The New Frontiers of extreme laser wakefield accelation

Colloquium
U. Rochester, March 9, 2015

T. Tajima, UCI and IZEST

Acknowledgments for Collaboration: G. Mourou, Y.M. Shin, U. Wienands, , K. Nakajima, U. Uggehroj, K. Abazajian, N. Canac, , S. Bulanov, A. Suzuki, T. Ebisuzaki, J. Koga, X. Q. Yan,, A. Chao, N.V. Zamfir, V. Shiltsev, J. Zuegel, C. Barty, M. Hogan, R. Heuer, Z. Siwy, P. Taborek

Eur. Phys. J. Spec. Top. **228**, 1037 (2014) ; Astropart. Phys. **56**, 9 (2014)

I ZEST

Content

- **High intensity frontier of lasers: large energy; high fluence; <u>ultrashort</u>:** Following Gerard's talk
- **2-step Laser Conversion** (Gerard's talk):

    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 (Porous nanomaterials)**

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

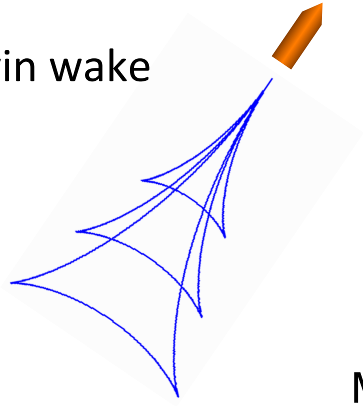
    wakefield energy gain $= 2mc^2 a_0^2 (n_{cr} / n) = a_0^2$ TeV
- Reaching out to **X-ray crystal optics and nanotechnology**

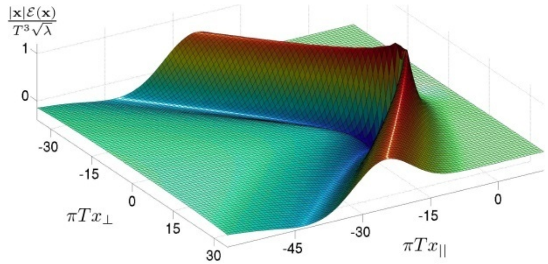
    X-ray (γ-ray) optics, nonlinear optics in vacuum----self-focus; porous nano materials
- **Nature (Blackhole jets):** create extremely strong EM pulse

    provides robust extreme acceleration (ZeV) and γ-ray bursts

Laser Wakefield (LWFA): nonlinear optics in plasma

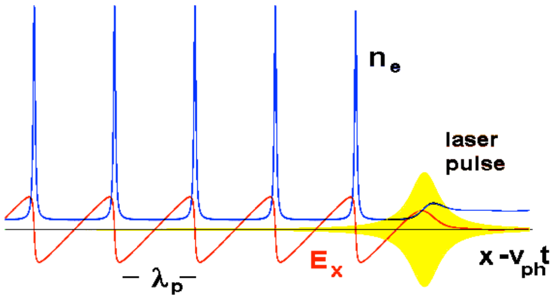
Kelvin wake





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

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



← **relativity regularizes**

(*relativistic coherence = "speeds are all spped og light c"*)

(The density cusps. Cusp singularity)

Wave **breaks** at v＜c

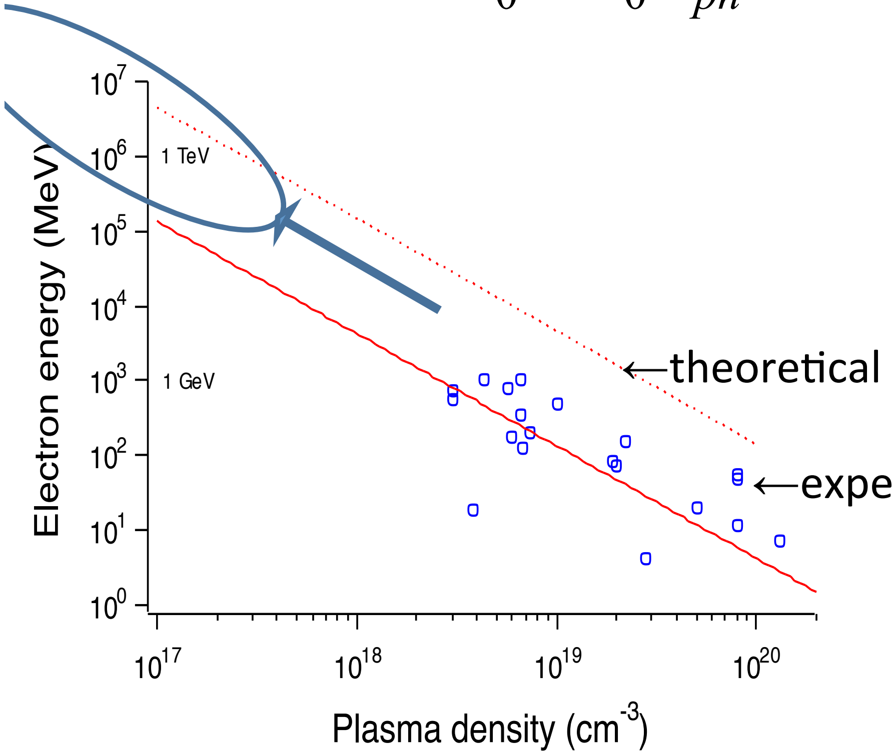
Hokusai

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)

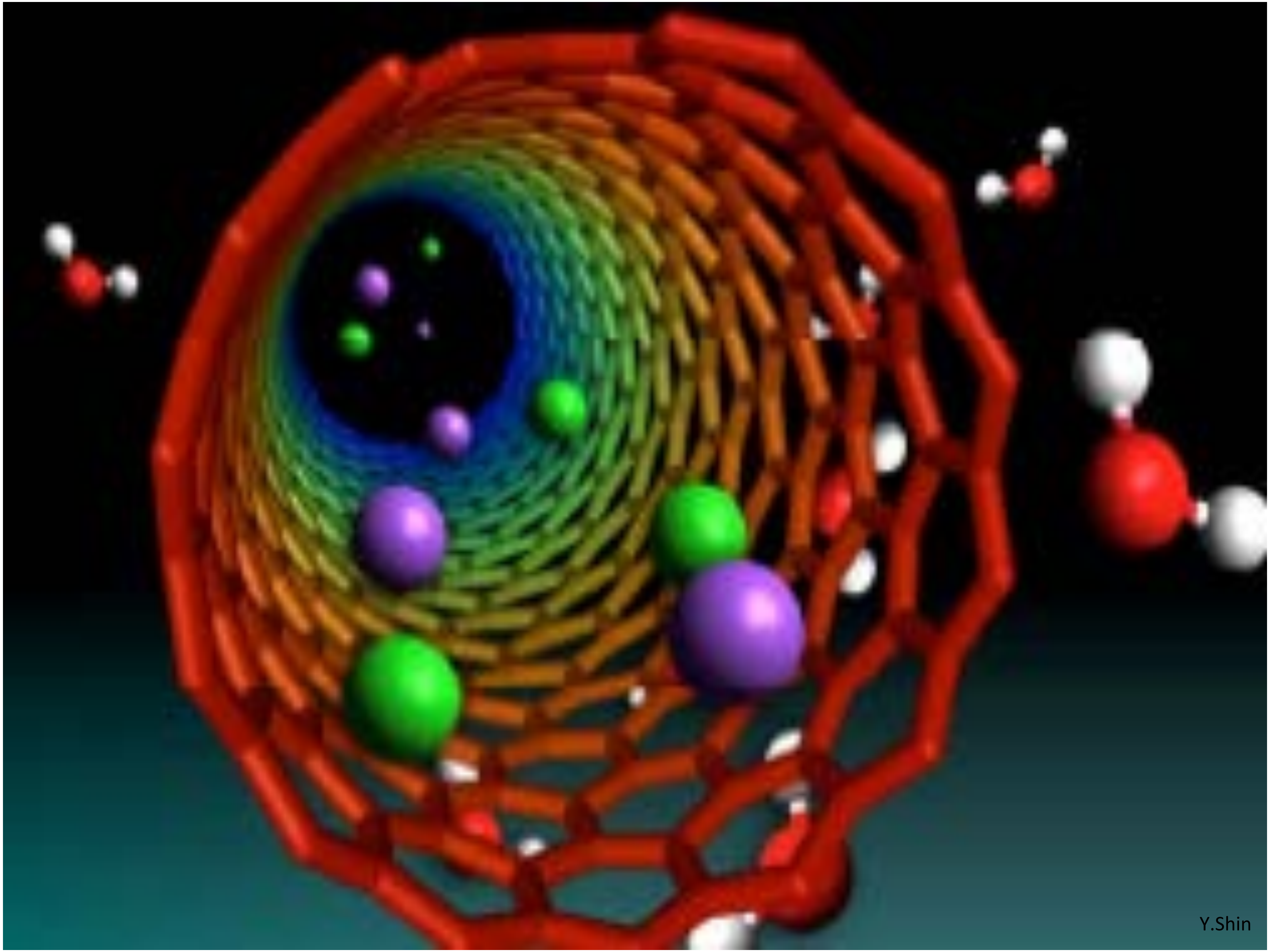
n_e $= 10^{16}$ (gas) → 10^{23} (solid)

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

dephasing length

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

pump depletion length


Y.Shin

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

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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]

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

where r_E is the classical electron radius, Z_{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

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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 $\hbar\omega \geq mc^2\alpha^2$, 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 $l_i = (3/2^8\pi) \times a_B^{-2}\alpha^{-1}n^{-1}(\hbar\omega/Z_{\text{eff}}^2\mathcal{R})^{7/2}$, where a_B is the Bohr radius, n the electron density, Z_{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

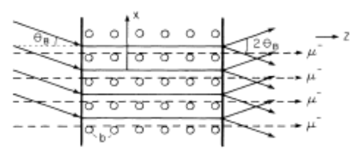
where b is the transverse lattice constant and later a the longitudinal lattice constant ($a \simeq b$) (see Fig. 1). The row of lattice ions (perhaps with inner-shell electrons) constitutes the "waveguide" wall for x rays, while they also act as periodic irises to generate slow waves. A superlattice[5]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

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



X-ray LWFA in crystal suggested

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

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

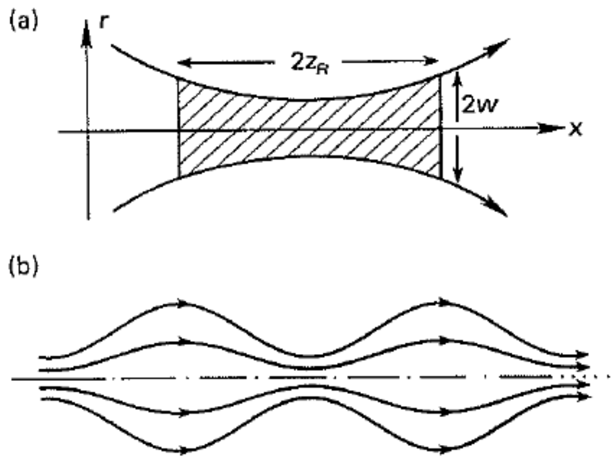
LWFA energy gain

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

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

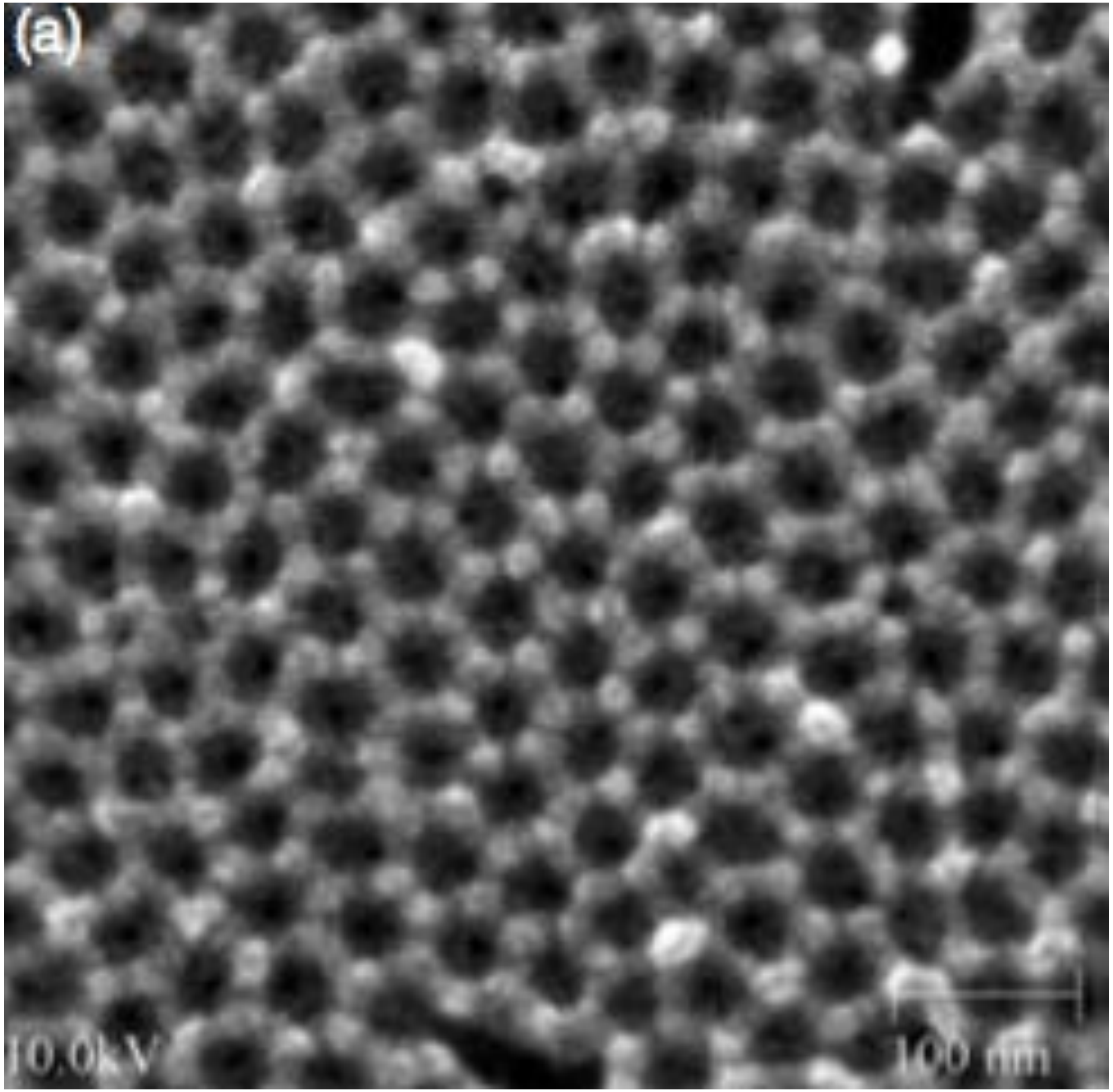
$$\omega = c\,\surd\,(k_z^2 + \langle k_{perp}^2 \rangle),$$

The vacuum dispersion relation with fiber self-modulation

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

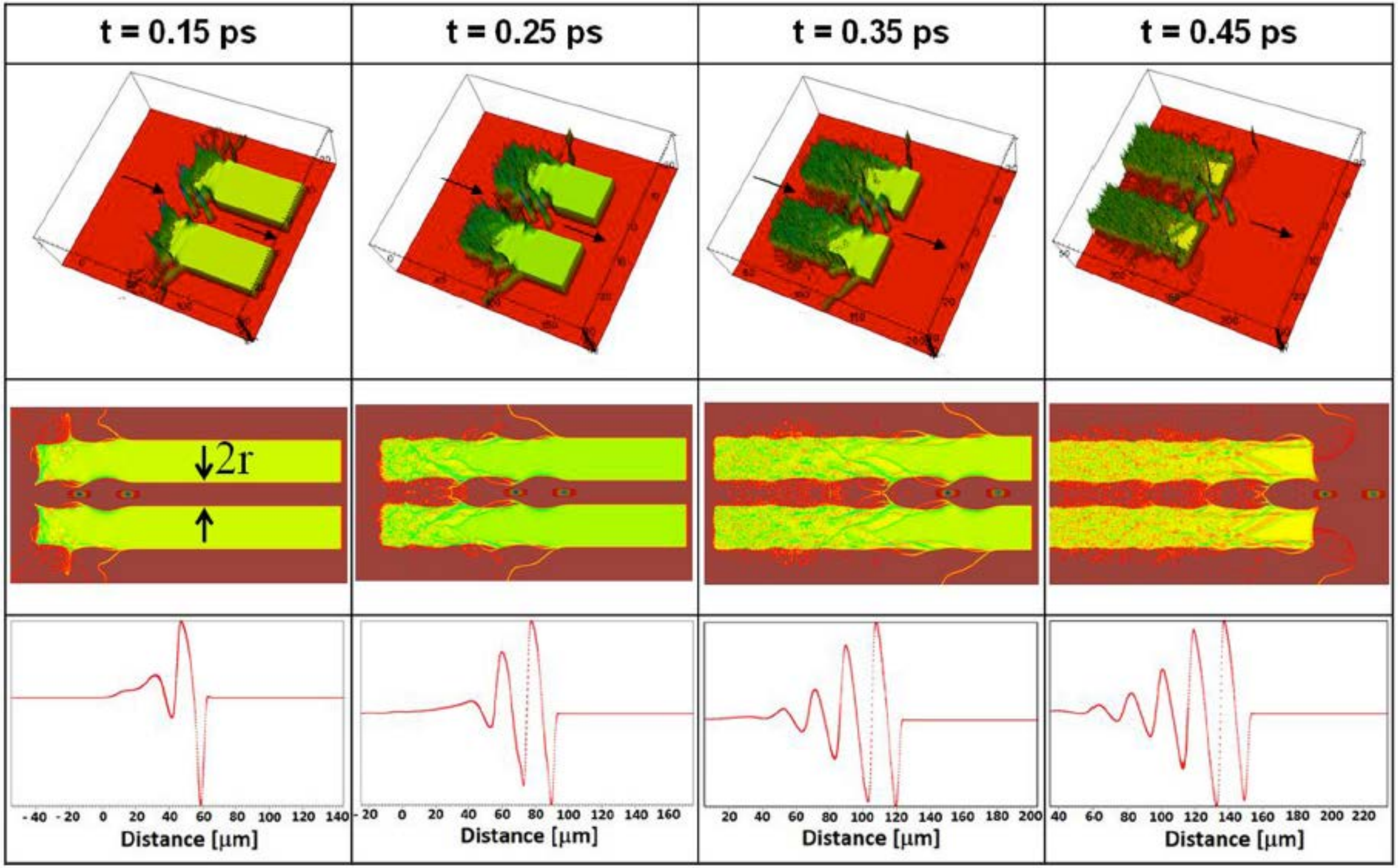
(Tajima and Cavenago, PRL, 1987)

Porous Nanomaterial



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

Beam-driven wakefield on a chip



Y. Shin (2014)

THEXAC (Transformative High Energy X-ray Acceleration in Crystal):

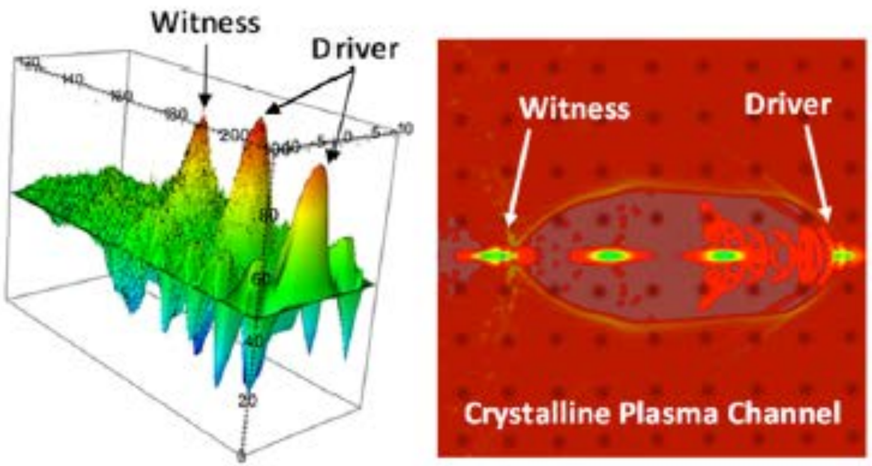
Collaboration [UCI, Stanford (SLAC), Fermilab, NIU, EP, ELI-NP, Aarhus U., LeCosPa] formed

What we'd like to do initially at FACET

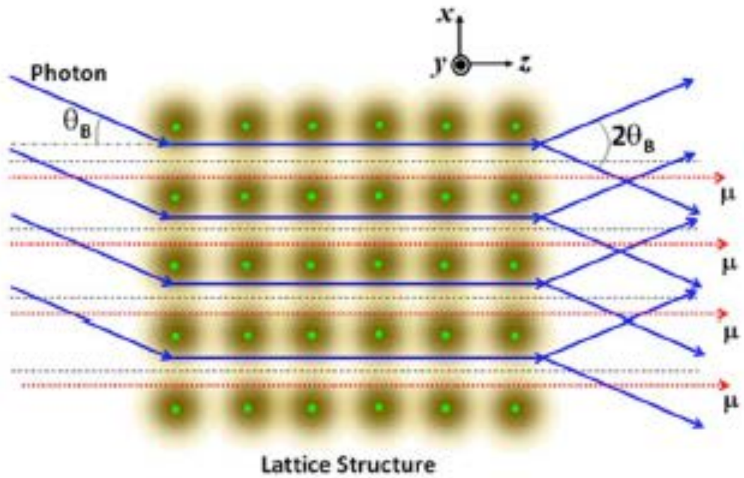
- Detect and quantify wakefield excitation in crystal
- SLAC FACET provides dense bunches of positrons
  - better channeling than e^{-}, less scattering of channeled beam
  - dense bunches can excite wakefields
- FACET has a spectrometer or the channeled particles
  - wake excitation => energy loss (can detect ≤ 0.1% *E*-loss)
  - the γ-ray spectrum should also indicate this.
- Synergy with SLAC FACET E212 (Uggehroj) and ESTest Beam T513 (Wienands)

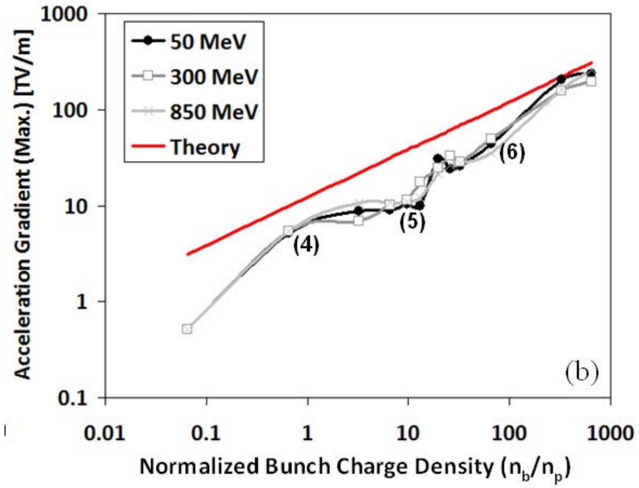
Wakefield excitation by electron (or positron) beam (vs. by X-ray pulse)

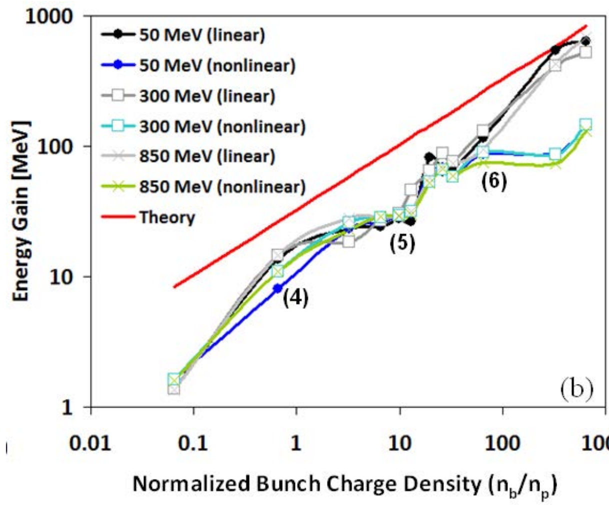
Wakefield Acceleration



Diffraction Acceleration





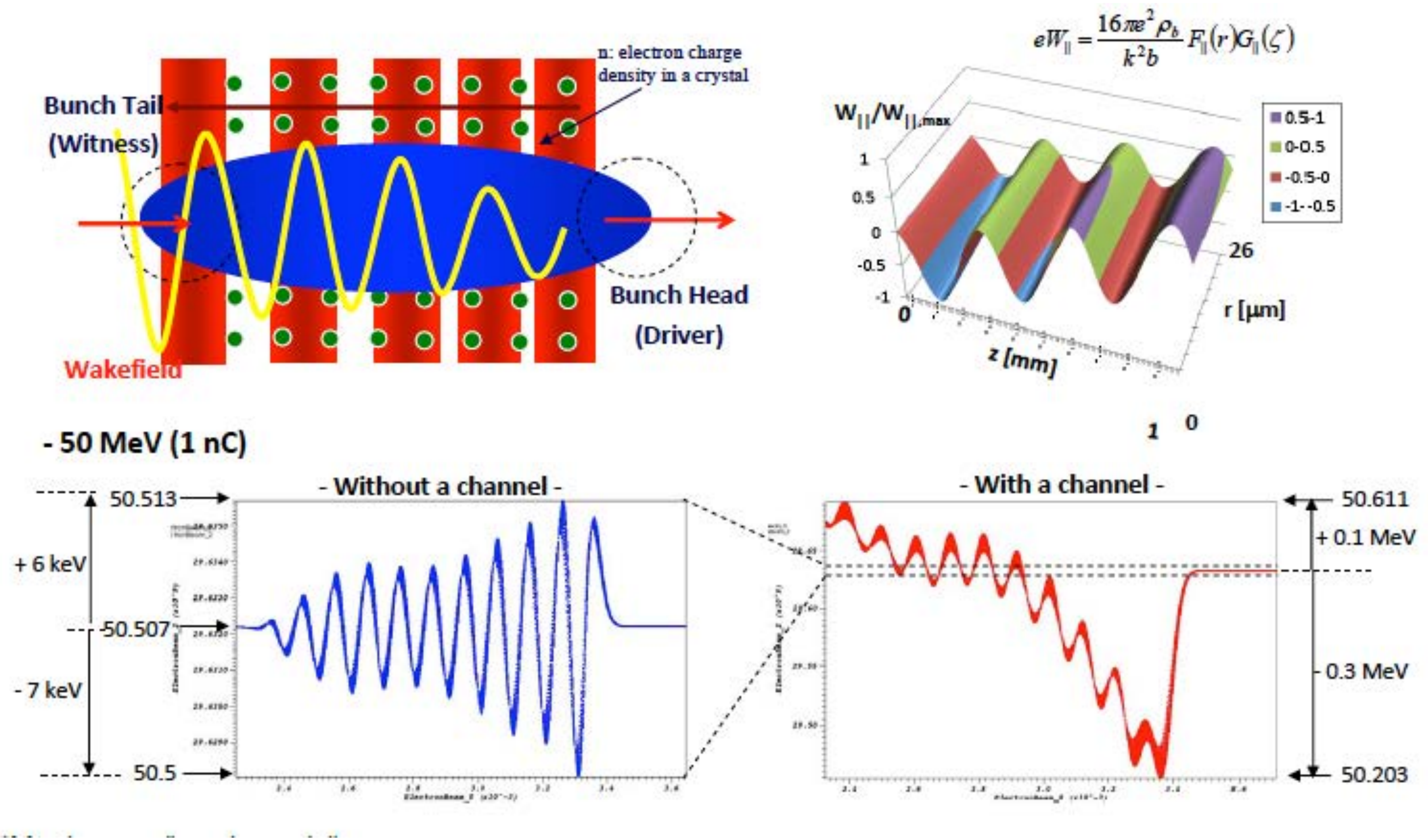


$n_p = 10^{28}\ m^{-3}$

Length of Plasma $= 10\ \lambda_p$

Y.M.Shin, APL (2014)

Wakefield excitation and witness bunch that is accelerated

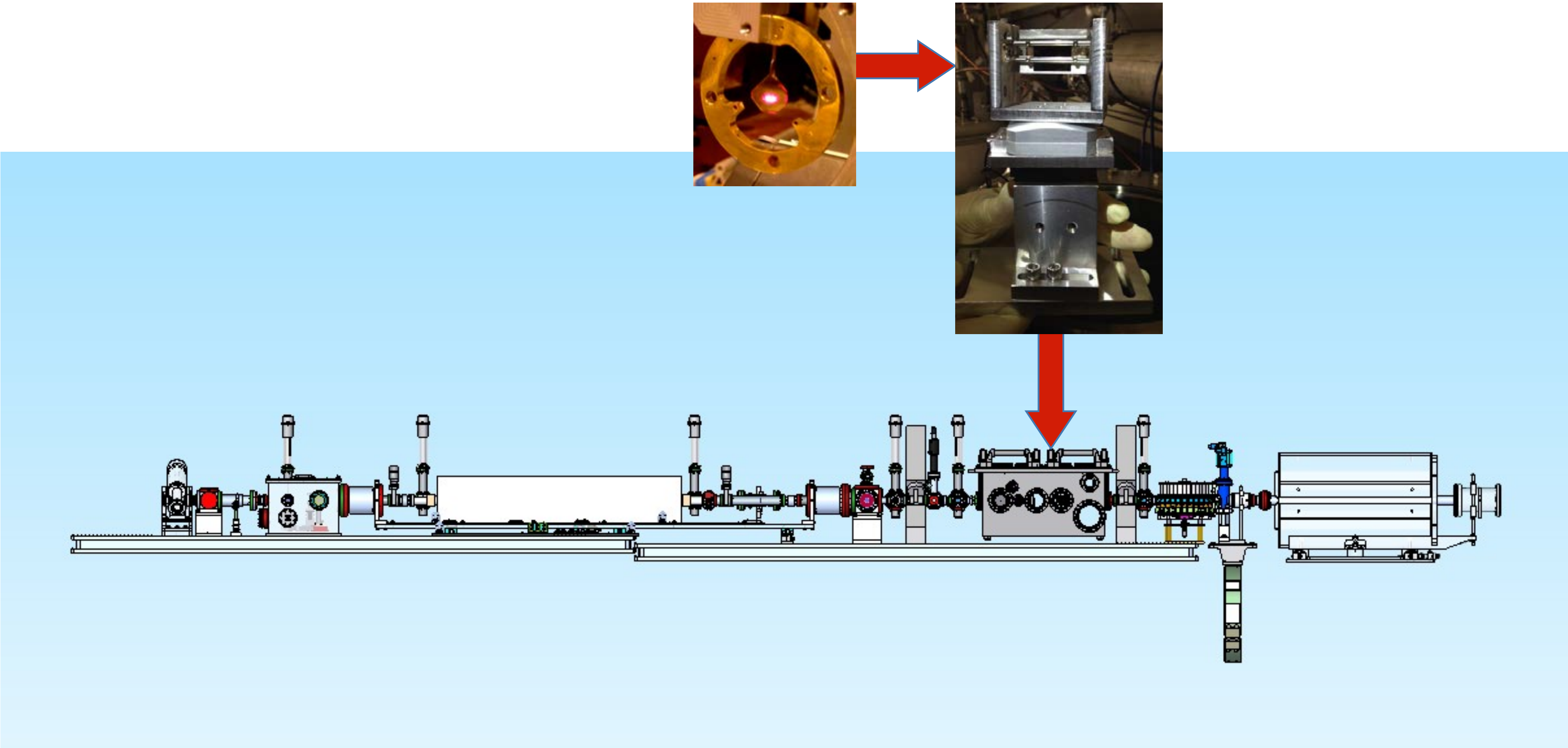


Shin (2014)

In collaboration with E212 (Uggerhoj)

Placement of Crystal

^{12}C T513 stage



Fermilab efforts on crystal wakefield acceleration

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]

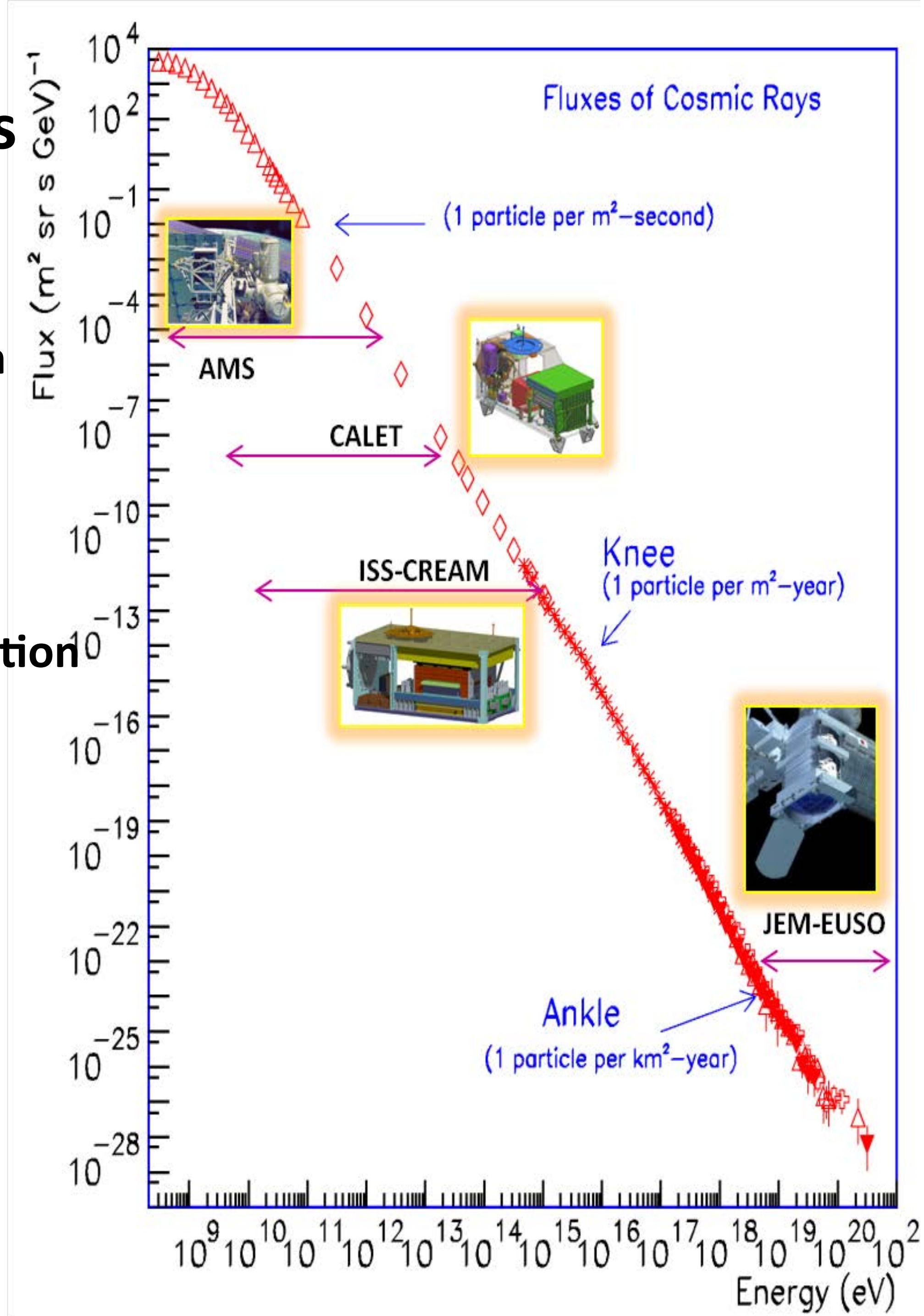
Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, and E. Harms

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

[2]Fermi National Accelerator Laboratory (FNAL)

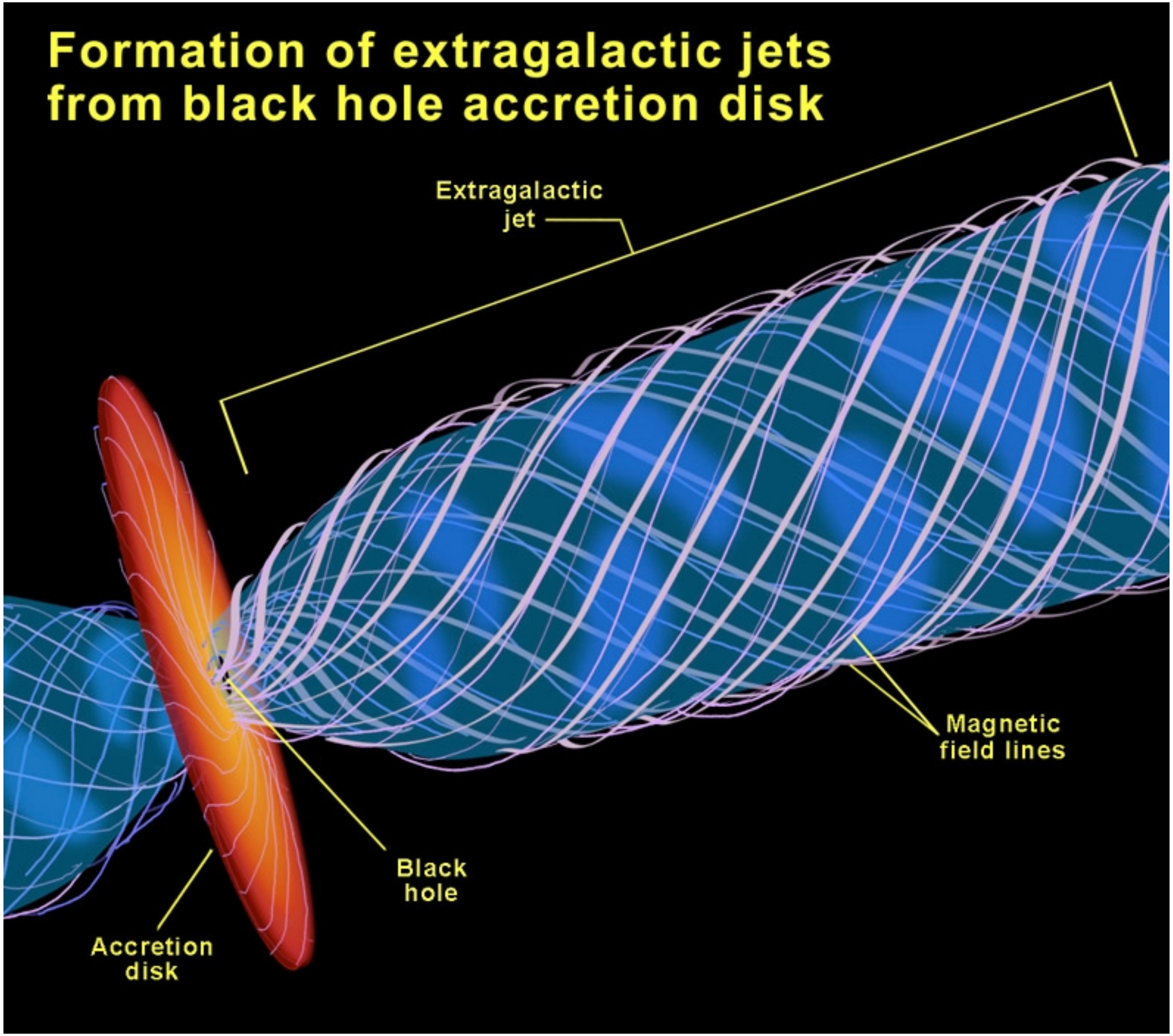
Ultrahigh Energy Cosmic Rays (UHECR)

- 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?

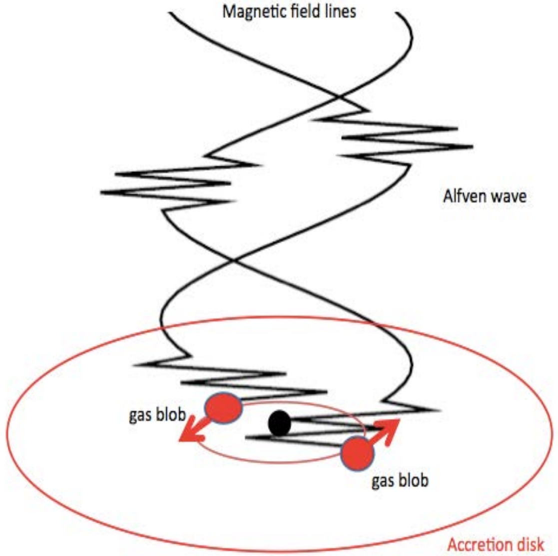


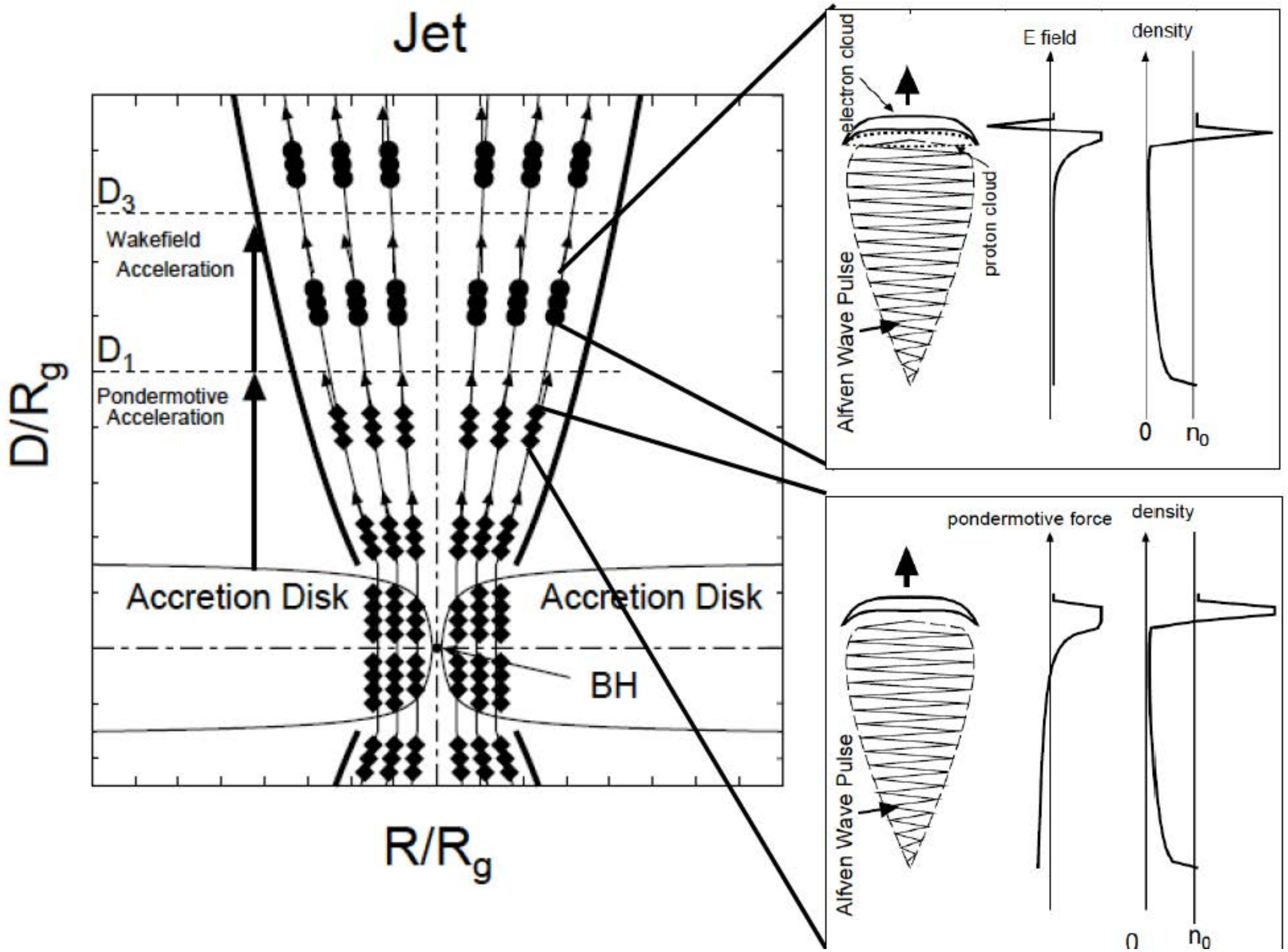
Cen A

- 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 ($a_0 \sim 10^6$ -10^{10}, large z)





Ebisuzaki and Tajima, Astropart. Phys.(2014)

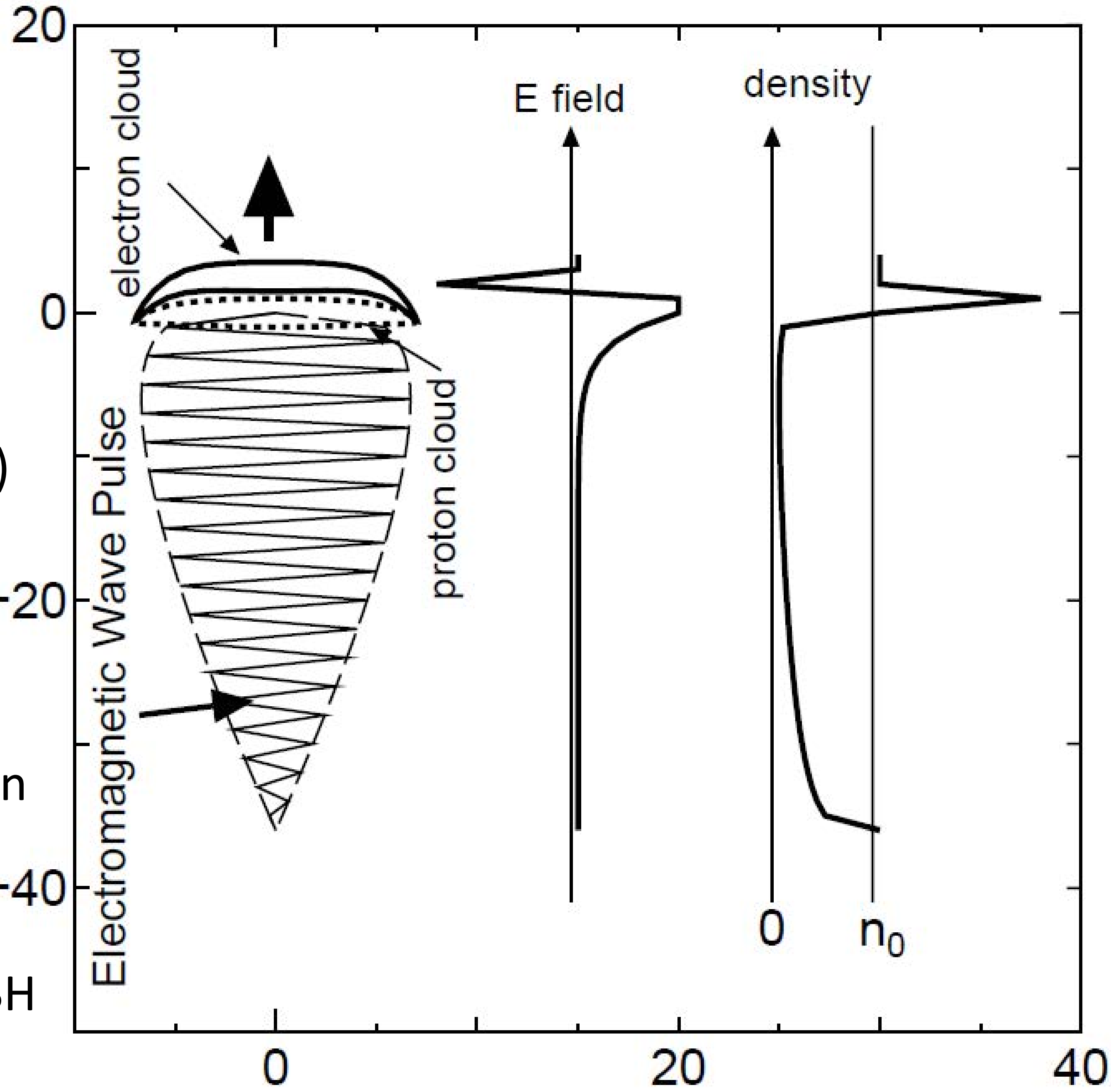
Phys.Rev. STAB, **18**, 024401 (2015).

Wakefield vs. Ponderomotive Acceleration

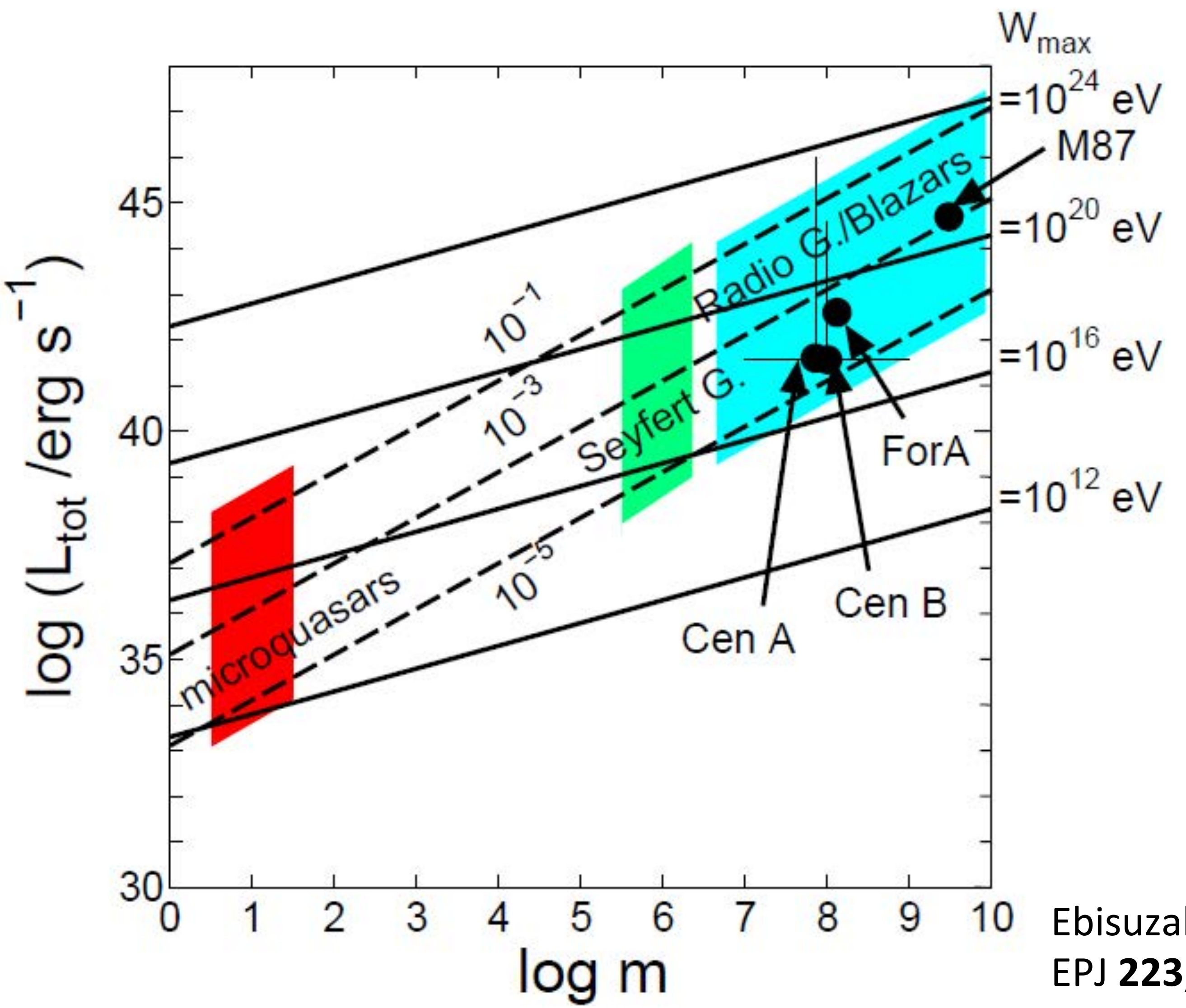
wavebreak (1D or 2D) in higher a_0
→ wakefield less important

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

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



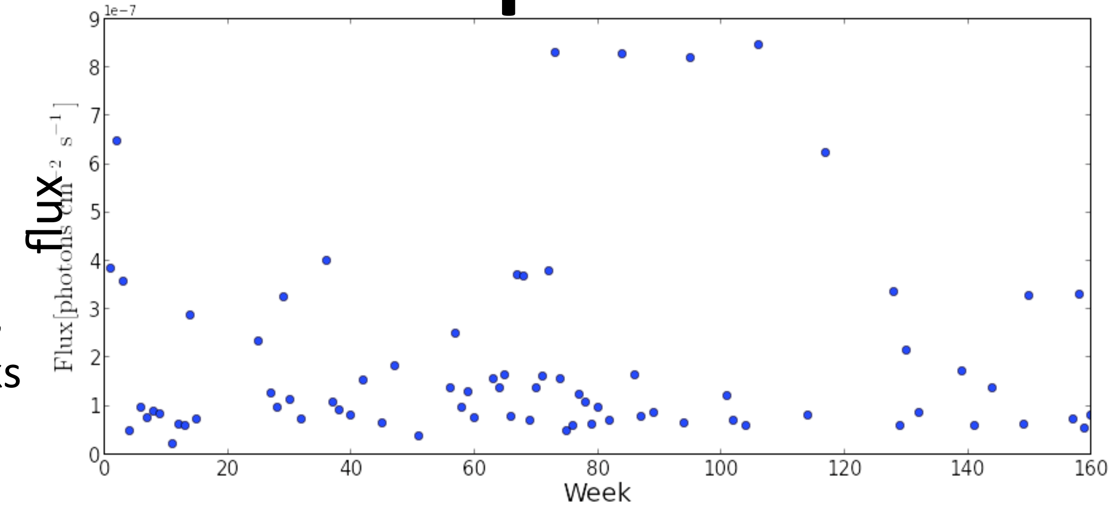
Comic ray acceleration and γ-ray emission



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

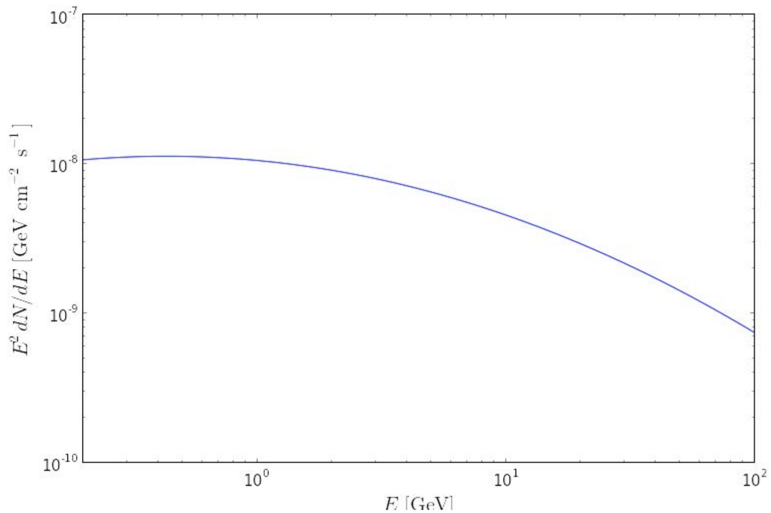
Blazar shows anti-correlation between γ burst flux and spectral index

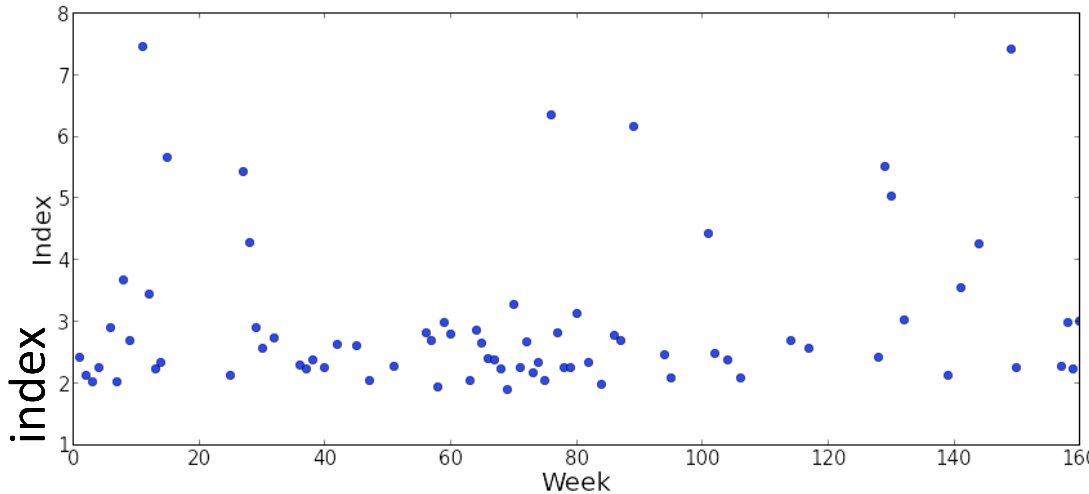
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



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

→ all quantitatively consistent with Wakefield theory





time

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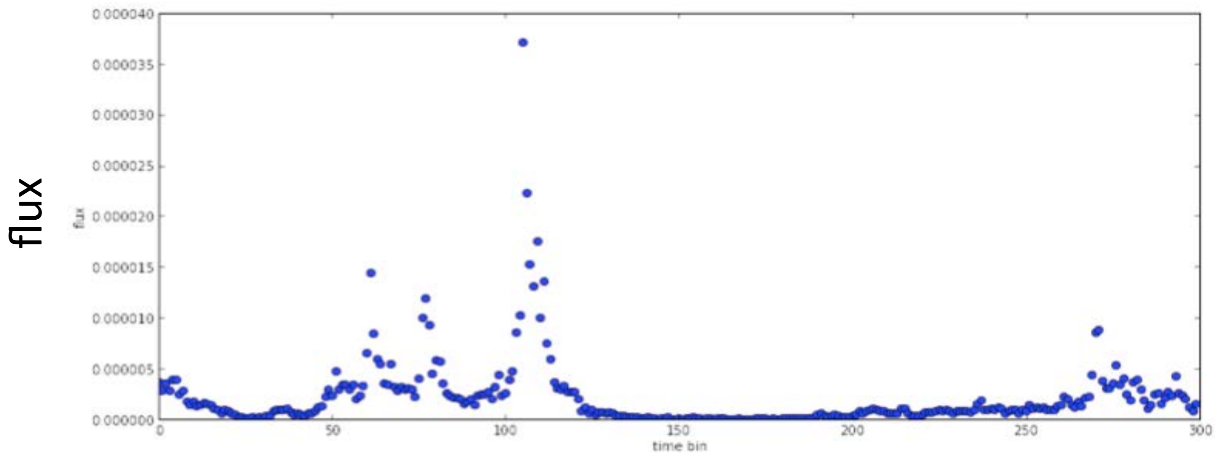
Again, Anti-correlation even in a bigger blazar

Blazar: 3C454.3

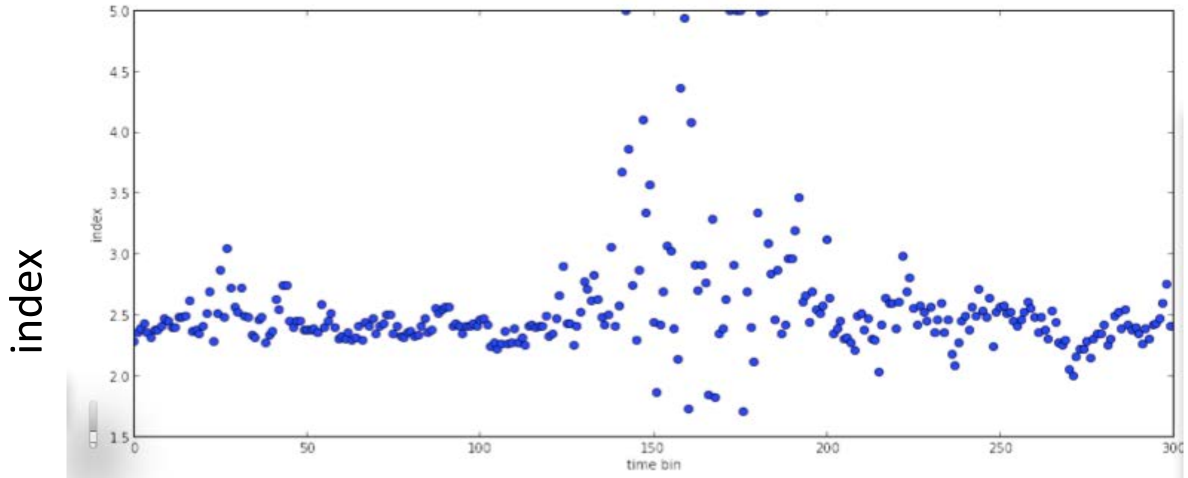
M ~ 10^9 M_{Sun}



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
(Ebisuzaki/Tajima)



time

N. Canac, K. Abazajian

Conclusions: from zeptoscience to ZeV

- A new direction of ultrahigh intensity: **zeptosecond lasers**
- **EW 10keV X-rays laser** from 1PW optical laser
- **X-ray LWFA in porous 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
- Start of zeptoscience; Start of Blazar accelerators
- Mother Nature shows **LWFA** is a **ubiquitous** natural process of particles acceleration (i.e. gamma ray bursts (GRB) and cosmic ray acceleration)
- From smallest (nm) wakefield acceleration in (porous) solid to largest (M Parsec) Blazars (Active Galactic Nuclei--AGN) acceleration (ZeV)