Local Lorentz Invariance

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Outline

- Local Lorentz Invariance
- Standard Model Extension
- Experiments
- Clock-Comparison Experiment
- Current Limits
- Summary

Local Lorentz Invariance

- Rotations (3) and Boosts (3)
- Lorentz Covariant quantities
  - Scalars
    - Space-time interval $s^2 = (ct)^2 - r^2$, rest mass $(mc^2)^2 = E^2-(\mathbf{p}c)^2$, proper time τ
  - Four-vectors
    - Four-velocity, Four-momentum $p^{\mu}{}_i = (E_i, \mathbf{p}_i)$
  - Four-tensors
    - Electromagnetic Field tensor $F_{a\beta}$
  - Spinors
    - Majorana and Dirac spinors $\omega = \begin{bmatrix} \phi \\ \frac{\sigma\cdot\mathbf{p}}{E+m}\phi \end{bmatrix}$
- Addition of Gravity (Special Relativity) requires only local Lorentz covariance
- CPT Violation implies Lorentz violation
  - O.W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002)

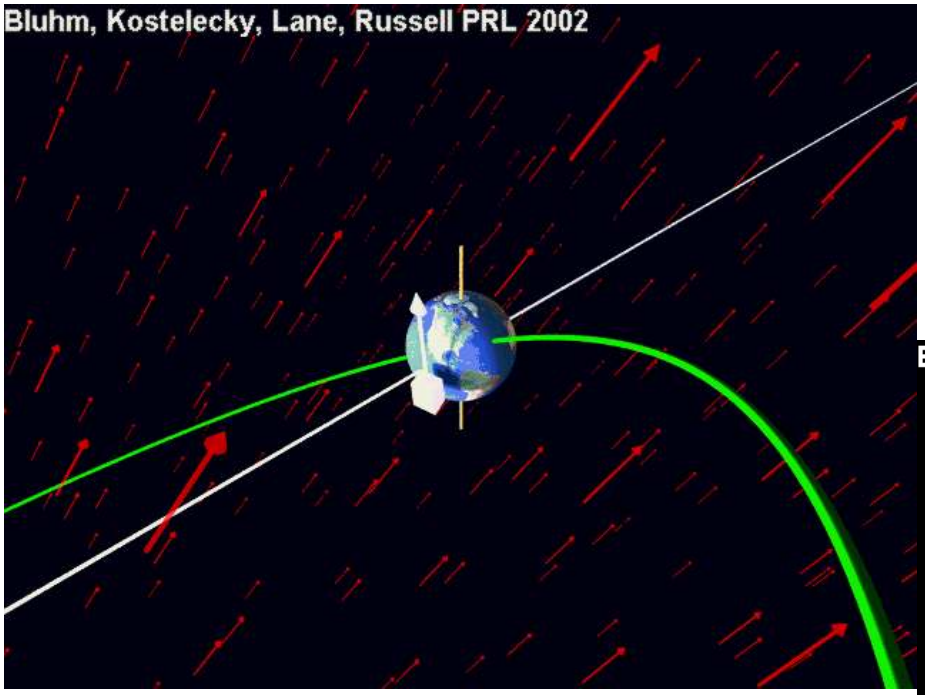
Particle vs. Observer Transformation

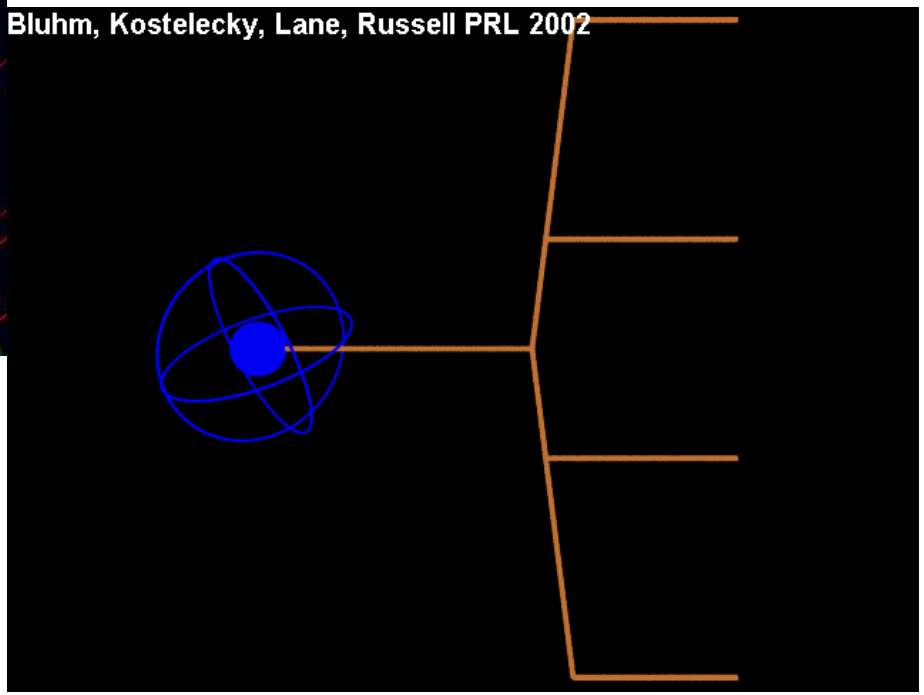
- Observer transformation invariance means laws of physics do not depend on orientation
- Particle transformation is when the particle is moving with respect to a fixed reference frame
- If there is a Lorentz violation, physical laws could be different for a moving observer vs. a stationary one

Standard Model Extension

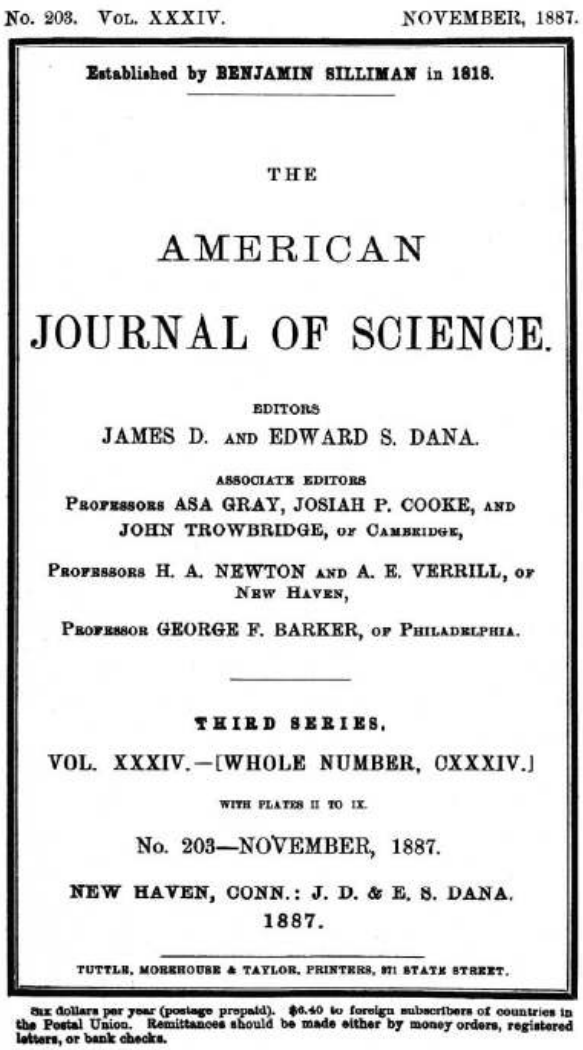
- Proposed and developed by Alan Kostelecky
- Generalization of RMS theory-
  - CMB as vacuum expectation value
- Observer transformations are still valid
- Particle boosts or transformations relative to vacuum expectation values can give apparent violations
- Similar to a particle moving through a crystal
  - Symmetries are broken, not due to a problem with the theory, but due to background fields
- SME contains all properties of the Standard Model and GR, except it allows the breaking of Lorentz and CPT symmetries
- Adds all possible coordinate-invariant operators formed by Standard Model and gravitational fields combining with couplings having Lorentz indices.
- Makes no predictions of magnitude or the "best test"
- All possible couplings = lots of experiments needed
- Sidereal time variation – 360° rotation of Earth

Atomic Clocks in Space





Doesn't this look familiar?



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ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

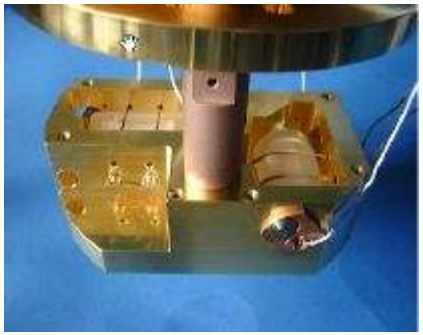
THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

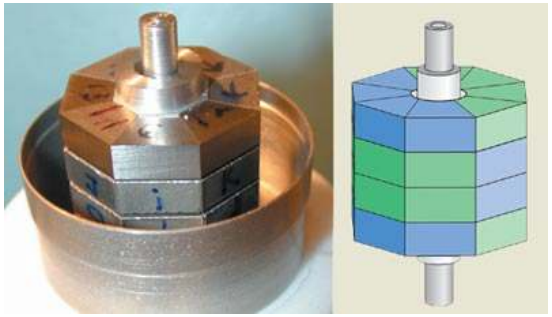
* This research was carried out with the aid of the Bache Fund.

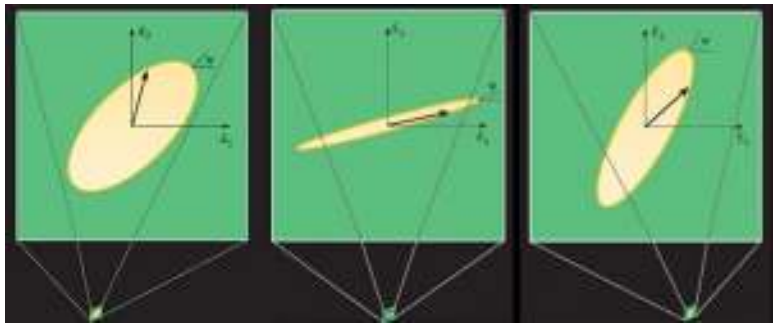
† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

Current Experiments

- Clock-Comparison Experiments
  - ^{199}Hg and ^{133}Cs
  - ^{129}Xe and ^{3}He **
  - Hydrogen Masers
  - Atomic Clock on ISS in 2005
- QED tests in Penning Traps
  - Electron-Positron g-2 measurement, and Proton-Antiproton g-2
- Oscillation Experiments
  - Neutral-B BaBar
  - Neutral-D FOCUS
  - Neutrino LSND
  - Kaon KTeV
- Spin-polarized torsion pendulum
- Muonium spectroscopy
- Vacuum-birefringence
- Limits set from astronomy







Clock Comparison Experiment

- Walsworth Group at Harvard
- ^{129}Xe and ^{3}He co-located masers
- 1.7 kHz ^{129}Xe, 4.9 kHz ^{3}He
- Extremely Stable- 100 nHz hr
- Nuclear spin-1/2 Zeeman transitions
- Single $^{1}S_{1/2}$ valence neutron
- Magnitude and sign of Lorentz violating shift is the same for both masers
- $\delta\nu_J = \delta\nu_J^{Lorentz} \, |1 - \gamma_{He}/\gamma_{Xe}|$
  $\approx 1.75 \, \delta\nu_J^{Lorentz}$
- Referenced to master Hydrogen maser
  - Hyperfine; insensitive to Zeeman effect in first order

$$\mathcal{L} = \frac{1}{2} i\bar{\psi}\Gamma_\nu \overleftrightarrow{\partial^\nu}\psi - \bar{\psi}M\psi$$

$$\Gamma_\nu = \gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu + e_\nu + if_\nu\gamma_5 + \frac{1}{2}g_{\lambda\mu\nu}\sigma^{\lambda\mu}$$

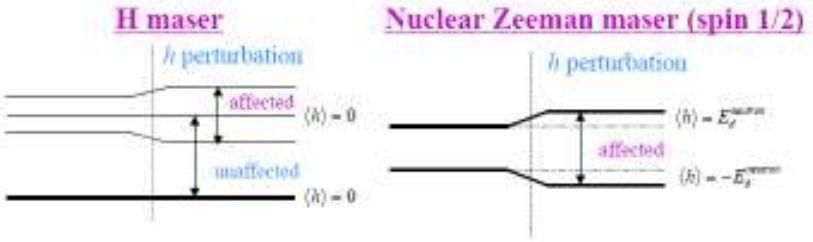
$$M = m + a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu + \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu}$$

[Kostelecky, *CPT and Lorentz symmetry*, World Scientific, Singapore 1999]

$$\mathcal{L} = -b_\mu\bar{\psi}\gamma_5\gamma^\mu\psi \Rightarrow h = -\vec{b}\cdot\vec{\sigma} + b_0\frac{\vec{p}\cdot\vec{\sigma}}{m} - \frac{1}{2}\frac{(\vec{b}\cdot\vec{p})(\vec{p}\cdot\vec{\sigma})}{m^2}$$

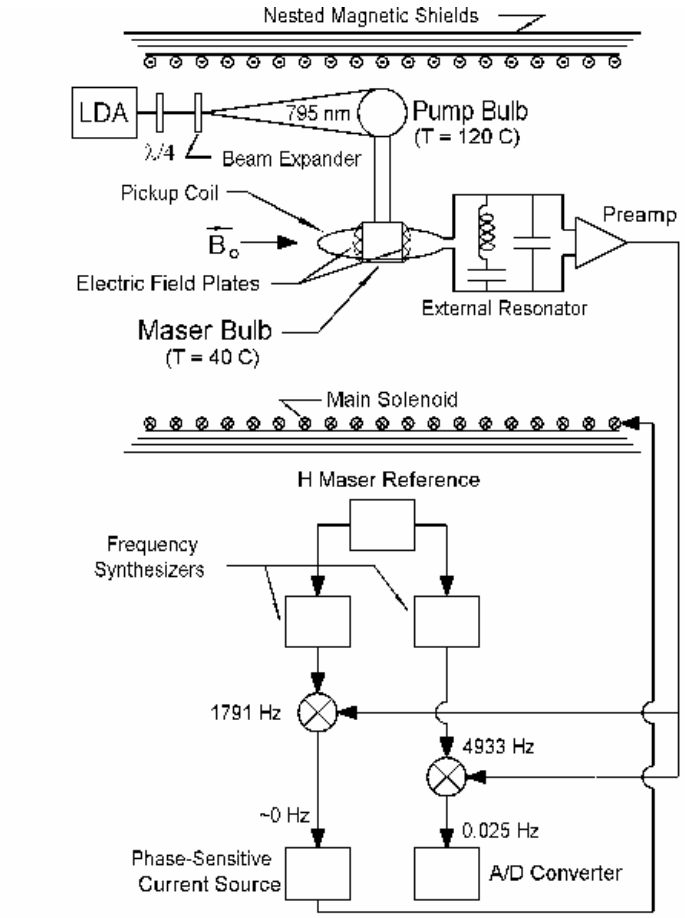
For spin 1/2 particles...

$$\langle F, m_F | h | F, m_F \rangle = \frac{m_F}{F} E^n_{dipole}$$



[Kostelecky *et al.*, Phys. Rev. D. **60**, 116010 (1999)]

Experimental Schematic



- ^{129}Xe used as magnetometer, phase locked to 1.7 kHz reference signal
- Signal fed back to 1.5 G solenoid
- B fields would shift frequencies proportional to magnetic moments
- Population inversion from Rb spin flip collision
- Systematic effects eliminated/recorded
  - Temperature of vacuum
  - East-West room B-field
  - Magnetization of Rb
    - Stable for days by servo loop
  - Power of Rb repumper laser
    - Controls population inversion rate
  - Noble-gas polarization frequency shifts were primary source of noise

Clock Comparison Experiment Continued

Rotation...

Earth's rotation frequency $\omega_\oplus = \frac{2\pi}{23\,\mathrm{h}\,56\,\mathrm{min}} = 2\pi\cdot 10^{-5}\,\mathrm{Hz}$

Laboratory co-latitude $\chi = 47.6^\circ$

$$R_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\chi\cos\omega_\oplus t & \cos\chi\sin\omega_\oplus t & -\sin\chi \\ 0 & -\sin\omega_\oplus t & \cos\omega_\oplus t & 0 \\ 0 & \sin\chi\cos\omega_\oplus t & \sin\chi\sin\omega_\oplus t & \sin\chi\sin\omega_\oplus t \end{pmatrix}$$

Boost...

Earth's angular revolution velocity $\Omega_\oplus = \frac{2\pi}{365\,\mathrm{d}} = 2\cdot 10^{-7}\,\mathrm{Hz}$

Earth's revolution velocity $\beta_\oplus = v_\oplus / c = 10^{-4}$

Laboratory rotational velocity $\beta_\perp = r_\oplus \omega_\oplus \sin\chi / c = 1.1\cdot 10^{-6}$

Earth's axis inclination $\eta = 23.4^\circ$

$$\vec{\beta} = \beta_\oplus \begin{pmatrix} \sin\Omega_\oplus t \\ \sin\eta\cos\Omega_\oplus t \\ \sin\eta\cos\Omega_\oplus t \end{pmatrix} + \beta_\perp \begin{pmatrix} -\sin\omega_\oplus t \\ \cos\omega_\oplus t \\ 0 \end{pmatrix} \qquad \gamma = (1-\beta^2)^{-1/2} \approx 1 \qquad \Rightarrow \qquad B_\nu{}^\mu \simeq \begin{pmatrix} 1 & \beta_X & \beta_Y & \beta_Z \\ \beta_X & 1 & 0 & 0 \\ \beta_Y & 0 & 1 & 0 \\ \beta_Z & 0 & 0 & 1 \end{pmatrix}$$

$$2\pi\nu_{2\mathrm{meas}} = \gamma_{sg} B(t) + 2b^{\mathrm{lab}}_{\mathrm{Earth}} = \gamma_{sg} B(t) + 2b_Y\beta_\perp - 2\left(b_X + b_Y\beta_\oplus \sin\Omega_\oplus t\right)\sin\omega_\oplus t + 2\left(b_Y - b_Y\beta_\oplus \cos\eta\cos\Omega_\oplus t\right)\cos\omega_\oplus t$$

Co-Magnetometry...

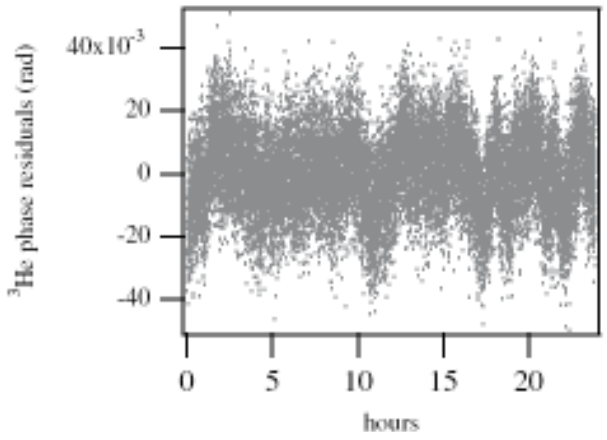
$$\delta\nu = \nu_{\mathrm{Hg}} - \frac{\gamma_{\mathrm{Hg}}}{\gamma_{\mathrm{Xe}}}\nu_{\mathrm{Xe}} \simeq k\left[-\left(b_X + b_Y\beta_\oplus \sin\Omega_\oplus t\right)\sin\omega_\oplus t + \left(b_Y - b_Y\beta_\oplus \cos\eta\cos\Omega_\oplus t\right)\cos\omega_\oplus t\right]$$

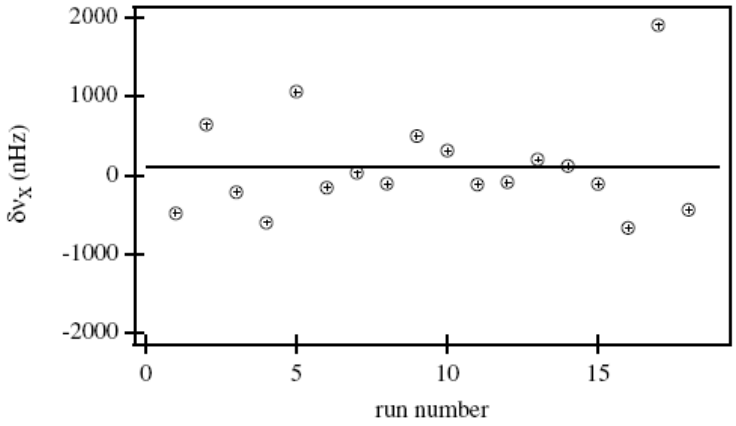
$$k = \frac{\left(1 - \gamma_{\mathrm{Hg}}/\gamma_{\mathrm{Xe}}\right)}{\pi} = -8.3\cdot 10^{10}\ \mathrm{nHz/GeV},\ \beta_\perp \ll \beta_\oplus$$

$$\delta\nu^{\mathrm{sig}} = \delta\nu_Y(t)\sin\omega_\oplus t + \delta\nu_Y(t)\cos\omega_\oplus t$$

Data Analysis

- Minimal fit model
- $\delta\varphi_{He} = \varphi_0 + 2\pi\nu_0 t + 2\pi\Omega_s^{-1}\,[\delta\nu_X \sin(\Omega_s t) - \delta\nu_Y \cos(\Omega_s t)]$
- Linear least-squares fit to $\delta\nu_X$ and $\delta\nu_Y$ to minimize χ^2
- Check with false signal of known frequency and phase to make sure covariance matrix is preserved
- 90 total days of data over 3 runs
- $R = (\delta\nu_X^2 + \delta\nu_Y^2)^{1/2}$
- R= 53 ± 45 nHz
- (6.4 ± 5.4) × 10-31 GeV for SME neutron parameter





Current Limits

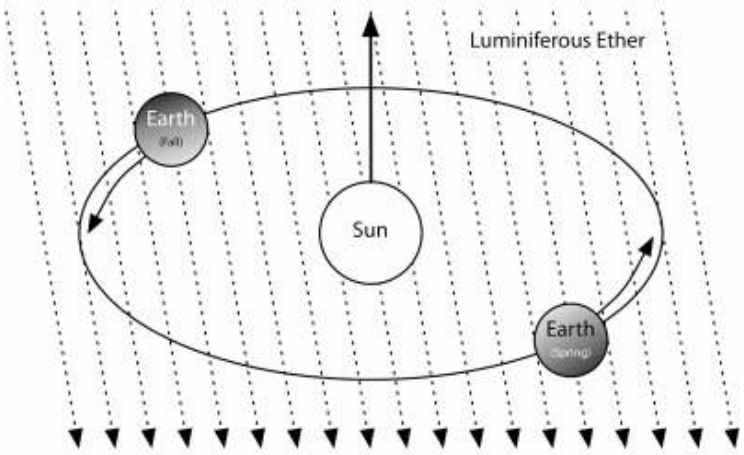
- Proton
  - 10^{-27} GeV — Maser, ^{199}Hg and ^{133}Cs clock experiments
  - 10^{-26} GeV — Proton-Antiproton (g-2) measurements
- Neutron
  - 10^{-31} GeV — Walsworth clock experiment
- Electron
  - 10^{-27} GeV — Maser, ^{199}Hg and ^{133}Cs clock experiments
  - 10^{-29} GeV — Spin-polarized torsion pendulum
  - 10^{-25} GeV — Electron-Positron (g-2) measurements
- Photon
  - 10^{-11} GeV — Rotating cryogenic-temperature sapphire oscillators

**Also limits on neutral-B, neutral-D, neutrinos and kaons

Summary

- Lorentz and CPT violations included in some theories attempting to unify GR and Standard Model
- SME makes no predictions of magnitude or sector
- Lots of precision experiments needed

- No ether wind yet



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- R.L. Walsworth, et al., Phys. Rev. Lett. **85**, 5038 (2000)
- A. A. Michelson and E.W. Morley, Philos. Mag. S.5, **24** (151), 449-463 (1887)
- See my paper on the class website for articles on specific experiments