

# 220 mode ringdown, Kerr deviation parameter from geometric deviations of final metric

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# Introduction

- We are interested in the ringdown of black holes.
- We like to fit damped sinusoids (QNMs).
- Five parameters for each mode: Starting time, amplitude, phase, frequency, damping time.
- Perturb around a background BH (Kerr in GR), to find frequency and damping time (2 parameters  $\rightarrow$  2 parameters in standard GR).
- Starting time, amplitude, phase determined by inspiral.

# General Stationary, Axisymmetric Metrics have more than 2 parameters<sup>{1}</sup>

$$ds^2 = -[1 + h(r, \theta)](1 - \frac{2Mr}{\Sigma})dt^2 - [1 + h(r, \theta)]\frac{4aMr \sin^2 \theta}{\Sigma}dt d\phi$$

$$+ \frac{\Sigma[1 + h(r, \theta)]}{\Delta + a^2 \sin^2 \theta h(r, \theta)}dr^2 + \Sigma d\theta^2$$

$$+ [\sin^2 \theta(r^2 + a^2 + \frac{2a^2 Mr \sin^2 \theta}{\Sigma}) + h(r, \theta)\frac{a^2(\Sigma + 2Mr) \sin^4 \theta}{\Sigma}]d\phi^2$$

$$\text{where; } h(r, \theta) = \sum_{k=0}^{\infty} (\epsilon_{2k} + \epsilon_{2k+1} \frac{Mr}{\Sigma}) (\frac{M^2}{\Sigma})^k$$



$$g_{tt}^{JP} = -(1 - \frac{2Mr}{\Sigma}) - \epsilon_3 \frac{M^3(r - 2M)}{r^4}$$

$$g_{rr}^{JP} = \frac{\Sigma}{\Delta} + \epsilon_3 \frac{M^3(r - 2M)}{\Delta^2}$$

$$g_{\theta\theta}^{JP} = \Sigma$$

$$g_{\phi\phi}^{JP} = (r^2 + a^2 \frac{2Ma^2 r \sin^2 \theta}{\Sigma}) \sin^2 \theta + \epsilon_3 \frac{a^2 M^3(r + 2M)}{r^3}$$

$$g_{t\phi}^{JP} = -\frac{2Mar \sin^2 \theta}{\Sigma} - \epsilon_3 \frac{2aM^4}{r^4}$$

- Non-GR (not a vacuum solution), parametric deviation, reduces to Kerr
- $\epsilon_0 = \epsilon_1 = 0$ , for the metric to be asymptotically flat
- $\epsilon_2 = 4.6 \times 10^{-4}$ , Lunar Laser Ranging experiment
- $\epsilon_3$ , first unconstrained parameter  $\rightarrow h(r, \theta) = \epsilon_3 \frac{M^3 r}{\Sigma^2}$
- Real and imaginary parts of the QNM spectrum for equatorial orbits in Johannsen-Psaltis geometry up to linear order in  $\epsilon_3$ :

$$\omega_R^{JP} = \omega_R^K + \epsilon_3 \left( \frac{1}{81\sqrt{3}M} + \frac{10}{729M}\chi + \frac{47}{1458\sqrt{3}M}\chi^2 \right)$$

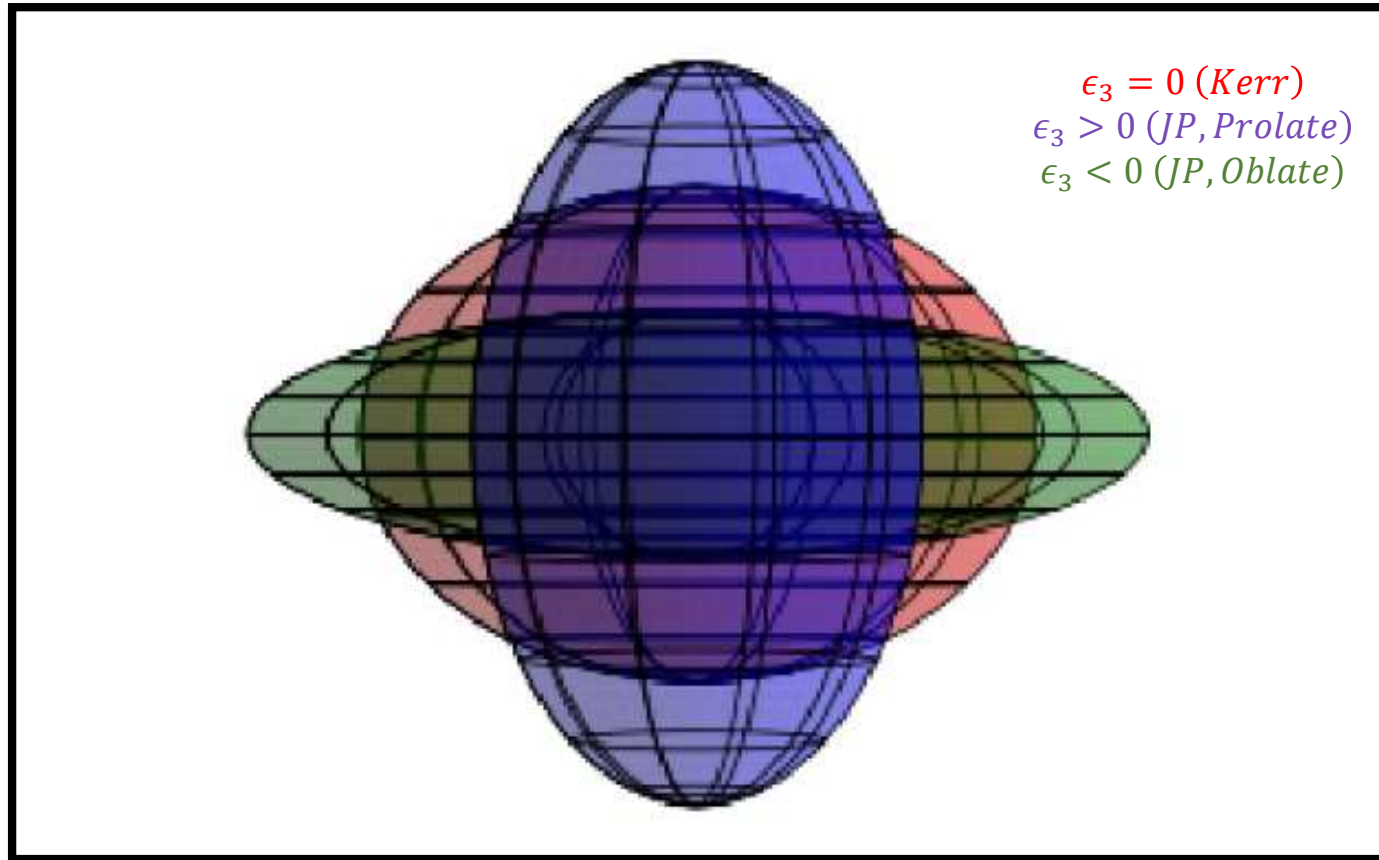
$$\omega_I^{JP} = \omega_I^K - \epsilon_3 \left( \frac{1}{486M}\chi + \frac{16}{2187\sqrt{3}M}\chi^2 \right)$$

<sup>{2}</sup>

(2 params -> 3 params)

<sup>{1}</sup> A metric for rapidly spinning black holes suitable for strong-field test of the no-hair theorem <https://link.aps.org/doi/10.1103/PhysRevD.83.124015>

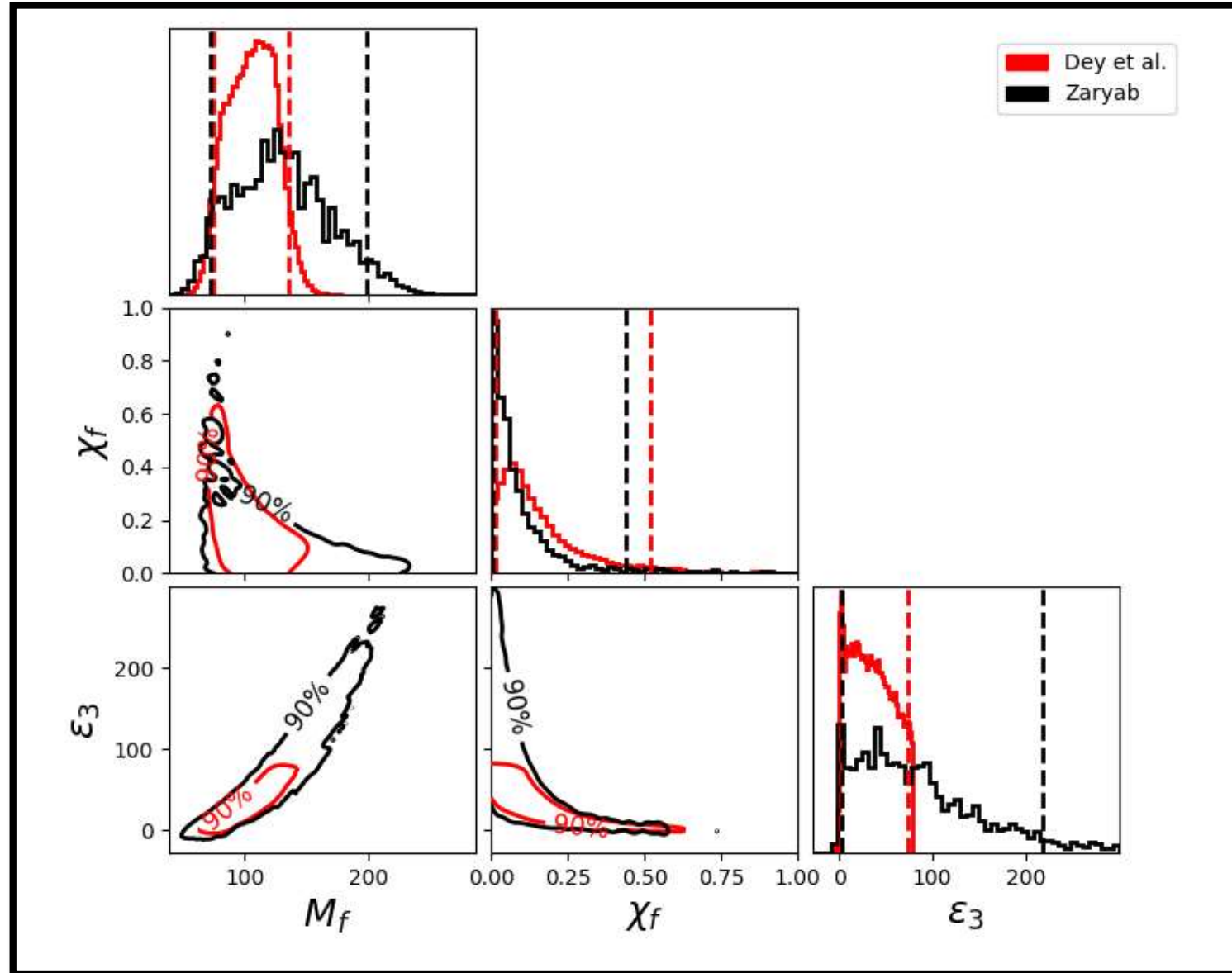
<sup>{2}</sup> Probing beyond-Kerr spacetimes with inspiral-ringdown corrections to gravitational waves <https://link.aps.org/doi/10.1103/PhysRevD.101.084050>



A visual representation of how  $\epsilon_3$  affects the ergospheres of Kerr and JP spacetimes.

# Posterior Distribution GW150914 220 mode,

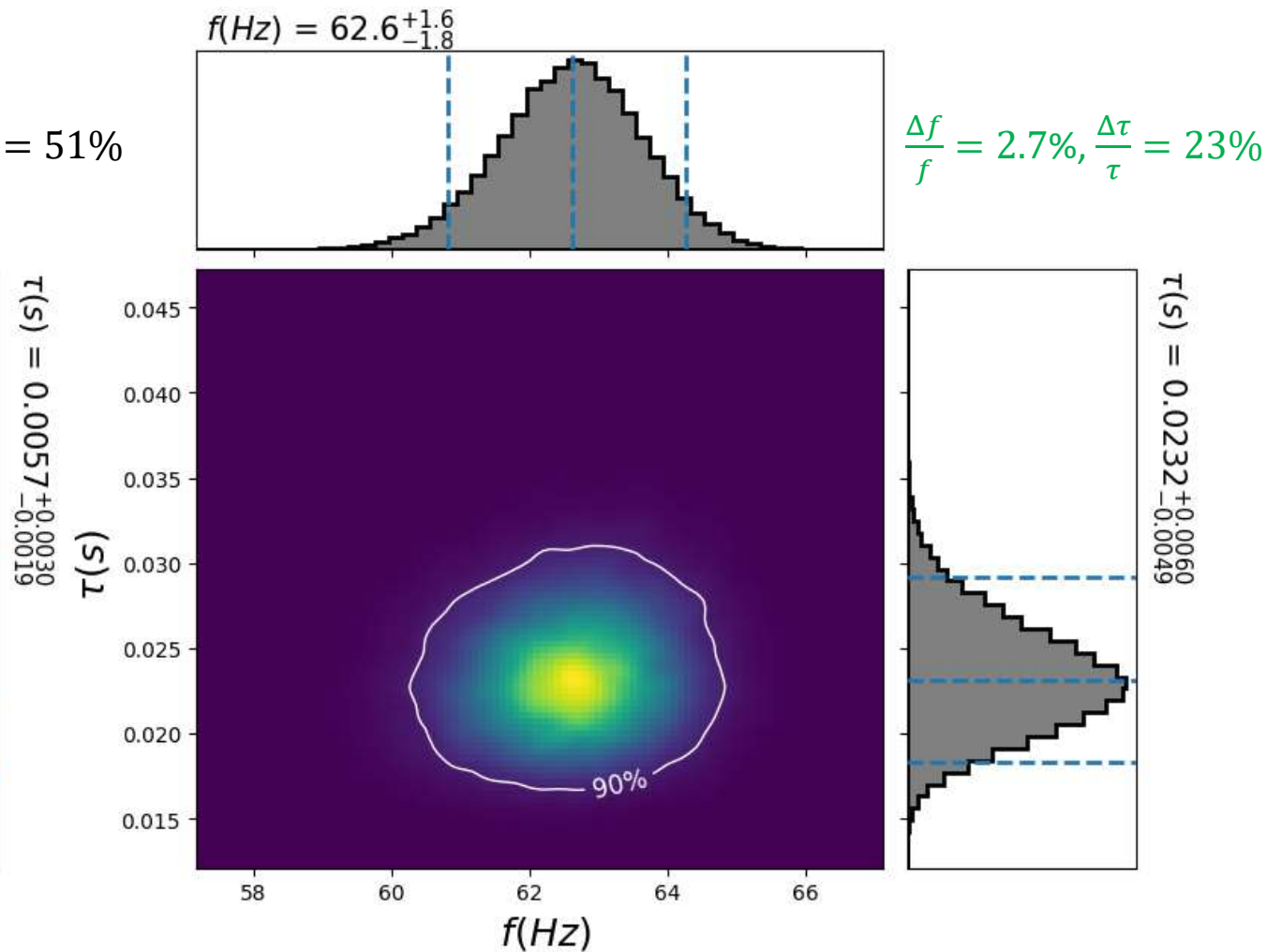
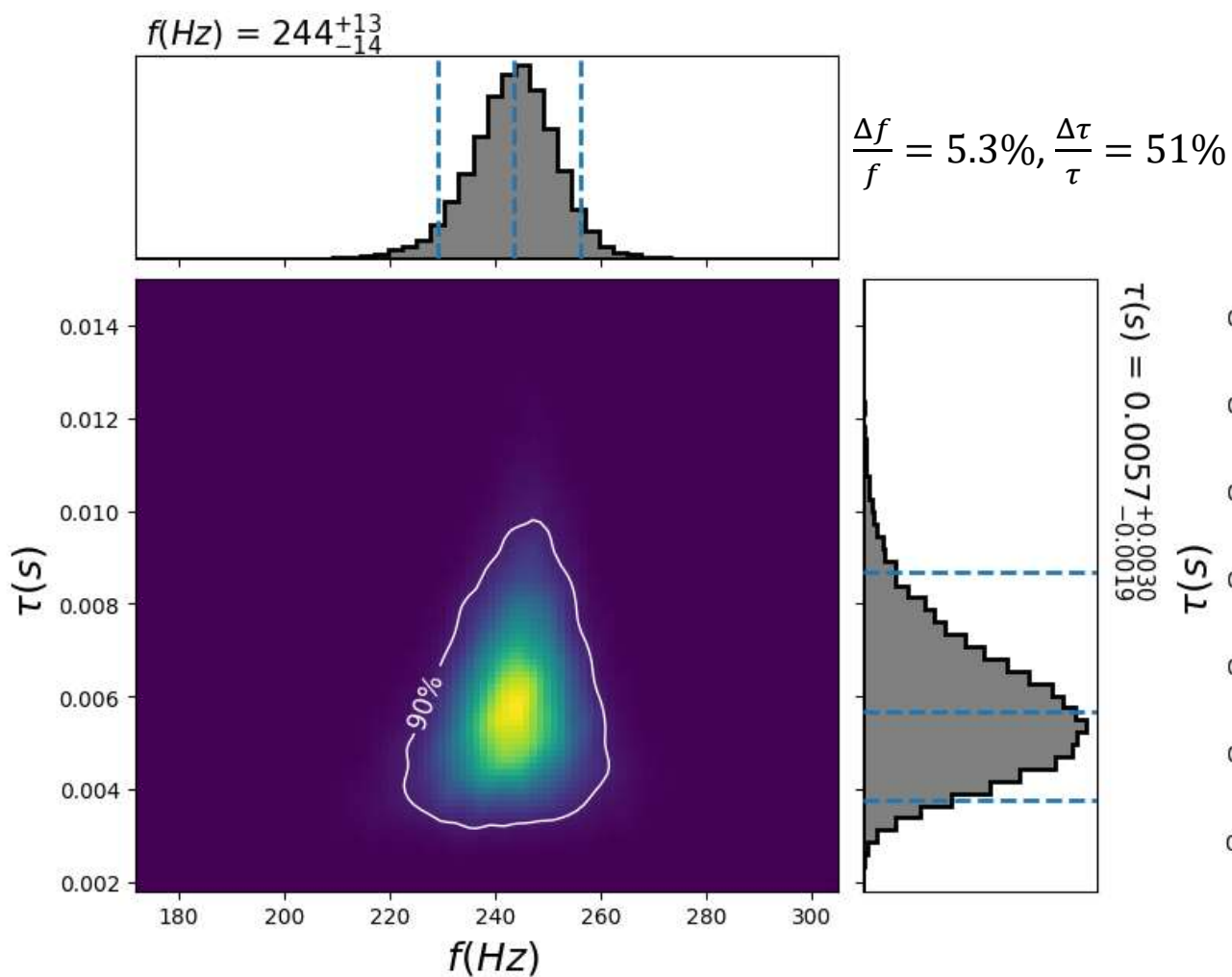
( $\epsilon_3 = [-30, 300]$ ,  $M=[20, 300]$ )

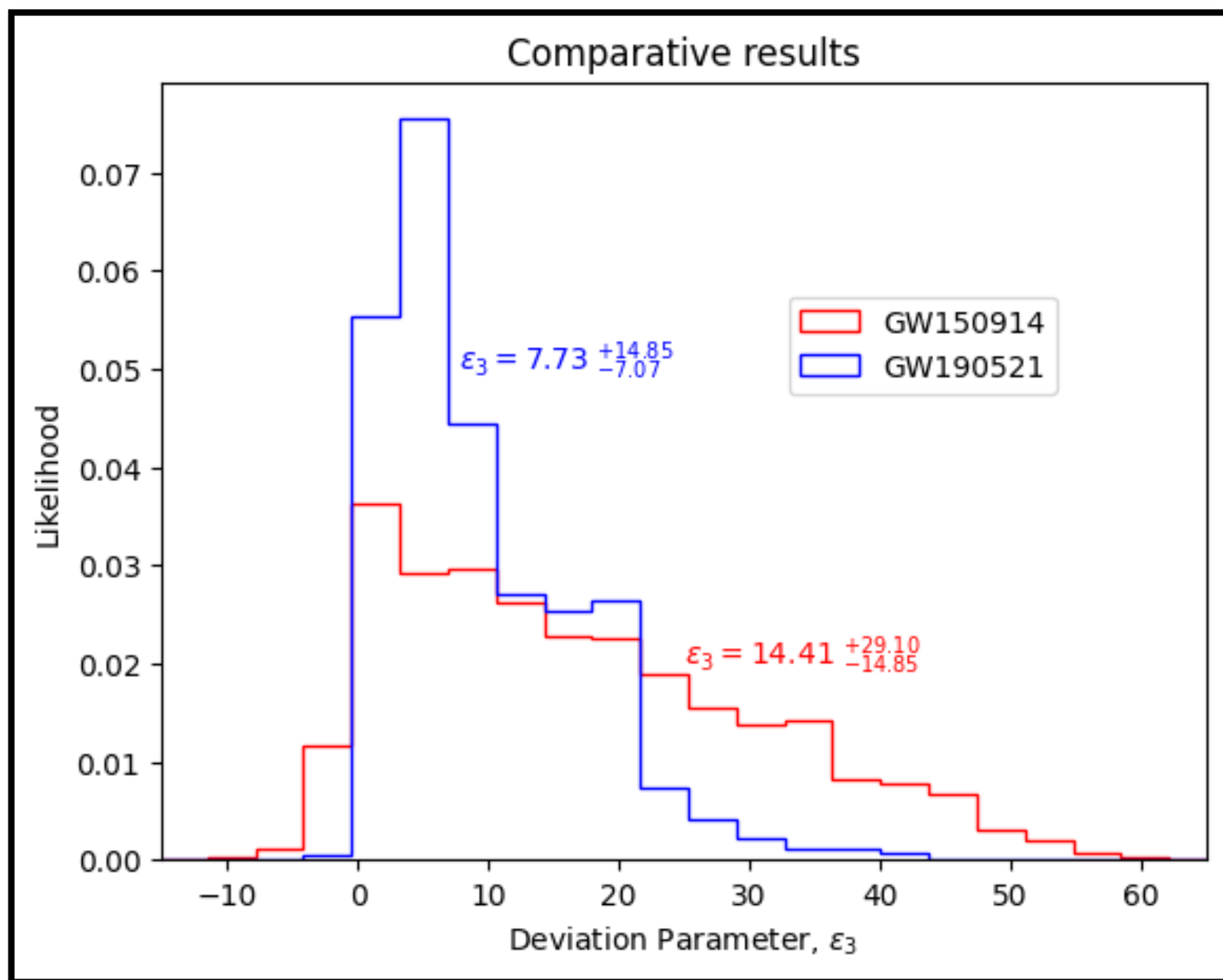


# Frequency-Tau Distribution

• GW150914

• GW190521



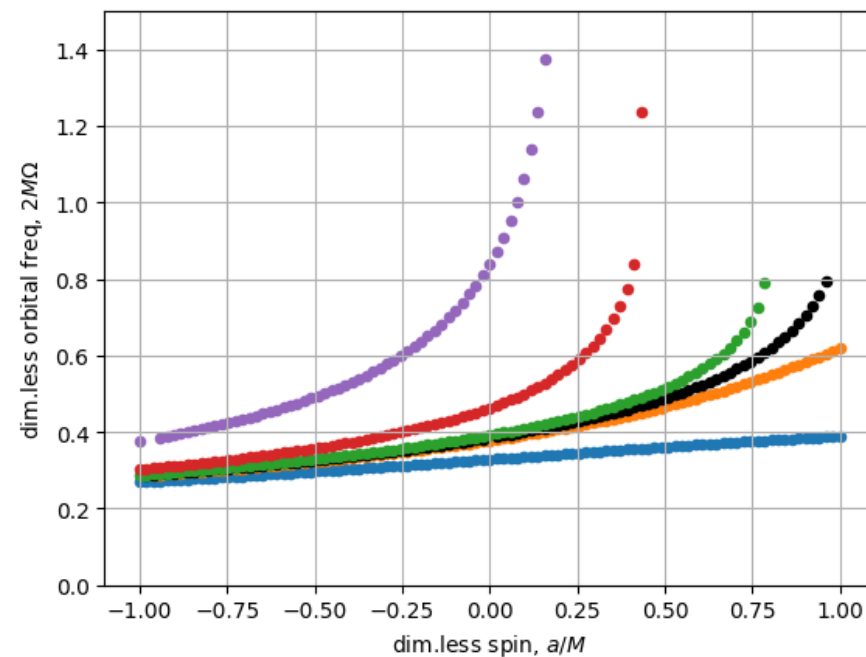
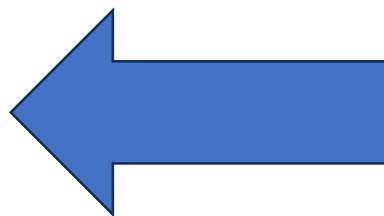
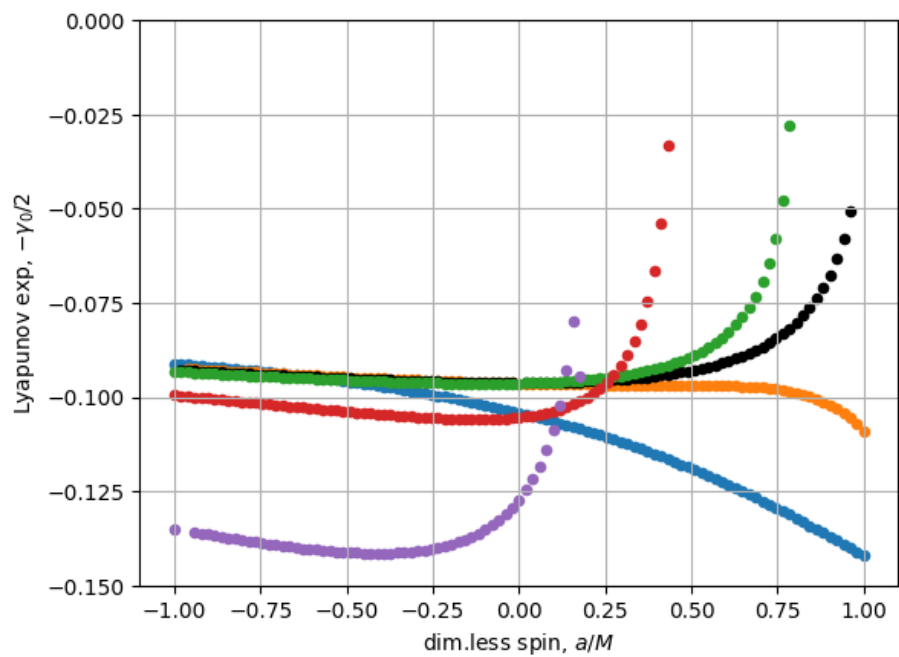
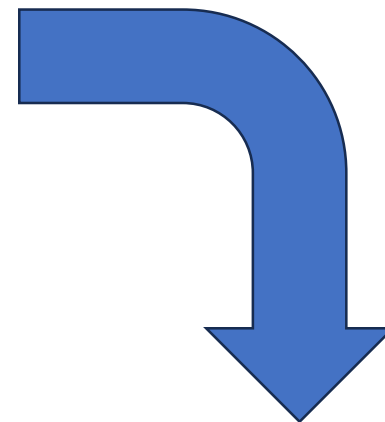
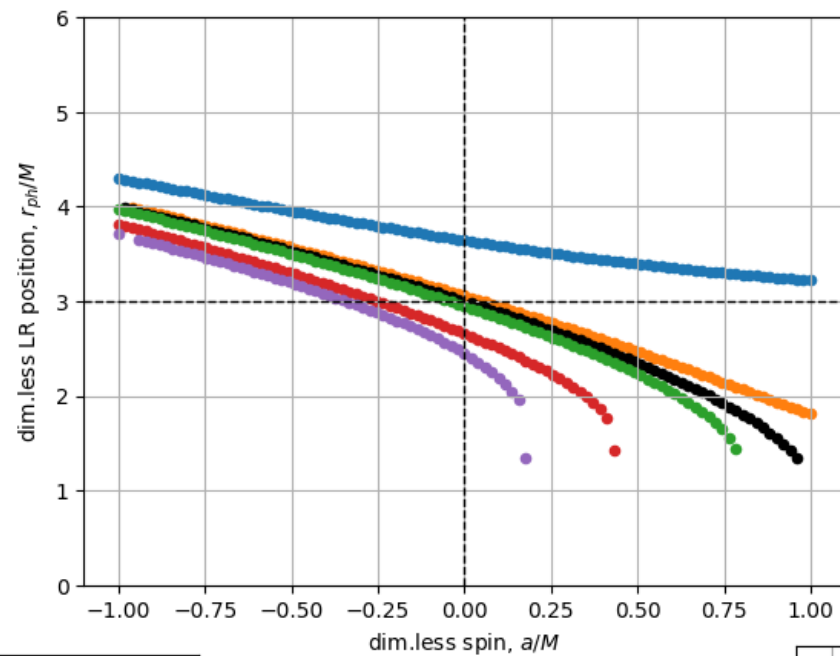
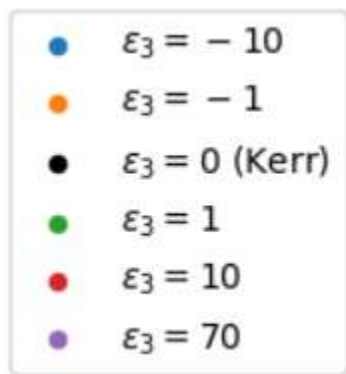


# Conclusions

- Ringdown is sensitive to post-merger metric.
- Spin is anti-correlated with  $\epsilon_3$  in the ringdown.
- GW190521 is a good candidate for ringdown analysis.
- A single ringdown mode is unlikely to be competitive with the inspiral.
- $\omega_R^{330} = \frac{3}{2} \omega_R^{220}$ , in the eikonal-limit.
- Use multimode observation in GW190521 😊



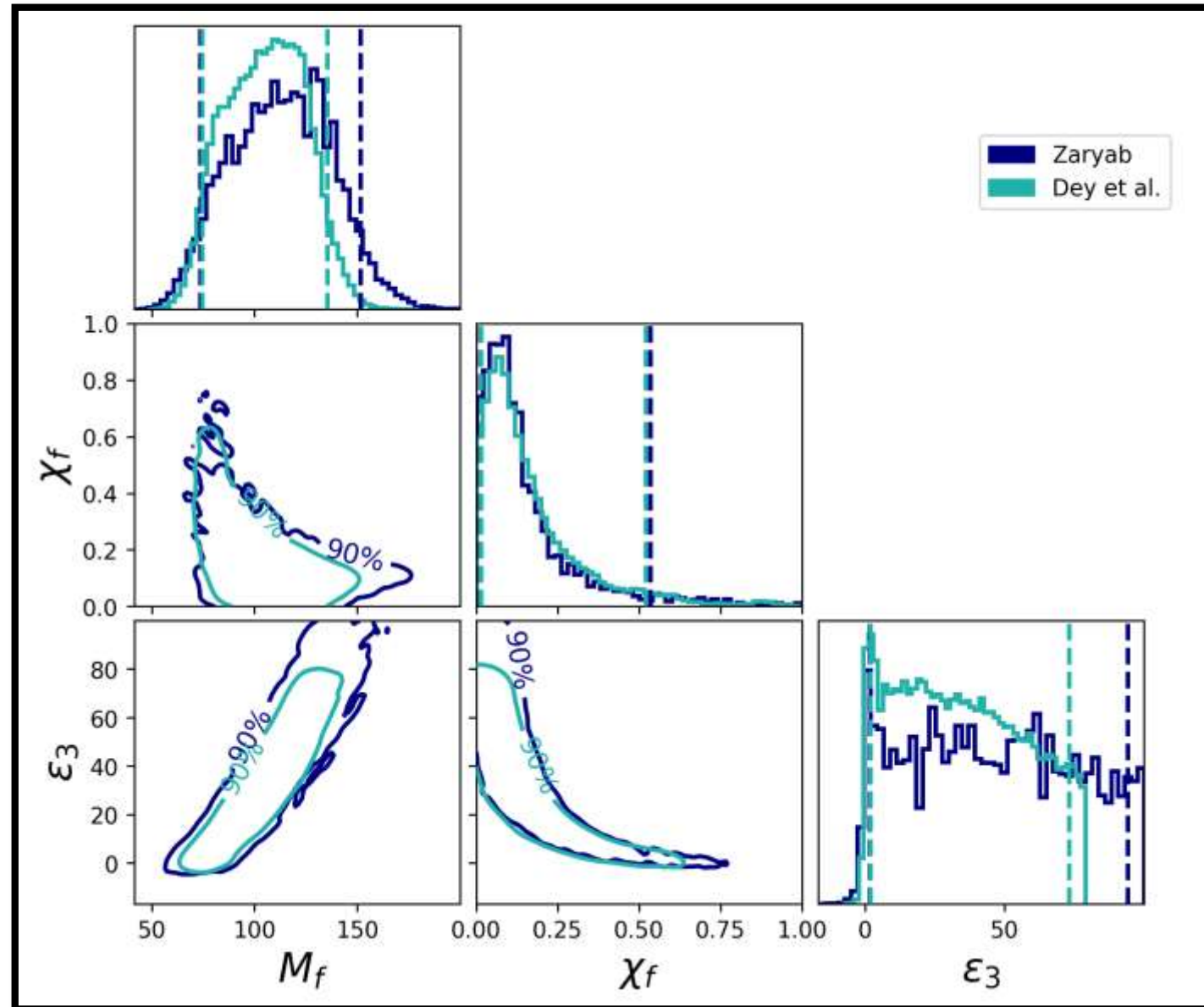
THANK YOU!



# Posterior Distribution GW150914, ( $\epsilon_3 = [-30,100], M=[20,200]$ )

Dey et al. priors

- $\epsilon_3 = [-30,100]$
- $\chi = [0,0.99]$
- $M=[20,200]$



# Post-Kerr QNM Validity<sup>{5}</sup>

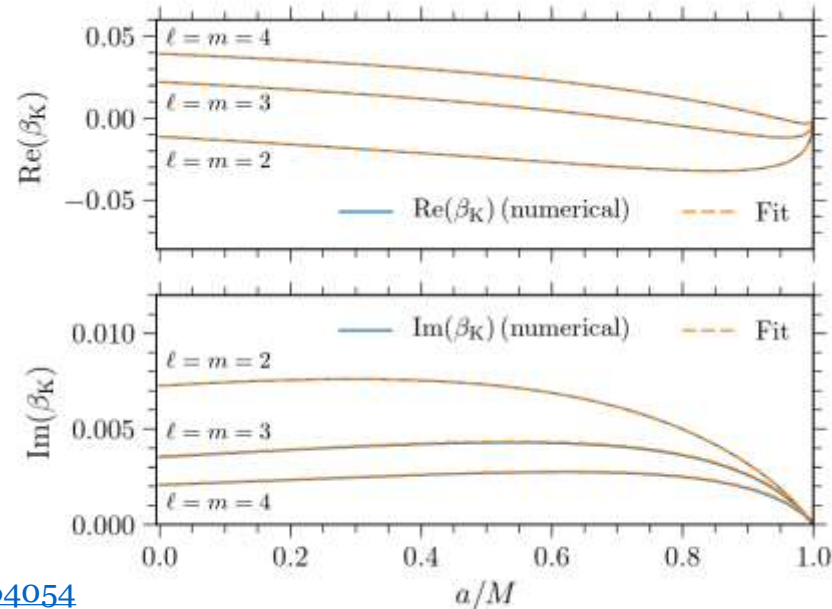
- QNM spectrum used for GW analysis based on Kerr metric
- Ensure that it is valid for a non-Kerr geometry
- Introduce an offset function,  $\beta_K$

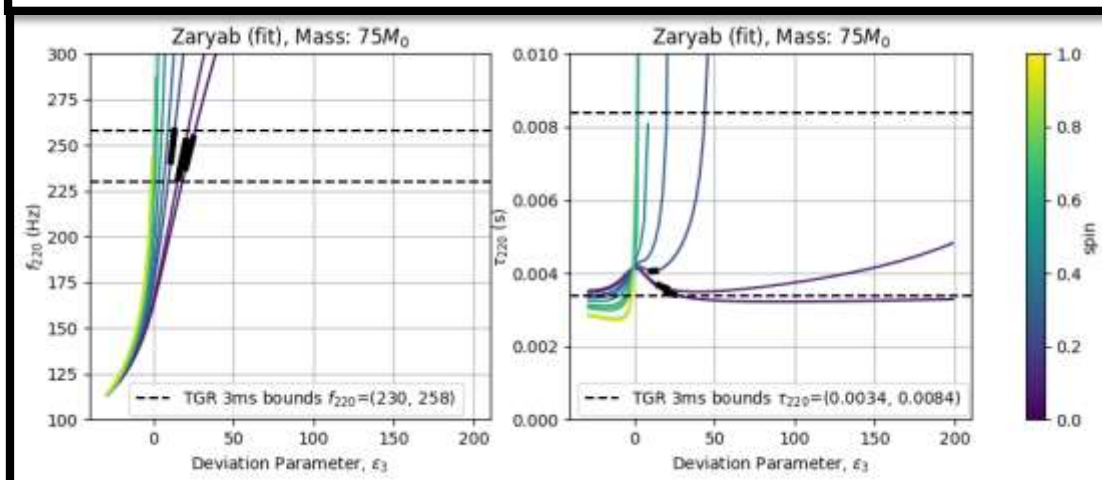
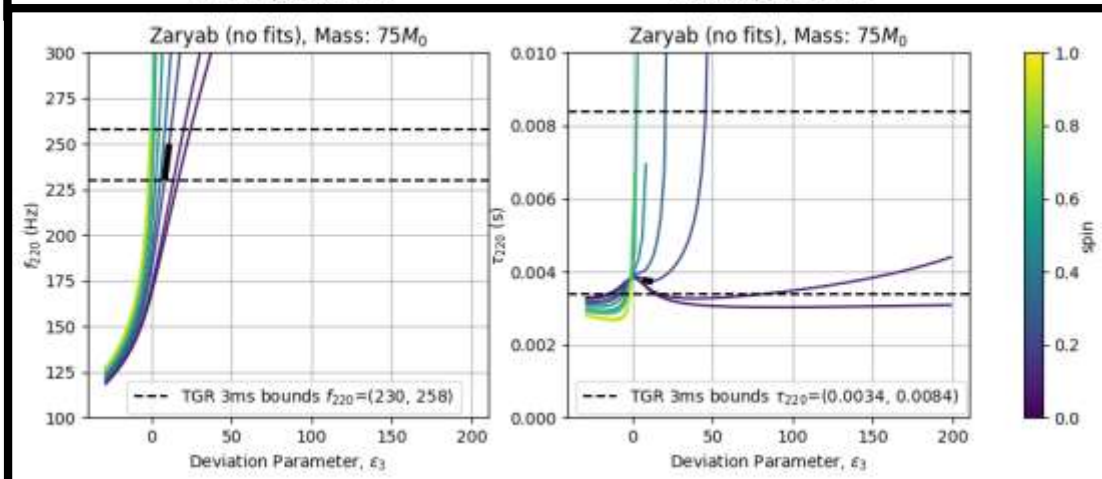
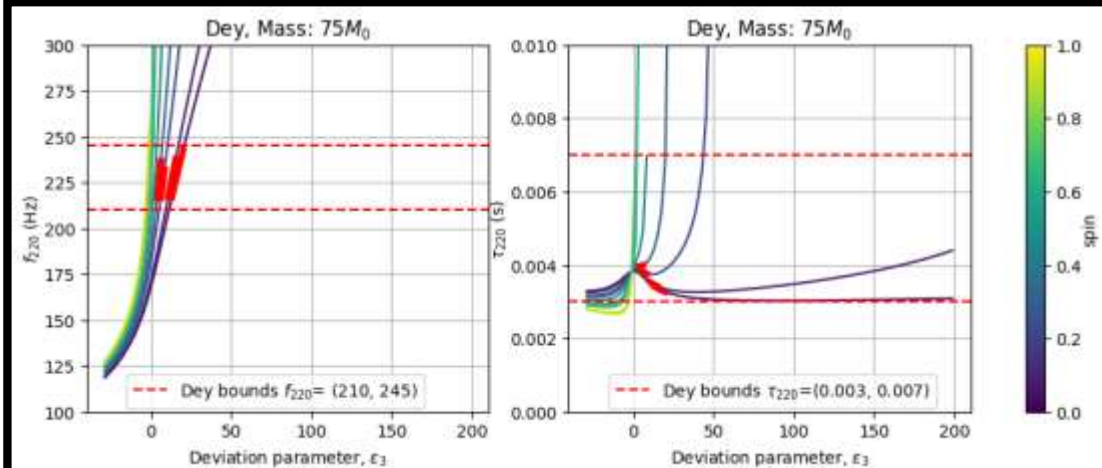
$$\omega_{\text{obs}} = \sigma + \beta_K$$

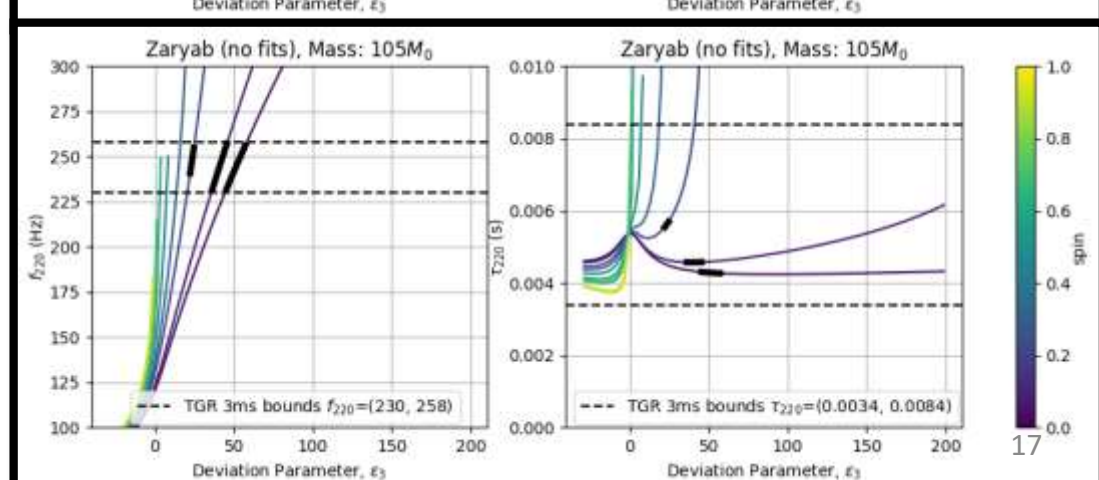
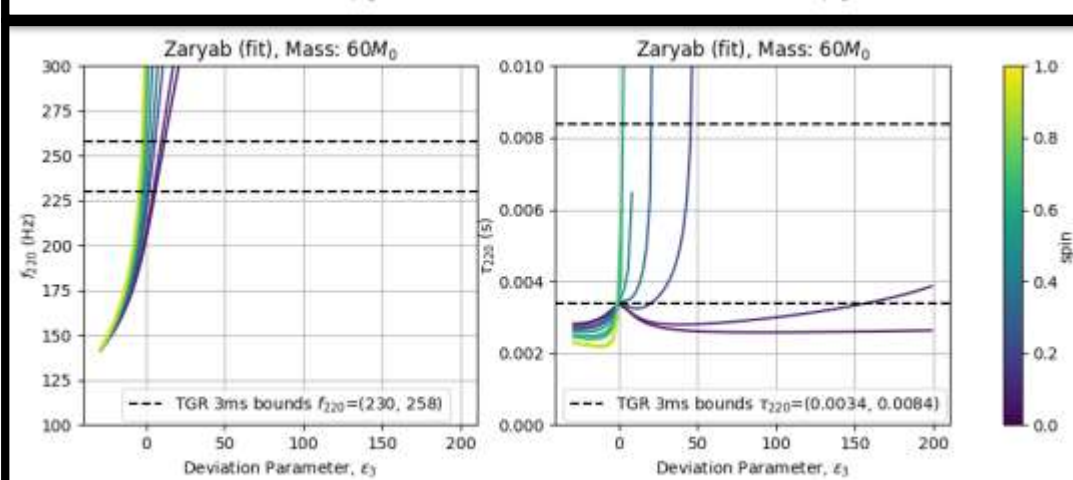
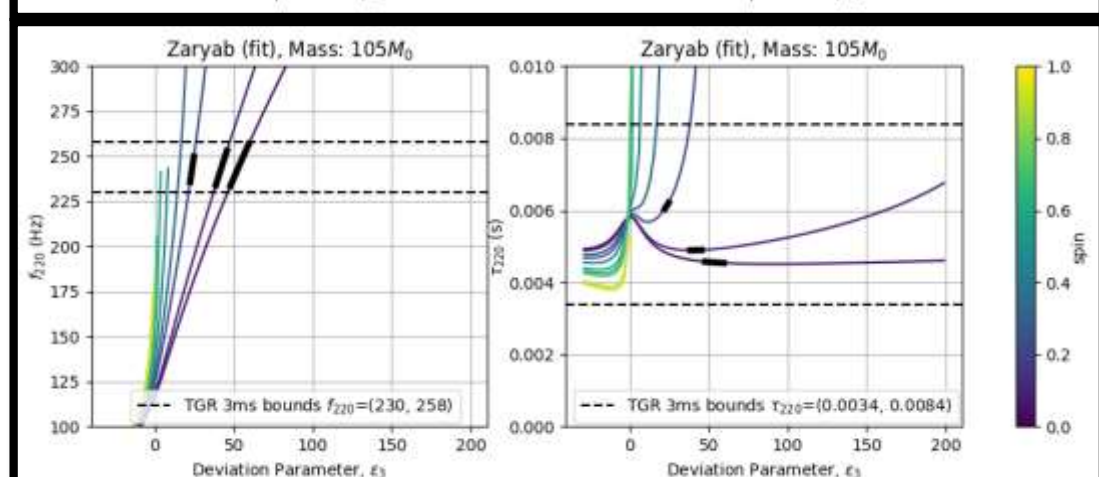
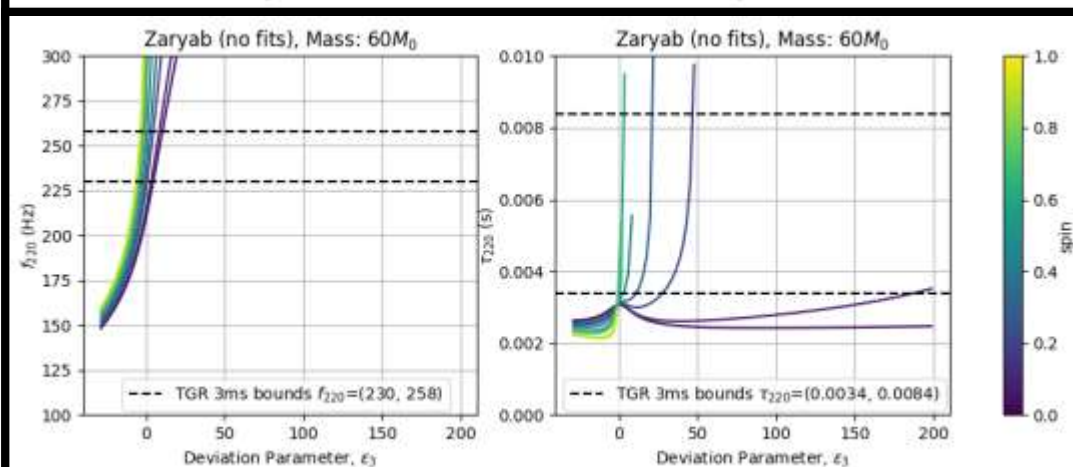
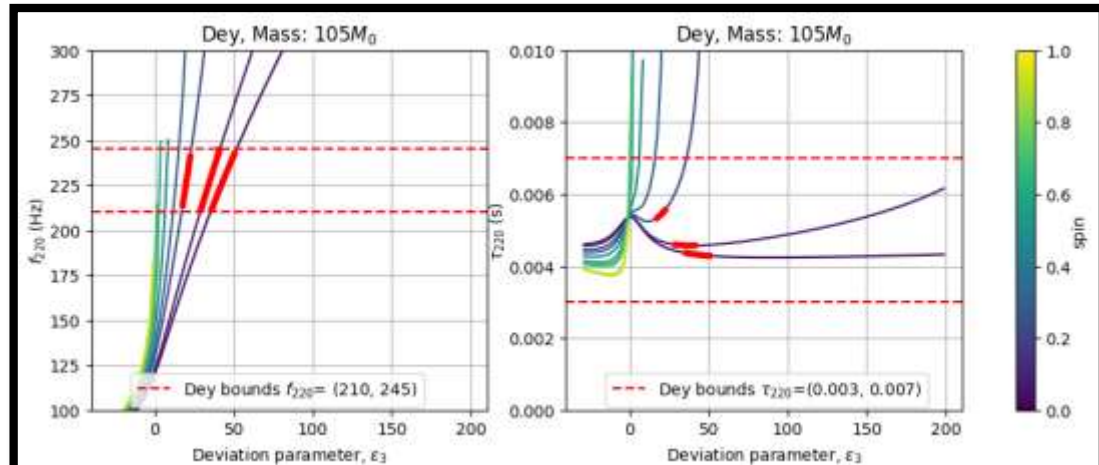
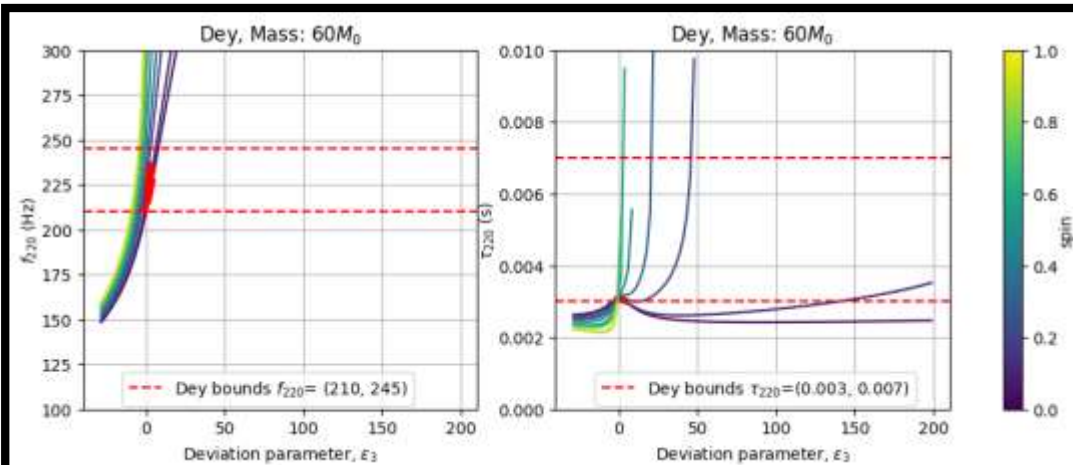
$$\omega_K = \sigma_K + \beta_K$$

$$\omega_{\text{obs}} - \omega_K = \sigma - \sigma_K \neq 0$$

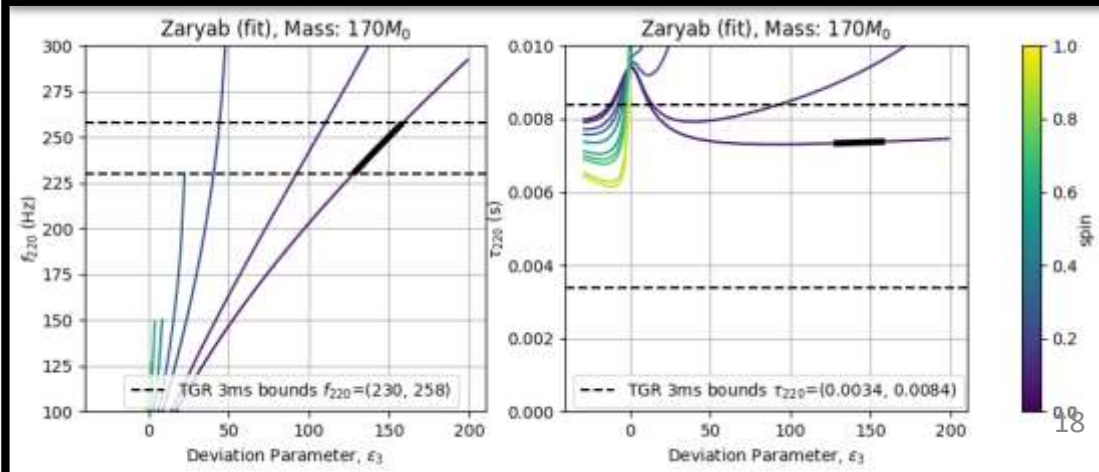
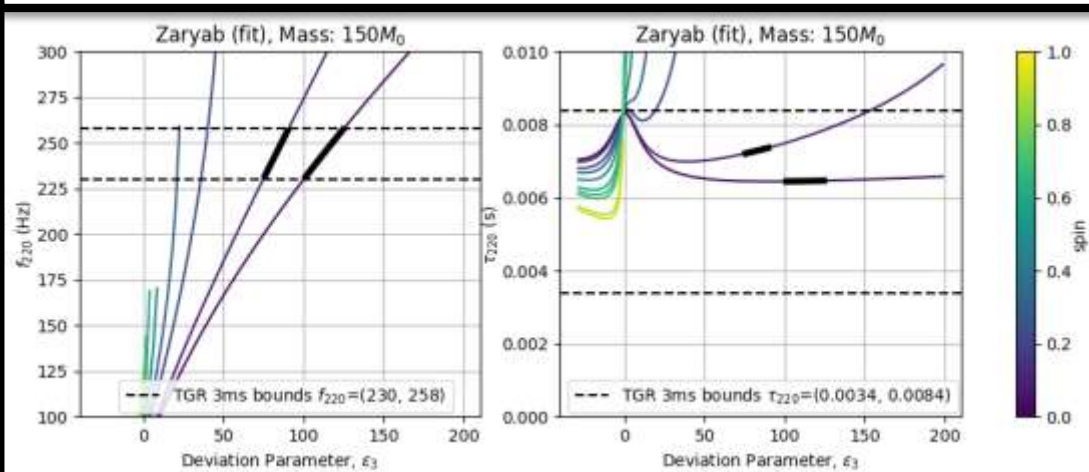
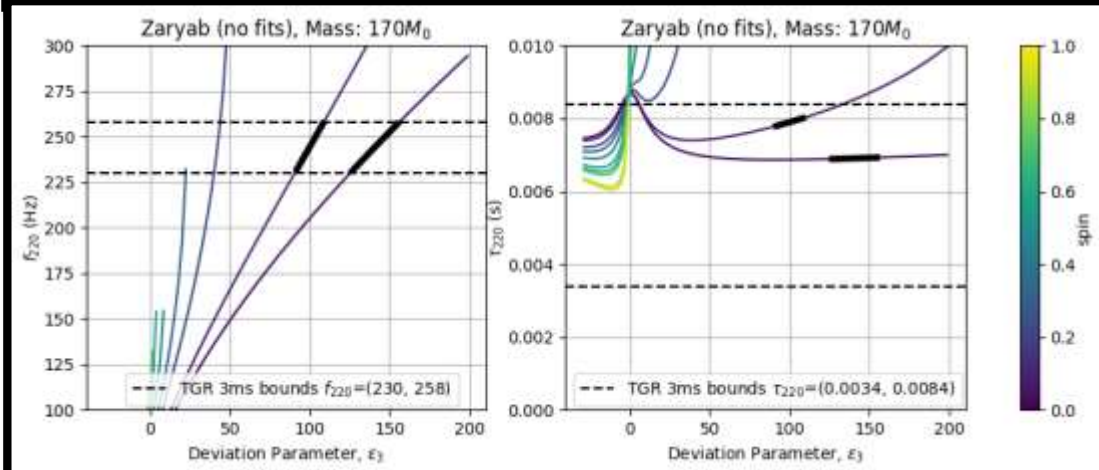
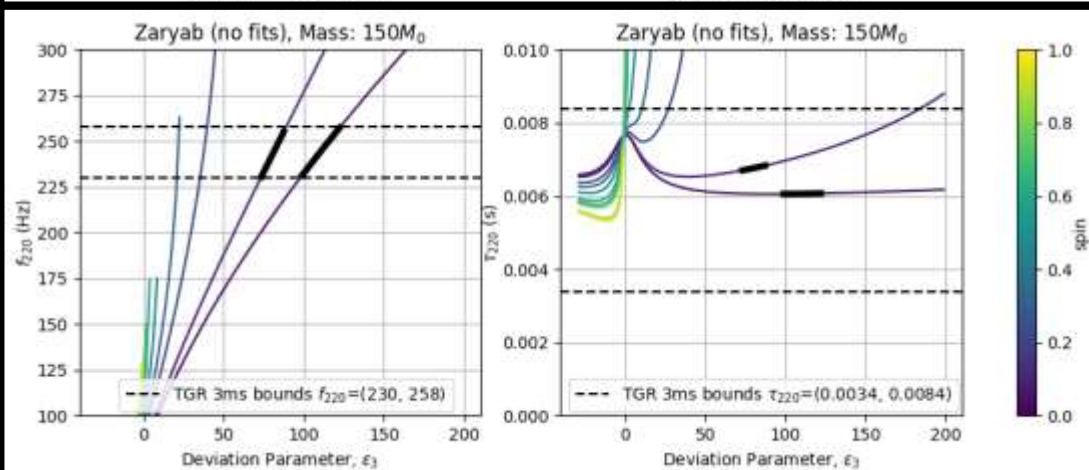
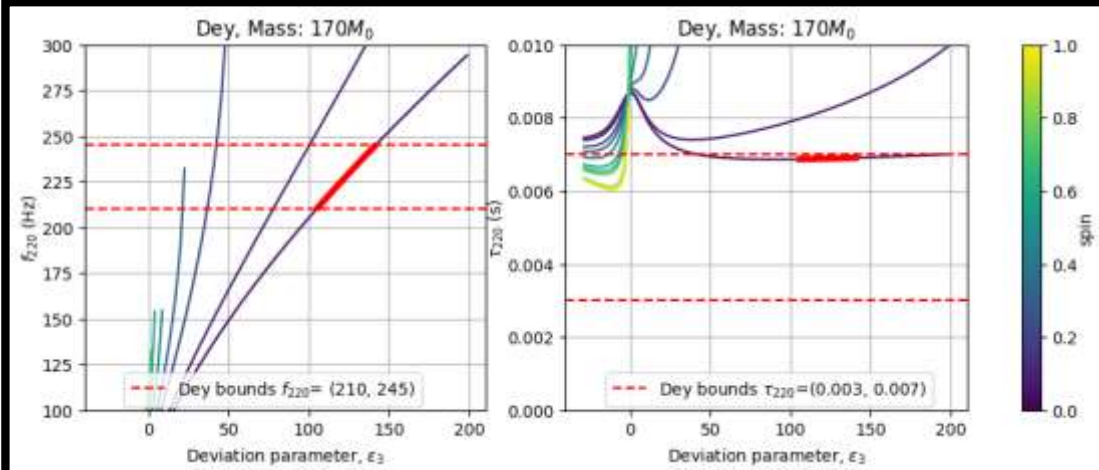
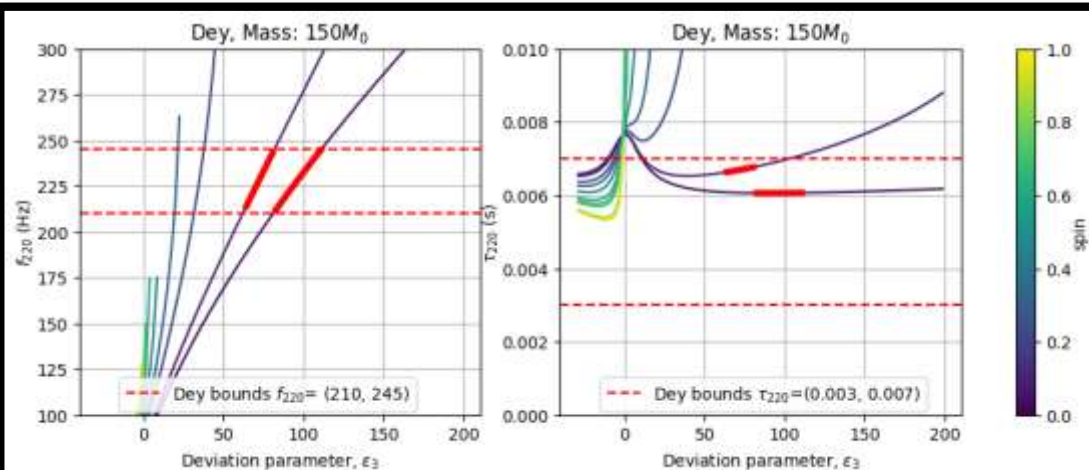
$$\sigma = \sigma_K + \delta\sigma$$











# Extras

