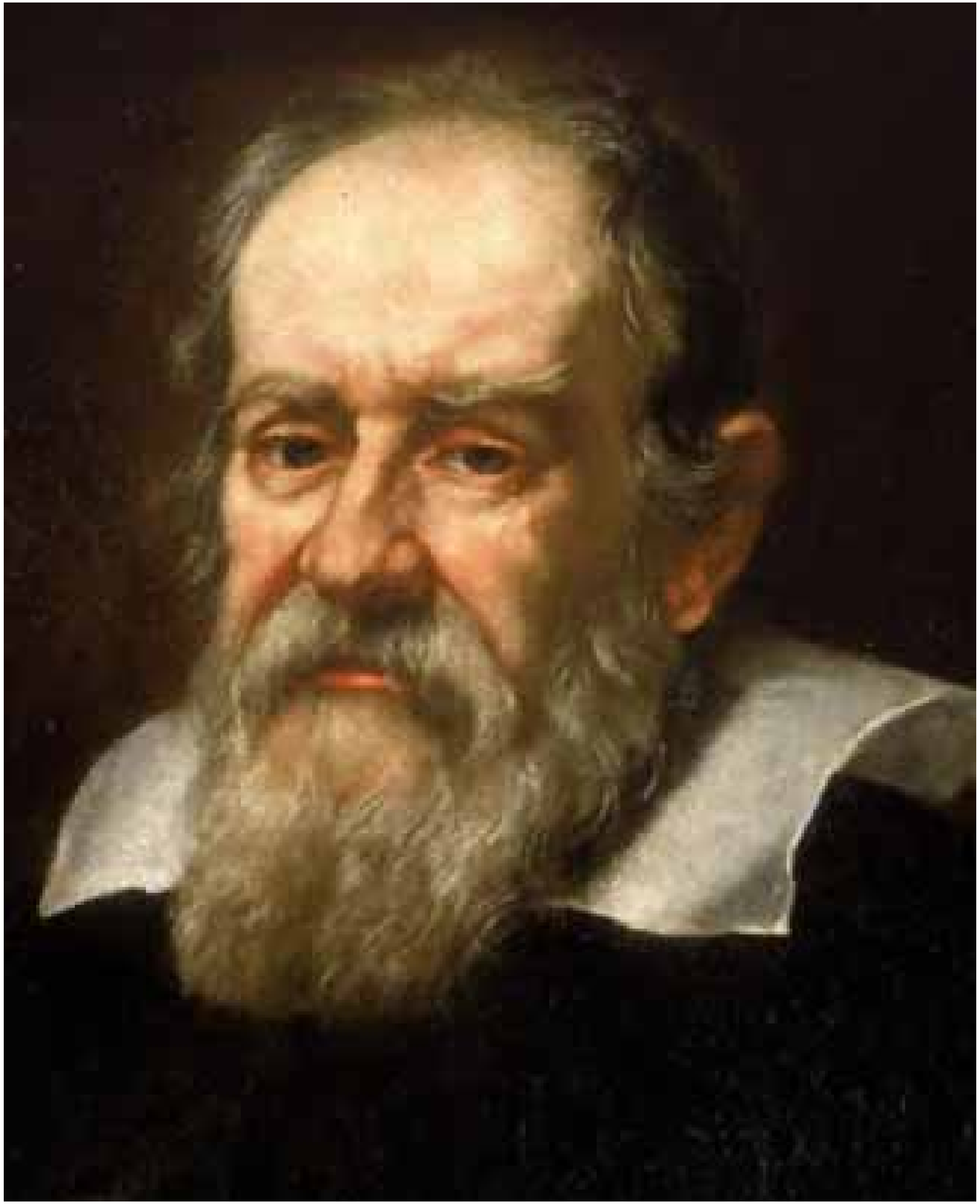
Galileo Galilei Colloquium
University of Pisa
1/15/09

What is relativity?

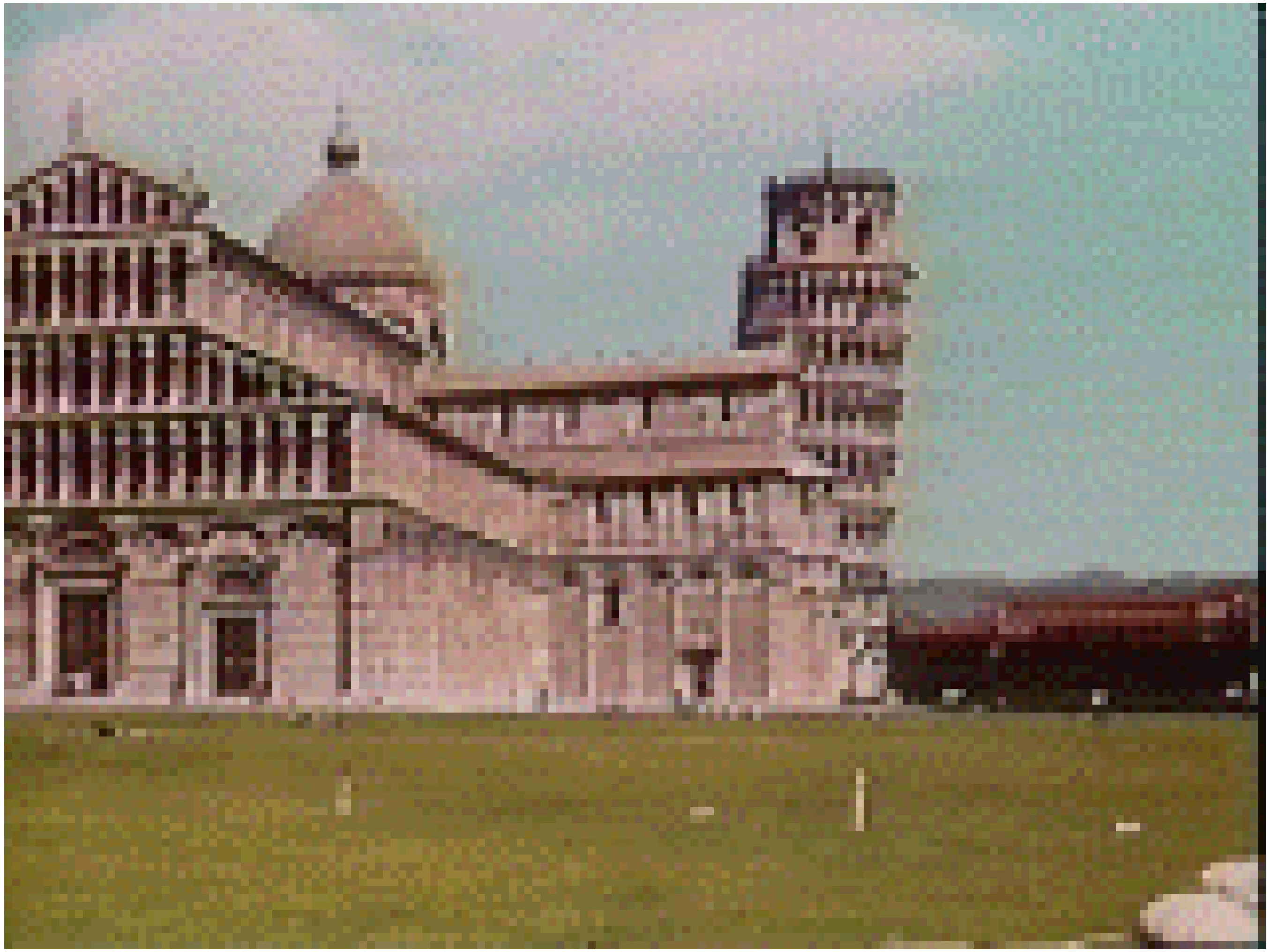
From Galileo Galilei to Albert Einstein and beyond

Toshi Tajima
LMU,MPQ

Acknowledgments for Advice and Collaboration: S. Bulanov, G. Mourou, T. Esirkepov, C. Barty, M. Fujiwara, M. Kando, K. Nakajima, A. Chao, Y.Fukuda, D. Habs, F. Krausz, M. Nozaki, T. Tauchi, K, Fujii, T. Takahashi, K. Homma, K. Ueda, K. Kawase, T. Omori, K. Yokoya, K. Kondo, F. Takasaki, A. Suzuki, Y .Kamiya, M. Hegelich, H. Gies, G. Dunne, T. Tanaka, V. Serbo, J. Rafelski, F. Pegoraro, M. Teshima, H. Sato, Y. Takahashi, G. Korn, P. Chen



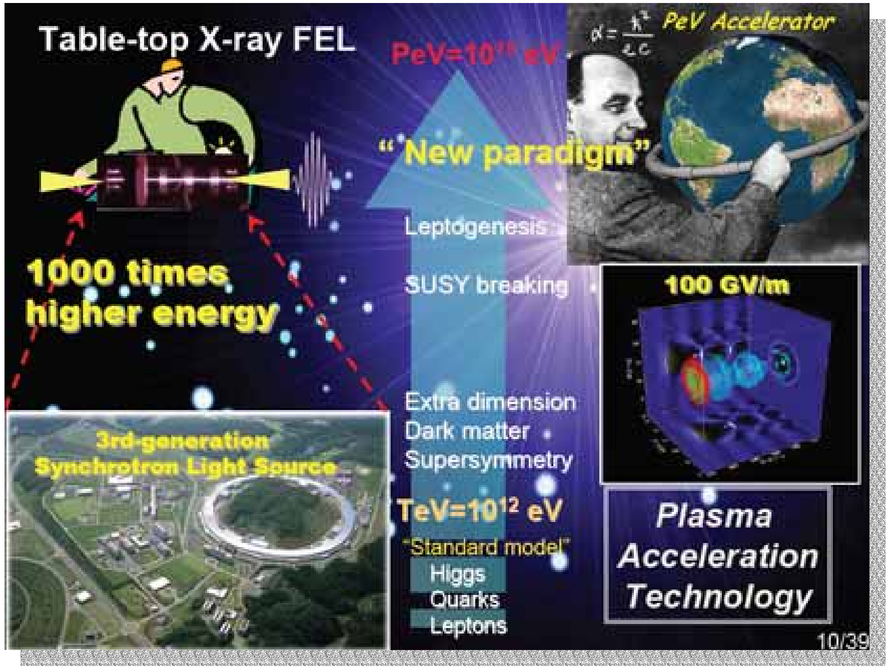
Galileo Galilei
(1564-1642)

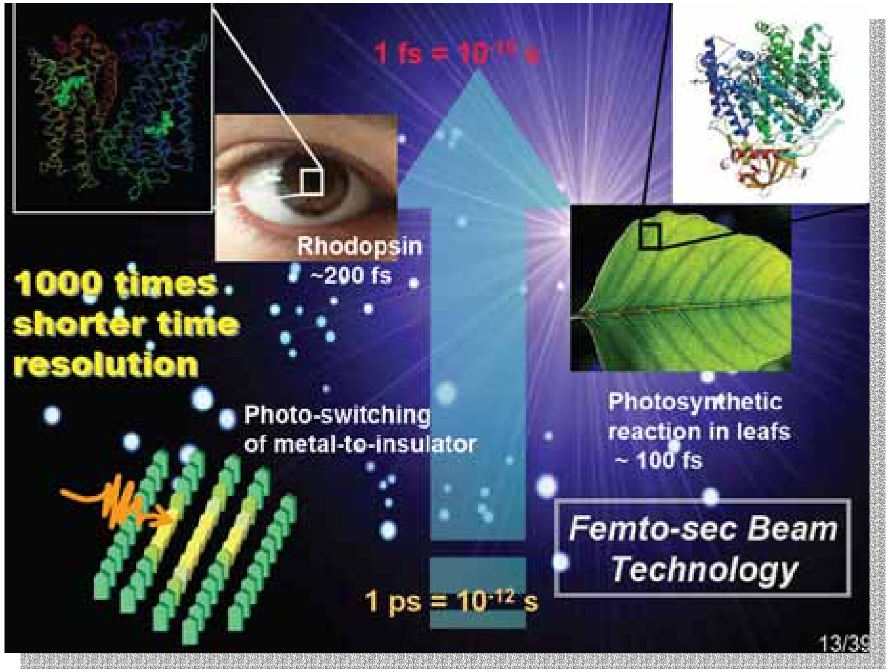


The most famous site for experimental science,
the *birth place of (empirical) physics* (as distinct from Aristotlean metaphysics): Pisa

Challenges

Frontier science driven by advanced accelerator



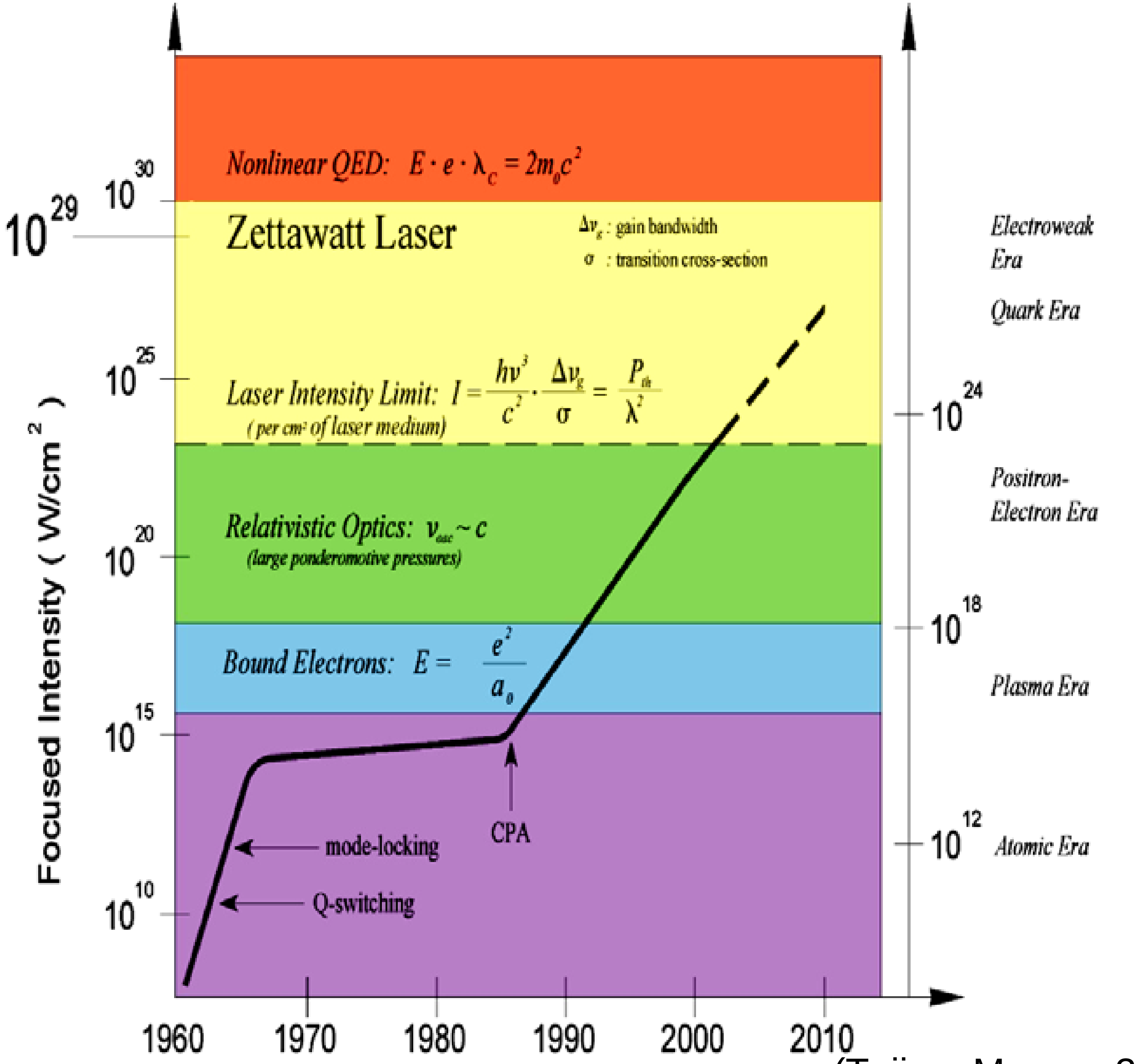


(Suzuki,KEK,2007)

compact, ultrastrong *a* atto-, zeptosecond

Can we meet the challenge?
How can we meet it ?

Lasers



(Tajima,Mourou,2002)

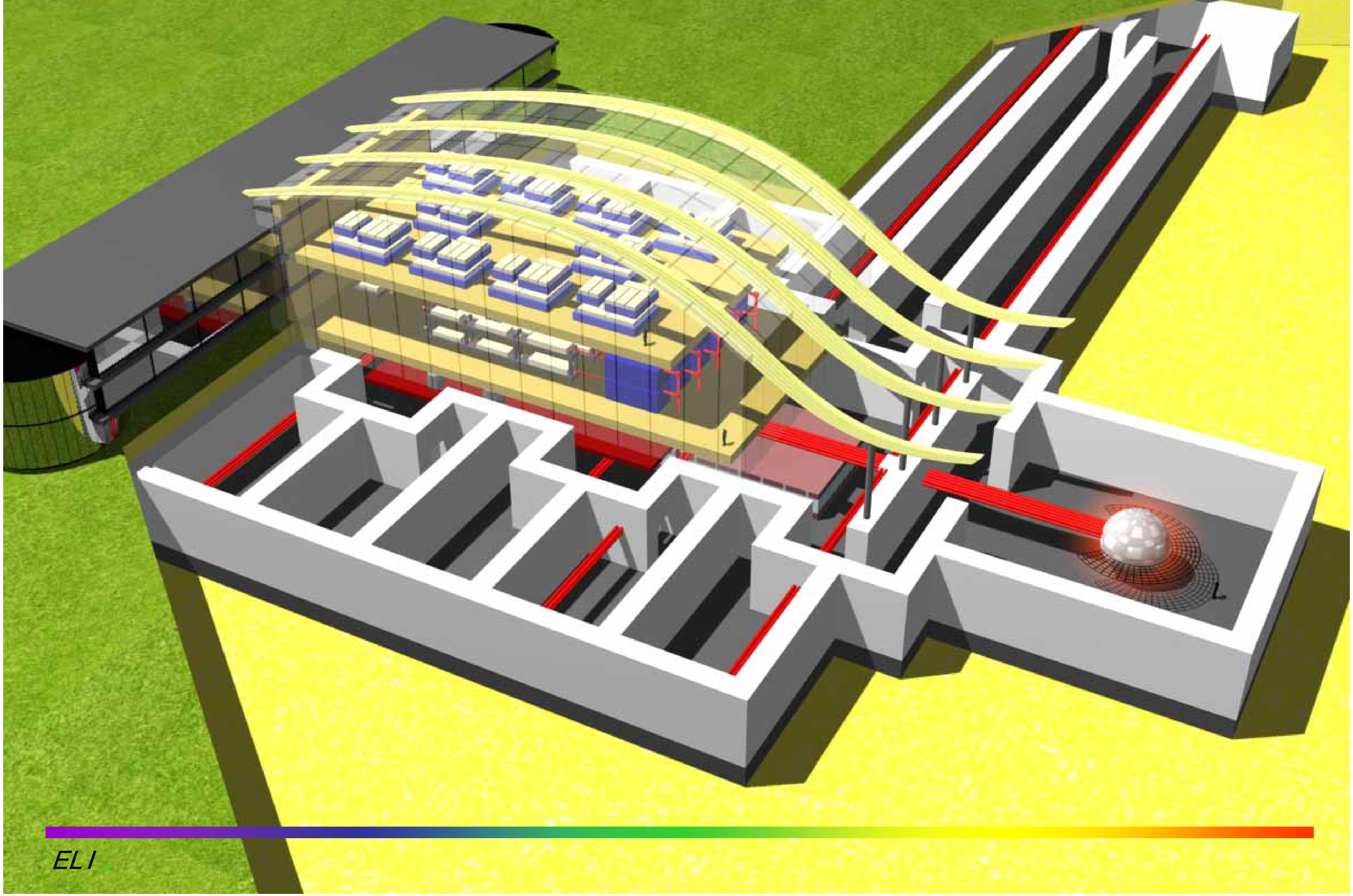
High Peak Power Laser

- 100TW/10Hz system is on a commercial base.
- 1PW with a low rep. rate system is also on a commercial base.
- 1PW/10Hz system could be possible with improving 100TW/10Hz system.

  A larger aperture ceramic YAG could be used for pumping the final Ti:S amplifier.
- A large aperture deformable can be used for tight focusing.

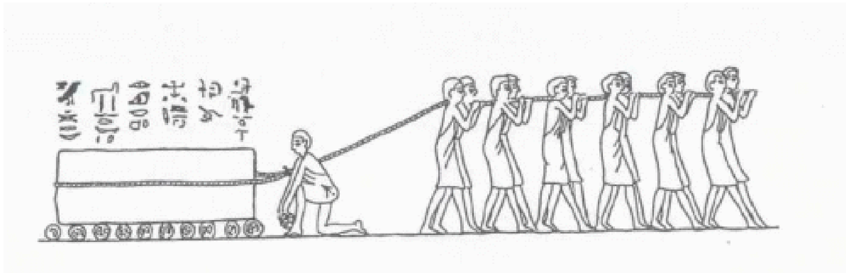
  → 10^22 W/cm^2 has been already achieved.
- now ELI ----- and other systems

ELI laser (artist's rendition)



What is *collective force*？

How can a Pyramid have been built?



<u>Individual</u> particle dynamics vs. <u>Coherent</u> movement

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

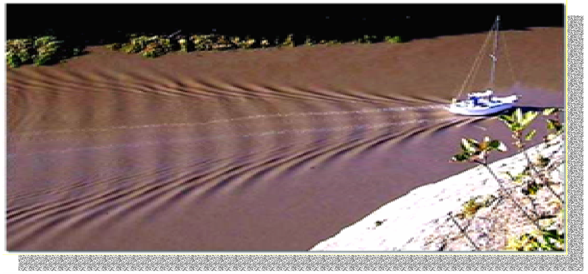
Collective radiation (N^2 radiation)

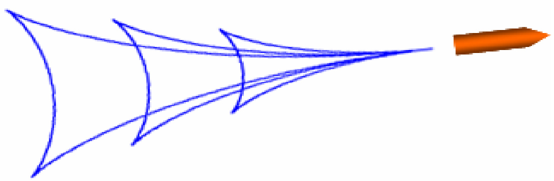
Collective ionization (N^2 ionization)

Collective deceleration (Tajima & Chao,2007; Kando et al,2008)

Wake

Kelvin's Ship Wake





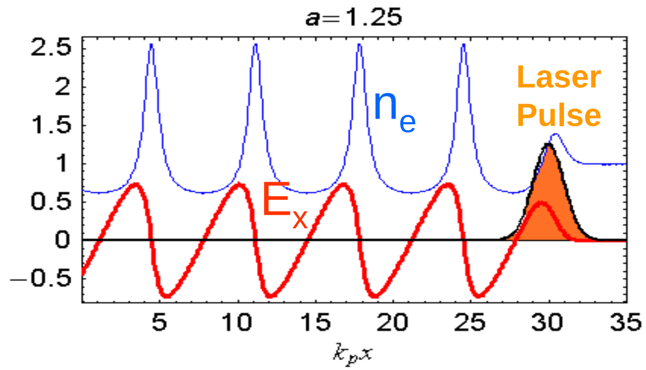
$$\omega = \sqrt{kg}$$

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

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

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

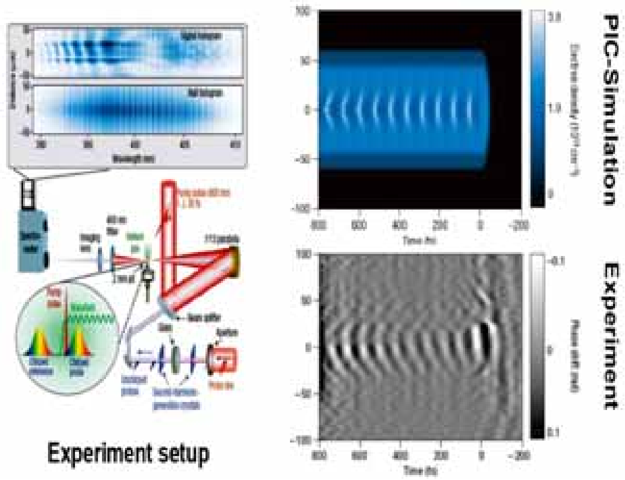
Laser Plasma Wake

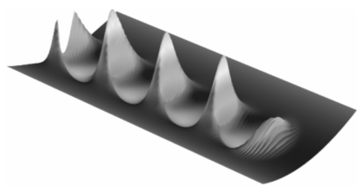


$$\lambda_p = 2\pi / k_p \qquad k_p v_{ph} = \omega_{pe}$$

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

Snapshots of Laser Wake Waves

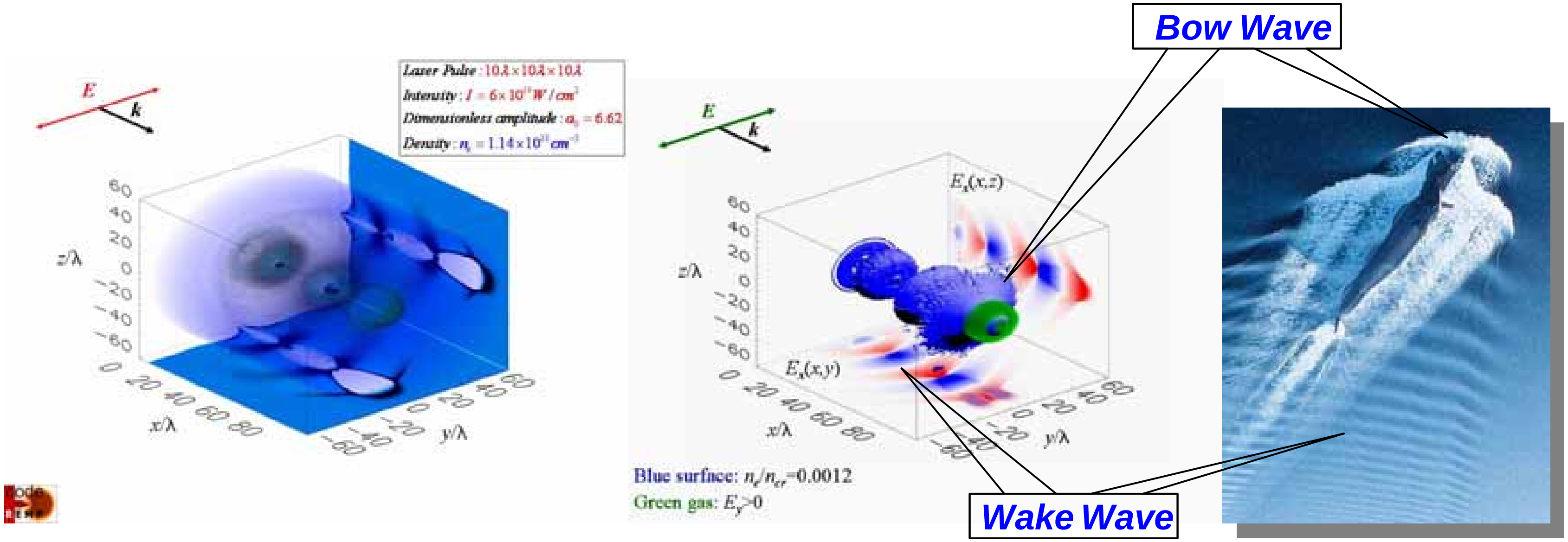


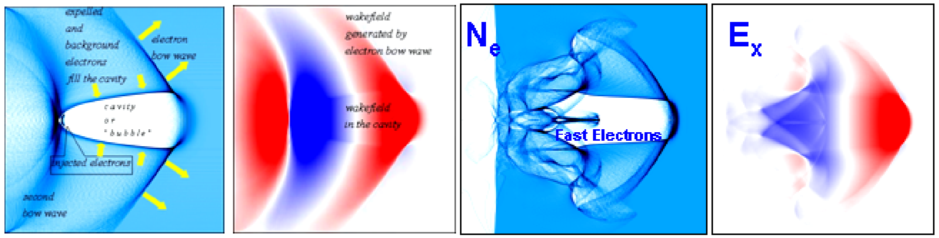


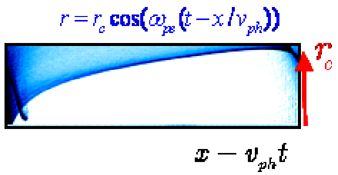
Paraboloidal Form of the Wake

N. H. Matlis et al, Nature Phys. (2006)

Laser-driven Bow and Wake







Depletion length

$$l_{depl} = l_{las} \frac{n_{cr}}{n} a_0$$

M87

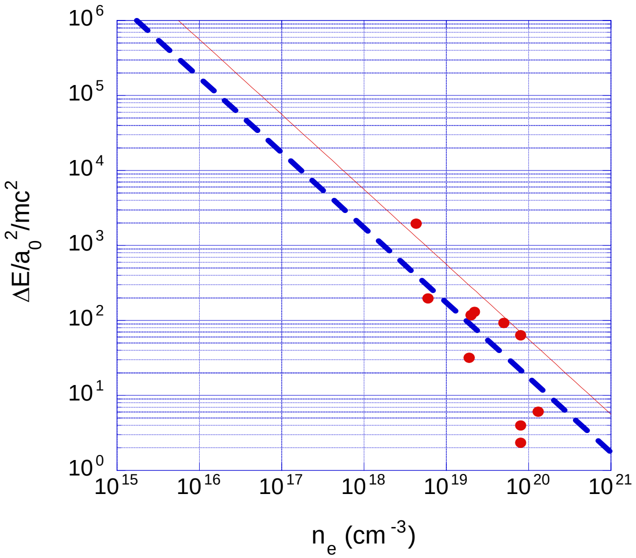
(Bulanov, Esirkepov)

Meeting Suzuki's Challenge:

Laser acceleration toward ultrahigh energies

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}{}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (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 gammas) are possible, albeit with lesser amount

→ exploration of new physics such as the reach of relativity and beyond?

(laser energy of 50kJ, plasma density of 10^{16}/cc)

Fundamental Physics following (and beyond)Einstein

Laser x Accelerator, Laser x Laser

→ **ELI's special unique capacity beyond any other infrastructure**

Quantum Gravity:
“Why is the sky blue?”
(for high energy gamma rays)

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

  high energy γ has dispersion:

  ω = kc + (extra mass-like term?)
- 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?

<u>Non-luminosity paradigm</u> possible (though in very high energies)?

Superstrong acceleration *a* = superstrong gravity *g*

The horizon approaches:
$d = c^2/a$

Quantum gravity extra-dimension leaks out? →

N·H
LSEVIER

18 June 1998

PHYSICS LETTERS B

Physics Letters B 429 (1998) 263–272

The hierarchy problem and new dimensions at a millimeter

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bstract

We propose a new framework for solving the hierarchy problem which does not rely on either supersymmetry or chnicolor. In this framework, the gravitational and gauge interactions become united at the weak scale, which we take as ie only fundamental short distance scale in nature. The observed weakness of gravity on distances $\gtrsim$ 1 mm is due to the cistence of $n \geq 2$ new compact spatial dimensions large compared to the weak scale. The Planck scale $M_{Pl} \sim G_N^{-1/2}$ is not fundamental scale; its enormity is simply a consequence of the large size of the new dimensions. While gravitons can eely propagate in the new dimensions, at sub-weak energies the Standard Model (SM) fields must be localized to a -dimensional manifold of weak scale "thickness" in the extra dimensions. This picture leads to a number of striking gnals for accelerator and laboratory experiments. For the case of $n = 2$ new dimensions, planned sub-millimeter ieasurements of gravity may observe the transition from $1/r^2 \to 1/r^4$ Newtonian gravitation. For any number of new imensions, the LHC and NLC could observe strong quantum gravitational interactions. Furthermore, SM particles can be icked off our 4 dimensional manifold into the new dimensions, carrying away energy, and leading to an abrupt decrease in vents with high transverse momentum $p_T \gtrsim$ TeV. For certain compact manifolds, such particles will keep circling in the ctra dimensions, periodically returning, colliding with and depositing energy to our four dimensional vacuum with equencies of $\sim 10^{12}$ Hz or larger. As a concrete illustration, we construct a model with SM fields localized on the -dimensional throat of a vortex in 6 dimensions, with a Pati-Salam gauge symmetry $SU(4) \times SU(2) \times SU(2)$ in the bulk.

. Introduction

There are at least two seemingly fundamental nergy scales in nature, the electroweak scale m_{EW} $\cdot 10^3$ GeV and the Planck scale $M_{Pl} = G_N^{-1/2} \sim$ 0^{18} GeV. Explaining the enormity of the ratio I_{Pl}/m_{EW} has been the prime motivation for con-tructing extensions of the Standard Model such as models with technicolor or low-energy supersymmetry. It is remarkable that these rich theoretical structures have been built on the assumption of the existence of two very disparate fundamental energy scales. However, there is an important difference between these scales. While electroweak interactions have been probed at distances approaching $\sim m_{EW}^{-1}$, gravitational forces have not remotely been probed at

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High energy cosmic gamma rays may experience the texture of vacuum at that energy (or distance)

→

Possibility to change the Lorentz transformation, the speed of light c varying

Tests of quantum gravity from observations of γ-ray bursts

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The recent confirmation that at least some γ-ray bursts originate at cosmological distances[1–4] suggests that the radiation from them could be used to probe some of the fundamental laws of physics. Here we show that γ-ray bursts will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. Many of the bursts have structure on relatively rapid timescales[5], which means that in principle it is possible to look for energy-dependent dispersion of the radiation, manifested in the arrival times of the photons, if several different energy bands are observed simultaneously. A simple estimate indicates that, because of their high energies and distant origin, observations of these bursts should be sensitive to a dispersion scale that is comparable to the Planck energy scale (~10^{19} GeV), which is sufficient to test theories of quantum gravity. Such observations are already possible using existing γ-ray burst detectors.

Our interest is in the search for possible *in vacuo* dispersion, $\delta v \approx E/E_{QG}$, of electromagnetic radiation from γ-ray bursts (GRBs), which could be sensitive to a type of candidate quantum-gravity effect that has been recently considered in the particle-physics literature. (Here E is the photon energy and E_{QG} is an effective quantum-gravity energy scale). This candidate quantum-gravity effect would be induced by a deformed dispersion relation for photons of the form $c^2\mathbf{p}^2 = E^2[1 + f(E/E_{QG})]$, where f is a model-dependent function of the dimensionless ratio E/E_{QG}, $\mathbf{p}$ is the photon momentum and c is the velocity of light. In quantum-gravity models in which the hamiltonian equation of motion $\dot{x}_i = \partial H/\partial p_i$ is still valid at least approximately, as in the frameworks discussed later, such a deformed dispersion relation would lead to energy-dependent velocities $c + \gamma v$ for massless particles, with implications for all the electromagnetic signals that we receive from astrophysical objects at large distances. At small energies $E \ll E_{QG}$, we expect that a series expansion of the dispersion relation should be applicable: $c^2\mathbf{p}^2 = E^2[1 + \xi E/E_{QG} + O(E^2/E_{QG}^2)]$, where $\xi = \pm 1$ is a sign ambiguity that would be fixed in a given dynamical framework. Such a series expansion would correspond to energy-dependent velocities:

$$v = \frac{\partial E}{\partial p} \approx c\left(1 - \xi \frac{E}{E_{QG}}\right) \quad (1)$$

This type of velocity dispersion results from a picture of the vacuum as a quantum-gravitational 'medium', which responds differently to the propagation of particles of different energies and hence velocities. This is analogous to propagation through a conventional medium such as an electromagnetic plasma[6]. The gravitational 'medium' is generally believed to contain microscopic quantum fluctuations, which may occur on scale sizes of order the Planck length $L_P \approx 10^{-33}$ cm on timescales of the order of $t_P \approx 1/E_P$, where $E_P \approx 10^{19}$ GeV. These may[7,8] be analogous to the thermal fluctuations in a plasma, that occur on timescales of the order of $t \approx 1/T$, where T is the temperature. As it is a much 'harder' phenomenon associated with new physics at an energy scale far beyond typical photon energies, any analogous quantum-gravity effect could be distinguished by its different energy dependence: the quantum-gravity effect would increase with energy, whereas conventional medium effects decrease with energy in the range of interest[6].

Equation (1) encodes a minute modification for most practical purposes, as E_{QG} is believed to be a very high scale, presumably of the order of the Planck scale $E_P \approx 10^{19}$ GeV. Even so, such a deformation could be rather significant for even moderate-energy signals, if they travel over very long distances. According to equation (1), a signal of energy E that travels a distance L acquires a 'time delay', measured with respect to the ordinary case of an energy-independent speed c for massless particles:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \frac{L}{c} \quad (2)$$

This is most likely to be observable when E and L are large while the interval δt, over which the signal exhibits time structure, is small. This is the case for GRBs, which is why they offer particularly good prospects for such measurements, as we discuss later.

We first review briefly how modified laws for the propagation of particles have emerged independently in different quantum-gravity approaches. The suggestion that quantum-gravitational fluctuations might modify particle propagation in an observable way can already be found in refs 7 and 9. A phenomenological parametrization of the way this could affect the neutral kaon system[9–11] has been already tested in laboratory experiments, which have set lower limits on parameters analogous to the E_{QG} introduced above at levels comparable to E_P (ref. 12). In the case of massless particles such as the photon, which interests us here, the first example of a quantum-gravitational medium effect with which we are familiar occurred in a string formulation of an expanding Robertson–Walker–Friedman cosmology[13], in which photon propagation appears tachyonic. Deformed dispersion relations that are consistent with the specific formula in equation (1) arose in approaches based on quantum deformations of Poincaré symmetries[14] with a dimensional parameter. Within this general class of deformations, one finds[14,15] an effect consistent with equation (1) if the deformation is rotationally invariant: the dispersion relation for massless particles $c^2\mathbf{p}^2 = E_{QG}^2[1 - \exp(E/E_{QG})]^2$, and therefore $\xi = 1$. We noted that a deformed dispersion relation has also been found in studies of the quantization of point particles in a discrete space time[16].

A specific and general dynamical framework for the emergence of the velocity law (equation (1)) has emerged[17] within the Liouville string approach[7] to quantum gravity, according to which the vacuum is viewed as a non-trivial medium containing 'foamy' quantum-gravity fluctuations. The nature of this foamy vacuum may be visualized by imagining processes that include the pair creation of virtual black holes. Within this approach, it is possible to verify that massless particles of different energies excite vacuum fluctuations differently as they propagate through the quantum-gravity medium, giving rise to a non-trivial dispersion relation of Lorentz 'non-covariant' form, just as in a thermal medium. The form of the dispersion relation is not known exactly, but its structure has been studied[17] via a perturbative expansion, and it was shown in ref. 17 that the leading $1/E_{QG}$ correction is in agreement with equation (1).

It has been recently suggested[8] the vacuum might have analogous 'thermal' properties in a large class of quantum-gravity approaches, namely all approaches in which a minimum length L_{min}—such as the Planck length $L_P \approx 10^{-33}$ cm—characterizes short-distance physics. These should in general lead to deformed photon dispersion relations with $E_{QG} \approx 1/L_{min}$, though the specific form of equation (1) may not hold in all models, and hence may be used to discriminate between them. In support of equation (1), though, we recall[15,17] that this type of non-trivial dispersion in the quantum-gravity vacuum has implications for the measurability of distances in quantum gravity that fit well with the intuition emerging from

Observation of positron excess from high energy gamma rays (PAMELA observation)

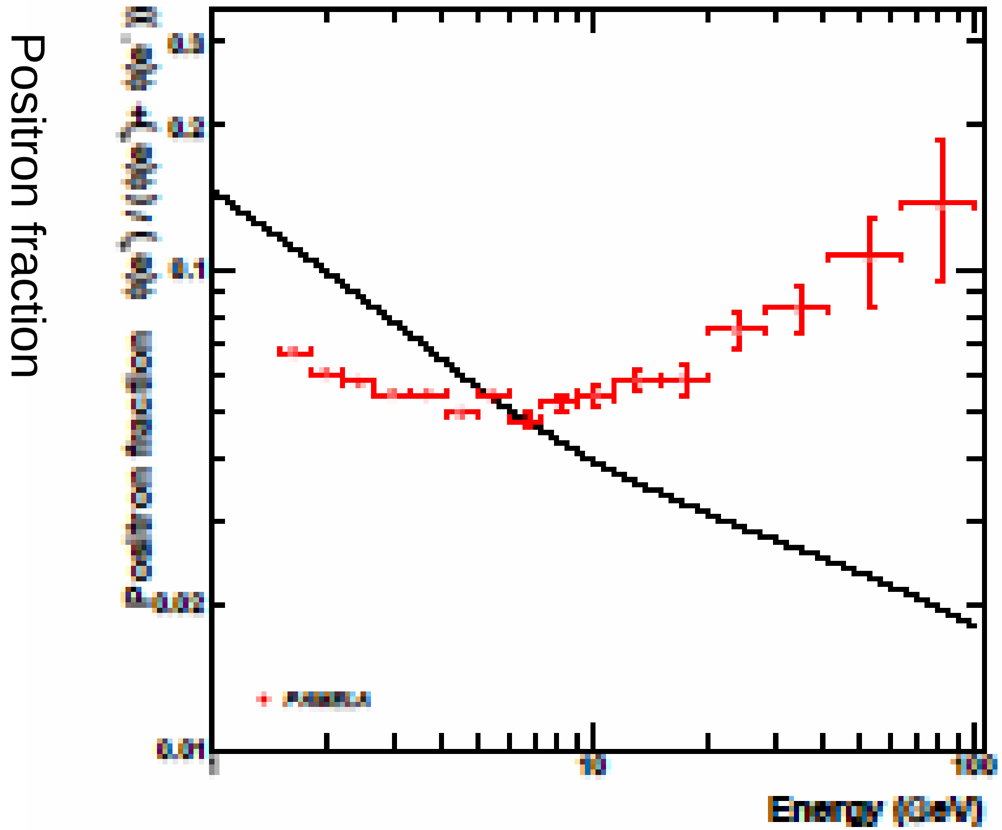


FIG. 4: PAMELA positron fraction with theoretical models. The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.

O. Adriani, et al. (2008)
(Pamela collaboration):
"Observation of an anomalous positron abundance in the cosmic radiation"

One way Preparing for the Future following Galilei's adventure

- Laser acceleration (and intense laser irradiation in 'vacuum'):
  revolutionary step, 3-4 orders of magnitude leap in size and accuracy
- Collider paradigm (smaller and cheaper collider?)
  quantum mechanics $\Delta E \Delta t \sim \hbar \rightarrow \mathscr{L} \propto E^2$
- Non-collider approaches
  <u>relativity: the higher the energy, the pronounced the effect</u>
  - horizon ~ 1/ a (extradimensions?)
  - $a = g$?
  - Unruh-Hawking radiation?
  - special theory (*no preferred frame*?) vs Big Bang
  - coherence and macroscopic field effects---temporal domain
  - <u>extreme field physics</u> (merger of research on special and general theories of relativity)
    property of vacuum (QED, QCD(axion), dark energy,…)

From an ELI Workshop talk (Gies, 2008)

Conclusions

▷ Why strong-field physics ...?

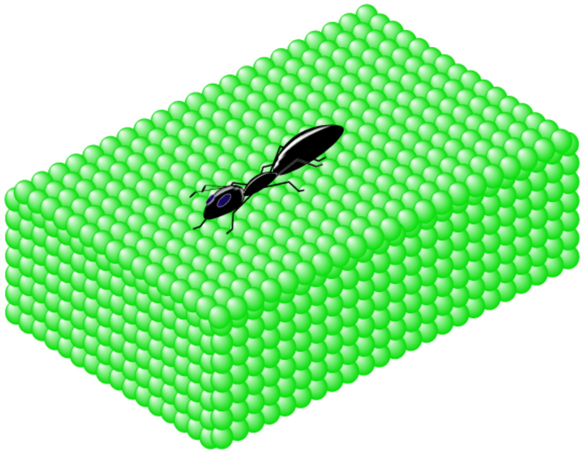
- "...exploring some issues of fundamental physics that have eluded man's probing so far" (TAJIMA'01)

- 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

What is vacuum?
What is relativity?

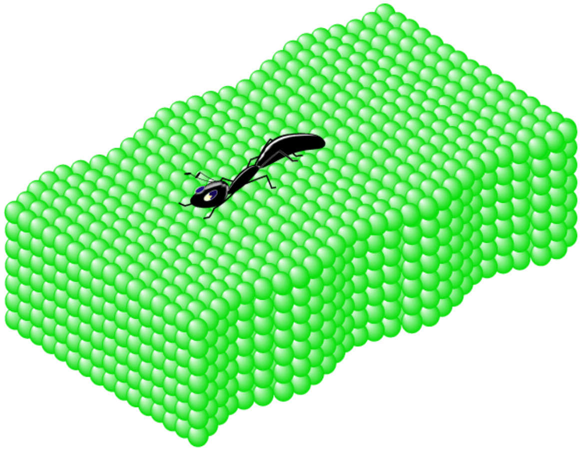


An observer in a crystal as vacuum

↓

「(真)空」
'(true) vacuum'

「Wiltanschauung of Buddhist」

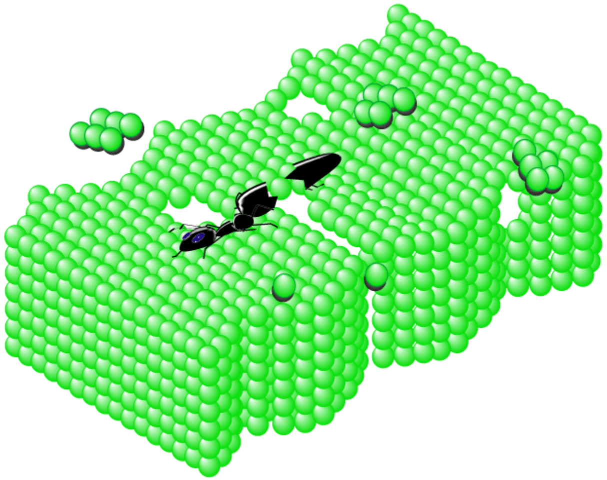


Phonon is an excitation of vacuum

↓

Photon is a distortion of vacuum

「色即是空」
' "color (phenomena)" = vacuum'

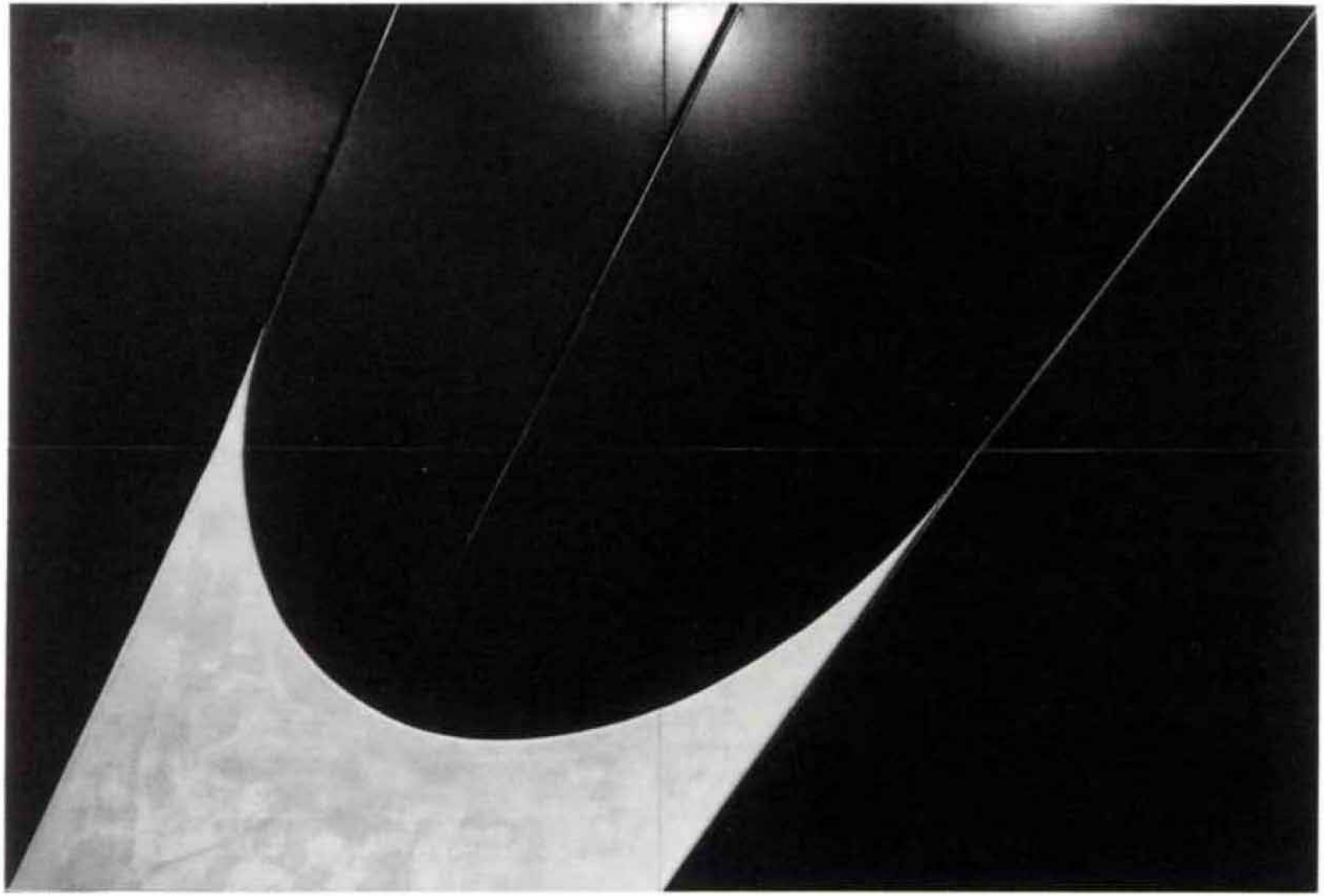


Strong field breaks vacuum

↓

e+e- pair production
out of vacuum

「空即是色」
'vacuum = "color (matter)" '



98　高橋　秀　《宇宙起源》　1988年
TAKAHASHI, Shu　*Principio dell'Universo*

(original colors are red and black)

Lucio Fontana (1961)
Space Concept M364

Check of Special and General Relativity

Check of Equivalence Principle
by neutron interferometry→
under small *a*

How far have we checked,
can we check?

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

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(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

In most phenomena of interest in terrestrial physics, gravity and quantum mechanics do not *simultaneously* play an important role. Such an experiment, for which the outcome necessarily depends upon both the gravitational constant and Planck's constant, has recently been proposed by two of us.[1]

A neutron beam is split into two beams by an interferometer of the type first developed by Bonse and Hart[2] for x rays. The relative phase of the two beams where they recombine and interfere, at point D of Fig. 1, is varied by rotating the interferometer about the line AB of the incident beam. The dependence of the relative phase β on the rotation angle φ is

$$\beta = q_{\text{grav}} \sin\varphi, \tag{1}$$

where

$$q_{\text{grav}} = 4\pi\lambda g h^{-2} M^2 d(d + a\cos\theta)\tan\theta. \tag{2}$$

The neutron wavelength is $\lambda = 1.445$ Å, g is the acceleration of gravity, h is Planck's constant, M is the neutron mass, and θ is the Bragg angle, 22.1°. The dimensions $a = 0.2$ cm and $d = 3.5$ cm are shown in Fig. 1. $q_{\text{grav}}/\pi = (\Delta N)_{180}$, the number of fringes which will occur during a 180° rotation. Except for the term $a\cos\theta$, which accounts for the thickness of the interferometer slabs, Eq. (2) is equivalent to Eq. (8) of Ref. 1. For our experiment $(\Delta N)_{180} \approx 19$ fringes.

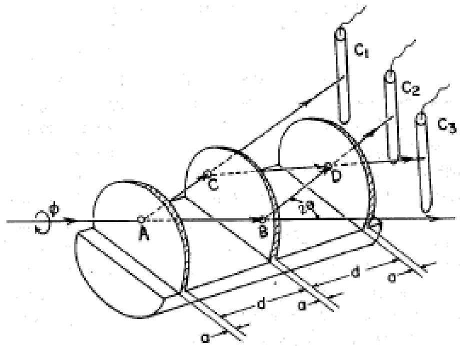

FIG. 1. Schematic diagram of the neutron interferometer and [3]He detectors used in this experiment.

The interferometer was cut from a dislocation-free silicon crystal approximately 2 in. in diameter and 3 in. long. Our particular design was chosen so that the experiment could also be carried out with 0.71-Å x rays. This is extremely important because the bending of the interferometer under its own weight varies with φ and introduces a contribution q_{bend} to β:

$$\beta = (q_{\text{grav}} + q_{\text{bend}}) \sin\varphi. \tag{3}$$

The major problem was finding[3] a method for mounting the crystal so that the relative phase β is constant across the transverse dimensions (3 mm× 6 mm) of the interfering beams at D. The best results were obtained with the crystal freely resting on two felt strips (3 mm wide and perpendicular to the axis of the cylindrical crystal). These strips were located 15 mm from either end of a V block equal in length to the crystal. This arrangement limited rotations to $-30° < \varphi < 30°$.

Three small, high-pressure He[3] detectors were used to monitor one noninterfering beam (C_1) and the two interfering beams (C_2 and C_3) as shown in Fig. 1. These detectors, the interferometer, and an entrance slit were rigidly mounted in a metal box which could be rotated about the incident beam. This entire assembly was placed inside an auxiliary neutron shield.

The counting rates at C_2 and C_3 are expected to

More check of Equivalence Principle

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Measurement of Neutron Quantum Interference in Noninertial Frames

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(Received 11 July 1983)

Neutron interferometry has been performed on an accelerated interferometer under conditions where gravitational effects on the interfering beams very nearly compensate each other. The observed neutron phase shift is found to be in excellent agreement with that calculated from Schrödinger's equation transformed to the accelerated frame where it is found essential to include the spherical wave aspect. The present experiment thus verifies the validity of the classical transformation laws for noninertial frames also in the quantum limit.

PACS numbers: 03.65.Bz, 14.20.Dh

The influence of gravity on the phase in a neutron interferometer was measured by Colella, Werner, and Overhauser in a series of beautiful experiments which have become known as the COW experiment.[1,2] In these investigations a single-crystal interferometer of Laue type[3,4] is used which is rotated about the incident beam so that the interfering beams travel at different height (and thus potential) in the gravitational field. From the observed interference pattern a gravity-induced phase shift is deduced which increases with increasing potential difference between the two interfering beams. Apart from corrections which were attributed to bending of the interferometer crystal, the major part of the observed phase shift could be calculated from Schrödinger's equation by introducing the varying gravitational potential $-m_g\vec{g}\cdot\vec{r}$ as an ordinary potential[5-8] into the equation. The conclusion drawn from the COW experiment was that the classical principle of equivalence has been experimentally proven to be valid also in the quantum limit.[8] This means that the laws of quantum physics are the same in a frame with gravitational potential $-m_g\vec{g}\cdot\vec{r}$ as in a corresponding frame lacking this potential but having acceleration $-\vec{g}$ instead. It was noted by COW themselves[8] that, strictly speaking, there is a missing link in the argument and that a complete test of the equivalence principle in the quantum limit would involve repeating the experiment in an accelerated frame of reference traveling in gravitation-free space. However, COW surmised such an experiment unnecessary "if we believe that the Schrödinger equation holds in an accelerated frame."[8] We considered this belief to be worth checking by experiment in a very direct manner.

In our experiment the interferometer is accelerated (while oscillating in the horizontal plane) and the neutrons are free from any force (potential) in that plane, while in the COW experiment the interferometer is at rest and the neutrons are subject to the gravitational potential. Thus our experiment yields complementary information.

With the D18 neutron interferometer at the Institute Laue-Langevin in Grenoble we noted the sensitivity of the interference pattern to vibrations.[9,10] Following these observations we designed a special traverse support for the interferometer crystal in order to expose it to controlled forced oscillations normal to the (220) Bragg planes that served for division and recombination of the interfering beams. The principal experimental setup is illustrated in Fig. 1. The traverse features leaf-spring guidance for smooth and practically frictionless movement. The interferometer performs sinusoidal oscillation when it is driven by a function generator via a pair of standard loudspeaker magnets the coils of which are coupled to the sliding part of the traverse. The leaf springs have a structure of special design by which spurious rotation is kept below the detection limit of 0.7 μrad. This is an essential point since rotation can cause an additional phase shift of its own.[8,11-14]

In a typical measurement, the intensity I_0 of the outgoing beam is measured in a stroboscopic manner at the inversion points of the oscillation, i.e., when the momentary acceleration $a_\pm$ corresponds to $a_+ = X_0\omega^2$ and $a_- = -X_0\omega^2$, respectively, where X_0 is the amplitude and ω the frequency of the oscillation. In order to obtain a complete

Check of Special Relativity

PHYSICAL REVIEW LETTERS

VOLUME 63 | 9 OCTOBER 1989 | NUMBER 15

Results of a New Test of Local Lorentz Invariance: A Search for Mass Anisotropy in ^{21}Ne

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(Received 23 March 1989; revised manuscript received 10 July 1989)

We test Lorentz invariance by searching for a time-dependent quadrupole splitting of Zeeman levels in ^{21}Ne. A component at twice the Earth's sidereal frequency would suggest a preferred direction which affects the local physics of the nucleus. The technique employs polarized ^{21}Ne and ^{3}He gases produced by spin exchange with laser optically pumped Rb. Both species are contained in the same glass cell; ^{3}He provides magnetometry and a monitor of systematic effects. Our data produce an upper limit (1σ confidence level) of 2×10^{-21} eV (0.45×10^{-6} Hz) on the Lorentz-invariance–violating contribution to the binding energy. This result is comparable to that of the most precise previous experiment.

PACS numbers: 04.80.+z, 07.58.+g, 32.60.+i

Local Lorentz invariance (LLI) along with the postulates of local position invariance and the weak equivalence principle form the Einstein equivalence principle, the basis of all single-metric gravitational theories.[1,2] LLI requires that the local, nongravitational physics of a bound system of particles be independent of its velocity and orientation relative to any preferred frame, for example, the rest frame of the Universe.[3] If LLI were violated and such a frame existed, the energy levels of a bound system such as a nucleus could be shifted in a way that correlates the motion of the bound particles in each state with the preferred direction. Such a shift would lead to an orientation-dependent binding energy, i.e., an anisotropy of inertial mass. The lowest-order, nonvanishing effect of this sort would lead to a quadrupole splitting of the nuclear Zeeman levels since a dipole coupling of the preferred direction to the position or velocity of the particles in the bound system would have vanishing expectation value. (We note, however, that there may exist the coupling of the dipole moment of the nucleus to a cosmic field such as that of relic neutrinos or that postulated to be produced by axions.[4]) The first tests of this sort, known as Hughes-Drever experiments, were performed by Hughes, Robinson, and Beltran-Lopez[5] and by Drever,[6] with modern, much more precise measurements by Prestage *et al.*[7] and by Lamoreaux *et al.*[8] The most precise previous measurement[8] set a 2σ upper limit of 0.5×10^{-6} Hz on any such LLI-violating quadrupole splitting, which is 10^{-28} of the binding energy per nucleon. Our work provides a comparable limit.

We have chosen ^{21}Ne with nuclear spin $I_{21}=\frac{3}{2}$ to perform such a test. A mixture of ^{21}Ne and ^{3}He (nuclear spin $I_3=\frac{1}{2}$) can be simultaneously polarized by spin exchange with laser optically pumped Rb vapor.[9–11] The energy differences among the Zeeman levels of each species are measured by observing the free precession of the spins. The ^{21}Ne would be sensitive to the preferred direction, leading to a shift of the $m=\pm\frac{3}{2}$ levels different from that of the $m=\pm\frac{1}{2}$ levels. The ^{3}He is not sensitive to the quadrupole splitting and has the multiple role of a magnetometer and a monitor of systematic effects.

The apparatus is shown in Fig. 1. The laser system is a krypton-ion laser pumping LD-700 dye in a standing-wave, multimode dye laser. A 500-mW diode-laser array has also been used; however, the results presented here are based on runs with the dye-laser system. The laser light optically pumps the Rb-$D1$ resonance line which is pressure broadened so that the absorption linewidth is about 25 GHz. The Rb is contained in a nearly spherical alumino-silicate glass cell with about 400 Torr (at 300 K) each of ^{21}Ne and ^{3}He and 60 Torr of N_2 to

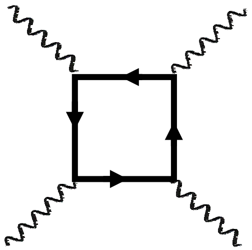
Laser Energy & Power Required to Achieve the Schwinger Field

The driver and source must carry **10 kJ** and **30 J**, respectively
(**Parameters on the order of ELI and HiPER Lasers**)

Reflected intensity can approach **the Schwinger limit**

$$E_{QED} = \frac{m_e^2 c^3}{e\hbar}$$

It becomes possible to investigate such the fundamental problems of nowadays physics, as e.g. the electron-positron pair creation in vacuum and the photon-photon scattering



$$\mathcal{L} = \frac{1}{16\pi} F_{\alpha\beta} F^{\alpha\beta} - \frac{\kappa}{64\pi}\left[5\left(F_{\alpha\beta}F^{\alpha\beta}\right)^2 - 14 F_{\alpha\beta}F^{\beta\gamma}F_{\gamma\delta}F^{\delta\mu}\right]$$

The critical power for nonlinear vacuum effects is $\mathcal{P}_{cr} = \frac{45\pi^2}{\alpha}\frac{cE_{QED}^2\lambda^2}{4\pi}$

for $\lambda = 1\mu m$ it yields $\mathcal{P}_{cr} \approx 2.5 \times 10^{24} W$

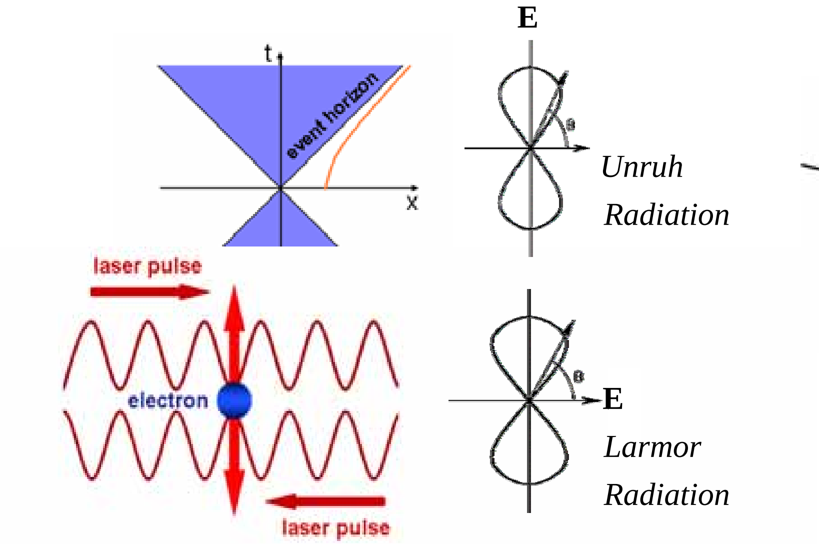
Light compression and focusing with the FLYING MIRRORS yields

for $\lambda = \lambda_0 / 4\gamma_{ph}^2$ $\mathcal{P} = \mathcal{P}_0 \gamma_{ph}$ with $\gamma_{ph} \approx 30$ the driver power $\mathcal{P}_{cr} \approx 10 PW$

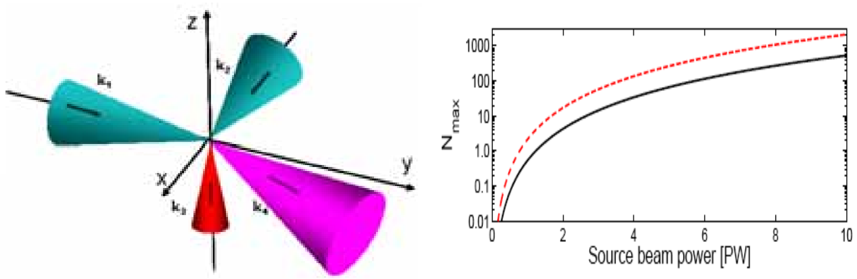
(Bulanov et al 2003)

Laser self-focuses in vacuum with RE!

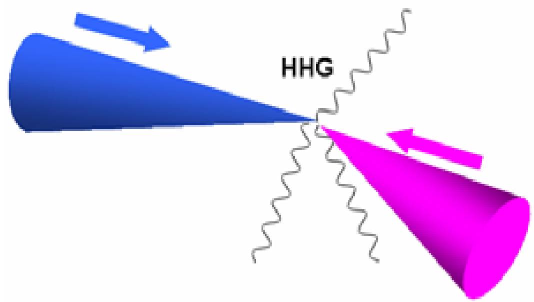
Some on Horizon of High Field Science



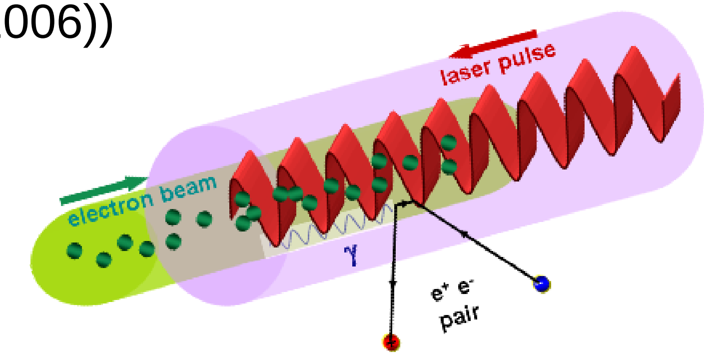
Unruh radiation (Chen&Tajima (1999))



4-wave mixing (Lundström et al (2006))



Higher harmonic generation through quantum vacuum interaction (Fedotov & Narozhny (2006))

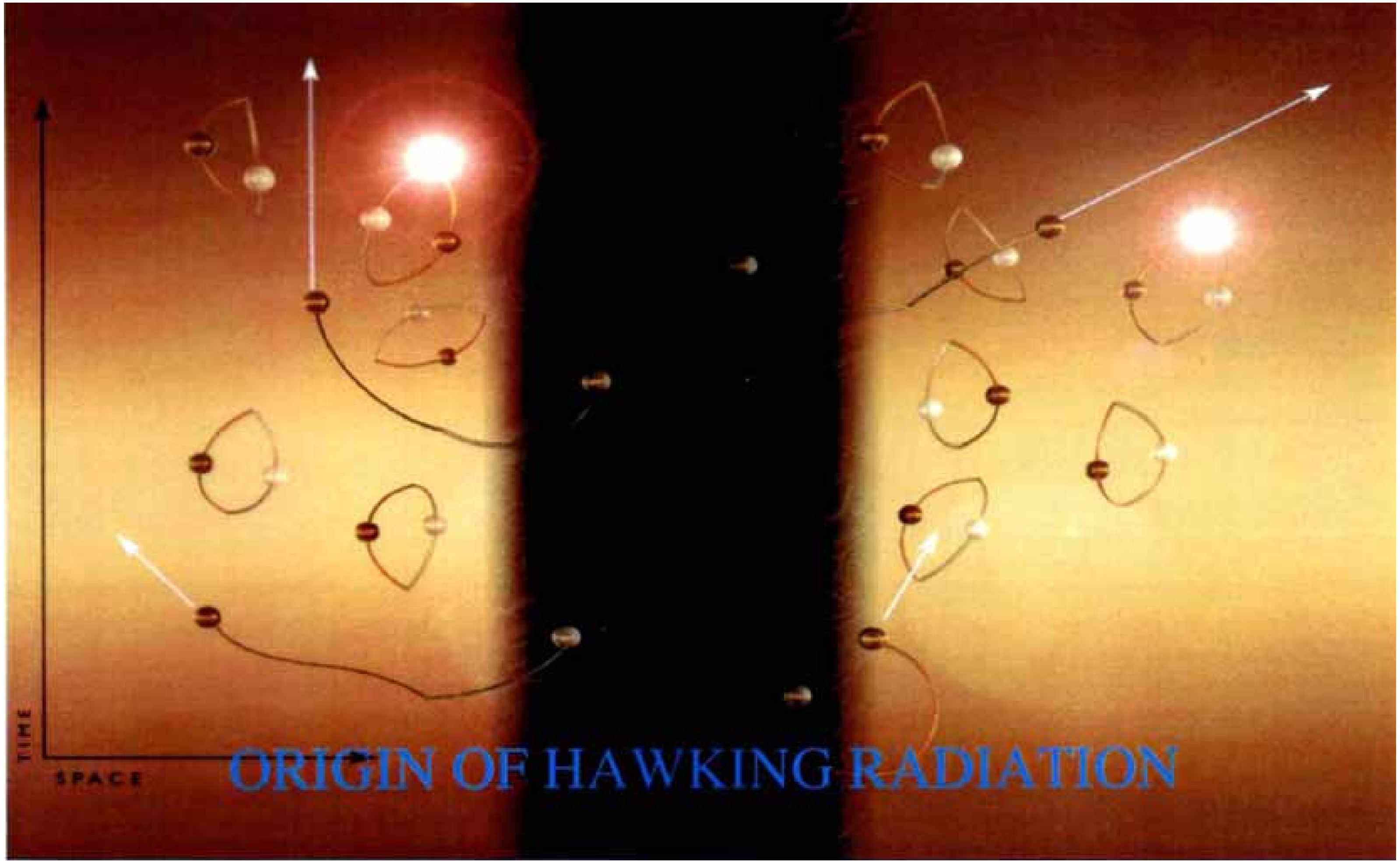


Electron-positron pair production in the laser interaction with the electron beam

$e^+ + n\gamma \rightarrow \gamma, \ \gamma + n\gamma' \rightarrow e^+ + e^-$

(Bula et al (1996); Burke et al (1997))

Hawking radiation



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

「空」＝「色」？ 「混沌」⇔「秩序」？

vacuum = ‘matter‘ ? chaos ⇔ information ?

Event Horizon Analog?,…..

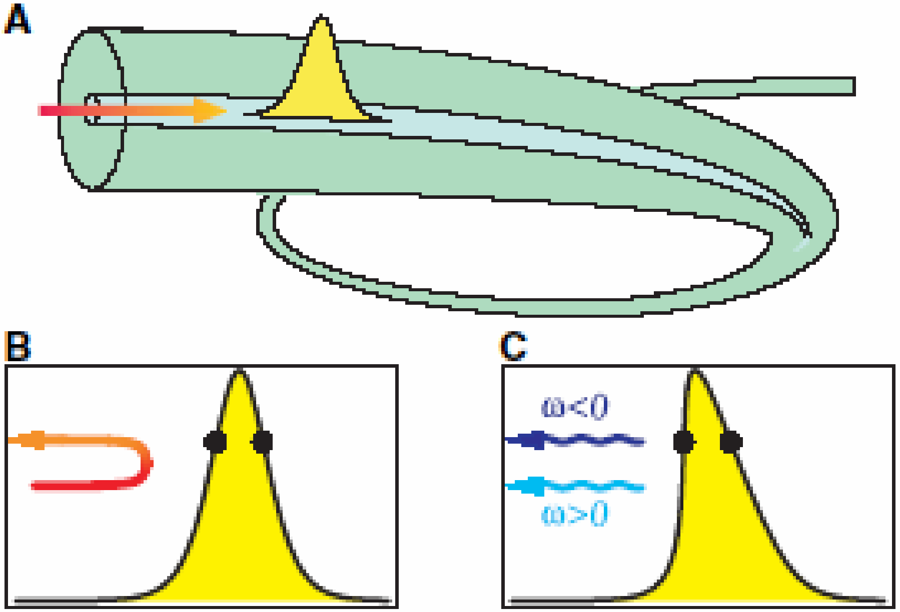


Fig. 1. Fiber-optical horizons. **(A)** A light pulse in a fiber slows down infrared probe light, attempting to overtake it. The diagrams below are in the co-moving frame of the pulse. **(B)** Classical horizons. The probe is slowed down by the pulse until its group velocity matches the pulse speed at the points indicated by black dots, establishing a white-hole horizon at the back and a black-hole horizon at the front of the pulse. The probe light is blue-shifted at the white hole until the optical dispersion releases it from the horizon. **(C)** Quantum pairs. Even if no probe light is incident, the horizon emits photon pairs corresponding to waves of positive frequencies from the outside of the horizon paired with waves at negative frequencies from beyond the horizon. An optical shock has steepened the pulse edge, increasing the luminosity of the white hole.

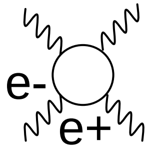
T.Philbin et al., Science **319**, 1367 (2008)

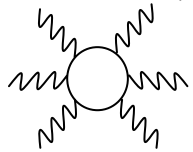
Higher order QED and QCD

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

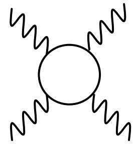
$$\frac{\alpha}{\pi}F^2 \to \left\langle \frac{\alpha_s}{\pi}G^2 \right\rangle + \frac{\alpha}{\pi}q^2F^2 \qquad \left\langle 0 \middle| \frac{\alpha_s}{\pi}G^2 \middle| 0 \right\rangle \approx (2.3 \pm 0.3)10^{-2}GeV^4$$

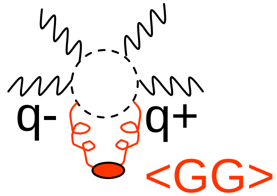
(K.Homma, 2007)

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

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

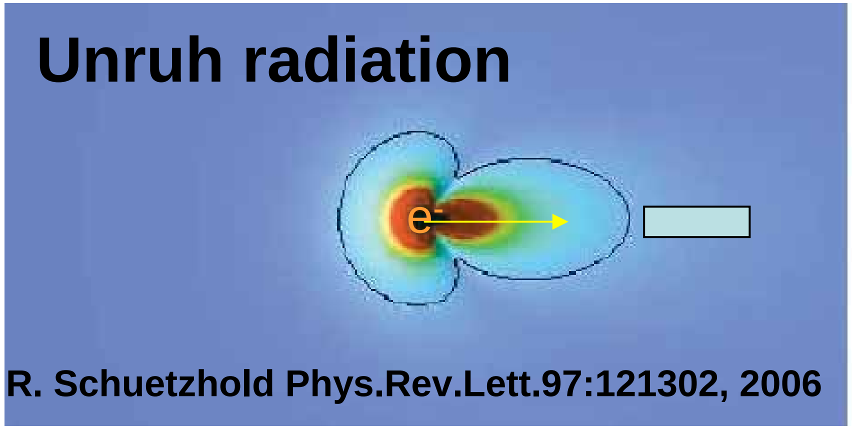
Check of Euler-Heisenberg yet to come. Any deviation from it?

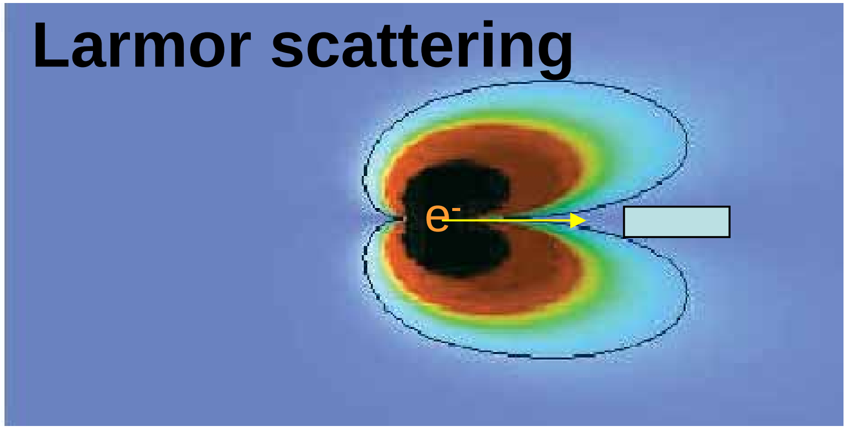
→ axion field?; extended fields(such as dark energy, Tajima-Niu, 1997, etc.)?

Explore relativity with strong fields (Unruh radiation)

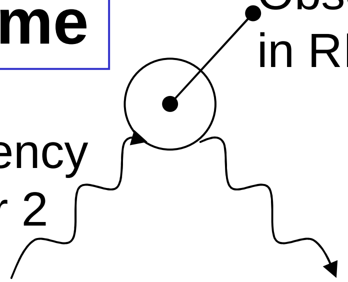
$I = 10^{17}[W/cm^2] \Rightarrow E \approx 10^{12}[V/m]$ (Chen, Tajima,1999)

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





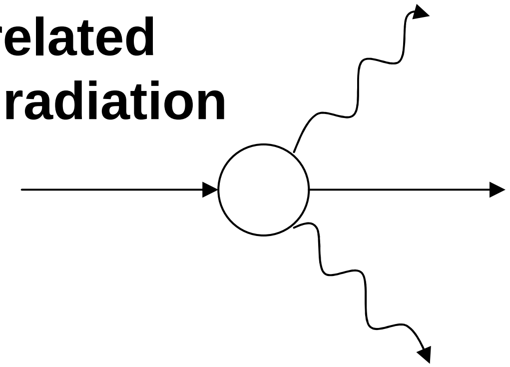
Rindler frame



Strong correlation between absorption and emission despite of causal disconnection

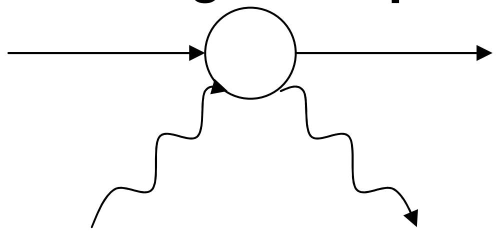
G. Unruh PRD 29 1047-1056, 1984

Correlated pair radiation



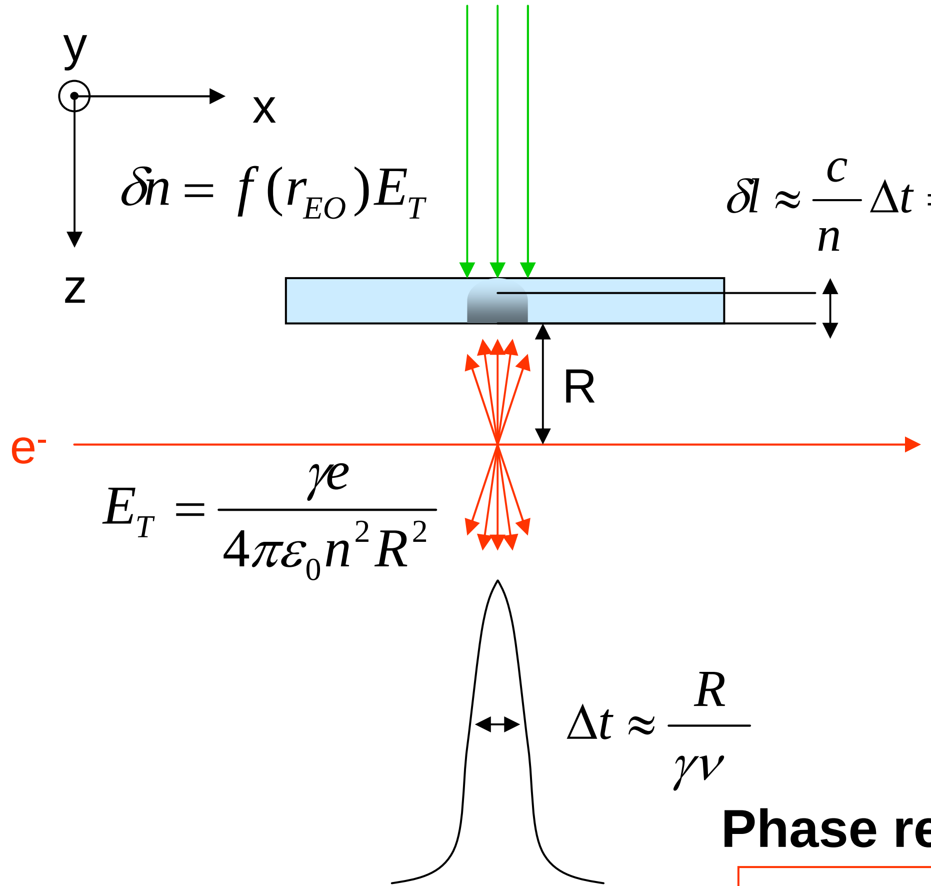
Inertial frame

No correlated pair in background process



Homma proposes: experimental test

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



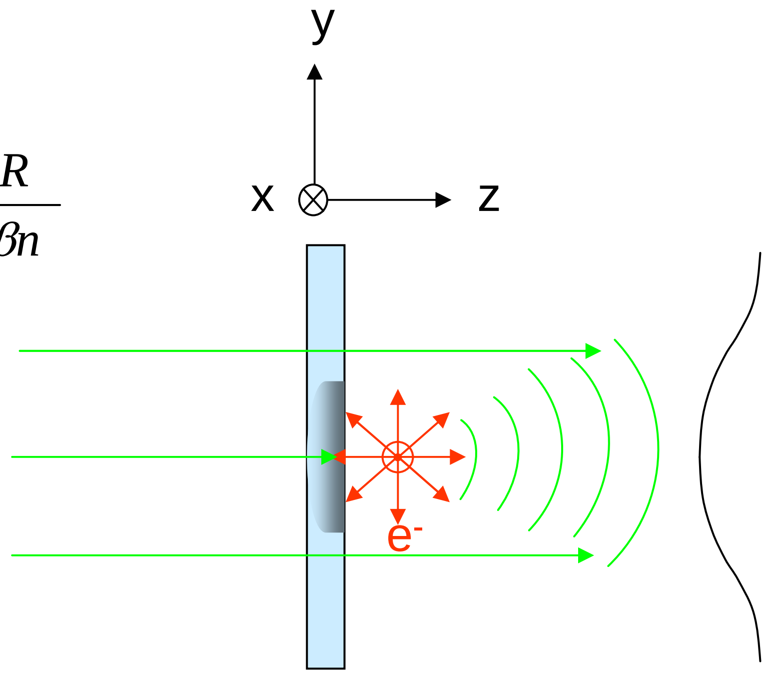
$$\delta n = f(r_{EO}) E_T$$

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

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

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

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



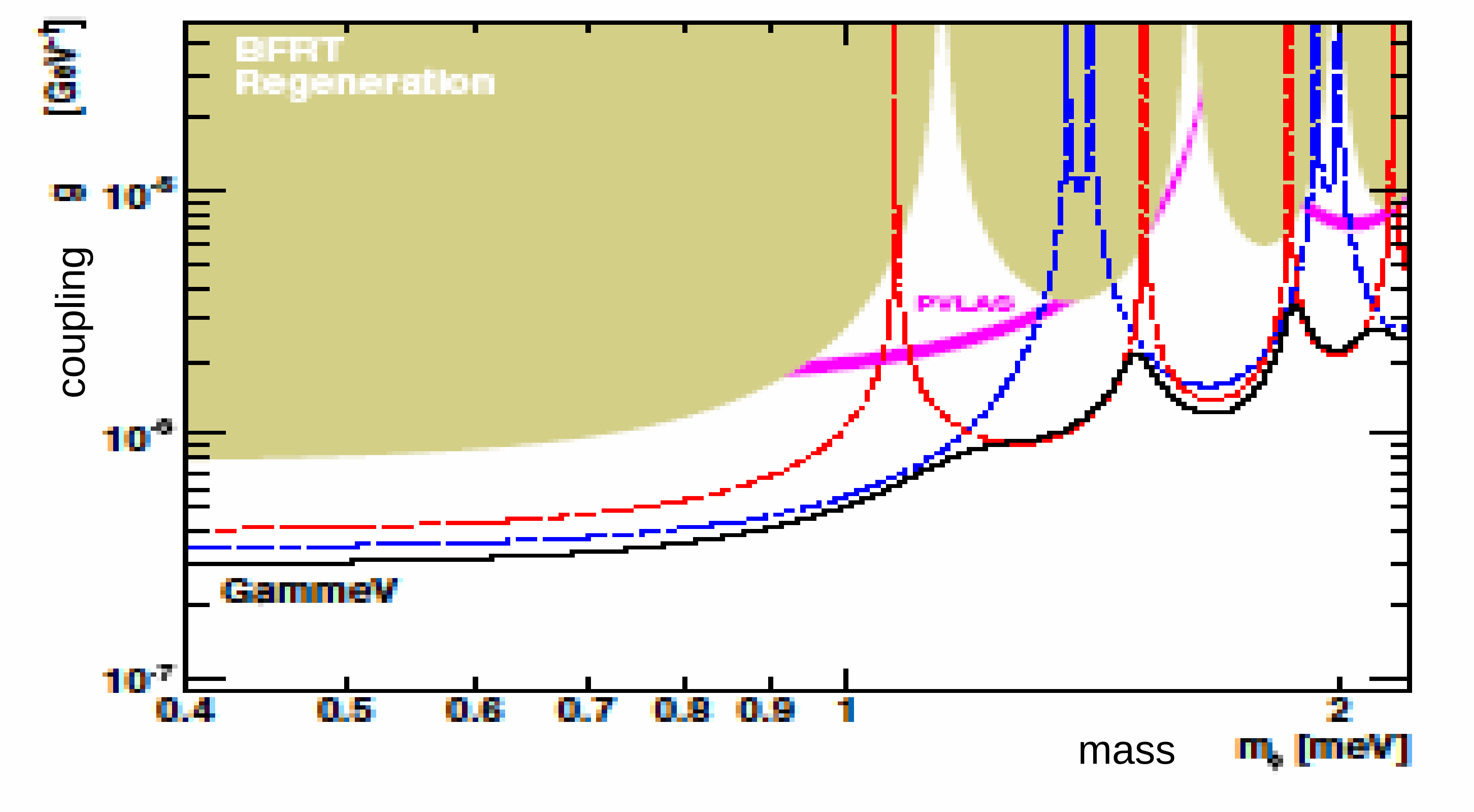
$$\Delta y \approx R\tan(\cos^{-1}(0.5)^{1/3})$$

Phase retardation

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

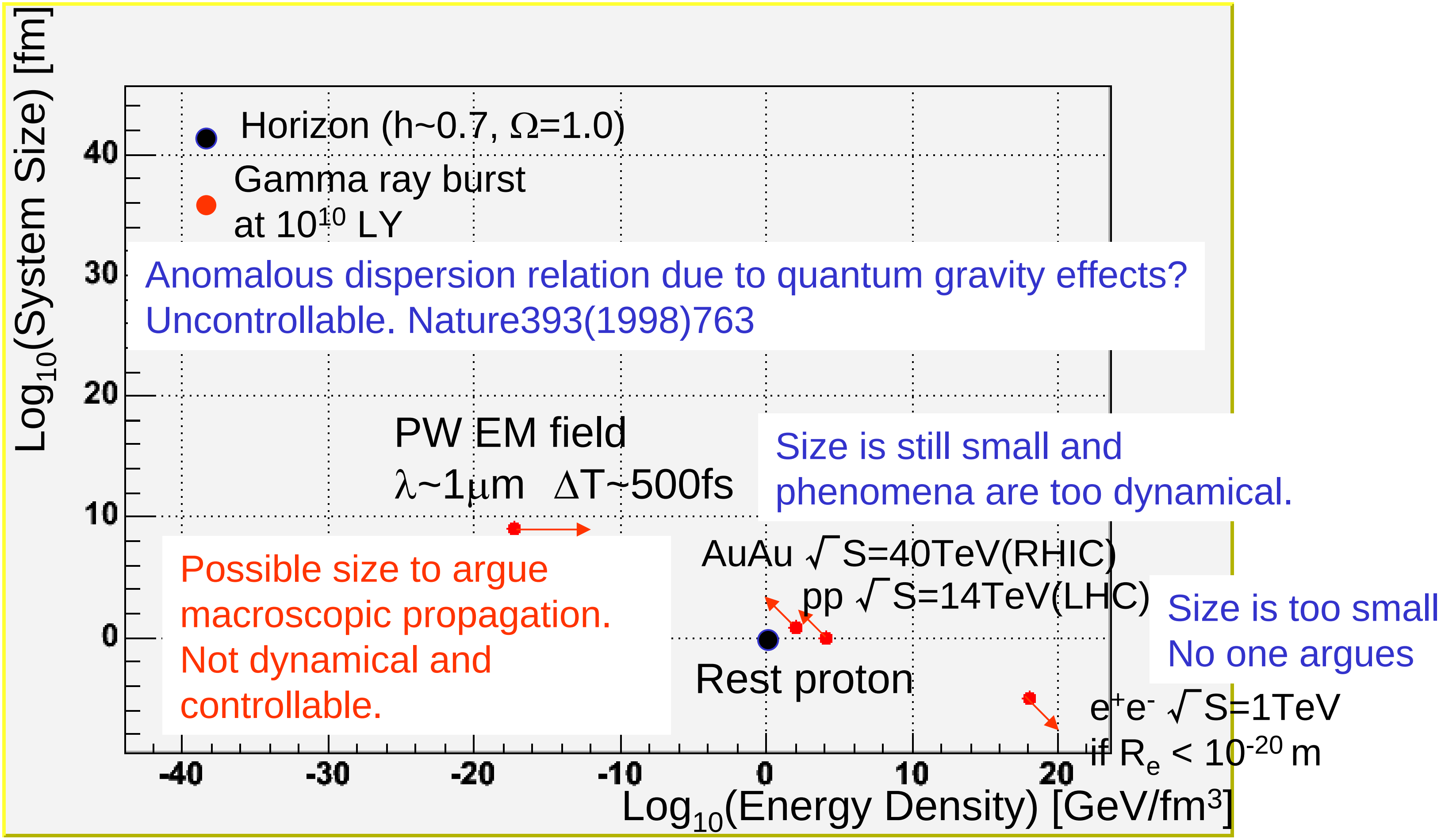
(Homma, 2007)

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)

Experimentally available systems

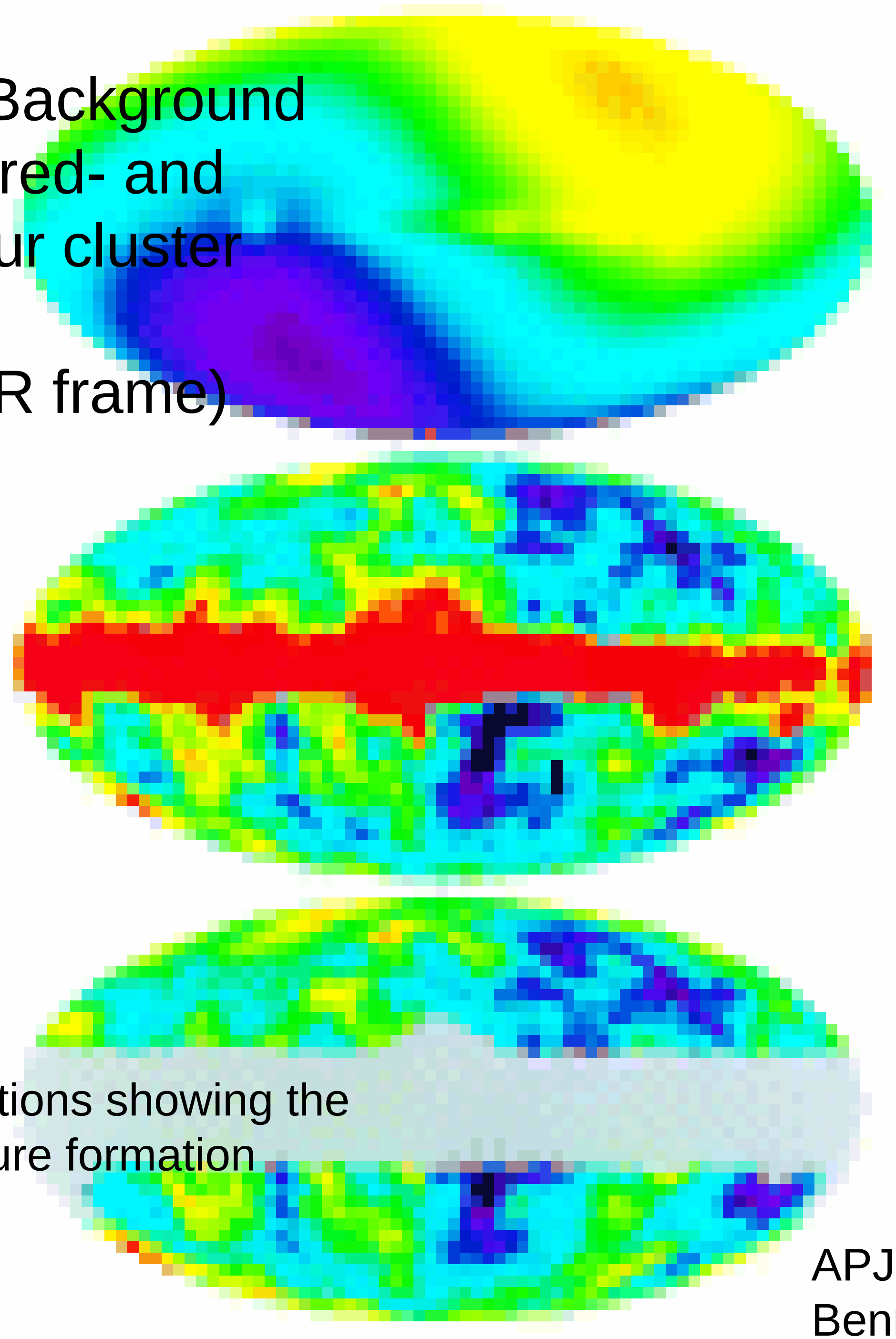


(K.Homma)

Cosmic Microwave Background Radiation (CMBR) red- and blue-shifted from our cluster

↓

Unique frame (CMBR frame) in the cosmos?



Typical CMBR fluctuations showing the structure formation

APJ, **464,**L1(1996)
Bennet et al.

Why is every frame 'relative'?

(relativity's cornerstone)

Sato:

There may be a unique frame of reference due to the Big Bang. Theory of relativity may need to be modified

⇕

Einstein:

Relativity dictates no preferred frame

Prog. Theor. Phys. Vol. 47 (1972), No. 5

Hot Universe, Cosmic Rays of Ultrahigh Energy and Absolute Reference System

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**Research Institute for Theoretical Physics Hiroshima University, Takehara, Hiroshima*

January 10, 1971

Shortly after the discovery of the cosmic thermal radiation with temperature of $\sim 3°K$,[1] it was noted that such radiation would have a strong attenuation effect on cosmic rays with energies exceeding 10^{20} eV.[2] Although the average energy of these thermal photons is as small as 10^{-3}eV, they interact with the cosmic rays to produce π-mesons, because the thermal photons look like γ-rays with energies of ~ 200 MeV in the rest system of the cosmic rays. As the mesons resulting from the photoproduction carry off a significant fraction of the cosmic-ray energy, the attenuation mean-free-path of the cosmic rays with energies above 10^{20}eV becomes as small as $10^{6.0} \sim 10^{7.3}$ parsec.[3] On the other hand, analysis of an extremely large air shower have revealed that the energy spectrum of cosmic rays extends smoothly beyond 10^{20}eV, and moreover, cosmic rays with energies of 4.10^{21} eV have been observed by Suga et al.[4] Therefore, the non-existence of the expected cutoff in the vicinity of 10^{20}eV offers a critical discrepancy between the theory and the observation.

There might be astronomical ways to get rid of this discrepancy: One is to assume a non-universal existence of the isotropic thermal radiation and another is to assume a local origin of the ultrahigh energy cosmic rays. However these ways are not so promising from the following arguments. About the first way, there is no reasonable mechanism of generating such radiation in our Galaxy[5] and, further, the hot universe model which predicts the universal existence has other powerful assertions such as an explanation of the helium abundance and a theory of galaxy formation.[6] About the second way, some authors have proposed the Galactic origin such as the pulsar origin or the explosive origin in the Galactic nuclei.[7] However these theories necessarily meet very great difficulties to explain the mechanism of acceleration in a compact region and the arrival directions. There might be other way to assume exotic primaries like neutrinos or dusts.[8]

We now propose a different way to get rid of this discrepancy. Usually it is assumed that all inertial systems are totally equivalent for the performance of all physical experiments, i.e., the assumption of the relativity principle. However we have no experimental evidence to verify this principle for the reference systems moving with Lorentz factors of above $\gamma \sim 10^{5}$ relative to our laboratory system on the earth. In the above discussion on the attenuation of cosmic rays, we have assumed that the conventional relativity principle is correct even for the reference systems of $\gamma \geq 10^{11}$. Therefore we must notice that the attenuation of cosmic rays is not a consequence of experiment.[9] Inversely, if the attenuation were really found experimentally, it might be a remarkable evidence to expand the applicable realm of the relativity principle.

Now we put forward the following unconventional hypotheses:

1) All inertial systems are not equivalent and there exists an universal time-like unit vector N_μ. Our laboratory system is not very different from the N-system in which N_μ is $(1, 0, 0, 0)$.

2) The production of hadrons at high-energy collisions is suppressed when their momenta in the N-system become larger

Does gamma's dispersion relation
change from $\omega = kc$ in high energies?

Does Lorentz transform change ijn high energies ?

24 July 1997

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 405 (1997) 249–252

Cosmic ray and neutrino tests of special relativity

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Received 4 May 1997
Editor: H. Georgi

Abstract

Searches for anisotropies due to Earth's motion relative to a preferred frame – modern versions of the Michelson–Morley experiment – provide precise verifications of special relativity. We describe other tests, independent of this motion, that are or can become even more sensitive. The existence of high-energy cosmic rays places strong constraints on Lorentz non-invariance. Furthermore, if the maximum attainable speed of a particle depends on its identity, then neutrinos, even if massless, may exhibit flavor oscillations. Velocity differences far smaller than any previously probed can produce characteristic effects at accelerators and solar neutrino experiments. © 1997 Elsevier Science B.V.

Is the special theory of relativity, for reasons unspecified and unknown, only an approximate symmetry of nature? To investigate possible violations of Lorentz symmetry, we follow earlier analyses [1] by assuming the laws of physics to be invariant under rotations and translations in a preferred reference frame $\mathcal{F}$. This frame is often taken to be the 'rest frame of the universe,' the frame in which the cosmic microwave background is isotropic. To parameterize departures from Lorentz invariance, standard practice has been to modify Maxwell's equations while leaving other physical laws intact.

Although we shall shortly consider more general Lorentz non-invariant perturbations, let us for the moment adhere to standard practice: we assume that the only Lorentz non-invariant term in $\mathcal{L}$ is proportional to the square of the magnetic field strength. Thus, the in vacua speed of light c differs from the maximum attainable speed of a material body (here taken to be unity). The small parameter $1 - c$ completely characterizes this departure from special relativity in $\mathcal{F}$. In a frame moving at velocity $\boldsymbol{u}$ relative to $\mathcal{F}$, the velocity of light c' depends on its angle θ relative to $\boldsymbol{u}$. For $u \ll 1$, we find $c'(\theta) \simeq c + 2(c-1)u\cos\theta$. The failure of rotational invariance in the laboratory frame leads to potentially observable effects that are proportional to $u^2(1-c^2)$. Searches for these anisotropies yielding null results have provided precision tests of special relativity.

A laser-interferometric Michelson–Morley experiment [2] found $|1-c| < 10^{-9}$. Atomic physicists obtained stronger constraints using techniques pioneered by Hughes and Drever [3]. Prestage et al. [4] found $< 10^{-18}$ and Lamoreaux et al. [5] set the current limit on the velocity difference,

$$|1-c| < 3 \times 10^{-22}. \qquad (1)$$

These limits are obtained for $\mathcal{F}$ at rest relative to the cosmic background radiation and $u \simeq 10^{-3}$. They would be two orders of magnitude weaker were $\mathcal{F}$ at rest relative to the Sun.

We find additional limits on $1 - c$ that do not require precision experiments, yet are comparable in

PII S0370-2693(97)00638-2

More on these topics

Tests of quantum gravity from observations of γ-ray bursts

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The recent confirmation that at least some γ-ray bursts originate at cosmological distances[1–4] suggests that the radiation from them could be used to probe some of the fundamental laws of physics. Here we show that γ-ray bursts will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. Many of the bursts have structure on relatively rapid timescales[5], which means that in principle it is possible to look for energy-dependent dispersion of the radiation, manifested in the arrival times of the photons, if several different energy bands are observed simultaneously. A simple estimate indicates that, because of their high energies and distant origin, observations of these bursts should be sensitive to a dispersion scale that is comparable to the Planck energy scale ($\sim 10^{19}$ GeV), which is sufficient to test theories of quantum gravity. Such observations are already possible using existing γ-ray burst detectors.

Our interest is in the search for possible *in vacuo* dispersion, $\delta v \approx E/E_{QG}$, of electromagnetic radiation from γ-ray bursts (GRBs), which could be sensitive to a type of candidate quantum-gravity effect that has been recently considered in the particle-physics literature. (Here E is the photon energy and E_{QG} is an effective quantum-gravity energy scale). This candidate quantum-gravity effect would be induced by a deformed dispersion relation for photons of the form $c^2\mathbf{p}^2 = E^2[1 + f(E/E_{QG})]$, where f is a model-dependent function of the dimensionless ratio E/E_{QG}, $\mathbf{p}$ is the photon momentum and c is the velocity of light. In quantum-gravity models in which the hamiltonian equation of motion $\dot{x}_i = \partial H/\partial p_i$ is still valid at least approximately, as in the frameworks discussed later, such a deformed dispersion relation would lead to energy-dependent velocities $c + \gamma v$ for massless particles, with implications for all the electromagnetic signals that we receive from astrophysical objects at large distances. At small energies $E \ll E_{QG}$, we expect that a series expansion of the dispersion relation should be applicable: $c^2\mathbf{p}^2 = E^2[1 + \xi E/E_{QG} + O(E^2/E_{QG}^2)]$, where $\xi = \pm 1$ is a sign ambiguity that would be fixed in a given dynamical framework. Such a series expansion would correspond to energy-dependent velocities:

$$v = \frac{\partial E}{\partial p} \approx c\left(1 - \xi\frac{E}{E_{QG}}\right) \qquad (1)$$

This type of velocity dispersion results from a picture of the vacuum as a quantum-gravitational 'medium', which responds differently to the propagation of particles of different energies and hence velocities. This is analogous to propagation through a conventional medium such as an electromagnetic plasma[6]. The gravitational 'medium' is generally believed to contain microscopic quantum fluctuations, which may occur on scale sizes of order the Planck length $L_P \approx 10^{-33}$ cm on timescales of the order of $t_P \approx 1/E_P$, where $E_P \approx 10^{19}$ GeV. These may[7,8] be analogous to the thermal fluctuations in a plasma, that occur on timescales of the order of $t \approx 1/T$, where T is the temperature. As it is a much 'harder' phenomenon associated with new physics at an energy scale far beyond typical photon energies, any analogous quantum-gravity effect could be distinguished by its different energy dependence: the quantum-gravity effect would increase with energy, whereas conventional medium effects decrease with energy in the range of interest[6].

Equation (1) encodes a minute modification for most practical purposes, as E_{QG} is believed to be a very high scale, presumably of the order of the Planck scale $E_P \approx 10^{19}$ GeV. Even so, such a deformation could be rather significant for even moderate-energy signals, if they travel over very long distances. According to equation (1), a signal of energy E that travels a distance L acquires a 'time delay', measured with respect to the ordinary case of an energy-independent speed c for massless particles:

$$\Delta t \approx \xi \frac{E}{E_{QG}}\frac{L}{c} \qquad (2)$$

This is most likely to be observable when E and L are large while the interval δt, over which the signal exhibits time structure, is small. This is the case for GRBs, which is why they offer particularly good prospects for such measurements, as we discuss later.

We first review briefly how modified laws for the propagation of particles have emerged independently in different quantum-gravity approaches. The suggestion that quantum-gravitational fluctuations might modify particle propagation in an observable way can already be found in refs 7 and 9. A phenomenological parametrization of the way this could affect the neutral kaon system[9–11] has been already tested in laboratory experiments, which have set lower limits on parameters analogous to the E_{QG} introduced above at levels comparable to E_P (ref. 12). In the case of massless particles such as the photon, which interests us here, the first example of a quantum-gravitational medium effect with which we are familiar occurred in a string formulation of an expanding Robertson–Walker–Friedman cosmology[13], in which photon propagation appears tachyonic. Deformed dispersion relations that are consistent with the specific formula in equation (1) arose in approaches based on quantum deformations of Poincaré symmetries[14] with a dimensional parameter. Within this general class of deformations, one finds[14,15] an effect consistent with equation (1) if the deformation is rotationally invariant: the dispersion relation for massless particles $c^2\mathbf{p}^2 = E_{QG}^2[1 - \exp(E/E_{QG})]^2$, and therefore $\xi = 1$. We noted that a deformed dispersion relation has also been found in studies of the quantization of point particles in a discrete space time[16].

A specific and general dynamical framework for the emergence of the velocity law (equation (1)) has emerged[17] within the Liouville string approach[7] to quantum gravity, according to which the vacuum is viewed as a non-trivial medium containing 'foamy' quantum-gravity fluctuations. The nature of this foamy vacuum may be visualized by imagining processes that include the pair creation of virtual black holes. Within this approach, it is possible to verify that massless particles of different energies excite vacuum fluctuations differently as they propagate through the quantum-gravity medium, giving rise to a non-trivial dispersion relation of Lorentz 'non-covariant' form, just as in a thermal medium. The form of the dispersion relation is not known exactly, but its structure has been studied[17] via a perturbative expansion, and it was shown in ref. 17 that the leading $1/E_{QG}$ correction is in agreement with equation (1).

It has been recently suggested[8] the vacuum might have analogous 'thermal' properties in a large class of quantum-gravity approaches, namely all approaches in which a minimum length L_{min}—such as the Planck length $L_P \approx 10^{-33}$ cm—characterizes short-distance physics. These should in general lead to deformed photon dispersion relations with $E_{QG} \approx 1/L_{min}$, though the specific form of equation (1) may not hold in all models, and hence may be used to discriminate between them. In support of equation (1), though, we recall[15,17] that this type of non-trivial dispersion in the quantum-gravity vacuum has implications for the measurability of distances in quantum gravity that fit well with the intuition emerging from more

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Lorentz-violating extension of the standard model

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In the context of conventional quantum field theory, we present a general Lorentz-violating extension of the minimal SU(3)×SU(2)×U(1) standard model including CPT-even and CPT-odd terms. It can be viewed as the low-energy limit of a physically relevant fundamental theory with Lorentz-covariant dynamics in which spontaneous Lorentz violation occurs. The extension has gauge invariance, energy-momentum conservation, and covariance under observer rotations and boosts, while covariance under particle rotations and boosts is broken. The quantized theory is Hermitian and power-counting renormalizable, and other desirable features such as microcausality, positivity of the energy, and the usual anomaly cancellation are expected. Spontaneous symmetry breaking to the electromagnetic U(1) is maintained, although the Higgs expectation is shifted by a small amount relative to its usual value and the Z^0 field acquires a small expectation. A general Lorentz-breaking extension of quantum electrodynamics is extracted from the theory, and some experimental tests are considered. In particular, we study modifications to photon behavior. One possible effect is vacuum birefringence, which could be bounded from cosmological observations by experiments using existing techniques. Radiative corrections to the photon propagator are examined. They are compatible with spontaneous Lorentz and CPT violation in the fermion sector at levels suggested by Planck-scale physics and accessible to other terrestrial laboratory experiments. [S0556-2821(99)01601-X]

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I. INTRODUCTION

The minimal SU(3)×SU(2)×U(1) standard model, although phenomenologically successful, leaves unresolved a variety of issues. It is believed to be the low-energy limit of a fundamental theory that also provides a quantum description of gravitation. An interesting question is whether any aspects of this underlying theory could be revealed through definite experimental signals accessible with present techniques.

The natural scale for a fundamental theory including gravity is governed by the Planck mass M_P, which is about 17 orders of magnitude greater than the electroweak scale m_W associated with the standard model. This suggests that observable experimental signals from a fundamental theory might be expected to be suppressed by some power of the ratio $r \simeq m_W/M_P \simeq 10^{-17}$. Detection of these minuscule effects at present energy scales would be likely to require experiments of exceptional sensitivity, preferably ones seeking to observe a signal forbidden in conventional renormalizable gauge theories.

To identify signals of this type, one approach is to examine proposed fundamental theories for effects that are qualitatively different from standard-model physics. For example, at present the most promising framework for a fundamental theory is string (M) theory. The qualitative difference between particles and strings means that qualitatively new physics is expected at the Planck scale. An interesting challenge would be to determine whether this could lead to observable low-energy effects.

In the present work, we consider the possibility that the new physics involves a violation of Lorentz symmetry. It has been shown that spontaneous Lorentz breaking may occur in the context of string theories with Lorentz-covariant dynamics [1]. Unlike the conventional standard model, string theories typically involve interactions that could destabilize the naive vacuum and trigger the generation of nonzero expectation values for Lorentz tensors. Note that some kind of spontaneous breaking of the higher-dimensional Lorentz symmetry is expected in any realistic Lorentz-covariant fundamental theory involving more than four spacetime dimensions. If the breaking extends into the four macroscopic spacetime dimensions, apparent Lorentz violation could occur at the level of the standard model. This would represent a possible observable effect from the fundamental theory, originating outside the structure of conventional renormalizable gauge models.

A framework has been developed for treating the effects of spontaneous Lorentz breaking in the context of a low-energy effective theory [2], where certain terms can be induced that appear to violate Lorentz invariance explicitly. It turns out that, from a theoretical perspective, the resulting effects are comparatively minimal.

An important point is that Lorentz symmetry remains a property of the underlying fundamental theory because the breaking is spontaneous. This implies that various attractive features of conventional theories, including microcausality and positivity of the energy, are expected to hold in the low-energy effective theory. Also, energy and momentum are conserved as usual, provided the tensor expectation values in the fundamental theory are spacetime-position independent. Moreover, standard quantization methods are unaffected, so a relativistic Dirac equation and a nonrelativistic Schrödinger equation emerge in the appropriate limits.

Another important aspect of the spontaneous breaking is that both the fundamental theory and the effective low-energy theory remain invariant under *observer* Lorentz transformations, i.e., rotations or boosts of an observer's inertial frame [2]. The presence of nonzero tensor expectation values in the vacuum affects only invariance properties under *par-*

Our ponderation on relativity continues….

Lorentz Invariance on Trial

Precision experiments and astrophysical observations provide complementary tests of Lorentz invariance and may soon open a window onto new physics. They have already constrained models of quantum gravity and cosmology.

Maxim Pospelov and Michael Romalis

The null result of the celebrated 1887 Michelson–Morley experiment was surprising and difficult to explain in terms of then prevalent physics concepts. It required a fundamental change in the notions of space and time and was finally explained, almost 20 years later, by Albert Einstein's special theory of relativity. (See the May 1987 special issue of PHYSICS TODAY devoted to the centennial of the experiment.) Special relativity postulates that all laws of physics are invariant under Lorentz transformations, which include ordinary rotations and changes in the velocity of a reference frame. Subsequently, quantum field theories all incorporated Lorentz invariance in their basic structure. General relativity includes the invariance through Einstein's equivalence principle, which implies that any experiment conducted in a small, freely falling laboratory is invariant under Lorentz transformations. That result is known as local Lorentz invariance.

Experimental techniques introduced throughout the 20th century led to continued improvements in tests of special relativity. For example, 25 years ago, Alain Brillet and John L. Hall used a helium–neon laser mounted on a rotary platform to improve the accuracy of the Michelson–Morley experiment by a factor of 4000. In addition to the Michelson–Morley experiments that look for an anisotropy in the speed of light, two other types of experiments have constrained deviations from special relativity. Kennedy–Thorndike experiments search for a dependence of the speed of light on the lab's velocity relative to a preferred frame, and Ives–Stilwell experiments test special relativistic time dilation.

In 1960, Vernon Hughes and coworkers and, independently, Ron Drever conducted a different kind of Lorentz invariance test.[1] They measured the nuclear spin precession frequency in lithium-7 and looked for changes in frequency or linewidth as the direction of the magnetic field rotated, together with Earth, relative to a galactic reference frame. Such measurements, known as Hughes–Drever experiments, have been interpreted, for example, in terms of a possible difference between the speed of light and the limiting velocity of massive particles.[2]

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Why bother?

Theorists and experimentalists in disciplines ranging from atomic physics to cosmology have been increasingly interested in tests of Lorentz invariance. The high sensitivity of experimental tests combined with recent advances in their theoretical interpretation allows one to probe ultrashort distance scales well beyond the reach of conventional particle-collider experiments. In fact, both the best experiments and astrophysical observations can indirectly probe distance scales as short as the Planck length $L_{Pl} = (G\hbar/c^3)^{1/2} \sim 10^{-35}$ m. Experiments that probe such short scales can constrain quantum gravity scenarios.

The breaking of Lorentz symmetry enables the *CPT* symmetry, which combines charge conjugation (C), parity (P), and time-reversal (T) symmetries, to be violated. In conventional field theories, the Lorentz and *CPT* symmetries are automatically preserved. But in quantum gravity, certain restrictive conditions such as locality may no longer hold, and the symmetries may be broken. The breaking of *CPT*, combined with baryon-number violation, could be the source of the dynamically generated dominance of matter over antimatter in the universe. Unlike a more conventional scenario involving only *CP* violation, baryogenesis based on *CPT* violation would not require a departure from thermal equilibrium. (See the article by Helen Quinn, PHYSICS TODAY, February 2003, page 30.)

Cosmology provides an additional important impetus to look for violations of Lorentz symmetry. The recognition that the universe is dominated by dark energy suggests a new field—known as quintessence—that permeates all space. The interaction of that field with matter would manifest itself as an apparent breaking of Lorentz symmetry.

It could be argued on aesthetic grounds that the Lorentz and *CPT* symmetries should be preserved. Such arguments, however, do not find support in the history of physics. Nearly all known or proposed symmetries, such as parity and time reversal, electroweak symmetry, chiral symmetry, and supersymmetry, are spontaneously broken. Whatever the true origin of Lorentz or *CPT* breaking may be, the fact that it hasn't yet been observed means it must be small at the energy scales corresponding to known standard-model physics.

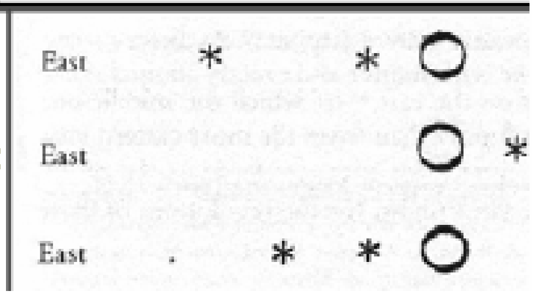
Effective field theory

How can one break Lorentz invariance in a controllable way? The least radical approach would be to assume that low-energy physics can be described by the Lorentz-invariant dynamics of the standard model plus a number of possible background fields. Those fields, taken to be constant or slowly varying, are vectors or tensors under Lorentz transformations and are coupled to ordinary particles in such a way that the whole Lagrangian remains invariant. In that framework, called an effective field the-

Conclusions

- Glalileo's and Einstein's relativity: Cornerstone of modern science
- Advance of rapid progress in ultrafast ultrastrong lasers (particularly) ELI, poses special opportunities to extend the horizon of Galileo and Einstein.
- laser acceleration toward GeV TeV, PeV: new opportunities
- Revolutionary (not evolutionary) technology apt for 21st Century challenges, just like Galilei's was in 17th
- Test Einstein's (special and general) relativity in more extreme limits
- Is 'relative' frame really relative or some unique?
- Does photon see vacuum differently when its energy is high or its intensity high? Does the 'Blue Sky' appear also in vacuum with high energies? Does strong field warp space? Do we see vacuum structure and property with intense laser? Does 'relativity' hold (Lorentz transform as well as Equivalence Principle, and Hawking radiation etc.)?
- We learn a lot from Galilei 400 years later

Observation of Jupiter and its Moons - Some of the most profound observations of Galileo were the motions of the moons of Jupiter. Galileo reasoned that if planets could orbit Jupiter, then the Earth could orbit the Sun.



2009: *International Year of Astronomy*

(400 year after Galilei's invention of the Galilei telescope and discovery of the moons of Jupiter)

Grazie!