

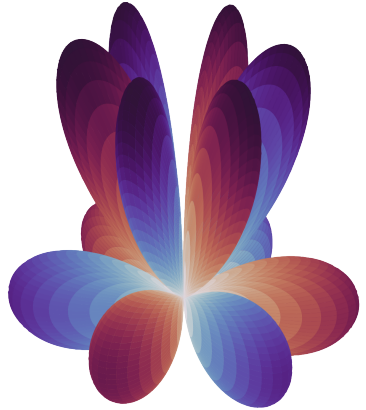
Memory Effect from Neutron Star Merger Counterparts

Detectability in Next-Generation Detectors

Thomas Brabant

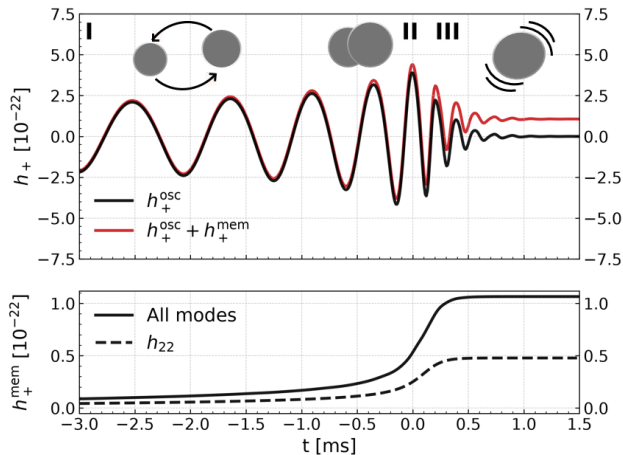
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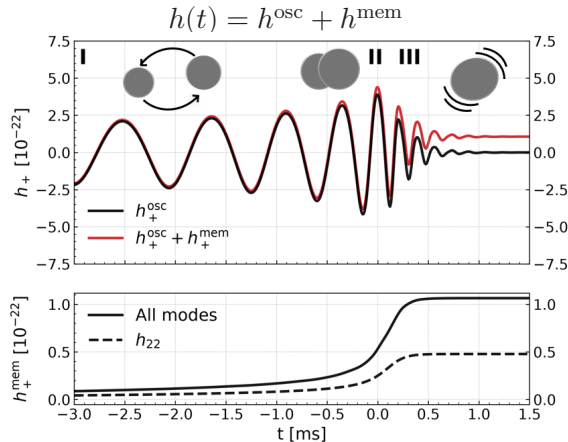
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- 1 The Memory Effect
- 2 A Case Study
- 3 Detectability in 3G detectors
- 4 Conclusion & Perspectives



The Gravitational-Wave Memory Effect

- **Definition:** A permanent change in the spacetime metric predicted by General Relativity



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$$h(t) = h^{\text{osc}} + h^{\text{mem}}$$

The nature of this energy loss produces *two types of memory effects*:

- 1 **Nonlinear memory:** sourced by GW emission

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- **Challenge:** Extremely difficult to detect → low frequency and low amplitude
- **Solution ?** Next-generation detectors such as **ET** and **LISA**

In a multimessenger context ?!

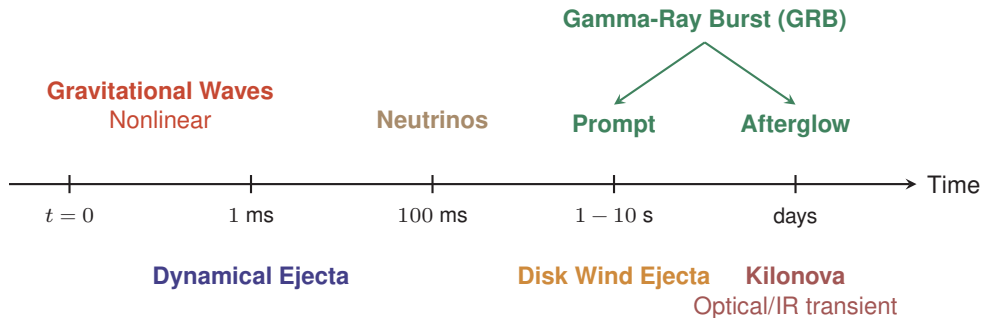
Recall: linear memory arises from the anisotropic emission of unbound matter or radiation

- Hyperbolic encounters [Zel'dovich & Polnarev (1974)]
- Gamma-ray bursts [Sago et al. (2004), Birnholtz & Piran (2013)]
- Anisotropic ejection of matter (supernovae) [Mukhopadhyay et al. (2021)]

In binary neutron star (BNS) mergers, we expect many sources of memory, with distinct amplitudes and timescales !

Multimessenger Counterparts and Their Memory Signature

BNS mergers are rich multimessenger sources. The different emissions span **a wide range of timescales**:



Focus of the Work

Two directions:

- 1 A case study:** GW170817 – GRB170817A – AT2017gfo
 - The first and only multimessenger BNS event to date
 - Allows us to combine all counterparts in a single, realistic scenario

- 2 A population study:** focus on GRB memory
 - How does the memory signal vary across a synthetic population of GRBs?
 - Which configurations are most promising for detection?

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 - The first and only multimessenger BNS event to date
 - Allows us to combine all counterparts in a single, realistic scenario **Detectable ?**
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Methods for Modeling the Memory Effect

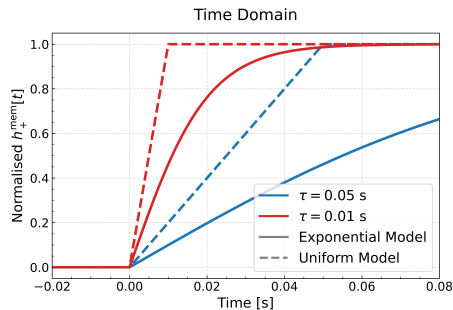
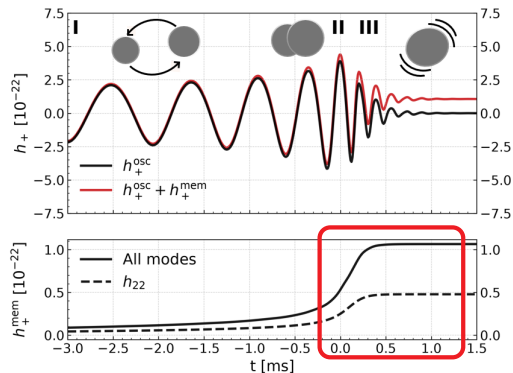
Nonlinear Memory

- Modeled using the **GWMemory** Python package
- Applied to a **GW170817-like** case
- Uses numerical relativity surrogates (NRSur7dq2) with modes up to $\ell \leq 4$

Linear Memory

- Modeled using **two different methods**:
 - 1 **Toy-Model**: Phenomenological approach using analytical functions (ejecta and GRB)
 - 2 **Simulations**: Extracting numerical data from hydrodynamical models (neutrinos and kilonova)

Linear Memory: A Toy-Model Approach



- Inspired by the jump of the *nonlinear* memory, we use a toy-model for the *linear* memory of ejecta/GRB using **two step functions** (uniform and exponential)

Toy-Model: Amplitude Estimates

Ejecta (Dynamical & Wind)

$$\Delta h = \frac{2M_{\text{ej}}v_{\text{ej}}^2}{r}$$

[Lopez et al. (2024)]

Gamma-Ray Burst (GRB)

$$\Delta h = \frac{2E\beta^2}{r}$$

[Sago et al. (2004), Birnholtz & Piran (2013)]

Major Simplification

We use a *point-particle assumption* (matter ejected radially as a single block)

→ **This overestimates the memory effect!**

Linear Memory: Using Simulations

We extract the **luminosity** $L(\Omega, t)$ directly from numerical simulations to estimate the memory effect

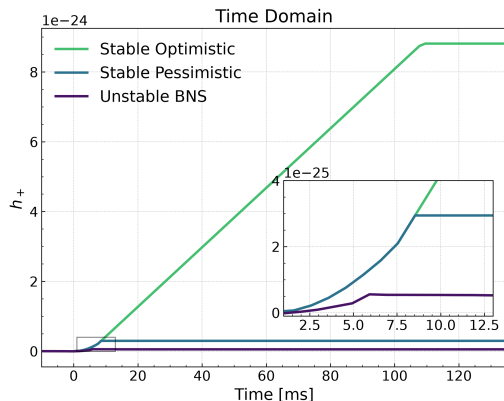
1. Neutrinos

■ Evaluated across **2 scenarios**:

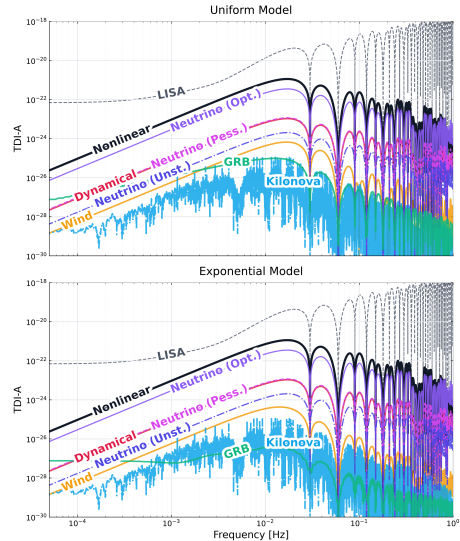
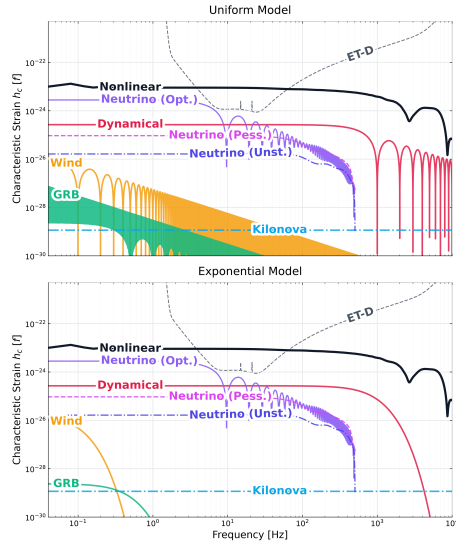
- 1 Long-lived neutron star $\mathcal{O}(100 \text{ ms})$
- 2 Prompt collapse into a black hole $\mathcal{O}(\text{ms})$

2. Kilonova

■ We use radiative transfer simulations to extract the anisotropic photon flux over $\mathcal{O}(\text{days})$



Case study: ET & LISA



Conclusion & Perspectives

Main Findings

- **First combination of all expected BNS memory** sources across ET and LISA bands
- Total signal should be **detectable by ET**, predominantly *driven by the nonlinear memory*; LISA signals remain undetectable
- Wind, GRB, KN (linear memory) are *negligible*, whereas **dynamical ejecta & neutrino detectability are more promising targets**
- Spoiler for the paper: *only nearby, sub-second duration, and highly energetic GRB* memory would be detectable in ET

Future Work

- Multi-Messenger Synergy: Using EM counterparts with GW memory to break parameter degeneracies

For more details, check the paper ! [Memory effect from neutron star merger counterparts]

GRB memory: Context and population

Goal: assess whether GRBs can produce a detectable memory effect in ET and LISA

Approach:

- Select 5 observed GRBs covering the extremes of the parameter space (energy, distance, duration)
- Generate two synthetic populations of 10 000 samples:
 - *unweighted*: uniform sampling over all ranges
 - *realistic*: same ranges, but weighted by observational priors
- Afterglow assumed to last $T_{\text{aft}} \sim 1$ day

Table 1: Properties of selected GRBs.

GRB	r [Mpc]	$E_{\gamma, \text{iso}}$ [erg]	E_K [erg]	T_{90} [s]
BOAT	724	1×10^{55}	3×10^{54}	600
250702B	7093	2.2×10^{54}	8×10^{54}	25 000
980425	36.9	6×10^{47}	1×10^{49}	30
170817A	40	3×10^{46}	$10^{52.2}$	2
211211A	350	7.6×10^{51}	5×10^{52}	51.37

Note: $\Gamma = 100$, $T_{\text{aft}} = 1$ day for all.



ET-D results: only extreme cases

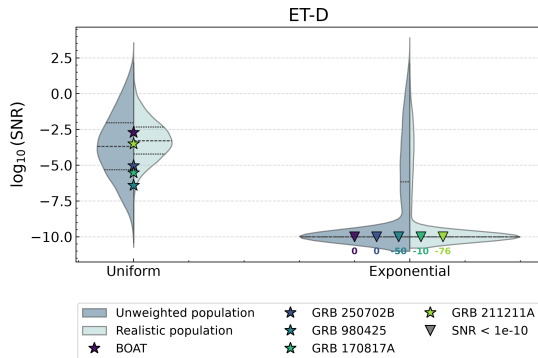
Detectable configurations ($\rho > 8$):

- *unweighted*: 246/10 000 (uniform), 122/10 000 (exponential)
- *realistic*: 17/10 000 (uniform), 6/10 000 (exponential)

Best candidates combine:

- 1 Prompt energy
 $\sim 10^{54-55}$ erg (BOAT-like)
- 2 Very short duration (sub-second)
- 3 Distance of ~ 100 Mpc

No observed GRB combines all three



ET-D results: only extreme cases

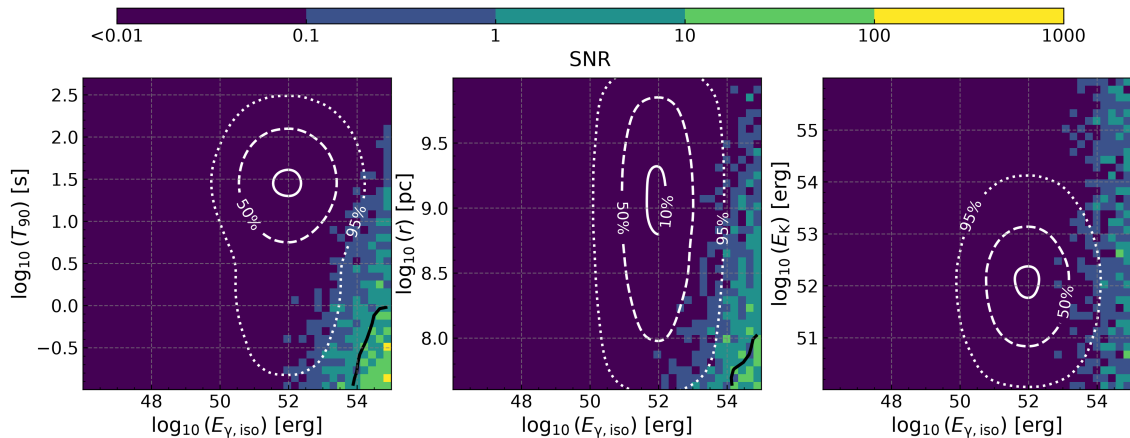


Figure 1: SNR heatmaps for ET (uniform model). White contours: realistic population (dotted 95%, dashed 50%, solid 10%). Black contour: $\rho = 8$ threshold.

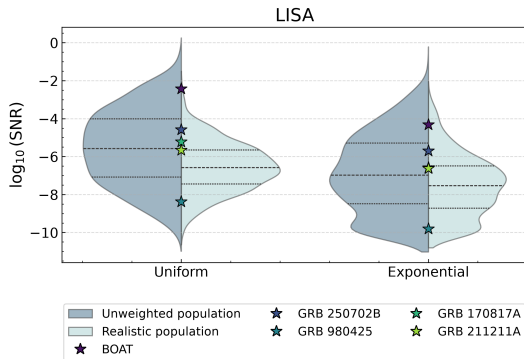
LISA results: no detection

Two main reasons:

- 1 The amplitude of the memory effect is too weak for these configurations
- 2 The afterglow (~ 1 day) is too long: signal falls outside LISA's optimal band

Extreme test case:

- $E_{\gamma, \text{iso}} = 10^{55}$ erg, $T_{90} = 100$ s,
 $E_{\text{aft}} = 10^{56}$ erg, $\Gamma = 1000$, $r = 40$ Mpc,
 $\theta = 0.001$ rad
- Maximum SNR for $T_{\text{aft}} \sim 100$ s, barely reaching $\rho \sim 10$
- Realistic afterglows (> 1 day) remain undetectable



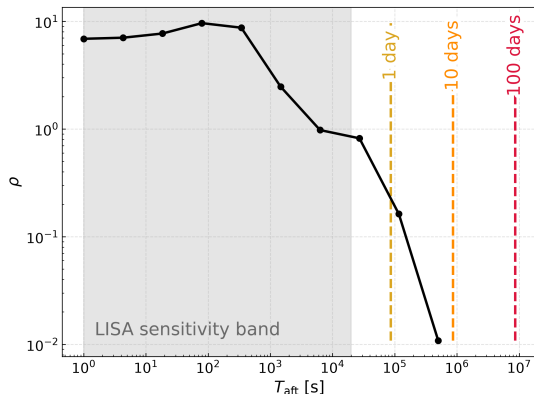
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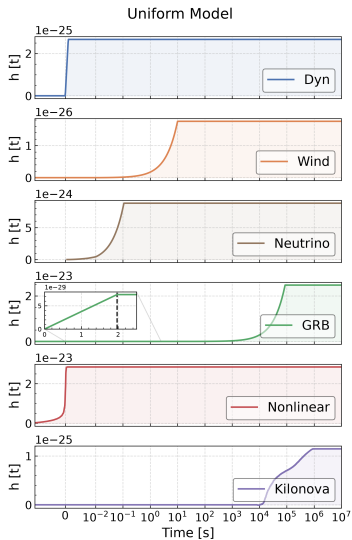


Case study: 17 August 2017

m_1	$1.46 M_\odot$
m_2	$1.27 M_\odot$
r	40 Mpc
θ	32°
$M_{\text{ej,dyn}}$	$0.005 M_\odot$
$v_{\text{ej,dyn}}$	$0.25 c$
τ_{dyn}	10^{-3} s
$M_{\text{ej,wind}}$	$0.01 M_\odot$
$v_{\text{ej,wind}}$	$0.05 c$
τ_{wind}	10 s
$E_{\gamma,\text{iso}}$	$3 \times 10^{46} \text{ erg}$
T_{90}	2 s
E_K	$10^{52.2} \text{ erg}$
t_{dec}	50 s
t_{break}	1 day



Case study: 17 August 2017



SNR Summary for GW170817: ET vs LISA

Einstein Telescope

Nonlinear	10.77
Dyn. ejecta (uni./exp.)	0.32 / 0.32
Wind ejecta (uni./exp.)	$4.0 \times 10^{-5} / < 10^{-9}$
GRB (uni./exp.)	$2.1 \times 10^{-6} / < 10^{-9}$
Kilonova	1.4×10^{-5}
Neutrinos (opt./pess.)	0.61 / 0.11
↳ Unstable	0.021
Total (no ν)	10.77
Total (opt. ν)	10.79

Dominated by nonlinear memory. Dyn. ejecta $\sim$ optimistic neutrinos

LISA

Nonlinear	2.3×10^{-2}
Dyn. ejecta (uni./exp.)	$2.2 \times 10^{-4} / 2.2 \times 10^{-4}$
Wind ejecta (uni./exp.)	$1.2 \times 10^{-5} / 1.4 \times 10^{-5}$
GRB (uni./exp.)	$7.6 \times 10^{-6} / 3.2 \times 10^{-7}$
Kilonova	1.1×10^{-6}
Neutrinos (opt./pess.)	$7.2 \times 10^{-3} / 2.4 \times 10^{-4}$
↳ Unstable	4.2×10^{-5}
Total (no ν)	1.87×10^{-2}
Total (opt. ν)	1.96×10^{-2}

All signals below detection threshold ($\rho \ll 3$)

Nonlinear Memory: Sourced by GW Energy

1. Metric Decomposition & Scale Separation

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}^L + h_{\mu\nu}^H \rightarrow \text{Hierarchy: } f_L \ll f_H \text{ (frequencies) and } L_H \ll L_L \text{ (lengths)}$$

- $\bar{g}_{\mu\nu}$: Static background (exact solution)
- $h_{\mu\nu}^H$: High-frequency perturbations
- $h_{\mu\nu}^L$: Low-frequency perturbations

More details in [Zosso *et al.*, Phys. Rev. D 113, 104033 (2026)]



Nonlinear Memory: Sourced by GW Energy

2. Isaacson's Equations of Motion (Leading Order)

Application of multi-scale analysis to Einstein's equations:

$$\text{High Frequency: GWs} \longrightarrow G_{\mu\nu}^{(1)}[h^H] = 0 \implies \square h_{\mu\nu}^H = 0$$

$$\text{Low Frequency: Source term} \longrightarrow G_{\mu\nu}^{(1)}[h^L] = -G_{\mu\nu}^{(2)}[h^H] \equiv 16\pi G t_{\mu\nu}[h^H]$$

with the effective energy-momentum tensor of GWs:

$$t_{\mu\nu}[h^H] = \frac{1}{32\pi G} \langle \partial_\mu h_H^{\alpha\beta} \partial_\nu h_{\alpha\beta}^H \rangle$$

Spacetime averaging operator $\langle \dots \rangle$ over short scales

More details in [Zosso *et al.*, Phys. Rev. D 113, 104033 (2026)]



Nonlinear Memory: Sourced by GW Energy

3. Asymptotic Resolution & Memory Effect

Gauge fixing (TT) $\rightarrow$ Wave equation with effective source:

$$\square h_{\mu\nu}^L = -16\pi G t_{\mu\nu}[h^H]$$

$\Downarrow$ Resolution via retarded Green's function ($u \equiv t - r$) and limit to future null infinity $\Downarrow$

Integration of cumulative energy flux $\rightarrow$ **Nonlinear Memory Effect:**

$$h_{ij}^{TT}(u, r, \Omega) = \frac{4G}{r} \int_{-\infty}^u du' \int d\Omega' \left(\frac{dE}{du' d\Omega'} \right) \left[\frac{n'_i n'_j}{1 - \vec{n}' \cdot \vec{n}} \right]^{TT}$$

More details in [Zosso *et al.*, Phys. Rev. D 113, 104033 (2026)]



GRB Memory: Impact of the Jet Opening Angle

Point-particle model (previous work):

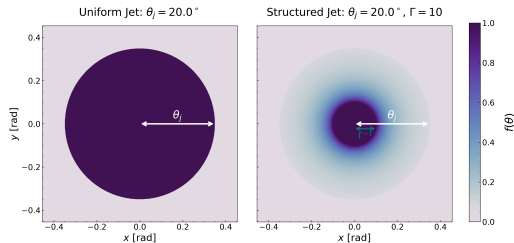
- Uses the *isotropic* energy $E_{\gamma, \text{iso}}$
- No jet geometry: the GRB is treated as a single point-particle
- Gives an **upper limit** on the memory amplitude

1 True jet energy:

$$E_{\text{jet}} = E_{\text{iso}} (1 - \cos \theta_j)$$

2 Jet geometry

- *Top-hat*: energy uniform in the cone.
- *Structured*: energy concentrated at the core



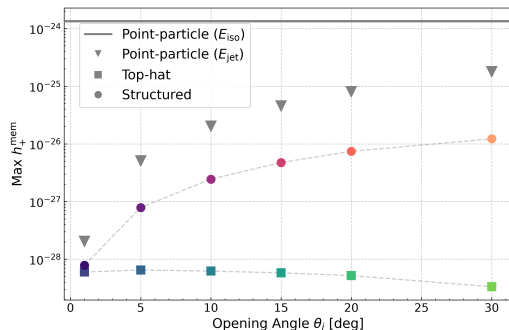
$$f(\theta) = \begin{cases} 1 & \theta < \Gamma^{-1} , \\ (\Gamma\theta)^{-2} & \Gamma^{-1} < \theta < \theta_j , \\ 0 & \theta > \theta_j , \end{cases}$$

[Birnholtz & Piran (2013), Phys. Rev. D 87, 123007]

GRB Memory: Amplitude vs Opening Angle

Four models compared (fixed $\Gamma = 100$, $\theta_v = 0.1$ rad):

- **Point-particle with E_{iso}** (grey dashed): constant, sets the upper limit
- **Point-particle with E_{jet}** : modulated by $(1 - \cos \theta_j)$, strongly reduced at small θ_j
- **Top-hat jet**: energy uniform, destructive interference reduces the amplitude
- **Structured jet**: energy concentrated at the core, stronger memory than top-hat



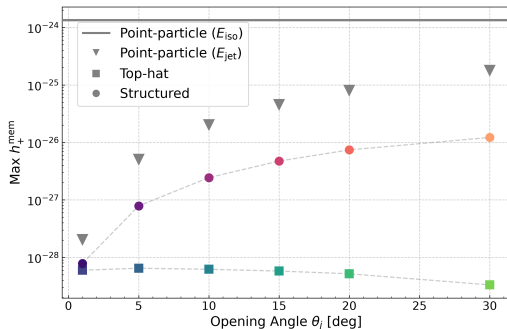
[Birnholtz & Piran (2013), Phys. Rev. D 87, 123007]



GRB Memory: Amplitude vs Opening Angle

Key trends:

- The amplitude **increases with** θ_j : more energy inside the cone
- Interference effects become **more destructive** for wider jets
- Structured jets are up to $\sim 350\times$ stronger than top-hat for large θ_j



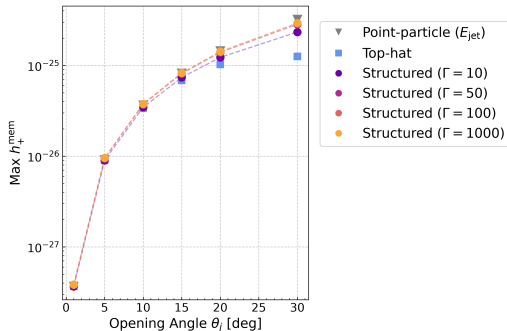
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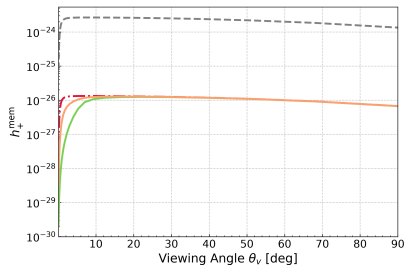
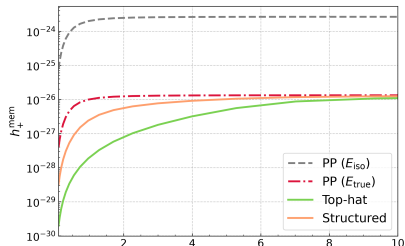


GRB Memory: Amplitude vs Viewing Angle

Two regimes:

- **On-axis** ($\theta_v \rightarrow 0$): the observer is aligned with the jet axis
 - Contributions from different parts of the jet **interfere destructively**
 - The memory amplitude vanishes
- **Off-axis** ($\theta_v > 0$): anti-beaming effect
 - The signal peaks at $\theta_v \sim \theta_j$
 - Then decays smoothly for larger angles
 - At very large angles, the signal stabilizes to a constant plateau

The fall-off towards the jet axis is slow: each point-particle quadrupole is broad. So even within the γ -ray cone, a non-negligible GW memory can be observed



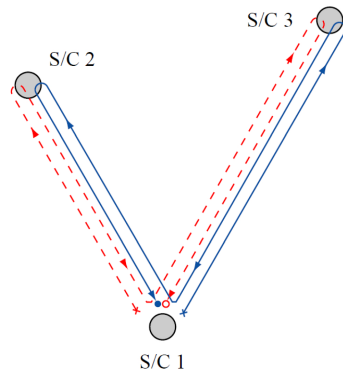
[Birnholtz & Piran (2013), Phys. Rev. D 87, 123007]



LISA: Time-Delay Interferometry

Why TDI?

- LISA is a constellation of 3 spacecraft, with 6 one-way laser links
- The raw single-link measurements are dominated by laser frequency noise, far above the GW signal
- TDI combines time-shifted copies of the 6 link signals to cancel the laser noise, forming virtual equal-arm interferometers (coherent noise)



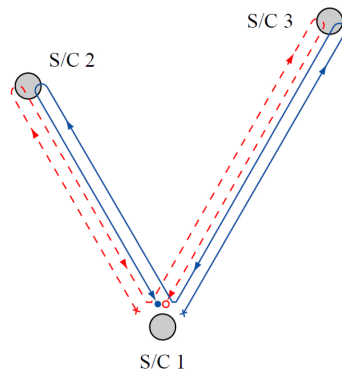
More details in [Inchauspé, H *et al.* (2024)]

LISA: Time-Delay Interferometry

From 6 links to 3 channels:

- XYZ Michelson-like combinations are built from delayed link signals (e.g., X uses links 12, 21, 13, 31)
- Rotated into the A, E, T basis via an orthogonal transformation:

$$\begin{pmatrix} A \\ E \\ T \end{pmatrix} = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$



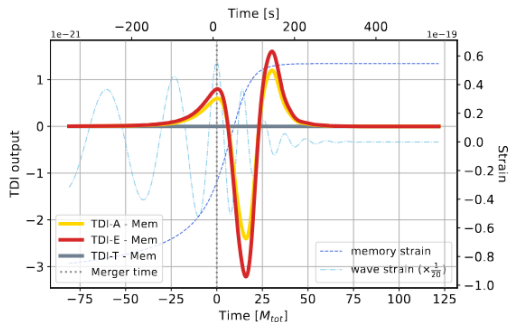
More details in [Inchauspé, H *et al.* (2024)]



LISA: Time-Delay Interferometry

Properties of A, E, T:

- A and E: two independent GW-sensitive channels, equivalent to two orthogonal Michelson interferometers
- T: a *null* channel. By construction, the GW response cancels at leading order:
 - In the ideal, equal-arm, noise-free case, T contains no GW signal
 - In practice, T is used as a diagnostic / veto channel: any excess power in T signals a non-GW artifact (instrumental glitch, laser noise residual, etc.)
 - The A/E/T basis is chosen so that the noise in A , E , T is nearly uncorrelated



More details in [Inchauspé, H *et al.* (2024)]

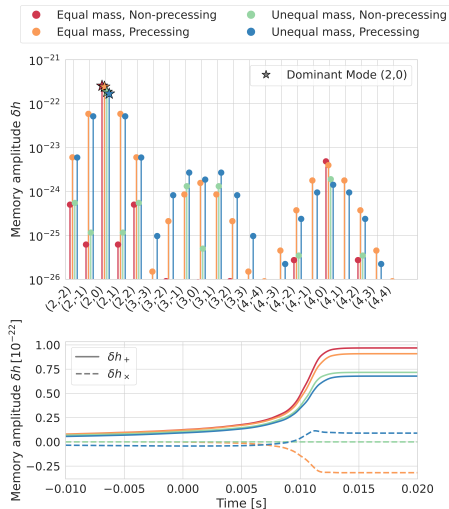


Nonlinear Memory: Multipolar Decomposition

One can decompose the strain into spin-weighted spherical harmonics:

$$h_+ - ih_\times = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} h_{\ell m}(t) {}_{-2}Y_{\ell m}(\theta, \phi)$$

The sum starts at $\ell = 2$: no monopole or dipole GW emission



Nonlinear Memory: Multipolar Decomposition

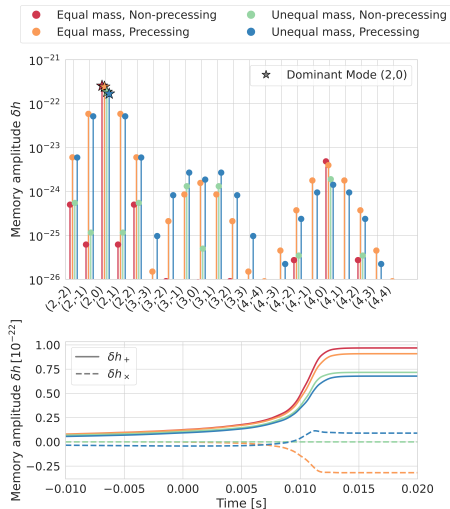
The memory becomes a sum over modes (ℓ, m) ,

$$h_{\ell m}^{\text{mem}} \propto \sum_{\ell', \ell'', m', m''} g_{mm'm''}^{\ell\ell'\ell''} \int_{-\infty}^{t_r} dt \dot{h}_{\ell'm'} \dot{h}_{\ell''m''}$$

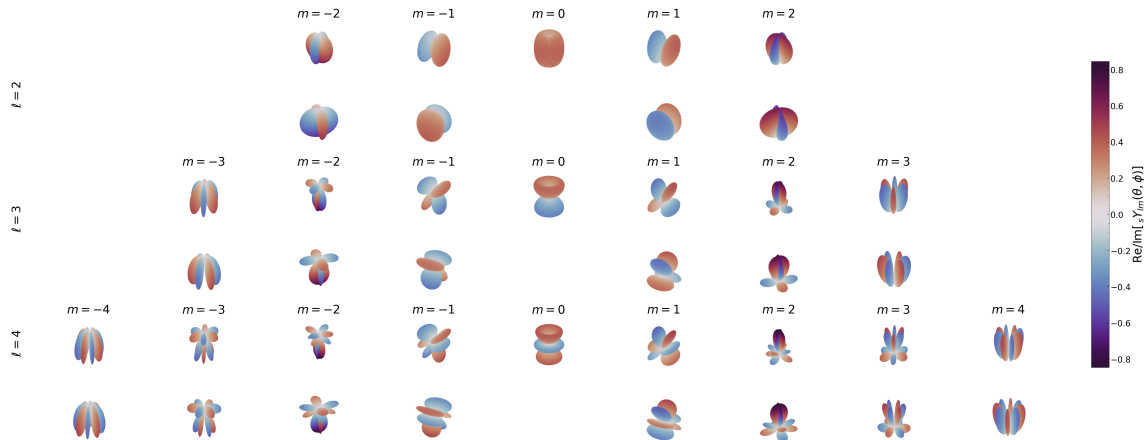
with

$$g_{mm'm''}^{\ell\ell'\ell''} = \int d\Omega {}_{-2}\bar{Y}^{\ell m} {}_{-2}Y^{\ell'm'} {}_{-2}\bar{Y}^{\ell''m''}$$

Numerical implementation through GWMemory
Python package [Talbot *et al.* (2018), (2019)]



Spin-weighted spherical harmonics



Toy-model boundaries

Component	Parameter	Min	Max
Dynamical ejecta	$\log_{10}(\text{Mass}) [M_{\odot}]$	-4	-2
	Velocity [c]	0.1	0.4
	$\tau_{\text{dyn}} [\text{ms}]$	1	10
Disk wind ejecta	$\log_{10}(\text{Mass}) [M_{\odot}]$	-3	-2
	Velocity [c]	0.1	0.2
	$\tau_{\text{wind}} [\text{s}]$	1	10
GRB prompt	$\log_{10}(E_{\gamma, \text{iso}}) [\text{erg}]$	46	55
	$T_{90} [\text{s}]$	0.1	10
GRB afterglow	$\log_{10}(E_K) [\text{erg}]$	50	56
	$T_{\text{aft}} [\text{days}]$	0.1	10

