# Searches for Lorentz Invariance Violation

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# Precis

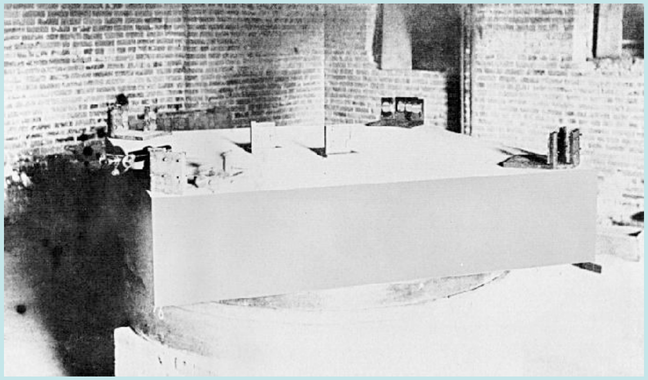
All of physics as we know it exhibits Lorentz symmetry—invariance under rotations and boosts—and CPT symmetry.

These invariances have been tested in matter-antimatter comparisons, meson oscillations, atomic clocks, and astrophysical polarimetery.

There are numerous candidate quantum gravity theories with LV, but nobody knows whether these are the exception or the rule.

We have been testing relativity experimentally for a long time.

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

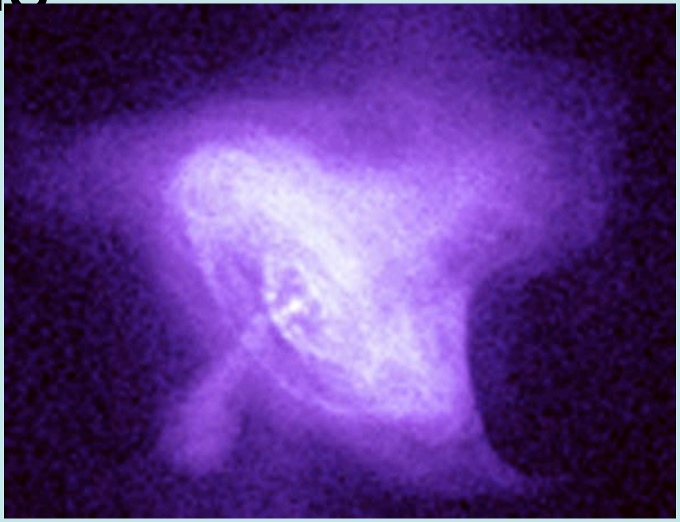


Michelson & Morley, 1887

And even 127 years later, Lorentz tests are still an active area of experimentation.

# Outline

- Intro: Why Lorentz and CPT Violation?
- The Standard Model Extension (SME)
- Synchrotron Emission Bounds
- Inverse Compton Bounds
- Conclusion



Synchrotron radiation from the Crab.

# Introduction

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

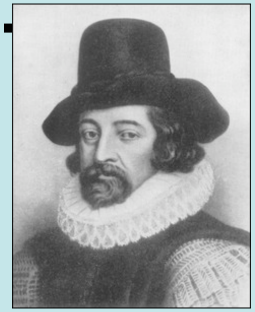
There are two broad reasons for this interest:

**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 theoretical physics is how important symmetries do not hold exactly.



*There is no excellent beauty that hath not some strangeness in the proportion.* — Francis Bacon

Although many quantum gravity theories involve LV and CPTV, it is not clear how ubiquitous the violations really are.

For example, the discovery that in string theory the tachyon potential often contains a minimum where Lorentz symmetry would be spontaneously broken spurred a great deal of interest in this subject.

[Kostelecký and Samuel, PRD **39**, 683 (1989)]

However, it now seems that this minimum is probably **NOT** the true vacuum.

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)]

So it would be good to have a systematic framework for studying any possible Lorentz and CPT violations. This framework is the standard model extension (SME), which uses the known tools of effective field theory to describe all possible forms of Lorentz violation involving standard model fields.

# Standard Model Extension (SME)

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

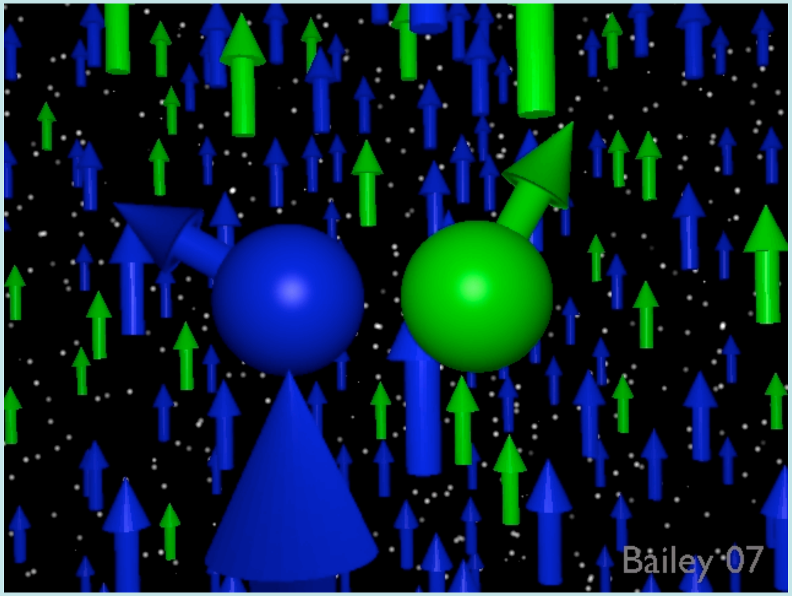
[Kostelecký and Colladay, PRD **58**, 116002 (1998)]

Then one usually adds restrictions:

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

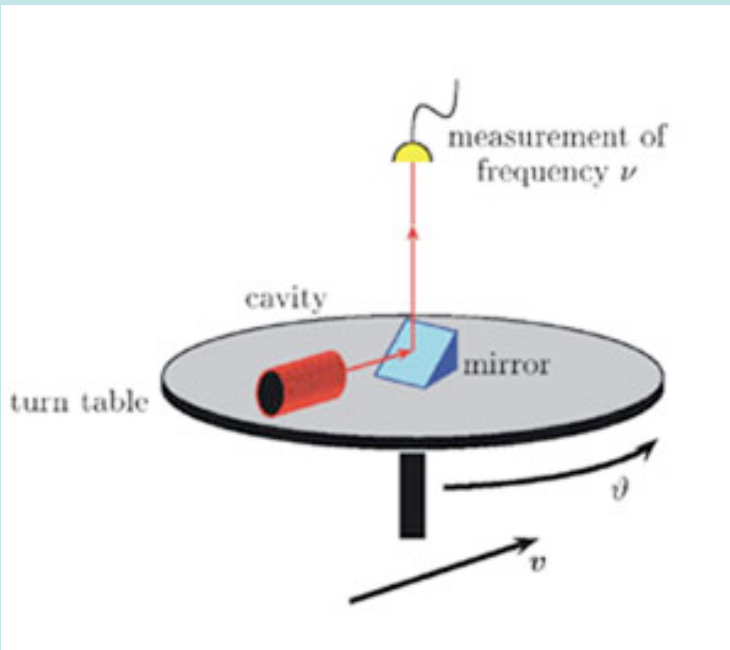
Many other formalisms turn out to be special cases of the SME.

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.

However, using only the Earth's motion will prevent us from measuring certain Lorentz-violating quantities. (Some newer experiments are using actively rotating apparatuses to get around this.)




This adds sensitivity to a preferred direction parallel to the Earth's rotation axis.

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

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

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

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

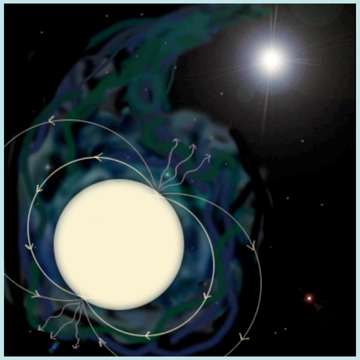
$a$, $b$, $e$, $f$, and $g$ also violate CPT.

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

When Lorentz symmetry is broken, angular momentum is not conserved.

One can look for this effect directly—by looking for wobbling in pulsars, for example. The effective moment of inertia of a pulsar is:

$$I_{jk} = I_0 \left[ \delta_{jk} + \frac{1}{2} c_{(jk)} \right]$$



The observed absence of wobbles lets one place bounds of $10^{-8}$ on the neutron $c$.

[BA, PRD **75,** 023001 (2006)]

The photon sector contains more superficially renormalizable couplings.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}(k_F)_{\mu\nu\upsilon\sigma}F^{\mu\nu}F^{\rho\sigma} + \frac{1}{2}(k_{AF})^{\mu}\varepsilon_{\mu\nu\rho\sigma}A^{\nu}F^{\mu\nu}$$

Most of these couplings are easy to constrain with astrophysical polarimetry.

However, some will require more complicated measurements (e.g. with resonant cavities, Doppler shifts or electromagnetostatics).

The most sensitive accelerator tests of Lorentz symmetry involve CPT tests with neutral mesons.

CPT-violating quantities, such as the $K^0 - \overline{K}^0$ mass difference are controlled by the phase

$$\delta_K \propto \gamma \frac{v_\mu \left( a_q^\mu - a_{q'}^\mu \right)}{m_{K_L} - m_{K_S}}$$

[Kostelecký, PRL **80**, 1818 (1998)]

The dependence on the meson velocity has important consequences.

Experiments at higher energies are more sensitive, even when they apparently have the same sensitivity to the $K^0 - \bar{K}^0$ mass difference.

The rate of CPT violation also generally depends on the meson direction, and so will change as the Earth-based laboratory rotates.

CPT violation has been searched for in neutral K, D, and B meson systems, using both time-averaged and day-night asymmetry measurements.

| Measurement Type | System | Coefficients | *log* Sensitivity | Source |
|---|---|---|---|---|
| oscillations | K (averaged) | *a* (d, s) | —20 | E773<br>Kostelecký |
| | K (sidereal) | *a* (d, s) | —21 | KTeV |
| | D (averaged) | *a* (u, c) | —16 | FOCUS |
| | D (sidereal) | *a* (u, c) | —16 | FOCUS |
| | B (averaged) | *a* (d, b) | —16 | BaBar, BELLE,<br>DELPHI, OPAL |
| | neutrinos | *a*, *b*, *c*, *d* | —19 to —26 | SuperK<br>Kostelecký, Mewes |
| birefringence | photon | $k_{AF}$ (CPT odd) | —43 | Carroll, Field, Jackiw |
| | | $k_F$ (CPT even) | —32 to —37 | Kostelecký, Mewes |
| resonant cavity | photon | $k_F$ (CPT even) | —17 | Muller et al. |
| anomaly frequency | e-/e+ | *b* (e) | —23 | Dehmelt et al. |
| | e- (sidereal) | *b*, *c*, d (e) | —23 | Mittleman et al. |
| | mu/anti-mu | *b* (mu) | —22 | Bluhm, Kostelecký, Lane |
| cyclotron frequency | H-/anti-p | *c* (e, p) | —26 | Gabrielse et al. |
| hyperfine structure | H (sidereal) | *b*, *d* (e, p) | —27 | Walsworth et al. |
| | muonium (sid.) | *b*, *d* (mu) | —23 | Hughes et al. |
| clock comparison | various | *b*, *c*, *d* (e, p, n) | —22 to —30 | Kostelecký, Lane |
| | He-Xe | *b*, *d* (n) | —32 | Bear et al.<br>Cane et al. |
| torsion pend. | spin-polarized solid | *b*, *d* (e) | —29 | Heckel et al.<br>Hou et al. |
| gamma-ray astronomy | e- /photons | *c*, *d* (e) | —15 to —20 | Altschul |

# Synchrotron Emission Bounds

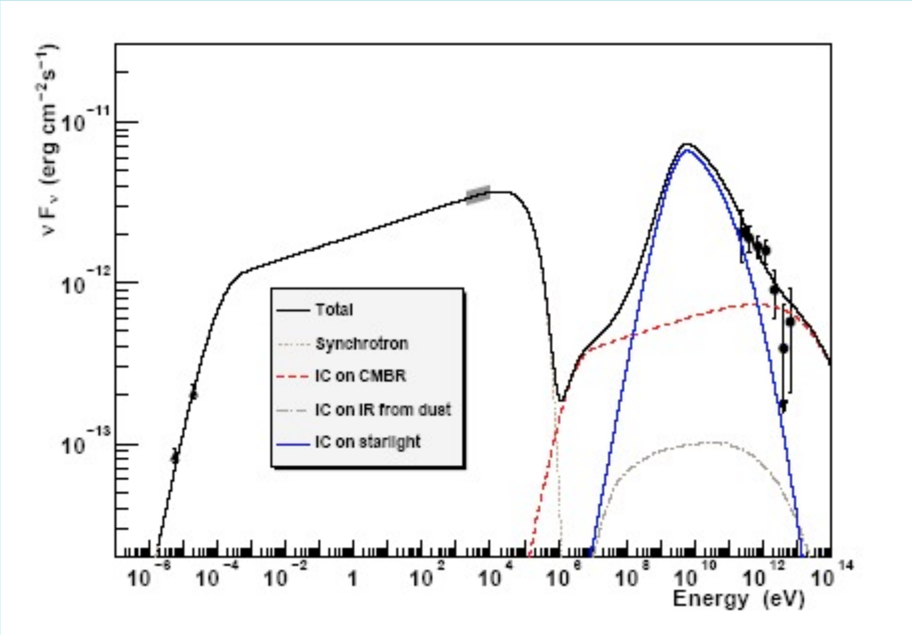
[BA, PRL **96**, 201101 (2006); PRD **72**, 085003 (2005); **74**, 083003 (2006)]

Some of the effects of Lorentz violation should become more important at high energies, so it is natural to look for their effects on astrophysics, where the very highest energies are available.

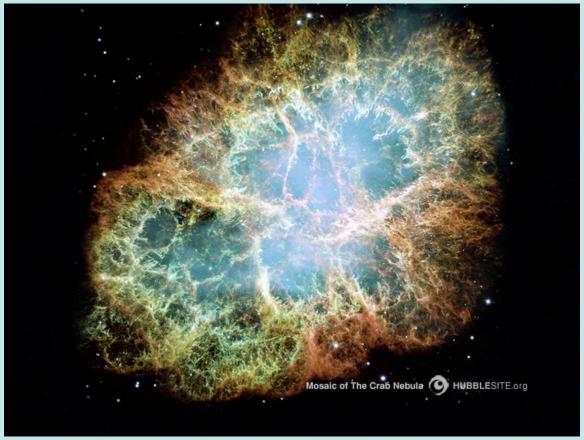
(Other astrophysical bounds may make use of the extremely large distances available, to magnify small light propagation effects.)

There’s a lot we can learn from the radiation we see from very energetic sources.

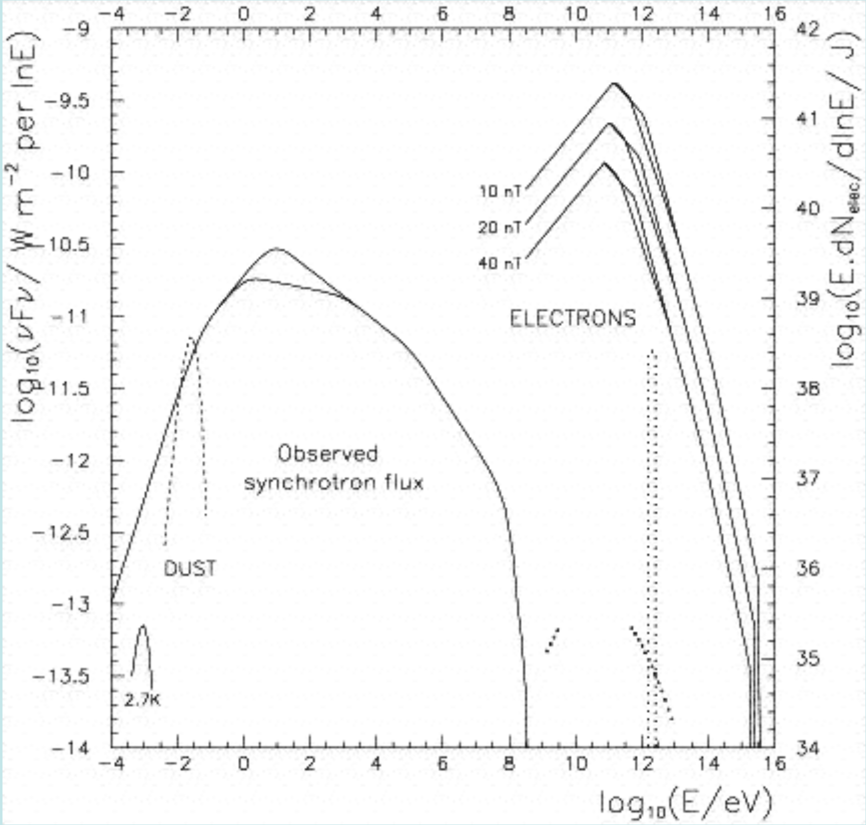
Different parts of the spectrum can tell us about different kinds of Lorentz violation.



The highest energy particles we see are cosmic rays above the GZK limit, but we do not understand them all that well.




So the best thing to concentrate on is high-energy sources that we *do* understand.



At high energies, the $c$-type Lorentz violation mentioned earlier is the most important.

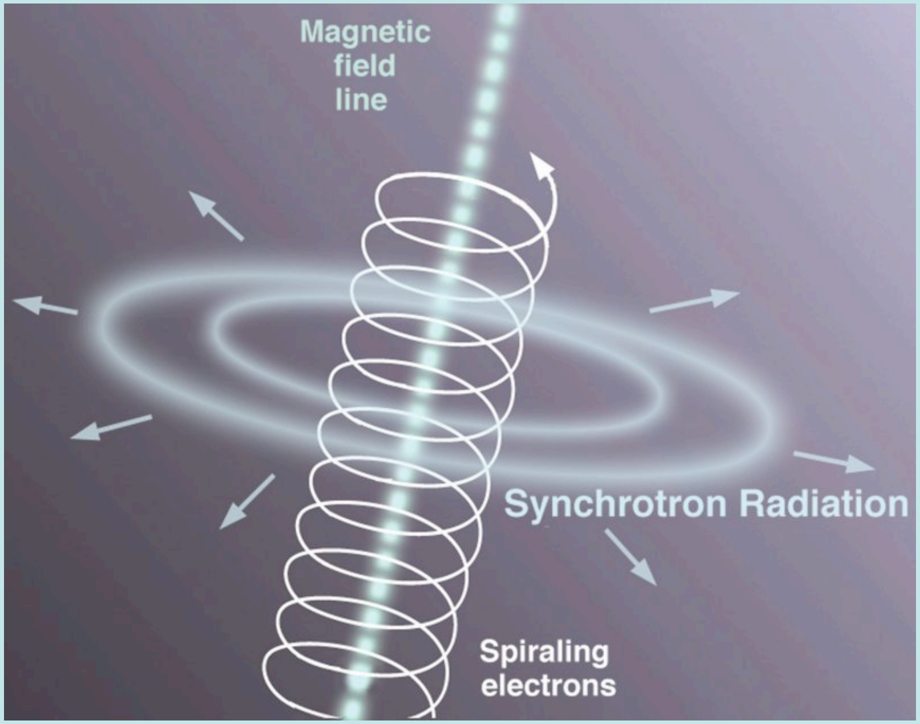
(Its effects grow as $\gamma^2$.)

Neglecting higher order corrections, the maximum electron velocity in a direction $\hat{e}$ is:

$$v < 1 - c_{jk}\hat{e}_j\hat{e}_k - c_{0j}\hat{e}_j$$

This turns out to have readily measurable consequences.

In models of PWN, the cutoff of the synchrotron spectrum depends strongly on the maximum velocity (not energy or momentum!) of electrons moving in an Earthward direction:




$$\omega_c^2 \propto \frac{|\vec{B}|}{\left(1 - v_{\max}^2\right)}$$

The magnetic field is "easy" to estimate.

If velocities up to $v_{\max}$ are observed, this limits the Lorentz violation to be smaller than:

$$c_{jk}\hat{e}_j\hat{e}_k + c_{0j}\hat{e}_j < \frac{1}{2\gamma_{\max}^2} = \frac{1 - v_{\max}^2}{2}$$

Observations in different directions give bounds on different combinations, but ***we can only get bounds this way if the maximum electron speed is less than the speed of light.***

# Inverse Compton Bounds

*So what happens if the maximum electron speed is greater than the speed of light?*

I don’t know exactly, but whatever it is, it is definitely “new physics.”

One thing we would expect is vacuum Cerenkov radiation.

Can we detect vacuum Cerenkov radiation?

**Perhaps.** It has some characteristic features, such as a power spectrum linear in the frequency.

However, there are many unanswered questions, and anyway, we expect the radiation to be of short duration. Superluminal electrons could be expected to lose energy at a rate of about $10^{14}$ GeV/s.

[BA, PRL **98,** 041603 (2007)]

We want to find secure bounds, that don’t rely on any inferences about “new physics.”

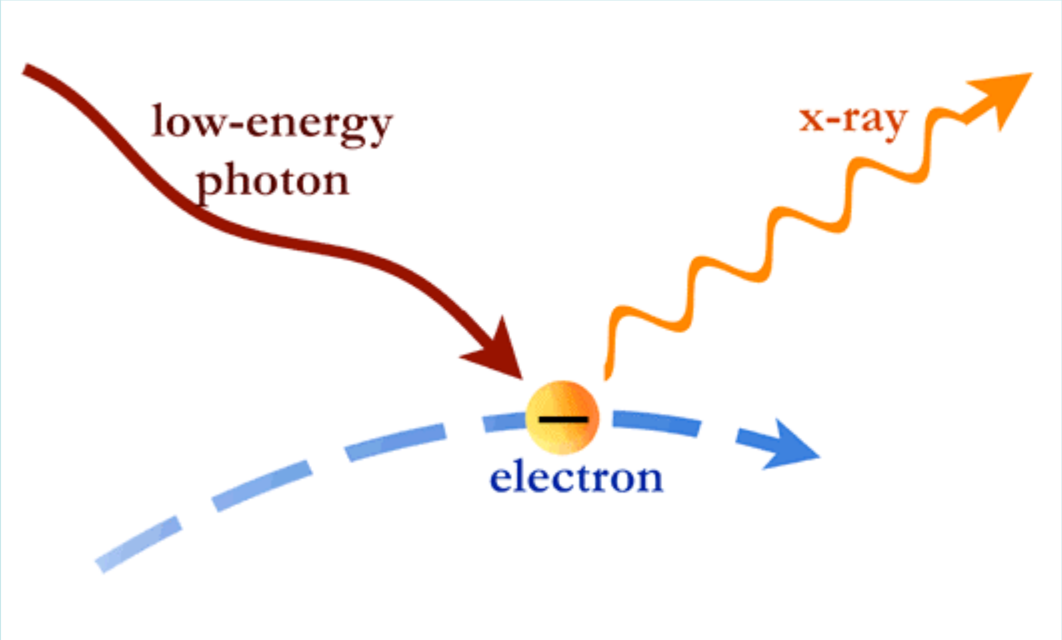
This means we can only look at electrons moving subluminally, and if the maximum electron speed is greater than one, there will be a maximum energy for these electrons:

$$E_{\mathrm{max}} = \frac{m}{\sqrt{-2c_{jk}\hat{e}_j\hat{e}_k - 2c_{0j}\hat{e}_j}}$$

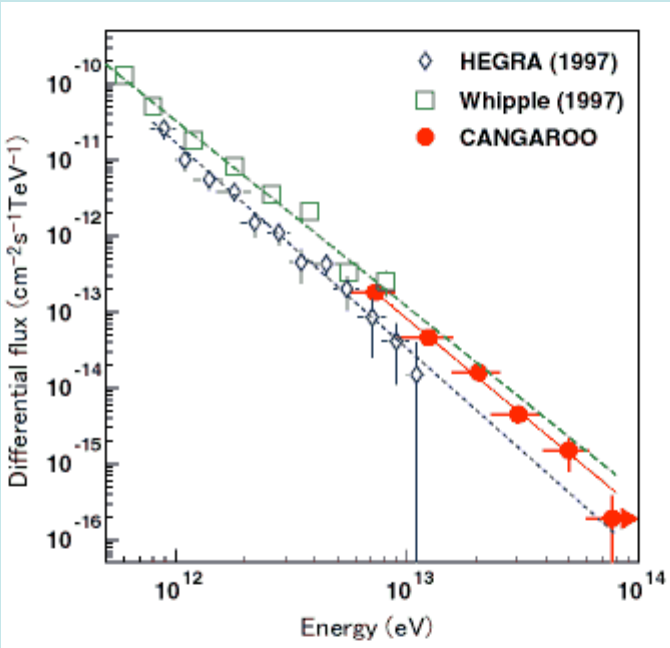
This also turns out to be something we can measure.

In inverse Compton scattering, $e^- + \gamma \rightarrow e^- + \gamma$

an ultrarelativistic electron collides with a lower energy photon and transfers a sizeable fraction of its energy.



Sources with superluminal electrons would exhibit anomalous emission features. The absence of such features indicates there are only subluminal particles, and the energy of observed inverse Compton photons is a lower limit on the highest electron energies.



This gives us the other half of the bound we need:

$$-\frac{1}{2\left(E_{obs}/m\right)^2} < c_{jk}\hat{e}_j\hat{e}_k + c_{0j}\hat{e}_j < \frac{1}{2\gamma_{\max}^2}$$

The best bounds of this sort are at the $10^{-20}$ level, coming from electrons with energies above 1 PeV.

By looking at different sources spread across the sky, we can get enough bounds to restrict all nine components of $c$ to lie in a bounded region of parameter space.

With linear programming, one can then place independent bounds on the individual components. These are typically at the $10^{-15}$ level or better.

Currently, these are the best bounds on some of the electron $c$ coefficients.

# Conclusion

Tests of special relativity are still interesting and relevant.

Many Lorentz-violating coefficients are strongly constrained, but LV remains a strong candidate to appear in a fundamental theory.

Emissions from high-energy astrophysical sources provide some of the best bounds for electrons.

*Thanks to V. A. Kostelecký, E. Pfister-Altschul, and Q. Bailey.*

That's all, folks!