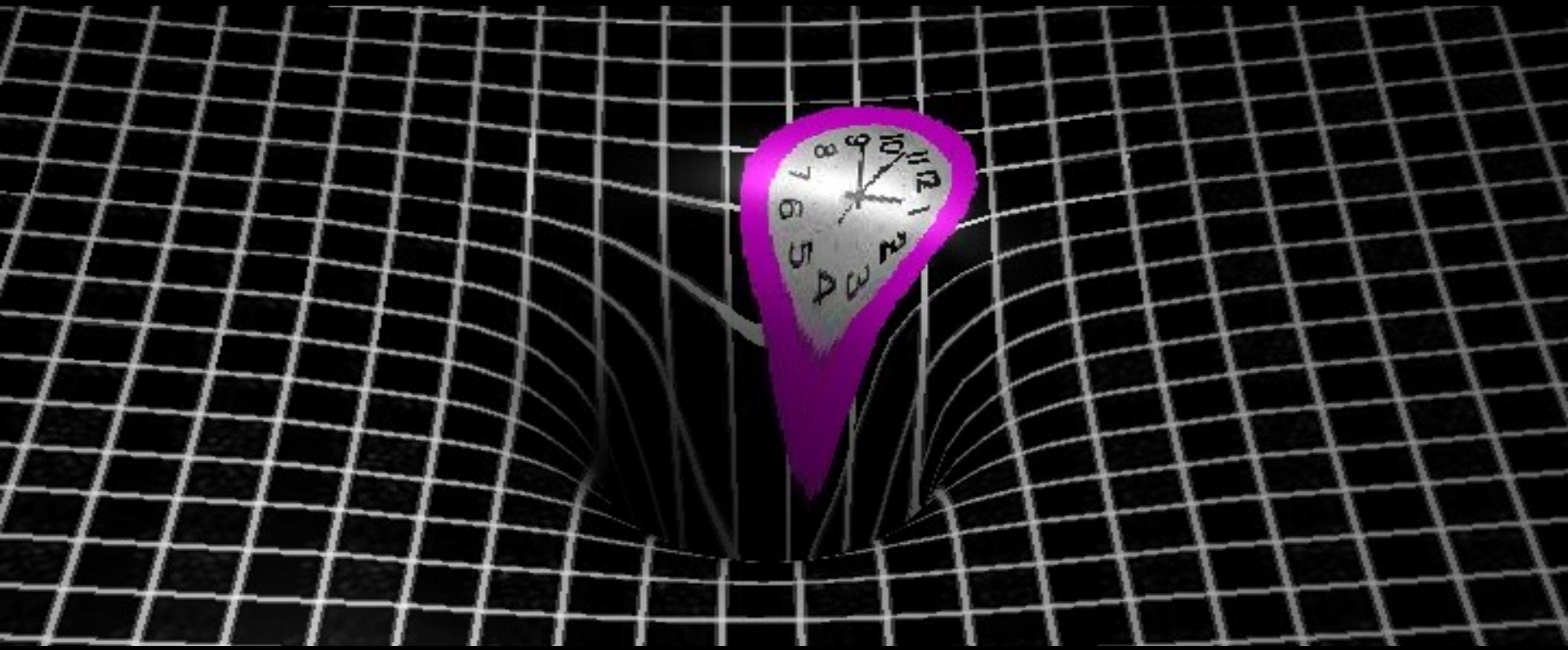
Antimatter-Gravity Couplings, and Lorentz Symmetry



Jay D. Tasson

Carleton College

outline

- antimatter gravity
  - motivation
  - constraints
- CPT and Lorentz violation
  - background
  - trapped antiparticles & spectroscopy
  - gravity

motivation—why gravity with antimatter?

- Physics requires experimental confirmation, even if there were no reasonable doubt .... but theory helps too!

- General Relativity and the Standard Model are inconsistent

- Consistent models exist that provide a different gravitational response for matter and antimatter. (look at SME-based one later[1])

1) Kostelecký, JT, PRD ‘11

constraints - CPT

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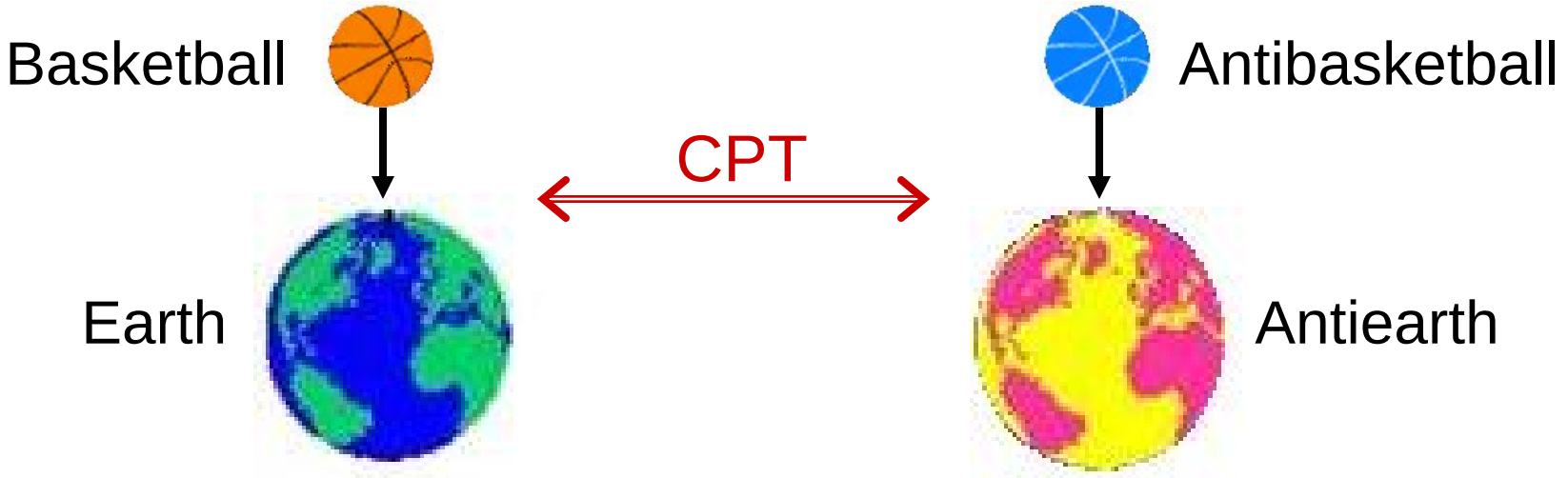
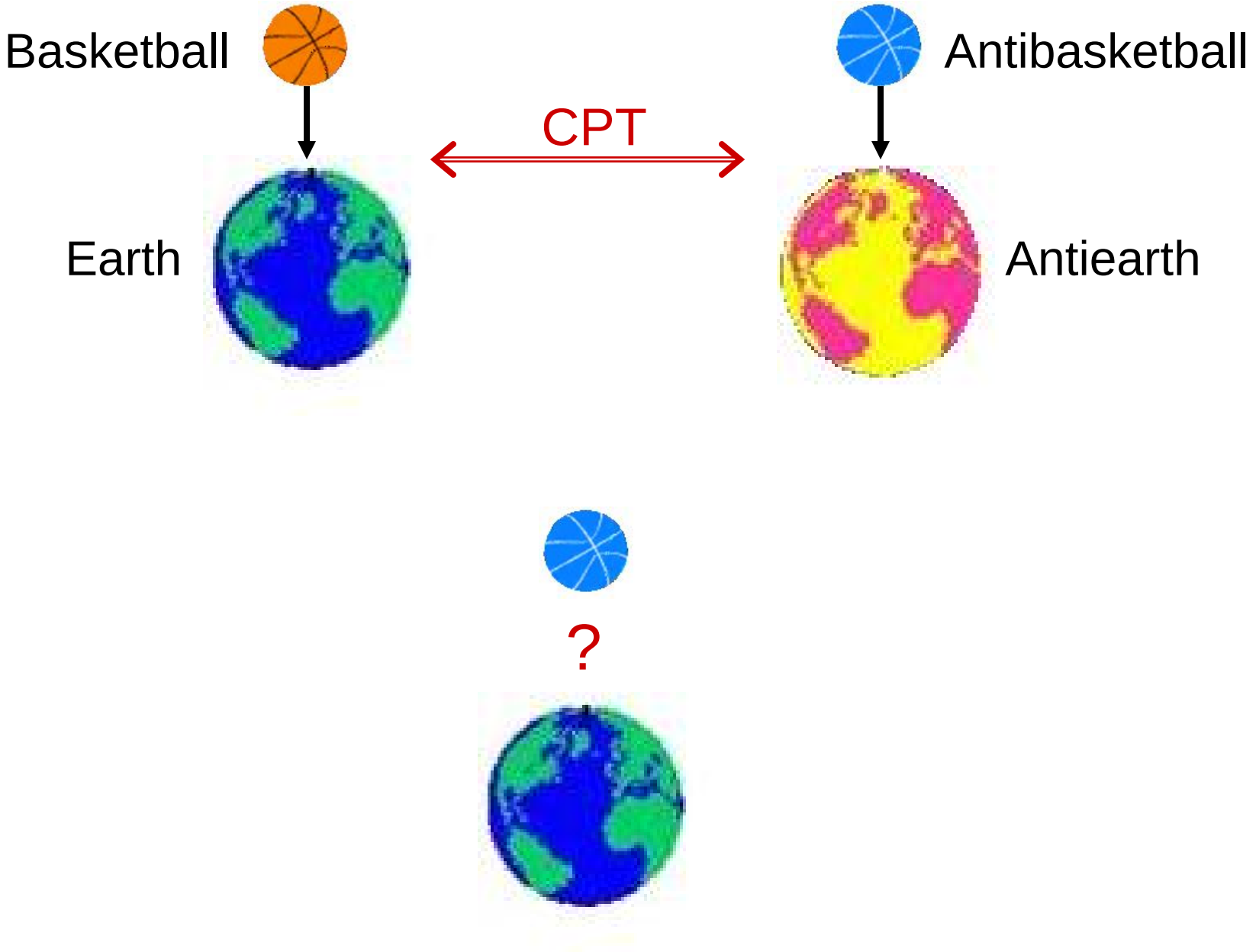


constraints - CPT



constraints

- particle antiparticle pair vs. photon

$$E = 2m$$

h

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

Morrison, Am. J. Phys. ’58

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concern

- energy conservation

Morrison, Am. J. Phys. ’58

constraints

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

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

While experimental and theoretical constraints exist,

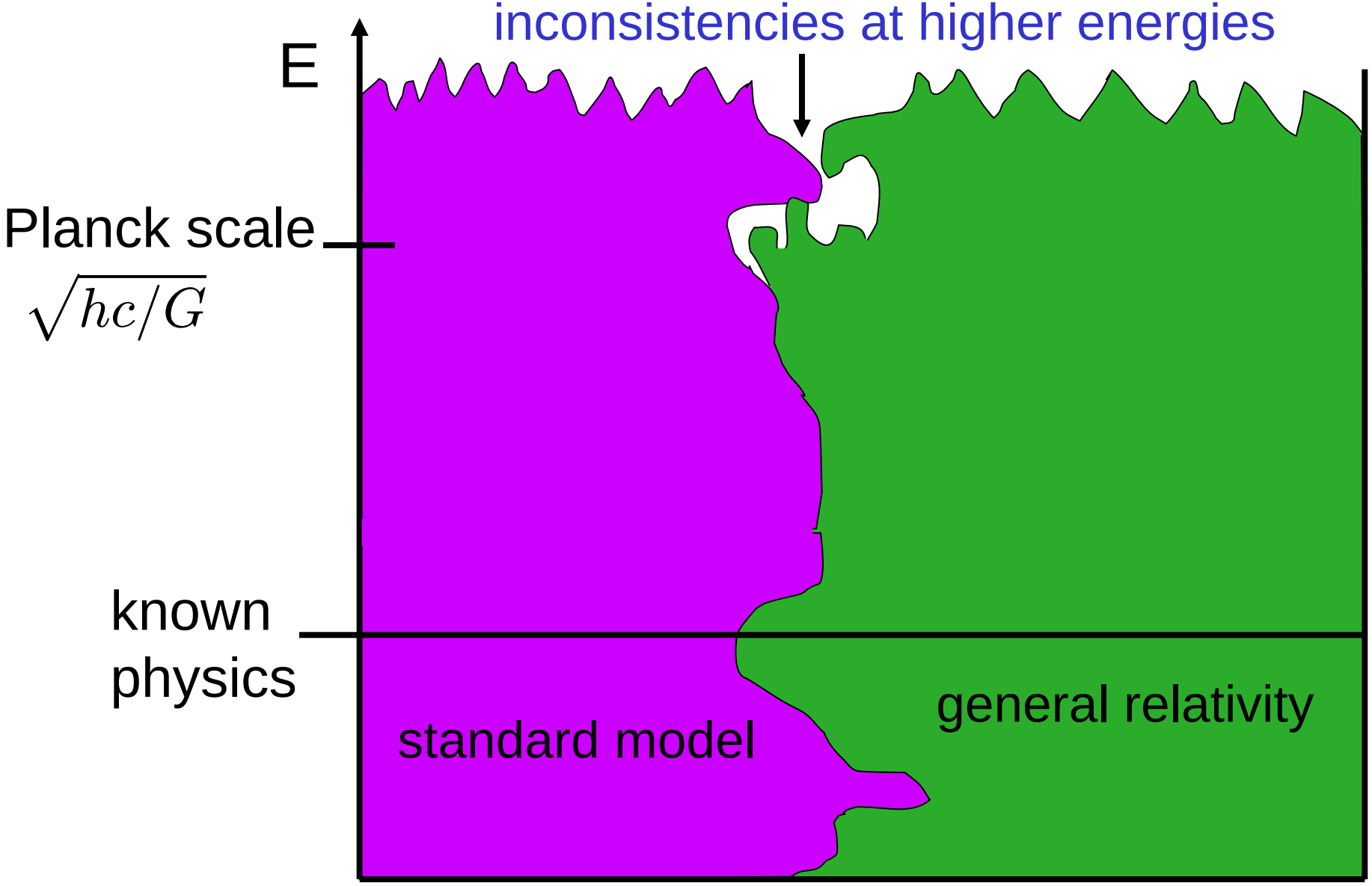
it appears that it is not possible to rule out

the anomalous response of antimatter to gravity.

Impressive direct tests in progress!

SME-based toy model evades the usual constraints

motivation – CPT & Lorentz tests



underlying theory at Planck scale

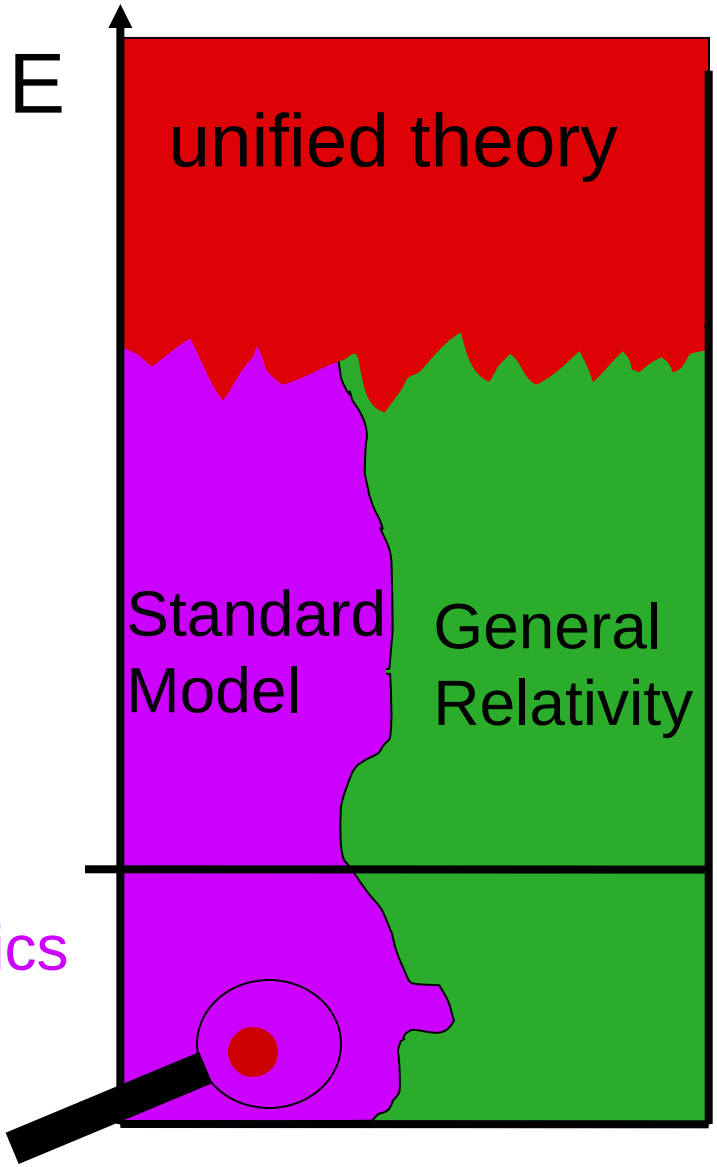
options for probing experimentally

- 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

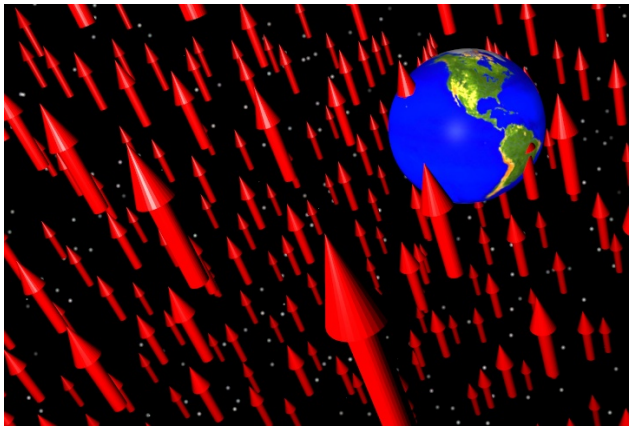
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L_{\mathrm{LV}}$$

- CPT violation comes with Lorentz violation

CPT & Lorentz-violating terms

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

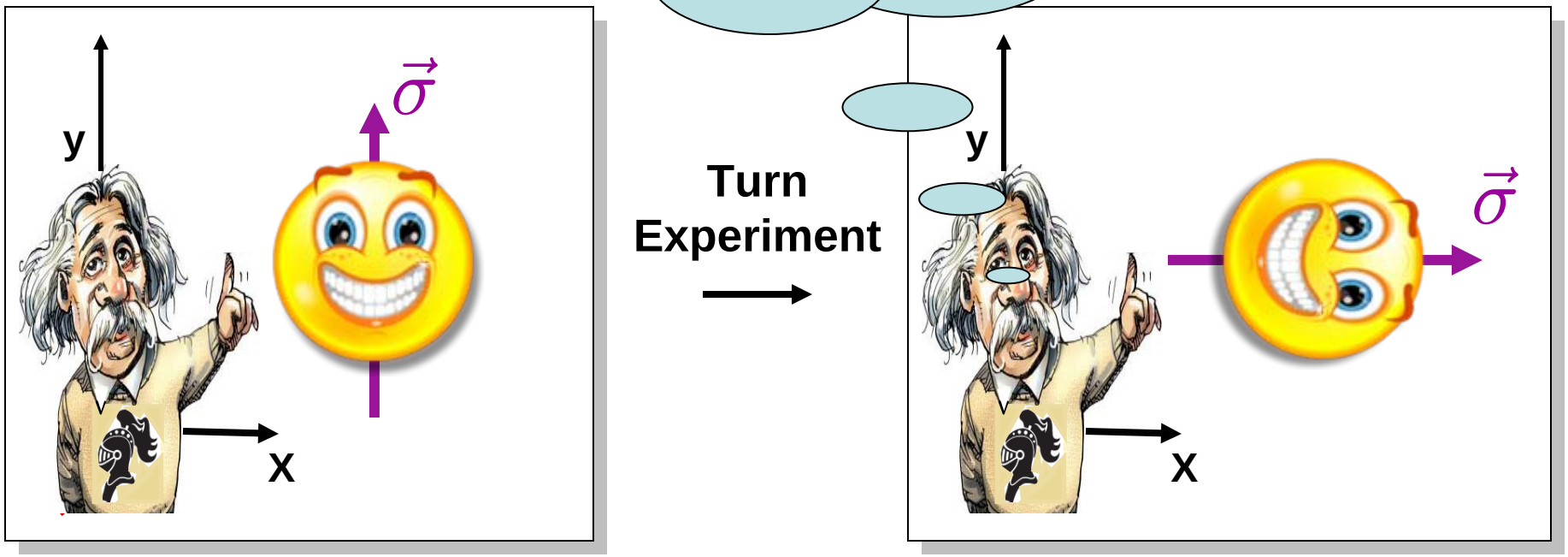
$$s^{\mu\nu} R_{\mu\nu} \qquad \bar{\psi} a_\mu \gamma^\mu \psi$$



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

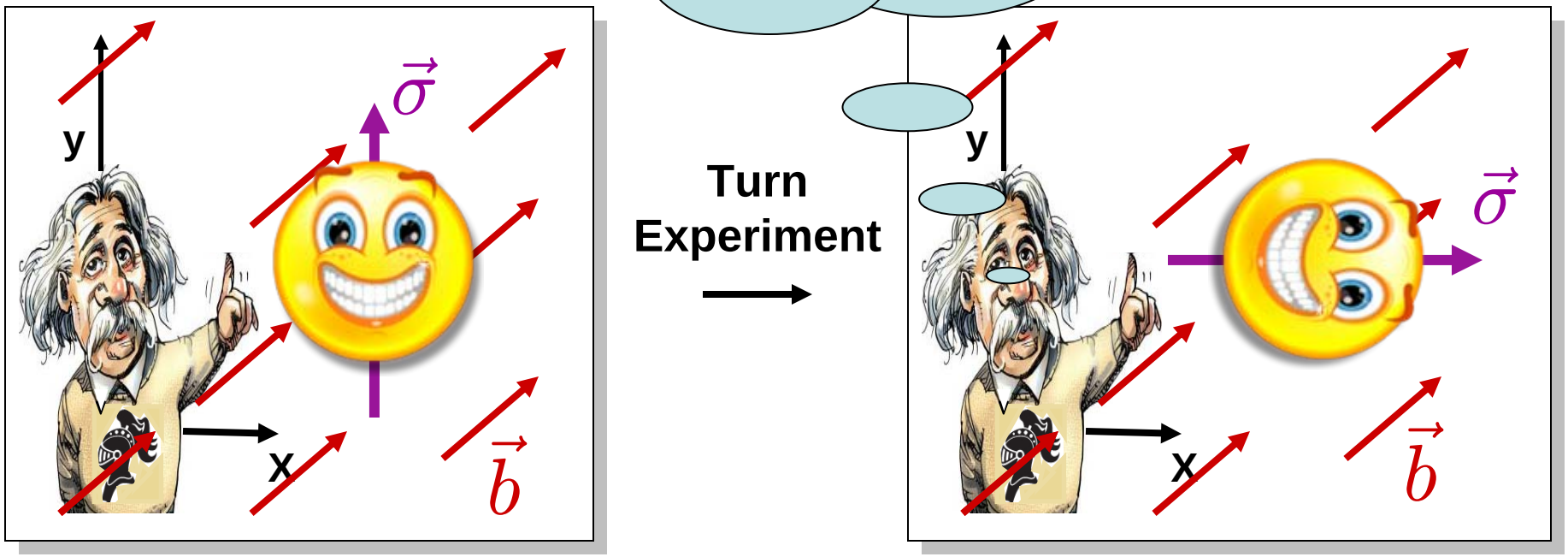
What is relativity violation?

If I turn my head, it's clear that nothing has changed and relativity is preserved.



What is relativity violation?

I can't fix this by rotating my coordinates. Relativity is violated



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

tests

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

- SME
  - predictive
  - quantitative comparisons

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
- .....

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- only ~1/2 of lowest order couplings explored

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- .....

antimatter efforts

$$L_{\rm LV} = L_{\rm pure\,gravity} + L_{\rm photon} + L_{\rm fermion} + \dots$$

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

- 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

periodic energy level perturbations

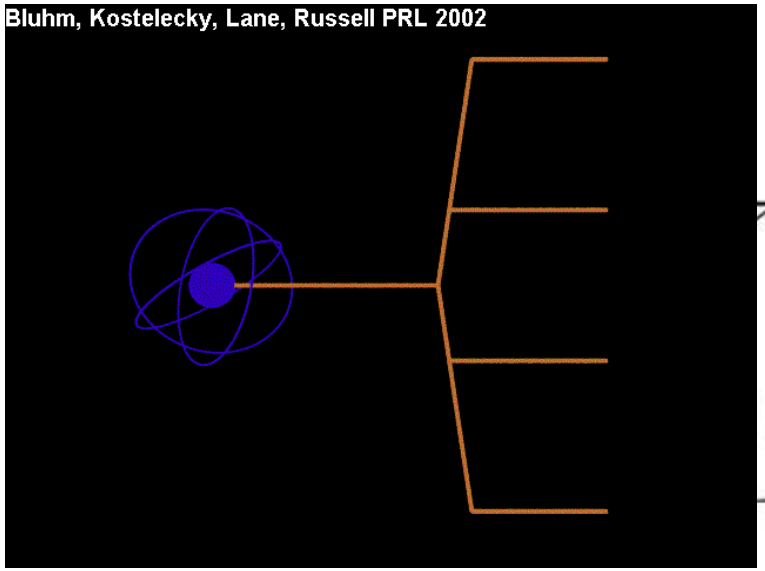
$$< F, m_F | H_{\rm nonrel} | F, m_F >= \ldots + \frac{m_F}{F} \sin\chi \sum_w \beta_w b_Y^w \sin\omega t + \ldots$$

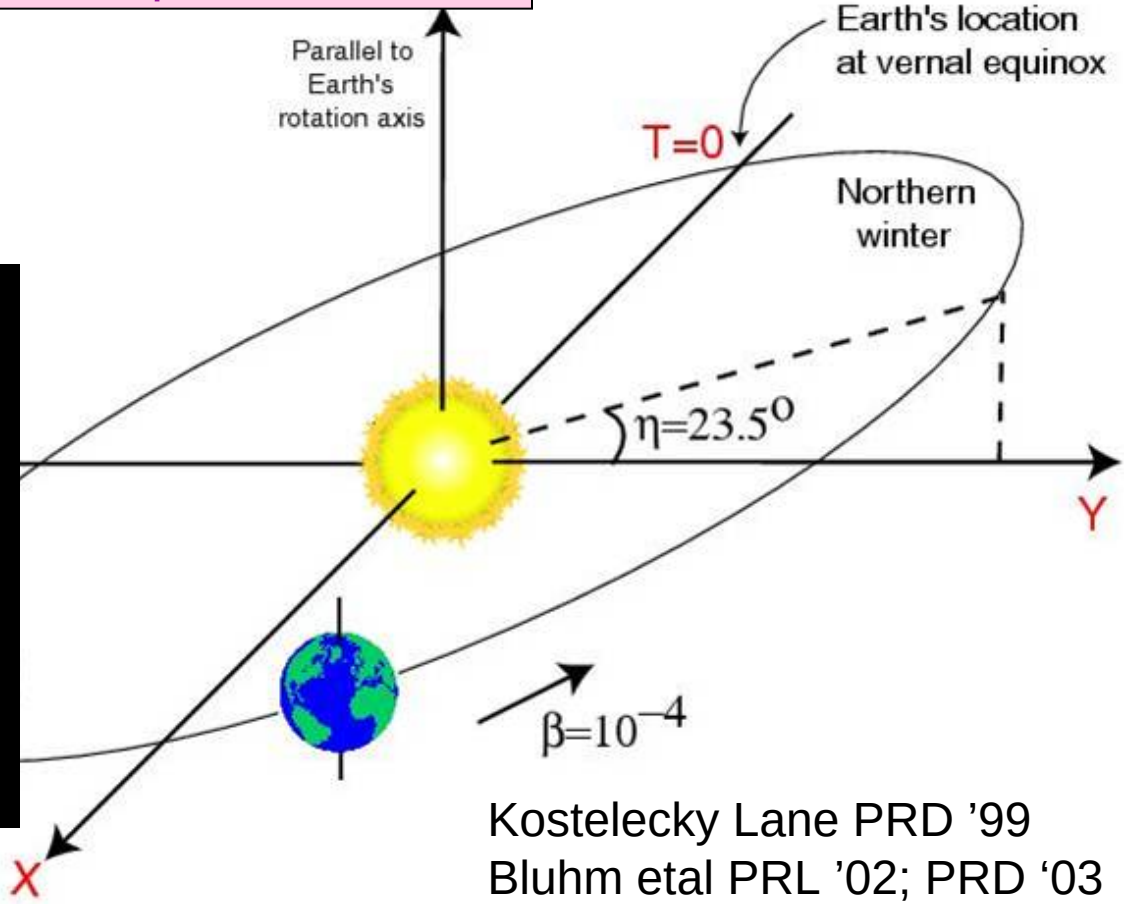
total angular momentum

$$\beta_w := -\sum_{N=1}^{N_w} \langle [\sigma^3]_{w,N} \rangle$$

sum over N particles of species w

rotation frequency





Kostelecky Lane PRD '99
Bluhm etal PRL '02; PRD '03

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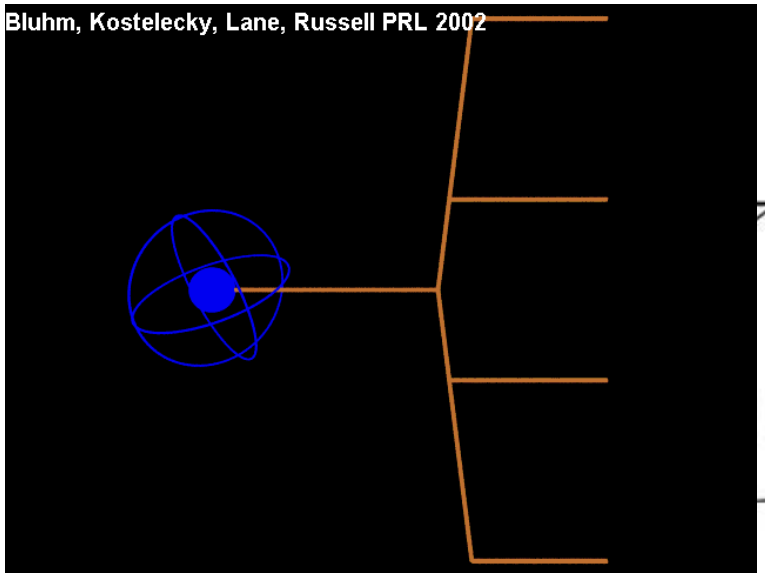

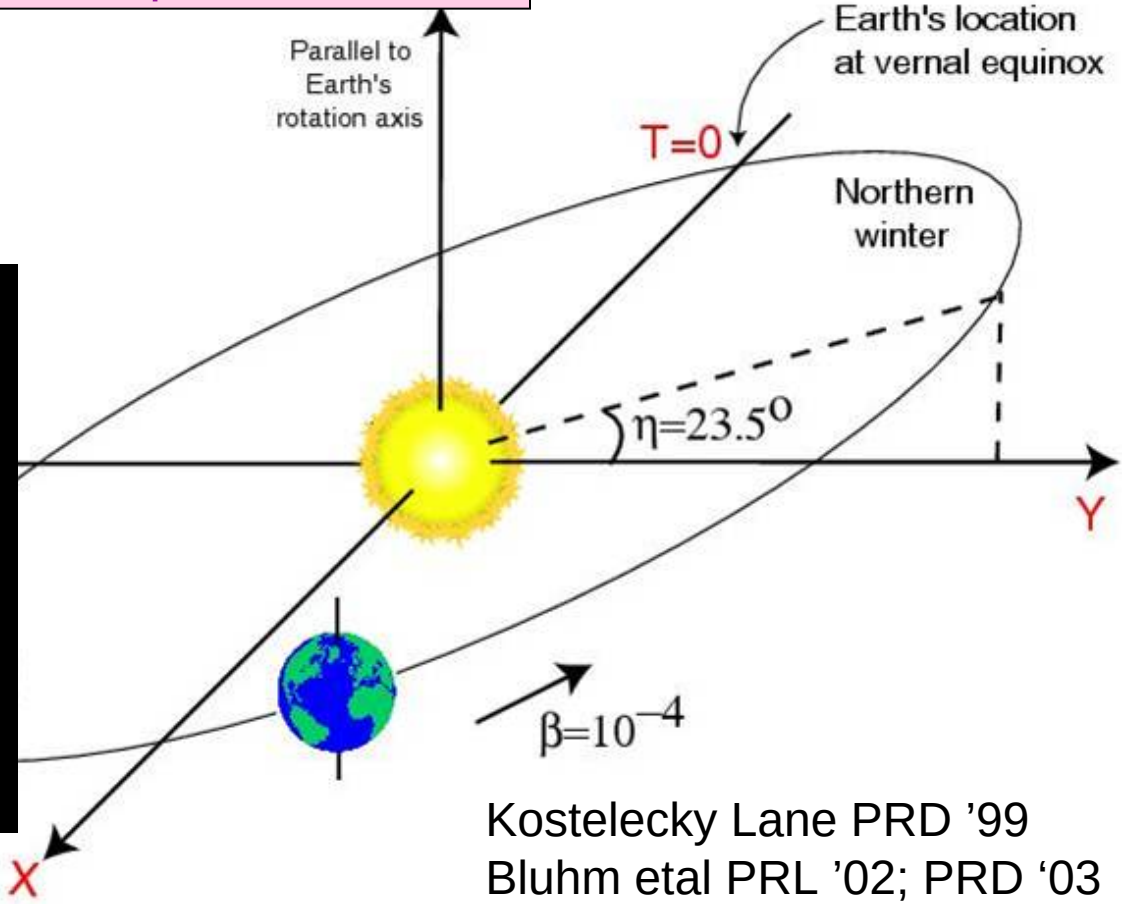

Kostelecky Lane PRD '99
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SME lagrangian with gravity[1]

$$L_{\rm SME} = L_{\rm fermion} + L_{\rm gravity} + \dots$$

Kostelecký, JT, PRD '11

Bailey, Kostelecký, PRD '06

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

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

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

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

S and T denote
composite coefficients
for source and test respectively

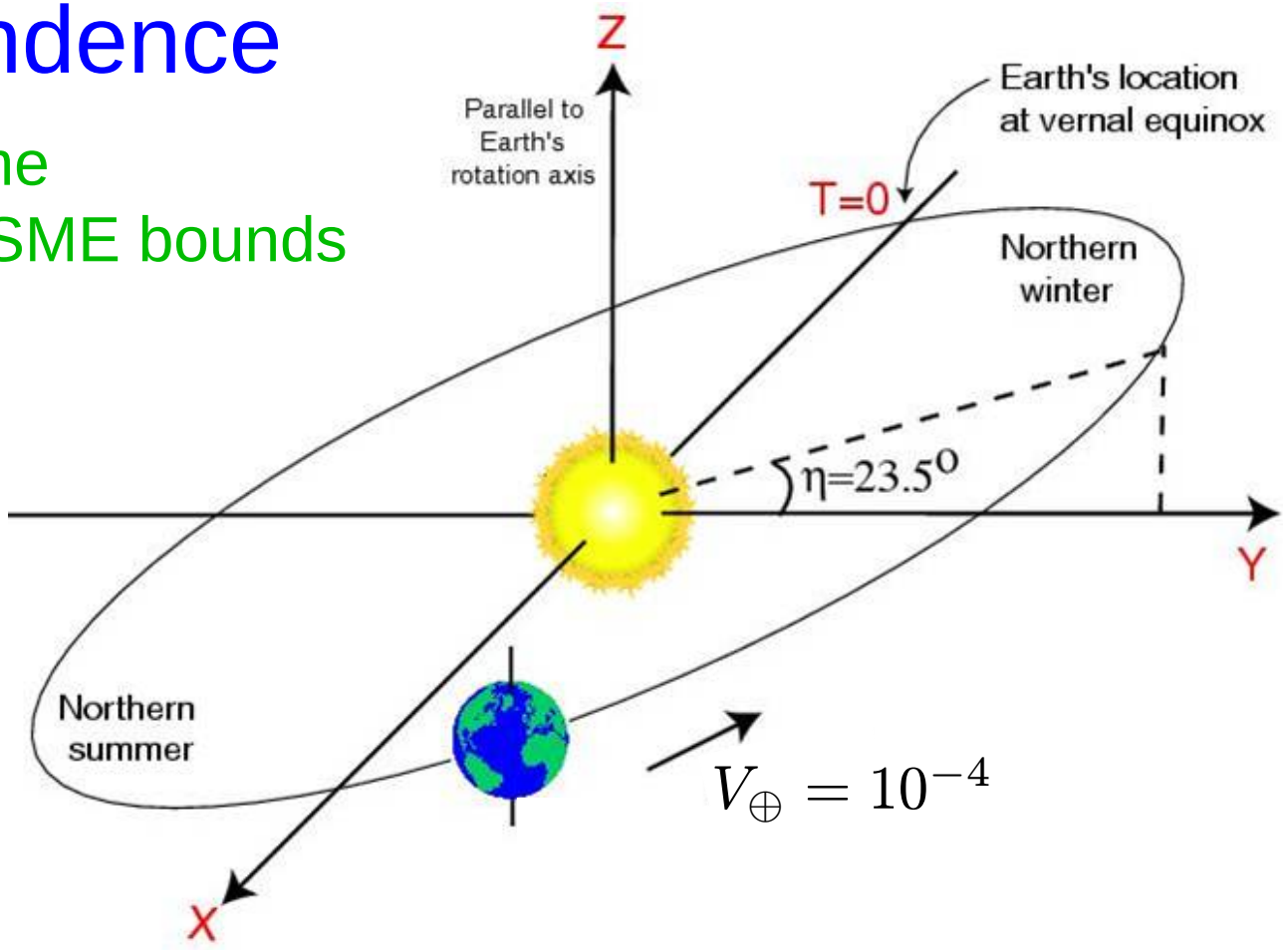
$$(a_{\rm eff})_\mu = a_\mu - me_\mu$$

experimental hooks

- particle-species dependence
- time dependence

time dependence

- standard frame
  for reporting SME bounds



- boost and rotation of test ⟶ annual & sidereal variations

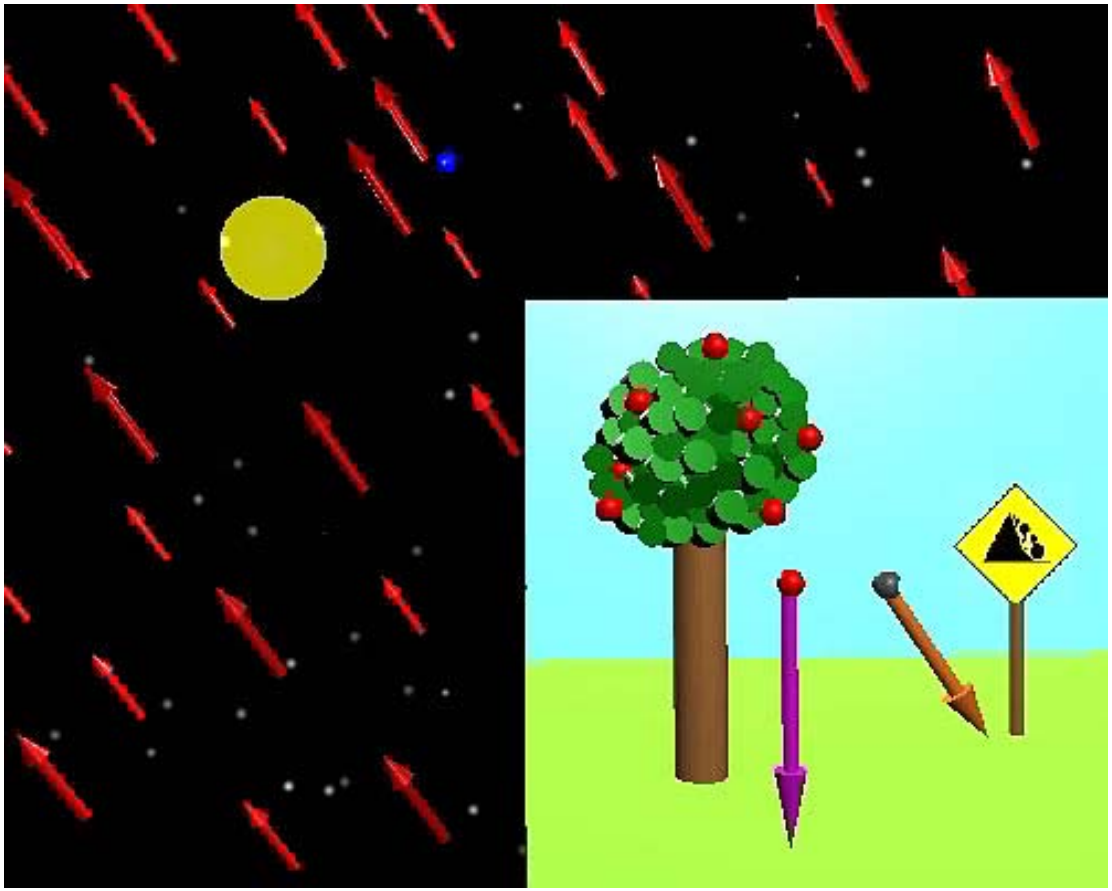
$$\ddot{\vec{x}} \supset -2g\ \alpha\overline{a}_T\hat{z} - 2gV_\oplus\ \alpha\overline{a}_X\sin(\Omega T)\hat{z} - \tfrac{2}{5}gV_L\ \alpha\overline{a}_X\sin(\omega T+\psi)\hat{y}$$

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

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

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

  - differing gravitational response for matter and antimatter

a toy model for antimatter gravity

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

- Isotropic 'Parachute' Model (IPM) Kostelecký, Tasson PRD '11

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

Matter

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

Antimatter

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

How large could the anomalous acceleration be?

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

~~Parachuting Fried-Antichicken Model~~

- ~~Isotropic 'Parachute' Model~~

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

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constraints?

- particle antiparticle pair vs. photon

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

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concern

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Morrison, Am. J. Phys. ’58

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IPM – nonissue

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

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constraints

- vacuum polarization, binding energy, and equivalence-principle tests
  - atomic masses are composed of:
    - leptons
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    in varying amounts from atom to atom
  - place limits on anomalous gravitational response of antimatter using limits from conventional EP tests

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IPM
- binding forces are largely conventional
- anomalous gravitational effects

associated with flavor content

constraints?

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

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

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

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

potentially hidden effects
- 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 antimater gravity

Ordinary matter constraints

- double boost suppressed effects

Bottom line?

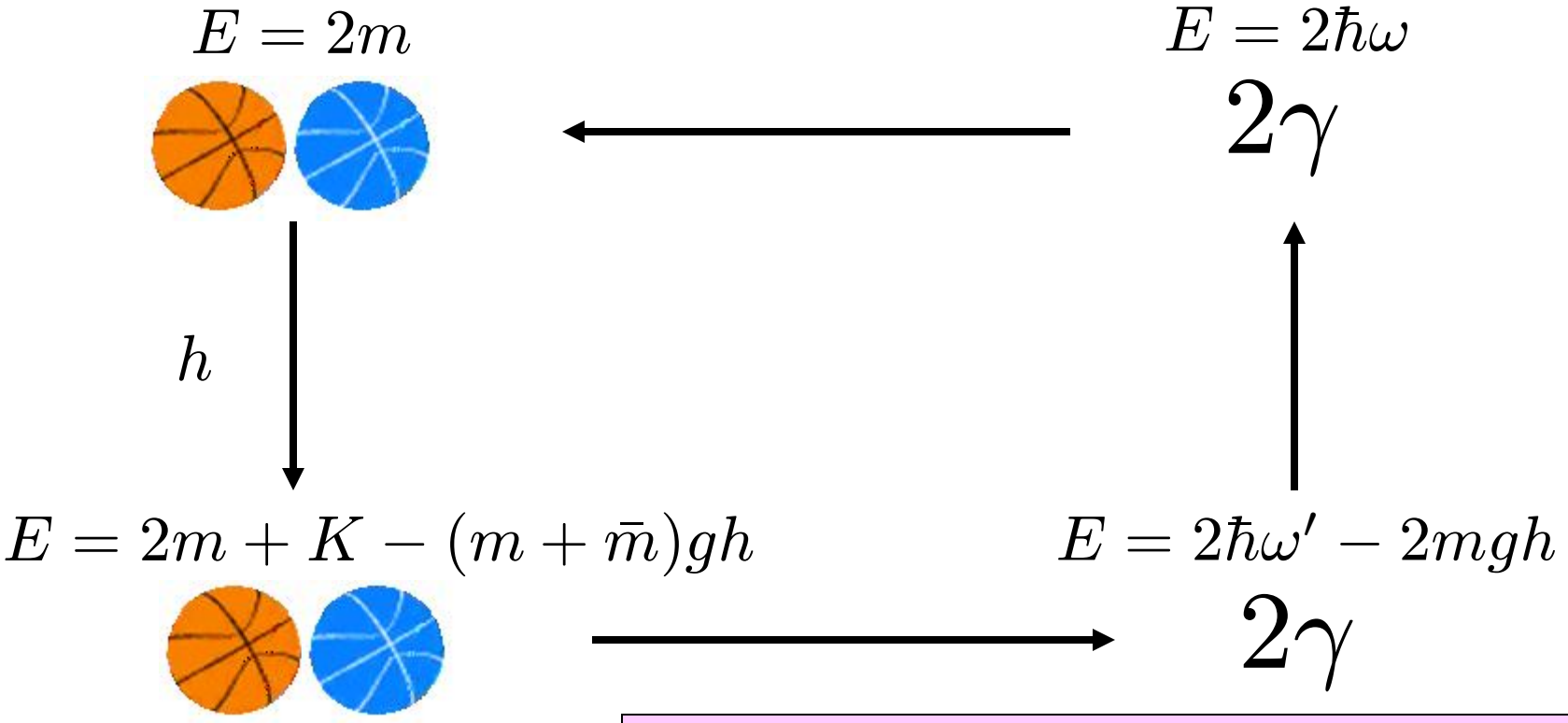
- the IPM is an interesting toy model that highlights interesting features of antimatter gravity constraints
- higher order SME terms???

Summary

- Antimatter tests offer new opportunities to test ‘known’ physics
- Indirect constraints on antimatter gravity exist in some cases
- 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
- tests with antimatter may provide access to coefficients that are challenging to measure in conventional tests

constraints?

- particle antiparticle pair vs. photon



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