Tests of Relativity In the τ Sector

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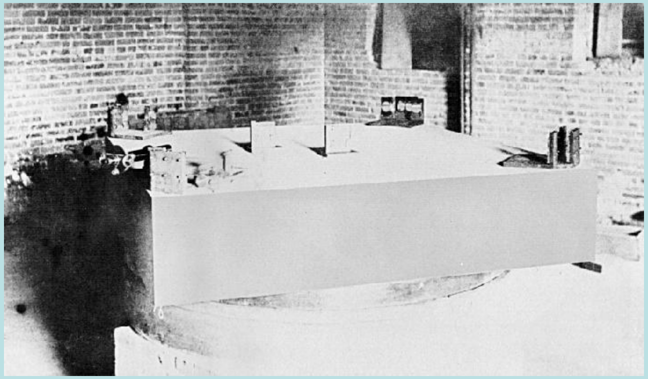
We have been testing relativity experimentally for a long time.

The first good test was done in 1887, before special relativity was even understood.



Michelson & Morley, 1887

And even 134 years later, Lorentz tests are still an active area of experimentation.

Introduction

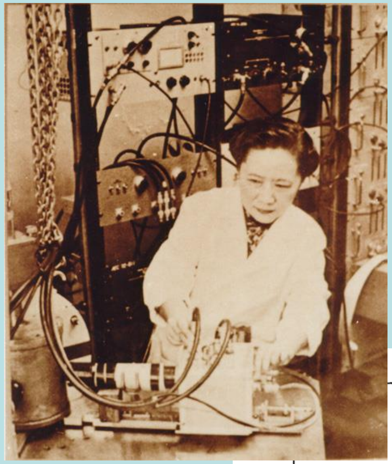
In the last twenty-five years, there has been growing interest in the possibility that Lorentz and CPT symmetries may not be exact.

There are two broad reasons for this interest:

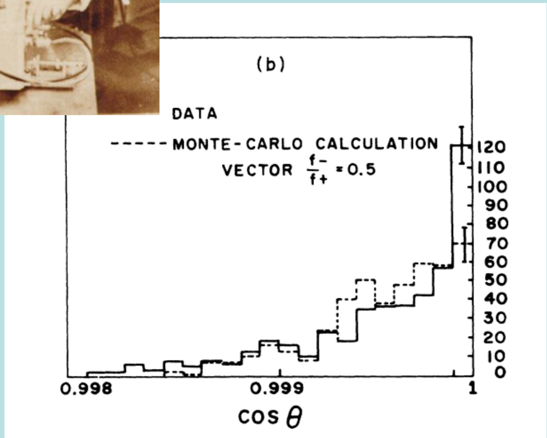
Reason One: Many theories that have been put forward as candidates to explain quantum gravity involve LV in some regime.

(For example, string theory, non-commutative geometry, loop quantum gravity…)

Reason Two: Lorentz symmetry is a basic building block of both quantum field theory and the General Theory of Relativity, which together describe all observed phenomena.



Anything this fundamental should be tested. Much of the story of modern particle physics is how important symmetries do not hold exactly.



Ultimately, we don't know where Lorentz violation might come from. However, any theory with CPT violation must also be Lorentz-violating.

[Greenberg, PRL **89**, 231602 (2002)]

Without evidence for LV, it makes sense to have a systematic framework for searching for it.

This framework is the SME, an effective field theory.

Standard Model Extension (SME)

Idea: Look for all operators that can contribute to Lorentz violation.

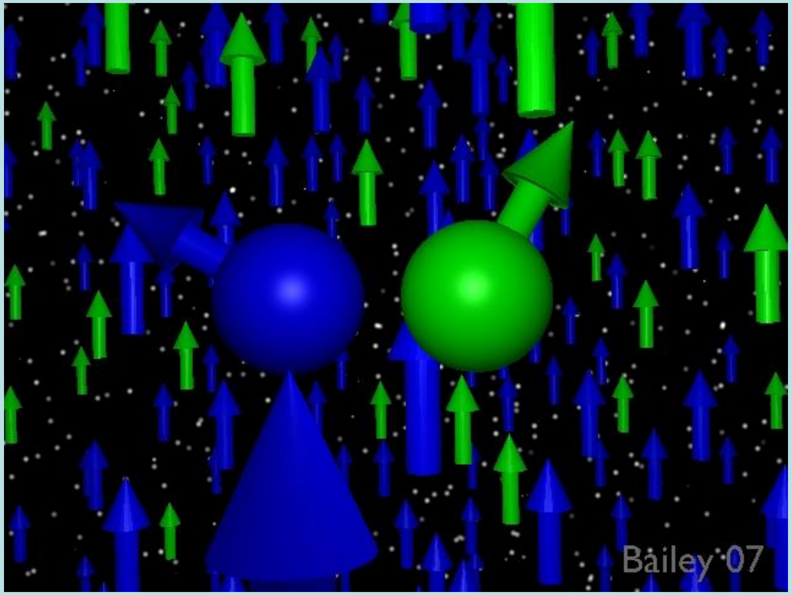
[Kostelecký and Colladay, PRD **58**, 116002 (1998)]

Then one usually adds restrictions:

- locality
- superficial renormalizability
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariance
- etc…

Many other formalisms turn out to be special cases of the SME.

Lorentz violating operators have objects built up from standard model fields, contracted with constant background tensors.



Earth-based laboratories will see slightly different local physics as the planet rotates and revolves.

The Lagrange density for a Lorentz-violating free Fermion theory is:

$$\mathfrak{L} = \bar{\psi}\left(i\Gamma^{\mu}\partial_{\mu} - M\right)\psi$$

$$M = m + \not{a} - \not{b}\gamma_5 + \frac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

$$\Gamma^{\mu} = \gamma^{\mu} + c^{\nu\mu}\gamma_{\nu} - d^{\nu\mu}\gamma_{\nu}\gamma_5 + e^{\mu} + if^{\mu}\gamma_5 + \frac{1}{2}g^{\lambda\nu\mu}\sigma_{\lambda\nu}$$

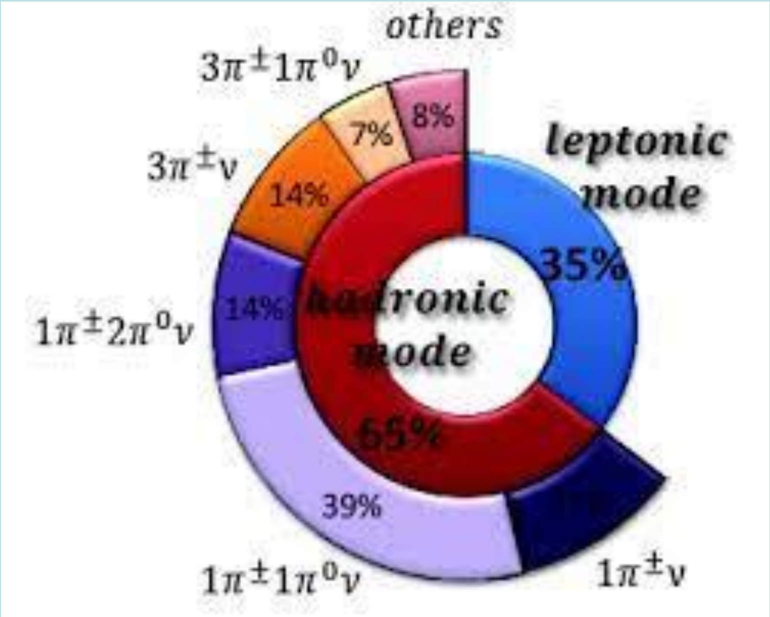
a, b, e, and g also violate CPT.

A separate set of coefficients will exist for every elementary particle in the theory, like the τ.

Experimental Bounds

For short-lived particles, practically the only way to place bounds is by looking at modified kinematics in high-energy reactions.

So we would want to look at τ production and decay, right?



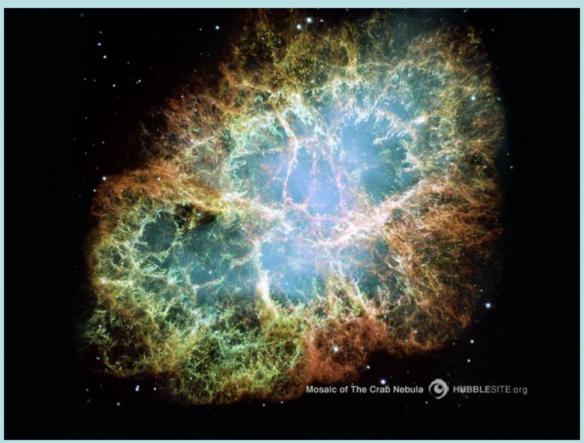
Actually, it turns out that there are no published bounds based on experiments in which actual τ leptons appear!

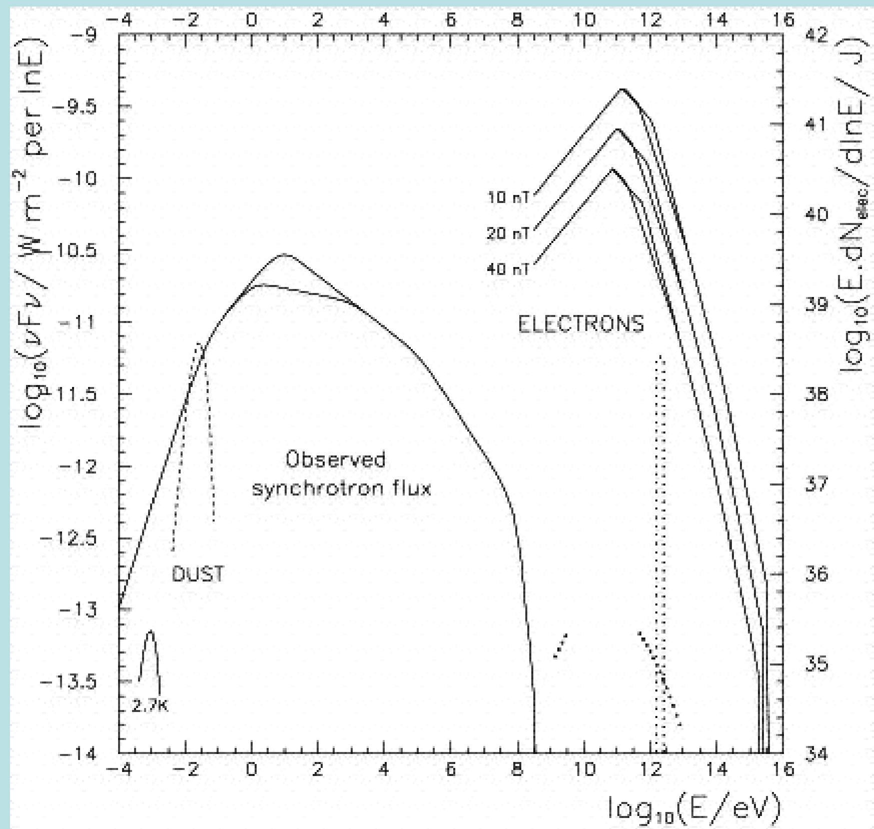
The few bounds are based on the absence of forbidden τ processes that could become allowed with Lorentz violation.

How? Well, with c coefficients, the behavior of the energy for ultrarelativistic fermions is

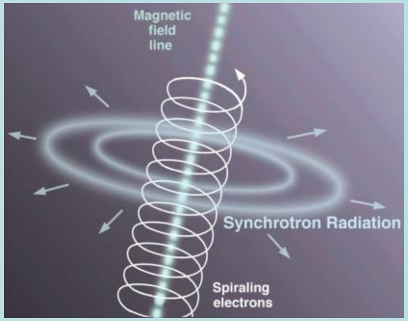
$$E = [1 - c_{00} - c_{(j0)}\hat{p}_j - c_{jk}\hat{p}_j\hat{p}_k]p + \frac{m^2}{2p^2}$$

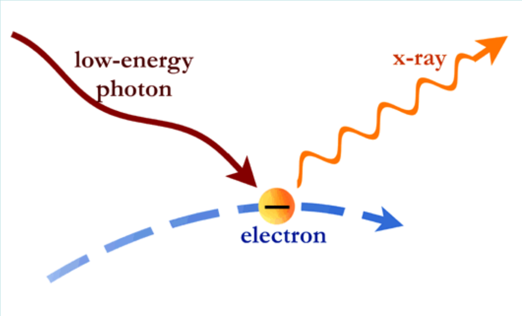
Even for electrons, the best bounds on boost violations come from looking at blazing hot sources. The radiation they emit tells us about the energy-momentum relations for photons and other particles.





We can draw inferences from the Crab spectrum, since we see evidence of PeV electrons emitting synchrotron and inverse Compton radiation.



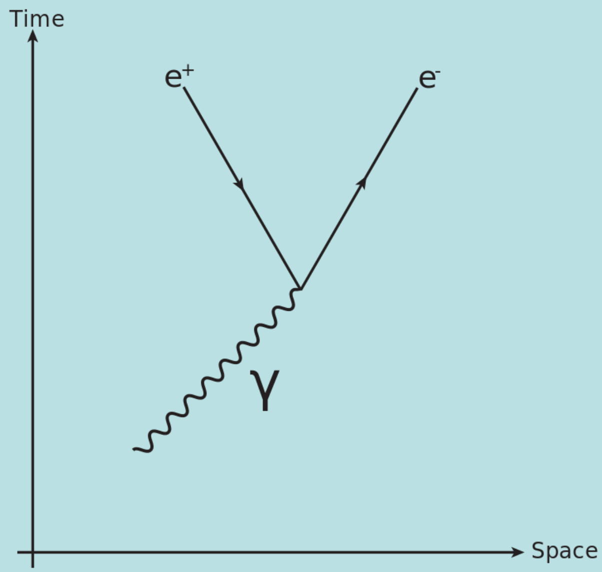


That these are possible tell us a lot about the electrons. The electron c and d are bounded at the $\left(m_e/E_\gamma\right)^2$ level.

This can be ~ 10^{-20} !

Some of these bounds actually apply to any kind of charged species!

If photon decay into pairs $\gamma \to X^{+} + X^{-}$ is kinematically allowed, it will happen… fast.



The order of the constraints is roughly $\left(m_X/E_\gamma\right)^2$.

$$E = \left[1 - c_{00} - c_{(j0)}\hat{p}_j - c_{jk}\hat{p}_j\hat{p}_k\right]p + \frac{m^2}{2p^2}$$

If the term in brackets is less than one (for particles moving toward Earth), the τ dispersion relation grows more slowly with p than conventionally.

This makes photon decay via $\gamma \rightarrow \tau^+ + \tau^-$ possible above a certain threshold.

For the c coefficients, the resulting bounds are at the ~ 10^{-8} – 10^{-13} levels for various linear combinations.

[BA, Astropart. Phys. **28**, 380 (2007)]

A similar analysis for the b coefficients yields bounds at the 10^{-11} GeV level for the b coefficients.

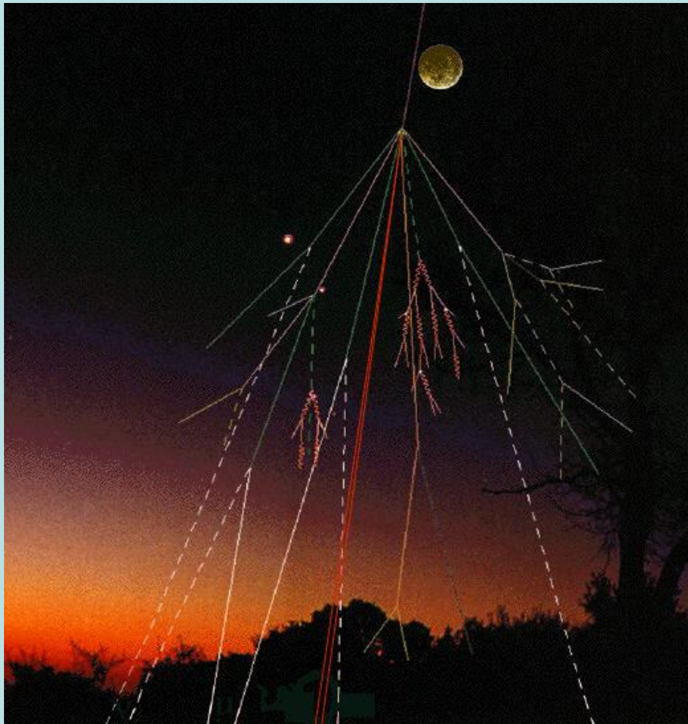
[Escobar, Noordmans, Potting, PRD **97**, 115030 (2018)]

Lots of parameter space remains unexplored.

Summary

Testing Lorentz and CPT symmetries is an active area of research in fundamental physics.

However, in the τ sector, essentially all the bounds come from the absence of certain τ-related processes in cosmic-ray physics.



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That's all, folks!