



PHENIICS Fest - 08/06/26

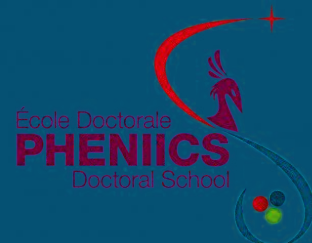


# Detecting the memory effect

## with LISA



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cea

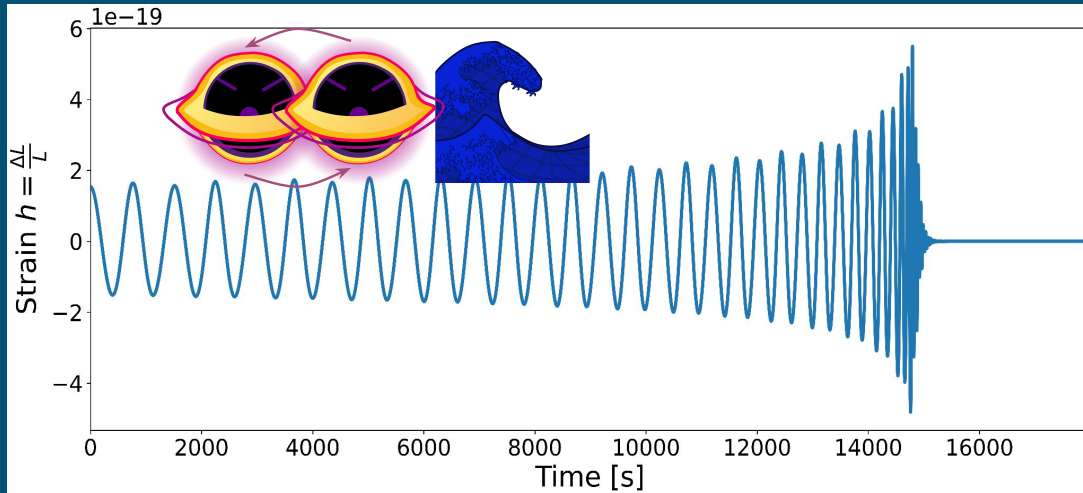
irfu

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# Gravitational waves from MBHBs

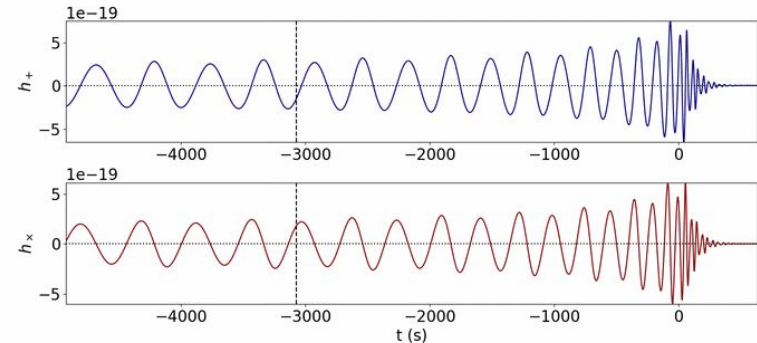
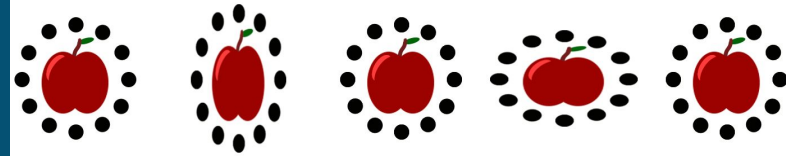
(Massive Binary Black Holes)



Real duration: 5565.0s = 92.75min = 1.55h

Time acceleration: 185.5×

Wave amplification:  $10^{18.0} \times$



# THE SPECTRUM OF GRAVITATIONAL WAVES

You are here

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

$10^{-2}$

$10^{-4}$

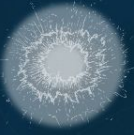
$10^{-6}$

$10^{-8}$

$10^{-16}$

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



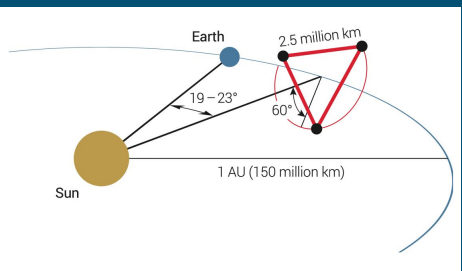
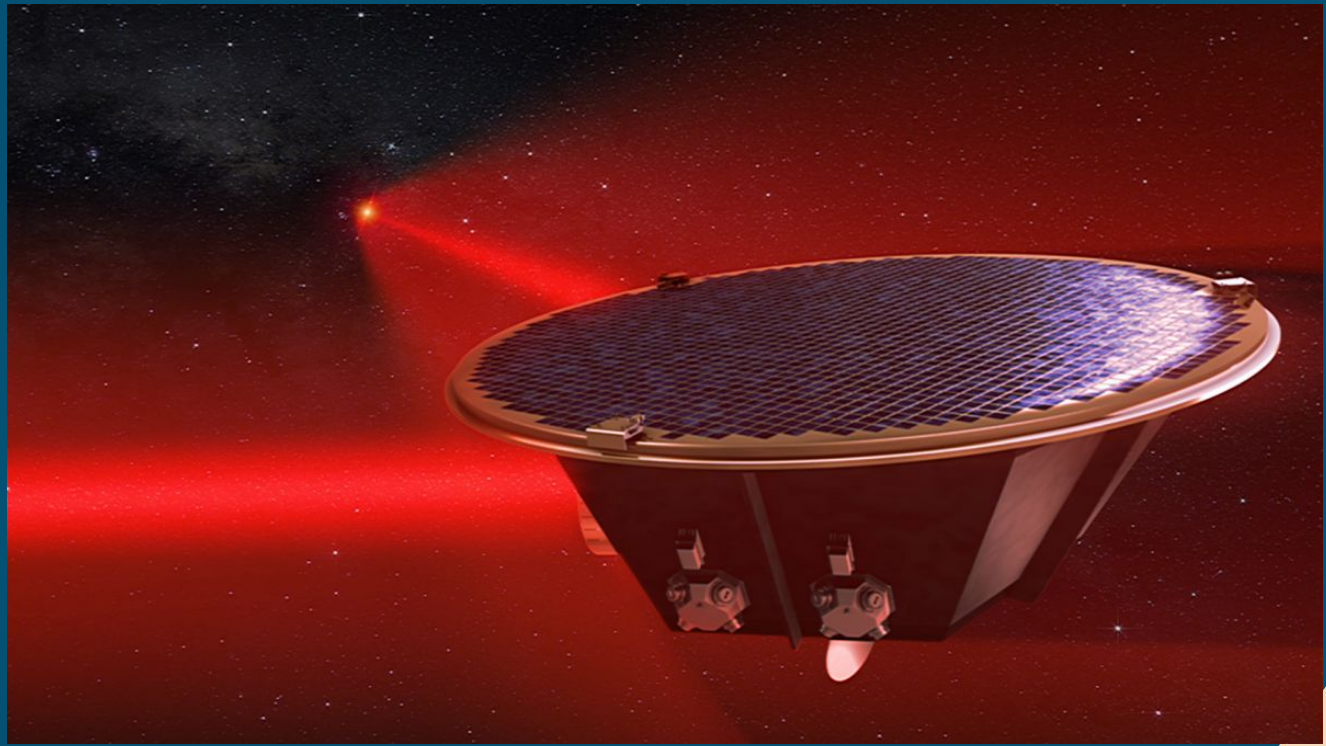
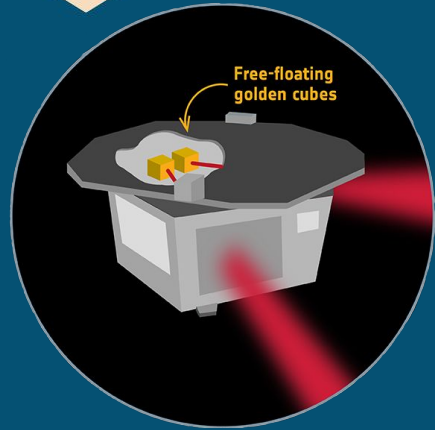
Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

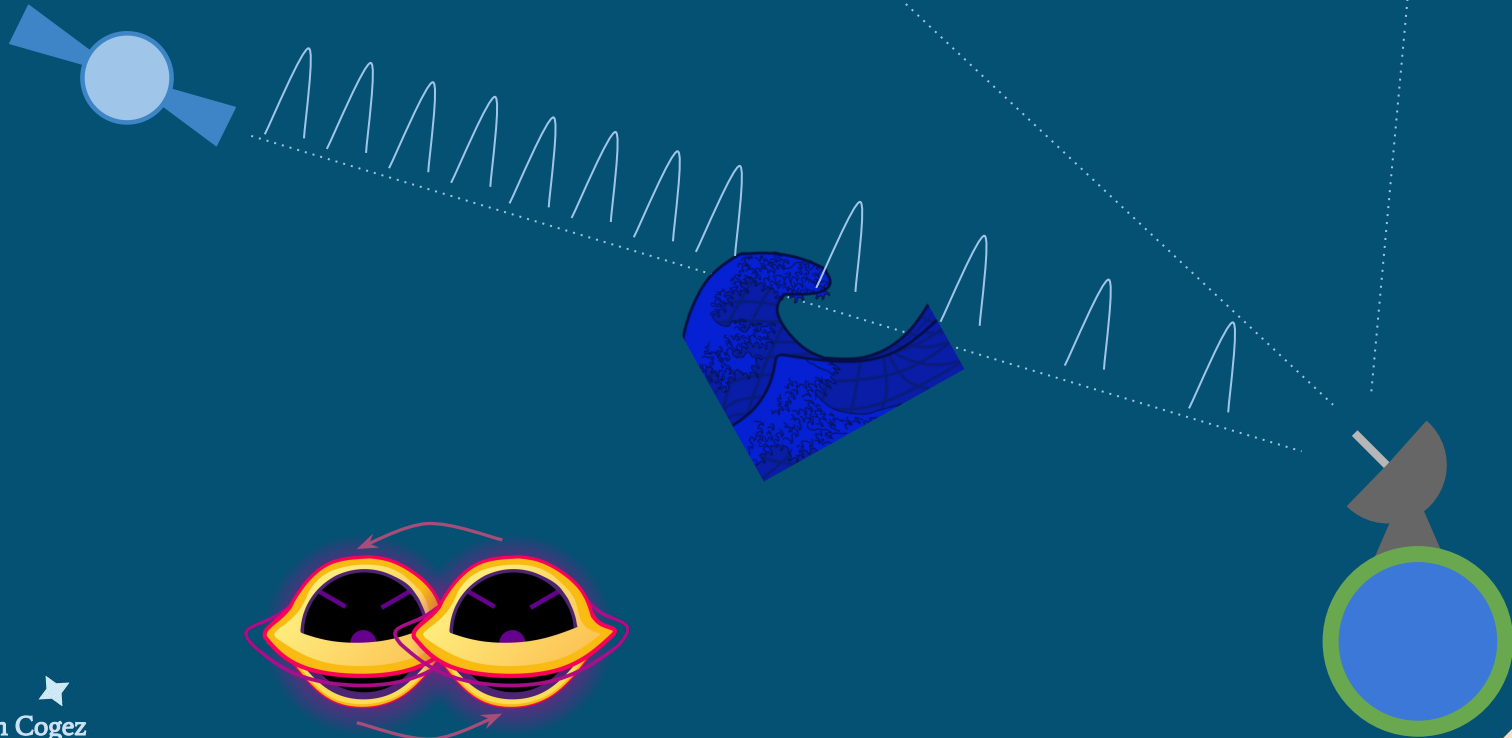


# LISA principle



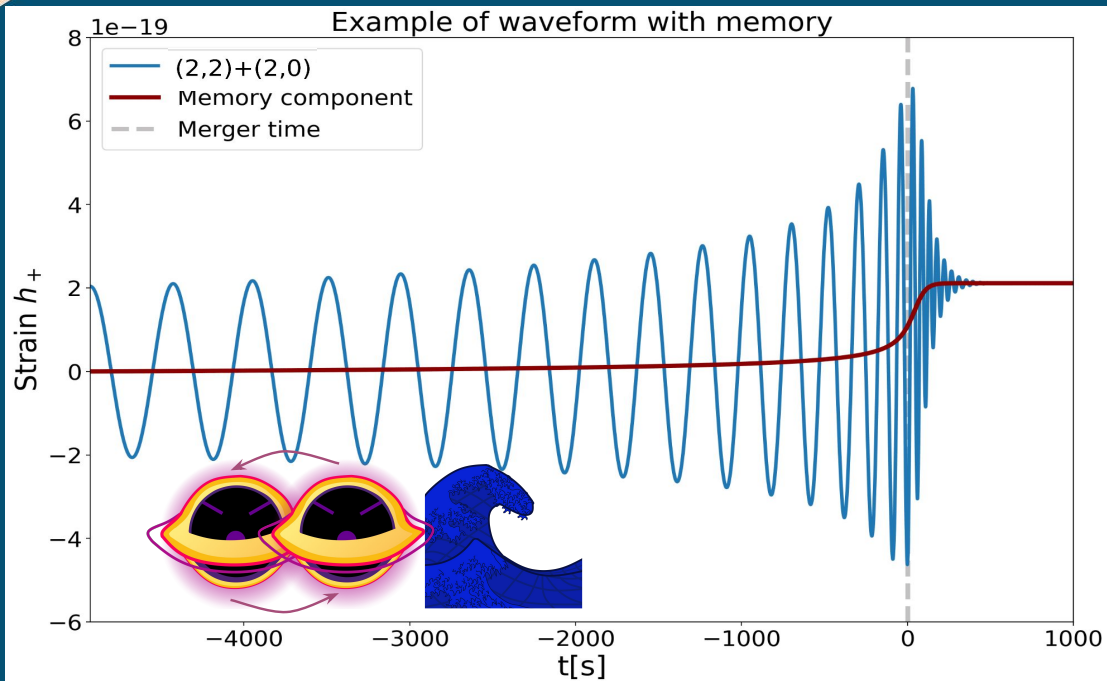


# PTA principle





# 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).

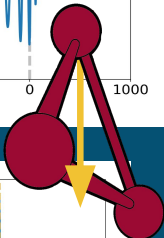
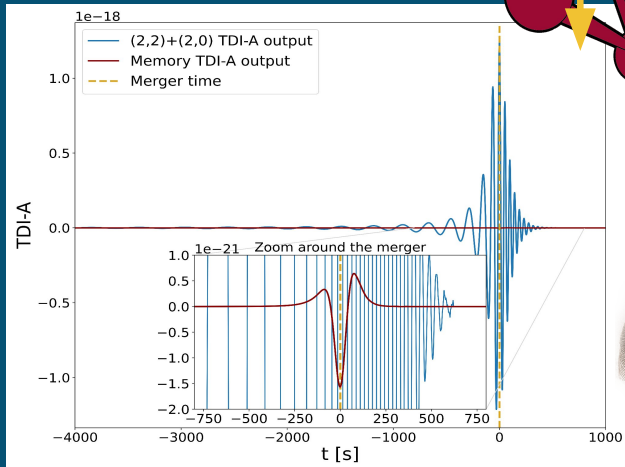
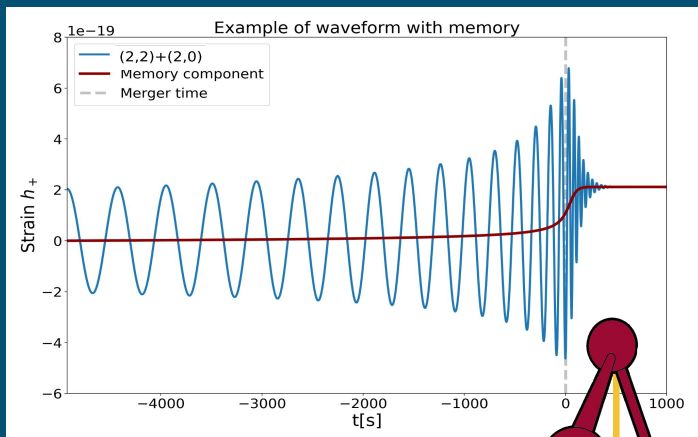
☆ Note: Parameters used:

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

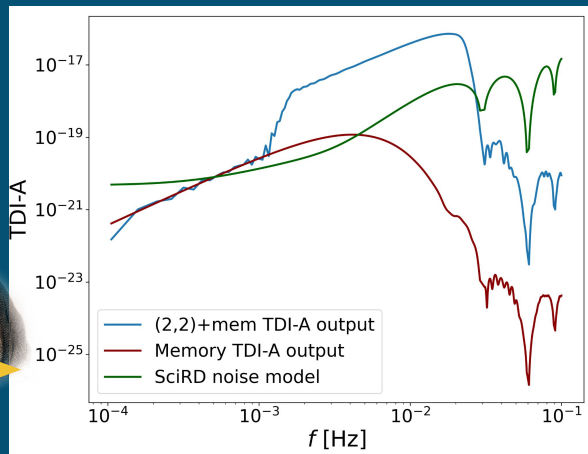
☆ Note: Here with NRHybSur3dq8\_CCE, restricted to (2,2) + memory



# Observing memory with LISA



- ★ In the physical signal, the memory strain is around  $\sim 10\%$  of the GW max amplitude.
- ★ Damped by LISA's response



LISA response  
+  
Time-Delay  
Interferometry



# Analysis choices: Waveforms and HM

Waveforms	Considered modes
<i>NRHybSur3dq8_CCE</i>	(2,2)
<i>NRHybSur3dq8_CCE</i>	(2,2) + HM: (2,1), (3,3), (3,2), (4,4), (4,3)
<i>SEOBNRv5HM</i>	(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

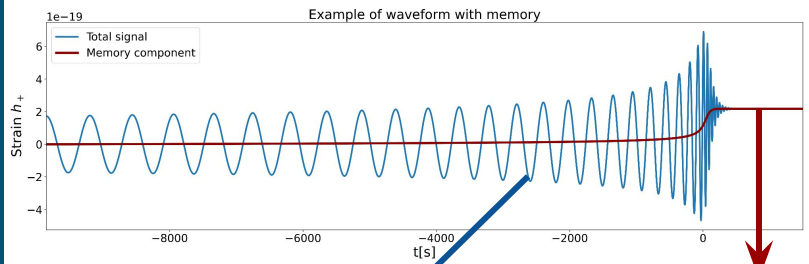
+ associated memory component:

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

See Zosso et al. [[arXiv:2601.23019](https://arxiv.org/abs/2601.23019) / DOI: [10.1103/51xv-zlfy](https://doi.org/10.1103/51xv-zlfy)]



# Signal-to-noise ratio hints



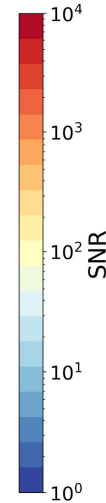
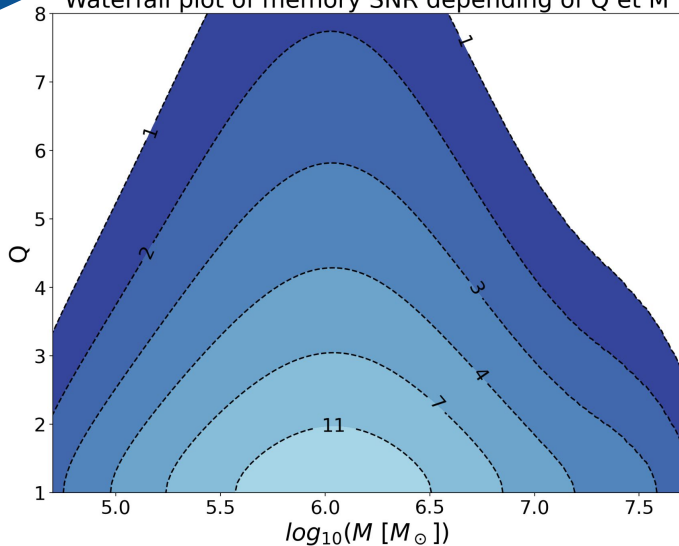
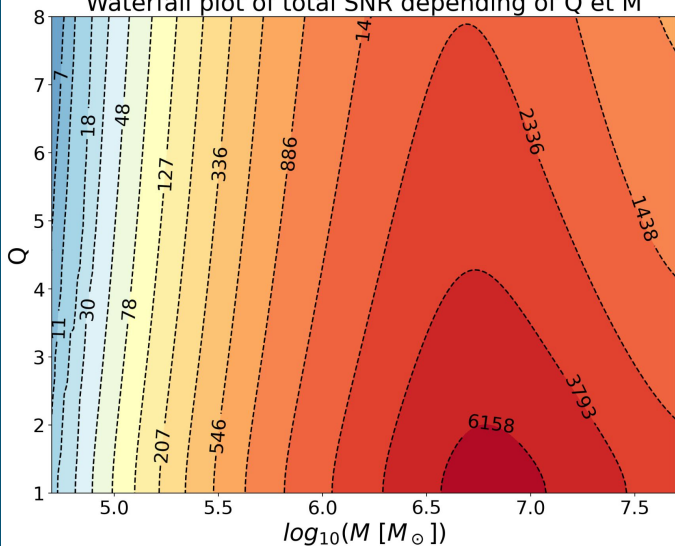
See Inchauspé et al. (2025)  
DOI: 10.1103/PhysRevD.111.044044

SNR<sub>tot</sub>

SNR<sub>mem</sub>

Waterfall plot of total SNR depending of Q et M

Waterfall plot of memory SNR depending of Q et M



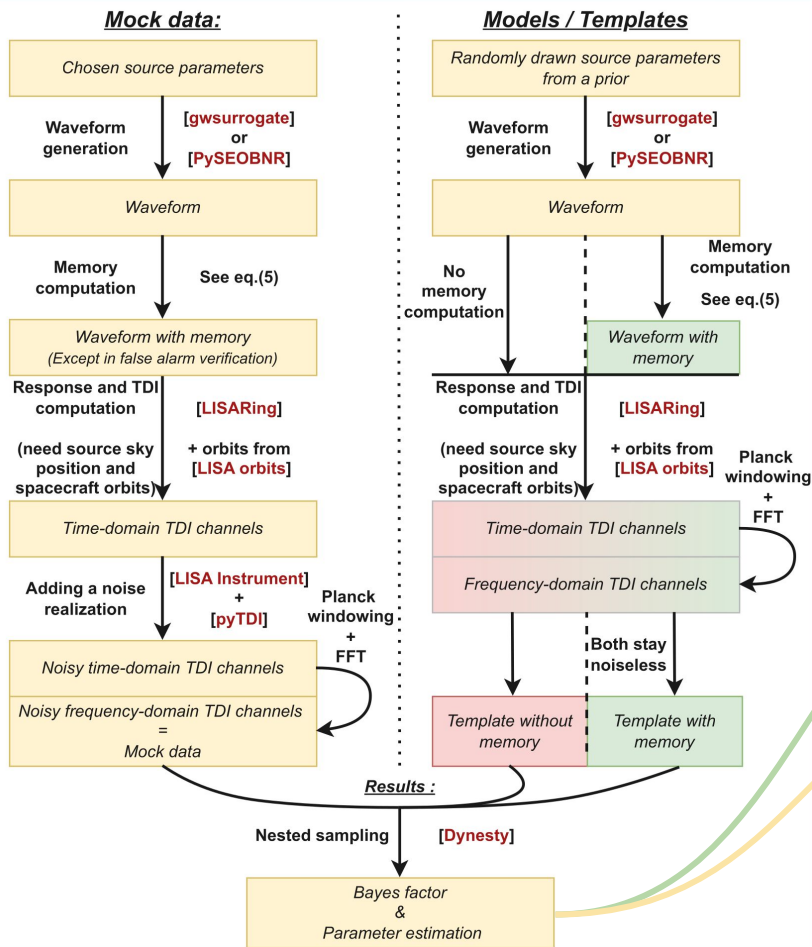
Encouraging results but it assumes that we can perfectly disentangle memory from the oscillatory signal.

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



Posterior distributions

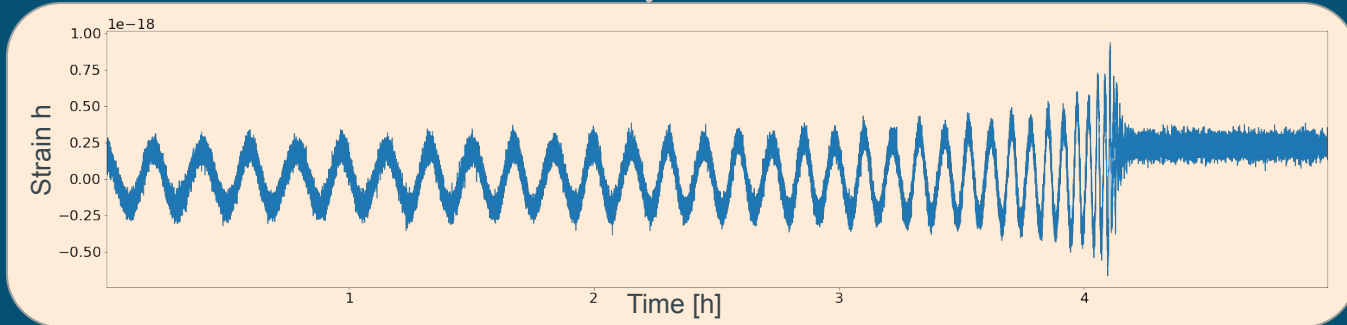
$$\log_{10} \mathcal{B} = \log_{10} \mathcal{Z}_{o+m} - \log_{10} \mathcal{Z}_o$$

☆ Note: o = oscillatory  
m = memory



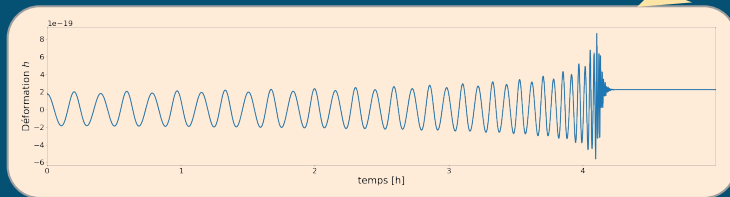
# Bayesian Analysis

## Noisy data

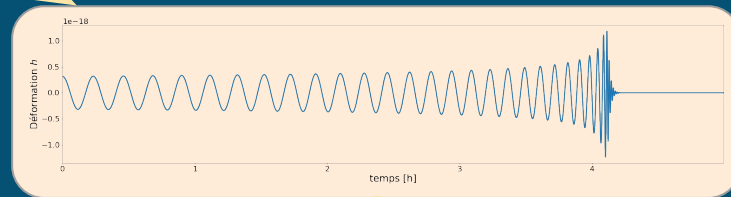


(For illustration only,  
in practice we work in  
Frequency Domain)

## Template with memory



## Template without memory



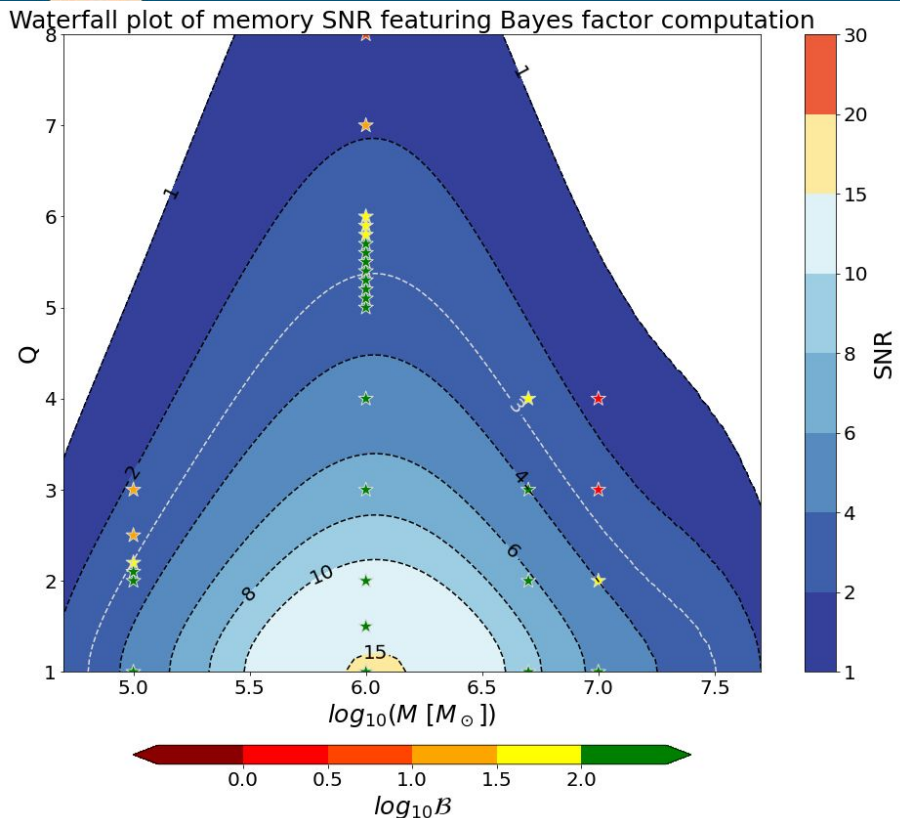
$$\log_{10} \mathcal{Z}_{o+m}$$

$$\log_{10} \mathcal{Z}_o$$

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



# 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 ( $\rightarrow$  stars).

★ **Memory is detected** when  $\log_{10} \mathcal{B} > 2$  (=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

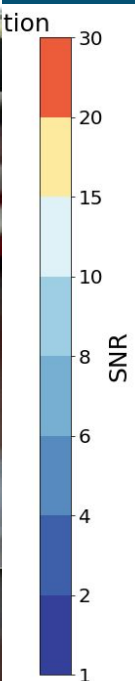
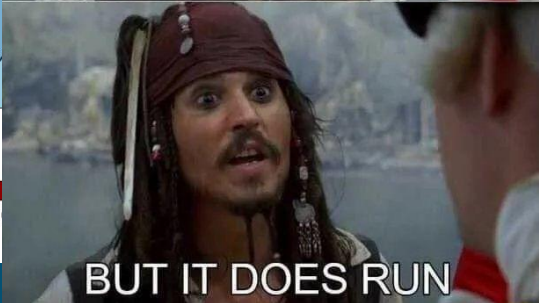
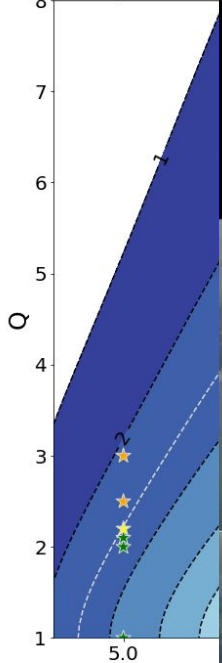




# Bayesian detectability criterion



Waterfall plot of m



★ Bayes factor estimation = 2 jobs using 100 CPUs each. Depending on parameters and HM inclusion, each job take between 20 to 100h !

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

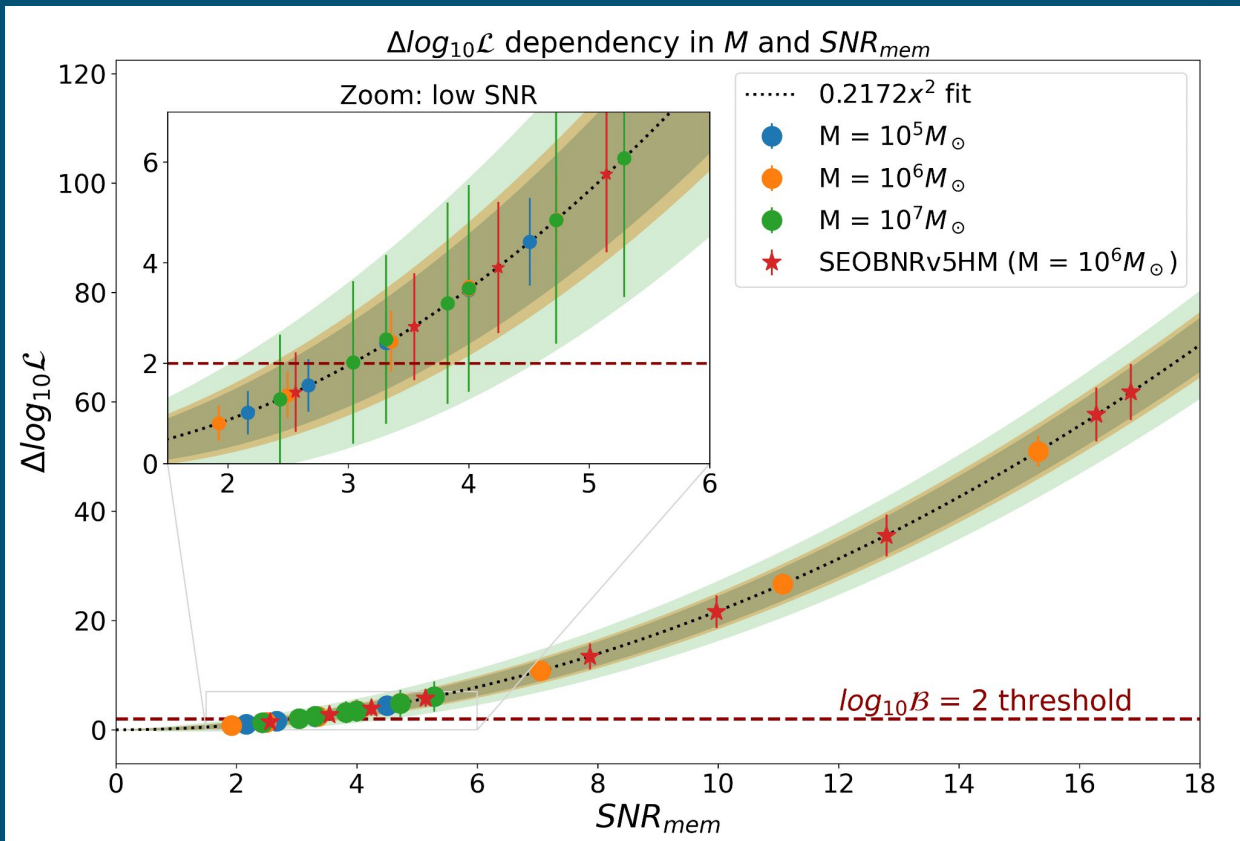


★ Power law relation between the (mean) Bayes factor value and the SNR of memory,  $SNR_{mem}$

★ 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  $SNR_{mem} \geq 5!$



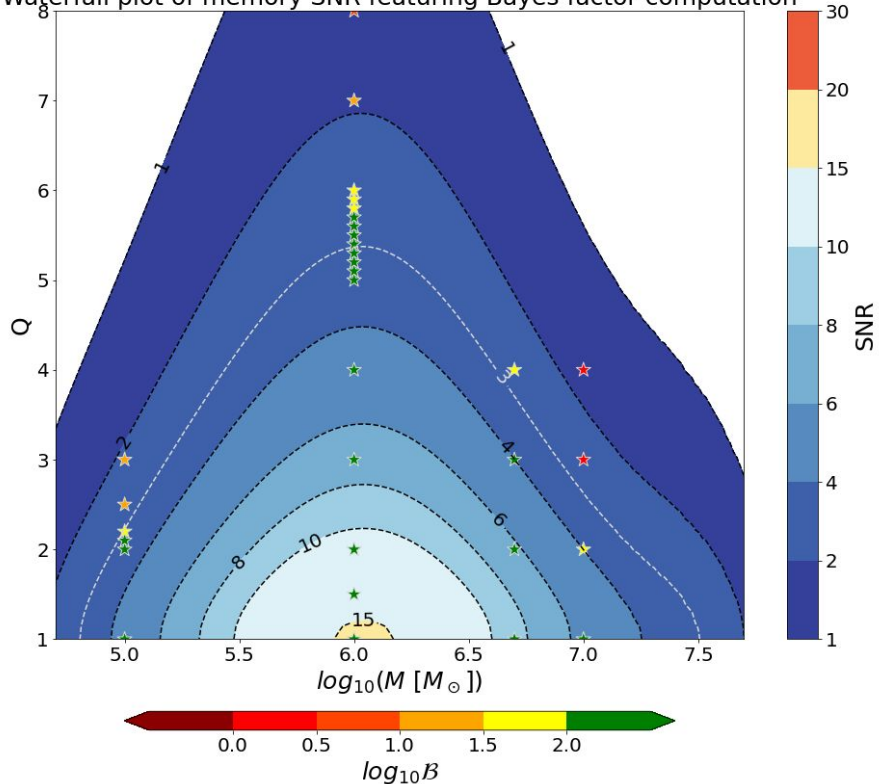
★ Note: Done with NRHybSur3dq8\_CCE, restricted to (2,2) + memory, validated with SEOBNRv5HM



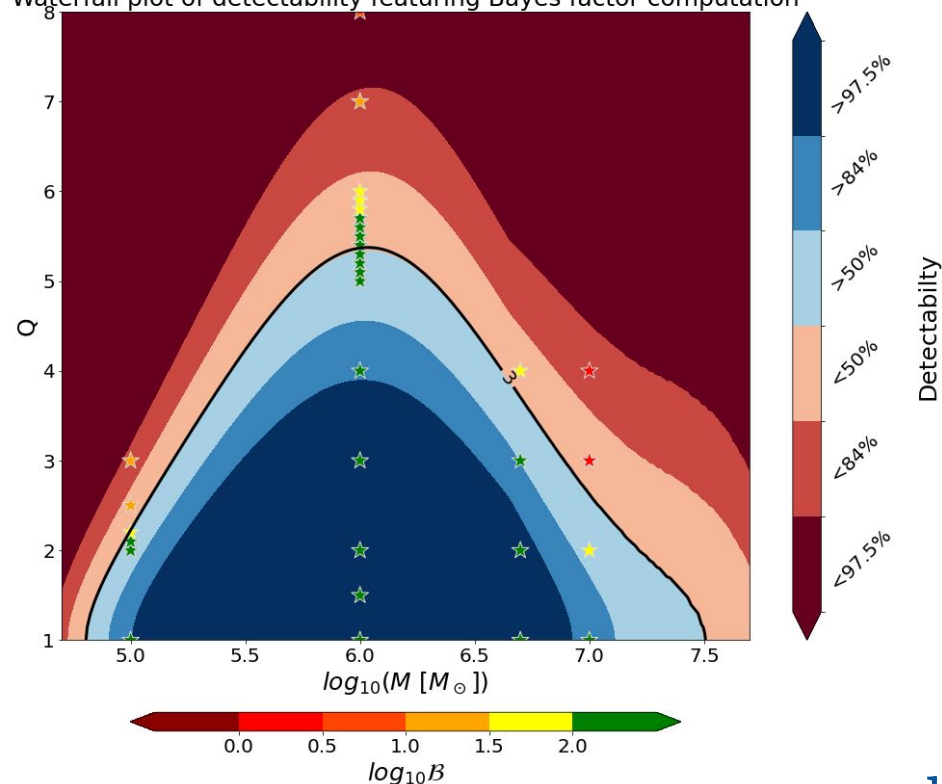


# Detectability map

Waterfall plot of memory SNR featuring Bayes factor computation

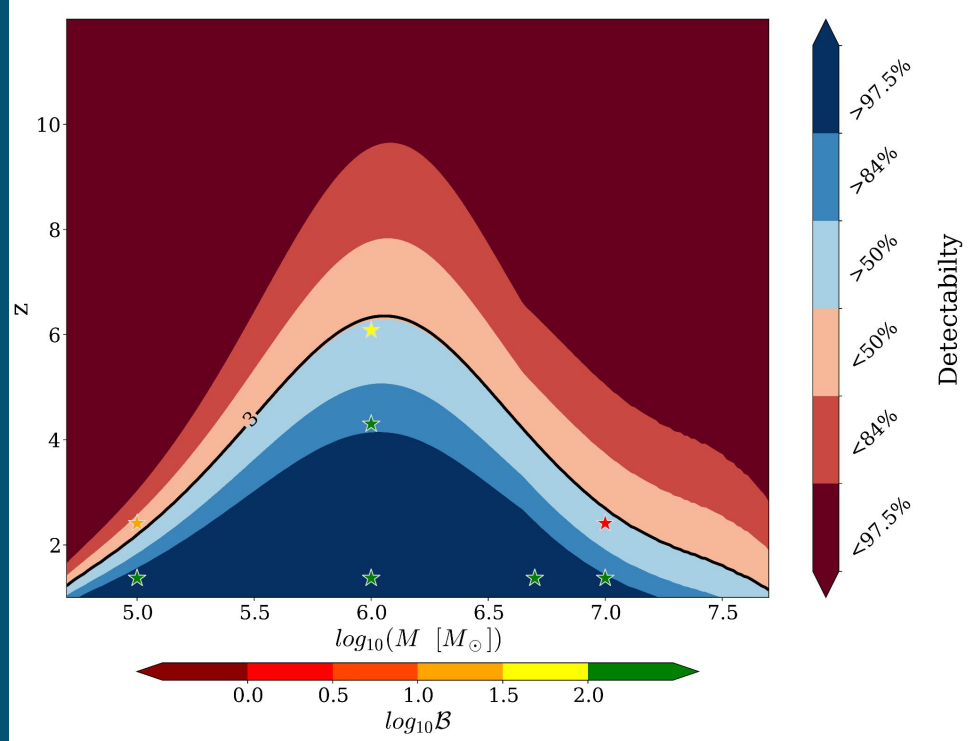
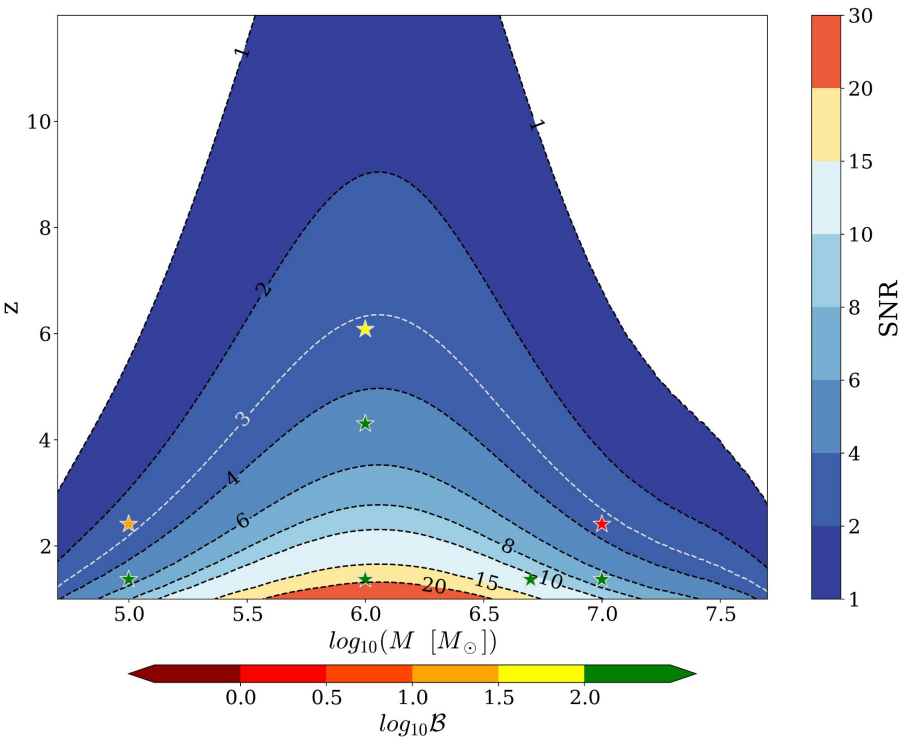


Waterfall plot of detectability featuring Bayes factor computation





# Redshift waterfall plots





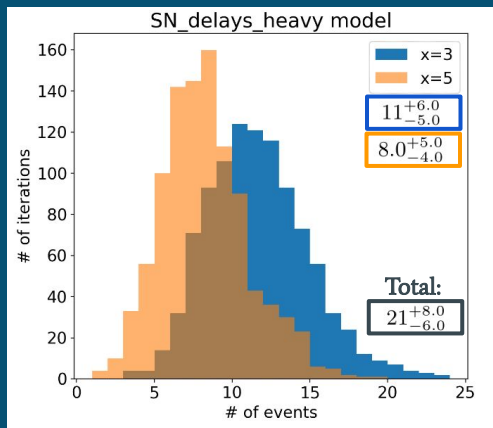
# Forecast using population models

Thanks to E. Barausse for the population models.  
See Barausse et al. (2020) DOI: [10.3847/1538-4357/abba7f](https://doi.org/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:  
 $\text{SNR}_{\text{mem}} \geq 3$  (resp. 5)

$$21^{+8.0}_{-6.0}$$

Nb of total events:  
 $\text{SNR}_{\text{tot}} \geq 8$

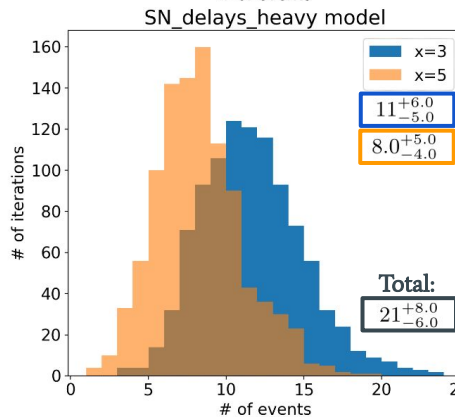
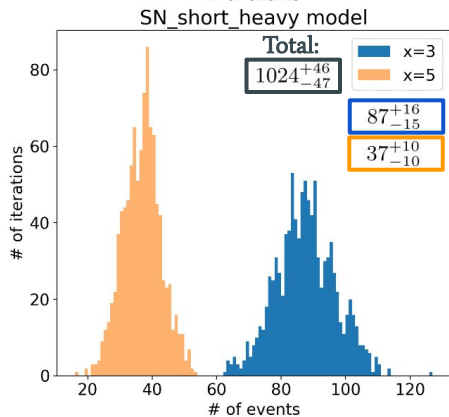
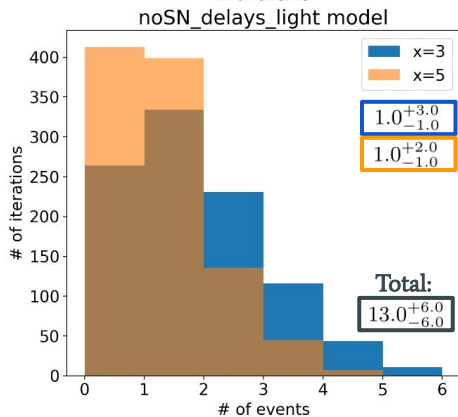
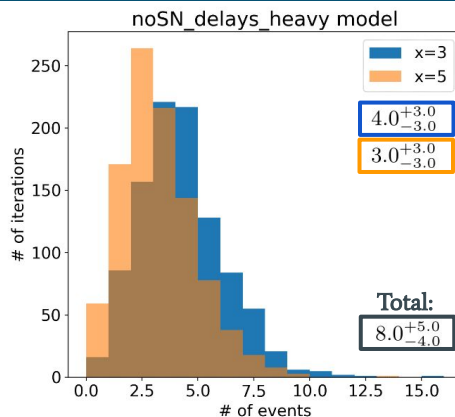
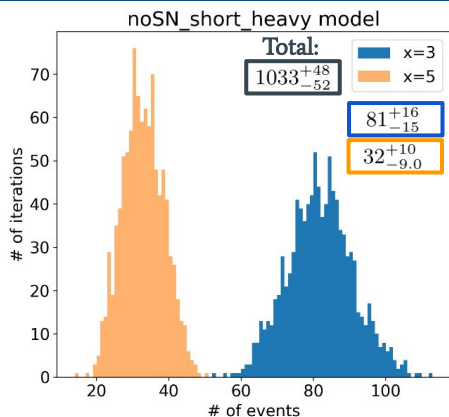
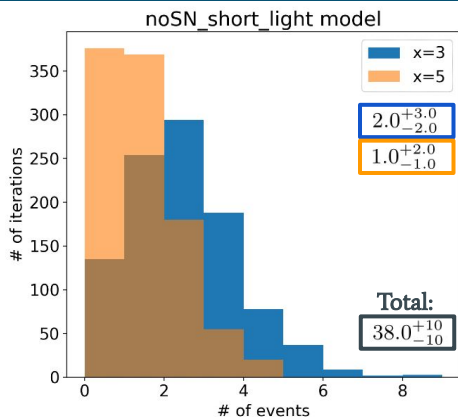


# Forecast using population models

- ★ 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  
 $SNR_{tot} > 8$

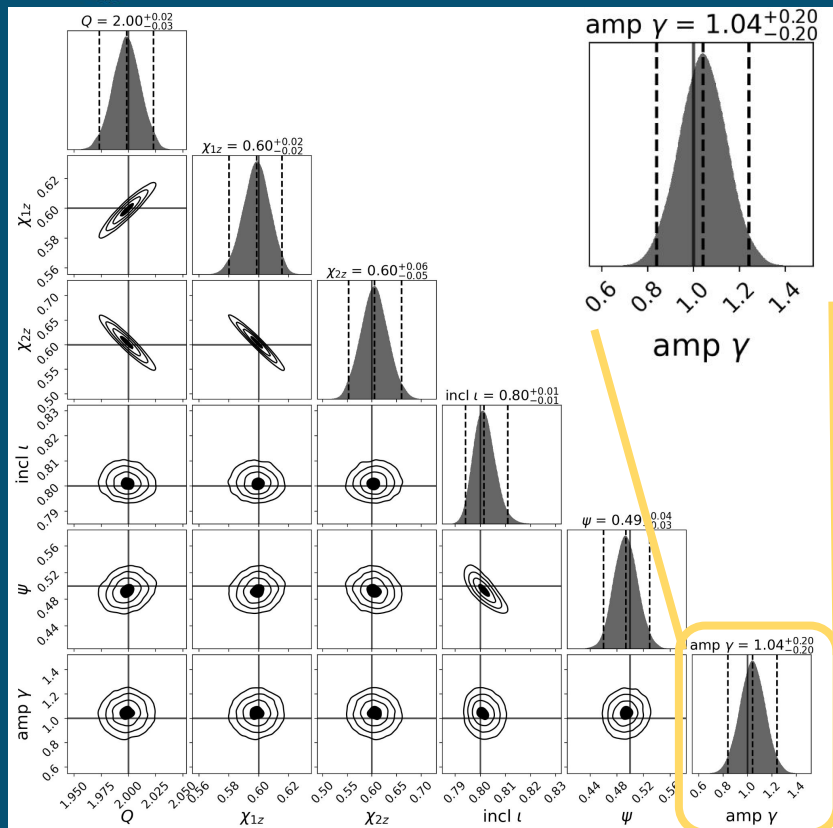




# Probing GR through memory

- ★ Possibility to define a free parameter to describe the amplitude of the memory. Here we define  $\gamma$  as:

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

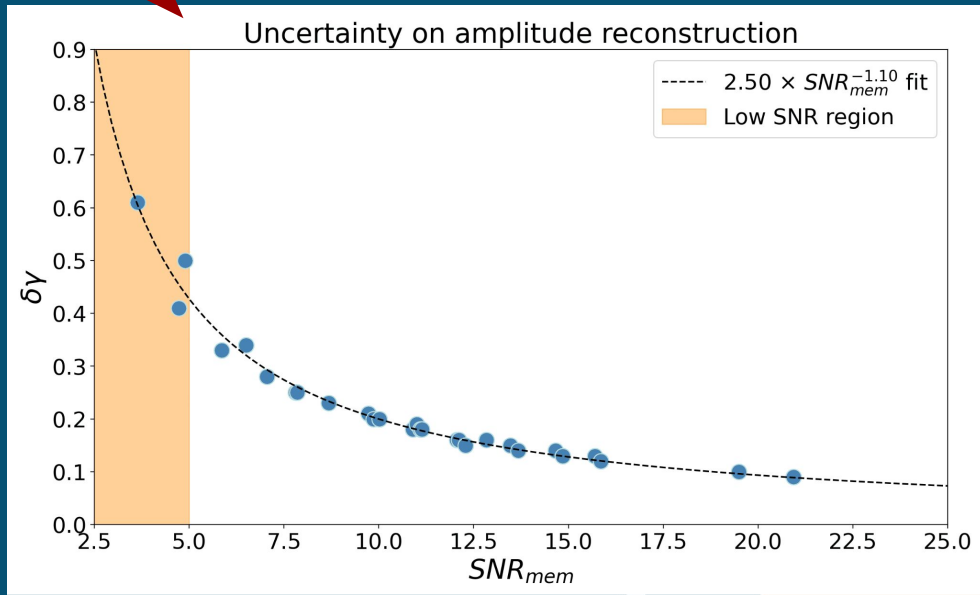
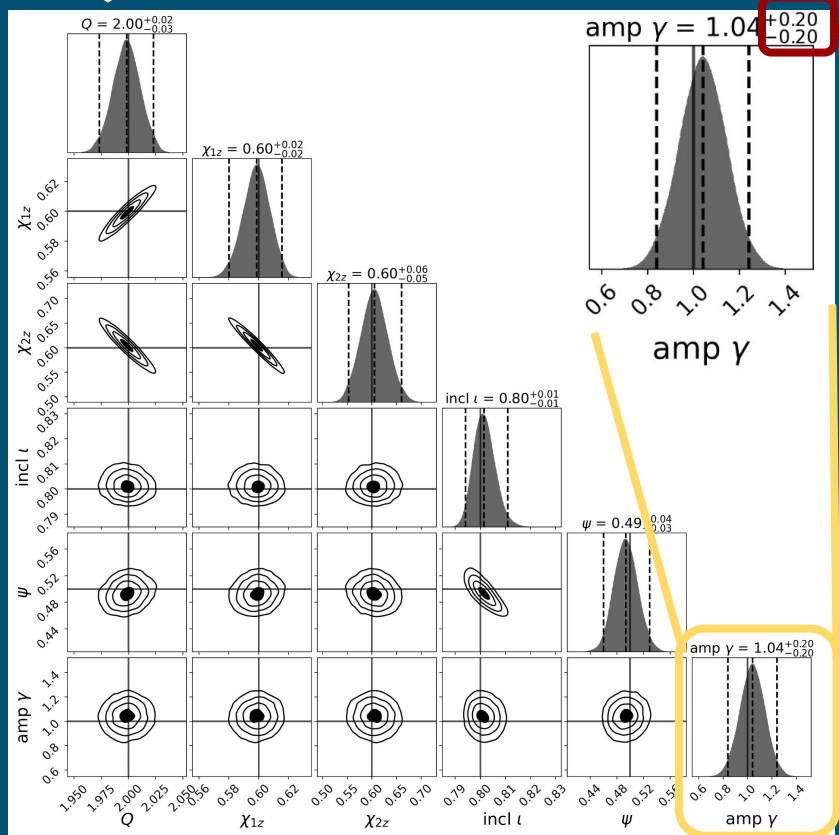




# Probing GR through memory

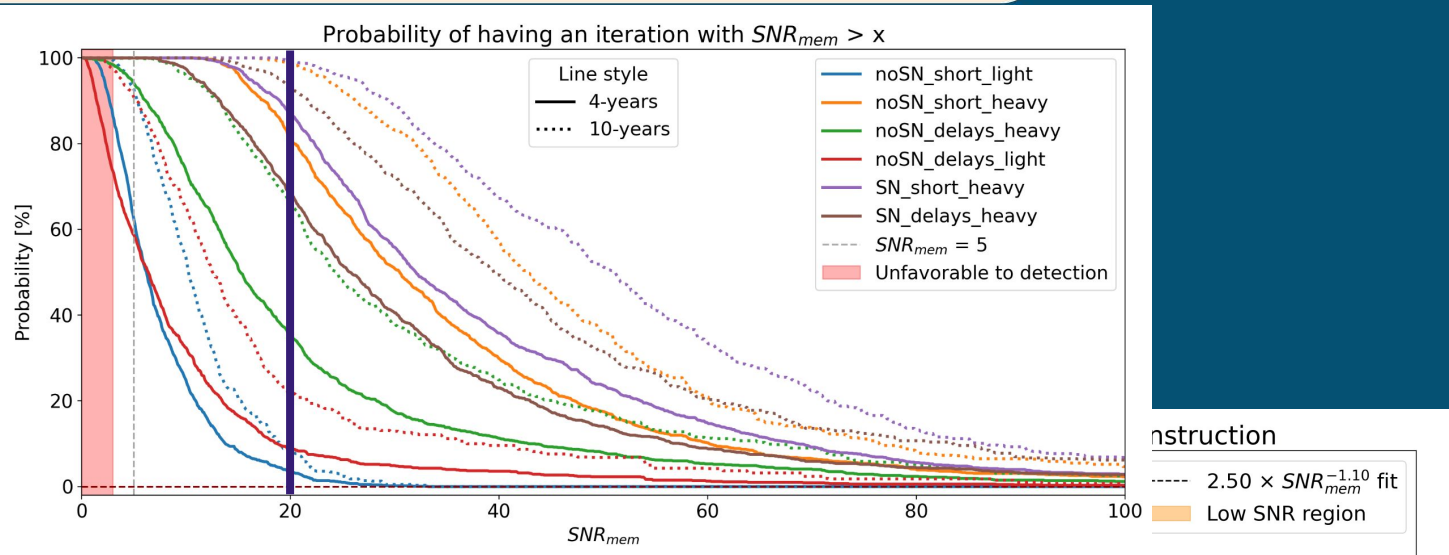
★ We can also monitor the uncertainty  $\delta\gamma$  on the reconstructed  $\gamma$ . As a result,  $\delta\gamma$  only depend on  $\text{SNR}_{\text{mem}}$  following:

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

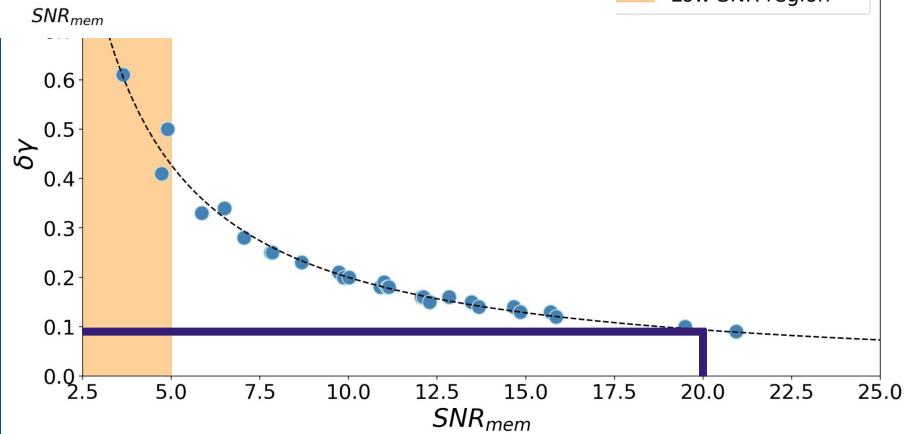




# Probing GR through memory



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





# Conclusion

- ★ 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.



# Bonus: GWaver & Scientific Game Jam

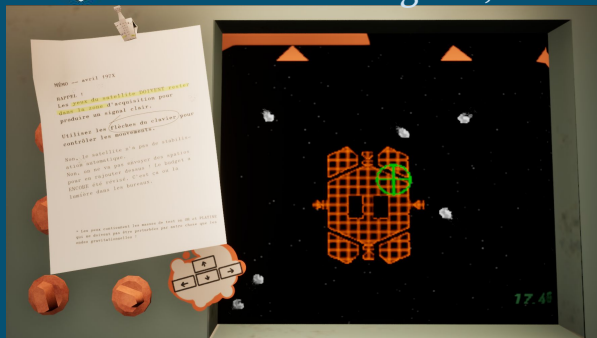
Scientific game jam = ~ 2 days to make a small, fun & instructive video game, in collaboration with devs, graphists & so on



<https://tiom311.itch.io/gwaver>



(Only available in french & on Windows, sorry :c)





PHENIICS Fest - 08/06/2026



École Doctorale  
**PHENIICS**  
Doctoral School

# Thanks for your attention !

Any question ? :)

And if you want more details: [[arXiv:2601.23230](https://arxiv.org/abs/2601.23230) / DOI: [10.1103/b9ld-dqq4](https://doi.org/10.1103/b9ld-dqq4)]  
Companion theory paper [[arXiv:2601.23019](https://arxiv.org/abs/2601.23019) / DOI: [10.1103/51xv-zlfy](https://doi.org/10.1103/51xv-zlfy)]



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# 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\*.

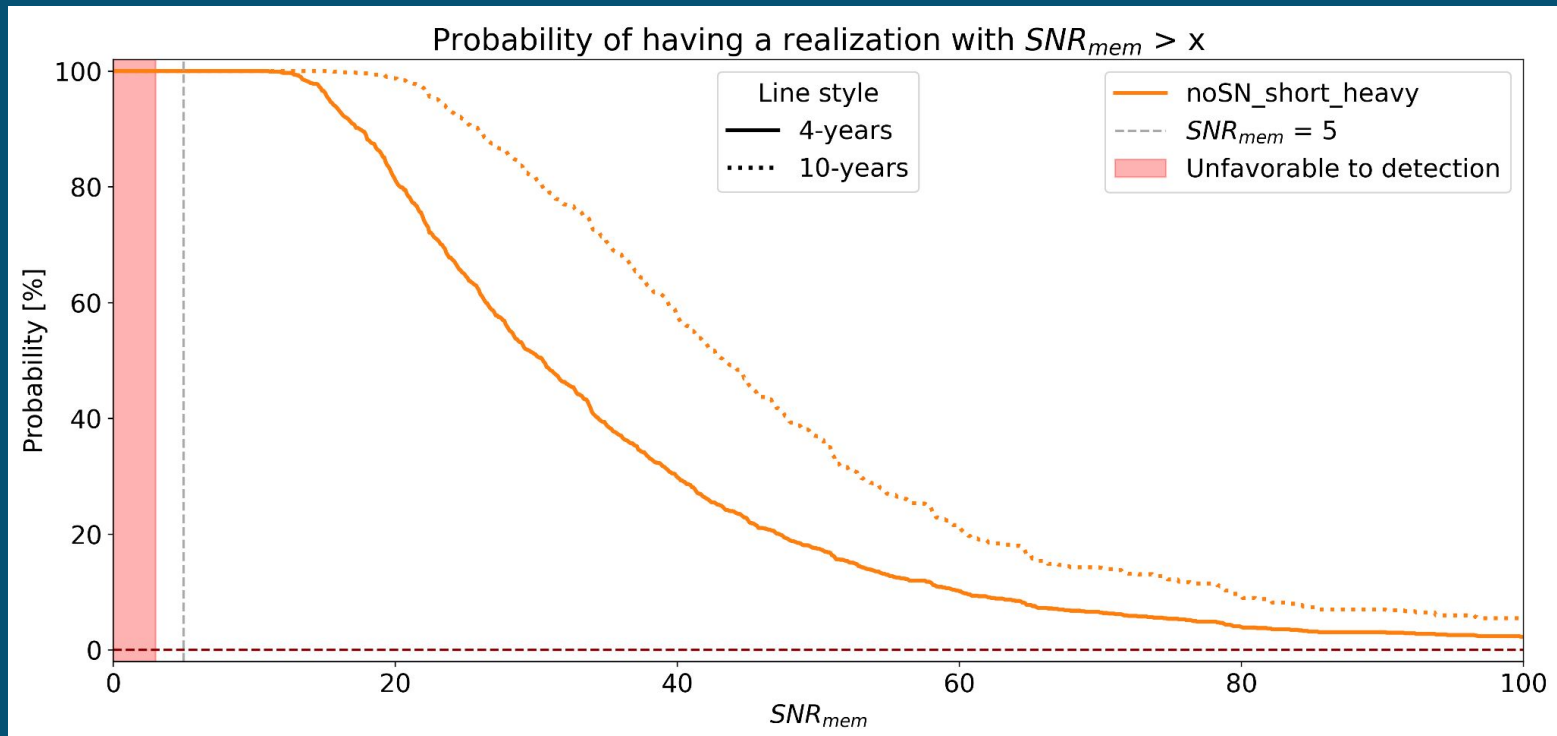
\* See Cheung et al. (2024)

DOI: [10.1088/1361-6382/ad3ffe](https://doi.org/10.1088/1361-6382/ad3ffe)



# Possibility of loud memory events

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

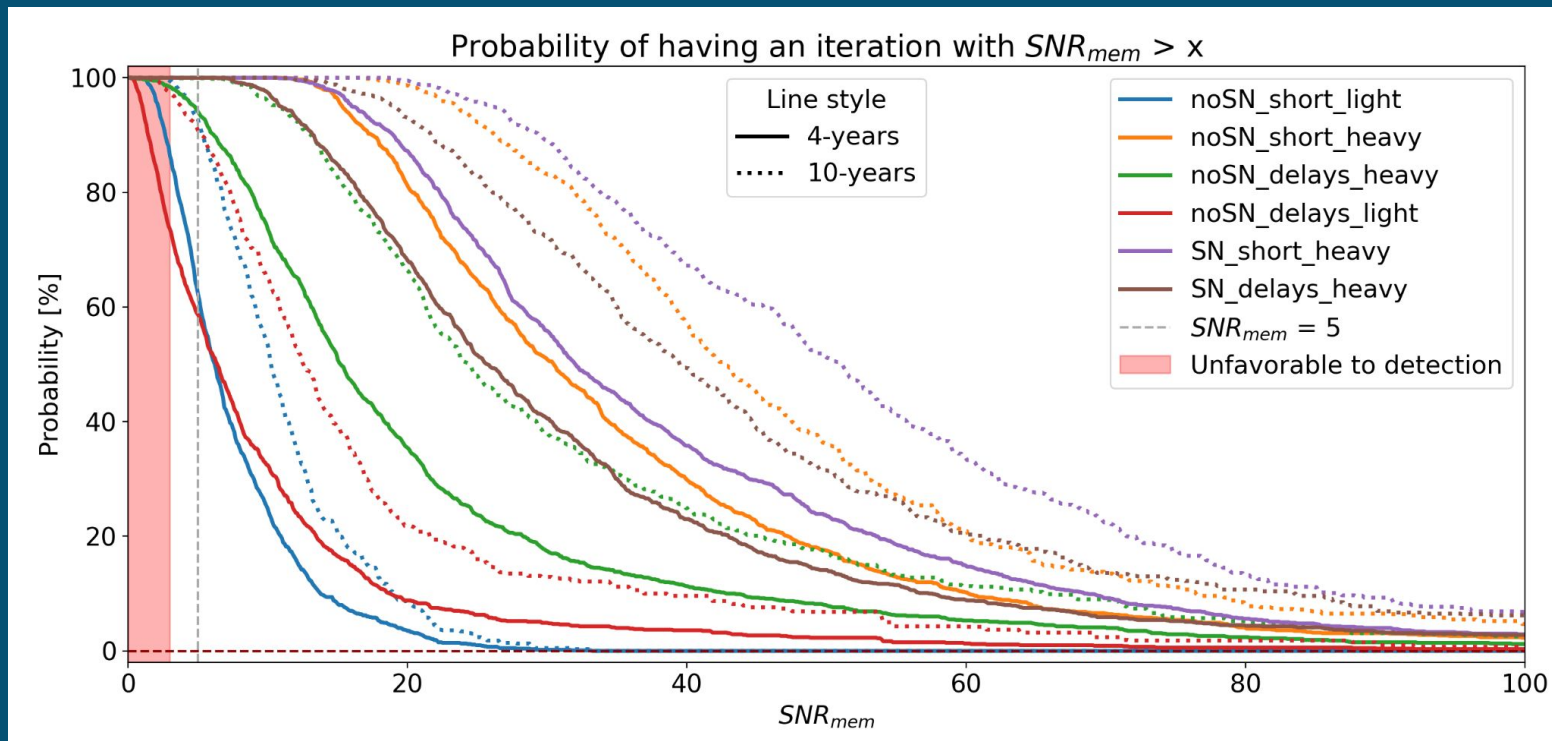


☆ Note: Probability estimated using 1000 realizations for each model



# Possibility of loud memory events

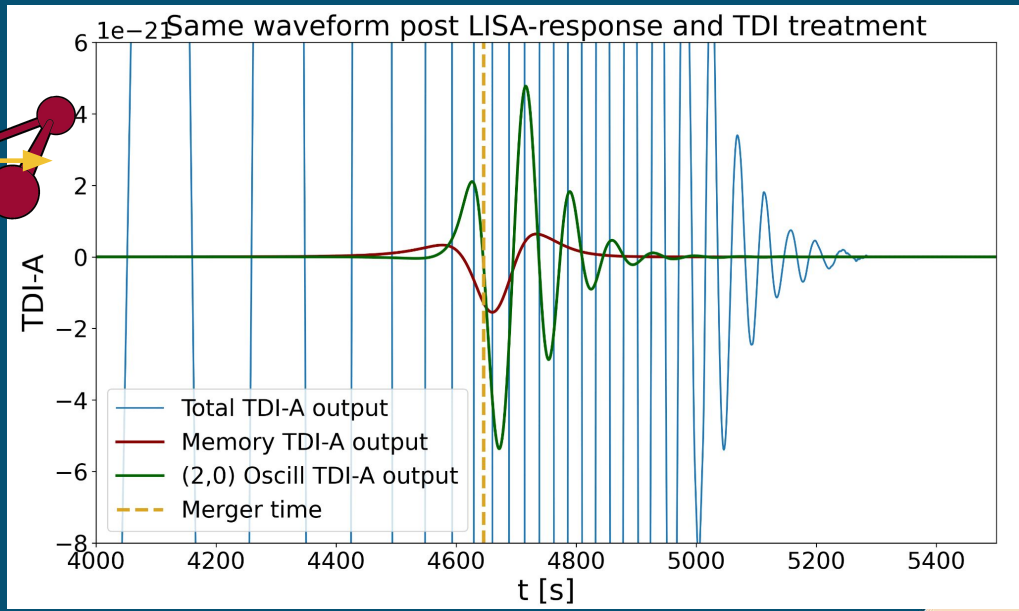
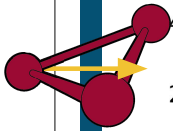
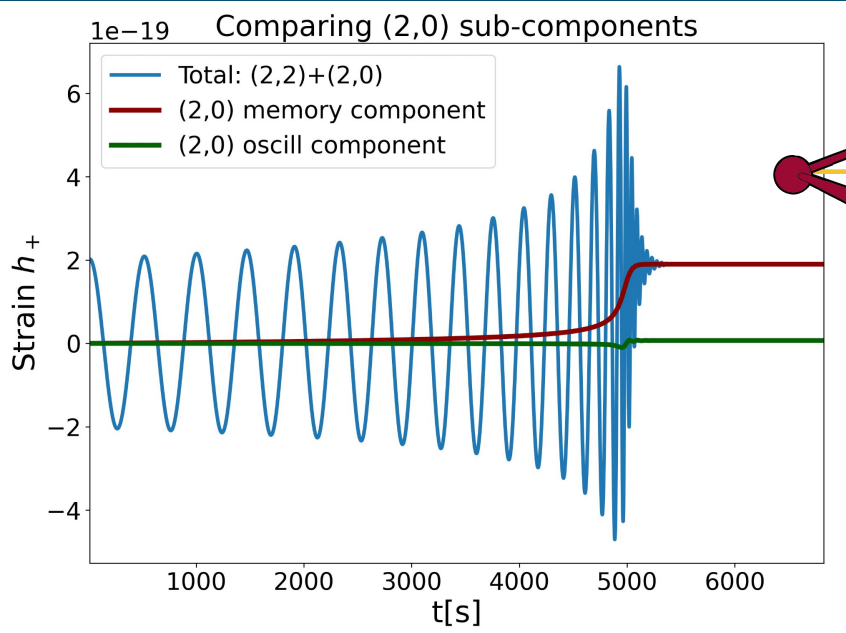
★ We can expect loud memory event, especially under the heavy seed hypothesis



☆ Note: Probability estimated using 1000 realizations for each model



# Analysis choices: Native memory



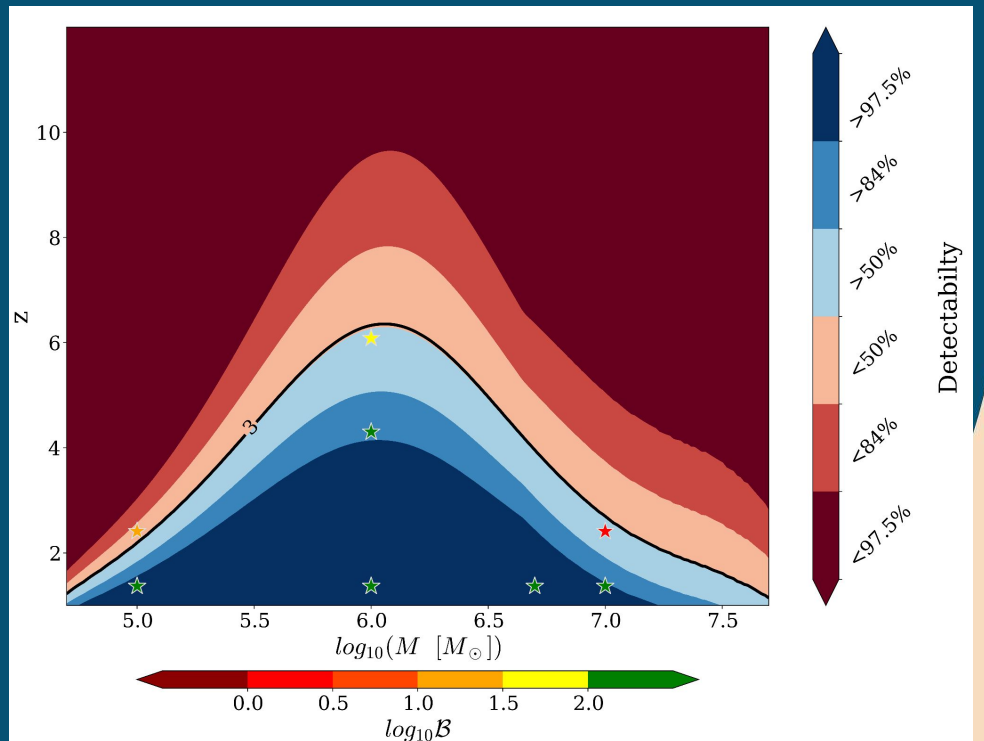
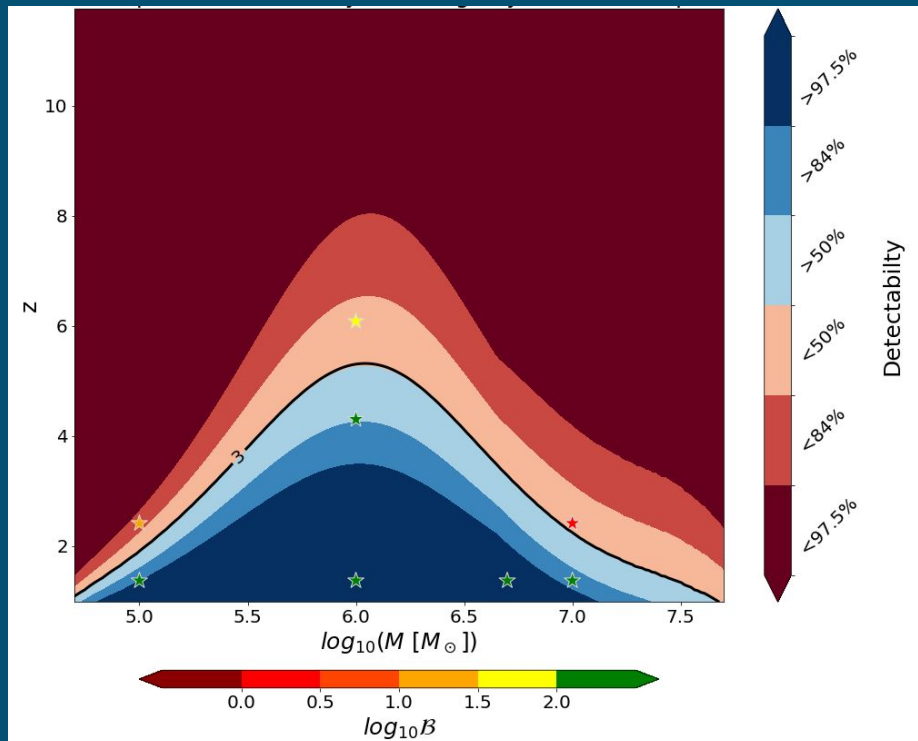
★ Post-response and TDI, (2,0) oscillatory component is far less damped than memory and therefore should really not be neglected.



# Redshift waterfall plots

☆ Without HM

☆ With HM



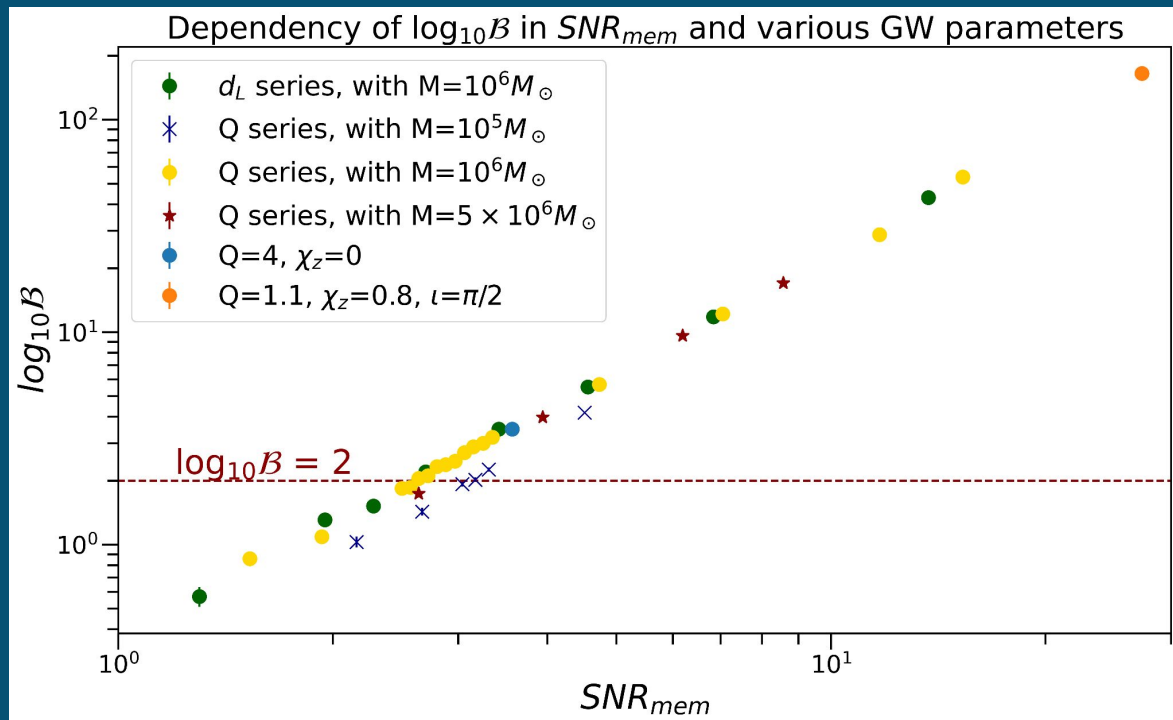


# Using $\text{SNR}_{\text{mem}}$ as a proxy

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

★ For the usual case of MBHB in LISA, we have bright sources ( $\text{SNR}_{\text{tot}} > 100$ ), 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  $\theta_{\text{source}}$ .  
Allowing this approximation:

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



☆ Note: Done with NRHybSur3dq8\_CCE, restricted to (2,2) + memory



# Loglikelihood approximation

