Possible quantum gravity experiments?

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1. Gamma ray bursts and others
2. Conceptual frameworks
3. A word of warning

This field has grown rapidly in the last few years. I can only attempt to mention some particular proposals and aspects. Consider the talk a personal view.

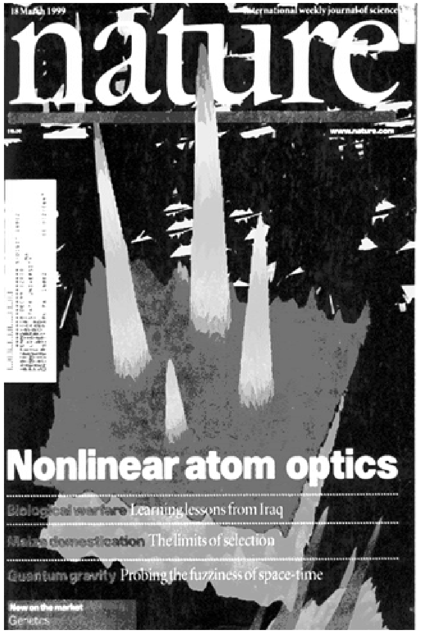
Among the topics that could be included:

- Large extra dimensions (Randall-Sundrum).
- Varying speed of light cosmologies.
- UHE Cosmic rays
- Production of black holes in accelerators
- Effect in precision experiments (LIGO)
- Light from gamma ray bursts
- Doubly-special relativity
- many others…

Conventional wisdom for many years was that, in order to produce "typical particle physics phenomenology" due to quantum gravity one needed accelerator energies of the order of the Planck energy (10^{19} GeV), way beyond what is possible on Earth.

But paraphrasing Salam: how can one be sure there are no observable effects of a theory one doesn't know the details of ?

The field burst onto the scene with two proposals by
Giovanni Amelino-Camelia and collaborators at CERN.
These proposals received a significant amount of attention:
-First prize Gravity Research Foundation 1999.
-Two covers of Nature.
-Several experimental groups published papers concerning them.



Limits to Quantum Gravity Effects on Energy Dependence of the Speed of Light from Observations of TeV Flares in Active Galaxies

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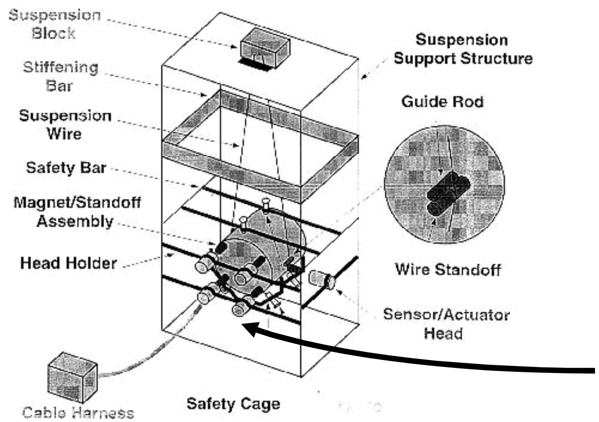
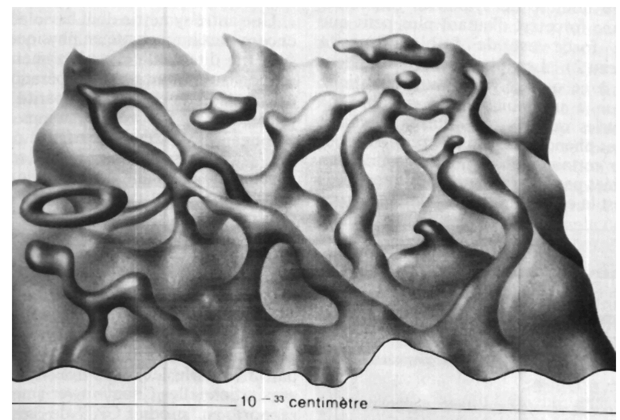
(Received 13 October 1998)

We have used data from a TeV γ-ray flare associated with the active galaxy Markarian 421 to place bounds on the possible energy dependence of the speed of light in the context of an effective quantum gravitational energy scale. Recent theoretical work suggests that such an energy scale could be less than the Planck mass and perhaps as low as 10^{16} GeV. The limits derived here indicate this energy scale to be in excess of 6×10^{16} GeV for at least one approach to quantum gravity in the context of D-brane string theory. To the best of our knowledge, this constitutes the first convincing limit on such phenomena in this energy regime.

PACS numbers: 98.70.Rz, 03.30.+p, 04.60.–m

First scenario: are LIGO and other interferometers sensitive enough to see the “jolting” of the mirrors due to the space-time foam?





Masses are “jolted” about 10^{-35}m or in units of h=10^{-38}, way below the instrument sensitivity. One can make statements of this sort without resorting to detailed models of quantum gravity.

Amelino-Camelia (Nature 398, 216 (1999)) adds an apparently "reasonable" ingredient: he claims that since the "space-time foam" effects occur in quantum gravity scales, the mirrors of LIGO really carry out a "**random walk**" in which each step is of Planck length but also where the "stepping frequency" is given by the inverse of a Planck time.

Therefore the deviation of the position of the particles is given by,

$$\boxed{s_D = \sqrt{L_{Planck} c T_{obs}}}$$

Notice that this implies that:

a) The deviation increases the longer your measurement lasts!

b) Since T_{obs} is proportional to the inverse of the gravitational wave frequency, the deviation is HUGE!

At the peak of the LIGO sensitivity f=100Hz, $cT_{obs} \sim 10^{42} L_{Planck}$

Therefore $s_D \approx 10^{21} L_{Planck}$ $h \approx 10^{-17}$ And even the Caltech 40m prototype would see this!

The previous calculation of the deviation is unorthodox. To illustrate this, let us consider the same problem in a more conventional setting: that of perturbative quantum gravity. After all, at the length scales of interest to gravity leading order low energy approximations should work well.

$$\hat{L} = \int_{-L/2}^{L/2} \sqrt{\hat{g}_{\mu\nu} \frac{dx^{\mu}}{d\lambda} \frac{dx^{\nu}}{d\lambda}} d\lambda = \int_{-L/2}^{L/2} \sqrt{\hat{g}_{xx}} dx \sim \int_{-L/2}^{L/2} (1 + \frac{\hat{h}_{xx}}{2}) dx$$

$$< 0|\hat{L}^2|0 > - < 0|\hat{L}|0 >^2 = \frac{1}{4} \int_{-L/2}^{L/2} dx_1 \int_{-L/2}^{L/2} dx_2 < 0|\hat{h}_{xx}(x_1)\hat{h}_{xx}(x_2)|0 >$$

$$\sim \int_{-L/2}^{L/2} dx_1 \int_{-L/2}^{L/2} dx_2 L_{\text{Planck}}^2 \int_0^{\infty} \frac{d^3k}{k} e^{ik(x_1 - x_2)}$$

$$\sim L_{\text{Planck}}^2 \int_0^{1/L_{\text{Planck}}} \frac{dk}{k} [\sin(kL)]^2$$

$$\sim \boxed{L_{\text{Planck}}^2 \ln\left(\frac{L}{L_{\text{Planck}}}\right)}$$

Summarizing, in order to have visible effects in the interferometers one has to recourse to a model of measurement that is unusual in quantum mechanics and quantum field theory. Applied in other contexts (e.g. measurements of magnetic fields by squids) it would probably lead to catastrophic fluctuations that are simply not observed.

This is a usual occurrence in this field. One can construct models of quantum gravity phenomena that yield observable consequences, but usually the models are stretches of what is credible to begin with.

Second scenario: The light that comes to us from gamma ray bursts has traveled a very long distance in terms of the number of wavelengths involved. If each wavelength is disturbed by a quantum gravity effect of order L_{planck} during the wave propagation then there is a chance we could observe the effects.

G. Amelino-Camelia, J. Ellis, N. Mavromatos, D. Nanopoulos, S. Sarkar, Nature 393, 763 (1998).

Effects stem from the fact that perhaps one does not necessarily expect Lorentz invariance to be a true symmetry of nature at the quantum gravity scale. Therefore one could conjecture that the dispersion relation of a photon propagating in vacuum will acquire corrective terms,

$$c^2 p^2 = E^2 \left[1 + x \frac{E}{E_{\text{Planck}}} + O\left(\frac{E^2}{E_{\text{Planck}}{}^2} \right) \right]$$

Two photons moving with the modified dispersion relation would suffer a time delay,

$$\Delta t \approx x \frac{\Delta E}{E_{\text{Planck}}} \frac{L}{c}$$

For a gamma ray like the ones current experiments observe, $\Delta E \approx 300 keV$

and assuming that the burst happens happens at $z = 1$ then $L / c \approx 3 \times 10^{17} s.$

If we demand $\Delta t < 0.01s$

$\boxed{\text{Then } \mathrm{E}_{\text{Planck}} > 10^{16}\,\text{GeV}}$

So if the measurement could be refined by three orders of magnitude, we would be probing the real Planck scale at 10^{19}GeV.

How do we know that $\Delta t < 0.01s$?

Evidence for sub-millisecond structure in a γ-ray burst

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GAMMA-RAY bursts (GRBs) vary in duration from hundreds of seconds down to several milliseconds. Early studies[1] suggested that bursts with durations of <100 ms form a distinct class, accounting for a few per cent of the total number of detected bursts, and there is some evidence[2] for a break in the distribution of GRB durations at ~600 ms, perhaps implying separate physical mechanisms for long and short bursts. Recently the estimated number of short GRBs has risen substantially. The shortest burst recorded so far is GRB820405, with duration ~12 ms (ref. 3), and the shortest spike within a burst, an unresolved feature with width <5 ms, was in GRB841215 (refs 4–7). GRB790305 had the shortest rise-time, 0.2 ms. We report here that GRB910711, with apparently the shortest duration (~8 ms) yet seen by the Burst and Transient Source Experiment (BATSE), has a time profile that shows significant submillisecond structure. The responses to this burst in the different BATSE detectors, from both direct and Earth-scattered γ-rays, show that the burst is both narrower and of higher energy than is indicated by a light-curve summed over all detectors. We detected a narrow spike of duration 200 μs in the light curve; variations on this timescale have not previously been observed in GRBs, and their explanation should be a stringent test of any GRB theory.

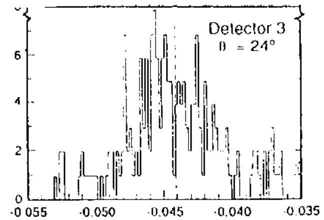
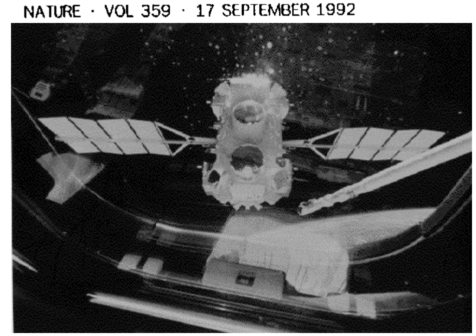


FIG. 1 Time profiles for the different triggered detectors in 200-μs bins for energy $E > 30$ keV. The vertical dashed line shows the position of the centroid for each. The detector numbers are indicated, along with θ, the angle between the detector axis and the Earth's centre. ($\theta = 180°$ corresponds to a detector pointed towards the zenith.) The spike is indicated by the arrow.

NATURE · VOL 359 · 17 SEPTEMBER 1992



CGRO/
BATSE

The bursts arrive at the same
time in all energy channels, 30keV-300keV

But how do we know that the dispersion relation looks like

$$c^2 p^2 = E^2 \left[1 + x \frac{E}{E_{\text{Planck}}} + O\left(\frac{E^2}{E_{\text{Planck}}{}^2} \right) \right]$$

In particular, what happens if ξ vanishes?

Then we are quite away from the Planck scale. However, proposed gamma ray observatories (like AMS, GLAST) claim they will be able to observe gamma rays in the 10-100GeV energy range and with resolutions of microseconds. This would again put the theoretical prediction within experimental range.

A quantum gravity model with non-vanishing ξ is provided by (non-critical) Liouville strings. This was the model put forward by Amelino-Camelia et. al. in their original proposal.
This model does not appear to have a wide following among string theorists.

We took a look at the possibility that a nonvanishing ξ could appear in loop quantum gravity. (R. Gambini, JP, PRD59, 124021 (1999)).

What one is interested in is in studying the propagation of light in a "semiclassical state". At the moment all of this is very vague since there is not available a rigorous semiclassical picture in this approach. One handwaving picture that has been put forward is the idea of the "weave" in which a loop state with many strands intersecting and knotting approximates a classical geometry in a certain sense (for instance, the area and volume operators have expectation values close to classical values and small dispersions).

$$< \Delta | \hat{\underset{\sim}{g}}_{ab} | \Delta >= \delta_{ab} + O(\frac{\ell_P}{\Delta}),$$

Where Δ is a large characteristic distance.

The idea would therefore be to examine the propagation of light on such a state. One should expect a vast phenomenology akin to propagation of light in solids.

As a first cut for a calculation we consider the term in the Hamiltonian constraint that couples the Maxwell theory to gravity.

$$H = \frac{e_a^{\ i} e_b^{\ i}}{\sqrt{\det g}} \left(E^a E^b + B^a B^b \right)$$

Thiemann (Class. Quan. Grav. 15, 1281 (1998)) has proposed a quantization of the Hamiltonian constraint of gravity (including couplings to matter) in the loop representation that is finite and consistent (anomaly-free). Within such framework, the electric term in the Hamiltonian above looks like,

$$\hat{H} = \int d^3x \int d^3y \, w_a(x) w_b(y) \hat{E}^a(x) \hat{E}^b(y) f_e(x-y)$$

Where the w's are well defined operators associated with the geometry that are non-vanishing at intersections of the weave. A similar expression can be written for the magnetic term.

We have also made the assumption, following Thiemann, that quantum gravity acts as a “fundamental regulator” and therefore delocalized the product of electric fields to two different points tied together by the regulator f

We now consider the electric and magnetic fields to be in a coherent states such that their dynamics can be thought of as classical, and evaluate the expectation value of the term in the Hamiltonian on a weave state for the gravitational field. Since the w’s are only non-vanishing on the vertices of the weave, one obtains an expression like,

$$< \Delta|\hat{H}^{E}_{\rm Maxwell}|\Delta >= \frac{1}{2}\sum_{v_i,v_j} < \Delta|\hat{w}_a(v_i)\hat{w}_b(v_j)|\Delta > E^a(v_i)E^b(v_j)$$

Where the sum runs over all vertices. We now proceed to average this expression over the weave keeping the leading terms and the first order corrections in O(Lp).

The end result is a modification of Maxwell's equations in vacuum,

$$\partial_t \vec{E} = -\nabla \times \vec{B} + 2\chi\ell_P \Delta^2 \vec{B}$$

$$\partial_t \vec{B} = \nabla \times \vec{E} - 2\chi\ell_P \Delta^2 \vec{E}.$$

The terms are not Lorentz invariant, as expected. If one works out the modified wave equation,

$$\partial_t^2 \vec{E} - \Delta^2 \vec{E} - 4\chi\ell_P \Delta^2 (\nabla \times \vec{E})$$

And seeks solutions with a definite helicity

$$\vec{E}_\pm = \mathrm{Re}\left((\hat{e}_1 \pm i\hat{e}_2) e^{i(\Omega_\pm t - \vec{k}\cdot\vec{x})}\right).$$

The dispersion relation implies a birrefringence,

$$\Omega_\pm = \sqrt{k^2 \mp 4\chi\ell_P k^3} \sim |k|(1 \mp 2\chi\ell_P |k|).$$

That is, one helicity propagates faster than the other.

What broke the symmetry? The weave chosen. If we choose a parity-conserving weave then the constant χ vanishes identically and there is no effect.

How do we know if the weave is parity conserving? At the moment we do not. There is no definite dynamical mechanism that could break the invariance. So we do not have a prediction, we rather have a constraint on the quantum states allowed by the theory: they should not break parity at the level constrained by gamma ray burst observations.

A paper by Alfaro, Morales and Urrutia (PRL **84:2318-2321,2000)** Has studied similar calculations for propagation of neutrinos. They find similar effects.

Words of caution:

Should one believe these calculations? A big question mark on them is the issue of the kinematical nature of the calculations.

If one is doing canonical quantum gravity presumably one wishes states that are annihilated by the constraints. The states we are considering are not. The states that are annihilated by the constraints tend to have distinctive properties. For instance, they are diffeomoprhism invariant, therefore one cannot compute operators like q_{ab} on them. That is, calculations like the ones presented simply do not work on states annihilated by the constraints.

The anomalous dispersion relations on Fermions
have been significantly limited by particle physics phenomenology
(Sudarsky, Urrutia, Vucetich **Phys.Rev.D68:024010,2003).**

The helicity dependent phenomena in photons
are extremely severely constrained,
First by optical observations (Gleiser, Kozameh, **Phys.Rev.D64:083007,2001**)
and also by gamma ray data
(Jacobson, Liberati, Mattingly, Nature 424 1019 (2003)
I. Mitrofanov, *Nature* **426**, 139 (2003) **(GRB) 021206** $\chi < 10^{-14}$**)**

(essentially, if there were helicity dependence, one would not find polarized sources across a broad spectrum of energies).

More words of caution:

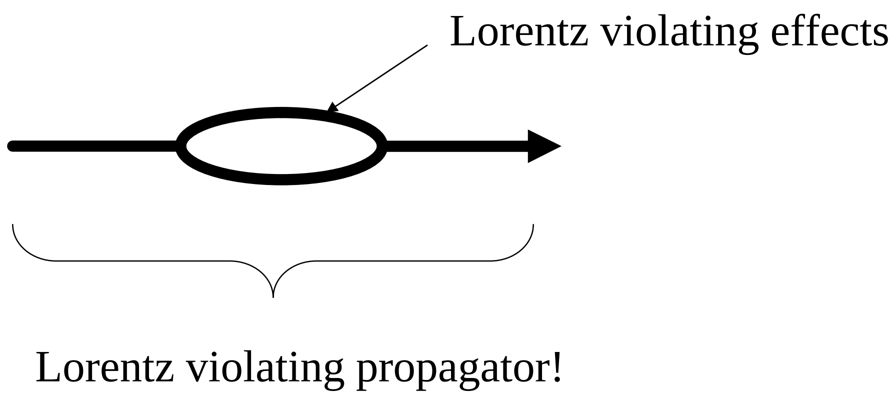
It is fun and exciting to explore these possibilities. But all of them imply tampering with Lorentz invariance, and this should not be taken lightly.

There have been attempts to construct conceptual frameworks in which this can be possible. I cannot summarize this here for lack of time, but the attempts include “doubly special relativities” where a “nonlinear additivity of energies” is postulated (see for instance Kowalski-Glikman **hep-th/0312140).**

These frameworks also imply different production rates for particle phenomenology that may influence, for instance, the GZK cutoff for cosmic rays (see for instance Konopka, Major NJP4, 57 (2002)).

Attempts have also been made to reconcile the existence of a Fundamental length at the Planck scale with a *lack of breakage* of Lorentz invariance (Rovelli, Speziale **Phys.Rev.D67:064019,2003)**

Tampering with Lorentz invariance can have dire consequences. Sudarsky and Perez **gr-qc/0306113** have argued that non-Lorentz invariant loop corrections to ordinary propagators could have visible effects in ordinary particle physics, therefore placing extremely stringent limits on their existence. This argument has to be tempered by the fact that ordinary particle physics calculations may not work all the way down to the Planck scale where Lorentz invariance is supposed to be broken, but even at intermediate scales it would place very severe limits on what is possible.



Summary

- It has been fun, thought provoking and exciting to see quantum gravity confronted with experiment, even if the models are shaky.
- There is no convincing conceptual framework to accommodate the Lorentz violations, both at the motivational level but also at a level of making it compatible with physics we all believe in.
- Expect activity in this field to continue...