Astrophysical consequences of Lorentz violations in gravity
Outline

- Lorentz violation in gravity: motivation, phenomenology & experimental constraints
- Lorentz violation implies violations of the strong equivalence principle:
  The motion of neutron stars (the “sensitivities” and dipolar gravitational-wave emission) and constraints from pulsars. Based on
  Yagi, Blas, Yunes, EB arXiv:1307.6219, PRL in press;
  Yagi, Blas, EB, Yunes arXiv:1311.7144, PRD in press
- Black hole solutions and universal horizons. Based on
  EB, Jacobson & Sotiriou PRD 83, 124043 (2011);
  EB and Sotiriou CQG 30 244010 (2013)
- Talk by Ian Vega this afternoon: more on black holes (rotating case)
Lorentz violation in gravity: why?

- LV may give better UV behavior (Horava), quantum-gravity completions generally lead to LV

- LV allows MOND-like (Bekenstein, Blanchet & Marsat) or dark-energy-like phenomenology

- Strong constraints in matter sector, weaker ones in gravity sector (caveat: constraints expected to percolate from gravity to matter sector)

- Solar system/isolated & binary pulsar experiments historically used to constrains LV in weak field (1 PN) regimes (“preferred-frame parameters”: Nordvedt, Kramer, Wex, Freire, Shao, Damour, Esposito Farese...), but surprises may happen in stronger-field regimes
Einstein-aether theory

• We want to specify a (local) preferred time “direction” timelike aether field \( U_\mu \) with unit norm

• Most generic action (in 4D) quadratic in derivatives is given (up to total derivatives) by

\[
S_{ae} = \frac{1}{16\pi G_{ae}} \int d^4x \sqrt{-g} \left( -R - M^{\alpha\beta}_{\mu\nu} \nabla_\alpha U^\mu \nabla_\beta U^\nu \right)
\]

\[
M^{\alpha\beta}_{\mu\nu} = c_1 g^{\alpha\beta} g_{\mu\nu} + c_2 \delta^\alpha_\mu \delta^\beta_\nu + c_3 \delta^\alpha_\nu \delta^\beta_\mu + c_4 U^\alpha U^\beta g_{\mu\nu}
\]

• To satisfy weak equivalence principle, matter fields couple minimally to metric (and not directly to aether)

\[
S = S_{ae} + S_{\text{matter}}(\psi, g_{\mu\nu})
\]
Khronometric gravity

- To specify a global time, U must be hypersurface orthogonal ("khronometric" theory)

\[ U_\mu = \frac{\partial_\mu T}{\sqrt{g^{\mu\nu} \partial_\mu T \partial_\nu T}} \quad S_\infty = \frac{1}{16\pi G_\infty} \int d^4x \sqrt{-g} \left( -R - M^{\alpha\beta}_{\mu\nu} \nabla_\alpha U^\mu \nabla_\beta U^\nu \right) \]

- Because \( U \) is timelike, \( T \) can be used as a time coordinate

\[ U_\alpha = \delta^T_\alpha (g^{TT})^{-1/2} = N\delta^T_\alpha \quad a_i = \partial_i \ln N \]

\[ S_K = \frac{1}{16\pi G_K} \int dT d^3x N \sqrt{h} (K_{ij}K^{ij} - \mu K^2 + \xi^{(3)}R + \eta a_i a^i) \]

- 3 free parameters vs 4 of AE theory (because aether is hypersurface orthogonal)
Khronometric vs Horava gravity

\[ S_H = \frac{1}{16\pi G_K} \int dT d^3x \, N \sqrt{h} \left( L_2 + \frac{1}{M_\star^2} L_4 + \frac{1}{M_\star^4} L_6 \right) \]

\[ L_2 = K_{ij} K^{ij} - \mu K^2 + \xi^{(3)} R + \eta a_i a^i , \]

- \( L_4 \) and \( L_6 \) contain 4th- and 6th-order terms in the spatial derivatives.
- Lower bound on \( M_\star \) depends on details of percolation of Lorentz violations from gravity to matter: from Lorentz violations in gravity alone, \( M_\star \gtrsim 10^{-3} \text{ eV} \), but precise bounds depend on percolation.
- Theory remains perturbative at all scales if \( M_\star \lesssim 10^{16} \text{ GeV} \).
- Terms crucial in the UV, but unimportant astrophysically, i.e. error scales as \( \sim M_{\text{Planck}}^4 / (M M_\star)^2 \sim 10^{-14} (M_{\odot} / M)^2 \).
Constraints on the coupling constants: the Parametrized Post-Newtonian expansion

- At 1PN, theories = to GR except for preferred-frame parameters $\alpha_1$ and $\alpha_2$ which are zero in GR but not in LV gravity
- Solar system & pulsar experiments require $|\alpha_1| \lesssim 10^{-5}$, $|\alpha_2| \lesssim 10^{-9}$

Imposing $\alpha_1 = \alpha_2 = 0$ reduces couplings from 4 to 2 (AE theory): $c_+, c_- \ldots$

... and from 3 to 2 (khronometric theory): $\lambda$, $\beta$

- $c_+, c_-$ and $\lambda$, $\beta$ enter at PN order $> 1$ (they are “strong-field couplings”)
Constraints on the coupling constants: stability

• AE theory has propagating spin-0, spin-1 and spin-2 gravitational modes
• Khronometric theory has spin-0, spin-2 modes
• For classical/quantum stability, real propagation speeds and positive energies
• Propagation speed must be larger than speed of light to avoid gravitational Cherenkov radiation
• Well posedness proved in flat space and in spherical symmetry
Stability+Cherenkov constraints
How about cosmological constraints?

- Weak for AE theory
- For khronometric theory,
  \[
  \frac{G_N}{G_C} = \frac{2 + \beta + 3\lambda}{2(1 - \beta)}
  \]
  and BBN requires
  \[
  \left|\frac{G_N}{G_C} - 1\right| < \frac{1}{8}
  \]
- No constraints from CMB in khronometric theory yet
Why are astrophysical effects expected?

- Matter couples minimally to metric, but metric couples non-minimally to aether effective matter-aether coupling in strong-field regimes.

- For strongly gravitating body (e.g. neutron star), binding energy depends on velocity relative to the aether \( \gamma = U_\mu u^\mu \) (i.e. structure depends on motion relative to preferred frame, as expected from Lorentz violation!)

- Gravitational mass depends on velocity relative to the aether

\[
S_{\text{matter}} = \sum_i \int m_i(\gamma) \, d\tau_i \quad \Rightarrow \quad u_a^\mu \nabla_\mu (m_a u^\nu) = -\frac{d m_a}{d\gamma} u^\mu \nabla^\nu U_\mu
\]

Violations of strong equivalence principle (aka Nordtvedt effect in Brans Dicke theory, scalar tensor theories, etc)
Why are astrophysical effects expected?

Whenever strong equivalence principle (SEP) is violated, dipolar gravitational-wave emission may be produced

- In GR, dipolar emission not present because of SEP + conservation of linear momentum

\[ M_1 \equiv \int \rho x_i \, d^3 x \]

\[ h \sim \frac{G}{c^3} \frac{d}{dt} \frac{M_1}{r} \sim \frac{G}{c^3} \frac{P}{r} \quad \text{not a wave!} \]

- If SEP is violated,

\[ h \sim \frac{1}{R} \frac{d}{dt} [m_1(\gamma)x_1 + m_2(\gamma)x_2] \propto \left( \frac{d \log m_1}{d \log \gamma} - \frac{d \log m_2}{d \log \gamma} \right) \]

- Dipolar mode might be observable directly by interferometers, or indirectly via its backreaction on a binary's evolution
A PN analysis: the violation of the SEP

\[ S_A = - \int d\tau \tilde{m}_A[\gamma] = -\tilde{m}_A \int d\tau \left\{ 1 + \sigma_A (1 - \gamma_A) + \frac{1}{2} \sigma'_A (1 - \gamma_A)^2 + \mathcal{O} \left[ (1 - \gamma_A)^3 \right] \right\} \]

\[ \gamma = U^\mu u_\mu \quad \sigma_A \equiv - \frac{d \ln \tilde{m}_A[\gamma_A]}{d \ln \gamma_A} \bigg|_{\gamma_A = 1} \quad \sigma'_A \equiv \sigma_A + \sigma_A^2 + \frac{d^2 \ln \tilde{m}_A[\gamma_A]}{d \ln \gamma_A^2} \bigg|_{\gamma_A = 1} \]

body's "sensitivities"

Define "active" gravitational mass \( m_A = (1 + \sigma_A)\tilde{m}_A \)

and "strong-field" gravitational constant \( g_{AB} = \frac{G_N}{(1 + \sigma_A)(1 + \sigma_B)} \)

Modified Newton's law:

\[ \dot{u}^i_A = \sum_{B \neq A} \frac{-G_N \tilde{m}_B}{(1 + \sigma_A) r_{AB}^3} r^i_{AB} \equiv \sum_{B \neq A} \frac{g_{AB} m_B}{r_{AB}^3} r^i_{AB} \quad \text{Foster 2007} \]
A PN analysis: the dissipative dynamics

- GWs carry energy away from binaries

\[ \dot{E} = -\frac{32}{5} G_N (G_N M)^{4/3} \mu^2 \left( \frac{P_b}{2\pi} \right)^{-10/3} \langle A \rangle \]

\[ \langle A \rangle = \frac{1}{(1 + \sigma_1)^{4/3}(1 + \sigma_2)^{4/3}} \left[ A_1 + S A_2 + S^2 A_3 \right. \]

\[ + \frac{5}{32} (s_1 - s_2)^2 C (1 + \sigma_1)^{2/3}(1 + \sigma_2)^{2/3} \left( \frac{P_b}{2\pi G_N M} \right)^{2/3} \left. \right] \]

- Dipole, Quadrupole

\[ S = \frac{(s_1 m_2 + s_2 m_1)}{M} \]
\[ M = m_1 + m_2 \]
\[ \mu = \frac{m_1 m_2}{M}, \quad s_A = \sigma_A / (1 + \sigma_A) \]

\[ A_1, A_2, A_3 \] are functions of the coupling constants \((c_+, c_-)\) or \((\beta, \lambda)\);

in GR \(A = 1\) (Foster 2007, Yagi, Blas, EB, Yunes 2013, Yagi, Blas, Yunes, EB 2013)

- As binary's binding energy decreases, period decreases

\[ \frac{\dot{P}_b}{P_b} = -\frac{3}{2} \frac{\dot{E}}{E} = \frac{3}{2} \frac{\dot{E}}{E} \]

The Strong Gravity Regime of Black Holes and Neutron Stars
Bad Honnef, March 31 – Apri 4, 2014
Why is this interesting?

Binary pulsars are the strongest test of GR to date

To calculate rate of change of orbital period we need sensitivities

$$\sigma = - \left. \frac{\partial \log M}{\partial \log \gamma} \right|_{v=0} = -2 \left. \frac{\partial \log M}{\partial (v^2)} \right|_{v=0}$$

PSR B1913+16
(Weisberg & Taylor 2004)
The sensitivity of neutron stars
(Yagi, Blas, Yunes, EB 2013; Yagi, Blas, EB, Yunes 2013)

Calculation is non trivial!
Requires solving numerically for stars in motion relative to aether, to first order in velocity (thanks to Gauss theorem)

\( C^* = M^* / R^* \)

Red = weak field prediction
(Foster 2007)

\( s_{\text{wf}} = \left( \alpha_1 - \frac{2}{3} \alpha_2 \right) \frac{\Omega}{M_*} + \mathcal{O} \left( \frac{\Omega^2}{M_*^2} \right) \)
Constraints from binary pulsars

We choose pulsar-pulsar and pulsar-WD binaries with small eccentricities (PSR J1141-6545, PSR J0348+0432, PSR J0737-3039, PSR J1738+0333), and impose that difference from GR is $<$ data uncertainties.
Constraints from binary pulsars
Constraints on Lorentz violation in gravity
(Yagi, Blas, Yunes, EB 2013; Yagi, Blas, EB, Yunes 2013)

- Red = weak field prediction for $\alpha_1 = \alpha_2 = 0$ (by requiring exactly same fluxes as GR)
- Combined constraints from almost-circular WD-pulsar and pulsar-pulsar systems (PSR J1141-6545, PSR J0348+0432, PSR J0737-3039, PSR J1738+0333)
- Includes observational uncertainties (masses, spins, eccentricity, EOS)
Are BHs possible in LV gravity?

- BHs in GR defined in terms of spacetime causal structure eg in static spherical spacetime, horizon lies where light cones “tilt inwards” (cf Eddington Finkelstein coordinates).
- In GR, matter (photons) and gravitons have same speed $c$.
- In LV gravity, photon, spin-2, spin-1 and spin-0 gravitons have different propagation speeds, different propagation cones, multiple horizons.
- If higher-order terms included in the action, non-linear dispersion relations for gravitons $\omega^2 = k^2 + \alpha k^4 + \ldots$ give infinite speed in the UV limit, do BHs exist at all?
Spherical BHs in infrared LV gravity
(EB, Jacobson & Sotiriou 2011)

- Once fixed mass, one-parameter family of solutions characterized by aether charge $A_2$

- For $A_2 \neq A_2^{\text{reg}}$ naked curvature singularity at spin-0 horizon, but gravitational collapse picks regular solution $A_2 \neq A_2^{\text{reg}}$ (Garfinkle, Eling & Jacobson 2007)

- Impose regularity at spin-0 horizon by solving field eqs perturbatively, and pick asymptotically flat solution by shooting method (asymptotic flatness does not follow from field eqs, unlike in GR)

- UV corrections due to higher curvature terms small away from central singularity $\sim \frac{M_4^{\text{Planck}}}{(MM_*)^2} \lesssim 10^{-14} \left(\frac{M_\odot}{M}\right)^2$
BH exterior structure

- Because of Cherenkov bound, spin-0 horizon is inside matter horizon ("metric horizon")
- Outside metric horizons, BHs similar to Schwarzschild
\[ \frac{\Delta \left( \frac{b_{ph}}{r_g} \right)}{b_{ph}/r_g} = \frac{\Delta \left( \Omega_{ph} r_g \right)}{\Omega r_g} \]

Measurable with GWs?
BH interior structure

Metric qualitatively similar to Schwarzschild (curvature singularity at $r=0$), aether oscillates

$$\theta_r = \arccosh \gamma_r$$

$$\gamma_r \equiv u^\alpha_{\text{obs}} u_\alpha = -\frac{u^r}{\sqrt{g^{rr}}}$$

$\gamma_r$ is aether's Lorentz factor relative to observer orthogonal to (spacelike) hypersurface $r = \text{const}$
BH interior structure

\[ c_+ = 0.99, \quad c_- = 0.01 \]

\[ \beta = 0.4, \quad \mu = -1.8 \]
Implications for causal structure in BH interior

\[ \theta_r = 0 \quad \Rightarrow \text{aether orthogonal to (spacelike) hypersurface } r = r_u = \text{const} \]

Any signal \( r < r_u \) can only propagate inwards, whatever its speed, because future=inwards \( r = r_u \) is a Universal Horizon

(EB, Jacobson & Sotiriou 2011; Blas and Sibiryakov 2011)
A universal horizon for signals of infinite speed

(EB, Jacobson & Sotiriou 2011; Blas and Sibiryakov 2011)

Figure adapted from Cropp, Liberati and Mohd, arXiv:1312.0405
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Figure adapted from Cropp, Liberati and Mohd, arXiv:1312.0405
Further developments about Universal Horizons

• Universal horizon seems to exist also in slowly rotating BHs (at least in Horava gravity, Barausse and Sotiriou 2013, cf also Ian Vega’s talk) and is robust to UV corrections to the action

• Universal horizons satisfy first law of BH thermodynamics (Berglund, Bhattacharyya, Mattingly 2012, 2013; Mohd 2013), and evidence that Hawking radiation is associated to it (Cropp, Liberati and Mohd 2013)

• Confirmation that universal horizons form in gravitational collapse (Saravani, Afshordi, Mann 2013)

• Universal horizon linearly stable, but clues of non-linear instability (Blas and Sibiryakov 2011); cf also Ian Vega’s talk
Conclusions

- Lorentz violations in gravity generically introduces violations of strong equivalence principle and thus dipole emission
- Placing precise constraints with binary pulsars requires exact values of sensitivities (non-trivial calculation)
- Resulting constraints are strong-field and ~ order of magnitude stronger than previous ones
- BH solutions very similar to GR in the “exterior”, but causal structure is very different in the “interior” (universal horizon acts as boundary for perturbations with infinite speed)