



GDR OG - 05/10/26



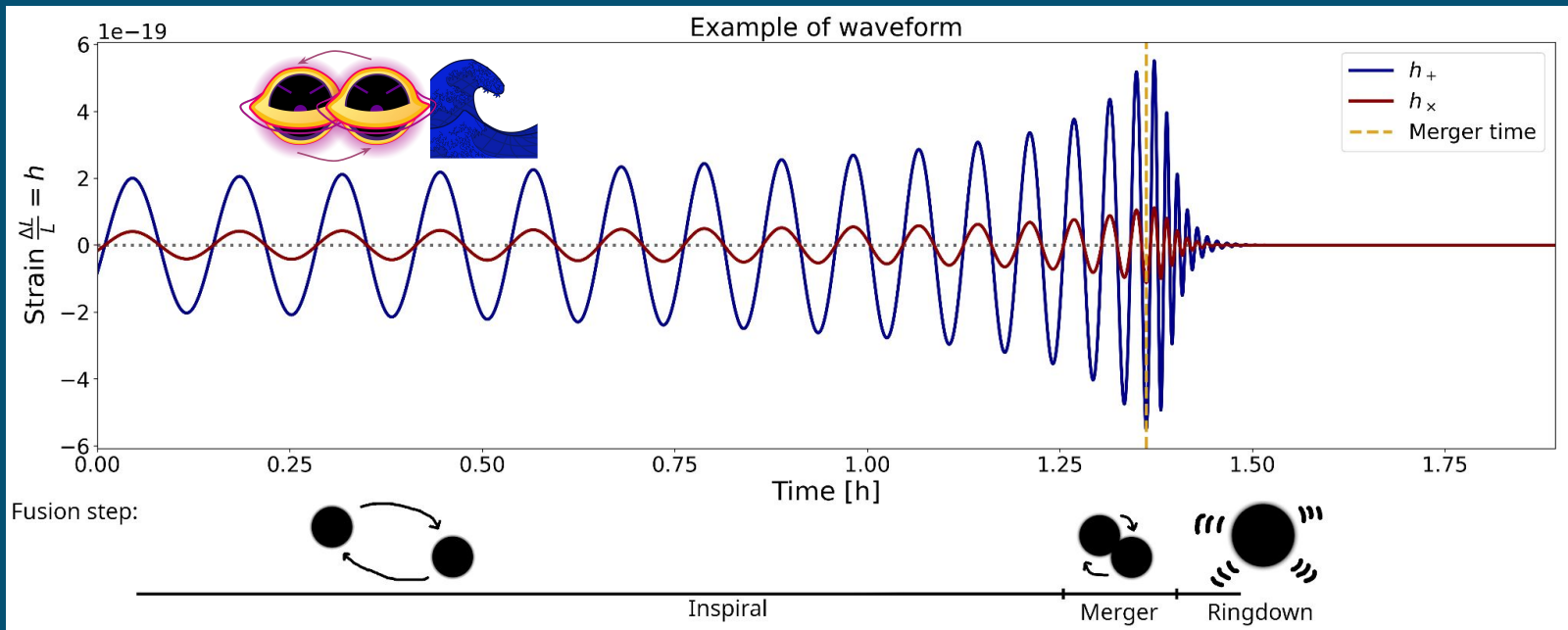
Catching non-linear memory effect with LISA & PTA

Adrien Coge





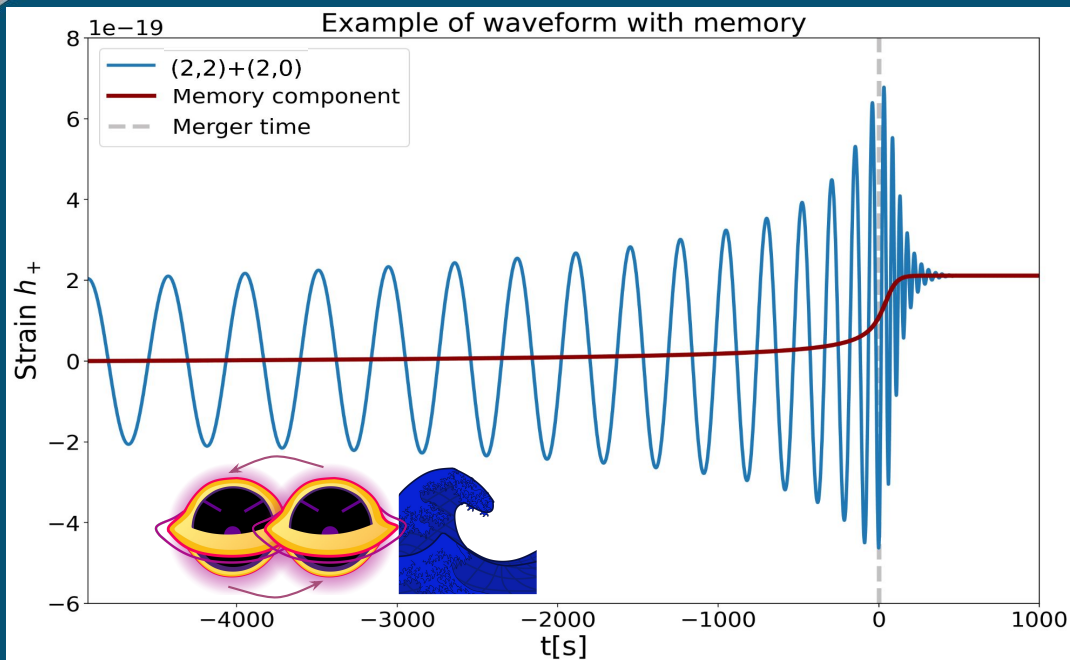
What is memory effect ?





What is memory effect ?

(*Non-linear displacement memory)



★ Permanent strain remaining after the passage of Gravitational Waves

☆ Predicted by GR

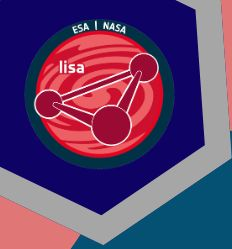
☆ Low frequency component of the GW

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

☆ 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



Why it's interesting ?

Memory effect is linked to asymptotic symmetries of spacetime (BMS symmetries)
⇒ Infrared triangle

↳ See Pierre Piovesan's talk

Asymptotic symmetries

Observable(s) for GW observatories

**Soft
theorems**

**Memory
effect(s)**

THE SPECTRUM OF GRAVITATIONAL WAVES

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}

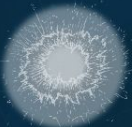
10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic
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

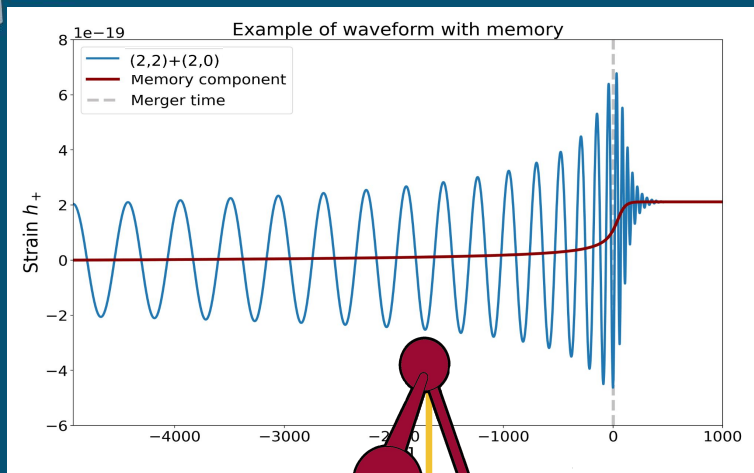


Merging white dwarfs
in our Galaxy

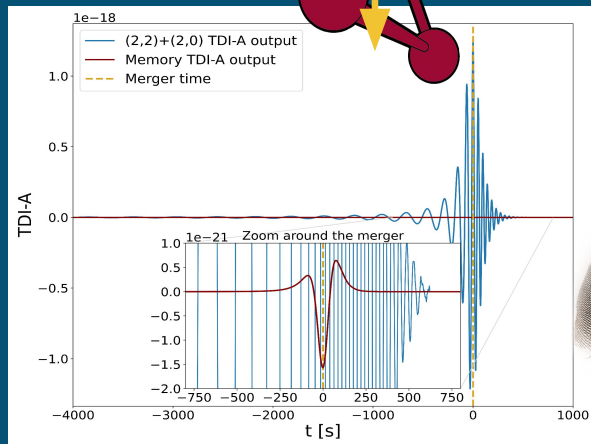
Cosmic fluctuations in the early Universe



Observing memory with LISA

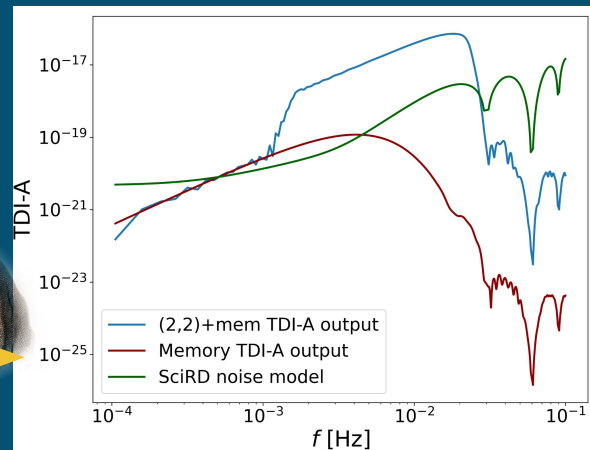


LISA response
+
Time-Delay
Interferometry



★ In the physical signal, the memory strain is around $\sim 10\%$ of the GW max amplitude.

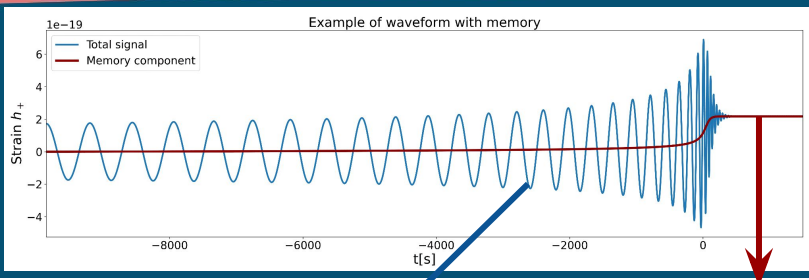
★ Strongly damped by LISA's response





Signal-to-noise ratio hints

See Inchauspé et al. (2025)
DOI: [10.1103/PhysRevD.111.044044](https://doi.org/10.1103/PhysRevD.111.044044)



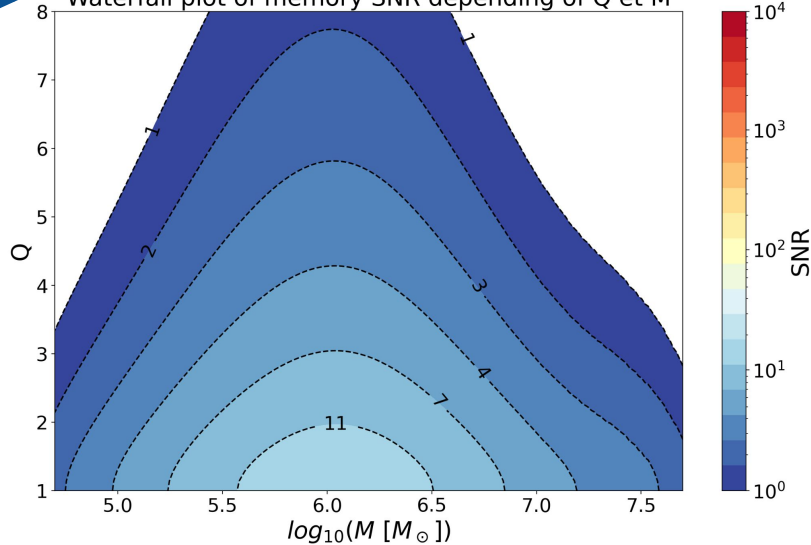
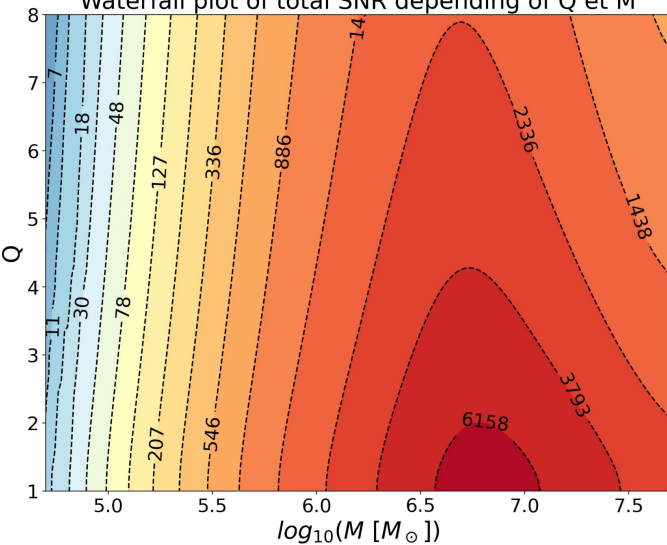
SNR_{tot}

SNR_{mem}

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

Waterfall plot of total SNR depending of Q et M

Waterfall plot of memory SNR depending of Q et M



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

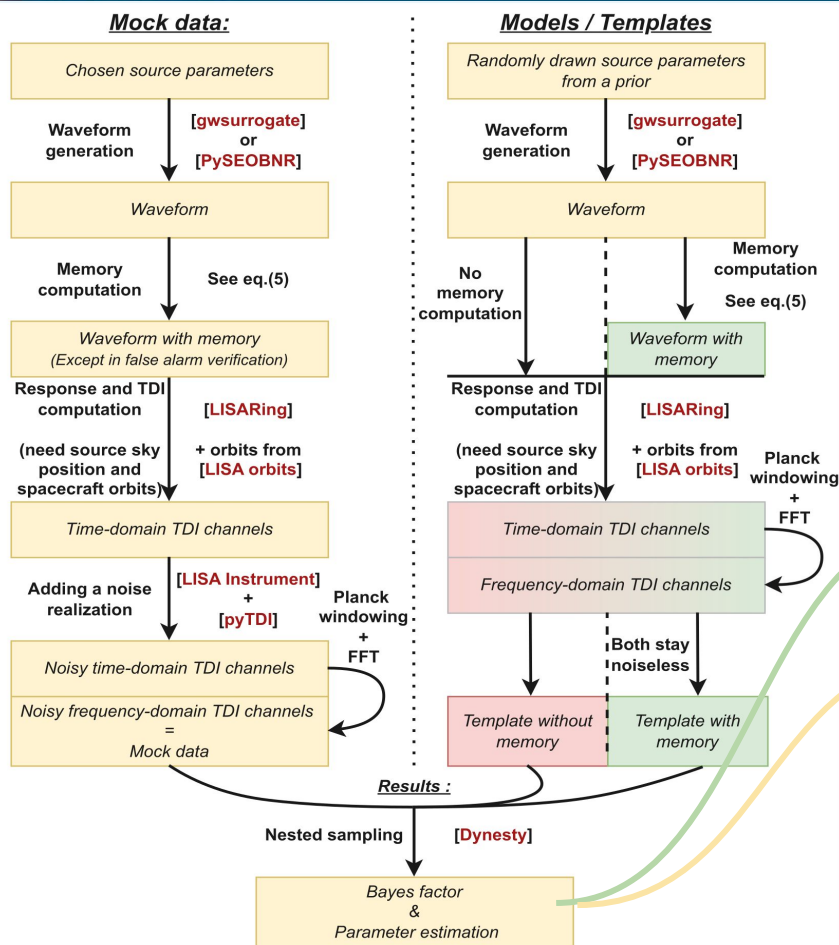
M total mass,
in detector-frame

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

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



Bayesian analysis



Posterior distributions

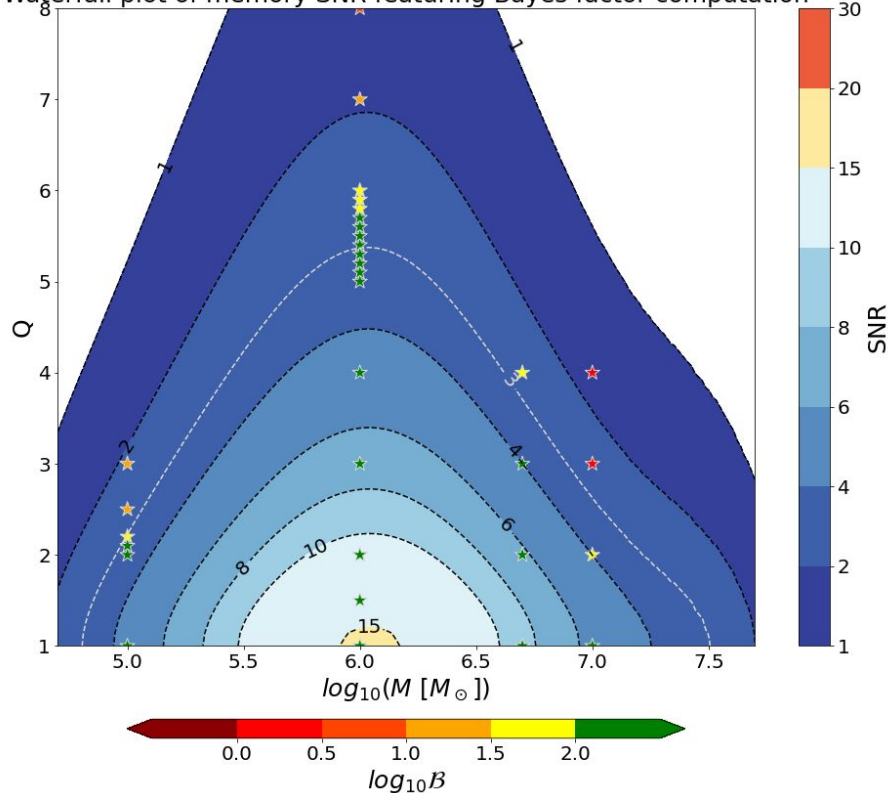
$$\log_{10}\mathcal{B} = \log_{10}\mathcal{Z}_{o+m} - \log_{10}\mathcal{Z}_o$$

☆ Note: o = oscillatory
m = memory



Bayesian detectability criterion

Waterfall plot of memory SNR featuring Bayes factor computation



★ Need Bayes factor to evaluate model preference.

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

★ 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



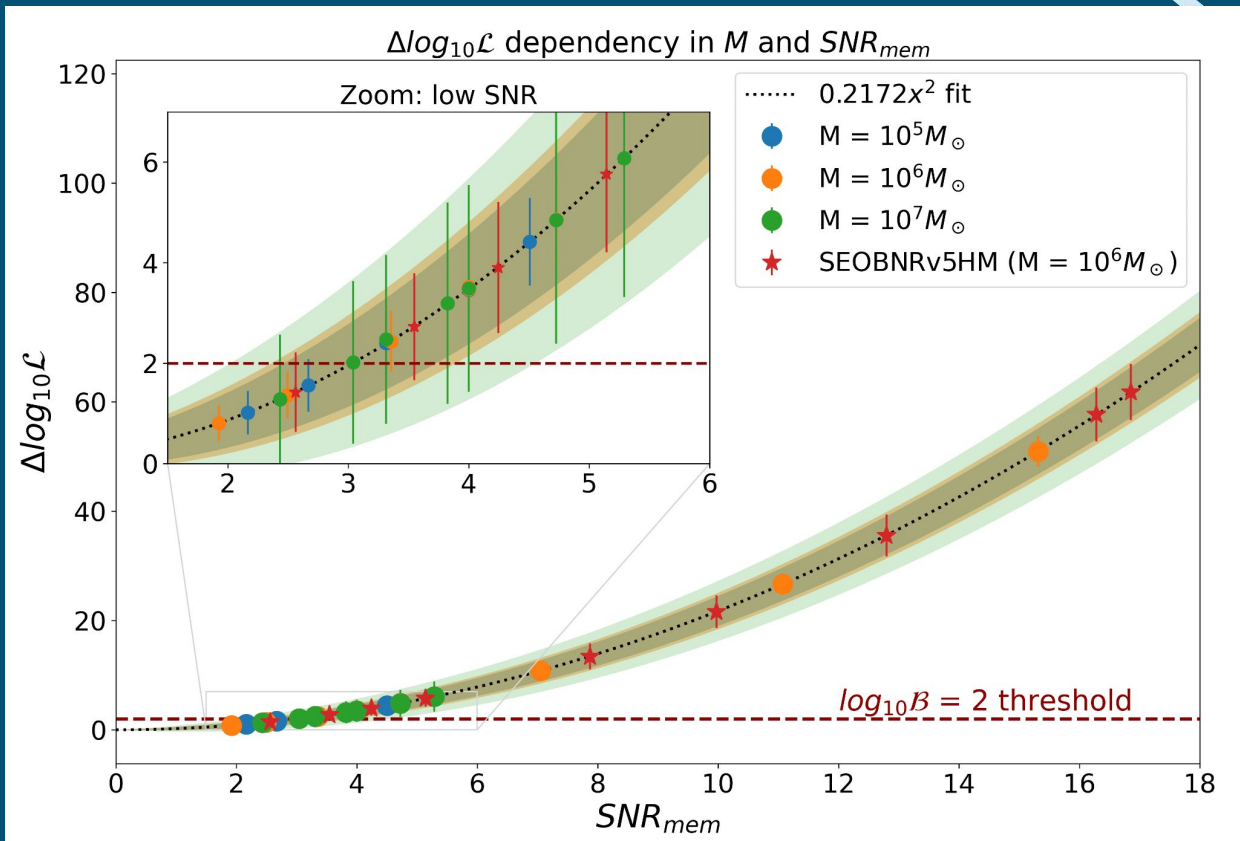
Using SNR_{mem} as a proxy

★ 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 $\text{SNR}_{\text{mem}} \geq 3$

★ Expected detection for every event with $\text{SNR}_{\text{mem}} \geq 5$!

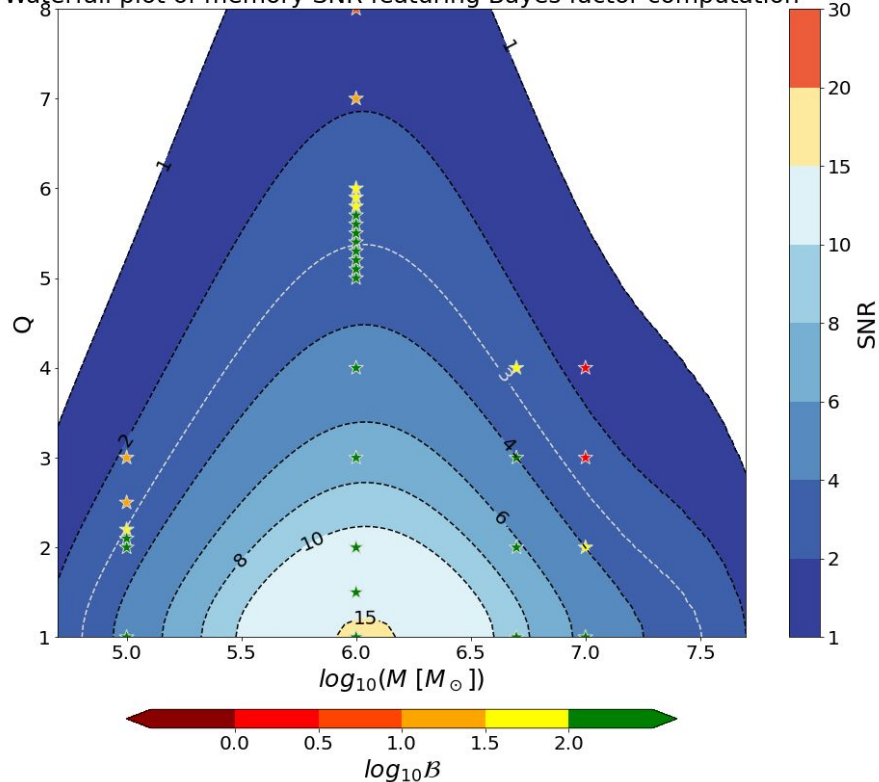


★ Note: Done with NRHybSur3dq8_CCE, restricted to (2,2) + memory, validated with SEOBNRv5HM

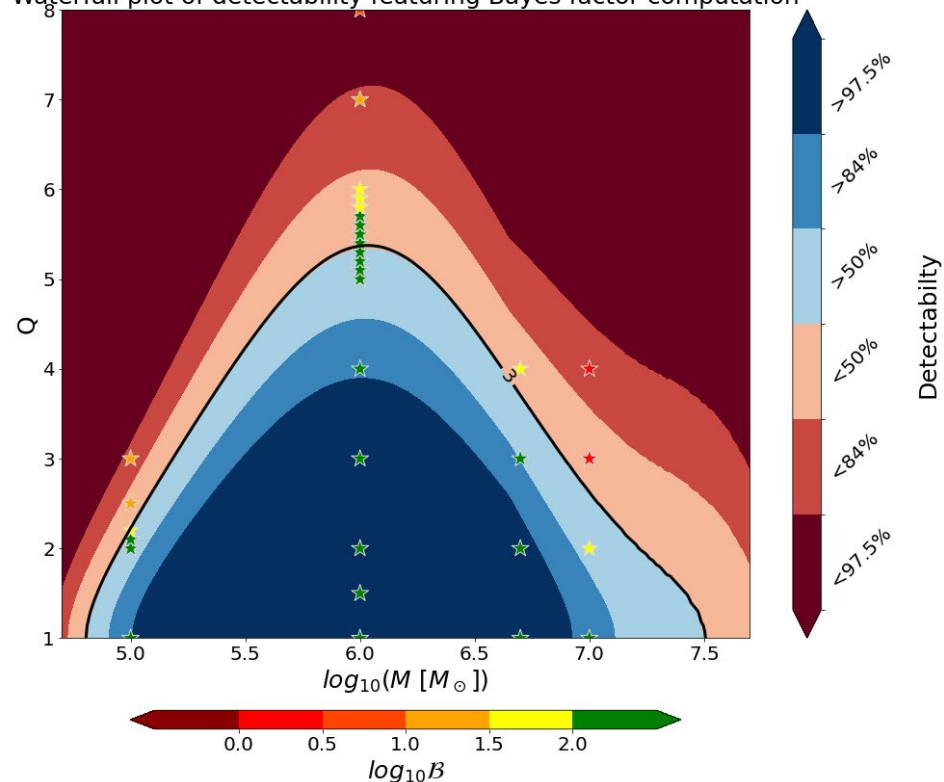


Detectability map

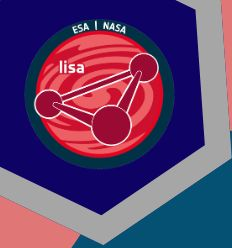
Waterfall plot of memory SNR featuring Bayes factor computation



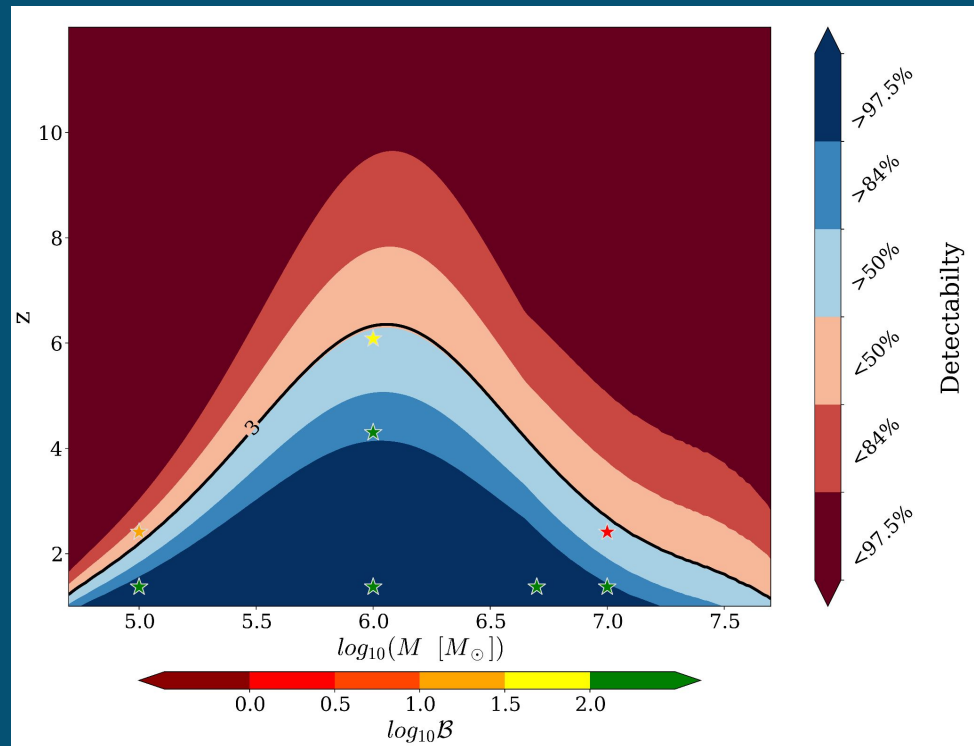
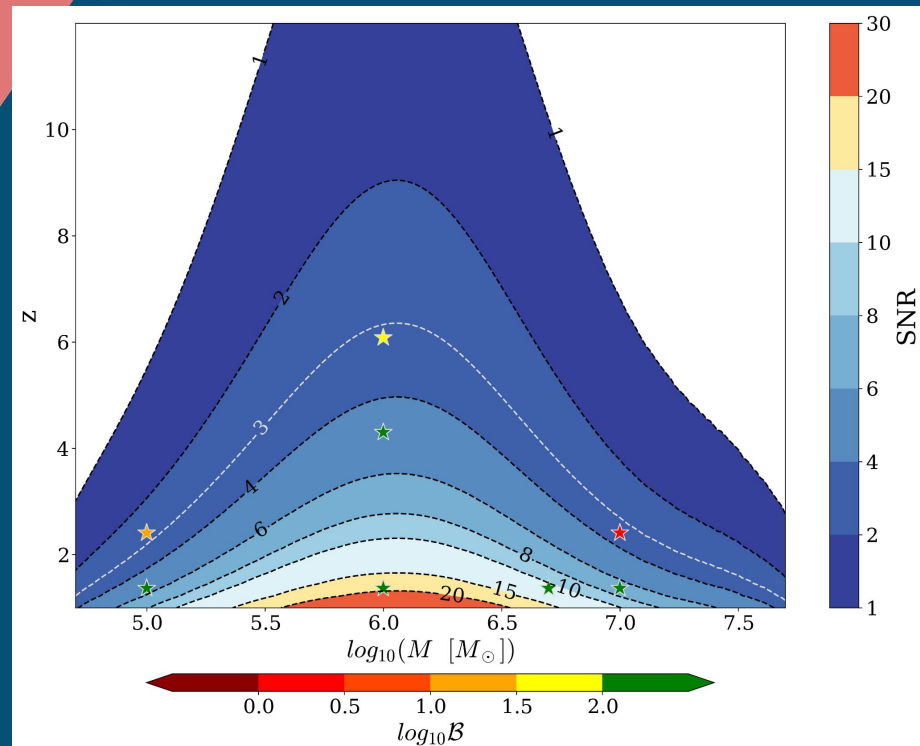
Waterfall plot of detectability featuring Bayes factor computation



☆ 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

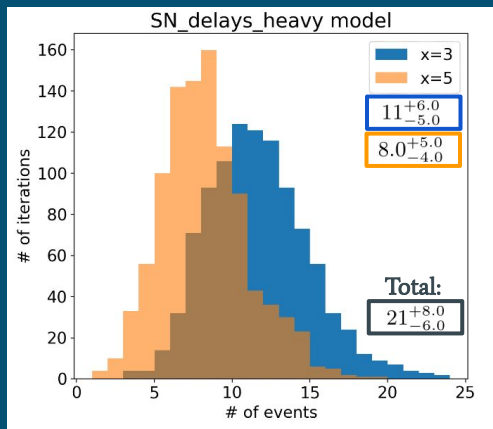
Thanks to E. Barausse for the population models.

See Barausse et al. (2020) DOI: [10.3847/1538-4357/abba7f](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

$$\begin{matrix} 11^{+6.0} \\ -5.0 \end{matrix}$$

Nb of memory event:
 $\text{SNR}_{\text{mem}} \geq 3$ (resp. 5)

$$\begin{matrix} 8.0^{+5.0} \\ -4.0 \end{matrix}$$

$$\begin{matrix} 21^{+8.0} \\ -6.0 \end{matrix}$$

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



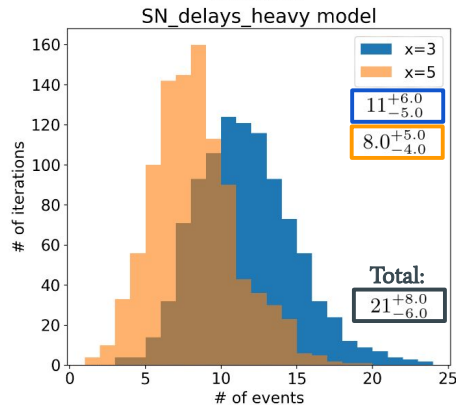
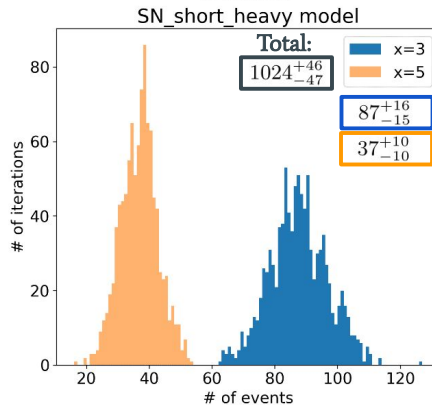
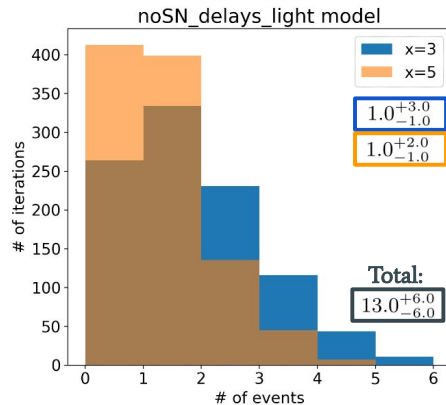
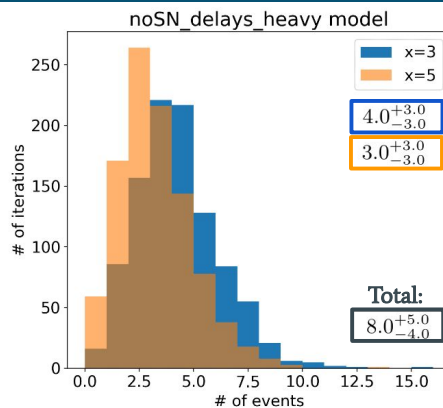
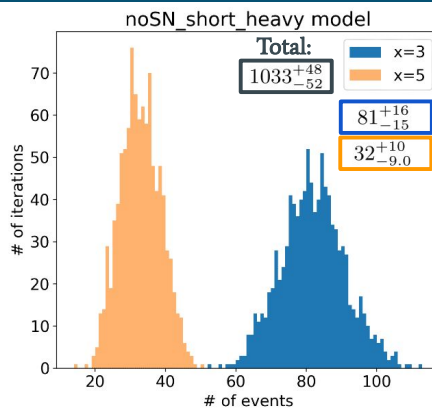
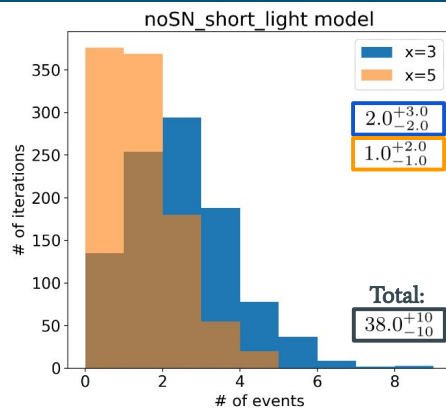
Forecast using population models

★★ 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
 $\text{SNR}_{\text{tot}} > 8$



THE SPECTRUM OF GRAVITATIONAL WAVES

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Ground-based
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Space-based observatory



Pulsar timing array



Cosmic microwave
background polarisation



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10^{-2}

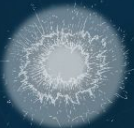
10^{-4}

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Cosmic
sources



Supernova



Pulsar



Compact object falling
onto a supermassive
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Merging supermassive black holes



Merging neutron
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Merging stellar-mass black holes
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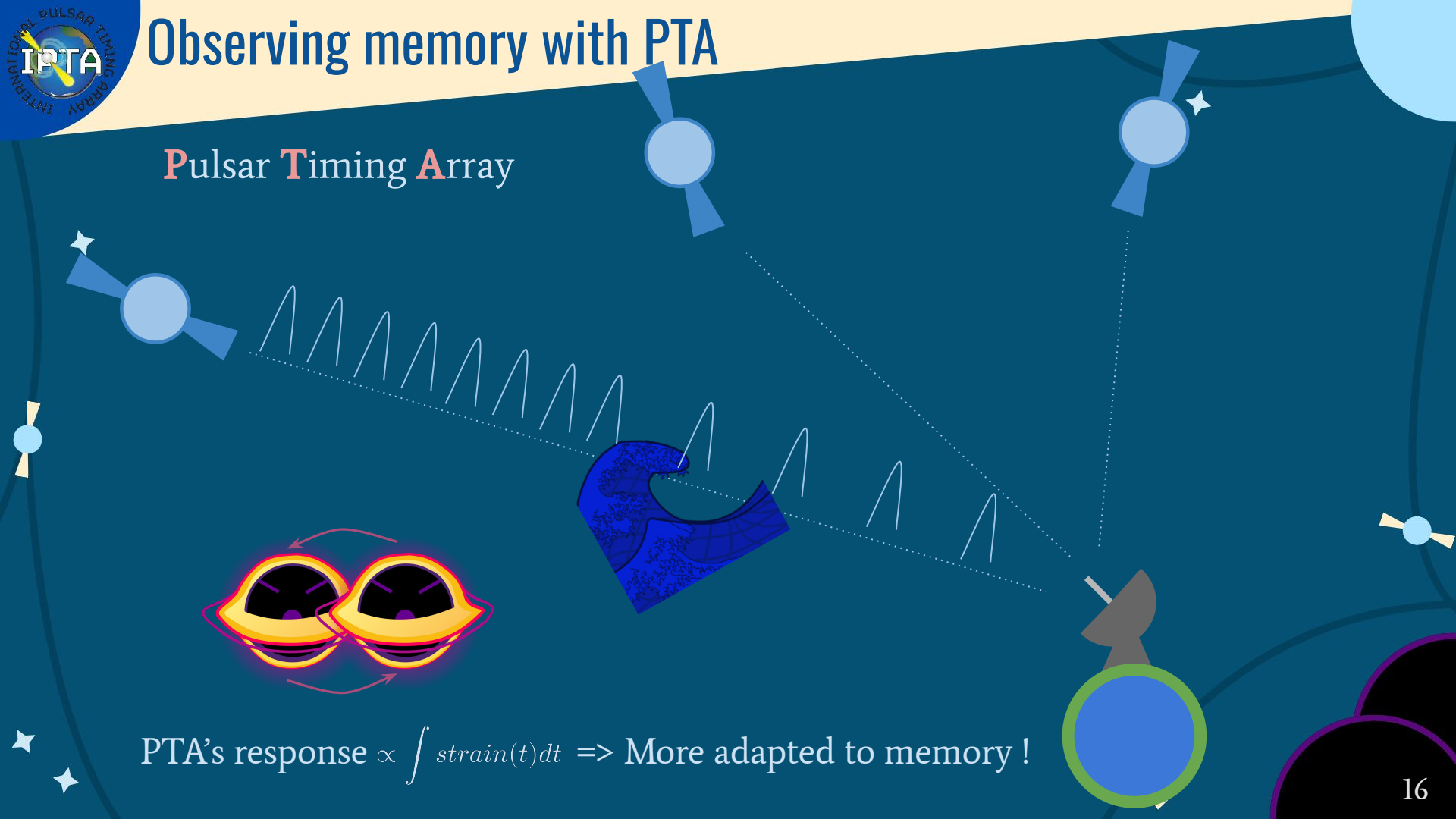


Merging white dwarfs
in our Galaxy

Cosmic fluctuations in the early Universe

Observing memory with PTA

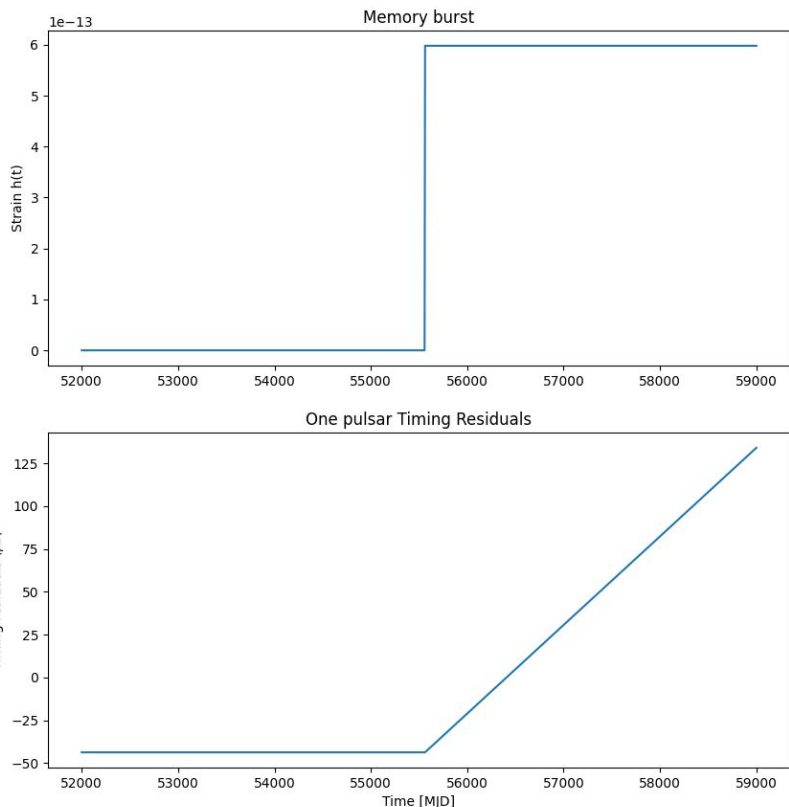
Pulsar Timing Array



PTA's response $\propto \int strain(t)dt \Rightarrow$ More adapted to memory !

Common simplification for PTA

Memory burst model



Simplified non-physical model.

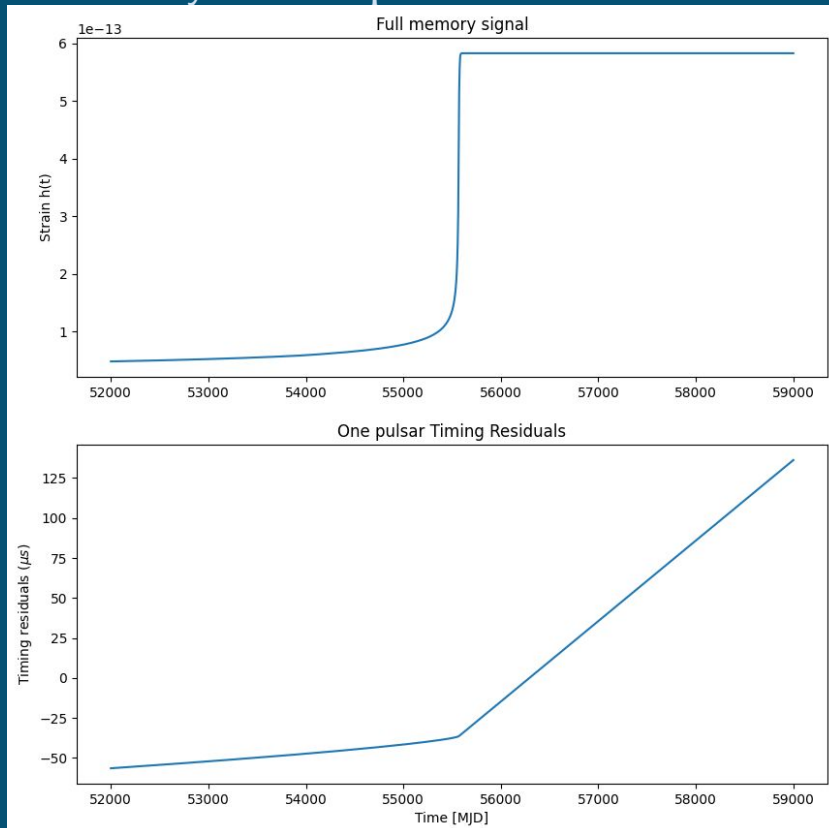
5 parameters:

- Merger time t_0
- Sky position (α, δ)
- Polarisation ψ
- Amplitude A

WIDELY used as the model for memory.

Using a realistic waveform

NRHybSur3dq8_CCE model



Realistic physical model.

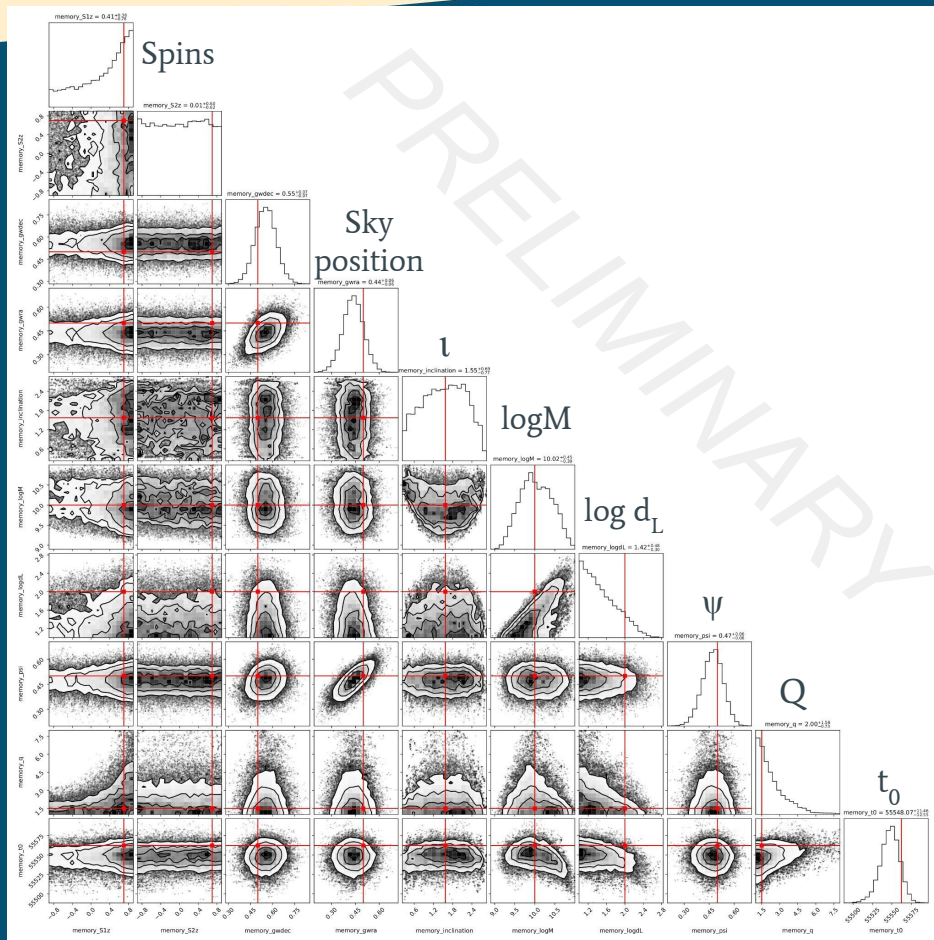
Intrinsic parameters:

- Total mass M
- Mass ratio Q
- Spins (z-axis only) $\chi_{z(1/2)}$

Extrinsic parameters:

- Polarisation ψ
- Inclination ι
- Luminosity distance d_L
- Merger time t_0
- Sky position (α, δ)

Recovering binaries parameters



10 pulsars test run

- Noises (white, red and DM) are included in the data but fixed in the search for parameters
- Works pretty nicely...
... but it took 19 days to converge

Issue: it's (really) long to compute

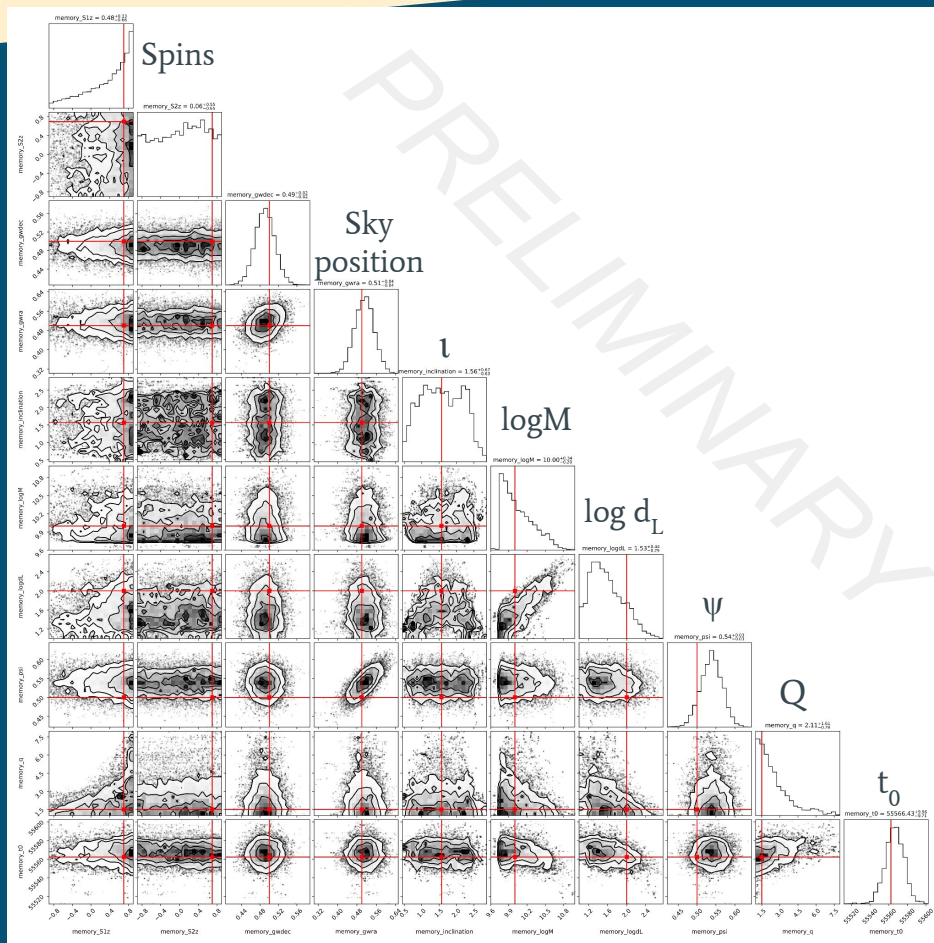
Objectives:

- ★ ☆ Having a trained model than can quickly mimic the waveform of the memory without really computing it.
- ☆ Bypass numerical integration on strain by training on a pre-integrated signal on which we only need to apply the antenna response.

In practice:

- ★ Simpler than expected ! We can reduce to 4 inputs parameters only !
 - $Q, \chi_{z,1}, \chi_{z,2}, \iota$
- ★ Easy-to-train model, based on the (2,0)-mode of NRHybSur3dq8_CCE.
 - We can get some sort of 'pre-residuals' ready to be used

Parameter estimation in practice



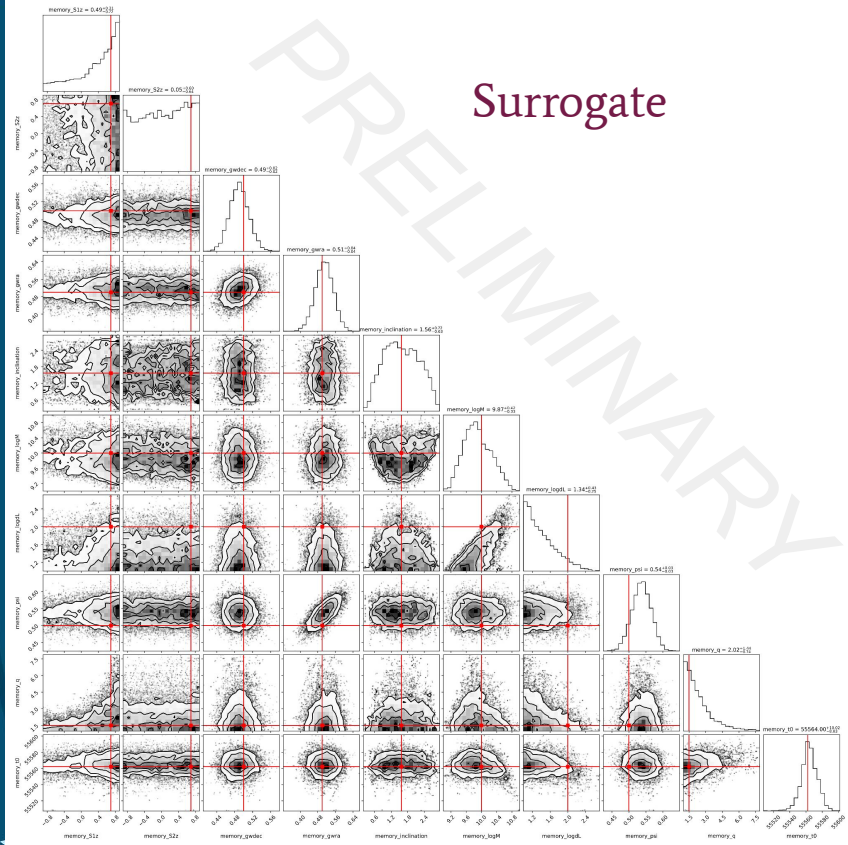
25 pulsars run with parallel tempering

- Noises (white, red and DM) are included in the data but fixed in the search for parameters

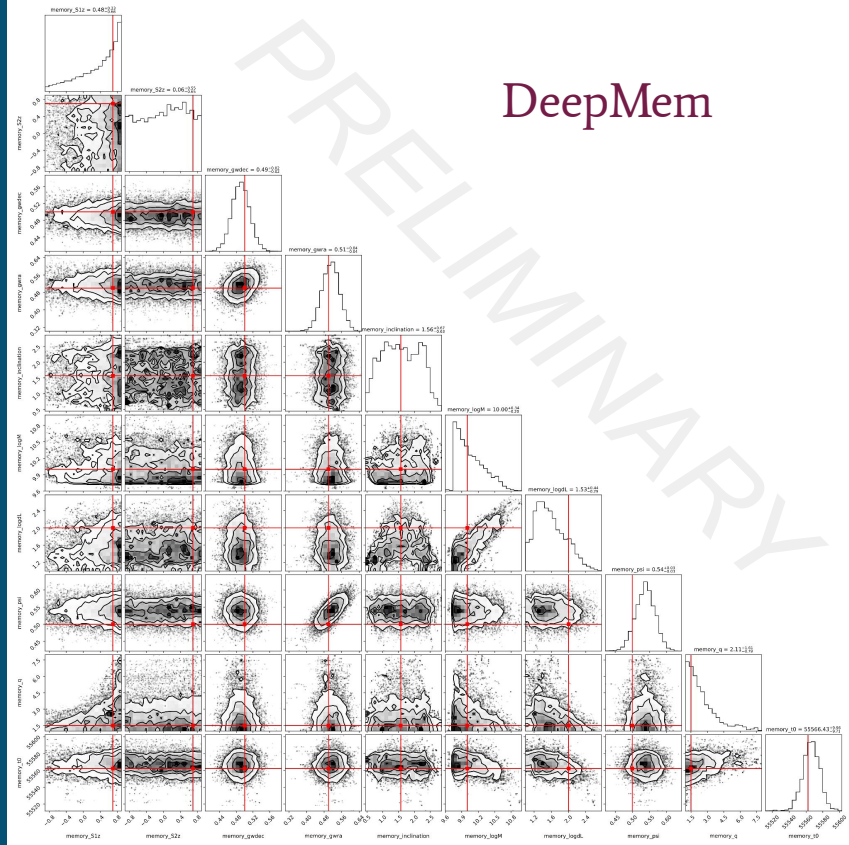
- Now in “only” 4 hours !

Model comparison

Surrogate

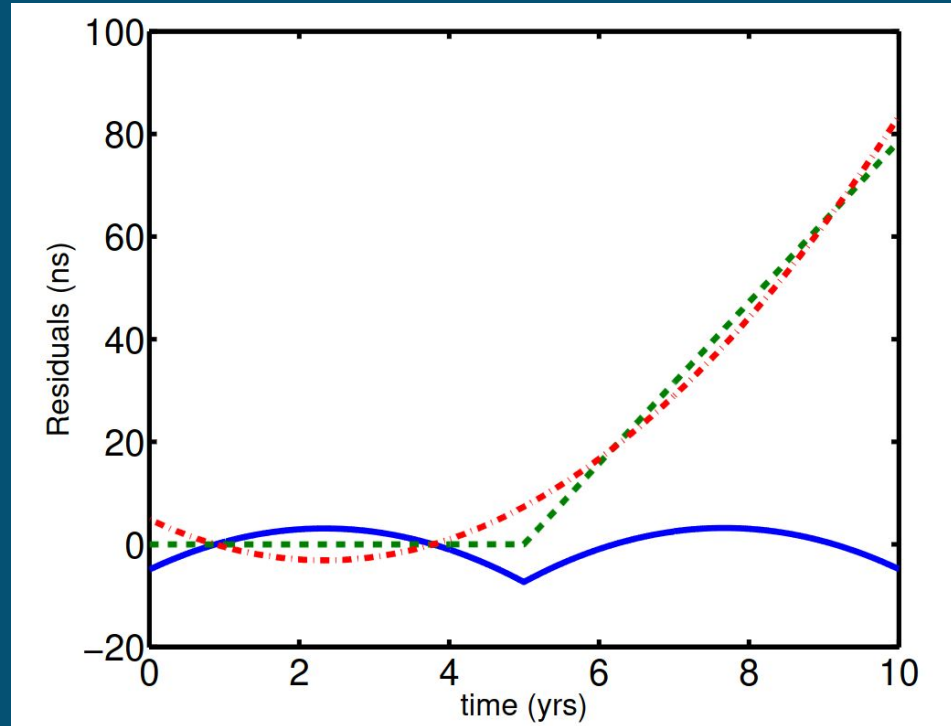


DeepMem



I need to put gyroscopes on pulsars

Another issue: Memory can be easily confused with a change of pulsars' spin



From M. S. Pshirkov et al. (MNAS, 2010)
<https://doi.org/10.1111/j.1365-2966.2009.15887>



PTA next steps

- Preparing the analysis for IPTA-DR3 & EPTA-DR3
- Preparing an upper limit procedure and testing it on EPTA-DR2
- Changing the underlying software from Enterprise to Discovery



Expectation for memory detection



Unlikely to resolve single event

Effort on memory detection expect a statistical detection of displacement memory with a dataset around $O(2000)$ events.

☆ Cheung et al (Class. Quantum Grav. 41 115010 (2024))

DOI 10.1088/1361-6382/ad3ffe

Gen 3 detectors (Einstein Telescope / Cosmic Explorer) are most likely to resolve unique memory event.



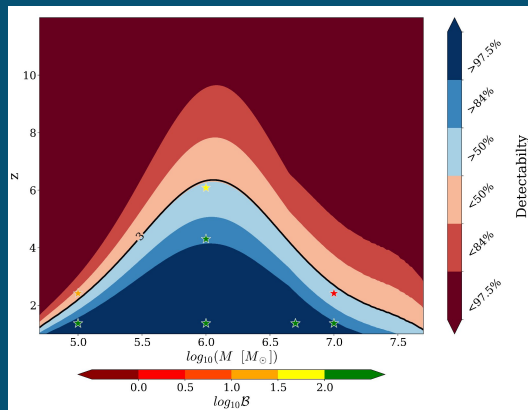
Will resolve single event

☆ Cogez et al. (Phys.Rev.D 113 (2026) 10, 104034)

DOI <https://doi.org/10.1103/b9ld-dqq4>

☆ Zosso et al. (Phys.Rev.D 113 (2026) 10, 104033)

DOI <https://doi.org/10.1103/51xv-zlffy>



Capable to detect single event

Ongoing efforts in different PTA, few examples:

☆ Nanograv - simple model

Agazie et al. (ApJ (2025))

DOI 10.3847/1538-4357/add874

☆ EPTA & PPTA - realistic model

Tomson et al. (ApJL (2026))

DOI 10.3847/2041-8213/ae2912



GDR OG - 05/10/26



Thanks for your attention !

Any question ? :)





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*.

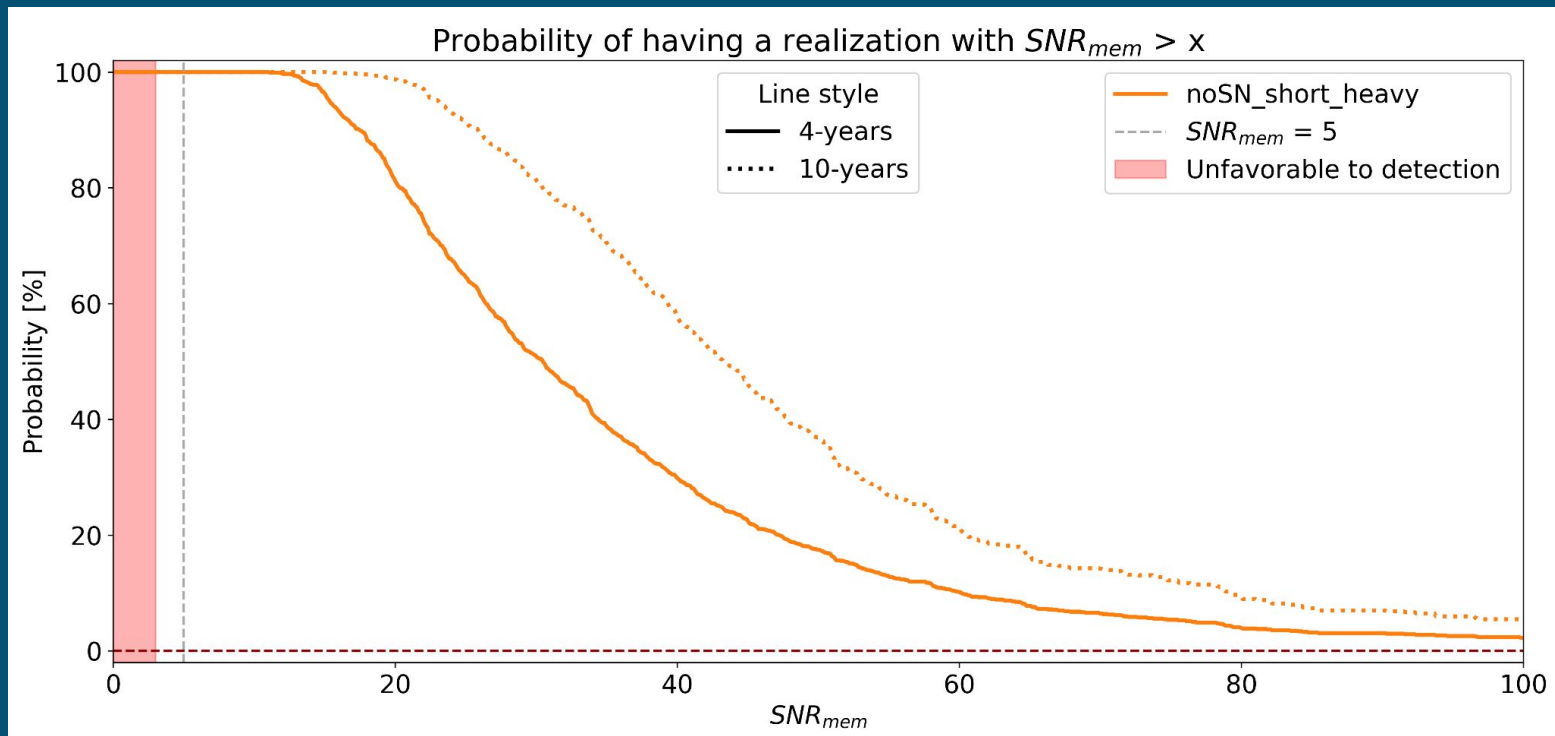
* See Cheung et al. (2024)

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

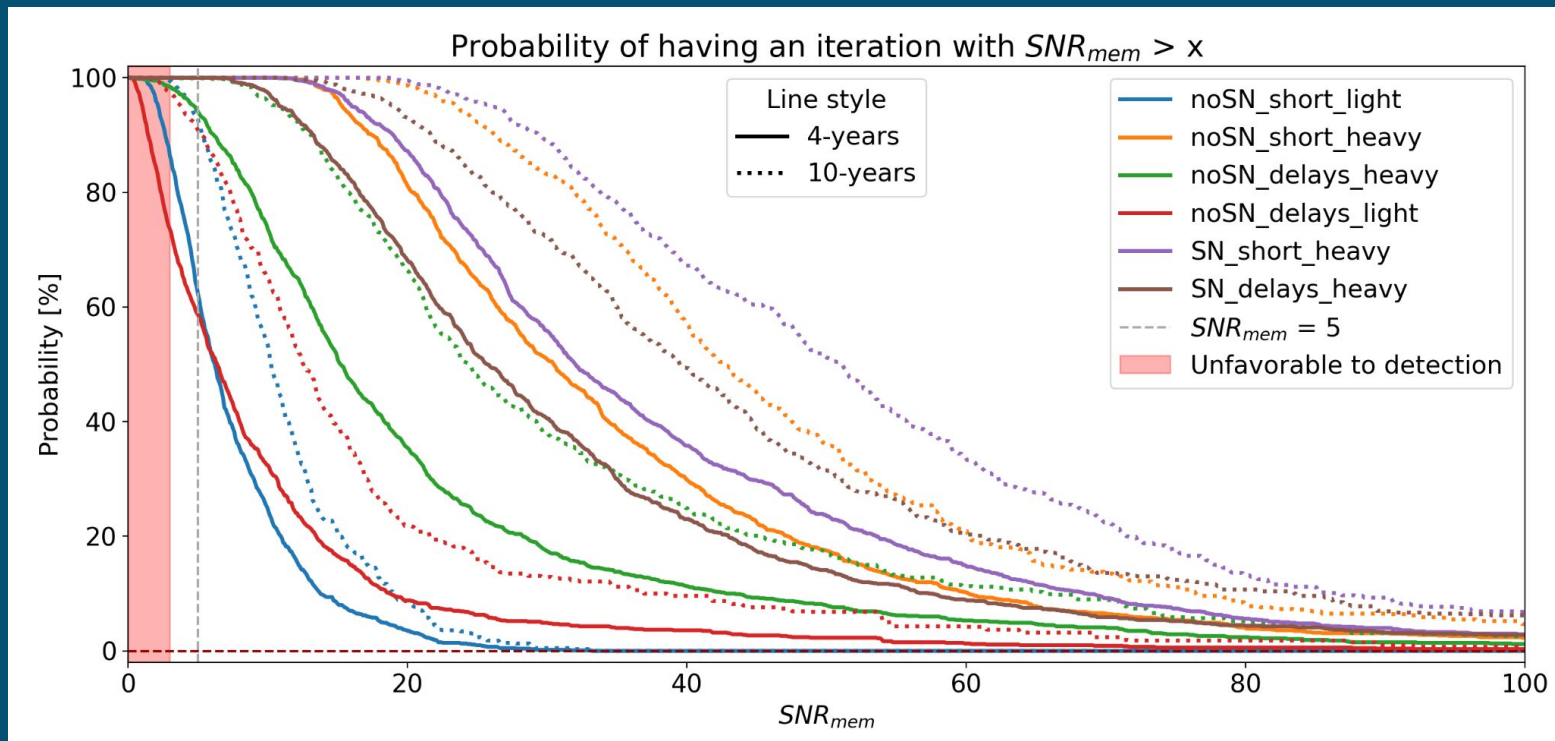


☆ Note: Probability estimated using 1000 realizations for each model



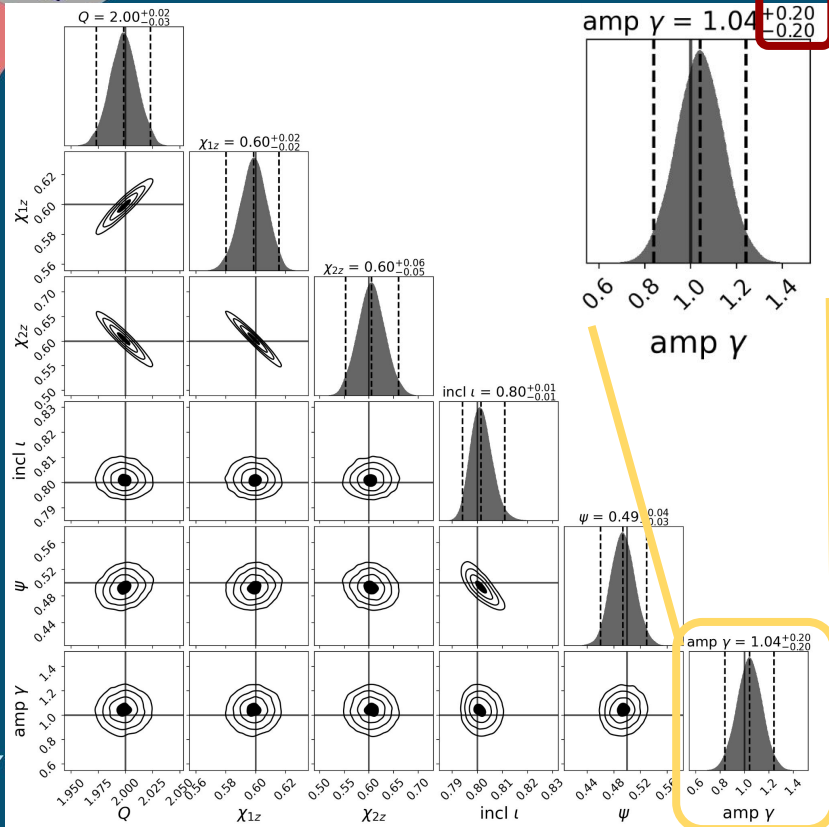
Possibility of loud memory events

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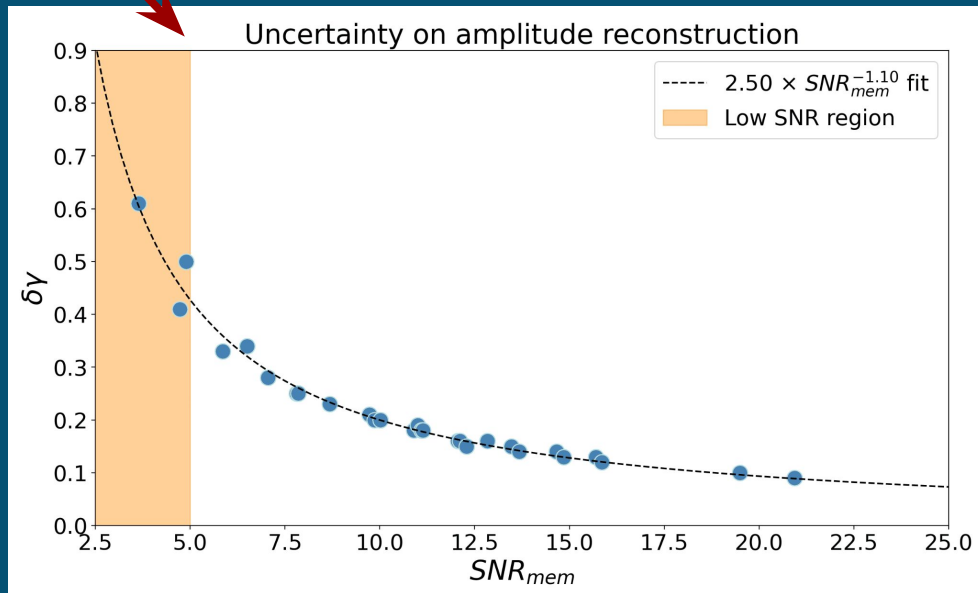
☆ Note: Probability estimated using 1000 realizations for each model

Probing GR through memory



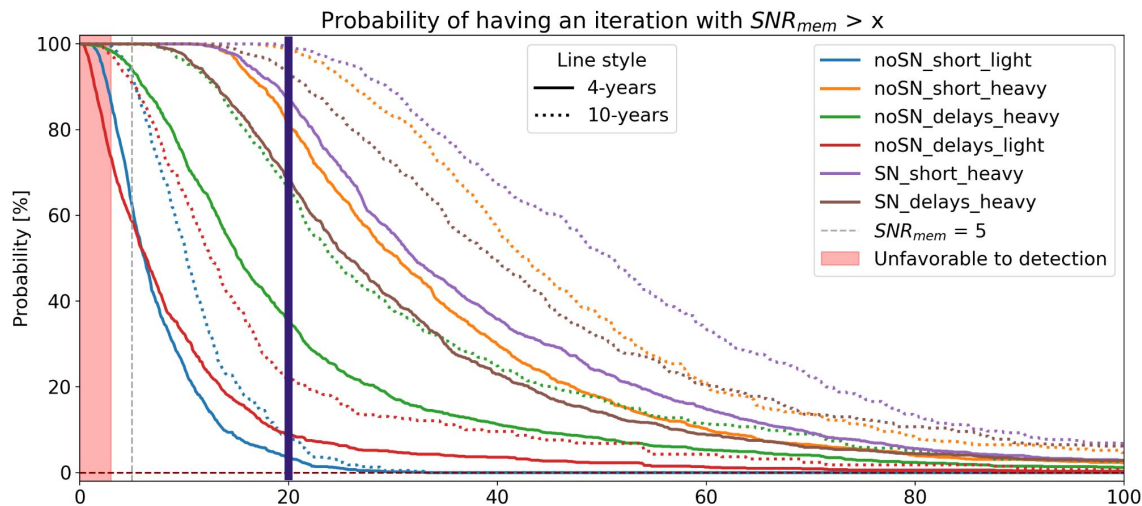
★ We can also monitor the uncertainty $\delta\gamma$ on the reconstructed γ . As a result, $\delta\gamma$ only depend on SNR_{mem} , following:

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



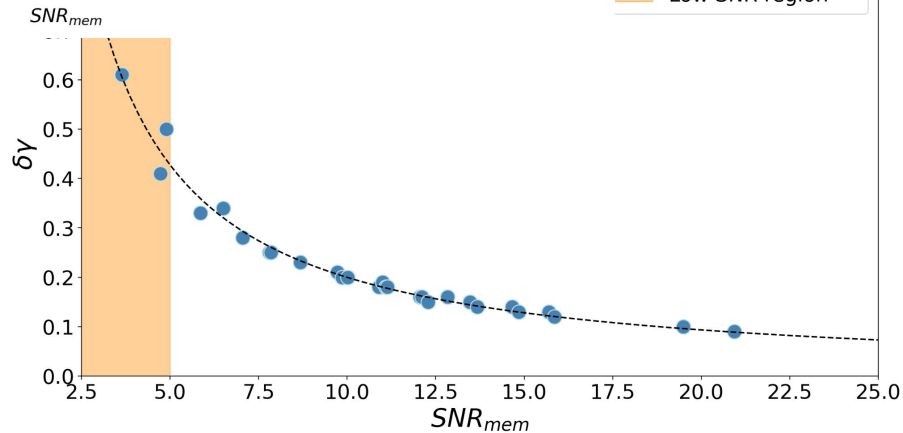


Probing GR through memory



Instruction

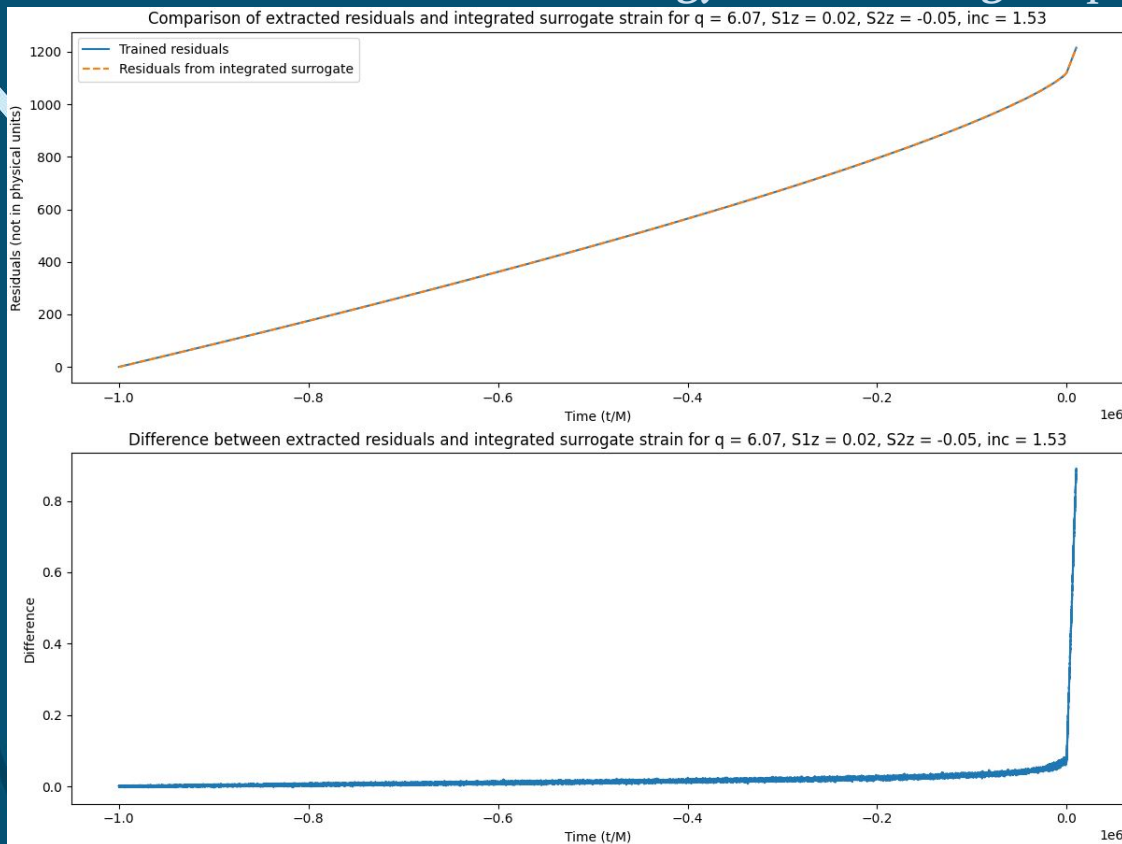
- $2.50 \times SNR_{mem}^{-1.10}$ fit
- Low SNR region



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

Issue: it's (still) long to compute

Advanced strategy (WIP): Using deep learning



Trained pre-residuals, ready to be put at the correct physical scale with M and d_L .

Shift the merger from $t = 0$ to $t = t_0$.

Then, considering memory is quasi-exclusively in + polarisation at source frame, use polarisation ψ and sky position (α, δ) to get the response function !

RMSE quick test

