Time-delay interferometry as a coronagraph

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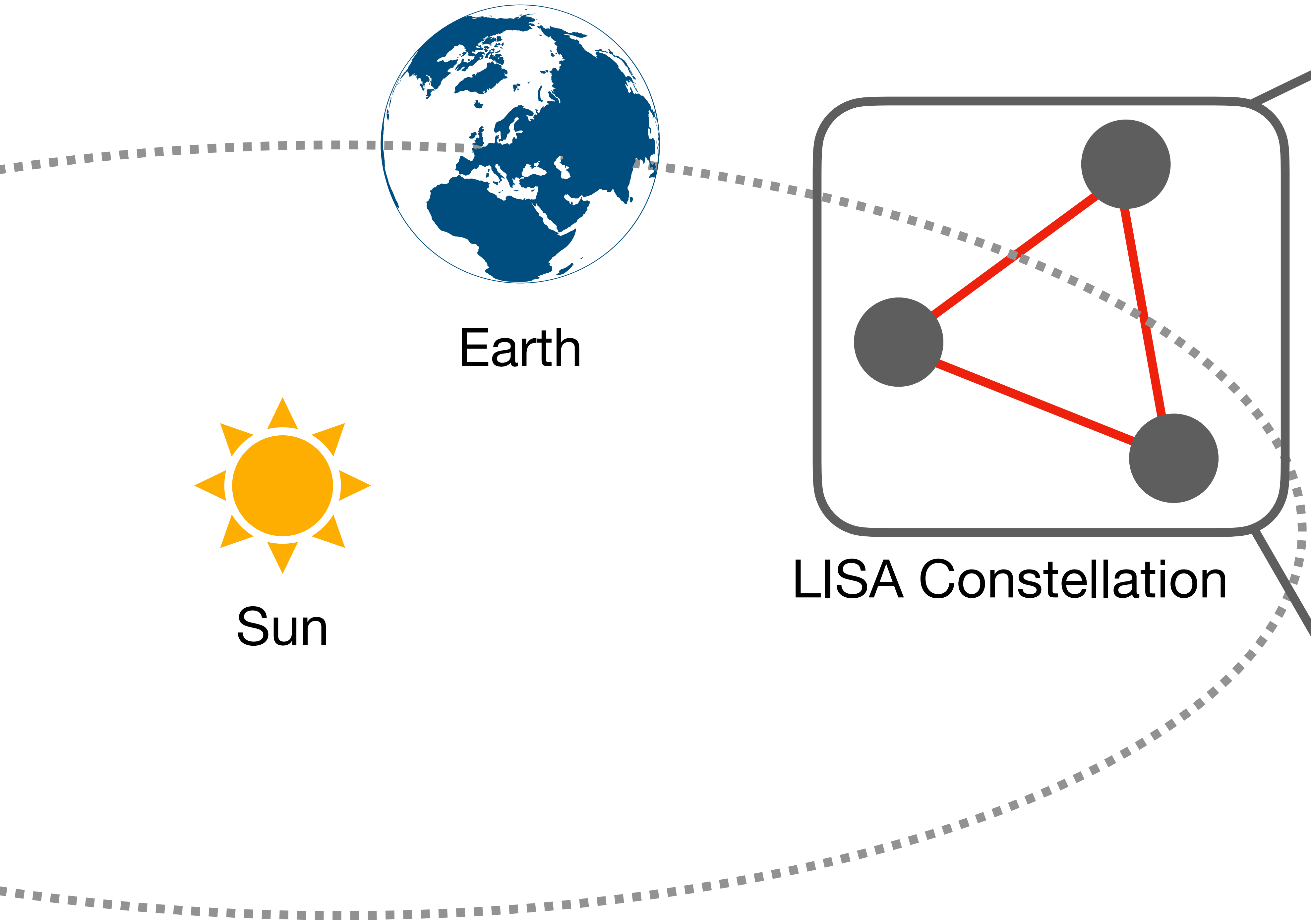
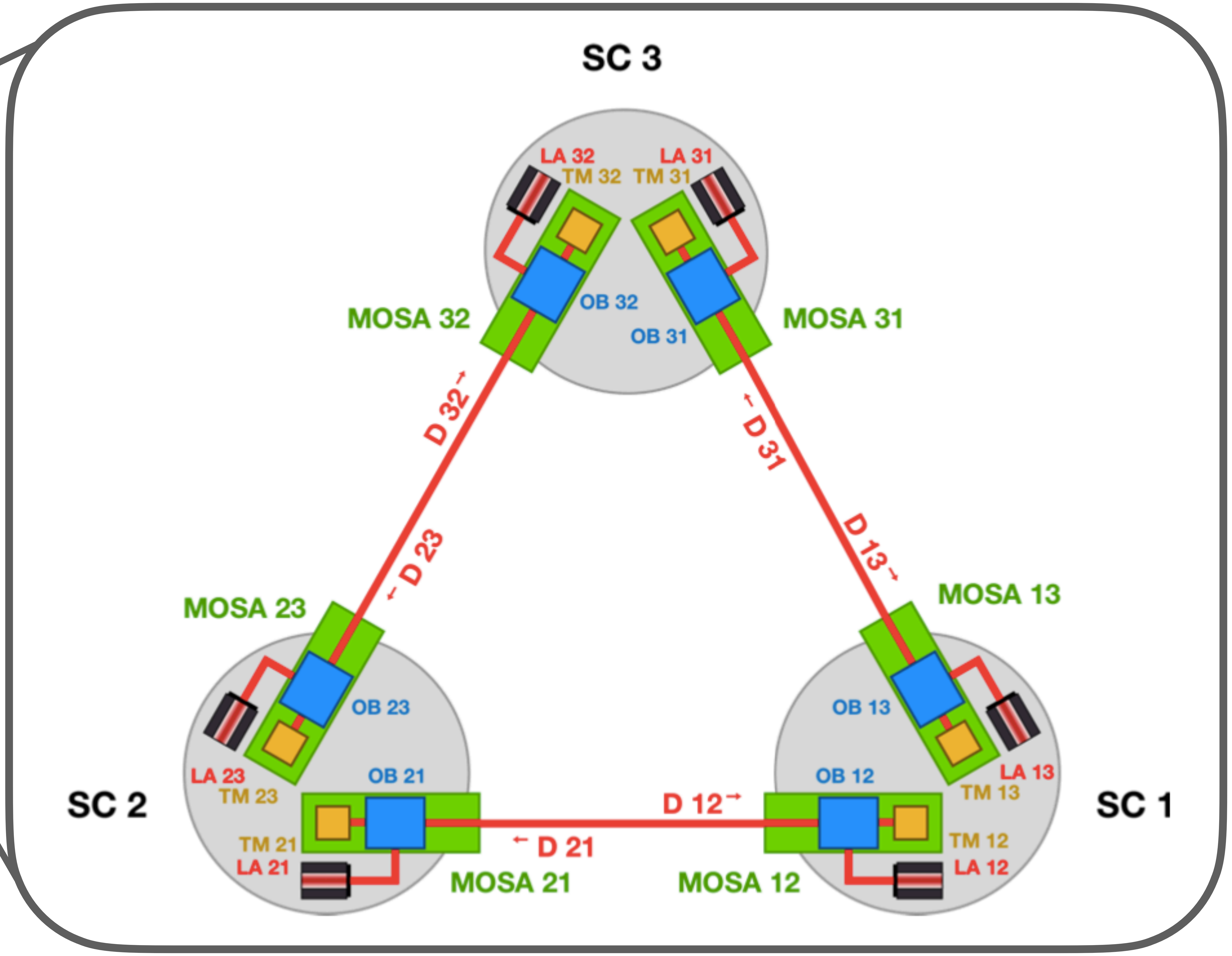
Overview

What is LISA?



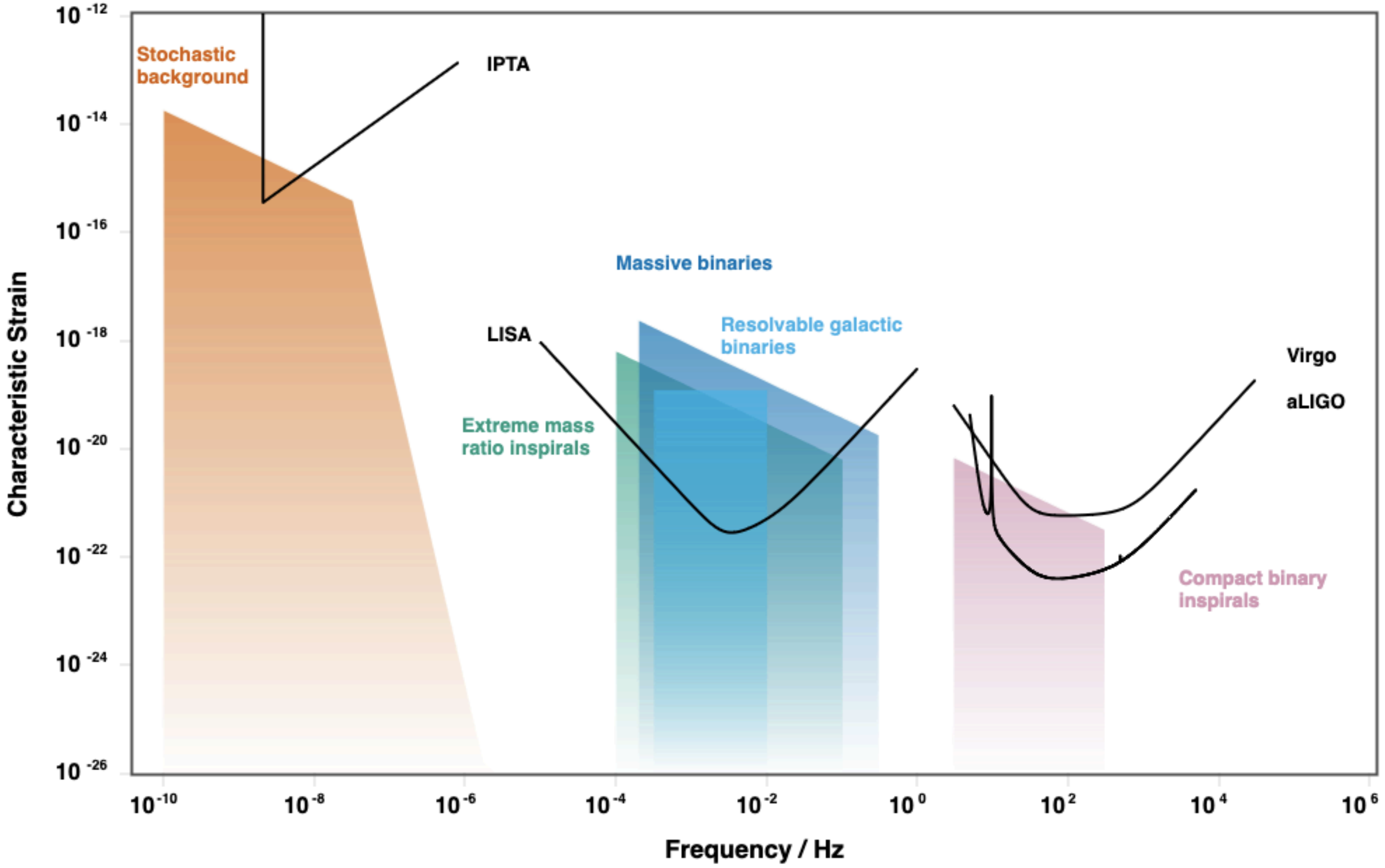
Schematic LISA orbit

Schematic LISA instrument [1]



[1] Jean-Baptiste Bayle and Olaf Hartwig. Instrumental simulation (lisa instrument). 2022.

Landscape



[2] Christopher Moore, Robert Cole and Christopher Berry. gwplotter.com

LISA data analysis

Global fit

- **Global** analysis of LISA GW data
- All sources
- Long timescale (~ 1 month)
- Full parameter estimation (~ 10 parameters)
- **Goal:** astrophysical catalog

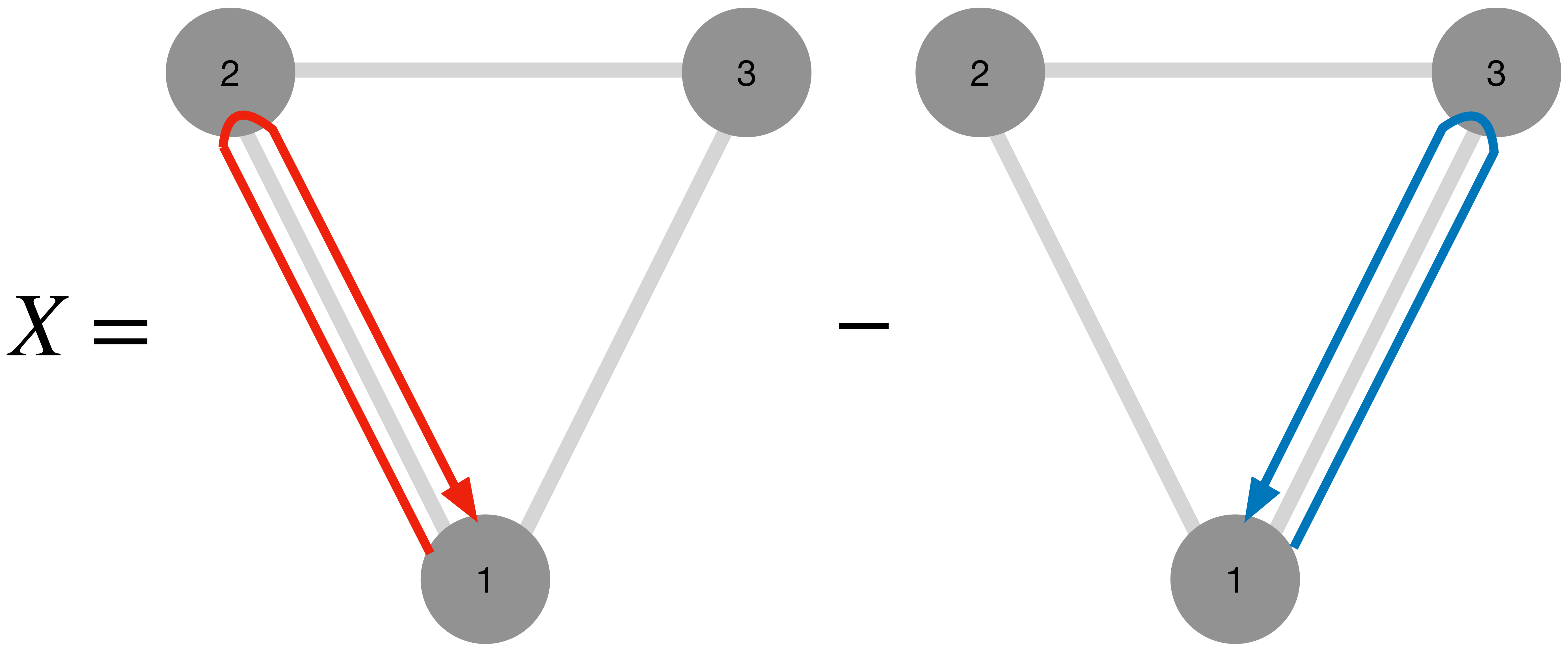
Low latency

- Electromagnetic counterpart
- Short lived high SNR sources
- Short timescale (~ 1 hour)
- Sky localization (< 10 deg^2) and time of coalescence
- **Goal:** alerts

Principle

Time-delay interferometry (TDI)

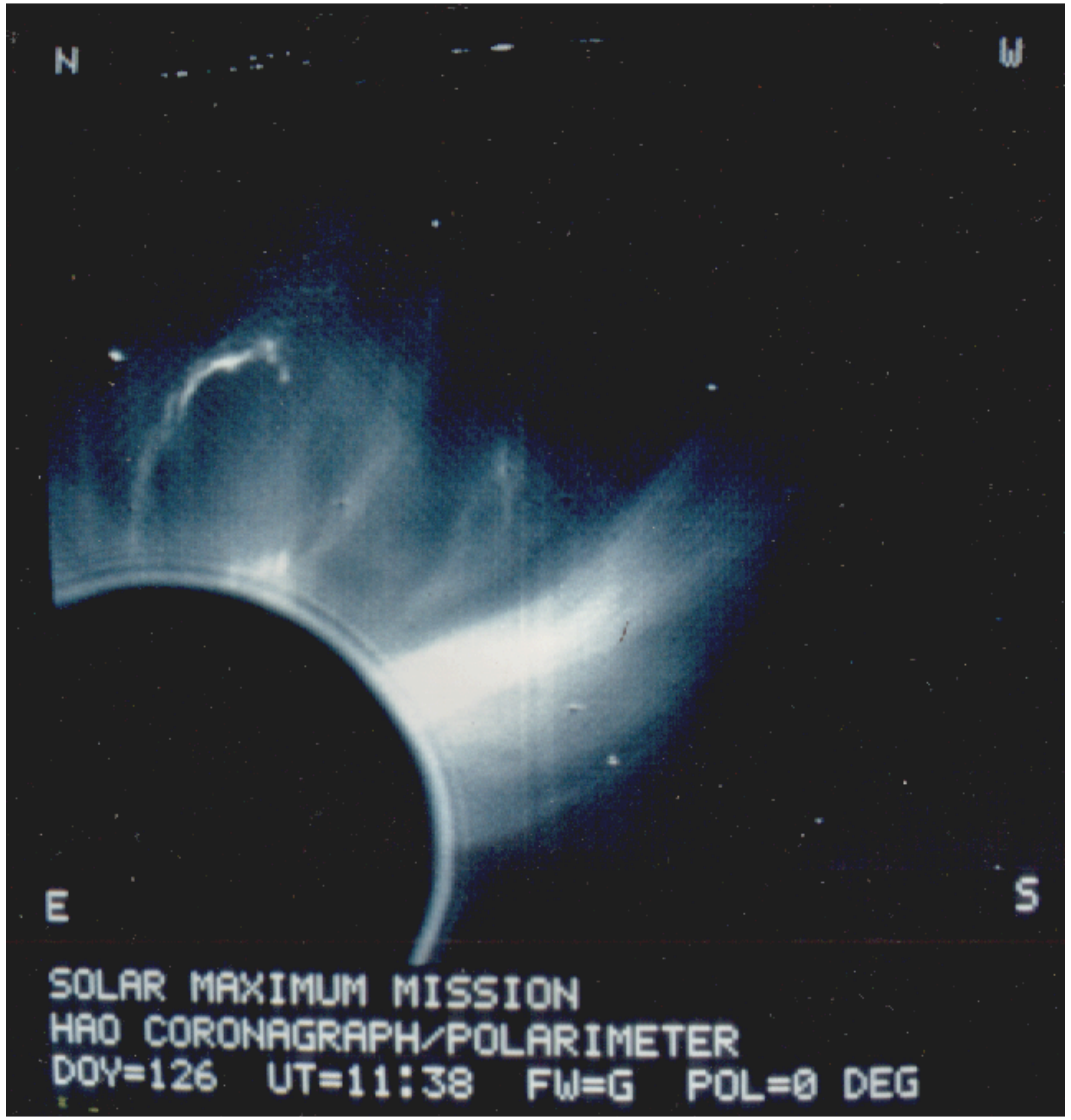
- **Problem:** laser frequency noise
- Clever combination of interferometric data
- Rules but more than one combination
- Bases: (X, Y, Z), (α, β, γ)…



[3] M. Vallisneri, Phys. Rev. D **72**, 042003 (2005); **76**, 109903 (E) (2007).

Coronagraphic TDI

- **Problem:** construct a TDI channel such that it suppresses GW signal coming from a specific direction.
- **Solution:** linear combination of a set of TDI variables with carefully chosen coefficients.
- **Key property:** dependence on two parameters directly related to the sky position of the source.



Coronagraph image of the Sun (NASA) [4]

[4] https://en.wikipedia.org/wiki/Coronagraph#/media/File:Cp22liberationdaytransient.png

In the context of low latency analysis

- Coronagraphic TDI could be used for sky localization.
- It does not rely on waveform templates.
- It should work for **any** source, including unmodeled sources.
- It should be robust against glitches.
- Coronagraphic TDI sounds promising, but there is a lot of work to be done!

Testing coronagraphic TDI

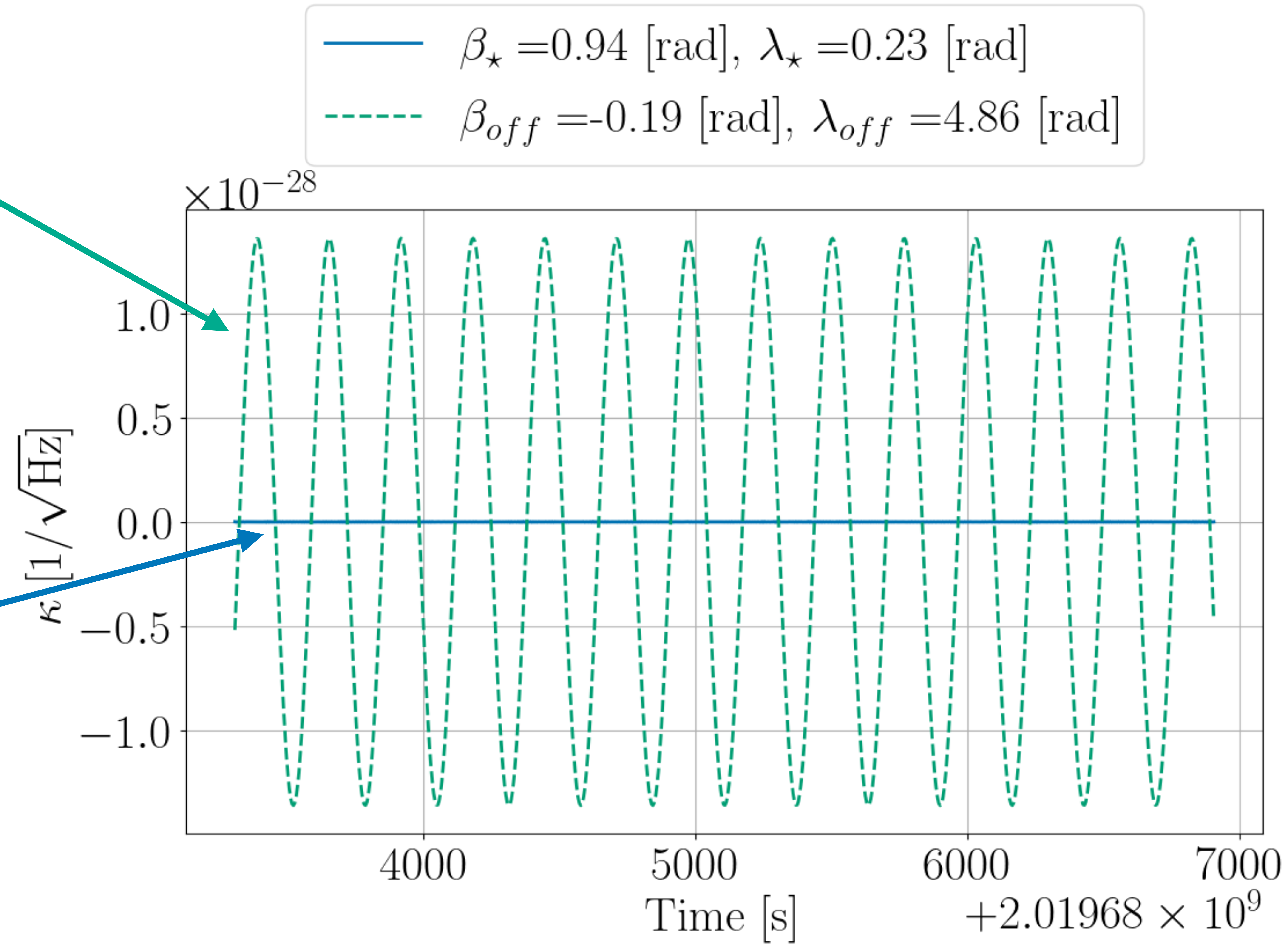
Assumptions	Datasets
• Orbits: static constellation with unequal arm lengths • Duration: 5.8 days • 1st generation TDI (α, β, γ) • One source • No noise	• Quasi monochromatic source: verification galactic binary (**VGB**) • Polychromatic source: Sangria (LDC2a) [5] massive black hole binary merger (**MBHB**)

[5] Le Jeune, Maude, & Babak, Stanislav. (2022). LISA Data Challenge Sangria (LDC2a) (Version v2)

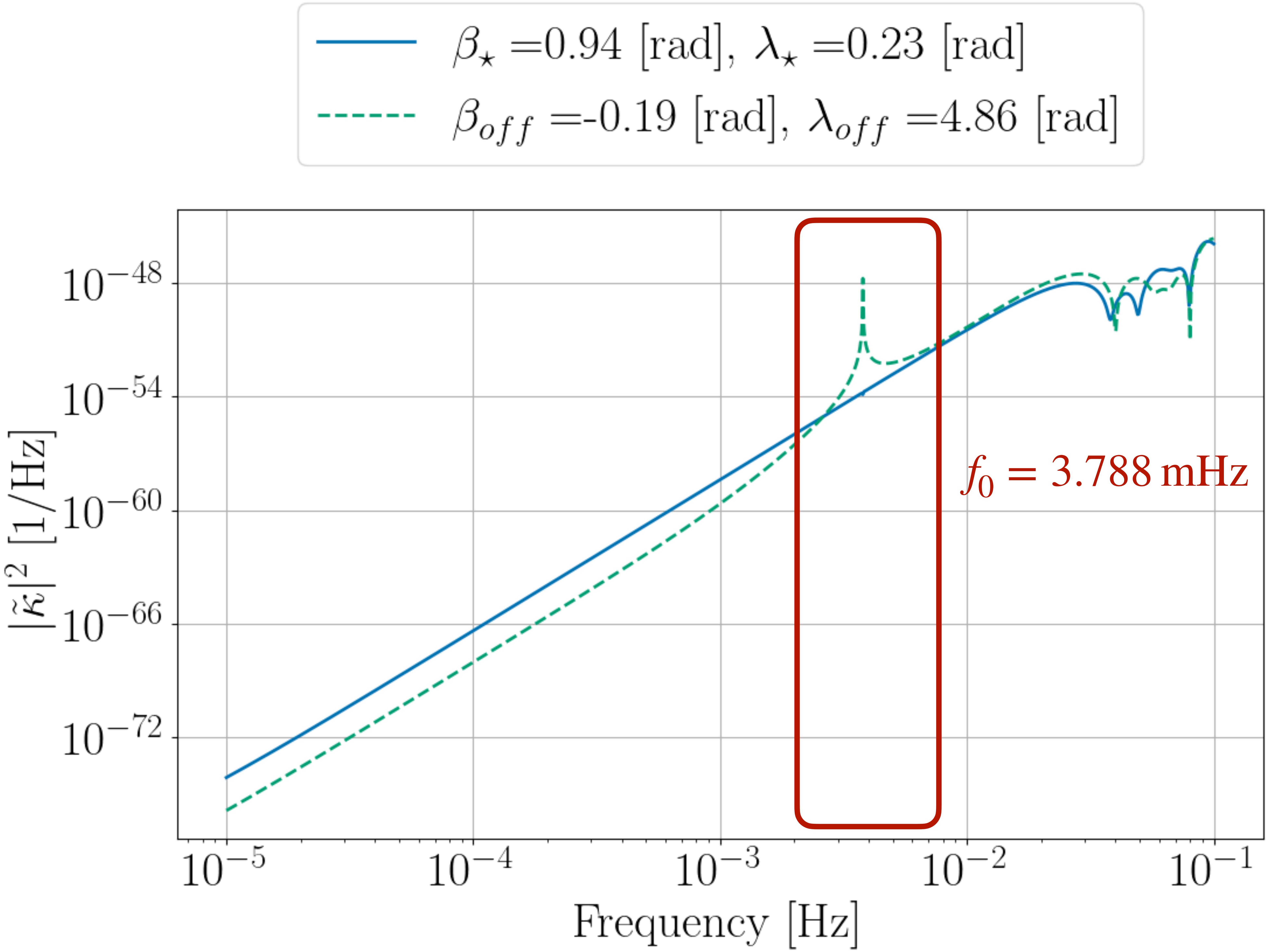
Results for a VGB

Not pointing at the source

Pointing at the source

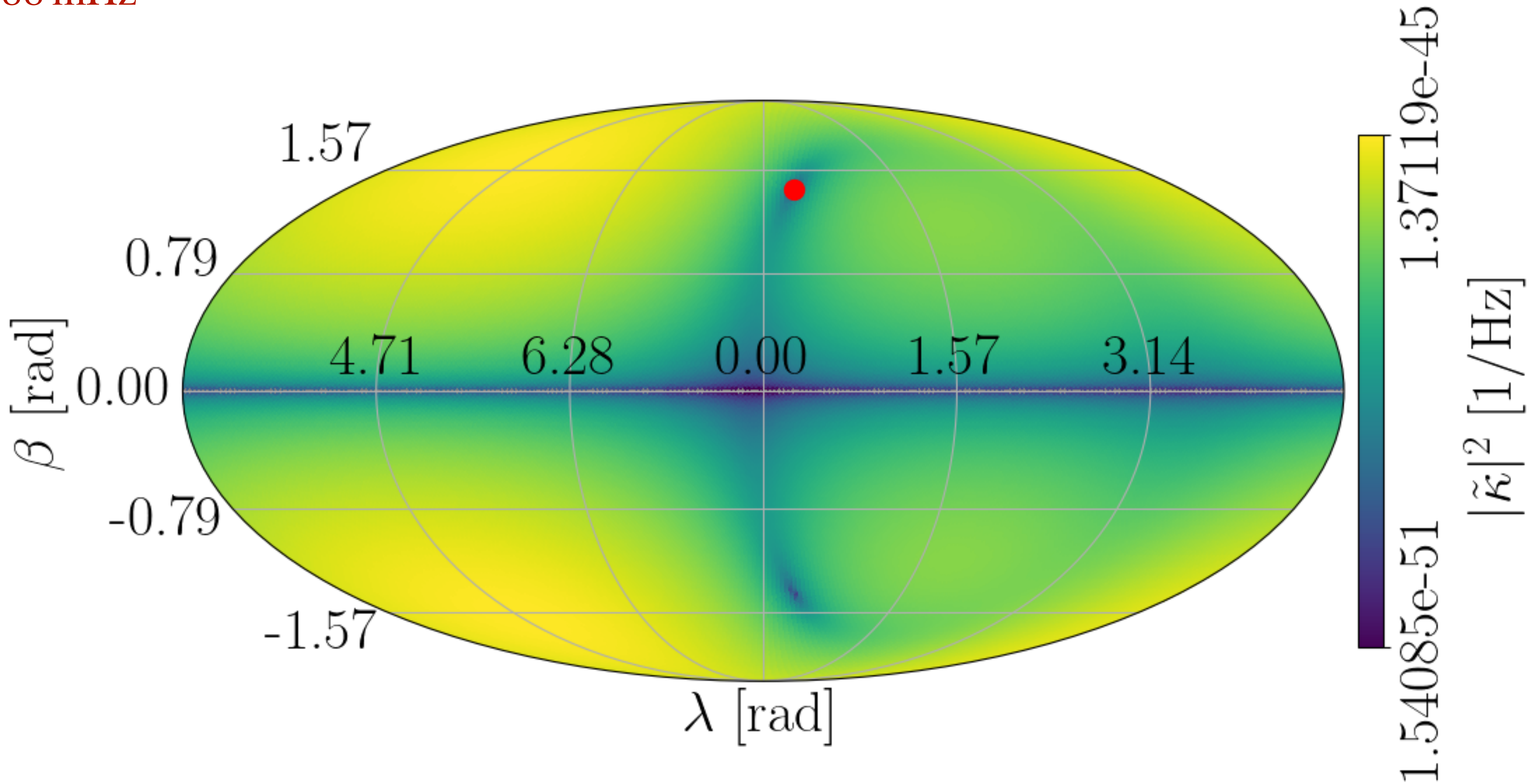


VGB: ZTFJ2243



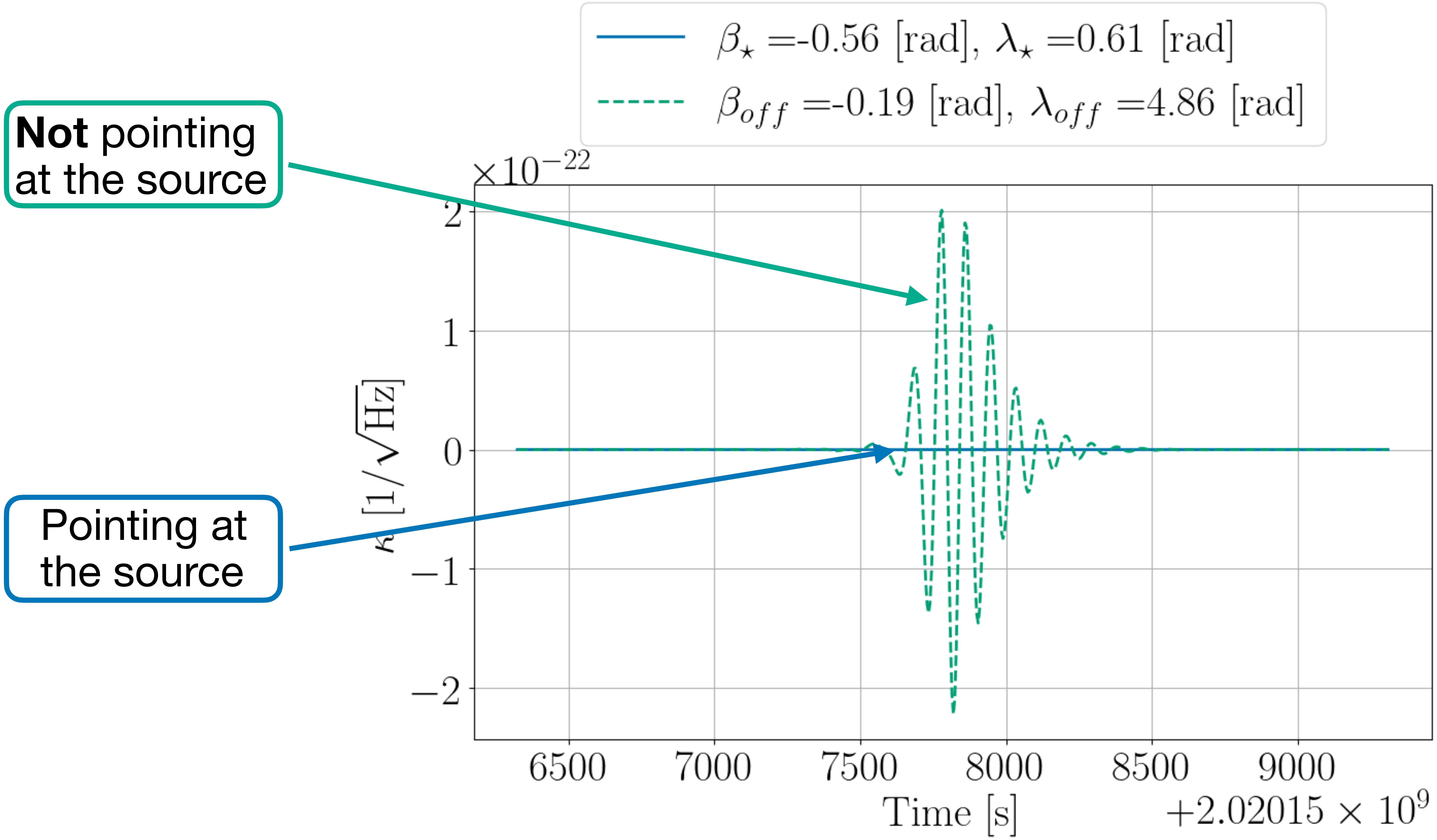
$\beta_\star$ =0.94 [rad], $\lambda_\star$ =0.23 [rad]
β_{off} =-0.19 [rad], λ_{off} =4.86 [rad]
10^{-48}
10^{-54}
10^{-60}
10^{-66}
10^{-72}
$|\tilde{\kappa}|^2$ [1/Hz]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]
$f_0 = 3.788\,\mathrm{mHz}$

$f = 3.788\,\mathrm{mHz}$



VGB: ZTFJ2243

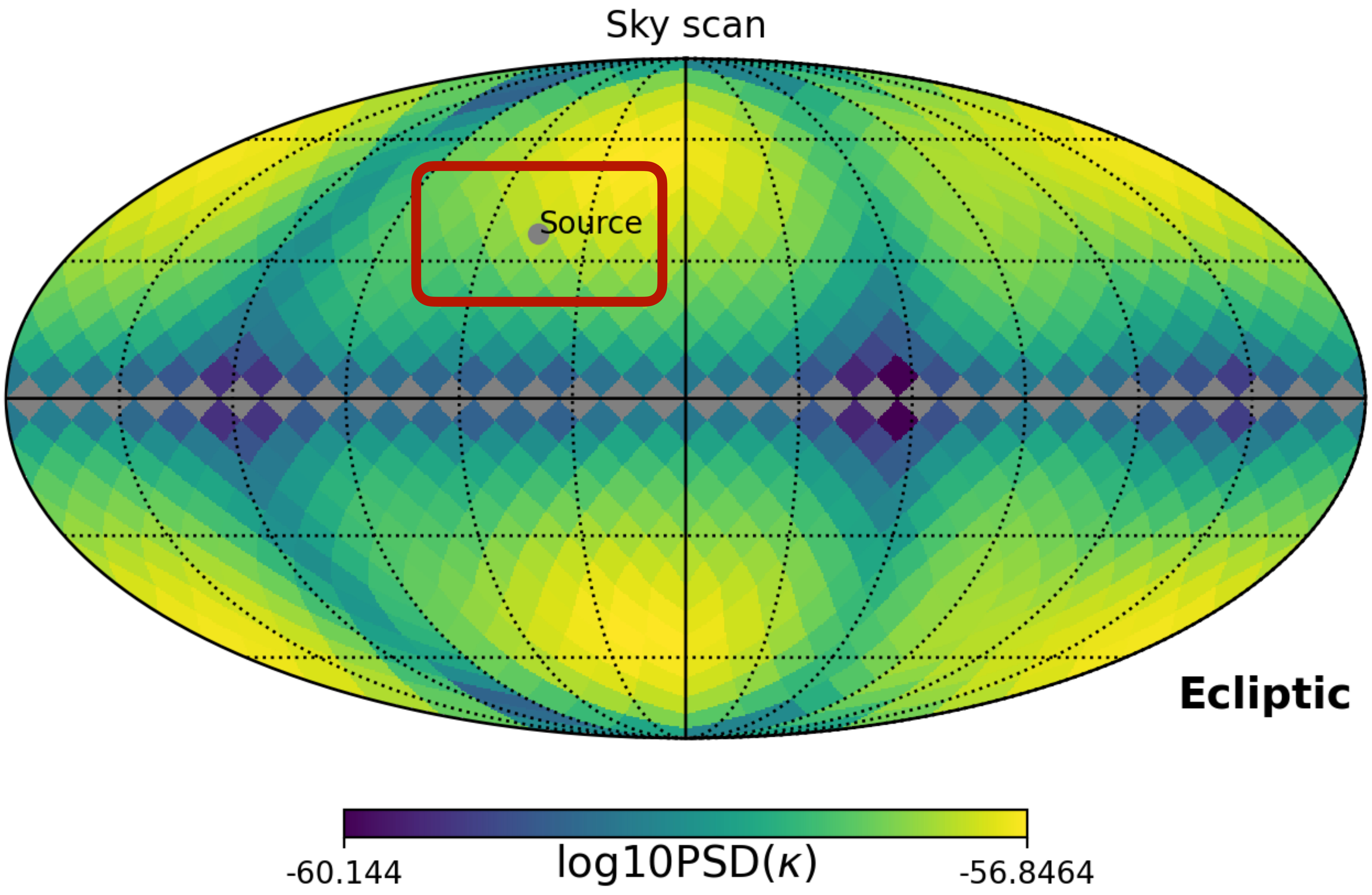
Results for a MBHB



MBHB_00

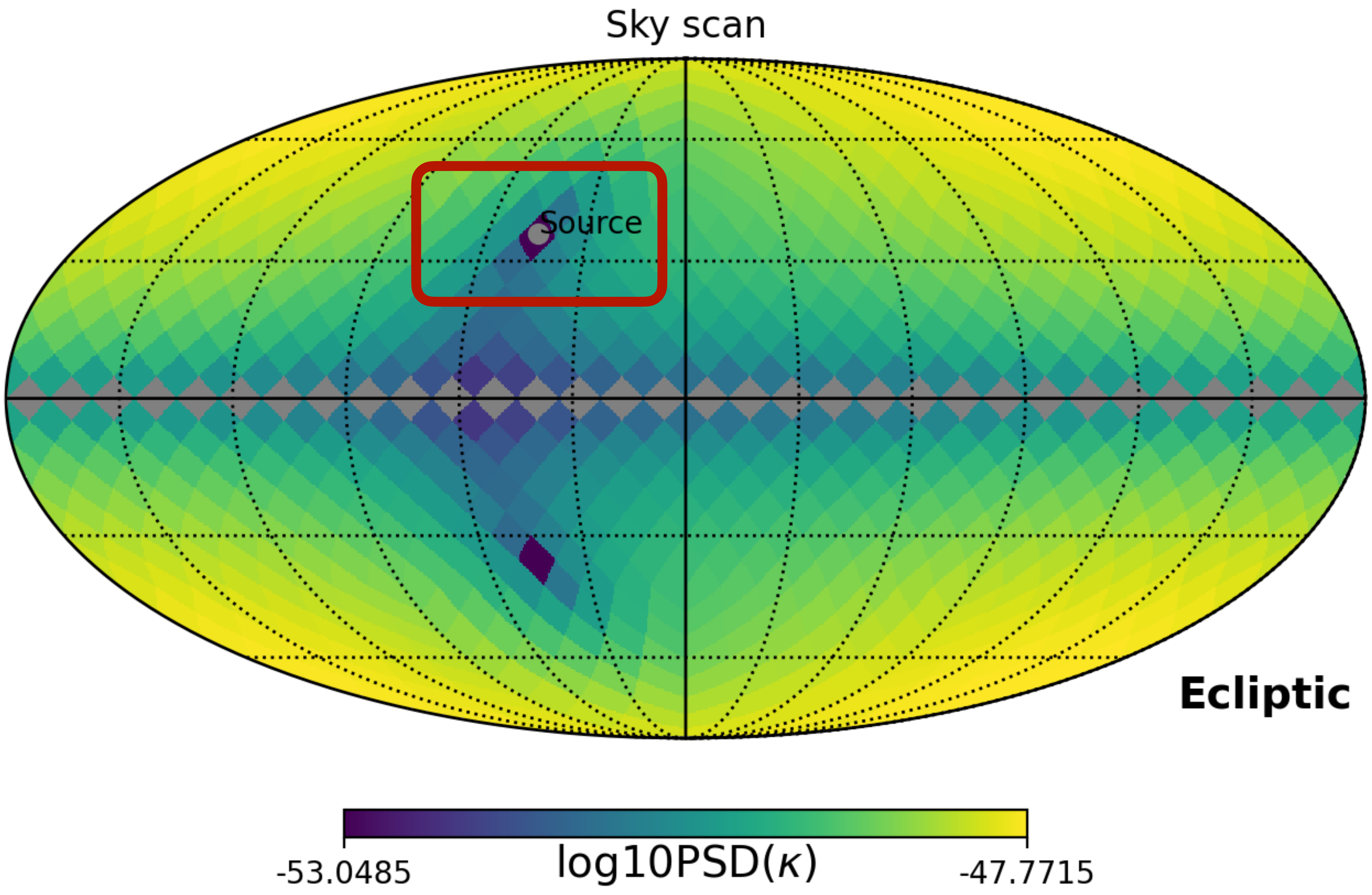
Out of MBHB band

$f = 85.8\,\mathrm{mHz}$



In MBHB band

$f = 9.58\,\mathrm{mHz}$



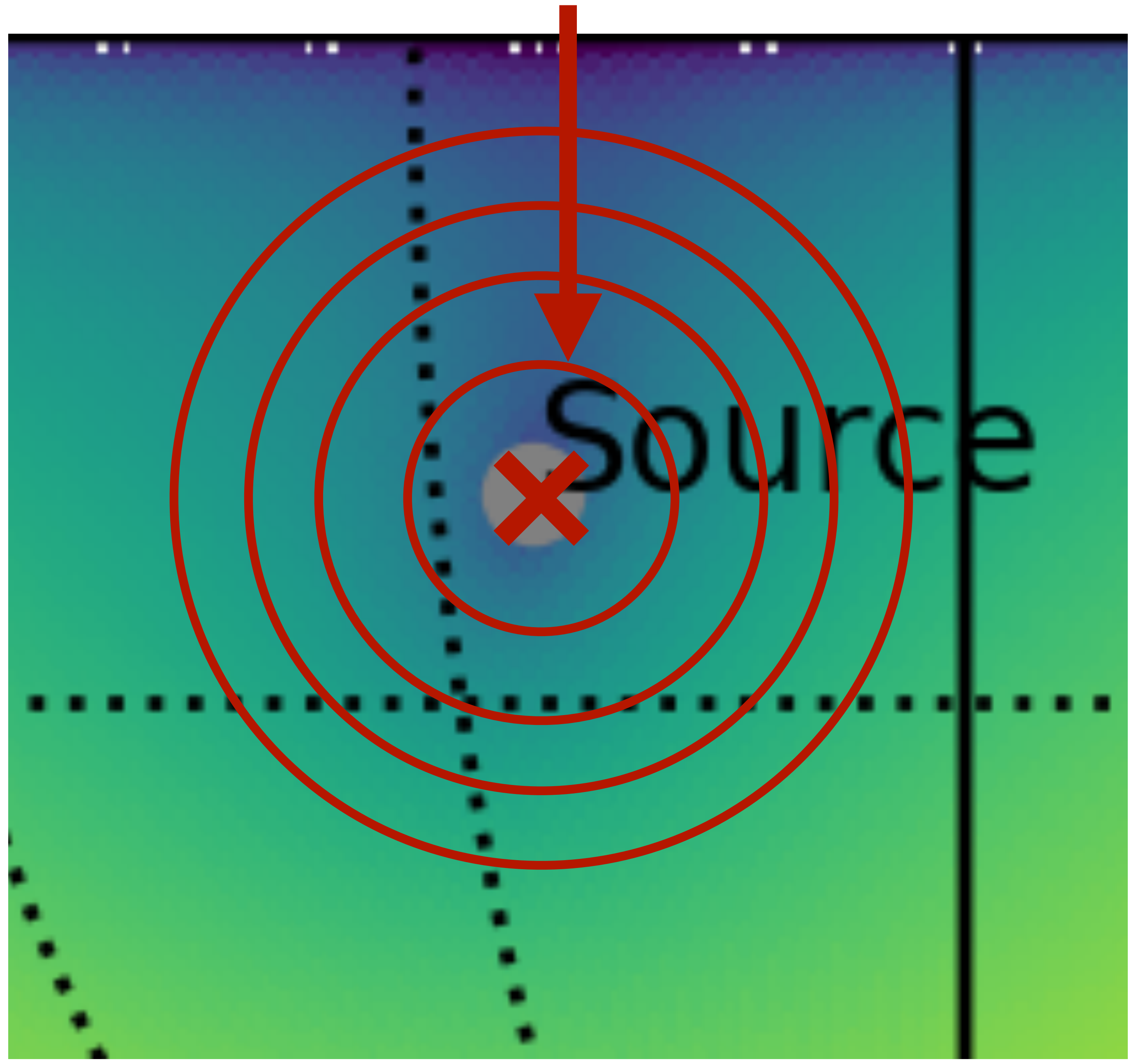
Signal

Questions

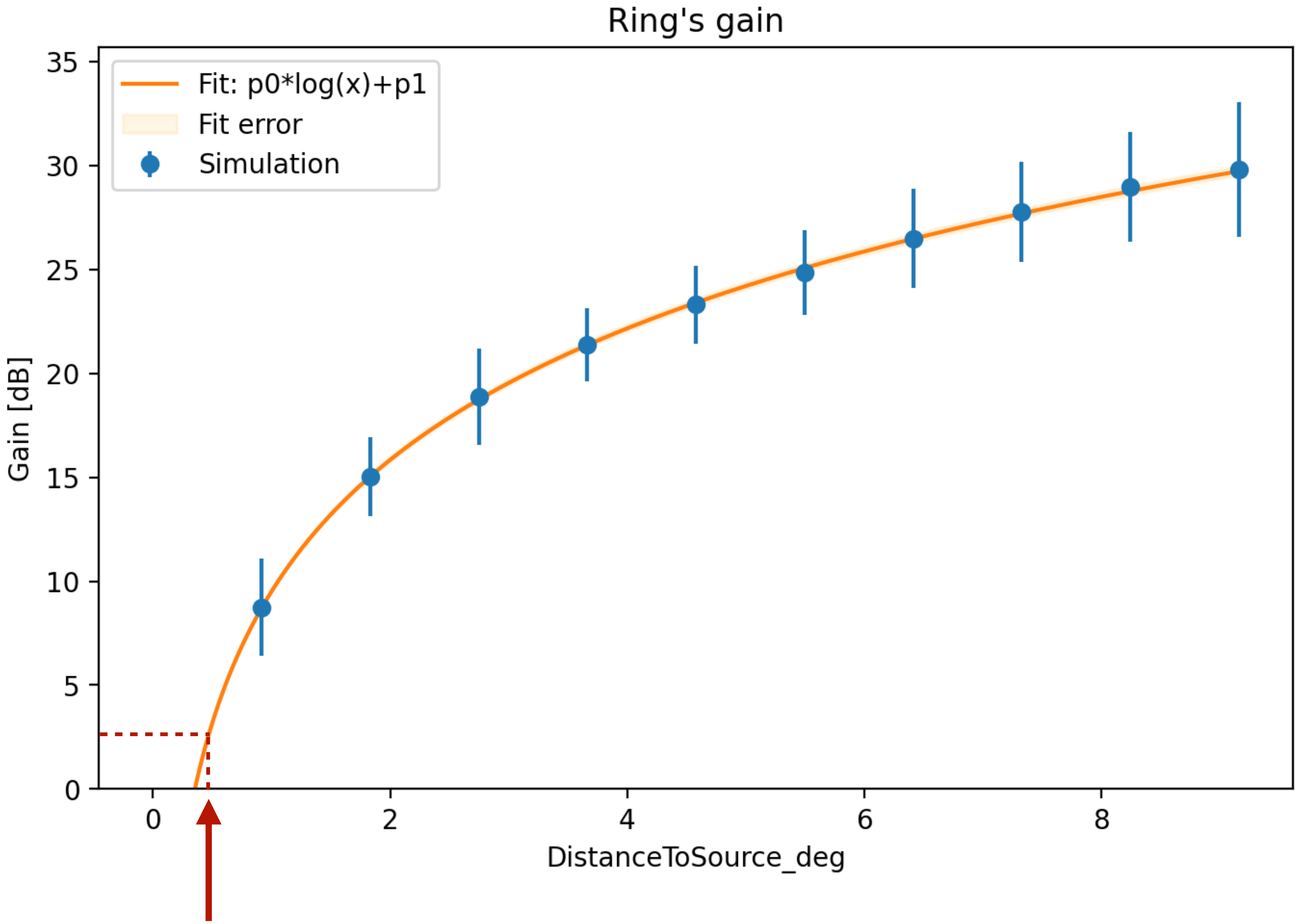
- How does one define angular resolution?
- Could this technique be used to localize MBHBs in the sky?
- What happens if we add noise?
- What happens when there is more than one GW source in the data?

Quantifying cancellation

$|\tilde{\kappa}_i^2|$ is the set of $|\tilde{\kappa}^2|$ on ring *i*



$$g_i = 10 \cdot \log_{10} \frac{\text{median}(|\tilde{\kappa}_i|^2)}{|\tilde{\kappa}_0|^2}$$

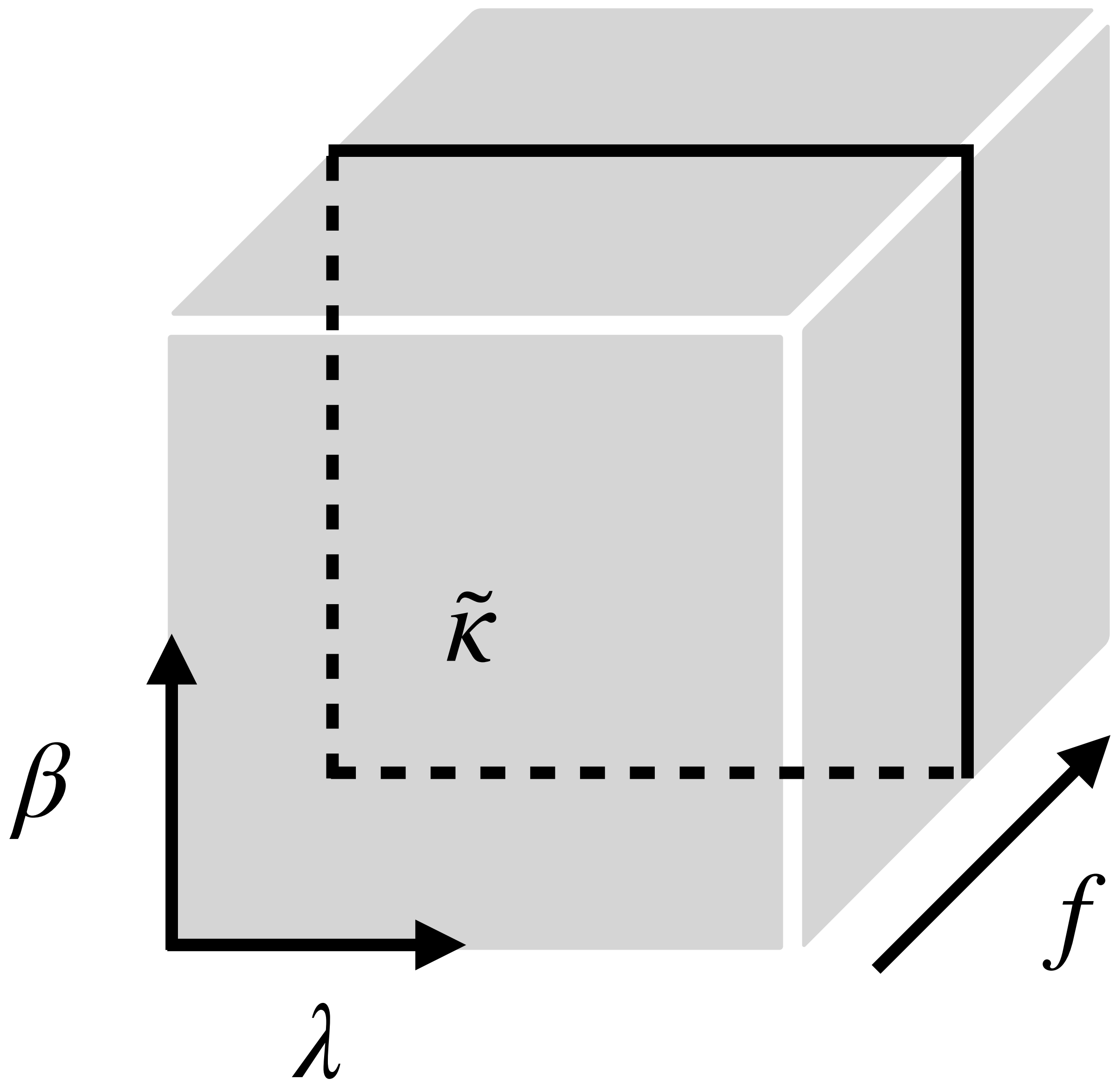


Extrapolation at 3dB: 0.49 deg ($8.5 \cdot 10^{-3}$rad)

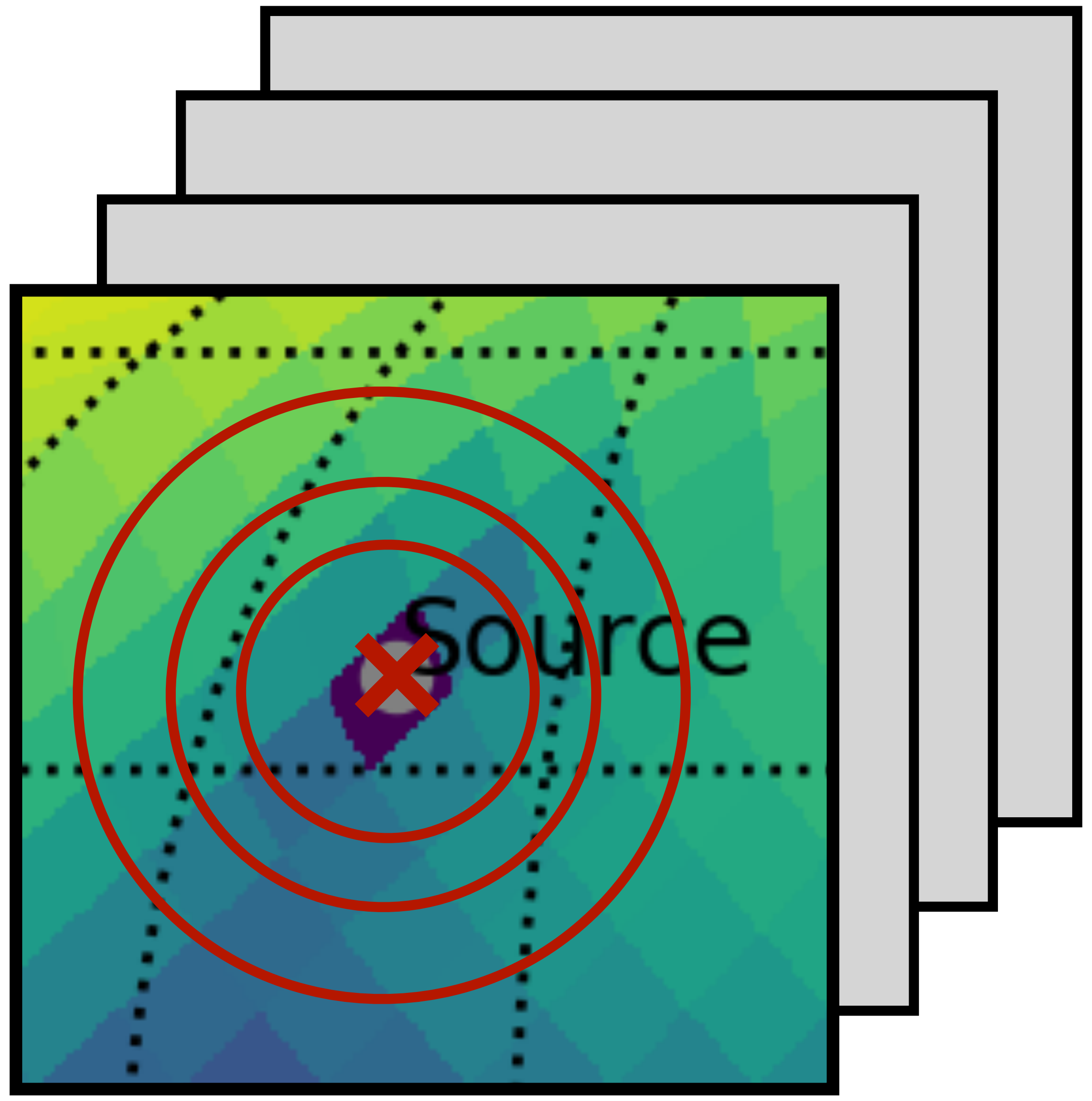
VGB: ESCet

Analyzing MBHBs

①

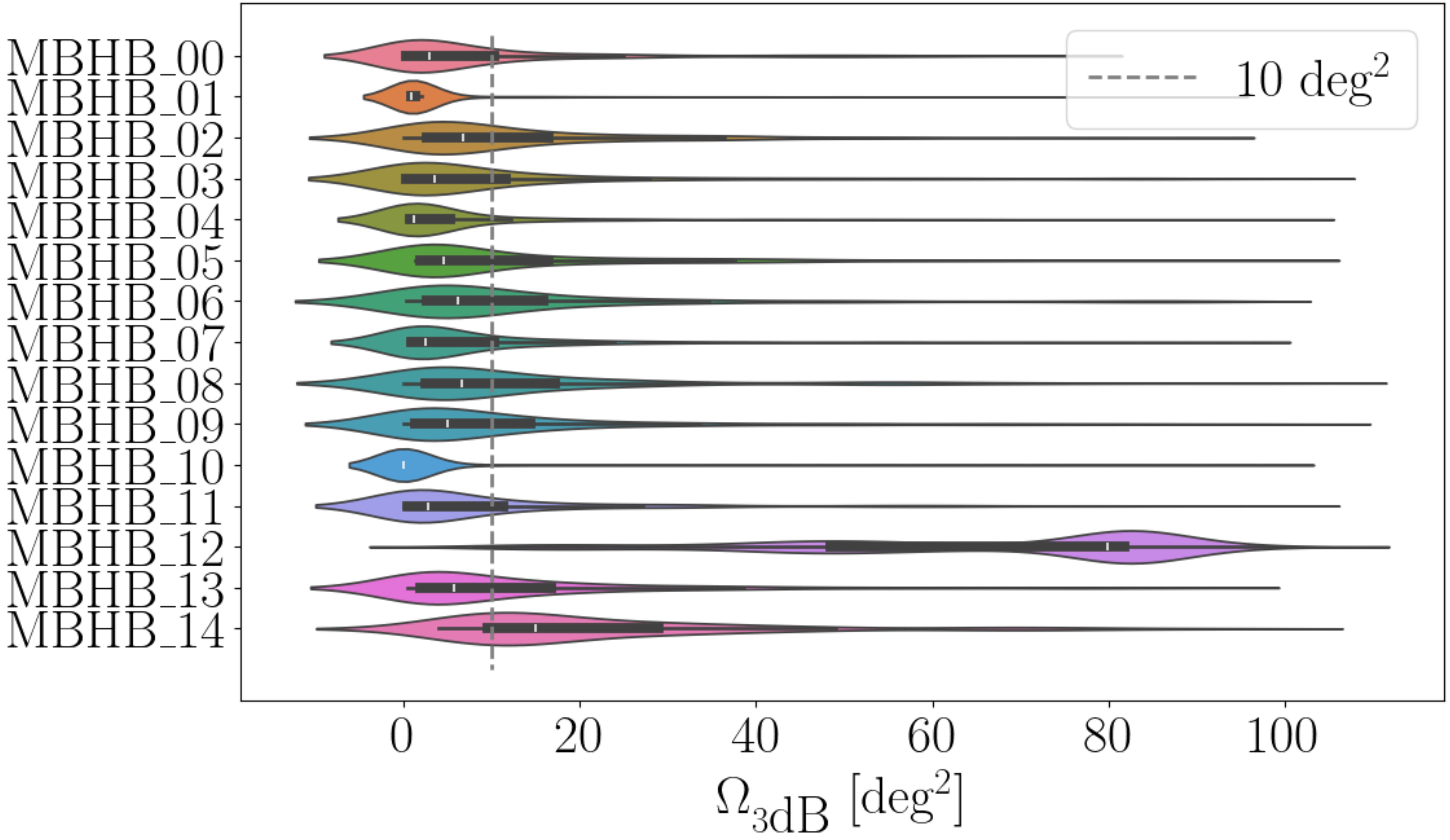


②



→ Fit and extrapolate at 3 dB

Results for MBHBs



Answers

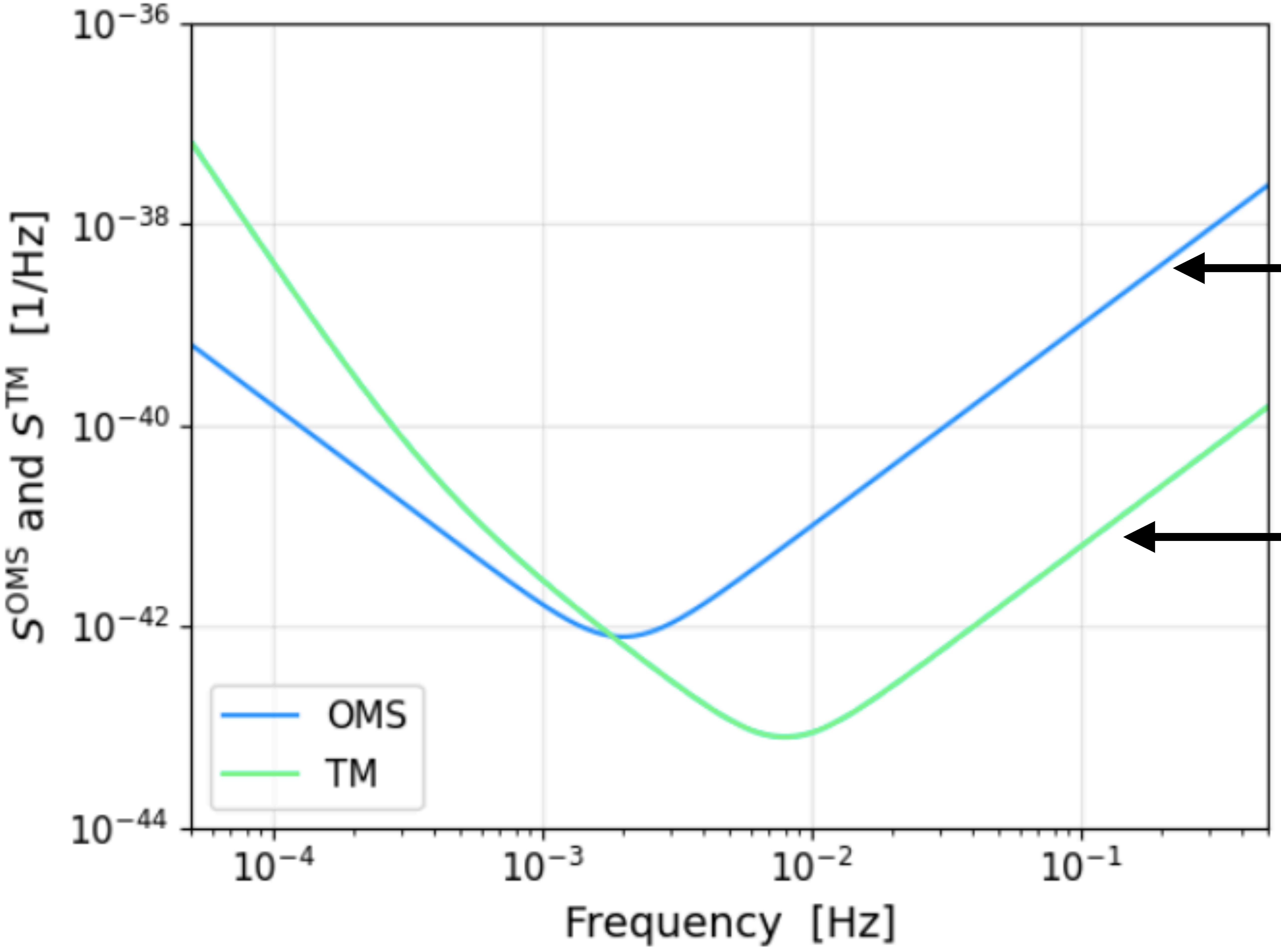
- We estimate coronagraphic TDI's resolution with an ad hoc method.
- Coronagraphic TDI can be used for MBHB sky localization.
- Among tested MBHBs the best angular resolution was $(6.89 \pm 3.01)\,\mathrm{deg}^2$.

Detector’s response

Questions

- How does coronagraphic TDI respond to noise?
- What happens when the constellation is moving?

Analytic noise model



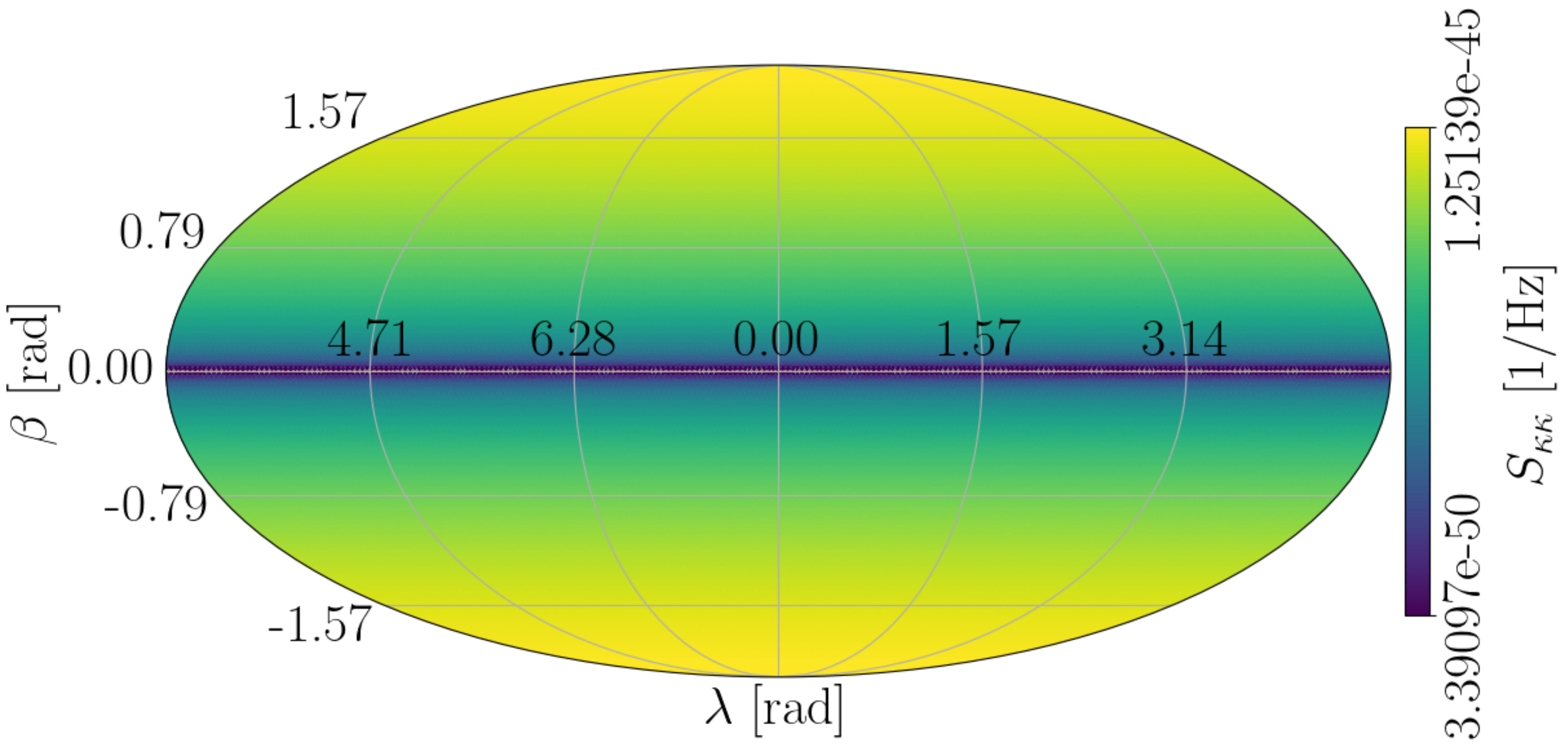
Optical metrology system (OMS)

Test mass acceleration (TM)

[6] Fig. 1 in arXiv:2303.15929

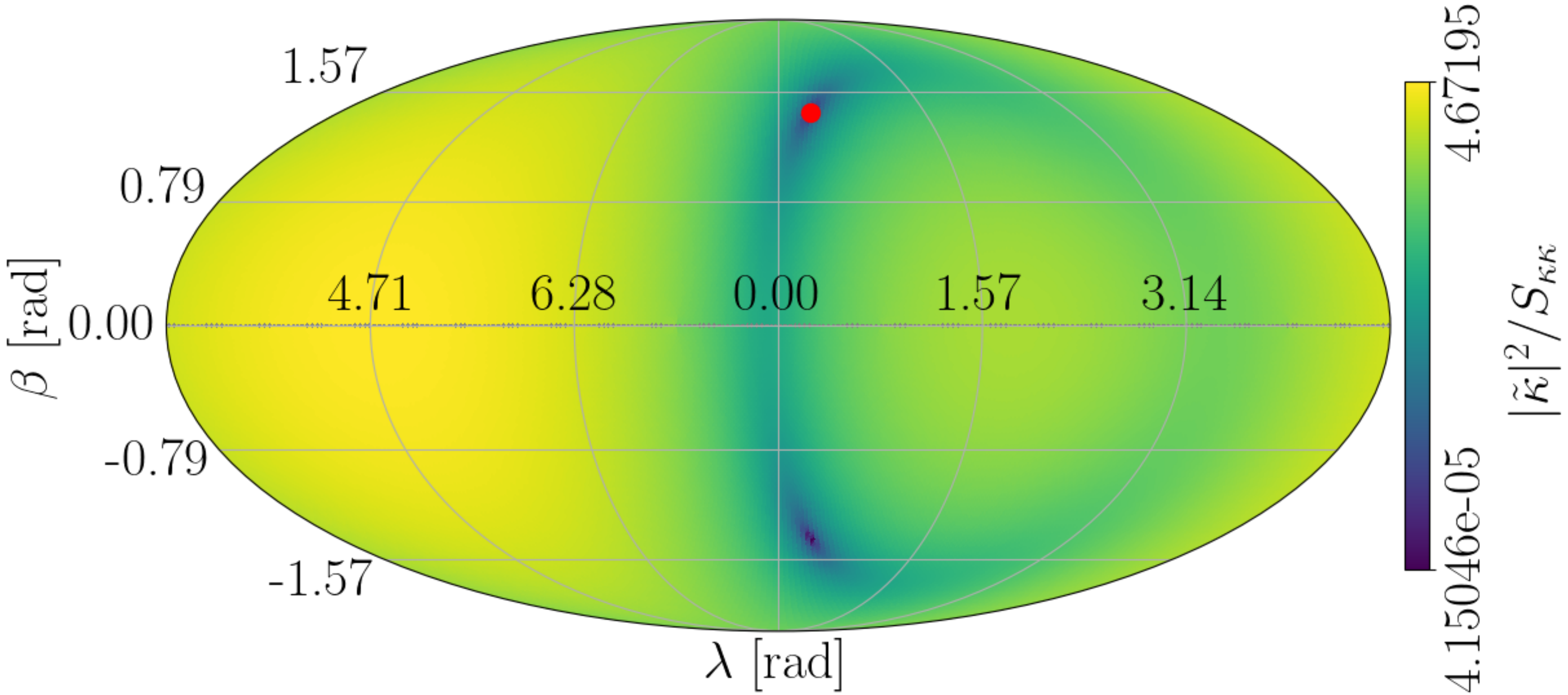
Coronagraphic TDI's response

$f = 3.788\,\mathrm{mHz}$



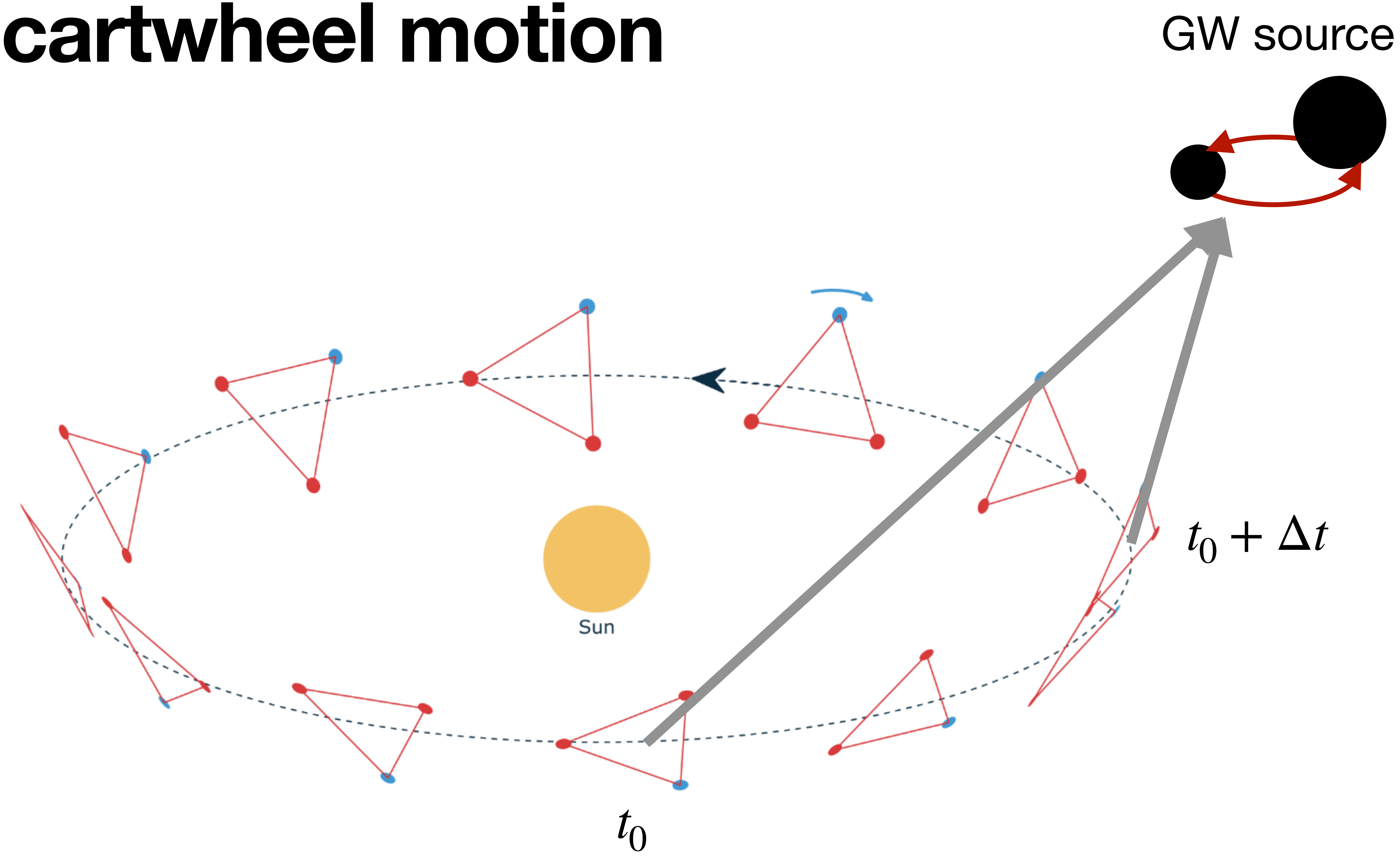
Towards SNR

$f = 3.788\,\mathrm{mHz}$



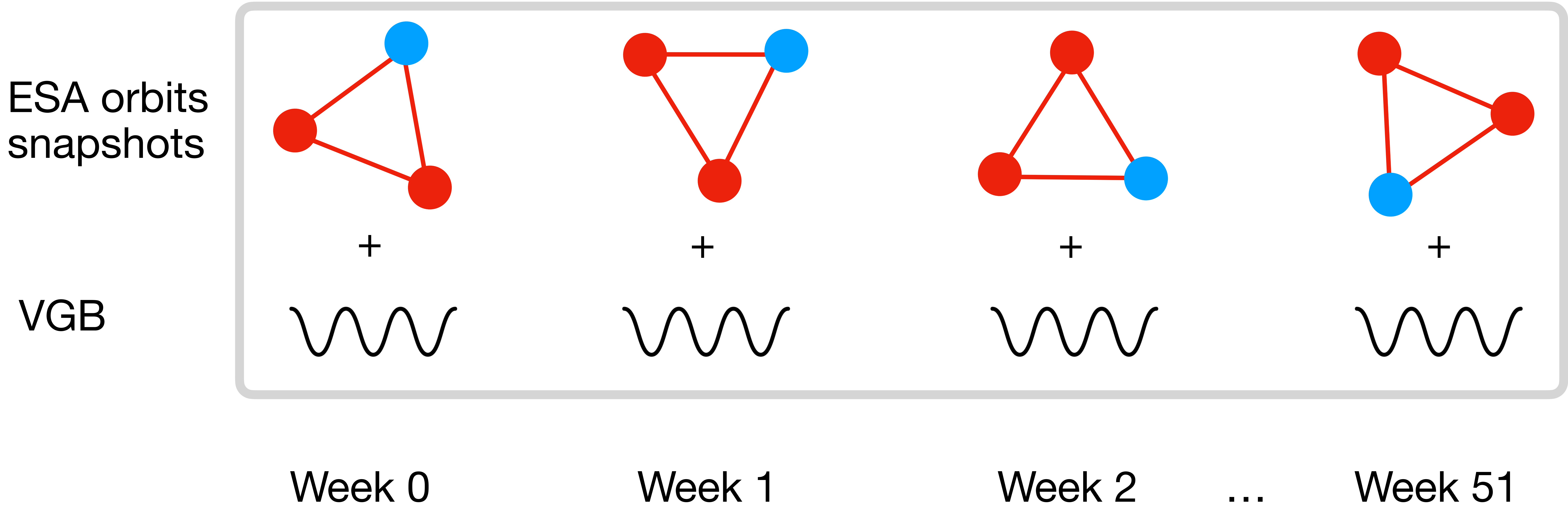
VGB: ZTFJ2243

LISA's cartwheel motion

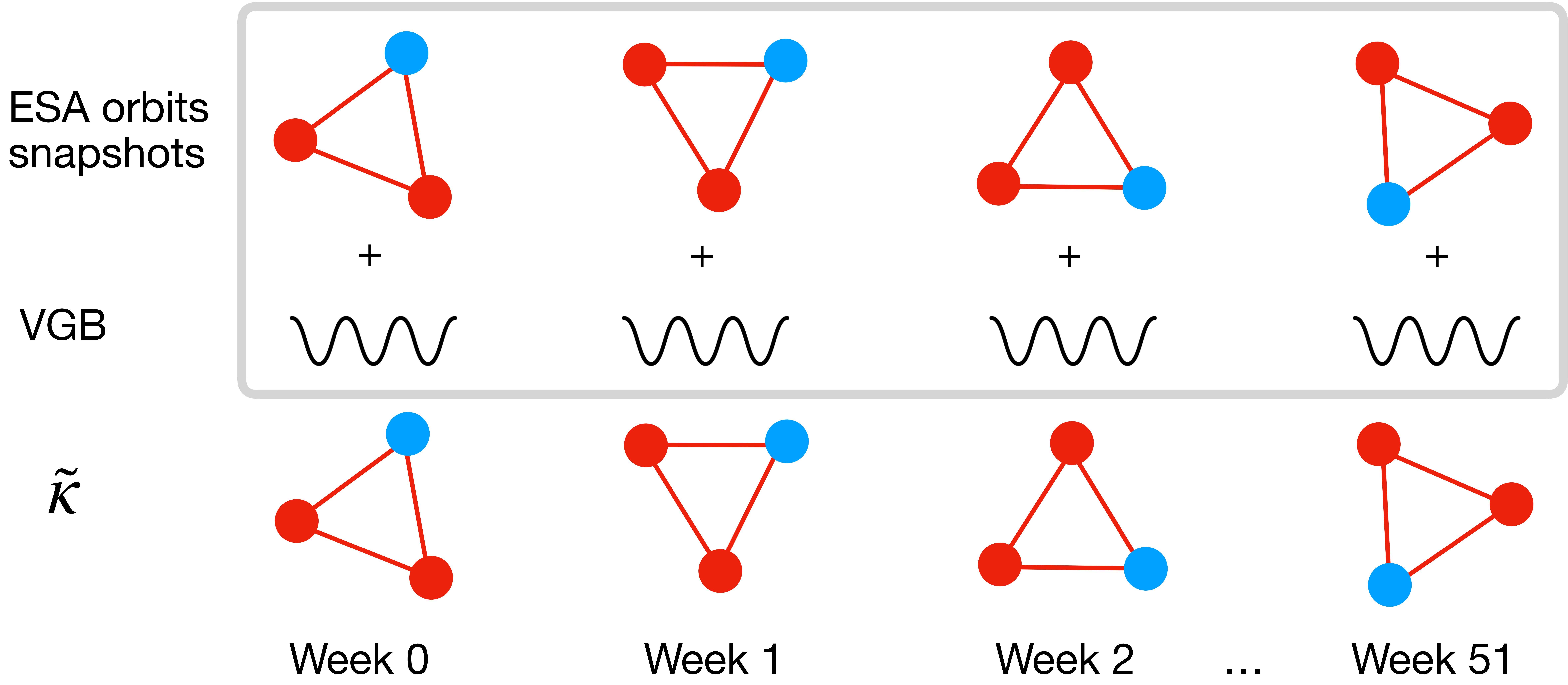


[7] Adapted from Fig. 6.3 in arXiv:2402.07571

Simulation

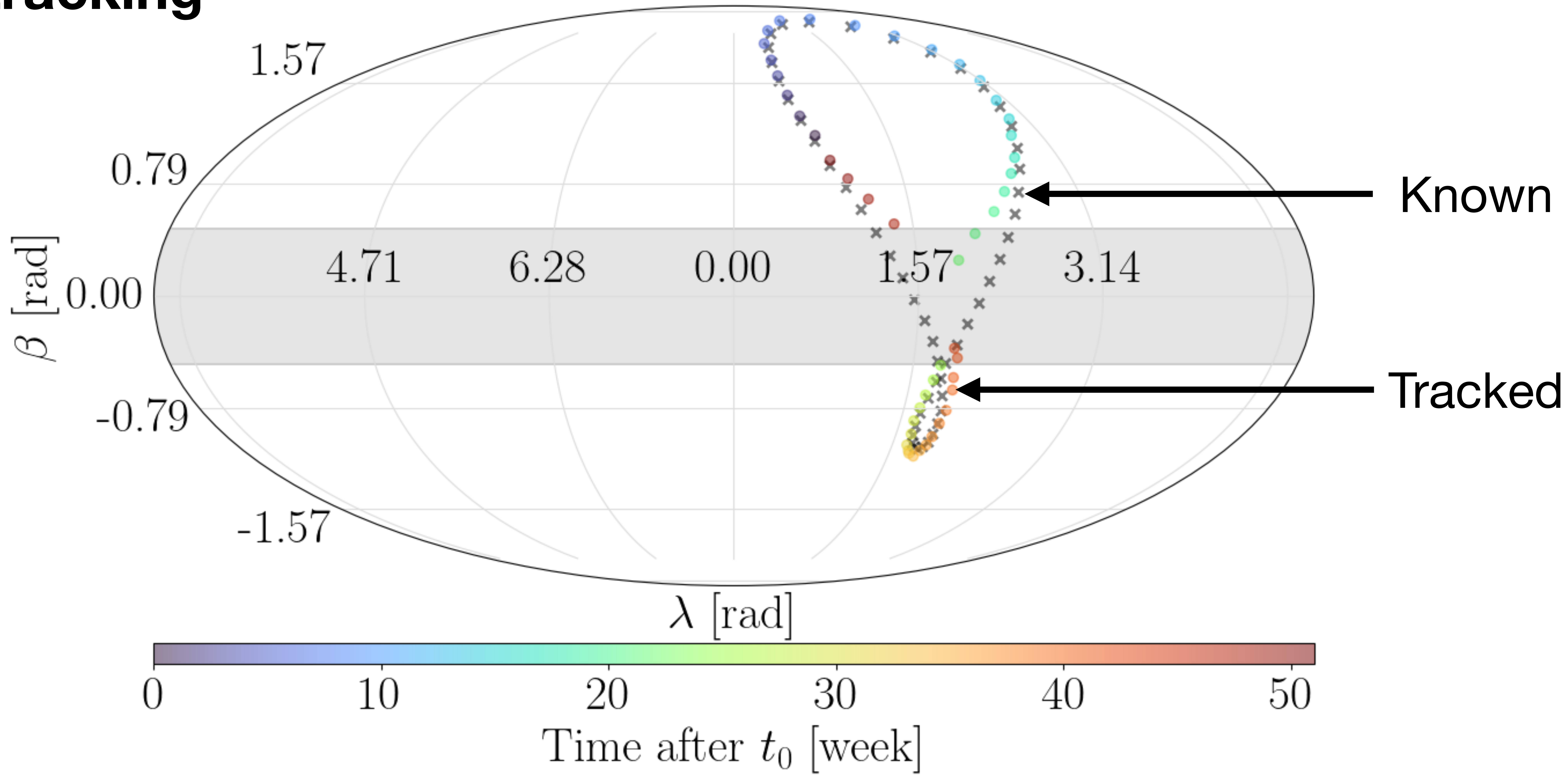


Synchronous case

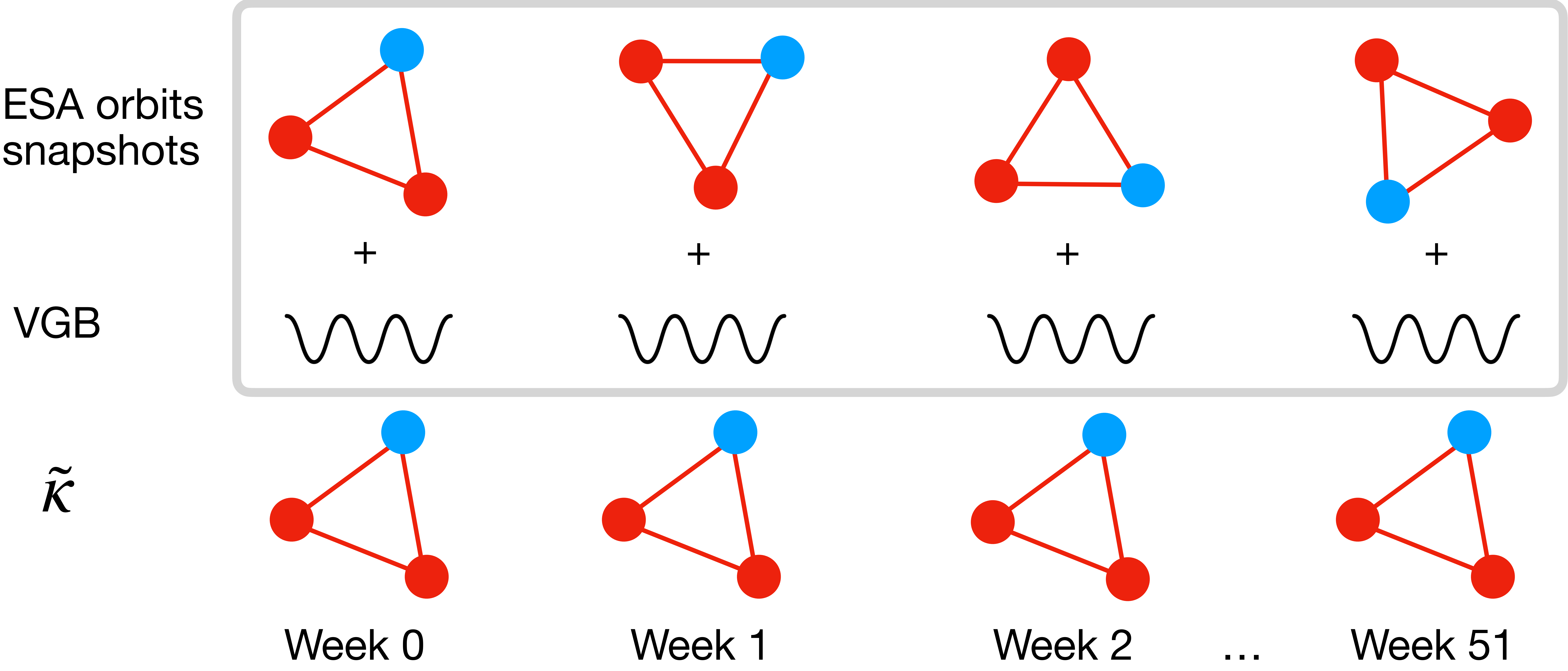


Synchronous case

Source tracking

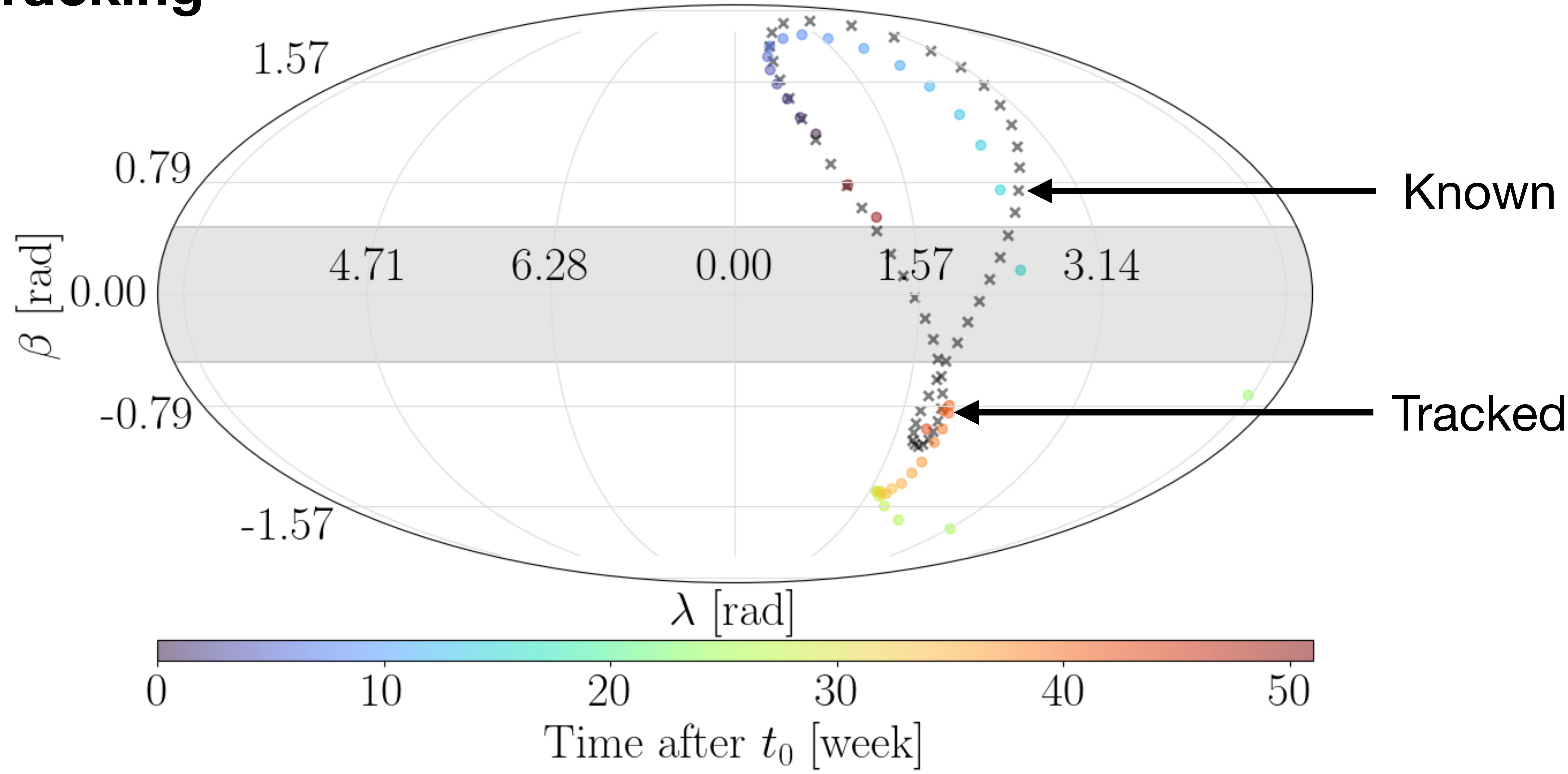


Asynchronous case



Asynchronous case

Source tracking



Answers

- We compute coronagraphic TDI’s response to an analytic noise model.
- Synchronous case: the method successfully follows the position of source in the LISA plane.
- Asynchronous case: there is a mismatch between expected and estimated position of the source of 5% in latitude and of 11% on longitude after 4 weeks.

Conclusion

Next steps

Current results are encouraging and show that coronagraphic TDI has the potential to find concrete applications in LISA data analysis.

- Detection of unmodeled sources.
- Sky localization of MBHBs for low latency analysis.
- Glitch veto.

Backup

What It Looks Like

Theory

- For Sagnac TDI variables $(\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma})$ in frequency domain, the null stream TDI variable reads:

$$\tilde{\kappa}(f, \beta, \lambda) = \begin{bmatrix} \beta_+(f,\beta,\lambda)\gamma_\times(f,\beta,\lambda) - \beta_\times(f,\beta,\lambda)\gamma_+(f,\beta,\lambda) \\ \gamma_+(f,\beta,\lambda)\alpha_\times(f,\beta,\lambda) - \gamma_\times(f,\beta,\lambda)\alpha_+(f,\beta,\lambda) \\ \alpha_+(f,\beta,\lambda)\beta_\times(f,\beta,\lambda) - \alpha_\times(f,\beta,\lambda)\beta_+(f,\beta,\lambda) \end{bmatrix} \cdot \begin{bmatrix} \tilde{\alpha}(f) \\ \tilde{\beta}(f) \\ \tilde{\gamma}(f) \end{bmatrix}$$

Sky position

TDI + antenna information

TDI basis

- From frequency domain we can go back to time domain.

[8] M. Tinto and S. Larson, LISA time-delay interferometry zero-signal solution: Geometrical properties, Phys. Rev. D 70, 062002 (2004).

What It Looks Like

Implementation

Input simulations from LISA Orbits [3] + LISA GW Response [4]

Computed with PyTDI [5]

$$\tilde{\kappa}(f, \beta, \lambda) = \overrightarrow{A}(f, \beta, \lambda) \cdot \overrightarrow{D}(f)$$

$(L_{ij}, \hat{n}_{ij}, \vec{x}_i)$ from LISA Orbits

[9] J.-B. Bayle, A. Hees, M. Lilley, and C. Le Poncin-Lafitte, LISA Orbits (2022).
[10] J.-B. Bayle, Q. Baghi, A. Renzini, and M. Le Jeune, LISA GW Response (2022).
[11] M. Staab, J.-B. Bayle, and O. Hartwig, PyTDI (2023).

Which parameters matter