Gravity Effects on Antimatter in the Standard-Model Extension

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outline

- Lorentz violation/Standard-Model Extension (SME) basics

- Lorentz violation in gravitational experiments (including some with nontraditional matter)

- Isotropic Parachute Model (a special limit of the SME) and antimatter

a subset of the SME lagrangian with gravity[1]

$$L_{\mathrm{fermion}} = \tfrac{1}{2} i e^{\mu}{}_{a}\, \overline{\psi}(\gamma^{a} - c_{\nu\lambda} e^{\nu a} e^{\lambda}{}_{b} \gamma^{b} - e_{\nu} e^{\nu a}) \overleftrightarrow{D_{\mu}} \psi$$
$$- \overline{\psi}(m + a_{\mu} e^{\mu}{}_{a} \gamma^{a}) \psi + \ldots$$

coefficients for Lorentz violation
- particle-species dependent

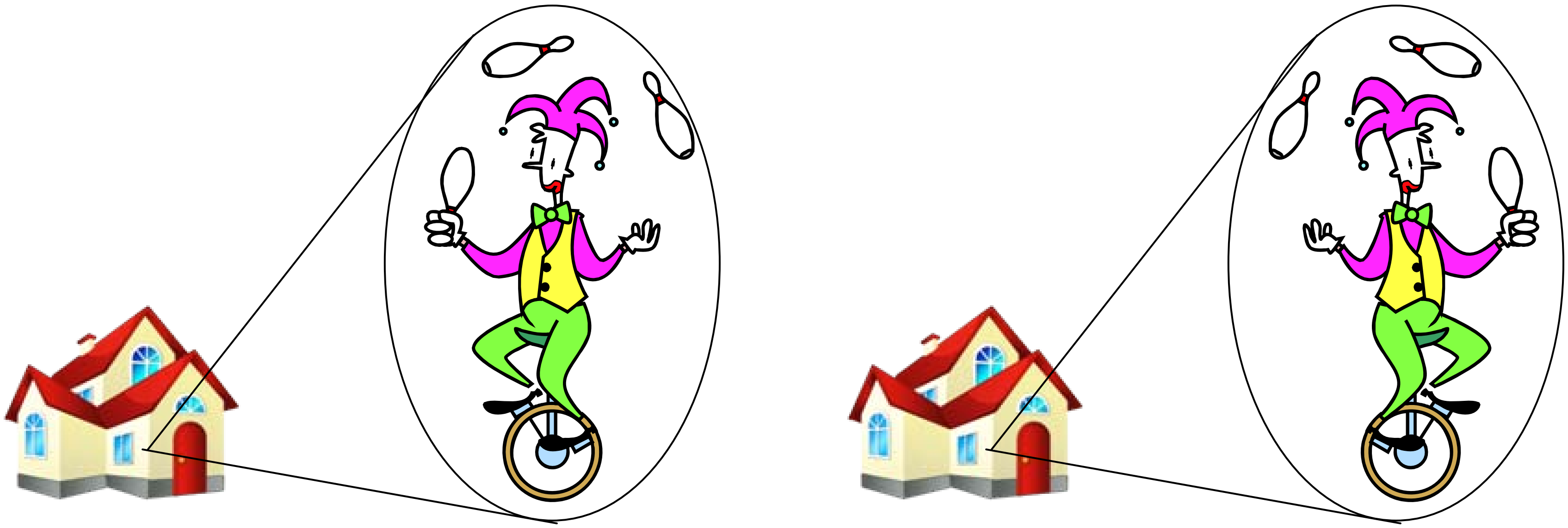
- vierbein – gravitational effects

- basis for most comments
- complete field theory
- most of the usual properties, except *particle Lorentz invariance*
- can calculate answers to any question

1) Kostelecký, PRD ’04

What is Lorentz symmetry?

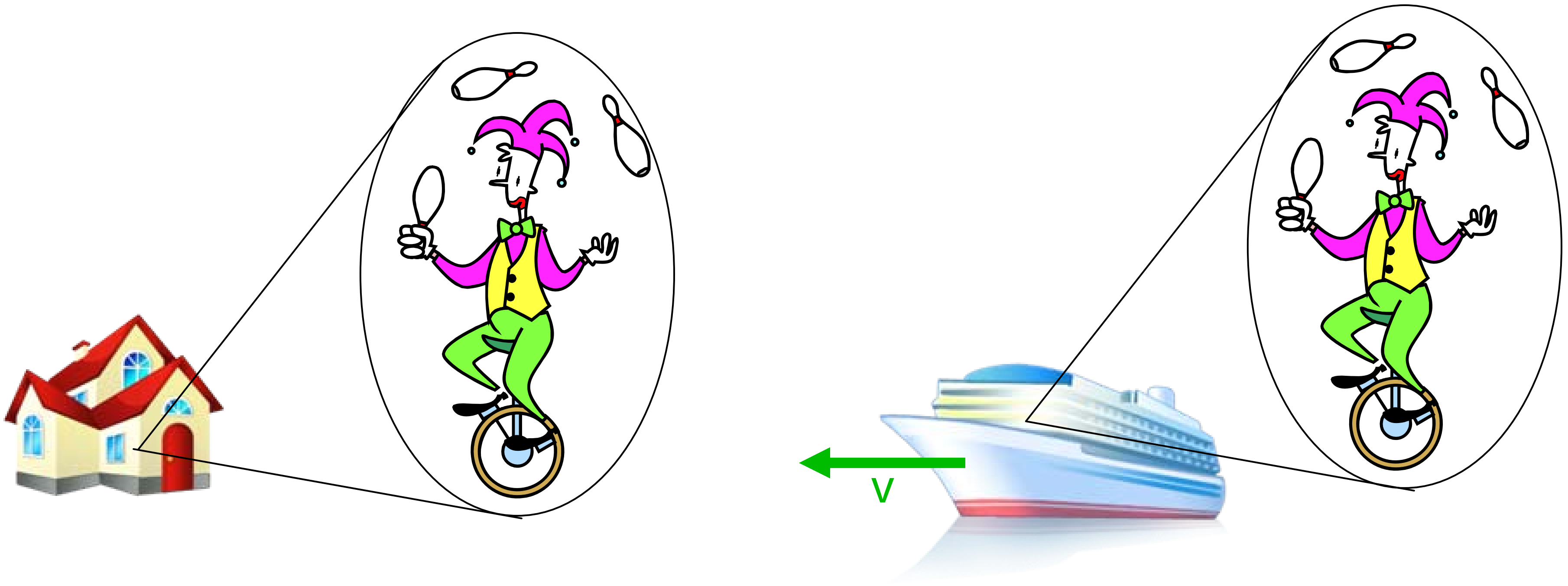
- physical results are independent of the velocity of the experiment and the ***direction*** it points



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

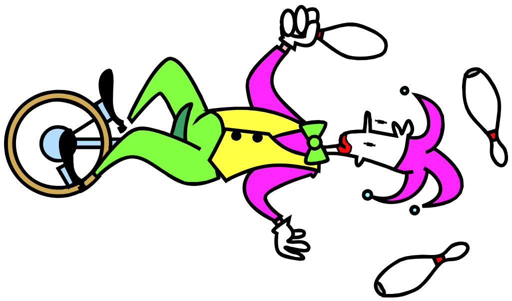
What is Lorentz symmetry?

- 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

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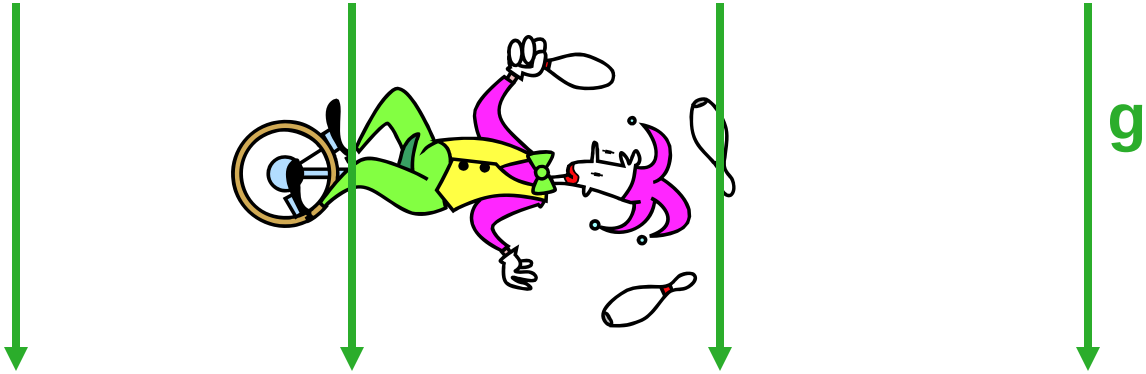
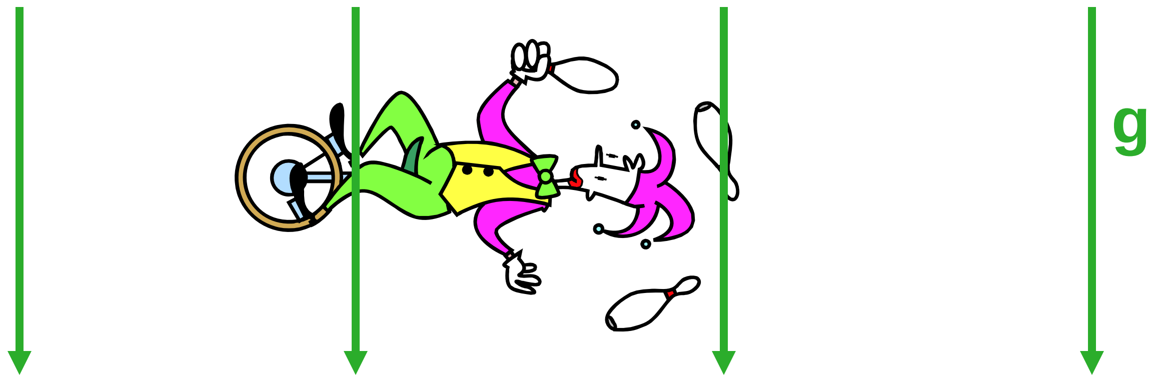


- juggling while lying on your back is different
- apparent relativity violation

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.

a subset of the SME lagrangian with gravity[1]

$$L_{\text{fermion}} = \frac{1}{2} i e^{\mu}{}_{a}\, \overline{\psi}(\gamma^a - c_{\nu\lambda} e^{\nu a} e^{\lambda}{}_{b} \gamma^b - e_\nu e^{\nu a}) \overleftrightarrow{D_\mu} \psi$$
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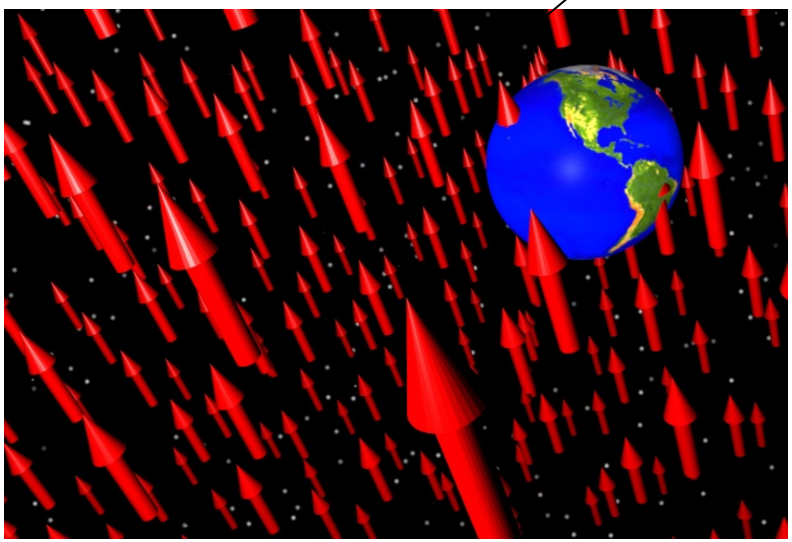

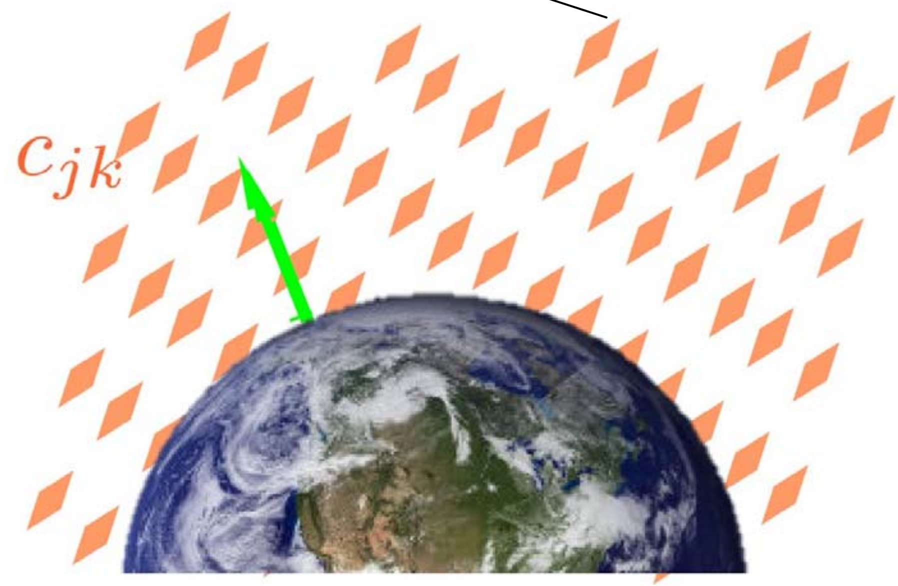

coefficients provide ‘directions’ to spacetime

1) Kostelecký, PRD ’04

a simple example with Lorentz violation

- rotation invariance violation

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} m_{xx} & 0 & 0 \\ 0 & m_{yy} & 0 \\ 0 & 0 & m_{zz} \end{pmatrix} \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix}$$

- magnitude of acceleration is different depending on which way you push
- rotation invariance violation – laws of physics depend on direction
- viable theory for sufficiently similar masses
- more general alternative that Newton could have considered
- presented in ‘preferred coordinates’ (diagonal mass)

arises as newtonian limit with spatial c coefficients

$$\begin{pmatrix} F_{x'} \\ F_{y'} \\ F_{z'} \end{pmatrix} = m \begin{pmatrix} 1 + c_{x'x'} & c_{x'y'} & c_{x'z'} \\ c_{y'x'} & 1 + c_{y'y'} & c_{y'z'} \\ c_{z'x'} & c_{z'y'} & 1 + c_{z'z'} \end{pmatrix} \begin{pmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{pmatrix}$$

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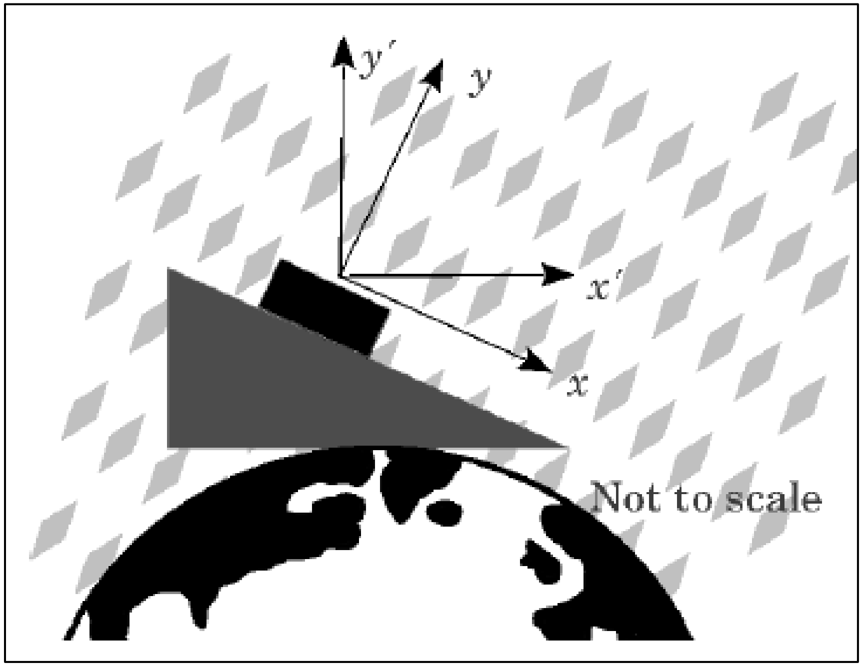
observer rotation



acceleration down the plane is unchanged

Bertschinger, Flowers, JT arXiv:1308.6572 arises as newtonian limit with spatial c coefficients

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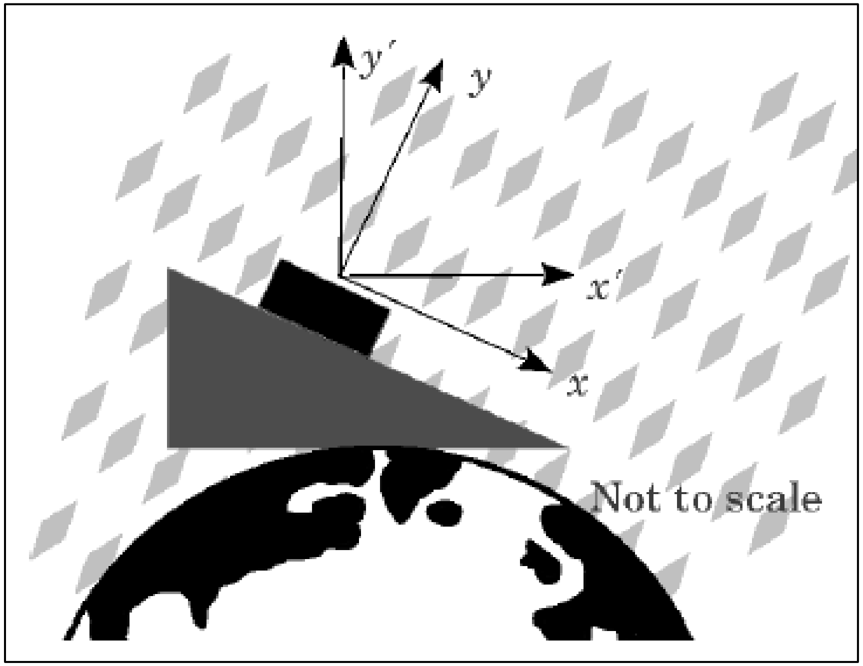
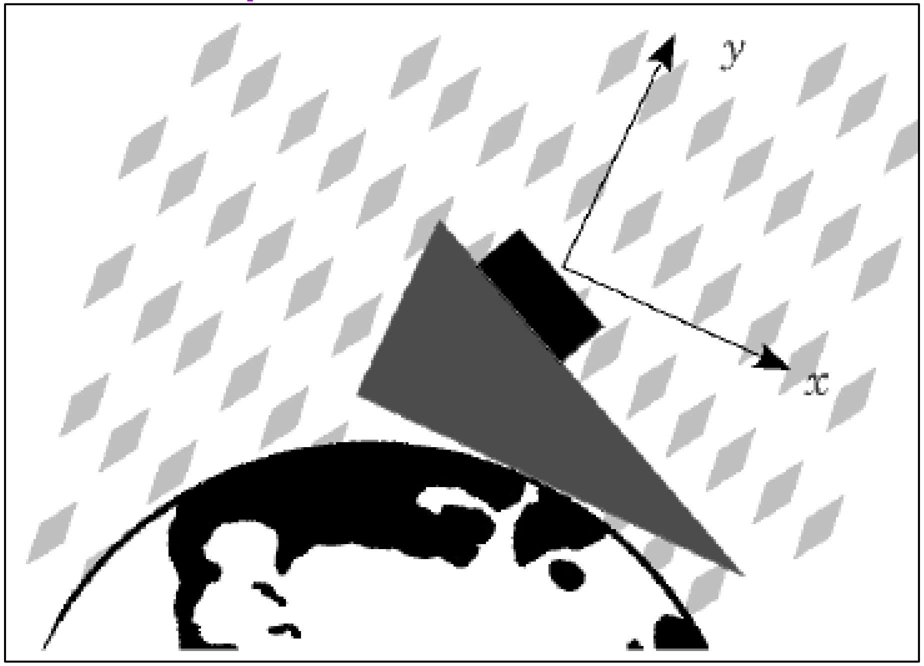


acceleration down the plane is unchanged

particle rotation



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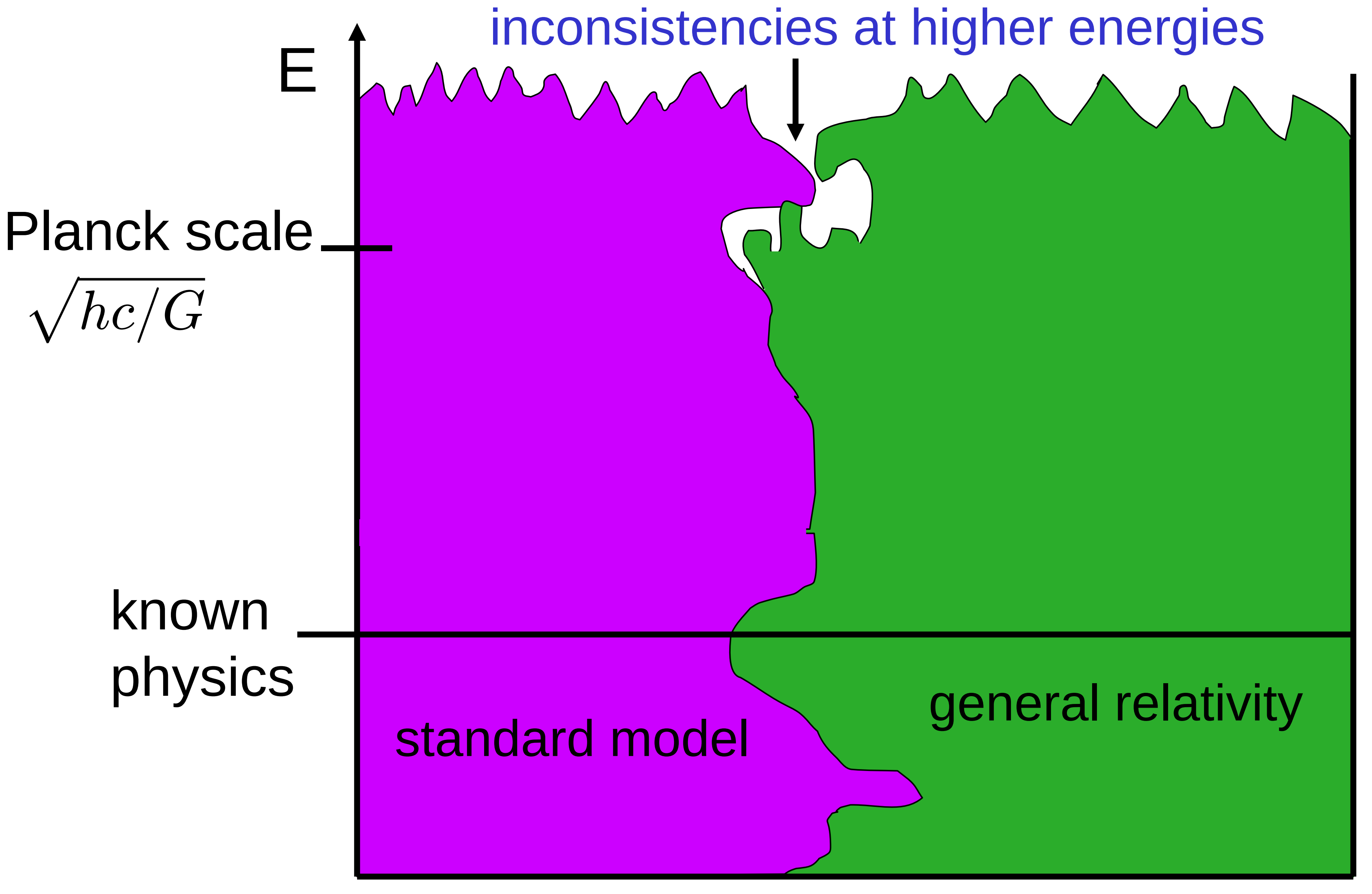
Motivation SM + GR



underlying theory at Planck scale

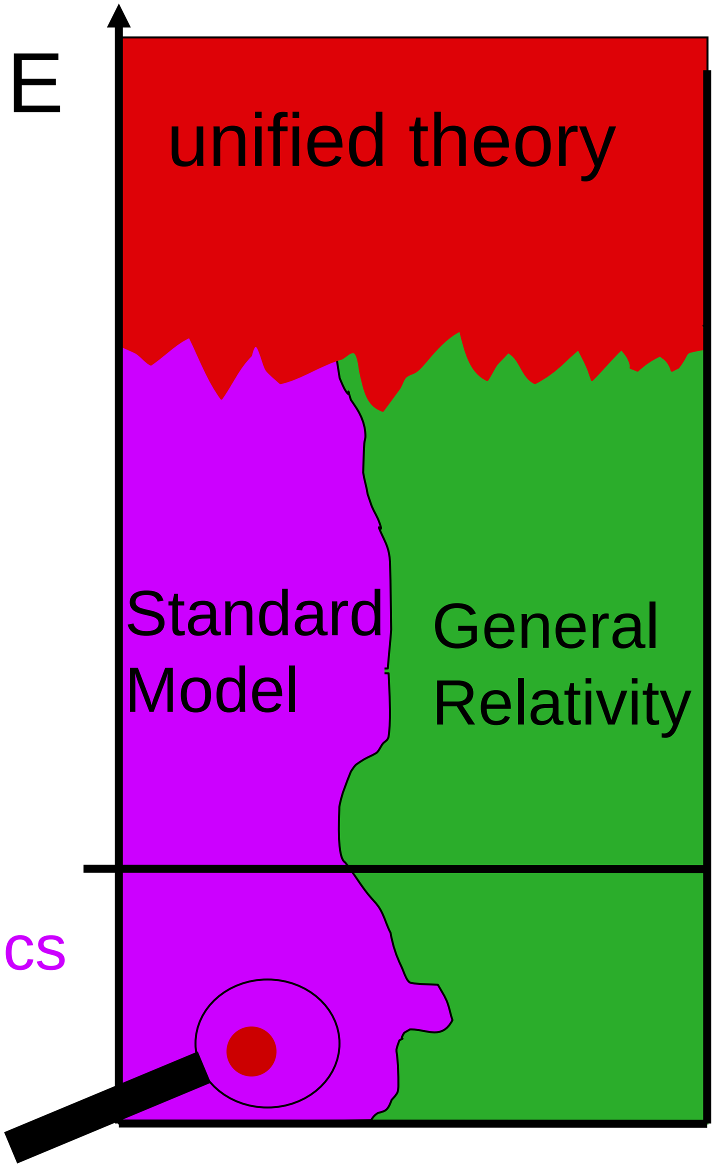
options for probing experimentally

- 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

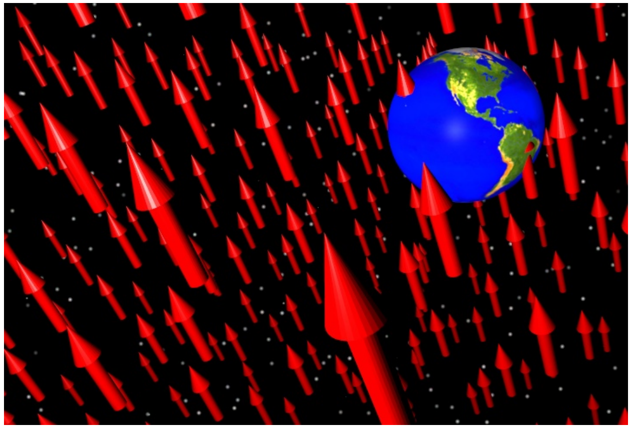
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L_{\mathrm{LV}}$$

- CPT violation comes with Lorentz violation

CPT & Lorentz-violating terms

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

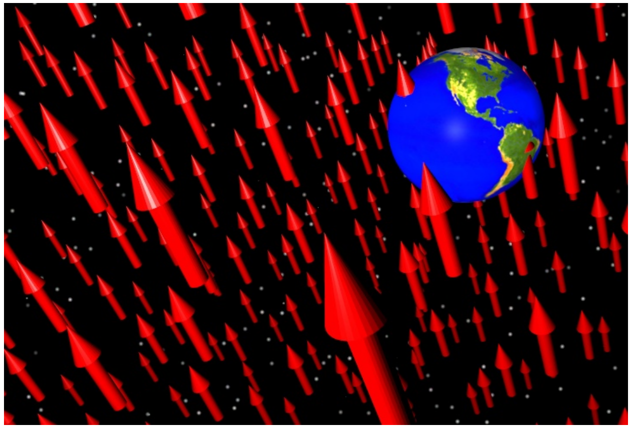
$$\bar{\psi} a_\mu \gamma^\mu \psi$$



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

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

- explicate Lorentz violation
  - the universe just looks that way
  - inconsistent 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

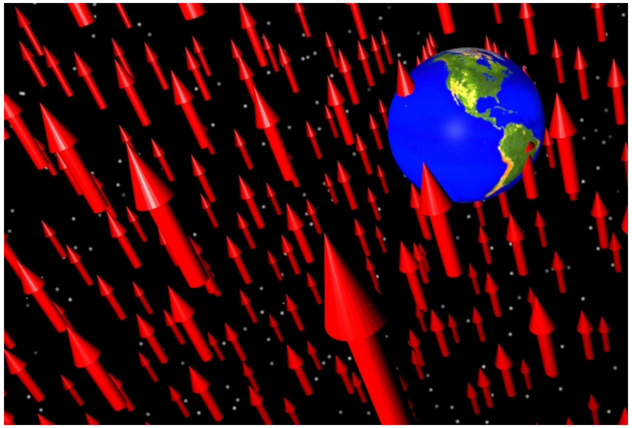
1) Kostelecký PRD '04

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

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
- .....

antimatter efforts

$$L_{\text{LV}} = L_{\text{pure gravity}} + L_{\text{photon}} + L_{\text{fermion}} + \ldots$$

$$L_{\text{fermion}} = \tfrac{1}{2} i \overline{\psi} (\gamma^\mu - c^\mu{}_\lambda \gamma^\lambda - e^\mu) \overleftrightarrow{D_\mu} \psi - \overline{\psi} (m + a_\mu \gamma^\mu) \psi + \ldots$$

- even number of indices – CPT even
- odd number of indices – CPT odd

- antihydrogen spectroscopy – Bluhm, Kostelecky, Russell ’98
- trapped antiparticles – Bluhm, Kostelecky, Russell ’99
- Isotropic Invisible Models (IIM) – models in which isotropic CPT odd coefficients largely cancel effect of isotropic CPT even coefficients for matter but not antimatter

Kostelecky & JT PRD ’11

SME experimental and observational searches

- trapped particle tests (Dehmelt,Gabrielse, ...)
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- 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
- .....

path to experimental analysis

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

↓ field redefinition

$L'_{fermion}$

↓ Euler-Lagrange eq.

$H_{Relativistic}$ → relativistic quantum experiments

↓ Foldy-Wouthuysen expansion

H_{NonRel} → non-relativistic quantum experiments

↓ inspection

$L_{Classical}$

↓ variation

non-relativistic quantum experiments
classical experiments

Newtonian equation of motion

classical results

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

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

S and T denote
composite coefficients
for source and test respectively

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

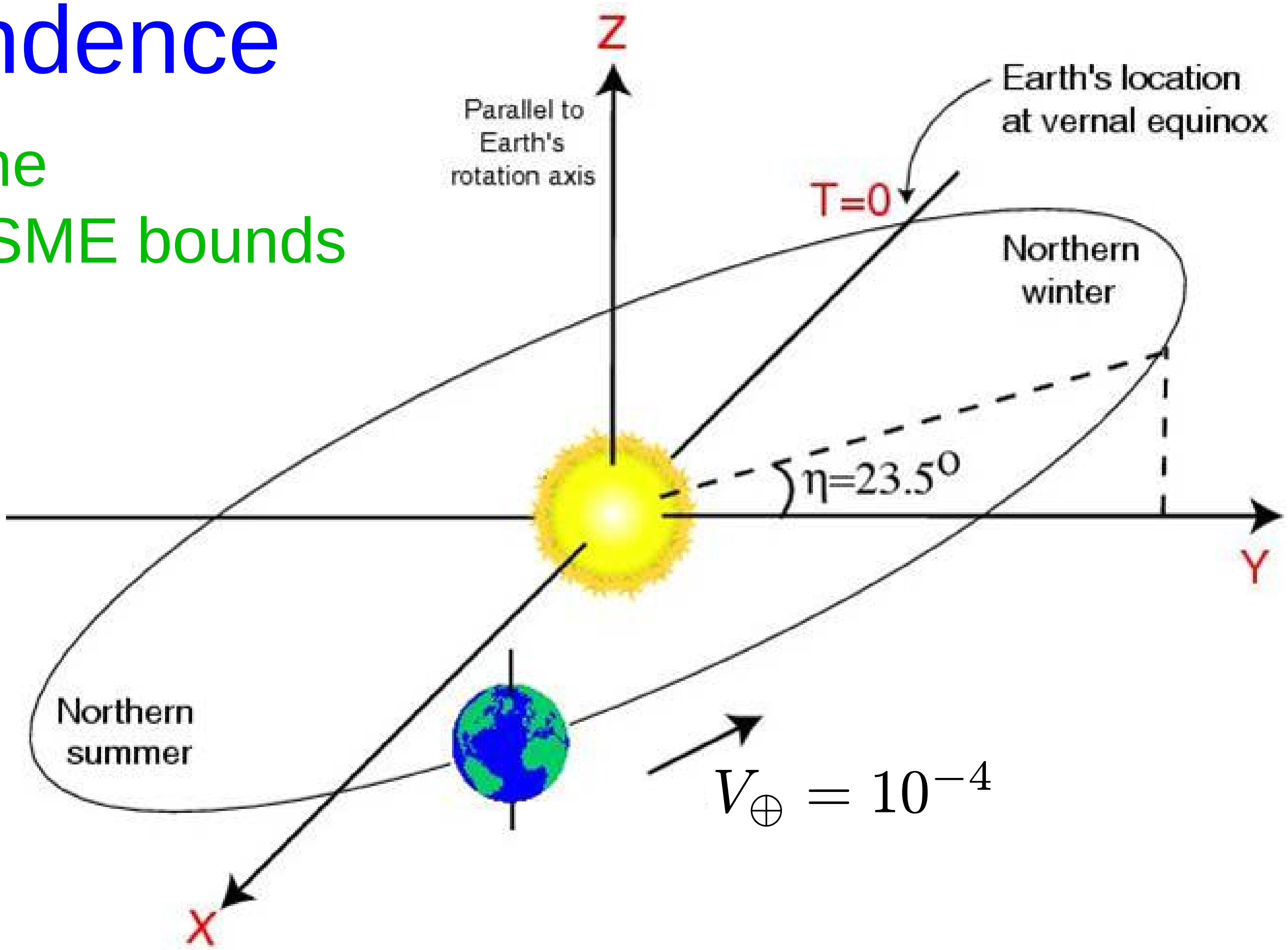
experimental hooks

– particle-species dependence

– time dependence

time dependence

- standard frame
  for reporting SME bounds



- boost and rotation of test ⟶ annual & sidereal variations

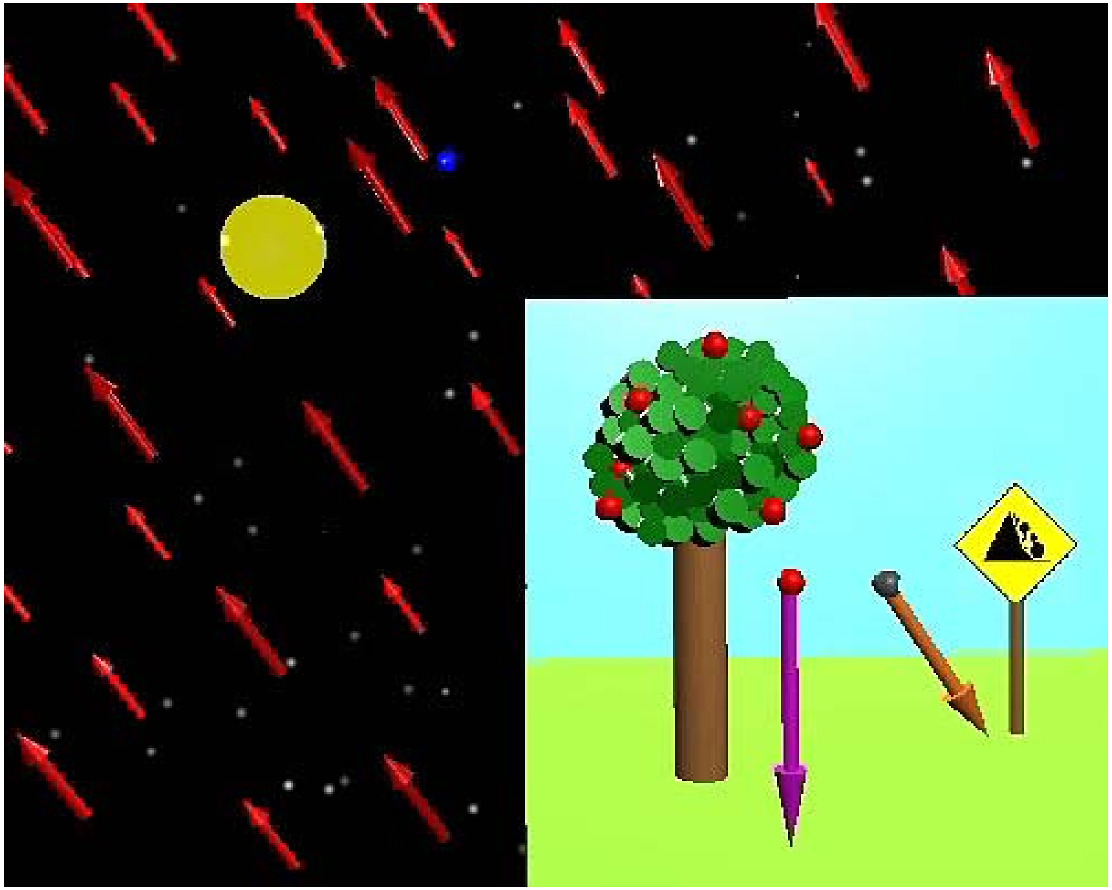
$$\ddot{\vec{x}} \supset -2g\ \alpha\bar{a}_T \hat{z} - 2gV_\oplus\ \alpha\bar{a}_X \sin(\Omega T)\hat{z}$$
$$-\ \tfrac{2}{5} g V_L\ \alpha\bar{a}_X \sin(\omega T + \psi)\hat{y}$$

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 → gravimeter
- monitor relative behavior of particles → EP test
- periodic EP violation qualitatively new proposal?
- frequency and phase distinguish from other effects

experiments

time and species dependent equations of motion imply signals in:

- 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
- light-travel/clock tests
  - time delay
  - Doppler shift
  - red shift
- ...

Kostelecký, JT, PRD ’11

experimental limits on a

- to date, 8 limits on the 12 combinations for p, n, e
- time-component limits (assuming $\overline{c}_{TT} = 0$)[1,2]

$$|\alpha(\overline{a}^n_{\rm eff})_T| \lesssim 10^{-10}\ {\rm GeV}, \qquad |\alpha(\overline{a}^e_{\rm eff})_T + \alpha(\overline{a}^p_{\rm eff})_T| \lesssim 10^{-10}\ {\rm GeV},$$

- space components

two constraints[1] at 10^{-6} GeV

four constraints[3,4] at 10^{-1} GeV

1) Kostelecky & JT PRD '11
2) Schlamminger etal PRL '94
3) JT PRD '12
4) Panjwani, Carbone, Speake '11

vast space for improvement

- improvement possible with up-coming/existing tests
- Earth-based WEP up to10 orders of magnitude
- space-based WEP up to 11 orders of magnitude
- gravimeters up to 9 orders of magnitude
- lunar laser ranging 5 orders of magnitude
- gravitational tests with muons could provide the first sensitivities to $\overline{a}_\mu$ for higher generation matter
- gravitational tests with antihydrogen and positronium could provide clean separation of a and c coefficients.

exotic tests

- variation on gravitational tests involving experimentally challenging matter
- charged matter
  - separate proton and electron coefficients
  - theoretically interesting -- bumblebee electrodynamics
- higher-generation matter
  - few existing bounds
- antimatter
  - separate CPT even and odd coefficients

CPT odd

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

  - differing gravitational response for matter and antimatter

a toy-model limit of SME for antimatter gravity

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

- Isotropic 'Parachute' Model (IPM)[1]

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

Matter

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

Antimatter

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

"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]

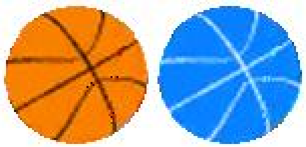
1) Kostelecký, JT PRD '11

constraints?

constraints?

- particle antiparticle pair vs. photon

$E = 2m + m(g_b + g_{\bar{b}} - 2g_\gamma)h$

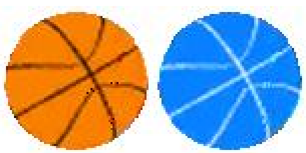


$E'' = 2m + m(g_b + g_{\bar{b}} - 2g_\gamma)h$

2γ

h

$E' = 2m + m(g_b + g_{\bar{b}})h$



$E' = 2m + m(g_b + g_{\bar{b}})h$

2γ

concern

- energy conservation

Morrison, Am. J. Phys. '58

constraints?

- particle antiparticle pair vs. photon

$$E = 2m + m(g_b + g_{\bar{b}} - 2g_\gamma)h \quad E'' = 2m + m(g_b + g_{\bar{b}} - 2g_\gamma)h$$

IPM – nonissue

- conserved energy-momentum tensor

How does it work in detail?

- photons are normal (no a or c effects)
- the a coefficient is CPT odd – effect cancels for the pair
- at the newtonian level, c results in the following energy relation for a (anti)particle

$$E = m_{\text{eff}} + \frac{1}{2} m_{\text{eff}} (1 + \frac{2}{3} \bar{c}_{00}) v^2 + m_{\text{eff}} g h$$

- same energy exchange with gravitational field, but acceleration is modified

$E' =$

conce

- ene

Morrison, Am. J. Phys. ’58

constraints

- vacuum polarization, binding energy, and equivalence-principle tests
  - atomic masses are composed of:
    - leptons
    - valence quarks
    - gauge bosons
    - particle-antiparticle pairs

    in varying amounts from atom to atom
  - simplistically, quarks in hydrogen contain ~10% of mass remainder is comparable for hydrogen and antihydrogen. Thus the gravitational response can't differ by more than 10%
  - place limits on anomalous gravitational response of antimatter using limits from conventional EP tests
    - Schiff PRL '58
    - Nieto, Goldman Phys. Rep. '91
    - And others

constraints

- vacuum polarization, binding energy, and equivalence-principle tests
  - atomic masses are composed of:
    - leptons
    - valence quarks
    - ga
    - pa

    in va
  - simp

    rema

    Thus

    10%

IPM

- binding forces are largely conventional
- anomalous gravitational effects associated with flavor content
- apply the IPM conditions after renormalization
- implications?

  - place limits on anomalous gravitational response of antimatter using limits from conventional EP tests

- Schiff PRL ’58
- Nieto, Goldman Phys. Rep. ’91
- And others

constraints?

- 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]

1) Good PR '61

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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]

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

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 interesting features of antimatter-gravity constraints
- 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 may provide access to coefficients that are challenging to measure in conventional tests