The Review Talk
PIF (Physics in Intense Fields) 2010
Friday, Nov. 26, 2010
KEK, Tsukuba

High Field Science

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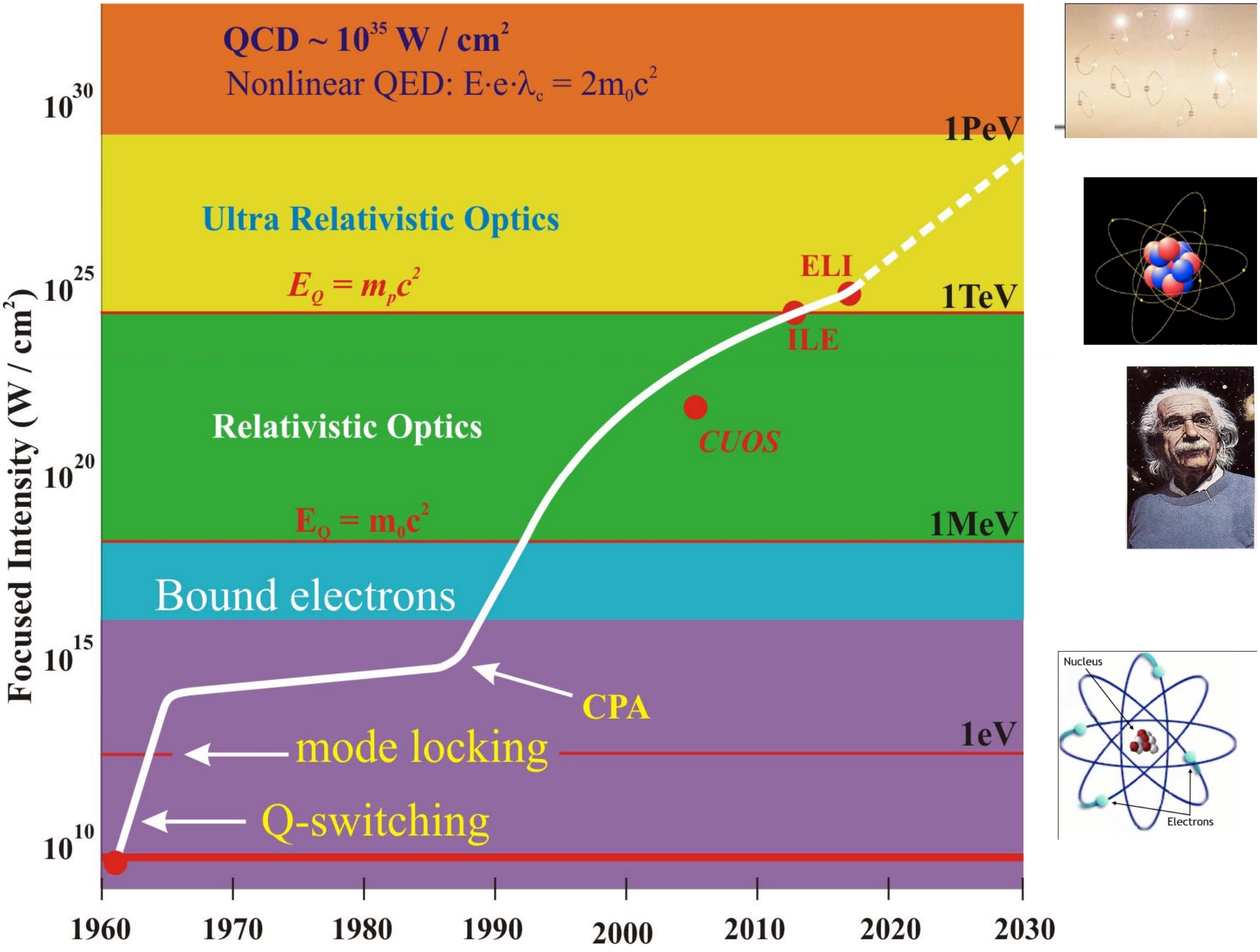
Acknowledgments for collaboration and advice: G. Mourou, F. Krausz, G. Tsakiris, D. Habs, K. Homma, . Esirkepov, S. Bulanov, M. Kando, W. Sandner, X. Q. Yan, S. Karsch, F. Gruener, M. Zepf, N. Naumova, H. Gies, E. Moses, M. Downer, P. Corkum, Y. Kato, C. Barty, G. Dunne, R. Schuetzhold, K. Homma, A. Suzuki, F. Takasaki, M. Nozaki, K. Nakajima, E. Goulielmakis, M. Teshima, Y. Fujii, A. Caldwell, W. Leemans, L. Veisz

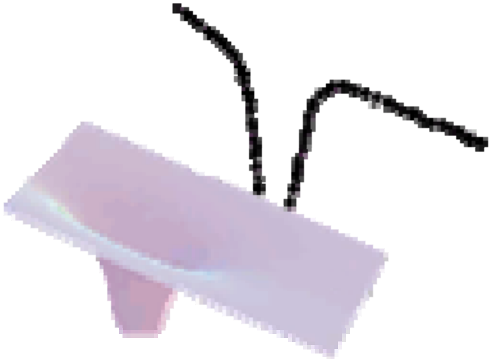
1. Laser intensity and nonlinearities
2. Relativistic Nonlinearity = Laser Wakefield Acceleration
3. Radiation Pressure Acceleration x LWFA toward TeV over cm
4. ICAN: toward fiber laser with100MW @ 50%
5. Prof. Suzuki's Challenge:
   1000 times higher energies, 1000 times shorter time scales
6. PeV acceleration to probe quantum gravity fluctuations
7. Ultrafast science: toward attosecond, zeptosecond,
   yoctosecond(?)
8. Integration of high field science and ultrafast science
9. Exploration of vacuum
10. High field science as a tool to explore light-mass new fields (dark
    matter such as ALP and dark energy)


QCD ~ 10^35 W / cm^2
Nonlinear QED: E·e·λc = 2m0c^2
Ultra Relativistic Optics
EQ = mpc^2
ELI
ILE
Relativistic Optics
CUOS
EQ = m0c^2
Bound electrons
CPA
mode locking
Q-switching
1PeV
1TeV
1MeV
1eV
10^30
10^25
10^20
10^15
10^10
Focused Intensity (W / cm^2)
1960
1970
1980
1990
2000
2010
2020
2030
Nucleus
Electrons

Nonlinearities in atom, plasma, and vacuum

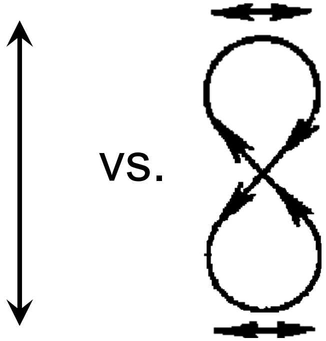
MPQ
LMU
www.attoworld.de

Atomic
nonlinear potential



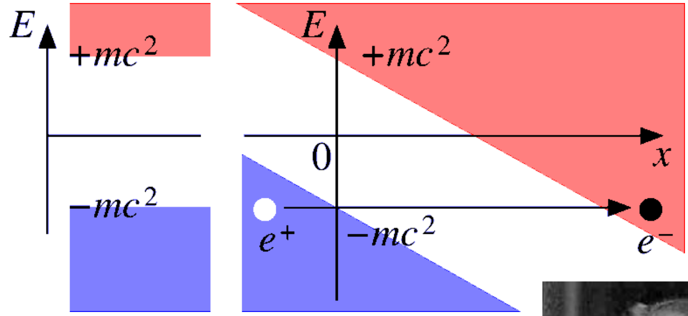
Keldysh field for
laser atomic
ionization

Plasma electron
nonlinear
relativistic motion

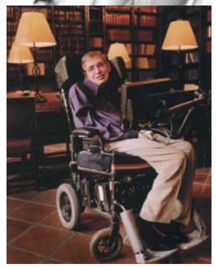


Laser wakefield

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:

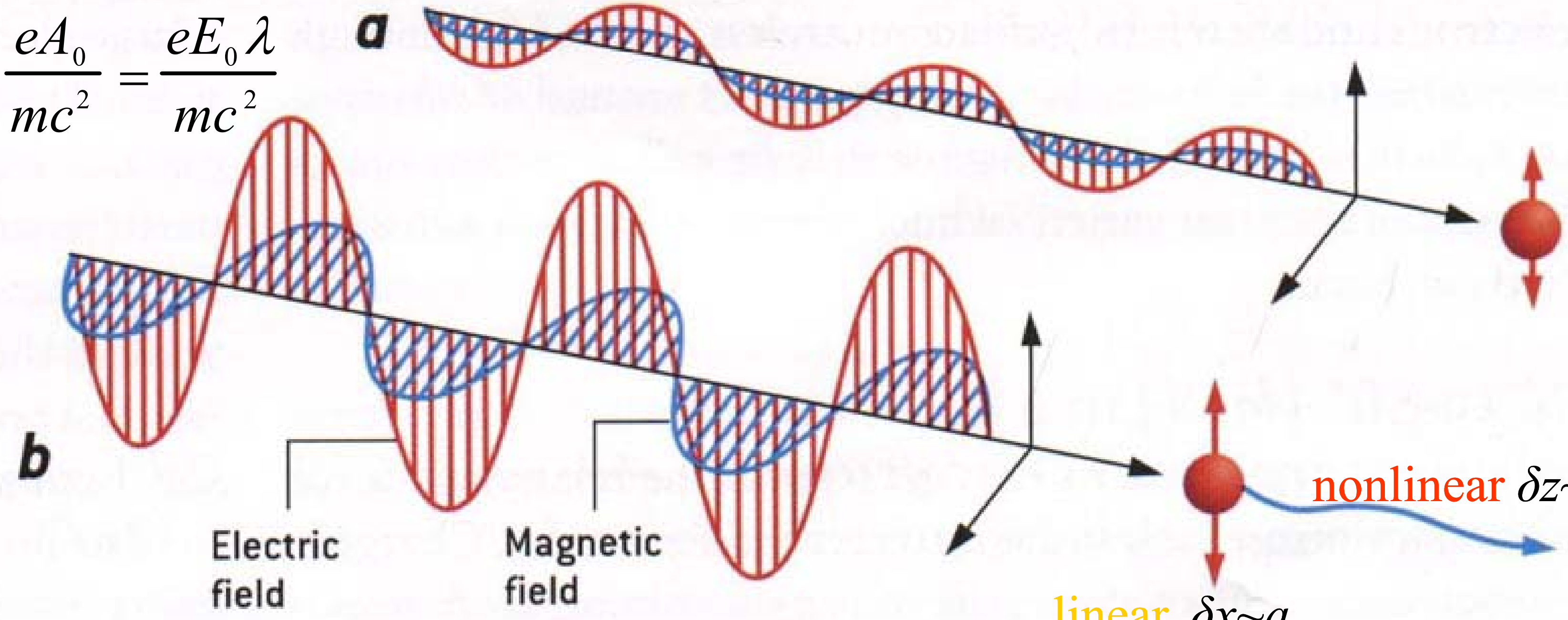
a) Classical optics : $v << c$,

$a_0 << 1$: δx only

b) Relativistic optics: $v \sim c$

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

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



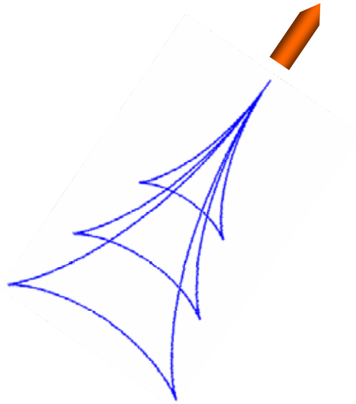
nonlinear $\delta z \sim a_o^2$

linear $\delta x \sim a_o$

Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]



Kelvin wake

$$\omega = \sqrt{kg}$$

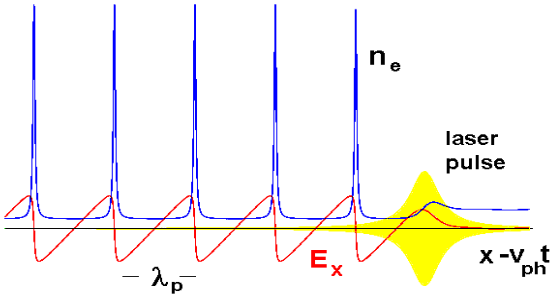
$$x = X_1 \cos\theta \left(1 - \frac{1}{2}\cos^2\theta\right)$$

$$y = X_1 \cos^2\theta \sin\theta$$

$$-\pi/2 < \theta < \pi/2$$

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

Wave **breaks** at v<c



← relativity regularize

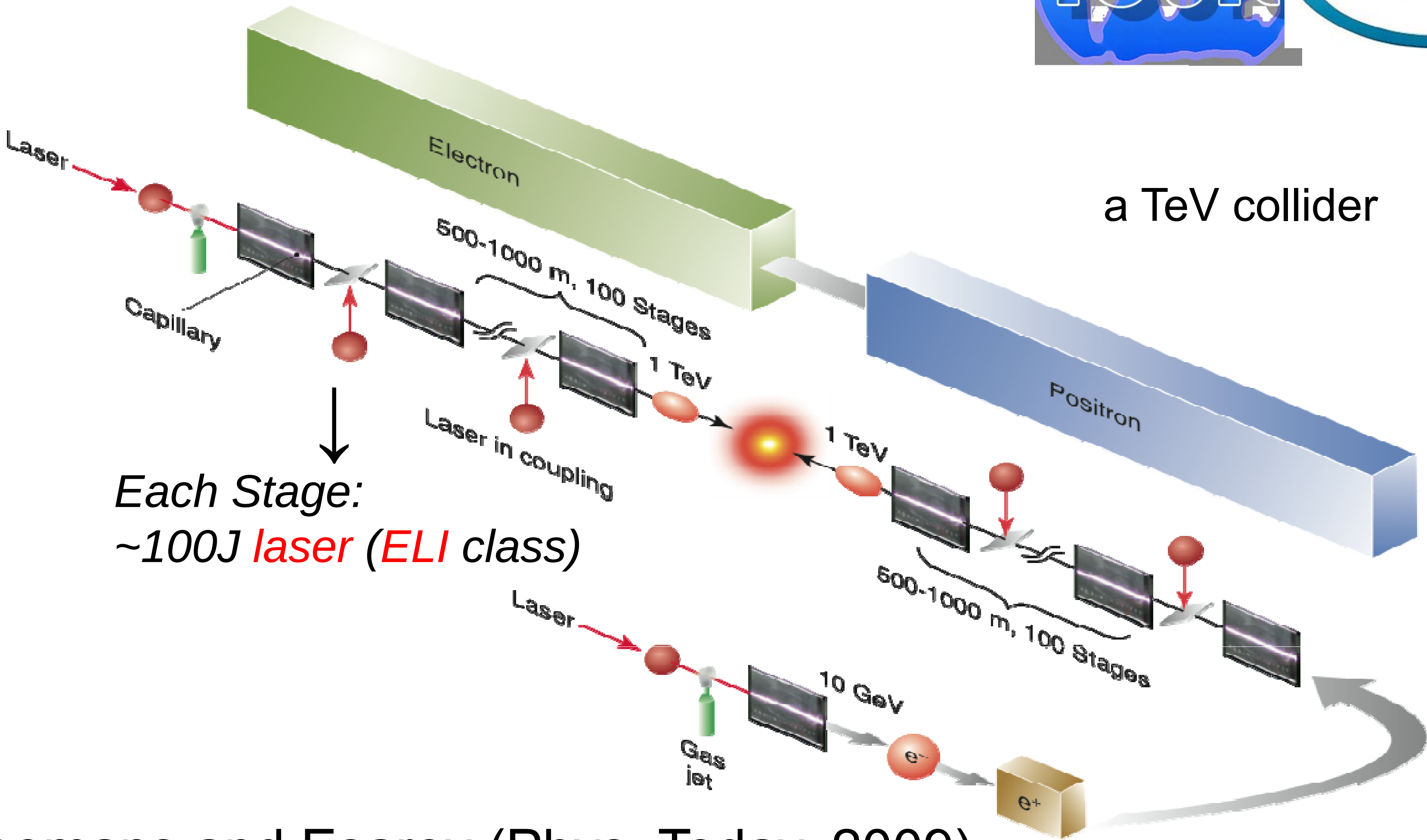
$$\lambda_p = 2\pi / k_p \qquad k_p v_{ph} = \omega_{pe}$$

$$\omega_{pe} = \left(4\pi n e^2 / m_e\right)^{1/2}$$

(The density cusps. Cusp singularity)

(Plasma physics vs. String theory?)

Laser driven collider concept



a TeV collider

Each Stage:
~100J laser (ELI class)

Leemans and Esarey (Phys. Today, 2009)
ICFA-ICUIL JTF on Laser Acceleration (Darmstadt, 2010)

ICFA-ICUIL Joint Task Force

on laser acceleration (Darmstadt, 2010)

W. Leemans, Chair

Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Energy per beam (TeV)	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	1.2	71.4	71.4
Electrons per bunch ($\times 10^9$)	4	4	1.3
Bunch repetition rate (kHz)	13	17	170
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	700	200	200
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	700	200	200
β* (mm)	0.2	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	12	2	2
Vertical beam size at IP σ^*_y (nm)	12	2	2
Luminosity enhancement factor	1.04	1.35	1.2
Bunch length σ_z (μm)	1	1	1
Beamstrahlung parameter Υ	148	8980	2800
Beamstrahlung photons per electron n_γ	1.68	3.67	2.4
Beamstrahlung energy loss δ_E (%)	30.4	48	32
Accelerating gradient (GV/m)	10	10	10
Average beam power (MW)	4.2	54	170
Wall plug to beam efficiency (%)	10	10	10
One linac length (km)	0.1	1.0	0.3

Collider subgroup
List of parameters
(W. Chou)

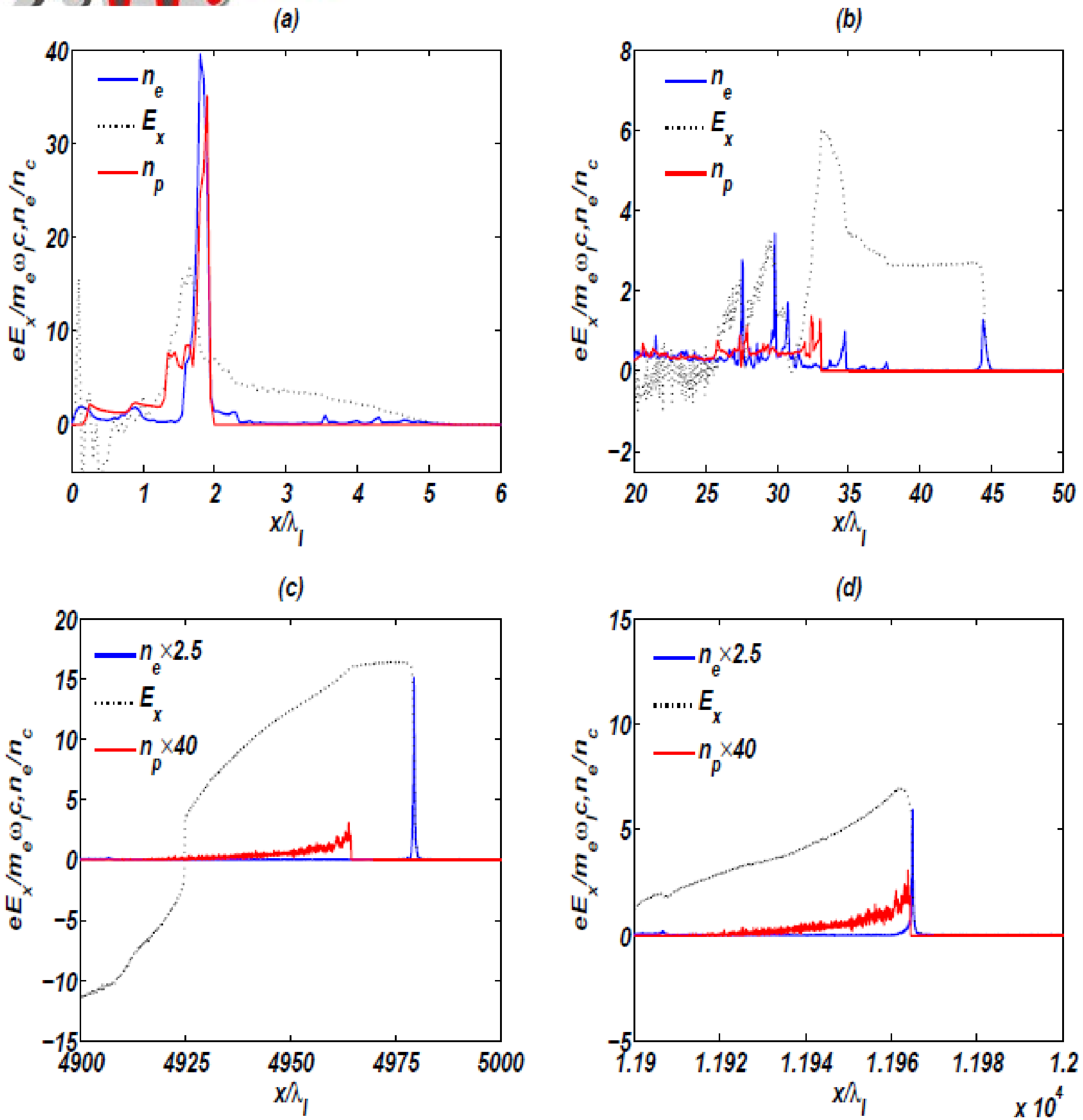
Table 1
Collider parameters

ICFA-ICUIL JTF Conclusions
(April, 2010; Darmstadt)

- *Science of LWFA* (US, Europe, Asia) matured to extend toward HEP accelerators
- *Laser technology* lacking suited for HEP accelerators: **laser efficiency, average power**
- *Technologies* to rectify emerging and credible: **1. thin disk; 2. ceramic; 3. fiber laser,..**
- *ICFA-ICUIL collaboration*: important guide of direction

→ Bridge Lab between HEP and Laser communities
"Symposium on Bridgelab for Laser Accelerator: Route toward Reality"
L'orme (Paris), Jan. 14, 2011 (Organizers: Mourou, Tajima, ….)

TeV ion acceleration in ELI regime



Snowplow LWFA
of ions injected by RPA

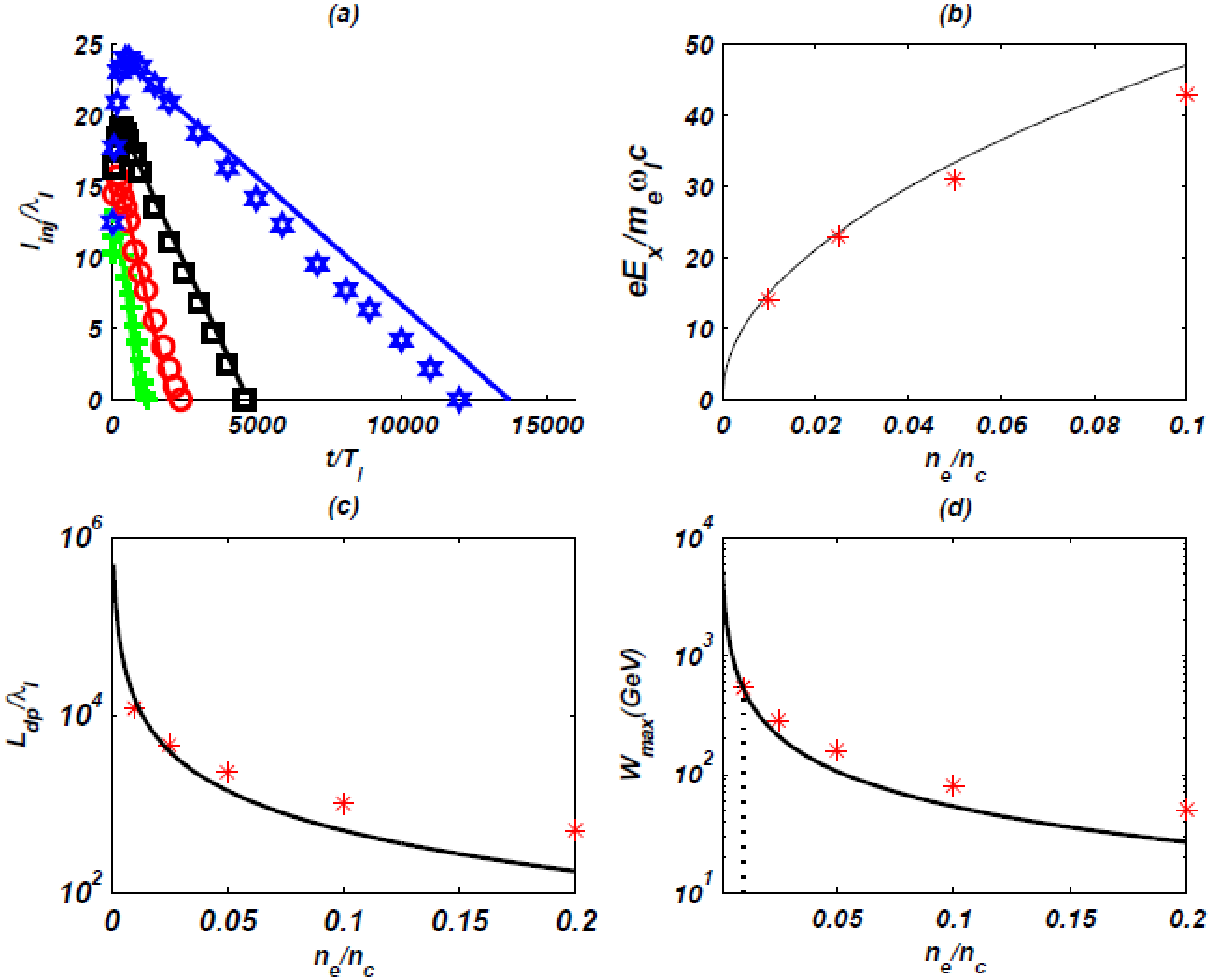
$$\varepsilon_i = (1/6)\, a_0^2\, (n_c / n_e)\, mc^2$$

0.5TeV over

dephasing length of 1cm

Zheng et al., 2010

TeV Ion Energy Scalings(RPA x LWFA)



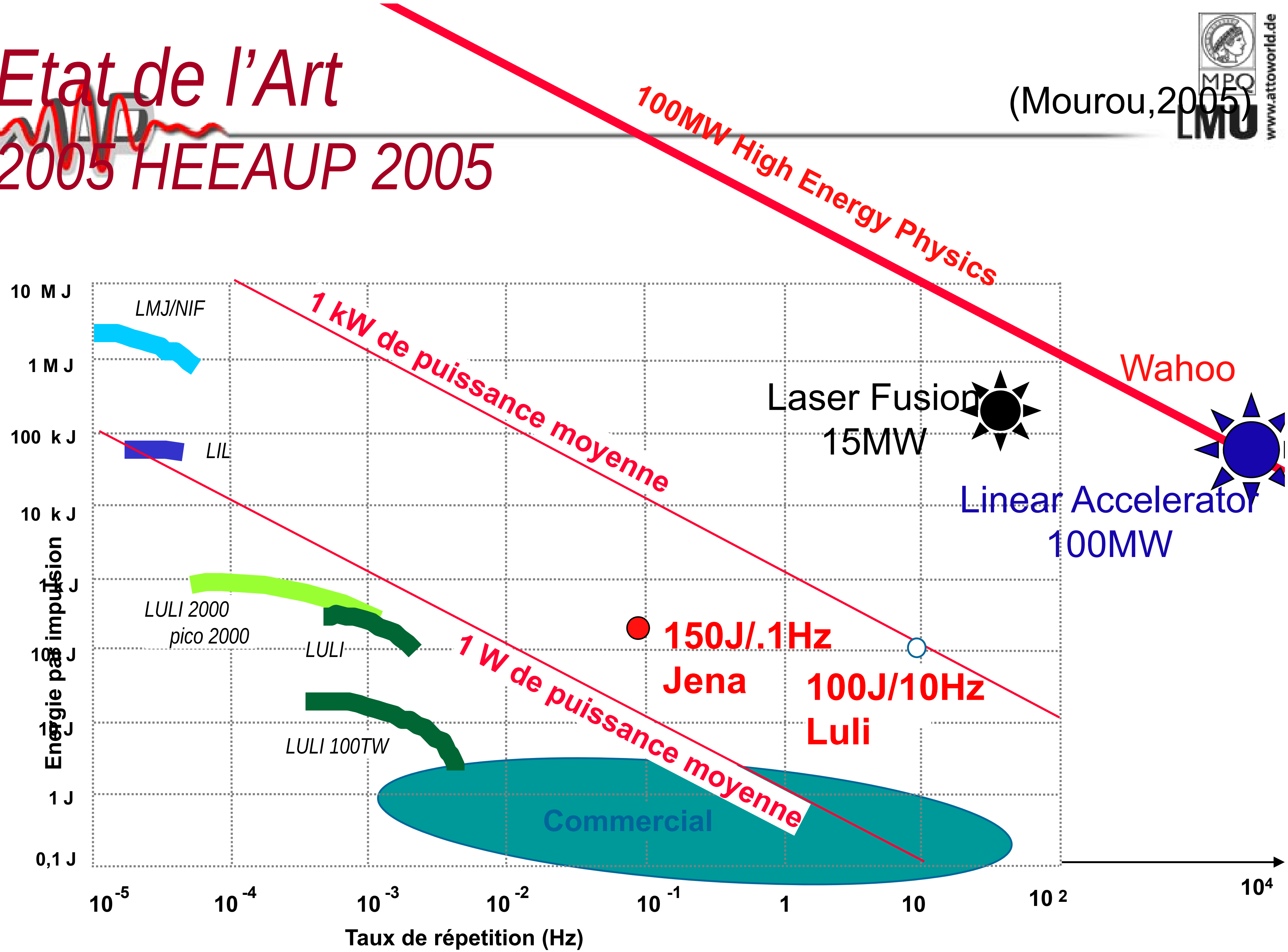
TeV over cm @ 10^{23}W/cm^2

(Zheng et al. 2010)

Etat de l'Art

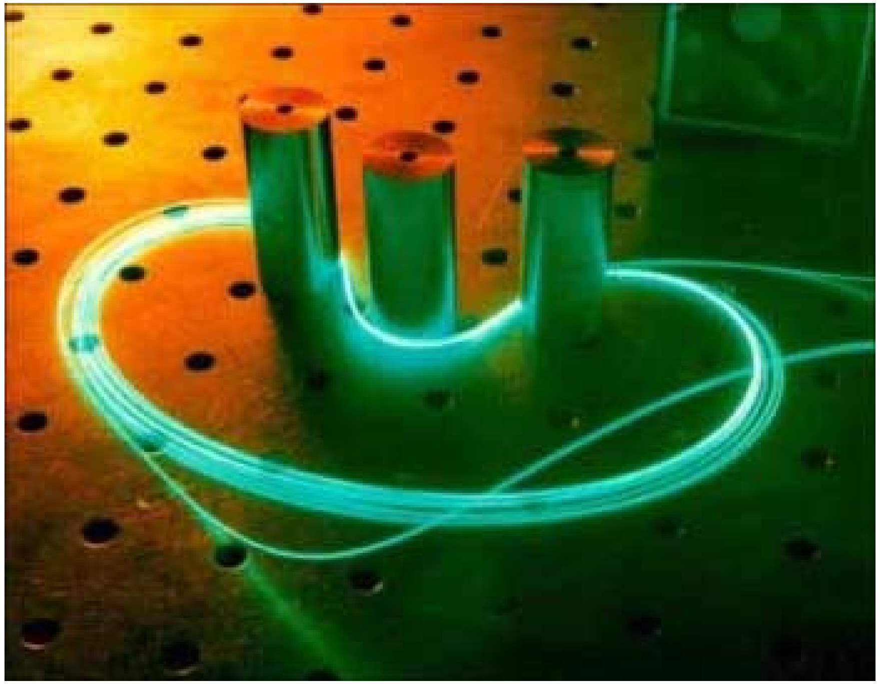
2005 HEEAUP 2005

(Mourou,2005)



Fiber vs. Bulk Lasers

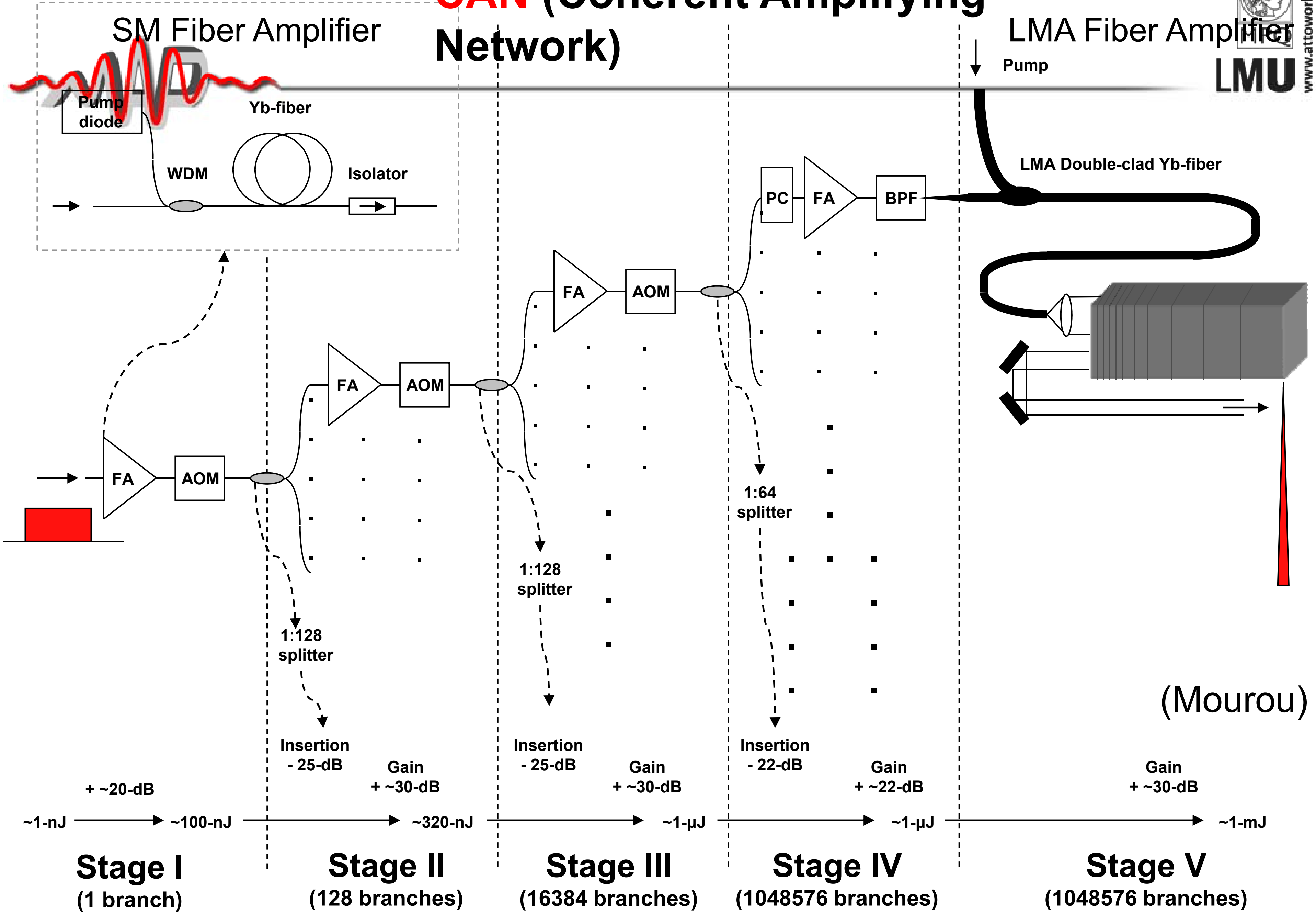
- High Gain *fiber* amplifiers allow ~ 50% total plug-to-optical output efficiency
- Single mode *fiber* amplifier reached multi-kW optical power.
- large bandwidth (100fs)
- immune against thermo-optical problems
- excellent beam quality
- efficient, diode-pumped operation
- high single pass gain
- can be mass-produced at low cost



(G. Mourou)

→ ICAN Consortium formed (Nov. 25, 2010)

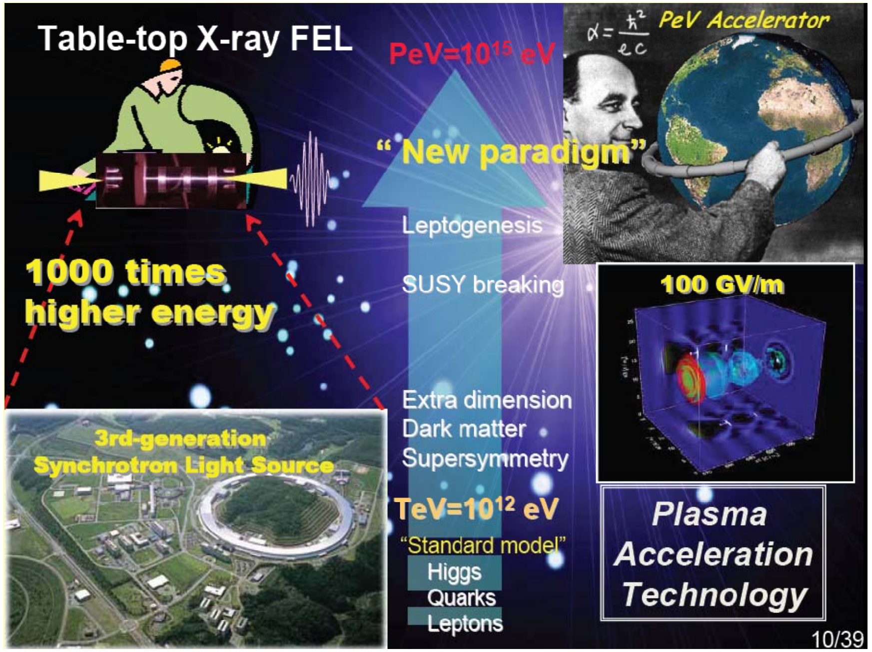
CAN (Coherent Amplifying Network)

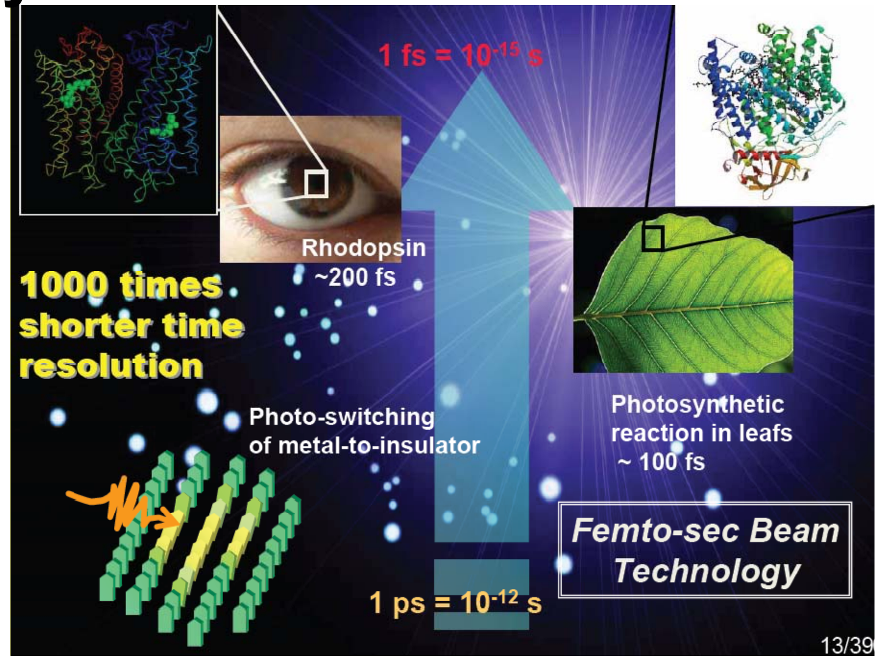


(Mourou)

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





compact, ultrastrong *a*

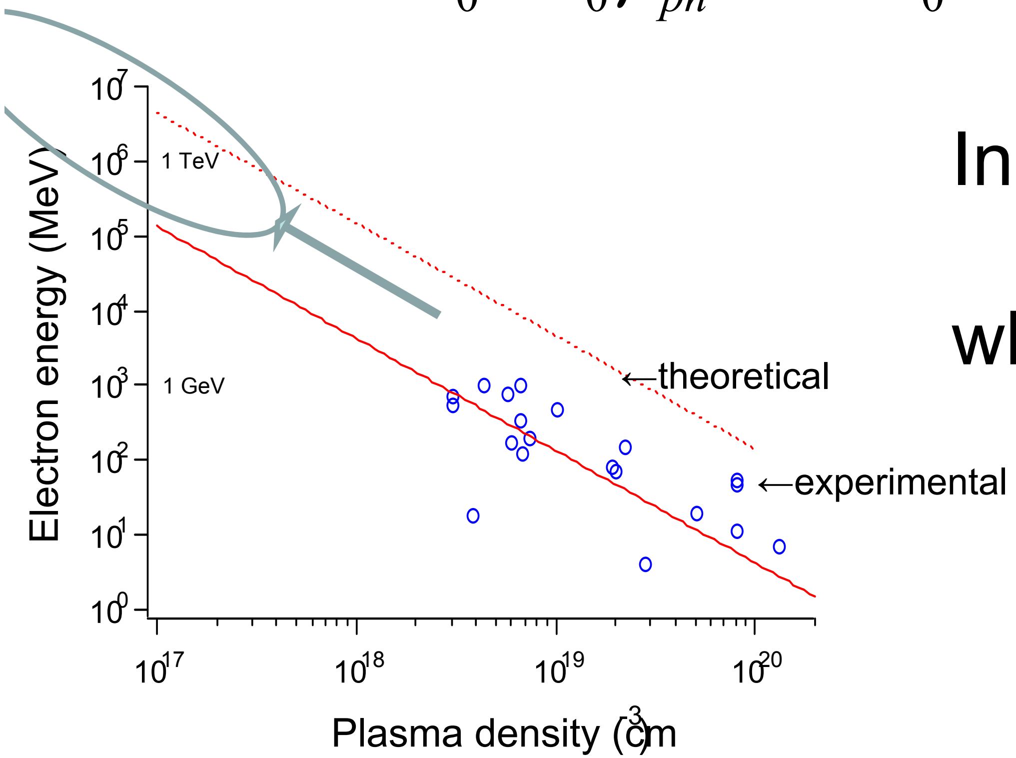
atto-, zeptosecond

Can we meet the challenge?

A. Suzuki @KEK(2008)

Theory of wakefield toward extreme energy

$$\Delta E \approx 2 m_0 c^2 a_0^2 \gamma_{ph}{}^2 = 2 m_0 c^2 a_0^2 \left(\frac{n_{cr}}{n_e} \right),$$ (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)

→ 0.7PeV

(with Kando, Teshima)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

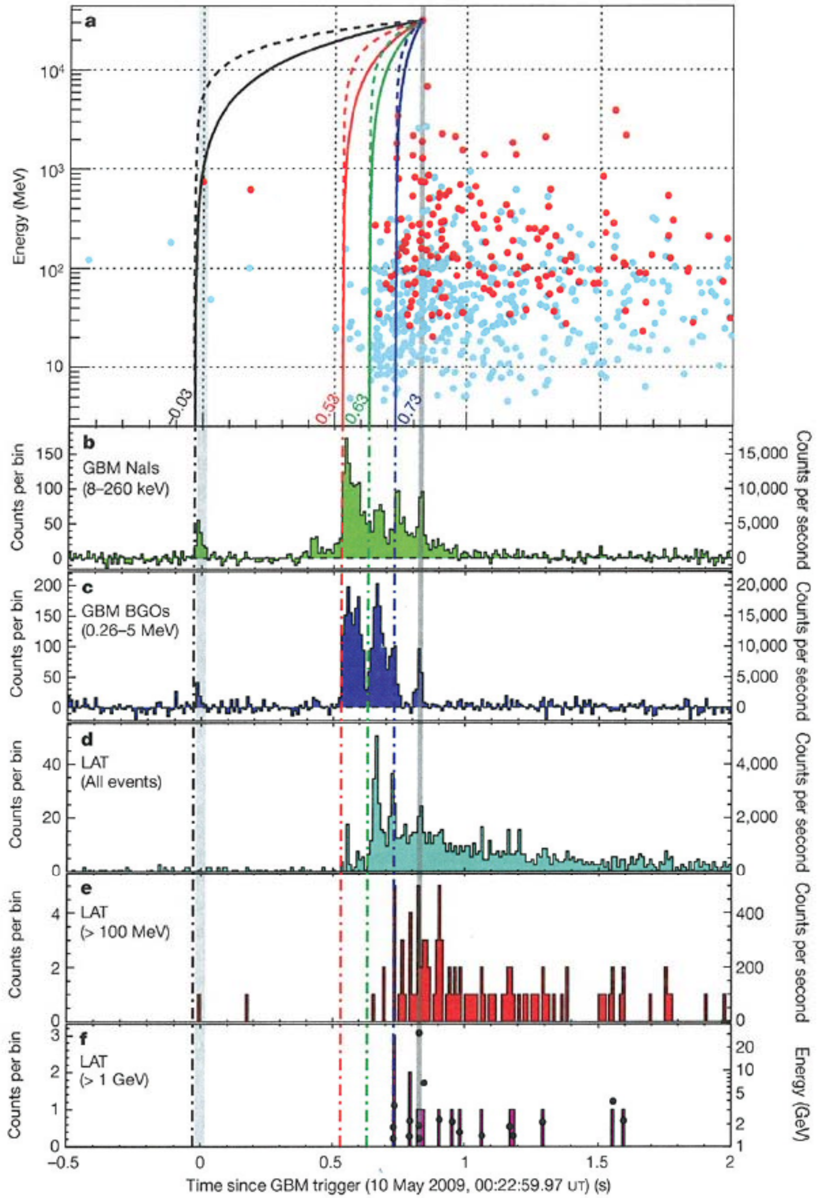


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. **f** also overlays energy versus arrival time for each

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

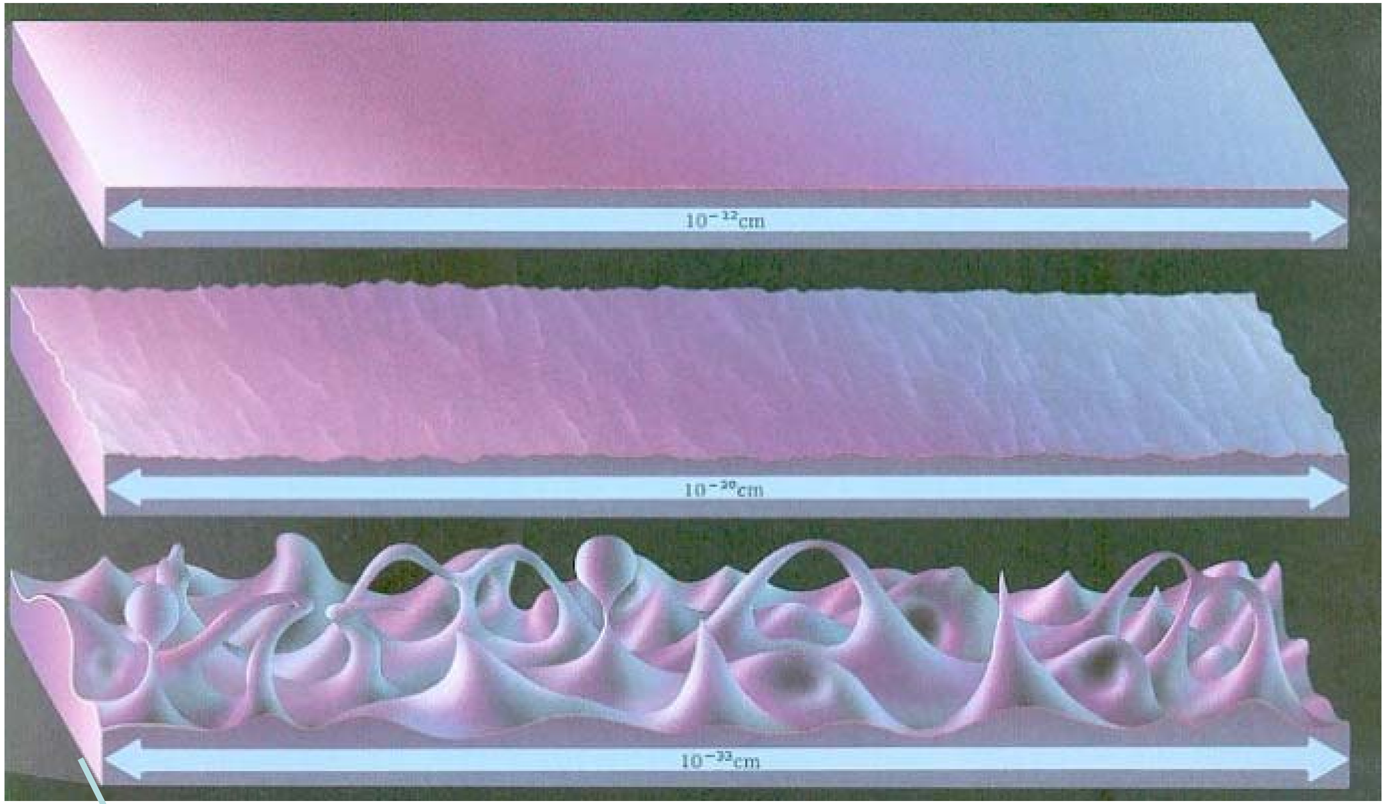
Lab PeV γ (from e-) can explore this with control

MPQ LMU www.attoworld.de

Feel vacuum texture: PeV energy γ

MPQ
LMU
www.attoworld.de

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



Coarser, lower energy texture

↕

Finer, higher energy texture

$c < c_0$

1km

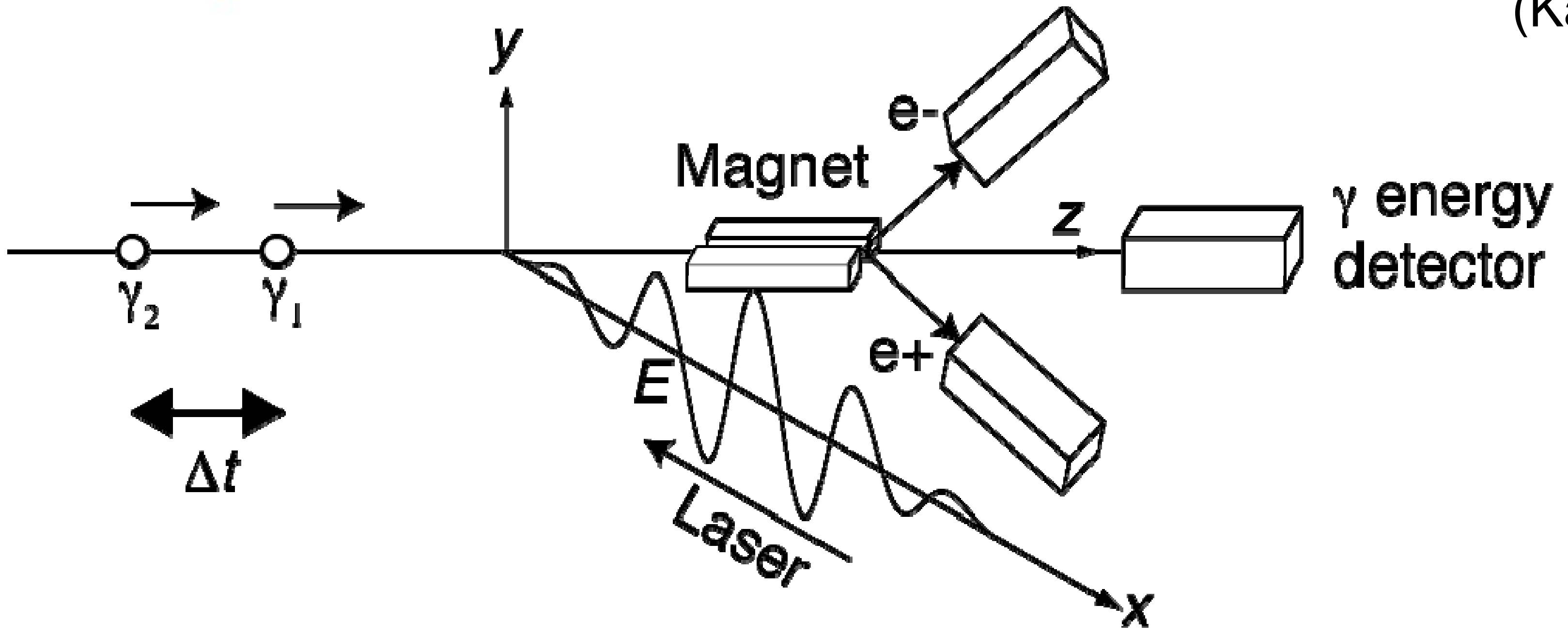
← (0.1PeV)

←(1PeV : fs behind)

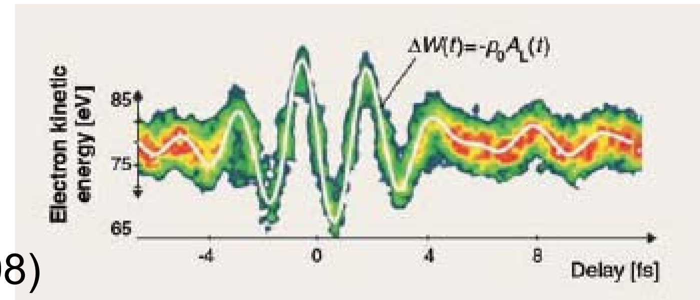
⇐ PeV γ (converted from e^-)

Attosecond Resolution of PeV γ Arrivals

(Kando, 2010)



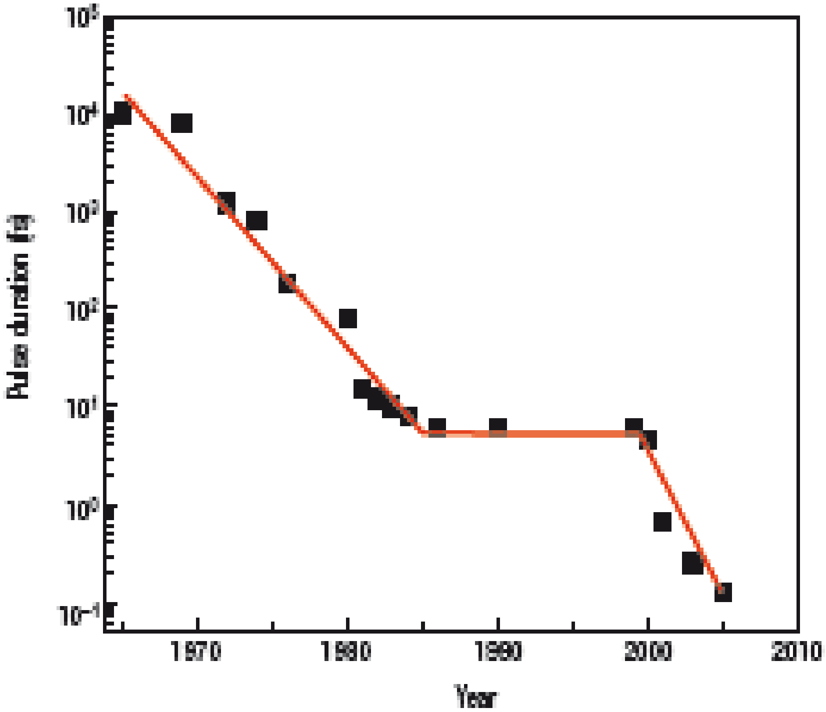
High energy γ- induced Schwinger breakdown (Narozhny, 1968)
CEP phase sensitive electron-positron acceleration
Attosecond electron streaking
γ- energy tagging possible



Goulielmakis(2008)

Pulse Progress from fs to as

Corkum and Krausz (2007)



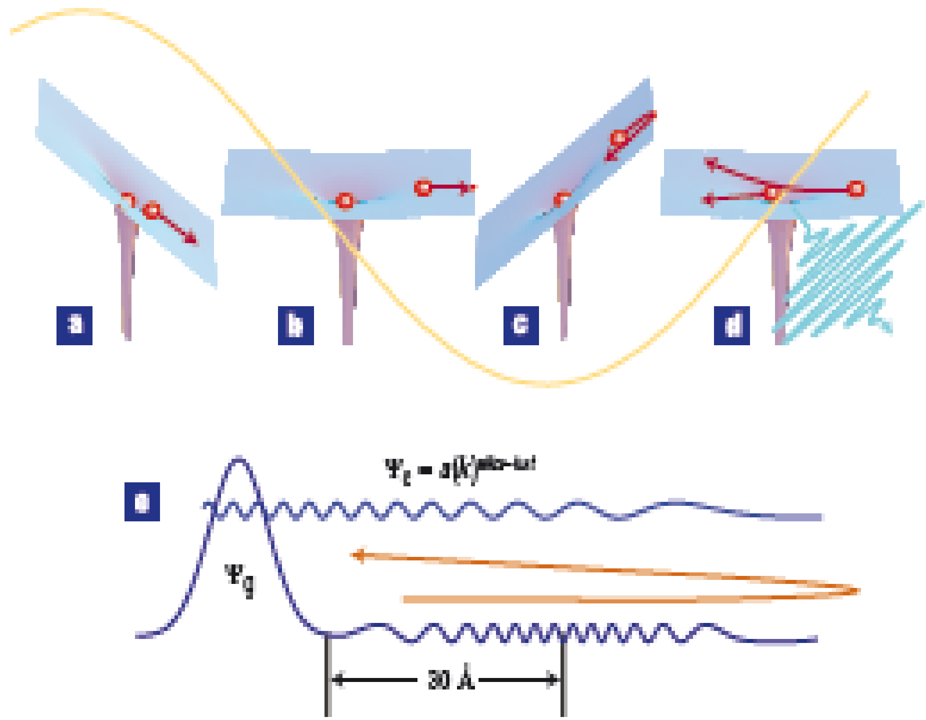


Figure 1 Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1964 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making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

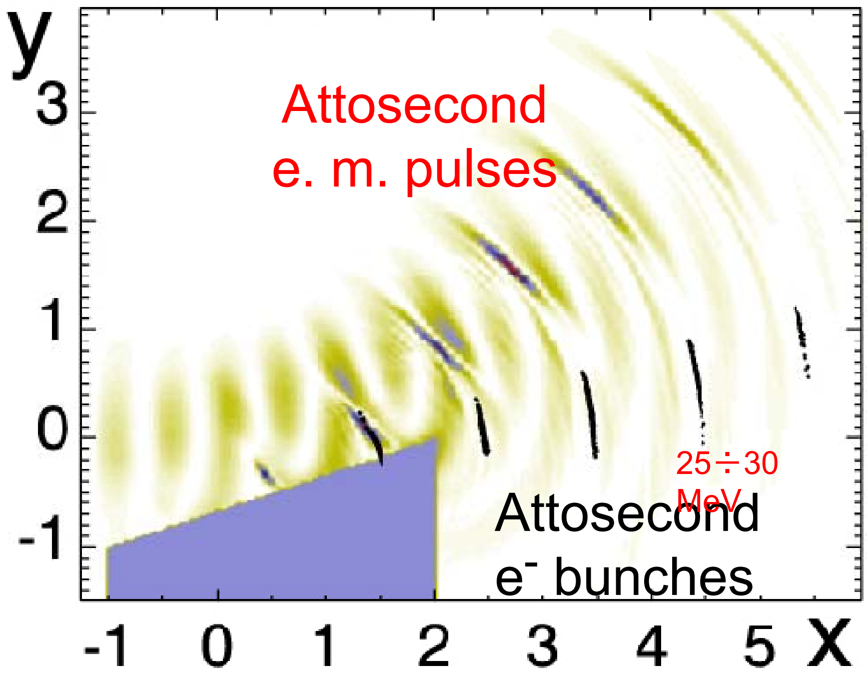
Figure 2 Creating an attosecond pulse. **a–d**, An intense femtosecond near-infrared or visible (henceforth: optical) pulse (shown in yellow) extracts an electron wavepacket from an atom or molecule. For ionization in such a strong field (**a**), Newton's equations of motion give a relatively good description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

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.

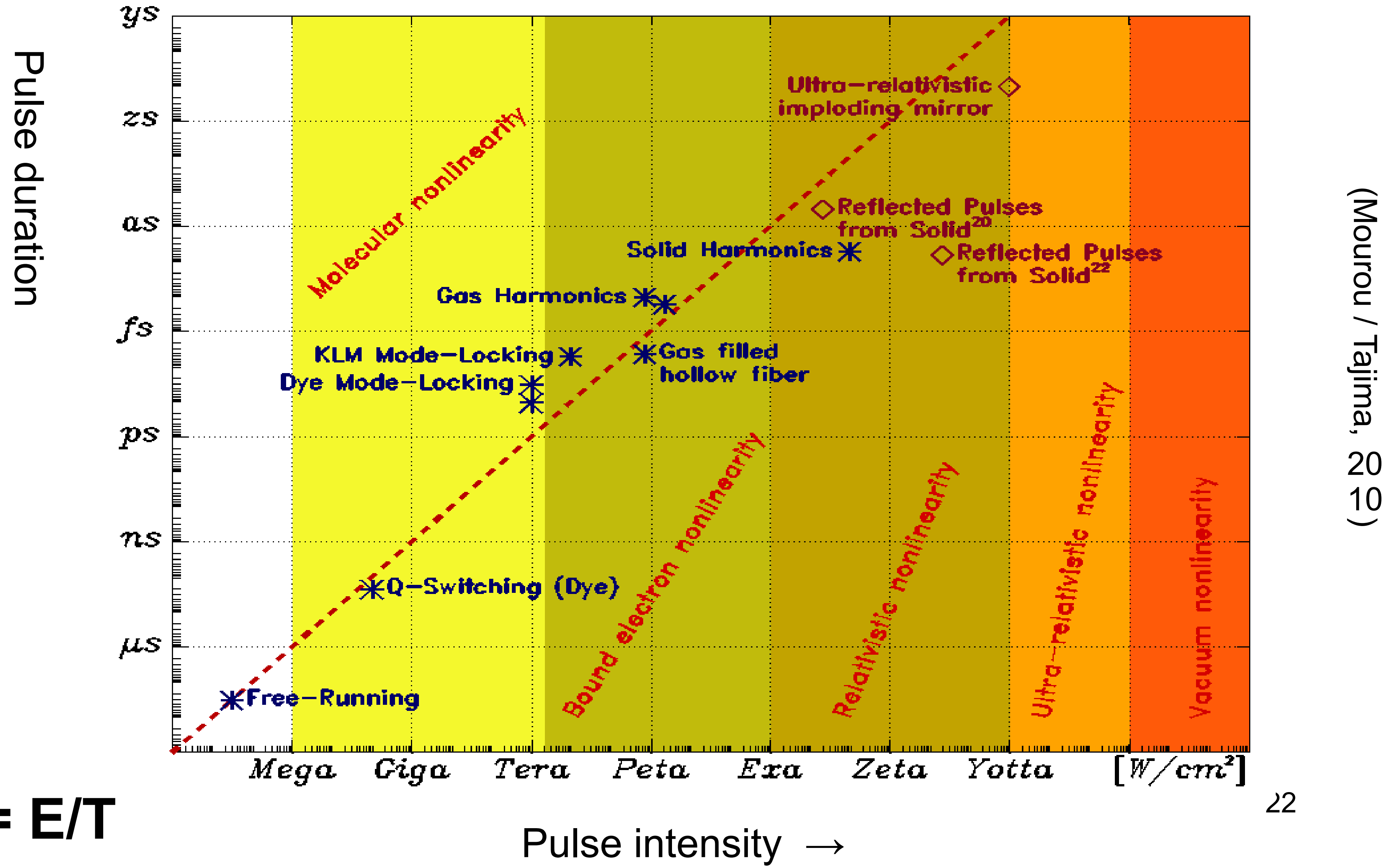


a=10, 15fs, f/1, $n=25n_{cr}$

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

The Mourou Conjecture

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



P= E/T

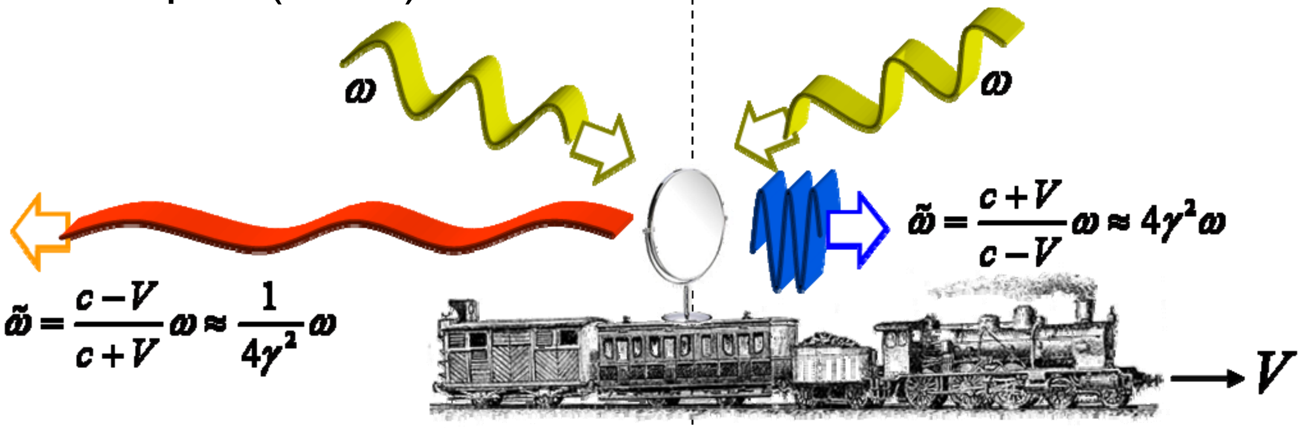
Yoctosecond coherent γ-beam

The Mourou-Tajima Conjecture tells us
that ys coherent gamma pulse
may be generated by Yottawatt/cm^2
Go beyond 10KeV coherent X-rays: solid is not dense enough
How can one make an Einstein mirror
that can backscatter gamma rays (several 100MeV)?
Suggest: the imploded ultra-relativistic shell
to increase the density by 10 x 10 x 10.
The relativistic flying object with $\gamma = 100$. The lab frame
density enhanced by 10^5
Takes large energy ~MJ, Yottawatt/cm^2
$\rightarrow$ yielding 100ys coherent gamma rays

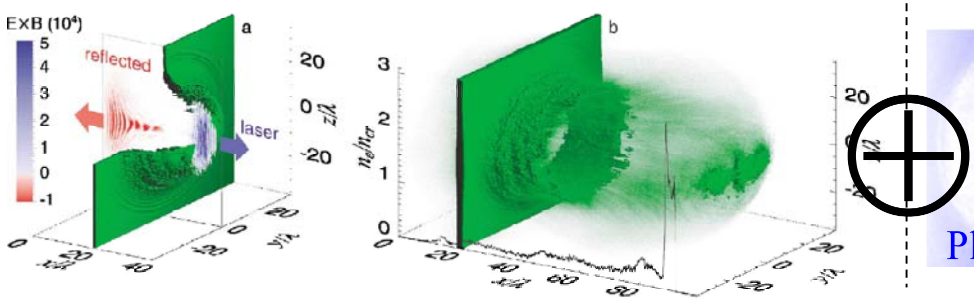
Can we streak a nucleus with this gamma beam? :
Photonuclear Physics. (Any other new physics?)

Relativistic flying mirror and shorter pulses

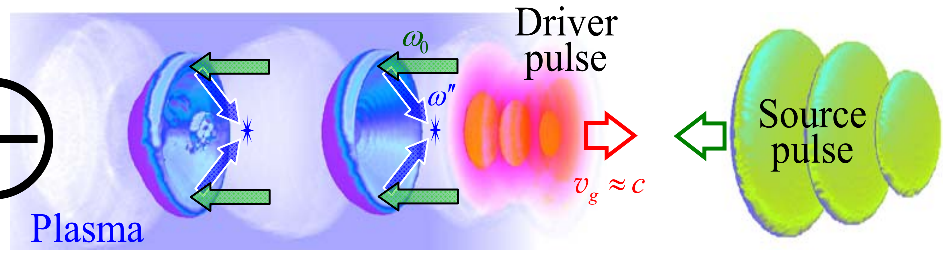
Esirkepov (2010)



Laser Piston

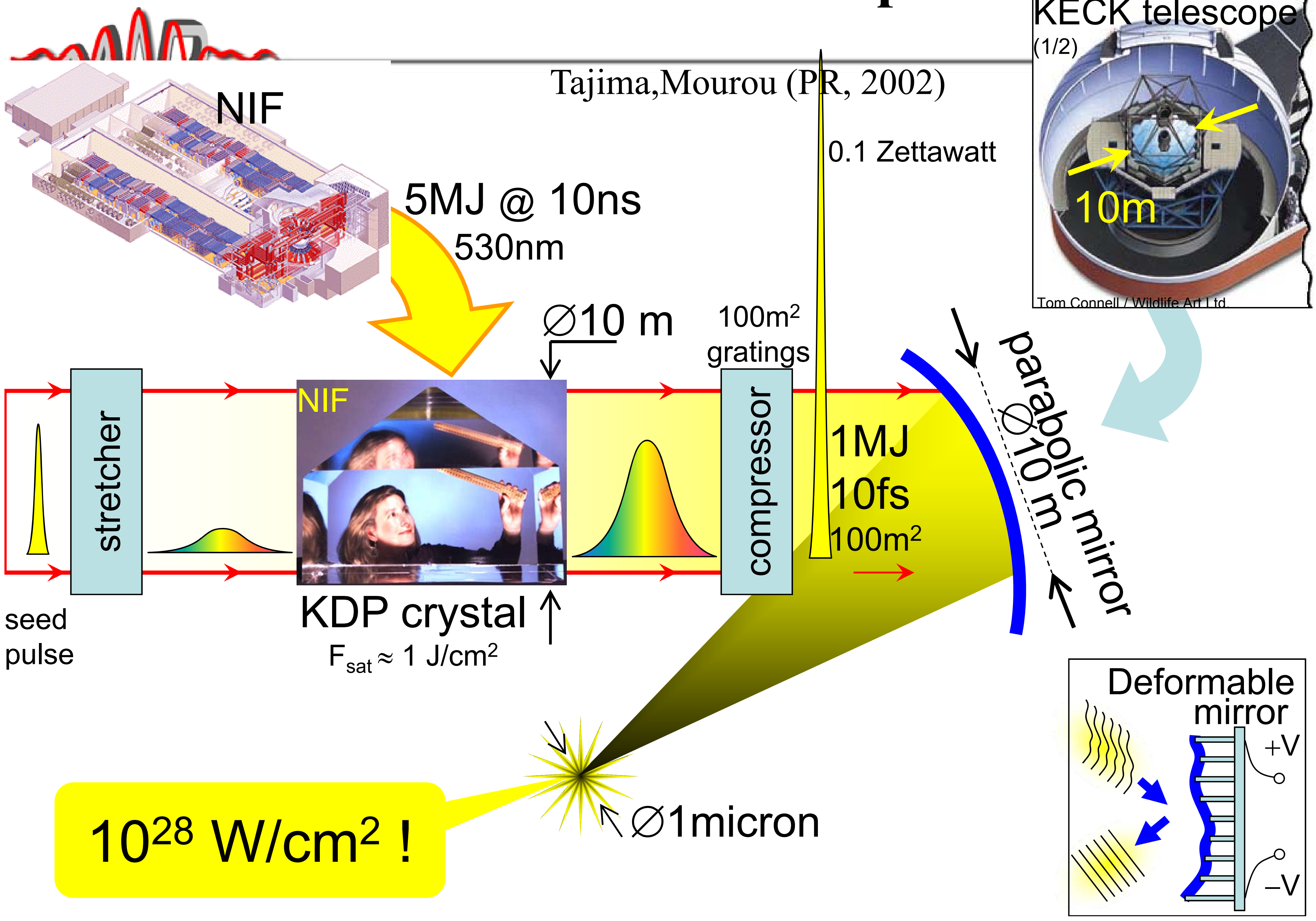


Flying Mirror



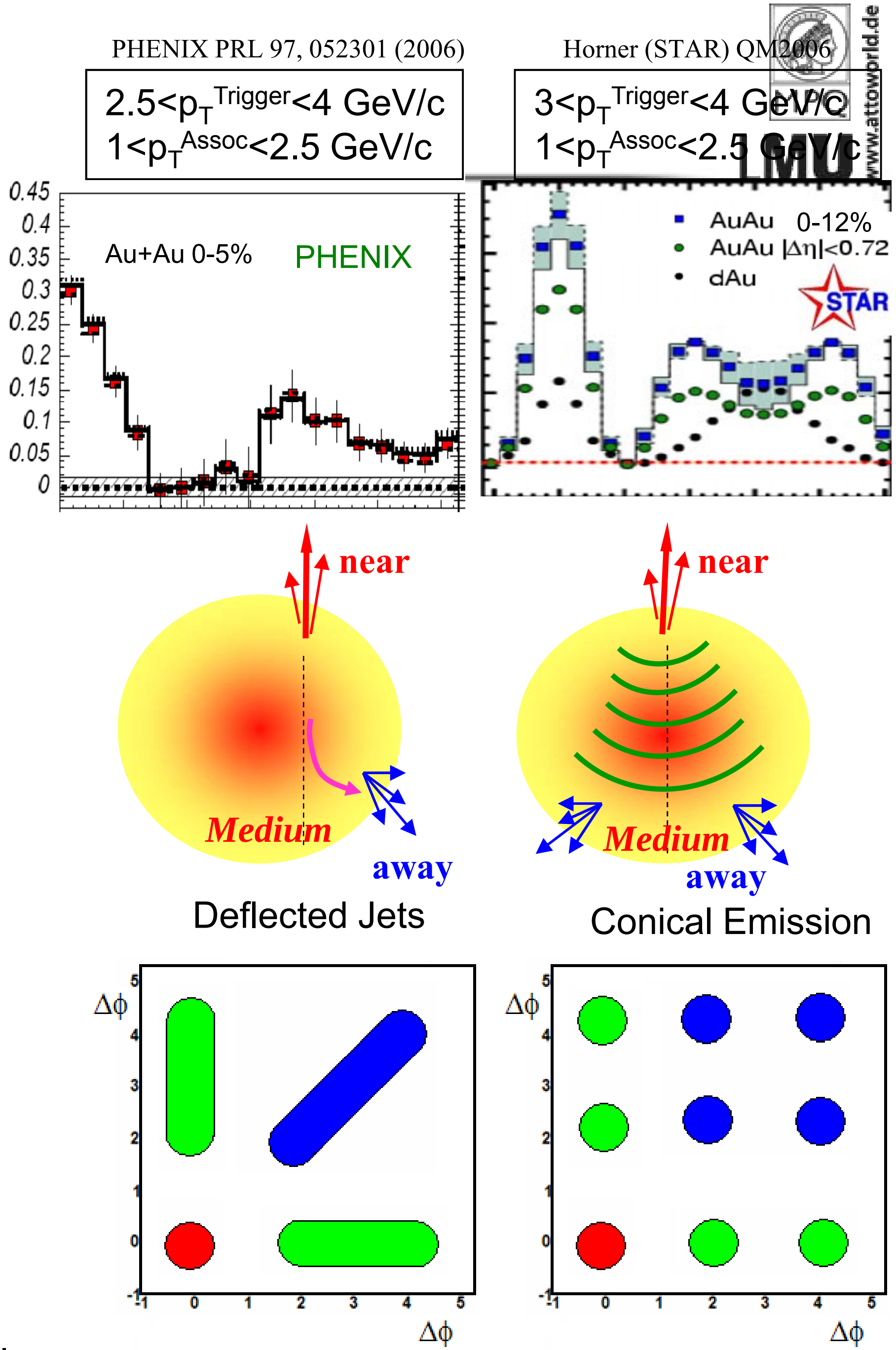
Tajima/Mourou/Moses(2010): use NIF ---ultra-relativistic imploding mirror → ys!

MJ laser→Zettawatt→ultrashort pulse



Nuclear Wake?

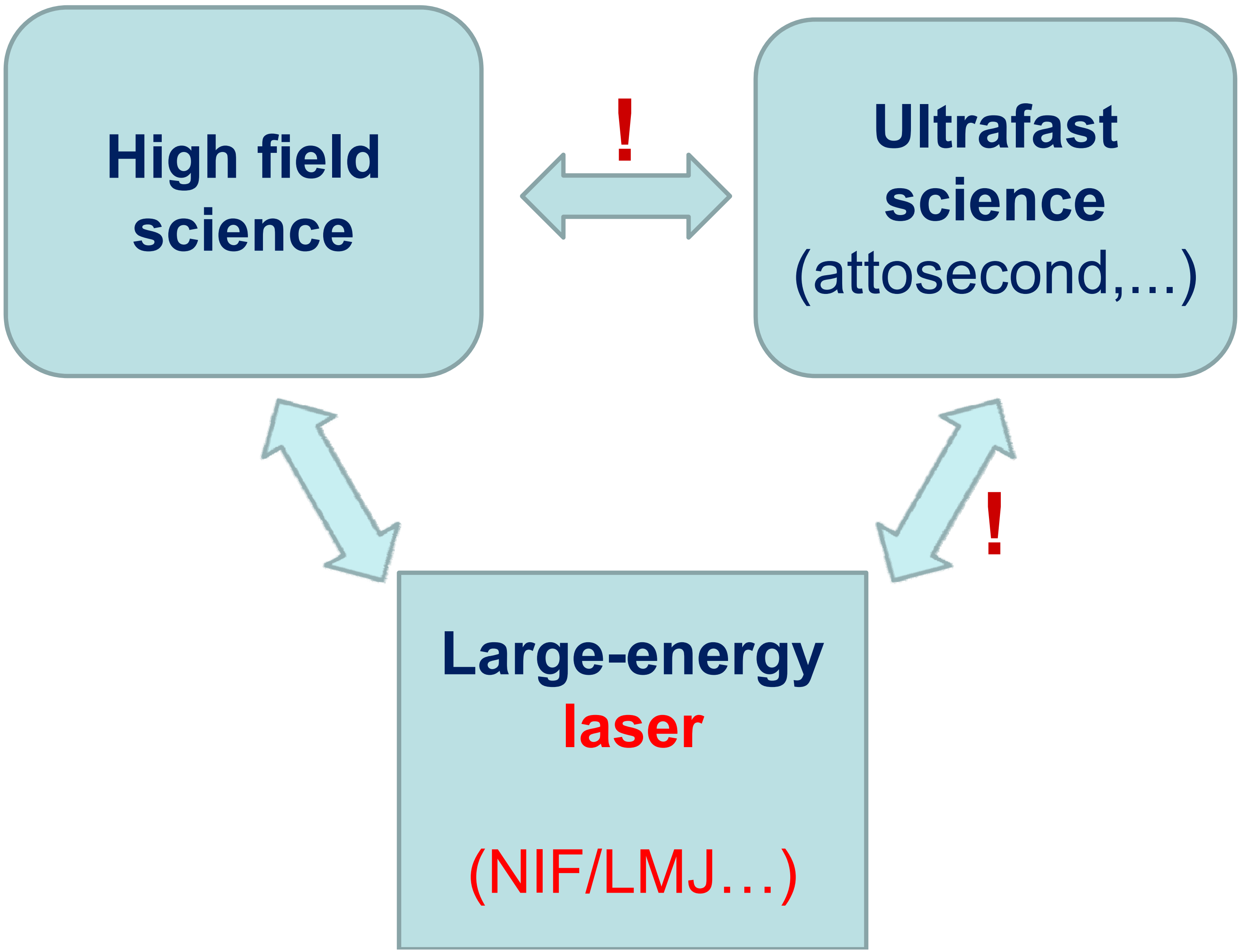
- Broadened and maybe double humped structure on the away-side in 2-particle correlations.
- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- Jet quenching: collective deceleration by wakefield?
  - LWFA method, or Maldacena method?



High energy physics← High field science, high intensity laser

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

Ultrafast science ← High field science, Large-energy laser



Self-focusing in air to vacuum

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

χ_3 nonlinearity

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

relativistic plasma nonlinearity

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

vacuum nonlinearity

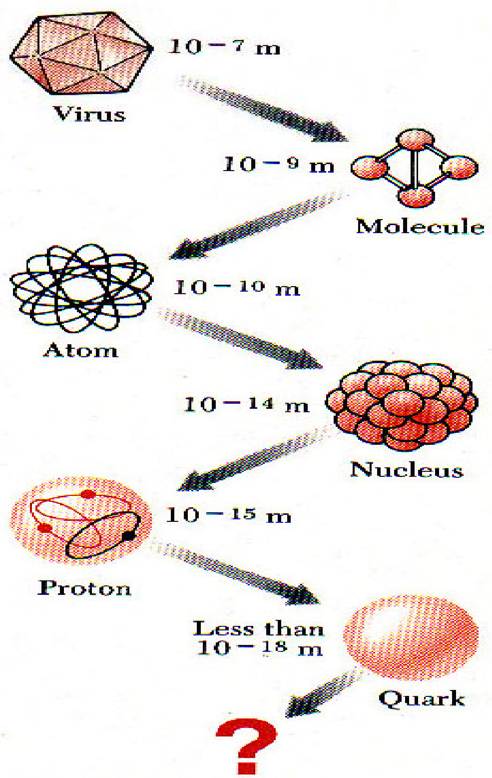
$$P_{cr} = (90/28)\ c\ E_S^2\lambda^2/\alpha \sim 10^{15}\ (\lambda/\lambda_{1\mu})^2\ \text{GW}$$

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

‘ELI Long-term Ambition’ =

Studying the Atomic Structure to the Vacuum Structure

(Mourou)



Vacuum structure

Does the atomic world repeat itself in vacuum?

Keldysh field

Keldysh parameter

$$\gamma_K = \omega\sqrt{2m\Phi}/eE,$$

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

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

Vacuum parameter

$$\gamma_V = 1/a_0.$$

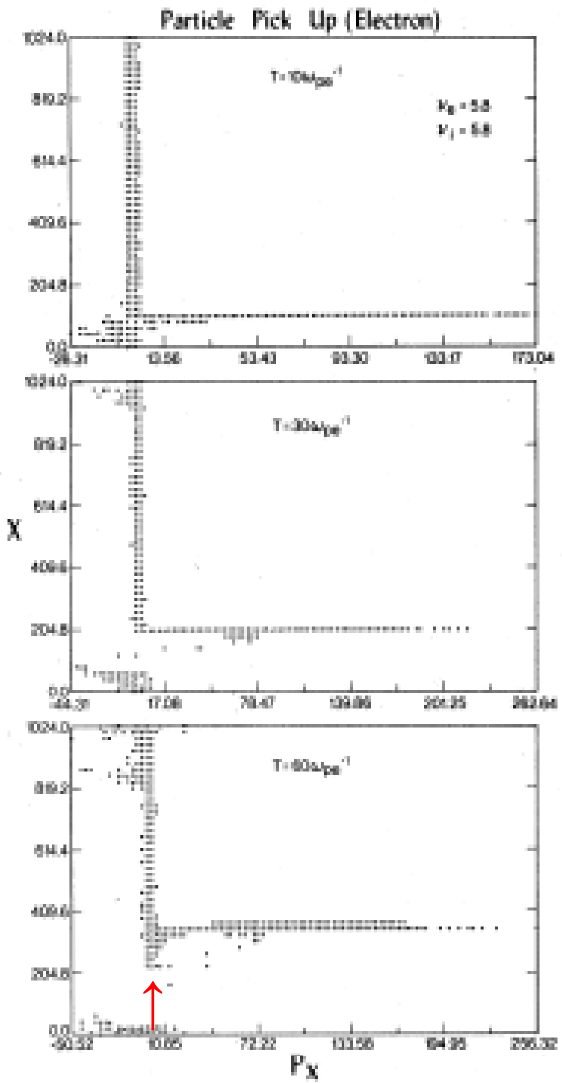
$$\gamma_V \geq 1.$$

Schwinger field

= Path toward superSchwinger

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 $\langle p_x\rangle_L \simeq \frac{1}{2}p_x^m$ and $\langle n\rangle_L \simeq \frac{1}{2}n_{max}$, 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

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

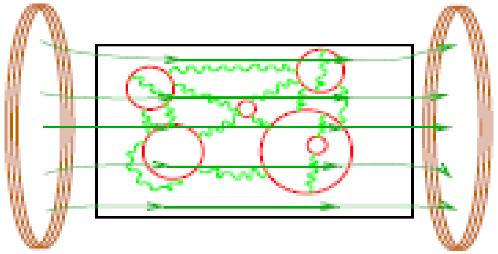
→ Laser acceleration in vaccum by
self-focused X-ray crossed with laser ?

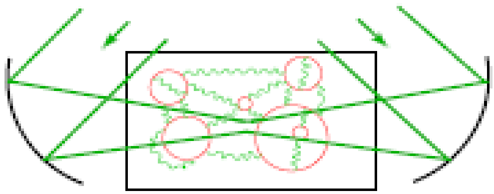
Can we repeat LWFA and plasma physics
in vacuum?
Laser vacuum acceleration with ‘snowplow’

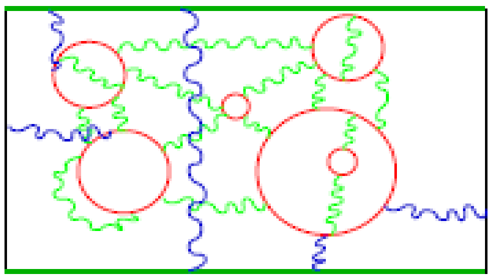
Ashour-abdalla, et al. (1981)

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)

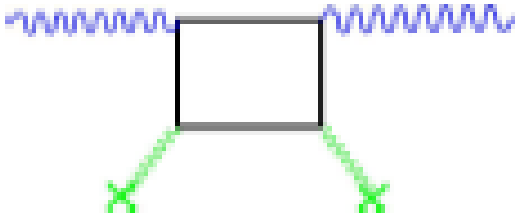
Light Propagation in a B field.

▷ 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]

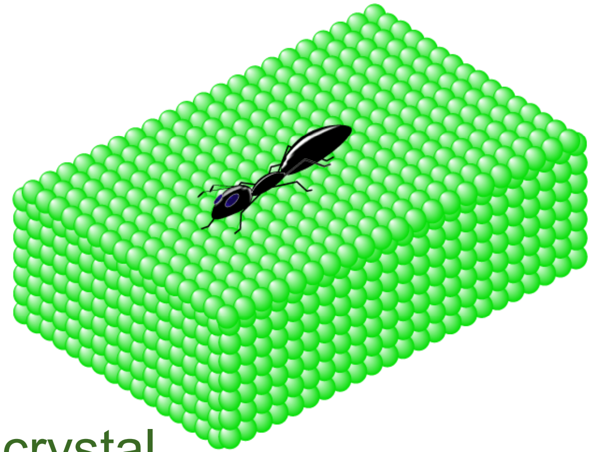
▷ detection schemes: PVLAS, BMV, Q&A, OSQAR, TR18-B7

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))

H. Gies (2008)

What is vacuum?



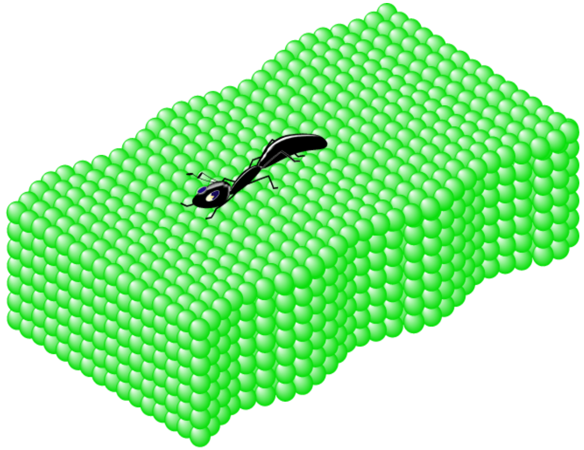
crystal

An observer (bug) in crystal looks at vacuum

↓

vacuum

「真(true)空(nothing)」

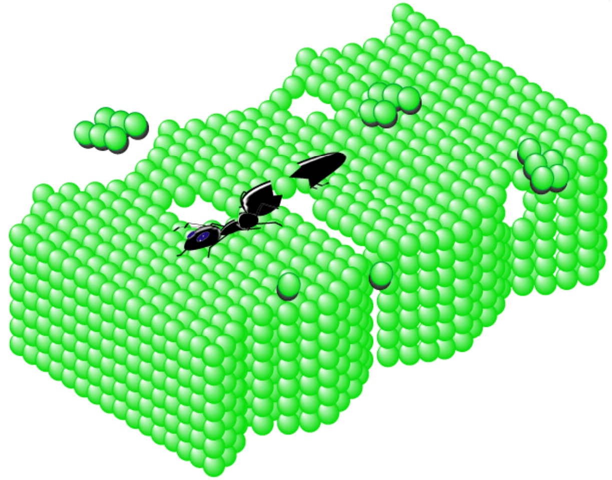


Phonon : excitation of vacuum

↓

Photon : distortion of vacuum

「色=(即是)空」



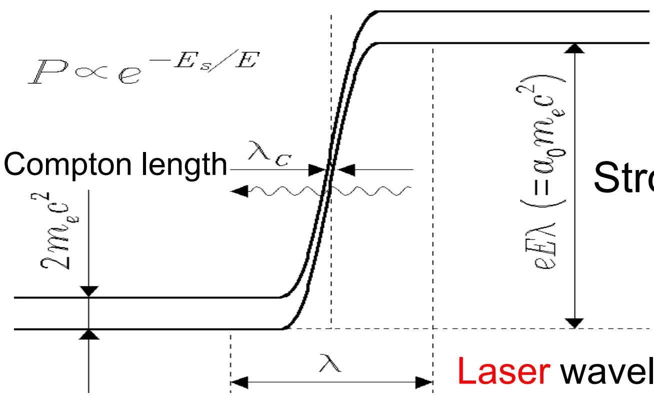
Strong field breaks vacuum

↓

vacuum produces e+e- pair

「空=(即是)色」

QED vacuum breakdown

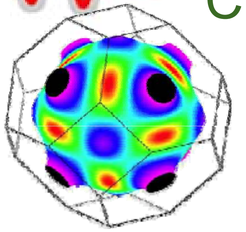


Strong laser field

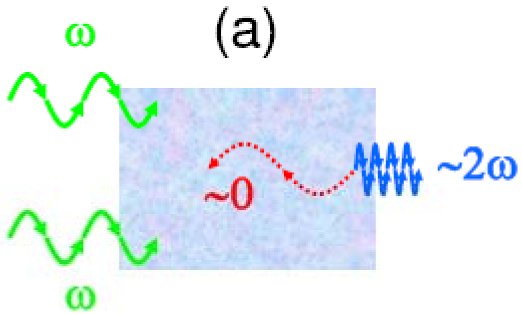
Laser wavelength

(Naumova Mourou)

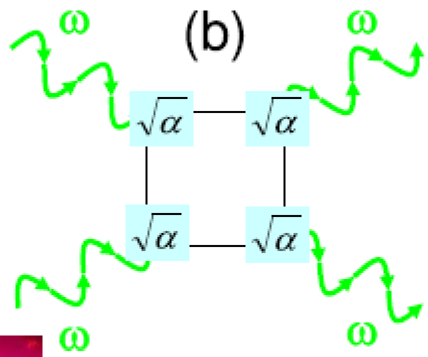
Intense laser probes matter /vacuum nonlinearity

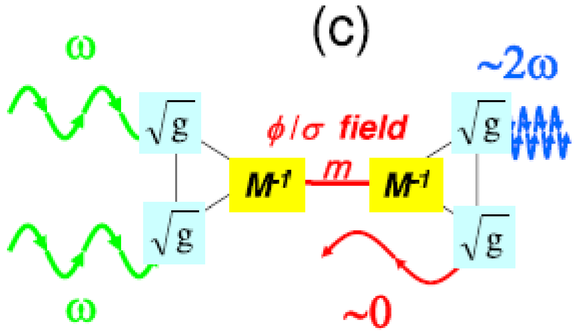


Crystal nonlinearity →
second harmonic generation (Franken et al)



Learn from **Nonlinear Optics** of matter for vacuum:





QED nonlinearity

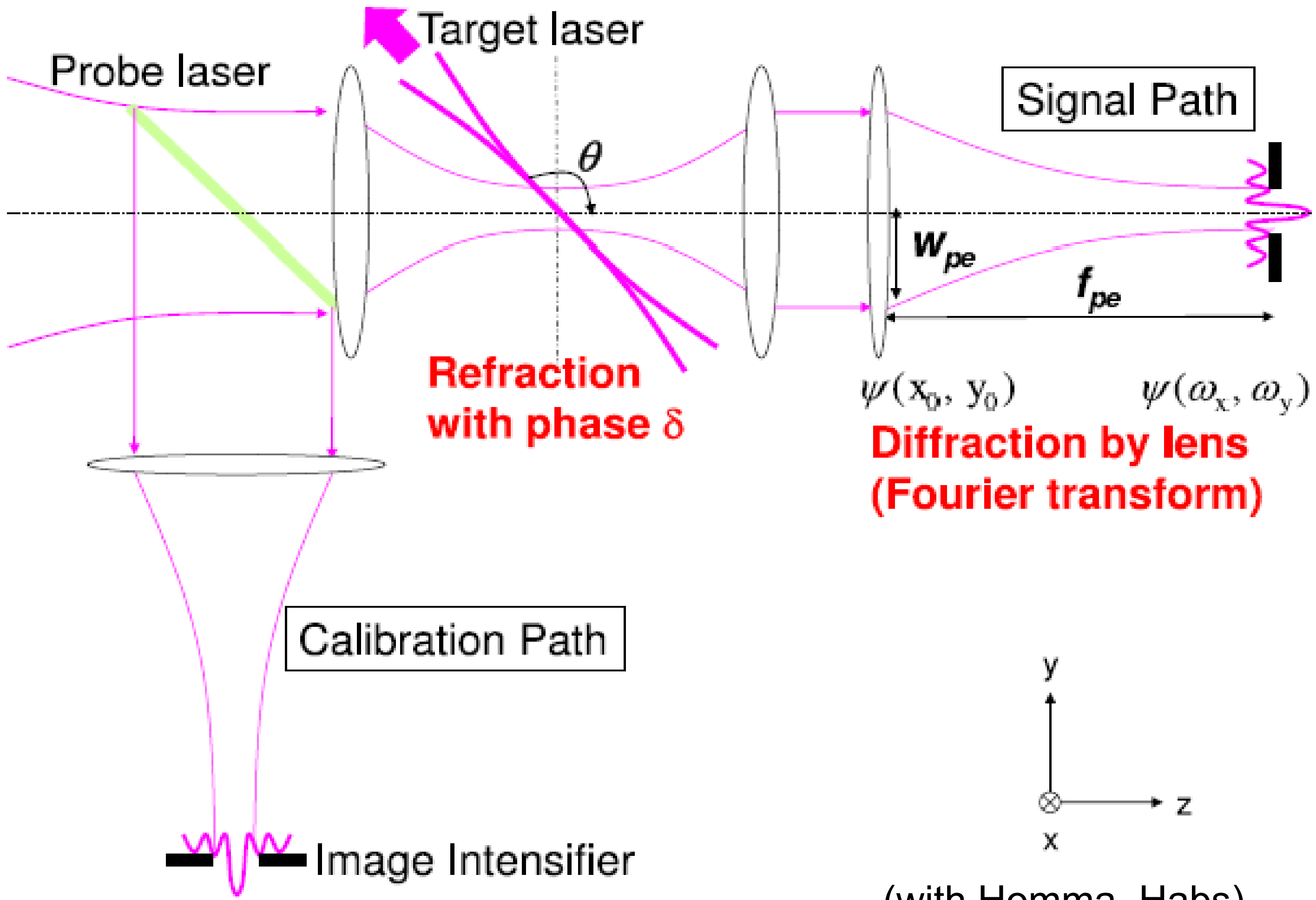
Vacuum nonlinearity by light- mass field (dark energy, axion,..)
→ second harmonic

QED vacuum probe by intense laser

Heisenberg-Euler Langrangian: tiny nonlinearity, never observed

→ intense laser needed; sensitive probe, avoid blinding laser

Phase contrast imaging(refractive index →diffraction, noise reduction)



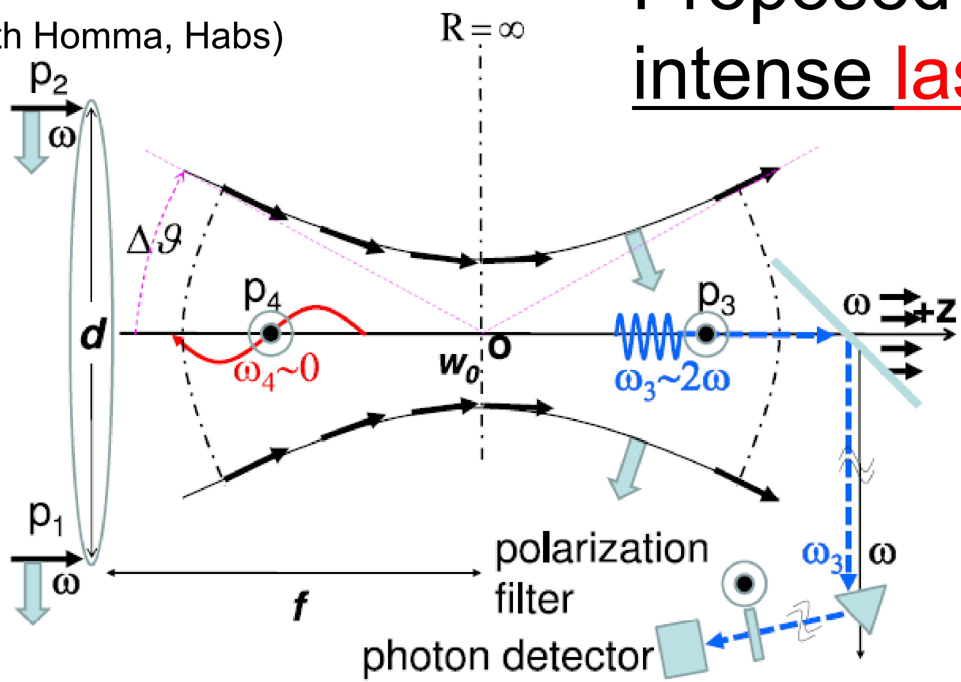
(with Homma, Habs)

Learning from laser parametric scattering: low energy (meV - neV) fields (vacua)

MPQ LMU www.attoworld.de

Proposed scheme of co-parallel intense laser probe of vacuum

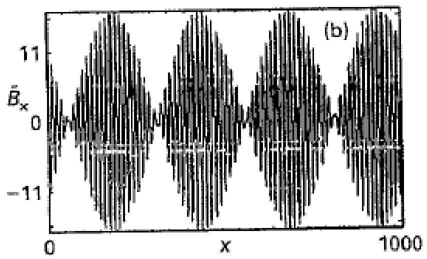
(with Homma, Habs)



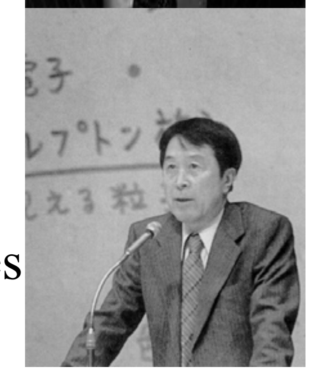
Many orders of magnitude gain in resonant coupling and sensitivity over long interaction:

Nonlinearity of vacuum

$\omega + \omega \rightarrow 2\omega$ (SHG a la Franken)

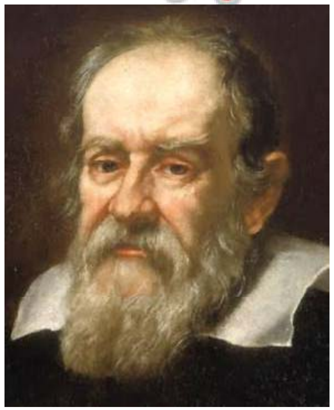


cf. Brillouin forward scattering beat / optical parametric excitation = phonon mediating (Nambu-Goldston boson)



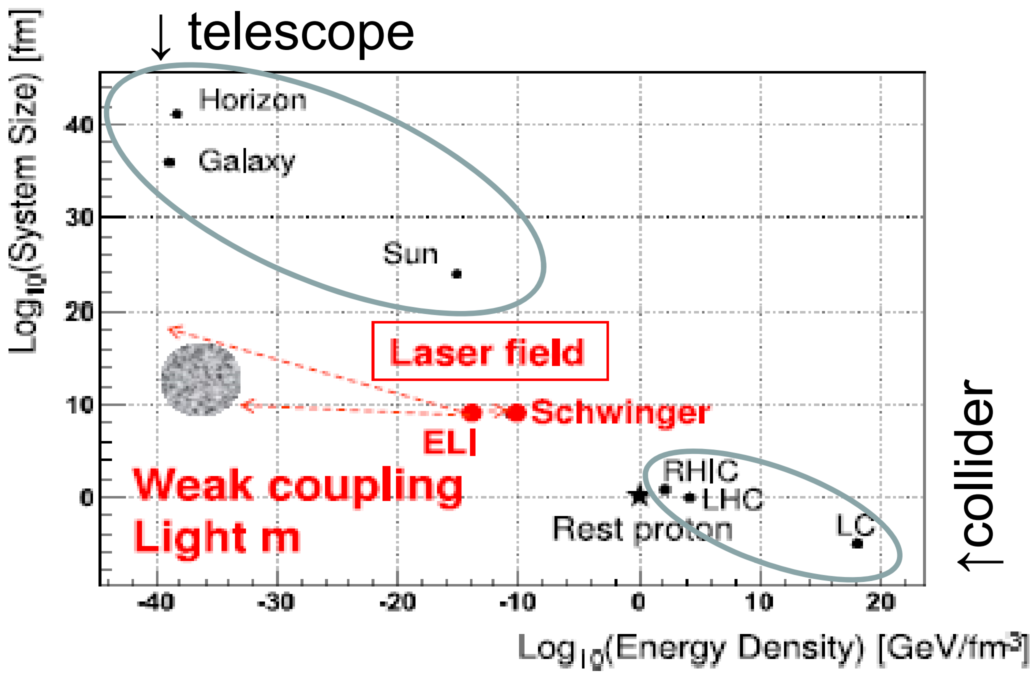
Mass of light fields(dark energy fields, axion-like fields) resonates with specific crossing angle of co-propagating lasers

Scope of High Field Science vs traditional approaches



Cosmological observation

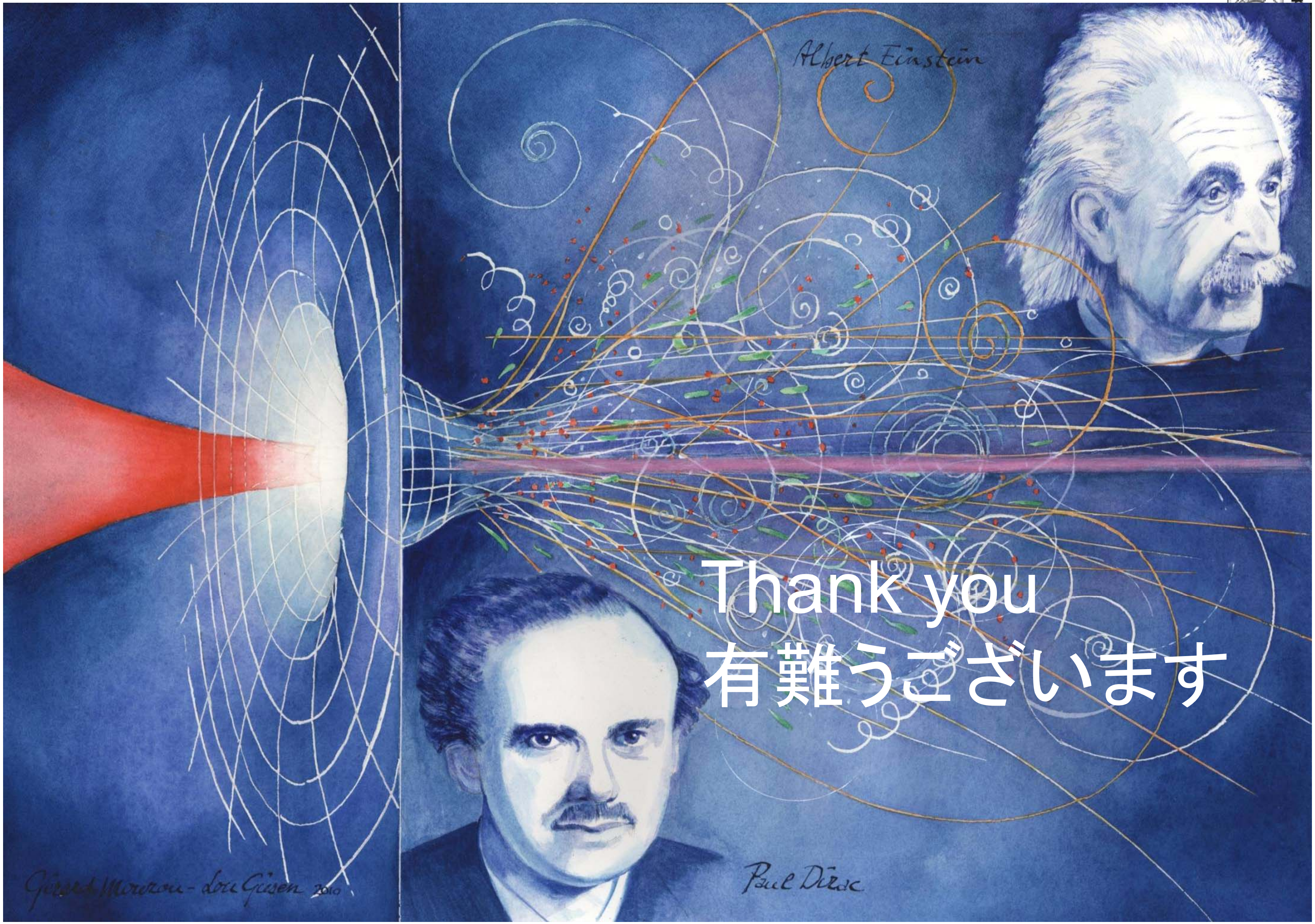
Weak coupling m=0



Strong coupling Heavy m

High energy collider

(with Homma, Habs)



(Mourou, 2010)