History and Future of Laser Technology
"Next Generation of
Extreme Optical Tools and Applications"
On the occasion of 50th Anniversary of
Laser Invention
2010 AAAS Annual Meeting
San Diego
2/21/10

Relativistic Optics and High Field Science

Toshi Tajima

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and

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Acknowledgments for Advice and Collaboration: G. Mourou, F. Krausz, D. Habs, S. Karsch, L. Veisz, T. Esirkepov, M. Kando, K. Nakajima, A. Suzuki, F. Takasaki, S. Bulanov, W. Leemans, T. Raubenheimer, K. Kondo, M. Teshima, C. Keitel, S. Kawanishi, P. Shukla, C. Barty, Y. Kato, K. Homma, H. Gies, T. Heinzl, P. Chen, W. Sandner, T. Kessler, A. Giulietti, D. Jaroszynski, F. Gruener, M. Uesaka, T. Yamazaki, E. Moses

International Committee for Ultra Intense Lasers

International promotion of highest intensity lasers and its applications

Inaugurated in 2004, Oxford under IUPAP

(above: initial Committee members)

Chair: T. Tajima,

Co-chair: C. Barty, W. Sandner

www.ICUIL.org

Can the society continue to support ever escalating accelerators?

Accelerator = crown-jewel of 20th C science

beam dump

LHC at CERN

supermagnets quench

Terminated Texas tunnel. The SSC was abandoned after about 25% of the tunnel for the 87-kilometer-circumference large collider ring had been bored.

SSC tunnel

hadron therapy accelerator and gantry

Demise of SSC (Super collider)

Terminated Texas tunnel. The SSC was abandoned after about 25% of the tunnel for the 87-kilometer-circumference large collider ring had been bored.

By largest machine to probe smallest of structure of matter

size	10^2km
energy	20TeV
cost	$10B

US :

Texas site decided (1989)

US Government decided to terminate its work: 1993

Tajima: 'Tamura Symposium' on the Future of Accelerator Physics @ UT Austin (1995)

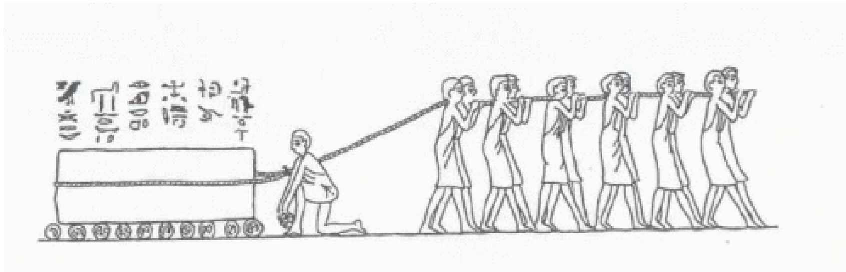
Dream Beams Symposium

MPQ Garching
Feb. 26 – 28, 2007

High intensity laser driven beams

What is *collective force*？:Secret behind laser accelerator

How can a Pyramid have been built?



Individual particle dynamics → Coherent and collective movement

Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)

Collective radiation (N^2 radiation)

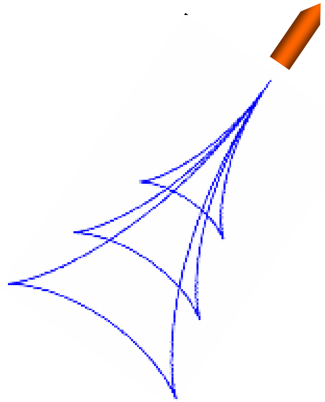
Collective ionization (N^2 ionization)

→ Laser driven collective accelerating field

Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

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



Kelvin wake

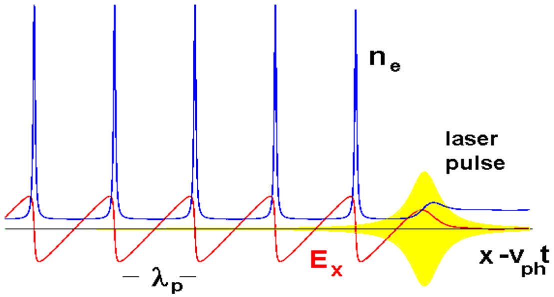
$$\omega = \sqrt{kg}$$

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

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

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

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



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

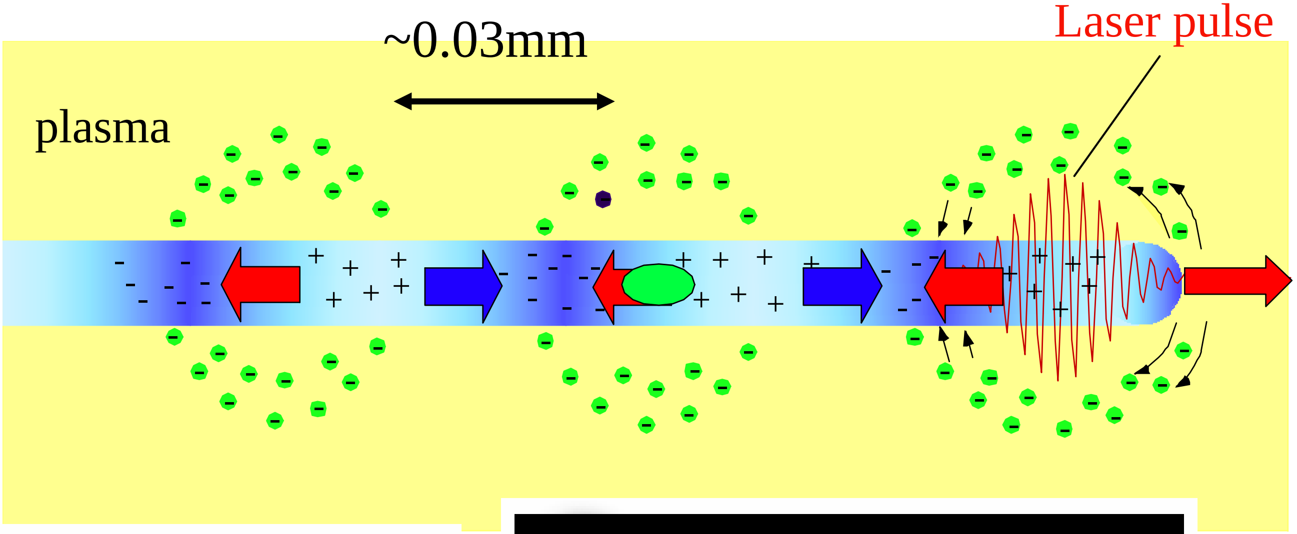
$$\omega_{pe} = \left(4\pi n e^2 / m_e\right)^{1/2}$$

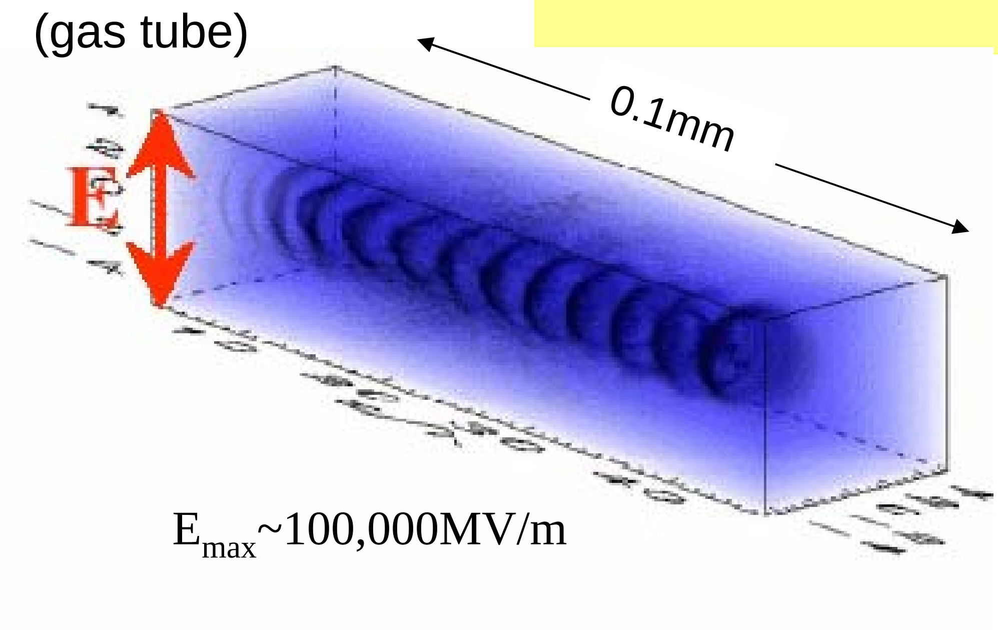
(The density cusps.
Cusp singularity)

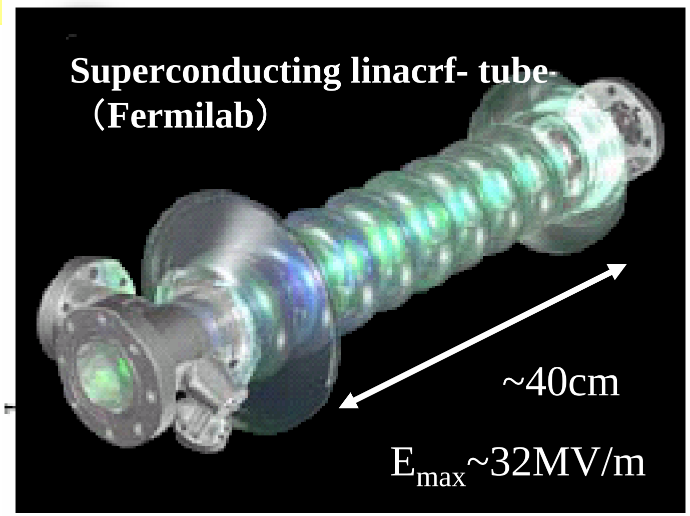
Wave **breaks** at v<c

Thousand-fold Compactification

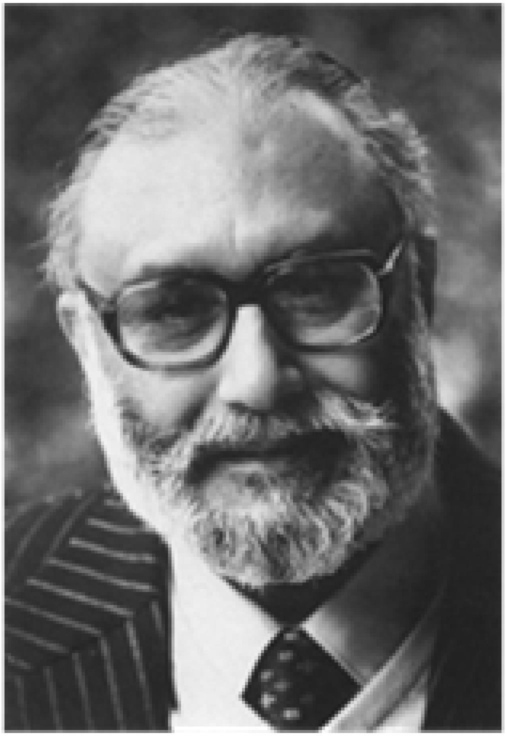
Laser wakefield: thousand folds gradient (and emittance reduction?)







The late Prof. Abdus Salam



At ICTP Summer School (1981),
Prof. Salam summoned me and discussed
about laser wakefield acceleration.

Salam***: 'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'.*** (1981)

He organized the Oxford Workshop
on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

Laser technology invented (1985)

(Professor Gerard Mourou: ELI Coordinator)

Chirped pulse amplification (CPA) invented:

to overcome the gain medium nonlinearities in spatially expanded amplification to temporal expansion:

smaller, shorter pulse, more intense, higher reprate,

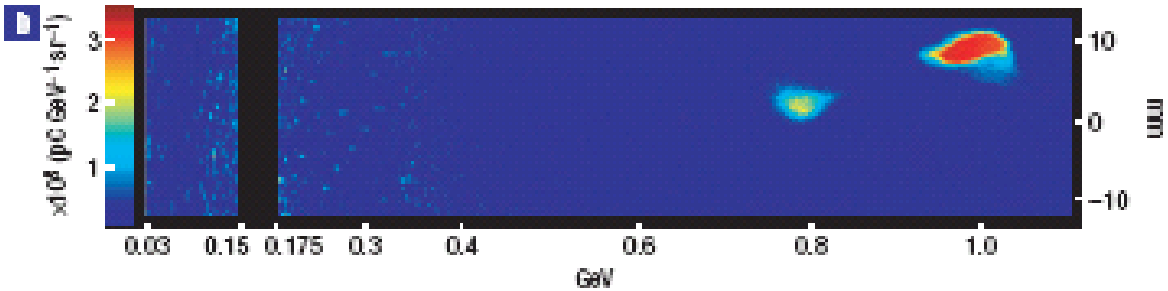
all simultaneous.

→ many table-top TW and PW lasers world-wide
first Chair, ICUIL (International Committee for Ultra Intense Lasers)
toward EW laser (*Extreme Light Infrastructure* ELI)

→First LWFA experiments
(Nakajima et al 1994; Modena et al1995)

→now drives *High Field Science*

GeV electrons from a centimeter accelerator
(a slide given by S. Karsch)



310-μm-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

Leemans et al., Nature Physics, september 2006

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)

Key issues of future colliders

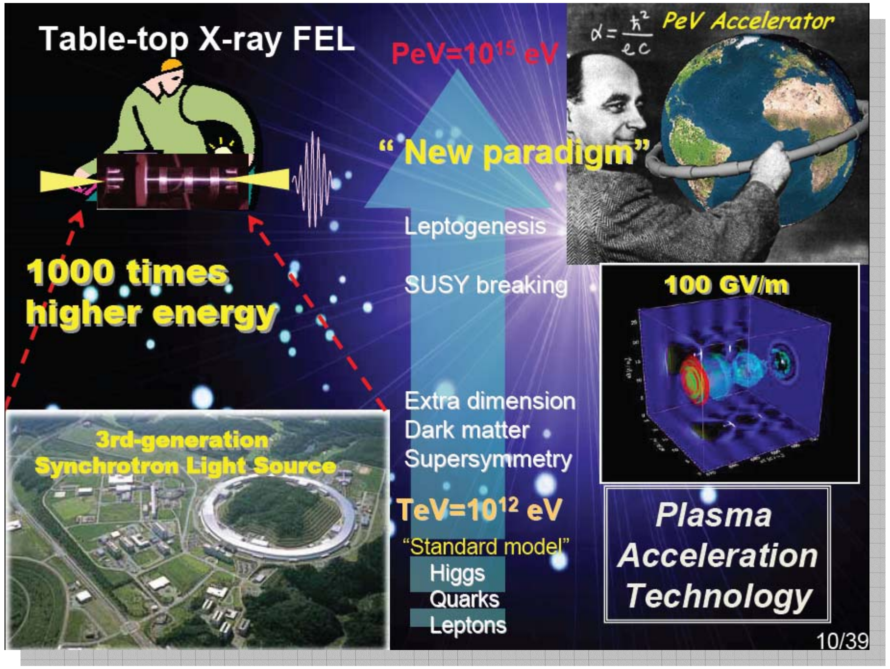
(T. Raubenheimer, SLAC, 2008)

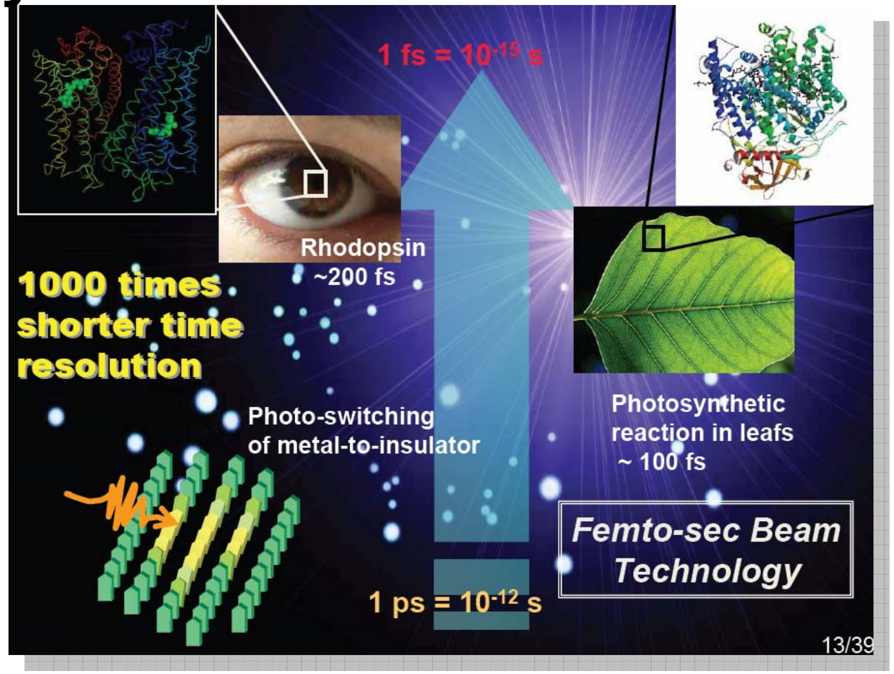
Beam Acceleration

* Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
* Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
* Many paths towards high gradient acceleration
  - High gradient microwave acceleration } ~100 MV/m
  - Acceleration with laser driven structures } ~1 GV/m
  - Acceleration with beam driven structures } ~1 GV/m
  - Acceleration with laser driven plasmas } ~10 GV/m
  - Acceleration with beam driven plasmas } ~10 GV/m

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





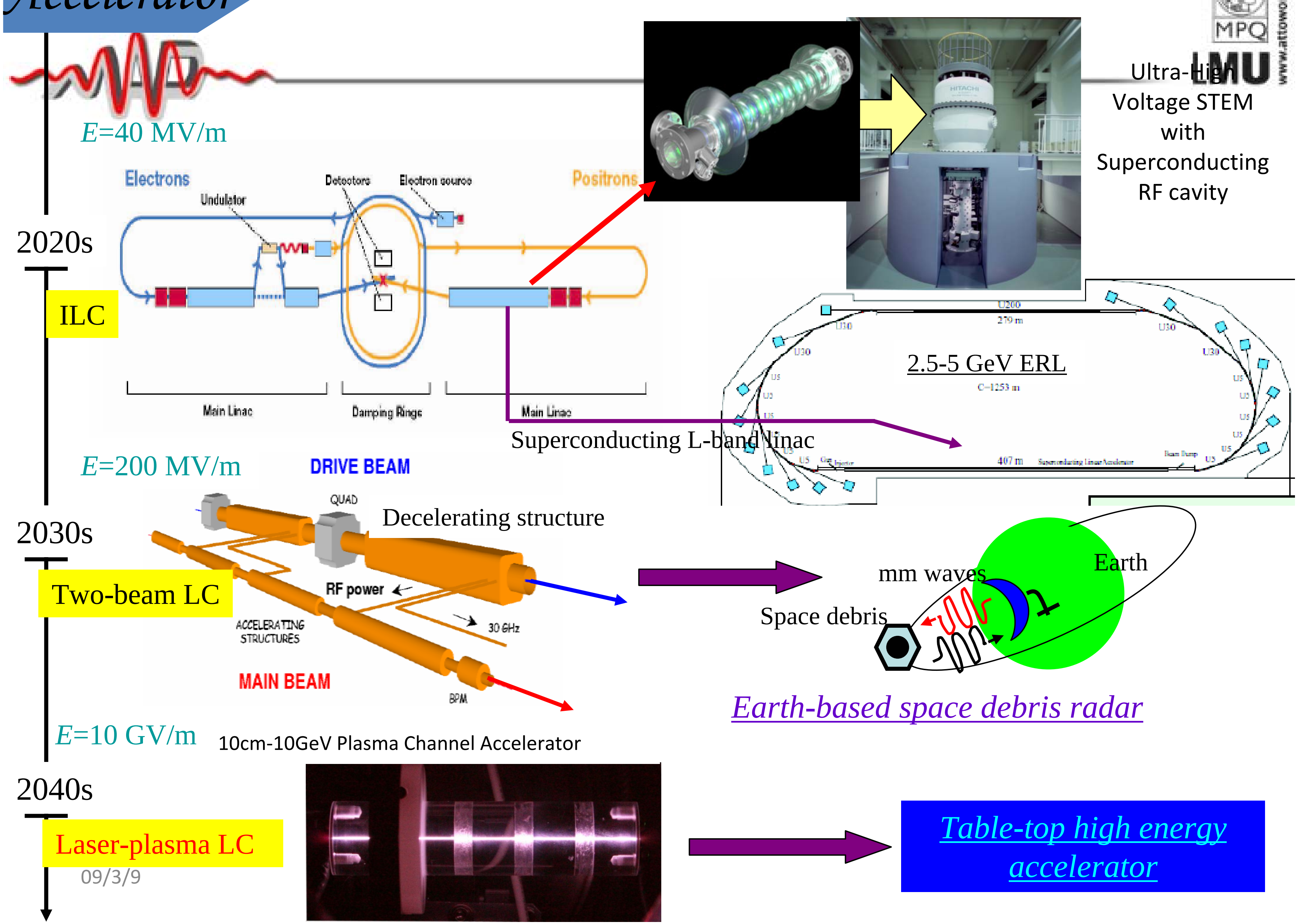
compact, ultrastrong *a*

atto-, zeptosecond

Can we meet the challenge?

A. Suzuki @KEK(2008)

Evolution of Accelerators and their Possibilities （Suzuki,2008)



Additional way preparing for the future in Fundamental Physics

- Collider paradigm ('high momentum' approach)
  quantum mechanics $\Delta E \Delta t \sim \hbar \rightarrow \mathscr{L} \propto E^2$
- Non-collider approaches ('high field' approach)
  relativity: the higher the energy, the pronounced the effect
    horizon ~ 1/ *a* (extradimensions?)
    a = *g* (Einstein's Equivalence Principle)?
    Unruh(a)-Hawking(g) radiation?
    special theory (*no preferred frame*? ; c(ε)?)
    extreme field physics (merger of research on special and general theories of relativity; Can E also warp space; $c(|E|^2)$)
    what is vacuum? (QED, QCD(axion), dark energy,…)

(Gies, Marlund, Di Piazza, Dunne, Schuetshold, Heinzl, Reiss, DeKieviert, Rafelski, Zayakin, Smilga, Cohen, Thirolf, Weinfurter, Labun,.. discussed)

Quantum Gravity:

“Why is the sky blue?”

(for extreme high energy gamma rays)

- Amelino-Camelia et al., Nature (1998)

  high energy γ has dispersion:

  $\omega = kc$ + (extra mass-like term?), i.e. $c(\varepsilon)$
- May be regarded as scattering off quantum fluctuations of vacuum (gravitational origin).
- Other proposals, such as H. Sato (1972); Coleman-Glashow(1997), ….

  breakdown of Lorentz invariance?

  (cosmic γ rays cease to exist beyond certain energy)

May be testable in PeV energy regimes.

Special theory of relativity OK?

doi:10.1038/nature08574

nature

LETTERS

A limit on the variation of the speed of light arising from quantum gravity effects

A list of authors and their affiliations appears at the end of the paper

A cornerstone of Einstein's special relativity is Lorentz invariance—the postulate that all observers measure exactly the same speed of light in vacuum, independent of photon-energy. While special relativity assumes that there is no fundamental length-scale associated with such invariance, there is a fundamental scale (the Planck scale, $l_{\rm Planck} \approx 1.62 \times 10^{-33}$ cm or $E_{\rm Planck} = M_{\rm Planck}c^2 \approx 1.22 \times 10^{19}$ GeV), at which quantum effects are expected to strongly affect the nature of space–time. There is great interest in the (not yet validated) idea that Lorentz invariance might break near the Planck scale. A key test of such violation of Lorentz invariance is a possible variation of photon speed with energy[1–7]. Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in γ-ray burst (GRB) light-curves[2]. Here we report the detection of emission up to ~31 GeV from the distant and short GRB 090510. We find no evidence for

scale (when $E_{\rm ph}$ becomes comparable to $E_{\rm Planck} = M_{\rm Planck}c^2$). For $E_{\rm ph} \ll E_{\rm Planck}$, the leading term in a Taylor series expansion of the classical dispersion relation is $|v_{\rm ph}/c - 1| \approx (E_{\rm ph}/M_{{\rm QG},n}c^2)^n$, where $M_{{\rm QG},n}$ is the quantum gravity mass for order n and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm(\Delta E/M_{\rm QG,1}c^2)D/c$ in the arrival time of photons emitted together at a distance D from us, and differing by $\Delta E = E_{\rm high} - E_{\rm low}$. At cosmological distances this simple expression is somewhat modified (see Supplementary Information section 4).

Because of their short duration (typically with short substructure consisting of pulses or narrow spikes) and cosmological distances, GRBs are well-suited for constraining LIV[2,11,12]. Individual spikes in long[13] (of duration >2 s) GRB light-curves (10–1,000 keV) usually show[14] intrinsic lags: the peak of a spike occurs earlier at higher photon-energies. However, there are either no lags or very short lags

(Abdo et al, 2009)

γ -ray signal (GRB) from primordial GRB

LETTERS NATURE

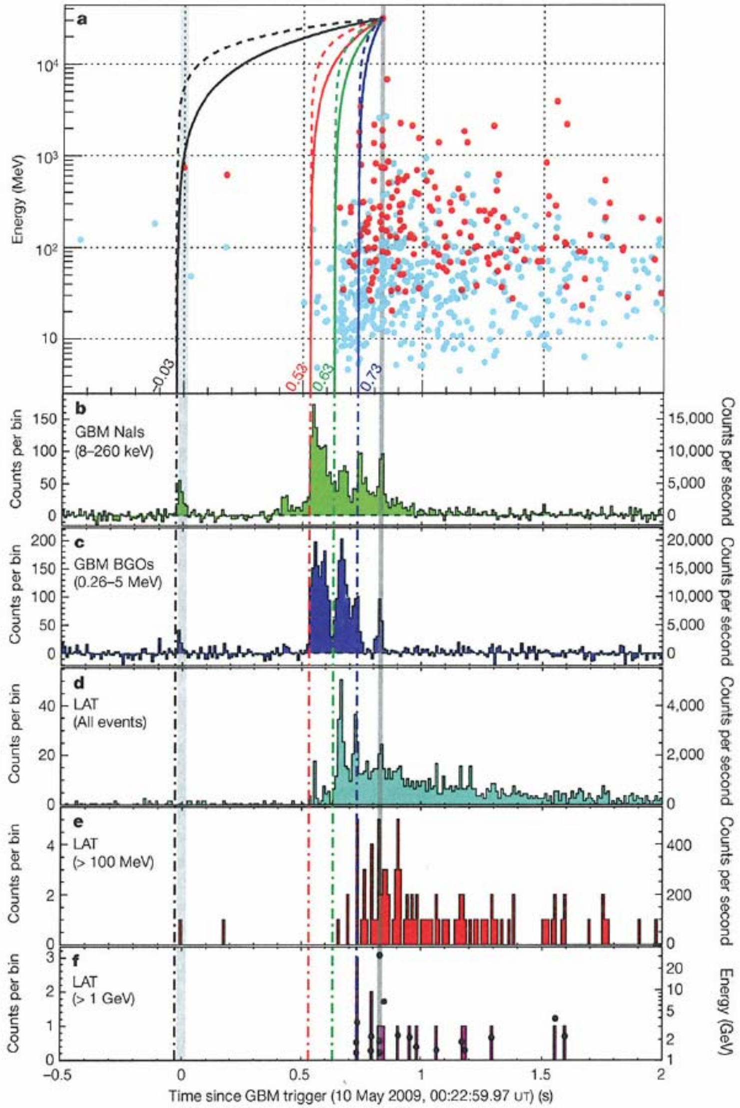


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy … lowest to highest energies. **f** also overlays energy versus arrival time for each

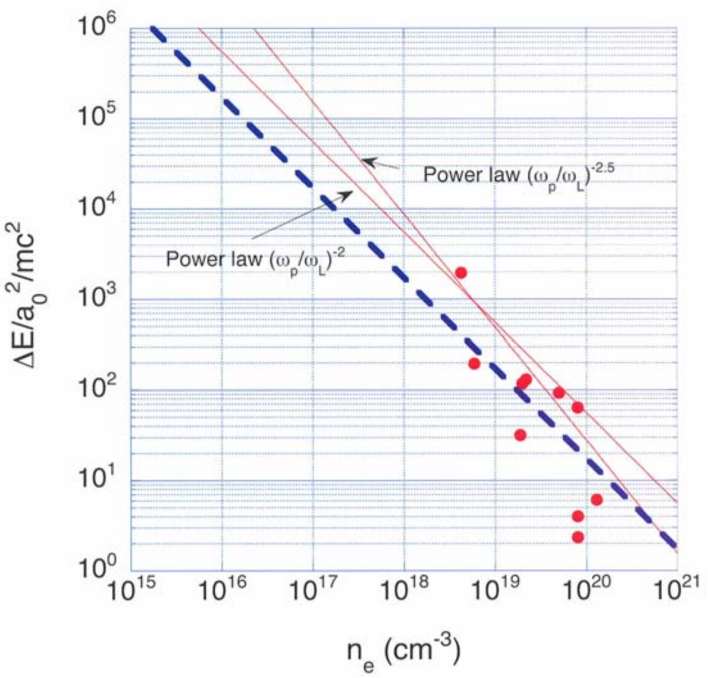
(Abdo, eta l, 2009)

Energy-dependent
Photon mass?
limit is pushed up
to near Planck mass

PeV γ (from e-)
Can explore this

Meeting Suzuki's Challenge toward PeV

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}{}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)

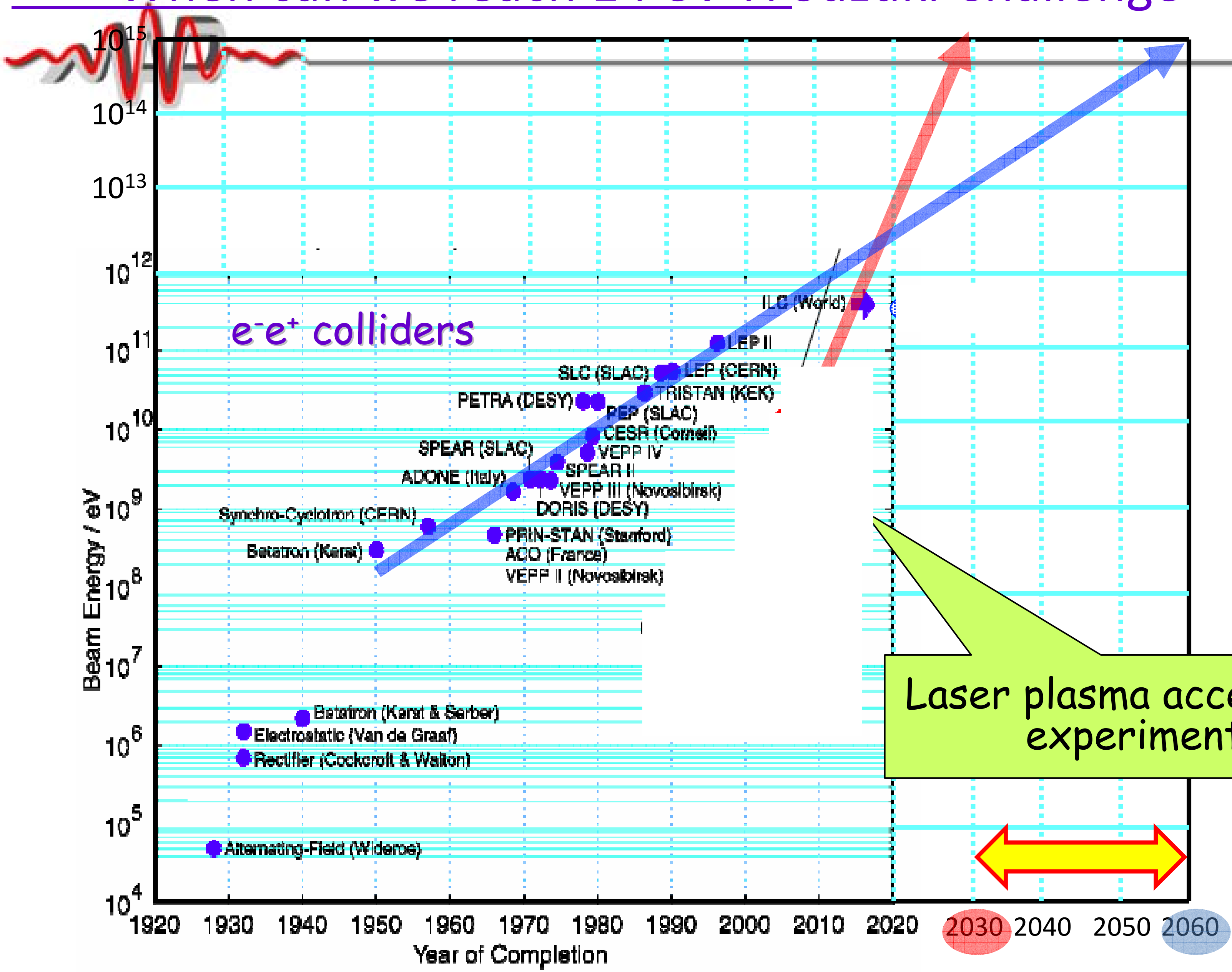


$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right), \qquad L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

		case I	case II	case III
a_0		10	3.2	1
energy gain	GeV	1000	1000	1000
plasma density	cm^{-3}	5.7×10^{16}	5.7×10^{15}	5.7×10^{14}
acceleration length	m	2.9	29	290
spot radius	μm	32	100	320
peak power	PW	2.2	2.2	2.2
pulse duration	ps	0.23	0.74	2.3
laser pulse energy	kJ	0.5	1.6	5

Even 1PeV electrons (and γ s) are possible, albeit with lesser amount
→ exploration of new physics such as the **reach of relativity** and quantum gravity (correlating with primordial gamma-ray burst [GRB] observation)?
(laser energy of 10MJ@plasma density of 10^{16}/cc; maybe reduced with index 5/4)

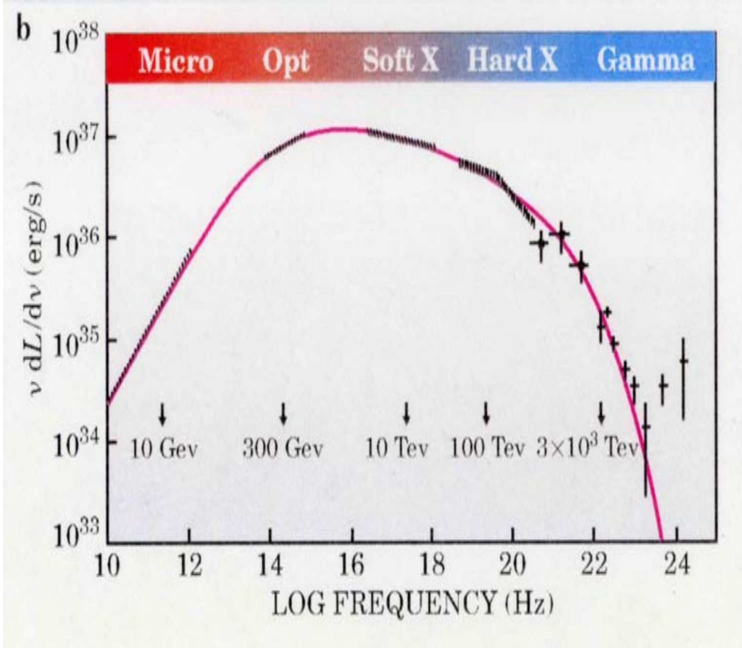
When can we reach 1 PeV ?: Suzuki Challenge



(Suzuki, 2009)

V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

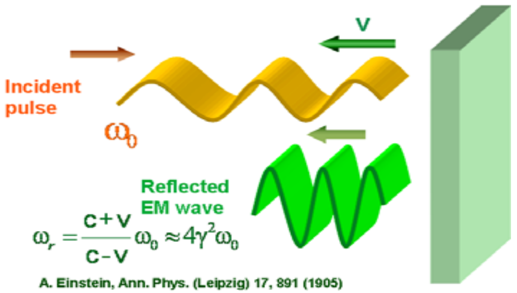
PeV γ from Crab Nebula

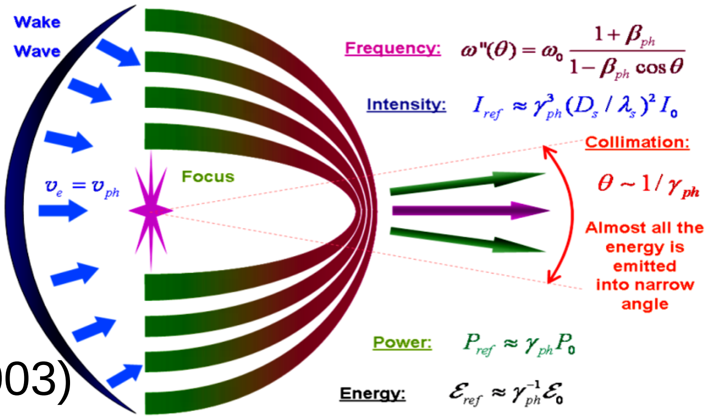


Can we see manifestation of quantum gravity, Lorentz variance in high energy γ?
How PeV electrons accelerated?

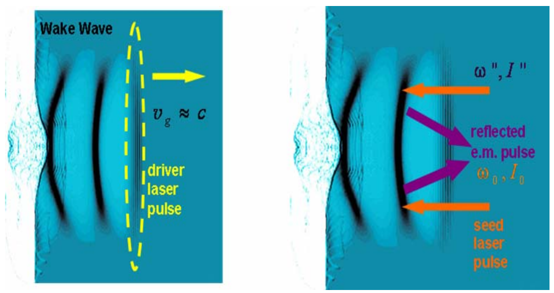
The Crab Pulsar, a city-sized, magnetized neutron star spinning 30 times a second, lies at the center of this composite image of the inner region of the well-known Crab Nebula. The spectacular picture combines optical data (red) from the Hubble Space Telescope and x-ray images (blue) from the Chandra Observatory, also used in the popular Crab Pulsar movies. Like a cosmic dynamo the pulsar powers the x-ray and optical emission from the nebula, accelerating charged particles and producing the eerie, glowing x-ray jets. Ring-like structures are x-ray emitting regions where the high energy particles slam into the nebular material.

EM Pulse Intensification and Shortening by the Flying Mirror toward the Schwinger field

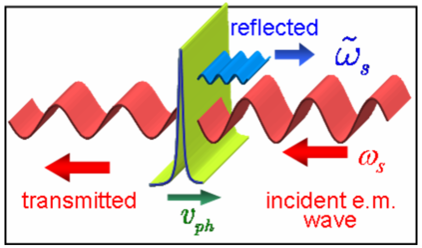




(Bulanov, Esirkepov, Tajima, 2003)

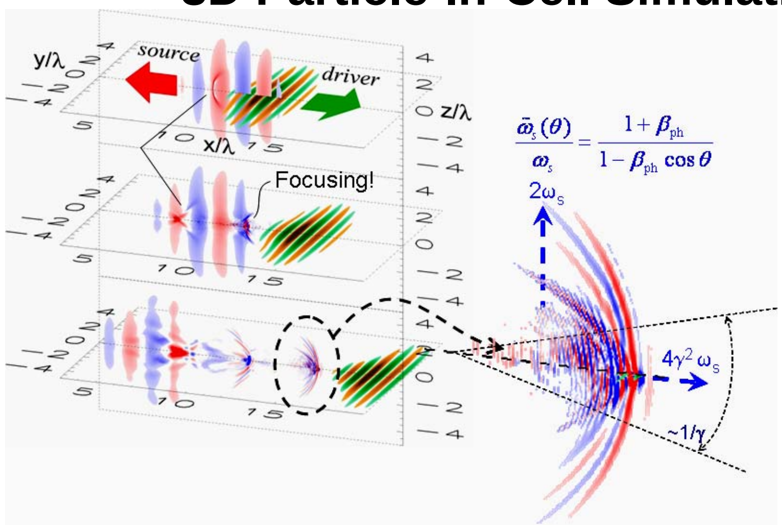


$$\omega'' = \frac{c+v_{ph}}{c-v_{ph}}\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{max}}{I_0} \approx \kappa\,\gamma_{ph}^6 \left(\frac{D}{\lambda}\right)^2$$



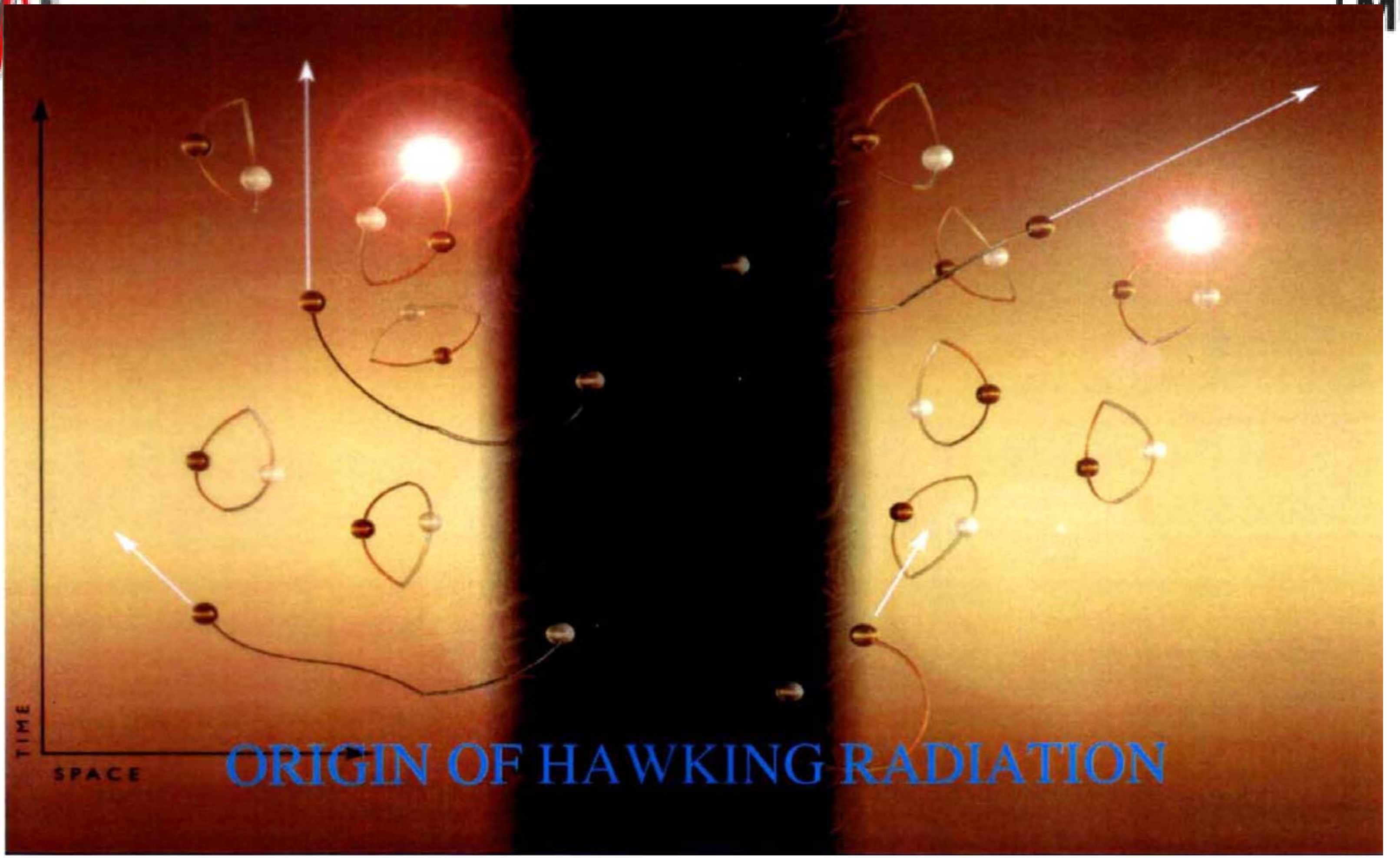
$$\kappa \sim \gamma_{ph}^{-3}$$

3D Particle-In-Cell Simulation



A lot of ideas for new attosecond pulses

Hawking radiation



What is ‘vacuum’? Does ‘something’ emerge from ‘nothing’?

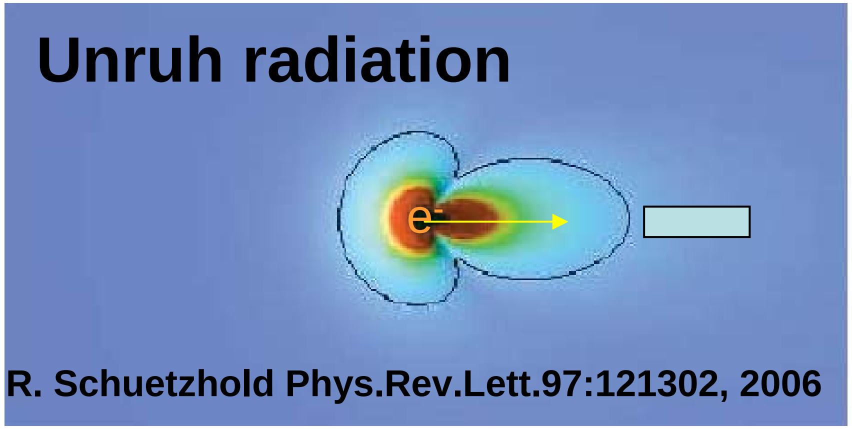
「空」＝「色」？　　「混沌」⇔「秩序」？

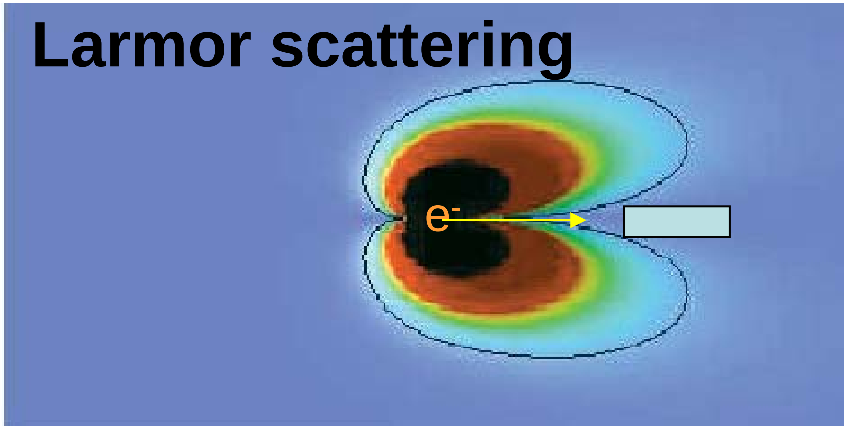
vacuum = ‘matter‘ ?　　chaos ⇔ information ?

Explore relativity with strong fields（Unruh radiation）

$I = 10^{17}[W/cm^2] \Rightarrow E \approx 10^{12}[V/m]$ (Chen, Tajima,1999)

$\Rightarrow k_B T = 0.06eV \Rightarrow$ **~10eV (blue shift in lab. frame)**

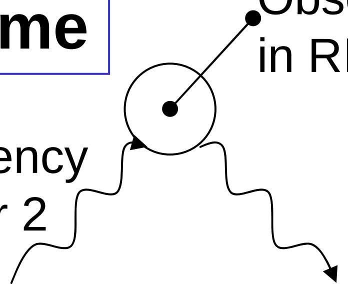




Rindler frame

Observer
in RIndler 1

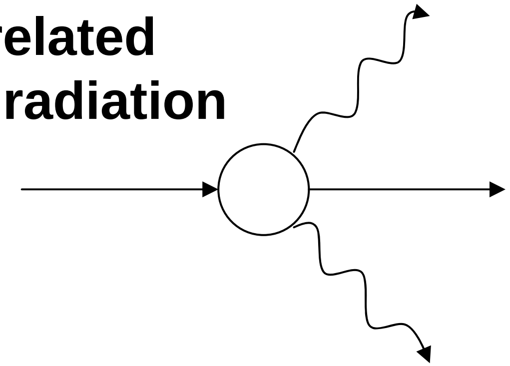
negative frequency
mode in Rinder 2



Strong correlation between absorption and emission despite of causal disconnection

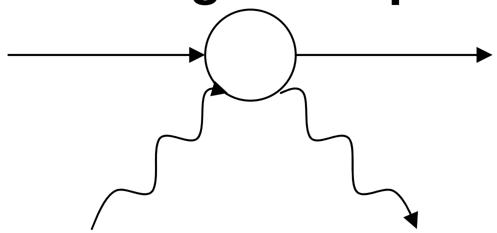
G. Unruh PRD 29 1047-1056, 1984

Correlated pair radiation

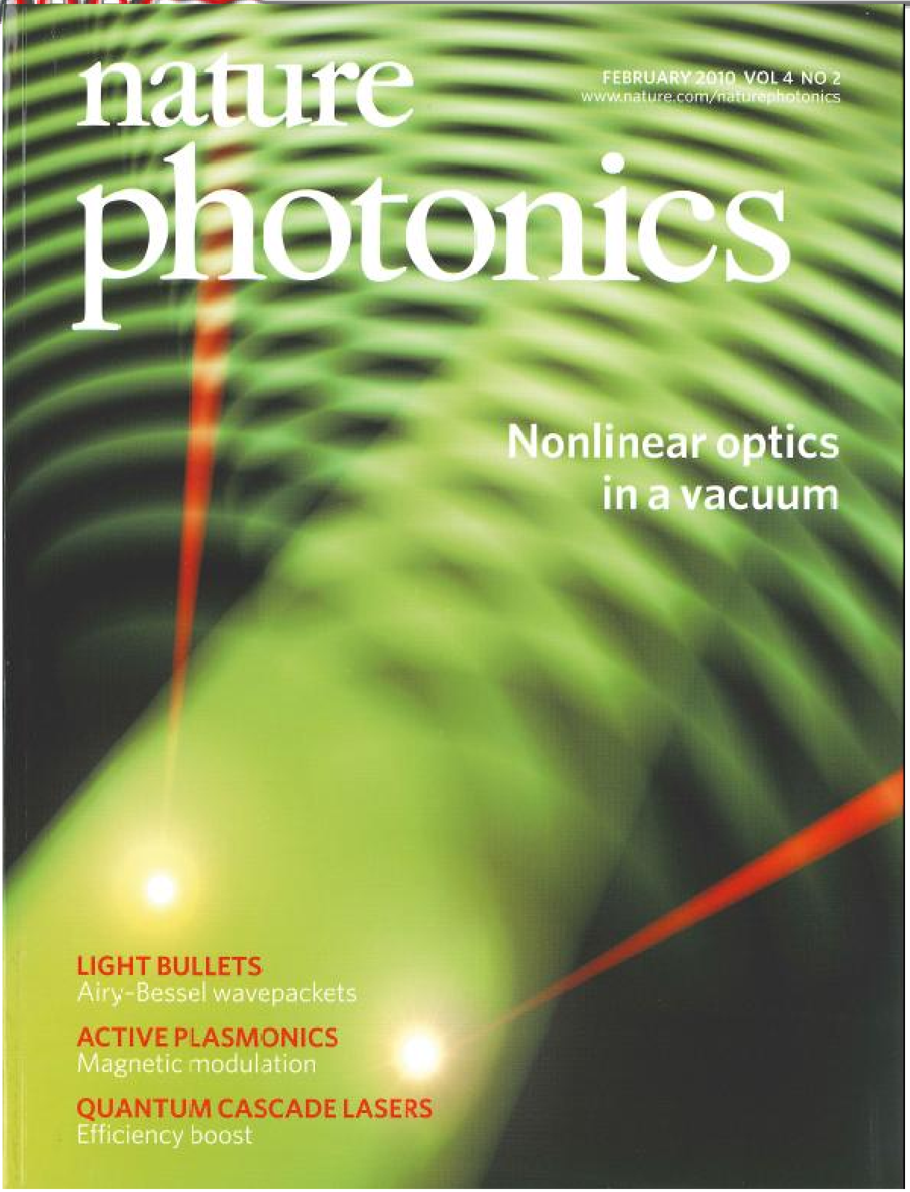


Inertial frame

No correlated pair in background process



Nonlinear Optics in vacuum



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

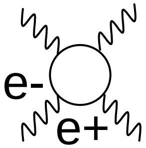
B. King, A. Di Piazza and C. H. Keitel, Nature Photon. **4**, 92 (2010)

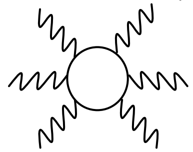
Higher order QED and QCD

hep-ph/9806389

Euler-Heisenberg effective action in constant Abelian field U(1) can be expressed as

$$L^{1-loop}{}_{LO+NLO}(A_\mu) = -\frac{1}{90}\frac{\pi^2}{m^4}\left[(\frac{\alpha}{\pi}F^2)^2 + \frac{7}{4}(\frac{\alpha}{\pi}F\tilde{F})^2\right] + \frac{1}{315}\frac{\pi^4}{m^8}\left[4(\frac{\alpha}{\pi}F^2)^3 + \frac{13}{2}\frac{\alpha}{\pi}F^2(\frac{\alpha}{\pi}F\tilde{F})^2\right] +$$





If U(1)→U(1) + condensed SU(3) due to self-interacting attractive force of gluons

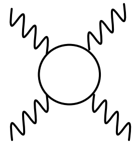
$$\frac{\alpha}{\pi}F^2 \rightarrow \left\langle \frac{\alpha_s}{\pi}G^2 \right\rangle + \frac{\alpha}{\pi}q^2F^2 \qquad \langle 0|\frac{\alpha_s}{\pi}G^2|0\rangle \approx (2.3 \pm 0.3)10^{-2}GeV^4$$

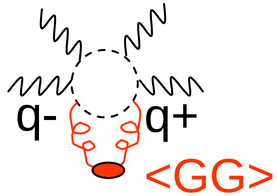
(K.Homma, 2007)

Focus on only light-light scattering amplitude after the substitution

$$L^{1-loop}{}_{LO+NLO}(A_\mu + G^a{}_{\mu\nu}) = -\frac{1}{90}\frac{\pi^2}{m^4}\left[(\frac{\alpha}{\pi}F^2)^2 + \frac{7}{4}(\frac{\alpha}{\pi}F\tilde{F})^2\right]$$

$$+\sum_{i=u,d}\frac{1}{315}\frac{q_i^2\pi^4}{m_i^8}\left[12(\frac{\alpha}{\pi}F^2)^2\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle + \frac{13}{2}(\frac{\alpha}{\pi}F\tilde{F})^2\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle\right]$$





QCD effect dominates pure QED 1-loop vacuum polarization to light-light scattering

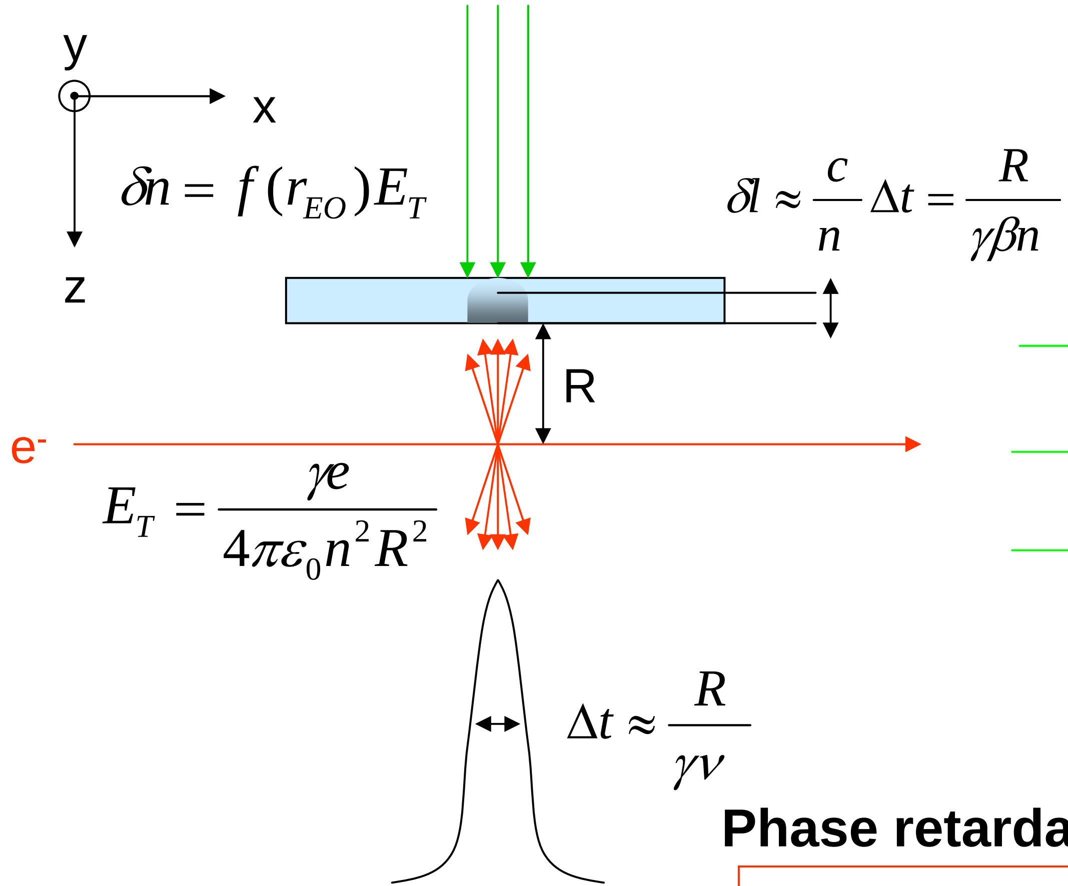
$$\frac{2nd-term}{1st-term} = \sum_{i=u,d}\frac{24}{7}\frac{q_i^2\pi^4}{m_i^8}m^4{}_e\left\langle\frac{\alpha}{\pi}G^2\right\rangle \approx e^{9\pm2.5} \qquad m_u \approx \frac{1}{2}m_d \approx 5\pm1.5MeV, q_u{}^2 = 4q_d{}^2 = \frac{4}{9}$$

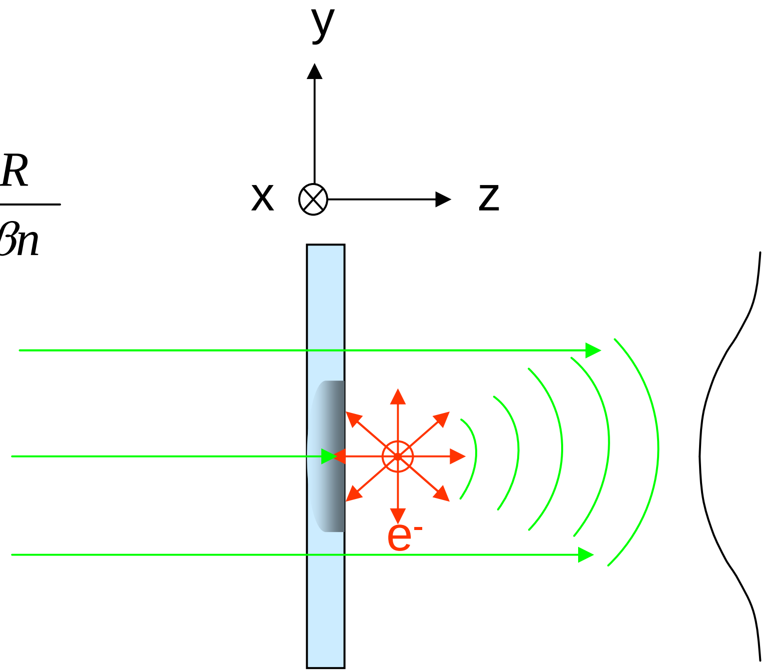
Check of Euler-Heisenberg yet to come. Any deviation from it?

→ axion field?; extended fields(such as dark energy, Tajima-Niu, 1997, etc.)?

Homma proposes: experimental test

Measure instantaneous variation of refractive index in Electro-Optical crystal by external electric fields.





$$\Delta y \approx R \tan(\cos^{-1}(0.5)^{1/3})$$

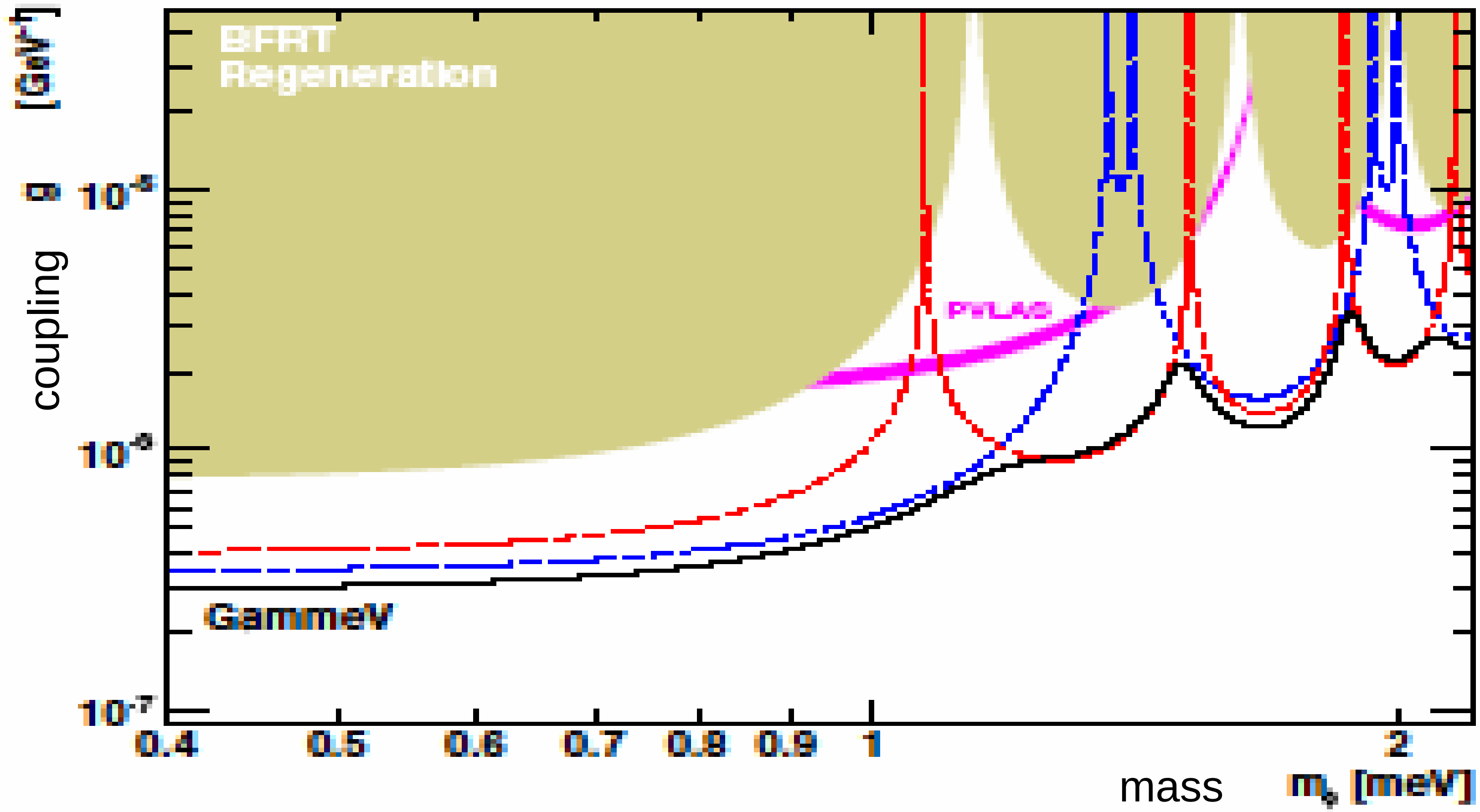
(Homma, 2007)

$$\Delta x \approx \frac{R}{\gamma}$$

Phase retardation

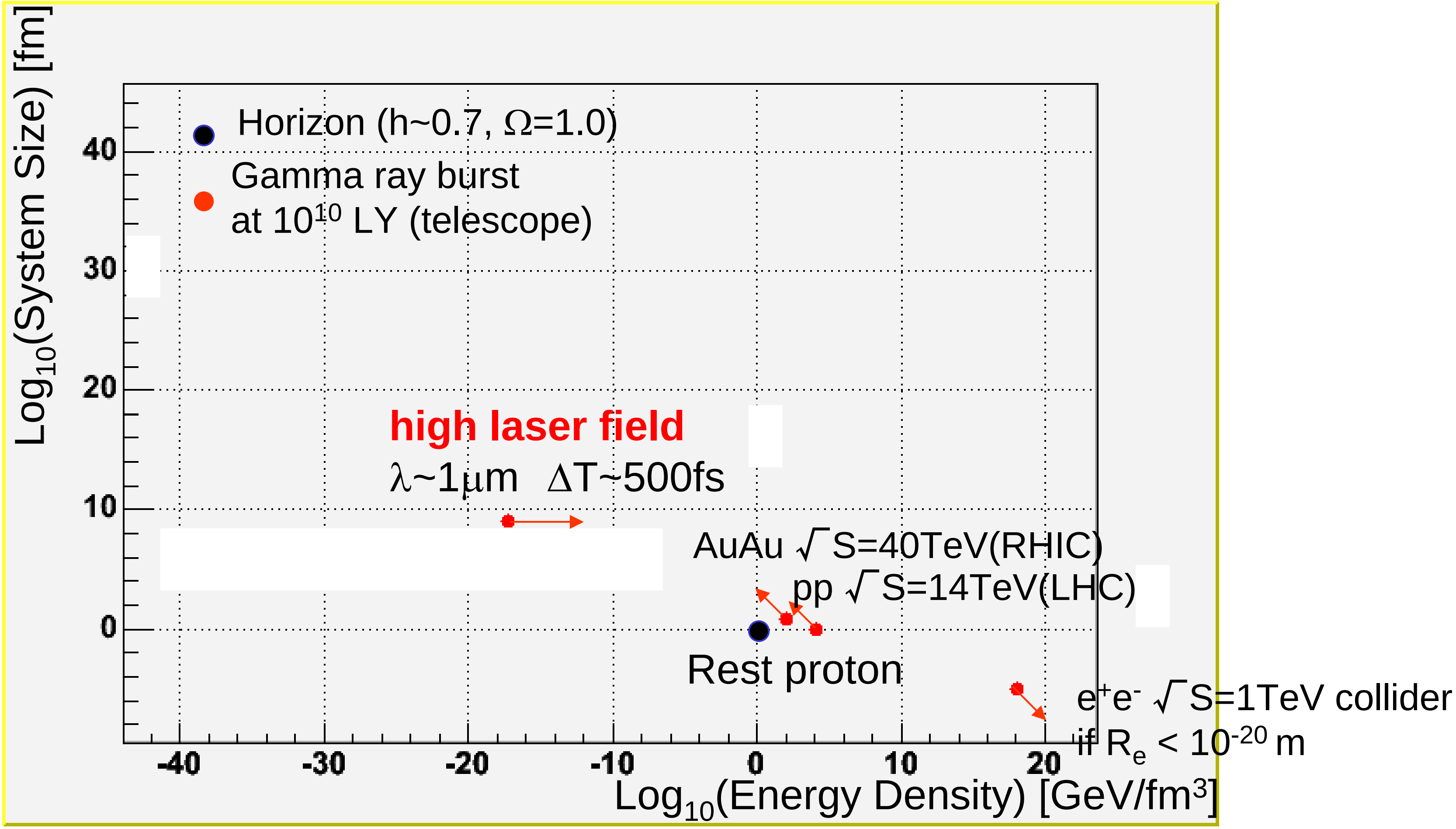
$$\delta\Gamma = \frac{2\pi}{\lambda}\delta n \delta l = \frac{f(r_{EO})}{2\varepsilon_0 n^3}\frac{e}{\lambda\beta R}$$

Detection of (light) fields-particles missed by collider: exploring new fields such as axion……



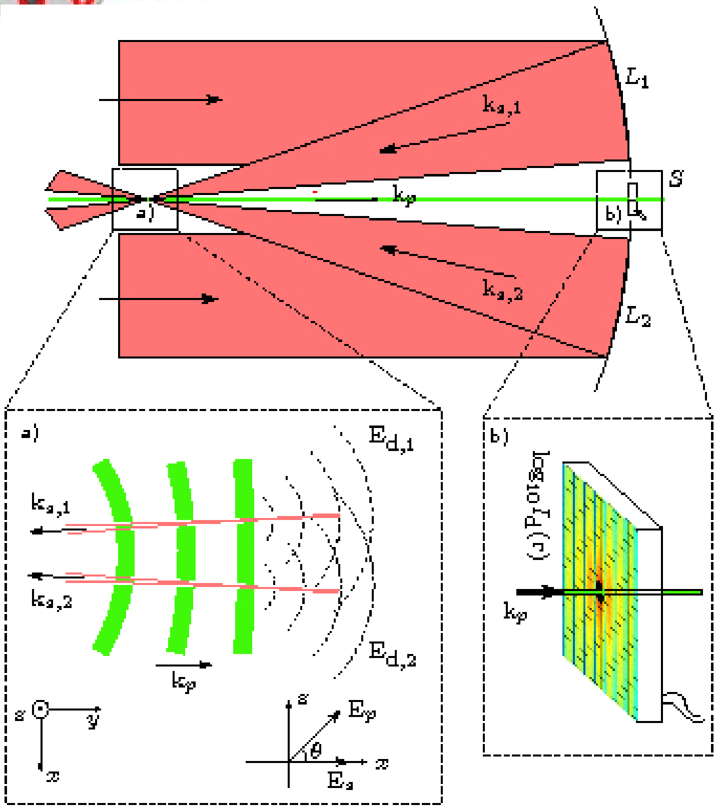
A.Chou et al.,PRL (2008) observed no signal so far (Note:claim of axion by PVLAS was withdrawn)

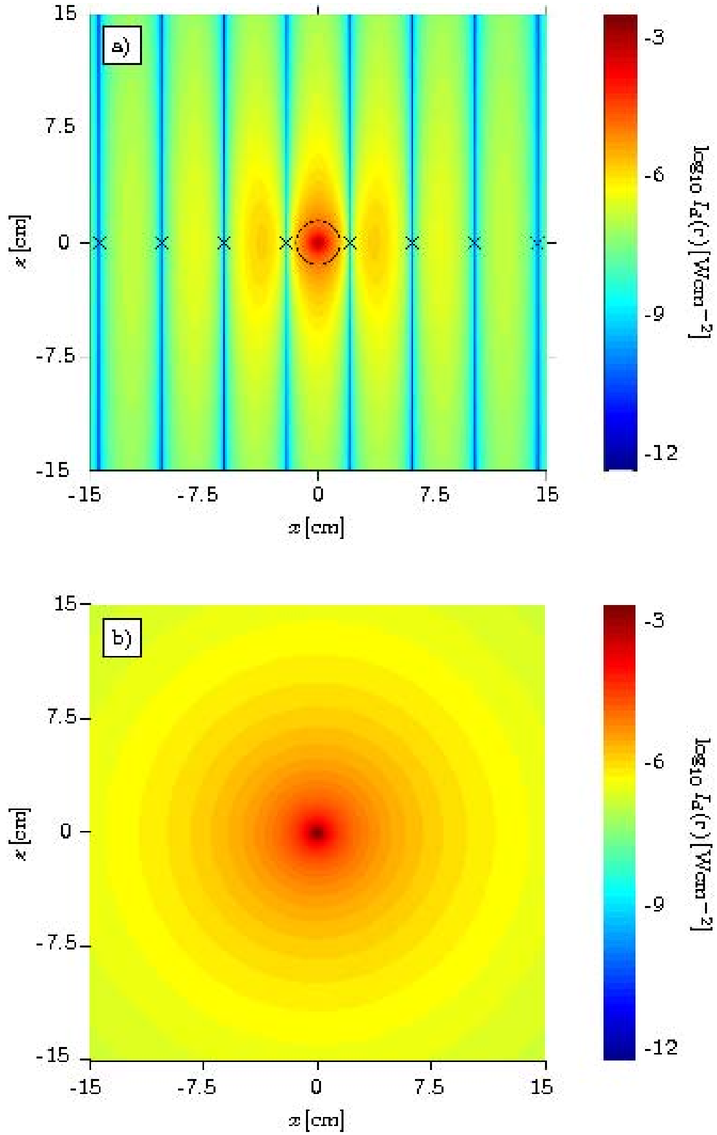
High Field Science
and other (telescope, collider) approaches



(K.Homma)

High amplitude photon-photon interaction





B. King et al., Nature Photon. 4, 92(2010)

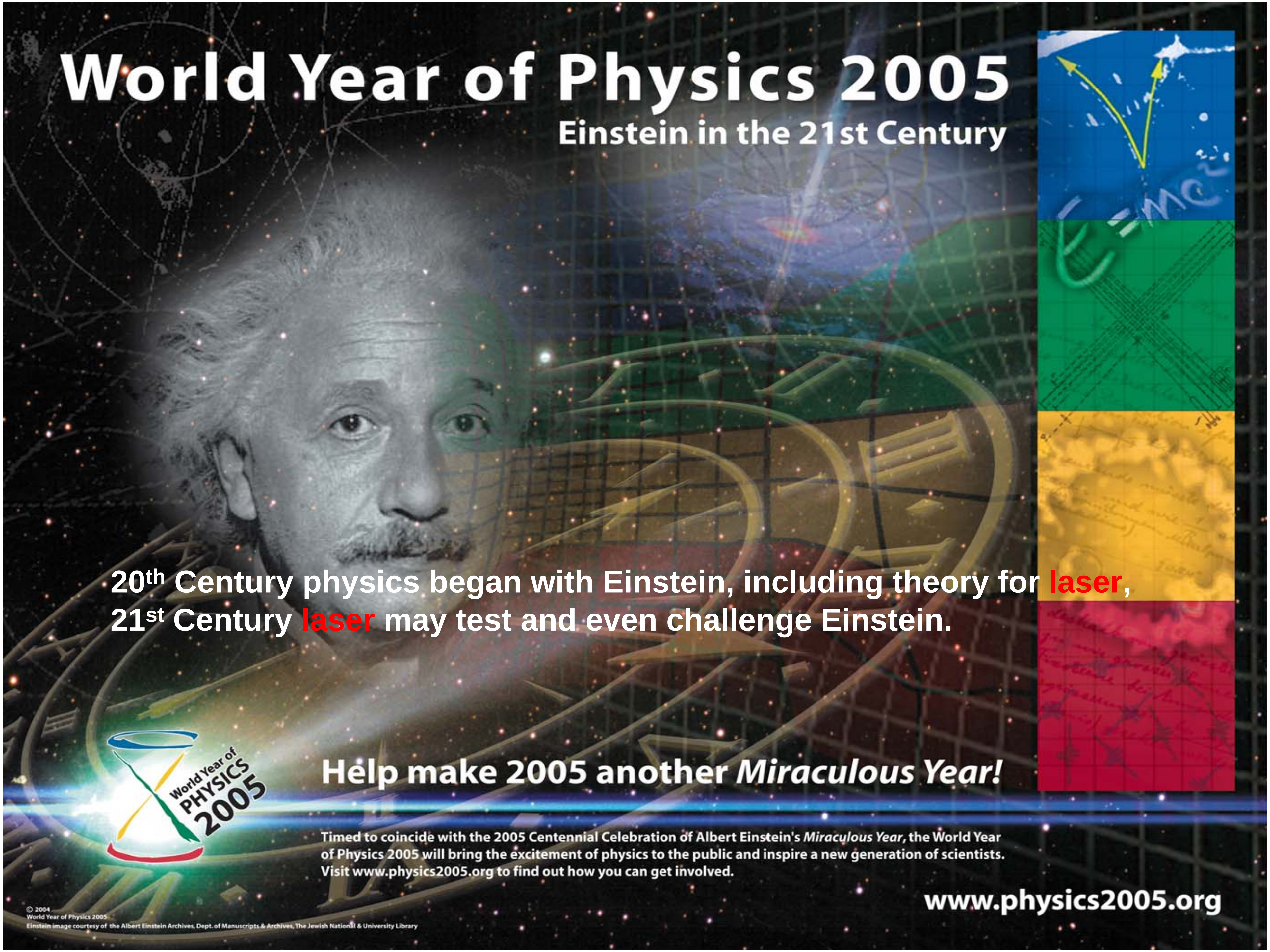
High Field Science from an ELI Workshop talk

Conclusions

▷ Why strong-field physics . . . ?

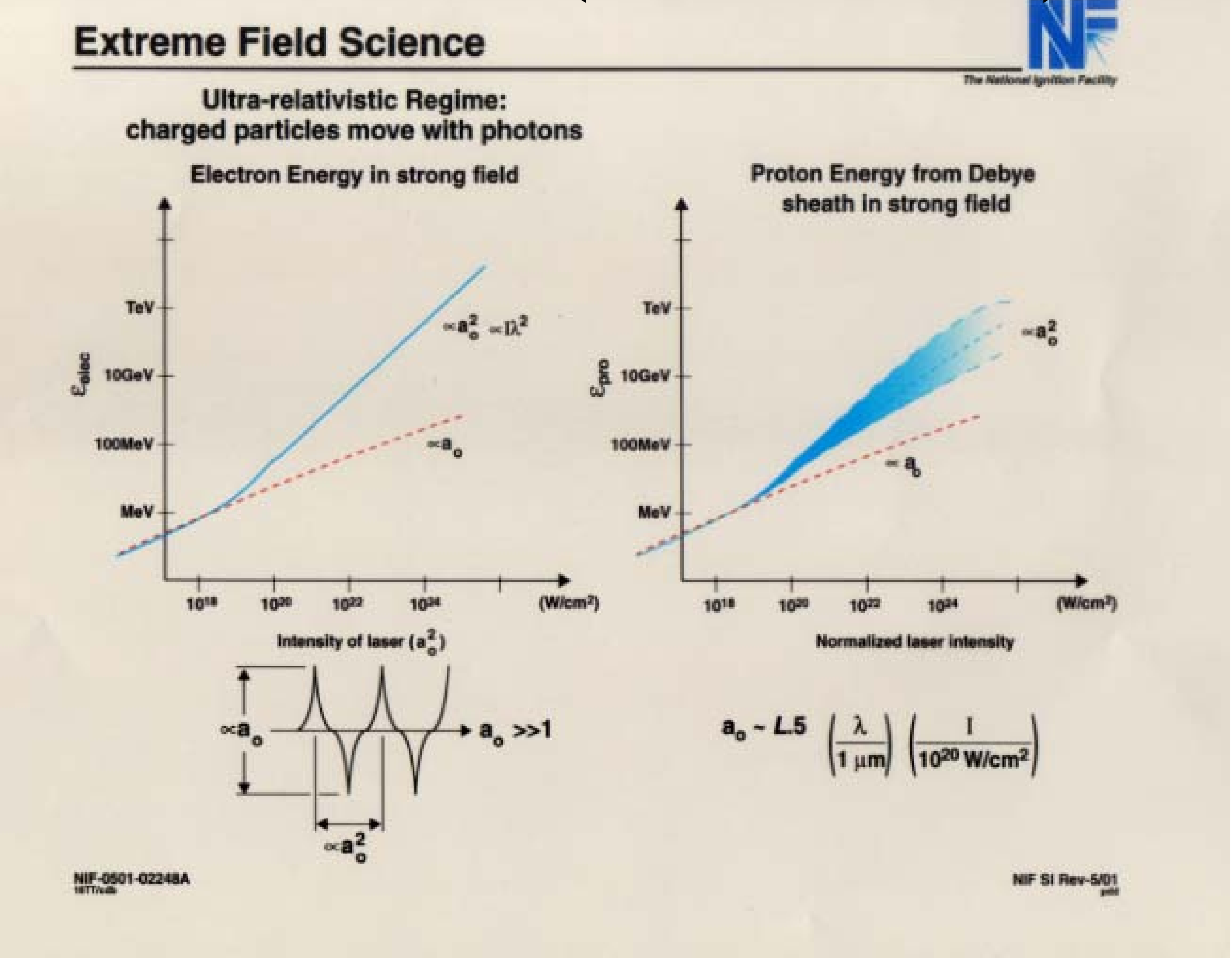
- " . . .exploring some issues of fundamental physics that have eluded man's probing so far" (TAJIMA'01)
- QFT: high energy (momentum) vs. high amplitude
- "Fundamental-Physics" discovery potential:
  - ALPs: hypothetical NG bosons (axion, majoron, familon, etc.)
  - MCPs: minicharged particles
  - paraphotons
  - sub-millimeter forces
  - . . .
- high physics/costs ratio

(H. Gies discussed
at Extreme Light Infrastructure (ELI)
Meeting, 2008)



20th Century physics began with Einstein, including theory for laser,
21st Century laser may test and even challenge Einstein.

Relativity Helps Acceleration (for Ions, too!)



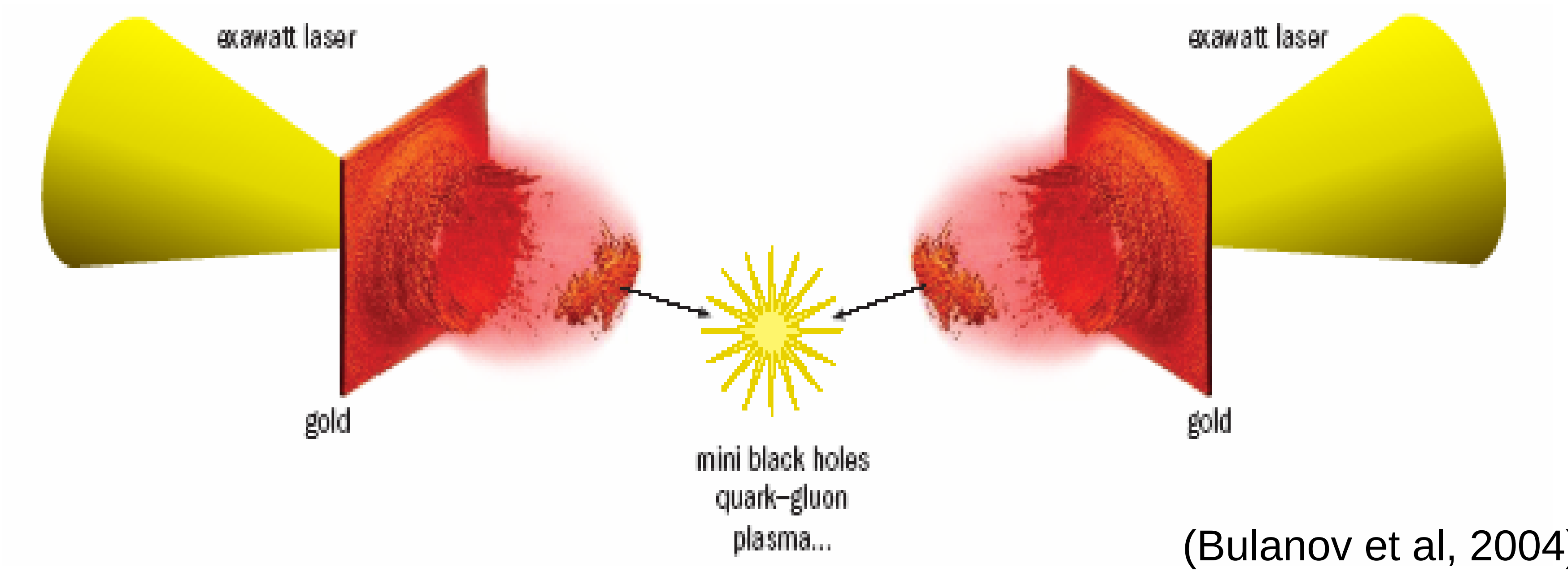
Strong fields:
rectifies laser
to longitudinal
fields

In relativistic regime,
photon x electrons
and even protons
couple stronger.

(Tajima, 1999 @LLNL; Esirkepov et al., PRL,2004)

Beyond laser intensity 10^{24}W/cm^2 ions move relativistically like e$^-$

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



(Bulanov et al, 2004)

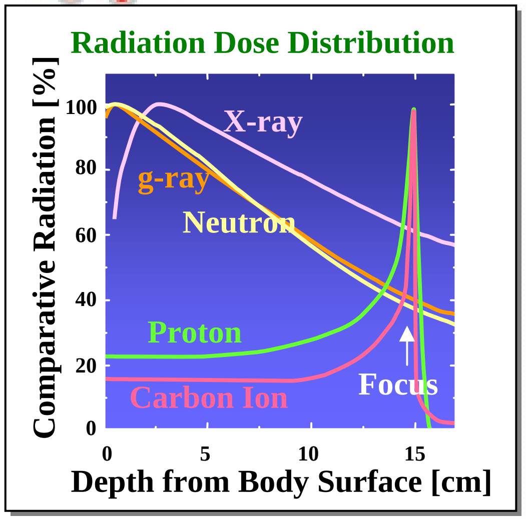
Societal impact and contributions

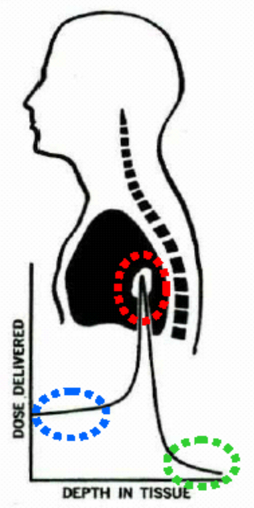
some examples:

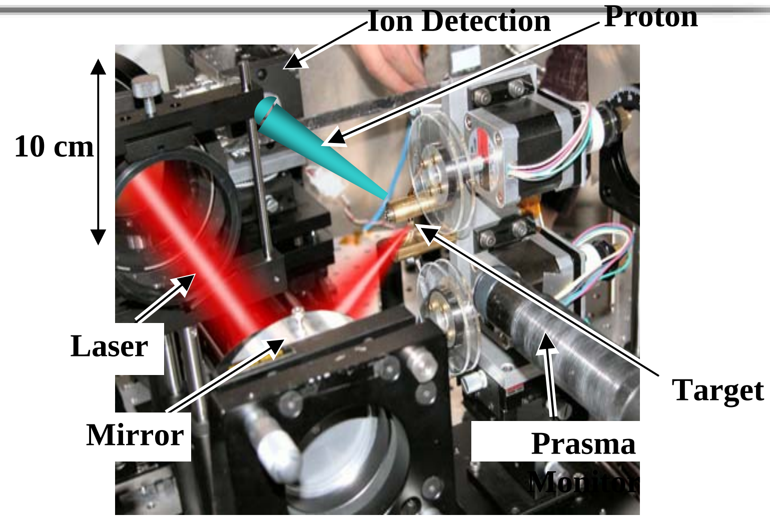
- Compact cancer hadron therapy devices (JAEA, LIBRA, SAPHIR, Dresden collaborations; will be discussed more)
- Intraoperative Radiation Therapy (IORT):

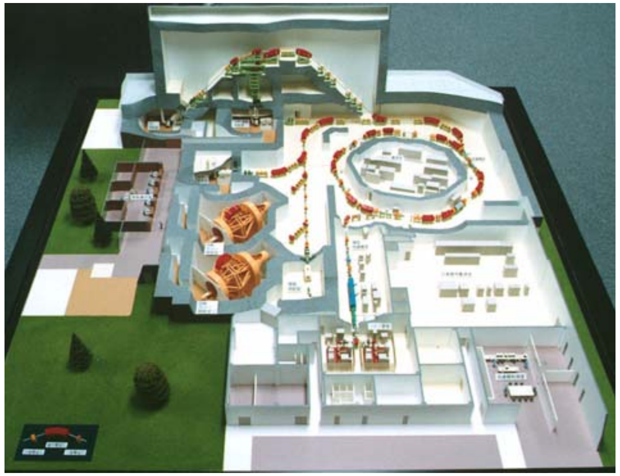
  INFN + CEA (Saclay)
- Untrafast radiolysis (LOA etc.)
- Injector for ultrabright X-ray sources (for medicine etc.) (LBL, MPQ etc.)

Compactification of Laser Ion Accelerator for Cancer Therapy

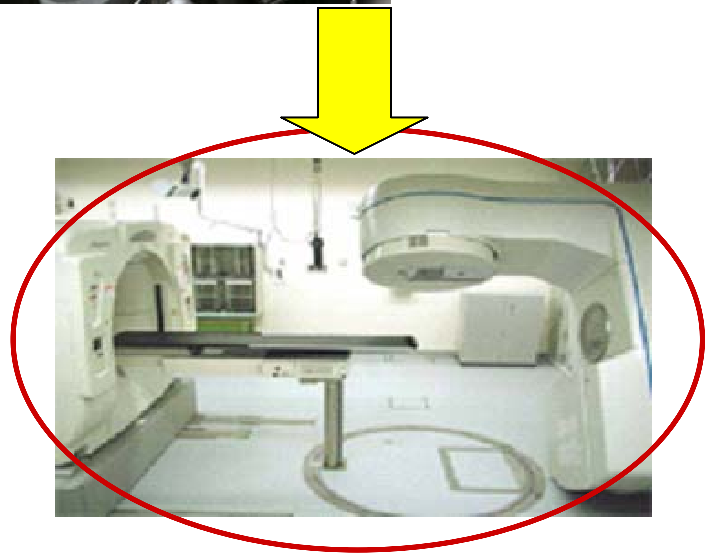








(Hyogo Ion Beam Medical Center)



Building Size,
> $ 100 M

Size Down
Cost Down

10m,
$ 10 M

Conclusions

- **Collective acceleration driven by intense laser:** leap by **many orders** (≥ 3) , GeV electrons; 10 GeV soon; 100GeV considered; TeV laser collider contemplated; PeV possible?
- High momentum approach vs high amplitude approach: high field science's new paradigm
- Test of Einstein's relativity (special and general theories), nonlinear QED (and QCD), high acceleration (=gravitational) physics, radiation dominant regime, quantum gravity, *nonlinear optics in vacuum*
- **Societal applications**: already beginning, soon to flourish (e.g., **cancer therapy**, radiolysis)
- Compact new paradigm of fundamental physics in 21st Century