Astrometry, gravitational waves and synergies with Pulsar Timing Arrays

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Based on work in progress with Marisol Cruz, Gianmassimo Tasinato and Ivonne Zavala

Outline

PTA SGWB detection

SGWB and Astrometry

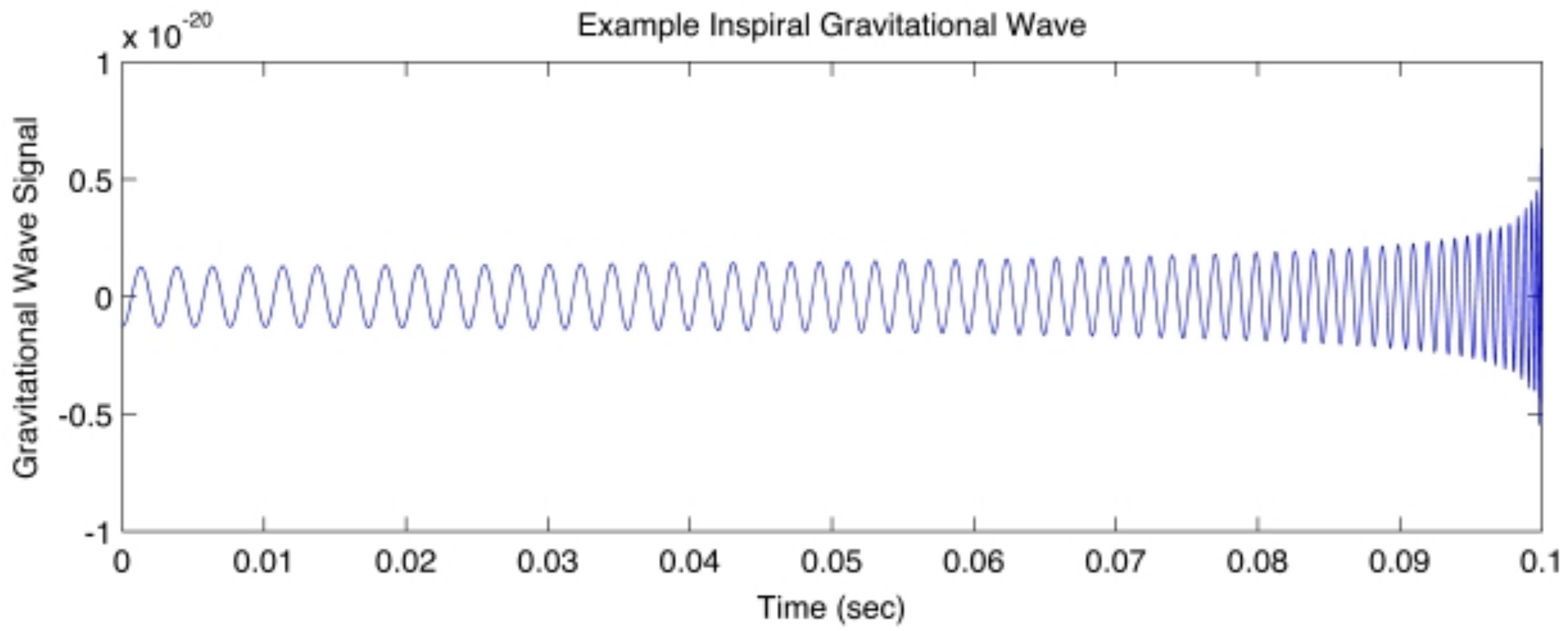
Forecasts with PTA + Astrometry

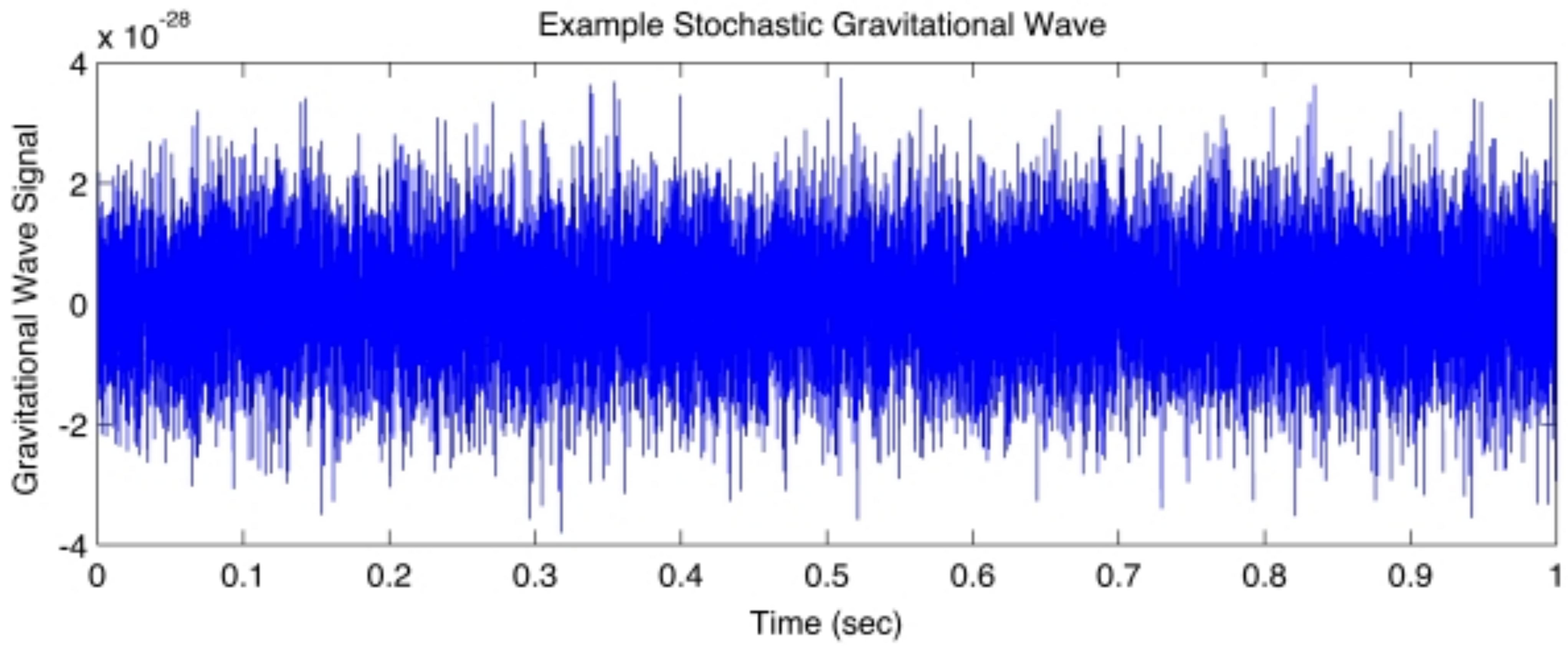
Summary

SGWB

Stochastic Gravitational Wave Background

Independent sources which are not individually resolvable lead to an incoherent superposition, large number of such sources —> SGWB





[Images: A. Stuver/LIGO]

Events can be individually detected e.g. by matched filtering

Looks like noise!

SGWB detection

The cross-correlation method

Suppose we have the data from two different detectors

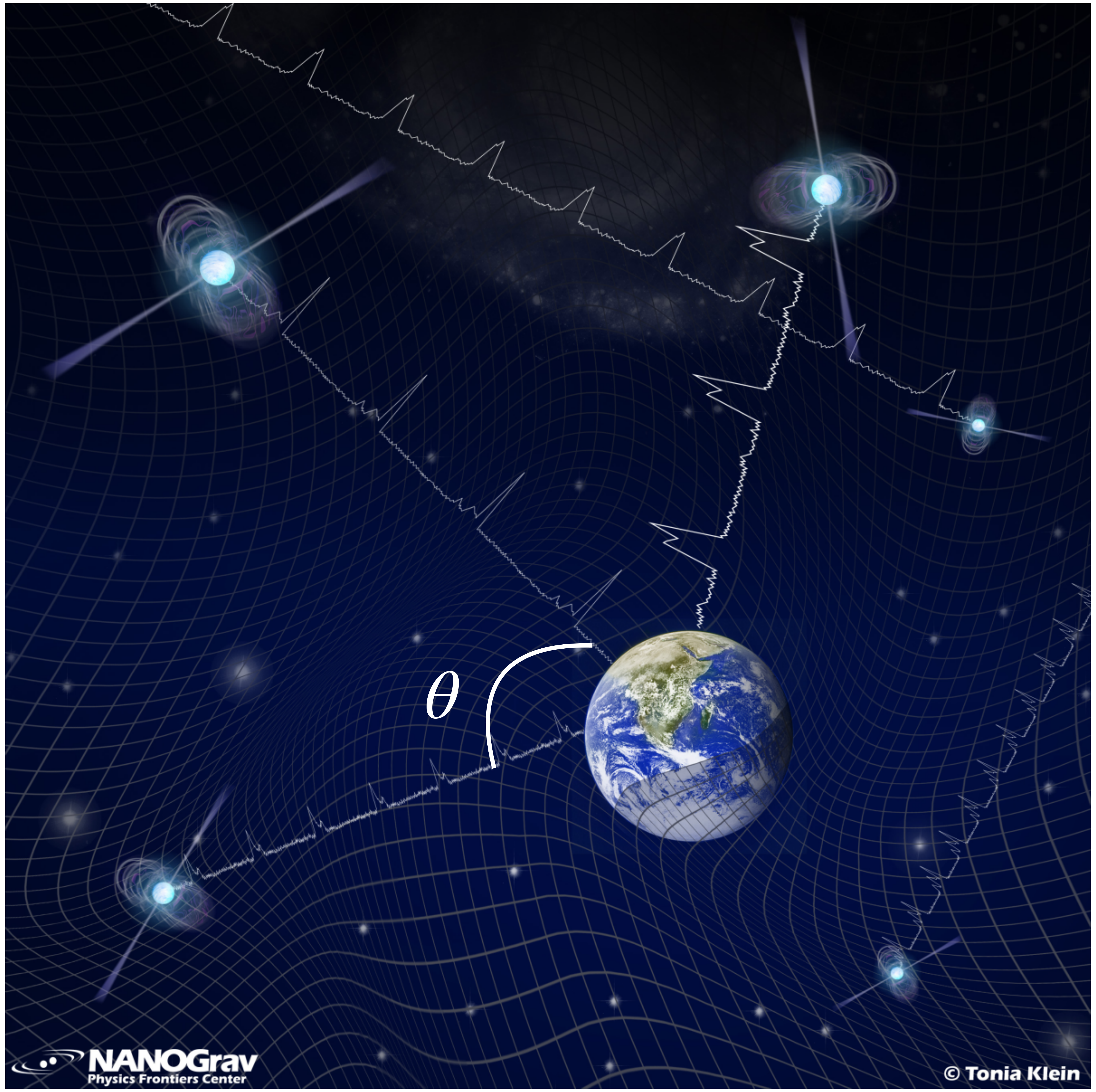
$$d_I = h_I + n_I$$
$$d_J = h_J + n_J$$

Now, if we build the cross-correlation

$$C_{IJ} \equiv d_I d_J = h_I h_J + n_I h_J + n_J h_I + n_I n_J$$
$$\langle C_{IJ} \rangle = \langle h_I h_J \rangle + \langle n_I h_J + n_J h_I \rangle + \langle n_I n_J \rangle$$

THE SPECTRUM OF GRAVITATIONAL WAVES
PPTA, EPTA, NANOGrav, InPTA, CPTA, SKA (2030s)
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
BICEP/Keck, CMB-S4, LiteBIRD
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
ESA | NASA
lisa
#lisa

SGWB and PTAs



GW induce correlated deviations from expected time of arrival across pulsars

$$\langle d_I(f) d_J(f) \rangle \propto \gamma_{IJ}(f) S_h(f)$$

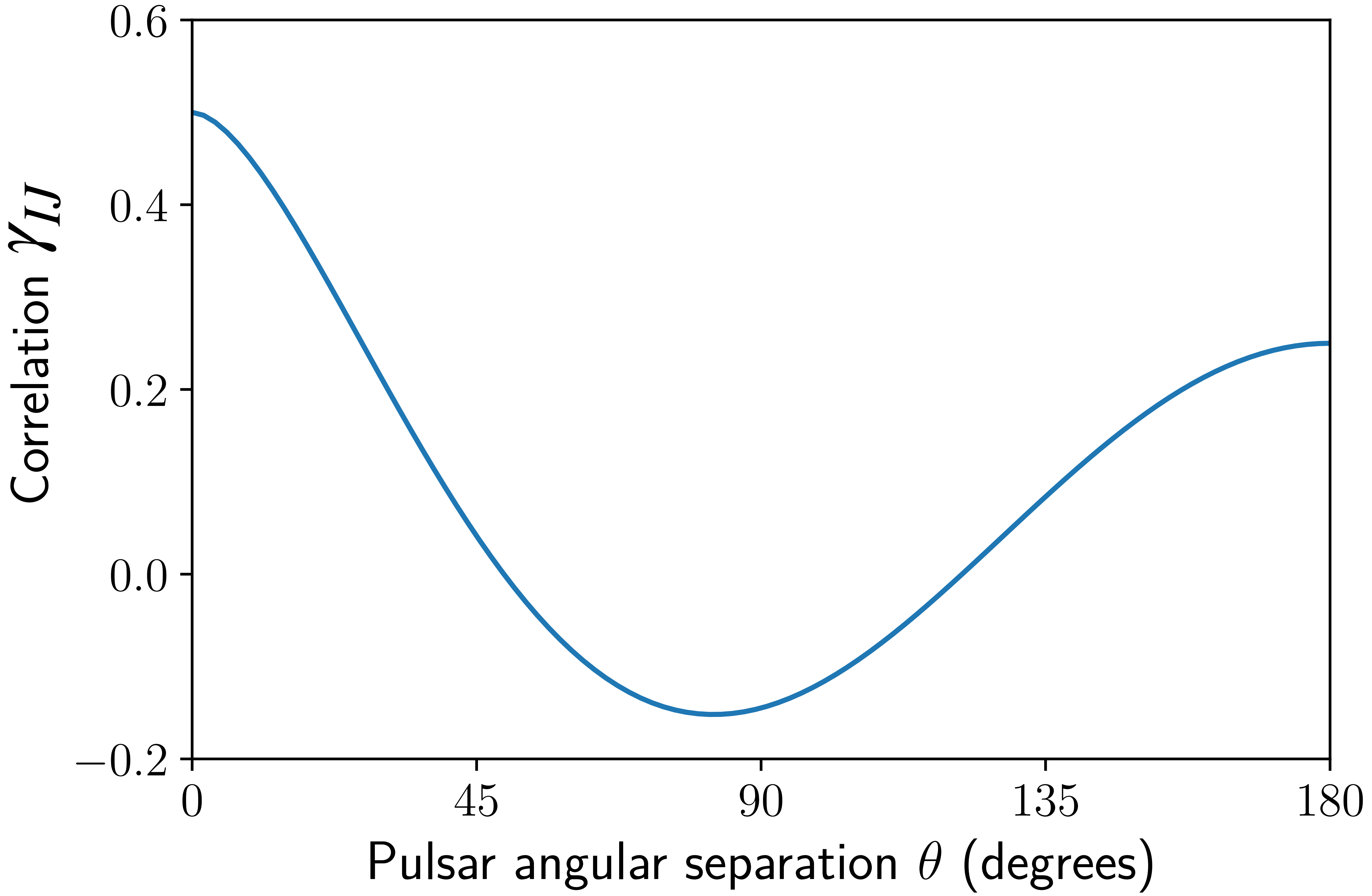
Geometric factor that depends on the relative positions of the 2 pulsars

SGWB detection

Overlap function: Pulsar Timing

The Hellings-Downs curve: PTA response to isotropic SGWB

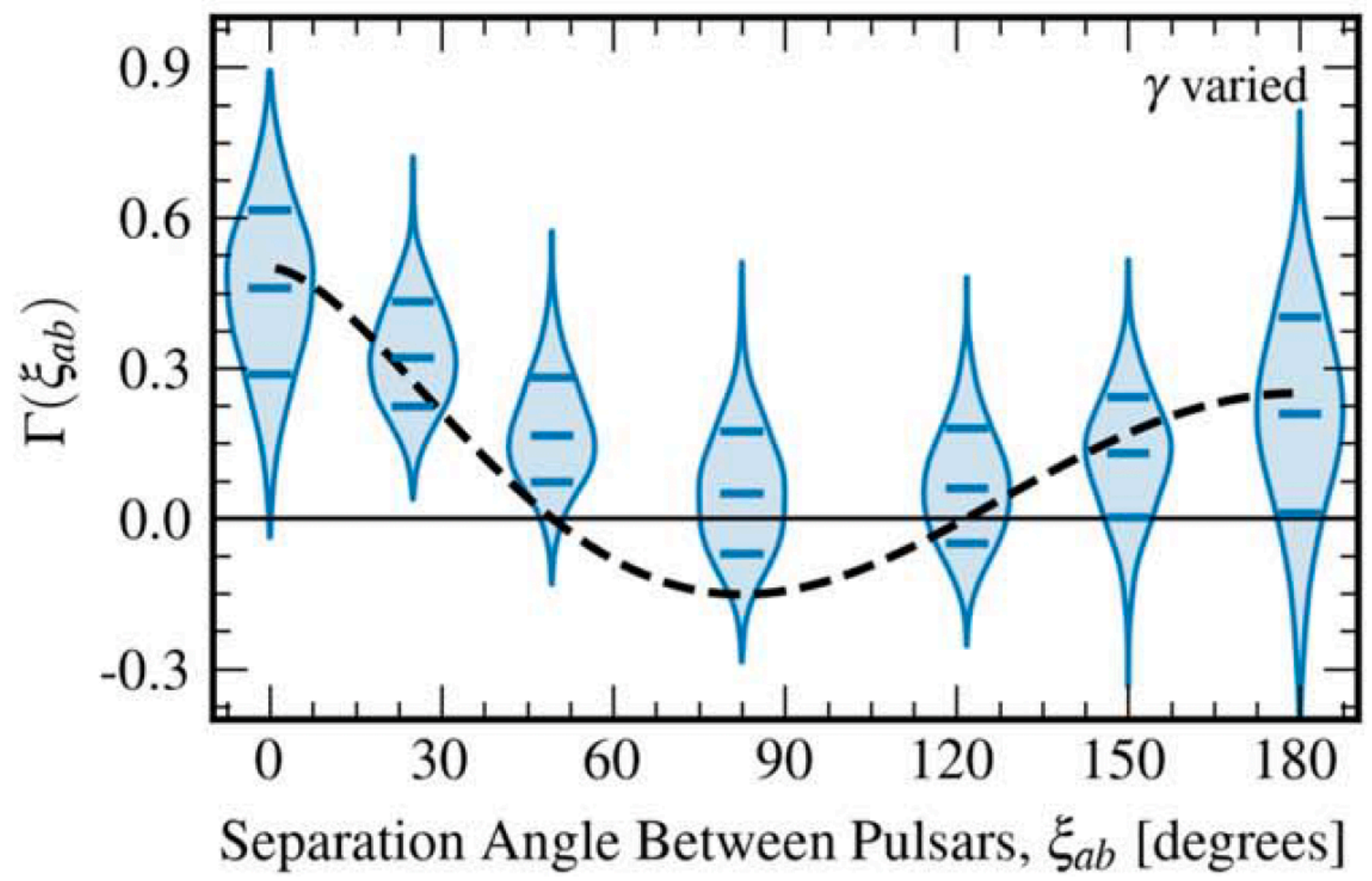
$$\gamma(\theta_{ij}) = 1 + \frac{\cos\theta_{ij}}{3} + 2(1-\cos\theta_{ij})\ln\left(\frac{1-\cos\theta_{ij}}{2}\right)$$



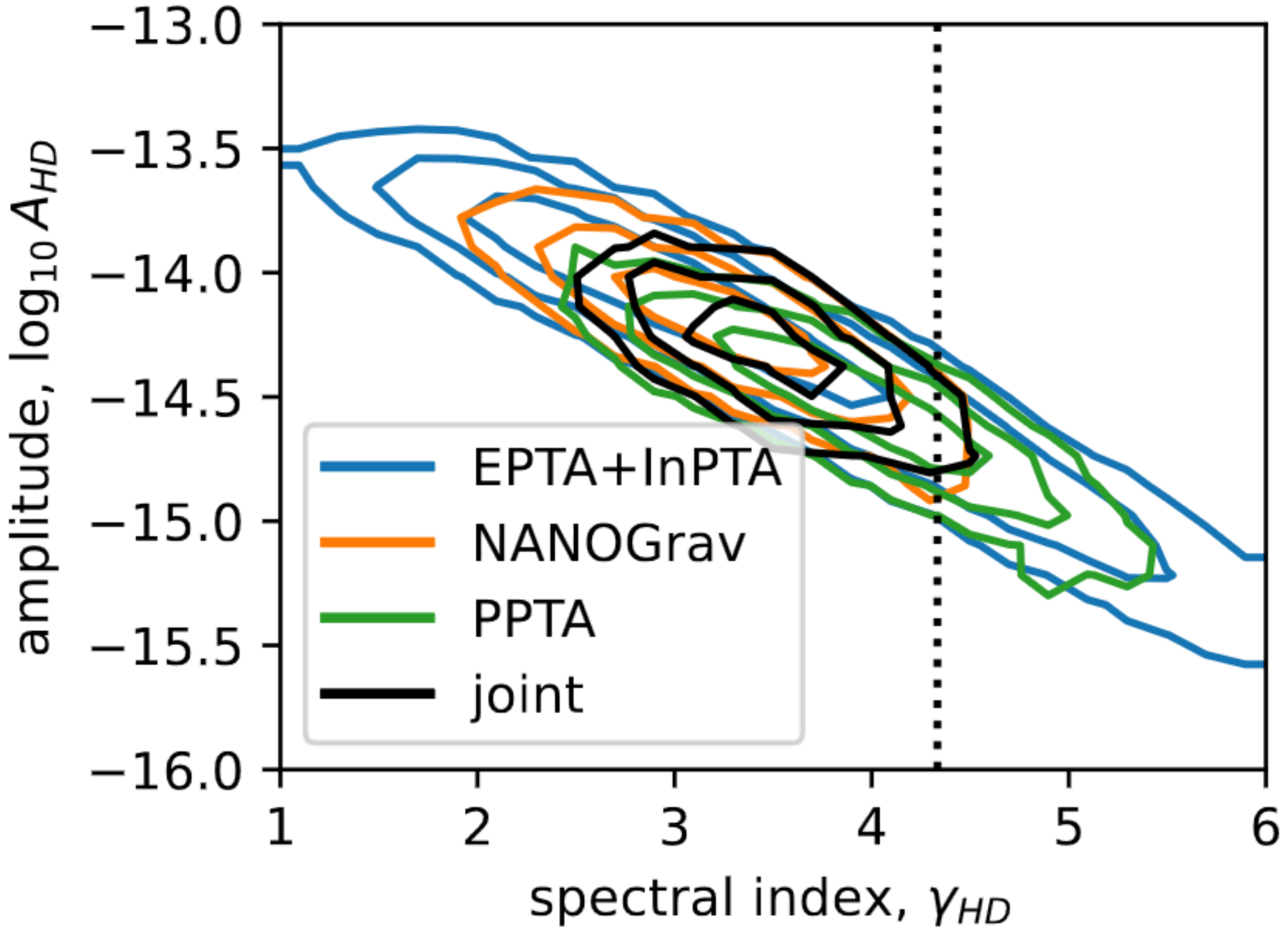
News from PTAs

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

$$S_h(f) = \frac{A^2}{2f}\left(\frac{f}{f_{\rm ref}}\right)^{2\alpha}, \quad \gamma = 3 - 2\alpha$$

What comes next?

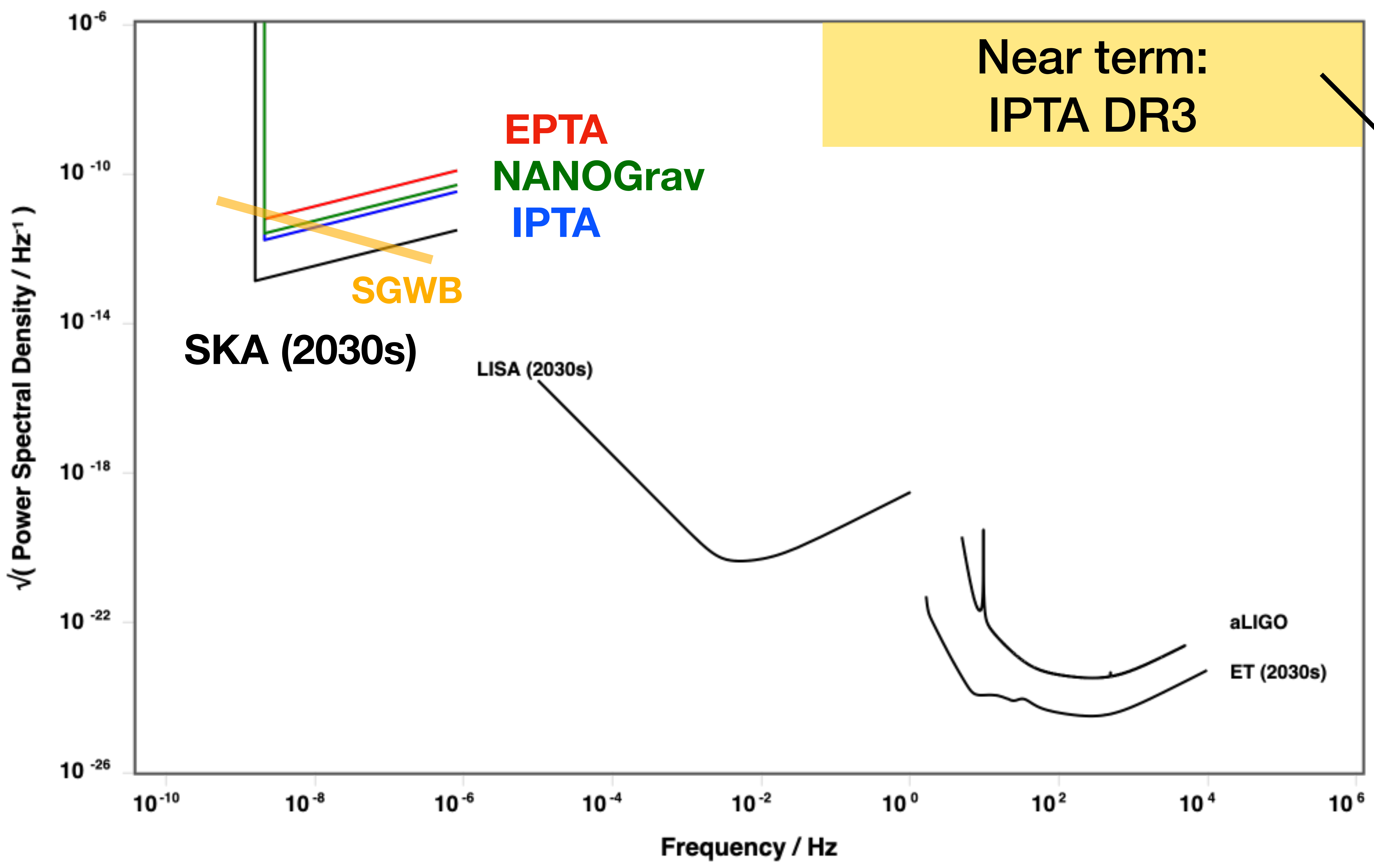
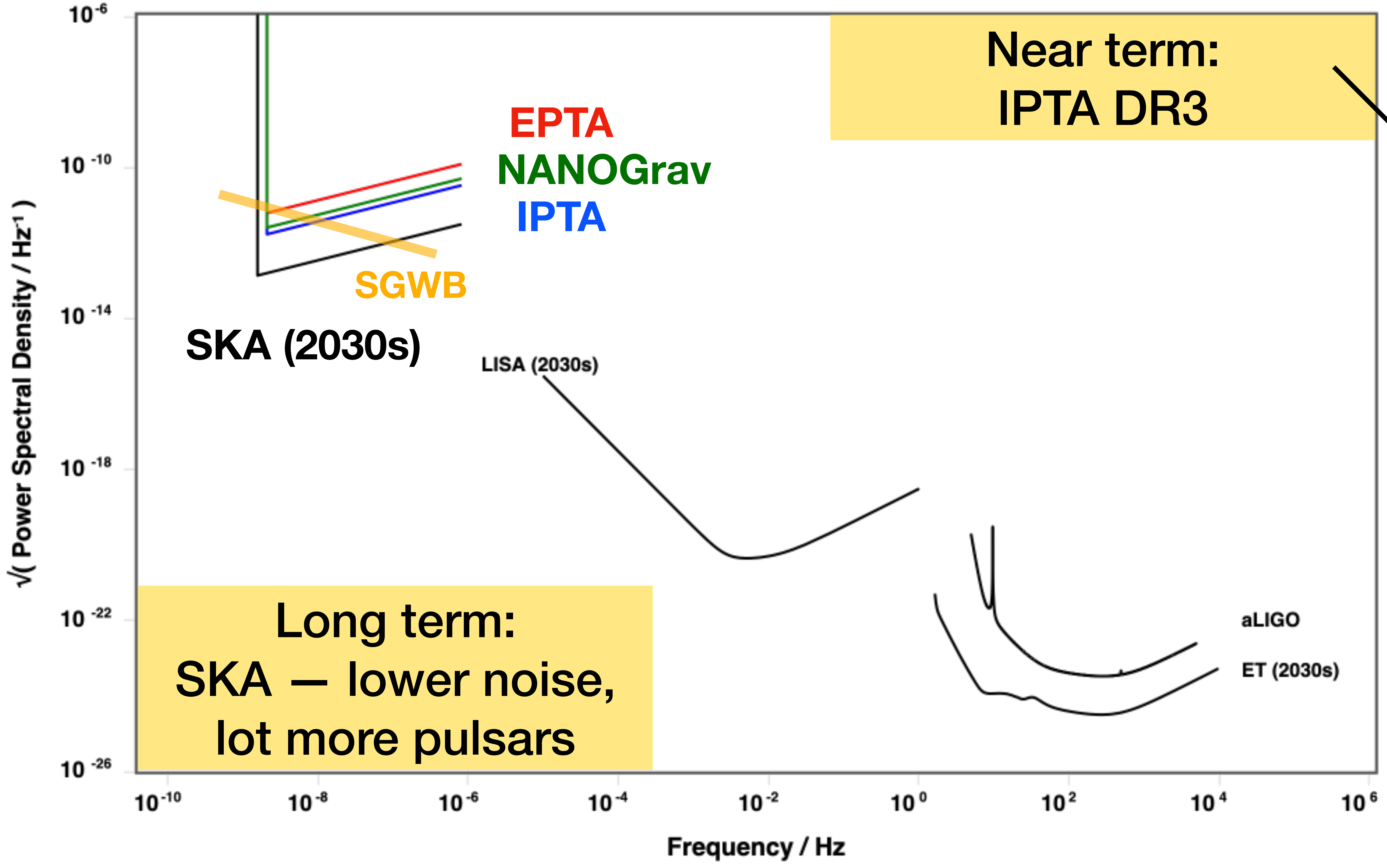


Image: GWplotter.com

Improved constraints and increased HD correlation significance

What comes next?



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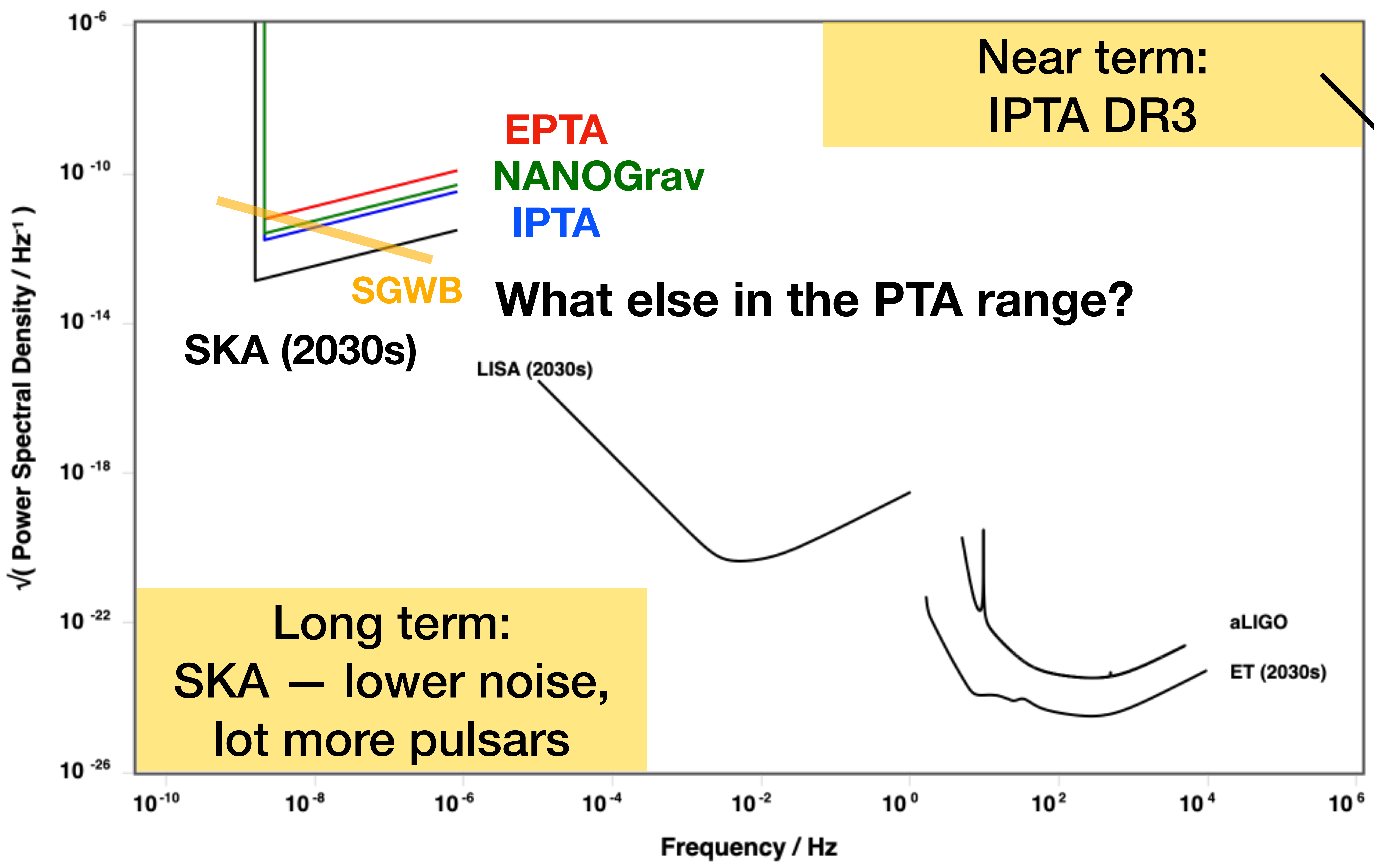

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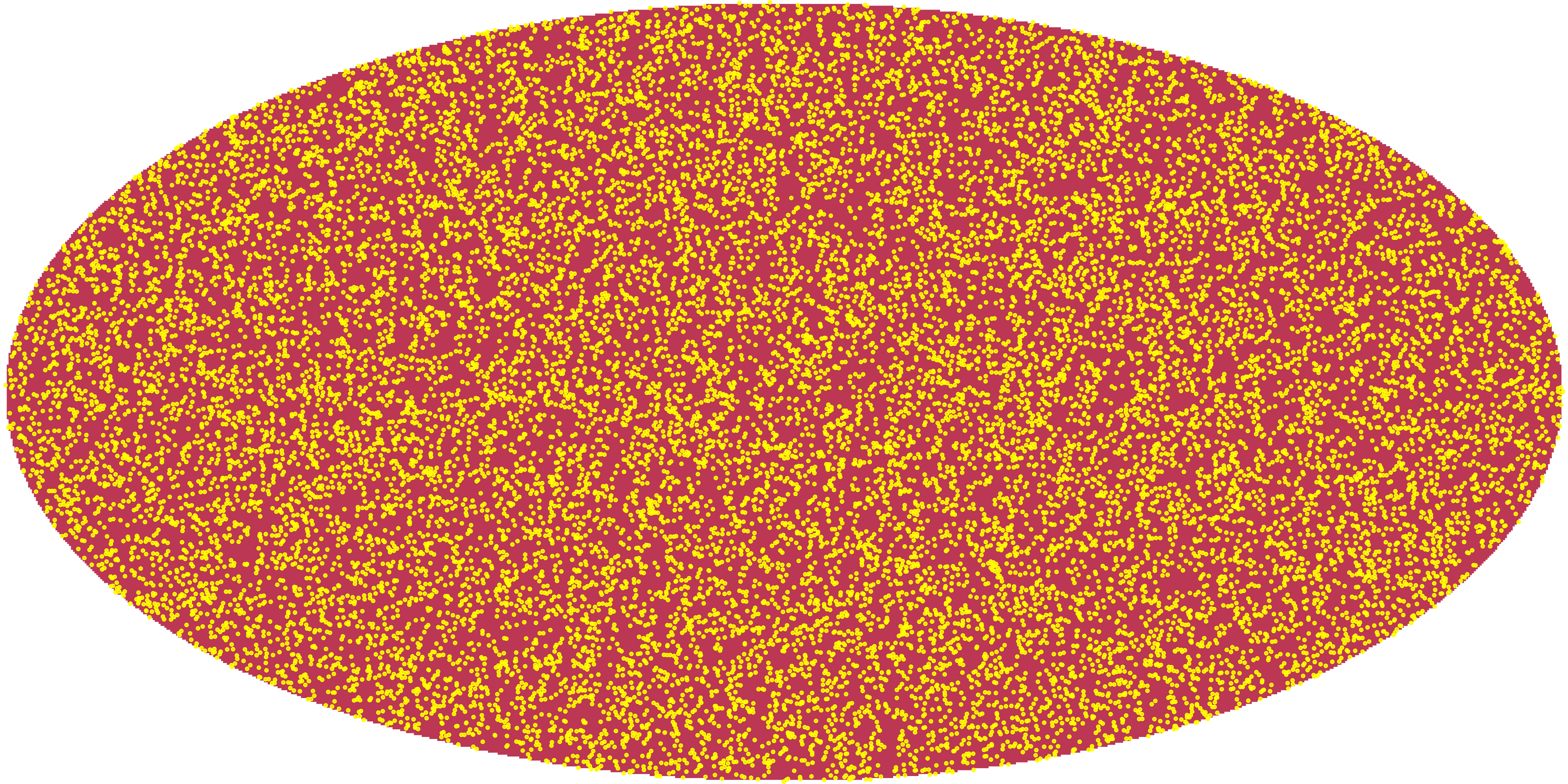
Image: GWplotter.com

Astrometry and SGWB

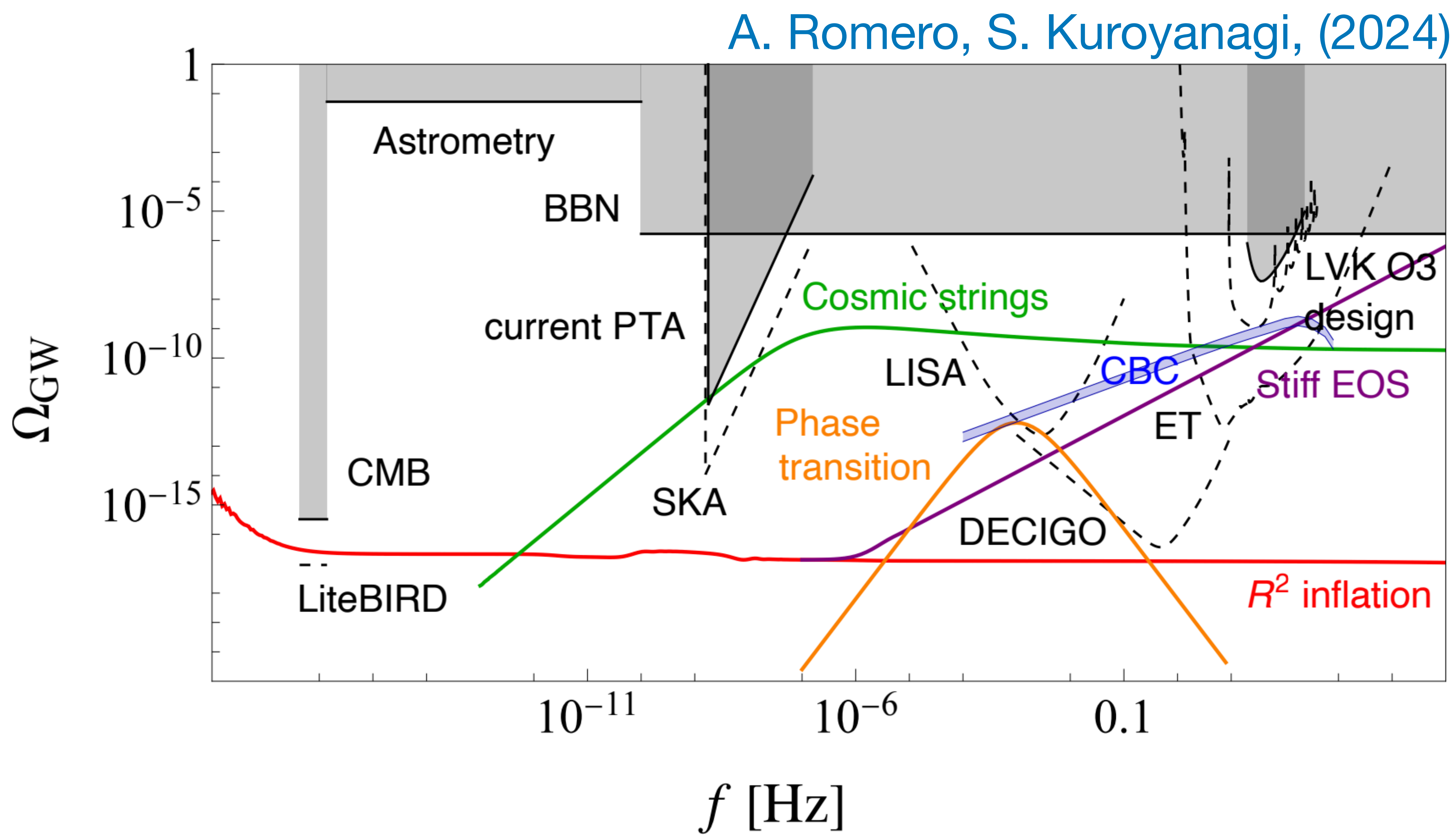
Precision astrometry with a large number of stars as a SGWB detector

[see Book, Flanagan (2010) for a review]



Gaia has $N \sim 10^9$ observed over 10 years with $\mathcal{O}(mas)$ precision. Already used to put constraints on low-frequency SGWB [Darling et al. 2018; Aoyama et al. 2021; Jaraba et al. (2023)]

Astrometry and SGWB



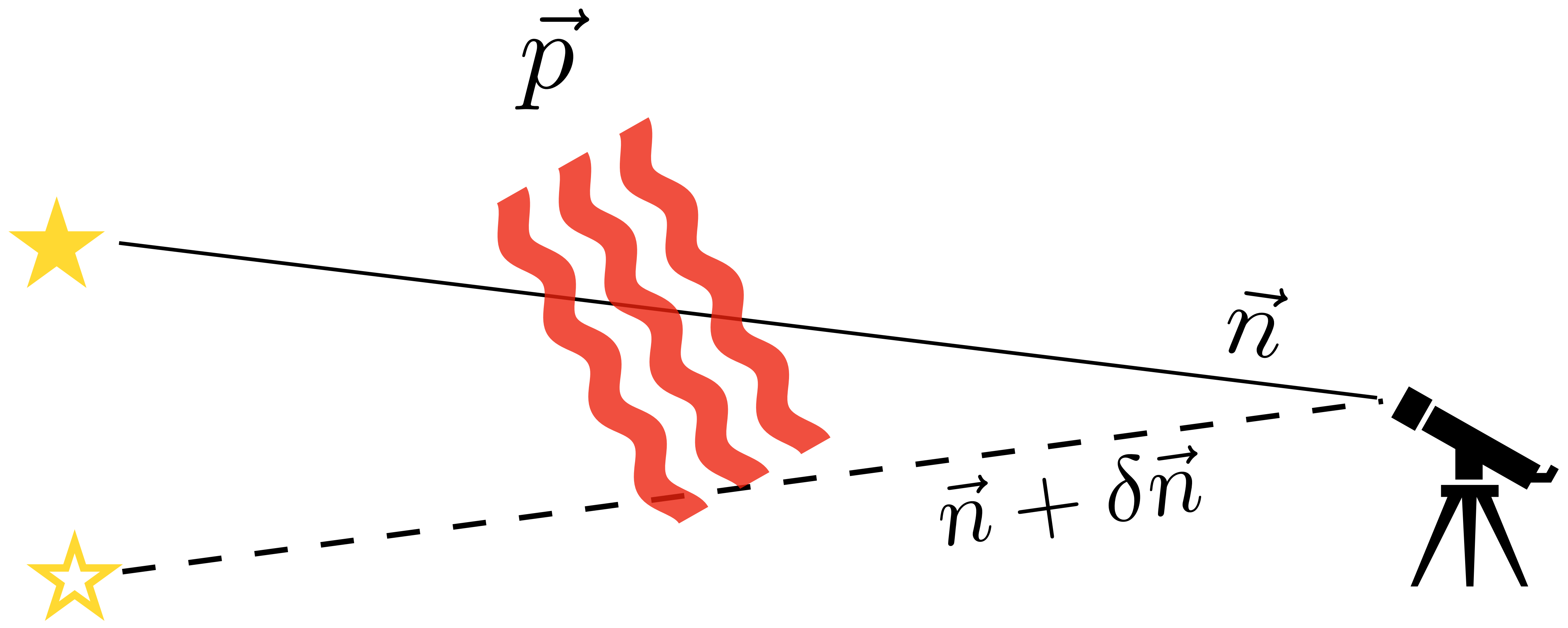
More Gaia data is coming in the next few years + future experiments (Roman, Theia…)

Forecasts for Theia $\mathcal{O}(10^{-10})$, much better angular resolution and lot more stars [J. García-Bellido et al. 2021]

Astrometry and SGWB

GW induced deflection

GWs affect the observed position of the star



For distant sources, $D \gg \lambda_{\rm GW}$

$$\delta n^i(t,\vec{n}) = \mathcal{R}_{ikl}(\vec{n},\vec{p})\, h_{ij}(t)|_{\rm earth}, \quad \mathcal{R}_{ikl}(\vec{n},\vec{p}) = \frac{n_k}{2}\left[\frac{(n_i+p_i)n_l}{1+\vec{n}\cdot\vec{p}} - \delta_{il}\right]$$

[Book, Flanagan (2010)]

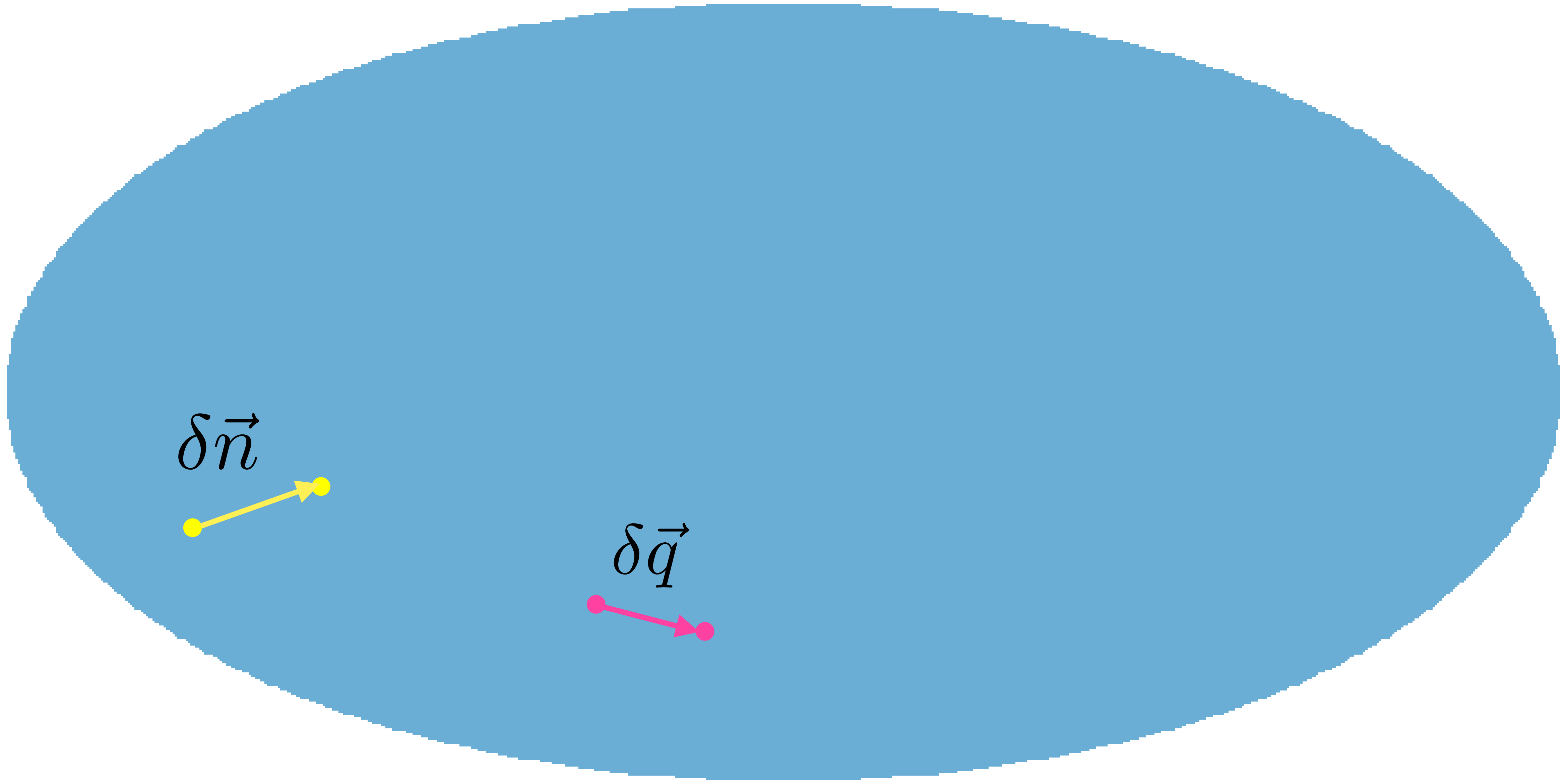
Astrometry and SGWB

Correlated deflections

SGWB PSD

$$\langle \delta n^i \delta q^j \rangle \propto \int df\, S_h(f)\, H^{(0)}_{ij}(\vec{n}, \vec{q})$$

Geometry dependent correlation



$$H^{(0)}_{ij}(\vec{n}, \vec{q}) = \frac{\pi}{3(1-y)^2}\left(1 - 8y + 7y^2 - 6y^2 \ln y\right)$$
$$\times \left[(2-2y)\delta_{ij} - n_i n_j - q_i q_j - q_i n_j + (1-2y) q_j n_i\right]$$

$$y \equiv \frac{1 - \vec{n}\cdot\vec{q}}{2}$$

Astrometry x PTA

Cross-correlations

The angular deflections and timing residuals induced by the SGWB are correlated

$$K_i^{(0)}(\vec{n},\vec{x}) = \frac{16\pi}{3}\,\frac{(1-2y)\,n_i - x_i}{4y(1-y)}\,\left(2y - 2y^2 + 3y^2\ln(y)\right)$$

Pulsar direction

Star direction

Astrometry x PTA

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Pulsar direction

Star direction

Can cross-correlating Astrometry with PTA help?

Astrometry x PTA

The setup

Forecasts with PTA at current sensitivity and an astrometric survey with $0.01\,mas$ precision and 10^6 stars.

Joint Gaussian likelihood in the timing residuals and angular deflections.

$$-\ln \mathcal{L} \sim (\delta t, \delta \vec{n}) \mathcal{C}^{-1} (\delta t, \delta \vec{n})^T$$

PTA | PTA x Astro

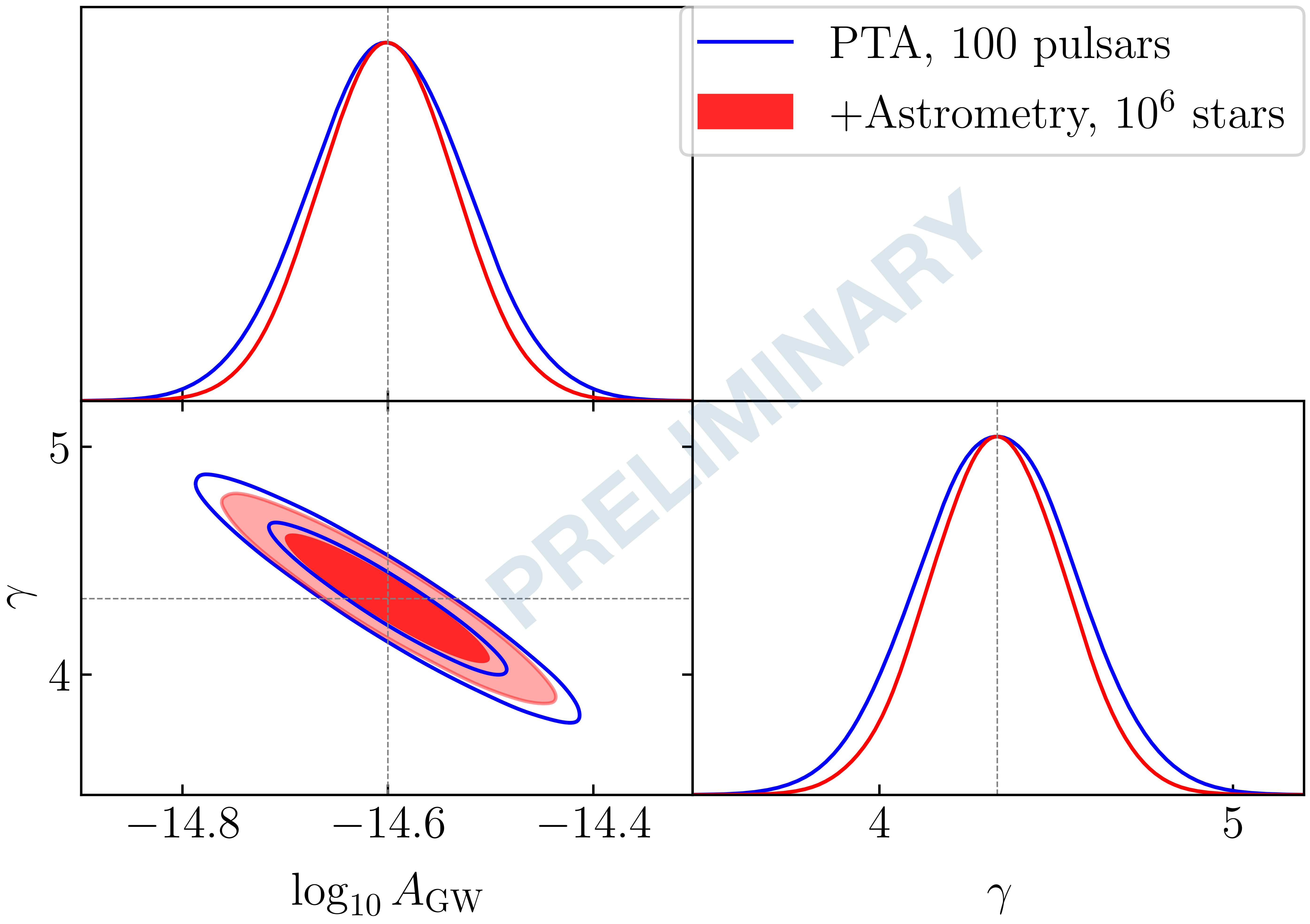
$$\mathcal{C} = \begin{bmatrix} C_{\delta t \delta t} & C_{\delta t \delta \vec{n}} \\ C^T_{\delta t \delta \vec{n}} & C_{\delta \vec{n} \delta \vec{n}} \end{bmatrix}$$

PTA x Astro | Astro

Astrometry x PTA

Power-law

~10 % improvement over current PTA constraints

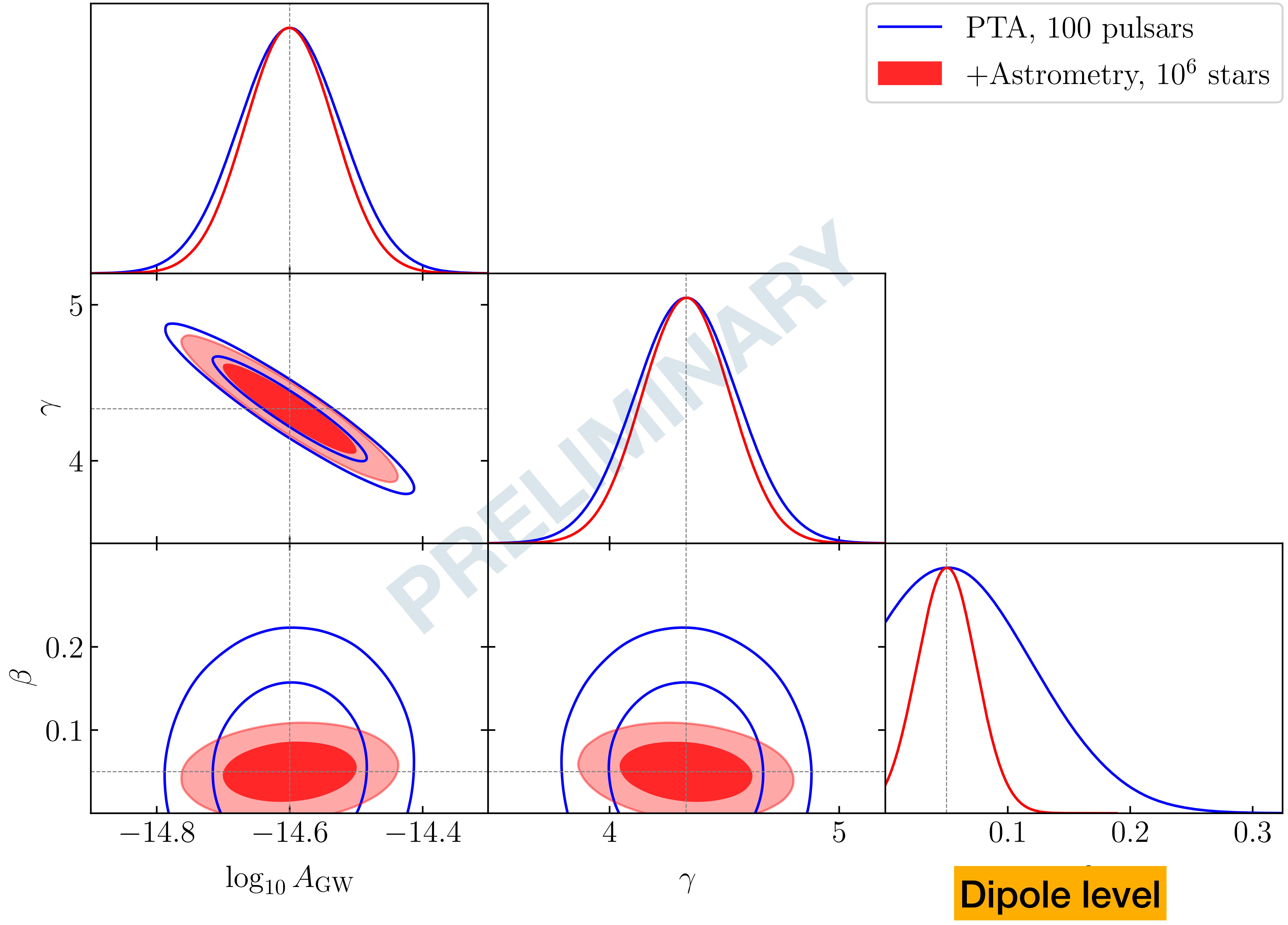


Astrometry x PTA

Dipole anisotropy

Minimum detectable dipole anisotropy relative to monopole ~ 0.05.

Current PTA level ~ 0.1



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Future work: how to implement this in practice?

Thank you!