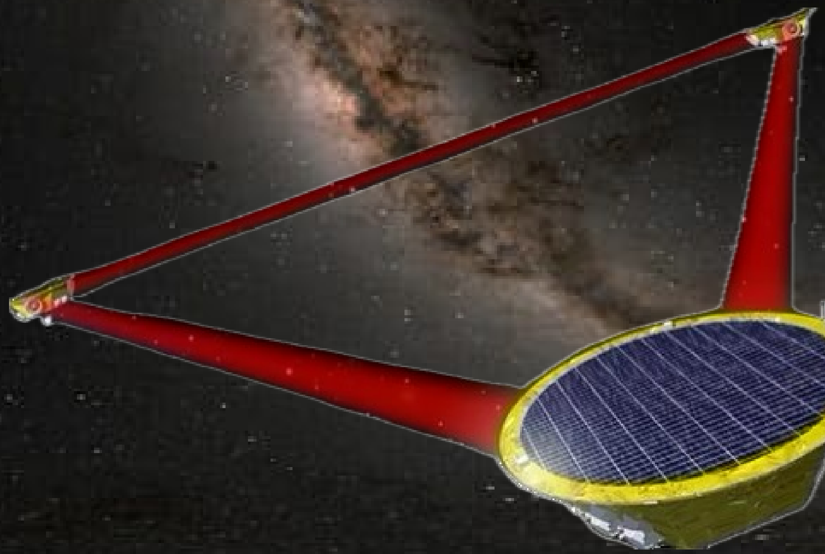
Milky Way structure and morphology from its gravitational wave signal

Federico Pozzoli (fpozzoli@uninsubria.it)
R.Buscicchio, A. Klein, V. Korol, A. Sesana, F. Haardt

Ten Years to LISA

UNIVERSITÀ DEGLI STUDI DELL'INSUBRIA
INFN



Introduction

Modelling galactic foreground

Benefits:

- Reducing biases in reconstructing stochastic and individual signals.
- Extracting astrophysical information (binary population, Milky Way assembly, and structure).

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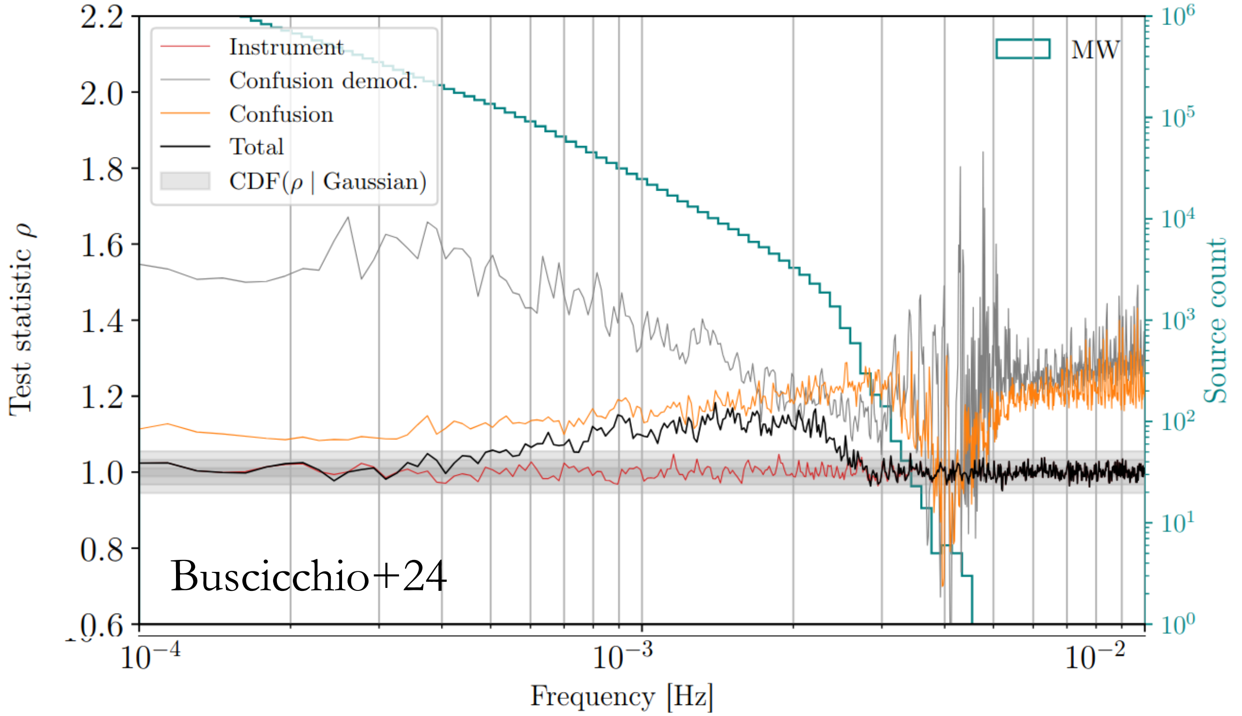
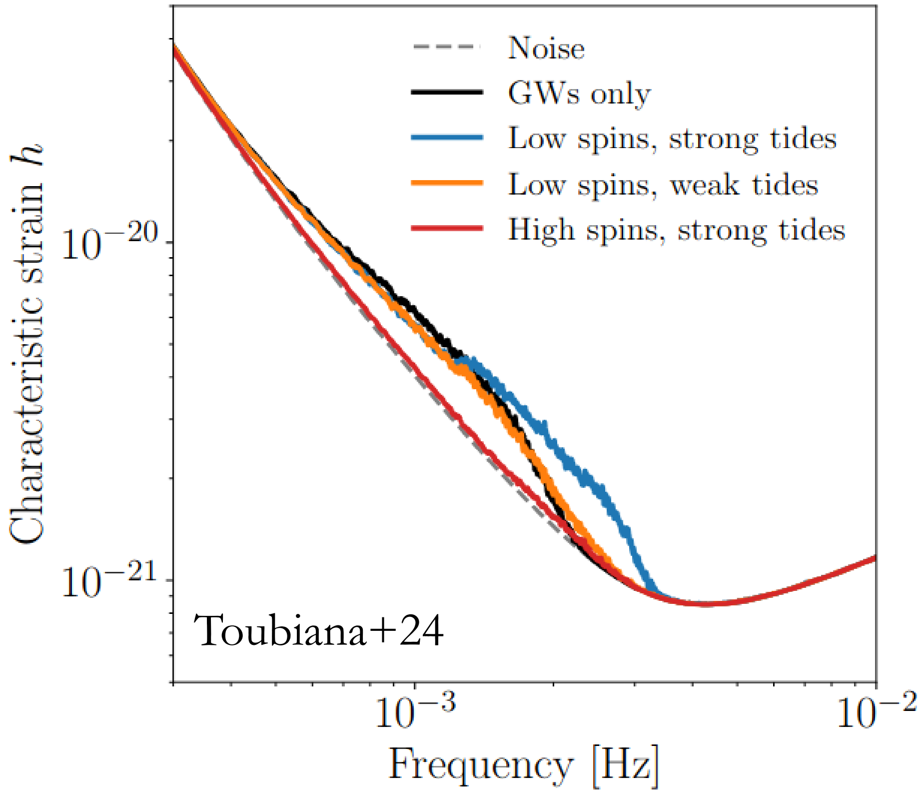




Challenges:

- Population uncertainties (Delfavero+25, Toubiana+24, Korol+22, Lamberts+19, ...)
- Non Gaussianity (Buscicchio+24, Karnesis+25...)
- Non stationarity

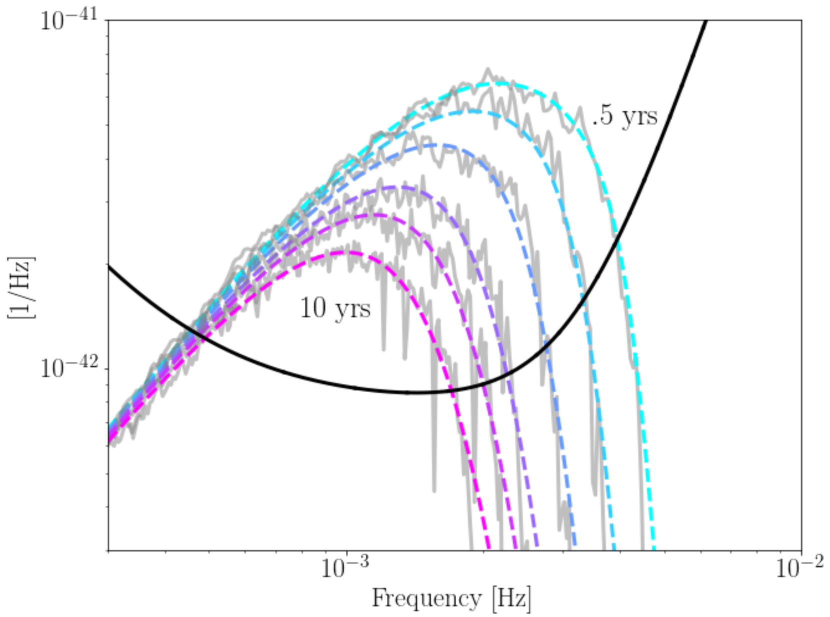
Galactic Foreground in Time

- **Long Timescale Effect**
  Detection and removal of **WD binaries** from the foreground.

$$S_h(f) = \frac{A}{2} f^{-7/3} e^{-(f/f_1)^\alpha} \left(1 + \tanh\left(\frac{f_{\text{knee}} - f}{f_2}\right)\right)$$

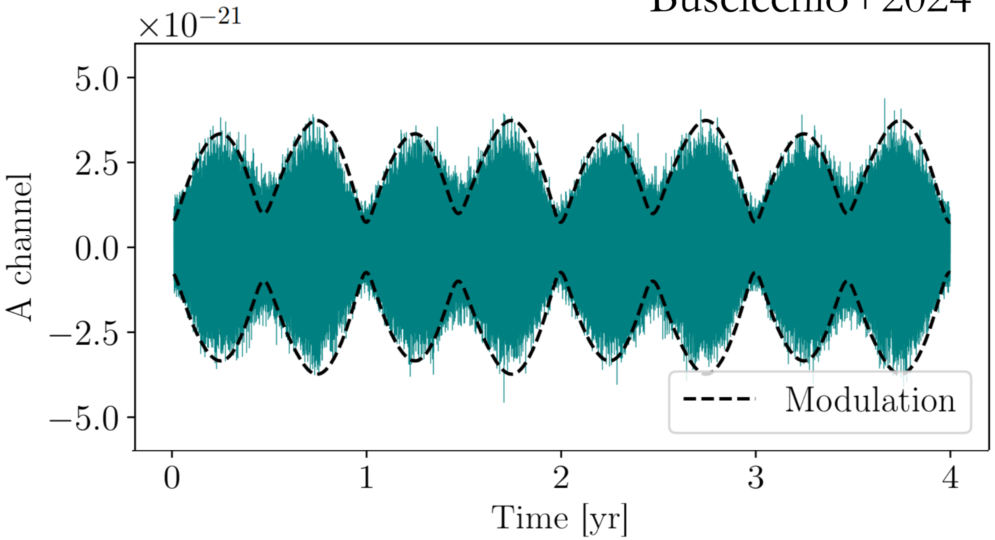
$$\log_{10} f_{1/\text{knee}} = a_{1/\text{knee}} \log_{10}(T_{\text{obs}}) + b_{1/\text{knee}}$$

Karnesis+2021



- **Short Timescale Effect**
  Modulation of the signal due to the interaction between **Milky Way anisotropies** and **LISA's orbital motion**.

Buscicchio+2024

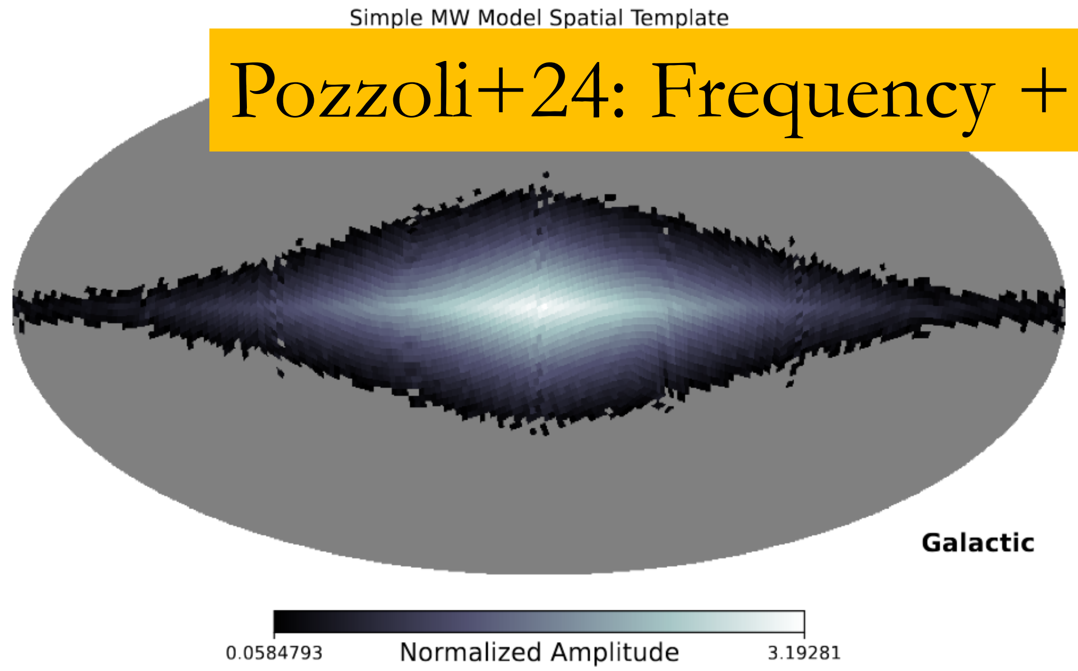


Galaxy Time Dependence

Method: Non-Stationarities or Anisotropies?

$$S_{IJ}^{\mathrm{GW}}(f,t) = \int \mathcal{P}(\mathbf{n})\, \mathcal{R}_{IJ}(f,t,\mathbf{n})\, d^2\mathbf{n} \times S_{\mathrm{GW}}(f)$$
$$= \mathcal{R}_{IJ}(f,t) \times S_{\mathrm{GW}}(f).$$

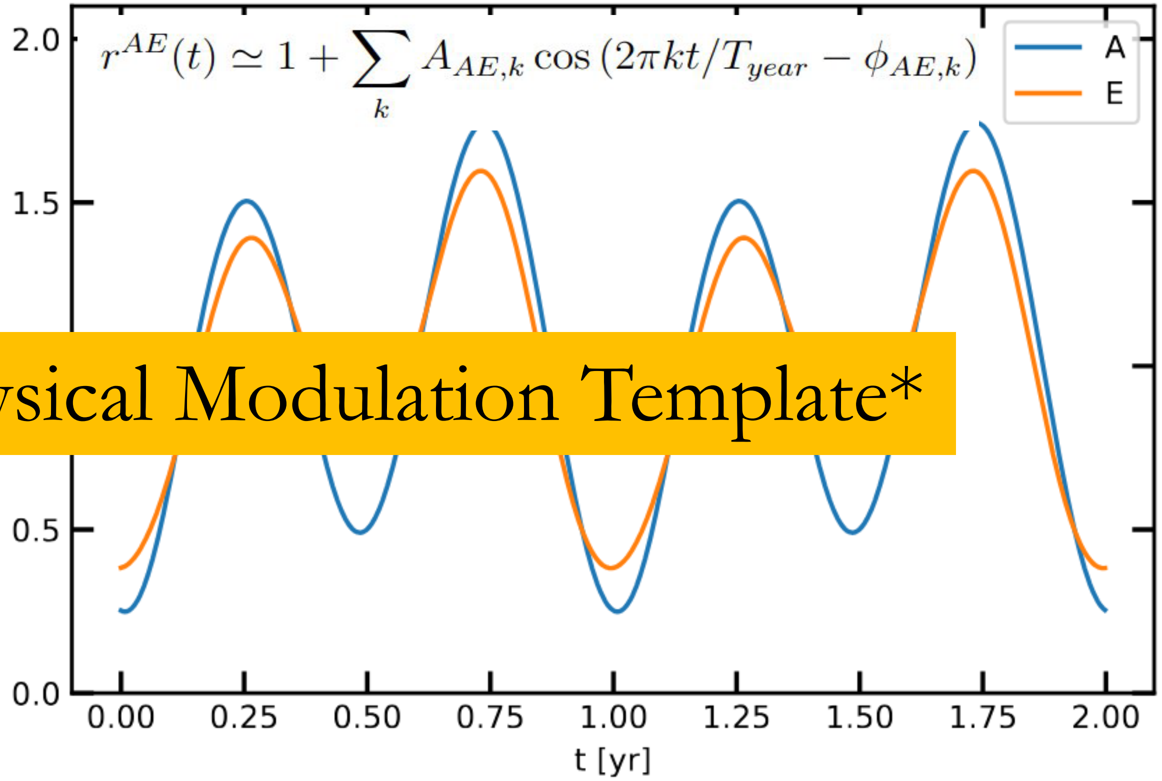
Spherical Harmonic Decomposition + Pixelation



Criswell, Rieck, Mandic 2025

Pozzoli+24: Frequency + Physical Modulation Template*

Digman, Cornish 2022



Time-Frequency + Phenomenological template

$$S_{gal}(t,f) \simeq r^{AE}(t) S_{gal}(f)$$

*Applicable also for Time-Frequency

Cyclostationary Process

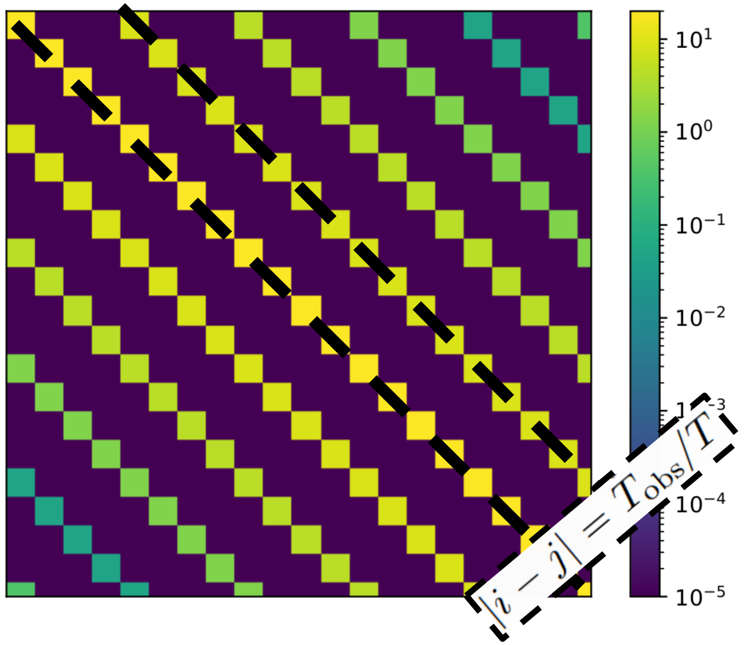
Cyclostationary processes are stochastic processes whose **statistical properties are periodic** in time

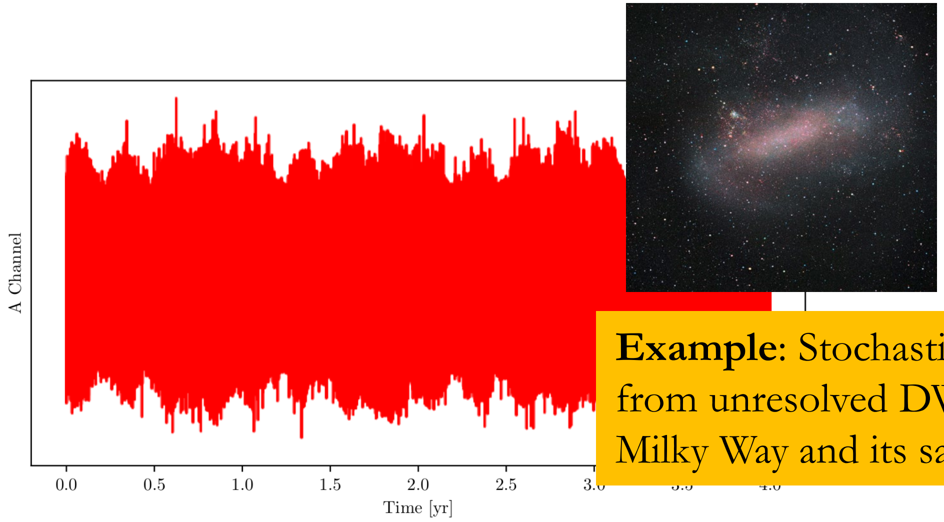
$$E\left[X(t)\right] = m(t) = m(t+T)$$

$$E\left[X(t')X(t)\right] = \Sigma(t', t) = \Sigma(t'+T, t+T)$$

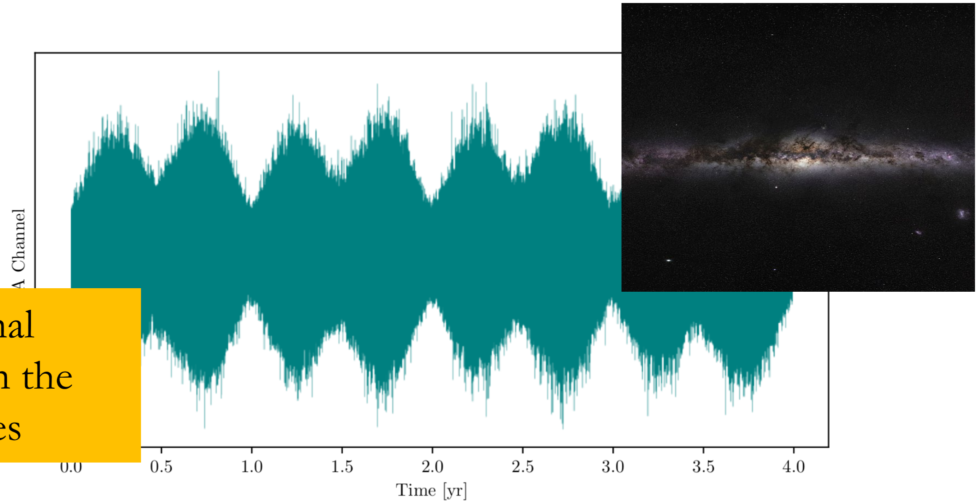
Covariance Matrix in frequency domain

$$C(f, f') = \sum_{n=-\infty}^{\infty} B_n S_h\left(\frac{f'+f}{2}\right)\delta\left(f - f' + \frac{n}{T}\right)$$





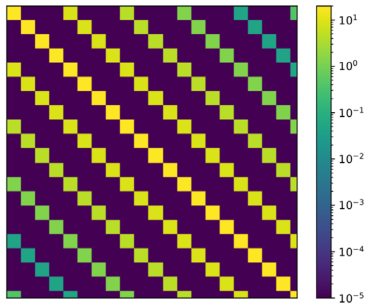
Example: Stochastic signal from unresolved DWD in the Milky Way and its satellites



Credit: ESO

Cyclostationary Process in LISA

$$C(f,f') = \sum_{n=-8}^{8} B_n S_h\left(\frac{f'+f}{2}\right)\delta\left(f - f' + \frac{n}{T}\right)$$



Cyclostationary Process in LISA

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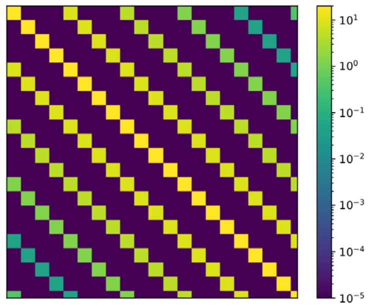


Astrophysical Spectrum:

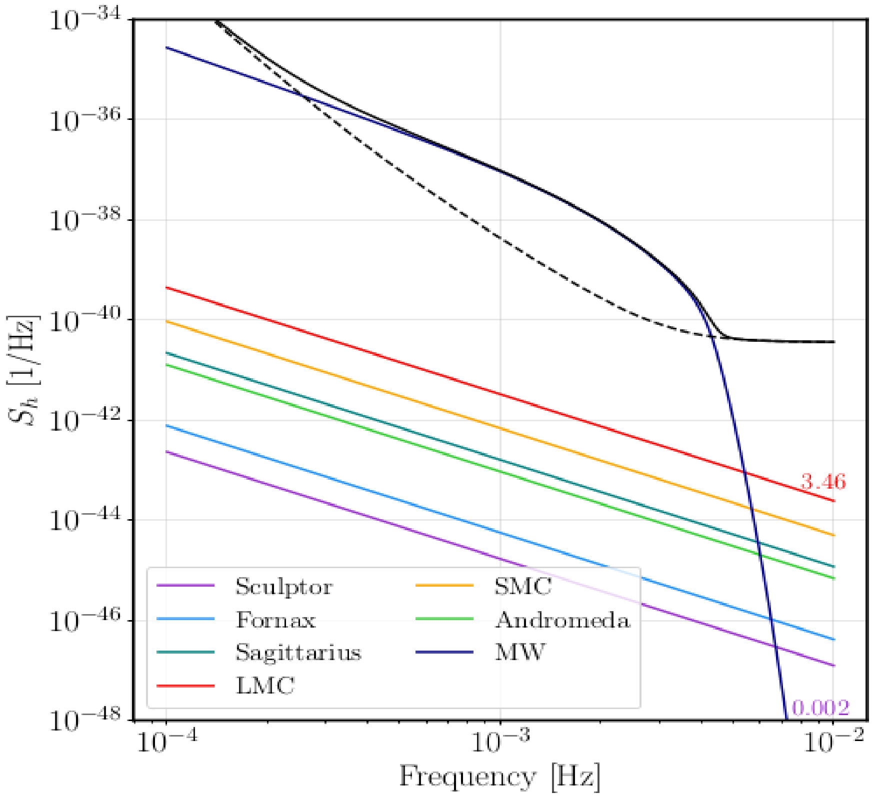
- Karnesis+21 for **Galactic Foreground:**

$$S_h(f) = \frac{A}{2} f^{-7/3} e^{-(f/f_1)^\alpha} \left(1 + \tanh\left(\frac{f_{\text{knee}} - f}{f_2}\right)\right)$$

- For the **Satellite Background**: integrate the squared inspiral amplitude over the orbital frequency and chirp mass.

$$S_h(f) = \int d\mathcal{M}_c p(\mathcal{M}_c) \int df_s p(f_s) \delta(f - f_s) \frac{(G\mathcal{M}_c)^{10/3}}{(c^4 D)^2} (\pi f_s)^{4/3}$$

We get a **Power law** template

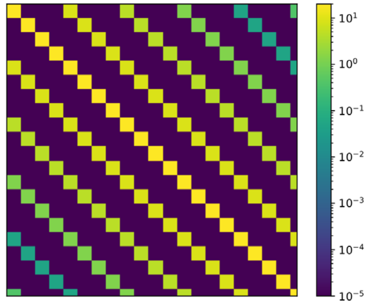


See Pozzoli+24 for more details

★ Giampieri&Polnarev1997

Cyclostationary Process in LISA

$$C(f,f') = \sum_{n=-8}^{8} B_n S_h\left(\frac{f'+f}{2}\right)\delta\left(f - f' + \frac{n}{T}\right)$$



Fourier Coefficient of Modulation:

We want to perform the sky average of signal^2

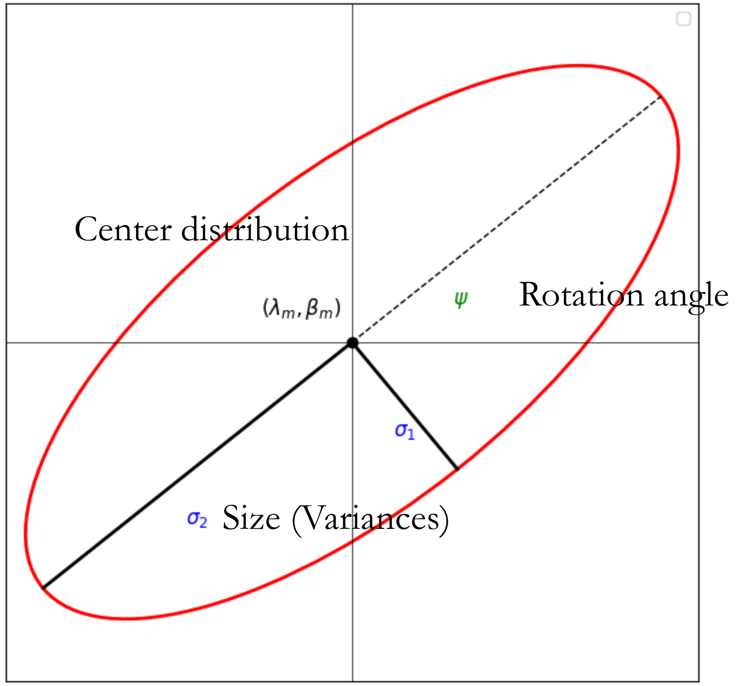
$$\int d\lambda \int d\beta \cos\beta p(\lambda,\beta) h^2(t,\lambda,\beta)$$

We decompose the integrals into several of this type:

$$\int_{\mathcal{R}} d\theta_r \int_{\mathcal{R}} d\phi_r p(\theta_r)\, p(\phi_r)\, e^{im\theta_r} e^{in\phi_r} = \varphi_{\theta_r}(m)\varphi_{\phi_r}(n)$$

The solution is analytical for many distributions:
CHARACTERISTIC FUNCTION.

We **parametrize the modulation** as function of distribution parameters.



See Pozzoli+24, Buscicchio+24 for more details

★ Giampieri&Polnarev1997

Galactic Modulation: Influence of Latitude

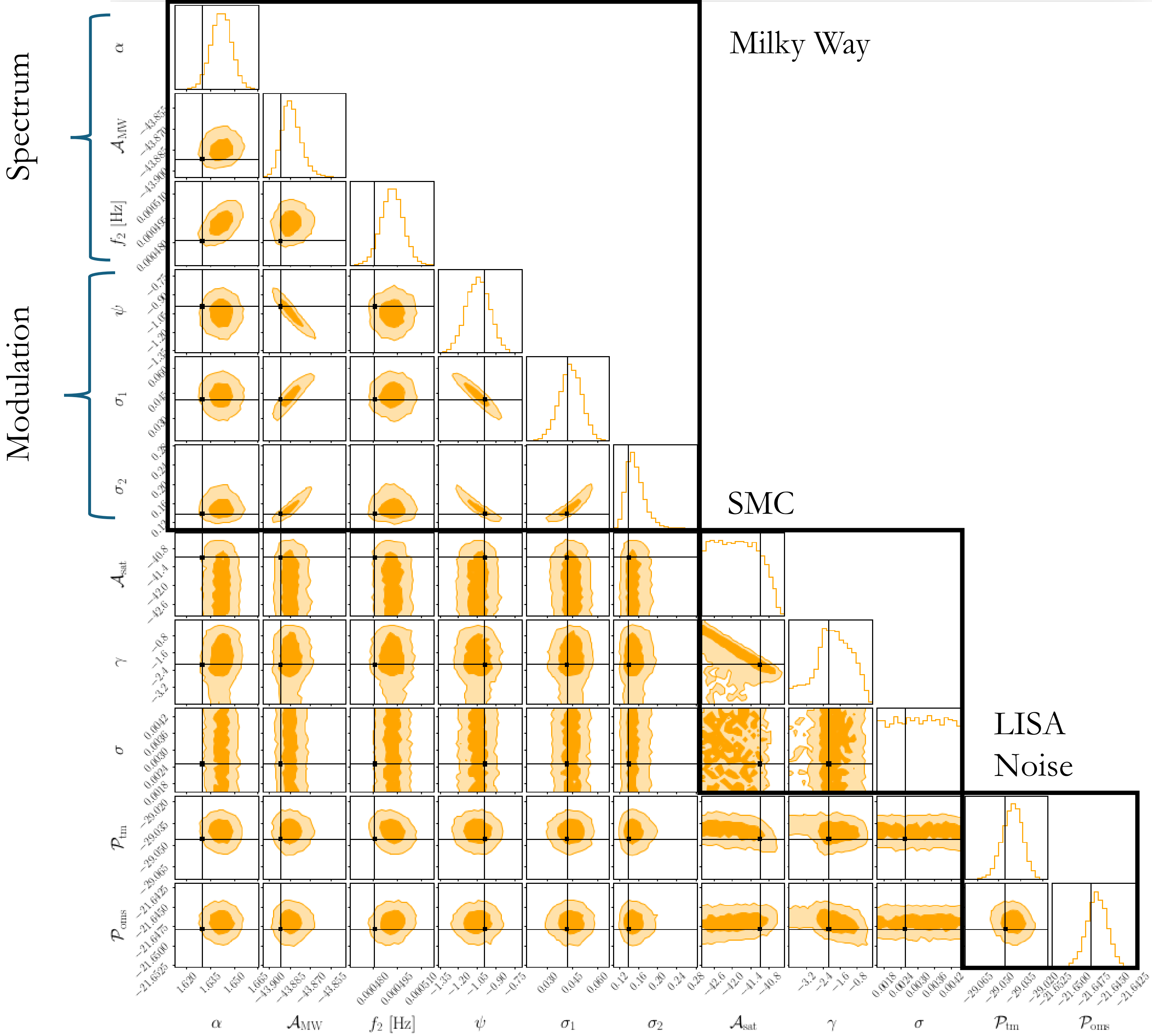
Galactic Modulation: Influence of Size

Results

- Simultaneous reconstruction of LISA instrumental noise, Milky Way Foreground and Satellite background.

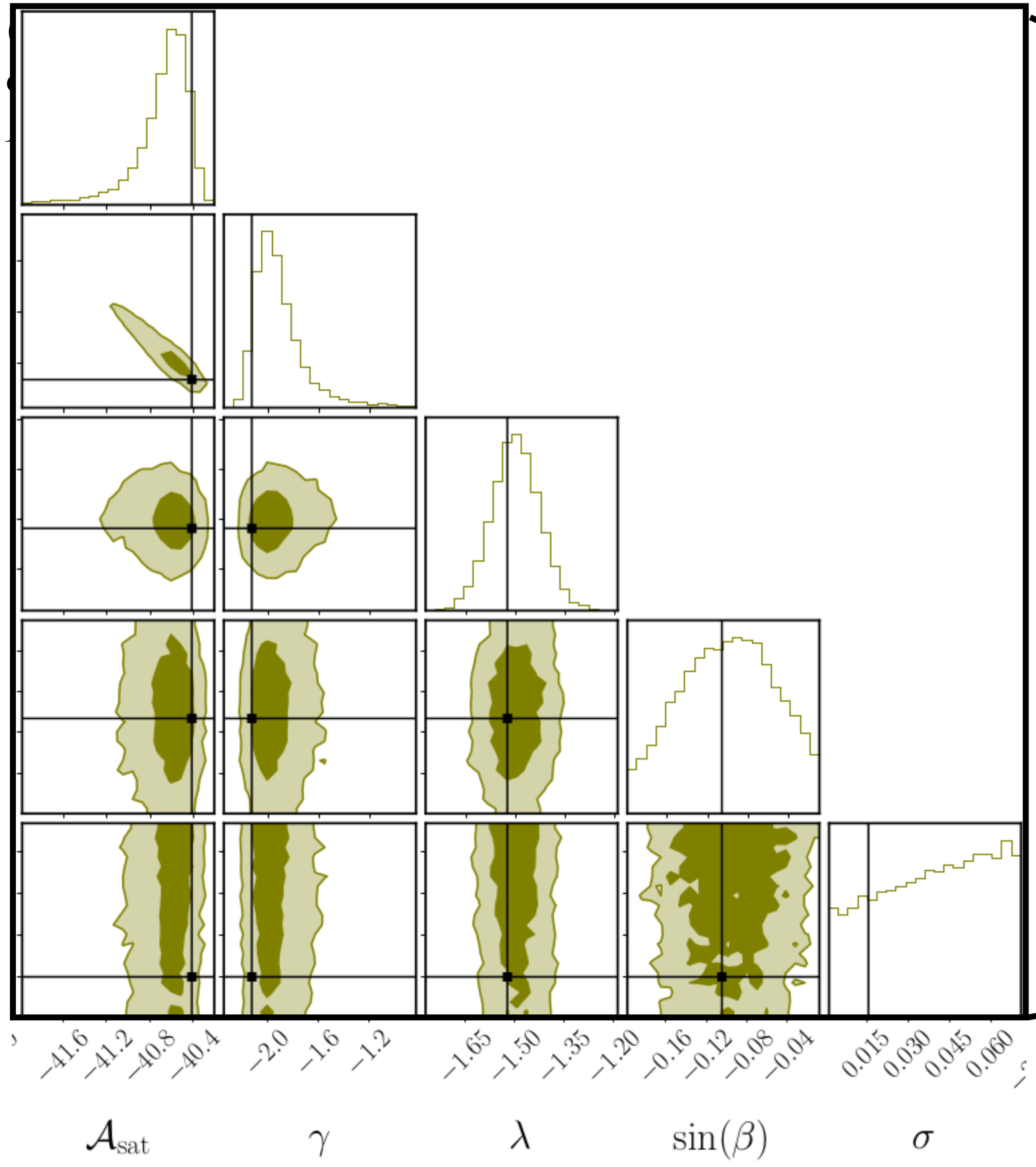
- Simultaneous **Inference of spectrum and modulation**

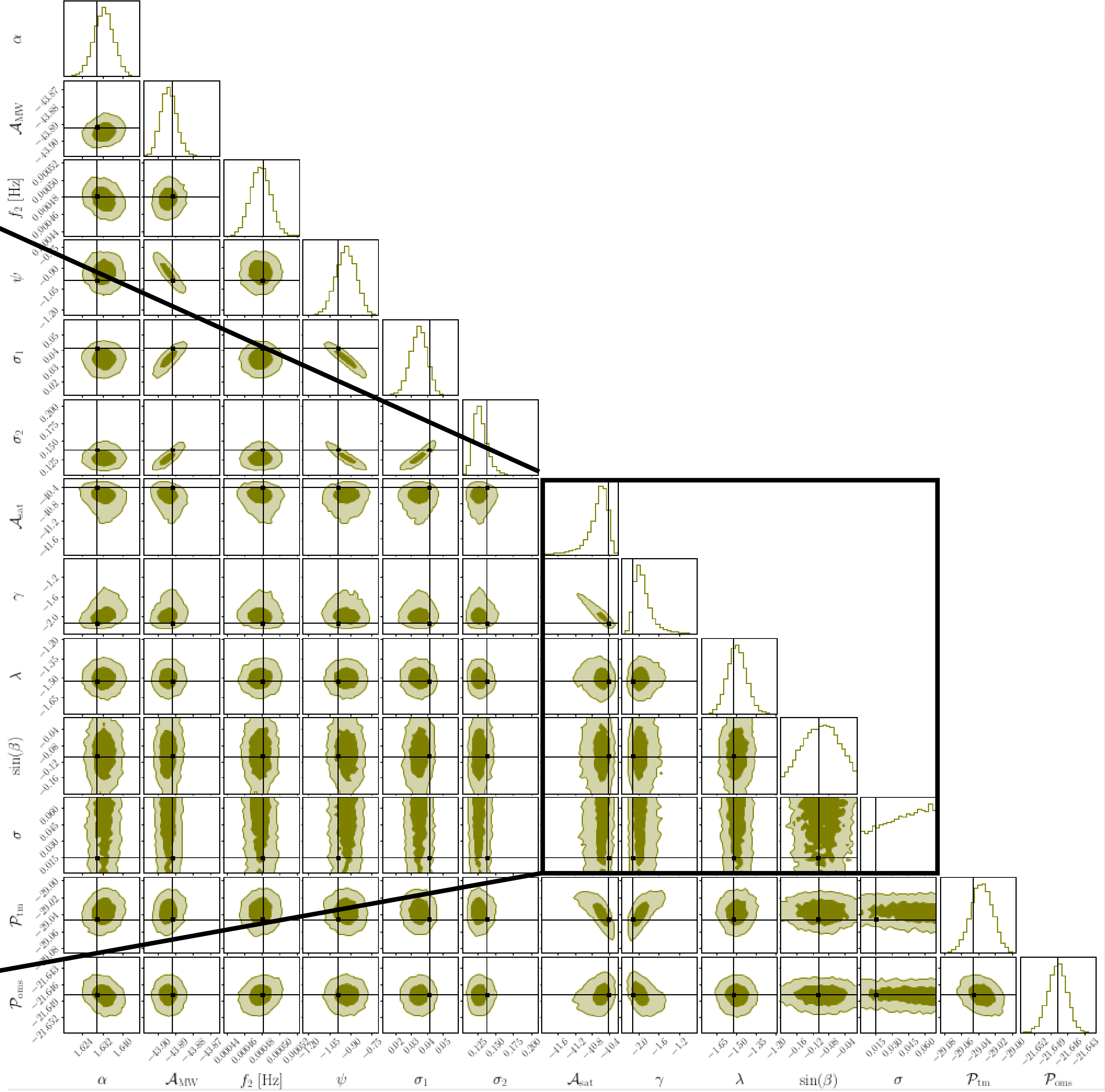
What else?



Results

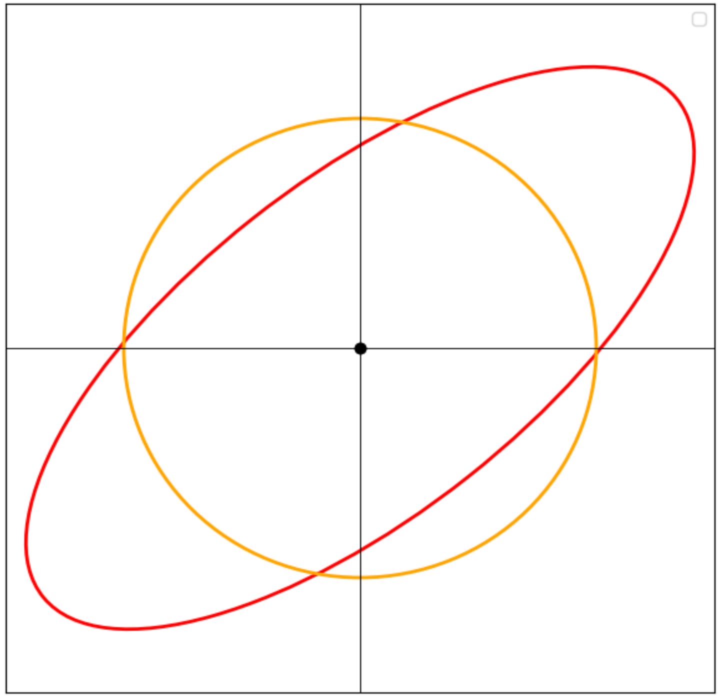
LISA has the potential to observe beyond the galactic plane .
We consider an **LMC-like satellite behind the Milky Way**

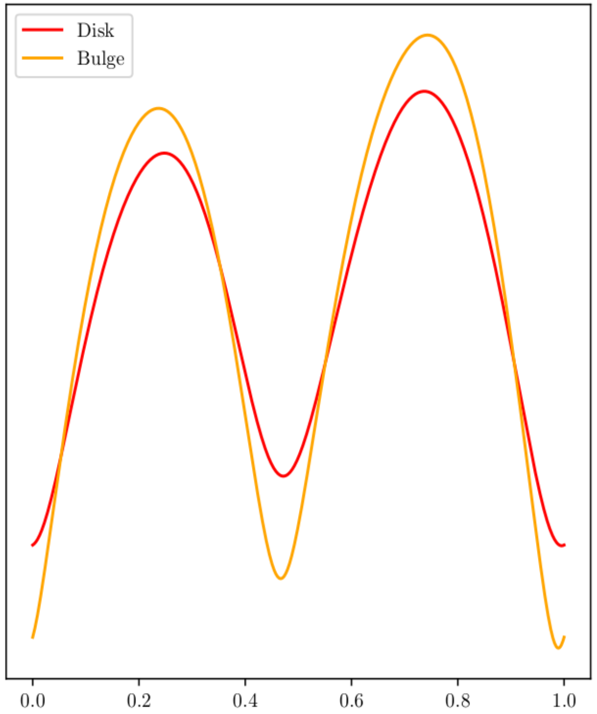


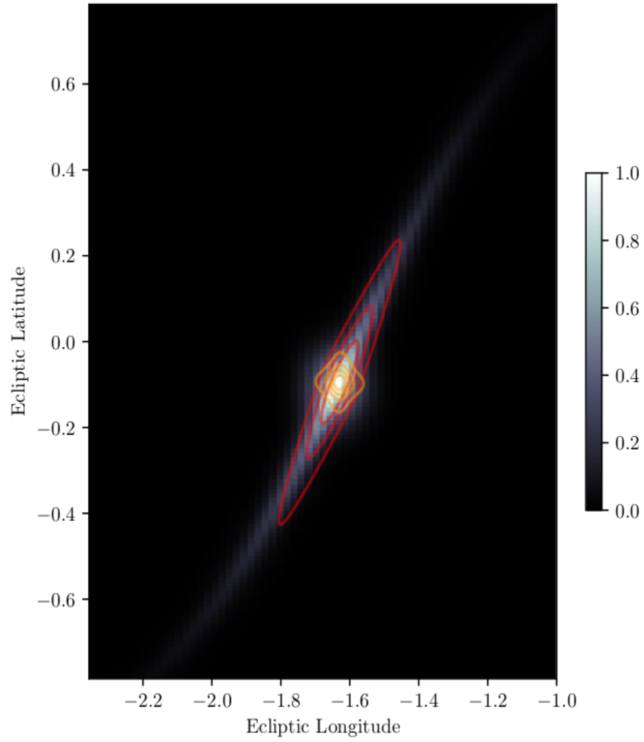


What' next?

$$\int_{\mathcal{R}} d\theta_r \int_{\mathcal{R}} d\phi_r p\left(\theta_r\right) p\left(\phi_r\right) e^{im\theta_r} e^{in\phi_r} = \varphi_{\theta_r}(m)\varphi_{\phi_r}(n)$$







Bulge-Disk Decomposition of Milky Way with GWs!

Conclusion

What do we propose?

- Cyclostationarity prescription to study MW foreground
- New realistic modulation model (compatible also with Time-Frequency)

What can we do?

- Studying MW structure:
    - Satellite
    - Geometry and Structure

Next challenges:

- Non-Gaussianity
- Data Gaps