Time-delay interferometry as a coronagraph

Septième assemblée générale du GdR ondes gravitationnelles
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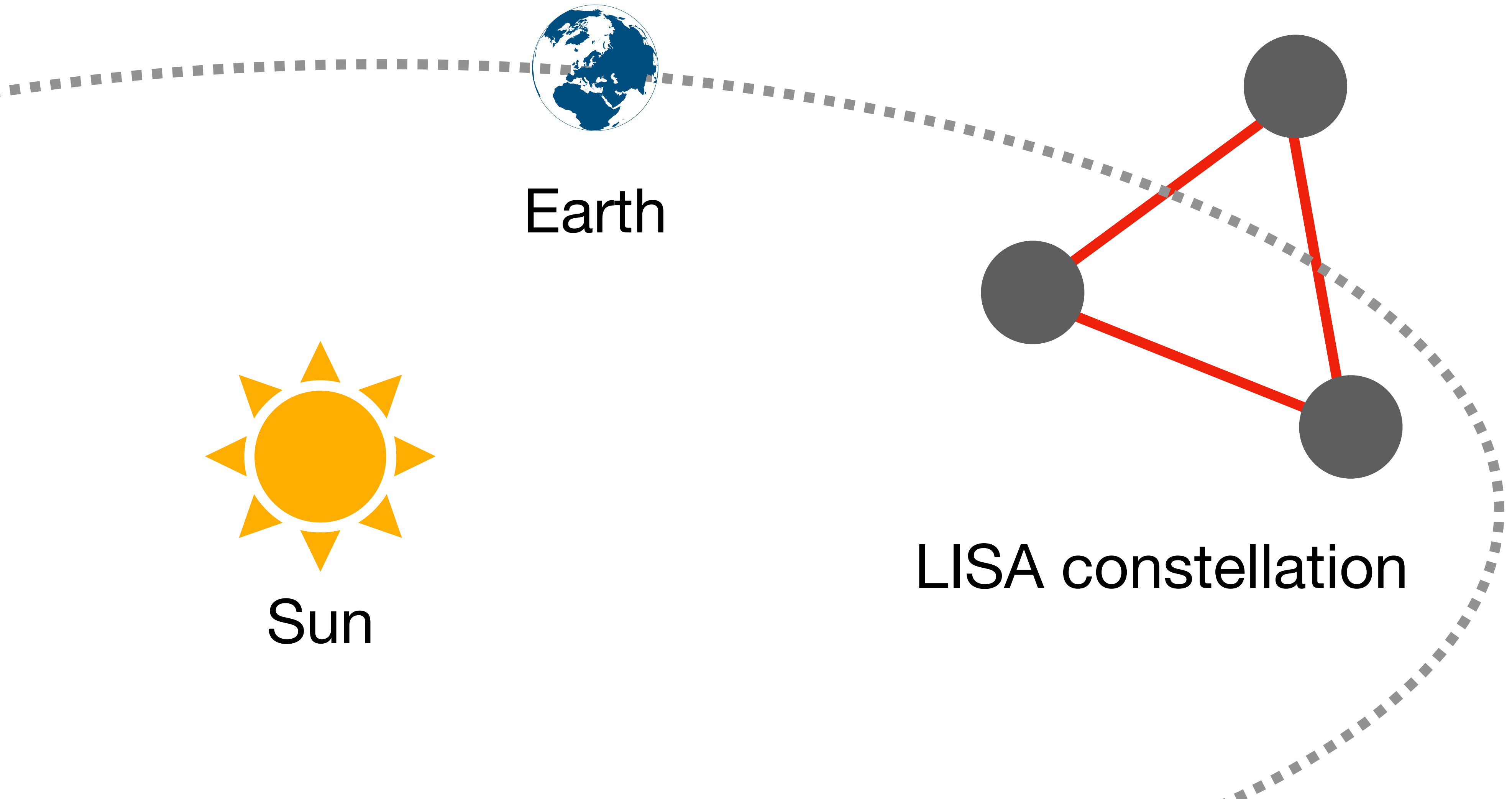
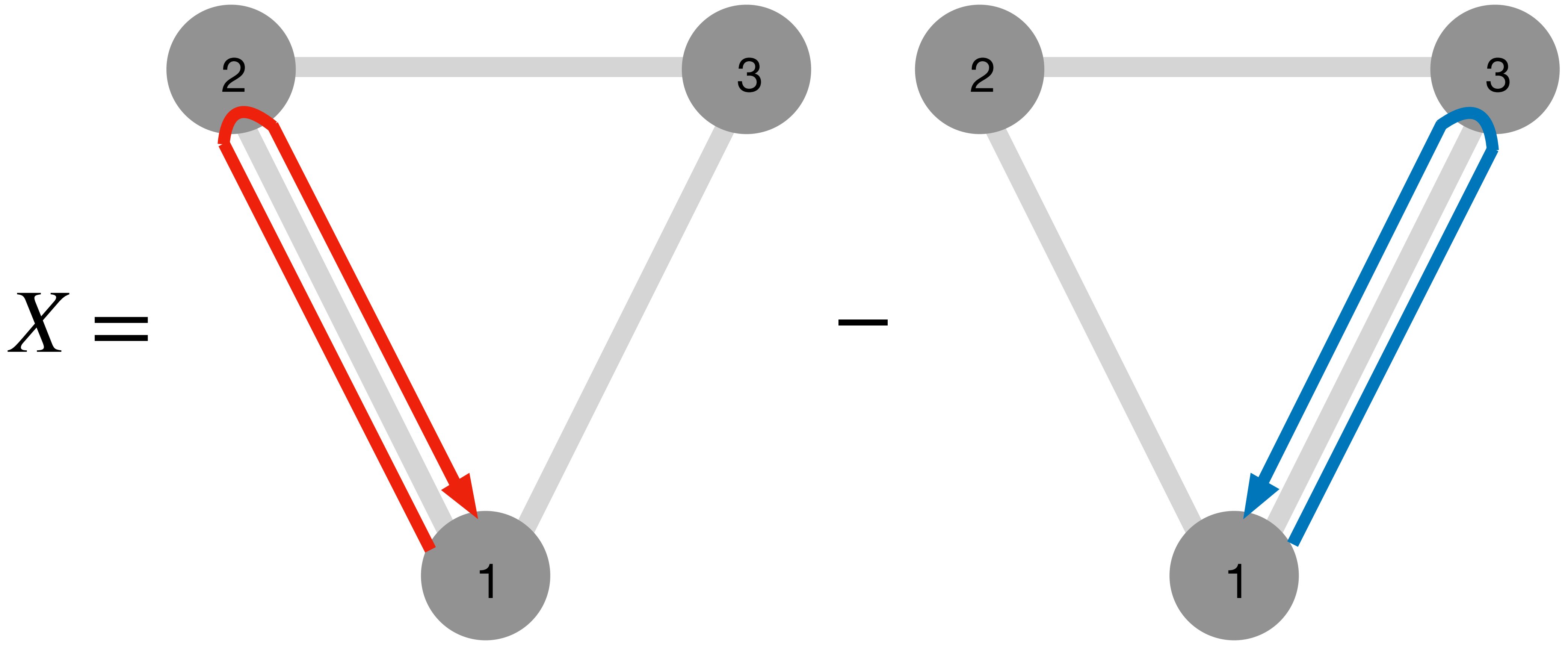
LISA and TDI

- Laser interferometer space antenna (LISA):
  - mHz range
  - Expected sources: galactic binaries, massive black hole merger, extreme mass ratio inspiral, stochastic GW background
- **Problem:** laser noise
- **Solution:** time-delay interferometry (TDI)



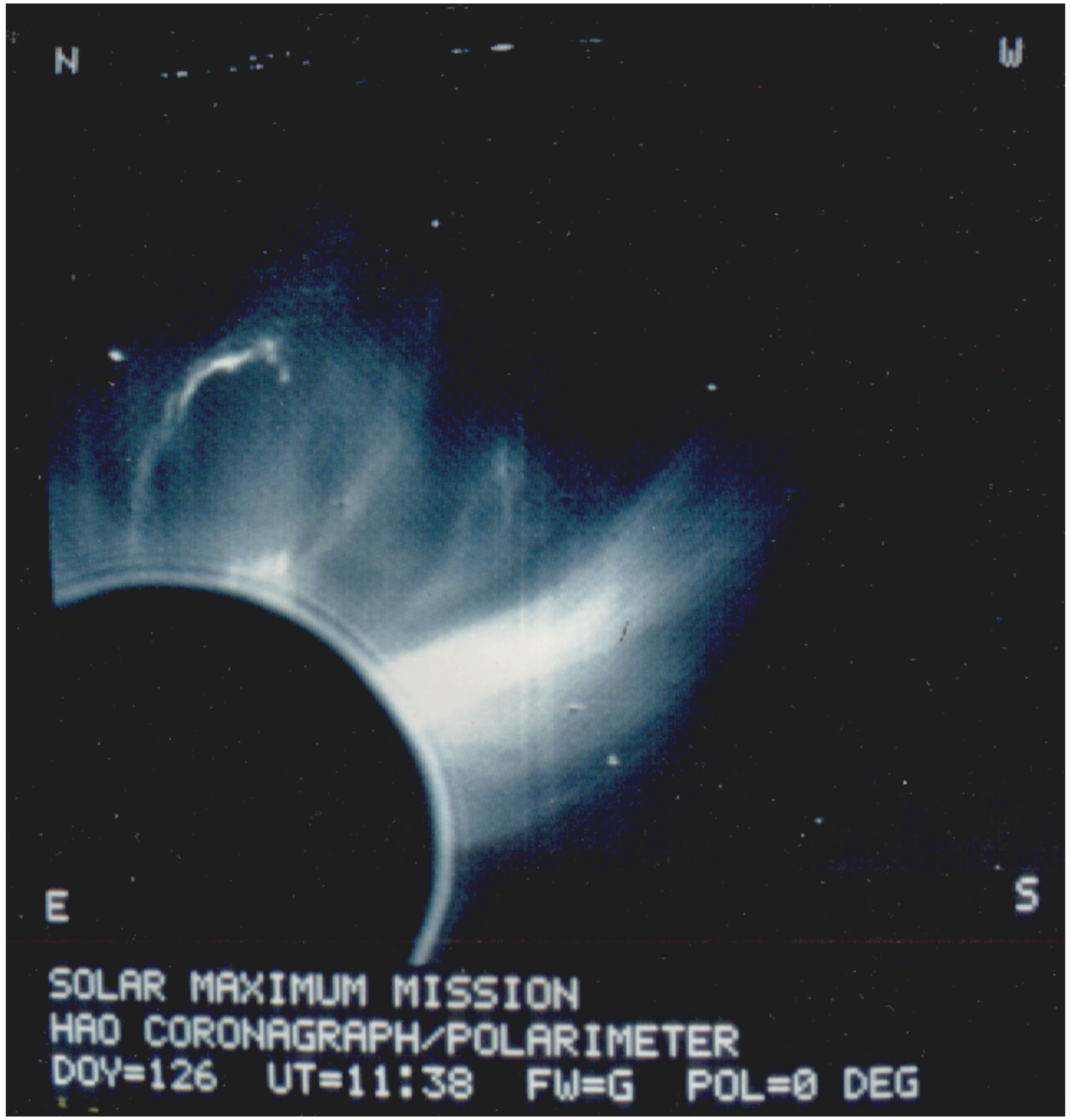


- Clever combination of interferometric data
- Rules but more than one combination
- Bases: (X, Y, Z), (α, β, γ)...

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

Coronagraph

- **Problem :** construct a TDI channel such that it suppresses GW signal coming from a specific direction.
- **Solution :** such a TDI variable can be constructed as a linear combination of a set of TDI variables which form (loosely) a basis with carefully chosen coefficients.
- **Key property :** this linear combination depends on two parameters directly related to the sky position of the source.



Coronagraph image of the Sun (NASA) [2]

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

What It Looks Like

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

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

Sky position　　TDI + antenna information　　TDI basis

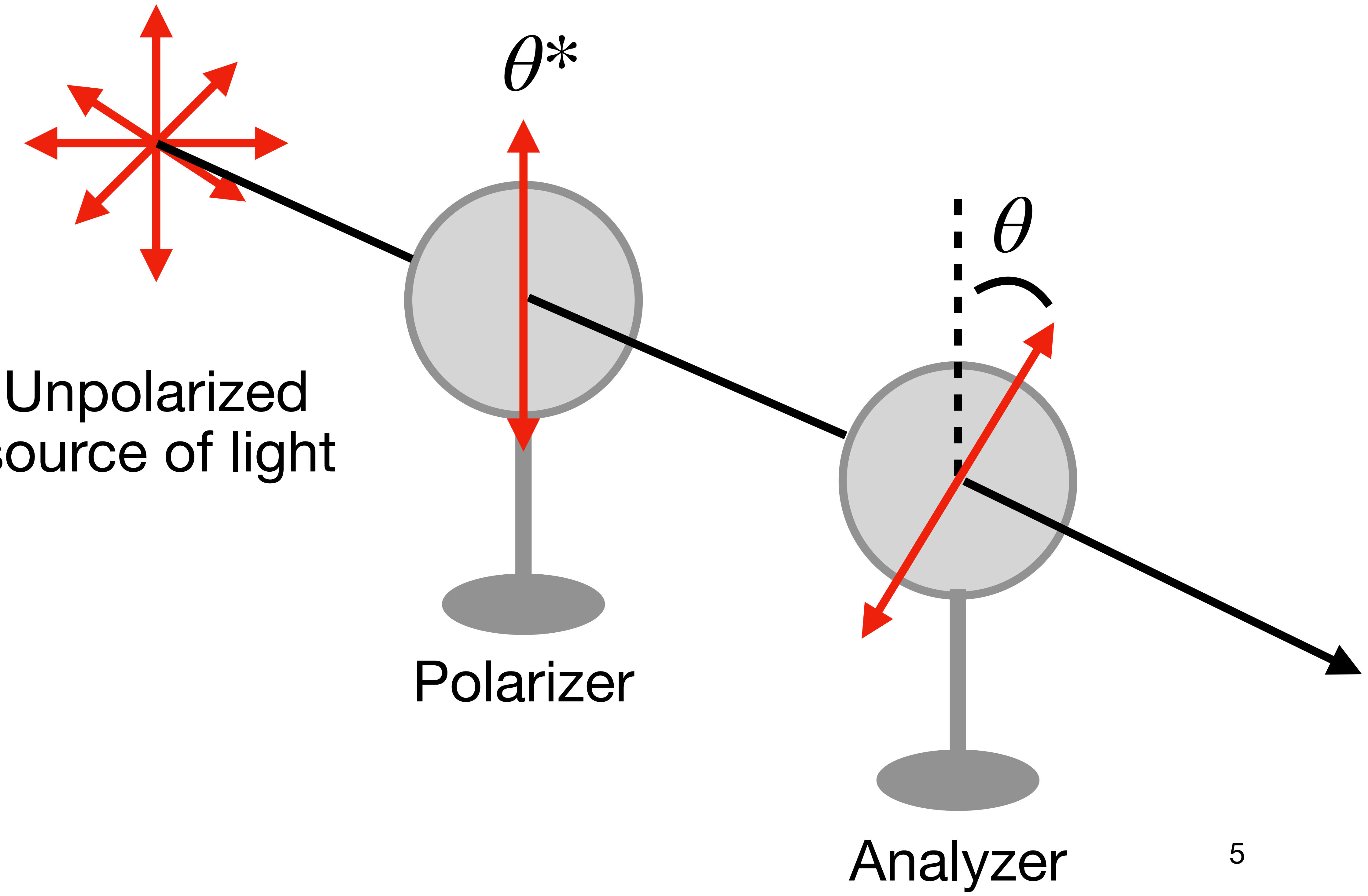
- From frequency domain we can go back to time domain.

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

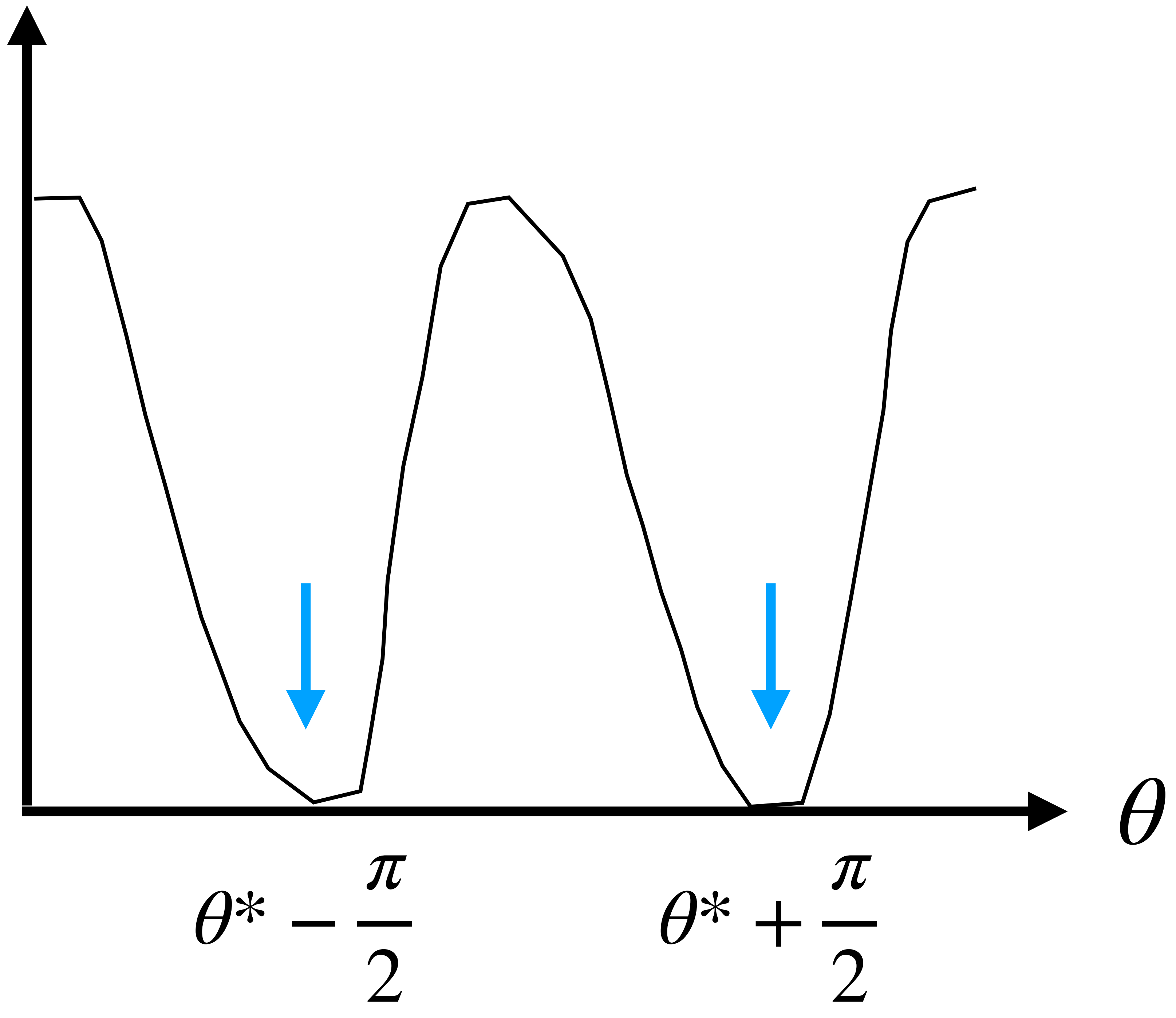
Application to Sky Position Estimation

- By construction, $\tilde{\kappa}(f, \lambda, \beta)$ has the property to tend to zero as $(\lambda, \beta) \to (\lambda_\star, \beta_\star)$ where $(\lambda_\star, \beta_\star)$ denotes the source's position.

- **Idea:** find (λ, β) which minimize $\tilde{\kappa}(f, \lambda, \beta)$.



$I = I_0 \cos\theta$ Malus Law



About the simulations

Assumptions

- Orbits: static constellation with unequal arm lengths
- Duration: 5.8 days
- 1st generation TDI (α, β, γ)
- One source
- No noise

Datasets

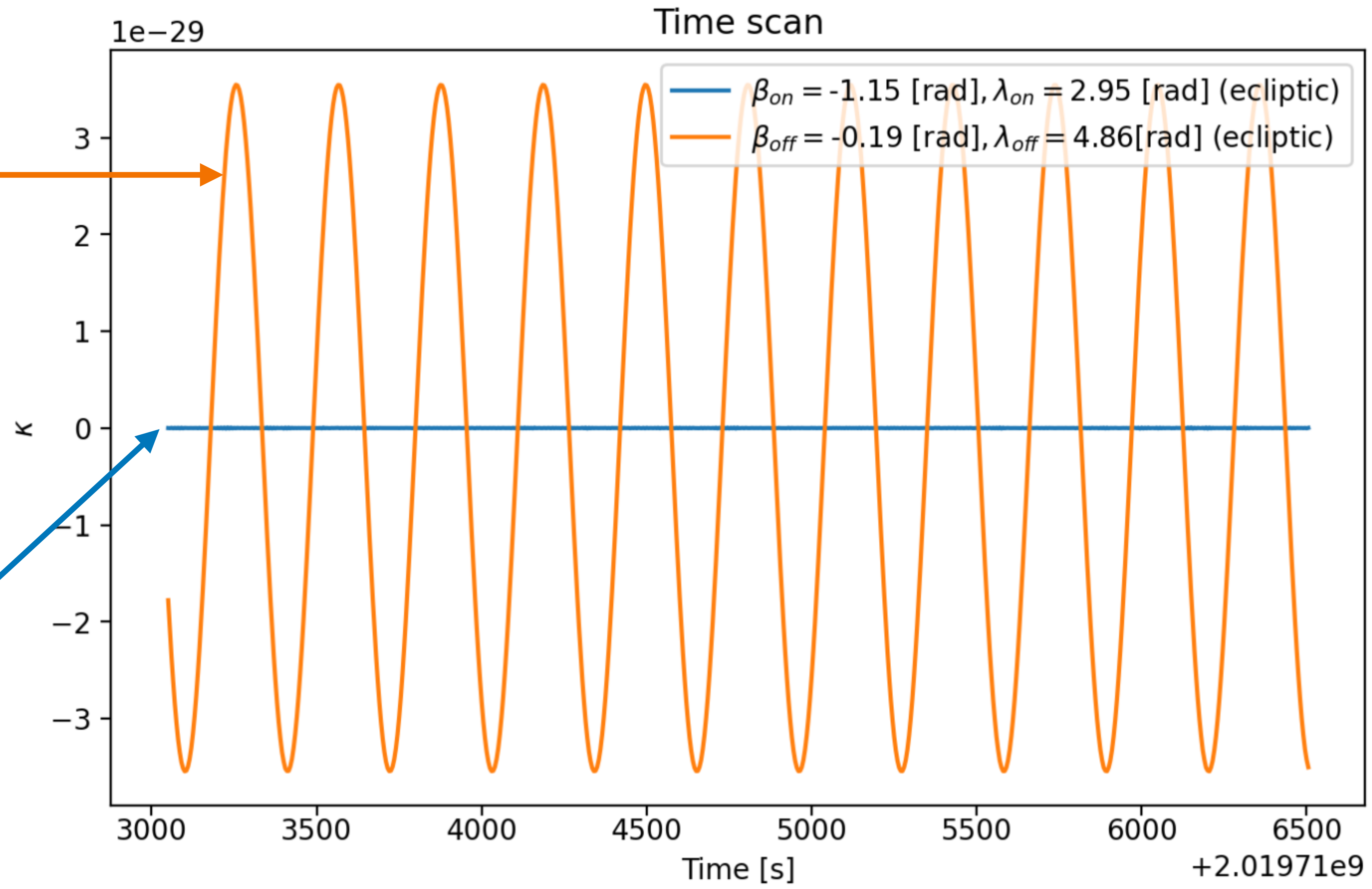
- Quasi monochromatic source:
  - Verification galactic binary (VGB)
  - Parameters $\{\lambda, \beta, f_0, D_L, \mathcal{M}_c, \iota, \phi_0, \psi\}$
- Multi-band source: Sangria (LDC2a) [4] massive black hole binary merger (MBHB)

[4] Le Jeune, Maude, & Babak, Stanislav. (2022). LISA Data Challenge Sangria (LDC2a) (Version v2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7132178

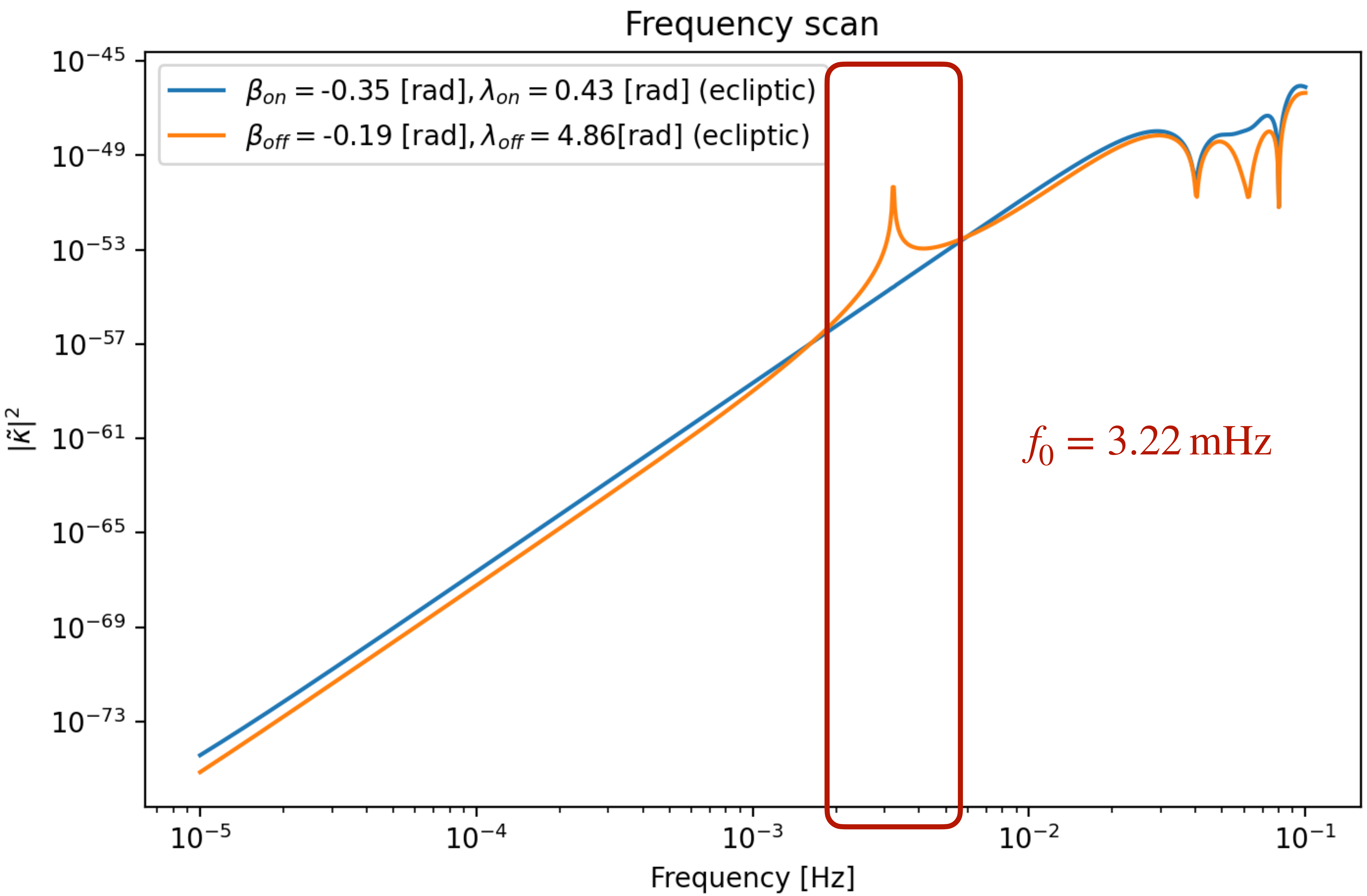
Results for a VGB

Not pointing at the source

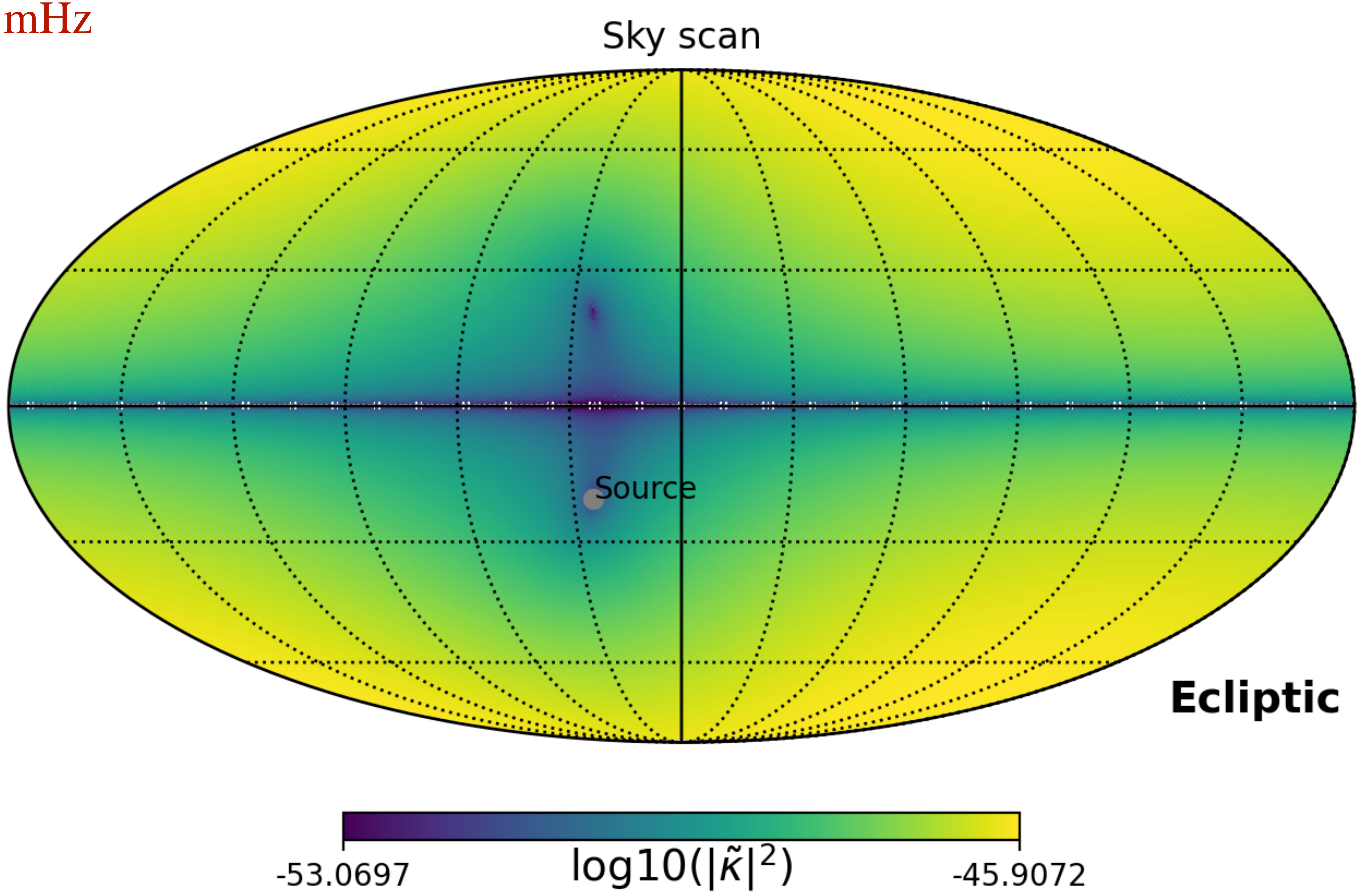
Pointing at the source



VGB: ESCet

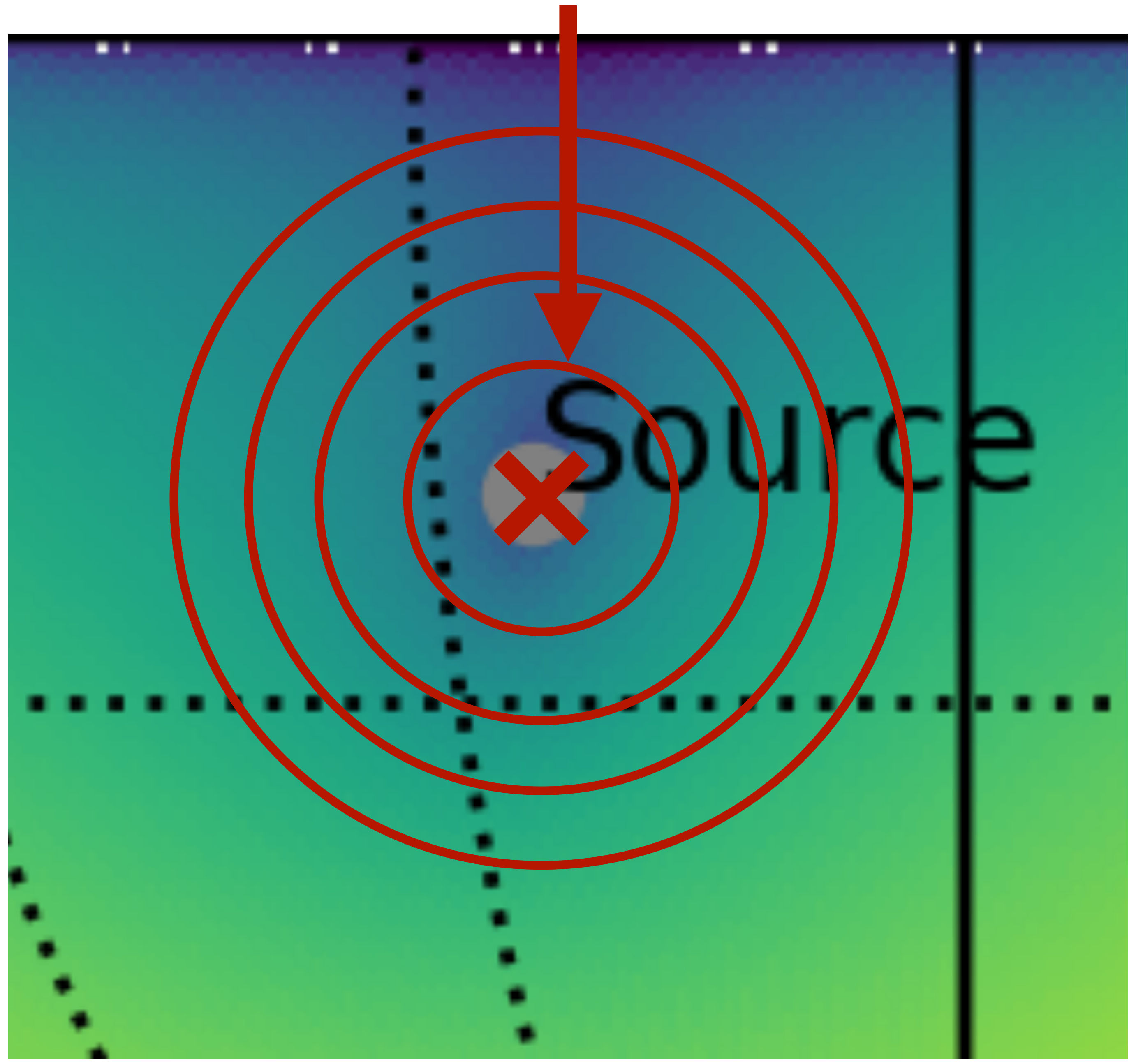

Frequency scan
β_{on} = -0.35 [rad], λ_{on} = 0.43 [rad] (ecliptic)
β_{off} = -0.19 [rad], λ_{off} = 4.86[rad] (ecliptic)
$f_0 = 3.22\,\mathrm{mHz}$
$|\tilde{\kappa}|^2$
10^{-45}
10^{-49}
10^{-53}
10^{-57}
10^{-61}
10^{-65}
10^{-69}
10^{-73}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]

$f_0 = 3.22\,\mathrm{mHz}$

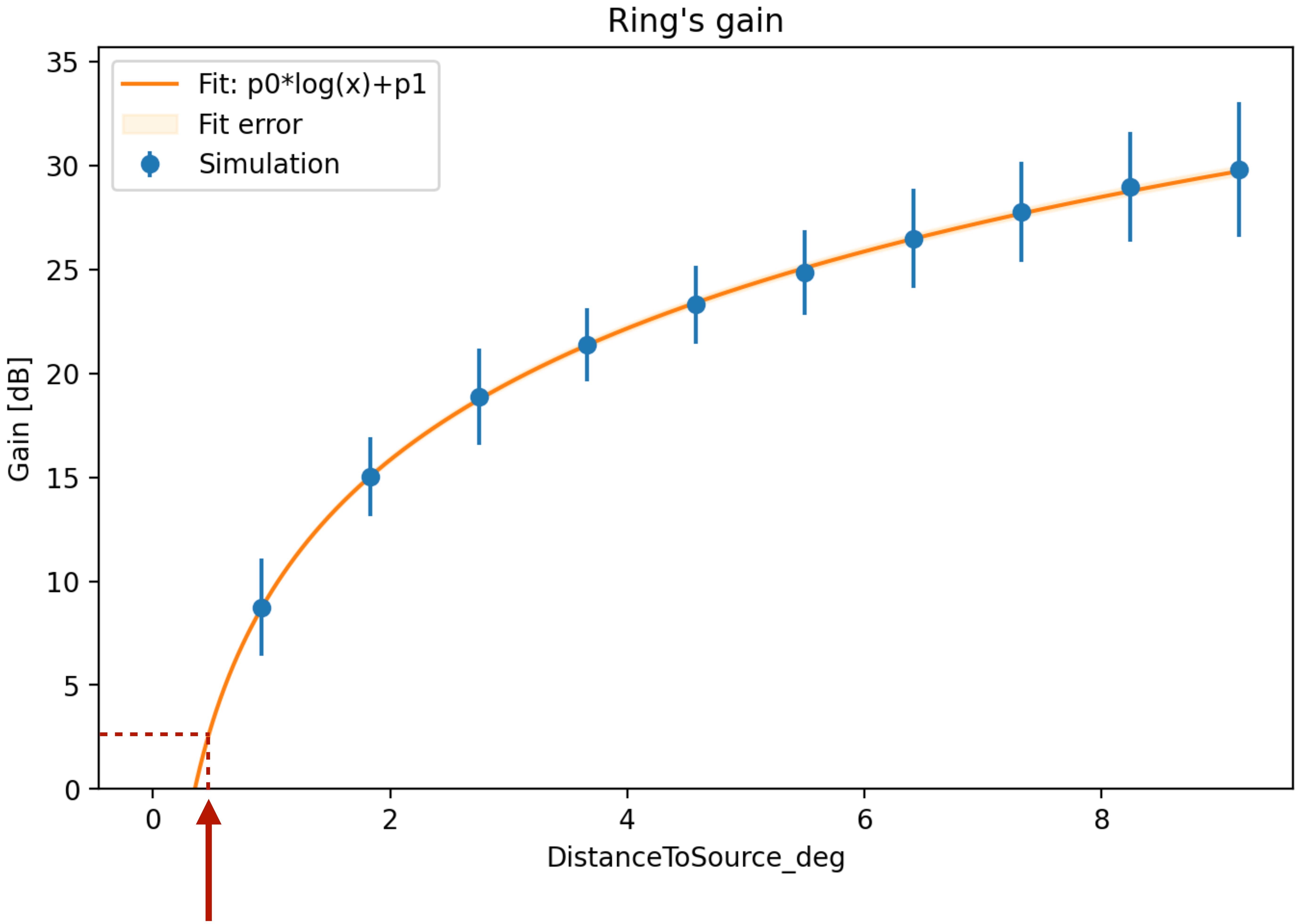


Quantifying cancellation

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



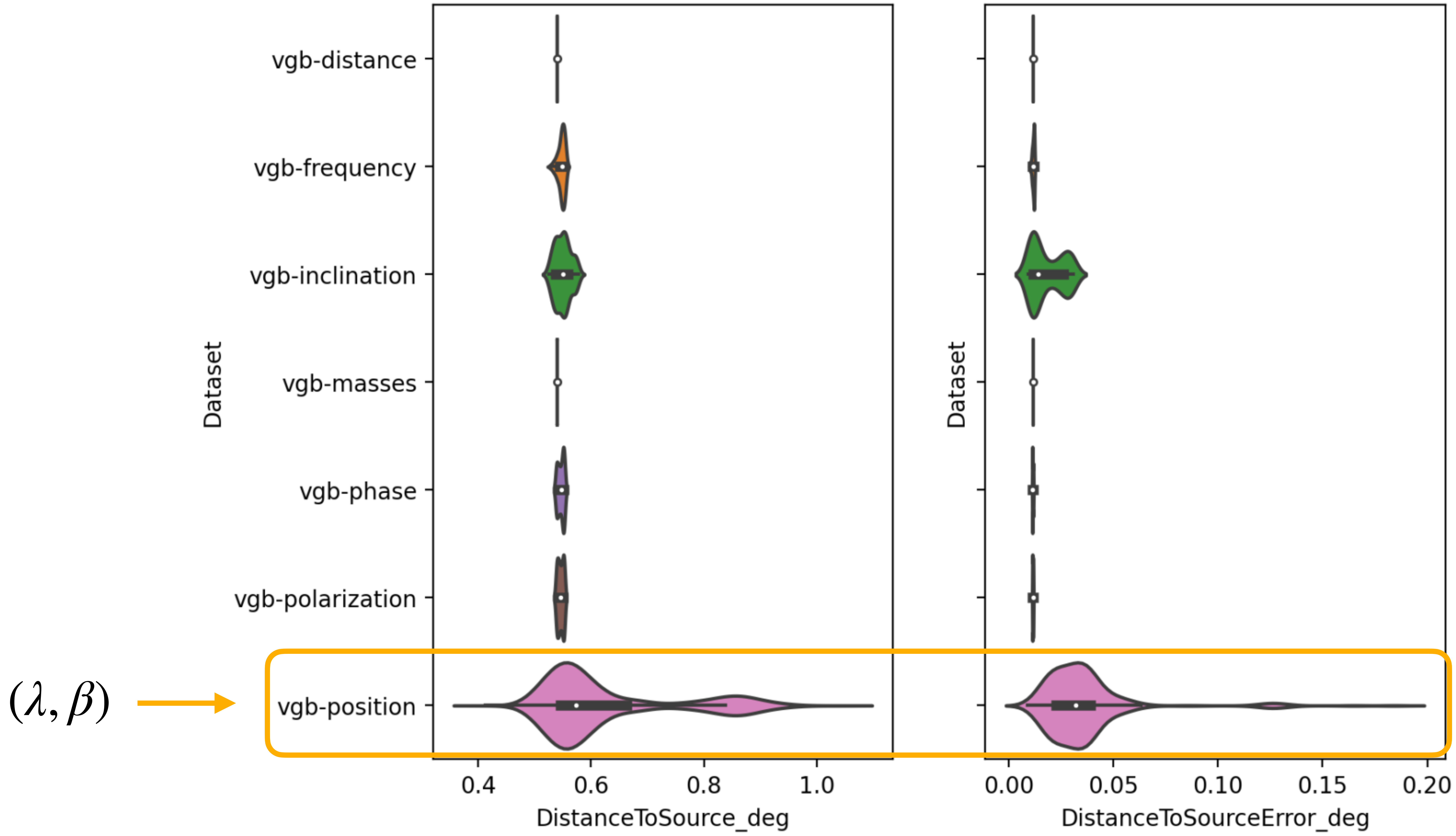
$$g_i = 10 \cdot \log_{10} \frac{\text{median}(|\tilde{\kappa}_i|^2)}{|\tilde{\kappa}_0|^2}$$



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

VGB: ESCet

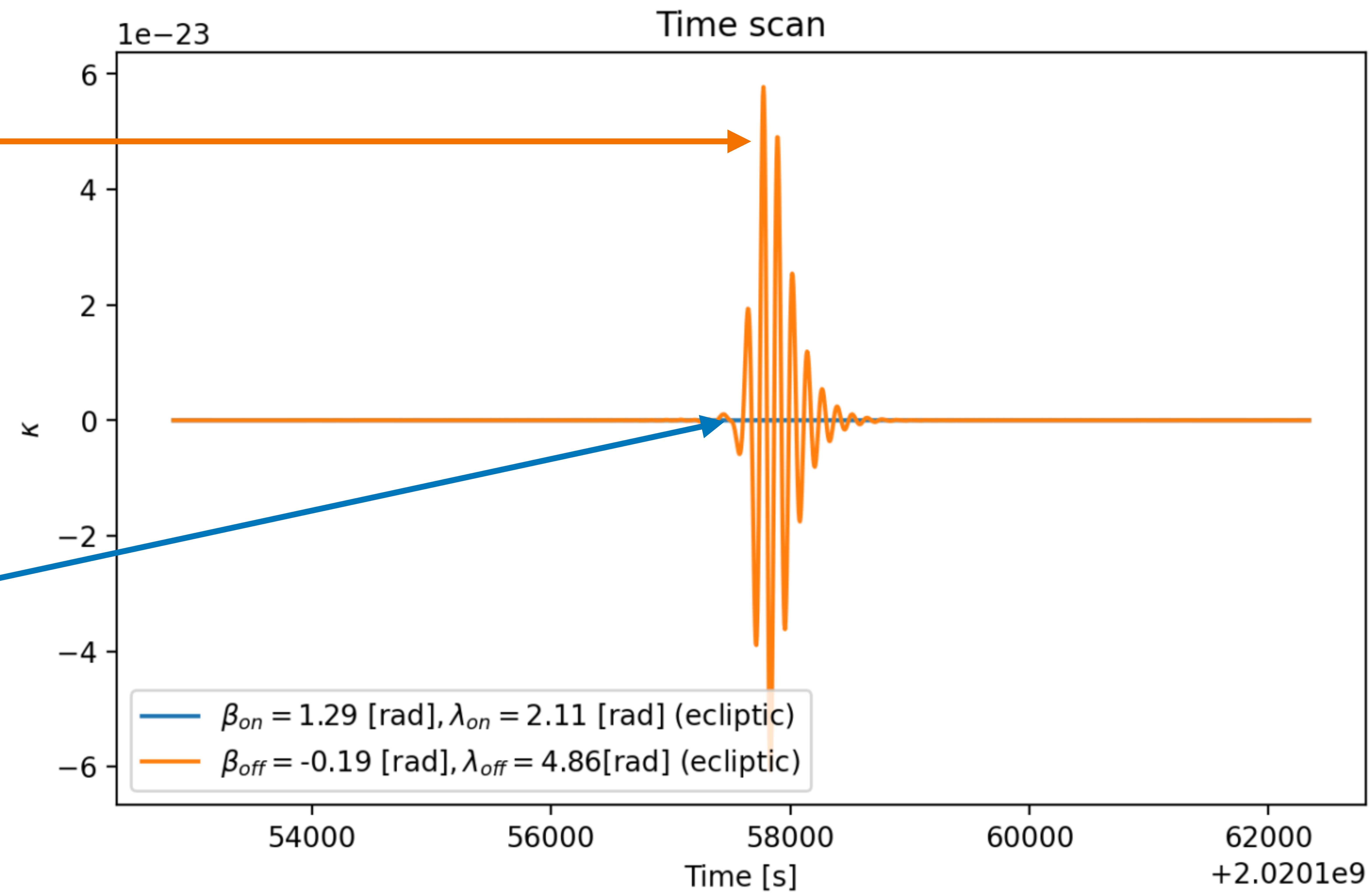
Which parameters matter



Results for MBHB

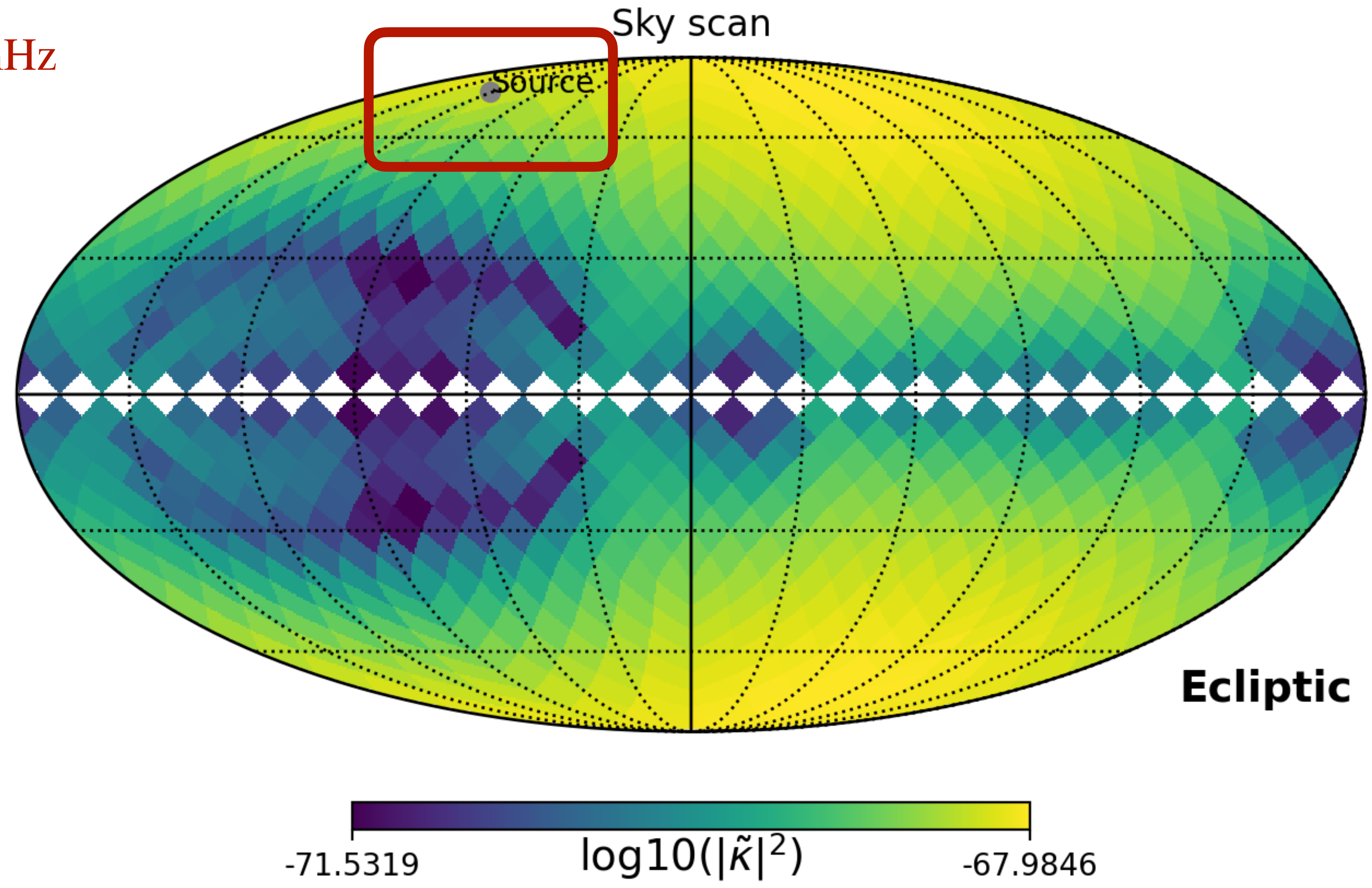
Not pointing at the source

Pointing at the source



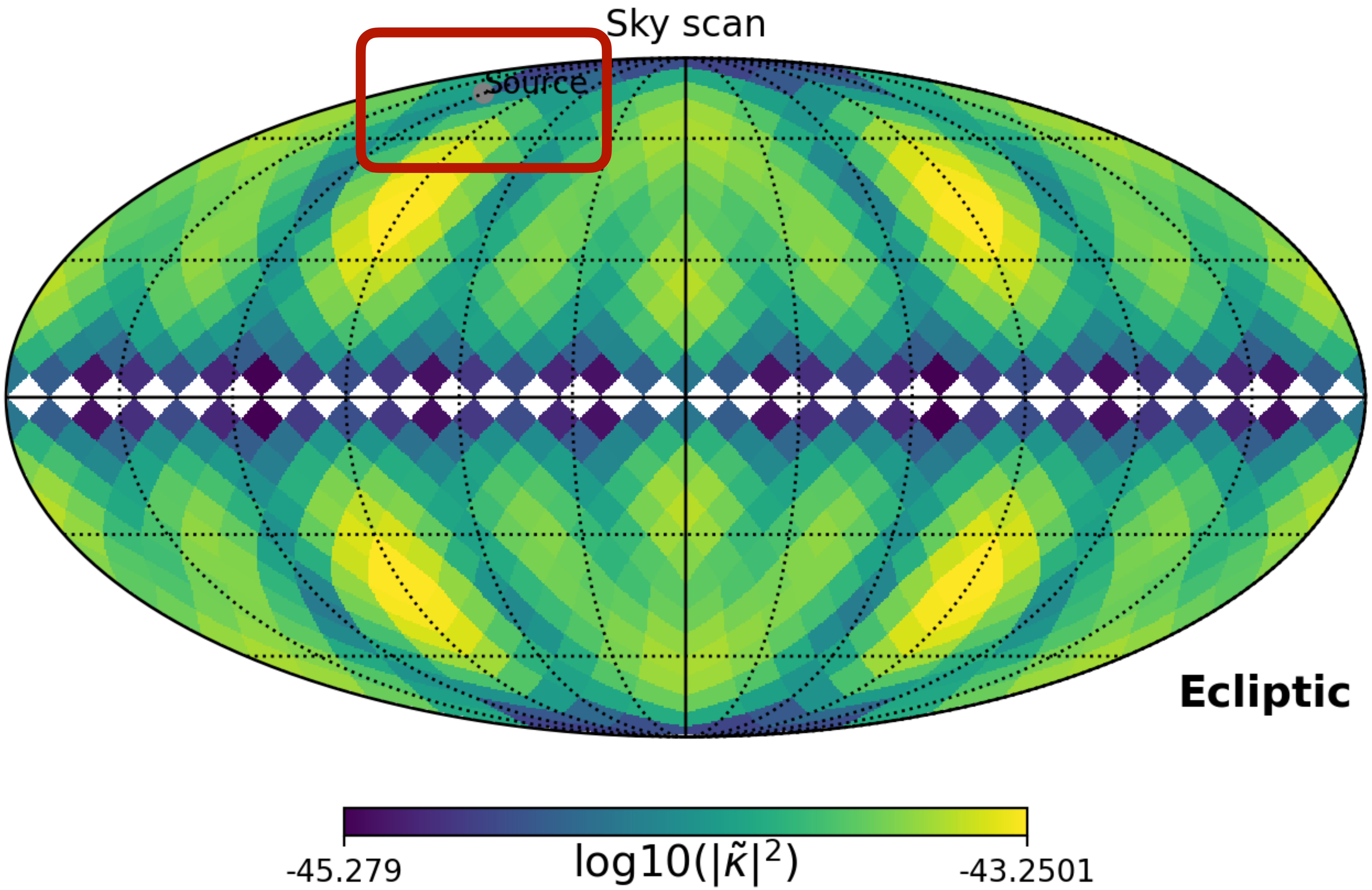
Out of MBHB band

$f = 0.0341\ \mathrm{mHz}$



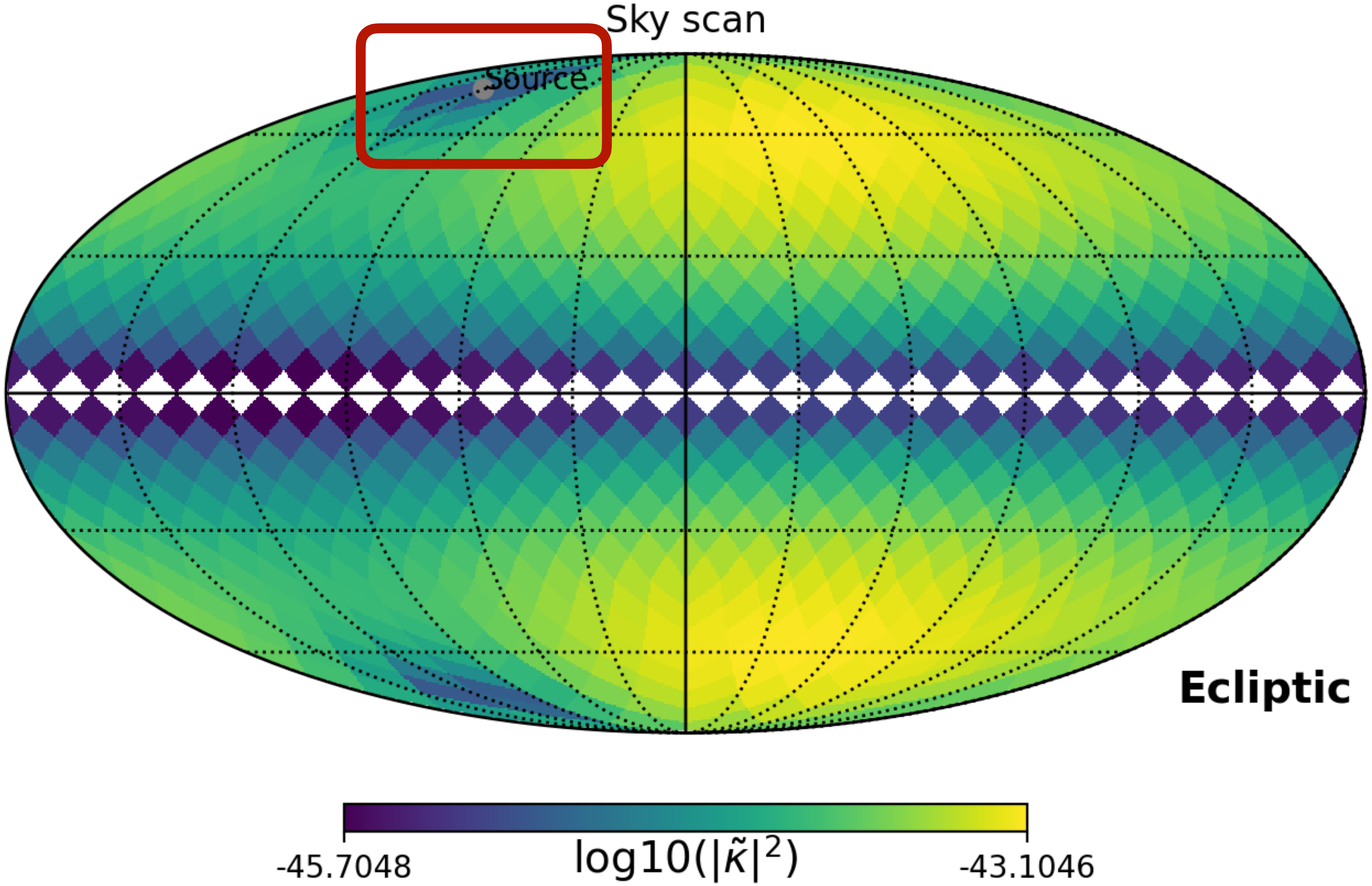
Out of MBHB band

$f = 55.4\,\mathrm{mHz}$



In MBHB band

$f = 4.23\,\mathrm{mHz}$



Conclusion and outlooks

The application of a coronagraph TDI variable works under simplified assumptions.

- Work in progress:
  - Including two sources
  - Adding noise

- Further applications:
  - Early detection in a model agnostic manner
  - Glitch veto