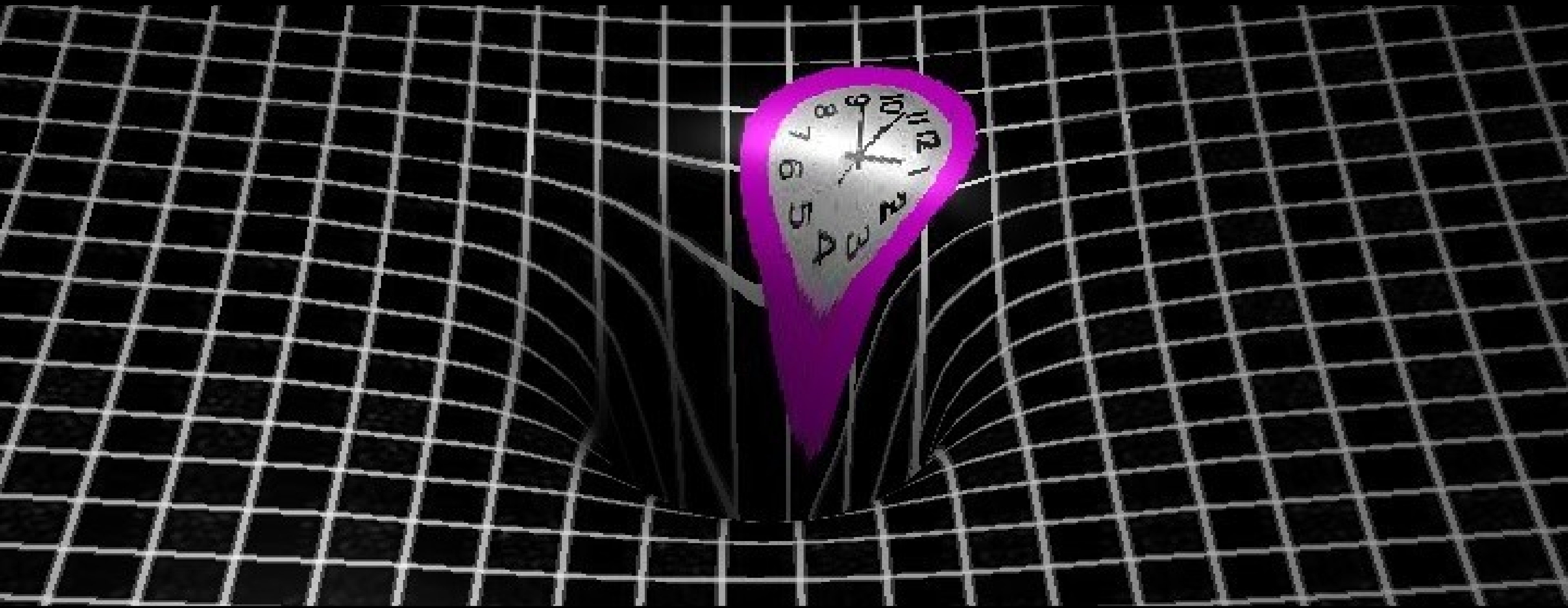
Gravity, CPT, and the Standard-Model Extension



Jay D. Tasson

St. Olaf College

outline

- Lorentz violation/Standard-Model Extension (SME) basics
- exotic atoms with muons
- Lorentz violation in gravitational experiments (including some with nontraditional matter)
- Isotropic Parachute Model (a special limit of the SME) and antimatter

What is CPT symmetry?

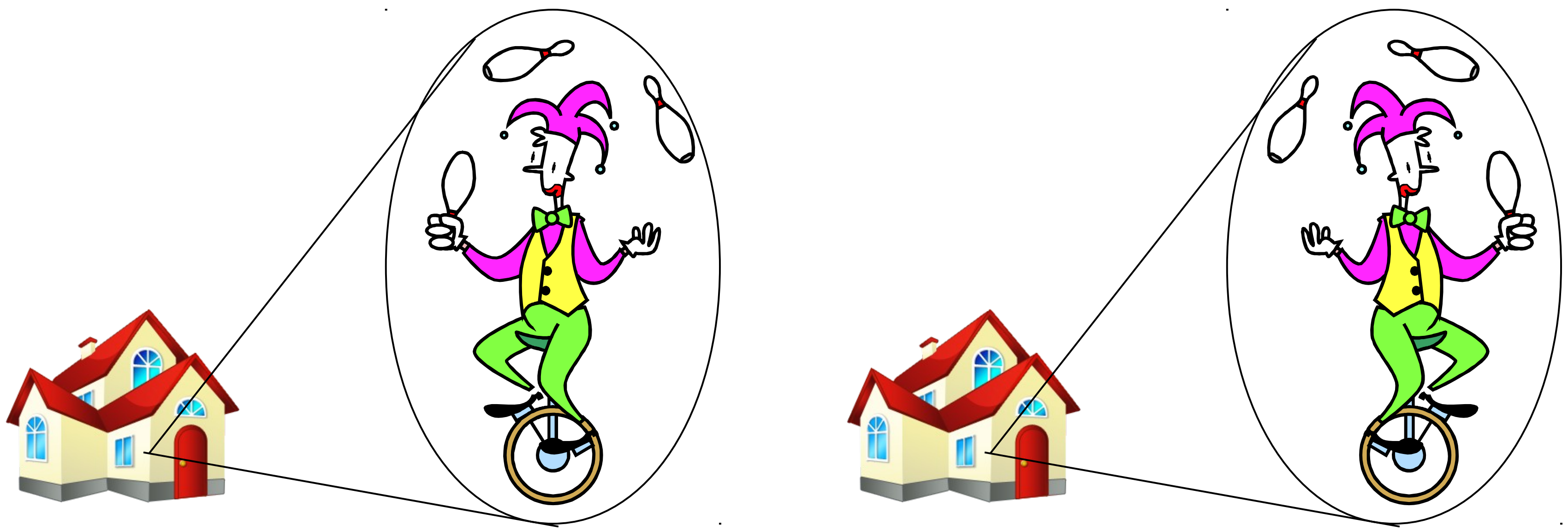
- physical results are unchanged under the combination of the 3 discrete symmetries
  - Charge conjugation 'C'
  - Parity 'P'
  - Time reversal 'T'

- intimately linked to Lorentz symmetry:

  realistic field theories with CPT violation also have Lorentz violation

What is Lorentz symmetry?

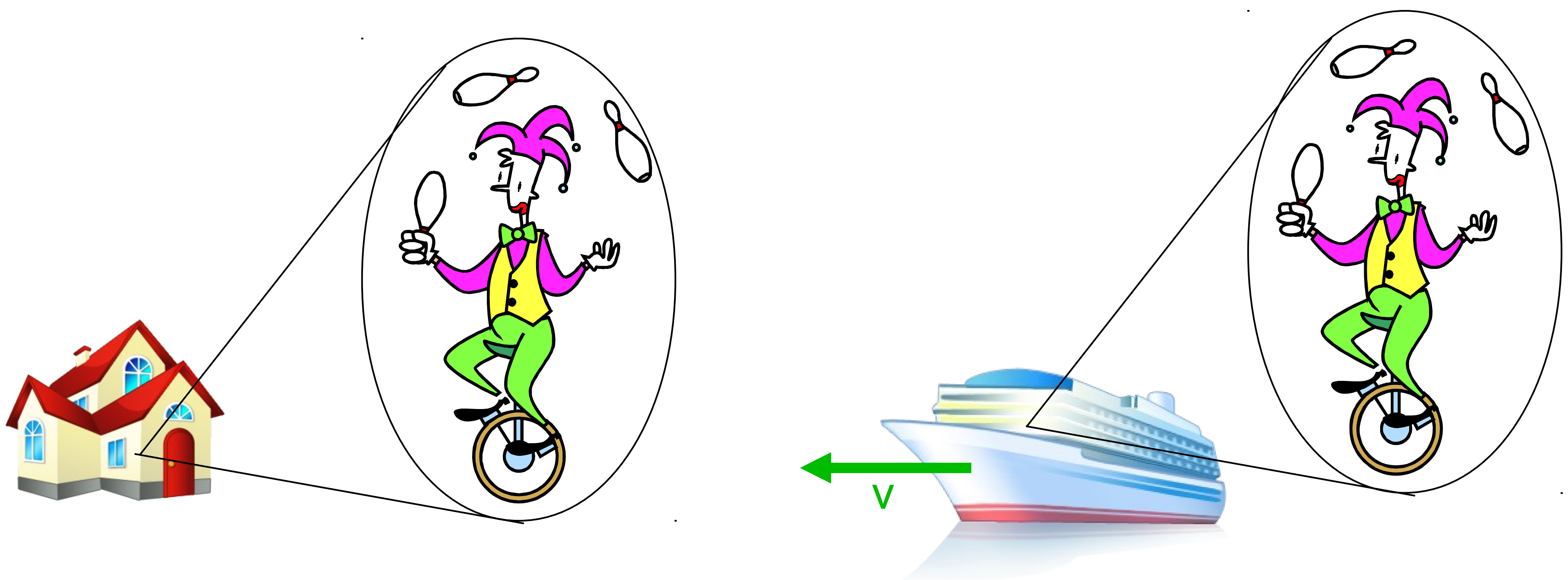
- physical results are independent of the velocity of the experiment and the ***direction*** it points



- juggling facing the other way still works
- rotation invariance – results are independent of the direction the experiment points

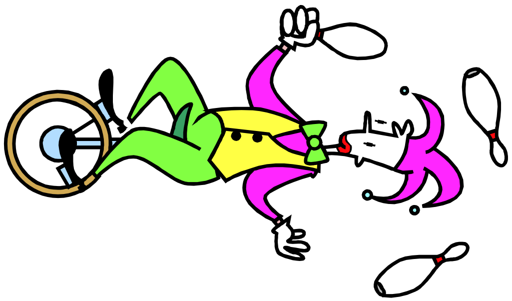
What is Lorentz symmetry?

- physical results are independent of the ***velocity*** of the experiment and the direction it points



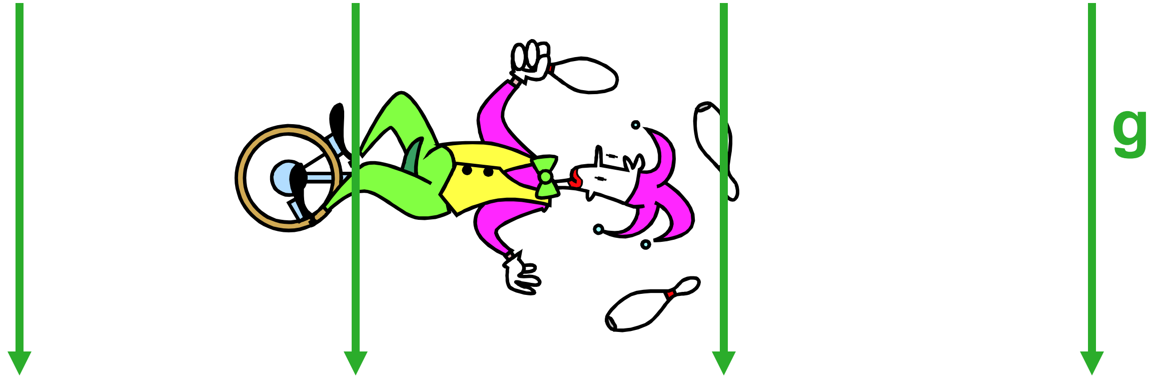
- juggling on ship moving at constant velocity without rocking still works
- boost invariance – results are independent of the constant velocity of the experiment

What does Lorentz violation look like?



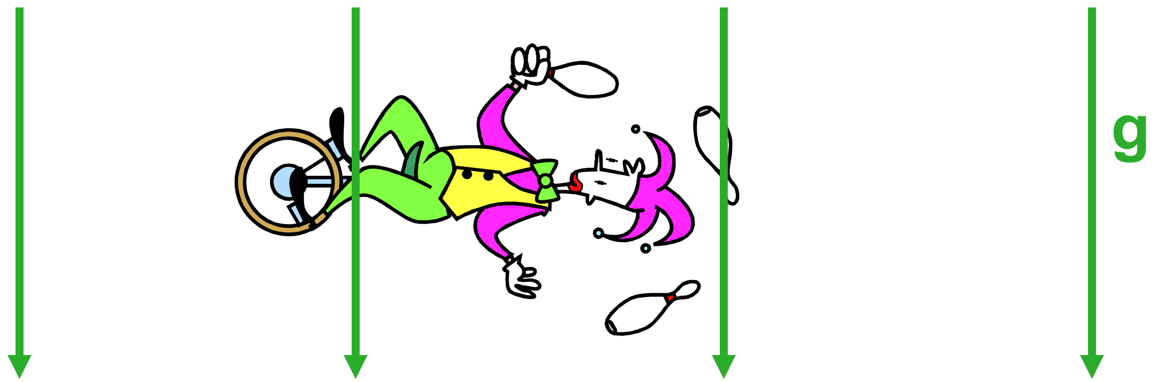
- juggling while lying on your back is different

What does Lorentz violation look like?



- juggling while lying on your back is different
- apparent relativity violation

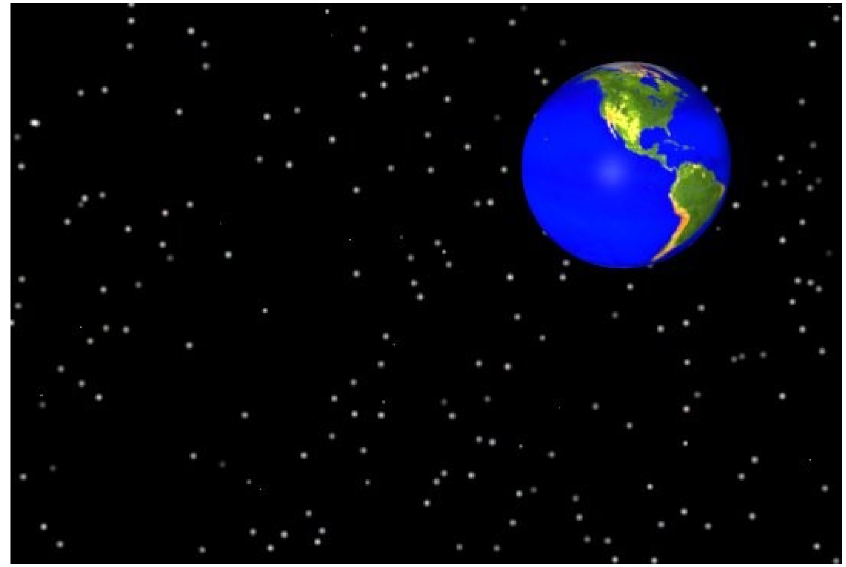
What does Lorentz violation look like?



- juggling while lying on your back is different
- apparent relativity violation
- resolution: Earth is part of experiment. It should be turned with the juggler.

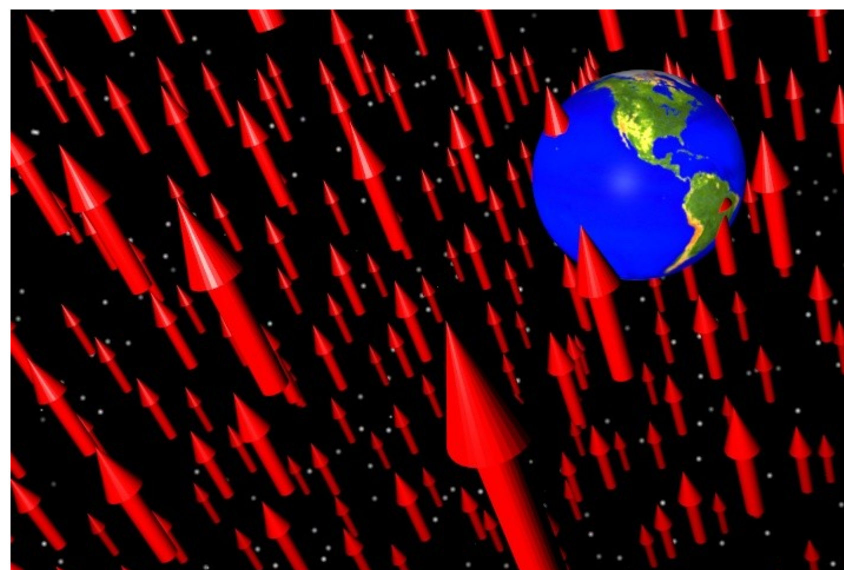
fundamental relativity violation

- relativity

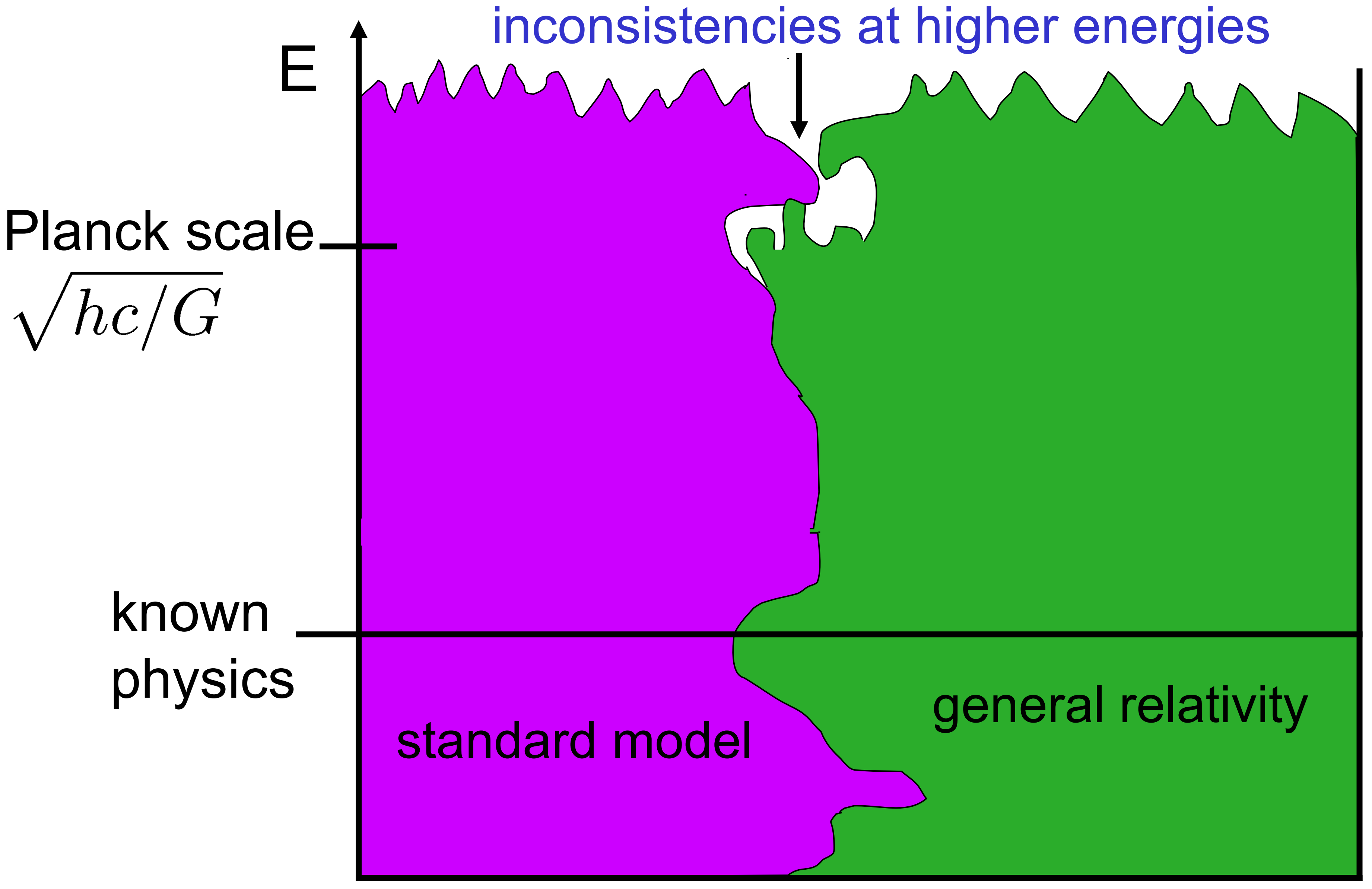


- relativity violation

(in general, there can be time components and higher rank tensors, but they're hard to draw)



Motivation SM + GR



underlying theory at Planck scale

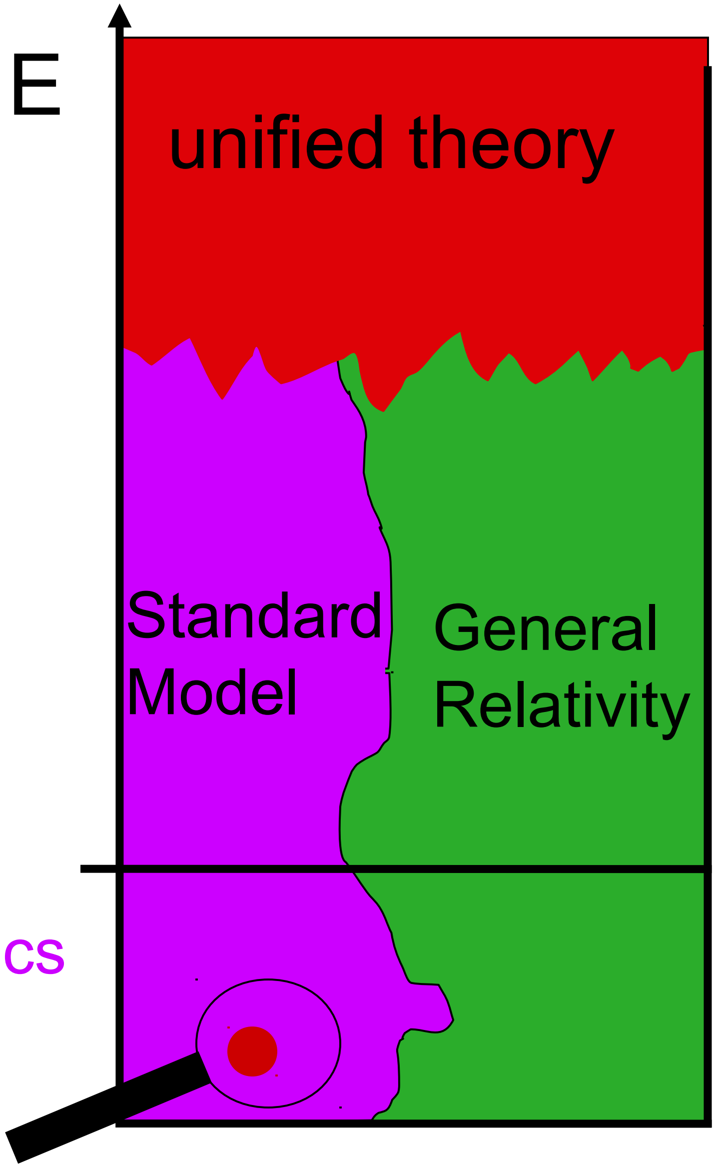
options for probing experimentally

- galaxy-sized accelerator

- suppressed effects in sensitive experiments

CPT and Lorentz violation

- can arise in theories of new physics
- difficult to mimic with conventional effects



Standard-Model Extension (SME)

effective field theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent CPT & Lorentz violation

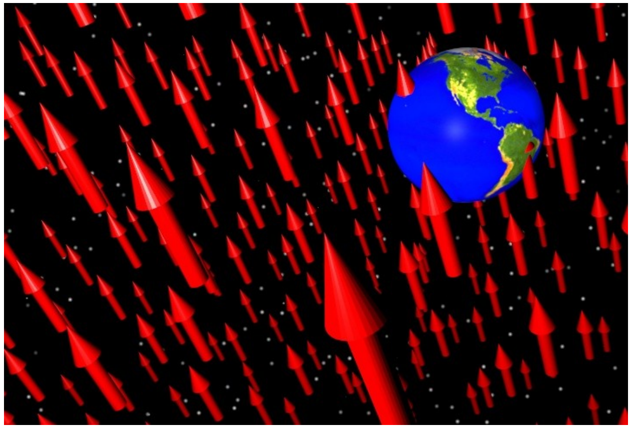
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L_{\mathrm{LV}}$$

- CPT violation comes with Lorentz violation

CPT & Lorentz-violating terms

- constructed from GR and SM fields
- parameterized
  by coefficients for Lorentz violation
- samples

$$\bar{\psi} a_\mu \gamma^\mu \psi$$



Colladay & Kostelecký PRD ’97, ’98   Kostelecký PRD ’04

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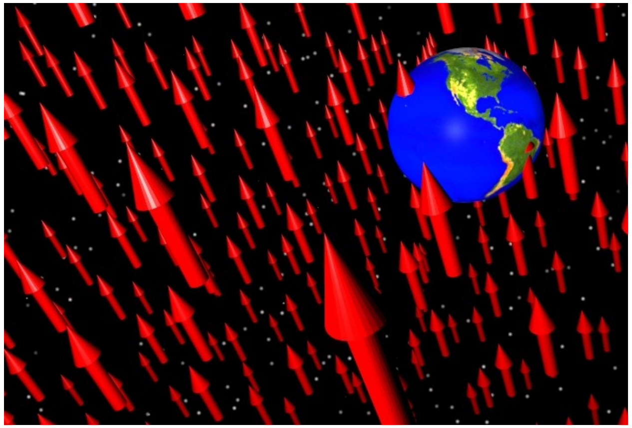
A broad and general search for new physics

CPT & Lorentz-violating … …s

- constructed fr… …R and SM fields
- parameteri…
  by coeff… …s for Lorentz violation
- sam…

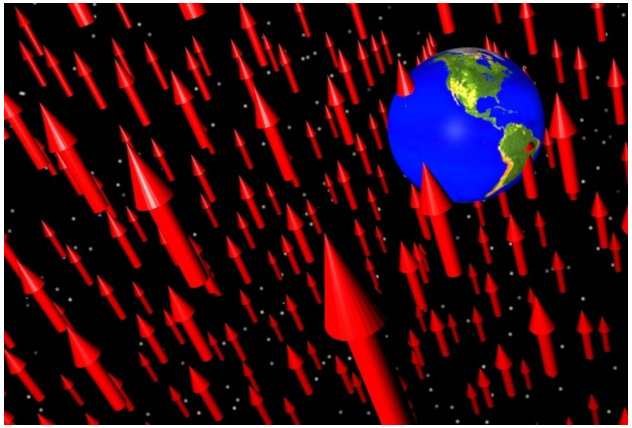
$$\bar{\psi} a_\mu \gamma^\mu \psi$$



Colladay & Kostelecký PRD ’97, ’98   Kostelecký PRD ’04

background vectors and tensors are cute, but where could the come from?

- explicate Lorentz violation
  - the universe just looks that way
  - not in general consistent with Riemann geometry[1]



- spontaneous Lorentz violation
  - a vector or tensor field gets a vacuum-expectation value
  - nonzero VEV observed for a scalar particle, the Higgs (no Lorentz violation)
  - VEV for vector or tensor would be my red arrows $\overline{a}_\mu$
  - consistent with Riemann geometry

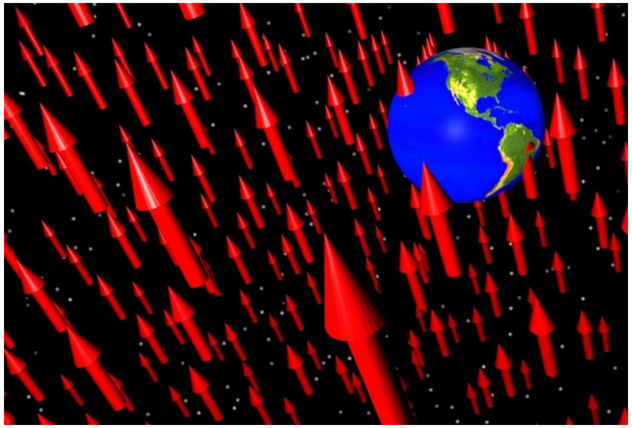
1) Kostelecký PRD '04

tests

- compare experiments pointing in different directions
- compare experiments at different velocities
- compare particles and antiparticles

- SME
  - predictive
  - quantitative comparisons

avoid averaging over the signal

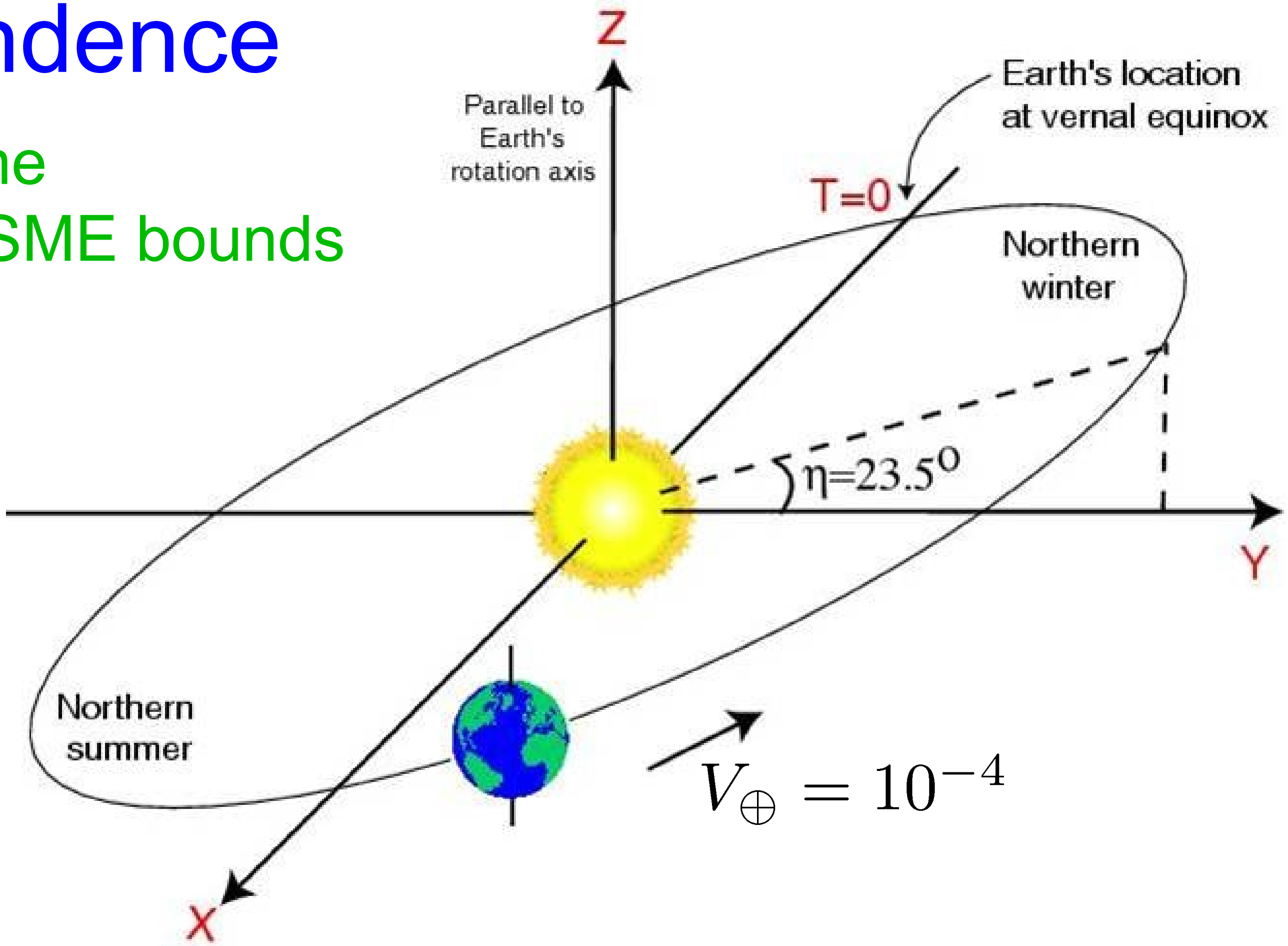


- observe:
  - Lorentz and CPT violation
  - ‘conventional’ field associated with larger-scale source eg. spacetime torsion[1], gravitomagnetism[2]

1) Kostelecký, Russell, JT, PRL ’08
2) JT, PRD ‘12

time dependence

- standard frame
  for reporting SME bounds



- boost and rotation of test ⟶ annual & sidereal variations

SME experimental and observational searches

- trapped particle tests (Dehmelt,Gabrielse, …)
- spin-polarized matter tests (Adelberger, Heckel, Hou, …)
- clock-comparison tests (Gibble, Hunter, Romalis, Walsworth, …)
- tests with resonant cavities (Lipa, Mueller, Peters, Schiller, Wolf, …)
- neutrino oscillations (LSND, Minos, Super K, …)
- muon tests (Hughes, BNL g-2)
- meson oscillations (BABAR, BELLE, DELPHI, FOCUS, KTeV, OPAL, …)
- atom-interferometer tests (Mueller, Chiow, Herrmann, Chu, Chung)
- astrophysical photon decay
- pulsar-timing observations
- cosmological birefringence
- CMB analysis
- lunar laser ranging
- short-range gravity tests
- .....

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- …..

but also lots of unexplored space...

overview of Lorentz violation/SME

Tasson, Rep. Prog. Phys. 77, 062901 (2014), arXiv:1403.7785

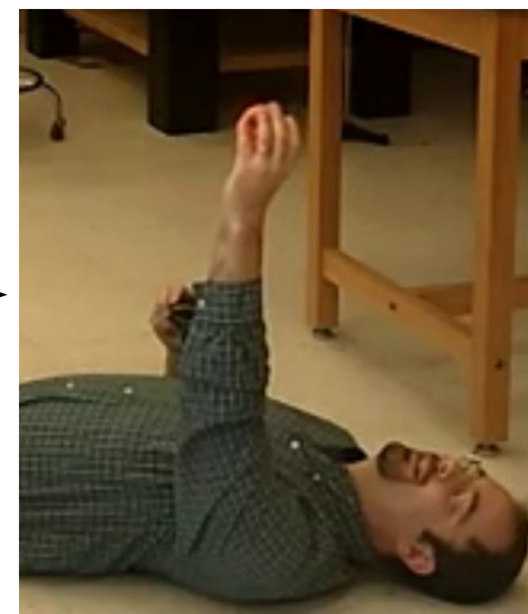
IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. **77** (2014) 062901 (16pp) — doi:10.1088/0034-4885/77/6/062901

Key Issues Review

What do we know about Lorentz invariance?

– simple examples
– general overview
– video abstract



exotic atom tests

- recent flat spacetime results

Laboratory tests of Lorentz and CPT symmetry with muons

André H. Gomes,[1] V. Alan Kostelecký,[2] and Arnaldo J. Vargas[2]
[1] *Departamento de Física, Universidade Federal de Viçosa, 36570-000 Viçosa, MG, Brazil*
[2] *Physics Department, Indiana University, Bloomington, Indiana 47405, USA*
(Dated: IUHET 586, July 2014)

The prospects are explored for testing Lorentz and CPT symmetry in the muon sector via the spectroscopy of muonium and various muonic atoms, and via measurements of the anomalous magnetic moments of the muon and antimuon. The effects of Lorentz-violating operators of both renormalizable and nonrenormalizable dimensions are included. We derive observable signals, extract first constraints from existing data on a variety of coefficients for Lorentz and CPT violation, and estimate sensitivities attainable in forthcoming experiments. The potential of Lorentz violation to resolve the proton radius puzzle and the muon anomaly discrepancy is discussed.

arXiv:1407.7748

- gravitational tests

PHYSICAL REVIEW D **83,** 016013 (2011)

Matter-gravity couplings and Lorentz violation

V. Alan Kostelecký and Jay D. Tasson
Physics Department, Indiana University, Bloomington, Indiana 47405, USA
(Received 7 July 2010; published 24 January 2011)

completed theory for exotic atom analysis

L_{fermion}

$$\mathcal{L} \supset \tfrac{1}{2}\overline{\psi}(\gamma^\mu i\partial_\mu - m_\mu + \widehat{\mathcal{Q}})\psi + \text{h.c.}$$

series of LV corrections

$\downarrow$ Euler-Lagrange eq.

$H_{\text{Relativistic}}$ $\longrightarrow$ relativistic quantum experiments

$\downarrow$ Foldy-Wouthuysen expansion

H_{NonRel} $\longrightarrow$ non-relativistic quantum experiments

$\downarrow$ perturbation theory

$\delta\nu$ $\longrightarrow$ match to experimental observations!

II. MUONIC BOUND STATES

B. Muonium

1. Hyperfine transitions

$$
\begin{aligned}
\delta\nu_{12} &= -\delta\nu_{34} \\
&= \sum_{q=0}^{2} \frac{1}{\sqrt{12\pi^3}} [(\alpha m_{\rm r})^{2q} + 4\delta_{q2}] \\
&\quad \times \boxed{\left(g^{\rm NR(0\it B)}_{(2q)10} + H^{\rm NR(0\it B)}_{(2q)10} + 2 g^{\rm NR(1\it B)}_{(2q)10} + 2 H^{\rm NR(1\it B)}_{(2q)10} \right)}
\end{aligned}
$$

Coefficients for LV containing sidereal dependence

- initial constraints via published limits (Hughes et al.)
- improvement potential: about a factor of 5 via MuHFS

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Coefficients for LV containing sidereal dependence

- initial constraints via published limits (Hughes et al.)
- improvement potential: about a factor of 5 via MuHFS

2. 1S-2S transition and Lamb shift

II. MUONIC BOUND STATES

C. Muonic atoms and ions

1. Generalities

2. Zeeman transitions

3. Proton radius puzzle

- coefficients for Lorentz violation can lead to shifts in the Lamb energy leading to the discrepancy in the inferred proton radius

4. Negligible magnetic field

5. Other muonic atoms and ions

III. MUON MAGNETIC MOMENT

- complementary sensitivities possible via CERN experiment, J-PARC experiment, and BNL data
- anomaly discrepancy could also be due to Lorentz violation

SME experimental and observational searches

- trapped particle tests (Dehmelt,Gabrielse, …)
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- tests with resonant cavities (Lipa, Mueller, Peters, Schiller, Wolf, …)
- neutrino oscillations (LSND, Minos, Super K, …)

- only ~1/2 of lowest order couplings explored

- pulsar-timing observations
- cosmological birefringence
- CMB analysis
- lunar laser ranging
- short-range gravity tests
- .....

gravitationally coupled fermions[1]

$$\mathcal{L} \supset \frac{1}{2}\overline{\psi}(\gamma^\mu i\partial_\mu - m_\mu + \widehat{Q})\psi + \text{h.c.}$$

$$L_{\text{fermion}} = \frac{1}{2} i e^\mu{}_a \ \overline{\psi}(\gamma^a - c_{\nu\lambda} e^{\nu a} e^\lambda{}_b \gamma^b - e_\nu e^{\nu a} \ldots) \overleftrightarrow{D_\mu}\psi$$
$$- \overline{\psi}(m + a_\mu e^\mu{}_a \gamma^a + \ldots)\psi$$

$$g_{\mu\nu} = e_\mu{}^a e_\nu{}^b \eta_{ab}$$

coefficients for Lorentz violation

- particle-species dependent
- even number of indicies = CPT even
- odd number of indicies = CPT odd

Idea :

- new gravitational couplings provide new LV sensitivity
- access a_μ coefficient challenging to observe in flat spacetime along with other spin-independent effects

Kostelecký, Tasson PRL '09

1) Kostelecký PRD '04

current $(\bar{a}_{\rm eff})_\mu$ limits

- Data Tables: Kostelecký & Russell, arXiv:0801.0287v7
  - gravity summary

Coefficient	Electron	Proton	Neutron
$\alpha(\bar{a}_{\rm eff})_T$	10^{-11} GeV	10^{-11} GeV	10^{-11} GeV
$\alpha(\bar{a}_{\rm eff})_X$	10^{-6} GeV	10^{-6} GeV	10^{-5} GeV
$\alpha(\bar{a}_{\rm eff})_Y$	10^{-5} GeV	10^{-6} GeV	10^{-4} GeV
$\alpha(\bar{a}_{\rm eff})_Z$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV

"...the displayed sensitivity for each coefficient assumes for definiteness that no other coefficient contributes."

- 12 independent coefficients
- constraints: 2 at 10^{-11}GeV
  2 at 10^{-6}GeV
  4 at 10^{-1}GeV

considerable space for improvement!

- 4 unconstrained combinations require gravitational experiments with charged matter to separate

path to experimental analysis

L_{fermion} expand to desired order in LV and gravity

$\downarrow$ field redefinition

L'_{fermion}

$\downarrow$ Euler-Lagrange eq.

$H_{\text{Relativistic}} \longrightarrow$ relativistic quantum experiments

$\downarrow$ Foldy-Wouthuysen expansion

$H_{\text{NonRel}} \longrightarrow$ non-relativistic quantum experiments

$\downarrow$ inspection

$L_{\text{Classical}}$

$\downarrow$ variation

non-relativistic quantum experiments
classical experiments

Newtonian equation of motion

classical results

$$U = \frac{2Gm}{r}\left(1+\overline{c}^{\mathrm{S}}_{00}+\frac{2}{m}(\overline{a}^{\mathrm{S}}_{\mathrm{eff}})_0\right)+\ldots$$

$$\ddot{x}^j = -\tfrac{1}{2}\partial^j U+(\overline{c}^{\mathrm{T}})^j{}_k\partial^k U+\frac{1}{m^{\mathrm{T}}}\alpha(\overline{a}^{\mathrm{T}}_{\mathrm{eff}})_0\partial^j U+\ldots$$

S and T denote
composite coefficients
for source and test respectively

$$\boxed{(a_{\mathrm{eff}})_\mu = a_\mu - m e_\mu}$$

experimental hooks

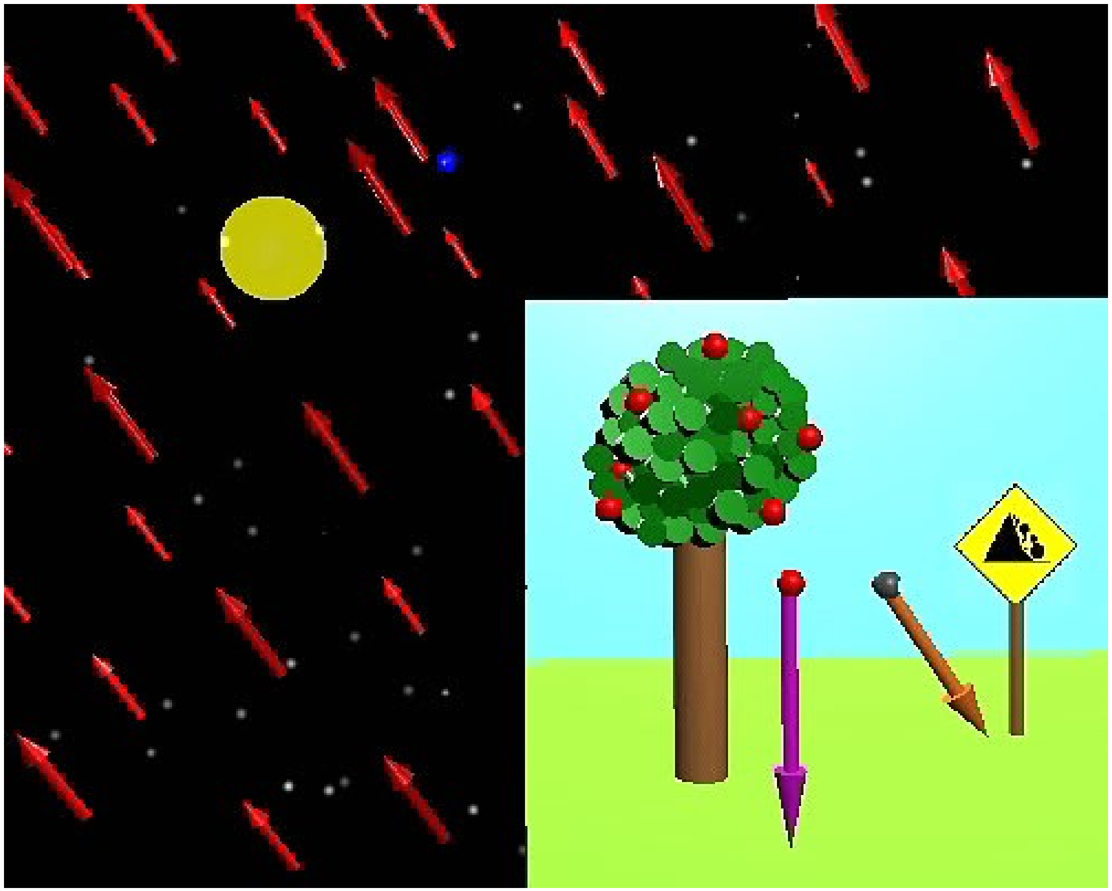
- particle-species dependence
- time dependence

lab tests

acceleration of a test particle T

annual variations

$$\ddot{\vec{x}} \supset -2\frac{1}{m} g V_\oplus \, \alpha(\overline{a}^{\mathrm{T}}_{\mathrm{eff}})_X \sin(\Omega T)\hat{z} + g V_\oplus \overline{c}^{\mathrm{T}}_{TX} \sin 2\chi \sin(\Omega T)\hat{x}$$



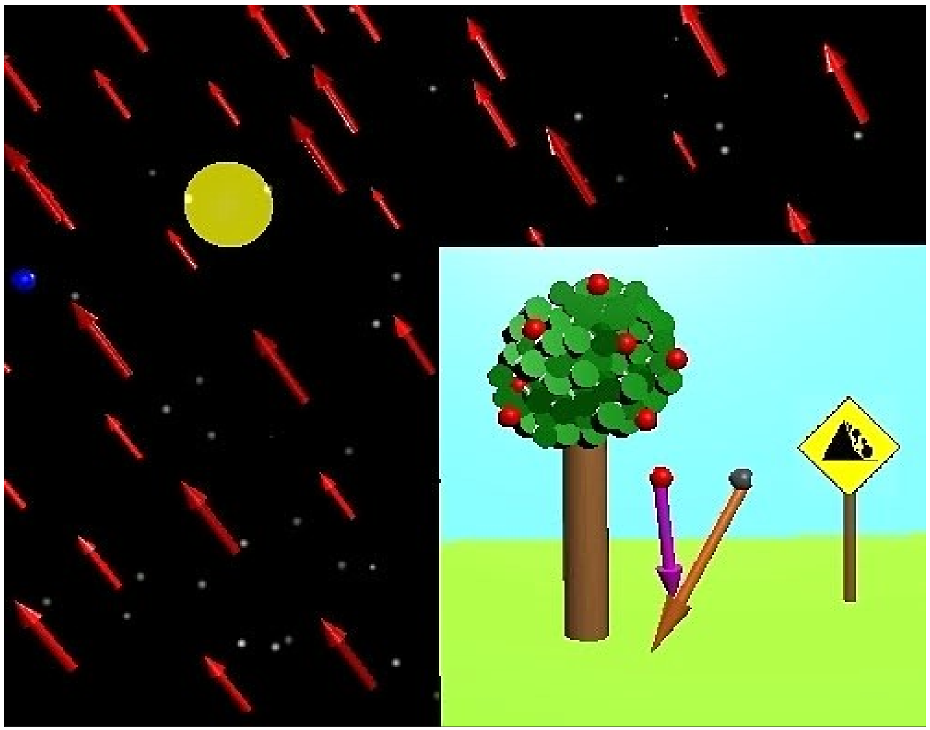
- monitor acceleration of one particle over time $\longrightarrow$ gravimeter
- monitor relative behavior of particles $\longrightarrow$ EP test
- periodic EP violation qualitatively new proposal?
- frequency and phase distinguish from other effects

lab tests

acceleration of a test particle T

$$\ddot{\vec{x}} \supset -2\frac{1}{m} g V_\oplus \, \alpha(\overline{a}^{\mathrm{T}}_{\mathrm{eff}})_X \sin(\Omega T)\hat{z} + g V_\oplus (\overline{c}^{\mathrm{T}})_{TX} \sin 2\chi \sin(\Omega T)\hat{x}$$

annual variations



- monitor acceleration of one particle over time ⟶ gravimeter
- monitor relative behavior of particles ⟶ EP test
- frequency and phase distinguish from other effects

experiments

- lab tests
  - gravimeter
  - Weak Equivalence Principle (WEP)
- space-based WEP
- exotic tests
  - charged matter
  - antimatter
  - higher-generation matter
- solar-system tests
  - laser ranging
  - perihelion precession
- pulsar tests
- light-travel tests
  - time delay
  - Doppler shift
  - red shift
- clock tests
  - null redshift
  - comagnetometers

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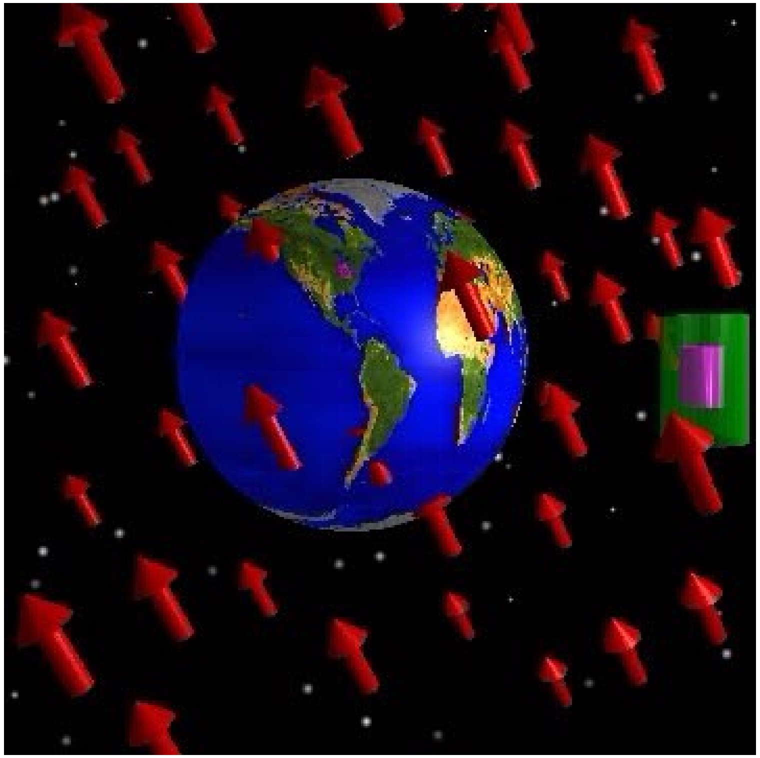
space-based E.P. tests



long free-fall times

$\Longrightarrow$ improved sensitivity

differential acceleration sensitivity	
test	$\Delta a/a$
MicroSCOPE	10^{-15}
STE-QUEST	10^{-15}
Galileo Galilei	10^{-17}
STEP	10^{-18}

improvement potential:

- max reach 5 to 7 orders of magnitude
- special linear combinations 11 orders

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exotic tests

- variations of above tests involving experimentally challenging matter
- charged matter
  - separate proton and electron coefficients
  - theoretically interesting -- bumblebee electrodynamics

improvement potential:
sensitivity to remaining 4 unconstrained $(\overline{a}_{\mathrm{eff}})_\mu$ coefficients

- higher-generation matter

improvement potential:
first sensitivity to $(\overline{a}_{\mathrm{eff}})_\mu$ for muons, for example

- antimatter
  - separate CPT even and odd coefficients
  - differing gravitational response for matter and antimatter

a toy model for antimatter gravity

$$L = \underbrace{\tfrac{1}{2}\left(m + \tfrac{5}{3}N^w m^w \overline{c}^w_{TT}\right)}_{m_{\mathrm{i,eff}}} v^2 - \underbrace{gz\left(m + N^w m^w \overline{c}^w_{TT} + 2\alpha N^w (\overline{a}_{\mathrm{eff}})^w_T\right)}_{m_{\mathrm{g,eff}}}$$

CPT odd

- Isotropic ‘Parachute’ Model

$$\tfrac{1}{3} m^w \overline{c}^w_{TT} = \alpha (\overline{a}_{\mathrm{eff}})^w_T$$

Matter

$$m_{\mathrm{i,eff}} = m_{\mathrm{g,eff}}$$
$$\mathrm{a} = g$$

Antimatter

$$m_{\mathrm{i,eff}} \neq m_{\mathrm{g,eff}}$$
$$\bar{\mathrm{a}} = g\left(1 - \frac{4 m^w N^w}{3m} \overline{c}^w_{TT}\right)$$

a toy model for antimatter gravity

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Matter	Antimatter
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$\mathrm{a} = g$	$\bar{\mathrm{a}} = g(1 - \frac{4m^w N^w}{3m} \overline{c}^w_{TT})$

"Rather than a serious effort at realistic theory, the IPM is constructed as a simplistic playground within which to explore field-theoretic limitations on unconventional properties of antimatter..."[1]

1) Kostelecký, JT PRD '11

a toy model for antimatter gravity

$$L = \frac{1}{2}\underbrace{\left(m + \frac{5}{3} N^w m^w \overline{c}^w_{TT}\right)}_{m_{\mathrm{i,eff}}} v^2 - gz \underbrace{\left(m + N^w m^w \overline{c}^w_{TT} + 2\alpha N^w (\overline{a}_{\mathrm{eff}})^w_T\right)}_{m_{\mathrm{g,eff}}}$$

- Isotropic ‘Parachute’ Model

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Matter	Antimatter
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- limited for ordinary matter by work at higher post-newtonian order
- could still imply large signals in antimatter tests with higher generation matter?
- more from the nonminimal sector?

gravitationally coupled fermions[1]

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coefficients for Lorentz violation

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Kostelecký, Tasson PRL ’09

1) Kostelecký PRD ’04

constraints?

- The K^0 system $\quad K^0 = d\bar{s}$

$$|K_L\rangle = \frac{(1+\epsilon)|K^0\rangle - (1-\epsilon)|\overline{K^0}\rangle}{\sqrt{2(1+\epsilon^2)}}$$

$$|K_S\rangle = \frac{(1+\epsilon)|K^0\rangle + (1-\epsilon)|\overline{K^0}\rangle}{\sqrt{2(1+\epsilon^2)}}$$

gravitational difference for matter/antimatter could imply $K_L - K_S$ oscillations[1]

1) Good PR '61

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- The K^0 system $K^0 = d\bar{s}$

$$|K_L\rangle = \frac{(1+\epsilon)|K^0\rangle - (1-\epsilon)|\overline{K^0}\rangle}{\sqrt{2(1+\epsilon^2)}}$$

$$|K_S\rangle = \frac{(1+\epsilon)|K^0\rangle + (1-\epsilon)|\overline{K^0}\rangle}{\sqrt{2(1+\epsilon^2)}}$$

gravitational difference for matter/antimatter could imply $K_L - K_S$ oscillations[1]

nonissue for IPM

- differences in SME coefficients for quarks have been bounded[2]
- does not limit anomalous gravitational effects on antibaryons and antileptons

1) Good PR '61
2) Kostelecky PRL '98 (theory);
   Data Tables for Lorentz and CPT Violation, Rev. Mod. Phys. '11 (experimental summary)

constraints?

- anomalous redshift of cyclotron frequency[1]

likely nonissue for IPM

- redshifts typically involve the CPT even coefficient only
- example: redshift of Bohr levels involves

$$\xi_{\mathrm{H,Bohr}} = -\frac{2}{3(m^p + m^e)}\left(m^p(\overline{c}^e)_{00} + m^e(\overline{c}^p)_{00}\right)$$

- the effect is the same for particle and antiparticle

1) Hughes & Holzscheiter PRL '91

key method of constraining the IPM

- index structure implies CPT properties and hence permits the construction of the model
- however, index structure also implies that studies involving higher powers of velocity can limit it[1]
  - redshift tests with matter[2]
  - consideration of bound kinetic energy in matter equivalence-principle tests[3]

$$\frac{1}{3} m^w \overline{c}^w_{TT} = \alpha (\overline{a}_{\text{eff}})^w_T < 10^{-6}\ \text{GeV}$$

1) Kostelecky & JT PRD ’11
2) Hohensee etal PRL ‘11
3) Hohensee etal PRL ‘13

constraints?

IPM model:

- field-theory based
- incorporates known physics
- appears to evade many usual arguments against antimatter gravity

Ordinary matter constraints

- double boost suppressed effects

Bottom line?

- the IPM is an interesting toy model that highlights features of antimatter-gravity constraints
- 'Second-generation Isotropic Parachute Model'
- higher order SME terms??? ‘Isotropic Hang-glider Model’?

Summary

- Lorentz & CPT violation searches have potential to detect Planck-scale physics with existing technology

- Much work has been done in Minkowski spacetime, but much remains unexplored

- Lorentz violation in matter-gravity couplings introduces qualitatively new signals in experiments, offers models that appear to avoid many of the antimatter gravity constraints

- Gravitational tests with atypical matter may provide access to additional Lorentz-violating possibilities, particularly via the new Muon proposals