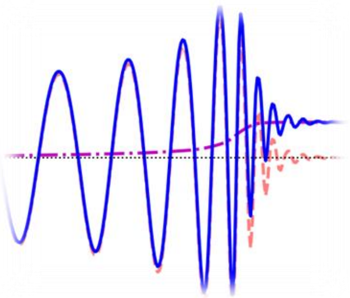
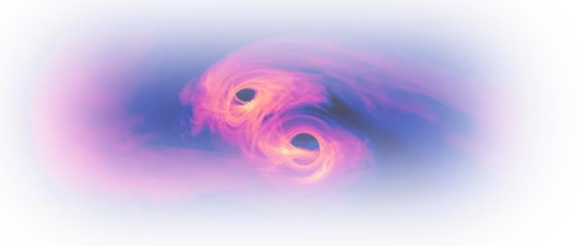




Observing GW Memory (with LISA)

Silvia Gasparotto (IFAE)

Based on Phys.Rev.D 107 (2023) 12 and 2406.09228

Universitat Autònoma de Barcelona

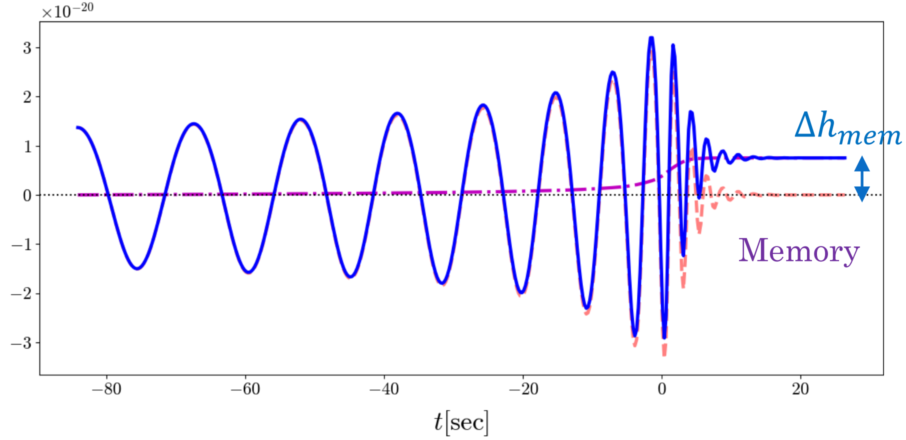
Generalitat de Catalunya
Departament de Recerca i Universitats

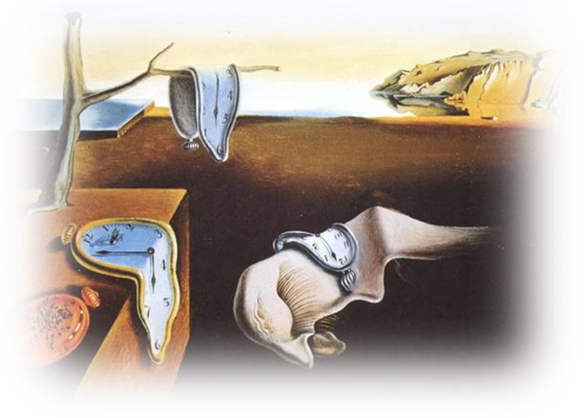
New Frontiers in Strong Gravity,
Benasque 2024

Institut de Física d'Altes Energies

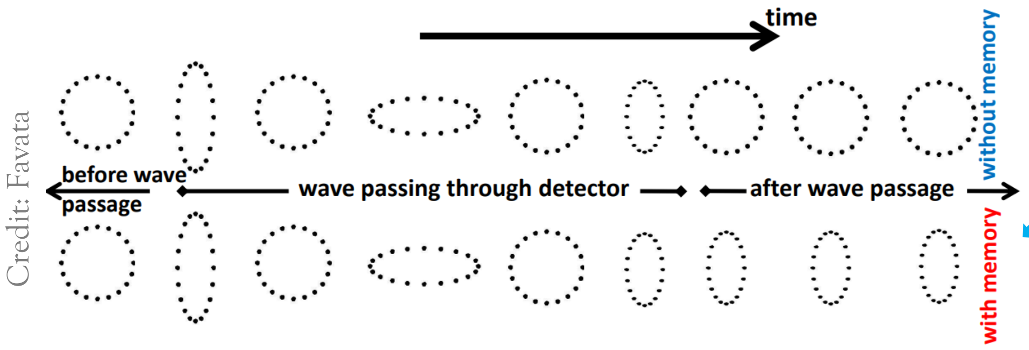
AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca

Gravitational Wave Memory





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



Persistent off-set of the GW strain

The effect is a net displacement between two comoving observers

Linear and Non-linear Memory

- **Linear memory** (Zeldovich & Polnarev'74, Brangisky & Grischchuk '85, Brangisky & Thorne '87)

Related to the motion of <u>unbound objects or radiation to infinity</u> (ex: neutrino emission in SN, hyperbolic objects etc)

- **Non-linear memory** (Christodoulou '91, Blanchet & Damour '92, Wiseman & Will '91...)

The GW itself sources GWs!

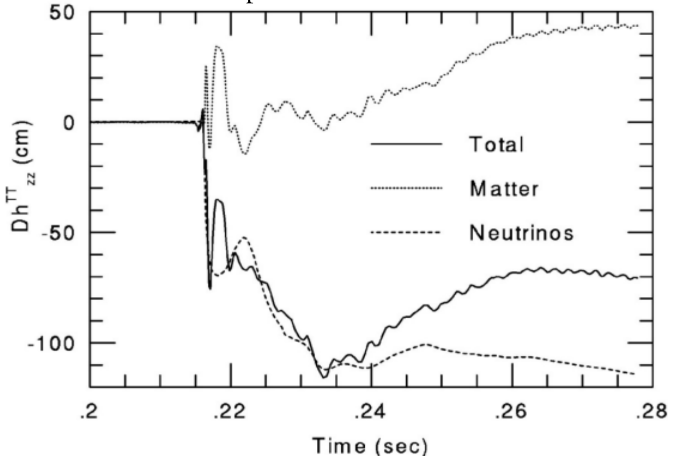
$$\partial^{\mu}\partial_{\mu}\bar{h}^{\ j,k} = 16\pi\left(T^{jk}_{matter} + T^{jk}_{GW}\right)$$

$$T^{jk}_{GW} = \frac{1}{R^2}\frac{dE_{GW}}{dtd\Omega}n_j n_k \sim \mathcal{O}(h^2)$$

Thorne Formula:

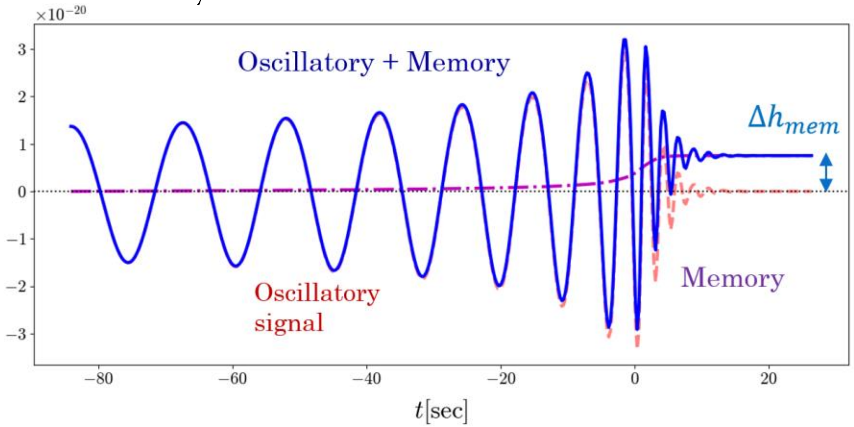
$$\delta\bar{h}^{TT}_{ij}(T_R) = \frac{4}{R}\int_{-\infty}^{T_R} dt' \left[\int \frac{dE_{GW}}{dt'd\Omega'}\frac{n'_j n'_k}{|1 - n'\cdot N|}\, d\Omega'\right]^{TT}$$

Core-Collapse SN

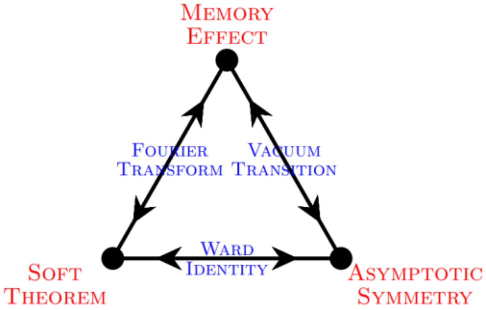


Credit: Burrows & Hayes '96

Binary Black Hole



Non-linear GW memory



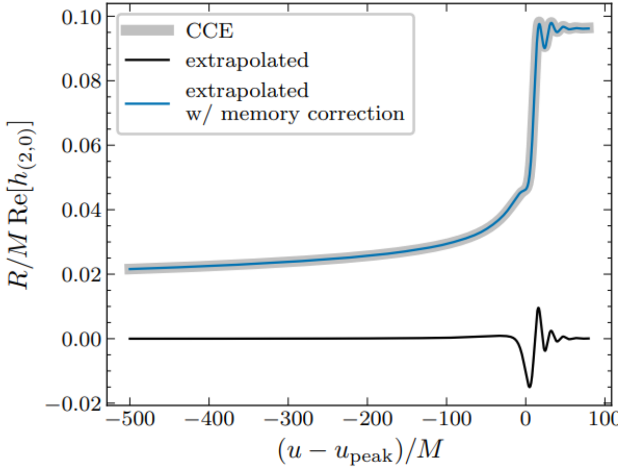
Why do we care?

- Non-linear prediction of GR, still undetected
- Relation with the BMS symmetries and the Soft theorem (Strominger and A. Zhiboedov 2016)
- Related to the super-translation symmetry, renamed "Displacement memory" , but new (subdominant) memories from other symmetries

See Alexander Grant talk

How do we compute it?

- Traditional waveforms don't present the memory → difficulties in extracting from NR simulations
- Memory can be computed from the energy flux of GW (GWMemory, BMS flux balance laws); the main (2,0)-mode
- First Surrogate model with the memory (J. Yoo et al. 2306.03148), with new Cauchy Characteristics Extraction (CCE) scheme NRHybSur3dq8_CCE



Detecting GW memory

Earth-based interferometers

- Ligo-Kagra-Virgo: no detection so far.

  Estimated O(2000) sources to claim detection

  (1911.12496,2105.02879,2210.16266,2404.11919)

- Einstein Telescope & Cosmic Explorer: $O(1)\ yr^{-1}$ (2210.16266)

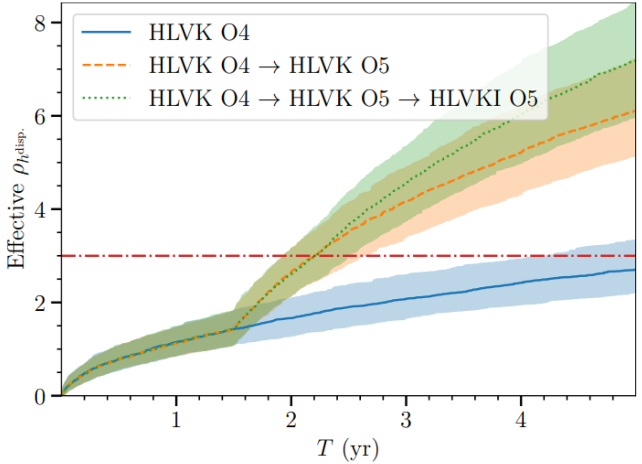
Space-based interferometers

- LISA: previous prospects 1906.11936, updates H. Inchauspé & S.Gasparotto et al. 2406.09228

- TianQin: 2207.13009,2401.11416

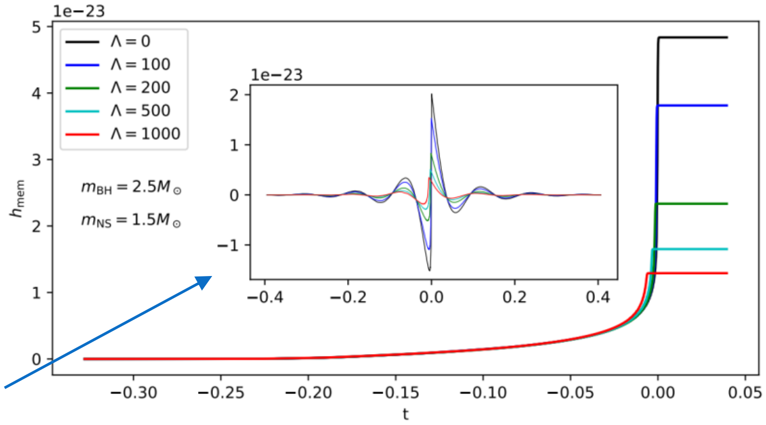
PTA: Search for burst-like signal with memory as mergers of SMBH $M \sim 10^8 M_\odot$ (0909.0954, 2307.13797)

Others???



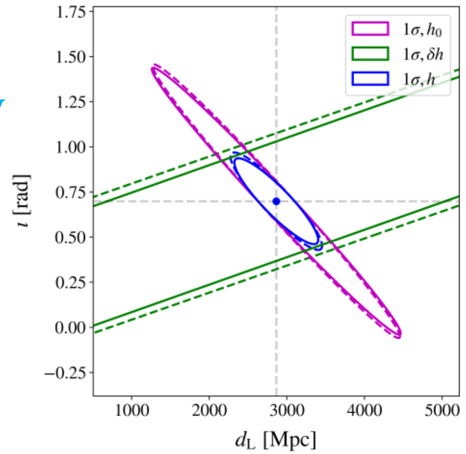
Credit: A. M. Grant & D.A.Nichols

In ground-based interferometers, we don't observe the persistent off-set, high-passed signal



"Leveraging gw memory to distinguish NS-BH binaries from BH binaries" 2110.1117

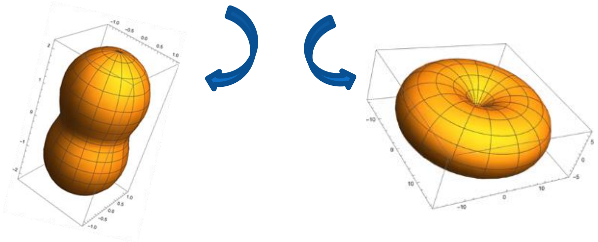
Enhancing parameter estimation with the memory

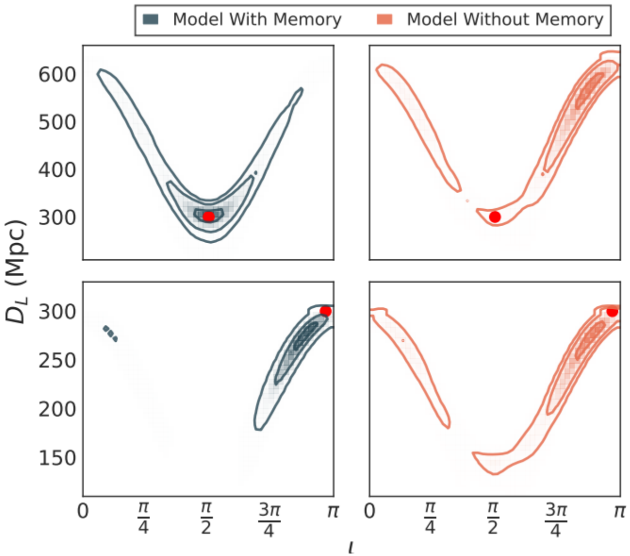


- Importance of adding the (2,0)-mode to the waveform

$$h_{+,0PN} = \left[-(1+\cos^2\iota)\cos 2\Phi(t) + \frac{1}{96}\sin^2\iota(17+\cos^2\iota)\right]\frac{2\eta M(M\omega(t))^{2/3}}{R}$$

Can the memory break the luminosity distance-inclination degeneracy?





- Results for LISA: Gasparotto et al. 2301.13228 (Fisher matrix)
- Results for (Advanced) LIGO: 2403.00441 (Bayesian)

Common outcome:

- Memory extends the signal at a lower frequency, which helps for short inspiral and almost out-of-band sources

Credit: Yumeng Xu et al. 2403.00441

Measuring GW memory with LISA

Based on 2406.09228 with H. Inchauspé, D. Blas, L. Heisenberg, J. Zosso and S. Tiwari.

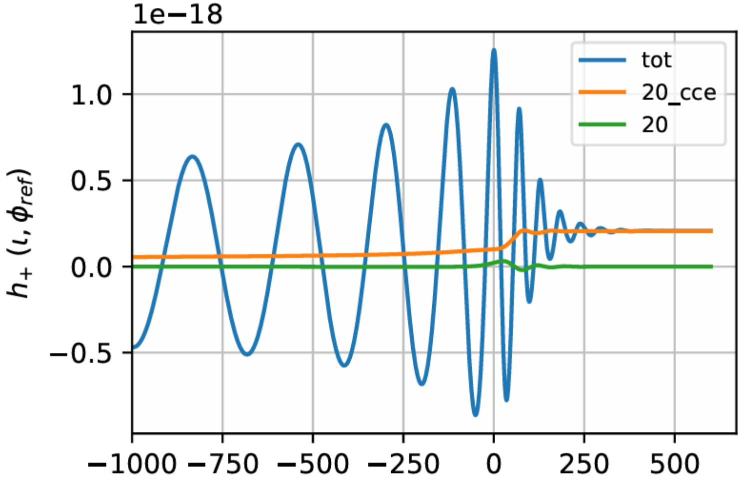
Part of the *Ringdown* collaborative projects of the LISA FPWG.

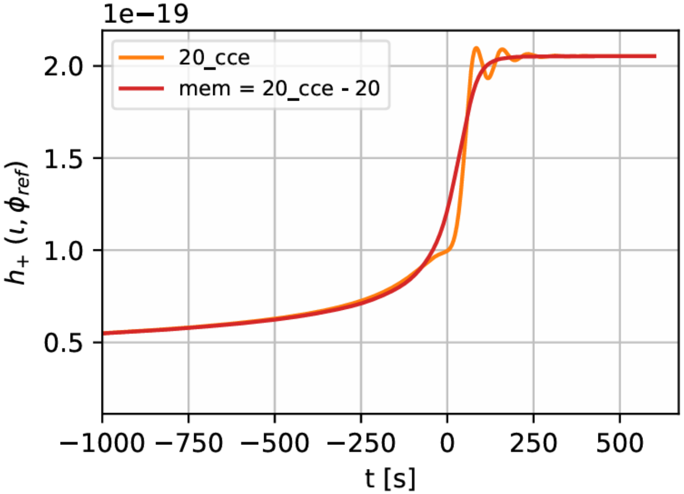
How is the imprint of the GW memory left in the LISA detector?

How do we separate the memory from the non-memory signal?

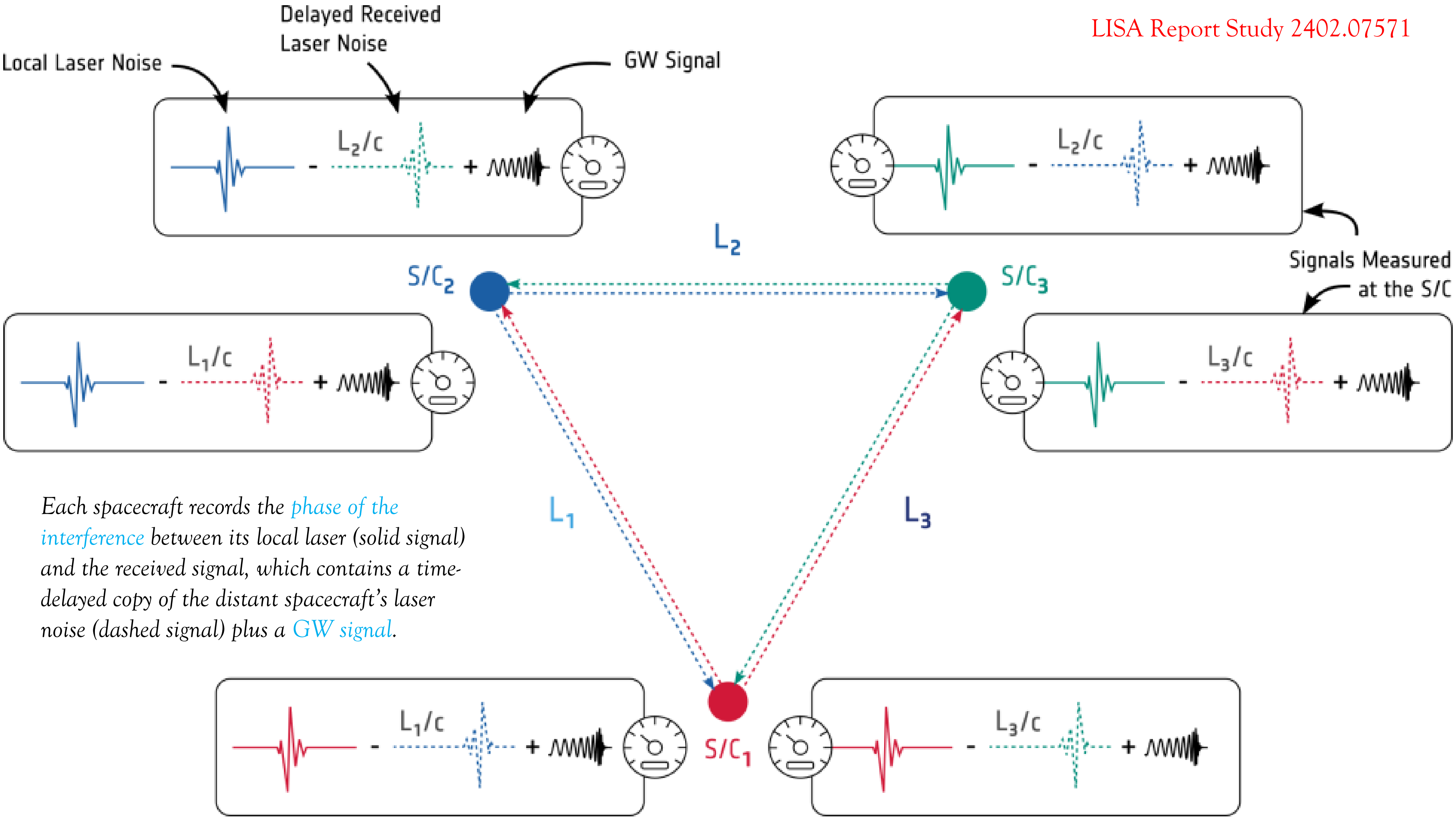
What is the scientific reach of LISA for the GW memory?

We simulate the full time-domain response of the detector down to the TDI (Time-delay-Interferometry) data streams → a combination of the data stream at different edges of LISA





LISA Report Study 2402.07571



Each spacecraft records the phase of the interference between its local laser (solid signal) and the received signal, which contains a time-delayed copy of the distant spacecraft's laser noise (dashed signal) plus a GW signal.

TDI imprint of GW memory

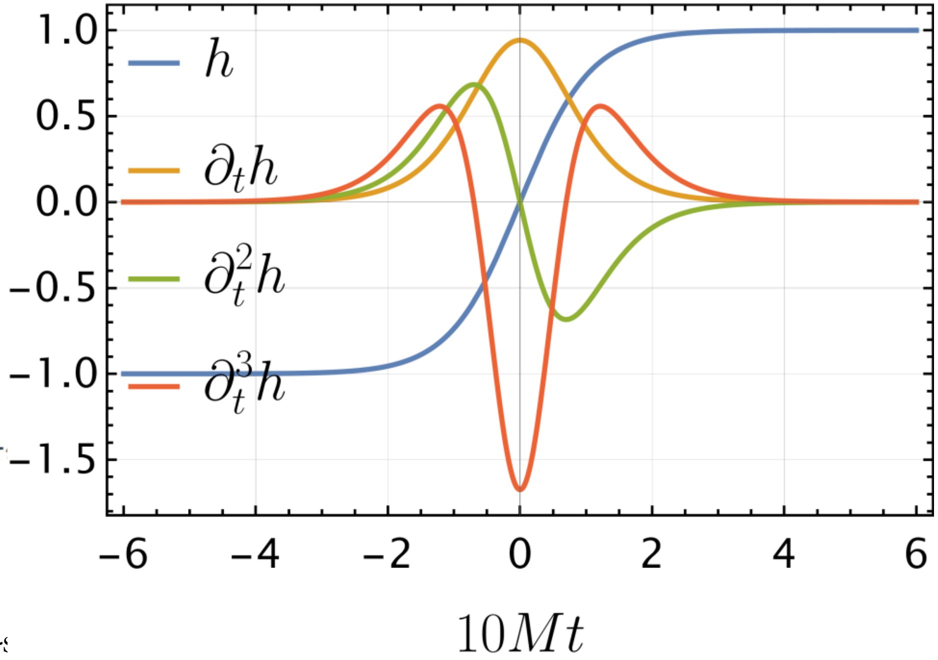
$$X_2 = X_{1.5} + \mathbf{D}_{13121}y_{12} + \mathbf{D}_{131212}y_{21} + \mathbf{D}_{1312121}y_{13} + \mathbf{D}_{13121213}y_{31} - \left[\mathbf{D}_{12131}y_{13} + \mathbf{D}_{121313}y_{31} + \mathbf{D}_{1213131}y_{12} + \mathbf{D}_{12131312}y_{21}\right],$$

with

$$X_{1.5} = y_{13} + \mathbf{D}_{13}y_{31} + \mathbf{D}_{131}y_{12} + \mathbf{D}_{1312}y_{21} - \left(y_{12} + \mathbf{D}_{12}y_{21} + \mathbf{D}_{121}y_{13} + \mathbf{D}_{1213}y_{31}\right).$$

$$\mathbf{D}_{ij}x(t) = x(t - L_{ij}(t)) \xrightarrow{FT} \tilde{\mathbf{D}}_{ij}\tilde{x}(f) = \tilde{x}(f)\, e^{-2\pi}$$

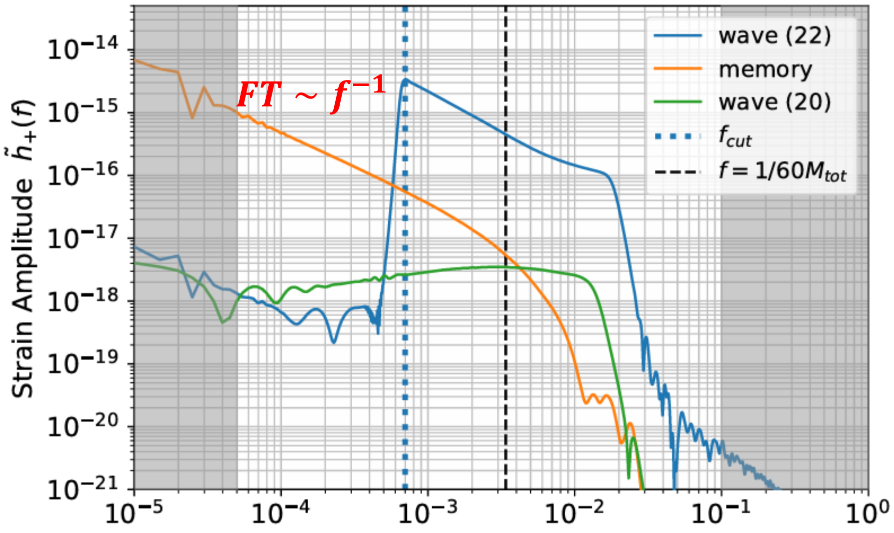
Delay operator

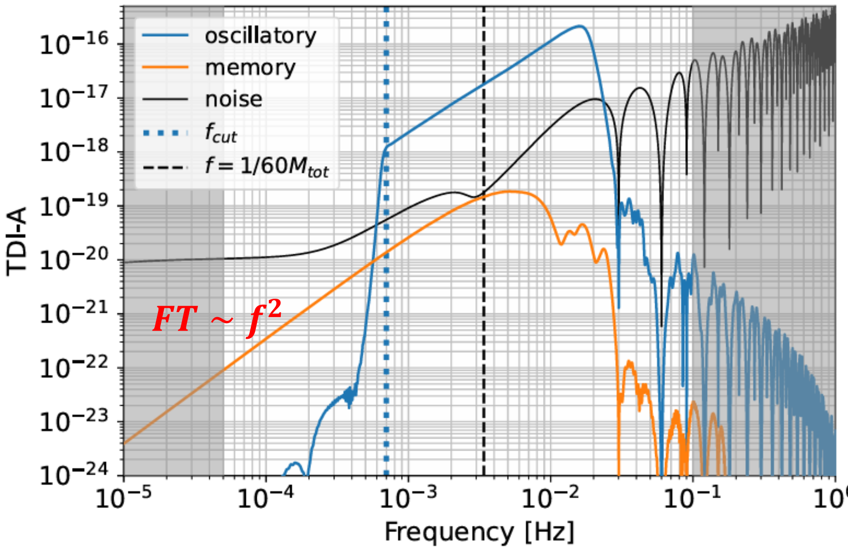


Burst-like signal: We don’t observe the persistent off-s
the memory, but just its time-variation $X \propto \partial^3 h$

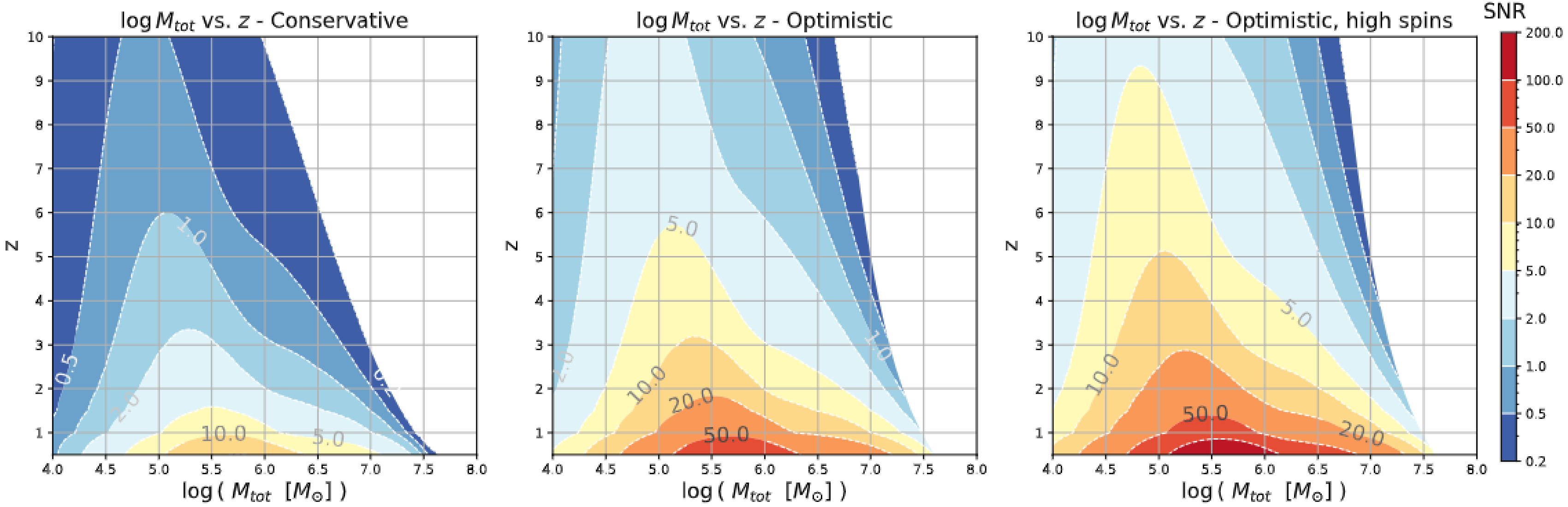
Time domain vs Frequency domain

Fourier Transform of a step like function $\sim f^{-1}$ $\rightarrow$ Extends the signal at lower frequencies





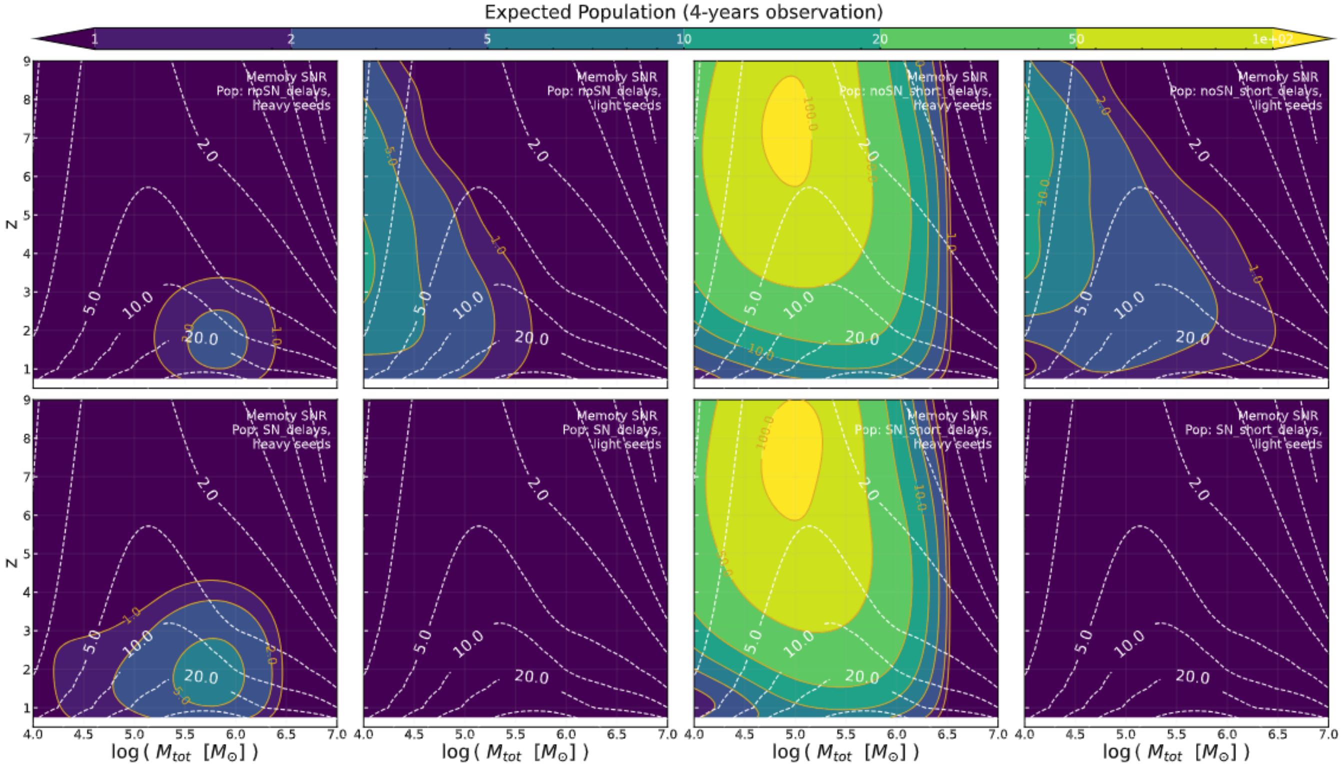
Scientific Reach of LISA: Memory Waterfall Plots



Baseline	q	χ	inclination ι [rad]	lat. β [rad]	long. λ [rad]	pixel p
1. Conservative	2.5	0.0	1.047	0.62	0.20	145
2. Optimistic	1.0	0.0	1.571	0.52	3.24	192
3. Opt. & Spin.	1.0	0.8	1.571	0.52	3.24	192

Astrophysical population models

Population from Barausse et al. 2020



8 different astrophysical models

- Initial Seed: Light vs Heavy
- SN Feedback: Yes or No
- Different delay model on the SMBH merger

Results for the optimistic baseline scenario

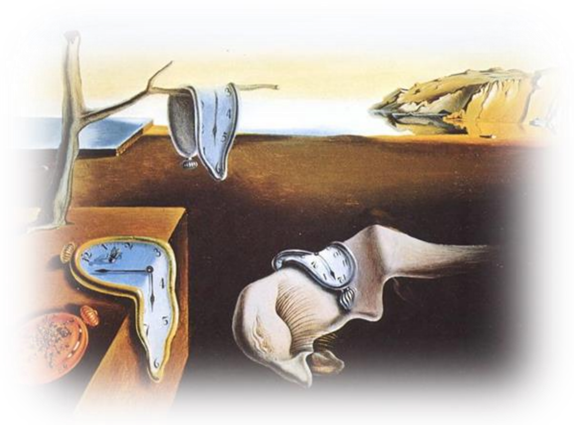
Discussion and Future Directions

- GW memory as a powerful tool for testing GR in a strong regime
  - Which kind of modifications do we expect?
  - Can we probe additional channels of radiation?
  - Can we use GW memory to guide us in understanding the underlying theory of gravity and its asymptotic symmetries?

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

L.Heisenberg et al 2303.02021

- Consequences on the posteriors of the GW signal
- New ideas to look for the GW memory (stochastic background?)



Thank you for your attention!

Time-Frequency representation

Oscillatory and memory signals have very separate time-frequency representation.
Can we use this to separate the two?

Look at the different scales!