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

(LOVELOCK'S THEOREM)

$$\left.\begin{array}{c} 4D \\ g_{\mu\nu} \\ \text{LOCAL} \\ 2^{\text{nd}}\text{ order EOM} \end{array}\right\} \quad \text{GR} \quad \rightarrow \quad S = \int d^4x \sqrt{-g}\, R[g_{\mu\nu}]$$

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$$\left.\begin{array}{c} \text{4D} \\ g_{\mu\nu} + \phi \\ \text{LOCAL} \\ 2^{\text{nd}}\text{order EOM} \end{array}\right\} \quad \text{HORNDESKI} \quad \rightarrow \quad S = \int d^4x \sqrt{-g}\; H[g_{\mu\nu}, \phi]$$

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

$G_{4X} := \partial_X G_4$ $\qquad$ $(\phi_{\mu\nu})^2 := \phi_{\mu\nu}\phi^{\mu\nu}$

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

TESTING GRAVITY

THEORY	$S = \int d^4x \sqrt{-g}\, R$	$S = \int d^4x \sqrt{-g}\, H$	
$\downarrow$	$\downarrow$	$\downarrow$	
OBSERVABLE	$\alpha = 0$	$\alpha \neq 0$	$\longrightarrow$ "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

$\boxed{\text{GR}}$

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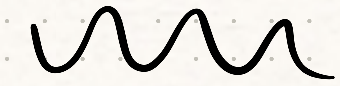
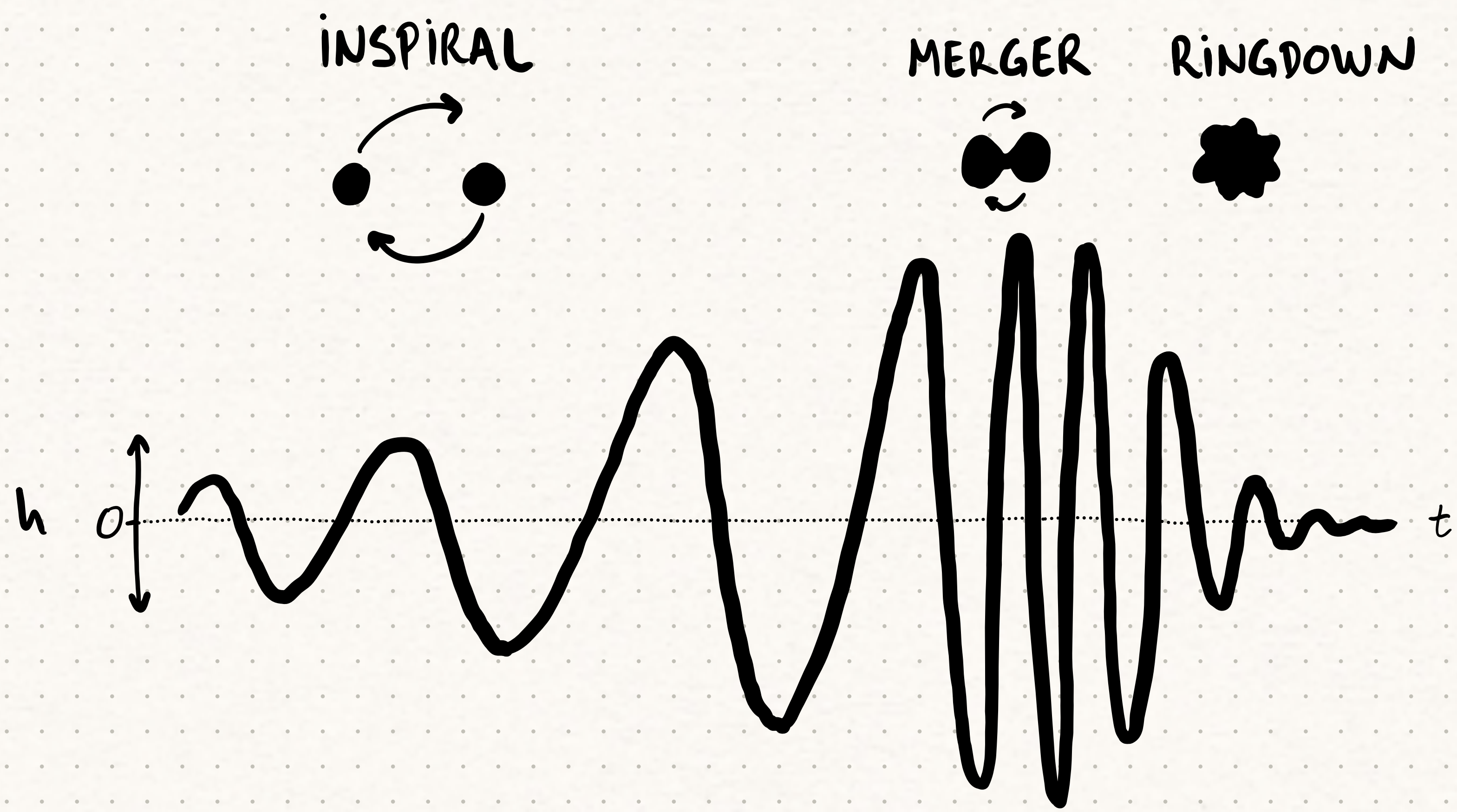


ASTROPHYSICAL SOURCES: MERGERS (BLACK HOLES / NEUTRON STARS)



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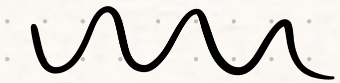

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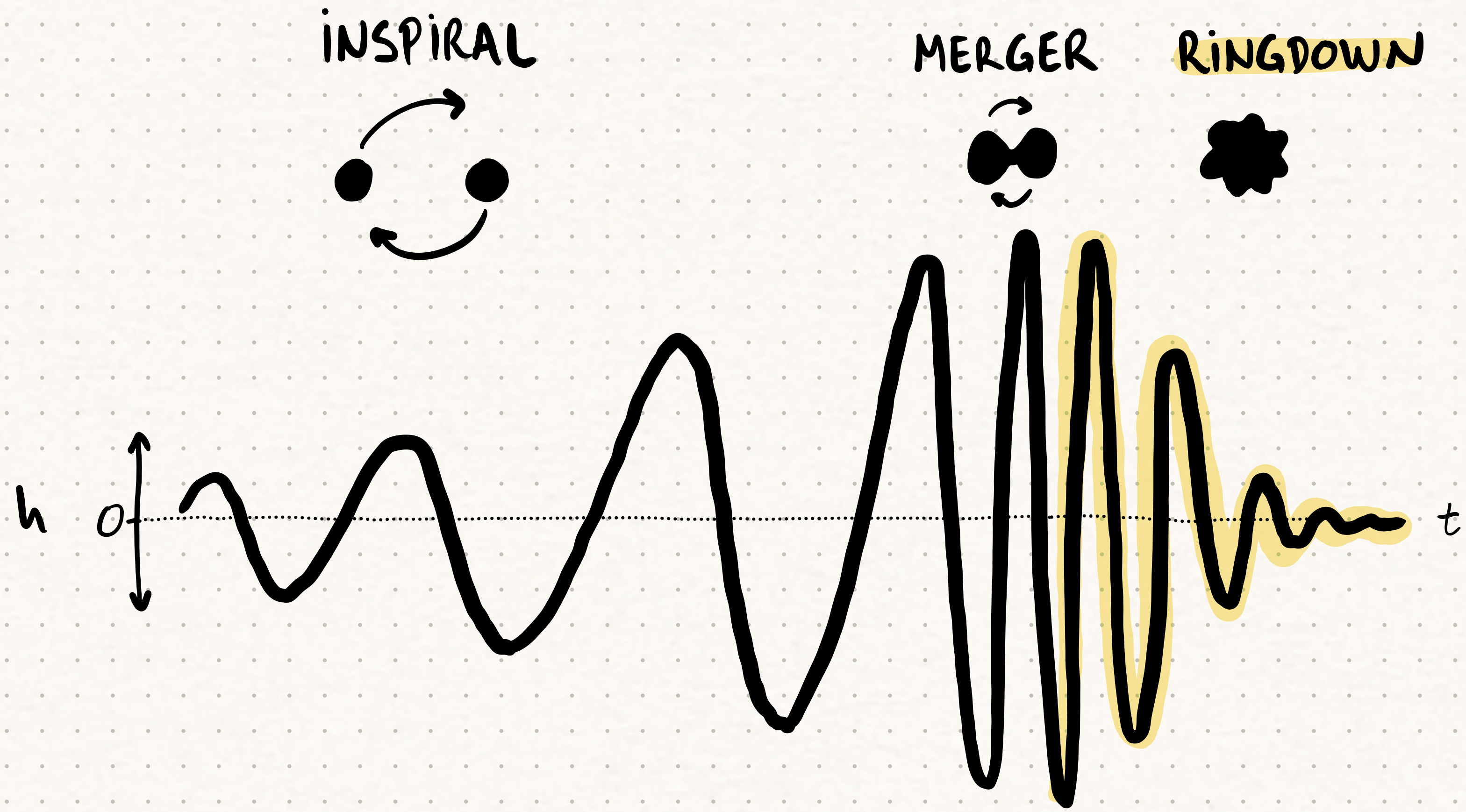
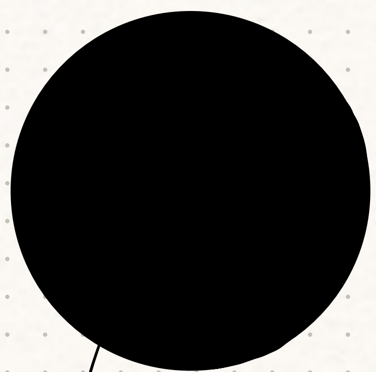


GRAVITATIONAL WAVES

$\boxed{\text{GR}}$ RINGDOWN : BLACK HOLE PERTURBATION THEORY



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

BACKGROUND

- SCHWARZSCHILD
- KERR
- REISSNER-NORDSTRÖM
- ...

GRAVITATIONAL WAVES

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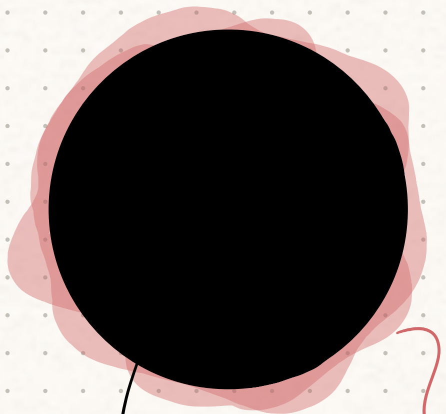

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

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PERTURBATIONS

ODD

EVEN

GRAVITATIONAL WAVES

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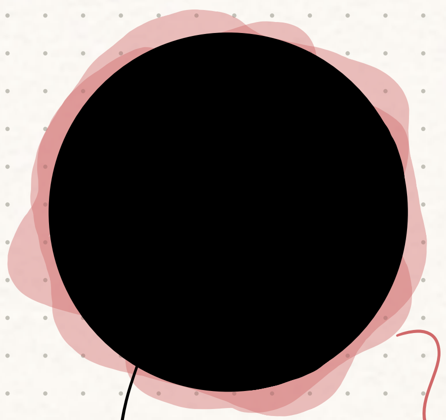

$$G_{\mu\nu} = 0$$

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

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

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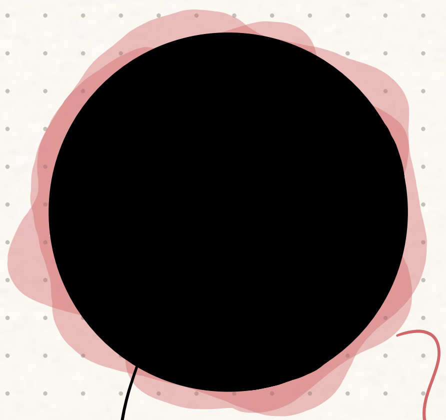

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$$G_{\mu\nu} = 0$$

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

$$\omega(M, a)$$

QUASINORMAL MODES

(NO HAIR THEOREM)

BACKGROUND

- SCHWARZSCHILD
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PERTURBATIONS

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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

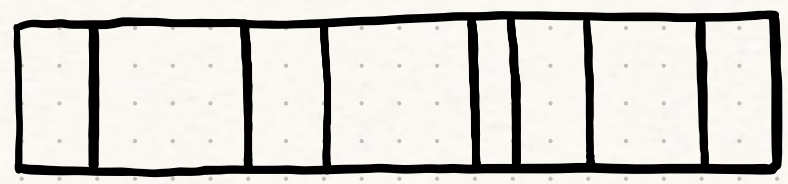
BLACK HOLE SPECTROSCOPY

$\omega(M, a)$

- 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

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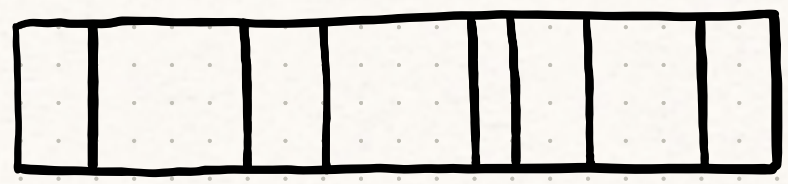
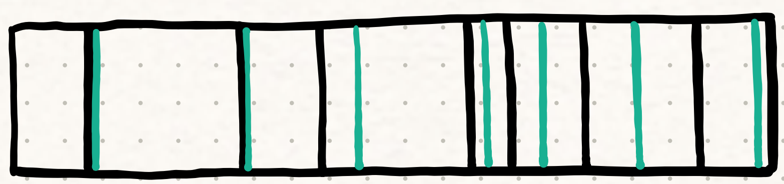


MEASURING QNMs PROVIDES CLEAN TESTS OF BACKGROUND GEOMETRY AND UNDERLYING THEORY



GR $\omega(M,a)$

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

Speed of Gravity

GR

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

$$\downarrow$$

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

$$\downarrow$$

$$w(M, a)$$

$$\alpha_T = 0$$

Horndeski

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

$$\downarrow$$

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

$$\downarrow$$

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

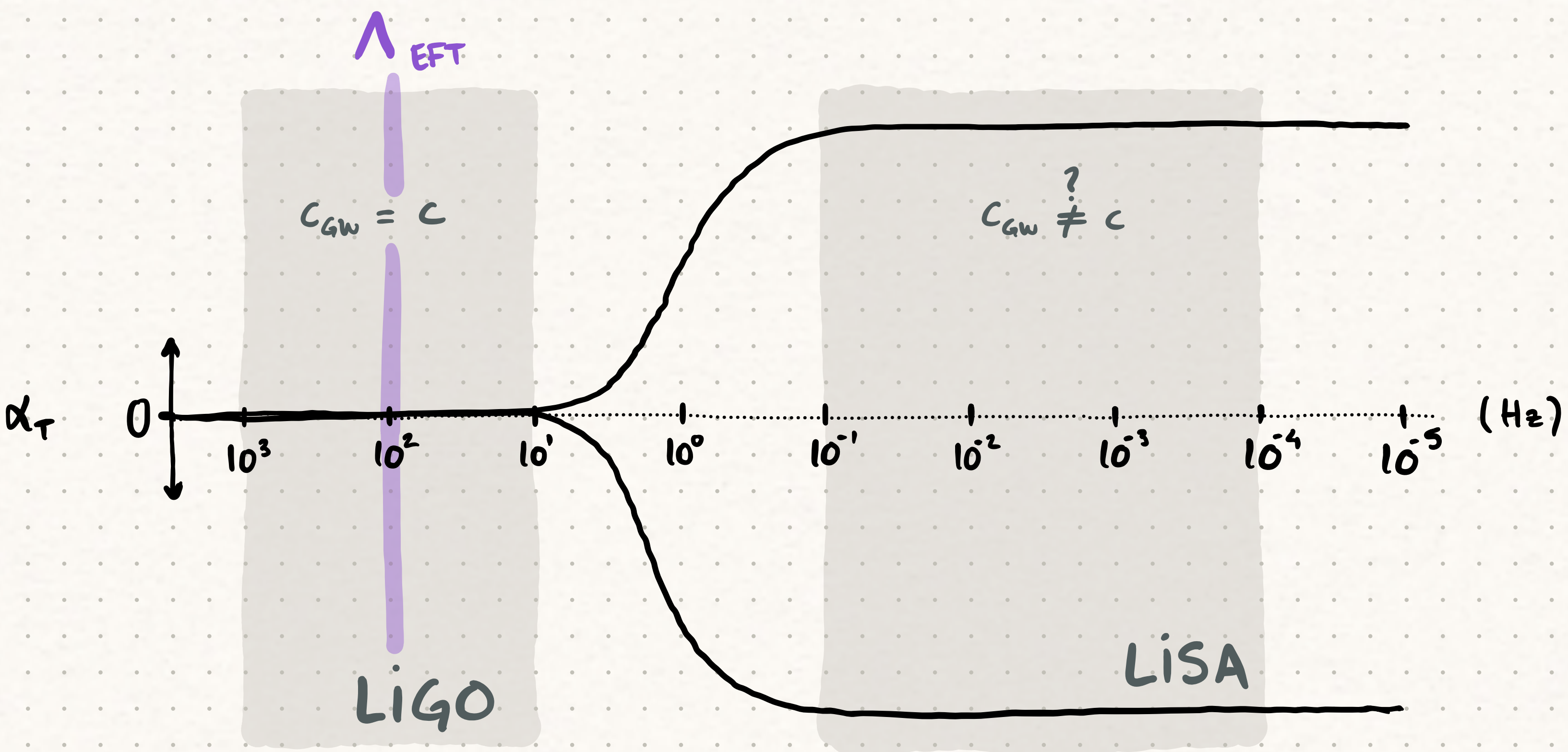
$$\alpha_T = \frac{c_{GW} - c}{c} \neq 0$$

Gravitational wave speed excess

SPEED OF GRAVITY

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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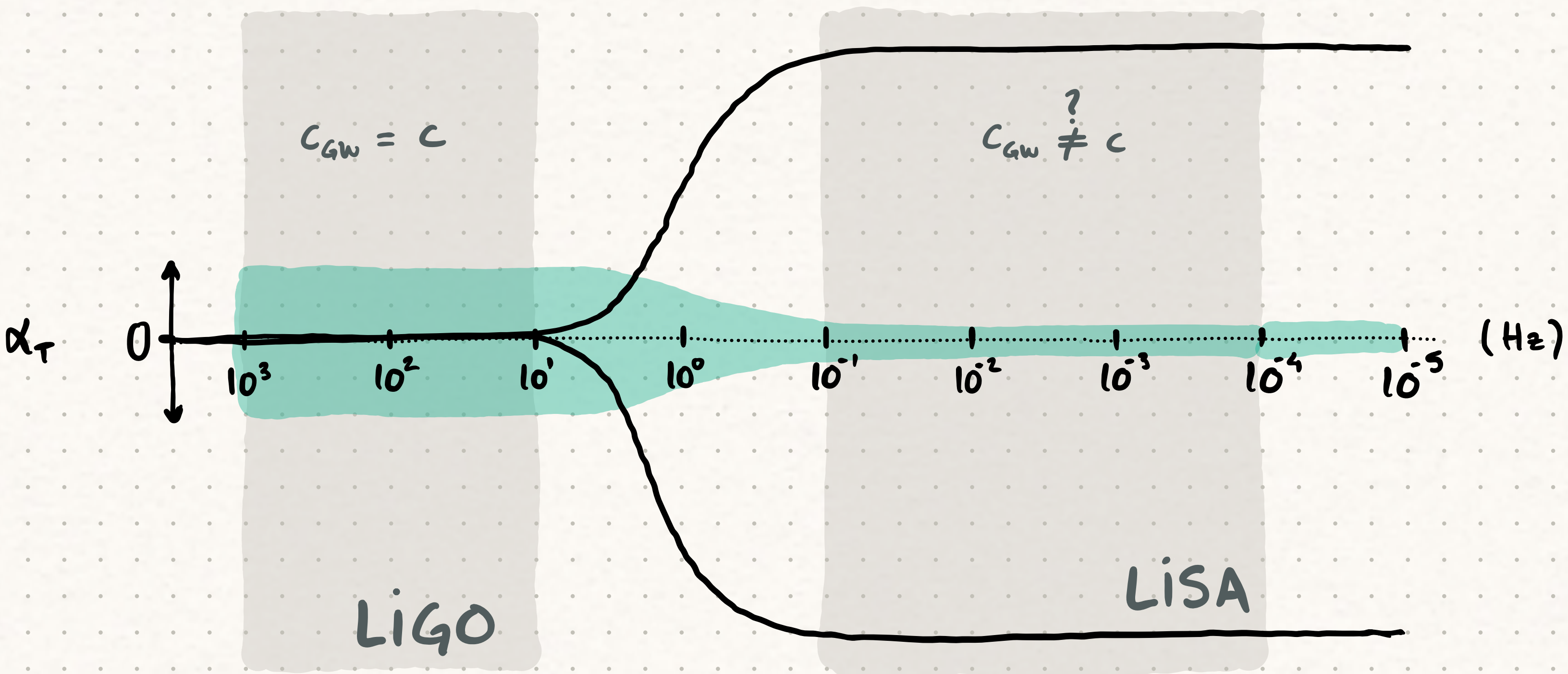

FISCHER FORECASTS :

FOR 1 LOUD MERGER :

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

[2301.10272]

└ SS, JOHANNES NOLLER

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SPEED OF GRAVITY

[2301.10272] SS, JOHANNES NOLLER

BACKGROUND:

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

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

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

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MODIFIED REGGE - WHEELER EQUATION

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

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

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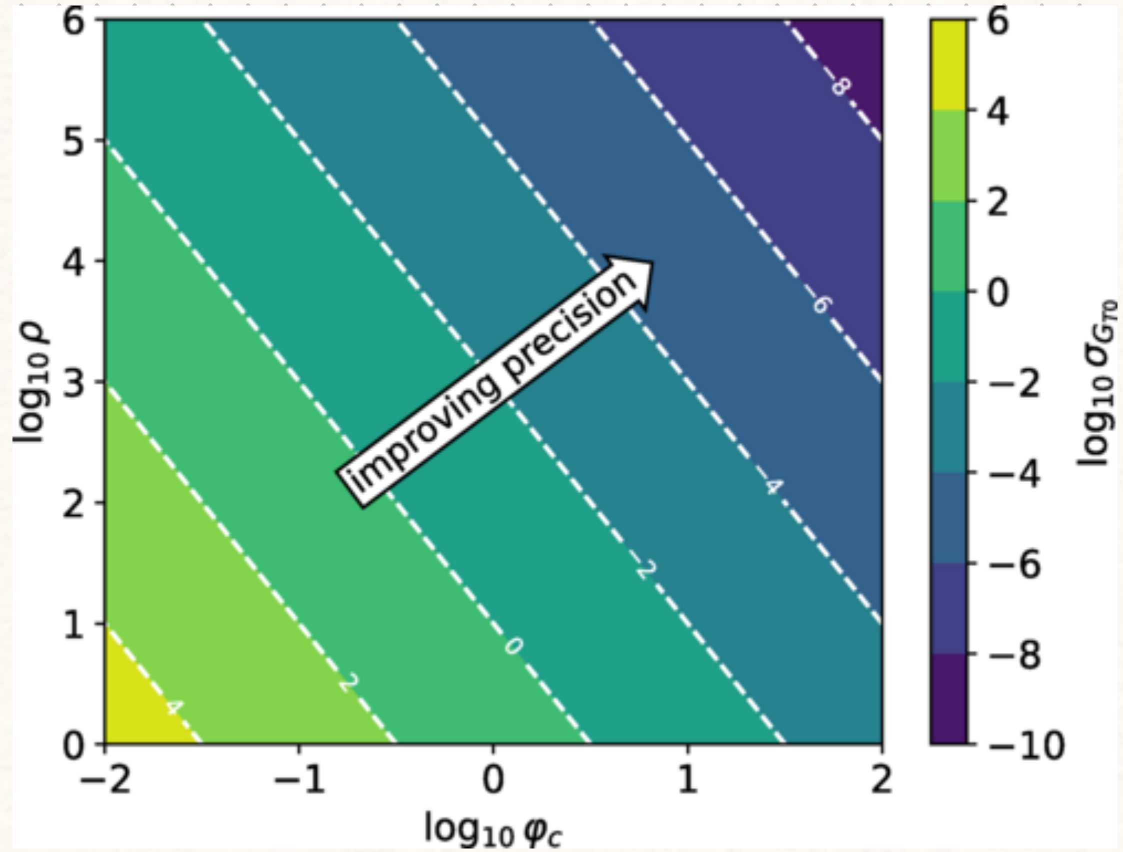

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SUMMARY

- QNMs CAN BE USED TO TEST NEW GRAVITATIONAL PHYSICS
- SPEED OF GWs $\neq$ SPEED OF LIGHT IN SOME HORNDESKI THEORIES
- QNMs ARE α_T-DEPENDENT IF $\exists$ SCALAR HAIR
- LISA CAN CONSTRAIN $|\alpha_T| \lesssim 10^{-4}$ WITH RINGDOWN OF ONE SMBH MERGER

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 & WALTER DEL POZZO

THANKS!

@sergisirera

Backup Slides

BLACK HOLE PERTURBATIONS IN REGGE-WHEELER GAUGE

$$h_{\mu\nu} = h_{\mu\nu}^{\text{odd}} + h_{\mu\nu}^{\text{even}}$$

$$h_{\mu\nu}^{\text{odd}} = \begin{pmatrix} 0 & 0 & -h_0 \frac{1}{\sin\theta}\partial_\phi Y_{\ell m} & h_0 \sin\theta\, \partial_\theta Y_{\ell m} \\ 0 & 0 & -h_1 \frac{1}{\sin\theta}\partial_\phi Y_{\ell m} & h_1 \sin\theta\, \partial_\theta Y_{\ell m} \\ -h_0 \frac{1}{\sin\theta}\partial_\phi Y_{\ell m} & -h_1 \frac{1}{\sin\theta}\partial_\phi Y_{\ell m} & 0 & 0 \\ h_0 \sin\theta\, \partial_\theta Y_{\ell m} & h_1 \sin\theta\, \partial_\theta Y_{\ell m} & 0 & 0 \end{pmatrix}$$

$$h_{\mu\nu}^{\text{even}} = \begin{pmatrix} f H_0 & H_1 & 0 & 0 \\ H_1 & \frac{1}{f} H_2 & 0 & 0 \\ 0 & 0 & r^2 K & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta\, K \end{pmatrix} Y_{\ell m}$$

QUADRATIC ACTION IN GR

$$S^{(2)} = \frac{1}{4}\int \sqrt{-g}\, d^4x \Big[-h_{\mu\nu}h^{\mu\nu} + \nabla_\sigma h \nabla^\sigma h - \nabla_\mu h_{\nu\sigma}\nabla^\mu h^{\nu\sigma} + 2\nabla_\mu h^{\mu\nu}\nabla_\sigma h_\nu{}^\sigma - 2\nabla^\mu h \nabla_\nu h_\mu{}^\nu$$

$$+ 2\left(h_\sigma{}^\nu h^{\sigma\mu} - h h^{\mu\nu}\right) R_{\mu\nu} - \left(h_{\mu\nu}h^{\mu\nu} - \frac{1}{2}h^2\right) R \quad + \quad 2 h^{\mu\nu} h^{\sigma\lambda} R_{\mu\sigma\nu\lambda} \Big]$$

QUADRATIC ACTION HORNDESKI ODD SECTOR IN COMPONENTS

$$S^{(2)} = \int dt\,dr \left[a_1 h_0^2 + a_2 h_1^2 + a_3\left(\dot{h}_1^2 + h_0'^2 - 2h_0'\dot{h}_1 + \frac{4}{r}\dot{h}_1 h_0\right)\right]$$

$$a_1 = \frac{\ell(\ell+1)}{2r^2}\left[(r\mathcal{H})' + \frac{(\ell-1)(\ell+2)\mathcal{F}}{2B} + \frac{r^2}{B}\mathcal{E}_A\right]$$

$$a_2 = -\frac{\ell(\ell+1)}{2}B\left[\frac{(\ell-1)(\ell+2)\mathcal{G}}{2r^2} + \mathcal{E}_B\right]$$

$$a_3 = \frac{\ell(\ell+1)}{4}\mathcal{H}$$

$$\mathcal{F} = 2\left(G_4 + \frac{1}{2}B\phi' X' G_{5X} - X G_{5\phi}\right)$$

$$\mathcal{G} = 2\left[G_4 - 2XG_{4X} + X\left(\frac{B'}{2}\phi' G_{5X} + G_{5\phi}\right)\right]$$

$$\mathcal{H} = 2\left[G_4 - 2XG_{4X} + X\left(\frac{B}{r}\phi' G_{5X} + G_{5\phi}\right)\right]$$

$$S^{(2)} = \frac{\ell(\ell+1)}{4(\ell-1)(\ell+2)}\int dt\,dr_* \left[\frac{\mathcal{F}}{\mathcal{G}}\dot{Q}^2 - \left(\frac{dQ}{dr_*}\right)^2 - V(r)Q^2\right]$$

$$h_0 = -\frac{(r^2 a_3 q)'}{r^2 a_1 - 2(r a_3)'}$$

$$h_1 = \frac{a_3}{a_2}\dot{q}$$

$$q = \frac{\sqrt{\mathcal{F}}}{r\mathcal{H}}Q$$

EXISTING & UPCOMING α_T CONSTRAINTS

$\lvert\alpha_T\rvert \lesssim 10^{0}$	$f \sim 10^{-18} - 10^{-14}$ Hz	CMB & LSS
$\lvert\alpha_T\rvert \lesssim 10^{-2}$	$f \sim 10^{-5}$ Hz	HULSE - TAYLOR BINARY [1507.05047] BELTRAN JIMENEZ ET. AL.
$\lvert\alpha_T\rvert \lesssim 10^{-12}$	$f \sim 10^{-1} - 10^{-4}$ Hz	ECLIPSING WHITE-DWARF BINARY [1908.00678] LITTENBERG ET. AL.
$\lvert\alpha_T\rvert \lesssim 10^{-4}$	$f \sim 10^{-1} - 10^{-4}$ Hz	REDSHIFT-INDUCED f-DEPENDENCE [2203.00566] BAKER ET. AL.
$\lvert\alpha_T\rvert \lesssim 10^{-17}$	$f \sim 10^{-1} - 10^{-4}$ Hz	f-DEPENDENT WAVEFORMS [2207.10096] HARRY AND NOLLER
$\lvert\alpha_T\rvert \lesssim 10^{-15}$	$f \sim 10^{3} - 10^{-4}$ Hz	MULTIBAND [2209.14398] BAKER ET. AL. [1602.06951] SESANA [2207.10096] HARRY AND NOLLER
$\lvert\alpha_T\rvert \lesssim 10^{-15}$	$f \sim 10^{2}$ Hz	GW170817