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The Nineth Blaise Pascal Lecture
Wednesday, Oct. 27, 2010
Ecole Polytechnique

Ultrafast Science and High Field Sceince

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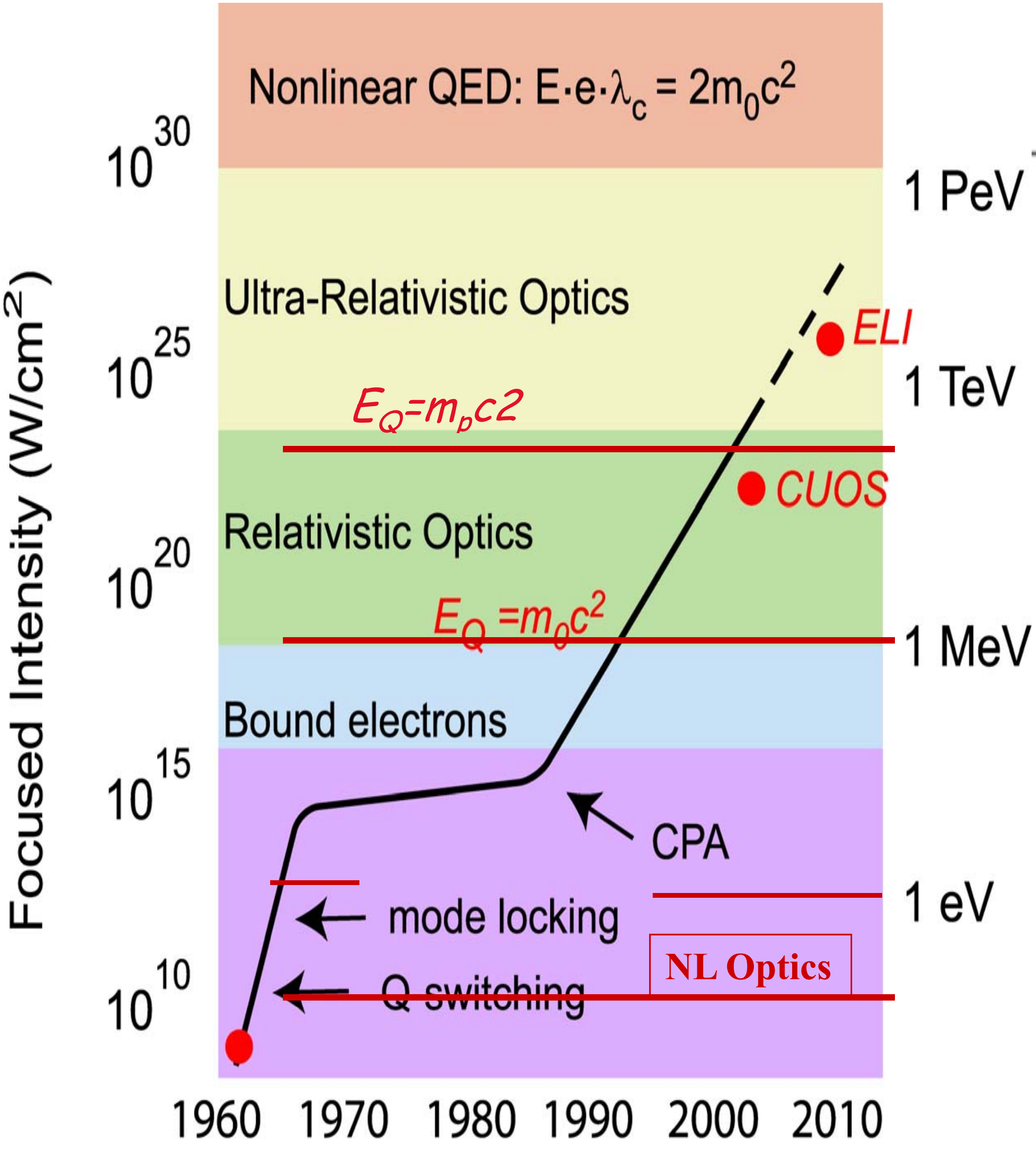


← **Schwinger field**

Vacuum nonlinearity
Radiative nonlinearity

Ultra-relativistic nonlinearity

Relativistic nonlinearity

← **Keldysh field**

Atomic nonlinearity

Nonlinearities in atom, plasma, and vacuum

Atomic
nonlinear potential

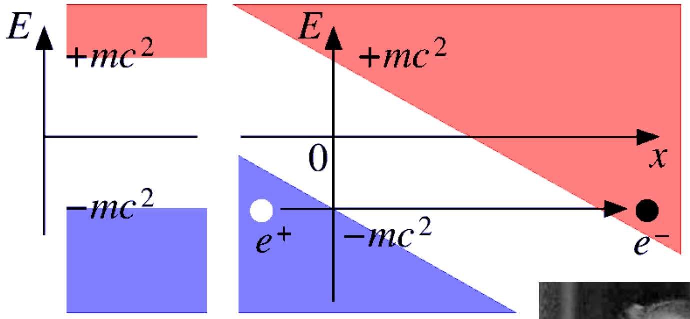
Keldysh field for
laser atomic
ionization

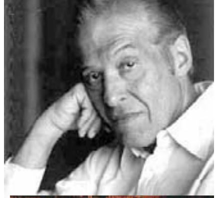
Plasma electron
nonlinear
relativistic motion

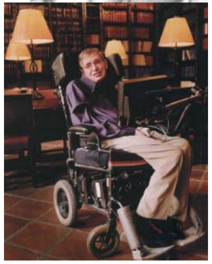
vs.

Laser wakefield

Vacuum nonlinearity







Schwinger field for
vacuum breakdown

Compact high energy colliders
Compact accelerator applications
PeV acceleration for quantum gravity →

Nonlinear QED fields
General relativistic effects
Vacuum probe (s.a. Dark energy)

Relativistic nonlinearity under intense laser

Plasma free of binding potential , but its electron responses:

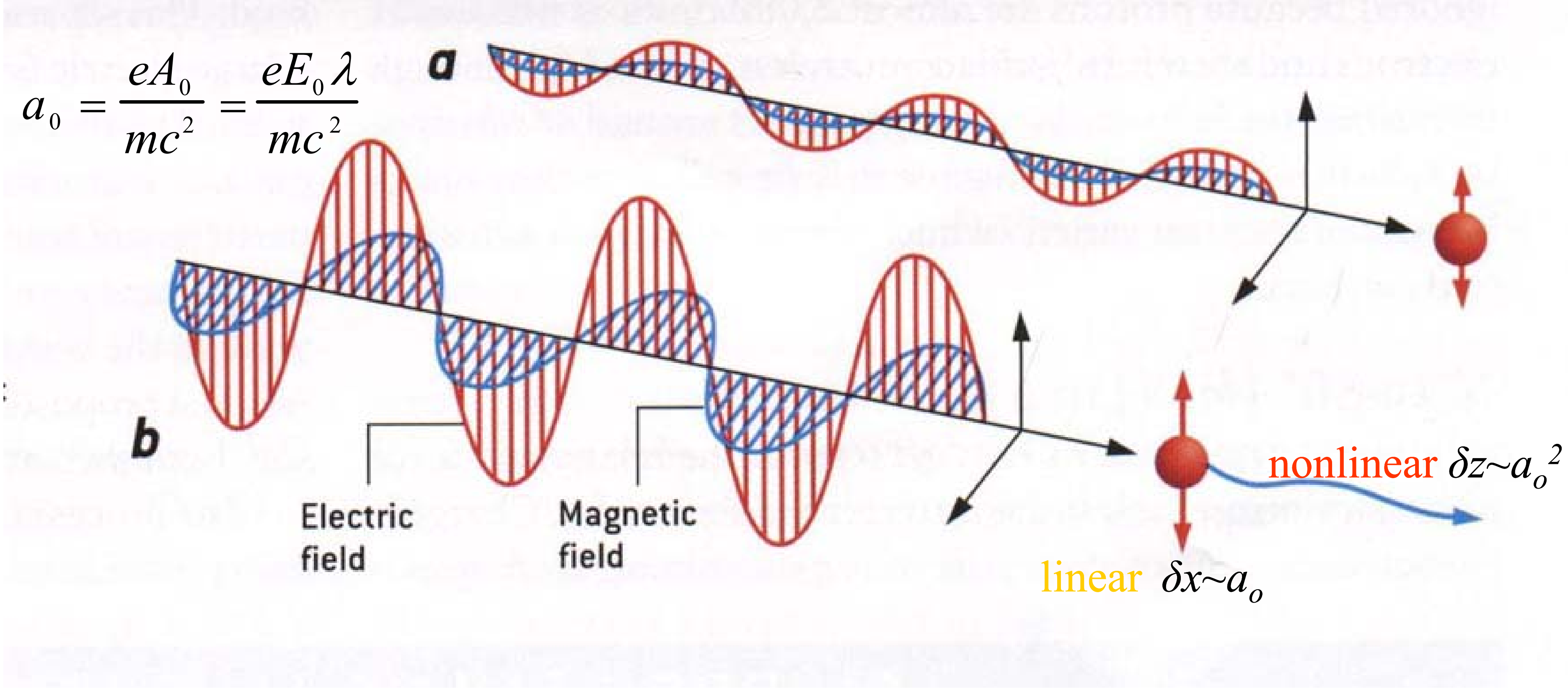
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v \sim c$

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

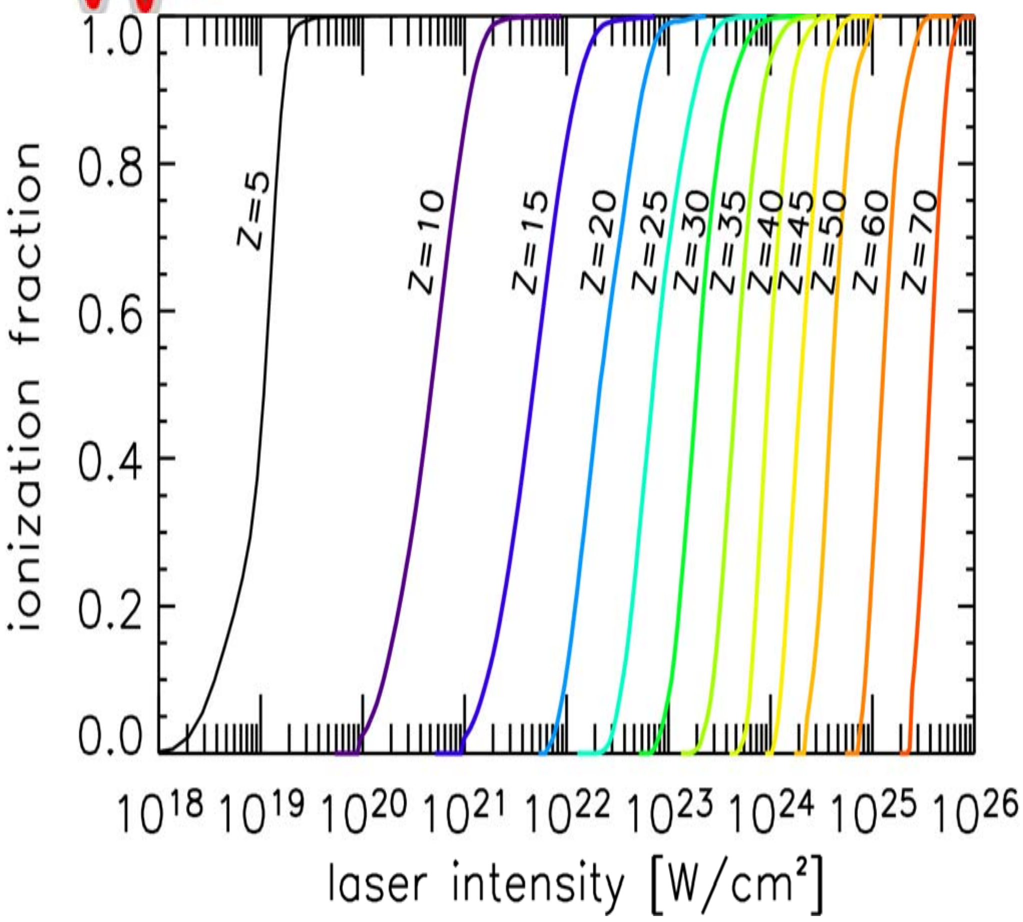
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



nonlinear $\delta z \sim a_o^2$

linear $\delta x \sim a_o$

Strong intensity dependence of electron ionization

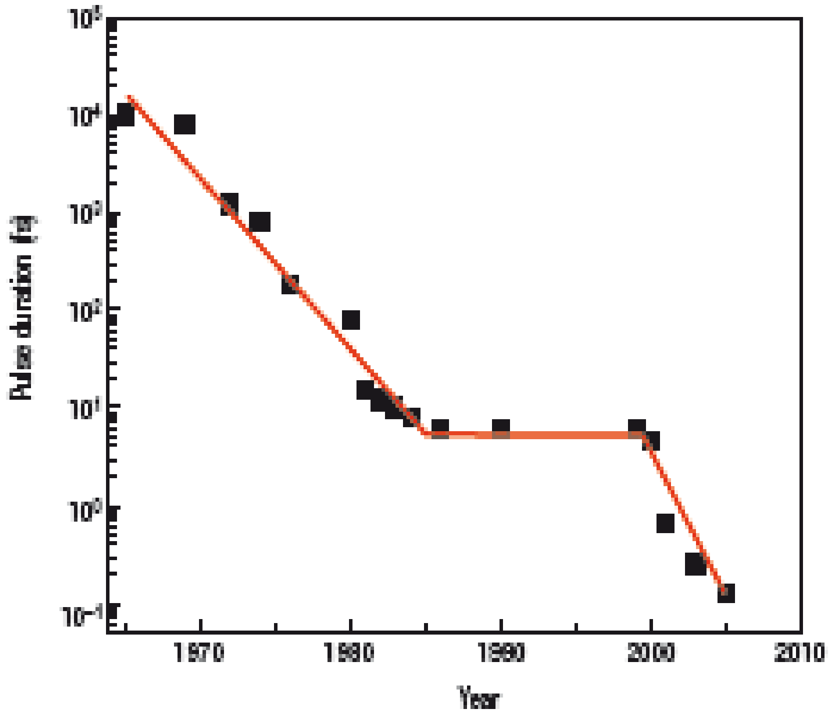


Ionization strongly dependent on laser intensity, typically as a function of I^n

Hetzheim (2009)

Pulse Progress from fs to as

Corkum and Krausz (2007)



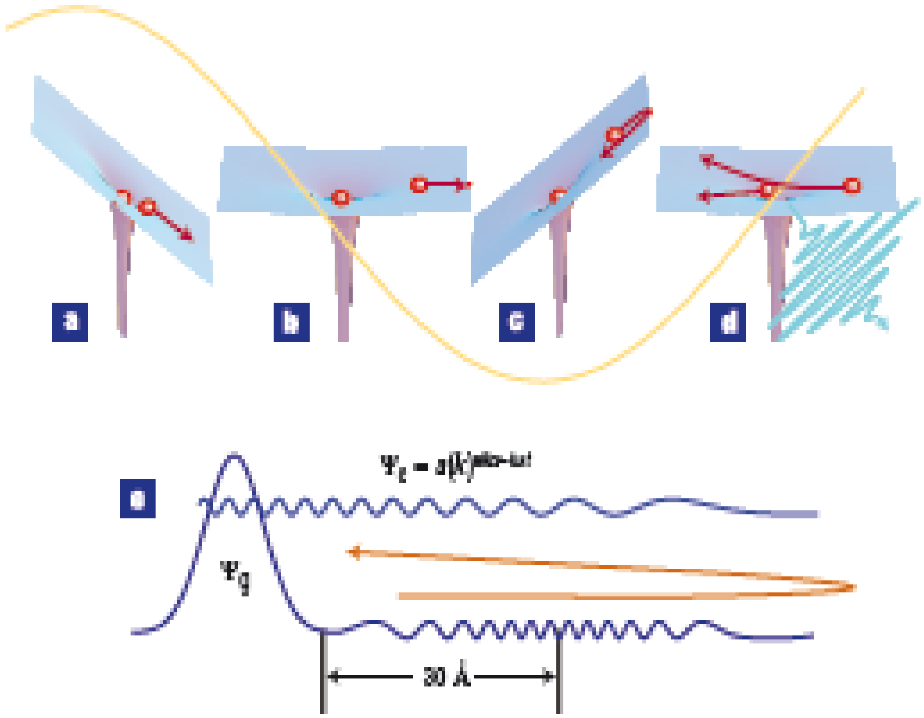
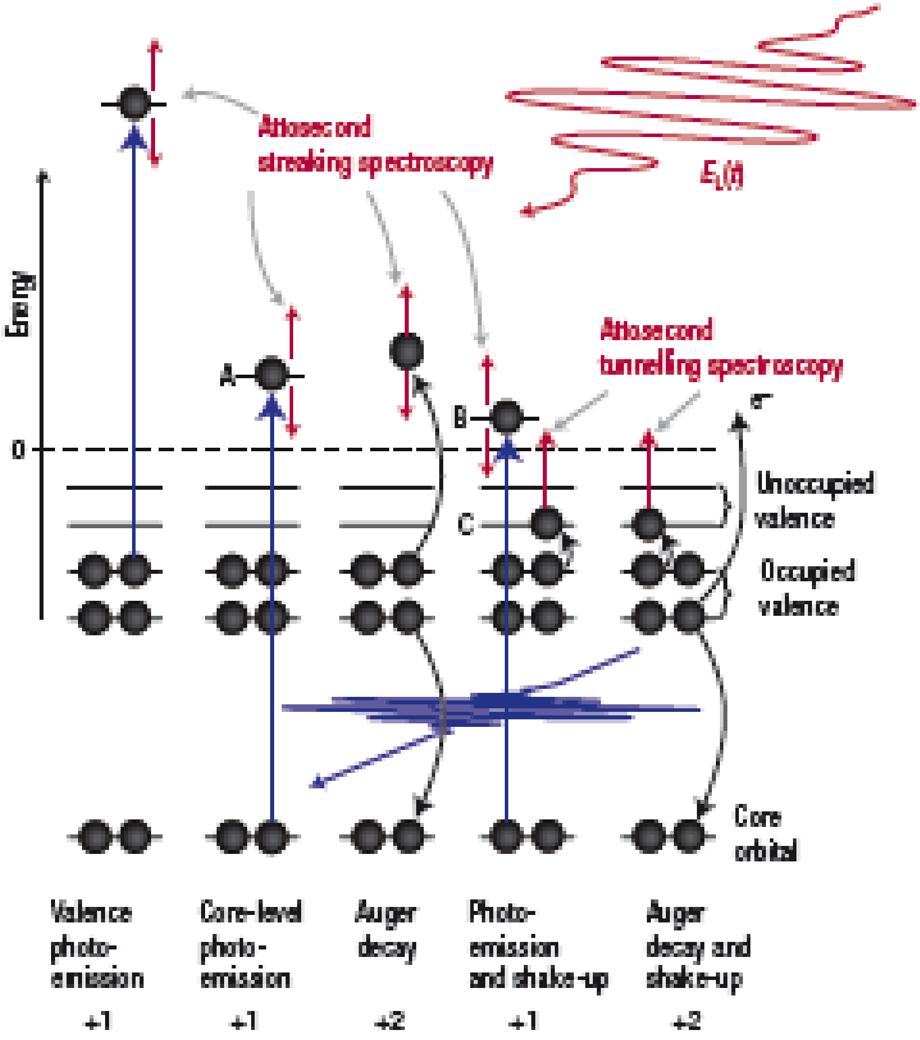


Figure 1 Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1964 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making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

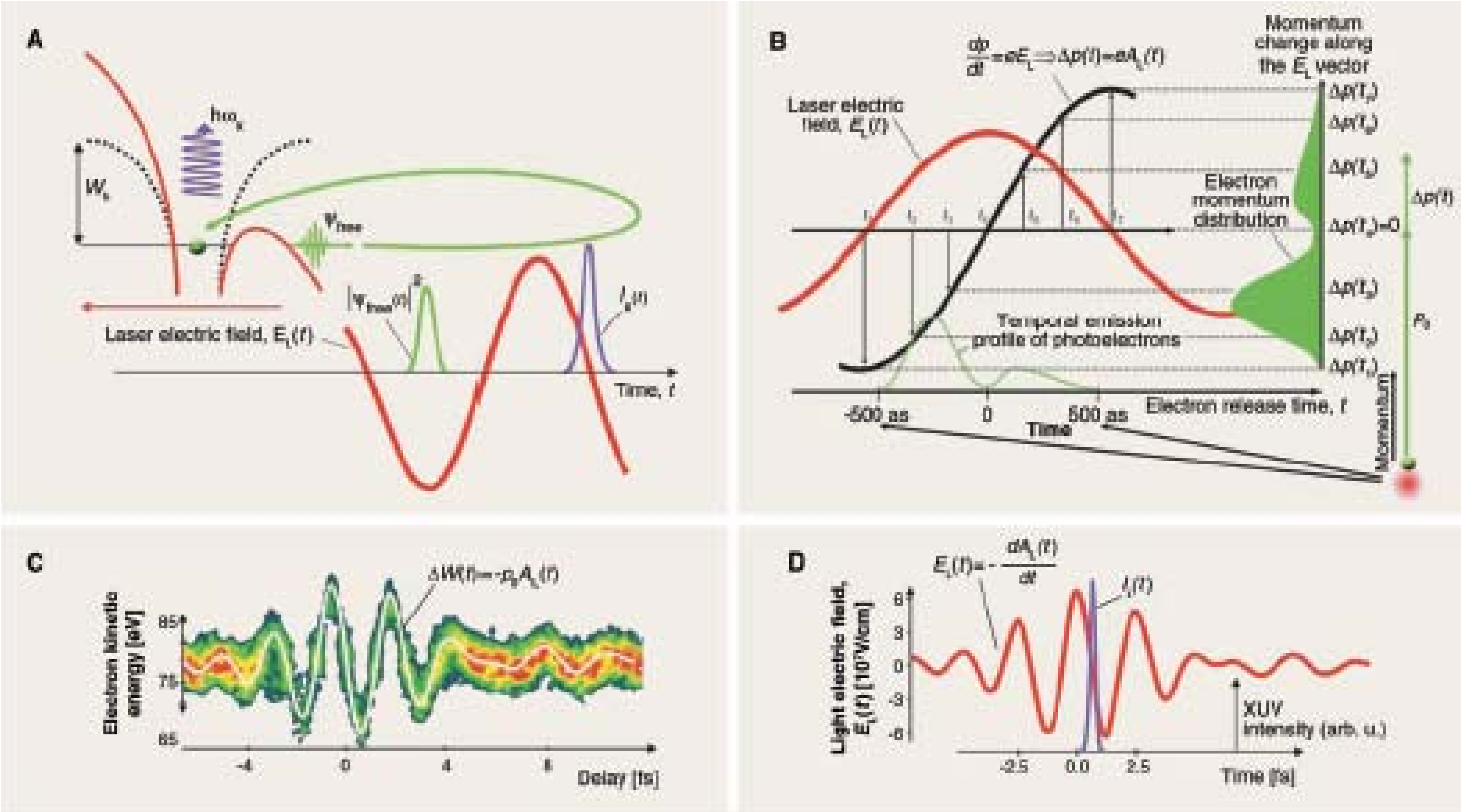
Figure 2 Creating an attosecond pulse. **a–d**, An intense femtosecond near-infrared or visible (henceforth: optical) pulse (shown in yellow) extracts an electron wavepacket from an atom or molecule. For ionization in such a strong field (**a**), Newton's equations of motion give a relatively good description 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

Some of electronic nonlineairies in atoms



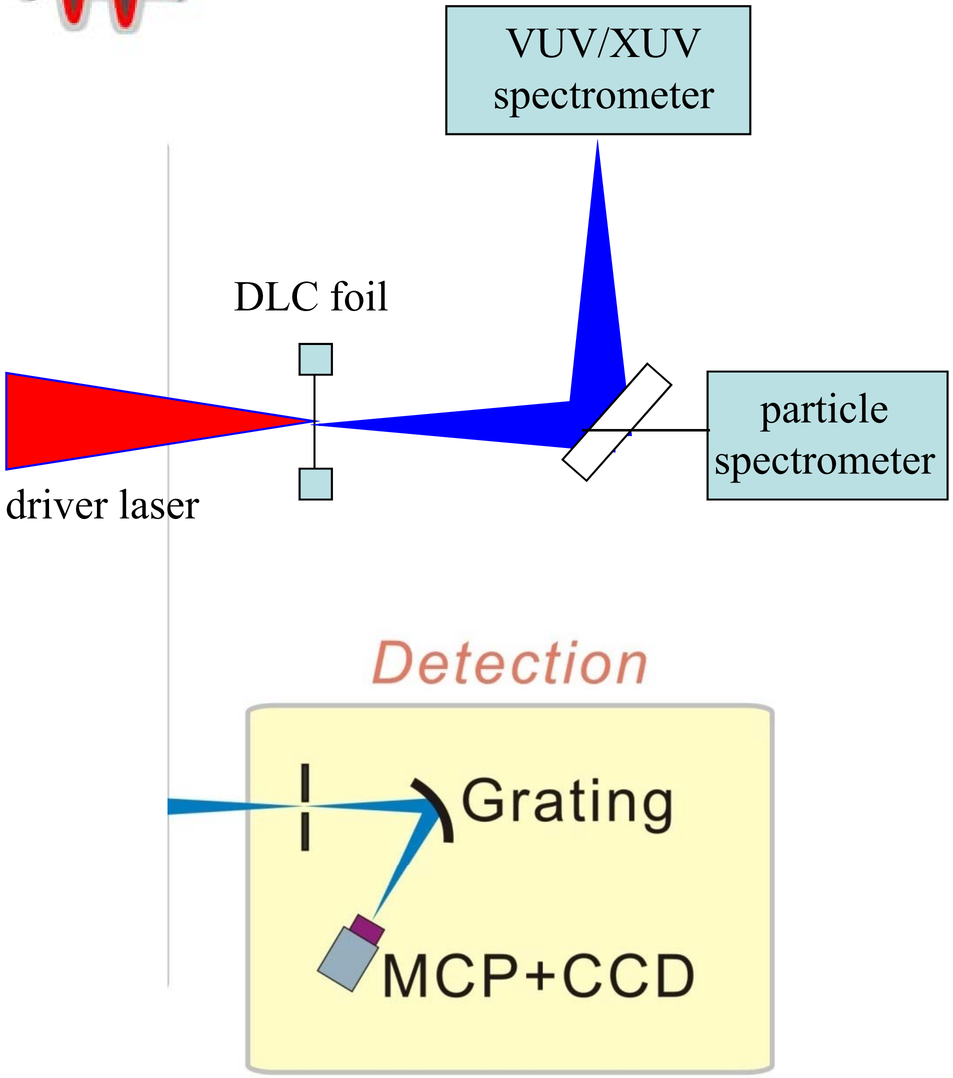
Corkum and Krausz(2007)

Keldysh field and beyond



E. Goulielmakis et al (2008)

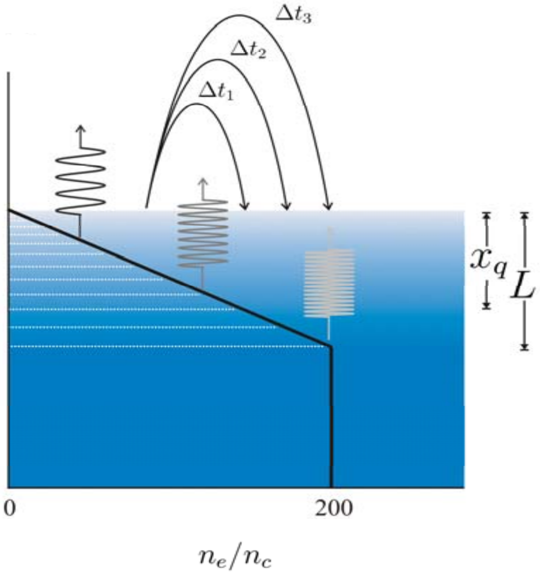
Sold plasma HHG (The Setup)

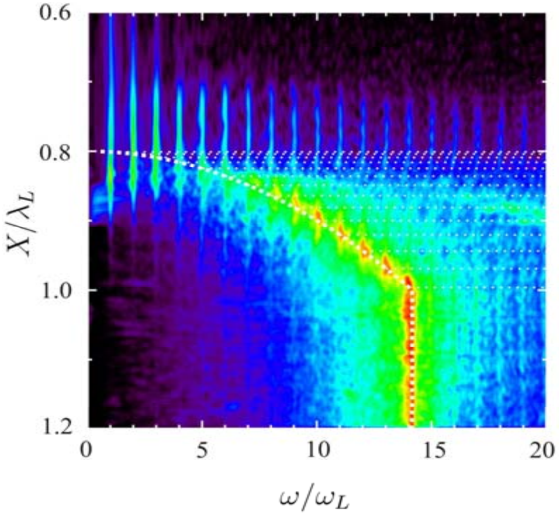


- Laser incident normally onto target
- Collection of XUV-light with spherical mirror
  - ➢ stronger signal for first test
  - ➢ loss of spatial information
- Observable spectral window limited to harmonics 6 to 16
- Gold mirror and grating have polarization dependent reflectivity

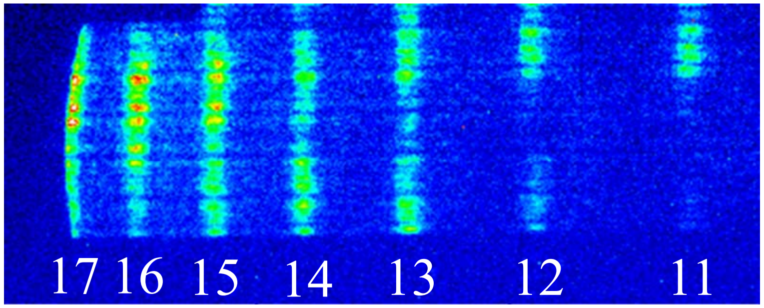
R. Hoerlein (2010)

The Coherent Wake Emission



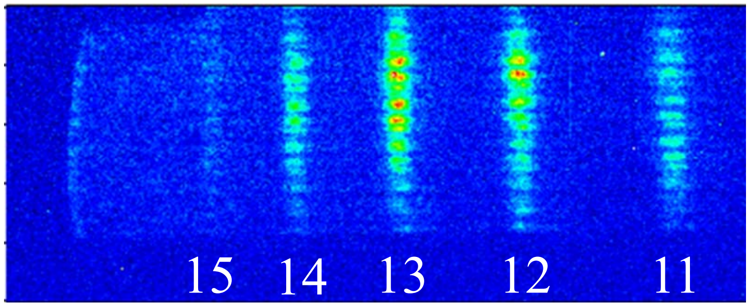


Glass Target (Density 🕔2.6 g/cm^3):



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

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



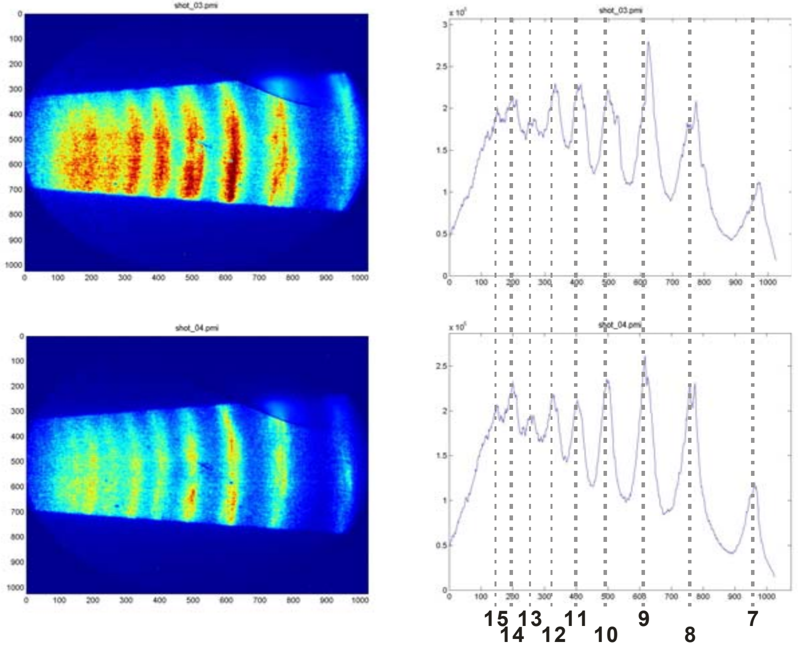
F. Quéré, *et al.*, PRL, **96**, 125004 (2006)

Laser Polarization Dependence

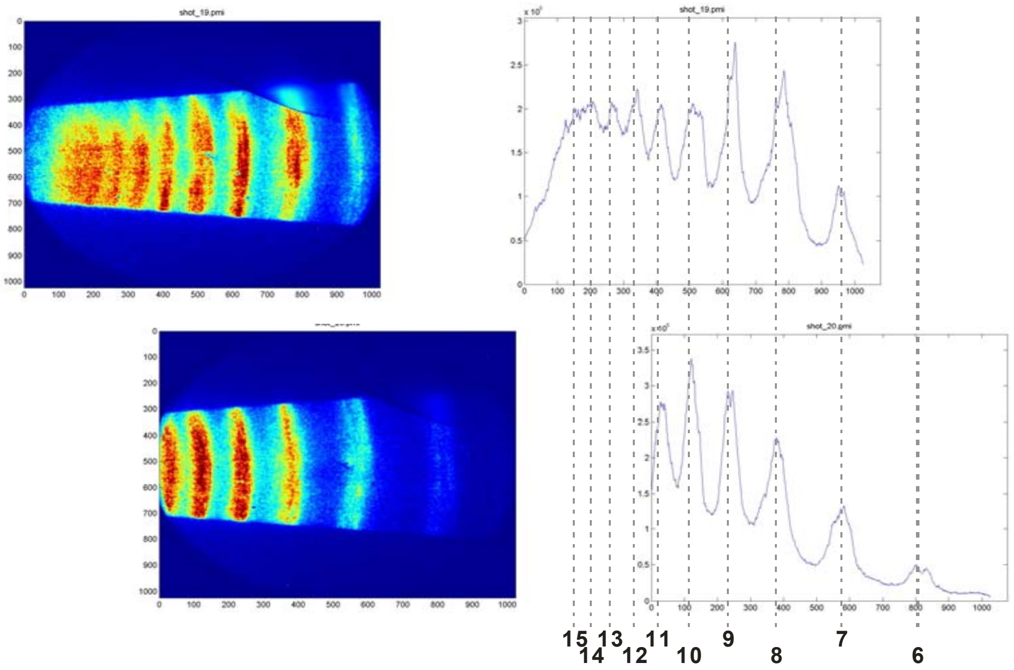
R. Hoerlein (2010)

30nm target

linear polarization



circular polarization



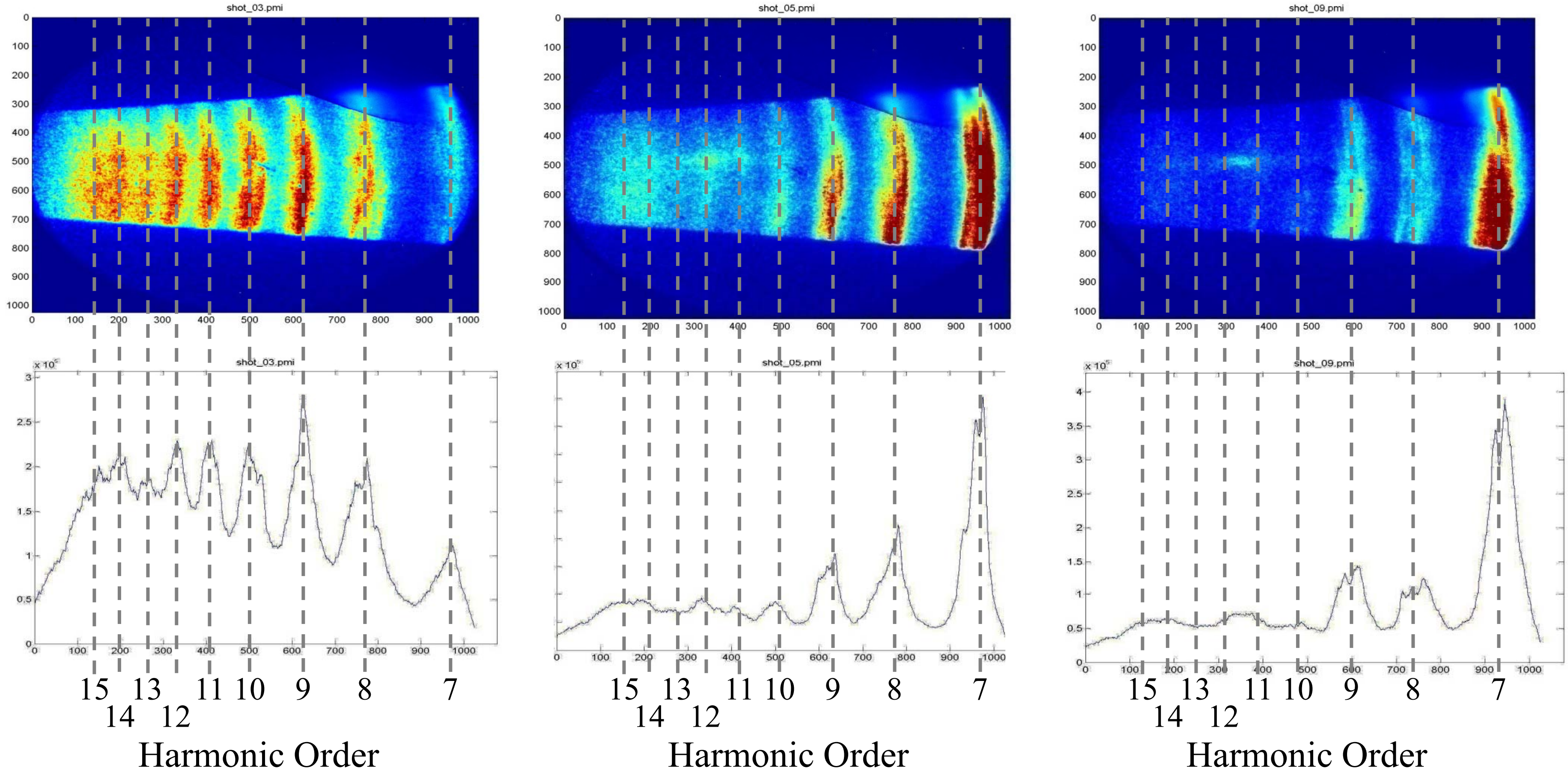
- All harmonic orders (odd and even) are observed
- The harmonic spectra are independent of the laser polarization
- Harmonic generation eficiency is similar in both cases

Target Thickness Dependence

Hoerlein(2010)

Linear Polarization

30 nm DLC　　7 nm DLC　　4.5 nm DLC

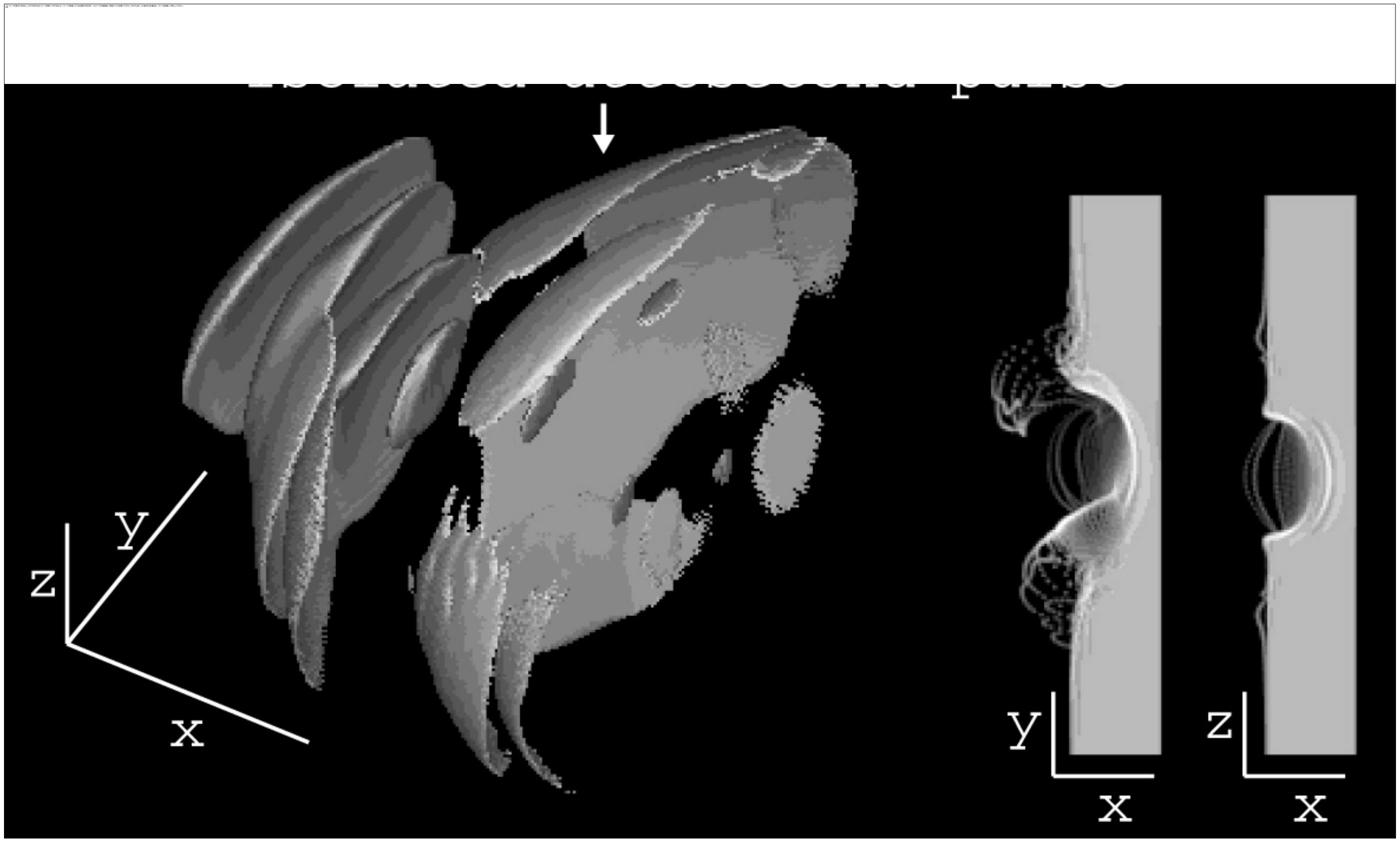


Relativistic oscillating mirror

M. Zepf: up to 4000th harmonics

Isolated attosecond electromagnetic pulses in 3D simulation

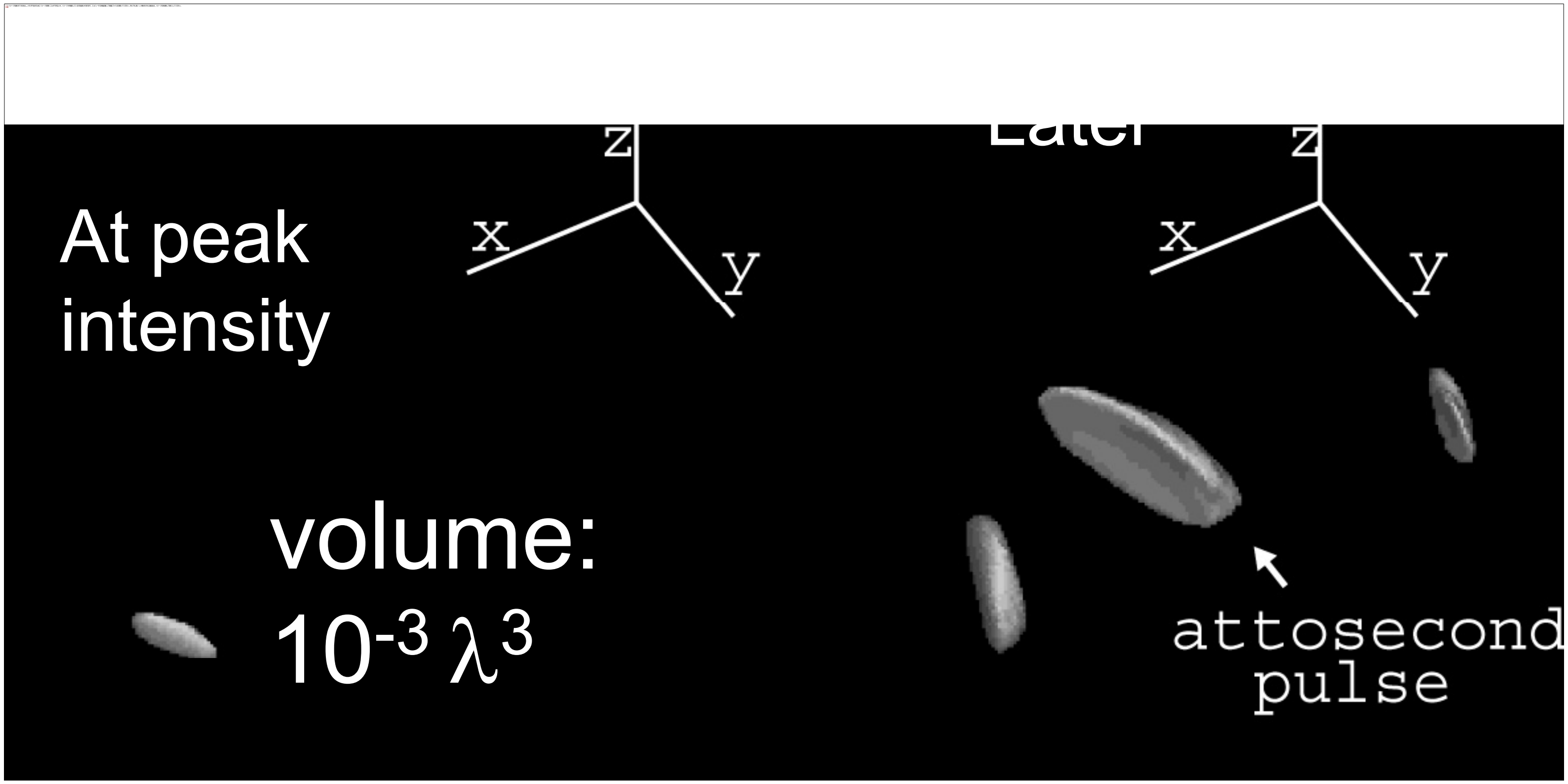
$a_0=3$, $\tau=5\text{fs}$, f/1, $n=1.5n_{cr}$



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, $n=4n_{cr}$



At peak intensity

volume: $10^{-3}\,\lambda^3$

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

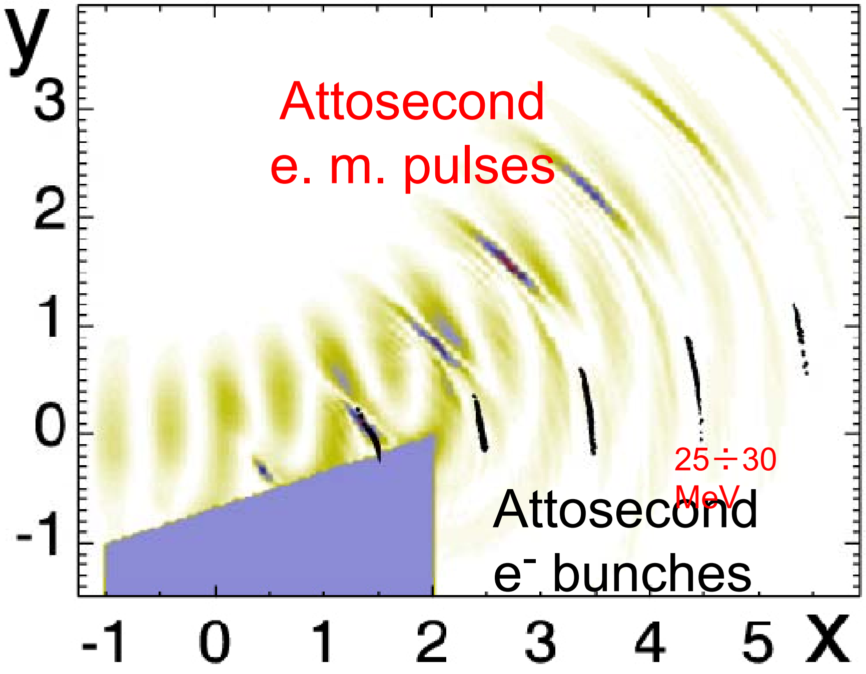
Electron ejection is synchronized with attosecond pulse generation

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!

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

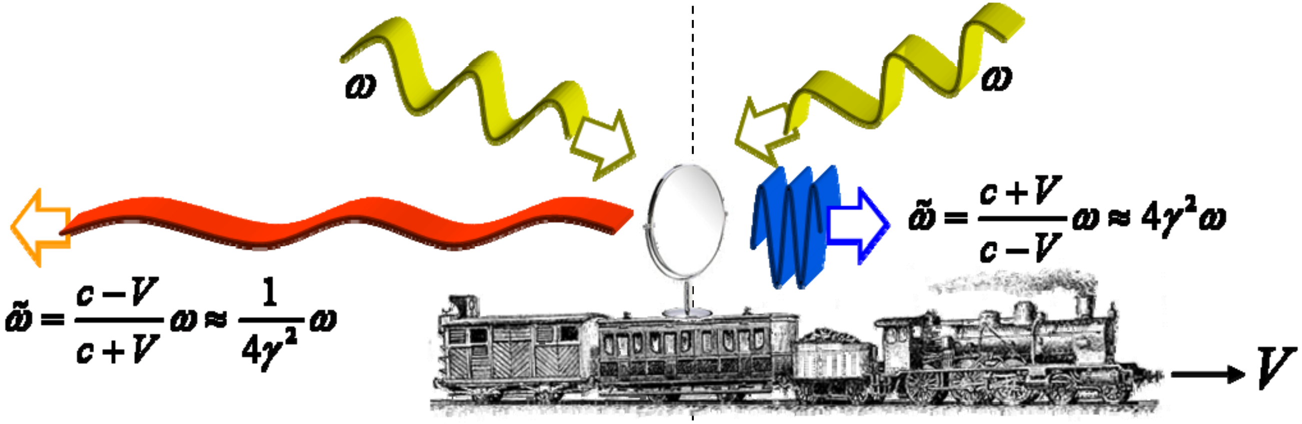
Efficiency of attosecond phenomena: ~15% converted to attosecond pulses, ~15% to electron bunches.



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

Relativistic flying mirror and shorter pulses

Esirkepov (2010)

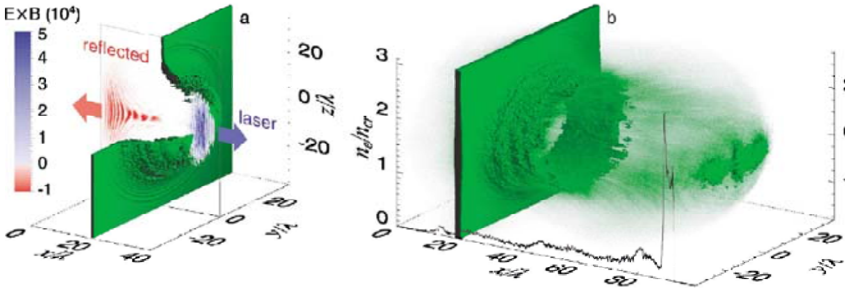


$$\tilde{\omega} = \frac{c+V}{c-V}\omega \approx 4\gamma^2\omega$$

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

Laser Piston

Flying Mirror



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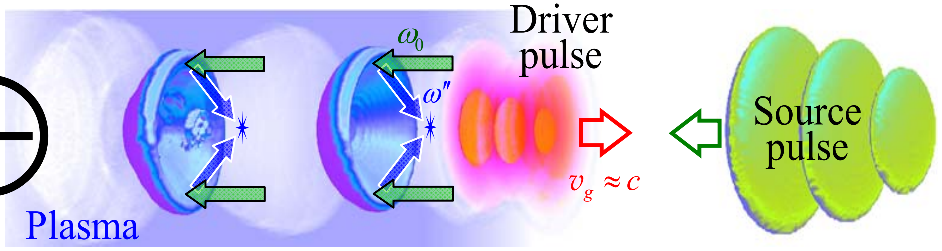
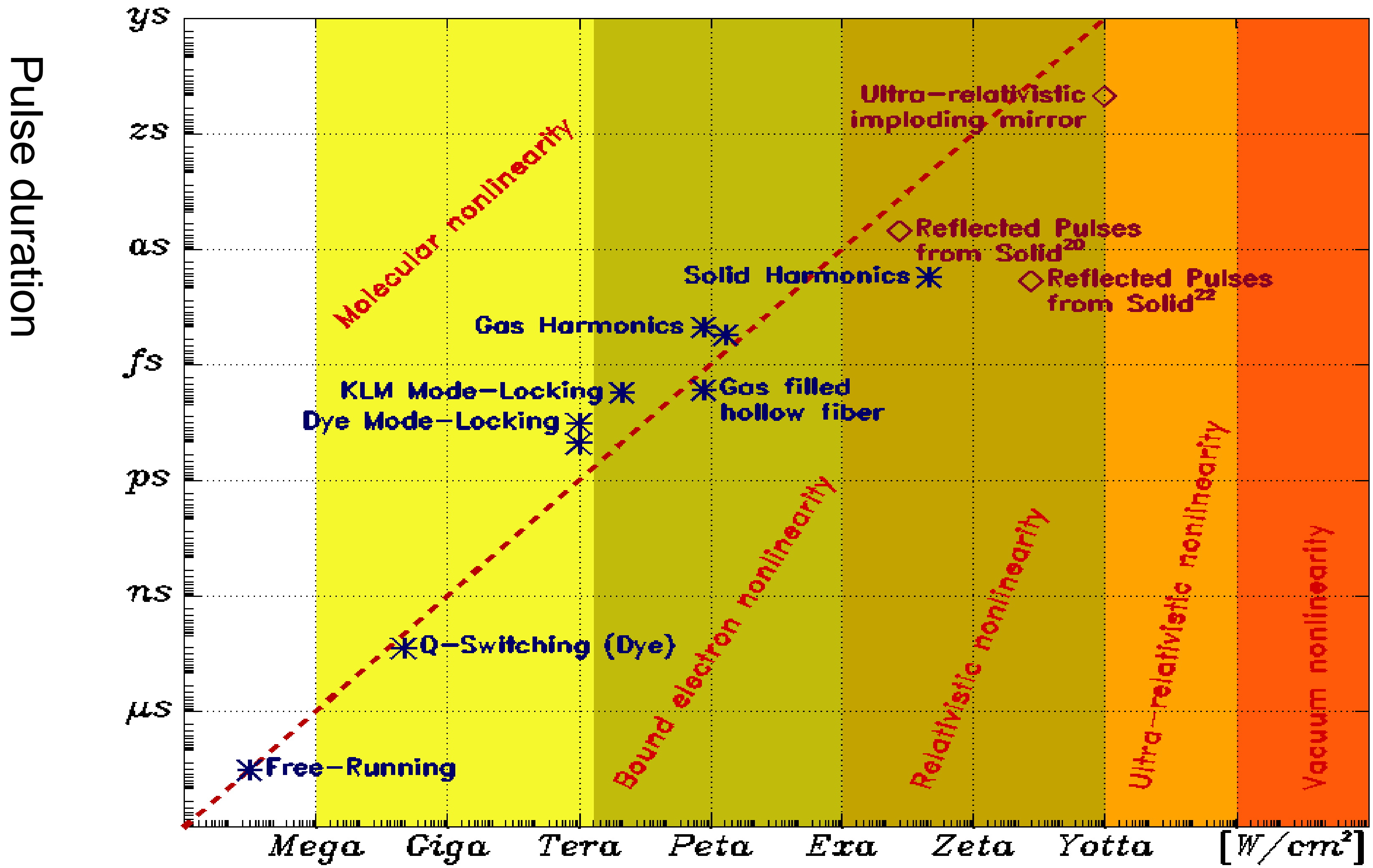


Tajima/Mourou/Moses(2010): use NIF ---ultra-relativistic imploding mirror → ys!

The Mourou Conjecture

(← physics: “Matter is nonlinear” “The rigider nonlinearity, the more intense to manipulate it”)

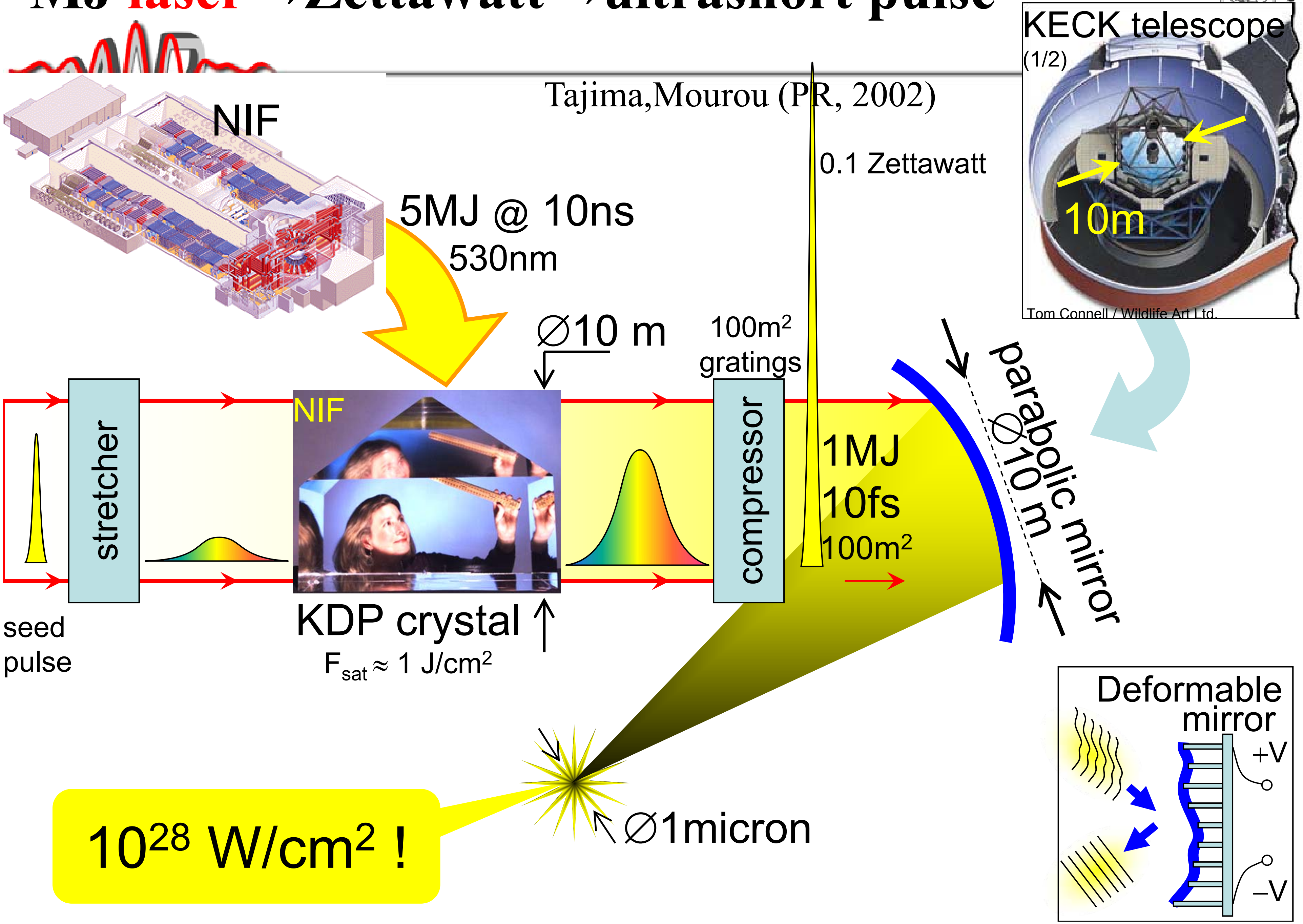


Pulse intensity →

(Mourou / Tajima, 2010)

P= E/T

MJ laser→Zettawatt→ultrashort pulse



Tajima,Mourou (PR, 2002)

NIF

5MJ @ 10ns
530nm

0.1 Zettawatt

KECK telescope
(1/2)

10m

Tom Connell / Wildlife Art Ltd

∅10 m

100m^2
gratings

NIF

seed
pulse

stretcher

KDP crystal

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

compressor

1MJ
10fs
100m^2

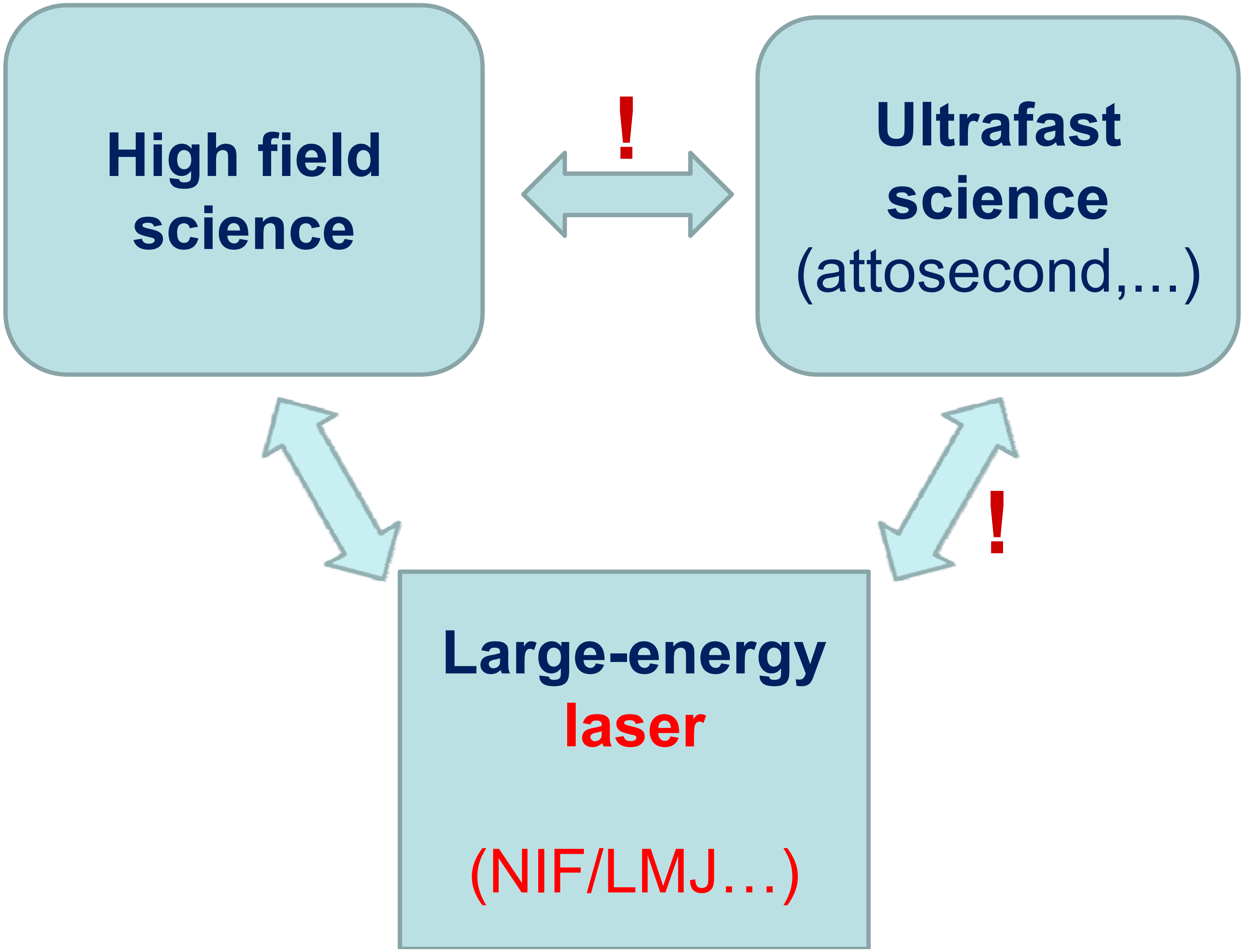
parabolic mirror
∅10 m

Deformable
mirror
+V
−V

∅1micron

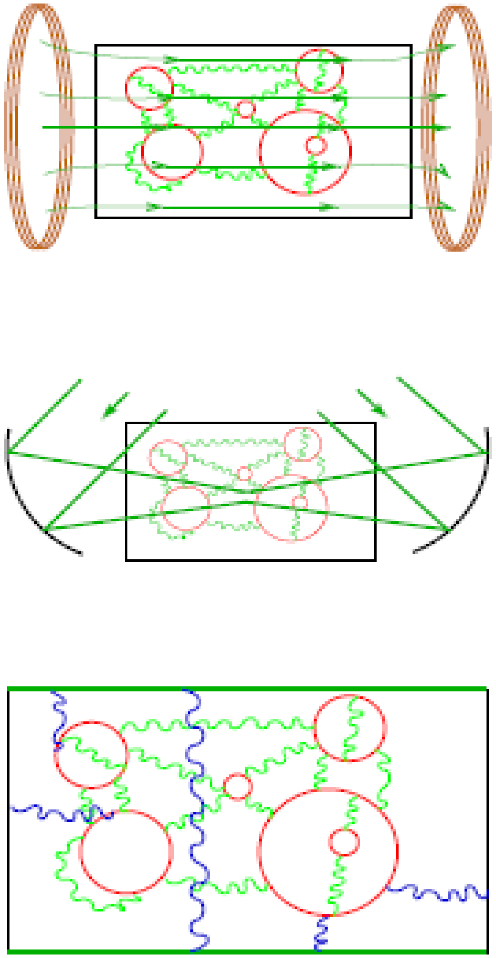
10^{28} W/cm^2 !

Ultrafast science ← High field science, Large-energy laser



Why quantum vacuum physics?

Vacuum nonlinearities



- Heisenberg-Euler/Casimir in mathematical physics
  - QFT in strong fields or with boundaries
  - functional determinants
- applied quantum vacuum physics
  - quantum fluctuations as a building block
  - dispersive forces in micro/nano machinery [DeKieviet @ ThisWorkshop]
- fundamental effect of QFT
  - ($\sim$ Lamb shift, $g-2$, ...)
- fundamental physics
  - search for new physics
  - new particles or forces

H. Gies (2008)

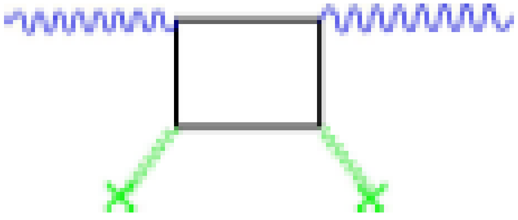
Light Propagation in a B field.

- quantum Maxwell equation for a "light probe" $f^{\mu\nu}$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45}\frac{\alpha^2}{m^4} F_{\alpha\beta}F^{\mu\nu}\partial_\mu f^{\alpha\beta} - \frac{14}{45}\frac{\alpha^2}{m^4}\tilde{F}_{\alpha\beta}\tilde{F}^{\mu\nu}\partial_\mu f^{\alpha\beta}$$

↑ vacuum nonlinearity ↑

Phase and group velocity



$$v_\parallel \simeq 1 - \frac{14}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

$$v_\perp \simeq 1 - \frac{8}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

(Toll'54)

(Baier, Breitenlohner'67; Narozhny'69)

(Bialynicka-Birula, Bialynicki-Birula'70)

(Adler'71)

$\Longrightarrow$ magnetized quantum vacuum induces birefringence

[DiPiazza @ ThisWorkshop]

- detection schemes: PVLAS, BMV, Q&A, OSQAR, TR18-B7

H. Gies (2008)

Self-focusing: $P_{cr} = (90/28)\, c\, E_S{}^2\lambda^2/\alpha \;\rightarrow P_{cr} \approx 10^{24}\, (\omega_1 \text{ (at } 1\mu) /\omega)^2$ W

(Mourou/Tajima/Bulanov (2006))

Self-focusing in air to 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

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

vacuum nonlinearity

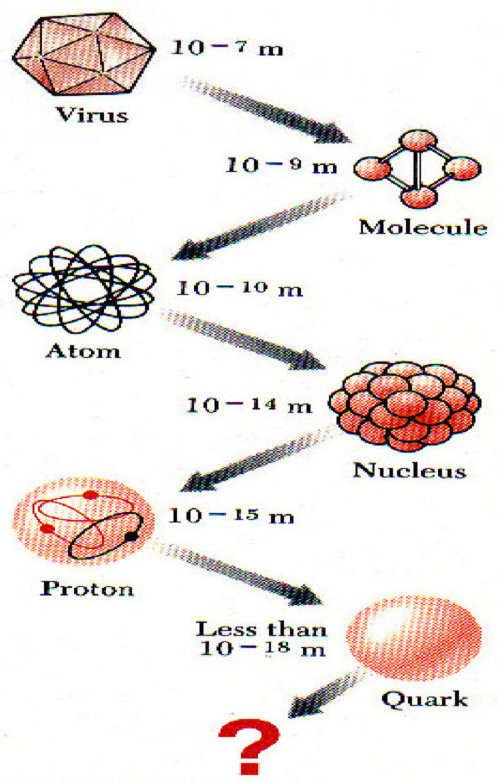
$$P_{cr} = (90/28)\,c\,E_S^2\lambda^2/\alpha \sim 10^{15}\,(\lambda/\lambda_{1\mu})^2\ \mathrm{GW}$$

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

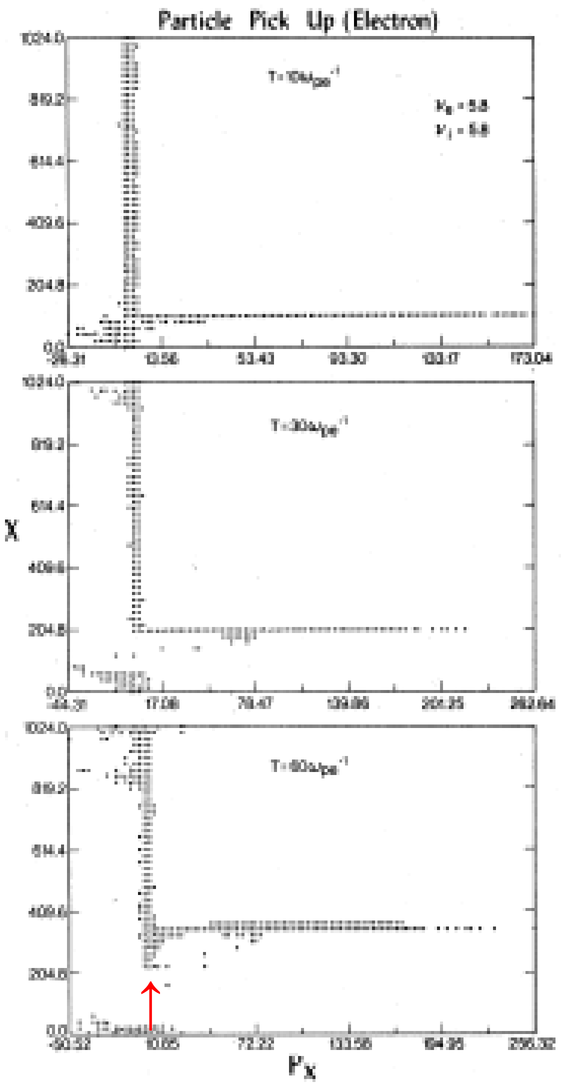
Schwinger intensity / Keldysh intensity $= \alpha^{-6} \sim 10^{14}$
Vacuum self-focusing /χ_3 self-focusing power $\sim \alpha^{-6} \sim 10^{15}$

Schwinger field

Does the atomic world repeat itself in vacuum?

Self-focusing and laser acceleration in vacuum

3 ULTRARELATIVISTIC ELECTROMA



on the piston, and pressure balance yields

$$2\langle n\rangle_w\langle p_x\rangle_w v_g = \tfrac{1}{2}[(E_w^2 + B_w^2)/8\pi] , \qquad (10)$$

where v_g is the piston (wave-front) velocity, the subscript w indicates that the fields, momentum, and density are to be evaluated in the moving frame of the interace, and $\langle n\rangle$ and $\langle p_x\rangle$ are, respectively, the average density and momentum at the leading edge of the pulse (over a length c/ω_{pe} in the laboratory frame). Lorentz transformations from the moving to the lab frame yield

$$2v_g(\langle n\rangle_L/\gamma_g)(\langle p_x\rangle_L/2\gamma_g) = \tfrac{1}{2}E_L^2/\gamma_g^2 , \qquad (11)$$

where the subscript L denotes laboratory frame variables and the relativistic factor $\gamma_g = [1-(v_g^2/c^2)]^{-1/2}$.

Our simulations show that $\langle p_x\rangle_L \simeq \tfrac{1}{2}p_x^m$ and $\langle n\rangle_L \simeq \tfrac{1}{2}n_{\max}$, with $n_{\max} \simeq 20n_0$ (twenty times the original density) at saturation, so that

$$p_x^m = 2(c/v_g)[\omega^2/\omega_{pe}^2(n_0)][\omega_{pe}^2(n_0)/\omega_{pe}^2(n_{\max})]\nu^2 mc . \qquad (12)$$

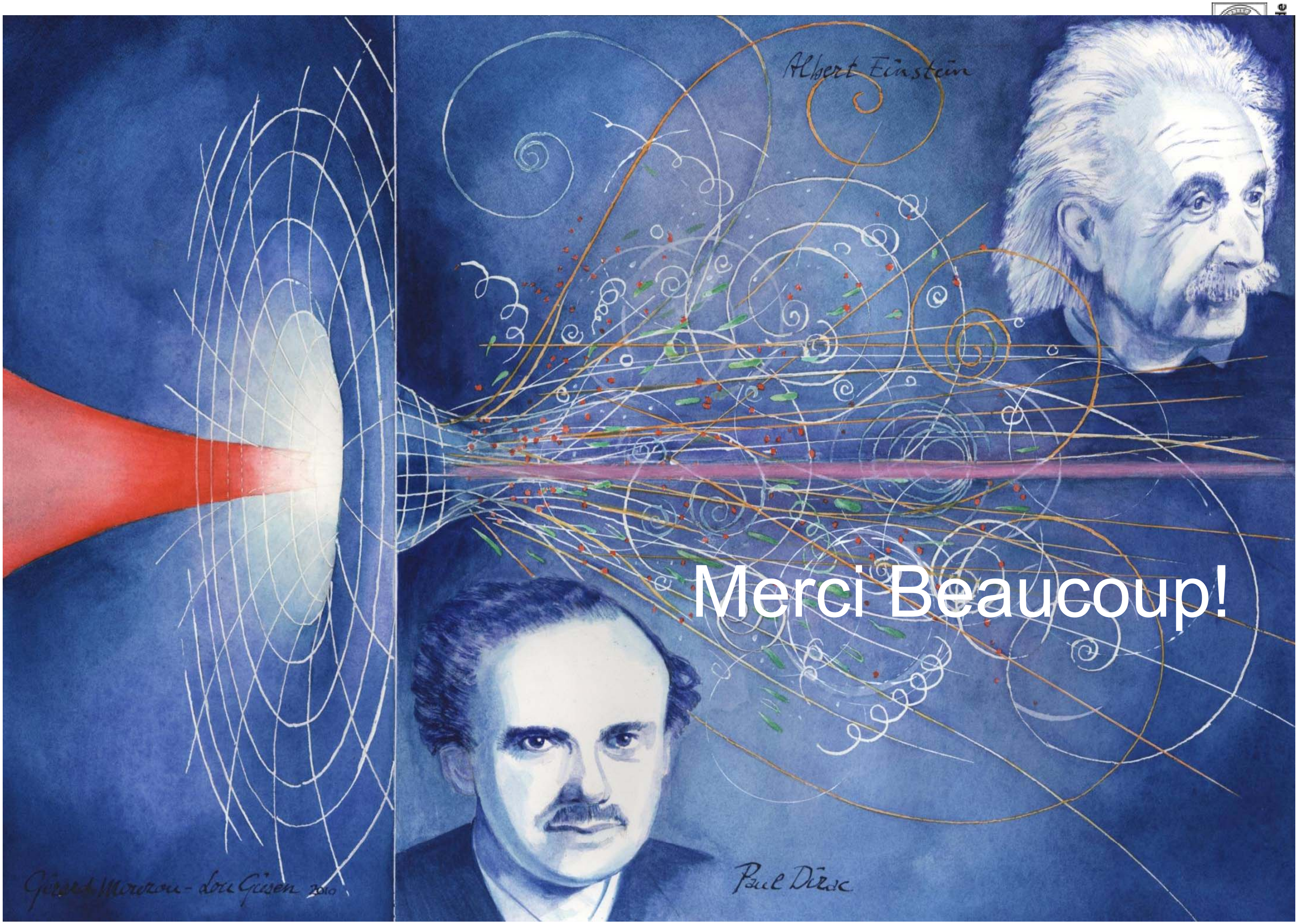
With $\omega^2/\omega_{pe}^2(n_0) \simeq 10$ and $\omega_{pe}^2(n_0)/\omega_{pe}^2(n_{\max}) \simeq \frac{1}{20}$, we obtain

$$P_x^m \simeq (c/v_g)\nu^2 mc \sim \nu^2 mc , \qquad (13)$$

→ Laser acceleration in vaccum by
self-focused X-ray crossed with laser ?

Can we repeat LWFA and plasma physics
in vacuum?
Laser vacuum acceleration with ‘snowplow’

Ashour-abdalla, et al. (1981)



Merci Beaucoup!

(Mourou, 2010)