The Systematic Search for Lorentz Violation

Jay D. Tasson

Carleton College

jtasson@carleton.edu

September 30, 2019

About Jay...Carleton College

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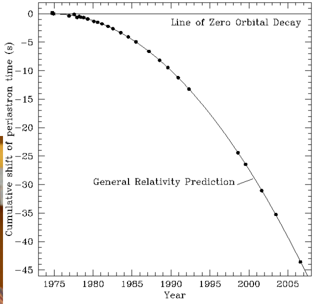
- 2000 undergrads, no grad students
- $\approx$ 20 physics majors graduate per year
- 8 physics/astronomy faculty
- gravitational physics

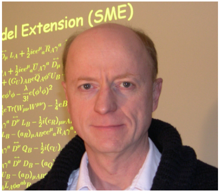


  - Joel Weisberg

  - Nelson Christensen $\rightarrow$ Nice, Fr
  - Jay Tasson: Lorentz violation in gravity/LIGO

CPT'19

Alan Kostelecký:
Advisor



Eighth Meeting on

CPT and Lorentz Symmetry

May 12-16, 2019

Indiana University, Bloomington

PHYSICAL REVIEW D **100,** 064031 (2019)

Lorentz violation and Sagnac gyroscopes

Serena Moseley,[1] Nicholas Scaramuzza,[2] Jay D. Tasson,[1,*] and Max L. Trostel[1]

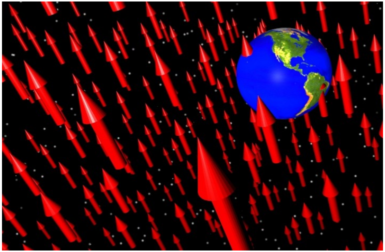
Outline

- introduction
  - Lorentz violation & the Standard-Model Extension (SME)
  - gravity
- tests: recent and proposed
  - lab
    - gravimeters
    - Sagnac gyroscopes
    - weak equivalence principle
  - astrophysics
    - multimessenger astronomy
    - gravitational Čerenkov radiation

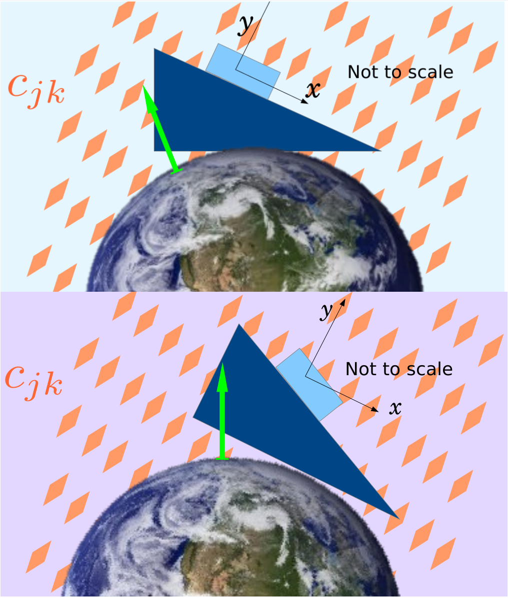
Lorentz violation

- Lorentz symmetry

- Lorentz violation

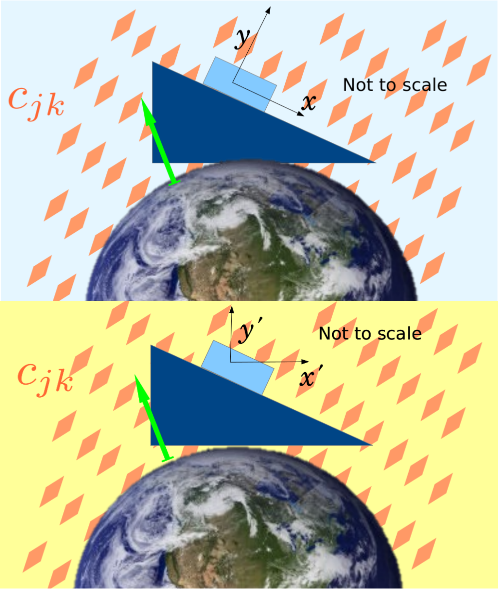


What is Lorentz violation?



- particle rotation (Lorentz symmetry is boosts and rotations)

What is *not* Lorentz violation?



- observer transformation

Bertschinger *et al.* (JT) Symmetry '19

motivation

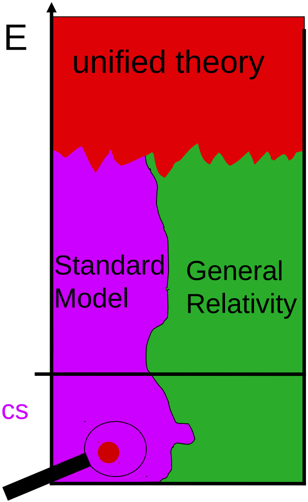
options for probing experimentally

- 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



broad & systematic search

	pure phenomenology	theoretical framework
advantage	• easy parameterization	• quantitative comparisons of very different experiments eg: lab gravity & atomic • calculate predictions • consistent analysis
disadvantage	• not predictive • unclear assumptions • no relation between experiments	• more work!

the Standard-Model Extension (SME)

effective field theory which contains:

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

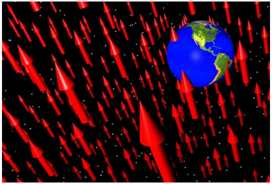
$$L_{\mathrm{SME}} = L_{\mathrm{GR}} + L_{\mathrm{SM}} + L_{\mathrm{LV}}$$

- 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

the Standard-Model Extension (SME)

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- General Relativity (GR)
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$$L_{\rm SME} = L_{\rm GR} + L_{\rm SM} + L_{[illegible]}$$

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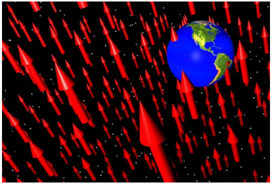


A broad and general search for new physics

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

SME structure

known physics SM + GR + ○ + ∘ + . + ... = quantum gravity

minimal SME

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

coefficient for Lorentz violation

gravitational coupling

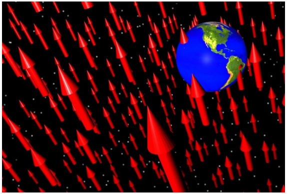
coefficient properties

- odd number of indicies → CPT odd
- even number of indicies → CPT even
- particle-species dependent

explicate vs. spontaneous

background tensors are cute, but where could the come from?

- explicate Lorentz violation
  - the universe just looks that way
  - typically consistency issues with Riemann geometry



- 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
  - consistent with Riemann geometry

Nongravitational Tests

System	E.g.	
meson oscillations	LHCb	PRL 116, 241601 (2016)
neutrino osc.	MINOS,	PRL 105, 151601 (2010)
quark production	D0	PRL 108, 261603 (2012)
muon g2 experiments	Muon g-2	PRL 100, 091602 (2008)
torsion pendula	Heckel *et al.*	PRL 97, 021603 (2006)
atomic clocks	Hohensee *et al.*	PRL 111, 050401 (2013)
comagnetometers	Smiciklas *et al.*	PRL 107, 171604 (2011)
particle traps	Smorra *et al.*,	Nature 550, 371 (2017)
resonant cavities	Baynes *et al.*	PRL 108, 260801 (2012)
vacuum birefringence	Friedman *et al.*	PRL 108, 260801 (2012)

. . .

Gravitational Tests

System	E.g.	
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 117, 071102 (2016)
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

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road-map to SME gravity

minimal gravitational SME $\mathcal{L}$
Kostelecký PRD'04

→

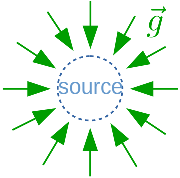
linearized pure-gravity
Bailey&Kostelecký PRD'06

Lorentz violation in gravity

- pure-gravity sector: c.f. Maxwell's eqs.
- given mass-energy, provides the form of the gravitational field

conventional pure-gravity

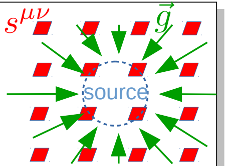
$$\mathcal{L}_{\mathrm{GR}} = eR$$



Lorentz violation

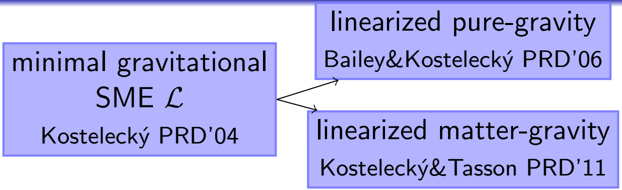
$$\mathcal{L}_{\mathrm{grav}} = \mathcal{L}_{\mathrm{GR}} + \mathcal{L}_{\mathrm{LV,grav}}$$

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



Bailey&Kostelecký PRD'06

road-map to SME gravity



Lorentz violation in gravity

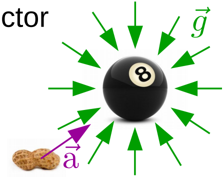
matter sector: kinematics and interactions of particles

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

conventional gravitationally coupled matter sector

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

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

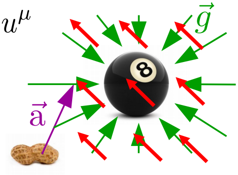


Lorentz violation

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

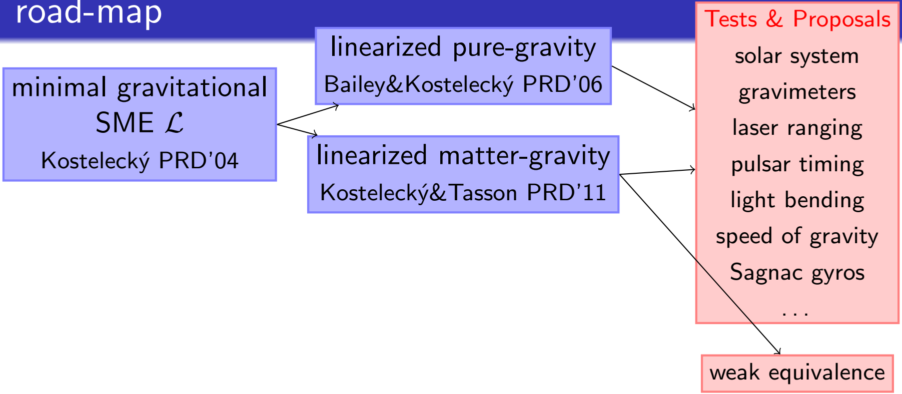
$$L_{\rm LV,SM} = -m\sqrt{-(g_{\mu\nu} u + 2c_{\mu\nu}) u^{\mu} u^{\nu}} + (a_{\rm eff})_{\mu} u^{\mu}$$

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



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

road-map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Kostelecký PRD'04
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Kostelecký&Tasson PRD'11
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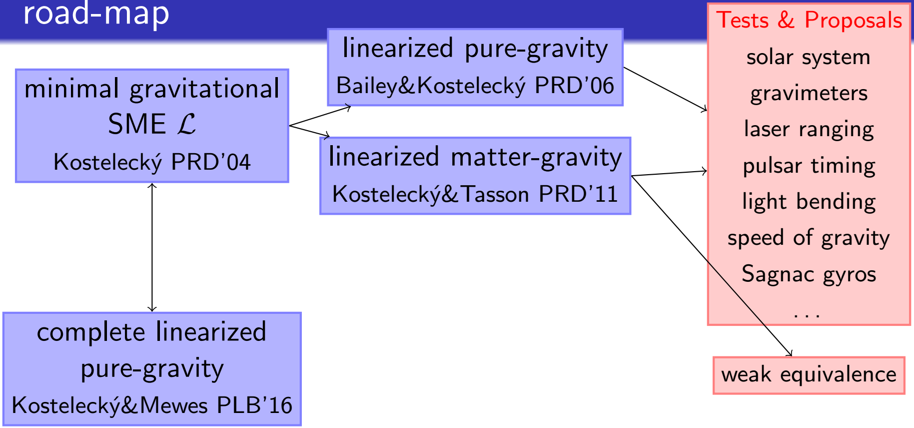
solar system
gravimeters
laser ranging
pulsar timing
light bending
speed of gravity
Sagnac gyros
...
weak equivalence

road-map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Complete linearized pure gravity

known physics SM + GR + ○ + ∘ + . + … = quantum gravity

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

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

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

Kostelecký&Mewes PLB'16

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

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Kostelecký&Mewes PLB'16

Complete linearized pure gravity

known physics SM + GR + ○ + ∘ + . + ... = quantum gravity

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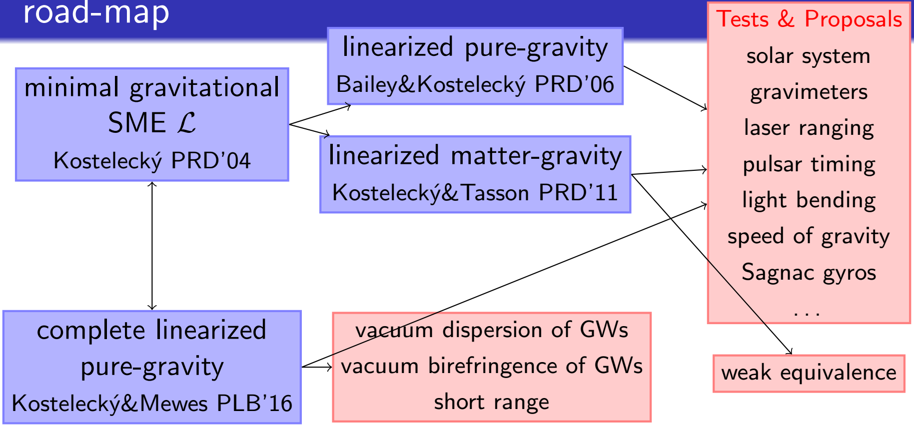
3) $d = 5$ example

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

Kostelecký&Mewes PLB'16

road-map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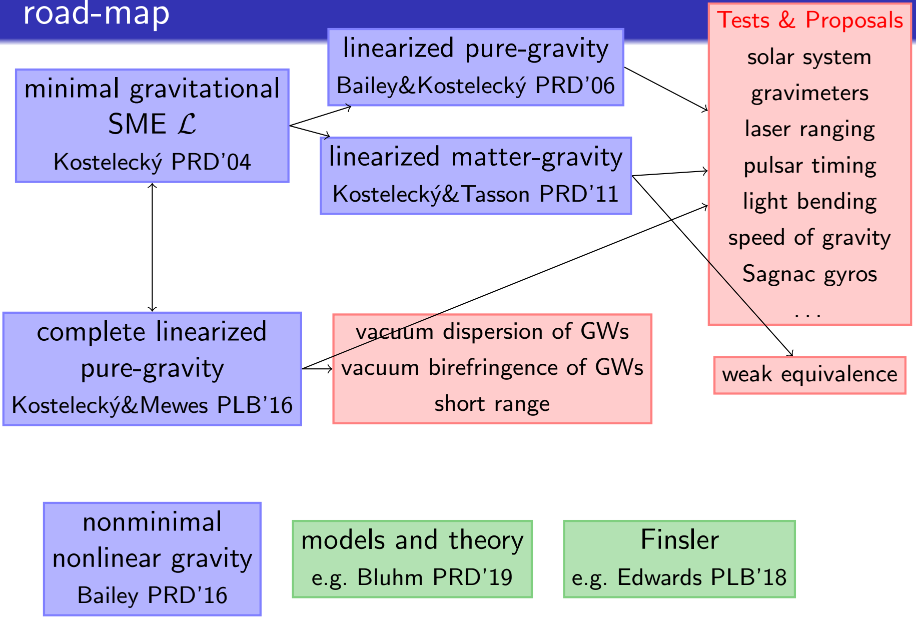
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vacuum birefringence of GWs
short range
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nonminimal nonlinear gravity
Bailey PRD'16
models and theory
e.g. Bluhm PRD'19
Finsler
e.g. Edwards PLB'18

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in the lab ... gravimeters

Lorentz violation

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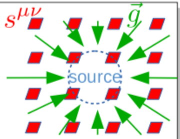
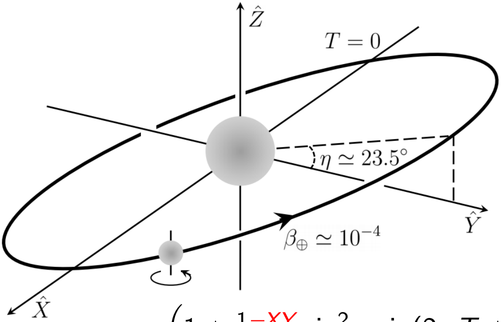


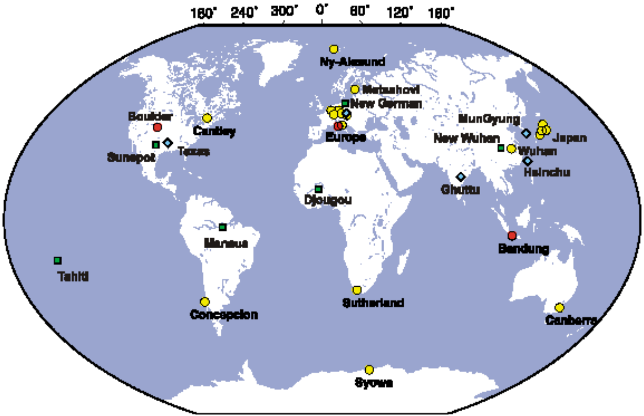


$$a = g\left(1 + \tfrac{1}{2}\bar{s}^{XY} \sin^2\chi \sin(2\omega T + \phi) + \ldots\right)$$

χ = colatitude $\qquad \omega$ = sidereal frequency

in the lab ... gravimeters

global geodynamics project



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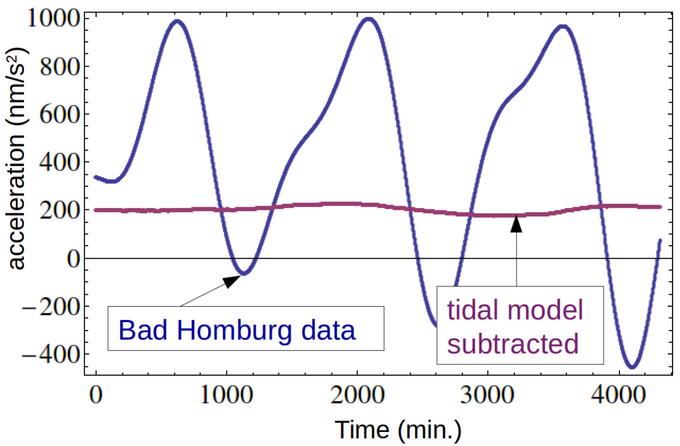
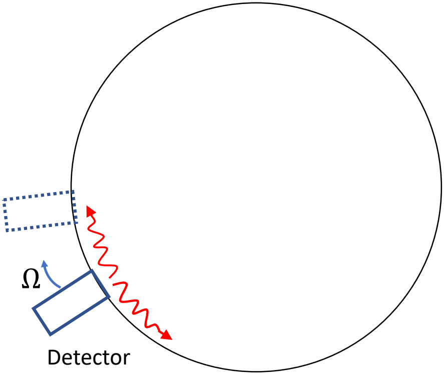
in the lab ... gravimeters



- 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

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

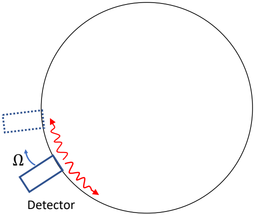
N – orbits to be in phase

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

beat period/frequency via parimeter 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
$\Delta \tau \approx 2 \oint g_{0j} dx^j$

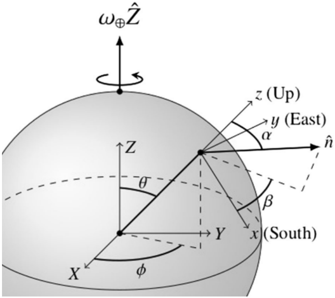
note that
$2\Omega_j = \epsilon_{jkl} \partial_k g_{0l}$

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

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

- gravitomagnetism
- Lorentz violation

SME results



beat frequency[2]

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

post-Newtonian metric[1]

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

(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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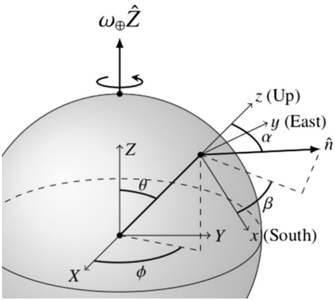
[1] Bailey&Havert PRD'17

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

SME results



beat frequency[2]

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

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

- 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[1]

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

(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

---

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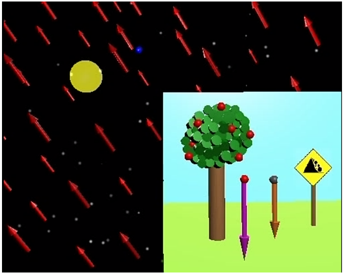
in the 'lab' ... MICROSCOPE

- 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, . . . submitted

Outline

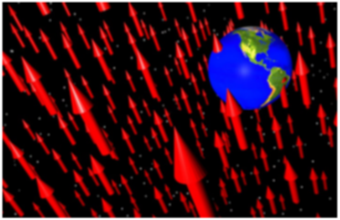
- introduction
  - Lorentz violation & the Standard-Model Extension (SME)
  - gravity
- tests: recent and proposed
  - lab
    - gravimeters
    - Sagnac gyroscopes
    - weak equivalence principle
  - astrophysics
    - multimessenger astronomy
    - gravitational Čerenkov radiation

gravitational waves

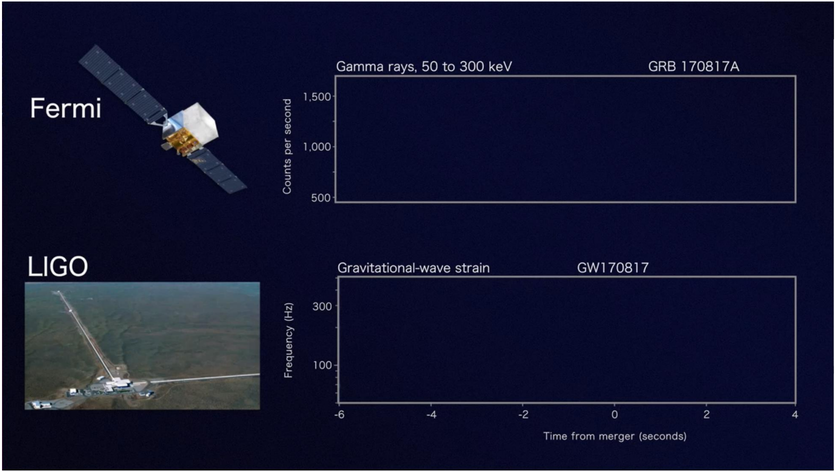
1. effects on generation at the source
2. effects on the physics of the detectors
3. effects on vacuum propagation
   - dispersion (isotropic or not)
   - birefringence (isotropic or not)
   - speed (isotropic or not)
4. kinematic effects on gravitational wave interactions

spherical harmonic basis

$\bar{s}_{\mu\nu}\hat{n}^{\mu}\hat{n}^{\nu} \to Y_{jm}(\hat{n})\bar{s}_{jm}$



Aug. 17, 2017 ...



Credit: NASA GSFC & Caltech/MIT/LIGO Lab

26Mpc $\approx$ 100 million years

Image credit: Newscientist.com

BNS-GRB speed of gravity (SoG)

- observed arrival time difference
  $\Delta t_{\rm a} = t_{{\rm a}\gamma} - t_{\rm ag} \approx 1.7$ s

- astrophysical models $\Rightarrow \gamma$ emission a few seconds after GW peak
  $\Delta t_{\rm emit} = t_{{\rm emit}\gamma} - t_{\rm emitg} = (0, 10)\,{\rm s}$

- at leading order in small $\Delta t, \Delta v$
  $\Delta v = \frac{1}{D_L}\Big(\Delta t_{\rm a} - \Delta t_{\rm emit}\Big) \quad \Rightarrow \quad -3 \times 10^{-15} < \Delta v < 7 \times 10^{-16}$

- one 2-sided constraint on
  $\Delta v = -\sum_{jm} Y_{jm}(\hat{n}) \left(\frac{1}{2}(-1)^{1+j}\overline{s}_{jm} - c^{(4)}_{(I)jm} \right)$

- $d = 4$ is nondispersive $\Rightarrow$ distinct from other GW LV tests

  LIGO&Virgo PRL'17 (GW170104), LIGO&Virgo arXiv:1811.00364

LIGO, Virgo, Fermi GBM, INTEGRAL, ApJ '17

astrophysical $\overline{s}_{jk}$

Previous Lower	SoG max reach Lower [1]	Coeff.	SoG max reach Upper [1]	Previous Upper
-3×10^{-14} [2]	-2×10^{-14}	$\overline{s}^{(4)}_{00}$	5×10^{-15}	8×10^{-5} [3]
-1×10^{-13} [2]	-3×10^{-14}	$\overline{s}^{(4)}_{10}$	7×10^{-15}	7×10^{-14} [2]
-8×10^{-14} [2]	-2×10^{-15}	$\mathrm{Re}\ \overline{s}^{(4)}_{11}$	1×10^{-14}	8×10^{-14} [2]
-7×10^{-14} [2]	-3×10^{-14}	$\mathrm{Im}\ \overline{s}^{(4)}_{11}$	7×10^{-15}	9×10^{-14} [2]
-7×10^{-14} [2]	-8×10^{-15}	$\overline{s}^{(4)}_{20}$	4×10^{-14}	1×10^{-13} [2]
-7×10^{-14} [2]	-2×10^{-15}	$\mathrm{Re}\ \overline{s}^{(4)}_{21}$	1×10^{-14}	7×10^{-14} [2]
-5×10^{-14} [2]	-4×10^{-14}	$\mathrm{Im}\ \overline{s}^{(4)}_{21}$	8×10^{-15}	8×10^{-14} [2]
-6×10^{-14} [2]	-1×10^{-14}	$\mathrm{Re}\ \overline{s}^{(4)}_{22}$	3×10^{-15}	8×10^{-14} [2]
-7×10^{-14} [2]	-4×10^{-15}	$\mathrm{Im}\ \overline{s}^{(4)}_{22}$	2×10^{-14}	7×10^{-14} [2]

[1] LIGO, Virgo, Fermi GBM, INTEGRAL ApJ'17
[2] (Čerenkov) Kostelecký&Tasson PLB'15
[3] (Pulsar) L.Shao PRD'14

astrophysical $\bar{s}_{jk}$

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-8×10				10^{-14} [2]
-7×10				10^{-14} [2]
-7×10				10^{-13} [2]
-7×10				10^{-14} [2]
-5×10				10^{-14} [2]
-6×10^{-14} [2]	-1×10^{-14}	Re $\bar{s}^{(4)}_{22}$	3×10^{-15}	8×10^{-14} [2]
-7×10^{-14} [2]	-4×10^{-15}	Im $\bar{s}^{(4)}_{22}$	2×10^{-14}	7×10^{-14} [2]

Note:

- 10 order of magnitude improvement
- one missing Čerenkov constraint
- ⇒ 1000 yr arrival-time difference was allowed
- different: GW vs. matter, GW vs. light

[1] LIGO, Virgo, Fermi GBM, INTEGRAL ApJ'17
[2] (Čerenkov) Kostelecký&Tasson PLB'15

an data-analysis question ...

- How many coefficients for Lorentz violation should we fit at once?
- no single right answer
- things to think about
  - an infinite series $\Rightarrow$ you must stop somewhere
  - test framework vs. model
  - number of independent tests
  - the data tables
- JT answer: do as many of the following as possible
  - each LV degree of freedom one at a time "max reach" (e.g. $\overline{s}^{TX}$, $\overline{s}^{TY}$, ...)
  - all components of one coefficient together (e.g. all 9 $\overline{s}^{\Sigma\Xi}$)
  - all coefficients of a given sector/mass dimension together

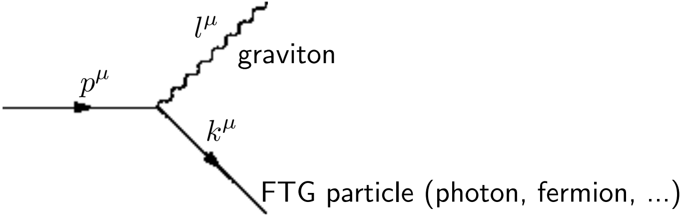
GW next steps

- SoG next steps
  - greater distance $\Rightarrow$ better "max reach" sensitivity
  - constrain all 9 $\bar{s}_{jk}$ together
  - disentangle SoG from astrophysical uncertainty
  - triple comparison with neutrinos
- improved dephasing
  - birefringence
  - anisotropy

gravi-Čerenkov Radiation

4. kinematic effects on gravitational wave interactions

- $v_g = 1 - \frac{1}{2}\sum_{jm} Y_{jm}(\hat{n})(-1)^{1+j}\overline{s}_{jm}$
  $\Rightarrow$ faster-than-gravity (FTG) particles may exist
  $\Rightarrow$ kinematics allow:



- high-energy cosmic ray observations
  distance traveled, observed energy, and reaction rate $\Rightarrow$ $\overline{s}_{jm}$ bounds
- *billion-fold* improvement on 9 minimal coefficients
- first-ever constraints on 74 nonminimal coefficients

Kostelecký&Tasson PLB'15, Tasson Symmetry'16

summary

- systematic search for new physics
- basic theory in place for many limits of gravity
- expanding phenomenological & experimental breadth & depth

extras

dispersion relation & group velocity

$$\omega = \left(1 - \varsigma^0 \pm \sqrt{(\varsigma^1)^2 + (\varsigma^2)^2 + (\varsigma^3)^2}\right) |\vec{p}|$$

Note: $\pm \Rightarrow$ birefringence (interesting!)
nonbirefringent limit for now

$$\varsigma^0 = \frac{1}{4p^2}\left(-\frac{1}{2}\widehat{s}^{\mu\nu}{}_{\mu\nu} + \widehat{k}^{\mu\nu}{}_{\mu\nu}\right) \equiv \sum_{djm} \omega^{d-4} Y_{jm}(\hat{n}) k^{(d)}_{(I)jm}$$

$$\xrightarrow[d=4]{} \sum_{jm} Y_{jm}(\hat{n}) k^{(4)}_{(I)jm} \equiv \frac{1}{2}\sum_{jm} Y_{jm}(\hat{n})(-1)^{1+j}\overline{s}_{jm}$$

direction-dependent group velocity

$$v_g = 1 - \frac{1}{2}\sum_{jm} Y_{jm}(\hat{n})(-1)^{1+j}\overline{s}_{jm}$$

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