Chaires internationales de recherche Blaise Pascal

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50 Years of the Laser in the City of Light
Wednesday, June 23, 2010
Ecole Polytechnique
Palaiseau

High Field Science: A Second Wave of Laser

Toshiki Tajima
Blaise Pascal Chair,
Fondation Ecole Normale Supérieure
Institut de Lumière Extrême
and
LMU,MPQ, Garching

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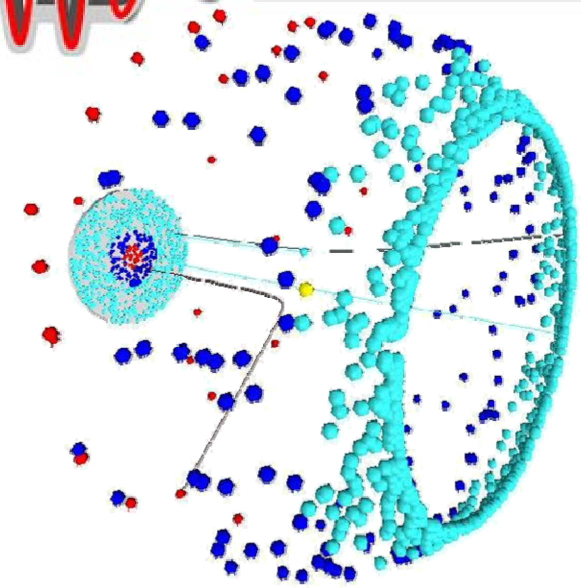
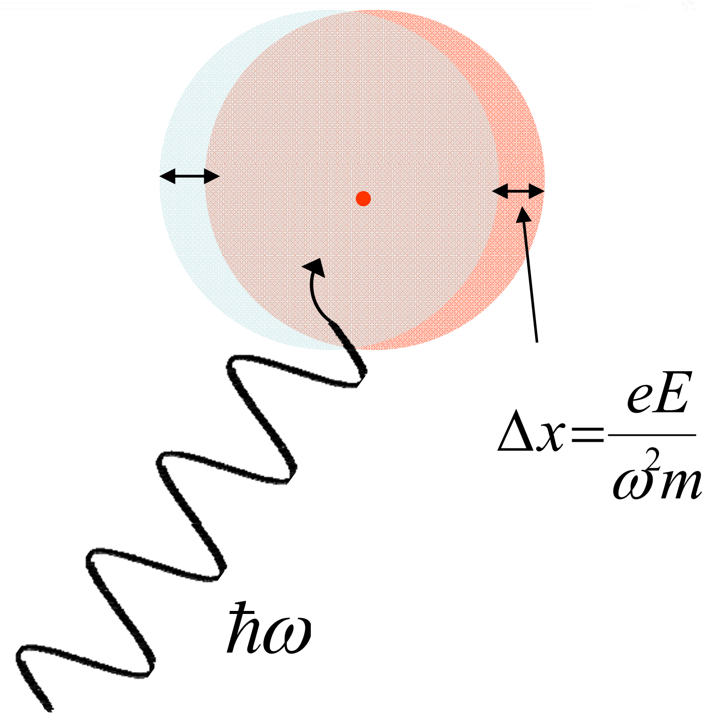
Laser probing <u>nonlinearities</u> in matter



$$\Delta x \sim \frac{\hbar}{p}$$

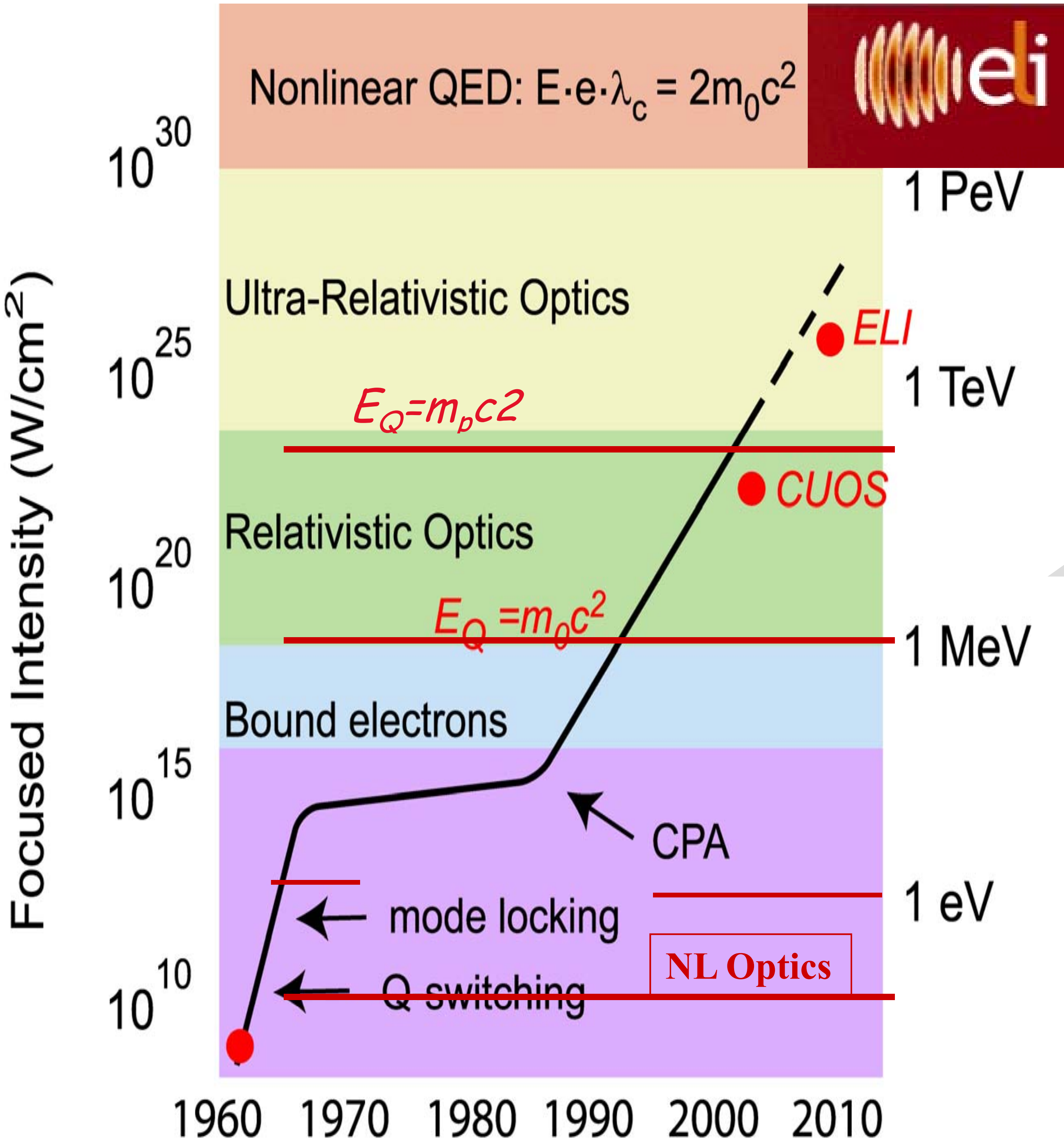
vs

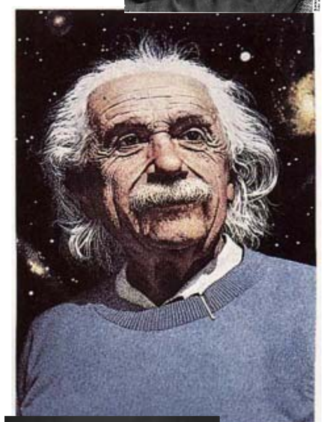


Rutherford's (accelerator) approach vs **Laser approach**

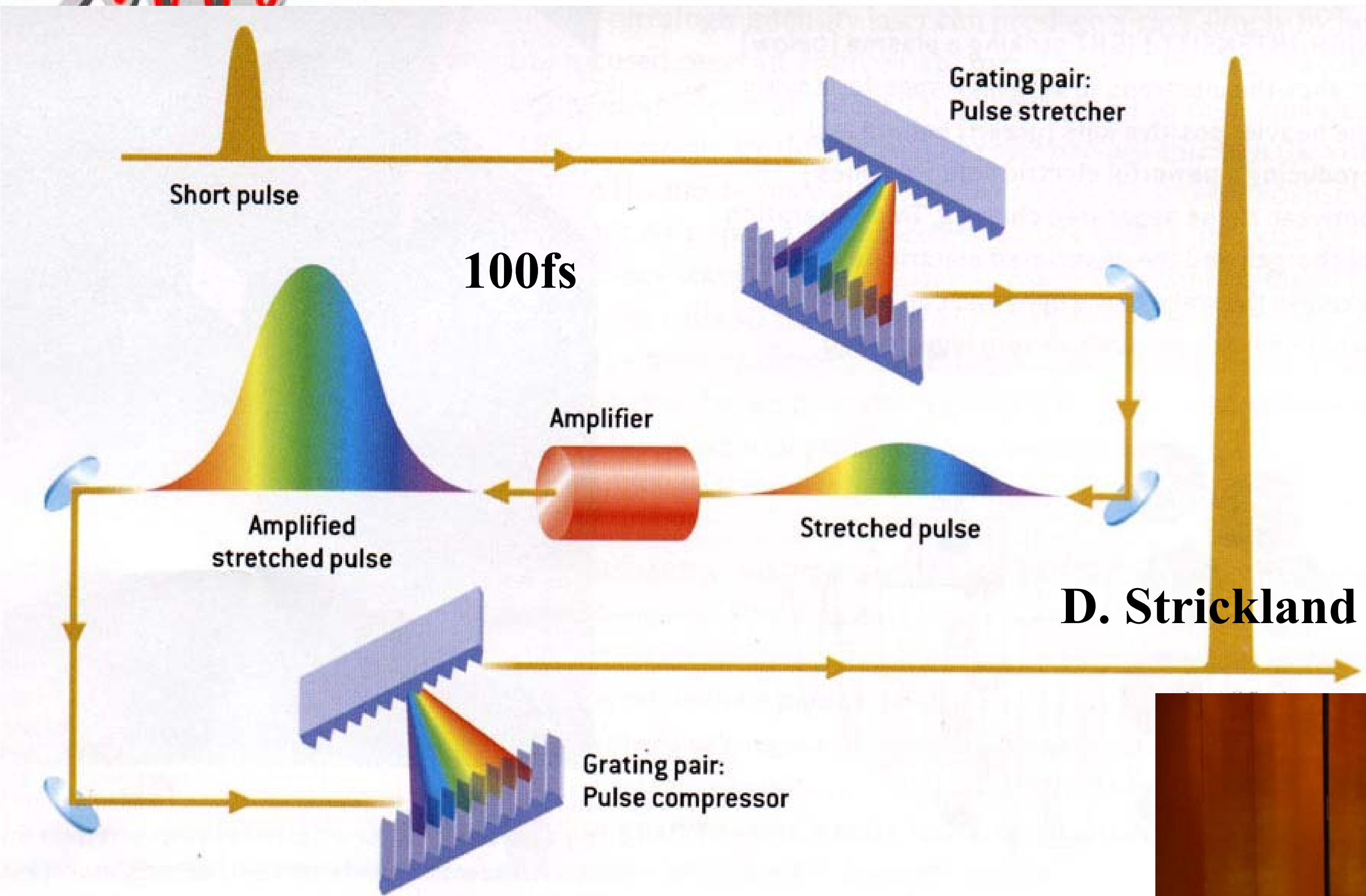
discover particles (colliders)

nonlinear optics, spectroscopy


Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$
eli
Ultra-Relativistic Optics
ELI
E_Q=m_pc2
CUOS
Relativistic Optics
$E_Q = m_0c^2$
Bound electrons
CPA
mode locking
NL Optics
Q switching
1 PeV
1 TeV
1 MeV
1 eV
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
Focused Intensity (W/cm^2)
1960
1970
1980
1990
2000
2010



Chirped Pulse Amplification did it!



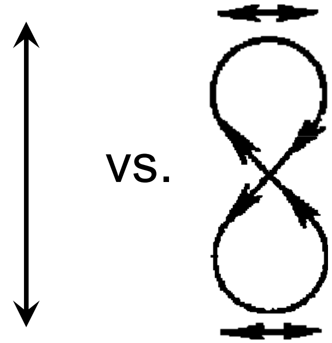
D. Strickland and G. Mourou 1985

<u>Nonlinearities</u> in atom, plasma, and vacuum

Atomic
nonlinear potential

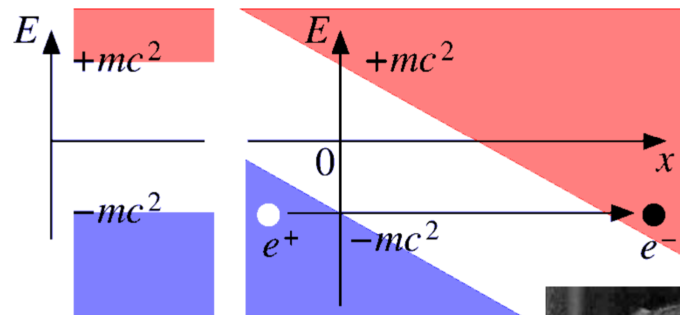
Keldysh field for
laser atomic
ionization

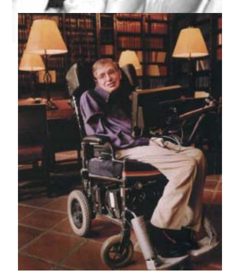
Plasma electron
nonlinear
relativistic motion



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

Plasma free of binding potential , but its electron responses:

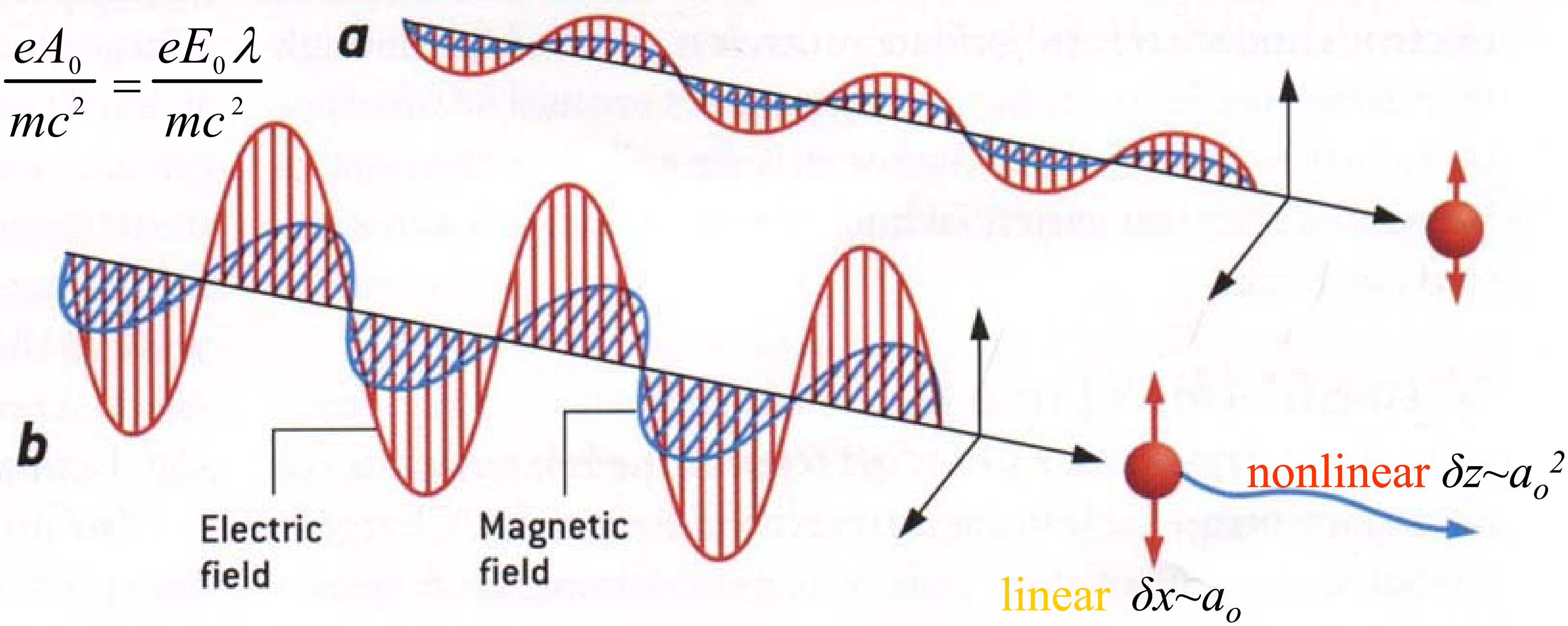
a) Classical optics : $v<<c,$

$a_0<<1$: δx only

b) Relativistic optics: $v \sim c$

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

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



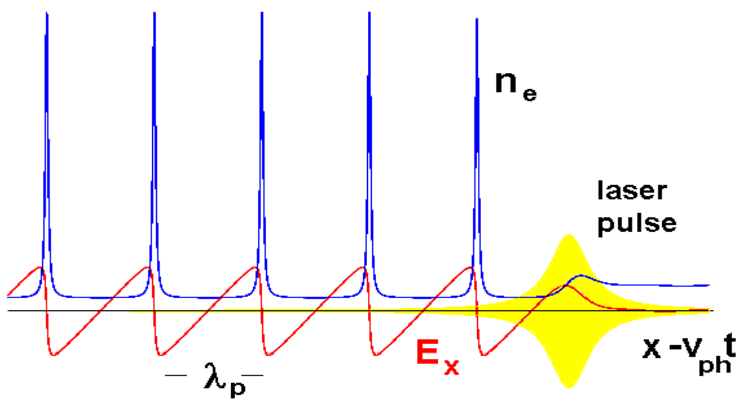
Wakefield : <u>Nonlinearity</u>-driven, <u>Collective</u>

<u>Collective</u> phenomenon = all particles in medium participate

Kelvin wake

<u>Nonlinearities</u> of plasma and water waves

No wave breaks and wake **peaks** <u>at v≈c</u>



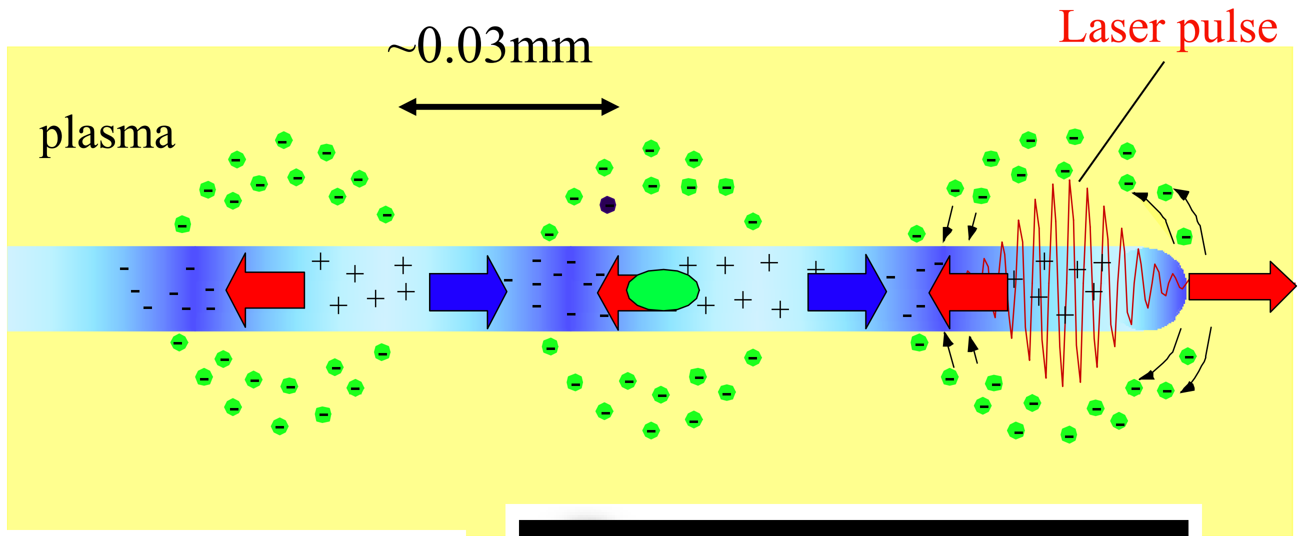
(Wave-head *hard* to overtake trough.
→ density cusp singularity)

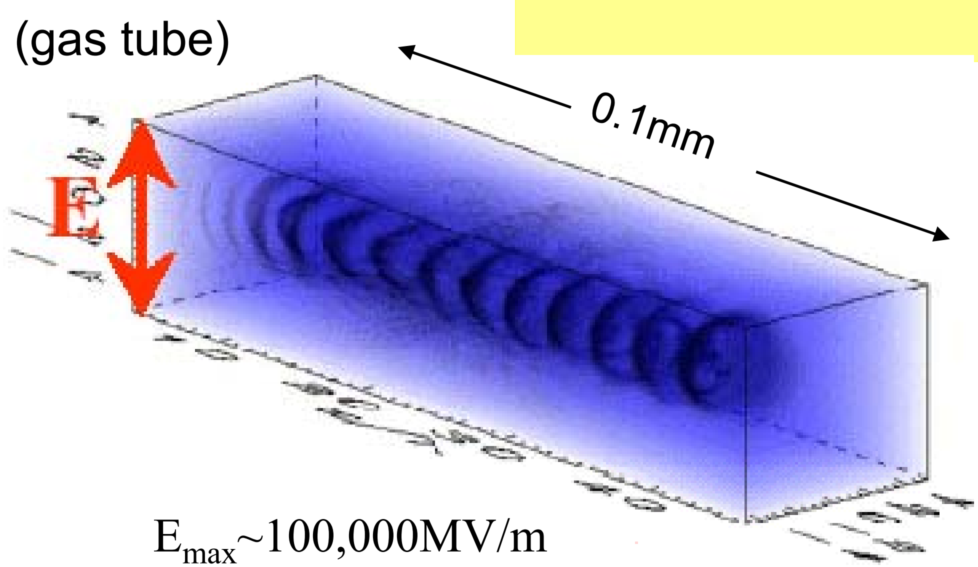
Wave **breaks** at v<c

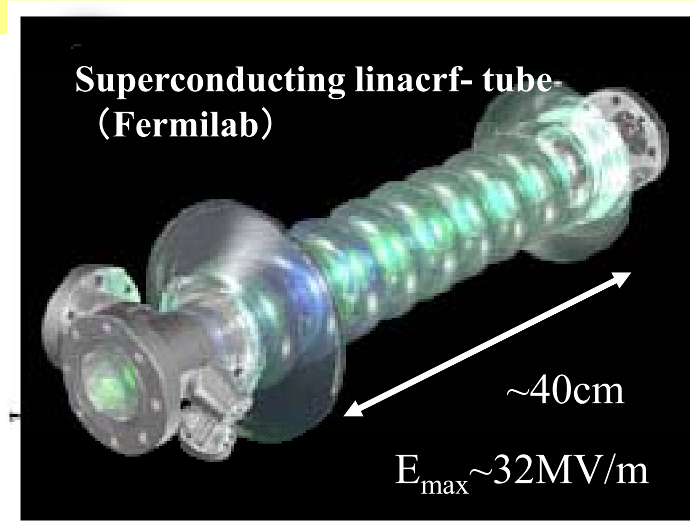
(Wave-head overtakes trough)

Thousand-fold Compactification

Laser Wakefield Acceleration (LWFA): $10^{3\text{-}4}$ fold gradient

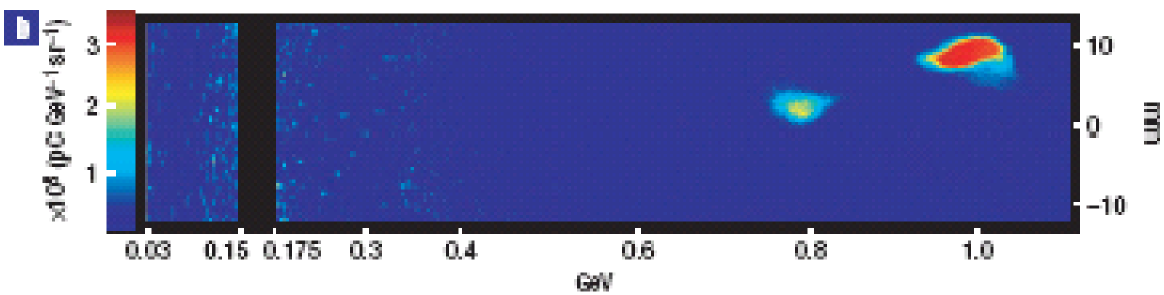






GeV electrons from a centimeter LWFA

(a slide given to me by S. Karsch)



Leemans et al., Nature Physics, september 2006

310-μm-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

laser intensity 10^{18} W/cm^2

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

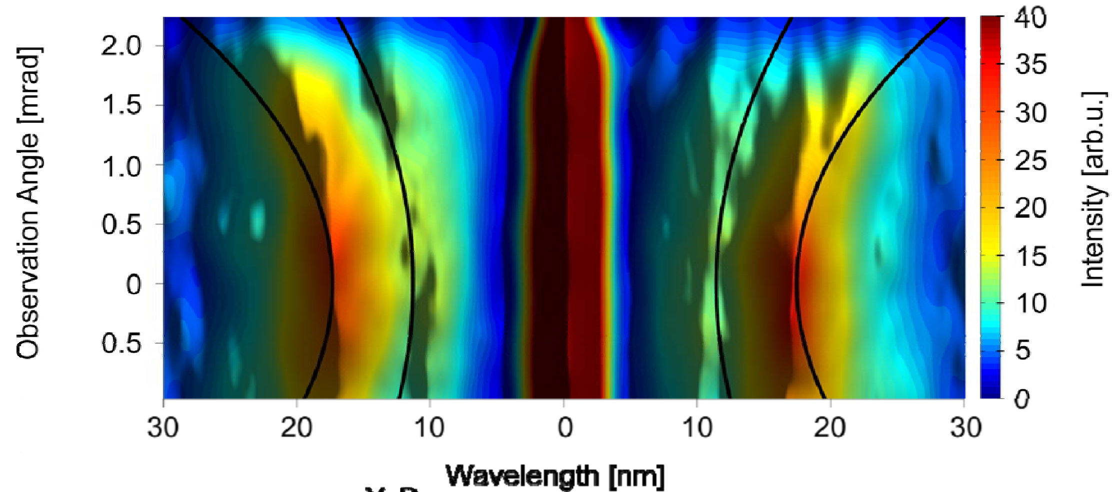
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

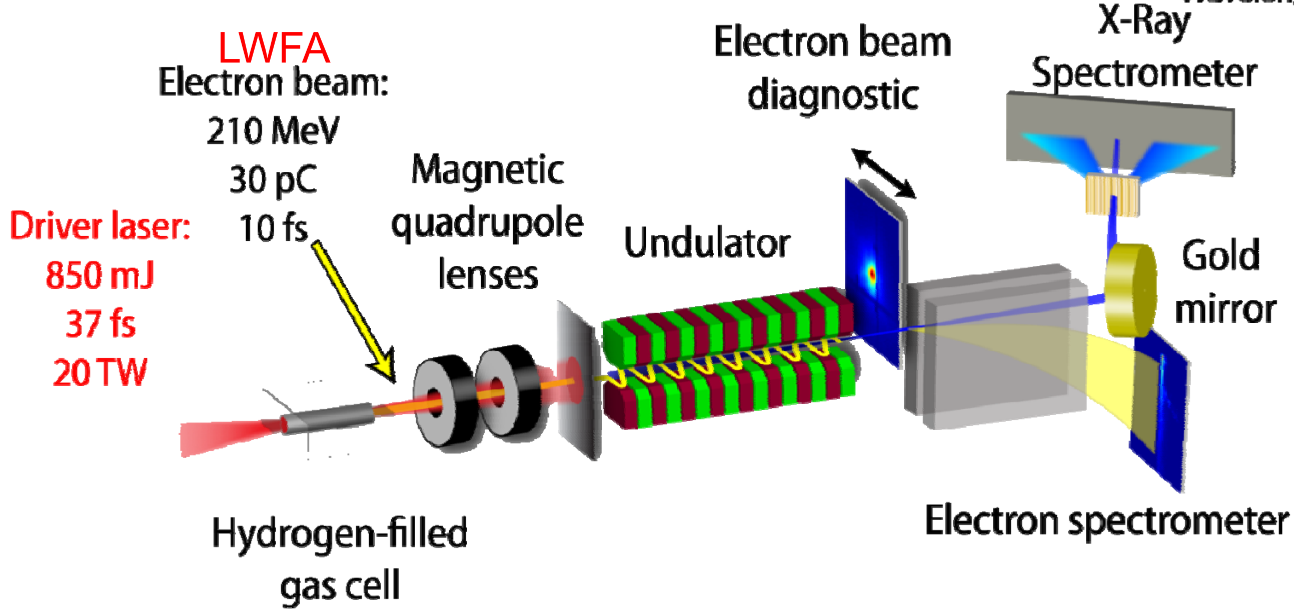
(emphasis by S. Karsch)

Table-top Brilliant Undulator X-ray Radiation from LWFA

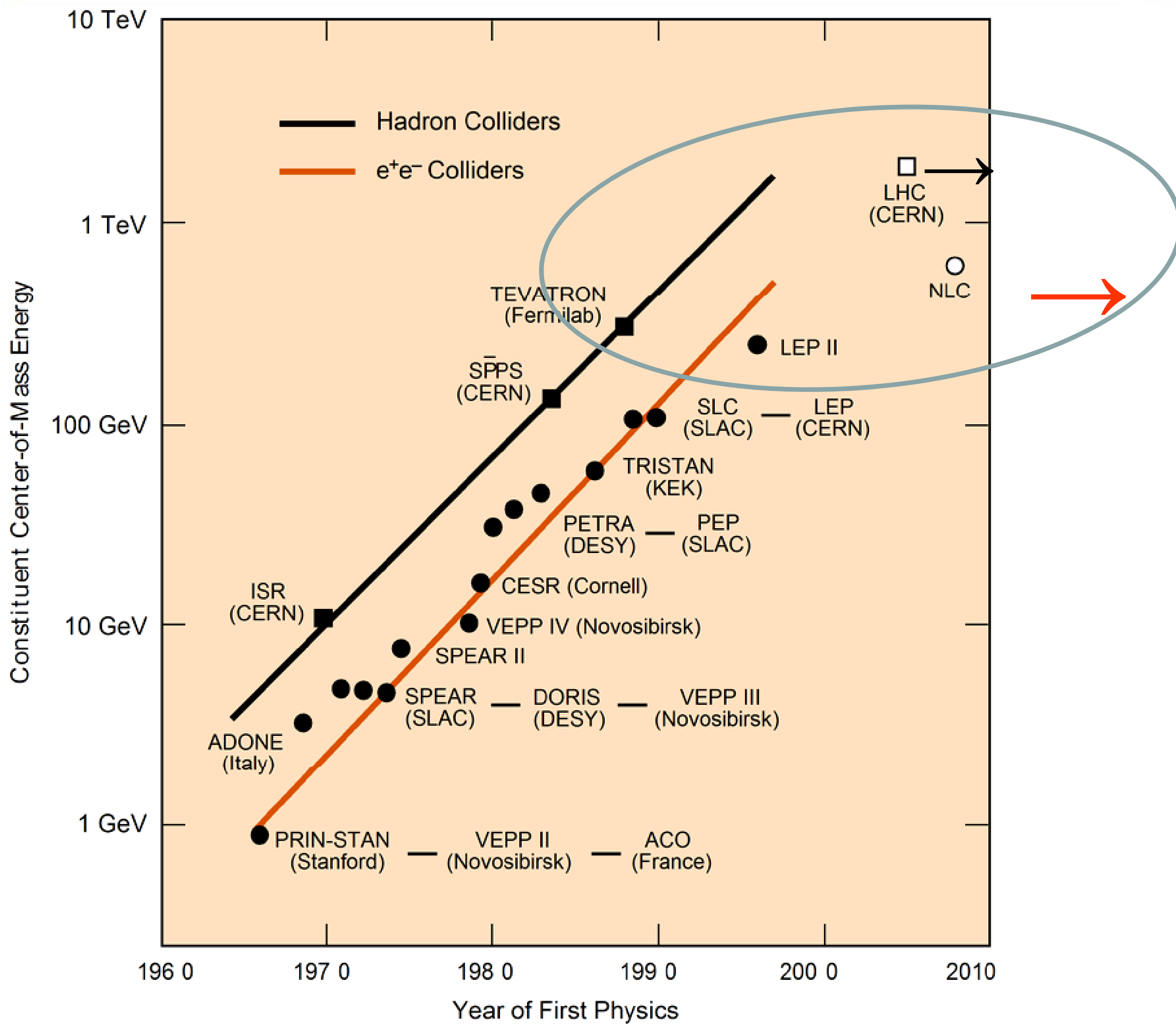
(F. Gruener, S. Karsch, et al., Nature Phys., 2009)

Observed undulator radiation spectrum





Livingston Chart and Recent Saturation

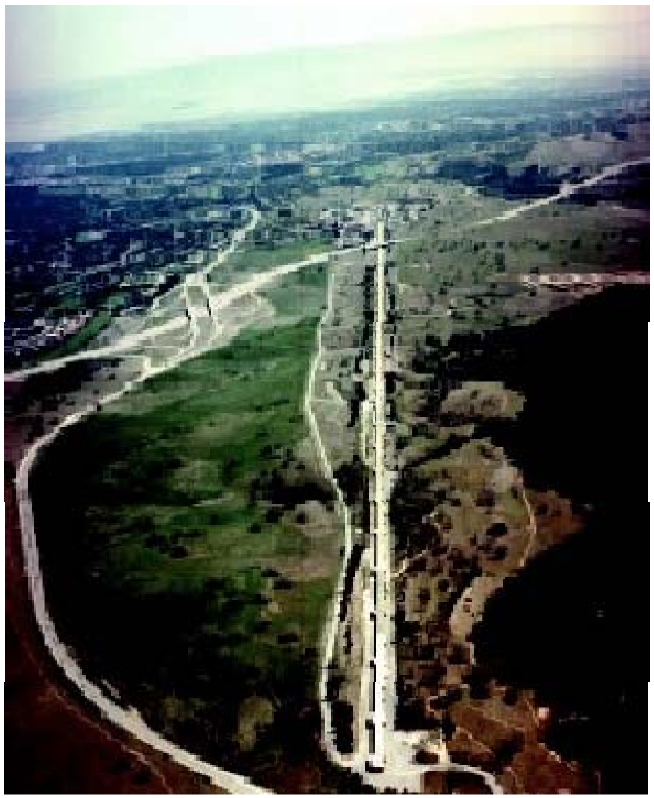


(Suzuki, 2009)

(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

World Lab goal =
Put *SLAC* on a football field

Initiatives considered, emerging: *French; CERN; KEK; LBL*



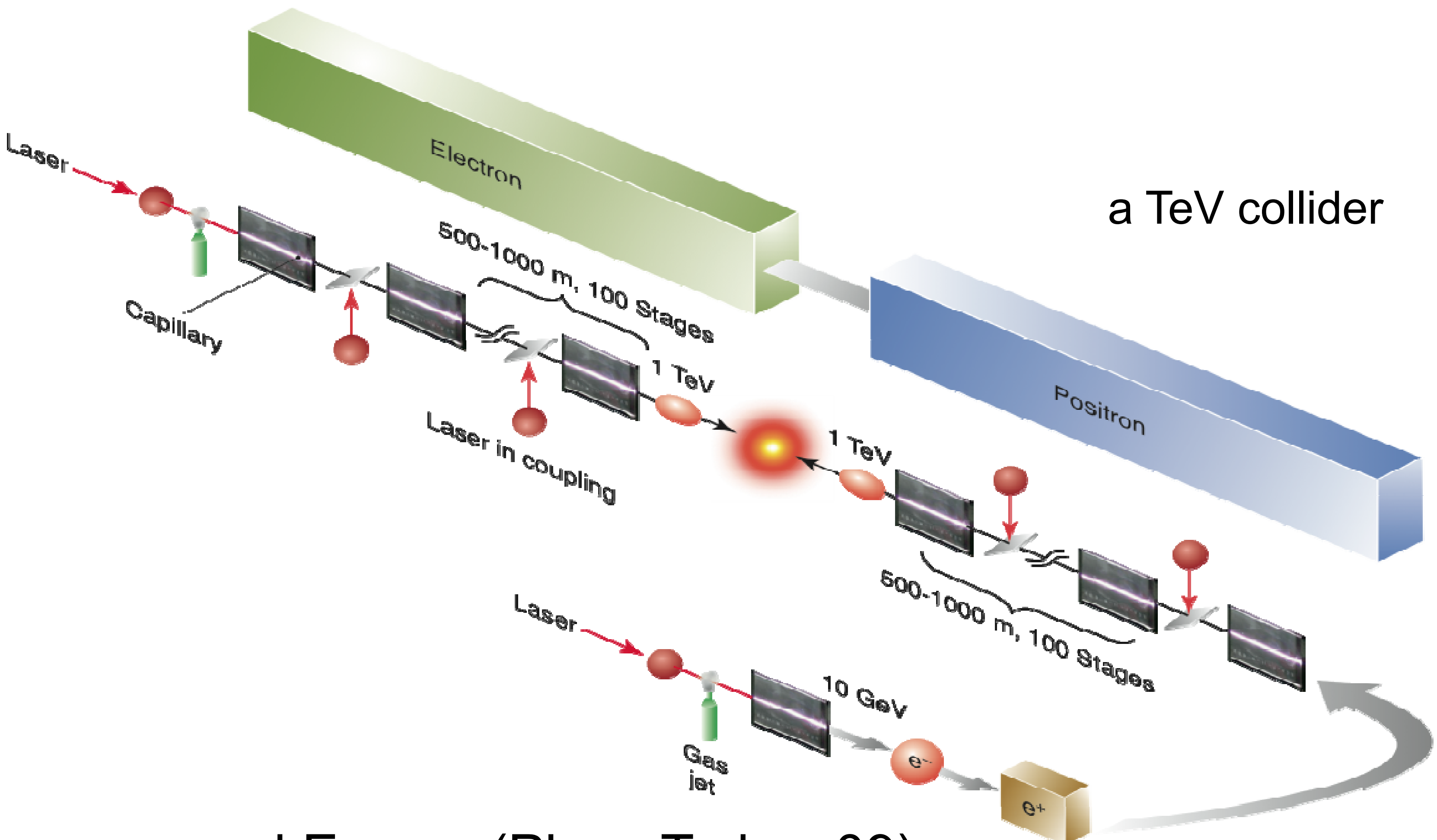
***SLAC*'s 2 mile linac**
(50GeV)

→

Laser acceleration =

- no material breakdown (→ 3/4 orders higher gradient); however:
- 3 orders finer accuracy, and 2 orders more efficient laser needed

Laser driven collider concept



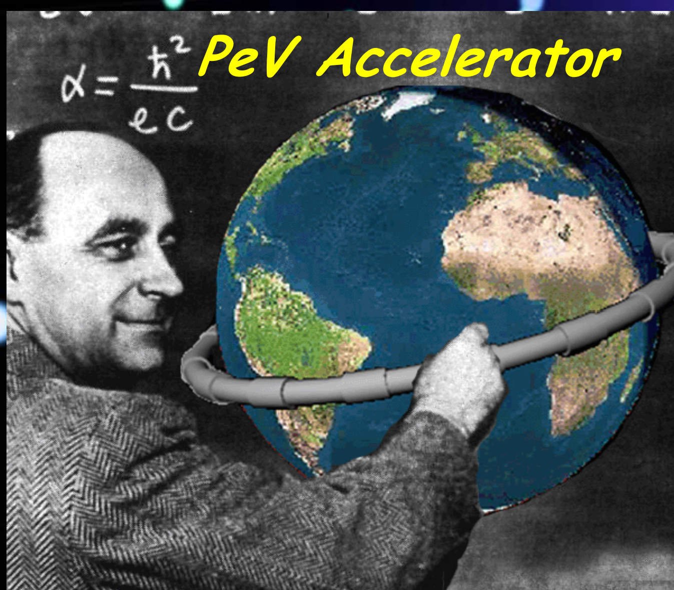
a TeV collider

Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

A. Suzuki (KEK)

1000 times higher energy



1 PeV=10^{15} eV

" New paradigm"

Leptogenesis

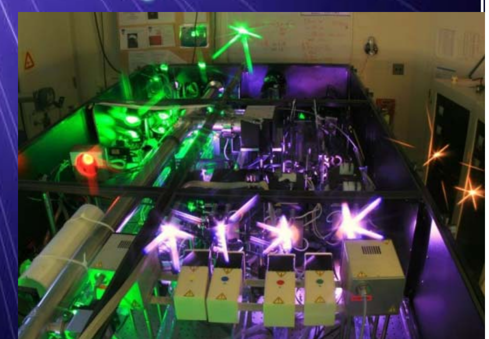
SUSY breaking

Extra dimension
Dark matter
Supersymmetry

1 TeV=10^{12} eV

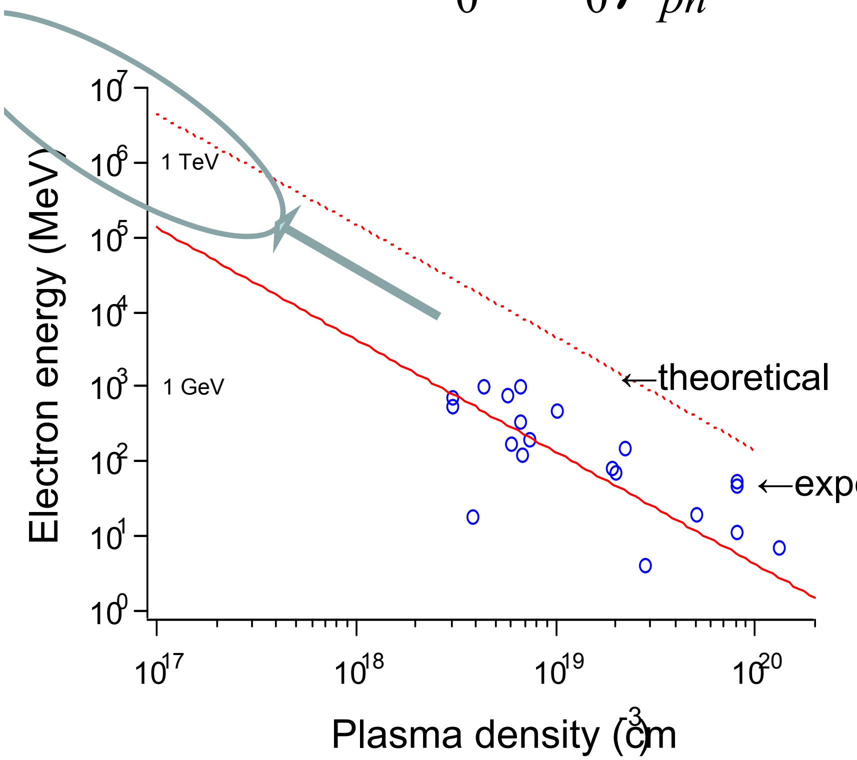
"Standard model"
Higgs
Quarks
Leptons

Laser Acceleration Technology



Theory of wakefield toward extreme energy

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

(Abdo, et al, 2009)

←lower energy

higher→

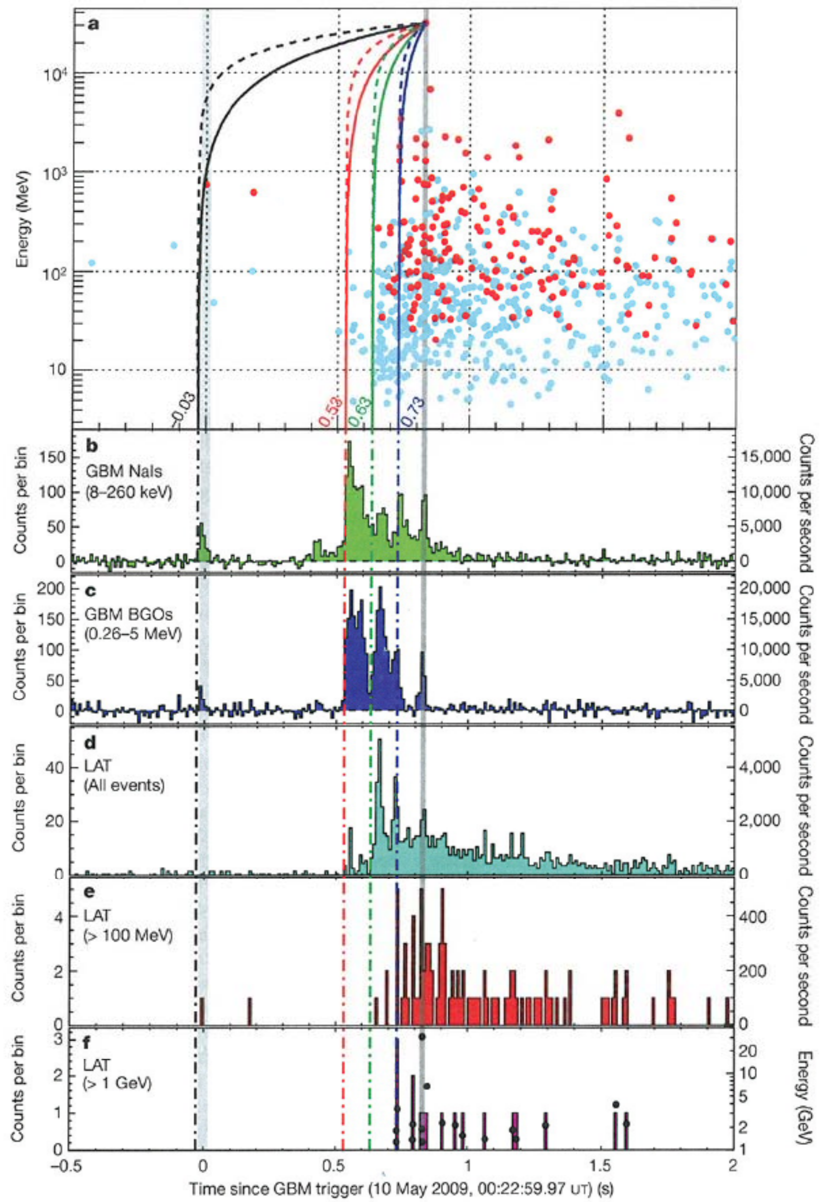


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy ... lowest to highest energies. **f** also overlays energy versus arrival time for each

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

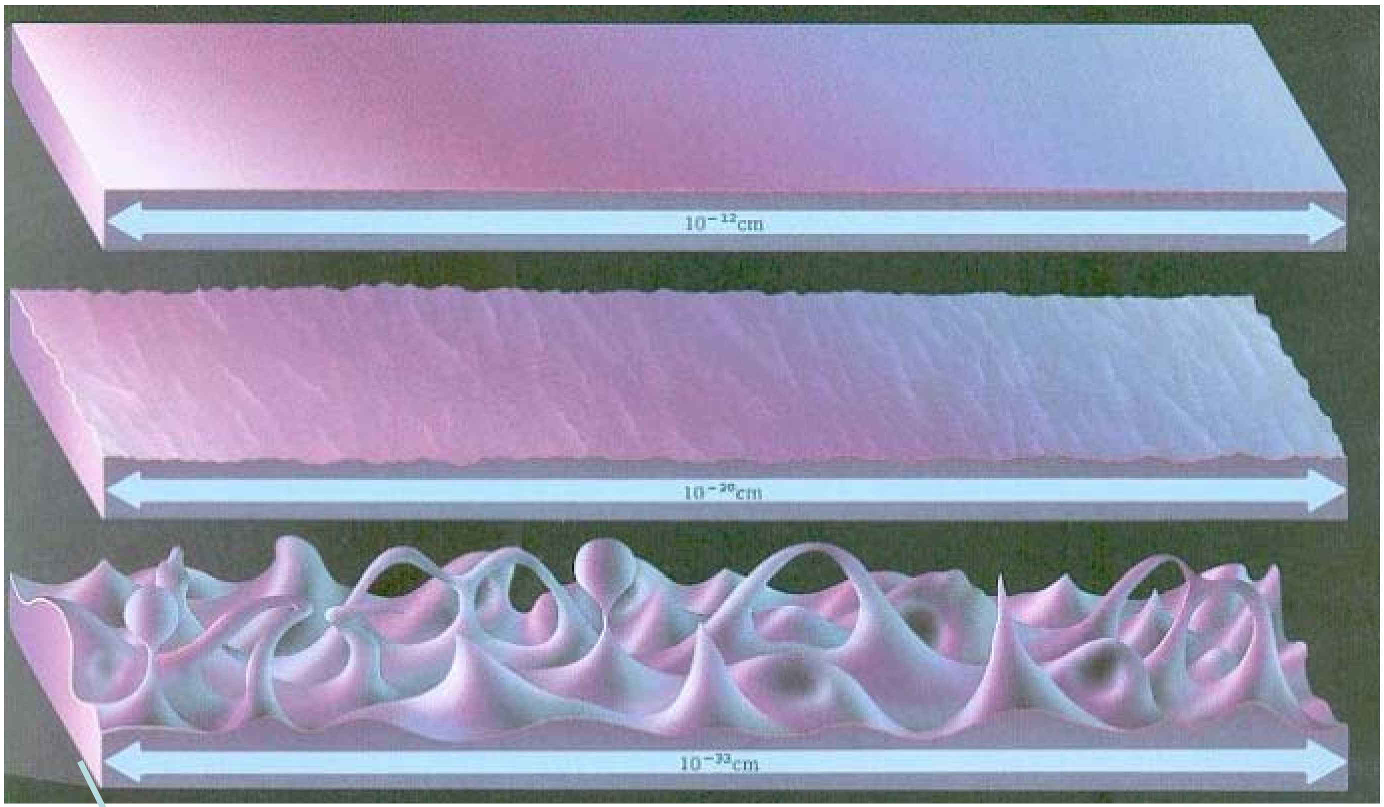
Lab PeV γ (from e-) can explore this with control

www.attoworld.de

Feel vacuum texture: PeV energy γ

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

$c < c_0$



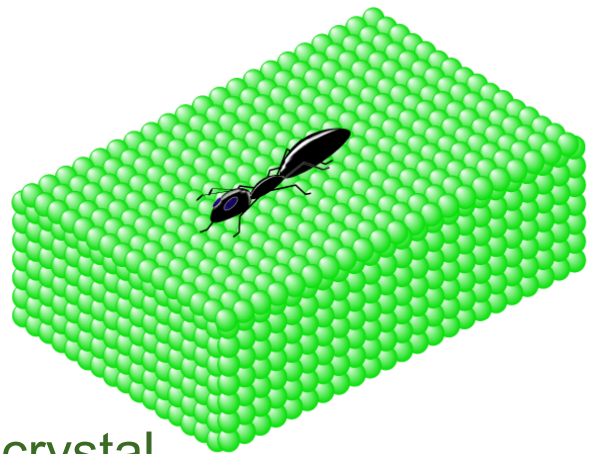
1km

← (0.1PeV)

←(1PeV : fs behind)

PeV γ (converted from e^-)

What is vacuum?



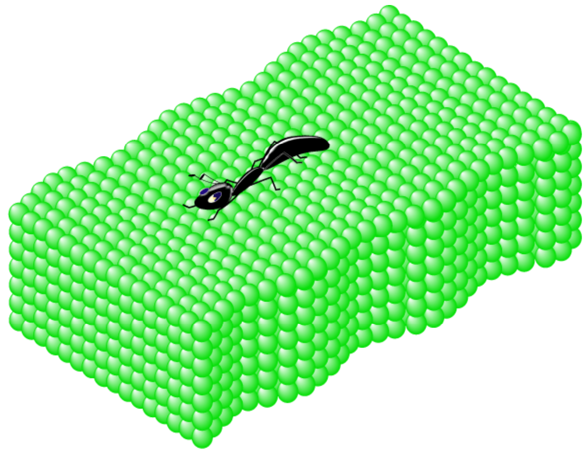
crystal

An observer (bug) in crystal looks at vacuum

↓

vacuum

「真(true)空(nothing)」

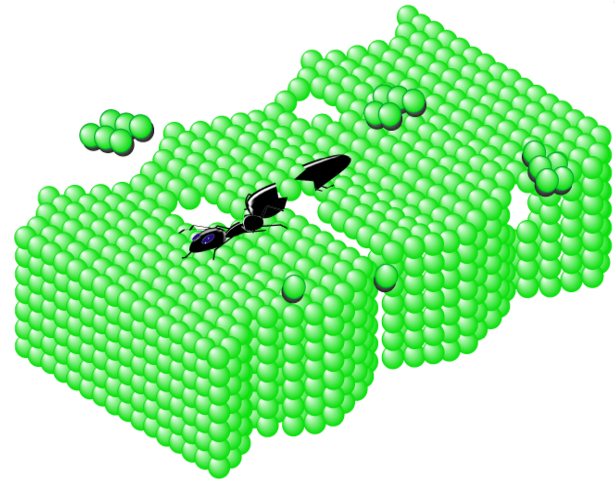


Phonon : excitation of vacuum

↓

Photon : distortion of vacuum

「色=(即是)空」



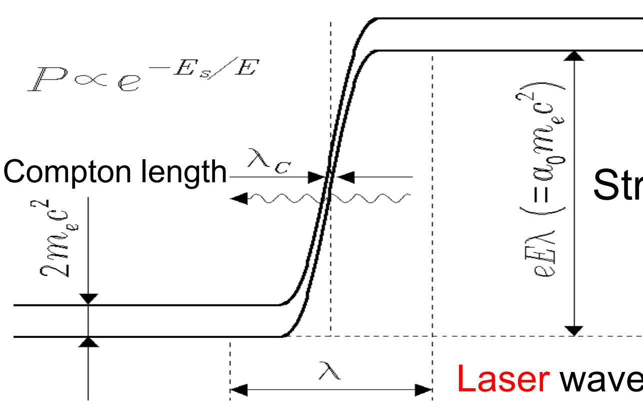
Strong field breaks vacuum

↓

vacuum produces e+e- pair

「空=(即是)色」

QED vacuum breakdown

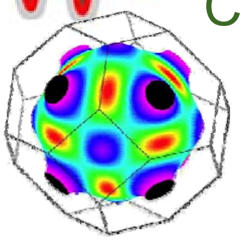


Strong laser field

Laser wavelength

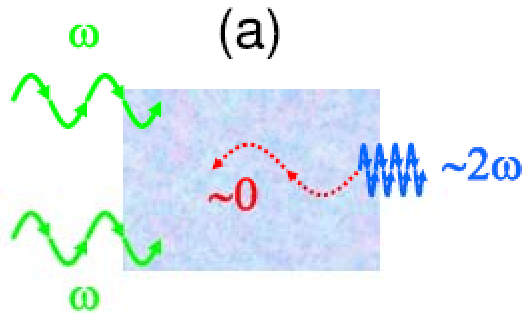
(Naumova Mourou)

Intense laser probes matter /vacuum nonlinearity

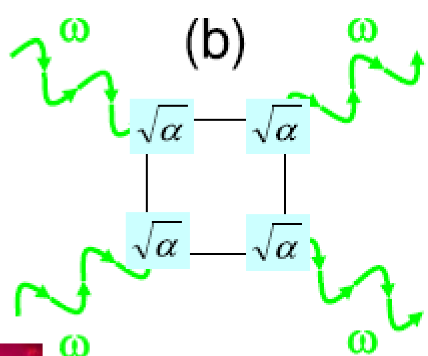


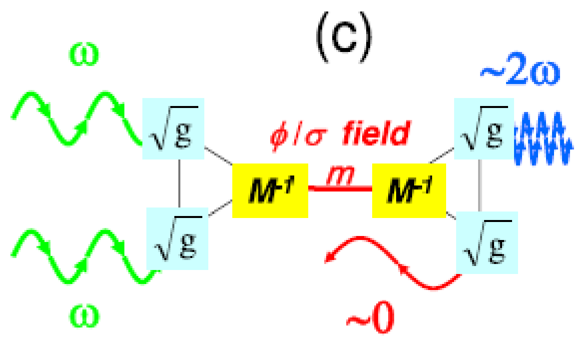
Crystal nonlinearity →

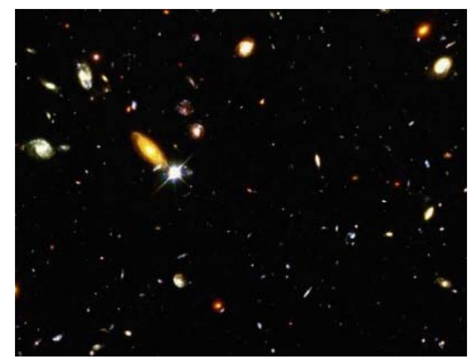
second harmonic generation (Franken et al)

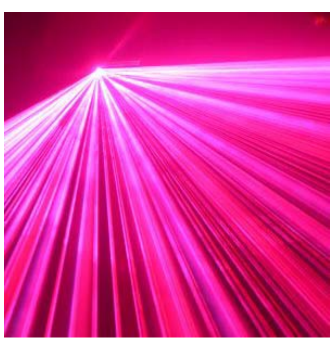


Learn from **Nonlinear Optics** of matter for vacuum:









QED nonlinearity

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

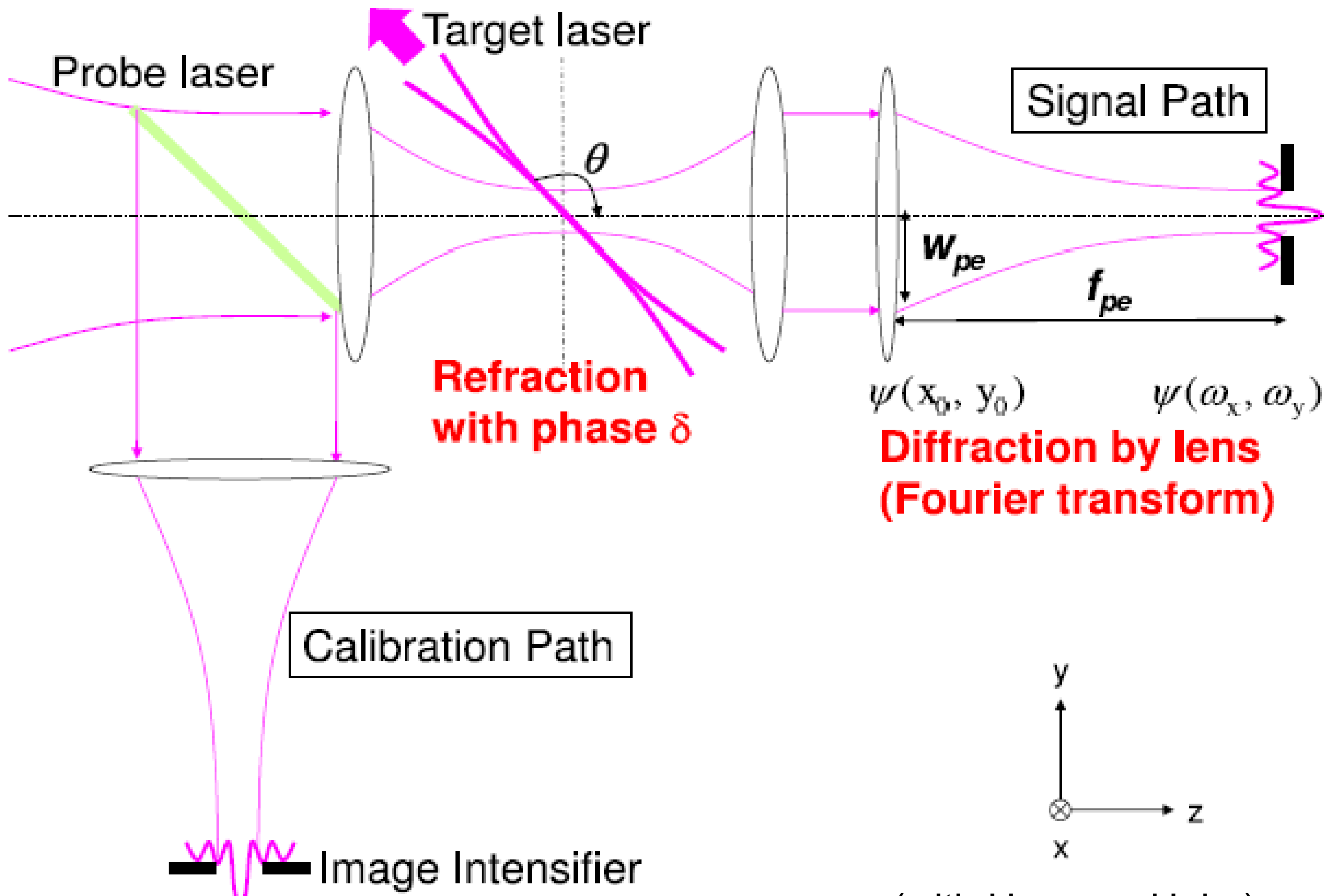
→ second harmonic

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)

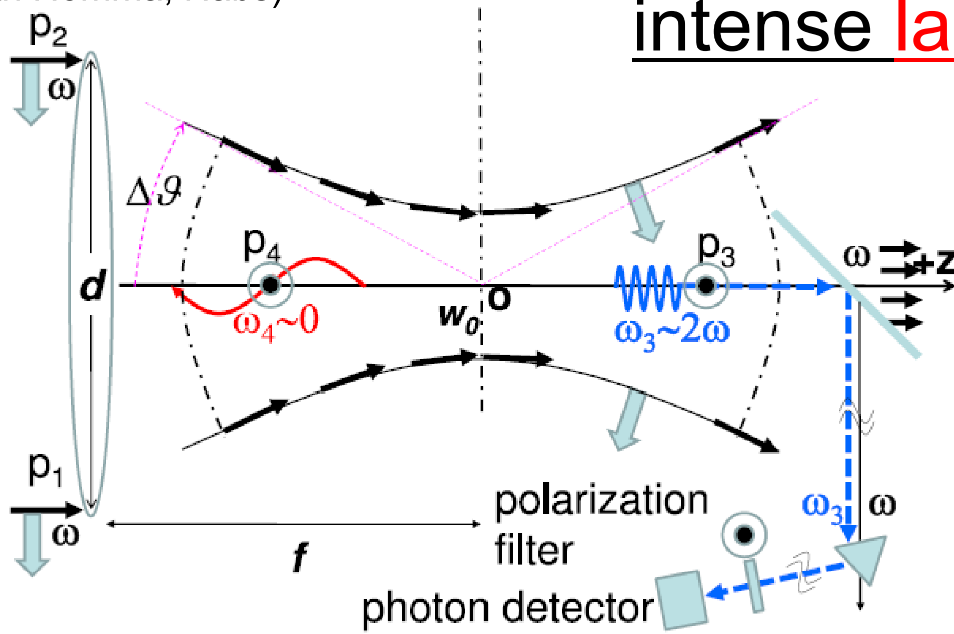


(with Homma, Habs)

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

Proposed scheme of co-parallel intense laser probe of vacuum

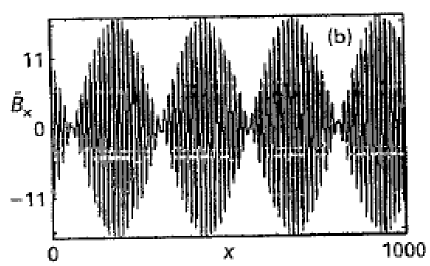
(with Homma, Habs)



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

Nonlinearity of vacuum

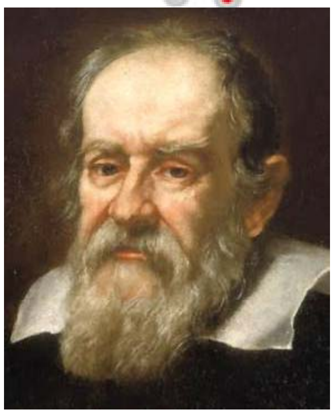
$\omega + \omega \rightarrow 2\omega$ (SHG a la Franken)



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

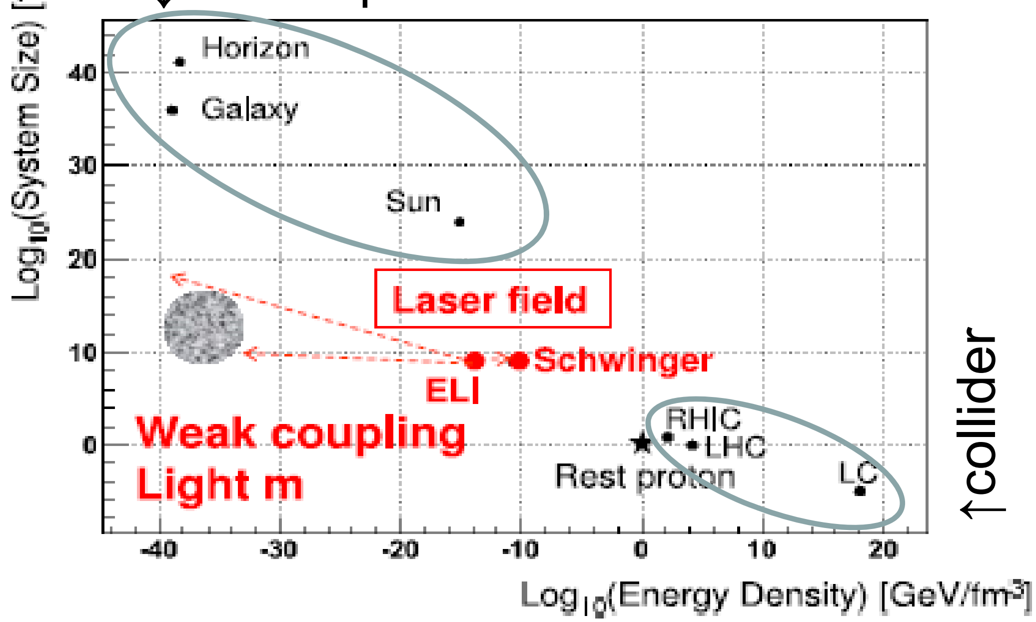
Scope of High Field Science vs traditional approaches



Cosmological observation

Weak coupling
m=0

↓ telescope



↑collider

Strong coupling
Heavy m

High energy collider

(with Homma, Habs)

Conclusions

- Laser: intensity sees no plateau/ceiling since 1990
- Nonlinearities of matter by Laser: nonlinear optics (atomic or solid nonlinearity) : Rutherford method vs Laser method
- Nonlinearity of relativistic plasma → laser wakefield
- Laser wakefield acceleration: experimentally well established; unique properties getting known/applications spawn out
- GeV electrons; 10 GeV soon; 100GeV *world lab* suggested;

  TeV laser collider contemplated; PeV frontier (*primordial GRBs in the lab*)
- Vacuum nonlinearities: Heisenberg QED vacuum probed by intense laser by phase contrast imaging
- Vacuum nonlinearities with weakly coupling light energy fields (meV- neV): co-propagating intense lasers to find beat resonance ← axion-like particles, dark energy fields
- ***High Fields Science***: emerging, carves out new frontier, horizon yet to be seen --------a second wave of laser revolution------------

Centaurus A:

cosmic wakefield linac?

Merci Beaucoup!