Aspiration of high energies and intense lasers

APSA, University of Tokyo
Tokyo, Japan Oct. 23, 2014

T. Tajima, UCI, KEK

Acknowledgments for Collaboration: G. Mourou, N. Naumova, K. Nakajima, Y.M. Shin, S. Bulanov, A. Suzuki, T. Ebisuzaki, J. Koga, X. Q. Yan, U. Wienands, U. Uggerhoj, A. Chao, N.V. Zamfir, V. Shiltsev, M. Hogan, K. Ishikawa, Y. Tobita, M. Spiro, R. Kumar, N. Rostoker, Y. Kato, the late Professor H. Takuma

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

Content

- **High intensity frontier of lasers $I = E/\tau$: (A) large energy; (B)ultrashort; (C) high fluence $(P = fE)$**
- Laser can accelerate particles: laser wakefield
- (A) Large energy laser: Higgs energy (>100GeV) over 10m
- **(B) Ultrashort (zeptosecond) X-ray laser : TeV on a chip (cm)**→ zeptoscience ($\tau = E/I$)
- Nature finds wakefield acceleration: blackhole jets

  → ultrahigh energy cosmic rays (ZeV)
- (C) High fluence laser: CAN (Coherent Amplification Network) laser

Relativistic nonlinearity under intense laser

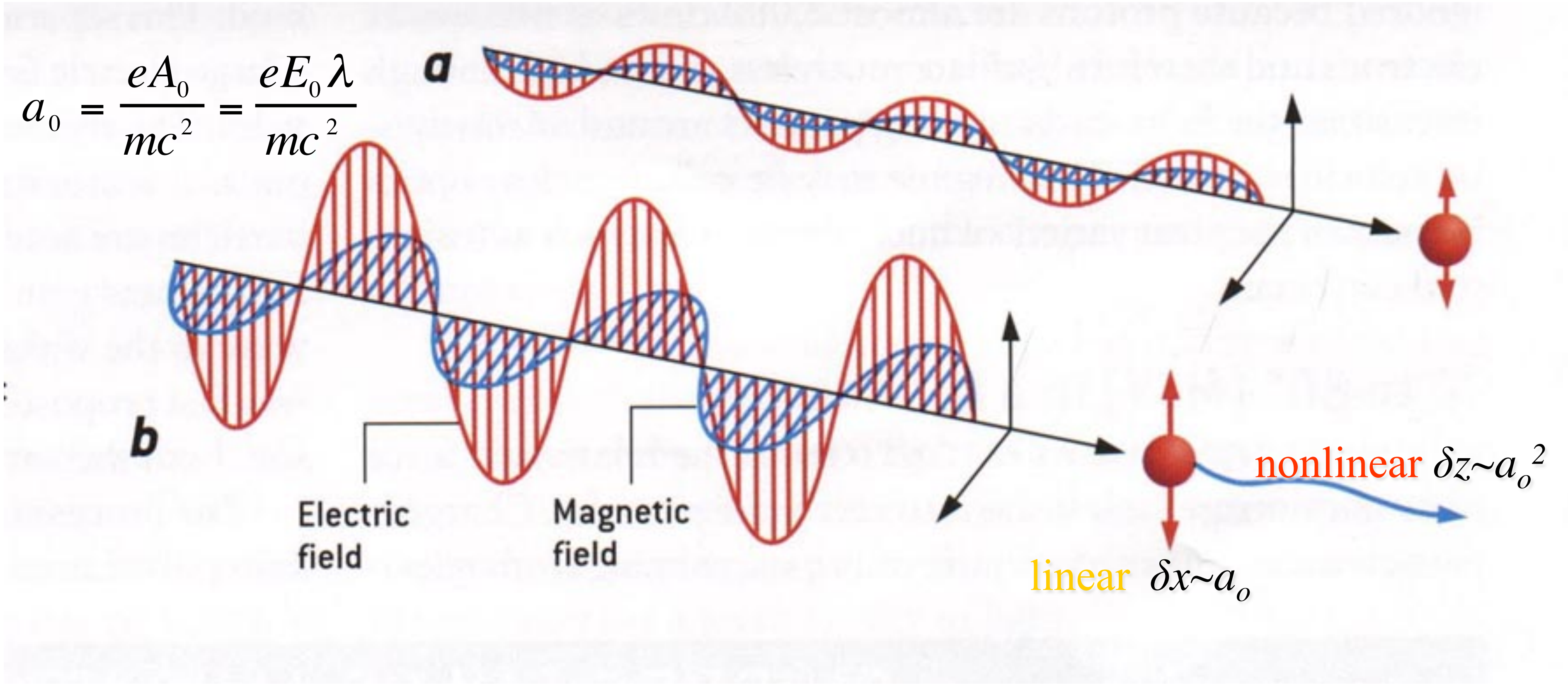
Plasma free of binding potential , but its electron responses:

a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

$a_0>>1$: $\delta z >> \delta x$



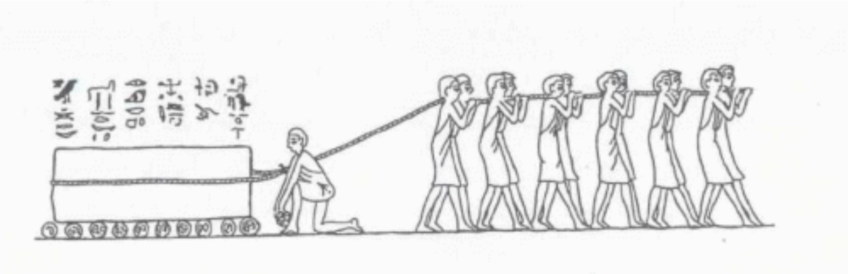
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$

nonlinear $\delta z\sim a_o^2$

linear $\delta x\sim a_o$

What is *collective force*？:Secret behind laser accelerator

How can a Pyramid have been built?



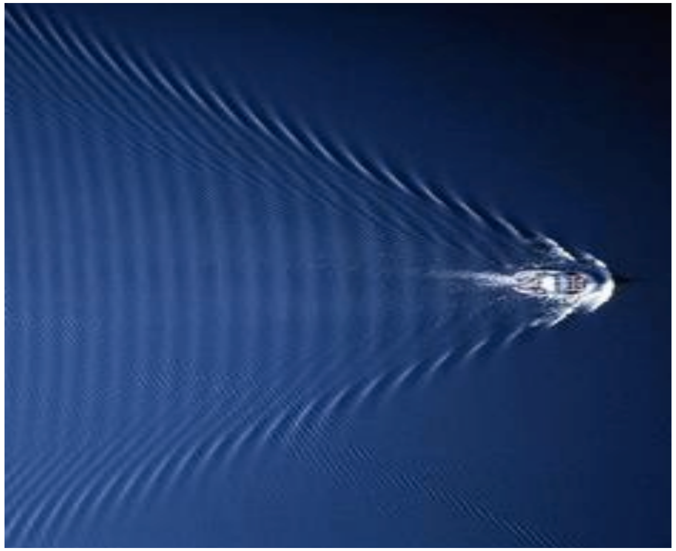
Individual particle dynamics → Coherent and collective movement

Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)
Collective radiation (N^2 radiation)
Collective ionization (N^2 ionization)

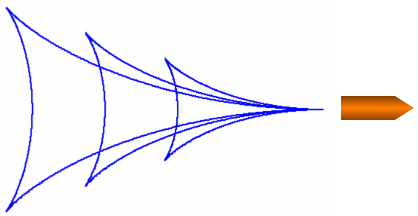
→ Laser driven collective accelerating field

Wakefield : a Collective Phenomenon + Relativistic Coherence

All particles in the medium participate = collective phenomenon

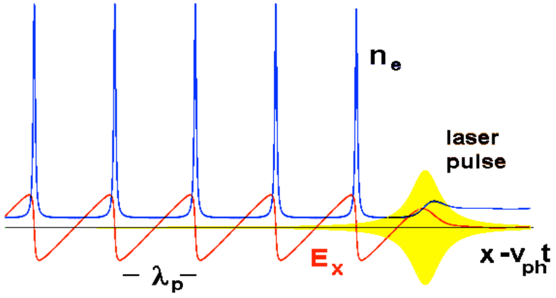


Kelvin wake



No wave breaks and wake peaks at $v \approx c$

Wave breaks at $v < c$



vs.

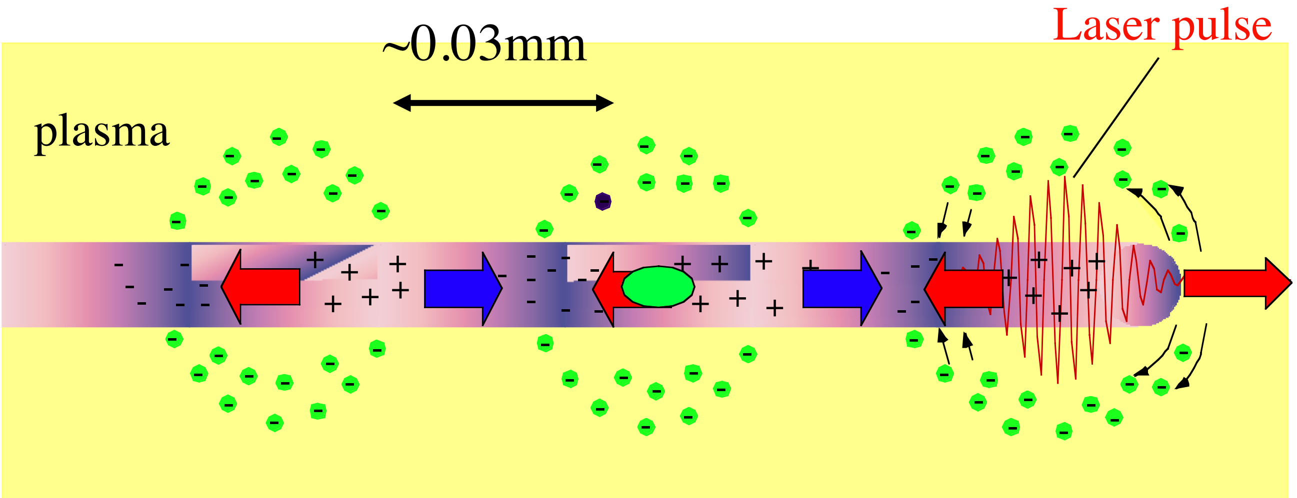
(electrons cohere; density cusps)
→ Relativistic Coherence

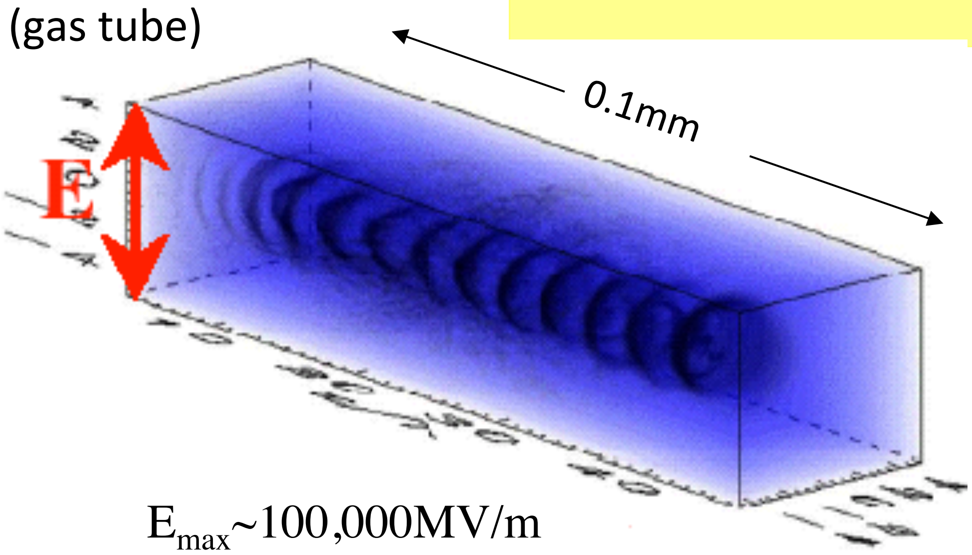
No relativistic coherence

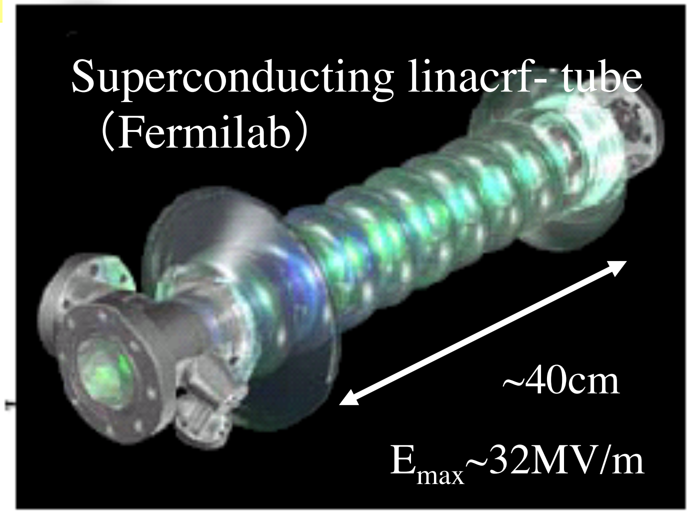
Hokusai

Thousand-fold Compactification

Laser wakefield: thousand folds gradient (and emittance reduction?)

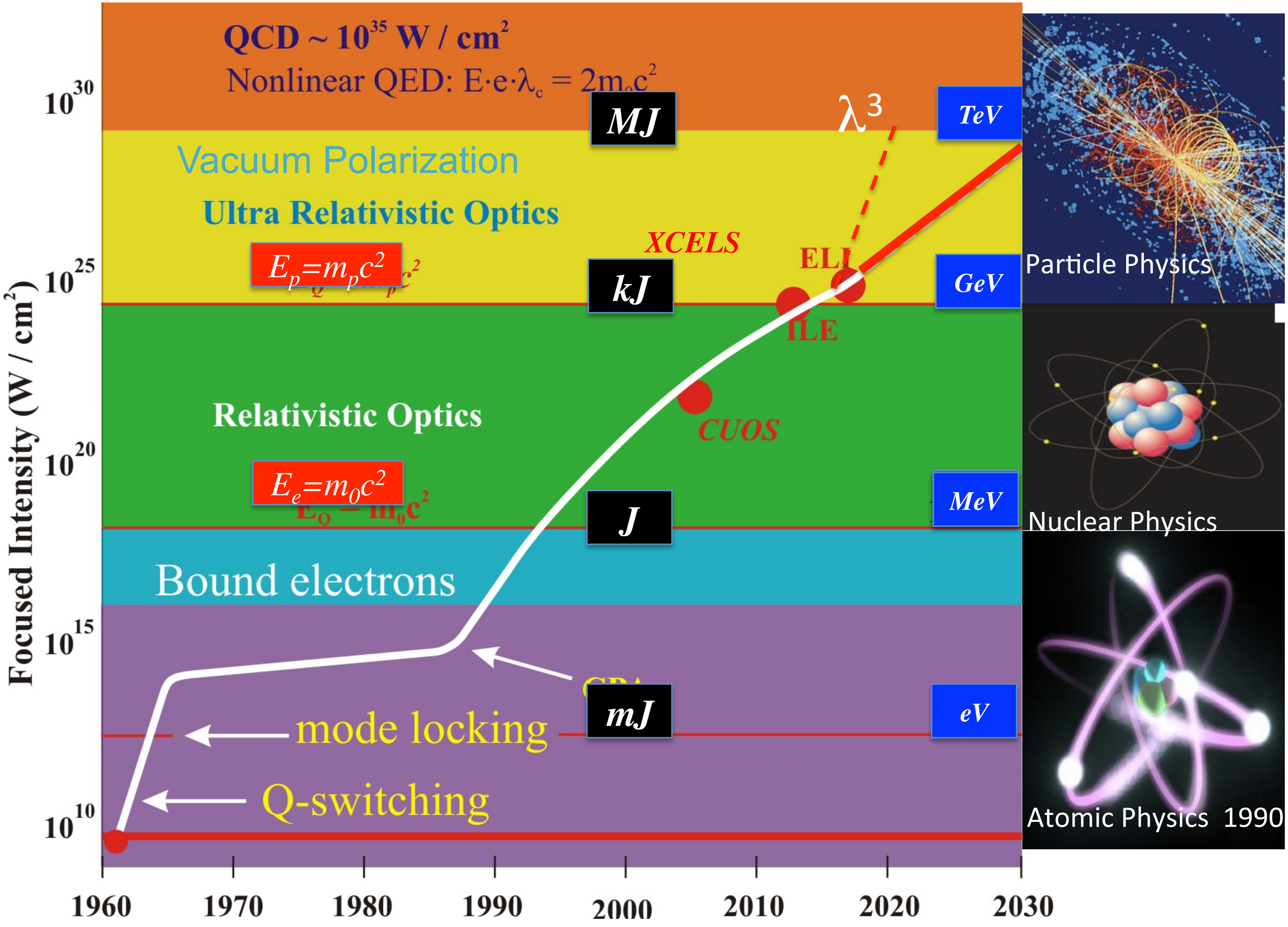




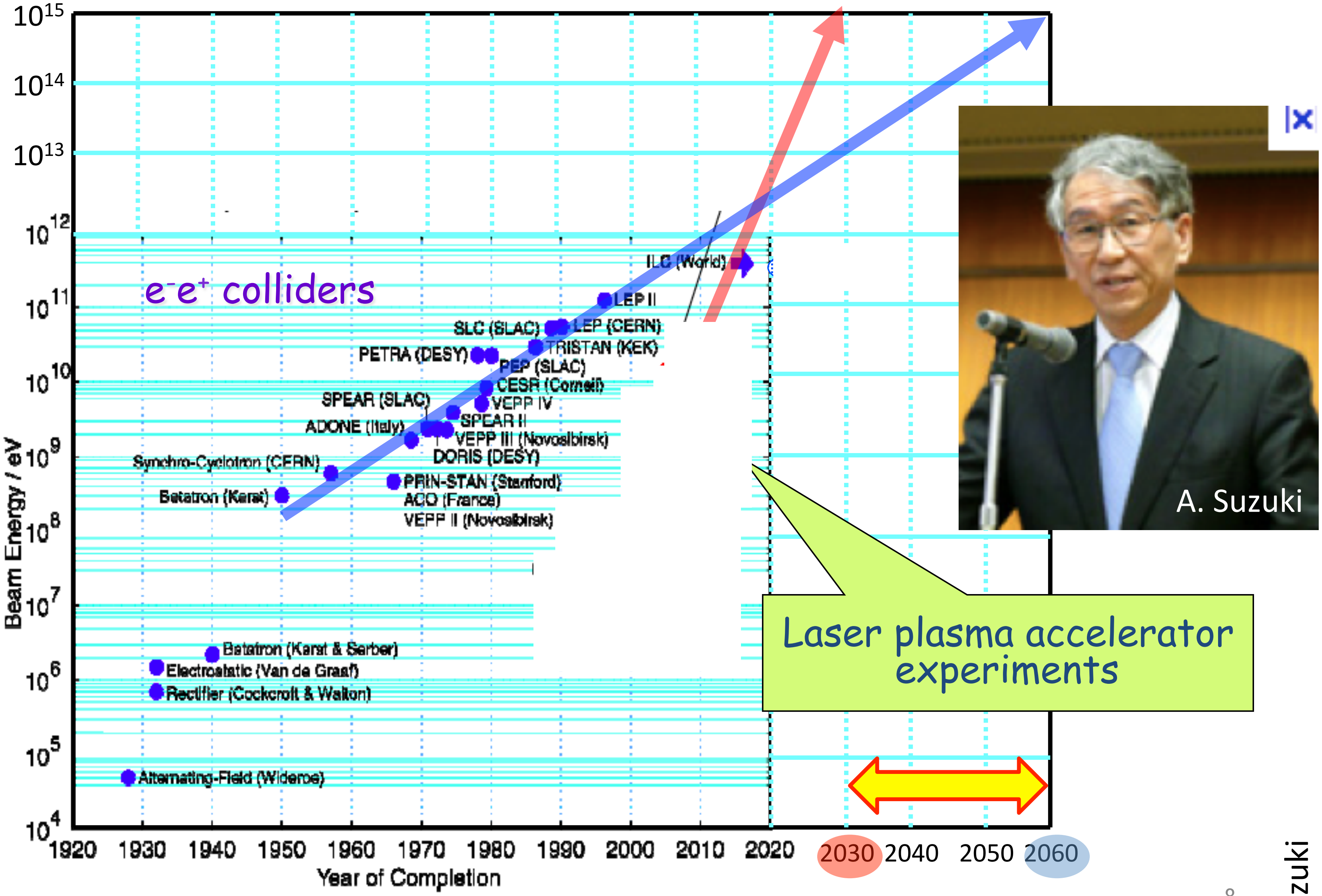


Extreme **Light** Roadmap

(modified from Tajima and Mourou, PR 2002)



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



Laser plasma accelerator experiments

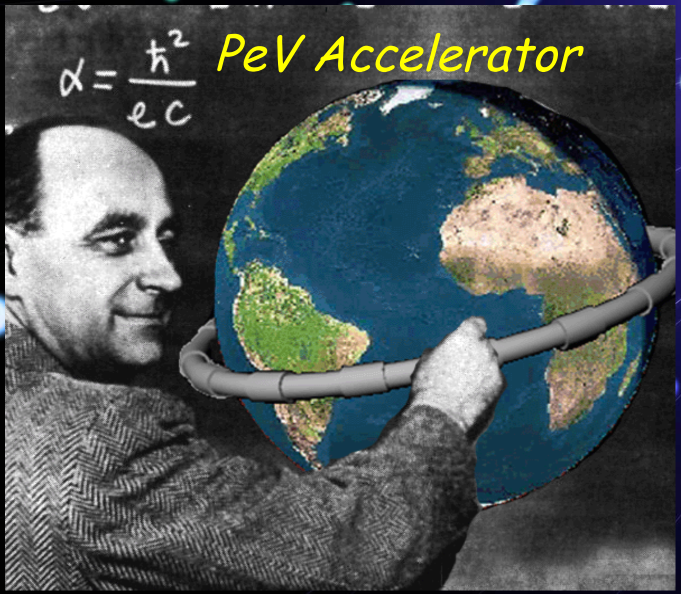
V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

Suzuki

Suzuki's Challenges

suzuki

1000 times higher energy



PeV Accelerator

1 PeV=10^{15} eV

“ New paradigm”

Leptogenesis

SUSY breaking

Extra dimension
Dark matter
Supersymmetry

1 TeV=10^{12} eV

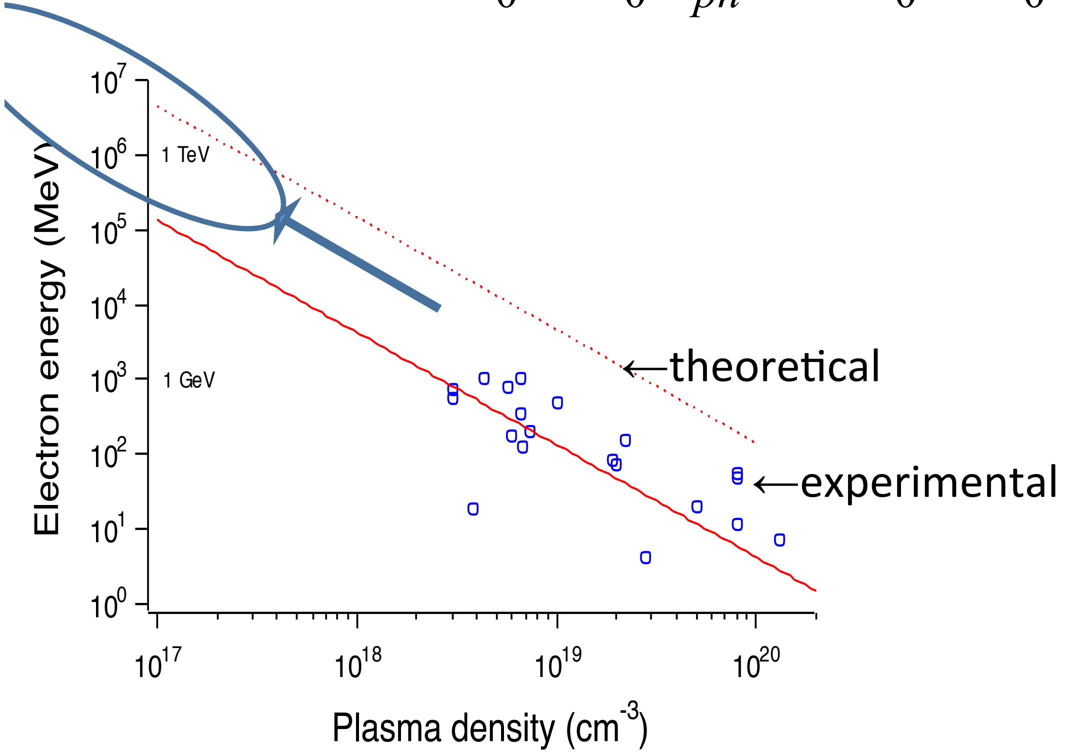
“Standard model”
Higgs
Quarks
Leptons

Laser wakefield Acceleration Technology

This talk

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)



Large energy laser → *X-ray laser approach*

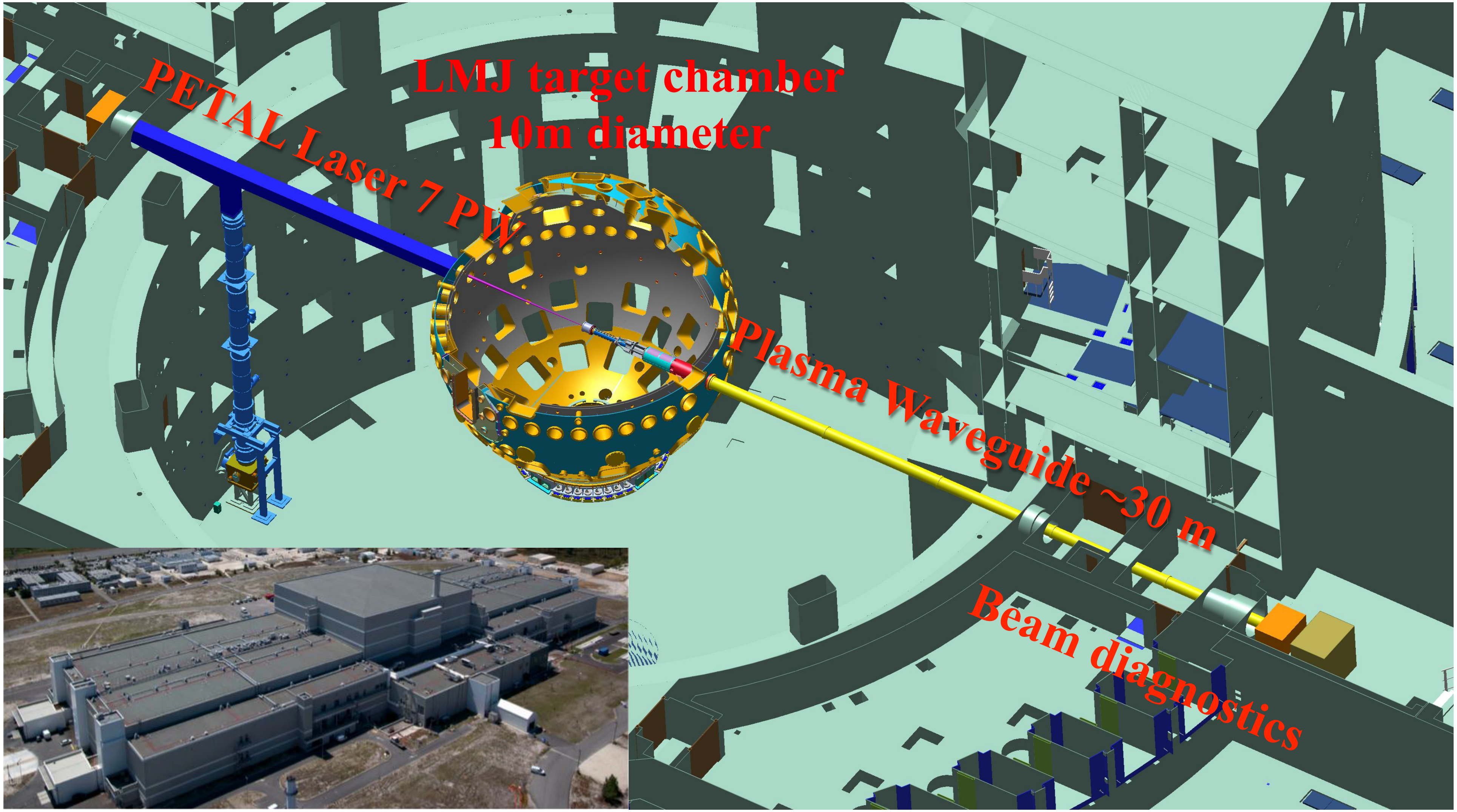
n_{cr} =10^{21} (1eV photon) → 10^{29} (10keV photon)

n_e = 10^{16} (gas) → 10^{23} (solid)

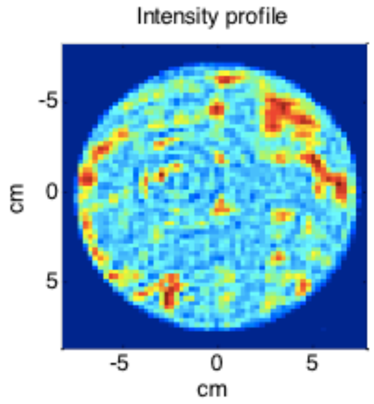
IZEST proposes 100 GeV Ascent Experiment using 3.5 kJ, 500fs, 7 PW PETAL laser

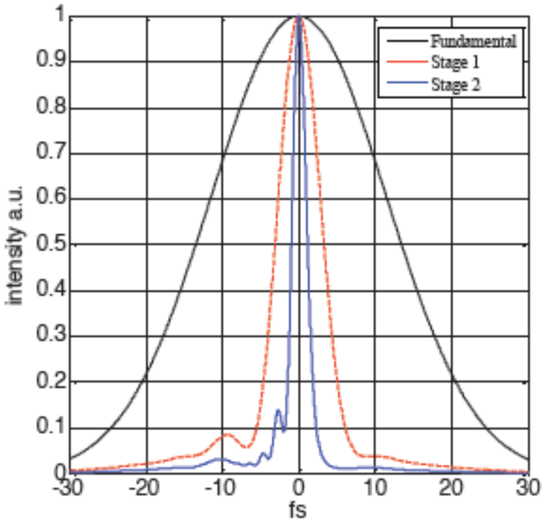
⇧ Large Energy Laser

K. Nakajima

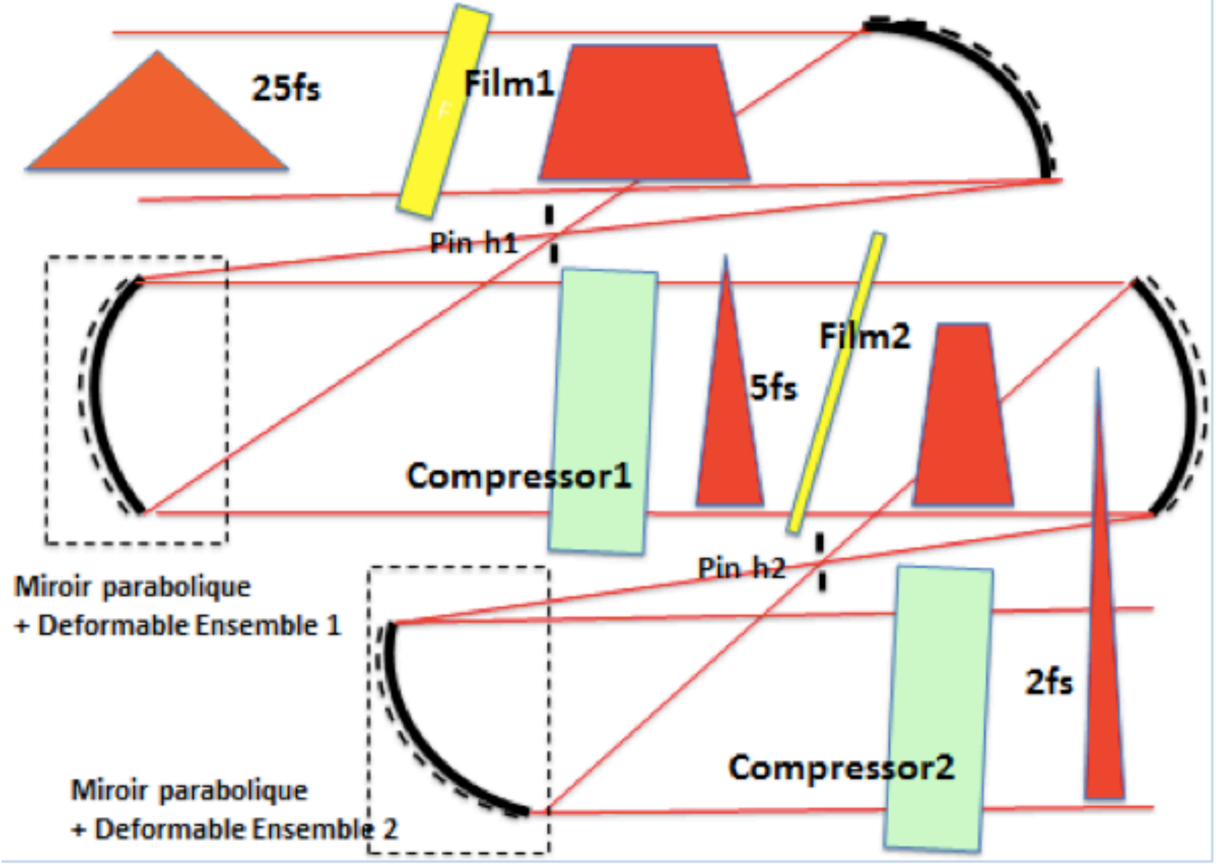


Single-Cycle Laser Compressor w/thin film





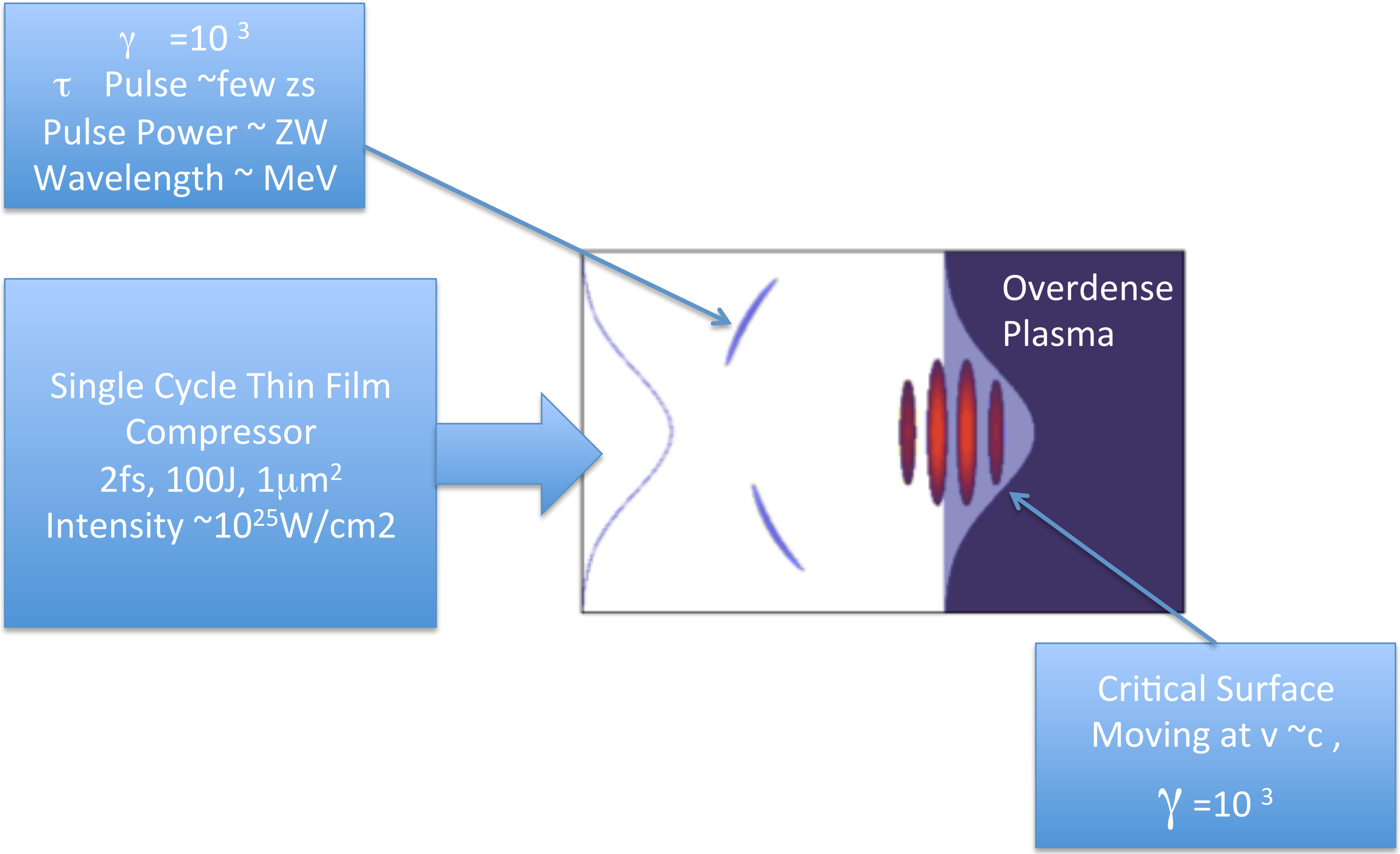
(first step)



G. Mourou, 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)



γ =10^3
τ Pulse ~few zs
Pulse Power ~ ZW
Wavelength ~ MeV

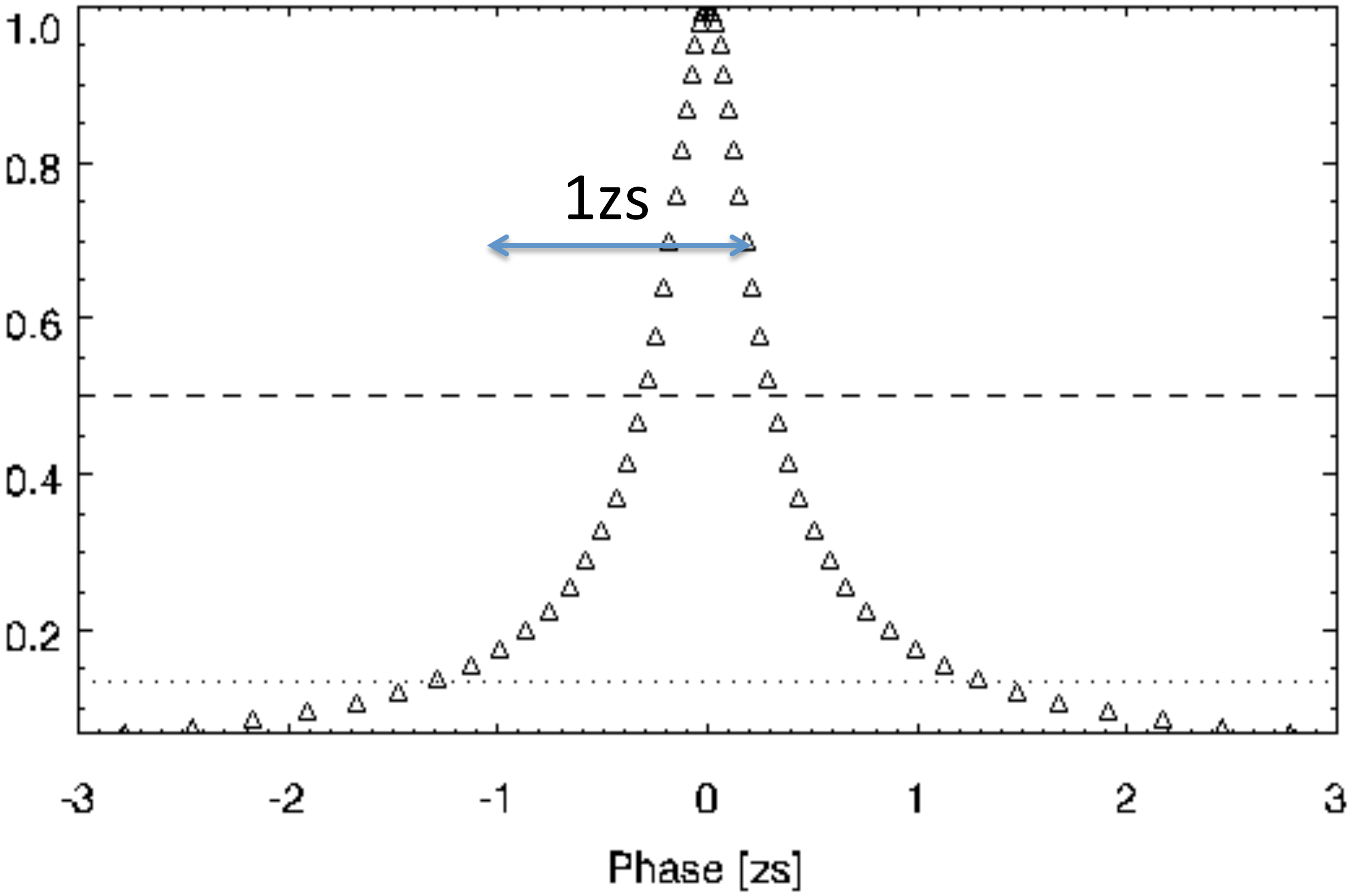
Single Cycle Thin Film
Compressor
2fs, 100J, 1μm^2
Intensity ~10^{25}W/cm2

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).

Even, Isolated zeptosecond X-ray laser pulse possible

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



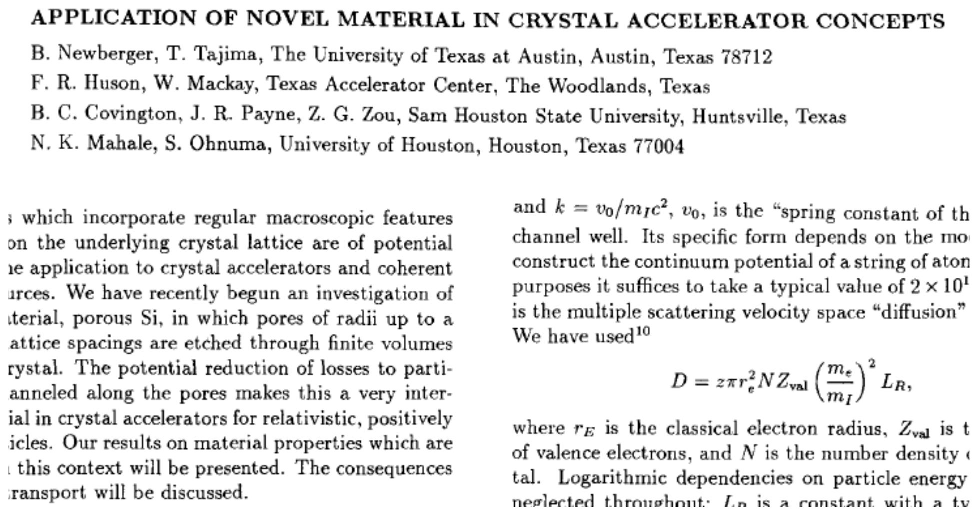
⇨

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

→ EW single osc. X-ray laser

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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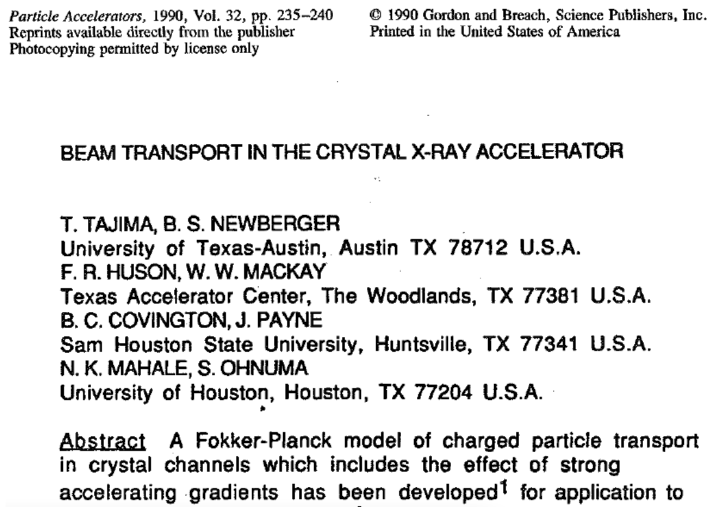
; which incorporate regular macroscopic features on the underlying crystal lattice are of potential ne application to crystal accelerators and coherent urces. We have recently begun an investigation of aterial, porous Si, in which pores of radii up to a attice spacings are etched through finite volumes 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]

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

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
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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

VOLUME 59, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1987

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 $l_i = (3/2^8\pi) \times a_B^{-2}\alpha^{-1}n^{-1}(\hbar\omega/Z_{\rm eff}^2\mathcal{R})^{7/2}$, 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 $\mathrm{Ge}_c\mathrm{Si}_{1-c}\mathrm{S}_l$ (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

$$\omega/(k_z + k_s) = c, \tag{2}$$

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

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

X-ray LWFA in crystal suggested

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

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

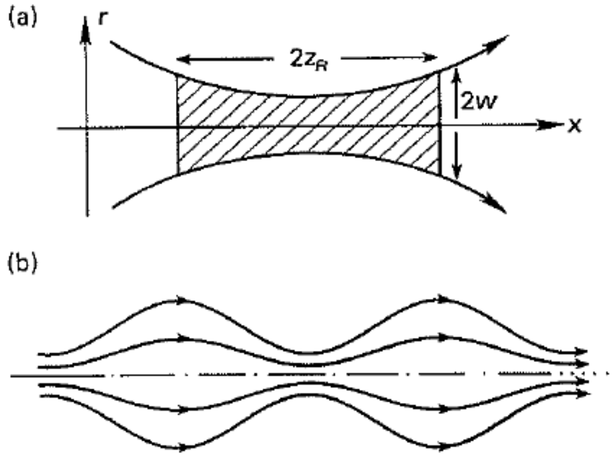
LWFA energy gain

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

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

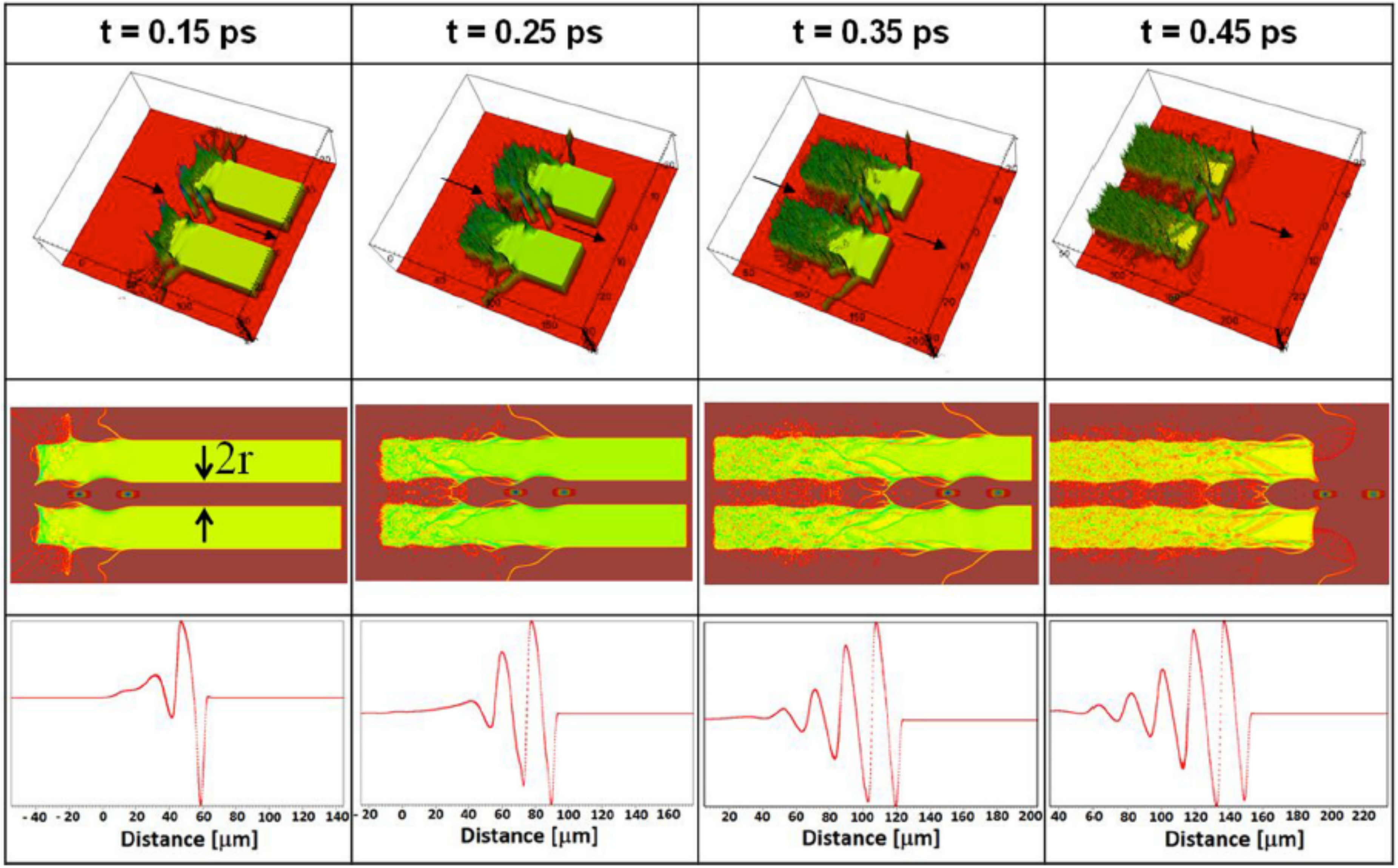
$$\omega = c\,\sqrt{(k_z^2 + \langle k_{perp}^2\rangle)},$$

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 on a chip
toward TeV over cm



Y. Shin (2014)

With Fermilab: carbon nanotube 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

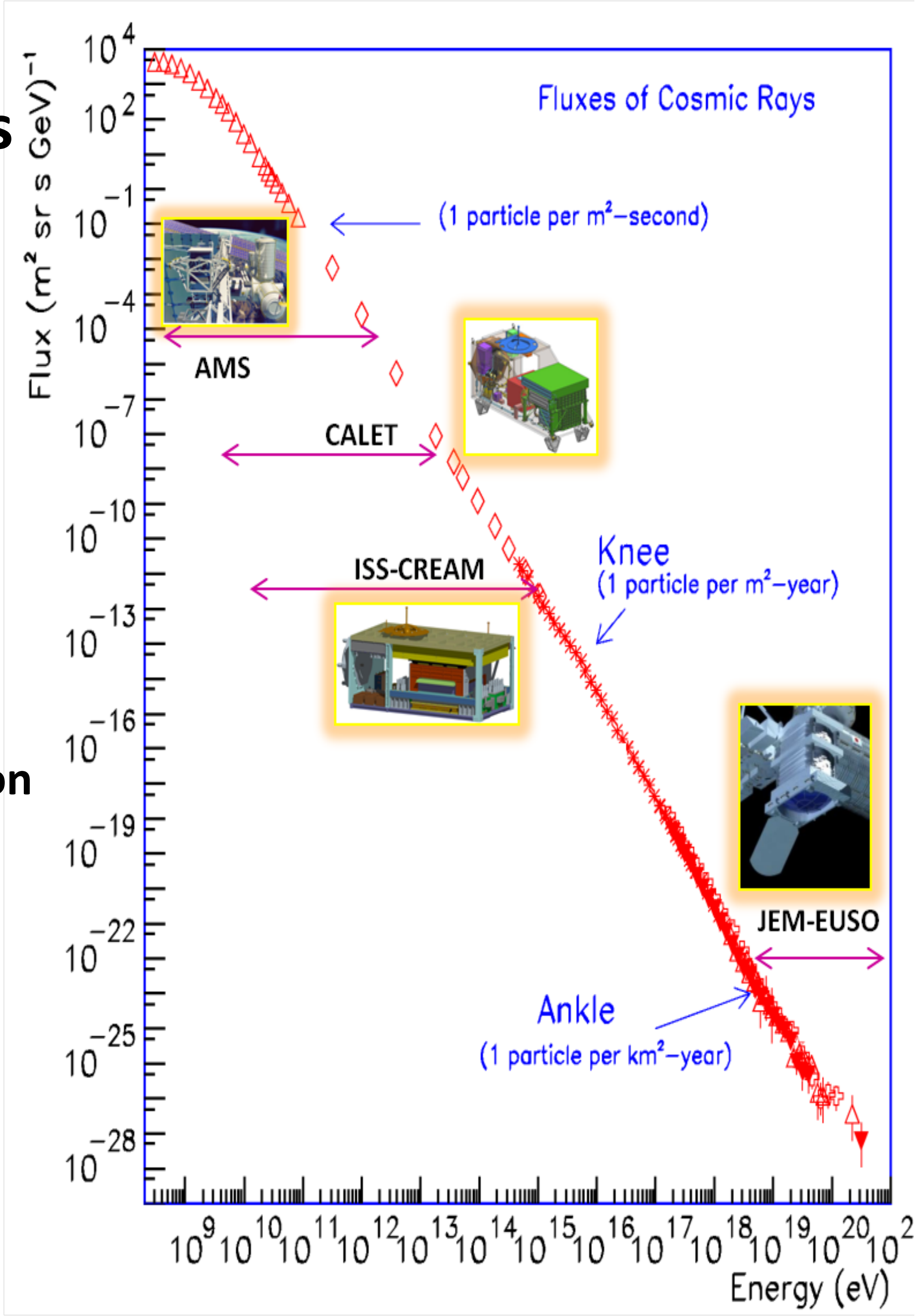
[1]Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University

[2]Fermi National Accelerator Laboratory (FNAL)

Ultrahigh Energy Cosmic Rays (UHECR)

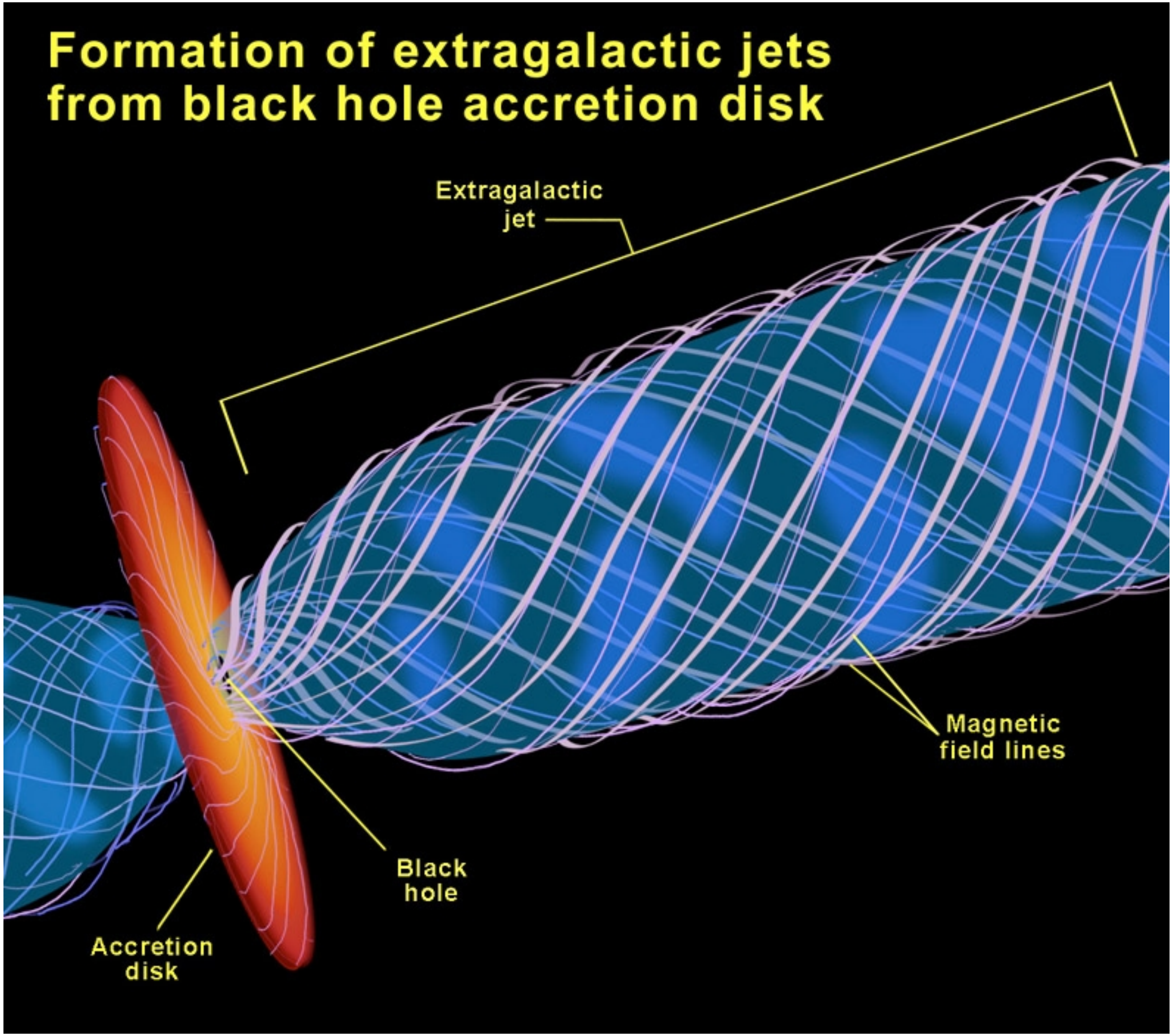
Fermi mechanism runs out of steam
  beyond 10^{19} eV
  due to synchrotron rad

Wakefield acceleration
  comes in rescue
  prompt, intense, linear acceleration



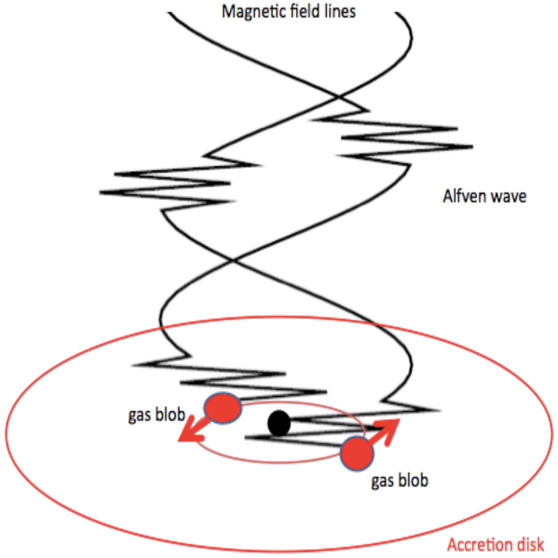
Cen A

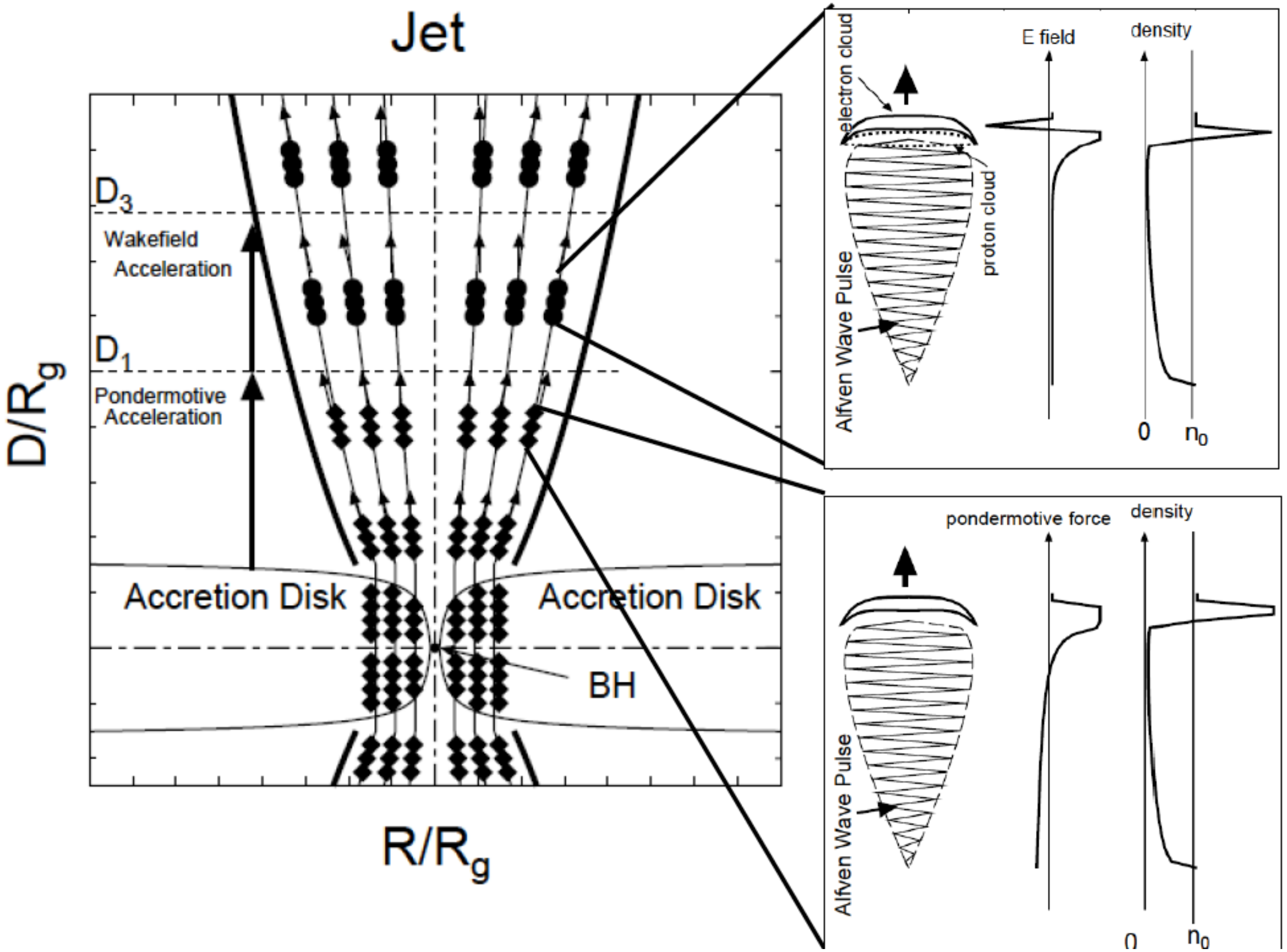
- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets



Formation of extragalactic jets from black hole accretion disk

Astrophysical wakefield acceleration: Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays ($a_0 \sim 10^6$ -10^{10}, large z)





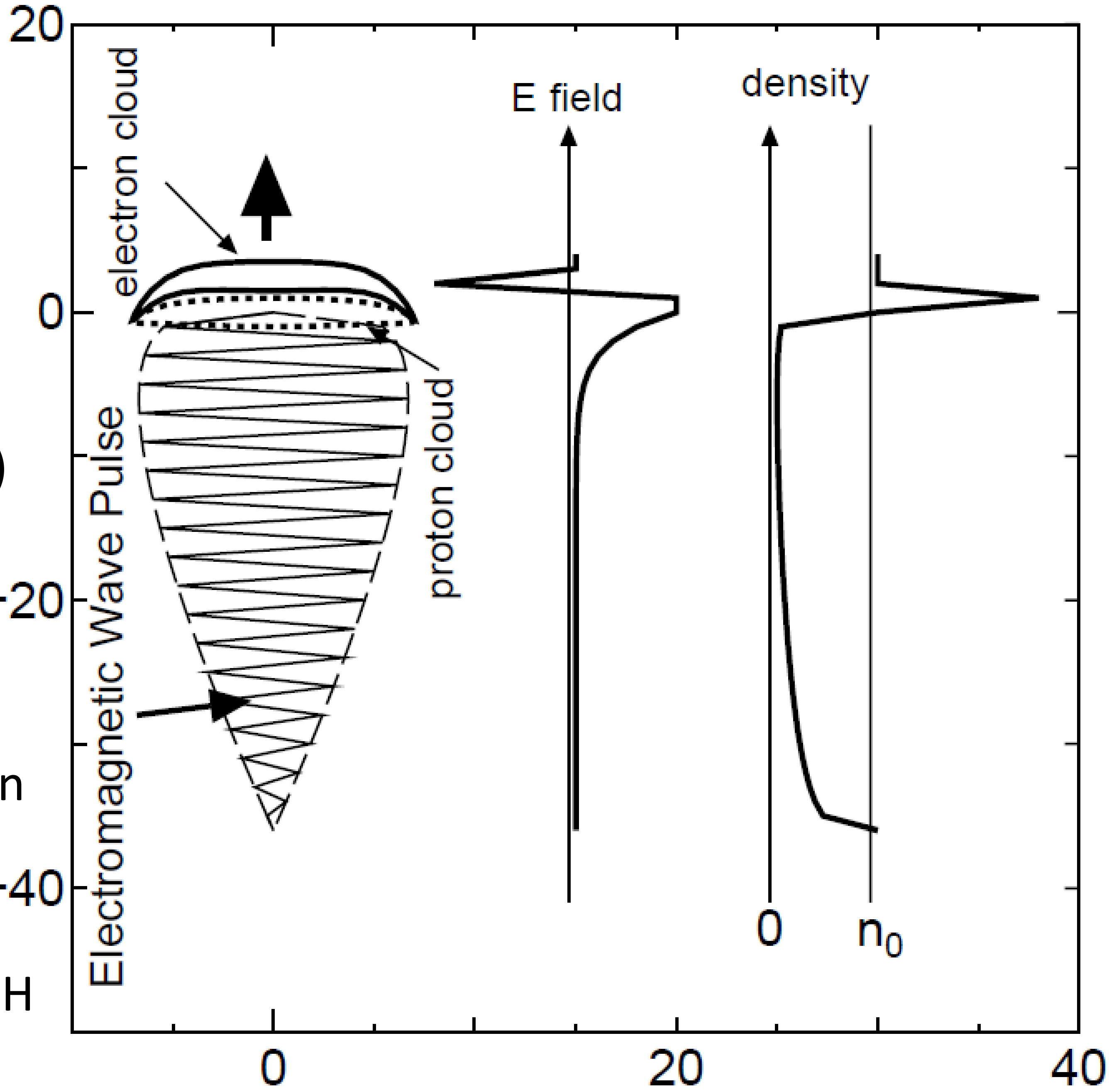
Ebisuzaki and Tajima, Astropart. Phys.(2014)

Wakefield vs. Ponderomotive Acceleration

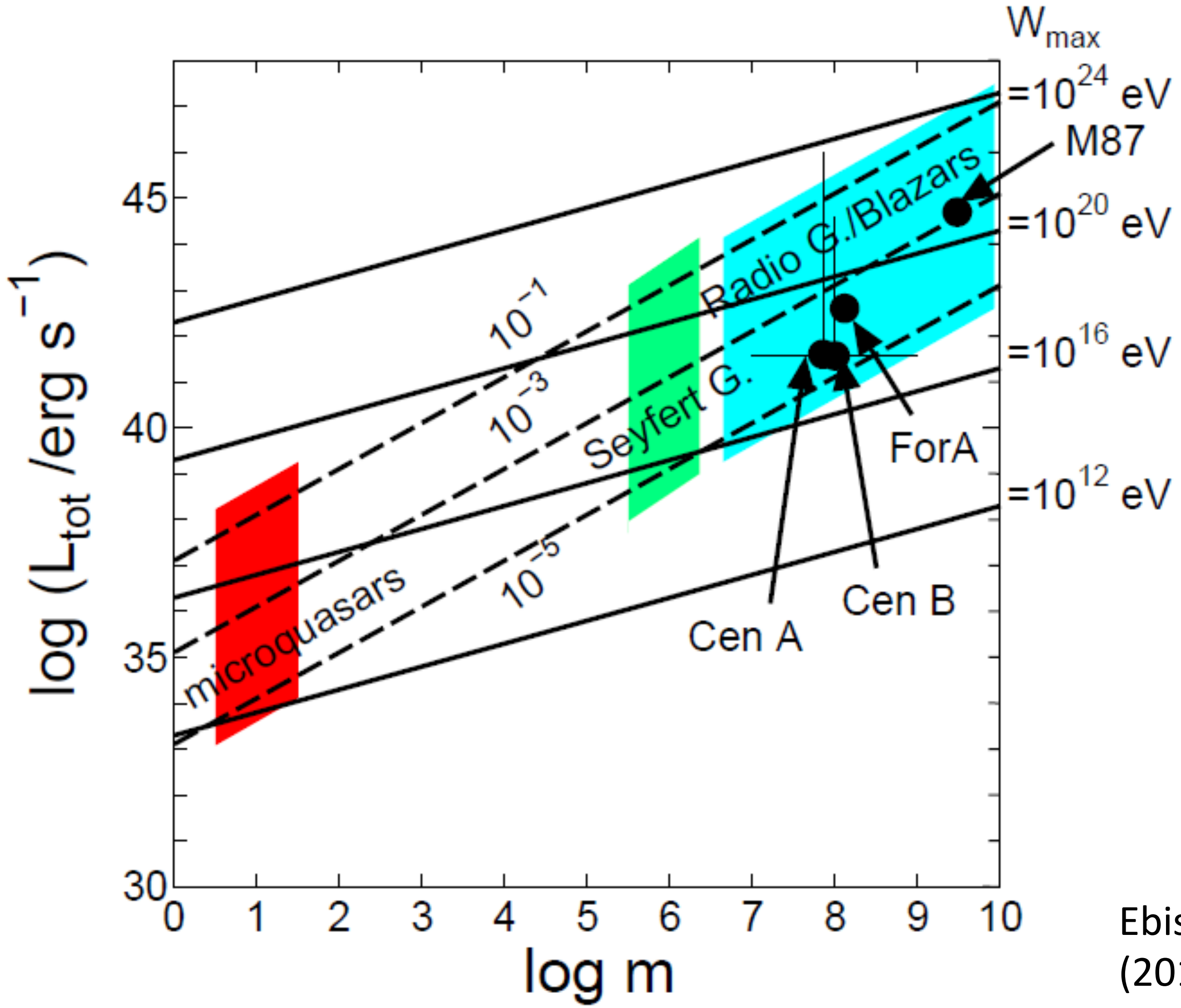
wavebreak (1D or 2D) in higher a_0 → wakefield less important

Ponderomotive-driven Acceleration more robust ($a_0 \gg 1$)

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



comic ray acceleration and gamma-ray emission



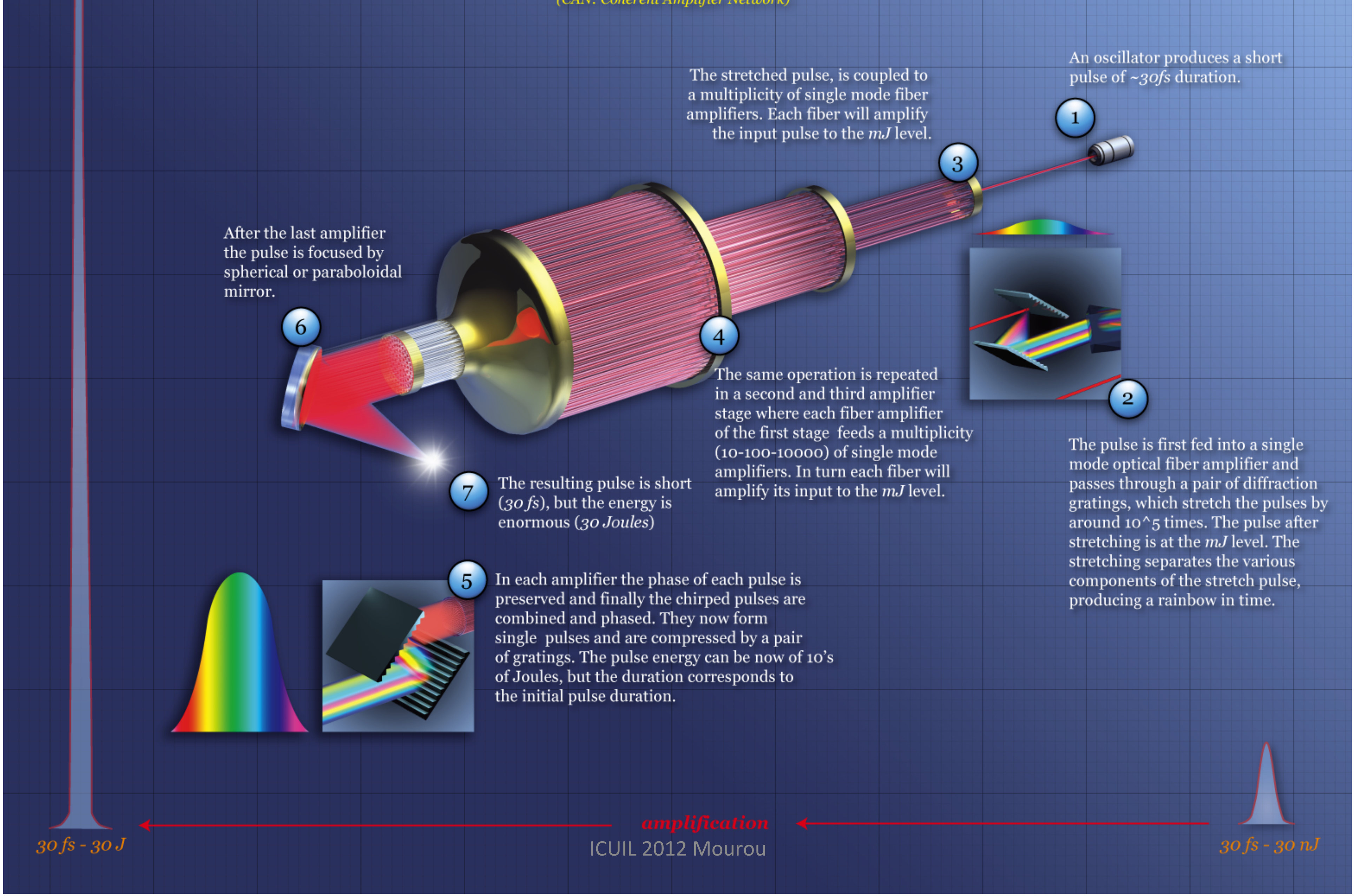
Ebisuzaki, Tajima (2014)

ican
International Coherent
Amplification Network

HOW A “CAN” LASER AMPLIFIER WORKS

Producing High Peak Power and High Average Power, Mitigating Heat

(CAN: Coherent Amplifier Network)



① An oscillator produces a short pulse of *~30fs* duration.

② The pulse is first fed into a single mode optical fiber amplifier and passes through a pair of diffraction gratings, which stretch the pulses by around 10^5 times. The pulse after stretching is at the *mJ* level. The stretching separates the various components of the stretch pulse, producing a rainbow in time.

③ The stretched pulse, is coupled to a multiplicity of single mode fiber amplifiers. Each fiber will amplify the input pulse to the *mJ* level.

④ The same operation is repeated in a second and third amplifier stage where each fiber amplifier of the first stage feeds a multiplicity (10-100-10000) of single mode amplifiers. In turn each fiber will amplify its input to the *mJ* level.

⑤ In each amplifier the phase of each pulse is preserved and finally the chirped pulses are combined and phased. They now form single pulses and are compressed by a pair of gratings. The pulse energy can be now of 10’s of Joules, but the duration corresponds to the initial pulse duration.

⑥ After the last amplifier the pulse is focused by spherical or paraboloidal mirror.

⑦ The resulting pulse is short (*30 fs*), but the energy is enormous (*30 Joules*)

ICUIL 2012 Mourou

Conclusions

- 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, TeV on a chip
- **Crystal nanoengineering**: s.a. nanoholes, arrays, focus optics
- **Zeptosecond nanobeams** of electrons, protons (ions), muons (neutrinos), coherent γ-rays
- Start of **zeptoscience**

In dedication to the late Professor Hiroshi Takuma:

「道を問ひ　学に魅入りし　木津の地に
御霊残れり　微笑みととも」

"Inquiring the Tao
Lured in beauty of physics
Your Spirit remains
Here in the Kizu 'Shrine'
You founded, with smile on us...."

T. Tajima

ありがとうございました！

Y.Shin