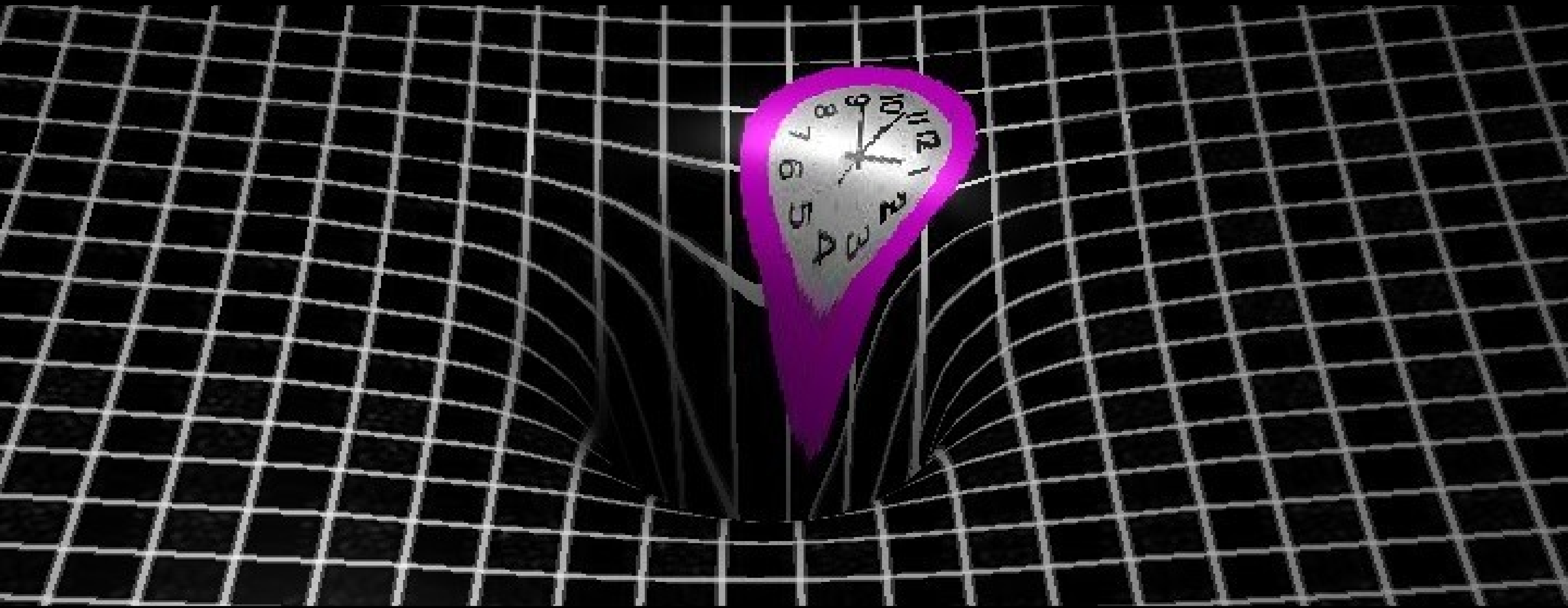
Searches for Local Lorentz Violation



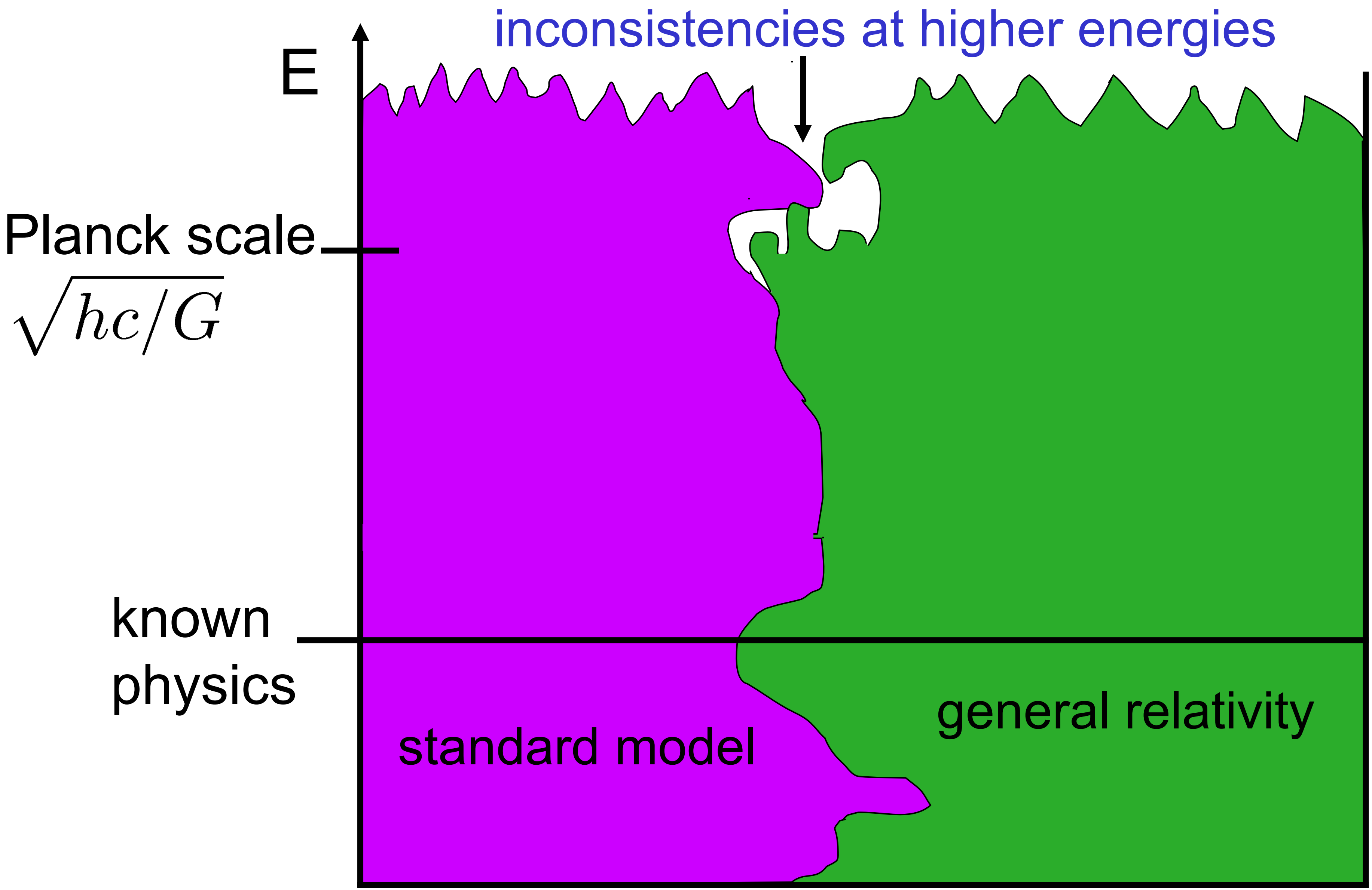
Jay D. Tasson

St. Olaf College

outline

- background
  - motivation
  - SME
- gravity theory
  - pure-gravity sector
  - matter-gravity couplings
- experiments & observations

motivation



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

underlying theory at Planck scale

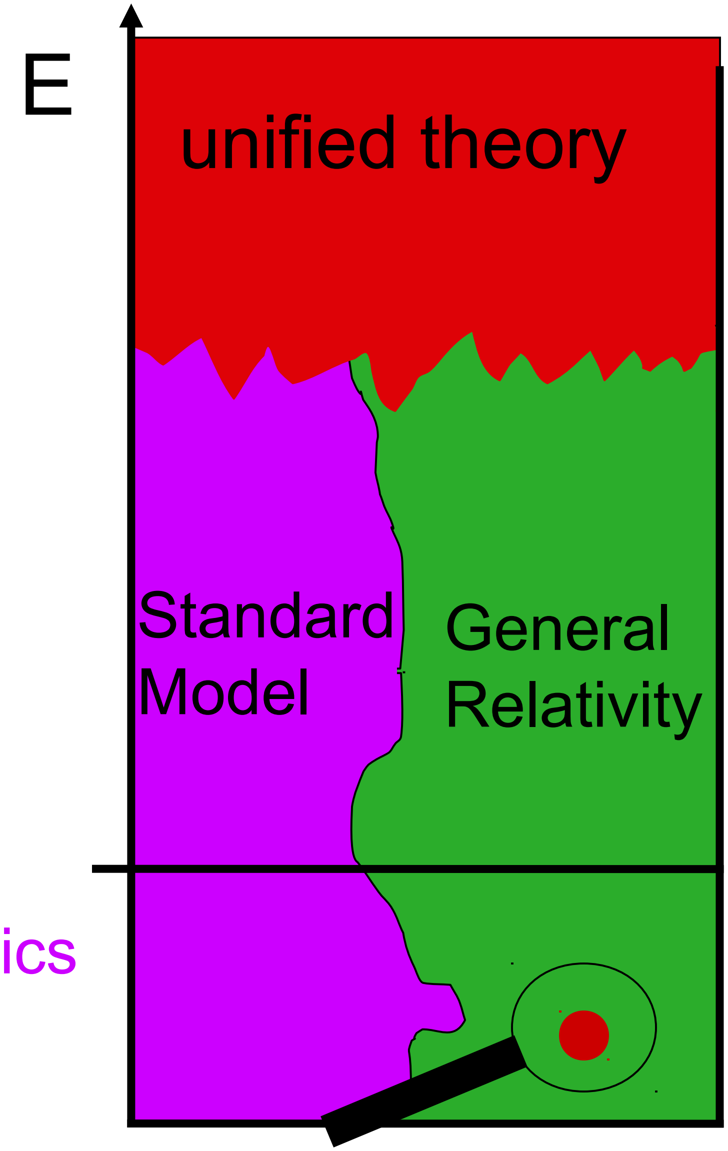
options for probing experimentally

- galaxy-sized accelerator

- suppressed effects in sensitive experiments

local Lorentz violation

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



Standard-Model Extension (SME)

test framework based on effective field theory which contains:

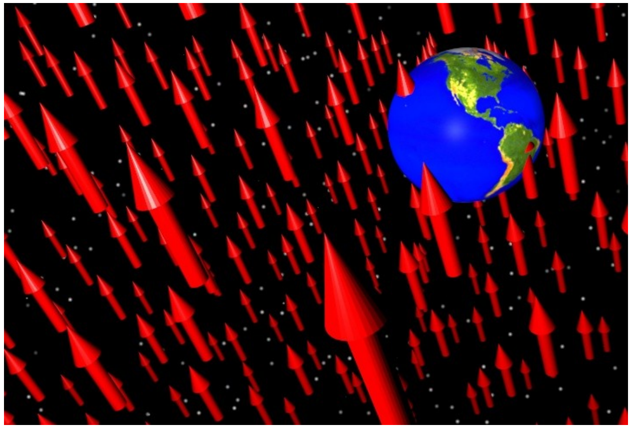
- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent Lorentz violation

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

Lorentz-violating terms

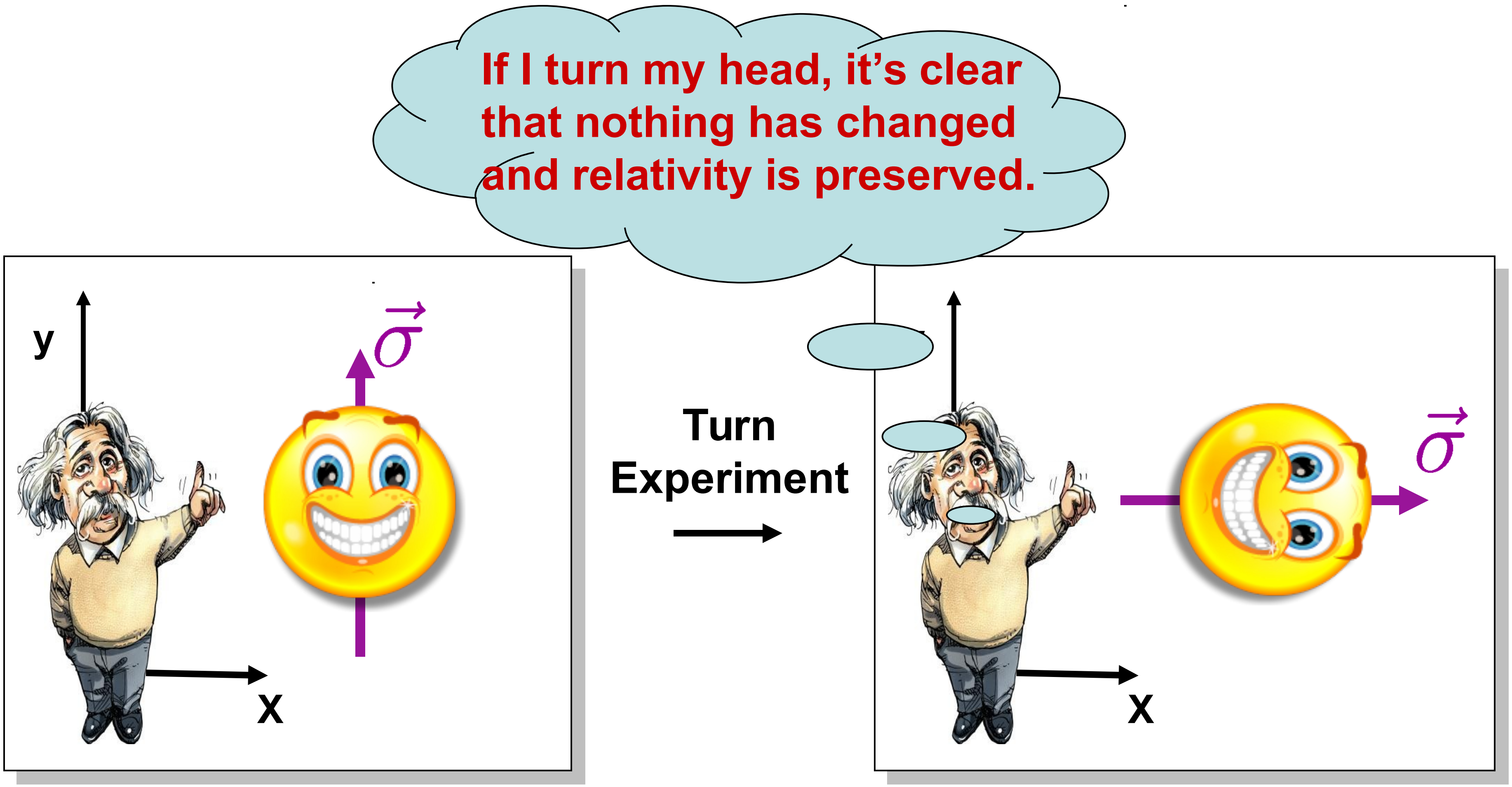
- constructed from GR and SM fields
- parameterized
  by coefficients for Lorentz violation
- samples

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

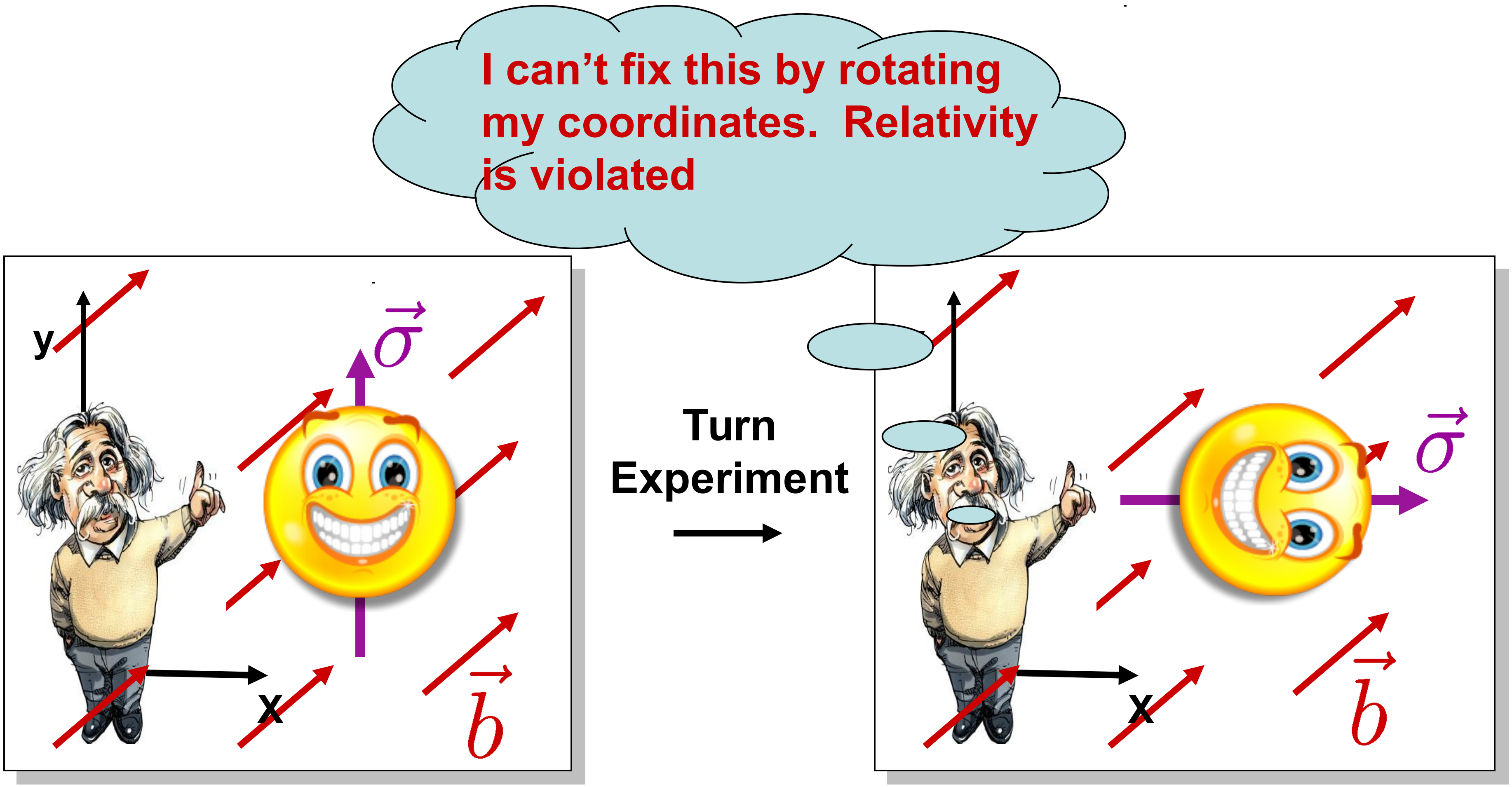


Colladay Kostelecký PRD '97, '98,   Kostelecký PRD '04

What is Lorentz (rotation) violation?



What is Lorentz (rotation) violation?



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

Standard-Model Extension (SME)

test framework based on effective field theory wh… ontains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independen… entz violation

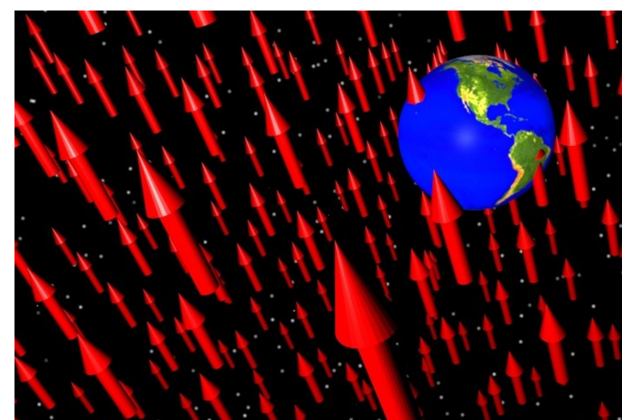
$$L_{\rm SME} = L_{\rm GR} + L_{\rm S} \ldots L_{\rm LV}$$

A broad and general search for new physics

Lorentz-violating terms

- constructed fro… and SM fields
- parameteriz…
  by coeffi… for Lorentz violation
- sampl…

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



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

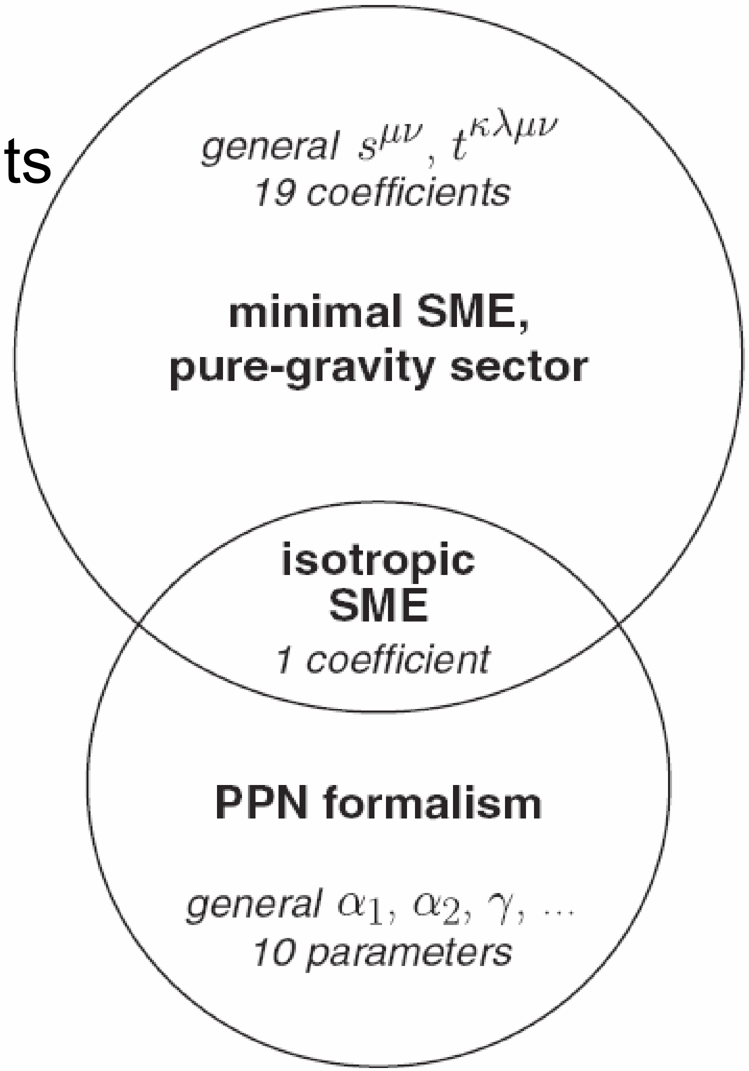
PPN vs. SME

framework	PPN	SME
parameterizes deviations from:	General Relativity (including some LLV)	exact LLI (including some corrections to GR)
expansion about:	GR metric	GR + standard model lagrangian
GR corrections?	Yes	Yes, different ones!
matter sector /standard model corrections?	No	Yes
Lorentz invariant corrections?	Yes	(not primary interest)

parameterized deviations from GR are different!

Example: pure-gravity sector of minimal SME vs. PPN

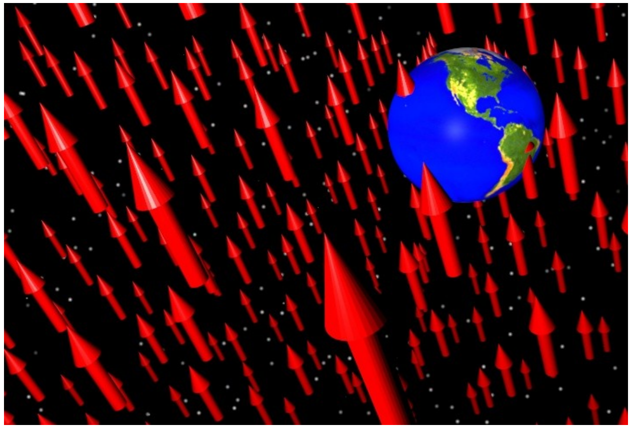
- different coefficients
- can lead to qualitatively different results



If you currently investigate the PPN, you may be able to test additional physics using the SME!

Bailey Kostelecký PRD '06

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



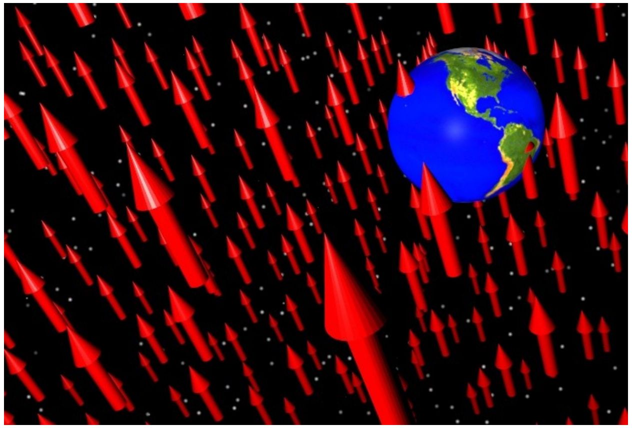
- explicit Lorentz violation
  - the universe just looks that way
  - consistency problems with Riemann geometry can arrise[1]
- spontaneous Lorentz violation
  - a vector or tensor field gets a vacuum-expectation value
  - nonzero VEV observed for a scalar particle, the Higgs (no Lorentz violation)
  - VEV for vector or tensor would be my red arrows
  - 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



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

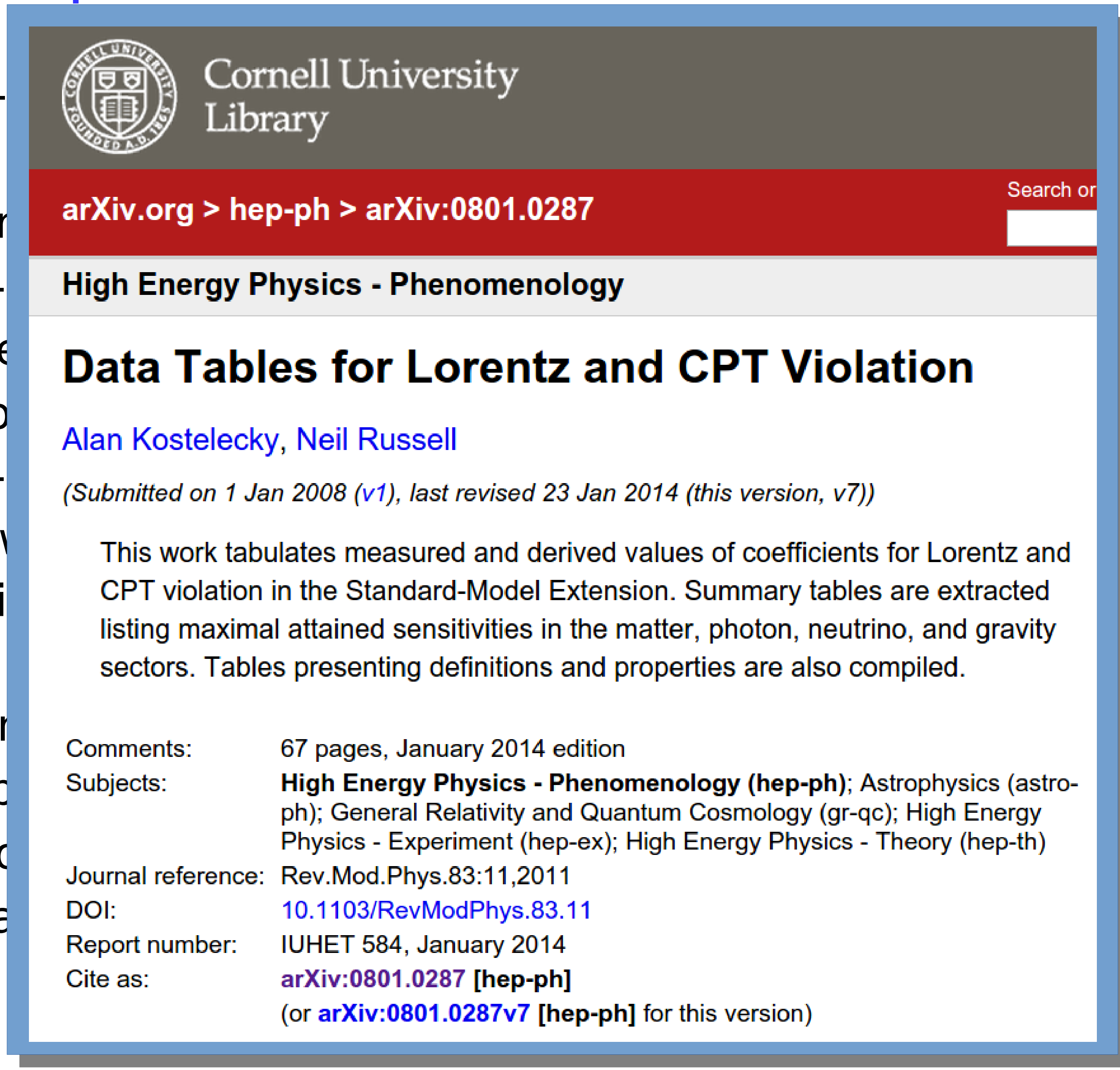
1 Kostelecký Russell JT PRL '08
2 JT PRD '12

SME experimental and observational searches

- atom-interferometer tests (Mueller, Chiow, Herrmann, Chu, Chung)
- lunar laser ranging (Battat, Chandler, Stubbs)
- pulsar-timing observations (Shao)
- short-range gravity tests (Speake, Long,...)
- 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, ...)
- astrophysical photon decay
- cosmological birefringence
- CMB analysis
- .....

SME experimental and observational searches

- atom- Chung)
- lunar
- pulsar
- short-
- trappe
- spin-p
- clock- ...)
- tests v Wolf, ...)
- neutri
- muon
- meson AL, ...)
- astrop
- cosmo
- CMB a
- .....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Search or

High Energy Physics - Phenomenology

Data Tables for Lorentz and CPT Violation

Alan Kostelecky, Neil Russell

(Submitted on 1 Jan 2008 (v1), last revised 23 Jan 2014 (this version, v7))

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

Comments:	67 pages, January 2014 edition
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**; Astrophysics (astro-ph); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Experiment (hep-ex); High Energy Physics - Theory (hep-th)
Journal reference:	Rev.Mod.Phys.83:11,2011
DOI:	10.1103/RevModPhys.83.11
Report number:	IUHET 584, January 2014
Cite as:	**arXiv:0801.0287 [hep-ph]**
	(or **arXiv:0801.0287v7 [hep-ph]** for this version)

SME experimental and observational searches

- atom- … Chung)
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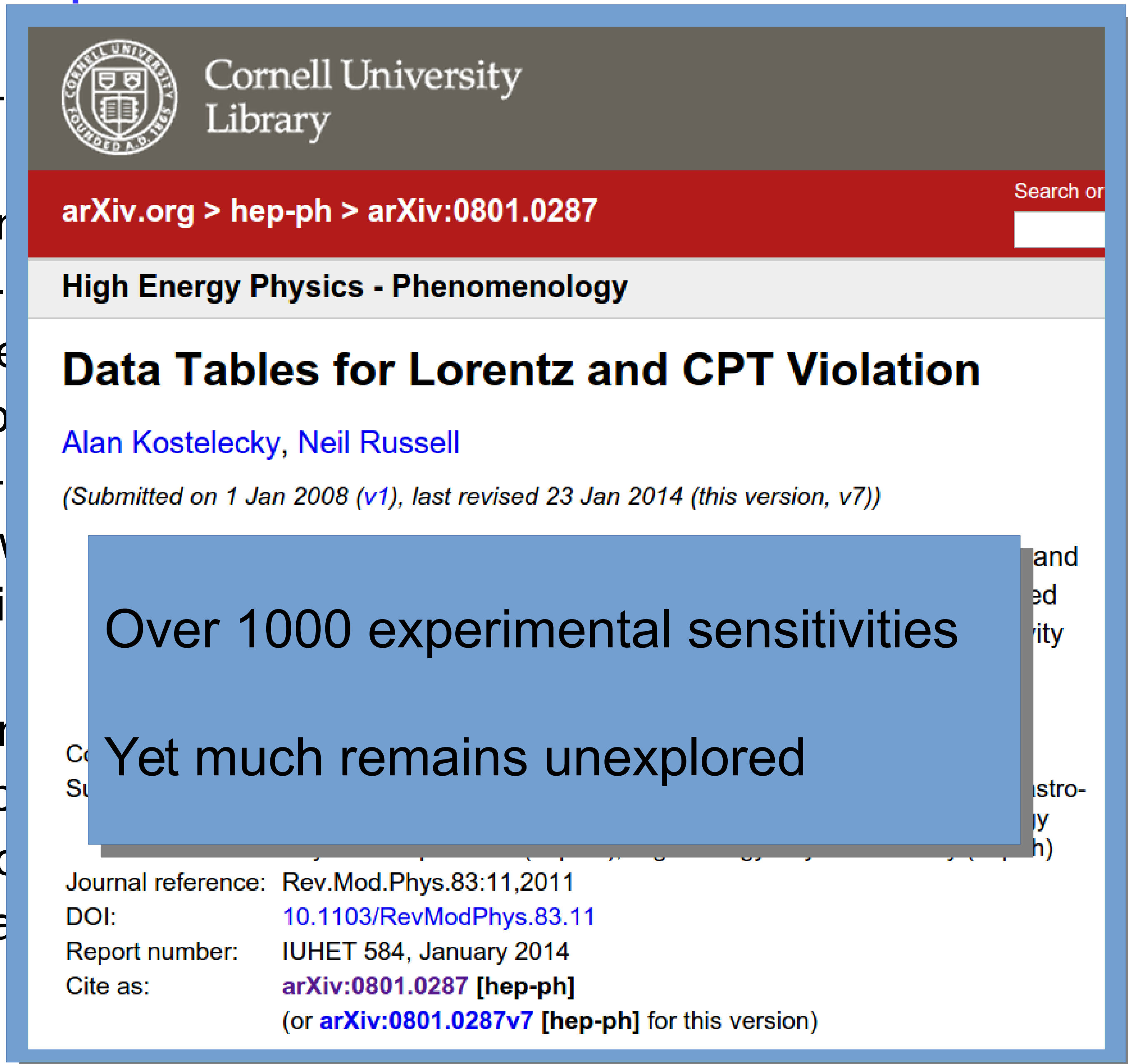
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Over 1000 experimental sensitivities

Yet much remains unexplored

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

Lorentz violation in gravitational experiments

gravitational sector[1]:

- Lorentz violation in the gravitational field
- Einstein-Hilbert + corrections

gravitationally coupled matter sector[2]:

- Lorentz violation in matter gravity couplings
- species dependent couplings leads to WEP violation

1 Bailey Kostelecký PRD '06, Bailey Kostelecký Xu arXiv:1410.6162
2 JT Kostelecký PRD '11

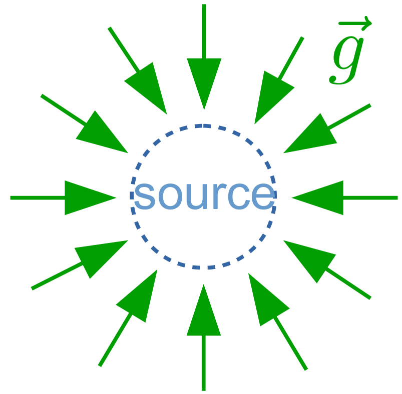
gravity sector

gravity sector: dynamics of gravitational field alone

$$\mathcal{L}_{\rm grav} = \mathcal{L}_{\rm GR} + \mathcal{L}_{\rm LV,grav}$$

conventional pure-gravity

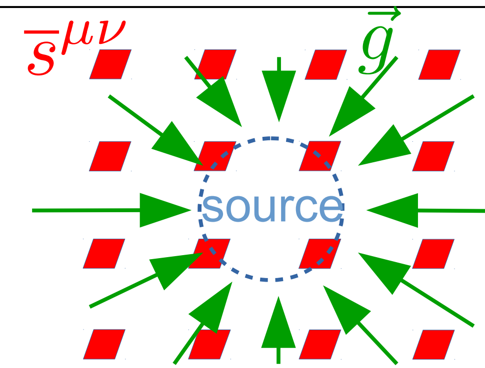
$$\mathcal{L}_{\rm GR} = eR$$



leading Lorentz violation

$$\mathcal{L}_{\rm LV,grav} = e s^{\mu\nu} R_{\mu\nu} \ldots$$

$$s^{\mu\nu} = \overline{s}^{\mu\nu} + \widetilde{s}^{\mu\nu}$$



- minimal post-Newtonian effects originate from $\overline{s}^{\mu\nu}$
- experiments that involve the gravitational field are relevant

gravity sector

- minimal effects (mass dimension 4 operators) via post Newton metric[1]

$$g_{00} = -1 + 2U + 3\overline{s}^{00}U + \overline{s}^{jk}U^{jk} + \ldots$$

$$g_{0j} = \overline{s}^{0j}U - \tfrac{7}{2}V^j + \tfrac{3}{4}\overline{s}^{jk}V^k + \ldots$$

$$\ldots$$

- dimension 6 operators[2]

$$\mathcal{L}^{(6)}_{\mathrm{LV,grav}} = \tfrac{1}{2}(k_1^{(6)})_{\alpha\beta\gamma\delta\kappa\lambda}\{D^\kappa, D^\lambda\}R^{\alpha\beta\lambda\delta} + \ldots$$

- dimension 6 effects via modified 1/r behavior

$$U(r) = G_N \int d^3r' \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|}\left(1 + \frac{\overline{k}(\hat{R})}{|\vec{r} - \vec{r}'|^2}\right)$$

anisotropic combination of dim 6 coefficients

1 Bailey Kostelecký PRD '06
2 Bailey Kostelecký Xu arXiv:1410.6162

gravitationally coupled matter sector

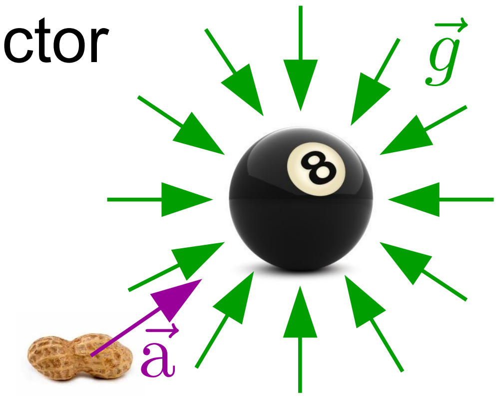
matter sector: kinematics and interactions of particles

$$\mathcal{L}_{\text{matter}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LV,SM}}$$

conventional gravitationally coupled matter sector

$$\mathcal{L}_{\text{SM}} = \tfrac{1}{2} i e^{\mu}{}_{a} \overline{\psi} \gamma^{a} \overleftrightarrow{D}_{\mu} \psi - \overline{\psi} m \psi$$

$$L_{\text{SM}} = -m\sqrt{-g_{\mu\nu}u^{\mu}u^{\nu}} \approx \tfrac{1}{2} m \dot{x}^{2} - U$$

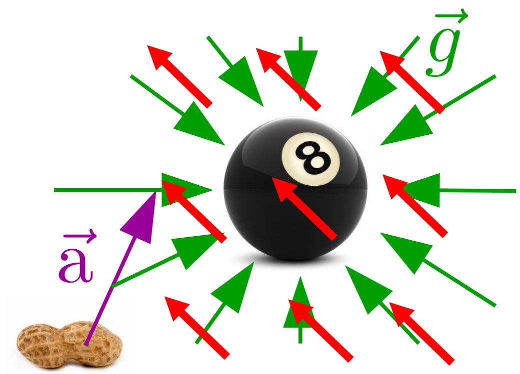


Lorentz violation

$$\mathcal{L}_{\text{LV,SM}} = -\tfrac{i}{2} e^{\mu}{}_{a} \overline{\psi} \left(c_{\nu\lambda} e^{\nu a} e^{\lambda}{}_{b} \gamma^{b} + e_{\nu} e^{\nu a} \ldots \right) \overleftrightarrow{D}_{\mu} \psi - \overline{\psi} \left(a_{\mu} e^{\mu}{}_{a} \gamma^{a} \ldots \right) \psi$$

$$L_{\text{LV,SM}} = -m\sqrt{-(g_{\mu\nu}u + 2c_{\mu\nu})^{\mu}u^{\nu}} + (a_{\text{eff}})_{\mu}u^{\mu}$$

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



- source-dependent field distortions
- test-particle dependent responses

countershaded Lorentz violation

- upon investigating spontaneous breaking we find

Minkowski-spacetime coefficients

$$a_\mu = \overline{a}_\mu + \frac{1}{2}\alpha \overline{a}^\nu h_{\mu\nu} - \frac{1}{4}\alpha \overline{a}_\mu h^\nu{}_\nu$$

unobservable shift in fermion phase

observable effects via gravity coupling

- $\overline{a}_\mu$ for matter is unobservable in flat-spacetime tests

- observable $\overline{a}_\mu$ effects are suppressed by the gravitational field

- $\overline{a}_\mu$ could be large (~ 1eV) relative to existing matter-sector bounds $b_\mu < 10^{-30}$

Kostelecký JT PRL '09

classical results

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

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

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

experiments

- Earth-source lab tests
  - gravimeter

    Chung et al. PRD '09

    Mueller et al. PRL '08
  - WEP

    Hohensee Mueller Wiringa PRL '13

    Hohensee et al. PRL '11
- space-based WEP
- exotic tests
  - charged matter
  - antimatter
  - higher-generation matter
- solar-system tests
  - laser ranging

    Battat Chandler Stubbs PRL '07
  - perihelion precession
- light-travel tests
  - time delay
  - Doppler shift
  - red shift
- clock tests
  - null redshift
  - comagnetometers
- short-range gravity

  Long Kostelecký arXiv:1412:6362

  Panjwani Carbone Speake in CPT'10
- gravity probe B

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  Shao arXiv:1412.2320

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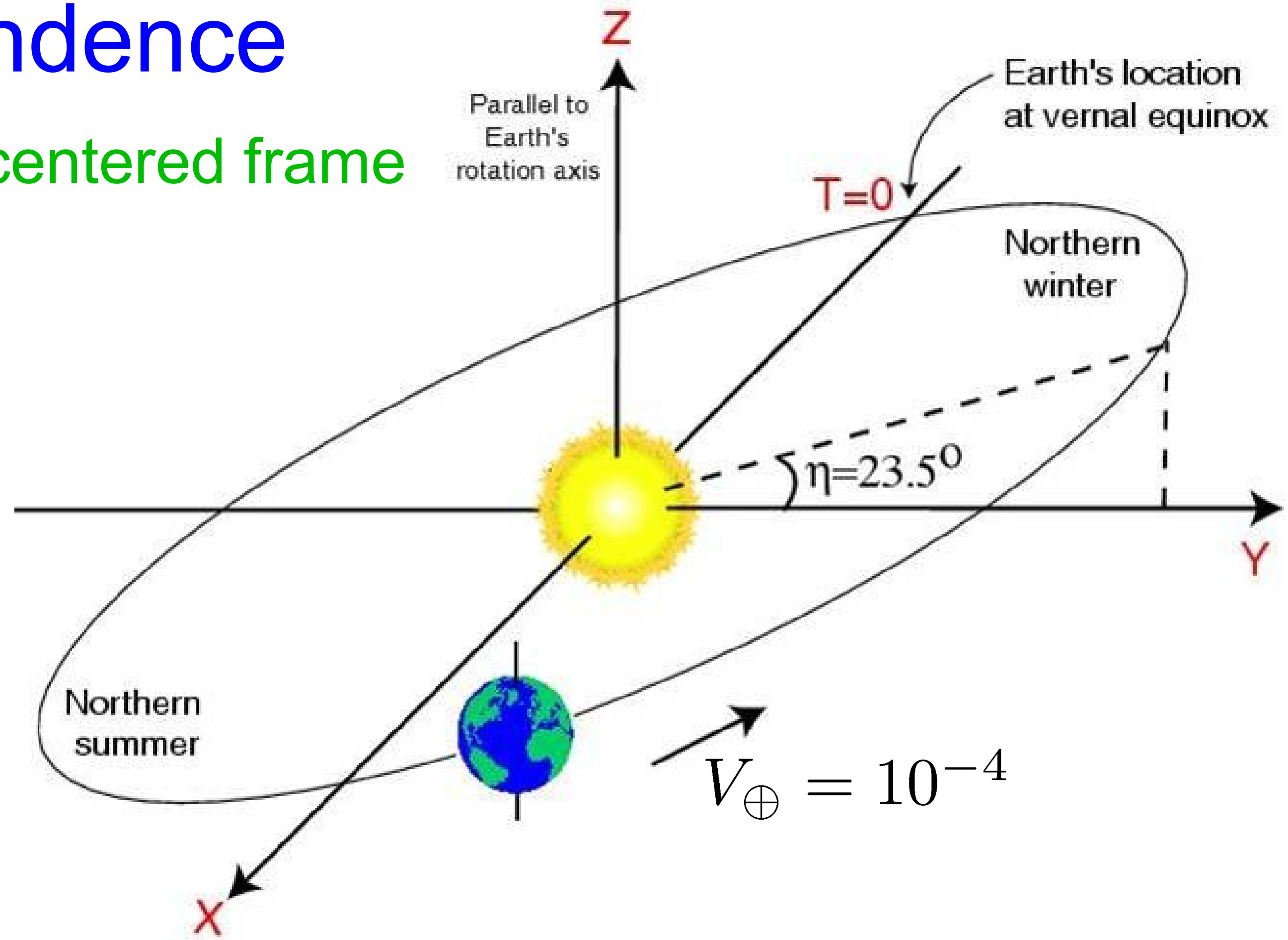
time dependence

- standard Sun-centered frame



- boost and rotation of test ⟶ annual & sidereal variations

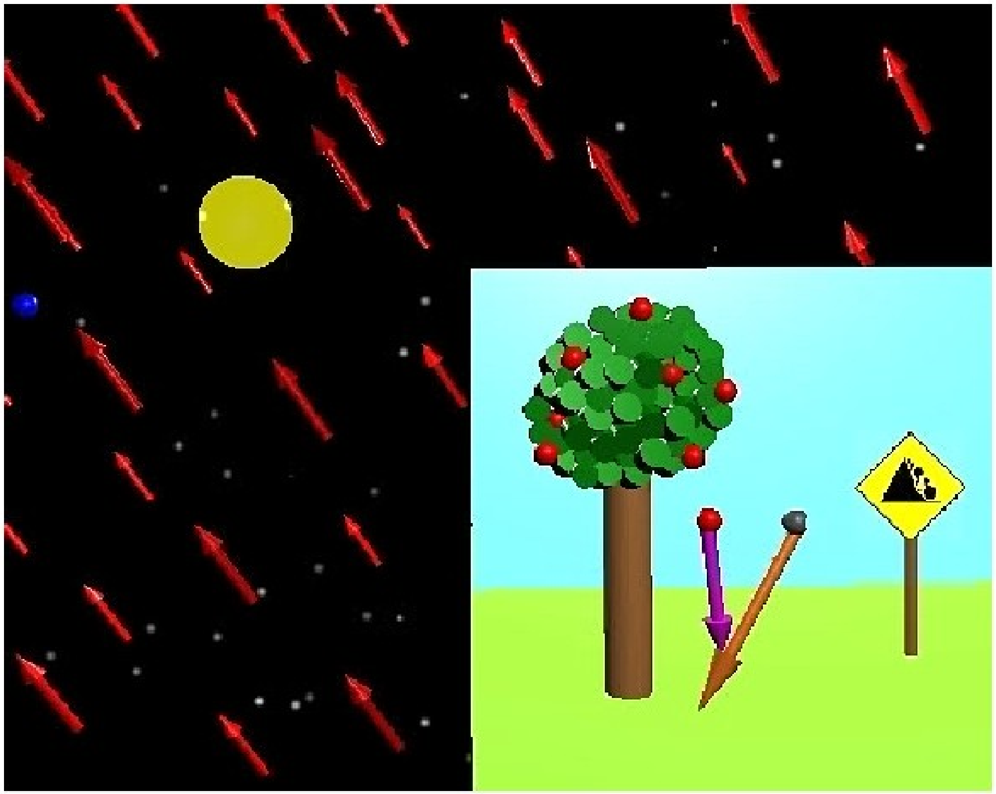
$$\ddot{\vec{x}} \supset -2g\ \alpha\bar{a}_T\hat{z} - 2gV_\oplus\ \alpha\bar{a}_X\sin(\Omega T)\hat{z} - \tfrac{2}{5}gV_L\ \alpha\bar{a}_X\sin(\omega T + \psi)\hat{y}$$

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

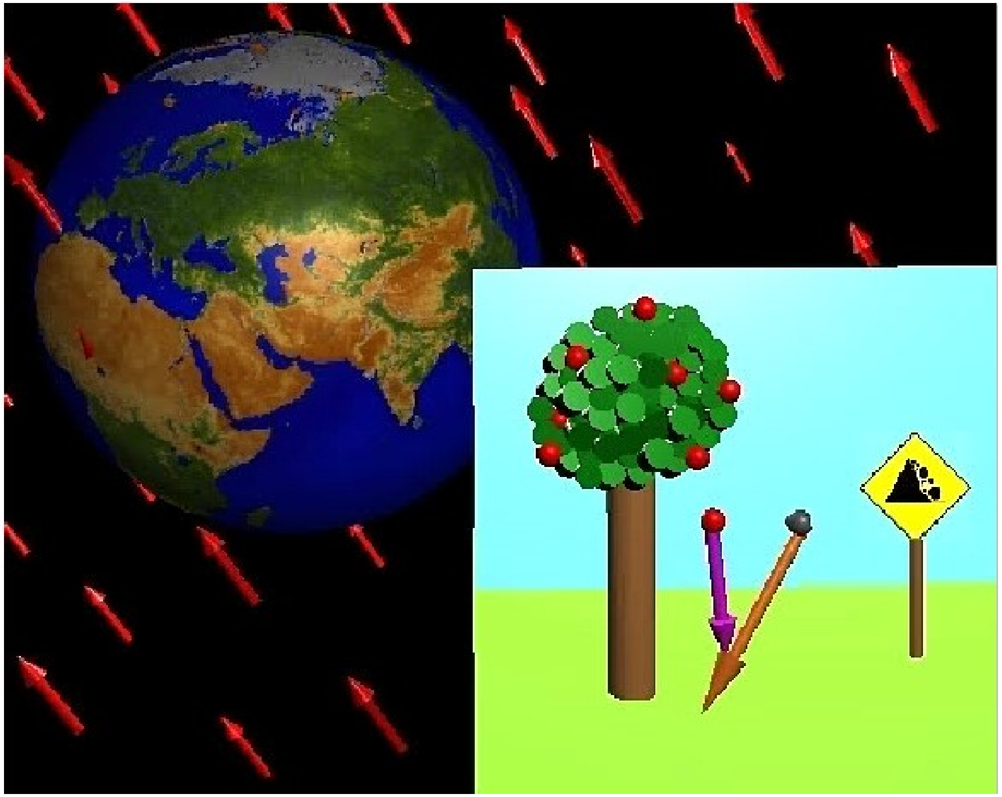
lab tests

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



unsuppressed in some tests having horizontal sensitivity

Kostelecký & Tasson PRD 2011

B. Free-fall gravimeter tests

In this subsection, we consider laboratory tests that monitor the motion of a test body in free fall near the surface of the Earth. The equation of motion for the

Kostelecký & Tasson PRD 2011

B. Free-fall gravimeter tests

In ...
moni...
surfa...

$$
\begin{aligned}
\mathrm{a}_{\hat{z}} &= -g + \omega^2 R_\oplus \sin^2\chi \\
&\quad + \sum_{n,w} g\Big[\Big(\frac{N^w}{m^{\mathrm{T}}} E_n^w + \frac{N_\oplus^w}{m^{\mathrm{S}}} E_n'^w + \tfrac{1}{3} E_n \Big) \cos(\omega_n T + \psi_n) \\
&\qquad + \Big(\frac{N^w}{m^{\mathrm{T}}} F_n^w + \frac{N_\oplus^w}{m^{\mathrm{S}}} F_n'^w + \tfrac{1}{3} F_n \Big) \sin(\omega_n T + \psi_n) \Big].
\end{aligned}
\tag{138}
$$

Kostelecký & Tasson PRD 2011

B. Free-fall gravimeter tests

In
moni
surfa

$$a_{\hat z} = -g + \omega^2 R_\oplus \sin^2\chi + \sum_{n,w} g\Big[\Big(\frac{N^w}{m^{\rm T}} E_n^w + \frac{N^w_\oplus}{m^{\rm S}} E_n^{\prime w} + \tfrac{1}{3} E_n\Big)\cos(\omega_n T + \psi_n)$$

Table IV. Amplitudes for the acceleration $a_{\hat z}$.

Amplitude	Phase
$E_0^w = -2\alpha(\overline{a}^w_{\rm eff})_T + 2m^w(\overline{c}^w)_{ZZ}\cos^2\chi + m^w\big((\overline{c}^w)_{XX} + (\overline{c}^w)_{YY}\big)\sin^2\chi$	0
$E_0^{\prime w} = -2\alpha(\overline{a}^w_{\rm eff})_T - m^w(\overline{c}^w)_{TT}$	0
$E_\omega^w = 2m^w(\overline{c}^w)_{(XZ)}\sin 2\chi - \frac{4}{5}V_L\alpha(\overline{a}^w_{\rm eff})_Y\sin\chi$	ψ
$E_\omega^{\prime w} = -\frac{4}{5}V_L\big(3\alpha(\overline{a}^w_{\rm eff})_Y + m^w(\overline{c}^w)_{(TY)}\big)\sin\chi$	ψ
$F_\omega^w = 2m^w(\overline{c}^w)_{(YZ)}\sin 2\chi + \frac{4}{5}V_L\alpha(\overline{a}^w_{\rm eff})_X\sin\chi$	ψ
$F_\omega^{\prime w} = \frac{4}{5}V_L\big(3\alpha(\overline{a}^w_{\rm eff})_X + m^w(\overline{c}^w)_{(TX)}\big)\sin\chi$	ψ

Kostelecký & Tasson PRD 2011

B. Free-fall gravimeter tests

In
moni
surfa

$$a_{\hat{z}} = -g + \omega^2 R_\oplus \sin^2 \chi + \sum_{n,w} g \Big[\Big(\frac{N^w}{m^{\mathrm{T}}} E_n^w + \frac{N_\oplus^w}{m^{\mathrm{S}}} E_n^{\prime w} + \tfrac{1}{3} E_n \Big) \cos(\omega_n T + \psi_n)$$

Table IV. Amplitudes for the acceleration $a_{\hat{z}}$.

Amplitude	Phase
$E_n^w = -2\alpha(\overline{a}^w_{\mathrm{eff}})_T + 2m^w(\overline{c}^w)_{ZZ}\cos^2\chi$	
$F_\omega^{\prime w} = \frac{4}{5} V_L \left(3\alpha(\overline{a}^w_{\mathrm{eff}})_X + m^w(\overline{c}^w)_{(TX)}\right) \sin\chi$	ψ

improvement potential via atom interferometry:

- max reach 4 to 6 orders of magnitude improvement
- special linear combinations 10 orders of magnitude improvement

Dimopoulos et al. PRD 2008

Kostelecký & Tasson PRD 2011

D. Free-fall WEP tests

In thi[s] signals f[o] the relat[...]

E. Force-comparison WEP tests

Typical force-comparison WEP tests can be viewed as comparing the motion of two or more bodies joined through electromagnetic forces with that predicted by

signals are qualitatively distinct from other sources of WEP violation due to characteristic periodicity

improvement potential:

- max reach 4 to 6 orders
- special combinations 10 orders

WEP tests considered

atom interferometry
torsion pendulum
drop tower
balloon drop
tossed masses

...and any WEP test can be used

experiments

- Earth-source lab tests
  - gravimeter
    Chung et al. PRD '09
    Mueller et al. PRL '08
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  Shao arXiv:1412.2320

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

experiments

- Earth-source lab tests
  - gravimeter

  Chung et al. PRD '09
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  - null redshift
  - comagnetometers
- short-range gravity

  Long Kostelecký arXiv:1412:6362
  Panjwani Carbone Speake in CPT'10
- gravity probe B

  Bailey Everett Overduin PRD '13
- pulsar tests

  Shao PRL '14
  Shao arXiv:1412.2320

short range

$$U(r) = G_N \int d^3r' \frac{\rho(\vec{r}')}{|\vec{r}-\vec{r}'|}\left(1 + \frac{\bar{k}(\hat{R})}{|\vec{r}-\vec{r}'|^2}\right)$$

anisotropic combination of dim 6 coefficients

Time & orientation dependence $\Rightarrow$

- qualitatively different from other 1/r deviations
- sensitivities require data analysis
- crude estimate of reach for given experiment

$$U_{\rm Yukawa} = G_N M (1 + \alpha e^{-r/\lambda})/r \;\Rightarrow\; |\bar{k}(\hat{r}, T)| \approx \alpha\lambda^2/e$$

improvement:

- first dimension 6 sensitivities via Indiana cantilever experiment 10^{-9} m^2 Long Kostelecký arXiv:1412:6362
- additional experiments offer improved sensitivity & additional coefficients

Bailey Kostelecký Xu arXiv:1410.6162

experiments

- Earth-source lab tests
  - gravimeter

  Chung et al. PRD '09
  Mueller et al. PRL '08
  - WEP

  Hohensee Mueller Wiringa PRL '13
  Hohensee et al. PRL '11
- space-based WEP
- exotic tests
  - charged matter
  - antimatter
  - higher-generation matter
- solar-system tests
  - laser ranging

  Battat Chandler Stubbs PRL '07
  - perihelion precession
- light-travel tests
  - time delay
  - Doppler shift
  - red shift
- clock tests
  - null redshift
  - comagnetometers
- short-range gravity

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pulsars

- minimal gravity sector implies $\overline{s}^{\mu\nu}$ effects on orbits and timing[1]

- constraints on $\overline{s}^{\mu\nu}$ coefficients achieved using observations of[2]:

B1937+21, J1744−1134, B1913+16, B1534+12, J0737−3039A, B2127+11C, J1738+0333, J1012+5307, J0348+0432, J1802−2124, J0437−4715, B1855+09, J1909−3744

- "The null detection of any beyond-GR effects in binary pulsars constrains LV orbital dynamics."

improvement:

- first consideration of strong gravity
- several orders of magnitude improvement
- further improvement via direct fit to SME, observation improvements, & additional SME phenomenology

1. Bailey Kostelecký PRD '06 2. Shao PRL '14

Summary

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

- The SME provides a field-theory based test framework

- Lorentz violation introduces qualitatively new signals in experiments

- Much work has been done but much remains unexplored