Testing the Speed of Gravity with Black Hole Ringdown

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TESTING GRAVITY

- SO WHY SHOULD WE TEST GR?
  - DARK ENERGY
  - SINGULARITIES
  - NOT QUANTIZABLE
  - ...
  - WHY NOT?

TESTING GRAVITY

4D
$g_{\mu\nu}$
LOCAL
2nd order EOM

GR $\rightarrow$ $S = \int d^4x \sqrt{-g}\, R[g_{\mu\nu}]$

(LOVELOCK'S THEOREM)

TESTING GRAVITY

(LOVELOCK'S THEOREM)

4D

$g_{\mu\nu}$

LOCAL

2nd order EOM

GR $\rightarrow$ $S = \int d^4x \sqrt{-g}\, R[g_{\mu\nu}]$

4D

$g_{\mu\nu} + \phi$

LOCAL

2nd order EOM

HORNDESKI $\rightarrow$ $S = \int d^4x \sqrt{-g}\, H[g_{\mu\nu}, \phi]$

TESTING GRAVITY

$$S = \int d^4x \sqrt{-g} \left(\mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 \right)$$

HORNDESKI GRAVITY

$$\mathcal{L}_2 = G_2(\phi, X)$$

$$\mathcal{L}_3 = G_3(\phi, X)\,\Box\phi$$

$$\mathcal{L}_4 = G_4(\phi, X) R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{\mu\nu})^2 \right]$$

$$\mathcal{L}_5 = G_5(\phi, X) G_{\mu\nu}\phi^{\mu\nu} - \frac{1}{6} G_{5X}(\phi, X)\left[(\Box\phi)^3 - 3(\phi_{\mu\nu})^2 \Box\phi + 2(\phi_{\mu\nu})^3 \right]$$

WHERE $X = -\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$, $\phi_\mu := \nabla_\mu\phi$, $\phi_{\mu\nu} := \nabla_\nu\nabla_\mu\phi$, ...

$G_{4X} := \partial_X G_4$

$(\phi_{\mu\nu})^2 := \phi_{\mu\nu}\phi^{\mu\nu}$

$(\phi_{\mu\nu})^3 := \phi_{\mu\nu}\phi^{\mu\sigma}\phi_\sigma{}^\nu$

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TESTING GRAVITY

THEORY

$S = \int d^4x \sqrt{-g}\, R$

$S = \int d^4x \sqrt{-g}\, \mathbf{H}$

OBSERVABLE

$\alpha = 0$

$\alpha \neq 0$

"SMOKING GUN SIGNAL"

GRAVITATIONAL WAVES

GR

$$S = \int d^4x \sqrt{-g}\, R \longrightarrow G_{\mu\nu} = T_{\mu\nu} \xrightarrow[\text{WEAK FIELD}]{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}} \Box h_{\mu\nu} = T_{\mu\nu}$$

GRAVITATIONAL WAVES

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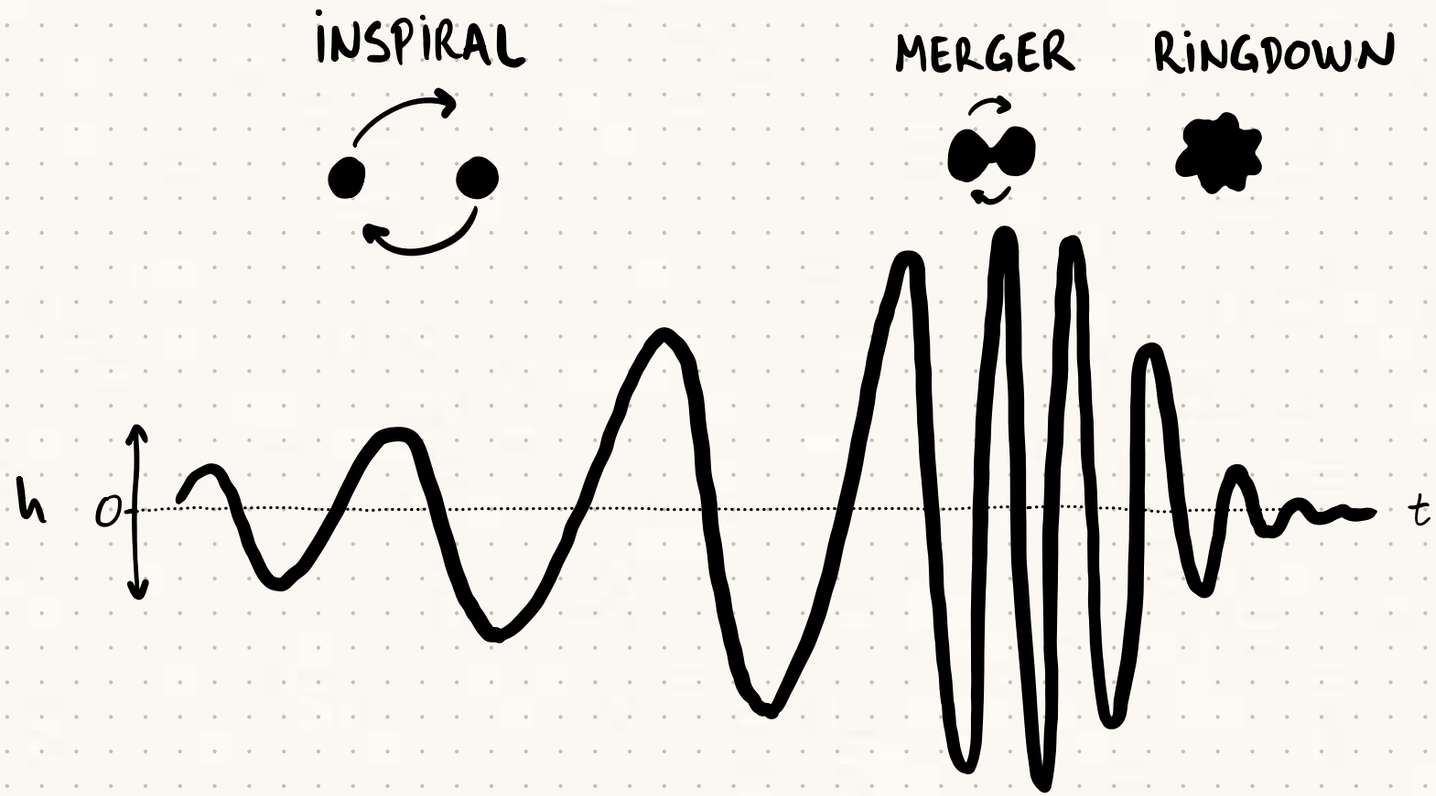
ASTROPHYSICAL SOURCES: MERGERS (BLACK HOLES / NEUTRON STARS)



GRAVITATIONAL WAVES

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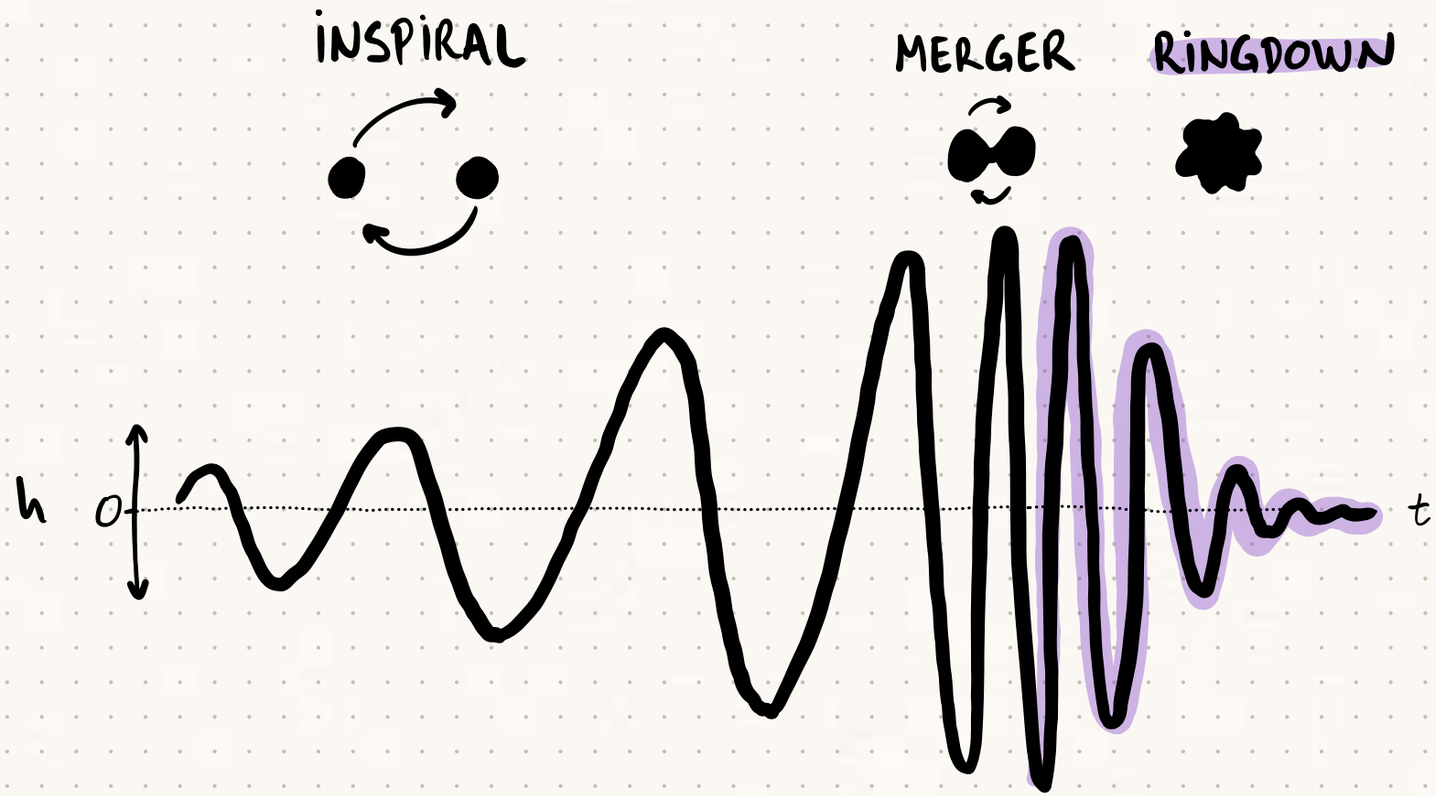
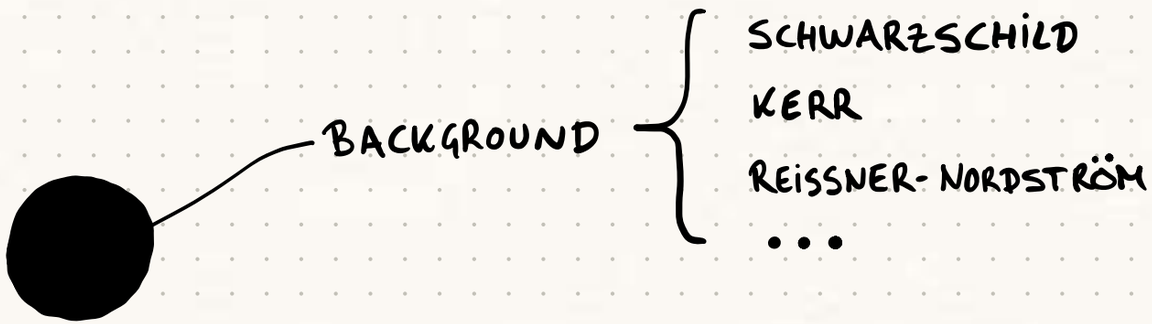


GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

$$g_{\mu\nu} = \bar{g}_{\mu\nu}$$



GRAVITATIONAL WAVES

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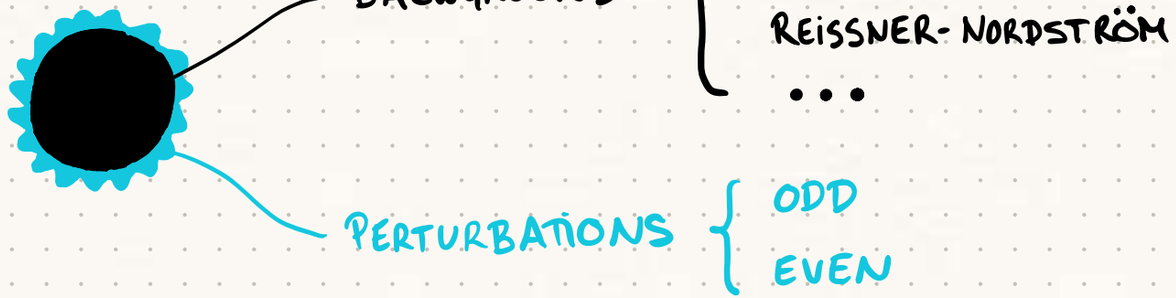

GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

$$\downarrow$$

$$G_{\mu\nu} = 0$$

$$\downarrow$$

$$\frac{d^2 h}{dr_*^2} + \left[\omega^2 - V\right] h = 0$$

BACKGROUND { SCHWARZSCHILD, KERR, REISSNER-NORDSTRÖM, ... }

PERTURBATIONS { ODD, EVEN }

GRAVITATIONAL WAVES

GR

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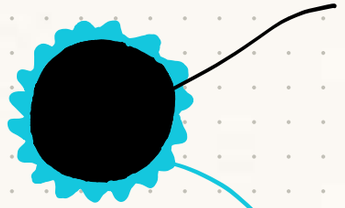


BACKGROUND { SCHWARZSCHILD, KERR, REISSNER-NORDSTRÖM, ... }

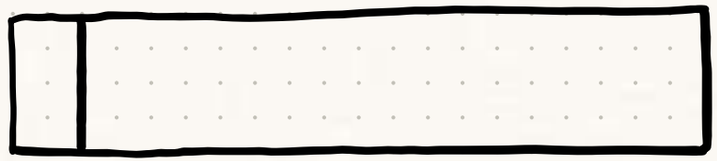
PERTURBATIONS { ODD, EVEN }

QUASINORMAL MODES : $\omega(M, a)$ (NO HAIR THEOREM)

GRAVITATIONAL WAVES

BLACK HOLE SPECTROSCOPY

$\omega(M,a)$ • 1st QNM sets M



GRAVITATIONAL WAVES

BLACK HOLE SPECTROSCOPY

$\omega(M,a)$

- 1st QNM sets M

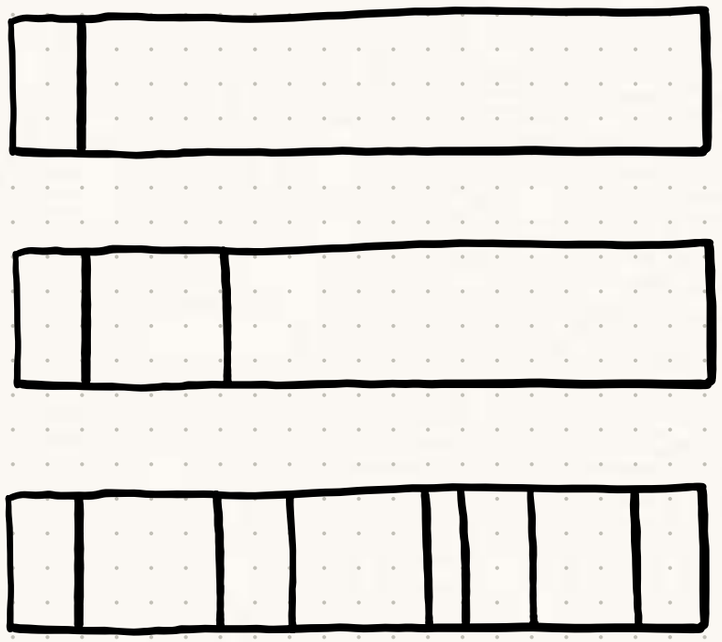
- 2nd QNM sets a

GRAVITATIONAL WAVES

BLACK HOLE SPECTROSCOPY

$\omega(M,a)$

- 1st QNM sets M
- 2nd QNM sets a
- All other QNMs are fixed in GR



GRAVITATIONAL WAVES

BLACK HOLE SPECTROSCOPY

$\omega(M,a)$

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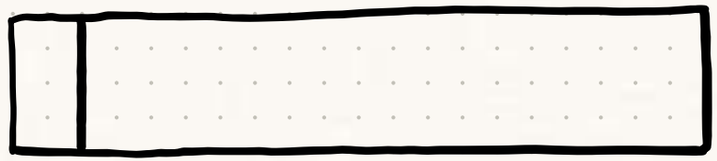
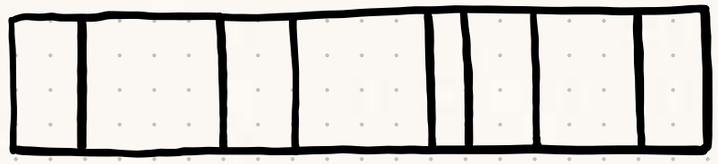
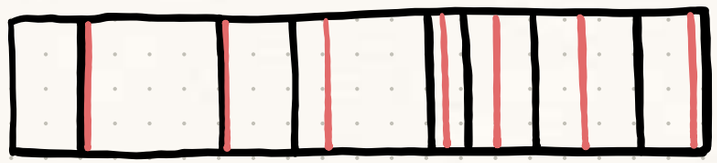


- 2nd QNM sets a

- All other QNMs are fixed in GR



⇒ MEASURING QNMs PROVIDES CLEAN TESTS OF BACKGROUND GEOMETRY AND UNDERLYING THEORY



GR $\omega(M,a)$

MG $\omega(M,a,\alpha)$

TESTING GRAVITY WITH GRAVITATIONAL WAVES

GR

$$S = \int d^4x \sqrt{-g}\, R(g_{\mu\nu})$$

$$\downarrow$$

$$\frac{d^2h}{dr_*^2} + \left[\omega^2 + V\right]h = 0$$

$$\downarrow$$

$$\omega(M, a)$$

$$\alpha_T = 0$$

HORNDESKI

$$S = \int d^4x \sqrt{-g}\, H(g_{\mu\nu}, \Phi)$$

$$\downarrow$$

$$\frac{d^2h}{dr_*^2} + \left[\omega^2(1+\alpha_T) + V + \alpha_T \delta V\right]h = 0$$

$$\downarrow$$

$$\omega(M, a, \alpha_T)$$

$$\alpha_T = \frac{c_{GW} - c}{c} \neq 0$$

GRAVITATIONAL WAVE SPEED EXCESS

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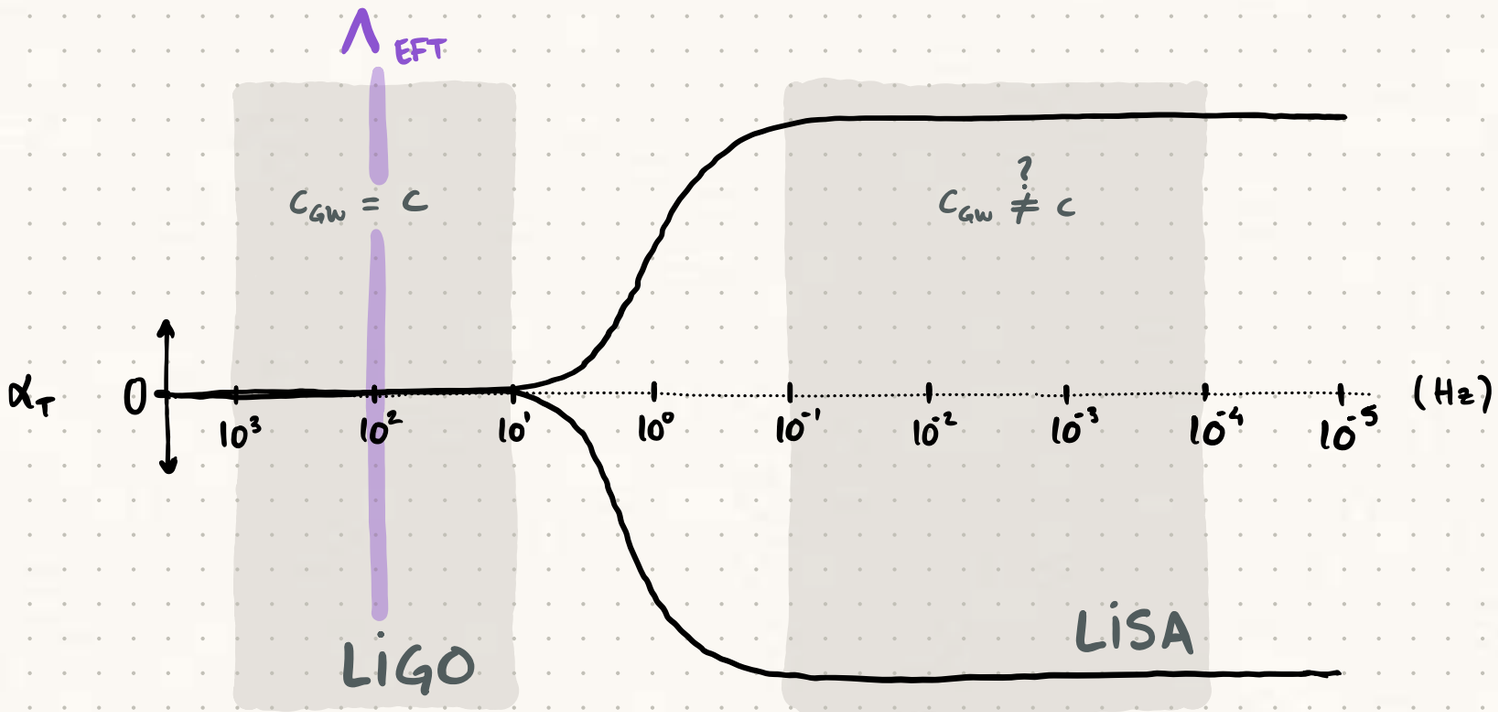
TESTING GRAVITY WITH GRAVITATIONAL WAVES

WHAT DO WE KNOW ABOUT α_T?

- LIGO : $\alpha_T \lesssim 10^{-15}$ (GW170817)
- DARK ENERGY EFTs : CUTOFF AT $\sim 10^2$ Hz



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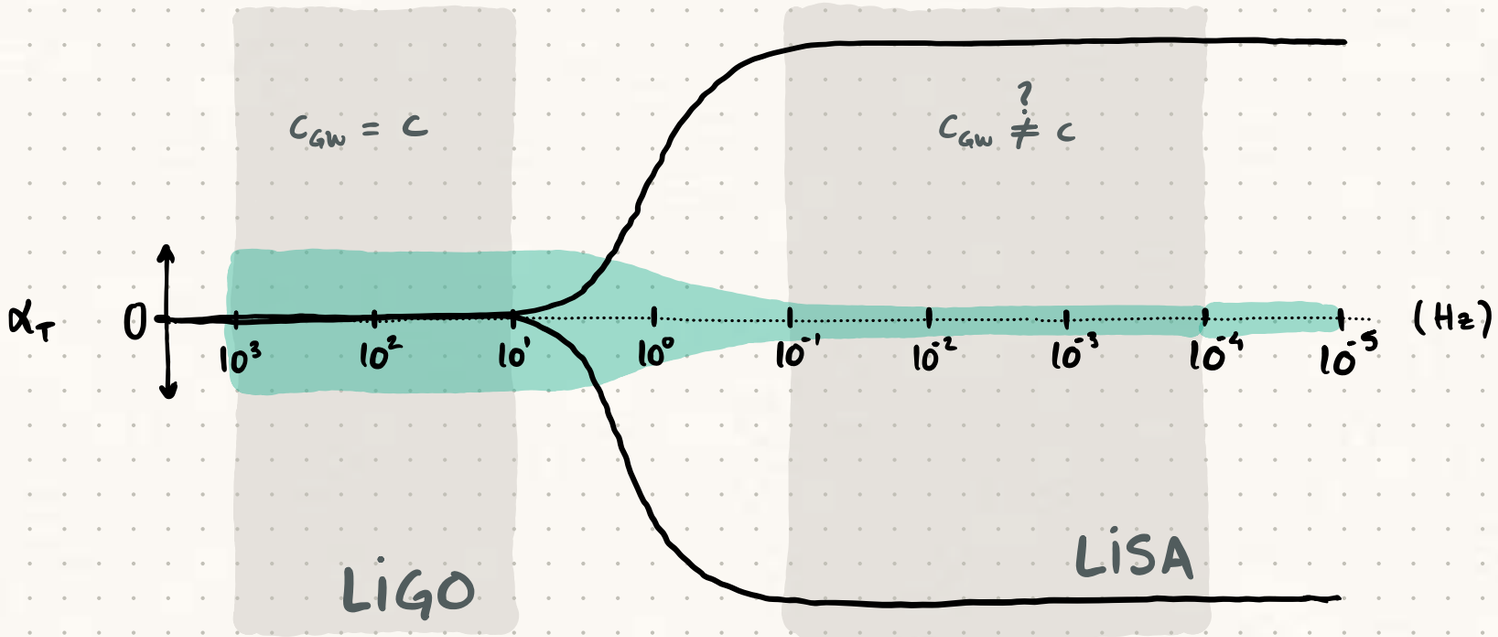

FISCHER FORECASTS:

FOR 1 LOUD MERGER:

- LISA : $\alpha_T \lesssim 10^{-4}$
- LIGO/ET $\alpha_T \lesssim 10^{-1}$

[2301.10272]

└ SSL, JOHANNES NOLLER

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TESTING GRAVITY WITH GRAVITATIONAL WAVES

[2301.10272] SSL, JOHANNES NOLLER

BACKGROUND:

$$\bar{g}_{\mu\nu} = -f\,dt^2 + f^{-1}dr^2 + r^2 d\Omega_2^2, \qquad f = 1 - \frac{2M}{r}$$

$$\bar{\phi} = \hat{\phi} + \varepsilon\,\delta\phi(r), \qquad \delta\phi = \varphi_c \frac{2M}{r}$$

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THEORY:

HORNDESKI WITH $G_{4\phi} = 0$

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MODIFIED REGGE-WHEELER EQUATION

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$$\alpha_T = -f(2M)^2 G_T\,\delta\phi'^2 \qquad G_T = \frac{G_{4X} - G_{5\phi}}{G_4}$$

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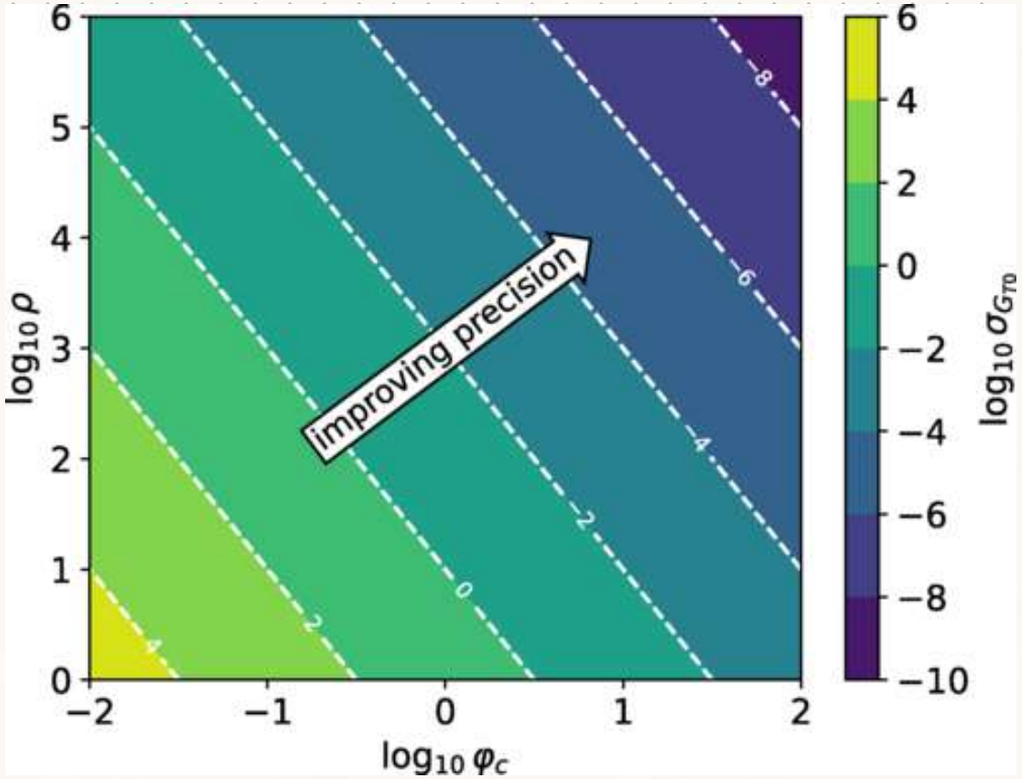

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ONGOING WORK

- RINGDOWN OF BHs IN EXPANDING UNIVERSE WITH TIMELIKE SCALAR
  - WITH JOHANNES NOLLER
- IMPLEMENT SOME MODIFIED GRAVITY PARAMETERS IN LIGO ANALYSIS PIPELINE (PYRING)
  - WITH JOHANNES NOLLER, GREGORIO CARULLO & GIADA CANEVA SANTORO
- REVIEW ON GRAVITATIONAL WAVE PROBES OF DARK ENERGY
  - WITH MACARENA LAGOS

THANKS!