Lorentz Violation and Sagnac Gyroscopes

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Outline

- introduction
  - Lorentz violation & the Standard-Model Extension (SME)
  - gravity
- tests: recent and proposed tests
  - gravimeters
  - **Sagnac gyroscopes**
  - gravitational waves

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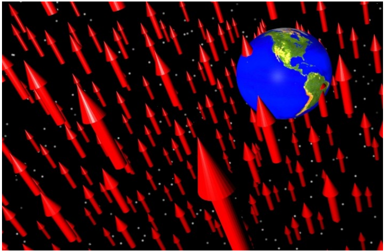
[1] Moseley...Tasson... PRD'19

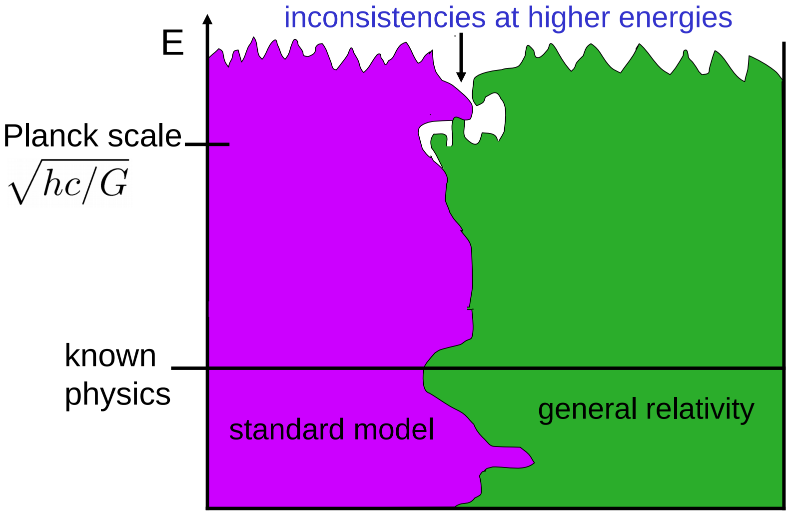
Lorentz violation

- Lorentz symmetry

- Lorentz violation



motivation


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

motivation

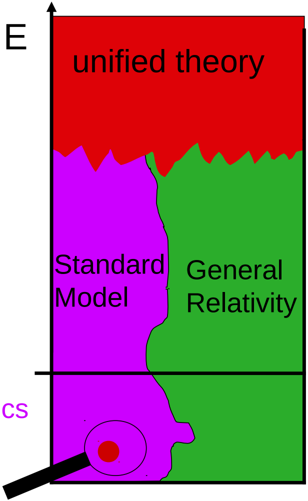
options for probing experimentally

- 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

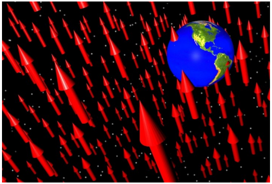
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L_{\mathrm{LV}}$$

- CPT violation comes with Lorentz violation

CPT & Lorentz-violating terms

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

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



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

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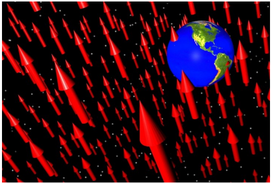
A broad and general search for new physics



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

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

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

Kostelecký&Mewes PLB'16

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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

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1) linearized limit of Einstein-Hilbert

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

Kostelecký&Mewes PLB'16

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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

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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

$$g_{00} = -1 + 2U + 3\overline{s}^{00}U + \overline{s}^{jk}U^{jk}$$
$$g_{0j} = -\overline{s}^{0j}U - \overline{s}^{0k}U^{jk} + \tfrac{1}{2}\hat{Q}^{j}\chi$$
$$g_{jk} = \delta^{jk} + (2 - \overline{s}^{00})\delta^{jk}U$$
$$+(\overline{s}^{lm}\delta^{jk} - \overline{s}^{jl}\delta^{mk} - \overline{s}^{kl}\delta^{jm} + 2\overline{s}^{00}\delta^{jl}\delta^{km})U^{lm}$$

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

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

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

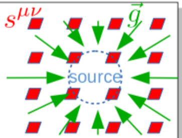
Bailey&Havert PRD'17, Bailey PRD'06

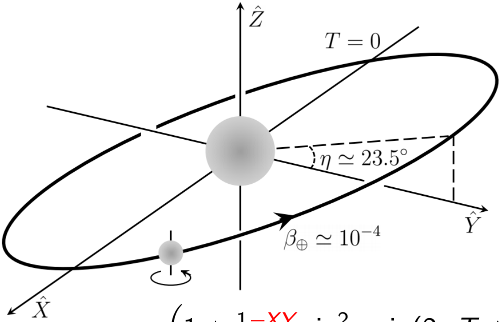
in the lab ... gravimeters

Lorentz violation

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

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



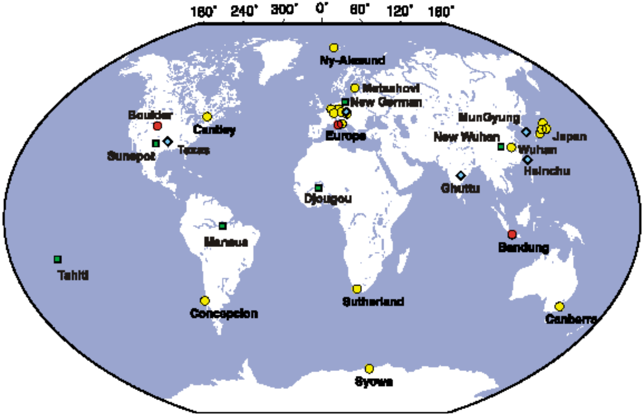


$$a = g\left(1 + \tfrac{1}{2}\bar{s}^{XY}\sin^2\chi \sin(2\omega T + \phi) + \ldots\right)$$

χ = colatitude $\quad\quad$ ω = sidereal frequency

in the lab ... gravimeters

global geodynamics project



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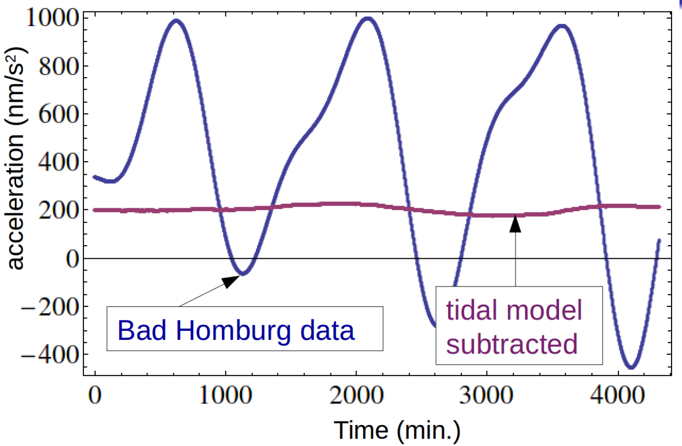
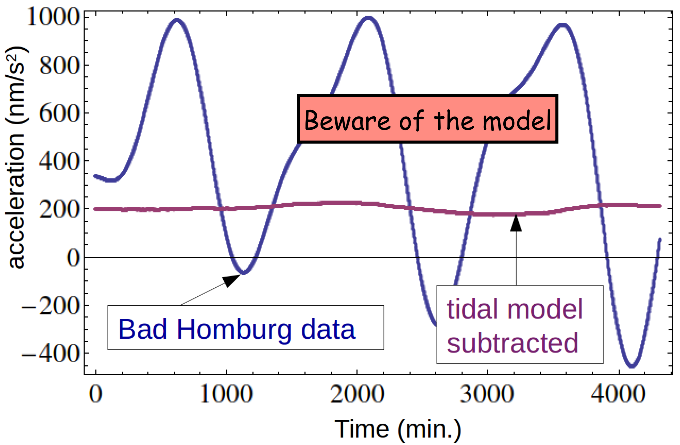


- among best lab bounds $\overline{s}^{JK} < 10^{-10}$
  (c.f. solar system 10^{-12}, astrophysics 10^{-14})

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

in the lab ... gravimeters



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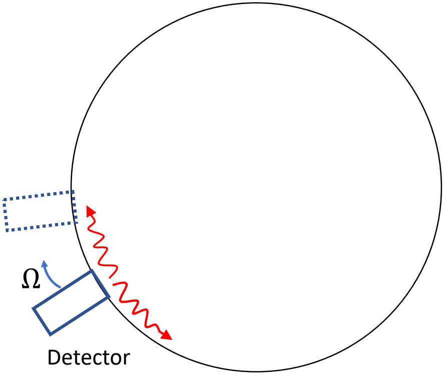
Sagnac gyros – Minkowski spacetime



Arrival time difference

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

Phase difference per orbit

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

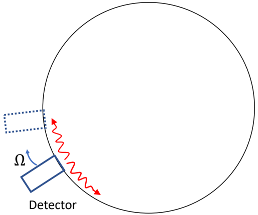
N – orbits to be in phase

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

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

quadratic in dt with 2 solutions
$\Delta t = 2\oint \frac{g_{0j}}{g_{00}} dx^j$

in the cases of interest
$\Delta\tau \approx 2\oint g_{0j}dx^j$

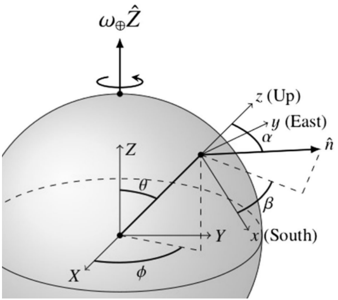
note that
$2\Omega_j = \epsilon_{jkl}\partial_k g_{0l}$

Ampere's law analogy
$\Delta\tau \approx 4\int \vec{\Omega} \cdot d\vec{A}$

Conclusion: 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

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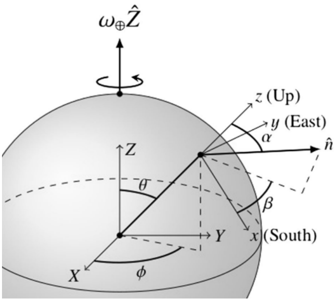
[2] Bailey&Havert PRD'17

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

SME results



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

post-Newtonian metric[2]

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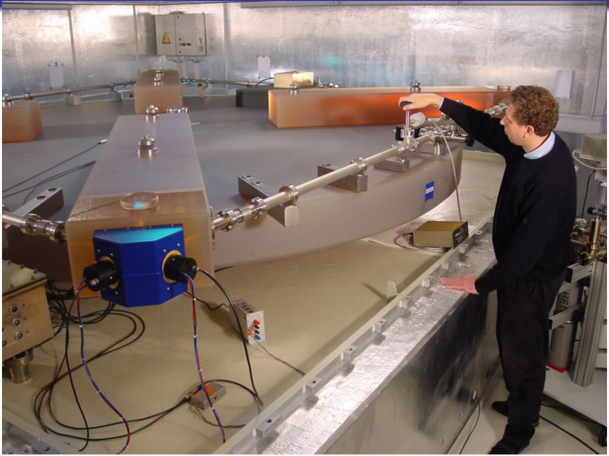
the experiment...G-ring



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

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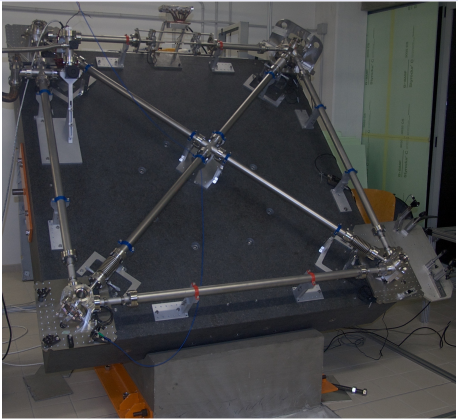
http://www.fs.wettzell.de/LKREISEL/G/G-s̄ring.jpg

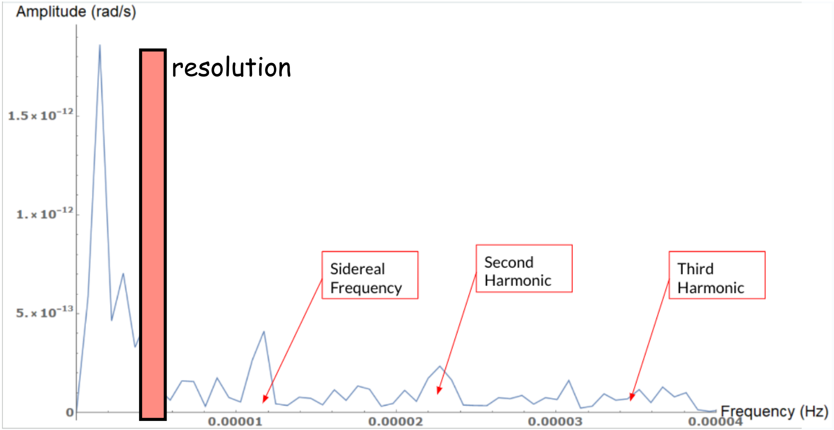
the experiment...GINGER



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

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

15 days of G-ring



- polar motion corrected

preliminary maximum reach sensitivities

K_{xxxy}	K_{xxxz}	K_{xxyy}	K_{xxyz}	K_{xxzz}	K_{xyyy}	K_{xyyz}	K_{xyzz}
-16 m	10 m	-113 m	32 m	113 m	48 m	-10 m	-16 m

K_{xzzz}	K_{yxxz}	K_{yxyz}	K_{yxzz}	K_{yyyz}	K_{yyzz}	K_{yzzz}
190 m	10 m	-5 m	-16 m	8 m	-113 m	48 m

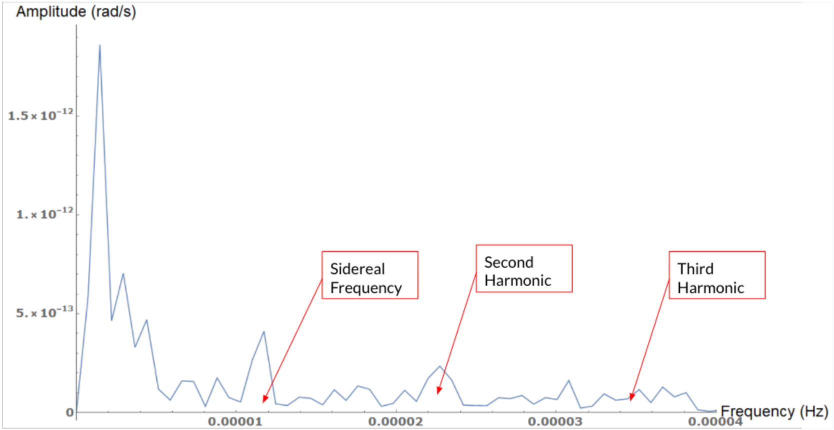
- compare with pulsar results

$$K_{XXXY} = \frac{1}{3}\left(-q^{TXYTXTX} + q^{TXYXYXY} + q^{TXYXZXZ} - q^{XYZXZXT}\right)$$

Coefficient	1-σ limit [m]	Coefficient	1-σ limit [m]
q^{TXYTXTX}	22	q^{TXYTXTY}	11
q^{TXYTYTY}	10	q^{TXYTYTZ}	5.7
q^{TXYXYXY}	8.0	q^{TXYXYXZ}	8.3

Shao & Bailey PRD'18

15 days of G-ring



- polar motion corrected

what needs doing? Uncertainty!

- We see a signal at some of the frequencies of interest
  - what is the uncertainty in the polar motion correction?
  - is the polar motion modeling trained on data?
  - systematics at the solar day frequency?
- how should we quantify uncertainty?
  - rms of neighboring frequencies $\rightarrow$ more resolution needed
  - understanding of systematics and modeling uncertainties
- want to collaborate?

summary

- systematic search for new physics
- basic theory in place for many gravitational tests
- expanding phenomenological & experimental breadth & depth
- Sagnac Gyroscopes can be an interesting test
- More data/better understanding of error needed