Chaires internationales de recherche Blaise Pascal

*Financée par l'État et la Région d'Ile de France,*
*gérée par la Fondation de l'École Normale Supérieure*

**The Fourth Blaise Pascal Lecture**
**Wednesday, January 20, 2009**
**Ecole Polytechnique**

# Relativistic Engineering

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Acknowledgments for Collaboration and advice: G. Mourou, N. Naumova, V. Malka, J. Fuchs, C. Labaune, P. Mora, F. Krausz, D. Habs, T. Esirkepov, S. Bulanov, A. Henig, R. Hoerlein, W. Sandner, A. Faenov, P. Bolton, T. Pikuz, A. Pirozgkov, M. Borghesi, M. Gross, M. Kando, A. Pirozhkov, L. M. Chen, Y. Kato, A. Ogata, K. Kawase, T. Hayakawa, R. Hajima, C. Barty, Y. Fukuda

# Pascal Lecture Plan

**(tentative, need your feedback)**

- Oct.22: First Lecture (General) “ Laser Acceleration and High Field Science: 1979-2009”
- Nov.18: Second Lecture “Laser Electron Acceleration and its Future”
- Dec.9: Third Lecture “Laser Ion Acceleration”
- January,20,2010: “Relativistic Engineering”
- February, 26: “High Field Science”
- March: “Photonuclear Physics”
- April: “Medical Applications”
- ……

# 1000-fold Challenges

## Frontier science driven by advanced accelerator

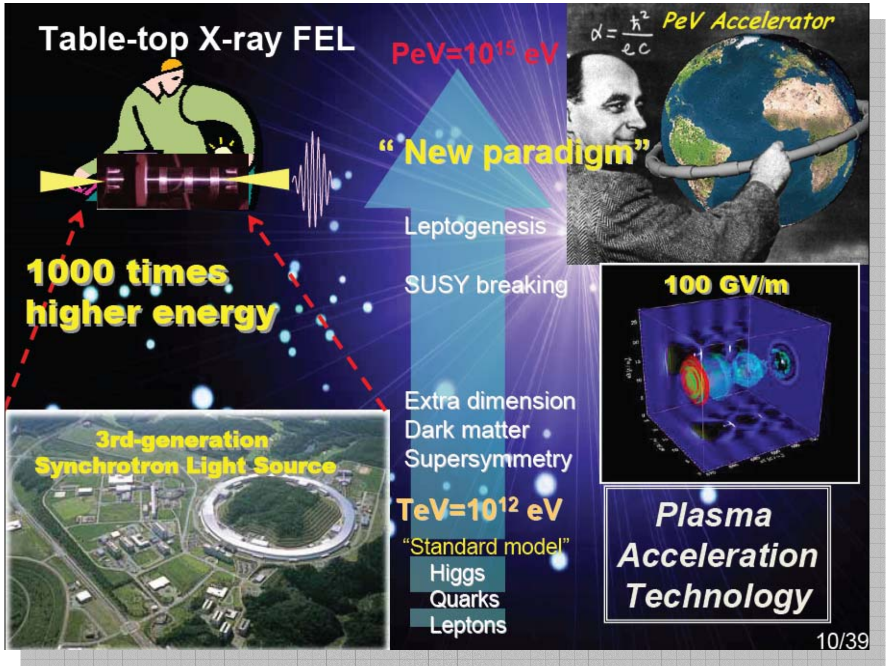


Table-top X-ray FEL

PeV=$10^{15}$ eV

$\alpha = \frac{\hbar^2}{ec}$ PeV Accelerator

"New paradigm"

Leptogenesis

SUSY breaking

100 GV/m

1000 times higher energy

Extra dimension
Dark matter
Supersymmetry

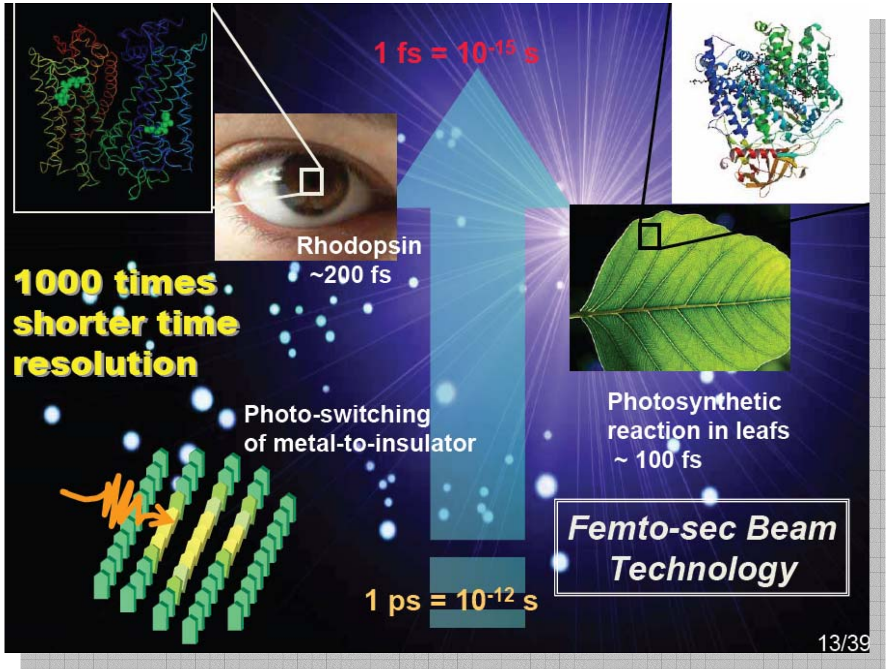
3rd-generation Synchrotron Light Source

TeV=$10^{12}$ eV

"Standard model"
Higgs
Quarks
Leptons

Plasma Acceleration Technology

10/39



1 fs = $10^{-15}$ s

Rhodopsin
~200 fs

1000 times shorter time resolution

Photo-switching
of metal-to-insulator

Photosynthetic
reaction in leafs
~ 100 fs

Femto-sec Beam Technology

1 ps = $10^{-12}$ s

13/39

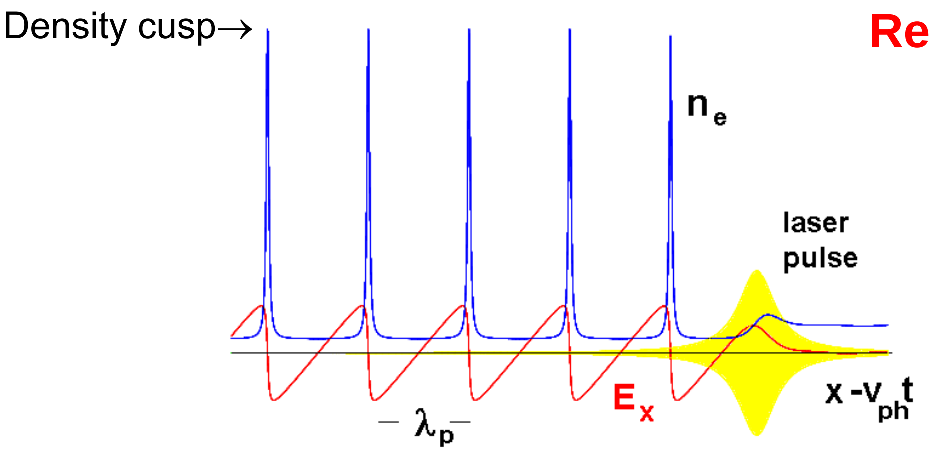
(KEK：A. Suzuki)

compact, ultrastrong *a*

atto-, zeptosecond

***Can we meet the challenge?***
***How can we meet it ?***

# Relativistic Dynamics and Wakefields



**Relativistic coherence**

← *v* tends to *c; *velocities condense toward *c*

(cf. **quantum coherence**; energies condense toward 0)

**T. Tajima and J. Dawson, Phys. Rev. Lett. 43, 267 (1979)**

Condition for density cusp formation :

$$J = |\partial x / \partial x_0| \rightarrow 0$$

(δEulerian coordinate/ δLagrangian coordinate) → 0

Cusp density happens : $v_e \rightarrow v_{ph} \sim c$

Density diverges at wavehead

$$n_e\Big|_{x=x_{br}} \rightarrow \infty$$

# RE / Flying Mirror Concept:

S. V. Bulanov, T. Zh. Esirkepov, and T. Tajima,
"Light Intensification towards the Schwinger Limit"
Phys. Rev. Lett. **91**, 085001 (2003)

N. Naumova et al. Phys. Rev. Lett. 93, 195003 (2004).

M. Kando, et al. Phys. Rev. Lett. **99**, 135001 (2007)

A. S. Pirozhkov,et al.,
Phys. Plasmas 14, 123106 (2007)

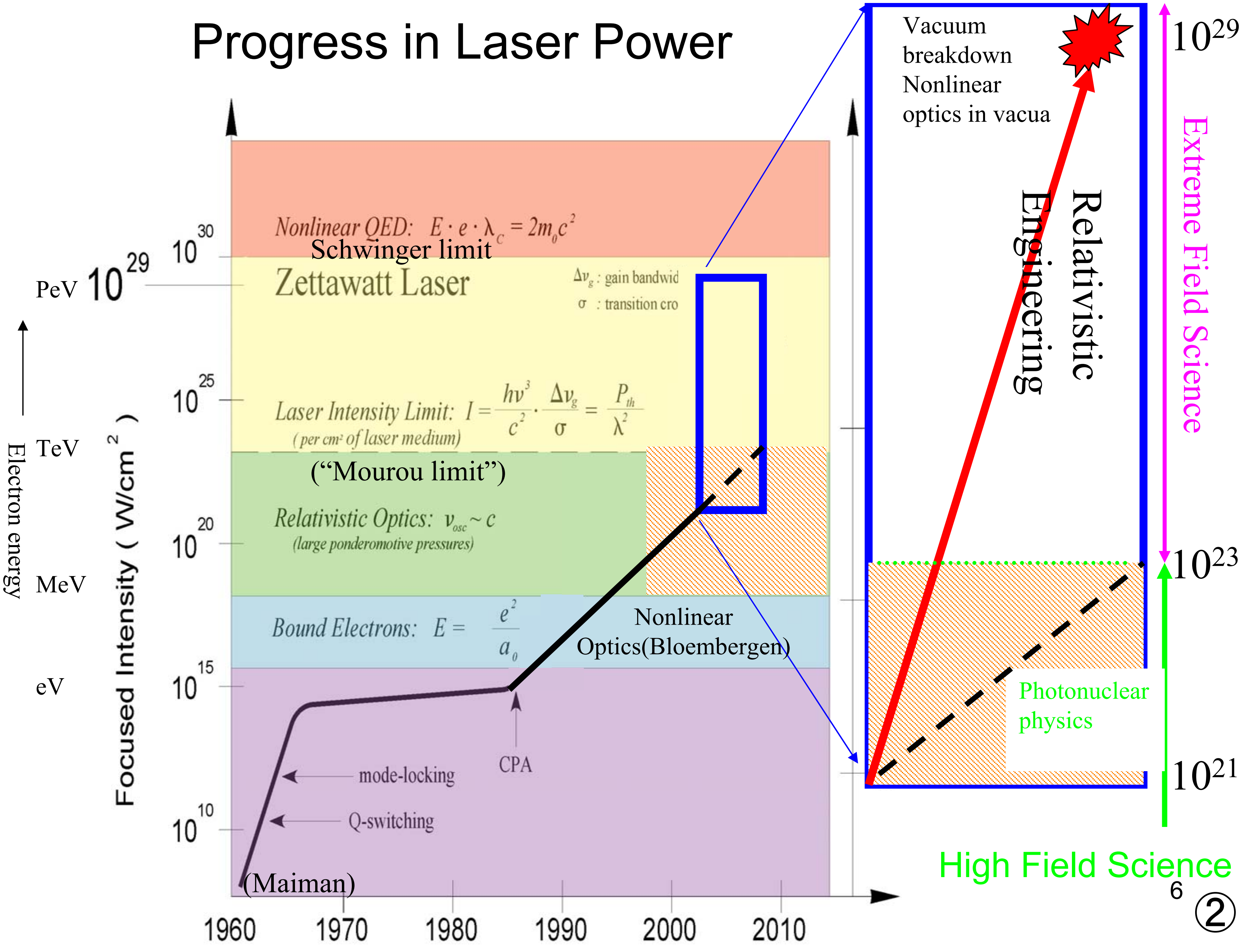
M.Kando, et al. Phys. Rev. Lett. **103**, 235003 (2009).

T. Esirkepov. et al., Phys. Rev. Lett. **103**, 025002 (2009).

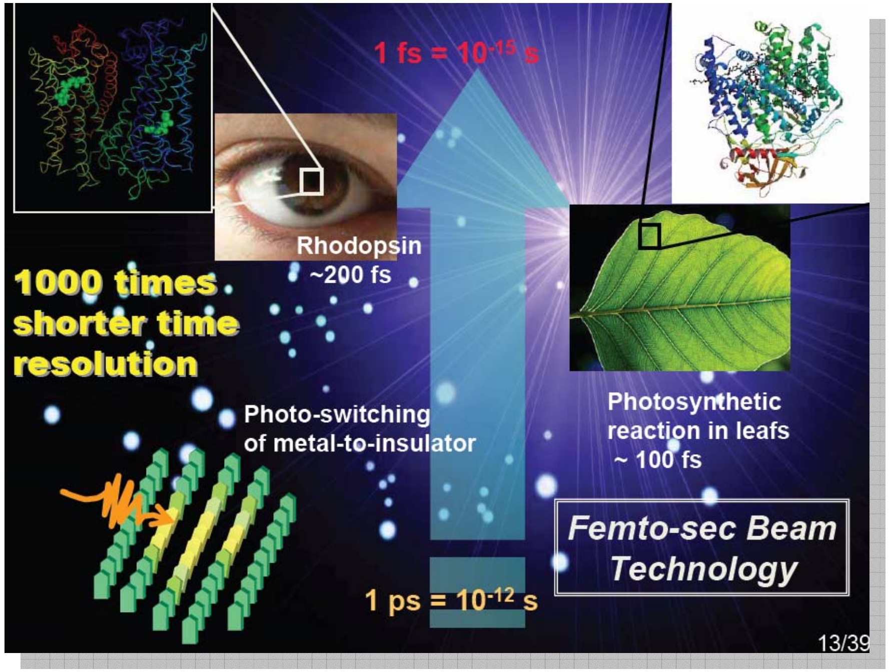
And more

In relativistic regimes, matter coheres more due to
the consequence of relativity. (cf. quantum coherence)
→ *'relativistic engineering'*

# Progress in Laser Power



# Flying Mirror for Femto-, Atto-second, ... Science



$1\ \mathrm{fs} = 10^{-15}\ \mathrm{s}$

Rhodopsin
~200 fs

**1000 times shorter time resolution**

Photo-switching
of metal-to-insulator

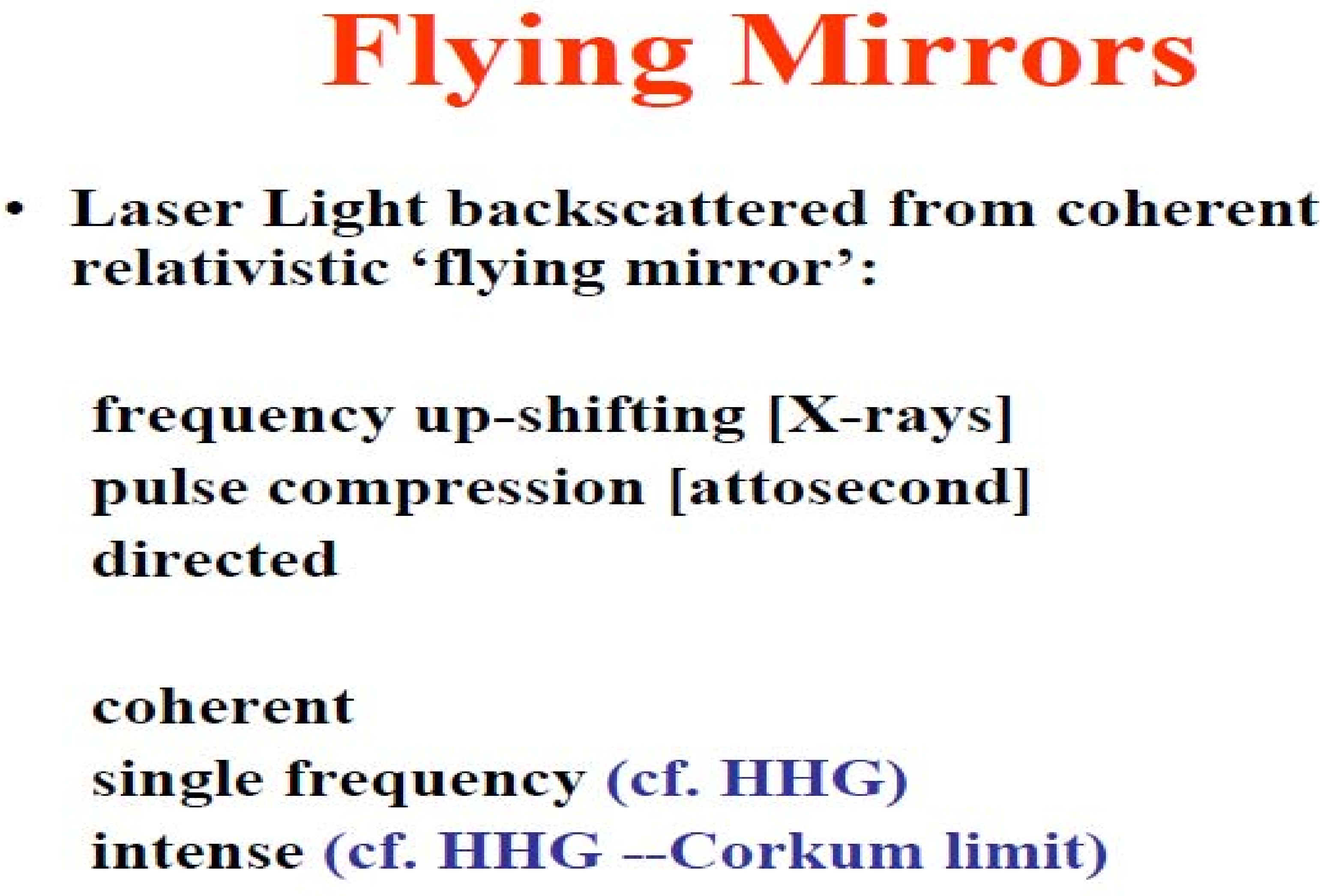
Photosynthetic
reaction in leafs
~ 100 fs

***Femto-sec Beam Technology***

$1\ \mathrm{ps} = 10^{-12}\ \mathrm{s}$

13/39

(KEK: A. Suzuki)



# Flying Mirrors

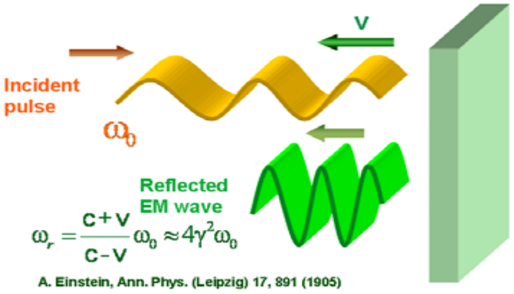
- Laser Light backscattered from coherent relativistic 'flying mirror':

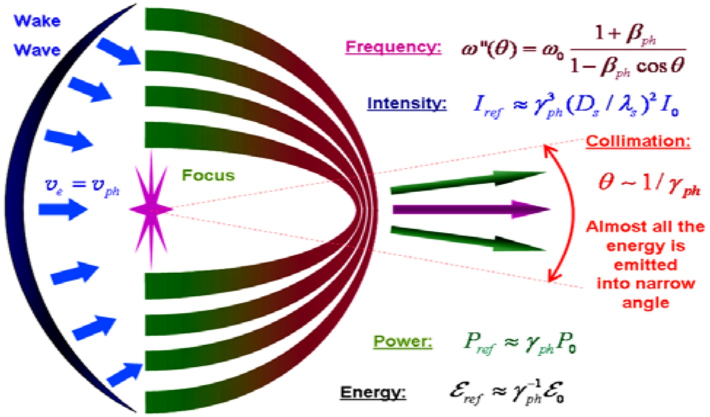
frequency up-shifting [X-rays]
pulse compression [attosecond]
directed

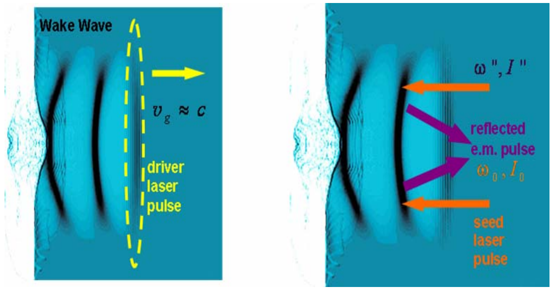
coherent
single frequency (cf. HHG)
intense (cf. HHG --Corkum limit)

Duality Conjecture : "**Intensity** and **shortness** of pulse go hand in hand."
Relativistic flying mirrors are an example of this

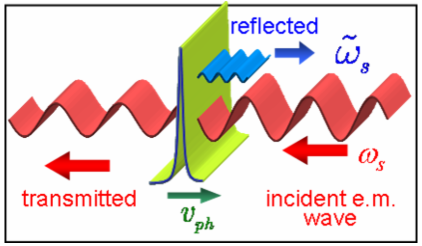
# EM Pulse Intensification and Shortening by the Flying Mirror





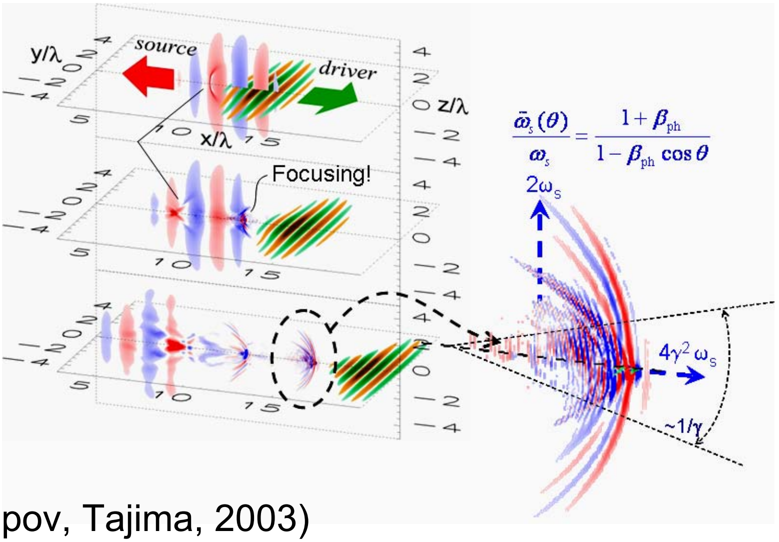


$$\omega'' = \frac{c+v_{ph}}{c-v_{ph}}\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{\max}}{I_0} \approx \kappa\,\gamma_{ph}^6 \left(\frac{D}{\lambda}\right)^2$$



$$\kappa \sim \gamma_{ph}^{-3}$$

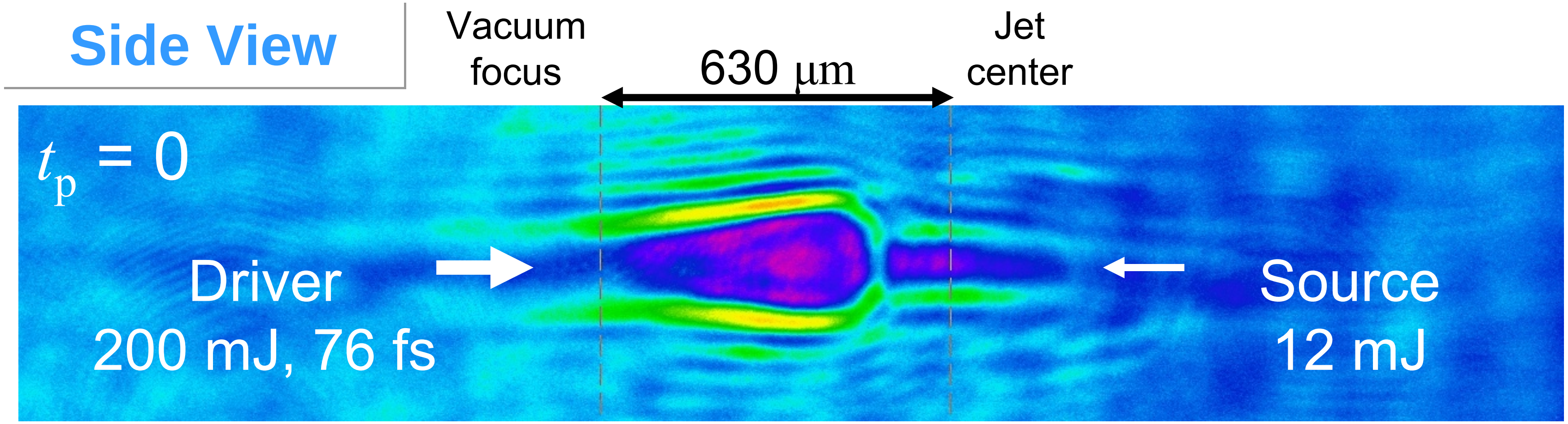
## 3D Particle-In-Cell Simulation



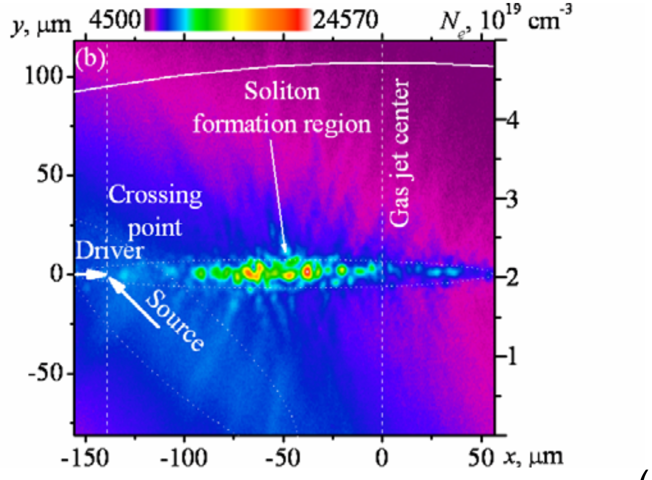
(Bulanov, Esirkepov, Tajima, 2003)

# Space-Time Overlapping of Driver and Source pulses

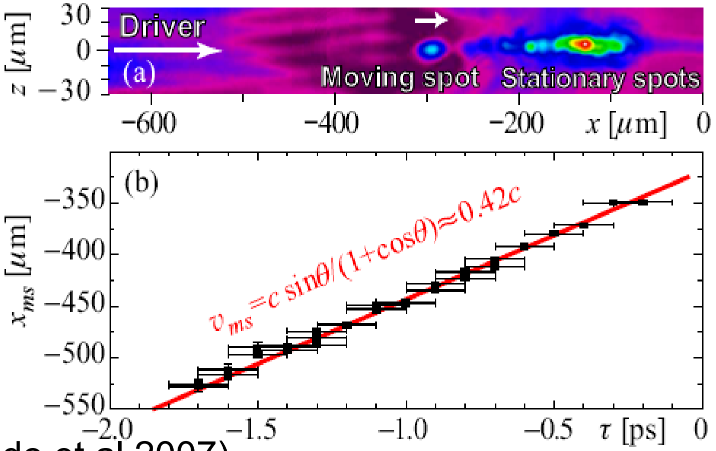
## Side View

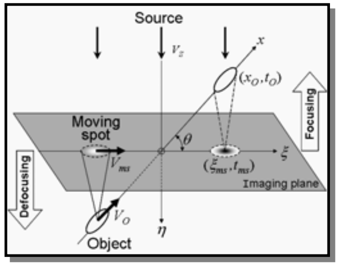


## Top View



## Relativistic Microlens

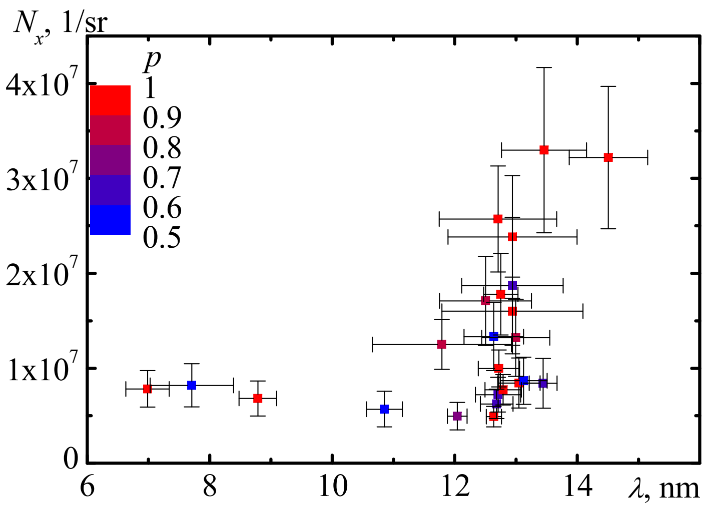


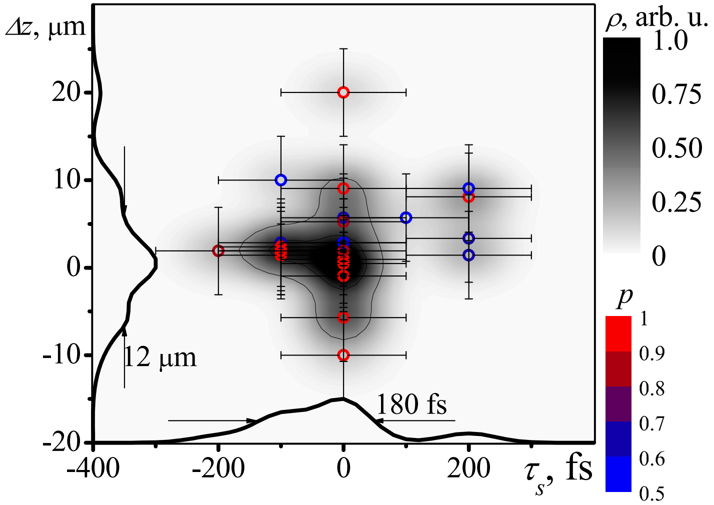


(Kando et al 2007)

# Signals of backreflected photons off flying mirror at *c* (p>0.5)

### Estimated reflected photon number/sr

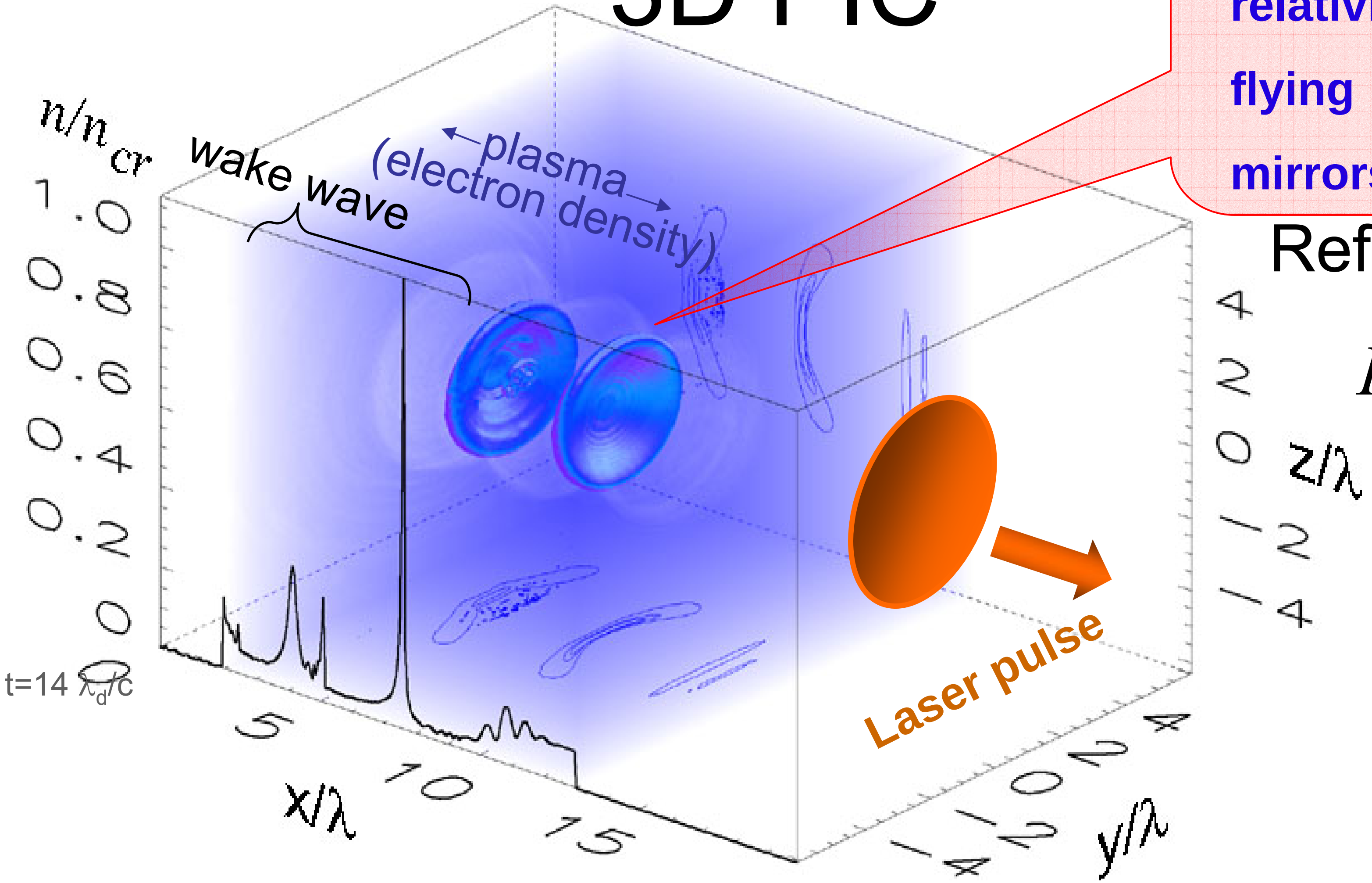




- $\lambda_x$ = 14.3 nm
- $\Delta\lambda_x$ = 0.3 nm, $\Delta\lambda_x / \lambda_x$ = 0.02
- Wake wave parameters: $\gamma$ = 4.1, $\Delta\gamma/\gamma$ = 0.01
- ~ 4 × $10^7$ photons/sr
- Reflected pulse duration: $\tau_x$ ~ 1.4 fs (femtosecond pulse)

(Kando et al, 2007)

# 3D PIC



**paraboloidal**
**relativistic**
**flying**
**mirrors**

Reflectivity

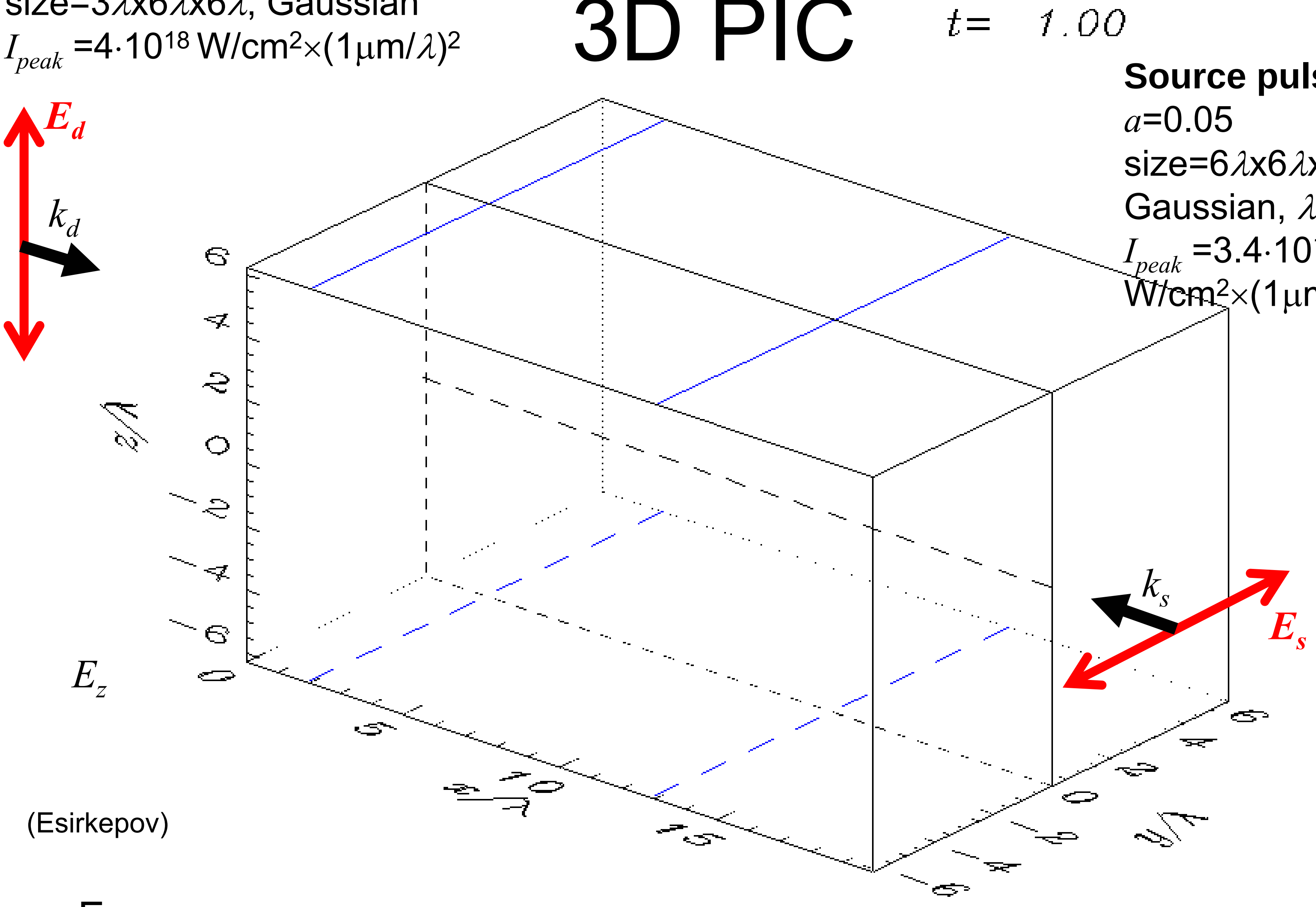
$$R \approx \frac{1}{2\gamma}$$

S. V. Bulanov, T. Zh. Esirkepov, and T. Tajima, *PRL* **91**, 085001 (2003)

**Driver pulse: $a$=1.7**
size=3λx6λx6λ, Gaussian
$I_{peak}$ =4·10$^{18}$ W/cm$^2$×(1μm/λ)$^2$

# 3D PIC

**Source pulse**:
$a$=0.05
size=6λx6λx6λ,
Gaussian, $\lambda_s$ = 2λ
$I_{peak}$ =3.4·10$^{15}$
W/cm$^2$×(1μm/λ)$^2$



$E_z$

(Esirkepov)

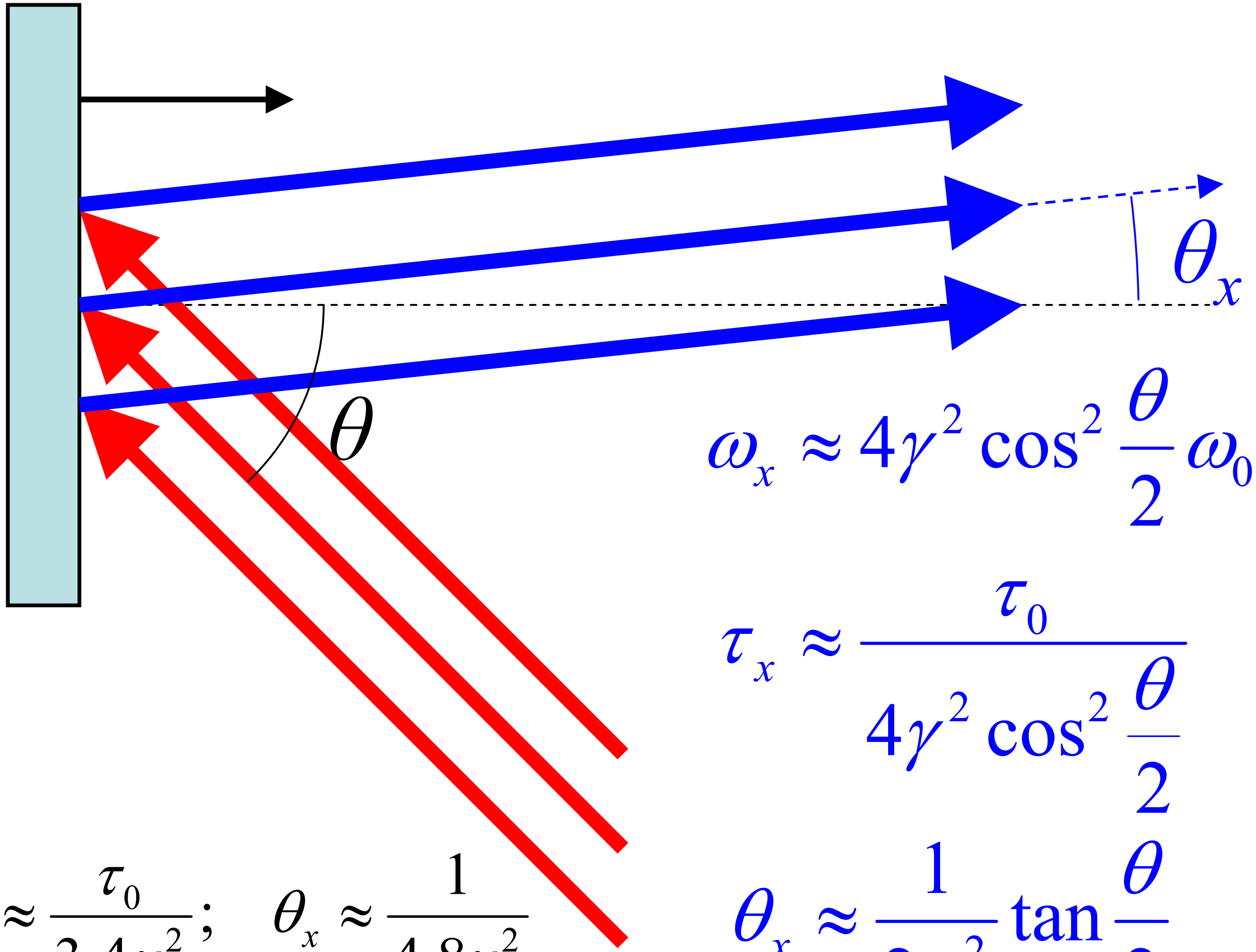
$E_x$

$XZ$,color: $E_y$ $XY$,contour: $E_z$ $XY$,color: $E_x$ at $z$ = 0

# Oblique incidence

$$\beta = \frac{V}{c};$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$



$$\omega_x \approx 4\gamma^2 \cos^2\frac{\theta}{2}\,\omega_0$$

$$\tau_x \approx \frac{\tau_0}{4\gamma^2 \cos^2\frac{\theta}{2}}$$

$$\theta_x \approx \frac{1}{2\gamma^2}\tan\frac{\theta}{2}$$

Example: $\theta = 45^\circ$

$$\omega_x \approx 3.4\gamma^2\omega_0; \quad \tau_x \approx \frac{\tau_0}{3.4\gamma^2}; \quad \theta_x \approx \frac{1}{4.8\gamma^2}$$

# Compact Coherent Ultrafast X-Ray Sources

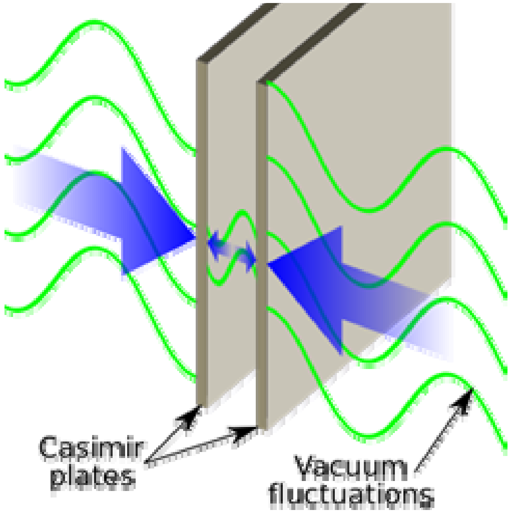
| X-ray source | Wavelength | Pulse Duration | Pulse Energy | Monochromaticity | Coherence |
|---|---|---|---|---|---|
| XFEL (DESY) | 13.8 nm | 50 fs | 100 μJ | $10^{-3}$ | spatial good |
| Plasma XRL | 13.9 nm | 7 ps | 1 μJ | $10^{-4}$ | spatial good |
| Laser plasma | wide spectrum<br>1 nm – 40 nm | 10 ps – 1 ns | 10 μJ | 1 | no |
| HHG | 30 – 40 nm | fs | 1 μJ | $10^{-2}$ – $10^{-3}$ | spatial good |
| Flying Mirror | 0.1 – 20 nm | attosec | mJ | $10^{-2}$ – $10^{-4}$ | spatial and temporal good |

**Predicted by the FM theory parameters of the x-ray pulse compared with the parameters of power x-ray generated by other sources**

# Moving mirrors in quantum electrodynamics

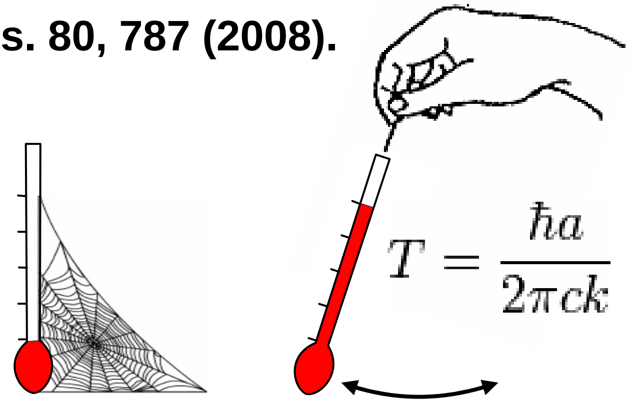
## Dynamical Casimir effect

**H. B. G. Casimir, Proc. Kon. Nederland. Akad. Wetensch. B51, 793 (1948).**
**…**
**M. Bordag, et al., Phys. Rep. 353, 1 (2001).**



## Unruh radiation

**W. G. Unruh, Phys. Rev. D 14, 870 (1976).**
**…**
**L. Crispino, et al., Rev. Mod. Phys. 80, 787 (2008).**

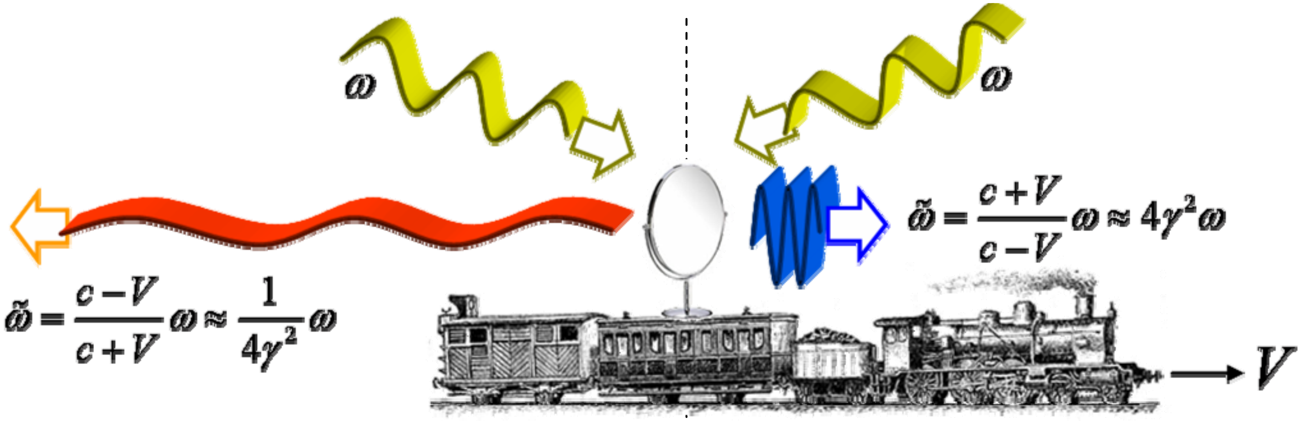


$$T = \frac{\hbar a}{2\pi c k}$$

Unruh effect: accelerating observer sees black-body radiation.

(Esirkepov)

# Double-Sided Mirror



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

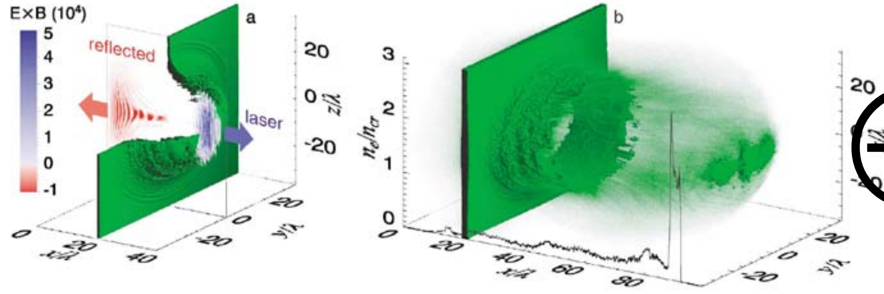
$$\tilde{\omega} = \frac{c+V}{c-V}\omega \approx 4\gamma^2\omega$$

**Wave loses energy**

$$\Delta\mathcal{E}_{\mathrm{loss}} = \hbar\tilde{\omega} - \hbar\omega \approx \left(1 - \frac{1}{4\gamma^2}\right)\hbar\omega$$

**(energy is transferred to the mirror)**

### Radiation Pressure Dominant Acceleration (Laser Piston)



S.V.Bulanov, et al., Plasma Phys.Rep. 30, 196 (2004);
T.Esirkepov, et al. Phys. Rev. Lett. 92, 175003 (2004).

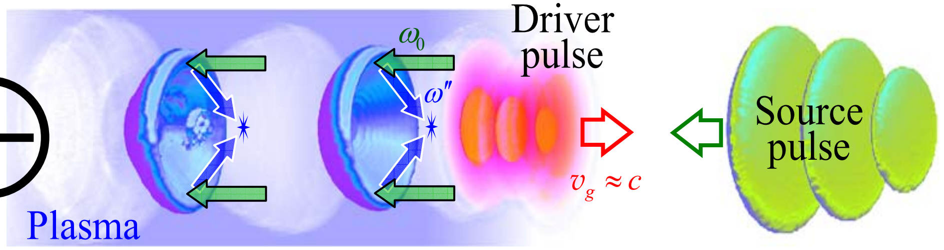
⊕

**Wave gains energy**

$$\Delta\mathcal{E}_{\mathrm{gain}} = \hbar\tilde{\omega} - \hbar\omega \approx \left(4\gamma^2 - 1\right)\hbar\omega$$

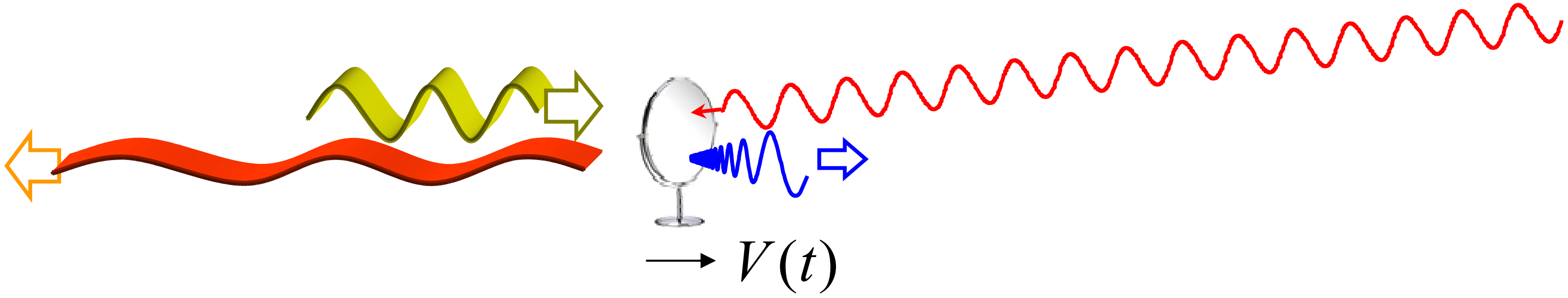
**(energy is taken from the mirror)**

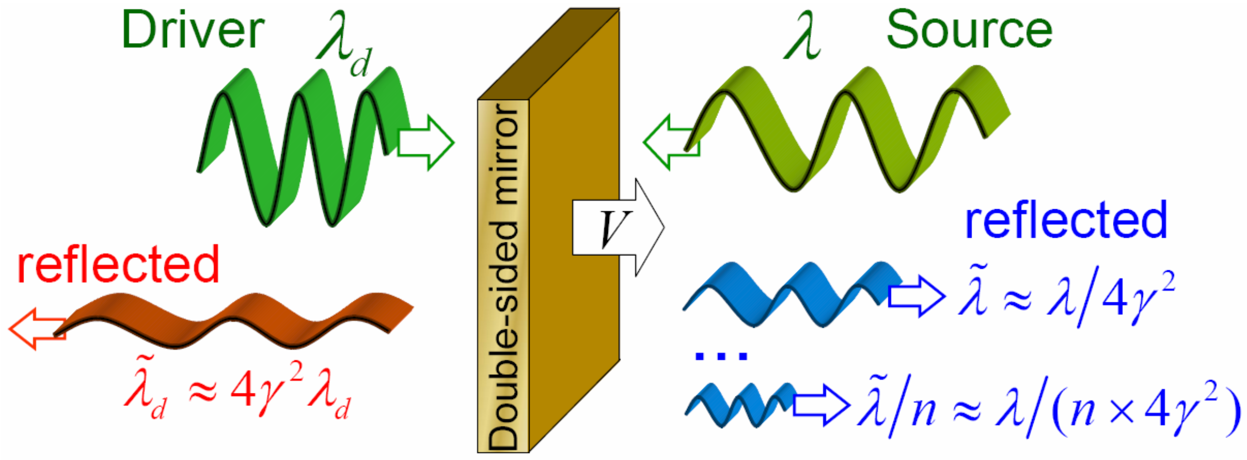
### Flying Mirror



S.V.Bulanov et al., Kratk. Soobshch. Fiz. 6, 9 (1991);
S.V.Bulanov, et al., Phys.Rev.Lett. 91, 085001 (2003).

# Accelerating Double-Sided Mirror



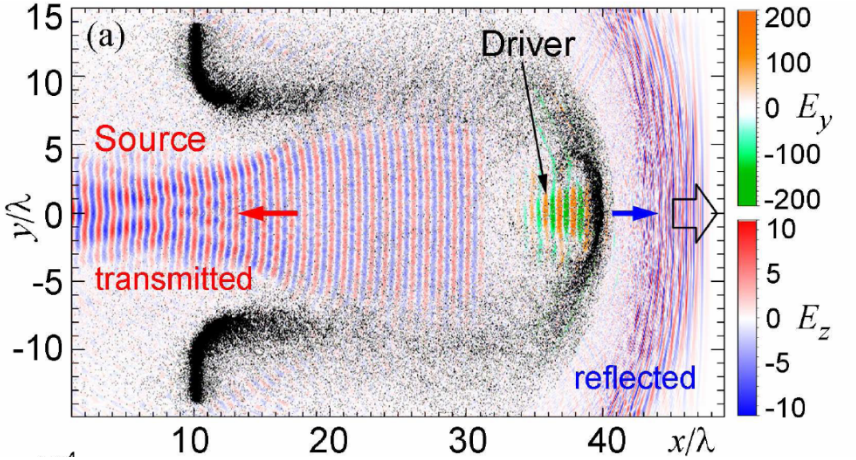


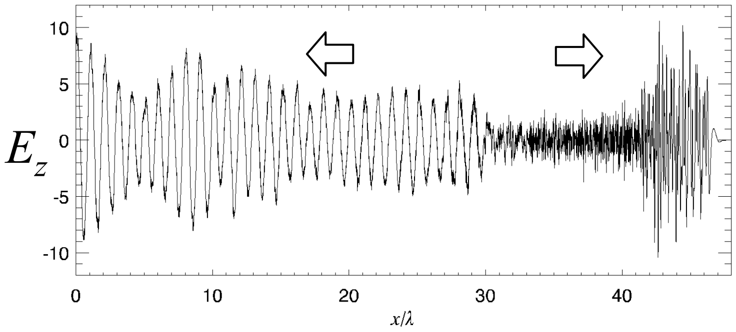
**Kagami 鏡**

(“mirror” in Japanese)

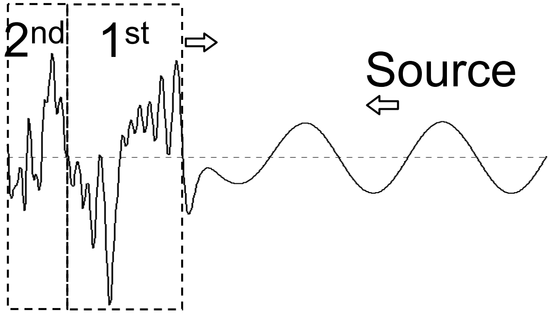
# Accelerating Double-Sided Mirror (Kagami)

## Accelerating harmonics





Reflected cycles

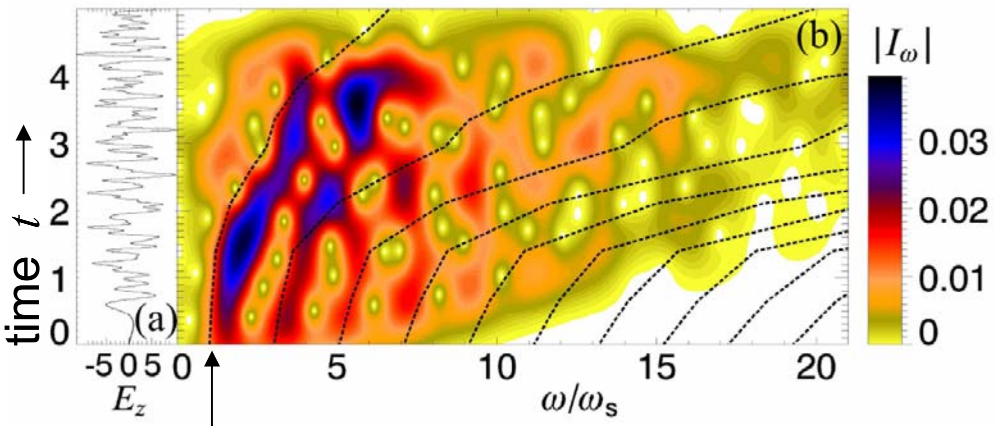


(Esirkepov)

Field along $x$-axis

Spectrum at fixed time

$$I_\omega(t) = \int_{-\infty}^{+\infty} E_z(\tau) e^{-i\tau\omega - c^2(\tau-t)^2/\lambda^2} d\tau$$



**Dashed curves:** $\frac{1+\beta(\tau)}{1-\beta(\tau)}\omega_0 \times (2n-1),\ n=1,2,3\ldots$

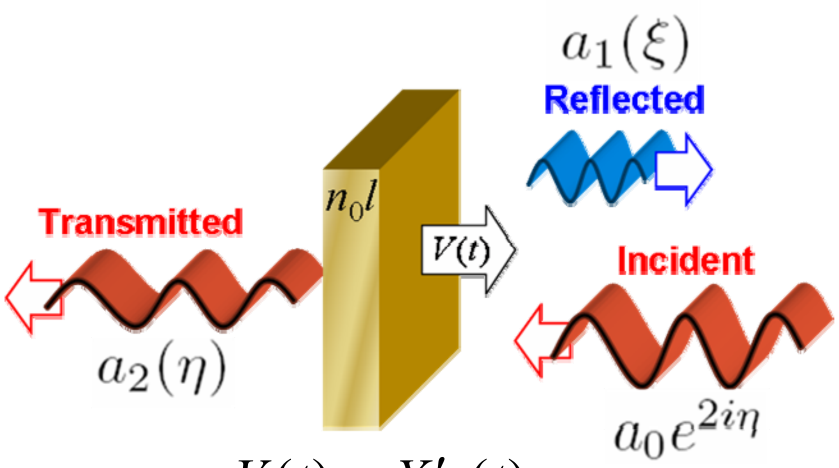
$\tau$ – time of emission

time of detection: $t = \tau - \int_0^\tau \beta(\tau) d\tau$

**Reflected light structure:**

- Fundamental mode $\times 4\gamma^2$
- High harmonics $\times 4\gamma^2$
- Shift due to acceleration

# Interaction of an electromagnetic wave with an infinitely thin plasma slab



$$V(t) = X'_M(t)$$

**We seek the solution in the form:**

$$A(\xi,\eta) = \begin{cases} a_1(\xi) + a_0 e^{2i\eta}, & \psi(\xi,\eta) > 0; \\ a_2(\eta), & \psi(\xi,\eta) \le 0. \end{cases}$$

$$e^{2i\eta} = e^{ik(x+ct)}$$

**Maxwell equation in terms of $\xi$, $\eta$ reduces to ordinary differential equations:**

$$a_1'(\xi) = \chi\left(a_1(\xi) + a_0 e^{2i\eta_0(\xi)}\right) \mathsf{F}_\mathrm{M}(\xi, \eta_0(\xi)),$$

$$2ia_0 e^{2i\eta} - a_2'(\eta) = \frac{\chi}{\mathsf{F}_\mathrm{M}(\xi_0(\eta), \eta)} a_2(\eta)\,.$$

$$\psi(\xi_0(\eta), \eta) = 0 \text{ for } \forall \eta,$$
$$\psi(\xi, \eta_0(\xi)) = 0 \text{ for } \forall \xi.$$

$$\mathsf{F}_\mathrm{M}(\xi,\eta) = \left[\frac{1 + X'_M(\eta - \xi)}{1 - X'_M(\eta - \xi)}\right]^{1/2} \approx 2\gamma_M$$

Details and references: T.Zh. Esirkepov, et al. Phys. Rev. Lett. 103, 025002 (2009)

# Uniformly accelerating mirror

Acceleration: $gkc^2$

$$X_M(\bar{t}) = g^{-1}\{1 + (g\bar{t})^2\}^{1/2}$$

**Solution**

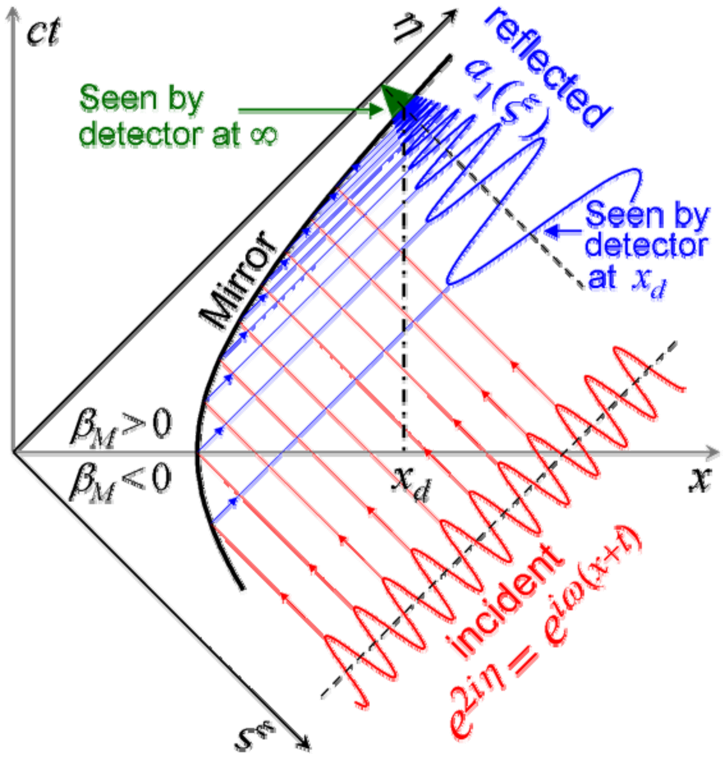
Reflected wave:

$$a_1(\xi) = \frac{\chi a_0}{2g}\left(2ig^2\xi\right)^{\frac{\chi}{2g}}\Gamma\left(\frac{\chi}{2g}, \frac{1}{2ig^2\xi}, 0\right)$$

Transmitted wave:

$$a_2(\eta) = \frac{\chi a_0}{2g}\left(-2i\eta\right)^{-\frac{\chi}{2g}}\Gamma\left(\frac{\chi}{2g}, -2i\eta, 0\right) + a_0 e^{2i\eta}$$

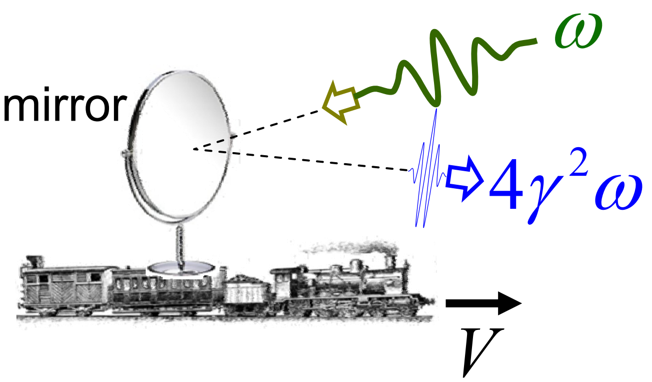
$$\Gamma(a, z_1, z_2) = \int_{z_1}^{z_2} t^{a-1}e^{-t}dt$$



$$a_1(\xi) = \underline{-\frac{\chi a_0}{2g}\left(2ig^2\xi\right)^{\frac{\chi}{2g}}\Gamma\left(\frac{\chi}{2g}\right)} + \underline{i\chi a_0 g\exp\left(\frac{i}{2g^2\xi}\right)}\left(\underline{\xi} + O(\xi^2)\right)$$

cf. J. R. Van Meter, S. Carlip, F. V. Hartemann
**Reflection of plane waves from a uniformly accelerating mirror**
Am. J. Phys. **69** (7), July 2001

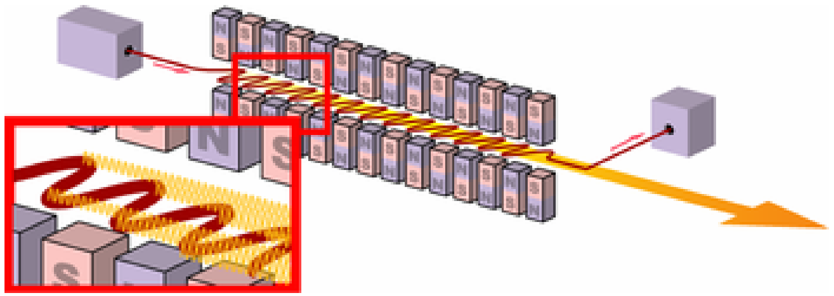
# Moving mirrors in classical electrodynamics



## Relativistic Doppler effect

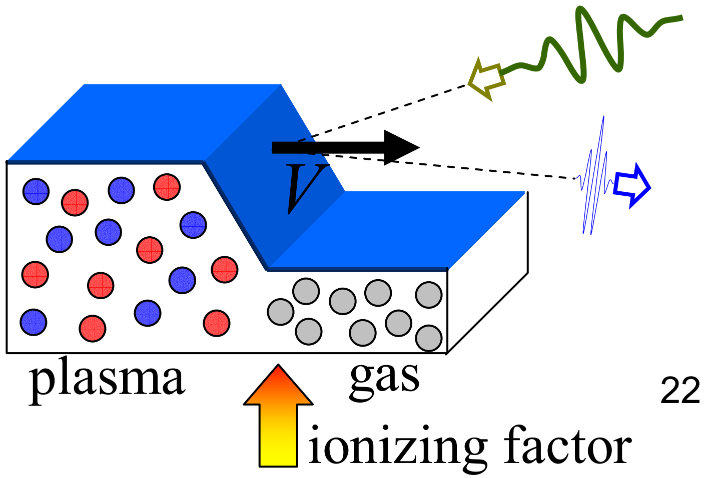
**A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905).**
**…**

## Free Electron Laser



**J.M.J. Madey, 1971.**
**D.A.G. Deacon, et al, Phys. Rev. Lett. 38, 892, (1977).**
**…**

## Moving optical inhomogeneity

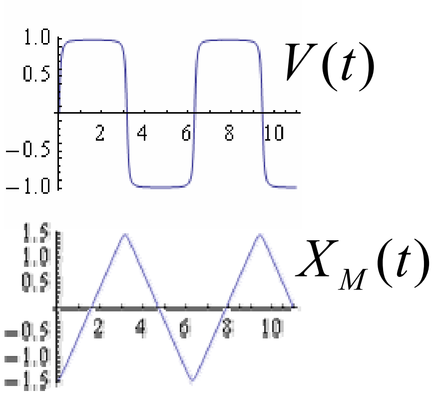


**V. I. Semenova, Sov. Radiophys. Quantum Electron. 10, 599 (1967).**
**…**
**N. N. Rosanov, JETP Lett. 88, 577 (2008).**

# Quivering mirror

$$\frac{d}{d\bar{t}}\left(V(\bar{t})/\sqrt{1-V^2(\bar{t})}\right) = g\cos(\Omega\bar{t})$$

$$X_M(\bar{t}) = \frac{1}{\Omega}\arctan\left(-\frac{\cos(\Omega\bar{t})}{\sqrt{\Omega^2/g^2+\sin^2(\Omega\bar{t})}}\right)$$

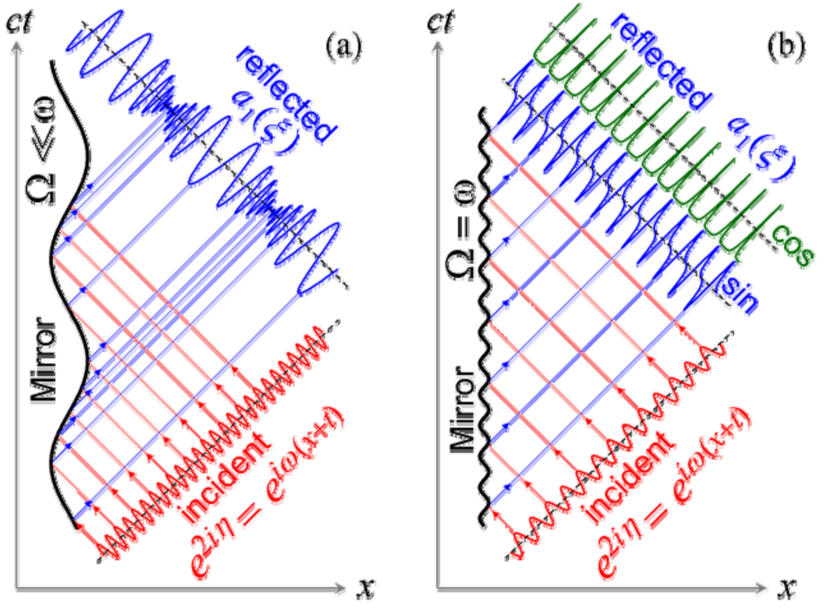


## Solution

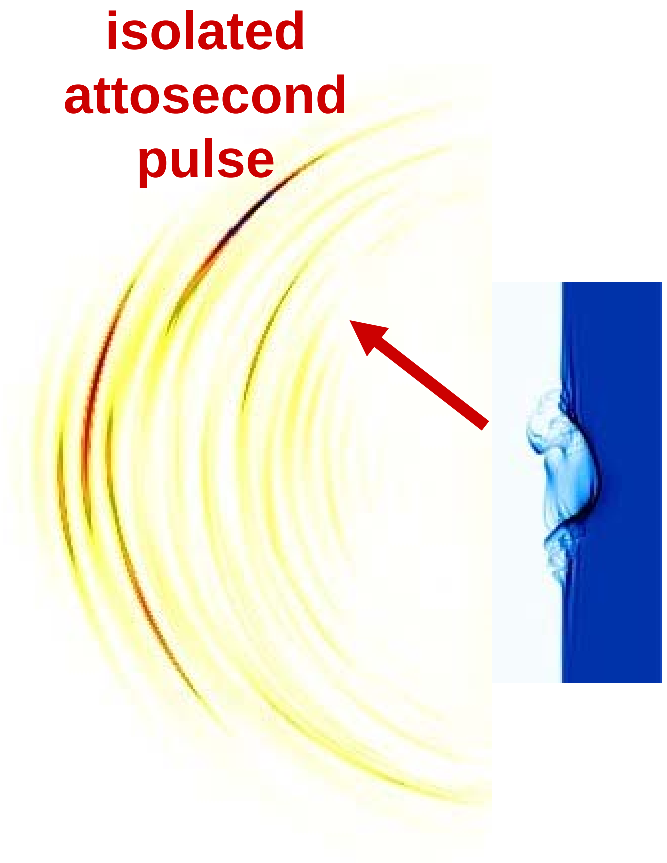
Reflected wave:

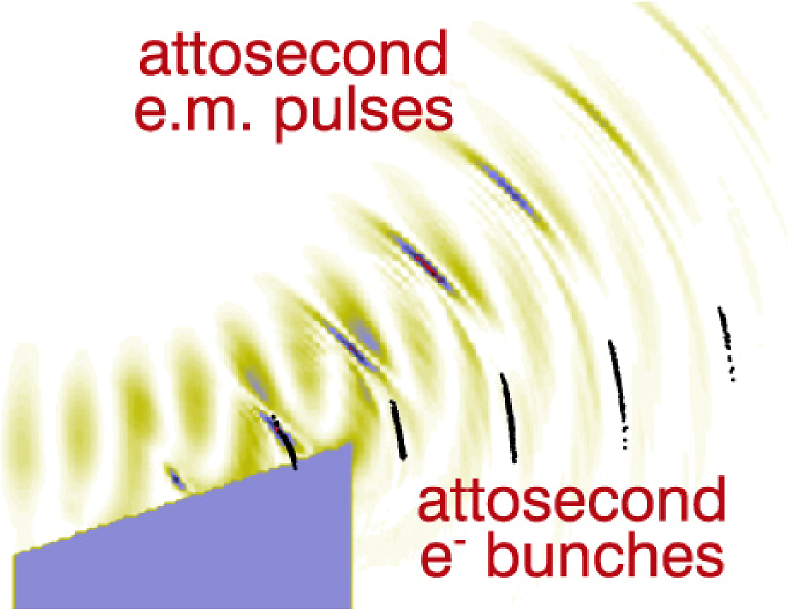
$$a_1(\xi) = \frac{\chi a_0}{g}\int_{\Omega\xi}^{+\infty}\frac{E(\Omega\xi)}{E(\tau)}\frac{e^{-\frac{2i\tau}{\Omega}}(h-ie^{2i\tau})^{\frac{2}{\Omega}}\;d\tau}{(h^2+1+2h\sin(2\tau))^{\frac{2+\Omega}{2\Omega}}},\quad E(\tau) = \exp\left\{\frac{\chi}{g(h+1)}\mathrm{F}\left(\tau-\frac{\pi}{4}\middle|\,\frac{4h}{(h+1)^2}\right)\right\}.$$

$\mathrm{F}(z|m)$ – elliptic integral of the 1st kind.



# http://www.eecs.umich.edu/CUOS/attosecond





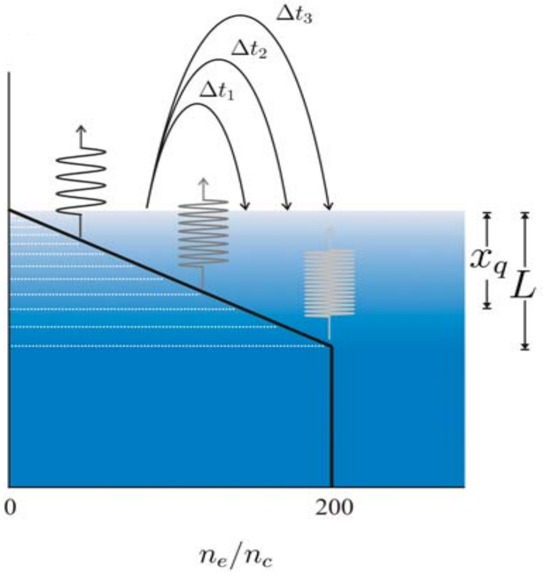
The short pulse formation occurs whenever relativistically strong laser pulses interact with near-critical or overcritical plasmas, but, more responsive plasmas act more efficiently.

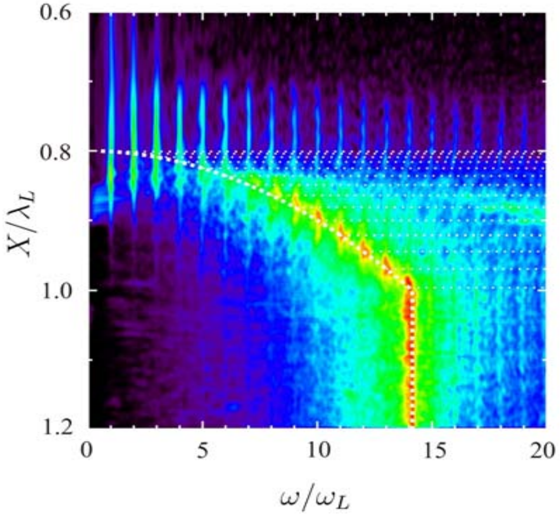
(N. Naumova et al)

# Overview over SHHG Data from Berlin and first (preliminary) Interpretations

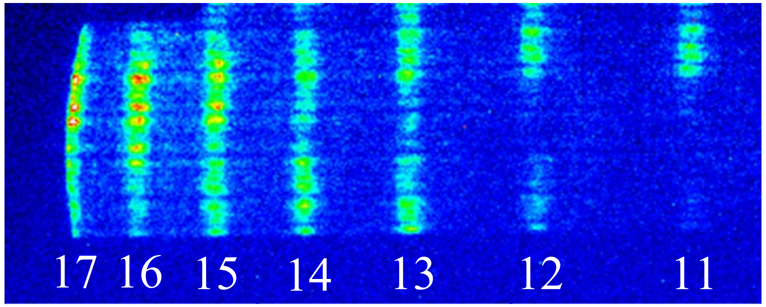
R. Hoerlein, D. has, S. Steinke, W. Sandner et al.

# The CWE Mechanism



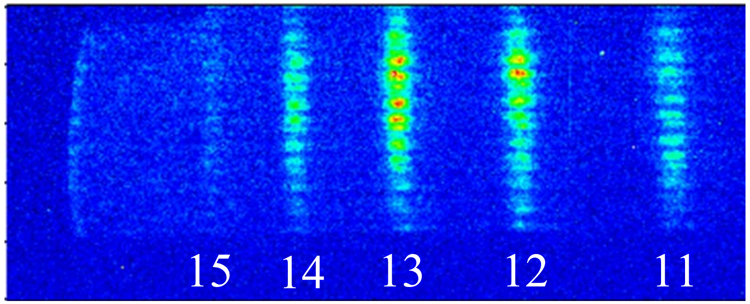


Glass Target (Density 🕓2.6 g/cm^3):



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

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



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

# … the only similar experiment …

VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

**Harmonic Emission from the Rear Side of Thin Overdense Foils Irradiated with Intense Ultrashort Laser Pulses**

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(Received 25 November 2003; published 4 May 2004)

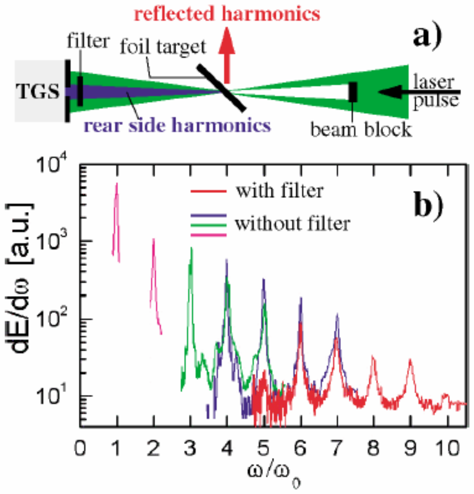


FIG. 1 (color). (a) Scheme of the experimental setup (see text). (b) Typical harmonic spectra measured at the rear side of a 60 nm carbon foil in different spectral windows, either with filter (no beamblock) or without filter (with beamblock). The fundamental and 2nd harmonic spectra were obtained from the diffraction at the support grating.

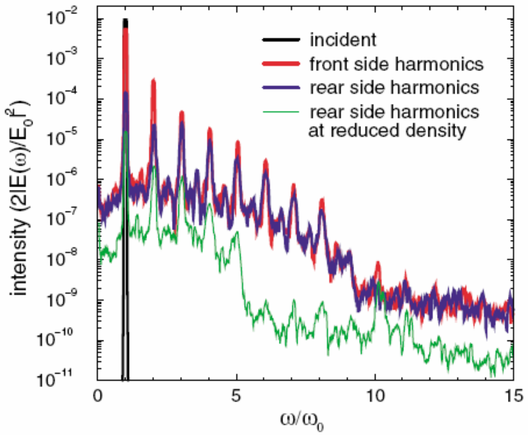


FIG. 3 (color). Simulated front (red) and rear side (blue) spectra at standard parameters (see text). Green line (for clearness it is shifted down by a factor of 10) shows the rear side spectrum at lower density $n_e/n_c = 27$, but the same areal mass (thickness $= 0.6\lambda$), while the other parameters correspond to the standard ones. To get rid of the numerical noise, the spectra were smoothed over a region of $\Delta\omega/\omega_0 = 0.1$.

- foils 50nm to 400nm
- a0=0.5 (at 2 omega)
- oblique incidence
- p-polarization

- harmonics visible from front and rear side
- density dependent cutoff in simulation
- experiment showed no signal for normal incidence

# Odd – Even Asymmetry

## unknown origin

- odd harmonics also exhibit cutoff (thus probably not relativistic)
- polarization of CWE not well studied (if at all!)

Possible reasons for observation

**Odd generated more efficiently?**

**Polarization of odd and even harmonics different?**

- strong influence of vxB? Not probable as circular polarization also shows effect…
- Different polarization of add and even? But why… anybody got ideas?

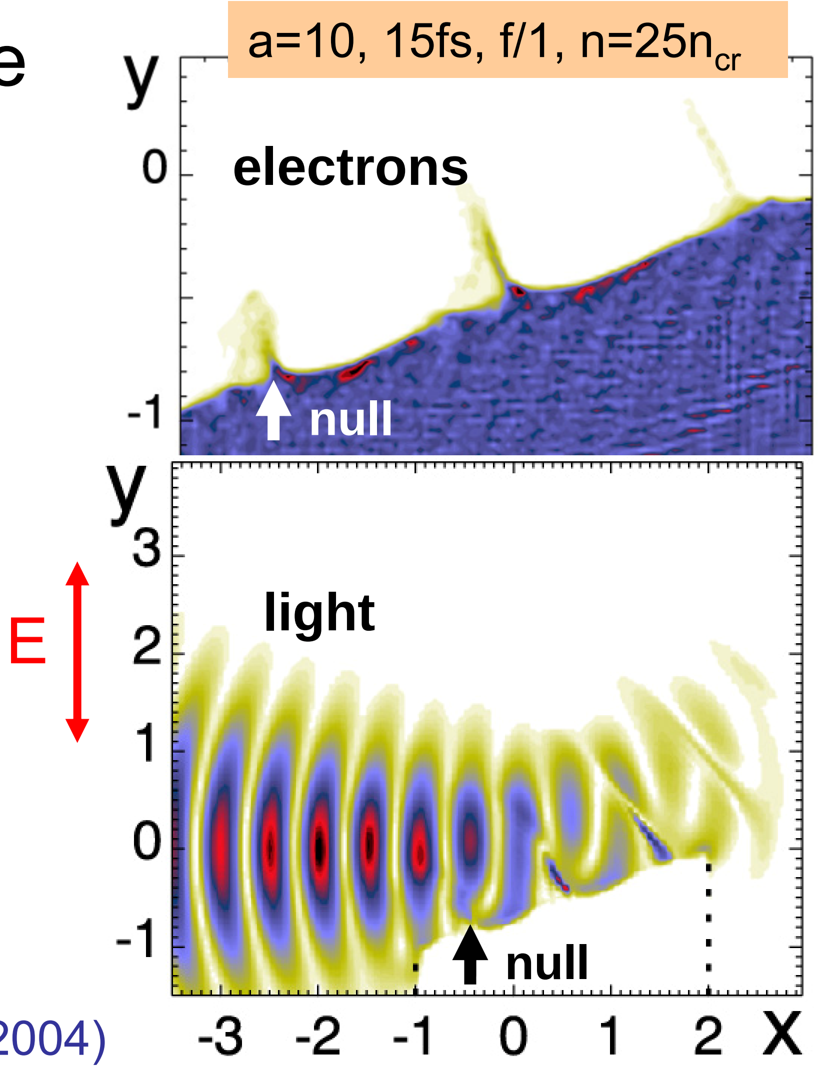
## My newest idea…

- perhaps E-field effect but symmetry due to normal incidence?
- interference of two harmonic sources Pi out of phase left and right of center of focus???

# Electron ejection can be achieved with large angles of incidence

A tightly focused laser pulse pushes plasma electrons inwards, creating:

- peaked electron density distribution,
- counter-streaming electrons,
- regions with minimal pressure (nulls), through which electrons jet.



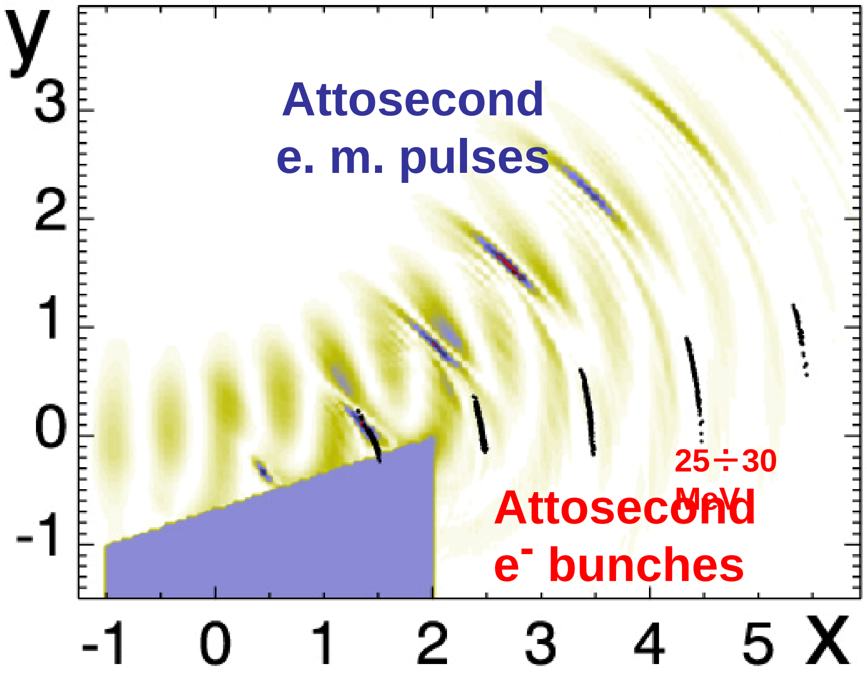
Naumova *et al*., Phys. Rev. Lett. **93**, 195003 (2004)

# 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.



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

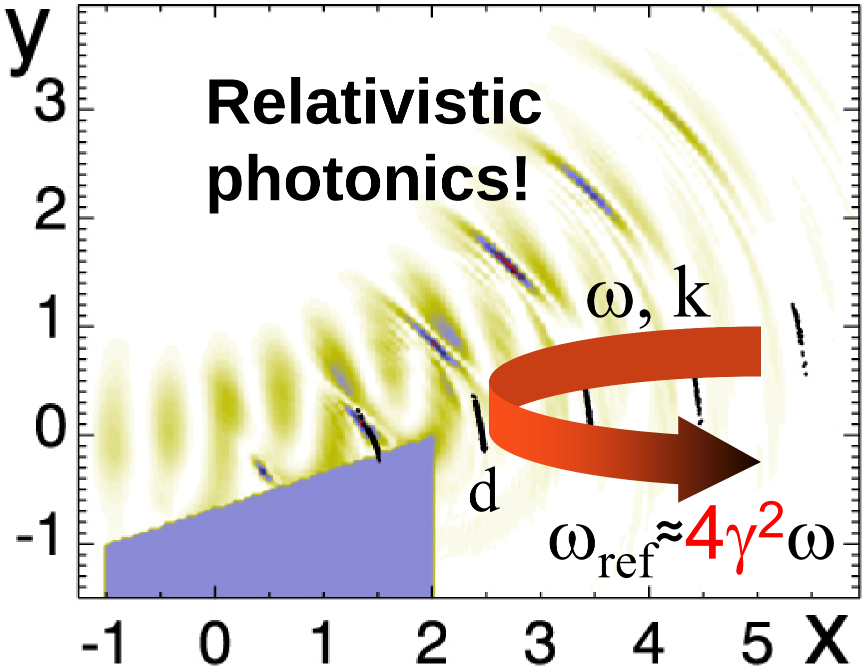
Naumova *et al*., Phys. Rev. Lett. **93**, 195003 (2004)

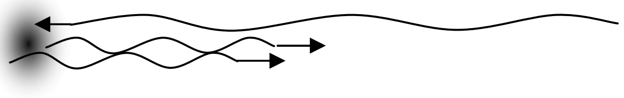
# …short electron bunches scatter coherently

- For counter-propagating light coherent scattering occurs with near unity efficiency when the bunch is short enough:

  $kd \sim 1/2\gamma^2$
- Then, $10^8$ electrons are sufficient to reflect in $1 \mu m^2$

Further investigation of the bunch characteristics and spectral content of the scattered radiation are needed





Naumova *et al.*, Phys. Rev. Lett. **93**, 195003 (2004)

# How to Produce Short Bunches

duality

plasma acceleration!

(AS. Ogata)

# Creation of a short bunch.

1 Use of high-density plasma with small $a_0$.

2 Bunch compression
sacrificing the energy width, to which the radiolysis is generous.

This talk is mainly on the 1st term.

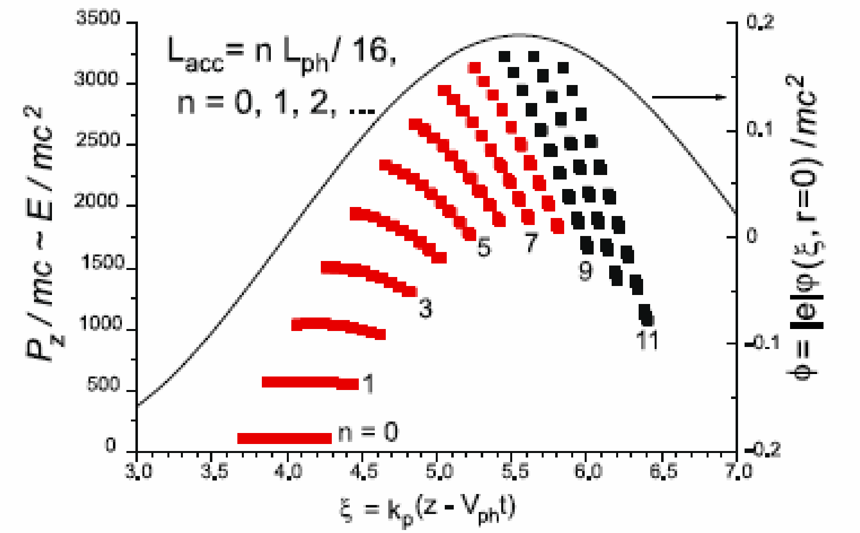
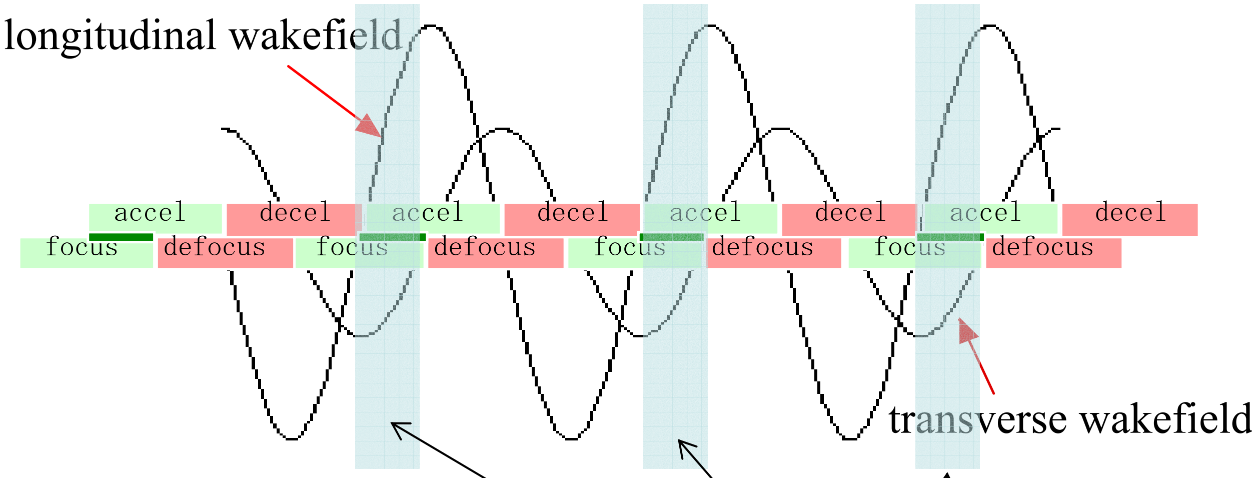


FIG. 2. (Color) Wakefield acceleration of an electron bunch by channel guided $CO_2$ laser pulse; $a = 0.71$, $k_p r_L = 3.8$, $k_p R_{ch} = 14.3$, $L_{ph} = 512$ cm, $E_{inj} = 100mc^2$, $L_b = r_b = 0.1\lambda_p$.

N.E.Andreev, et al.,
Phys. Rev. STAB 3 (2000) 021301.

# LWFA Linear model says fwhm bunch length < plasma wavelength/4



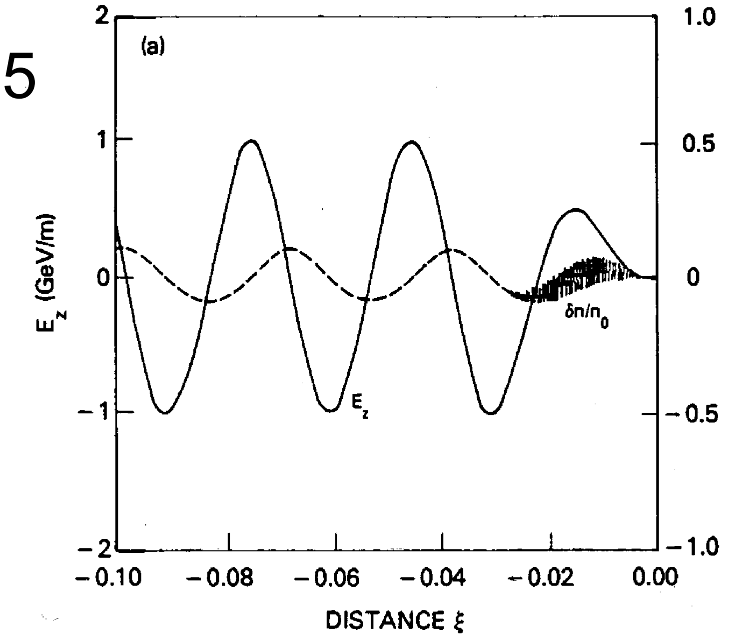
phases of acceleration and focusing

Different in nonlinear waves.

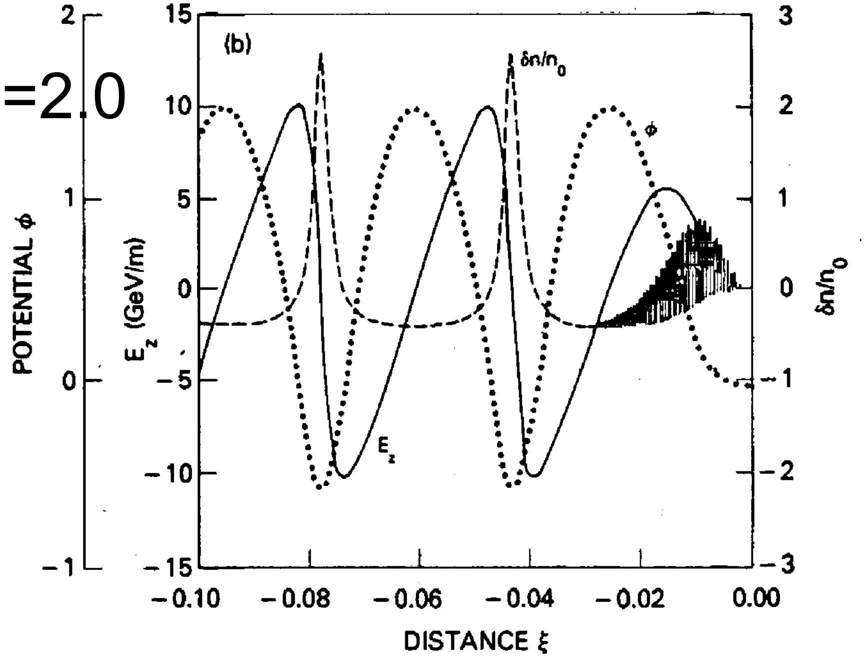
# In nonlinear waves, $\omega_p$ decreases

$$\omega_p = \frac{\omega_{p0}}{\sqrt{1 + a_0{}^2}}$$

$a_0$=0.5



$a_0$=2.0



P.Sprangle et al., PRL 64 (1990) 2011.

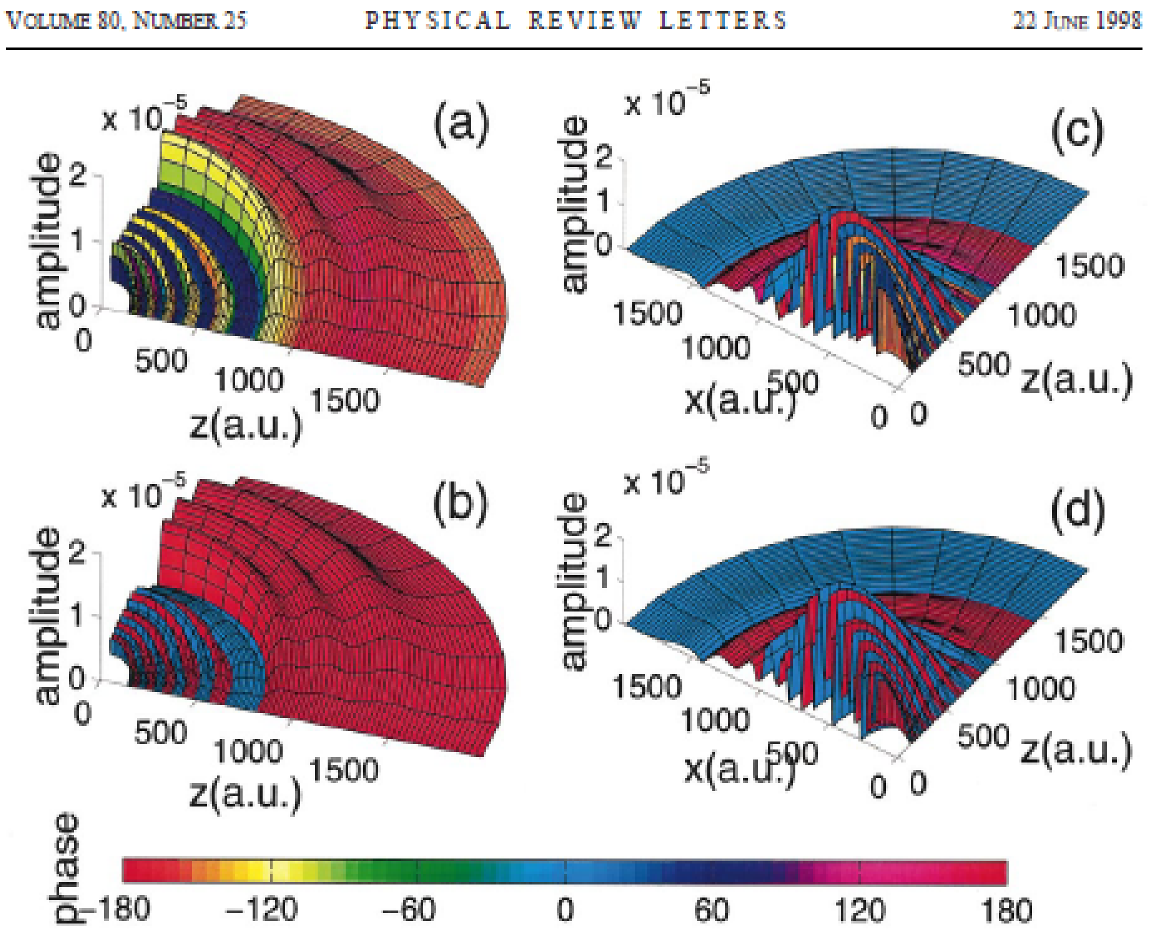
# Paradigm shift by atto- and zepto-seconds ： $|\Psi|^2 \Rightarrow \Psi$

- measurement of electron wavefunction modulus squared $|\Psi|^2$
  - e.g.） according to textbooks of QM this quantity is measureable, by such methods as X-ray inelastic scattering
- measurement of electron wavefunction itself Ψ
  - according to textbooks of QM this quantity is unmeasurable.
  - Ψ： arbitrary phase with each electron。 Phase of an individual electron in as range
    - ⇒ origin of non-measurability of Ψ
- <u>emergence of coherent attosecond X-rays</u>（relativistic engineering etc）
  - first ever possibility of <u>electron wavefunction itself Ψ</u>（or its phase）
  - outstanding problems of contemporary physics：
    - e.g.） behavior of strongly-coupled systems
    - （quantum coherent state due to electron many-body interaction
      - e.g.） high Tc superconductors：10nm coherent length）
- new paradigm of matter control
  - <u>quantum control including the phase of matter</u>
    - departure from control philosophy in 1D energy demain（ω）
    - toward multidimensional control philosophy including phase(Φ)

- Can we observe entangled quantum states？ーーーnew question

# Example of wavefunction of a Rydberg atom by ultrashort pulse laser

Weinacht, Ahn, and Buchsbaum, PRL(1998);
*ibid*.,.Nature (1999)

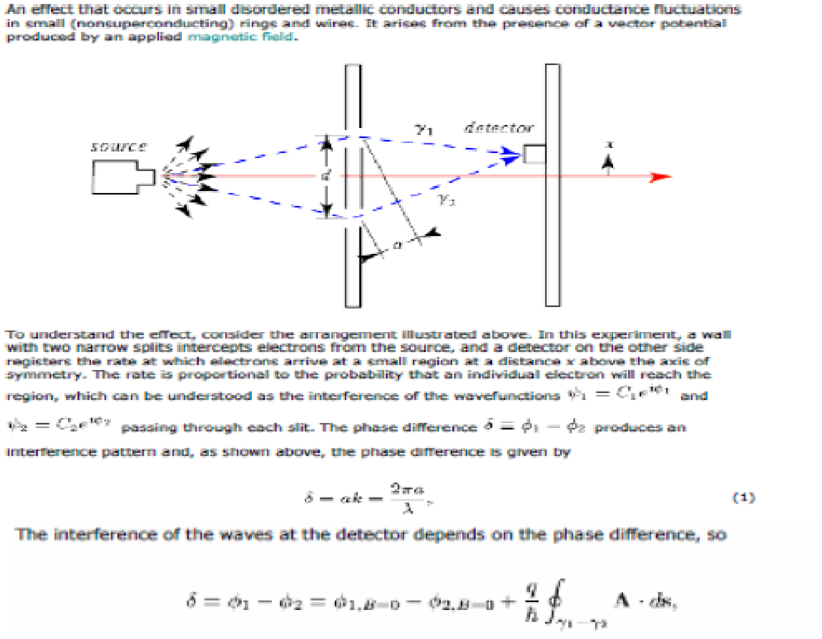


VOLUME 80, NUMBER 25 PHYSICAL REVIEW LETTERS 22 JUNE 1998

# Example of quantum phase/wavefunction sensitive physics

## 現実から夢へ: Aharonov-Bohm effect

Quantum dots, Nanotubes, ….



An effect that occurs in small disordered metallic conductors and causes conductance fluctuations in small (nonsuperconducting) rings and wires. It arises from the presence of a vector potential produced by an applied magnetic field.

To understand the effect, consider the arrangement illustrated above. In this experiment, a wall with two narrow splits intercepts electrons from the source, and a detector on the other side registers the rate at which electrons arrive at a small region at a distance $x$ above the axis of symmetry. The rate is proportional to the probability that an individual electron will reach the region, which can be understood as the interference of the wavefunctions $\psi_1 = C_1 e^{i\phi_1}$ and $\psi_2 = C_2 e^{i\phi_2}$ passing through each slit. The phase difference $\delta = \phi_1 - \phi_2$ produces an interference pattern and, as shown above, the phase difference is given by

$$\delta = ak = \frac{2\pi a}{\lambda}, \qquad (1)$$

The interference of the waves at the detector depends on the phase difference, so

$$\delta = \phi_1 - \phi_2 = \phi_{1,B=0} - \phi_{2,B=0} + \frac{q}{\hbar}\oint_{\gamma_1-\gamma_2} \mathbf{A}\cdot d\mathbf{s},$$

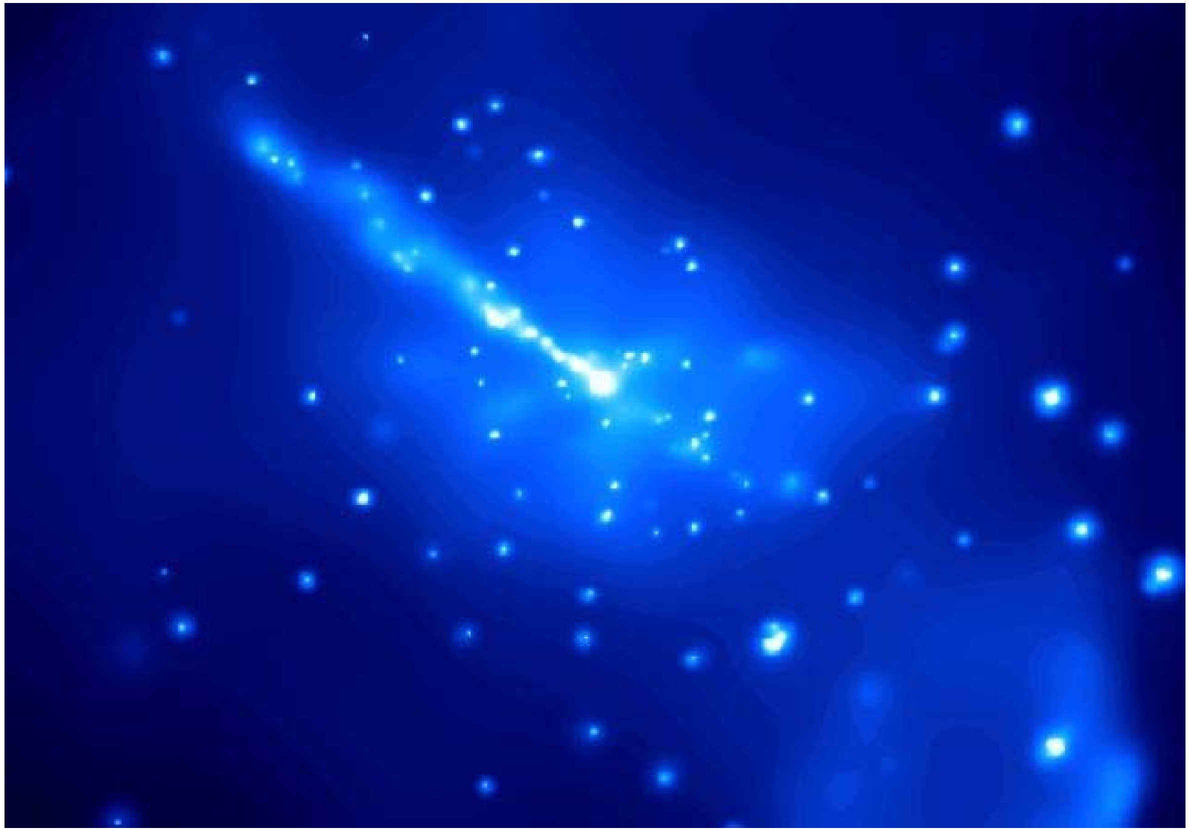
Possible to see if the Einstein-Podolsky-Rosen effect?

E. Weisstein:’World of Physics’

# Conclusions

Relativistic engineering using intense lasers and relativistic coherence

- RE allows unprecedented regime of physical parameters: pulse length, intensity (of photons and other particles)…. Manifestation of the Duality Conjecture (Mourou)
- RE accesses Atto- and zepto- second regimes of (coherent) photon science, a paradigm change from $|\Psi|^2 \rightarrow \Psi$
- RE accesses extreme fields
- We may get more parameter regimes than explored so far



Centaurus A:

cosmic
wakefield
linac?

# Merci Beaucoup
# et a la Prochaine Fois!