Gravitational Wave Memory Detection & Beyond

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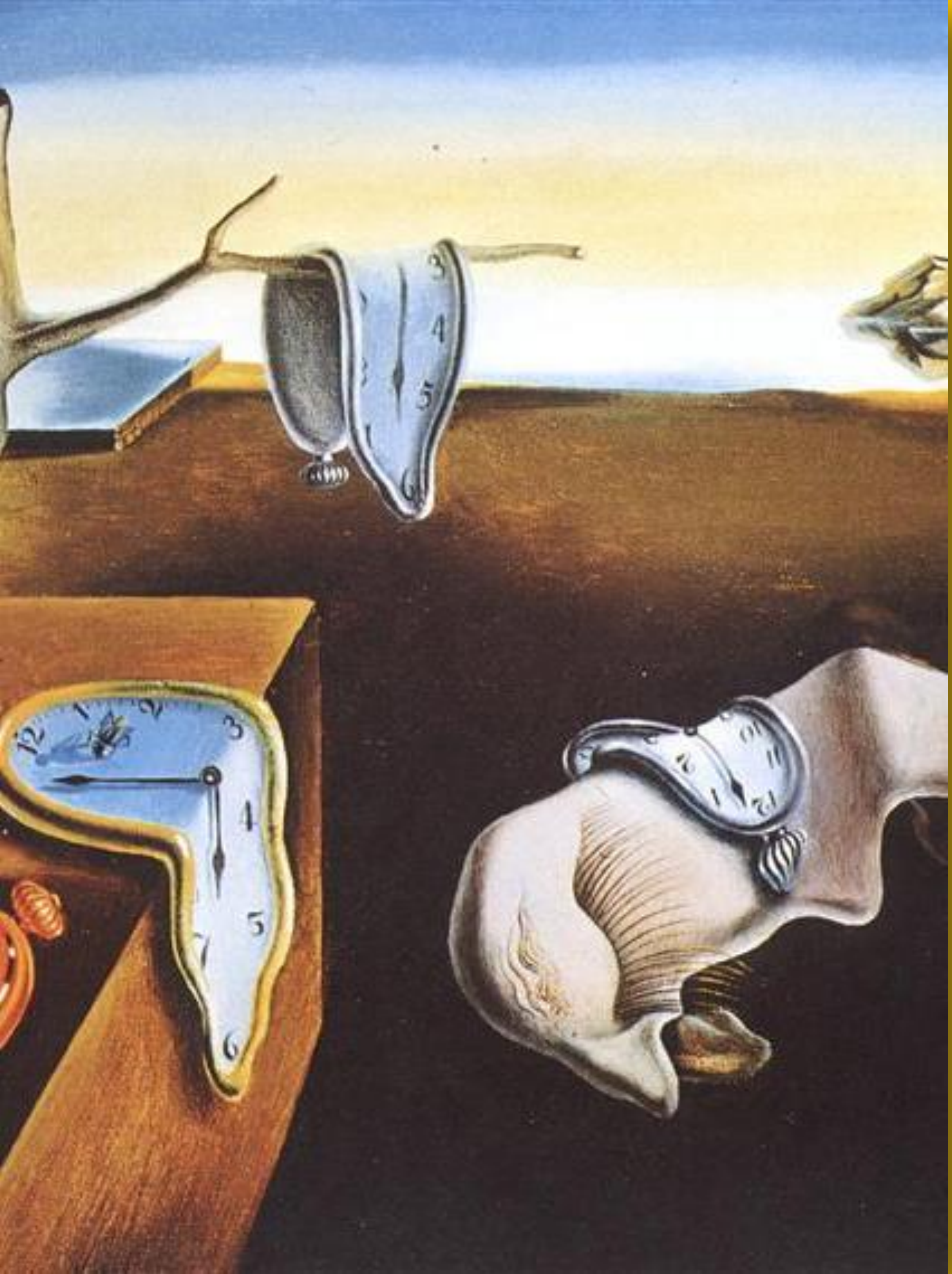
IFPU, 12/6/2026



Outline

- Intro memory signal
- Detecting memory in LISA

  H. Inchauspé, SG, D. Blas, L. Heisenberg, J. Zosso, S. Tiwari '25

  J. Zosso, L. Magaña Zertuche, SG, A. Cogez, H. Inchauspé, M. Jacobs '26

  A. Cogez, SG., J. Zosso, L. Magaña Zertuche, H. Inchauspé, C. Pitte, A. Petiteau, M. Besancon '26

- Memory in beyond GR

  SG, J. Zosso, L. Aresté Saló, D. Doneva, S. S. Yazadjiev '26

  J. Zosso, SG, L. Aresté Saló, D. Doneva, S. S. Yazadjiev '2

- Memory in multiband searches: PBH case

  SG, G. Franciolini, V. Domcke '25

"The Persistence of Memory"
(also known as "The Soft Watches")
Salvador Dalí, 1931

Gravitational wave memory

$$\Delta h_{mem} = h(t_{in} \to -\infty) - h\left(t_{fin} \to \infty\right) \neq 0$$

- **Linear (ordinary) memory** generated by unbound energy flux (e.g. hyperbolic encounters…)

  Zeldovich & Polnarev'74, Brangisky & Grischchuk '85, Brangisky & Thorne '87

- **Nonlinear (null) memory** generated by **outgoing radiative energy flux** to null infinity

  Christodoulou '91, Blanchet & Damour '92, Wiseman & Will '91…

$$g_{\mu\nu} = g^{L}_{\mu\nu} + h^{H}_{\mu\nu} \qquad\qquad \langle g_{\mu\nu} \rangle = g^{L}_{\mu\nu} = \eta_{\mu\nu} + h^{L}_{\mu\nu}$$

$$G_{\mu\nu} = 0 \quad \Longrightarrow \quad \begin{cases} \Box h^{H}_{\mu\nu} = 0 \\ \Box h^{L}_{\mu\nu} = -16\pi G \; t_{\mu\nu}[h^{H}] \end{cases}$$

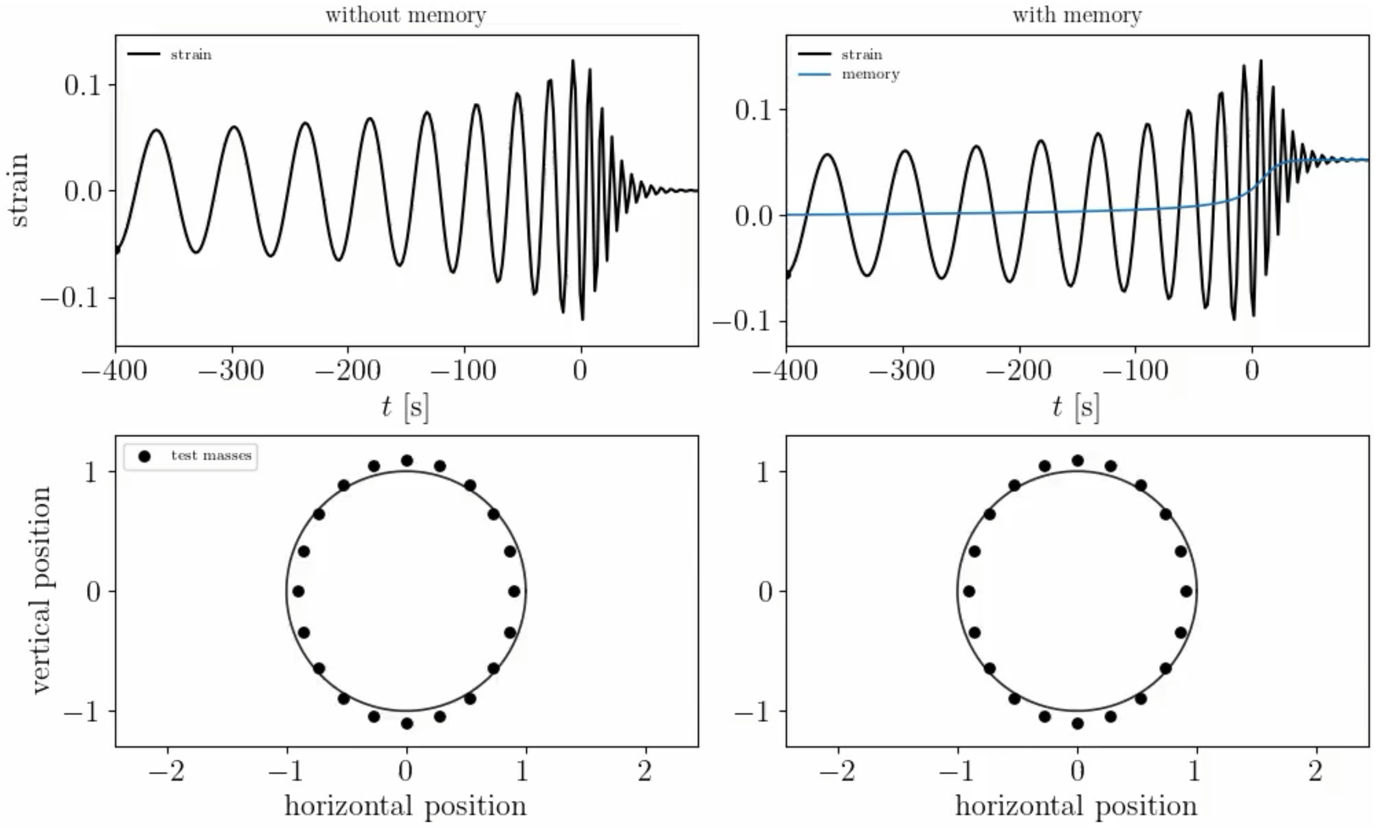
Wave equation

Backreaction of high frequency component

Non-linear GW memory

Christodoulou '91, Blanchet & Damour '92,Wiseman & Will '91…

GW of a binary BH system:



$$t_{ij} = \frac{1}{R^2}\frac{dE_{GW}}{dt d\Omega} n_j n_k \sim \frac{c^3}{16\pi G}\left\langle \left|\dot{h}^H(t,\Omega)\right|^2 \right\rangle$$

spacetime average over the short scales important for conservation and gauge-invariance of GW e.m. tensor

Thorne Formula:

$$\bar{h}_{ij}^{TT,L}(T_R) = \frac{4}{R}\int_{-\infty}^{T_R} dt' \left[\int \frac{dE_{GW}}{dt' d\Omega'} \frac{n'_j n'_k}{|1 - n' \cdot N|} \, d\Omega' \right]^{TT}$$

Integrating the energy flux

$$h_+ - i h_\times = \sum_{\ell \geq 2} \sum_{|m| \leq \ell} h^{\ell,m}(u,r)\ {}_{-2}Y_{\ell m}(\iota,\phi)$$

$$\delta h^{\ell m}(u) = -R \sum_{\ell',\ell'' \geq 2} \sum_{m',m''} \sqrt{\frac{(\ell-2)!}{(\ell+2)!}}$$

$$\boxed{\times \int d\Omega\, Y^*_{\ell m}\ {}_{-2}Y^*_{\ell' m'}\ {}_{-2}Y_{\ell'' m''}} \boxed{\int_{-\infty}^{u} du'\, \dot{h}_0^{*\ell' m'} \dot{h}_0^{\ell'' m''}, \quad (4)}$$

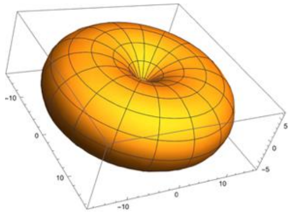
Angular integral,

$$\propto \int e^{i(m'-m''-m)\phi}\, d\phi,$$

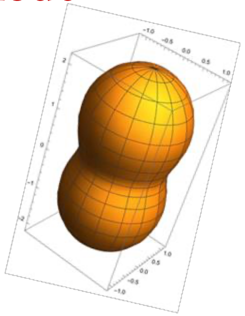
Harmonics decomposition of the oscillatory GW source as input

Selection rules m=0, l=2 mode

(2,0) mode



(2,2) mode

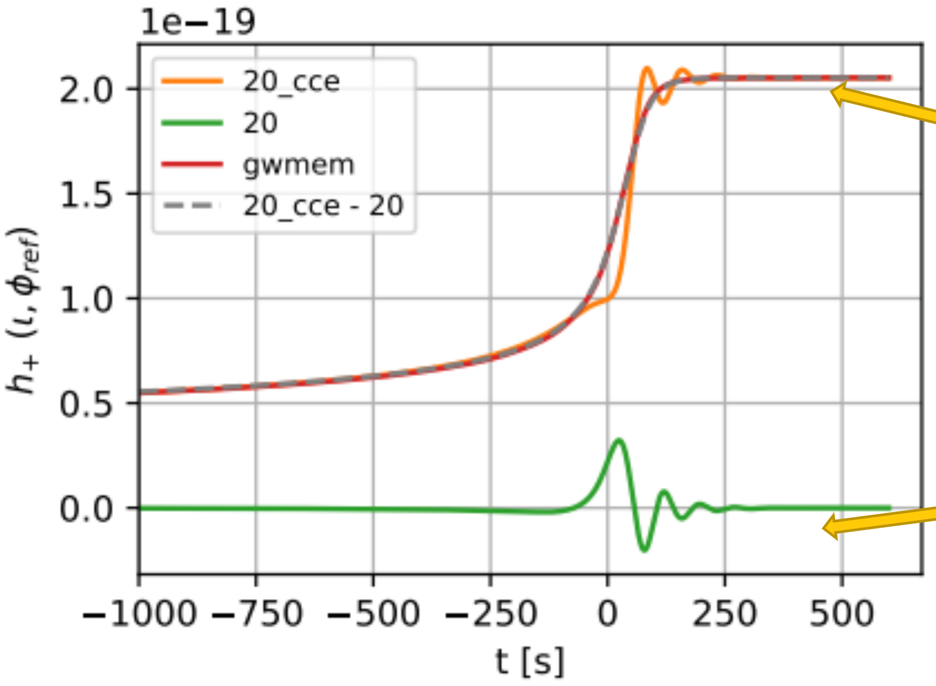


$$\dot{h}_{l'm'} \dot{h}^*_{l''m''} \propto x^n \langle e^{-i(m'-m'')\phi} \rangle \qquad x = (M\omega)^{2/3}$$

Non-oscillatory for $m' = m''$
Other oscillatory modes suppressed by the average procedure

Memory waveform

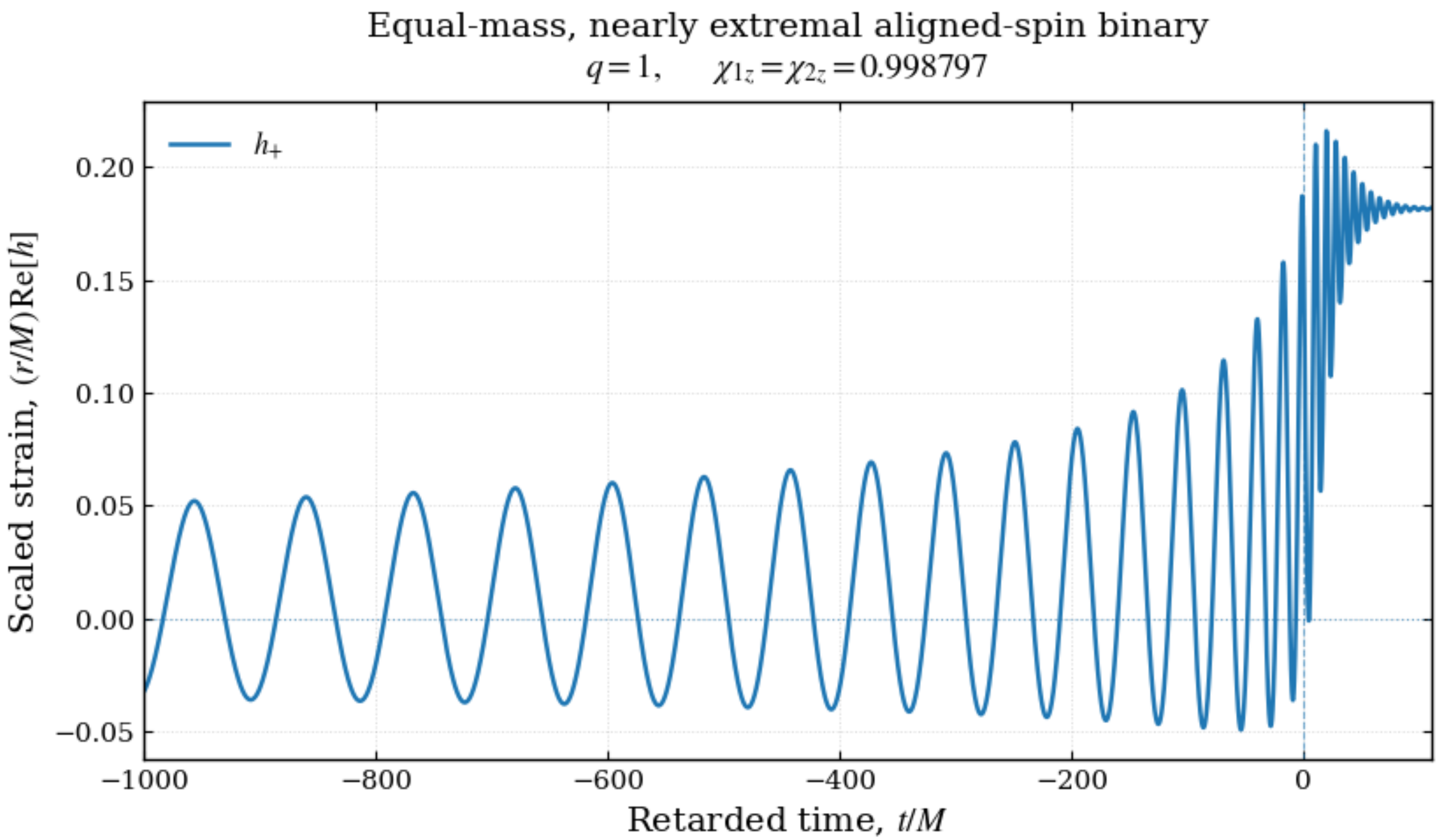
$$
\begin{aligned}
h^L_{20} = \frac{1}{r}\int_{-\infty}^{u} du' r'^2 \Bigg\langle & \frac{1}{7}\sqrt{\frac{5}{6\pi}}|\dot{h}^H_{22}|^2 - \frac{1}{14}\sqrt{\frac{5}{6\pi}}|\dot{h}^H_{21}|^2 - \frac{1}{14}\sqrt{\frac{5}{6\pi}}|\dot{h}^H_{20}|^2 + \frac{5}{4\sqrt{42\pi}}\left(\dot{h}^H_{22}\dot{\bar{h}}^H_{32} + \dot{\bar{h}}^H_{22}\dot{h}^H_{32}\right) \\
& + \frac{5}{28\sqrt{6\pi}}\left(\dot{h}^H_{22}\dot{\bar{h}}^H_{42} + \dot{\bar{h}}^H_{22}\dot{h}^H_{42}\right) + \frac{1}{8}\sqrt{\frac{5}{21\pi}}\left(\dot{h}^H_{21}\dot{\bar{h}}^H_{31} + \dot{\bar{h}}^H_{21}\dot{h}^H_{31}\right) + \frac{5}{28\sqrt{3\pi}}\left(\dot{h}^H_{21}\dot{\bar{h}}^H_{41} + \dot{\bar{h}}^H_{21}\dot{h}^H_{41}\right) \\
& + \frac{1}{28}\sqrt{\frac{5}{2\pi}}(\dot{h}^H_{20}\dot{\bar{h}}^H_{40} + \dot{\bar{h}}^H_{20}\dot{h}^H_{40}) + \frac{1}{2\sqrt{10\pi}}\left(\dot{h}^H_{33}\dot{\bar{h}}^H_{43} + \dot{\bar{h}}^H_{33}\dot{h}^H_{43}\right) + \sqrt{\frac{2}{105\pi}}\left(\dot{h}^H_{32}\dot{\bar{h}}^H_{42} + \dot{\bar{h}}^H_{32}\dot{h}^H_{42}\right) \\
& + \frac{1}{2\sqrt{42\pi}}\left(\dot{h}^H_{31}\dot{\bar{h}}^H_{41} + \dot{\bar{h}}^H_{31}\dot{h}^H_{41}\right) - \frac{2}{11}\sqrt{\frac{2}{15\pi}}|\dot{h}^H_{44}|^2 - \frac{1}{11\sqrt{30\pi}}|\dot{h}^H_{43}|^2 + \frac{1}{77}\sqrt{\frac{10}{3\pi}}|\dot{h}^H_{40}|^2 \\
& - \frac{17}{77\sqrt{30\pi}}|\dot{h}^H_{41}|^2 + \frac{4}{77}\sqrt{\frac{2}{15\pi}}|\dot{h}^H_{42}|^2 \Bigg\rangle ,
\end{aligned}
$$



"soft" memory mode

"Hard" oscillatory mode

Extreme memory case



- equal mass, edge on
- average memory

$$\frac{r}{M}\Delta h_{2,0} \simeq 0.08$$

- close to maximally aligned spins

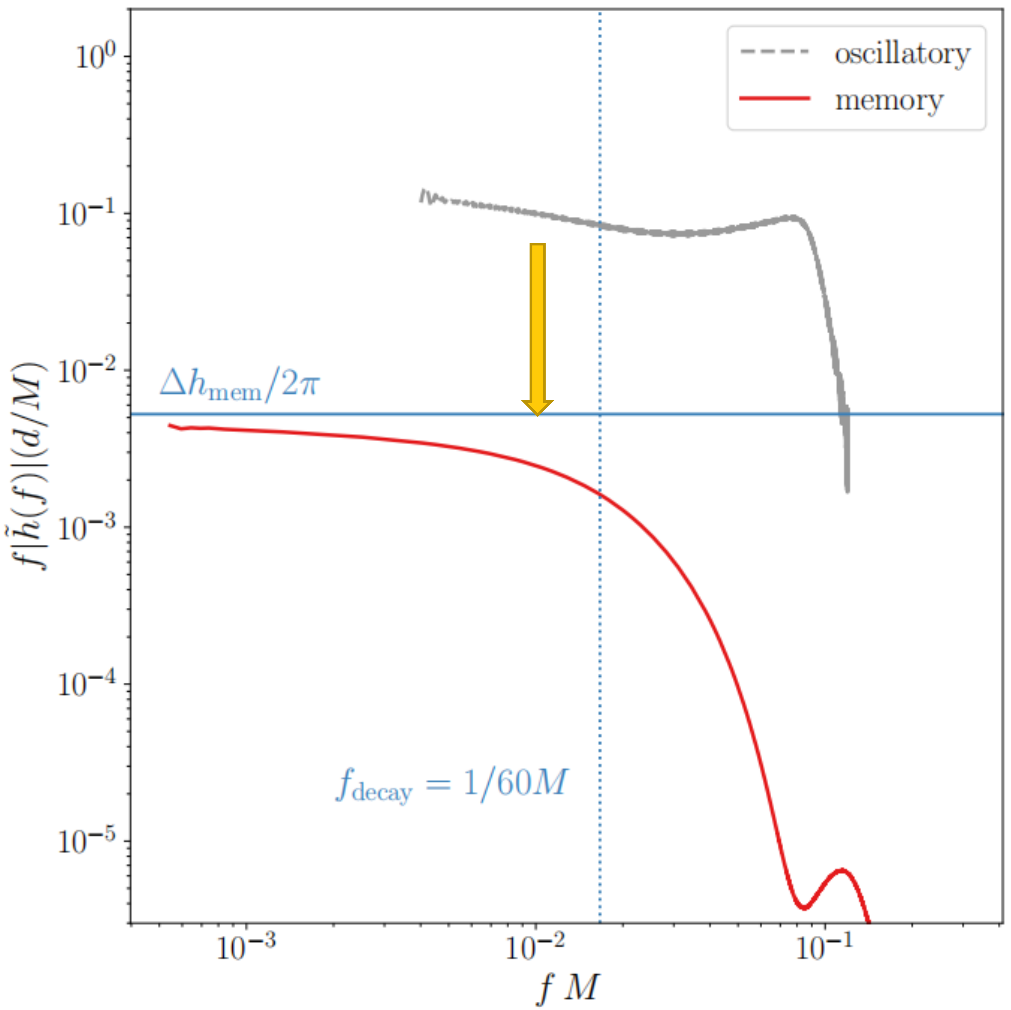
$$\frac{r}{M}\Delta h_{2,0} \simeq 0.48$$

Fourier Transform of the memory

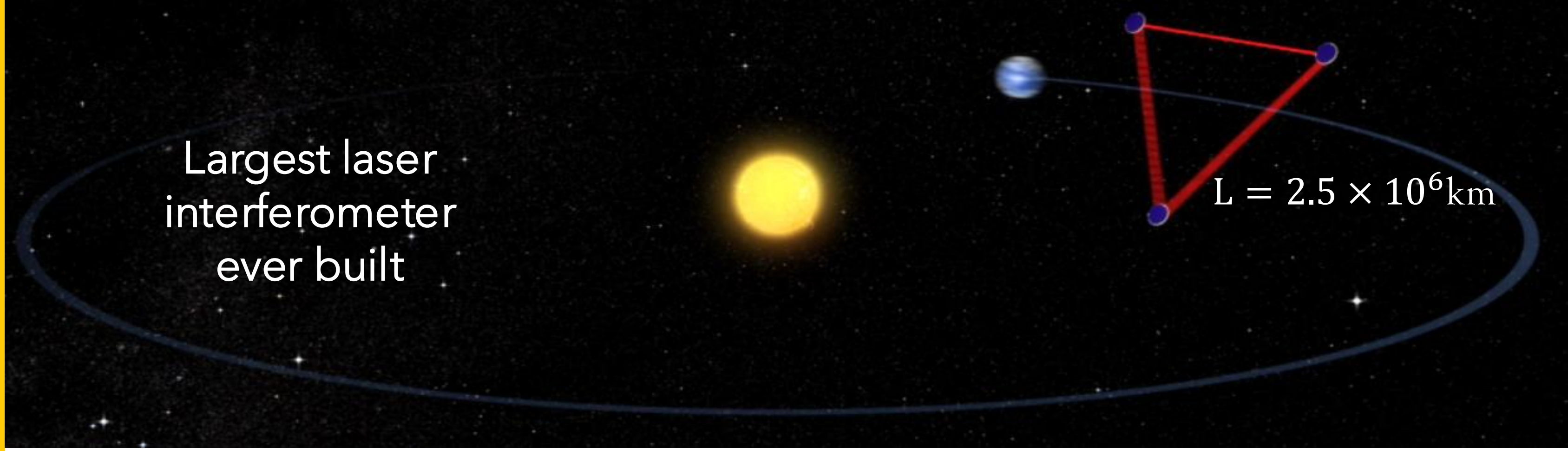
Fourier Transform of a **step function** $\rightarrow -\frac{i\Delta h_{mem}}{2\pi f}$

Characteristic strain for $f \ll f_{merger}$,

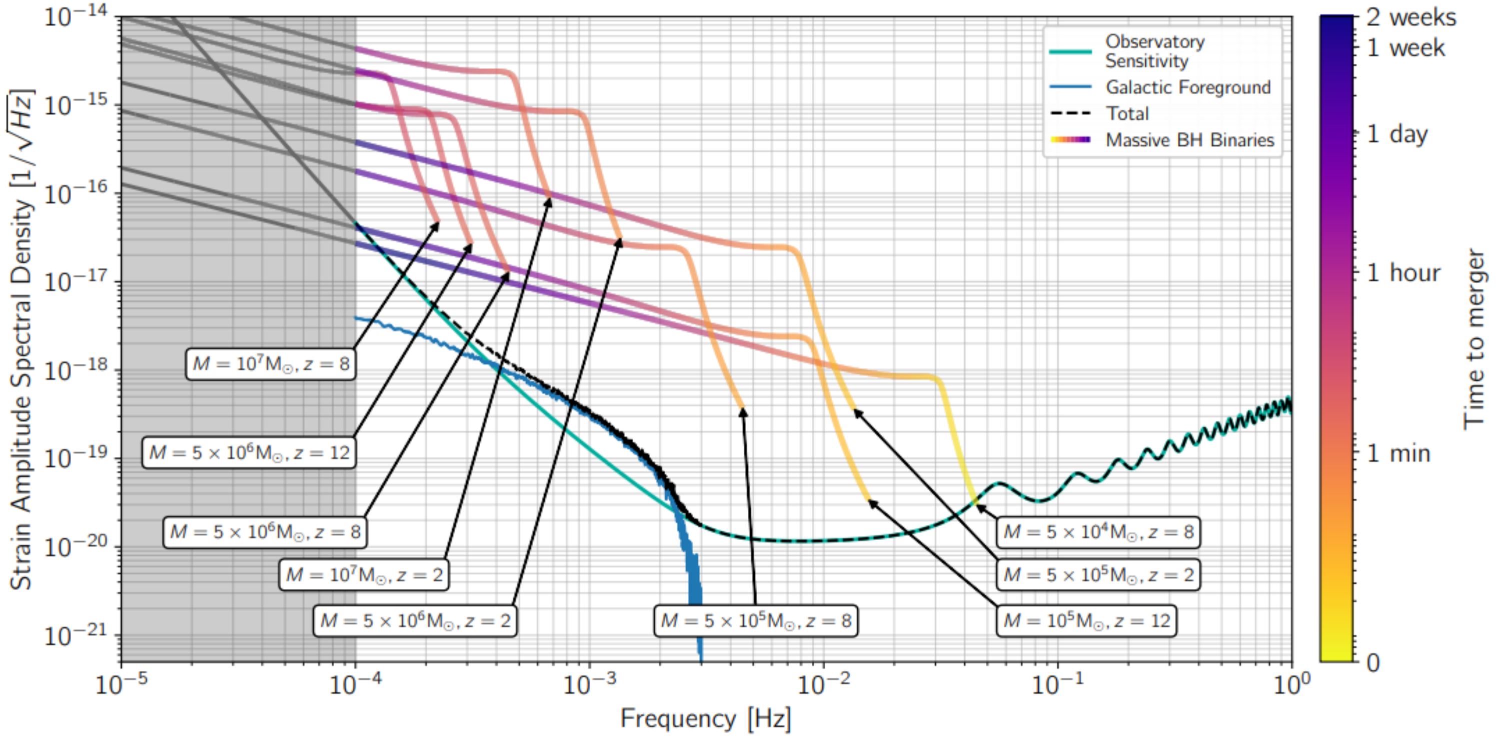
$$f\left|\tilde{h}(f)\right| \rightarrow \Delta h_{mem}/2\pi$$



LISA :
Laser Interferometer Space Antenna

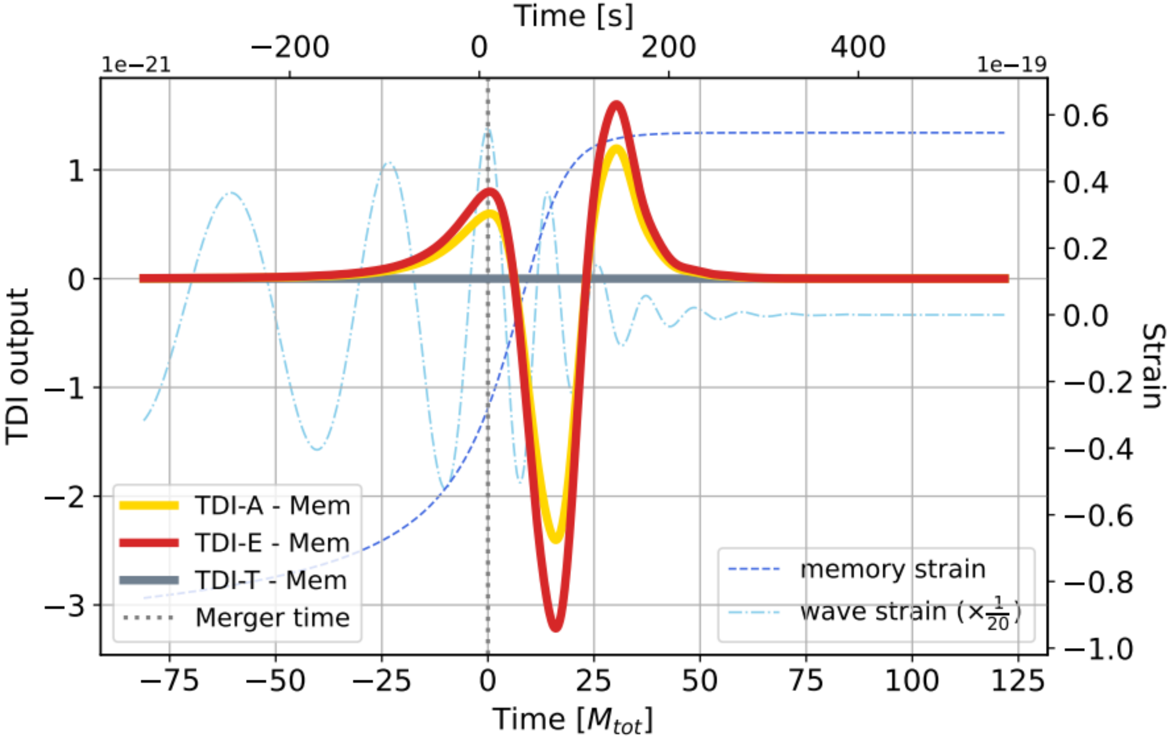


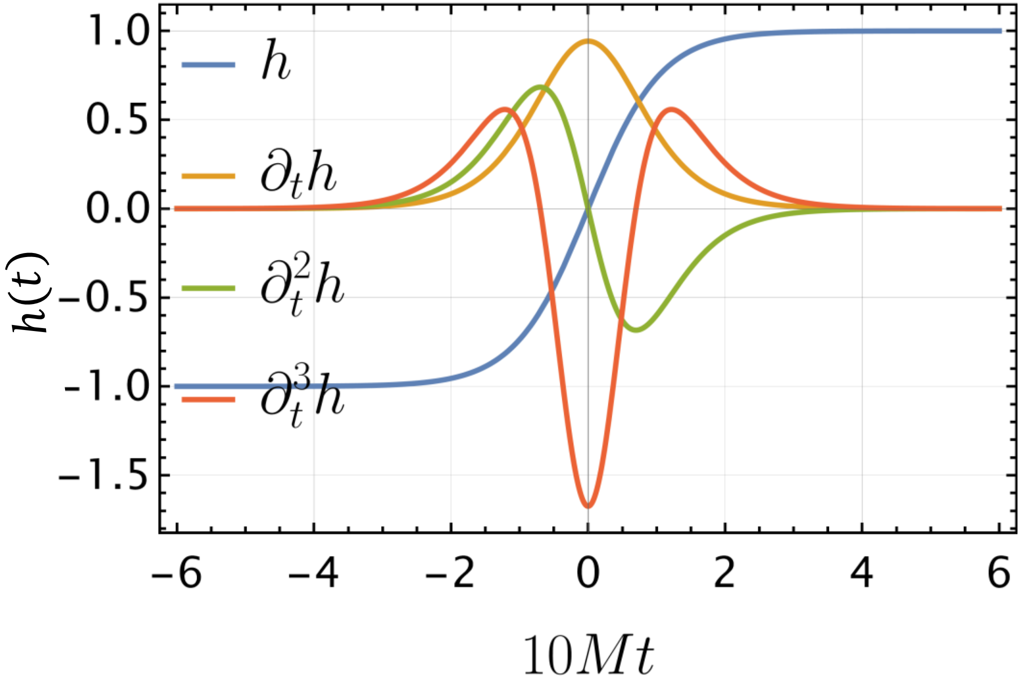
LISA golden sources:
Massive Black Hole Binaries (MBHBs)



LISA response to GW Memory: time domain

GW memory imprint of a binary merger with $M_{tot} = 10^6 M_\odot, q = 1, z = 1, \iota = \frac{\pi}{2}$



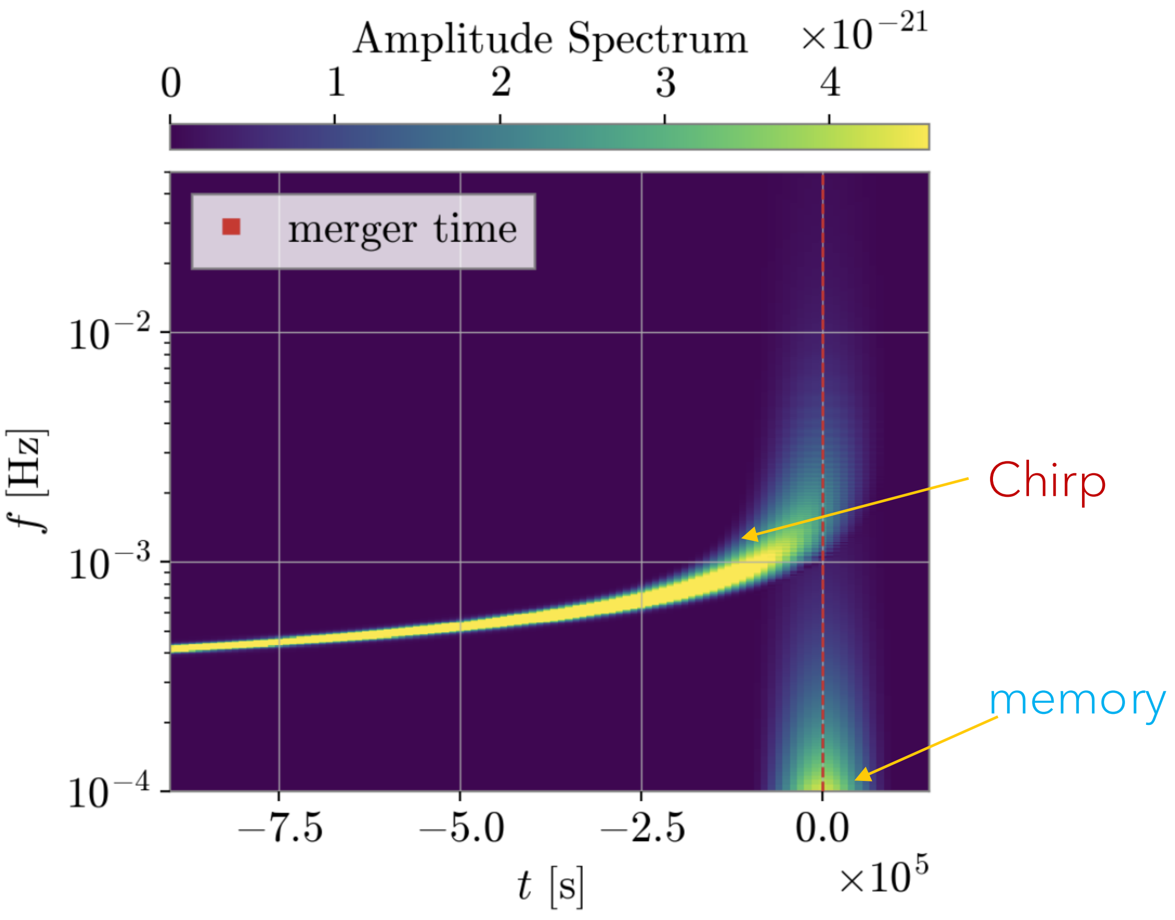


Burst-like signal: We don't observe the persistent off-set of the memory, but just its time-variation $X \propto \partial^3 h$

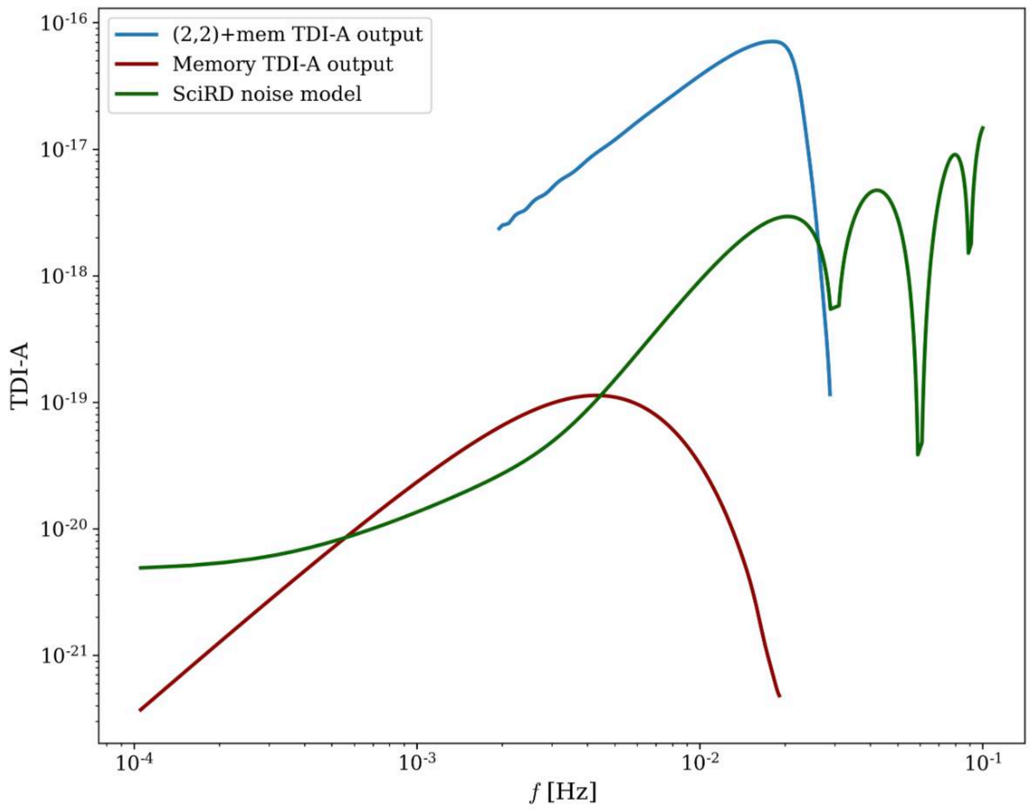
$$h^{mem} = \Delta h \tanh\left(\frac{t - t_c}{\Delta T}\right) \text{ with } \Delta T = 60\ M$$

Time-frequency representation

LISA fundamental Physics WG
A.Cogez, **SG** et al. '26
J.Zosso, L. Zertuche, SG et al '26

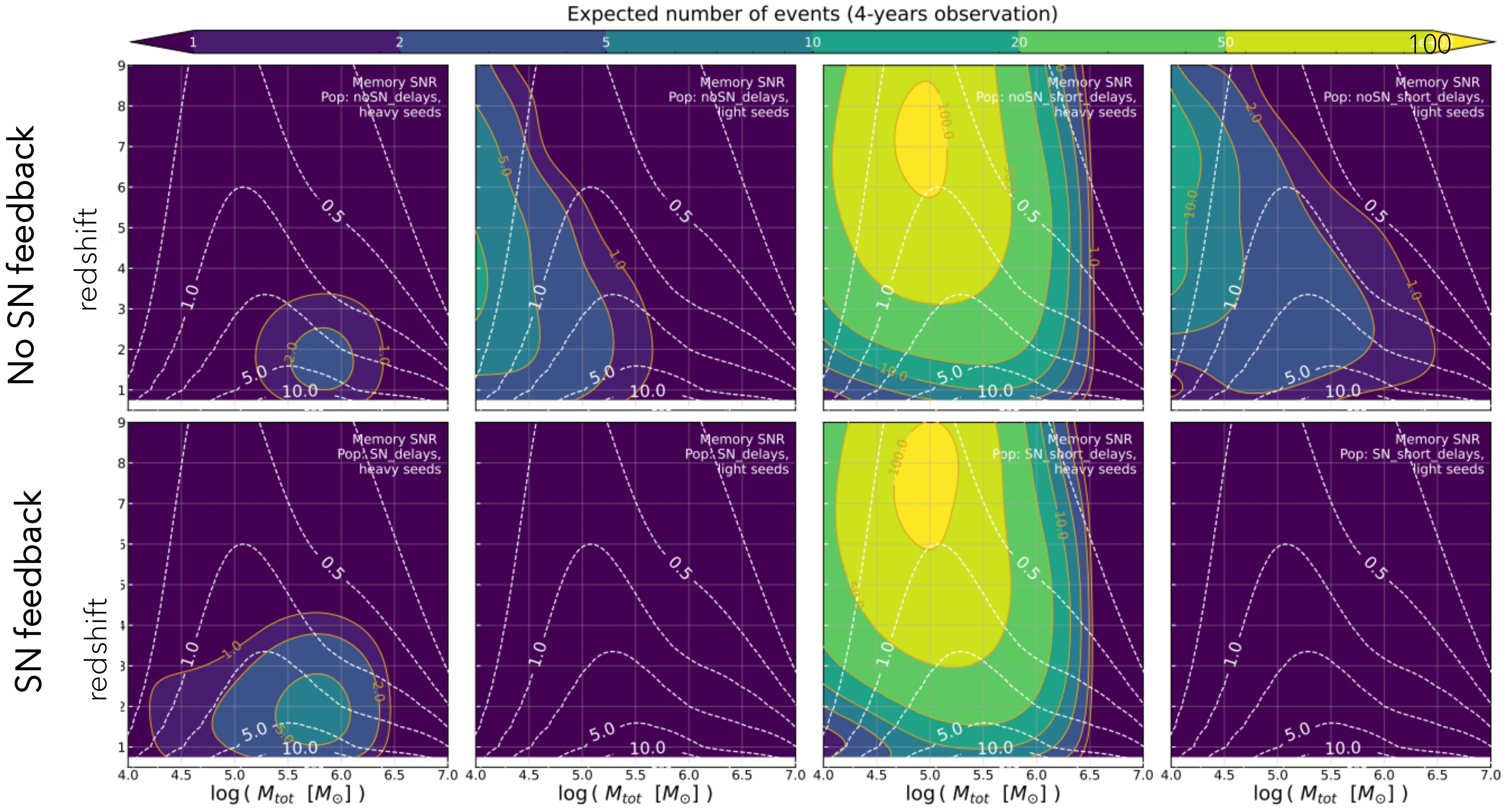


Fourier transform:



SNR vs SMBH population models

LISA fundamental Physics WG
H.Inchauspé, SG et al. '24



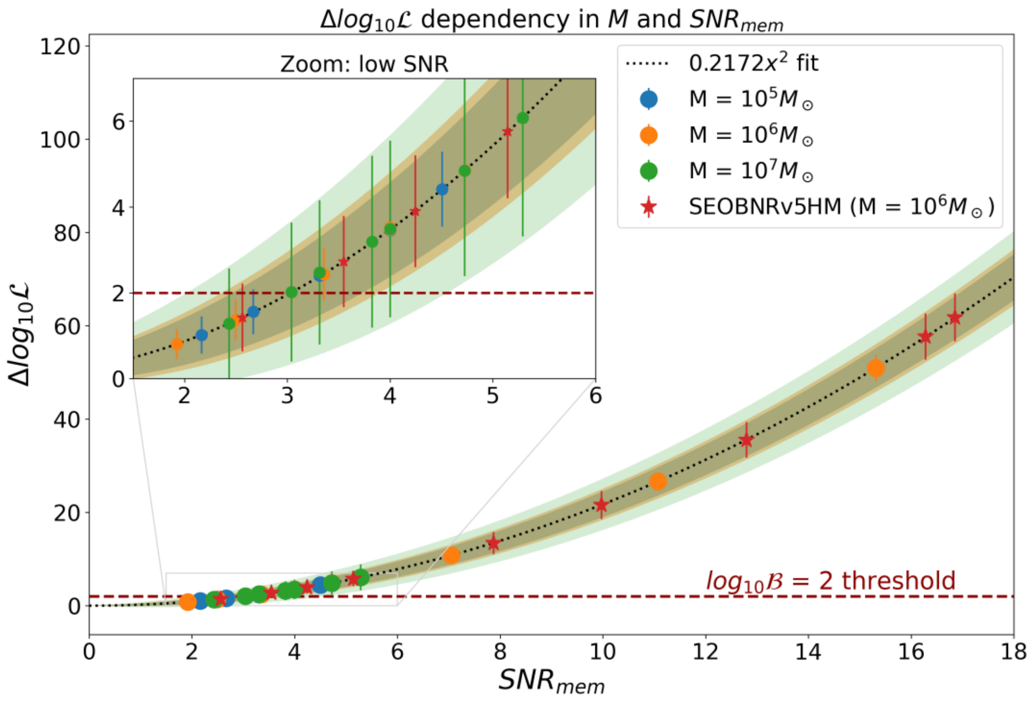
HS LS HS, short delays LS, short delays

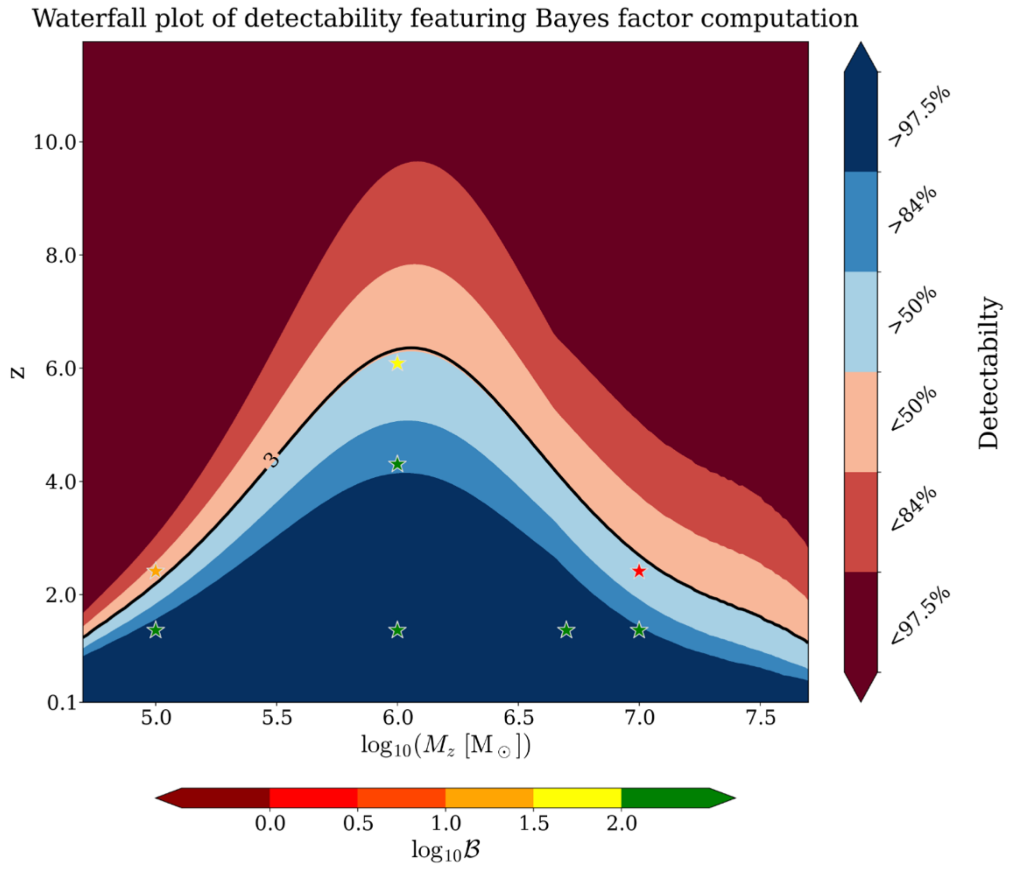
Full parameter exploration

LISA fundamental Physics WG
A.Cogez, **SG** et al. '26

Bayes factor: $\mathcal{B} = \frac{Z_{o+mem}}{Z_o}$ with evidence $Z = p(d|m)$, decisive evidence $\log_{10}\mathcal{B} \gtrsim 2$ for $SNR_{mem} \sim 3$

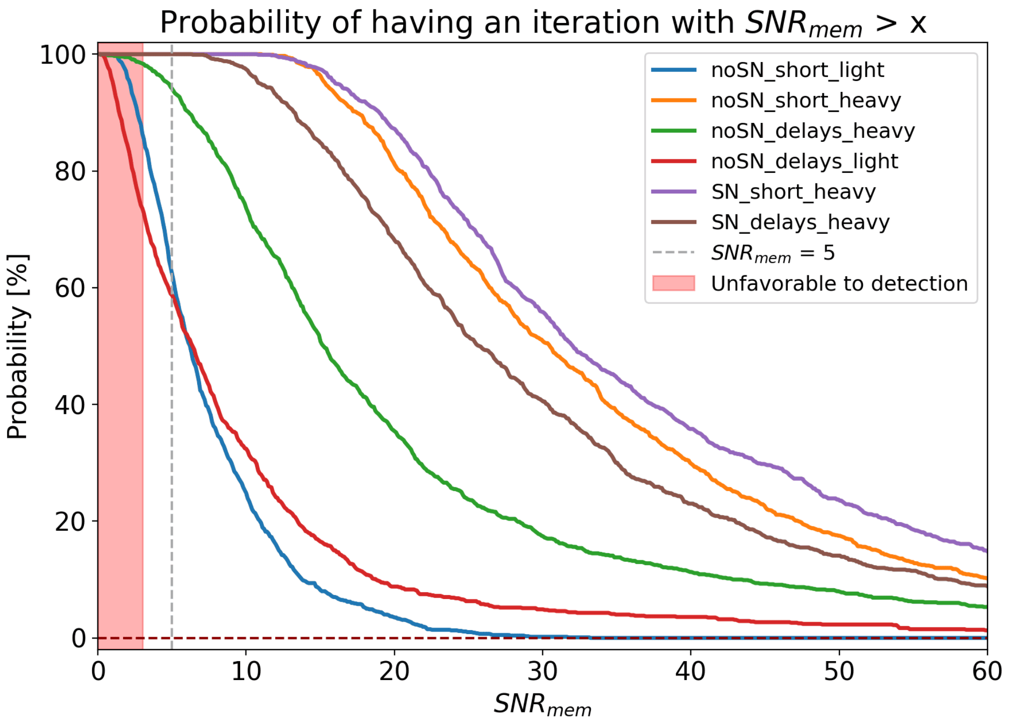
$$\log_{10}\mathcal{B} \approx \log_{10}\mathcal{L}^{o+mem}(d|\theta_s) - \log_{10}\mathcal{L}^{o}(d|\theta_s) = \Delta\log_{10}\mathcal{L}$$





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	$8.0^{+5.0}_{-4.0}$	$4.0^{+3.0}_{-3.0}$	$3.0^{+3.0}_{-3.0}$	$1.8^{+1.4}_{-0.6}$

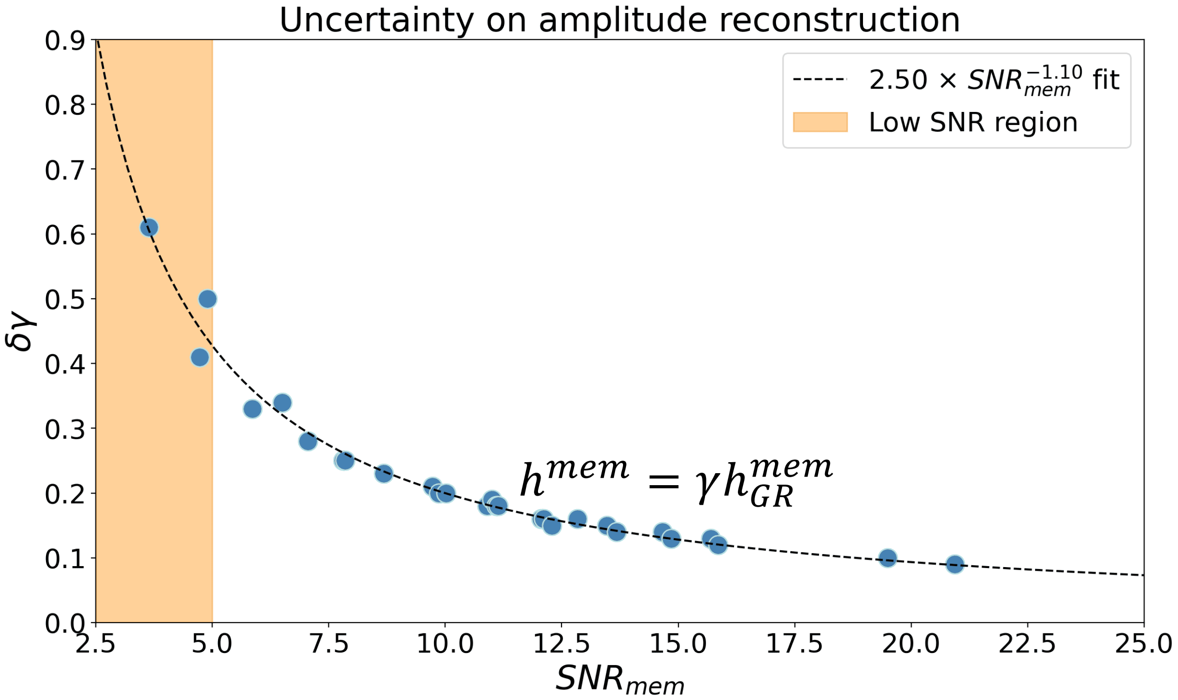
TABLE V: Table with the expectation of detection for different models, using Barausse's populations. The values are provided as median$^{+2\sigma}_{-2\sigma}$ to reflect the asymmetries of the distributions.

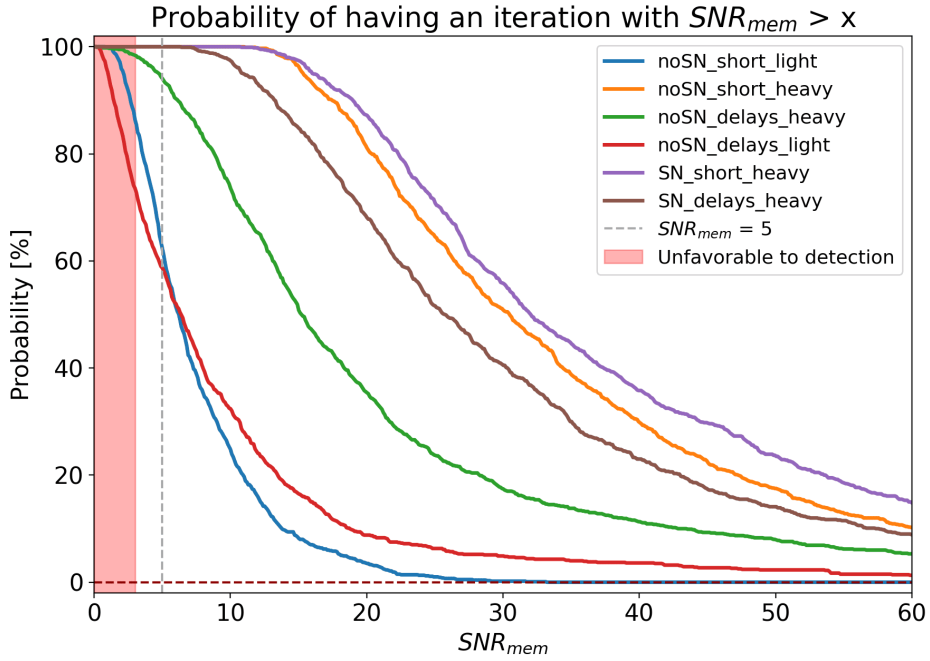


LISA fundamental Physics WG
A.Cogez, SG et al. '26

Latest updates on population studies

A. Cogez, S. Gasparotto et al., '26





❓ GW memory as a powerful tool for testing GR in a strong regime ❓

Relative error on the memory amplitude

Scalar-vector-tensor (STV) theories:

$$S = \frac{1}{2\kappa_0}\int d^4x\sqrt{g}\left[\sum_{i=1}^{5} L_i[g,\Phi,A] + L_m[g]\right]$$

Dynamical degrees of freedom $2+2+1=5$ d.o.f.

Grav. polarizations $\mathrm{P_{ij}} = e^{+}_{ij}h_{+} + e^{\times}_{ij}h_{\times} - e^{b}_{ij}\sigma\varphi$ (3 polarizations)

SVT theories include: Brans-dicke $\sigma \neq 0$, scalar Gauss-Bonnet $\sigma = 0$

Previous calculation of the memory in BD in Post-Newtonian limit

Motivation: no calculation of memory from full waveform including the merger → relevant for observations

The **structure of the tensor memory is unchanged**, but all massless radiating d.o.f. contribute to it

$$\boxed{\delta h_H^{lm}(u,r) = \frac{1}{r}\sqrt{\frac{(l-2)!}{(l+2)!}}\int_{S^2} \mathrm{d}^2\Omega'\,\bar{Y}^{lm}(\Omega') \times \int_{-\infty}^{u} \mathrm{d}u'\,r^2\left\langle \underbrace{|\dot{\hat{h}}_{+}|^2 + |\dot{\hat{h}}_{\times}|^2}_{\text{Tensor induced memory}} + \underbrace{\sum_{\lambda=1}^{N} |\dot{\hat{\psi}}_{\lambda}|^2}_{\text{Other radiating d.o.f.}}\right\rangle}$$

Heisenberg, Yunes, Zosso '23

Memory in SVT theories

Scalar Gauss Bonnet Theory

S. Gasparotto, J. Zosso, L.Aresté Saló, D. Doneva, S. Yazadjiev, '26

- Example of Hordenski theory, motivated by string theory and EFT perspective
- **Well-posed theory** for which we have **NR waveform** and we can study deviation from GR
- Differences at strong curvature (small BHs)
- Both static and rotating black hole solutions exist and carry scalar charge (BH hair) → non-zero scalar field Φ, value depending on λ, M, χ

    A. *Linear coupling* (all BHs have hairs)

    B. *Gaussian coupling* → dynamical transition can happen in binaries

sGB coupling

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R - \frac{1}{2}(\nabla\Phi)^2 + \lambda f(\Phi)\mathcal{L}_{\rm GB}\right)$$

$$\mathcal{L}_{\rm GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

$$f_A(\Phi) = \Phi$$

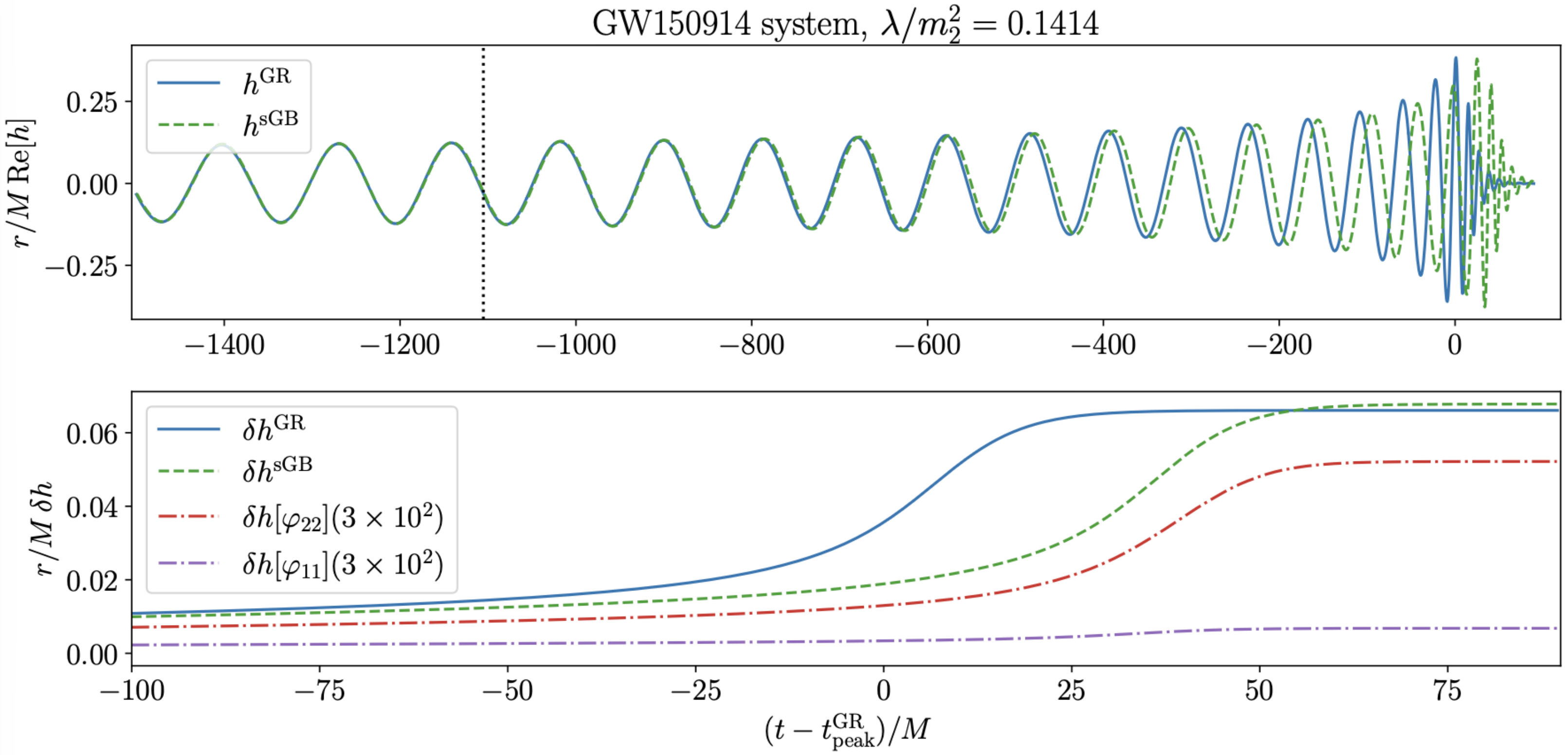
$$f_B(\Phi) = \frac{1}{2\beta}(1 - e^{-\beta\Phi^2}) \approx \frac{1}{2}\Phi^2 - \frac{\beta}{4}\Phi^4$$

Memory in scalar Gauss Bonnet

$$h(u,r,\Omega) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} h_{lm}(u,r)\ {}_{-2}Y_{lm}(\Omega)\,,$$

$$\varphi_1(u,r,\Omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \varphi_{lm}(u,r)\ Y_{lm}(\Omega)\,,$$

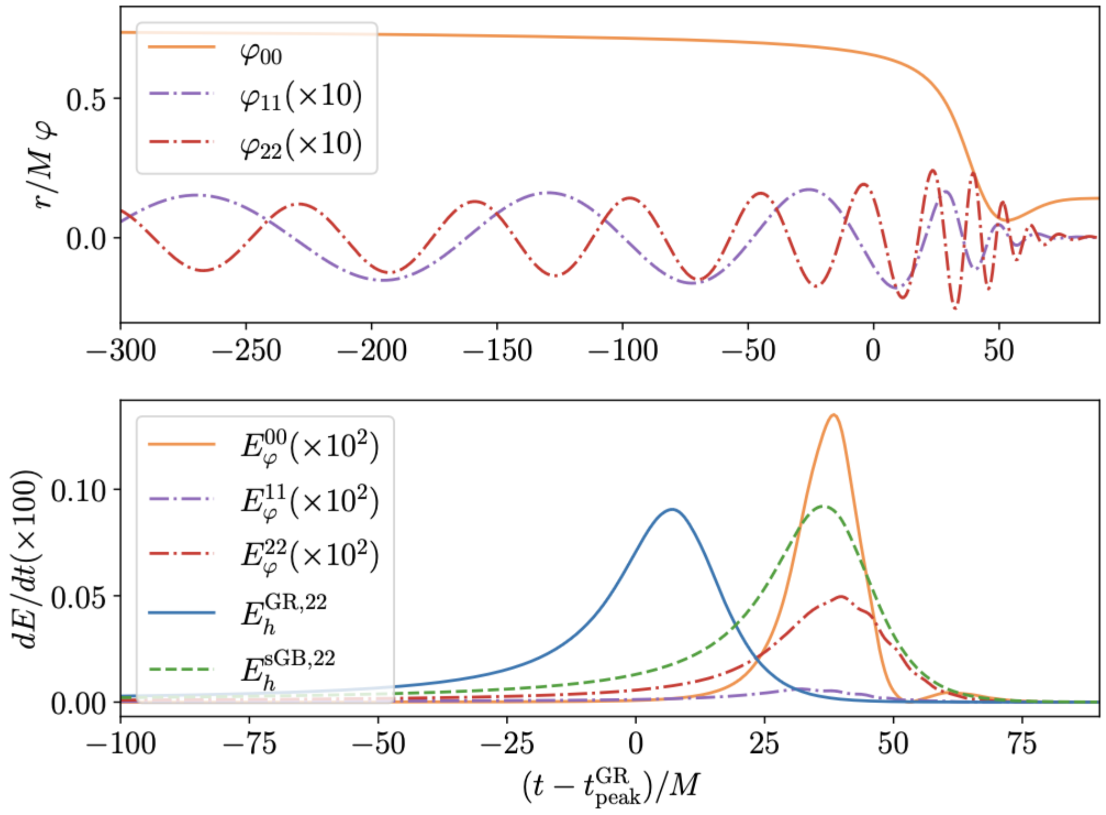
$$\delta h_{20}(u) = \frac{r}{7}\sqrt{\frac{5}{6\pi}} \int_{-\infty}^{u} du' \langle |\dot{h}_{22}|^2 - |\dot{\varphi}_{22}|^2 \rangle - \frac{r}{2\sqrt{30\pi}} \int_{-\infty}^{u} du' \langle |\dot{\varphi}_{11}|^2 \rangle\,,$$



	aligned at max (inf)	aligned at freq (inf)	$R = 100M$	$R = 150M$	$R = 200M$
sGB	0.0634	0.0635	0.068	0.067	0.0648
GR	0.0619	0.0619	0.066	0.066	0.0631
Ratio%	2.36	2.53	2.54	2.54	2.52

Waveforms from M. Corman, L. Aresté Saló, and K. Clough (2025)

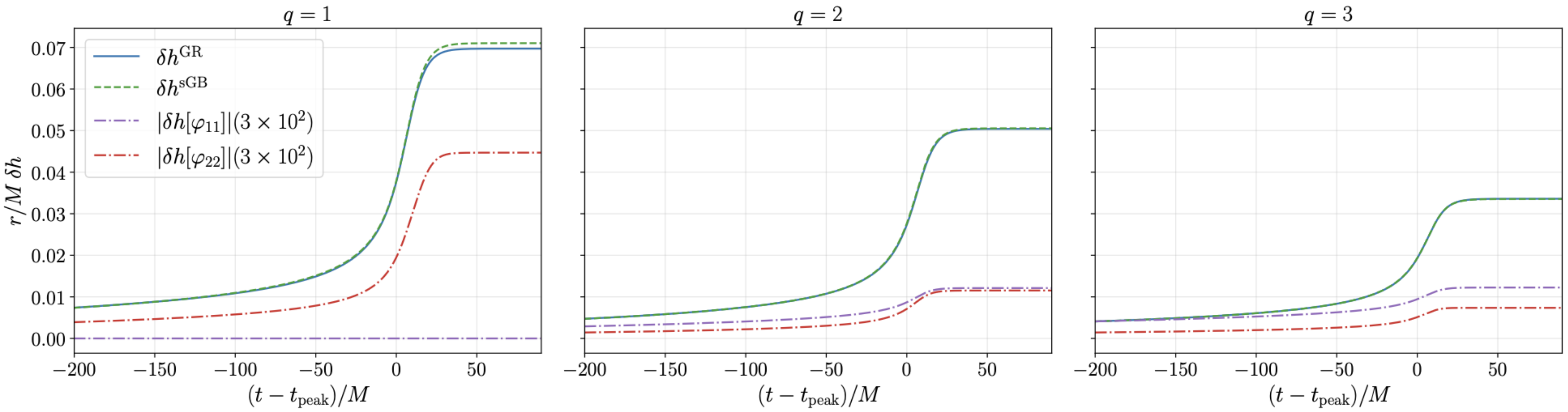
Memory and scalar radiation



- Memory in sGB is higher than in GR of ~ 2,5% for $\frac{\lambda}{m_2^2} = 0.14$ and $q = 1.2$
- Most of the **energy radiated in the 00 scalar mode** → does NOT generate memory. Memory generated from scalar field is suppressed
- The difference in the GW comes from the backreaction of the scalar field and non linear terms

Memory for higher mass ratios

$\lambda/m_2^2 = 0.106$

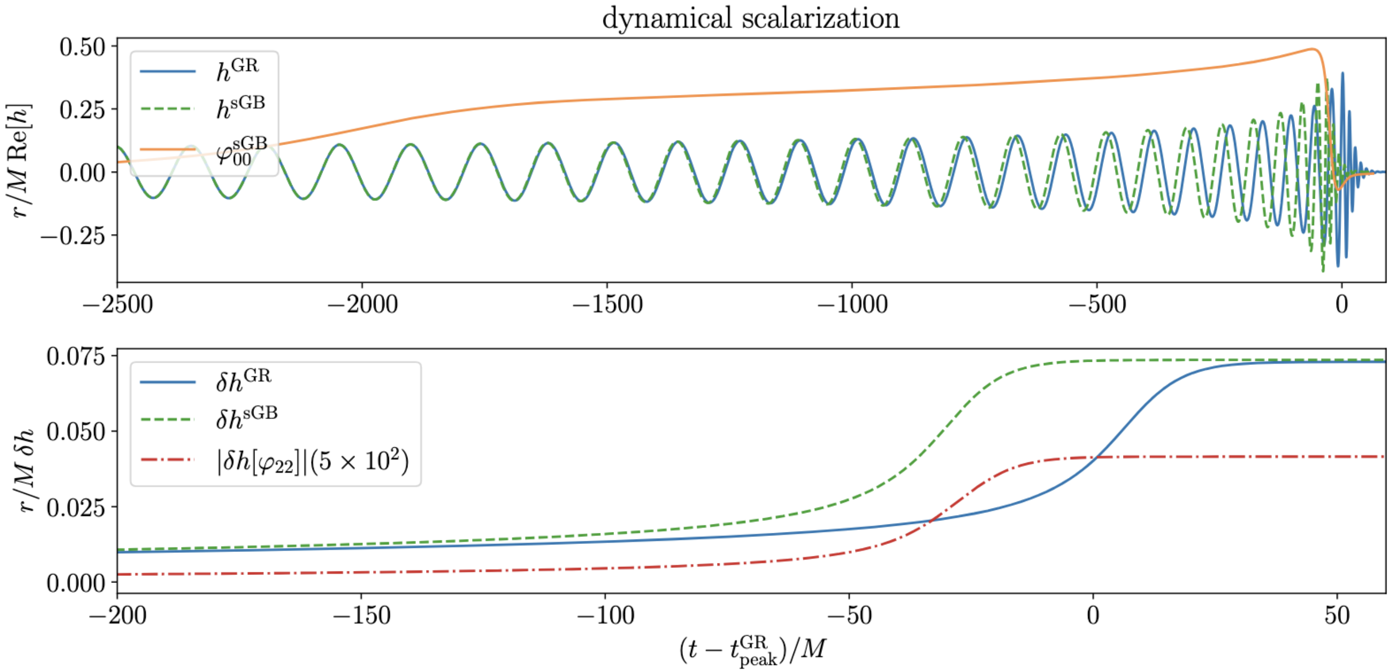


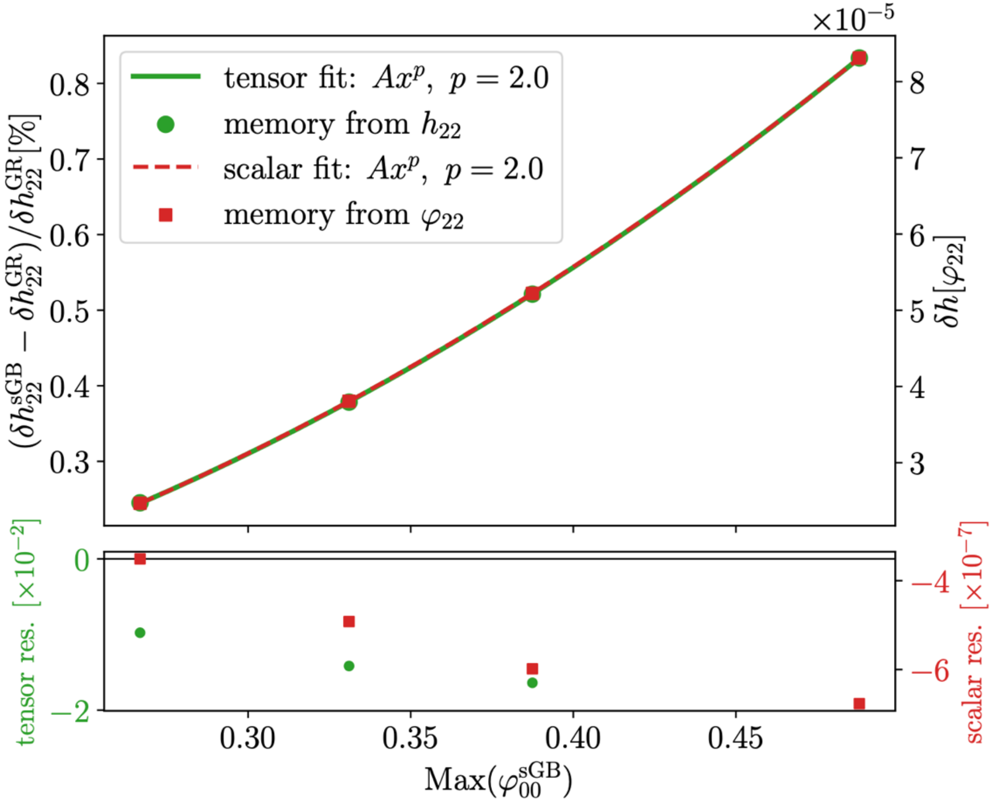
Effect for different mass ratios $q = m_1/m_2$:

- overall memory amplitude decreases → difficult to detect
- relative difference of the tensor-induced memory decreases
- the importance of scalar-induced memory increases

	$\Delta(\delta h^{\rm GR})$	$\Delta(\delta h^{\rm GB})$	Rel difference [%]
$q=1$	0.0697	0.0710	1.24
$q=2$	0.0504	0.0505	0.27
$q=3$	0.0335	0.0335	<0.1

Dynamical scalarization





$\frac{\lambda}{m^2} = 0.703$ and $\beta = 4$. $\Delta h^{GR} = 0.0729 r/M$ & $\Delta h^{GB} = 0.0735\, r/M$

Difference in memory scale with the square of the scalar charge

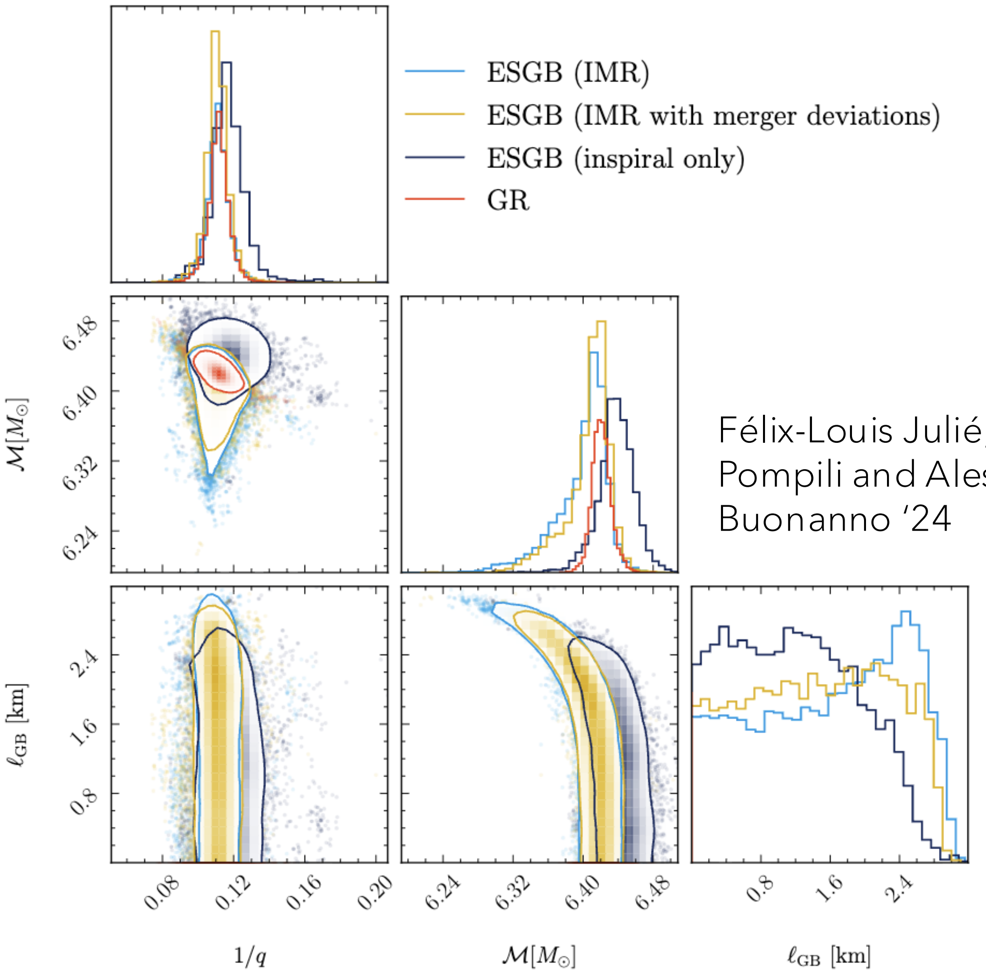
Waveforms degeneracies

Is the difference of the waveforms degerate with variation of other parameters?

Can the information of the memory bring complementary information to break this degeneracy?

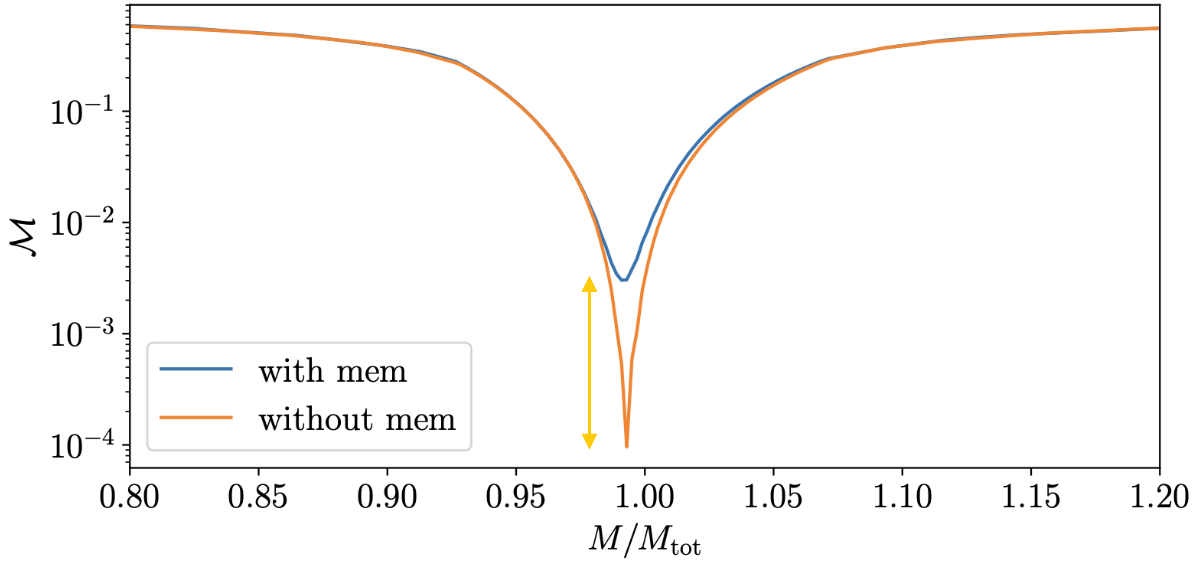
Example of degeneracy between the GB coupling scale and chirp mass

We have limited waveforms, we can simply scale the total mass of the system



Félix-Louis Julié, Lorenzo Pompili and Alessandra Buonanno '24

Waveforms distinguishability



Mismatch between GR and non-GR waveforms for a GW150914, computed for ET with $M = 20\ M_\odot, d = 420\ Mpc, \iota = 90°, SNR \sim 82$

Minimum mismatch for $M \sim 0.99 M_{tot} \rightarrow$ memory would be 4% higher than in GR

$$\langle h_1 | h_2 \rangle = 4\,\mathrm{Re} \int_{f_{\min}}^{f_{\max}} \frac{\tilde{h}_1(f)\,\tilde{h}_2^*(f)}{S_n(f)}\, df$$

Overlap $$\mathcal{O}(h_1, h_2) = \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}}$$

Mismatch $$m = 1 - \max_{\Delta t,\, \Delta\phi} \mathcal{O}(h_1, h_2)$$

Distinguishability criterium $$m \leq \frac{D}{2\,\mathrm{SNR}^2}\,, \qquad \mathrm{SNR}^2 = \langle h_1 | h_1 \rangle$$

Short answer: Yes, bigger mismatch means more probability to distinguish the waveforms

For $20 M_\odot$, $N(z \leq 0.2) \sim (0.3 - 3)\,\mathrm{yr}^{-1}$ with ET

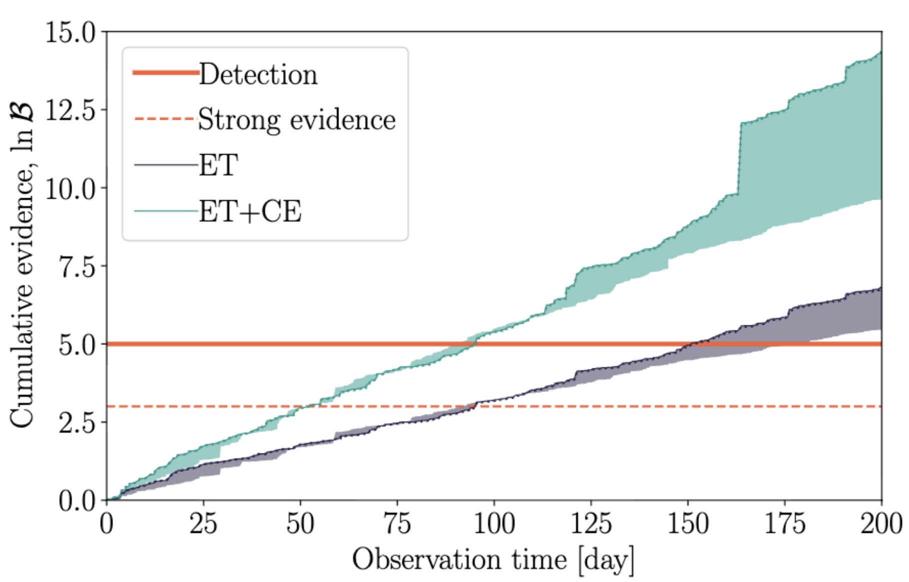
Observability and Relevance

Is this effect in the memory observable?

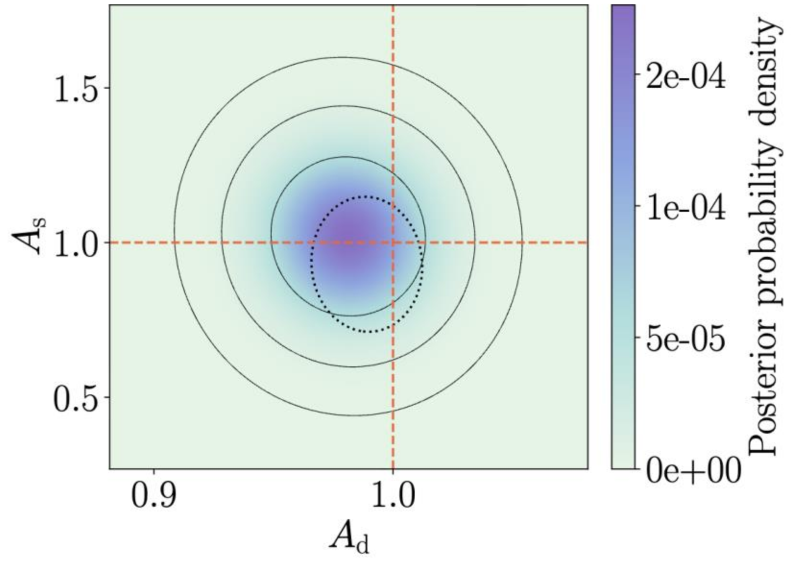
Einstein Telescope and **Cosmic Explorer** might have the capability to detect small deviations of the memory → **Goncharov et al. '23 claims a 2% precision** on the amplitude of the memory from a population BBHs

Outcomes:

- 💡 Deviation of the memory are small but potentially within reach
- 💡 Inclusion of the memory in test of GR because can add complementary information and help to break degeneracies
- 💡 A more careful analysis should be done…



Goncharov & al. '23



A modification of the theory

J. Zosso, S. Gasparotto, L.Aresté Saló, D. Doneva, S. Yazadjiev, '26

Scalar Gauss-Bonnet naturally arise in the low-energy effective actions of heterotic and bosonic string compactification dilaton multiplies not only the GB term but also the Ricci scalar → Ricci-coupled sGB (RcsGB)

Jordan frame, matter follows geodesics

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,f(\Phi)\Big(R + \omega(\Phi)X - \lambda\mathcal{G}\Big) + S_{\rm m}[g,\Psi_{\rm m}]\,,$$

$$X = -\frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi \quad \text{and} \quad f(\Phi) = e^{-\alpha\Phi}$$

Einstein frame, metric redefenition

$$g_{\mu\nu}(x) \to \tilde{g}_{\mu\nu}(x) = f(\Phi)g_{\mu\nu}(x)$$

$$S_E = \frac{1}{16\pi}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + \Omega(\Phi)X - \lambda f(\Phi)\tilde{\mathcal{G}}\right] + S_{\rm m}[f(\Phi)^{-1}\tilde{g}_{\mu\nu},\Psi_{\rm m}]\,,$$

Back to scalar Gauss-Bonnet

In the weak field limit

$$f_\alpha(\Phi) = e^{-\alpha\Phi} \approx 1 - \alpha\Phi$$

The theory is equivalent to sGB in einstein frame plus direct interaction with matter field

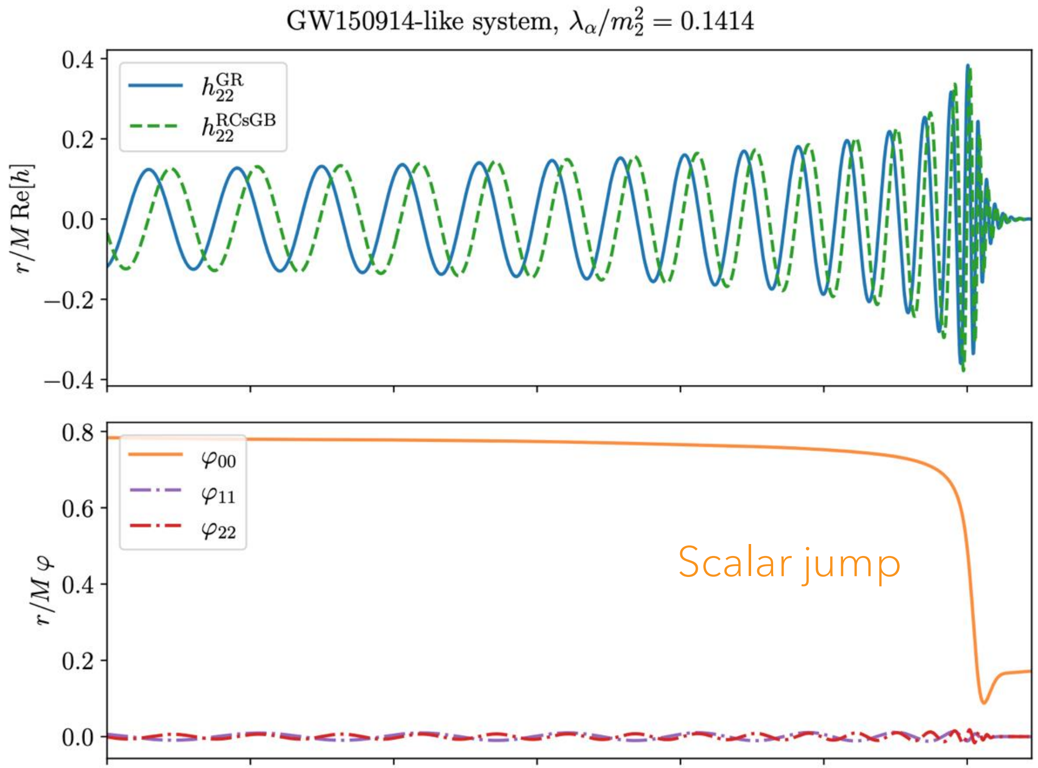
$$S_E^\alpha = \frac{1}{16\pi}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + X + \lambda_\alpha \Phi \tilde{\mathcal{G}}\right] + S_\mathrm{m}[(1+\alpha\Phi)\tilde{g}_{\mu\nu}, \Psi_\mathrm{m}]\,,$$

$\lambda_\alpha = \alpha\lambda$

Fifth-force tests (Cassini):

$$\alpha \lesssim \sqrt{10^{-5}} \approx 3\times 10^{-3}$$

Additional coupling does not change the vacuum structure, waveforms are the same:



Scalar memory

Polarization content of the theory

$$\mathrm{P_{ij}} = e_{ij}^{+} h_{+} + e_{ij}^{\times} h_{\times} - e_{ij}^{b} \sigma \varphi$$

breathing mode

Where $\sigma = \frac{f'(\varphi_0)}{f(\varphi_0)} = -\alpha$ in contrast to standard sGB where $\sigma = 0$.

Scalar memory: non-zero shift in the breathing polarization $\Longrightarrow$ no associated symmetry

New general mechanism to generate memory in an additional polarization: scalar d.o.f. + Ricci coupling

<u>Detector response:</u>

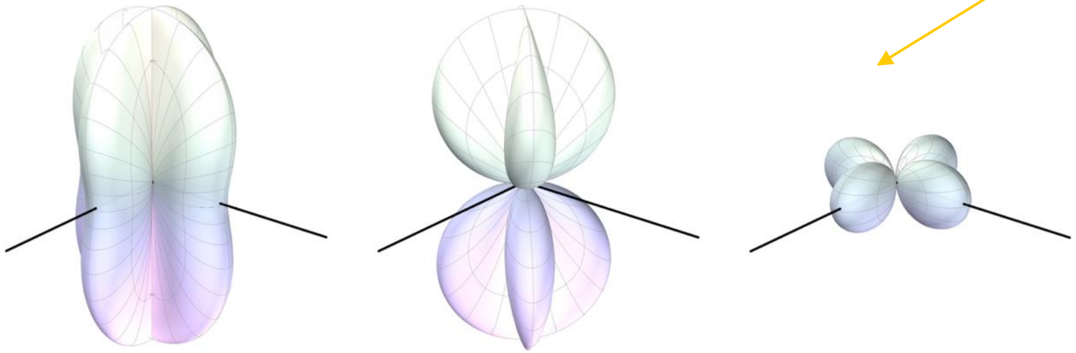
$$\begin{aligned} P(t) = {} & F_{+}(\Omega_d)\, h_{+}(t,\Omega) + F_{\times}(\Omega_d)\, h_{\times}(t,\Omega) \\ & + F_b(\Omega_d)\, \alpha\, \varphi_1(t,\Omega)\,, \end{aligned}$$

$$F_{+}(\Omega_d) = \frac{1}{2}\left(1 + \cos^2\theta_d\right)\cos 2\phi_d\,,$$

$$F_{\times}(\Omega_d) = -\cos\theta_d \sin 2\phi_d\,,$$

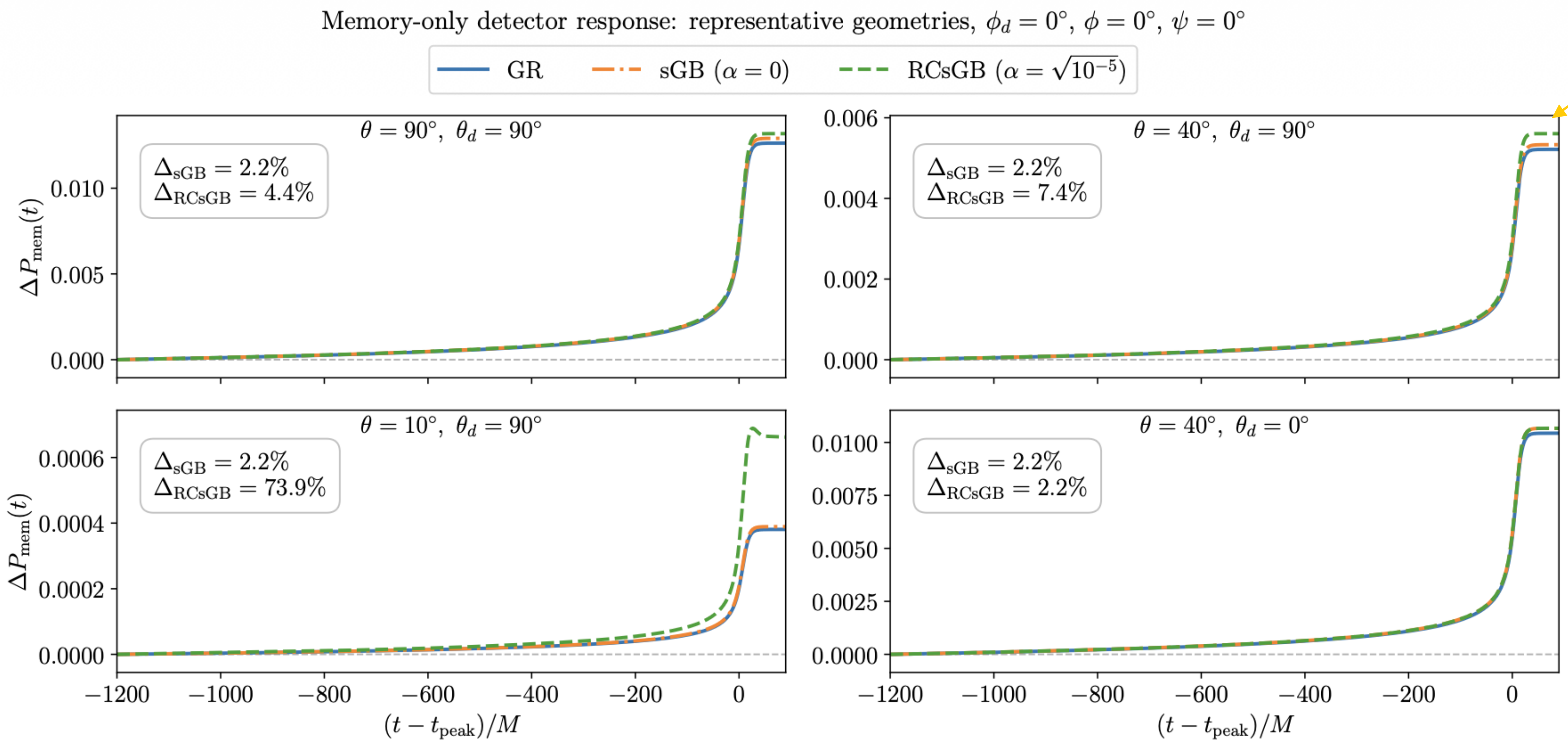
$$F_b(\Omega_d) = -\frac{1}{2}\sin^2\theta_d \cos 2\phi_d\,.$$

Different dependence on the direction of the perturbation



(a) $|F_{+}|$ (b) $|F_{\times}|$ (c) $|F_b|$

Modification of the memory

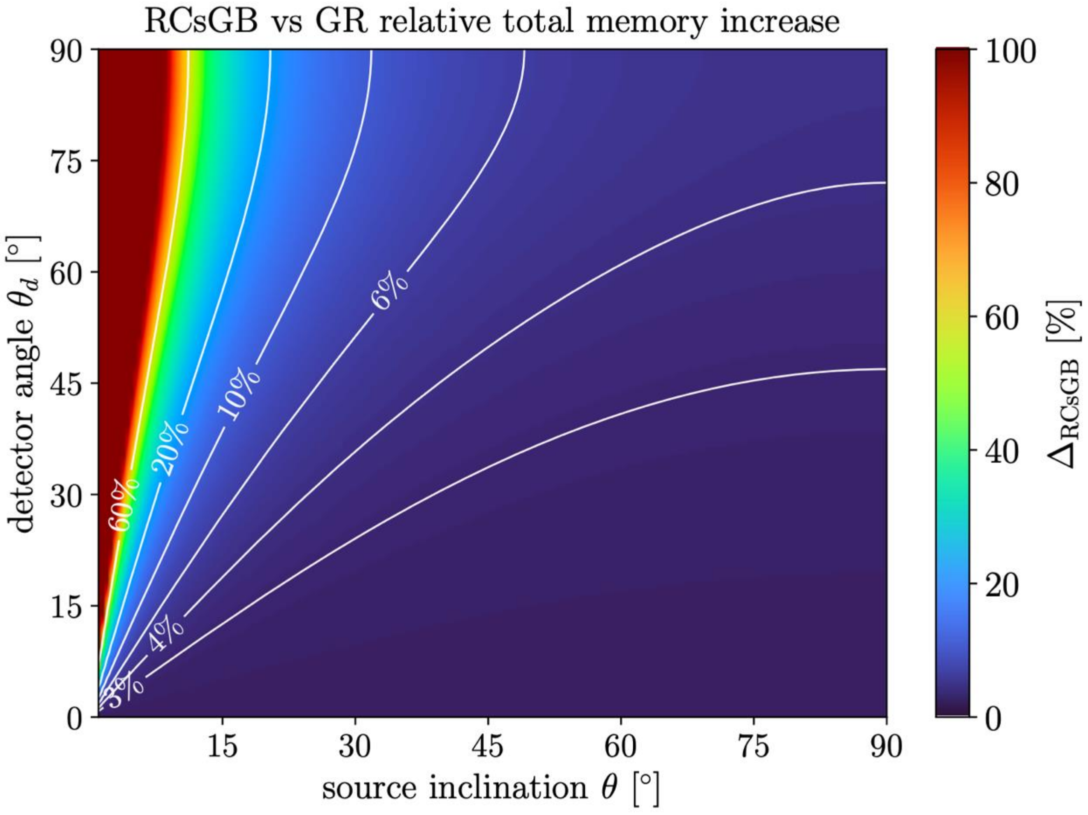


Constructive memory contribution from the scalar memory

$$\Delta_{\rm sGB} \equiv \frac{\Delta P^{\rm tot}_{\rm sGB} - \Delta P^{\rm tot}_{\rm GR}}{\Delta P^{\rm tot}_{\rm GR}}$$

$$\Delta_{\rm RCsGB} \equiv \frac{\Delta P^{\rm tot}_{\rm RCsGB} - \Delta P^{\rm tot}_{\rm GR}}{\Delta P^{\rm tot}_{\rm GR}}$$

Additing scalar memory



- scalar memory can dominate close to face-on configuration
- Non-trivial dependence on the sky direction, it vanishes for $\theta_d = 0$

<u>Analytic understanding of the RCsGB result</u>

$$\varphi^I_{00} \sim \frac{\lambda_\alpha}{r}\left(\frac{1}{m_1}+\frac{1}{m_2}\right), \qquad \varphi^F_{00} \sim \frac{\lambda_\alpha}{rM}.$$

$$\frac{\varphi^I_{00}}{\varphi^F_{00}} \simeq \frac{(1+q)^2}{q} = \frac{1}{\eta} \quad \sim 4 \text{ for nearly equal-mass}$$

Relative importance of the scalar memory increases with q, but the total amplitude decreases

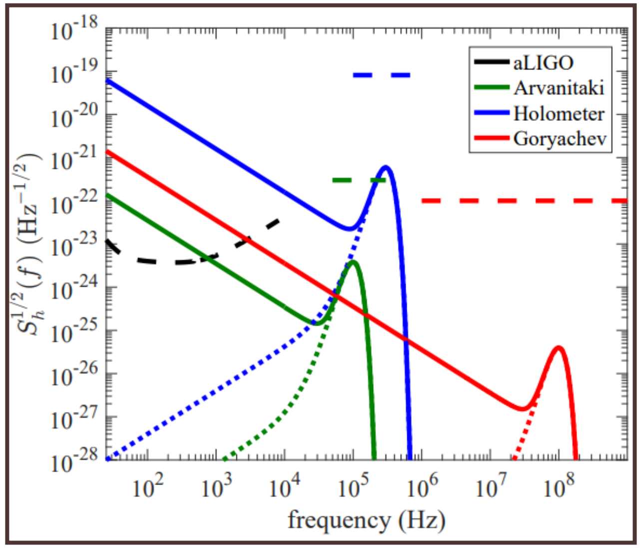
General outcome

Ricci-coupled term suggestes a mechanism to generate *scalar memory beyond the sGB theory*

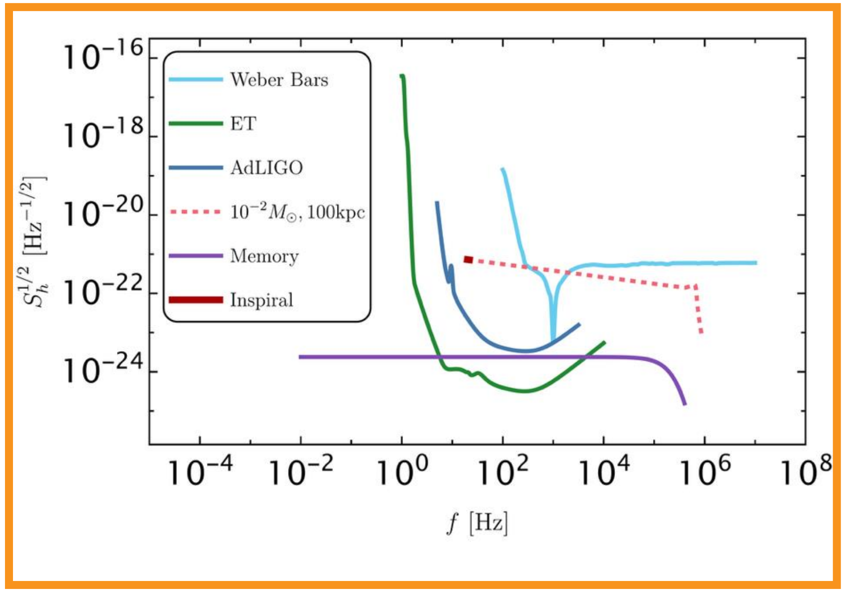
Ingredients:

- Additional dynamical gravitational d.o.f.
- Compact objects carry non-trivial charge which depepends on the eq. configuration (hairy BHs)
- Field enters in the polarization tensor throught an additional mode

$$\Delta P \sim \underbrace{F_\Lambda(\Omega_d)}_{\text{Detector response}}\underbrace{\alpha_\Lambda}_{\text{Coupling}}\underbrace{\Delta Q_\Lambda}_{\text{Asymptotic charge}}$$



Detecting Gravitational Wave Memory without Parent Signals (Orphan memory signal) 1702.01759



Memory and early inspiral low-frequency counterpart of a high-frequency merger

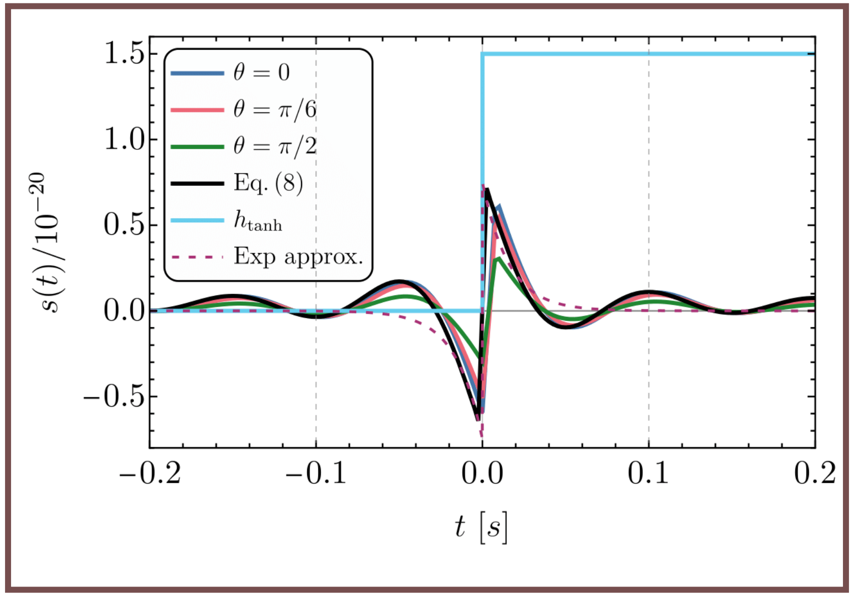
Memory from out-band mergers: the PBH case

SG, G. Franciolini, V. Domcke
[2505.01356]

Almost universal memory signal

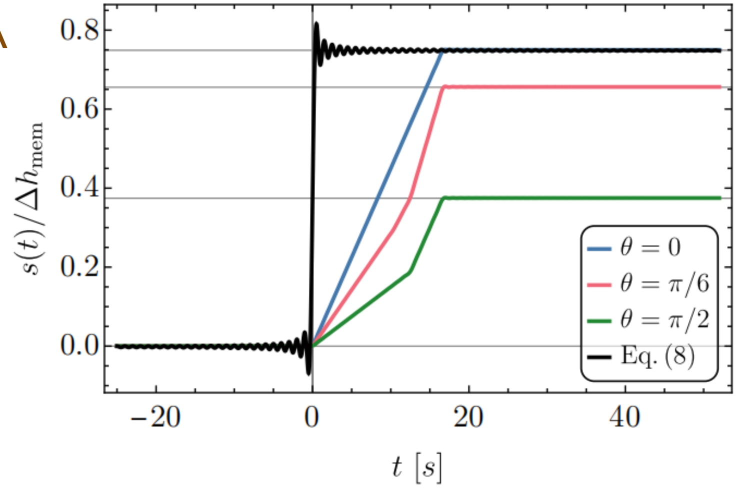
Band passed signal: $M_{tot} = 10^{-2} M_{\odot}, d = 1\ kpc$

LIGO

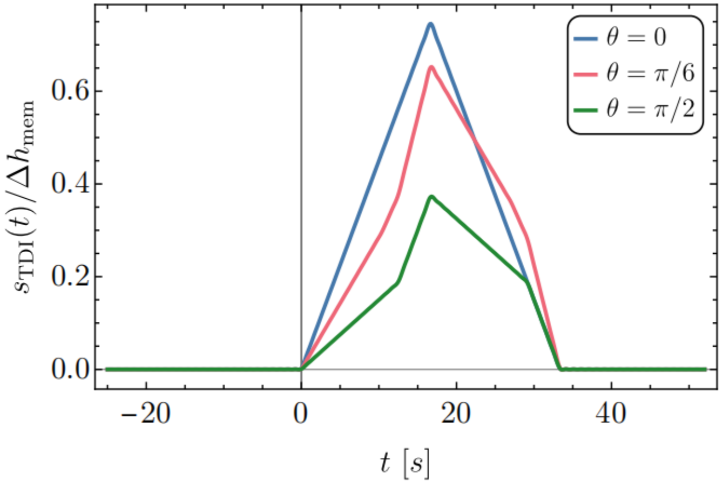


LISA

Simple interferometer response



After TDI post-processing



Depending only on **amplitude, merger time, and sky position**, the memory emerges as a simple and robust target for detection.

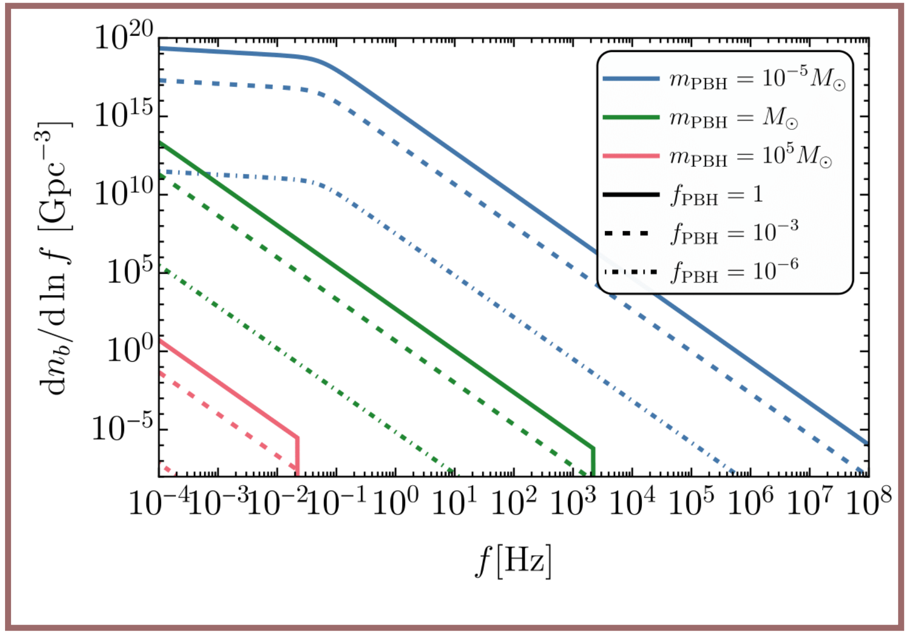
Number of detectable events

PBH merger rate in the **early-universe scenario** for **monochromatic mass** function

$$\frac{d^2\mathcal{R}(t,d)}{d\ln m_1 d\ln m_2} = \left(\frac{0.038}{\mathrm{kpc^3\,yr}}\right)[1+\delta(d)] f_{\mathrm{PBH}}^{\frac{53}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \times \left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-\frac{34}{37}} \left(\frac{m_1+m_2}{10^{-12}M_\odot}\right)^{-\frac{32}{37}} \times S(t, M, f_{\mathrm{PBH}}, \psi)\,\psi(m_1)\psi(m_2), \qquad (17)$$

The total **number of detectable events** during a certain observation window is

$$N_{\mathrm{det}} = \int df_{\mathrm{in}} \int dz \frac{1}{(1+z)} \frac{dV_c}{dz} \frac{dn_b(t(z), d(z), f_{\mathrm{in}})}{df_{\mathrm{in}}} \times \Theta(\hat{\rho}(f_{\mathrm{in}}, z) - \hat{\rho}_{\mathrm{th}})$$

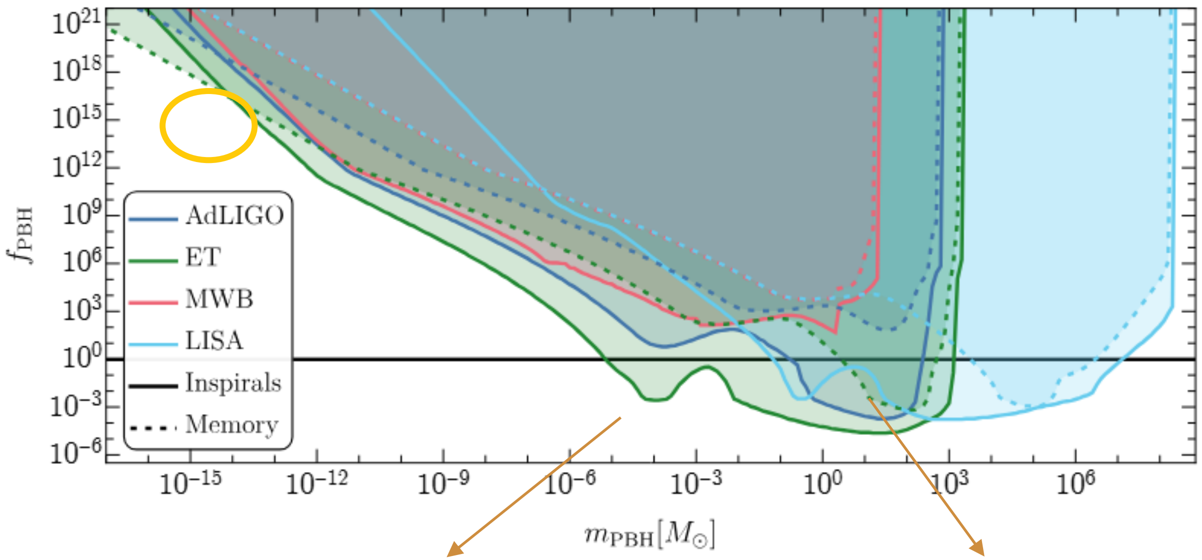


Many binary emitting **quasi-monochromatic GWs** in their **early inspiral**

Inspiral and memory probe **different stages** of the binary evolution

GW memory and PBH Bound

Constraints on the **fraction of PBH** from GW detection for one year of observation time requiring $N(f_{PBH}) > 1$



Effect of the over density of dark matter in the solar system

The memory can also probe value $\boldsymbol{f_{PBH} < 1}$

Inspiral signals outperform memory in SNR

Memory **becomes competitive only for extreme, out-of-band mergers,** though detection would require **unrealistically high PBH abundances**.

Memory is a promising target for sources lacking a strong inspiral phase (e.g., PBH encounters, hyperbolic flybys, EMRIs, cosmic strings)

Conclusions

- Gravitational memory is close to detection, we start exploring its phenomenology in beyond GR theories with full numerical waveforms
- The effect and the modification in the tensor sector are small but potentially bring *complementary information*
- We show a generic mechanism to produce memory in additional gravitational polarization in binary merger whenever there is a charge reconfiguration
- More studies on modification of the memory in beyond GR or exotic compact objects
- *More accurate forecasts should be done to understand the inclusion of the memory in tests of GR*

Thank you!