Lorentz Violation, Gravity, and Lasers

Jay D. Tasson

Carleton College

jtasson@carleton.edu

November 11, 2020

Outline

- introduction
  - Lorentz violation & the Standard-Model Extension (SME)
  - gravity
- tests: recent and proposed lab tests
  - gravimeters
  - **Sagnac gyroscopes**
  - MICROSCOPE
  - Sattelite Ranging

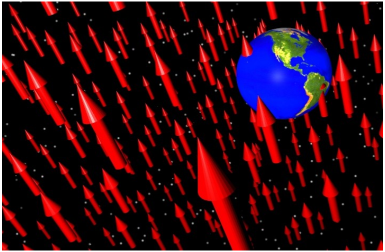
1

[1] Moseley...Tasson... PRD'19

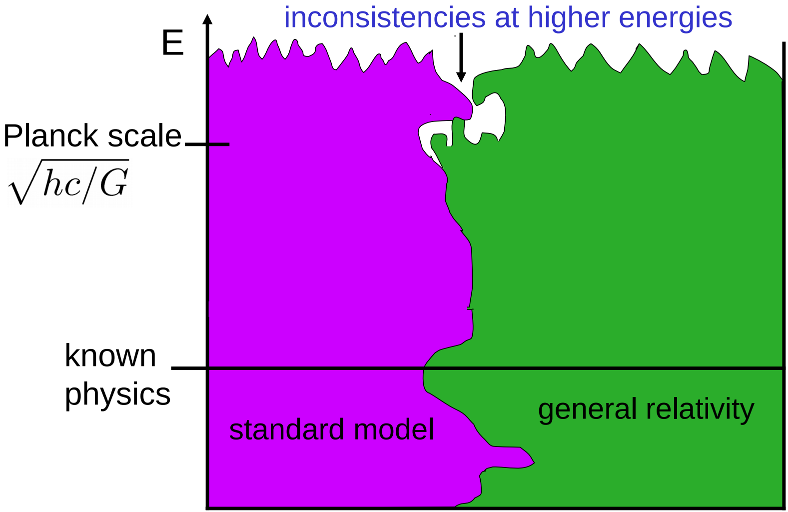
Lorentz violation

- Lorentz symmetry

- Lorentz violation



motivation



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

motivation

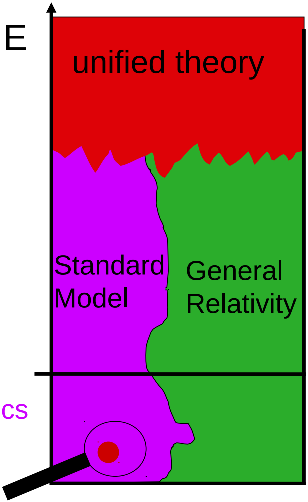
options for probing experimentally

- galaxy-sized accelerator

- suppressed effects in sensitive experiments

Lorentz and CPT violation

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



the Standard-Model Extension (SME)

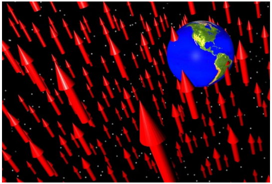
effective field theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent CPT & Lorentz violation
  $$L_{\rm SME} = L_{\rm GR} + L_{\rm SM} + L_{\rm LV}$$
- CPT violation comes with Lorentz violation

CPT & 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

the Standard-Model Extension (SME)

effective field theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent CPT & L... ntz violation

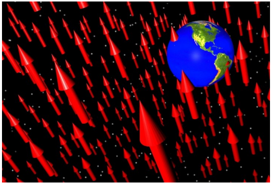
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L ...$$

- CPT violation comes with Loren... ation

CPT & Lorentz-violating terms

- constructed from GR a... fields
- parameterized
  by coefficients f... entz violation
- samples

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



A broad and general search for new physics

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

Recent Gravitational Tests

System	E.g.	
MICROSCOPE	Pihan-le Bars *et al.*	PRL 123, 231102 (2019)
gravimeters	Flowers *et al.*	PRL 119, 201101 (2017)
solar-system data	Hees *et al.*	PRD 92, 064049 (2015)
lunar laser ranging	Bourgoin *et al.*	PRL 117, 241301 (2016)
gravitational waves	LIGO,Virgo, FermiGBM,Integral	ApJL 848, L13 (2017)
WEP experiments	Hohensee *et al.*	PRL 111, 151102 (2013)
pulsar timing	L. Shao	PRL 112, 111103 (2014)
short-range gravity	C.-G. Shao *et al.*	PRL 122, 011102 (2019)
VLBI	Le Poncin-Lafitte *et al.*	PRD 94, 125030 (2016)

...

For a full list, see,

Kostelecký & Russell, *Data tables for Lorentz and CPT violation*,

arXiv:0801.0287

...updated annually

Complete linearized pure gravity

$\boxed{\text{known physics } \text{SM} + \text{GR}} + \circ + \circ + \cdot + \ldots = \boxed{\text{quantum gravity}}$

$$\mathcal{L} = \frac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma} \qquad \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma\epsilon_1\epsilon_2\ldots\epsilon_{d-2}} \partial_{\epsilon_1} \partial_{\epsilon_2} \ldots \partial_{\epsilon_{d-2}}$$

Complete linearized pure gravity

$\boxed{\text{known physics SM + GR}} + \circ + \circ + . + \dots = \boxed{\text{quantum gravity}}$

$$\mathcal{L} = \frac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma} \qquad \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma\epsilon_1\epsilon_2\ldots\epsilon_{d-2}} \partial_{\epsilon_1}\partial_{\epsilon_2}\ldots\partial_{\epsilon_{d-2}}$$

0) gauge-structure preserving operators

$$\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} \xrightarrow[\text{tensor decomposition}]{} \widehat{s}^{(d)\mu\nu\rho\sigma} + \widehat{k}^{(d)\mu\nu\rho\sigma} + \widehat{q}^{(d)\mu\nu\rho\sigma} + \ldots$$

Kostelecký&Mewes PLB'16

Complete linearized pure gravity

$\boxed{\text{known physics SM + GR}}$ + ○ + ∘ + . + ... = $\boxed{\text{quantum gravity}}$

$\mathcal{L} = \frac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma}$ $\qquad$ $\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma\epsilon_1\epsilon_2\ldots\epsilon_{d-2}} \partial_{\epsilon_1}\partial_{\epsilon_2}\ldots\partial_{\epsilon_{d-2}}$

0) gauge-structure preserving operators

$$\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} \xrightarrow[\text{tensor decomposition}]{} \widehat{s}^{(d)\mu\nu\rho\sigma} + \widehat{k}^{(d)\mu\nu\rho\sigma} + \widehat{q}^{(d)\mu\nu\rho\sigma} + \ldots$$

1) linearized limit of Einstein-Hilbert

$$\widehat{s}^{(4)\mu\nu\rho\sigma} \to \epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}\eta_{\kappa\lambda}\partial_\alpha\partial_\beta$$

Kostelecký&Mewes PLB'16

Complete linearized pure gravity

$\boxed{\text{known physics SM + GR}} + \circ + \cdot + . + \ldots = \boxed{\text{quantum gravity}}$

$$\mathcal{L} = \tfrac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma} \qquad \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma\epsilon_1\epsilon_2\ldots\epsilon_{d-2}} \partial_{\epsilon_1}\partial_{\epsilon_2}\ldots\partial_{\epsilon_{d-2}}$$

0) gauge-structure preserving operators

$$\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} \xrightarrow[\text{tensor decomposition}]{} \widehat{s}^{(d)\mu\nu\rho\sigma} + \widehat{k}^{(d)\mu\nu\rho\sigma} + \widehat{q}^{(d)\mu\nu\rho\sigma} + \ldots$$

1) linearized limit of Einstein-Hilbert

$$\widehat{s}^{(4)\mu\nu\rho\sigma} \to \epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}\eta_{\kappa\lambda}\partial_\alpha\partial_\beta$$

2) $d = 4$ (minimal) Lorentz violation

$$\widehat{s}^{(4)\mu\nu\rho\sigma} \to s^{(4)\mu\nu\rho\sigma\alpha\beta}\partial_\alpha\partial_\beta = \epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}\overline{s}_{\kappa\lambda}\partial_\alpha\partial_\beta$$

Kostelecký&Mewes PLB'16

Complete linearized pure gravity

$\boxed{\text{known physics SM + GR}} + \circ + \circ + \cdot + \ldots = \boxed{\text{quantum gravity}}$

$$\mathcal{L} = \frac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma} \qquad \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma\epsilon_1\epsilon_2\ldots\epsilon_{d-2}} \partial_{\epsilon_1}\partial_{\epsilon_2}\ldots\partial_{\epsilon_{d-2}}$$

0) gauge-structure preserving operators

$$\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} \xrightarrow[\text{tensor decomposition}]{} \widehat{s}^{(d)\mu\nu\rho\sigma} + \widehat{k}^{(d)\mu\nu\rho\sigma} + \widehat{q}^{(d)\mu\nu\rho\sigma} + \ldots$$

1) linearized limit of Einstein-Hilbert

$$\widehat{s}^{(4)\mu\nu\rho\sigma} \to \epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}\eta_{\kappa\lambda}\partial_\alpha\partial_\beta$$

2) $d = 4$ (minimal) Lorentz violation

$$\widehat{s}^{(4)\mu\nu\rho\sigma} \to s^{(4)\mu\nu\rho\sigma\alpha\beta}\partial_\alpha\partial_\beta = \epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}\overline{s}_{\kappa\lambda}\partial_\alpha\partial_\beta$$

3) $d = 5$ example

$$\widehat{q}^{(5)\mu\nu\rho\nu\sigma} \to q^{(5)\mu\rho\alpha\nu\beta\sigma\gamma}\partial_\alpha\partial_\beta\partial\gamma$$

Kostelecký&Mewes PLB'16

action to metric via spontaneous breaking

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

$$g_{0j} = -\overline{s}^{0j}U - \overline{s}^{0k}U^{jk} + \tfrac{1}{2}\hat{Q}^{j}\chi$$

$$g_{jk} = \delta^{jk} + (2 - \overline{s}^{00})\delta^{jk}U$$

$$+(\overline{s}^{lm}\delta^{jk} - \overline{s}^{jl}\delta^{mk} - \overline{s}^{kl}\delta^{jm} + 2\overline{s}^{00}\delta^{jl}\delta^{km})U^{lm}$$

$$U = G\int d^3x' \frac{\rho(\vec{x}',t)}{R}$$

$$\chi = -G\int d^3x' \rho(\vec{x}',t) R$$

$$U^{jk} = \partial_j\partial_k\chi + \delta_{jk}U$$

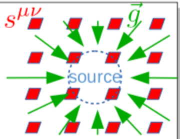
Bailey&Havert PRD'17, Bailey PRD'06

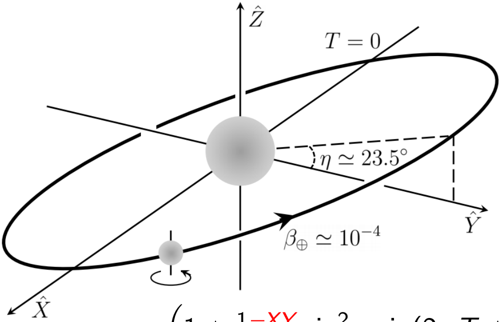
in the lab ... gravimeters

Lorentz violation

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

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



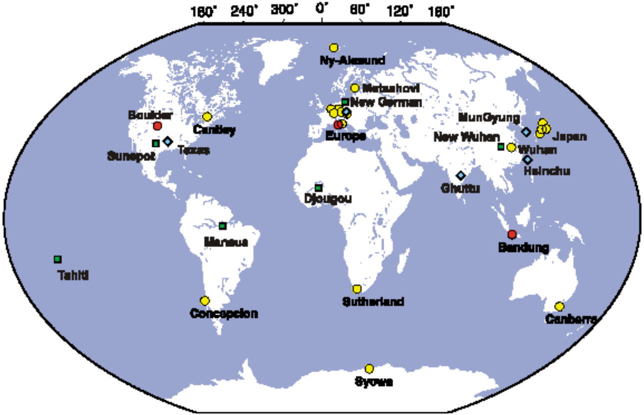


$$a = g\left(1 + \tfrac{1}{2}\bar{s}^{XY} \sin^2\chi \sin(2\omega T + \phi) + \ldots\right)$$

χ = colatitude $\qquad$ ω = sidereal frequency

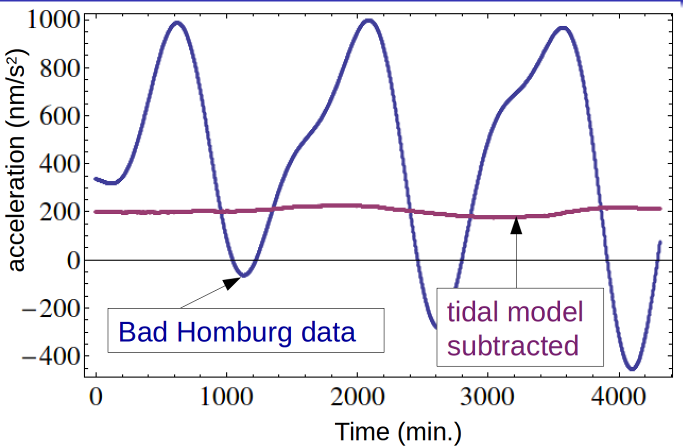
in the lab ... gravimeters

global geodynamics project



$$a = g\left(1 + \frac{1}{2}\bar{s}^{XY}\sin^2\chi\sin(2\omega T + \phi) + \ldots\right)$$

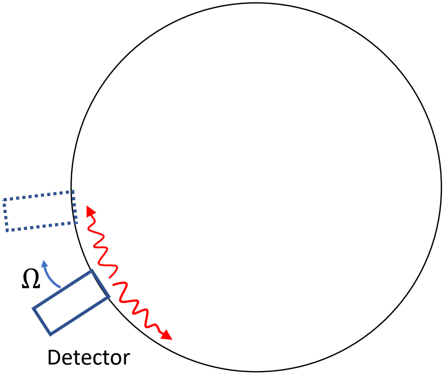
in the lab ... gravimeters



- among best lab bounds $\overline{s}^{JK} < 10^{-10}$
  (c.f. solar system 10^{-12}, astrophysics 10^{-14})

Flowers, Goodge, Tasson PRL'17; C.-G. Shao *et al.*PRD'18

Sagnac gyros – Minkowski spacetime



Arrival time difference

$$\Delta t \approx \frac{2\Omega r t}{c} = \frac{2\Omega r 2\pi r}{c^2} = \frac{4\Omega A}{c^2} \to 4\int \vec{\Omega}\cdot d\vec{A}$$

Phase difference per orbit

$$\Delta\psi = 2\pi\frac{c\Delta t}{\lambda}$$

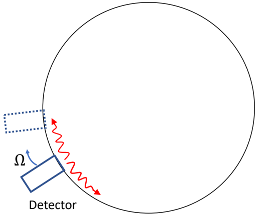
N – orbits to be in phase

$$2\pi = N\Delta\psi \qquad N = \frac{\lambda}{c\Delta t}$$

beat period/frequency via perimeter P

$$T = N\frac{P}{c} \Rightarrow f_b = \frac{\Delta t}{\lambda P}$$

Sagnac via the metric



...in rotating detector frame

light-like geodesics

$$0 = g_{00} dt^2 + \underline{2 g_{0j} dt dx^j} + g_{jk} dx^j dx^k$$

quadratic in dt with 2 solutions

$$\Delta t = 2 \oint \frac{g_{0j}}{g_{00}} dx^j$$

in the cases of interest

$$\Delta \tau \approx 2 \oint g_{0j} dx^j$$

note that

$$2\Omega_j = \epsilon_{jkl} \partial_k g_{0l}$$

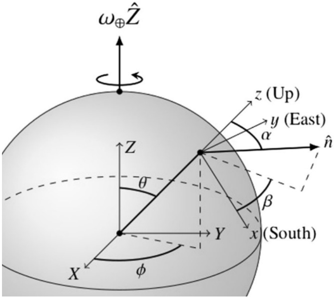
Ampere's law analogy

$$\Delta \tau \approx 4 \int \vec{\Omega} \cdot d\vec{A}$$

<u>Conclusion</u>: take the same approach for other contributions to g_{0j} in the detector frame

- gravitomagnetism
- Lorentz violation

SME results



beat frequency[3]

$$\frac{4AGM_\oplus}{\lambda P R_\oplus^2} \sin\alpha \Big[\cos\beta(\overline{s}^{TX} \sin\phi - \ldots) + \sin\beta\left(\cos\theta(\overline{s}^{TX}\cos\phi + \overline{s}^{TY}\sin\phi) + \ldots\right)\Big]$$

post-Newtonian metric[2]

$g_{0j} = -\overline{s}^{0j} U - \overline{s}^{0k} U^{jk} + \frac{1}{2}\hat{Q}^j \chi$

(U = Newton potential; U^{jk}, χ = post-Newton potentials)

where $\hat{Q}^j = [q^{(5)0jk0l0m} + q^{(5)n0knljm} + q^{(5)njknl0m}]\partial_k \partial_l \partial_m$

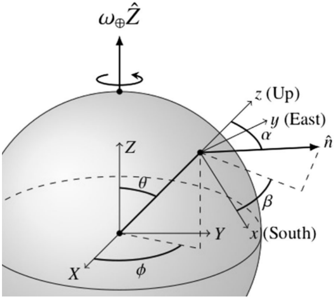
look gravitomagnetic but the source is at rest

---

[2] Bailey&Havert PRD'17

[3] Moseley *et al.* PRD'19

SME results



beat frequency[3]

$$\frac{4AGM_\oplus}{\lambda P R_\oplus^2} \sin\alpha \Big[\cos\beta(\bar{s}^{TX} \sin\phi - \dots)$$

$$+ \sin\beta \left(\cos\theta(\bar{s}^{TX}\cos\phi + \bar{s}^{TY}\sin\phi) + \dots\right) \Big]$$

- sidereal dependence $\phi = \omega_\oplus t + \phi_0$
- orientation dependence
- $q^5 \Rightarrow$ additional harmonics
- lab-competitive $\bar{s}$ sensitivities
- best q^5 sensitivities

post-Newtonian metric[2]

$g_{0j} = -\bar{s}^{0j} U - \bar{s}^{0k} U^{jk} + \frac{1}{2} \hat{Q}^j \chi$

(U = Newton potential; U^{jk}, χ = post-Newton potentials)

where $\hat{Q}^j = [q^{(5)0jk0l0m} + q^{(5)n0knljm} + q^{(5)njknl0m}]\partial_k \partial_l \partial_m$

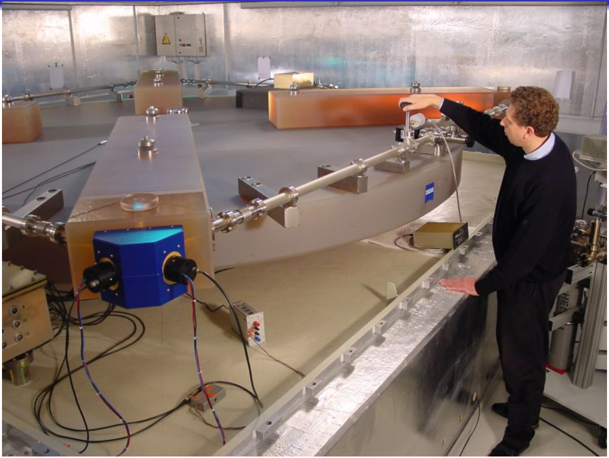
look gravitomagnetic but the source is at rest

---

[2] Bailey&Havert PRD'17

[3] Moseley *et al.* PRD'19

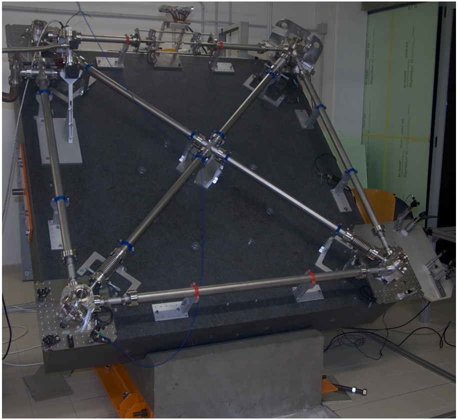
the experiment...G-ring



- G-ring, Germany
- insensitive to minimal Lorentz violation

http://www.fs.wettzell.de/LKREISEL/G/G-s̄ring.jpg

the experiment...GINGER

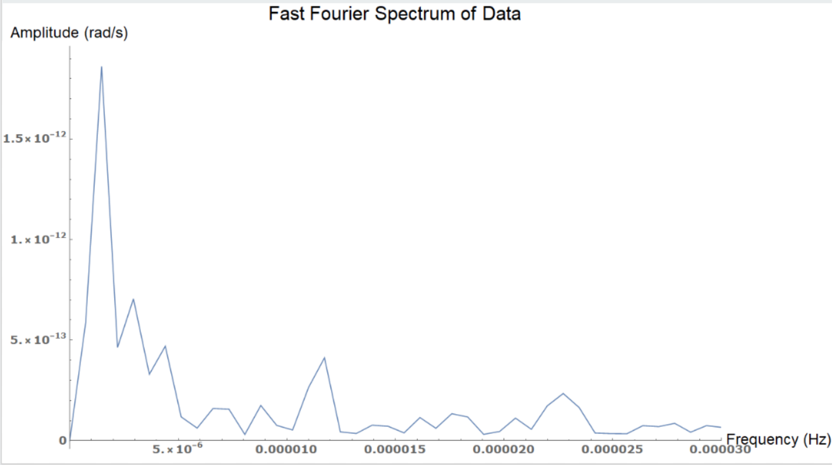


- GINGERINO, Gyroscopes IN GEneral Relativity, Italy
- sensitive to both minimal and $d = 5$ Lorentz violation

---

https://web.infn.it/GINGER/index.php/it/11-sexperiments

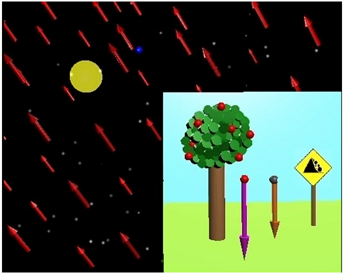
15 days of G-ring



- polar motion corrected

MICROSCOPE

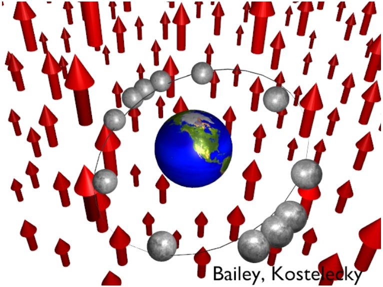
- matter-gravity couplings
  - particle-species dependent coefficients for Lorentz violation
  - effective weak-equivalence principle (WEP) violation



- MICROSCOPE
  - satellite-based WEP experiment
  - best-ever WEP constraint
  - Lorentz-violating signal at frequencies distinct from standard WEP
  - dedicated SME analysis performed[1]

[1] Pihan-Le Bars, . . . , Tasson, . . . PRL'19

Lunar Laser Ranging



- Phenomenology:
  - Bailey & Kostelecký PRD'06
- Experiment:
  - Matter-gravity couplings: Bourgoin *et al.*PRL'17
  - Pure-gravity: Bourgoin *et al.*PRL'16
  - Pure-gravity: Battat *et al.*PRL'07

summary

- systematic search for new physics
- basic theory in place for many gravitational tests
- expanding phenomenological & experimental breadth & depth