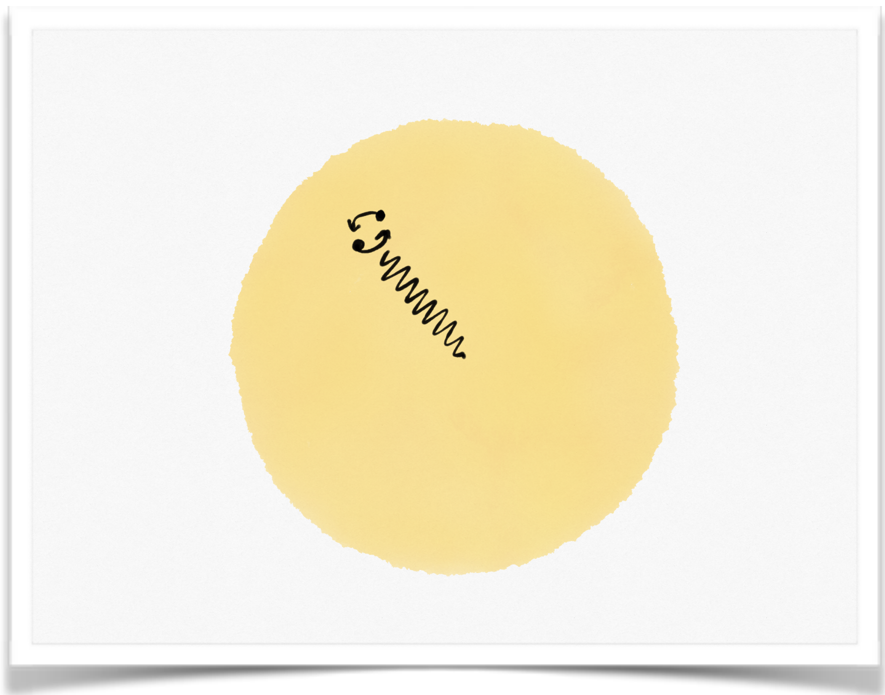
BH RINGDOWN AS A PROBE FOR DARK ENERGY

ENRICO TRINCHERINI
(SCUOLA NORMALE SUPERIORE)

Can we detect new light DOF using gravitational waves?

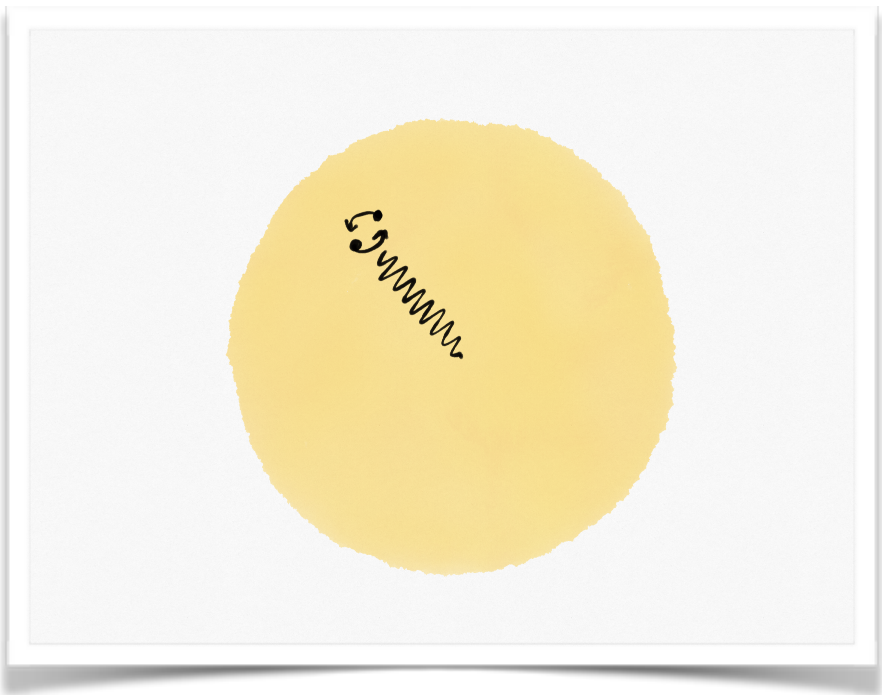


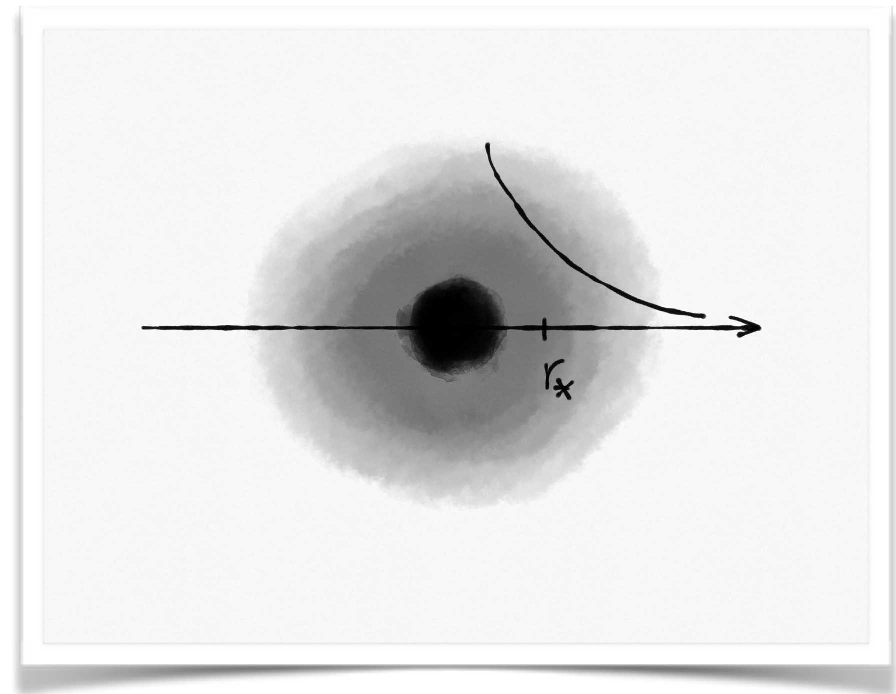
On cosmological scales, Dark Energy acts like a “medium” with a homogeneous and isotropic stress energy tensor that breaks spontaneously Lorentz invariance

Gravitational perturbations that travel on this background carry information about the underlying microscopic theory, already at the level of the quadratic action (speed of propagation can be different from c, damping)

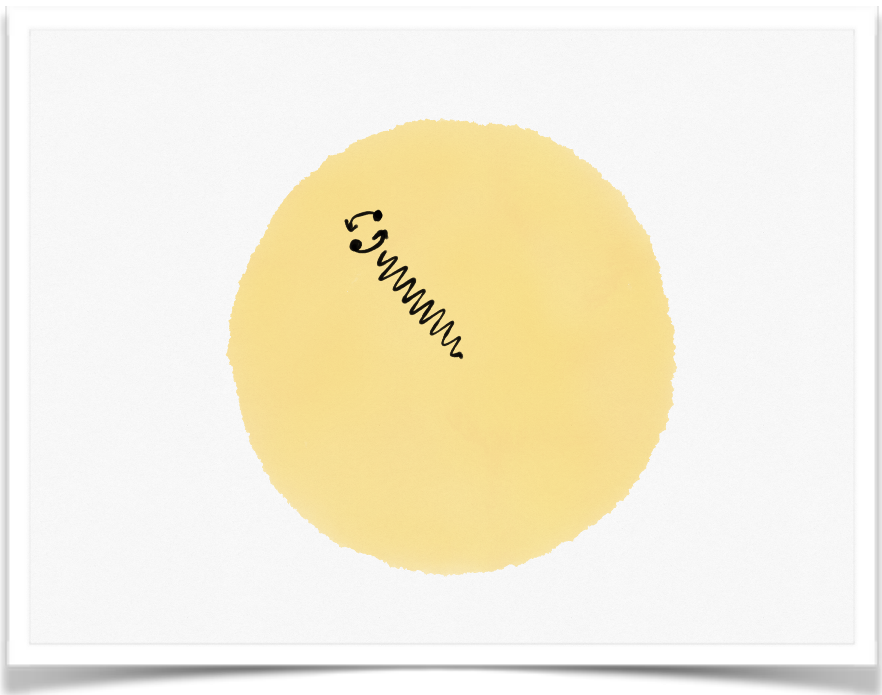
$$\ddot{\gamma}_{ij} + H(3+\alpha)\dot{\gamma}_{ij} + c_T^2 k^2 \gamma_{ij} = 0$$

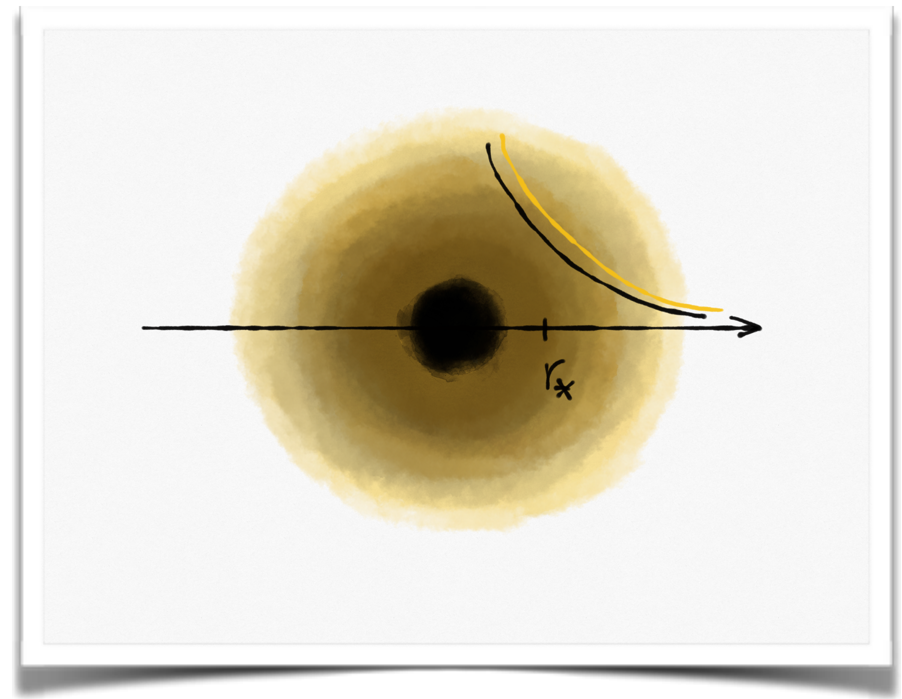
Can we detect new light DOF using gravitational waves?



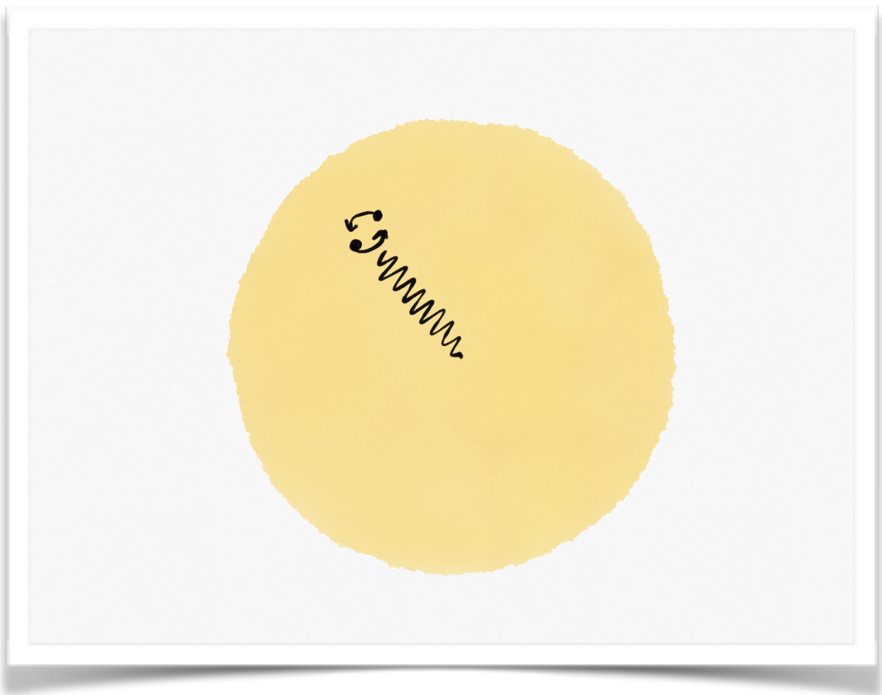


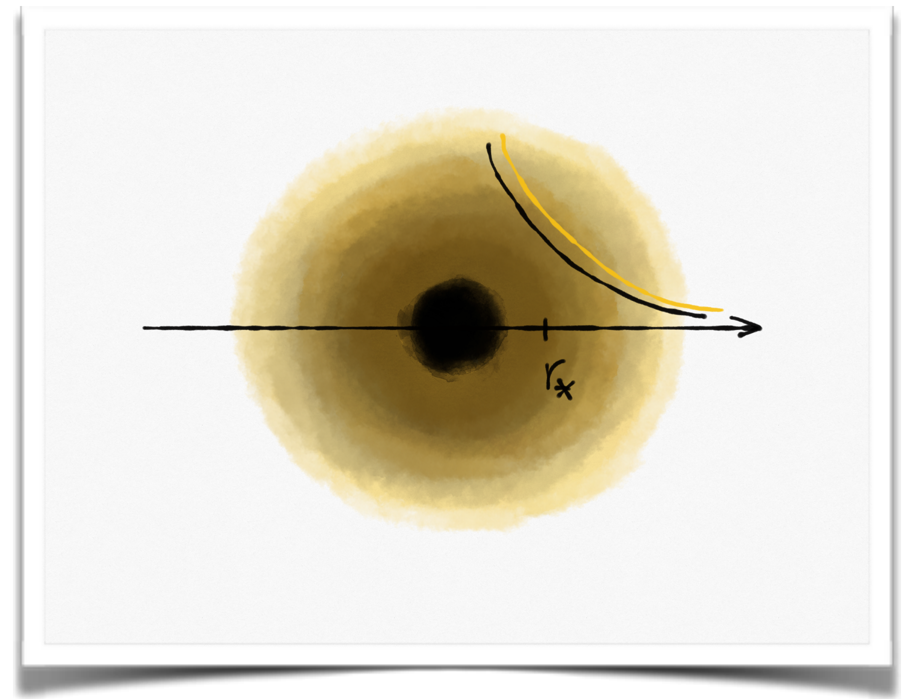
Can we detect new light DOF using gravitational waves?

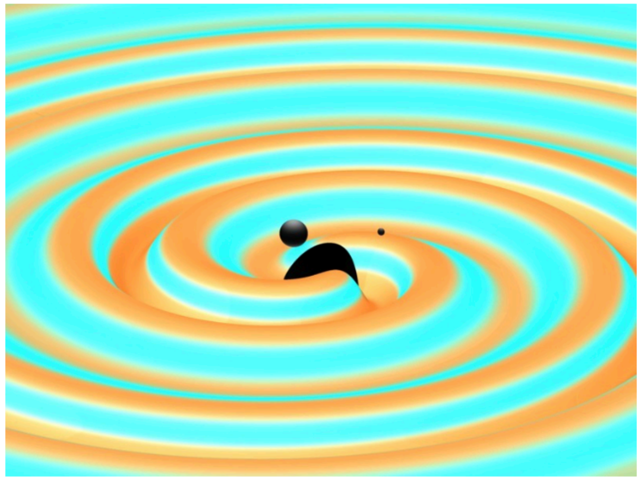




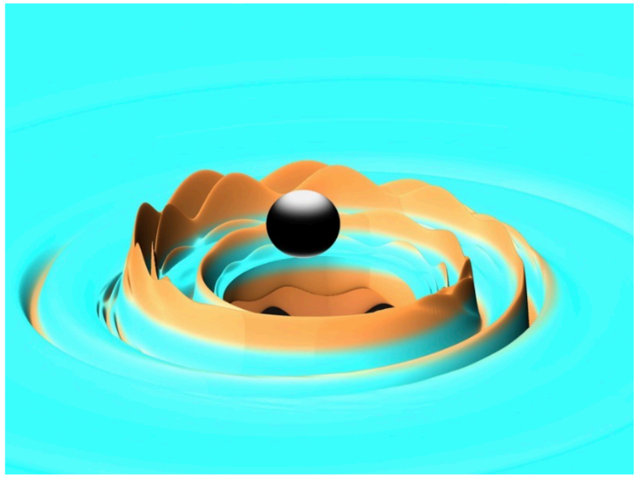
Can we detect new light DOF using gravitational waves?



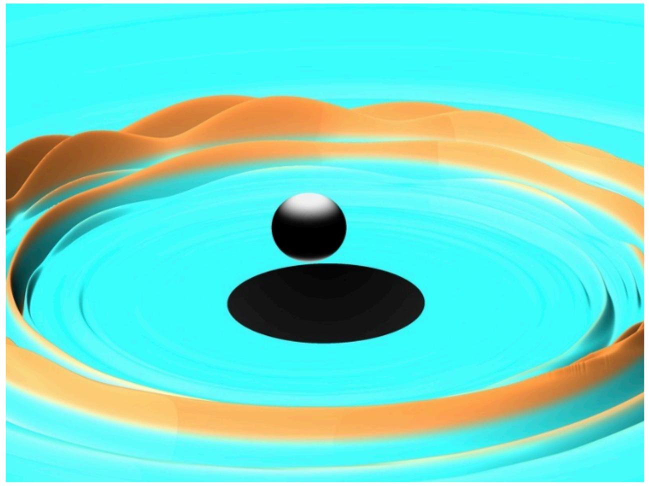




Inspiral



Merger

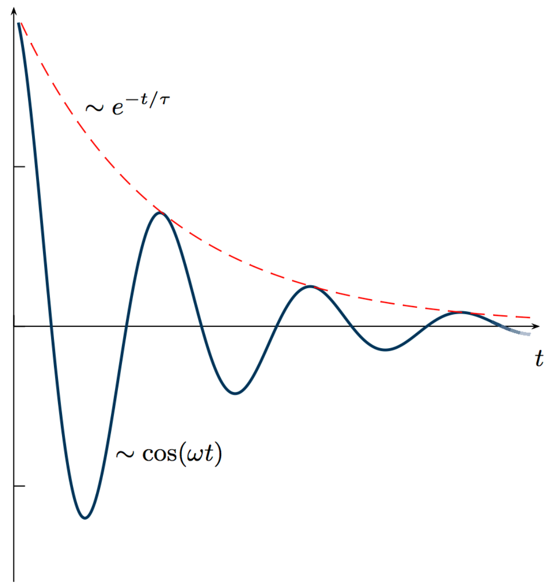


Ringdown

Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

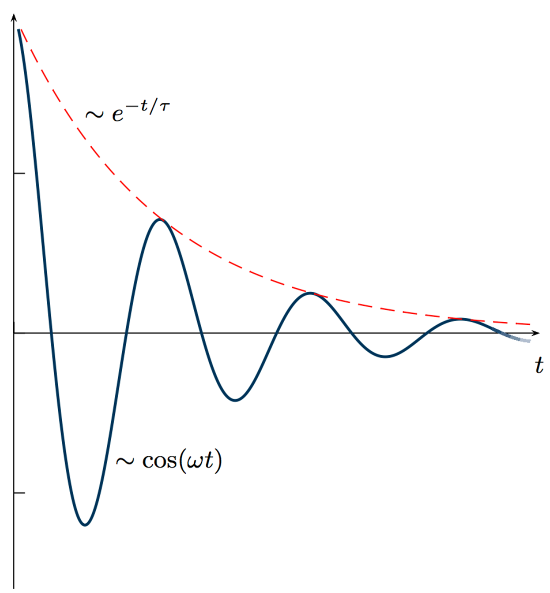
Spectrum of characteristic (complex) frequencies ω_{nlm}



Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

Spectrum of characteristic (complex) frequencies ω_{nlm}



Nollert '99

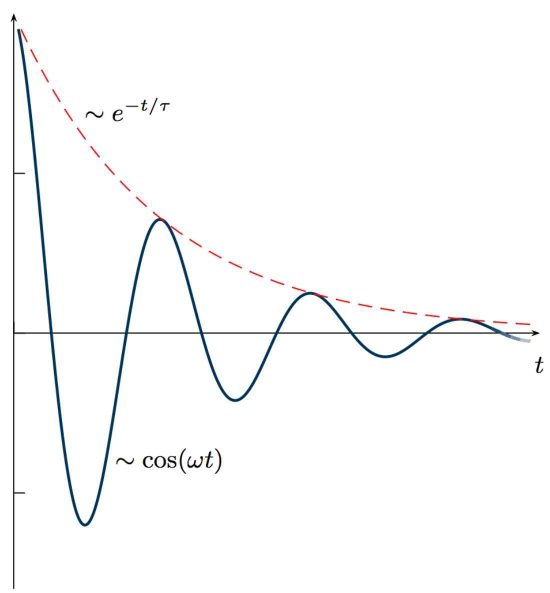
n	$2M_\bullet\omega\ (L=2)$	$2M_\bullet\omega\ (L=3)$	$2M_\bullet\omega\ (L=4)$
0	0.747 343 + 0.177 925i	1.198 887 + 0.185 406i	1.618 36 + 0.188 32i
1	0.693 422 + 0.547 830i	1.165 288 + 0.562 596i	1.593 26 + 0.568 86i
2	0.602 107 + 0.956 554i	1.103 370 + 0.958 186i	1.545 42 + 0.959 82i
3	0.503 010 +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

Perturbations around Black Holes

Exponentially damped sinusoidal waves: Quasi Normal Modes (QNM)

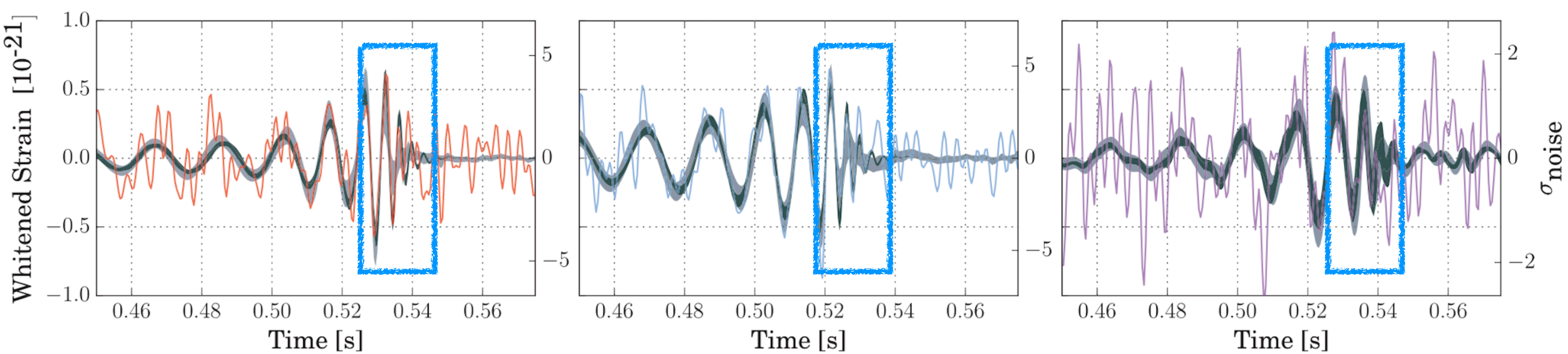
Spectrum of characteristic (complex) frequencies ω_{nlm}



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



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 $(\theta,\phi) \rightarrow (\pi-\theta, \phi+\pi)$

Axial (odd) perturbations

Regge Wheeler '57

Polar (even) perturbations

Zerilli '70

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

Fix the gauge + solve for the constraint

One propagating DOF in the odd sector

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

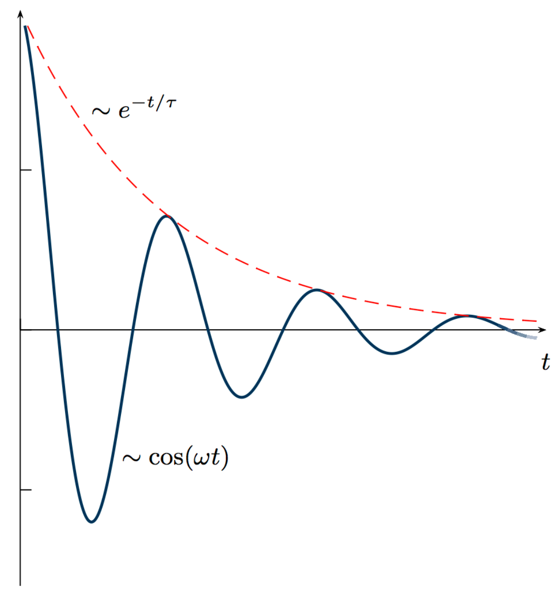
$$V^{(-)}(r) = \frac{l(l+1)}{r^2}\left(1-\frac{r_S}{r}\right) - 3\frac{r_S}{r^3}\left(1-\frac{r_S}{r}\right)$$

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

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

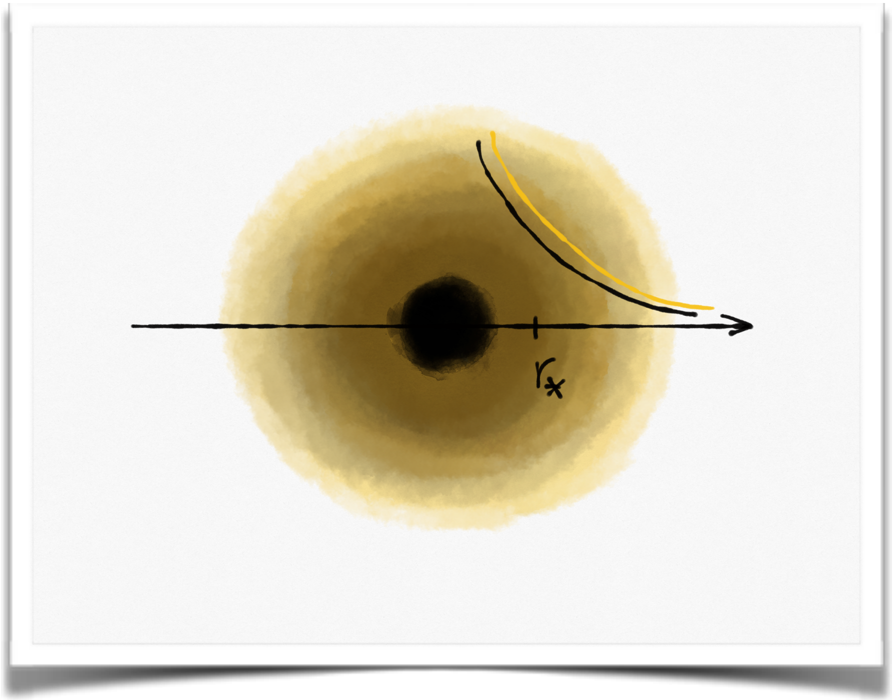
$$V^{(+)}(r) = \dots$$

EFT for perturbations in spher symm bkgrd

The propagation of gravity is different IF a black hole has a scalar background

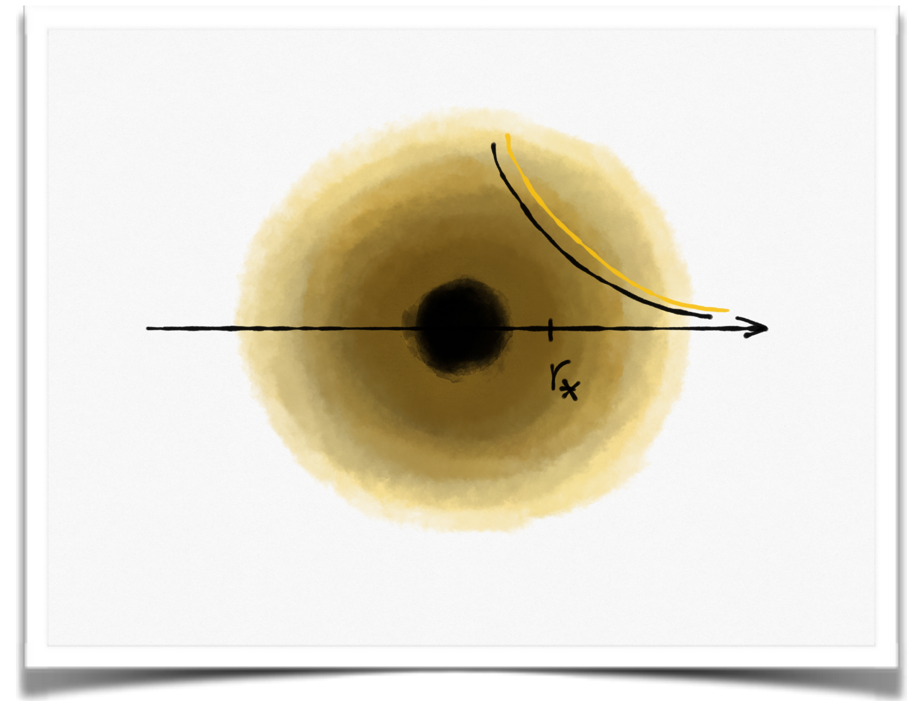
The linearized equations of motion are modified

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



EFT for perturbations in spher symm bkgrd

The propagation of gravity is different IF a black hole has a scalar background



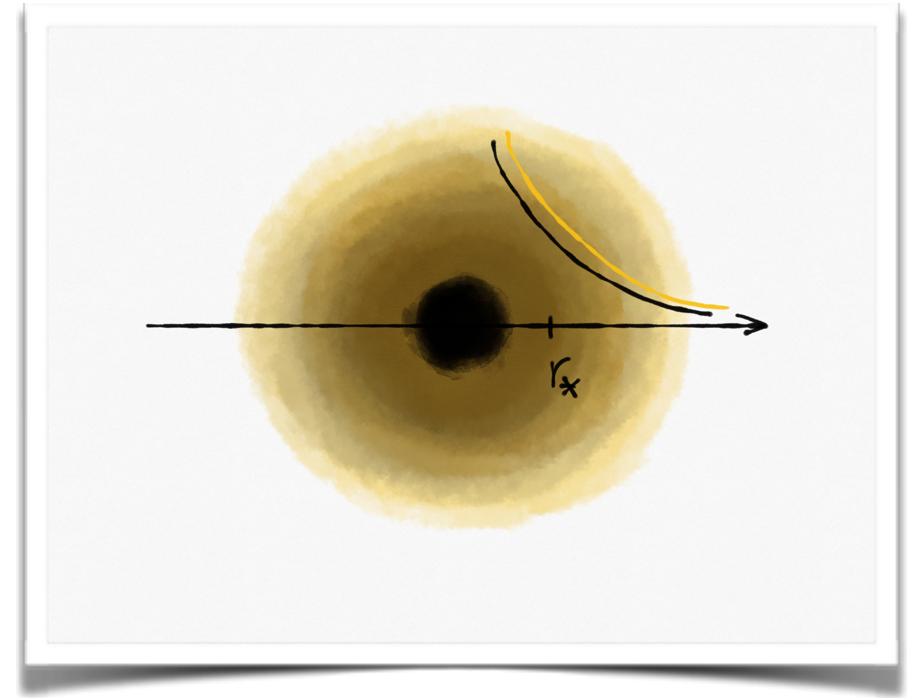
The linearized equations of motion are modified

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

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

EFT for perturbations in spher symm bkgrd

The propagation of gravity is different IF a black hole has a scalar background



The linearized equations of motion are modified

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

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

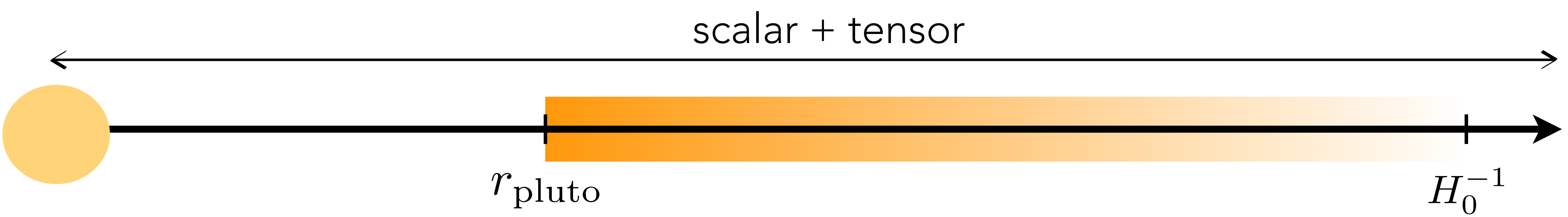
mix the even and odd modes if it is a pseudo-scalar

Why is a light scalar usually considered a problem?

When it is coupled gravitationally to SM fields $\frac{1}{M_{\rm Pl}}\pi T$

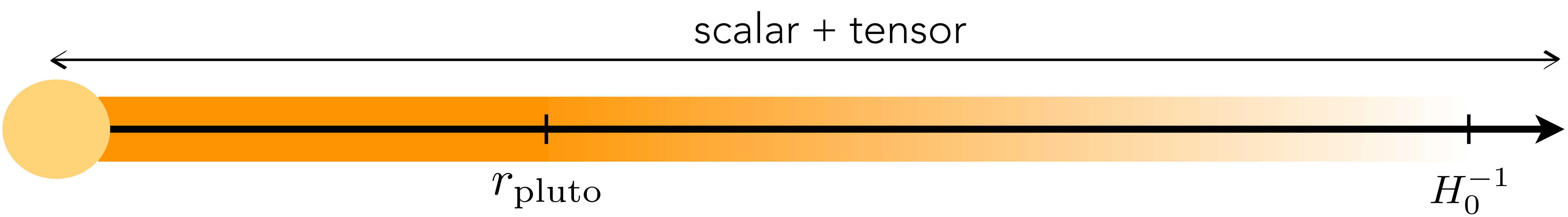
Why is a light scalar usually considered a problem?

When it is coupled gravitationally to SM fields $\dfrac{1}{M_{\rm Pl}}\pi T$



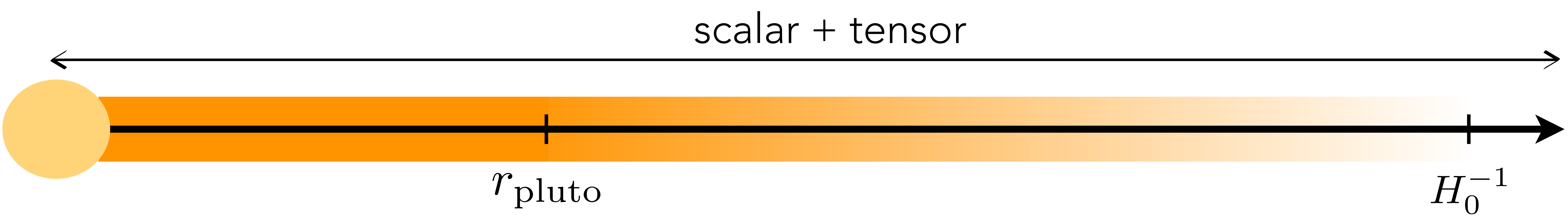
Why is a light scalar usually considered a problem?

When it is coupled gravitationally to SM fields $\dfrac{1}{M_{\rm Pl}}\pi T$ Screening mechanism is needed



Why is a light scalar usually considered a problem?

When it is coupled gravitationally to SM fields $\frac{1}{M_{\mathrm{Pl}}}\pi T$ Screening mechanism is needed



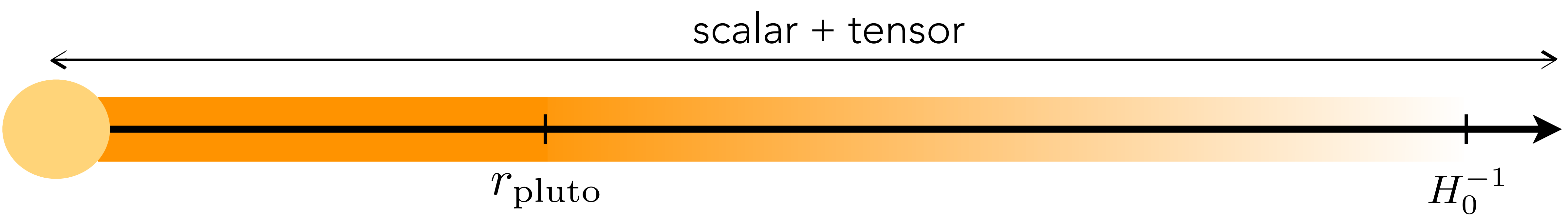
The observed accelerated expansion of the Universe can be given by new DOF that either:

1) have a background value that produce a sizable stress-energy tensor

2) affect the propagation of gravity, without any large contribution to T

Why is a light scalar usually considered a problem?

When it is coupled gravitationally to SM fields $\frac{1}{M_{\rm Pl}}\pi T$ Screening mechanism is needed



The observed accelerated expansion of the Universe can be given by new DOF that either:

1) have a background value that produce a sizable stress-energy tensor

2) affect the propagation of gravity, without any large contribution to T

Plan

Characterize the most general HD scalar with negligible coupling to matter without screening

Discuss if this scalar field can be observed during the ringdown after a BH merger

Work in progress with J. Noller, L. Santoni, L. Trombetta

$$M_{\rm Pl}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} + \ldots + \frac{\pi T}{M_{\rm Pl}}$$

$$\cancel{M_{\rm Pl}\pi R}$$

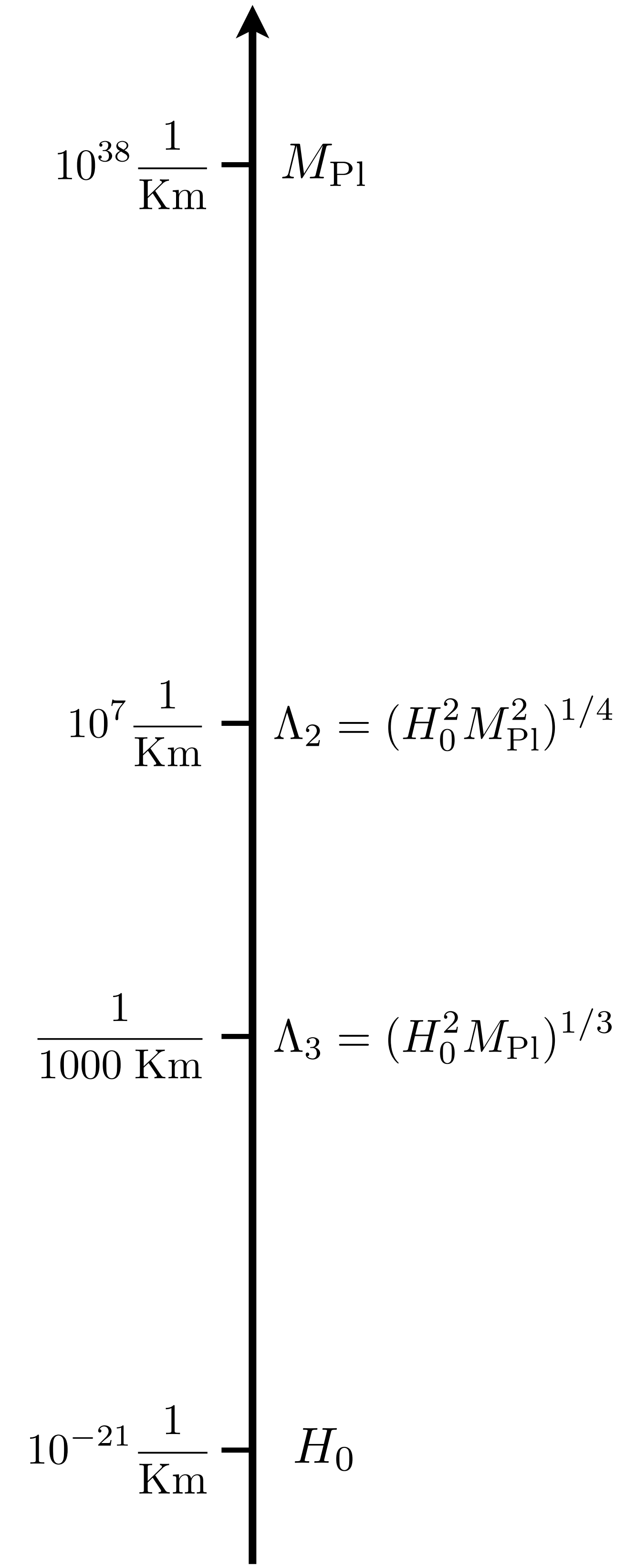
$$M_{\rm Pl}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} + \ldots + \cancel{\frac{\pi T}{M_{\rm Pl}}}$$

$$M_{\mathrm{Pl}}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} + \ldots$$

The scalar drives the accelerated expansion

$$(\partial\pi_0(t))^2 \sim \Lambda_2^4 = H_0^2 M_{\mathrm{Pl}}^2$$

$$\Box\pi_0(t) \sim \Lambda_3^3 = H_0^2 M_{\mathrm{Pl}}$$



$$M_{\rm Pl}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} + \dots$$

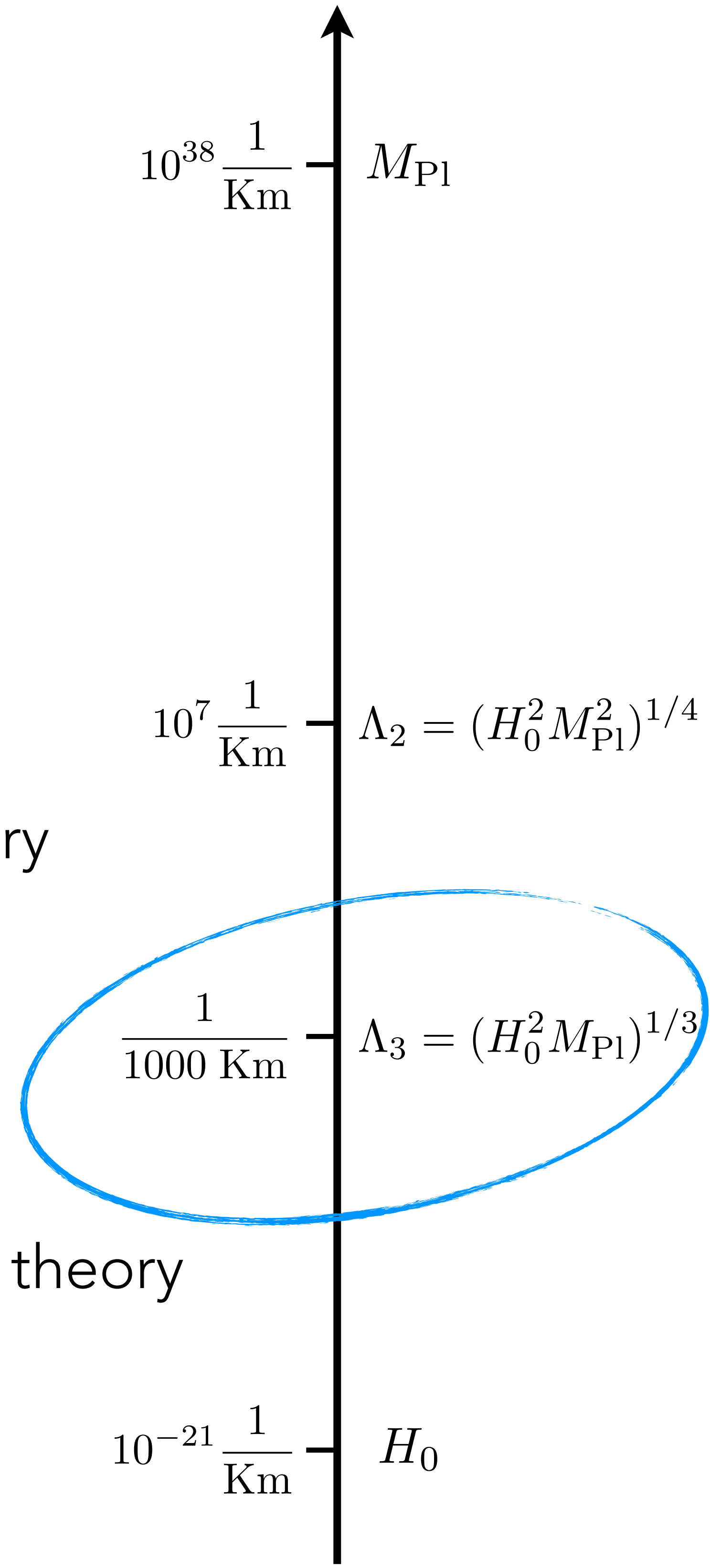
The scalar drives the accelerated expansion

$$(\partial\pi_0(t))^2 \sim \Lambda_2^4 = H_0^2 M_{\rm Pl}^2$$

$$\Box\pi_0(t) \sim \Lambda_3^3 = H_0^2 M_{\rm Pl}$$

This dynamics is made structurally robust by an approximate symmetry (plus exact shift symmetry)

$$\partial_\mu\pi \to \partial_\mu\pi + b_\mu$$



Λ_3 is the UV cutoff of the scalar theory

$$M_{\rm Pl}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} + \ldots$$

The scalar drives the accelerated expansion

$$(\partial\pi_0(t))^2 \sim \Lambda_2^4 = H_0^2 M_{\rm Pl}^2$$

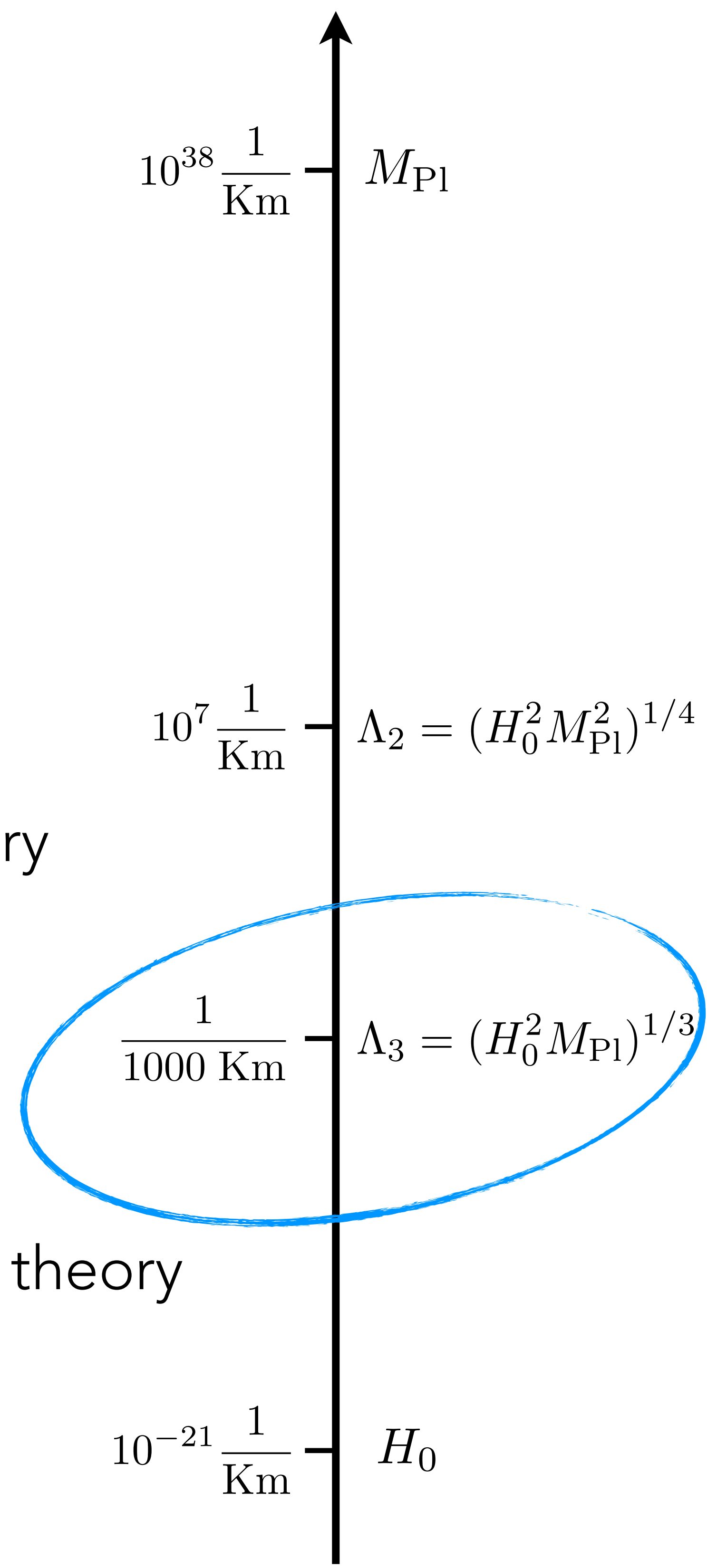
$$\Box\pi_0(t) \sim \Lambda_3^3 = H_0^2 M_{\rm Pl}$$

This dynamics is made structurally robust by an approximate symmetry (plus exact shift symmetry)

$$\partial_\mu\pi \to \partial_\mu\pi + b_\mu$$

$$\Box\pi \supset \frac{\partial\pi\partial h}{M_{\rm Pl}}$$

HD interactions induce *O(1)* kinetic mixing on the cosmological background



Λ_3 is the UV cutoff of the scalar theory

$$M_{\rm Pl}^2 R + (\partial\pi)^2 + \frac{(\partial\pi)^4}{\Lambda_2^4} + \cdots + \frac{(\partial\pi)^2\Box\pi}{\cancel{\Lambda_3^3}} \; M^3 + \dots$$

The scalar drives the accelerated expansion

$$(\partial\pi_0(t))^2 \sim \Lambda_2^4 = H_0^2 M_{\rm Pl}^2$$

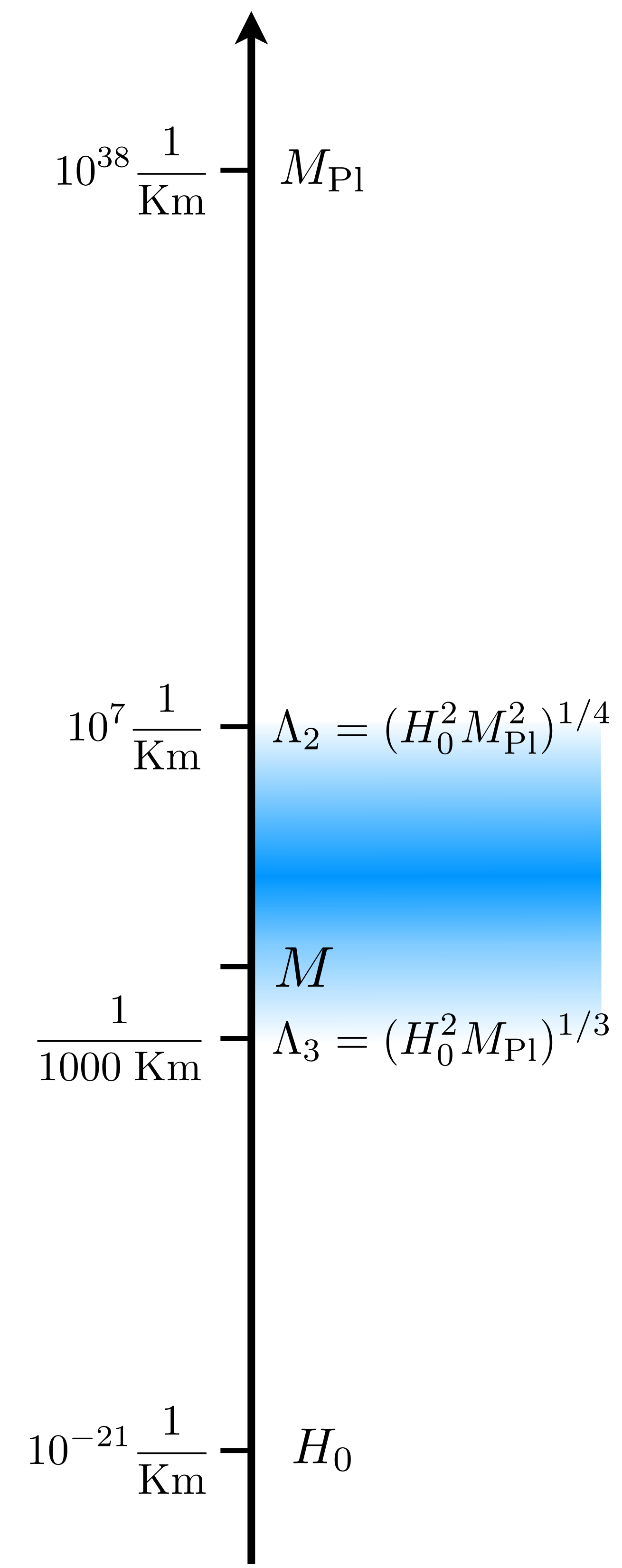
$$\Box\pi_0(t) \sim \Lambda_3^3 = H_0^2 M_{\rm Pl}$$

One option is to raise the strong coupling scale

The kinetic mixing (the coupling to matter) is suppressed by

$$\left(\alpha \equiv \frac{\Lambda_3}{M}\right)^{3m}$$

Of course all effects from HD operators are suppressed on the cosmological background

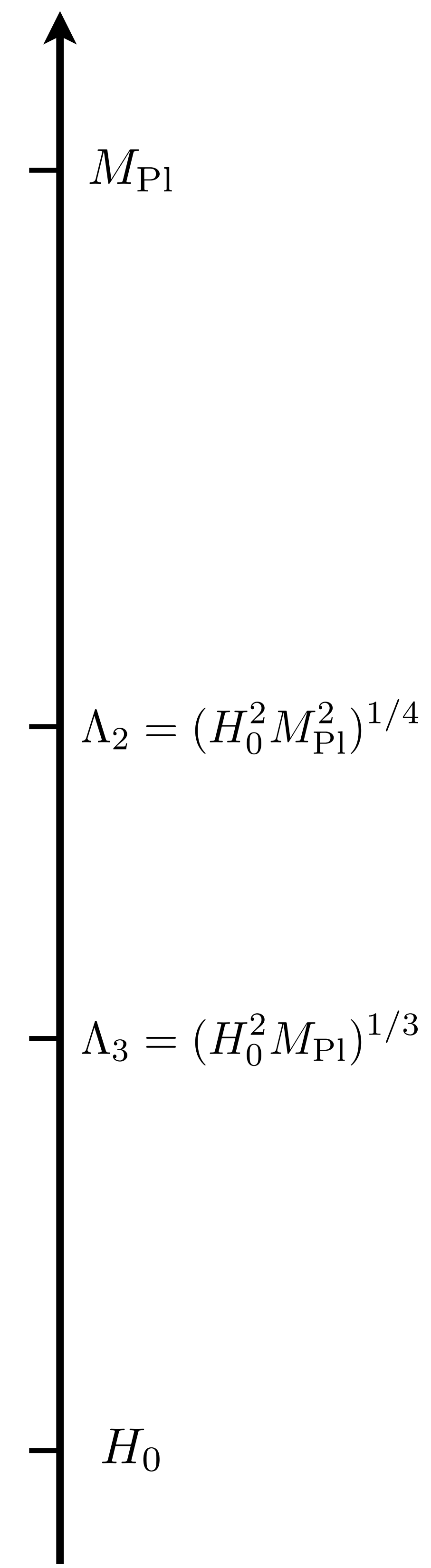


Quantum Corrections

$$\frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3}$$

$$\partial_\mu\pi \to \partial_\mu\pi + b_\mu$$

Only operators with al least $\partial^2\pi$ are generated



Quantum Corrections

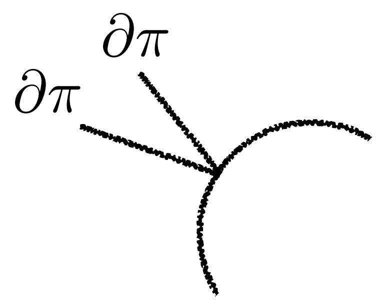
$$\frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3}$$

$$\partial_\mu\pi \to \partial_\mu\pi + b_\mu$$

Only operators with al least $\partial^2\pi$ are generated

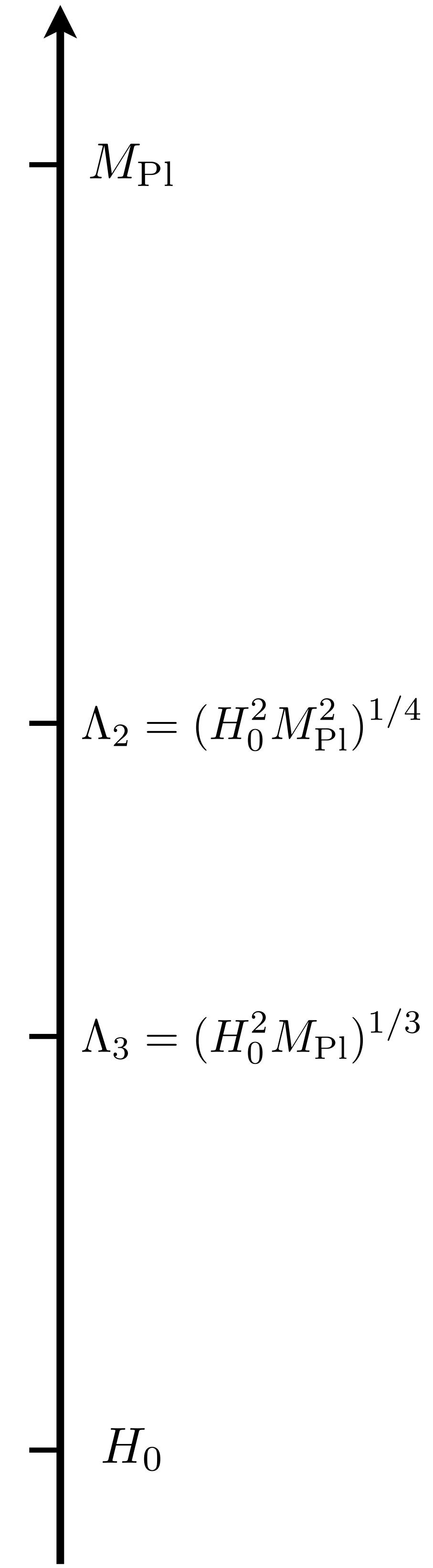
The coupling to gravity breaks the symmetry explicitly

$$\frac{(\partial\pi)^3\partial h}{M_{\rm Pl}\Lambda_3^3}$$



In loop induced operators for every external $(\partial\pi)^2$ there is a suppression $\frac{1}{M_{\rm Pl}}$

$$\frac{(\partial\pi)^{2n}}{\Lambda_3^{3n-4}M_{\rm Pl}^n} = \frac{(\partial\pi)^{2n}}{\Lambda_3^{3n-3}M_{\rm Pl}^{n-1}}\frac{\Lambda_3}{M_{\rm Pl}}$$



Quantum Corrections

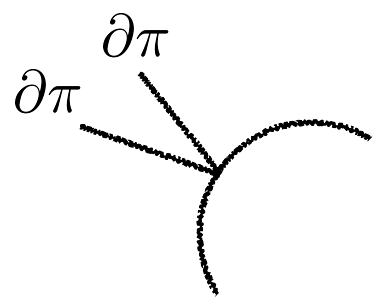
$$\frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3}$$

$$\partial_\mu\pi \to \partial_\mu\pi + b_\mu$$

Only operators with al least $\partial^2\pi$ are generated

The coupling to gravity breaks the symmetry explicitly

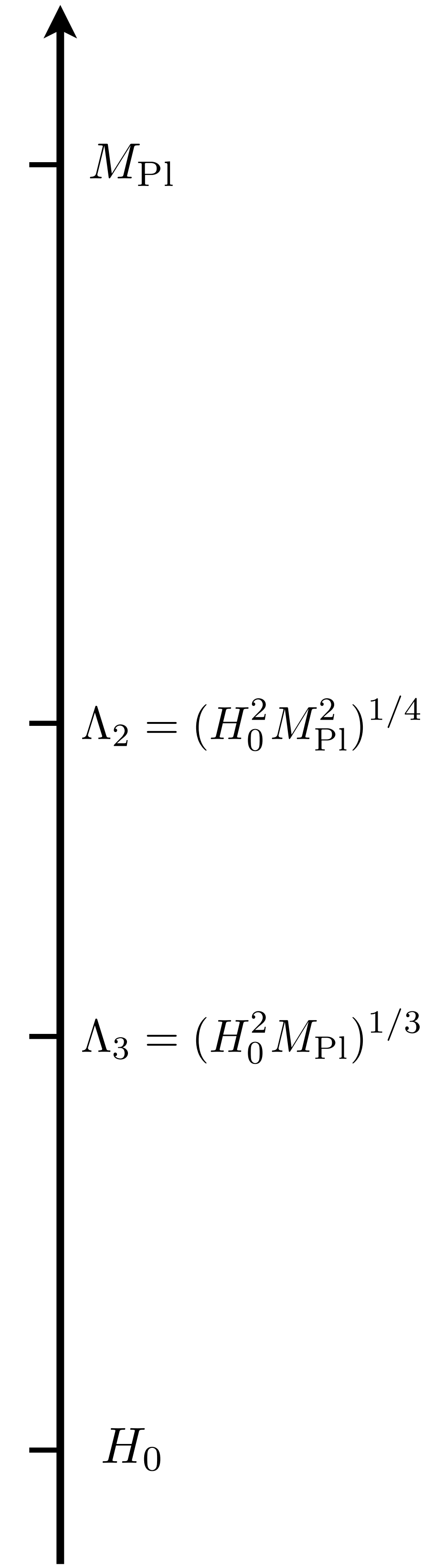
$$\frac{(\partial\pi)^3\partial h}{M_{\rm Pl}\Lambda_3^3}$$



In loop induced operators for every external $(\partial\pi)^2$ there is a suppression $\frac{1}{M_{\rm Pl}}$

$$\frac{(\partial\pi)^{2n}}{\Lambda_3^{3n-4}M_{\rm Pl}^n} = \frac{(\partial\pi)^{2n}}{\Lambda_3^{3n-3}M_{\rm Pl}^{n-1}}\frac{\Lambda_3}{M_{\rm Pl}}$$

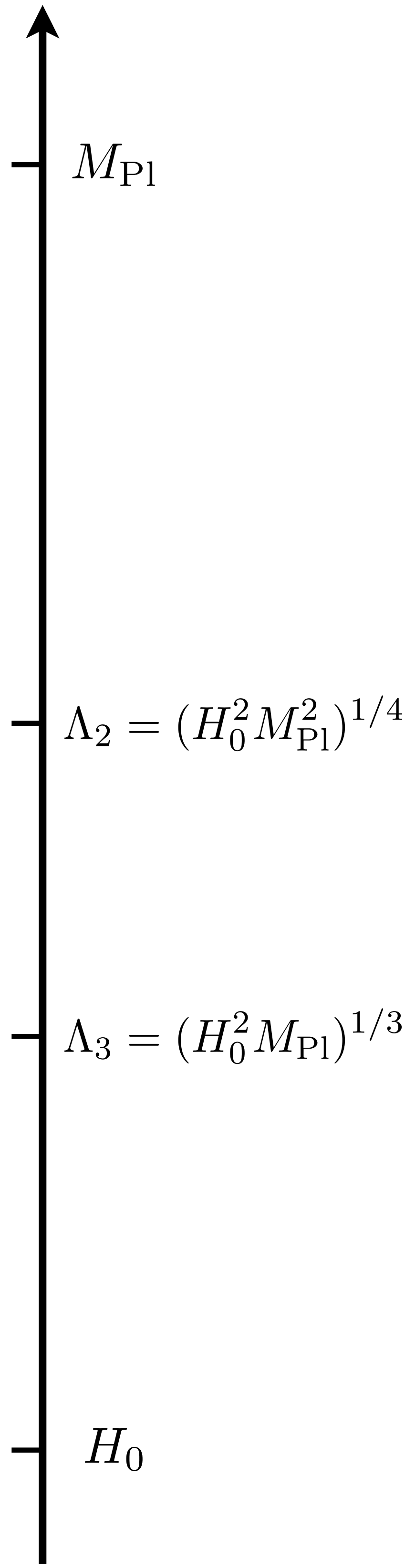
Additional sources of explicit breaking can be added: $\frac{(\partial\pi)^4}{M_{\rm Pl}\Lambda_3^3}$



Structurally robust HD EFTs

Galileon approximate symmetry provides, even in the absence of an explicit UV completion, a set of rules to consistently power count the EFT operators

$$\Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{\Lambda_3^{3m}}$$



Structurally robust HD EFTs

Galileon approximate symmetry provides, even in the absence of an explicit UV completion, a set of rules to consistently power count the EFT operators

$$\Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{\Lambda_3^{3m}}$$

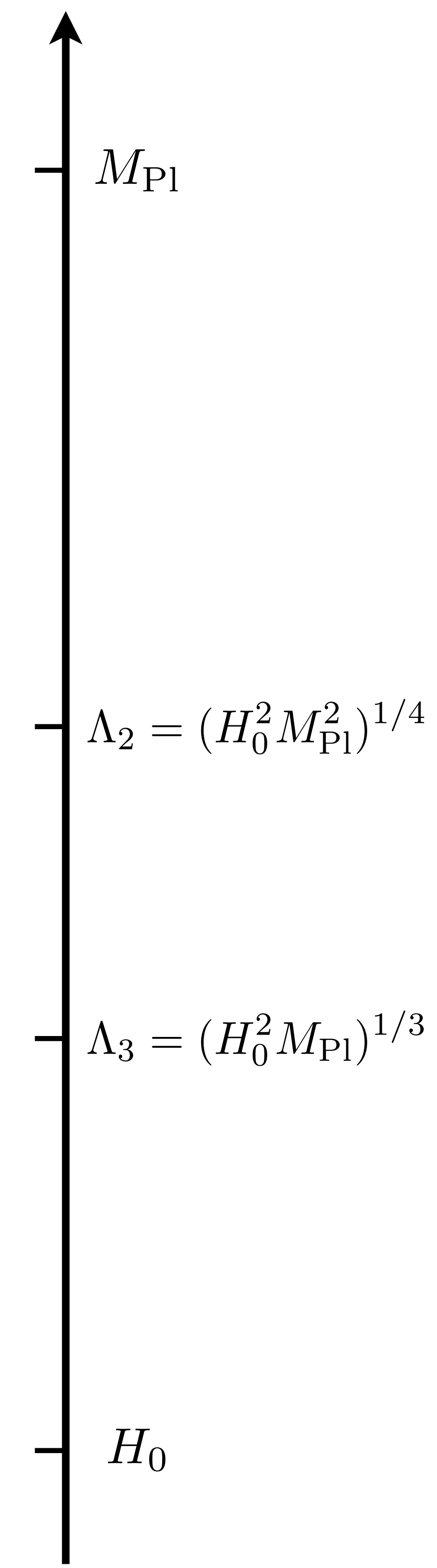
$n \geq 1$
$m = 0, 1, 2, 3$

$G_2(X)$ $\quad$ $G_3(X)$ $\quad$ $G_{4X}(X)$ $\quad$ $G_{5X}(X)$

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

$$L_4 \equiv G_4(\phi, X)\,{}^{(4)}R - 2G_{4,X}(\phi, X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu}) + F_4(\phi, X)\varepsilon^{\mu\nu\rho}{}_{\sigma}\varepsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\,,$$

$$L_5 \equiv G_5(\phi, X)\,{}^{(4)}G_{\mu\nu}\phi^{\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)(\Box\phi^3 - 3\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}_{\ \sigma}) + F_5(\phi, X)\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}$$



Structurally robust HD EFTs

Galileon approximate symmetry provides, even in the absence of an explicit UV completion, a set of rules to consistently power count the EFT operators

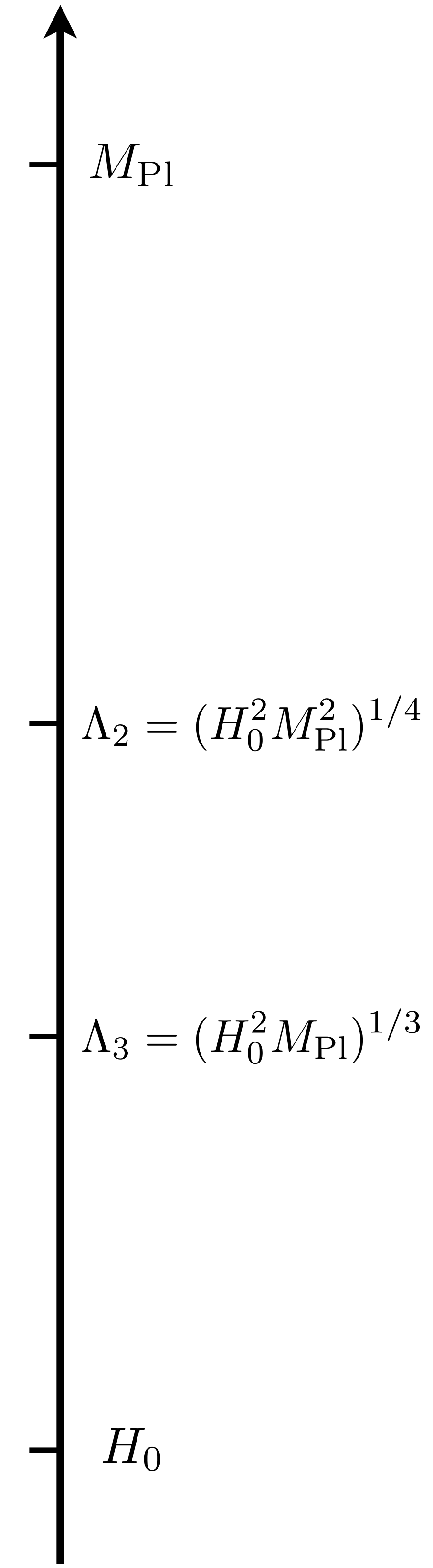
$$\Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{\Lambda_3^{3m}}$$

$$n \geq 1$$
$$m = 0, 1, 2, 3$$

$G_2(X)$

$G_3(X)$ $G_{4X}(X)$ $G_{5X}(X)$

$$\frac{(\partial\pi)^4}{\Lambda_2^4}\left(1 + \frac{\Lambda_3}{M_{\rm Pl}}\right)$$



Structurally robust HD EFTs

Galileon approximate symmetry provides, even in the absence of an explicit UV completion, a set of rules to consistently power count the EFT operators

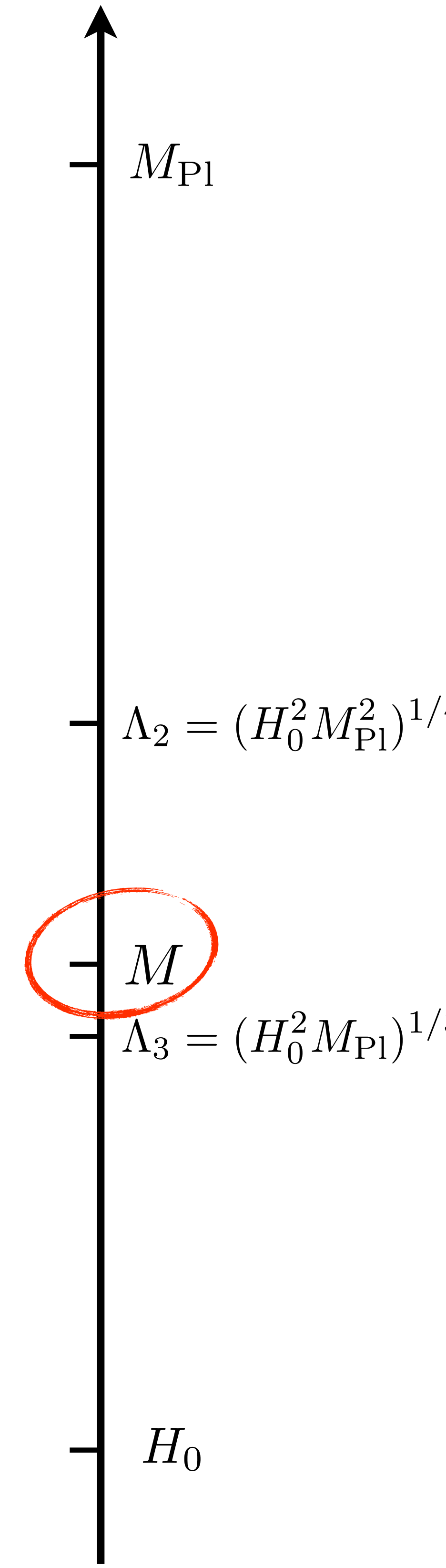
$$\Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{\Lambda_3^{3m}}$$

$$n \geq 1$$
$$m = 0, 1, 2, 3$$

$$G_2(X) \qquad G_3(X) \qquad G_{4X}(X) \qquad G_{5X}(X)$$

$$\Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}}$$

$$\frac{(\partial\pi)^4}{\Lambda_2^4}\left(1 + \frac{\Lambda_3}{M_{\rm Pl}}\right) \qquad \frac{(\partial\pi)^4}{\Lambda_2^4}\left(1 + \frac{M}{M_{\rm Pl}}\left(\frac{M}{\Lambda_3}\right)^3\right)$$



Why raising M might be useful

1. No fifth force even if there is no screening $\alpha \lesssim 10^{-3}$

Why raising M might be useful

1. No fifth force even if there is no screening $\alpha \lesssim 10^{-3}$

2. It explains why the speed of gravitational waves is the speed of light

$$\frac{(\partial\pi)^2(\partial^2\pi)^2}{M^6} \supset \alpha^6 \frac{(\partial\pi)^4(\partial h)^2}{\Lambda_3^6 M_{\mathrm{Pl}}^2} \qquad \alpha \lesssim 10^{-3}$$

Why raising M might be useful

1. No fifth force even if there is no screening $\alpha \lesssim 10^{-3}$

2. It explains why the speed of gravitational waves is the speed of light

$$\frac{(\partial\pi)^2(\partial^2\pi)^2}{M^6} \supset \alpha^6 \frac{(\partial\pi)^4(\partial h)^2}{\Lambda_3^6 M_{\rm Pl}^2} \qquad \alpha \lesssim 10^{-3}$$

3. Positivity bounds from scattering amplitudes suggest that the symmetry breaking operator $(\partial\pi)^4$ cannot be to small compared to the invariant ones

Positivity bounds

The general properties of the S-matrix (unitarity, analyticity) imply dispersion relations for forward elastic scattering amplitudes positivity bounds for amplitudes in the IR.

$$-(\partial\pi)^2 + a\frac{(\partial\pi)^4}{\Lambda_2^4} - \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} \qquad a > 0$$

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi '06

Positivity bounds

The general properties of the S-matrix (unitarity, analyticity) imply dispersion relations for forward elastic scattering amplitudes positivity bounds for amplitudes in the IR.

$$-(\partial\pi)^2 + a\frac{(\partial\pi)^4}{\Lambda_2^4} - \frac{(\partial\pi)^2\Box\pi}{\Lambda_3^3} \qquad a > 0$$

the scales Λ_2 and Λ_3 cannot be arbitrarily separated while keeping the UV cutoff fixed

$$a^{\pi\pi} = \frac{1}{\Lambda_2^4} > \frac{2}{\pi}\int^{\Lambda_{UV}^2} \frac{ds}{s^3}\mathrm{Im}\mathcal{M}^{\pi\pi}(s) \propto \frac{1}{16\pi^2}\frac{\Lambda_{UV}^8}{\Lambda_3^{12}}$$

$$\Lambda_{UV} < \left(H^3 m_{\mathrm{Pl}}\right)^{1/4}\left(\frac{16\pi^2}{c}\right)^{1/8} \sim \frac{1}{10^7\,\mathrm{km}}$$

Bellazzini, Lewandowski, Serra '19

Why raising M might be useful

1. No fifth force even if there is no screening $\qquad \alpha \lesssim 10^{-3}$

2. It explains why the speed of gravitational waves is the speed of light

$$\frac{(\partial\pi)^2(\partial^2\pi)^2}{M^6} \supset \alpha^6 \frac{(\partial\pi)^4(\partial h)^2}{\Lambda_3^6 M_{\rm Pl}^2} \qquad \alpha \lesssim 10^{-3}$$

3. Positivity bounds from scattering amplitudes suggest that the symmetry breaking operator $(\partial\pi)^4$ cannot be to small compared to the invariant ones

4. Extends the regime of validity at short length scales:
   20 solar masses black holes are within the EFT range
   (still above tabletop experiments but …)

Localized sources

$$(\partial\pi)^2$$

$$+\ \alpha^3 \frac{\pi T}{M_{\mathrm{Pl}}}$$

Localized sources

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \alpha^3 \frac{\pi T}{M_{\rm Pl}}$$

$$X_0(r) \equiv \frac{(\partial\pi)^2}{\Lambda_2^4}$$

$$Z_0(r) \equiv \frac{\partial^2\pi}{M^3}$$

Localized sources

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \alpha^3 \frac{\pi T}{M_{\rm Pl}}$$

$$X_0(r) \equiv \frac{(\partial\pi)^2}{\Lambda_2^4}$$

$$Z_0(r) \equiv \frac{\partial^2\pi}{M^3}$$

At scales where the scalar background is large there will be a contribution to the mixing

$$\Lambda_2^4 X_0^n Z_0^{m-1} \frac{\partial\pi\partial h}{M_{\rm Pl} M^3}$$

Using the scalar EOM

$$\Lambda_2^4 X_0^n Z_0^{m-2} \frac{1}{M^3 r^2} = \alpha^3 \frac{T}{M_{\rm Pl}}$$

Localized sources

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \alpha^3 \frac{\pi T}{M_{\rm Pl}}$$

$$X_0(r) \equiv \frac{(\partial\pi)^2}{\Lambda_2^4}$$

$$Z_0(r) \equiv \frac{\partial^2\pi}{M^3}$$

At scales where the scalar background is large there will be a contribution to the mixing

$$\Lambda_2^4 X_0^n Z_0^{m-1} \frac{\partial\pi\partial h}{M_{\rm Pl} M^3}$$

Using the scalar EOM

$$\Lambda_2^4 X_0^n Z_0^{m-2} \frac{1}{M^3 r^2} = \alpha^3 \frac{T}{M_{\rm Pl}}$$

$$\alpha^3 \frac{r_s}{r} \partial\pi\partial h$$

No need for a screening mechanism

No Hair Theorem

Hui, Nicolis '12

Scalar EOM $\nabla_\mu J^\mu = 0$

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + \rho^2(r)d\Omega^2$$

If the solution is static and spherical symmetric only $J^r \neq 0$

$J^\mu J_\mu = (J^r)^2/f$ should be regular at the horizon $\Longrightarrow$ $J^r = 0$ at the horizon

Using the conservation of the current $\Longrightarrow$ $J^r(r) = 0$

One last crucial step is need to conclude that a vanishing current implies a constant scalar

$$J^r = f \cdot \pi' \cdot F(\pi'; g, g', g'')$$

F is a polynomial

π' vanishes at infinity

F asymptotes to a constant at infinity

Then $\pi'(r) = 0$

Scalar coupled to Gauss-Bonnet

$$\Lambda\,\pi\mathcal{G} \qquad\qquad \mathcal{G} \equiv R^{\mu\nu\lambda\kappa}R_{\mu\nu\lambda\kappa} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$

The GB invariant is a total derivative: the coupling is shift invariant

Scalar coupled to Gauss-Bonnet

$$\Lambda\, \pi \mathcal{G} \qquad\qquad \mathcal{G} \equiv R^{\mu\nu\lambda\kappa} R_{\mu\nu\lambda\kappa} - 4 R^{\mu\nu} R_{\mu\nu} + R^2$$

The GB invariant is a total derivative: the coupling is shift invariant

$$J^r = f \cdot \pi' \cdot F(\pi'; g, g', g'') + \tilde{F}(g, g', g'')$$

$\pi'(r) = 0$ is no longer a solution

Sotiriou, Zhou '13

Every HD Lagrangian with the addition of the GB coupling will have non-trivial scalar bkgrd

Scalar coupled to Gauss-Bonnet

$\Lambda\, \pi \mathcal{G}$ $\qquad$ $\mathcal{G} \equiv R^{\mu\nu\lambda\kappa} R_{\mu\nu\lambda\kappa} - 4 R^{\mu\nu} R_{\mu\nu} + R^2$

The GB invariant is a total derivative: the coupling is shift invariant

$$J^r = f \cdot \pi' \cdot F(\pi'; g, g', g'') + \tilde{F}(g, g', g'')$$

$\pi'(r) = 0$ is no longer a solution

Sotiriou, Zhou '13

Every HD Lagrangian with the addition of the GB coupling will have non-trivial scalar bkgrd

What is Λ ? The GB coupling breaks explicitly the galileon symmetry

$\frac{\Lambda_2^8}{M^9} \pi \mathcal{G}$ is consistent with the power counting of the EFT

When R is linearized it can be rewritten as $\partial^2 \pi \partial h \partial h$

Hairy BH

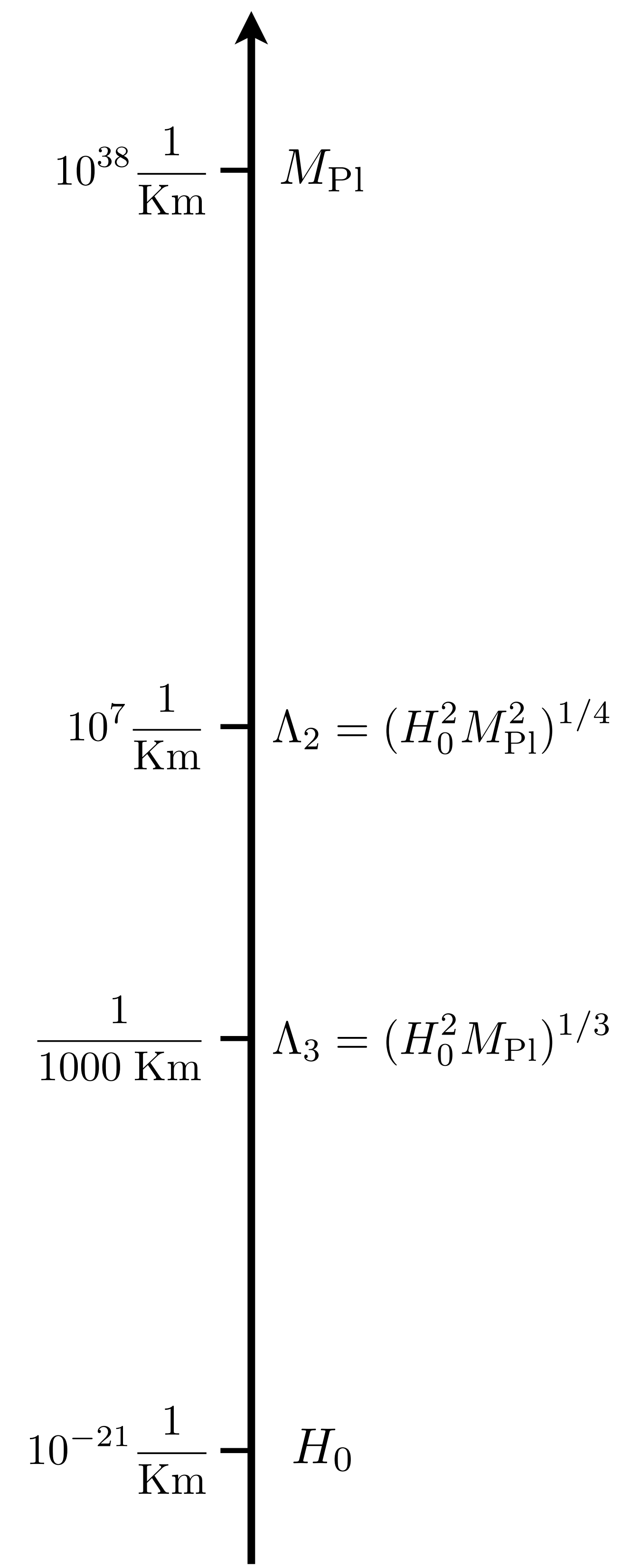
$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \frac{\Lambda_2^8}{M^9} \pi R^2$$

Hairy BH

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \frac{\Lambda_2^8}{M^9}\pi R^2$$

Can be probed in the BH ringdown?

There is a large kinetic mixing $\left(\frac{\Lambda_2}{M}\right)^9 \frac{R}{\Lambda_2 M_{\rm Pl}} \partial\pi\partial h$



Hairy BH

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \frac{\Lambda_2^8}{M^9}\pi R^2$$

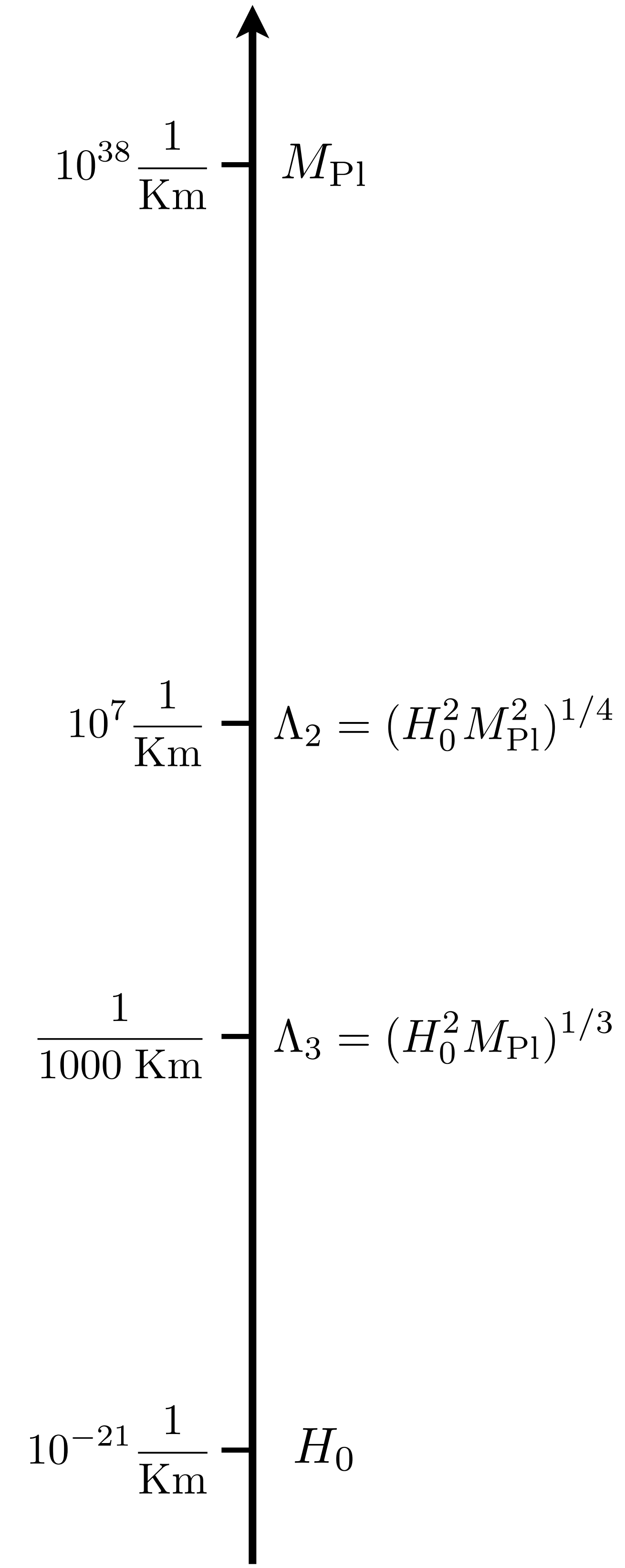
Can be probed in the BH ringdown?

There is a large kinetic mixing $\left(\frac{\Lambda_2}{M}\right)^9 \frac{R}{\Lambda_2 M_{\rm Pl}} \partial\pi\partial h$

It is not so simple…

$$K_\pi(\partial\pi)^2 + K_{\rm mix}\partial\pi\partial h$$

$$\frac{K_{\rm mix}}{K_\pi^{1/2}}(r = r_s) \sim \alpha^3 Z_0^{1/2}$$



Hairy BH

$$(\partial\pi)^2 + \Lambda_2^4 \frac{(\partial\pi)^{2n}}{\Lambda_2^{4n}} \frac{(\partial\partial\pi)^m}{M^{3m}} + \frac{\Lambda_2^8}{M^9}\pi R^2$$

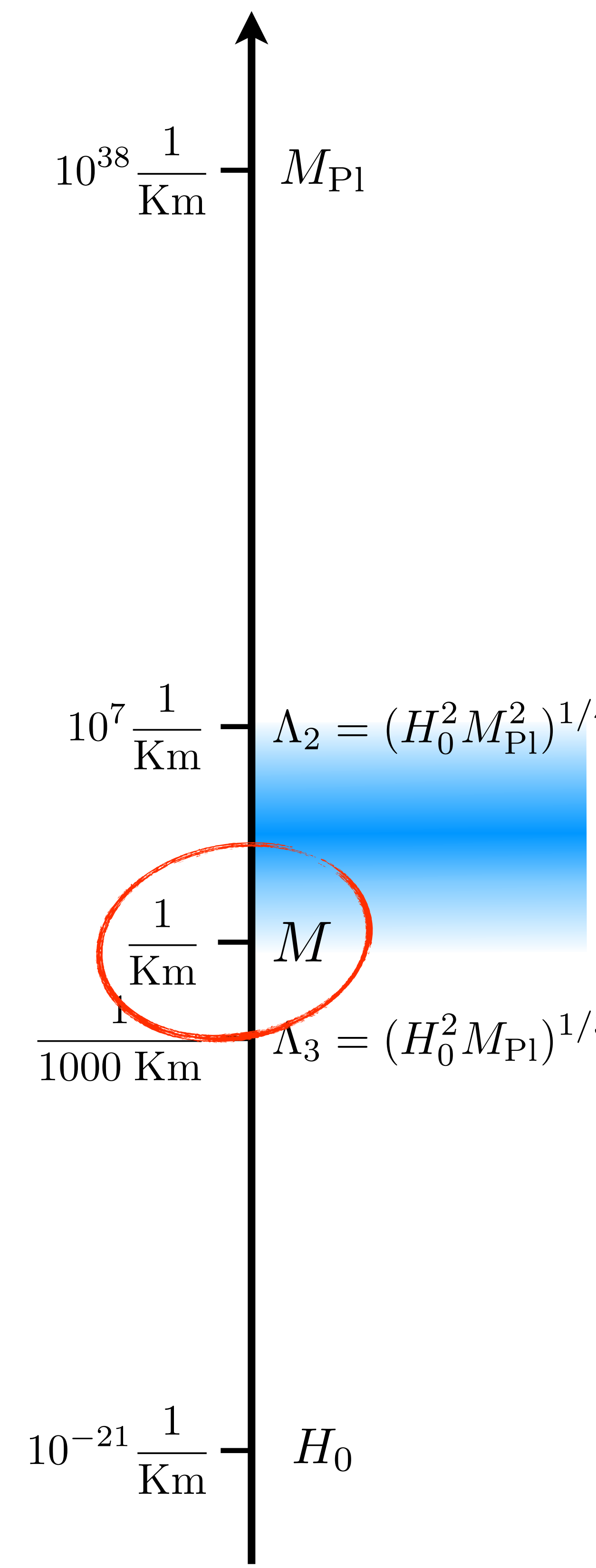
Can be probed in the BH ringdown?

There is a large kinetic mixing $\left(\frac{\Lambda_2}{M}\right)^9 \frac{R}{\Lambda_2 M_{\rm Pl}} \partial\pi\partial h$

It is not so simple…

$$K_\pi(\partial\pi)^2 + K_{\rm mix}\partial\pi\partial h$$

$$\frac{K_{\rm mix}}{K_\pi^{1/2}}(r = r_s) \sim \alpha^3 Z_0^{1/2} \qquad Z_0 \sim \left(\frac{\Lambda_2^2}{M^3 r_s}\right)^{\frac{2n+2}{2n+m-1}}$$



Gauss-Bonnet hair can give sizable deviation in the quadratic action during the ringdown only if M close to border of the allowed region

Subluminality problem

The cutoff can be lower around non-linear backgrounds

$$\frac{(\partial\pi)^2(\partial\partial\pi)^2}{\Lambda_3^6}$$

Around a point-like source $\quad Z_0^2(\partial_{||}\pi)^2 + (\partial_\perp\pi)^2$

The energy cutoff is significantly lowered due to the scattering
of the slow moving modes along the transverse directions

This is not true anymore in the BH background: there is no cancellation

$$Z_0^2\Big((\partial_{||}\pi)^2 + (\partial_\perp\pi)^2\Big)$$

Conclusions

Conclusions

Leave no stone unturned?

Conclusions

Leave no stone unturned?

A “decoupled” DE sector is still a possibility

Not easy to detect it. Maybe it leaves an imprint during BH ringdown

Not much is know about BH with non-trivial scalar backgrounds

Several ways to avoid the ho-hair theorems (non-trivial boundary conditions, time-dependent solutions, breaking of the shift symmetry, HD interactions,…)

Useful to use an EFT framework to describe QNMs of hairy black hole

Several important missing step: how to connect to the inspiral phase, generalize to Kerr,…