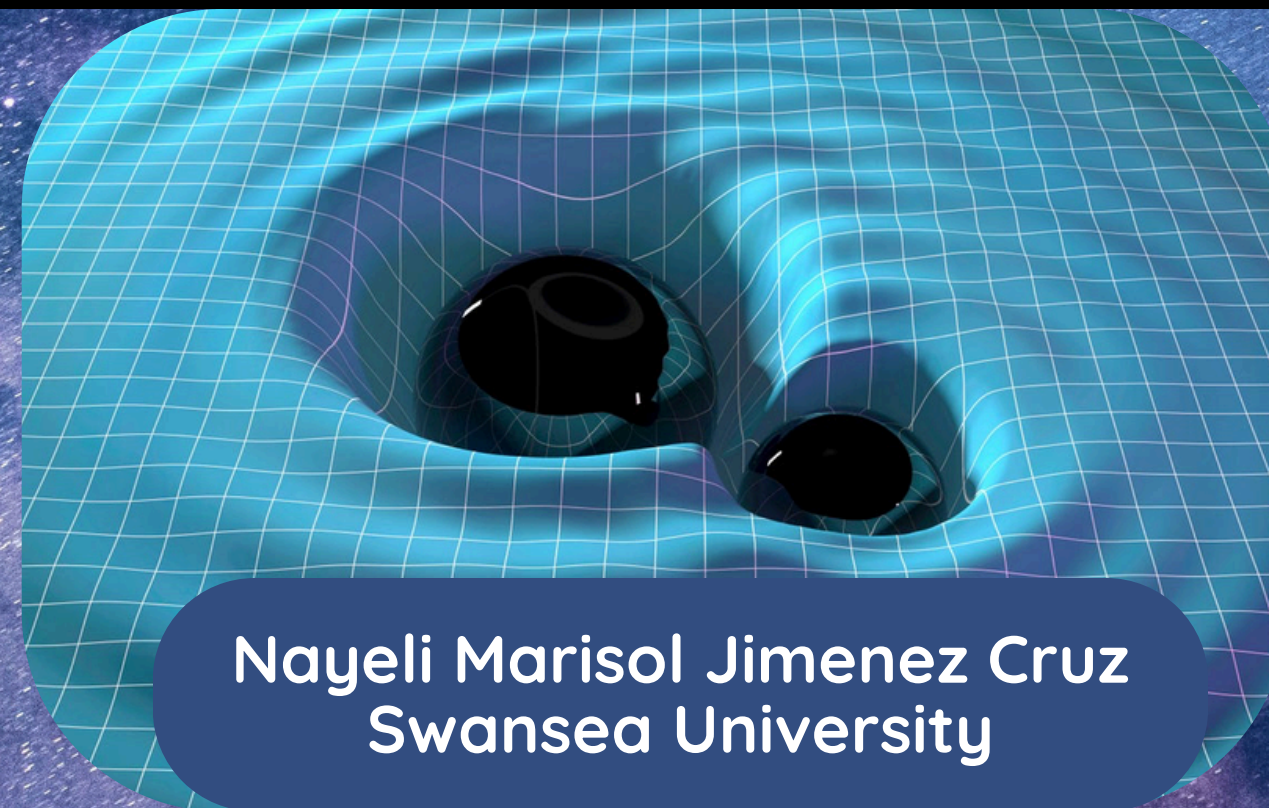


14th Iberian Gravitational Waves Meeting | Madrid, Spain
25th June 2025

Gravitational waves detection from PTA and Astrometry

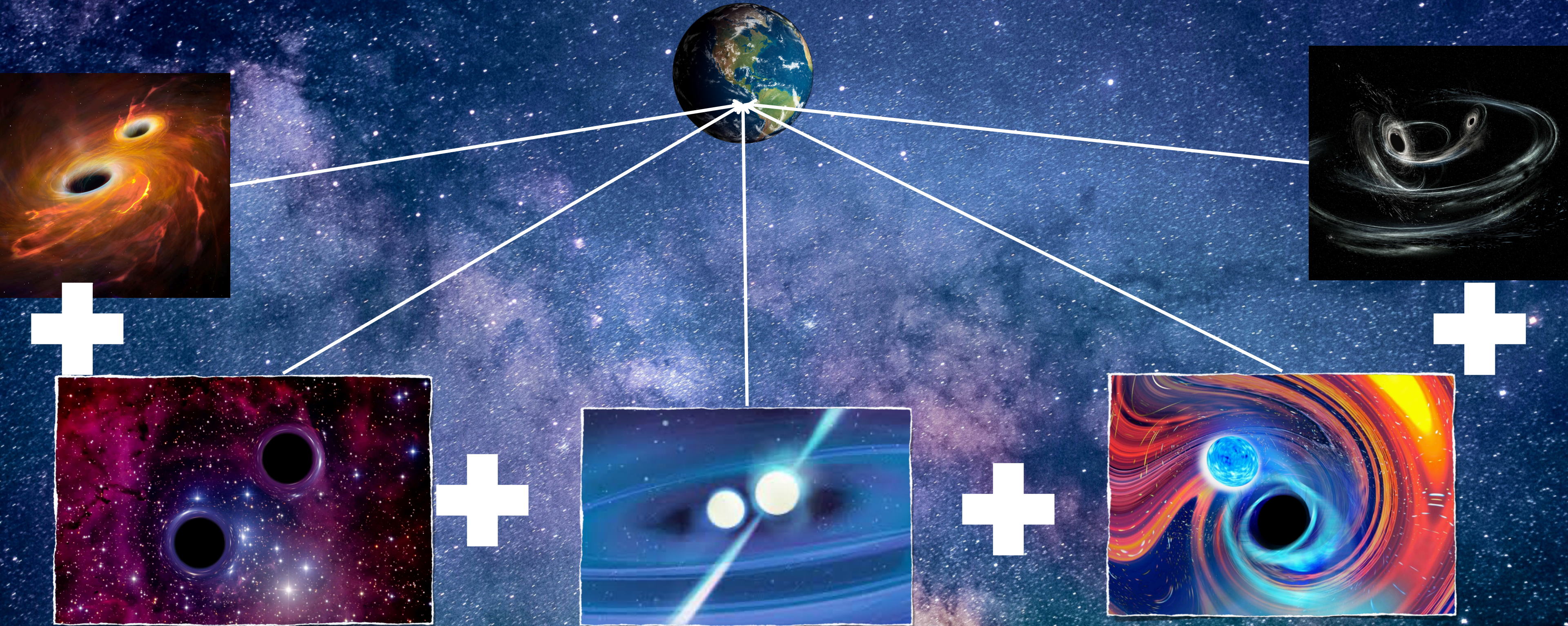


Nayeli Marisol Jimenez Cruz
Swansea University

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).

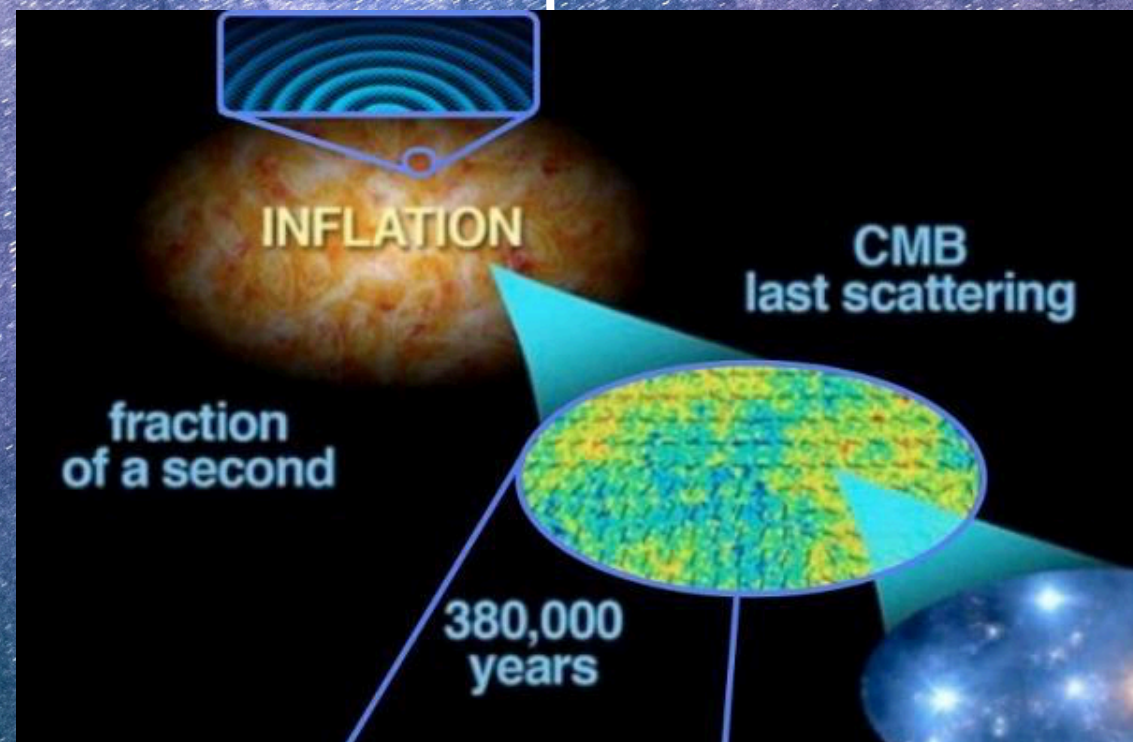
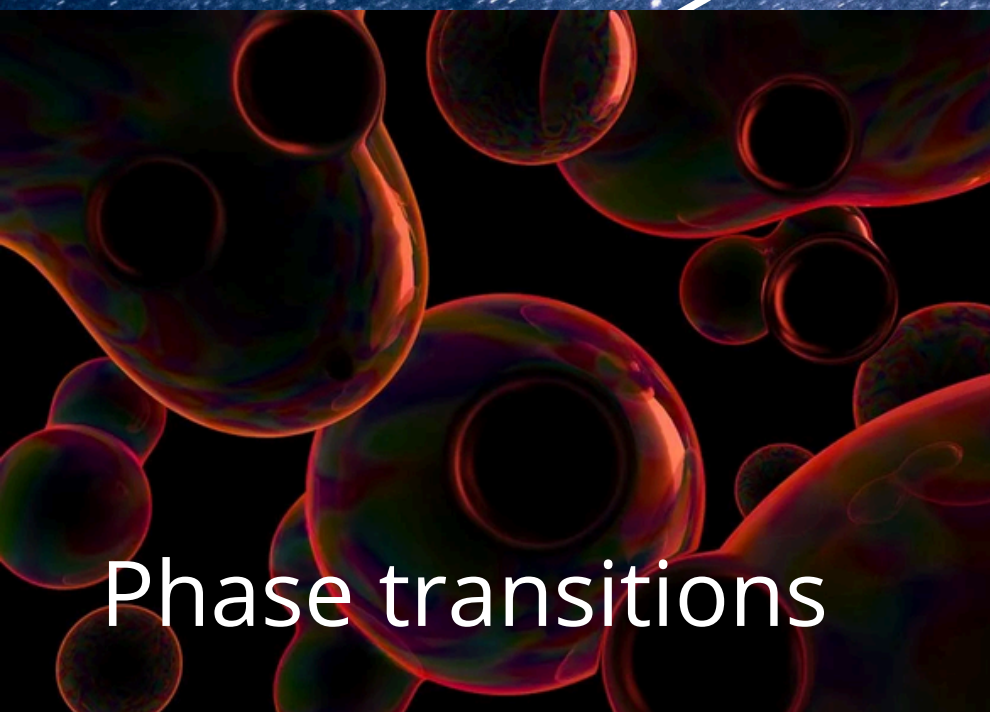
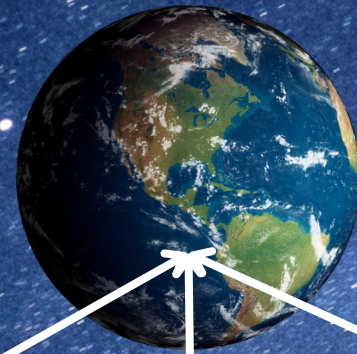
Stochastic Gravitational Wave Background

Astrophysical



Stochastic Gravitational Wave Background

Cosmological



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

$$n_I = -7/3$$



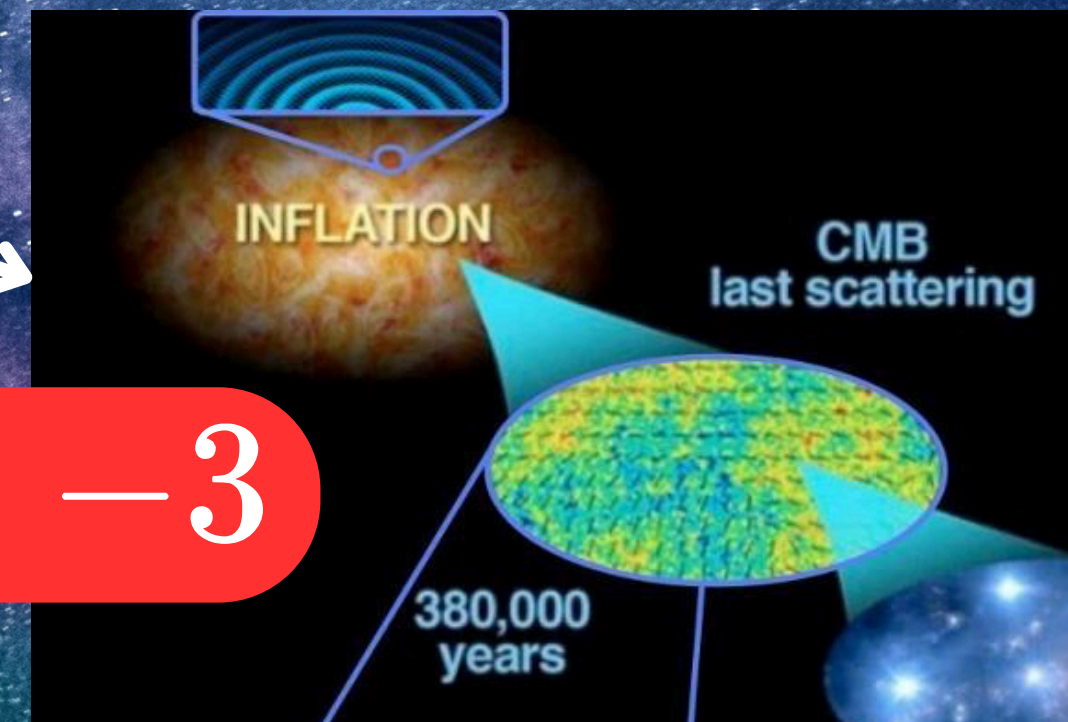
Spectral tilt

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

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

Maximal sensitivity

$$n_I = -3$$

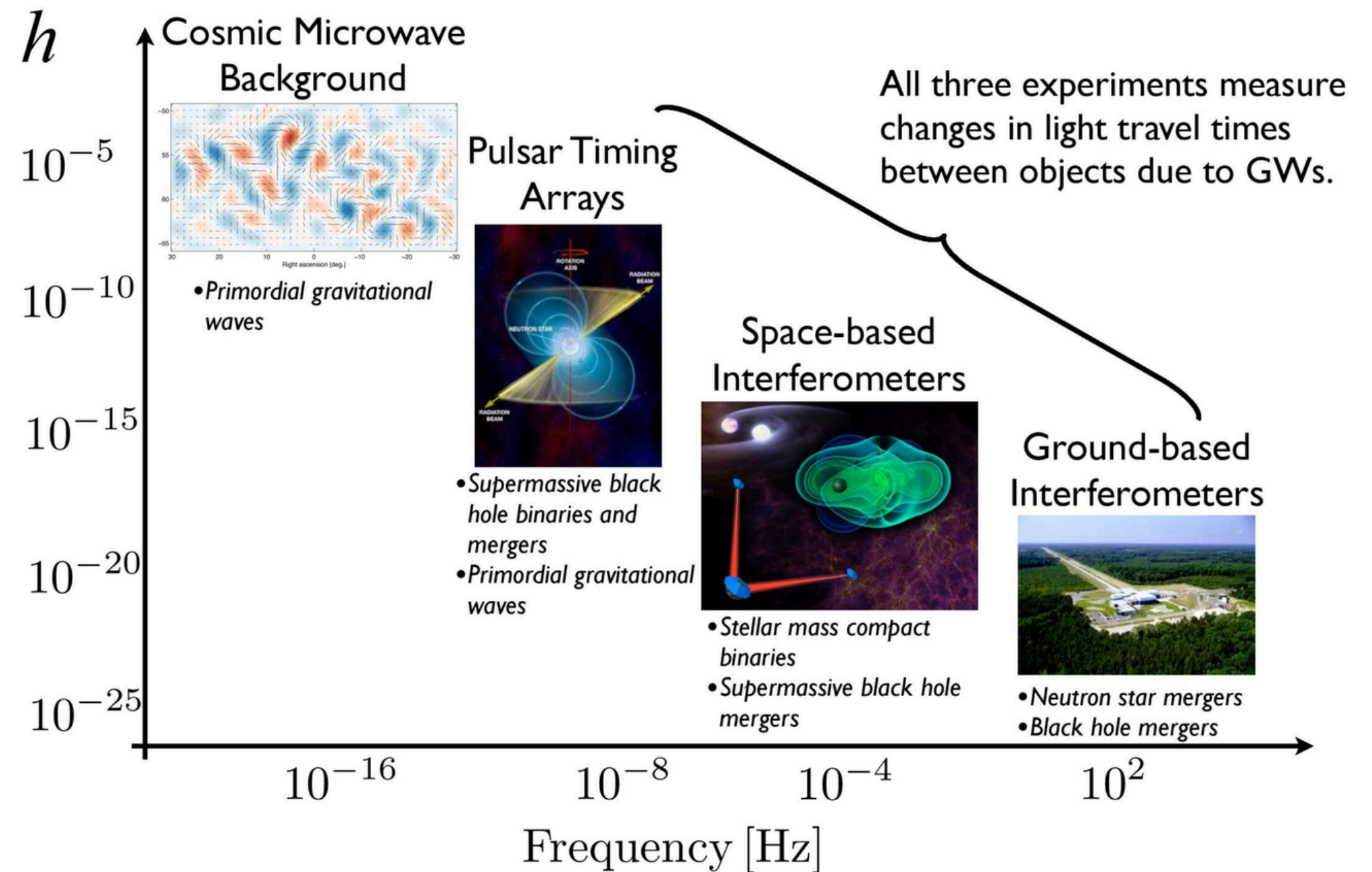


How to detect the SGWB

Detection at very low frequencies!



The spectrum of gravitational wave astronomy



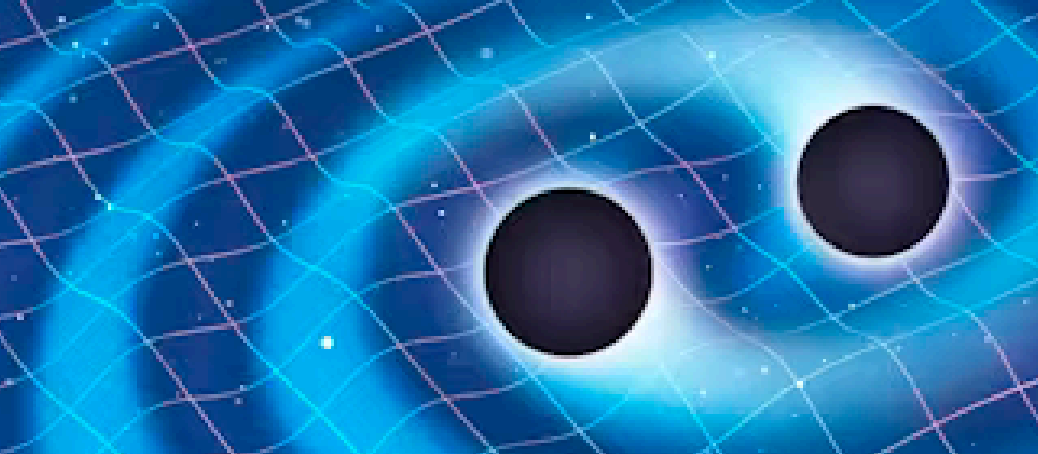
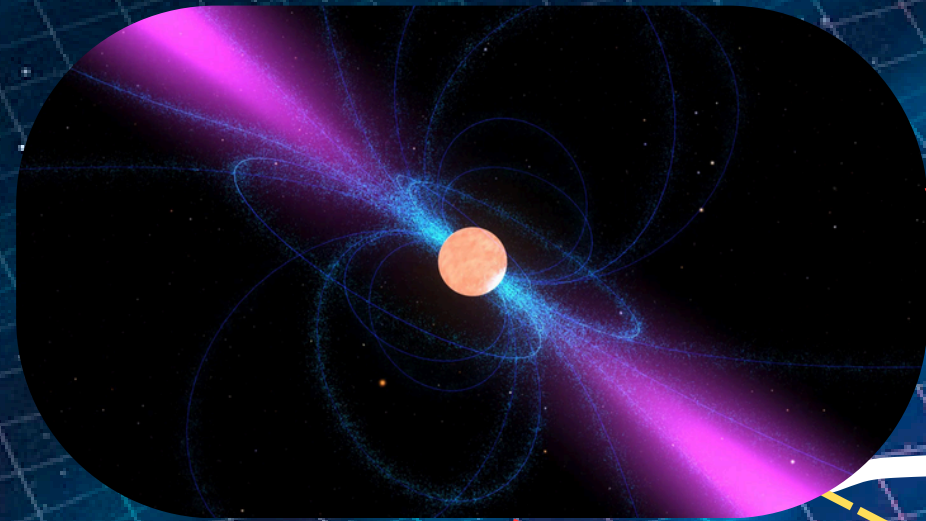
PTAs

Extremely precise
clocks sending
pulses of light.

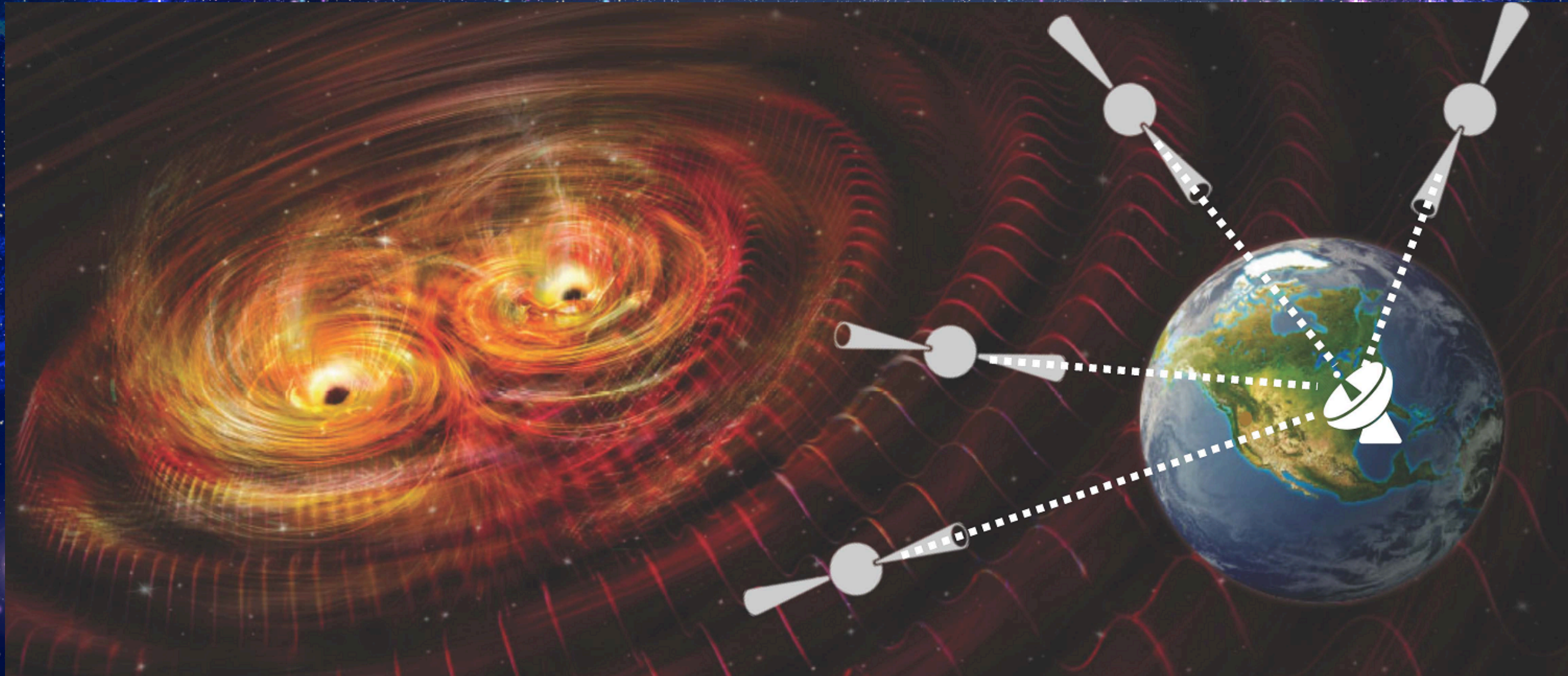
Cosmic
lighthouse

Time delay at a
certain period

$$z_a(t)$$

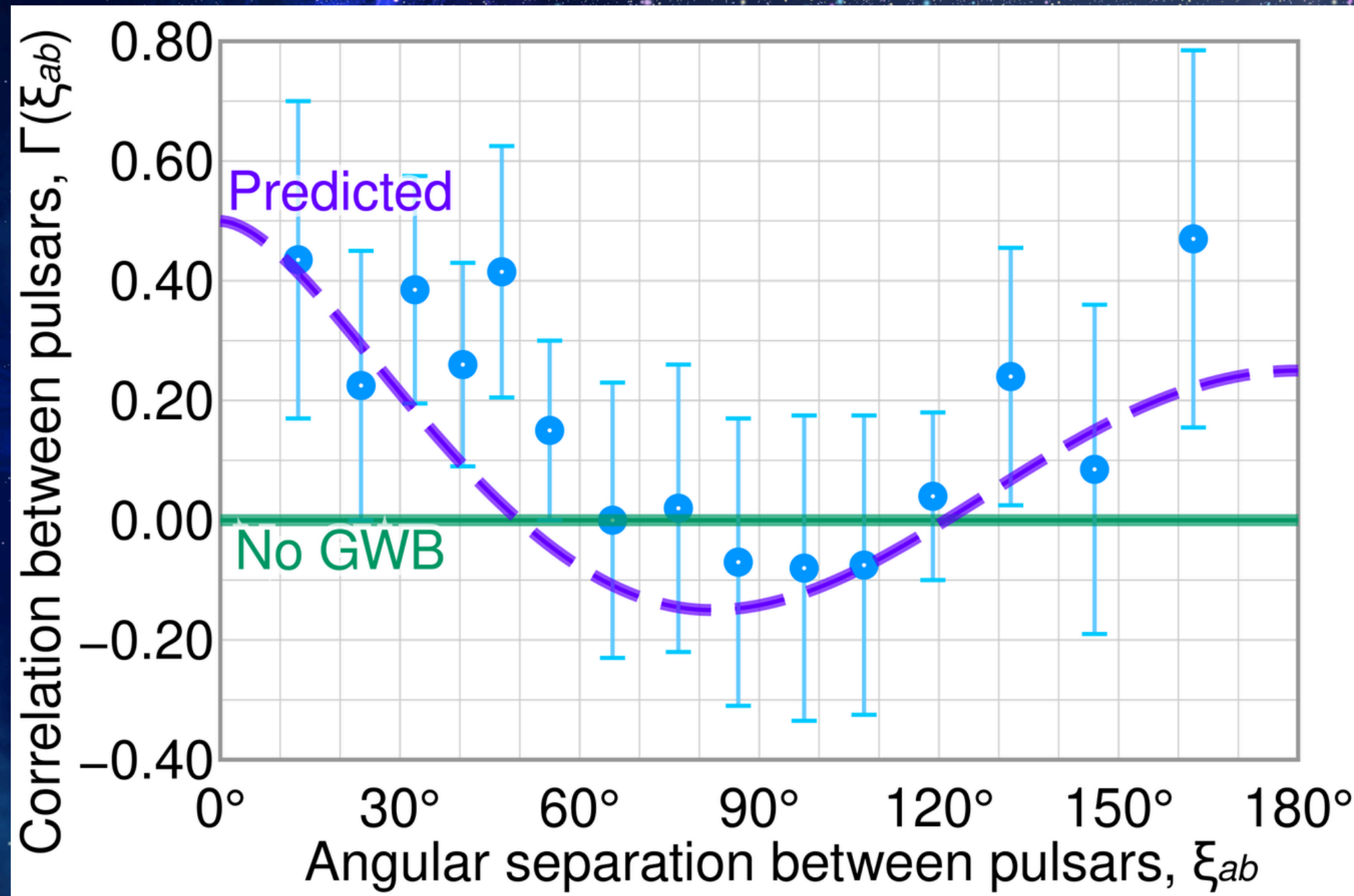


Pulsar Timing Arrays and the SGWB



The timing delays are correlated

Hellings-Downs curve



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

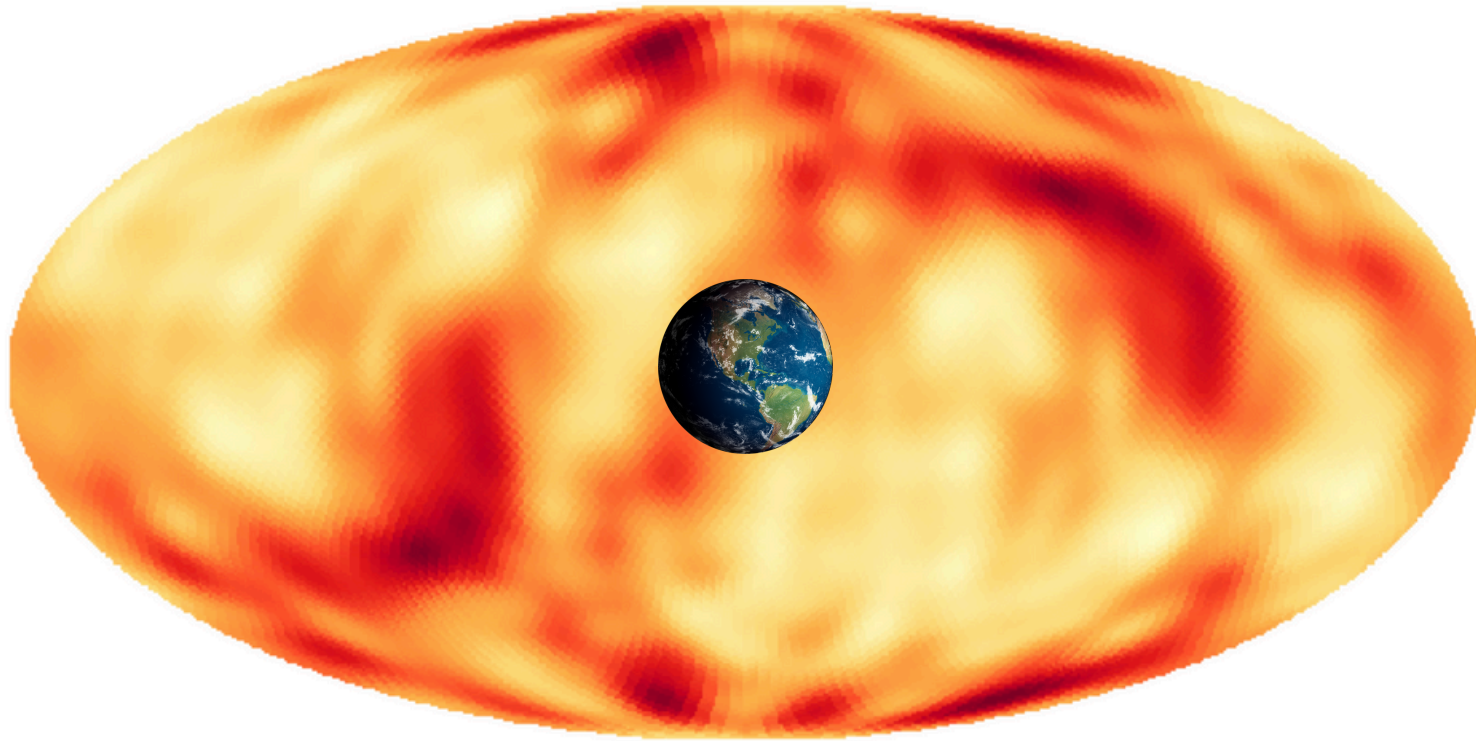
$$\langle z_a(t_1) z_b(t_2) \rangle \propto HD$$

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

PTA collaborations results * (2023)

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

Primordial SGWB

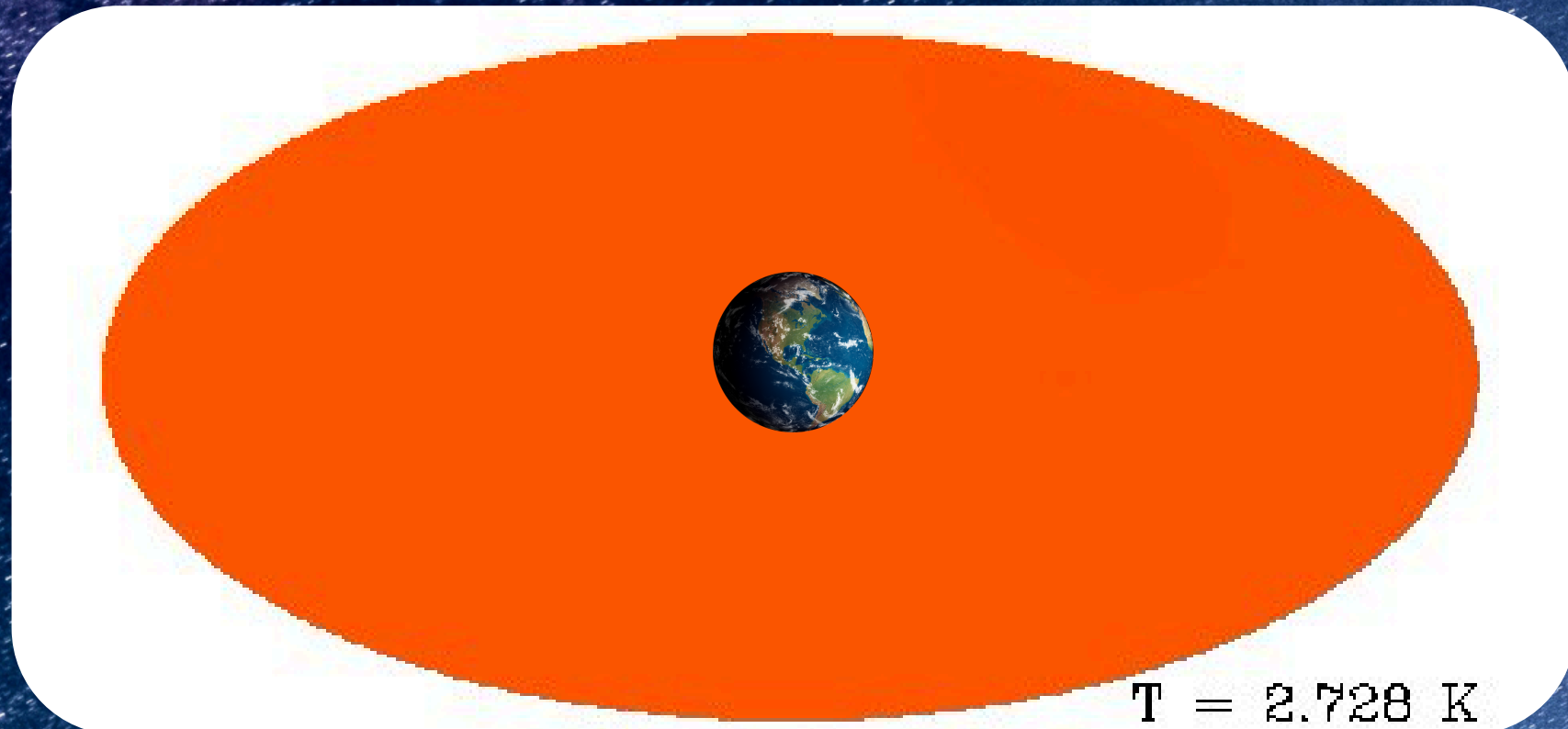


Astrophysical
Strongly anisotropic



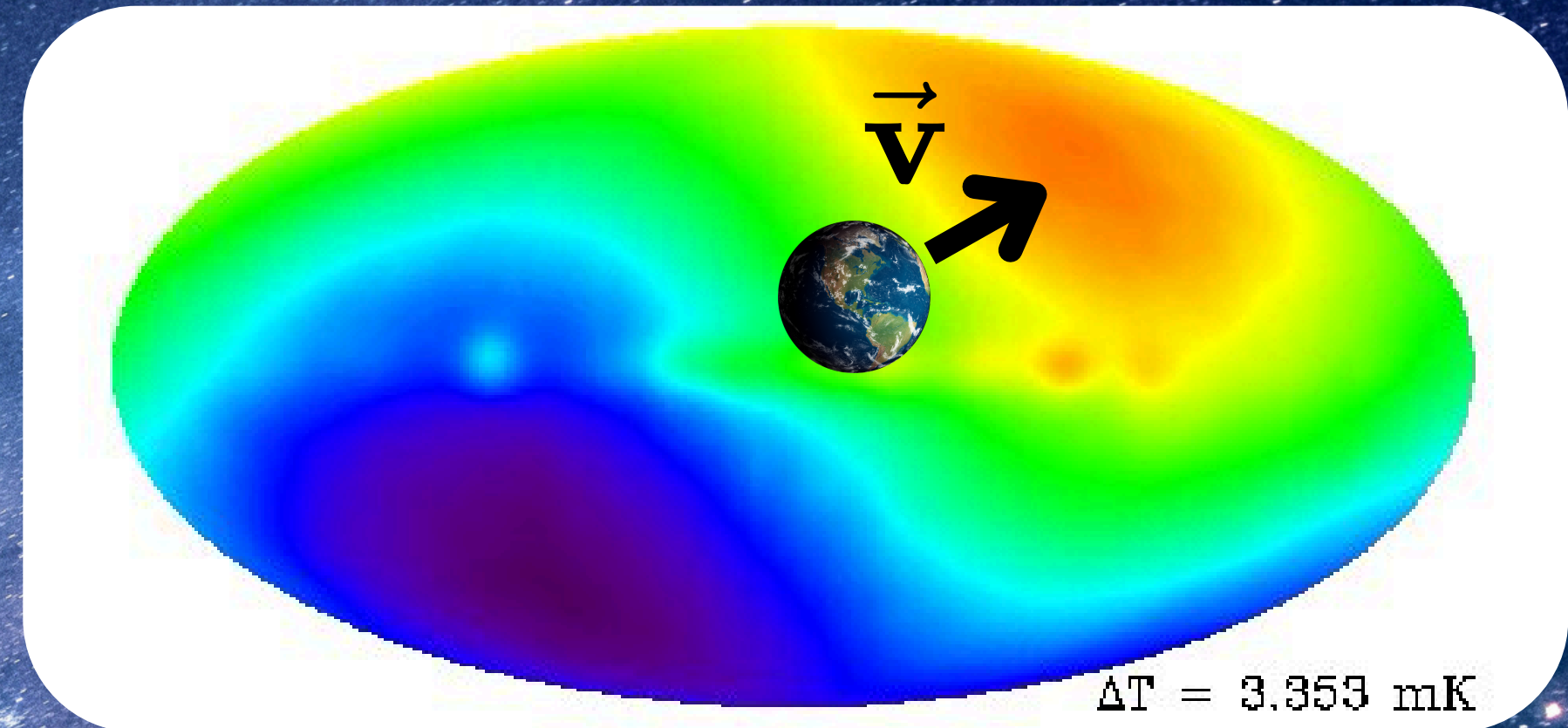
Cosmological
Predominantly isotropic
with small fluctuations.

Kinematic anisotropies



Isotropic signal

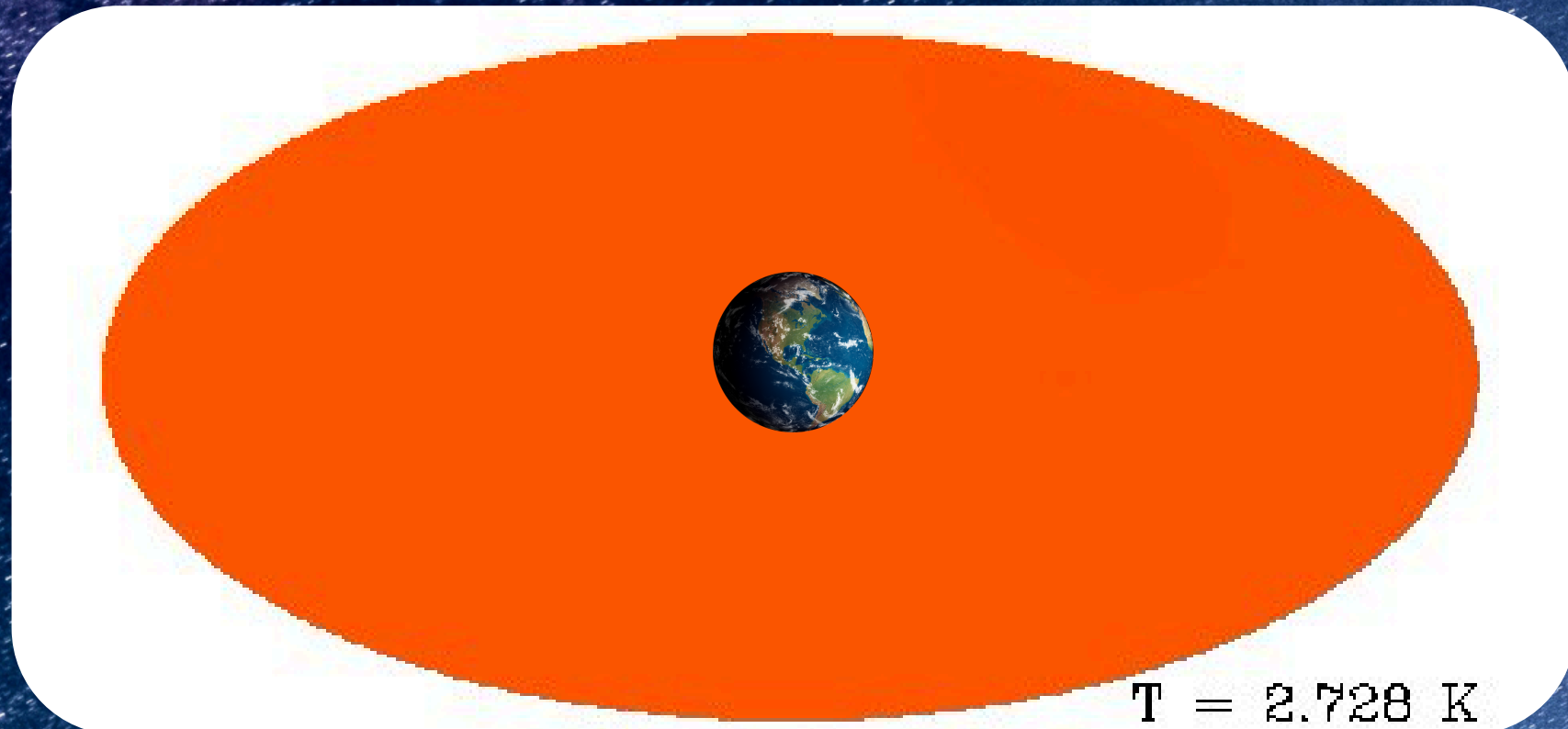
**Already observed
in the CMB!**



Kinematic anisotropies

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

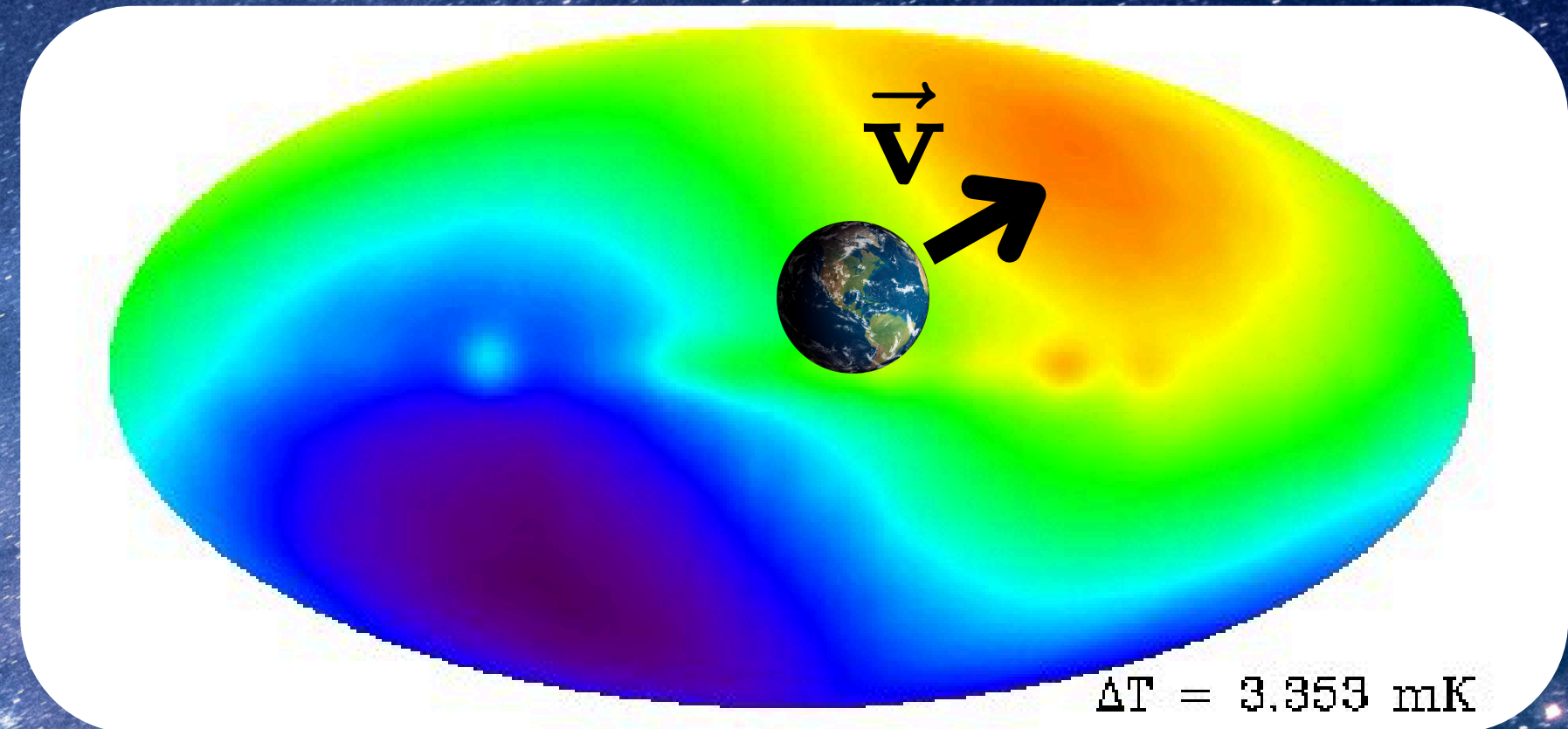
Kinematic anisotropies



Isotropic signal

Cosmic dipole tension

2111.03616

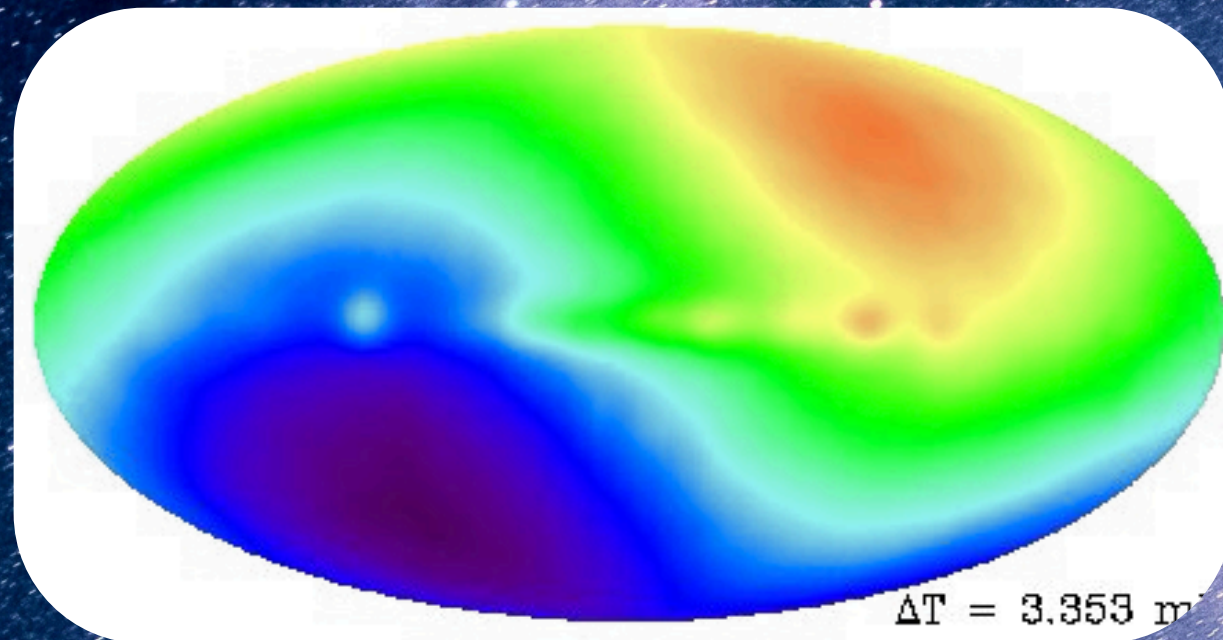


Kinematic anisotropies

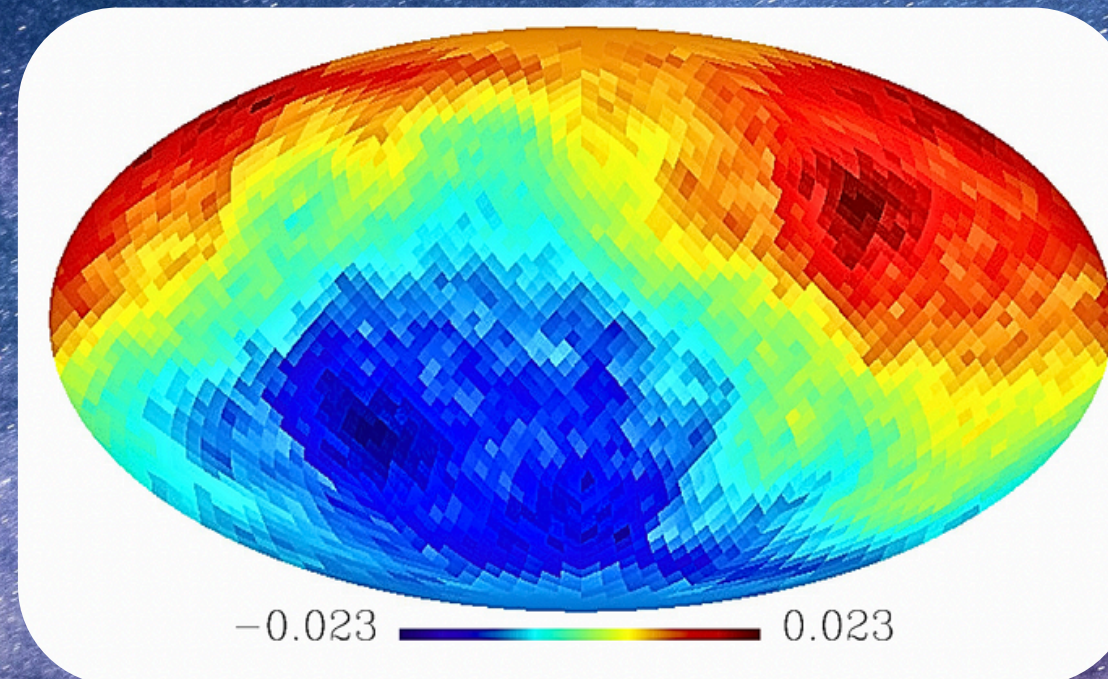
$$\beta = |\vec{v}|/c = 1.23 \times 10^{-3}$$
$$(l, b) = (264^\circ, 48^\circ)$$

Kinematic anisotropies

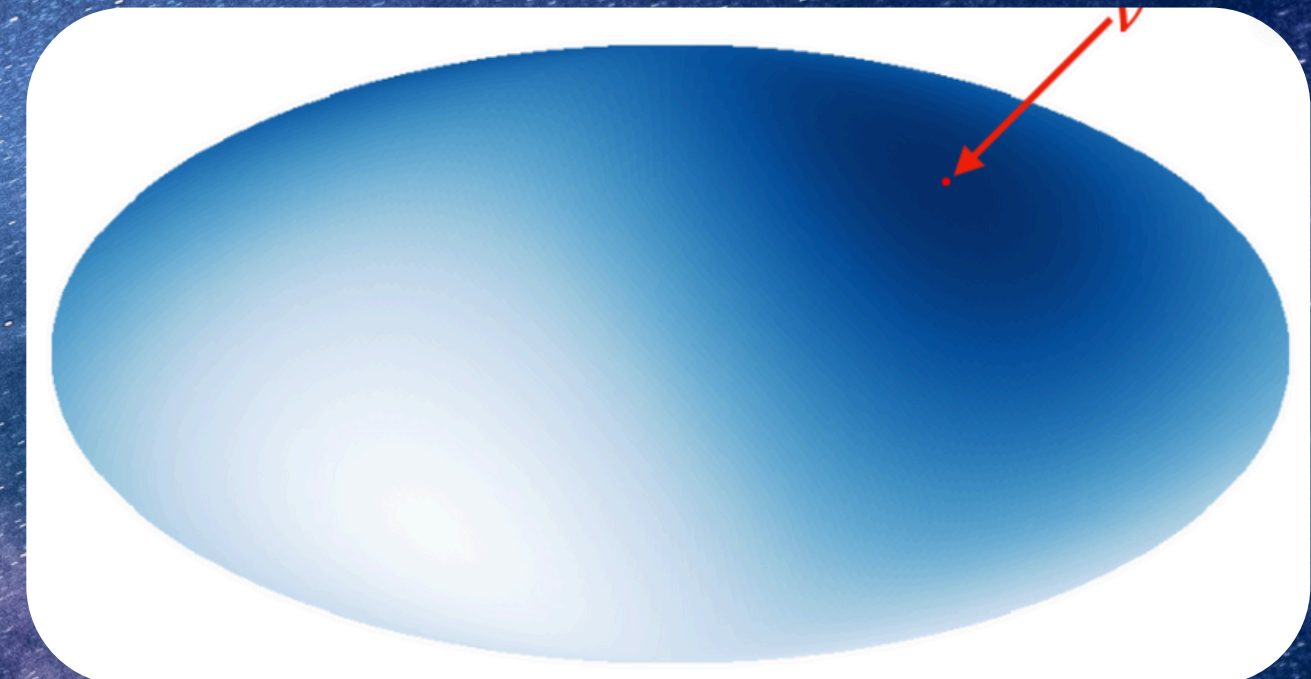
Three independent measurements



CMB

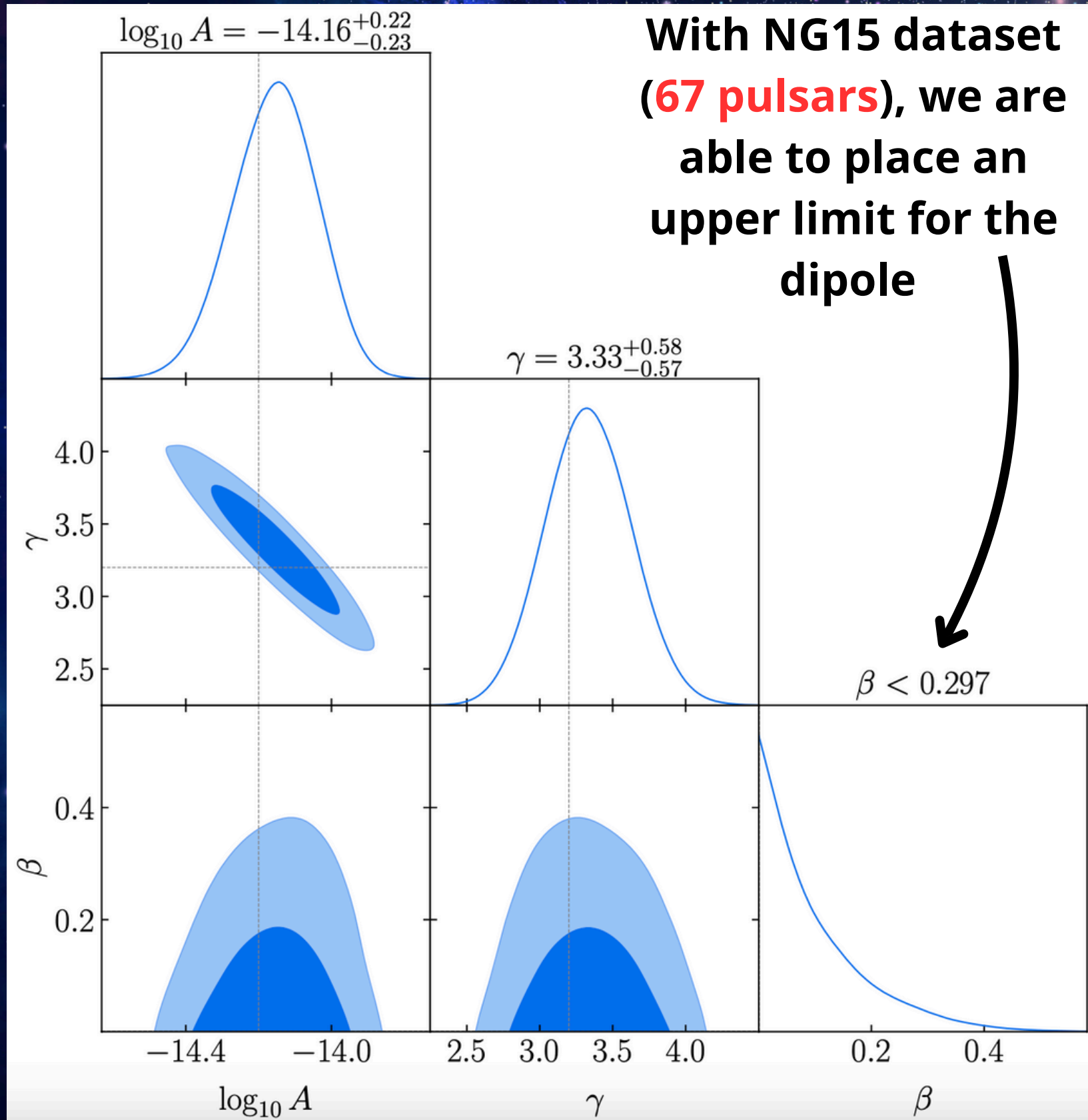


**Radio sources and
Quasars**



SGWB

Kinematic Anisotropies with PTAs



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

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

$$n_I = 2 - \gamma$$

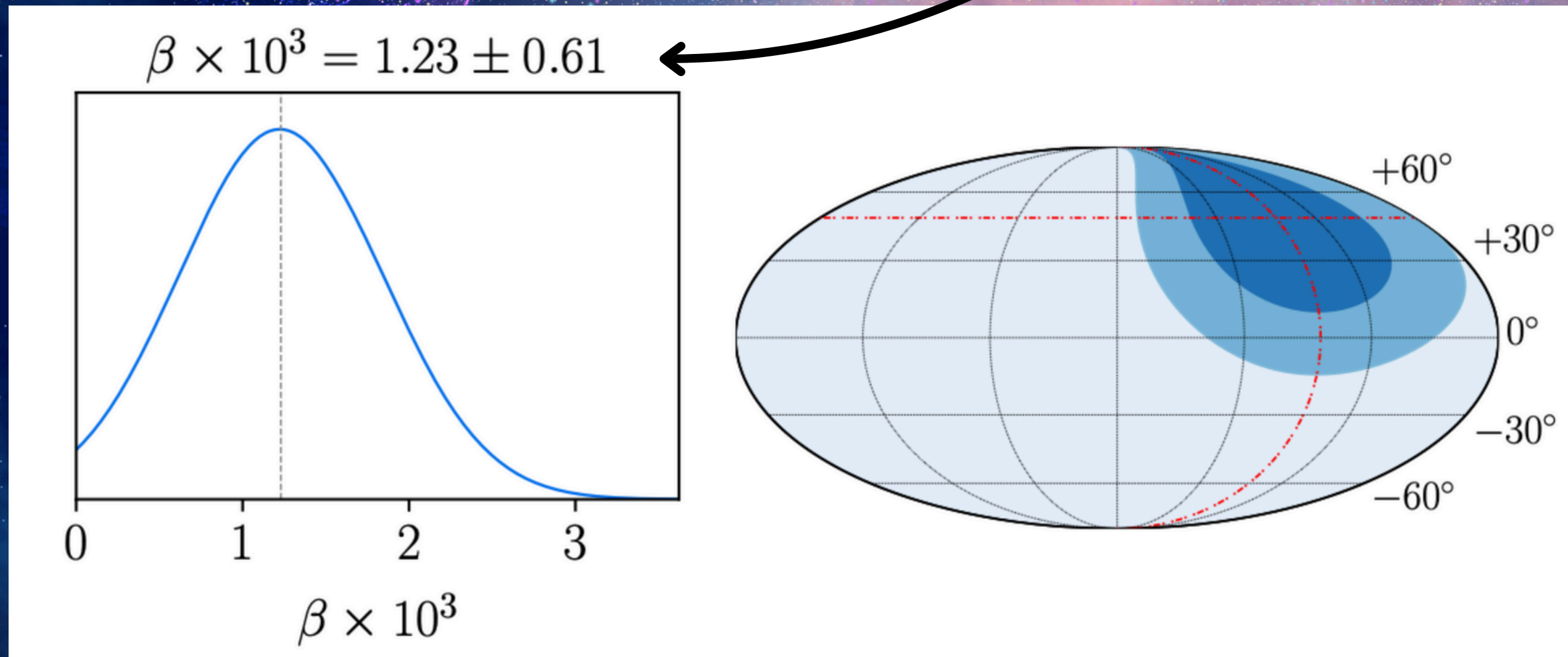
$$\beta = |\vec{\mathbf{v}}|/c$$

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 $T_{\text{obs}} = 20$ years

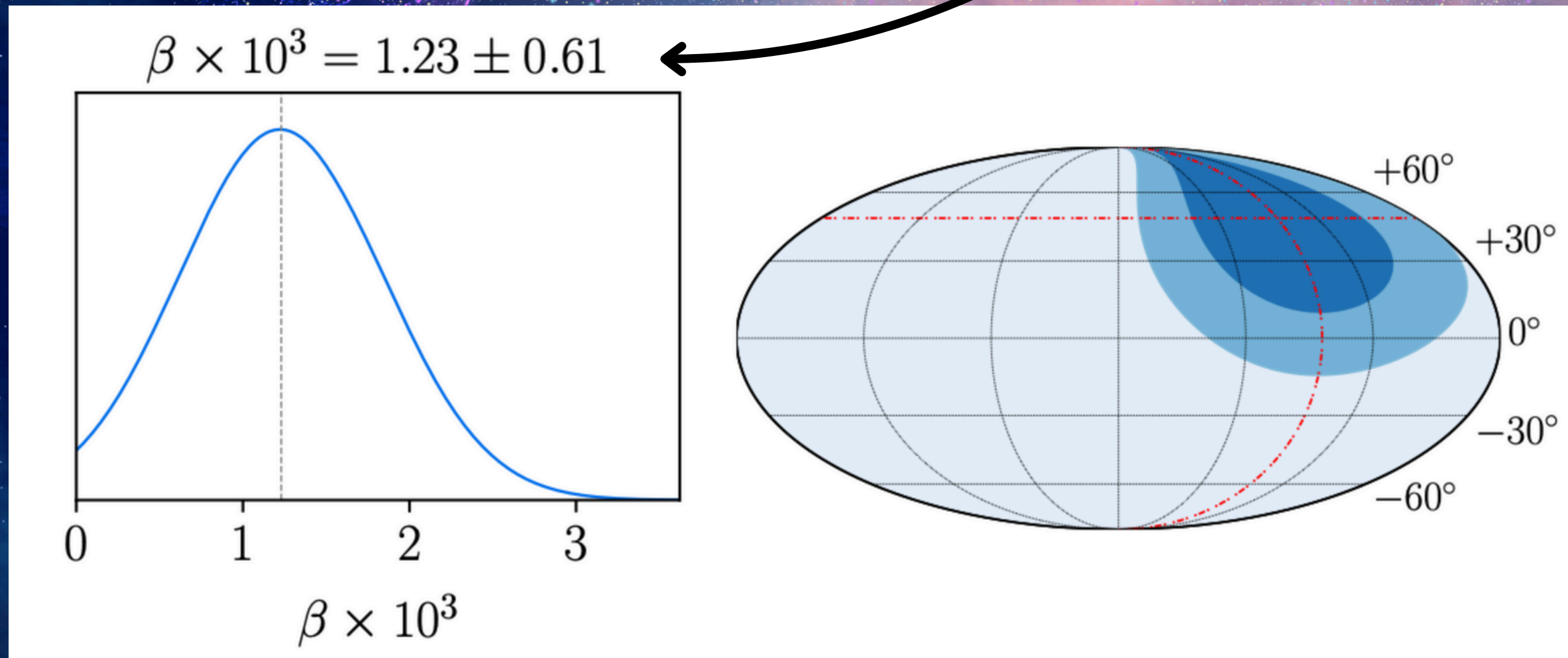
Large number of
pulsars
even for future
experiments in
SKA.



Kinematic Anisotropies with PTAs

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

Large number of
pulsars
even for future
experiments in
SKA.



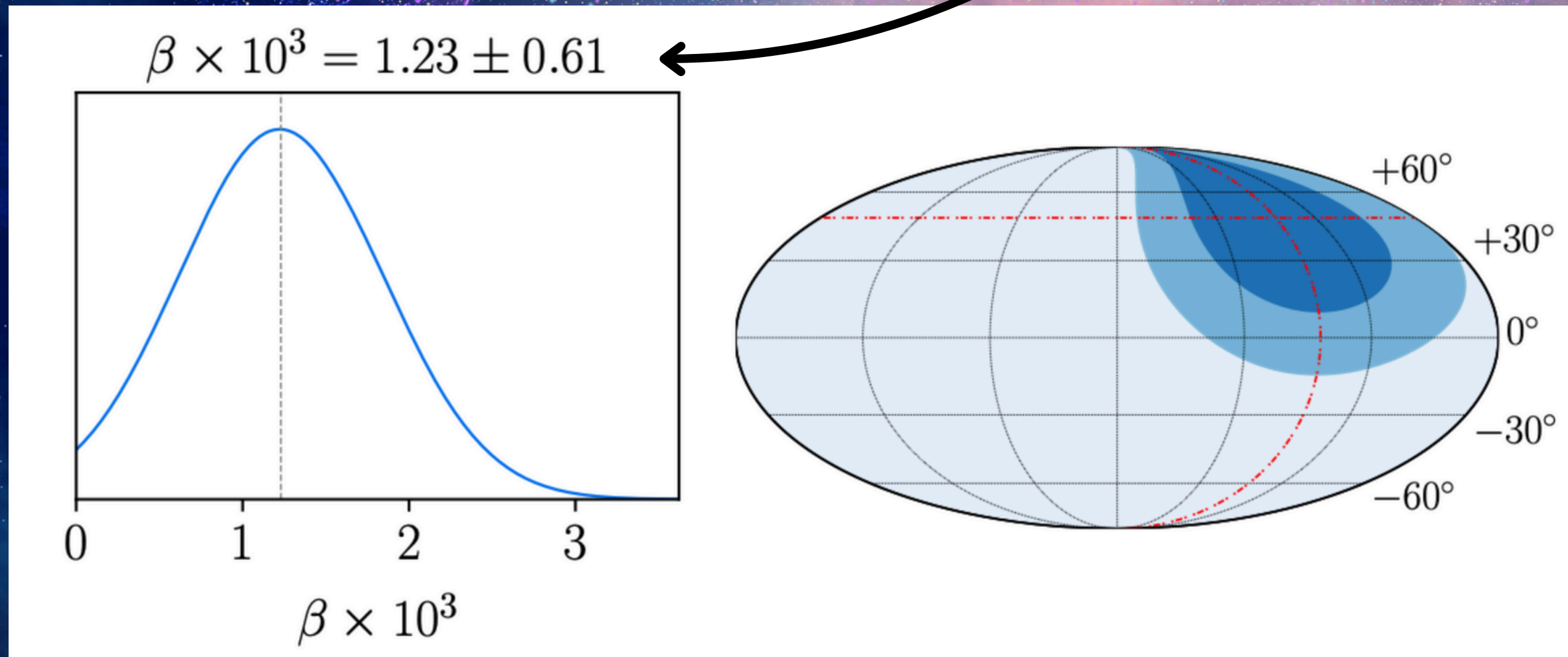
Kinematic Anisotropies with PTAs

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

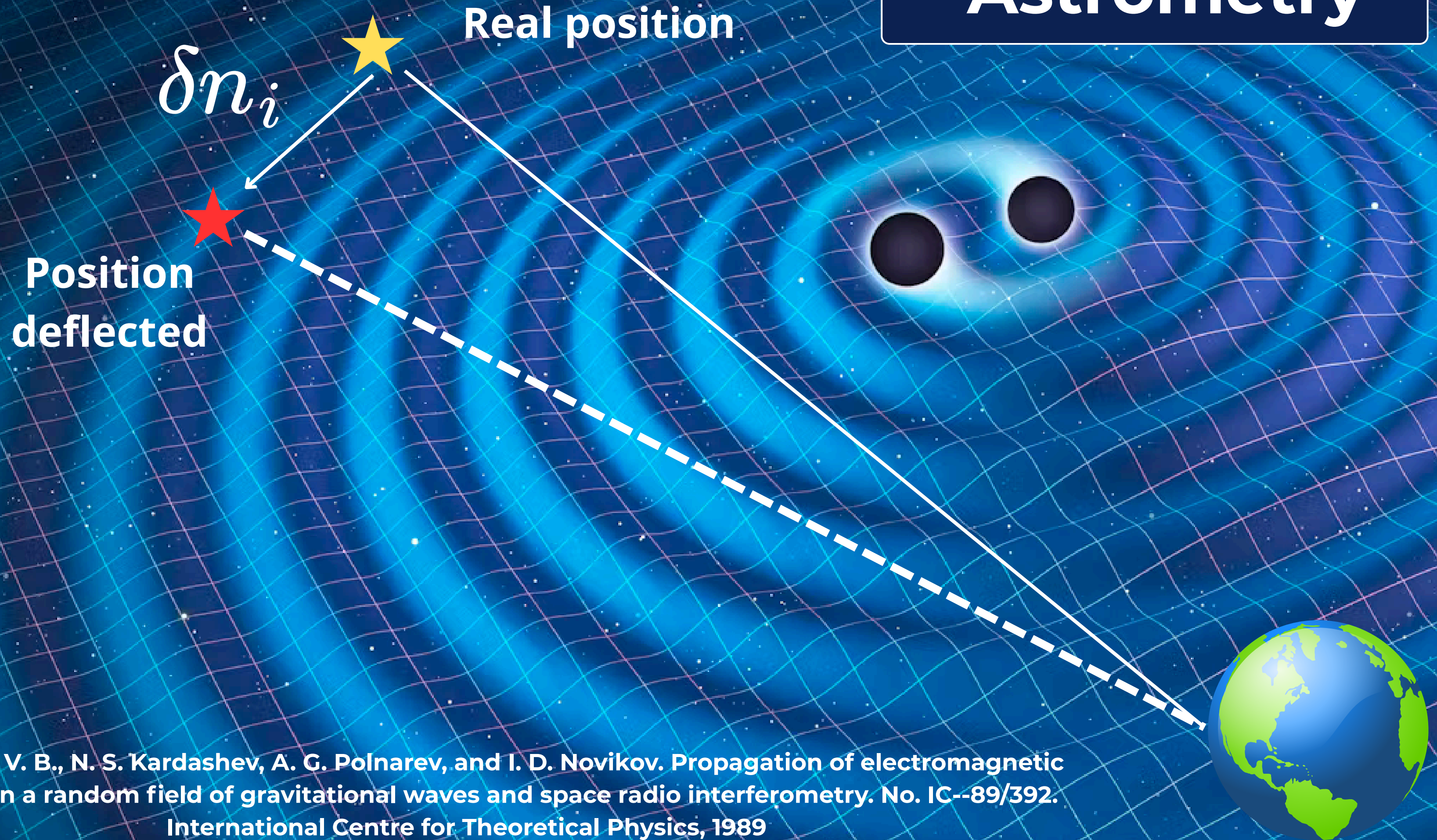
Large number of
pulsars
even for future
experiments in
SKA.



Could it be
achievable with
astrometry... ?

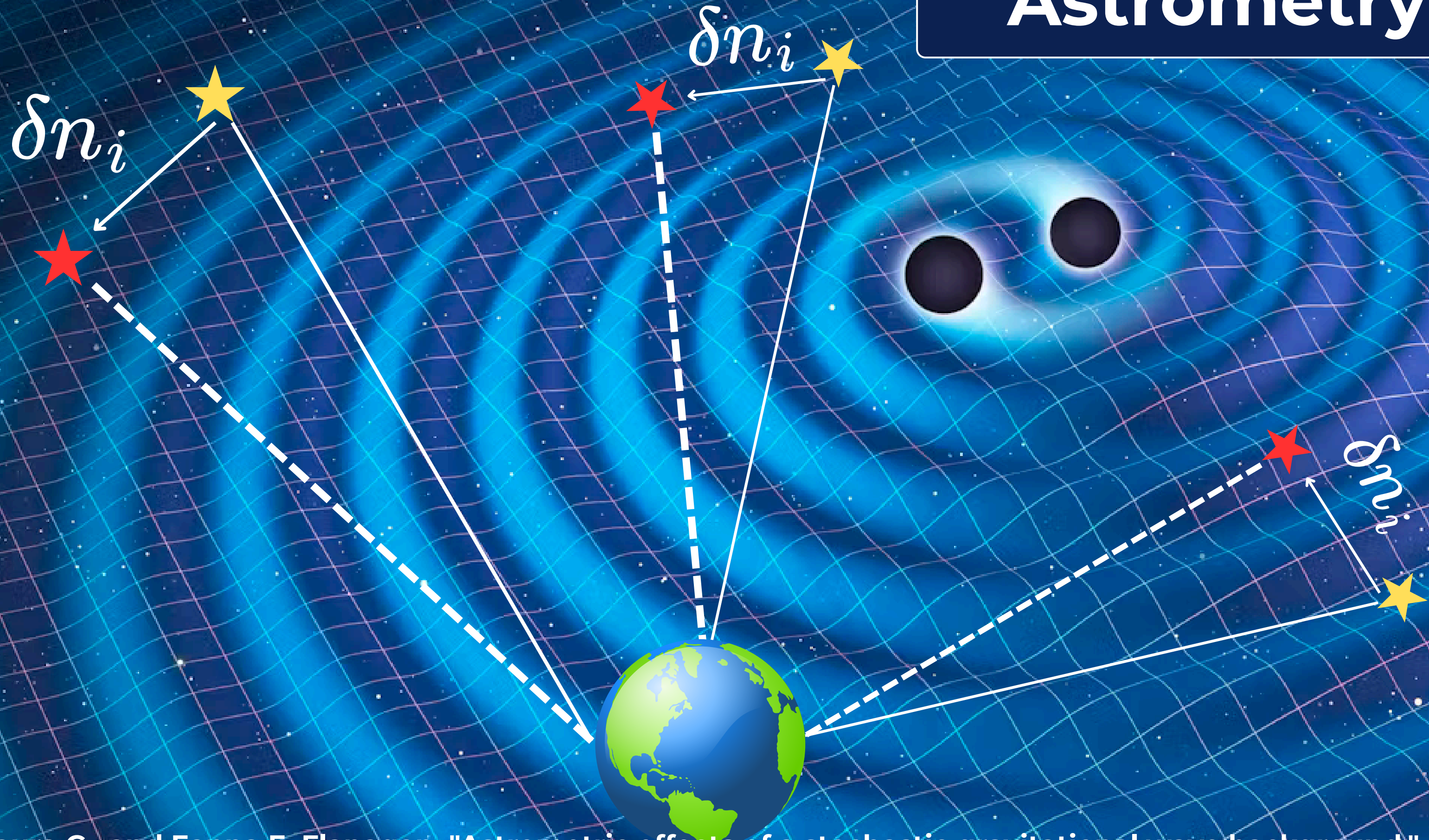


Astrometry



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

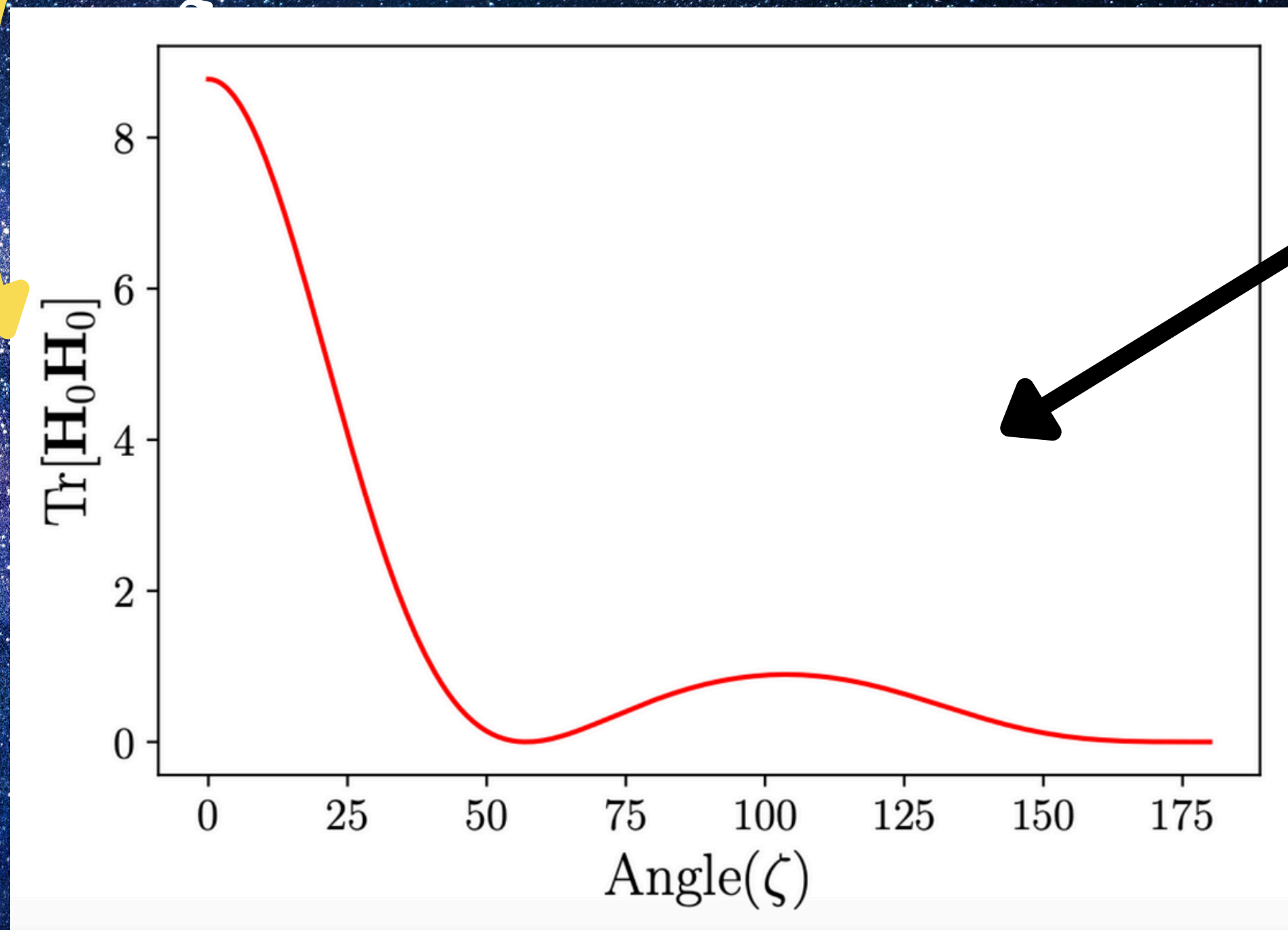


Book, Laura G., and Eanna E. Flanagan. "Astrometric effects of a stochastic gravitational wave background." *Physical Review D—Particles, Fields, Gravitation, and Cosmology* 83, no. 2 (2011): 024024.

Astrometry

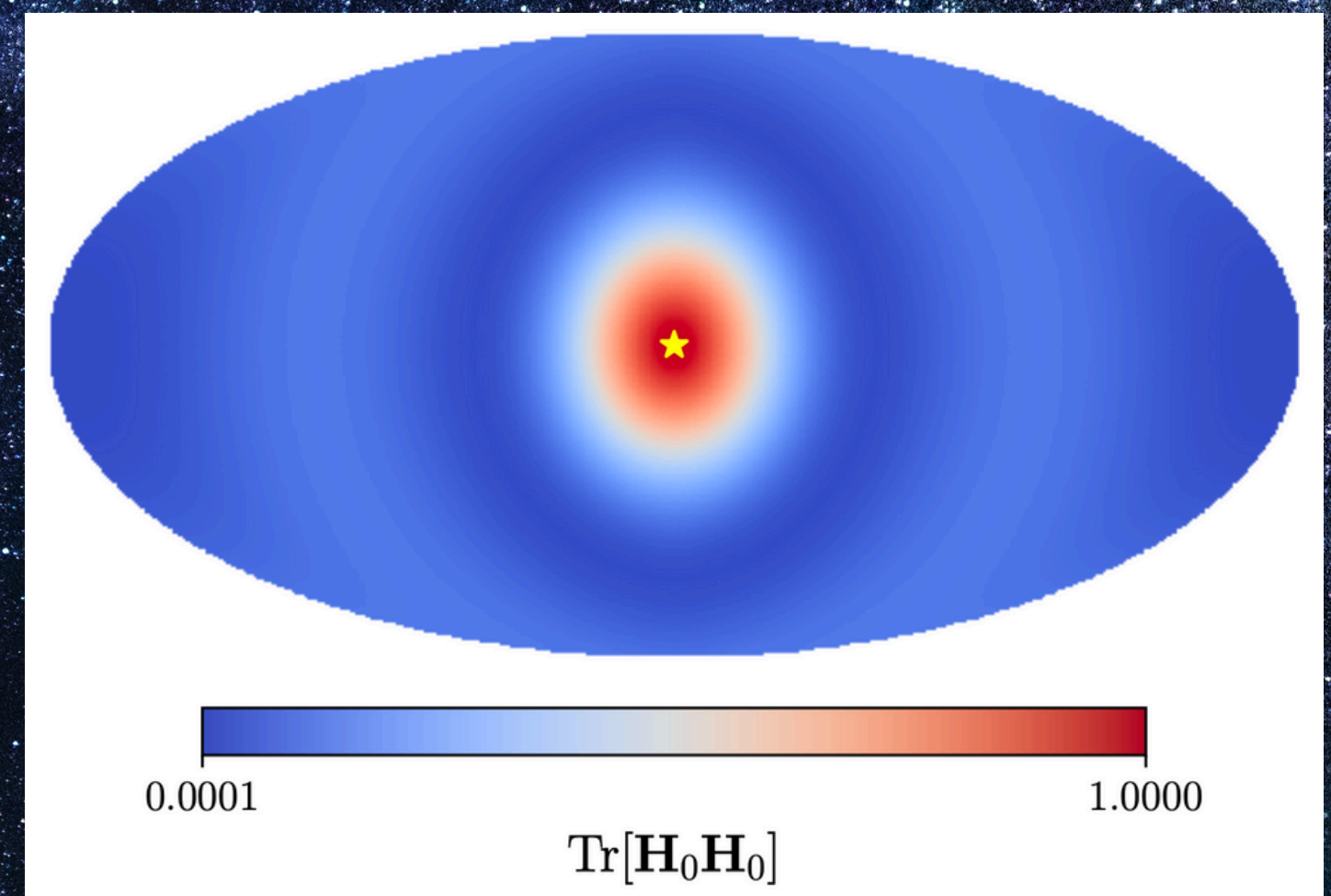
Representative of the sensitivity of
astrometry observations to the
monopole

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



Similar to Hellings-Downs
curve

$$\langle \delta n^i(\mathbf{n}, t) \delta n^j(\mathbf{q}, t') \rangle$$



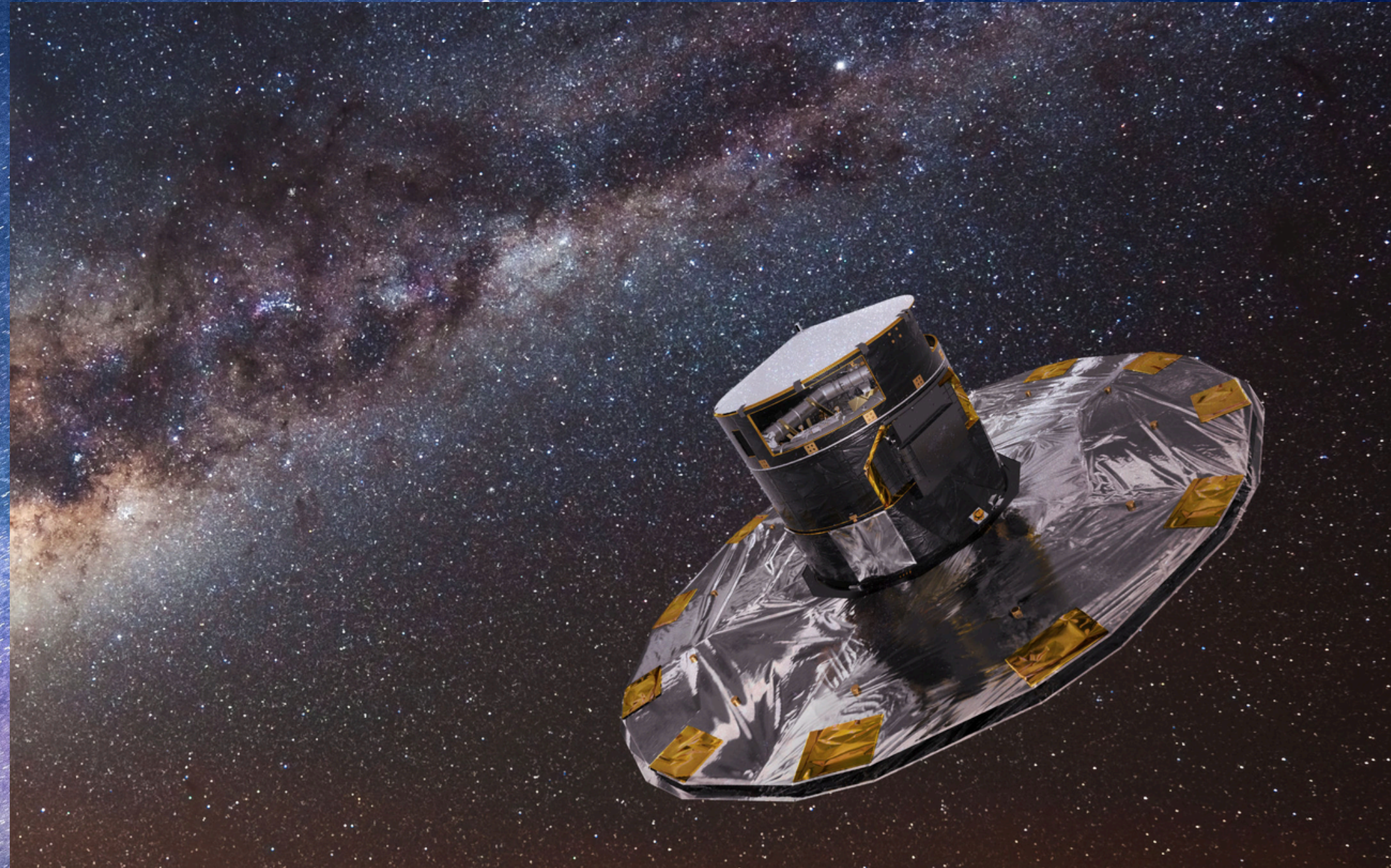
Jiménez Cruz, N. M., Ameek M., Gianmassimo T., and Ivonne Z.
ArXiv: 2412.14010 (2024).

Gaia mission

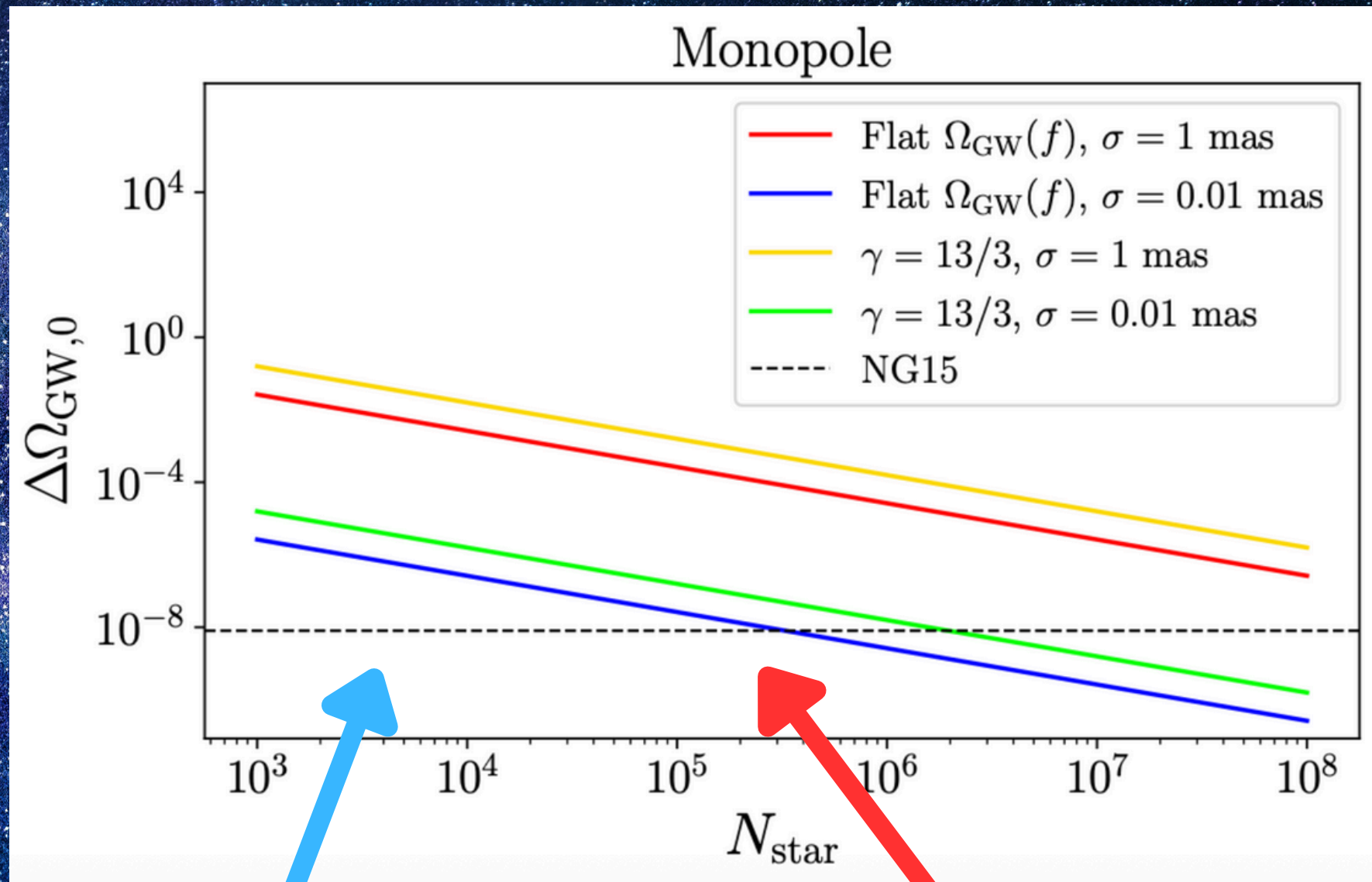
Gaia Data Release 5 is expected around the end of 2030, covering the full 10.5 years of mission data.

For the brightest objects in the survey:

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

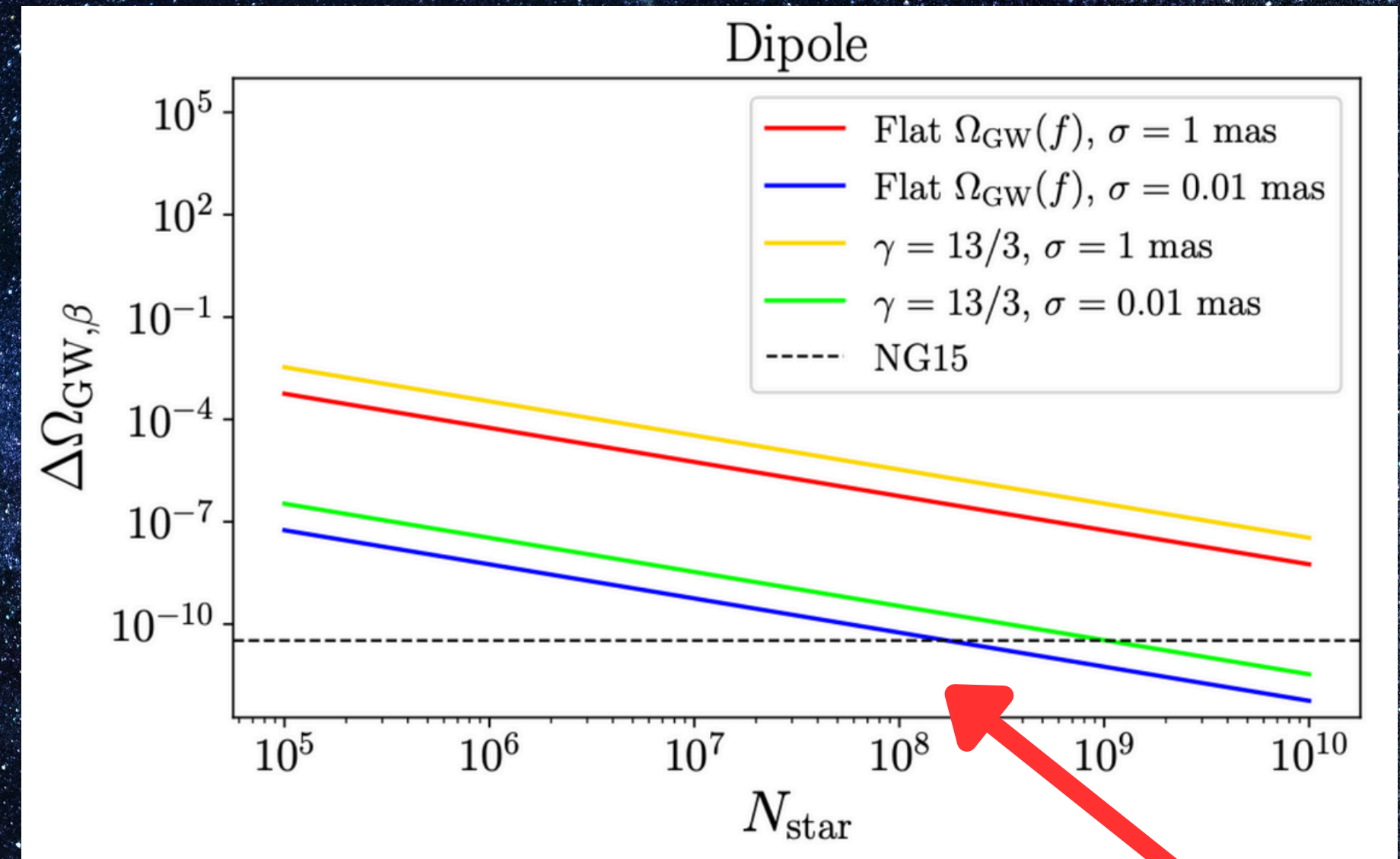


Astrometry forecast



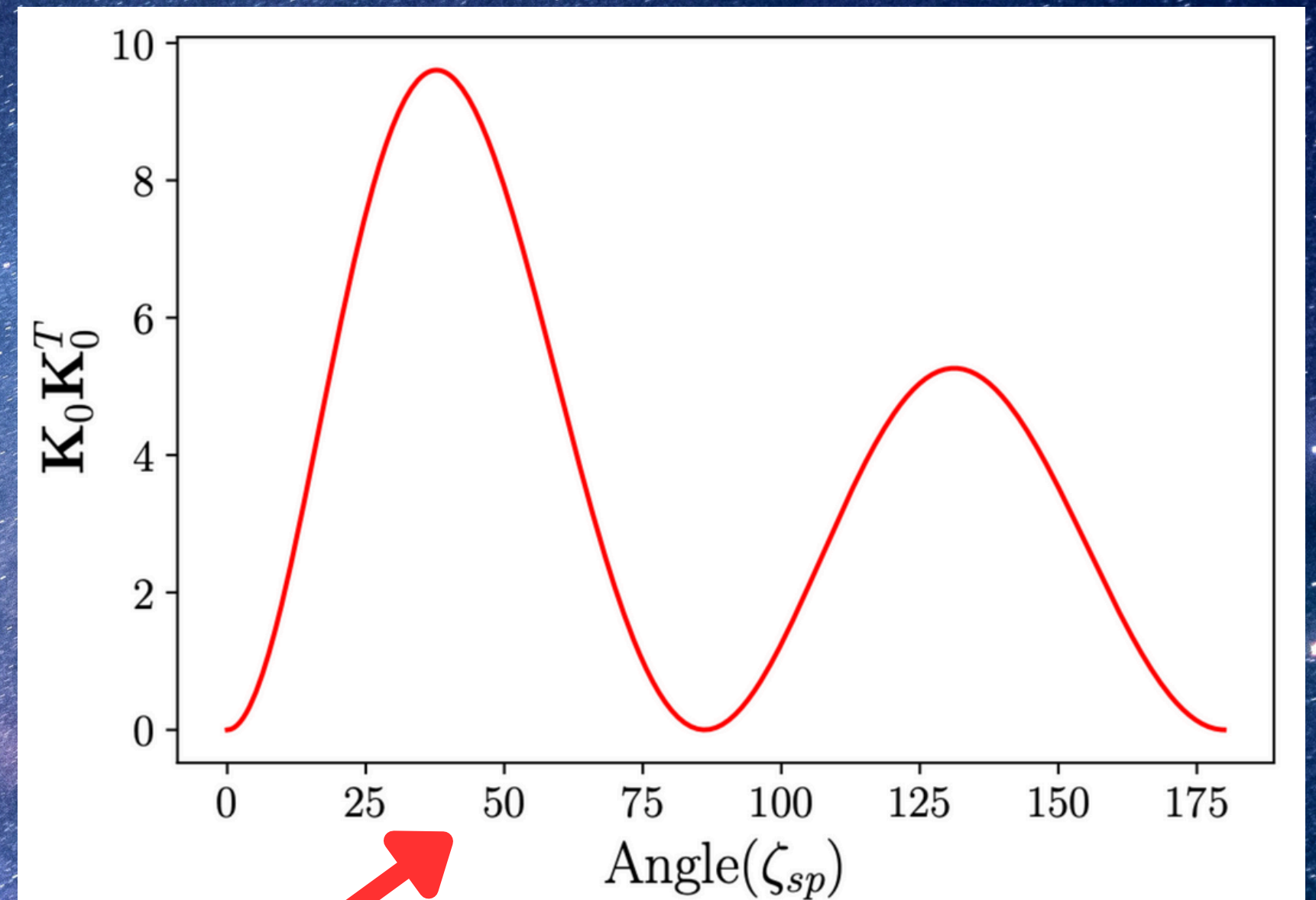
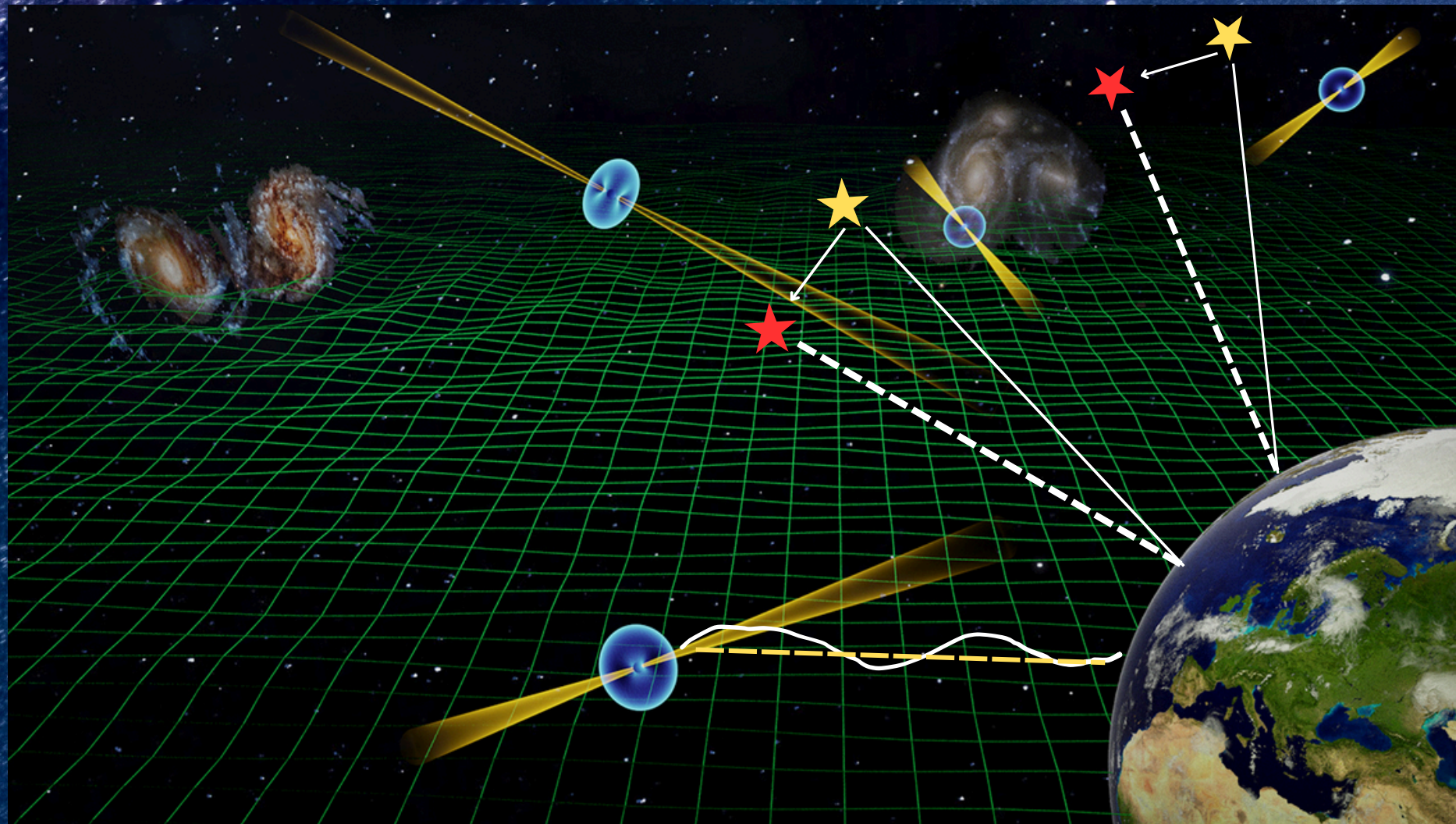
Energy density
with the NG15
results

$N_{\text{stars}} > 10^5$
to be competitive
with PTA



$N_{\text{stars}} > 10^8$
to be able to detect the
dipole

Astrometry meets PTA

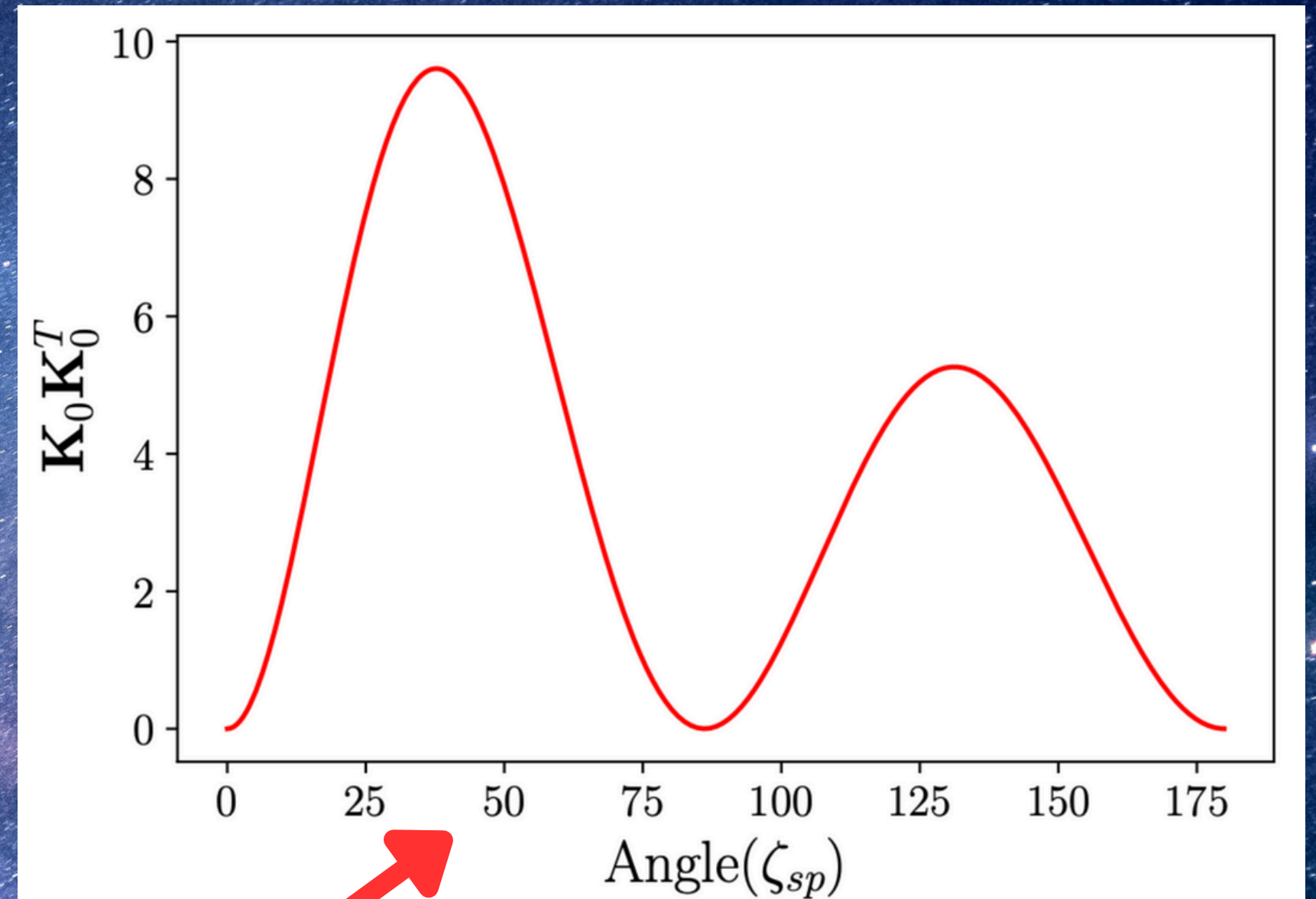
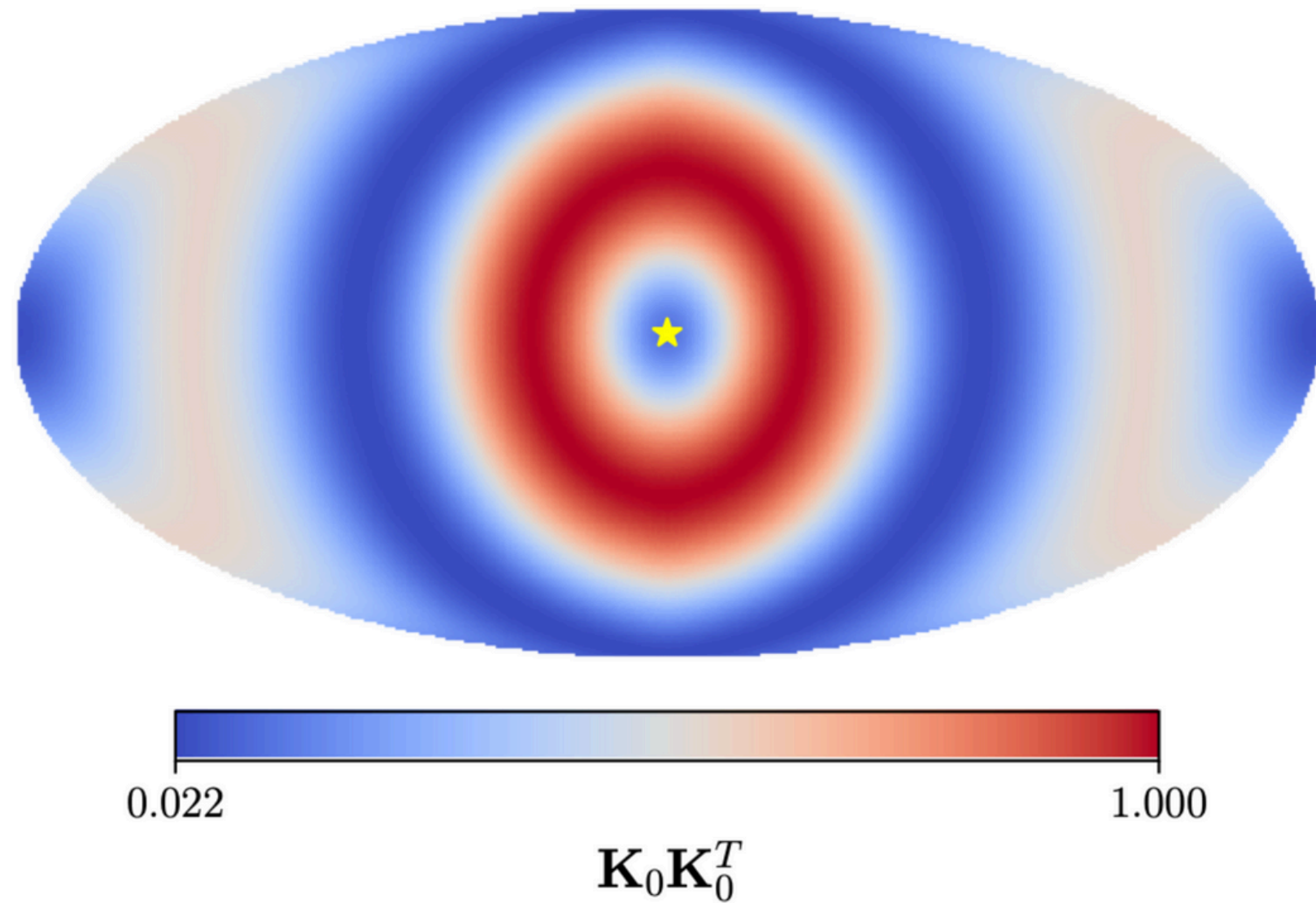


$$\langle \delta n_i(\mathbf{n}, t) z(t) \rangle$$

**Correlation between a
Star and a Pulsar**

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

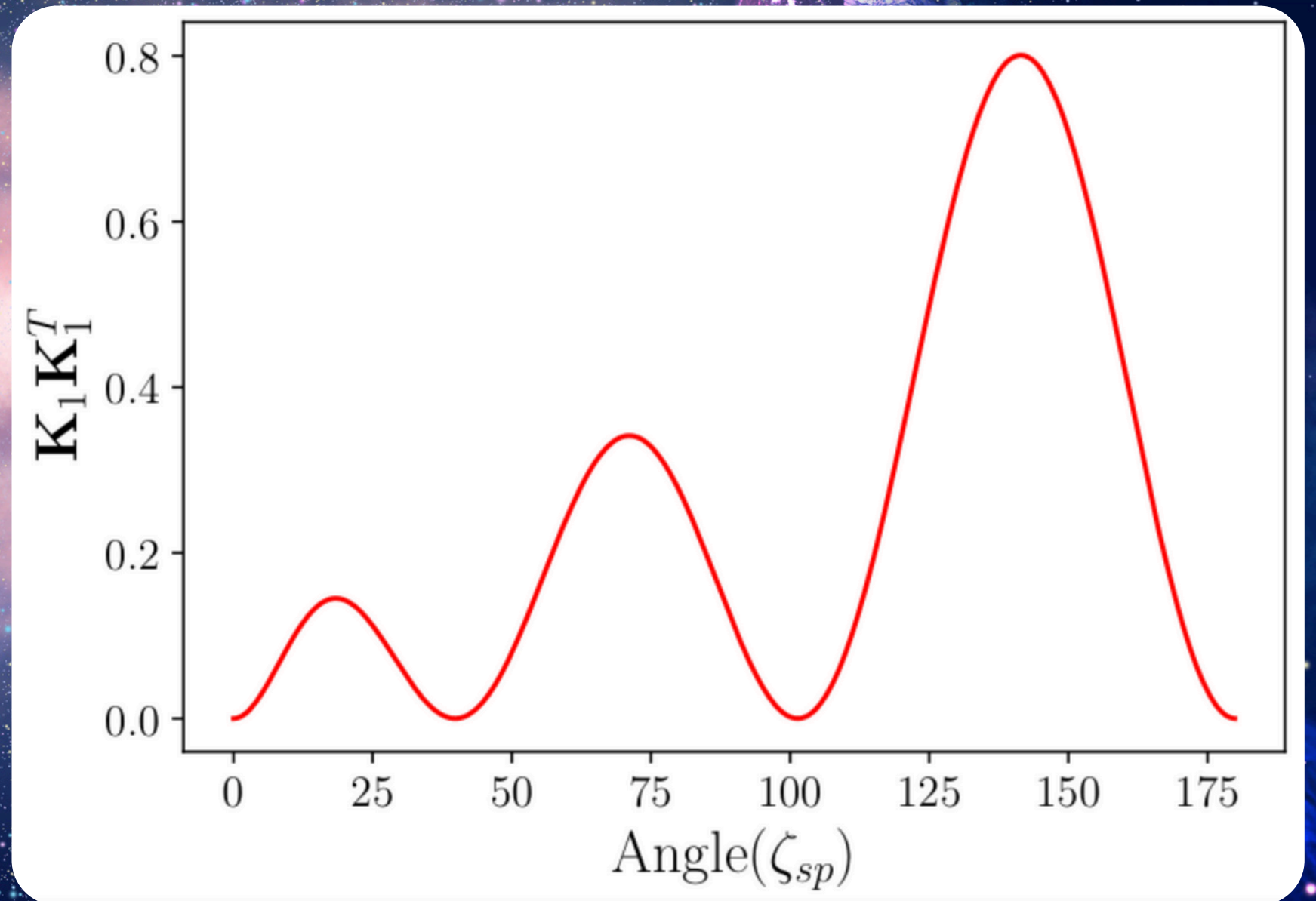
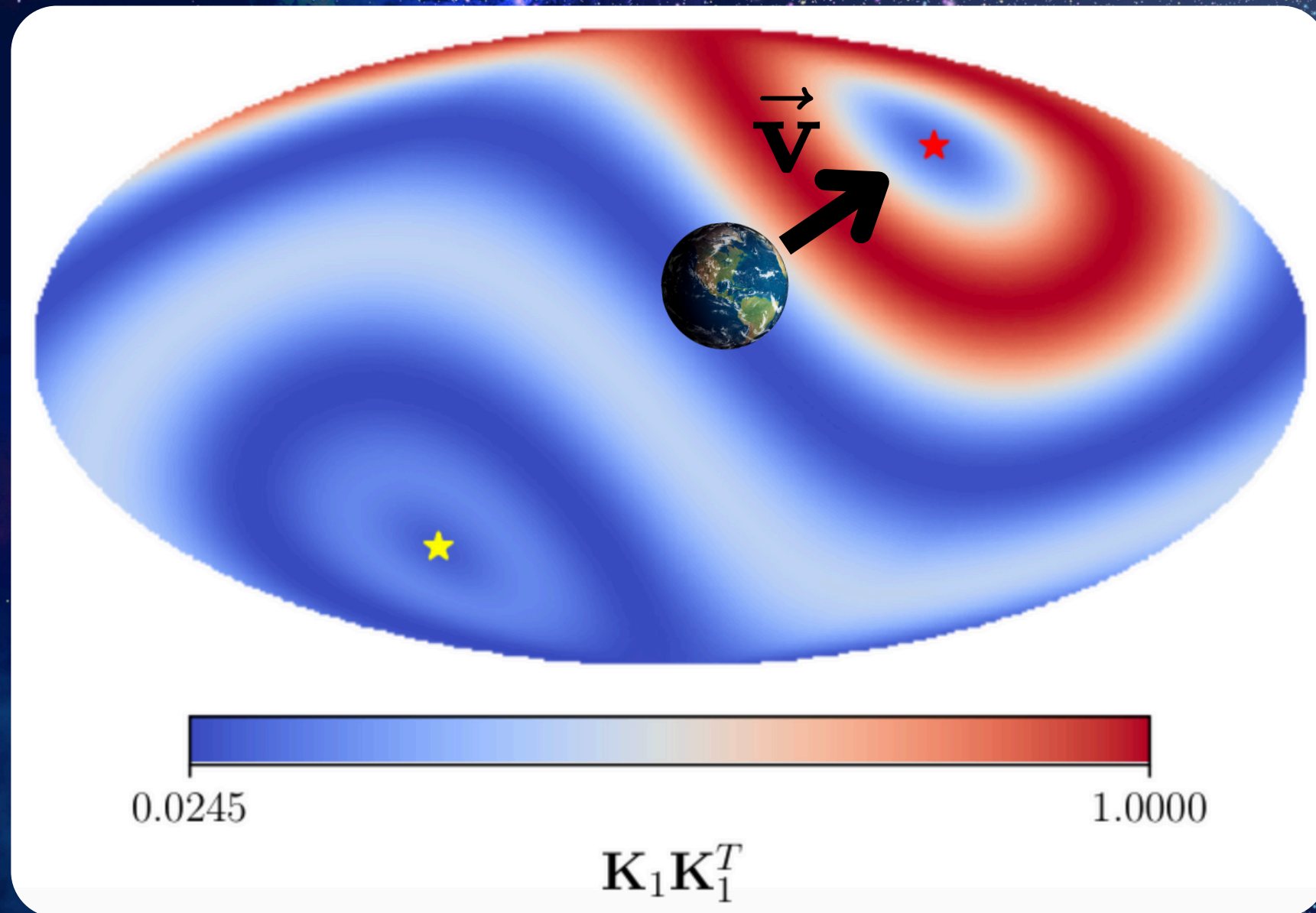
Astrometry meets PTA



**Correlation between a
Star and a Pulsar**

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

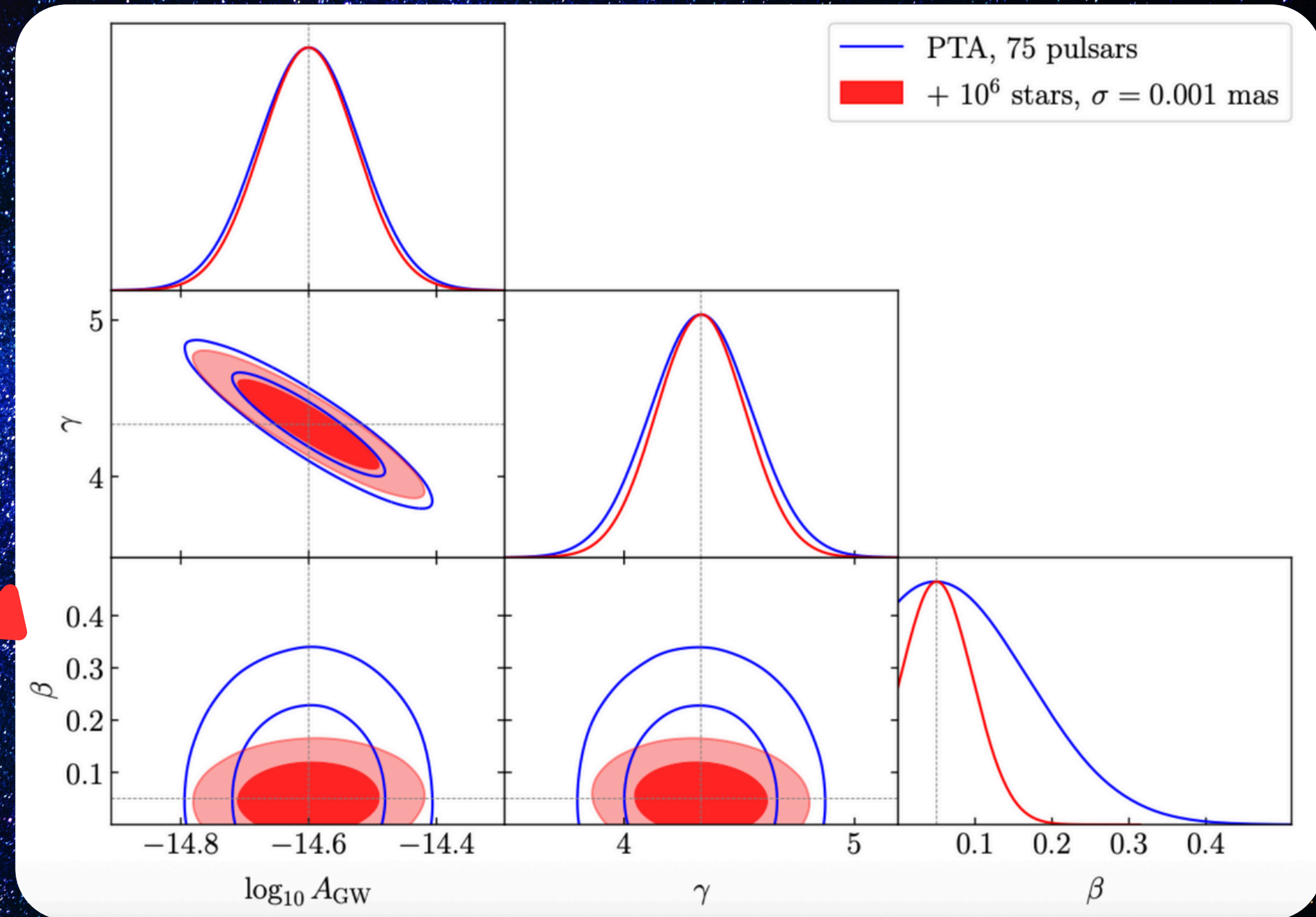
Astrometry meets PTAs (dipole)



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

Kinematic Anisotropies and PTA-Astrometry synergies

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



	$\log A_{\text{GW}}$	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 **futuristic astrometric surveys**.

Thanks!

If you are interested:

ArXiv: 2412.14010



Questions?

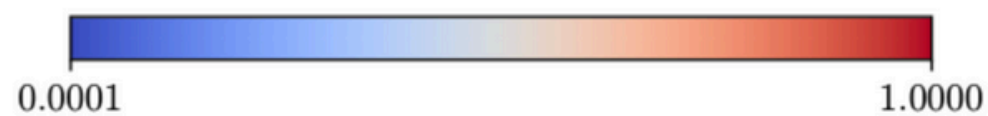
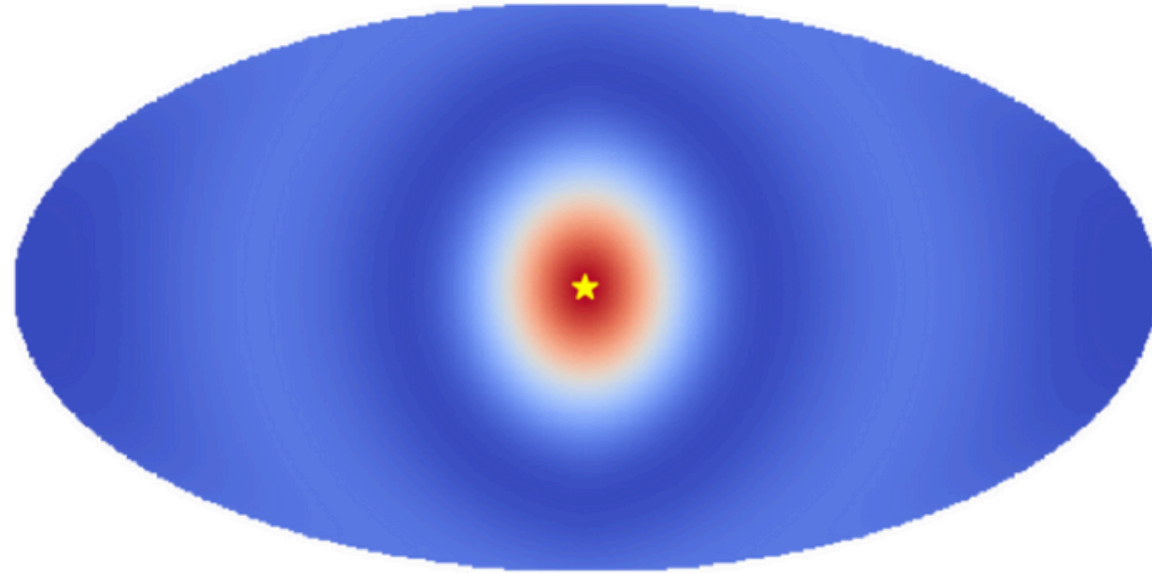
Astrometry Forecast (estimators)

$$\langle \delta n_a^i \delta n_b^j \rangle \equiv C_{ab}^{ij} = \sum_{n=1,2} p_n H_{ab,n}^{ij} + N_{ab}^{ij}$$

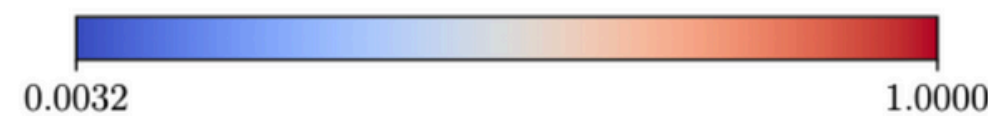
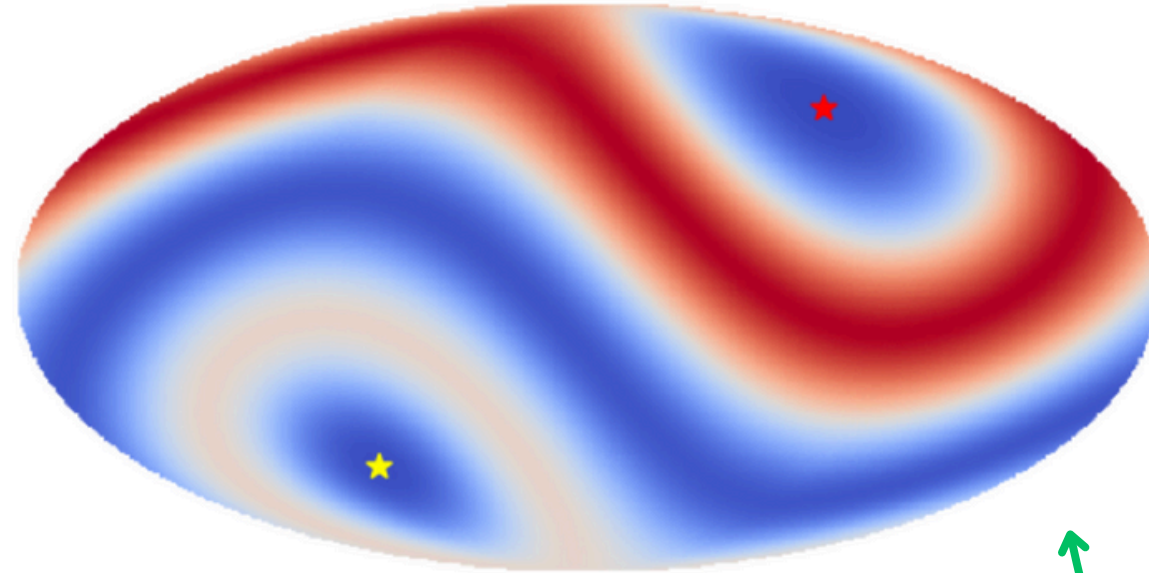
$$\mathcal{F} = \frac{1}{2\sigma_N^4} \begin{pmatrix} \text{Tr}[\mathbf{H}_0 \mathbf{H}_0] & \text{Tr}[\mathbf{H}_0 \mathbf{H}_1] \\ \text{Tr}[\mathbf{H}_1 \mathbf{H}_0] & \text{Tr}[\mathbf{H}_1 \mathbf{H}_1] \end{pmatrix}.$$

For $N \gg 100$ stars:

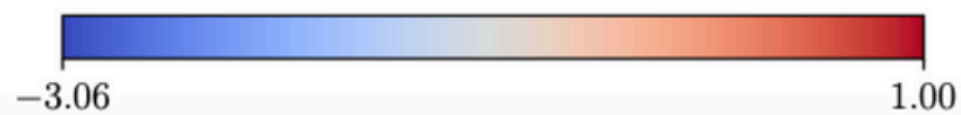
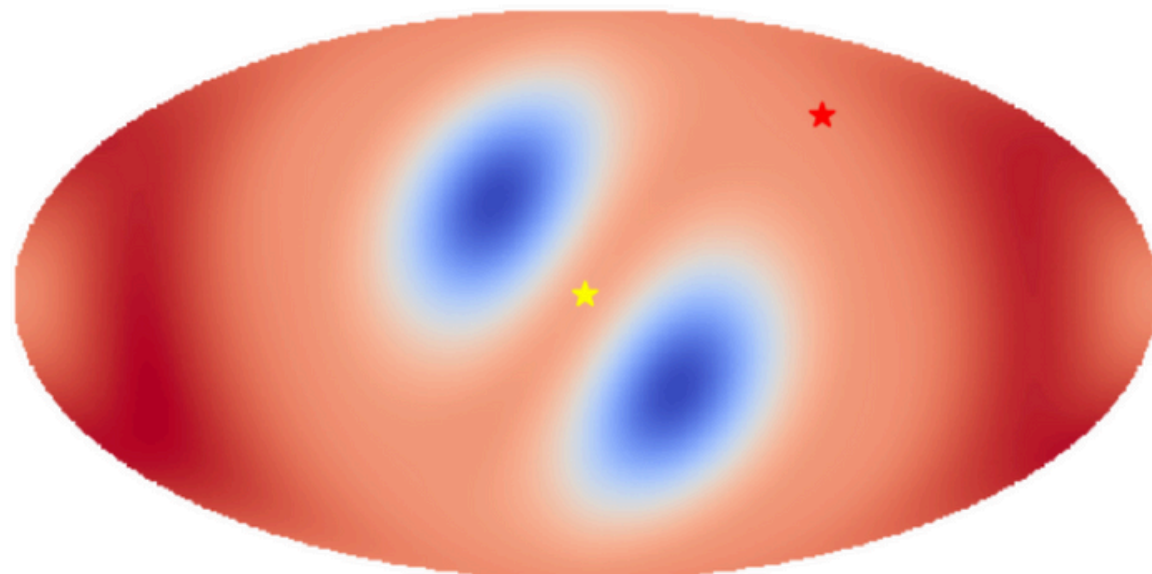
$$\begin{aligned} \mathcal{F}_0 &\equiv \text{Tr}[\mathbf{H}_0 \mathbf{H}_0] && \simeq 3 \times N_{\text{star}}^2 \\ \mathcal{F}_1 &\equiv \text{Tr}[\mathbf{H}_1 \mathbf{H}_1] && \simeq 0.65 \times N_{\text{star}}^2 \end{aligned}$$



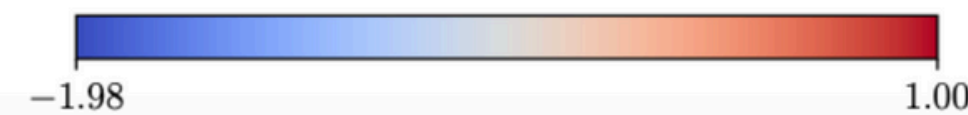
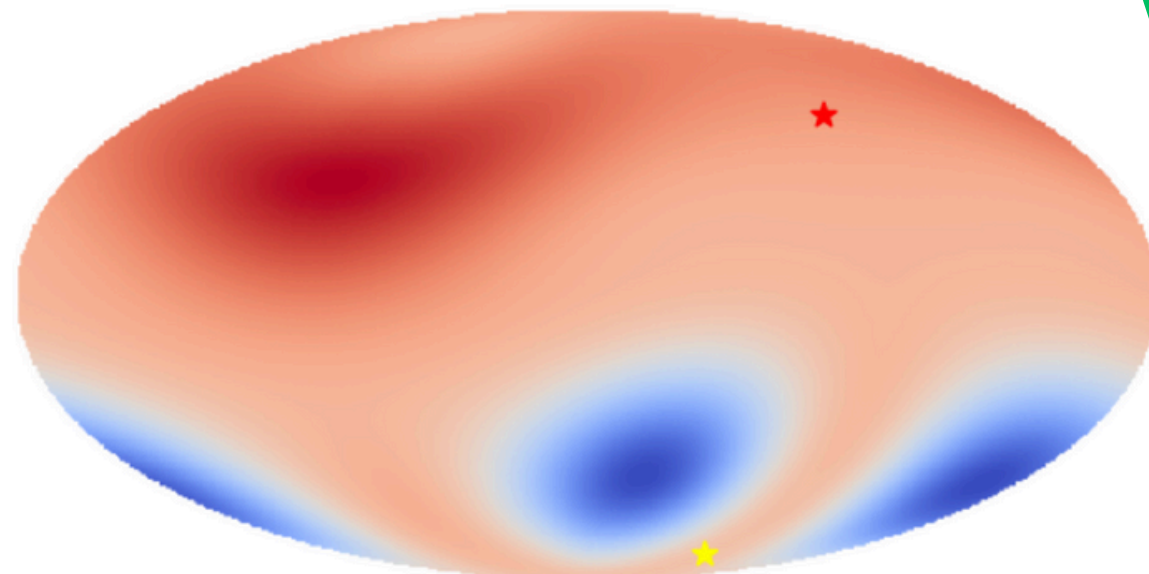
$\text{Tr}[\mathbf{H}_0\mathbf{H}_0]$



$\text{Tr}[\mathbf{H}_1\mathbf{H}_1]$



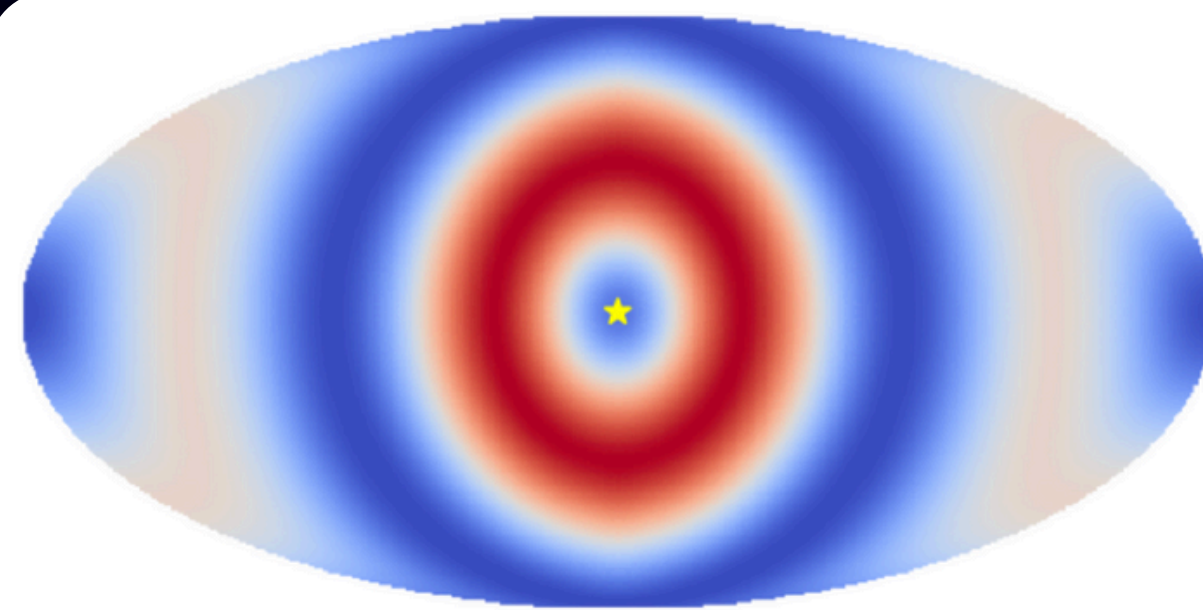
$\text{Tr}[\mathbf{H}_1\mathbf{H}_1]$



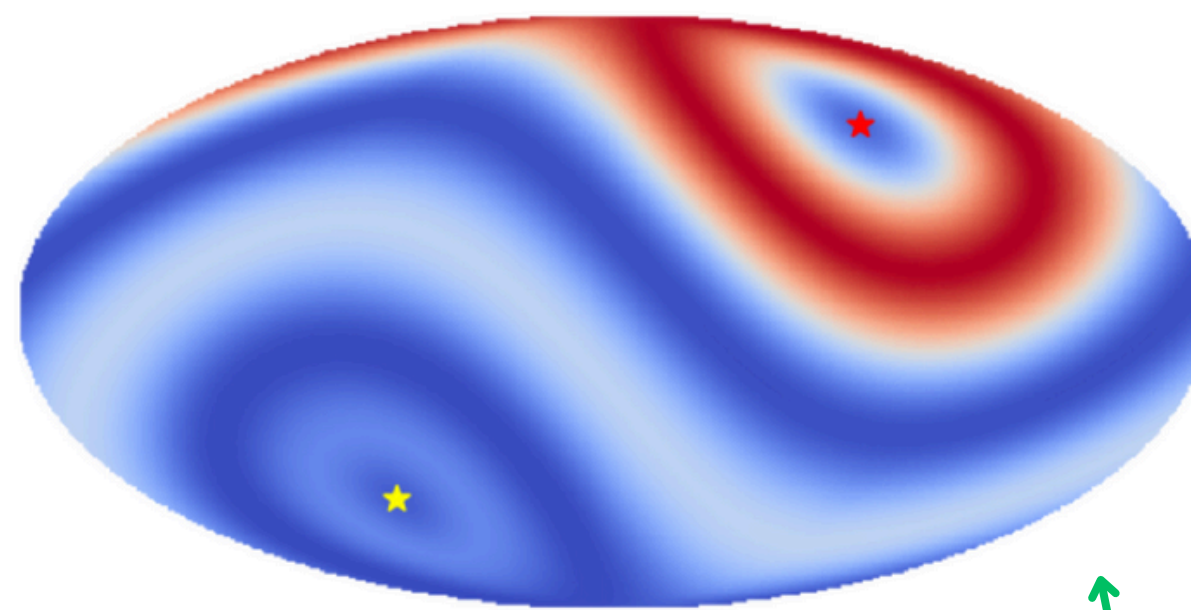
$\text{Tr}[\mathbf{H}_1\mathbf{H}_1]$

Complex patterns for the ORF sensitivity to GW arise, depending on the direction of star positions in the sky.

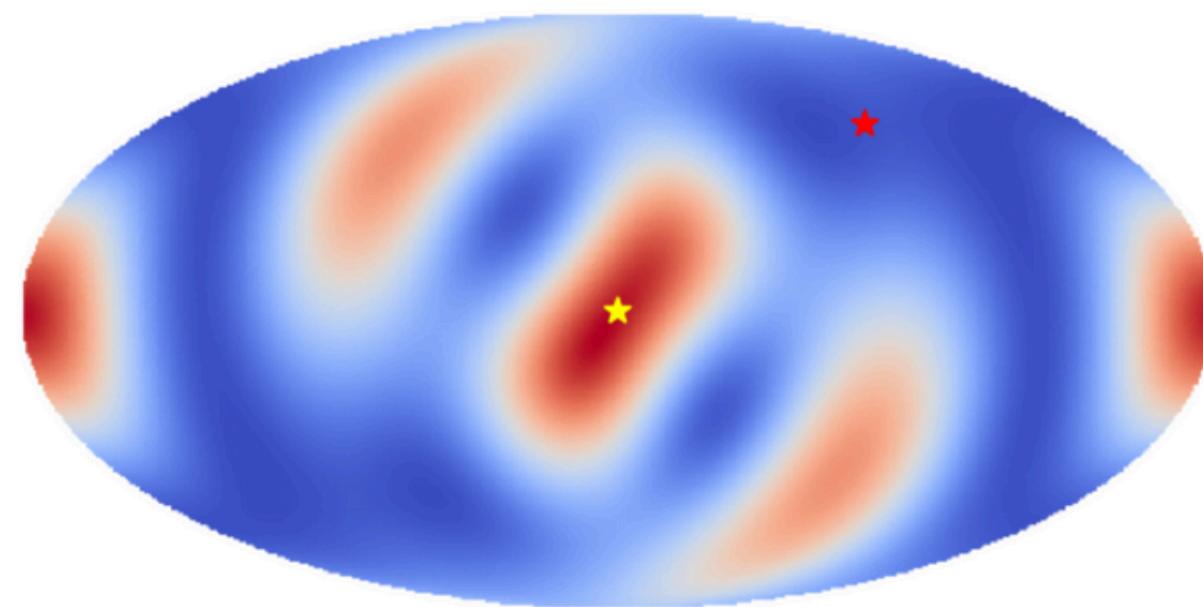
We consider a simple scenario where $\mathbf{n}$ is parallel to $\mathbf{v}$. This assumption simplifies the expression for $\text{Tr}[\mathbf{H}_1\mathbf{H}_1]$



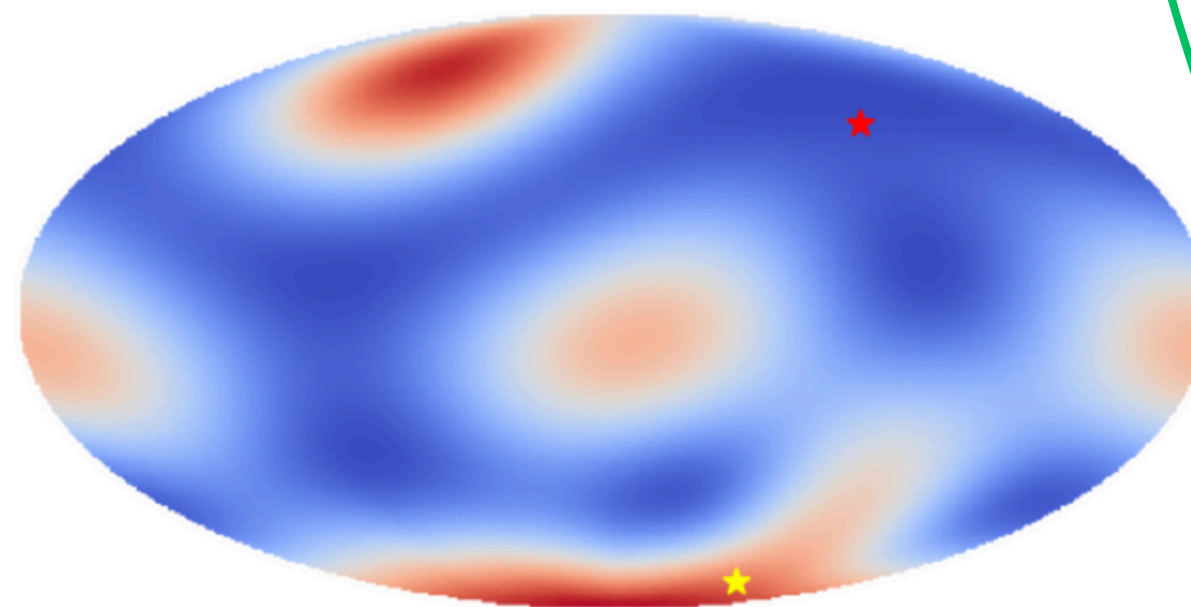
$$\mathbf{K}_0 \mathbf{K}_0^T$$



$$\mathbf{K}_1 \mathbf{K}_1^T$$



$$\mathbf{K}_1 \mathbf{K}_1^T$$



$$\mathbf{K}_1 \mathbf{K}_1^T$$

Complex patterns for the ORF sensitivity to GW arise, depending on the direction of star positions in the sky.

We consider a simple scenario where $\mathbf{n}$ is parallel to $\mathbf{v}$. This assumption simplifies the expression for

$$\mathbf{K}_1 \mathbf{K}_1^T$$