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Quantum Gravity and Physics:

How the former may become the latter

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Amherst College

7 October 2004

Quantum Gravity and Physics Outline

- What is Quantum Gravity? Why?
- Approaches to QG
- Some early results
- Particle Process Thresholds - Shifted!
- Another test? A Discrete Machian Model

What is Quantum Gravity?

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$\sim$1925 Quantum Theory $\hbar$

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Geometry is continuous
Geometry determines Motion of Matter determines Geometry determines ...

$\sim$1925 Quantum Theory $\hbar$

Built on fixed background spacetime
Discrete quantities e.g. H atom $E_n = -13.6/n^2$ eV
Fundamental uncertainty to physical quantities e.g. x, p
Superposition, measurement process, determining physical states
...
.

What is Quantum Gravity?

How about the QG scale?

Planck length

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 10^{-35} m$$

Planck energy

$$E_P = \sqrt{\frac{\hbar c^5}{G}} = 10^{28} eV = 10^9 J$$

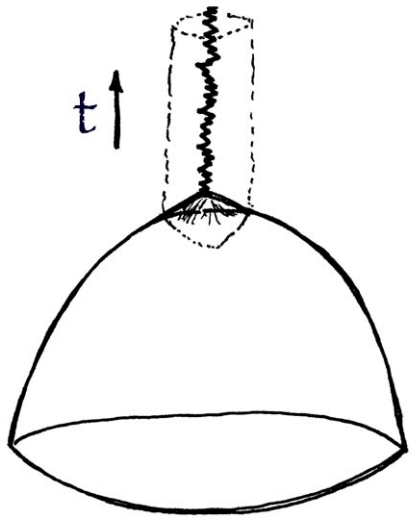
Figure of merit

$$\frac{E_{LHC}}{E_P} \sim 10^{-16}$$

Doing quark-physics by watching a soccer game !!

Why? Several areas need QG

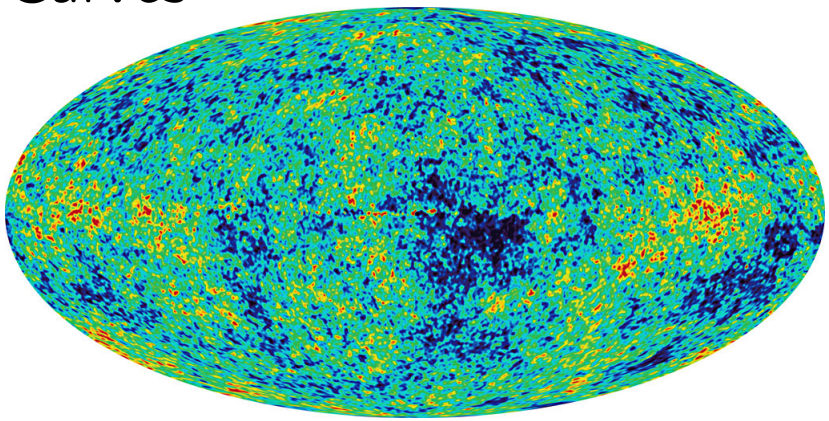
- Singularities in General Relativity; Big Bang and Gib Gnab
- Black Holes, Hawking Radiation, and Evaporation



More speculative reasons:

Why? Several areas need QG

- Cosmology: WMAP, Supernova Type IA, Galaxy Rotation Curves



http://map.gsfc.nasa.gov/

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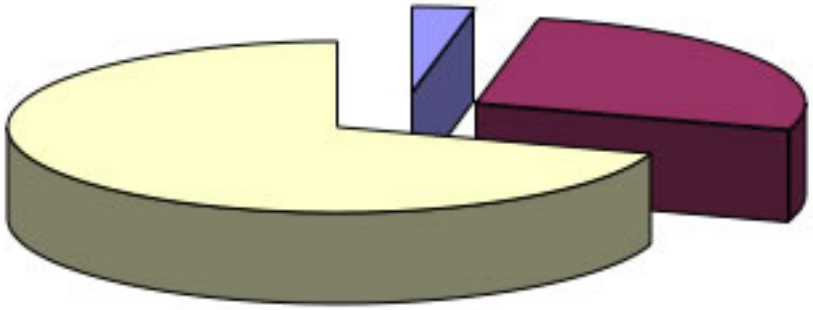

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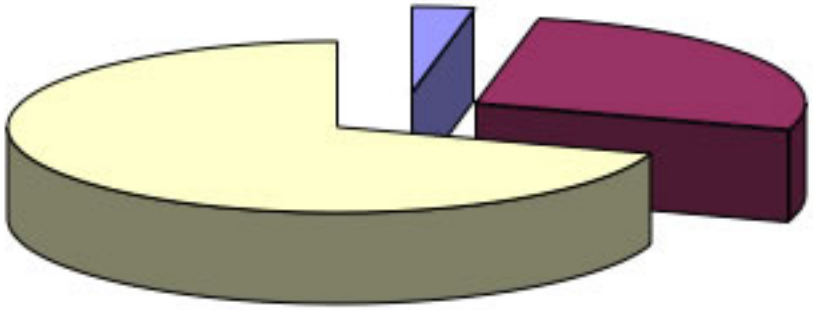

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- Pioneer 10 and 11?
- Quantum mechanics?
- "Low energy" relics - cosmic rays?

A Ultra-High Energy Cosmic Ray Paradox?

Greisen, Zatsepin and Kuzmin (GZK) observed in 1966 that high energy particles (protons) would interact with CMB photons

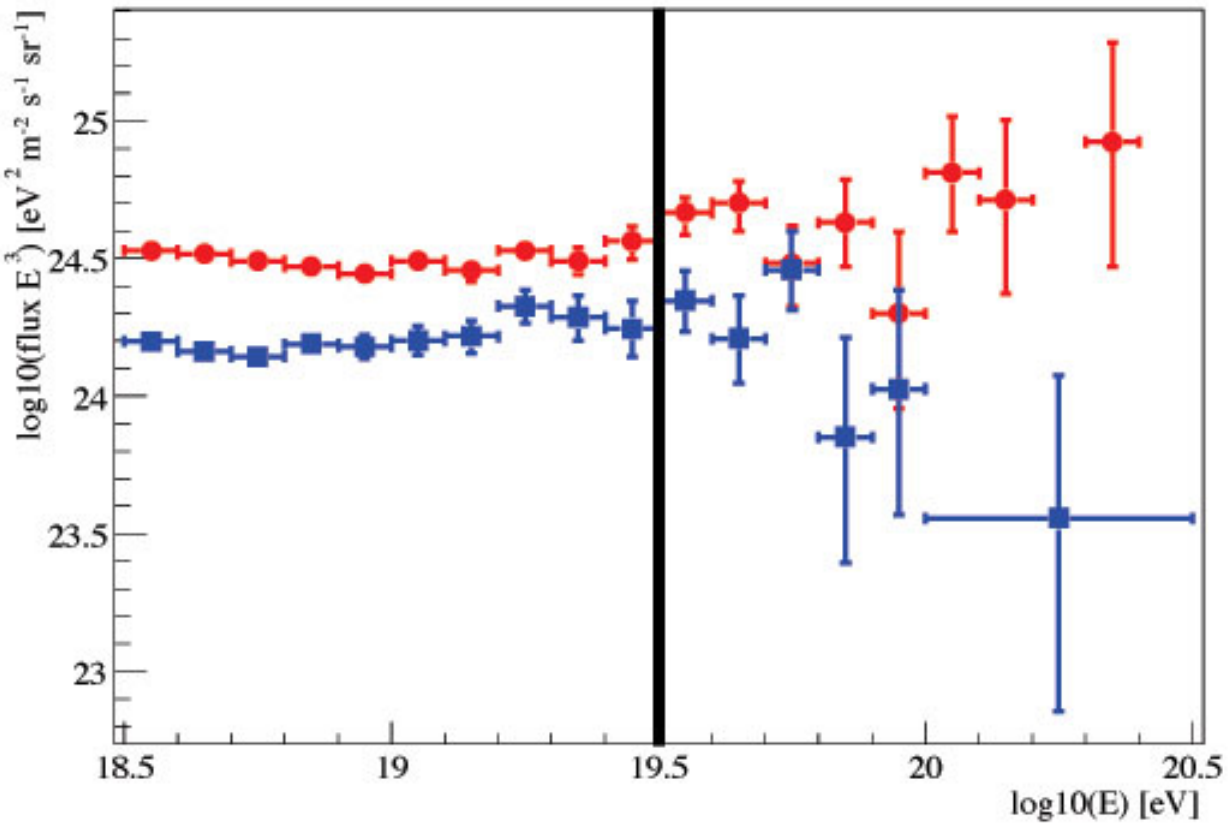
$$p + \gamma \rightarrow p + \pi$$

At large distances $\sim$ 1 Mpc this reaction yields a cutoff in the energy spectrum of protons at 5×10^{19} eV

Seen??

Is the GZK cutoff observed?

De Marco *et. al.* see no cutoff at a 2.5 σ level !

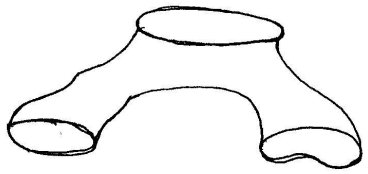


AGASA and HiRes Data

arXiv: astro-ph/0301497

Approaches to Quantum Gravity

String Theory: The whole kit and caboodle



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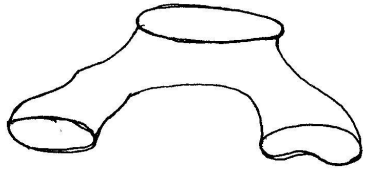
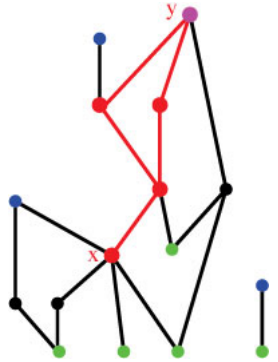


Causal Sets: Causal order is fundamental



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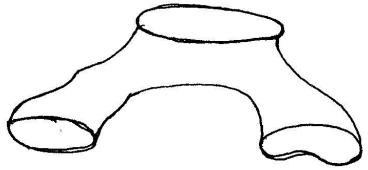

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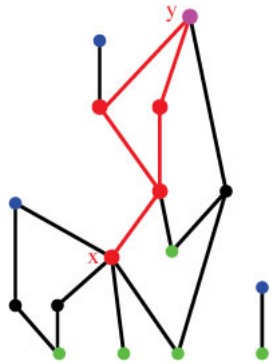

Loop Quantum Gravity: GR plus matter, quantize

Loop Quantum Gravity (lQG) A quantization of general relativity using connection variables yields quantum geometry

– Discrete structure to spatial geometry:

quantum states of geometry are represented by labeled graphs - *spin networks*

Discrete spectra for Geometry:

Area*: $\widehat{A}_S \mid s\rangle = a \mid s\rangle$

$$a = \ell_P \sum_{n=1}^{N} \sqrt{j_n(j_n+1)}$$

Angle†: $\widehat{\theta} \mid s\rangle = \theta \mid s\rangle$

$$\theta = \arccos\left(\frac{j_r(j_r+1) - j_1(j_1+1) - j_2(j_2+1)}{2\left[j_1(j_1+1)\, j_2(j_2+1)\right]^{1/2}}\right)$$

*Rovelli,Smolin NPB **422** (1995) 593; Asktekar,Lewandowski CQG **14** (1997) A43

†SM CQG **16** (1999) 3859

Physics of Quantum Gravity?

A history of an idea T. Konopka,SM arXiv: hep-ph/0201184

1999 Alfaro, Morales-Tecotl, Urrutia (gr-qc/9909079) suggested that certain states in lQG might modify the classical equations of motion

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Dispersion Relations

For massive particles (units with $c = 1$)

$$E^2 = p^2 + m^2$$

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Modified Dispersion Relations (MDR) For massive particles (units with $c = 1$)

$$\boxed{E^2 = p^2 + m^2 + \kappa \frac{p^3}{E_P}}$$

Modified Dispersion Relations (MDR)

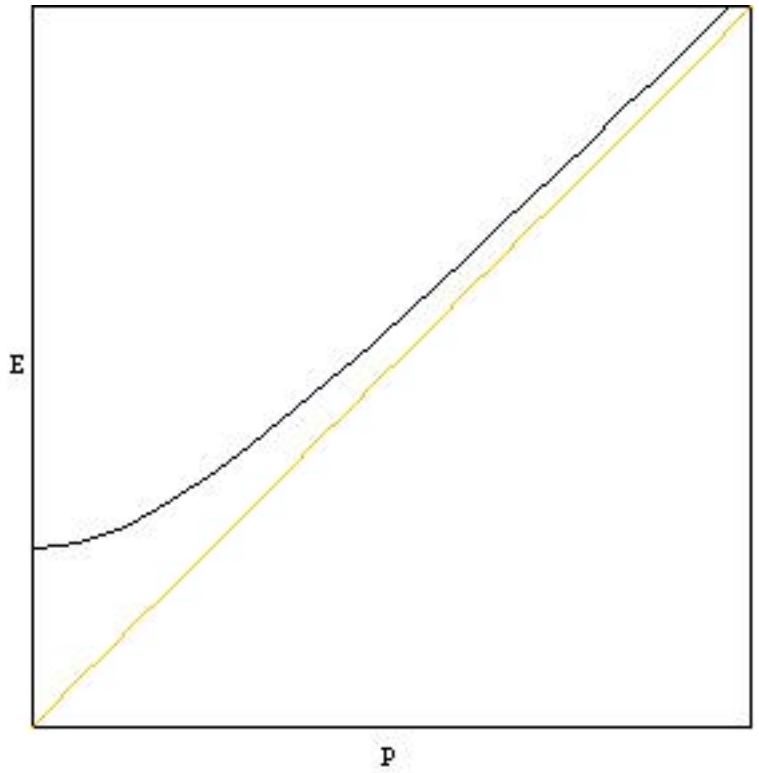
- κ order unity
- κ is positive or negative
- Not Lorentz invariant $\exists$ preferred frame !
- Effects are important when $p_{crit} \approx (m^2/\ell_p)^{1/3} \sim 10^{13}, 10^{14}$, and 10^{15} eV for electrons, pions, and protons
- Limited by $p << E_P/c$

Take leading order form

$$E \approx p + \frac{m^2}{2p} + \kappa \frac{p^2}{2E_P}$$

for which $m << p << E_P/c$

Modified Dispersion Relations (MDR)



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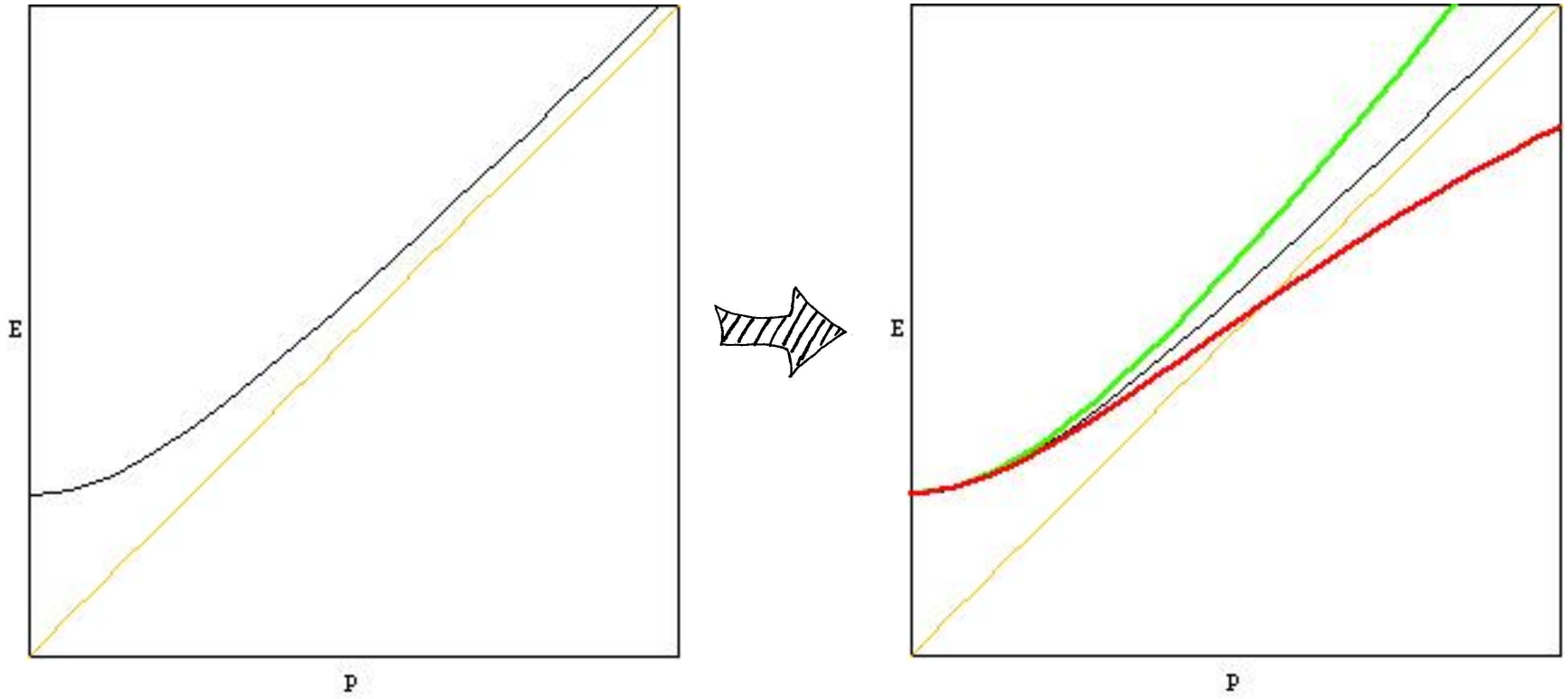

$E^2 = p^2 + m^2$

$E^2 = p^2 + m^2 + \kappa p^3 / E_P$

Model with MDR

- Assume exact Energy-momentum conservation
- Assume MDR "cubic corrections"
- Seperate parameters for photons, fermions, and hadrons

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Example Calculation: **Photon Stability**

SR forbids $\gamma \not\to e^+ + e^-$ MDR model allows photon decay

Simple condition

$$E_\gamma = E_+ + E_-$$

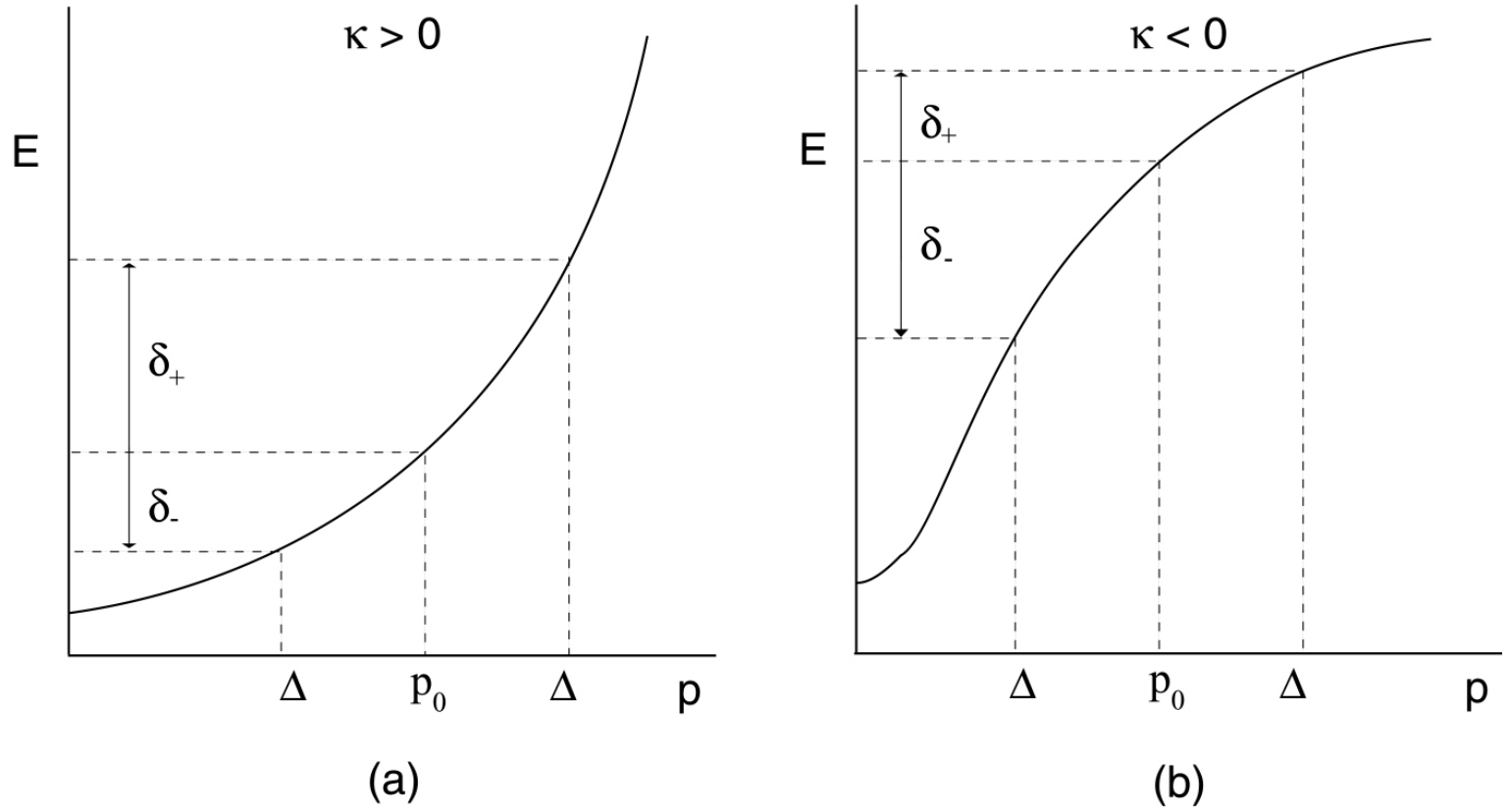
Call photon $\kappa \to \eta$ and electron $\kappa \to \xi$. 4-momentum conservation and MDR give

$$\xi \frac{p_\gamma^2}{E_P} = \frac{m_e^2}{p_+^2} + \eta \frac{p_+^2}{E_P} + \frac{m_e^2}{p_-^2} + \eta \frac{p_-^2}{E_P}$$

Photon Stablity

- Key question: How is the momentum partitioned?

Jacobson, Liberatti, Mattingly arXiv:hep-ph/0110094



From T. Konopka thesis Hamilton '02

Photon Stablity

Particle process thresholds are highly sensitive to this kind of modification!!

Thresholds become

$$p_{\gamma *} = \left[\frac{8 m_e^2 E_P}{(2\eta - \xi)}\right]^{1/3} \quad \text{for } \eta \geq 0$$

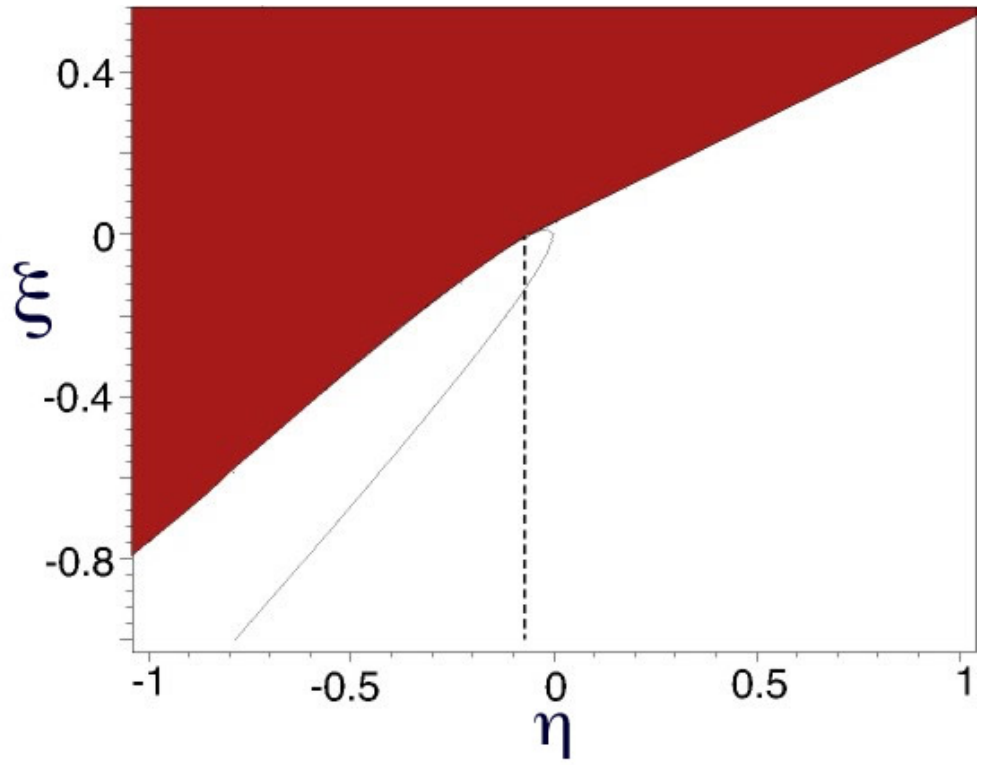
and

$$p_{\gamma *} = \left[\frac{-8 \kappa_e m_e^2 E_P}{(\eta - \xi)^2}\right]^{1/3} \quad \text{for } \xi < \eta < 0$$

Observations of high energy photons produce constraints on ξ and η. e.g. 50 TeV photons from Crab Nebula

Photon Stablity

Red region is ruled out by photon stability constraint



Model with MDR

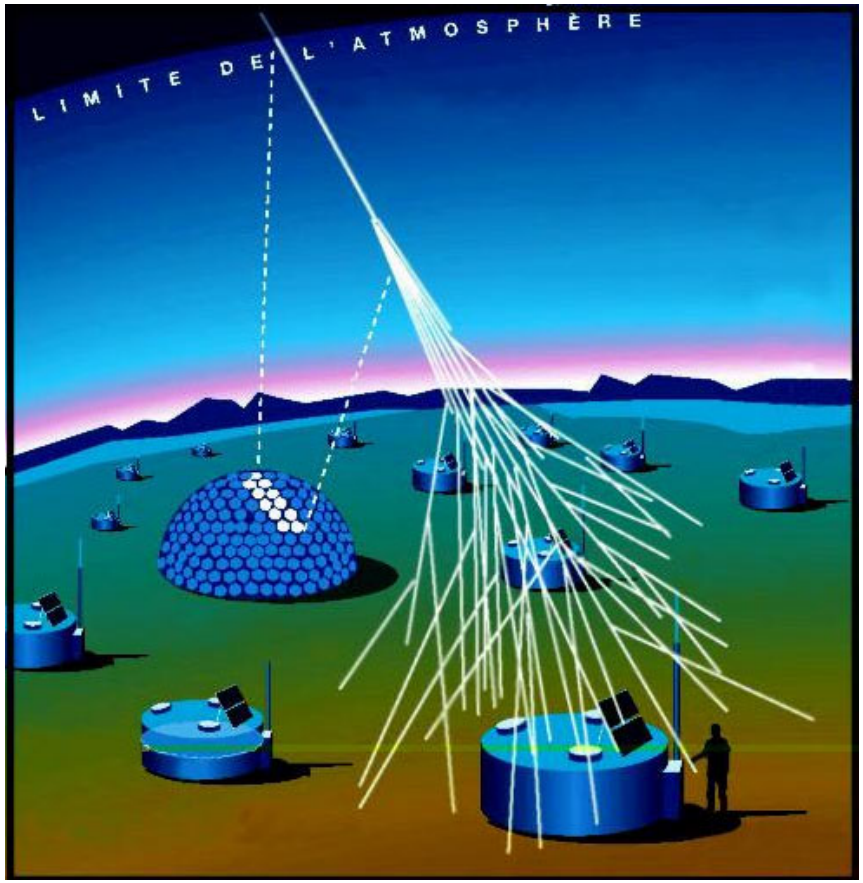
• Many other processes limit the extent of MDR: dispersion, birefringence, Vaccum Cerenkov radiation, photon absoprtion, pion stability, ...

What about the GZK cutoff? Can MDR raise the threshold?

Yes! If the modification is negative $\kappa \sim -10^{-15}$

If the GZK threshold is raised this way then Lorentz invariance is not preserved. Data?

Pierre Auger Observatory http://www.auger.org/



Auger is the largest cosmic-ray air shower array in the world (> 70 sq.mi.)

Pierre Auger Observatory http://www.auger.org/
One of 1600 Cerenkov detectors in Argentina

A Quantum Gravity detector??? For GZK, need more statistics...

Status of MDR 2004

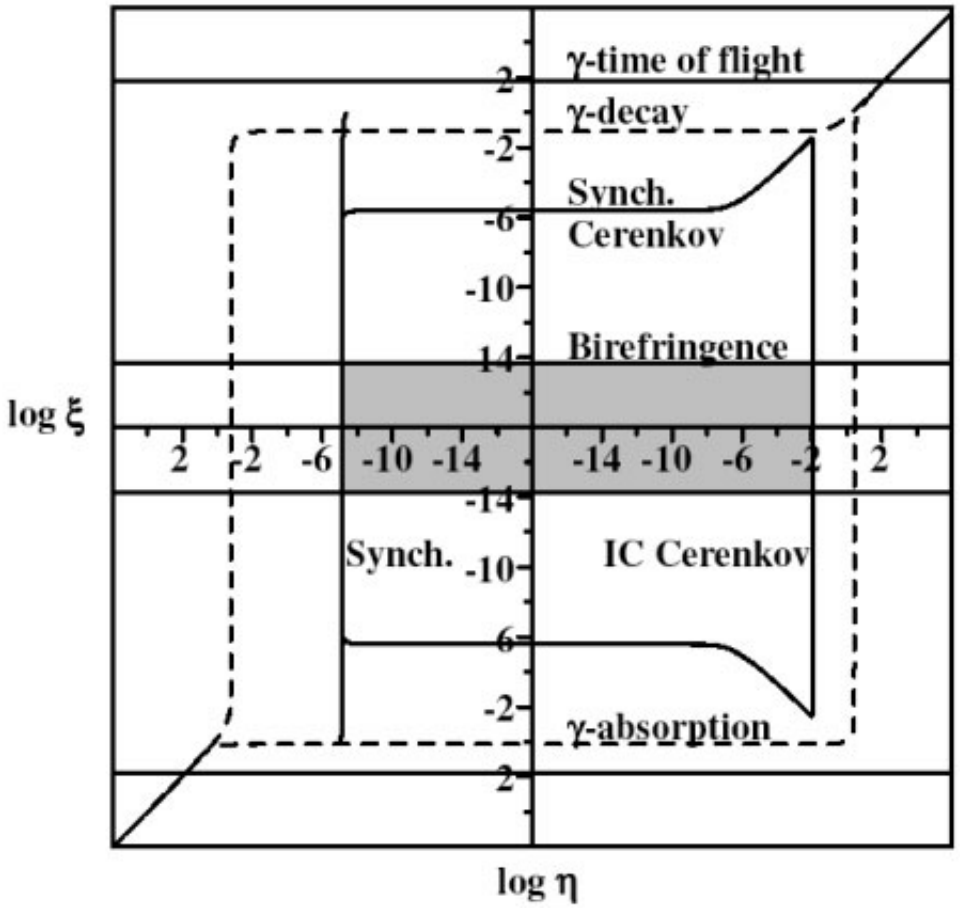
• Myers & Pospelov: Effective field theory framework → 3 parameters for QED - helicities independent

• Jacobson, Liberati, Mattingly, Stecker: Spectacular new constraints from synchotron radiation in SN remnants and polarization dependent dispersion from gamma ray burst GRB021206

• Collins, Perez, Sudarsky: A fine tuning problem → theoretical framework is questioned.

• Amelino-Camelia: Should be be using field theory at all for phenomenology?

Status of MDR 2004



from arXiv:astro-ph/0309681

Can we use tests of local Lorentz invariance?

A new Discrete Machian Model:

> *The motion of a body K can only be estimated by reference to other bodies A, B, C, ... When we reflect that we cannot abolish the isolated bodies A, B, C, ... that is, cannot determine by experiment whether the part they play is fundamental or collateral, that hitherto they have been the sole and only competent means of the orientation of motions ..., it will be found expedient provisionally to regard all motions as determined by these bodies.*
>
> E. Mach

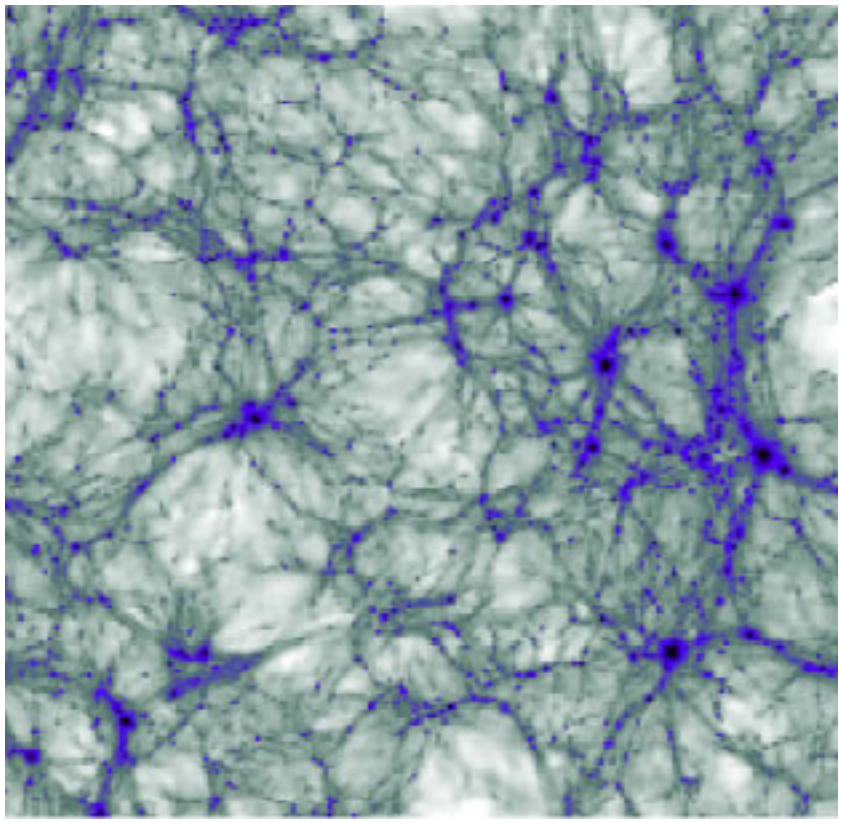
Model based on two assumptions:

(i) Underlying theory has a discrete structure to space e.g. a spin network state

(ii) Mass is determined by the distribution of matter

A Discrete Machian Model

Cocconi-Salpeter: Non-uniformities lead to **anisotropy of mass**



Springel, Hernquist, White (2000)

$m \rightarrow m_{ij}$ so $F^i = m_{ij} a^j$

where $m_{ij} = m + \Delta m_{ij}$

Quantitative form of Mach's principle:

$$\Delta m \propto \frac{M(r)}{r^\nu}$$
$$\Delta m \propto f(\theta)$$

θ between acceleration and preferred direction

A Discrete Machian Model

Idea (Cocconi-Salpeter): Look for sidereal variations in the fine structure of Zeeman transitions.
A short calculation shows

$$\Delta E = \frac{\Delta m}{m} \bar{T} \langle P_2(\cos\theta) \rangle$$

Not all transitions are affected, $\langle P_2 \rangle_{J=0} = 0$, so one transition can act as a reference.

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• Hughes-Drever Experiments

- Some of the most precise null experiments ever performed.
- No sidereal variation have been observed. Recent results show

$$\frac{\Delta m}{m} \leq 10^{-23}$$

A Discrete Machian Model

Combining Cocconi-Salpeter and discrete space assumptions

- Local matter variations cause deviations from isotropy
- Discrete geometry cannot support a continuously changing angle
- If the deviations away from continuum are random, and the path does not depend on history, then "the preferred direction" performs a random walk, with drift.

Can tests of local Lorentz invariance constrain the shape and scale of the discreteness?

A Discrete Machian Model

The recurrence time will affect c_ℓ in

$$\delta E = \sum_{\ell=1}^{2I} c_\ell(I) T_0^\ell(I)_{mm} \langle P_\ell(\cos\theta) \rangle_{\text{geom}}$$

θ is the angle between the axes of quantization ($\mathbf{B}$) and the preferred direction at the moment of the measurement. The vev is taken in the state of geometry.

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For instance, in regular cubic lattice $\langle P_2\rangle$ is a step function ($\cos\theta$ is 0 or 1). Possible to rule out on the $\approx 10^{-23}$ level.

Summary: Quantum Gravity and Physics

- **Physics from QG?** Not yet

But there are

- Preliminary results: Discrete geometry

- **New Middle Ground** Quantum Gravity Phenomenology

- MDR and Threshold effects yielding constraints : GZK cutoff?

- A Discrete Machian Model