Chaires internationales de recherche Blaise Pascal

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The last Blaise Pascal Lecture
ELI Getting Real
–from Inception to Implementation
Friday, Dec. 10, 2010
Czech Embassy in Paris

Extreme Light Infrastructure:
Icebreaker and Integrator of 21st Century Science

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Acknowledgments for Collaboration and advice: G. Mourou, F. Krausz, E. Goulielmakis, . G.Tsakiris, 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, E. Moses, C. Labaune; D. Normand, M. Downer, P. Corkum, Y. Kato, C. Barty, A. Zayakin, G. Dunne, D. Payne, J. Nilsson, W. Chou, R. Heuer, A. Suzuki, V. Zamfir, R. Hajima, M. Fujiwara, C. Cohen-Tannoudji

1. Dawn of ELI and Relativistic Optics
2. Relativistic Nonlinearity and
   Laser Wakefield Acceleration
3. The Conjecture = “The stronger the laser,
   the shorter the pulse”: Philosophical
   foundation of ELI
4. “Extreme Light” integrates science :
   atomic physics, ultrafast science,
   high energy and nuclear physics, medicine

ELI source code

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 5, 031301 (2002)

Zettawatt-exawatt lasers and their applications in ultrastrong-field physics

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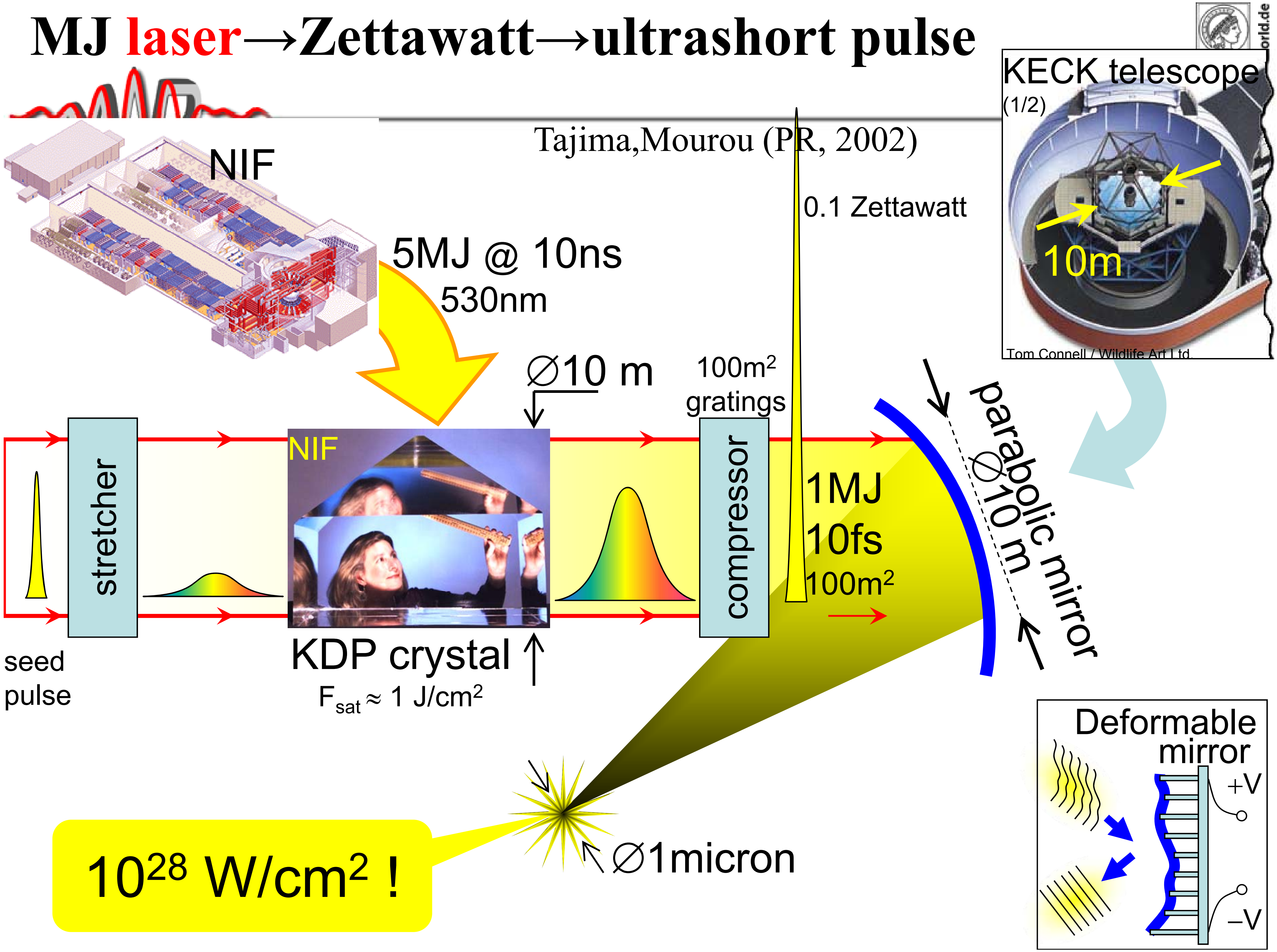
(Received 18 October 2001; published 7 March 2002)

Since its birth, the laser has been extraordinarily effective in the study and applications of laser-matter interaction at the atomic and molecular level and in the nonlinear optics of the bound electron. In its early life, the laser was associated with the physics of electron volts and of the chemical bond. Over the past fifteen years, however, we have seen a surge in our ability to produce high intensities, 5 to 6 orders of magnitude higher than was possible before. At these intensities, particles, electrons, and protons acquire kinetic energy in the megaelectron-volt range through interaction with intense laser fields. This opens a new age for the laser, the age of nonlinear relativistic optics coupling even with nuclear physics. We suggest a path to reach an extremely high-intensity level 10^{26-28} W/cm^2 in the coming decade, much beyond the current and near future intensity regime 10^{23} W/cm^2, taking advantage of the megajoule laser facilities. Such a laser at extreme high intensity could accelerate particles to frontiers of high energy, teraelectron volt, and petaelectron volt, and would become a tool of fundamental physics encompassing particle physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics, and cosmology. We focus our attention on high-energy applications, in particular, and the possibility of merged reinforcement of high-energy physics and ultraintense laser.

MJ laser→Zettawatt→ultrashort pulse

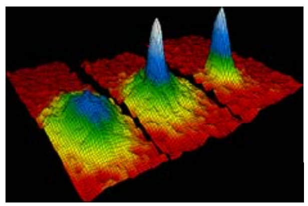


Energy frontier ← High field science, high intensity laser

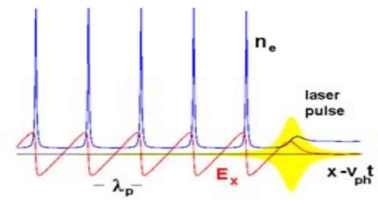
relativistic optics: *relativistic coherence*

cf. quantum optics: *quantum coherence*

Quantum optics
Cold Atoms
feV-neV



1eV



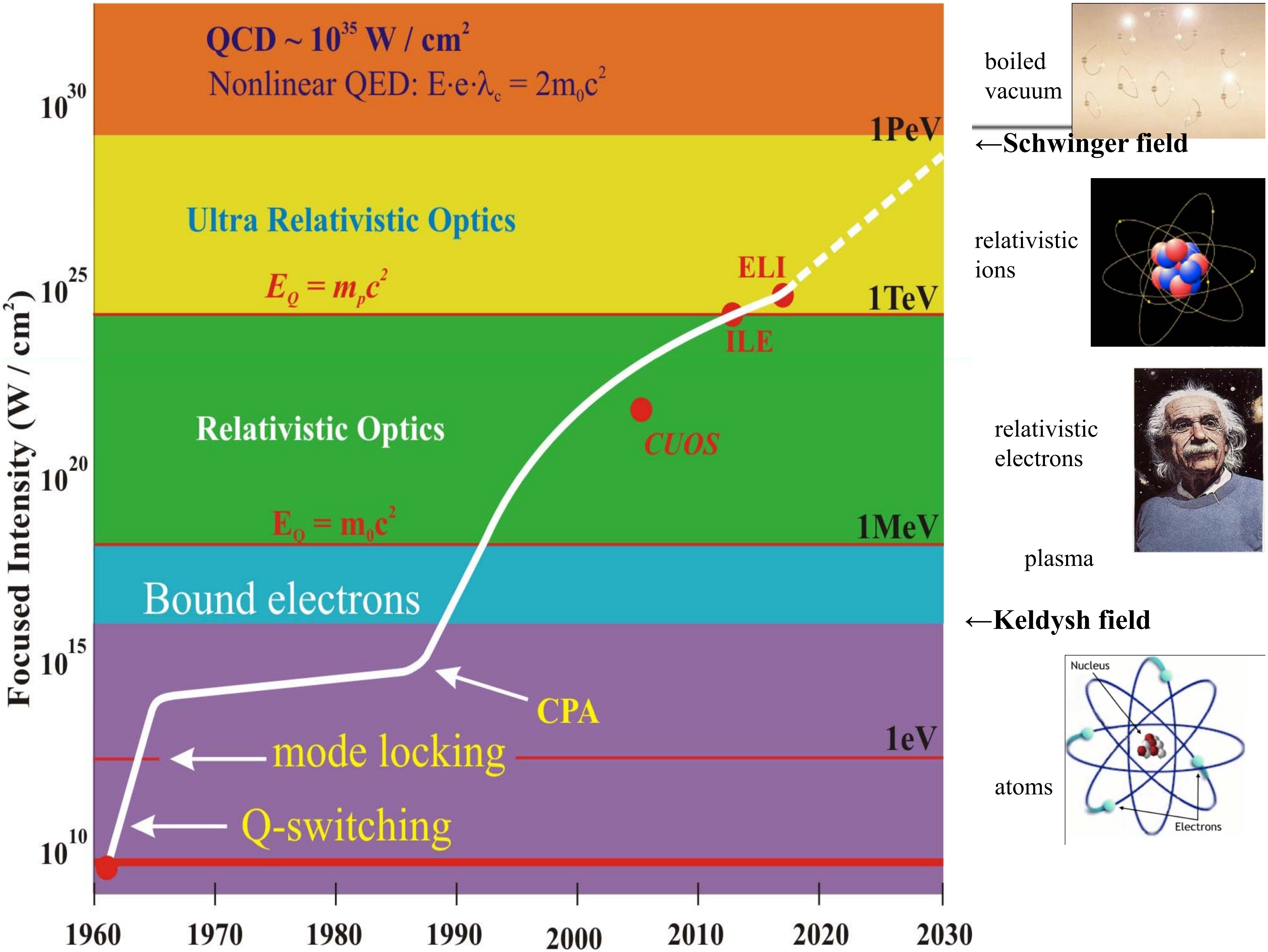
Relativistic optics
GeV-TeV

← 2010 ——— 1960 ——— 2010 →

Cohen-Tannoudji,Chu, Ketterle,…

Relativistic Optics, RMP, Mourou (2006)

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



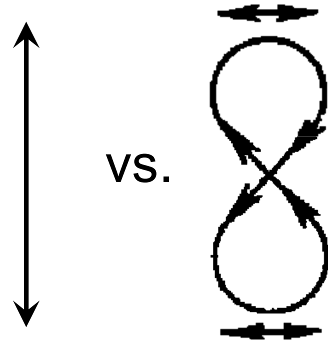
QCD ~ 10^35 W / cm^2
Nonlinear QED: E·e·λc = 2m0c^2
Ultra Relativistic Optics
EQ = mpc^2
Relativistic Optics
EQ = m0c^2
Bound electrons
mode locking
Q-switching
CPA
CUOS
ILE
ELI
1PeV
1TeV
1MeV
1eV
Focused Intensity (W / cm^2)
10^30
10^25
10^20
10^15
10^10
1960
1970
1980
1990
2000
2010
2020
2030
boiled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

Nonlinearities in atom, plasma, and vacuum

Atomic
nonlinear potential

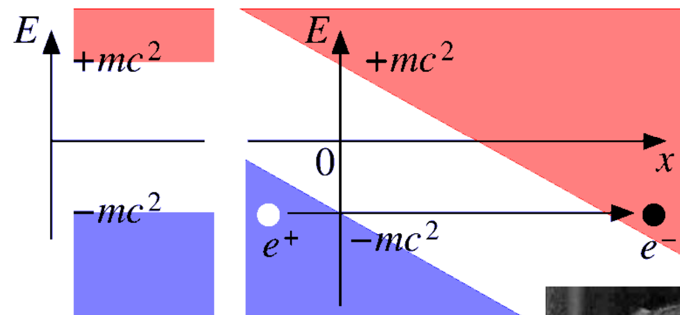
Keldysh field for
laser atomic
ionization

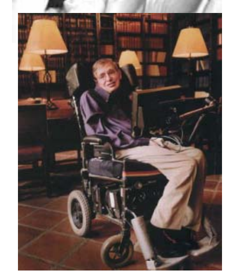
Plasma electron
nonlinear
relativistic motion



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

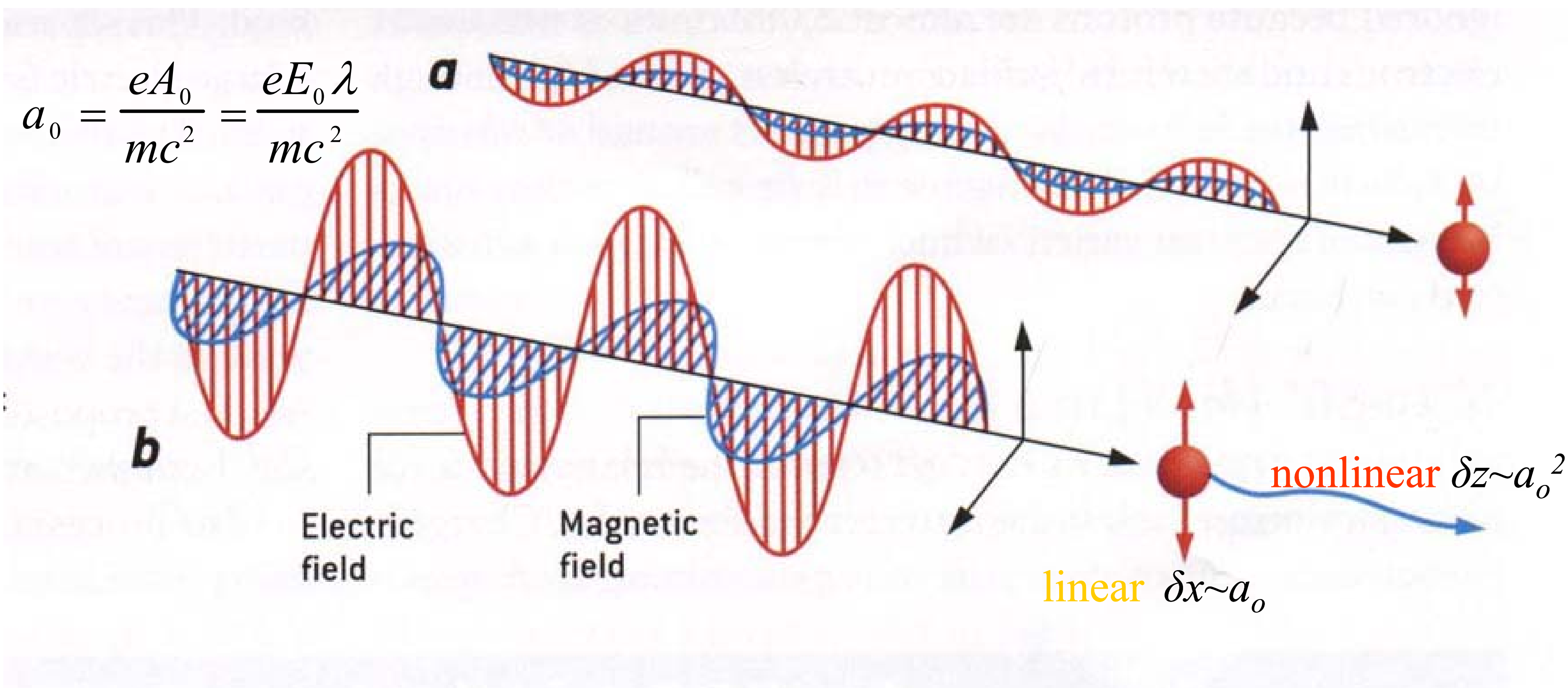
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

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

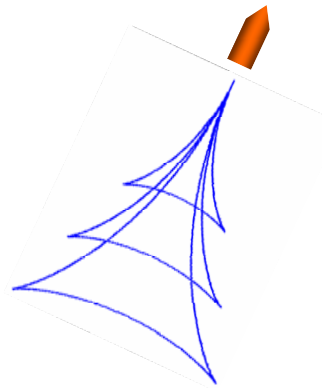
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



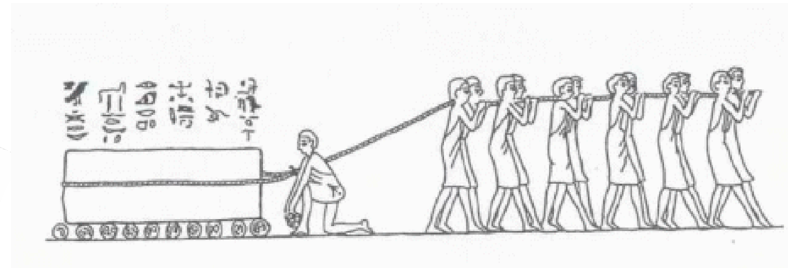
Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

Kelvin wake

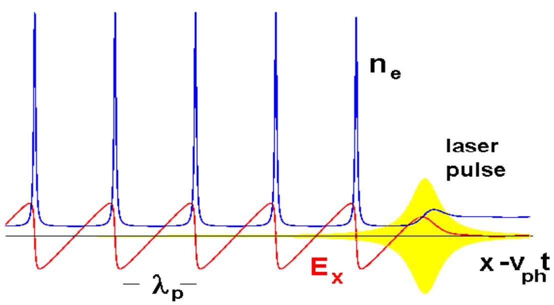


Colletive dynamics



(cf. individual
particle dynamics)

No wave breaks and wake **peaks** at $v \approx c$



(The density cusps.
Cusp singularity)

← **relativity regularizes**

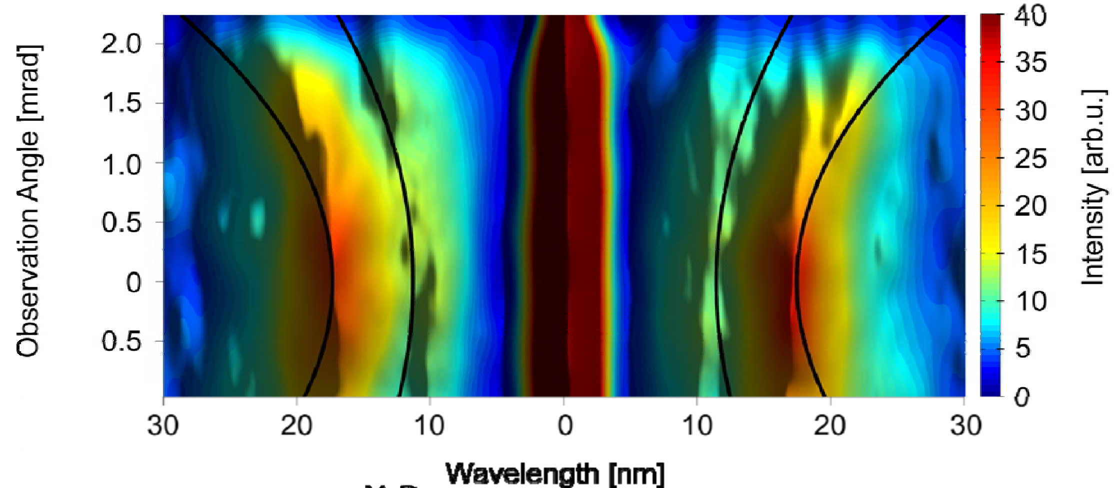
Wave **breaks** at v<c

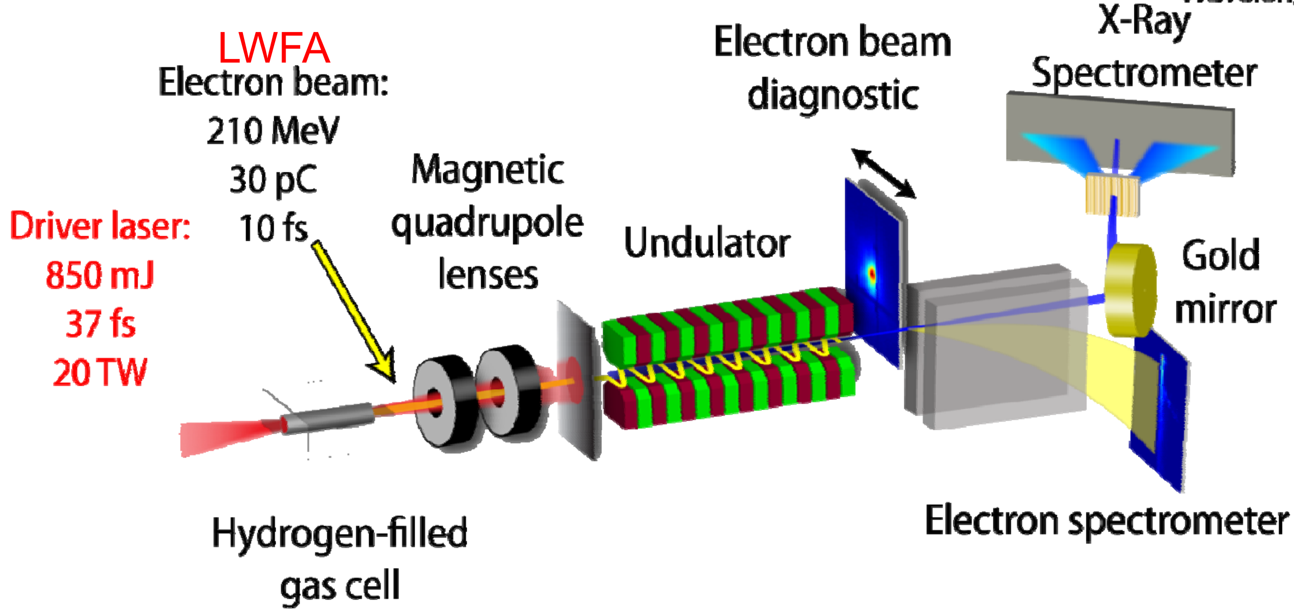
Hokusai

Table-top Brilliant Undulator X-ray Radiation from LWFA

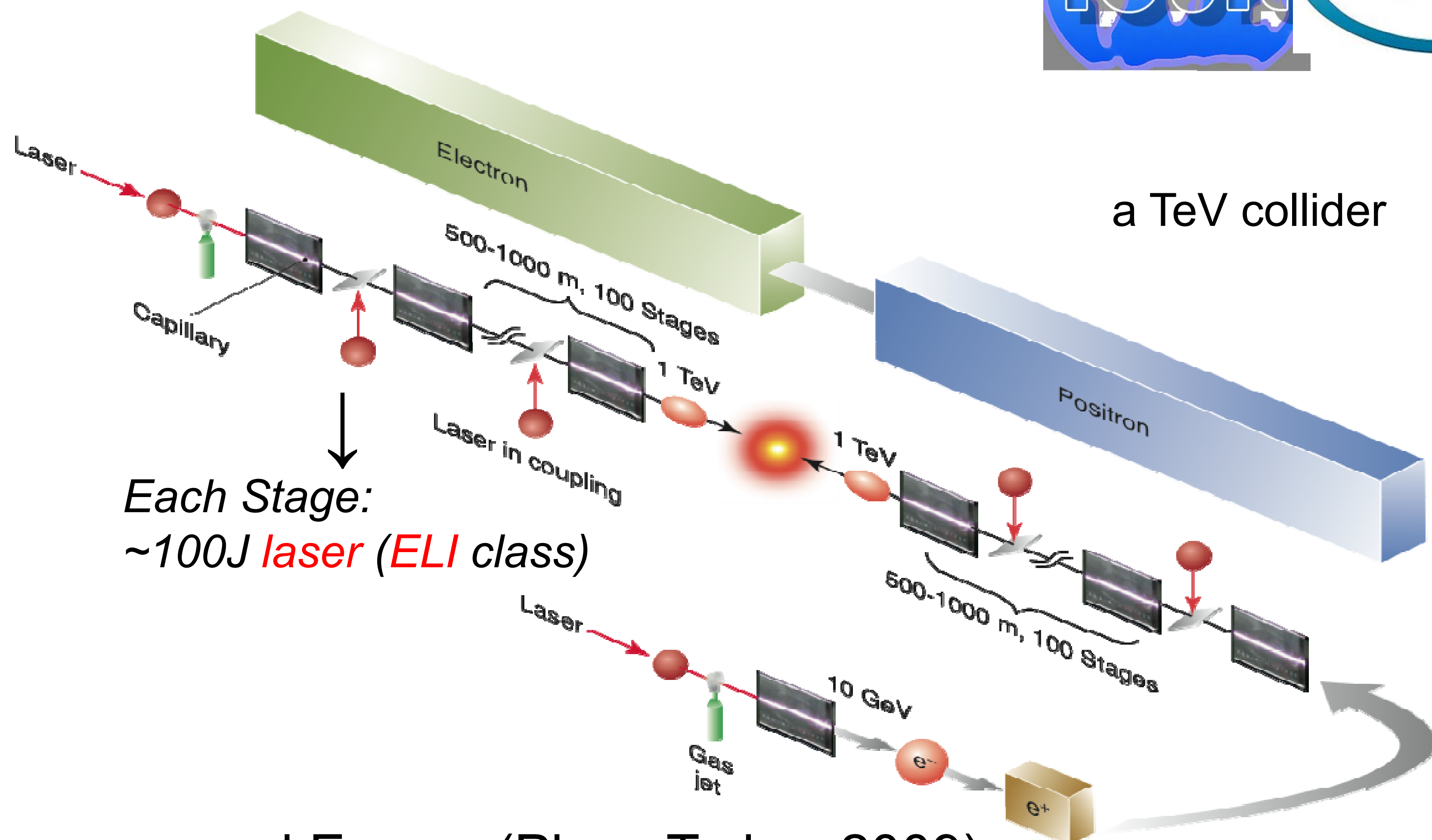
(M. Fuchs, et al., Nature Phys., 2009)

Observed undulator radiation spectrum





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)

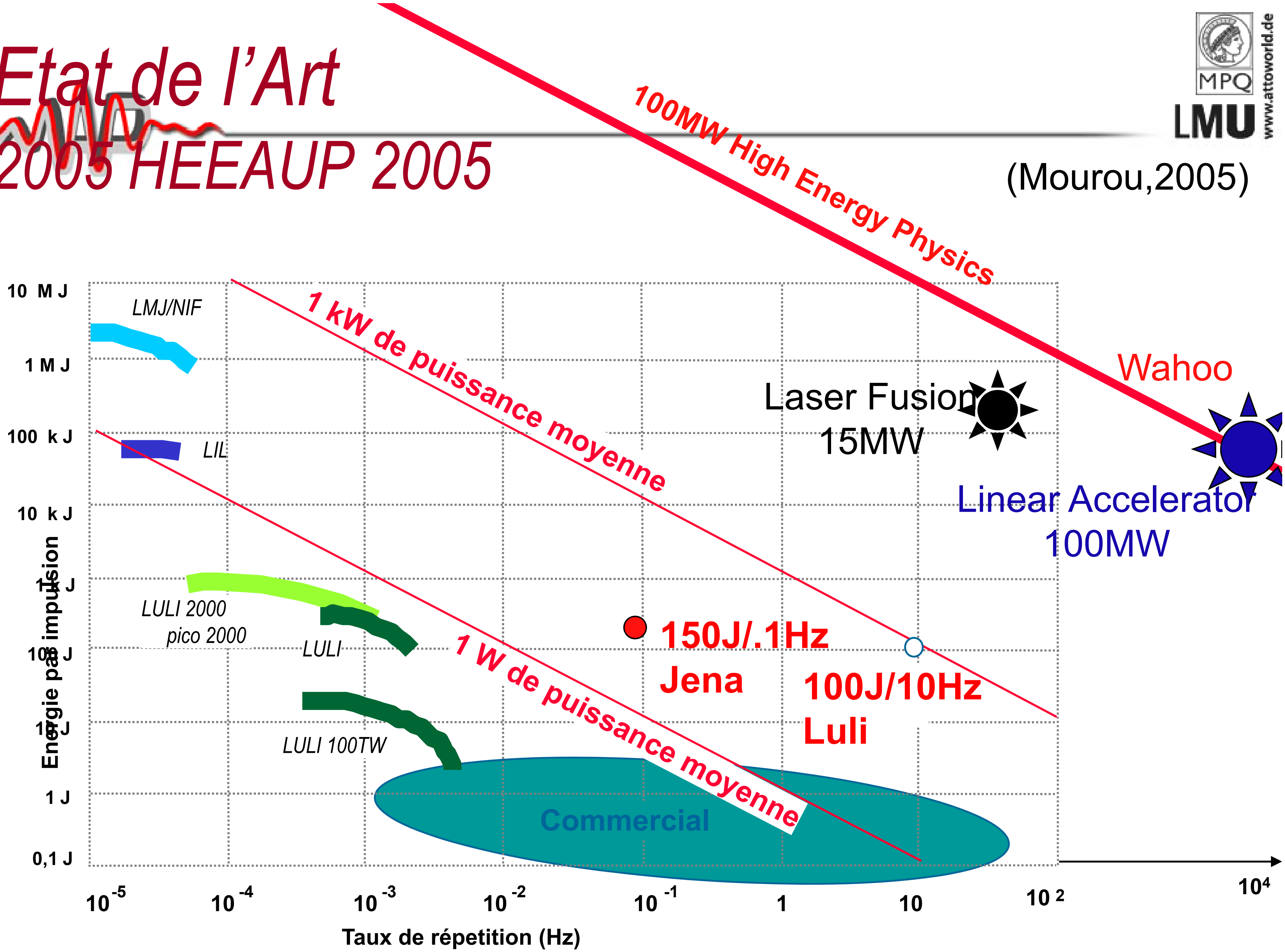
- *Science of LWFA* (US, Europe, Asia) matured to extend toward HEP accelerators
- *Laser technology* lacking suited for HEP accelerators: **laser efficiency, average power**
- *Technologies* to rectify emerging and credible: **1. thin disk; 2. ceramic; 3. fiber laser,..**
- *ICFA-ICUIL collaboration*: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

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

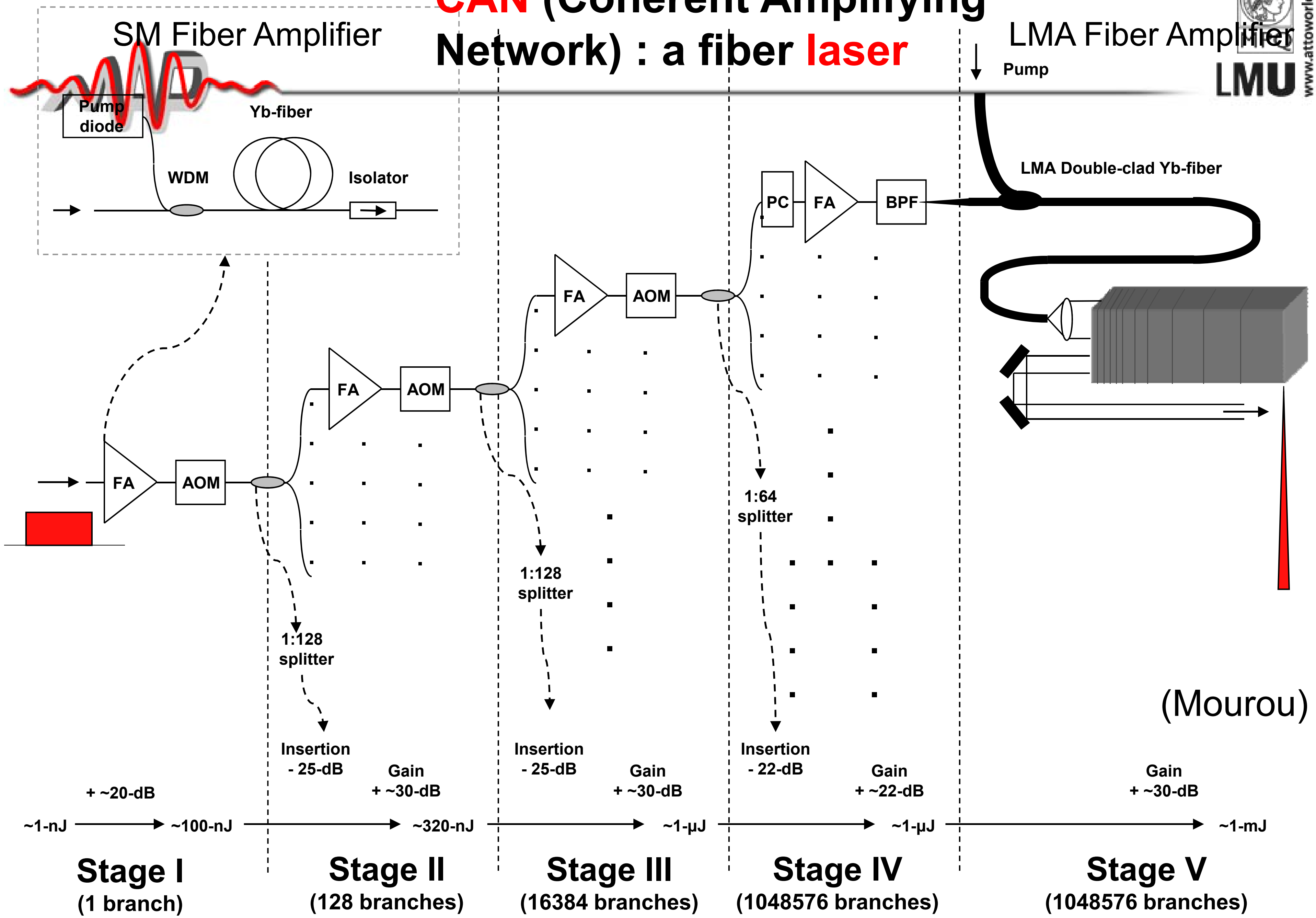
Etat de l'Art

2005 HEEAUP 2005

(Mourou,2005)

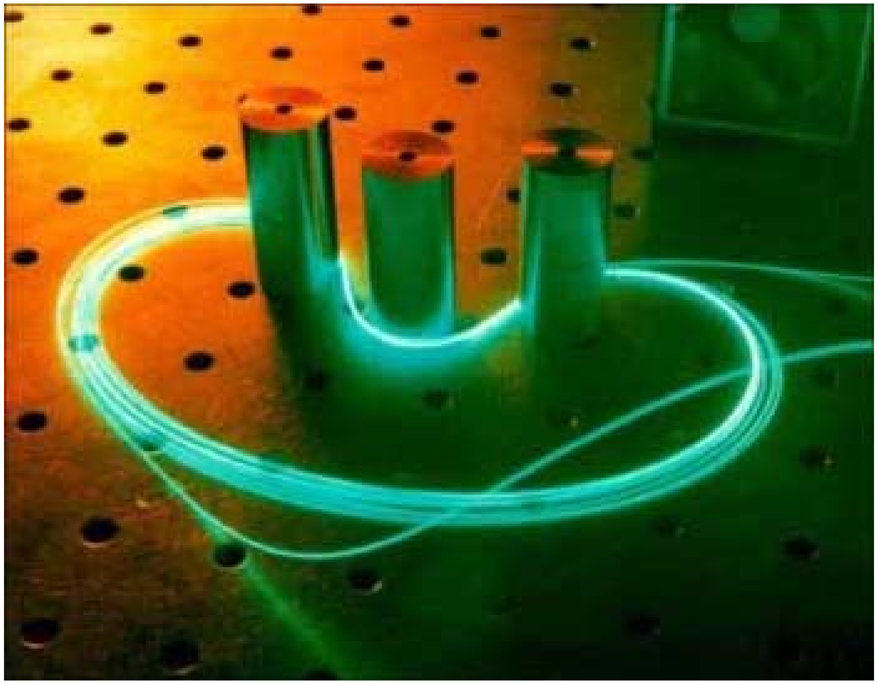


CAN (Coherent Amplifying Network) : a fiber laser



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

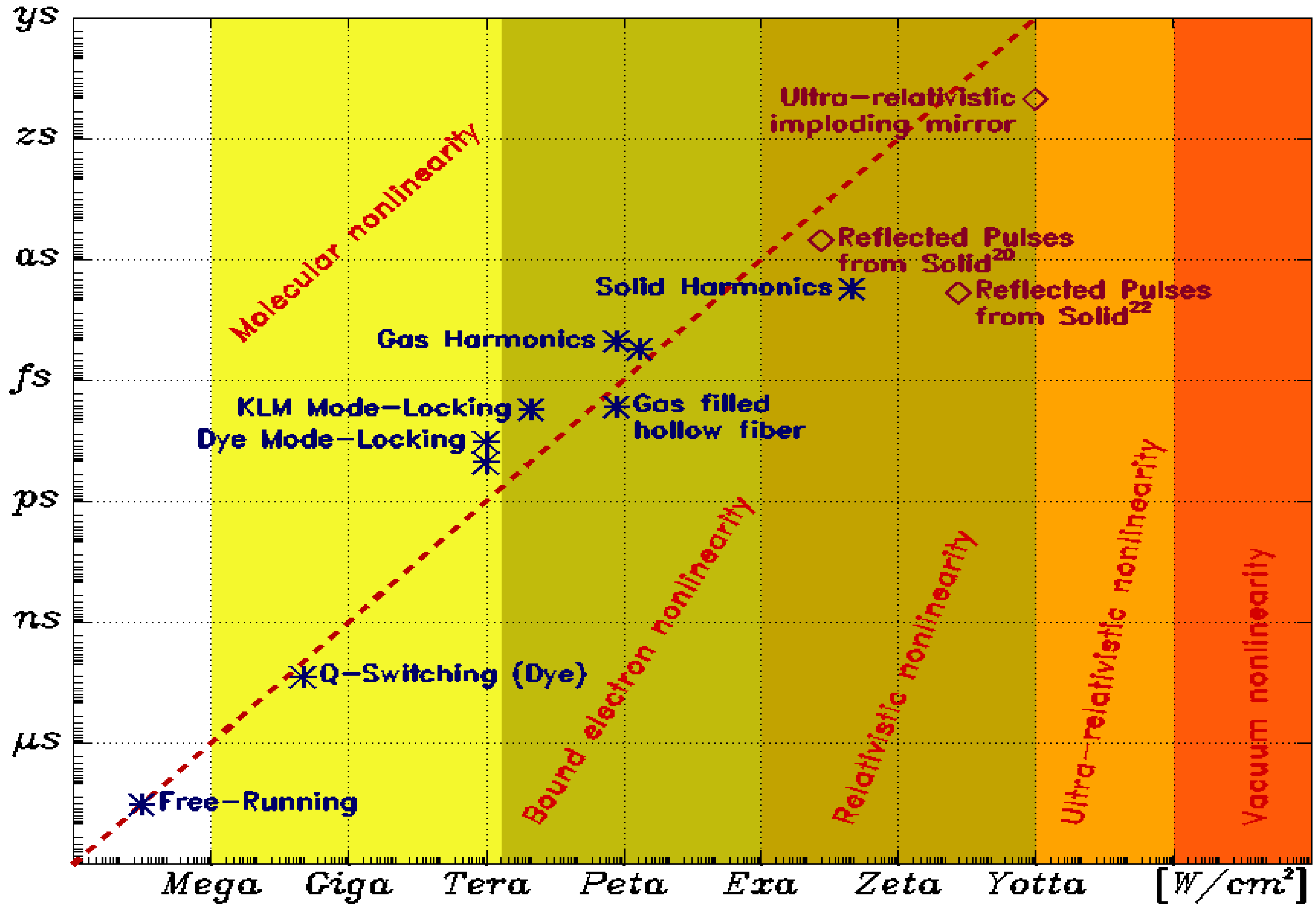


(G. Mourou)

→ ICAN (International CAN) Consortium formed (Nov. 25, 2010)

The Conjecture: *the stronger the laser, the shorter the pulse*

Pulse duration



(Mourou / Tajima, 2010)

I= J/T

Pulse intensity →

Ultrafast science ← High field science, Large-energy laser

ELI Founding Philosophy (from *the Conjecture*)

High field science

⇔ !

Ultrafast science
(attosecond,...)

⇕

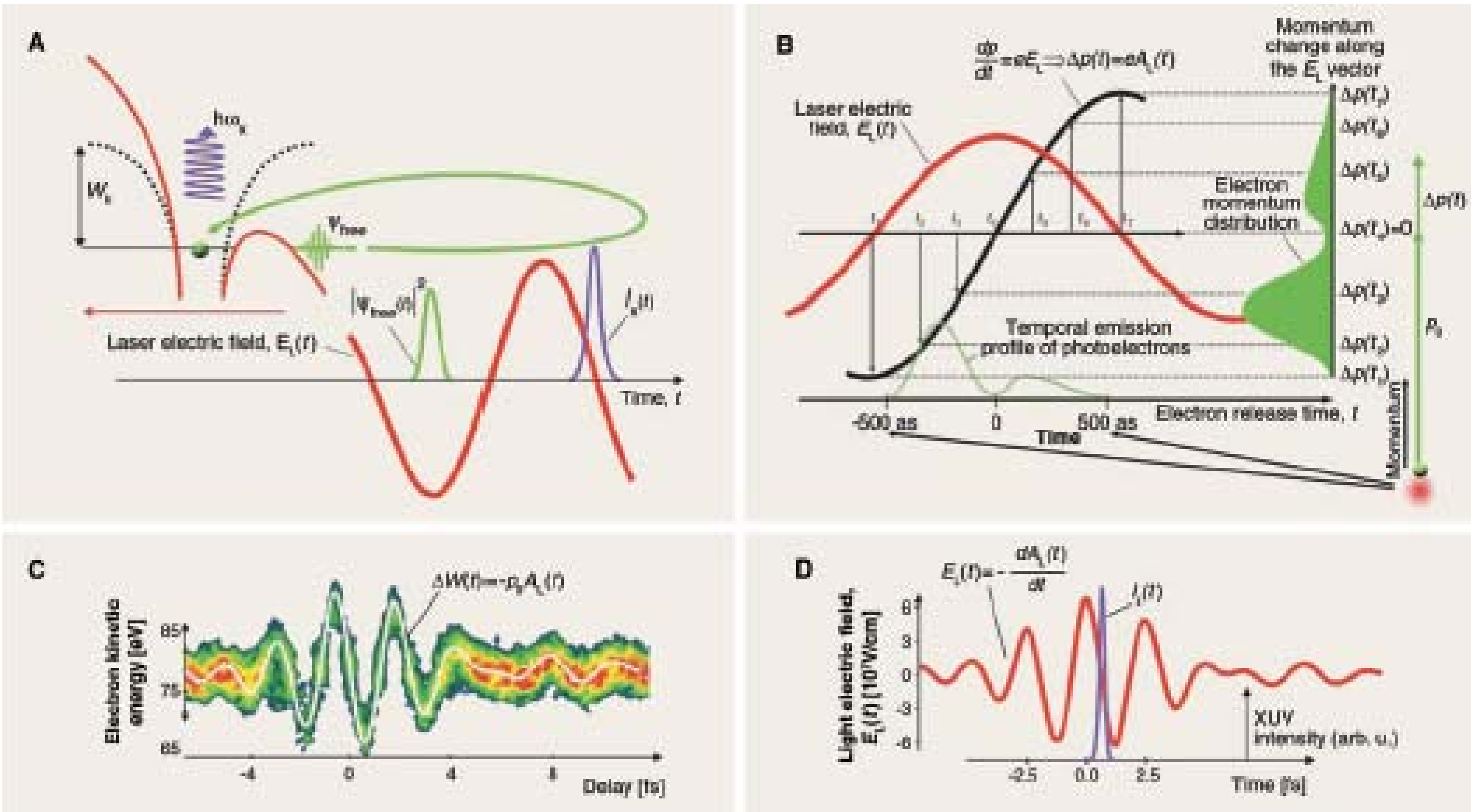
⇕ !

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

ELI pillars:
- attosecond science
- high energy beams
- photonuclear physics
- ultrahigh intensity physics

Streaking of atomic electron

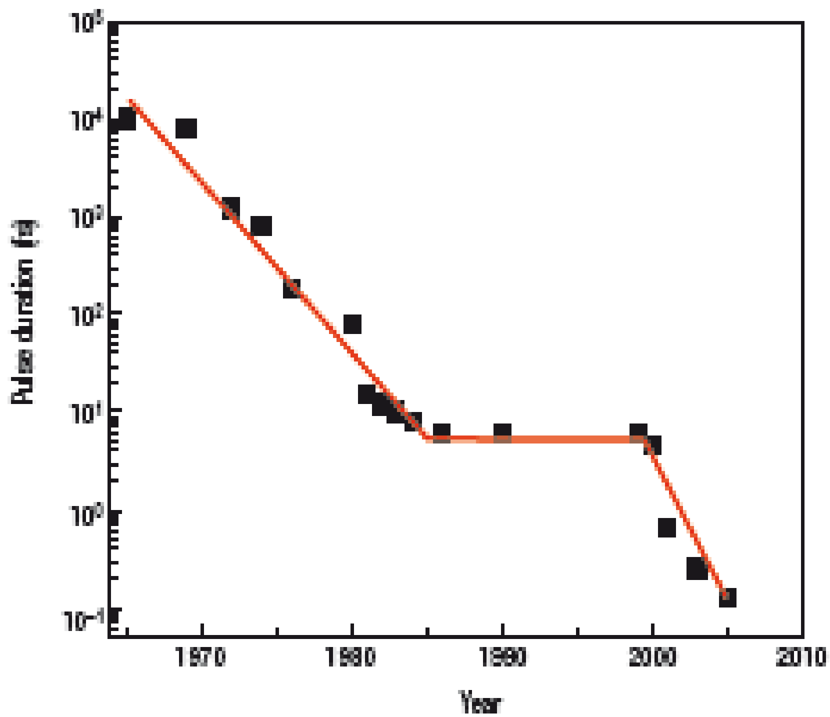
Keldysh field and beyond



E. Goulielmakis et al (2008)

Pulse from fs to as

Corkum and Krausz (2007)



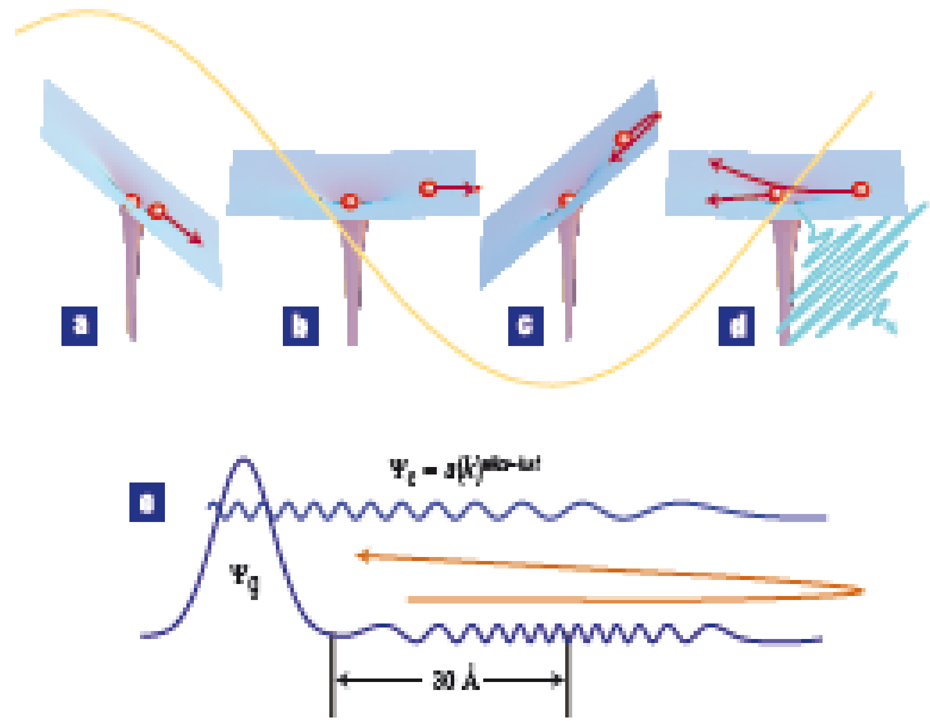
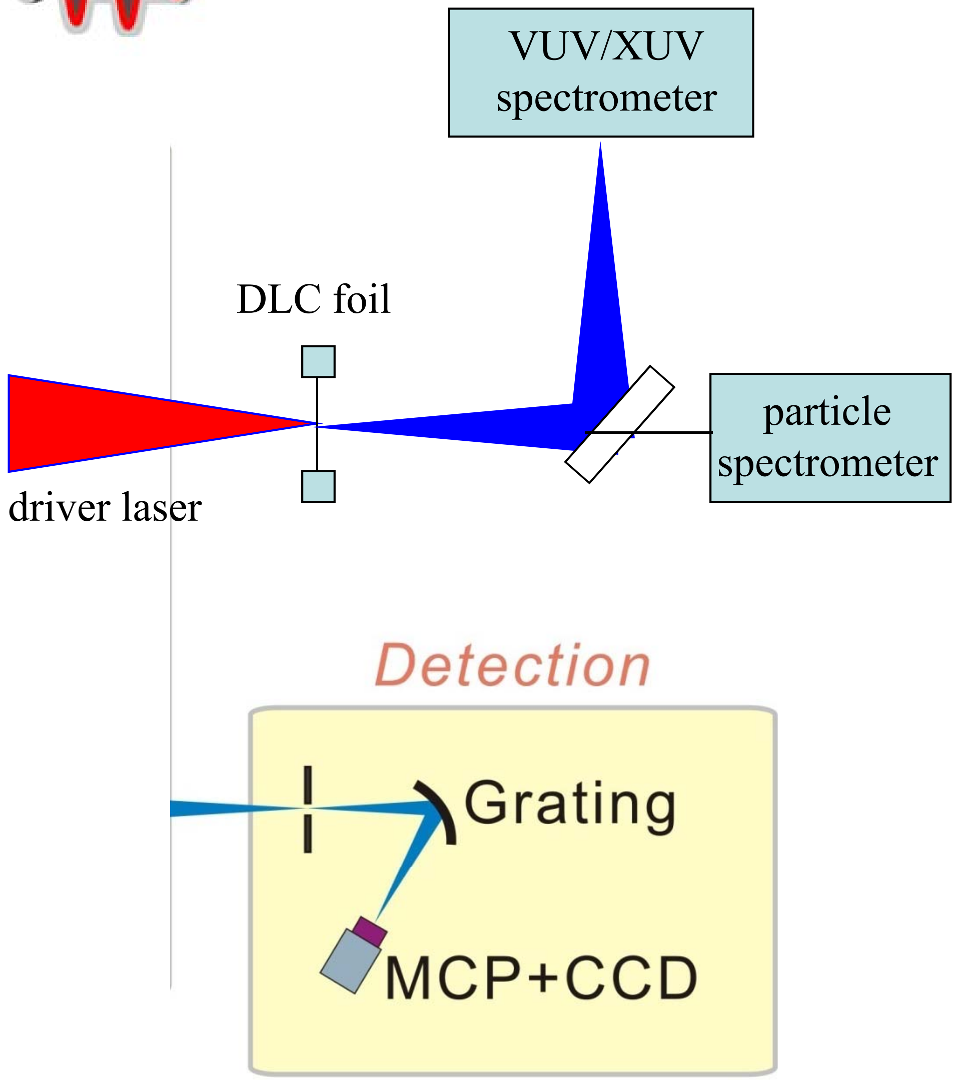


Figure 1 Shorter and shorter. The minimum duration of laser pulses fell continually from the discovery of mode-locking in 1964 until 1986 when 6-fs pulses were generated. Each advance in technology opened new fields of science for measurement. Each advance in science strengthened the motivation for making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

X-ray emission from Laser irradiation through solid film

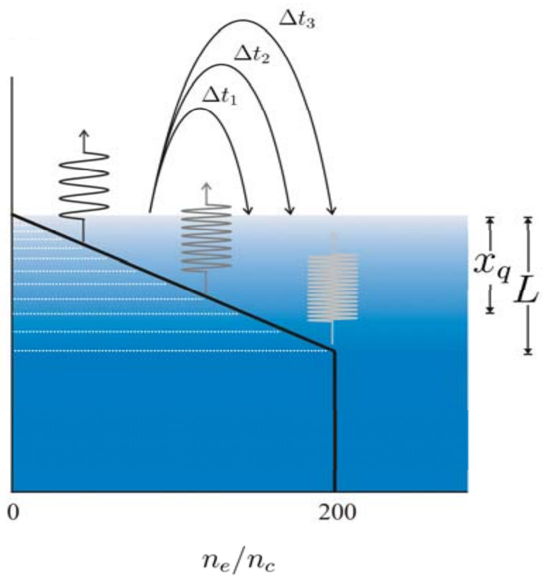


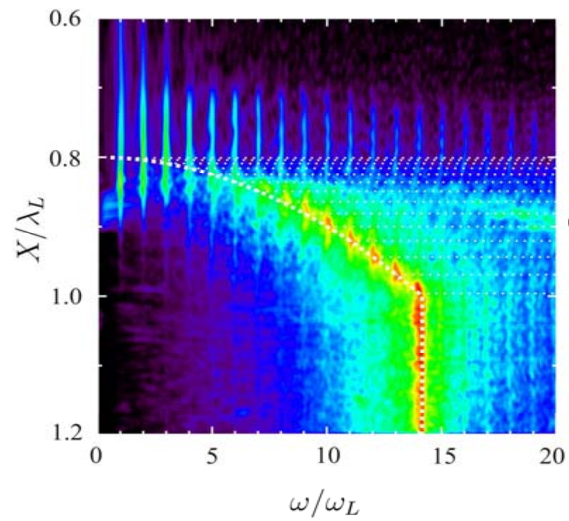
- Laser incident normally onto target
- Collection of XUV-light with spherical mirror
  - ➢ stronger signal for first test
  - ➢ loss of spatial information

R. Hoerlein (2010)

Coherent Wake Emission (laser irradiating solid surface)

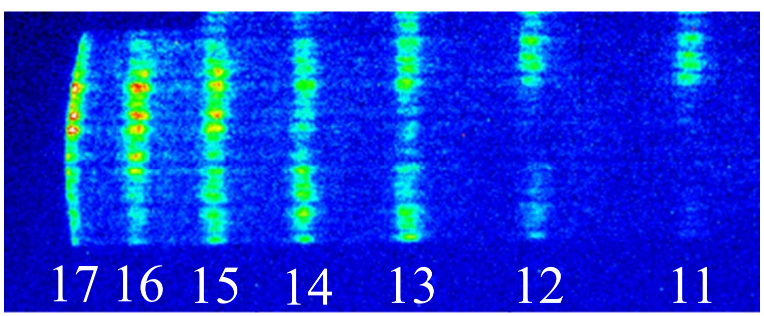
Laser hitting surface of solid emitting X-rays





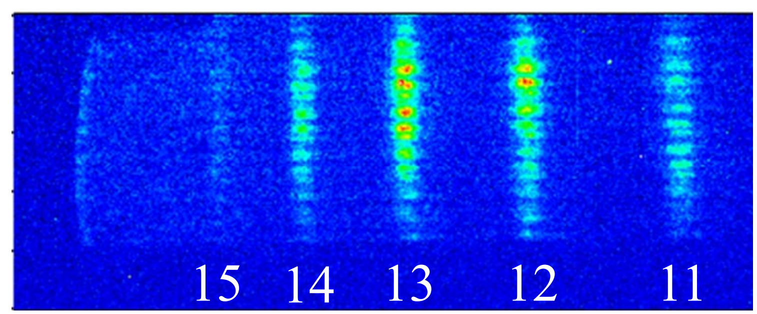
Generation of attosecond higher harmonics (HHG)

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)

(R. Hoerlein, 2010)

attosecond pulse generation by laser

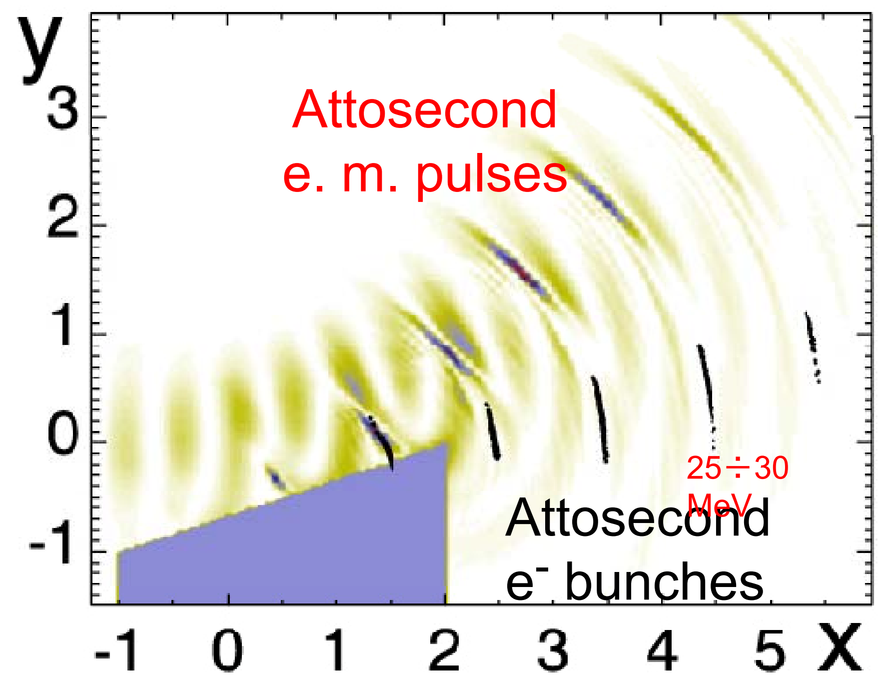
Intense (10^{20}W/cm^2) laser

Irradiation of a solid surface by a grazing angle induces

as pulse generation

←Relativistic electron dynamics on the solid surface

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

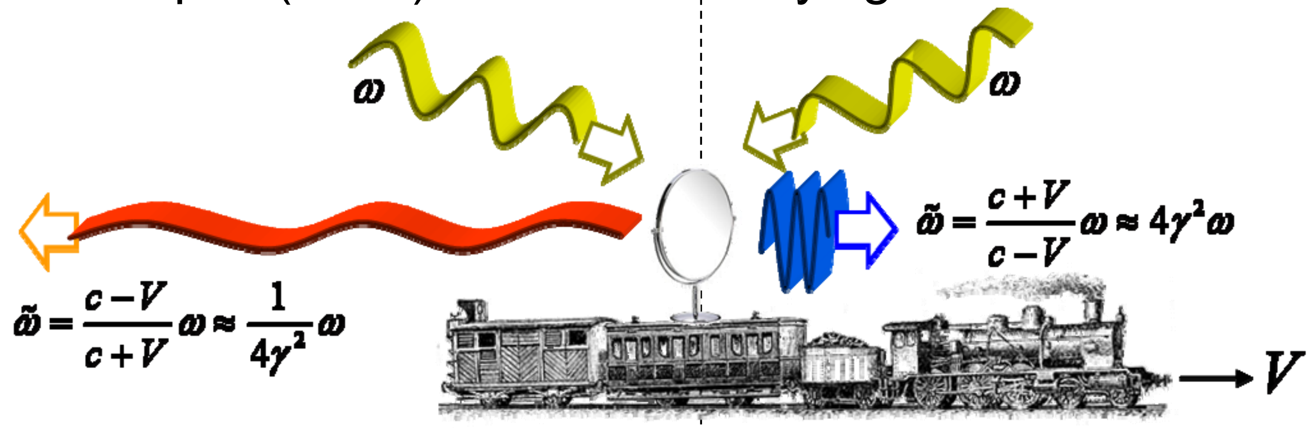


a=10, 15fs, f/1, $n=25n_{cr}$

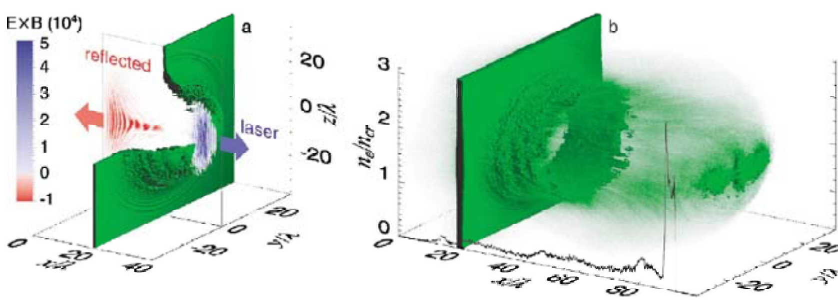
Naumova *et al*., Phys. Rev. Lett. (2004)

Relativistic flying mirror and shorter pulses

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

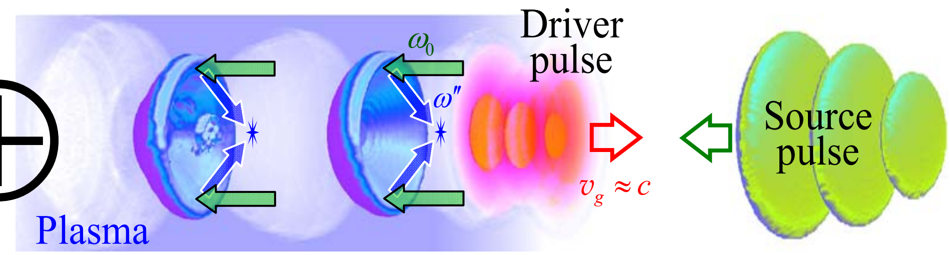


Laser Piston



⊕

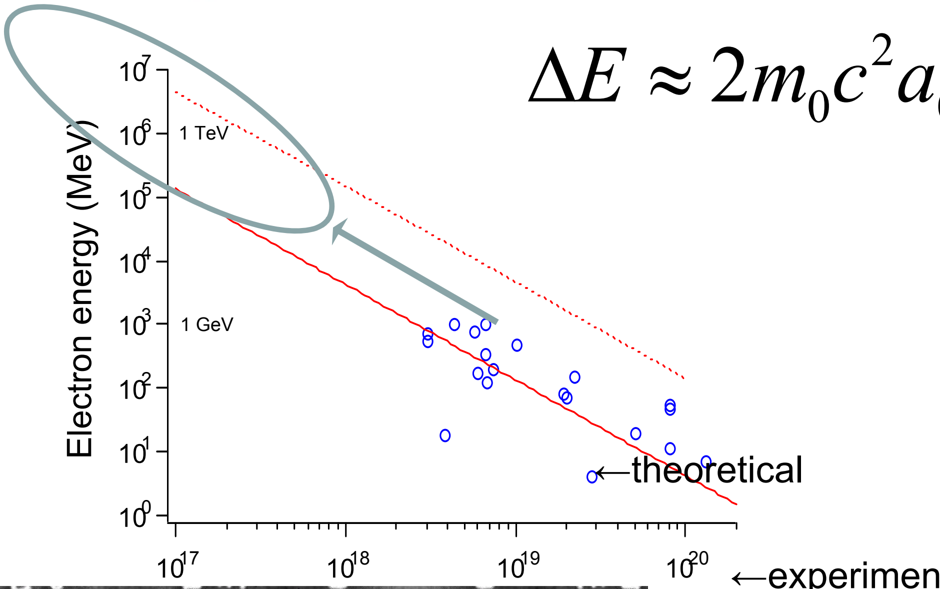
Flying Mirror (LWFA)

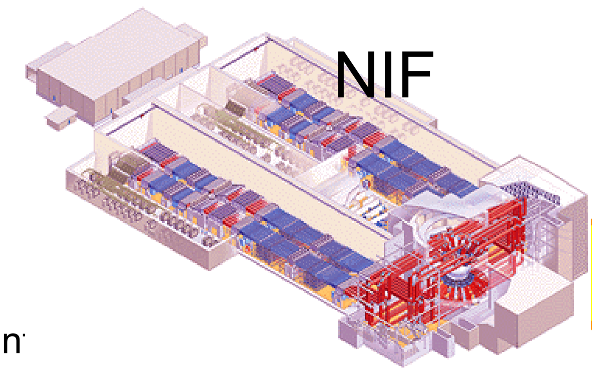


Tajima/Mourou/Moses(2010): use NIF ---ultra-relativistic imploding mirror → ys!

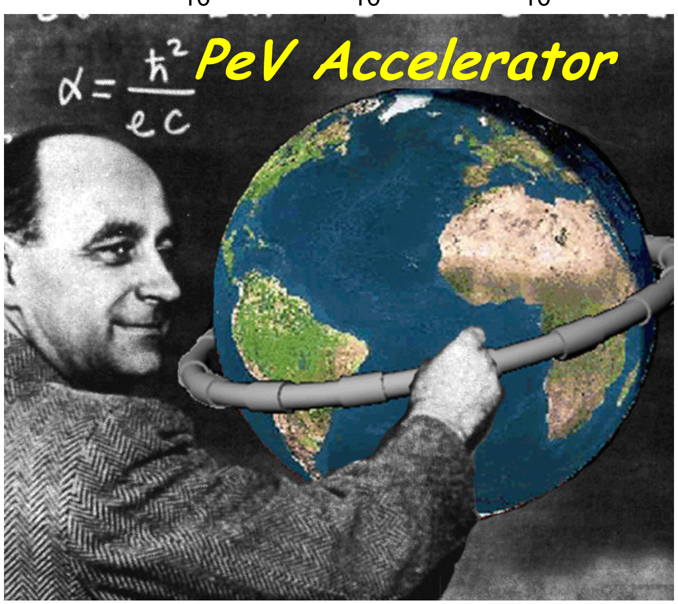
Theory of wakefield toward extreme energy

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





5MJ @ 10ns
530nm



1km

Adopt:
NIF laser (3MJ)
→ 0.7PeV
(with Kando, Teshima)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

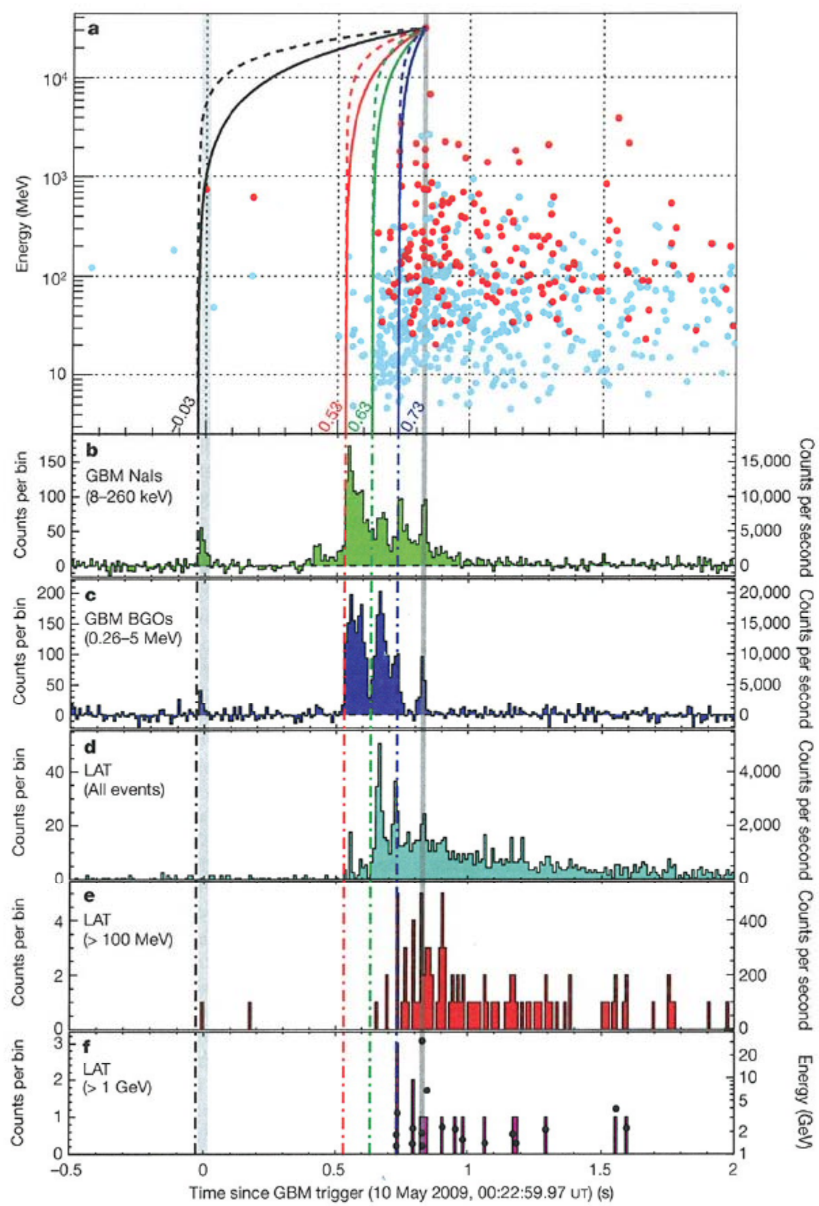
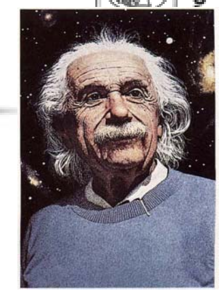


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy ... lowest to highest energies. **f** also overlays energy versus arrival time for each



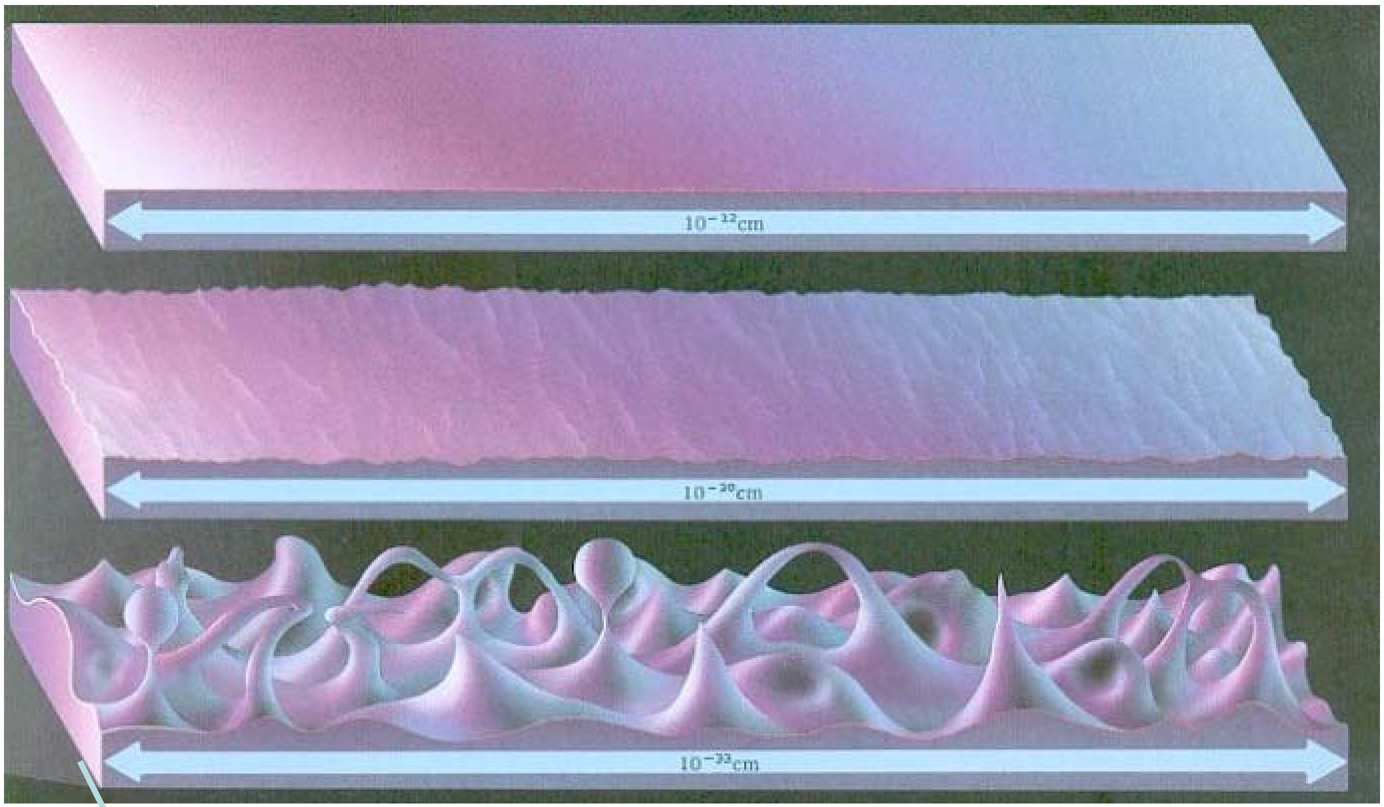
Einstein's relativity?

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)



Coarser, lower energy texture

Finer, higher energy texture

$c < c_0$

1km

← (0.1PeV)

←(1PeV : fs behind)

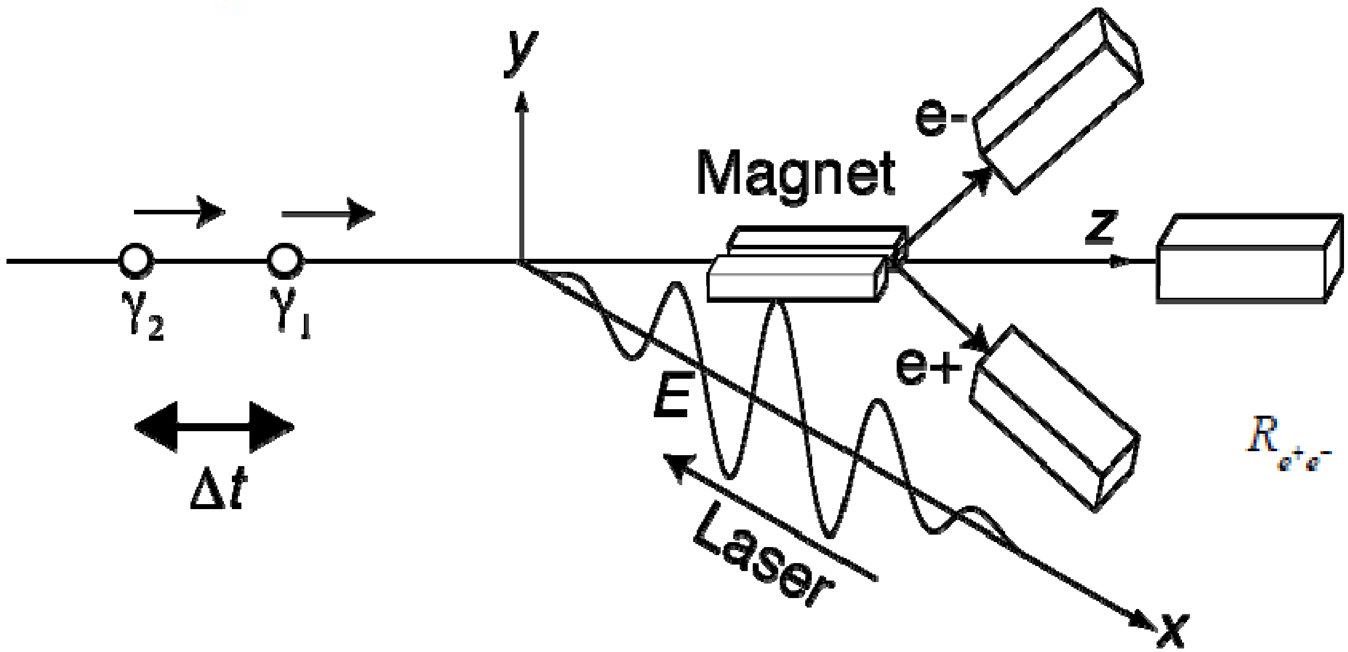
goalline

PeV γ (converted from e^-)

Attosecond Resolution of PeV γ Arrivals

"Goalline" detection

(Kando, 2010)



γ energy detector

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

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

Streaking vacuum (learning from atoms)

Vacuum:

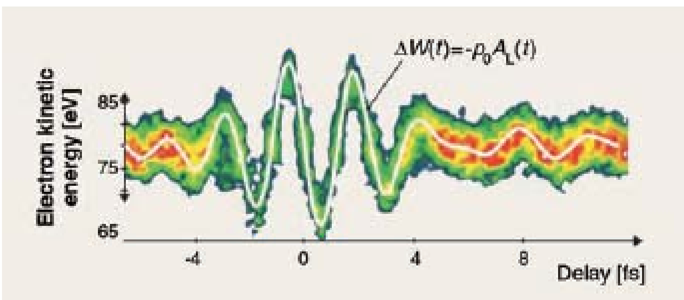
Schwinger/Narozhny field

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

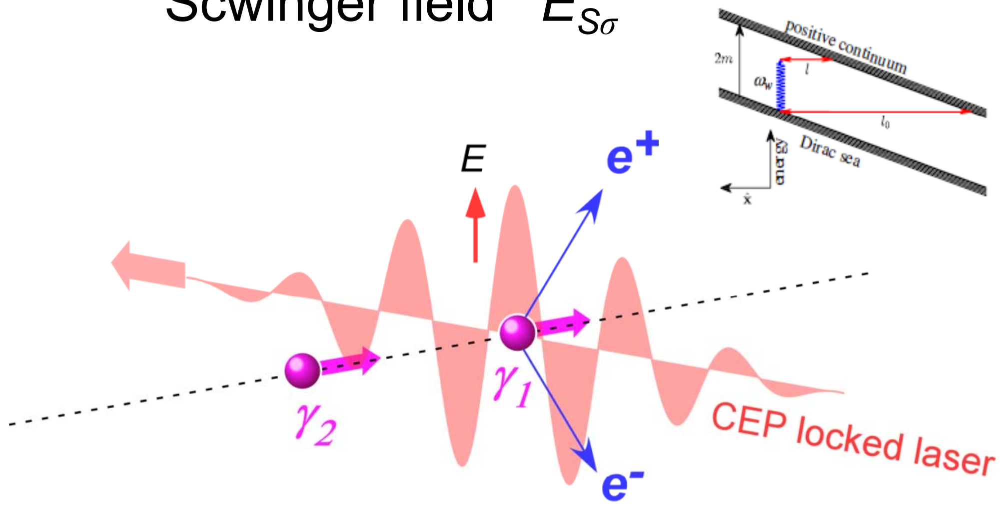
Scwinger field $E_{S\sigma}$

Atoms:

Keldysh field E_K



Goulielmakis(2008)



Keldysh parameter γ_K

$$\gamma_{V\sigma} = m_\sigma \omega c\,/eE$$

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

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

e.g.

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]

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

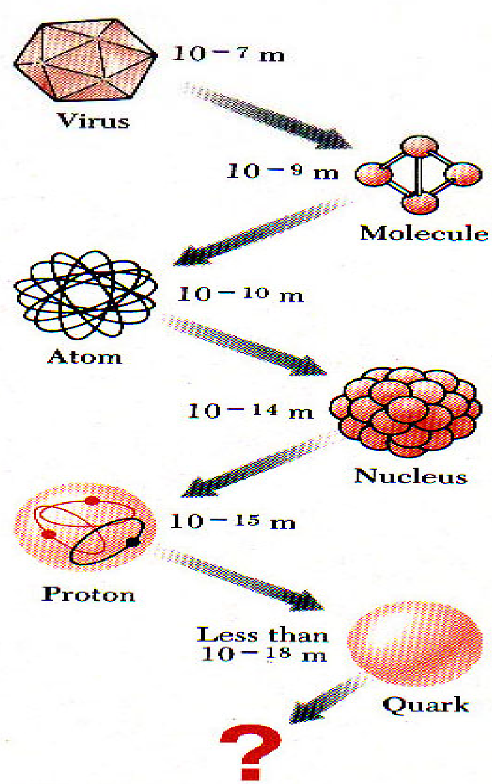
$$P_{cr} = (90/28)\, c\, E_S^2 \lambda^2/\alpha \sim 10^{15}\,(\lambda/\lambda_{1\mu})^2\ \text{GW}$$

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

‘*ELI* Long-term Ambition’ =

Studying the Atomic Structure to the Vacuum Structure

(Mourou)



Vacuum structure

Keldysh field

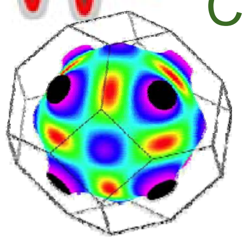
Schwinger intensity / Keldysh intensity $= \alpha^{-6} \sim 10^{14}$

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

Schwinger field

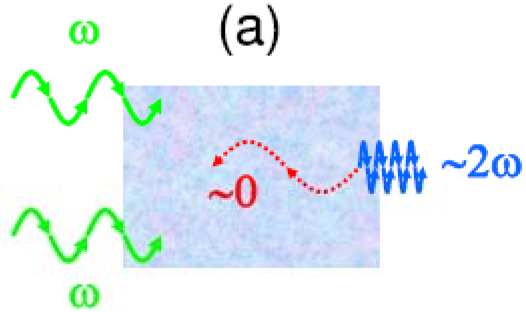
Does the atomic world repeat itself in vacuum?

Intense laser probes matter /vacuum nonlinearity

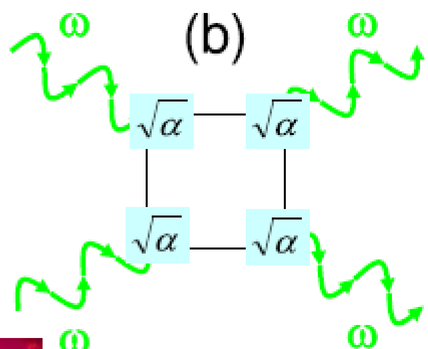


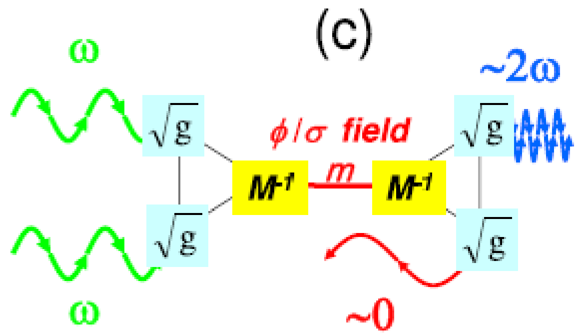
Crystal nonlinearity →

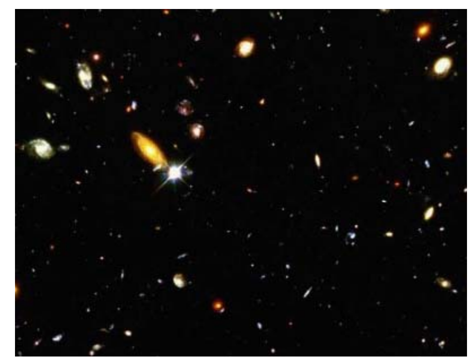
second harmonic generation (Franken et al)

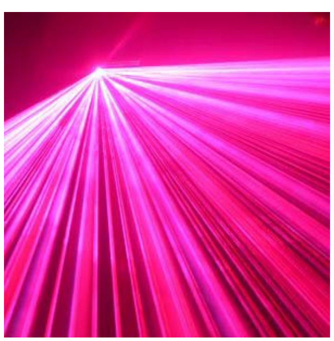


Learn from **Nonlinear Optics** of matter for vacuum:







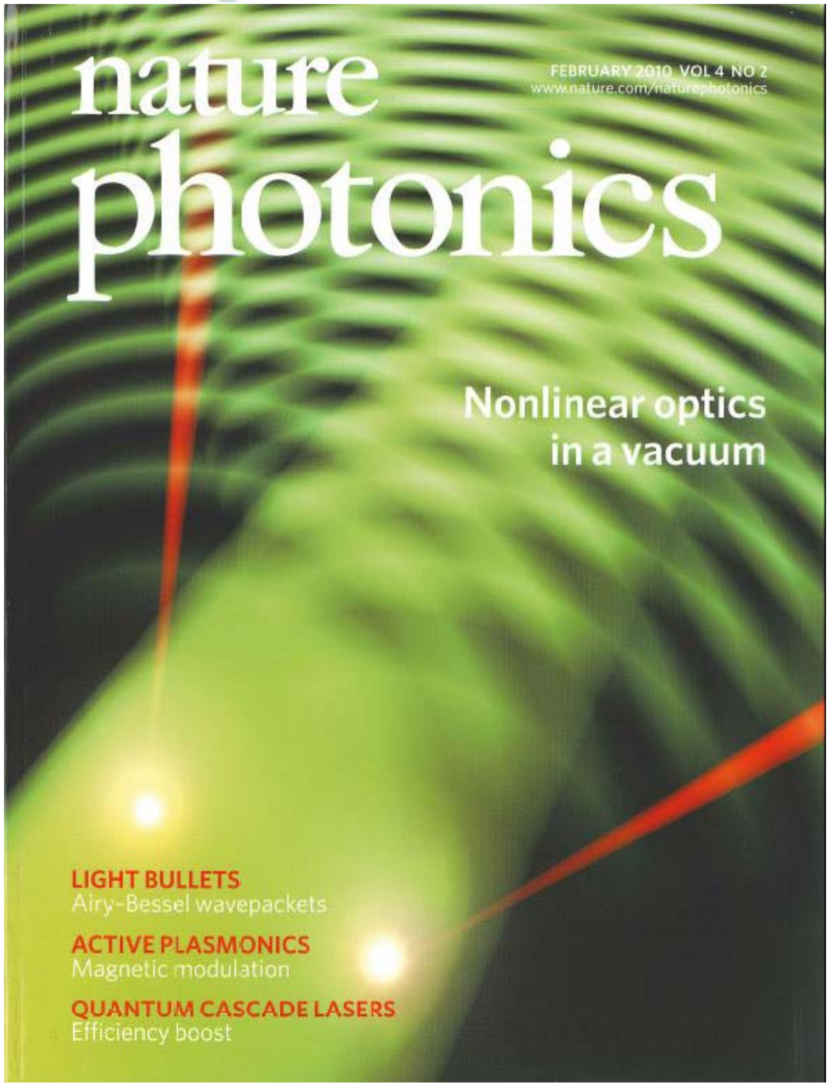


QED nonlinearity

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

→ second harmonic

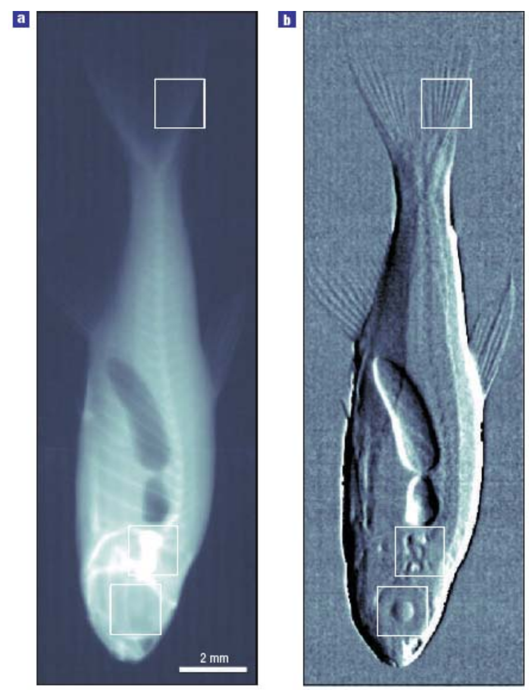
Nonlinear Optics in Vacuum



B. King, et al. (2010)

What is vacuum?
Can vacuum be nonlinear?
Is *c* constant?
What contribute to nonlinear vacuum?

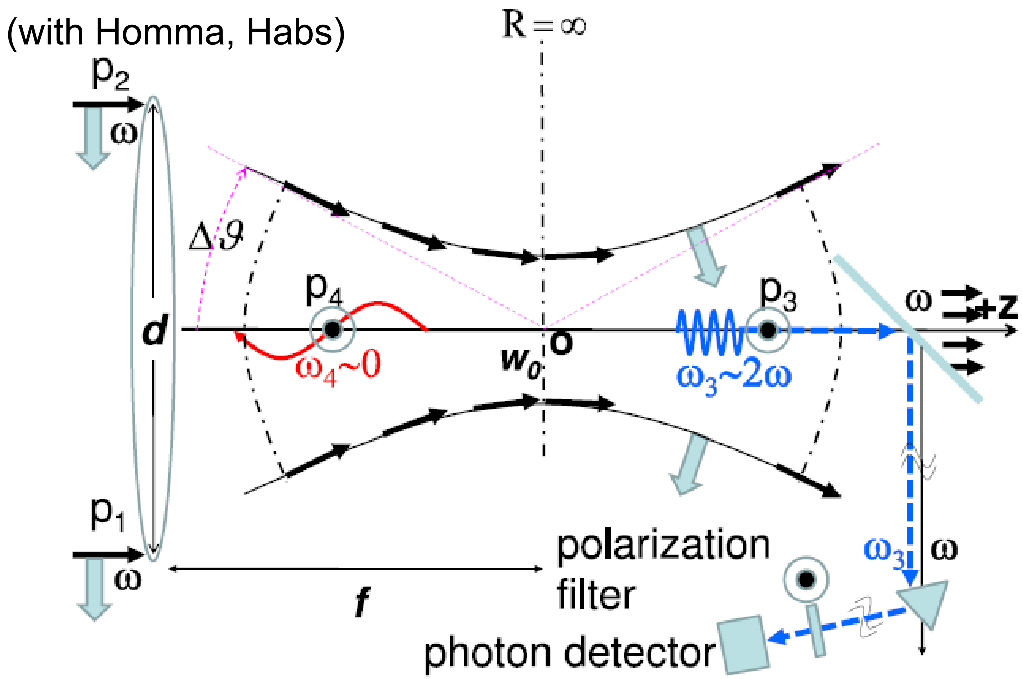
Phase Contrast Imaging applied to vacuum (Homma, et al. 2010)



Comparison of usual and Phase Contrast Imaging of X-ray photos of a fish (Pfeiffer, 2006)

Intense laser probe of vacuum:
low energy (meV - neV) particle fields

(with Homma, Habs)



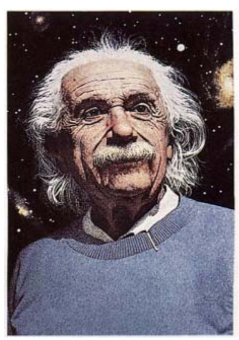
sensitivity over long interaction:

Nonlinearity of vacuum

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

Franken

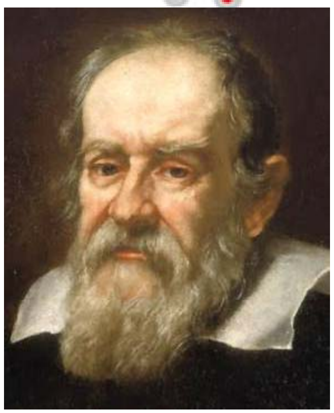
Nambu



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

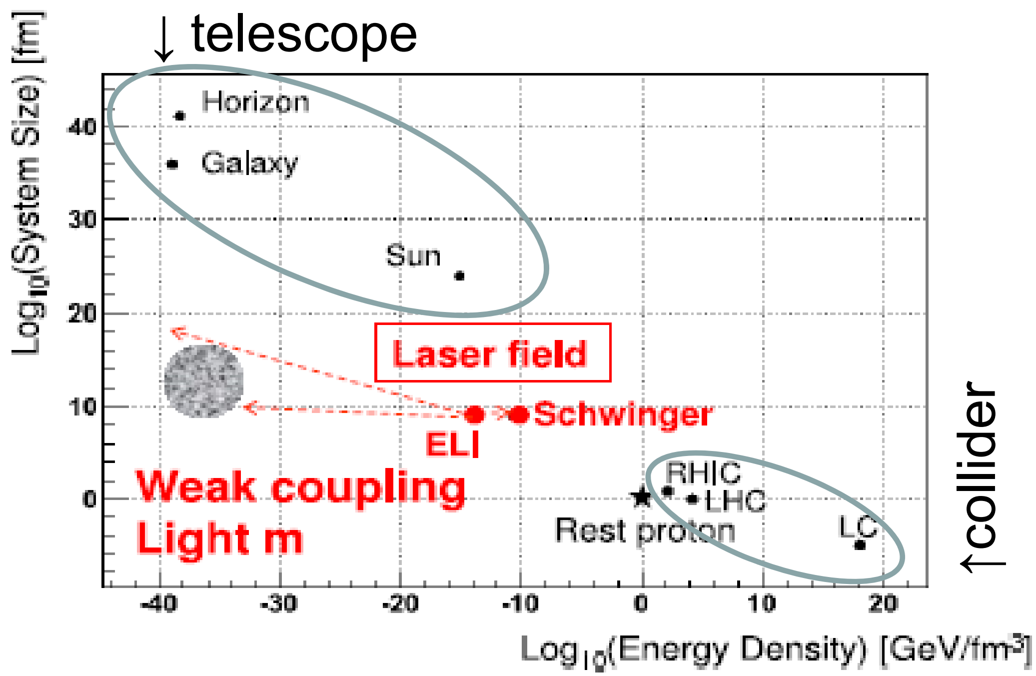
Scope of High Field Science vs traditional approaches

Telecsopes and Colliders



Cosmological observation

Weak coupling
m=0



Strong coupling
Heavy m

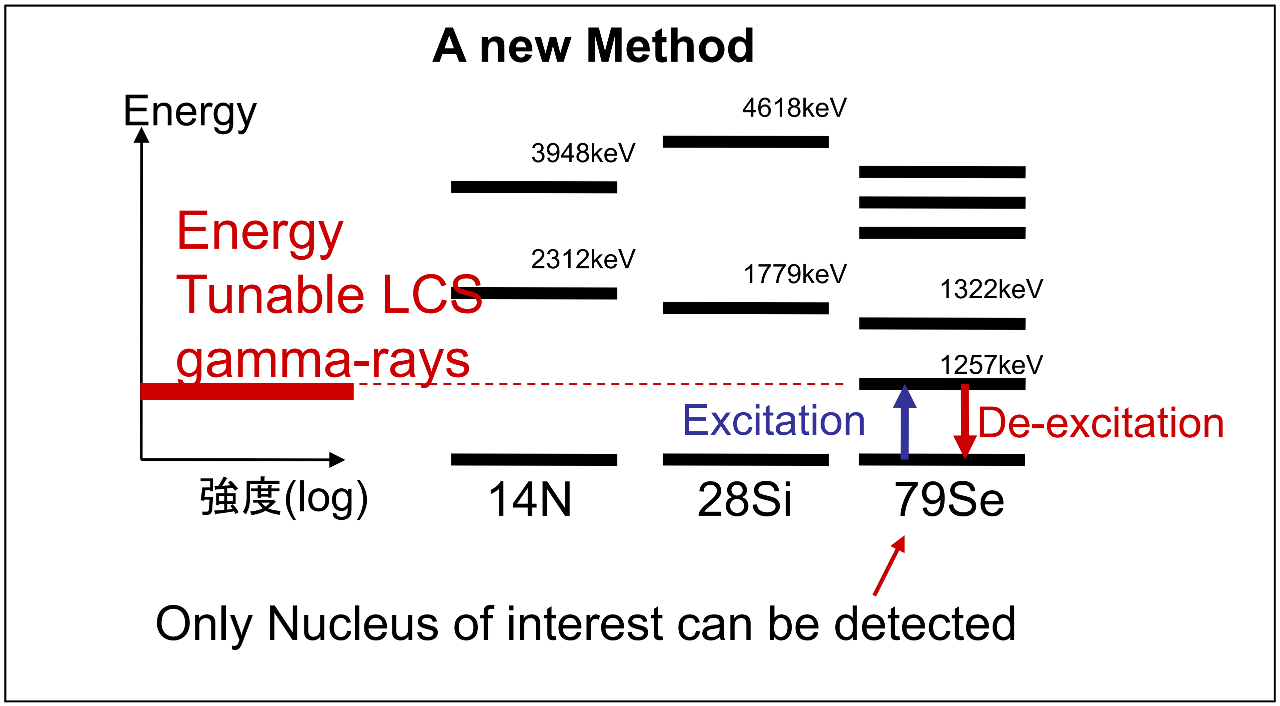
High energy collider

(with Homma, Habs)

gamma-rays to probe and excite nuclei

Laser : produces directed, energy-specific gamma-rays
Gamma-rays: probes nuclei--------- laser: probes atoms

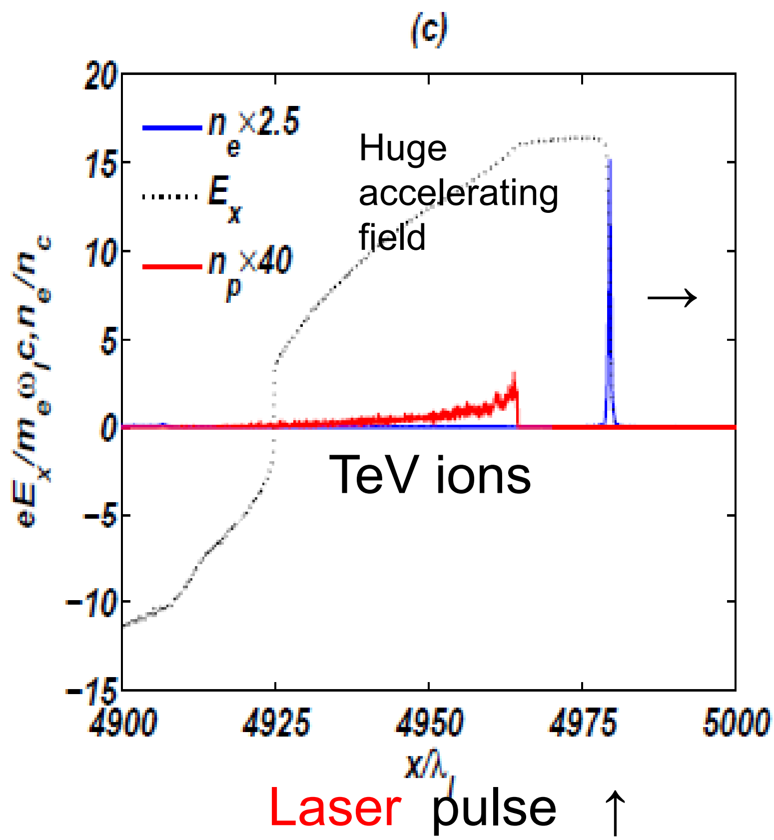
nuclear resonant fluorescence technique



(Hajima)

→ new nuclear mediocine: produce particular isotope such as Pt, vectored to specific molecules in body such as in cancer cell

TeV ion acceleration in ELI regime



Snowplow (bowshock)
LWFA
of ions injected by RPA

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

<u>0.5TeV</u> over
dephasing length of <u>1cm</u>

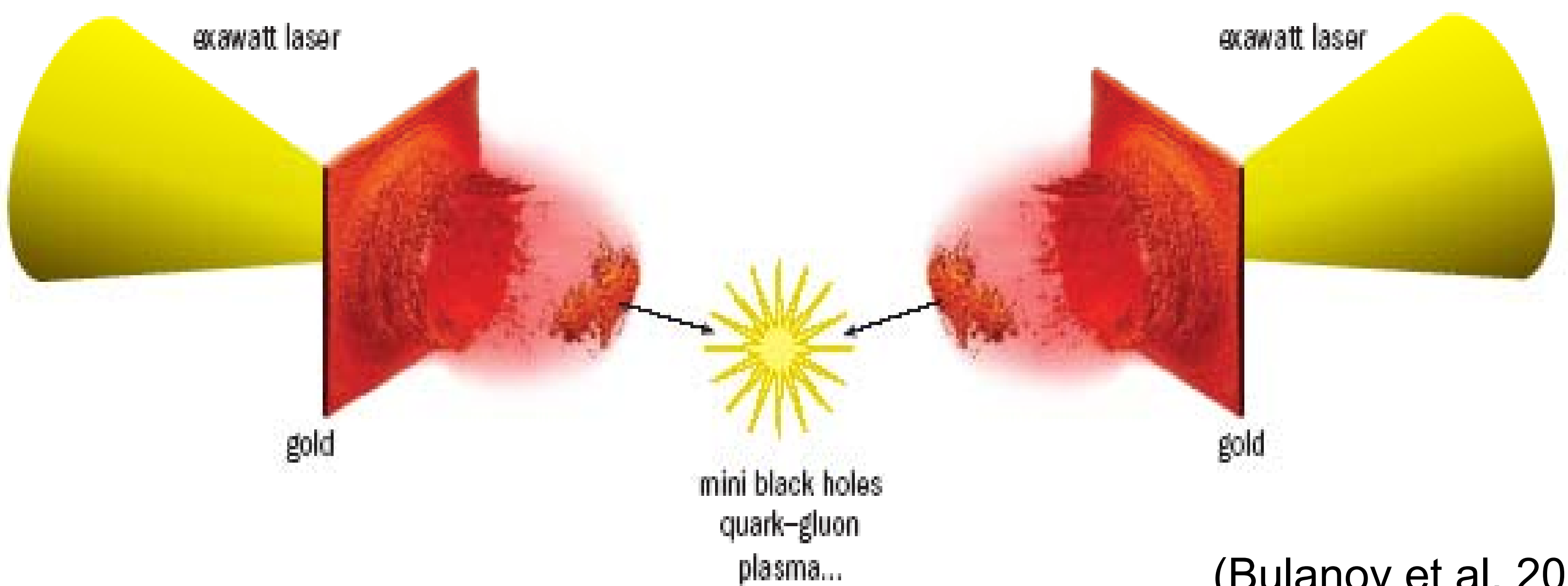
with <u>ELI laser (kJ)</u>

Zheng, Yan, et al., 2010

ELI laser drives ultra-relativistic ions

Laser-driven Ion collider

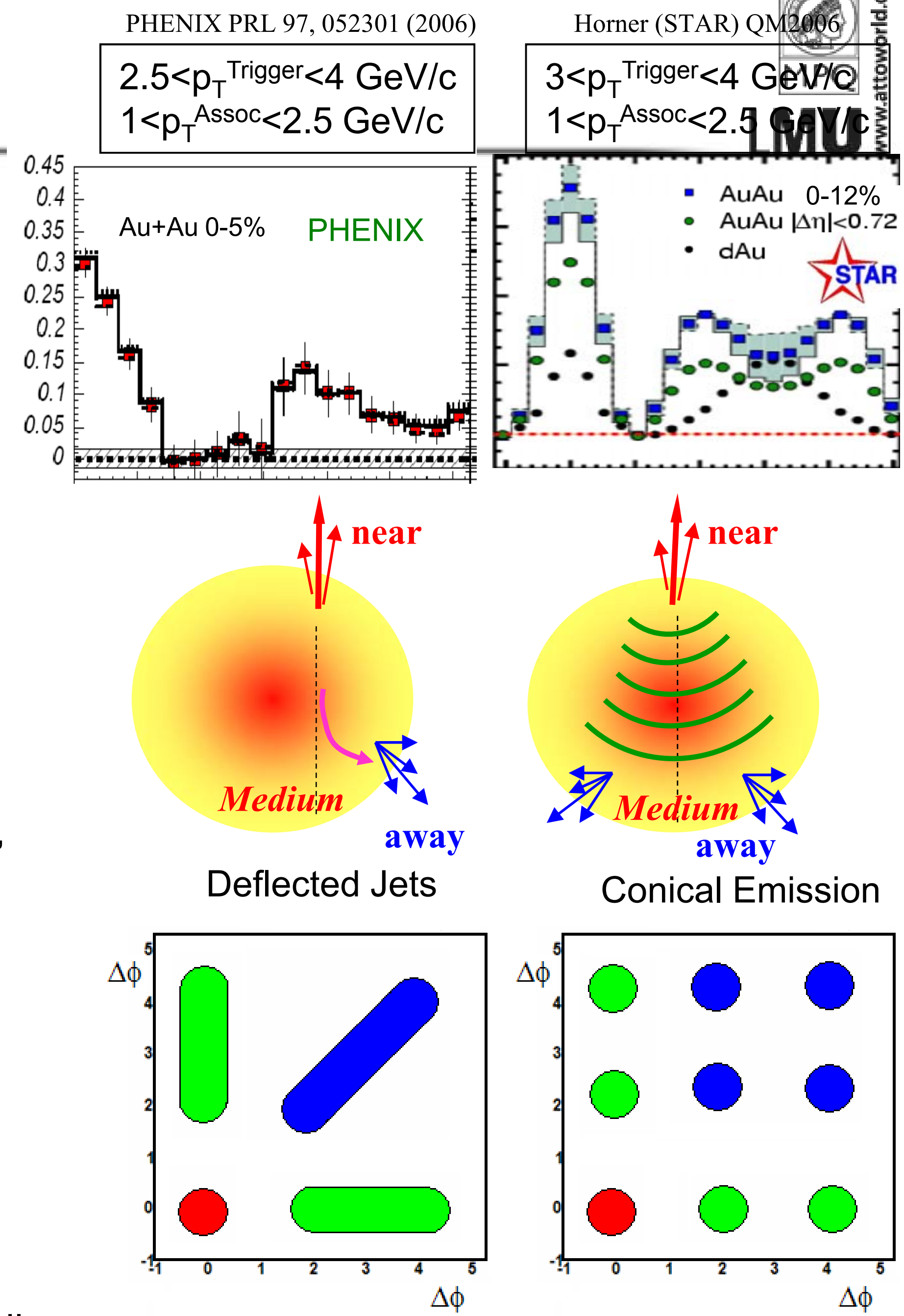
Relativistic and monoenergetic ion beam may constitute compact colliders of ions
→ QCD vacuum exploration



(Bulanov et al, 2004)

Nuclear Wake?

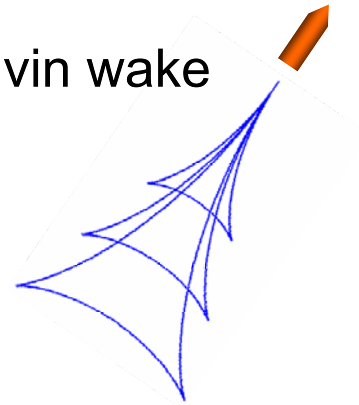
- BNL heavy ion collider
- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- Jet quenching: collective deceleration by wakefield?
  - LWFA method, or Maldacena method?

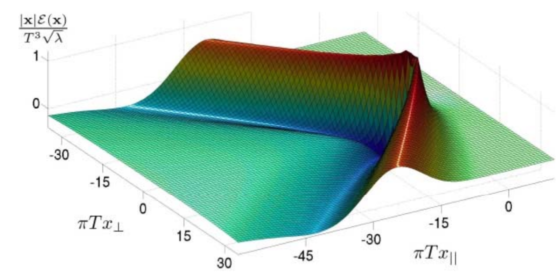


Wakefield even inside of a nucleus

All particles in the medium participate = collective phenomenon

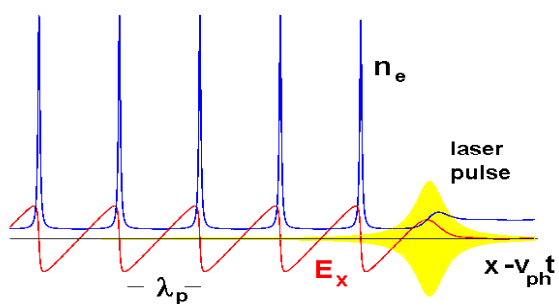
Kelvin wake





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

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



← relativity regularizes

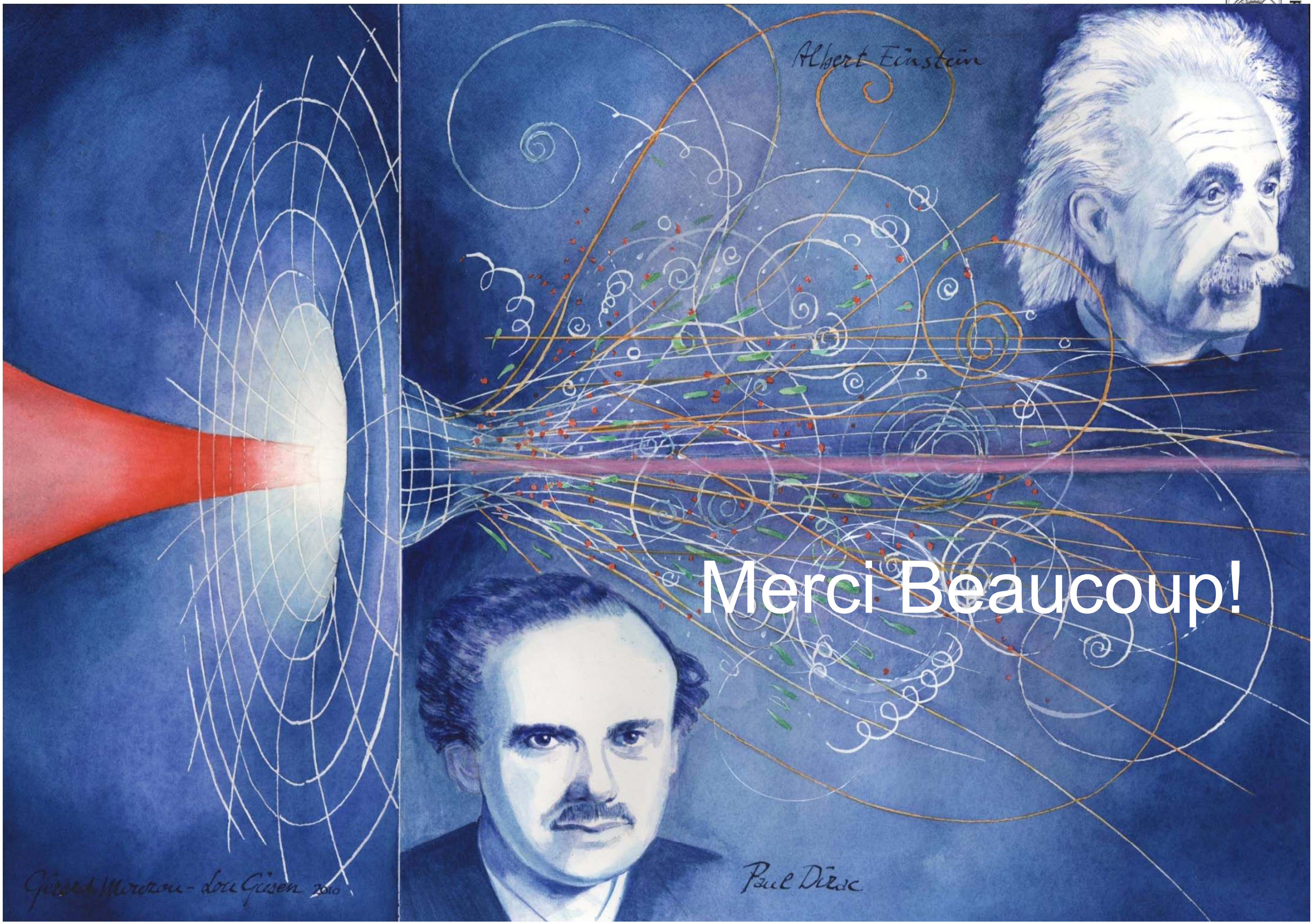
Wave **breaks** at v<c

(The density cusps.
Cusp singularity)

(Plasma physics vs.
String theory?)

Conclusions

- Contemporary science: fragmented (cf. Greek)
- Tough problems (cancer, gravitational physics, nonlinear science, environment,…) accessed by integration
- ELI: provides unifying approach to break logjam, integrates disciplines (oncology. biological imaging, attoseconds, high energy collider, nuclear energy,…)
- ELI: encompasses the past boundaries, enabler of the 21st C. science


Albert Einstein
Merci Beaucoup!
Paul Dirac
Gérard Mourou - Lou Geisen 2010

(Mourou, 2010)