TeV Acceleration in a Tiny Chip

IZEST
Romanian Embassy, Paris,Sept. 18, 2014

T. Tajima, UCI and IZEST

Acknowledgments for Collaboration: G. Mourou, N. Naumova, K. Nakajima, S. Bulanov, A. Suzuki, T. Ebisuzaki, J. Koga, X. Q. Yan, U. Wienands, U. Uggerhoj, A. Chao, N.V. Zamfir, Y. M. Shin, V. Shiltsev, M. Hogan, K. Ishikawa, Y. Tobita

IZEST

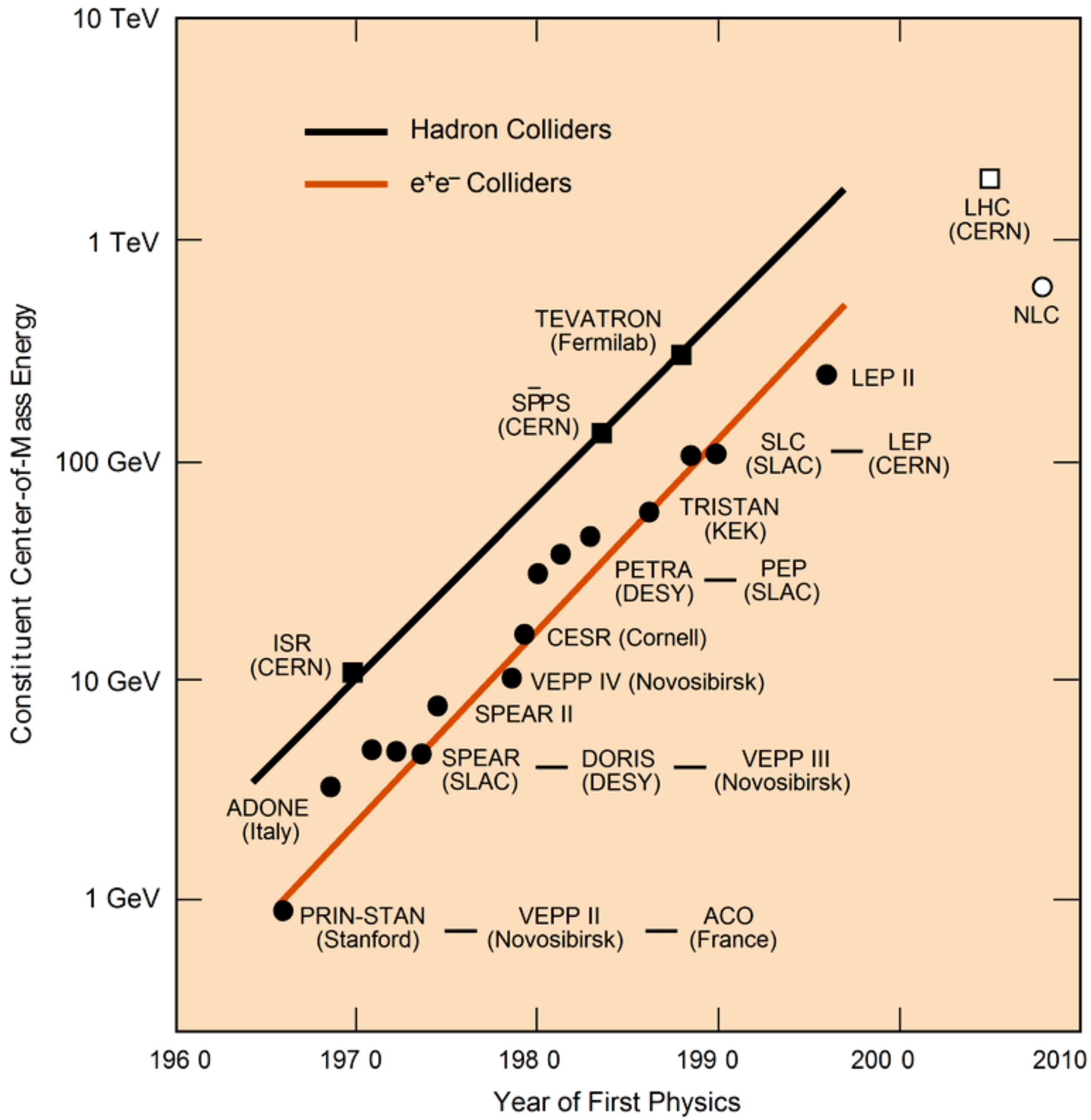
Eur. Phys. J. Spec. Top. **228**, 1037 (2014)

Content

- **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**
  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
  accelerating gradient = $a_0 (n / n_{18})^{1/2}$ 1GeV/cm = 300a_0GeV/cm
- **X-ray crystal optics**
  X-ray (γ-ray) optics------Habs et al.
  nonlinear optics in vacuum----self-focus ($P > P_{cr}$ ~ 25PW @10keV)
- **Vacuum acceleration: intense X-rays**
  Schwinger fiber acceleration
- **Collaboration THEXAC formed (7 organizations)**
- **Test of wakefield acceleration in crystal at FACET (SLAC)**

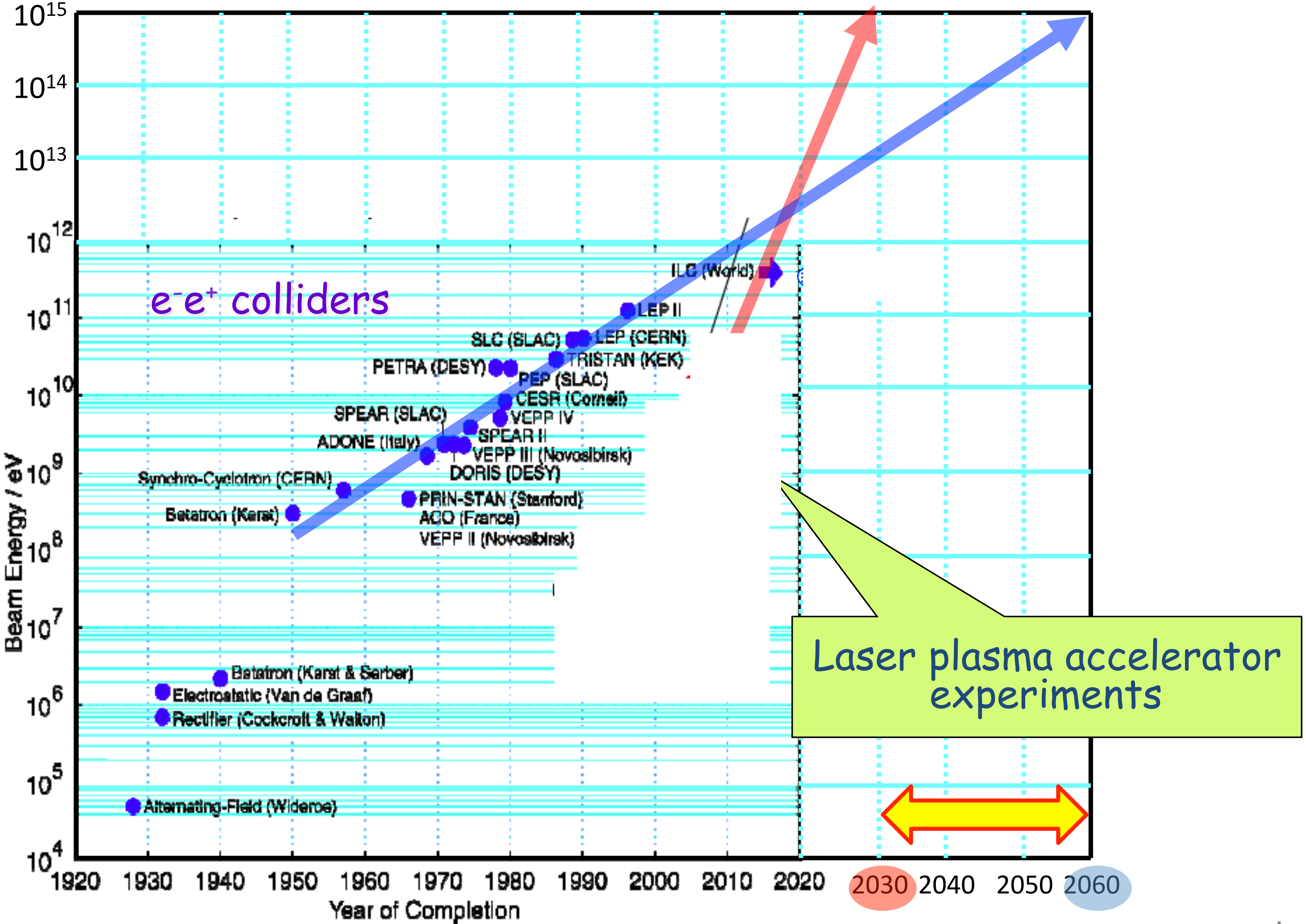
- **A preview == A new idea: catching neutrinos by lasers**

“When can we reach 1 PeV ?” (A. Suzuki/KEK DG/ former ICFA Chair)

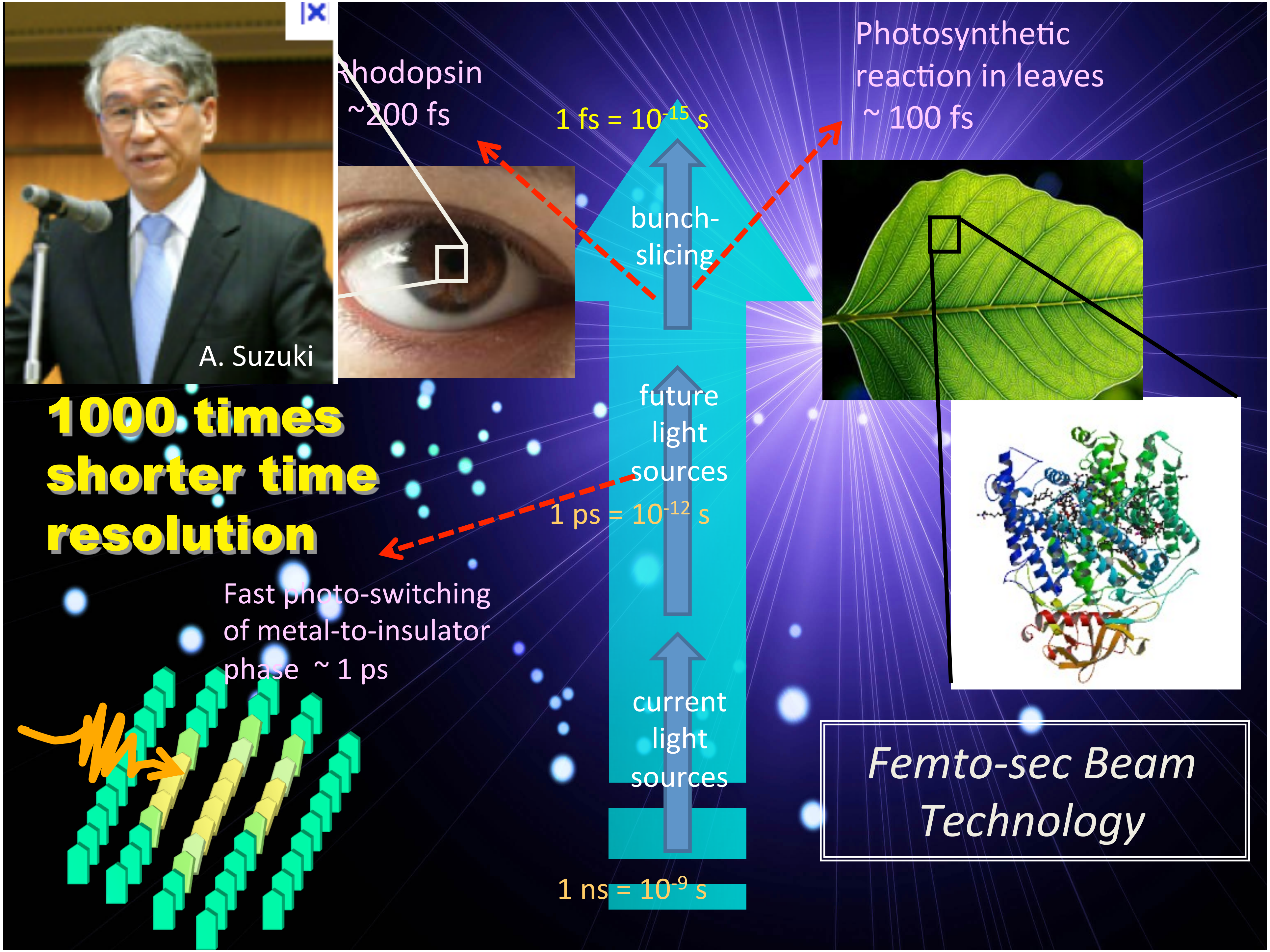


(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

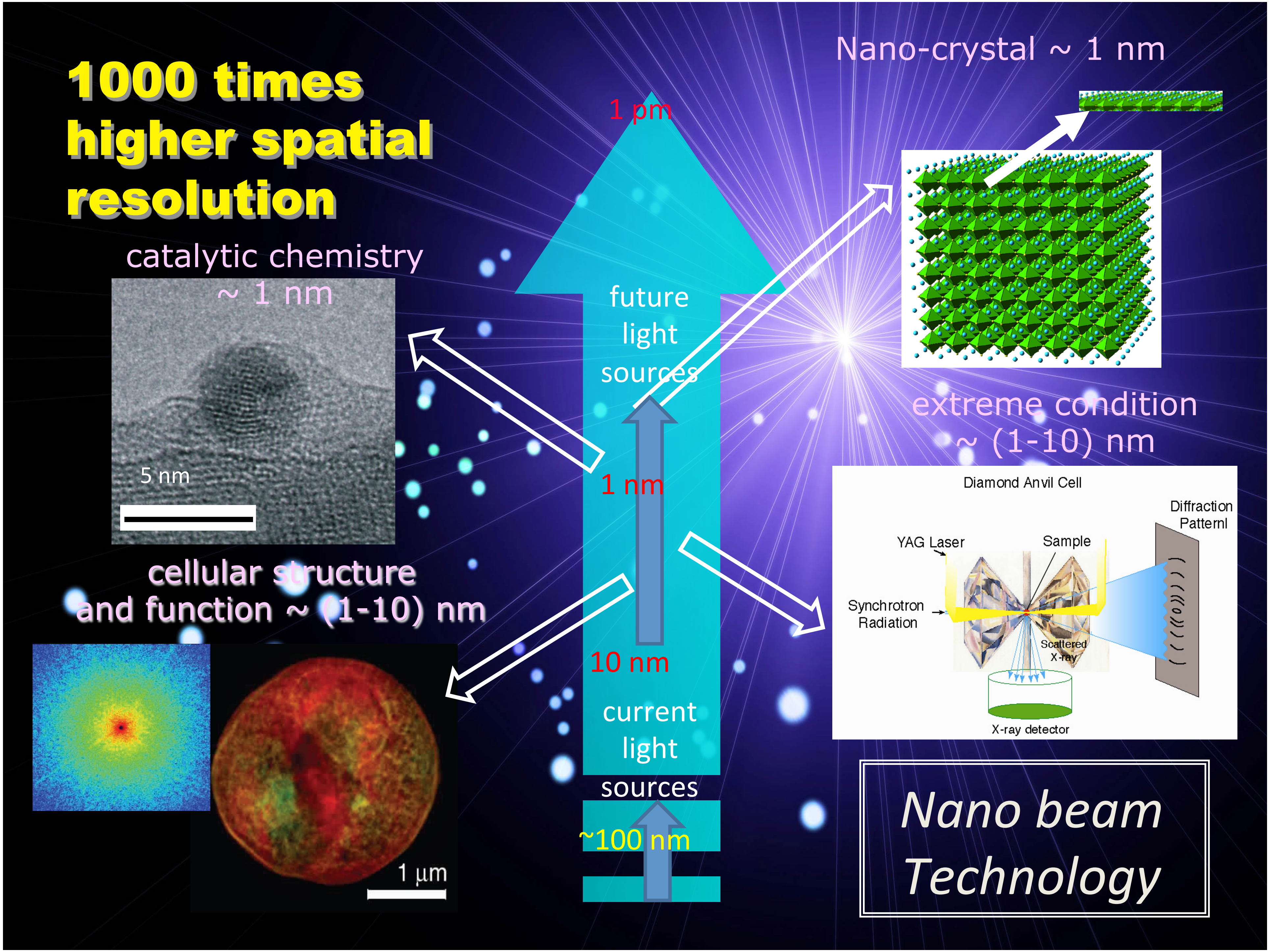
"When can we reach 1 PeV ?" (A. Suzuki)



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

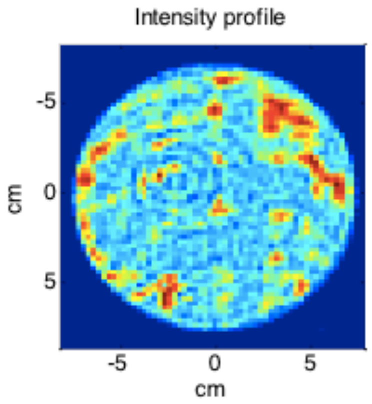


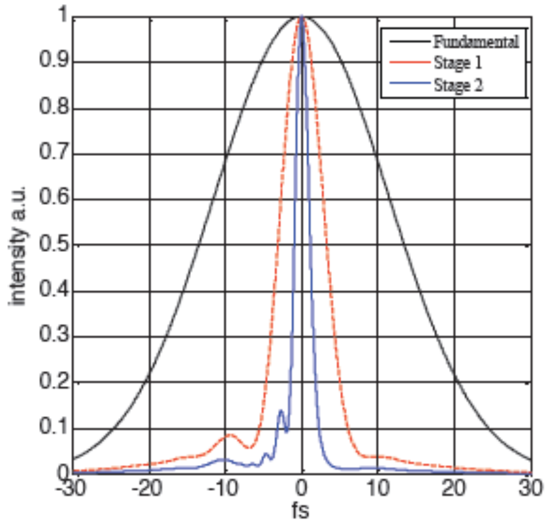
Rhodopsin
~200 fs
1 fs = 10-15 s
Photosynthetic
reaction in leaves
~ 100 fs
A. Suzuki
bunch-
slicing
future
light
sources
1000 times
shorter time
resolution
1 ps = 10-12 s
Fast photo-switching
of metal-to-insulator
phase ~ 1 ps
current
light
sources
Femto-sec Beam
Technology
1 ns = 10-9 s



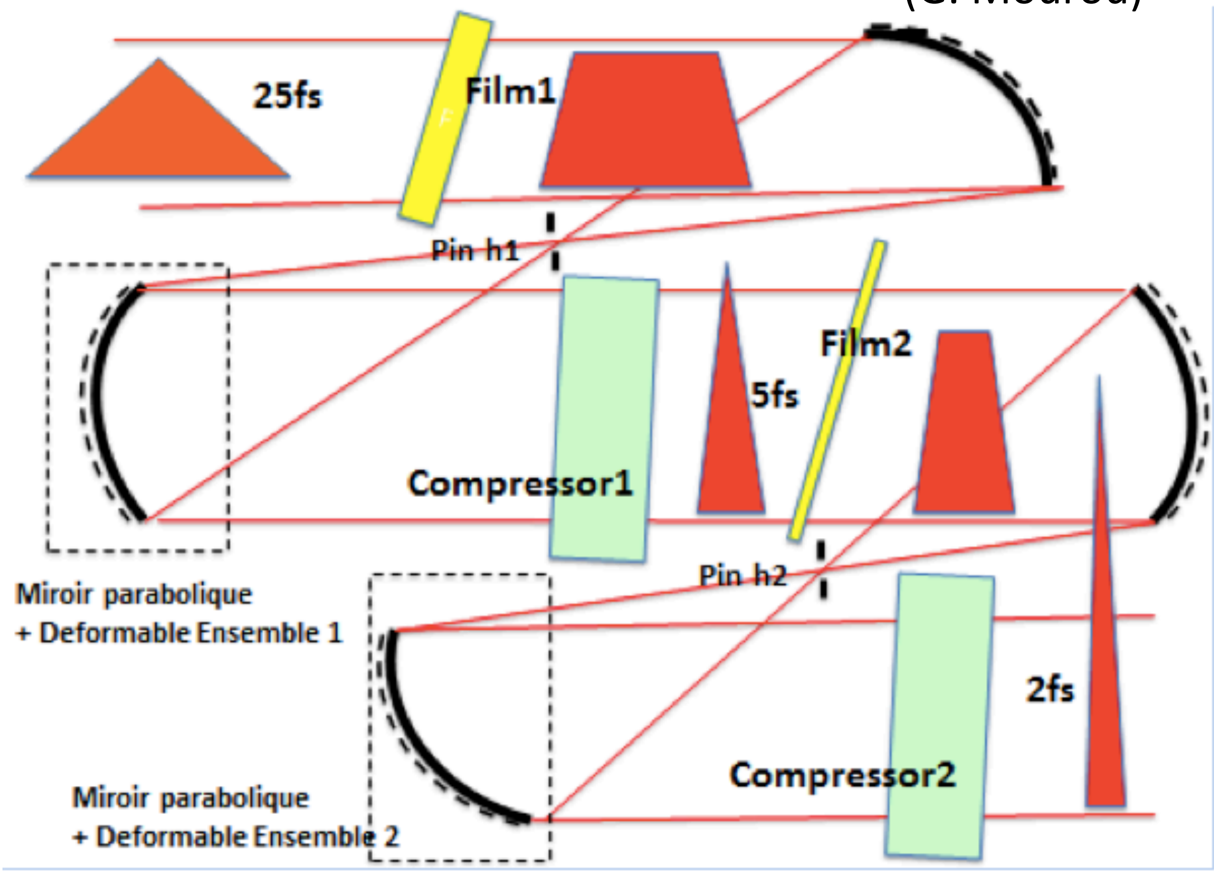
1000 times higher spatial resolution
catalytic chemistry ~ 1 nm
5 nm
cellular structure and function ~ (1-10) nm
1 μm
1 pm
future light sources
1 nm
10 nm
current light sources
~100 nm
Nano-crystal ~ 1 nm
extreme condition ~ (1-10) nm
Diamond Anvil Cell
Diffraction Patternl
YAG Laser
Sample
Synchrotron Radiation
Scattered X-ray
X-ray detector
Nano beam Technology

Single Cycle Thin Film Compressor





(G. Mourou)



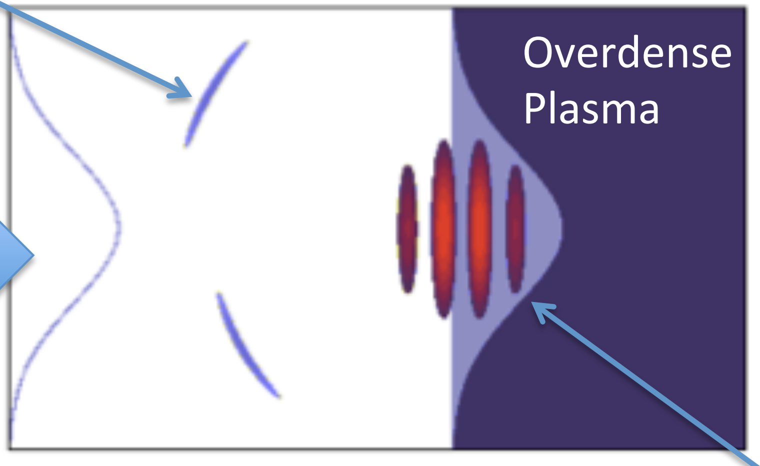
G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Single cycle thin film compressor opening the door to Zeptosecond-Exawatt Physics , Eur. Phys. J. Special Topics, **223**, 1181(2014)

Ultrarelativistic Mirror in the λ^3 Regime

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

(G. Mourou)

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



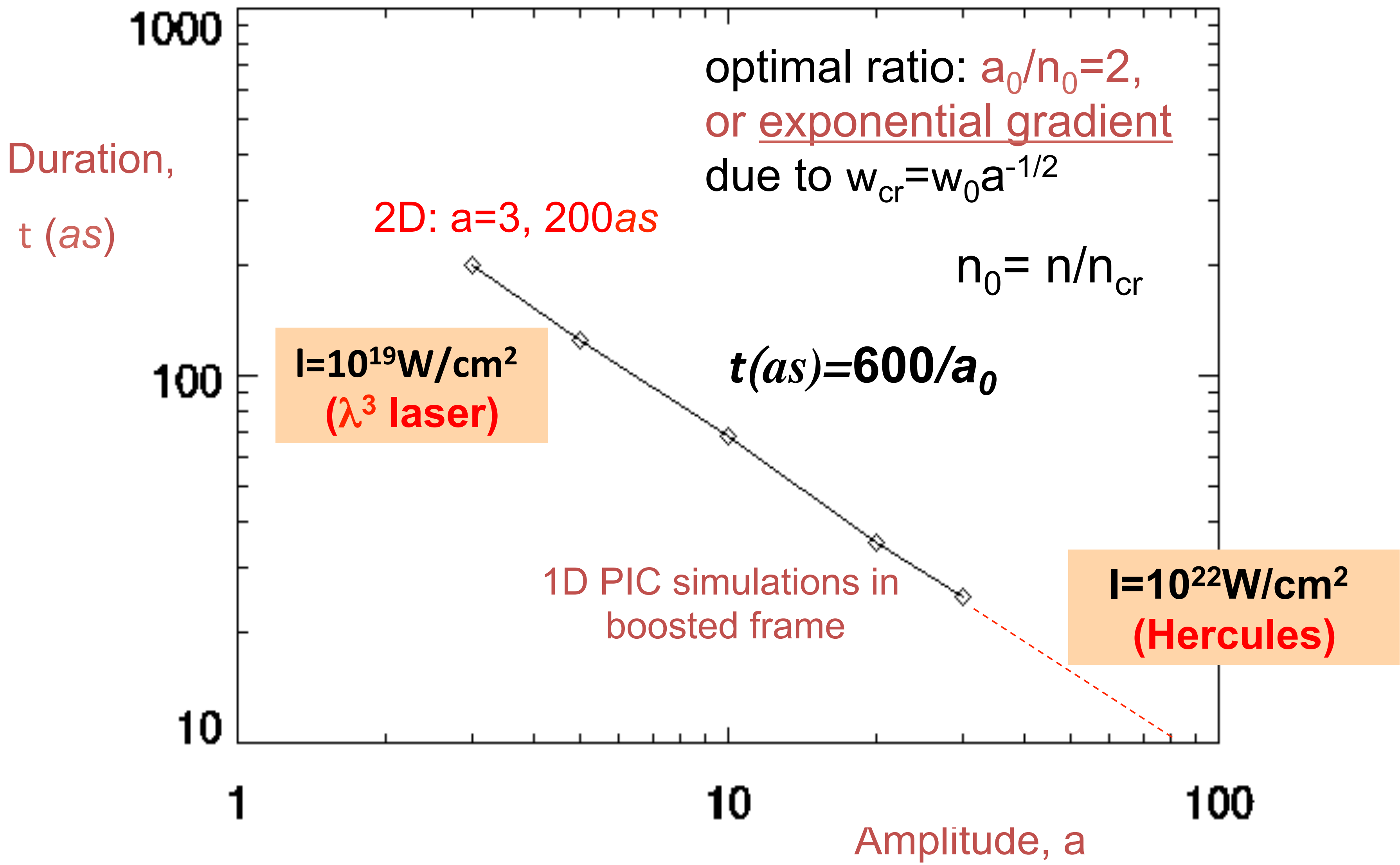
Critical Surface
Moving at v ~c ,
γ =10 ^{3}

G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Single cycle thin film compressor opening the door to Zeptosecond-Exawatt Physics , Eur. Phys. J. Special Topics, **223**, 1181(2014)

N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou, Relativistic generation of isolated attosecond pulses in a l3 focal volume, Phys. Rev. Lett. **92**, 063902-1 (2004).

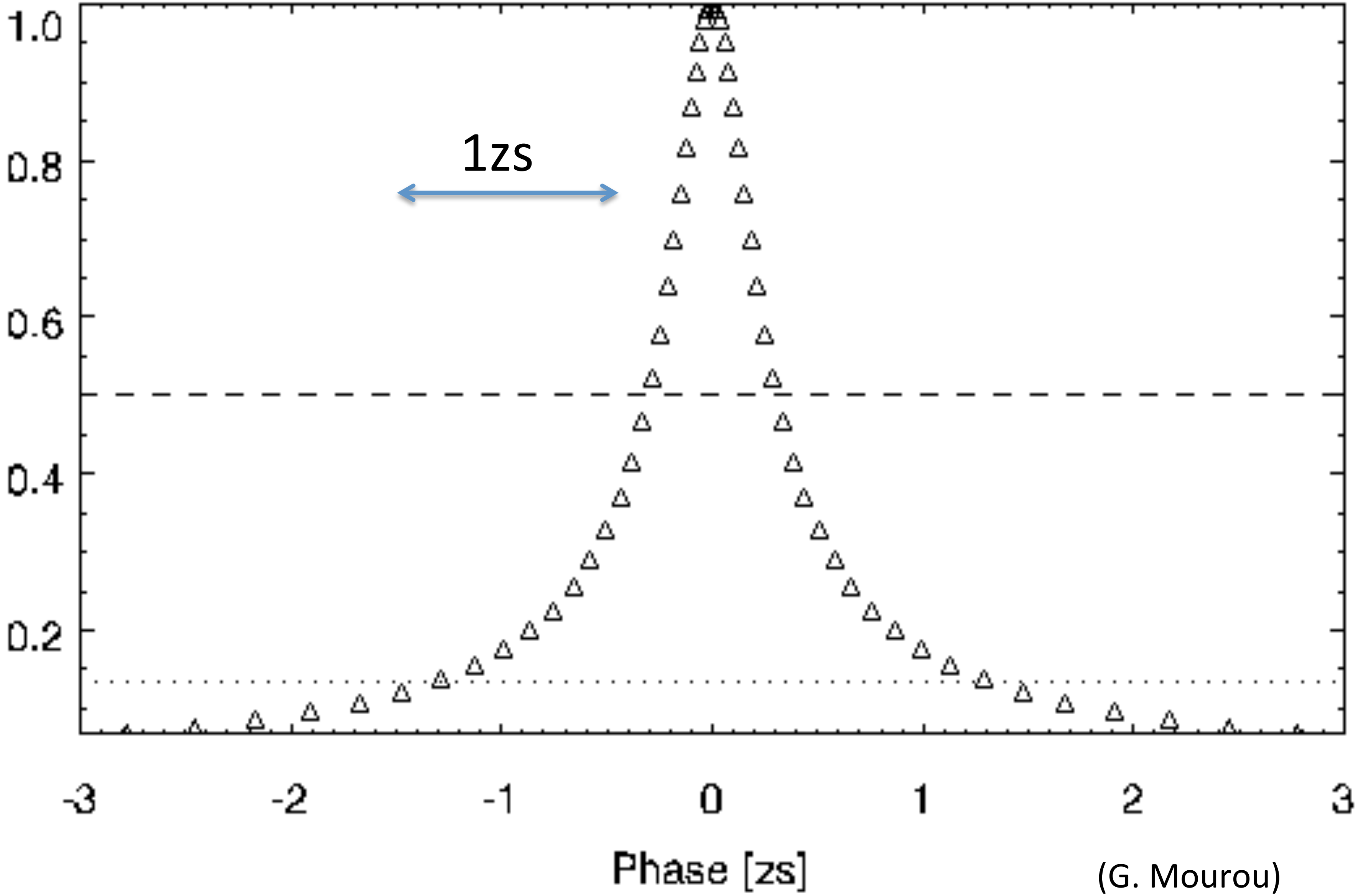
Scalable Isolated Attosecond Laser Pulses

(Naumova et al. PRL, 2004)



Isolated zeptosecond X-ray laser pulse

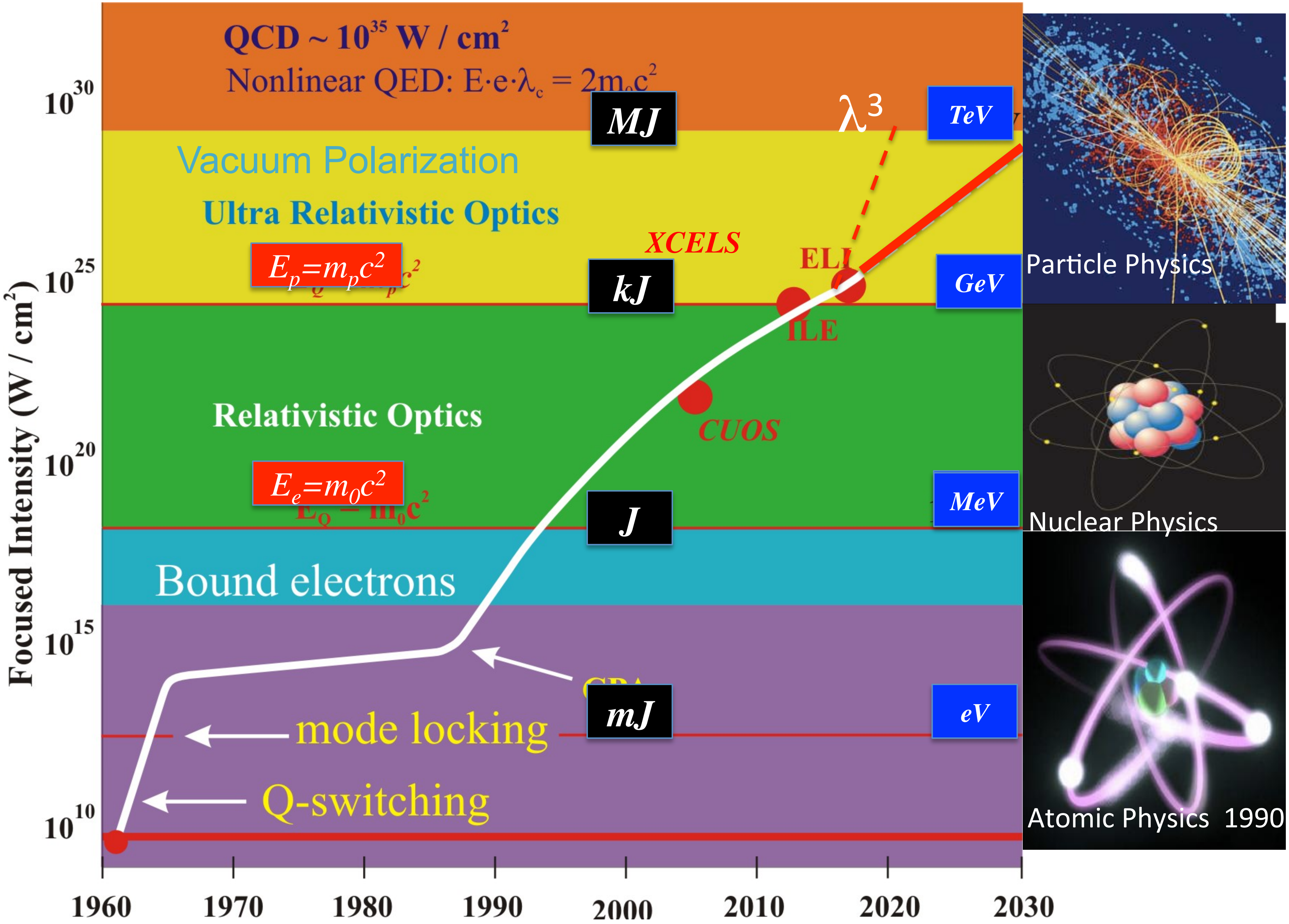
(simulation by N. Naumova, I. Sokolov, G. Mourou, 2014)



(G. Mourou)

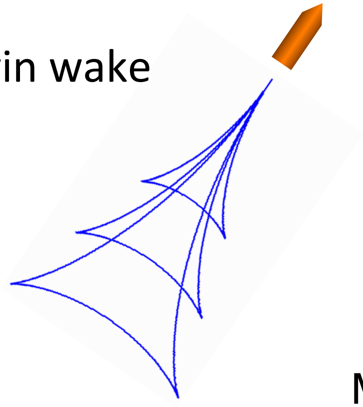
Extreme Light Roadmap

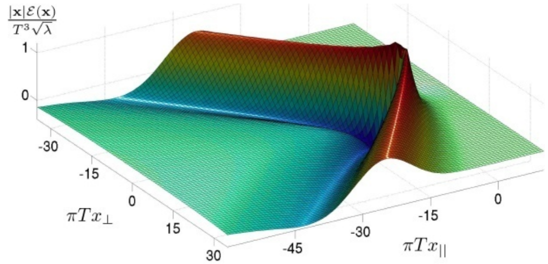
(modified from Tajima and Mourou, PR 2002)



Laser Wakefield (LWFA): nonlinear optics in plasma

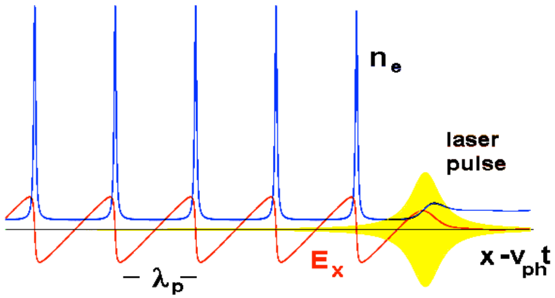
Kelvin wake





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

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



← relativity regularizes
(*relativistic coherence*)

(The density cusps.
Cusp singularity)

Wave **breaks** at v<c

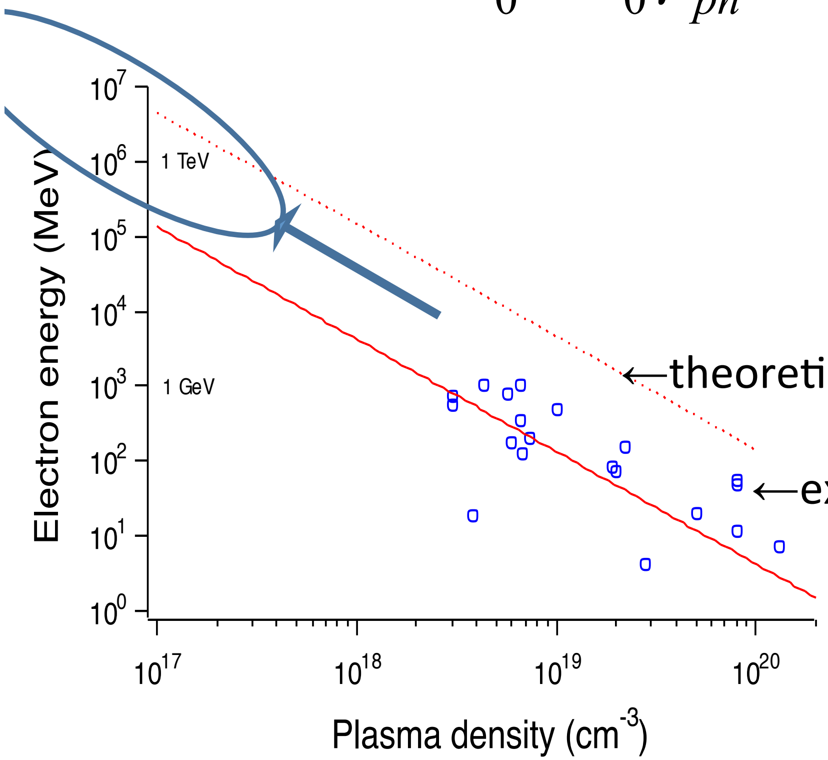
Hokusai

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

X-ray LWFA in crystal suggested

X-ray Laser Wakefield Accelerator in crystal:

LWFA pump-depletion length:

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

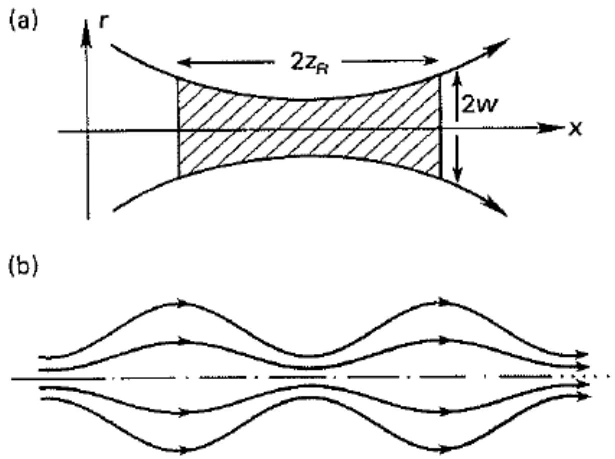
LWFA energy gain

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

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)

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 ıe application to crystal accelerators and coherent ırces. We have recently begun an investigation of ıterial, 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 ı 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 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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and
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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: $a_0 = \pi^{-1/2}\hbar c(f\mathcal{N})^{-1/2}P\epsilon^{-2}$, 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 $\hbar\omega = mc^2\alpha$ 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

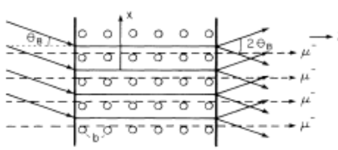
where b is the transverse lattice constant and later a the longitudinal lattice constant ($a \simeq b$) (see Fig. 1). The row of lattice ions (perhaps with inner-shell electrons) constitutes the "waveguide" wall for x rays, while they also act as periodic irises to generate slow waves. A superlattice[5]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

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

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

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



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

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

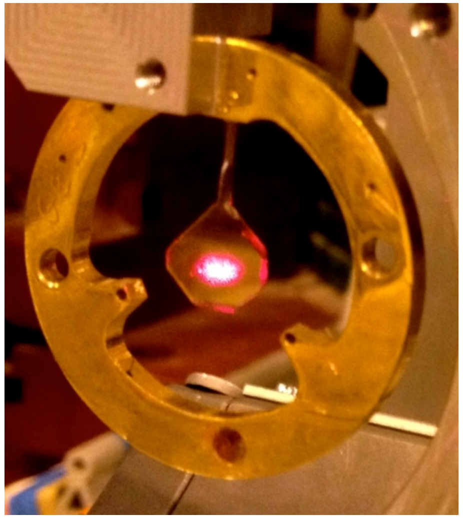
What we'd like to do initially at FACET

- Detect and quantify wakefield excitation
- 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 FACET E212 and ESTB T513.
  - we are combining forces.

In Collaboration with Stanford SLAC E212 (PI: Prof. Uggerhoj)

Radiation from GeV electrons in diamond – with intensities approaching the amplified radiation regime

… en route towards the 'gamma-ray laser'



Ulrik I. Uggerhøj

Department of Physics and Astronomy

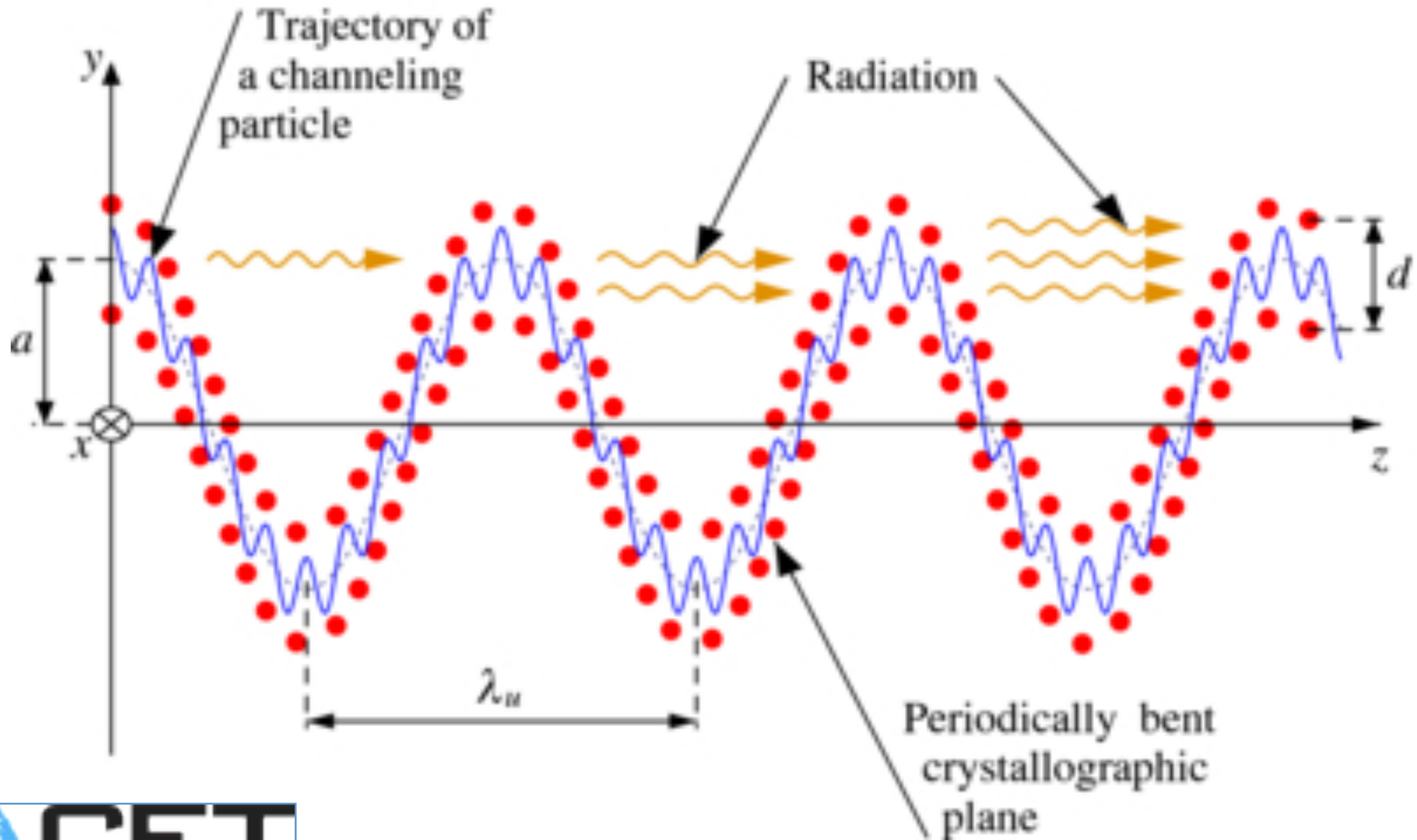
Aarhus University, Denmark

On behalf of the collaboration

In collaboration with E212: from Prof.Uggerhoj

Undulator Radiation from **Positron** Channeling in a Single Crystal

A. Solov'yov, A. Korol, W. Greiner *et al.*



FACET

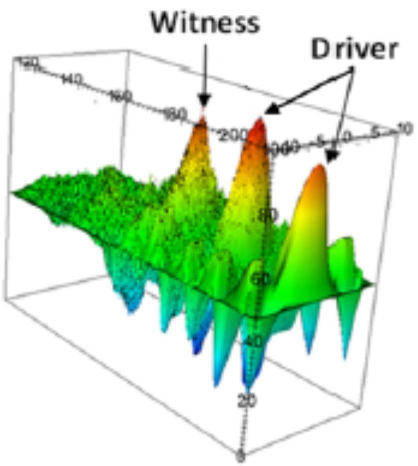
A possible route to a gamma-ray laser?

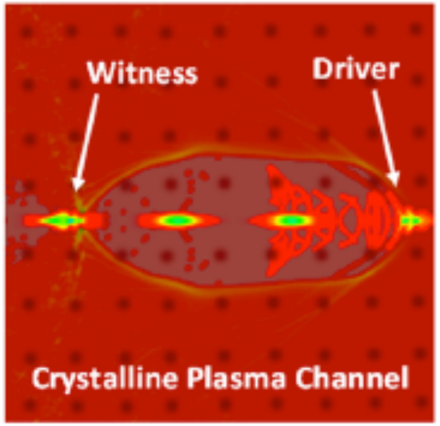
A first Positron Run

- Unique chance to study wake-field generation in crystal
  - Channeling parameters, etc.
  - Detect energy absorption into wake
    - charge-dependent *E*-loss.
- Use T-513 crystal, or Aarhus diamond (better)
- T-513 hardware should work in FACET
- Tune spectrometer vertically imaging
- Three 12-hour shifts likely sufficient
  - based on T513 and Aarhus experience, known crystal

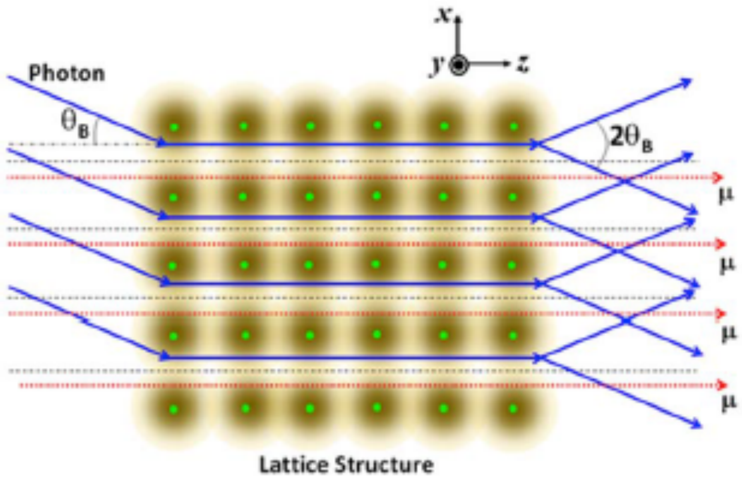
Wakefield excitation by electron (or positron) beam (vs. by X-ray pulse)

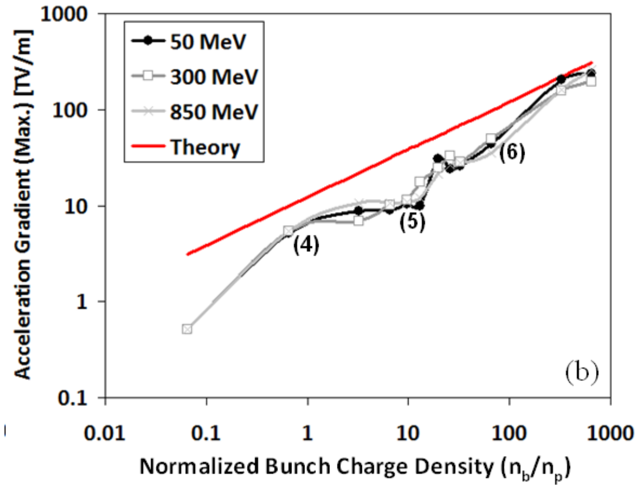
Wakefield Acceleration

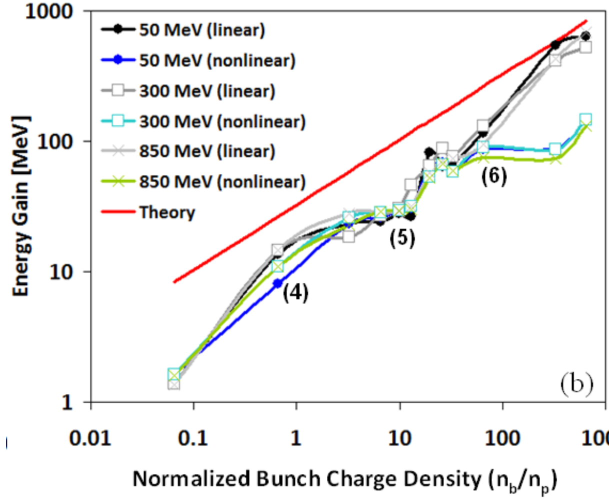




Diffraction Acceleration





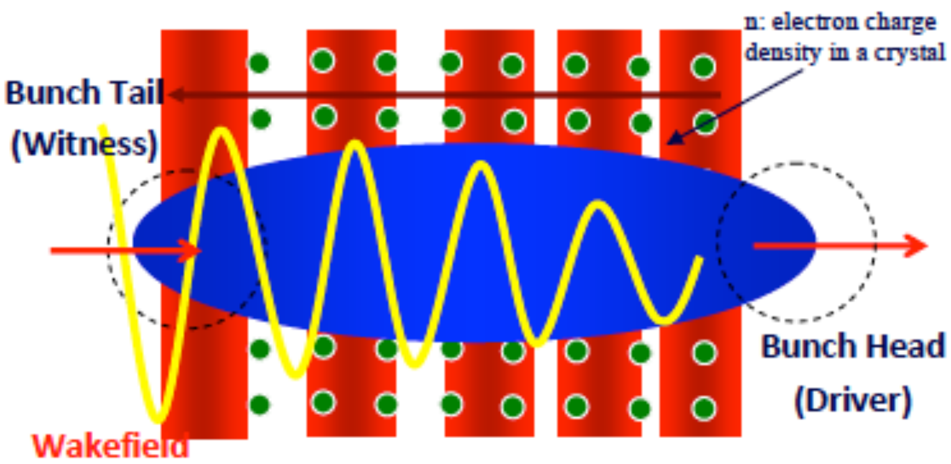


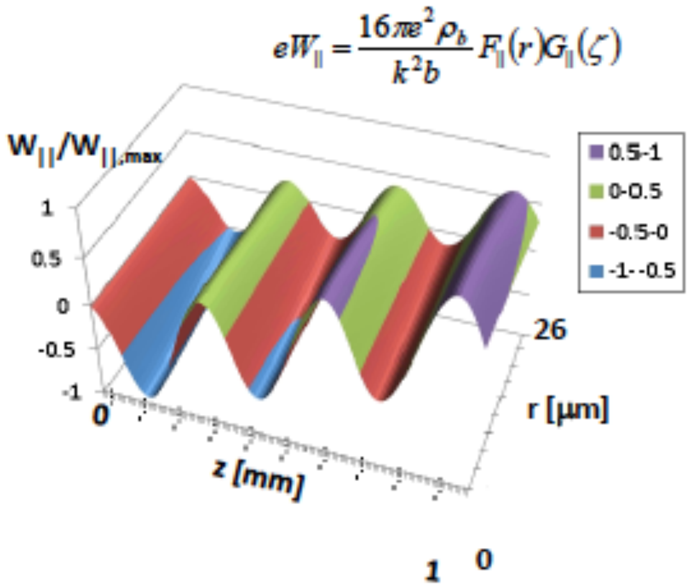
$n_p = 10^{28}\ m^{-3}$

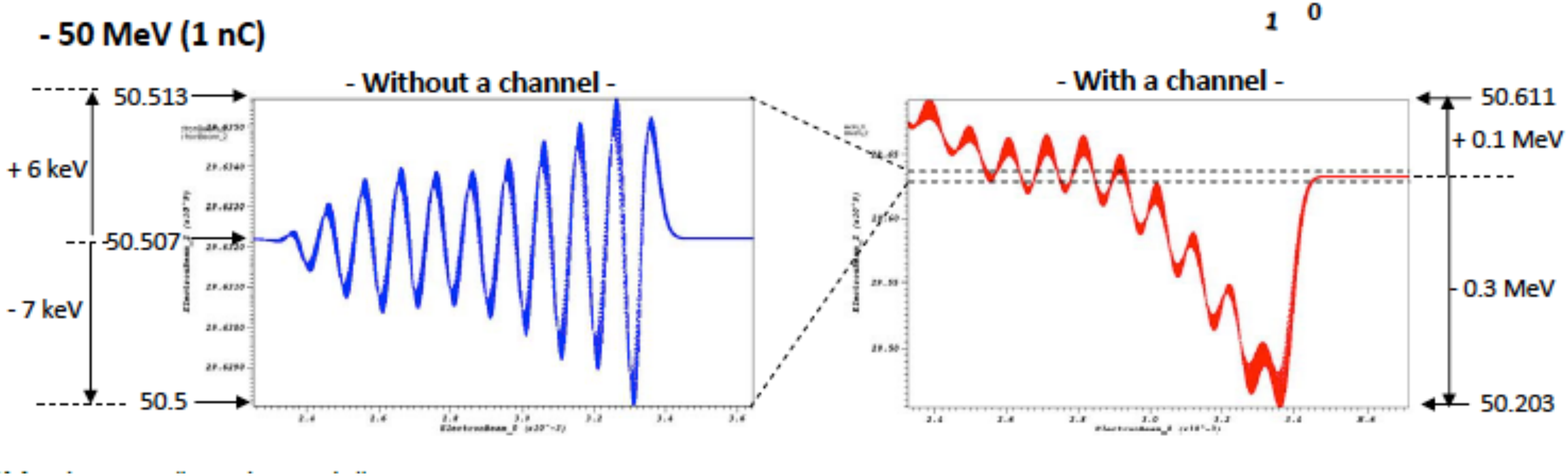
Length of Plasma $= 10\ \lambda_p$

Shin (2014)

Wakefield excitation and witness bunch that accelerated





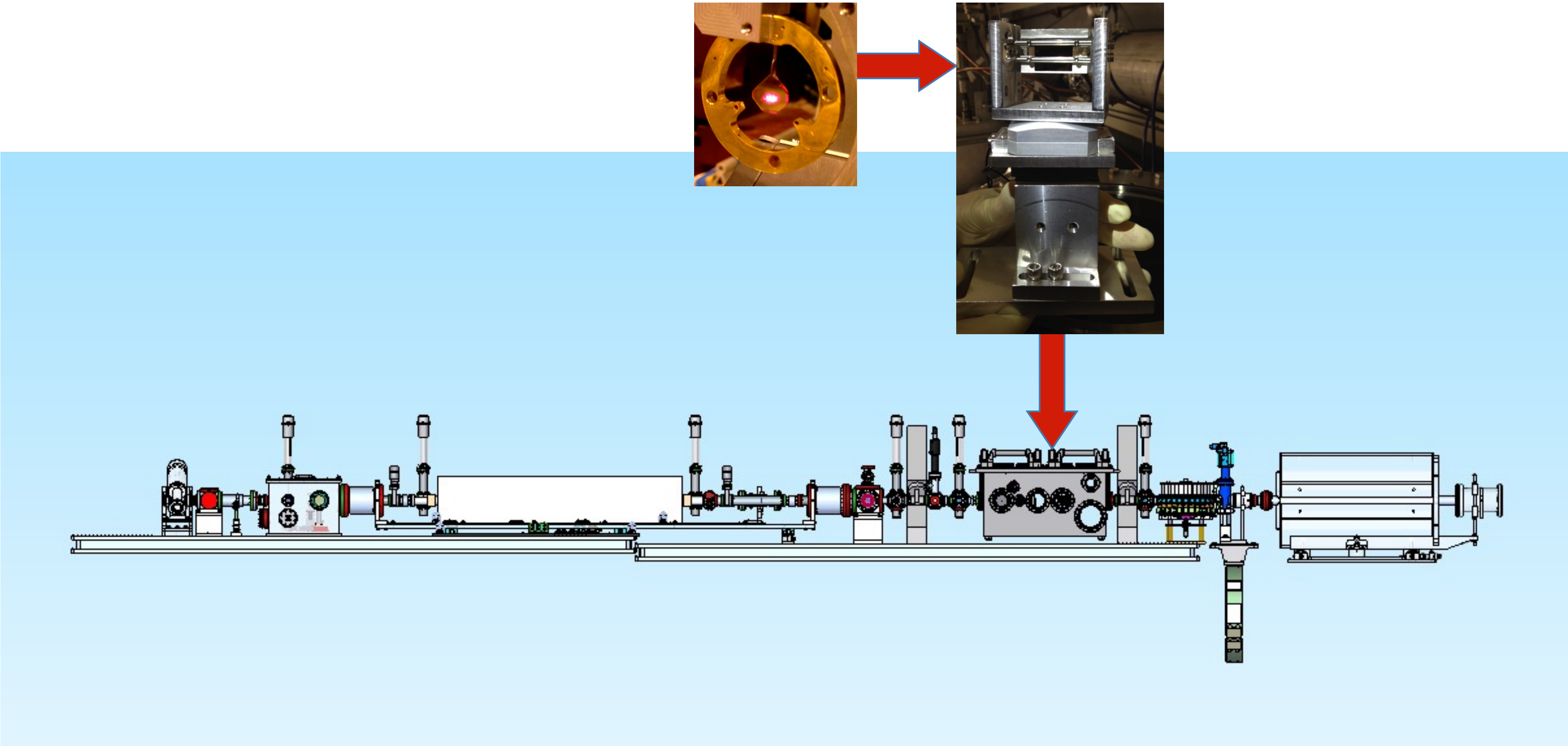


Shin (2014)

In collaboration with E212 (Uggerhoj)

Placement of Crystal

^{12}C T513 stage



Fermilab efforts on crystal 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)

Detecting neutrinos by strong laser

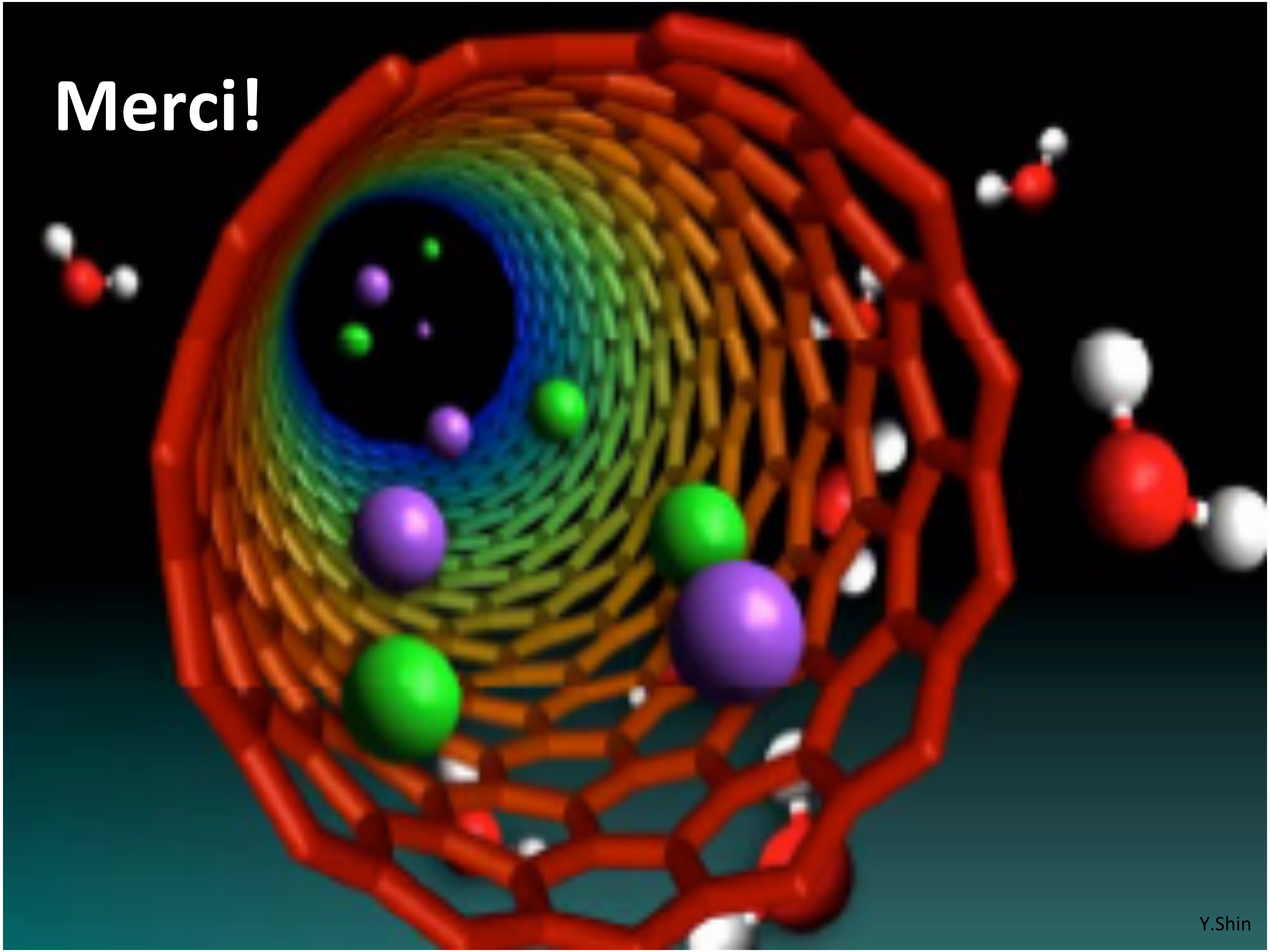
- Landau-Yang's theorem= no interaction between photons and neutrinos
- A new term (the diffractive term, i.e. the boundary sensitive wave-like, or global term) does NOT vanish for photons-neutrinos
- Contributions from this term: many orders of magnitude increase in sensitivity of detection neutrinos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

(Ishikawa, Tajima, Tobita, 2014)

Conclusions

- **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*
- Start of zeptoscience
- Vacuum self-threshold may be exceeded by this X-rays--- **self-acceleration in vacuum** (Schwinger) may be possible
- Collaboration THEXAC formed
- **Test of wakefield excitation** in crystal in FACET proposed
- More work, applications, and call for collaboration sought

- (preview) Laser can enhance the detectability of neutrinos


Merci!
Y.Shin