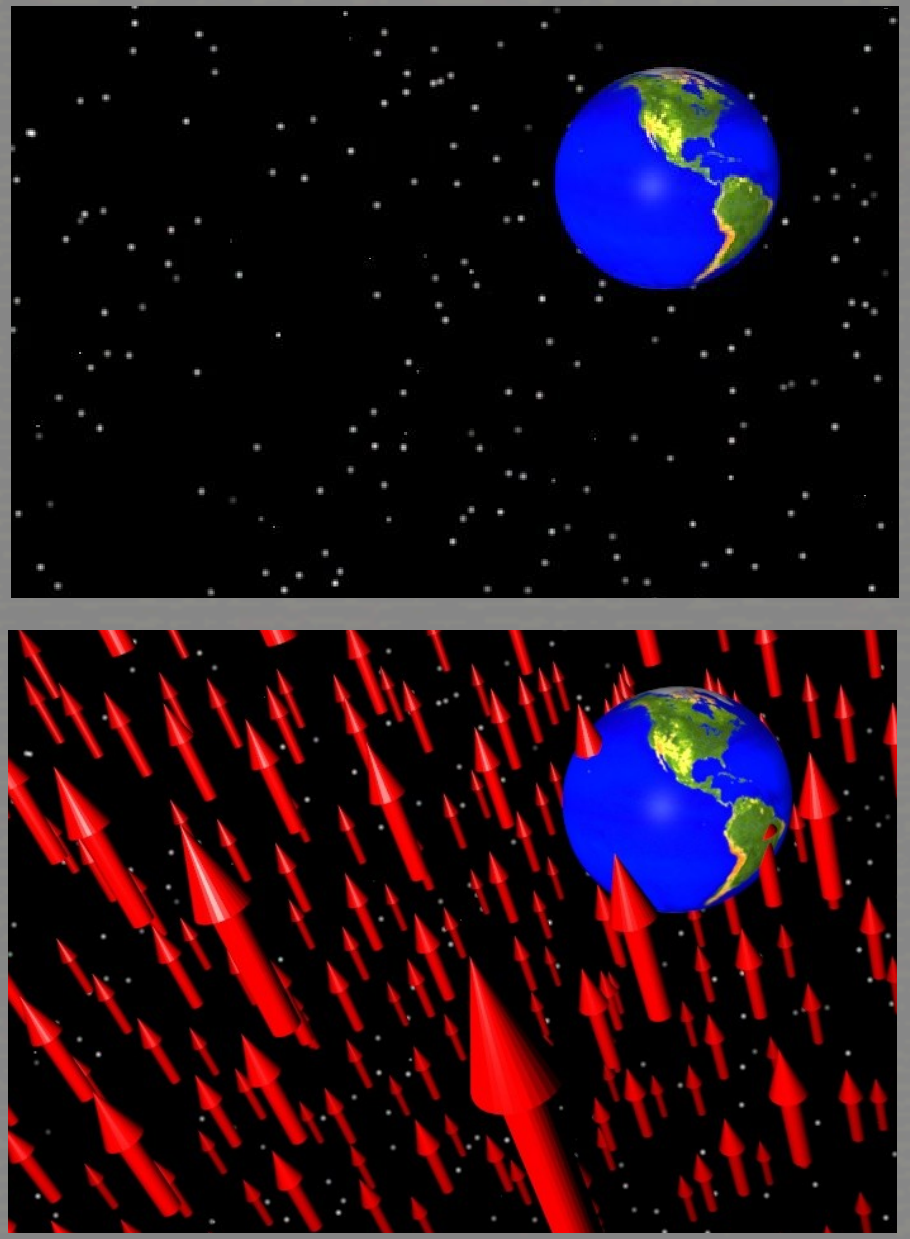
Test of Lorentz symmetry with MICROSCOPE



Christine Guerlin[1,2], Peter Wolf[2],
Quentin Bailey[3], Jay Tasson[4]

[1]LKB, [2]SYRTE,
[3]Embry-Riddle Aeronautical University, [4]St Olaf College

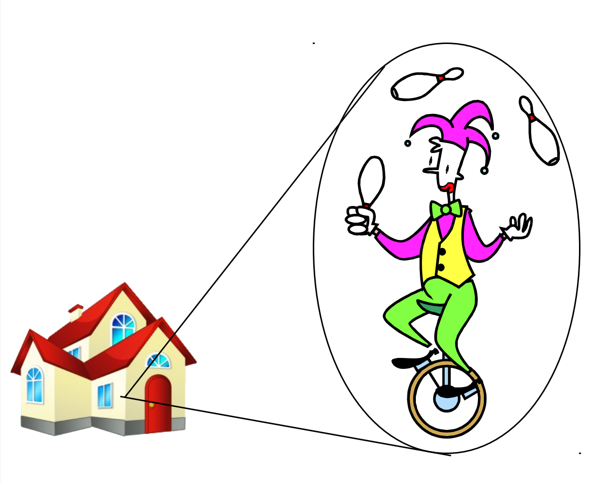
2015/11/16 MICROSCOPE Colloquium IV

Outline

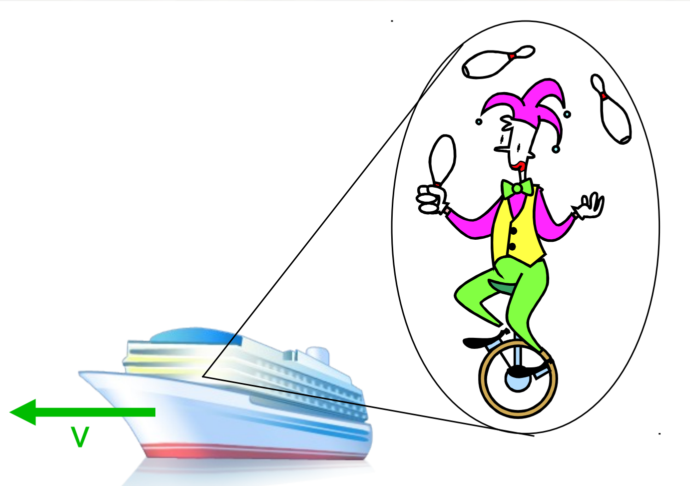
- Lorentz symmetry
- Lorentz and WEP violation in Standard Model Extension (SME)
- SME model for MICROSCOPE
- Data analysis

Lorentz symmetry (in short): what

- Lorentz symmetry: symmetry of spacetime under Lorentz transformations (boosts and rotations)
- Lorentz invariant theory: physical results of an experiment are independent of



- its **velocity** (magnitude and direction)



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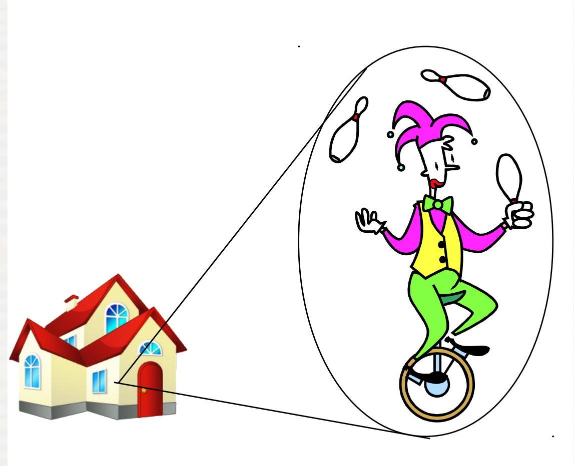

with the courtesy of J. Tasson

- General Relativity and Standard Model have Lorentz invariance (resp. local and global)

Lorentz symmetry (in short): why testing it

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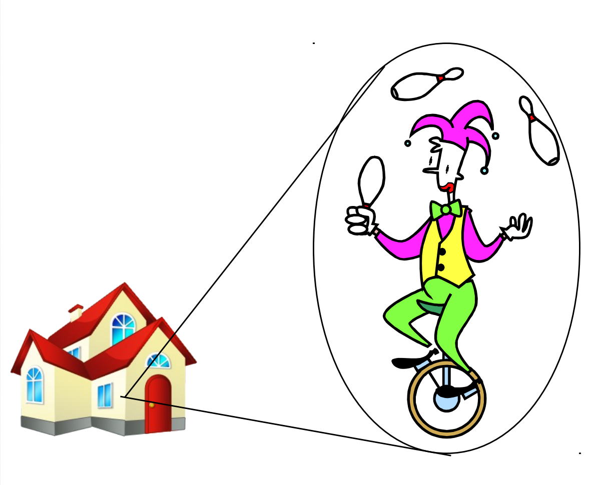

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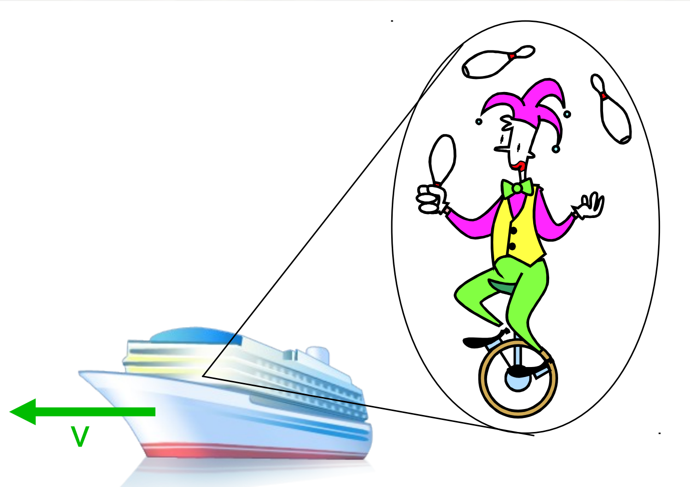

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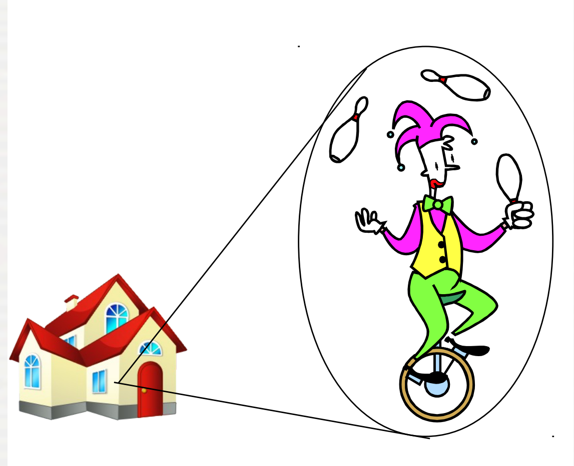

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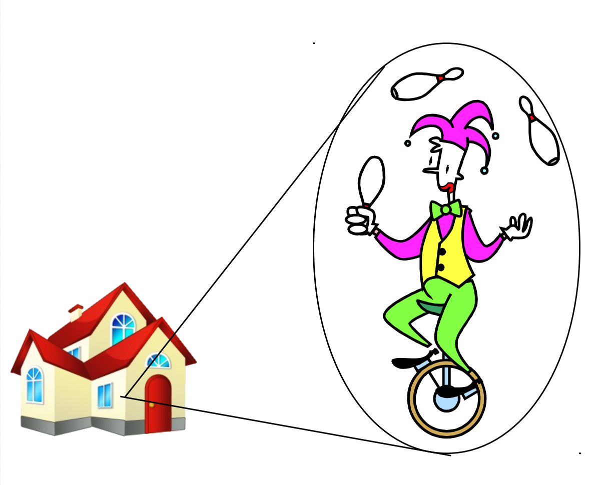

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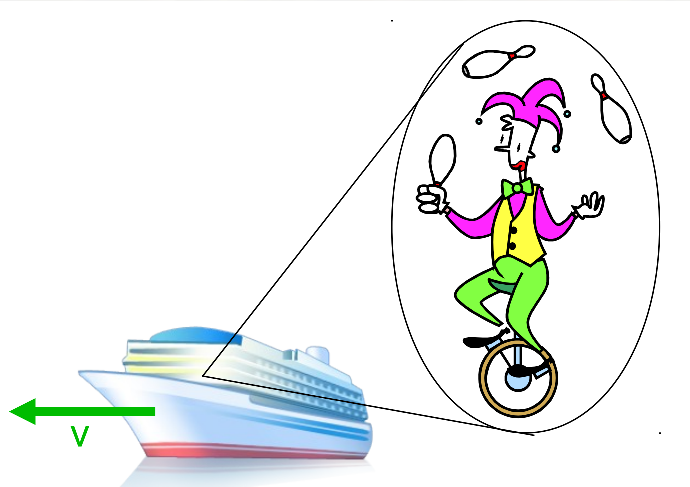

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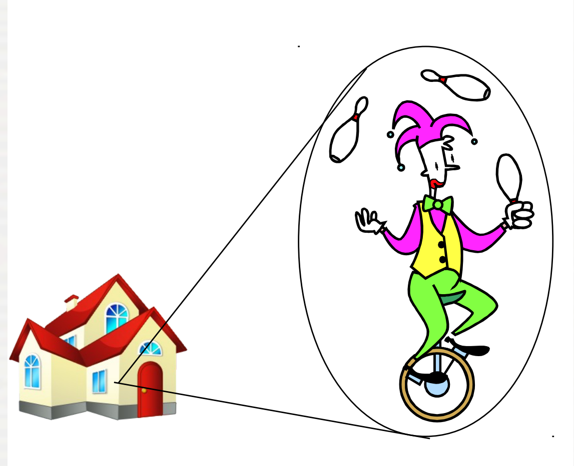

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- General Relativity and Standard Model have Lorentz invariance (resp. local and global)
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- Basic experimental approach for test:
  - rotate experiment
  - search for periodic signals
- Analysis of tests beyond GR and SM: specific theory or general framework

parametrization of deviations from Lorentz invariance

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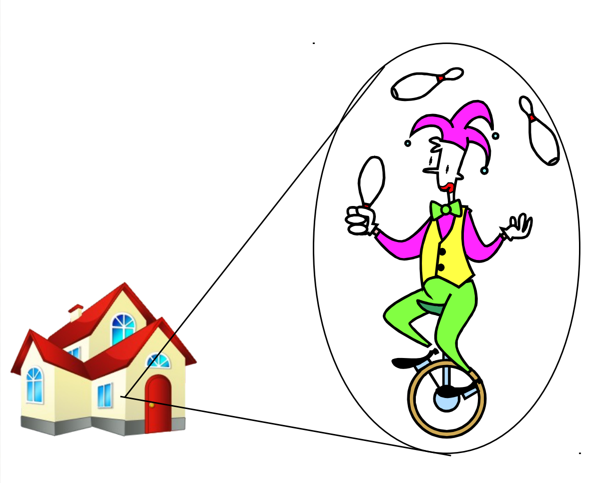

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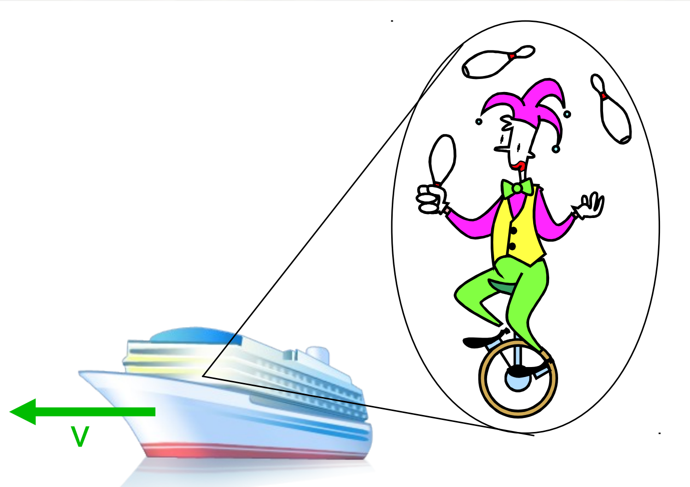

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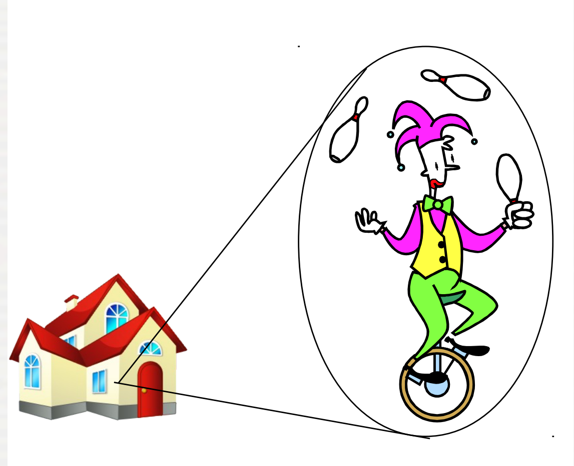

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parametrization of deviations from Lorentz invariance

Framework for LS test: Standard Model Extension (in short)

❖ Standard Model Extension (SME): very broad framework for Lorentz symmetry tests

D. Colladay and V.A. Kostelecky., Phys. Rev. D **58**, 116002 (1998)

❖ SME structure:

- parametrizing all possible Lorentz violations (LV) for SM and GR fields
- in the Lagrangian or action of SM and GR
- for fermions, test bodies, gravitational sources…

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

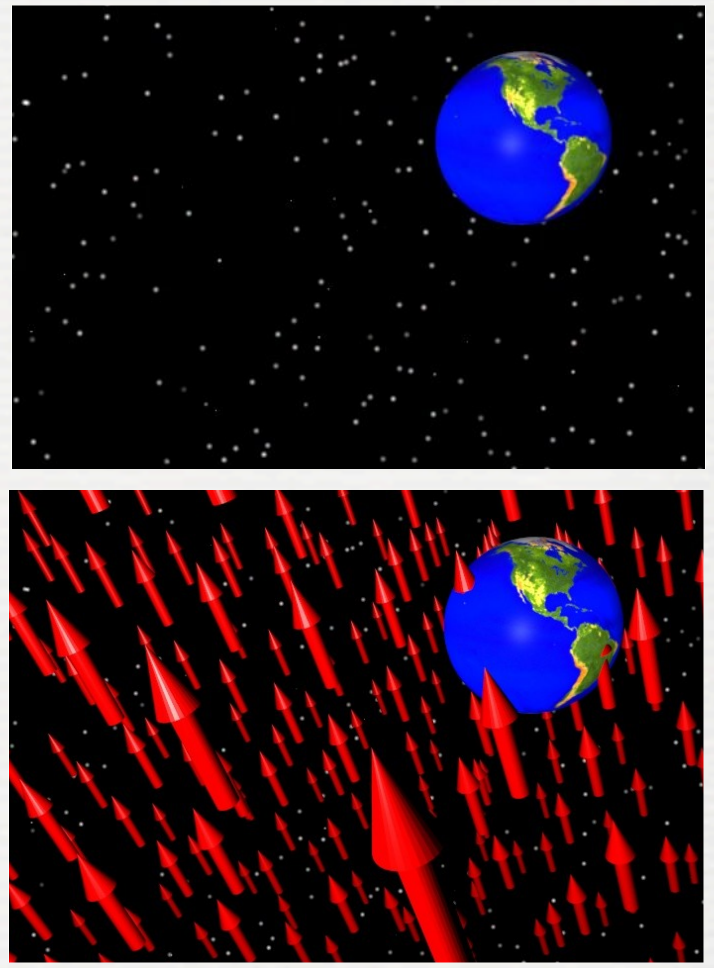
❖ Lorentz violations appear as coupling of dynamics to background fields, in general tensors (preferred directions)

- one element of one the tensors: one coefficient for LV
- coefficients are allowed to be species dependent

electron, proton, neutron

e.g. $(\bar{a}_{\mathrm{eff}})^{w}_{\mu}$

space-time component



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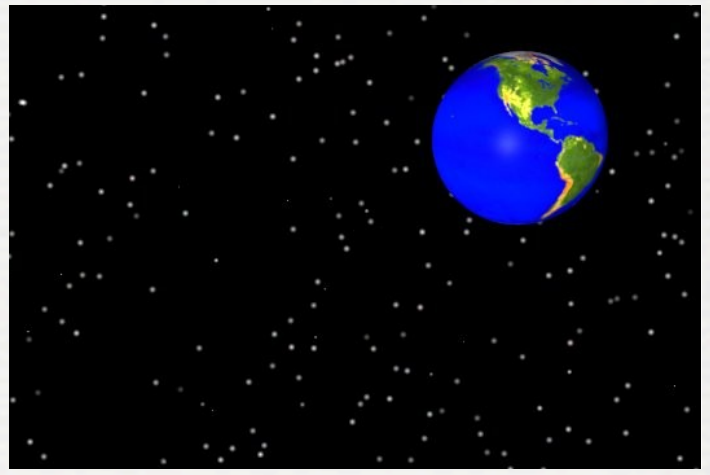
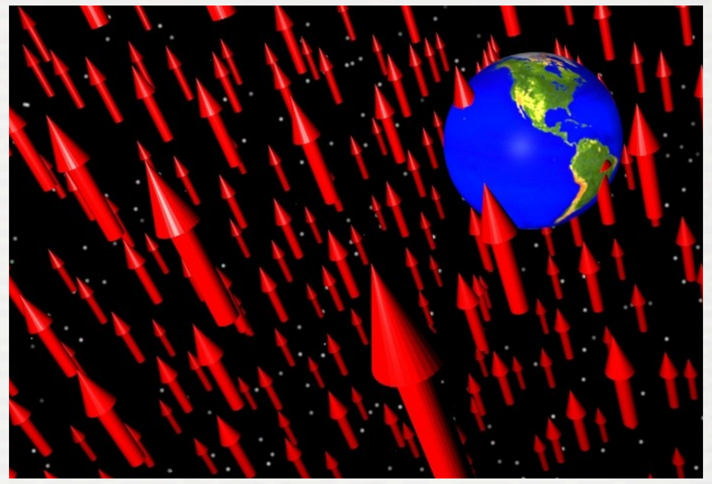
⇒ when rotating an experiment, background tensors lead to non zero signals at harmonics of rotation frequency in observables

predictive + avoids averaging over the signal





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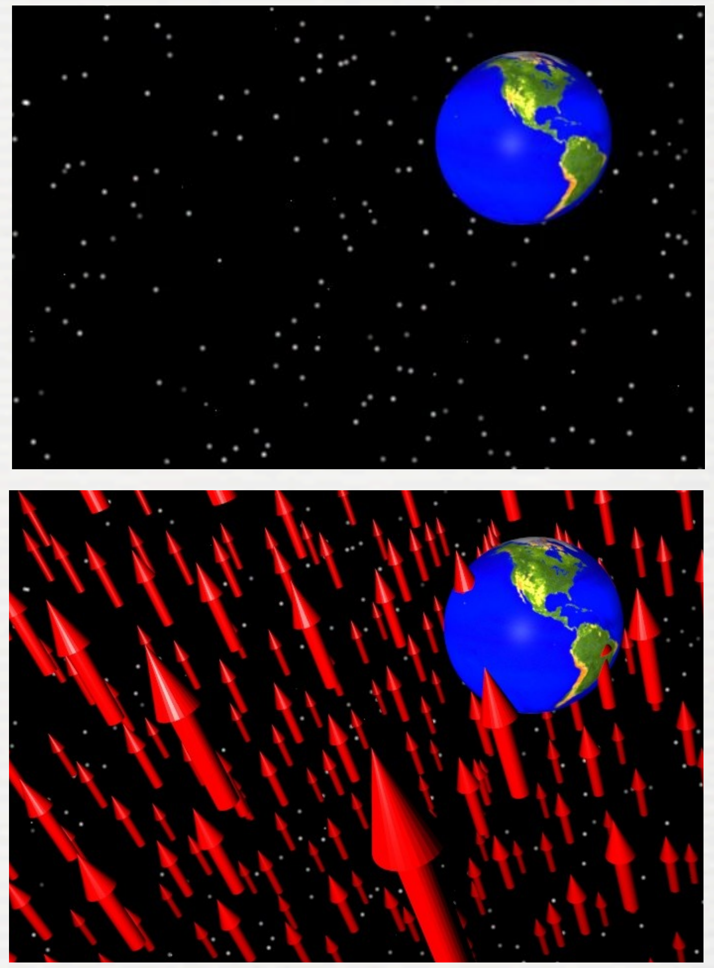

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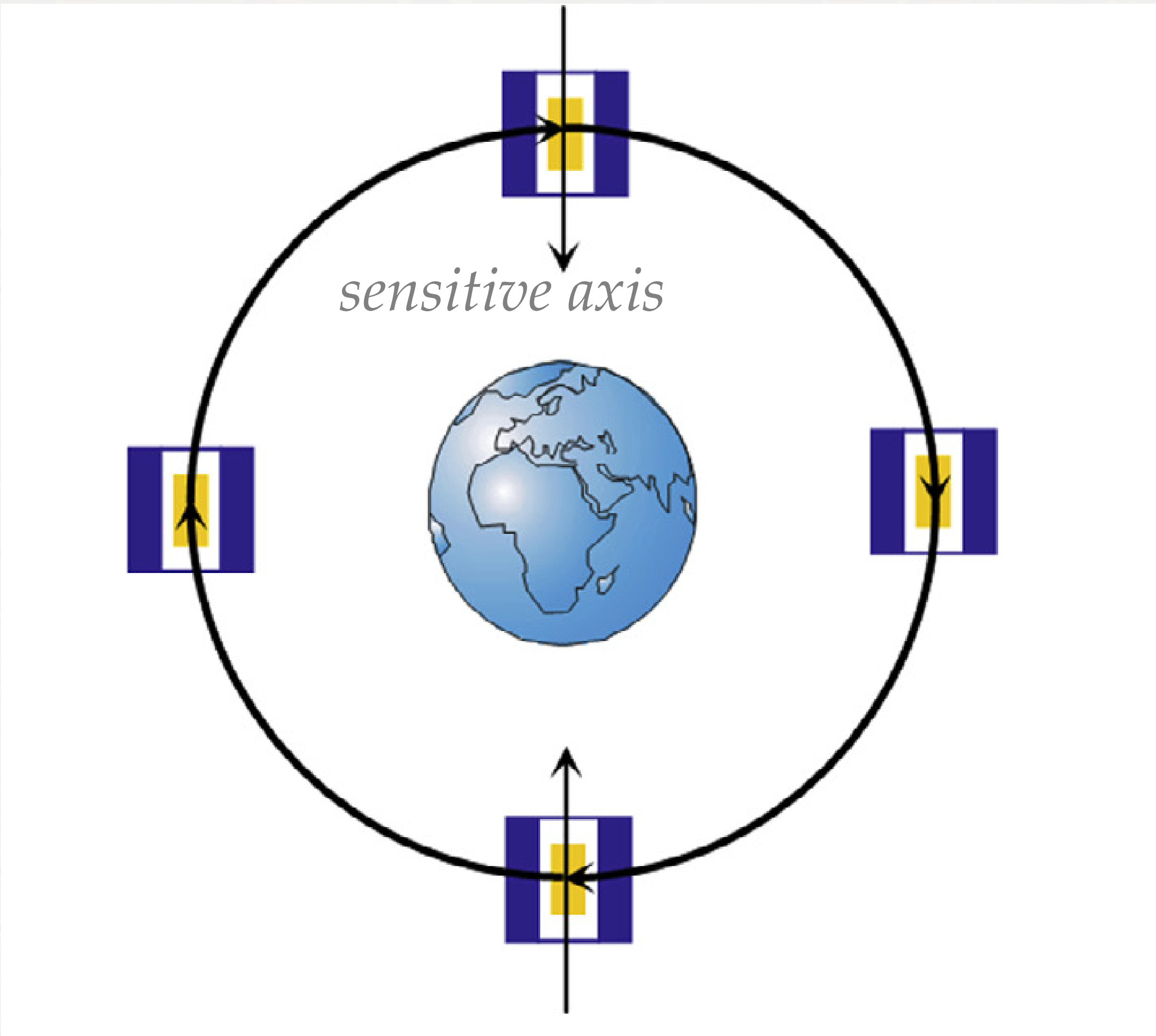
→ test-particle dependnt motion in a gravitational field:

LV WEP violation

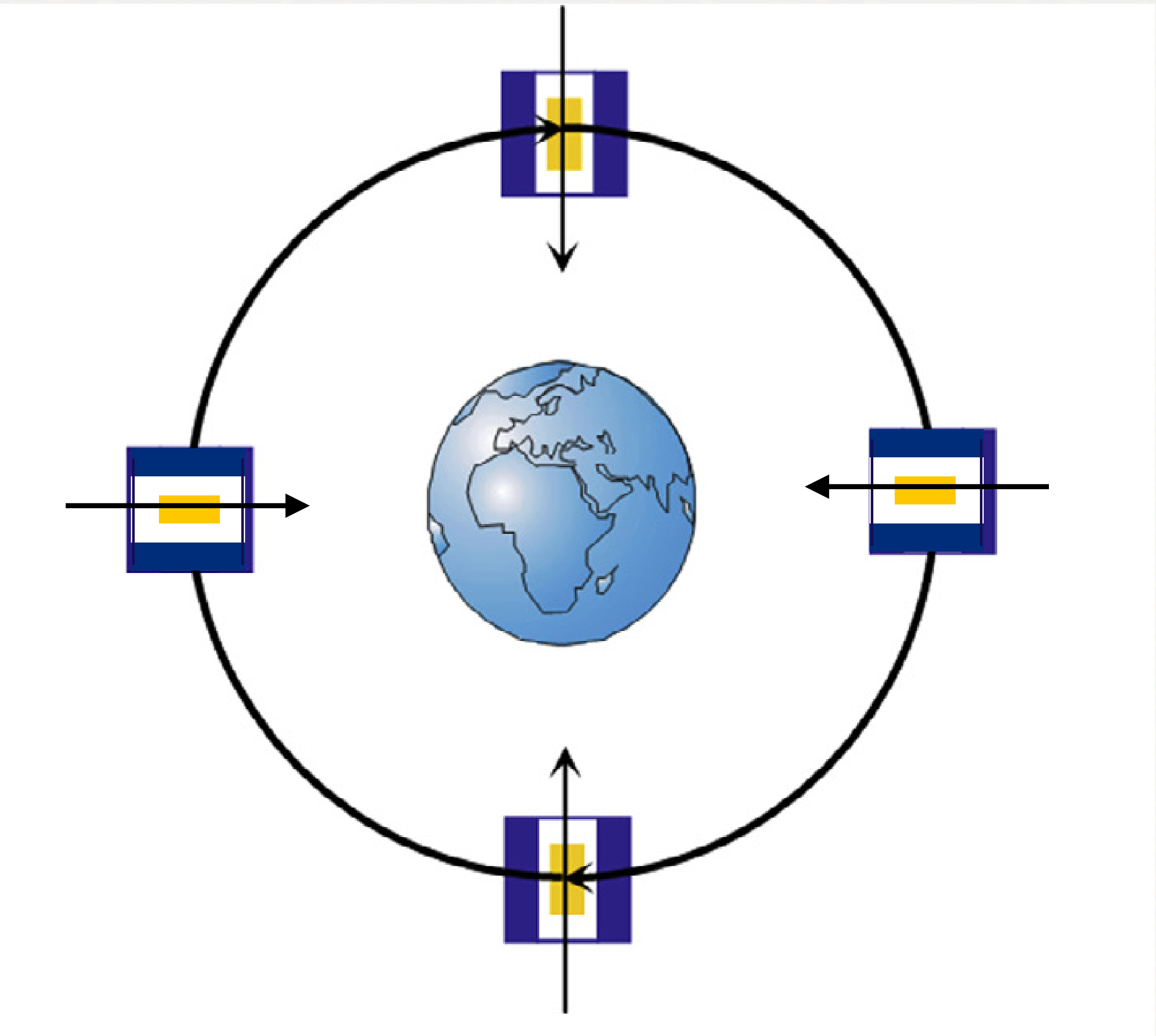
WEP violation through matter dependent Lorentz violation

Example of signals for differential acceleration in:

Inertial mode



Nadir pointing



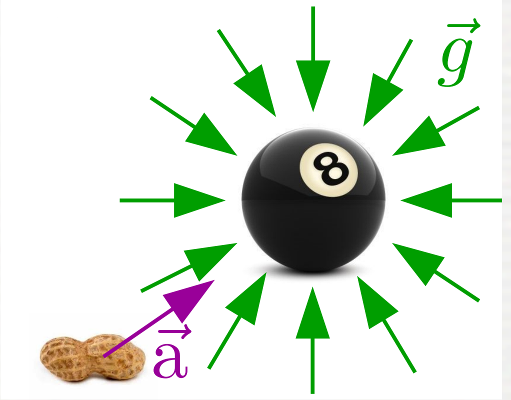
Signal frequency:

non LV WEP violation:	ω_r	DC
LV WEP violation:	DC (lowest order)	ω_r

WEP: SME coefficients for matter-gravity couplings

- Gravitationally coupled matter sector of SME:

  species dependence of motion of a test particle in a gravitational field:



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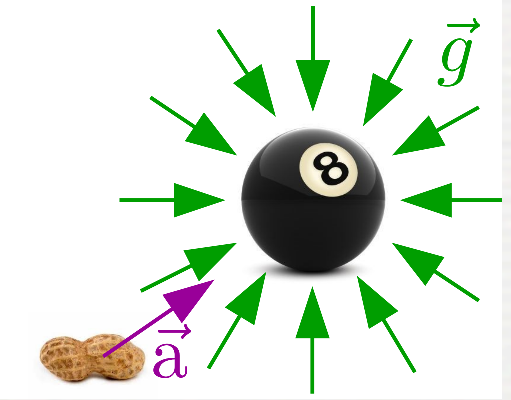
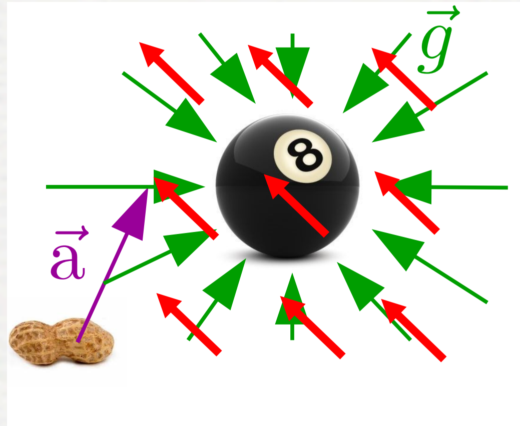


source dependent field distortions
+ test-particle dependent responses



due to background tensors $\bar{c}^{w}_{\mu\nu}, (\bar{a}_{\text{eff}})^{w}_{\mu}$

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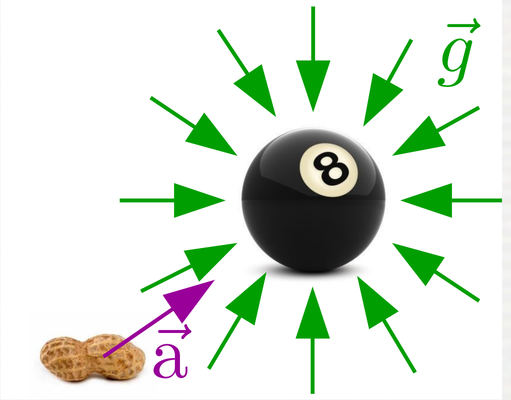

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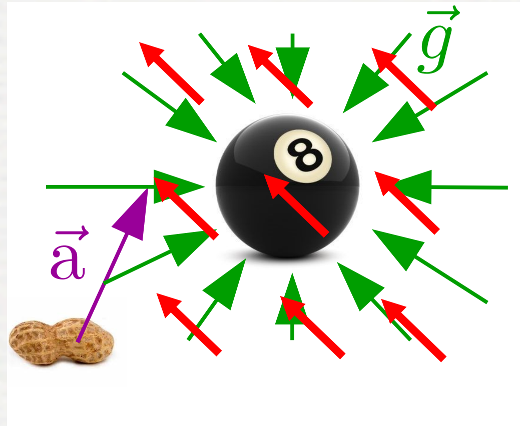

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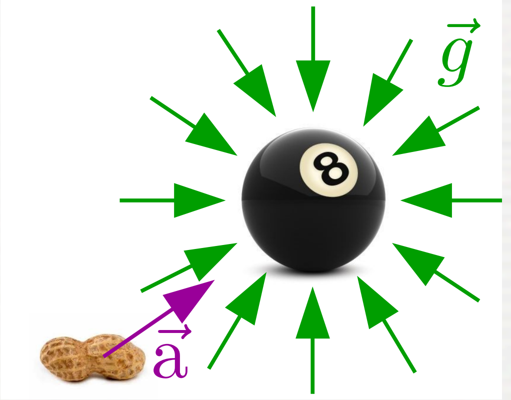

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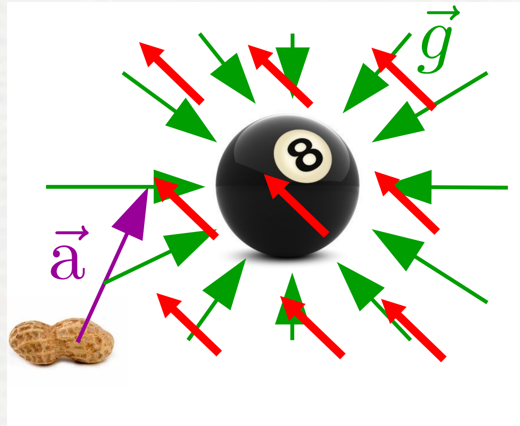


due to background tensors $\bar{c}^w_{\mu\nu}, \boxed{(\bar{a}_{\text{eff}})^w_\mu}$

«counter shaded» coefficients
appear only in gravitational experiments

poorly tested so far (gravimeter, ephemerides)

MICROSCOPE:
best constraints expected on 2 $\bar{c}^w_{\mu\nu}$ and all $(\bar{a}_{\text{eff}})^w_\mu$ coefficients

improvements from 3 to 6 orders of magnitude over state of the art

Modeling and analyzing an experiment in SME

1) model, lab frame: express dynamics or observable including LV coefficients in the «lab» frame

2) model, SCF frame: coefficients for LV are compared in a common frame, e.g. Sun Centered Celestial Equatorial Frame (SCF)

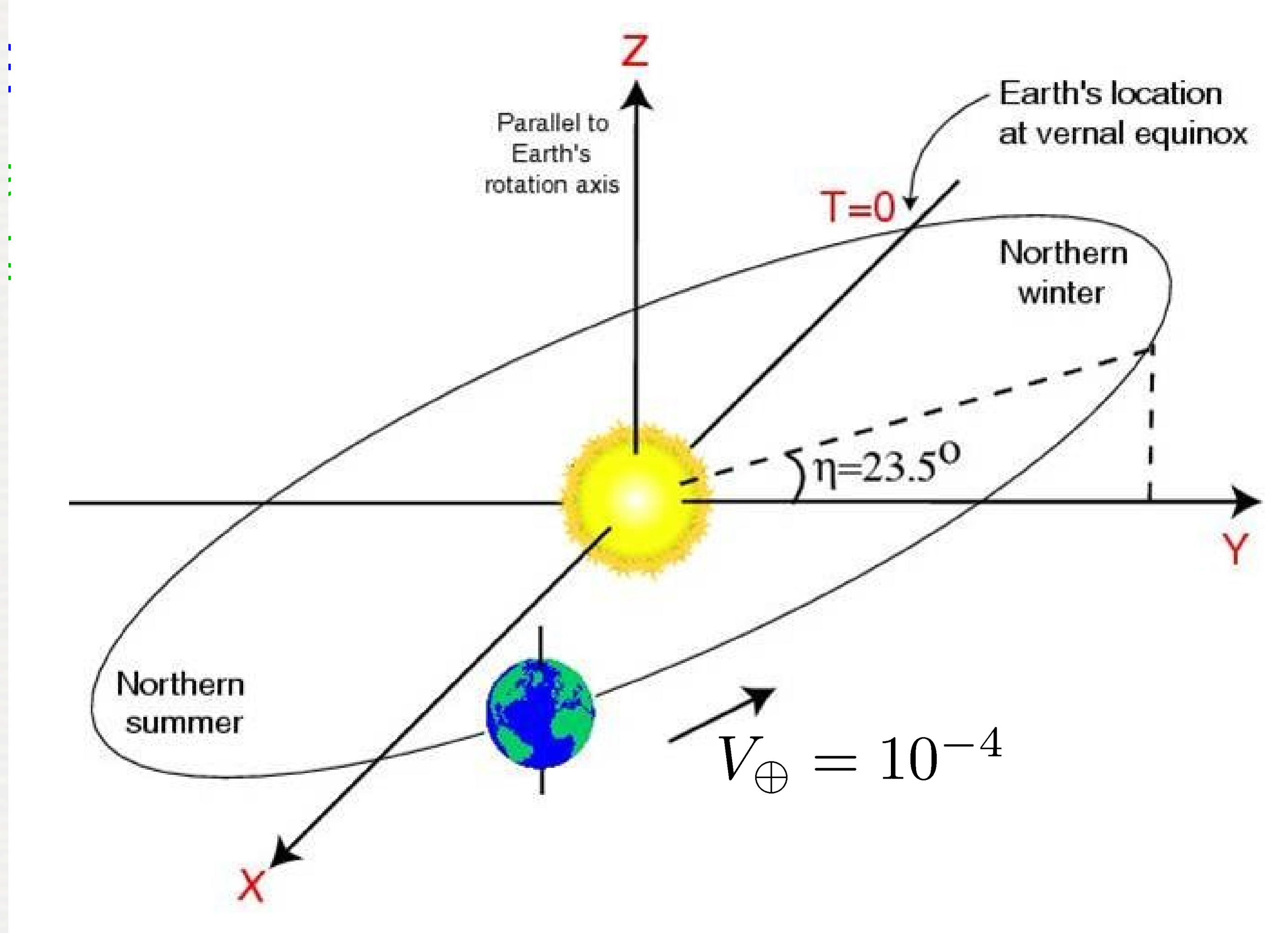
➡ use Lorentz transformation of LV tensors to express «lab» coefficients as a function of SCF coefficients

- leads to distinct time components due to: boost of the experiment wrt SCF, and rotation
- amplitudes = linear combinations of SCF LV coefficients

3) analysis: decorrelate LV coefficients

rich litterature where models derived for different experiments

numerous experimental tests done



SME model for MICROSCOPE in spin mode

SPIN MODE (most general case)

- Ideal observable:
  local differential acceleration of the well-centered test bodies along sensitive axis (0 in the absence of WEP or Lorentz violation)

$$\Delta a^{\hat{x}}$$

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- LV model:

  $$\Delta a^{\hat{x}} = \Delta a^{\hat{x}}_{LV}$$

  time series expansion:

$$\Delta a^{\hat{x}}_{LV} = r\omega_r^2 \sum_n (C_{\omega_n} \cos(\omega_n t + \alpha_n) + S_{\omega_n} \sin(\omega_n t + \alpha_n))$$

variation amplitude of relative differential acceleration

V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

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LV frequencies:

harmonics of spin, orbital and annual frequencies

ω_r

ω_s

$\omega_s \pm \omega_r$ overlap of 1 frequency with non LV EP model

$\omega_s \pm \omega_r \pm \Omega$

$\omega_s - 2\omega_r$

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$$\omega_s \pm \omega_r$$

overlap of 1 frequency with non LV EP model

$$\omega_s \pm \omega_r \pm \Omega$$

$$\omega_s - 2\omega_r$$

each amplitude: a linear combination of SME coefficients

$$C_{\omega_n},\ S_{\omega_n} = f(\bar{c}^w_{\mu\nu}, (\bar{a}_{\text{eff}})^w_\mu)$$

linear combination
depends on: boost factors, species composition of test masses

V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

Expected precision and state of the art

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- **Amplitudes**: if the relative uncertainty at each frequency is $\delta a/a \sim 10^{-15}$

  ➡ $C_{\omega_n}, \ S_{\omega_n}$ adjusted with uncertainty 10^{-15}

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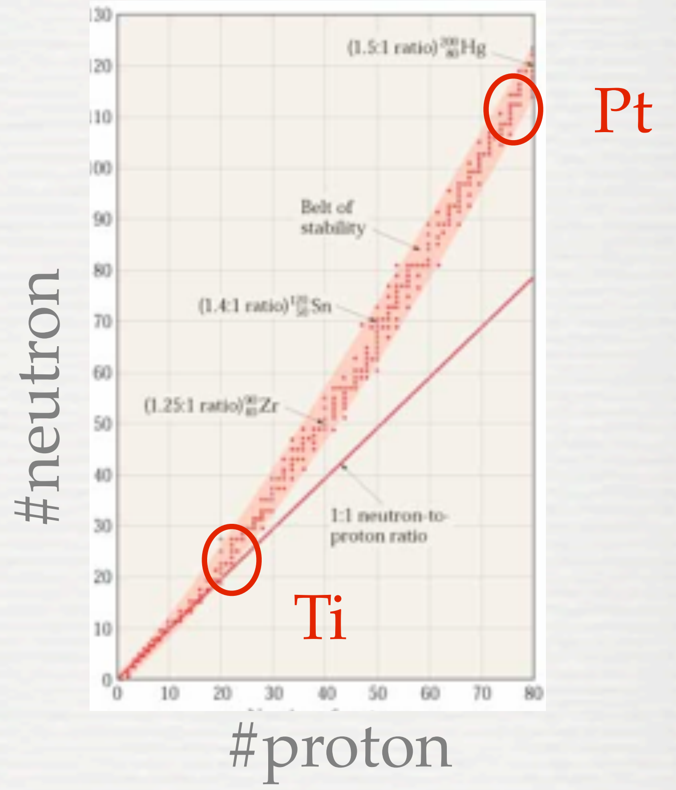
  scale factors in linear combination:

  - species dependence:

    prefactor on the order of differential neutron-to-proton ratio (/ GeV): 0.06 (/ GeV)

10^{-2} GeV^{-1}



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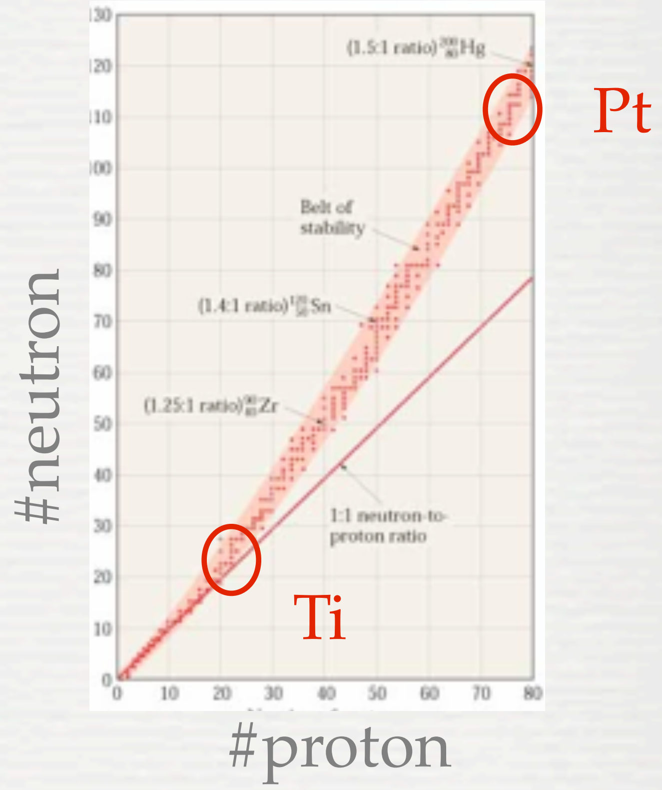

Uncertainty on SME coefficients:

Coefficient	MicroSCOPE
$\alpha(\bar{a}_{\text{eff}}^{e+p-n})_T - \frac{1}{3} m^p (\bar{c}^{e+p-n})_{TT}$	$\{10^{-13}\ \text{GeV}\}$
$(\bar{c}^n)_Q$	$\{10^{-13}\}$

from V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

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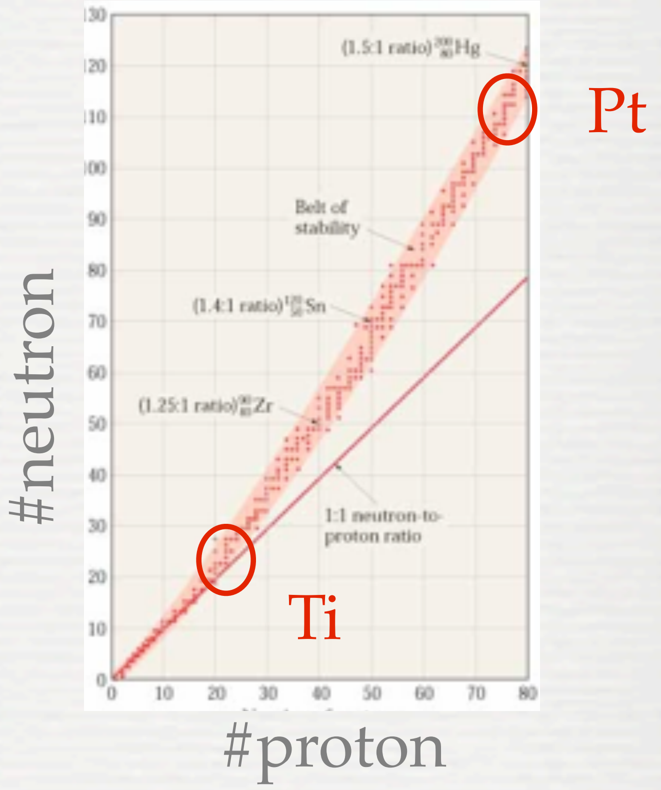

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$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_{Y+Z}$	$\{10^{-9}$ GeV$\}$
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from V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

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- Amplitudes: if the relative uncertainty at each frequency is $\delta a/a \sim 10^{-15}$

  $\Rightarrow$ C_{ω_n}, S_{ω_n} adjusted with uncertainty 10^{-15}

- SME coefficients: $C_{\omega_n}, \; S_{\omega_n} = f(\bar{c}_{\mu\nu}^{w}, (\bar{a}_{\text{eff}})_{\mu}^{w})$

  scale factors in linear combination:

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    0.06 (/ GeV)

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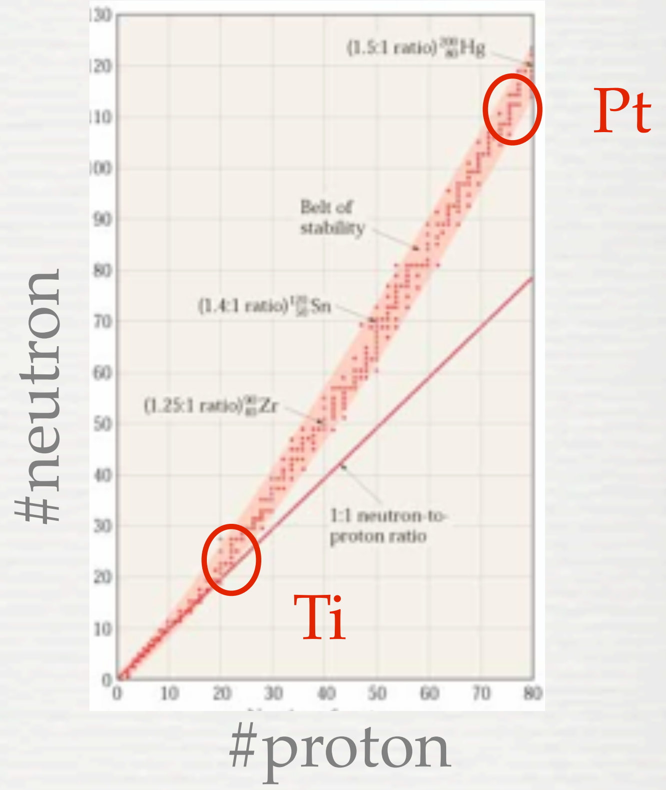
    10^{-5} (satellite)



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  - species dependence:

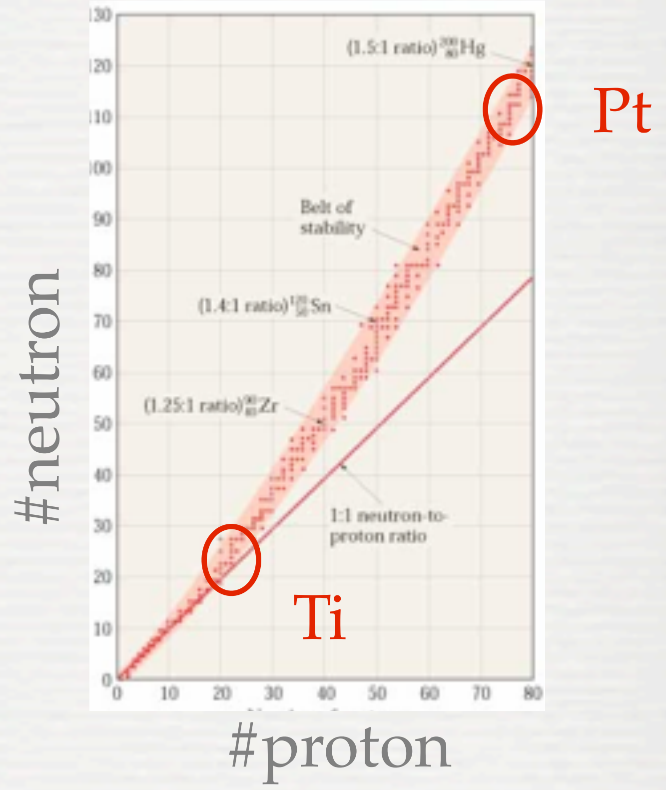
    prefactor on the order of differential neutron-to-proton ratio (/ GeV): 10^{-2} GeV^{-1}

    0.06 (/ GeV)

  - boost factors (at first order)

    10^{-4} (Earth)

    10^{-5} (satellite)



Uncertainty on SME coefficients:

Coefficient	MicroSCOPE
$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_T - \frac{1}{3}m^p(\bar{c}^{e+p-n})_{TT}$	$\{10^{-13}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_X$	$\{10^{-9}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_{Y+Z}$	$\{10^{-9}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_Y$	$\{10^{-7}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\text{eff}})_Z$	$\{10^{-7}$ GeV$\}$
$(\bar{c}^n)_Q$	$\{10^{-13}\}$
$(\bar{c}^n)_{(TJ)}$	$\{10^{-9}\}$

Improvement by at least 3 orders of magnitude

from V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

Data analysis

- Real observable / model:

differential acceleration from N2c level data: $\Delta a^{\hat{x}} = 2\Gamma_{mes,dx}$

$$\Delta \mathrm{a}^{\hat{x}} \equiv \frac{d^2 \Delta \hat{x}}{d\hat{t}^2} = \Delta \mathrm{a}^{\hat{x}}_{\mathrm{tidal}} + \Delta \mathrm{a}^{\hat{x}}_{\mathrm{LV}} \longrightarrow \Delta a^{\hat{x}}_{\mathrm{tidal}} = A + B\cos(2(\omega_s - \omega_r)t + \Phi)$$

cstt

ω_r

ω_s

$\omega_s \pm \omega_r$

$\omega_s \pm \omega_r \pm \Omega$

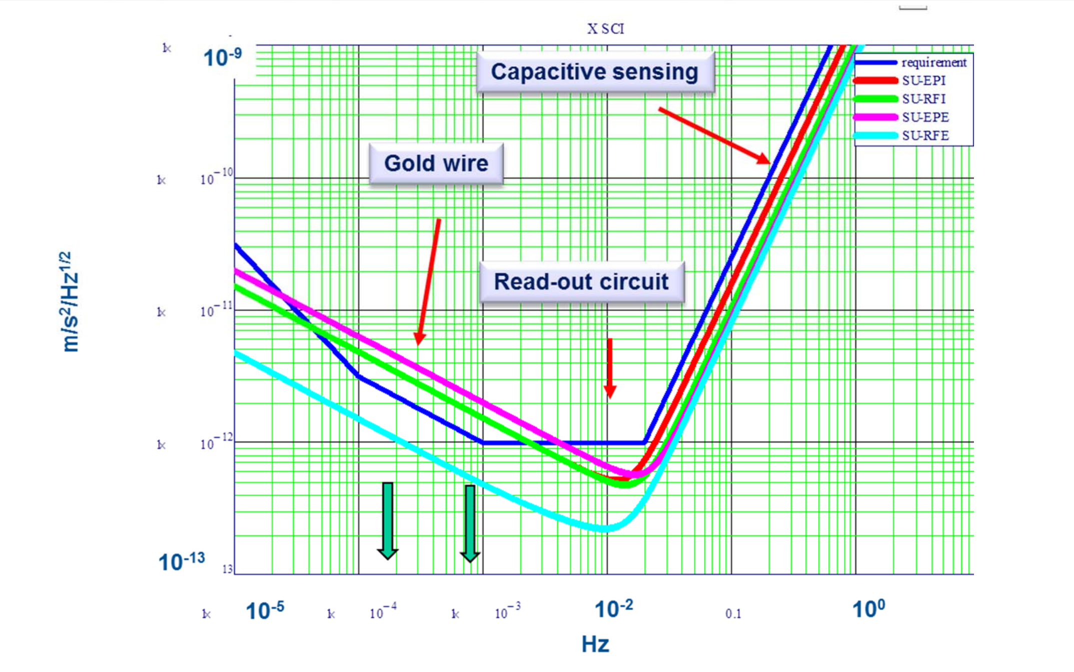
$\omega_s - 2\omega_r$

$2\omega_s - 2\omega_r$

additional frequencies from off-centering, to be included in time series fit

- Fit for amplitudes and estimation of **statistical uncertainty**:

  - characterize noise
  - fit e.g. by weighted least squares



M. Rodrigues, Moriond 2015

Data analysis

- Estimation of **systematic uncertainty**:

perturbations at
different frequencies
$f_{d,sing} = n_1 f_{orb} + n_2 f_{spin}$

f_{orb}
$f_{spin} - 2f_{orb}$
$2f_{orb}$
$f_{spin} - f_{orb}$
$3f_{orb}$
f_{spin}
$f_{spin} + f_{orb}$
$f_{spin} + 2f_{orb}$

errors on determinatin of f_{orb}
and realization of f_{spin}

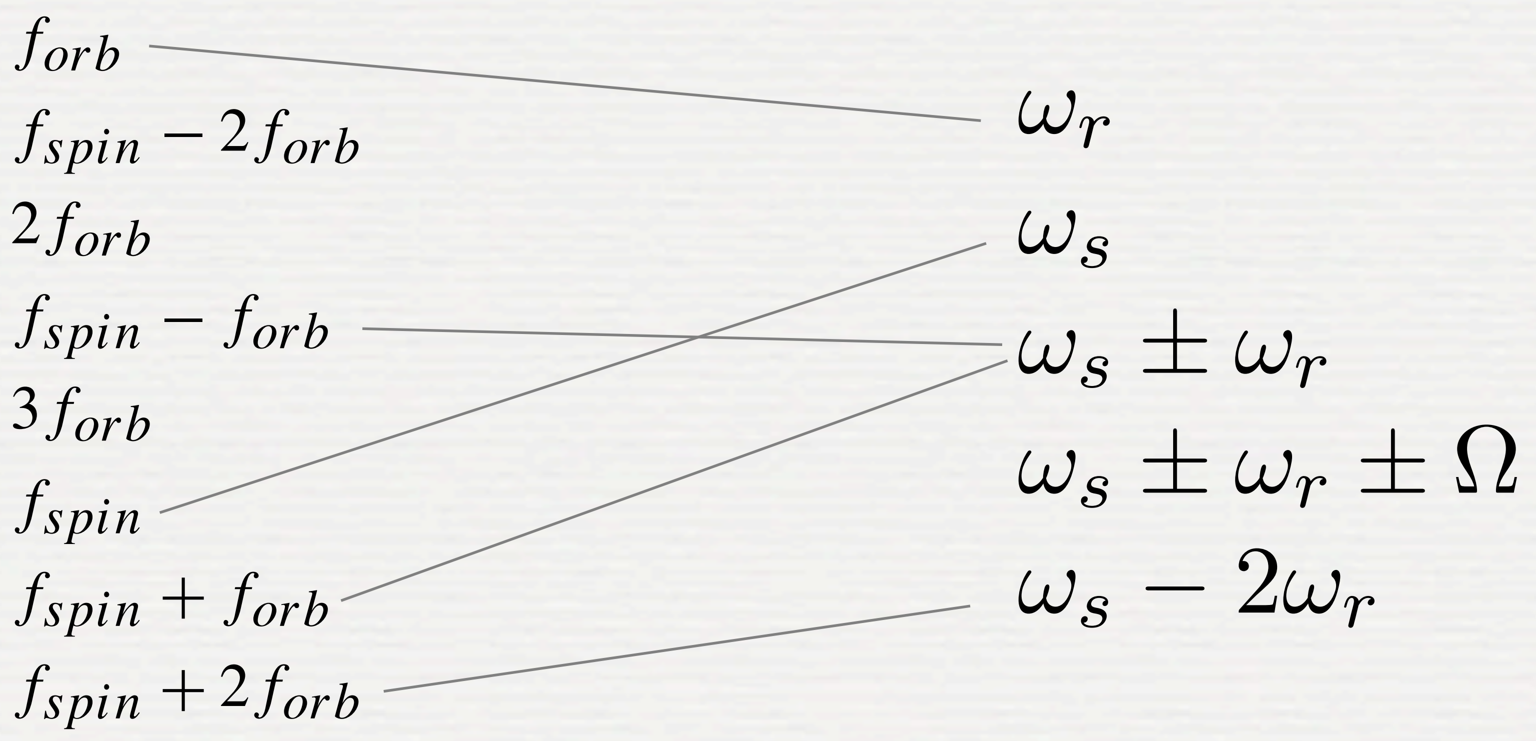
from E. Hardy *et al.*, Space Sci. Rev. 180, p. 177 (2013)

Data analysis

- Estimation of **systematic uncertainty**:

perturbations at different frequencies
$f_{d,sing} = n_1 f_{orb} + n_2 f_{spin}$

overlap with LV frequencies



errors on determinatin of f_{orb} and realization of f_{spin}

phase known

phase unknown (C_{ω_n}, S_{ω_n})

→ estimate systematic uncertainty of each frequency component (uncertainty on perturbation and projection on other frequencies)

might be higher than 10^{-15}

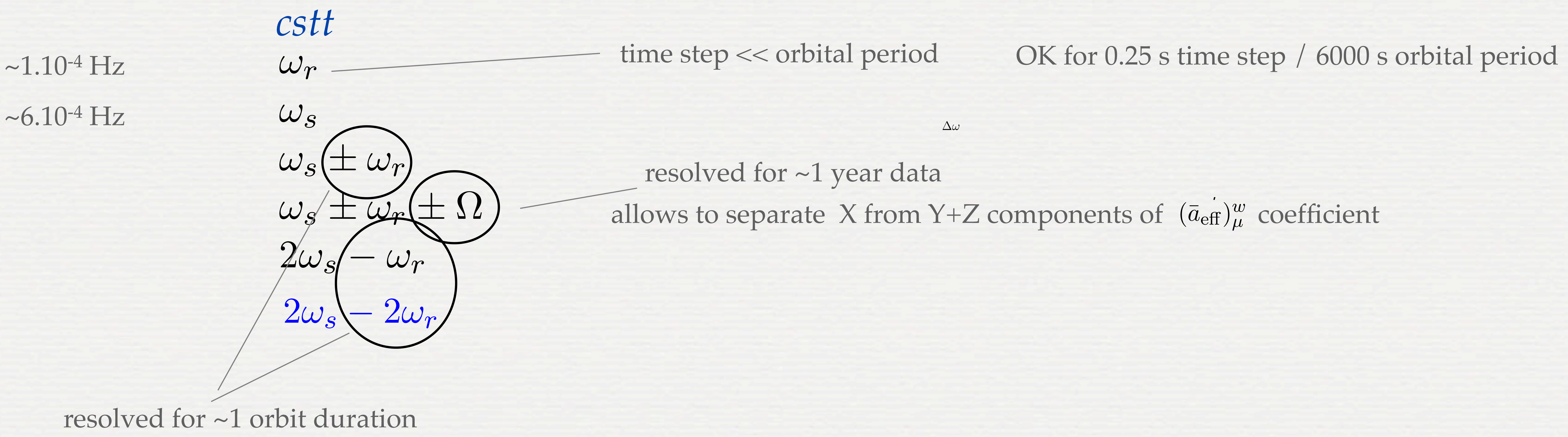
in collaboration with MICROSCOPE team

from E. Hardy *et al.*, Space Sci. Rev. 180, p. 177 (2013)

Data analysis

- Estimate **correlations** between fitted times series amplitudes

frequency difference $\Delta\omega$ resolved if time span of data longer than one period $T = 2\pi/\Delta\omega$



cstt

~1.10^{-4} Hz ω_r — time step << orbital period OK for 0.25 s time step / 6000 s orbital period

~6.10^{-4} Hz ω_s

$\Delta\omega$

$\omega_s \pm \omega_r$

$\omega_s \pm \omega_r \pm \Omega$ — resolved for ~1 year data

allows to separate X from Y+Z components of $(\bar{a}_{\text{eff}}^{'})_\mu^w$ coefficient

$2\omega_s - \omega_r$

$2\omega_s - 2\omega_r$

resolved for ~1 orbit duration

- decorrelate LV signal from perturbations/tidal signal
- decorrelate LV signals between them: helps to decorrelate LV coefficients

- Take precession into account: additional splitting by annual frequency around each frequency

(heliosynchronous orbit)

helps decorrelation of coefficients

Conclusion: 2014 questions adressed

SME search of LV with MICROSCOPE: possible improvement of several orders of magnitude on some coefficients

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Questions on 2014 proposal:

- The signals you would like to analyze and the measured ones that will be exploited;
- Which accuracies your objectives require;
- In which experimental conditions, you need the measurement.

1) signal to be analyzed: N2(c) differential acceleration

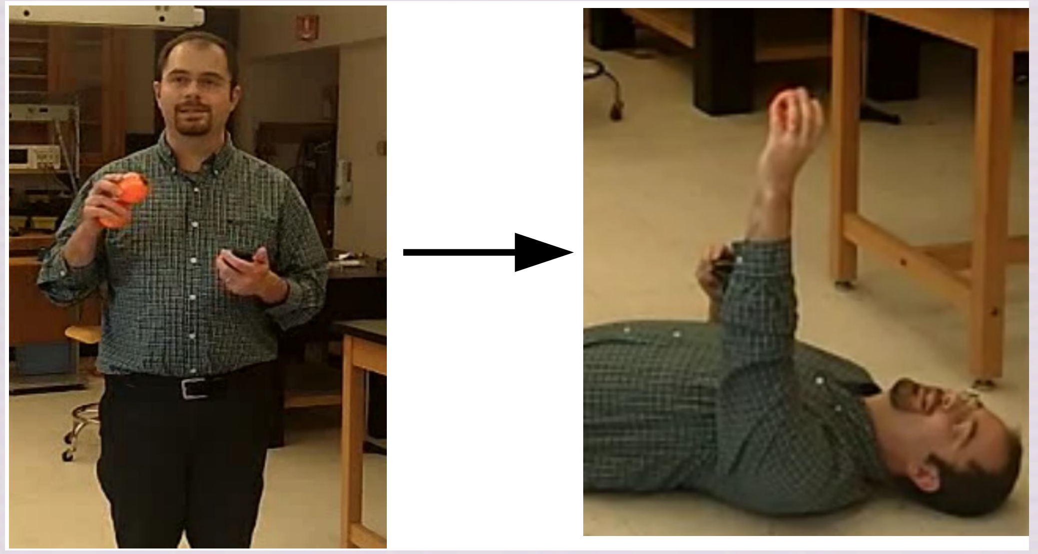
2) relative accuracy required for improvement of at least 3 orders of magnitude: 10^{-15} at frequencies of interest (harmonics of spin, orbital, and annual frequencies)

3) most favorable experimental conditions:
- spin mode
- continuous data series of several orbits
- data sets spread over one year

The collaboration

U.S.:

- Jay Tasson (St Olaf College)



- Quentin Bailey

(Embry-Riddle Aeronautical University)

+graduate student

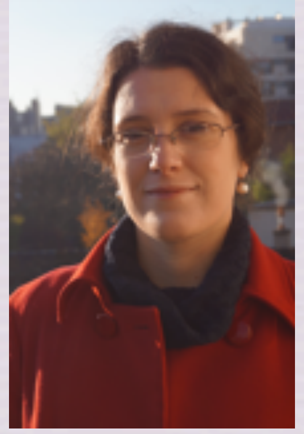
Theory of SME

MICROSCOPE analysis conducted in parallel in both teams

Paris:

- Peter Wolf (SYRTE)

- Christine Guerlin (LKB, SYRTE)



+ Hélène Pihan Le Bars, PhD student (SYRTE)

+ possibly M1 student 3 months 2016

Data analysis (ACES), SME tests

Status and roadmap

☑ SME model derived (U.S. team)

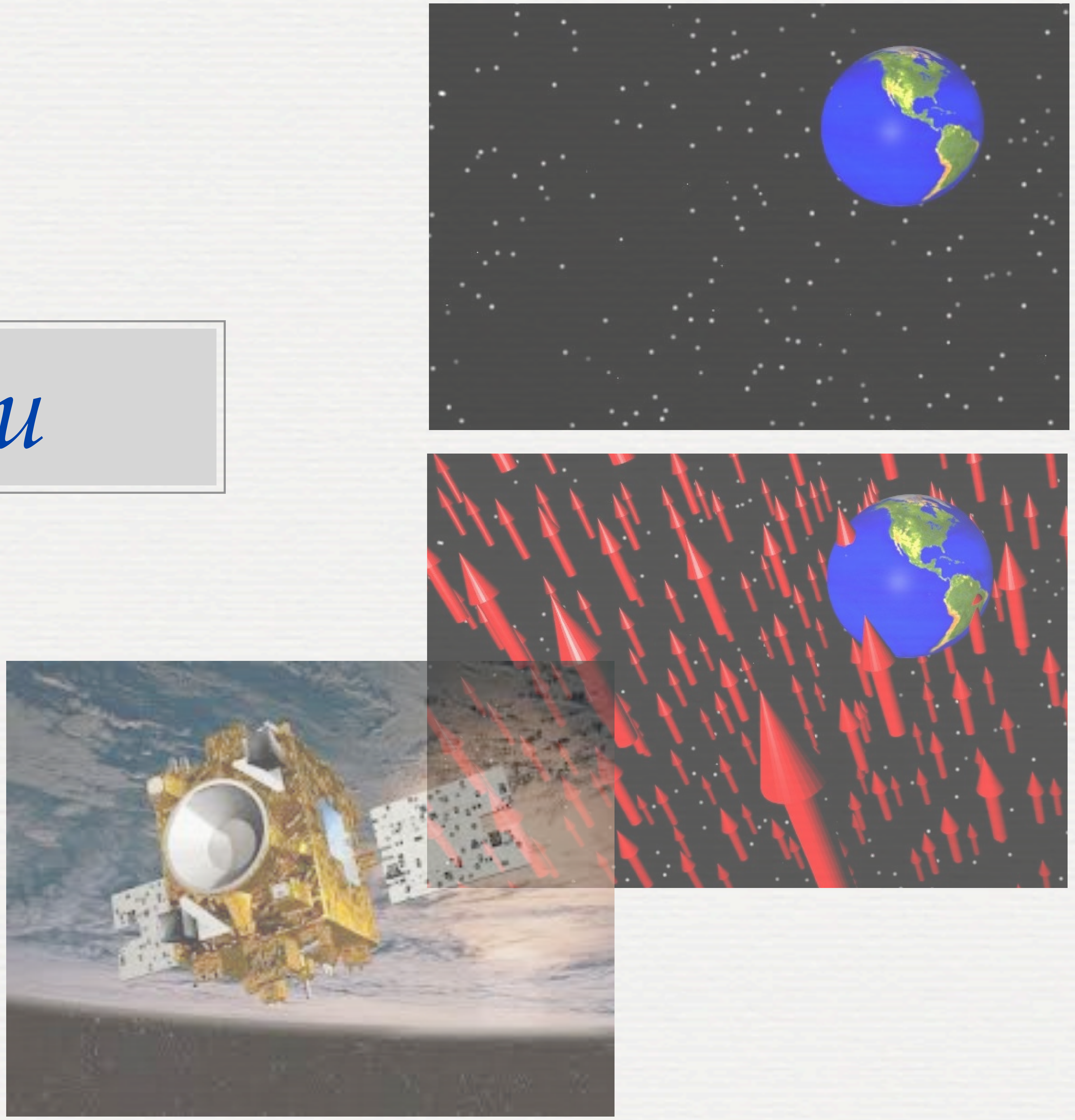
☑ SME simulation and data analysis of other experiments exist (Paris team)
  - collaboration with Q. Bailey in summer 2015
  - publication of present best limits on target coefficients in summer 2015
  - PhD thesis on SME tests a SYRTE

A. Hees, Q. Bailey, C. Guerlin, P. Wolf *et al.*, Phys. Rev. D **92**, 064049 (2015)

☐ Simulation/data analysis to be adapted for MICROSCOPE (both groups)

☐ Evaluate systematics at LV signal frequencies (in coll. with MICROSCOPE team)

Thank you



State of the art

Previous maximal sensitivities

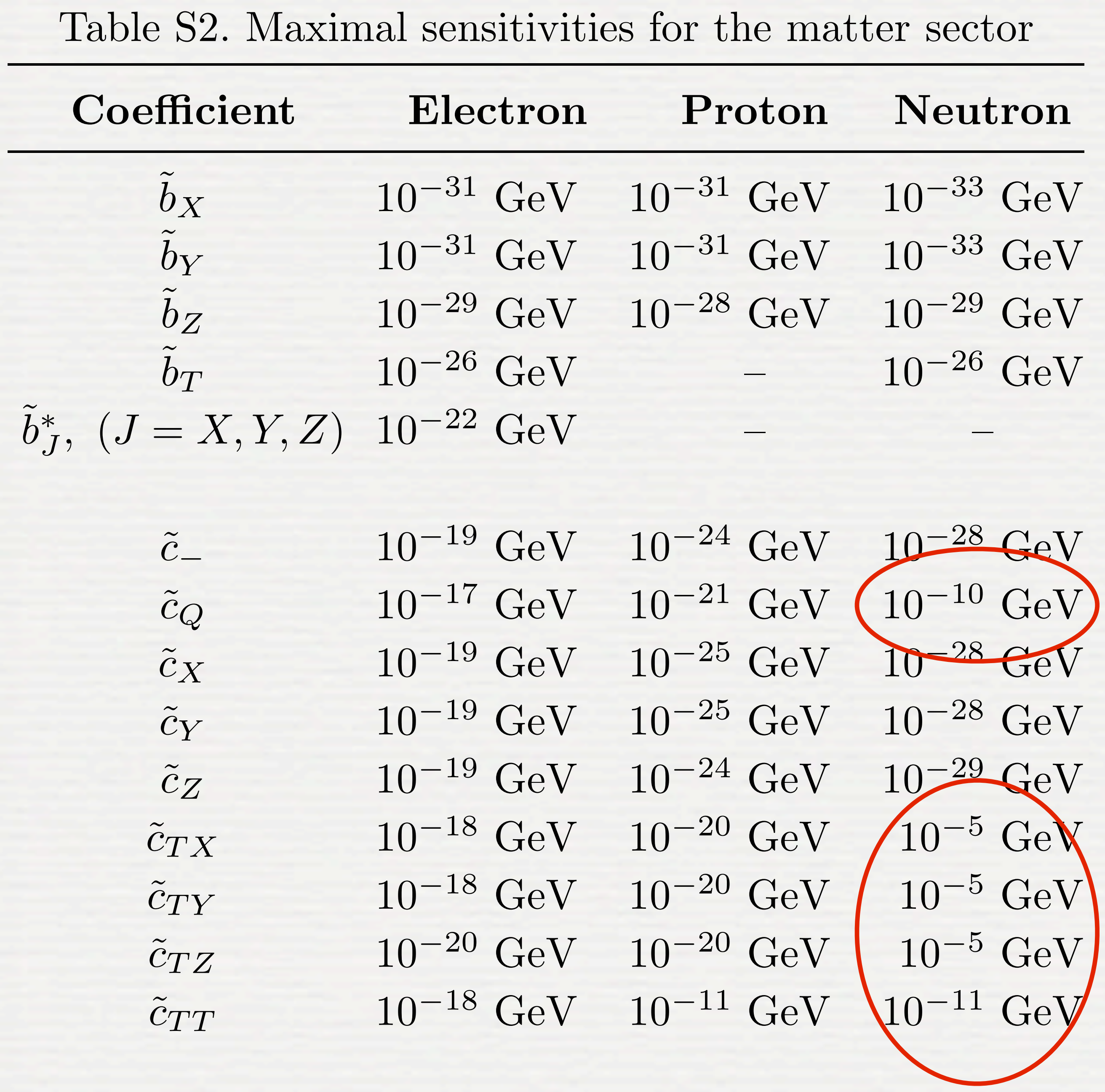


Table S2. Maximal sensitivities for the matter sector

Coefficient	**Electron**	**Proton**	**Neutron**
$\tilde{b}_X$	10^{-31} GeV	10^{-31} GeV	10^{-33} GeV
$\tilde{b}_Y$	10^{-31} GeV	10^{-31} GeV	10^{-33} GeV
$\tilde{b}_Z$	10^{-29} GeV	10^{-28} GeV	10^{-29} GeV
$\tilde{b}_T$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{b}^*_J,\ (J = X, Y, Z)$	10^{-22} GeV	–	–
$\tilde{c}_-$	10^{-19} GeV	10^{-24} GeV	10^{-28} GeV
$\tilde{c}_Q$	10^{-17} GeV	10^{-21} GeV	10^{-10} GeV
$\tilde{c}_X$	10^{-19} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{c}_Y$	10^{-19} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{c}_Z$	10^{-19} GeV	10^{-24} GeV	10^{-29} GeV
$\tilde{c}_{TX}$	10^{-18} GeV	10^{-20} GeV	10^{-5} GeV
$\tilde{c}_{TY}$	10^{-18} GeV	10^{-20} GeV	10^{-5} GeV
$\tilde{c}_{TZ}$	10^{-20} GeV	10^{-20} GeV	10^{-5} GeV
$\tilde{c}_{TT}$	10^{-18} GeV	10^{-11} GeV	10^{-11} GeV

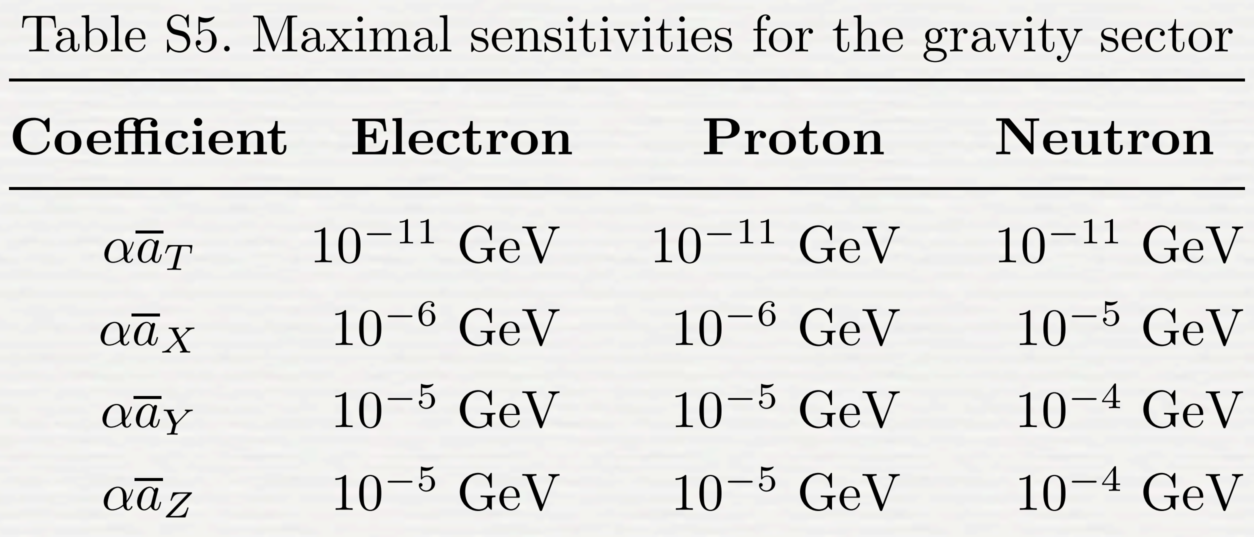


Table S5. Maximal sensitivities for the gravity sector

Coefficient	**Electron**	**Proton**	**Neutron**
$\alpha\bar{a}_T$	10^{-11} GeV	10^{-11} GeV	10^{-11} GeV
$\alpha\bar{a}_X$	10^{-6} GeV	10^{-6} GeV	10^{-5} GeV
$\alpha\bar{a}_Y$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV
$\alpha\bar{a}_Z$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV

from V.A. Kostelecky and N. Russel,
arXiv 0801.0285 (2015)

Last best measurement

from A. Hees, Q. Bailey, C. Guerlin,
P. Wolf *et al.*, Phys. Rev. D **92**,
064049 (2015)

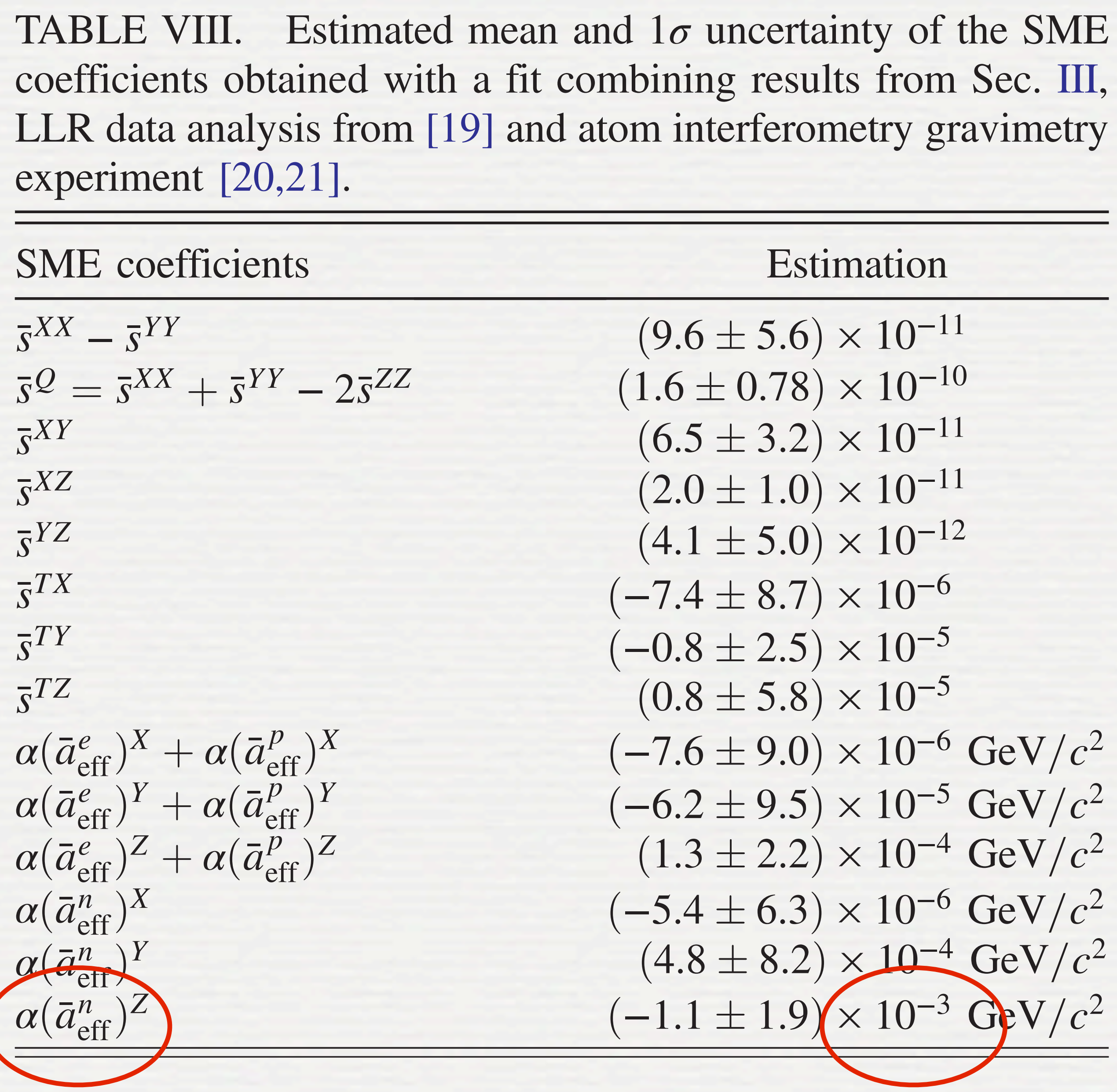


TABLE VIII. Estimated mean and 1σ uncertainty of the SME coefficients obtained with a fit combining results from Sec. III, LLR data analysis from [19] and atom interferometry gravimetry experiment [20,21].

SME coefficients	Estimation
$\bar{s}^{XX} - \bar{s}^{YY}$	$(9.6 \pm 5.6) \times 10^{-11}$
$\bar{s}^{Q} = \bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	$(1.6 \pm 0.78) \times 10^{-10}$
$\bar{s}^{XY}$	$(6.5 \pm 3.2) \times 10^{-11}$
$\bar{s}^{XZ}$	$(2.0 \pm 1.0) \times 10^{-11}$
$\bar{s}^{YZ}$	$(4.1 \pm 5.0) \times 10^{-12}$
$\bar{s}^{TX}$	$(-7.4 \pm 8.7) \times 10^{-6}$
$\bar{s}^{TY}$	$(-0.8 \pm 2.5) \times 10^{-5}$
$\bar{s}^{TZ}$	$(0.8 \pm 5.8) \times 10^{-5}$
$\alpha(\bar{a}^e_{\rm eff})^X + \alpha(\bar{a}^p_{\rm eff})^X$	$(-7.6 \pm 9.0) \times 10^{-6}\ {\rm GeV}/c^2$
$\alpha(\bar{a}^e_{\rm eff})^Y + \alpha(\bar{a}^p_{\rm eff})^Y$	$(-6.2 \pm 9.5) \times 10^{-5}\ {\rm GeV}/c^2$
$\alpha(\bar{a}^e_{\rm eff})^Z + \alpha(\bar{a}^p_{\rm eff})^Z$	$(1.3 \pm 2.2) \times 10^{-4}\ {\rm GeV}/c^2$
$\alpha(\bar{a}^n_{\rm eff})^X$	$(-5.4 \pm 6.3) \times 10^{-6}\ {\rm GeV}/c^2$
$\alpha(\bar{a}^n_{\rm eff})^Y$	$(4.8 \pm 8.2) \times 10^{-4}\ {\rm GeV}/c^2$
$\alpha(\bar{a}^n_{\rm eff})^Z$	$(-1.1 \pm 1.9) \times 10^{-3}\ {\rm GeV}/c^2$

MICROSCOPE

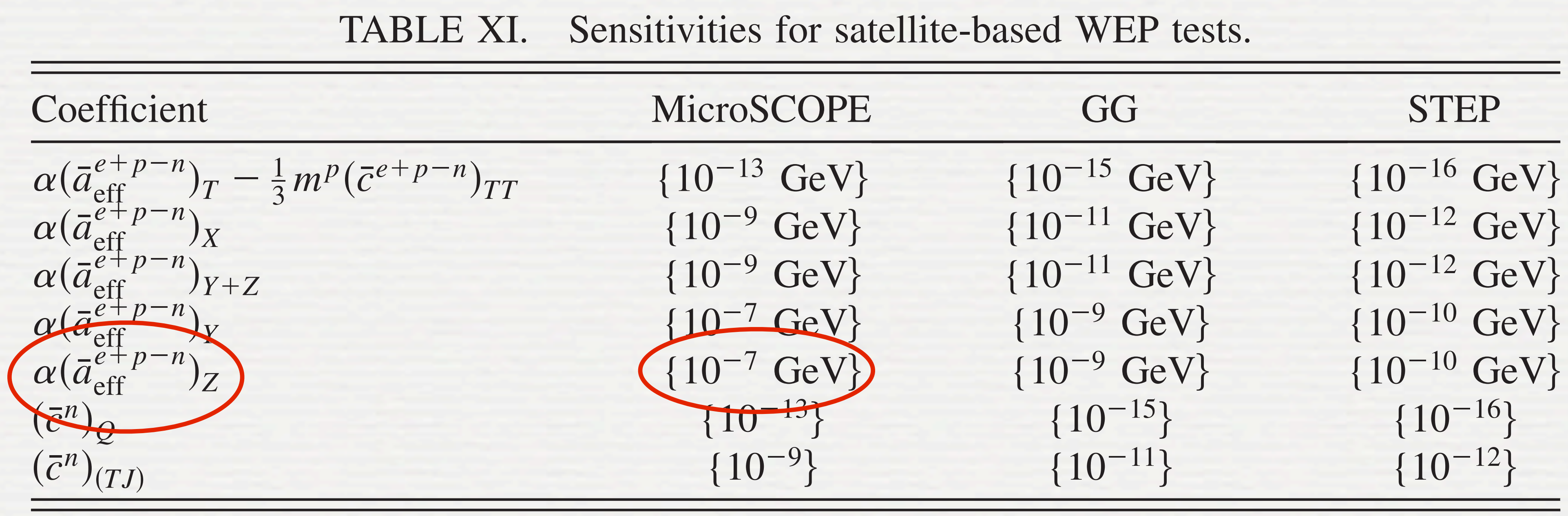


TABLE XI. Sensitivities for satellite-based WEP tests.

Coefficient	MicroSCOPE	GG	STEP
$\alpha(\bar{a}^{e+p-n}_{\rm eff})_T - \frac{1}{3}m^p(\bar{c}^{e+p-n})_{TT}$	$\{10^{-13}$ GeV$\}$	$\{10^{-15}$ GeV$\}$	$\{10^{-16}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\rm eff})_X$	$\{10^{-9}$ GeV$\}$	$\{10^{-11}$ GeV$\}$	$\{10^{-12}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\rm eff})_{Y+Z}$	$\{10^{-9}$ GeV$\}$	$\{10^{-11}$ GeV$\}$	$\{10^{-12}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\rm eff})_Y$	$\{10^{-7}$ GeV$\}$	$\{10^{-9}$ GeV$\}$	$\{10^{-10}$ GeV$\}$
$\alpha(\bar{a}^{e+p-n}_{\rm eff})_Z$	$\{10^{-7}$ GeV$\}$	$\{10^{-9}$ GeV$\}$	$\{10^{-10}$ GeV$\}$
$(\bar{c}^n)_Q$	$\{10^{-13}\}$	$\{10^{-15}\}$	$\{10^{-16}\}$
$(\bar{c}^n)_{(TJ)}$	$\{10^{-9}\}$	$\{10^{-11}\}$	$\{10^{-12}\}$

from V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

Composition dependence of test bodies

$$\sum_w \left(\frac{N_1^w}{m_1} - \frac{N_2^w}{m_2}\right)(\bar{a}^w_{\text{eff}})_\mu = \frac{N_1^p N_2^n - N_1^n N_2^p}{m_1 m_2} m^n (\bar{a}_{\text{eff}}^{e+p-n})_\mu$$

$$\longrightarrow C_{\omega_n},\ S_{\omega_n} = f(\bar{c}_{\mu\nu}^{e+p-n}, (\bar{a}_{\text{eff}}^{e+p-n})_\mu)$$

9 independent coefficients

4 independent coefficients

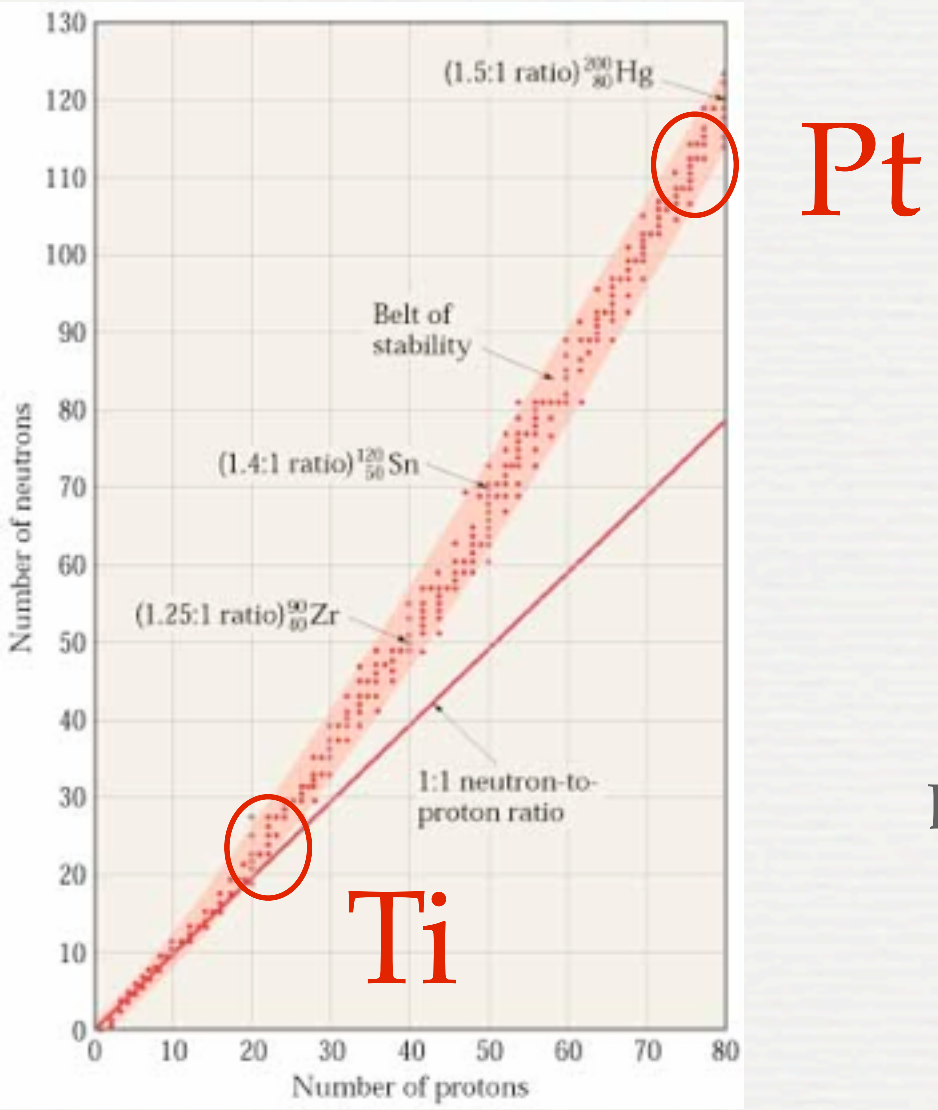
with

$$(\bar{a}_{\text{eff}}^{e+p-n})_\mu \approx (\bar{a}^e_{\text{eff}})_\mu + (\bar{a}^p_{\text{eff}})_\mu - (\bar{a}^n_{\text{eff}})_\mu$$

$$\bar{c}_{\mu\nu}^{e+p-n} \approx \frac{m_e}{m_p}\bar{c}^e_{\mu\nu} + \bar{c}^p_{\mu\nu} + \bar{c}^n_{\mu\nu}$$

Composition of test bodies

prefactor from $\frac{N_1^w}{m_1} - \frac{N_2^w}{m_2}$: ~ difference in neutron/nucleons ratios x GeV^{-1}



	p	p+n	n	n/n+p	p/n+p	n/p
Titanium	22	48	26	0.54	0.46	1.18
Platinum	78	193	115	0.6	0.4	1.47
Difference:				0.06		

SME model for satellite based WEP test

$$\Delta a^{\hat{x}}_{\mathrm{LV}} = r\omega_s^2 \sum_{w,n} \left(\frac{N_1^w}{m_1} - \frac{N_2^w}{m_2}\right)(P_n \sin(\omega_n T + \alpha_n) + Q_n \cos(\omega_n T + \alpha_n)).$$

with

TABLE IX. Notation for satellite-based WEP tests.

Quantity	Definition
$R_\oplus$	Mean Earth radius
$V_\oplus$	Mean Earth orbital speed
r^J	Earth-satellite separation
ω_s	Satellite orbital frequency
ω_r	Satellite rotational frequency
ξ_1	Inclination of satellite orbit
ξ_2	Longitude of satellite-orbit node
θ_1	Phase fixing satellite location at $T = 0$
θ_2	Phase fixing satellite orientation at $T = 0$

with orbital and spin frequencies defined around same direction

TABLE X. Amplitudes for satellite-based WEP tests.

Amplitude	Phase
$P_{\omega_r} = m^w r\omega_s[(\bar{c}^w)_{(TY)} \sin\xi_1 + (\bar{c}^w)_{(TX)} \cos\xi_1] + \frac{\omega R_\oplus^2 \alpha \cos\xi_2}{5r}[(\bar{a}^w_{\mathrm{eff}})_X \cos\xi_1 + (\bar{a}^w_{\mathrm{eff}})_Y \sin\xi_1]$	θ_2
$Q_{\omega_r} = m^w r\omega_s[(\bar{c}^w)_{(TX)} \sin\xi_1 \cos\xi_2 - (\bar{c}^w)_{(TY)} \cos\xi_1 \cos\xi_2 - (\bar{c}^w)_{(TZ)} \sin\xi_2] + \frac{\omega R_\oplus^2 \alpha}{5r}[(\bar{a}^w_{\mathrm{eff}})_X \sin\xi_1 - (\bar{a}^w_{\mathrm{eff}})_Y \cos\xi_1]$	θ_2
$P_{\omega_r+\omega_s} = 2m^w[\cos\xi_2 \cos2\xi_1(\bar{c}^w)_{(XY)} + \sin\xi_2 \sin\xi_1(\bar{c}^w)_{(YZ)} + \frac{1}{2} \sin2\xi_1 \cos\xi_2((\bar{c}^w)_{YY} - (\bar{c}^w)_{XX}) + \sin\xi_2 \cos\xi_1(\bar{c}^w)_{(XZ)}]$	$\theta_1 + \theta_2$
$Q_{\omega_s+\omega_r} = m^w[(\cos^2\xi_2\cos^2\xi_1 - \sin^2\xi_1 + \frac{1}{2}\sin^2\xi_2)((\bar{c}^w)_{XX} - (\bar{c}^w)_{YY}) + \frac{1}{2}\sin^2\xi_2((\bar{c}^w)_{XX} + (\bar{c}^w)_{YY} - 2(\bar{c}^w)_{ZZ})$ $- \cos\xi_1 \sin2\xi_2(\bar{c}^w)_{(YZ)} + \sin\xi_1 \sin2\xi_2(\bar{c}^w)_{(XZ)} + \sin2\xi_1(1 + \cos^2\xi_2)(\bar{c}^w)_{(XY)}]$	$\theta_1 + \theta_2$
$Q_{\omega_s-\omega_r} = m^w[(\cos^2\xi_1\sin^2\xi_2 + \frac{1}{2}\cos^2\xi_2 + \frac{1}{2})((\bar{c}^w)_{XX} - (\bar{c}^w)_{YY}) - \frac{1}{2}\sin^2\xi_2((\bar{c}^w)_{XX} + (\bar{c}^w)_{YY} - 2(\bar{c}^w)_{ZZ})$ $+ 2(\bar{c}^w)_{YY} + \sin2\xi_1(1 - \cos^2\xi_2)(\bar{c}^w)_{(XY)} - \sin\xi_1 \sin2\xi_2(\bar{c}^w)_{(XZ)} + \cos\xi_1 \sin2\xi_2(\bar{c}^w)_{(YZ)}] - 2\alpha(\bar{a}^w_{\mathrm{eff}})_T$	$\theta_1 - \theta_2$
$P_{2\omega_s-\omega_r} = -m^w r\omega_s[(\bar{c}^w)_{(TX)} \cos\xi_1 + (\bar{c}^w)_{(TY)} \sin\xi_1] - \frac{3\omega R_\oplus^2 \alpha \cos\xi_2}{5r}[(\bar{a}^w_{\mathrm{eff}})_X \cos\xi_1 + (\bar{a}^w_{\mathrm{eff}})_Y \sin\xi_1]$	$2\theta_1 - \theta_2$
$Q_{2\omega_s-\omega_r} = m^w r\omega_s[(\bar{c}^w)_{(TY)} \cos\xi_1 \cos\xi_2 - (\bar{c}^w)_{(TX)} \sin\xi_1 \cos\xi_2 + (\bar{c}^w)_{(TZ)} \sin\xi_2] - \frac{3\omega R_\oplus^2 \alpha}{5r}[(\bar{a}^w_{\mathrm{eff}})_X \sin\xi_1 - (\bar{a}^w_{\mathrm{eff}})_Y \cos\xi_1]$	$2\theta_1 - \theta_2$
$P_{\Omega+\omega_s+\omega_r} = m^w V_\oplus[(\cos^2\xi_1 - \sin^2\xi_1\cos^2\xi_2 - \cos\eta \cos\xi_2 \cos2\xi_1 - \sin\eta \sin\xi_2 \cos\xi_1)(\bar{c}^w)_{(TX)}$ $+ \sin\xi_1 \sin\xi_2(\cos\xi_2 - \cos\eta)(\bar{c}^w)_{(TZ)} + (\cos\xi_1 + \cos\xi_1\cos^2\xi_2 - \sin\eta \sin\xi_2 - 2\cos\eta \cos\xi_1 \cos\xi_2) \sin\xi_1(\bar{c}^w)_{(TY)}]$	$\theta_1 + \theta_2$
$Q_{\Omega+\omega_s+\omega_r} = m^w V_\oplus[(2\cos\xi_1 \cos\xi_2 - \sin\eta \sin\xi_2 \cos\xi_2 - \cos\eta \cos\xi_1(1 + \cos^2\xi_2)) \sin\xi_1(\bar{c}^w)_{(TX)}$ $- (\cos2\xi_1 \cos\xi_2 - \sin\eta \cos\xi_1 \sin\xi_2 \cos\xi_2 + \cos\eta(1 - \cos^2\xi_1\sin^2\xi_2))(\bar{c}^w)_{(TY)}$ $- (\cos\xi_1 - \sin\eta \sin\xi_2 - \cos\eta \cos\xi_1) \sin\xi_2(\bar{c}^w)_{(TZ)}]$	$\theta_1 + \theta_2$
$P_{\Omega+\omega_s-\omega_r} = m^w V_\oplus[(1 - \sin^2\xi_1\sin^2\xi_2)(\bar{c}^w)_{(TX)} + \frac{1}{2} \sin2\xi_1\sin^2\xi_2(\bar{c}^w)_{(TY)} - \frac{1}{2} \sin\xi_1 \sin2\xi_2(\bar{c}^w)_{(TZ)}] - \alpha V_\oplus(\bar{a}^w_{\mathrm{eff}})_X$	$\theta_1 - \theta_2$
$Q_{\Omega+\omega_s-\omega_r} = -m^w V_\oplus[\frac{1}{2}(\cos\eta \sin2\xi_1\sin^2\xi_2 - \sin\eta \sin\xi_1 \sin2\xi_2)(\bar{c}^w)_{(TX)} + (\frac{1}{2} \sin\eta \cos\xi_1 \sin2\xi_2$ $+ (1 - \sin^2\xi_2\cos^2\xi_1) \cos\eta)(\bar{c}^w)_{(TY)} + (\sin\eta\sin^2\xi_2 + \frac{1}{2} \cos\eta \cos\xi_1 \sin2\xi_2)(\bar{c}^w)_{(TZ)}]$ $+ \alpha V_\oplus[(\bar{a}^w_{\mathrm{eff}})_Z \sin\eta + (\bar{a}^w_{\mathrm{eff}})_Y \cos\eta]$	$\theta_1 - \theta_2$
$P_{\Omega-\omega_s+\omega_r} = m^w V_\oplus[(1 - \sin^2\xi_1\sin^2\xi_2)(\bar{c}^w)_{(TX)} + \frac{1}{2} \sin2\xi_1\sin^2\xi_2(\bar{c}^w)_{(TY)} - \frac{1}{2} \sin\xi_1 \sin2\xi_2(\bar{c}^w)_{(TZ)}] - \alpha V_\oplus(\bar{a}^w_{\mathrm{eff}})_X$	$-\theta_1 + \theta_2$
$Q_{\Omega-\omega_s+\omega_r} = m^w V_\oplus[\frac{1}{2}(\sin\eta \sin\xi_1 \sin2\xi_2 - \cos\eta \sin2\xi_1\sin^2\xi_2)(\bar{c}^w)_{(TX)} - (\frac{1}{2} \sin\eta \cos\xi_1 \sin2\xi_2$ $+ \cos\eta(1 - \cos^2\xi_1\sin^2\xi_2))(\bar{c}^w)_{(TY)} - (\sin\eta\sin^2\xi_2 + \frac{1}{2} \cos\eta \cos\xi_1 \sin2\xi_2)(\bar{c}^w)_{(TZ)}]$ $+ \alpha V_\oplus[(\bar{a}^w_{\mathrm{eff}})_Z \sin\eta + (\bar{a}^w_{\mathrm{eff}})_Y \cos\eta]$	$-\theta_1 + \theta_2$
$P_{\Omega-\omega_s-\omega_r} = m^w V_\oplus[(\cos^2\xi_1 - \sin^2\xi_1\cos^2\xi_2 + \sin\eta \cos\xi_1 \sin\xi_2 + \cos\eta \cos2\xi_1 \cos\xi_2)(\bar{c}^w)_{(TX)}$ $+ (\frac{1}{2} \sin2\xi_1(1 + \cos^2\xi_2) + \sin\eta \sin\xi_1 \sin\xi_2 + \cos\eta \sin2\xi_1 \cos\xi_2)(\bar{c}^w)_{(TY)} + (\frac{1}{2} \sin2\xi_2 + \cos\eta \sin\xi_2) \sin\xi_1(\bar{c}^w)_{(TZ)}]$	$-\theta_1 - \theta_2$
$Q_{\Omega-\omega_s-\omega_r} = m^w V_\oplus[-(\sin2\xi_1 \cos\xi_2 + \frac{1}{2} \sin\eta \sin\xi_1 \sin2\xi_2 + \frac{1}{2} \cos\eta \sin\xi_1(1 + \cos^2\xi_2))(\bar{c}^w)_{(TX)}$ $+ (\cos2\xi_1 \cos\xi_2 + \frac{1}{2} \sin\eta \cos\xi_1 \sin\xi_2 - \cos\eta(\sin^2\xi_1 - \cos^2\xi_1\cos^2\xi_2))(\bar{c}^w)_{(TY)}$ $+ (\cos\xi_1 \sin\xi_2 + \sin\eta\sin^2\xi_2 + \frac{1}{2} \cos\eta \cos\xi_1 \sin2\xi_2)(\bar{c}^w)_{(TZ)}]$	$-\theta_1 - \theta_2$

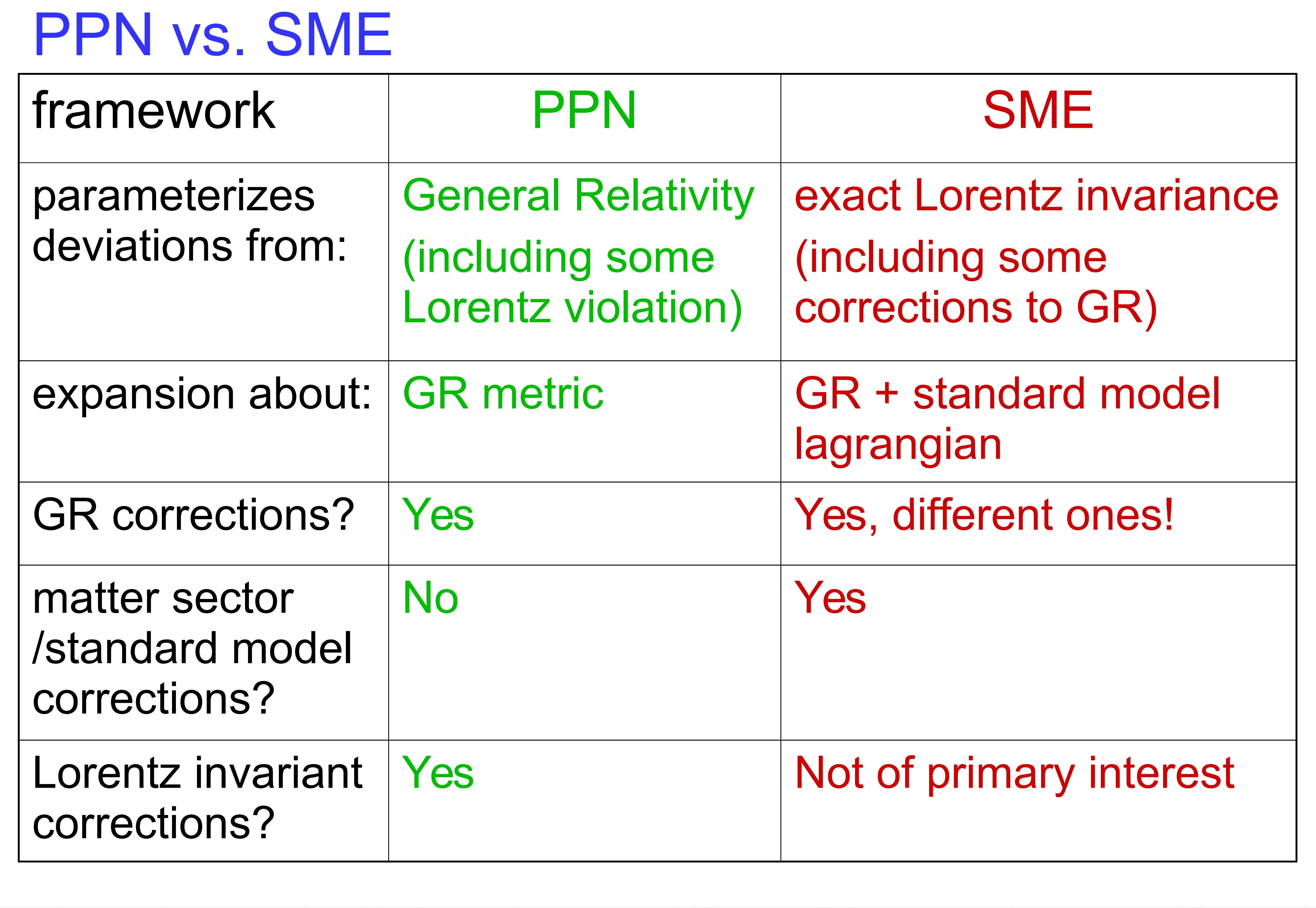
from V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

Constraints on Lorentz violation in the SME framework

- atom-interferometer tests (Mueller et al)
- lunar laser ranging (Battat et al)
- pulsar-timing observations (Shao)
- short-range gravity tests (Long et al)
- trapped particle tests (Dehmelt, Gabrielse, …)
- spin-polarized matter tests (EotWash)
- clock-comparison tests (Gibble, Hunter, Romalis, Hedges, Walsworth, Wolf, …)
- tests with resonant cavities (Lipa, Mueller, Peters, Schiller, Tobar, Wolf, Bize, …)
- neutrino oscillations (LSND, Minos, Super K, …)
- muon tests (Hughes, BNL g-2)
- meson oscillations (BABAR, BELLE, DELPHI, FOCUS, KTeV, OPAL, …)
- astroparticle physics (Altschul, …)
- cosmological birefringence (Mewes, …)
- …

Collected results-> Data Tables: Rev. Mod. Phys. 2011, arxiv: 0801.0287v8 (2015 edition)

PPN and SME



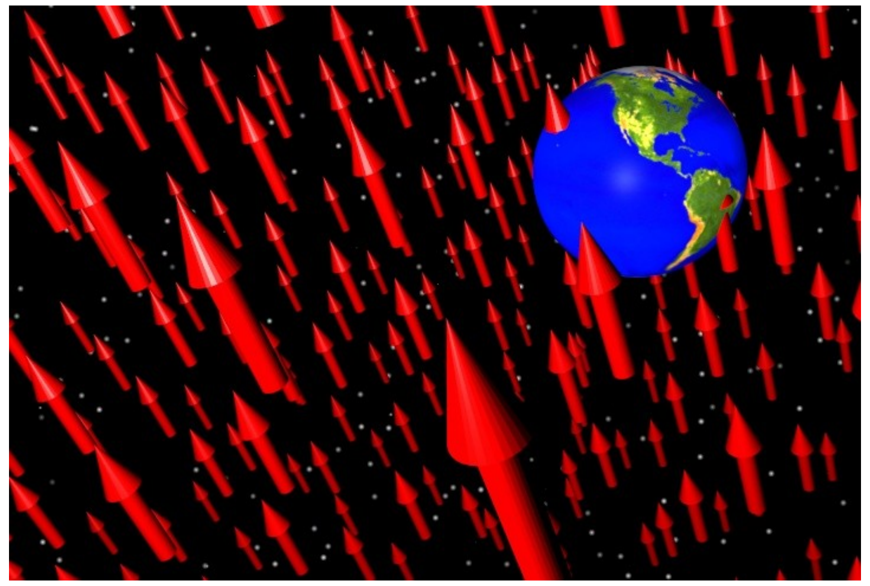
PPN vs. SME

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

Origin of Lorentz violating tensors

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

SME equations of motion in «lab» frame

$$F_{\hat{j}} = m_{\hat{j}\hat{k}}\ddot{x}_{\hat{k}}. \tag{132}$$

At this perturbative order, the inertial and gravitational forces acting on the test particle are given by

$$\begin{aligned}
F_{\hat{x}} &= m^{\mathrm{T}} g \bar{s}_{\hat{z}\hat{x}}, \\
F_{\hat{y}} &= m^{\mathrm{T}} g \bar{s}_{\hat{z}\hat{y}}, \\
F_{\hat{z}} &= -m^{\mathrm{T}} g \bigg[1 + \frac{2\alpha}{m^{\mathrm{T}}} (\bar{a}^{\mathrm{T}}_{\mathrm{eff}})_{\hat{t}} + \frac{2\alpha}{m^{\mathrm{S}}} (\bar{a}^{\mathrm{S}}_{\mathrm{eff}})_{\hat{t}} + (\bar{c}^{\mathrm{T}})_{\hat{t}\hat{t}} \\
&\quad + (\bar{c}^{\mathrm{S}})_{\hat{t}\hat{t}} + \frac{3}{2}\bar{s}_{\hat{t}\hat{t}} + \frac{1}{2}\bar{s}_{\hat{z}\hat{z}} \bigg],
\end{aligned} \tag{133}$$

while

$$m_{\hat{j}\hat{k}} = m^{\mathrm{T}}(1 + (\bar{c}^{\mathrm{T}})_{\hat{t}\hat{t}})\delta_{\hat{j}\hat{k}} + 2m^{\mathrm{T}}(\bar{c}^{\mathrm{T}})_{(\hat{j}\hat{k})} \tag{134}$$

V. A. Kostelecky and J. D. Tasson, Phys. Rev. D 83, 016013 (2011)

Frameworks for Lorentz violation

- Key Idea: Rotate or boost your experiment – physics changes!
- Approaches:

1) modified Lorentz transformation
    - vacuum empty
    - deformed lightcone
    - "simple", kinematical, phenomenological
    - e.g., RMS framework, DSR, …

2) "background" tensor fields (a_{μ}, b_{μ}, $c_{\mu\nu}$, $k_{\mu\nu\kappa\lambda}$,…)
    - vacuum contains background fields
    - dynamical, can incorporate QM, etc.
    - complicated, many possible effects
    - e.g., ***Standard-Model Extension***
    - contains test frameworks 1) as limiting cases

Tidal acceleration

$$\Delta \mathrm{a}_{\mathrm{tidal}}^{\hat{x}} = -\Big(\frac{3}{2}\omega_s^2 \cos(2\omega_r T - 2\omega_s T + \theta_2 - \theta_1) + \omega_r^2 + \frac{1}{2}\omega_s^2\Big)\Delta\hat{x}.$$

Orders of magnitude for SME coefficients

Sizes of Lorentz-violating effects

- Benchmark estimate:

  coefficient size ~ mass of particle²/Planck mass

  e.g., neutron a_μ^n ~ m_n^2 / 10^{19} GeV ≈ 10^{-19} GeV

- However, with gravity couplings coefficients could be quite large ("countershading")

  e.g., electron a_Z^e ~ m_e=.5 MeV (current sensitivity ~ .01 MeV)

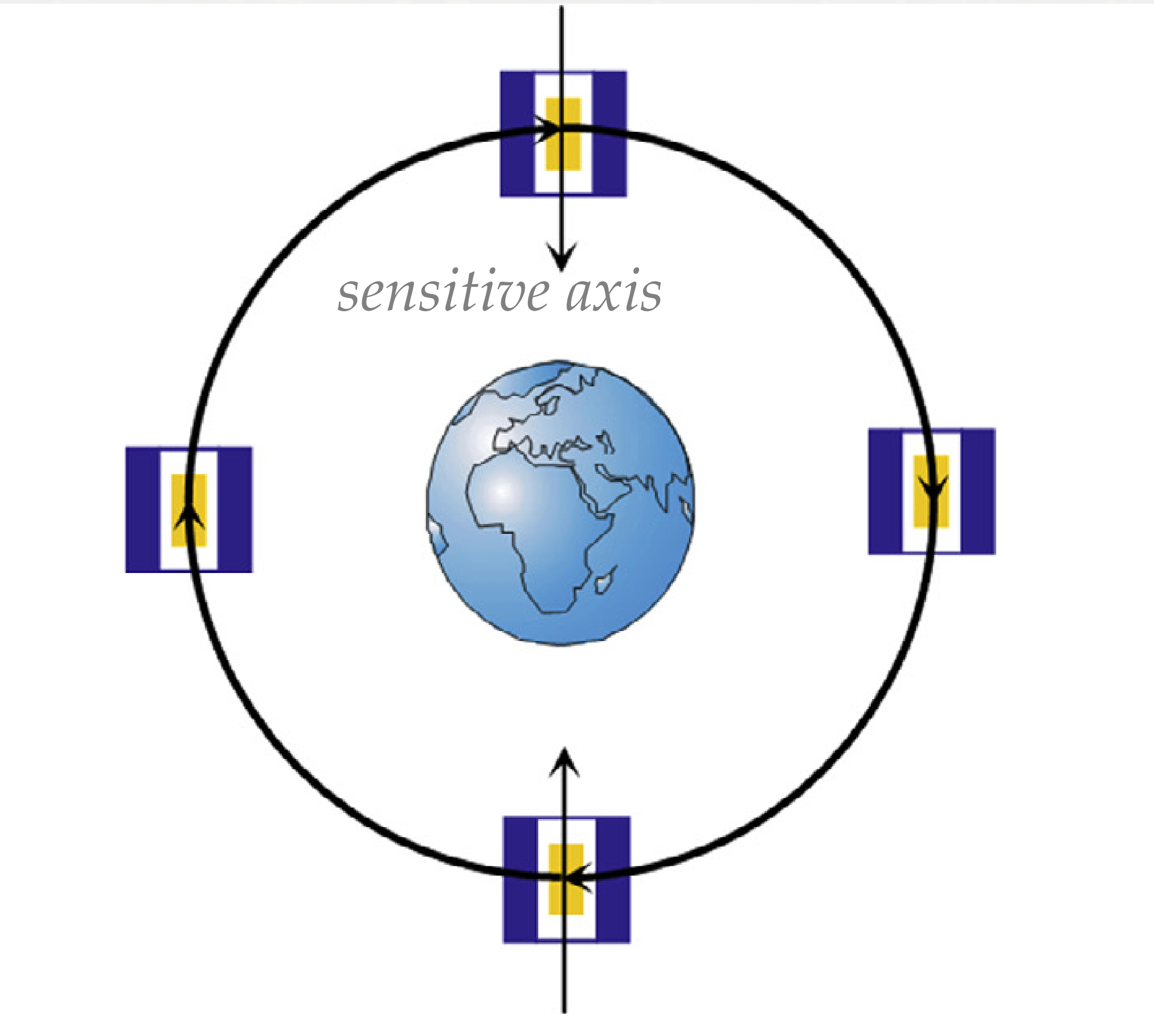
$\overline{s}^{\mu\nu}$ ~ 10^{-10}- 10^{-35}

$(\bar{k}_{\text{eff}})_{jklm}$ could be as big as 10^{-9} m² ~ 10^{21} GeV^{-2}

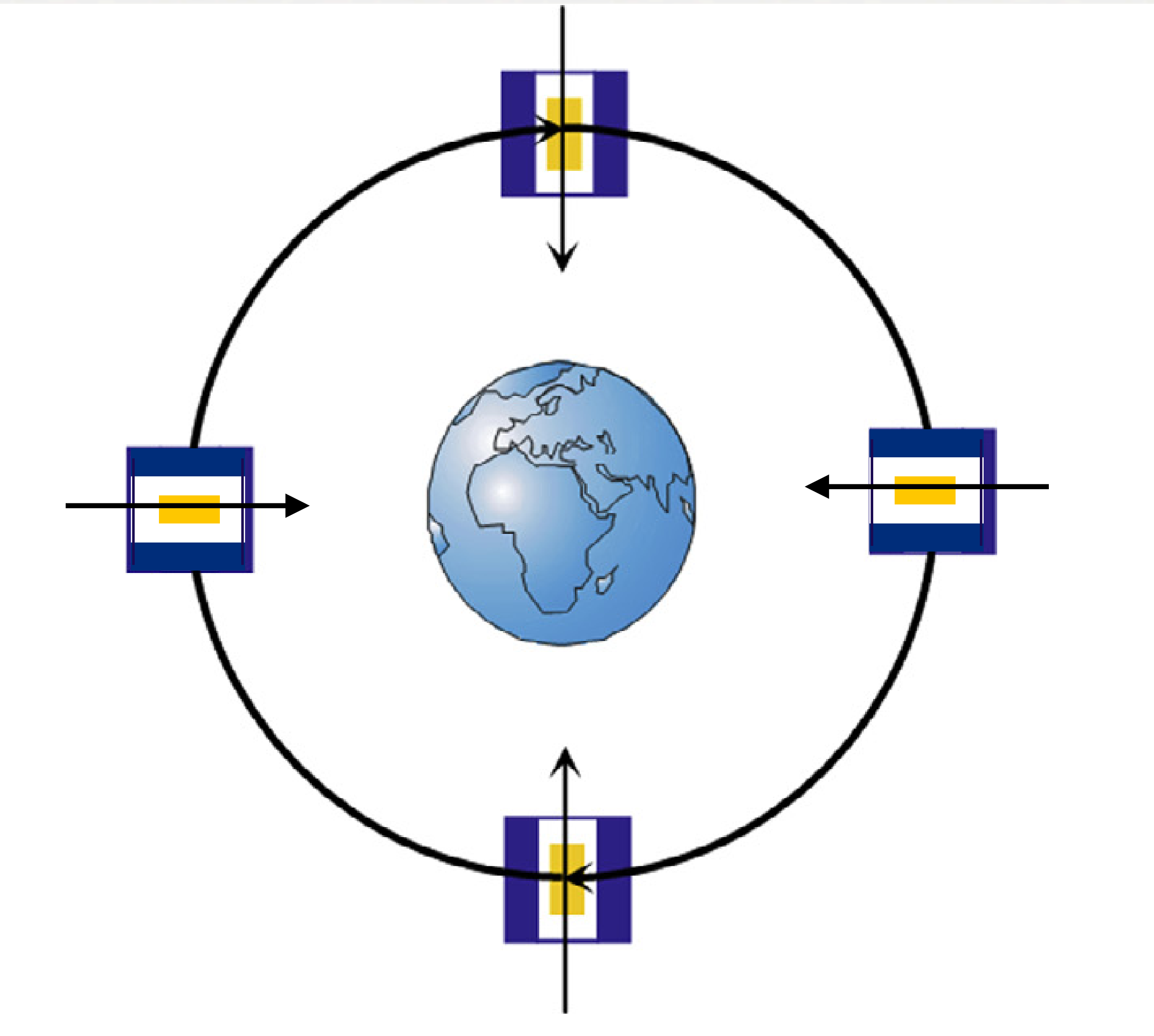
WEP violation through matter dependent Lorentz violation

Example of signals in:

Inertial mode



Nadir pointing



$$\eta = \frac{\frac{mg1}{mi1}-\frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1}+\frac{mg2}{mi2}\right)}$$

Signal frequency:

non LV WEP violation:	ω_r	DC
LV WEP violation:	DC (lowest order)	ω_r

modification to gravitational mass

inertial mass tensor

$$F_{\hat{j}} = m_{\hat{j}\hat{k}}\ddot{x}_{\hat{k}}.$$

species dependent, time varying

SME matter gravity couplings

SME matter-gravity couplings

- Start with lagrangian for fermions in curved spacetime -> Classical action for spinless matter:

$$S_M = \int d\lambda \left(-m\sqrt{-(g_{\mu\nu} + 2c_{\mu\nu})u^\mu u^\nu} - a_\mu u^\mu \right)$$

Species-dependent coefficients for Lorentz violation

Note: a_μ is **unobservable** in flat spacetime

- For basic matter (e, p, n) there are 36 coefficients
- Features:
  - Flavor-dependent anisotropic gravitational fields
  - Test-particle dependent motion in a gravitational field (**WEP violation!**)
  - Sidereal time variation
  - Can be probed in WEP tests, solar-system tests, ...

(Kostelecký & Tasson PRL 09, PRD 11)