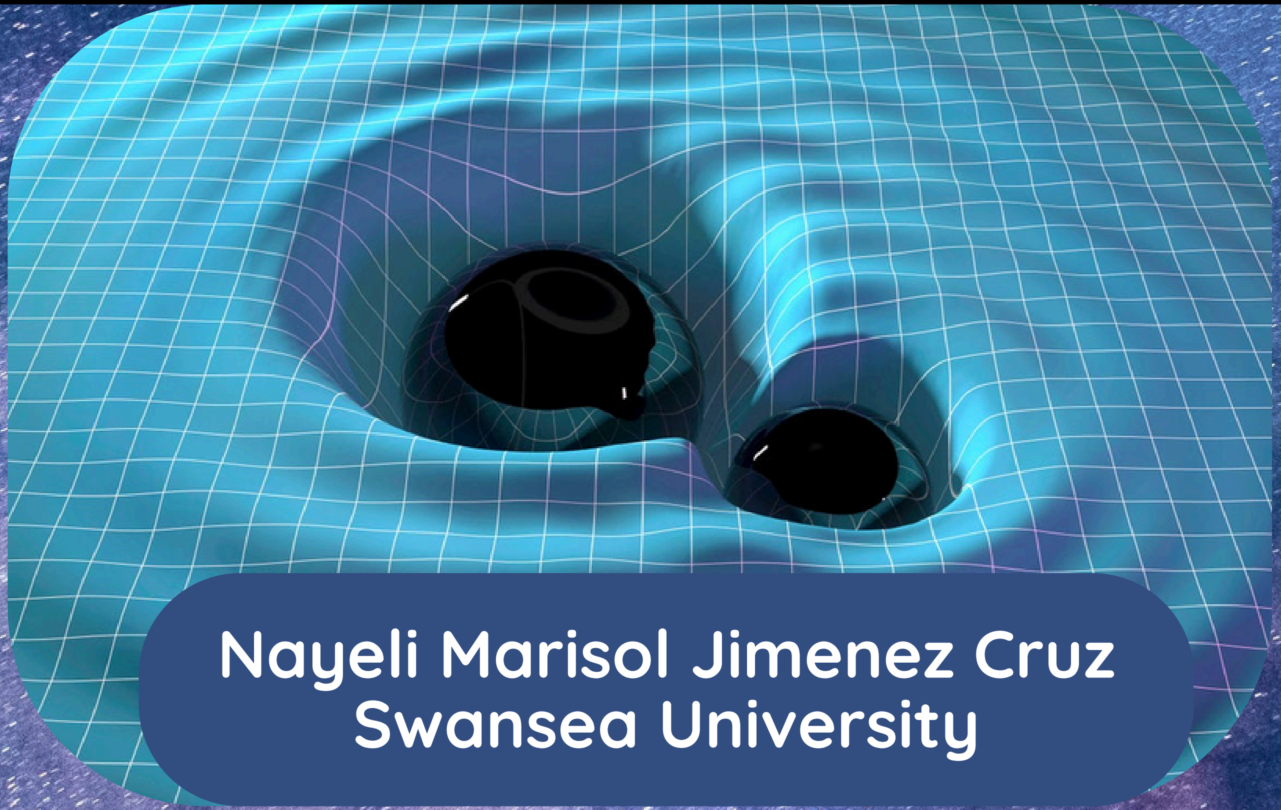
CosmoFONDUE | École de physique

11th June 2025

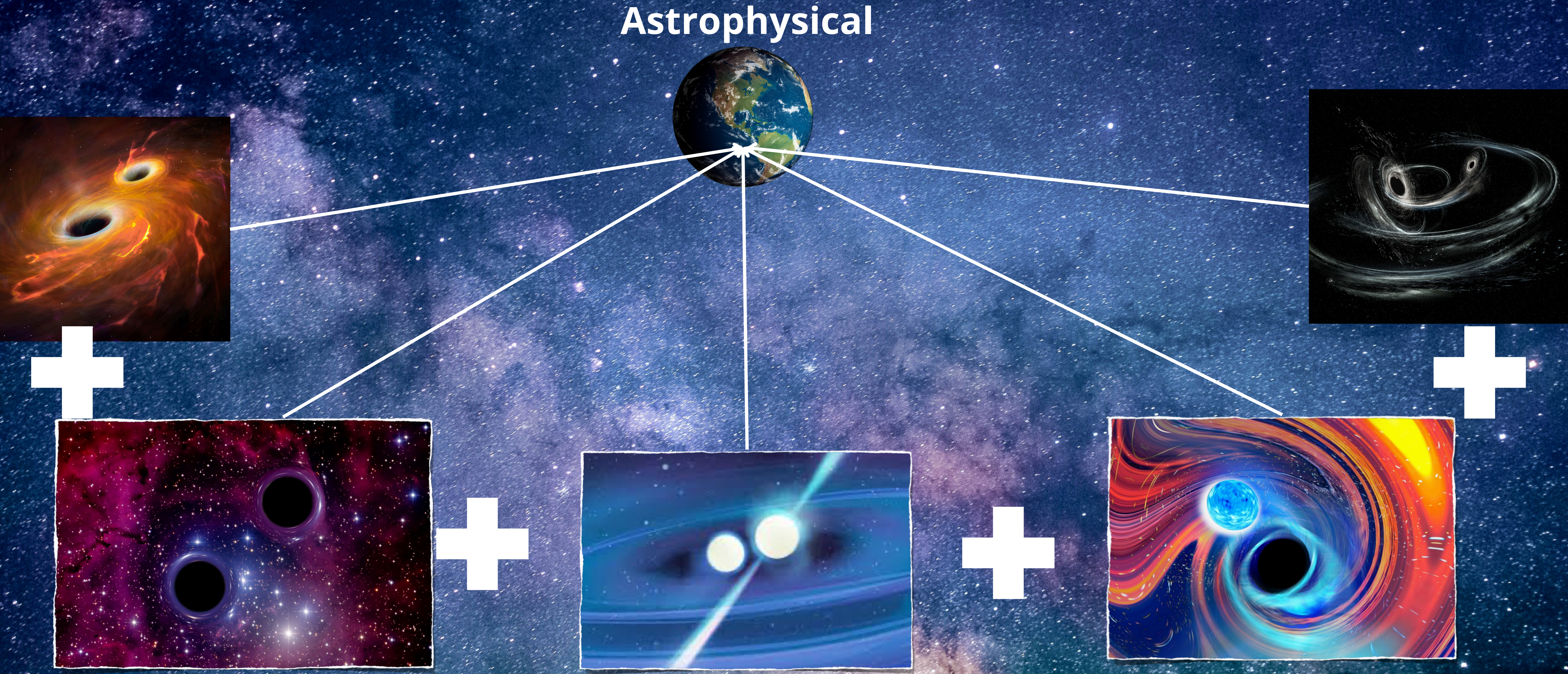
Gravitational waves detection from PTA and Astrometry



Nayeli Marisol Jimenez Cruz
Swansea University

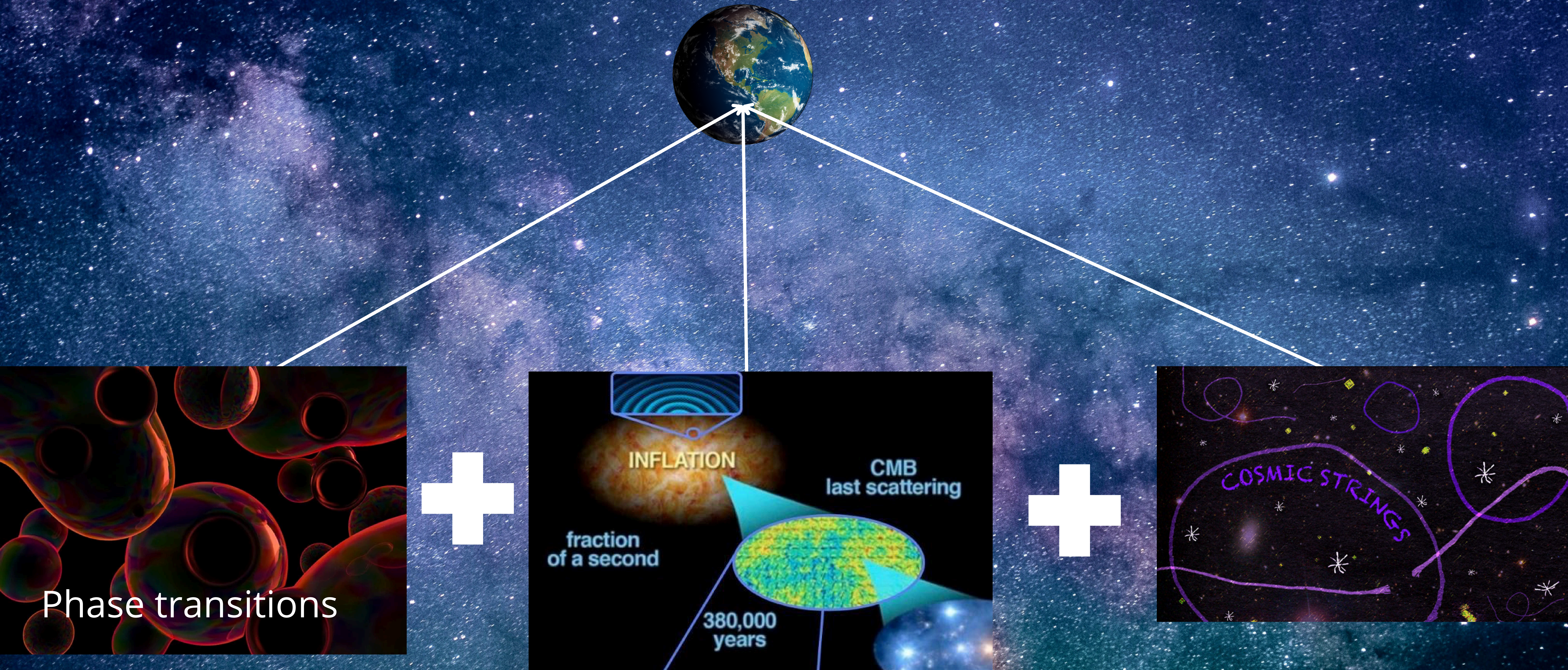
Jiménez Cruz, N. M., Ameek M., Gianmassimo T., and Ivonne Z.. "Astrometry meets Pulsar Timing Arrays: Synergies for Gravitational Wave Detection." ArXiv: 2412.14010 (2024).

Stochastic Gravitational Wave Background



Stochastic Gravitational Wave Background

Cosmological



How can we differentiate between an astrophysical and a cosmological SGWB?

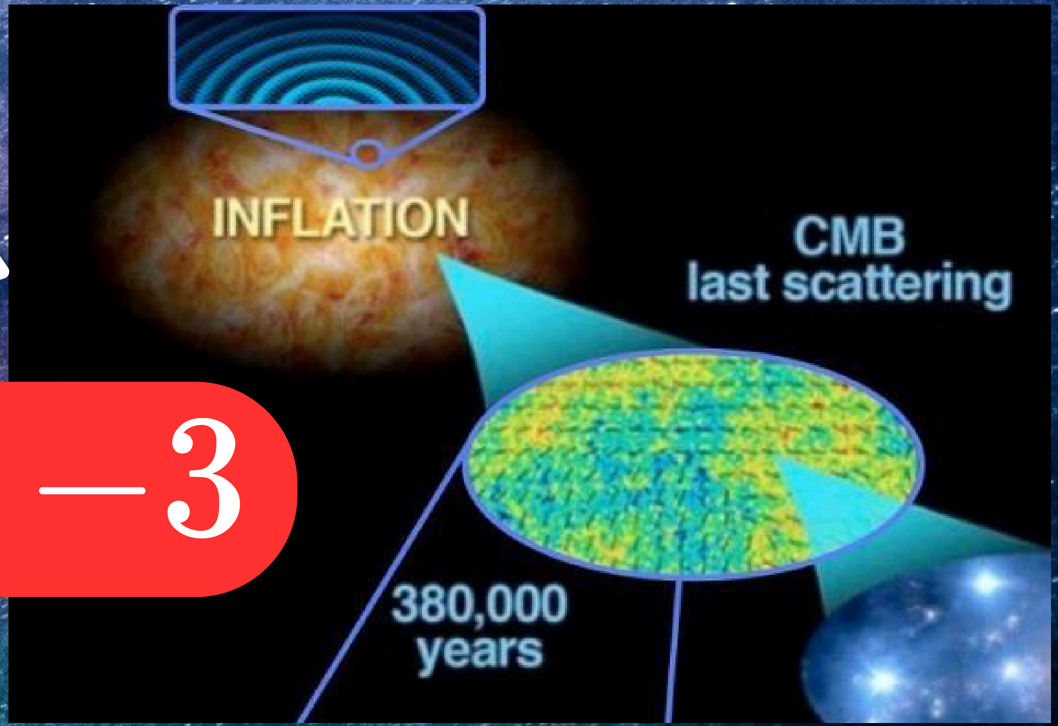
Spectral tilt

$$I(f) = I_0 \left(\frac{f}{f_{ref}} \right)^{n_I}$$

$$I_0 = \left(\frac{A^2}{2 f_{ref}} \right)$$

Maximal sensitivity

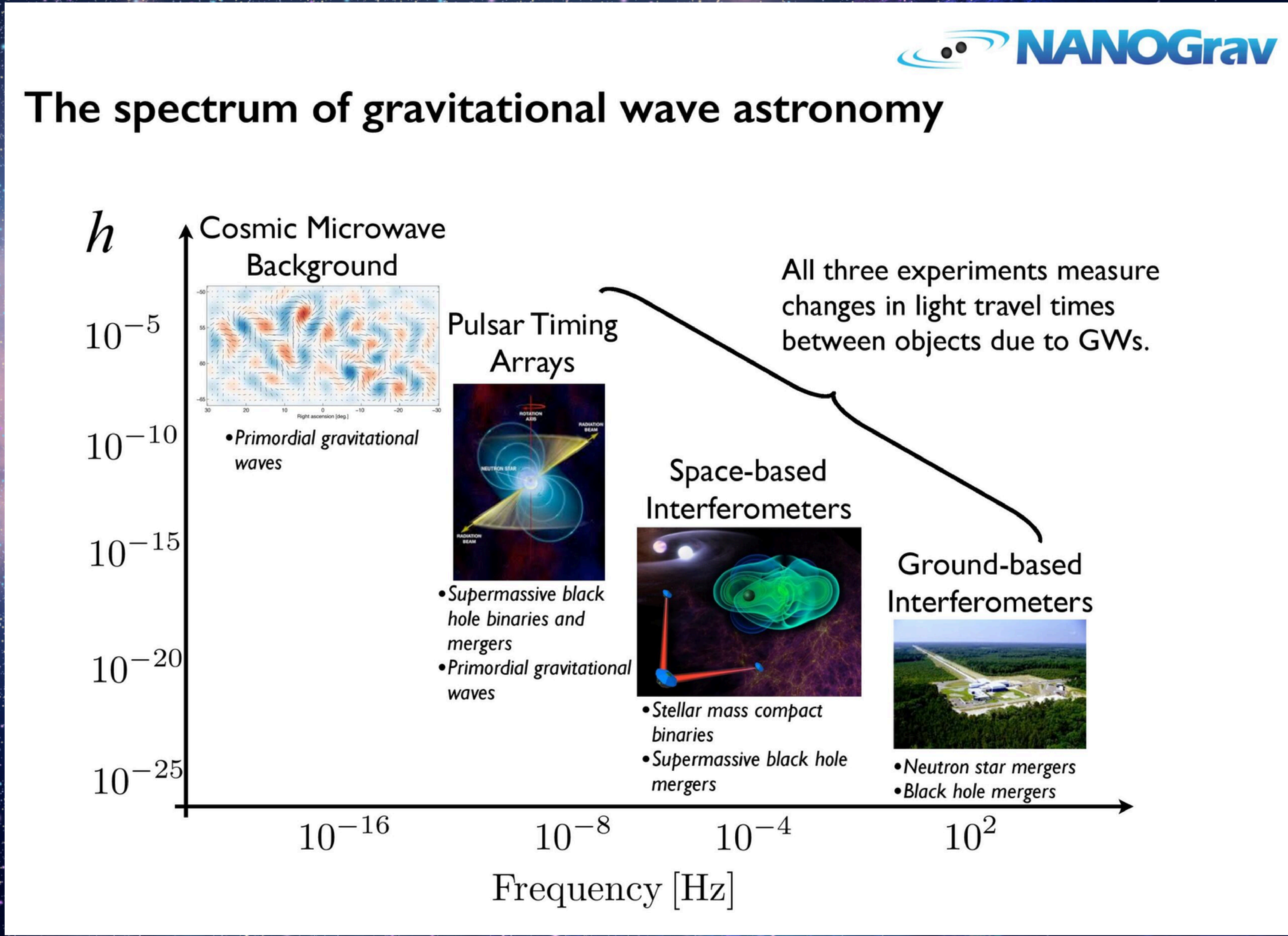
$n_I = -7/3$

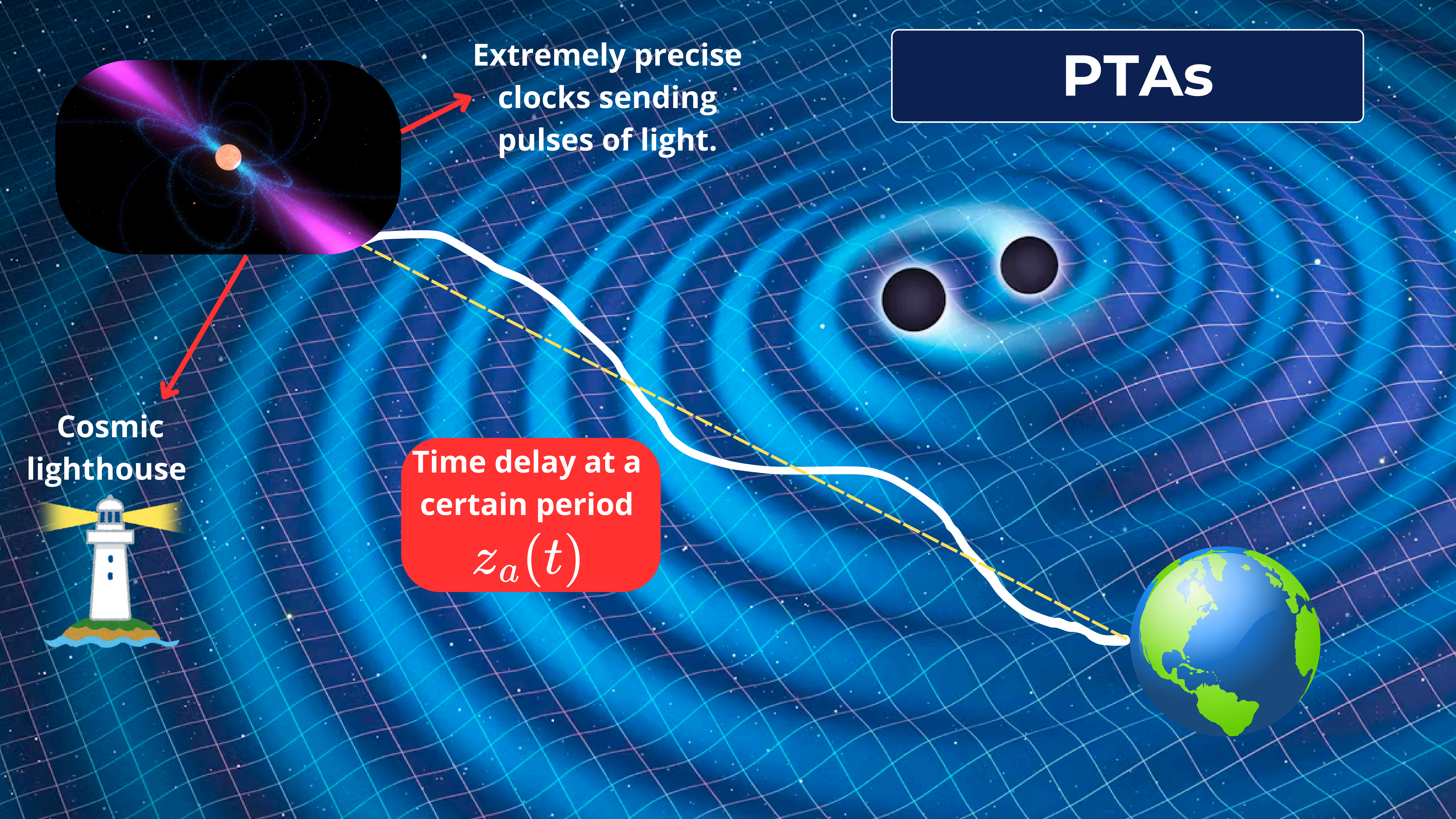


$n_I = -3$

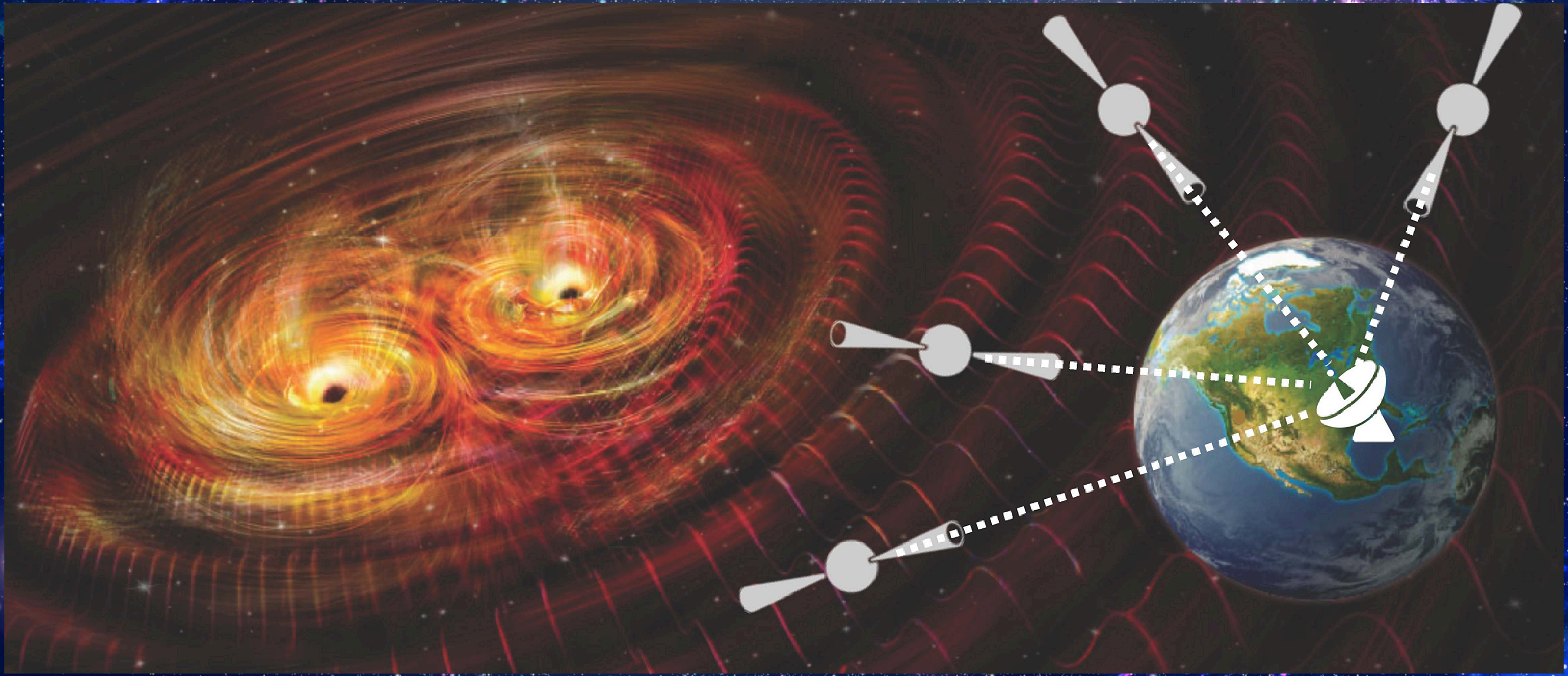
How to detect the SGWB

Detection at very low frequencies!



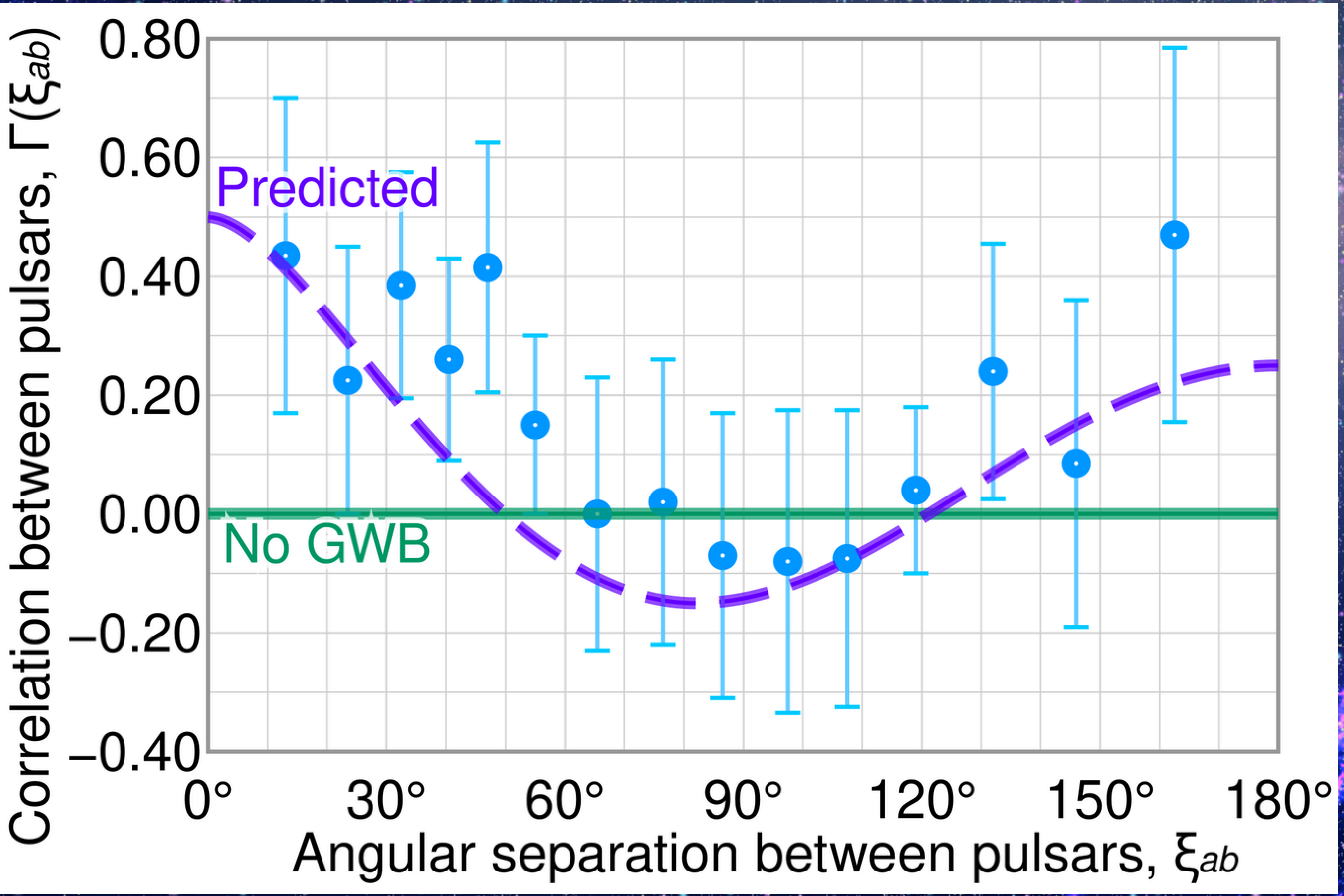

PTAs
Extremely precise clocks sending pulses of light.
Cosmic lighthouse
Time delay at a certain period
$z_a(t)$

Pulsar Timing Arrays and the SGWB



The timing delays could be correlated

Hellings-Downs curve



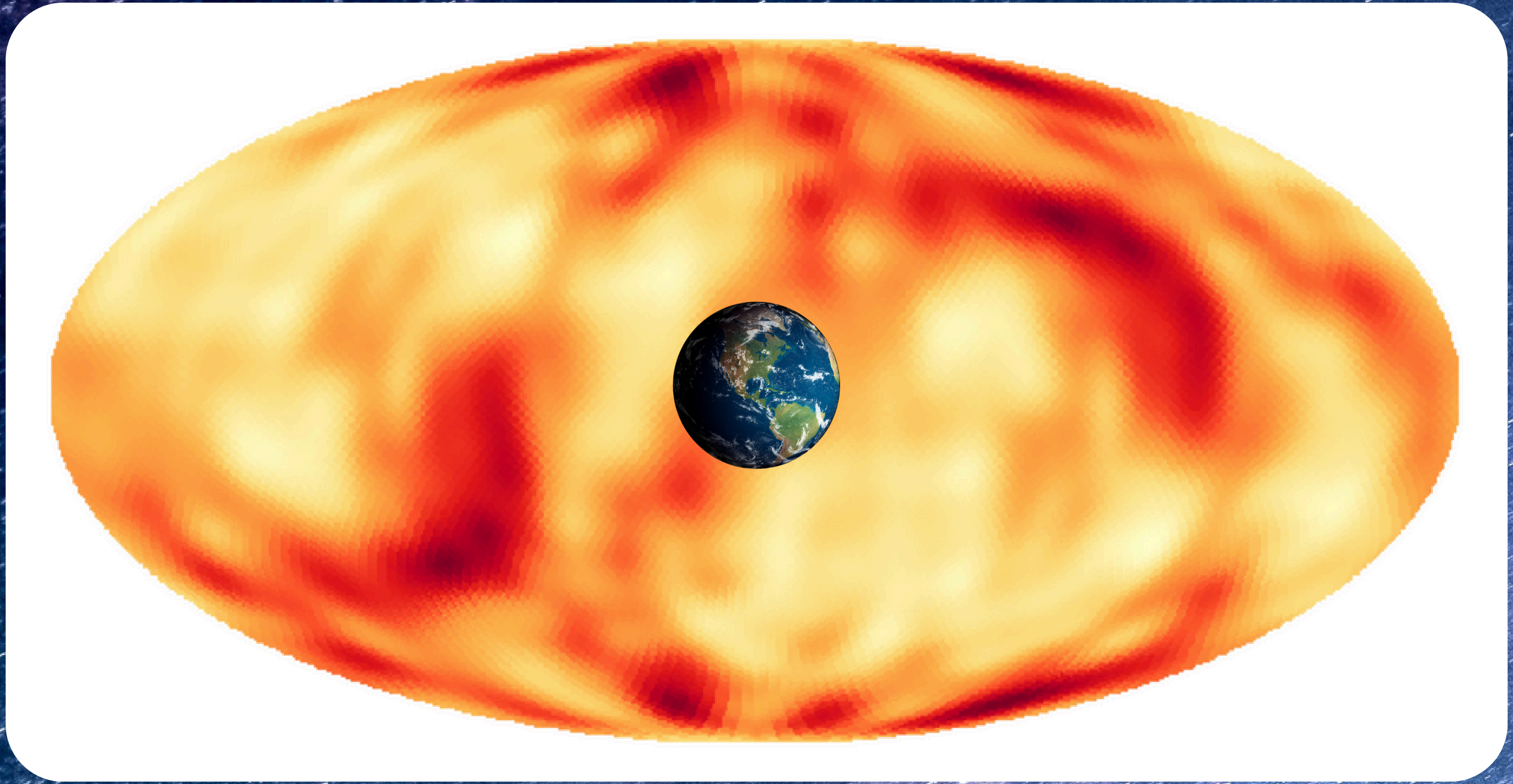
Still not clear if the source is Astrophysical or cosmological...

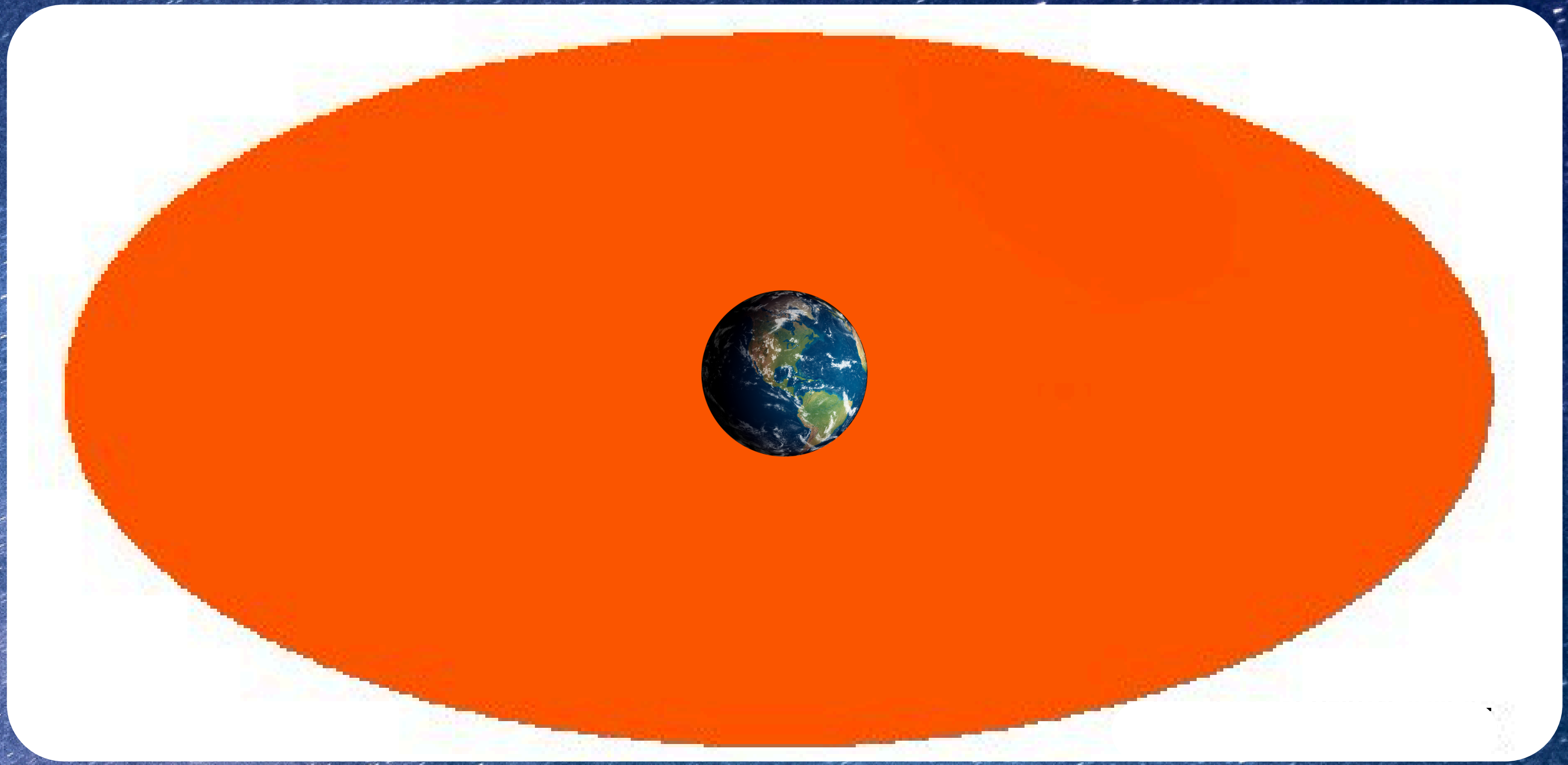
PTA collaborations results *

R. W. Hellings and G. S. Downs, Astrophys. J. Lett. 265, L39 (1983).

* NANOGrav (USA), EPTA (Europe), PPTA (Australia), CPTA (China)

Primordial SGWB





Astrophysical

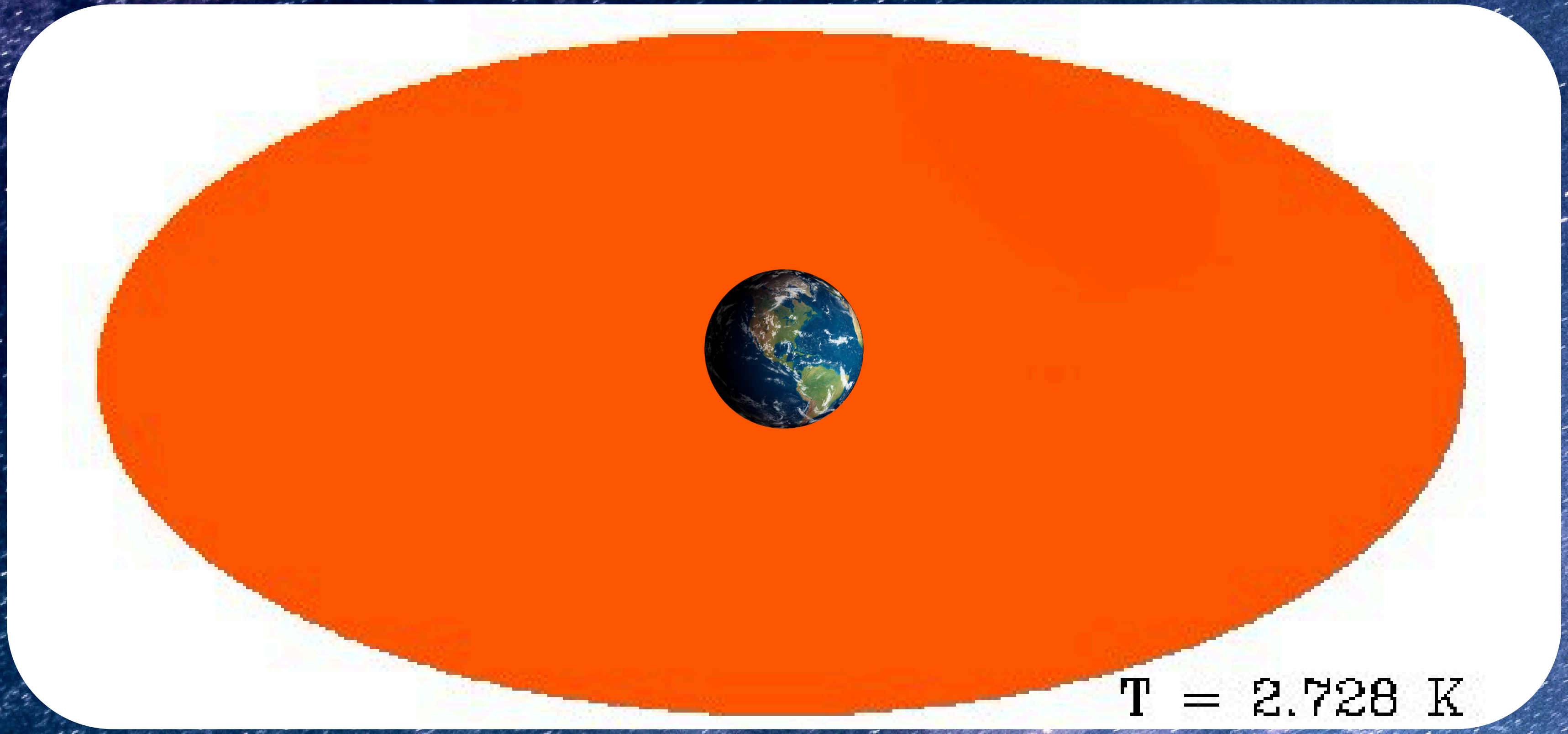
Strongly anisotropic

Cosmological

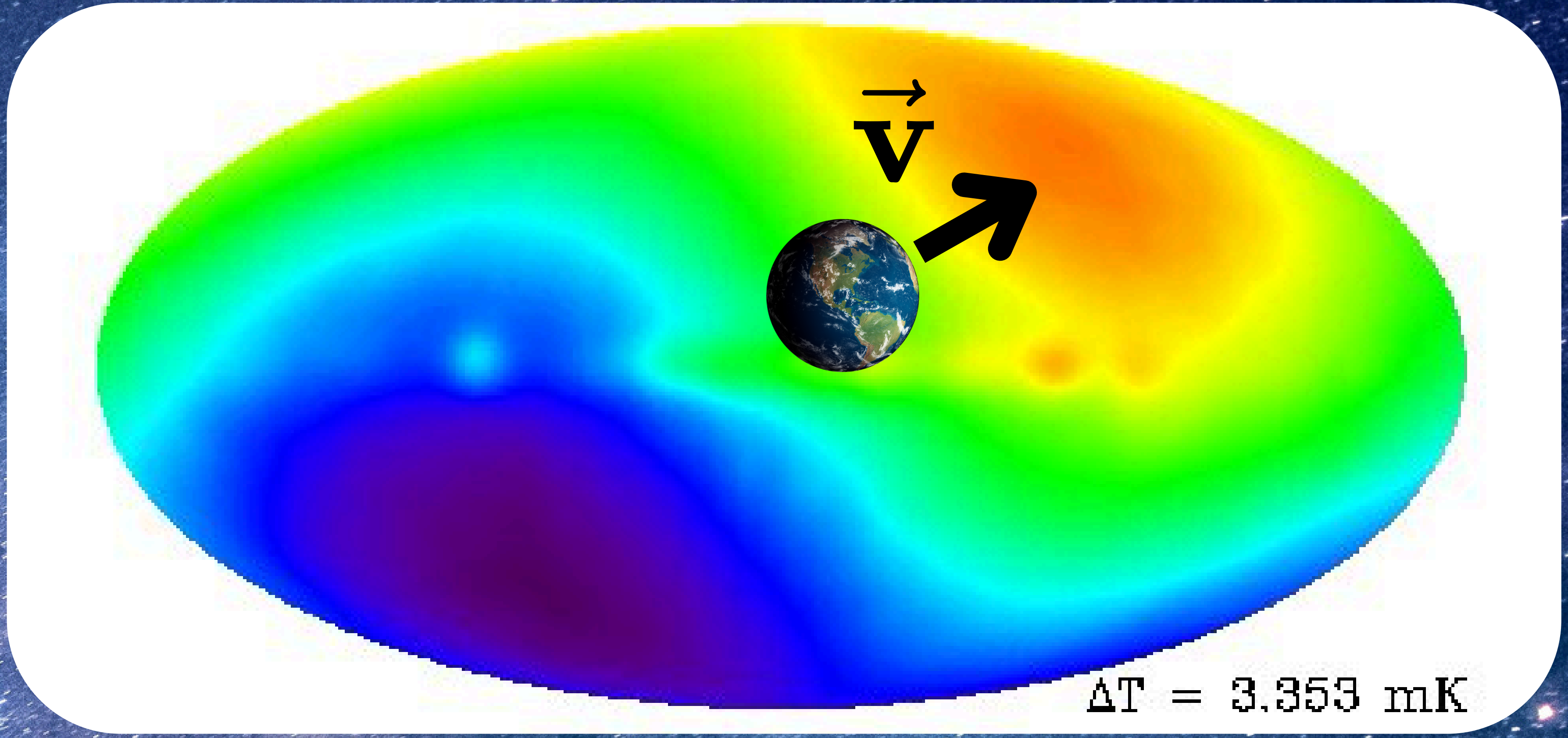
Predominantly isotropic
with small fluctuations.

Renzini, A. I., and C. R. Contaldi. "Improved limits on a stochastic gravitational-wave background and its anisotropies from Advanced LIGO O1 and O2 runs." Physical Review D100, no. 6 (2019): 063527.

Kinematic anisotropies



Isotropic signal



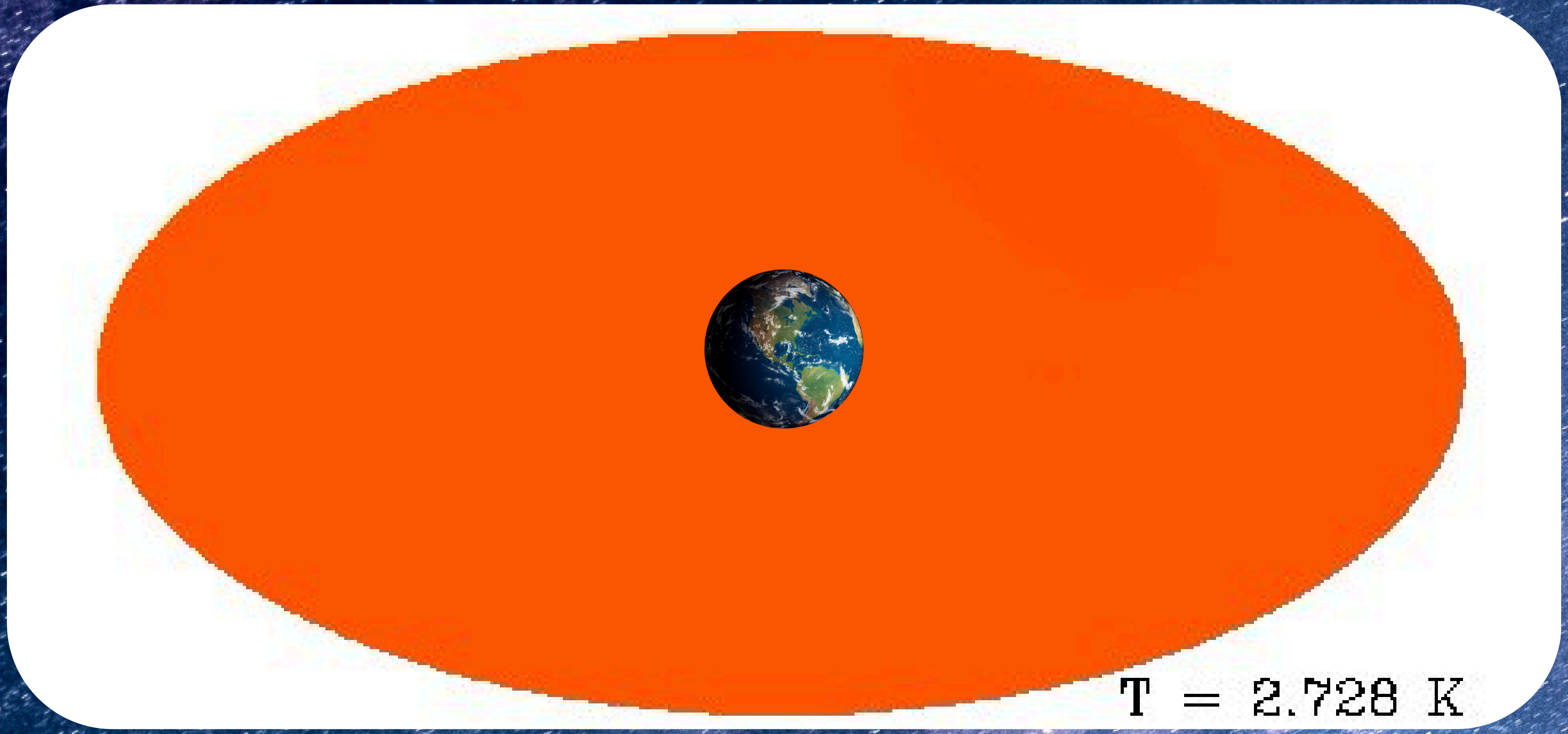
Kinematic anisotropies

Already observed in the CMB!

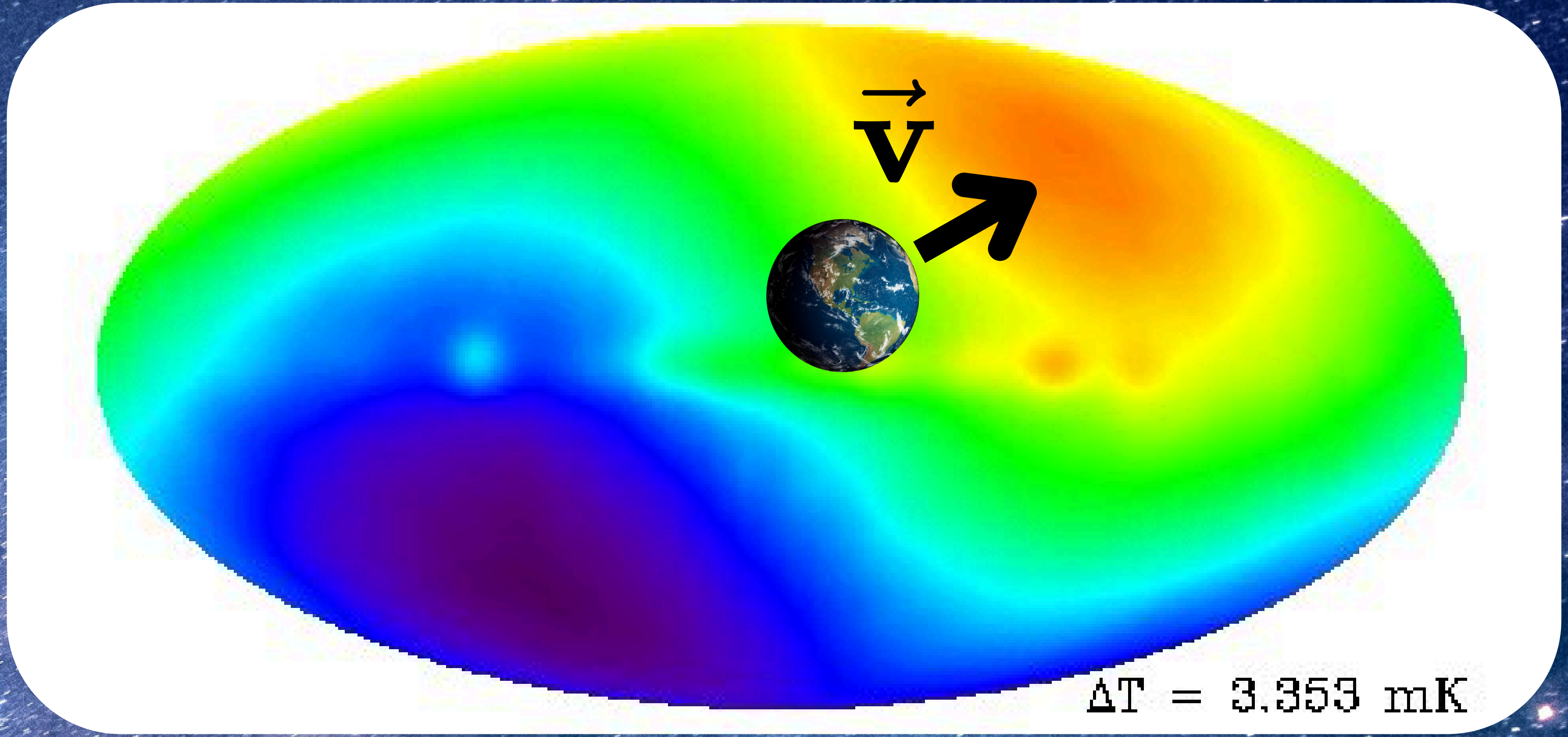
$$\beta = |\vec{\mathbf{v}}|/c = 1.23 \times 10^{-3}$$
$$(l, b) = (264^\circ, 48^\circ)$$

Credit: NASA/COBE Science Team

Kinematic anisotropies



Isotropic signal



Kinematic anisotropies

Cosmic dipole tension

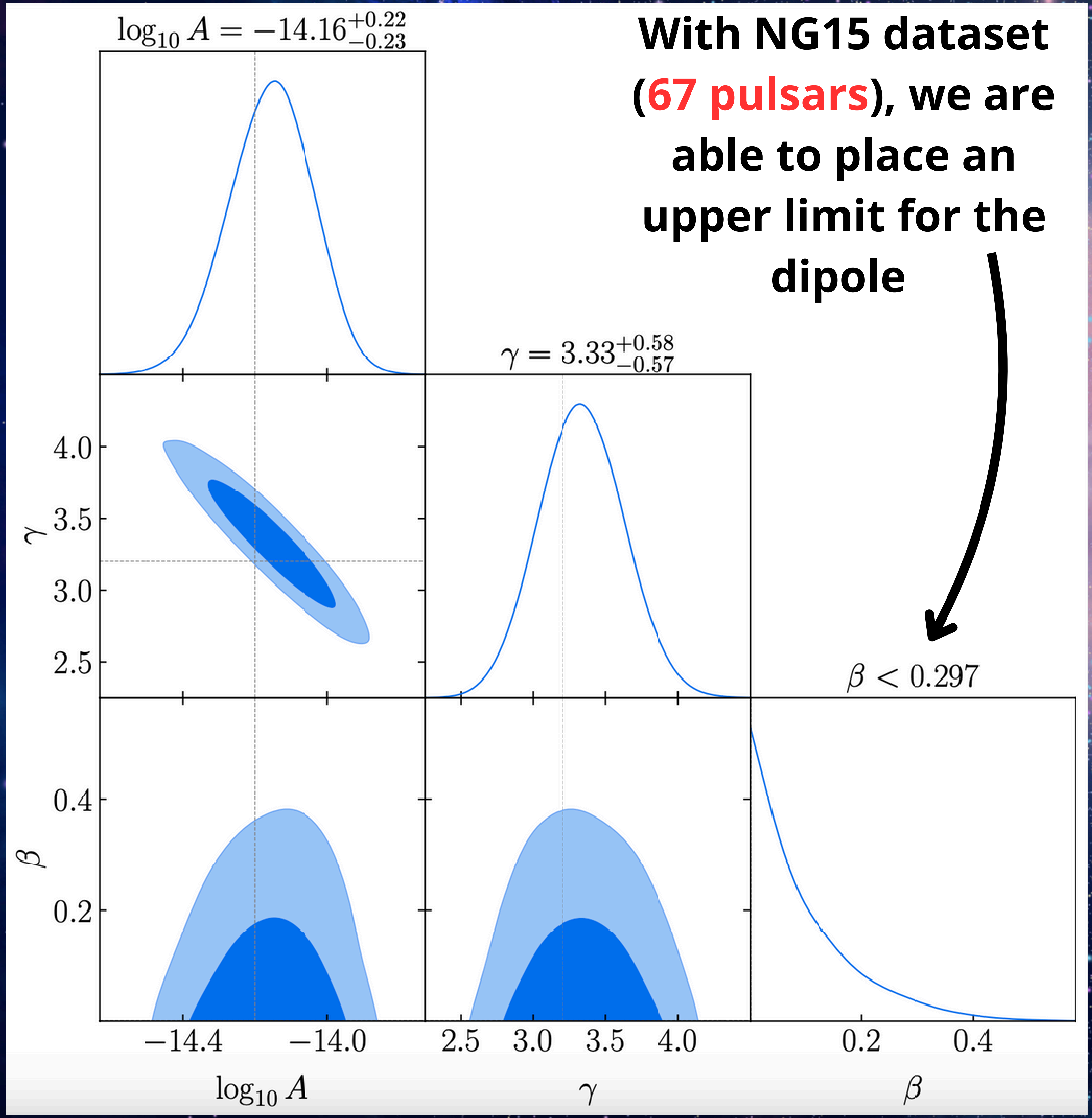
2111.03616

$$\beta = |\vec{\mathbf{v}}|/c = 1.23 \times 10^{-3}$$

$$(l, b) = (264^\circ, 48^\circ)$$

Credit: NASA/COBE Science Team

Kinematic Anisotropies with PTAs



$$I(f) = I_0 \left(\frac{f}{f_{ref}} \right)^{n_I}$$

$$I_0 = \left(\frac{A^2}{2 f_{ref}} \right)$$

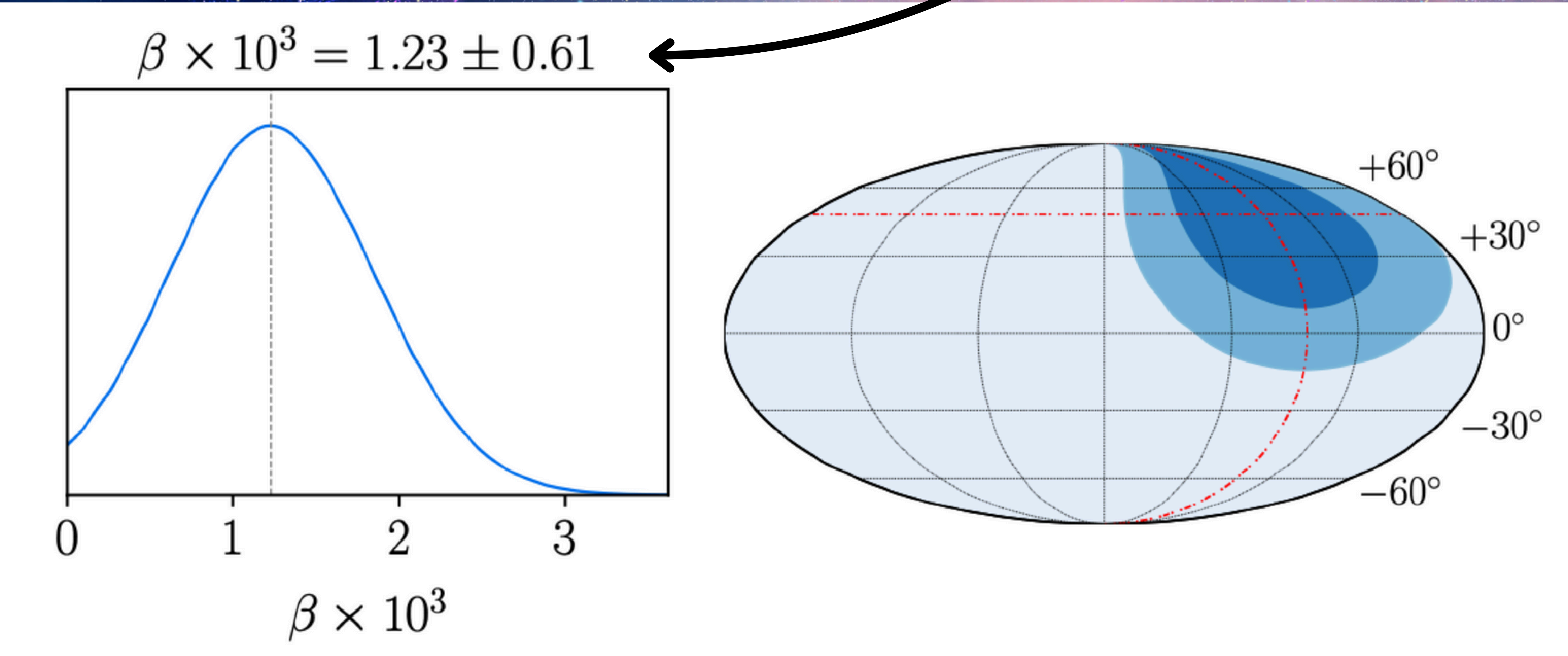
$$n_I = 2 - \gamma$$

$$\beta = |\vec{\mathbf{v}}|/c$$

Jiménez Cruz, N. M., Ameek M., Gianmassimo T., and Ivonne Z..
"Measuring kinematic anisotropies with pulsar timing arrays."
Physical Review D110, no. 6 (2024): 063526.

Kinematic Anisotropies with PTAs

68% C.L. with 4000 identical pulsars and $T_{\rm obs} = 20\,\mathrm{years}$



Large number of pulsars even for future experiments in SKA.

Jiménez Cruz, N. M., Ameek M., Gianmassimo T., and Ivonne Z.. "Measuring kinematic anisotropies with pulsar timing arrays." Physical Review D110, no. 6 (2024): 063526.

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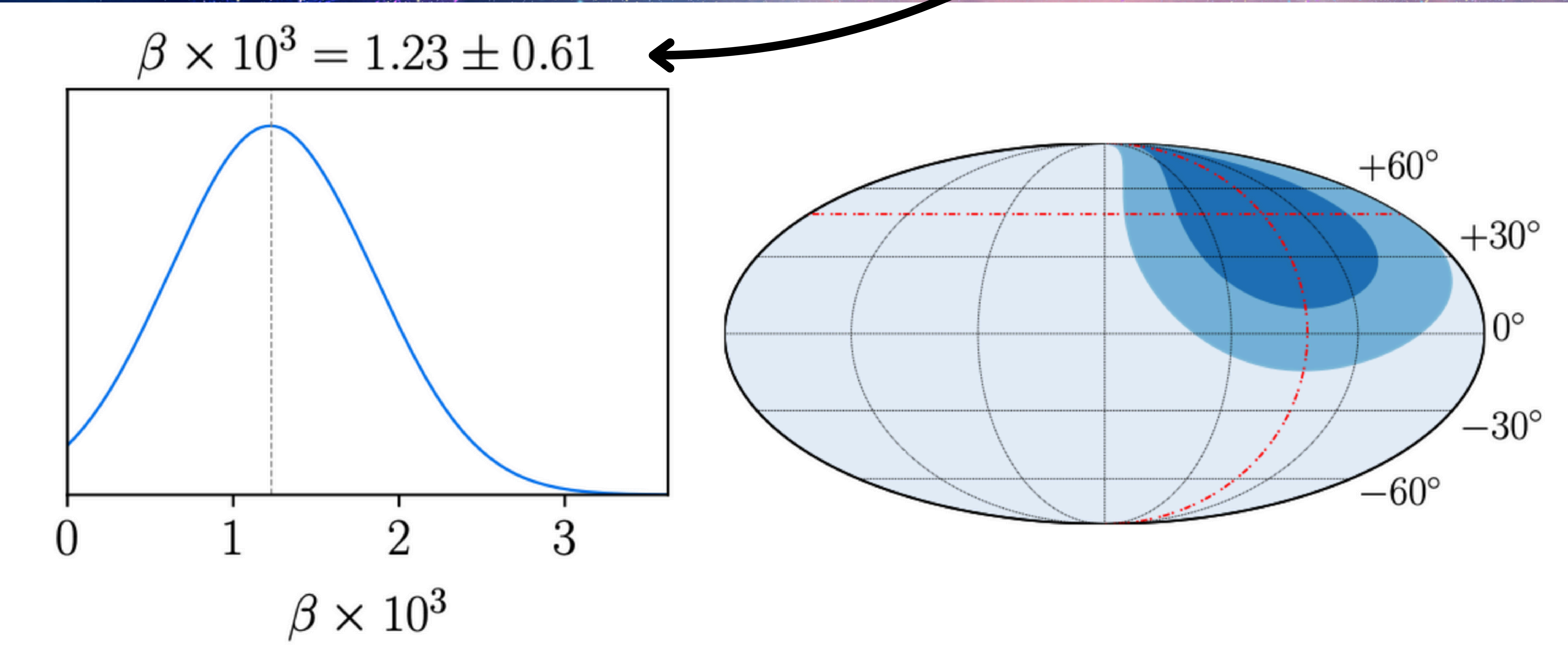

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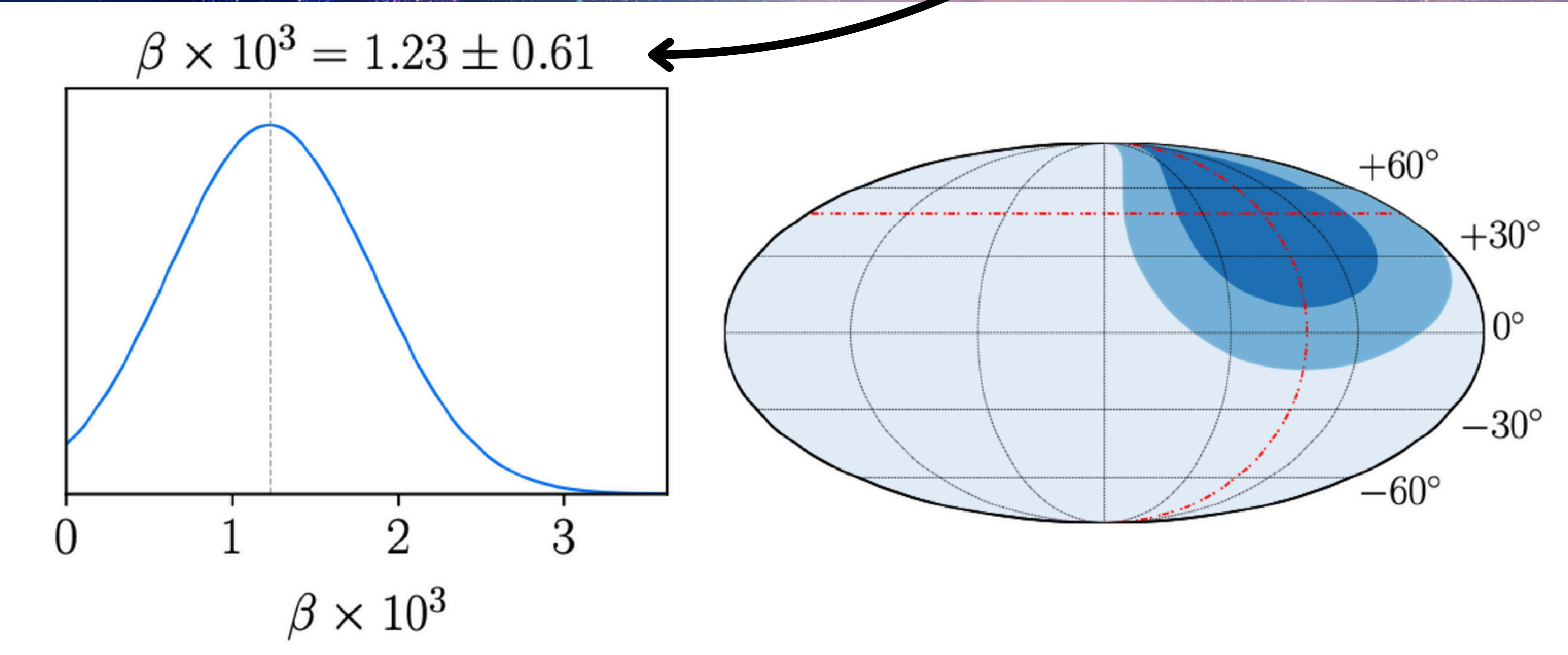
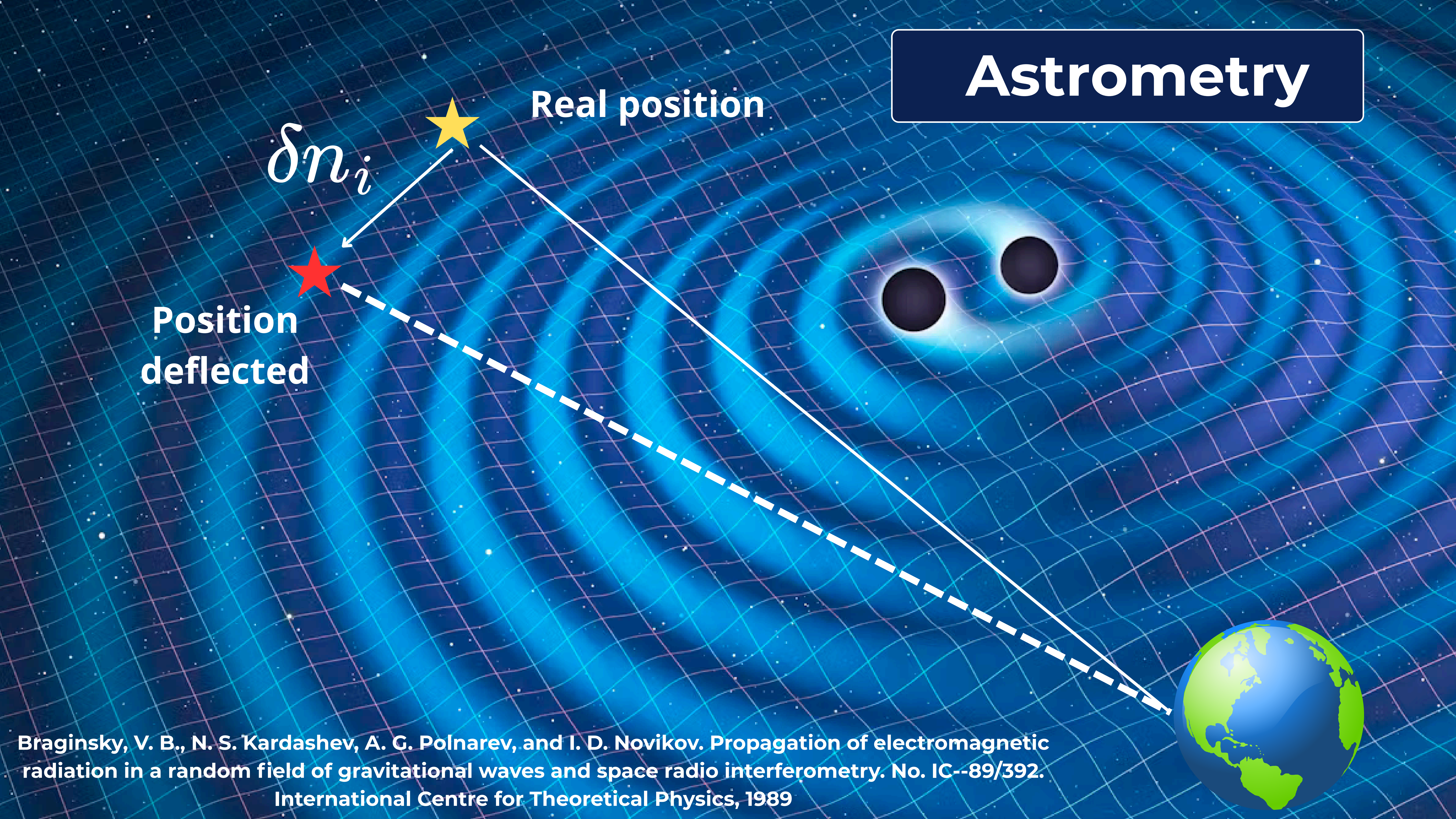


Large number of pulsars even for future experiments in SKA.

Could it be achievable with astrometry... ?

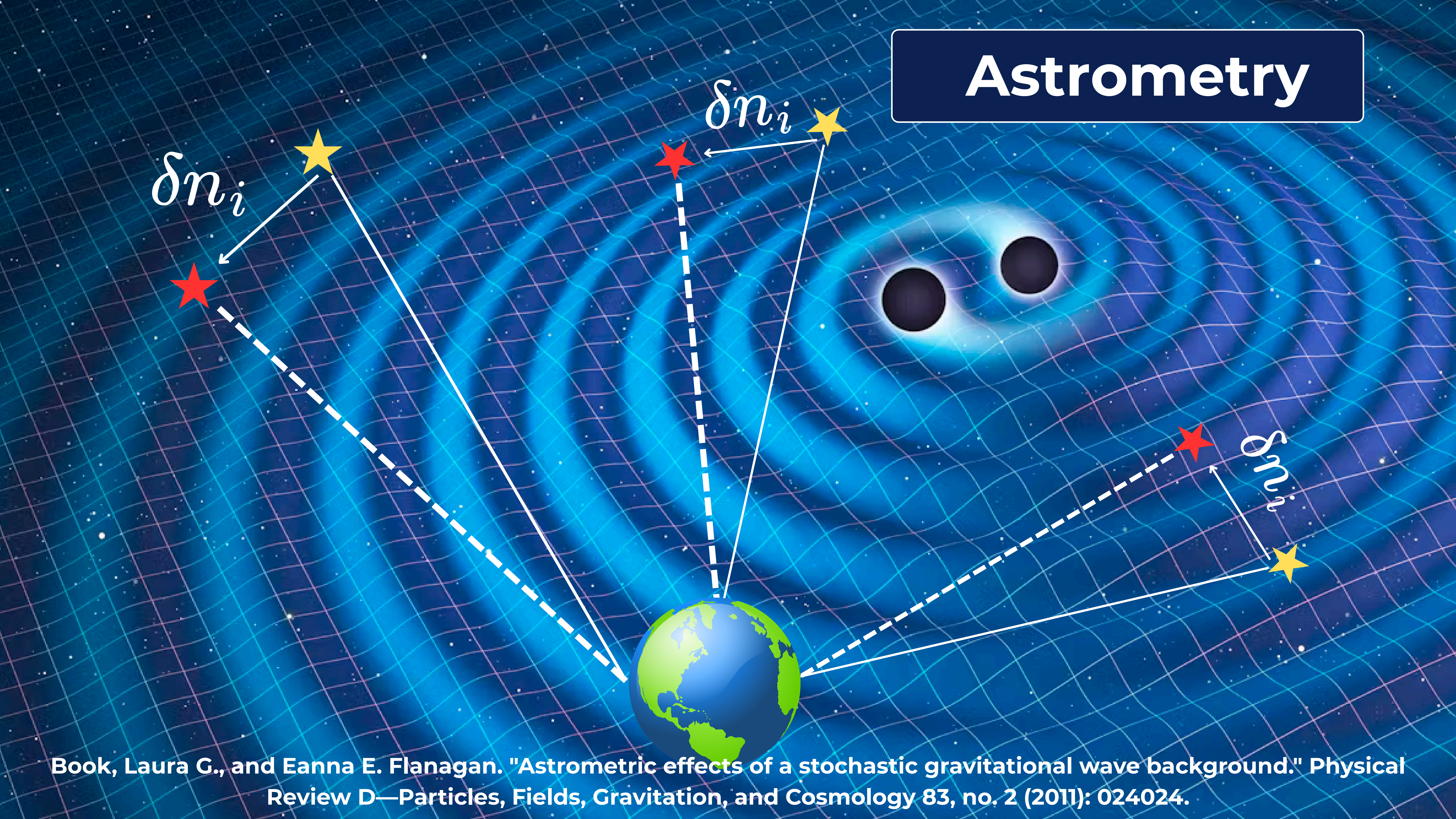
Jiménez Cruz, N. M., Malhotra, A., Tasinato, G., & Zavala, I. (2024). Measuring kinematic anisotropies with pulsar timing arrays. Physical Review D, 110(6), 063526.

Astrometry



Braginsky, V. B., N. S. Kardashev, A. G. Polnarev, and I. D. Novikov. Propagation of electromagnetic radiation in a random field of gravitational waves and space radio interferometry. No. IC--89/392. International Centre for Theoretical Physics, 1989

Astrometry

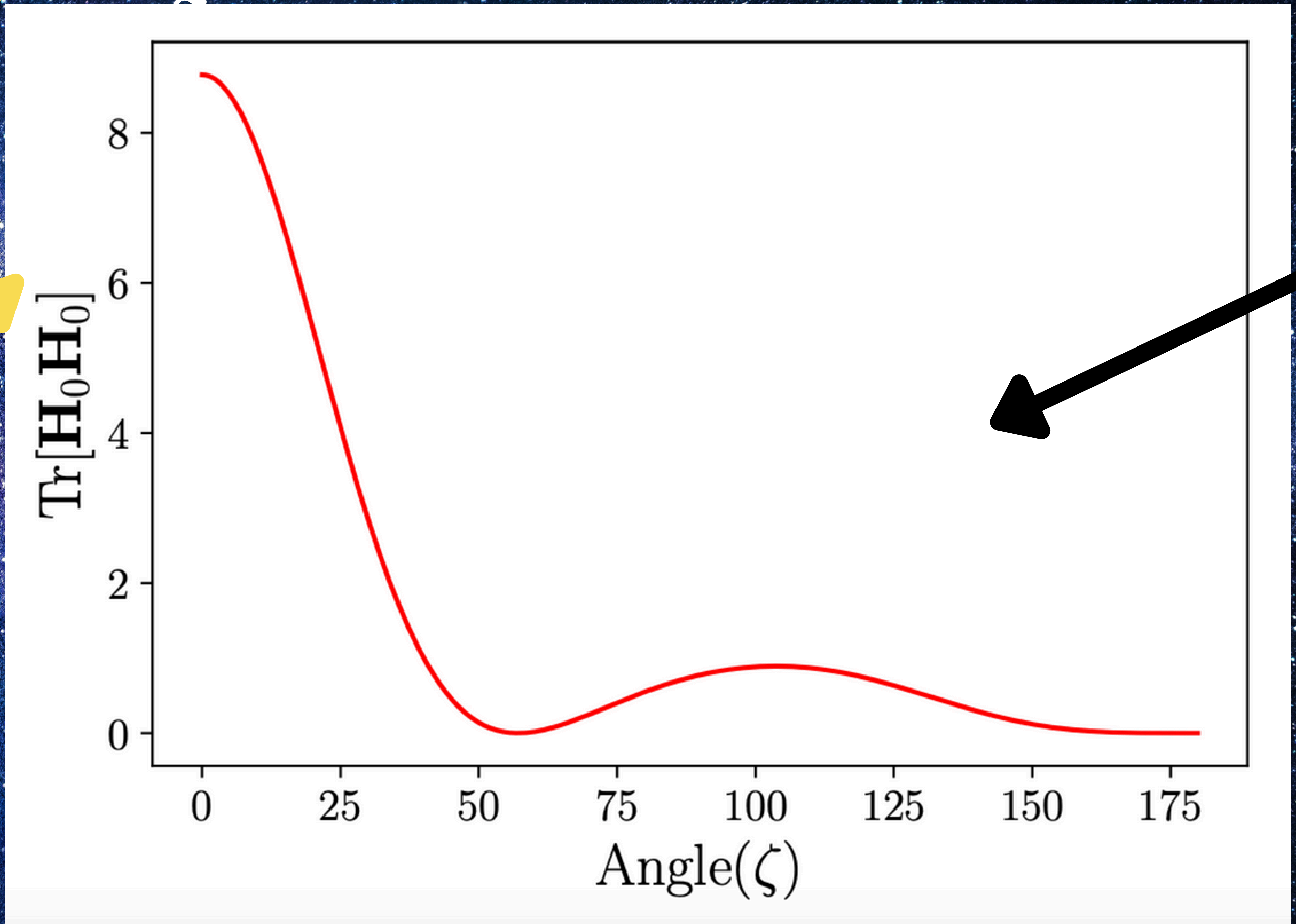


Book, Laura G., and Eanna E. Flanagan. "Astrometric effects of a stochastic gravitational wave background." Physical Review D—Particles, Fields, Gravitation, and Cosmology 83, no. 2 (2011): 024024.

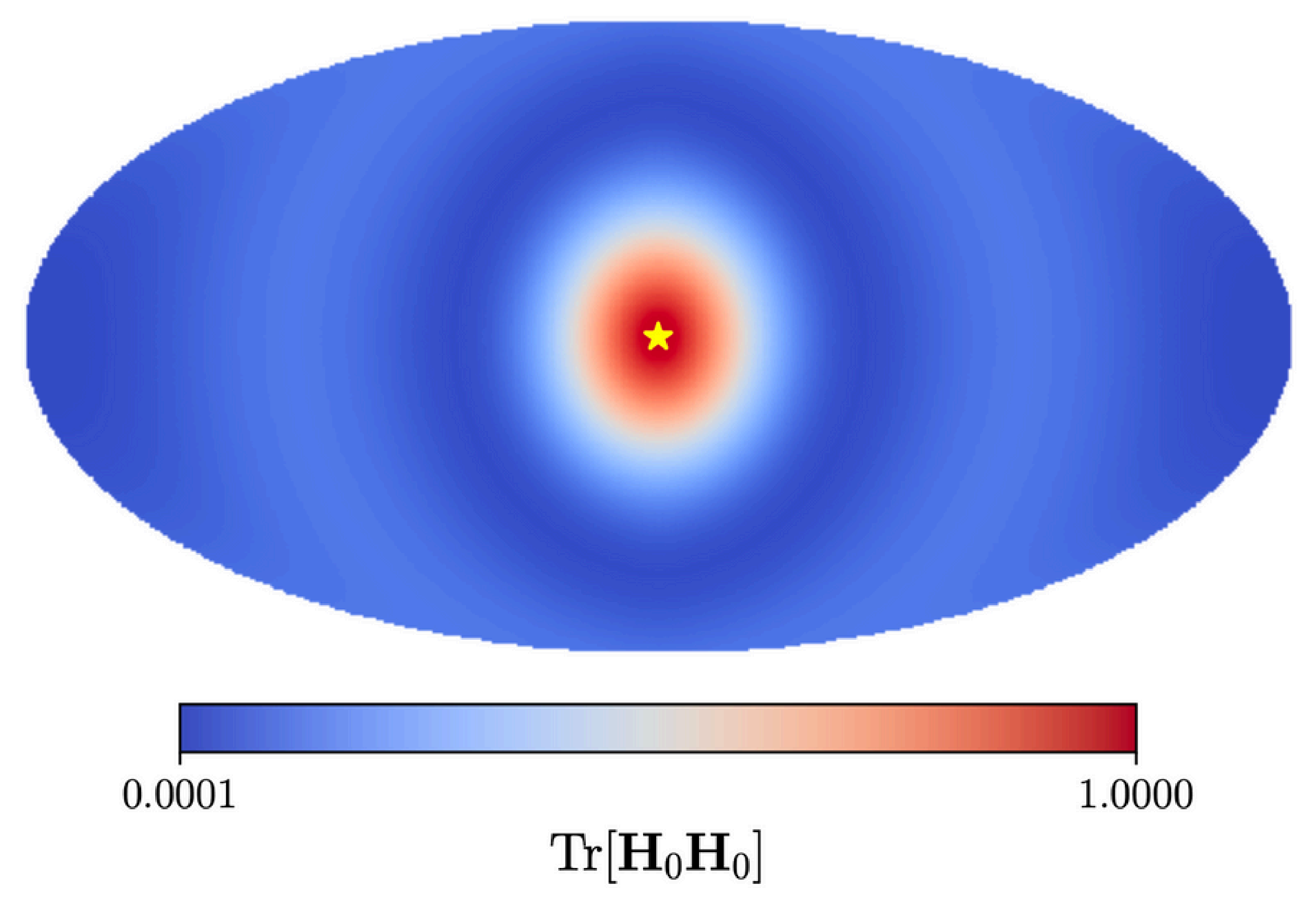
Astrometry

Representative of the sensitivity of astrometry observations to the monopole

$$H_{ij}^{(0)}(\mathbf{n}, \mathbf{q}) = f(n_i, q_i, \mathbf{n} \cdot \mathbf{q})$$



Similar to Hellings-Downs curve



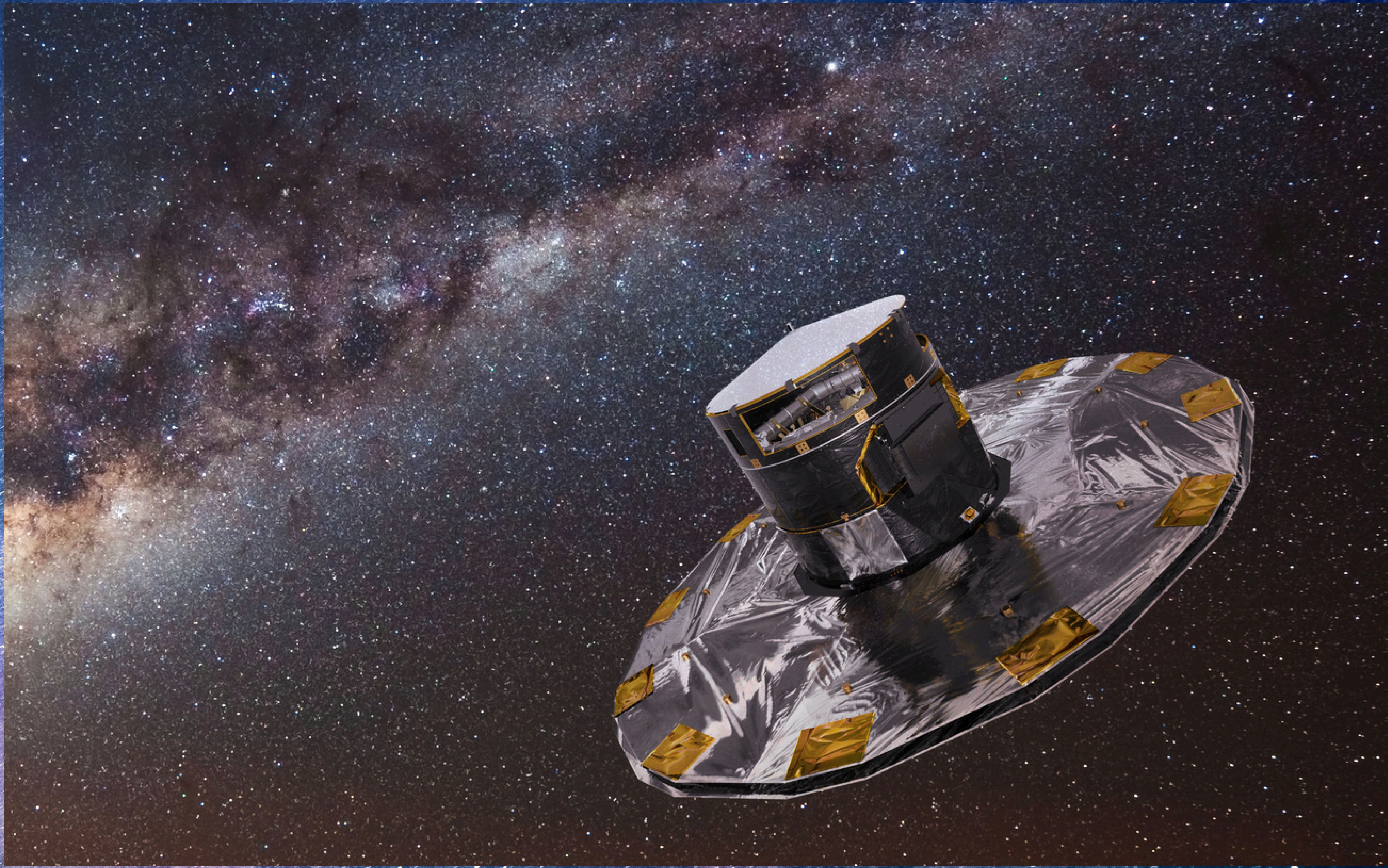
Jiménez Cruz, N. M., Ameek M., Gianmassimo T., and Ivonne Z. ArXiv: 2412.14010 (2024).

Gaia mission

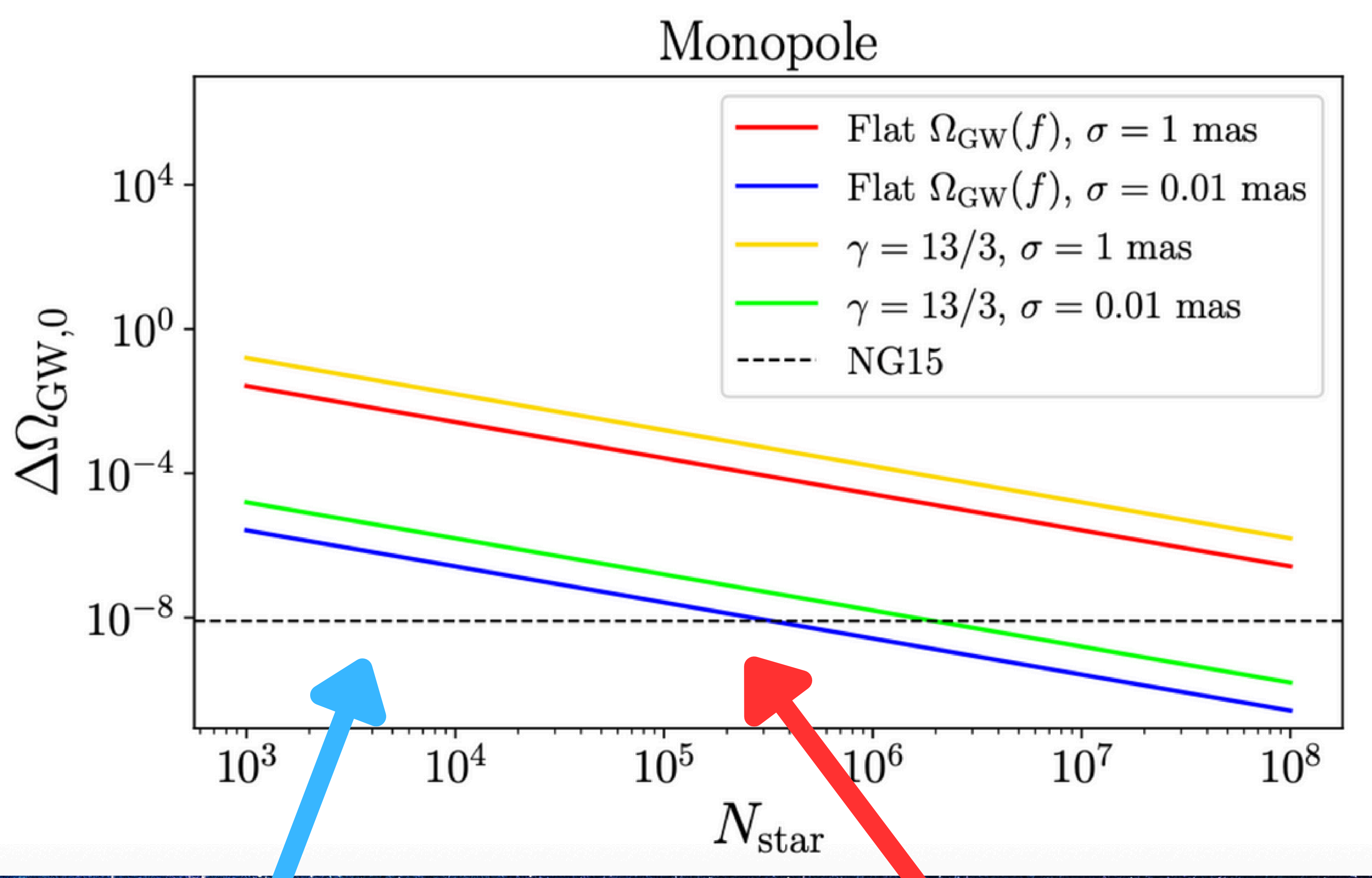
Gaia Data Release 5 is expected around the end of 2030, covering the full 10.5 years of mission data.

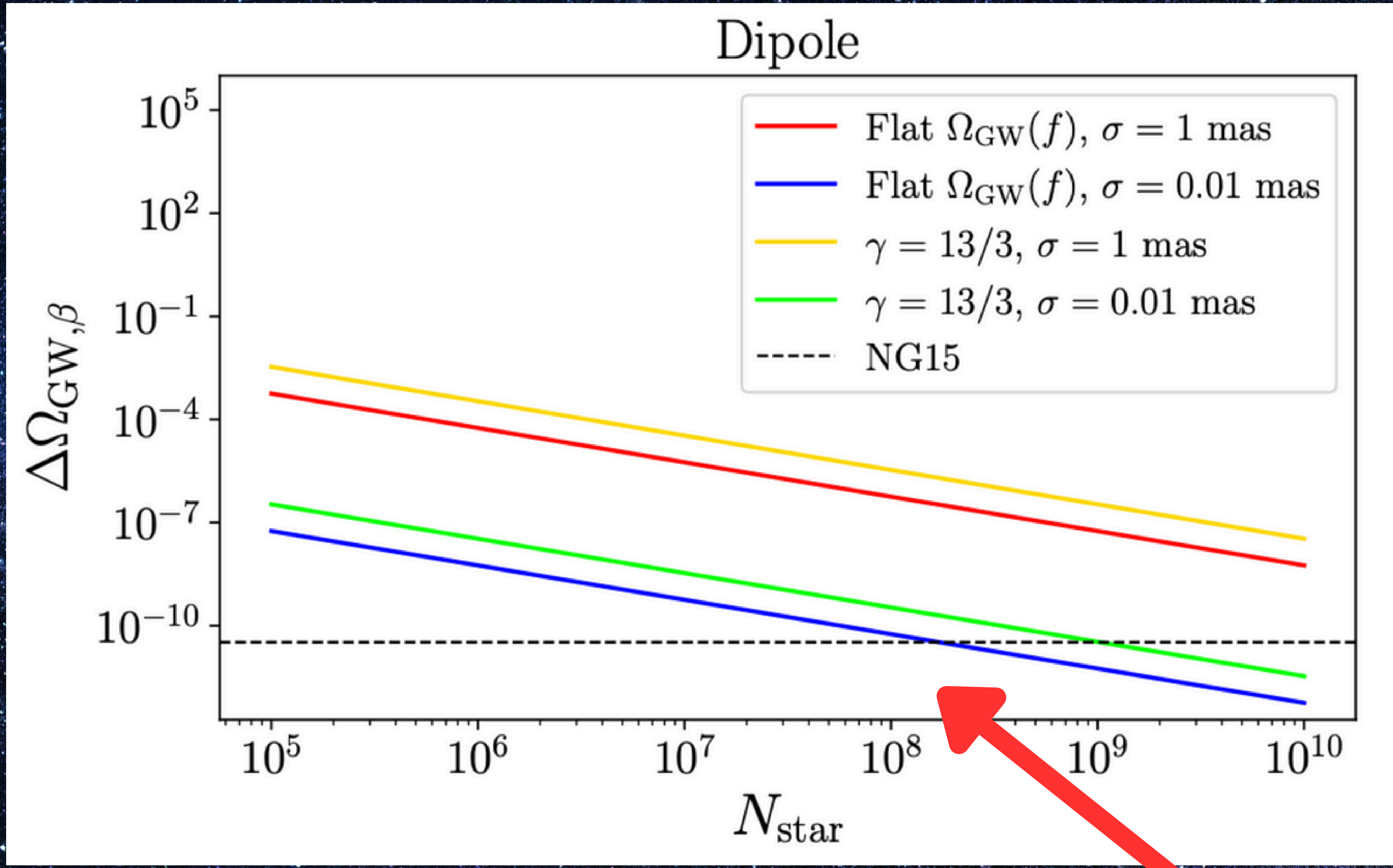
For the brightest objects in the survey:

$$\sigma = 0.01\text{mas}$$



Astrometry forecast





Energy density with the NG15 results

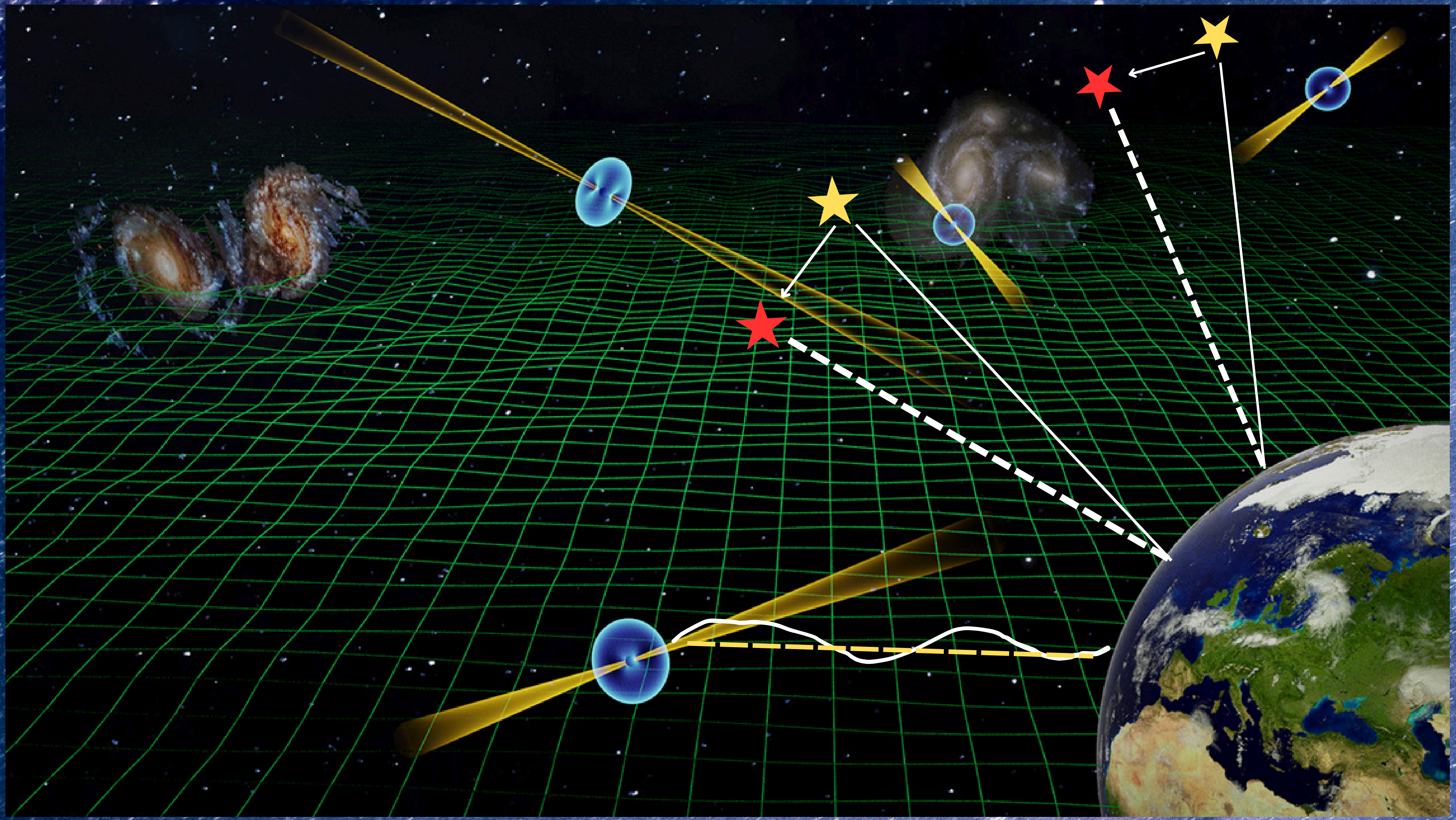
$$N_{stars} > 10^5$$

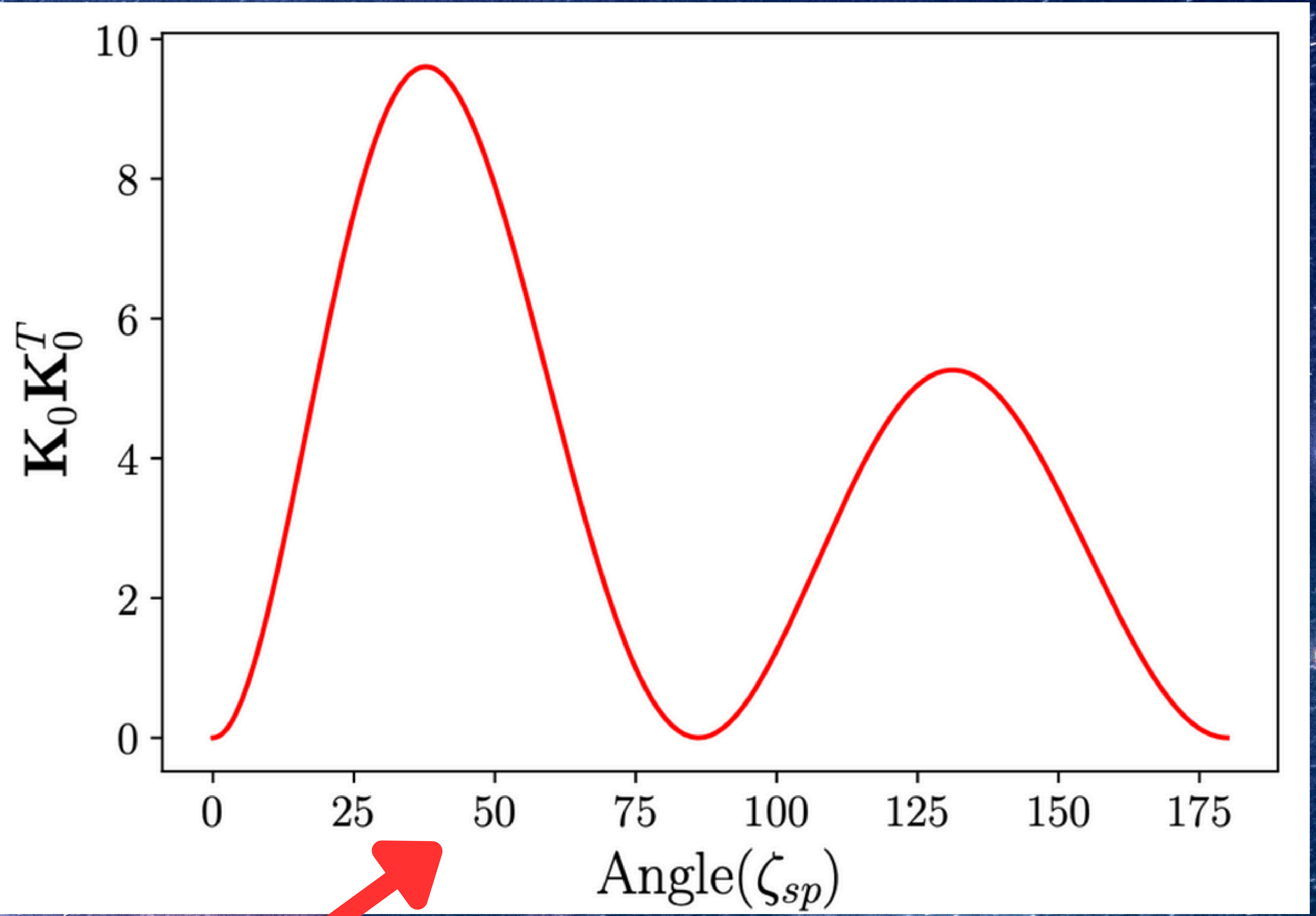
to be competitive with PTA

$$N_{stars} > 10^8$$

to be able to detect the dipole

Astrometry meets PTA

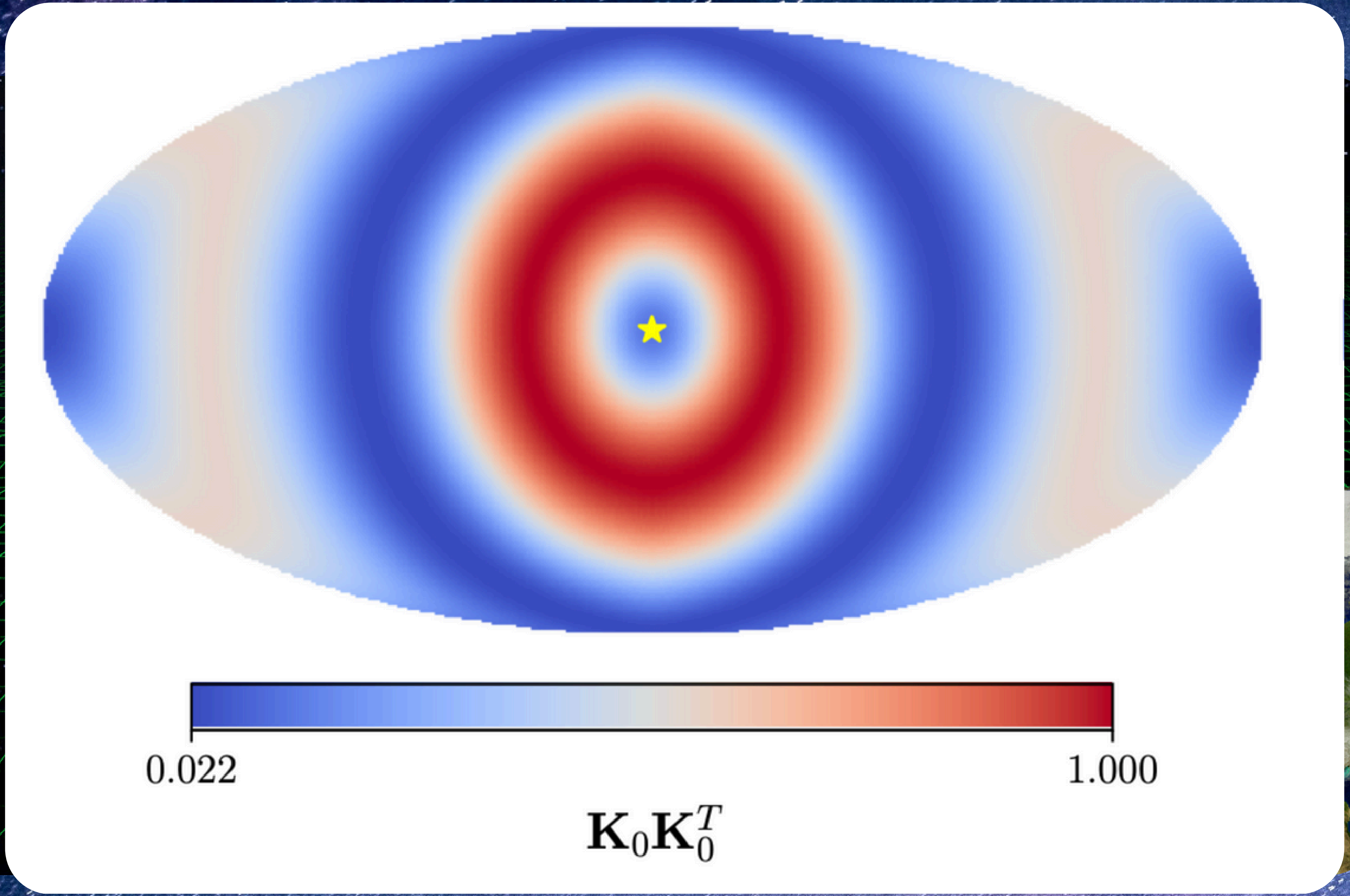


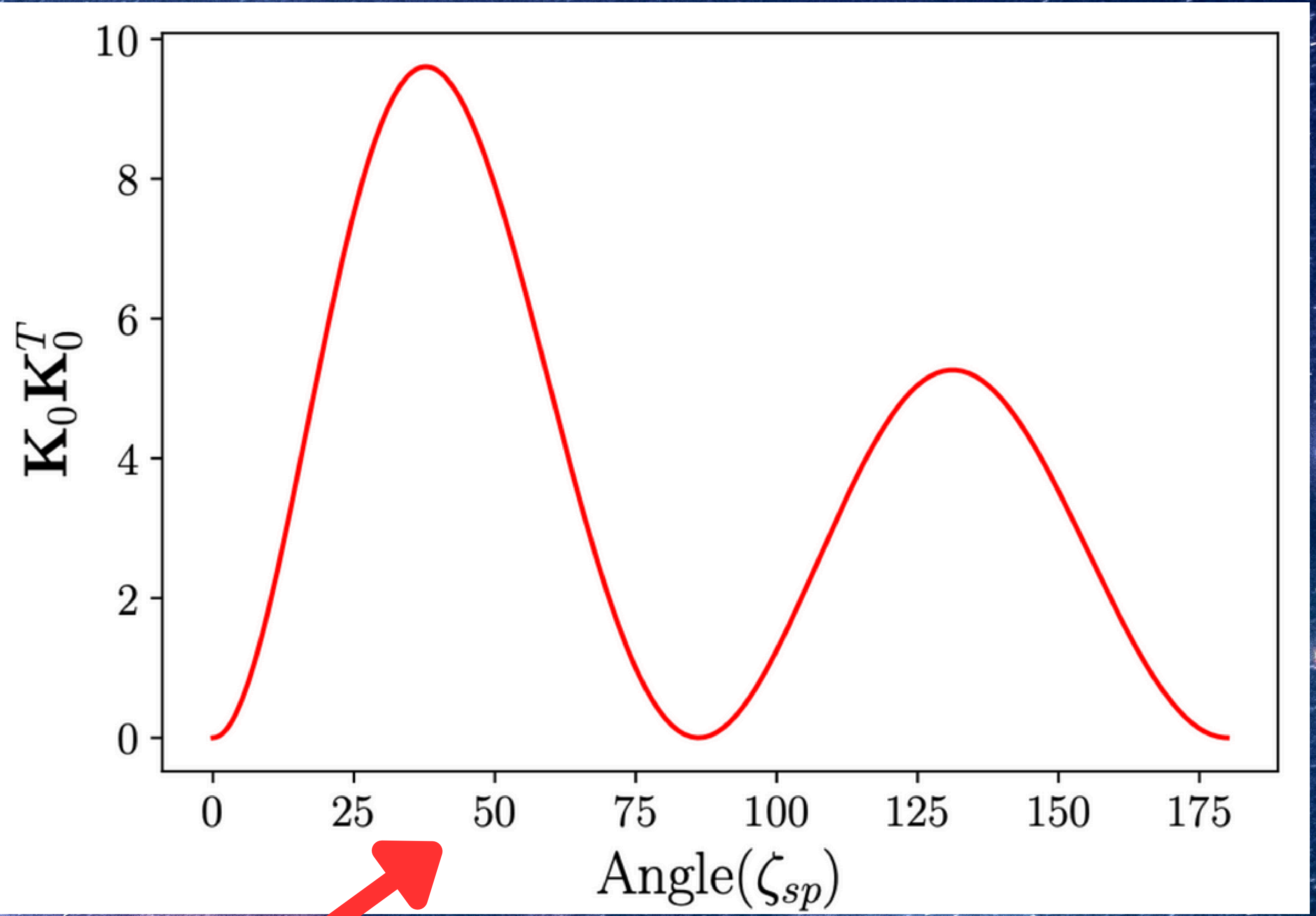


Correlation between a Star and a Pulsar

$$K_i^{(0)}(\mathbf{n}, \mathbf{x}) = f(n_i, x_i, \mathbf{n} \cdot \mathbf{x})$$

Astrometry meets PTA

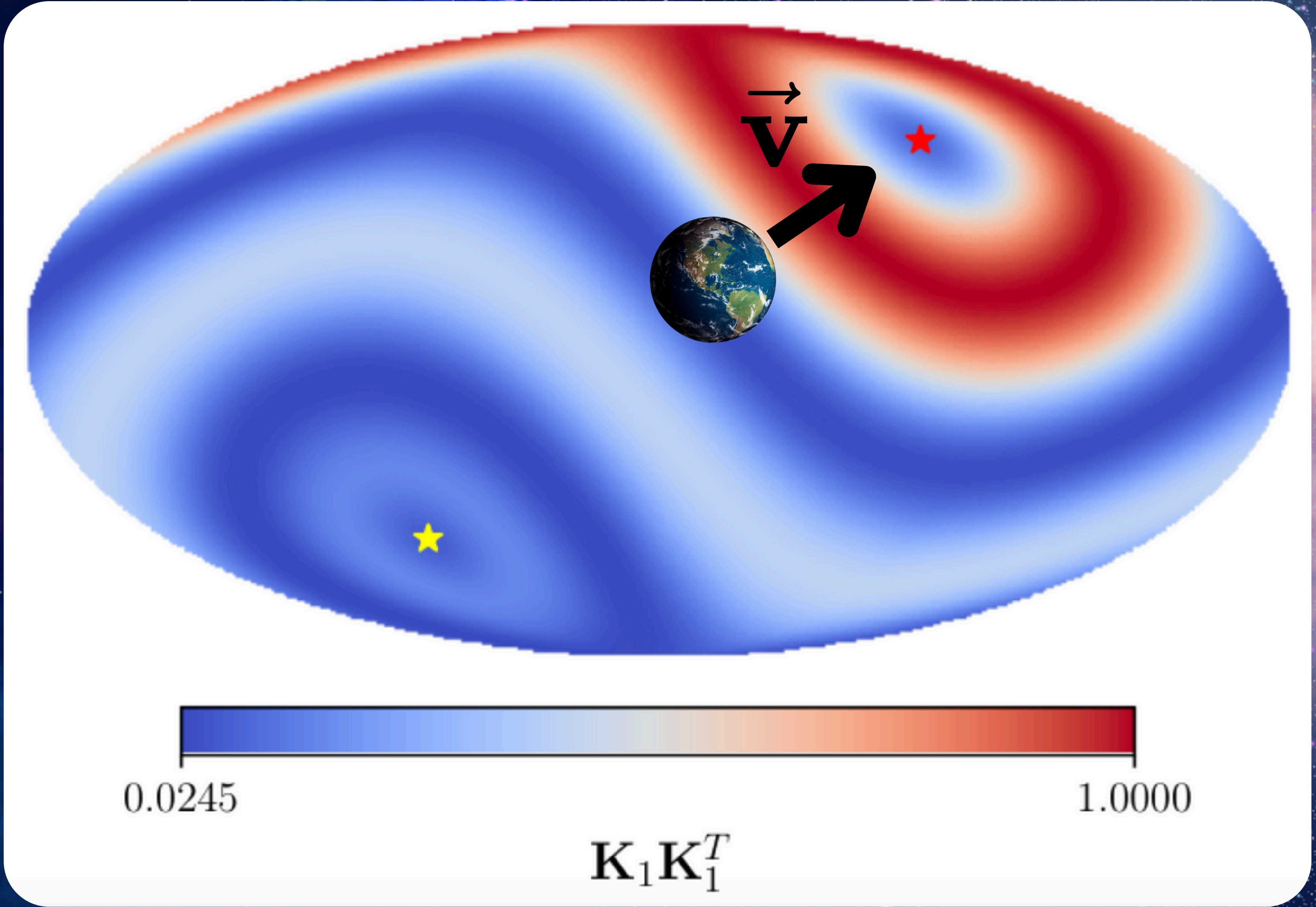


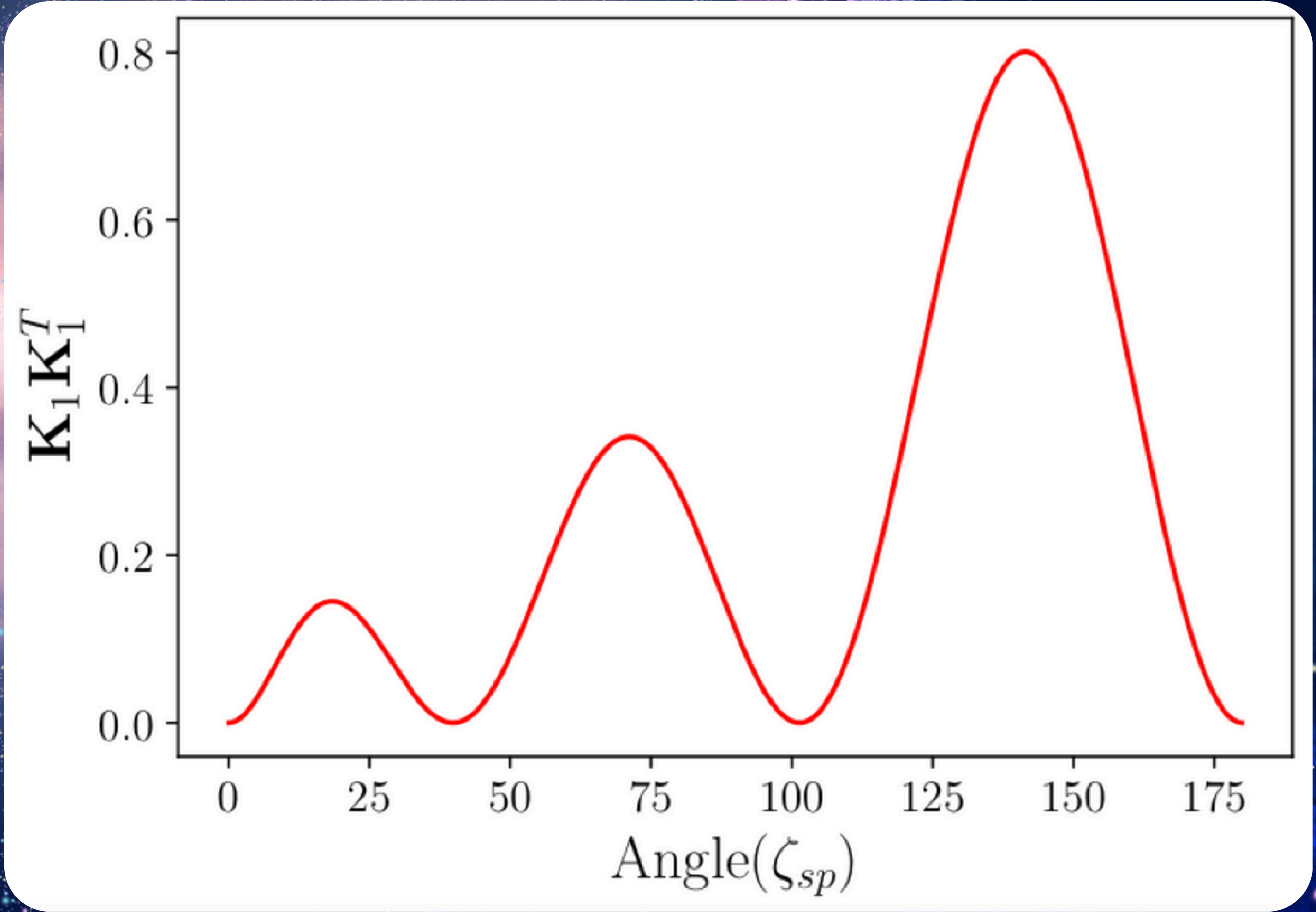


Correlation between a Star and a Pulsar

$$K_i^{(0)}(\mathbf{n}, \mathbf{x}) = f(n_i, x_i, \mathbf{n} \cdot \mathbf{x})$$

Astrometry meets PTAs (dipole)

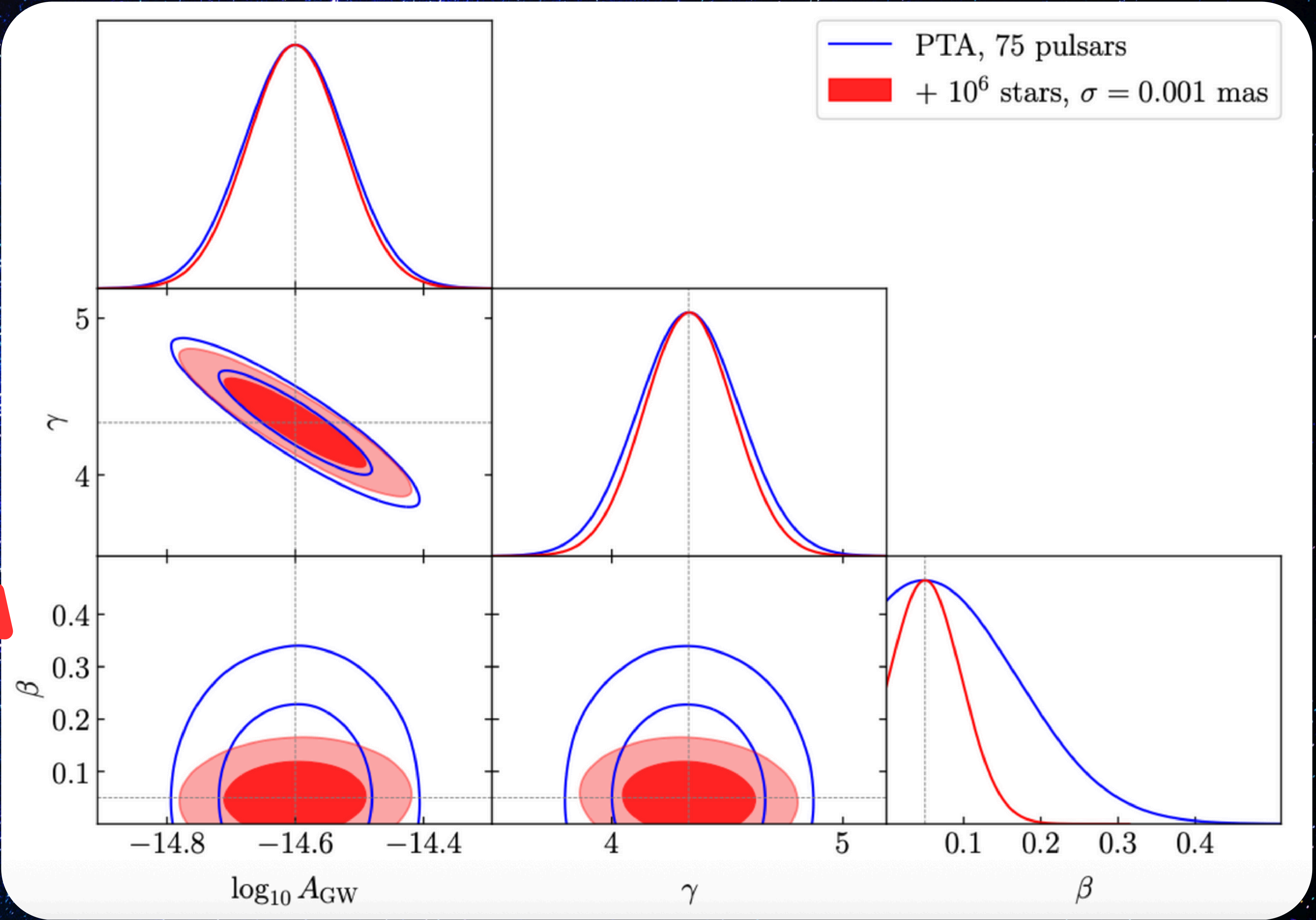




$$K_i^{(1)}(\mathbf{n} = -\mathbf{v}, \mathbf{x}, \mathbf{v}) = f(n_i, x_i, \mathbf{n}\cdot\mathbf{x})$$

Kinematic Anisotropies and PTA-Astrometry synergies

Astrometry can help to tighten the constraints on the dipole anisotropy!



	$\log A_{\rm GW}$	γ	β
PTA only	-14.6 ± 0.079	$13/3 \pm 0.24$	0.05 ± 0.081
PTA + Astrometry, $\sigma = 0.001$ mas	-14.6 ± 0.072	$13/3 \pm 0.18$	0.05 ± 0.048
PTA + Astrometry, $\sigma = 0.01$ mas	-14.6 ± 0.079	$13/3 \pm 0.24$	0.05 ± 0.080

Conclusions

- Astrometry data in the nHz band will complement PTA observations.
- An astrometric survey with 0.01 mas astrometric precision and the typical number of sources and cadence of Gaia could lead to noticeable improvements over current PTA only SGWB constraints.
- Tighter constraints on the SGWB parameters can be used to rule out models and potentially distinguish between and astrophysical or cosmological signal.
- Reaching the level of sensitivity required to detect the CMB level kinematic dipole anisotropy in the SGWB is likely to require both, futuristic PTA experiments such as SKA, as well as futurustic astrometric surveys.

Thanks!

Questions?