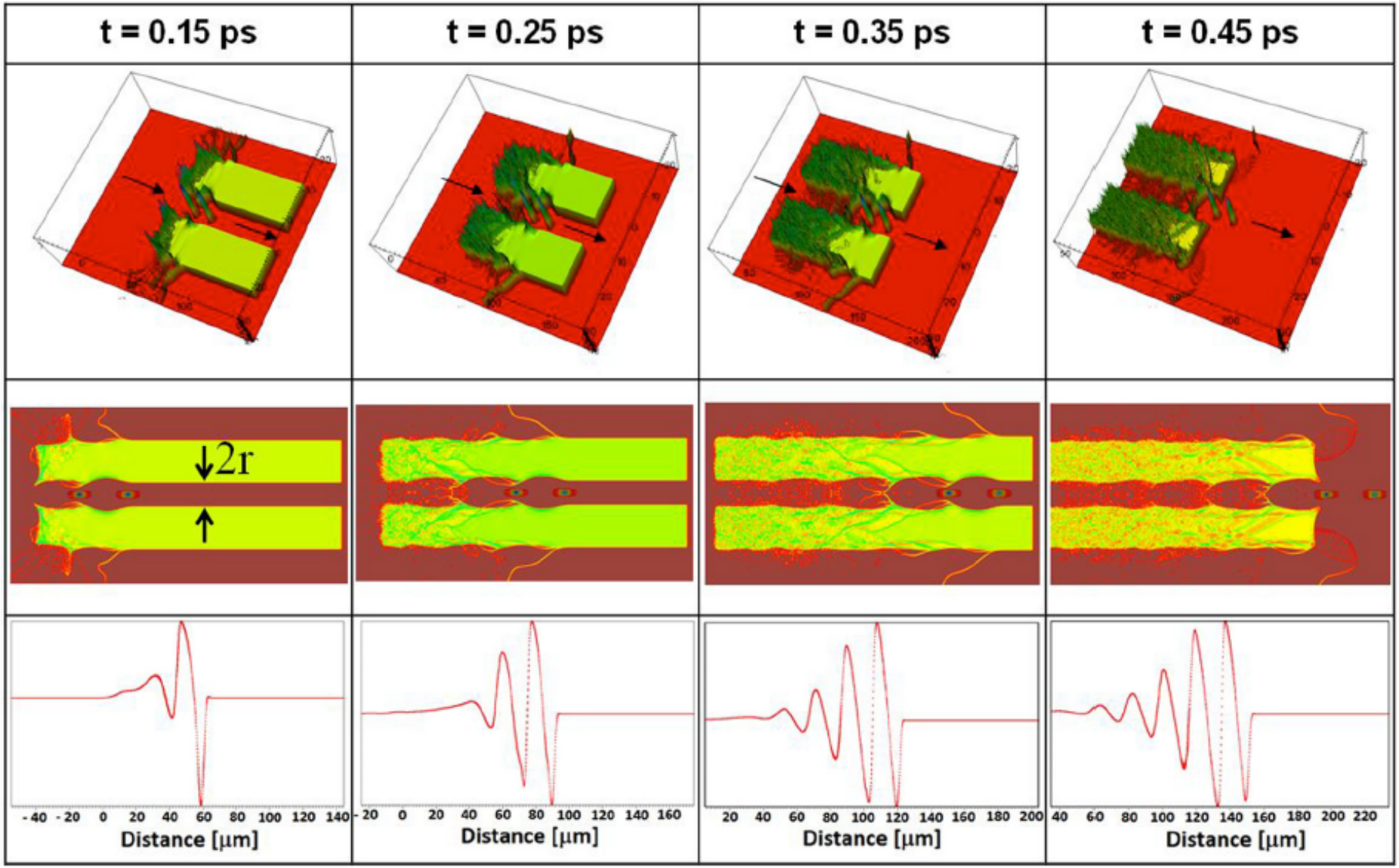
X. M. Zhnag (2015)

Wakefields and the tube geometry



X. M. Zhang (2015)

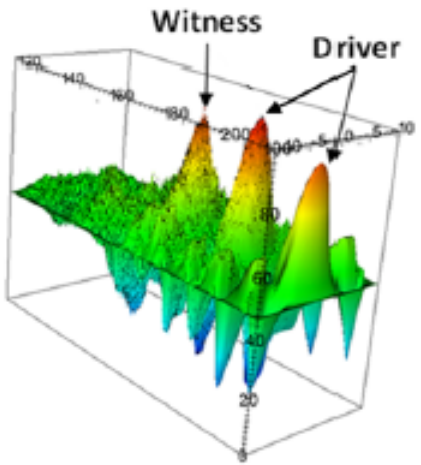
Wakefield on a chip toward TeV over cm (beam-driven)

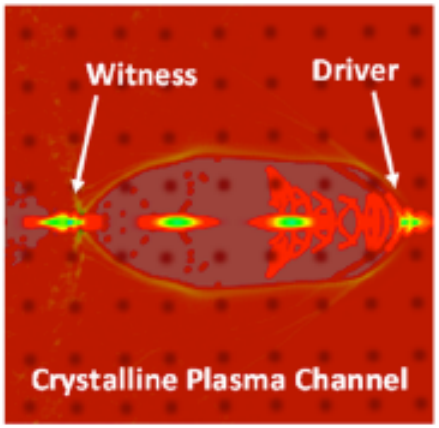


Y. Shin (2014)

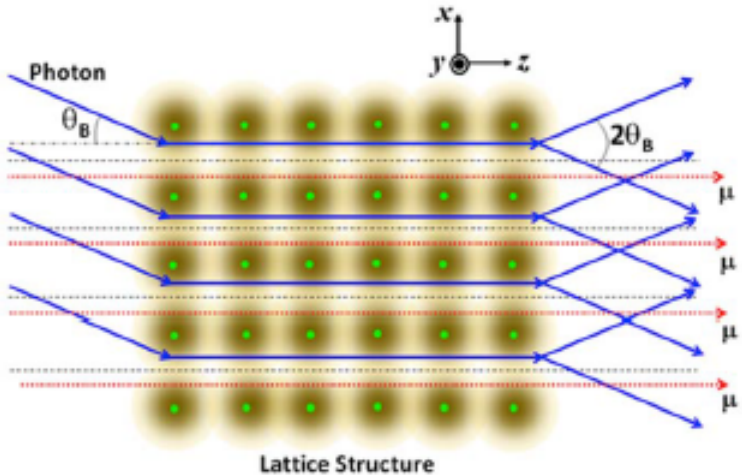
Wakefield excitation by electron (or positron) beam (vs. by X-ray pulse)

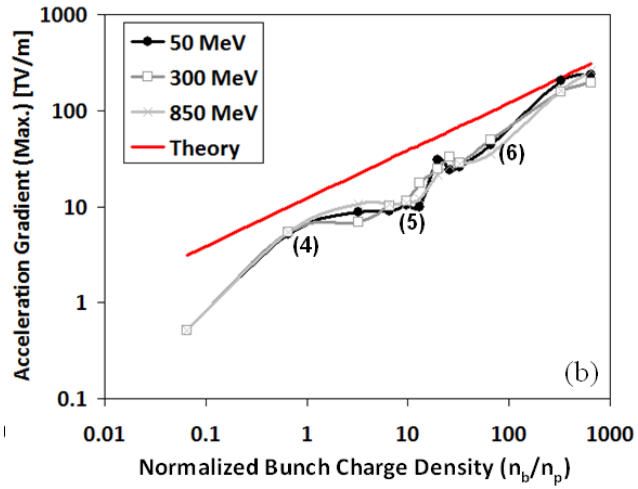
Wakefield Acceleration

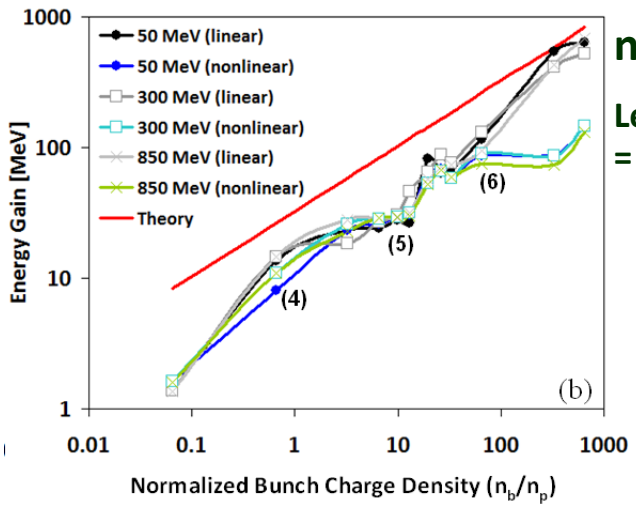




Diffraction Acceleration





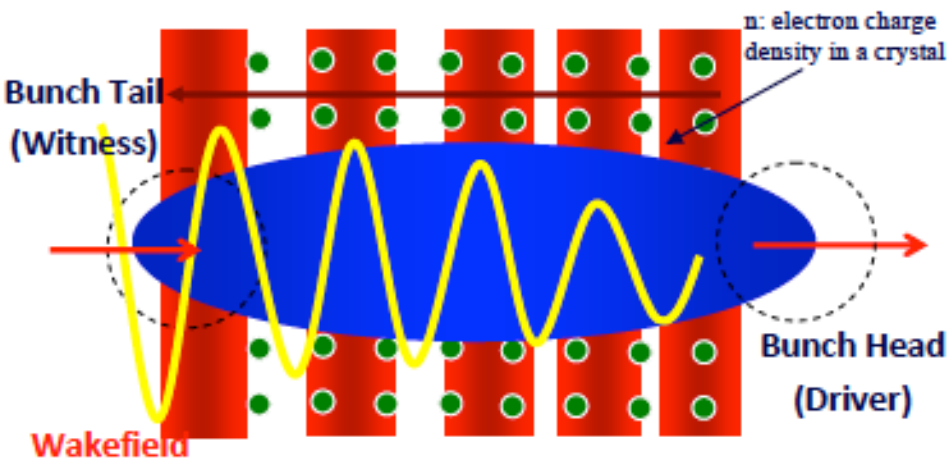


$n_p = 10^{28}\ m^{-3}$

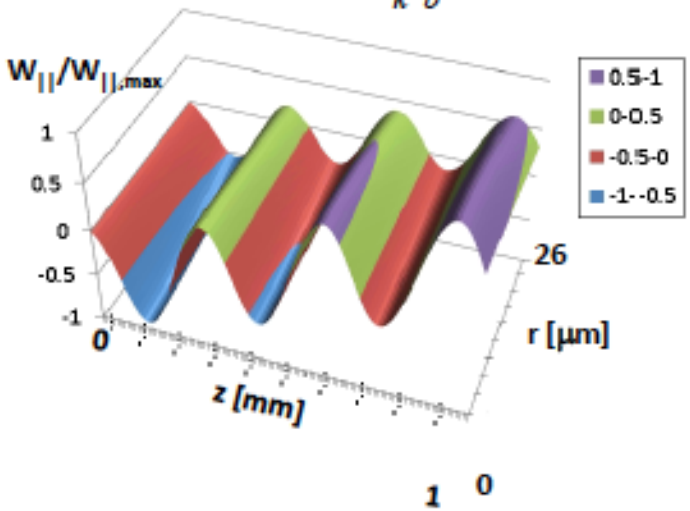
Length of Plasma $= 10\ \lambda_p$

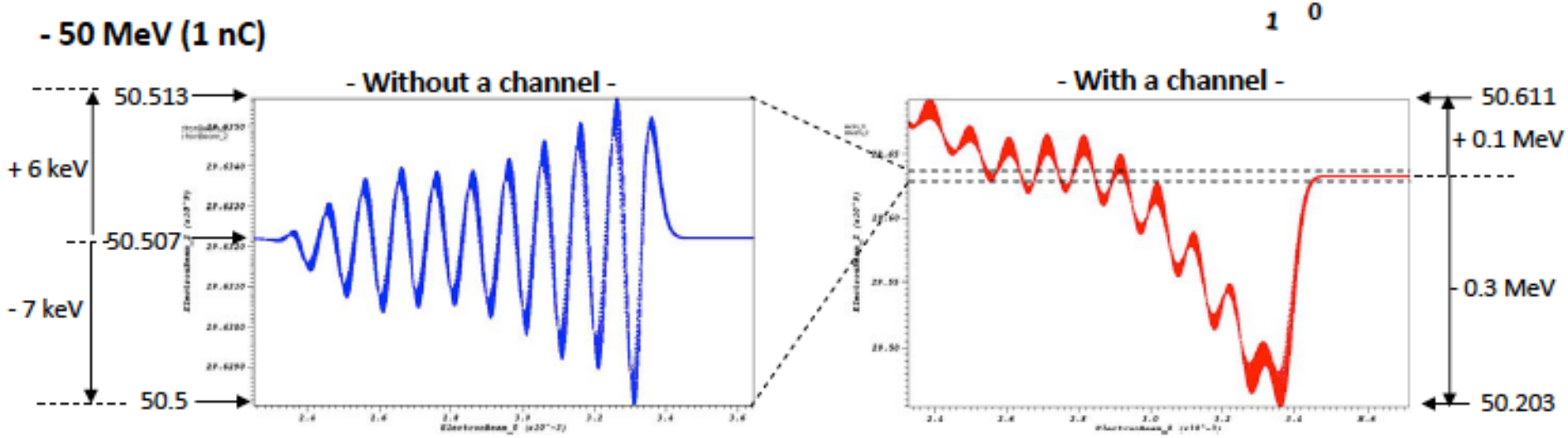
Shin, APL (2014)

Wakefield excitation and witness bunch that accelerated



$$eW_{\parallel} = \frac{16\pi e^2 \rho_b}{k^2 b} F_{\parallel}(r) G_{\parallel}(\zeta)$$



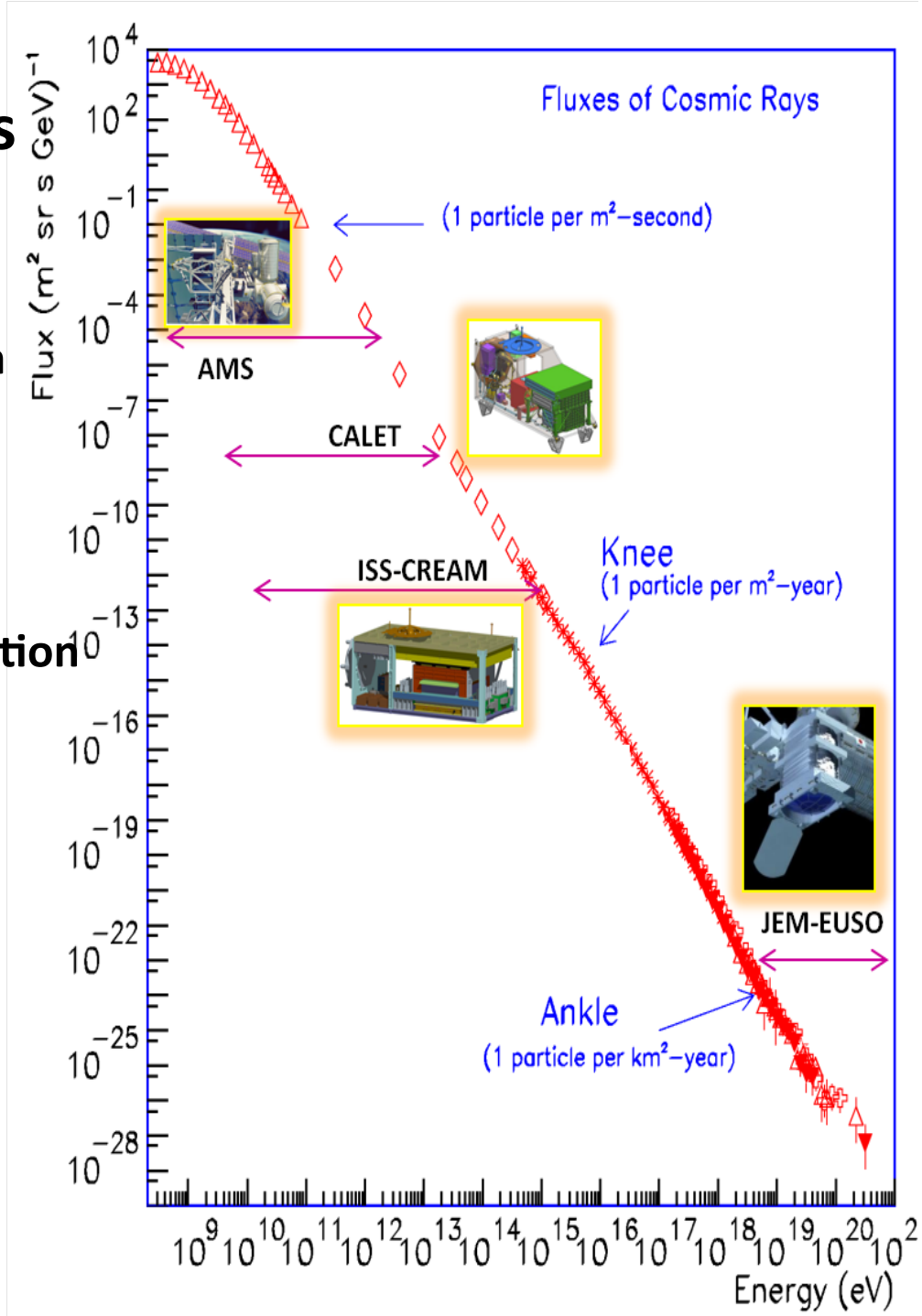


Shin (2014)

Ultrahigh Energy Cosmic Rays (UHECR)

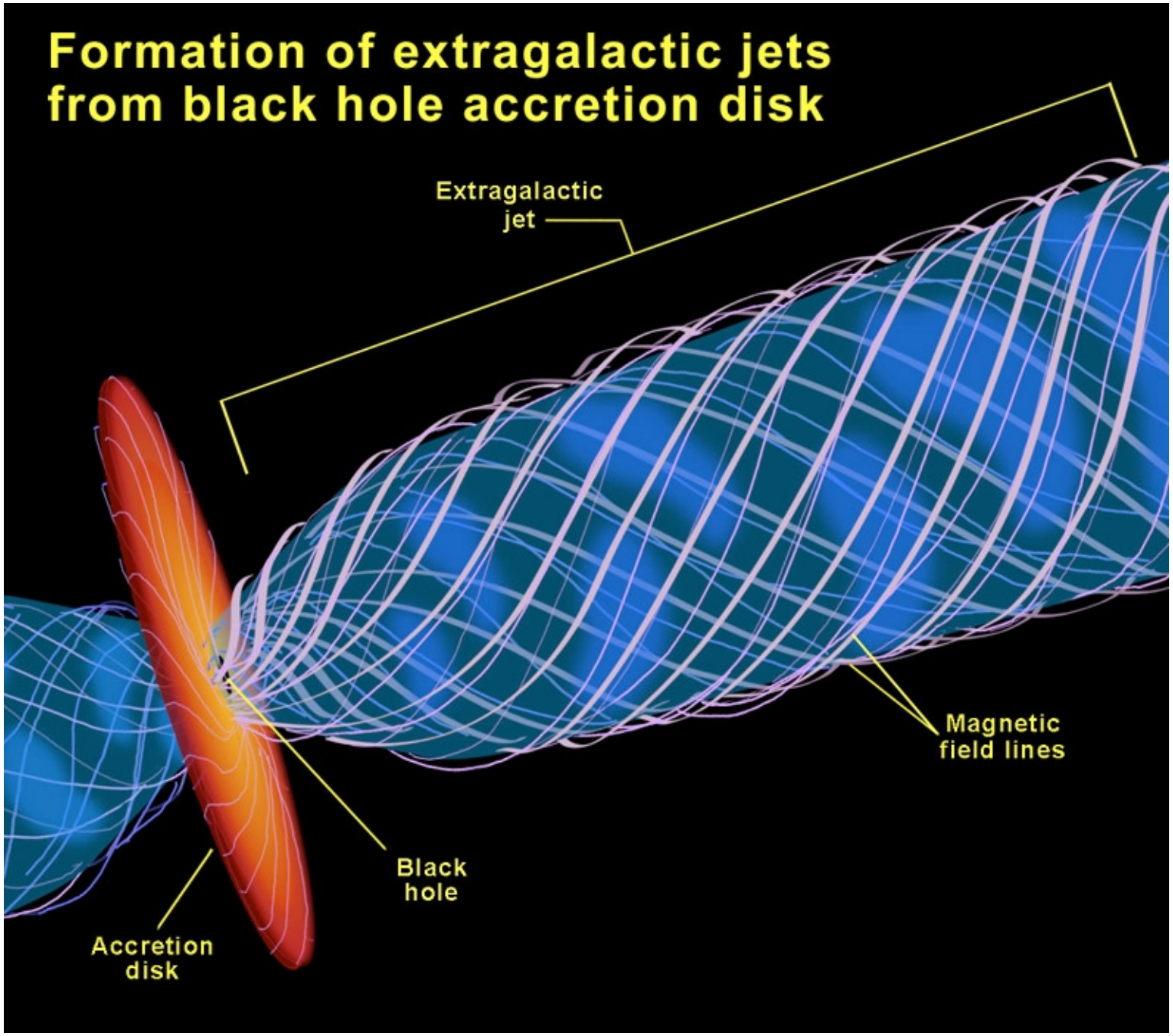
Fermi mechanism runs out of steam
- **beyond 10^{19} eV**
- **due to synchrotron radiation**

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

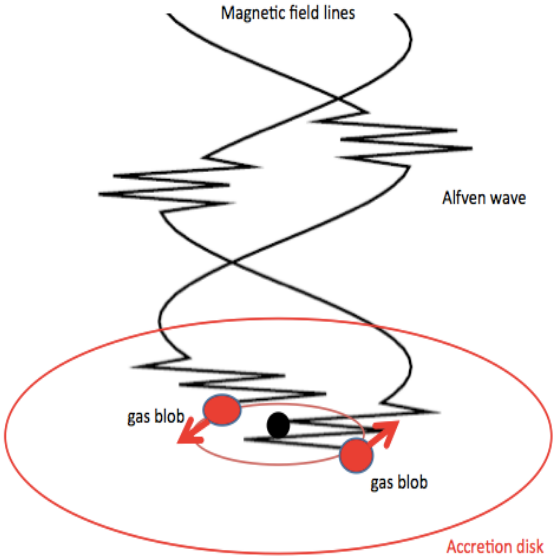


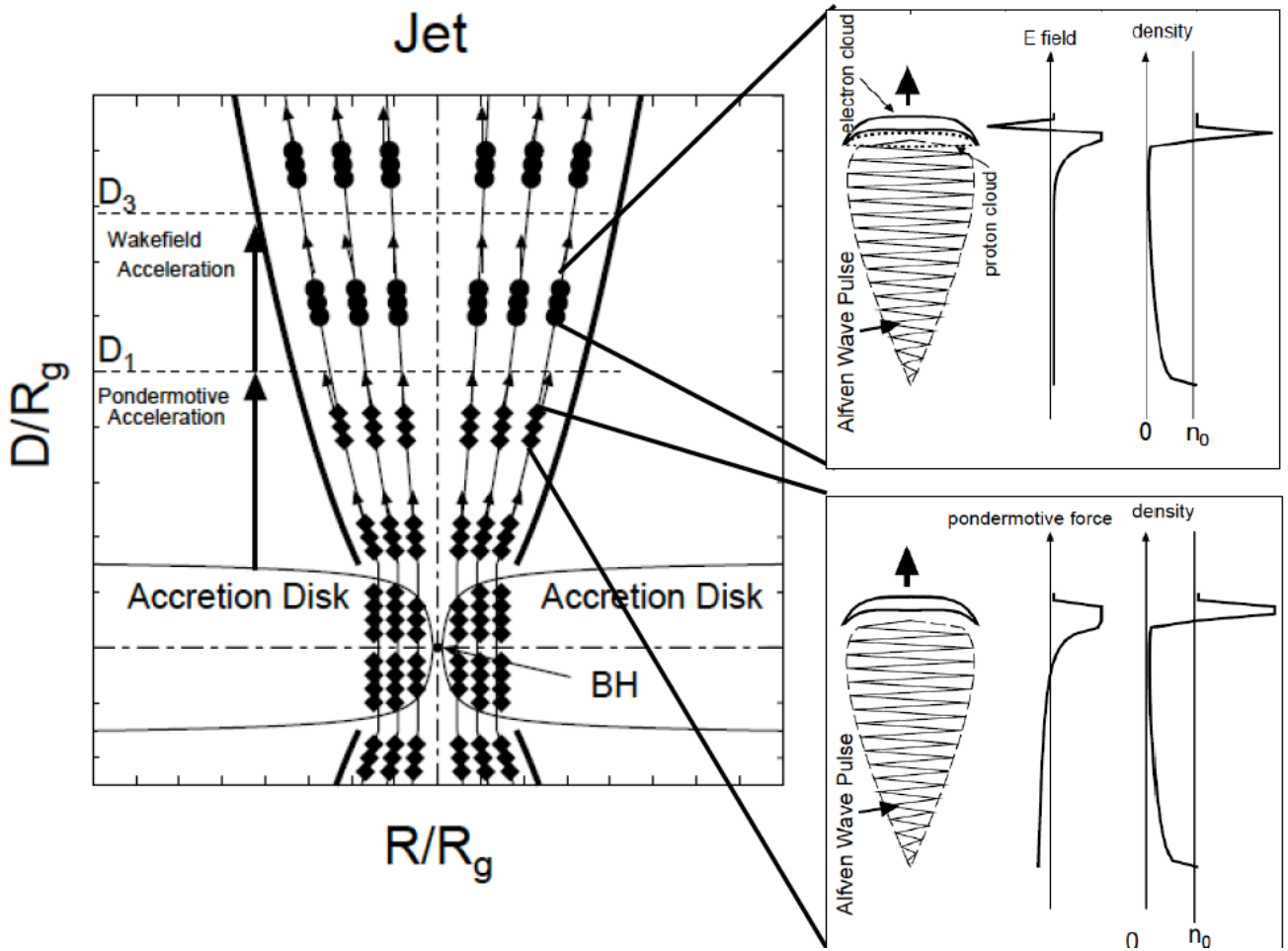
Cen A

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


Formation of extragalactic jets
from black hole accretion disk
Extragalactic
jet
Magnetic
field lines
Black
hole
Accretion
disk

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





Ebisuzaki and Tajima, Astropart. Phys.(2014)

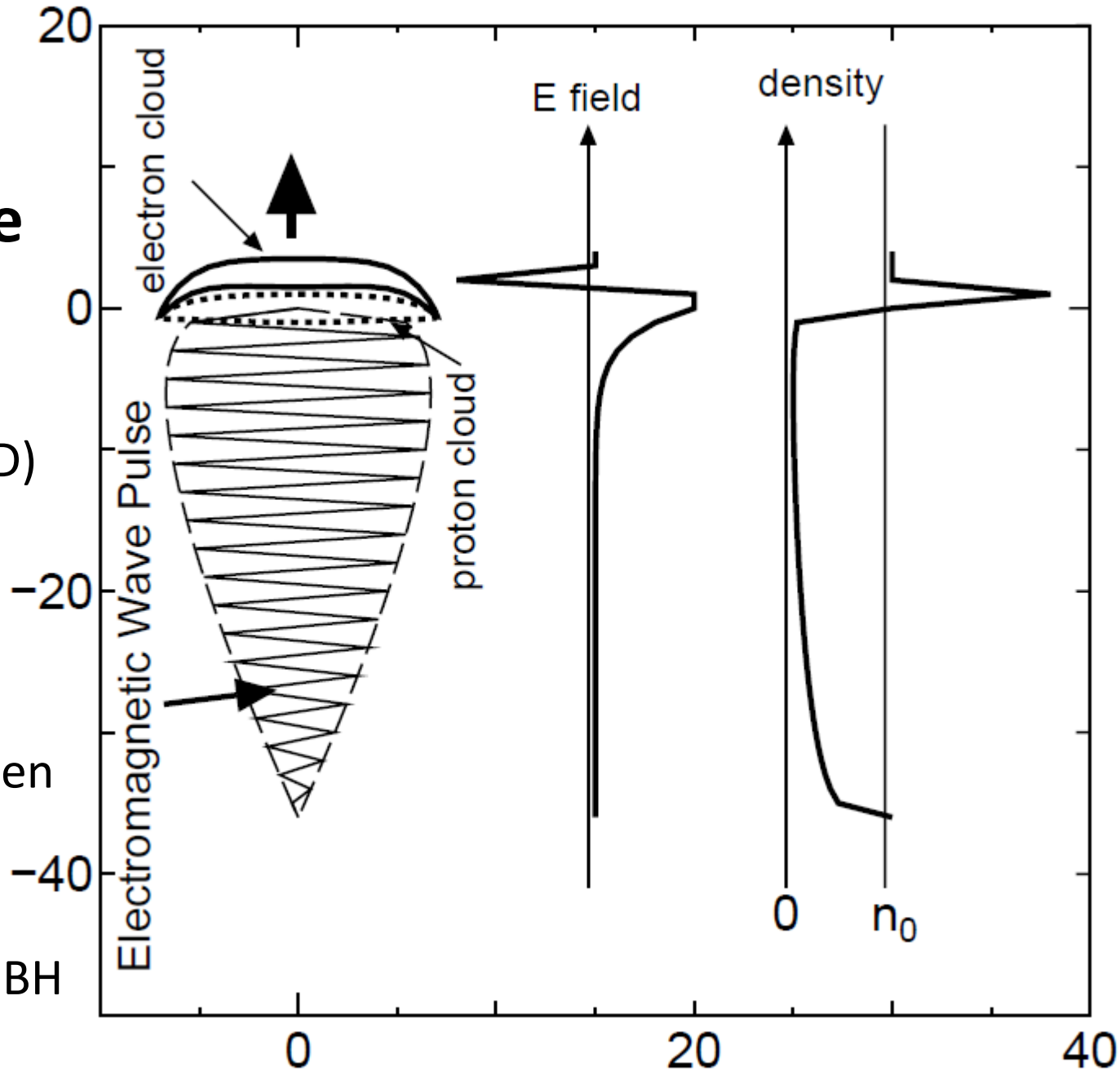
Phys.Rev. STAB, **18**, 024401 (2015).

Wakefield vs. Ponderomotive Acceleration

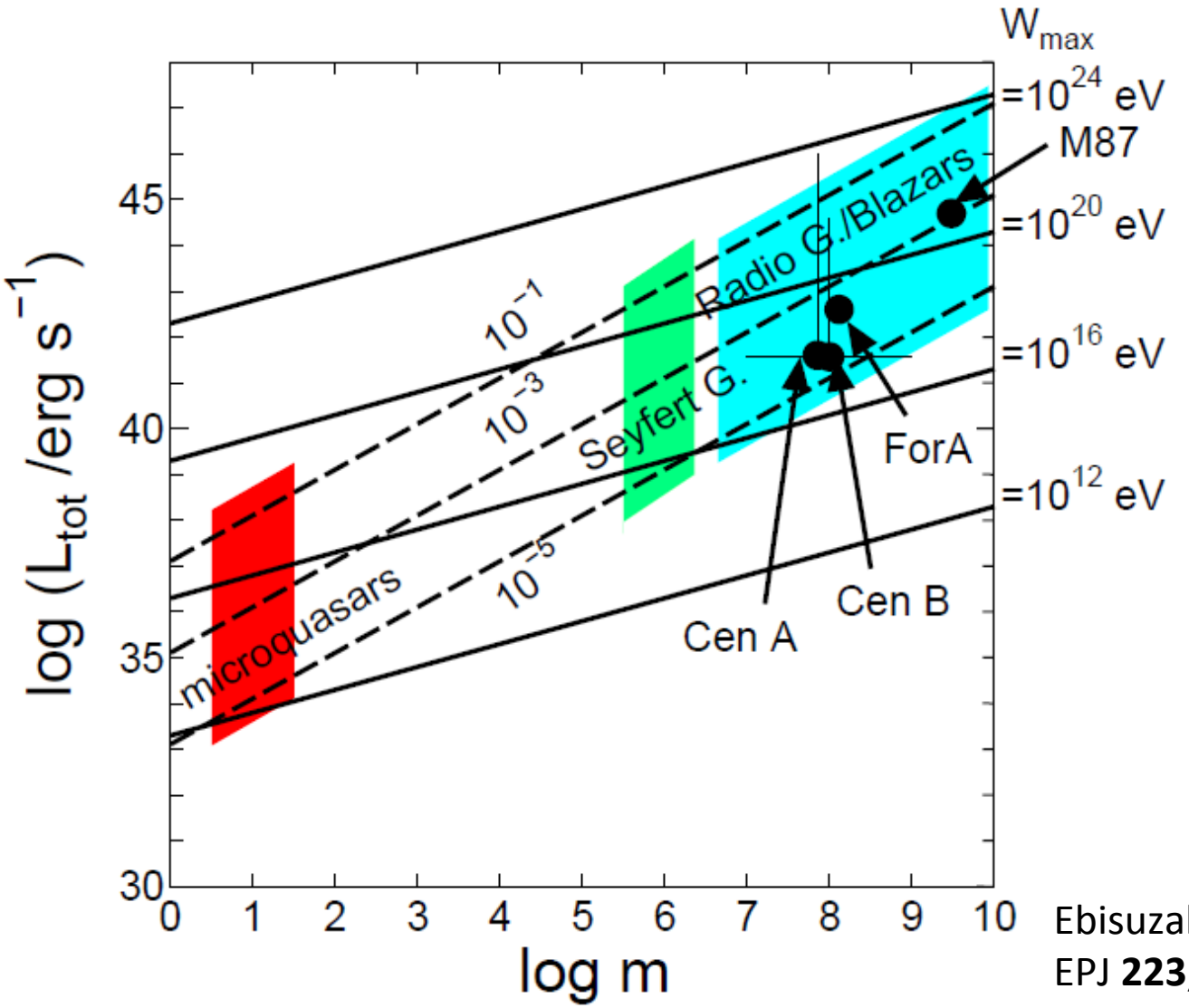
wavebreak (1D or 2D)
in higher a_0
→ wakefield
less important

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

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



Cosmic ray acceleration and γ-ray emission

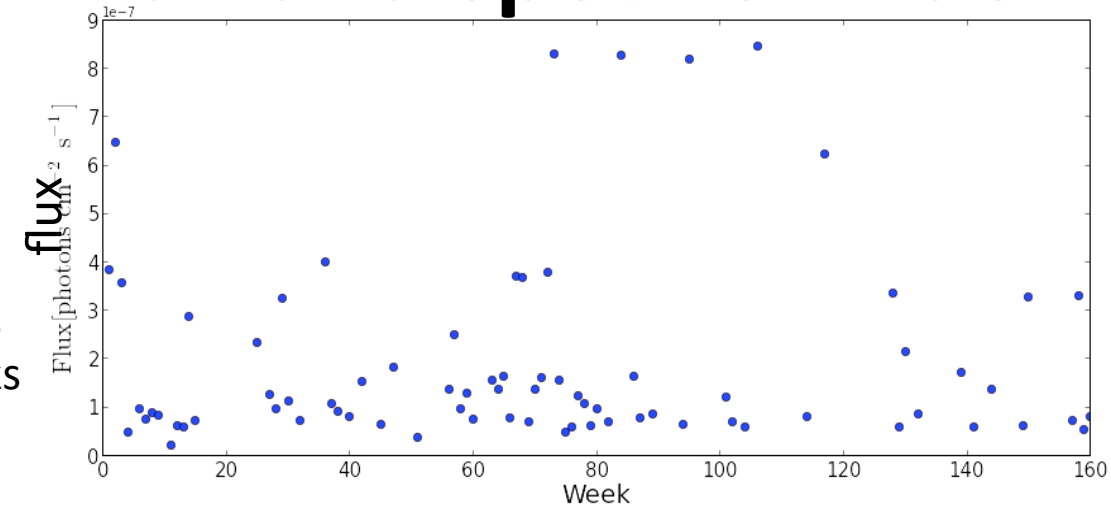


Ebisuzaki, Tajima
EPJ **223**, 1113(2014)

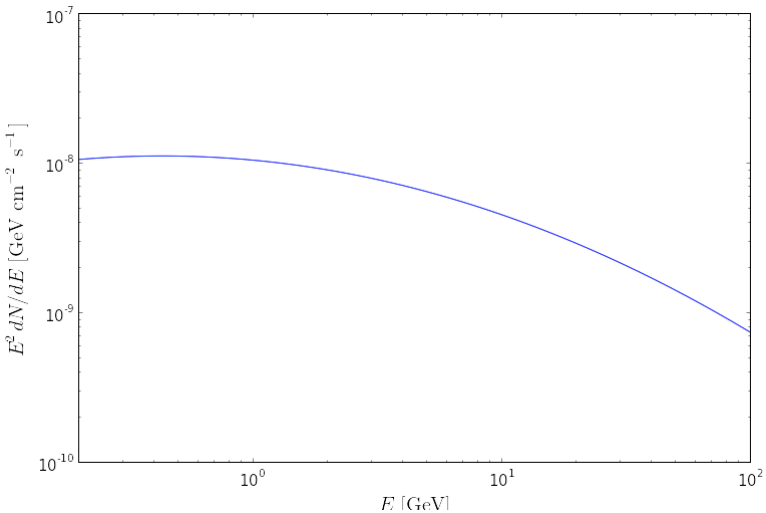
Blazar shows anti-correlation between γ burst flux and spectral index

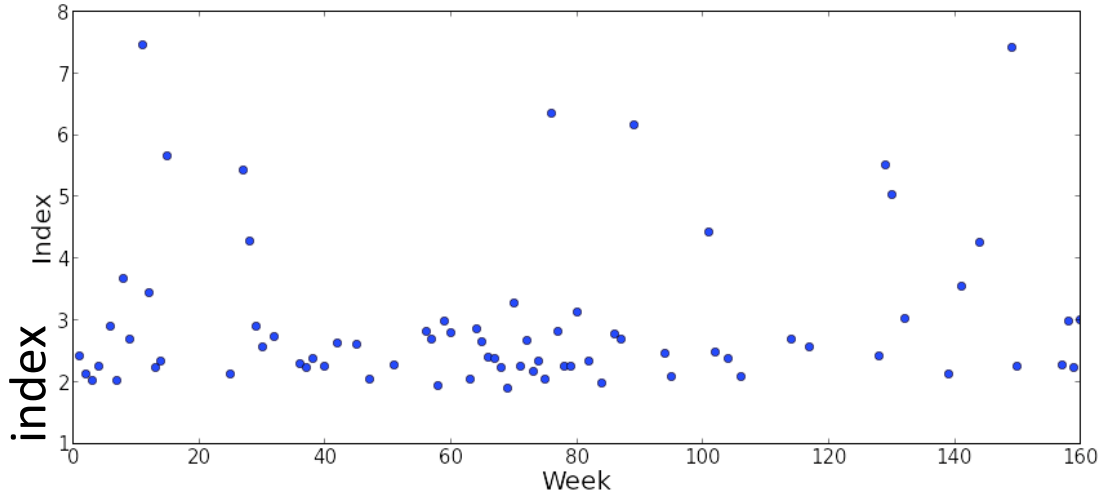
Blazar: AO0235+164
M ~ 10^8 M_{Sun}

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



→ all quantitatively consistent with Wakefield theory



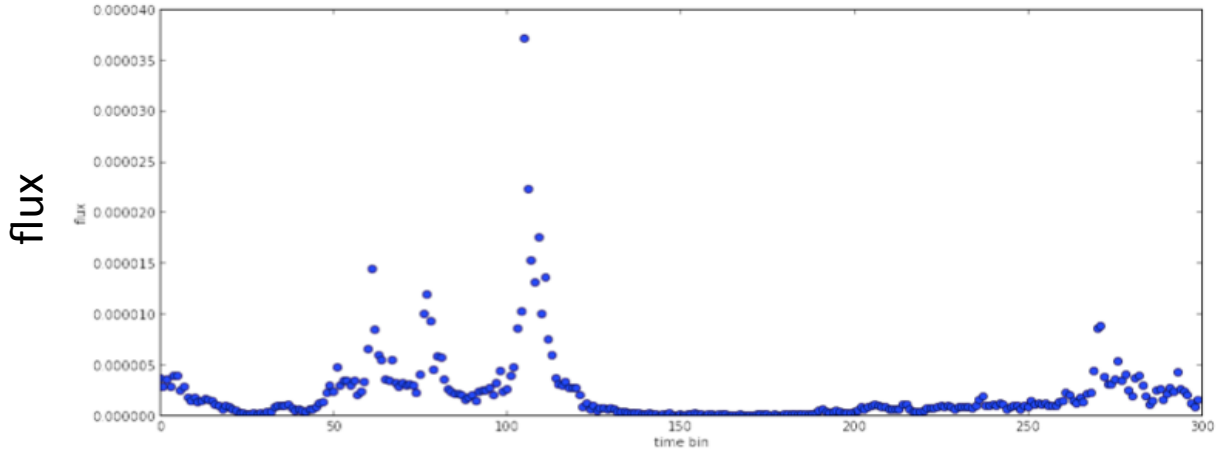


time

N. Canac, K. Abazajian, T.Tajima

Again, Anti-correlation even in a bigger blazar

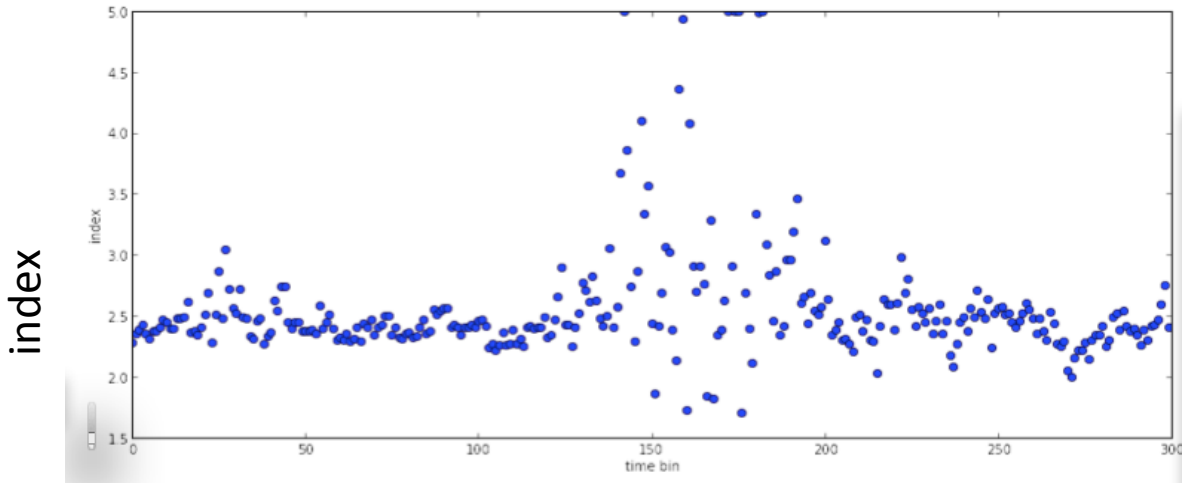
Blazar: 3C454.3
$M \sim 10^9 M_{Sun}$



Same anti-correlation as
AO0235+164

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

Quantitative agreement and
correct scaling with Blazar mass
with Wakefield theory
(Ebisuzaki/Tajima)

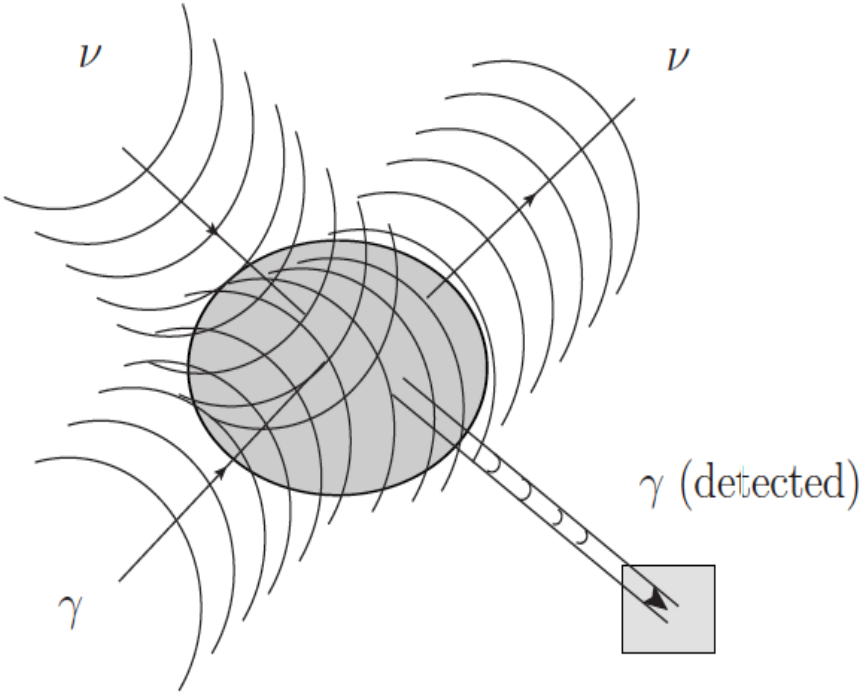


time

N. Canac, K. Abazajian, T. Tajima (2015)

Detecting neutrinos by strong laser

Prehistoric Feynman diagram (Feynman, PR **76**, 749(1949)



- Landau-Yang's theorem= no interaction between photons and neutrinos
- A new term (the diffractive term, i.e. the boundary sensitive wave-like, or global term) does NOT vanish for photons-neutrinos
- Contributions from this term: many orders of magnitude increase in sensitivity of detection neutrinos by laser
- Neutrinos from accelerators, reactors, the Sun are observable with much enhanced detectability
- Possibility of neutrino optics by lasers

Ishikawa, Tajima, Tobita, PTEP (2015)

Conclusions

- Wakefield research strides: beam-driven, laser-driven, X-ray-driven
- A new direction of ultrahigh intensity: **zeptosecond lasers**
- **EW 10keV X-rays laser** from 1PW optical laser
- **X-ray LWFA in crystal**: accelerating gradient 1-10TeV/cm, accelerating length 1-10m, energy gain per stage PeV; *mini-accelerators* (mm-m; portable) for GeV, TeV, PeV (and beyond)
- **Crystal nanoengineering**: s.a. nanoholes, arrays, focus optics
- **Zeptosecond nano beams** of *electrons*, *protons* (ions), muons (neutrinos), coherent γ-rays to very high energies over mm to m ------ answering *Suzuki's Challenge(s)*
- PIC (w/QED) simulation started to support the X-ray wakefields
- High energy gamma photons generated; photon signatures of wakefields
- Start of zeptoscience: ELI-NP zeptoproject (collaboration?)
- Nature likes coherent structure (relativistic coherence, going beyond Fermi acceleration) = wakefields in jets of blazars, ultrahigh energy cosmic rays, gamma ray bursts with telltale temporal variabilities

Thank you!
(Y.Shin)