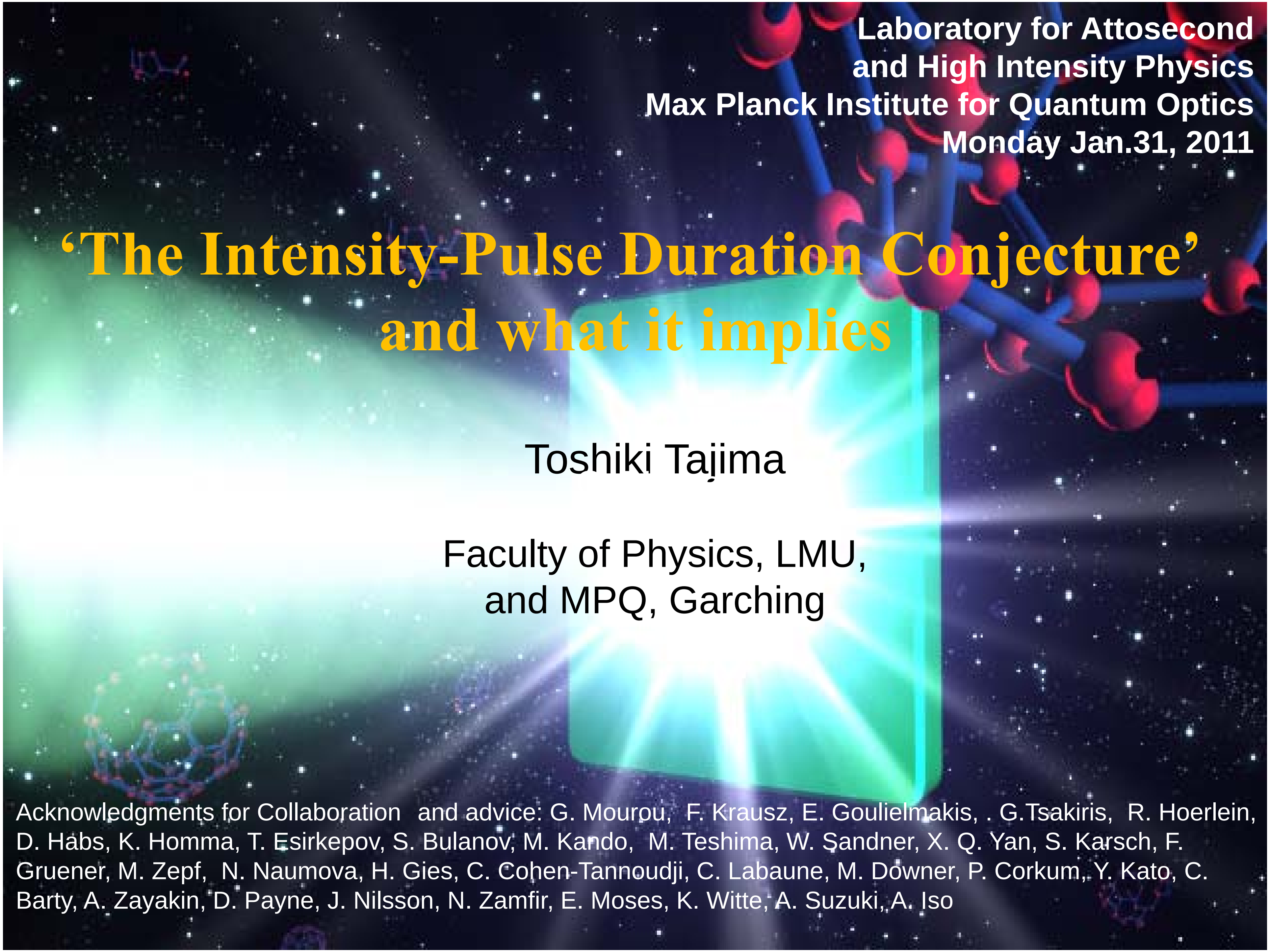


Laboratory for Attosecond
and High Intensity Physics
Max Planck Institute for Quantum Optics
Monday Jan.31, 2011

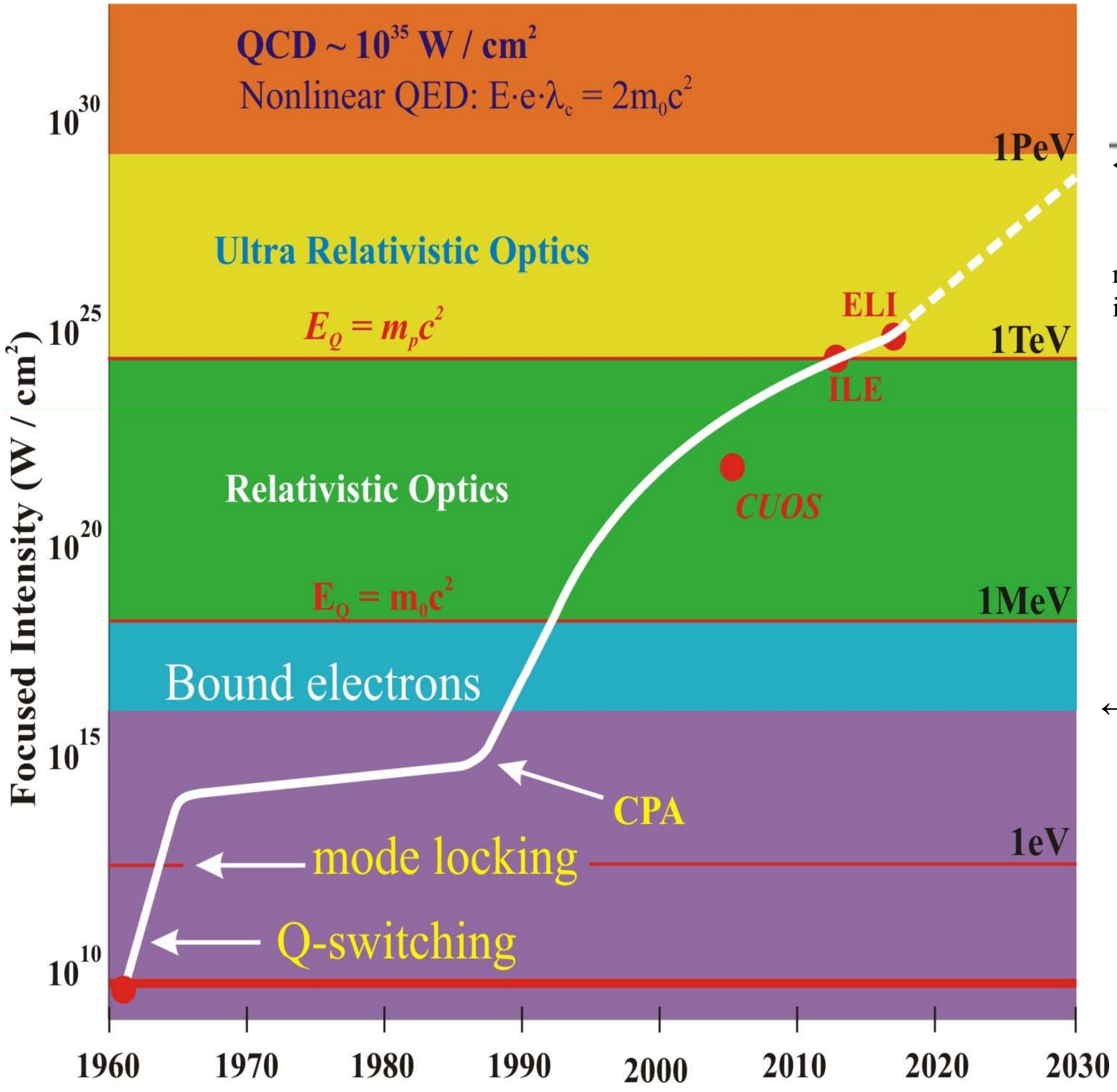
‘The Intensity-Pulse Duration Conjecture’ and what it implies

Toshiki Tajima

Faculty of Physics, LMU,
and MPQ, Garching

Acknowledgments for Collaboration and advice: G. Mourou, F. Krausz, E. Goulielmakis, . G.Tsakiris, R. Hoerlein, D. Habs, K. Homma, T. Esirkepov, S. Bulanov, M. Kando, M. Teshima, W. Sandner, X. Q. Yan, S. Karsch, F. Gruener, M. Zepf, N. Naumova, H. Gies, C. Cohen-Tannoudji, C. Labaune, M. Downer, P. Corkum, Y. Kato, C. Barty, A. Zayakin, D. Payne, J. Nilsson, N. Zamfir, E. Moses, K. Witte, A. Suzuki, A. Iso

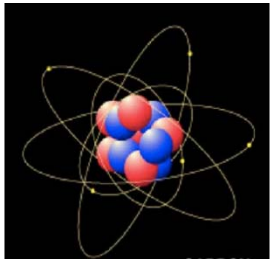
1. Ever higher intensity lasers
2. Ultrafast optics toward attosecond science
3. How can we reduce the pulse length?
   Answer---- intensity!
4. ‘*Intensity - Pulse Duration Conjecture*’
5. Examples of attosecond pulses and beyond
6. Confluence of ultrafast optics
   and high field science
7. Atom streaking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



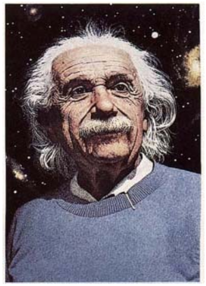
boiled vacuum

←**Schwinger field**

relativistic ions



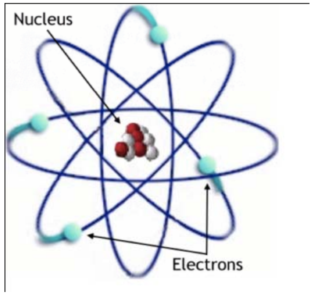
relativistic electrons



plasma

←**Keldysh field**

atoms



Intensification of Laser

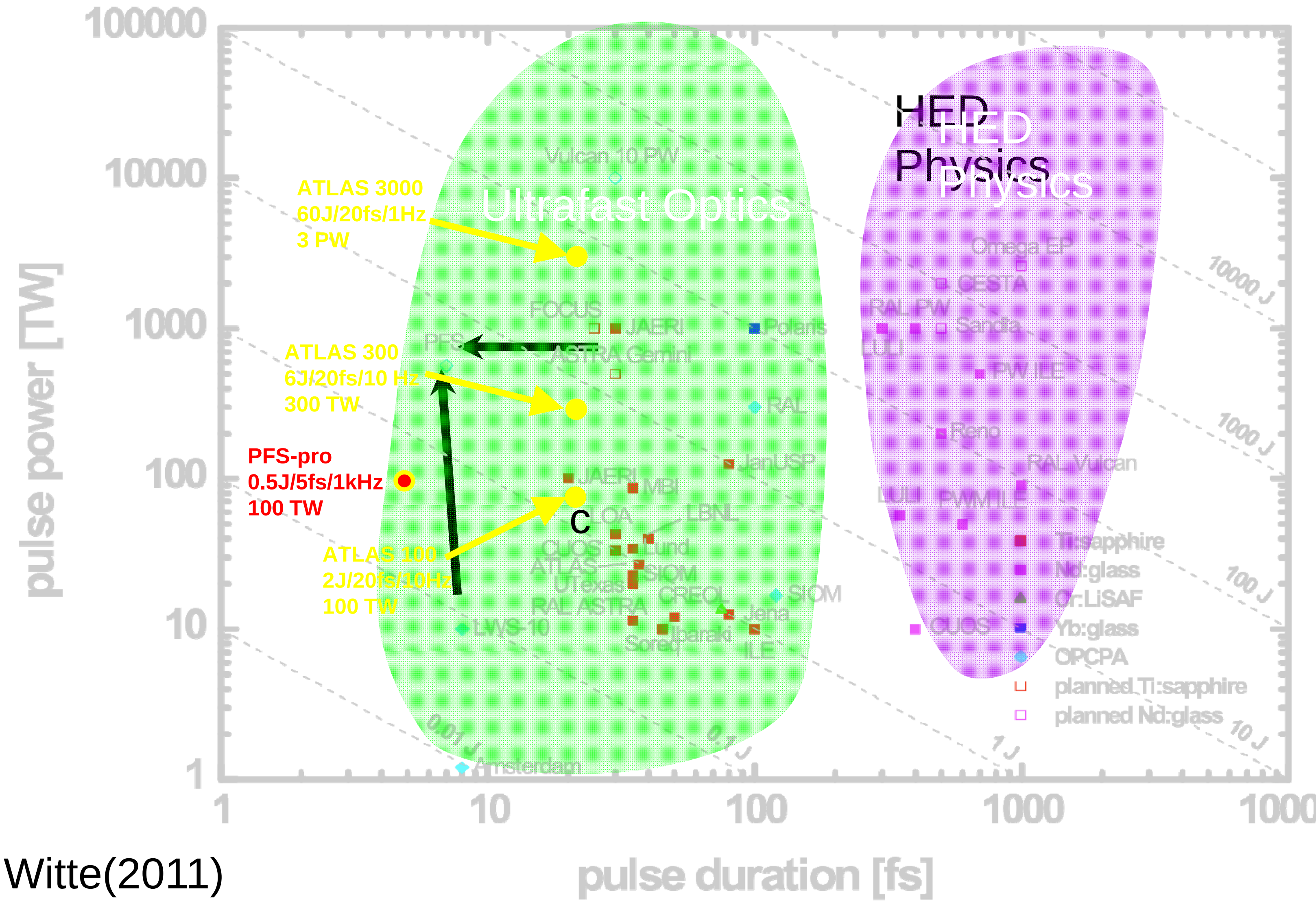
$$I = J/\tau$$

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*

Laser Landscape



ATLAS 3000
60J/20fs/1Hz
3 PW

ATLAS 300
6J/20fs/10 Hz
300 TW

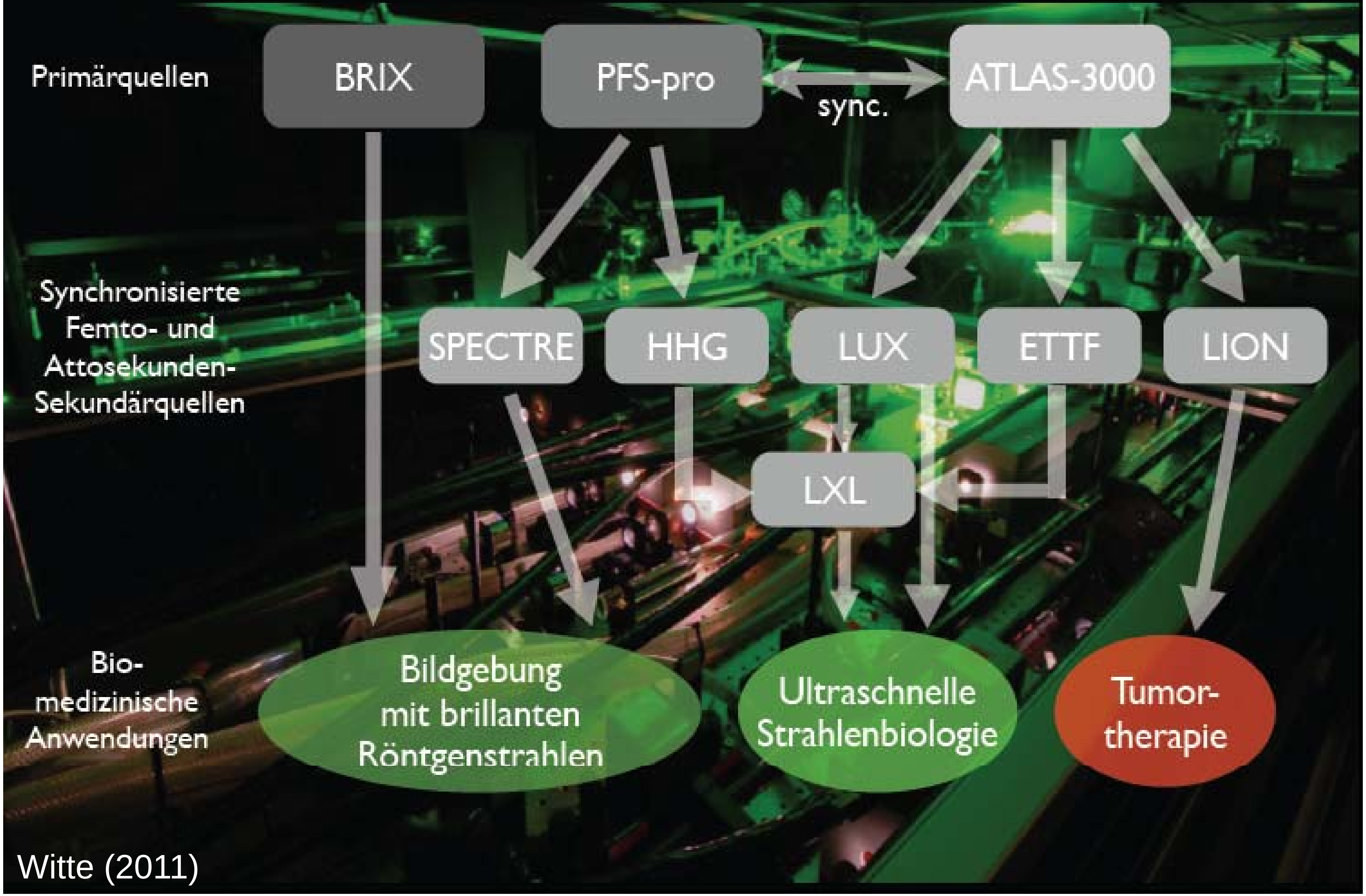
PFS-pro
0.5J/5fs/1kHz
100 TW

ATLAS 100
2J/20fs/10Hz
100 TW

Witte(2011)

→ **NIF/ LMJ** compression phys

CALA Infrastruktur und Hauptanwendungsfelder



Primärquellen

BRIX

PFS-pro

sync.

ATLAS-3000

Synchronisierte Femto- und Attosekunden-Sekundärquellen

SPECTRE

HHG

LUX

ETTF

LION

LXL

Bio-medizinische Anwendungen

Bildgebung mit brillanten Röntgenstrahlen

Ultraschnelle Strahlenbiologie

Tumor-therapie

Witte (2011)

Does $\tau = J/I$ hold?

One of Attosecond Lab missions: 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”

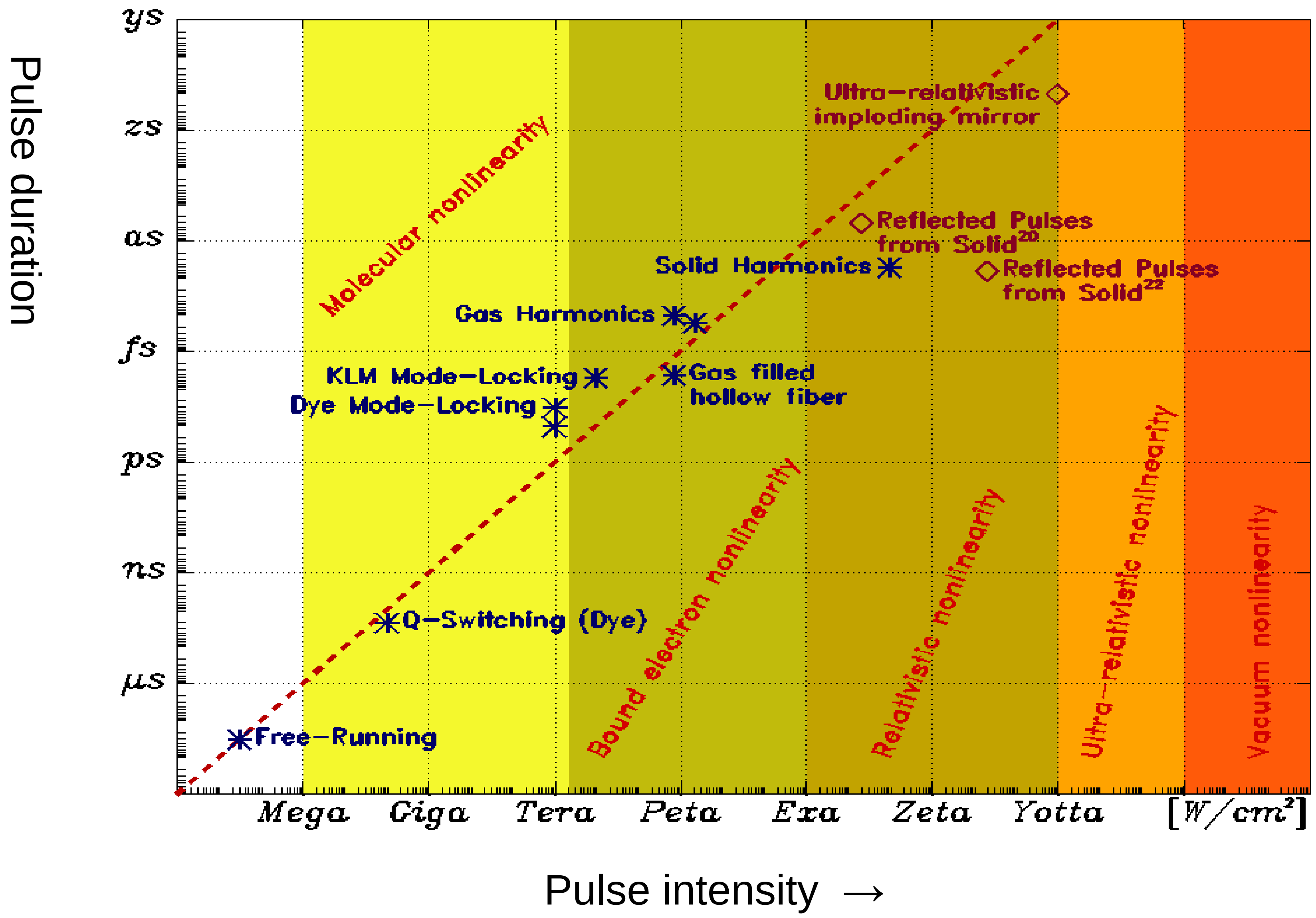
Is this true?

We cannot find a proof!

The Conjecture

(← physics: “Matter is nonlinear”

“The more rigid nonlinearity, the more intense to manipulate it”)



(Mourou / Tajima, 2011)

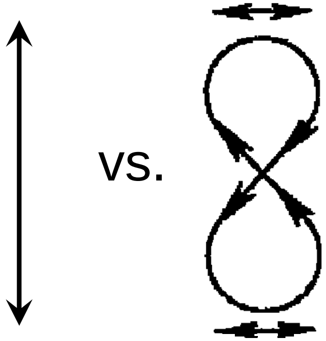
Nonlinearities in atom, plasma, and vacuum

Atomic
nonlinear potential

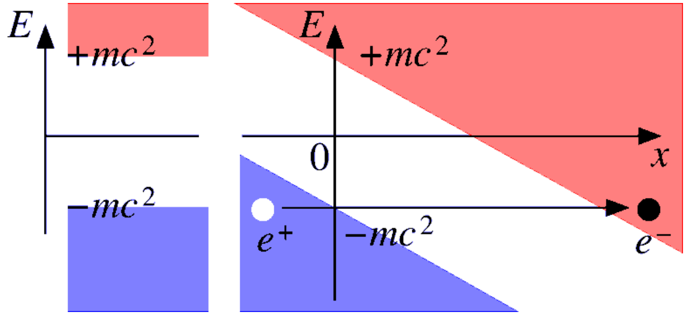
Plasma electron
nonlinear

relativistic motion

Vacuum nonlinearity



vs.



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:

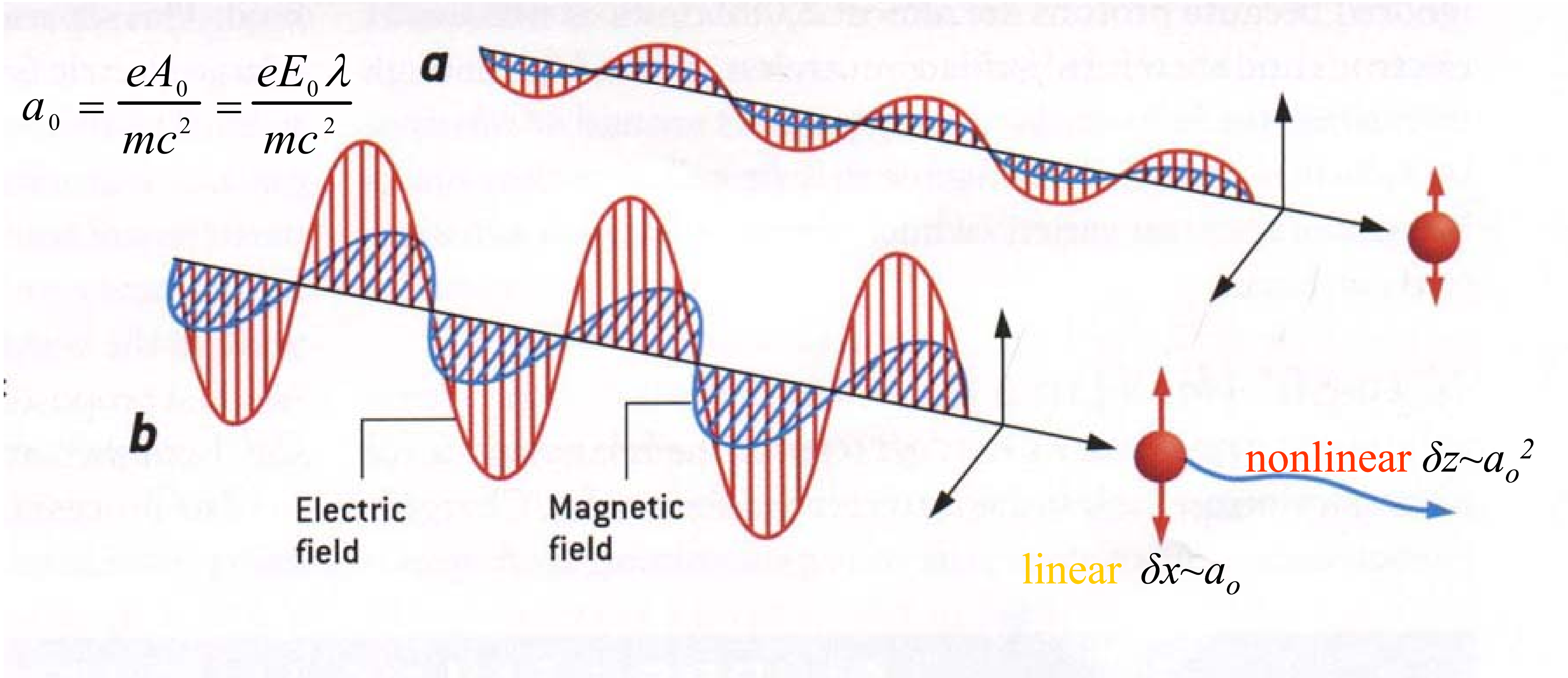
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

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

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

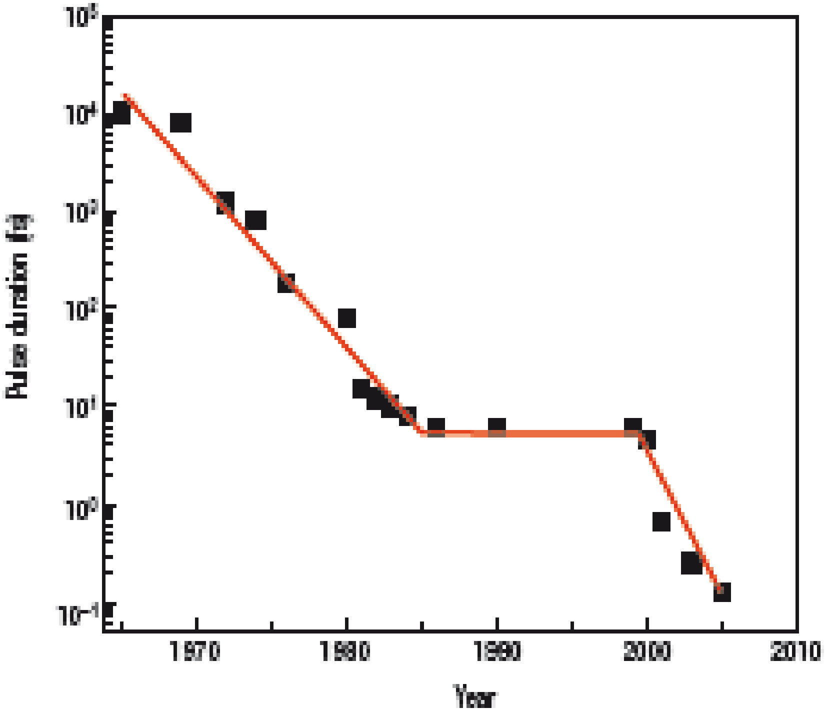


nonlinear $\delta z\sim a_o^2$

linear $\delta x\sim a_o$

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

Corkum and Krausz (2007)



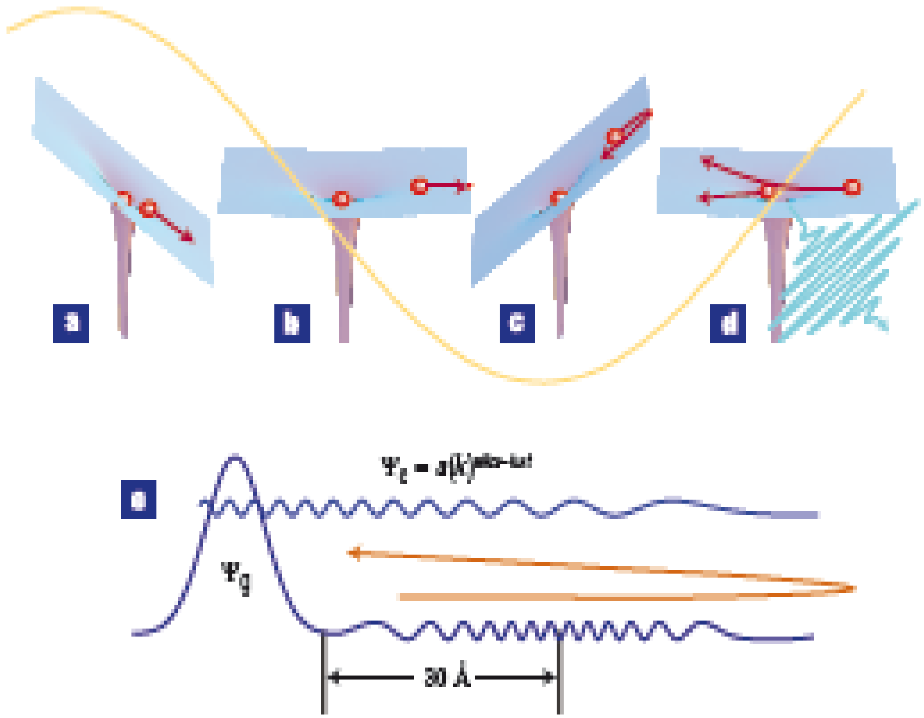
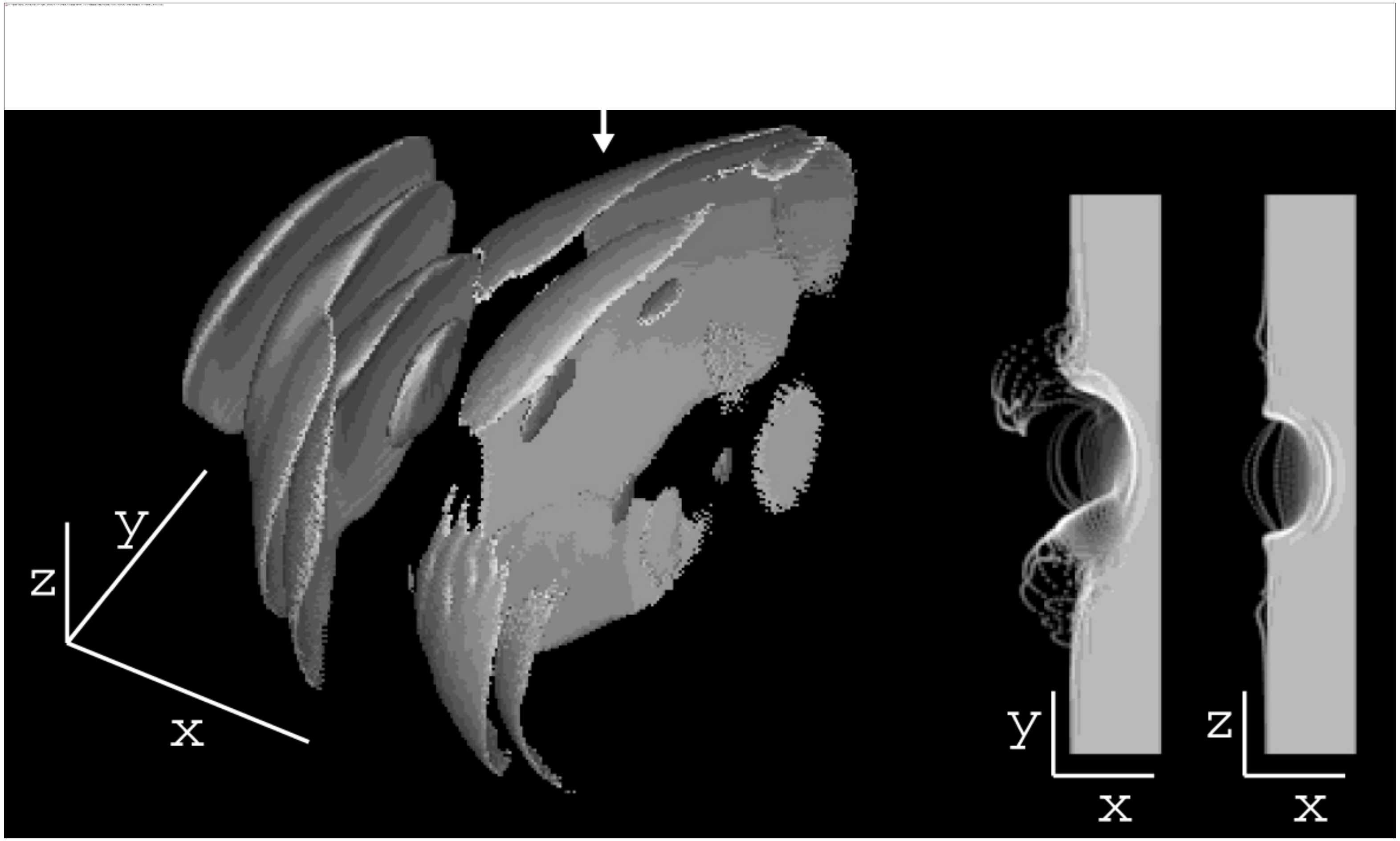


Figure 1 Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1964 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making 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

Isolated attosecond electromagnetic pulses in 3D simulation



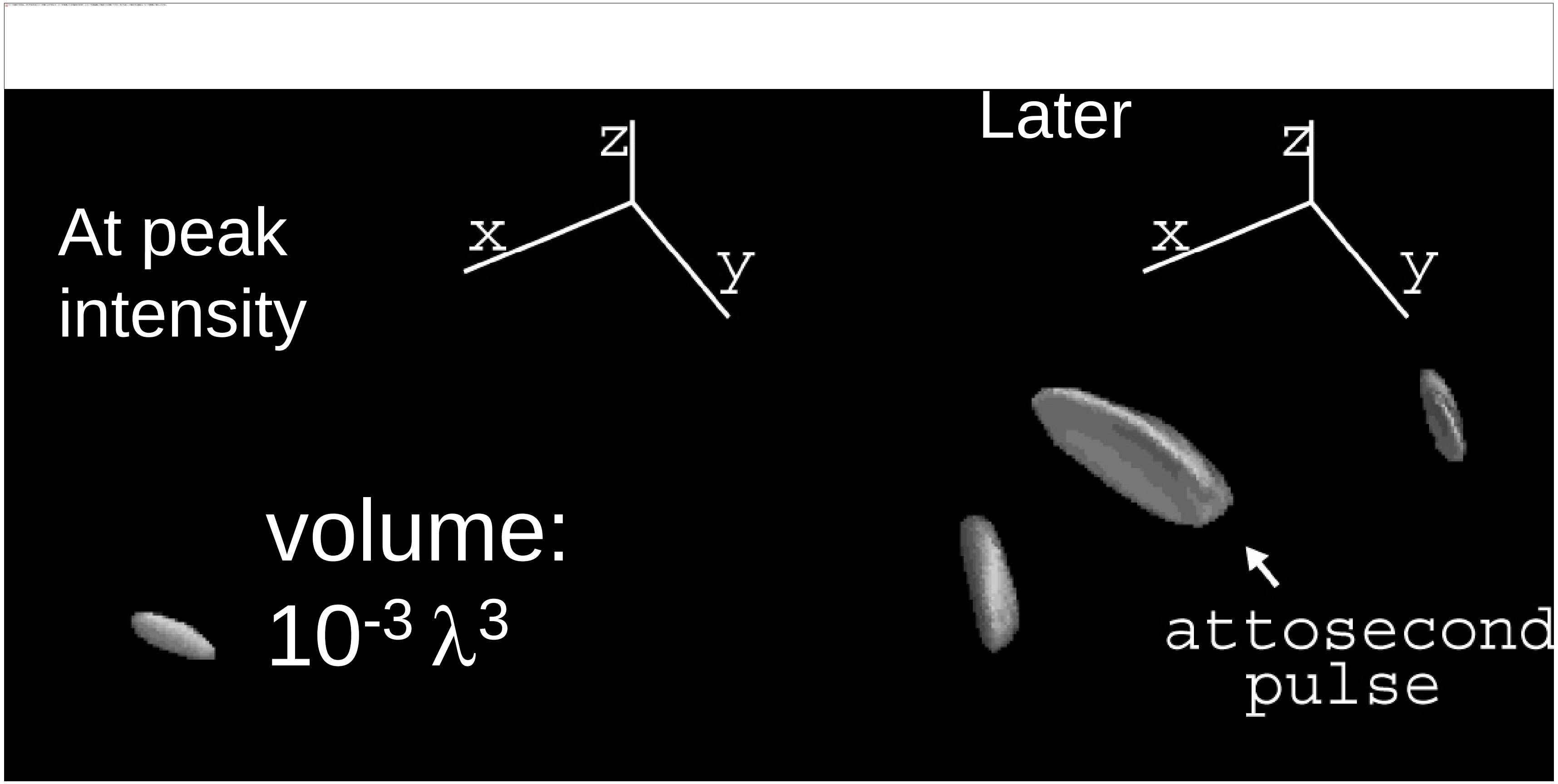
Relativistic oscillating mirror of solid surface

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

Nees *et al*., J. Mod. Opt. 52, 305 (2005)

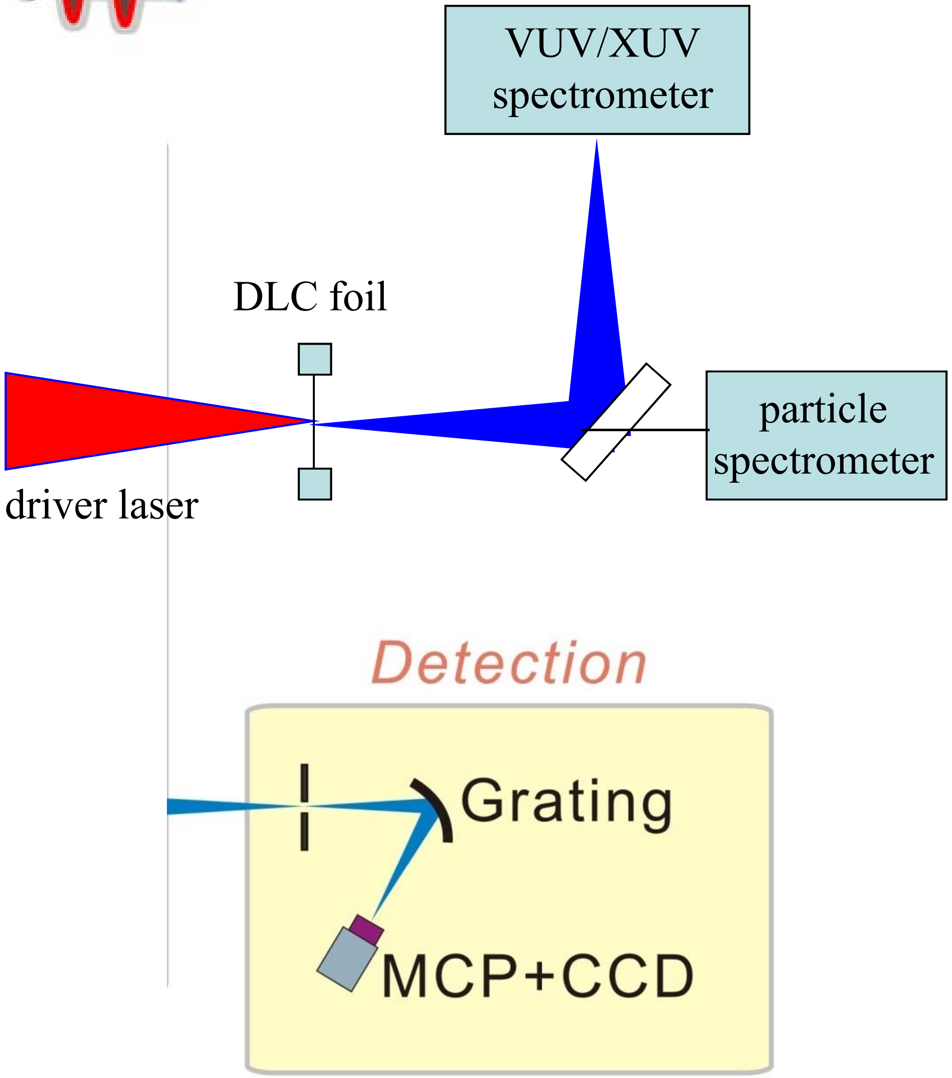
Self-induced concentration of light to smaller volume → higher intensity

$a_0=3$, $\tau=5$fs, f/1, $n=4n_{cr}$



N. Naumova, J. Nees, G. Mourou, Phys. Plasmas 12, 056707 (2005)

Sold plasma HHG (The Setup)

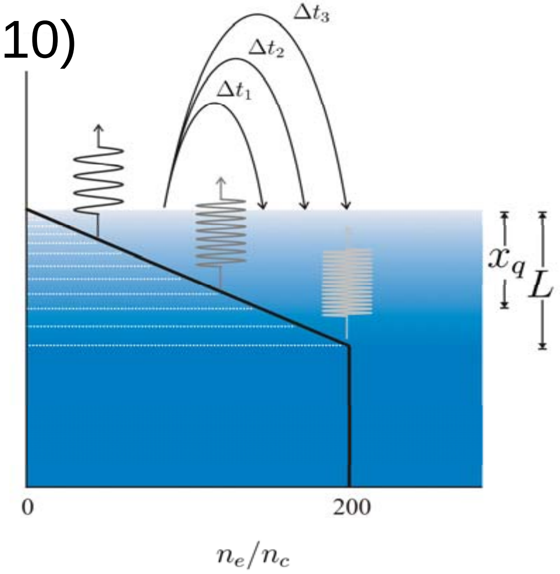


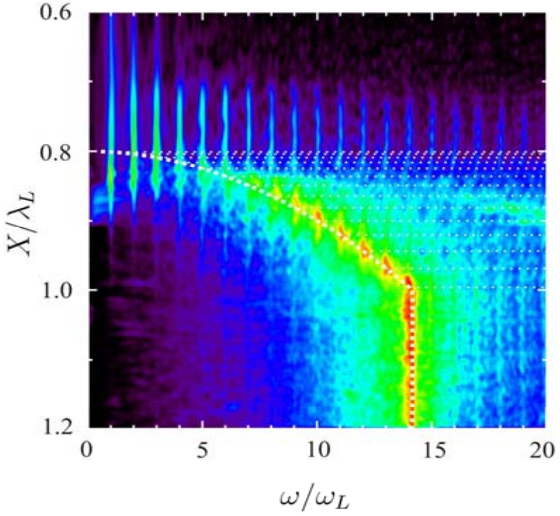
- Laser incident normally onto target
- Collection of XUV-light with spherical mirror
  - ➢ stronger signal for first test
  - ➢ loss of spatial information
- Observable spectral window limited to harmonics 6 to 16
- Gold mirror and grating have polarization dependent reflectivity

R. Hoerlein (2010)

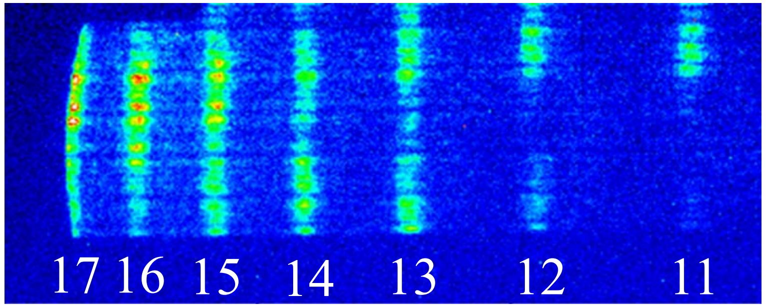
The Coherent Wake Emission

(R. Hoerlein, 2010)



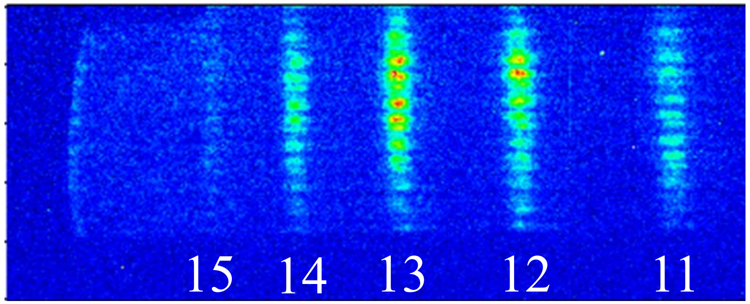


Glass Target (Density 🕓2.6 g/cm^3):



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

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



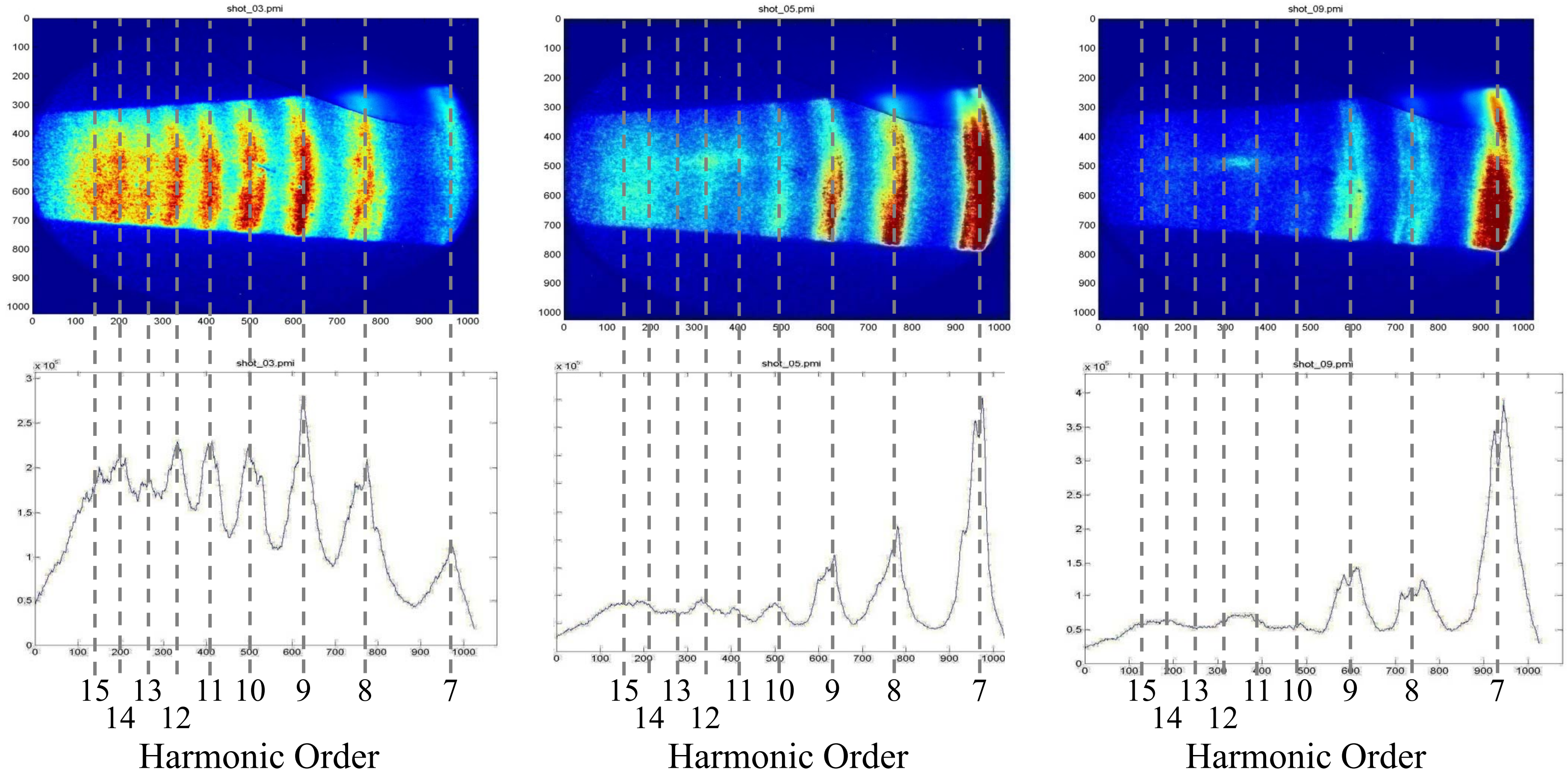
F. Quéré, *et al.*, PRL, **96**, 125004 (2006)

Target Thickness Dependence

Hoerlein(2010)

Linear Polarization

30 nm DLC 7 nm DLC 4.5 nm DLC



Relativistic oscillating mirror

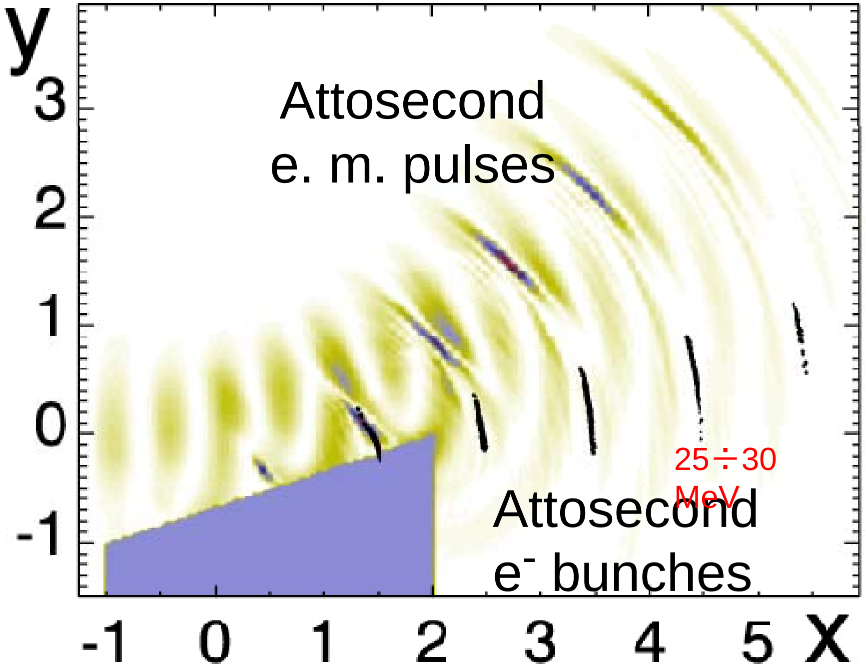
M. Zepf: up to 3200th harmonics

Electron ejection is synchronized with attosecond pulse generation

Escaped relativistic electrons

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

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

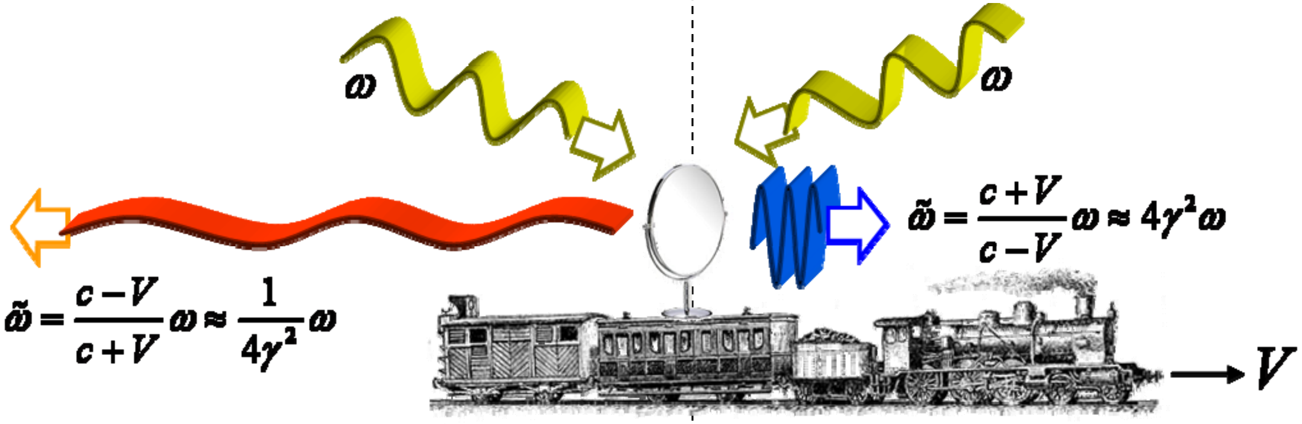


Naumova *et al*., Phys. Rev. Lett. (2004)

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

Relativistic flying mirror and shorter pulses

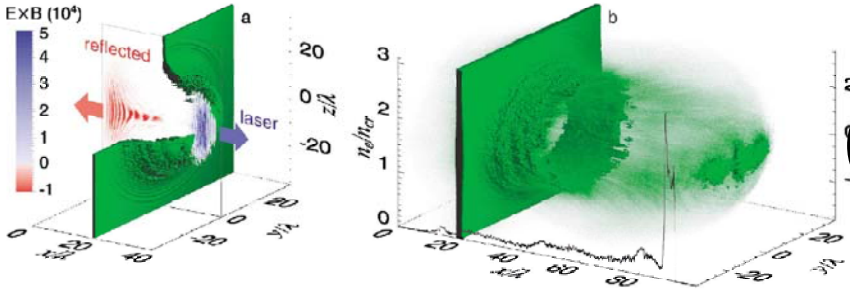
Esirkepov (2009) --- Einstein's flying mirror made of LWFA



$$\tilde{\omega} = \frac{c+V}{c-V}\omega \approx 4\gamma^2\omega$$

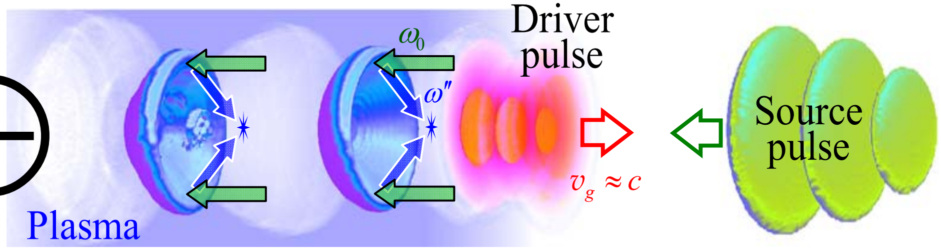
$$\tilde{\omega} = \frac{c-V}{c+V}\omega \approx \frac{1}{4\gamma^2}\omega$$

Laser Piston

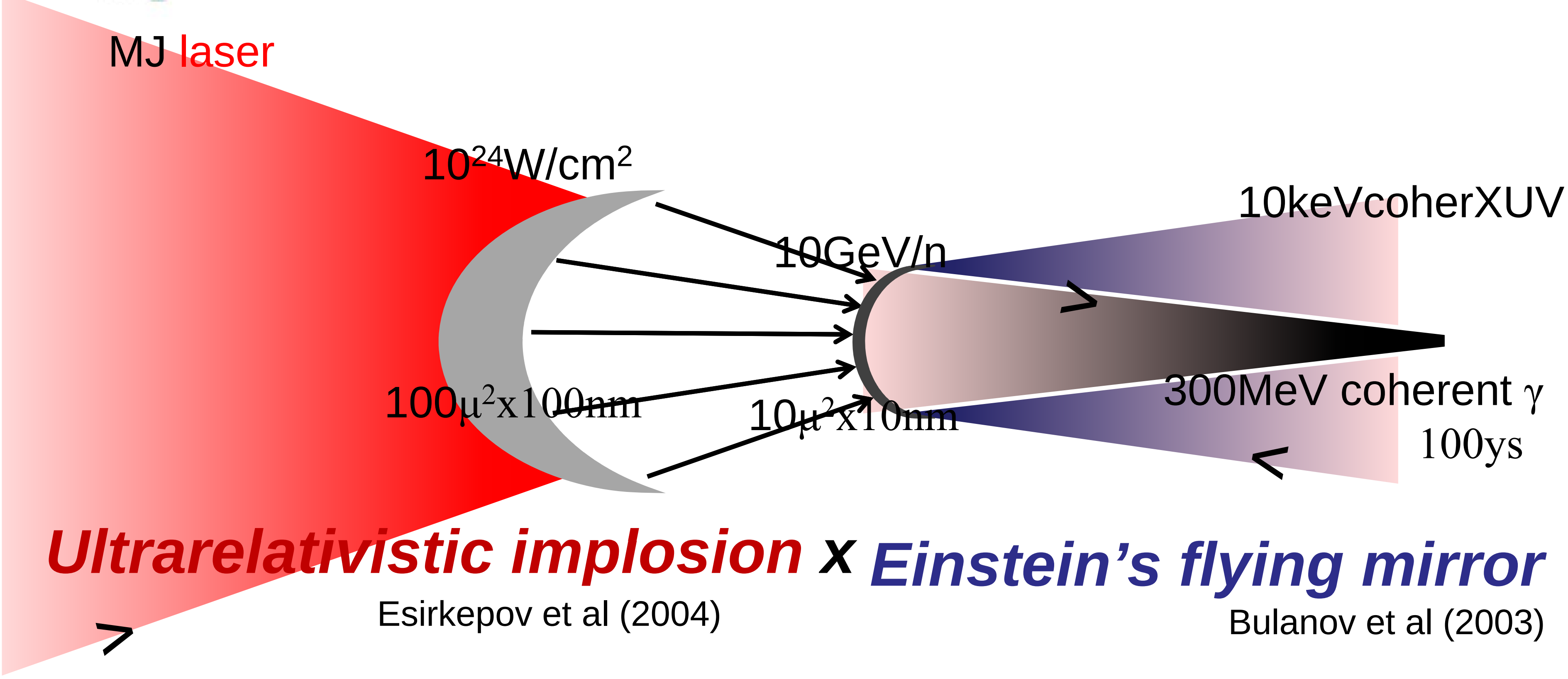


$\oplus$

Flying Mirror (LWFA)



Ultrarelativistic imploding mirror



Ultrarelativistic implosion **x** ***Einstein's flying mirror***

Esirkepov et al (2004)

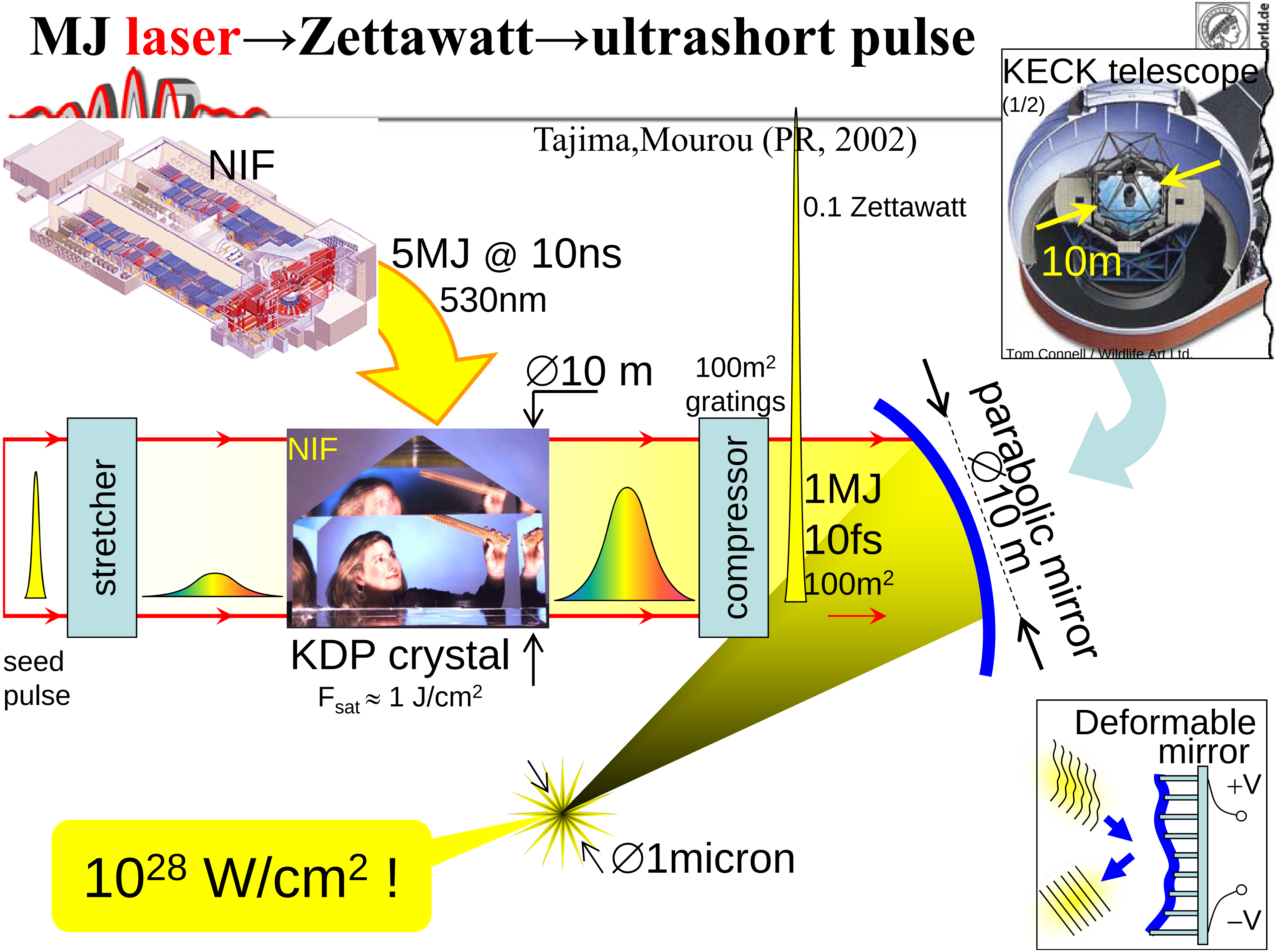
Bulanov et al (2003)

Large energy laser → → Ultrfast γ rays

Tajima/Mourou/et al(2011): use NIF ---ultra-relativistic <u>imploding</u> mirror → ys

MJ laser→Zettawatt→ultrashort pulse

Tajima,Mourou (PR, 2002)



NIF

5MJ @ 10ns

530nm

KECK telescope

(1/2)

10m

Tom Connell / Wildlife Art Ltd.

orld.de

0.1 Zettawatt

∅10 m

100m² gratings

seed pulse

stretcher

NIF

KDP crystal

$F_{sat} \approx 1\ J/cm^2$

compressor

1MJ

10fs

100m²

parabolic mirror

∅10 m

Deformable mirror

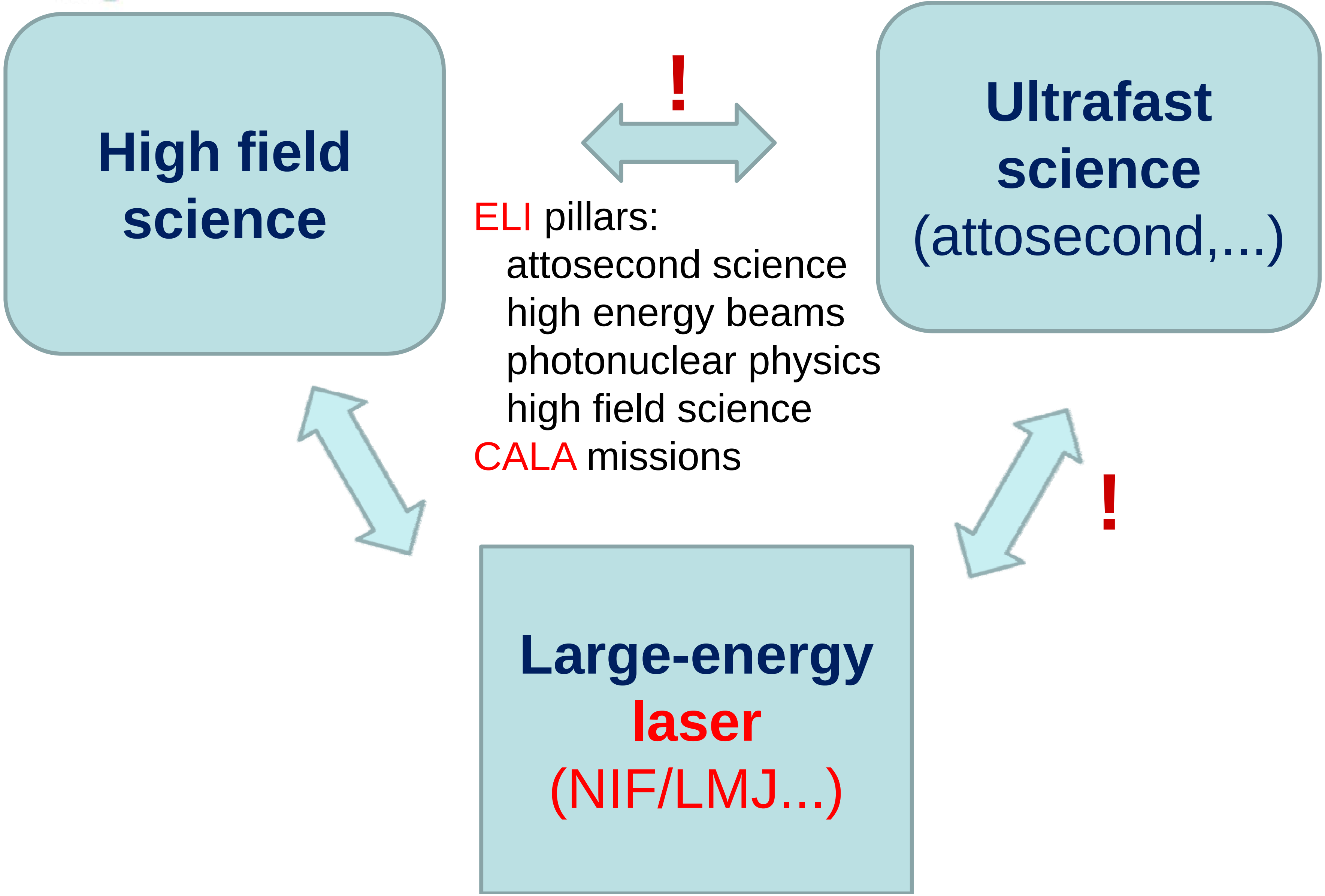
+V

–V

∅1micron

10^{28} W/cm² !

Ultrafast science ← High field science, Large-energy laser



High field science

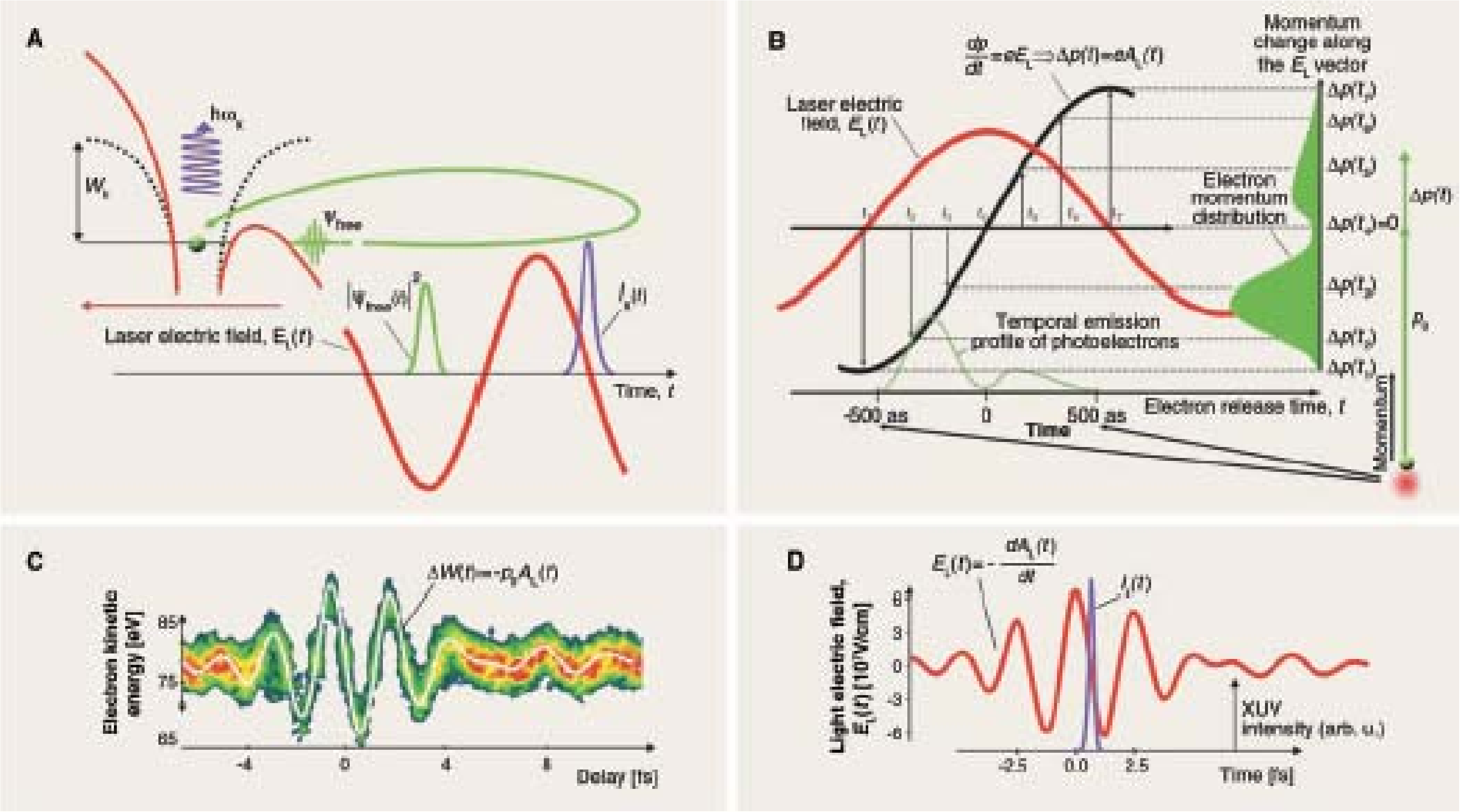
Ultrafast science
(attosecond,...)

ELI pillars:
- attosecond science
- high energy beams
- photonuclear physics
- high field science

CALA missions

Large-energy laser
(NIF/LMJ...)

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 nonlinearity

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

relativistic plasma nonlinearity

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

vacuum nonlinearity

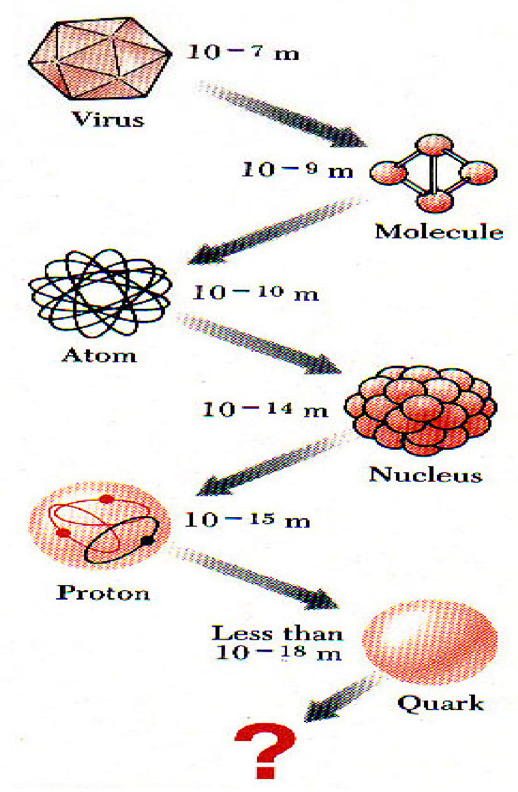
$$P_{cr} = (90/28)\, c\, E_S{}^2\lambda^2/\alpha \sim 10^{15}\,(\lambda/\lambda_{1\mu})^2\ \mathrm{GW}$$

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

‘ELI Long-term Ambition’ =

Studying the Atomic Structure to the Vacuum Structure

(Mourou)



Vacuum structure

Keldysh field

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

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

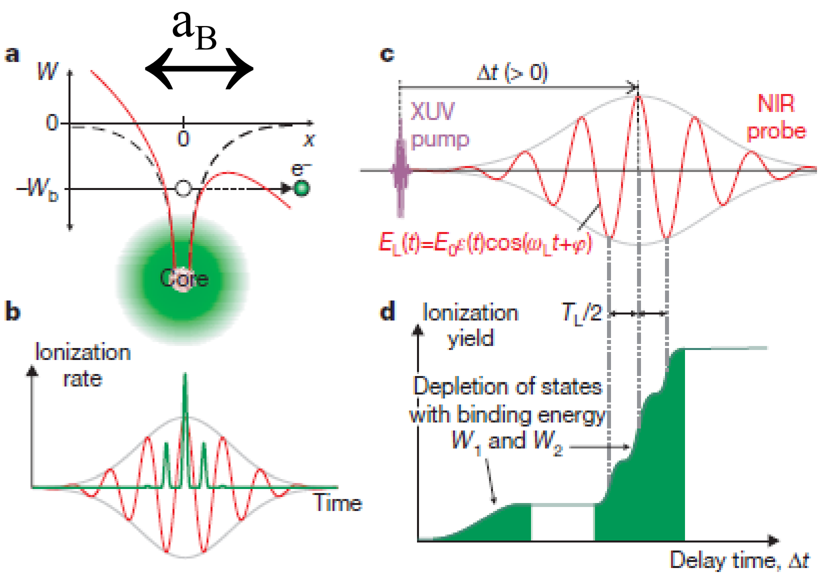
Schwinger field

Does the atomic world repeat itself in vacuum?

Streaking vacuum (1)

(from atomic physics to vacuum physics)

Uiberacker et al. (2007)



XUV photon ionization

Laser streaking

→ attosecond dynamics

atom

vacuum

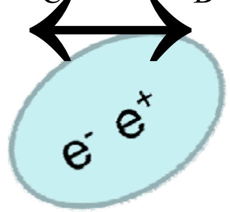
Gamma photon ‘ionization’

XUV streaking

→zeptosecond dynamics

size

$$\lambda_C = \alpha\, a_B$$



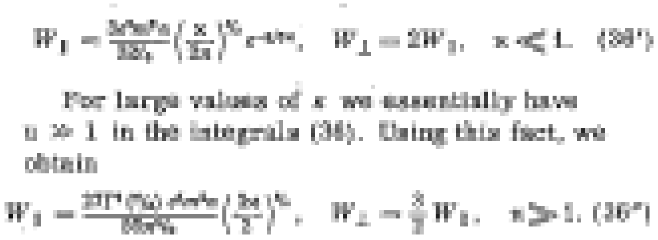
depth of potential

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

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

Nikishov(1964)

Nonperturbative:

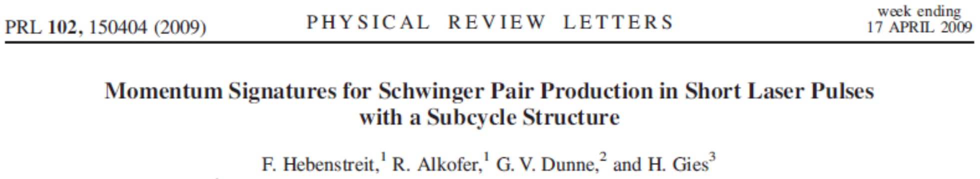


$W_\parallel =$ [illegible], $W_\perp = 2W_\parallel$, $\varkappa \ll 1$. (36′)

For large values of $\varkappa$ we essentially have $u \gg 1$ in the integrals (34). 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

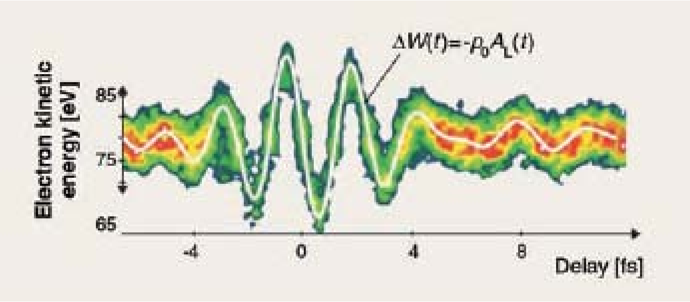
Momentum Signatures for Schwinger Pair Production in Short Laser Pulses with a Subcycle Structure

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 $\gamma = \frac{\omega_L \sqrt{2mW_b}}{|e|E_0}$

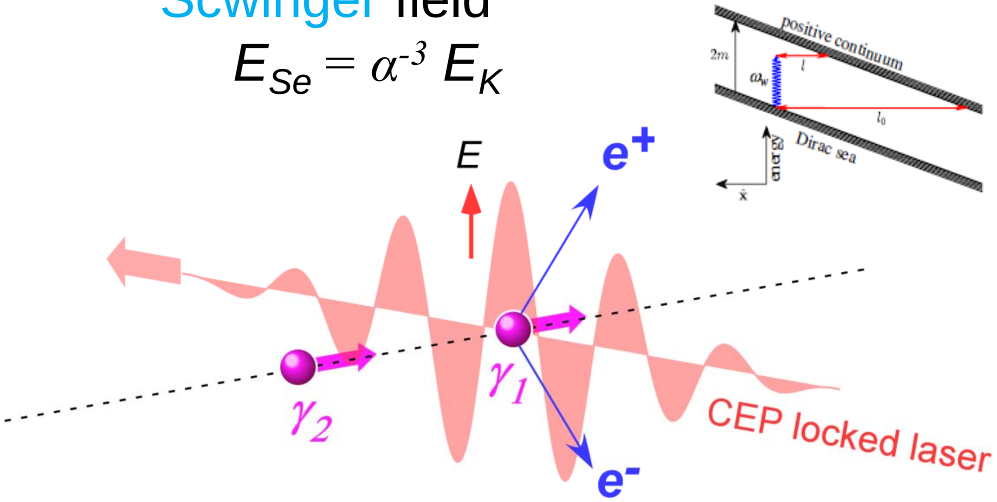
Vacuum:

Schwinger/Nishikov field

$$\boldsymbol{E_{SN} = E_{S\sigma}(m_\sigma c^2/\hbar\omega)}$$

Scwinger field

$$E_{Se} = \alpha^{-3} E_K$$



$$\boldsymbol{\gamma_{V\sigma} = m_\sigma\omega c/eE = 1/a_0}$$

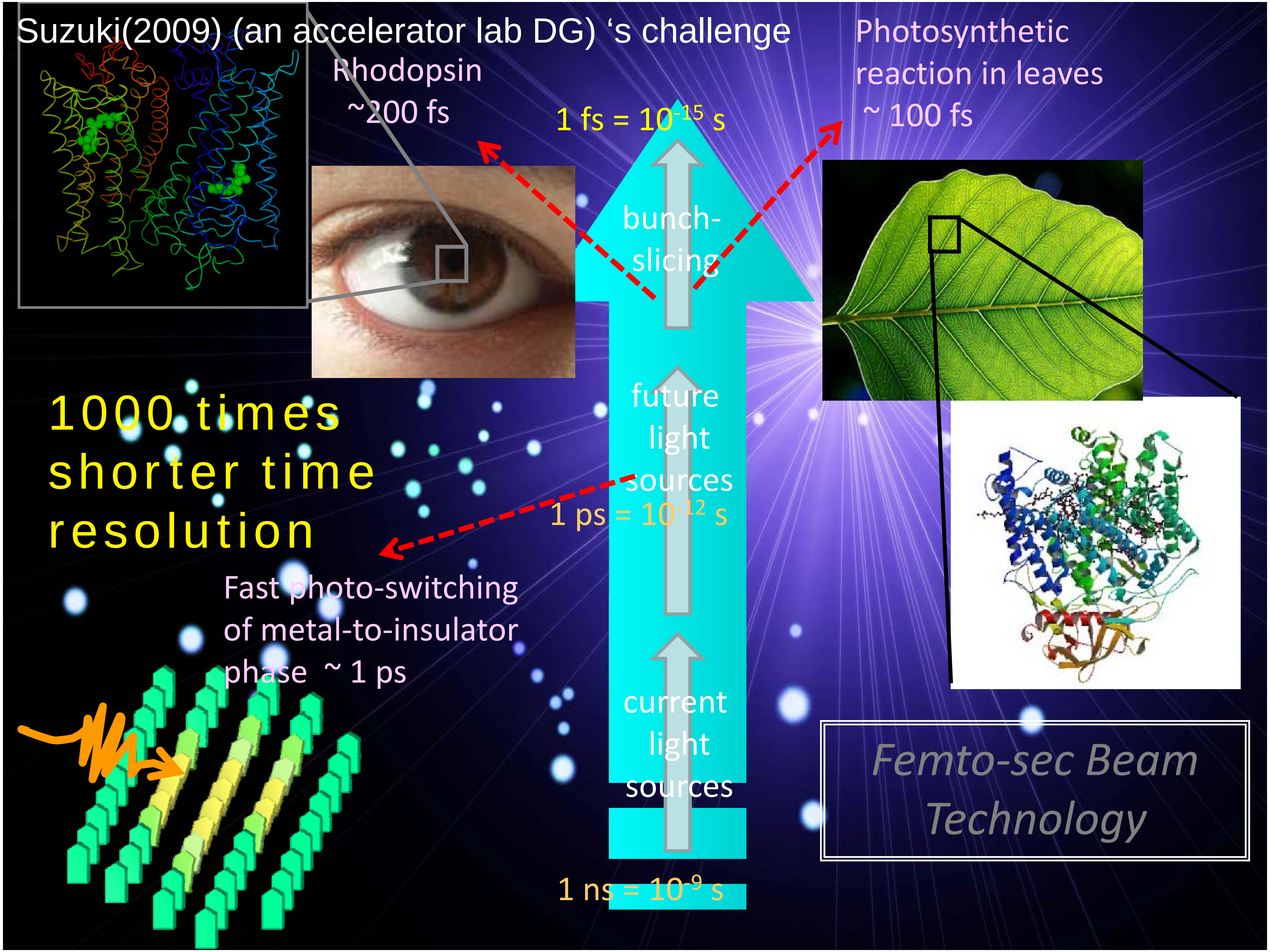
where $\sigma = e$, or q (quark)

Streaking resolving power (Itatani2002; Kienberger 2004):

$$\Delta t = \sqrt{(\hbar\omega m/eA_0p_0)} \sim \sqrt{[(\hbar\omega/\varepsilon_0)/a_0]}/\omega \sim zs$$

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

Suzuki(2009) (an accelerator lab DG) ‘s challenge



Rhodopsin
~200 fs

Photosynthetic
reaction in leaves
~ 100 fs

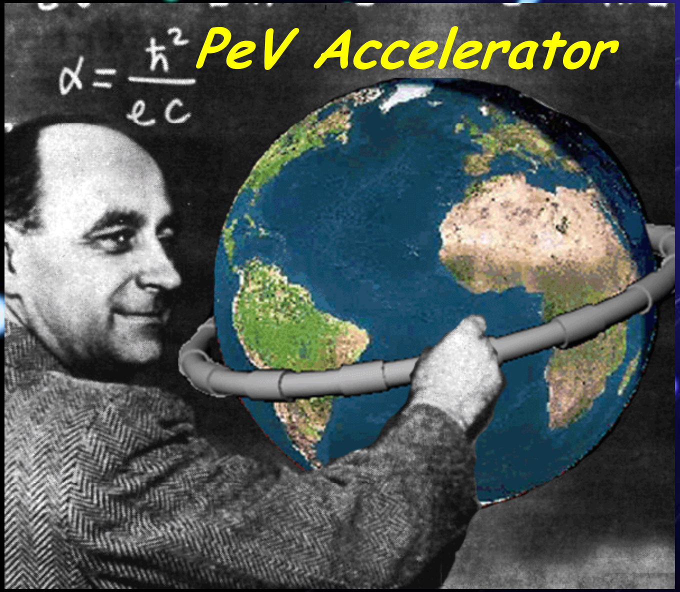
1000 times
shorter time
resolution

Fast photo-switching
of metal-to-insulator
phase ~ 1 ps

Femto-sec Beam
Technology

A. Suzuki (KEK)'s Challenge:

1000 times
higher energy



1 PeV=10^{15} eV

" New paradigm"

Leptogenesis

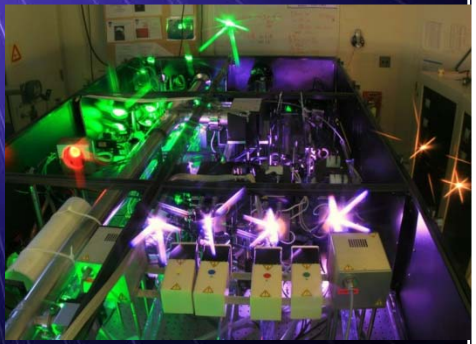
SUSY breaking

Extra dimension
Dark matter
Supersymmetry

1 TeV=10^{12} eV

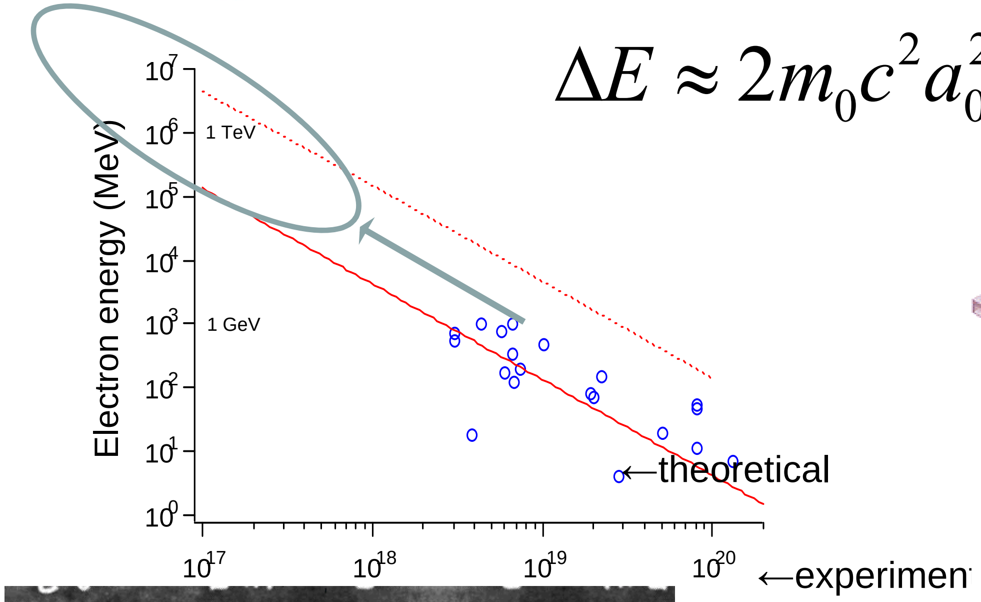
"Standard model"
Higgs
Quarks
Leptons

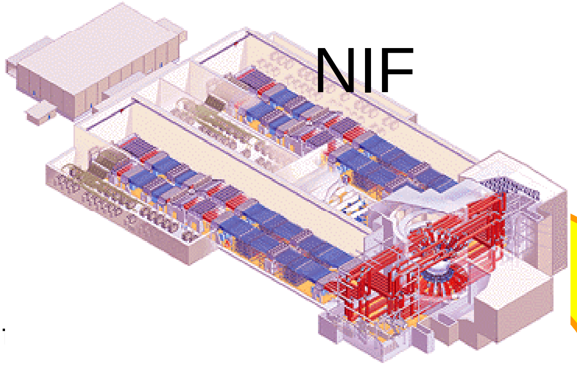
Laser Acceleration Technology



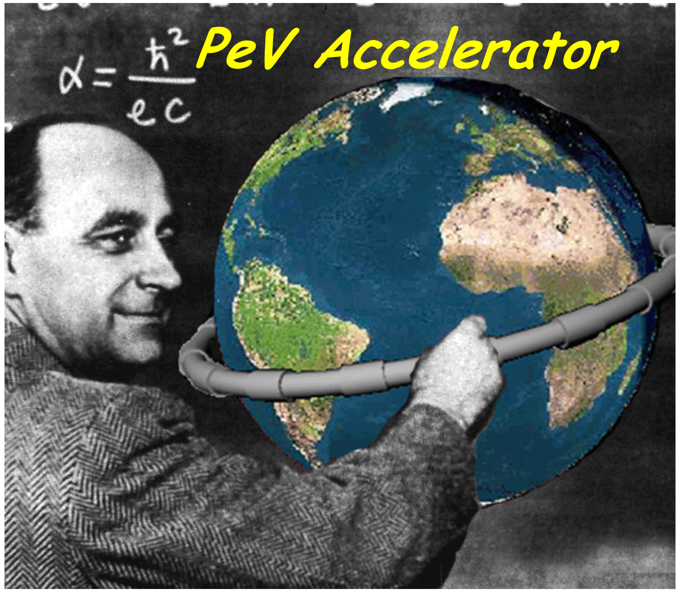
Wakefield toward extreme energy of PeV

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}{}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$





5MJ @ 10ns
530nm



1km

Adopt:

NIF laser (3MJ)

→ 0.7PeV

(PTP2011 with Kando, Teshima)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

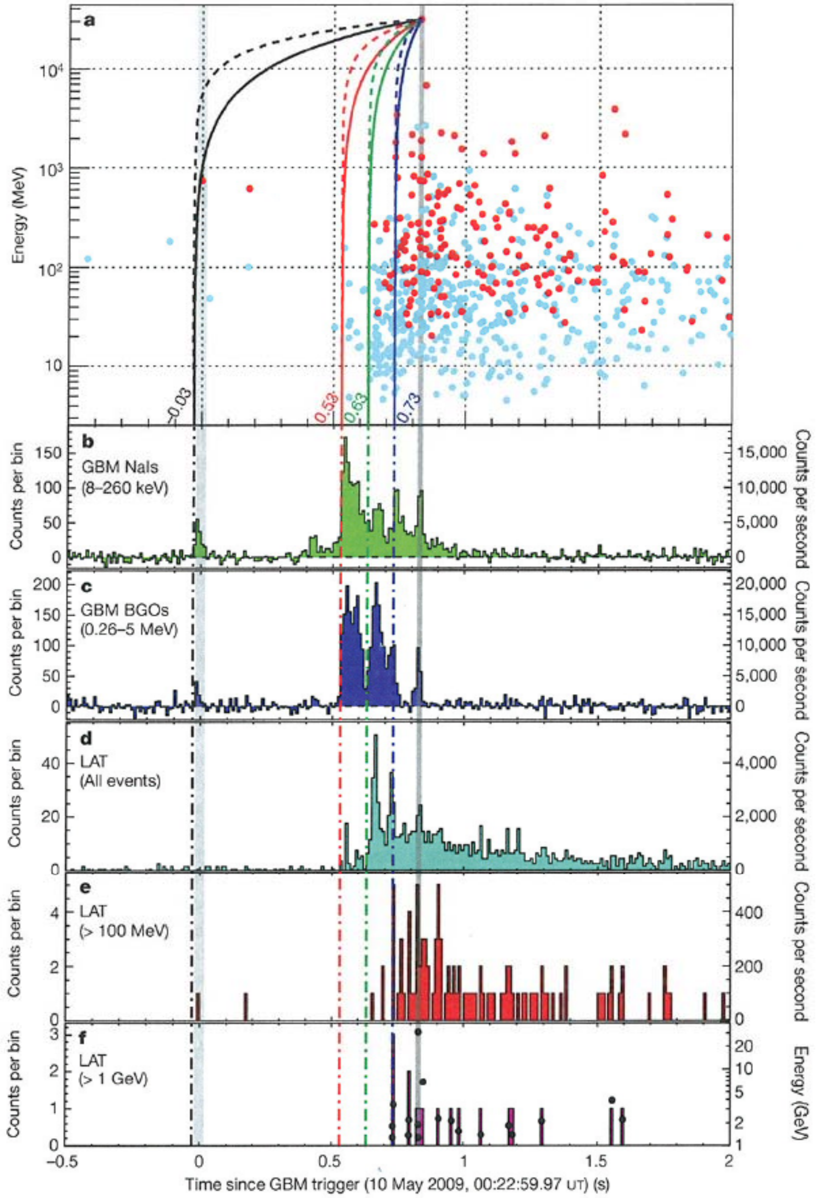
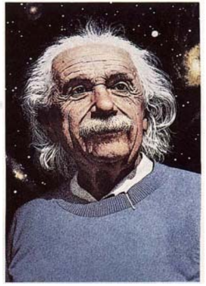


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. **f** also overlays energy versus arrival time for each



Einstein's relativity?

Energy-dependent
photon speed ?
Observation of primordial
<u>Gamma Ray Bursts (GRB)</u>
(limit is pushed up
close to Planck mass)

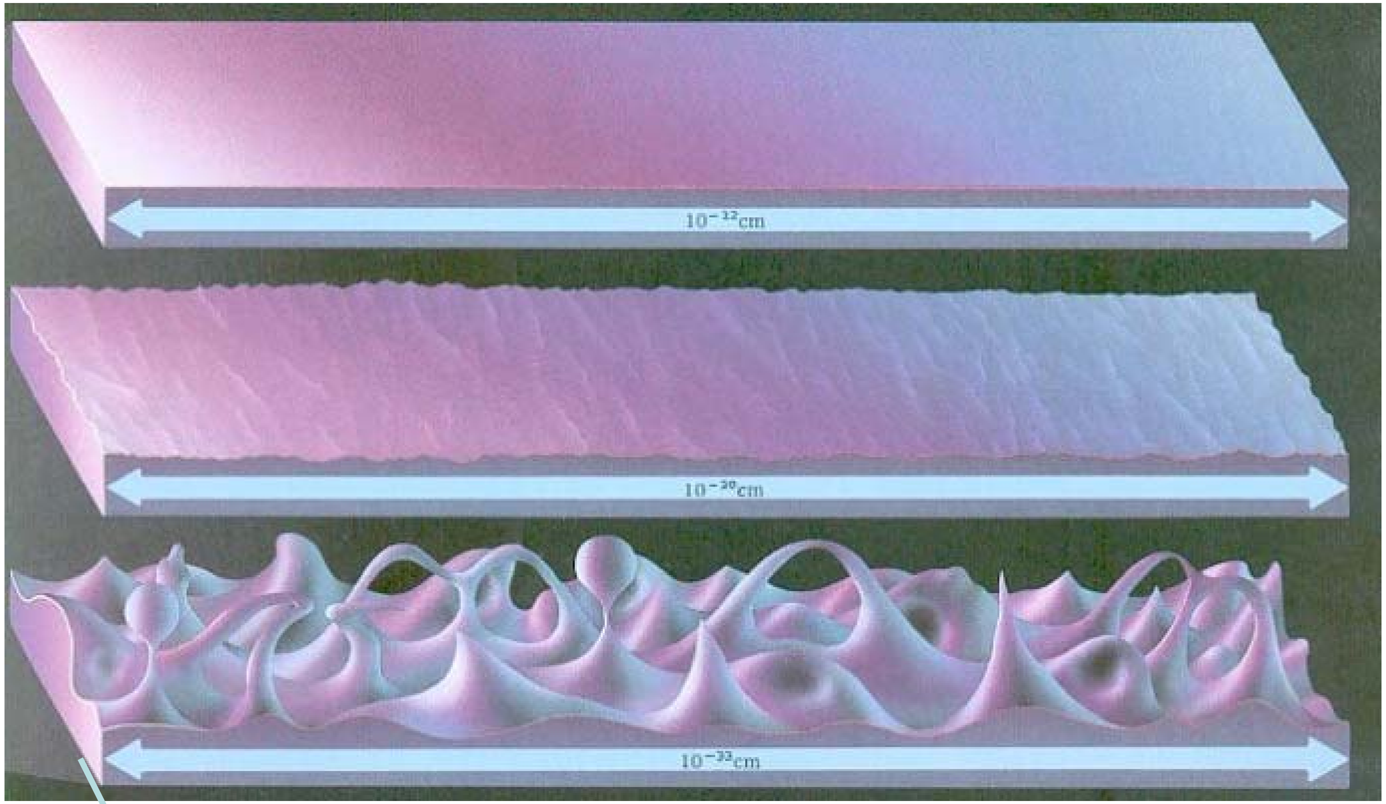
↓

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)

1km

←(1PeV : fs behind)

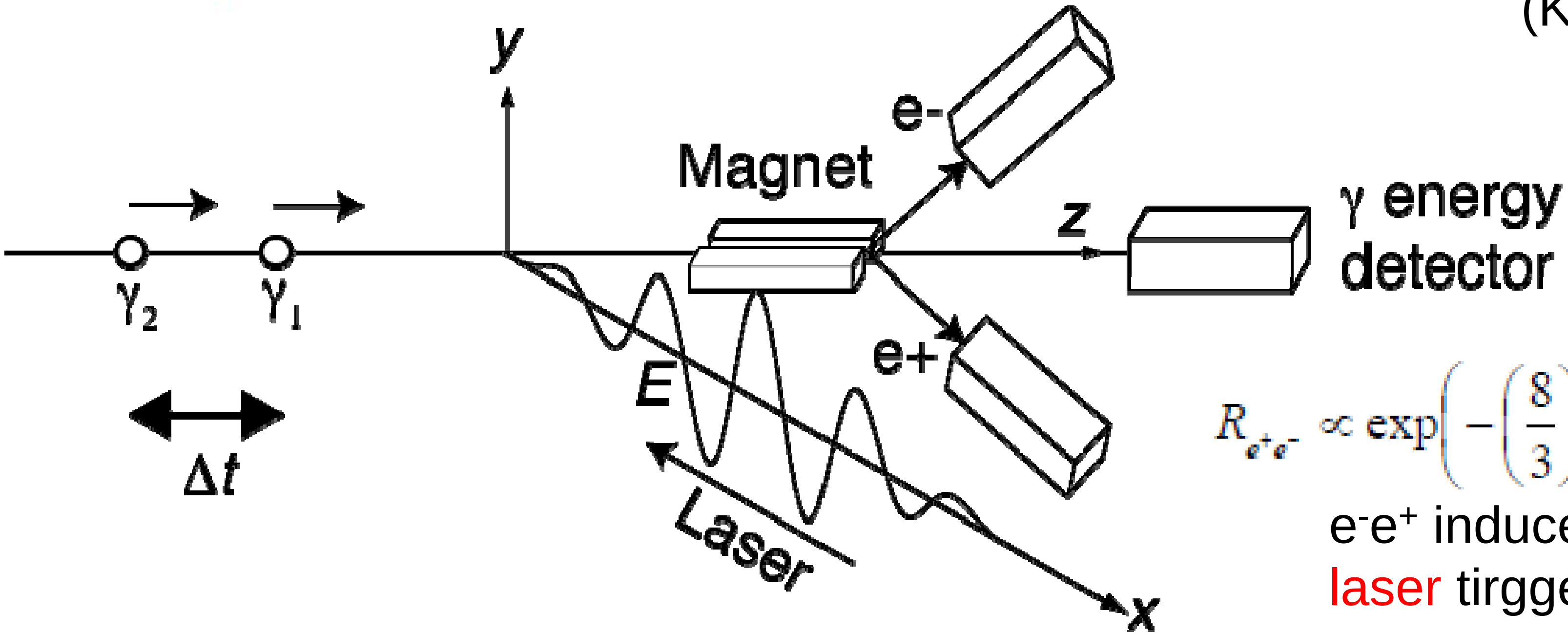
goalline

PeV γ (converted from e^-)

Attosecond Resolution of PeV γ Arrivals

“Goalline” detection

(Kando, 2011)



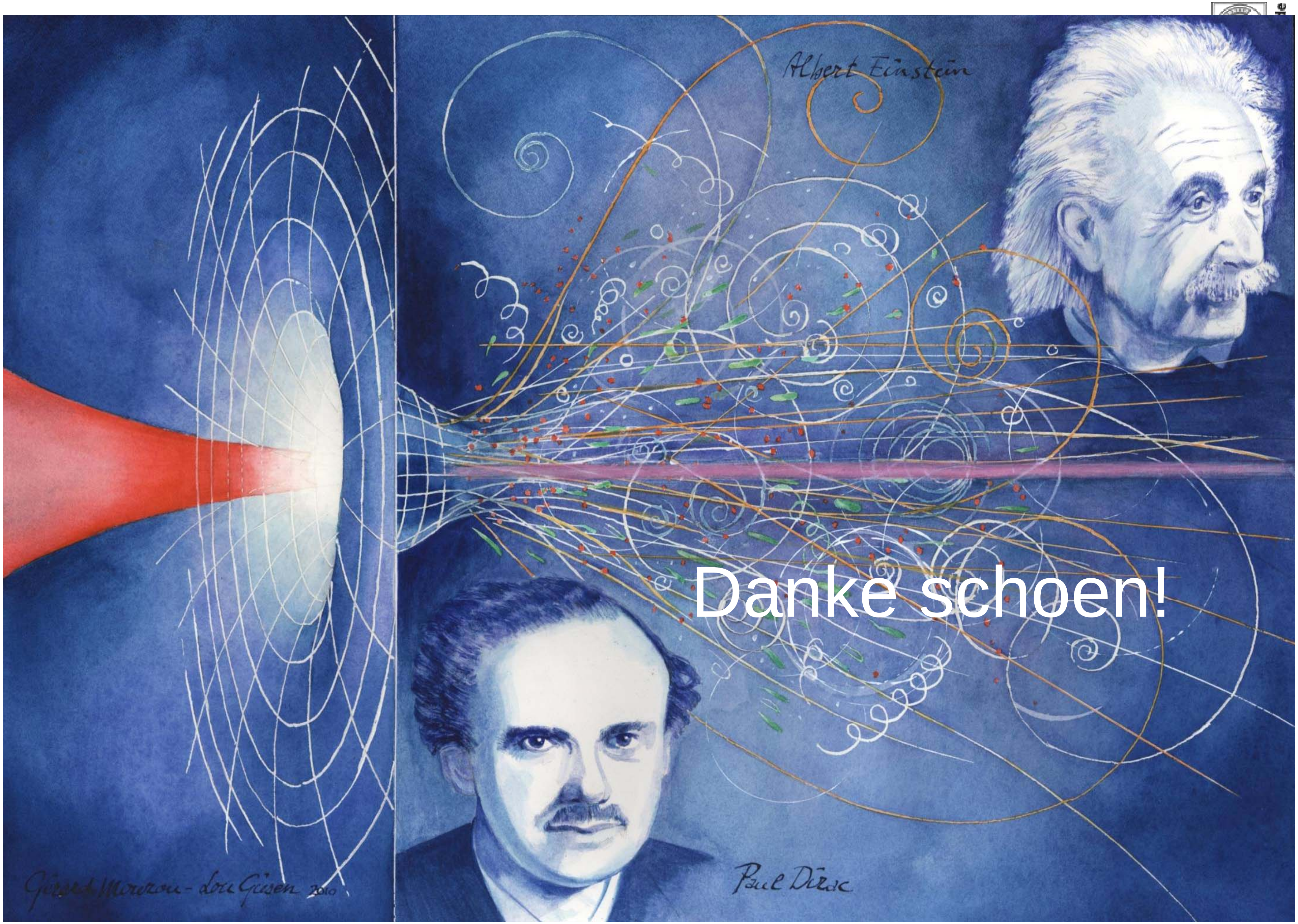
$$R_{e^+e^-} \propto \exp\left(-\left(\frac{8}{3}\right)\left(\frac{m}{\omega}\right)\left(\frac{E_S}{E}\right)\right)$$

e^-e^+ induced by
laser tirggered by γ

High energy γ- induced Schwinger breakdown (Narozhny, 1968; Baier 2010)
CEP phase sensitive laser: electron-positron acceleration
Attosecond electron streaking
γ- energy tagging possible

Conclusions

1. In order to reduce the pulse length,
   we need to increase the intensity
2. Ultrafast Optics ↔ High Field Science
3. Highest energy laser → Shortest pulses
4. Attosecond → Zeptosecond
5. Vacuum physics can learn from Atomic physics
   e.g. laser streaking of atom
6. Vacuum physics ↔ Atomic physics



Danke schoen!

(Mourou, 2010)