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

Based on

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- novel theory-agnostic test for ringdown;
- forecast with future detectors;
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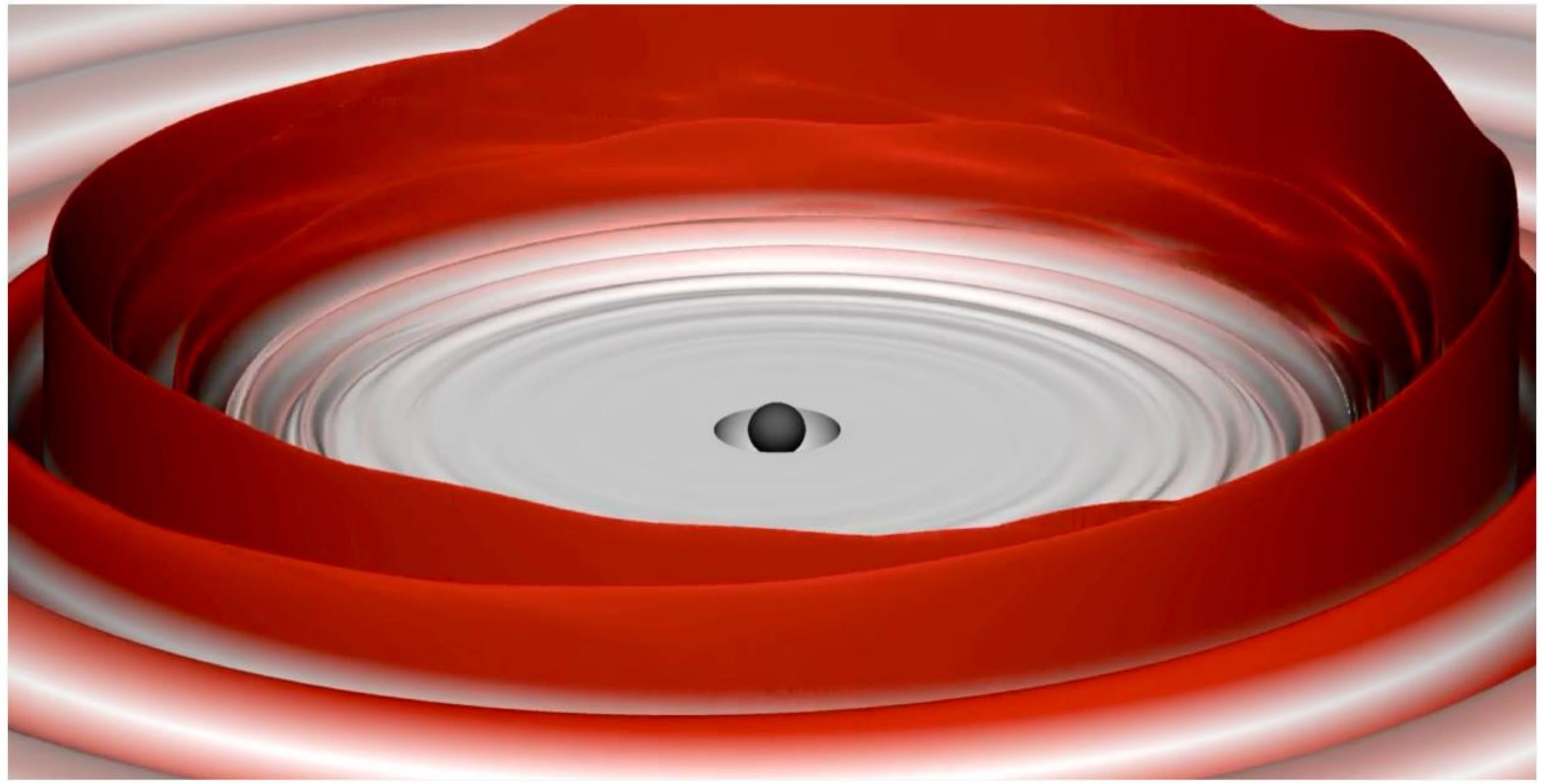
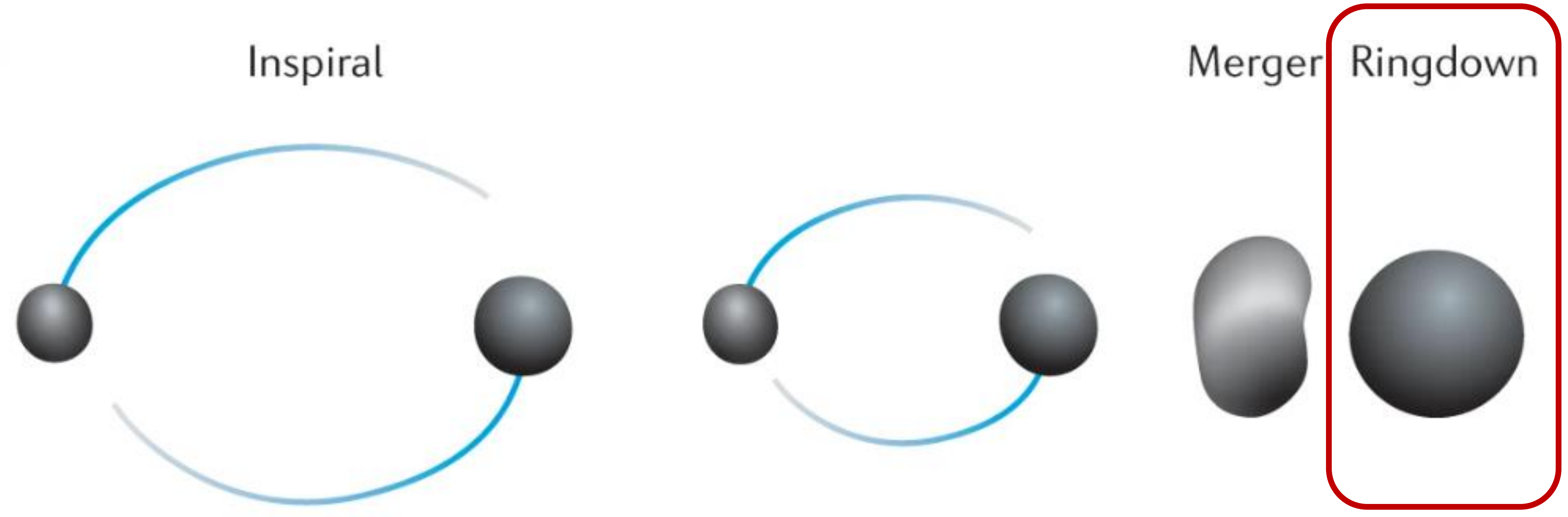


Credits: Max Planck Institute

Black Hole Spectroscopy in a nutshell



- At intermediate time after the merger, we can model the signal of the ringdown as a superposition of damped sinusoids [Berti+, 0905.2975]:

$$h(t) = \sum_{i=(l,m,n)} A_i \cos\left(2\pi f_i^{\mathrm{Kerr}} t + \phi_i\right) e^{-\frac{t}{\tau_i^{\mathrm{Kerr}}}}$$

- l = 2, 3, . . . and m = −l, . . . , +l are respectively the angular and the azimuthal index, and n = 0, 1, . .. is the overtone index.

Where do GR deviations enter in the ringdown?

$$h(t) = \underbrace{\sum_i A_i \cos\left(2\pi f_i^{\text{Kerr}}(1+\delta f_i)t + \phi_i\right) e^{-\frac{t}{\tau_i^{\text{Kerr}}(1+\delta\tau_i)}}}_{(1)} + \underbrace{\sum_i \hat{A}_i \cos\left(2\pi \hat{f}_i t + \hat{\phi}_i\right) e^{-t/\hat{\tau}_i}}_{(2)}$$

CONSTRAINED BY LVK (see e.g. Carullo+, 2109.13961)

CURRENTLY UNBEATEN PATH!

(1) Modifications of the Kerr QNMs (1):

$$f_i = f_i^{\text{Kerr}}(1+\delta f_i) \qquad \tau_i = \tau_i^{\text{Kerr}}(1+\delta\tau_i)$$

(2) the existence of extra modes in the gravitational signal, that can be excited during the ringdown [Molina-Pani-Cardoso-Gualtieri, 1004.4007; Lestingi-D'Addario-Sotiriou, appeared today on arxiv!].

Novel theory-agnostic test for non-gravitational modes

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

⇩

- First term: neglect the GR deviation (well studied and constrained by LVK ringdown test);

- Second term:

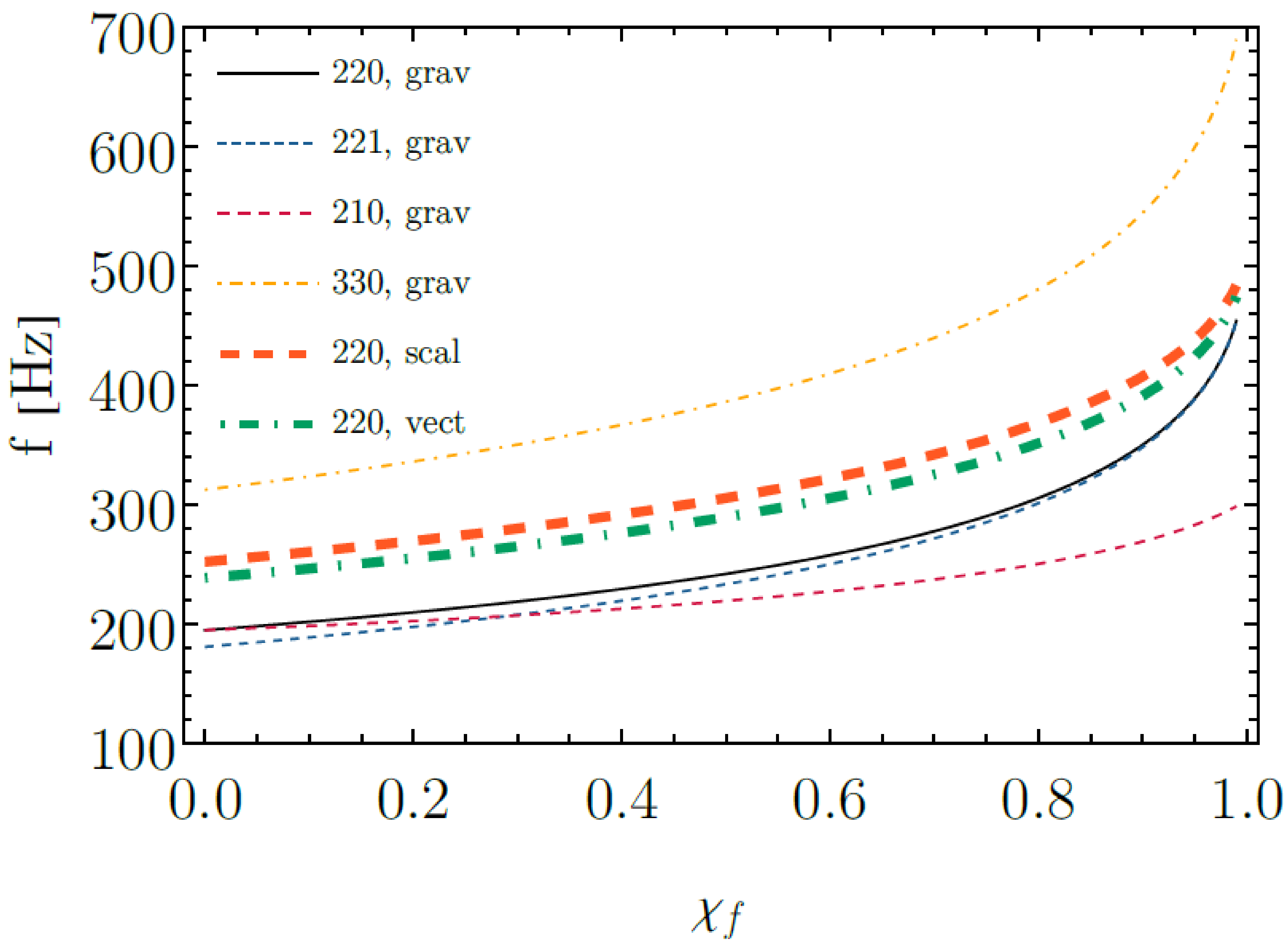
$$\hat{f}_i = f_i^{\rm Kerr,\, s=0}(1+\delta\hat{f}_i)\,, \qquad \hat{\tau}_i = \tau_i^{\rm Kerr,\, s=0}(1+\delta\hat{\tau}_i)$$

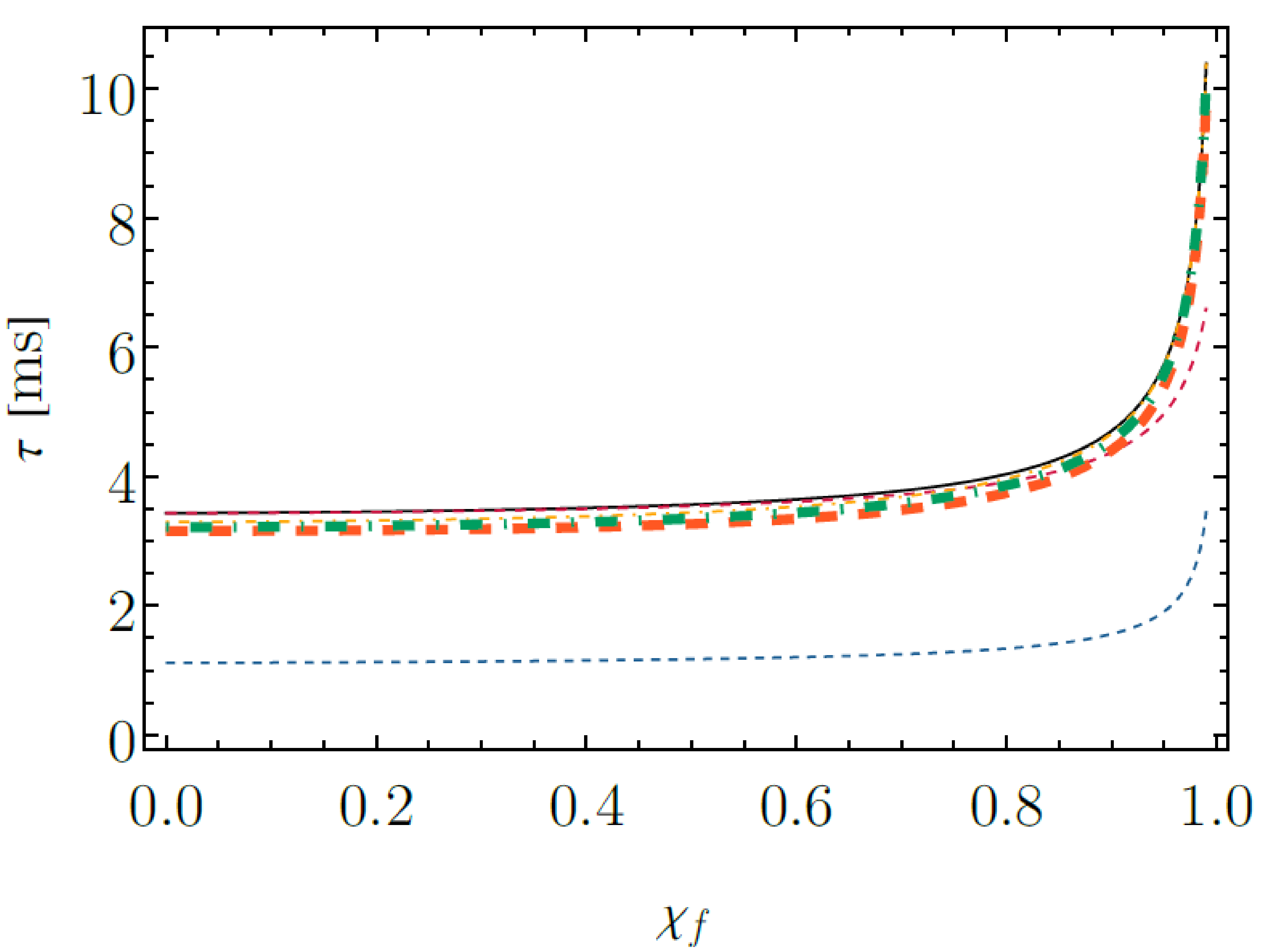
but since the amplitudes of the scalar depend on the power of the coupling constant, we reduce to:

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

NO DEPENDENCE FROM THE THEORY!

Frequencies and damping times of GR vs extra modes



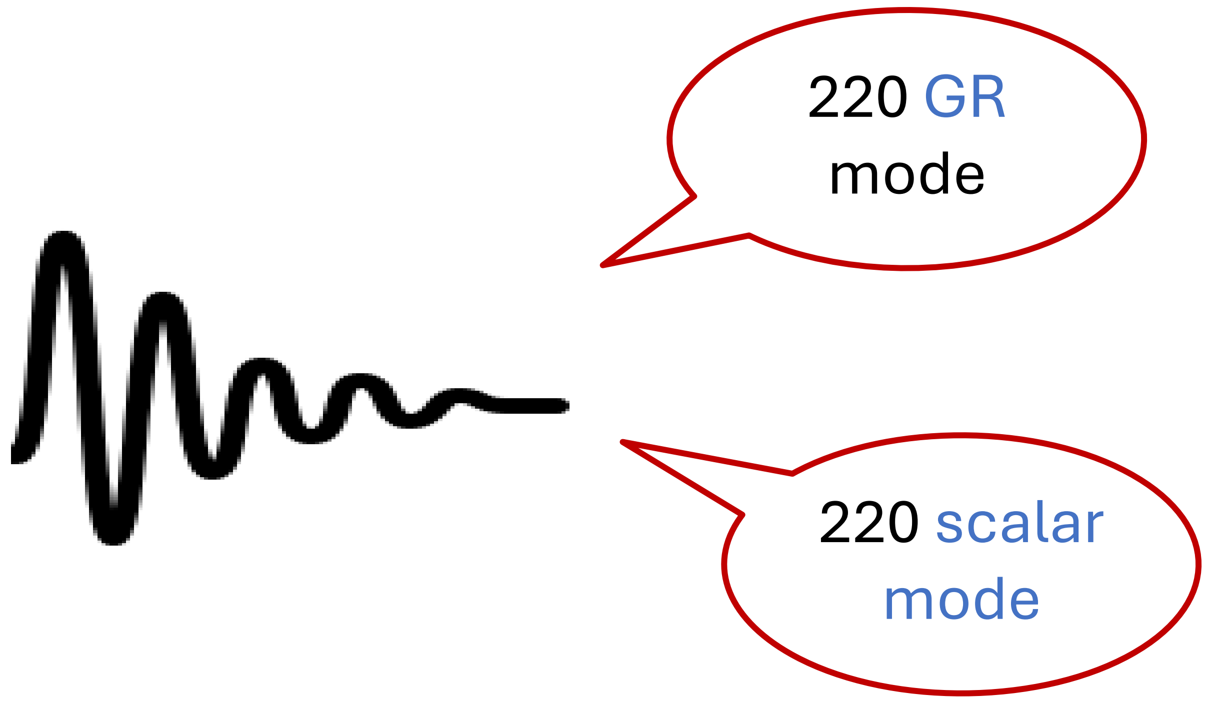


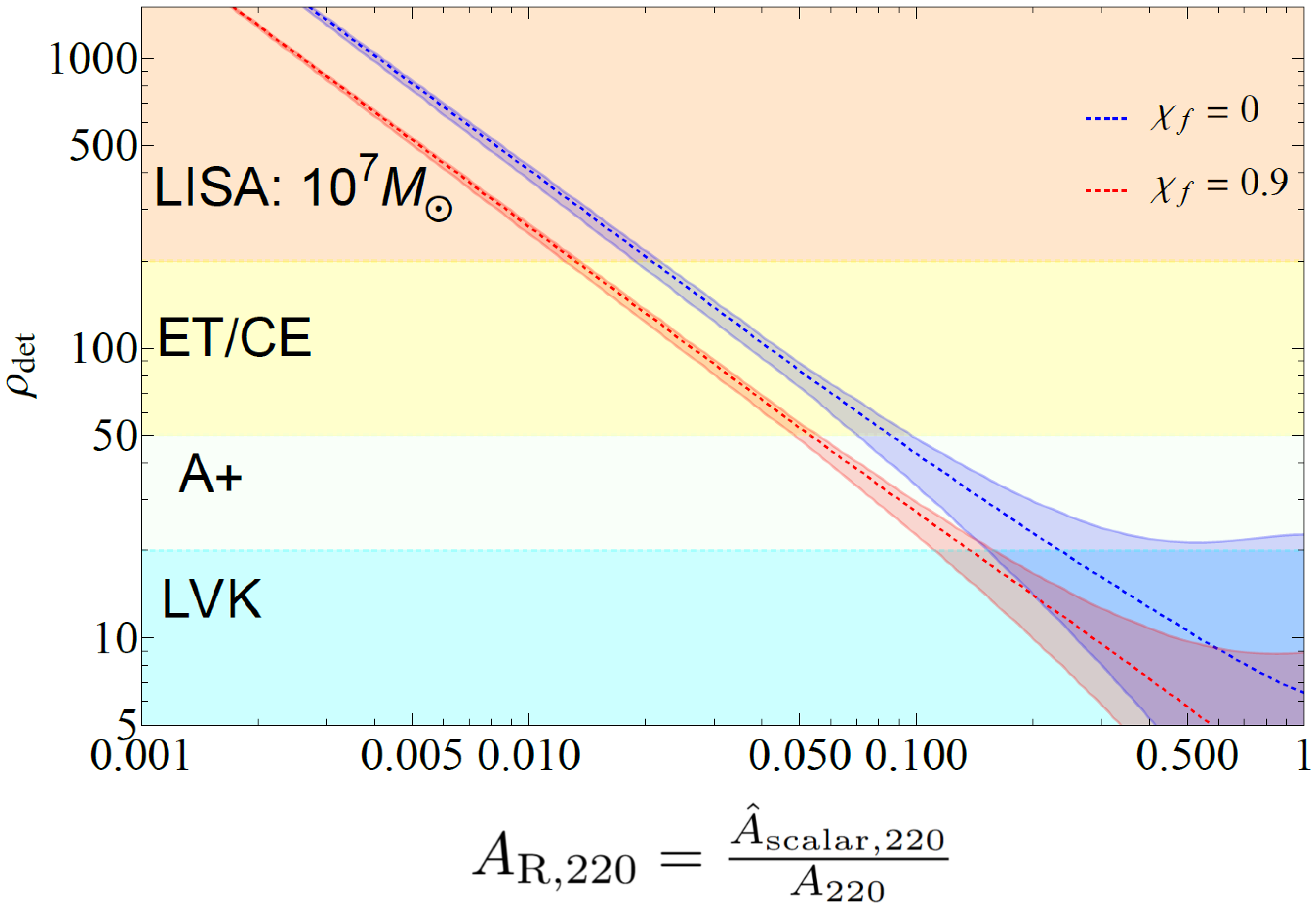
- Frequency is higher → easy to resolve.
- Damping time is similar → longer-lived than gravitational overtones.

Forecasts with future detectors:detectability

- We compute the minimum ringdown SNR, for detectability of an extra scalar mode in the ringdown signal.

- This is imposed by $\sigma(A_{R,220}) = A_{R,220}$.





Conclusions and future developments

Summary:

- We proposed a novel test to detect putative extra fundamental modes.

- Future detectors should have the required sensitivity to detect/constrain such modes.

Next steps:

- Apply this for a specific theory (e.g. dynamical Chern Simons) [Crescimbeni-Forteza-Pani, in prep.]

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

Thank you for your attention!

Back-up slides

Gravity modification: an overview

Lovelock's theorem

- Scalar fields in scalar-tensor theories and Horndeski's gravity [Horndeski, 2405.08303]
- High-curvature corrections to GR: predict extra (pseudo)scalars and dilaton fields [Alexander-Yunes, 0907.2562]
- Einstein-Aether [Jacobson-Mattingly, 0007031] and Horava–Lifshitz [Horava, 0901.3775] gravity: postulate an extra timelike vector field
- Massive gravity [de Ram+, 1011.1232]
- Effective field theory approaches: GR is the leading order [Endlich, 1704.01590]

Standard tests of General Relativity: study term (1)

Measure GR deviations and observe if are zero or not [LVK, 2112.06861]

Theory-agnostic approach

Known Kerr frequencies and damping time, and deviations are taken to be small (δf_i , $\delta \tau_i \ll 1$) and are proportional to some combination of the mass and coupling constants.

Theory-dependent approach

Compute QNMs in a given theory (can be done in small coupling limit and perturbatively in the spin).

CURRENTLY UNBEATEN PATH: EXPLORE TERM (2)

An explicit example: dynamical Chern-Simons

- Let's consider the Chern-Simons action [Alexander-Yunes, 0907.256] (in units G=c=1):

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

where we define ${}^*RR = \frac{1}{2}R_{abcd}\epsilon^{baef}R^{cd}{}_{ef}$.

- The Einstein-Hilbert action is modified by adding a parity-violating Chern-Simons term, which couples to gravity via a scalar field.

An explicit example: dynamical Chern-Simons

- Axial perturbations of the metric are coupled to those of the scalar field, and in the frequency domain they are given by:

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

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

$$\vartheta = \frac{\Theta^{\ell m}}{r}Y^{\ell m}e^{-i\omega t}$$

- We defined:

$$f(r) = 1 - 2M/r \qquad r_\star \equiv r + 2M\ln\left(r/2M - 1\right)$$

- Decoupling limit (α=0): obtain the standard Regge-Wheeler equation + scalar-perturbation equation of a Schwarzschild BH, respectively.

An explicit example: dynamical Chern-Simons

- There are both gravity and scalar-driven modes:

Order-unity constants, depend on the overtone

$$\omega = \omega^{\mathrm{GR,\ grav}} \left(1 + \gamma^{\mathrm{grav}} \frac{\alpha^2}{M^4}\right) \qquad \hat{\omega} = \omega^{\mathrm{GR,\ scal}} \left(1 + \gamma^{\mathrm{scal}} \frac{\alpha^2}{M^4}\right)$$

Complex QNM frequency

Standard Swartzshild QNMs

Test-scalar QNMs of Shwartzshild

- This leads to a system which acts as a coupled oscillator, with signal:

$$h(t) = \sum_j A_j e^{i(\omega_j t + \phi_j)} + \sum_j \hat{A}_j e^{i(\hat{\omega}_j t + \hat{\phi}_j)}$$

Ringdown + extra mode parameters and nomenclature

- We focus on the most constrained (l = 2, m=2) case and neglect spin precession of the progenitor binary.

- The ringdown waveform has the dependence on the following parameters:

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

where j=1, …, N, with N the number of overtones.

We denote a model with:

- N gravitational tones and no extra mode GRN;
- N gravitational tones and an extra scalar (vector) mode as GRN+S (GRN+V).

Gating window for the analysis

- For the analysis, we need to vary the starting time with respect to the peak of the waveform (in general, for a given model, there should be a valid starting time [Bhagwat+, 1910.08708; Crescimbeni-Carullo+, in prep.]).

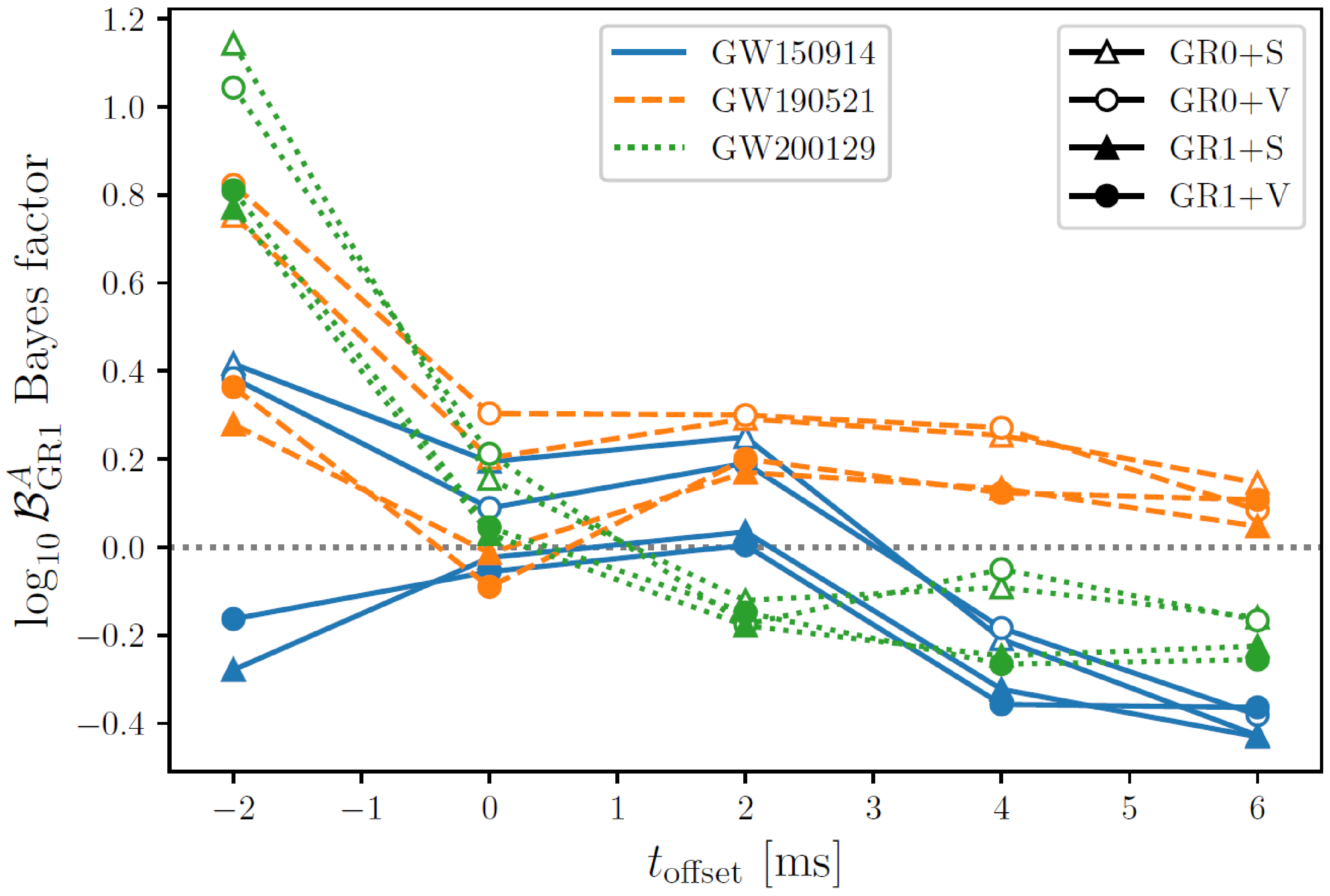
- We use a gated-and-inpainted Gaussian likelihood noise model to remove the influence of the pre-peak/non-ringdown times [Zackay+, 1908.05644].

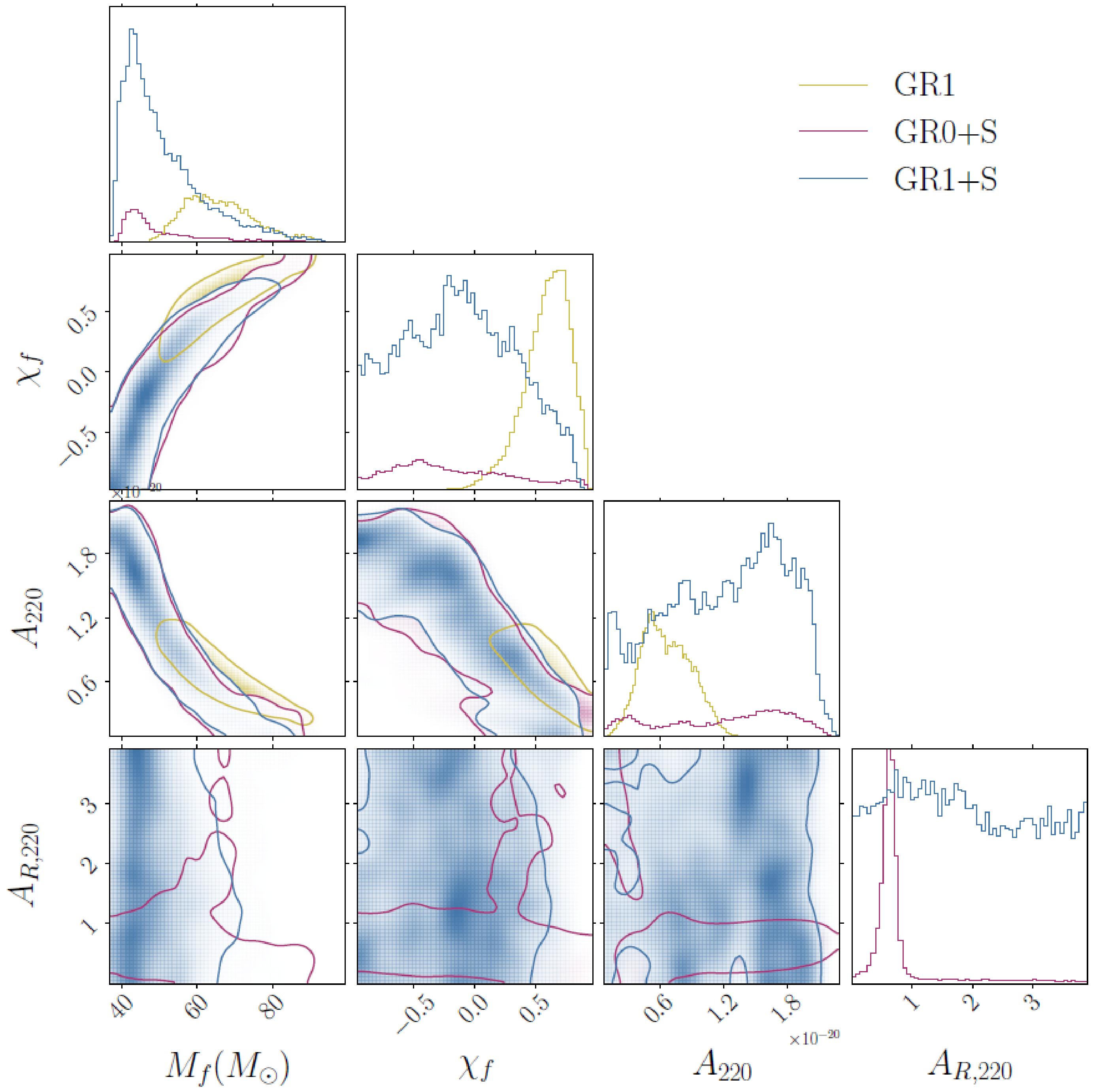
$$t \in [t_c + t_{\text{offset}} - 0.5, t_c + t_{\text{offset}}]$$

- The strain data within a time interval are replaced/inpainted such that the filtered inverse power spectral density is zero at all the times corresponding to the chosen interval.

Real data results

- 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]





- no strong evidence for an extra scalar or vector mode.

Detectability, resolvability, and measurability criteria for BH spectroscopy

For a 2-mode or 2-tone ringdown model we define the following criteria [Forteza+, 2005.03260]:

- Detectability → require that:

$$\sigma_{A_R} < A_R$$

where A_R is the ratio between the amplitude of the subdominant and the dominant mode.

- Resolvability → traditional Rayleigh resolvability criterion that was introduced in the context of BBH ringdown [Berti-Cardoso-Will]:

$$\max[\sigma_{f_{220}}, \sigma_{f_{\rm sub}}] < |f_{220} - f_{\rm sub}|$$
$$\max[\sigma_{Q_{220}}, \sigma_{Q_{\rm sub}}] < |Q_{220} - Q_{\rm sub}|$$

$$Q_{lmn} = \pi f_{lmn} \tau_{lmn}$$

- Measurability →

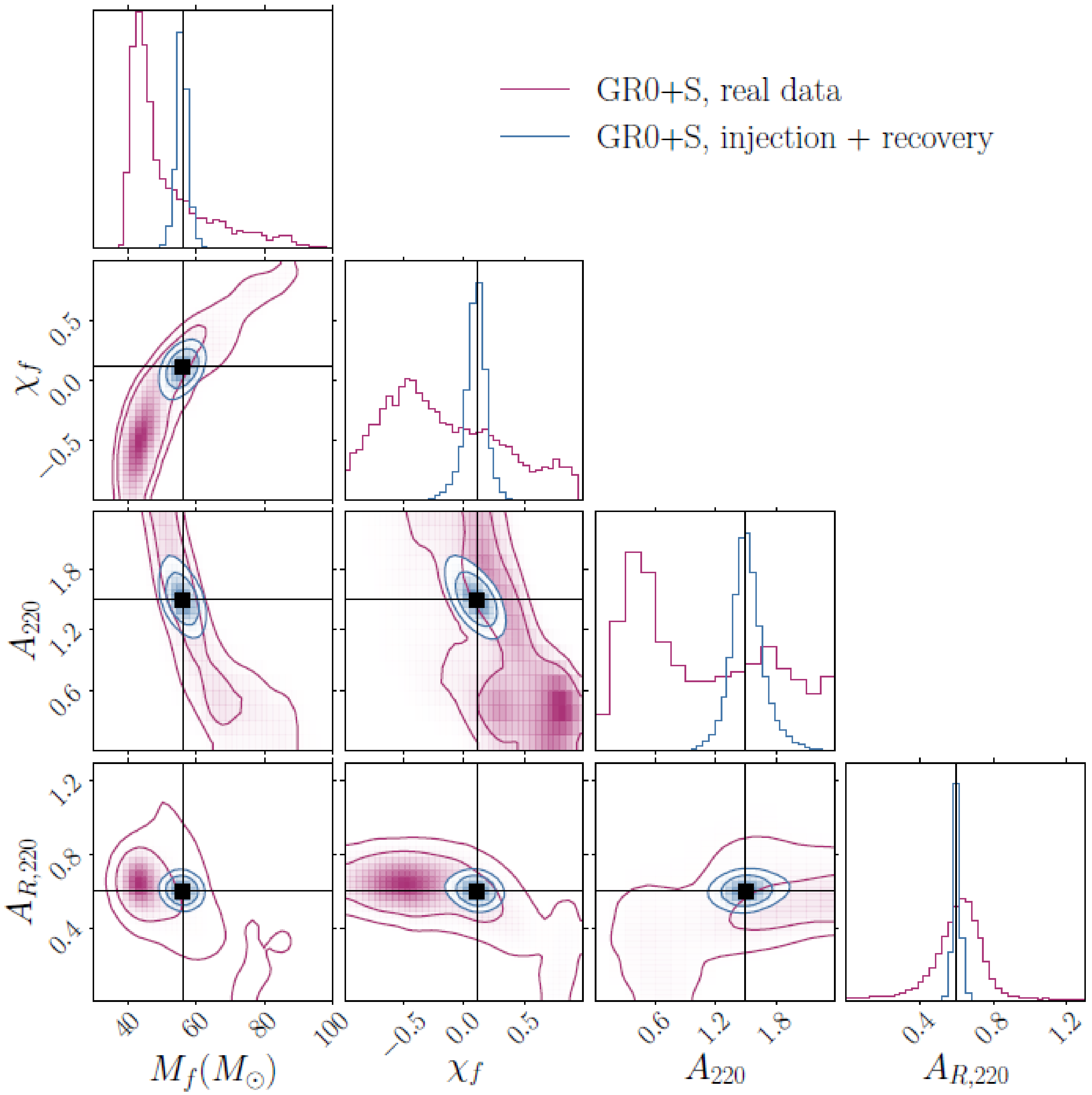
$$\left\{ \frac{\sigma_{f_{220}}}{f_{220}}, \frac{\sigma_{Q_{220}}}{Q_{220}}, \frac{\sigma_{f_{\rm sub}}}{f_{\rm sub}} \right\} \leq T$$

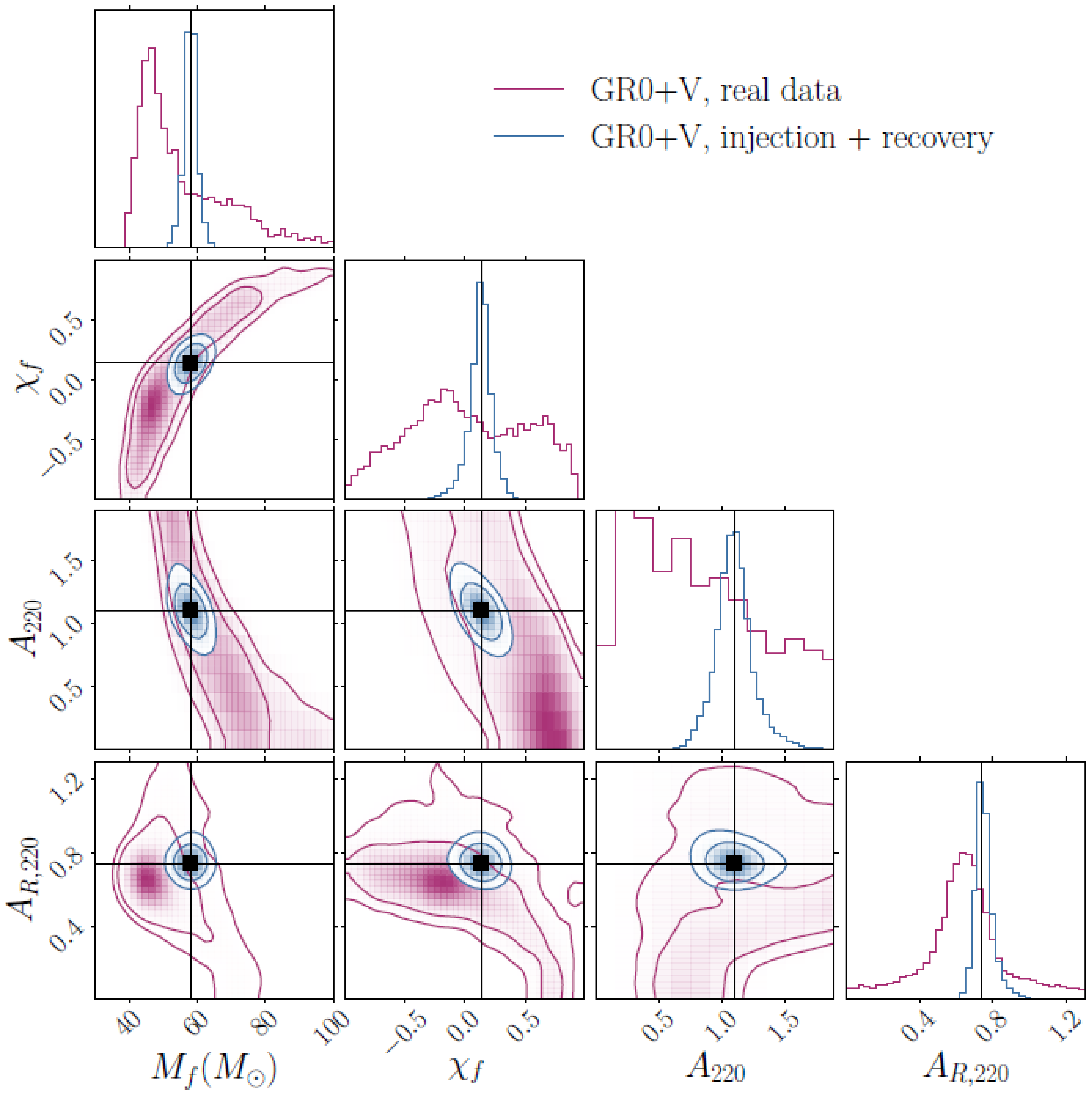
, with T a given threshold.

$$\left\{ \frac{\sigma_{f_{220}}}{f_{220}}, \frac{\sigma_{Q_{220}}}{Q_{220}}, \frac{\sigma_{Q_{\rm sub}}}{Q_{\rm sub}} \right\} \leq T$$

High SNR limit for LVK

We compare some representative posterior distributions obtained from the Bayesian inference on real data with forecasts using injections at higher SNR (equal to 100).





GW190521 analysis with the inclusion of precession