Theory-agnostic searches for non-gravitational modes in black hole ringdown

Based on
F. Crescimbeni, X. Jimenez Forteza, S. Bhagwat, J. Westerweck, PP
arXiv:**2408.08956**

Paolo Pani

Sapienza University of Rome & INFN Roma1
https://web.uniroma1.it/gmunu

INFN Istituto Nazionale di Fisica Nucleare
TeonGrav

BH spectroscopy (in a nutshell)

See Sberna's talk

- Post-merger signal → superposition of quasinormal modes (QNMs)

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

$$h(t) = F_+ h_+(t) + F_\times h_\times(t) \sim \sum_{i=(\ell,m,n)} A_i \sin(2\pi f_i t + \phi_i) e^{-t/\tau_i}$$

- Beyond GR: Shift of QNMs (bkg geometry + dynamics + boundary conditions):

$$\omega_{lmn} = \omega_{lmn}^{\rm Kerr}(M,\chi) + \delta\omega_{lmn}(M,\chi,\ell_{\rm new})$$

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LVK:

- Dominant QNM measured in some events [LVK, 2112.06861]
- Debates on secondary QNM in GW150914/GW190521 [Isi+, Cotesta+, Capuano+, ...]

ET/LISA:

- O(1-100) events/yr allowing for BH spectroscopy at 1-10% level for 3+ QNM quantities [Bhagwat+ PRD 2022, Bhagwat+ PRD 2023]

BH spectroscopy

- QNMs in GR depend only on mass and spin $\rightarrow$ Null-hypothesis tests
- Searches for GR deviations:

$$h(t) = \sum_i A_i \cos\left(2\pi f_i^{\mathrm{Kerr}}(1+\delta f_i)t + \phi_i\right) e^{-\frac{t}{\tau_i^{\mathrm{Kerr}}(1+\delta\tau_i)}}$$

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Limitations of this approach:

1. $\delta f_i, \delta\tau = \text{const}$ → no theory with this property
2. $\delta f_i(\chi), \delta\tau(\chi)$ functions of coupling and spin → need to solve PDEs

Small-spin expansion

- High order needed
- Many parameters or theory dependent

ParSpec: Maselli+ 2020, 2024; Carullo 2021
Small-spin: Pani+ 2009, 2013; Molina+ 2010; Pierini-Gualtieri 2021, 2022; Wagle+ 2022, 2024; Cano+ 2022, 2023

Brute force numerical resolution

- Accurate, but theory dependent

Review: Dias, Godazgar, Santos
Applications: Chung 2023-2024; Blázquez-Salcedo 2024

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$$\tau_i^{\rm Kerr}(1+\delta\tau_i)$$

Can we find a ringdown test that is theory-agnostic, accurate, and practical?

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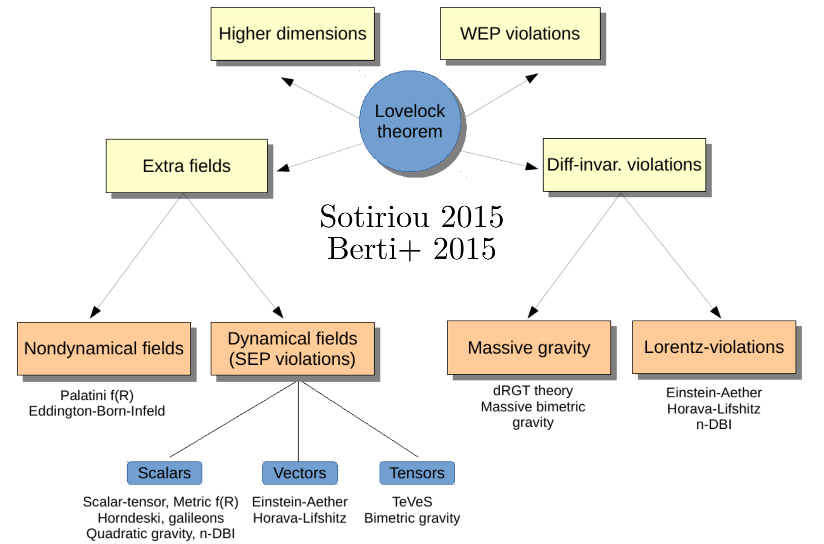
Not only QNM deviations

- **Lovelock theorem:** extra DOF are almost unavoidable beyond GR
  - **Scalar:** Horndeski, f(R)
  - **Vector:** Proca-Horndeski, Einstein-Aether, Horava, (Maxwell)
  - **Tensor:** massive/Weyl/quadratic gravity
  - EFT approach to GR
  - Low-energy string theory



Sotiriou 2015
Berti+ 2015

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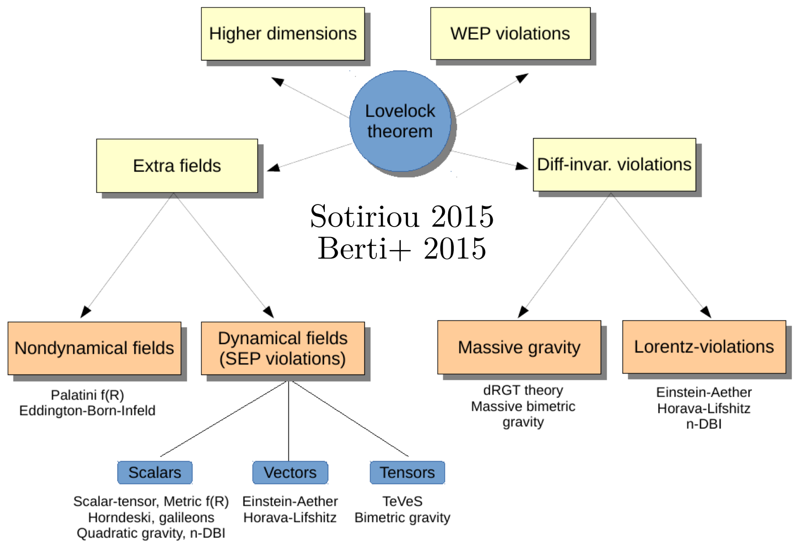

- Two generic predictions of extra fields in the ringdown:

✓ Deformation of the Kerr QNMs

✗ Extra modes in the gravitational signal, excited during the ringdown

This talk!

Example: Chern-Simons gravity

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}R - \frac{1}{2}\int d^4x\sqrt{-g}g^{ab}\nabla_a\vartheta\nabla_b\vartheta + \frac{\alpha}{4}\int d^4x\sqrt{-g}\vartheta\,{}^*RR$$

Alexander-Yunes, 2009

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Nonspinning BHs = Schwarzschild, but different (axial) perturbations:

Cardoso-Gualtieri, PRD 2009
Molina+ PRD 2010

$$\frac{d^2}{dr_\star^2}\Psi + \left\{\omega^2 - f\left[\frac{\ell(\ell+1)}{r^2} - \frac{6M}{r^3}\right]\right\}\Psi = \frac{96\pi Mf}{r^5}\alpha\Theta\,,$$

$$\frac{d^2}{dr_\star^2}\Theta + \left\{\omega^2 - f\left[\frac{\ell(\ell+1)}{r^2}\left(1+\frac{576\pi M^2\alpha^2}{r^6\beta}\right) + \frac{2M}{r^3}\right]\right\}\Theta = f\frac{(\ell+2)!}{(\ell-2)!}\frac{6M\alpha}{r^5\beta}\Psi$$

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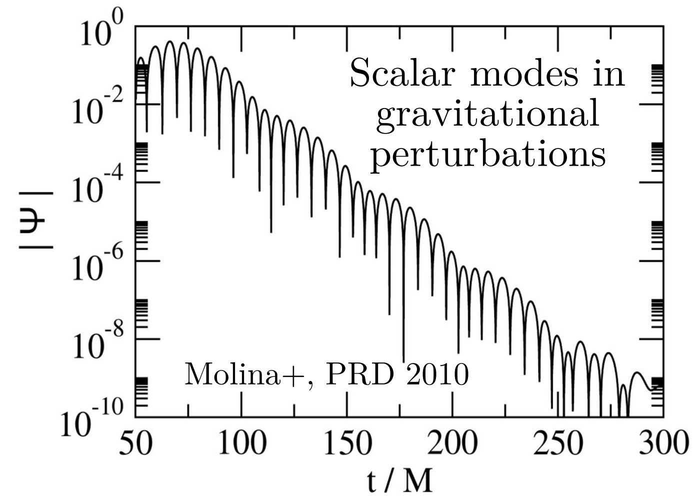
- Deformations in the effective potential
- Scalar & grav perturbations are coupled
  - Two classes of modes
  - Coupled system of harmonic oscillators



Unavoidable when extra fields couple to gravity:

- Gauss-Bonnet [Blázquez-Salcedo+ PRD 2016], Weyl gravity [Antoniou+ in prep.], even Maxwell

Modelling ringdown extra modes

$$h(t) = \sum_i A_i \cos\left(2\pi f_i^{\rm Kerr}(1+\delta f_i)t + \phi_i\right) e^{-\frac{t}{\tau_i^{\rm Kerr}(1+\delta\tau_i)}}$$

$$+ \sum_i \hat{A}_i \cos\left(2\pi \hat{f}_i t + \hat{\phi}_i\right) e^{-t/\hat{\tau}_i}$$

$$\hat{f}_i = f_i^{\rm Kerr,\, s=0}(1+\delta\hat{f}_i)$$

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$$\hat{f}_i = f_i^{\rm Kerr,\, s=0}(1+\delta\hat{f}_i)$$

$$\hat{\tau}_i = \tau_i^{\rm Kerr,\, s=0}(1+\delta\hat{\tau}_i)$$

- **Crucial simplification:** amplitude proportional to the coupling $\to$ to leading order

$$+ \sum_i \hat{A}_i \cos\left(2\pi f_i^{\rm Kerr,\, s=0} t + \hat{\phi}_i\right) e^{-\frac{t}{\tau_i^{\rm Kerr,\, s=0}}}$$

Pros:

- Kerr QNMs known for *any spin*, only beyond-GR parameters: **amplitudes** & **phases**!
- Same pattern function and spheroidal harmonics $\to$ Inclination angle factors out

Modelling ringdown extra modes

$$h(t) = \sum_i A_i \cos\left(2\pi f_i^{\rm Kerr} t + \phi_i\right) e^{-\frac{t}{\tau_i^{\rm Kerr}}} + \sum_i \hat{A}_i \cos\left(2\pi f_i^{{\rm Kerr},\, s=0} t + \hat{\phi}_i\right) e^{-\frac{t}{\tau_i^{{\rm Kerr},\, s=0}}}$$

- We neglect precession and QNM deviations in the standard gravity sector:

$$\underline{\theta} = \{M_f, \chi_f, A_{22j}, \phi_{22j}, \hat{A}_{220}^{s=0,1}, \hat{\phi}_{220}^{s=0,1}\} \qquad j = 0, 1, .., N$$

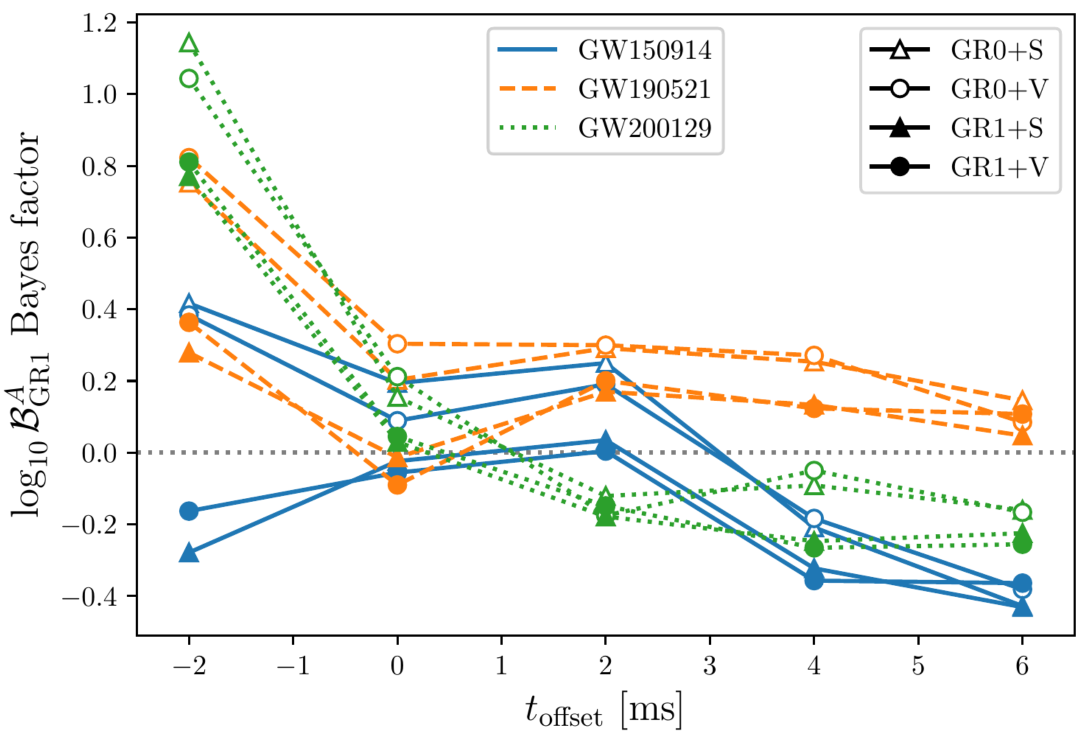
overtones

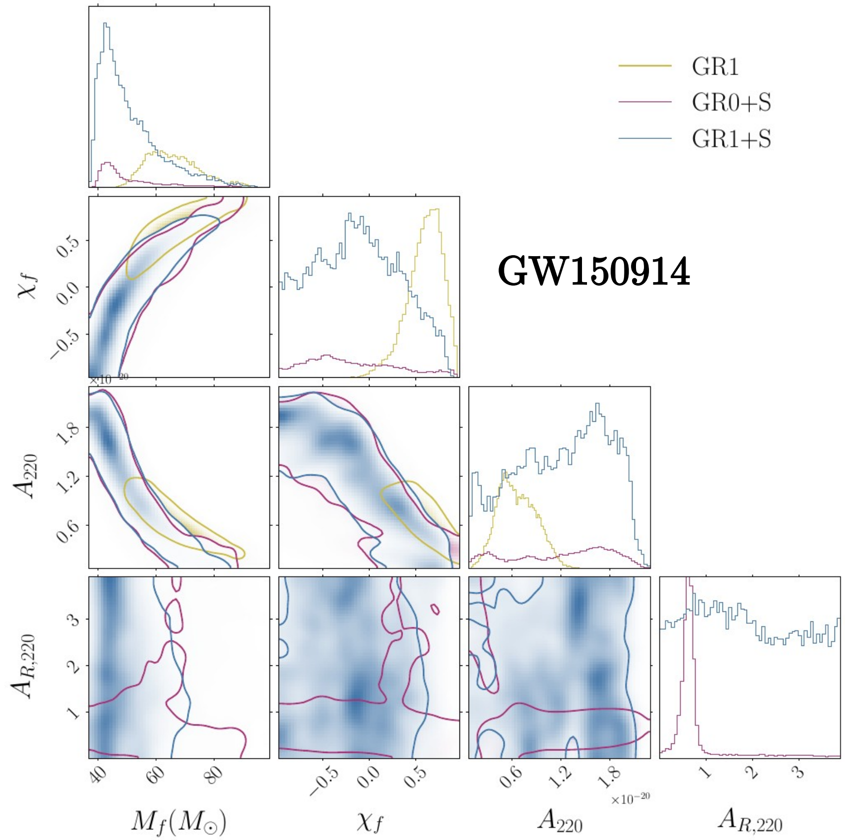
waveform parameters + ringdown start time ($t_{\rm offset}$)

- **GRN**: model with N gravitational tones and no extra mode
- **GRN+S (+V)**: GRN + extra fundamental scalar (vector) mode

Tests on real data

- **GW150914**: golden event, still largest ringdown SNR, overtone debate [Isi+, Cotesta+ ...]
- **GW190521**: upper mass gap, tentative detection of l=3 mode [Capano+ 2021]
- **GW200129**: "false" GR deviations, tentatively ascribed to precession [Maggio+ 2022]

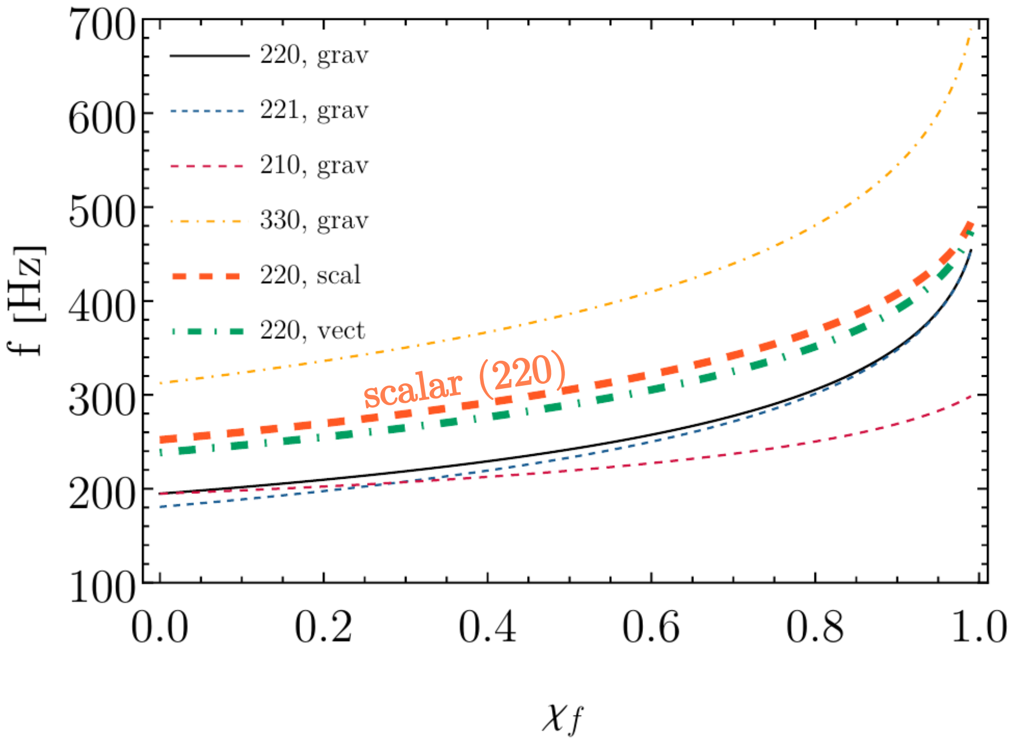


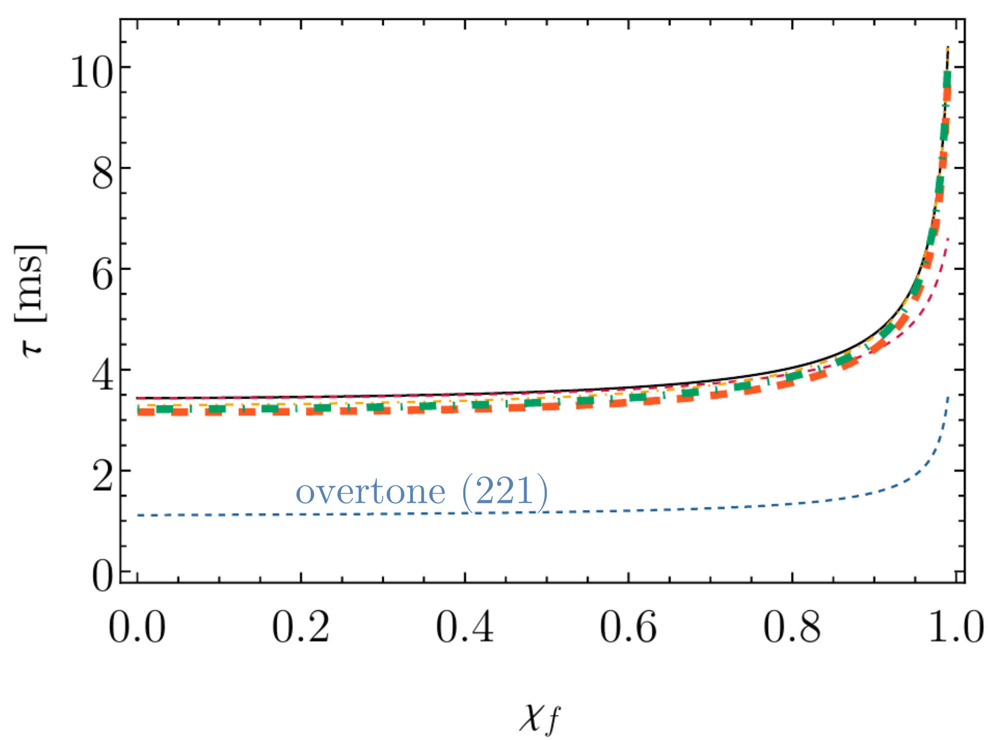


GR1 vs: GR0+S, GR1+S, GR0+V, GR1+V
→ no evidence

Scalar- or vector-driven modes affect parameter posteriors

Scalar & vector QNMs

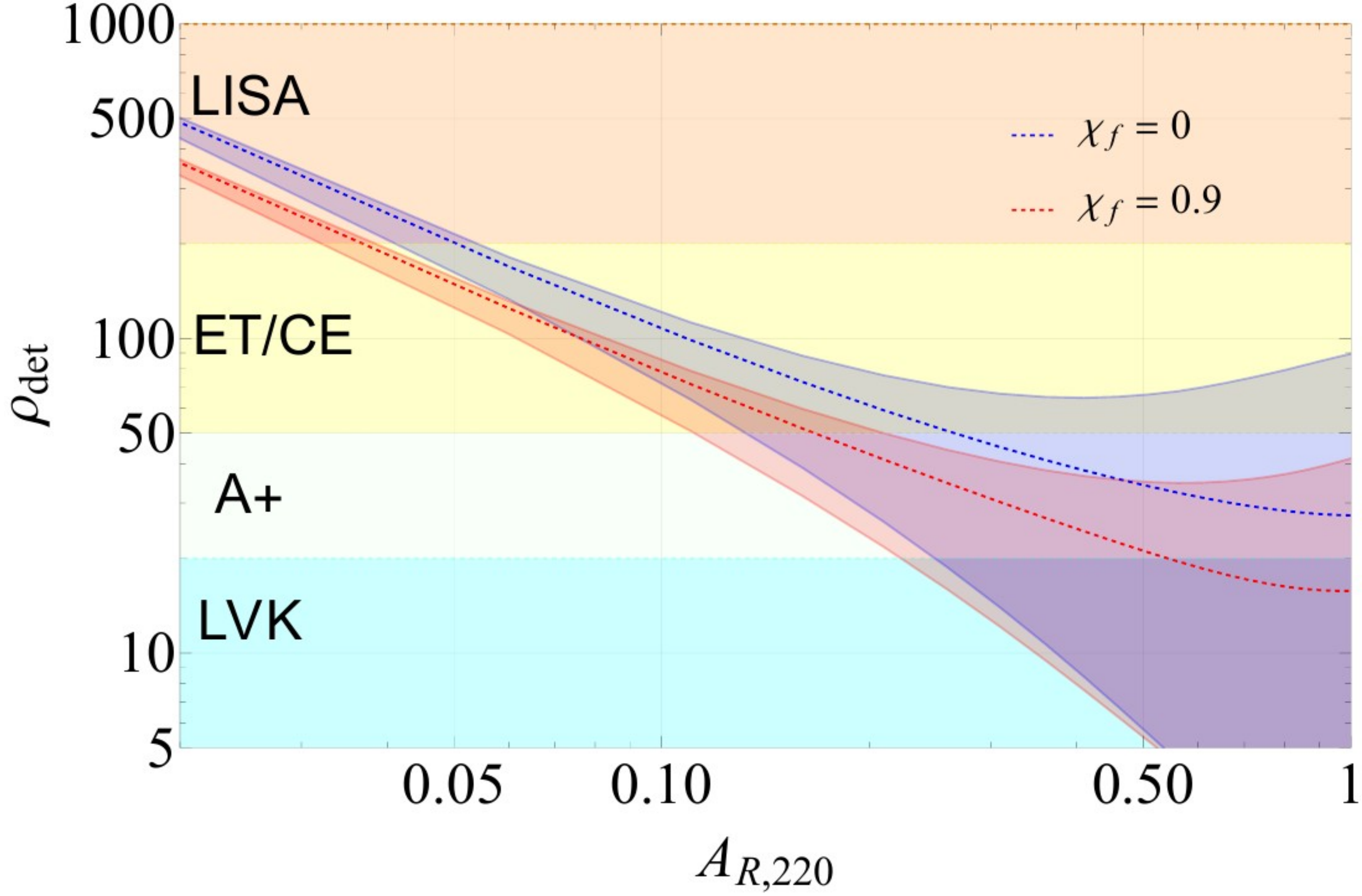




- Frequency is higher → easy to resolve
- Damping time is similar → longer-lived than gravitational overtones

Future prospects

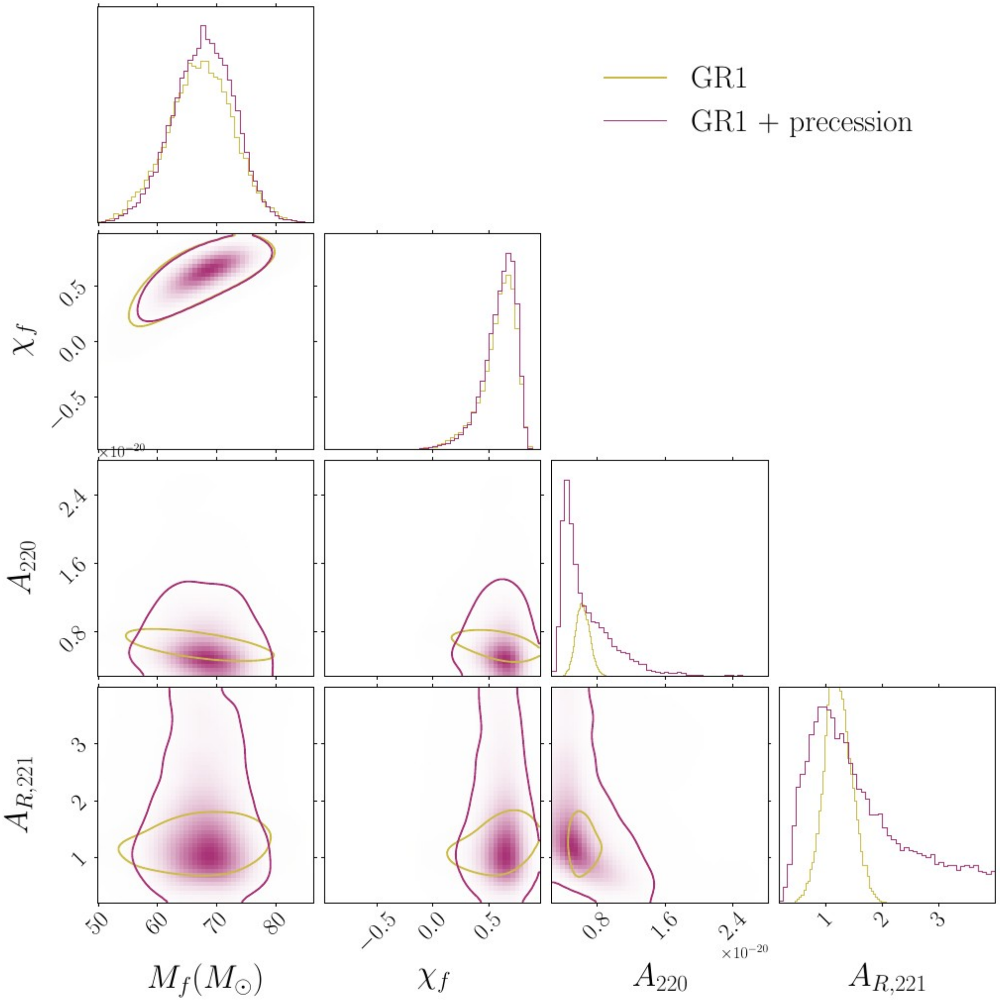
$\rho_{\rm det}$ such that $\sigma_{\rm A_R} < \rm A_R$

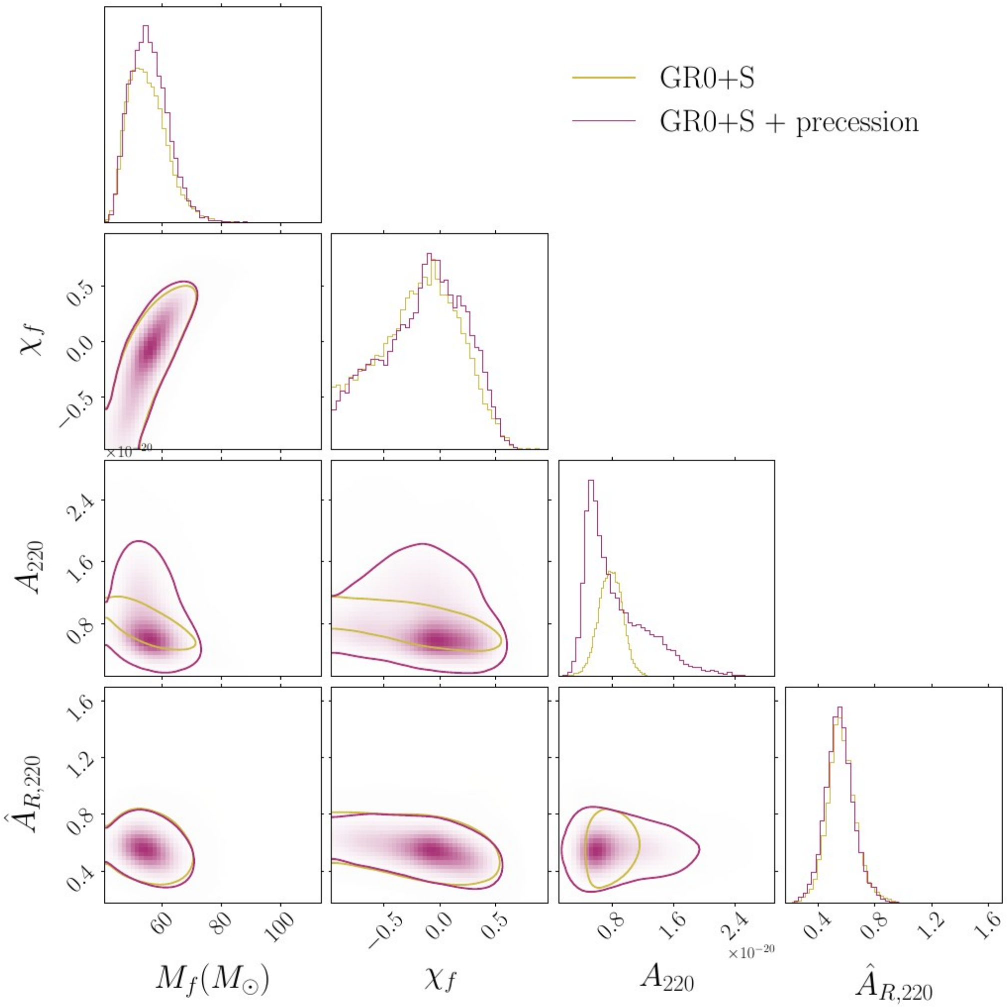


Adding precession

$$h_{lm} \neq (-1)^l h^*_{l-m} \rightarrow A_{22n} \neq A_{2-2n}, \quad \phi_{22n} \neq -\phi_{2-2n}$$

(~ double model parameters)



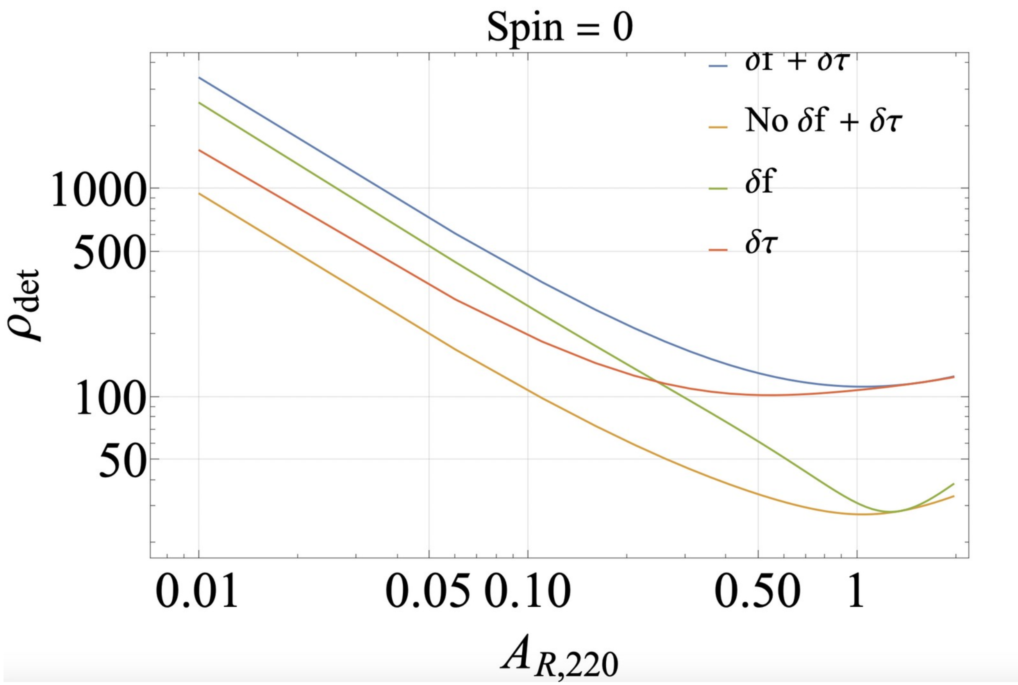


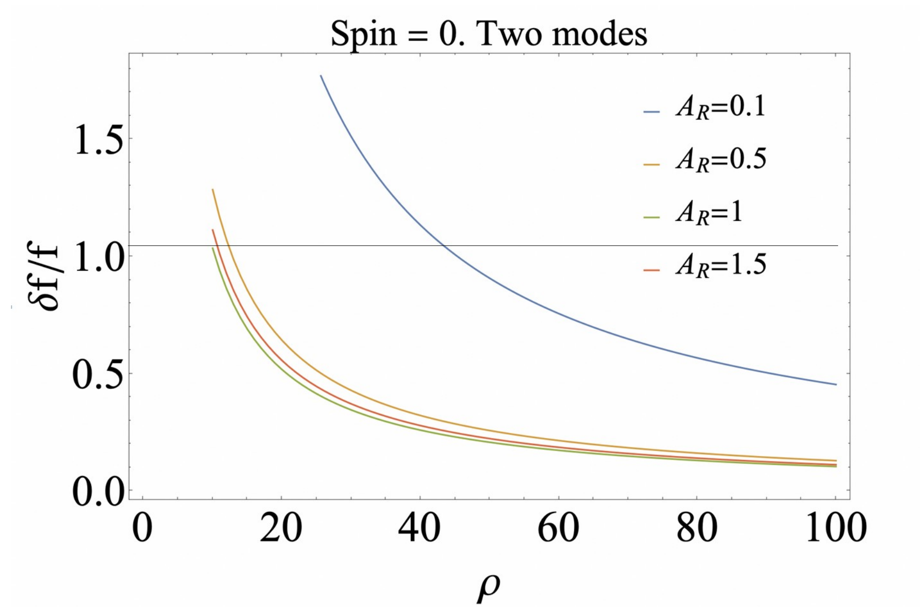
GW200129

QNM deviations + extra modes

WORK IN PROGRESS

with Xisco Jimenez Forteza &
Francesco Crescimbeni





- Extra mode breaks degeneracy and allows using only the fundamental grav QNM
- Errors on both amplitudes and frequencies increase

Nontrivial example: Weyl gravity

Quadratic gravity $$\mathcal{I} = \int \mathrm{d}^4x\sqrt{-g}\left(R - \alpha C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma} + \beta R^2\right)$$

WORK IN PROGRESS

with G. Antoniou & L. Gualtieri

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$\beta \to 0$

Weyl gravity $$\mathcal{I} = \int d^4x\sqrt{-g}\left[R - \frac{1}{2\mu^2}\left(2R_{\mu\nu}R^{\mu\nu} - \frac{2}{3}R^2\right)\right]$$ $\alpha \equiv 1/(2\mu^2)$

Auxiliar field:

$$f_{\mu\nu} = -\frac{1}{\mu^2}\left(R_{\mu\nu} - \frac{1}{6}R\,g_{\mu\nu}\right)$$

$$\mathcal{I}_0 = \int d^4x\sqrt{-g}\left[R + 2f_{\mu\nu}G^{\mu\nu} + \mu^2\left(f_{\mu\nu}f^{\mu\nu} - f^2\right)\right]$$

Two interacting spin-2 fields

Nontrivial example: Weyl gravity

WORK IN PROGRESS
with G. Antoniou & L. Gualtieri

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Two interacting spin-2 fields

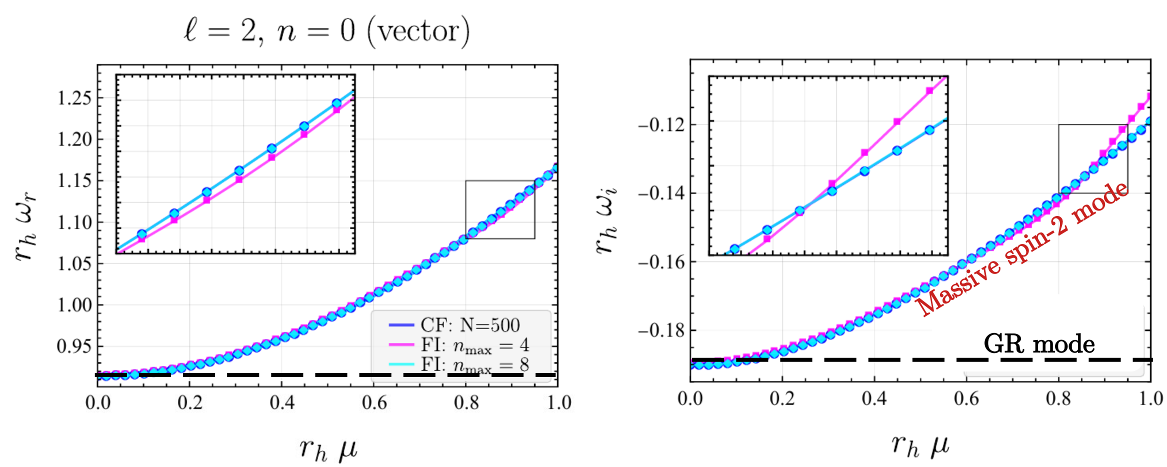
On Ricci-flat background:

$$0=\delta G_{\mu\nu}+\mu^2\delta f_{\mu\nu}\ ,$$

$$0=\bar{\Box}\,\delta f_{\mu\nu}+2\,\bar{R}_{\mu\sigma\nu\rho}\,\delta f^{\sigma\rho}-\mu^2\,\delta f_{\mu\nu}$$

On Schwarzschild:

$$\frac{d^2}{dr_*^2}\begin{pmatrix}Q\\ Z\end{pmatrix}+\begin{pmatrix}V_{11} & V_{12}\\ V_{21} & V_{22}\end{pmatrix}\begin{pmatrix}Q\\ Z\end{pmatrix}=0$$



Conclusion & Outlook

- Searching for extra QNMs: a novel theory-agnostic ringdown test
- Easy to implement, no problem with spinning remnants
- Extra amplitudes enter at the same order as QNM deviations
  $\rightarrow$ should always be modelled in beyond GR theories!
- Frequency or amplitude deviation? Depends on theory/source (eg. Chern-Simons)
- Mapping on specific theories ongoing

Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]