Testing local Lorentz invariance with gravitational waves

- effective field theory searches
- cosmic ray constraints
- interferometer constraints

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underlying theory at Planck scale

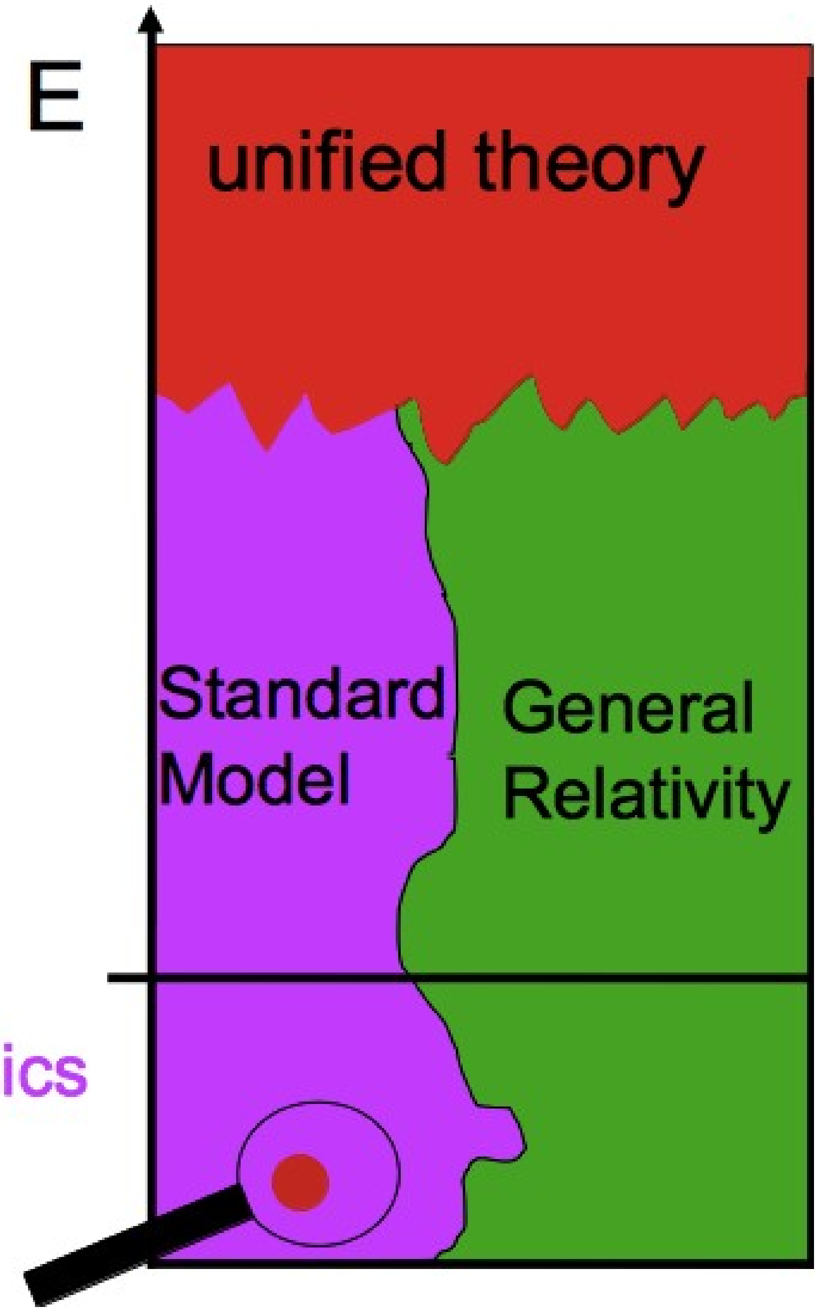
options for probing experimentally

- 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



effective field theory search for Lorentz violation (SME)

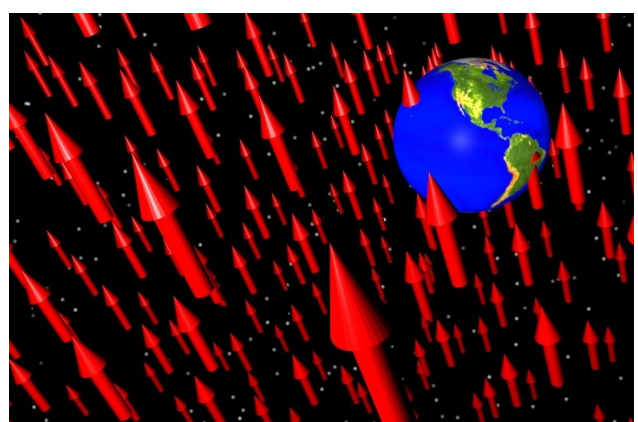
- perform a *systematic search* via an effective field theory

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

standard linearized gravity

coefficients for Lorentz violation

$$\mathcal{L} \supset \frac{1}{4}\epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}h_{\mu\nu}\Big(\eta_{\kappa\lambda} - \underbrace{\overline{s}_{\kappa\lambda}}_{d=4} - \underbrace{\overline{s}_{\kappa\lambda\delta\gamma}\partial^{\delta}\partial^{\gamma}}_{d=6}\Big)\partial_{\alpha}\partial_{\beta}h_{\rho\sigma}$$



On-going effort

Data Tables for Lorentz and CPT Violation arXiv:0801.0287v10

~250 Refs. with sensitivities, including:

gravitational Čerenkov radiation
superconducting gravimeters
short-range gravity devices
gravitational-wave interferometers
lunar laser ranging
binary-pulsar observations
planetary ephemerides
gravity probe B
bound kinetic energy WEP
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ring-laser gyroscopes
torsion pendula
binary pulsars
short-range gravity
gravitational-wave detectors
space-based WEP tests
antimatter gravity
charged matter WEP
muonium free fall
light bending
time-delay & Doppler tests

constraints via gravitational waves to date

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Constraints on Lorentz Violation from Gravitational Cherenkov Radiation,
Kostelecky and Tasson, Phys. Lett. B 749, 551 (2015).

The Standard-Model Extension and Gravitational Tests,
Tasson, Symmetry 8, 111 (2016).

Testing Local Lorentz Invariance with Gravitational Waves,
Kostelecky and Mewes, Phys. Lett. B 757, 510 (2016).

Theoretical Physics Implications of the Binary Black-Hole Mergers GW150914 and GW151226.
Yunes, Yagi, and Pretorius, Phys. Rev. D 94, 084002 (2016).

Searching for Photon-Sector Lorentz Violation using Gravitational-Wave Detectors,
Kostelecky, Melissinos, and Mewes, Phys. Lett. B 761, 1 (2016).

searching for symmetry violation

	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!

Lorentz-violating effects

1) boost violation

2) rotation invariance violation

3) dispersion relation effects

Lorentz-violation in gravitational waves

A) effects on generation at the source

B) effects on the physics of the detectors

C) effects on vacuum propagation

i) dispersion (isotropic or not)

ii) birefringence (isotropic or not)

D) kinematic effects on gravitational wave interactions

Definition – Isotropic Lorentz violation/preferred frame models:

Models such that coordinates can be found in which rotation invariance is preserved and only boost invariance is violated.

A limit of the general field theoretic approach in which coordinates can be found such that only the “0” components for Lorentz-violating tensors are nonzero

$$\mathcal{L} \supset \frac{1}{4}\epsilon^{\mu\rho\alpha\kappa}\epsilon^{\nu\sigma\beta\lambda}h_{\mu\nu}\left(\eta_{\kappa\lambda} - \overline{s}_{\kappa\lambda} - \overline{s}_{\kappa\lambda\delta\gamma}\partial^{\delta}\partial^{\gamma}\right)\partial_{\alpha}\partial_{\beta}h_{\rho\sigma}$$

effective field theory, linearized gravity

$$\mathcal{L}_{\mathcal{K}^{(d)}} = \tfrac{1}{4} h_{\mu\nu} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma},$$

$$\begin{aligned} \widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} &= \mathcal{K}^{(d)\mu\nu\rho\sigma\varepsilon_1\varepsilon_2\ldots\varepsilon_{d-2}} \partial_{\varepsilon_1}\partial_{\varepsilon_2}\ldots\partial_{\varepsilon_{d-2}} \\ &\equiv \mathcal{K}^{(d)\mu\nu\rho\sigma\circ^{d-2}} \end{aligned}$$

1) general action-based linearized theory of gravity
   based on a symmetric 2-tensor field,
   containing the GR limit,
   constructed from constant coefficients, derivatives, gravitational field

2) 14 classes of operators:
   3 of which maintain the usual GR gauge structure
   theory questions for the others

Notation: $\mathcal{K}^{(d)\mu\nu\rho\sigma\varepsilon_1\varepsilon_2\ldots\varepsilon_{d-2}} \supset \quad k^{(d)}_{(V)jm} \quad \bar{s}^{(d)}_{jm}$

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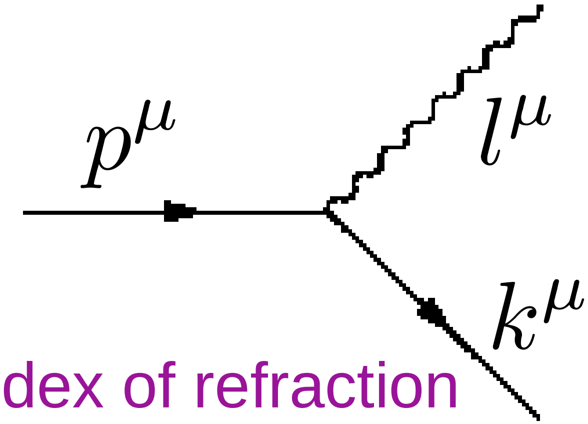
Čerenkov Radiation



effective direction and energy dependent index of refraction

$$n \approx 1 - \tfrac{1}{2} \sum_d (-1)^{d/2} s^{(d)} |\vec{l}|^{d-4}$$

$$s^{(d)}(\hat{p}) = \sum_{jm} Y_{jm}(\hat{p}) \bar{s}^{(d)}_{jm}$$

power loss to gravitons

$$\frac{dE}{dt} = -\frac{1}{8|\vec{p}|\sqrt{m_w^2 + \vec{p}^2}} \int \frac{d^3 l}{(2\pi)^2 |\vec{l}|} |\mathcal{M}|^2 \delta(\cos\theta - \cos\theta_C)$$

$$\cos\theta_C = \frac{\sqrt{m_w^2 + \vec{p}^2}}{|\vec{p}|} \frac{1}{n(|\vec{l}|)} + \frac{|\vec{l}|}{2|\vec{p}|} \left(1 - \frac{1}{[n(|\vec{l}|)]^2}\right)$$

natural cutoff at $l = p$

$$\frac{dE}{dt} = -F^w(d) G_N (s^{(d)})^2 |\vec{p}|^{2d-4}$$

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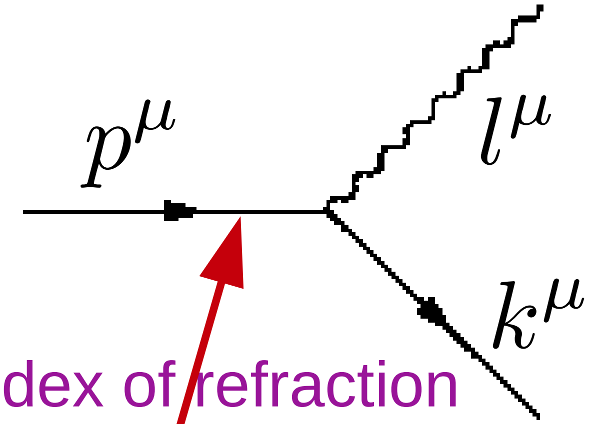
Čerenkov Radiation



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$$\frac{dE}{dt} = -F^w(d) G_N (s^{(d)})^2 |\vec{p}|^{2d-4}$$

scalars, fermions, photons

direction dependence
momentum dependence

Čerenkov Radiation

solve power loss for time of flight

$$t = \frac{\mathcal{F}^w(d)}{G_N (s^{(d)})^2}\left(\frac{1}{E_f^{2d-5}} - \frac{1}{E_i^{2d-5}}\right)$$

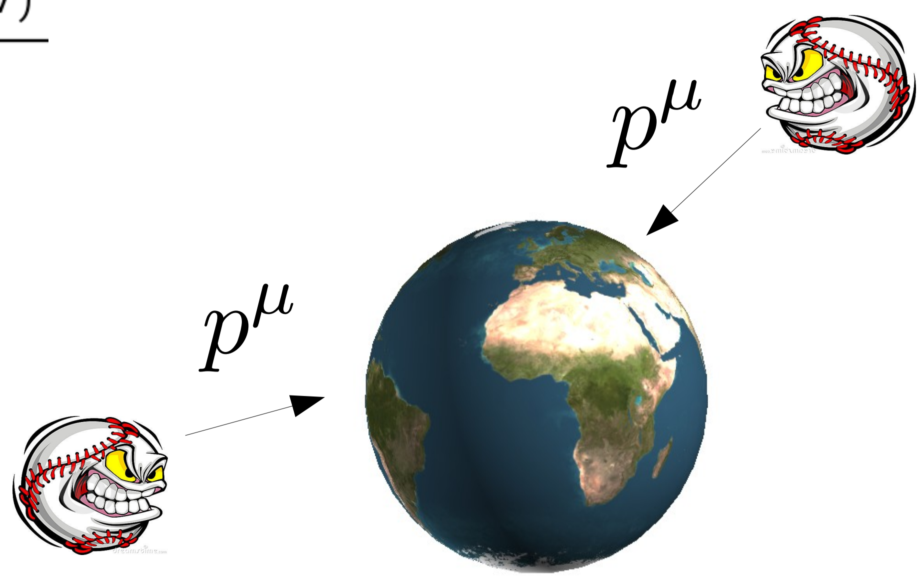
constraints via travel distance and observed energy

$$s^{(d)}(\hat{p}) \equiv (\bar{s}^{(d)})^{\mu\nu\alpha_1\ldots\alpha_{d-4}}\hat{p}_\mu\hat{p}_\nu\hat{p}_{\alpha_1}\ldots\hat{p}_{\alpha_{d-4}} = \sum_{jm} Y_{jm}(\hat{p})\bar{s}^{(d)}_{jm} < \sqrt{\frac{\mathcal{F}^w(d)}{G_N E_f^{2d-5} L}}$$

OMG particle and friends

we see 'em so they didn't gravi-Čerenkov away all energy

Observatory	Events	$E_{\max}$ (EeV)
AGASA	22	213
Fly's Eye	1	320
Haverah Park	13	159
HiRes	11	127
Pierre Auger	136	127
SUGAR	31	197
Telescope Array	60	162
Volcano Ranch	2	139
Yakutsk	23	160



Čerenkov radiation

constraints

- billion fold improvements on 9 d=4 coefficients
- first-ever constraints on 153 d=6, d=8, d=10 coefficients

Conservative constraints on coefficients $\bar{s}^{(8)}_{jm}$ in GeV^{-4}.

d	j	Lower bound	Coefficient	Upper bound
8	0	$-7 \times 10^{-49} <$	$\bar{s}^{(8)}_{00}$	
8	1	$-1 \times 10^{-45} <$	$\bar{s}^{(8)}_{10}$	$< 1 \times 10^{-45}$
		$-9 \times 10^{-46} <$	$\mathrm{Re}\ \bar{s}^{(8)}_{11}$	$< 8 \times 10^{-46}$
		$-9 \times 10^{-46} <$	$\mathrm{Im}\ \bar{s}^{(8)}_{11}$	$< 9 \times 10^{-46}$
8	2	$-9 \times 10^{-46} <$	$\bar{s}^{(8)}_{20}$	$< 1 \times 10^{-45}$
		$-1 \times 10^{-45} <$	$\mathrm{Re}\ \bar{s}^{(8)}_{21}$	$< 8 \times 10^{-46}$
		$-8 \times 10^{-46} <$	$\mathrm{Im}\ \bar{s}^{(8)}_{21}$	$< 9 \times 10^{-46}$
		$-1 \times 10^{-45} <$	$\mathrm{Re}\ \bar{s}^{(8)}_{22}$	$< 9 \times 10^{-46}$
		$-1 \times 10^{-45} <$	$\mathrm{Im}\ \bar{s}^{(8)}_{22}$	$< 9 \times 10^{-46}$
8	3	$-1 \times 10^{-45} <$	$\bar{s}^{(8)}_{30}$	$< 1 \times 10^{-45}$

effective field theory dispersion relation

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

$$\varsigma^0 = \sum_{djm} \omega^{d-4}\, Y_{jm}(\hat{\boldsymbol{n}})\, k^{(d)}_{(I)jm},$$

$$\varsigma^1 \mp i\varsigma^2 = \sum_{djm} \omega^{d-4}\, {}_{\pm 4}Y_{jm}(\hat{\boldsymbol{n}})\, \left(k^{(d)}_{(E)jm} \pm i k^{(d)}_{(B)jm}\right),$$

$$\varsigma^3 = \sum_{djm} \omega^{d-4}\, Y_{jm}(\hat{\boldsymbol{n}})\, k^{(d)}_{(V)jm}.$$

1) anisotropy
   convenient spherical harmonic direction dependence
2) birefringence
   plus/minus in dispersion
3) dispersion through various powers of frequency

$$\left|\sum_{jm} Y_{jm}(160°, 120°) k^{(5)}_{(V)jm}\right| \lesssim 2 \times 10^{-14}\ \mathrm{m}$$

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summary

- Effective field theory methods facilitate a broad and organized search for new physics.

- Much work has been done with gravitational systems.

- Much remains to explore, e.g. gravitational waves.