# *Is Nothing Sacred?*

## Lorentz Symmetry Breaking and High-Energy Cosmic Rays

*C.P. Burgess*

# Outline

- Motivations:
  - *Why Bother?* An opinionated survey…
- Implications:
  - Effective Field Theories
  - Implications of Nonstandard Kinematics
- High-Energy Cosmic Rays:
  - Constraints
  - Utility?
- Summary

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# Kinematics and the GZK Cutoff

- Lorentz-violating physics can radically change the inferences about the nature and sources of cosmic rays.
  - Failure of boost invariance makes high-energy hadrons interact differently with the CMB than they would in their CM frame.
  - Appropriate choices of dispersion relation for pions, protons and photons can change the threshhold for reactions like $p\,\gamma \rightarrow p\,\pi$
  - New energy-loss process become possible, like $p \rightarrow p\,\gamma$ or $p \rightarrow p\,e^{+}e^{-}\,x$
- Can such effects occur? Are they plausible?

# Why Break Lorentz Invariance?

- Lorentz invariance is well tested and successful. Is it fundamental?
  - Baryon number conservation is well tested at accessible energies, but this does *not* make us expect short-distance physics to conserve it.
  - Baryon number is an accidental symmetry of the Standard Model even in a GUT which breaks it.

$$\boxed{L_{eff} = \frac{g^2}{M^2}\varepsilon_{abc}\left(D_i^a \gamma_L D_j^b\right)\left(D_k^c \gamma_L E\right) + c.c.}$$

# Is Lorentz Symmetry Emergent?

- Quantum Gravity: Could Lorentz invariance be emergent at low energies in the same way?
  - Suppose spacetime is lattice-like at very small distances.
  - Rotational invariance *can* emerge at low energy from lattice symmetries.
- Boosts are much more difficult to achieve in this way.

$$\boxed{L_{eff,1} = M\left(\overline{\psi}\gamma_0\psi\right)}$$

$$\boxed{L_{eff,2} = \overline{\psi}\gamma^0\partial_0\psi + c\,\overline{\psi}\vec{\gamma}\cdot\nabla\psi}$$

$$c \sim \log M$$

# Guidance from String Theory

- String theory does not seem to break Lorentz invariance at short distances in a lattice-like way.

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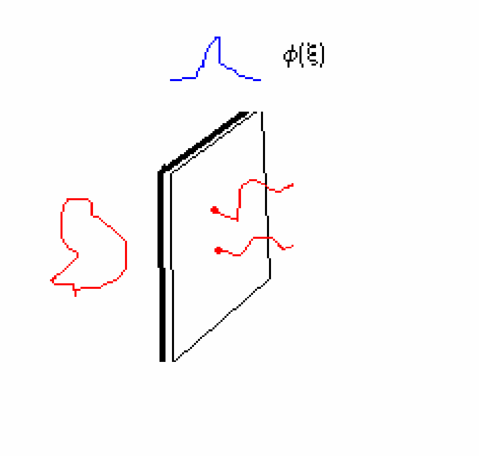
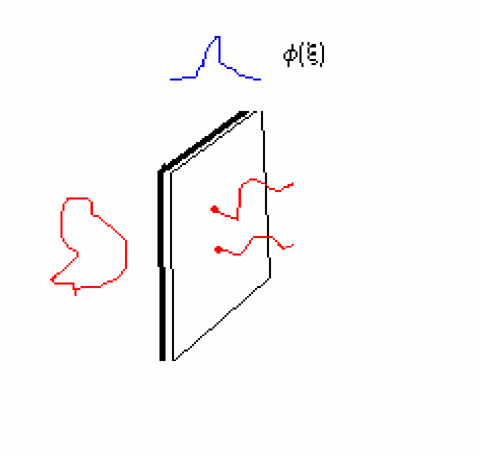
- String theory contains branes as well as strings.

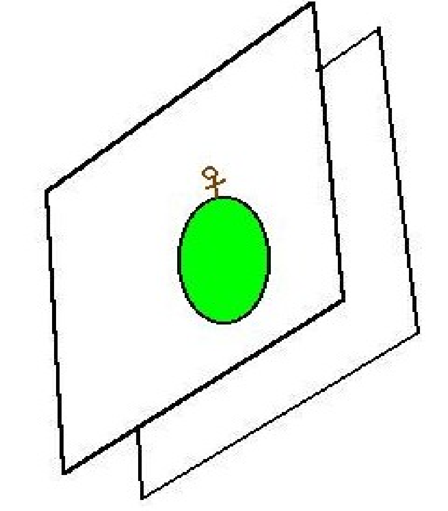


# Guidance from String Theory

- String theory does not seem to break Lorentz invariance at short distances in a lattice-like way.
- String theory contains branes as well as strings.
- All known particles (except for gravity) can be trapped on a brane at low energies.

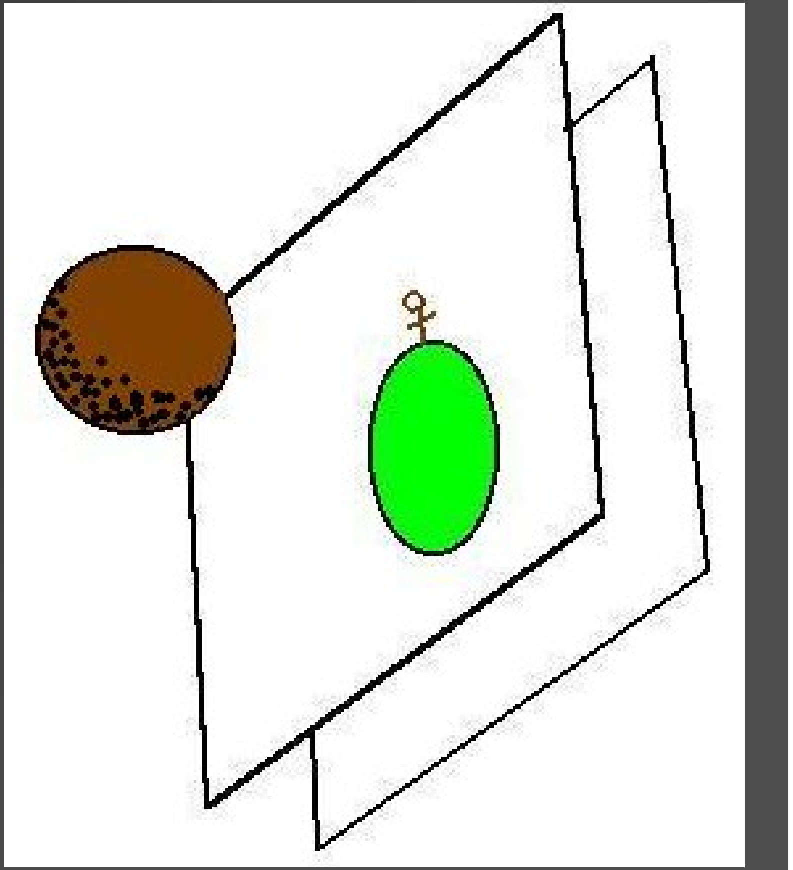
*‘The Brane World’*



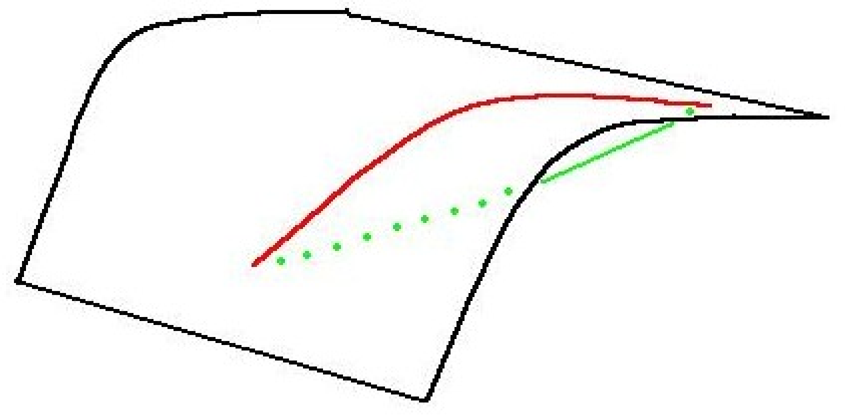


# Pandora's Box, opened

- Preferred-frame effects are *generic*, in presence of extra-dimensional objects.
  - Physics *can* depend on our absolute motion.
- Gravitons can take short-cuts through the bulk extra dimensions.*
  - Maximum speed can depend on particle species.



# Gravitational Shortcuts?



- ‘Brane’ and ‘bulk’ particles have different speeds because bulk particles can take shortcuts.
- *Not So Fast:* At low energies bulk particles are not localized in the extra dimensions due to uncertainty principle. Nevertheless, Lorentz-violating effects can arise…

$$\boxed{\Delta x \leq r \Rightarrow E \geq 1/r}$$

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# Effective Field Theory

- Suppose another symmetry (like CPT) eliminates effective Lorentz-violating terms proportional to *M*.
- At low energies modifications of kinetic terms dominate: different particles ‘see’ different metrics.
  - Multiple metrics break Lorentz invariance….

$$L = \frac{1}{2}\sqrt{g}\, g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}\sqrt{\gamma}\,\gamma^{\mu\nu}\partial_\mu\chi\partial_\nu\chi$$

$$+ k\sqrt{g}\, g^{\mu\nu} g^{\lambda\rho}\partial_\mu\partial_\lambda\phi\partial_\nu\partial_\rho\phi + \ldots$$

If rotation invariance is not broken, then

$$g_{\mu\nu} = \gamma_{\mu\nu} + \varepsilon u_\mu u_\nu$$

# Implications for Dispersion Relations

$$E^2 = \left(mc^2\right)^2 + p^2c^2 + bp^4 + \cdots$$

- From the effective action we find
  - Leading terms imply: $c^2 - 1 \sim O(\varepsilon)$
  - Next-order terms mply: $b \sim O(k\,\varepsilon^2)$

# And if from the Brane World….

- Integrate out KK modes to obtain 4D effective theory.
- At tree level only gravity sees a different metric.
- Calculations give

  $g_{\mu\nu} = \gamma_{\mu\nu} + \varepsilon\, u_\mu\, u_\nu$

  *with*

  $\varepsilon \sim (M\, r)^{-1}$

$$L = L_{bulk} + L_{branes}$$

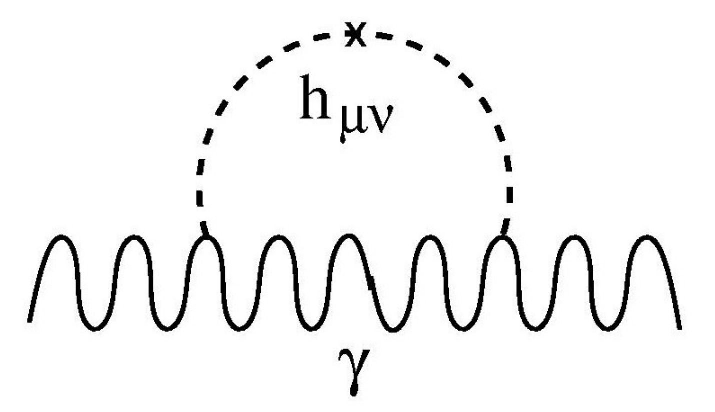
$$L_{bulk} = L_0 + L_1 + \cdots$$

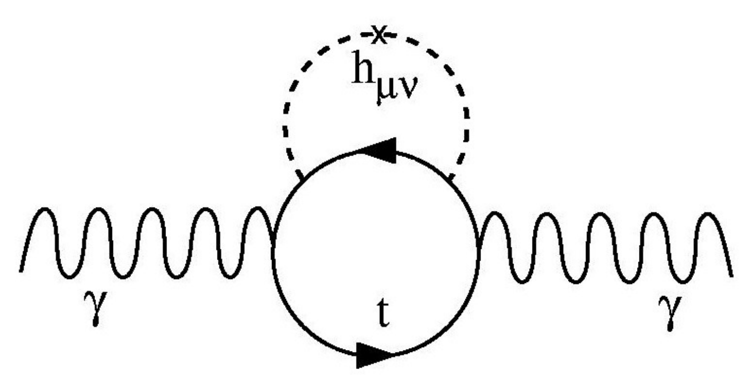
$$L_0 = \frac{M_p^2}{2} g^{\mu\nu} R_{\mu\nu}$$

$$L_1 = c_1 \frac{M_p^2}{2} \varepsilon\, u^\mu u^\nu R_{\mu\nu}$$

# And if from the Brane World….

- At one-loop level other particles acquire Lorentz-violating interactions.
- Self-energy graphs generate changes to maximum speed and dispersion of ordinary particles.





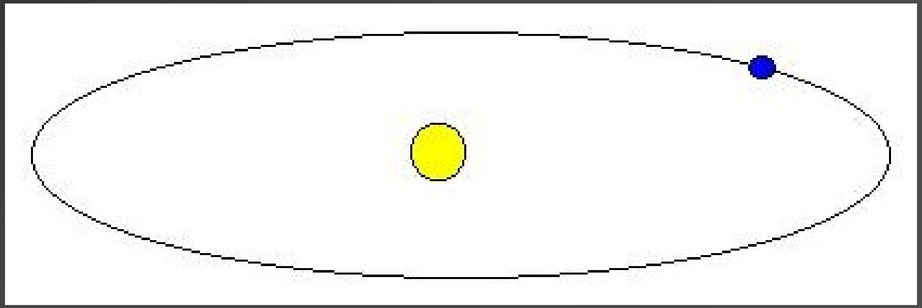
# Implications for Dispersion Relations

$$E^2 = \left(mc^2\right)^2 + p^2c^2 + bp^4 + \cdots$$

- For the brane world:
  - For gravity: $c^2 - 1 \sim \varepsilon\,, \qquad b \sim \varepsilon^2$
  - For other particles: $c^2 - 1 \sim \varepsilon\ \ m^2/(8\pi M_p)^2$,
    $b \sim \varepsilon^2/(8\pi M_p)^2$

# Terrestrial Constraints

- Very strong constraints exist for Lorentz-breaking terms for non-gravitational particles.



- Eg: Limits on variations in atomic spectra with Earth's motion:
  - $H_{eff} = E\,(v\,.\,s)$
  - $|c_\gamma - c_p| < 10^{-22}$

# In Brane World Case:

- No tree-level effect is predicted for brane bound particles, for which almost all of the bounds apply.
  - For almost all of parameter space the small contributions due to loops are smaller than the constraints. (Some come interestingly close!)
- Comparatively weak bounds on $c_g$ from tests of General Relativity:
  - Binary pulsar: $|c_\gamma - c_g| = O(\varepsilon) < 10^{-2}$
  - Terrestrial experiments: $|c_\gamma - c_g| = O(\varepsilon) < 10^{-3}$
  - Solar/Planetary Spins: $|c_\gamma - c_g| = O(\varepsilon) < 10^{-6}$

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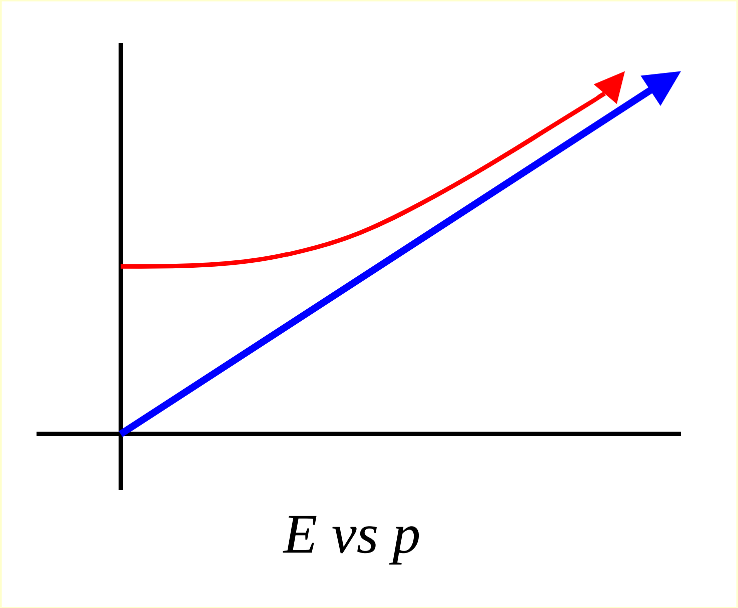
# Enter Cosmic Rays

- Cosmic rays provide very strong limits on violations of Lorentz invariance.
  - Very high-energy rays are seen: $E \sim 10^{11}$ GeV.
  - Lorentz-violating kinematics allow qualitatively new energy-loss processes:
    - Cerenkov radiation if $c_1 > c_2$
    - Photon decays, like $\gamma \rightarrow e^+e^-$, which normally are forbidden by energy-momentum conservation, become possible if $E > E_{min}$

# Why Are New Processes Possible?

- Processes like Cerenkov radiation, or photon dissociation are usually forbidden by the interplay of energy and momentum conservation.



# Why Are New Processes Possible?

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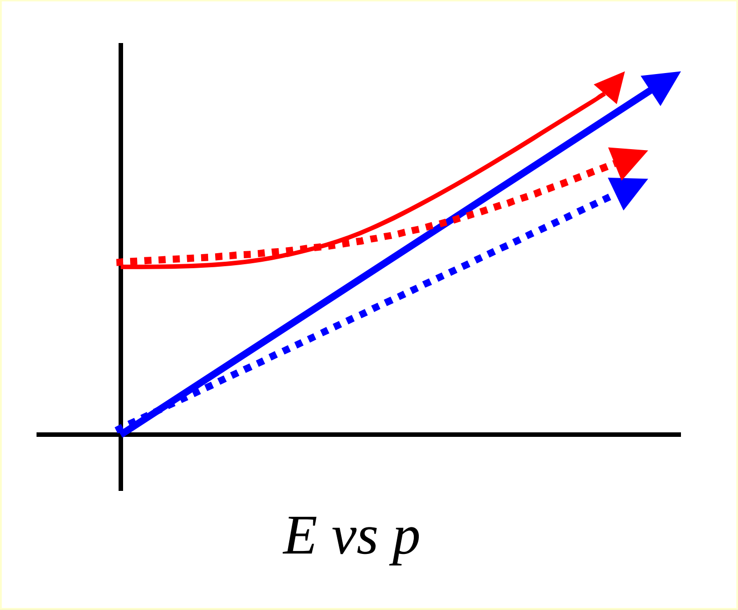
  - Modified dispersion relations can allow both to be satisfied.



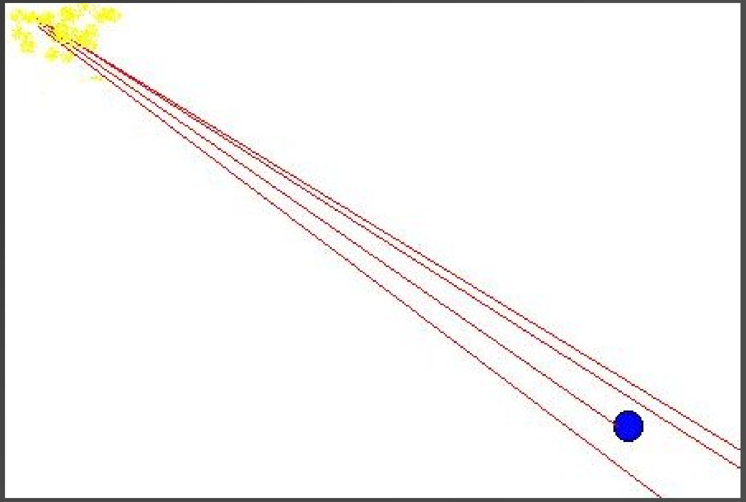
*E vs p*

# Cosmic Ray Constraints

Moore & Nelson,

Gagnon & Moore

- Assuming that energetic ($10^{11}$ GeV) cosmic rays go further than a metre:
  - $p \rightarrow p\,\gamma$, $p \rightarrow p\,g$ forbidden
  - $c_q - c_\gamma < 10^{-22}$
  - $b_q - b_\gamma < (10^{22}\text{ GeV})^{-2}$
- Assuming that very energetic ($10^{11}$ GeV) cosmic rays come *at least* as far as from the galactic center implies:
  - $c_q - c_g < 10^{-15}$
  - $b_q - b_g < (10^{22}\text{ GeV})^{-2}$



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- Preferred frame (PF) effects are possible, but not easy, to obtain in a phenomenologically interesting way.
  - Hard to make Lorentz violation decouple from low energies.
    - *This undermines most quantum-gravity proposals*
    - *Deserves serious consideration within brane-world scenarios, where it suggests PF effects may naturally hide in the gravity sector.*
- PF effects are very strongly constrained.
  - This is even true for many gravitational effects.
- Potential implications for high-energy cosmic rays.
  - So far CRs teach us more about PF effects than vice versa.

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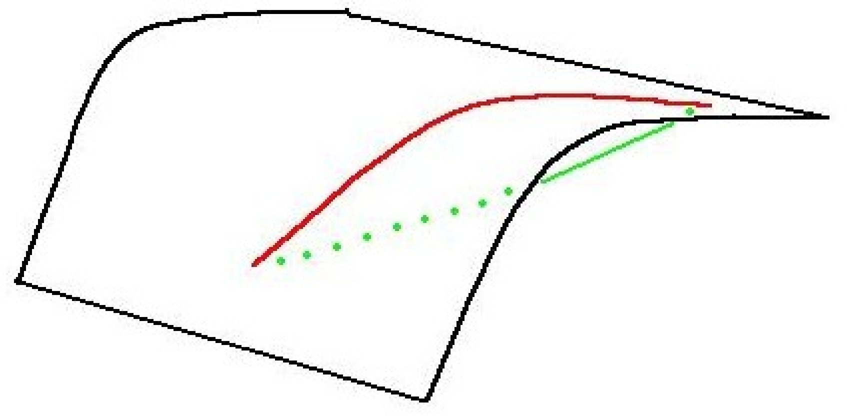
# How Not to Think About It



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$$L = \frac{1}{2}\sqrt{\gamma}\gamma^{\mu\nu}\partial_\mu\chi\partial_\nu\chi$$

$$\gamma^{\mu\nu} = G^{\mu\nu}(x, y = y_b)$$

$$\Phi(x,y) = \sum_k \phi_k(x)\, u_k(y)$$

$$L = \frac{1}{2}\int d^n y\sqrt{G}G^{MN}\,\partial_M\Phi\partial_N\Phi$$

$$= \frac{1}{2}\sqrt{g}\,g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \cdots$$

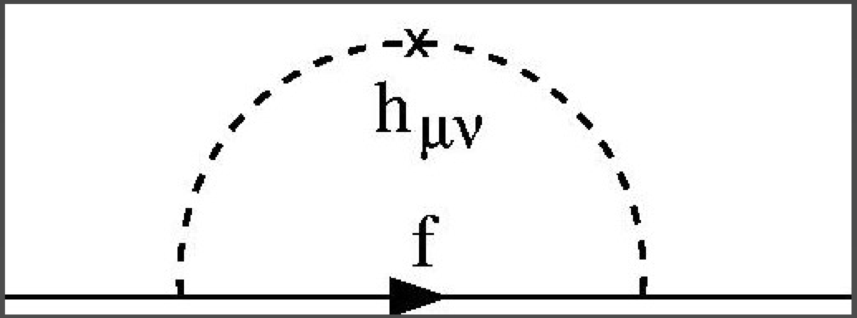
$$\sqrt{g}\,g^{\mu\nu}(x) = \int d^n y\sqrt{G}G^{\mu\nu}(x,y)\,u_0(y)u_0(y)$$

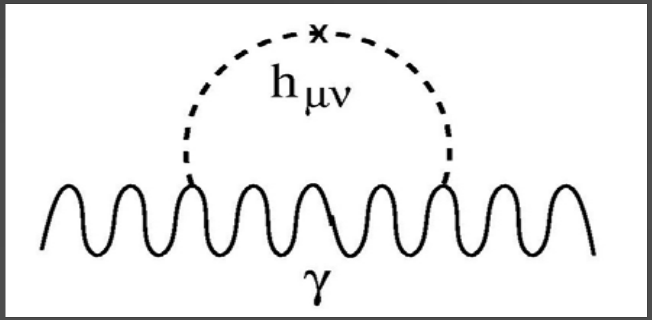
$\chi = \chi(x)$ on brane at $y = y_b$

$\phi(x)$ zero mode of $\Phi = \Phi(x,y)$

# From gravity to observed particles

- Quantum effects can carry the news of the preferred frame from gravity to brane particles.
  - For $c_g > c_p$ this can give the best bounds.
- Can compute the 1-loop prediction for changes to dispersion relation for fermions and gauge bosons:
  - Replace $g_{\mu\nu}$ by $g_{\mu\nu} + \varepsilon\, u_\mu\, u_\nu$ in graviton propagator
  - Can approximately sum KK graviton modes for energies $E > 1/R$.





# 4D graviton loop:

$$\delta c^2 \cong \left( \frac{\Lambda}{8\pi M_p} \right)^2, \quad b \cong \left( \frac{1}{8\pi M_p} \right)^2$$

- Loop integrals diverge in the ultraviolet
  - Contributions to $c^2$ are quadratically divergent
  - Contributions to *b* are logarithmically divergent
- Power divergences indicate sensitivity to UV.
  - Care required to interpret this (more about this later)
- In dimensional regularization Λ becomes m and divergences describe logarithmic running of effective couplings.

# 4D graviton results

- $\delta c^2$ largest for most massive particles:
  - Largest for W,Z bosons, Higgs and t-quarks.
  - Unobservably small.
- *b* same for all fermions
  - Negative for all ε.
  - $b_f > b_\gamma$
- $b_p$-$b_\gamma$ bounds $\varepsilon < 10^{-3}$

$$c_f^2 - 1 = -\frac{56\varepsilon}{3}\left(\frac{m_f}{8\pi M_p}\right)^2 \log\left(\frac{M^2}{m_f^2}\right)$$

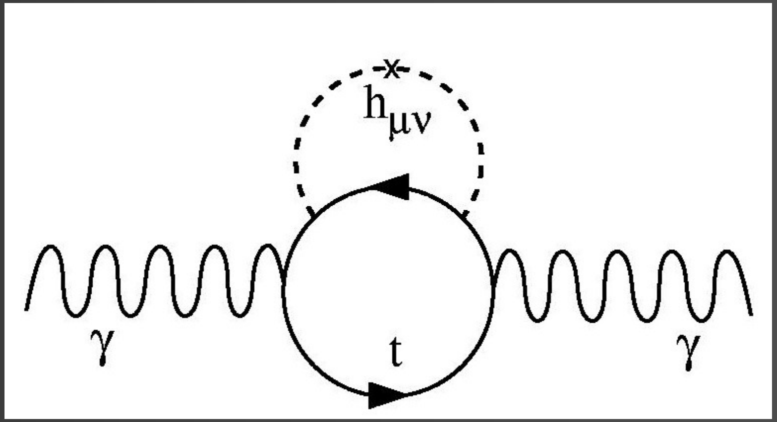
$$b_f = -\frac{12\varepsilon^2}{\left(8\pi M_p\right)^2}\log\left(\frac{M^2}{m_f^2}\right)$$

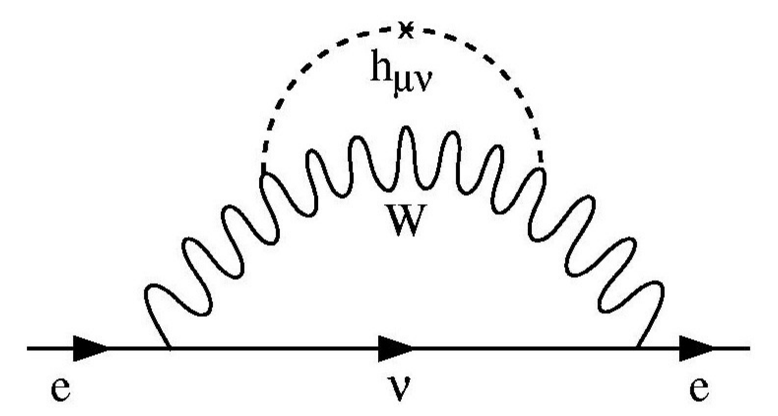
$$c_\gamma^2 - 1 = 0$$

$$b_\gamma = -\frac{304\varepsilon^2}{15\left(8\pi M_p\right)^2}\log\left(\frac{M^2}{\mu^2}\right)$$

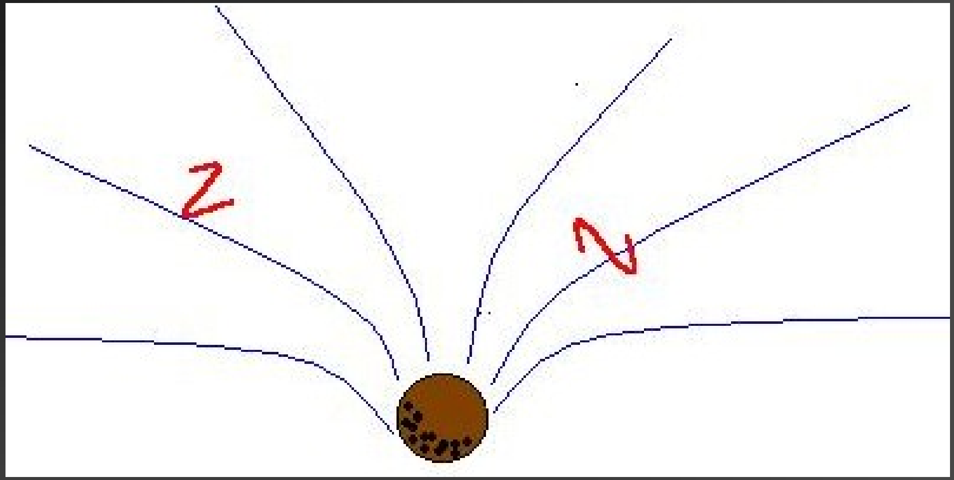
# 4D graviton revisited

- Strong mass dependence implies higher loops can compete for $\delta c^2$.
  - $\delta c_\gamma^2 \sim (\alpha/4\pi)\, \delta c_t^2$
- Protons are not elementary at scales larger than 1 GeV.
  - $\delta c_p^2 \sim \max(\delta c_g^2 , \delta c_q^2 )$
- Predictions for *b* not strongly affected.
- Cutoffs miss couplings!





# Graviton KK modes



- For scales larger than 1/R, bulk KK modes can also communicate preferred-frame effects within loops.
  - Summing KK modes is same as using higher-D graviton.
  - For short-wavelength gravitons background is essentially flat.

$$G_{\mu\nu} = g_{\mu\nu} + a\,\varepsilon\,u_\mu\,u_\nu$$

# Higher-D graviton results

- Both $\delta c_f^2$ and $b_f$ are more sensitive to mass than in 4D
  - More mass in an extra loop is even more worthwhile.
- Planck mass can be *much* smaller.
  - $M_d$ can be as low as 50 TeV.
  - Calculations apply to both ADD and RS scenarios.

D=5

$$c_f^2 - 1 = \frac{110\varepsilon\, m_f^3}{9(8\pi M_5)^2}$$

$$b_f = \frac{26\varepsilon^2 m_f}{3(8\pi M_5)^2}$$

D=6

$$c_f^2 - 1 = \frac{96\varepsilon\, m_f^4}{5(8\pi)^3 M_6^2}\log\left(\frac{M^2}{m_f^2}\right)$$

$$b_f = \frac{72\varepsilon^2 m_f^2}{5(8\pi)^3 M_6^2}\log\left(\frac{M^2}{m_f^2}\right)$$

# When do loops win?

Conditions for bounds to be better than $\varepsilon < 10^{-6}$

| Dimension | Spectroscopy (TeV) | Cosmic Rays (TeV) |
|---|---|---|
| $D = 5$ | $M_5 < 3 \times 10^4$ | $M_5 < 2 \times 10^7$ |
| $D = 6$ | $M_5 < 700$ | $M_5 < 9 \times 10^4$ |
| $D = 7$ | $M_5 < 50$ | $M_5 < 6 \times 10^4$ |
| $D = 8$ |  | $M_5 < 800$ |