

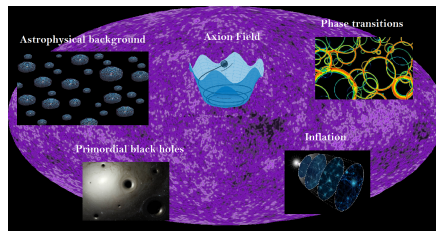
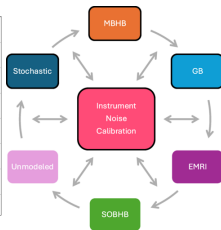
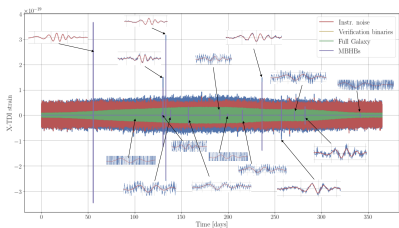
Separating the GW background components with LISA through anisotropies and time-frequency techniques

Giorgio Mentasti (APC, Paris)

October 6, 2026

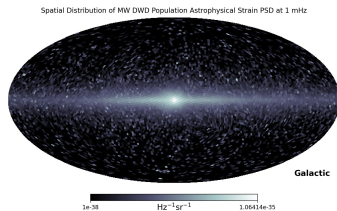
Global-fitting the stochastic background

- ▶ **Signal dominated:** tens of thousands of overlapping sources, and no stretch of data free of signals to learn the noise from
- ▶ **Global fit:** all the sources, in unknown number, and the noise, together (Littenberg & Cornish 2023; Katz+ 2025; Deng+ 2025)
- ▶ What is not resolved makes a **background:** astrophysical (Galactic and extragalactic binaries) and cosmological (phase transitions, cosmic strings, PBHs, inflation)
- ▶ The spectral shape alone is often not enough to tell them apart



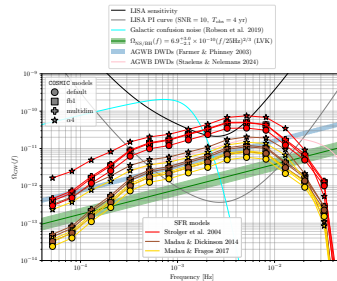
Backgrounds are searched for inside the global fit, and their skies help to tell them apart

Astrophysical backgrounds: Galactic and extragalactic



The white-dwarf binaries of the Milky Way at 1 mHz
[Rieck+, 2024]

- ▶ **Galactic:** tens of millions of white-dwarf binaries, $\sim 10^4$ resolved, the rest a foreground above the noise at $\sim 0.3\text{--}3$ mHz
- ▶ Anisotropic (disc and bulge) and yearly modulated: LISA's loudest background



Extragalactic double white dwarfs, several models;
Galactic foreground in cyan [Boileau+, 2025]

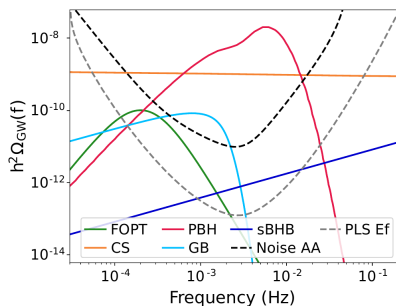
- ▶ **Extragalactic:** compact binaries all over the Universe, at mHz mostly double white dwarfs; SNR $\sim 100\text{--}1500$ in four years
- ▶ Nearly isotropic: its sky tells it from the Galaxy, not from a cosmological background

Two guaranteed foregrounds, with different skies: no cosmological search holds without them

Cosmological SGWB candidates

Early-universe backgrounds within reach, $h^2\Omega_{\text{GW}} \gtrsim 10^{-13}$
(arXiv:2507.05130):

- ▶ **First-order phase transitions:** a peak. The Standard Model has only a crossover, so a detection means new physics
- ▶ **Cosmic strings:** a nearly flat spectrum, down to $G\mu \sim 10^{-16}$
- ▶ **Primordial black holes:** the scalar-induced GWs of asteroid-mass PBHs, possibly all of the dark matter, peak in the band
- ▶ **Inflation:** only if enhanced on small scales
- ▶ The **anisotropies:** a LISA science objective itself (SO7)



Phase transition, cosmic strings, PBHs;
Galactic and stellar-mass BH foregrounds

[Colpi+, 2024]

Each candidate has its spectral shape: the first handle on the origin of a background

Modeling and search of an anisotropic background

- $g_{ab} = \eta_{ab} + h_{ab}$, summed over frequencies, directions and polarisations:

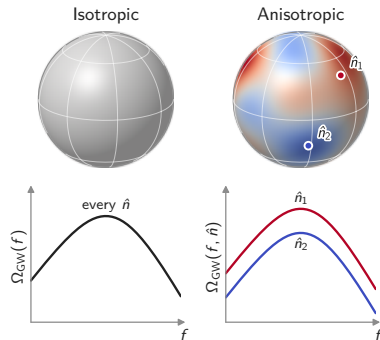
$$h_{ab}(t, \vec{x}) = \int df \int d^2 \hat{n} \underbrace{e^{2\pi i f(t - \hat{n} \cdot \vec{x})}}_{\text{plane wave}} \sum_{\lambda} \underbrace{h_{\lambda}(f, \hat{n})}_{\text{amplitude}} \underbrace{e_{ab}^{\lambda}(\hat{n})}_{\text{polarisation}}$$

- Zero mean, Gaussian, stationary, anisotropic:

$$\langle h_{\lambda}^*(f, \hat{n}) h_{\lambda}(f, \hat{n}) \rangle \propto \Omega_{\text{GW}}(f, \hat{n})$$

- If f and $\hat{n}$ are factorized, we can expand:

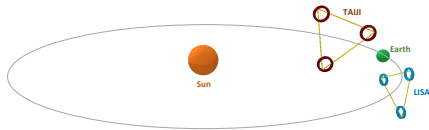
$$\Omega_{\text{GW}}(f, \hat{n}) = \Omega_0 \psi(f) \sum_{\ell m} \delta_{\ell m}^{\text{GW}} Y_{\ell m}(\hat{n})$$



Anisotropy exaggerated for the eye

An anisotropic background: an amplitude Ω_0 , a spectral shape $\psi(f)$ and a set of multipoles $\delta_{\ell m}^{\text{GW}}$

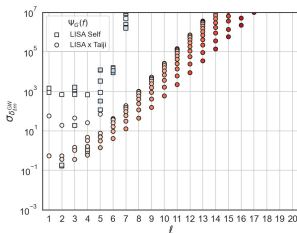
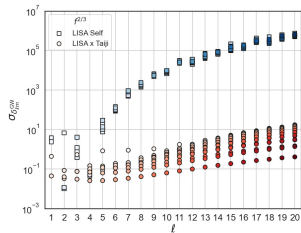
LISA+Taiji map-making: how well can we measure the $\delta_{\ell m}^{\text{GW}}$?



[Mentasti+, 2024]

- ▶ Taiji: LISA-like, $\sim 10^8$ km away. Independent noises, and a baseline ~ 40 times LISA's arms
- ▶ Correlators $C_{OO'}(f, t) = d_O(f, t) d_{O'}^*(f, t)$ between channels O, O' :

$$\langle C_{OO'}(f, t) \rangle \propto \Omega_0 \frac{\psi(f)}{f^3} \sum_{\ell m} \delta_{\ell m}^{\text{GW}} \mathcal{R}_{\ell OO'}(f, t)$$



- ▶ Fisher forecast: LISA $\times$ Taiji better up to $\ell = 20$, thanks to the baseline; LISA alone for $\ell = 2, 4$

Marginalised errors, Galactic map as fiducial, $\Omega_0 = 2 \times 10^{-11}$, $T_{\text{obs}} = 10$ yr. Left: $\psi \propto f^{2/3}$, a proxy for an extragalactic background; right: the Galactic spectrum $\psi_G(f)$ [Mentasti+, 2024]

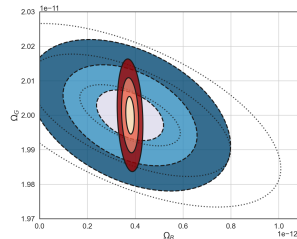
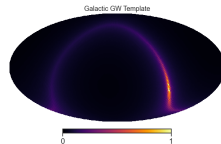
$|\delta_{\ell m}^{\text{GW}}| \lesssim 0.1$: no high-resolution maps, but angular template searches are possible

Disentangling the Galaxy and the background behind it

- ▶ Known Galactic template and spectra, two unknown amplitudes:

$$\Omega_{\text{GW}}(f, \hat{n}) = \Omega_G \psi_G(f) \sum_{\ell m} \delta_{\ell m}^{\text{gal}} Y_{\ell m}(\hat{n}) + \Omega_B \left(\frac{f}{f_0}\right)^{2/3}$$

- ▶ The Galaxy is modulated along the orbit, the isotropic background is not
- ▶ **LISA alone**: tightest, but only if the noise is known perfectly
- ▶ **LISA×Taiji**: wider, but blind to the noise; the time–frequency analysis beats the frequency-only one (dotted)



$$1, 2, 3\sigma; \Omega_G = 2 \times 10^{-11}, \\ \Omega_B = 3.78 \times 10^{-13}, 10 \text{ yr [Mentasti+, 2024]}$$

A background ~ 50 times weaker than the Galactic one at 1 mHz can be separated from it

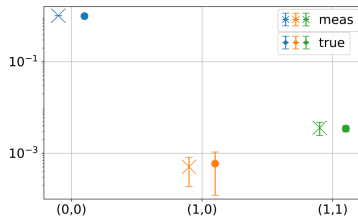
The kinematic dipole

- CMB: our motion, $\beta \simeq 1.2 \times 10^{-3}$, gives a dipole $\Delta T/T \simeq \beta$. For a smooth GW spectrum, with tilt n_Ω :

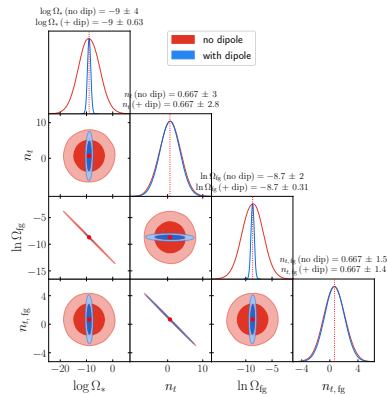
$$\Omega_{\text{GW}}(f, \hat{n}) \simeq \bar{\Omega}_{\text{GW}}(f) [1 + (4 - n_\Omega) \beta \hat{n} \cdot \hat{v}]$$

Steep spectra do *not* enhance it (Mentasti+ 2025)

- Extragalactic backgrounds share the CMB frame
- Measurable by LISA for strong backgrounds (Heisenberg+ 2024), it helps distinguishing SGWBs and a foreground



LISA: the $\ell \leq 1$ coefficients, reconstructed and injected [Heisenberg+, 2024]

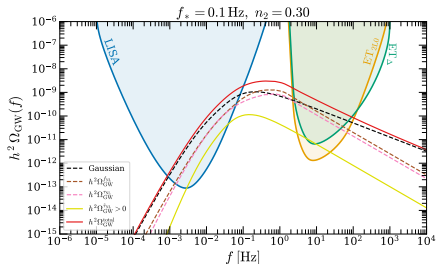


Primordial background plus a same-shape foreground without dipole: with the dipole (blue), $\sigma_{\log \Omega_*} = 4 \rightarrow 0.63$
[Fumagalli+, 2026]

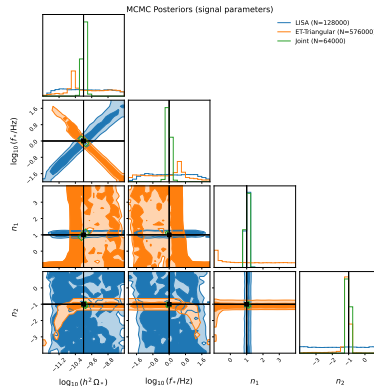
The dipole reveals the rest frame of a background, and helps tell a primordial one from a foreground

LISA×ET: one background, two bands

- ▶ LISA: 0.1 mHz–1 Hz; ET: a few Hz–kHz. Broad backgrounds span both
- ▶ A peak in the deci-Hz gap: LISA sees its rising tail, ET its falling one



Scalar-induced GWs, primordial non-Gaussianity



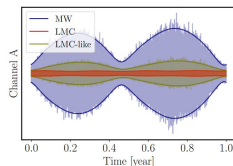
Broken power law, $h^2\Omega_* = 10^{-10}$ at $f_* = 1$ Hz, $n_1 = 1$, $n_2 = -1$. LISA (blue) fixes n_1 , ET (orange) n_2 , each leaving Ω_* and f_* degenerate; jointly (green) all four are measured [SGWB_LISA_ET, in prep.]

Together, LISA and ET measure the peak and both slopes, which neither pins down alone

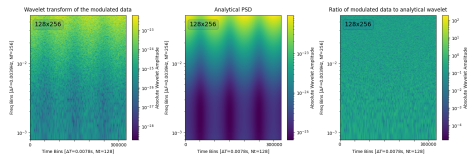
The power of the time–frequency domain

Stationary data: a diagonal covariance in frequency (Whittle). LISA's are not stationary:

- ▶ **Galactic foreground**, cyclostationary: its level changes by a factor ~ 2 in three months
- ▶ **Realistic orbits**: breathing arms. Response and noise drift, and A , E , T correlate
- ▶ **Gaps and glitches**: power leaks across frequencies
- ▶ **SGWB anisotropies**: time-dependent response to anisotropies $\delta_{\ell m}^{\text{GW}}$
- ▶ **The WDM transform**: pixels localised in time and frequency, $d[t] = \sum_{n,m} w_{nm} g_{nm}[t]$. Python tool, with Baghi, Burke, Speri, Vajpeyi: `wdm_transform`



Channel A over a year [Pozzoli+, 2025]



Modulated noise in the wavelet domain: data, analytical model, and their ratio

The time–frequency domain handles them all at once, with a covariance that stays diagonal

Conclusions

- ▶ LISA alone has poor angular resolution. LISA+Taiji do better, thanks to the longer baseline
- ▶ ... but still we can exploit known features (galactic templates, kinematics)
- ▶ In the time–frequency domain the Galactic foreground is easier to separate from an isotropic background
- ▶ The kinematic anisotropies tell the reference frame of each component

Follow-ups

- ▶ Kinematic anisotropies in the Mojito heavy simulated data: a LISA Consortium + DDPC project, now starting
- ▶ Intrinsic anisotropies, cross-correlated with the CMB
- ▶ Time–frequency approaches for non-stationarities and gaps
- ▶ LISA×ET (ongoing LISA Consortium + ET Consortium project)

Anisotropies and the time–frequency domain help tell the components of the background apart

Thank you!

Figure credits

Rieck+, 2024: arXiv:2308.12437, MNRAS 531, 2642

Boileau+, 2025: arXiv:2506.18390, A&A 702, A246

Colpi+, 2024: arXiv:2402.07571 (LISA Definition
Study Report)

Mentasti+, 2024: arXiv:2312.10792, JCAP (LISA and
Taiji)

Heisenberg+, 2024: arXiv:2401.14849, JCAP
(kinematic anisotropies)

Fumagalli+, 2026: arXiv:2604.08968, JCAP 09 (2026)
081

SGWB_LISA_ET: LISA $\times$ ET analysis code, in prep.

Pozzoli+, 2025: arXiv:2410.08274, PRD 111, 063005