Antimatter, Gravity, and Lorentz Symmetry

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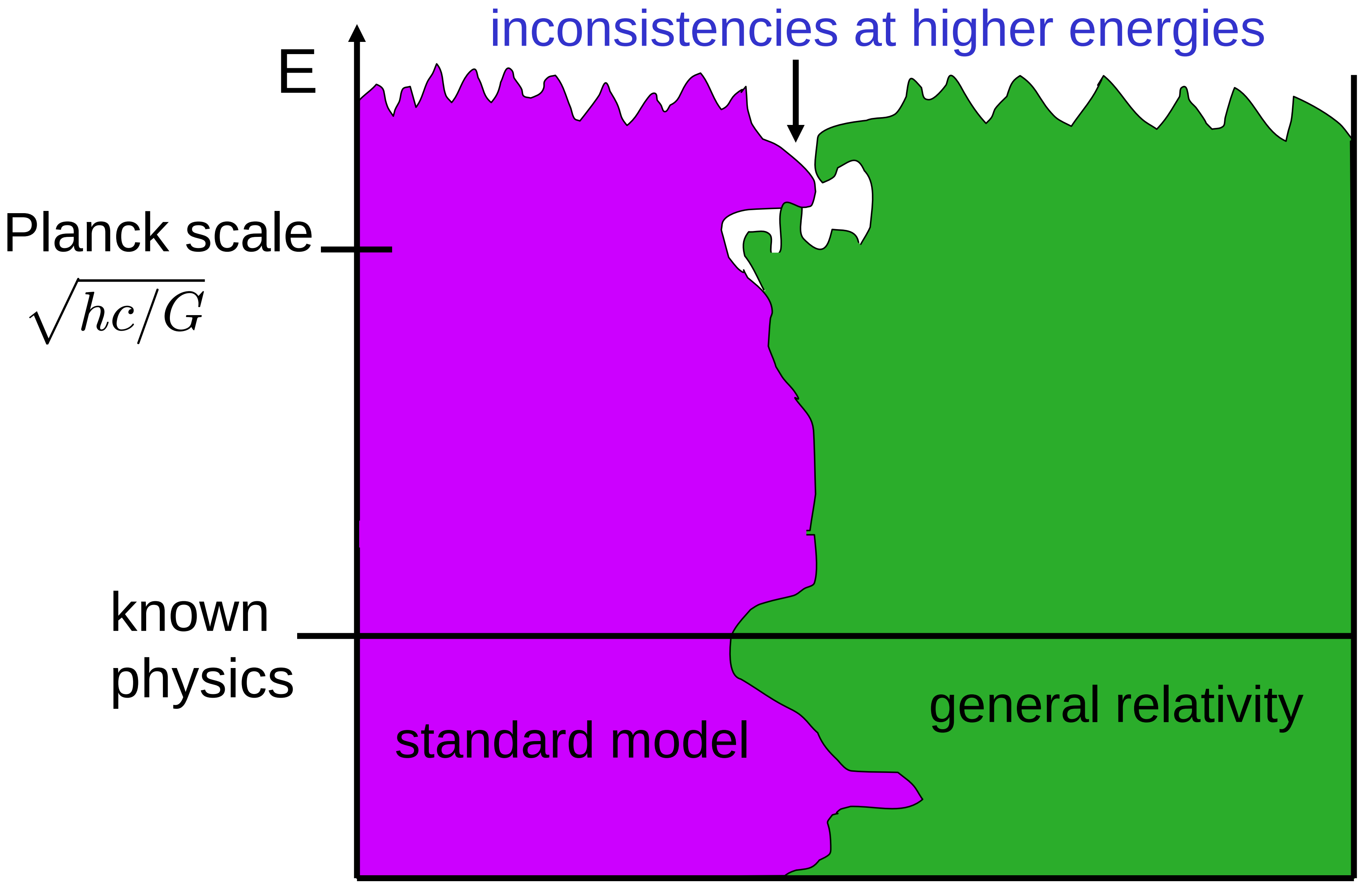
outline

- motivation for CPT & Lorentz symmetry tests
- SME
- Minkowski spacetime results
- matter-gravity couplings[1,2]
  - theoretical basics
  - experiments
  - antimatter-gravity experiments

1) Kostelecký, Tasson PRL ’09
2) Kostelecký, Tasson PRD ‘11

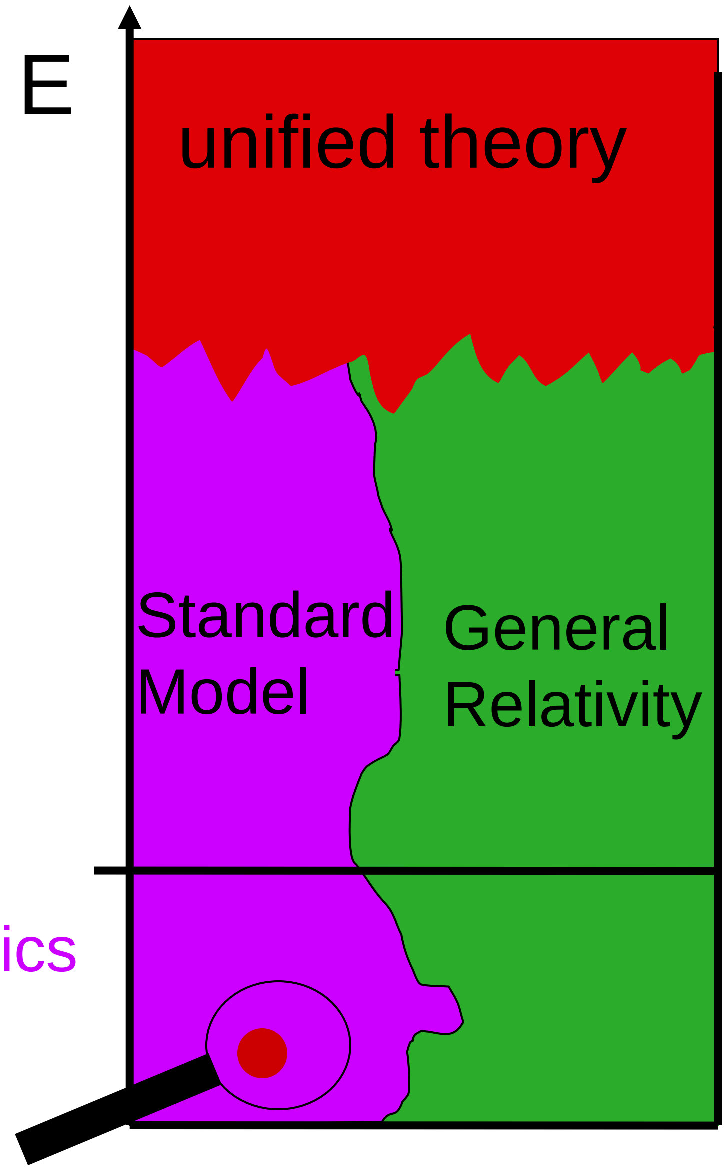
motivation


inconsistencies at higher energies
E
Planck scale
$\sqrt{hc/G}$
known
physics
standard model
general relativity

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

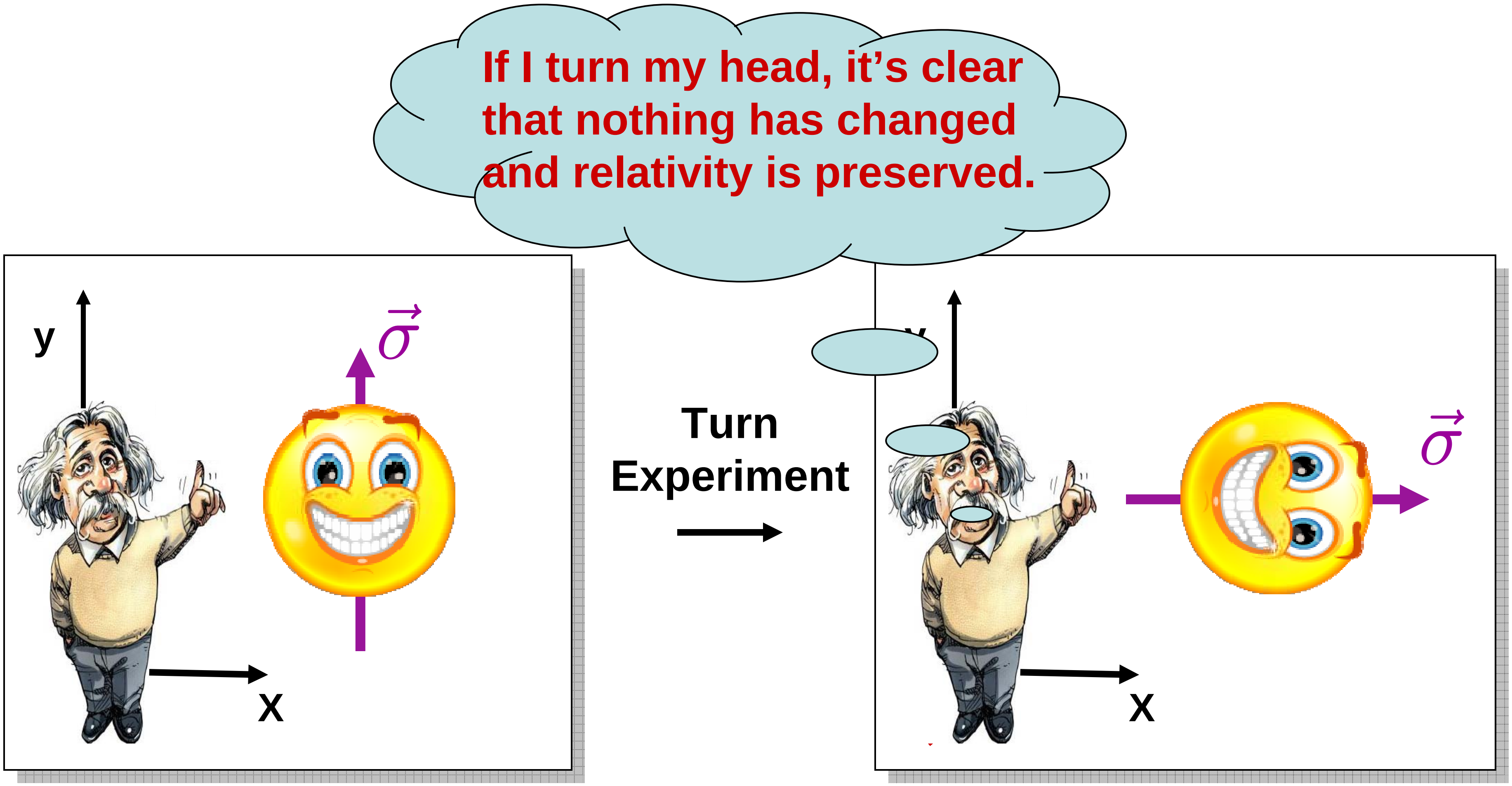
CPT & Lorentz-violating terms

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

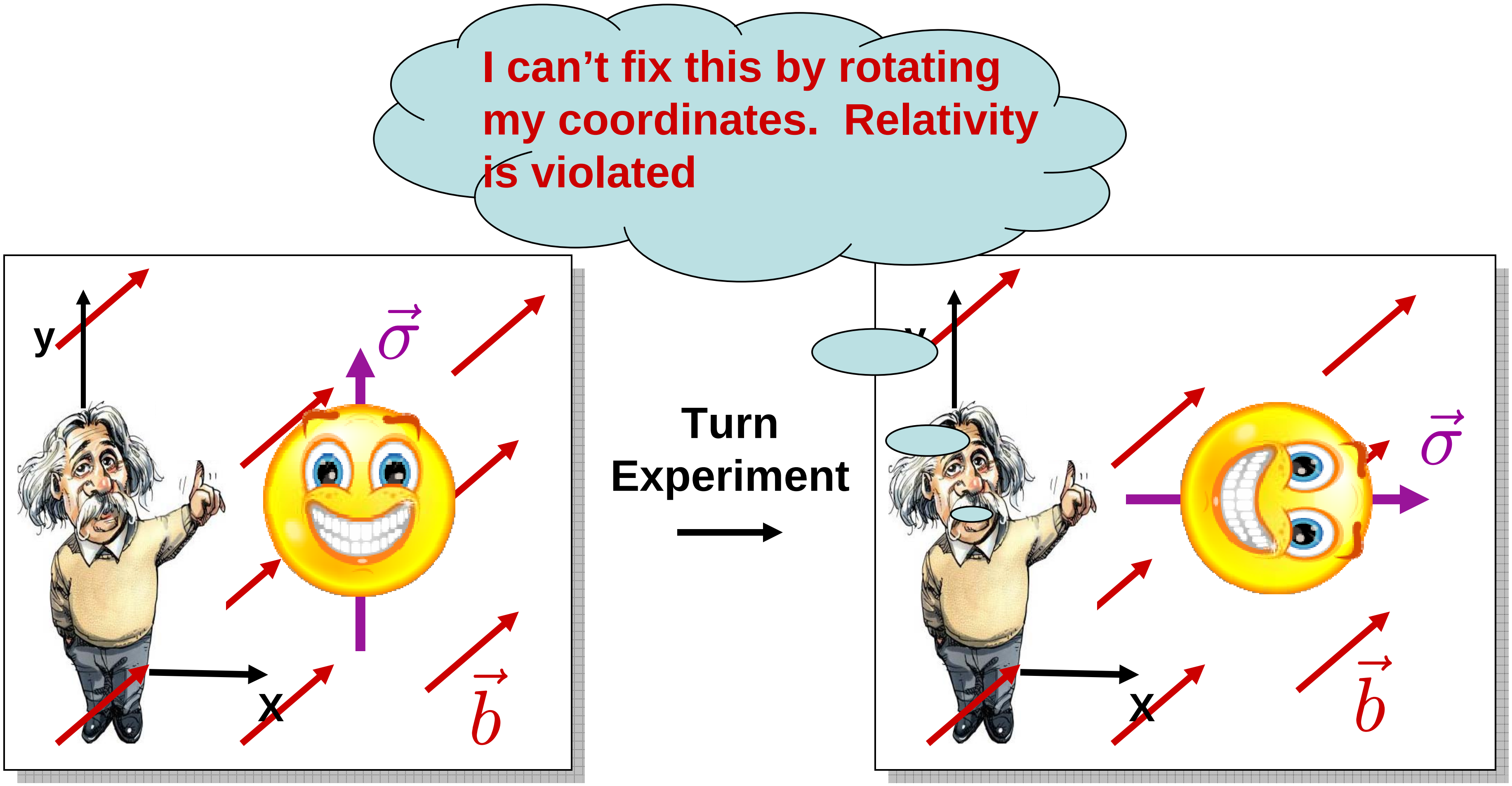
$$s^{\mu\nu} R_{\mu\nu} \qquad \bar{\psi} a_\mu \gamma^\mu \psi$$

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

What is relativity violation?



What is relativity violation?



$$\vec{\tau} = \vec{\sigma} \times \vec{b}$$

tests

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

- SME
  - predictive
  - quantitative comparisons

- find
  - Lorentz and CPT violation
  - field of unknown origin eg. best existing bounds on spacetime torsion[1]

1) Kostelecký, Russell, Tasson PRL ’08

SME experimental and observational searches (to date)

- 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

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

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

- 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 cancel effect of isotropic CPT even coefficients for matter but not antimatter

Kostelecky & Tasson PRD ’11

SME experimental and observational searches (to date)

- trapped particle tests (Dehmelt,Gabrielse, ...)
- spin-polarized matter tests (Adelberger, Heckel, Hou, ...)
- c
- te
- n
- m
- m
- a
- a
- p
- c
- C
- lu
- sl

- only ~1/2 of lowest order couplings explored
- use gravitational couplings and experiments to get more!

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Prospects for Large Relativity Violations in Matter-Gravity Couplings

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Matter-gravity couplings and Lorentz violation

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SME lagrangian with gravity[1]

$$L_{\text{SME}} = L_{\text{fermion}} + L_{\text{gravity}} + \ldots$$

this work

Bailey & Kostelecký PRD '06

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

coefficients for Lorentz violation

- particle-species dependent

additional coefficients for LV, non-minimal torsion, …

- a and e unobservable in Minkowski spacetime
- focus on spin independent effects

1) Kostelecký PRD '04

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

$$h_{00} = \frac{2Gm}{r}\Big(1 + (\overline{c}^{\mathrm{S}})_{00} + \frac{2}{m}(\overline{a}^{\mathrm{S}}_{\mathrm{eff}})_0\Big) + \dots$$

$$\ddot{x}^j = -\tfrac{1}{2}\partial^j h_{00} + (\overline{c}^{\mathrm{T}})^j{}_k \partial^k h_{00} + \frac{1}{m^{\mathrm{T}}}\alpha(\overline{a}^{\mathrm{T}}_{\mathrm{eff}})_0 \partial^j h_{00} + \dots$$

S and T denote
composite coefficients
for source and test respectively

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

- modified metric & particle equation of motion
- experimental hooks
  - particle-species dependence
  - time dependence

species dependence

- species dependence

$$\overline{c}^{T}_{\mu\nu} = \sum_{w=p,n,e} \frac{N^w m^w}{m^T} \overline{c}^{w}_{\mu\nu}$$

mass fraction of species w in test body

$$(\overline{a}_{\rm eff})^{T}_{\mu} = \sum_{w=p,n,e} N^w (\overline{a}_{\rm eff})^{w}_{\mu}$$

- combining data from multiple experiments

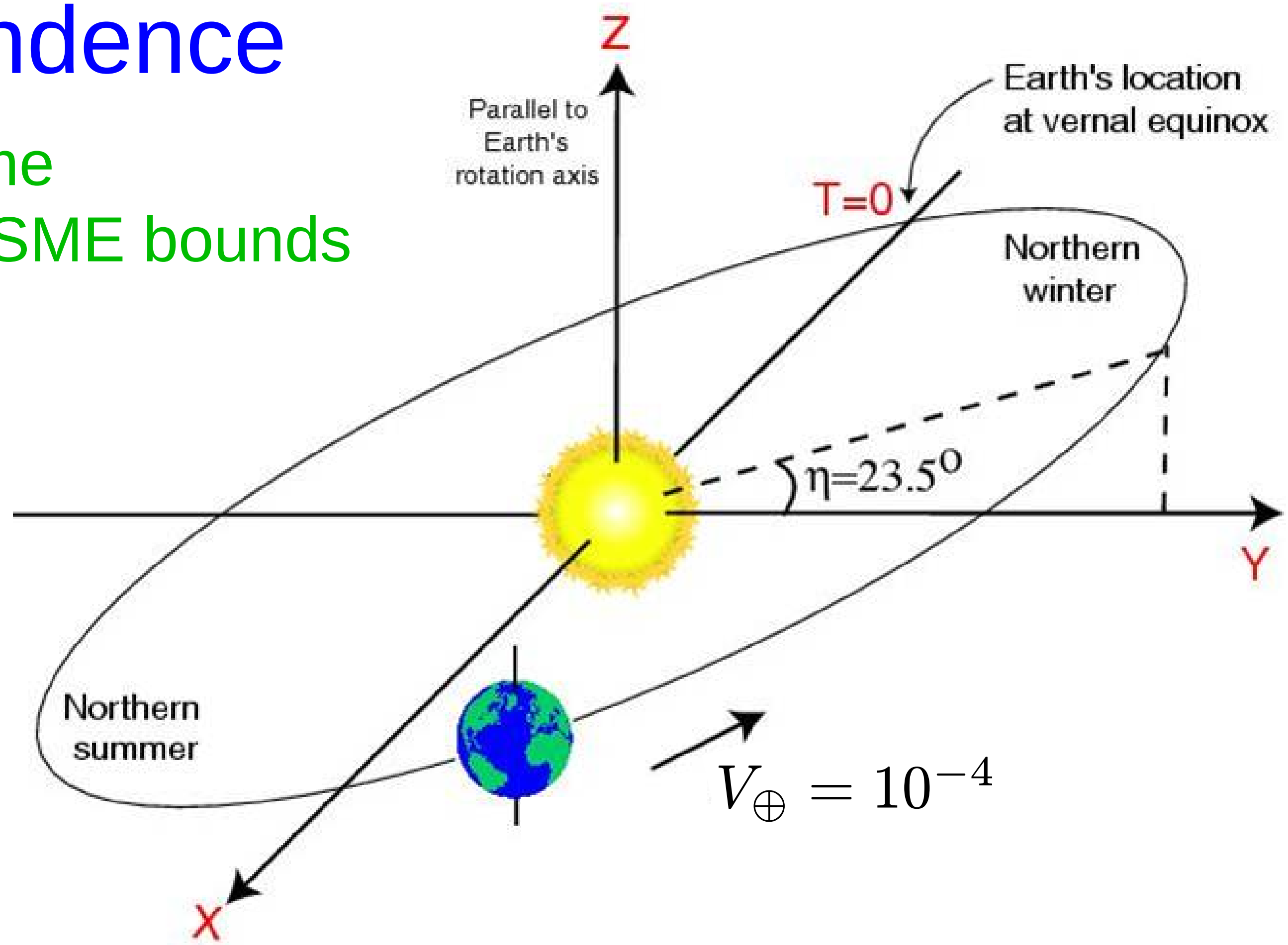
  $\Longrightarrow$ independent p, n sensitivity

- experiments with charged matter

  $\Longrightarrow$ independent e sensitivity

time dependence

- standard frame
  for reporting SME bounds



- boost and rotation of test ⟶ annual & sidereal variations

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

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, Tasson PRD '11

lab tests

annual variations

acceleration of a test particle T

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

- 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

lab tests

acceleration of a test particle T

$$\ddot{\vec{x}} \supset -\frac{2}{5m} g V_L \alpha(\overline{a}^{\mathrm{T}}_{\mathrm{eff}})_X \sin(\omega T + \psi)\hat{y}$$

$V_L \approx 10^{-2} V_\oplus$

sidereal variations

experimental sensitivities[1]

Experiment	$\alpha(\overline{a}_{\rm eff})^w_T$, $m^w\overline{c}^w_{TT}$ actual	$\alpha(\overline{a}_{\rm eff})^w_J$, $m^n\overline{c}^n_{TJ}$ feasible	$\alpha(\overline{a}_{\rm eff})^w_T$, $m^w\overline{c}^w_{TT}$ future	$\alpha(\overline{a}_{\rm eff})^w_J$, $m^n\overline{c}^n_{TJ}$ future
torsion pendulum	10^{-11}	10^{-7}	-	-
falling corner cube	10^{-8}	10^{-4}	-	-
atom interferometry	10^{-5}	10^{-5}	10^{-15}	10^{-11}
superconducting gravimeter	-	10^{-6}	-	-
drop tower	-	-	10^{-10}	10^{-6}
balloon drop	-	-	10^{-13}	10^{-9}
bouncing masses	-	-	10^{-14}	10^{-10}

$w = p, n, e$; $J = X, Y, Z$; sensitivities in GeV

- sensitivities are to various combinations of above coefficients
- actual = achieved in [1],
  feasible = attainable with existing data / operating experiments
  future = attainable in planned experiments

1) Kostelecký, Tasson PRD ‘11

space-based E.P. tests

long free-fall times

$\Longrightarrow$ improved sensitivity

differential acceleration sensitivity

test	Δa/a
MicroSCOPE	10^{-15}
Galileo Galilei	10^{-17}
STEP	10^{-18}

crude sensitivity estimates based on $\Delta \mathrm{a}/\mathrm{a} = 10^{-18}$

$\overline{c}^n_{JJ\,\mathrm{no\,sum}}$	10^{-16}
$\overline{c}^n_{(TJ)}$	10^{-12}
$\alpha(\overline{a}_{\mathrm{eff}})^w_J$	10^{-12}GeV
$\alpha(\overline{a}_{\mathrm{eff}})^w_T, m^w\overline{c}^w_{TT}$	10^{-16}GeV

$w = p, n, e;\ J = X, Y, Z$

exotic tests

- variations of above 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

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

  - differing gravitational response for matter and antimatter

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 (IPM) Kostelecký, Tasson PRD '11

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

Matter

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

$$\mathrm{a} = g$$

Antimatter

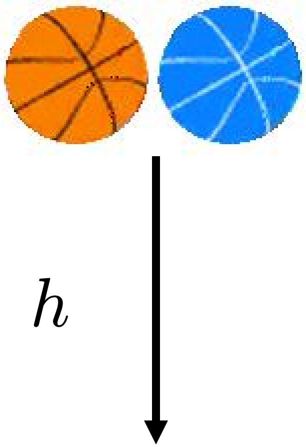
$$m_{\mathrm{i,eff}} \neq m_{\mathrm{g,eff}}$$

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

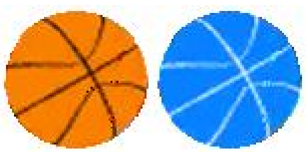
constraints?

- particle antiparticle pair vs. photon

$$E = 2m$$



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



Morrison, Am. J. Phys. ’58

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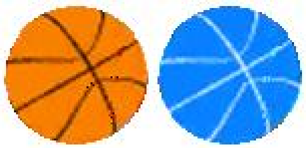

$$h$$

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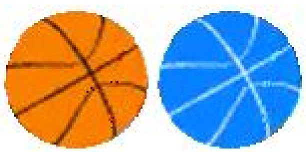

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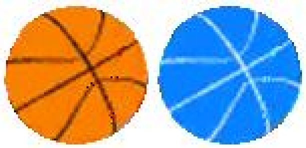

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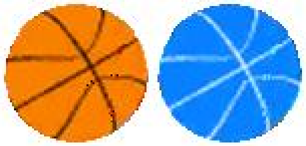

$$E' = 2m + m(g_b + g_{\bar{b}})h$$

$$2\gamma$$

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

$$2\gamma$$

Morrison, Am. J. Phys. '58

constraints?

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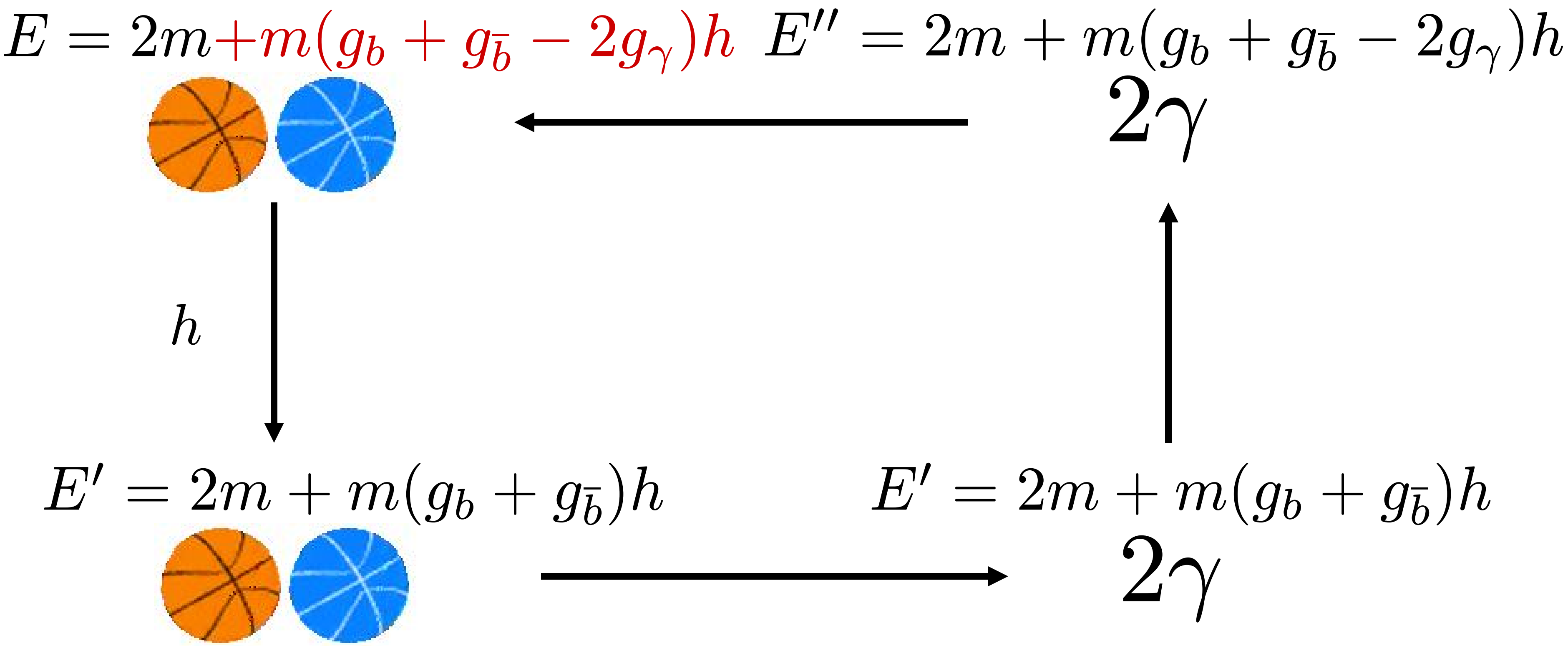

concern

- energy conservation

Morrison, Am. J. Phys. ’58

constraints?

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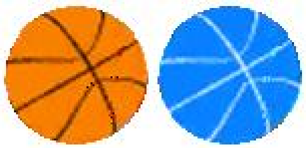

2γ

h

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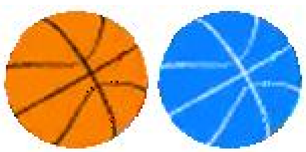

2γ

concern

- energy conservation

IPM – nonissue

- conserved energy-momentum tensor
- offsetting particle/antiparticle effects
- modified energy relation

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

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

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IPM
- binding forces are largely conventional
- anomalous gravitational effects

associated with flavor content

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

constraints?

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

SME

- 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?

IPM model:

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

Ordinary matter constraints

- double boost suppressed effects
- clock tests

Bottom line?

- the IPM is an interesting toy model that highlights interesting features of antimatter gravity constraints

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

- tests with antimatter may provide access to coefficients that are challenging to measure in conventional tests

- the IPM limit of the SME offers a toy model that evades many of usual limits on anomalous antimatter gravity