Testing Lorentz Invariance by binary black holes

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ICG @ 15

Outline

- **Motivations**
  - Going beyond GR: **why?**
  - Going beyond GR: **how?**
- **Lorentz-violating gravity**
  - Einstein-Æther and Horava Gravity
  - Modified dynamics: **sensitivities**
  - Black-holes in LV gravity
  - **Black hole perturbations in HL**
  - Extracting the sensitivities
  - Dipolar radiation
- **What's next?**
  - Exploring the allowed phase space
  - Constraining the theory

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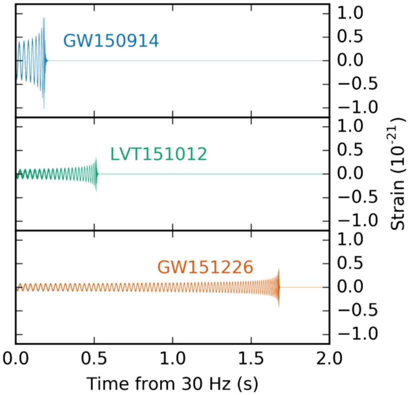
$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

- **Existing tests: weakly-gravitating, mildly relativistic regime of Einstein equations**

Going beyond GR: why?



First time we can detect GWs, providing direct proof of the existence of BHs.

The dynamics of the orbital motion affected by GW emission through **back-reaction**

$\Rightarrow$ **GWs can be used to test gravity in this high curvature and highly relativistic regime!**

Why Lorentz-violating gravity?

Lorentz invariance is at the core of theoretical physics

- High Energy Physics only constrains the matter sector and its coupling to gravity.
- **Phenomenology** $\rightarrow$ try to understand what would be the signature of these theories.
- A model for **Quantum Gravity**: Horava gravity

How to describe such a theory?

Going beyond GR: how?

Two experimentally verified principles are on the basis of the so-called metric theories of gravity:

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Among these, Einstein's General Relativity is the current "standard" theory of gravitation.

It can be defined by two postulates:

- The Lagrangian density $\mathcal{L}_{\mathrm{Einstein-Hilbert}}[g_{\alpha\beta}] = \frac{c^4}{16\pi G_N} R(g_{\alpha\beta})$,
- The metric $g_{\mu\nu}$ couples universally, and minimally, to all the fields of the Standard Model.

$$S_{\mathrm{matter}} \equiv S_{\mathrm{matter}}[\psi_{\mathrm{matter}};\, g_{\alpha\beta}]$$

Going beyond GR: how?

Lovelock's theorem

In a 4-dimensional spacetime, the only divergence-free symmetric rank-2 tensor constructed from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term, i.e., $G_{\mu\nu} + \Lambda g_{\mu\nu}$.

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How to break Lorentz invariance without giving up general covariance and still verify the EEP and SR?

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$\rightarrow$ **Extra dynamical field** that can define a preferred frame at the level of the solution!

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Æ-theory and HL gravity

A **unitary** vector field **u** which interacts with the metric **g**

$$S = \frac{1}{16\pi G_{Æ}} \int \big(- R + L_{æ} - \lambda(g_{\mu\nu}u^{\mu}u^{\nu} - 1)\big)\sqrt{-g}\, \mathrm{d}^4x \,,$$

where

$$\begin{array}{rcl} L_{æ} & = & -M^{\alpha\beta}{}_{\mu\nu}\, \nabla_{\alpha}u^{\mu}\nabla_{\beta}u^{\nu} \,, \\ M^{\alpha\beta}{}_{\mu\nu} & = & c_1 g^{\alpha\beta}g_{\mu\nu} + c_2\delta^{\alpha}_{\mu}\delta^{\beta}_{\nu} + c_3\delta^{\beta}_{\mu}\delta^{\alpha}_{\nu} + c_4 u^{\alpha}u^{\beta}g_{\mu\nu} \,. \end{array}$$

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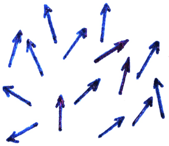
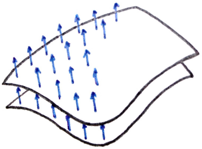
$$\begin{aligned} L_{\text{æ}} &= -M^{\alpha\beta}{}_{\mu\nu}\,\nabla_\alpha u^\mu \nabla_\beta u^\nu\,, \\ M^{\alpha\beta}{}_{\mu\nu} &= c_1 g^{\alpha\beta} g_{\mu\nu} + c_2 \delta^\alpha_\mu \delta^\beta_\nu + c_3 \delta^\beta_\mu \delta^\alpha_\nu + c_4 u^\alpha u^\beta g_{\mu\nu}\,. \end{aligned}$$

In the Horava-Lifshitz case we impose the orthogonality condition before variation

$$u_\mu = \frac{\nabla_\mu T}{\sqrt{g_{\alpha\beta}\nabla^\alpha T\,\nabla^\beta T}}\,.$$





$$U^\mu = \frac{\nabla^\mu T}{\sqrt{\nabla_\alpha T \nabla^\alpha T}}$$

Æ-theory and HL gravity

The metric and the aether must satisfy the set of modified field equations

$$G_{\mu\nu} - T^{\text{æ}}_{\mu\nu} - \frac{8\pi G_{\text{æ}}}{c^4} T^{\text{mat}}_{\mu\nu} = 0\,,$$

$$\Big(\nabla_\alpha J^{\alpha\nu} - c_4 \dot{u}_\alpha \nabla^\nu u^\alpha\Big)(g_{\mu\nu} - u_\mu u_\nu) = 0\,,$$

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\end{aligned}
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where $J^{\alpha}{}_{\mu} \equiv M^{\alpha\beta}{}_{\mu\nu}\, \nabla_\beta u^\nu$, $\dot{u}_\nu = u^\mu \nabla_\mu u^\nu$, and

$$
\begin{aligned}
T^{æ}_{\alpha\beta} \equiv \quad & \nabla_\mu \left(J_{(\alpha}{}^{\mu} u_{\beta)} - J^{\mu}{}_{(\alpha} u_{\beta)} - J_{(\alpha\beta)} u^\mu \right) \\
& + c_1 \left[(\nabla_\mu u_\alpha)(\nabla^\mu u_\beta) - (\nabla_\alpha u_\mu)(\nabla_\beta u^\mu) \right] \\
& + \left[u_\nu (\nabla_\mu J^{\mu\nu}) - c_4 \dot{u}^2 \right] u_\alpha u_\beta + c_4 \dot{u}_\alpha \dot{u}_\beta \\
& + \tfrac{1}{2} M^{\sigma\rho}{}_{\mu\nu} \nabla_\sigma u^\mu \nabla_\rho u^\nu g_{\alpha\beta}\,,
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plus the generalized Bianchi identity

$$\nabla_\mu (2E^{\mu\nu} + u^\mu Æ^\nu) = -Æ_\mu \nabla^\nu u^\mu\,.$$

Æ-theory and HL gravity

The metric and the aether must satisfy the set of modified field equations

$$\begin{aligned} E_{\mu\nu} &\equiv G_{\mu\nu} - T^{æ}_{\mu\nu} - \frac{8\pi G_{æ}}{c^4} T^{\rm mat}_{\mu\nu} = 0\,, \\ Æ_{\mu} &\equiv \Big(\nabla_\alpha J^{\alpha\nu} - c_4 \dot{u}_\alpha \nabla^\nu u^\alpha\Big)(g_{\mu\nu} - u_\mu u_\nu) = 0\,, \end{aligned}$$

where $J^{\alpha}{}_{\mu} \equiv M^{\alpha\beta}{}_{\mu\nu}\, \nabla_\beta u^\nu$, $\dot{u}_\nu = u^\mu \nabla_\mu u^\nu$, and

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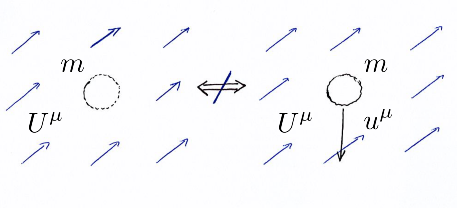
Modified dynamics: sensitivities

Generically, the motion of a self-gravitating object will depend on the external values of the field.



We can write

$$
\begin{aligned}
S_{\rm pp} &= -\int \mathrm{d}\tau\ \tilde{m}(\gamma) \\
&= -\tilde{m}\int \mathrm{d}\tau \left(1 + \sigma(1-\gamma) + \mathcal{O}[(1-\gamma)^2]\right)
\end{aligned}
$$

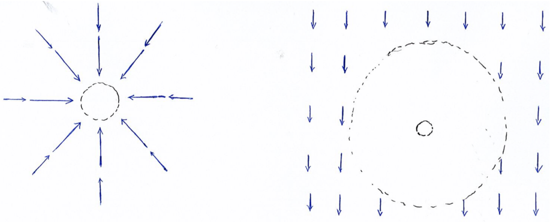
The Lorentz factor and the **sensitivity** :

$$
\gamma \equiv U_\mu u^\mu, \qquad \sigma \equiv -\frac{\mathrm{d}\ln\tilde{m}(\gamma)}{\mathrm{d}\ln\gamma}\Big|_{\gamma=1}
$$

Æ theory and HL gravity

By getting the PN solution to the Modified field equations, one finds that the dipolar emission is encoded in the numerical values of the sensitivities.

In order to get the sensitivities, we study the slow motion of a black-hole, defined as the asymptotically stationary flow of the aether in the z direction with an infinitesimal speed V.



Static, spherically symmetric black-holes in Einstein-Aether theory

In Eddington-Finkelstein coordinates $\{v, r, \phi, \theta\}$ the metric Ansatz of a static spherically symmetric black-hole is

$$\mathrm{d}s^2 = \Big(f(r)\mathrm{d}v^2 - 2B(r)\mathrm{d}r\mathrm{d}v - r^2\mathrm{d}\Omega^2 \Big) \tag{1}$$

while the æther field Ansatz reads

$$u^\mu \partial_\mu = A(r)\partial_v - \frac{1 - f(r)A^2(r)}{2B(r)A(r)}\partial_r.$$

This leads to a system of ordinary differential equations for $f''(r)$, $A''(r)$ and $B'(r)$.

Static, spherically symmetric black-holes in Einstein-Aether theory

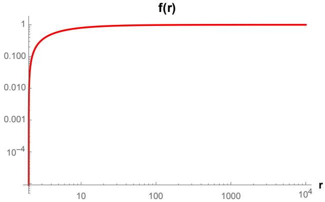
We fix c_1, c_2, c_3 and c_4.

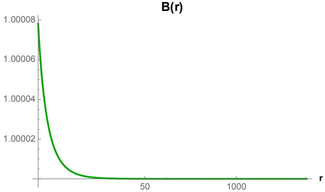
We can integrate this set from say, the black-hole's horizon.

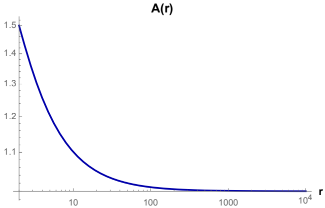
We obtain a 3-parameter family of solutions. However, asymptotic flatness reduces this to a 2-parameter set of solution and finally regularity at the universal horizon leads to a 1-parameter family of solution.

→ For each mass, there's only one static spherically symmetric black-hole.

Static, spherically symmetric black-holes in Einstein-Aether theory







Schwarzschild :
$f(r) = 1 - \frac{2GM}{c^2 r}$
$B(r) = 1$

The perturbed black-hole

In Eddington-Finkelstein coordinates $\{v, r, \phi, \theta\}$ the metric Ansatz reads

$$\begin{aligned}
\mathrm{d}s^2 = &\Big(f(r)\mathrm{d}v^2 - 2B(r)\mathrm{d}r\mathrm{d}v - r^2\mathrm{d}\Omega^2\Big) \qquad \text{(background)} \\
&+ V\Big(\cos\theta\,\psi(r)\mathrm{d}v^2 + 2\mathrm{d}v\,f(r)\big(\cos\theta\big[\delta(r) - B(r)\psi(r)\big]\mathrm{d}r - \sin\theta\,\chi(r)\mathrm{d}\theta\big) \\
&\qquad + B(r)\cos\theta\big(\psi(r) - 2\delta(r)\big)\mathrm{d}r^2 + 2\sin\theta\big(B(r)\chi(r) - \Sigma(r)\big)\Big)\mathrm{d}r\mathrm{d}\theta \\
&+ \mathcal{O}(V^2)
\end{aligned}$$

while the vector field Ansatz reads

$$\begin{aligned}
u_\mu &= u_\mu^{\mathrm{b}} + V\delta u_\mu + \mathcal{O}(V^2) \\
&= \{u_v^{\mathrm{b}} + V\cos\theta\,\delta u_v(r), u_r^{\mathrm{b}} + V\cos\theta\,\delta u_r(r), 0, 0\} + \mathcal{O}(V^2)
\end{aligned}$$

The black hole solution

This leads to a linear system of differential equations on $\delta''(r)$, $\chi''(r)$, $\psi''(r)$ and $\Sigma'(r)$ plus two **constraint equations**.

A few things could be done in order to simplify matters:

- Compactify our integration variable by solving for $s = 1/r$.
- Turn our system into a first order one.

This eventually leads to the following differential equations

$$X'(s) = \mathbf{M}(s) \cdot X(s)\,,$$

where $X(s) = \big(p_\delta,\, p_\chi,\, p_\psi,\, \delta,\, \chi,\, \psi,\, \Sigma\big)(s)$ and for instance, $p_\delta(s) \equiv \delta'(s)$.

The black hole solution

We would like to integrate the system

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given initial data at the horizon $\rightarrow$ 7 parameters

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Scaling invariance: $2 - 1 \rightarrow 1$ only **one free parameter** for the initial data.

Hair?

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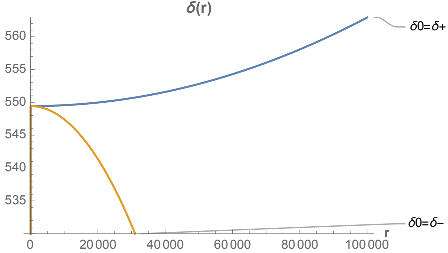
Generic solutions aren't regular at infinity. In fact, we can determine the value of the free parameter by a bisection procedure that converges to a regular solution.

The bisection procedure



$$\delta(r) = \delta_{\text{irregular}} r + \tilde{\delta}_0 + \frac{\tilde{\delta}_1}{r} + \frac{\tilde{\delta}_2}{r^2} + \mathcal{O}\left(\frac{1}{r^3}\right)$$

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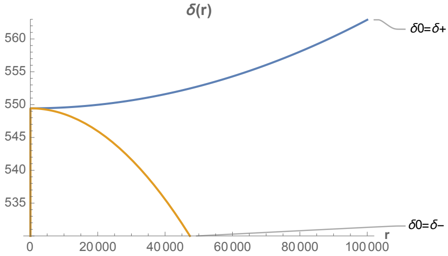

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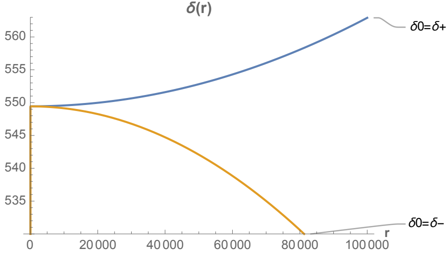

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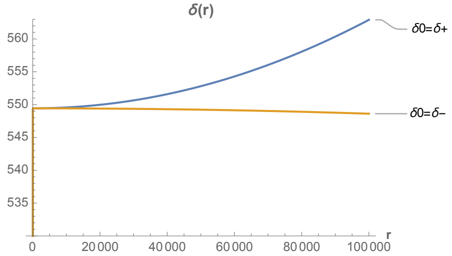

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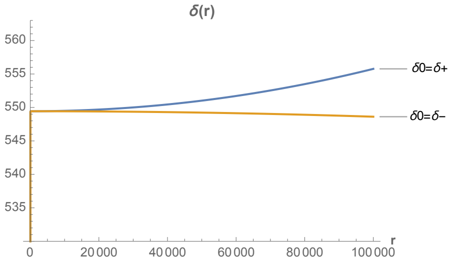

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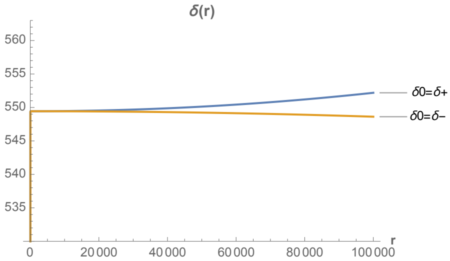

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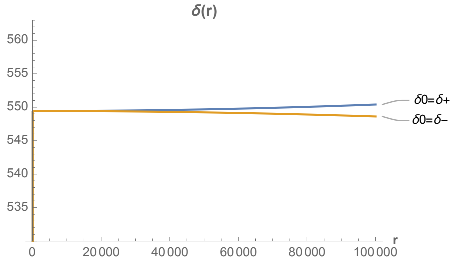

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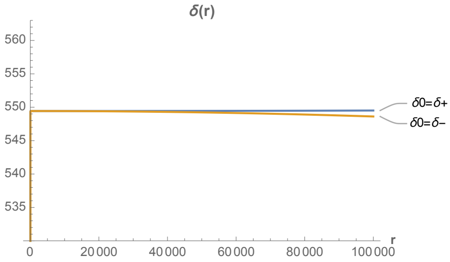

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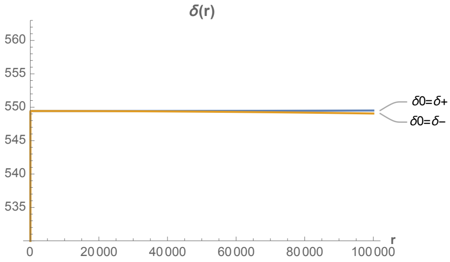

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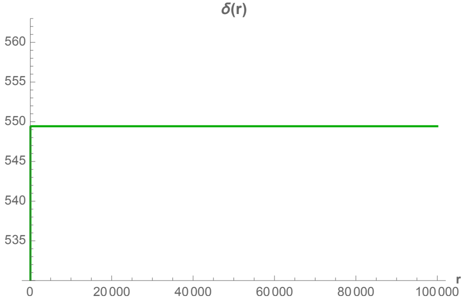

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The **sensitivities** are encoded in the coefficients of the asymptotic solution!

The sensitivities from the numerical solution

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& + V \Big(\cos\theta\, \psi(r)\mathrm{d}v^2 + 2\mathrm{d}v\, f(r) \big(\cos\theta \big[\delta(r) - B(r)\psi(r) \big] \mathrm{d}r - \sin\theta\, \chi(r)\mathrm{d}\theta \big) \\
& \qquad + B(r)\cos\theta \big(\psi(r) - 2\delta(r) \big) \mathrm{d}r^2 + 2\sin\theta \big(B(r)\chi(r) - \Sigma(r) \big) \Big) \mathrm{d}r\mathrm{d}\theta \\
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$$
\begin{aligned}
g_{0'0'} = \quad & 1 - \frac{1}{c^2}\frac{2G_N\tilde{m}_1}{r'_1} + \frac{1}{c^4}\Big[\frac{2G_N^2\tilde{m}_1^2}{{r'}_1^2} + \frac{2G_N^2\tilde{m}_1\tilde{m}_2}{r'_1 r'_2} + \frac{2G_N^2\tilde{m}_1\tilde{m}_2}{r'_1 r'_{12}} \\
& - \frac{3G_N^2\tilde{m}_1}{r'_1}{v'}_1^2(1+\sigma_1)\Big] + 1 \leftrightarrow 2 + \mathcal{O}(1/c^6)\,,
\end{aligned}
$$

and similar expressions for $g_{0'i'}$, $g_{i'j'}$.

- $\tilde{m}_A$ is the mass of the A-th point particle,
- ${v'}^i_A$ its velocity,
- ${r'}_{12}$ the binary's separation,
- r'_A the distance from the A-th particle to the field point, and
- G_N is the newtonian gravitational constant as measured by Cavendish-type experiments.

The effect of the sensitivities on the Motion of Binary Systems

The strong equivalence principle is defined as the universality of free fall for strongly gravitating bodies. GR satisfies this principle, but this is clearly not the case for theories in which the sensitivities are not zero.

The sensitivities affect both the conservative and dissipative sectors. For instance, at Newtonian order the motion of a binary is described by

$$\dot{v}_A^i = -\frac{\mathcal{G} m_B \hat{n}_{AB}^i}{r_{AB}^2}\,,$$

where we define the active gravitational masses as

$$m_B \equiv \tilde{m}_B(1+\sigma_B)\,,$$

and the 2-body coupling

$$\mathcal{G} \equiv \frac{G_N}{(1+\sigma_A)(1+\sigma_B)}$$

Outline

- **Motivations**
  - Going beyond GR: **why?**
  - Going beyond GR: **how?**
- **Lorentz-violating gravity**
  - Einstein-Æther and Horava Gravity
  - Modified dynamics: **sensitivities**
  - Black-holes in LV gravity
  - **Black hole perturbations in HL**
  - Extracting the sensitivities
  - Dipolar radiation
- **What's next?**
  - Exploring the allowed phase space
  - Constraining the theory

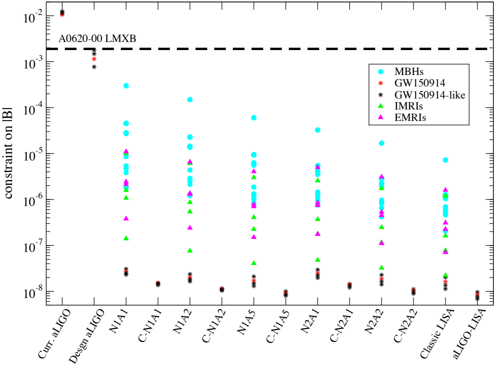
Exploring the allowed phase space

Recipe:

- Give c_1, c_2, c_3, c_4 within the allowed regions.
- Integrate for the static solution $\rightarrow f(r)$, $B(r)$, $A(r)$.
- Integrate for the stationary solution $\rightarrow \delta(r)$, $\chi(r)$, $\psi(r)$, $\Sigma(r)$.
- Read off the sensitivities σ as $\sigma(c_i, M)$.
- Check for the flux deviation.
- Constrain the parameter space!

Prospects

Future collaborations will improve our capacity to constrain dipolar emission



$$\frac{\dot{E}_{\rm GW}}{\dot{E}_{\rm GR}} = 1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}$$

where m and r_{12} are the binary's total mass and orbital separation.

B is a theory-dependent parameter regulating the strength of the dipole term.

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CONCLUSIONS

- We got the great opportunity to test GR in new extreme regimes.
- Lorentz invariance is yet to be tested within binary BHs
- One must check for deviations of the GR flux prediction
- **Prospects**:
  - Integration up to the universal horizon?
  - Exploring the allowed phase space for LV-gravities
  - Numerical simulations for the merging?