EFT for Black Hole Quasi Normal Modes: testing extensions to GR with GW

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Can we use BH merger to probe physics beyond GR?
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We can detect the presence of **new light DOF** even if they are **NOT coupled** to the SM
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DARK ENERGY

DARK MATTER
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DARK ENERGY  DARK MATTER

Today's perspective: put aside our prejudices in favor of empirical verification
How does it constrain physics beyond GR?

Measure observables and compare with GR
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Choose a model BGR and constrain its parameters
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Put constraints on the operators of an EFT  
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\mathcal{L} = \sum_n c_n \frac{\Lambda^4}{g^2_*} \hat{\mathcal{L}} \left( \frac{\partial}{\Lambda}, \frac{g_* \phi}{\Lambda} \right)
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What are the light degrees of freedom?

Assume the light degrees of freedom are the graviton + 1 extra scalar
EFT in Cosmology

On cosmological scales, FRW universes are characterized by a “medium” with a homogeneous and isotropic stress energy tensor.

This medium, at variance with a CC, breaks spontaneously Lorentz invariance.

The simplest example: in single field Inflation a scalar with a time-dependent expectation value breaks time translations and Lorentz boosts to \( ISO(3) \).
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Lorentz is spontaneously broken: no a priori reason to expect luminal speed.
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Two different approaches:

- “covariant” EFT (trivial background)
- EFT for perturbations around the relevant solution
The Standard Model EFT

\[ \mathcal{L} = -\mu^2 (H\dagger H) + \lambda (H\dagger H)^2 + c_6 (H\dagger H)^3 + \ldots \]

EFT before expanding
Full \(SU(2) \times U(1)\) gauge invariance

\[ H(x) = \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \]

\[ \mathcal{L} = m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4 + \ldots \]

EFT for perturbations around \(v\)
Only \(U(1)_{\text{EM}}\) gauge invariance
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EFT for perturbations around \( v \)
Only \( U(1)_{EM} \) gauge invariance

Resum the contribution of many operators if non-linearities are large
EFT around space-time dependent backgrounds

- Inflation
- Late time acceleration
EFT around space-time dependent backgrounds

- Inflation
- Late time acceleration
- Black Holes
The EFT of quasi de Sitter

Start from a background solution  \( ds^2 = -dt^2 + a(t)^2 d\bar{x}^2 \)

Construct an EFT for perturbations
The EFT of quasi de Sitter

Start from a background solution \( ds^2 = -dt^2 + a(t)^2 d\vec{x}^2 \)

Construct an EFT for perturbations

Choose a foliation of spacetime (unitary gauge) such that \( \phi = \phi_0(t) \)

Write down in a derivative expansions all the operators that are invariant under the residual symmetries (spatial diffs) \( x_i \to x_i + \xi_i(t, \vec{x}) \)

The EFT can contain:
- generic functions of time
- free 0 indices, like \( g^{00}, R^{00} \)
- geometric objects of the 3d spatial slices such as \( K^{\mu\nu}, R^{(3)} \)

Write the action already expanded in perturbations, e.g. \( \delta K_{\mu\nu} = K_{\mu\nu} - H h_{\mu\nu} \)

\[
S = \int d^4x \sqrt{-g} \left[ \frac{M_*^2}{2} f^{(4)}R - \Lambda - cg^{00} + \frac{m_2^4}{2} (\delta g^{00})^2 \right. \\
- \left. \frac{m_3^2}{2} \delta K \delta g^{00} - m_4^2 (\delta K^2 - \delta K^\nu_{\mu} \delta K^\mu_{\nu}) + \frac{\tilde{m}_4^2}{2} \delta g^{00} R + \ldots \right]
\]

Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore '07
Quasi de Sitter

\[ \sqrt{-g} \left( M_{\text{Pl}}^2 R - g_{\mu \nu} \partial^\mu \phi \partial^\nu \phi - V(\phi) \right) \]

\[ S = \int d^4x \sqrt{-g} \left[ \frac{M_*^2}{2} f^{(4)R} - \Lambda - c g^{00} + \frac{m_2^2}{2} (\delta g^{00})^2 
- \frac{m_3^2}{2} \delta K \delta g^{00} - m_4^2 (\delta K^2 - \delta K_\mu \delta K^\mu) + \frac{\tilde{m}_4^2}{2} \delta g^{00} R \right] \]

Solve the equation of motion to compute the background

\[ \phi(x) = \phi_0(t) \]

\[ ds^2 = -dt^2 + a(t)^2 d\bar{x}^2 \]

Expand in small perturbations

\[ \mathcal{L} = (\partial \varphi)^2 + (\partial h)^2 + \mathcal{O}(\varphi^3, h^3, \ldots) \]
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\[ \sqrt{-g} \left( M_{Pl}^2 R - g_{\mu\nu} \partial^\mu \phi \partial^\nu \phi - V(\phi) \right) + \sum_n a_n \frac{(\partial^\mu \phi \partial^\mu \phi)^n}{\Lambda^{4n-4}} + \sum_n b_n \frac{(\partial^\mu \phi \partial^\mu \phi)^n \Box \phi}{\Lambda^{4n-1}} \]

Expand in small perturbations

\[ S = \int d^4x \sqrt{-g} \left[ \frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_4^2}{2} (\delta g^{00})^2 - \frac{m_3^2}{2} \delta K \delta g^{00} - \frac{m_4^2}{2} (\delta K^2 - \delta K^\nu \delta K^\mu) + \frac{\tilde{m}_4^2}{2} \delta g^{00} R \right] \]

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\[ + \sum_n b_n \frac{(\partial_n \phi \partial^n \phi)^n \Box \phi}{\Lambda^{4n-1}} \]

These terms are fixed by the background solution

Only 3 indep. operators because of FRW symm.

These 4 give linear equations with 2 derivatives for the propagating DOF
Late time cosmology

\[ c_T^2 - 1 \lesssim 10^{-15} \]
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\[ c_T^2 - 1 = -2m_4^2/M^2 \]

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\[ \delta \mathcal{K}_2 \equiv \delta K^2 - \delta K_{\mu} \delta K_{\nu} \]

\[ m_4^2 \sim 0 \]

Abbott et al. '17

Creminelli, Vernizzi '17

Baker et al. '17
Late time cosmology

\[ c_T^2 - 1 \lesssim 10^{-15} \]

\[ c_T^2 - 1 = -2\frac{m_A^2}{M^2} \]

\[
S = \int d^4x \sqrt{-g} \left[ \frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_A^2}{2} (\delta g^{00})^2 - \frac{m_3^2}{2} \delta K \delta g^{00} - \frac{m_4^2}{2} \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R \right]
\]

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Depends on the background (dark matter abundance,…): robustly set it to zero!
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$$- \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 \delta \mathcal{H}_2 + \frac{m_4^2}{2} \delta g^{00} R - \frac{m_5^2}{2} \delta g^{00} \delta \mathcal{H}_2$$ 

$$- \frac{m_6^3}{3} \delta \mathcal{H}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{H}_2 - \frac{m_7}{3} \delta g^{00} \delta \mathcal{H}_3 \right]$$

$$\delta \mathcal{H}_2 \equiv \delta K^2 - \delta K^\mu_\nu \delta K^\nu_\mu$$

$$\delta \mathcal{G}_2 \equiv \delta K^\nu_\mu R^\mu_\nu - \delta K R/2$$

$$\delta \mathcal{H}_3 \equiv \delta K^3 - 3 \delta K \delta K^\mu_\nu \delta K^\nu_\mu + 2 \delta K^\nu_\mu \delta K^\mu_\rho \delta K^\rho_\nu$$

$$m_4^2 \sim 0$$

$$\tilde{m}_4^2 = m_5^2$$

$$m_6 = \tilde{m}_6 = m_7 = 0$$

Depends on the background (dark matter abundance,…): robustly set it to zero!
Very strong constraints on the Covariant Theory

\[ \mathcal{L} = \mathcal{L}(g_{\mu\nu}, \phi) \]

\[ L_2 \equiv G_2(\phi, X), \quad L_3 \equiv G_3(\phi, X) \Box \phi, \]
\[ L_4 \equiv G_4(\phi, X) e^{\mu\nu\rho} e^{\mu'\nu'\rho'} \phi_{\mu} \phi_{\mu'} \phi_{\nu} \phi_{\nu'} \phi_{\rho} \phi_{\rho'}, \]
\[ L_5 \equiv G_5(\phi, X) \epsilon_{\mu\nu} \phi_{\mu} \phi_{\nu} \]
\[ + \frac{1}{3} G_{5,X}(\phi, X) \Box^3 \phi - 3 \Box \phi_{\mu} \phi_{\nu} \phi_{\mu} + 2 \phi_{\mu} \phi_{\nu} \phi_{\mu} \phi_{\nu} \phi_{\sigma} \phi_{\sigma'} \]
\[ + F_5(\phi, X) \epsilon_{\mu\nu\rho} \phi_{\mu} \phi_{\nu} \phi_{\rho} \phi_{\mu} \phi_{\nu} \phi_{\rho} \phi_{\sigma} \phi_{\sigma'} \]

\[ G_{5,X} = 0, \quad F_5 = 0, \quad 2G_{4,X} - XF_4 + G_{5,\phi} = 0 \]

\[ X \equiv g_{\mu\nu} \nabla^\mu \phi \nabla^\nu \phi \]
\[ \phi_\mu \equiv \nabla_\mu \phi \]
\[ \phi_{\mu\nu} \equiv \nabla_\mu \nabla_\nu \phi \]
\[ G_i(\phi, X) = \sum_{nm} c_{nm} \phi^n X^m \]

\[ L_{CT} = 1 = G_2(\phi, X) + G_3(\phi, X) \Box \phi + B_4(\phi, X) e^{\mu\nu\rho} e^{\mu'\nu'\rho'} \phi_{\mu} \phi_{\mu'} \phi_{\nu} \phi_{\nu'} \phi_{\rho} \phi_{\rho'} \]
\[ - \frac{4}{X} B_{4,X}(\phi, X) (\phi^\mu \phi^\nu \phi_{\mu\nu} \Box \phi - \phi^\mu \phi_{\mu} \phi_{\lambda} \phi^\lambda^\nu), \]

\[ B_4 \equiv G_4 + XG_{5,\phi}/2. \]
Gravity can propagate differently in FRW \[ \rightarrow \] Constrain the scalar
Gravity can propagate differently in FRW ➔ Constrain the scalar

Can we study the propagation around some other background and maybe discover a new field?
Gravity can propagate differently in FRW \[\rightarrow\] Constrain the scalar

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Perturbations around Black Holes

Inspiral

Merger

Ringdown

Ligo & Virgo ‘17
Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

Spectrum of characteristic (complex) frequencies $\omega_{nlm}$
Perturbations around Black Holes

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Spectrum of characteristic (complex) frequencies $\omega_{nlm}$

In GR black holes are characterized only by 3 parameters: M, J, Q
No-hair hypothesis
Perturbations around Black Holes

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No-hair hypothesis

<table>
<thead>
<tr>
<th>$n$</th>
<th>$2M_\bullet \omega (L = 2)$</th>
<th>$2M_\bullet \omega (L = 3)$</th>
<th>$2M_\bullet \omega (L = 4)$</th>
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<tbody>
<tr>
<td>0</td>
<td>$0.747343 + 0.177925i$</td>
<td>$1.198887 + 0.185406i$</td>
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</tr>
<tr>
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Nollert '99
Perturbations around Black Holes

\[ g_{\mu \nu} = g_{\mu \nu}^{BH}(r) + h_{\mu \nu} \]

Schwarzschild: static, spherically symmetric background

\[ h(t, r, \theta, \phi) = \sum_{l,m} h_{lm}(r)Y_{lm}(\theta, \phi)e^{i\omega t} \]

 Classified accordingly to the behavior under parity \((\theta, \phi) \rightarrow (\pi - \theta, \phi + \pi)\)

Axial (odd) perturbations

Regge Wheeler '57

Polar (even) perturbations

Zerilli '70
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Fix the gauge + solve for the constraint

One propagating DOF in the odd sector

\[
\left[ \frac{d^2}{dr^2} + \omega^2 \right] h(r) = V^{(-)}(r) h(r)
\]

\[
V^{(-)}(r) = \frac{l(l + 1)}{r^2} \left(1 - \frac{r_s}{r}\right) - 3\frac{r_s}{r^3} \left(1 - \frac{r_s}{r}\right)
\]

One propagating DOF in the even sector

\[
\left[ \frac{d^2}{dr^2} + \omega^2 \right] h(r) = V^{(+)}(r) h(r)
\]

\[ V^{(+)}(r) = \ldots \]
In GR quasi-normal modes are \textit{isospectral}

One propagating DOF in the odd sector

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$$V^{(-)}(r) = \frac{l(l+1)}{r^2} \left(1 - \frac{r_S}{r}\right) - 3 \frac{r_S}{r^3} \left(1 - \frac{r_S}{r}\right)$$

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EFT for perturbations spher. symm.

The propagation of gravity is different IF BHs have scalar hair

The linearized equations of motion are modified

More information than just the velocity: the whole QNM spectra are modified
EFT for perturbations spher. symm.

The propagation of gravity is different \textbf{IF} BHs have scalar hair

The linearized equations of motion are \textbf{modified}

More information than just the velocity: the whole QNM spectra are modified

There are computations of QNM in specific models. \textbf{Different approach:} not case by case instead use an EFT around \textit{static} and \textit{spherically symmetric} backgrounds

Assumption: there is a non-trivial $r$-dependent scalar profile $\bar{\Phi}(r)$

\[
\delta \Phi \equiv 0
\]

\[
d s^2 = -a^2(r)dt^2 + \frac{dr^2}{b^2(r)} + c^2(r) \left( d\theta^2 + \sin^2 \theta d\phi^2 \right)
\]

\[
S = \int d^4x \sqrt{-g} \mathcal{L}(g_{\mu\nu}, R_{\mu\nu\alpha\beta}, g^{\alpha\beta}, K_{\mu\nu}, \nabla_{\mu}; r)
\]
EFT for perturbations spher. symm.

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There are computations of QNM in specific models. Different approach: not case by case instead use an EFT around static and spherically symmetric backgrounds

\[ S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} M^2(r) R - \Lambda(r) - f(r) g^{rr} - \alpha(r) \bar{K}_{\mu\nu} K^{\mu\nu} + M_2^4(r) (\delta g^{rr})^2 + \bar{M}_1^3(r) \delta g^{rr} \delta K + \bar{M}_2^3(r) \bar{K}_{\mu\nu} \delta g^{rr} \delta K^{\mu\nu} + \bar{M}_1^2(r) (\partial_r \delta g^{rr})^2 + \bar{M}_2^2(r) (\partial_r \delta g^{rr}) \delta K + \bar{M}_3^3(r) K_{ab}(\partial_r \delta g^{rr}) \delta K^{\mu\nu} + \bar{M}_1^2(r) (\delta K)^2 + \bar{M}_2^2(r) \delta K_{\mu\nu} \delta K^{\mu\nu} + \bar{M}_3^2(r) \bar{K}_{\mu\nu} \delta K \delta K^{\mu\nu} + \bar{M}_4^2(r) \bar{K}_{\mu\nu} \delta K^{\mu\rho} \delta K^{\nu\rho} + \bar{M}_5^2(r) \bar{K}_{\mu\rho} \bar{K}_{\nu\lambda} \delta K \delta K^{\mu\nu} + \bar{M}_6^2(r) (\delta g^{rr}) \delta \hat{R} + \bar{M}_7^2(r) \bar{K}_{\mu\nu} \delta g^{rr} \delta \hat{R}^{\mu\nu} + \ldots \right] , \]

Franciolini, Hui, Penco, Santoni, ET ’18
Phenomenology

If the strength of the scalar-matter coupling is gravitational or bigger, the most prominent observational signal would be the scalar mode itself (the extra mode in the even sector).

If the scalar-matter coupling is absent or very weak, introduce deviations from GR in the spectrum of even and odd modes while preserving isospectrality, break isospectrality, mix the even and odd modes if it is a pseudo-scalar.
Outlook

Generalize to Kerr Black Holes

Characterize the QNM spectrum in terms of the EFT operators

EFT of perturbations around spherically symmetric backgrounds

Study in full generality the coupling to matter
Outlook

- Generalize to Kerr Black Holes
- Characterize the QNM spectrum in terms of the EFT operators
- Study in full generality the coupling to matter
- Reanalyze the BH no-hair theorems

Assumption: non trivial scalar profile

Hui, Penco, Santoni, ET, Trombetta, *in progress*
Outlook

Generalize to Kerr Black Holes

Characterize the QNM spectrum in terms of the EFT operators

Extend to different light DOF

Study in full generality the coupling to matter

Reanalyze the BH no-hair theorems

Assumption: light scalar

Hui, Penco, Santoni, ET, Trombetta, in progress
Outlook

- Generalize to Kerr Black Holes
- Characterize the QNM spectrum in terms of the EFT operators
- Investigate the stability of wormholes
- Extend to different light DOF
- Study in full generality the coupling to matter
- Reanalyze the BH no-hair theorems

Assumption: light scalar

Franciolini, Hui, Penco, Santoni, ET '19

Hui, Penco, Santoni, ET, Trombetta, in progress
“[concerning the use of supernovae for cosmology] the optimists were theorists or newcomers who had not worked long in the field, and pessimists (or realists as we prefer to be called) were observers”

Robert Kirshner