Chaires internationales de recherche Blaise Pascal

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The Sixth Blaise Pascal Lecture
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Ecole Polytechnique

High Field Science

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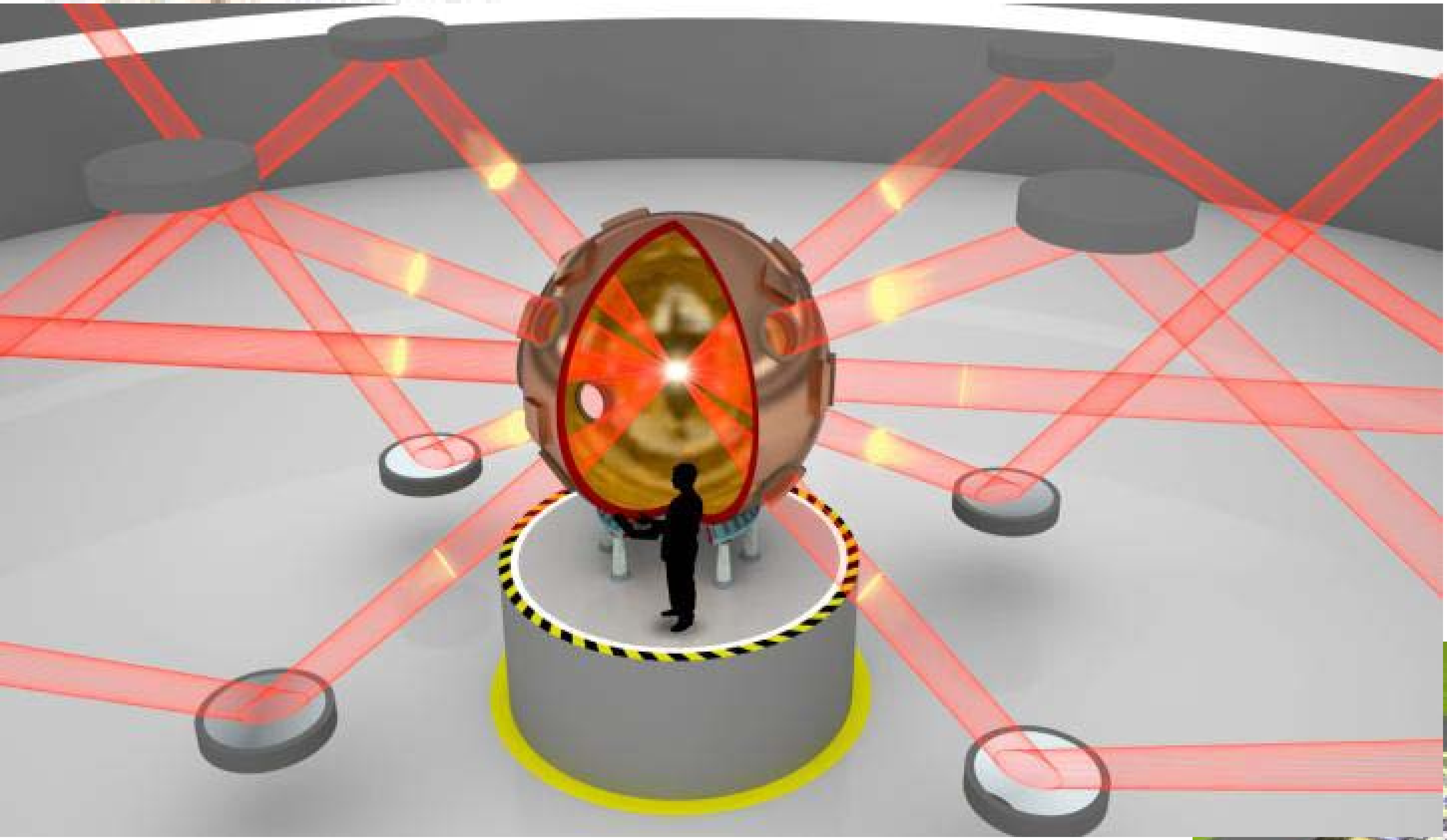
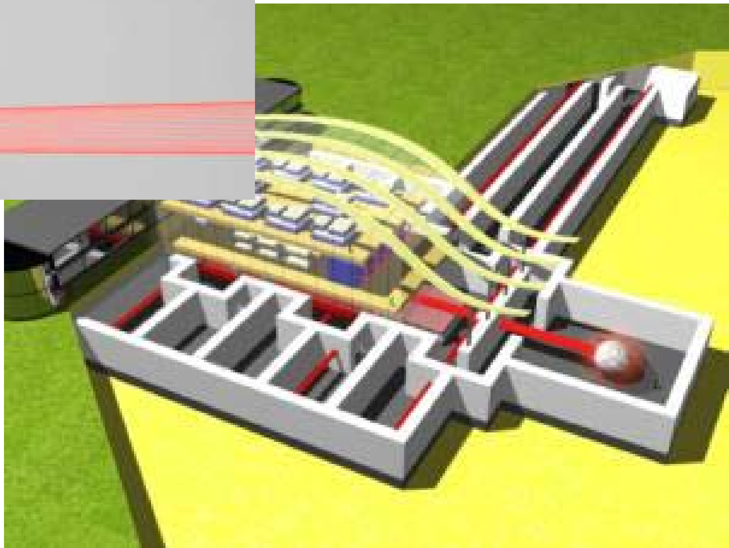
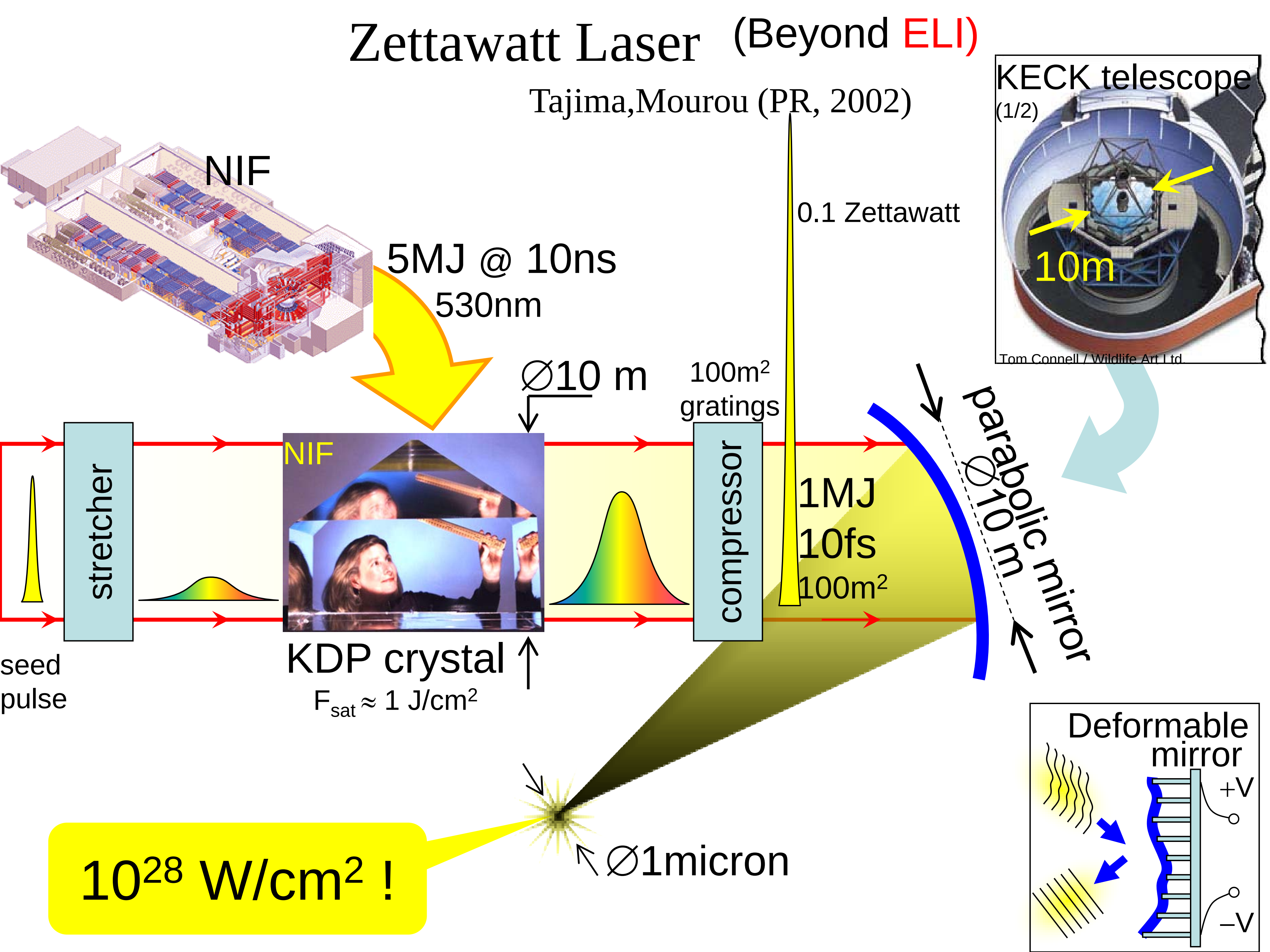
Extreme Light Infrastructure



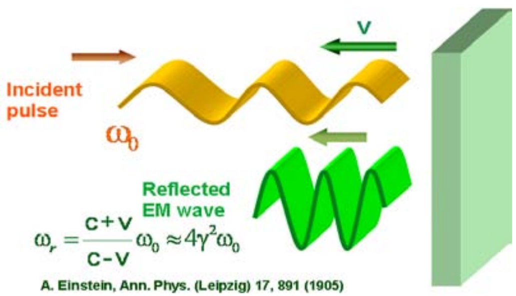


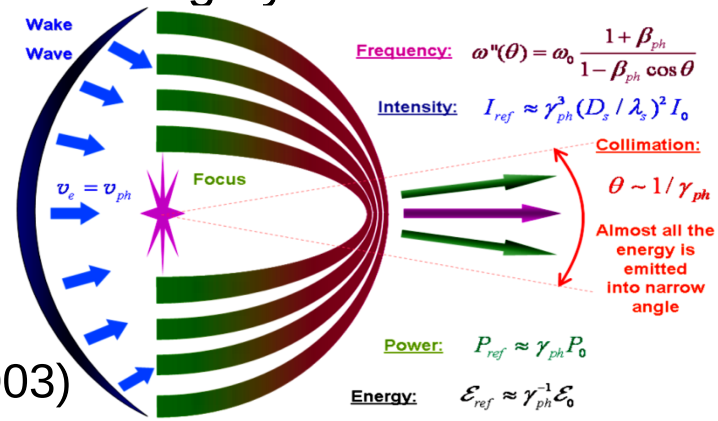


Zettawatt Laser (Beyond ELI)
Tajima,Mourou (PR, 2002)
NIF
5MJ @ 10ns
530nm
0.1 Zettawatt
KECK telescope
(1/2)
10m
Tom Connell / Wildlife Art Ltd.
∅10 m
100m²
gratings
NIF
stretcher
compressor
1MJ
10fs
100m²
parabolic mirror
∅10 m
seed
pulse
KDP crystal
F_sat ≈ 1 J/cm²
Deformable
mirror
+V
–V
∅1micron
10²⁸ W/cm² !

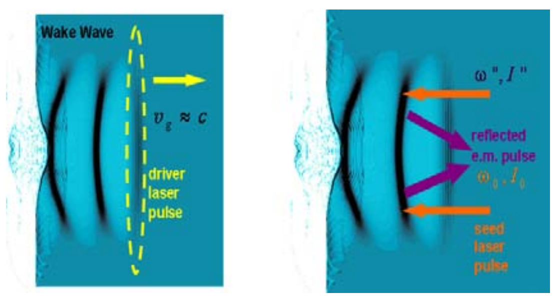
Relativistic Engineering: relativity as the guiding tool (cf. quantum engineering)

EM Pulse Intensification and Shortening by the Relativistic Mirror

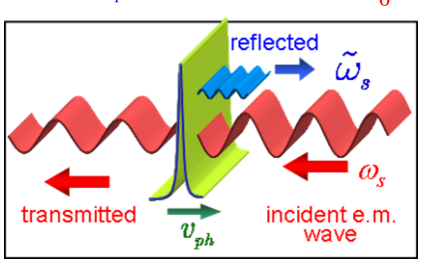




(Bulanov, Esirkepov, Tajima, 2003)

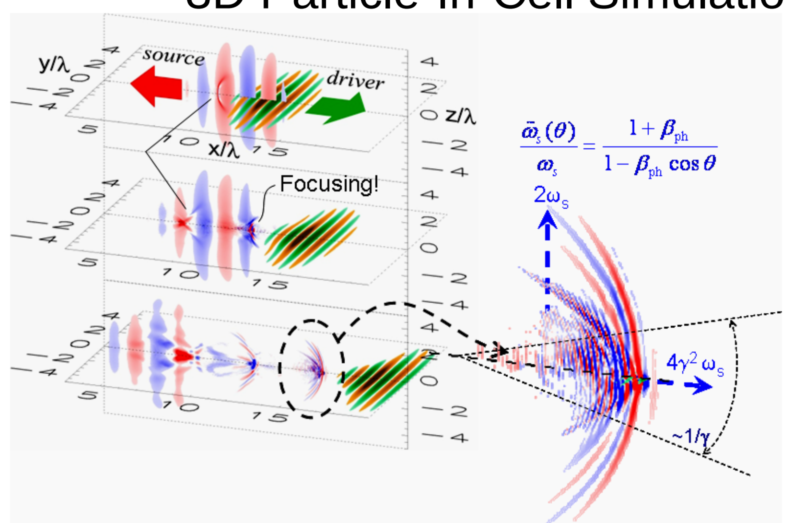


$$\omega'' = \frac{c + v_{ph}}{c - v_{ph}}\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{max}}{I_0} \approx \kappa\,\gamma_{ph}^6\left(\frac{D}{\lambda}\right)^2$$

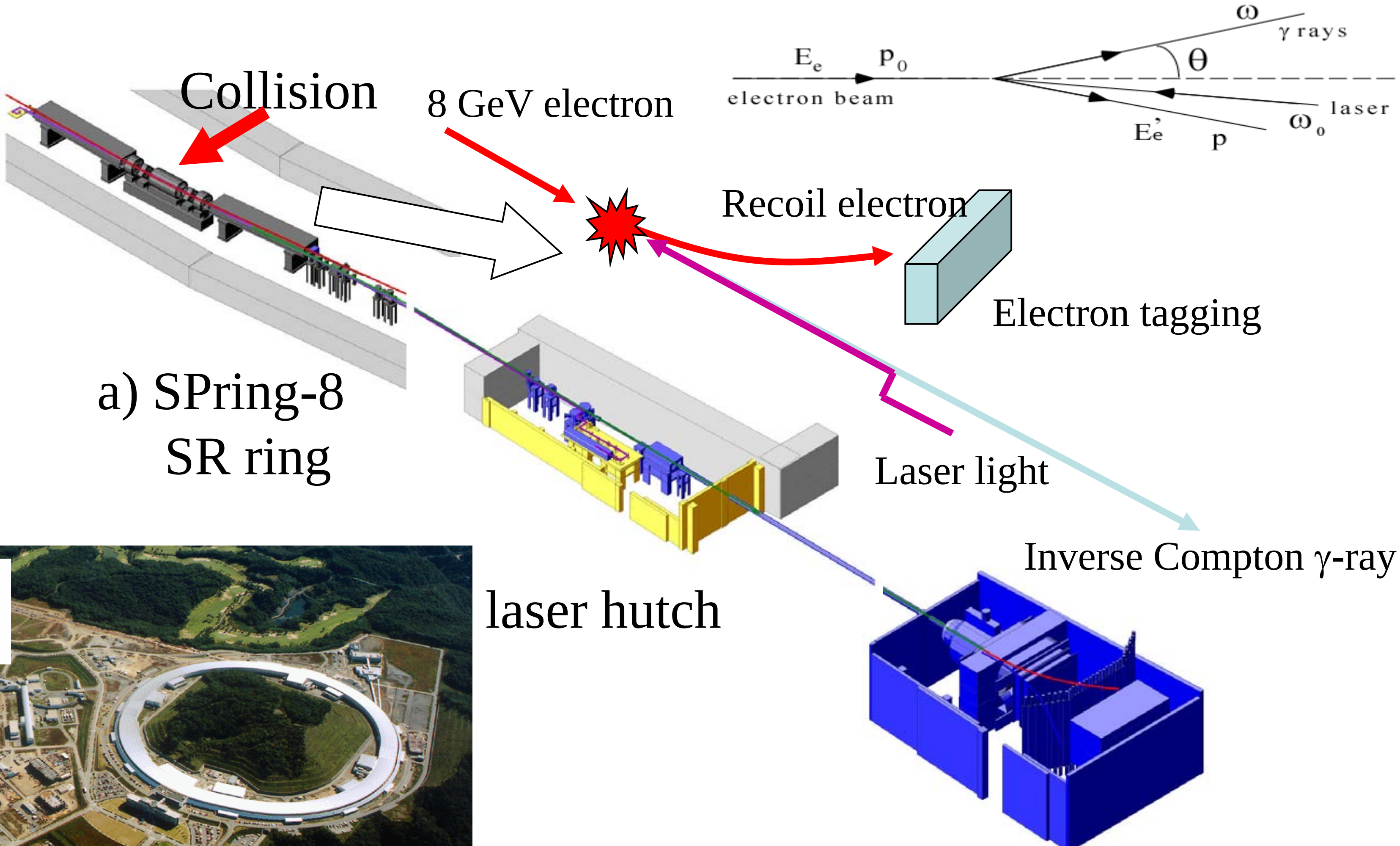


$$\kappa : \ \gamma_{ph}^{-3}$$

3D Particle-In-Cell Simulation



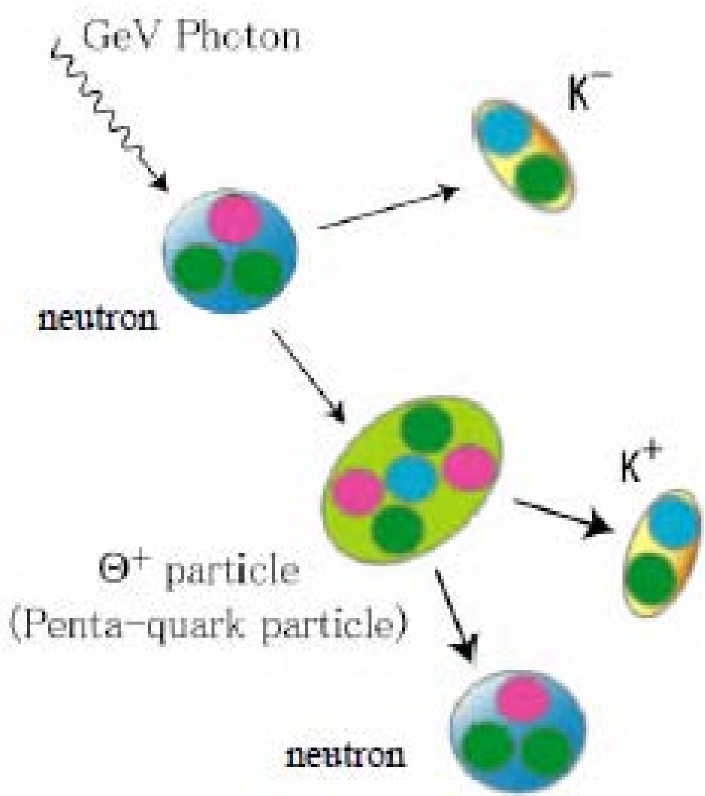
High energy γ beam facility

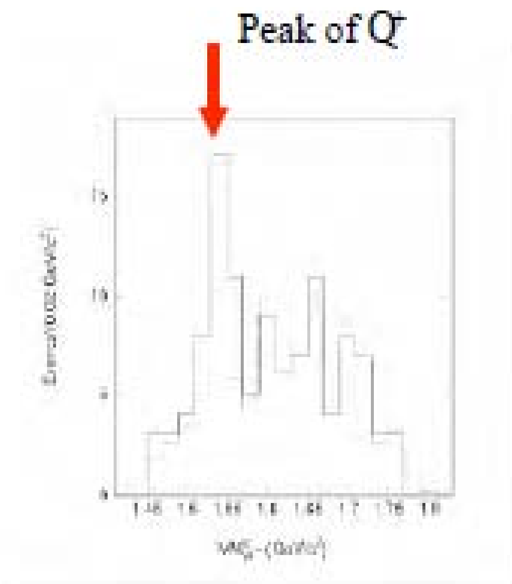


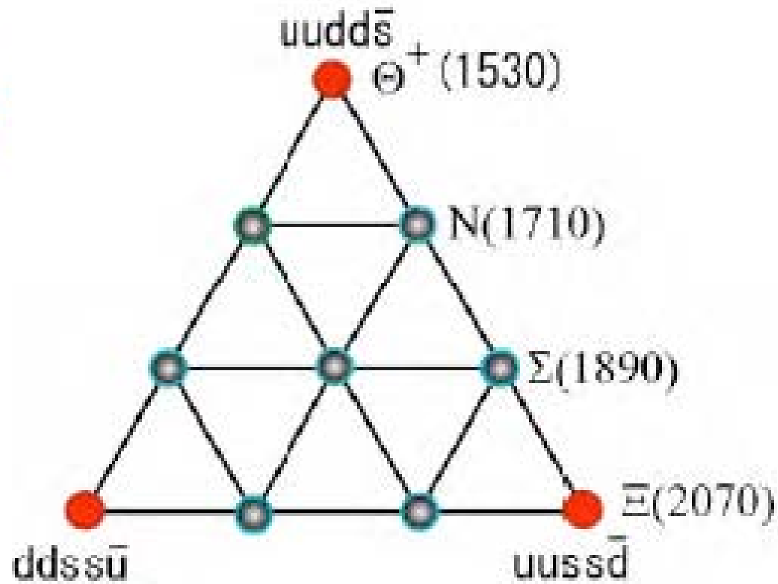
RCNP、JAERI、JASRI collaboration

New photonuclear processes(?)

Nakano et al., PRL 91, 012002 (2003)







(Spring-8)

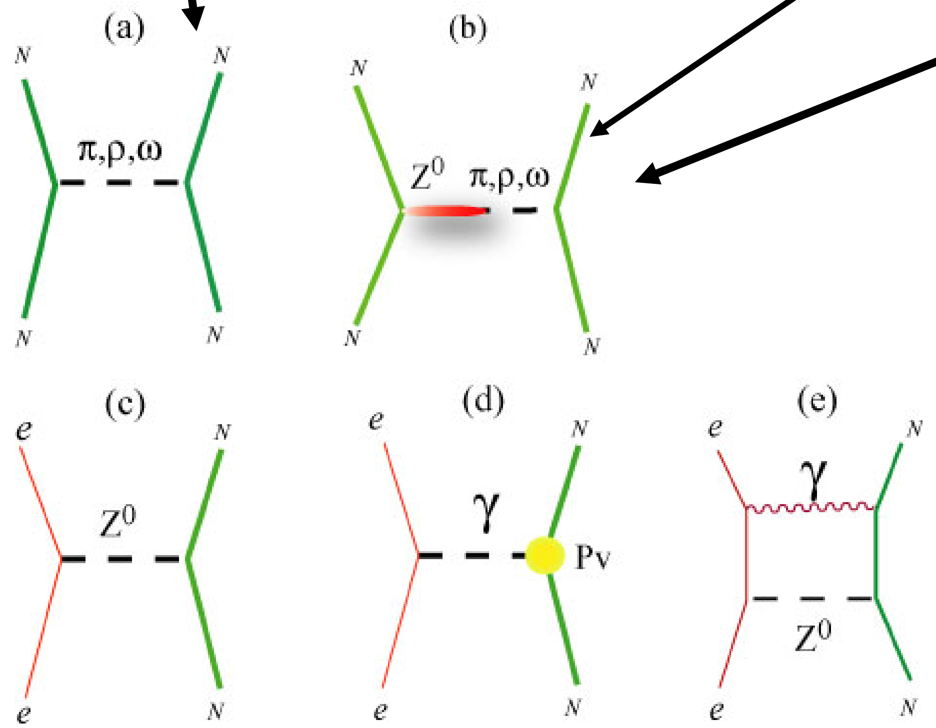
Parity Mixing in Nuclei

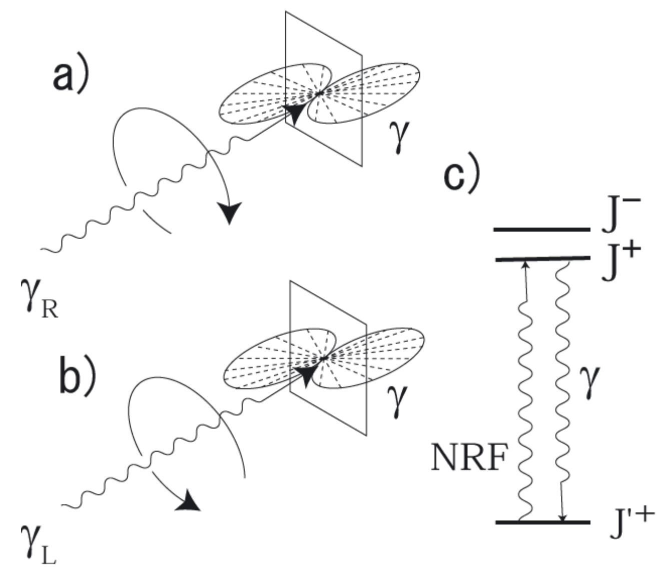
Interaction between Neutral Current Boson and Meson (Nucleon-Nucleon Interaction)

Z^0 : Neutral Current Boson

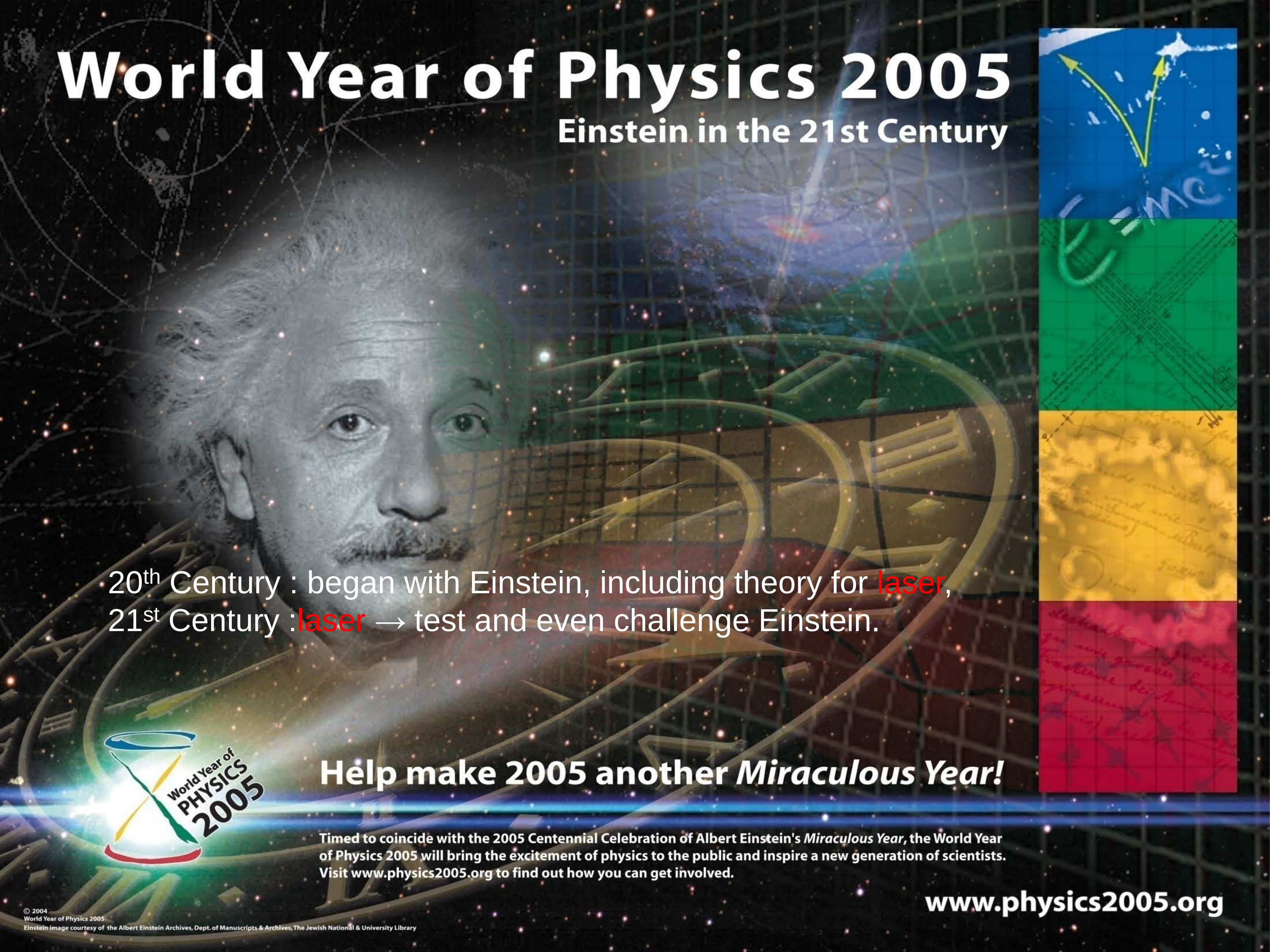
Standard Nucleon-Nucleon Interaction

Interaction between Z^0 and Mesons.





The interaction can be determined by polarized LCS gamma-rays. Fujiwara, J. Phys. G (2006).



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

Einstein and Ether

What is fundamentally new in the ether of the general theory of relativity as opposed to the ether of Lorentz consists in this, that the state of the former is at every place determined by connections with the matter and the state of the ether in neighbouring places, which are amenable to law in the form of differential equations; whereas the state of the Lorentzian ether in the absence of electromagnetic fields is conditioned by nothing outside itself, and is everywhere the same. The ether of the general theory of relativity is transmuted conceptually into the ether of Lorentz if we substitute constants for the functions of space which describe the former, disregarding the causes which condition its state. Thus we may also say, I think, that the ether of the general theory of relativity is the outcome of the Lorentzian ether, through relativation.

As to the part which the new ether is to play in the physics of the future we are not yet clear. We know that it determines the metrical relations in the space-time continuum, e.g. the configurative

(A. Einstein, 1922)

What γ beam brings in to nuclear physics

- Rutherford approach (collider and particle beam)

  high momentum penetrates deep interior of matter and scatters,

  sees smallest detail of matter

  $\lambda/a \leq 1$ (λ, a are probe and target sizes)

- 'laser' (and γ beam) approach

  photon beam penetrates, but not local real space structure,

  excites the structure, induces dynamics and spectroscopy,

  possibly controls

  $\lambda/a \sim 10^4$ (both for atoms and nuclei)

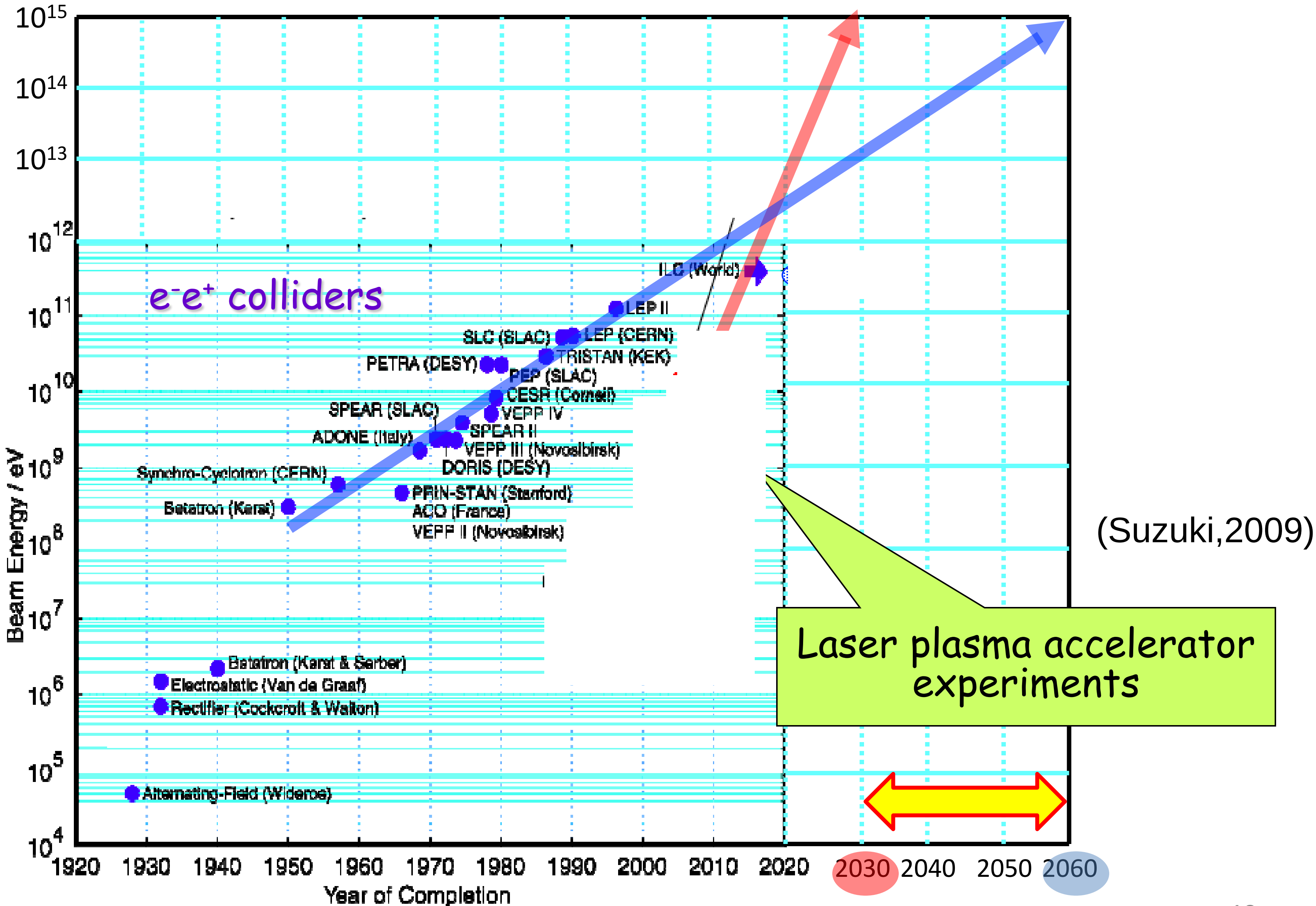
γ beam revolution of *nuclear physics*:
similar to laser revolution of *atomic physics* in'60s

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)

When can we reach 1 PeV ?: Suzuki Challenge



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

Quantum Gravity:

“Why is the sky blue?”

(for extreme high energy gamma rays)

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

  high energy γ has dispersion:

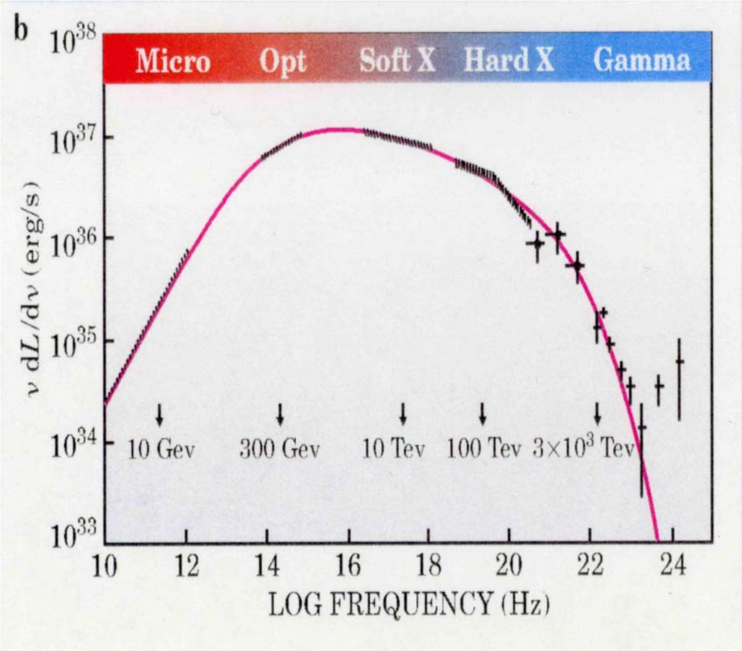
  $\omega = kc$ + (extra mass-like term?), i.e. $c(\varepsilon)$
- May be regarded as scattering off quantum fluctuations of vacuum (gravitational origin).
- Other proposals, such as H. Sato (1972); Coleman-Glashow(1997), ….

  breakdown of Lorentz invariance?

  (cosmic γrays cease to exist beyond certain energy)

May be testable in PeV energy regimes.

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.

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, $l_{Planck} \approx 1.62 \times 10^{-33}$ cm or $E_{Planck} = M_{Planck}c^2 \approx 1.22 \times 10^{19}$ 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_{ph} becomes comparable to $E_{Planck} = M_{Planck}c^2$). For $E_{ph} \ll E_{Planck}$, the leading term in a Taylor series expansion of the classical dispersion relation is $|v_{ph}/c - 1| \approx (E_{ph}/M_{QG,n}c^2)^n$, where $M_{QG,n}$ is the quantum gravity mass for order n and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm(\Delta E/M_{QG,1}c^2)D/c$ in the arrival time of photons emitted together at a distance D from us, and differing by $\Delta E = E_{high} - E_{low}$. 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

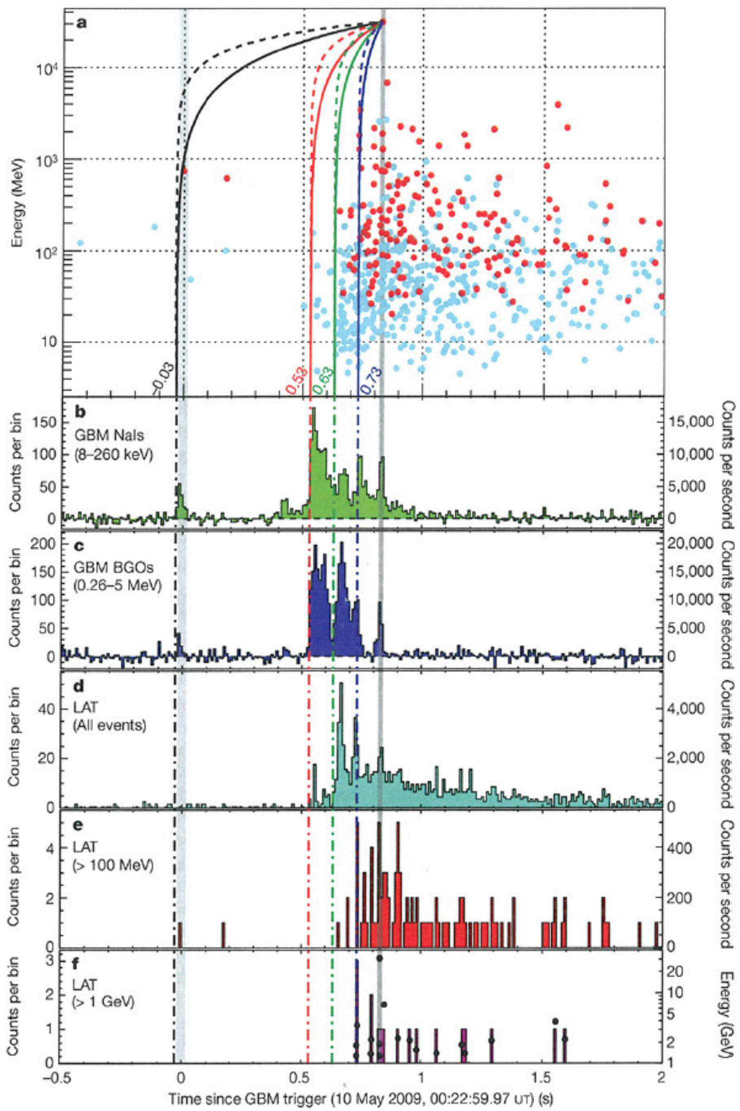


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy ... lowest to highest energies. **f** also overlays energy versus arrival time for each

(Abdo, eta l, 2009)

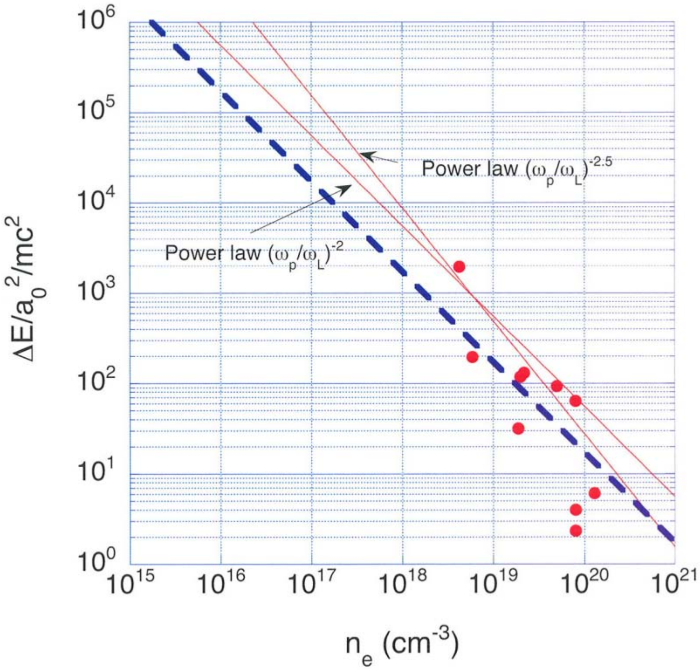
Energy-dependent
Photon mass?
limit is pushed up
to near Planck mass

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 γs) 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)?

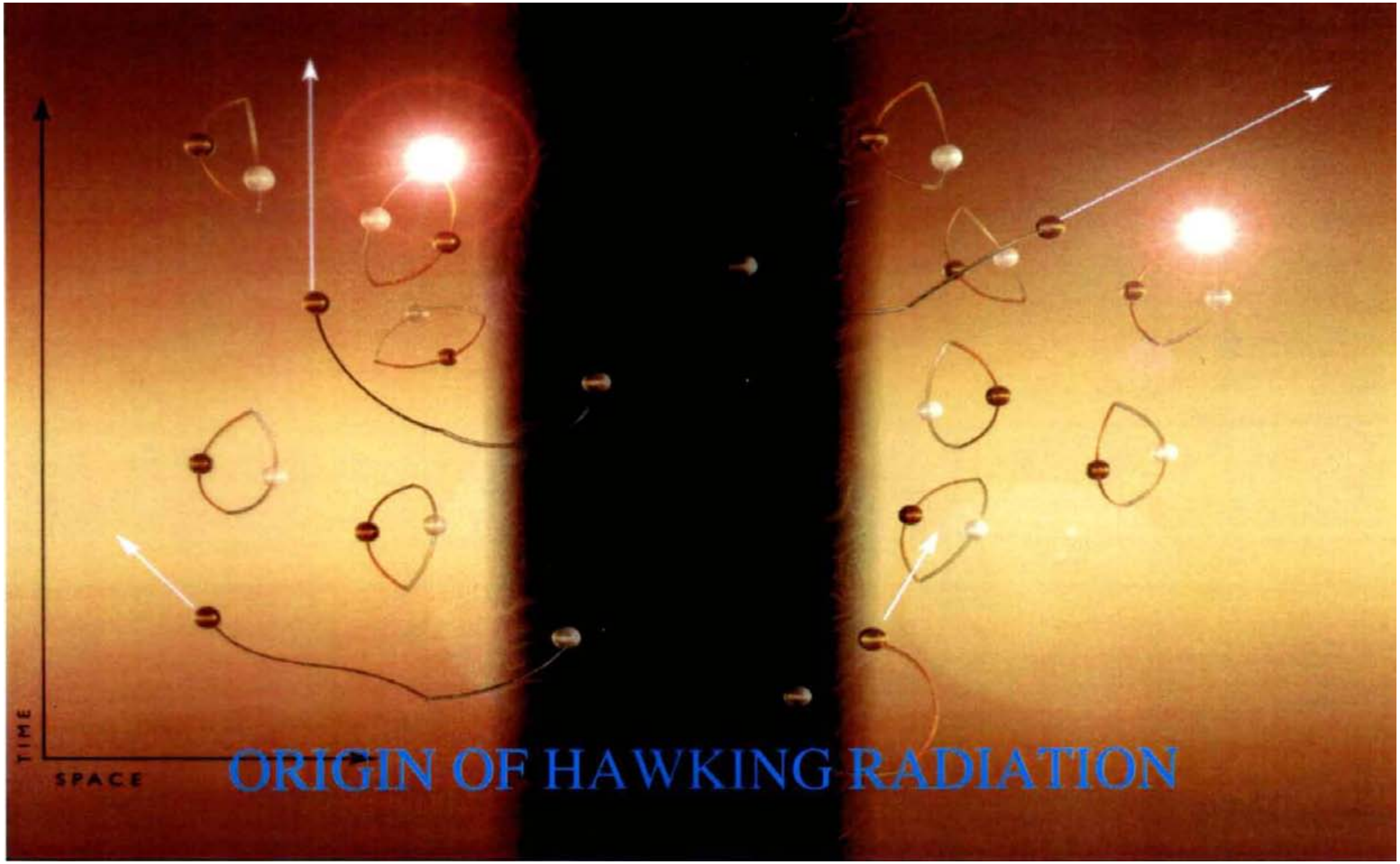
(laser energy of 10MJ@plasma density of 10^{16}/cc; maybe reduced with index 5/4)

A Path toward PeV

Parameters	Symbol	Case I	Case II	Case III	unit
number of stages	N_{stage}	1	100	1000	
wavelength	λ	1	1	1	um
norm. laser amplitude	a_0	56	26	18	
plasma density	n_e	$1.8\text{x}10^{15}$	$3.9\text{x}10^{16}$	$1.8\text{x}10^{17}$	cm^{-3}
gamma_ph	γ_{ph}	$7.9\text{x}10^{2}$	$1.7\text{x}10^{2}$	79	
laser energy/stage	$E_{L,1}$	$4.1\text{x}10^{4}$	88	4.1	kJ
total laser energy	$E_{L,t}$	$4.1\text{x}10^{2}$	8.8	4.1	MJ
total energy gain	ΔW	1	1	1	PeV
pump depletion length	L_p	$1.2\text{x}10^{4}$	57	3.9	m
dephasing length	L_d	$6.2\text{x}10^{3}$	29	2	m
total acc length	$L_{acc,t}$	$6.2\text{x}10^{3}$	2858.2	1957.8	m
spot radius	w_0	$7.9\text{x}10^{2}$	$1.7\text{x}10^{2}$	79	µm
pulse duraton	τ	$9.8\text{x}10^{2}$	$2.1\text{x}10^{2}$	98	fs
peak power	P	$4.2\text{x}10^{4}$	$4.2\text{x}10^{2}$	42	PW
number of electrons	N_{beam}	1.7E+11	1.7E+10	5.5E+09	

(Tajima, Kando, Teshima)

Hawking Radiation (Exploration of Horizon)



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

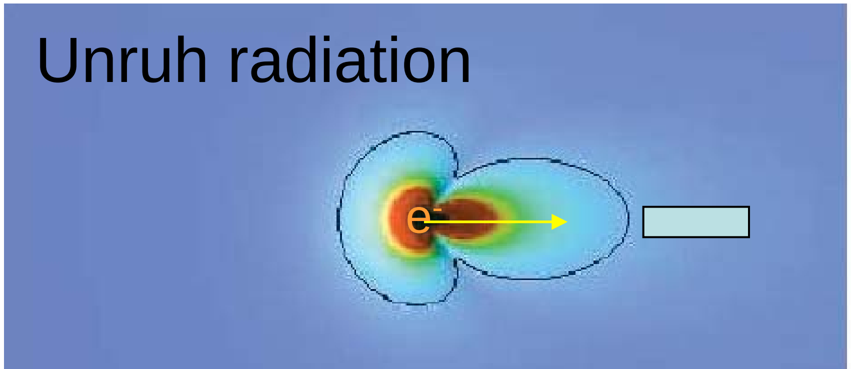
「空」＝「色」？ 「混沌」⇔「秩序」？

vacuum = ‘matter‘ ? chaos ⇔ information ?

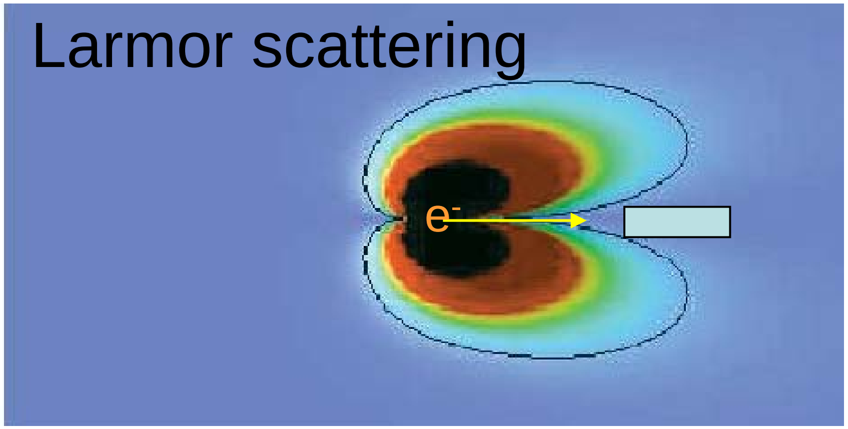
Explore relativity with strong fields（Unruh radiation）

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

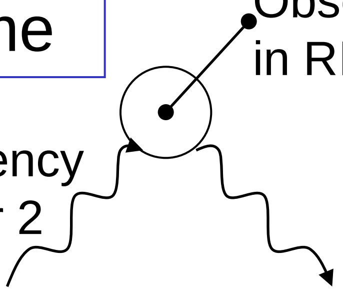
$\Rightarrow k_B T = 0.06eV \Rightarrow$ ~10eV (blue shift in lab. frame)



R. Schuetzhold Phys.Rev.Lett.97:121302, 2006



Rindler frame



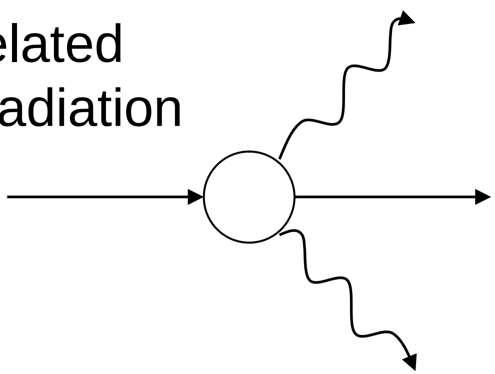
Observer in RIndler 1

negative frequency mode in Rinder 2

Strong correlation between absorption and emission despite of causal disconnection

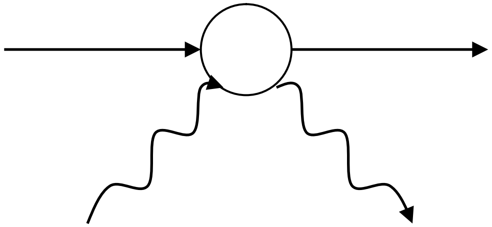
G. Unruh PRD 29 1047-1056, 1984

Correlated pair radiation



Inertial frame

No correlated pair in background process



Strong Acceleration Physics (Jackson, ch. 17)

(D. Habs)

Radiation damping: a heap of broken pieces

$F^{ik}_{\text{external}} + F^{ik}_{\text{self}}$ self-field influences motion of charged particles

J.D. Jackson: many unsolved problems $m\dot{\vec{v}} = \vec{F}_{\text{ext}} + \vec{F}_{\text{self}}$

$$\vec{F}_{\text{self}} = \frac{2}{3}\frac{q^2}{c^3}\ddot{\vec{v}} \quad \text{for} \quad v << c$$ (reference frame of resting charge)

Bad solution: $m\dot{\vec{v}} = \frac{2}{3}\frac{q^2}{c^3}\ddot{\vec{v}}$

Two solutions: $\vec{v} = \text{const.}$ and $\dot{\vec{v}} = \vec{a}_0 \cdot e^{t/\tau}$, $\tau = \frac{2}{3}\frac{q^2}{mc^3} = 6 \cdot 10^{-24}\ \text{s}$ → runaway solution

$\vec{a}_0 = \text{acceleration at } t = 0$

- wrong electromagnetic mass $(4/3)m_e$ occurs in the force equation for a rigid spherical electron
- causality is violated; “pre-acceleration” of charged particles before force is turned on

??? All is wrong ???

J.D. Jackson: “Classical Electrodynamics”, ch. 17 (Wiley, New York, 1998)

Lorentz force

(D.Habs)

Lorentz force = $mc\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{q}{c}F_{\mathrm{ext}}^{ik}u_k'$ usually leading order term

Constant B field = synchrotron

Circular orbit, sufficient precise, higher order terms are obscured by machine errors

a) Dynamics of electron with feed-back

b) Larmor formula for far-field radiations

Lorentz-Abraham-Dirac force

(LAD)

(D. Habs)

$$mc\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{q}{c}F^{ik}_{\mathrm{ext}}u_k + F^i_{\mathrm{self}}\ , \quad v << c \ \rightarrow \ \vec{f} = \frac{2}{3}\frac{q^2}{c^3}\ddot{u}$$

Finite velocity of interaction, development o[f] Lagrangian to higher orders (LL §75)

Generalization to: $\frac{2}{3}\frac{q^2}{c}\frac{\mathrm{d}^2u^i}{\mathrm{d}s^2}$ but $g^i u_i \neq 0$ $\left[u^i u_i = 1;\ \frac{\mathrm{d}u^i}{\mathrm{d}s}\cdot u_i = 0\right]$ but required

Add new 4-vector, which vanishes for $\vec{v} = 0 \ \rightarrow \ \alpha\, u^i$ with scalar α

$$\Rightarrow \quad g^i = \frac{2}{3}\frac{q^2}{c}\left(\frac{\mathrm{d}^2u^i}{\mathrm{d}s^2} - u^i u^k \frac{\mathrm{d}^2u_k}{\mathrm{d}s^2}\right)$$

LAD equation: $$mc\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{q}{c}F\mathrm{d}^{ik}_{\mathrm{ext}}u_k + \frac{q^2}{6\pi c}\left[\frac{\mathrm{d}^2u^i}{\mathrm{d}s^2} - \frac{1}{c^2}\frac{\mathrm{d}u^\lambda}{\mathrm{d}s}\cdot\frac{\mathrm{d}u_\lambda}{\mathrm{d}s}\cdot\frac{\mathrm{d}u^i}{\mathrm{d}s}\right]$$

LAD has exponentially fast runaway solutions: $F^{ik}_{\mathrm{ext}} = 0;$ small velocities $m\dot{\vec{v}} = \frac{e^2}{6\pi c^3}\ddot{\vec{v}}$

Dirac postulates: asymptotic condition $\lim_{s\to\infty}\dot{\vec{v}}(s) = 0$ equivalent to initial condition $\dddot{\vec{x}}(0) = 0$

In general solution chaotic, many physical and unphysical solutions, find a solution not hampered by instable solutions.

P.A.M. Dirac, Proc. R. Soc. London Ser. A 167, 148 (1938);

Landau-Lifshitz (LL) force

= LAD force + leading order approximation

Derive an effective second order equation, which stays on the critical surface without exploding solutions.

Landau-Lifshitz : Regard Lorentz force as leading order
and we insert it into radiation force (replace u)

$$\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{q}{mc^2} F^{ik} u_k \quad \rightarrow \quad \frac{\mathrm{d}^2 u^i}{\mathrm{d}s^2} = \frac{q}{mc^2} \frac{\partial F^{ik}}{\partial x^2} u_k u^l + \frac{q^2}{m^2 c^4} F^{ik} F_{kl} u^l$$

$$F^i_{\text{self}} = \frac{2q^2}{3mc^3} \frac{\partial F^{ik}}{\partial x^l} u_k u^l - \frac{2q^4}{3m^2 c^5} F^{il} F_{kl} u^k + \frac{2q^4}{3m^2 c^5} \left(F_{kl} u^l\right)\left(F^{km} u_m\right) u^i$$

Lower order substitution = accepted recipe of singular perturbation theory
= Pauli (1929), Heitler (1936)

The new equation does not have the difficulties of LAD,
stable solution, with correct long-time behavior.

But: 4-momentum not collinear with 4-velocity $\rightarrow$ mass = tensor

(D. Habs)

Landau-Lifshitz (II)

(D. Habs)

for 1 electron extremely small radiation damping

$$mc\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{e}{c}F^{ik}u_k + F^i_{\mathrm{self}}$$

$$F^i_{\mathrm{self}} = \frac{2}{3}\frac{e^3}{mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2e^4}{3m^2c^5}F^{ik}F_{kl}u^k + \underbrace{\frac{2e^4}{3m^2c^5}\left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i}_{\text{(III)}}$$

$v \to c$ (III) dominant term

$$\vec{f} = \frac{2e^4}{3m^2c^4}\left(F_{kl}u^l F^{km}u_m\right)\vec{v}$$ force opposite to velocity $\vec{v}$

$$\frac{F_{\mathrm{self}}}{F_{\mathrm{Lorentz}}} = \frac{\frac{2}{3}\frac{e^4}{m^2c^5}\left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i}{\frac{e}{c}F^{ik}u_k\left(F^{ik}u_k\right)} = \frac{2}{3}\frac{e^3}{m^2c^4}E_L(a=1) = \frac{2}{3}\frac{e^2}{r_0}\frac{2\pi}{m^2c^4}mc^2\frac{r_0}{\lambda_L} = 10^{-8}$$

with $\frac{\lambda_L}{2\pi}eE_L = mc^2, \quad \frac{e^2}{r_0} = mc^2, \quad r_0 = 2.82\,\mathrm{fm}, \quad \lambda = 1\,\mu\mathrm{m}$

L.D. Landau and E.M. Lifshitz, “The Classical Theory of Fields”, 2nd ed., ch 76

Basic idea

Coherent macroparticle

(D. Habs)

Assuming N electrons sitting on top of each other, so that they see all fields in phase, just like 1 giant electron with mass $M_{\text{mac}} = N \cdot m_{\text{e}}$ and charge $Q_{\text{mac}} = N \cdot q_{\text{e}}$.

$$\frac{F_{\text{self}}}{F_{\text{Lorentz}}} = \frac{2}{3} \frac{e^3}{m_e^2 c^4} E_L \quad \Rightarrow \quad \frac{2}{3} N \cdot \frac{e^3}{m_e^2 c^4} E_L$$

$N = 10^{10}$ for electron sheet, self force becomes dominant and can be studied experimentally in detail.

Testing all theories of radiation damping.

Landau-Lifshitz (III)

(Habs)

N > 10^8 electrons: dominant radiation damping

$$\frac{F_{\text{self}}}{F_{\text{ext}}} = 10^{-8} \cdot a \cdot \left(\frac{\omega}{\omega_L}\right) \cdot N$$

For a coherent bunch of $N = 10^{10}$ the self force is dominant.

If ω gets larger by Doppler boost, N gets smaller by the same factor.

From LL we have learnt the dominant force $F_{\text{self}}^{(1)} = \frac{2e^4}{3m^2c^5}\left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i$

Now we put this $F_{\text{self}}^{(1)}$ into the $\frac{\mathrm{d}^2u^i}{\mathrm{d}s^2}$ of the LAD equation $\rightarrow$ higher order LL equation.

$$\frac{\mathrm{d}^2u^i}{\mathrm{d}s^2} = (\ \dots F \cdot \frac{\mathrm{d}u^i}{\mathrm{d}s} \dots$$

replace by $\frac{\mathrm{d}u^i}{\mathrm{d}s} = \frac{2e^4}{3m^3c^6}(Fu)(Fu)u^i$ differentiate each term partially

Thus, the $(Fu)(Fu)$ occurs with power n and as $\left(\frac{2e^4}{3m^3c^6}\right)^n$

$$F_{\text{self}}^{(1)} \rightarrow F_{\text{self}}^{(2)} \rightarrow F_{\text{self}}^{(n)} \propto \left(10^{-8} \cdot N\right)^n$$

high harmonics with $(2\omega+3\omega\cdot n)$ $\quad -\frac{\mathrm{d}E^{\text{kin}}}{\mathrm{d}x} \propto \left(E^{\text{kin}}\right)^{2n}$

Fast collective deceleration = γ step function

These high harmonics are boosted by $(4\gamma^2)$

High harmonics of force result in multiples for far field radiation.

Strong coupling ($\tau_e \cdot N \gg \tau_L$)

for classical electrodynamics (I)

(D.Habs)

Lorentz-Abraham-Dirac: acceleration $\dot{\vec{u}} = \frac{F_{\text{ext}}}{mc} + \frac{2}{3}\frac{e^2}{mc^3}\ddot{\vec{u}} = \frac{F_{\text{ext}}}{mc} + \tau_e \ddot{\vec{u}}$

$\tau_e = 6 \cdot 10^{-24}$ s , runaway solution $\dot{u}(t) = a_0 \cdot e^{t/\tau_e}$

Repeated substitution: $\dot{\vec{u}} = \frac{1}{mc}\sum_{n=0}^{\infty}(\tau_e)^n \frac{d^n F_{\text{ext}}}{dt^n}$ $\qquad \frac{\tau_e}{\tau_L} = \frac{6 \cdot 10^{-24}\text{ s}}{2\text{ fs}/2\gamma} \approx 6 \cdot 10^{-8} = \frac{1}{N_{\text{thresh}}} = \frac{1}{2 \cdot 10^7}$

Coherent macroparticle: $\tau_{\text{mac}} = N\tau_e$, coherent scattering not only $\sigma = N^2 \sigma_T$

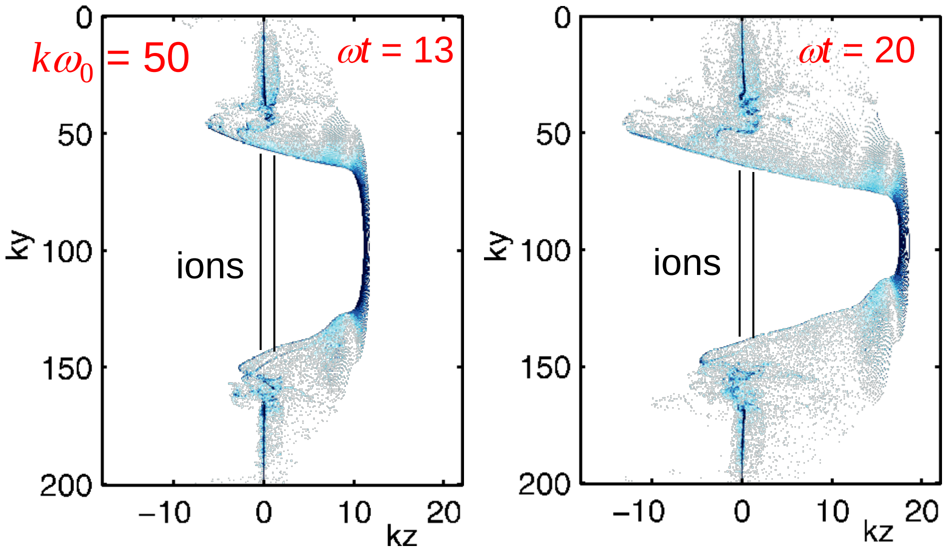
but $\sigma = N^2 \left\{ \sum_{n=0}^{\infty} \left(\frac{N}{N_{\text{thresh}}} \right)^{2n} \right\} \cdot \sigma_T$

Electron sheet break-out

from thin solid foil; Theory (I)

(D.Habs)

High-density overcritical e-sheet



V. Kulagin et al., PRL 99 (2007) 124801
B. Rau et al., PRL 78 (1997) 3310

$$2\alpha = 2\pi\sigma \le a_{\text{Laser}}$$

Break-out condition

$$\frac{E_s}{E_0} = N \cdot k_L \cdot d < a_0 = \frac{E_L}{E_0}$$

Electrostatic field
Poisson equation

$$E_S = \frac{e n_e d}{\varepsilon_0} \quad < \quad E_L$$

pressure balance

foil thickness : *d*

density ratio :

$$N = \frac{n_e}{n_{cr}} = \left(\frac{\omega_p}{\omega_L}\right)^2$$

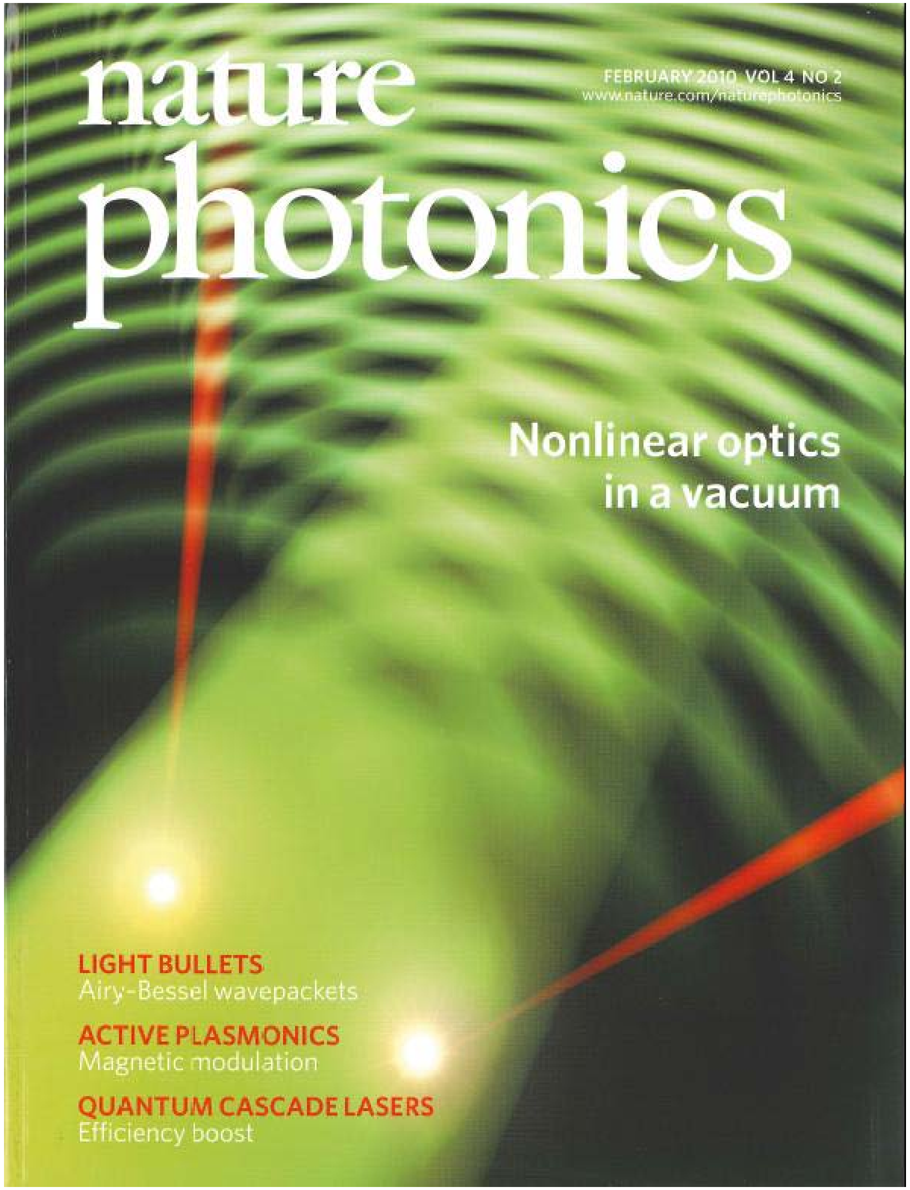
laser wave number :

$$k_L = \frac{2\pi}{\lambda_L}$$

$$E_0 = \frac{mc\omega_L}{e}$$

O. Klimo et al., Phys. Rev. ST AB 11 (2008) 031301

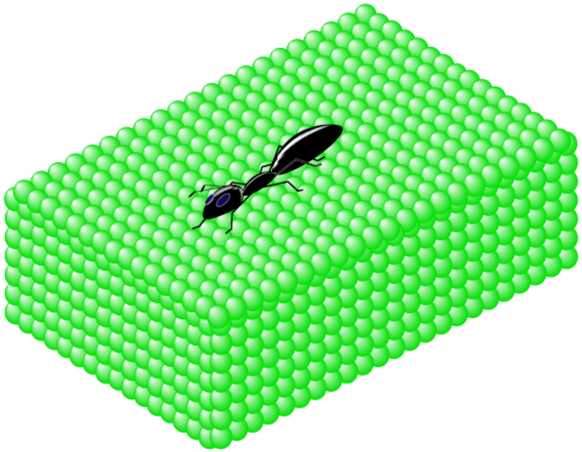
Nonlinear Optics in Vacuum



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)

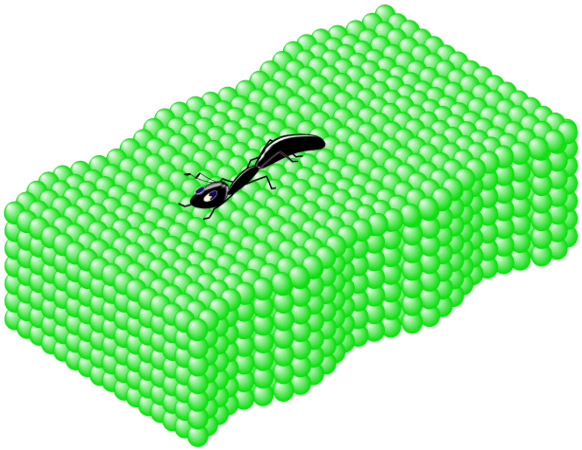
What is relativity?
What is vacuum?



An observer in a crystal as vacuum

↓

「（真）空」

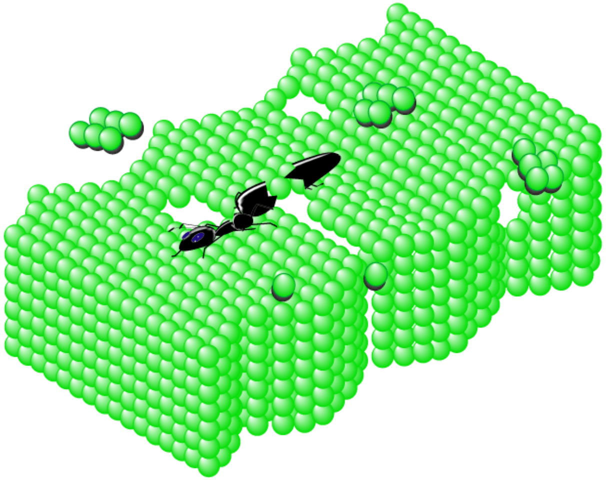


Phonon is an excitation of vacuum

↓

Photon is a distortion of vacuum

「色即是空」



Strong field breaks vacuum

↓

e+e- pair production out of vacuum

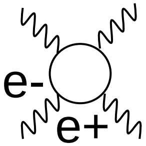
「空即是色」

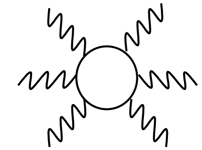
Higher order QED and QCD

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

$$\frac{\alpha}{\pi}F^2 \rightarrow \left\langle \frac{\alpha_s}{\pi}G^2 \right\rangle + \frac{\alpha}{\pi}q^2F^2$$

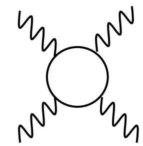
$$\left\langle 0 \left| \frac{\alpha_s}{\pi}G^2 \right| 0 \right\rangle \approx (2.3 \pm 0.3)10^{-2}GeV^4$$

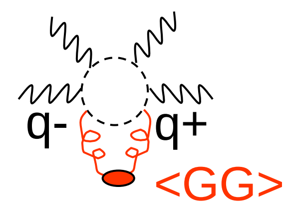
(K.Homma, 2007)

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

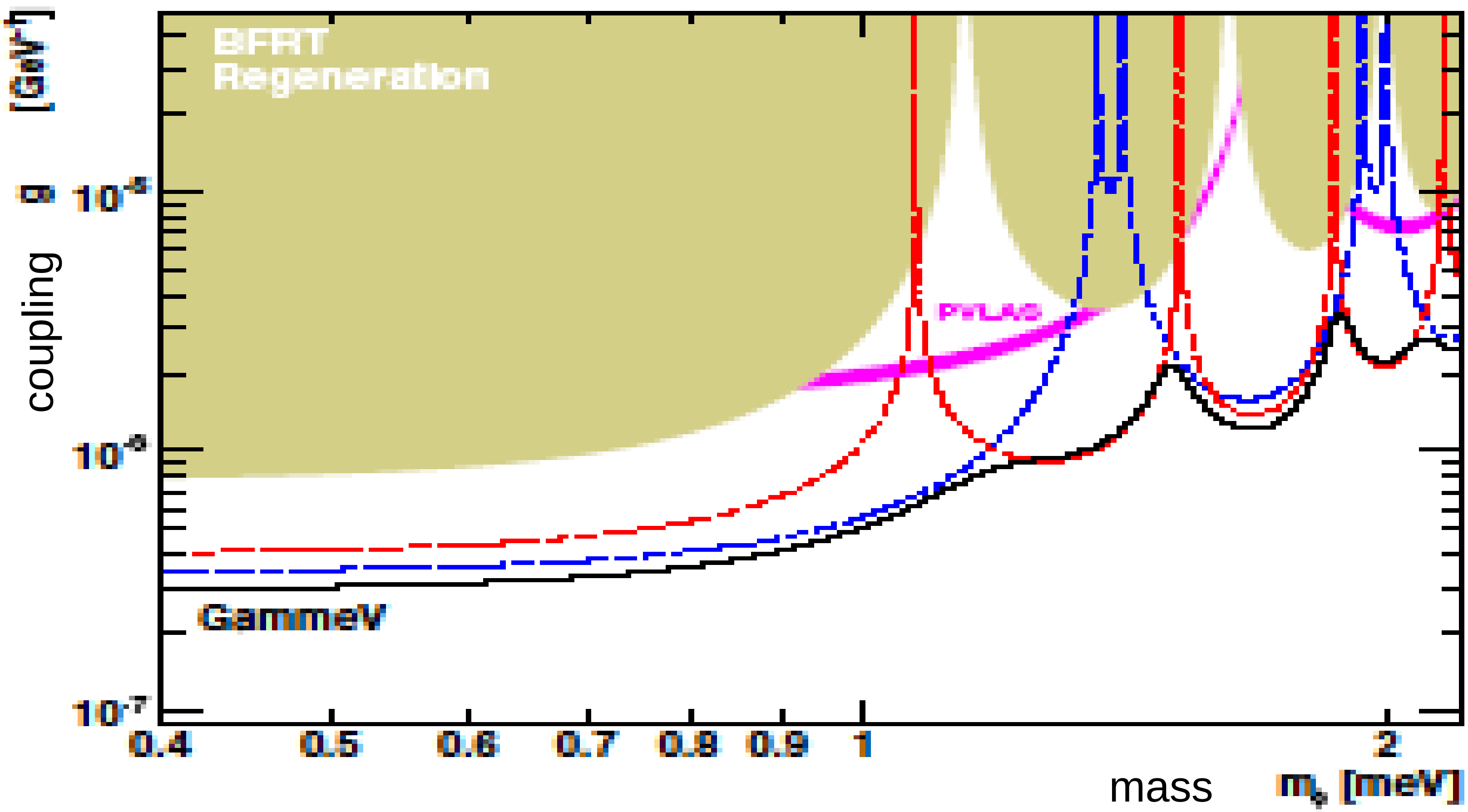
$$\frac{2nd-term}{1st-term} = \sum_{i=u,d}\frac{24}{7}\frac{q_i^2\pi^4}{m_i^8}m^4{}_e\left\langle\frac{\alpha}{\pi}G^2\right\rangle \approx e^{9\pm2.5}$$

$$m_u \approx \frac{1}{2}m_d \approx 5\pm1.5MeV, q_u^2 = 4q_d^2 = \frac{4}{9}$$

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

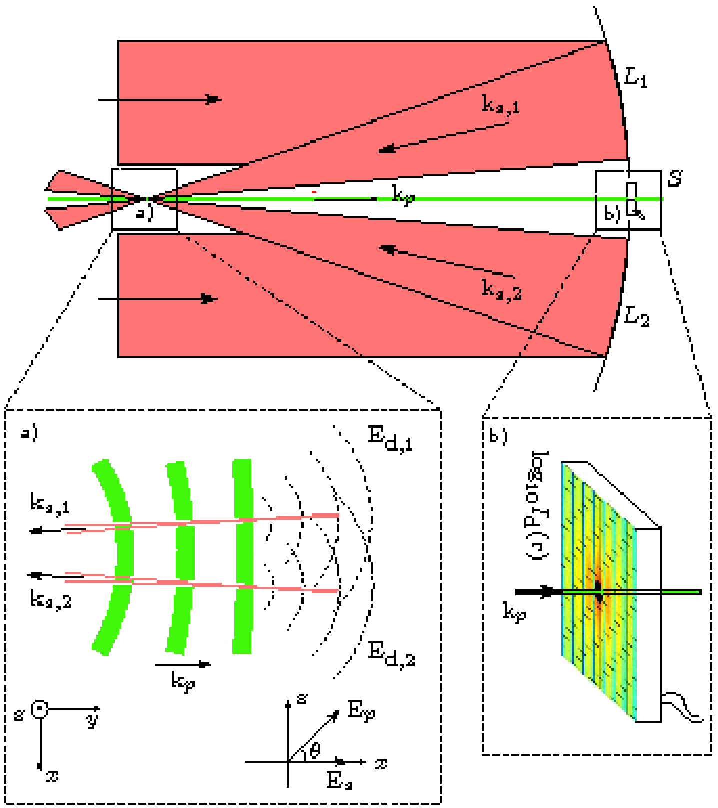
→ axion field?; extended fields(such as dark energy, Tajima-Niu, 1997, etc.)?

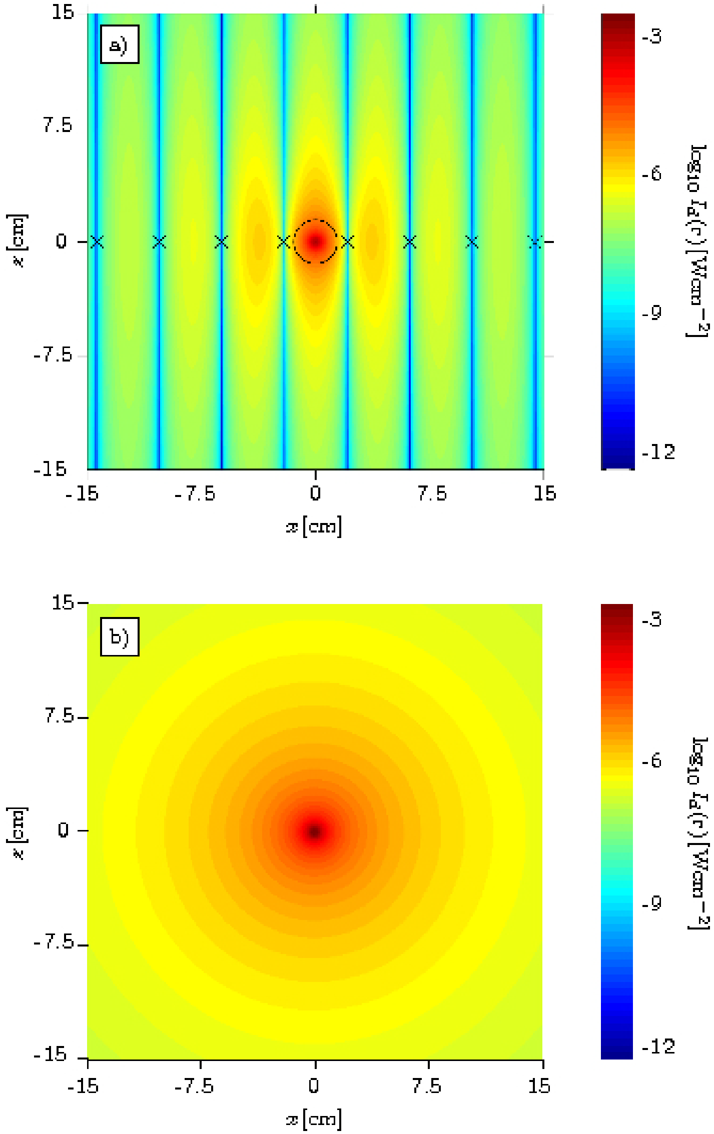
Detection of (light) fields-particles missed by collider: exploring new fields such as axion……



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

High amplitude photon-photon interaction

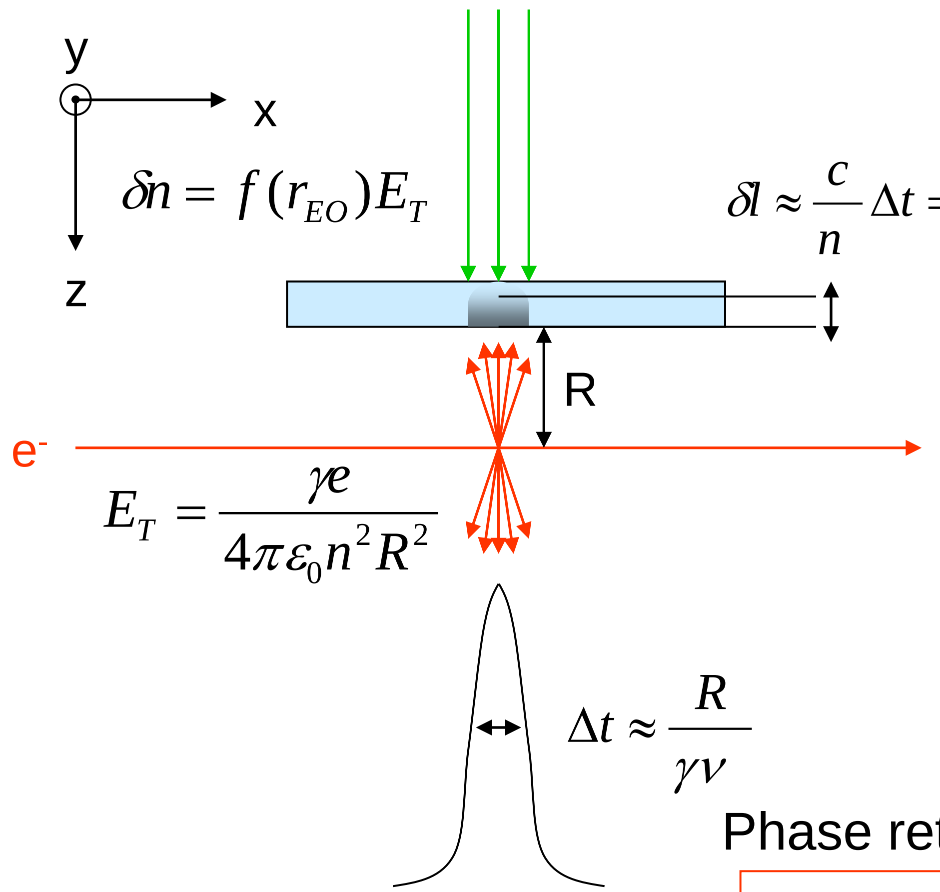




B. King et al., Nature Photon. 4, 92(2010)

Homma proposes: experimental test

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



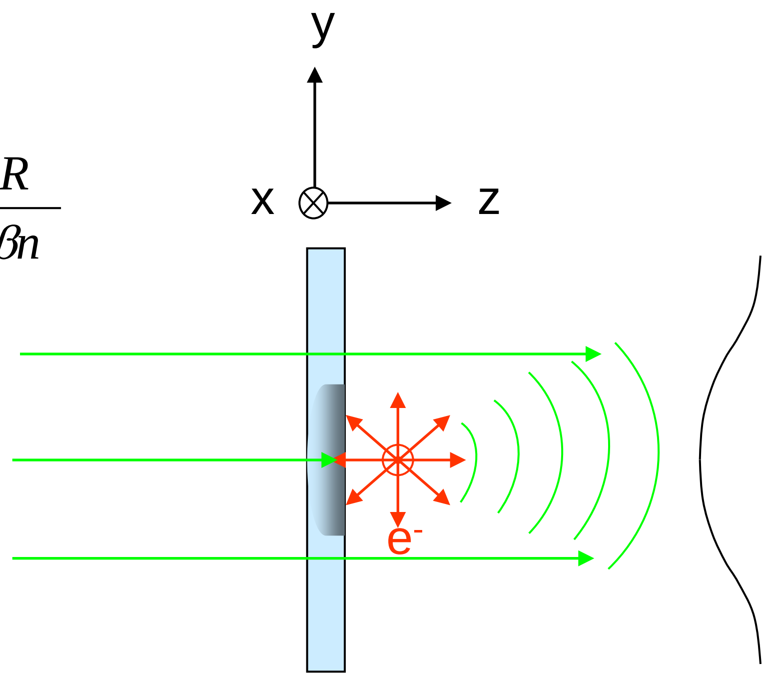
$$\delta n = f(r_{EO})E_T$$

$$\delta l \approx \frac{c}{n}\Delta t = \frac{R}{\gamma\beta n}$$

$$E_T = \frac{\gamma e}{4\pi\varepsilon_0 n^2 R^2}$$

$$\Delta t \approx \frac{R}{\gamma v}$$

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



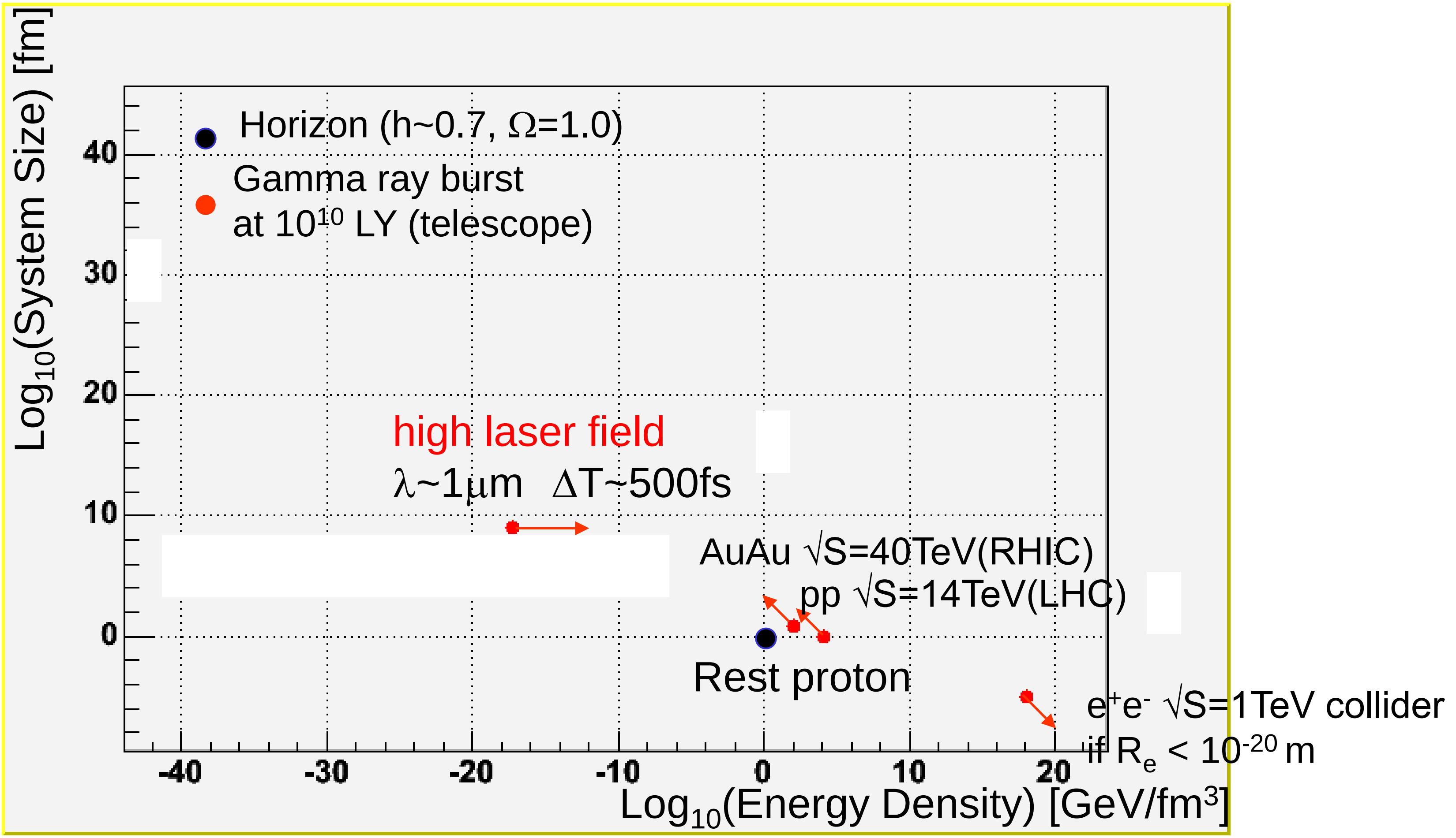
$$\Delta y \approx R\tan(\cos^{-1}(0.5)^{1/3})$$

Phase retardation

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

(Homma, 2007)

High Field Science and other (telescope, collider) approaches



(K.Homma)

High Field Science from an ELI Workshop talk

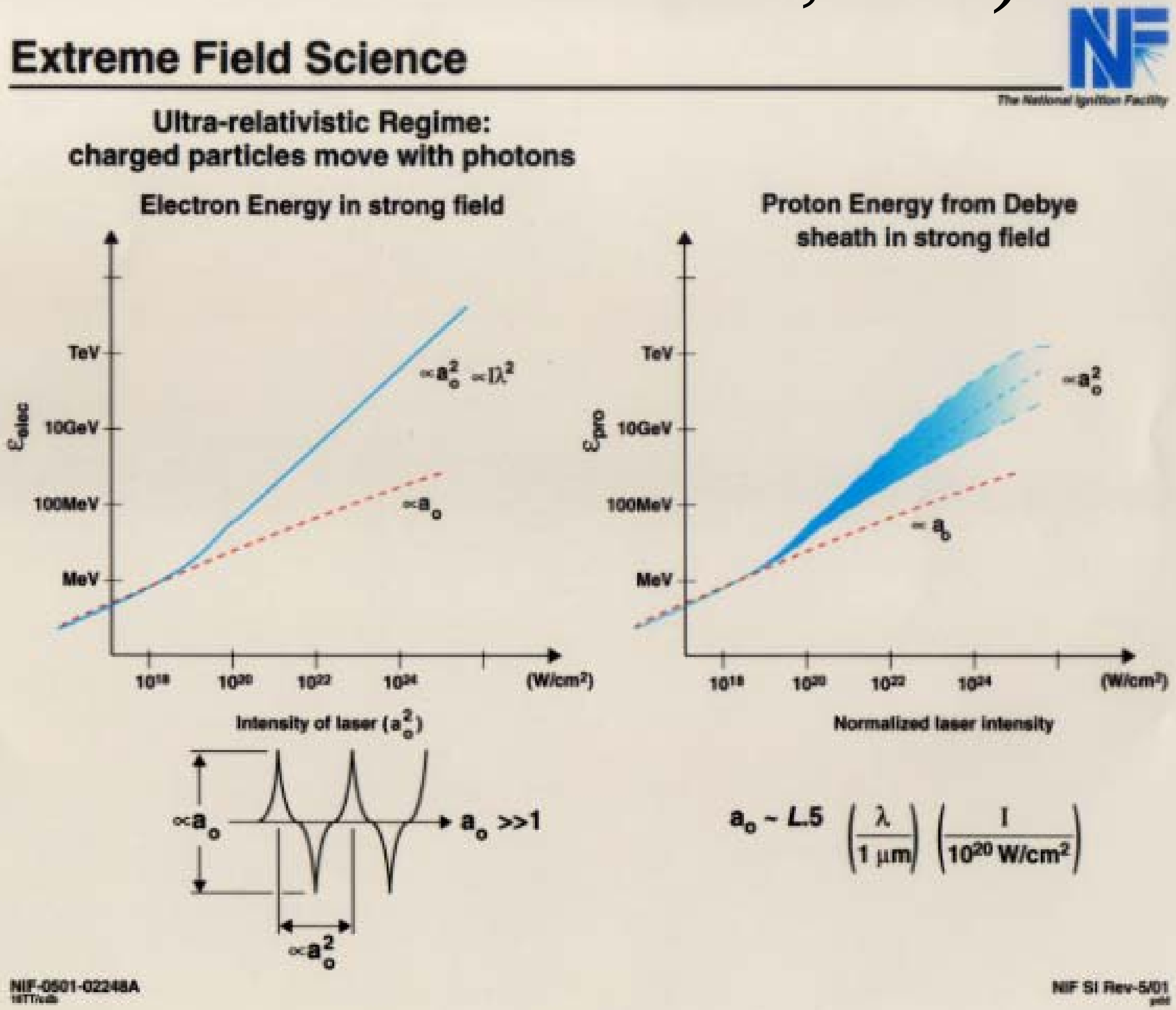
Conclusions

▷ 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)

Relativity Helps Acceleration (for Ions, too!)



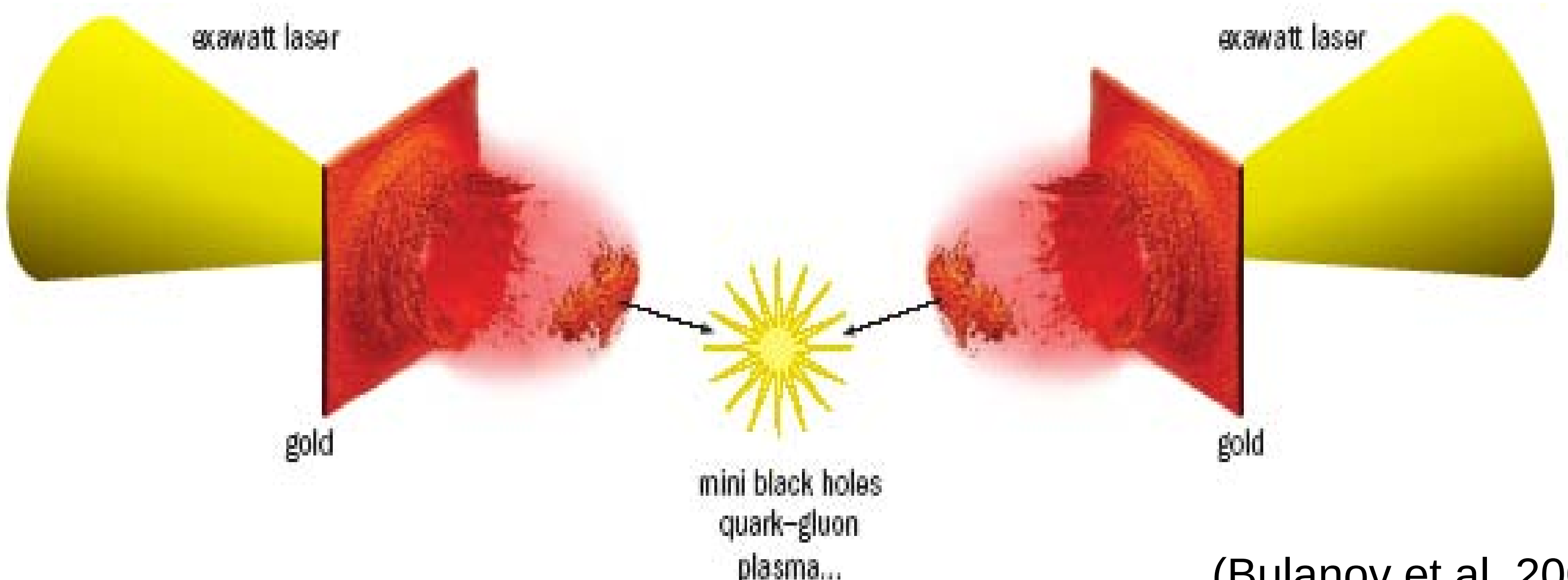
Strong fields:
rectifies laser
to longitudinal
fields

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)

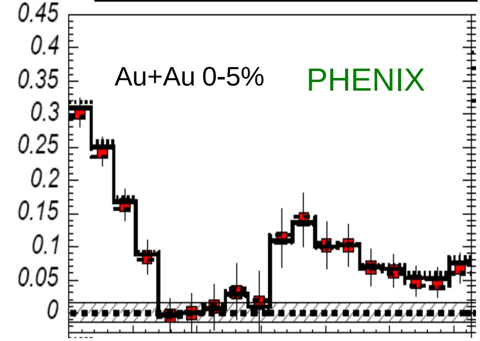
Nuclear wakefields

J. Ulery (2007)

- 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).
- Three-particle correlations to distinguish them.

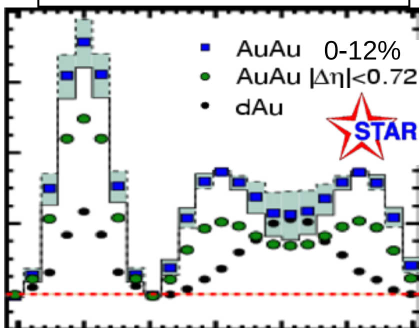
PHENIX PRL 97, 052301 (2006)

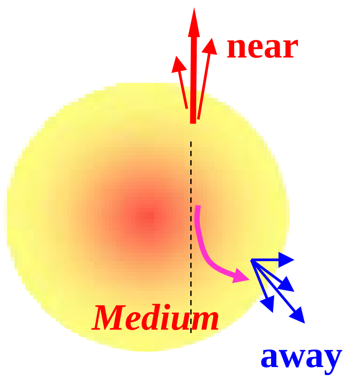
$2.5<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c



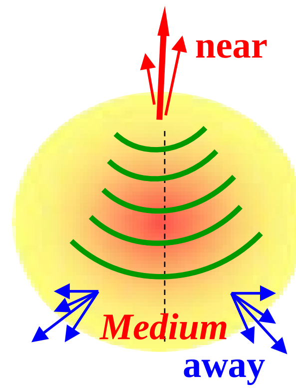
Horner (STAR) QM2006

$3<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c

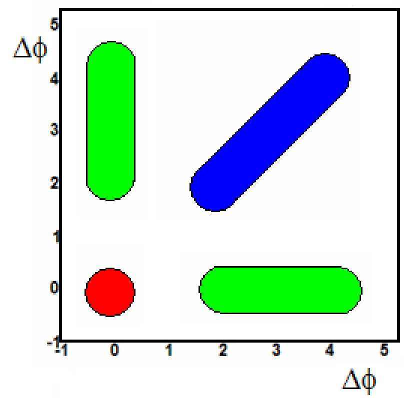


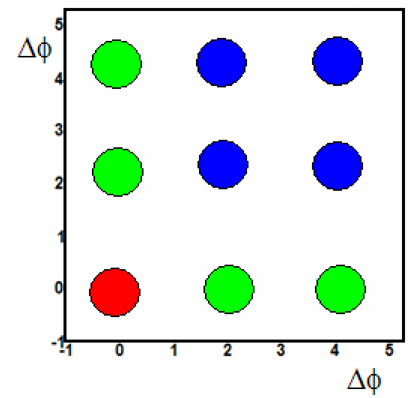


Deflected Jets



Conical Emission





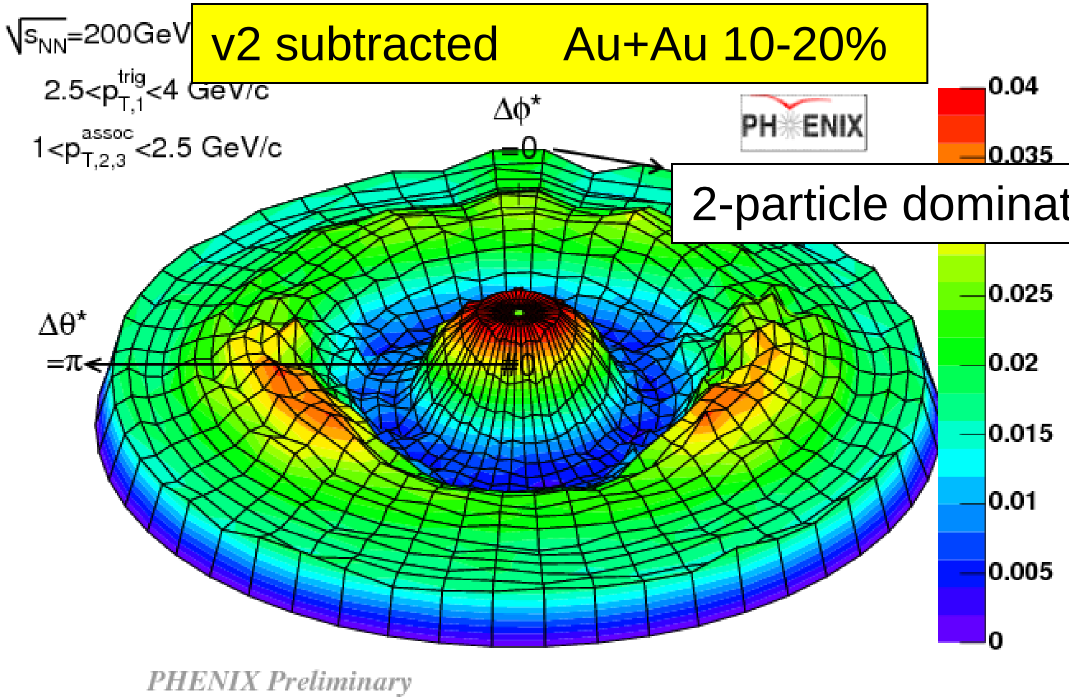
PHENIX Results: Nuclear Wake

$\Delta\phi^*$ Projections

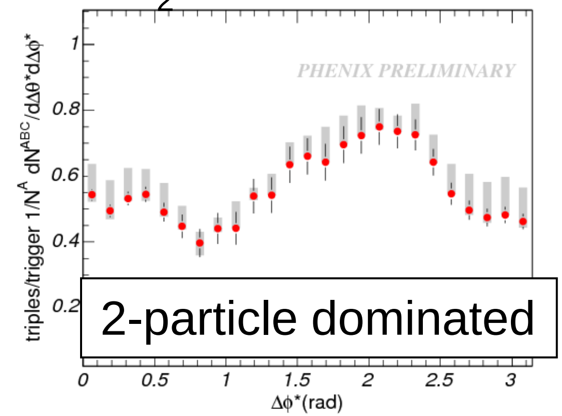
J. Ulery (2007)

Ajitanand (PHENIX) HP06, IWCF'06

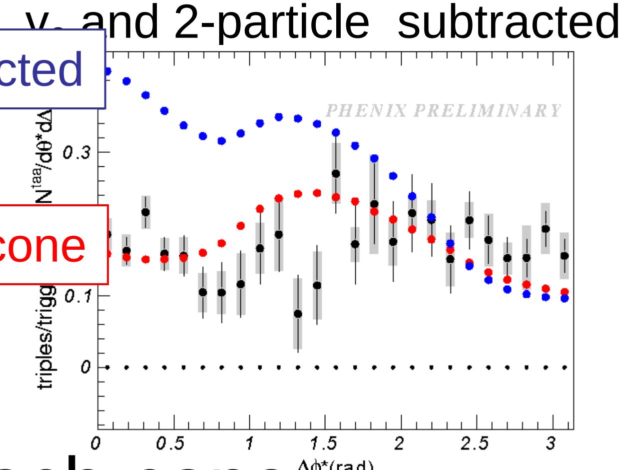
v2 subtracted Au+Au 10-20%



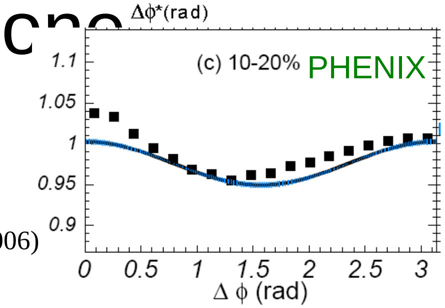
v_2 subtracted



v_2 and 2-particle subtracted



- Shape consistent with simulated mach-cone
- 3-particle/2-particle ~ 1/3, very large
  - Residual background?



PRL 97, 052301 (2006)

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 (Rutherford approach) vs high amplitude approach (laser approach): **high field physics**'s new paradigm
- Test of Einstein's relativity (special and general theories), nonlinear QED (and QCD) (Schwinger physics), high acceleration (=gravitational) physics (horizon physics), test of equivalence principle, radiation dominant regime (physics of large acceleration/gravitation), quantum gravity
- Can we detect **vacuum fields** that permeate vacuum (such as dark energy)? What is vacuum? How to enhance the signal (forward scattering approach)? **nonlinear optics in vacuum**

Pascal Lecture Plan

(tentative, need <u>your</u> feedback)

- Oct.22: First Lecture (General) “ Laser Acceleration and High Field Science: 1979-2009”
- Nov.18: Second Lecture “Laser Electron Acceleration and its Future”
- Dec.9: Third Lecture “Laser Ion Acceleration”
- January 20,2010: “Relativistic Engineering”
- March 10: “Photonuclear Physics”
- April 14: “High Field Science”
- May 19: “Medical Applications”
- ……

Merci Beaucoup
et a la Prochaine Fois!