Black holes in Lorentz violating gravity are (*almost*) unchanged

Andrew Kovachik in col. with *Morgan Kidnew, Pavel Petrov, Sergey Sibiryakov*

Motivation

Abandoning LI can allow renormalization

$$\boxed{\int \mathrm{d}^4p \quad \underbrace{\frac{1}{p^2}(\;)}_{\text{Bad Divergent}}} \qquad \boxed{\int \mathrm{d}^4p \quad \underbrace{\frac{1}{p^4}(\;)}_{\text{Good Divergent?}}}$$

$$p^4 = (\omega^2 + k^2)^2 = \mathcal{O}(\omega)^4$$

$$\mathcal{O}(\omega)^4 \implies \ddddot{\phi}$$

$$p^4 \to \omega^2 + k^6$$

$$\boxed{\int \mathrm{d}^4p \frac{1}{\omega^2 + k^6}(\;) \propto \int \mathrm{d}k \frac{1}{k^3}}$$

If LI is emergent, where can we probe it?

Black hole binaries

How do BHs move in LV theories?

Need to understand these questions to calculate modified binary waveforms

Theory

Einstein Aether Theory [1]

- All second derivative terms of vector

$$\boxed{u_\mu u^\mu = 1}$$

$$\mathcal{L}_{\mathrm{AE}} = \underbrace{\frac{c_\vartheta}{3}\vartheta^2}_{\text{Expansion}} + \underbrace{c_\sigma \sigma_{\mu\nu}\sigma^{\mu\nu}}_{\text{Shear}} + \underbrace{c_\omega \omega_{\mu\nu}\omega^{\mu\nu}}_{\text{Twist}} + \underbrace{c_a a_\mu a^\mu}_{\text{Acceleration}}$$

$$\boxed{s_S^2 = \frac{c_\vartheta + c_\sigma}{2c_a}} \qquad \boxed{s_V^2 = \frac{c_\omega + 2c_\sigma}{3c_a}}$$

Scalar Mode Vector Mode

Hypersurface orthogonal

Khronometric Theory [2]

$$\boxed{u_\mu = \frac{\partial_\mu \phi}{\sqrt{\partial_\nu \phi \partial^\nu \phi}}}$$

$$\mathcal{L}_{\mathrm{khr}} = \lambda\, \vartheta^2 + \beta\, \sigma_{\mu\nu}\sigma^{\mu\nu} + \alpha\, a_\mu a^\mu$$

Has a UV completion

Horava Gravity [3]

How does the field change?

- Schwarzchild [4]
- Reissner-Nordstrom [5]
- Kerr [6]

Static $\longrightarrow$ Moving

Do they exist?

What can we hope to measure?

Sensitivities

$$\boxed{S_{\mathrm{pp}} = -\int m \mathrm{d}\tau \quad \to \quad S_{\mathrm{pp}} = -\int m F(v^\mu u_\mu) \mathrm{d}\tau}$$

Standard point Particle view

Lorentz violating effects

$$F = 1 + \sigma(1 - v^\mu u_\mu) + \frac{\sigma'}{2}(1 - v^\mu u_\mu)^2$$

Sensitivity

$$S = S_{\mathrm{pp}} + S_{\mathrm{AE}}$$

$$g_{\mu\nu} = \eta_{\mu\nu} - \phi(\vec{x})\delta_{\mu\nu} \qquad \phi(\vec{x}) = -\frac{GM}{r}.$$

$$u^\mu = \bar{u}^\mu + b^\mu.$$

Expand to 2nd order in perturbation and 1st order in velocity. Take EOM of perturbed vector and identify components with sensitivity

Asymptotically flat point particle picture $\longleftrightarrow$ Lorentz violating black hole solution

Match asymptotic behaviour

Results

Khronometric Theory Schwarzchild [7]

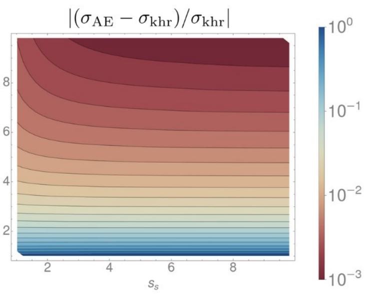
Leading sensitivity depends on a *single* small parameter

$$\boxed{\sigma = \frac{\alpha - 2\beta}{2} + 2\kappa\,\alpha}$$

$$\kappa = 0.0244$$

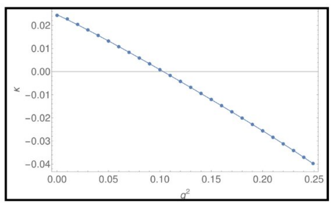
$$\boxed{\sigma \lesssim 3 \cdot 10^{-6}}$$

Einstein Aether Schwarzchild [8]



Rapidly approaches Khr. sensitivity value

Khr. & AE Reisner-Nordstrom [9]



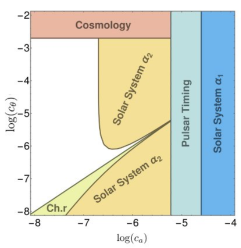
$$\boxed{f(r/r_s) = 1 - \frac{r_s}{r} + \frac{Q^2}{r^2}}$$

$$Q^2 = \frac{G_N}{4\pi}(Q_e^2 + Q_m^2) \qquad q^2 \equiv \frac{Q^2}{r_s^2}$$

- Limiting sensitivity changes
- No longer degenerate

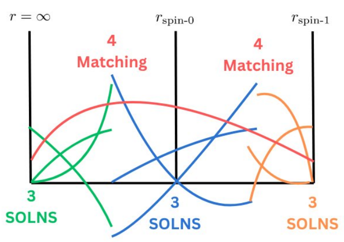
Methods

Small parameters. Aether decouples from metric. → **Solve for background aether field.** → **Black hole has small velocity.** → **Solve for perturbed aether field.** → **Match asymptotics to find sensitivity!**



Perturbed solution has singular behaviour at spatial infinity, spin-0, and spin-1 horizon

Shoot non singular behaviours and use matching solutions to create complete solution



Outlook

Black hole sensitivities are highly suppressed across LV gravity

- Binary waveforms and dipolar radiation
- Rotating (Kerr) black holes
- Higher-order velocity expansion

Understanding now that most numerics can be skipped and only κ needs to be calculated

[1] Einstein-Aether Waves. Jacobson, Mattingly. **gr-qc/0402005**
[2] Models of non-relativistic quantum gravity: the good, the bad and the healthy. Blas, Pujolas, Sibiryakov. **1007.3503**
[3] Quantum Gravity at a Lifshitz Point. Horava. **0901.3775**
[4] Thermodynamics of black holes in the deformed Horava-Lifshitz gravity. Myung. **0905.0957**
[5] Charged black holes in Horava gravity. Janiszewski, Karch, Robinson, Sommer. **1401.6479**
[6] Rotating black holes in Einstein-aether theory. Adam, Figueras, Jacobson, Wiseman. **2108.00005**
[7] Slowly moving black holes in khrono-metric model. **Kovachik**, Sibiryakov. **2311.12936**
[8] Slowly moving black holes in Einstein Aether theory. **Kovachik**, Kidnew, Sibiryakov. **In Preparation**
[9] Charged moving black holes in Lorentz violating theories. **Kovachik**, Petrov, Sibiryakov. **In Preparation**