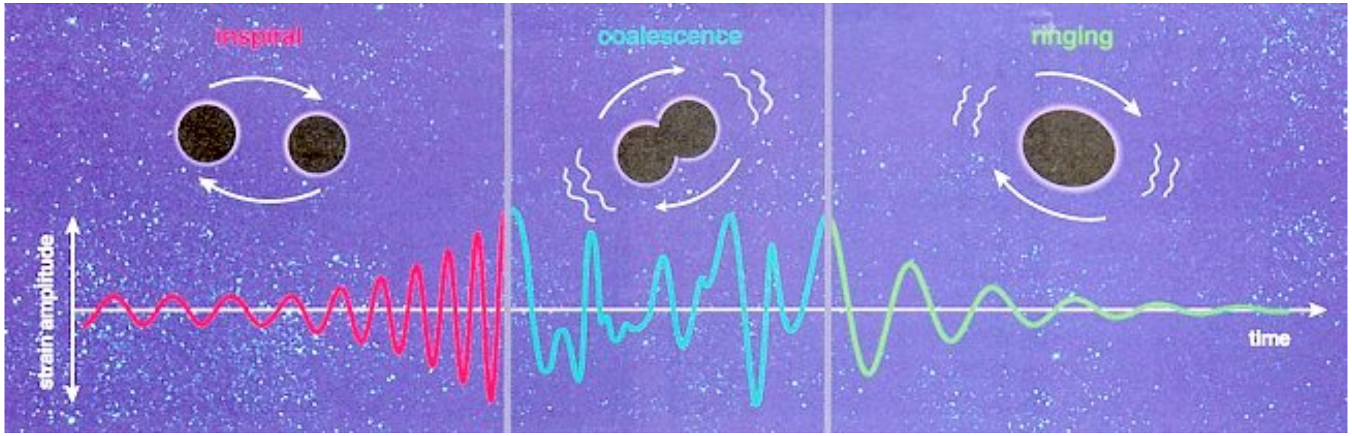
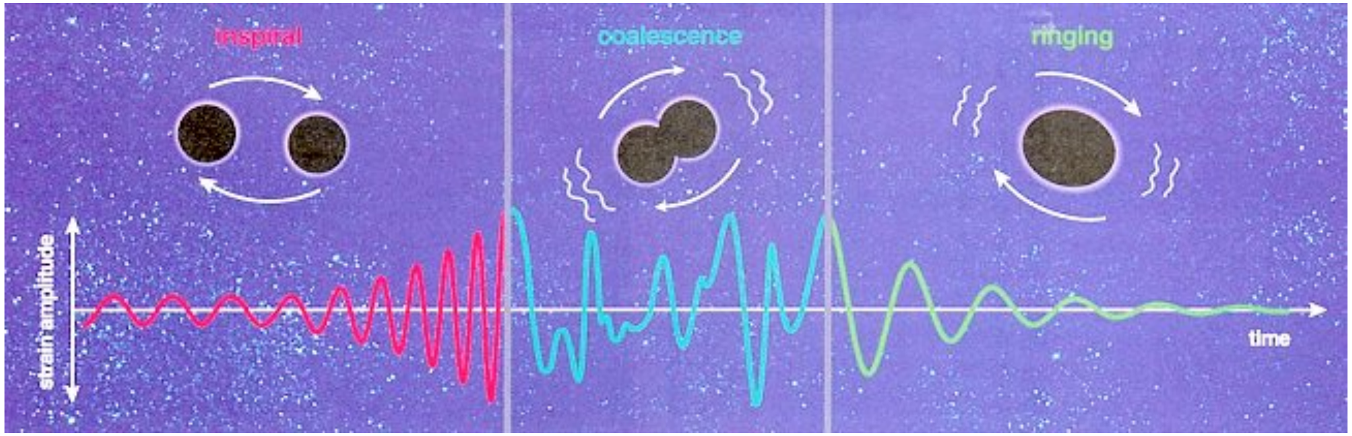
EFT for Black Hole Quasi Normal Modes: testing extensions to GR with GW

Enrico Trincherini
(SNS & INFN, Pisa)

with G. Franciolini, L. Hui, R. Penco & L. Santoni
arXiv:1810.07706

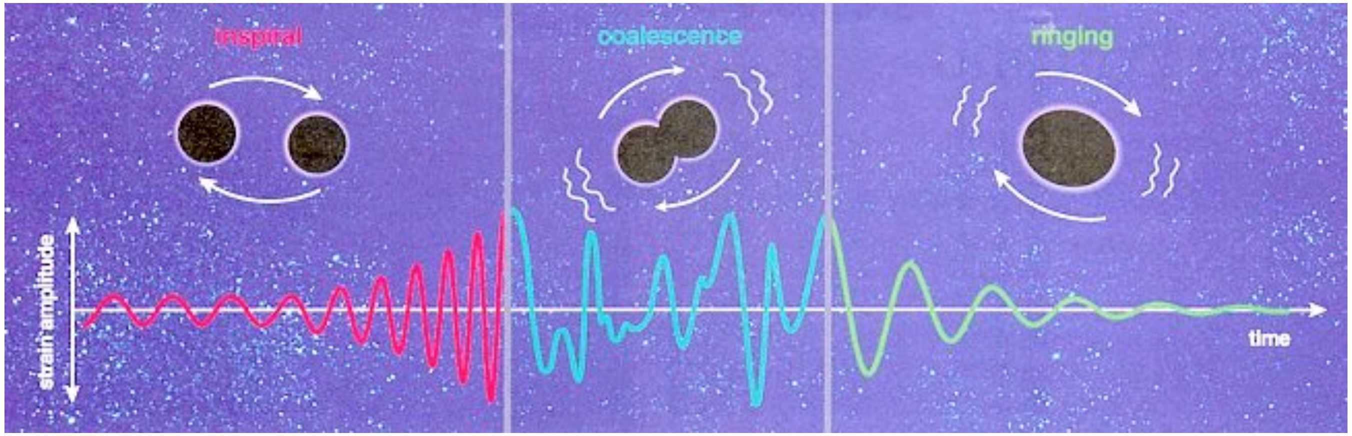


Can we use BH merger to probe physics beyond GR?



Can we use BH merger to probe physics beyond GR?

We can detect the presence of new light DOF
even if they are NOT coupled to the SM

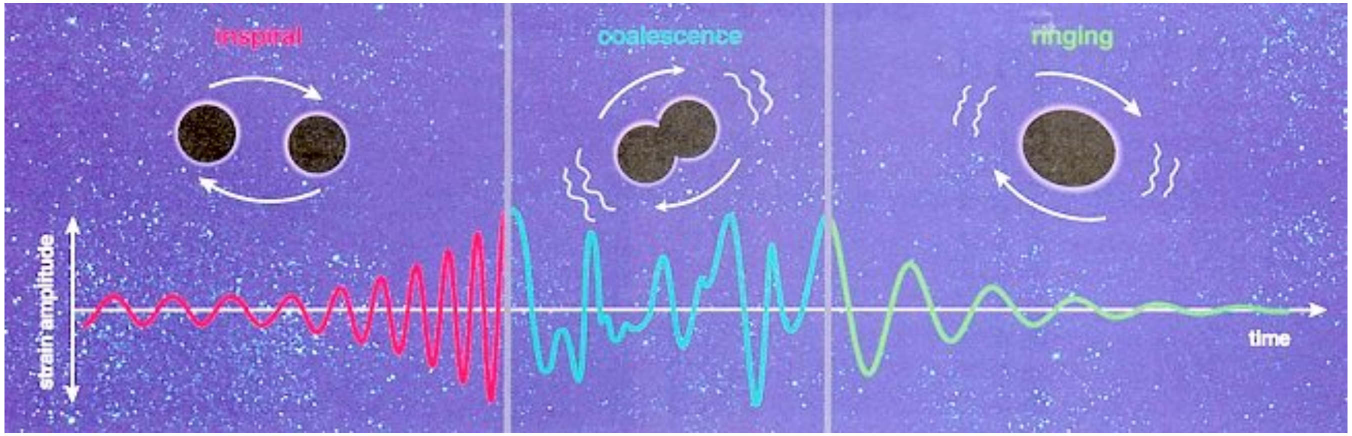


Can we use BH merger to probe physics beyond GR?

We can detect the presence of new light DOF
even if they are NOT coupled to the SM

DARK ENERGY

DARK MATTER



Can we use BH merger to probe physics beyond GR?

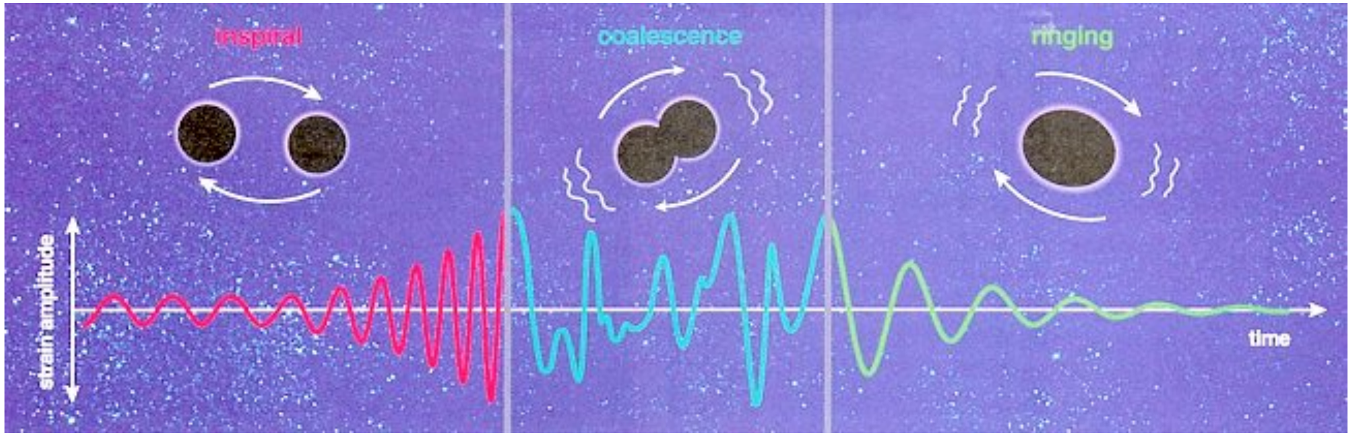
We can detect the presence of new light DOF
even if they are NOT coupled to the SM

DARK ENERGY

DARK MATTER

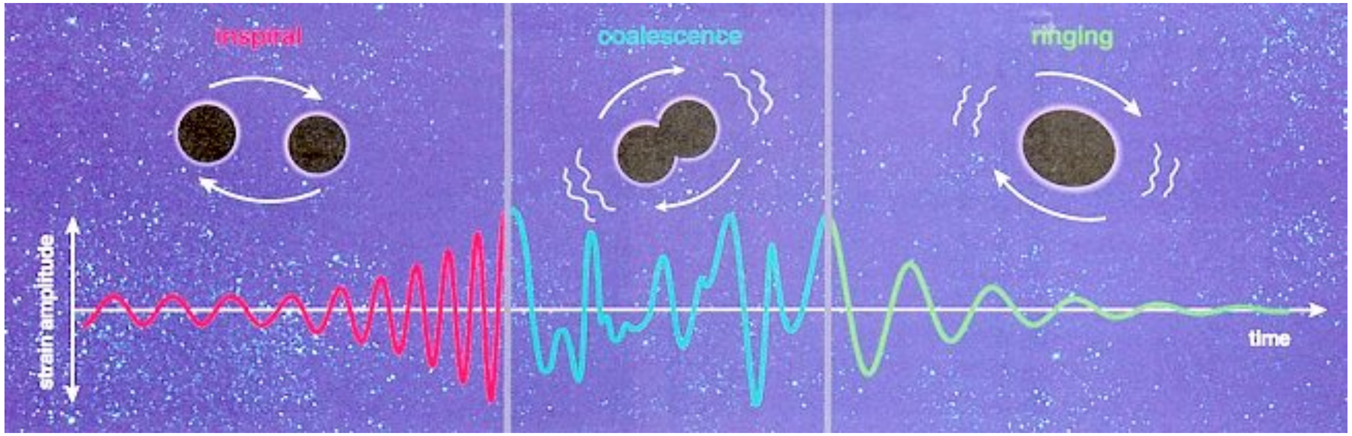
Today's perspective: put aside our prejudices in favor of empirical verification

How does it constrain physics beyond GR?



Measure observables
and compare with GR

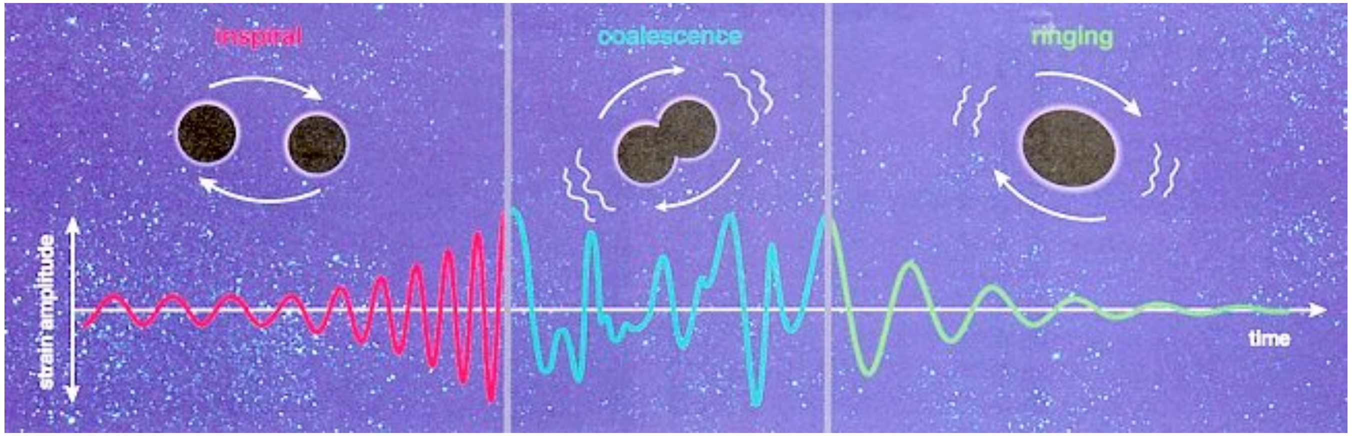
How does it constrain physics beyond GR?



Measure observables and compare with GR

Choose a model BGR and constrain its parameters

How does it constrain physics beyond GR?



Measure observables and compare with GR

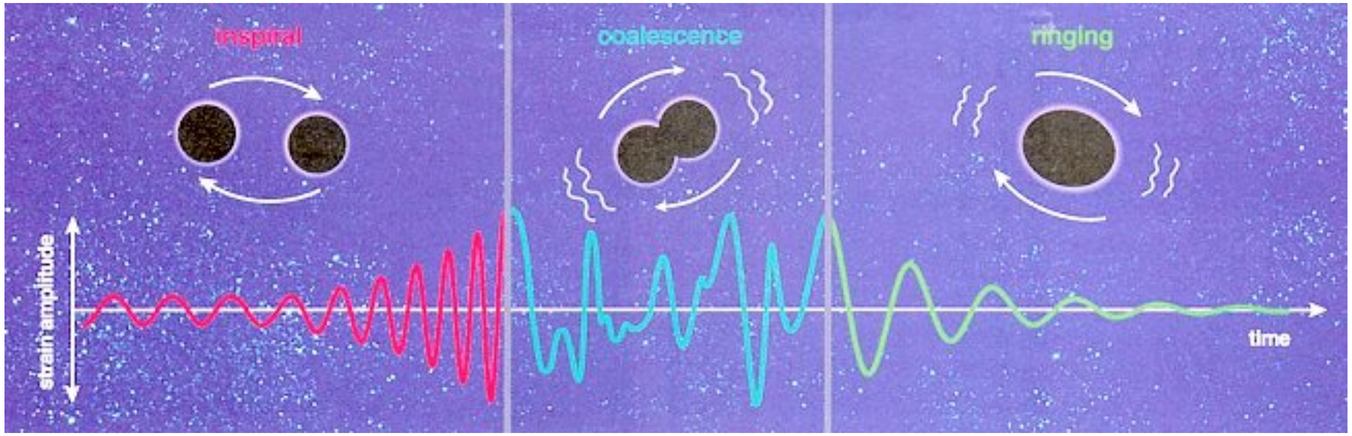
Put constraints on the operators of an EFT

Choose a model BGR and constrain its parameters

With no single 'best- motivated' proposal at hand, useful to resort to the maximally model-independent EFT approach

$$\mathcal{L} = \sum_n c_n \frac{\Lambda^4}{g_*^2} \hat{\mathcal{L}}\Big(\frac{\partial}{\Lambda}, \frac{g_* \phi}{\Lambda}\Big)$$

How does it constrain physics beyond GR?



Measure observables and compare with GR

Put constraints on the operators of an EFT

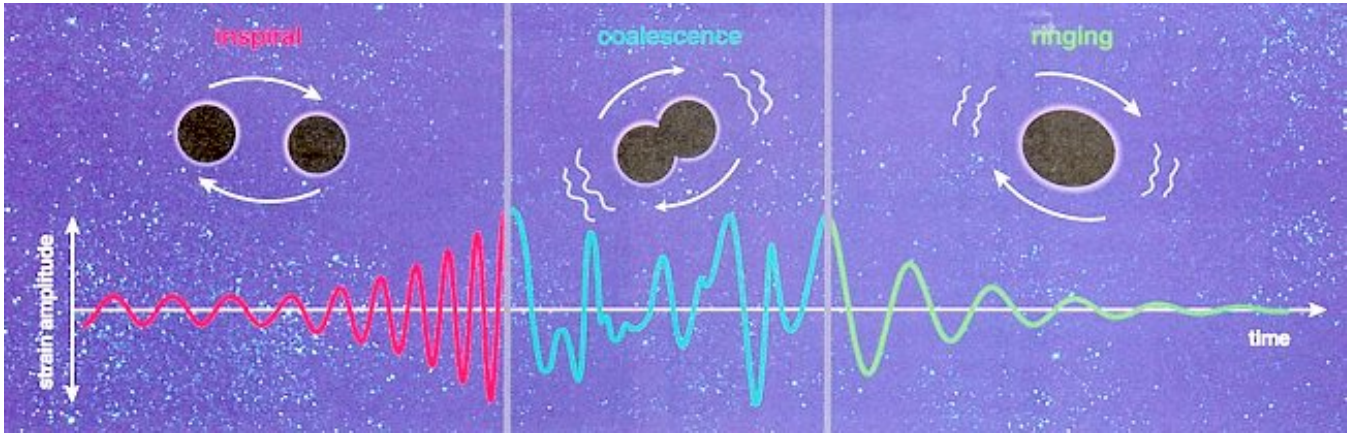
Choose a model BGR and constrain its parameters

With no single 'best- motivated' proposal at hand, useful to resort to the maximally model-independent EFT approach

$$\mathcal{L} = \sum_n c_n \frac{\Lambda^4}{g_*^2} \hat{\mathcal{L}}\left(\frac{\partial}{\Lambda}, \frac{g_* \phi}{\Lambda}\right)$$

What are the light degrees of freedom?

How does it constrain physics beyond GR?



Measure observables and compare with GR

Put constraints on the operators of an EFT

Choose a model BGR and constrain its parameters

With no single 'best- motivated' proposal at hand, useful to resort to the maximally model-independent EFT approach

$$\mathcal{L} = \sum_n c_n \frac{\Lambda^4}{g_*^2} \hat{\mathcal{L}}\left(\frac{\partial}{\Lambda}, \frac{g_* \phi}{\Lambda}\right)$$

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)*

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)*

Gravitational perturbations that travel on this background carry information about the underlying microscopic theory, already at the level of the quadratic action

EFT in Cosmology

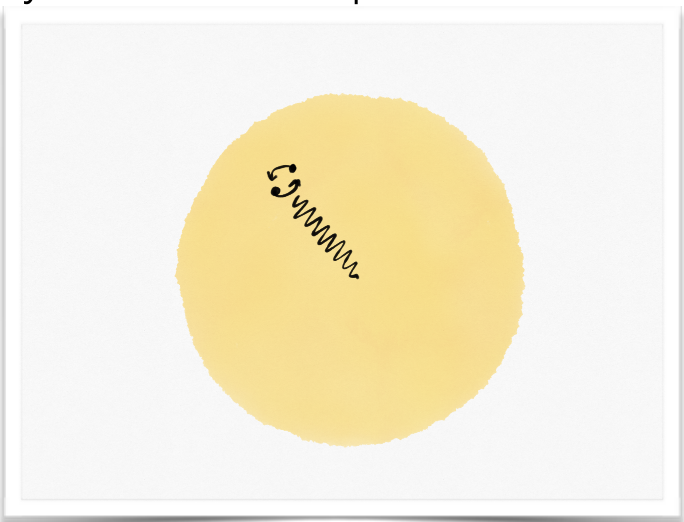
On cosmological scales, FRW universes are characterized by a "medium" with a homogeneous and isotropic stress energy tensor

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)*

Gravitational perturbations that travel on this background carry information about the underlying microscopic theory, already at the level of the quadratic action

Lorentz is spontaneously broken: no a priori reason to expect luminal speed



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)*

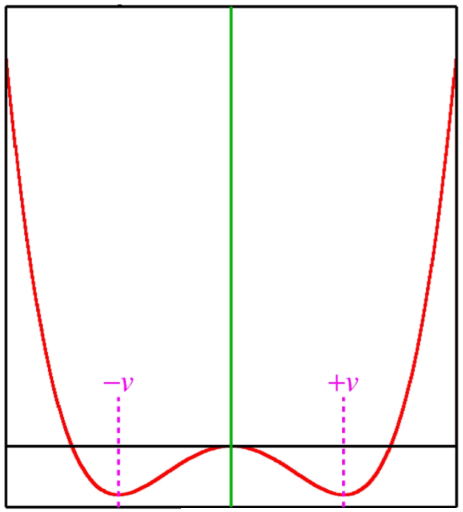
Gravitational perturbations that travel on this background carry information about the underlying microscopic theory, already at the level of the quadratic action

Two different approaches

"covariant" EFT
(trivial background)

EFT for perturbations around
the relevant solution

The Standard Model EFT



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

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

EFT before expanding

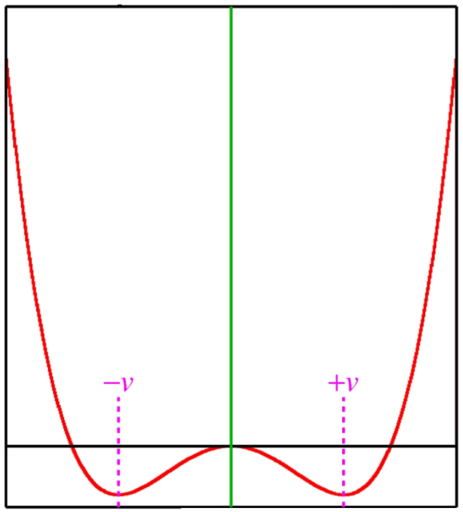
Full $SU(2) \times U(1)$ gauge invariance

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

EFT for perturbations around *v*

Only $U(1)_{\rm EM}$ gauge invariance

The Standard Model EFT



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

$$\mathcal{L} = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + c_6 (H^\dagger H)^3 + \dots$$

EFT before expanding

Full $SU(2) \times U(1)$ gauge invariance

$$\mathcal{L} = m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4 + \dots$$

EFT for perturbations around *v*

Only $U(1)_{\mathrm{EM}}$ gauge invariance

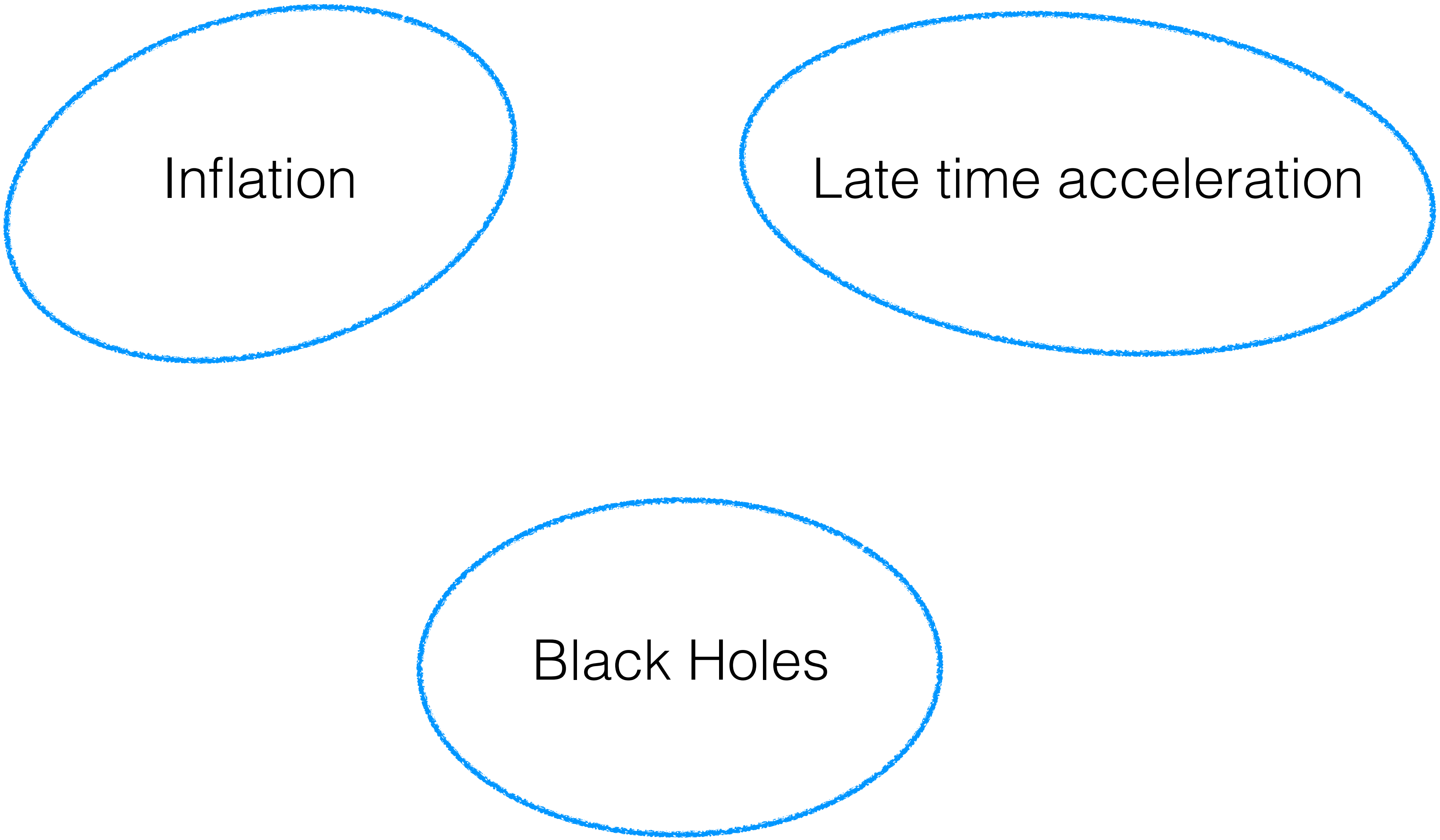
Resum the contribution of many operators if non-linearities are large

EFT around space-time dependent backgrounds

Inflation

Late time acceleration

EFT around space-time dependent backgrounds



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

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:

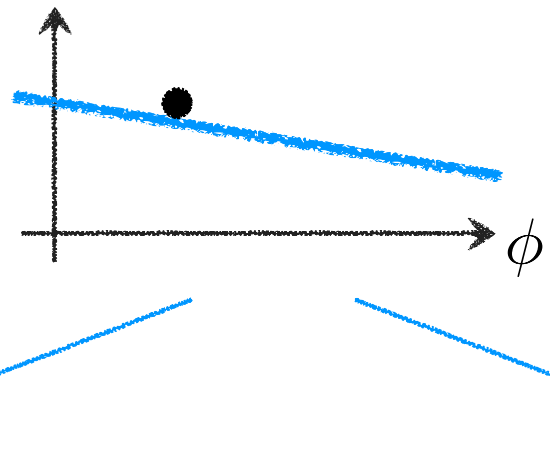
- generic functions of time
- free 0 indices, like g^{00}, R^{00}
- geometric objects of the 3d spatial slices such as $K^{\mu\nu}, \; R^{(3)}$

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

$$S = \int d^4x \sqrt{-g} \Big[\frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_2^4}{2} (\delta g^{00})^2 - \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 (\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu) + \frac{\tilde{m}_4^2}{2} \delta g^{00} R + \dots \Big]$$

Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore '07

Quasi de Sitter



$$\sqrt{-g}\Big(M_{\rm Pl}^2 R - g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi)\Big)$$

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2}f^{(4)}R - \Lambda - cg^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K \delta g^{00} - m_4^2(\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu) + \frac{\tilde{m}_4^2}{2}\delta g^{00} R\Big]$$

Solve the equation of motion
to compute the background

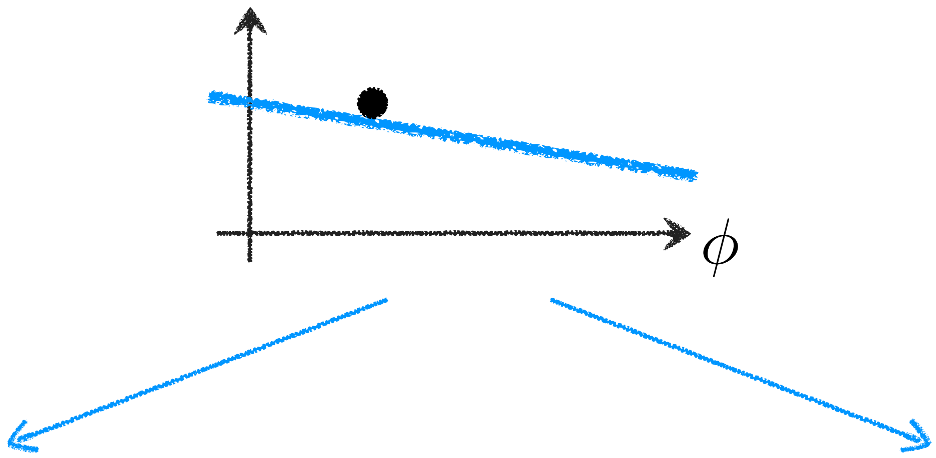
$$\phi(x) = \phi_0(t)$$

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

Expand in small perturbations

$$\mathcal{L} = (\partial\varphi)^2 + (\partial h)^2 + \mathcal{O}(\varphi^3, h^3, \ldots)$$

Quasi de Sitter



$$\sqrt{-g}\Big(M_{\rm Pl}^2 R - g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi) + \sum_n a_n \frac{(\partial_\mu\phi\partial^\mu\phi)^n}{\Lambda^{4n-4}}\Big)$$

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2}f\,{}^{(4)}\!R - \Lambda - cg^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K\delta g^{00} - m_4^2(\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu) + \frac{\tilde{m}_4^2}{2}\delta g^{00} R\Big]$$

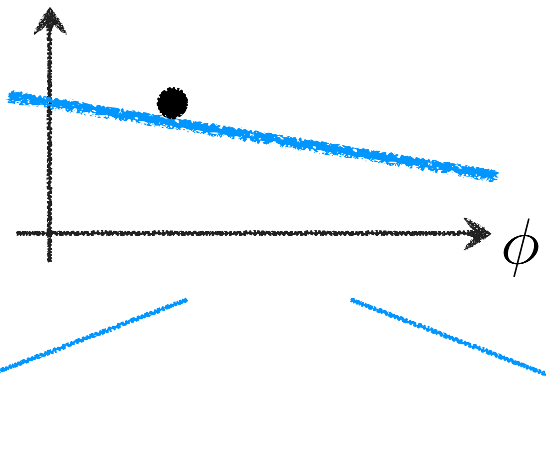
Solve the equation of motion
to compute the background

$$\phi(x) = \phi_0(t)$$
$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

Expand in small perturbations

$$\mathcal{L} = (\partial\varphi)^2 + (\partial h)^2 + \mathcal{O}(\varphi^3, h^3, \dots)$$

Quasi de Sitter



$$\sqrt{-g}\Big(M_{\rm Pl}^2 R - g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi) + \sum_n a_n \frac{(\partial_\mu\phi\partial^\mu\phi)^n}{\Lambda^{4n-4}} + \sum_n b_n \frac{(\partial_\mu\phi\partial^\mu\phi)^n \,\Box\phi}{\Lambda^{4n-1}}\Big)$$

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2} f^{(4)}R - \Lambda - c g^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K \delta g^{00} - m_4^2(\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu) + \frac{\tilde{m}_4^2}{2}\delta g^{00} R\Big]$$

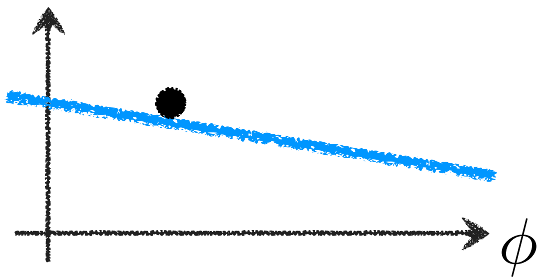
Solve the equation of motion
to compute the background

$$\phi(x) = \phi_0(t)$$
$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

Expand in small perturbations

$$\mathcal{L} = (\partial\varphi)^2 + (\partial h)^2 + \mathcal{O}(\varphi^3, h^3, \dots)$$

Quasi de Sitter



$$\sqrt{-g}\Big(M_{\rm Pl}^2 R - g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi)$$
$$+\sum_n a_n \frac{(\partial_\mu\phi\partial^\mu\phi)^n}{\Lambda^{4n-4}}$$
$$+\sum_n b_n \frac{(\partial_\mu\phi\partial^\mu\phi)^n\,\Box\phi}{\Lambda^{4n-1}}\Big)$$

Solve the equation of motion
to compute the background

$$\phi(x) = \phi_0(t)$$
$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

Expand in small perturbations

$$\mathcal{L} = (\partial\varphi)^2 + (\partial h)^2 + \mathcal{O}(\varphi^3, h^3, \dots)$$

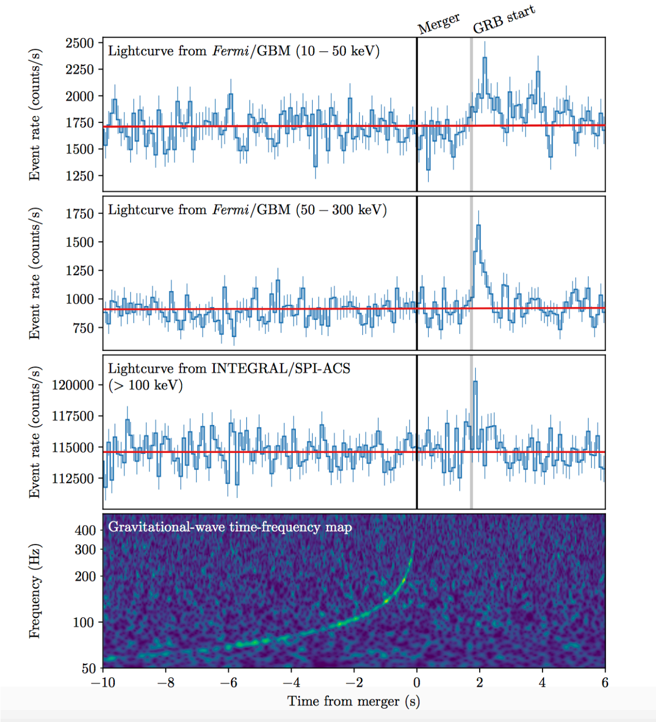
$$S = \int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_2^4}{2}(\delta g^{00})^2$$
$$- \frac{m_3^3}{2}\delta K \delta g^{00} - m_4^2(\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu) + \frac{\tilde{m}_4^2}{2}\delta g^{00} R\Big]$$

These terms are fixed by the background solution
Only 3 indep. operators because of FRW symm.

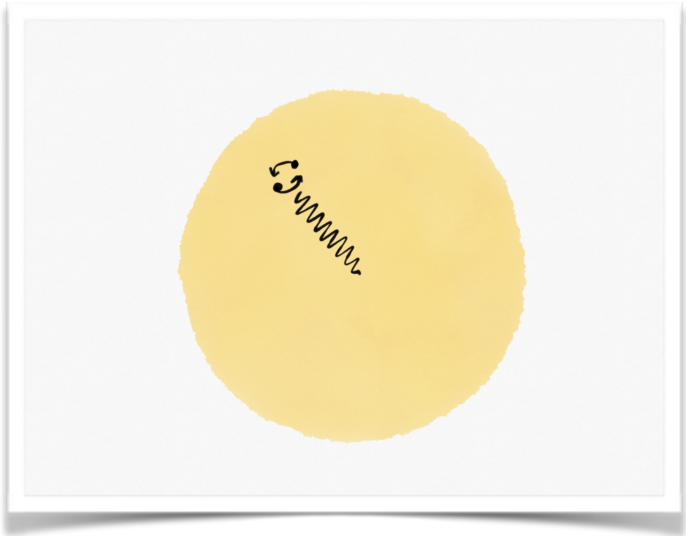
These 4 give linear equations with 2 derivatives
for the propagating DOF

Late time cosmology

Abbott *et al.* '17

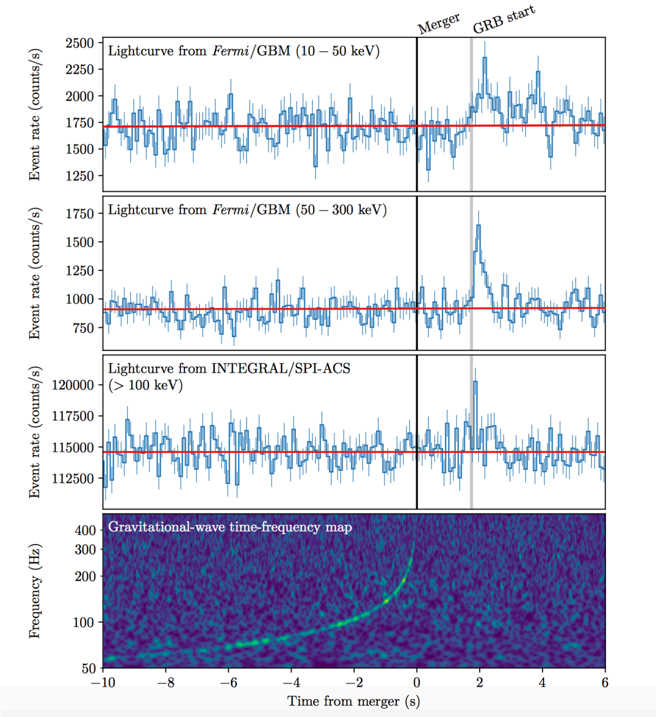


$$c_T^2 - 1 \lesssim 10^{-15}$$



Late time cosmology

Abbott *et al.* '17



$$c_T^2 - 1 \lesssim 10^{-15}$$

$$c_T^2 - 1 = -2m_4^2/M^2$$

$$S = \int d^4x\sqrt{-g}\left[\frac{M_*^2}{2} f^{(4)}R - \Lambda - c g^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K \delta g^{00} - m_4^2 \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2}\delta g^{00} R\right.$$

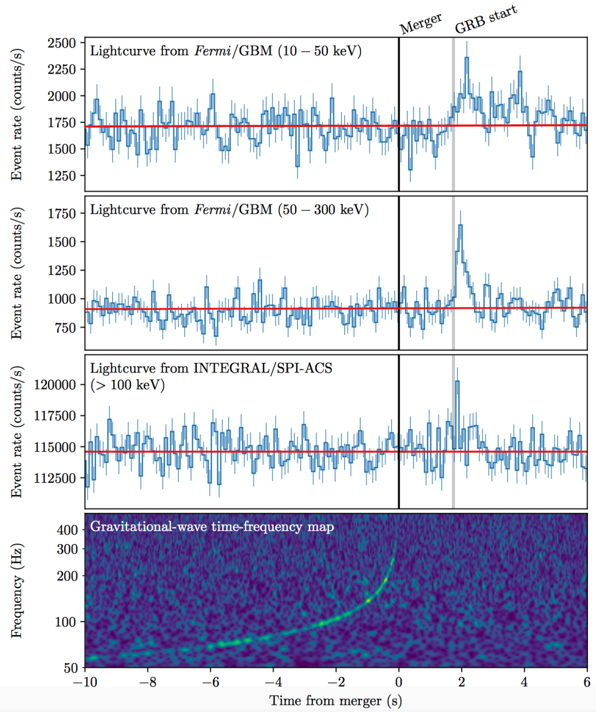
$$\delta \mathcal{K}_2 \equiv \delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu$$

$$m_4^2 \sim 0$$

Creminelli, Vernizzi '17
Baker *et al* '17

Late time cosmology

Abbott *et al.* '17



$$c_T^2 - 1 \lesssim 10^{-15}$$

$$c_T^2 - 1 = -2m_4^2/M^2$$

$$S = \int d^4x\sqrt{-g}\left[\frac{M_*^2}{2}f^{(4)}R - \Lambda - cg^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K\delta g^{00} - m_4^2\delta\mathcal{K}_2 + \frac{\tilde{m}_4^2}{2}\delta g^{00}R\right.$$

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

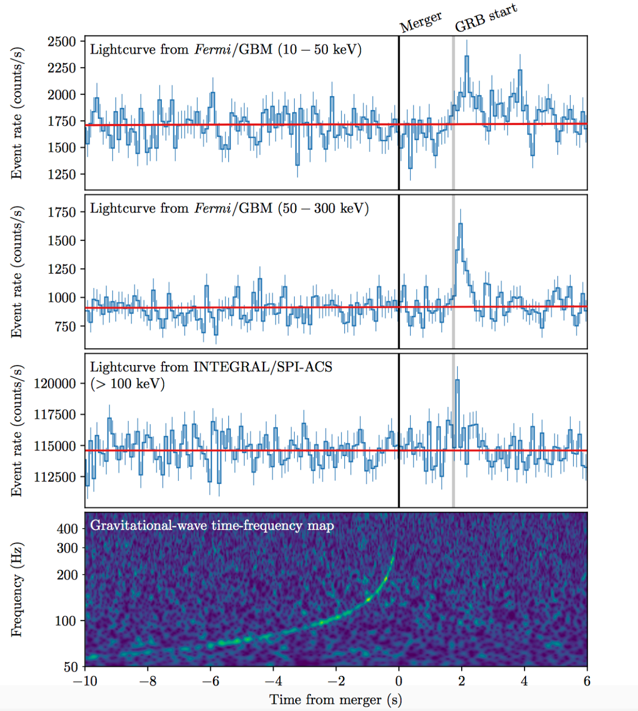
$$m_4^2 \sim 0$$

Depends on the background (dark matter abundance,…): robustly set it to zero!

Creminelli, Vernizzi '17
Baker *et al* '17

Late time cosmology

Abbott *et al.* '17



$$c_T^2 - 1 \lesssim 10^{-15}$$

$$c_T^2 - 1 = -2m_4^2/M^2$$

$$S = \int d^4x\sqrt{-g}\left[\frac{M_*^2}{2} f^{(4)}R - \Lambda - c g^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\delta K \delta g^{00} - m_4^2 \delta\mathcal{K}_2 + \frac{\tilde{m}_4^2}{2}\delta g^{00} R - \frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2 - \frac{m_6}{3}\delta\mathcal{K}_3 - \tilde{m}_6 \delta g^{00}\delta\mathcal{G}_2 - \frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\right]$$

$$\delta\mathcal{K}_2 \equiv \delta K^2 - \delta K_\mu^\nu \delta K_\nu^\mu \qquad \delta\mathcal{G}_2 \equiv \delta K_\mu^\nu R_\nu^\mu - \delta K R/2$$

$$\delta\mathcal{K}_3 \equiv \delta K^3 - 3\delta K \delta K_\mu^\nu \delta K_\nu^\mu + 2\delta K_\mu^\nu \delta K_\rho^\mu \delta K_\nu^\rho$$

$$m_4^2 \sim 0$$
$$\tilde{m}_4^2 = m_5^2$$
$$m_6 = \tilde{m}_6 = m_7 = 0$$

Depends on the background (dark matter abundance,…): robustly set it to zero!

Creminelli, Vernizzi '17
Baker *et al* '17
+ many others

Very strong constraints on the Covariant Theory

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

$$L_2 \equiv G_2(\phi, X)\,, \qquad L_3 \equiv G_3(\phi, X)\Box\phi\,,$$

$$L_4 \equiv G_4(\phi, X)\,{}^{(4)}R - 2G_{4,X}(\phi, X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu})$$

$$+ F_4(\phi, X)\varepsilon^{\mu\nu\rho}{}_{\sigma}\,\varepsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\,,$$

$$L_5 \equiv G_5(\phi, X)\,{}^{(4)}G_{\mu\nu}\phi^{\mu\nu}$$

$$+ \frac{1}{3}G_{5,X}(\phi, X)(\Box\phi^3 - 3\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\,\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}{}_{\sigma})$$

$$+ F_5(\phi, X)\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}$$

$$G_{5,X} = 0\,, \qquad F_5 = 0\,, \qquad 2G_{4,X} - XF_4 + G_{5,\phi} = 0$$

$$X \equiv g_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi$$

$$\phi_\mu \equiv \nabla_\mu\phi$$

$$\phi_{\mu\nu} \equiv \nabla_\mu\nabla_\nu\phi$$

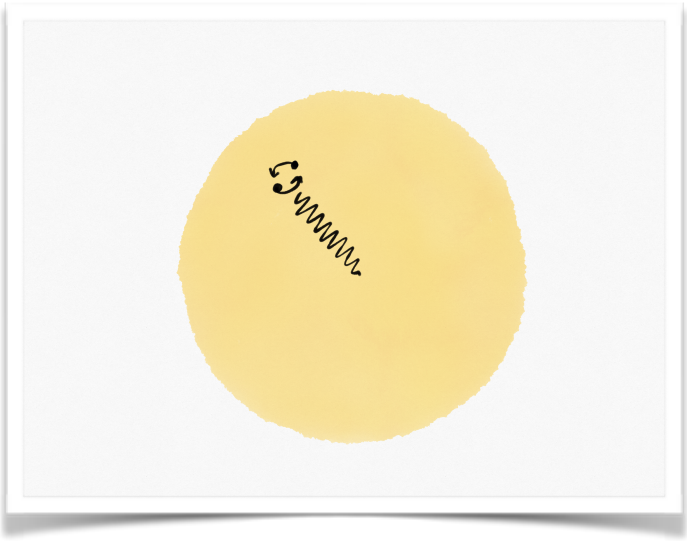
$$G_i(\phi, X) = \sum_{nm} c_{nm}\,\phi^n X^m$$

$$L_{c_T=1} = G_2(\phi, X) + G_3(\phi, X)\Box\phi + B_4(\phi, X)\,{}^{(4)}R$$

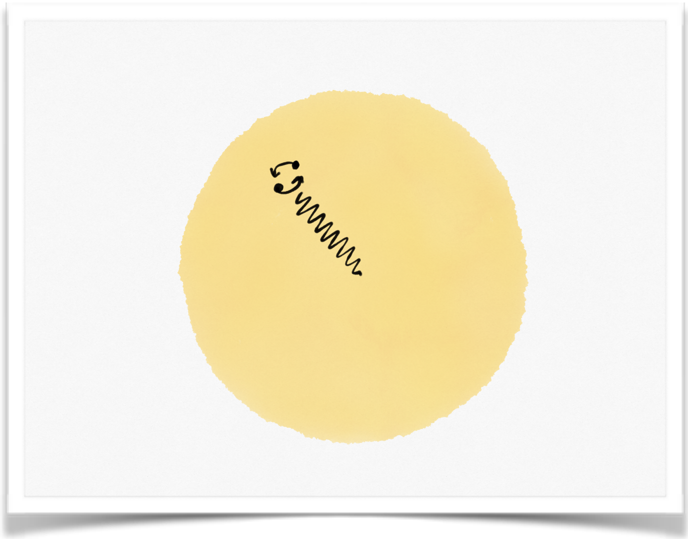
$$- \frac{4}{X}B_{4,X}(\phi, X)(\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi - \phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu})\,,$$

$$B_4 \equiv G_4 + XG_{5,\phi}/2.$$

Gravity can propagate differently in FRW ⟶ Constrain the scalar

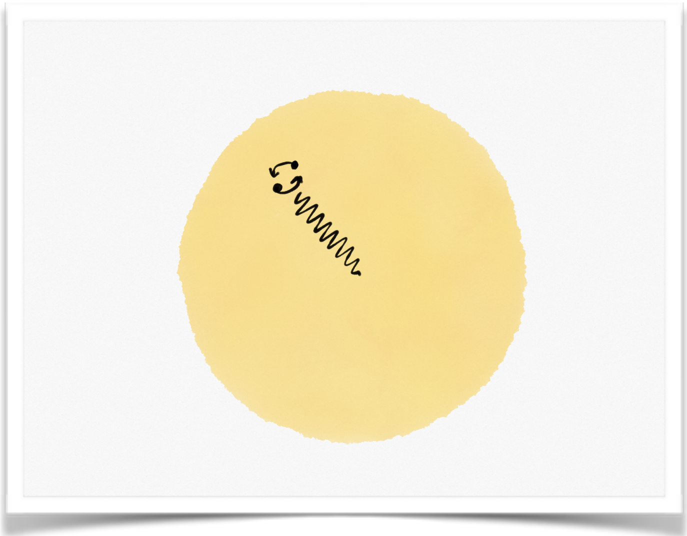


Gravity can propagate differently in FRW → Constrain the scalar

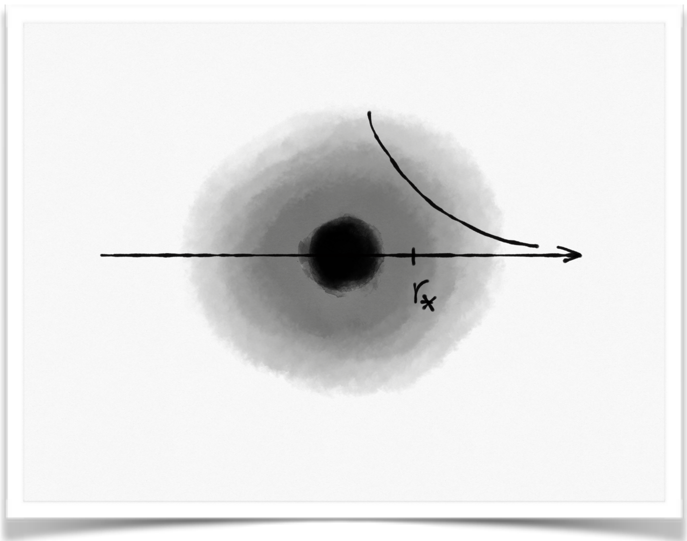


Can we study the propagation around some other background and maybe discover a new field?

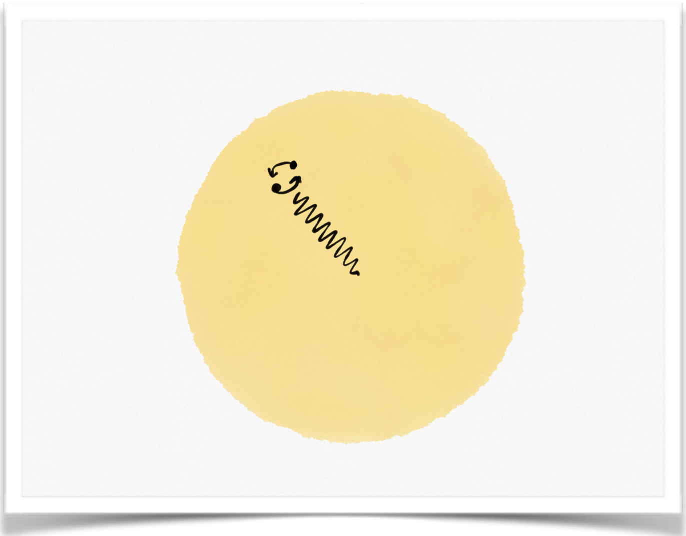
Gravity can propagate differently in FRW → Constrain the scalar



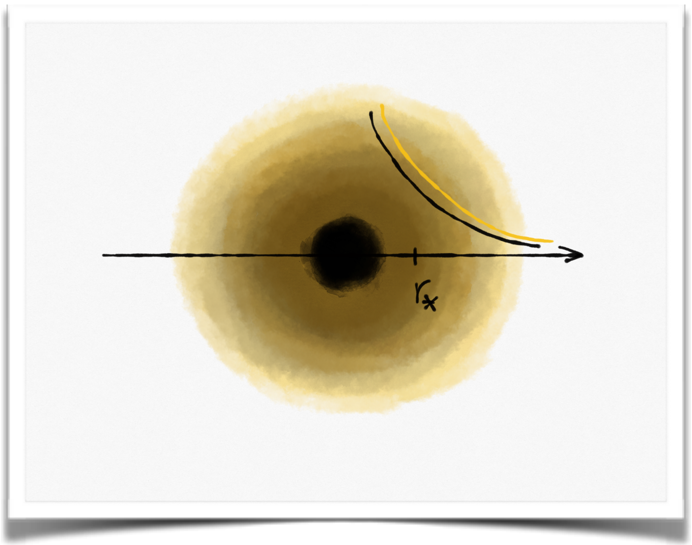
Can we study the propagation around some other background and maybe discover a new field?



Gravity can propagate differently in FRW → Constrain the scalar

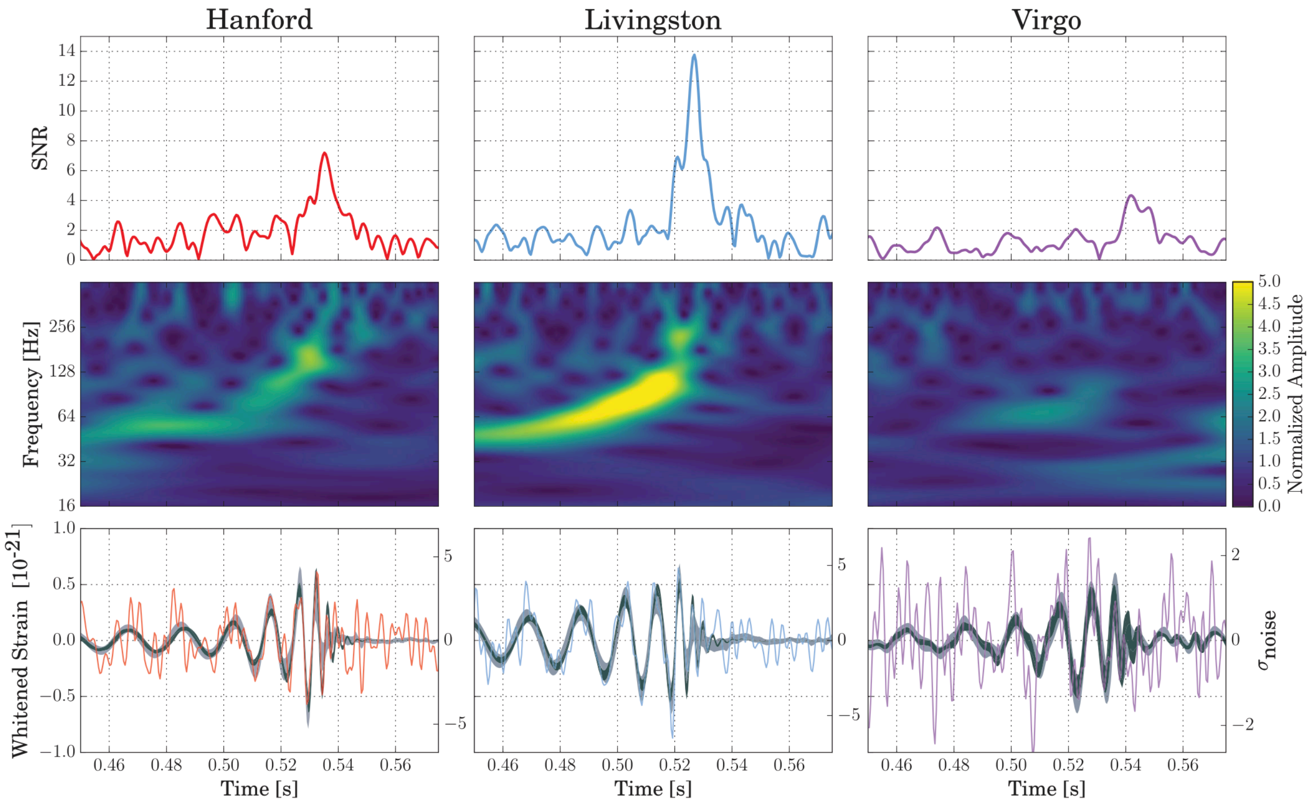


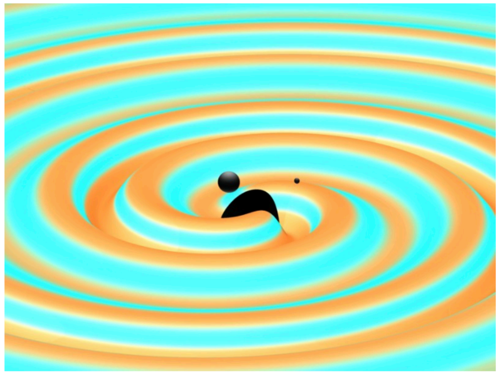
Can we study the propagation around some other background and maybe discover a new field?



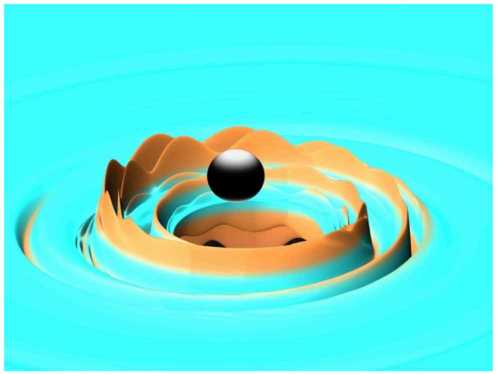
Perturbations around Black Holes

Ligo & Virgo '17

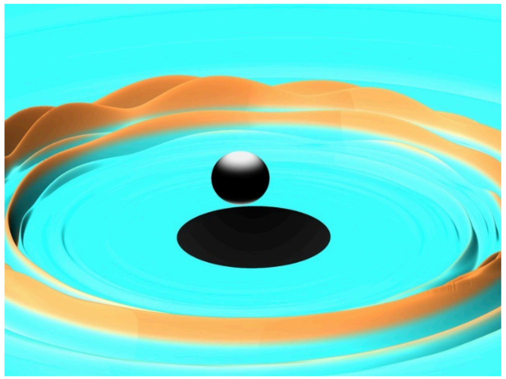




Inspiral



Merger

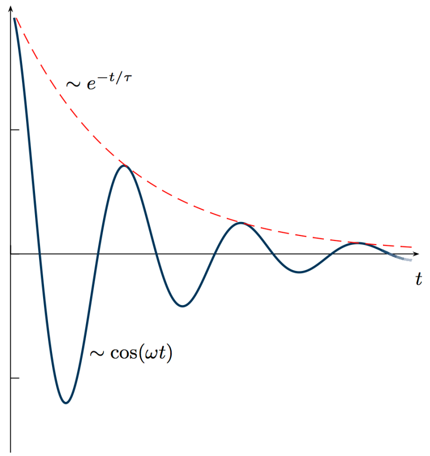


Ringdown

Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

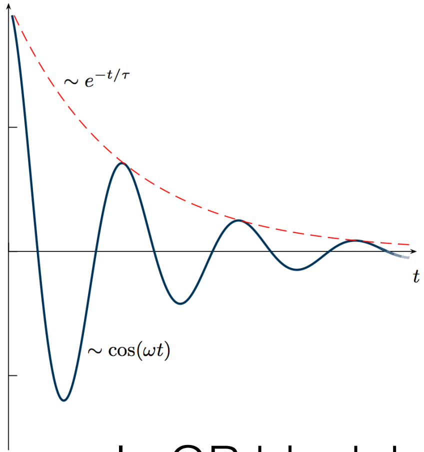
Spectrum of characteristic (complex) frequencies ω_{nlm}



Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

Spectrum of characteristic (complex) frequencies ω_{nlm}



Nollert '99

n	$2M_\bullet\omega$ ($L = 2$)	$2M_\bullet\omega$ ($L = 3$)	$2M_\bullet\omega$ ($L = 4$)
0	0.747 343 + 0.177 925i	1.198 887 + 0.185 406i	1.618 36 + 0.188 32i
1	0.693 422 + 0.547 830i	1.165 288 + 0.562 596i	1.593 26 + 0.568 86i
2	0.602 107 + 0.956 554i	1.103 370 + 0.958 186i	1.545 42 + 0.959 82i
3	0.503 010 + 1.410 296i	1.023 924 + 1.380 674i	1.479 68 + 1.367 84i

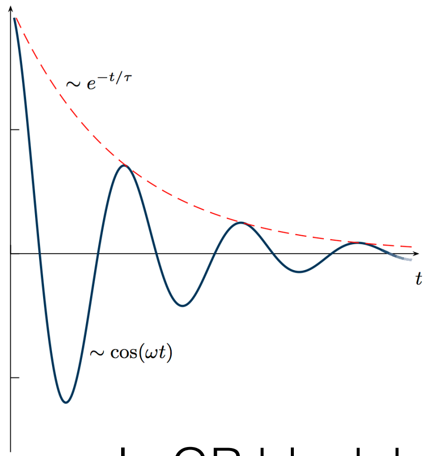
In GR black holes are characterized only by 3 parameters: M, J, Q

No-hair hypothesis

Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

Spectrum of characteristic (complex) frequencies ω_{nlm}

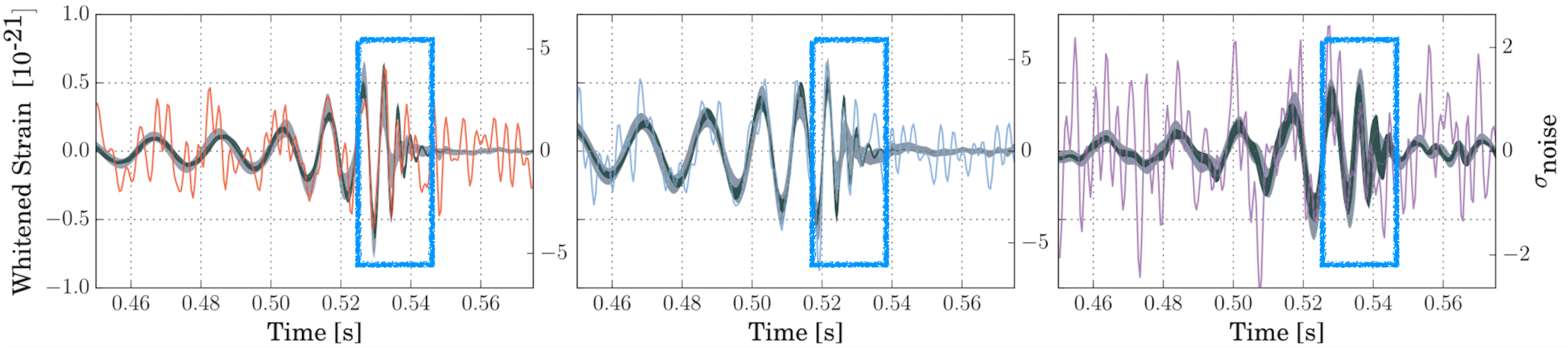


Nollert '99

n	$2M_\bullet\omega$ $(L = 2)$	$2M_\bullet\omega$ $(L = 3)$	$2M_\bullet\omega$ $(L = 4)$
0	0.747 343 + 0.177 925i	1.198 887 + 0.185 406i	1.618 36 + 0.188 32i
1	0.693 422 + 0.547 830i	1.165 288 + 0.562 596i	1.593 26 + 0.568 86i
2	0.602 107 + 0.956 554i	1.103 370 + 0.958 186i	1.545 42 + 0.959 82i
3	0.503 010 + 1.410 296i	1.023 924 + 1.380 674i	1.479 68 + 1.367 84i

In GR black holes are characterized only by 3 parameters: M, J, Q

No-hair hypothesis



Perturbations around Black Holes

$$g_{\mu\nu} = g^{\mathrm{BH}}_{\mu\nu}(r) + h_{\mu\nu}$$ Schwarzschild: static, spherically symmetric background

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

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

Axial (odd) perturbations

Regge Wheeler '57

Polar (even) perturbations

Zerilli '70

Perturbations around Black Holes

$$g_{\mu\nu} = g^{\rm BH}_{\mu\nu}(r) + h_{\mu\nu}$$ Schwarzschild: static, spherically symmetric background

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

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

Axial (odd) perturbations

Regge Wheeler '57

Polar (even) perturbations

Zerilli '70

Fix the gauge + solve for the constraint

One propagating DOF in the odd sector

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

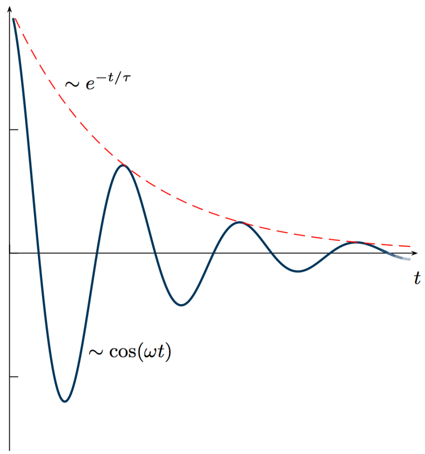
$$V^{(-)}(r) = \frac{l(l+1)}{r^2}\left(1-\frac{r_S}{r}\right) - 3\frac{r_S}{r^3}\left(1-\frac{r_S}{r}\right)$$

One propagating DOF in the even sector

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

$$V^{(+)}(r) = \dots$$

Perturbations around Black Holes



Nollert '99

n	$2M_\bullet\omega$ ($L=2$)	$2M_\bullet\omega$ ($L=3$)	$2M_\bullet\omega$ ($L=4$)
0	0.747 343 + 0.177 925i	1.198 887 + 0.185 406i	1.618 36 + 0.188 32i
1	0.693 422 + 0.547 830i	1.165 288 + 0.562 596i	1.593 26 + 0.568 86i
2	0.602 107 + 0.956 554i	1.103 370 + 0.958 186i	1.545 42 + 0.959 82i
3	0.503 010 + 1.410 296i	1.023 924 + 1.380 674i	1.479 68 + 1.367 84i

In GR quasi-normal modes are isospectral

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

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

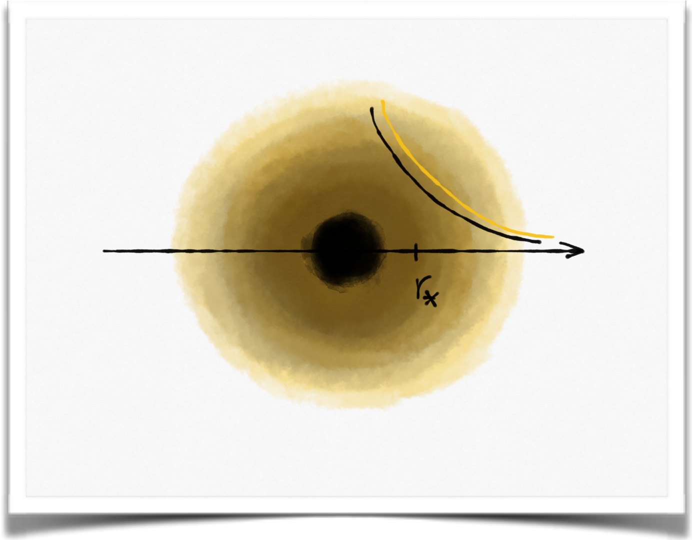
$$V^{(+)}(r) = \dots$$

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

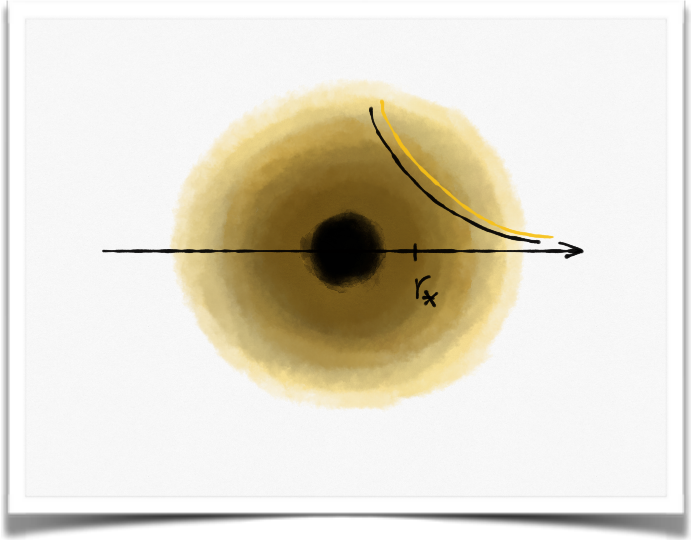


EFT for perturbations spher. symm.

The propagation of gravity is different IF BHs have scalar hair

The linearized equations of motion are modified

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



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

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

$$\mathrm{d}s^2 = -a^2(r)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{b^2(r)} + c^2(r)\left(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2\right)$$

Choose unitary gauge $\delta\Phi \equiv 0$

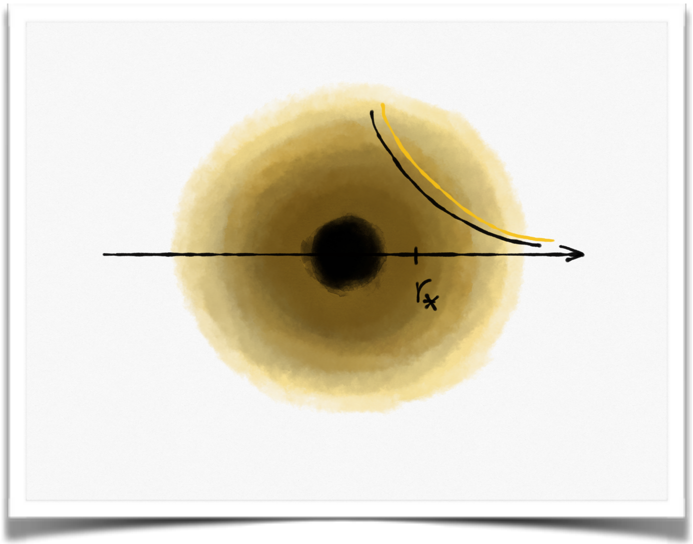
$$S = \int \mathrm{d}^4x\sqrt{-g}\,\mathcal{L}\left(g_{\mu\nu}, R_{\mu\nu\alpha\beta}, g^{rr}, K_{\mu\nu}, \nabla_\mu; r\right)$$

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



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

$$
\begin{aligned}
S = \int \mathrm{d}^4x \sqrt{-g}\Big[& \frac{1}{2}M^2(r)R - \Lambda(r) - f(r)g^{rr} - \alpha(r)\bar{K}_{\mu\nu}K^{\mu\nu} \\
& + M_2^4(r)(\delta g^{rr})^2 + \hat{M}_1^3(r)\delta g^{rr}\delta K + \hat{M}_2^3(r)\bar{K}_{\mu\nu}\delta g^{rr}\delta K^{\mu\nu} \\
& + \tilde{M}_1^2(r)(\partial_r\delta g^{rr})^2 + \tilde{M}_2^2(r)(\partial_r\delta g^{rr})\delta K + \tilde{M}_3^2(r)K_{ab}(\partial_r\delta g^{rr})\delta K^{\mu\nu} \\
& + \bar{M}_1^2(r)(\delta K)^2 + \bar{M}_2^2(r)\delta K_{\mu\nu}\delta K^{\mu\nu} + \bar{M}_3^2(r)\bar{K}_{\mu\nu}\delta K\delta K^{\mu\nu} + \bar{M}_4^2(r)\bar{K}_{\mu\nu}\delta K^{\mu\rho}\delta K^{\nu}{}_{\rho} \\
& + \bar{M}_5^2(r)\bar{K}_{\mu\rho}\bar{K}_{\nu}^{\rho}\delta K\delta K^{\mu\nu} + \bar{M}_6^2(r)\delta g^{rr}\delta\hat{R} + \bar{M}_7^2(r)\bar{K}_{\mu\nu}\delta g^{rr}\delta\hat{R}^{\mu\nu} + \dots \Big],
\end{aligned}
$$

Franciolini, Hui, Penco, Santoni, ET '18

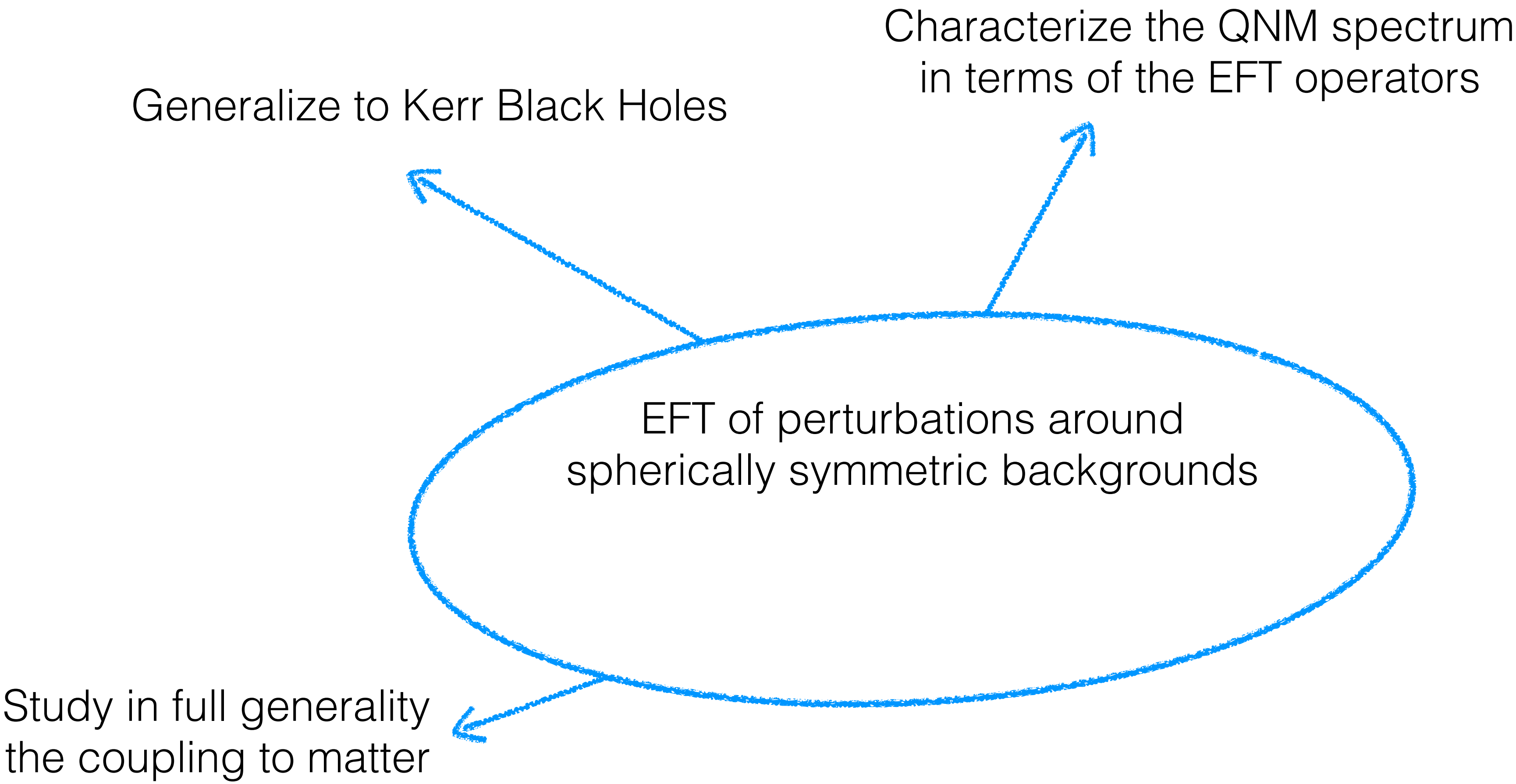
Phenomenology

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


Characterize the QNM spectrum
in terms of the EFT operators
Generalize to Kerr Black Holes
EFT of perturbations around
spherically symmetric backgrounds
Study in full generality
the coupling to matter

Outlook

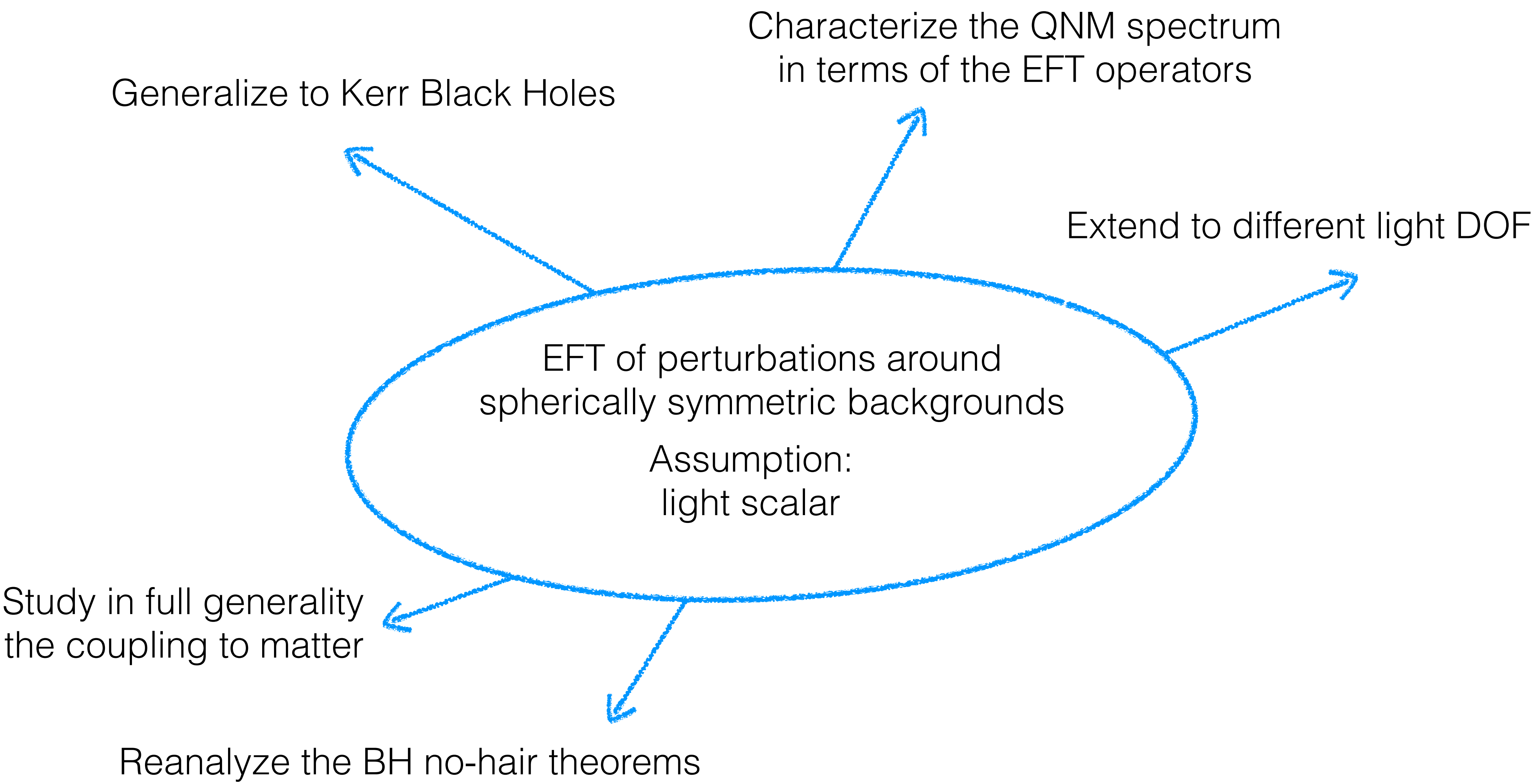
EFT of perturbations around spherically symmetric backgrounds

Assumption:
non trivial scalar profile

- 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

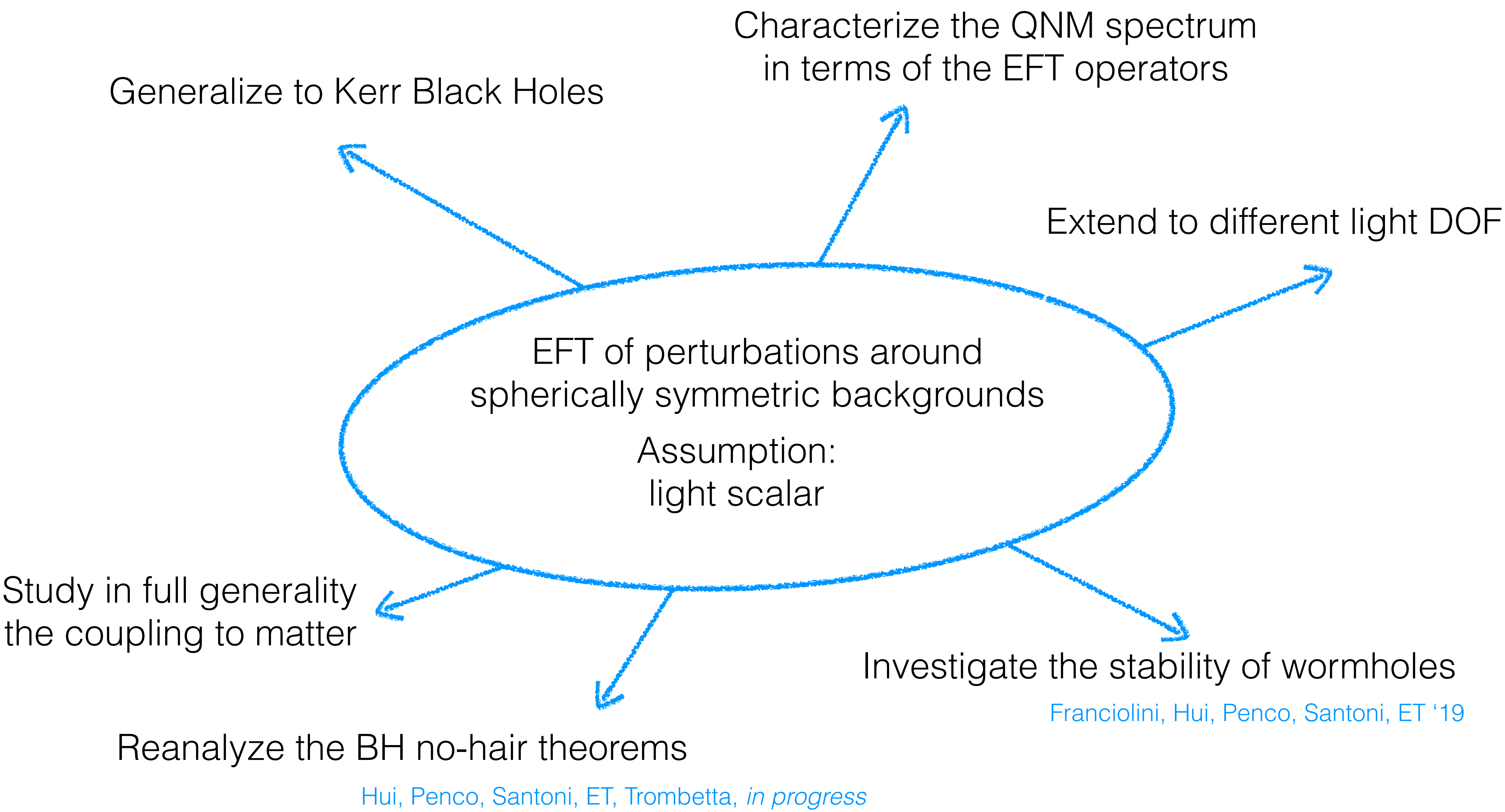
Hui, Penco, Santoni, ET, Trombetta, *in progress*

Outlook



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

Outlook


EFT of perturbations around
spherically symmetric backgrounds
Assumption:
light scalar
Generalize to Kerr Black Holes
Characterize the QNM spectrum
in terms of the EFT operators
Extend to different light DOF
Investigate the stability of wormholes
Franciolini, Hui, Penco, Santoni, ET ‘19
Reanalyze the BH no-hair theorems
Hui, Penco, Santoni, ET, Trombetta, *in progress*
Study in full generality
the coupling to matter

“*[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