Plenary Talk
SPIE
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The Frontier of High Field Science

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To Fukushima: With sympathy and camaraderie

Excerpt from *'Greetings from Chair: Epochal Lasers, Epochal Year'* in ***ICUIL Newsletter*** Toshiki Tajima, ICUIL Chair

'………….As Professor S. Gales has told us, the impact of progress of nuclear physics will be felt on the way to make progress in nuclear engineering such as the nuclear waste monitoring and management. Even though Fermi has made an impressive beginning of nuclear energy and engineering, few breakthroughs that rival his have happened. This is why I have been advocating the importance of what I called 'toilet science' as opposed to the predominant conventional efforts in 'kitchen science', where the latter focuses on the upstream side of energy and matter while the former on the downstream. In other words, the former tries to understand the science how best we can clean up what the nuclear energy production brings out. …………..

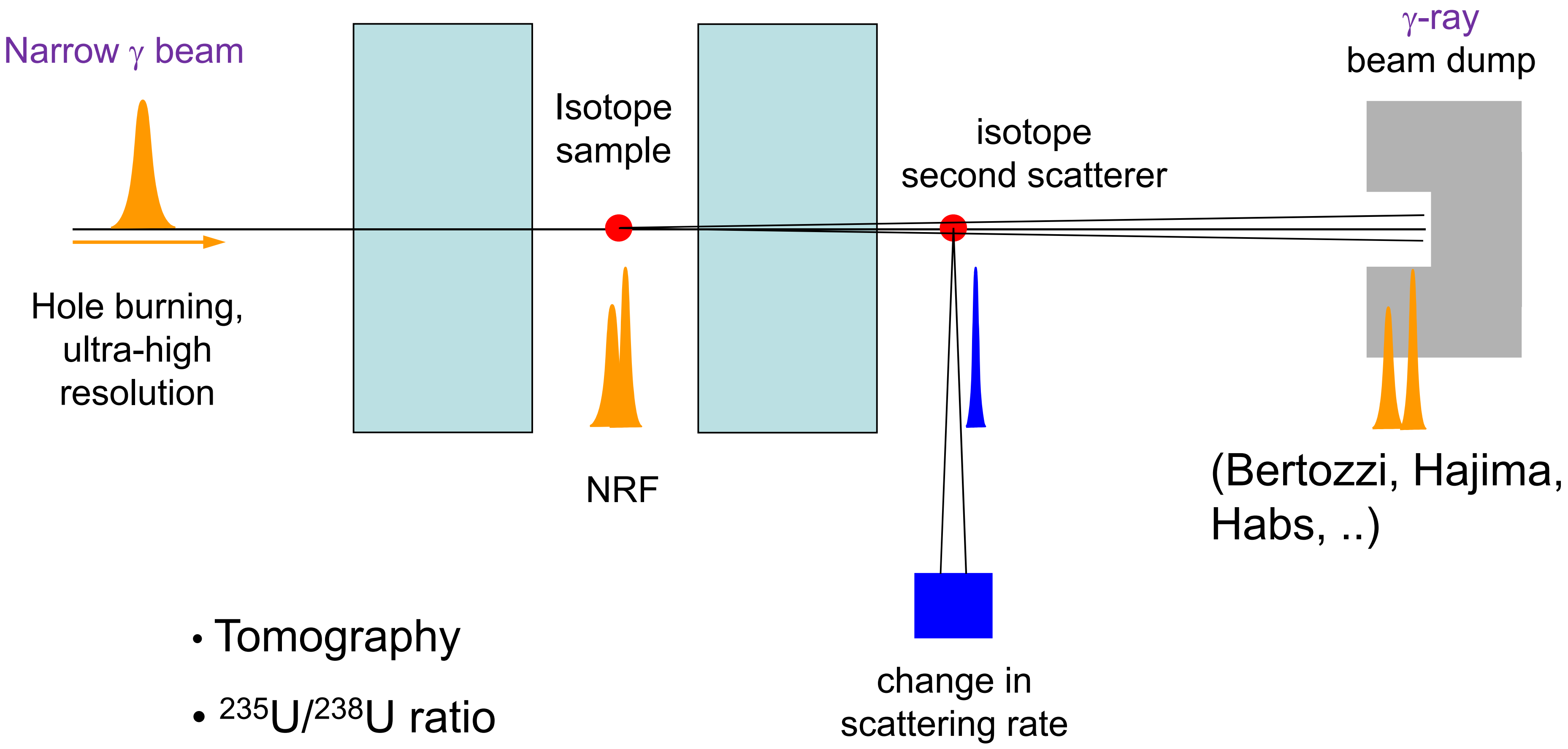
In retrospect of the recent nuclear reactor catastrophe after the most powerful earthquake in the recorded history of Japan, I believe that it is even more urgent to make further progress in 'toilet science' of nuclear energy. We are fortunate and proud that the ELI research and the intense laser research around ICUIL (and SPIE*) as a whole can make such a contribution to the society in its urgent problems.'

[1] ELI Scientific Advisory Committee Report: www.extreme-light-infrastructure.eu (March 18, 2011)

* I acknowledge **Prof. Katarina Svanberg**, President of SPIE, for her message toward this crisis.

High energy gammas and notch-detectors

for nuclear resonance fluorescence



- Tomography
- $^{235}U/^{238}U$ ratio

Gamma beam: directed, energy-specific, brilliant ← **laser** Compton (see Barty, Habs)

<u>May be employed for Fukushima reactors upon cleanup</u>

Extreme Light

-Photons with extremely high energy

example already mentioned and later
(see also Barty 8080B, Habs)

-Photons with extremely high fields (and coherence)

main topic today here (see also 8075, 8079A, 8079B, 8080A, 8080B)

Extreme Light Infrastructure

(G. Mourou, L. Giesen)

Czech

Hungary

Romania

…….

Content

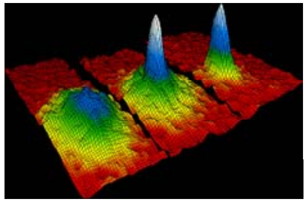
1. Ever higher intensity lasers
2. Ultrafast optics toward attosecond science
3. How can we reduce the pulse length?
   Answer---- intensity!
4. '*Intensity - Pulse Duration Conjecture*'
5. Examples of attosecond pulses and beyond
6. Confluence of ultrafast optics
   and high field science
7. Atom streaking in as → vacuum streaking in zs
8. Attosecond metrology of
   γ signals at the energy frontier

Energy frontier ← High field science, high intensity laser

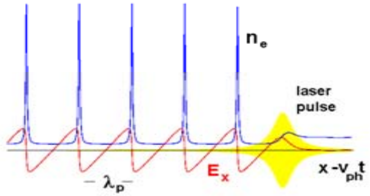
relativistic optics: *relativistic coherence*

cf. quantum optics: *quantum coherence*

Quantum optics
Cold Atoms
feV-neV



1eV



Relativistic optics
GeV-TeV

2010 ←→ 2010

2010

↓

(see also Session 8072B)

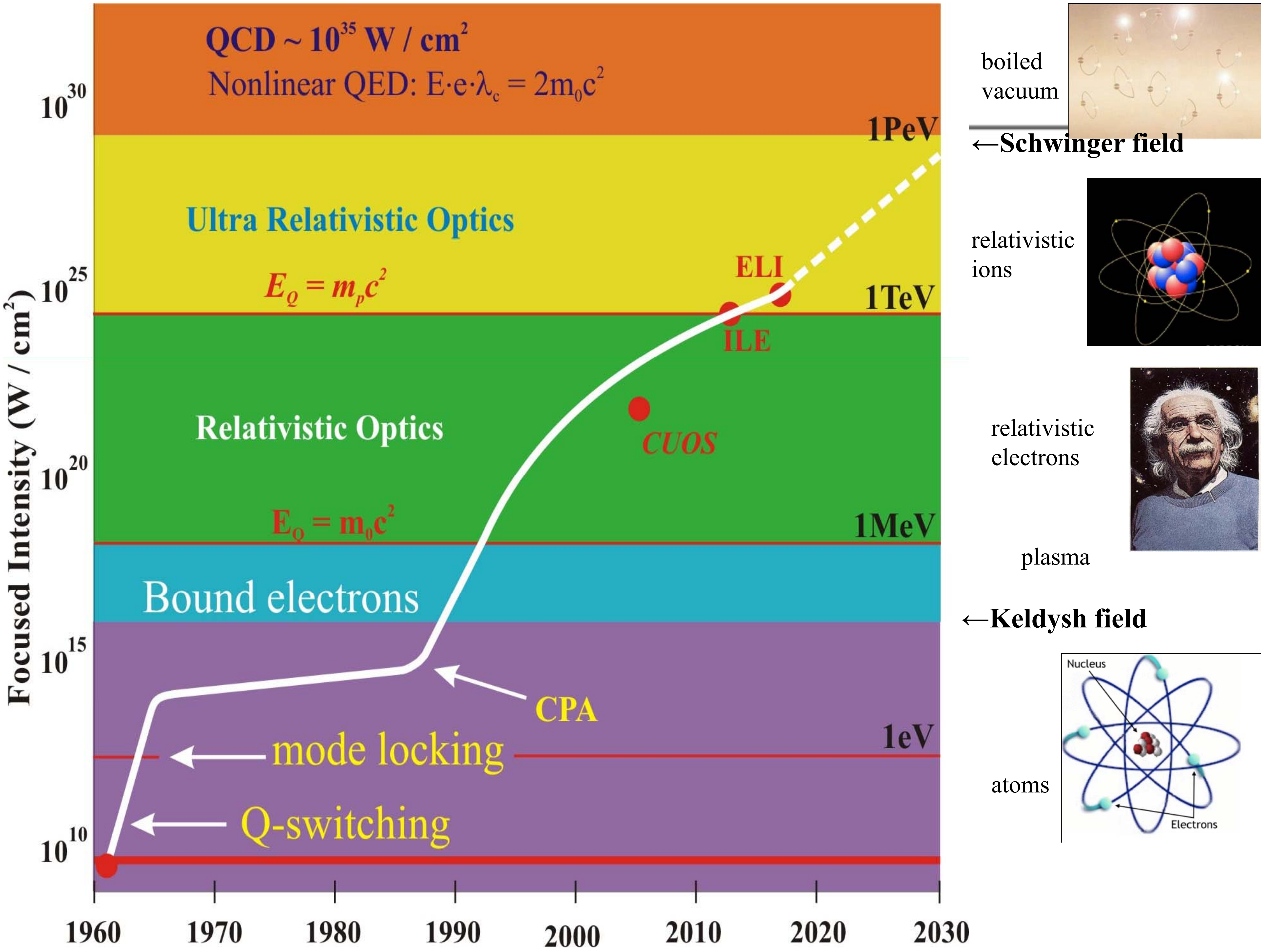
Cohen-Tannoudji,Chu, Ketterle,…

1960

2010

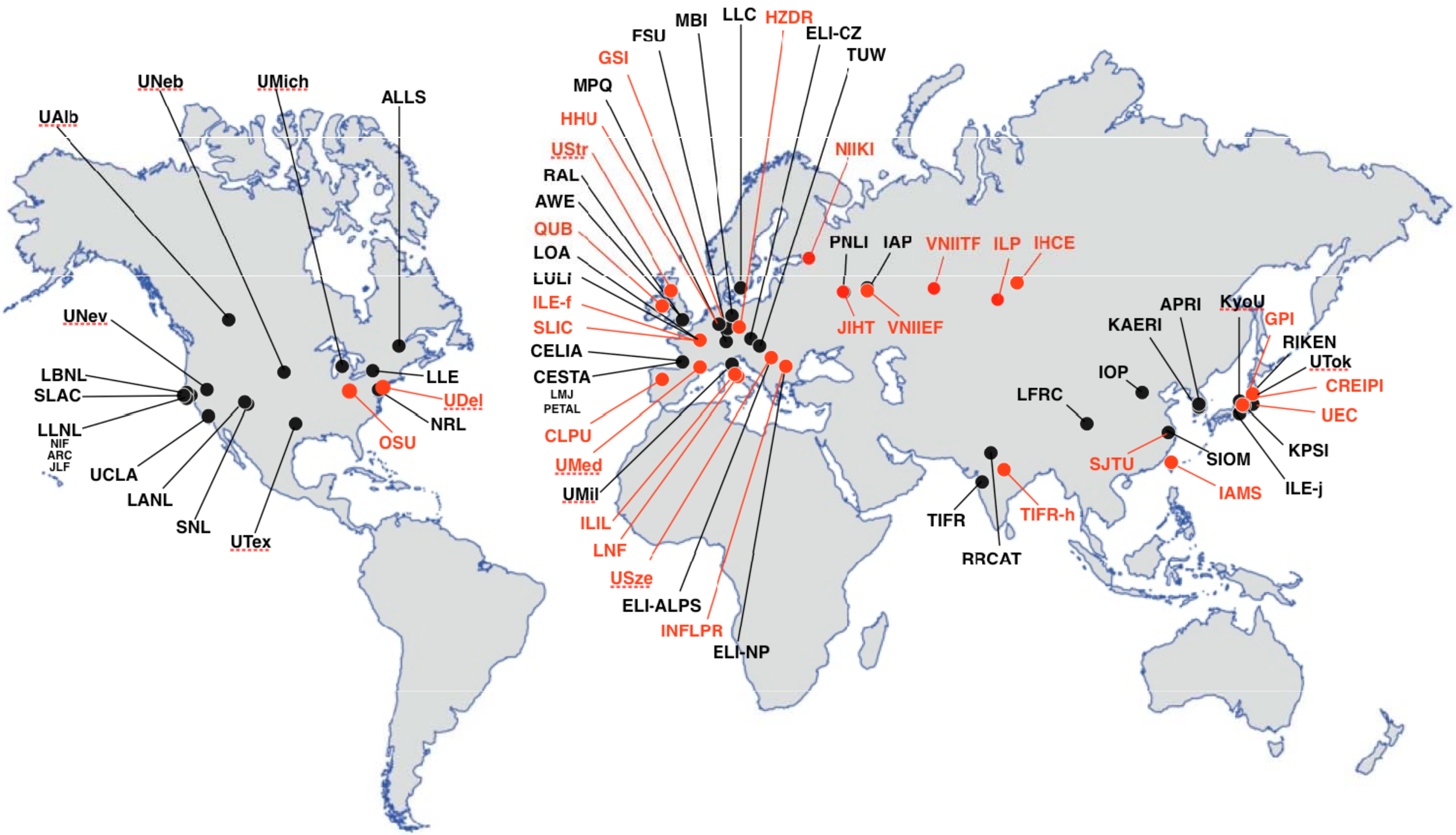
Relativistic Optics, RMP, Mourou (2006)

High field science ⟷ **High energy Physics (fundamental physics)**



QCD ~ 10^{35} W / cm^2
Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$
Ultra Relativistic Optics
$E_Q = m_pc^2$
Relativistic Optics
$E_Q = m_0c^2$
Bound electrons
mode locking
Q-switching
CPA
CUOS
ILE
ELI
1PeV
1TeV
1MeV
1eV
Focused Intensity (W / cm^2)
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
1960
1970
1980
1990
2000
2010
2020
2030
boiled vacuum
←Schwinger field
relativistic ions
relativistic electrons
plasma
←Keldysh field
atoms
Nucleus
Electrons

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities



(ICUIL, Barty)

CPJ Barty 101117

Intensification of Laser

$$I = J/\tau$$

2 paths:

#1 : increase the laser energy
(or fluence *J*); *the larger, the better*

#2 : decrease the laser pulse length τ;
the shorter, the better

Does τ = *J*/*I* hold?

To reduce τ

From trivial statement of $I = J/\tau$

↓

The nontrivial assertion:

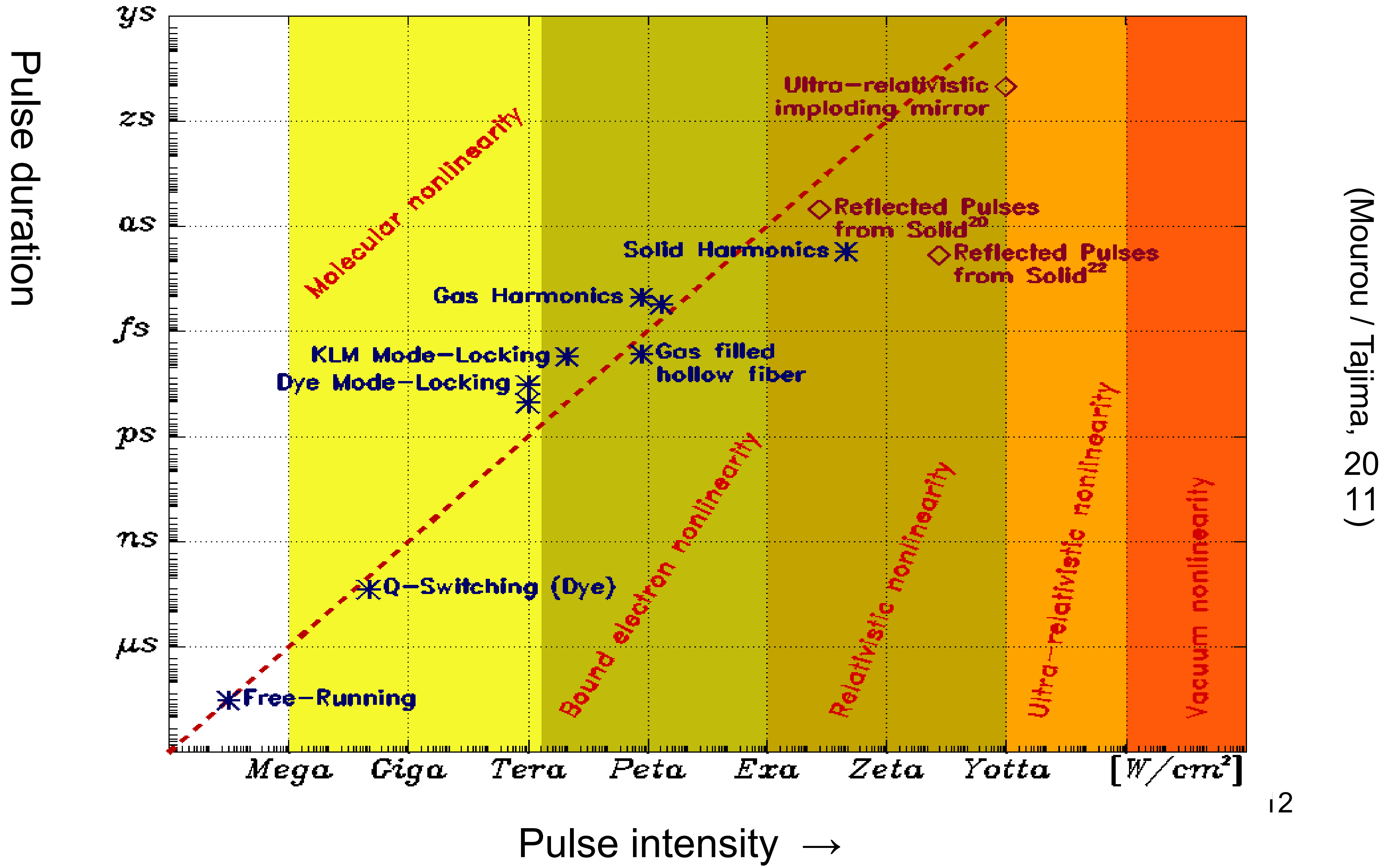
"***In order to compress the pulse further, we need to increase the intensity of laser***"

Is this true?

The Conjecture

(← physics: "Matter is nonlinear"

"The more rigid nonlinearity, the more intense to manipulate it")

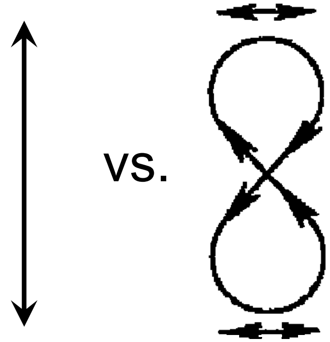


Nonlinearities in atom, plasma, and vacuum

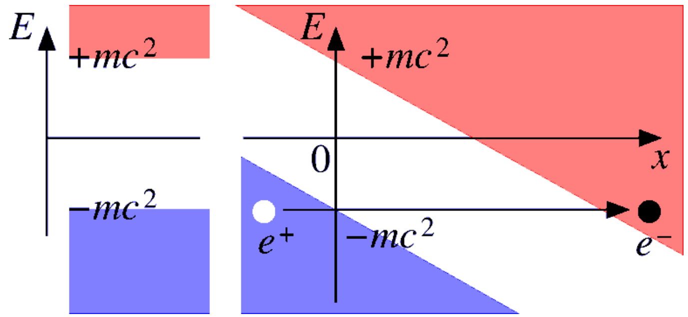
Atomic
nonlinear potential

Plasma electron
nonlinear

relativistic motion



Vacuum nonlinearity



Keldysh field for
laser atomic
ionization

Schwinger field for
vacuum breakdown

Relativistic nonlinearity under intense laser

Plasma free of binding potential , but its electron responses:

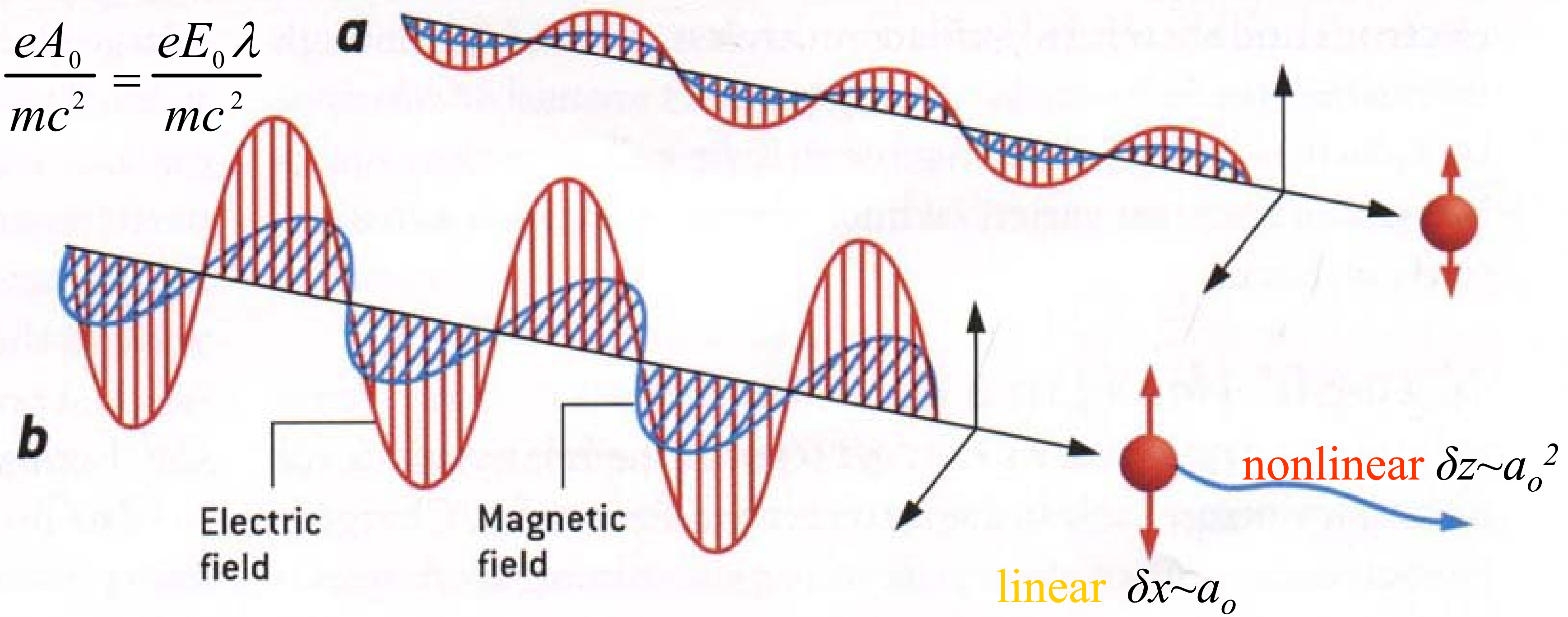
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

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

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



Pulse Progress from **fs** to **as**

Corkum and Krausz (2007)

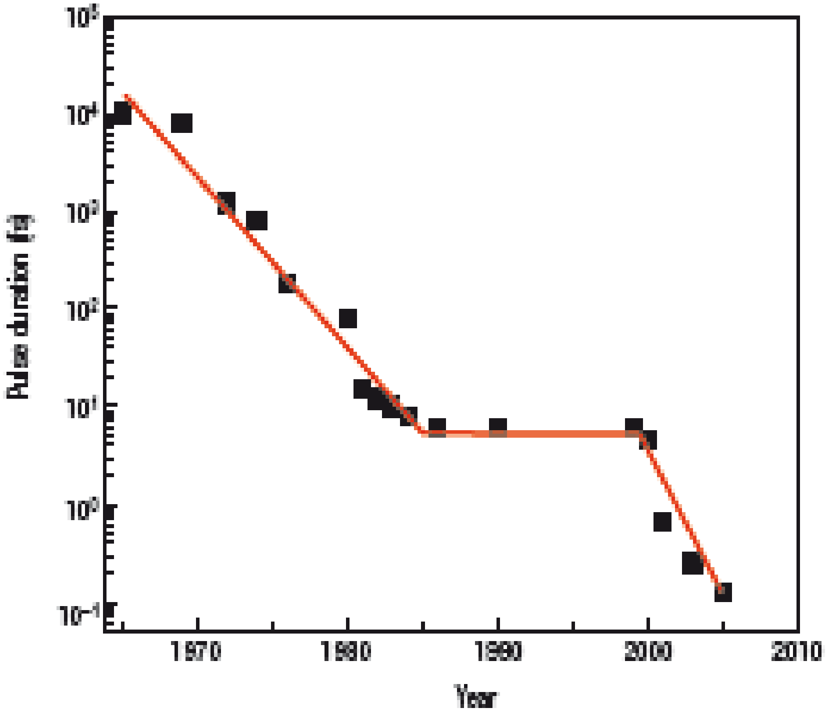


Figure 1 Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1964 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making even shorter laser pulses. However, at 6 fs (three periods of light), a radically different technology was needed. Its development took 15 years. Now attosecond technology is providing radically new tools for science and is yet again opening new fields for

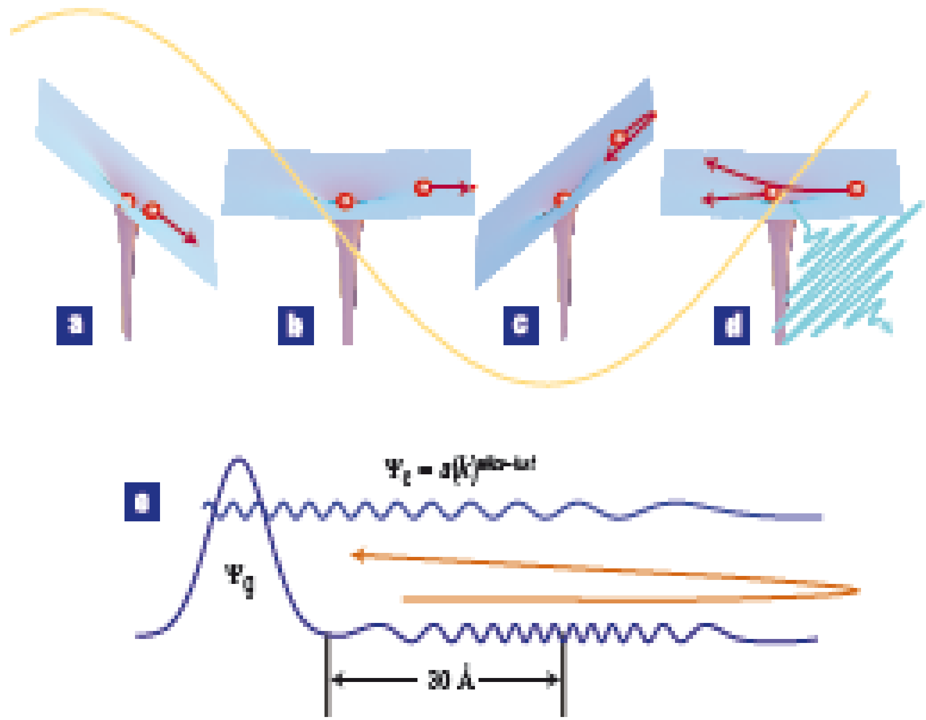
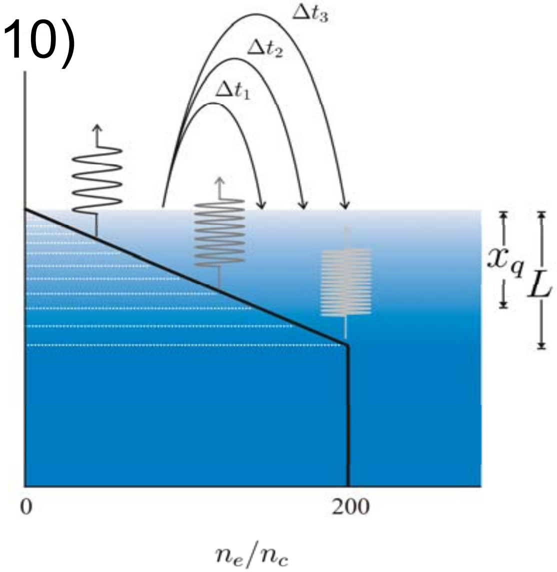
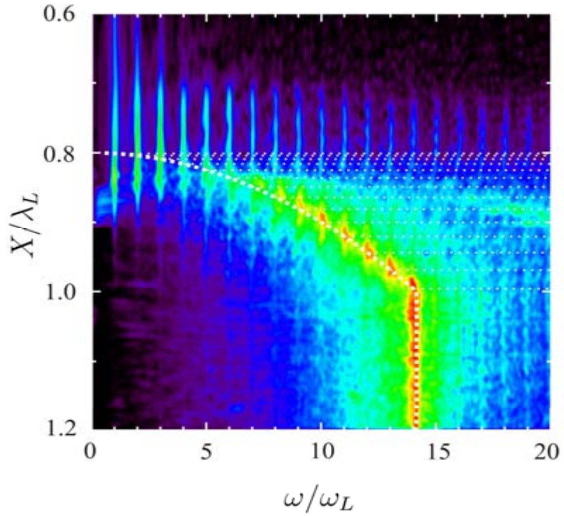


Figure 2 Creating an attosecond pulse. **a–d**, An intense femtosecond near-infrared or visible (henceforth: optical) pulse (shown in yellow) extracts an electron wavepacket from an atom or molecule. For ionization in such a strong field (**a**), Newton's equations of motion give a relatively good description of the response of the electron. Initially, the electron is pulled away from the atom (**a**, **b**), but after the field reverses, the electron is driven back (**c**) where it can 'recollide' during a small fraction of the laser oscillation cycle (**d**). The parent ion sees an attosecond electron pulse. This

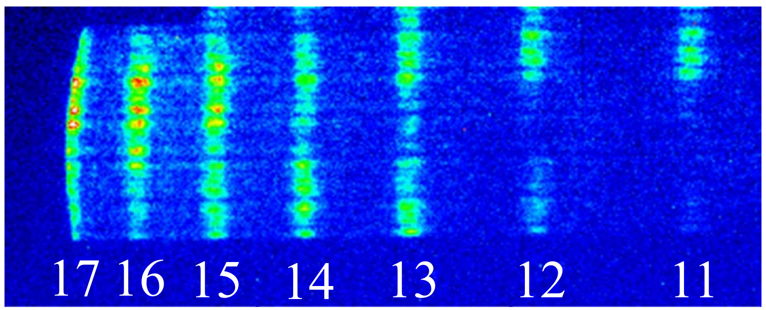
The Coherent Wake Emission

(R. Hoerlein, 2010)



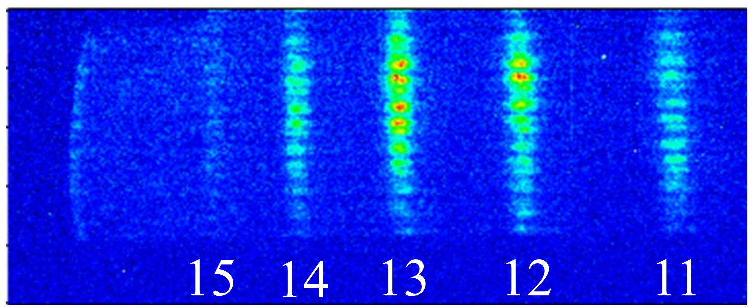


Glass Target (Density ≈2.6 g/cm^3):



U. Teubner, *et al.*, PRL, **92**, 185001 (2004)

Plexiglass Target (Density ≈1.3 g/cm^3):

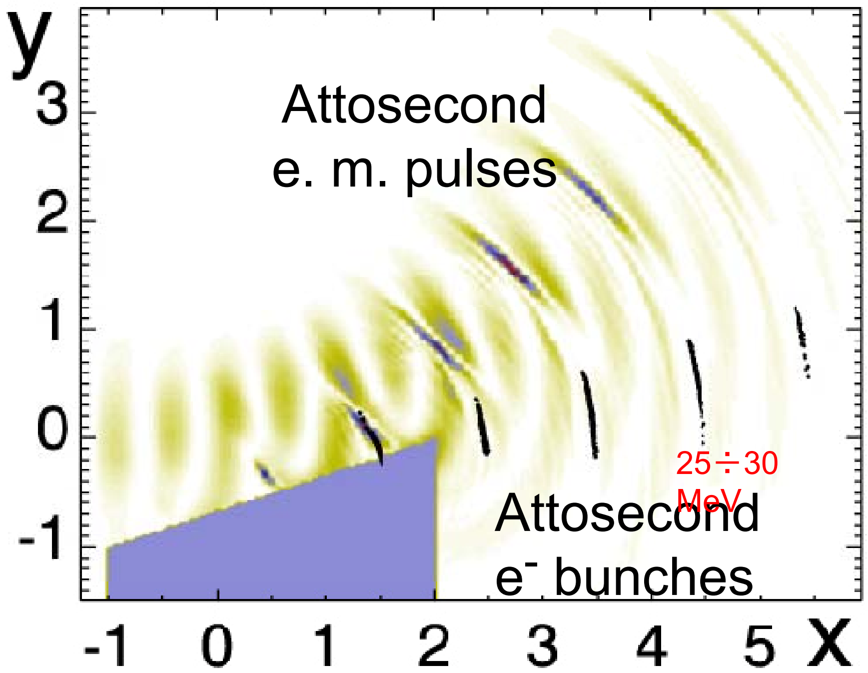


F. Quéré, *et al.*, PRL, **96**, 125004 (2006)

attosecond pulse generation

- compress the reflected radiation into attosecond pulses and
- inherit a peaked density distribution.
- Complete modulation of e.m. field occurs. This is relativistic engineering

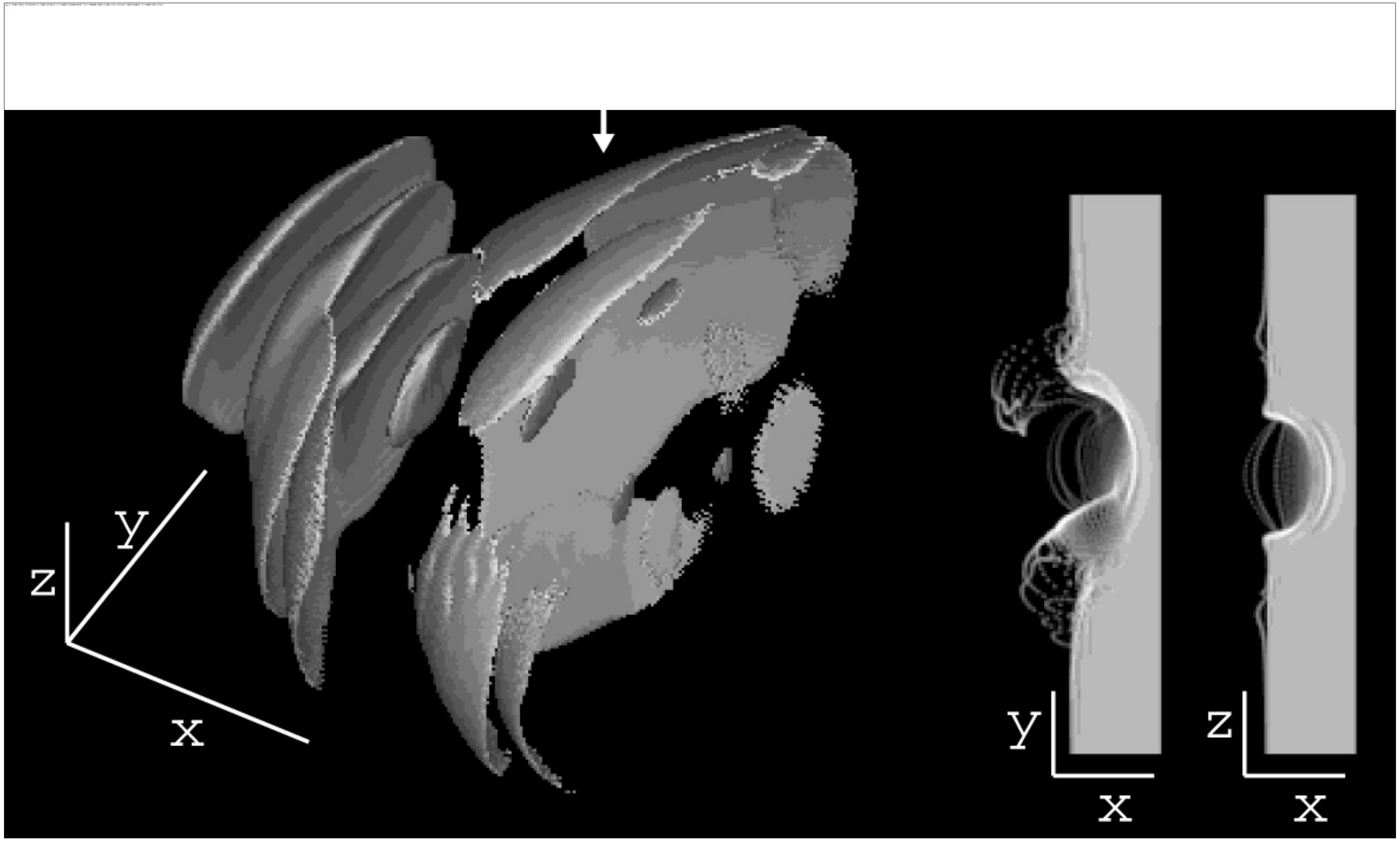
Efficiency of attosecond phenomena: ~15% converted to attosecond pulses, ~15% to electron bunches.



Naumova *et al*.(2004)

a=10, 15fs, f/1, n=25n_{cr}

Isolated attosecond EM pulses
3D simulation



Relativistic oscillating mirror of solid surface

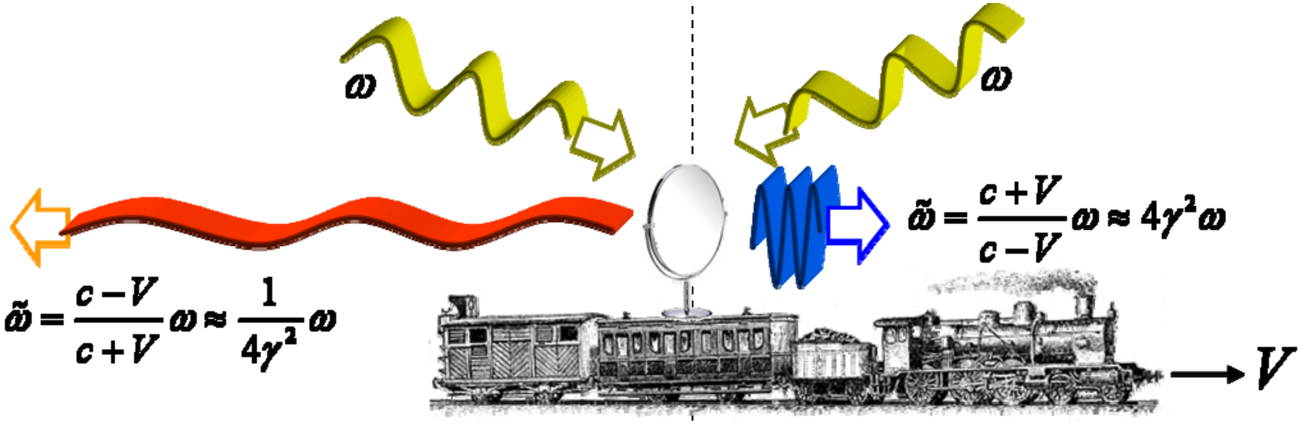
Bulanov (1994)

Nees (2005)

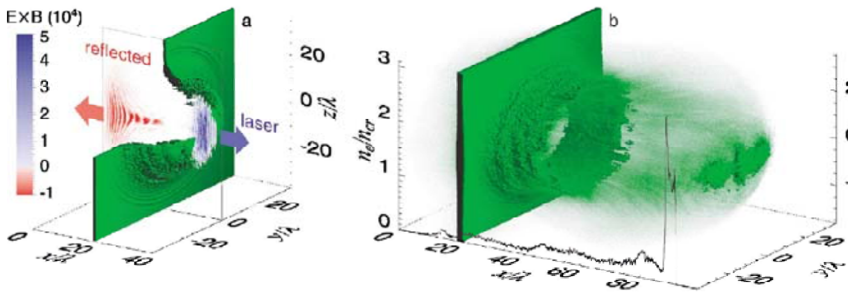
$a_0=3$, $\tau=5fs$, f/1, $n=1.5n_{cr}$

Relativistic flying mirror and shorter pulses

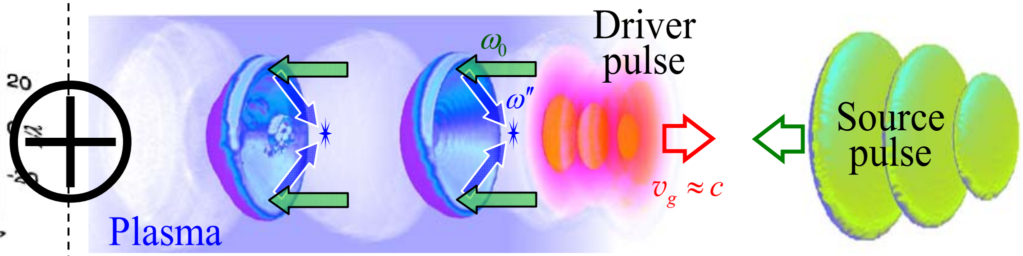
Esirkepov (2009) --- Einstein's flying mirror made of **LWFA**



Laser Piston

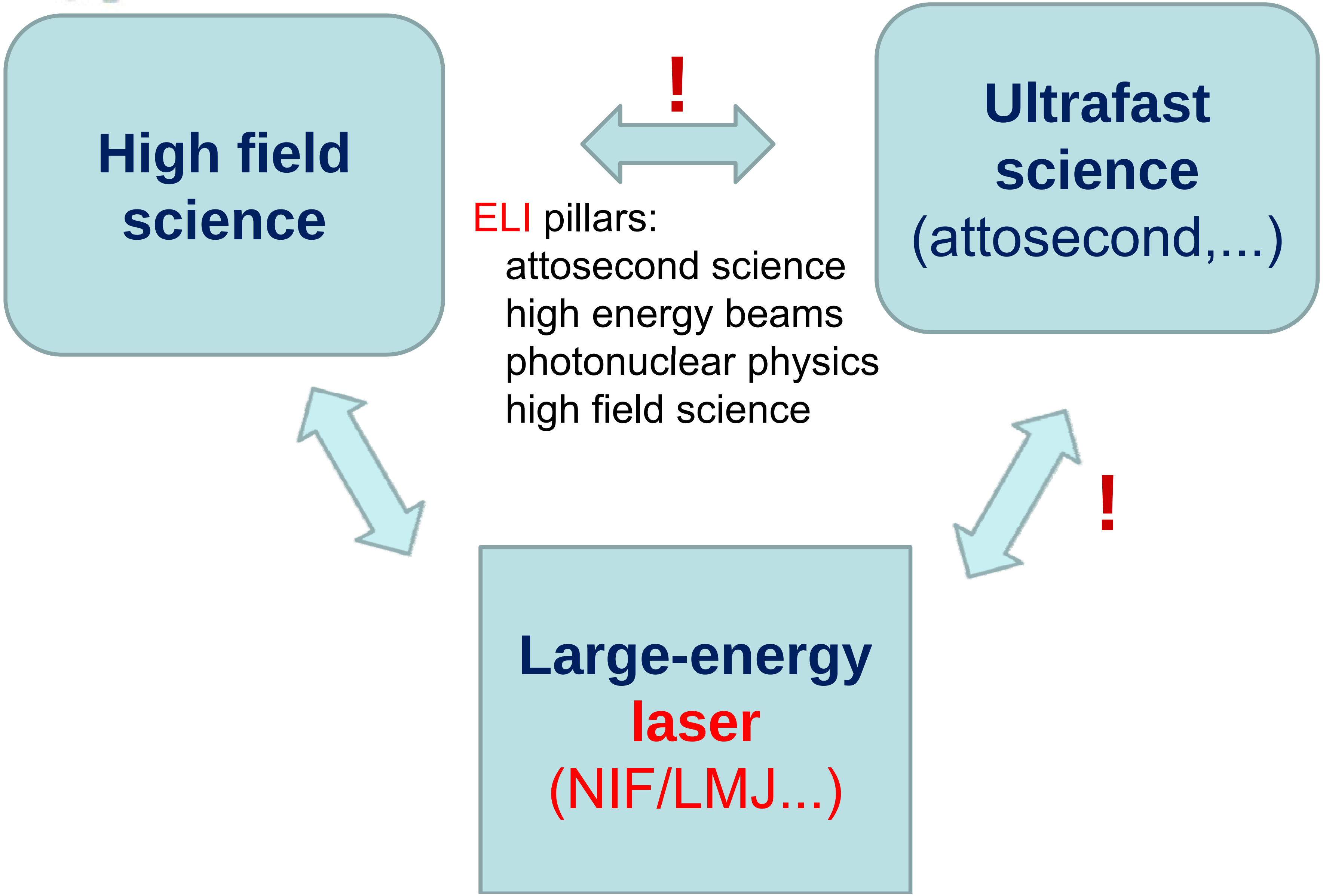


Flying Mirror (LWFA)

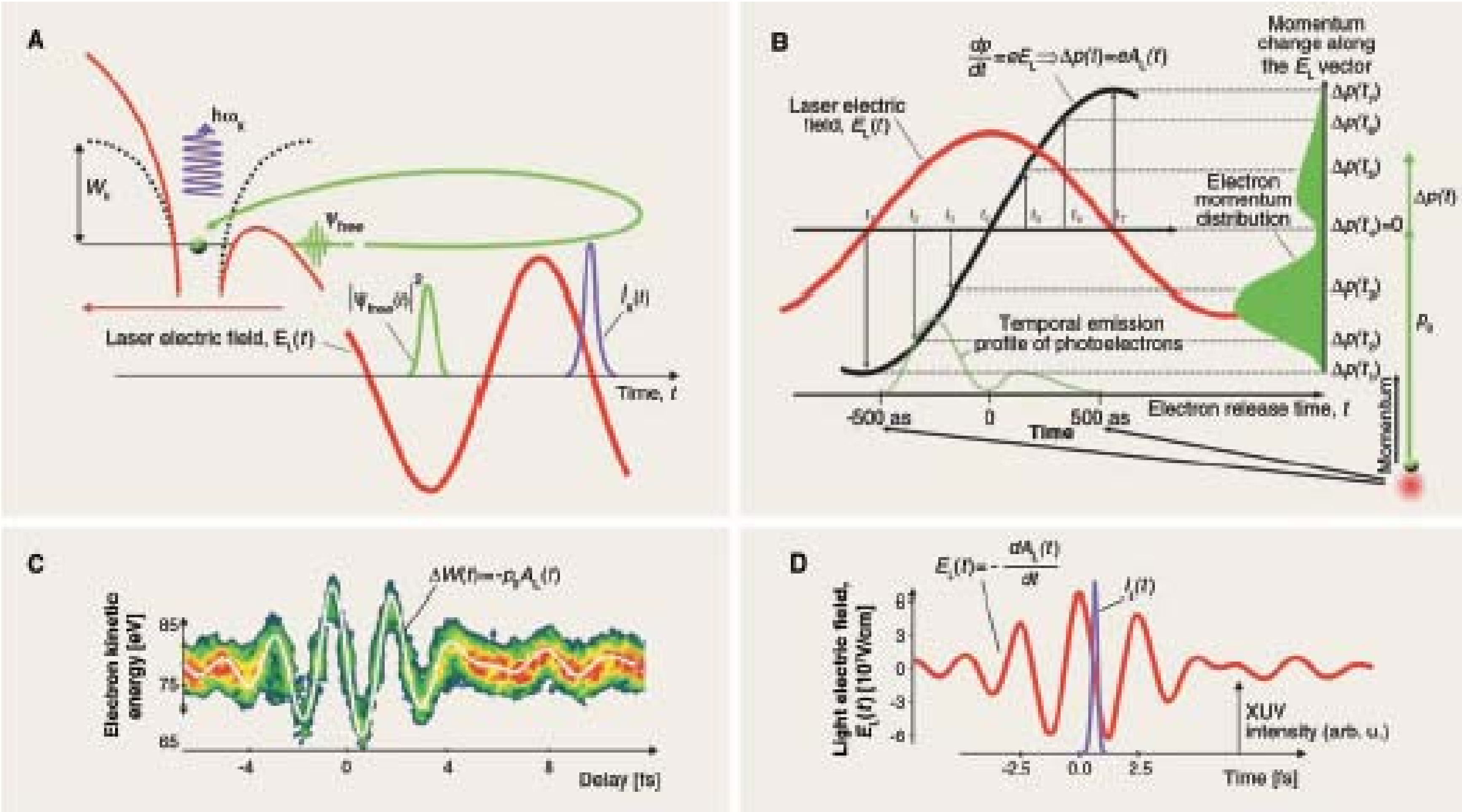


(see also Tajima, Wednesday)

Ultrafast science ← High field science, Large-energy laser



Streaking of **atomic** electron
Keldysh field and beyond



E. Goulielmakis et al (2008)

Self-focusing in air / vacuum

Critical power for self-focusing in matter /plasma / vacuum:

χ_3 (air) nonlinearity

$$P_{cr} = \lambda^2/(2\pi n_0 n_2) \sim \text{GW}$$

relativistic plasma nonlinearity

$$P_{cr} = mc^5/e^2(\omega/\omega_p)^2 \sim 17\ (\omega/\omega_p)^2\ \text{GW}$$

vacuum nonlinearity

$$P_{cr} = (90/28)\, c\, E_S^2 \lambda^2/\alpha \sim 10^{15}\ (\lambda/\lambda_{1\mu})^2\ \text{GW}$$

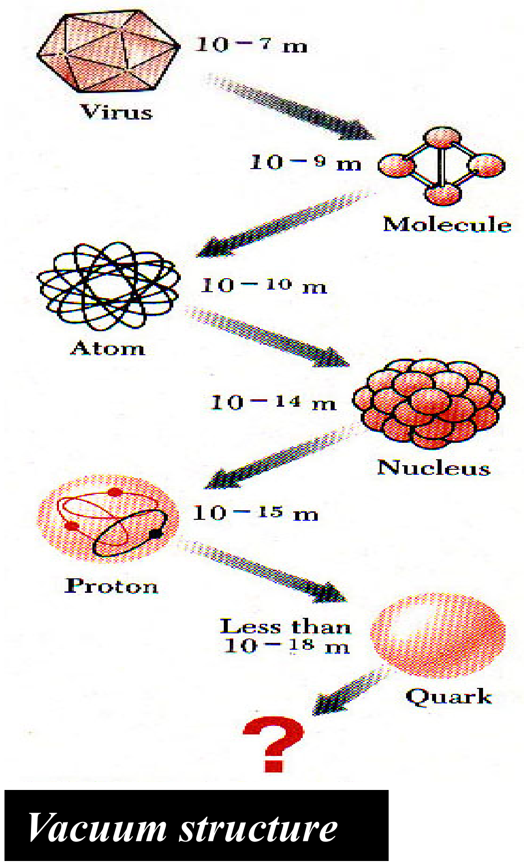
e.g. X-ray of 10keV, $P_{cr} \sim$ 10PW

‘ELI Long-term Ambition’ =

*Studying the **Atomic** Structure to the **Vacuum** Structure*

(Mourou)

(see also 8080B)



Keldysh field

Srchwinger intensity / Keldysh intensity $= \alpha^{-6} \sim 10^{14}$

Vacuum self-focusing /χ_3 self-focusing power $\sim \alpha^{-6} \sim 10^{15}$

Schwinger field

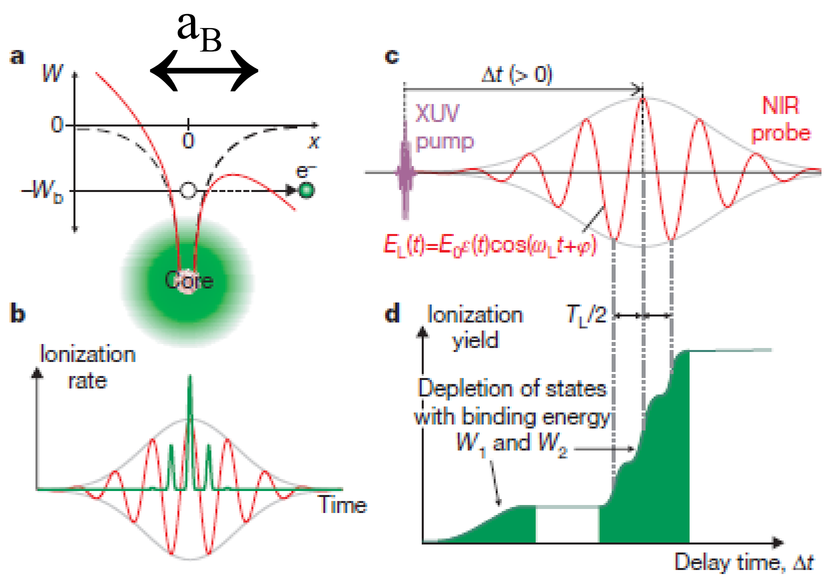
Does the atomic world repeat itself in vacuum?

Streaking vacuum (1)

(from atomic physics to vacuum physics)

atom

Uiberacker et al. (2007)



XUV photon ionization

Laser streaking

→ attosecond dynamics

vacuum

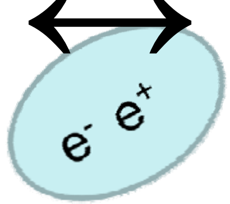
Gamma photon 'ionization'

XUV streaking

→zeptosecond dynamics

size

$\lambda_C = \alpha\, a_B$



depth of potential

$\Phi = \alpha^{-2} W_B$

$$R_{e^+e^-} \propto \exp\left(-\left(\frac{8}{3}\right)\left(\frac{m}{\omega}\right)\left(\frac{E_S}{E}\right)\right)$$

Nikishov(1964)

Nonperturbative: $W_\parallel =$ [illegible], $W_\perp = 2W_\parallel$, $\varkappa \ll 1$. (36')

For large values of $\varkappa$ we essentially have $u \gg 1$ in the integrals (36). Using this fact, we obtain

Multiphoton: $W_\parallel =$ [illegible], $W_\perp = \frac{2}{3} W_\parallel$, $\varkappa \gg 1$. (36'')

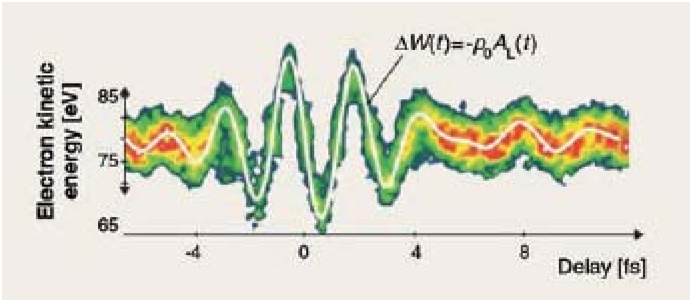
PRL 102, 150404 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

Momentum Signatures for Schwinger Pair Production in Short Laser Pulses with a Subcycle Structure

F. Hebenstreit,[1] R. Alkofer,[1] G. V. Dunne,[2] and H. Gies[3]

Streaking vacuum 2 (learning from atoms)

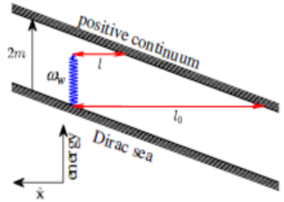
Atoms:
Keldysh field $E_K = W_B/a_B$

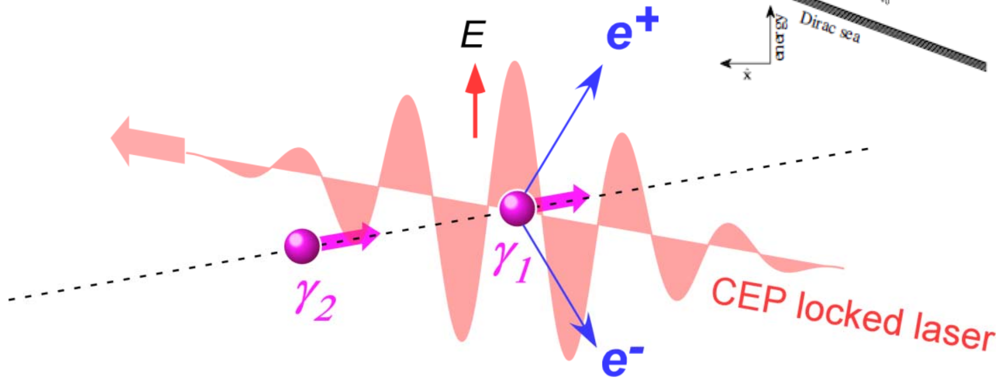


Goulielmakis(2008)

Keldysh parameter γ_K $\gamma = \frac{\omega_L \sqrt{2m W_b}}{|e| E_0}$

Vacuum:
Schwinger/Nishikov field
$$E_{SN} = E_{S\sigma}(m_\sigma c^2/\hbar\omega)$$
Scwinger field
$$E_{Se} = \alpha^{-3} E_K$$





$$\gamma_{V\sigma} = m_\sigma \omega c/eE = 1/a_0$$
where $\sigma = e$, or q (quark)

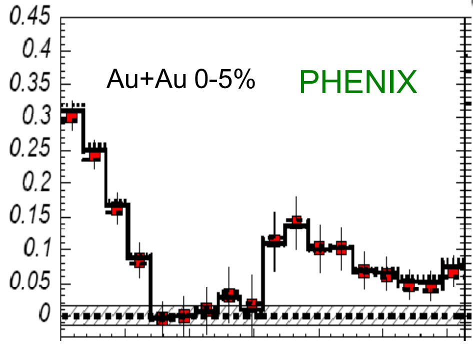
Streaking resolving power (Itatani2002; Kienberger 2004):
$$\Delta t = \sqrt{(\hbar\omega m/eA_0 p_0)} \sim \sqrt{[(\hbar\omega/\varepsilon_0)/a_0]}/\omega \sim zs$$

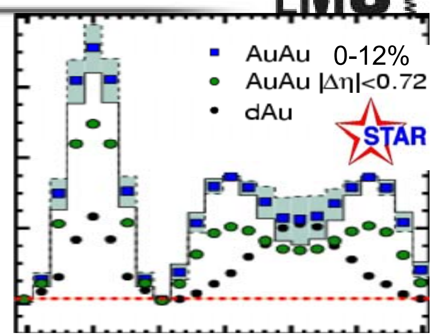
real spacetime mapping (instead of spectroscopy) of structure/dynamics of **vacuum** (QED and perhaps QCD)

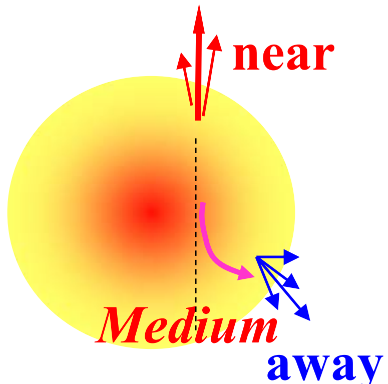
Gluon Plasma, Nuclear Wake, String Theory

J. Ulery (2007)

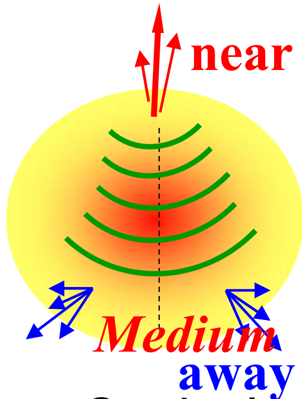
- Monojet (or jet suppression) in BNL and CERN **heavy ion collision.**
- Superstring theory (Maldacena Conjecture) on heavy ion collisions







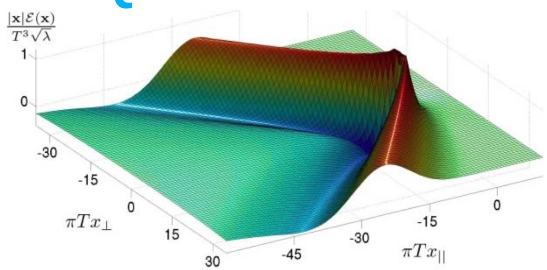
Deflected Jets



Conical

Emission

Quantum Gluon Plasma (QGP)



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

- Monojet could be caused by:

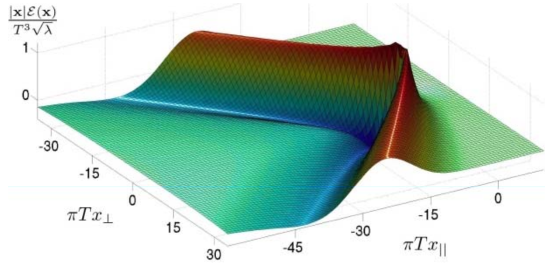
Collective deceleration of quark in the nuclear wakefield

(Homma, BNL collab2010)

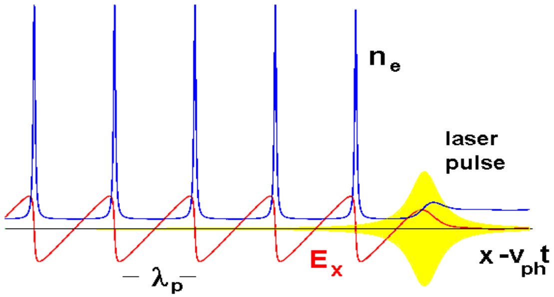
String theory sees wakefield(!?)

All particles in the medium participate = collective phenomenon

Kelvin wake



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



← relativity regularizes

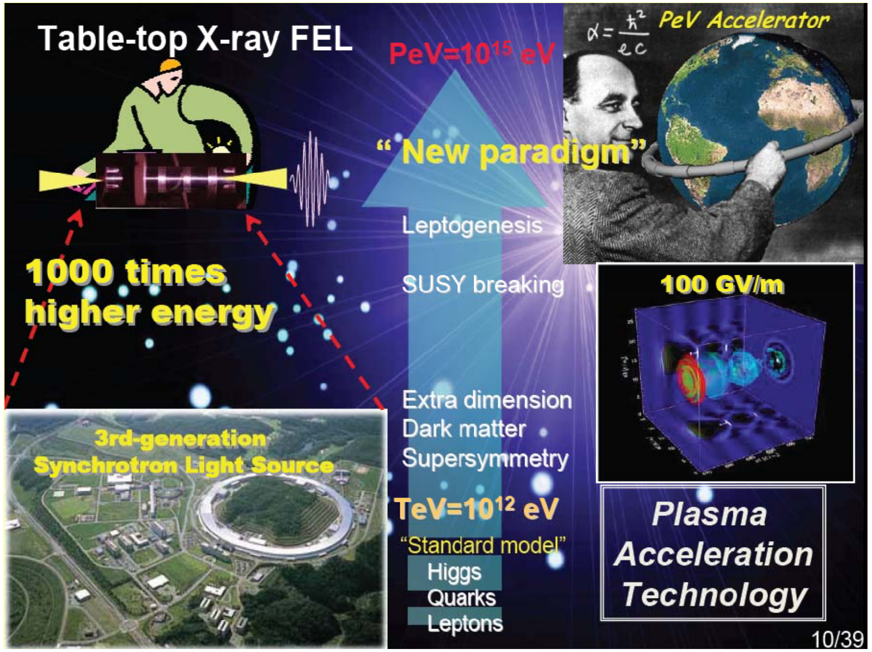
Wave **breaks** at v<c

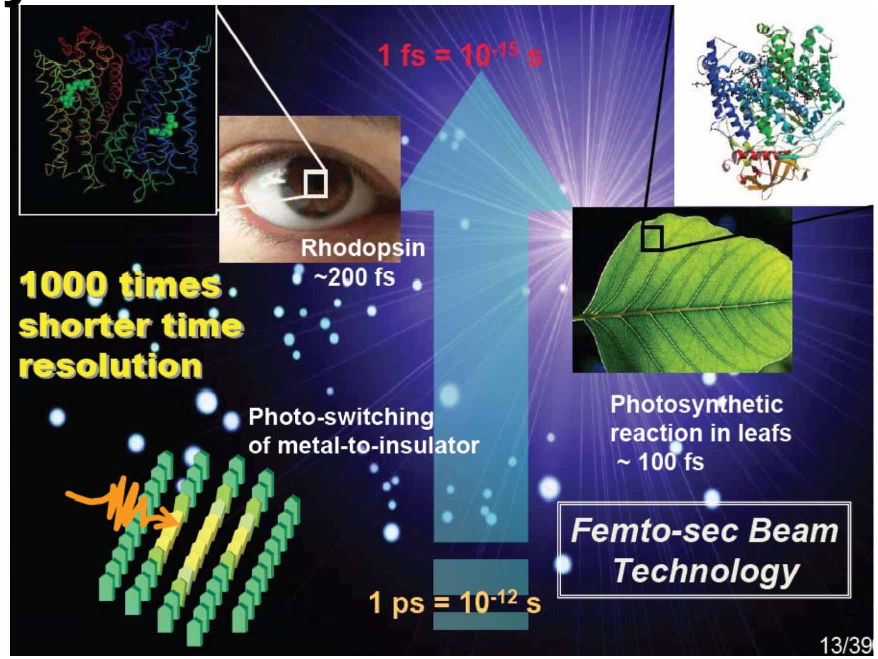
(The density cusps.
Cusp singularity) (see 8079A)

(Plasma physics vs.
superstring theory?)

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





compact, ultrastrong *a*

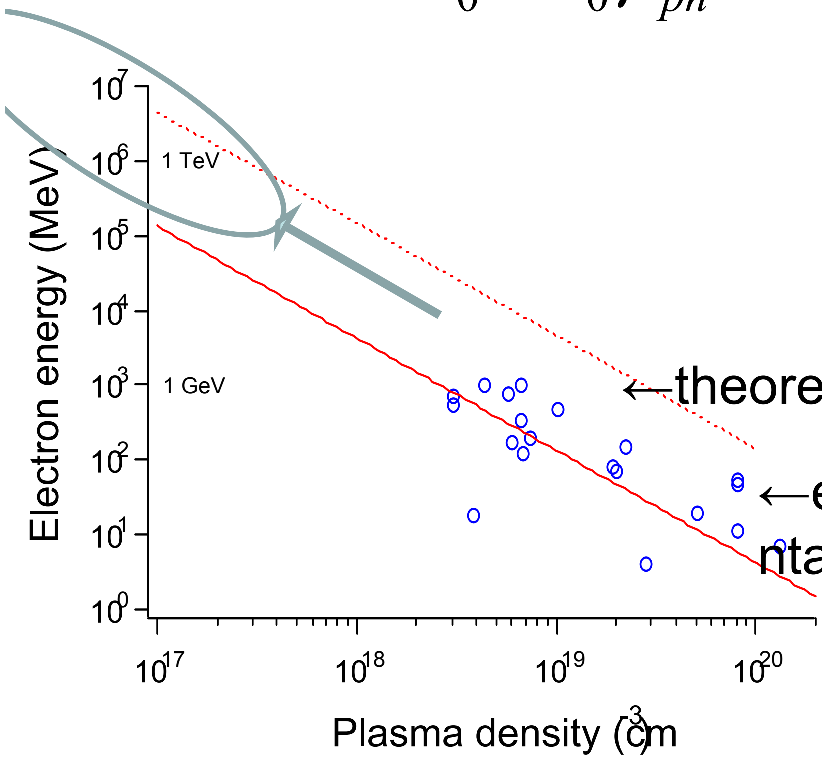
atto-, zeptosecond
(I have tried to show this)

Can we meet the challenge?

A. Suzuki @KEK(2008)

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

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

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

dephasing length

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

pump depletion length

Adopt:
NIF laser (3MJ)
$\rightarrow$ 0.7PeV
(with Kando, Teshima)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

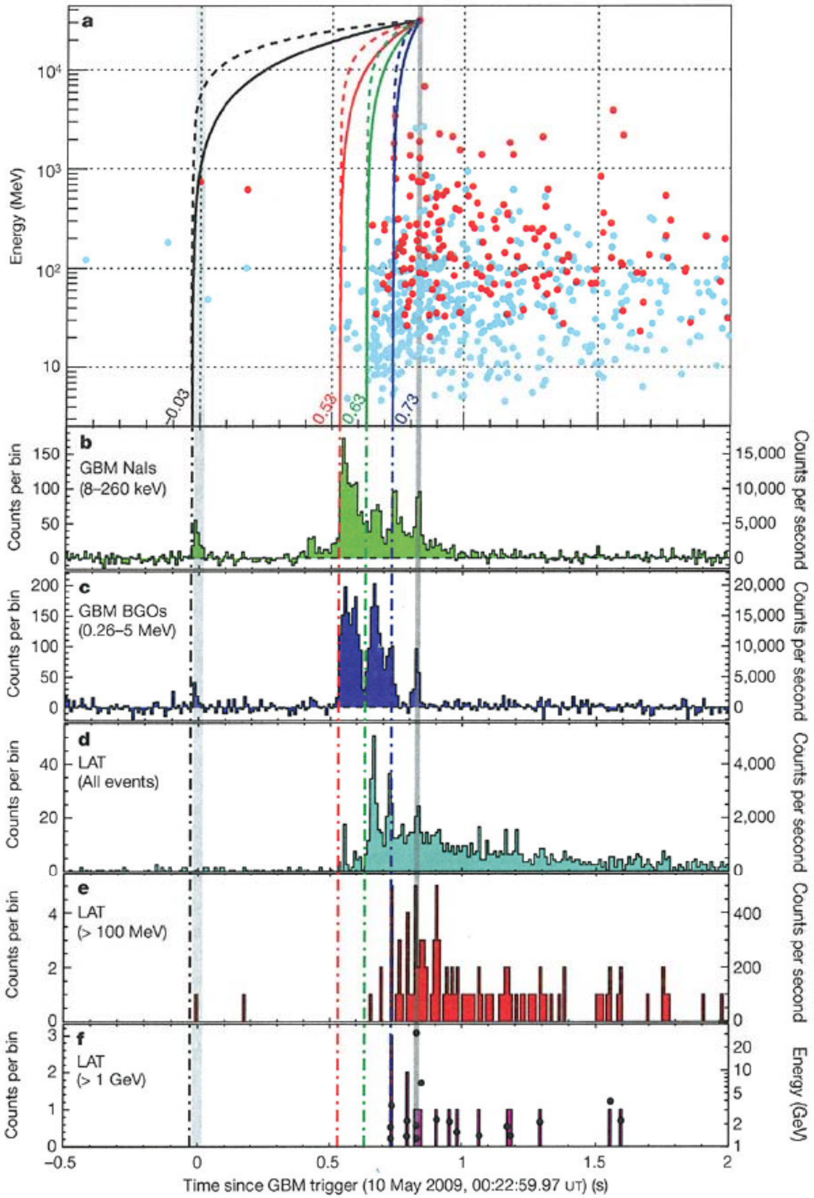


Figure 1 | Light curves of GRB 090510 at different energies. **a,** Energy lowest to highest energies. **f** also overlays energy versus arrival time for each

Energy-dependent photon speed ?

Observation of primordial

Gamma Ray Bursts (GRB)

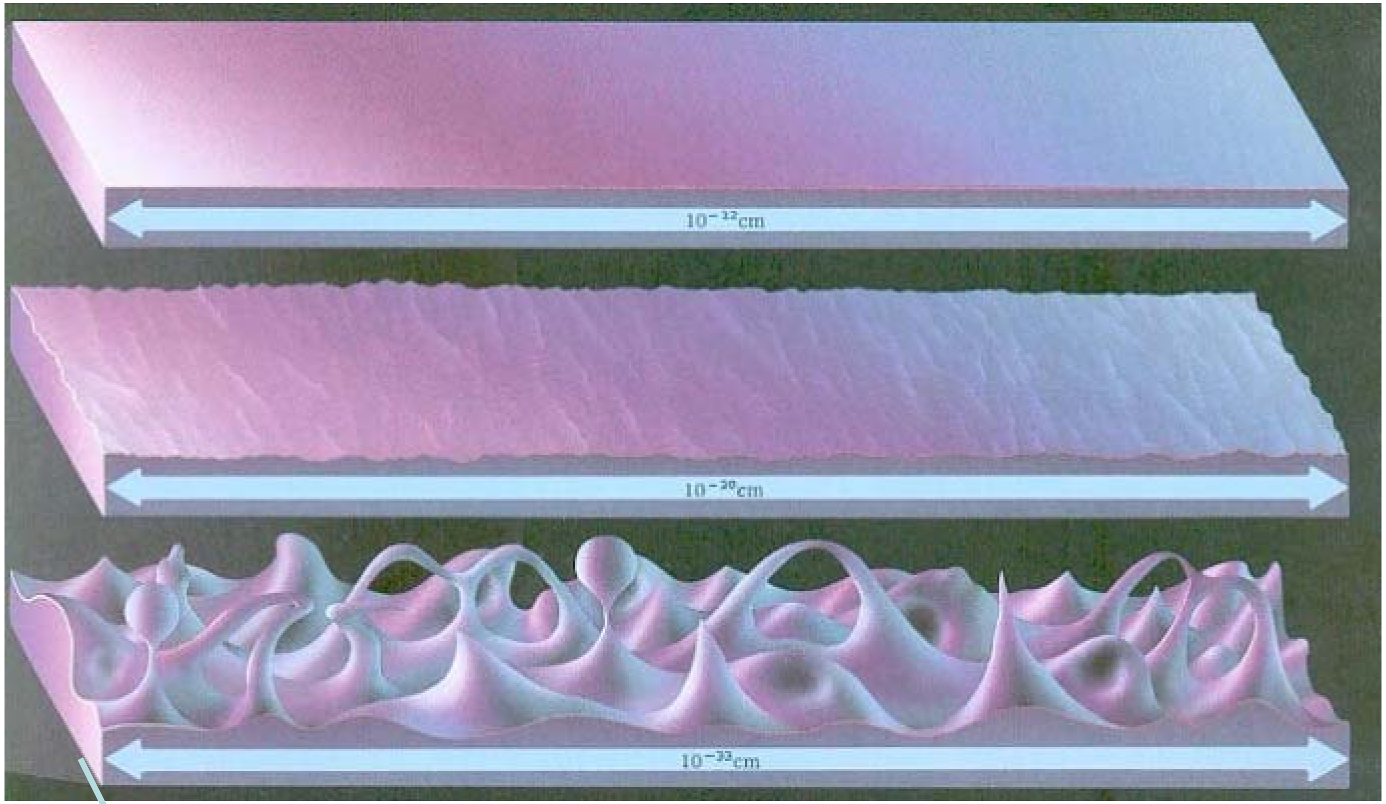
(limit is pushed up close to Planck mass)

Lab PeV γ (from e-) can explore this with control

Feel vacuum texture: PeV energy γ

Laser acceleration → controlled laboratory test to see quantum gravity texture on photon propagation (Special Theory of Relativity: c_0)

$c < c_0$



Coarser, lower energy texture

Finer, higher energy texture

← (0.1PeV)

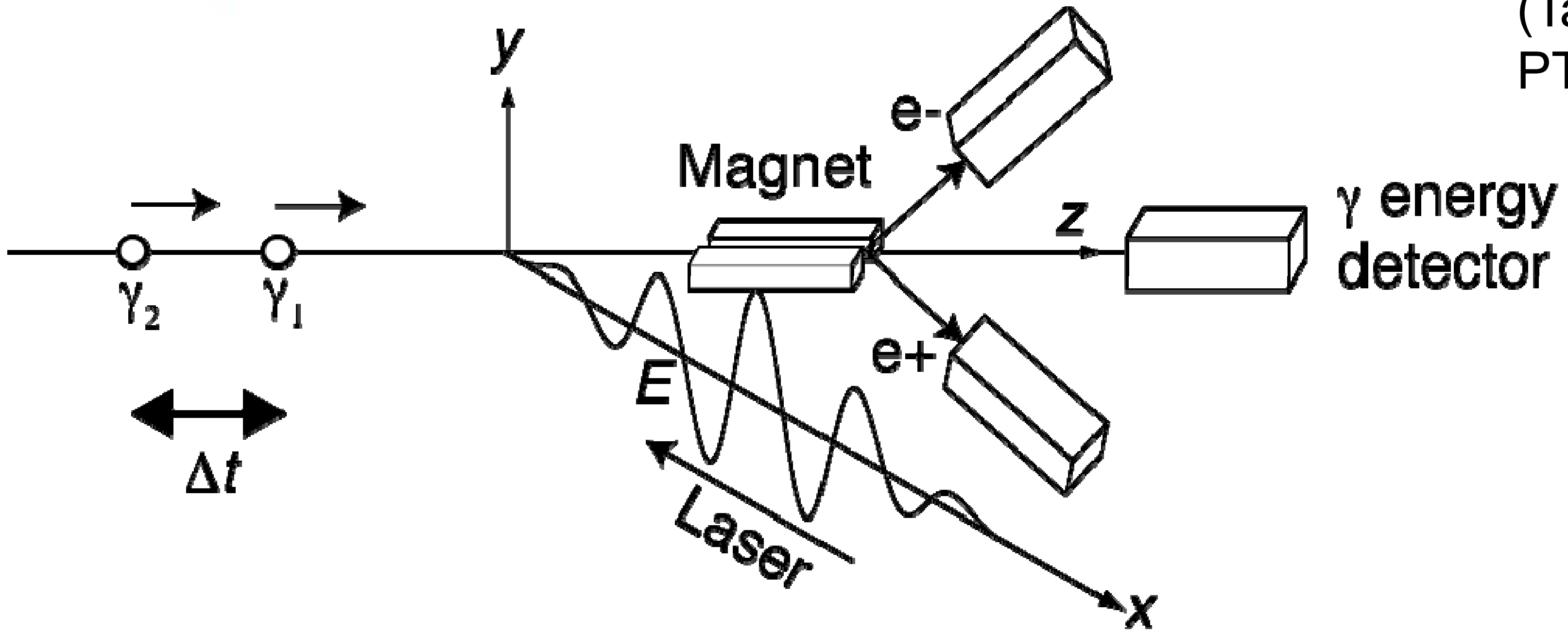
←(1PeV : fs behind)

1km

PeV γ (converted from e^-)

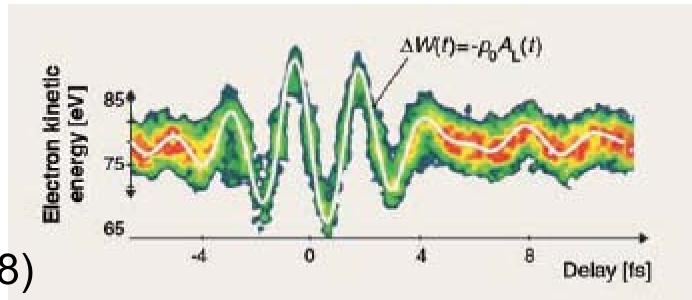
Attosecond Metrology of PeV γ Arrivals

(Tajima, Kando, PTP, 2011)



[γ-assisted Schwinger process--see p.27]

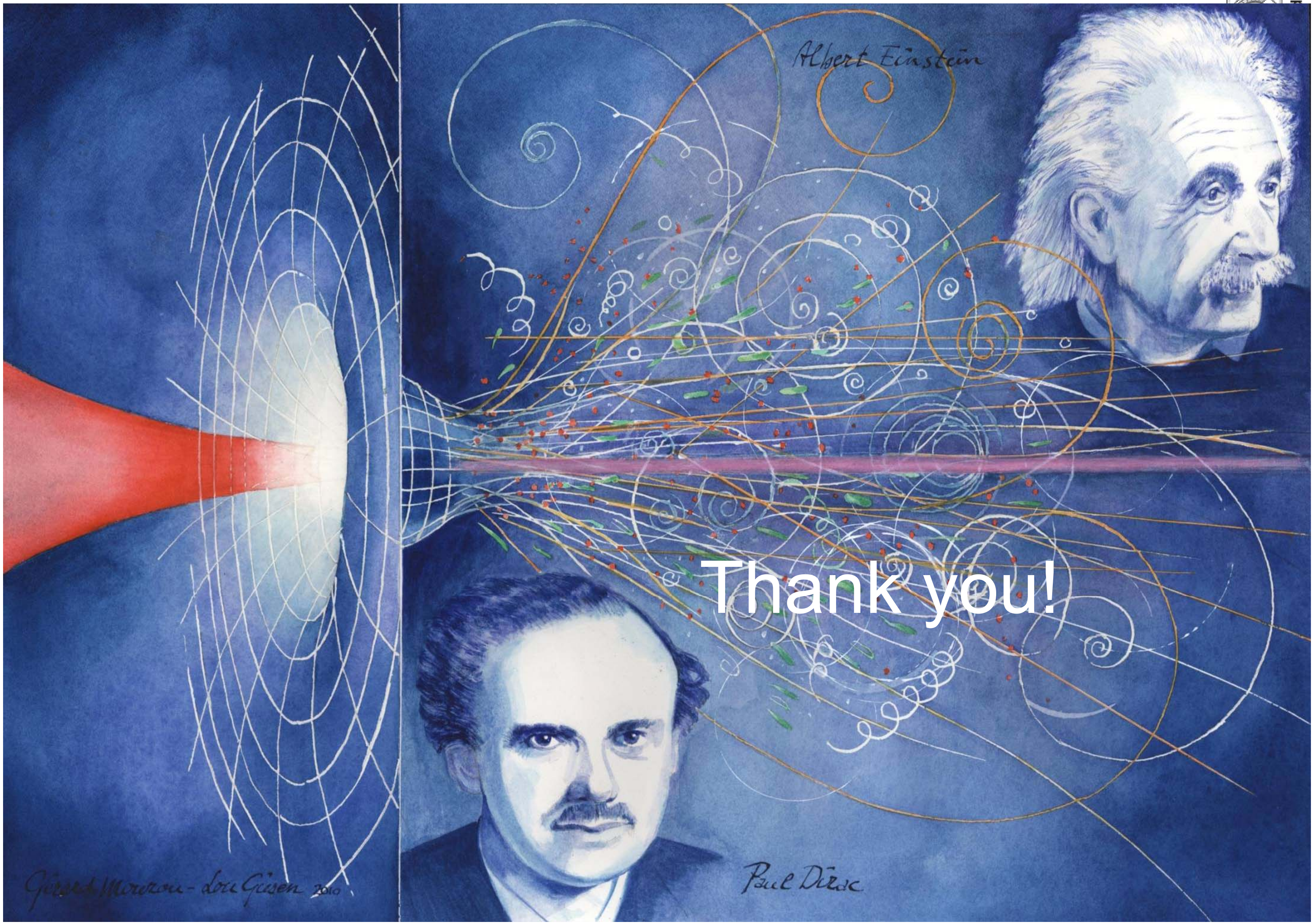
High energy γ- induced Schwinger breakdown (Narozhny, 1968)
CEP phase sensitive electron-positron acceleration
Attosecond electron streaking
γ- energy tagging possible



Goulielmakis(2008)

Conclusions

1. Extreme Light: γ-beams; high field lasers
2. Quantum Optics ↔ Relativistic Optics (rel. coherence)
2. To reduce the pulse length,
   need to increase the intensity
3. Ultrafast Optics ↔ High Field Science
4. Highest energy laser → Shortest pulses
5. Attosecond → Zeptosecond
6. Vacuum physics can learn from Atomic physics
   e.g. laser streaking of atom
7. Vacuum physics ↔ Atomic physics
8. High energy LWFA toward PeV with highest energy laser → examine Einstein's relativity, Quantum gravity w/ γ-assisted attosecond Schwinger process



(Mourou, 2010)