A parametrized test of General Relativity applied to LISA Massive Black Hole Binaries

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LISA in Toulouse

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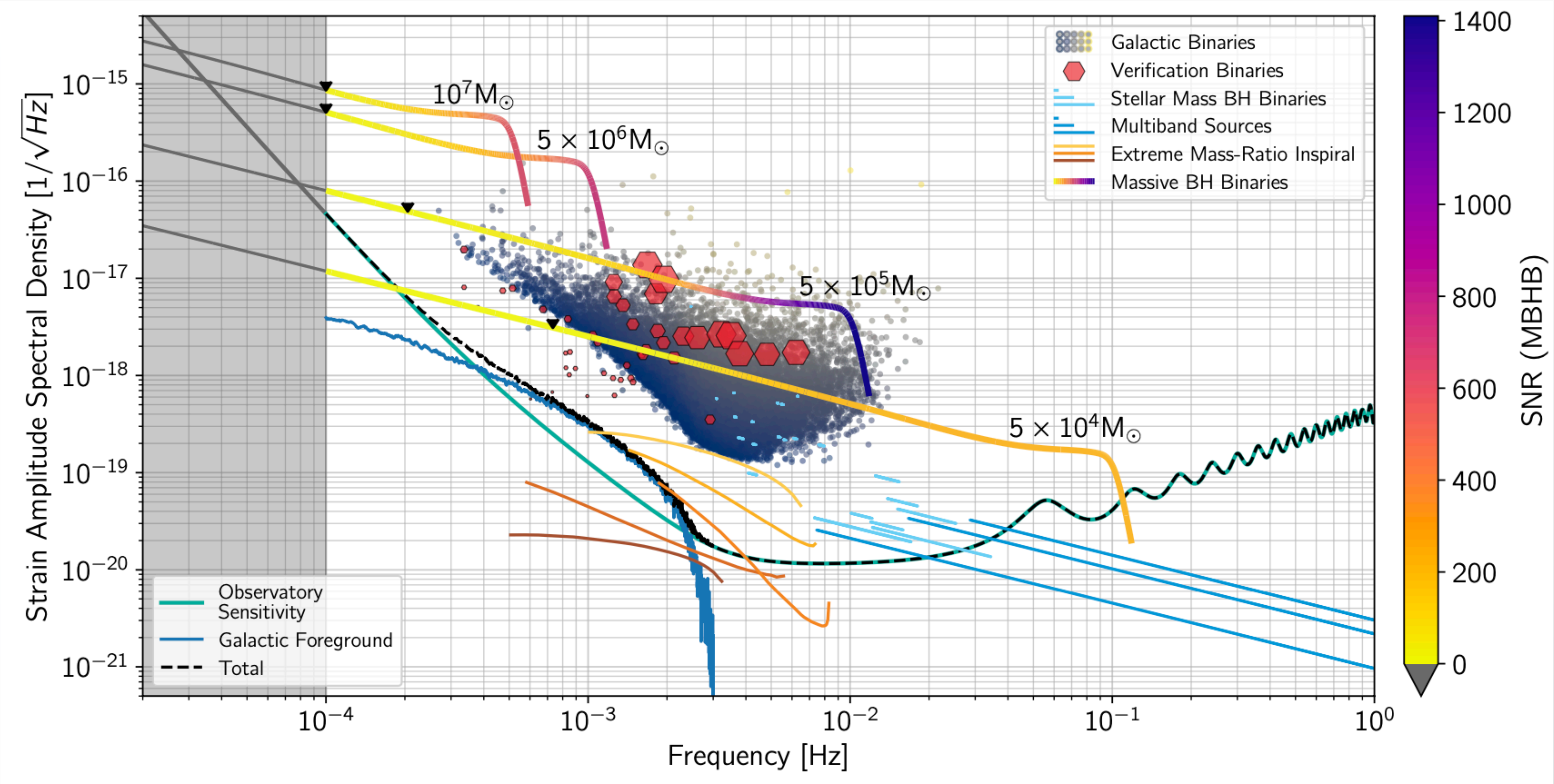
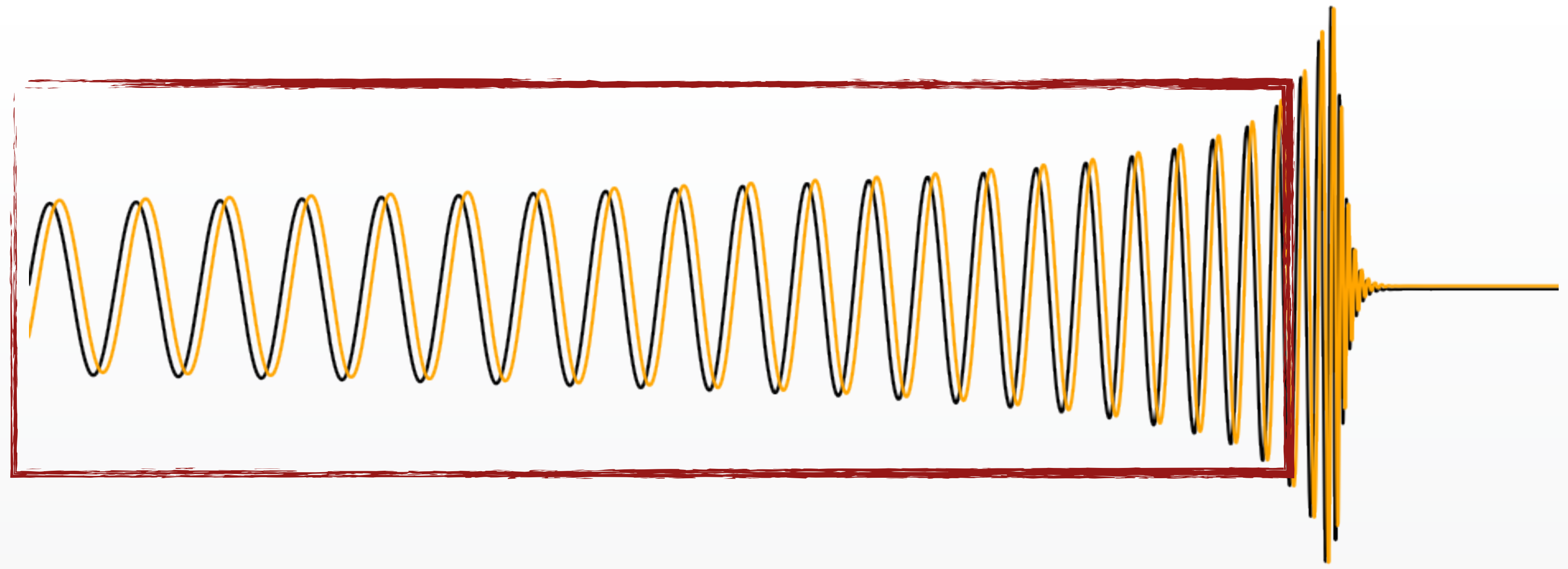
MBHBs:
Very different signal morphology depending on the total mass



Credits: LISA Definition Study Report [arxiv:2402.07571]

Flexible Theory Independent (FTI) method

A. K. Mehta, et. al. Phys. Rev. D 107, 044020 (2023)



1. The polarizations $h_+, h_\times$ decomposed in spin-weighted spherical harmonics

$$h_+ - ih_\times = \sum_{l\geq 2} \sum_{m=-l}^{l} -2Y_{l,m} h_{lm}$$

During the inspiral,
in Stationary Phase Approximation (SPA)
each mode can be written as

$$\tilde{h}_{lm}(f) = A_{lm}(f) e^{-i\psi_{lm}^{GR_{SPA}}(f)}$$

for each mode holds $\psi_{lm}^{GR_{SPA}}(\frac{mf}{2}) \sim \frac{m}{2}\psi_{22}(f)$

2. GR phase in PN theory

$$\psi_{lm}^{GR_{SPA}}(f) \sim \frac{1}{v^5}\frac{m}{2}\left[\sum_{n=0}^{7} \phi_n^{PN} v^n + \sum_{n=5}^{6} \phi_{n(log)}^{PN} v^n \log v\right]$$

$$v = (GM\omega/c^3)^{1/3}, \quad \omega = 2\pi f/m$$

3. we add a generic deviation to the GR phase

PN deviation parameters to infer

$$\delta\psi_{lm}(f) \sim \frac{1}{v^5}\frac{m}{2}\left[\sum_{n=-2}^{7} \delta\phi_n^{PN} v^n + \delta k_s \phi_{4,ks}^{PN} v^4 + \delta k_s \phi_{6,ks}^{PN} v^6 + \sum_{n=5}^{6} \delta\phi_{n(log)}^{PN} v^n \log v\right]$$

signal with GR deviation $\tilde{h}_{lm}(f) = A_{lm}(f) e^{-i(\psi_{lm}^{GR_{SPA}} + \delta\psi_{lm})}$

Flexible Theory Independent (FTI) method

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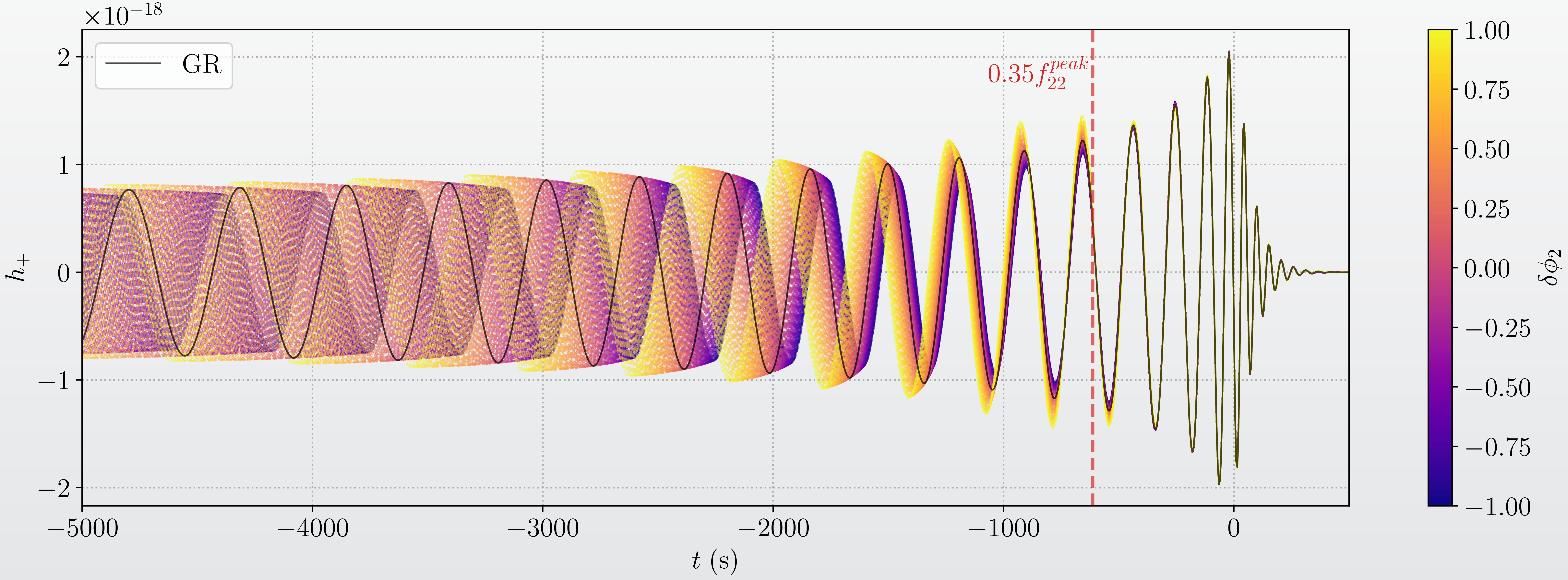
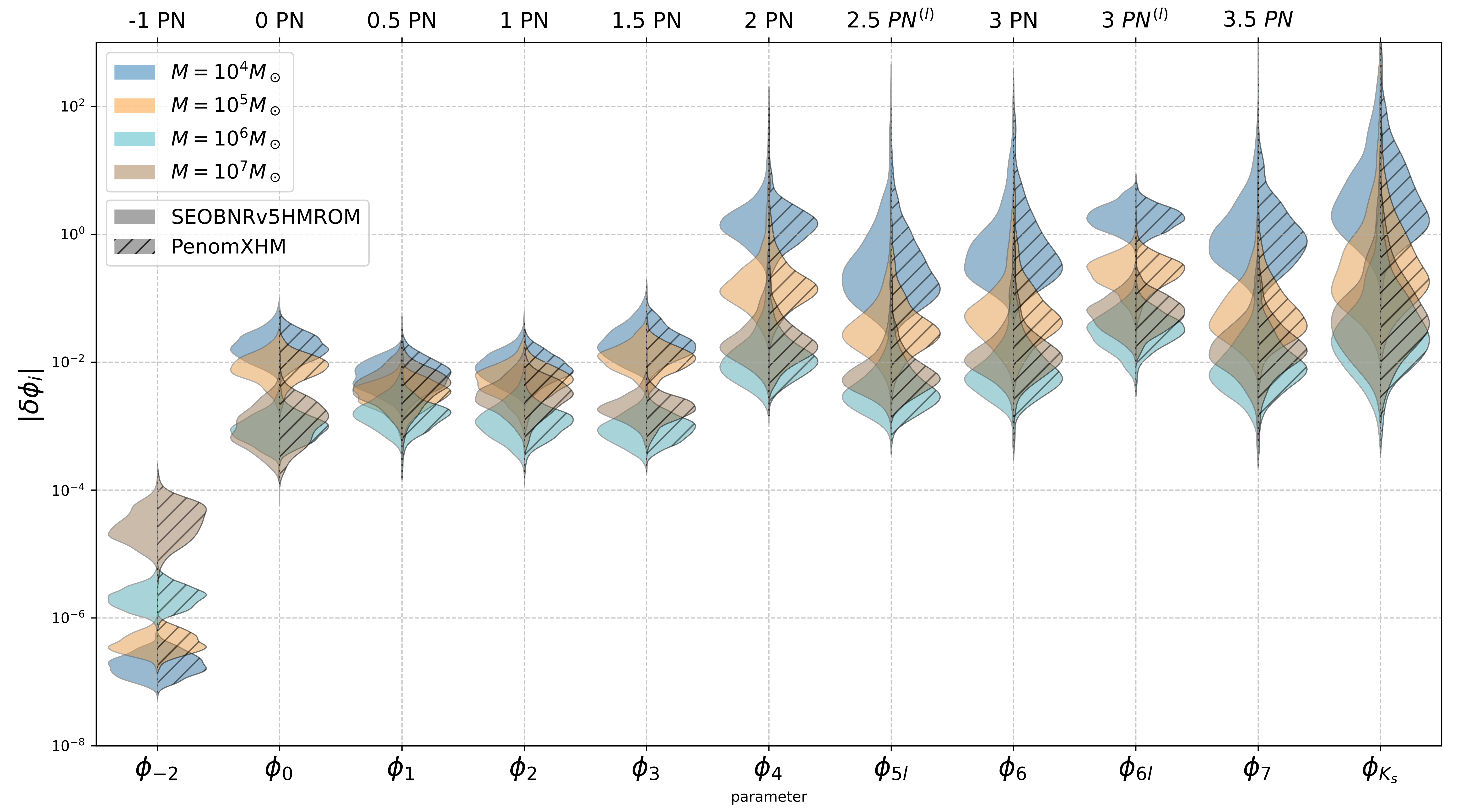
time-domain non-GR waveforms with
$\delta\phi_2 \in [-1,1]$





Those are constraints for **500 Fisher analyses** per mass
with fixed primary Mass $[10^4 - 10^5 - 10^6 - 10^7]\ M_\odot$ and redshift $z = 1$

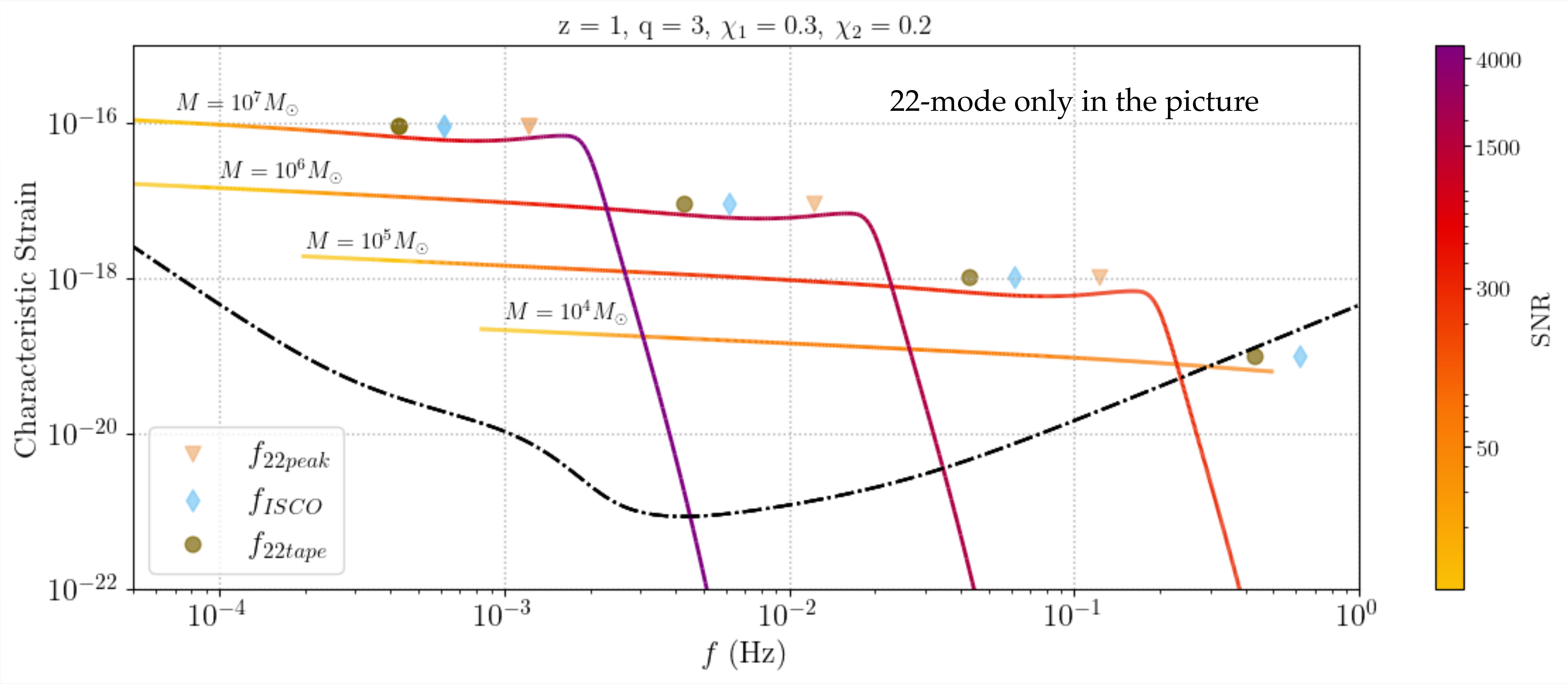
and random:
$q \in [0,\ 8]$
$\chi_1, \chi_2 \in [-1,\ 1]$
sky position

waveform models:

SEOBNRv5HMROM - PhenomXHM
(l, m) = (2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3) (5, 5)

How do our constraints change using only the inspiral?

inspiral-only vs IMR with GR merger analysis



why?

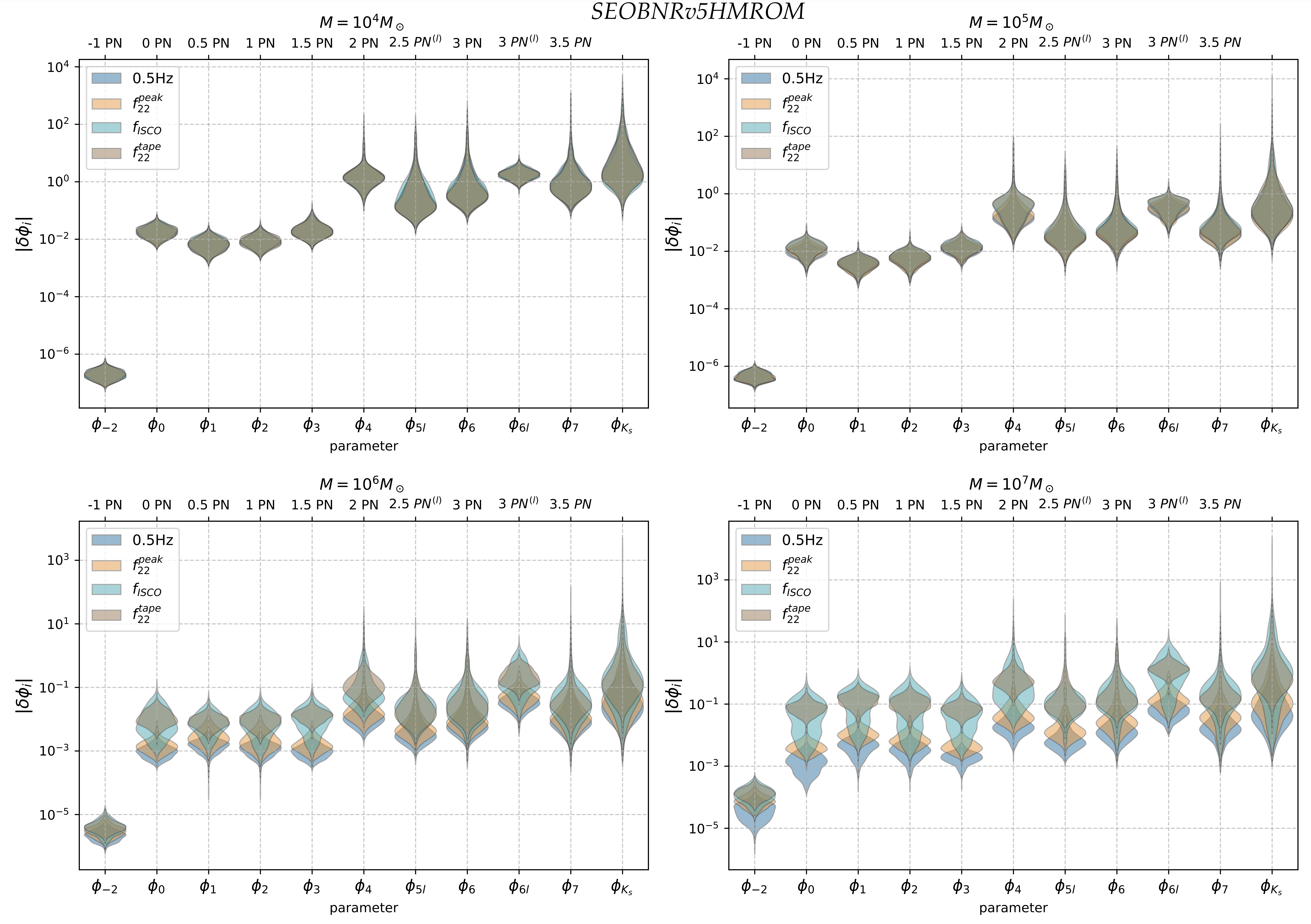
- the SPA approximation and the PN framework no longer hold when approaching the merger.
- being an inspiral test, is it consistent with including information driven by the merger-ringdown?
- is it consistent to use a GR merger when searching for GR deviation?

how?

- we cut the data at a certain frequency

  this is well-defined compared to setting to zero the signal after a certain point

IMR vs cut at: f_{22Peak} - f_{ISCO} - f_{22tape} with $SNR > 10$



what these plots are telling us?

- for **inspiral-dominated** signals, $M \in [10^4,\ 10^5]M_\odot$ there are no appreciable differences between the analysis
- moving to **merger-dominated** signals $M \in [10^6,\ 10^7]M_\odot$ the information given by the merger-ringdown becomes more and more important for constraining the PN deviation parameters

focusing on IMR vs f_{22Peak} : including also the *ringdown* part of the signal provides you better constraints

Bayesian setup

Parameter	Injected Value	Prior
Total Redshifted Mass (M_z) [$M_\odot$]	$10^4, 10^5, 10^6, 10^7$	Uniform(0.1, 10)·Inj. Val.
Mass ratio (q)	3	Uniform(1, 10)
Redshift (z)	1	Uniform(0.5, 3)
Luminosity Distance (d_L) [Mpc]	6791.8	Uniform(2863, 25924)
Dimensionless spin parameters (χ_1, χ_2)	-0.45, 0.2	Uniform(-1, 1)
Inclination (ι) [rad]	2.4127	Sine(0, π)
Phase (ϕ) [rad]	0.5251	Uniform($-\pi, \pi$)
Ecliptic longitude (λ) [rad]	-2.5523	Uniform($-\pi, \pi$)
Ecliptic latitude (β) [rad]	-0.3493	Cosine($-\pi/2, \pi/2$)
Polarization (ψ) [rad]	1.4014	Uniform(0, π)
GR deviation parameter ($\delta\phi_i$)	0	Uniform(-30, 30)

waveform model: *PhenomXHM*

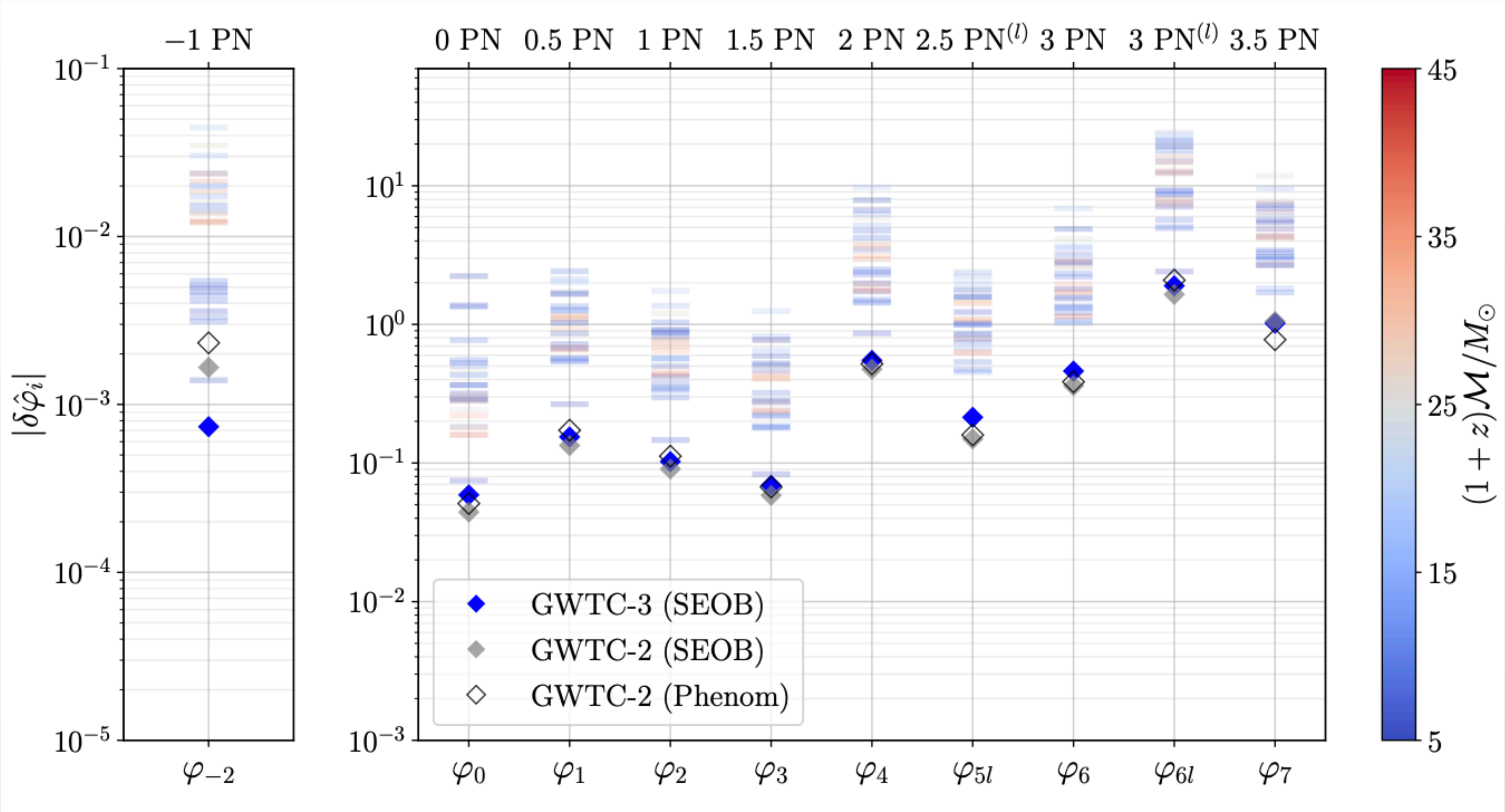
sampler: *ptmcmc*

LISA PSD: SciRDv1 with 4-yrs galactic foreground

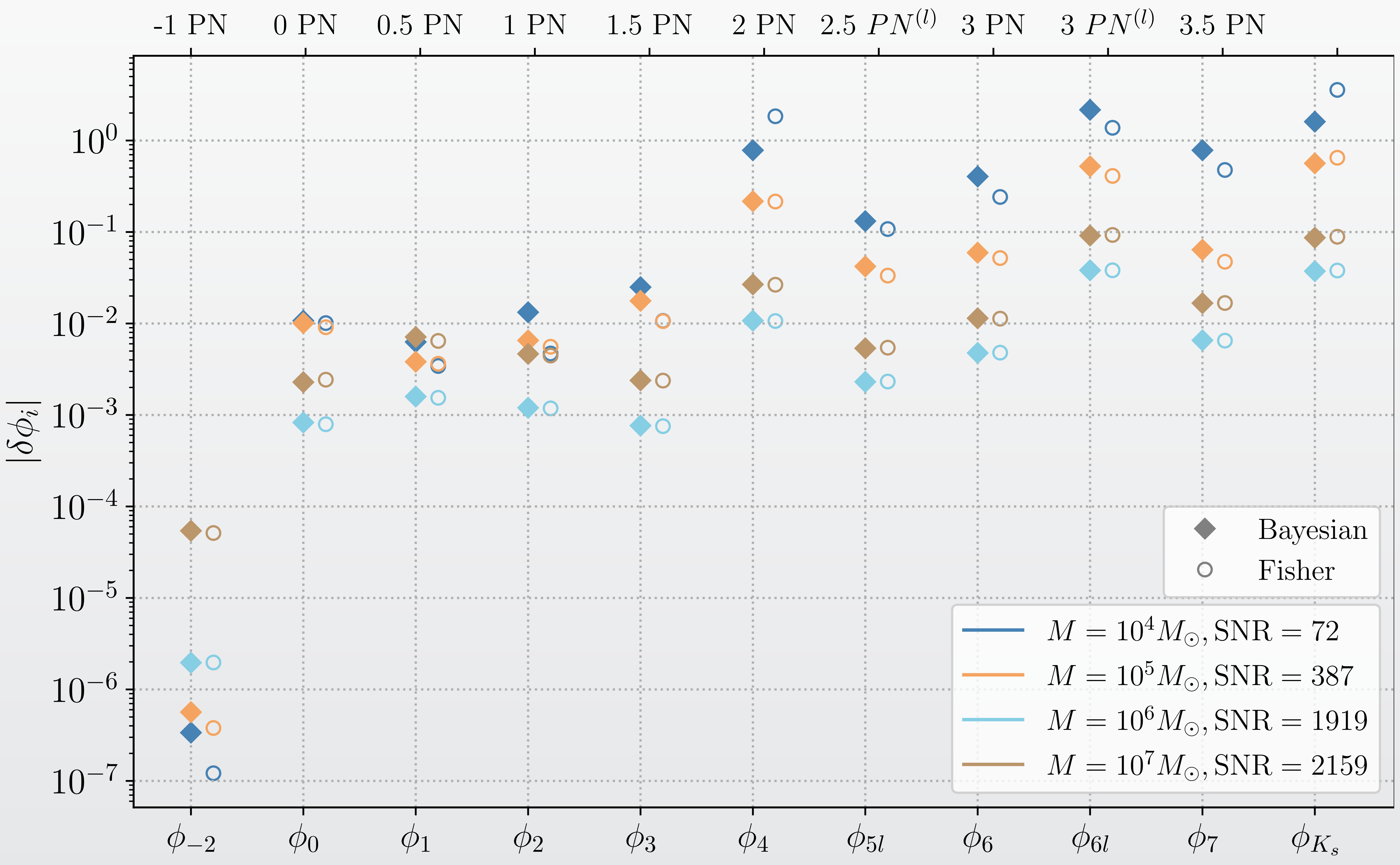
TDI Generation: 1st

Fisher Initialization

LVK GWTC-3 [arxiv:2112.06861] **combined** 90% upper bounds CL



single events 90% upper bounds CL



$q = 3, \ \chi_1 = -0.45, \ \chi_2 = 0.2, \ z = 1$

Next steps:

- What's the impact of waveform systematics on this test?
- Could systematics mimic false GR deviation, and how?
- How do systematic errors in the GR waveforms limit the constraints on deviations from GR?

What kinds of constraints can we impose on studying a realistic MBHB population?

IN PROGRESS (with V. Gennari)

A test for LISA foreground Gaussianity and stationarity
Extreme mass-ratio inspirals

Manuel PIARULLI
Riccardo BUSCICCHIO, Federico POZZOLI,
Ollie BURKE, Matteo BONETTI, Alberto SESANA

Piarulli et al. (2024) [arXiv:2410.08862]

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EMRIs with LISA

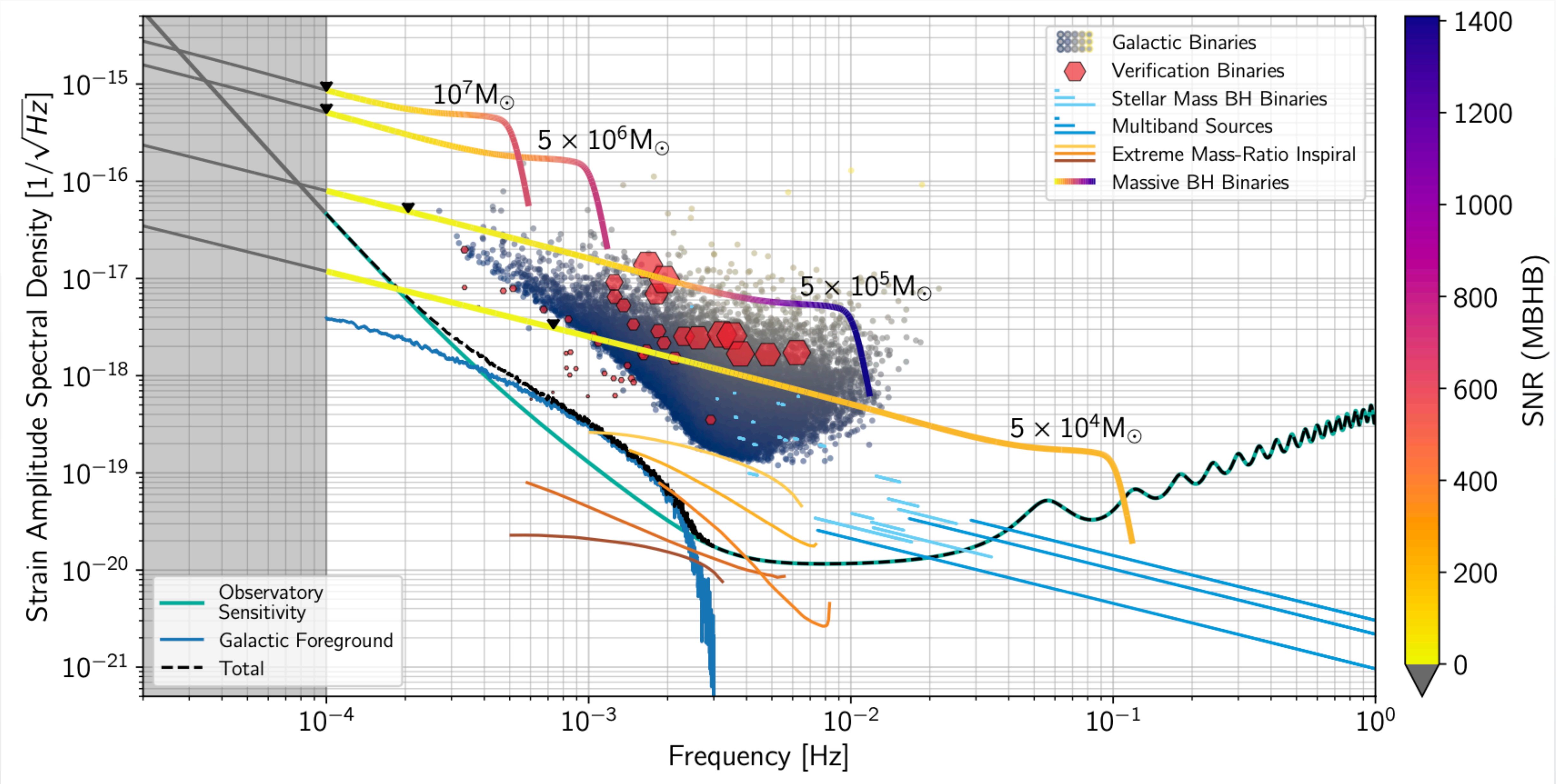
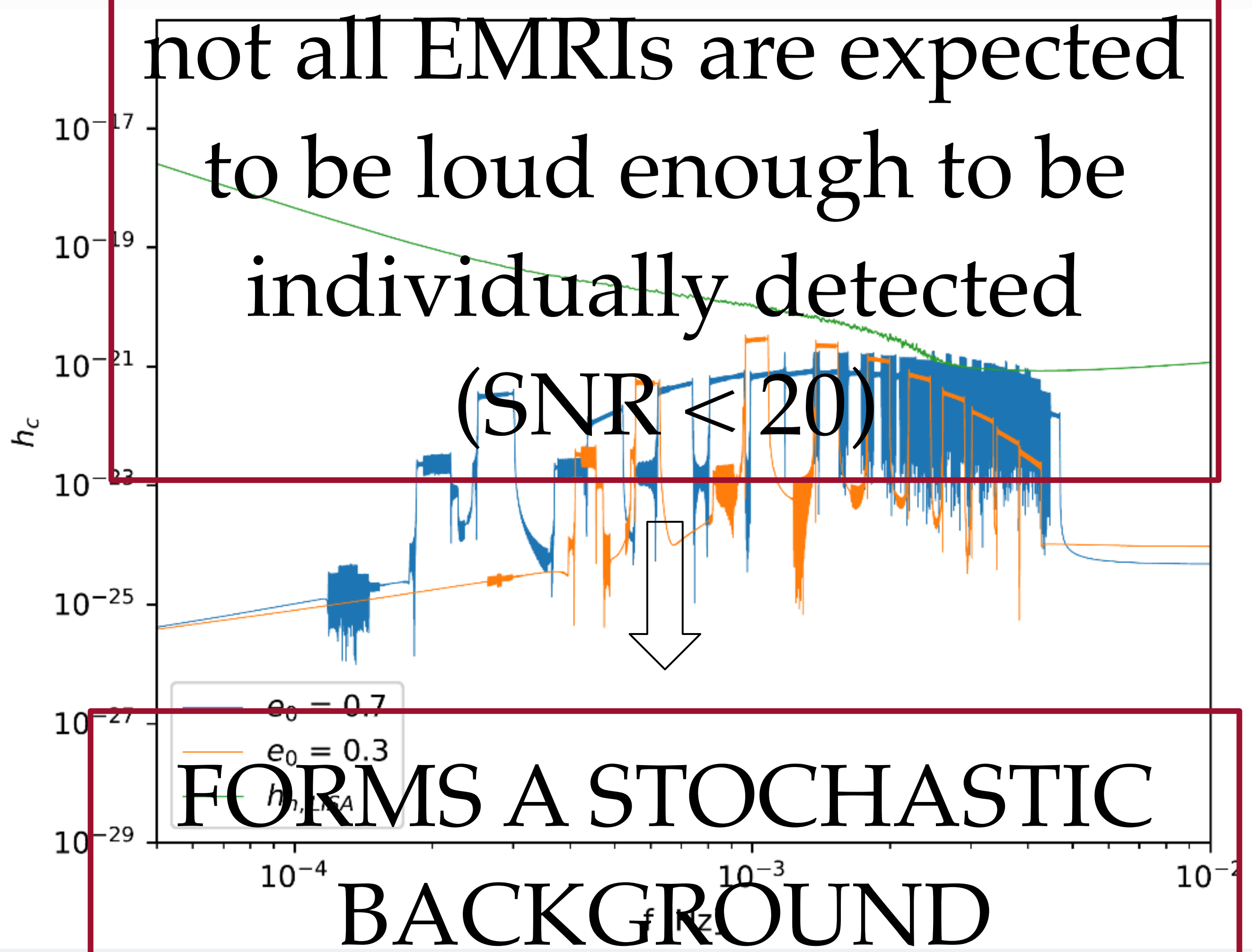


Figure: LISA sources.
Credits: [https://arxiv.org/abs/2402.07571]

$$f_n = n f_{orb}$$



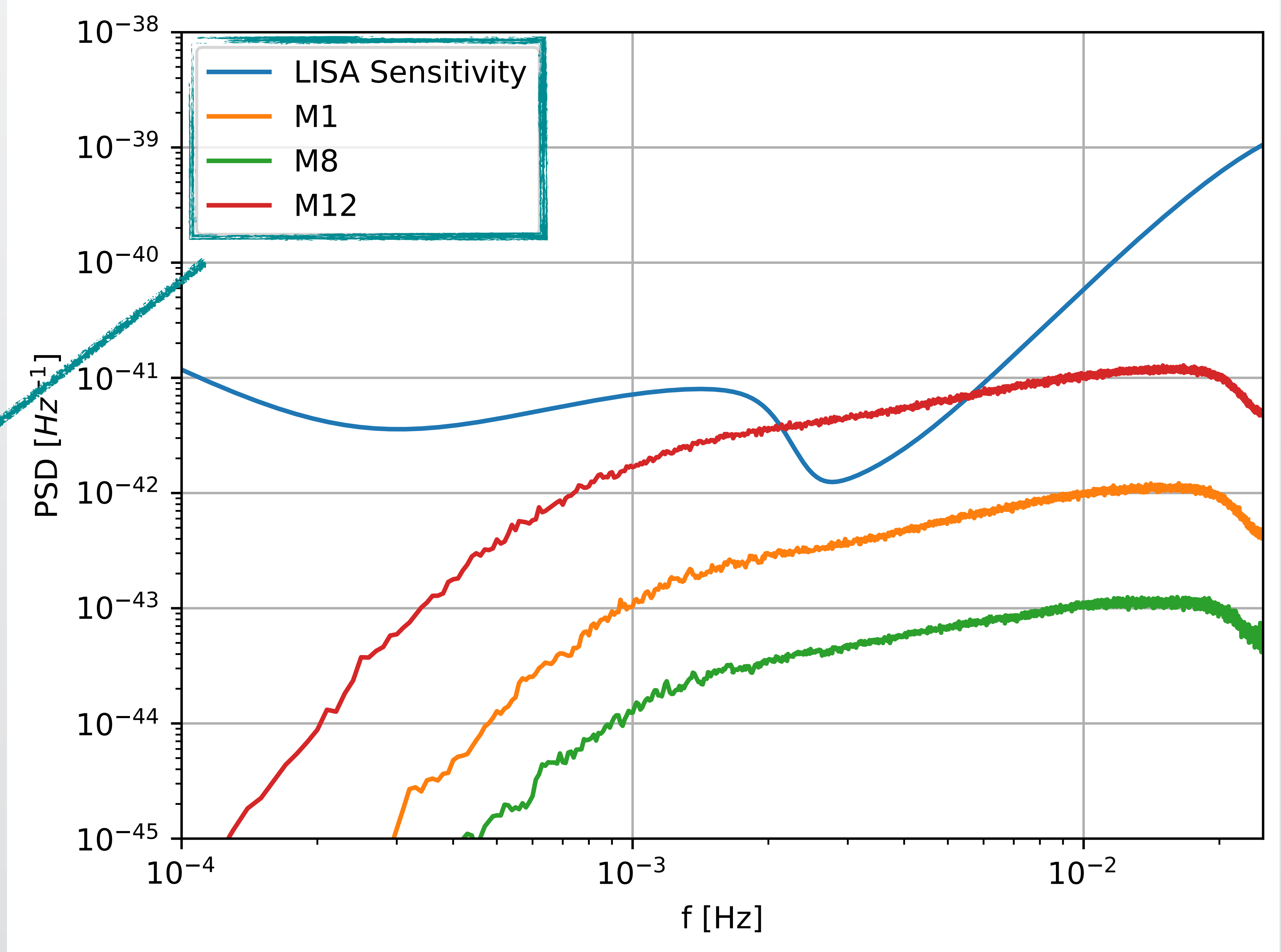
not all EMRIs are expected to be loud enough to be individually detected (SNR < 20)

FORMS A STOCHASTIC BACKGROUND

EMRIs: very eccentric systems involving light CO orbiting a MBH

$$q = \frac{m_2}{m_1} \leq 1 \qquad q \sim 10^{-3} \div 10^{-6}$$

Different astrophysical models due to uncertanties on the formation channels



Characterize the statistical properties of a time-series

a toy model to capture the relevant features

ergodicity of the signal

replace averages over statistical ensemble
with averages over time

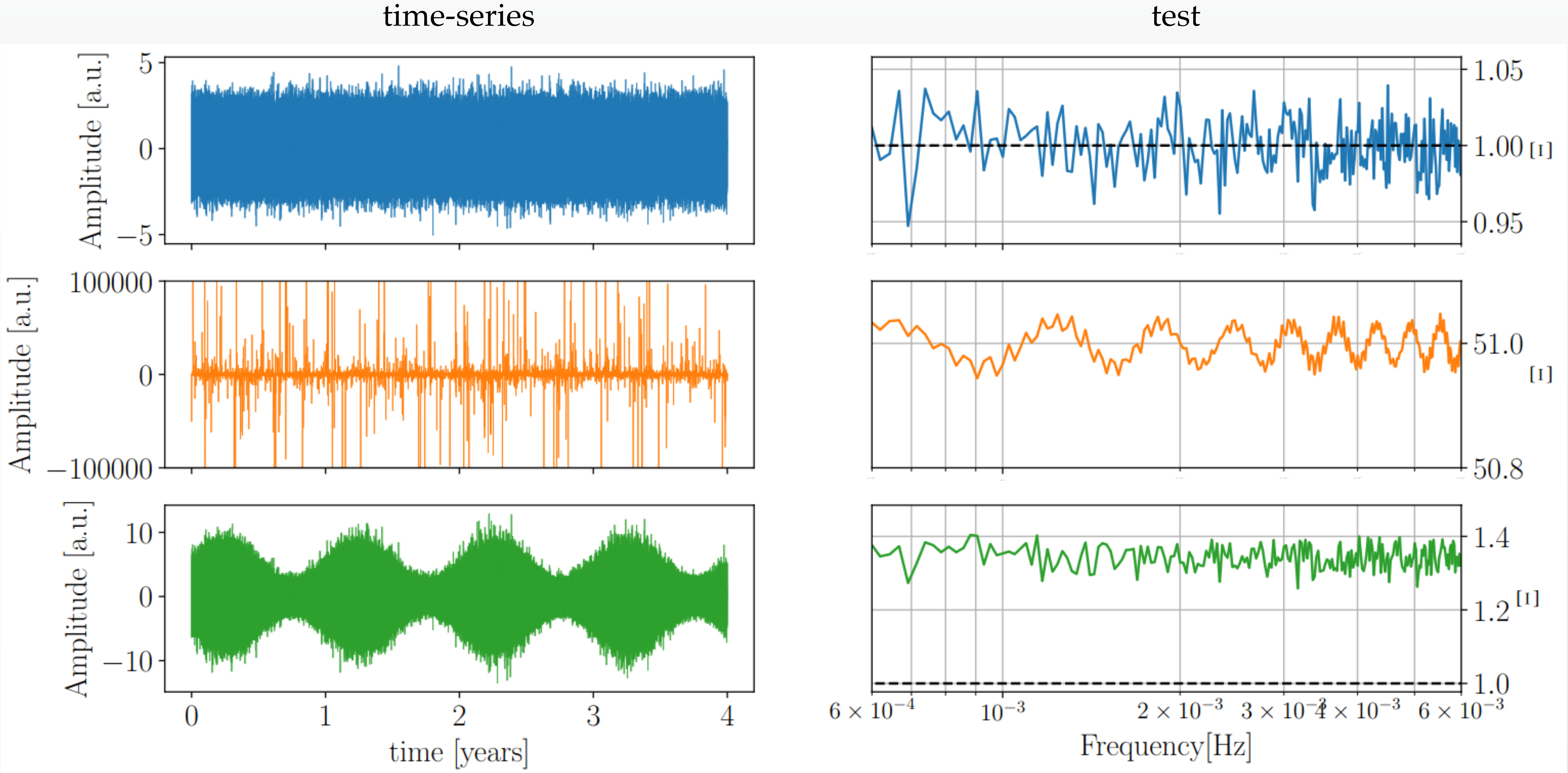
$$\Downarrow$$

split each time series into N_{chunks}

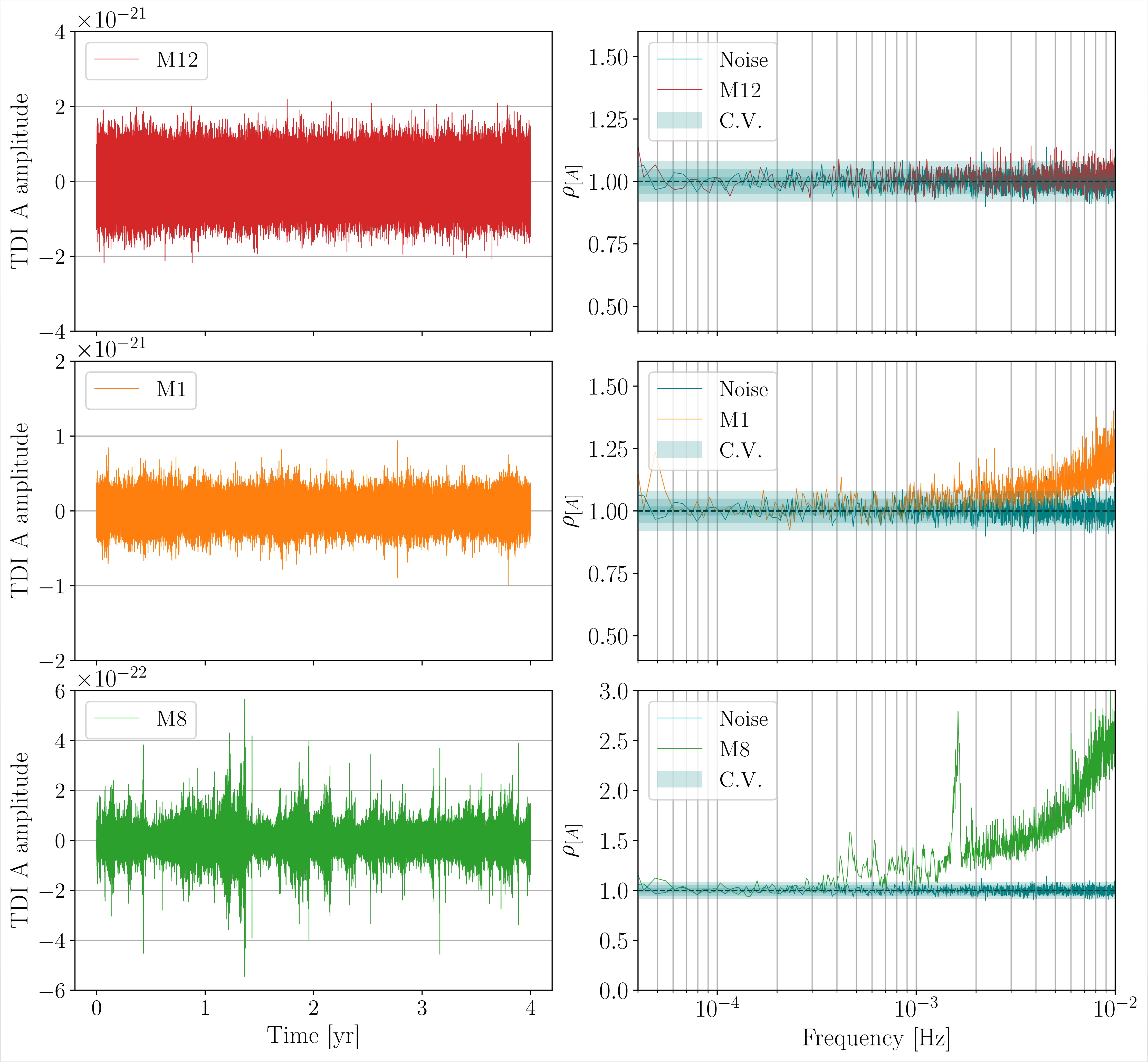
Rayleigh test

$$\Theta = \frac{\sigma(|\tilde{s}(f)|^2)}{\mu(|\tilde{s}(f)|^2)} \rightarrow 1$$ in the infinite sample limit

Acernese et. al 2023 [arXiv:2210.15634]



Is it Gaussian and Stationary?



Model	N_{final}	Detections	ρ_{gwb}
M1	26932	522	311
M8	3209	64	38
M12	319309	5909	3684

Consequences

- **Gaussian-likelihood could be only approximately valid**
- **Global fit couples SGWB detection, estimation, and resolvable source PE**

More work is needed to assess the impact of such biases.

Updating EMRI detection rates and parameter uncertainties

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Danny LAGHI, Ollie BURKE, Shubam KEJRIWAL,
Christian CHAPMAN-BIRD, Federico POZZOLI, Nikolaos KARNESIS

We focus on 5 EMRI catalogs

M1-M6 - M5-M11 - M7

intermediate - pessimistic - optimistic

MAIN DIFFERENCES with previous study:

2ndGenTDI

IFE for subtraction of resolvable sources

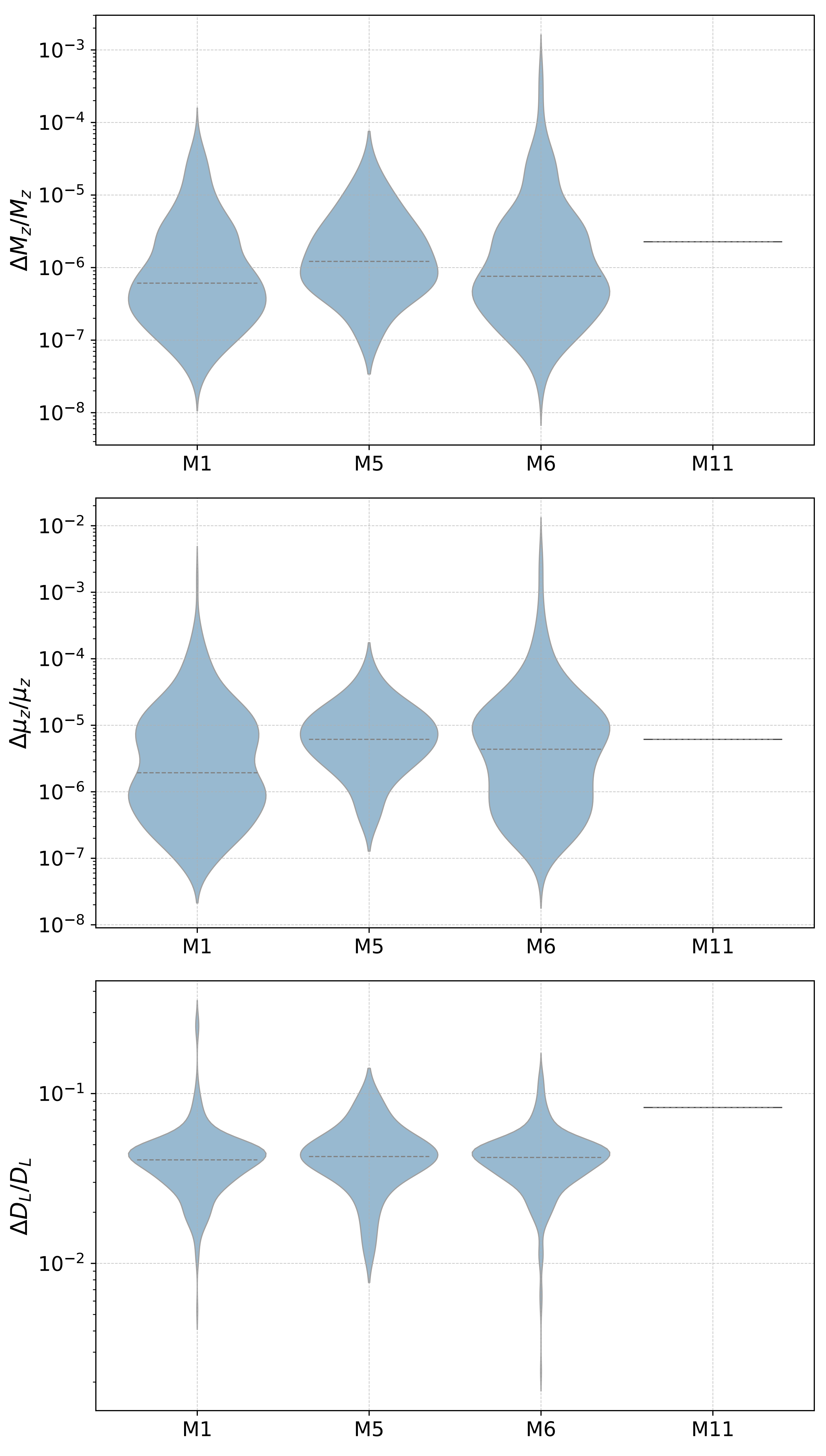
Model	# before IFE	# after IFE
M1	420	385
M5	26	26
M6	387	352
M7	3228	RUNNING
M11	1	1

Number of resolvable sources (before and after IFE)

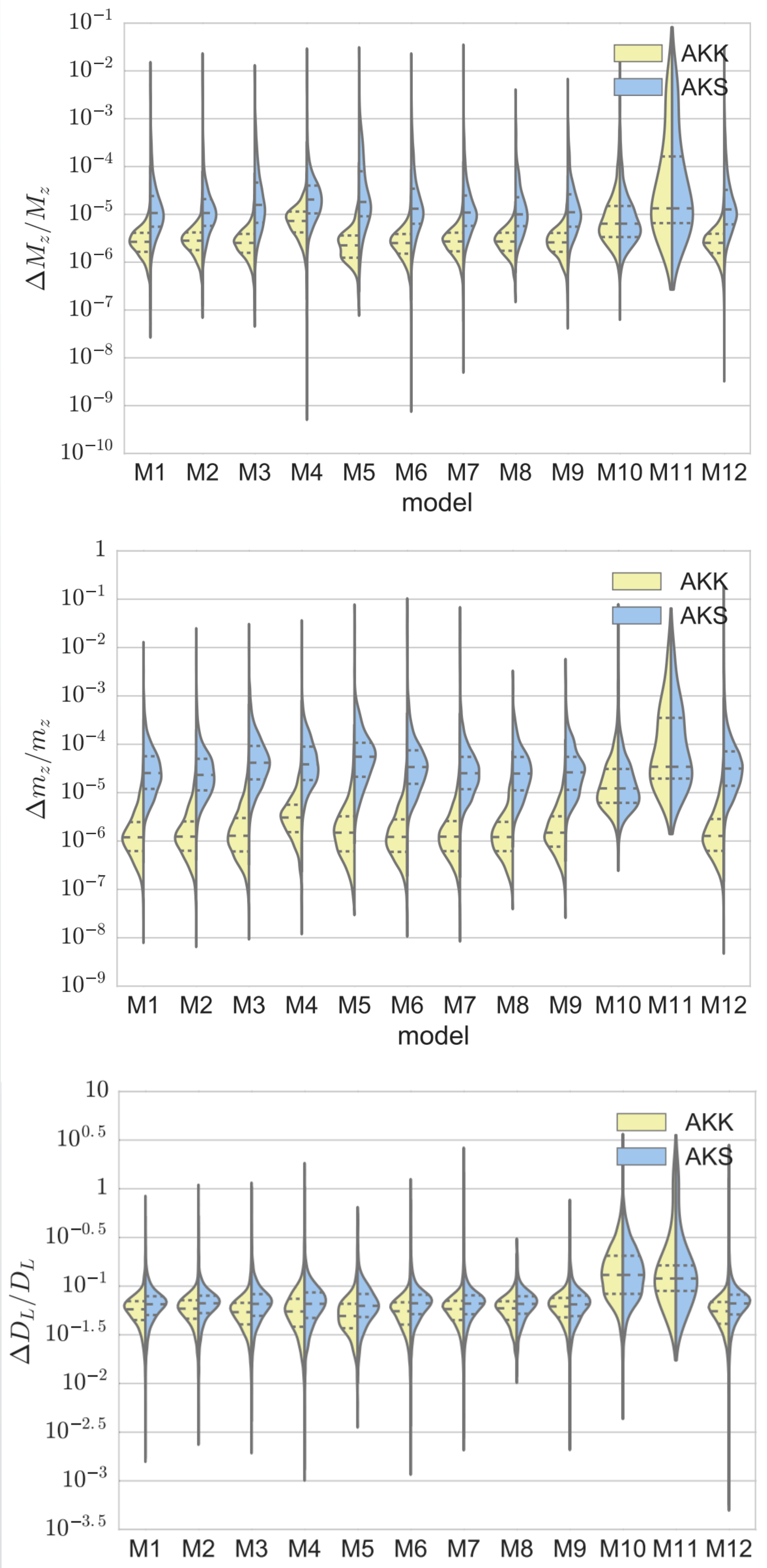
$T_{LISA} = 4$ years

and the 5PN-AAK waveform

5PN AAK



Babak et al. 2017 [arxiv:1703.09722]

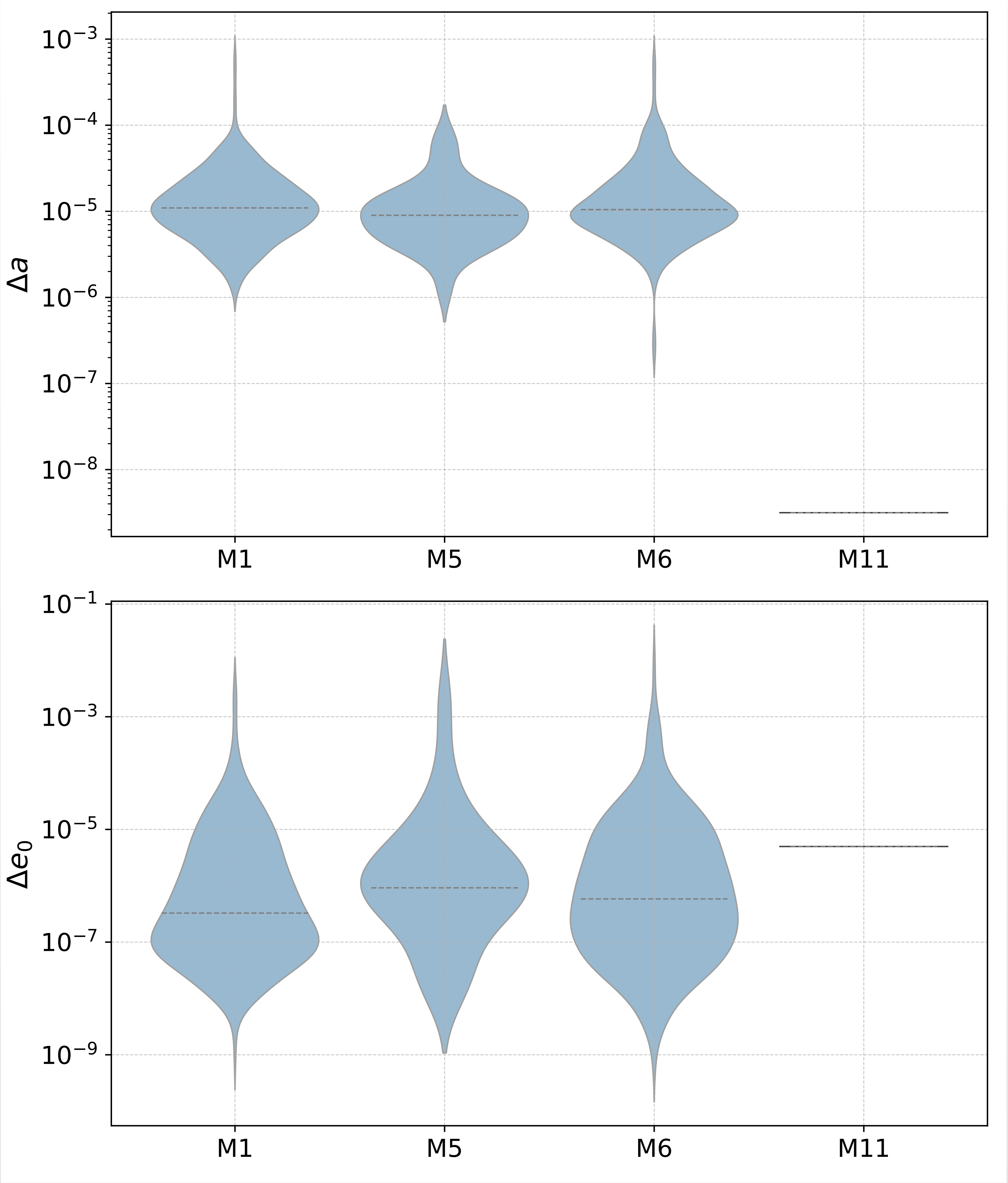


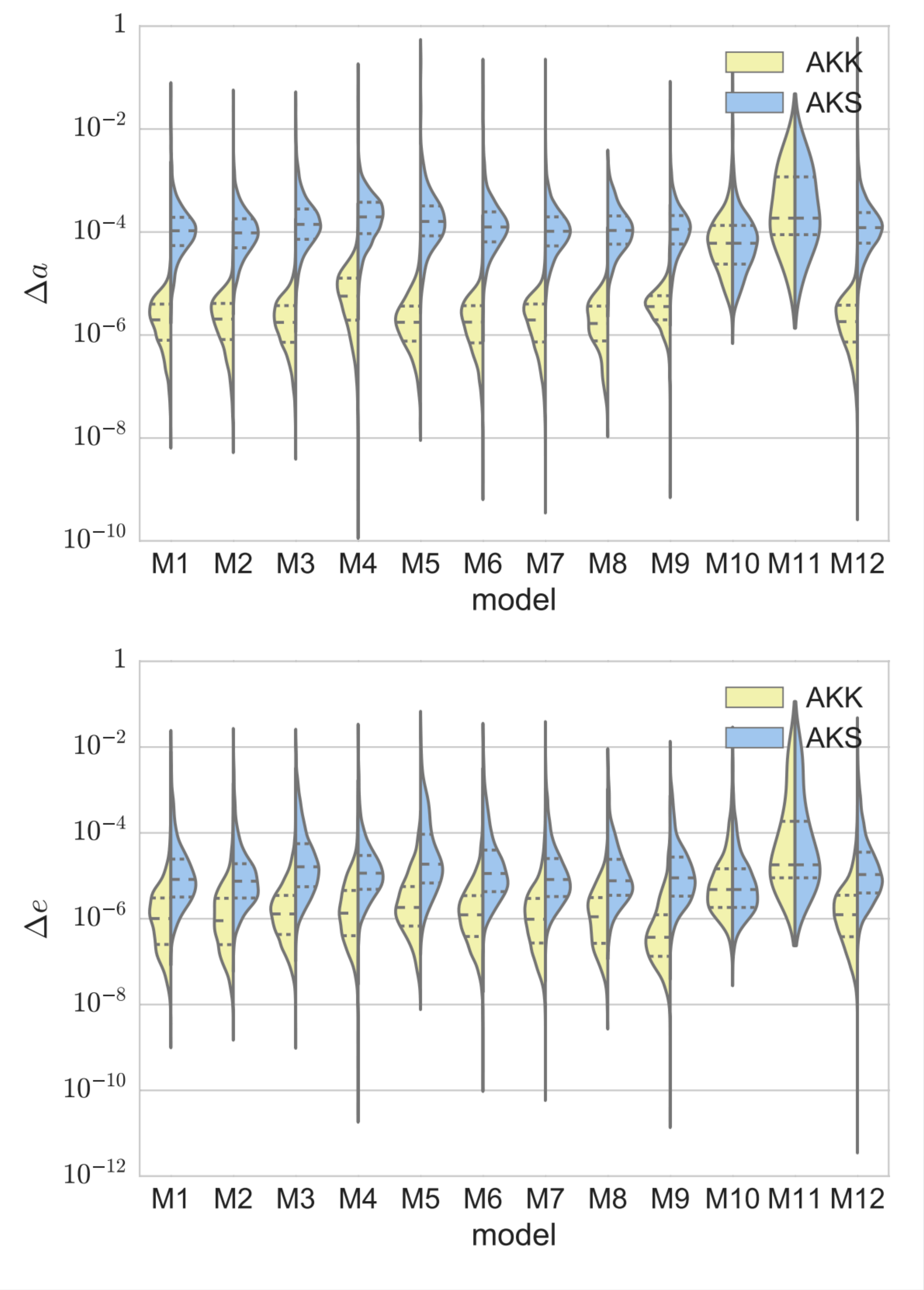
5PN AAK **PRELIMINARY**

Next steps:

- KerrEquatorialEccentric
(to asses SNR accuracy, and so possible changes in the detection rate)
limited parameter space (Equatorial and $e_0 < 0.9$)

- Full Bayesian PE validation on a few detections





Babak et al. 2017 [arxiv:1703.09722]

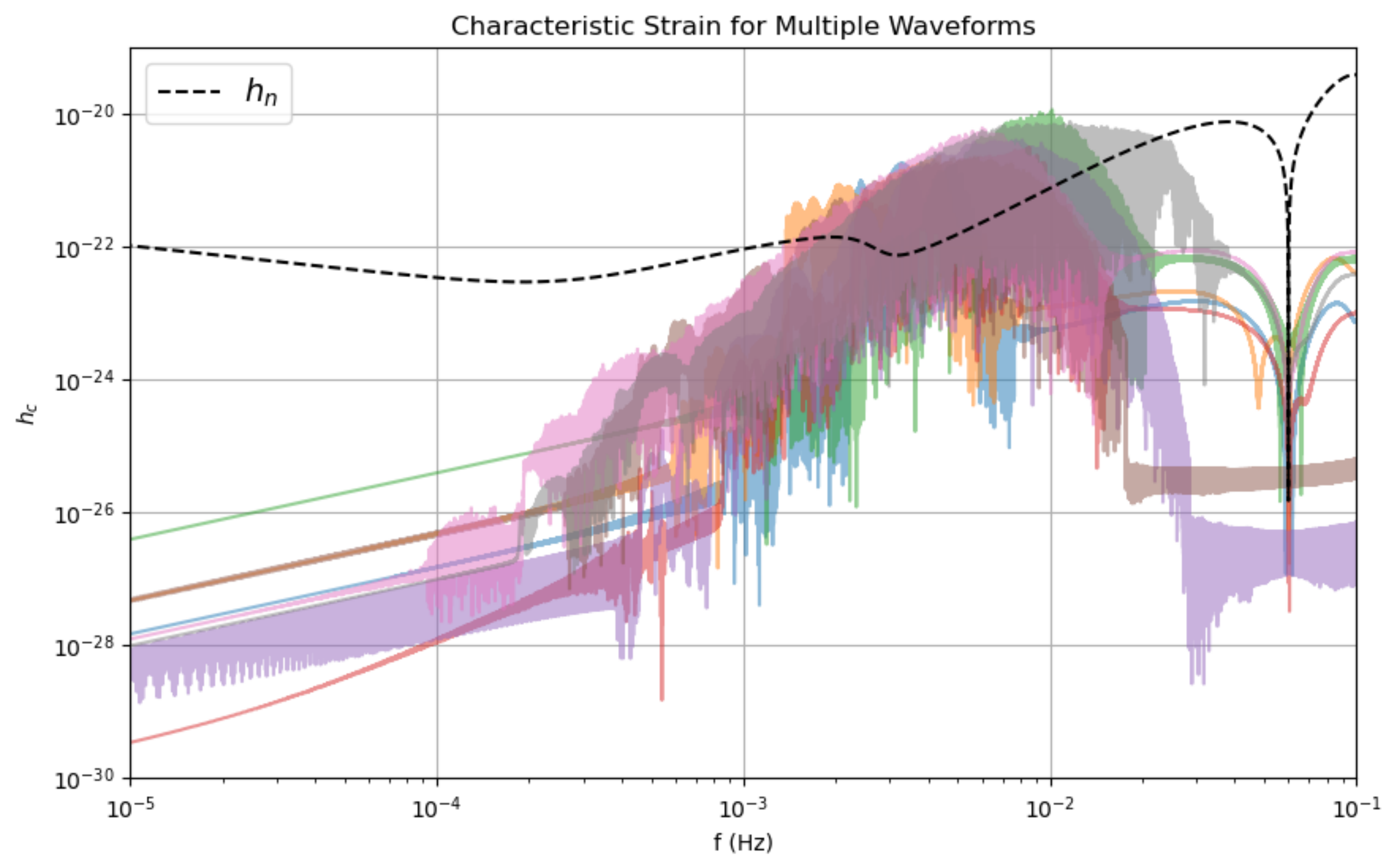
DDPC: Mojito EMRI generation

Ollie BURKE, Henri INCHAUSPÉ,
Manuel PIARULLI, Bert DEPOORTER

Choice of EMRI sources from realistic EMRI catalogs
to be injected in the next LISA Data Challenges

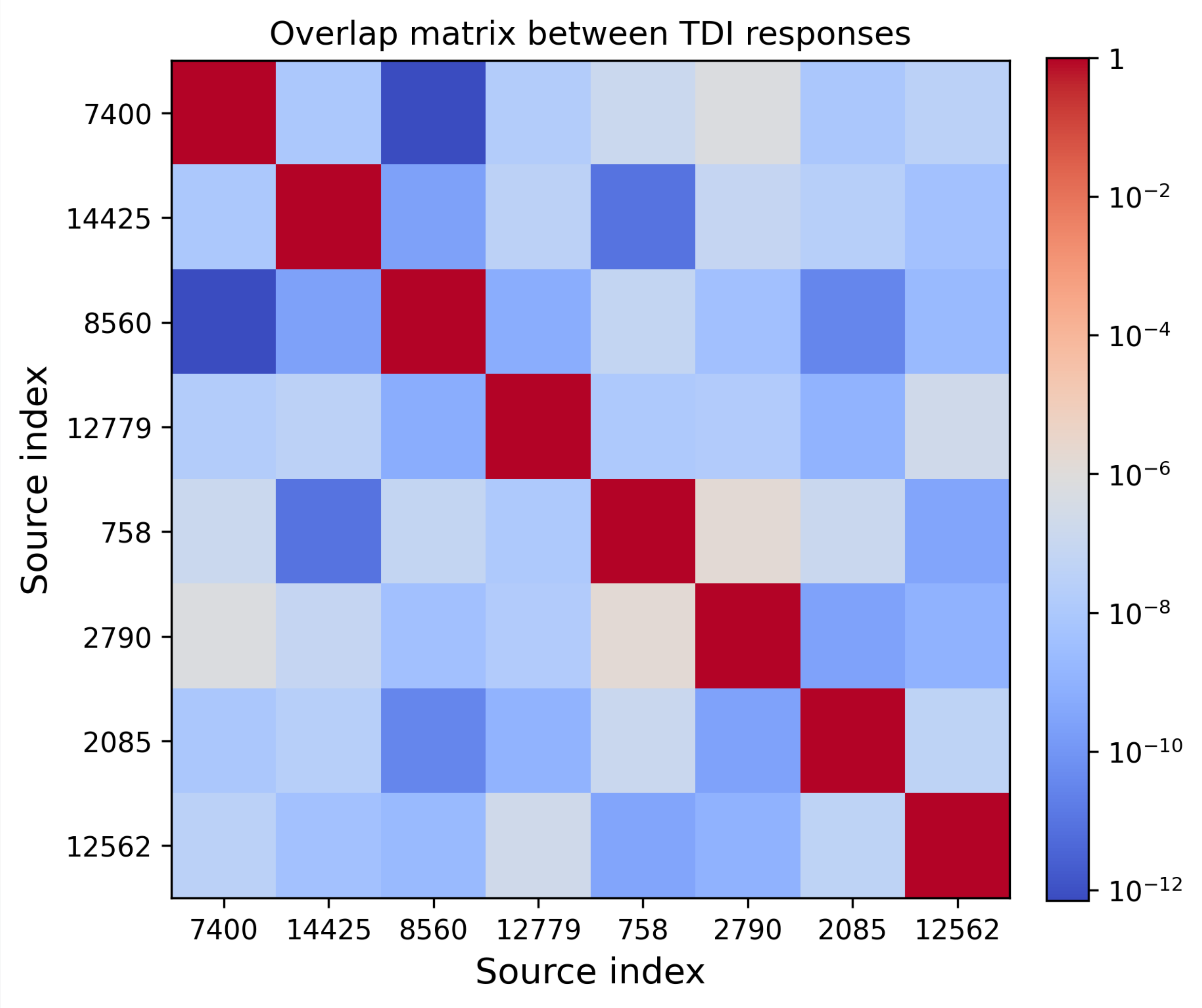
- Mojito LIGHT (8 sources)
- Mojito HEAVY (~100 sources)

KerrEccentricEquatorial Waveform



The **overlap matrix** compares
how similar two waveforms **d(t) and k(t) are.**
Each element in the matrix is a number between 0 and 1, where:

- **1** means the waveforms are identical
- **0** means they are completely orthogonal (no similarity)



Credit: Bert DEPOORTER

Thanks for the attention!

happy to take questions