Measuring kinematic anisotropies with pulsar timing arrays

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Based on Phys. Rev. D 110, 063526 and arxiv:2406.04957 with Marisol Cruz, Gianmassimo Tasinato and Ivonne Zavala

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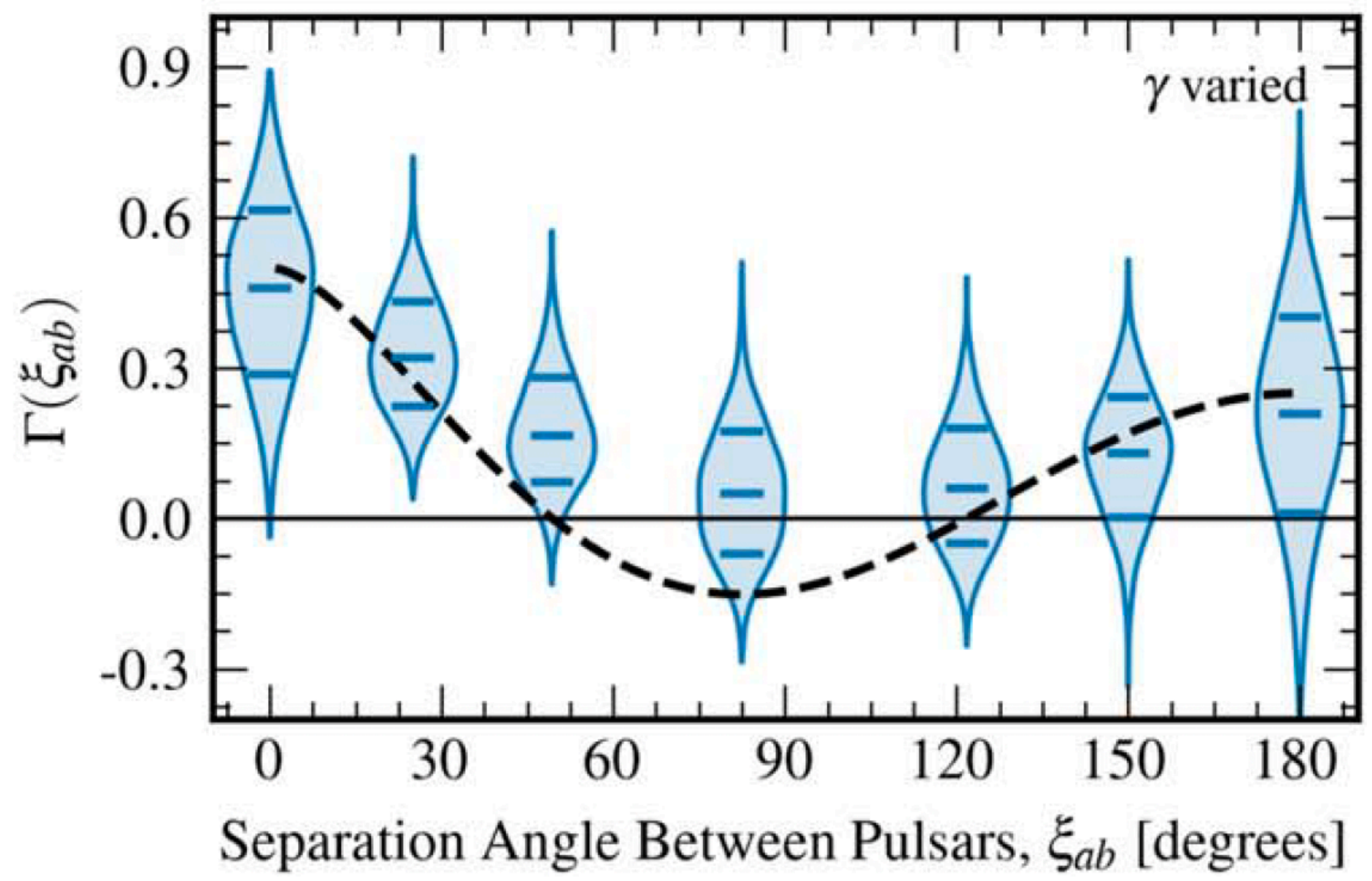
Outline

- PTA SGWB detection
  - SGWB Anisotropy
  - Kinematic dipole
  - Current Limits and forecasts
- Summary

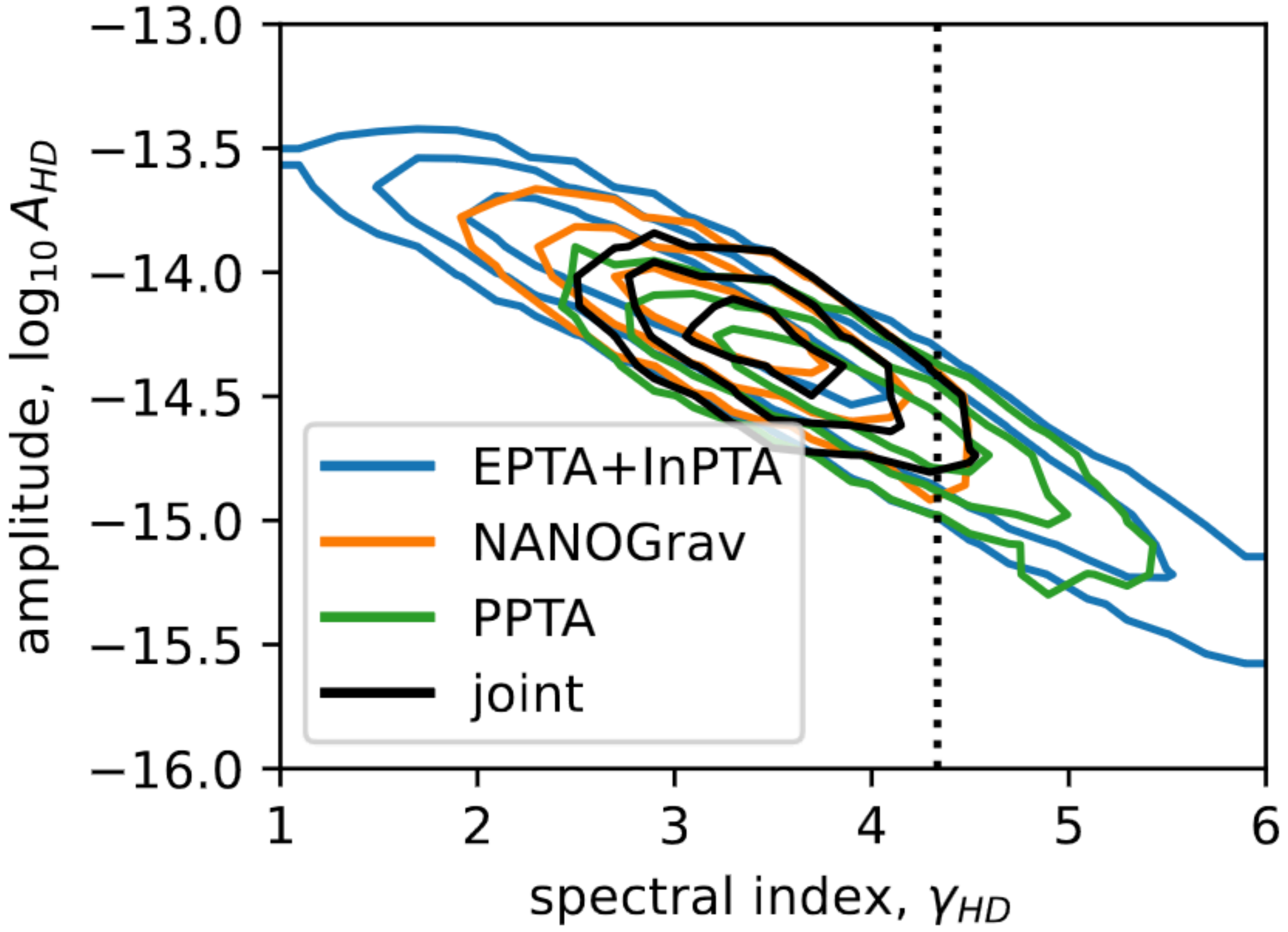
News from PTAs

- Strong evidence for SGWB detected by NANOGrav, EPTA, PPTA, InPTA, CPTA

- **HD correlations** detected with ~ $2-4\sigma$ significance



NANOGrav 15 year analysis



IPTA joint analysis, arxiv: 2309.00693

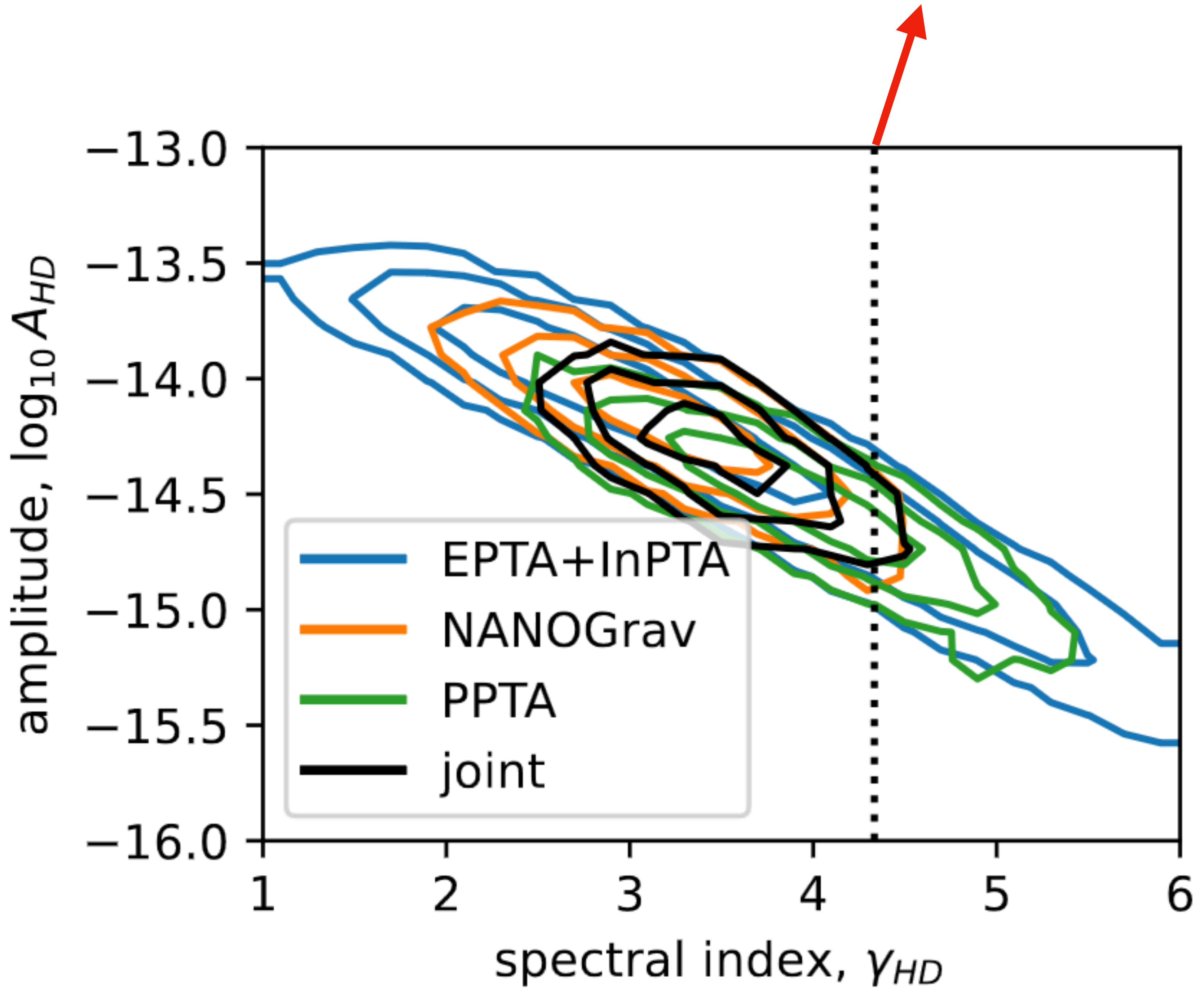
What is the origin of the PTA signal?

Origin of PTA signal

Supermassive BH mergers expected to produce amplitude $h_c \sim 10^{-15}$ and spectral index $\gamma = 13/3$ [Phinney (2001), Sesana et al. (2008)+]

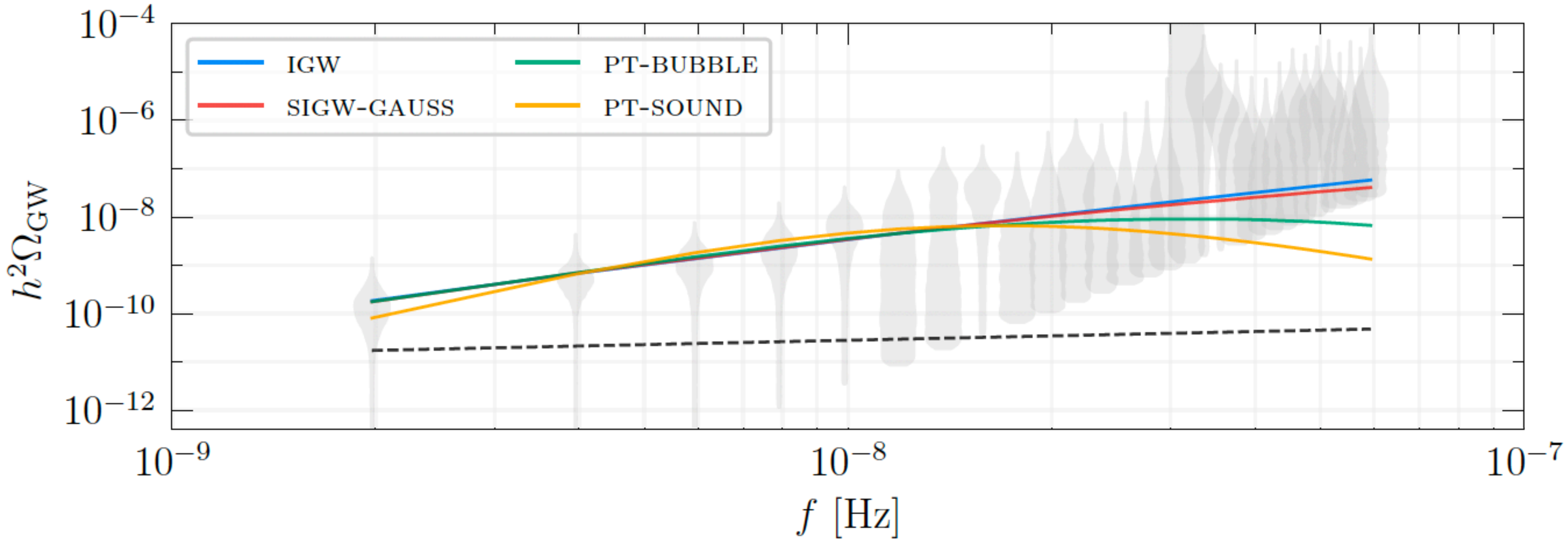
The likely one

SMBHB prediction from simplest models



Origin of PTA signal

Or is it from the early universe?



NANOGrav 15 year analysis: Search for signals from new physics

Inflation

Large density perturbations <—> PBH

Phase Transitions

Additional possibilities studied in
[arXiv: 2306.16219, 2306.16227 + many more!]

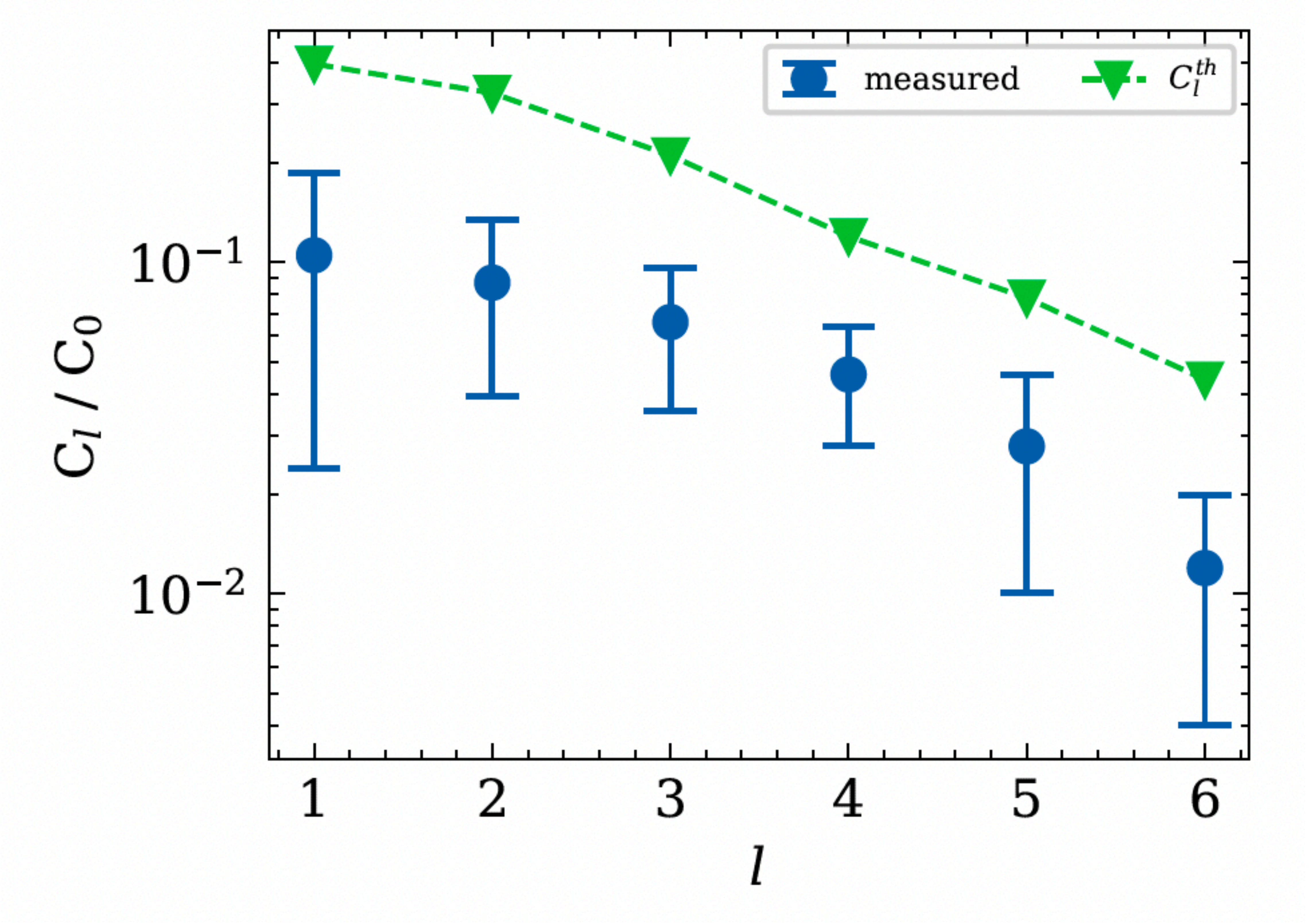
Origin of PTA signal

Too early to tell…

- Additional SGWB properties important to figure out origin(s)
- Can SGWB anisotropies help?

SGWB Anisotropies

Currently PTA data is consistent with isotropy

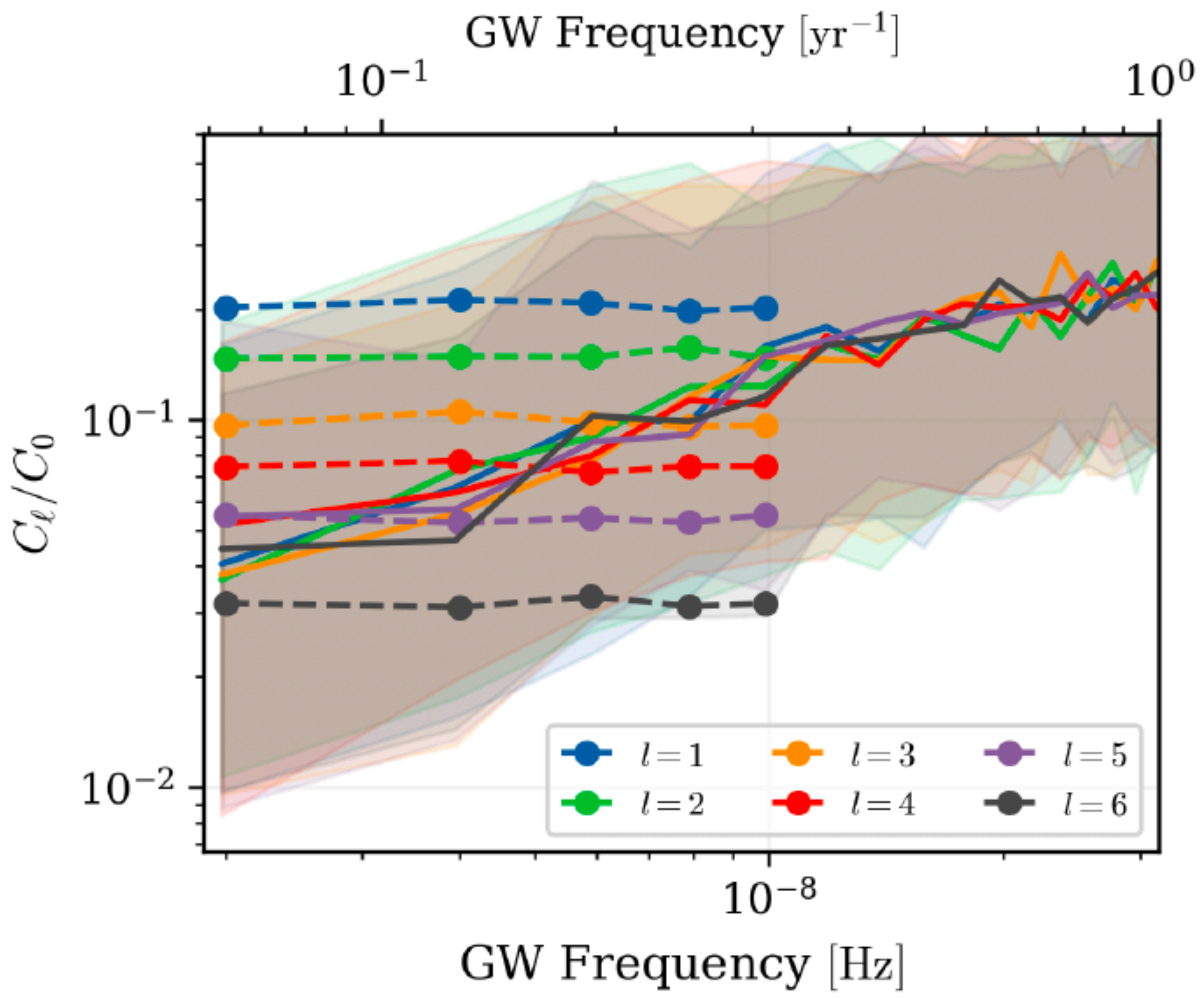


NG15: Search for Anisotropy in the Gravitational Wave Background

SMBHB Anisotropies

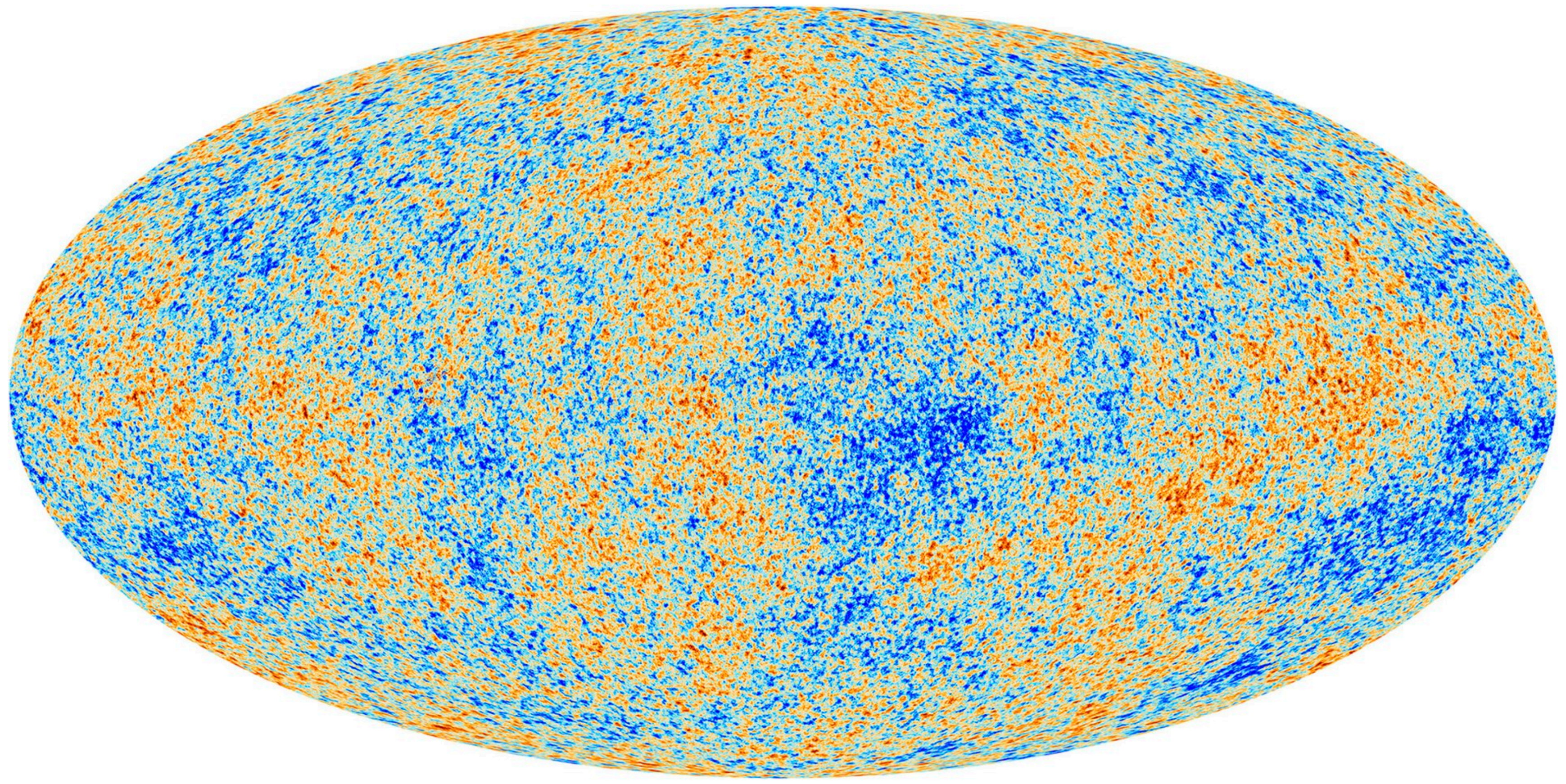
Estimates vary, but **SMBHB** anisotropies are expected to be large

[Mingarelli et al. 2013; Taylor & Gair 2013; Mingarelli et al. 2017), Sato-Polito & Kamionkowski (2023) + more]

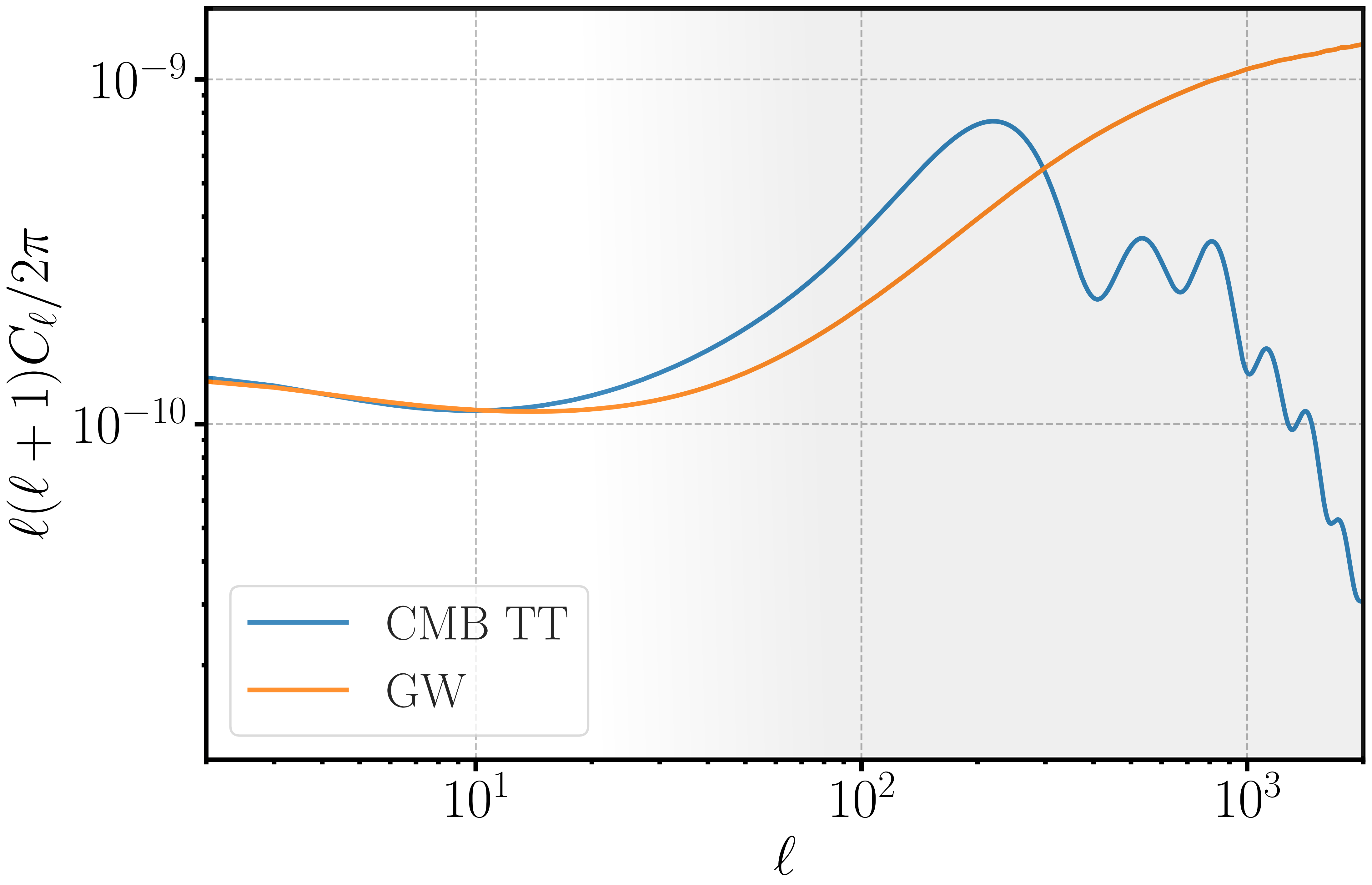


NANOGrav 15-year Anisotropic Gravitational-Wave Background

Cosmological SGWB anisotropies



CMB observations indicate large scale inhomogeneity at the 10^{-5} level



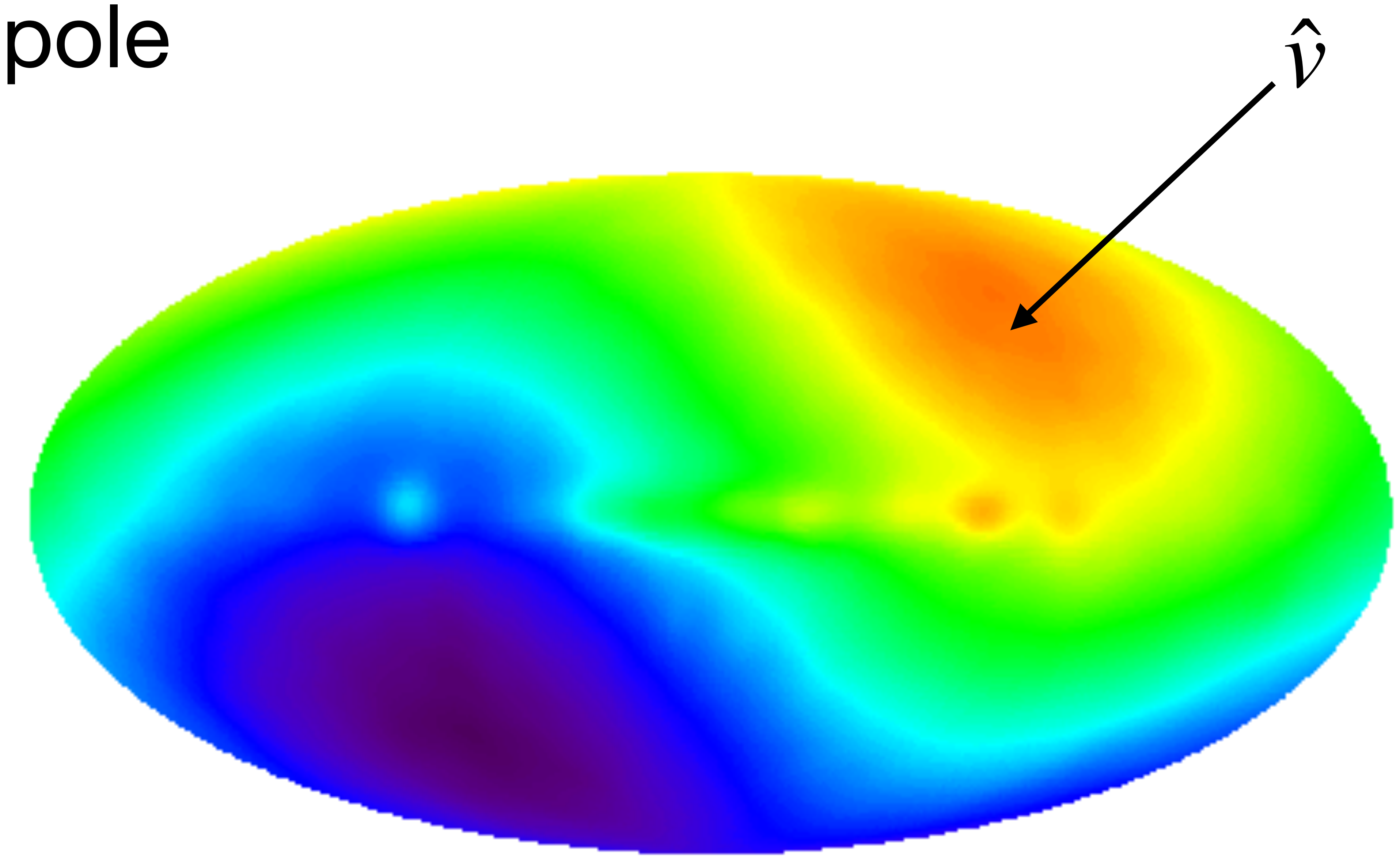
In general, cosmological SGWB anisotropies are expected to be small

See review by LISA CosWG (2022)

Kinematic dipole anisotropy

Largest anisotropy in the CMB is the kinematic dipole

Velocity $\beta = v/c = 1.23 \times 10^{-3}$ towards $(l, b) = (264°, 48°)$ in galactic coordinates



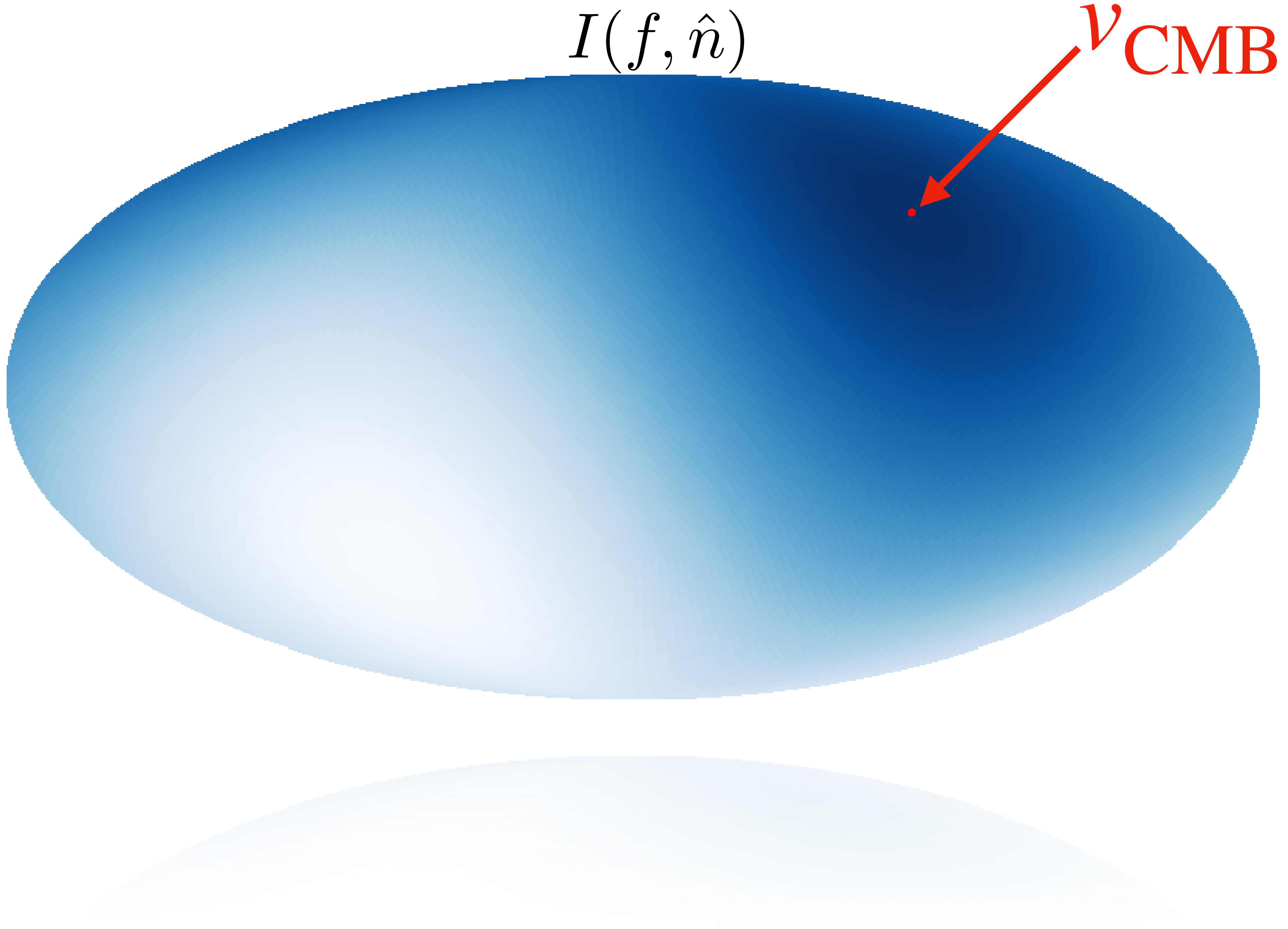
COBE dipole detection (1994)

SGWB Kinematic dipole

If SGWB is of early universe origin, then we can expect a kinematic dipole mirroring the CMB dipole

$$I(f,\hat{n}) = \bar{I}(f)\left[1 + (1 - n_I)\beta(\hat{n}\cdot\hat{v}) + \mathcal{O}(\beta^2)\right]$$

$$n_I \equiv \frac{d\ln \bar{I}}{d\ln f}$$



[Cusin and Tasinato (2022)]

PTA response to kinematic dipole

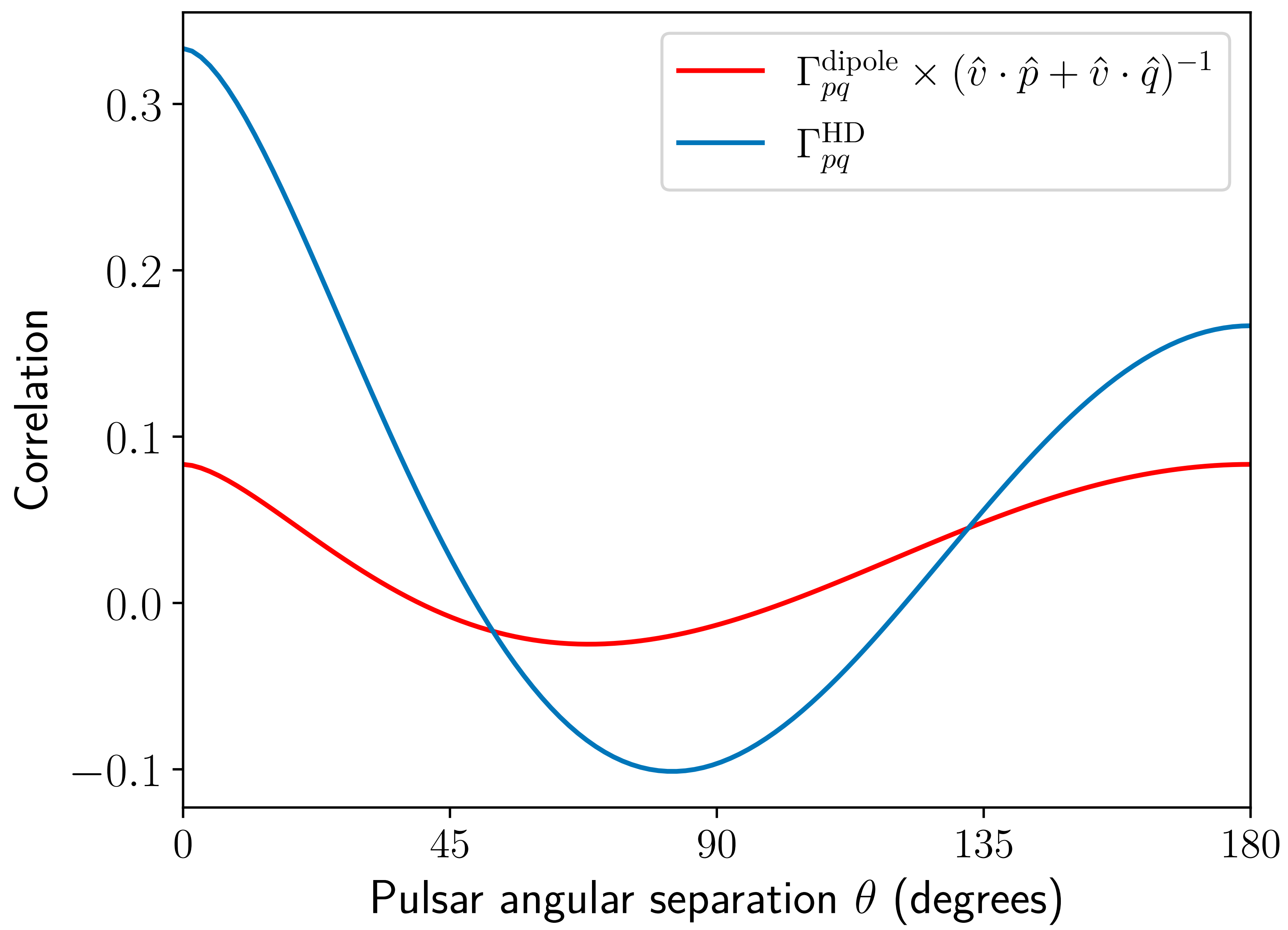
Cross-correlation of timing residuals

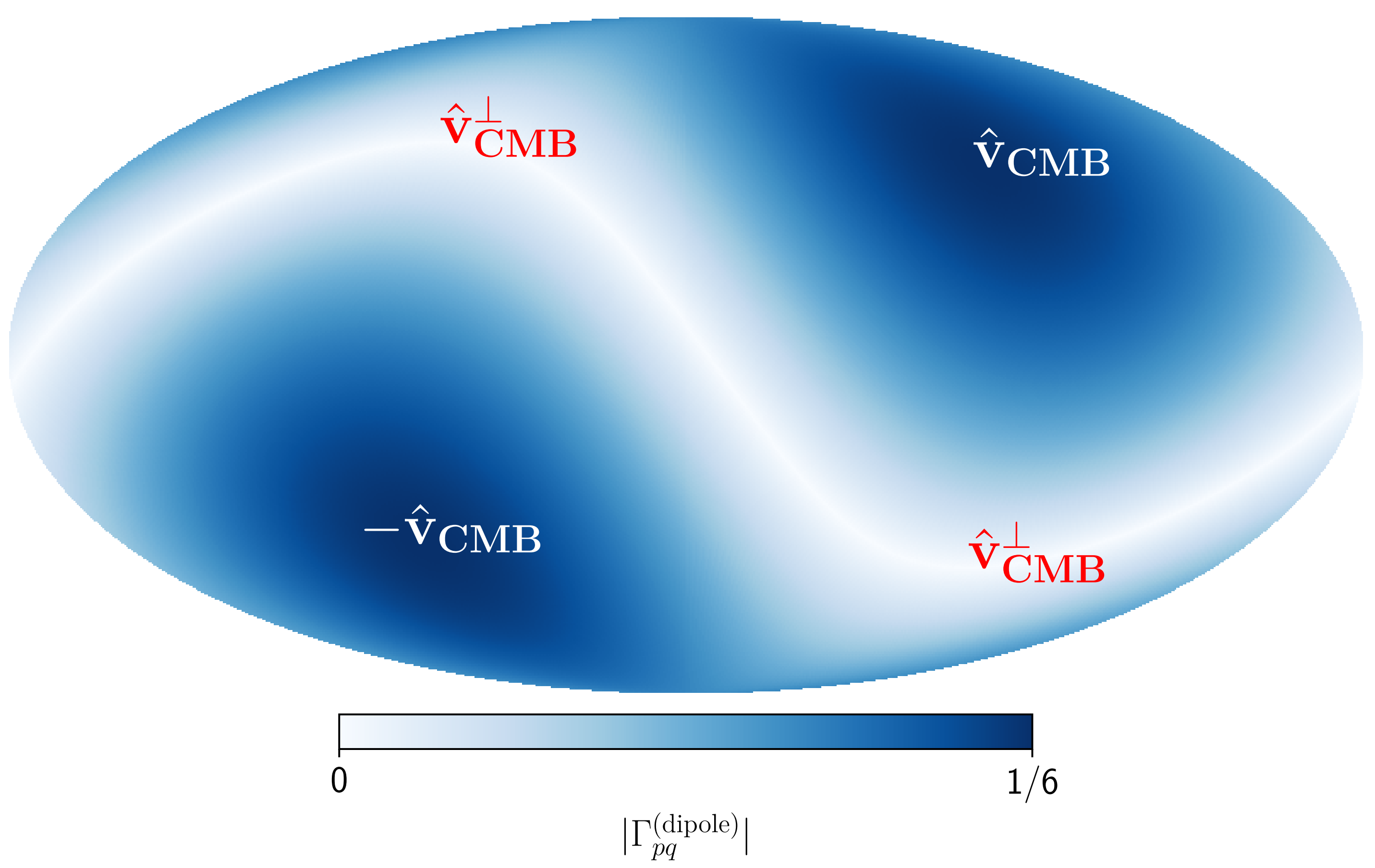
$$\langle \delta t_p \, \delta t_q \rangle \propto \Gamma_{pq}^{(\mathrm{HD})} I + \Gamma_{pq}^{(\mathrm{dipole})} \beta (1 - n_I) I$$

$$\Gamma_{pq}^{\mathrm{dipole}} = \left(\frac{1}{12} + \frac{y_{pq}}{2} + \frac{y_{pq} \ln y_{pq}}{2(1 - y_{pq})} \right) [\hat{v} \cdot \hat{p} + \hat{v} \cdot \hat{q}]$$

$$y_{pq} \equiv \frac{1 - \hat{p} \cdot \hat{q}}{2}$$

[Anholm et al. (2009), Mingarelli et al. (2013), Tasinato (2023)]

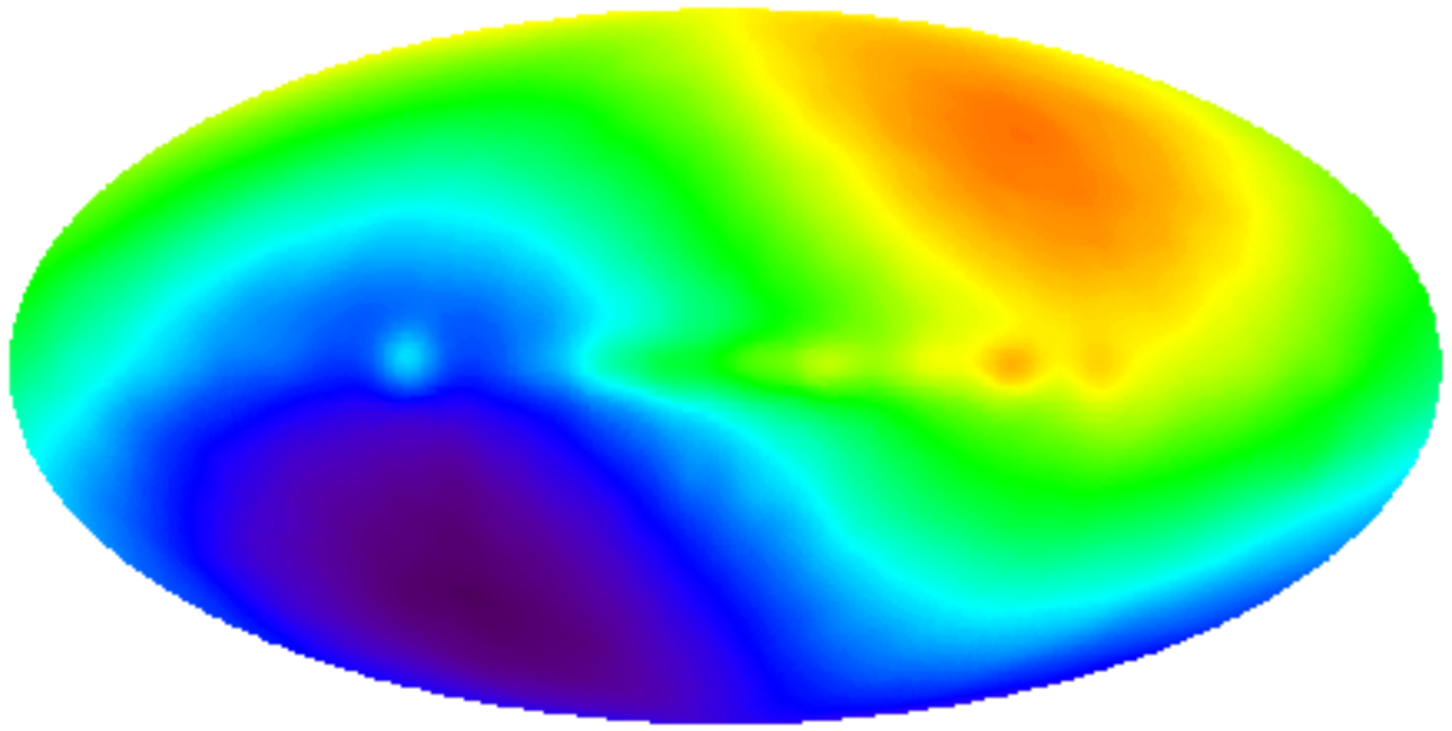




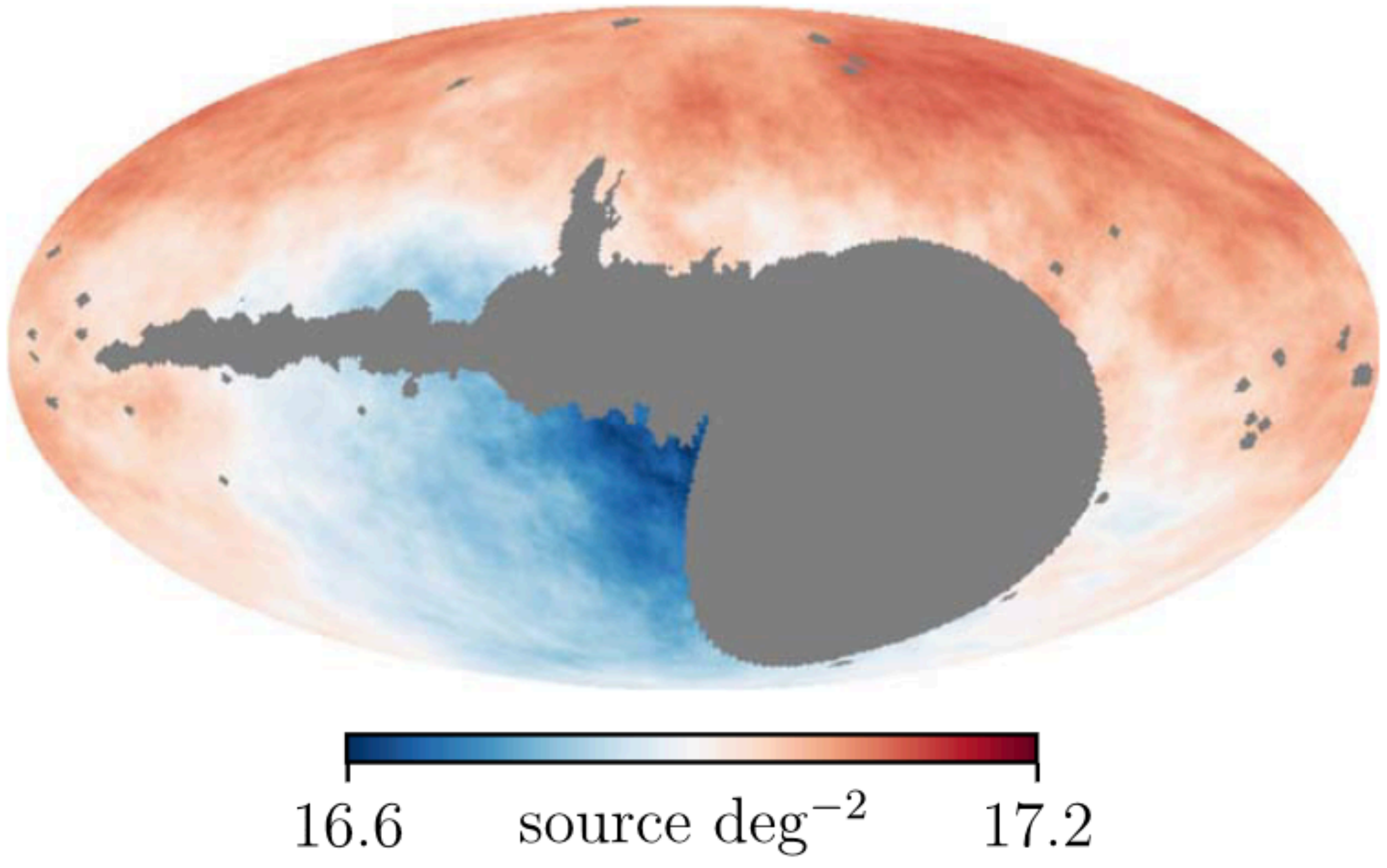
Dipole tension

CMB and LSS estimates of β appear to be in tension, $\beta_{\mathrm{LSS}} \approx 2\beta_{\mathrm{CMB}}$

[See Peebles (2022) for a review]



COBE dipole



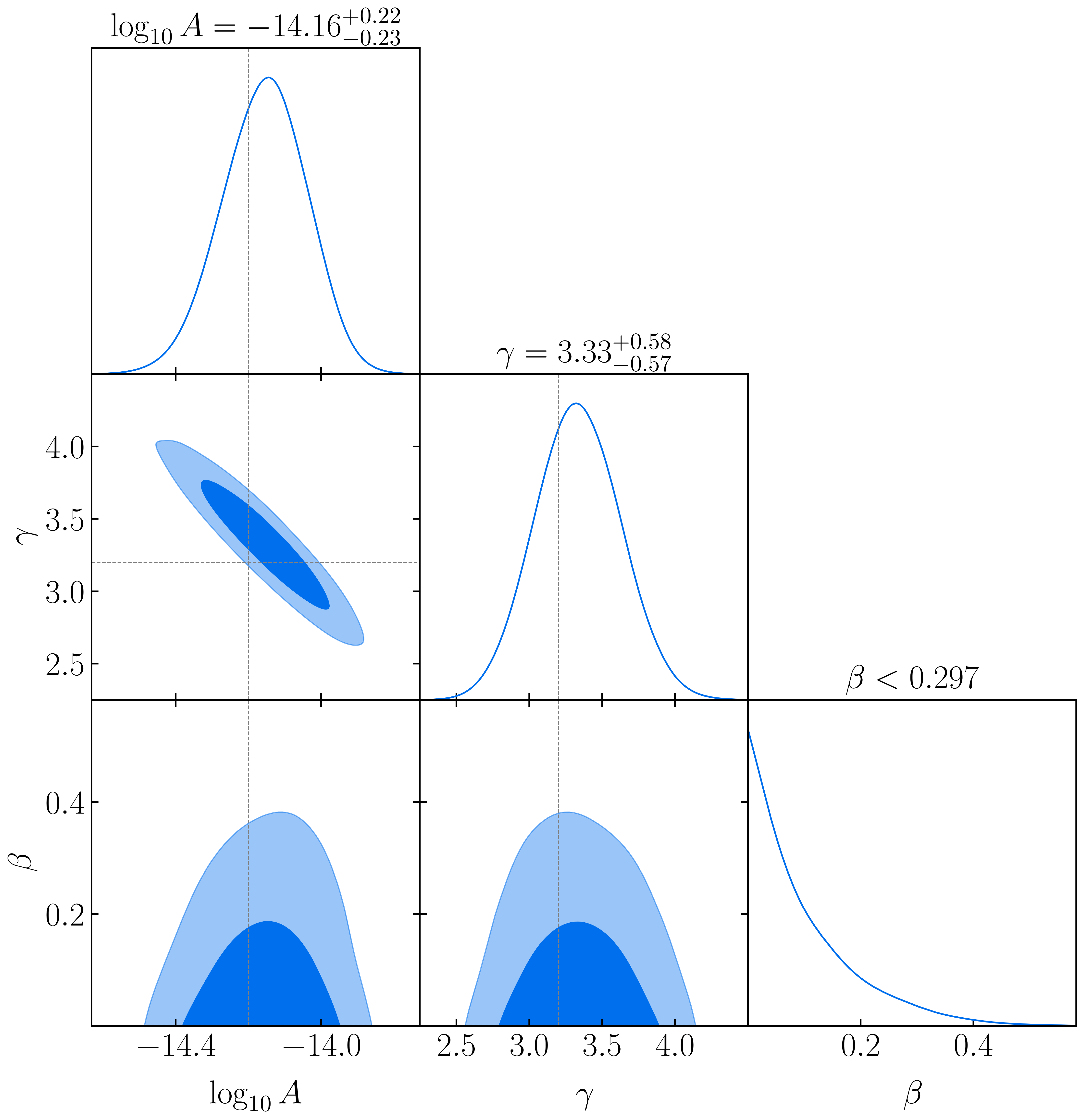
Secrest et al. (2020)

Analysis of NANOGrav data

We implement the kinematic dipole ORF in $\texttt{Enterprise}$[1] with $\hat{v} = \hat{v}_{\rm CMB}$

Note: this assumes SGWB of cosmological origin!

1. https://github.com/nanograv/enterprise



Parameter means and 95% C.L

What comes next?

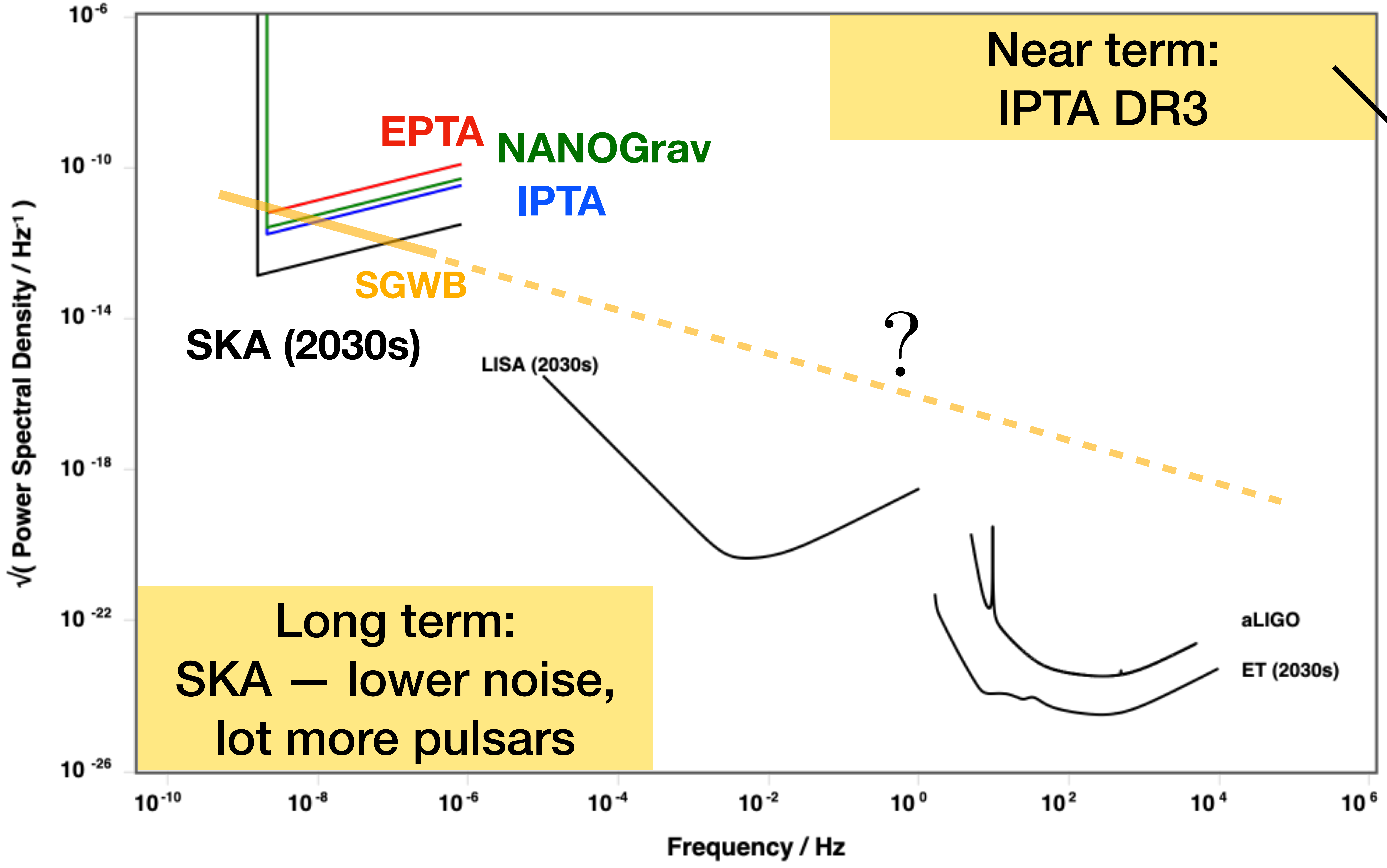


Image: GWplotter.com

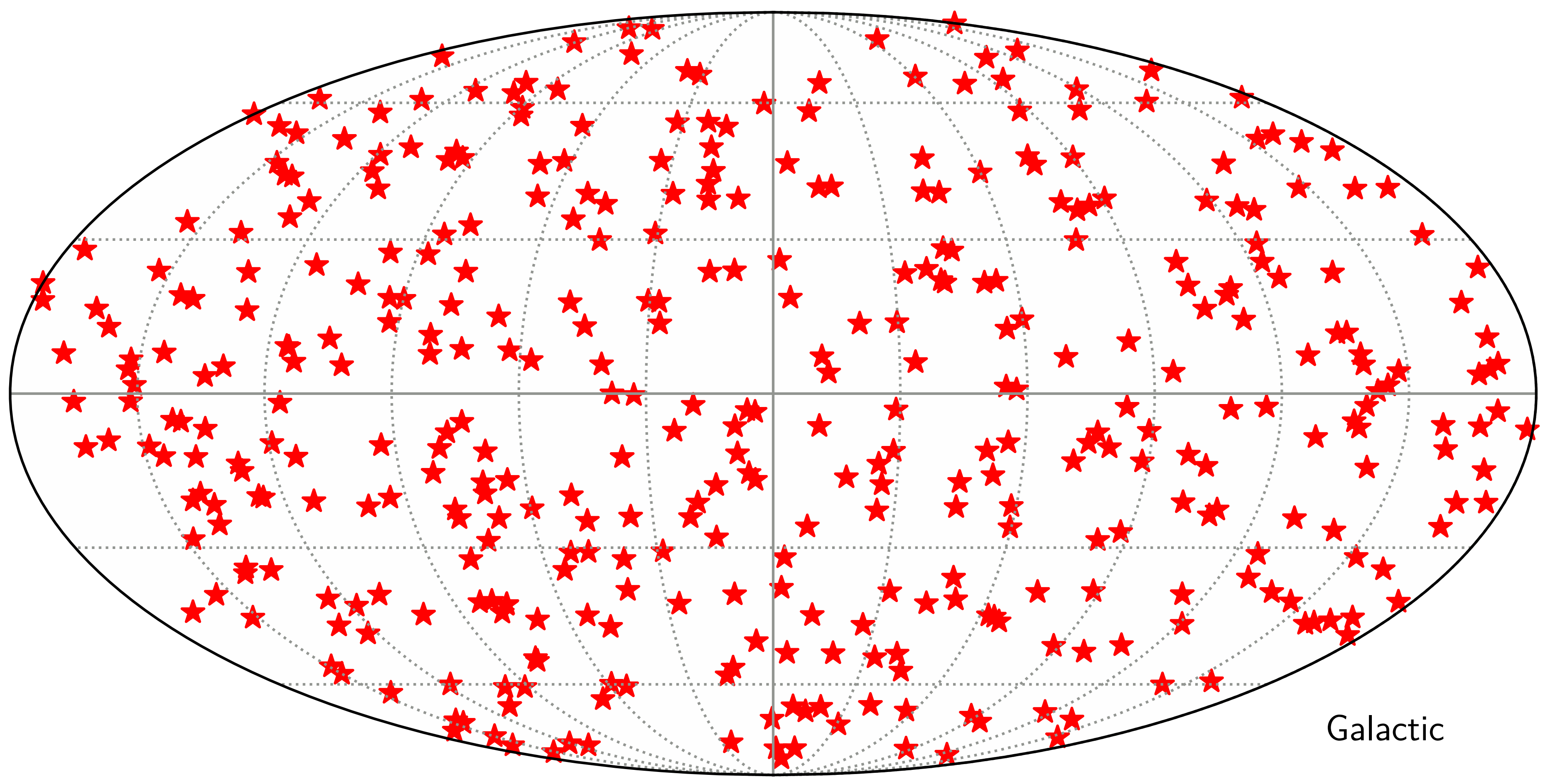
May be enough to detect SMBHB anisotropy

But not to be enough for the kinematic dipole…

Forecasts: SKA era

Idealised scenario with $N \gg 100$ identical pulsars distributed uniformly

We make several simplifying assumptions —> most optimistic estimate



[Keane et al. (2015), Janssen et al. (2015)]

Forecasts: SKA era

Assuming a Gaussian likelihood in the timing residual cross-spectra

A, B = pairs of pulsars

$$-2\ln\mathcal{L} = \sum_f \sum_{AB} \left(\hat{\mathcal{R}}_A - \frac{\Gamma_A \cdot I}{(4\pi f)^2}\right) C^{-1}_{AB} \left(\hat{\mathcal{R}}_B - \frac{\Gamma_B \cdot I}{(4\pi f)^2}\right)$$

$N_{\rm pair} \times N_{\rm pair}$ covariance matrix

Forecasts: SKA era

Weak signal Fisher matrix

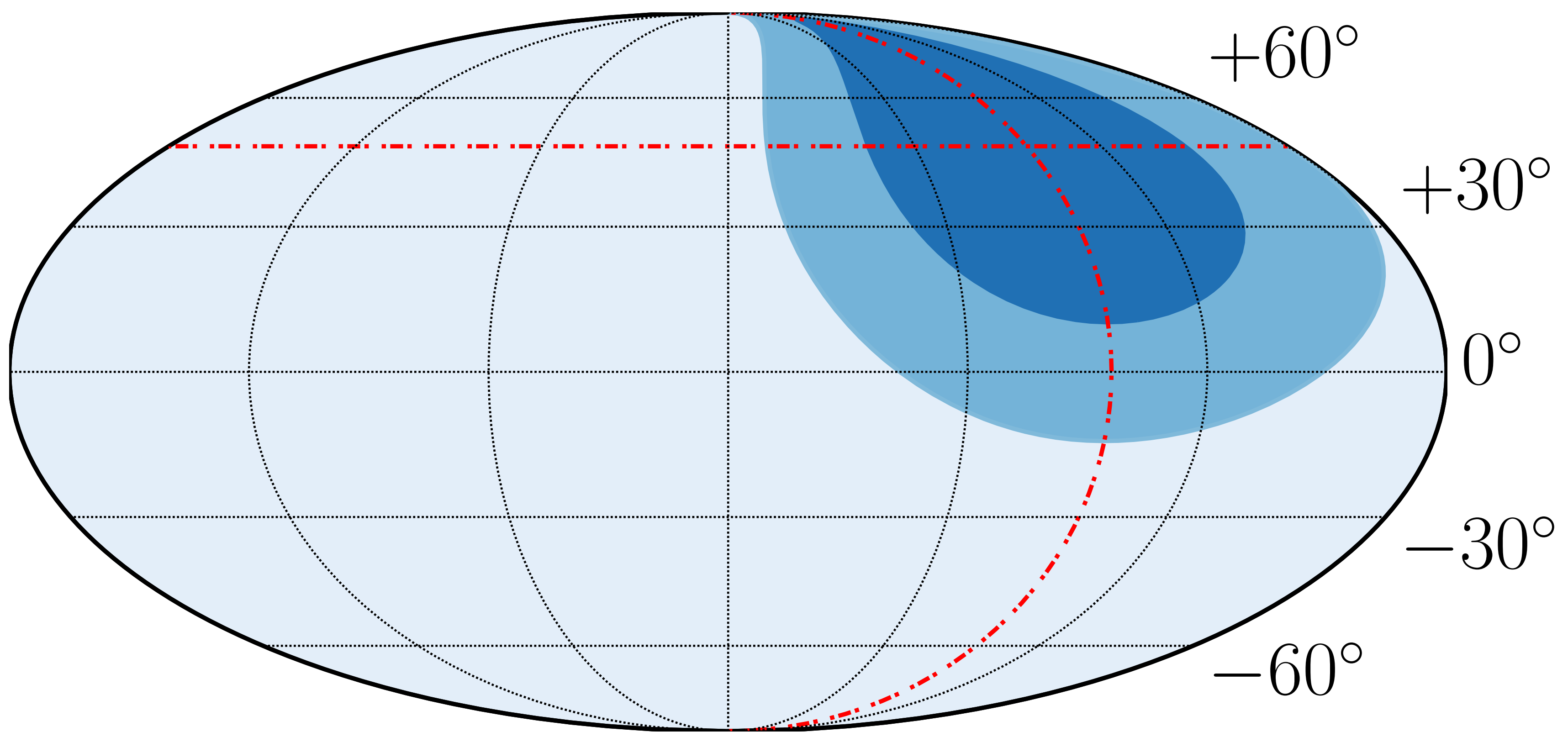
We extend results of Haïmoud, Smith & Mingarelli (2020)

$$\Delta\theta_i = \sqrt{(\mathcal{F}^{-1})_{ii}}, \quad \vec{\theta} = \{\beta, \theta, \phi\} \longrightarrow$$ dipole magnitude and direction

$$\mathcal{F}_{ij} \propto \frac{2T}{S_N^2} N_{\rm pair} \times \begin{bmatrix} \frac{I_0^2(1-n_I)^2 F_1}{3} & 0 & 0 \\ 0 & \frac{F_1 I_0^2(1-n_I)^2\beta^2}{3} & 0 \\ 0 & 0 & \frac{F_1\, I_0^2(1-n_I)^2\beta^2 \sin^2\theta}{3} \end{bmatrix}, \qquad F_1 \approx F_0/7$$

Forecasts: SKA era

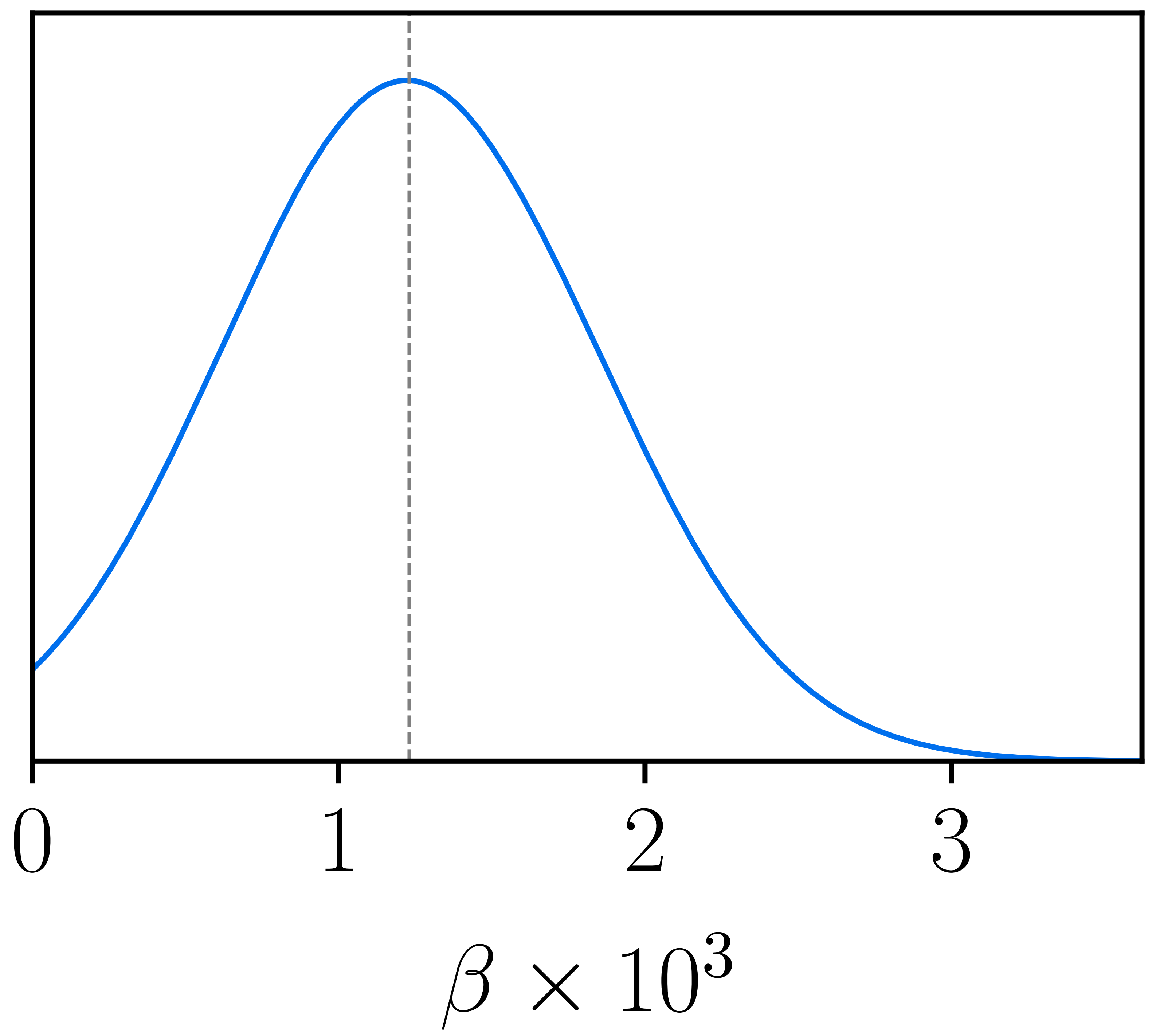
Weak signal results



~30° degree localisation of dipole direction

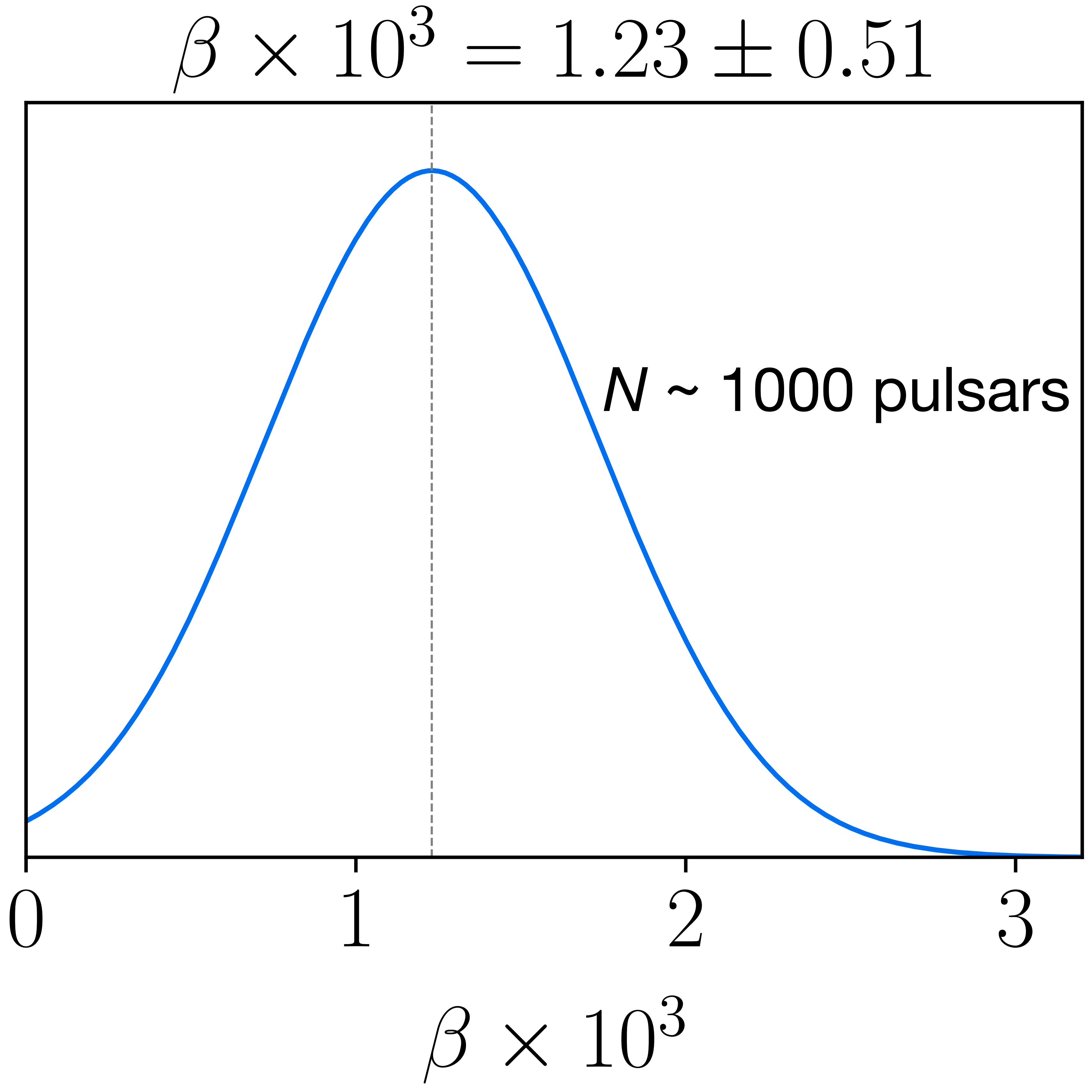
Challenging even with ~4000 pulsars

$\beta \times 10^3 = 1.23 \pm 0.61$



Forecasts: SKA era

Strong signal regime



Detection will be challenging even for futuristic experiments

See also Depta et al. (2024) for strong signal results

Circular polarisation

Cosmological sources e.g. GW from axion-gauge fields [Unal et al. 2023 + more]

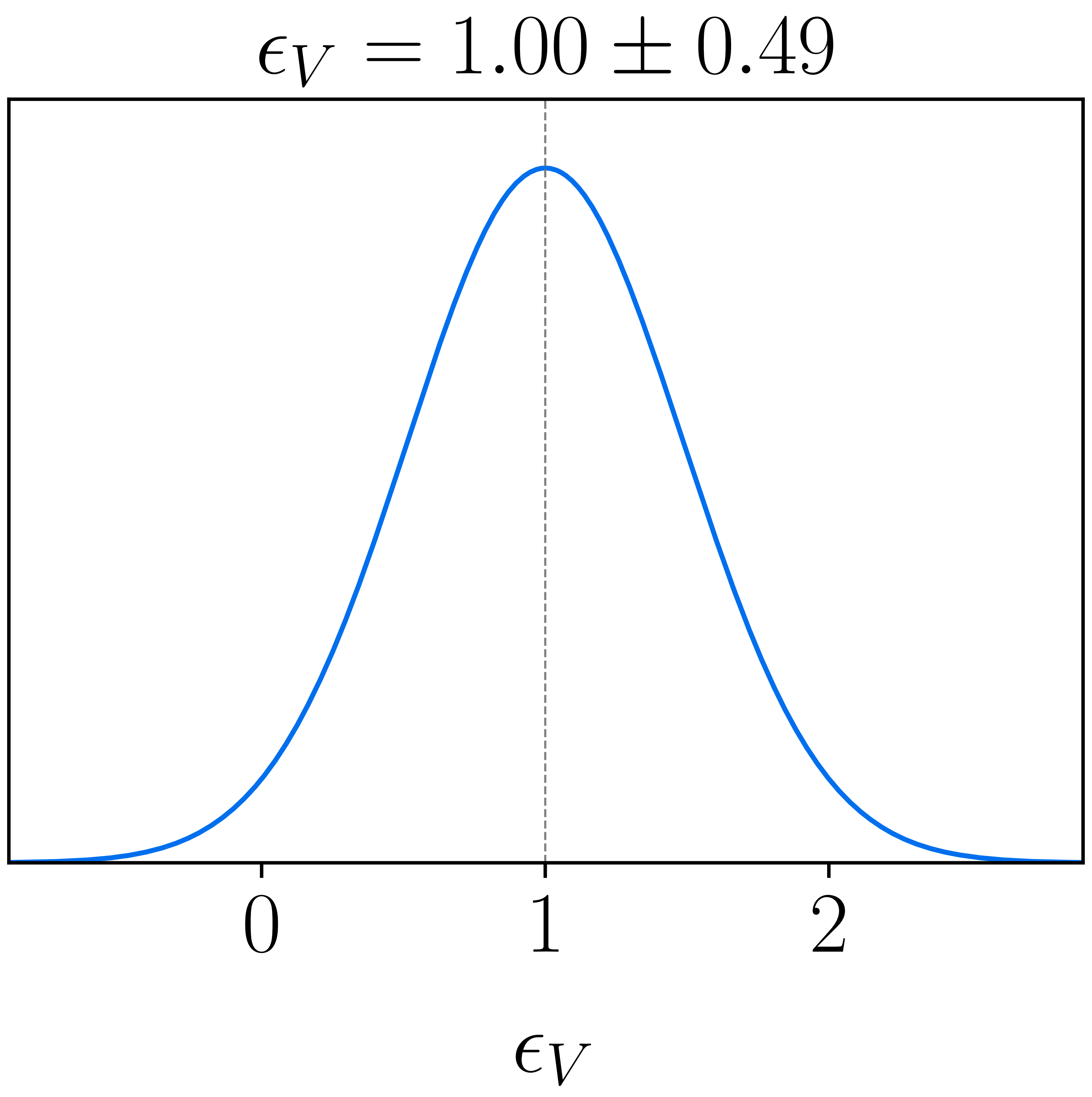
PTA blind to circular polarisation monopole — planar detector

$$\Gamma^{V}_{ab} = \beta \, (n_V - 1) \, G^{(1)}_{ab}$$

PTA response begins at dipole

$$G^{(1)}_{ab} = -\left(\frac{1}{3} + \frac{y_{ab} \ln y_{ab}}{4(1 - y_{ab})}\right) [\hat{v} \cdot (\hat{x}_a \times \hat{x}_b)]$$

Circular polarisation



$$\epsilon_V = \frac{V}{I}$$

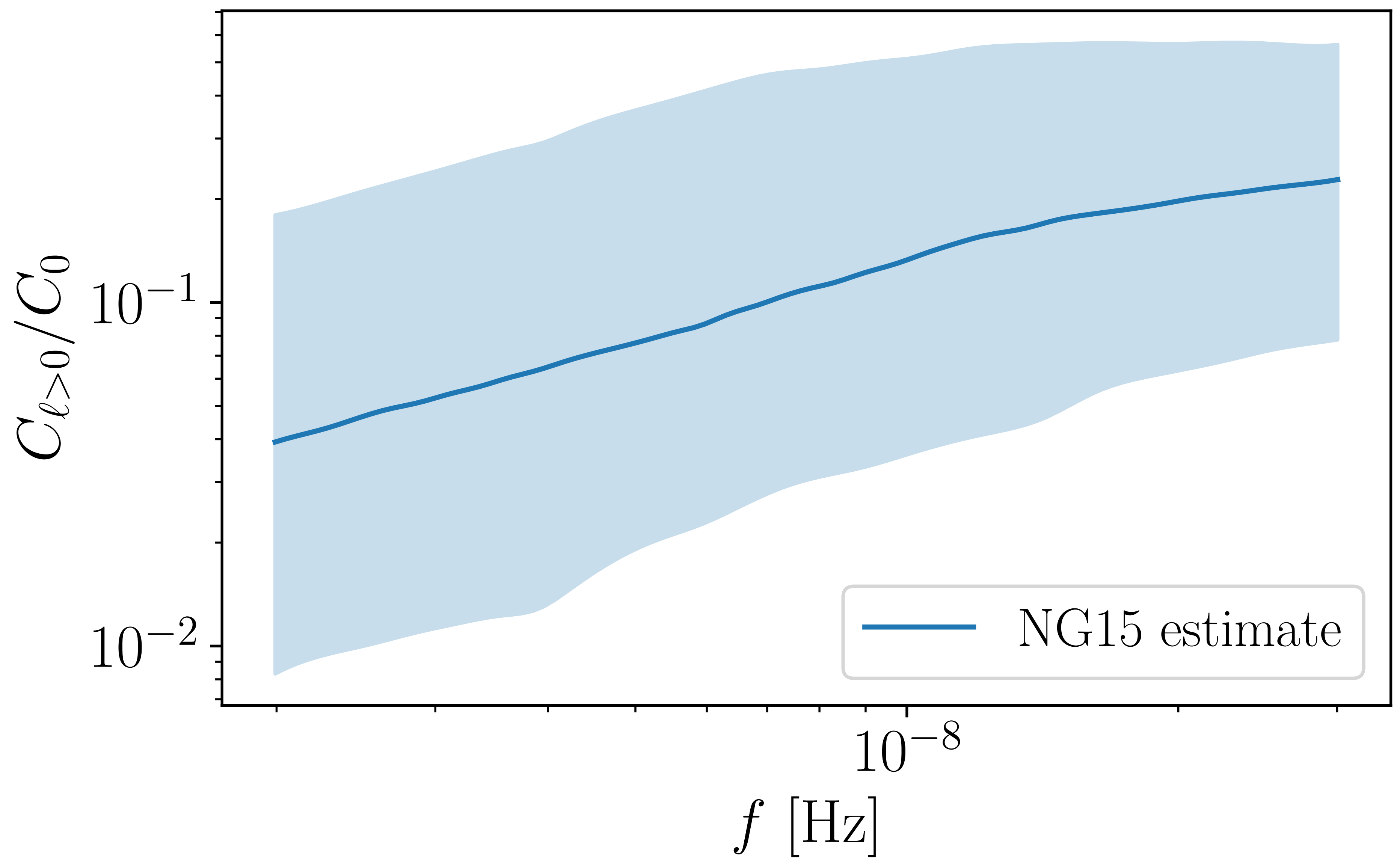
Unconstrained by current data (again for cosmo SGWB)

Near maximal polarisation may be detected with SKA ($N_{\rm psr} \gtrsim 10^3$)

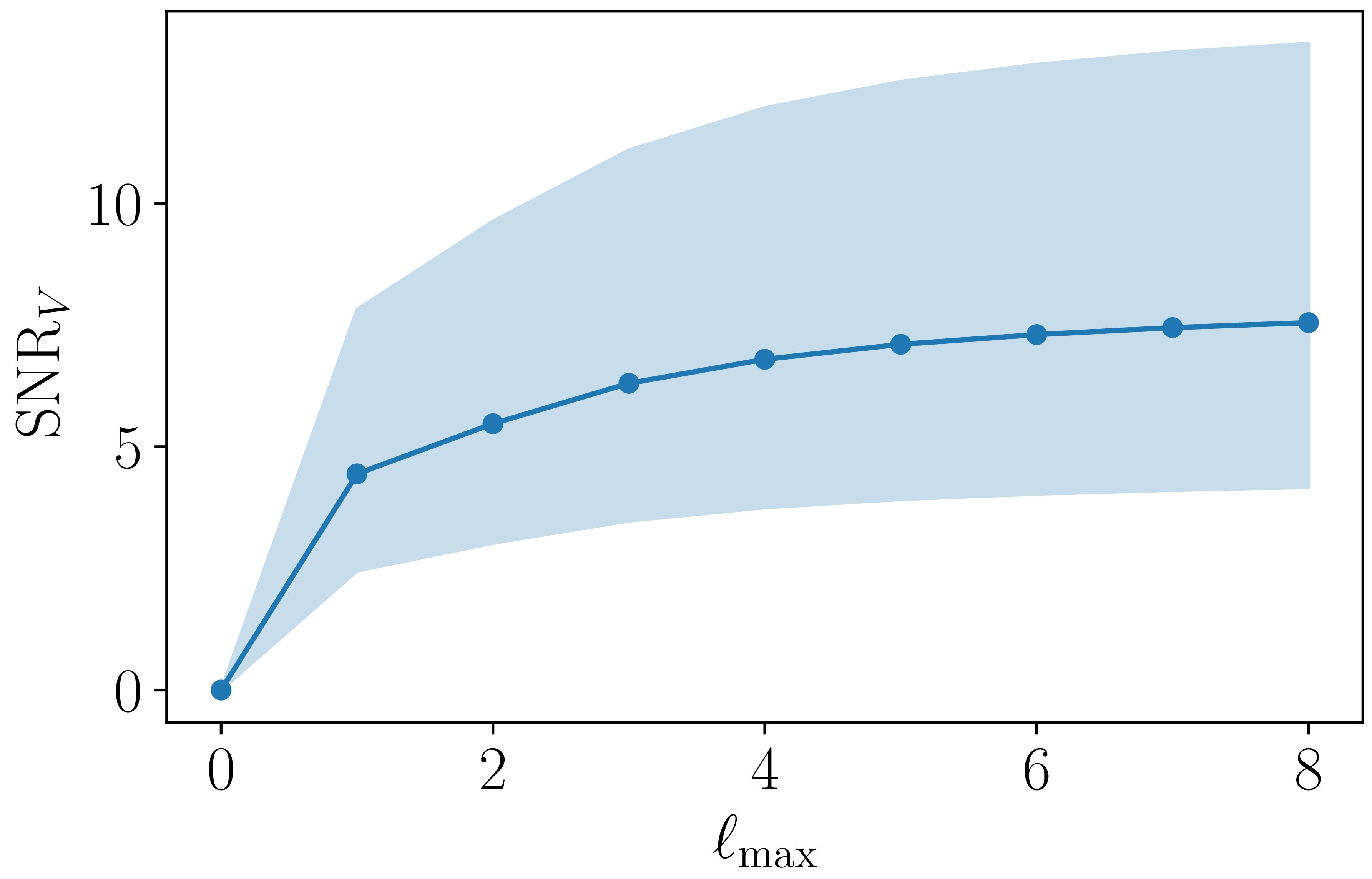
AGWB circular polarisation

Astrophysical estimate $C_\ell^V \simeq C_\ell^I$

[Dall'Armi et al (2023), Sato-Polito and Kamionkowski (2023)]



$\epsilon_V = 1$ with $N_{\rm psr} = 150$



Summary

Anisotropy could help distinguish **SMBHB** vs **cosmological scenarios**

Kinematic dipole the largest anisotropy for cosmological SGWB + dependence on pulsar direction w.r.t dipole — challenging even with SKA

Additional information in circular polarisation for both cosmological and astrophysical SGWB

Thank you!