Rencontres de Noirmoutier - 01/06/26

Detecting the memory effect with LISA

Adrien Cogez

CEA/IRFU/DPhP

adrien.cogez@cea.fr

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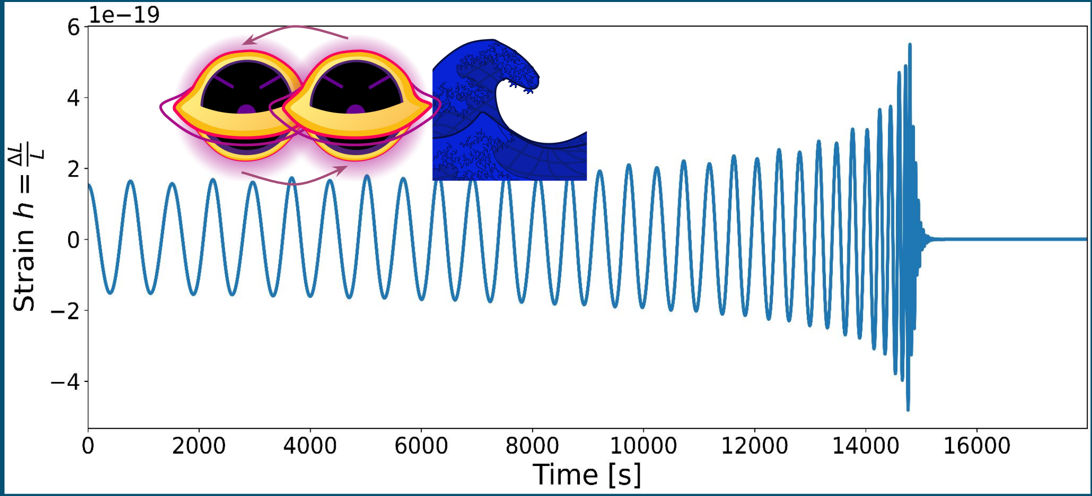
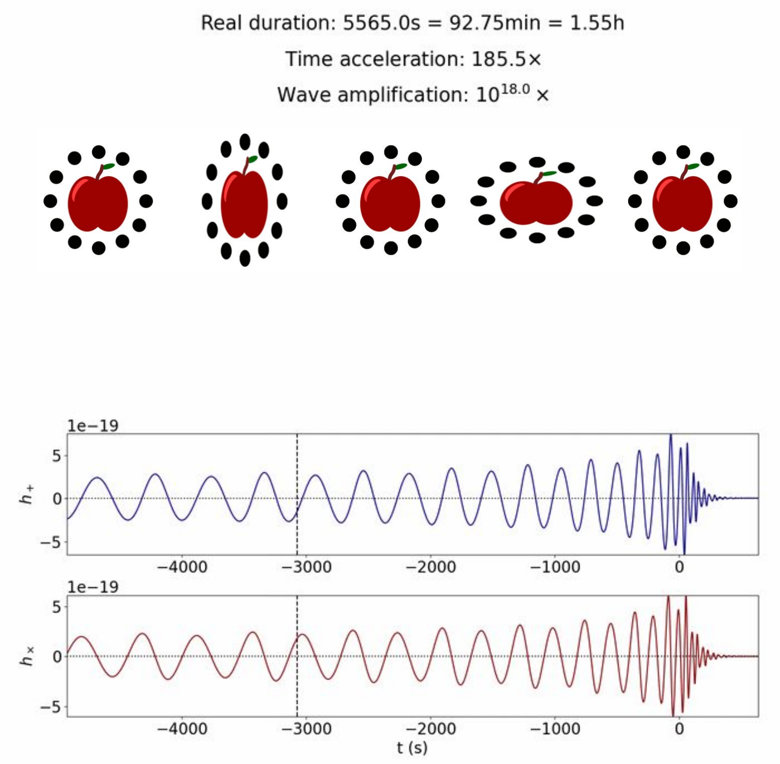
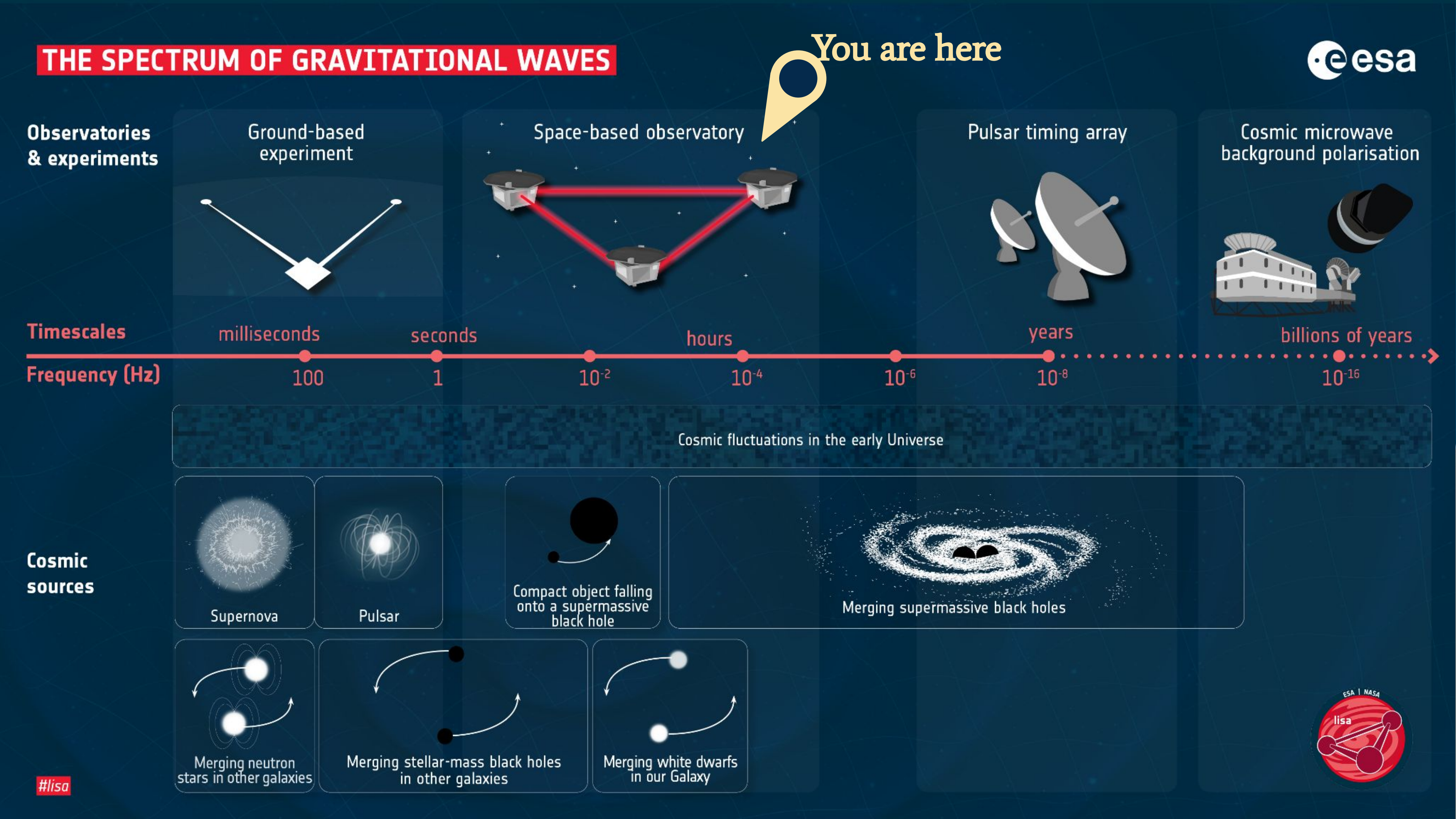
Gravitational waves from MBHBs

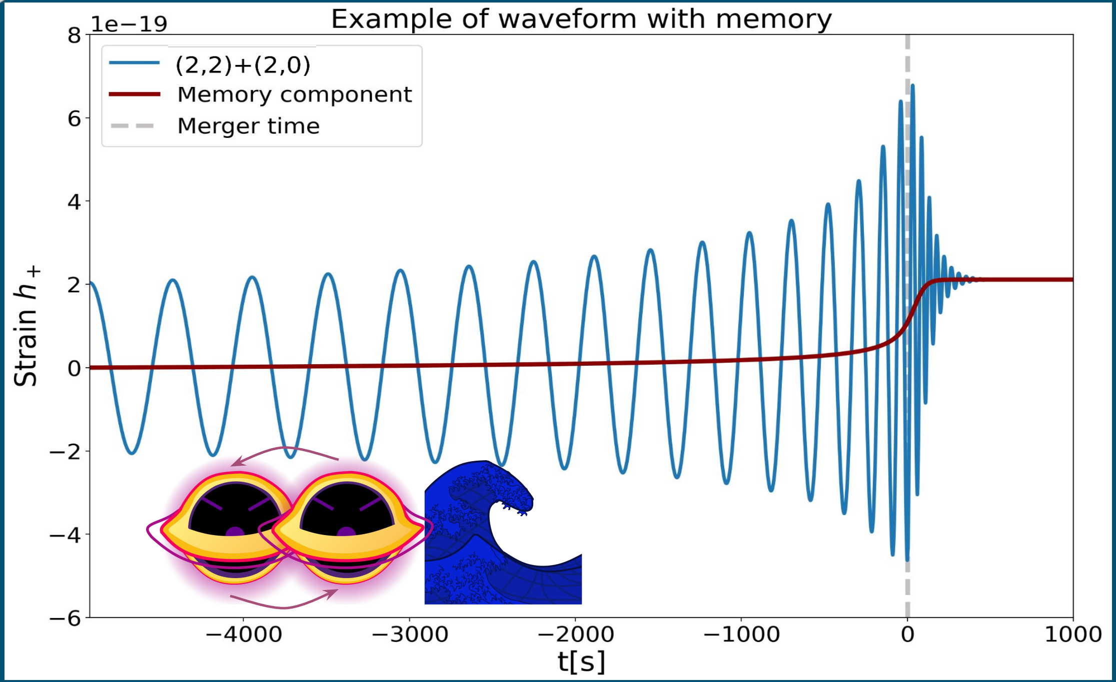
(Massive Binary Black Holes)






THE SPECTRUM OF GRAVITATIONAL WAVES
You are here
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
ESA | NASA
lisa
#lisa

What is memory effect ?



★ Permanent strain remaining after the passage of Gravitational Waves

☆ Predicted by GR

☆ Low frequency component of the GW

★ For MBHB, it looks like a sort of sigmoid step, mostly built during the merger.

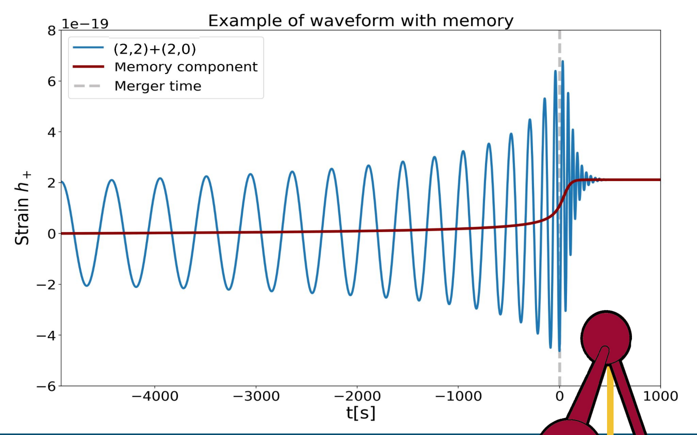
★ Linked to asymptotic symmetries of General Relativity (BMS symmetries).

☆ Note: Parameters used:

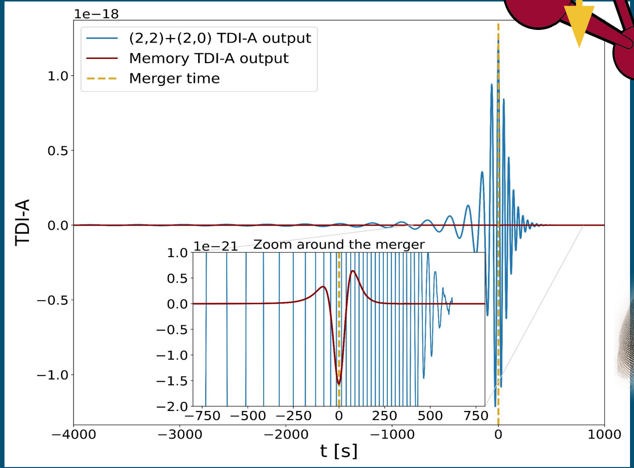
$Q = 1.5; \chi_{1z} = \chi_{2z} = 0.7; M = 10^6 M_\odot; d_L = 10^4 \mathrm{Mpc}; \iota = \pi/2; \psi = 0$

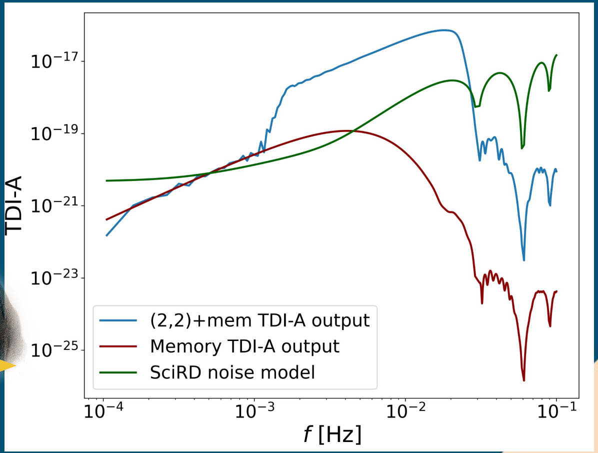
☆ Note: Here with NRHybSur3dq8_CCE, restricted to (2,2) + memory

Observing memory with LISA



LISA response
+
Time-Delay Interferometry





Analysis choices: Waveforms and HM

Waveforms	Considered modes
NRHybSur3dq8_CCE	(2,2)
NRHybSur3dq8_CCE	(2,2) + HM: (2,1), (3,3), (3,2), (4,4), (4,3)
SEOBNRv5HM	(2,2) + HM: (2,1), (3,3), (3,2), (4,4), (4,3)

★ Time-domain waveforms for spin-aligned binaries.

★ Memory is **mainly contained in the (2,0)-mode**, and **mainly sourced by the (2,2)-mode** of the waveform.

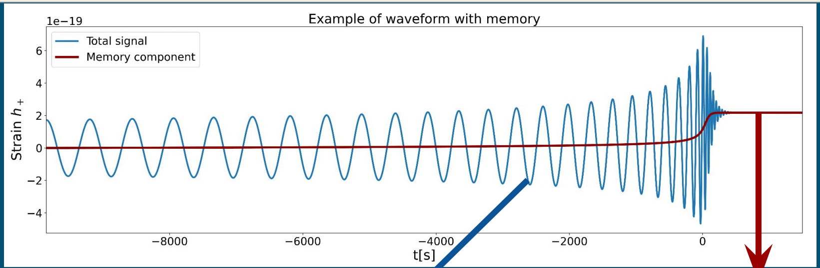
☆ up to ~10% improvement with Higher Modes

+ associated memory component:

$$h_{20}^{(\mathrm{mem})}(t) = \int_{-\infty}^{t} dt' \left[\frac{1}{7}\sqrt{\frac{5}{6\pi}}|\dot{h}_{22}|^2 - \frac{1}{14}\sqrt{\frac{5}{6\pi}}|\dot{h}_{21}|^2 + \frac{5}{4\sqrt{42\pi}}\left(\dot{h}_{22}\dot{h}_{32}^* + \dot{h}_{22}^*\dot{h}_{32}\right) + \frac{1}{2\sqrt{10\pi}}\left(\dot{h}_{33}\dot{h}_{43}^* + \dot{h}_{33}^*\dot{h}_{43}\right) - \frac{2}{11}\sqrt{\frac{2}{15\pi}}|\dot{h}_{44}|^2 \right]$$

See Zosso et al. [**arXiv:2601.23019** / DOI: **10.1103/51xv-zlfy**]

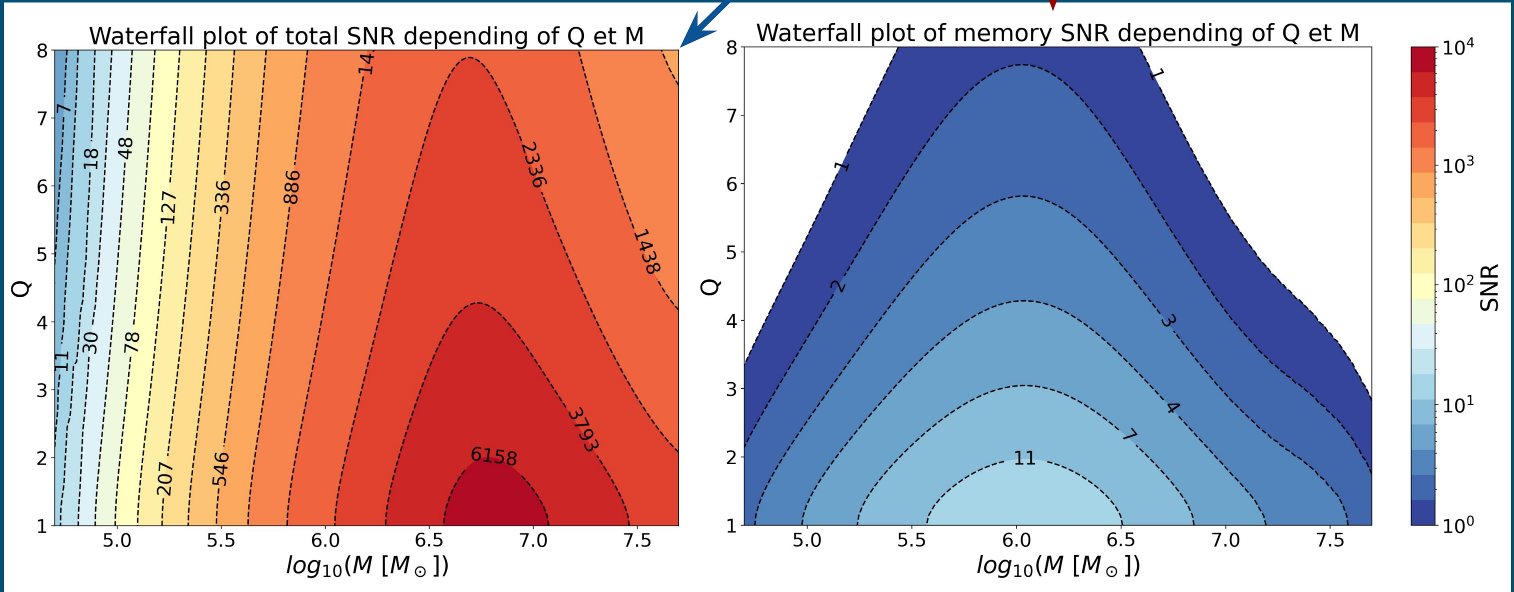
Signal-to-noise ratio hints



See Inchauspé et al. (2025)
DOI: **10.1103/PhysRevD.111.044044**

SNR$_{tot}$

SNR$_{mem}$



Encouraging results but it assumes that we can perfectly disentangle memory from the oscillatory signal.

Q mass ratio,
$Q = m_1/m_2 > 1$

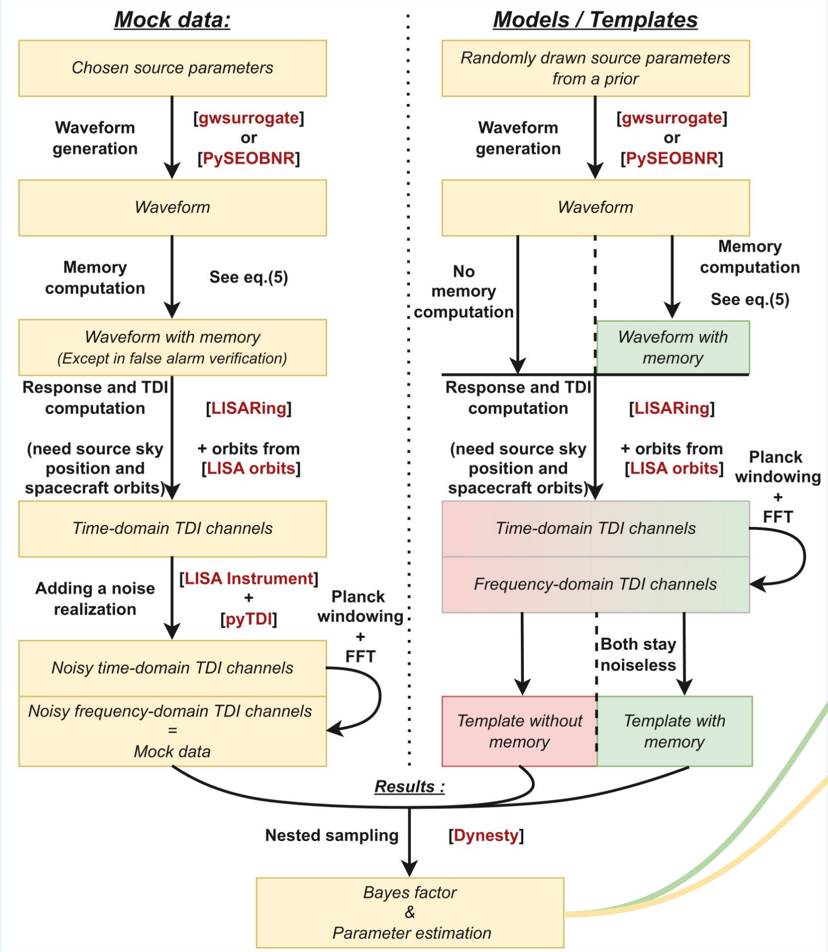
M total mass,
in detector-frame

— — —

$d_L = 10^4$ Mpc
inclination $\iota = \pi/3$
spins $\chi = 0.4$

☆ Note: Here with NRHybSur3dq8_CCE,
restricted to (2,2) + memory

Bayesian Analysis



(See Yves Lemière's talk on Friday)

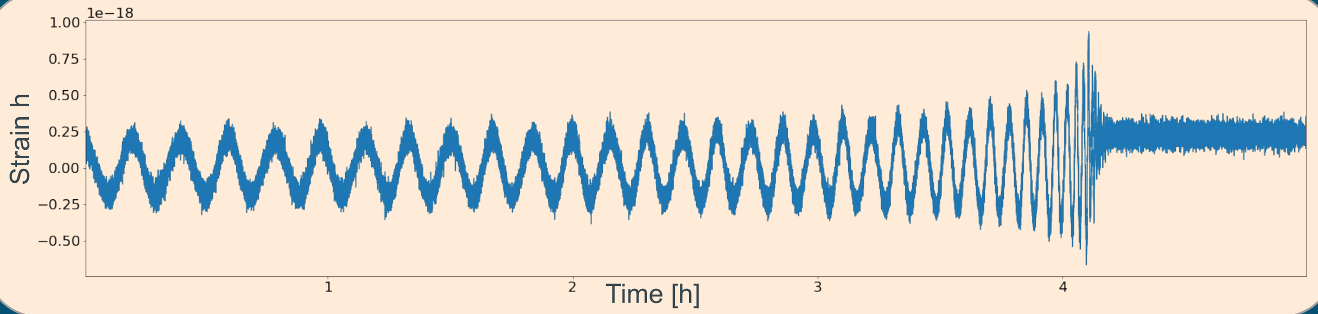
Posterior distributions

$$log_{10}\mathcal{B} = log_{10}\mathcal{Z}_{o+m} - log_{10}\mathcal{Z}_{o}$$

☆ Note: o = oscillatory
m = memory

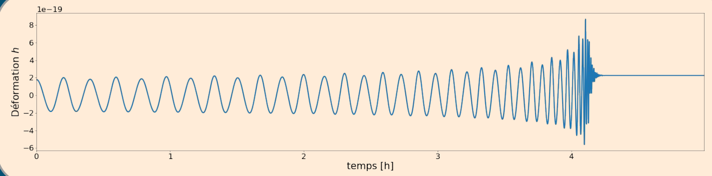
Bayesian Analysis

Noisy data

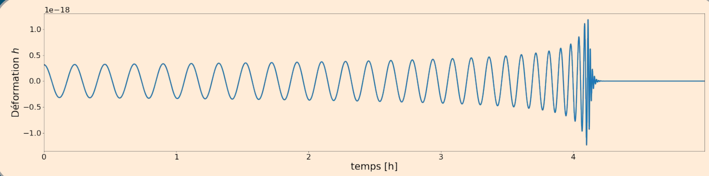


(For illustration only, in practice we work in Frequency Domain)

Template with memory



Template without memory

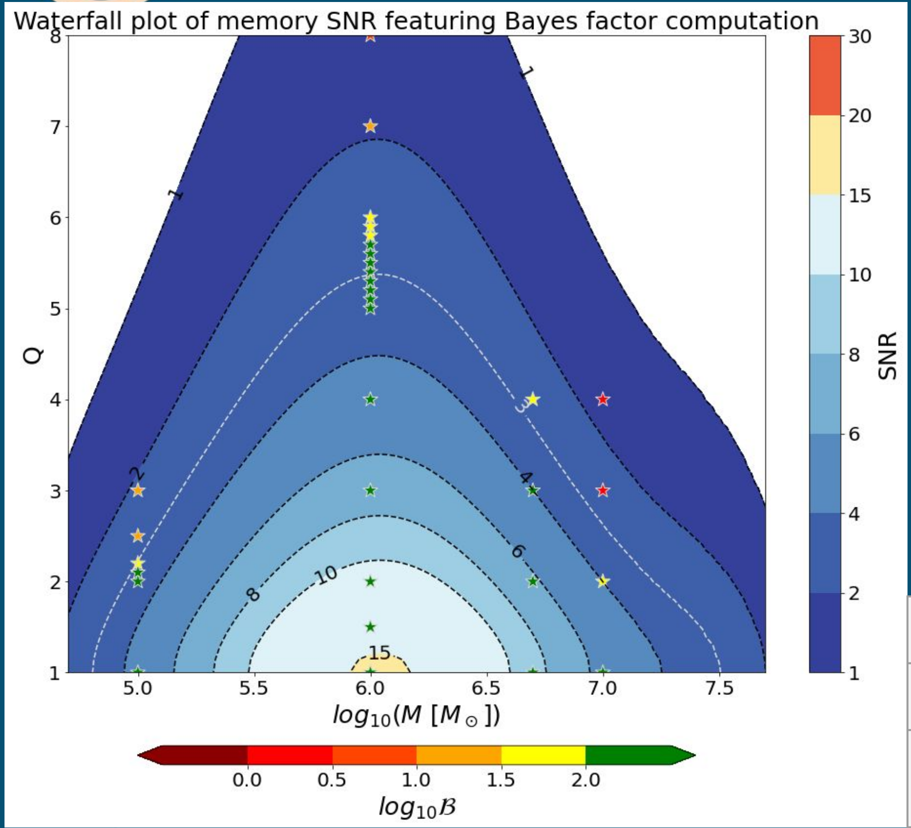


$$log_{10}\mathcal{Z}_{o+m}$$

$$log_{10}\mathcal{Z}_{o}$$

$$log_{10}\mathcal{B} = log_{10}\mathcal{Z}_{o+m} - log_{10}\mathcal{Z}_{o}$$

Bayesian detectability criterion



★ Need Bayes factor to evaluate model preference.

$$log_{10}\mathcal{B} = log_{10}\mathcal{Z}_{oscill+mem} - log_{10}\mathcal{Z}_{oscill}$$

★ On top of the previous memory map, we add some results of the Bayesian analysis (⟶ stars).

★ **Memory is detected when $\log_{10}B > 2$ (=green stars)**, using the threshold value from Jeffrey's scale.

Bayes factor	[1,3]	[3,10]	[10,32]	[32,100]	[100, +∞[
log_{10}Bayes factor	[0, ½]	[½, 1]	[1, 3/2]	[3/2, 2]	[2, +∞[
Interpretation	Barely worth mentioning	Substantial	Strong	Very strong	Decisive

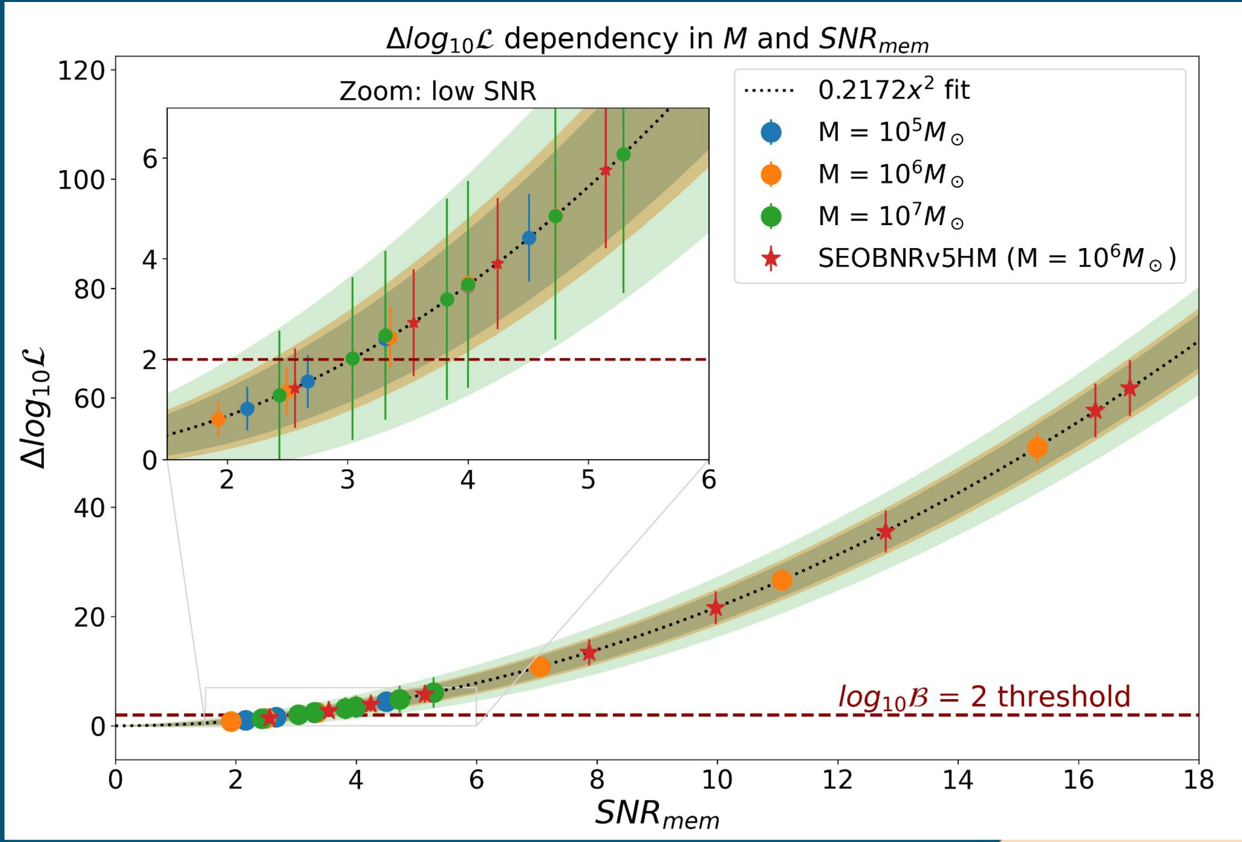
Using SNR_{mem} as a proxy

★ Power law relation between the (mean) Bayes factor value and the SNR of memory, SNR_{mem}.

★ Noise dispersion also depends on the total mass (= the frequencies where memory lies)

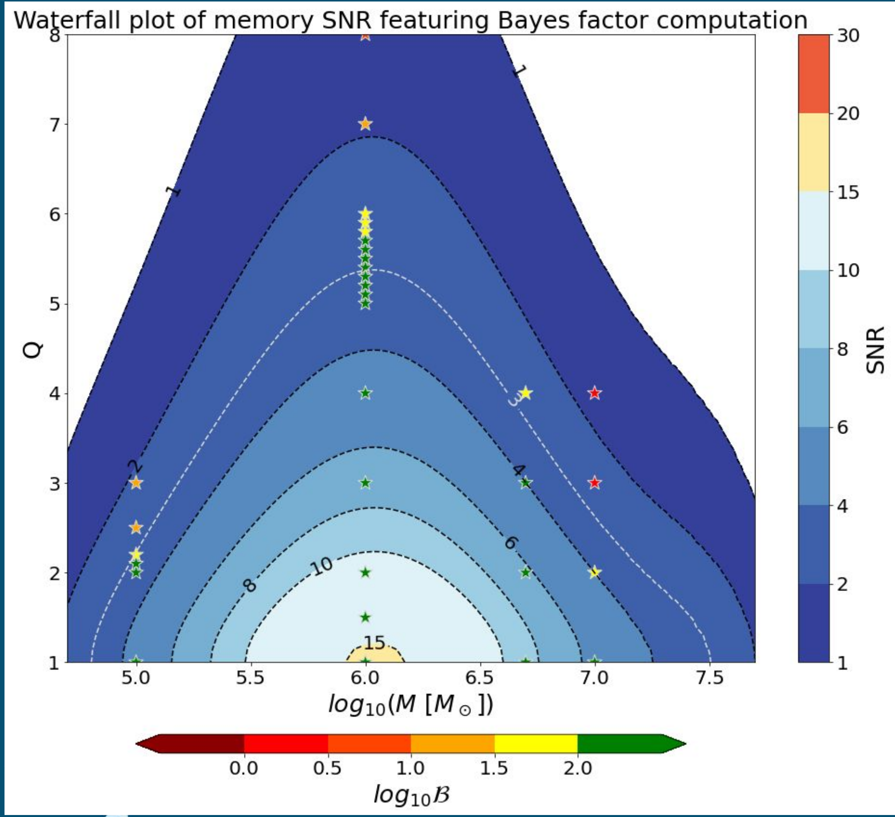
★ Favourable to detection for events with $SNR_{mem} \geq 3$

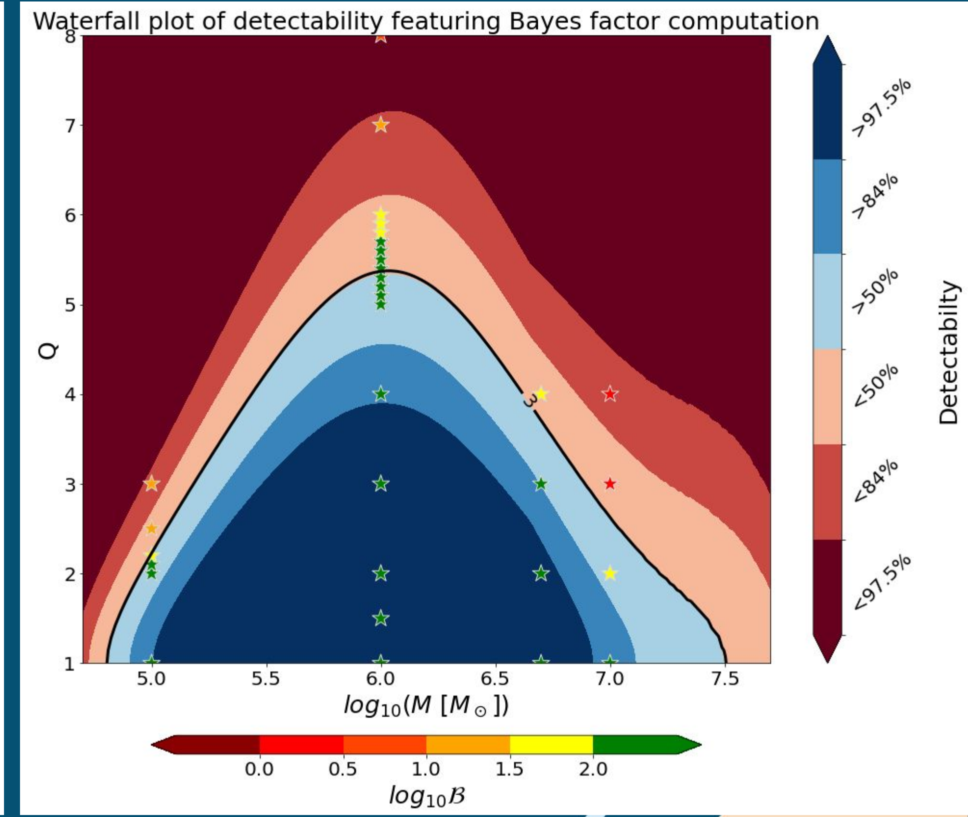
☆ Expected detection for every event with $SNR_{mem} \gtrsim 5$!



☆ Note: Done with NRHybSur3dq8_CCE, restricted to (2,2) + memory, validated with SEOBNRv5HM

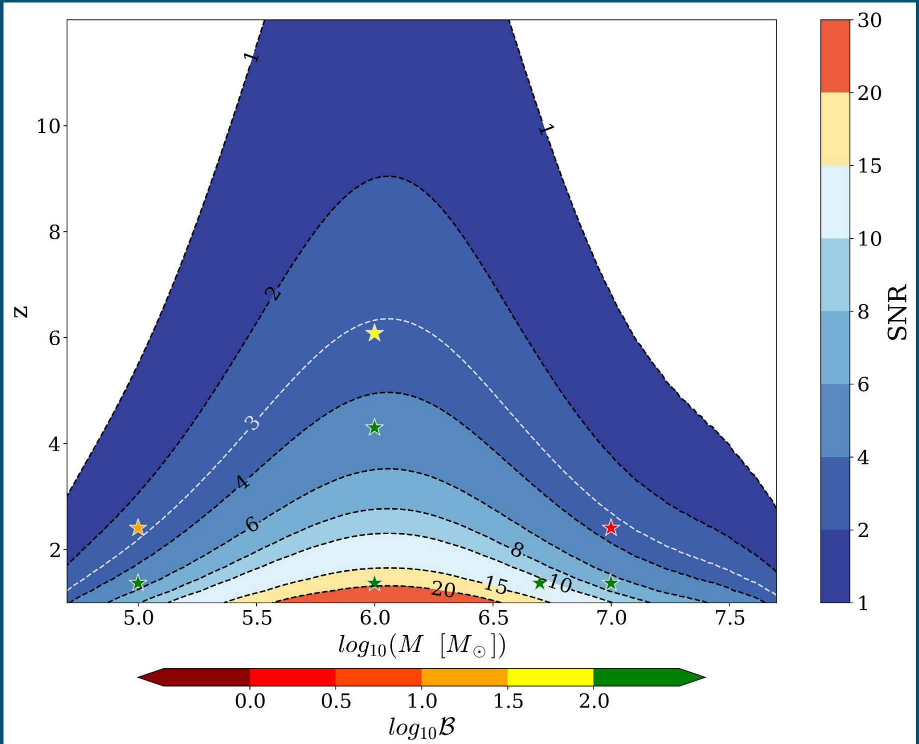
Detectability map

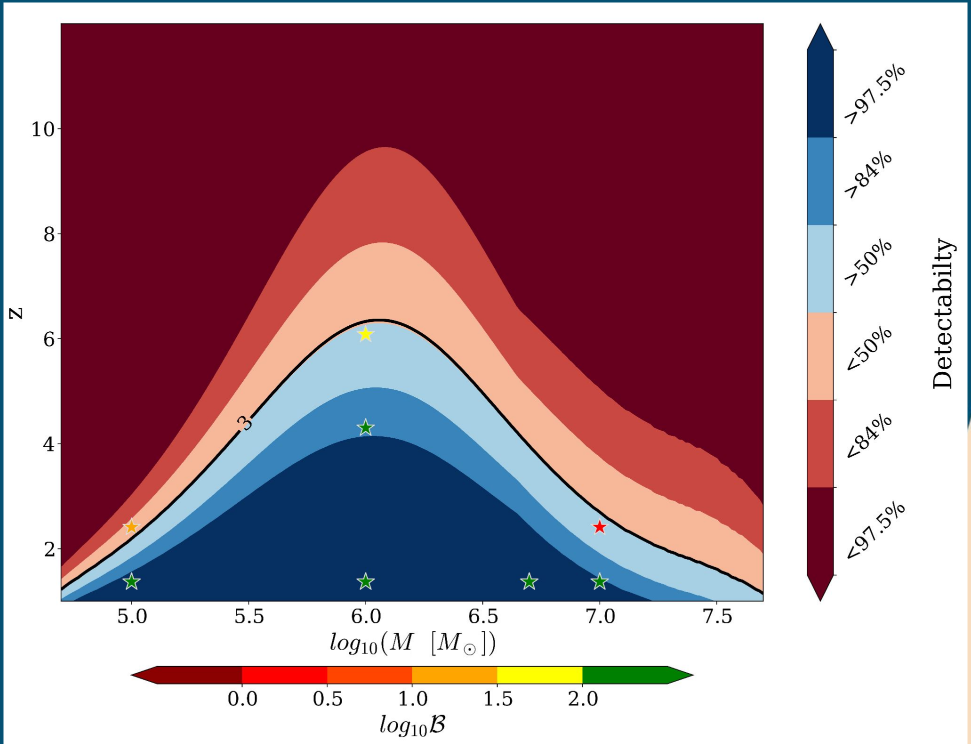




☆ Note: Done with NRHybSur3dq8_CCE, restricted to (2,2) + memory

Redshift waterfall plots





☆ Note: Done with NRHybSur3dq8_CCE, including HM and memory

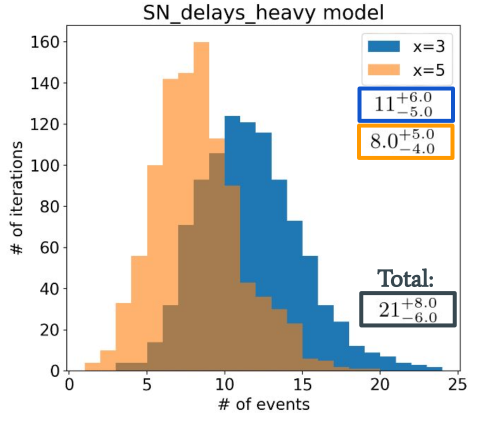
Forecast using population models

Thanks to E. Barausse for the population models.
See Barausse et al. (2020) DOI: **10.3847/1538-4357/abba7f**

★ We used 8 different population models, combining 3 different properties.

Supernovae feedback	Delay between host galaxies merger and MBHB merger	Black hole seeding
Yes {SN} // No {noSN}	Short delays {short} // Intermediate delays {delays}	Light seed {light} // Heavy seed {heavy}

★ Method and example:



☆ Compute SNRs for 1000 universe realizations of 4 years of data

↓

☆ Count how many of them see **x** events

$11^{+6.0}_{-5.0}$, $8.0^{+5.0}_{-4.0}$ → Nb of memory event: $\mathrm{SNR}_{\mathrm{mem}} \geq 3$ (resp. 5)

$21^{+8.0}_{-6.0}$ → Nb of total events: $\mathrm{SNR}_{\mathrm{tot}} \geq 8$

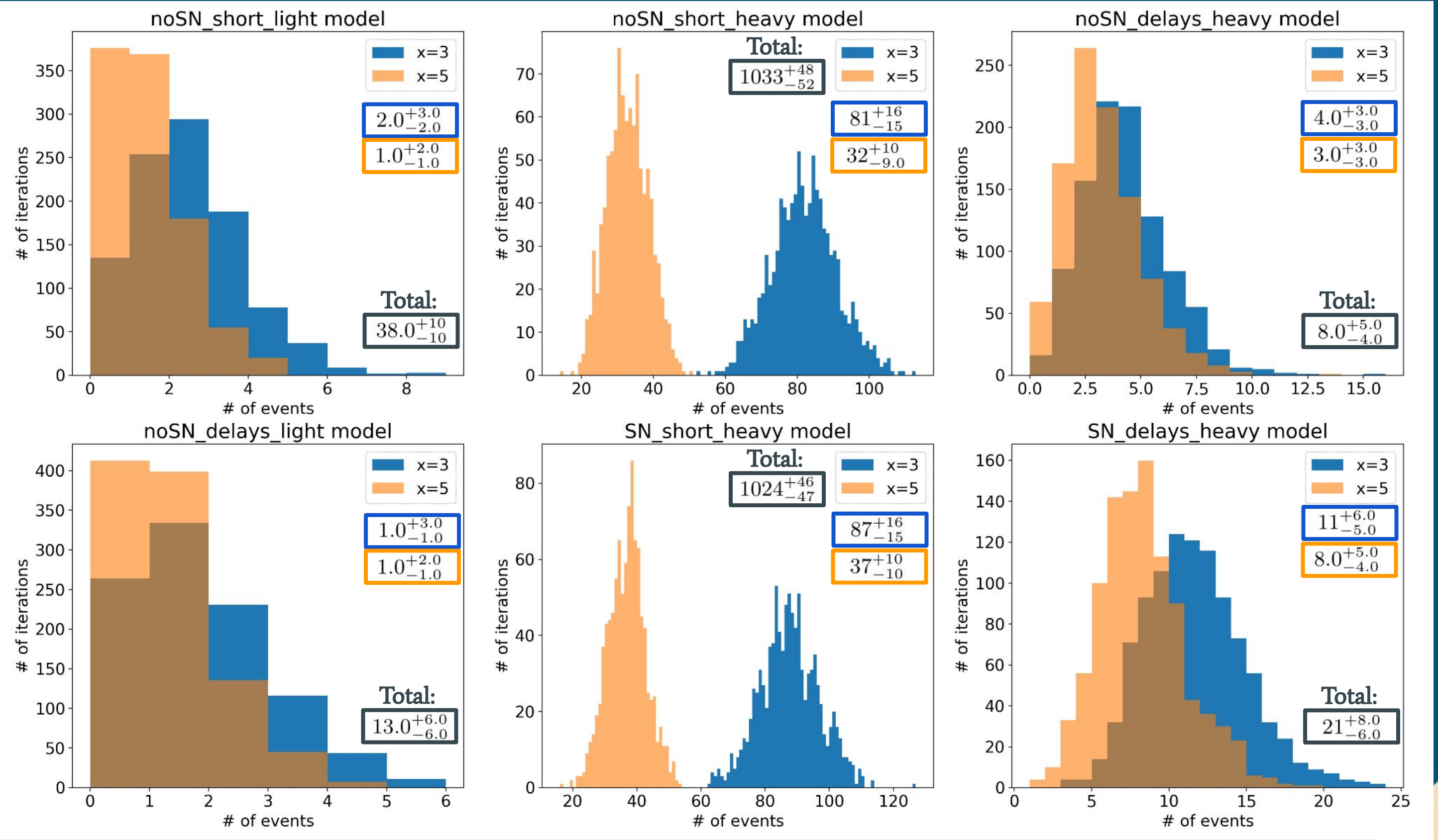
Forecast using population models

★ 6 out of the 8 different models present detectable memory event.

☆ In particular, **heavy seed models are really favourable to memory detection.**

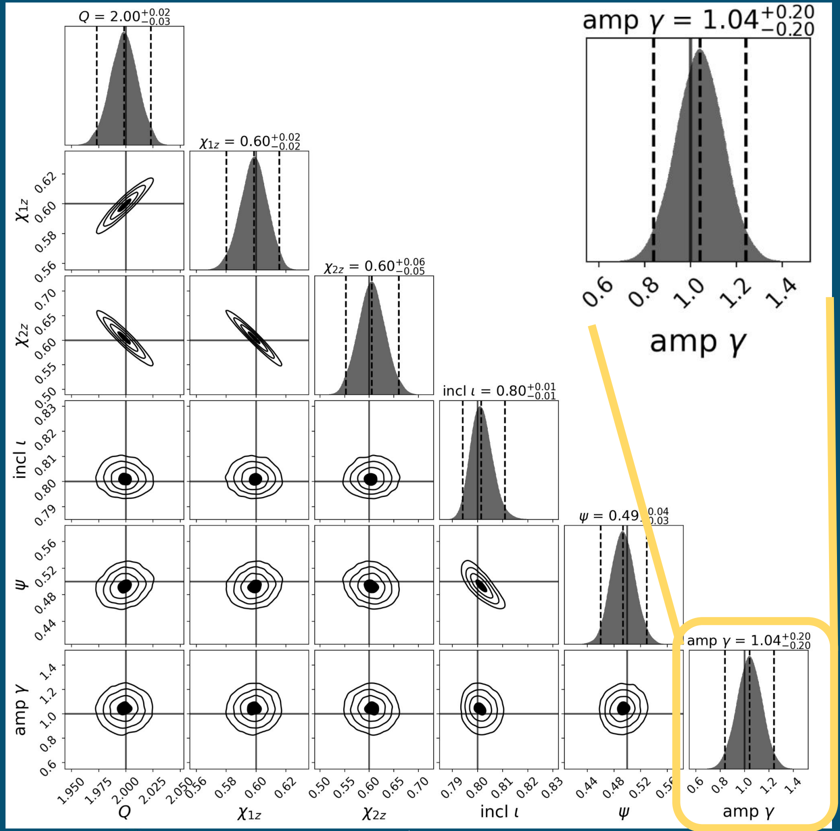
☆ 4 years realization s

☆ Total = Nb of sources with $SNR_{tot} > 8$



Adrien Cogez

Probing GR through memory

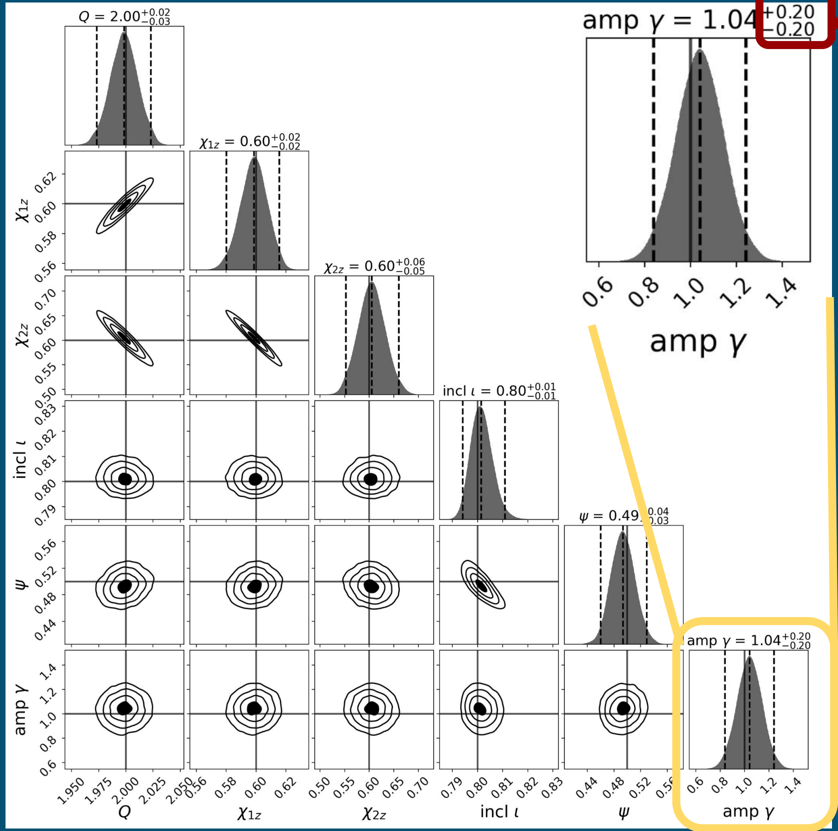


★ Possibility to define a free parameter to describe the amplitude of the memory. Here we define γ as:

$$h_{mem}(t) = \gamma \times h_{mem}^{GR}(t)$$

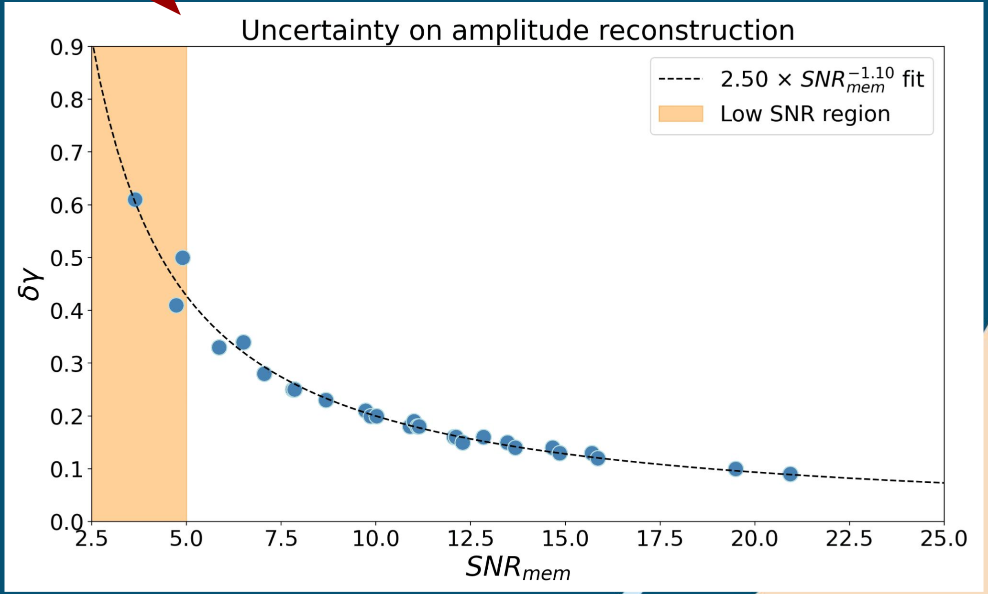
☆ Note: Done with NRHybSur3dq8_CCE, restricted to (2,2) + memory

Probing GR through memory

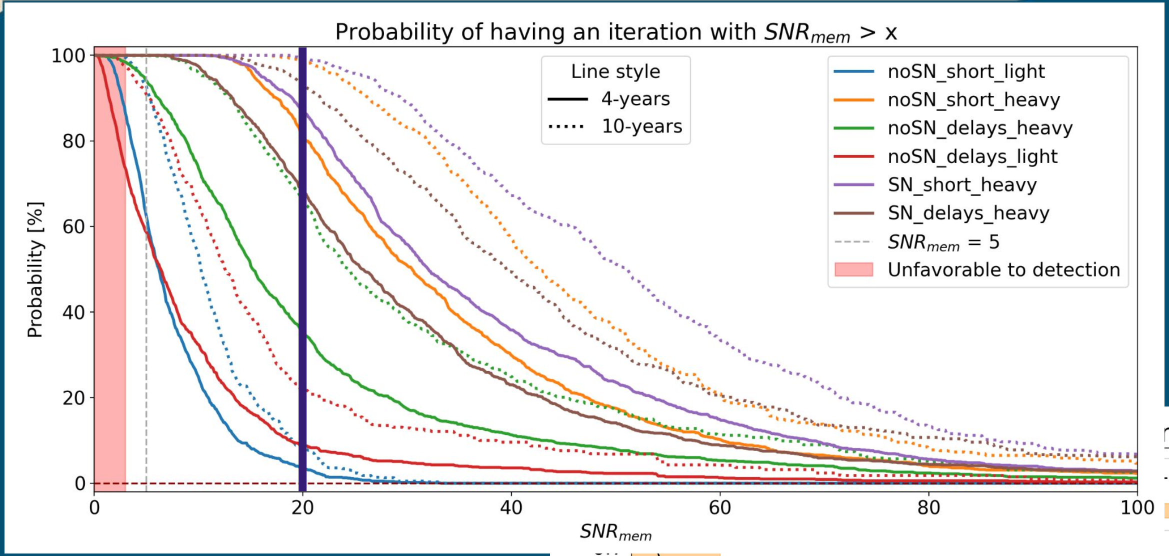


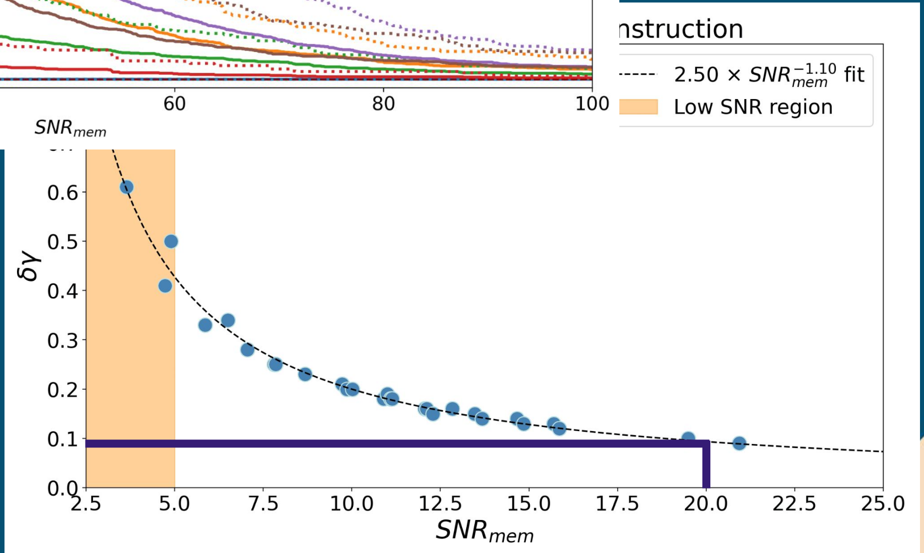
★ We can also monitor the uncertainty δγ on the reconstructed γ. As a result, δγ only depend on SNR_{mem}, following:

$$\delta\gamma = 2.5 \times \mathrm{SNR}_{\mathrm{mem}}^{-1.1}$$



Probing GR through memory





★ $SNR_{mem} = 20 \Rightarrow \approxeq 10\%$ constraint on amplitude

Take home message & Prospects

★ LISA will be able to identify the memory for a significant region of the parameter space.

★ Population models predicts MBHBs within the favourable region. The number of expected events will depend on the specific model but at least one event is very likely.

★ Observing memory is already a test of GR, but first attempts to characterize the shape of the memory signal offers promising perspectives.

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☆ Taking into account precessing MBHB and the memory contribution in every mode.

☆ Build a toy-model for memory that allow to test the shape of the memory.

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Thanks for your attention !

Any question ? :)

And if you want more details: [**arXiv:2601.23230** / DOI: **10.1103/b9ld-dqq4**]
Companion theory paper [**arXiv:2601.23019** / DOI: **10.1103/51xv-zlfy**]

Forecast using population models

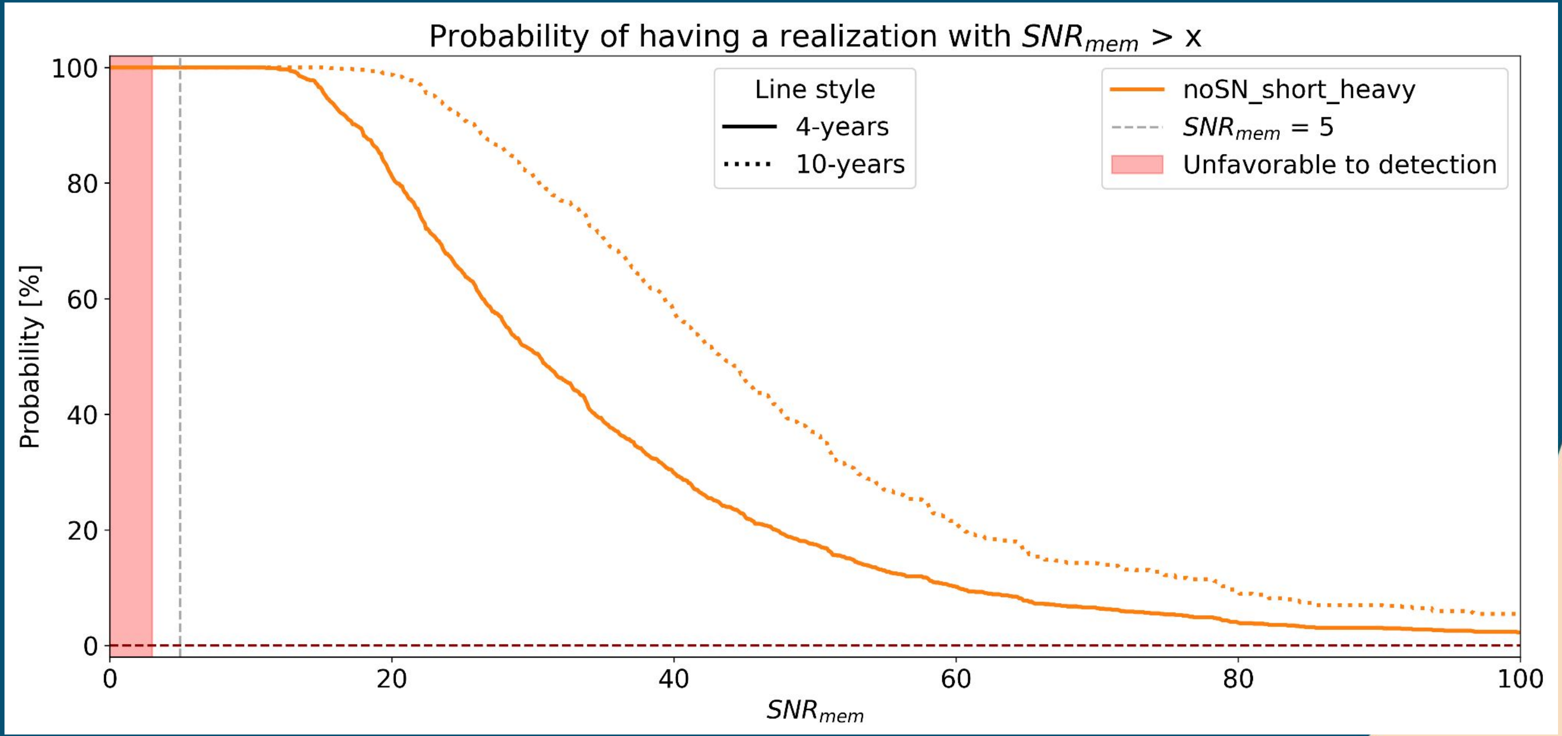
SN	Delays	Seeds	Nb of events detected	Nb of events with $SNR_{mem} > 3$	Nb of events with $SNR_{mem} > 5$	Nb of events to reach $\log_{10} B^{cumul} > 2$
Yes	Short delays	Light	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.0}_{-0.0}$	N\A
		Heavy	1024^{+46}_{-47}	87^{+16}_{-15}	37^{+10}_{-10}	$7.0^{+0.7}_{-0.6}$
	Delays	Light	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.0}_{-0.0}$	N\A
		Heavy	$21^{+8.0}_{-6.0}$	$11^{+6.0}_{-5.0}$	$8.0^{+5.0}_{-4.0}$	$1.7^{+0.7}_{-0.4}$
No	Short delays	Light	38.0^{+10}_{-10}	$2.0^{+3.0}_{-2.0}$	$1.0^{+2.0}_{-1.0}$	$10.8^{+8.7}_{-4.5}$
		Heavy	1033^{+48}_{-52}	81^{+16}_{-15}	$32^{+10}_{-9.0}$	$7.3^{+0.8}_{-0.7}$
	Delays	Light	$13.0^{+6.0}_{-6.0}$	$1.0^{+3.0}_{-1.0}$	$1.0^{+2.0}_{-1.0}$	$5.2^{+4.6}_{-2.2}$
		Heavy	$8.0^{+5.0}_{-4.0}$	$4.0^{+3.0}_{-3.0}$	$3.0^{+3.0}_{-3.0}$	$1.8^{+1.4}_{-0.6}$

★ Even if we don't observe an event alone, observing $\mathcal{O}(10)$ mergers should be enough to statistically assess the presence of memory.

☆For LVK, it's $\mathcal{O}(2000)$ events*.

* See Cheung et al. (2024)
DOI: **10.1088/1361-6382/ad3ffe**

Possibility of loud memory events

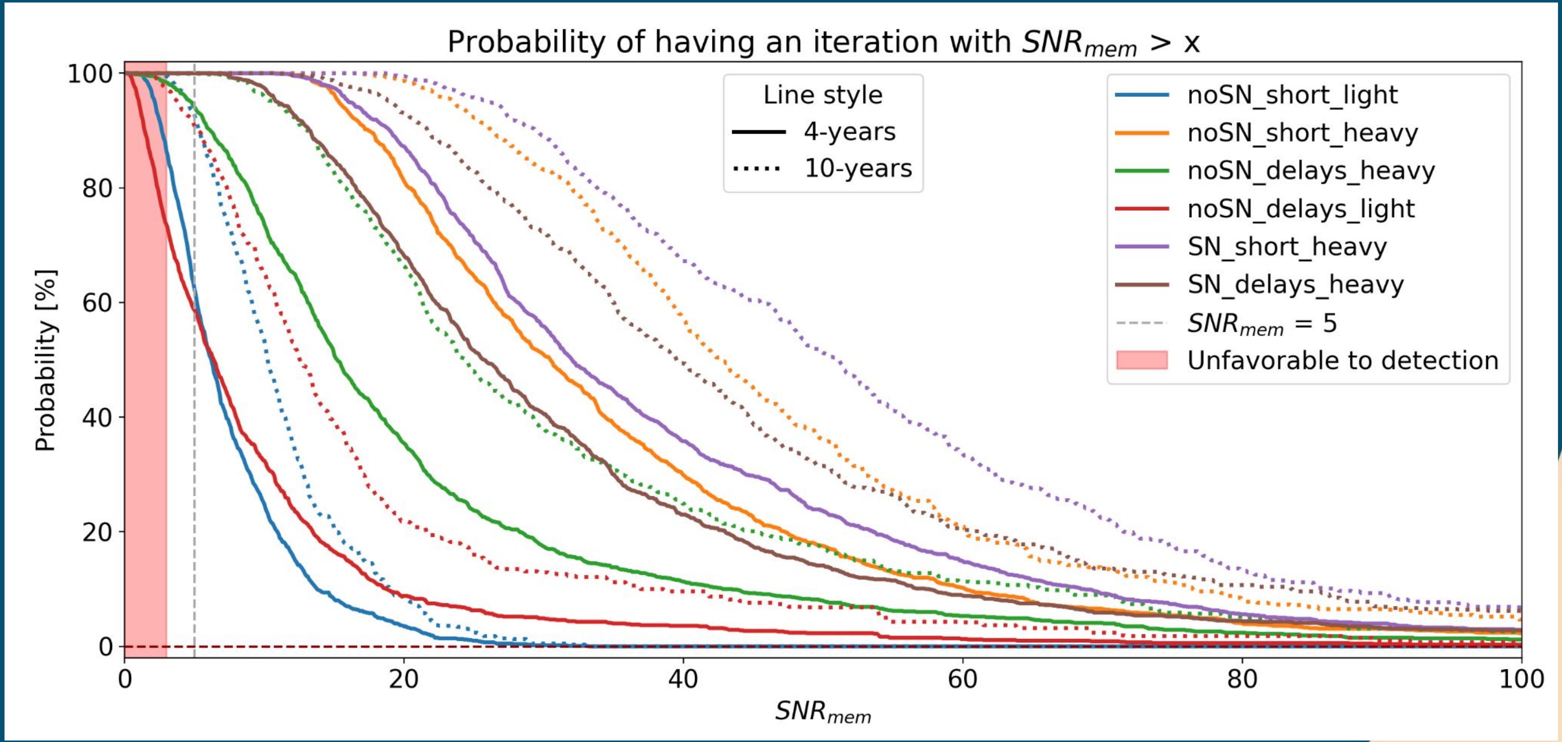


★ We can expect loud memory event, especially under the heavy seed hypothesis

☆ Note: Probability estimated using 1000 realizations for each model

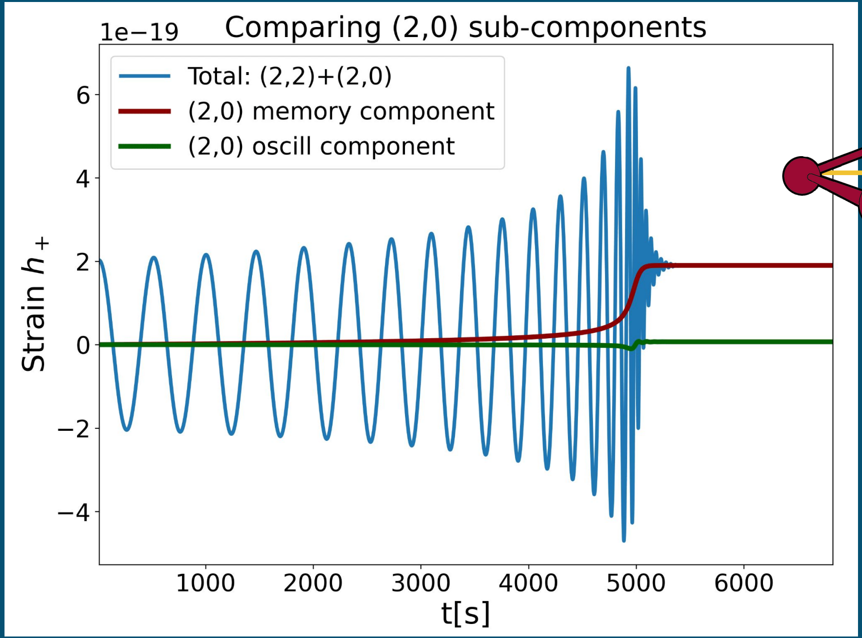
Possibility of loud memory events

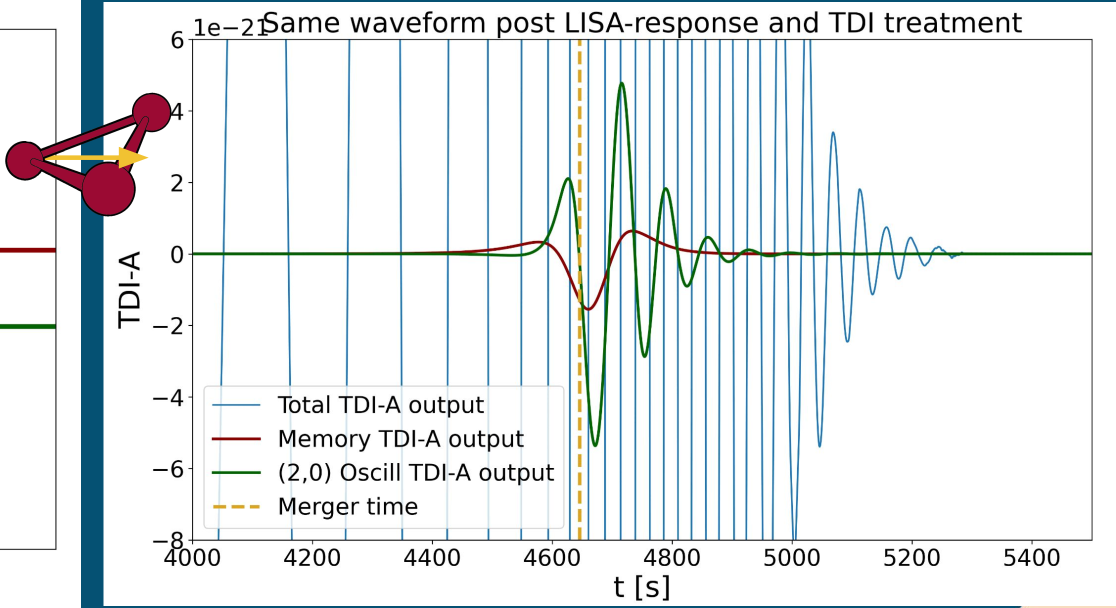
★ We can expect loud memory event, especially under the heavy seed hypothesis



☆ Note: Probability estimated using 1000 realizations for each model

Analysis choices: Native memory

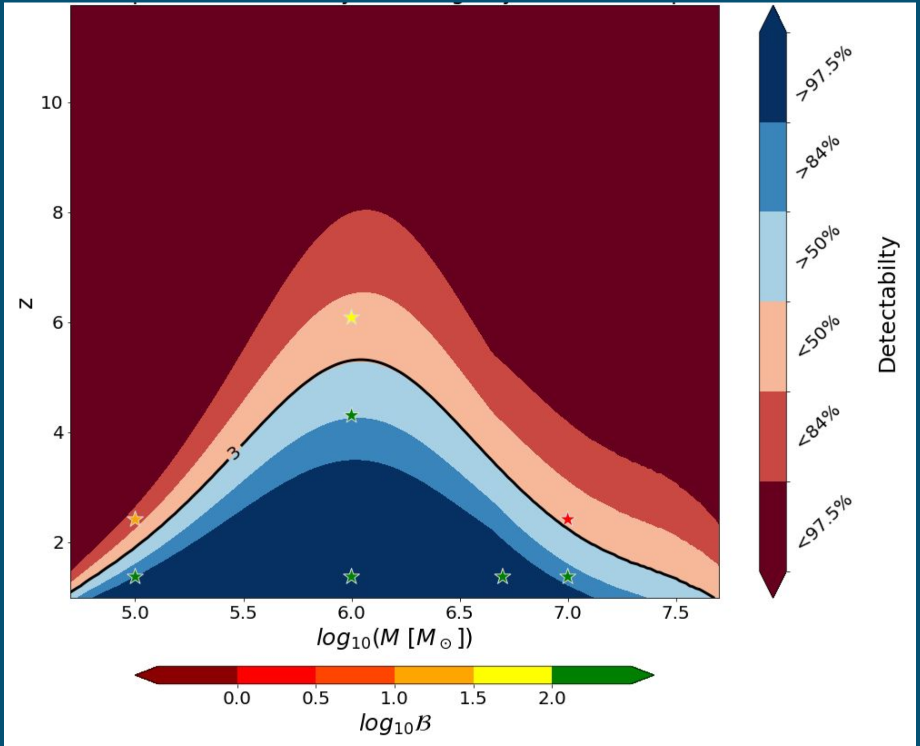




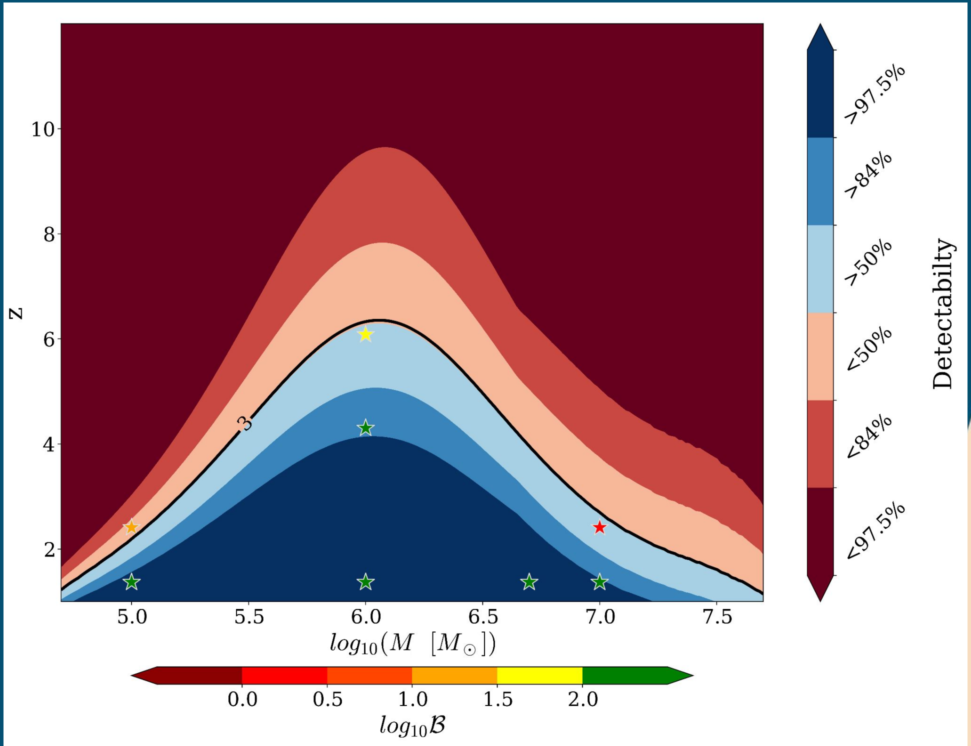
★ Post-response and TDI, (2,0) oscillatory component is far less damped than memory and therefore should really not be neglected.

Redshift waterfall plots

☆ Without HM



☆ With HM



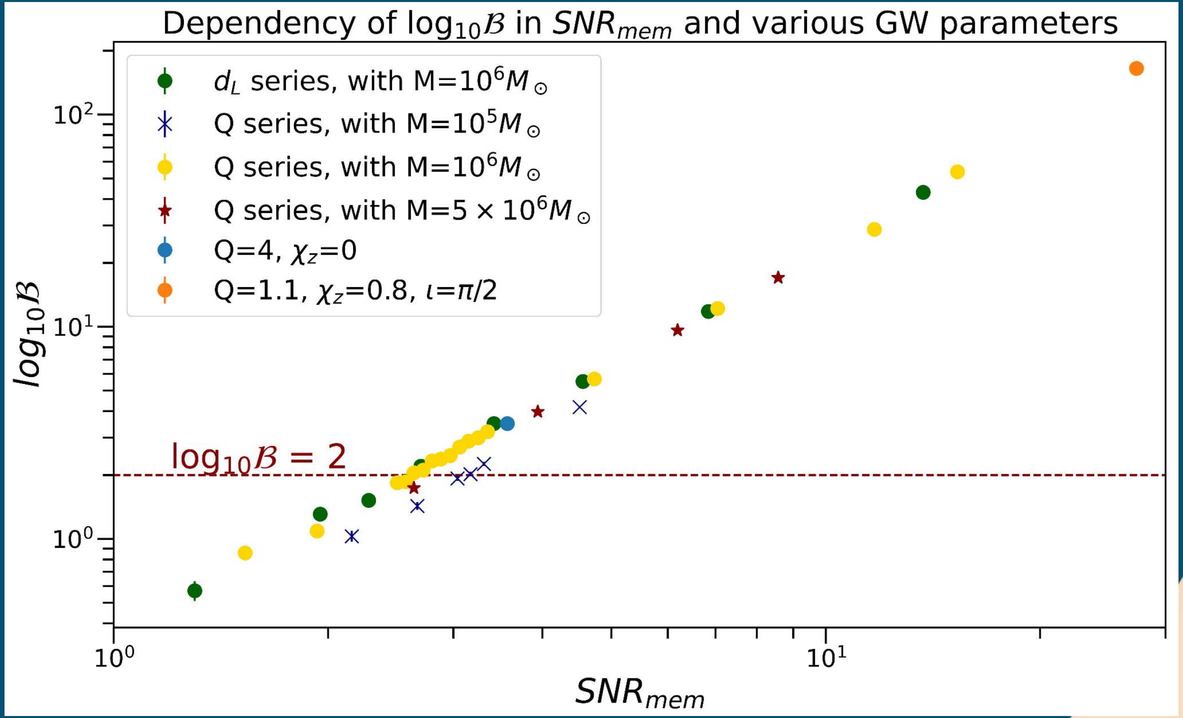
☆ Note: Done with NRHybSur3dq8_CCE

Using SNR_{mem} as a proxy

★ We observed a power law relation between the Bayes factor value and the SNR of memory, SNR_{mem}.

★ For the usual case of MBHB in LISA, we have bright sources ($SNR_{tot} > 100$), this implies that the likelihood function is highly peaked and so the evidence –the integration of the likelihood over parameter space– is dominated by the injected source parameters θ_{source}.
Allowing this approximation:

$$log_{10}\mathcal{B} = \Delta log_{10}\mathcal{Z} \approx \Delta log_{10}\mathcal{L}(\theta_{source})$$



☆ Note: Done with NRHybSur3dq8_CCE, restricted to (2,2) + memory

Loglikelihood approximation