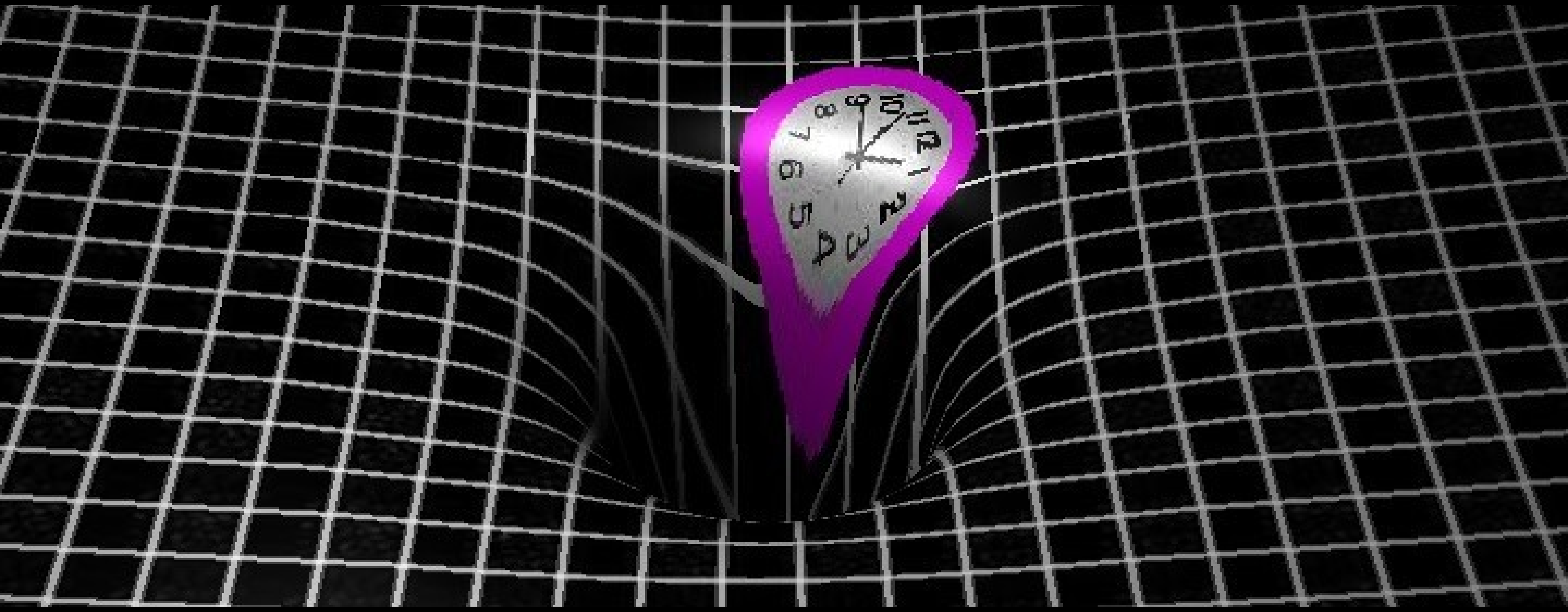
Testing Lorentz Symmetry with MICROSCOPE



Jay D. Tasson

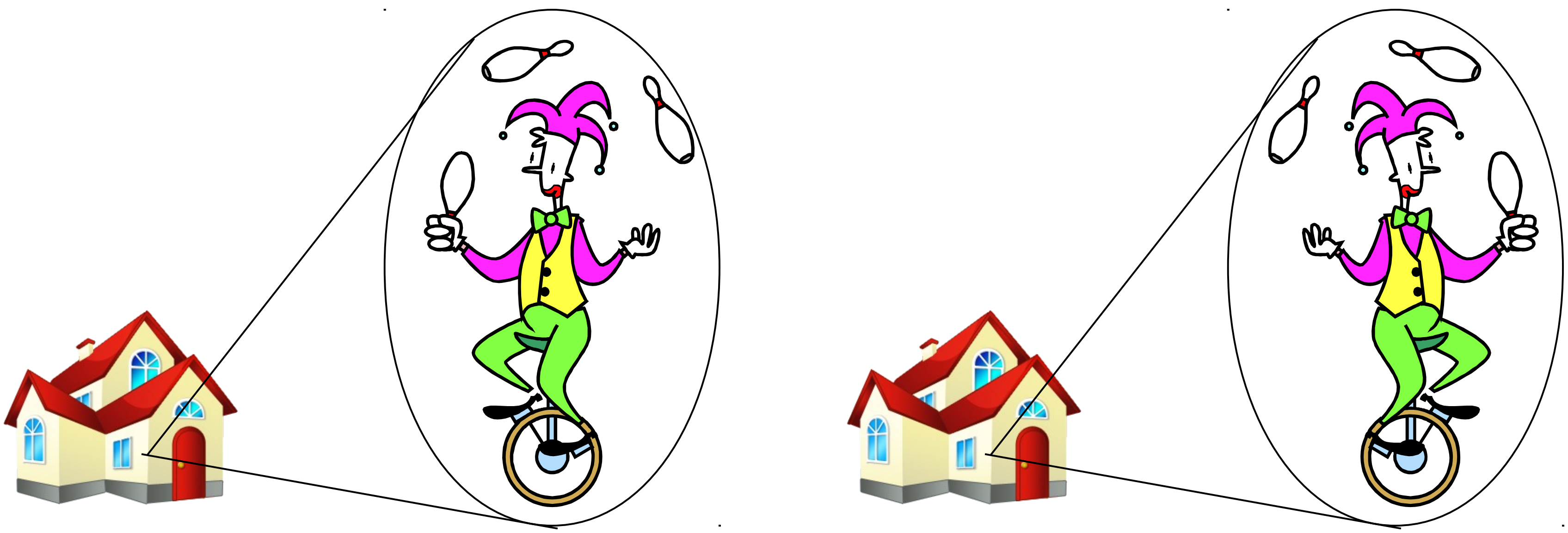
St. Olaf College

outline

- what is Lorentz violation?
- what is the Standard-Model Extension (SME)?
- gravitational Lorentz violation
- signals in MICROSCOPE data

What is Lorentz symmetry?

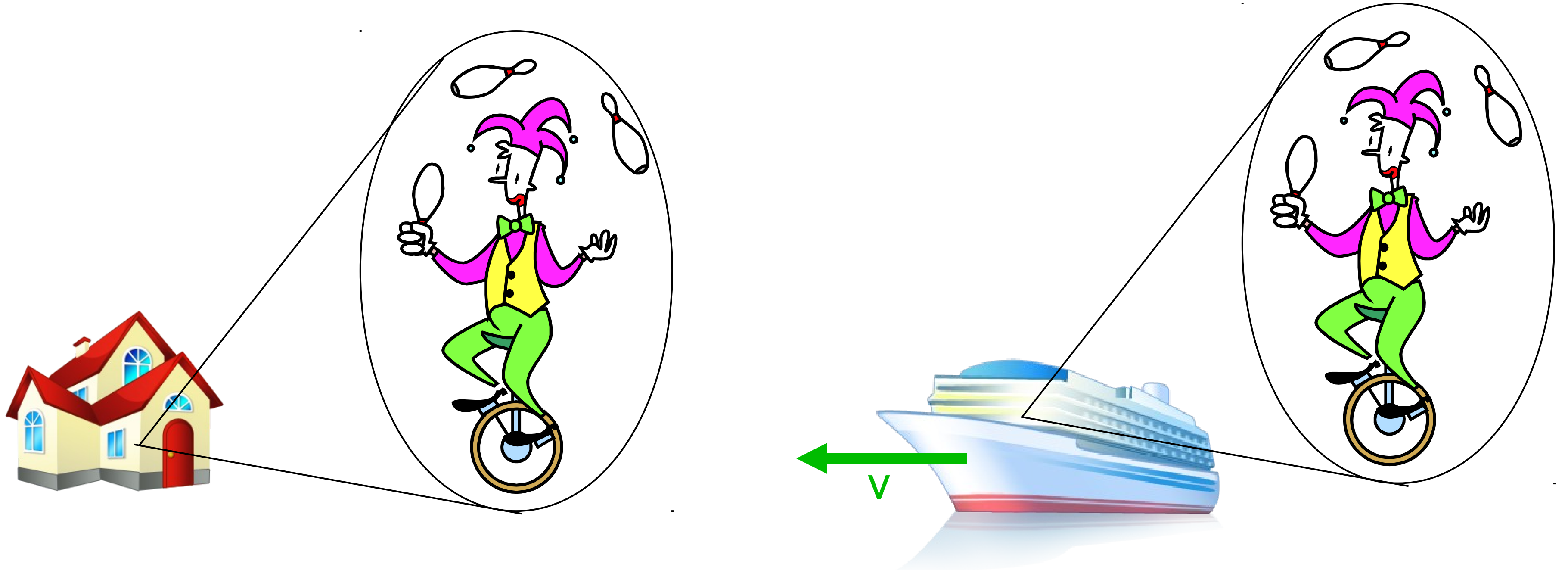
- physical results are independent of the velocity of the experiment and the ***direction*** it points



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

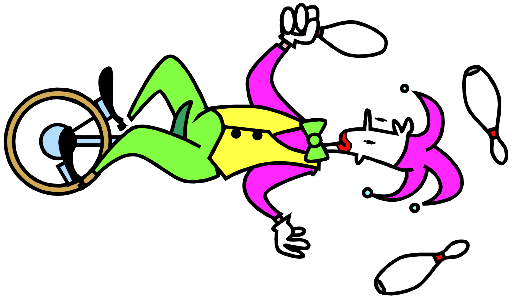
What is Lorentz symmetry?

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



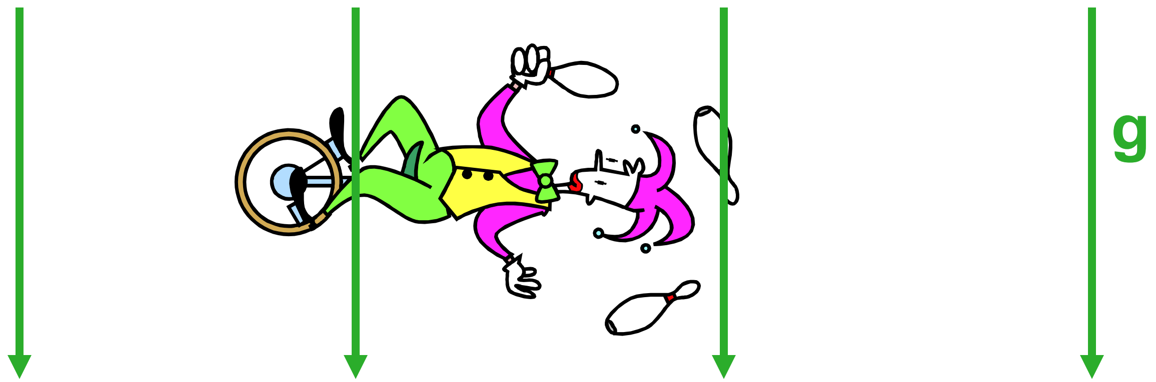
- juggling on ship moving at constant velocity without rocking still works
- boost invariance – results are independent of the constant velocity of the experiment

What does Lorentz violation look like?



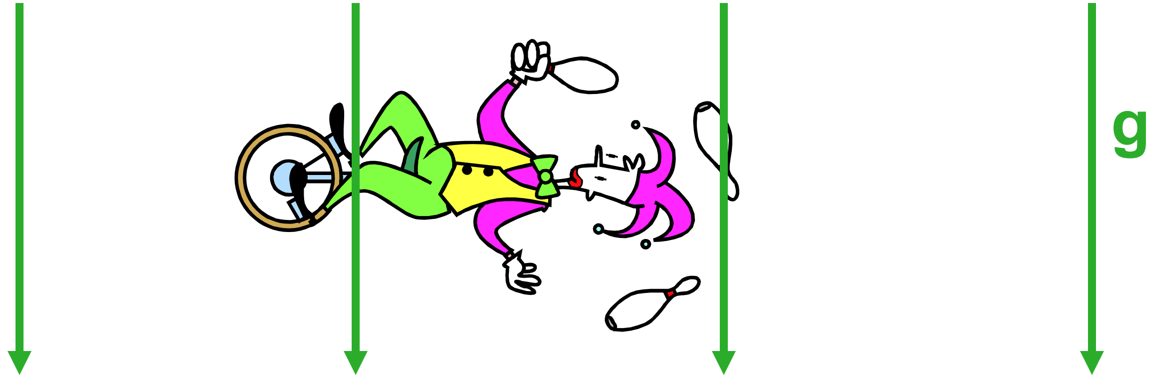
- juggling while lying on your back is different

What does Lorentz violation look like?



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

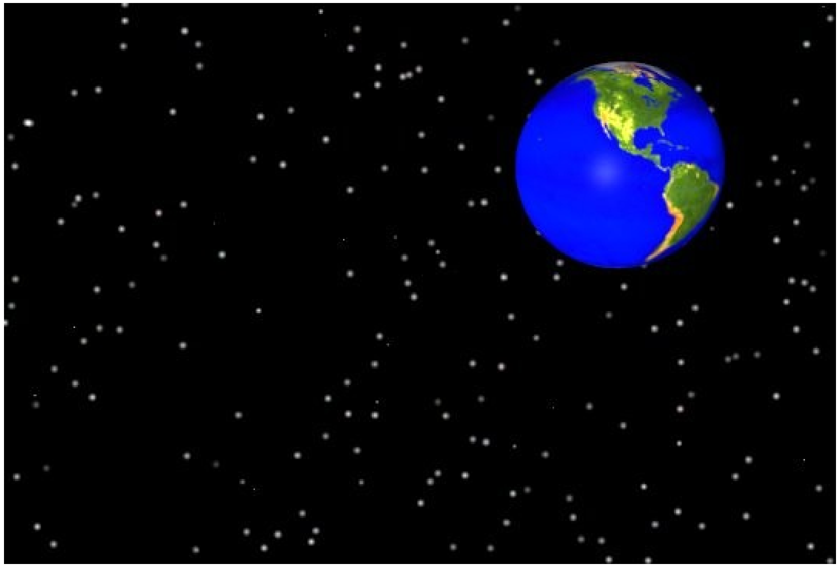
What does Lorentz violation look like?



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

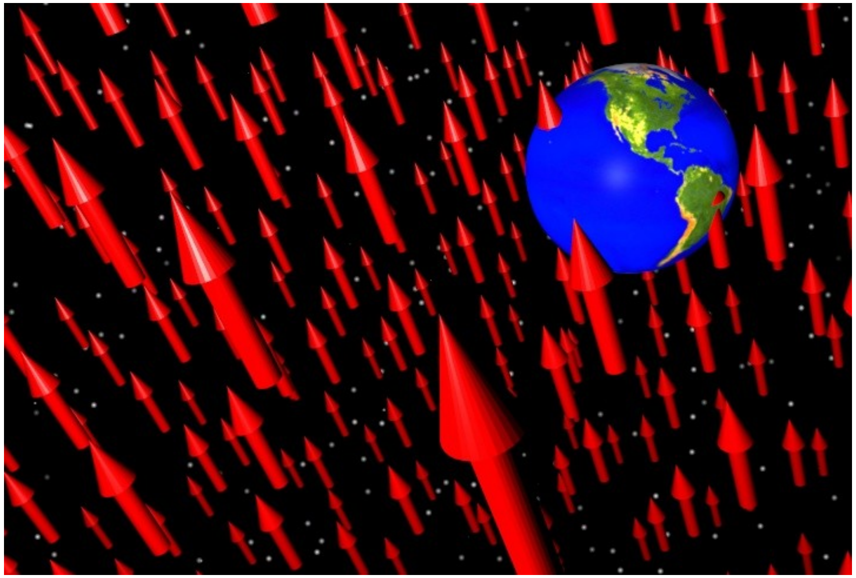
fundamental Lorentz violation

- relativity

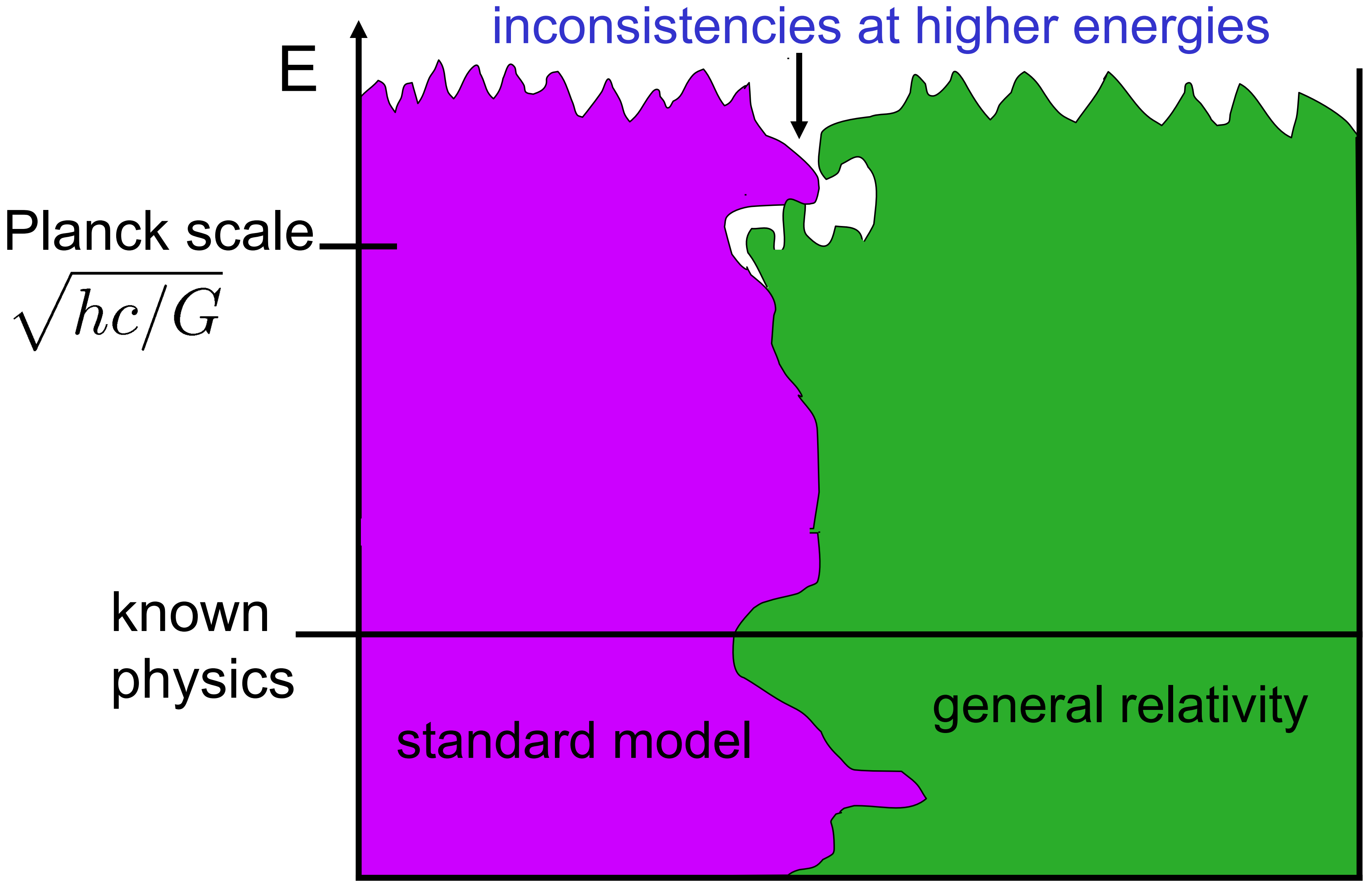


- relativity violation

(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

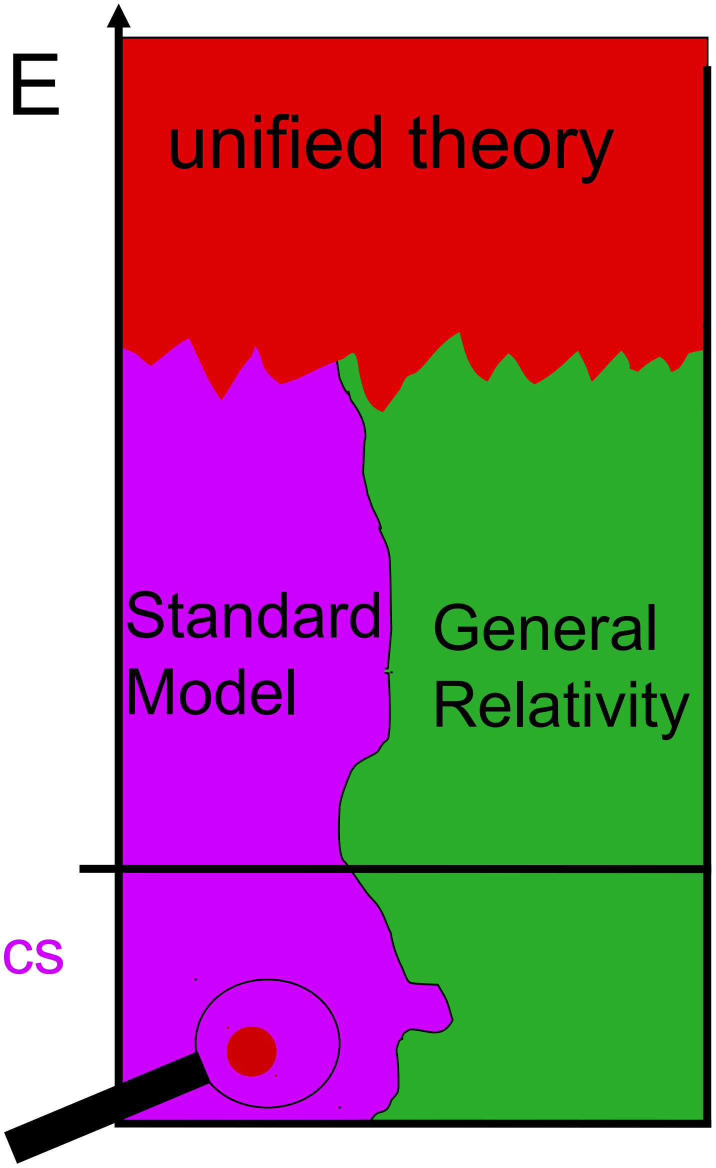
options for probing experimentally

- 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:

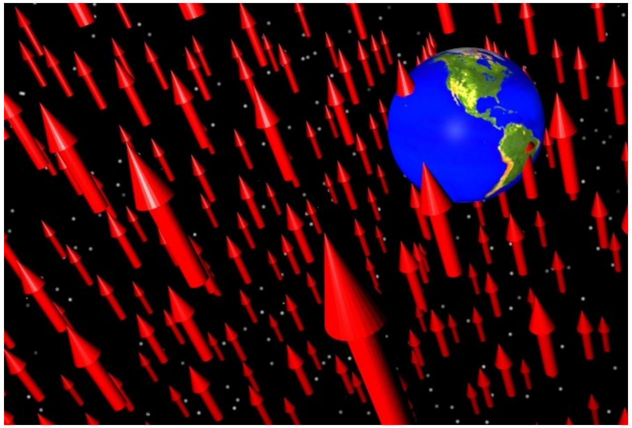
- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent Lorentz violation

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

Lorentz-violating terms

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

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



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

Standard-Model Extension (SME)

effective field theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independen... & Lorentz violation

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

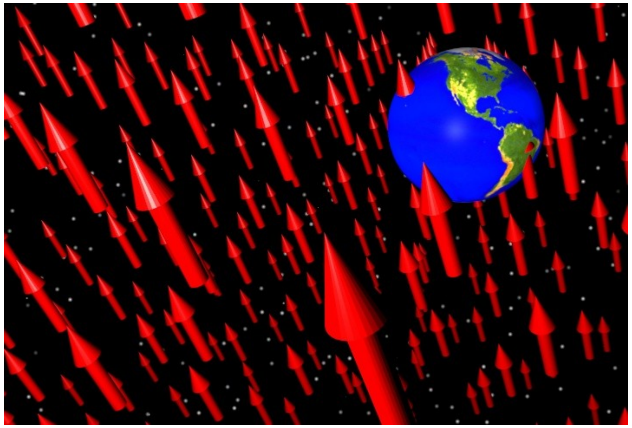
- CPT violation comes wi... ...entz violation

A broad and general search for new physics

CPT & Lorentz-violating ...s

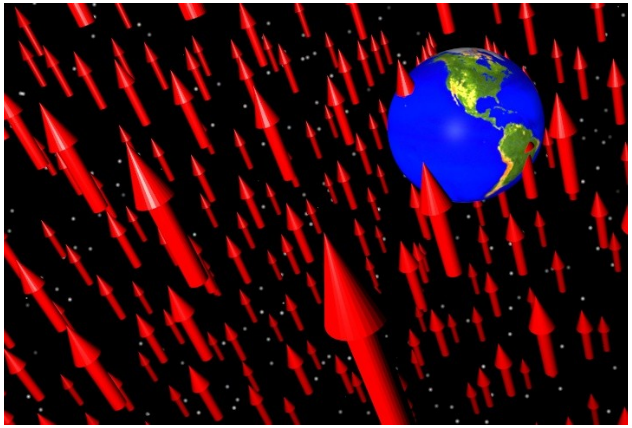
- constructed fr... ...R and SM fields
- parameteri...
  by coeff... ...s for Lorentz violation
- sam...

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



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

PPN vs. SME

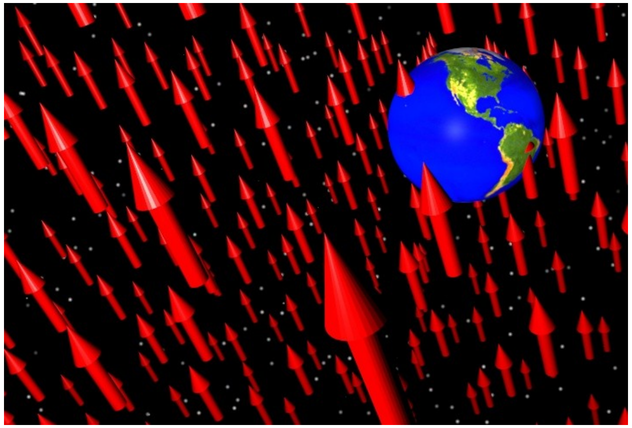
framework	PPN	SME
parameterizes deviations from:	General Relativity (including some Lorentz violation)	exact Lorentz invariance (including some corrections to GR)
expansion about:	GR metric	GR + standard model lagrangian
GR corrections?	Yes	Yes, different ones!
matter sector /standard model corrections?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

tests

- compare experiments pointing in different directions
- compare experiments at different velocities

- SME
  - predictive
  - quantitative comparisons

avoid averaging over the signal

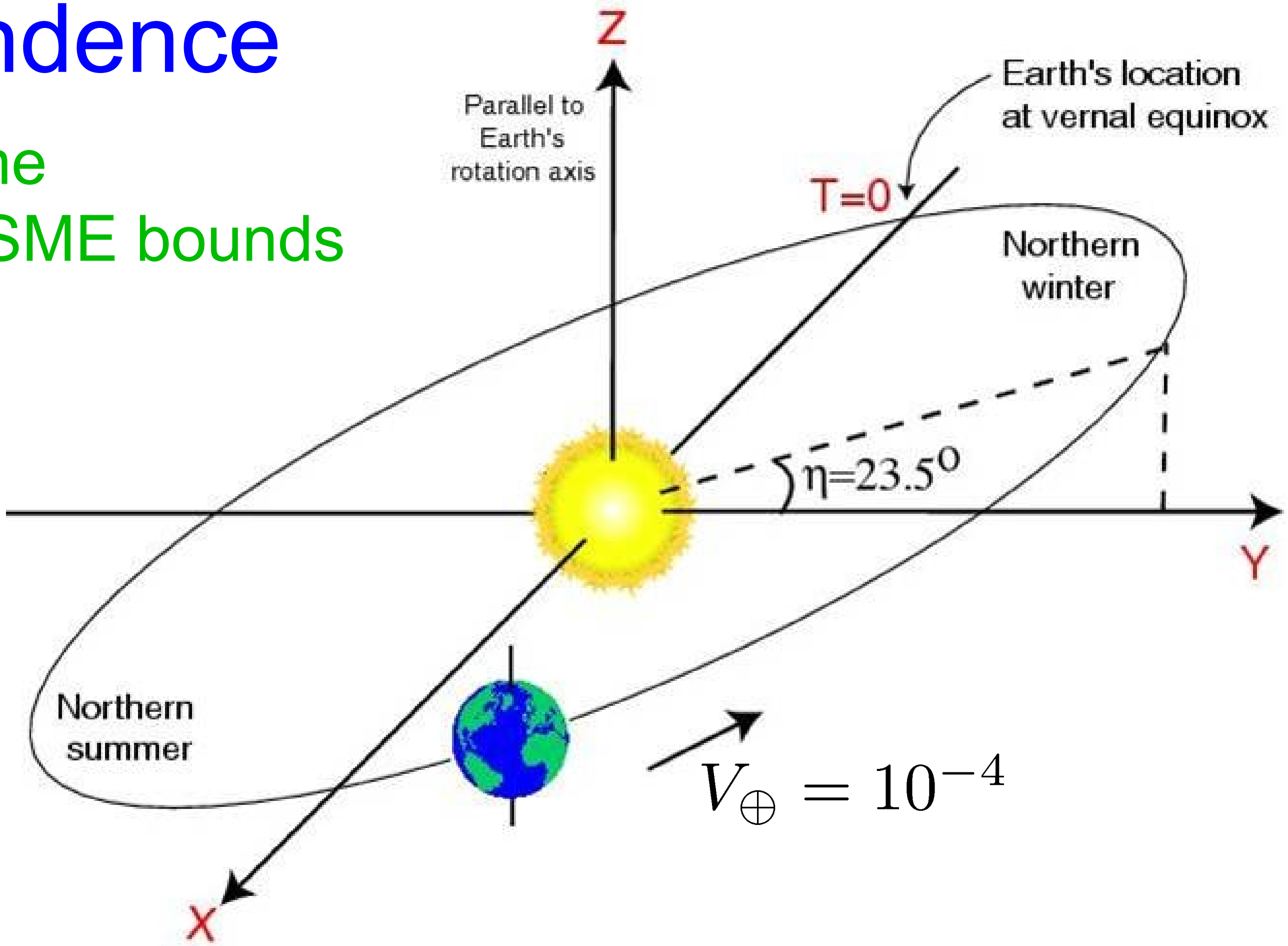


- observe:
  - Lorentz violation
  - 'conventional' field associated with larger-scale source eg. spacetime torsion[1], gravitomagnetism[2]

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

time dependence

- standard frame
  for reporting SME bounds



- boost and rotation of test ⟶

  annual & sidereal variations in Earth-based tests

  other frequencies in space-based tests

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
- .....

overview of Lorentz violation/SME

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

IOP Publishing

Reports on Progress in Physics

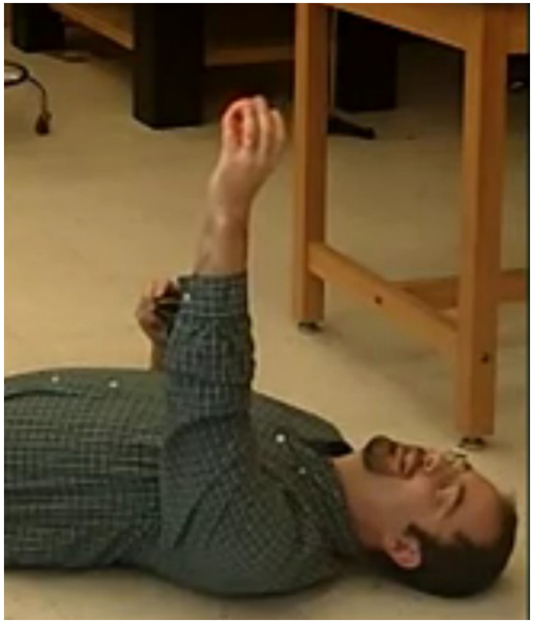
Rep. Prog. Phys. **77** (2014) 062901 (16pp)

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 gravity

gravitational sector:

- Lorentz violation in the gravitational field
- Einstein-Hilbert + corrections
- no WEP violation

gravitationally coupled matter sector

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

gravitationally coupled matter sector

matter sector: kinematics and interactions of particles

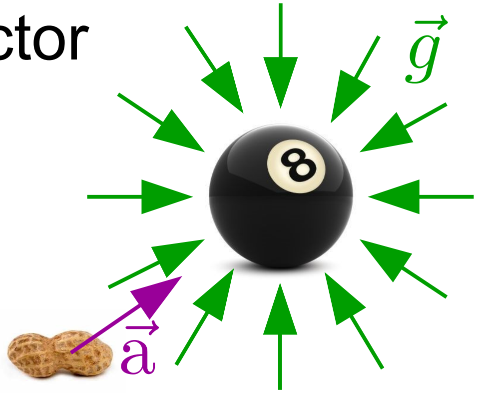
$$\mathcal{L}_{\rm matter} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm LV,SM}$$

conventional gravitationally coupled matter sector

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

$$L_{\rm SM} = -m\sqrt{-g_{\mu\nu} u^{\mu} u^{\nu}}$$

$$\approx \tfrac{1}{2} m \dot{x}^{2} - U$$



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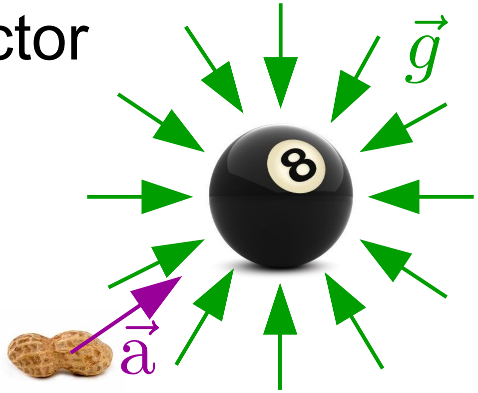
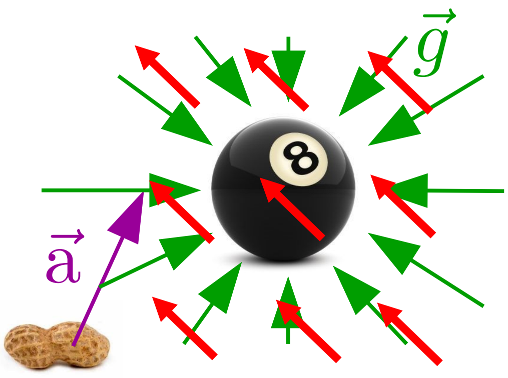


Lorentz violation

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

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

$$a_{\mu} + m e_{\mu}$$



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

why matter-gravity over matter?

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

- spin-polarized solids
- clock comparisons
- CMB analysis
- astrophysical photon decay
- cosmological birefringence
- pulsar-timing observations
- particle traps
- resonant cavities
- neutrino oscillations
- muons
- meson oscillations

why matter-gravity over matter?

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

- spin-polarized solids

- only ~2/3 of lowest order couplings explored
- use gravitational couplings and experiments to get more!

PRL 102, 010402 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

Prospects for Large Relativity Violations in Matter-Gravity Couplings

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Kostelecký & Tasson PRD 2011

Matter-gravity couplings and Lorentz violation

V. Alan Kostelecký and Jay D. Tasson

Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.

(Dated: IUHET 544, June 2010)

- meson oscillations

countershaded Lorentz violation

- upon investigating spontaneous breaking we find

Minkowski-spacetime coefficients

metric fluctuation $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

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

characterize couplings in dynamical theories

- $\overline{a}_\mu$ 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

species dependence

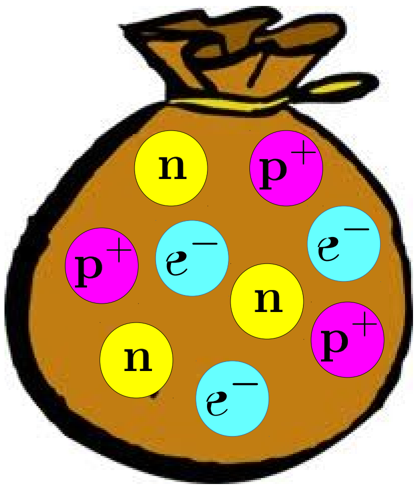
- species dependence

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

mass fraction of species w in test body

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

S and T denote composite coefficients for source and test



Multiple experiments needed for a maximum number of independent sensitivities.

current $(\overline{a}_{\rm eff})_\mu$ 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
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"...the displayed sensitivity for each coefficient assumes for definiteness that no other coefficient contributes."

- 12 independent coefficients
- constraints: 2 at $10^{-11}\mathrm{GeV}$
  2 at $10^{-6}\mathrm{GeV}$
  4 at $10^{-1}\mathrm{GeV}$ as summarized in JT arXiv:1308.1171
- 4 unconstrained combinations require gravitational experiments with charged matter to separate

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

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"...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

current $\overline{c}_{\mu\nu}$ limits

- Data Tables: Kostelecký & Russell, arXiv:0801.0287v7
  - limits likely to be improved via gravity experiments

Coefficient	Neutron
$\overline{c}_{XX} + \overline{c}_{YY} - 2\overline{c}_{ZZ}$	10^{-10}
$\overline{c}_{TX}$	10^{-5}
$\overline{c}_{TY}$	10^{-5}
$\overline{c}_{TZ}$	10^{-5}
$\overline{c}_{TT}$	10^{-11}
Coefficient	**Proton**
$\overline{c}_{TT}$	10^{-11}

- most gravitation experiments with ordinary matter are sensitive to various combination of many of the above coefficients

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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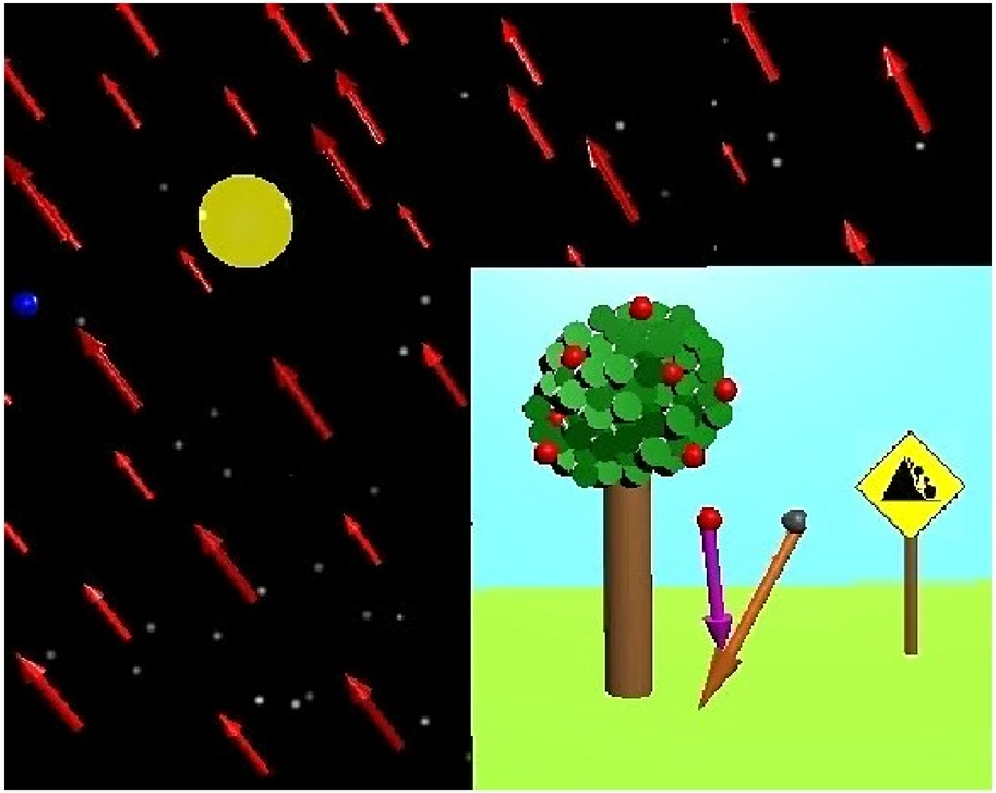
lab tests

acceleration of a test particle T

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

annual variations



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

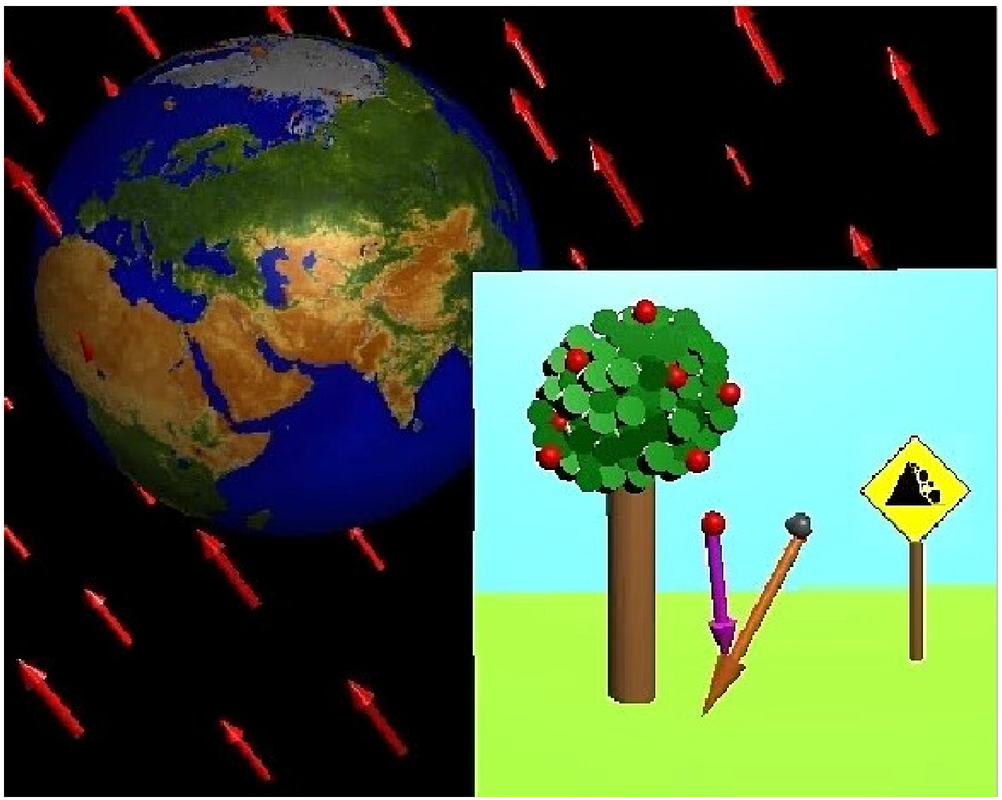
lab tests

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

C. Force-comparison gravimeter tests

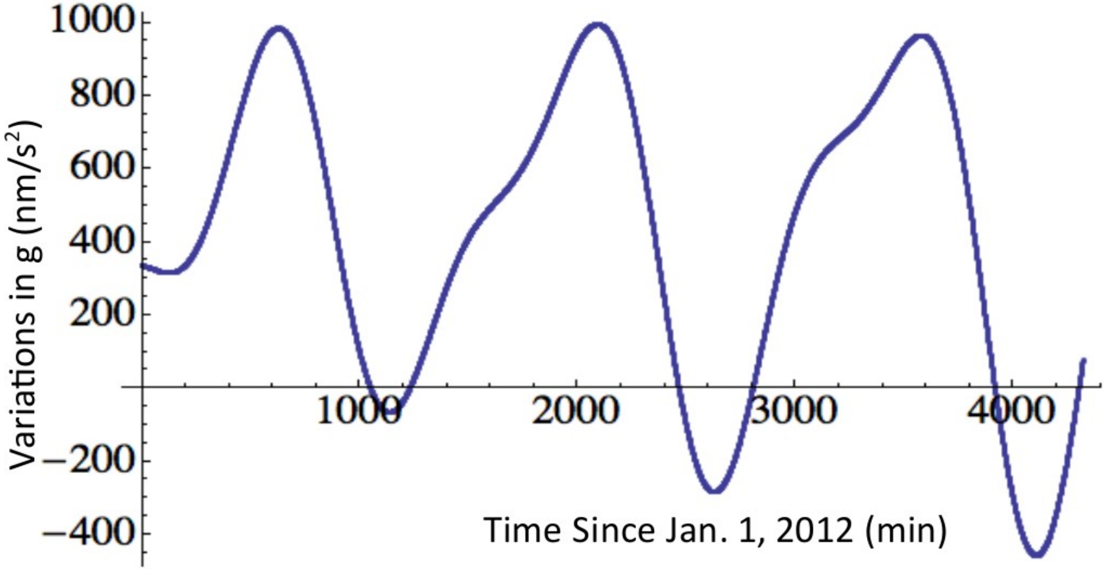
Another class of gravimeter tests is based on the idea of co[...]

ate e[...]

$$a_{\hat{x}} = \omega^2 R_\oplus \sin\chi\cos\chi$$
$$+g\sum\left[\left(\frac{N^w}{m^{\mathrm{T}}}A_n^w + \frac{N_\oplus^w}{m^{\mathrm{S}}}A_n'^w + \tfrac{1}{3}A_n\right)\cos(\omega_n T + \psi_n)\right.$$

Amplitude	Phase
$A_0^w = m^w \sin\chi\cos\chi[(\overline{c}^w)_{XX} + (\overline{c}^w)_{YY} - 2(\overline{c}^w)_{ZZ}]$	0
$A_\omega^w = 2m^w(\overline{c}^w)_{(XZ)}\cos 2\chi + \frac{2}{5}V_L\alpha(\overline{a}_{\mathrm{eff}}^w)_Y\cos\chi$	ψ
$A_\omega'^w = \frac{1}{5}V_L\left[\alpha(\overline{a}_{\mathrm{eff}}^w)_Y + 2m^w(\overline{c}^w)_{(TY)}\right]\cos\chi$	ψ
$B_\omega^w = 2m^w(\overline{c}^w)_{(YZ)}\cos 2\chi - \frac{2}{5}V_L\alpha(\overline{a}_{\mathrm{eff}}^w)_X\cos\chi$	ψ
$B_\omega'^w = -\frac{1}{5}V_L\left[\alpha(\overline{a}_{\mathrm{eff}}^w)_X + 2m^w(\overline{c}^w)_{(TX)}\right]\cos\chi$	ψ
$A_{2\omega}^w = \frac{1}{2}m^w((\overline{c}^w)_{XX} - (\overline{c}^w)_{YY})\sin 2\chi$	2ψ
$B_{2\omega}^w = m^w(\overline{c}^w)_{(XY)}\sin 2\chi$	2ψ

data analysis in preparation



Flowers, Goodge, JT in prep.

Kostelecký & Tasson PRD 2011

D. Free-fall WEP tests

In thi[...]
signals f[...]
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

WEP tests considered

atom interferometry
torsion pendulum
drop tower
balloon drop
tossed masses

...and any WEP test can be used

experiments

- lab tests
  - gravimeter
  - Weak Equivalence Principle (WEP)
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- exotic tests
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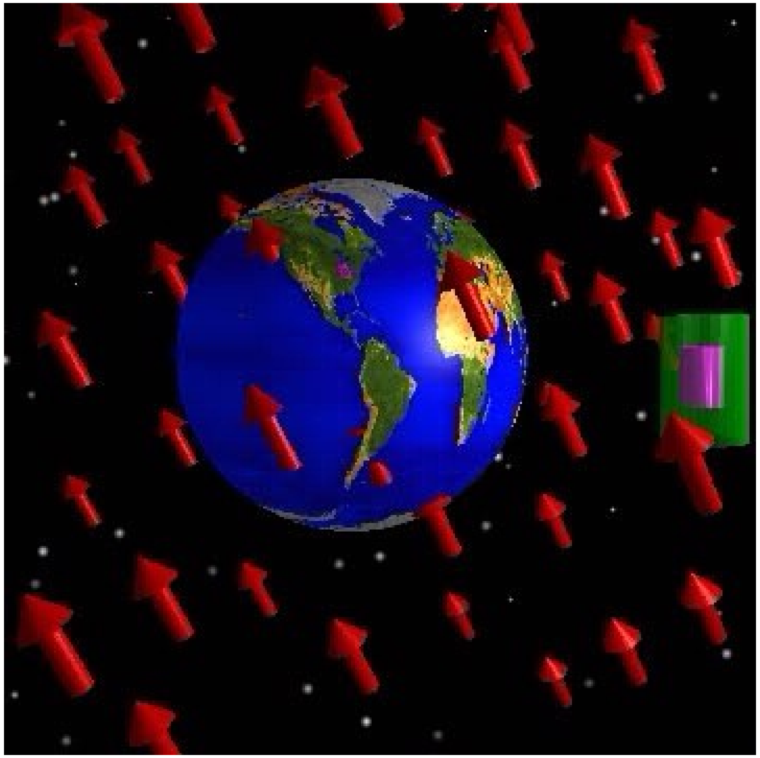
space-based E.P. tests



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}

space-based E.P. tests

definitions	
Ω	Earth orbital frequency
ω_s	satellite orbital frequency
ω_r	satellite rotation frequency

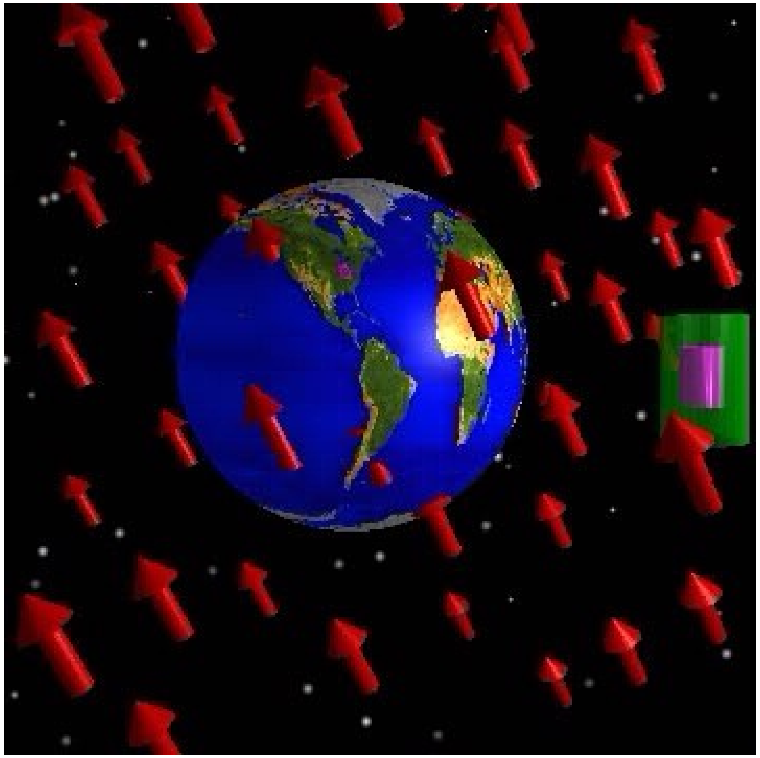
Lorentz-violating WEP signal frequencies	
ω_r	$\Omega + \omega_s + \omega_r$
$\omega_s + \omega_r$	$\Omega + \omega_s - \omega_r$
$\omega_s - \omega_r$	$\Omega - \omega_s + \omega_r$
$2\omega_s - \omega_r$	$\Omega - \omega_s - \omega_r$

Lorentz-invariant WEP signal frequency
$\omega_s - \omega_r$

how do these frequencies arise?

as a combination of the following effects:

- the relative orientation of the sensitive axis and the direction of Earth change as the system orbits and spins
- as the masses orbit, the orientation of the experiment effectively changes relative to the background field, which implies changes in the relative acceleration of the 2 bodies
- the relative acceleration changes as the system's boost changes during it's path around the sun.



space-based E.P. tests

definitions	
Ω	Earth orbital frequency
ω_s	satellite orbital frequency
ω_r	satellite rotation frequency

Lorentz-violating WEP signal frequencies	
ω_r	$\Omega + \omega_s + \omega_r$
$\omega_s + \omega_r$	$\Omega + \omega_s - \omega_r$
$\omega_s - \omega_r$	$\Omega - \omega_s + \omega_r$
$2\omega_s - \omega_r$	$\Omega - \omega_s - \omega_r$

Lorentz-invariant WEP signal frequency
$\omega_s - \omega_r$

sensitivity estimates

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

↓

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improvements of 8 orders of magnitude on some special combinations

Summary

Lorentz violation in matter-gravity couplings introduces qualitatively new signals in a wide variety of gravitational experiments

improvement potential is vast

MICROSCOPE offers the possibility of impressive improvement via signals at the "conventional" WEP frequency as well as others