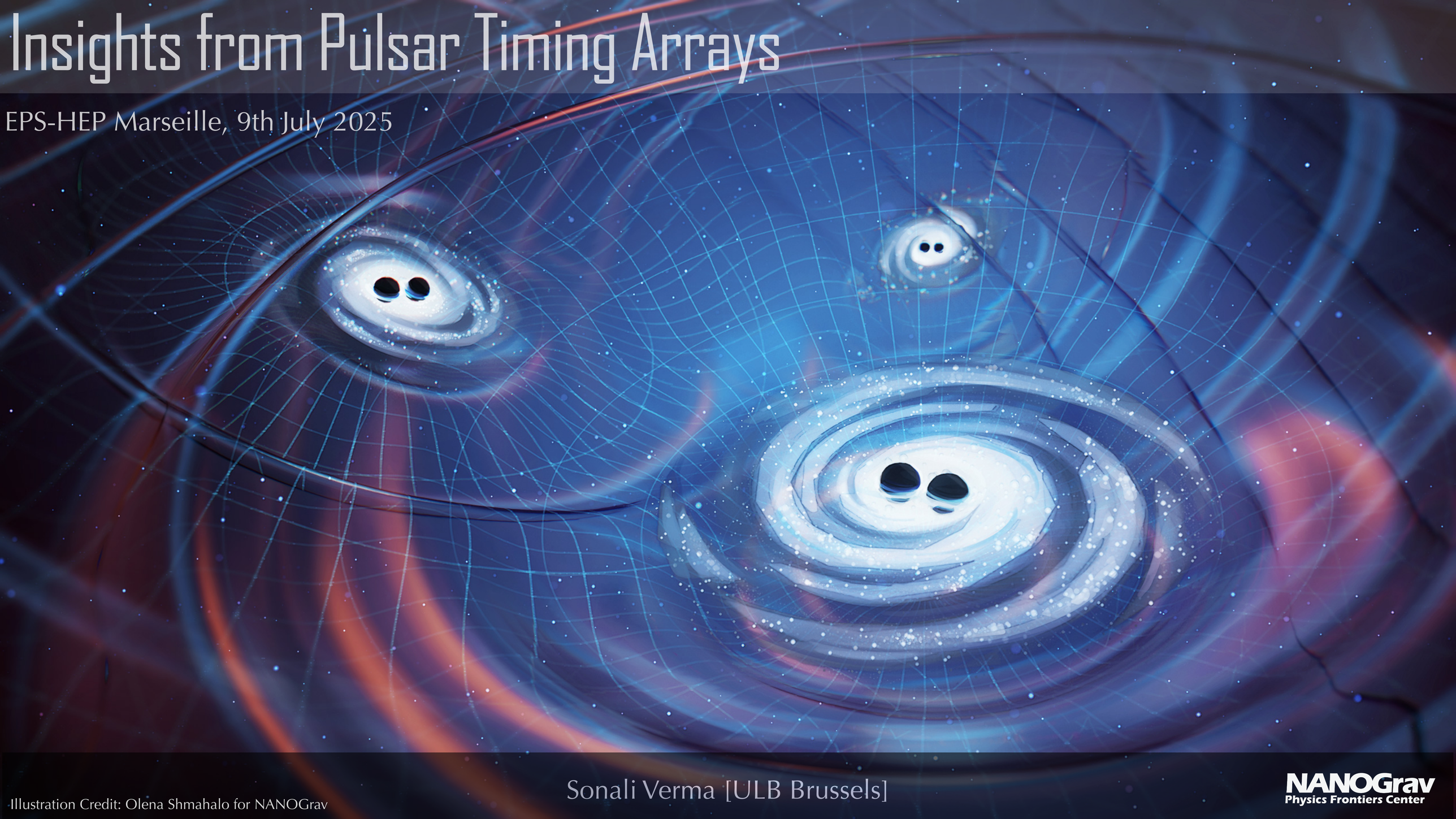
Insights from Pulsar Timing Arrays

EPS-HEP Marseille, 9th July 2025



Sonali Verma [ULB Brussels]

Illustration Credit: Olena Shmahalo for NANOGrav

NANOGrav Physics Frontiers Center

PULSAR

are rotating neutron stars

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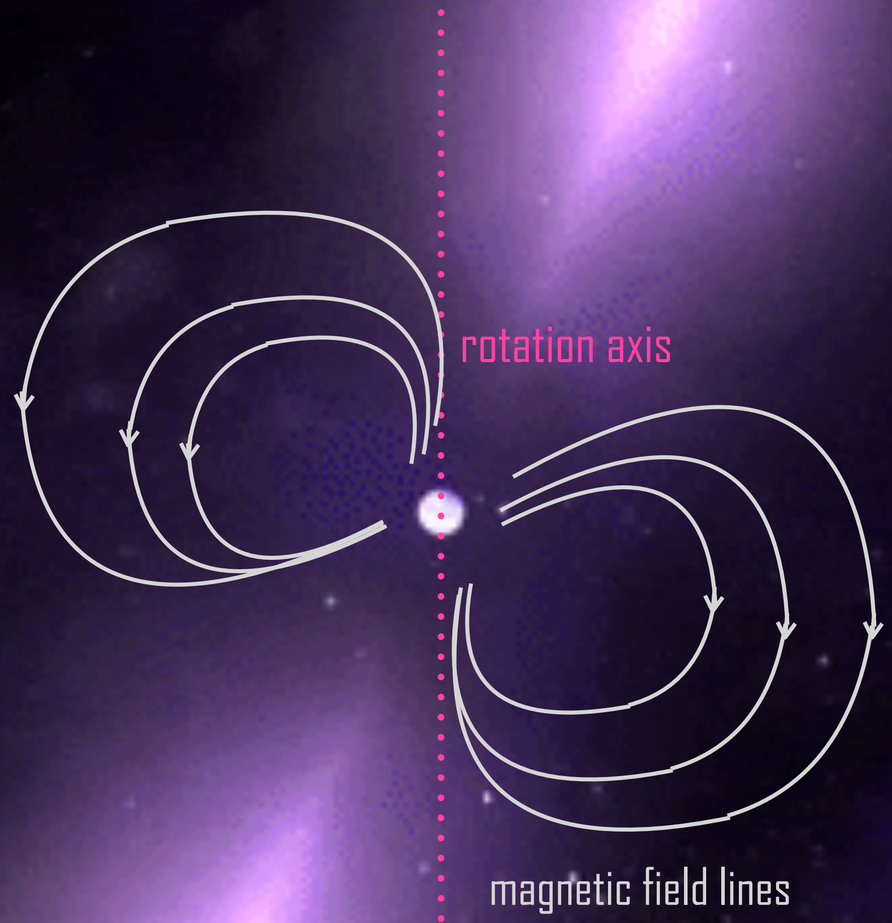
are rotating neutron stars

radio-beam emitters

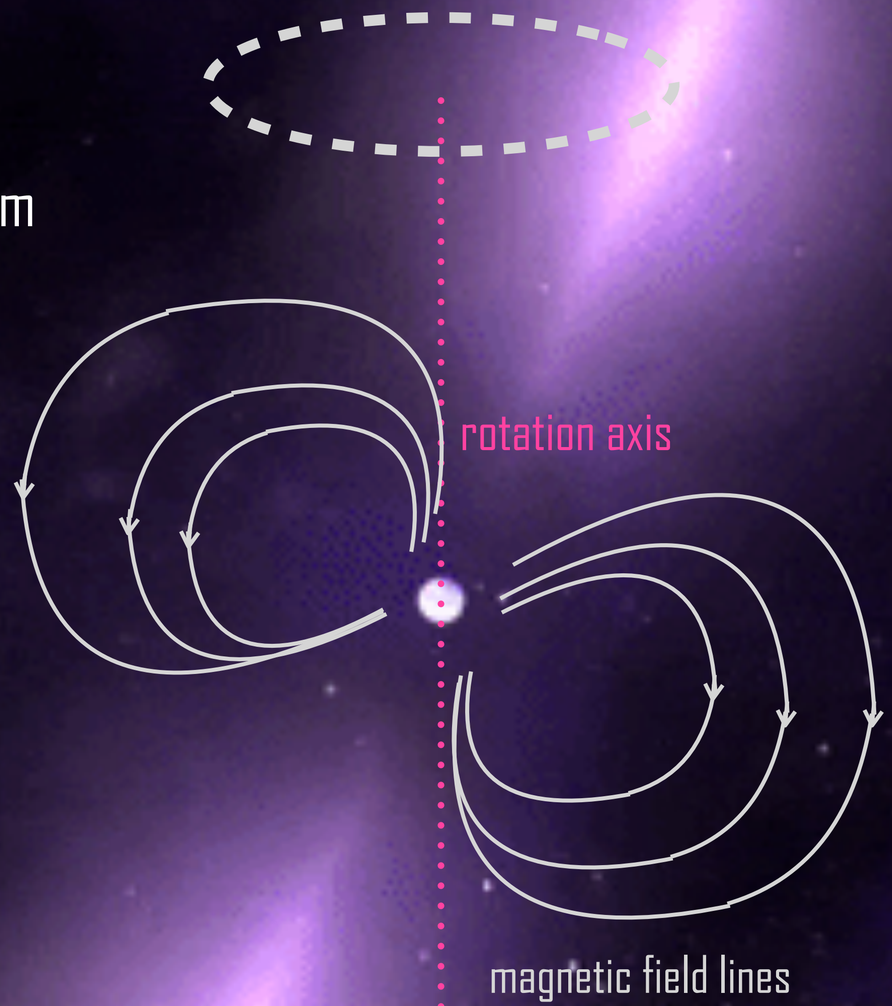


PULSAR

are rotating neutron stars

radio-beam emitters

like a light-house beam



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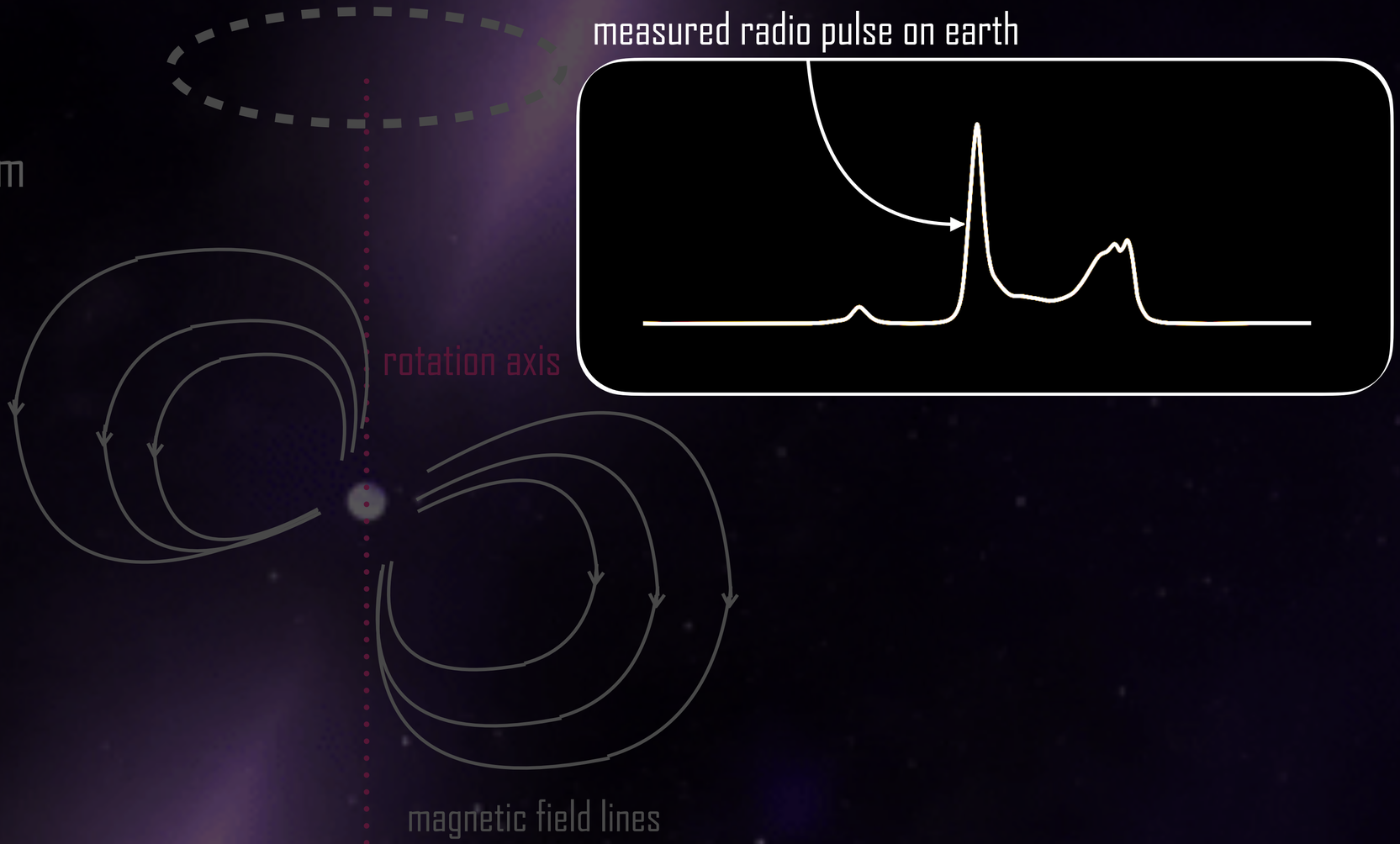

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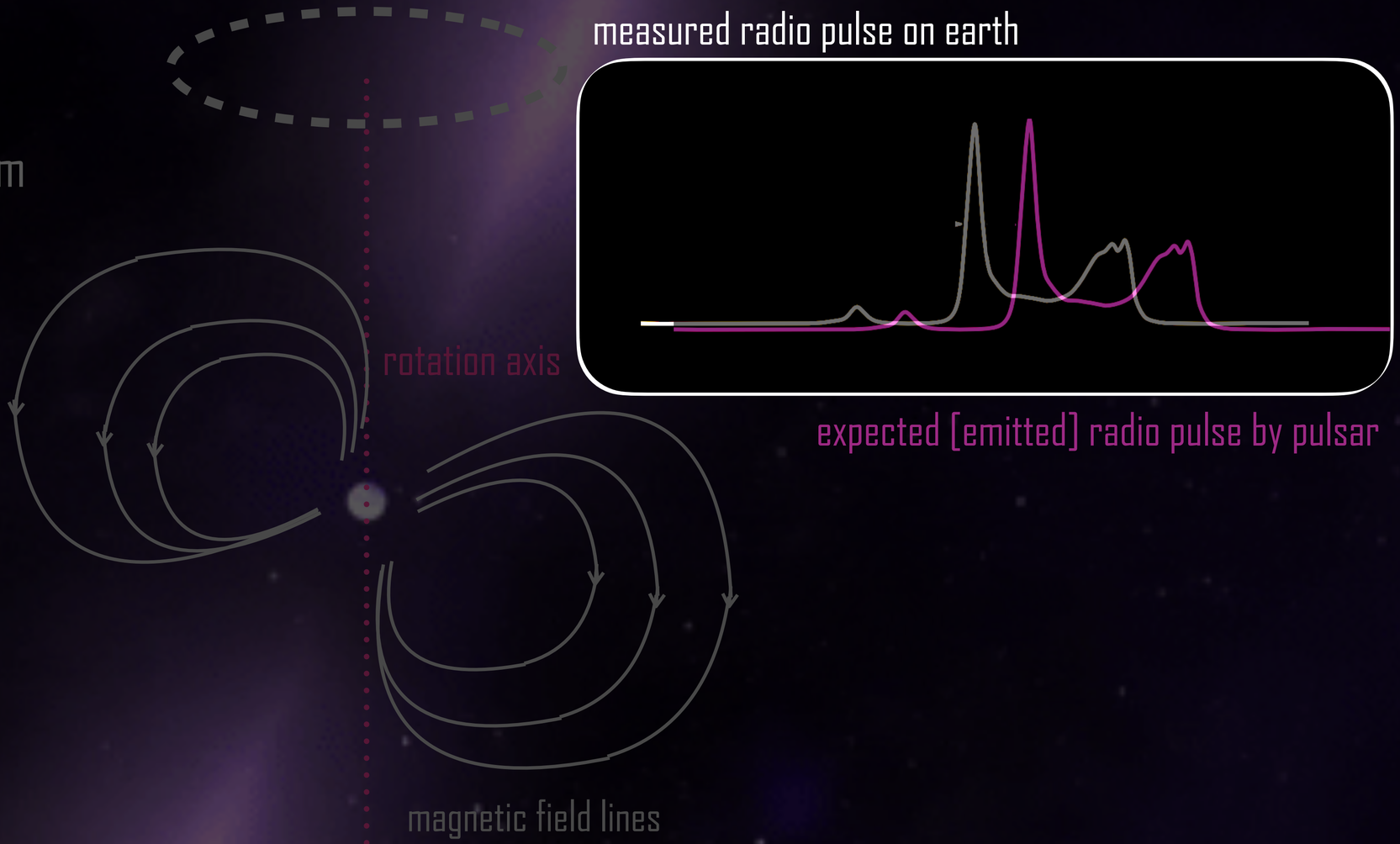

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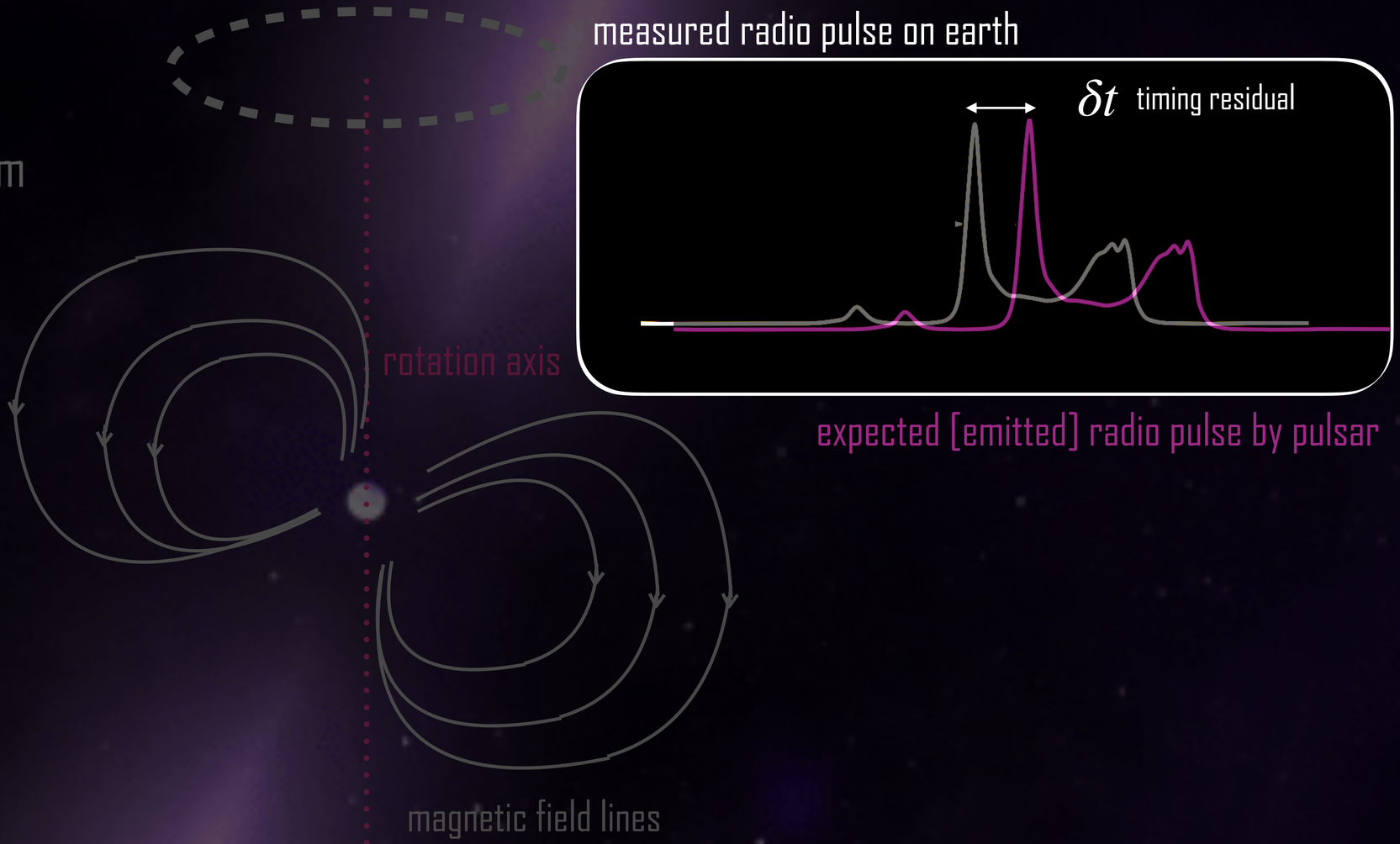
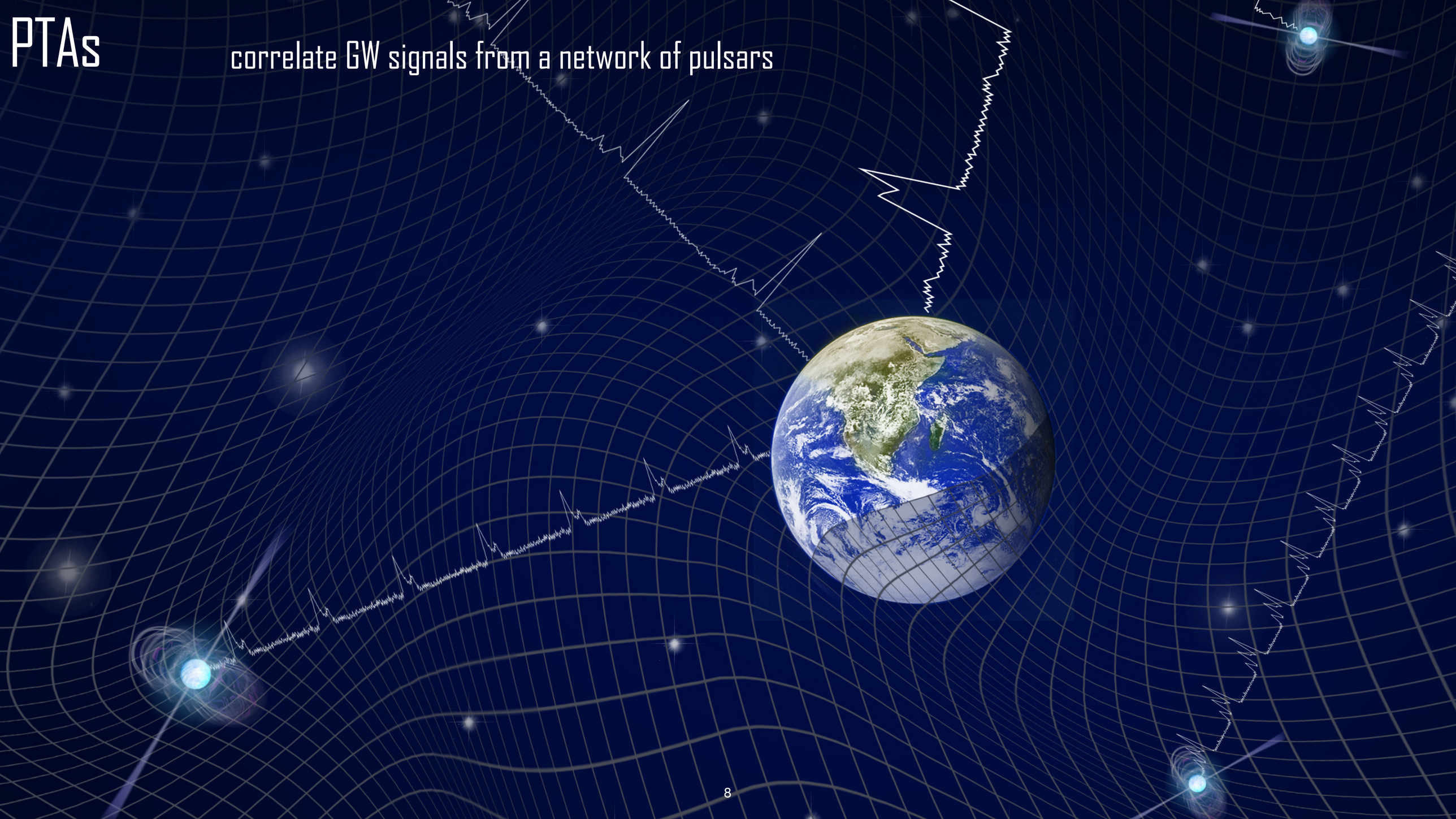


PTAs

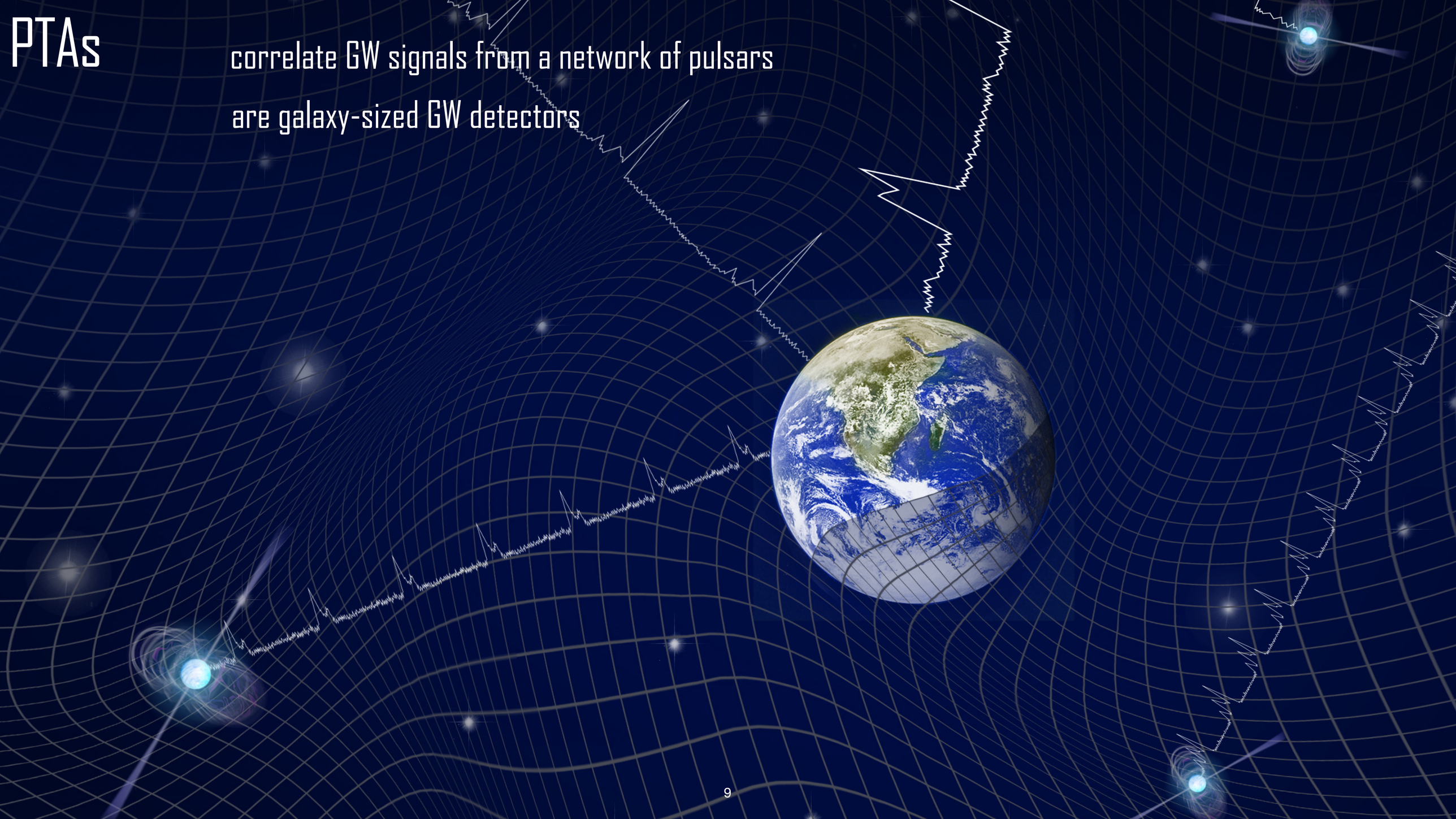
correlate GW signals from a network of pulsars



PTAs

correlate GW signals from a network of pulsars

are galaxy-sized GW detectors



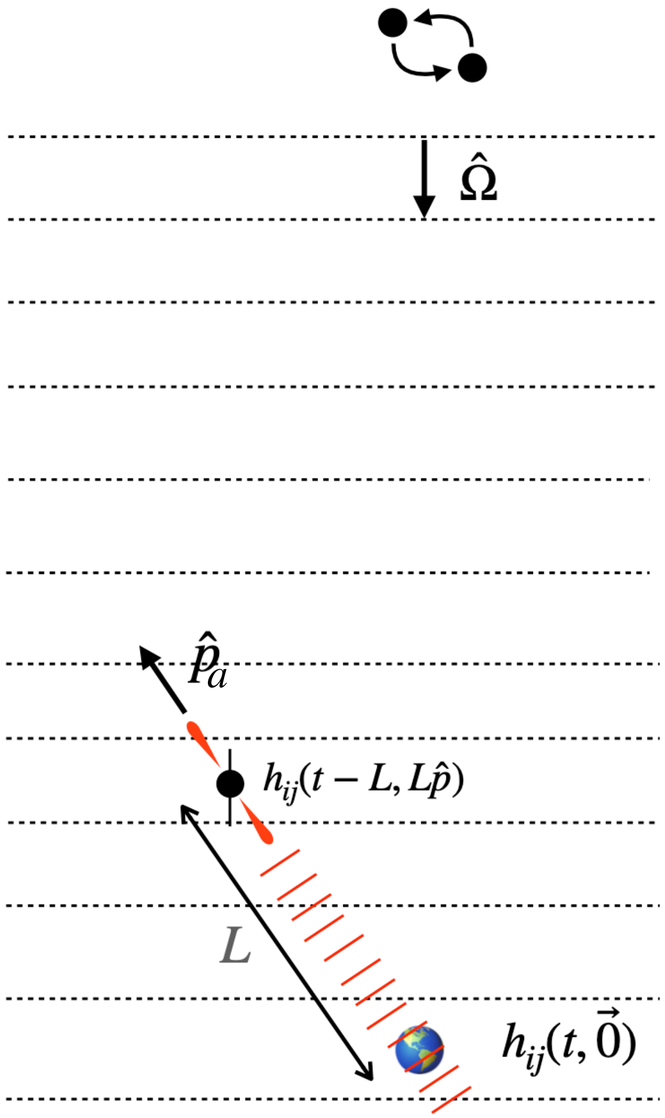
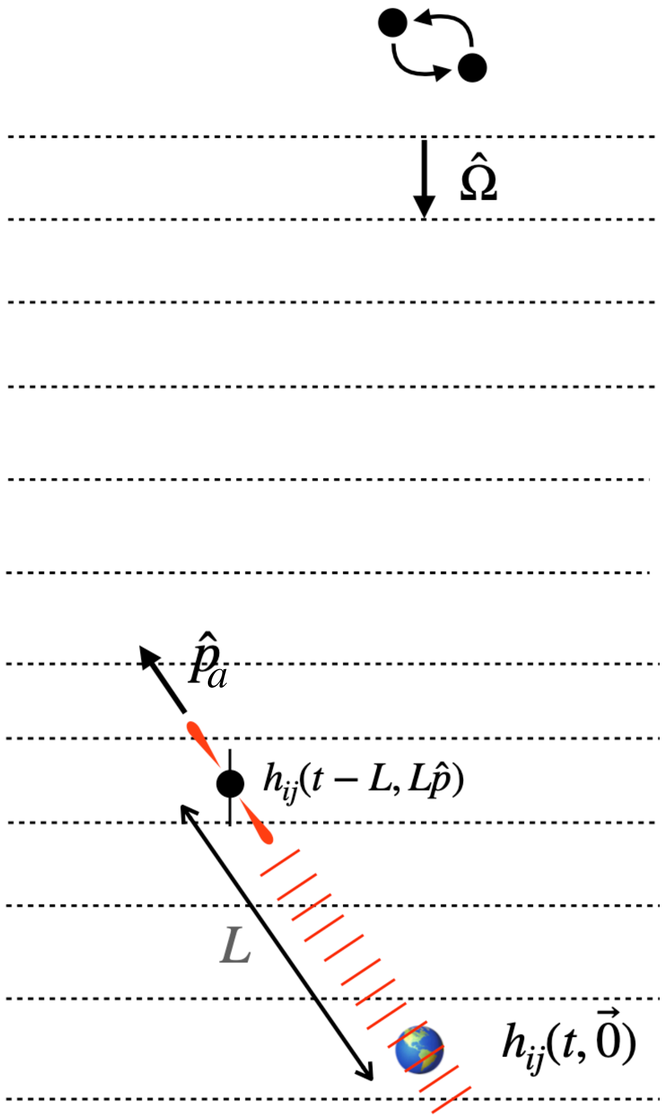


Figure from [arxiv: 2308.05847]

For a distant source of GW

$$z_a(t) \equiv \frac{\Delta\nu_a}{\nu_a} = \frac{1}{2}\frac{\hat{p}_a^i \hat{p}_a^j}{1+\hat{\Omega}\cdot\hat{p}_a}\left[h_{ij}(t,0) - h_{ij}(t-L, L\hat{p}_a)\right]$$



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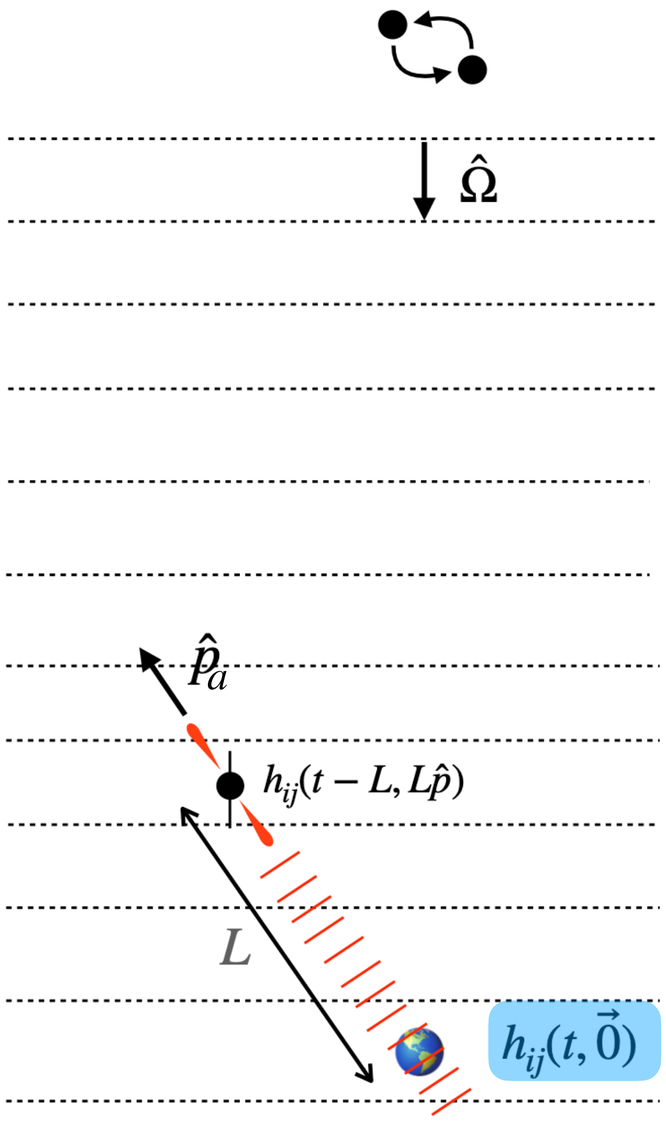
GW-induced change in pulse frequency

$$\delta t_a = \int_0^t dt' z_a(t')$$



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For a distant source of GW

Metric perturbation when pulse is received

$$z_a(t) \equiv \frac{\Delta\nu_a}{\nu_a} = \frac{1}{2}\frac{\hat{p}_a^i \hat{p}_a^j}{1+\hat{\Omega}\cdot\hat{p}_a}\left[h_{ij}(t,0) - h_{ij}(t-L, L\hat{p}_a)\right]$$

GW-induced change in pulse frequency

earth term

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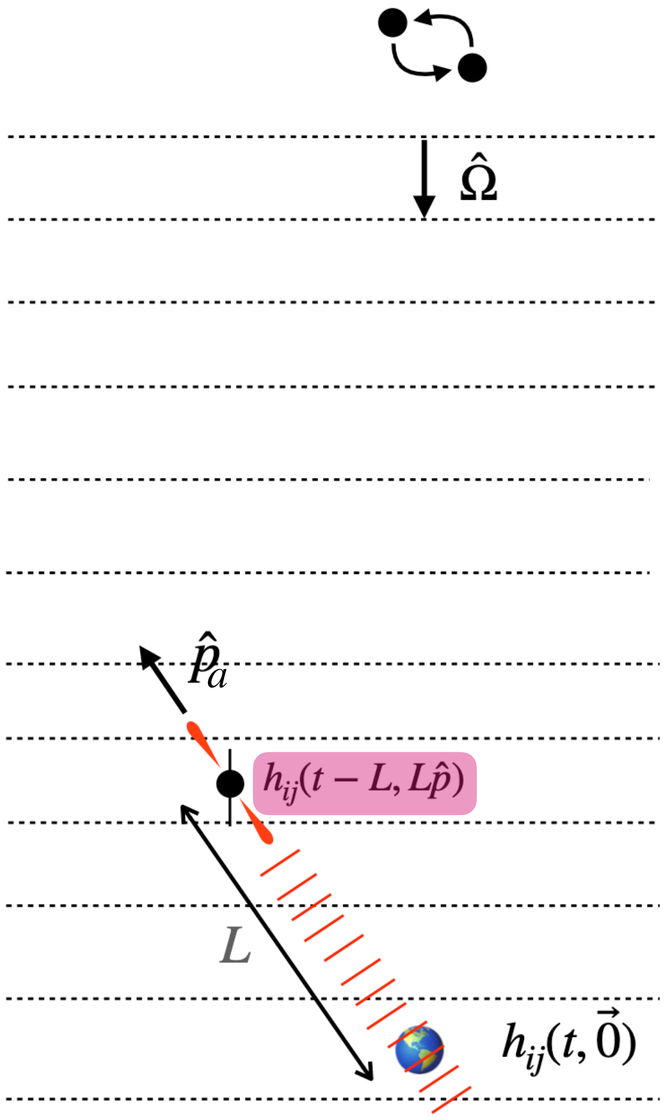


Figure from [arxiv: 2308.05847]

For a distant source of GW

Metric perturbation when pulse is emitted

$$z_a(t) \equiv \frac{\Delta\nu_a}{\nu_a} = \frac{1}{2}\frac{\hat{p}_a^i \hat{p}_a^j}{1+\hat{\Omega}\cdot\hat{p}_a}\left[h_{ij}(t,0) - h_{ij}(t-L, L\hat{p}_a)\right]$$

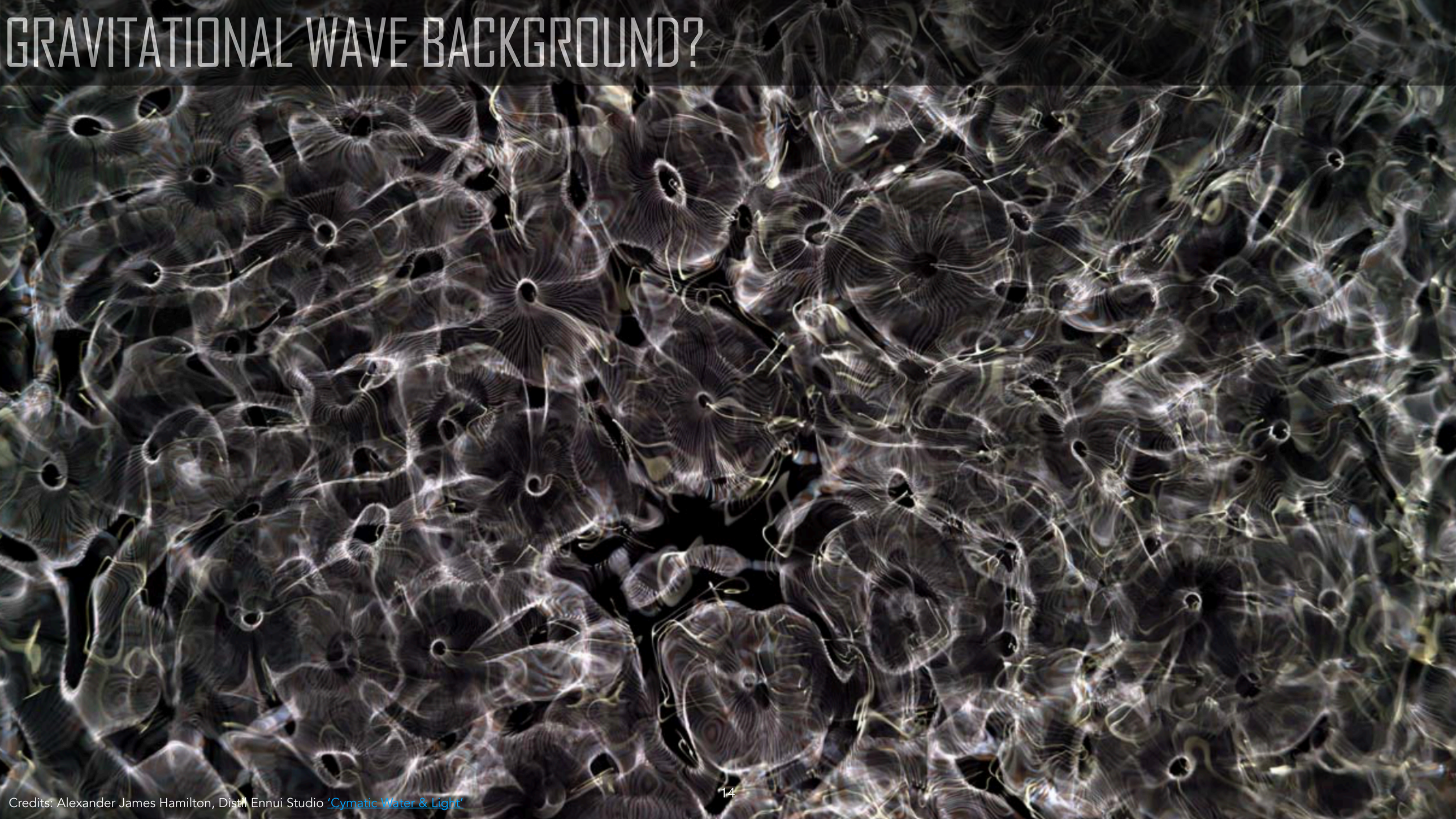
GW-induced change in pulse frequency

earth term

pulsar term

$$\delta t_a = \int_0^t dt' z_a(t')$$

GRAVITATIONAL WAVE BACKGROUND?



Credits: Alexander James Hamilton, Distil Ennui Studio 'Cymatic Water & Light'

GRAVITATIONAL WAVE BACKGROUND?

$$\langle \delta t_a(t) \delta t_b(t) \rangle$$

GRAVITATIONAL WAVE BACKGROUND?

Hellings and Downs Correlations

GWB characteristic strain

$$\langle \delta t_a(t) \delta t_b(t) \rangle \simeq \Gamma_{ab}(\zeta_{ab}) \int df \, \frac{1}{12\pi^2} f^{-3} h_c(f)^2$$

angular separation ζ_{ab} dependence

frequency f dependence

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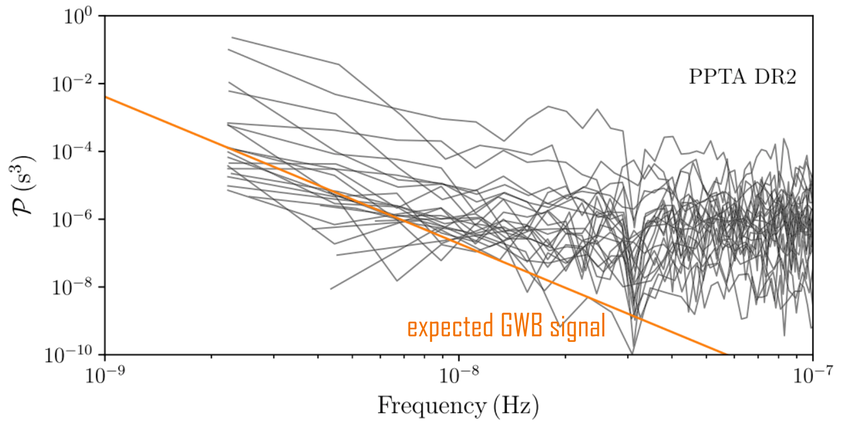
angular separation ζ_{ab} dependence

frequency f dependence

Not enough to find a low-frequency common spectrum for GWB signal!

[Zic et al. '22]



pulsar noise

GRAVITATIONAL WAVE BACKGROUND?

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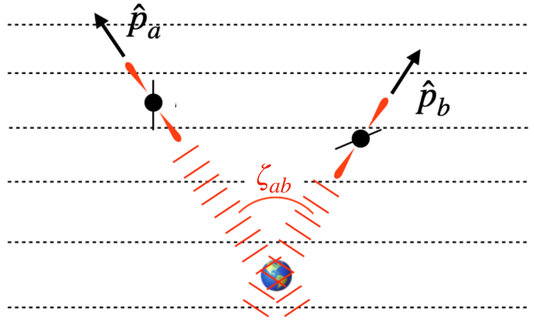
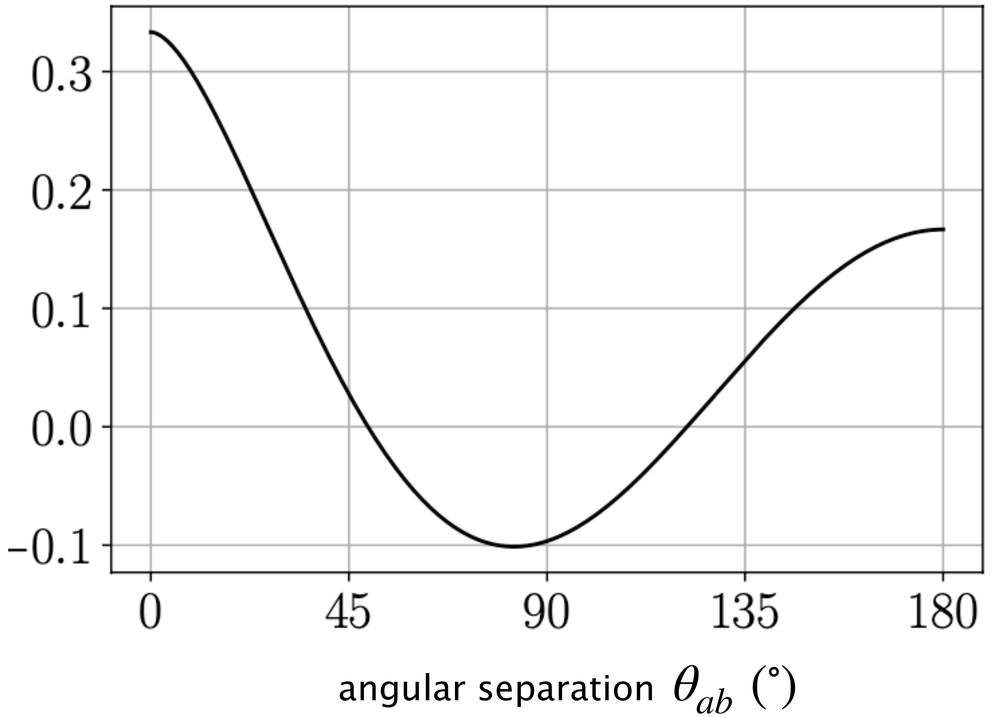


Expectation at PTAs for an isotropic, unpolarized gravitational wave background

Hellings and Downs Correlations

$$\Gamma_{ab}(\zeta_{ab})$$

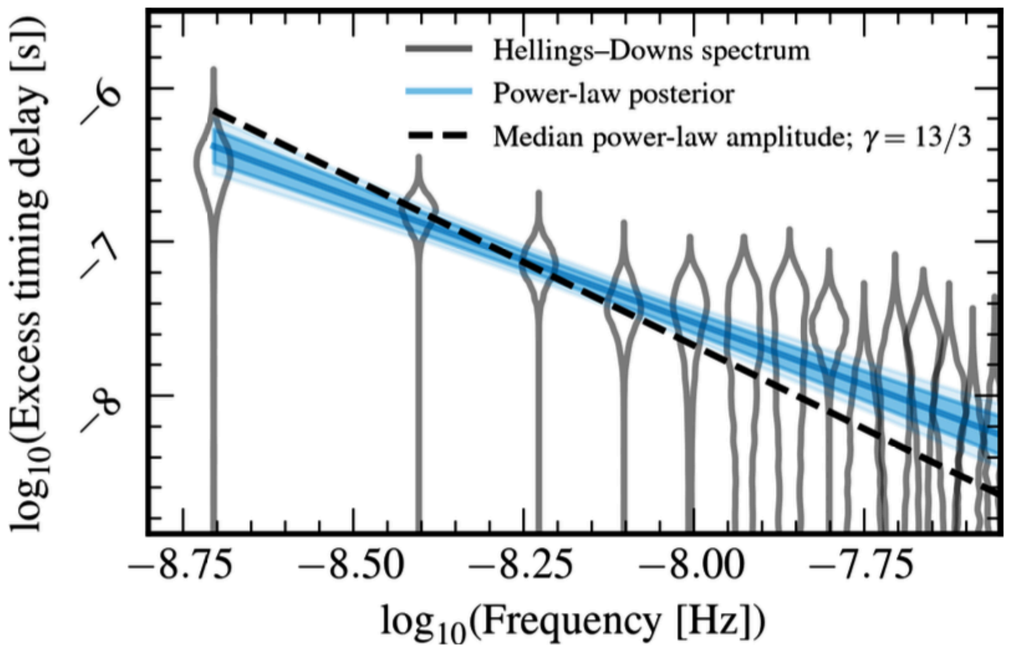


Evidence for GWB?

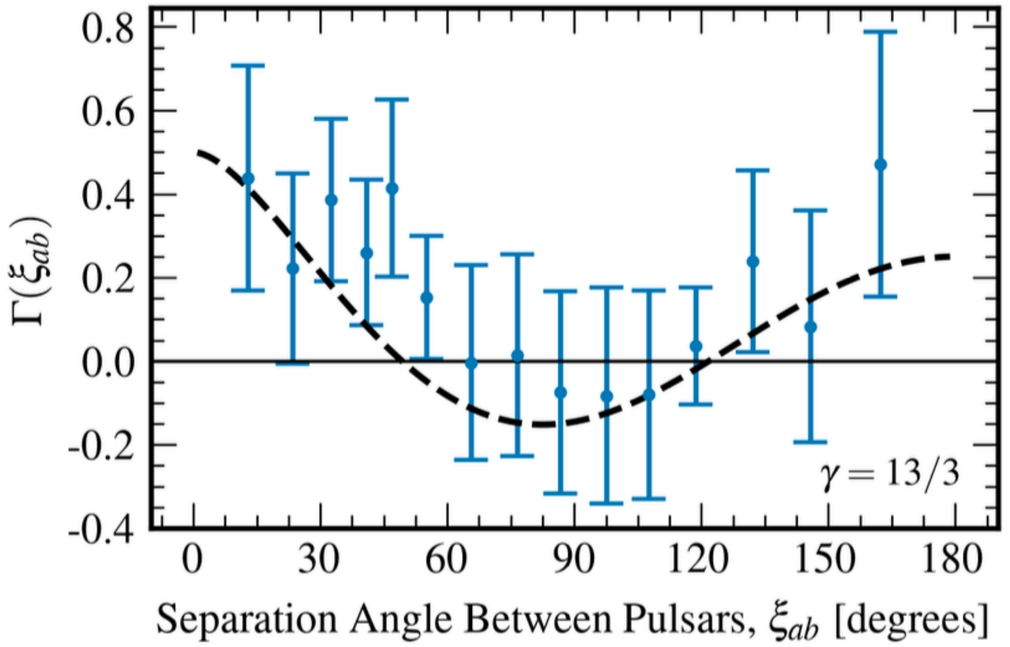
NANOGrav dataset: 68 pulsars, 16 yrs data

Agazie et al. [NANOGrav] arxiv:2306.16213

measured common spectrum



measured angular correlations

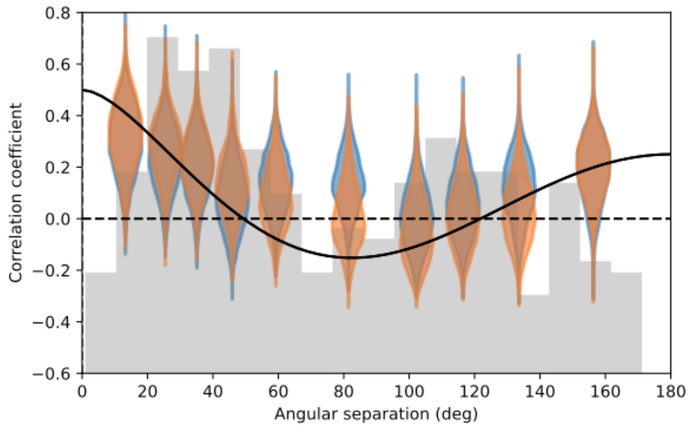


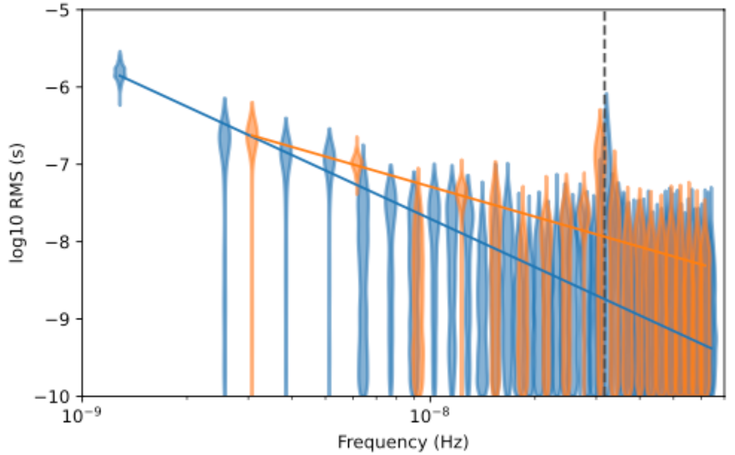
Compelling evidence of Hellings-Downs correlations with false-alarm probability of $p = 10^{-3}$ ($\sim 3 - 4\sigma$)

MORE EVIDENCE?

EPTA+InPTA : 25 pulsars, ~ 25 yrs data

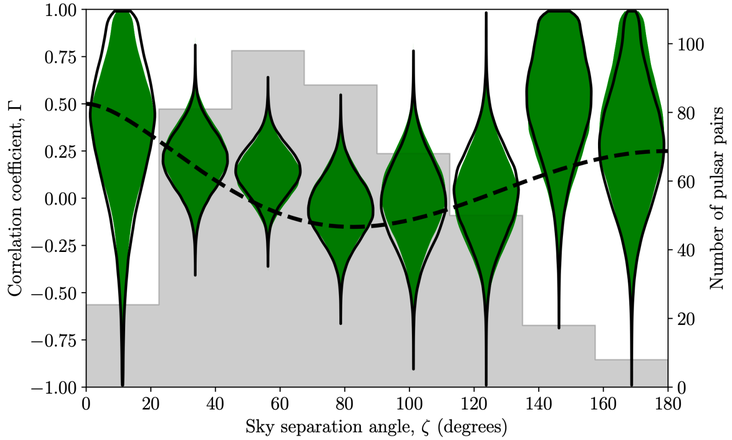
Antoniadis et al. [arxiv:2306.16214]

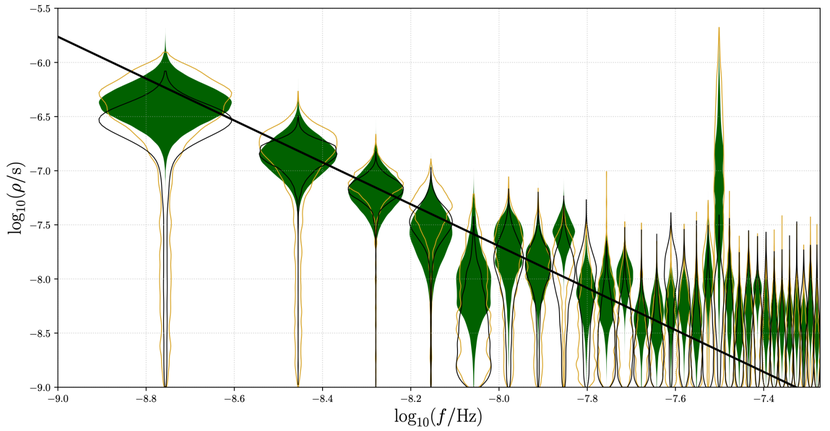




PPTA : 30 pulsars, ~ 18 yrs data

Reardon et al. [arxiv:2306.16215]





What is the source?

Implication #1

Credits: Artwork by Lia Halloran

Implication #1

$$h^2\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} A^2 \left(\frac{f}{yr^{-1}}\right)^{5-\gamma} \ {\rm yr}^{-2}$$

GWB spectrum from inspiralling Supermassive Black Hole Binaries [SMBHB]

Implication #1

$$h^2\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} A^2 \left(\frac{f}{yr^{-1}}\right)^{5-\gamma} \mathrm{yr}^{-2}$$

GWB spectrum from inspiralling SMBH binaries

Free parameters

Implication #1

$$h^2\Omega_{\rm GW} = \frac{2\pi^2}{3H_0^2} A^2 \left(\frac{f}{yr^{-1}}\right)^{5-\gamma} \mathrm{yr}^{-2}$$

GWB spectrum from inspiralling SMBH binaries

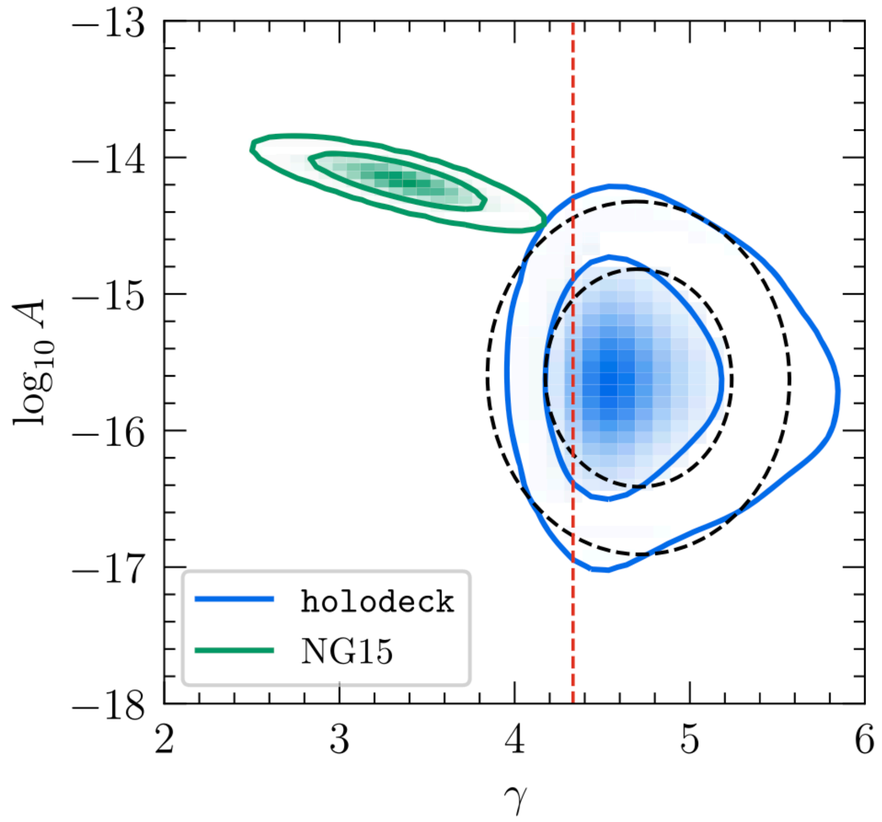
Free parameter

Very standard choice with only GW-driven binaries, $\gamma \to 13/3$ [Phinney 2001]

Life is not that simple...

GWB spectrum from inspir

[Afzal et. al. (NANOGrav) arxiv:2306.16219]



See also [Agazie et. al. (NANOGrav) arxiv:2306.16220] for other SMBH models

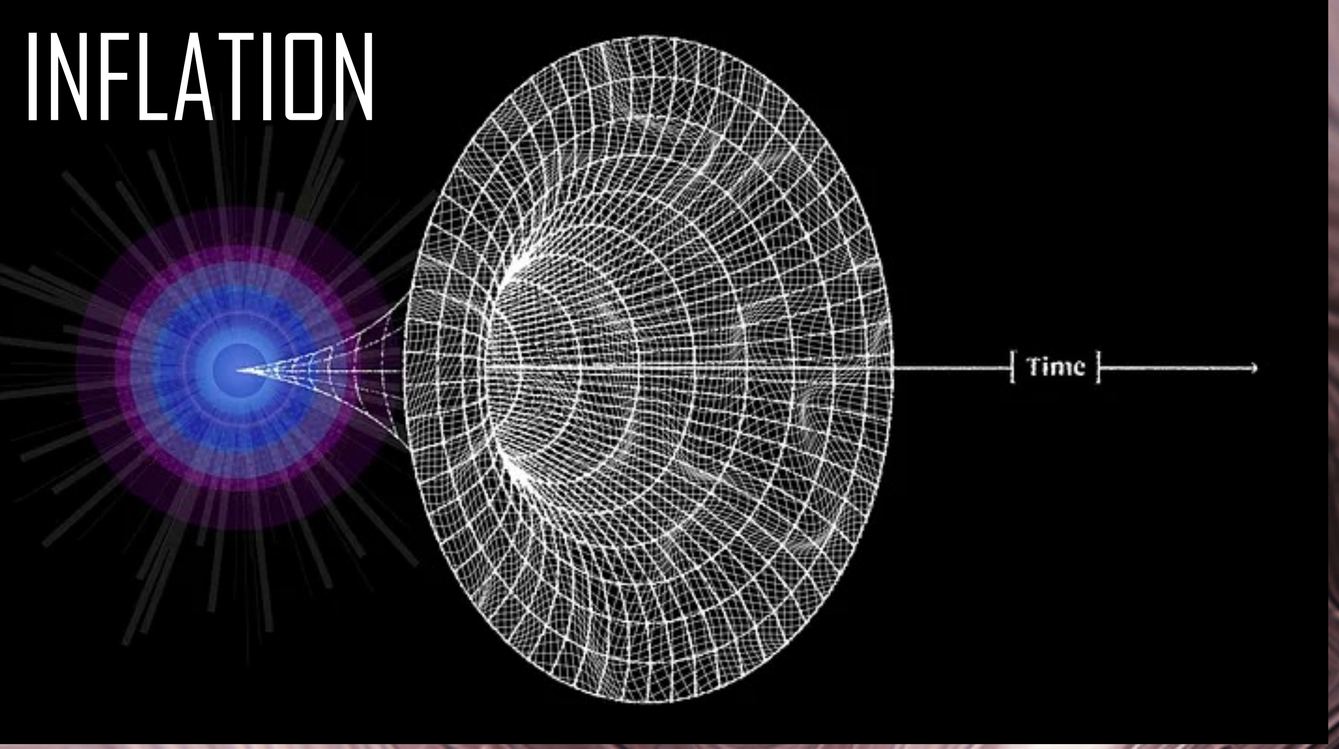
Implication #2

Credits: Artwork by Lia Halloran

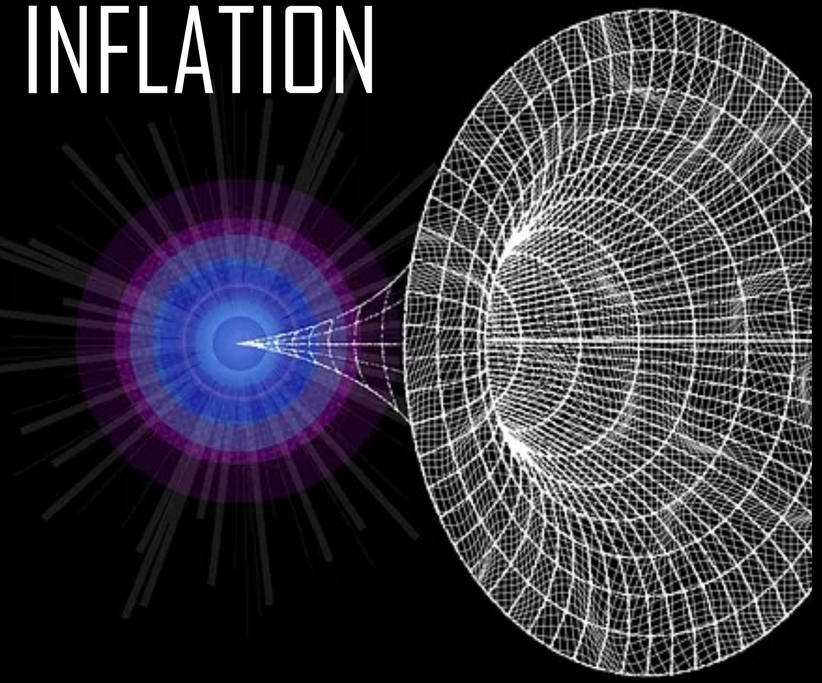
Implications #...

COSMIC STRINGS

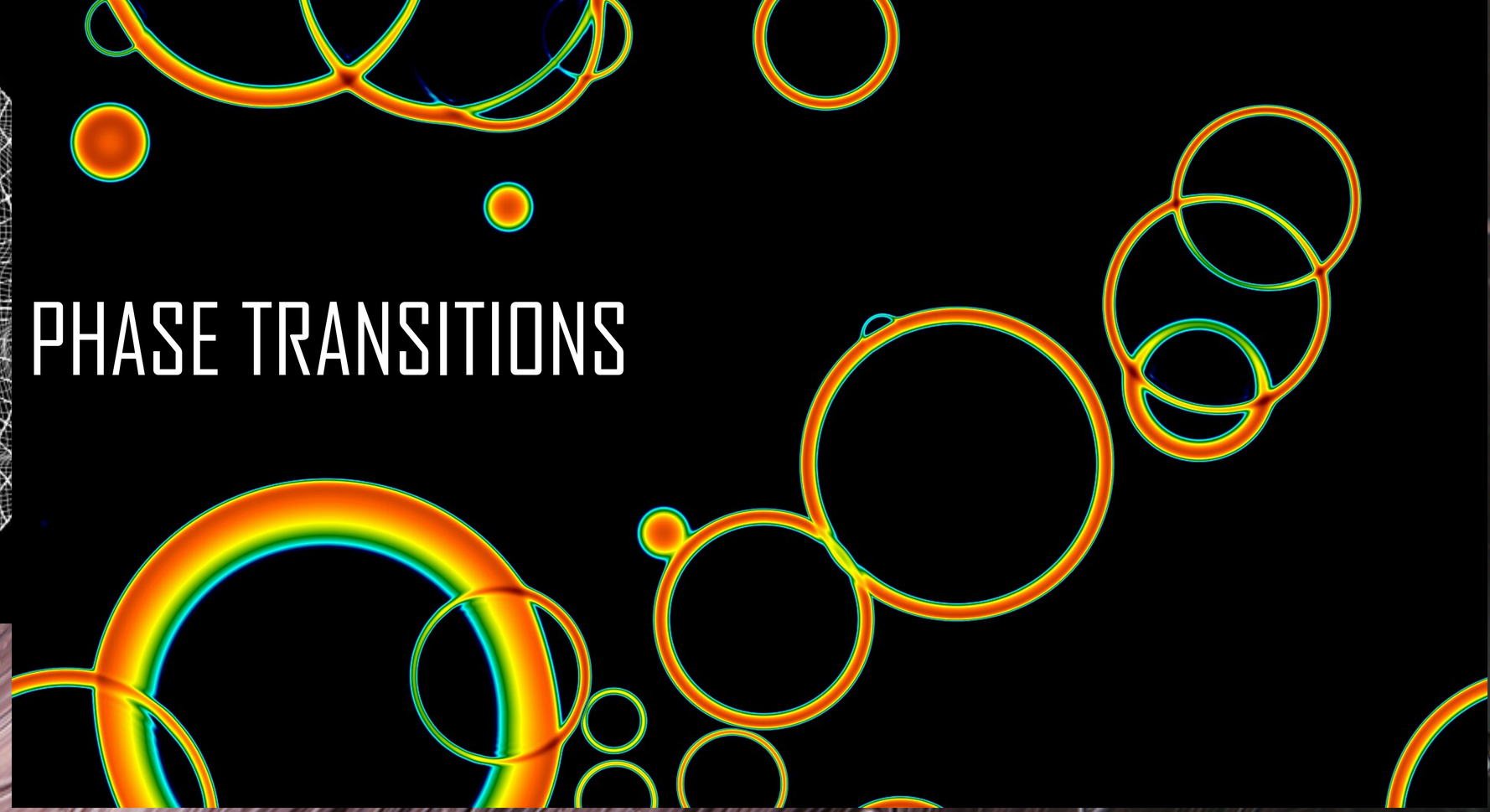
INFLATION

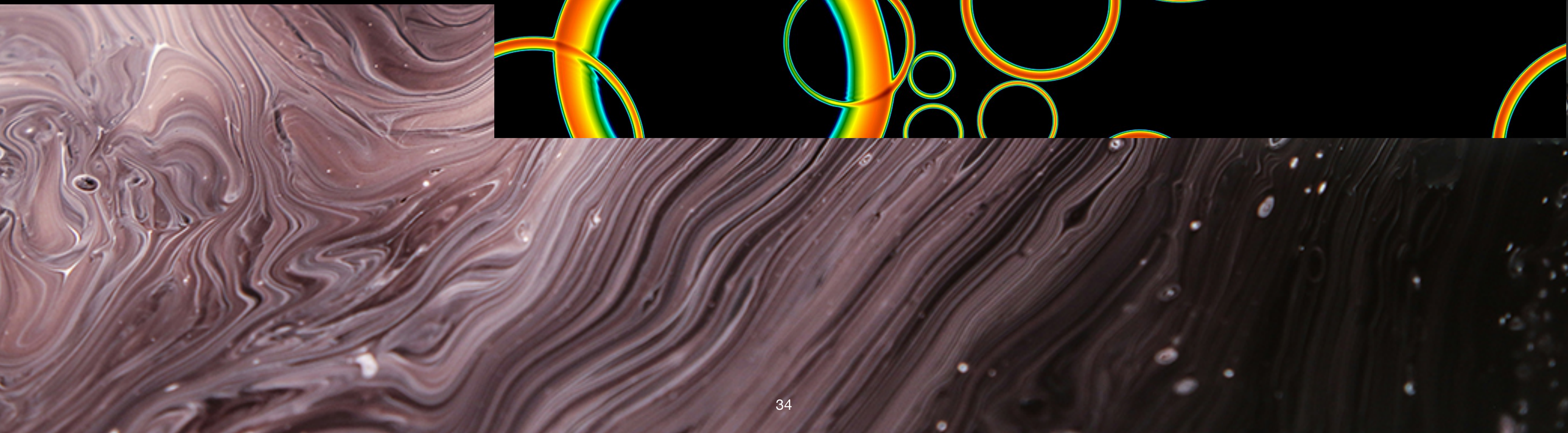


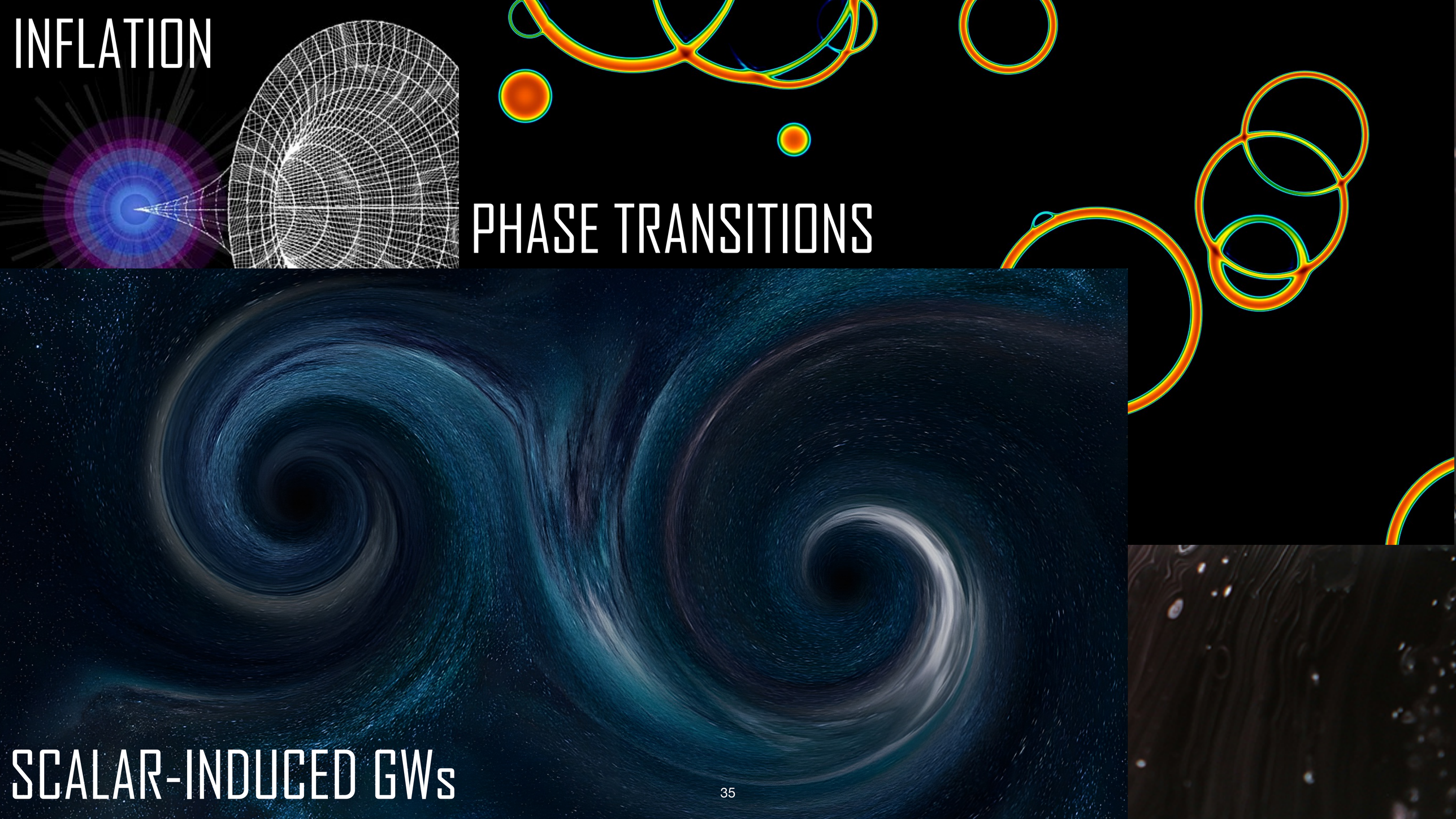
INFLATION



PHASE TRANSITIONS





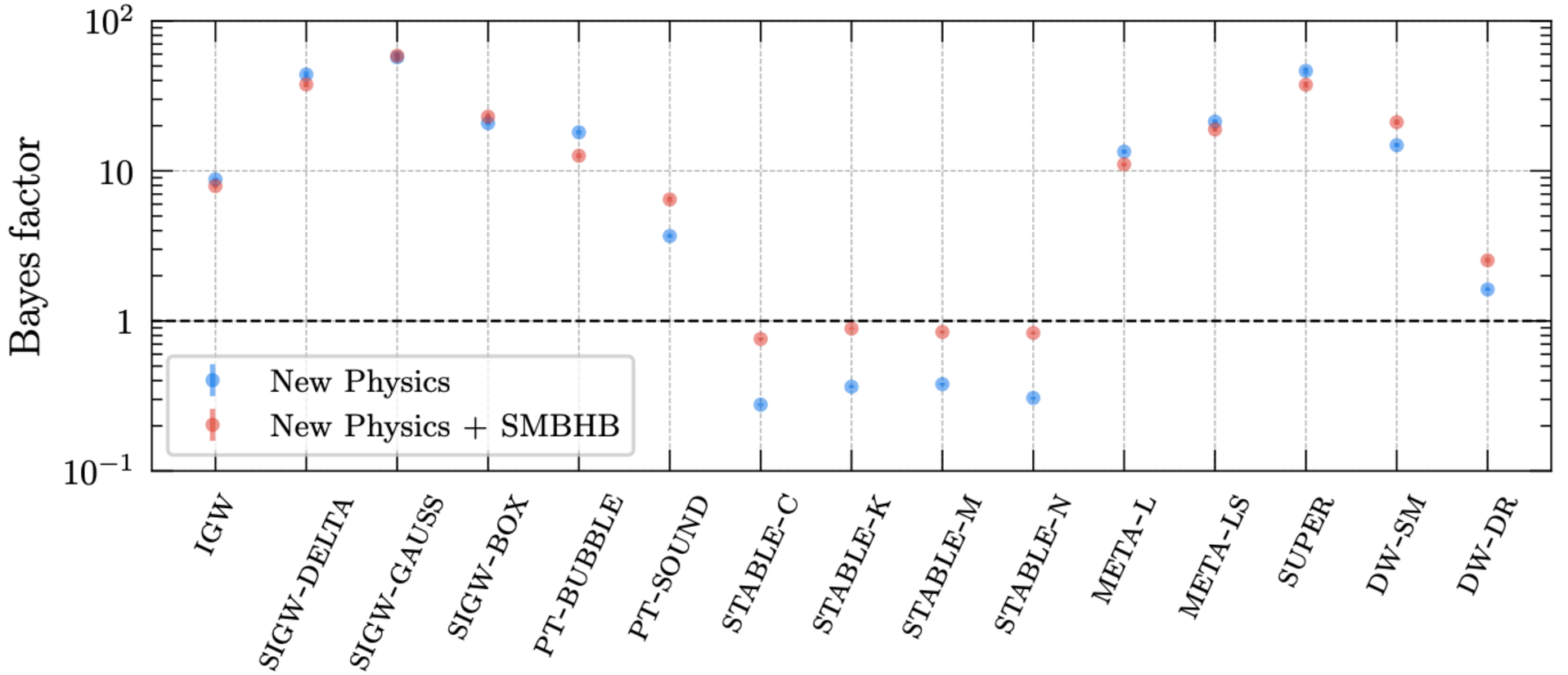

INFLATION
PHASE TRANSITIONS
SCALAR-INDUCED GWs

$$h^2\Omega_{\rm GW}(f;\Theta)$$

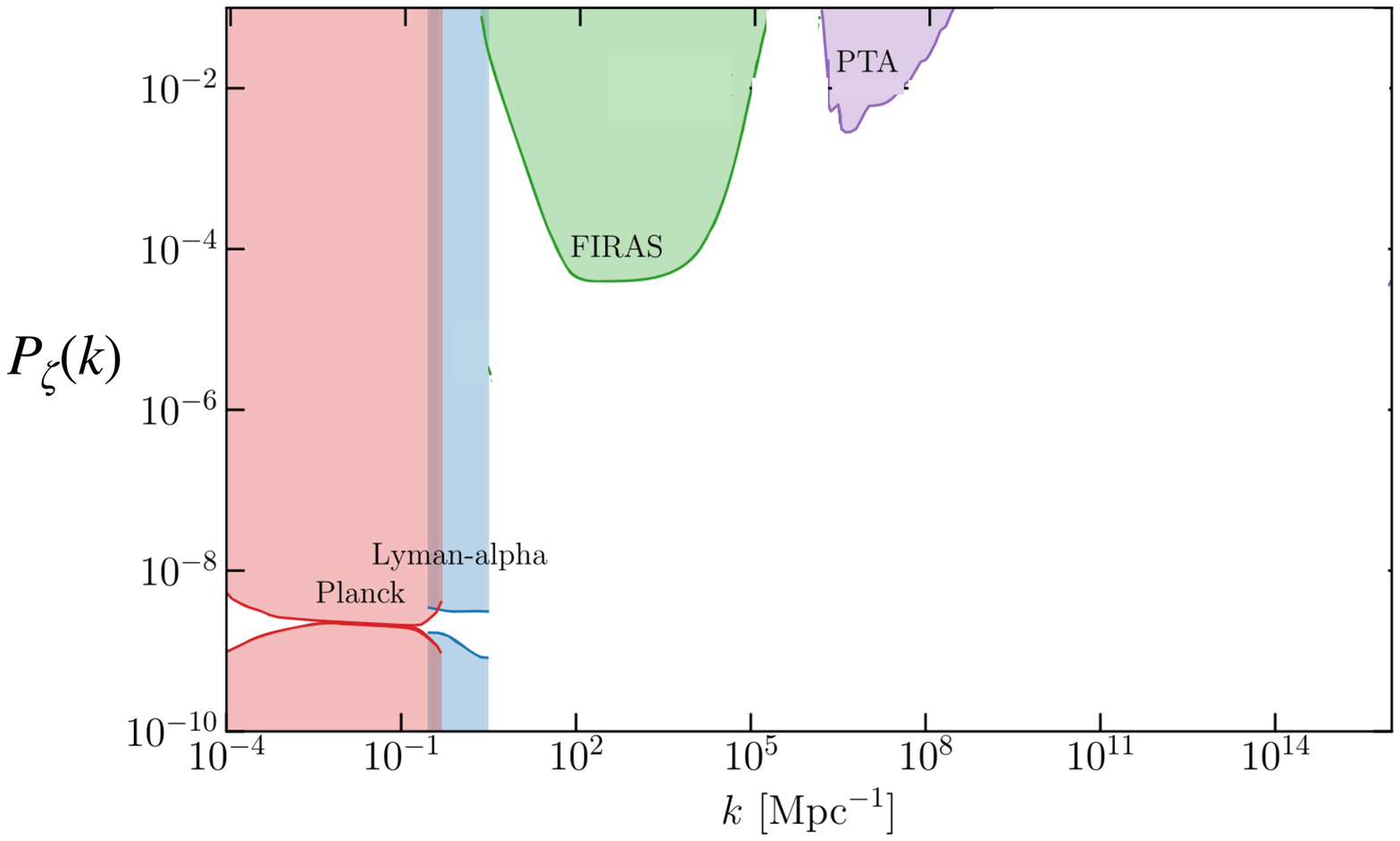
$$h^2\Omega_{\mathrm{GW}}(f;\Theta)$$

Set of free parameters

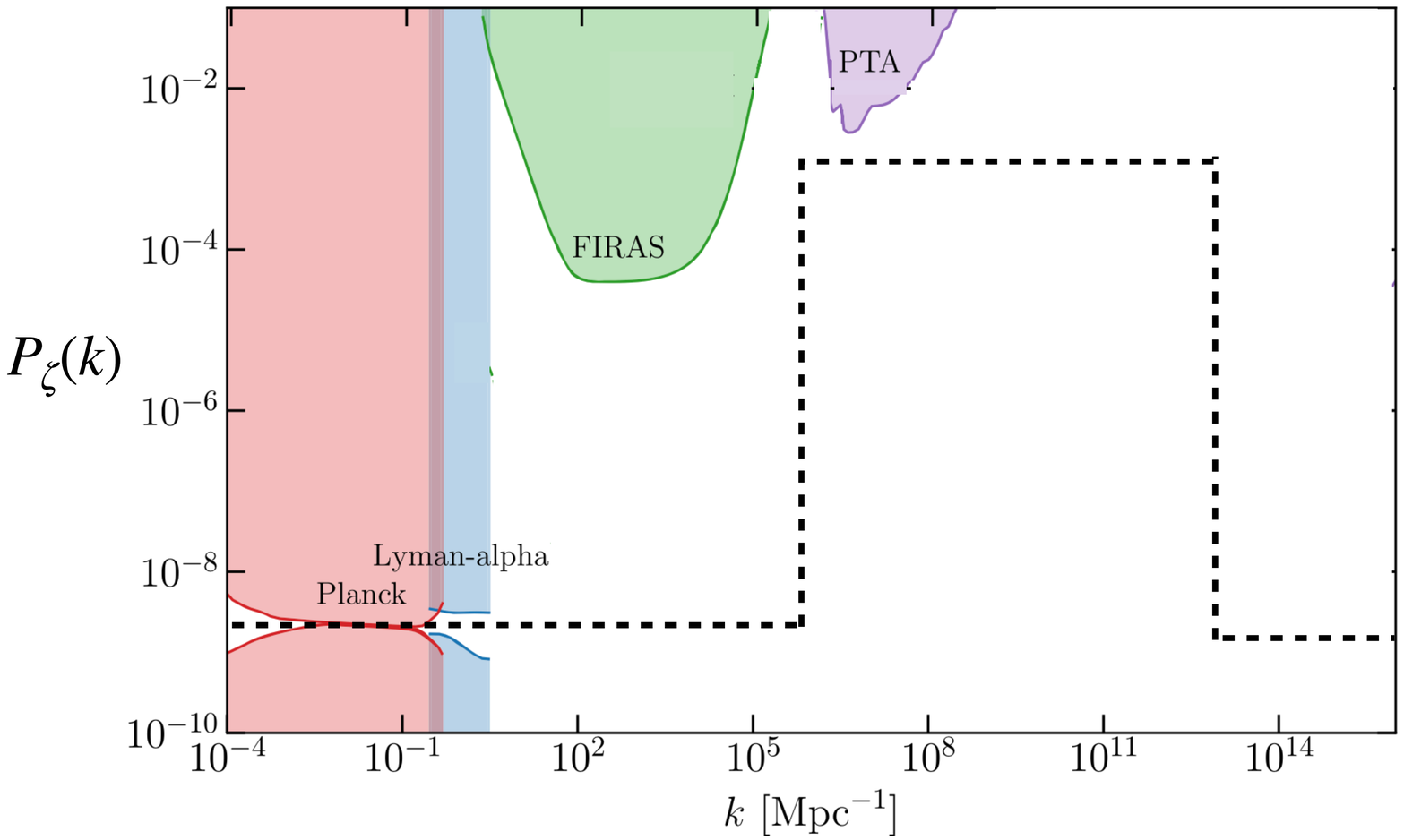
[Afzal et. al. (NANOGrav) arxiv:2306.16219]



Can we constrain new physics?



[Greene et al. '21]

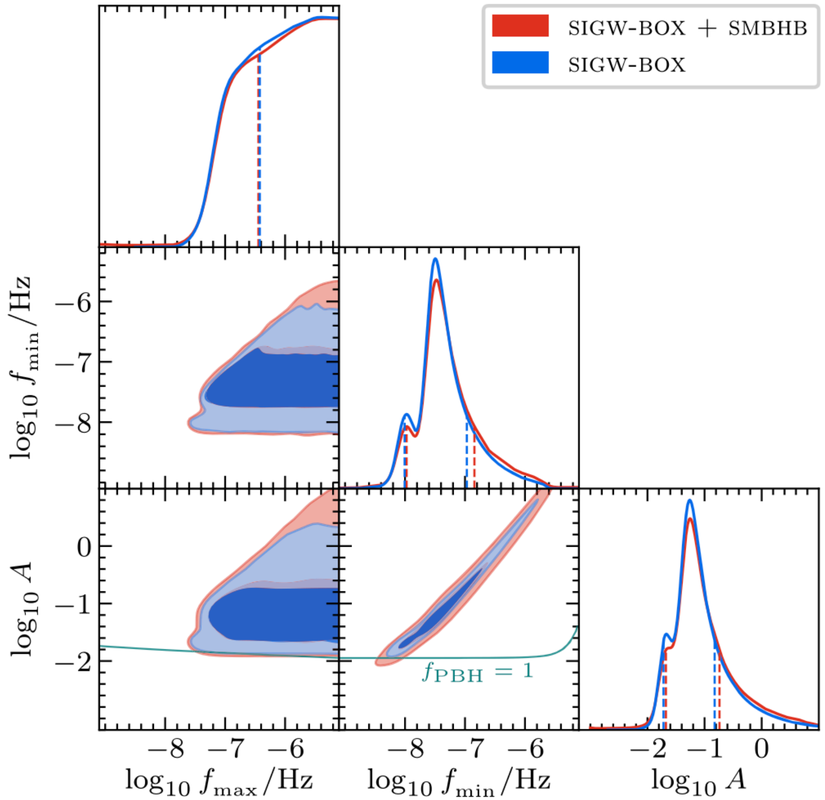


[Greene et al. '21]

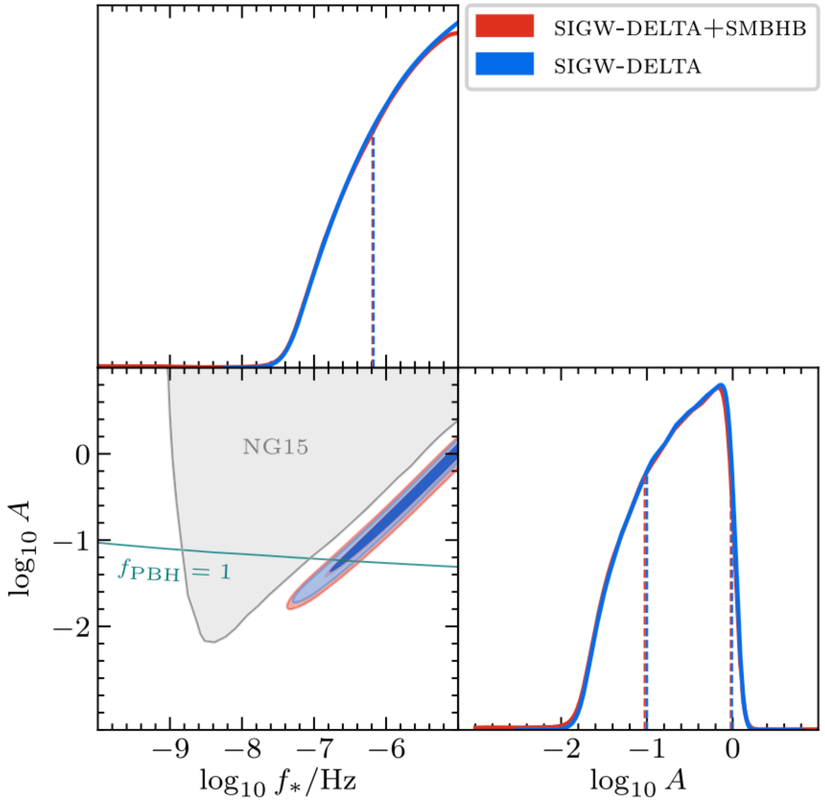
SCALAR-INDUCED GWs

[Afzal et. al. (NANOGrav) arxiv:2306.16219]

$$\mathcal{P}_R(k) = A\ \Theta(\ln k_{\rm max} - \ln k)\Theta(\ln k - \ln k_{\rm min}).$$



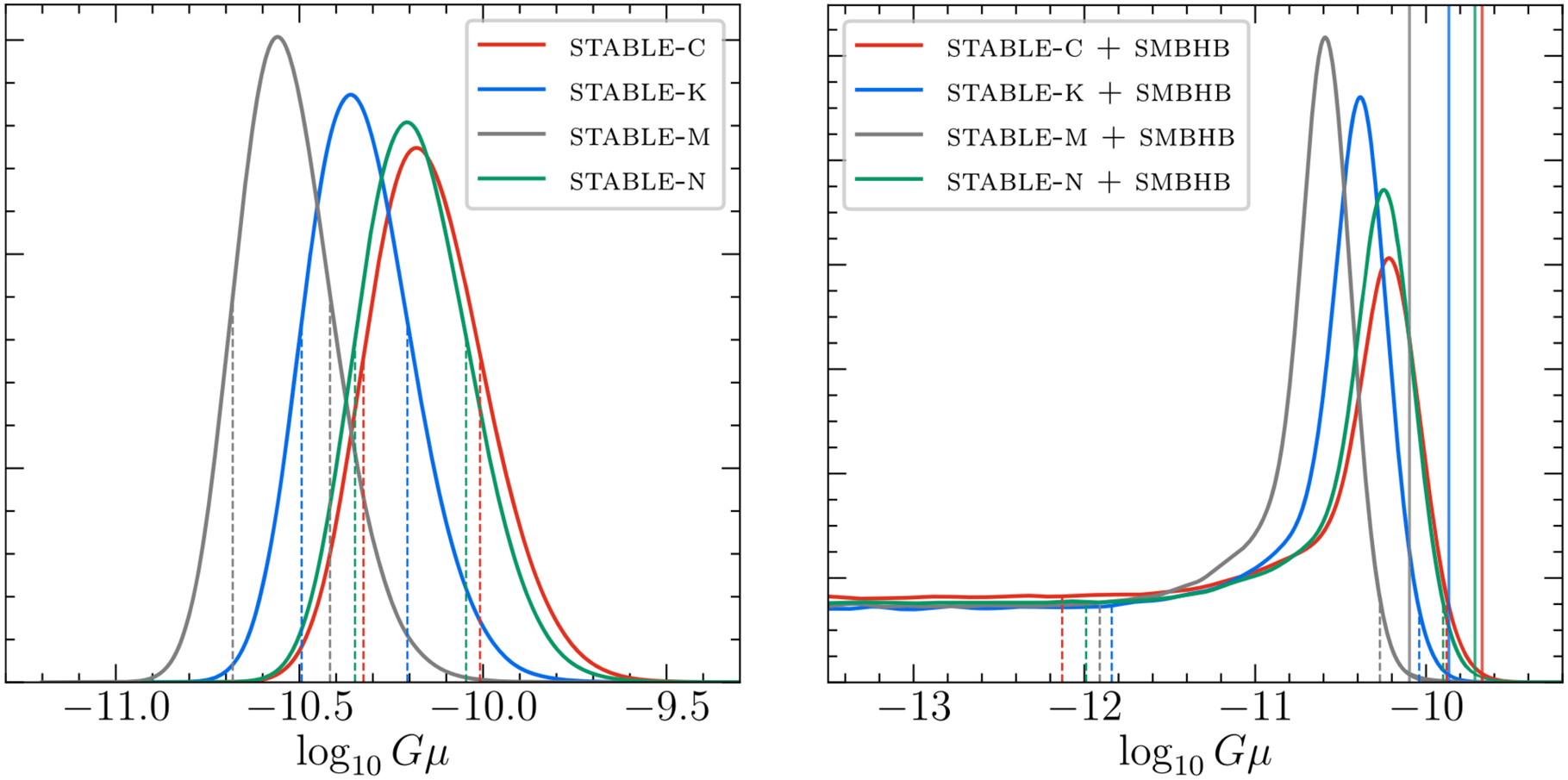
$$\mathcal{P}_R(k) = A\ \delta(\ln k - \ln k_*).$$



STABLE COSMIC STRINGS

[Afzal et. al. (NANOGrav) arxiv:2306.16219]

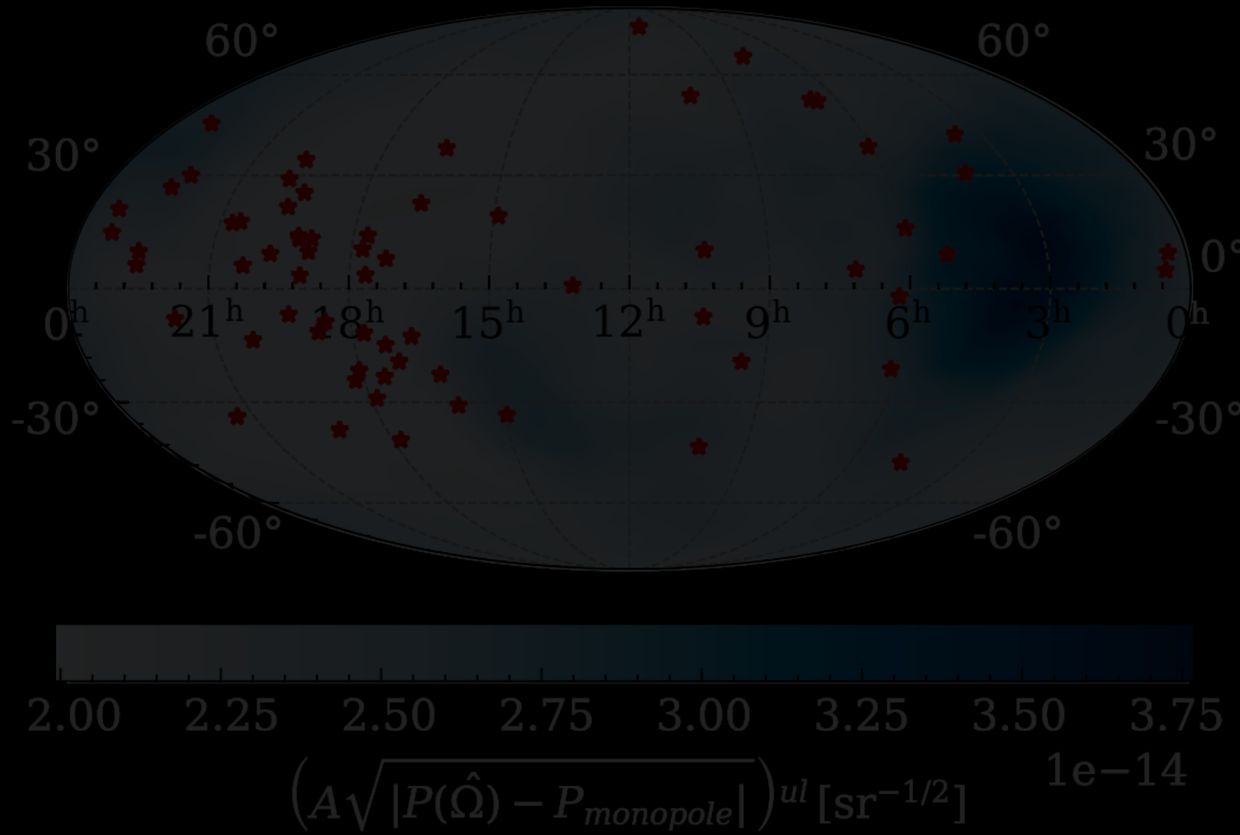
current strongest limits on string tension $G\mu$ come from PTA: $G\mu \lesssim 10^{-10}$



Astro vs Cosmo?

ANISOTROPIES

SMBHB-dominated GWB signal will lead to presence of signal anisotropy

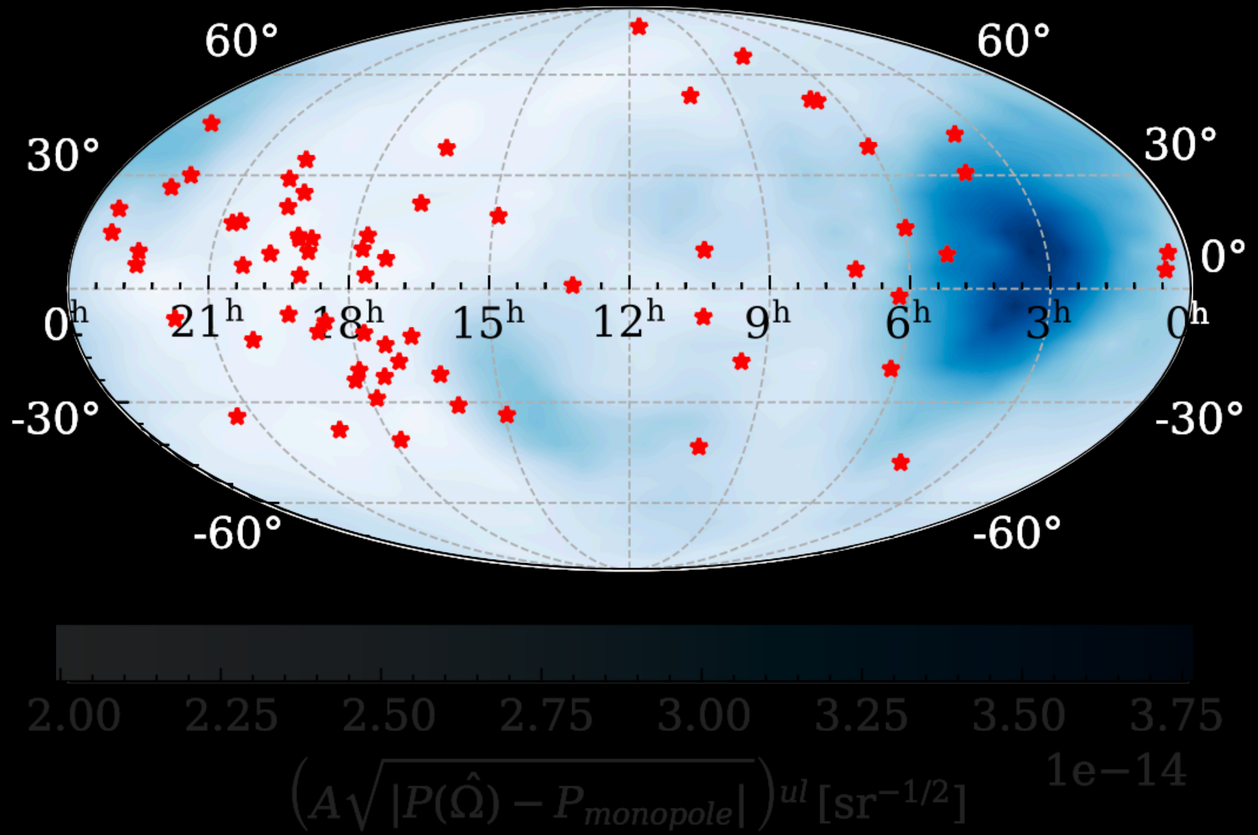


Deviations from isotropic GWB in terms of characteristic strain per steradian$^{1/2}$

ANISOTROPIES

Agazie et al. [NANOGrav] arxiv:2306.16221

SMBHB-dominated GWB signal will lead to presence of signal anisotropy



Deviations from isotropic GWB in terms of characteristic strain per steradian$^{1/2}$

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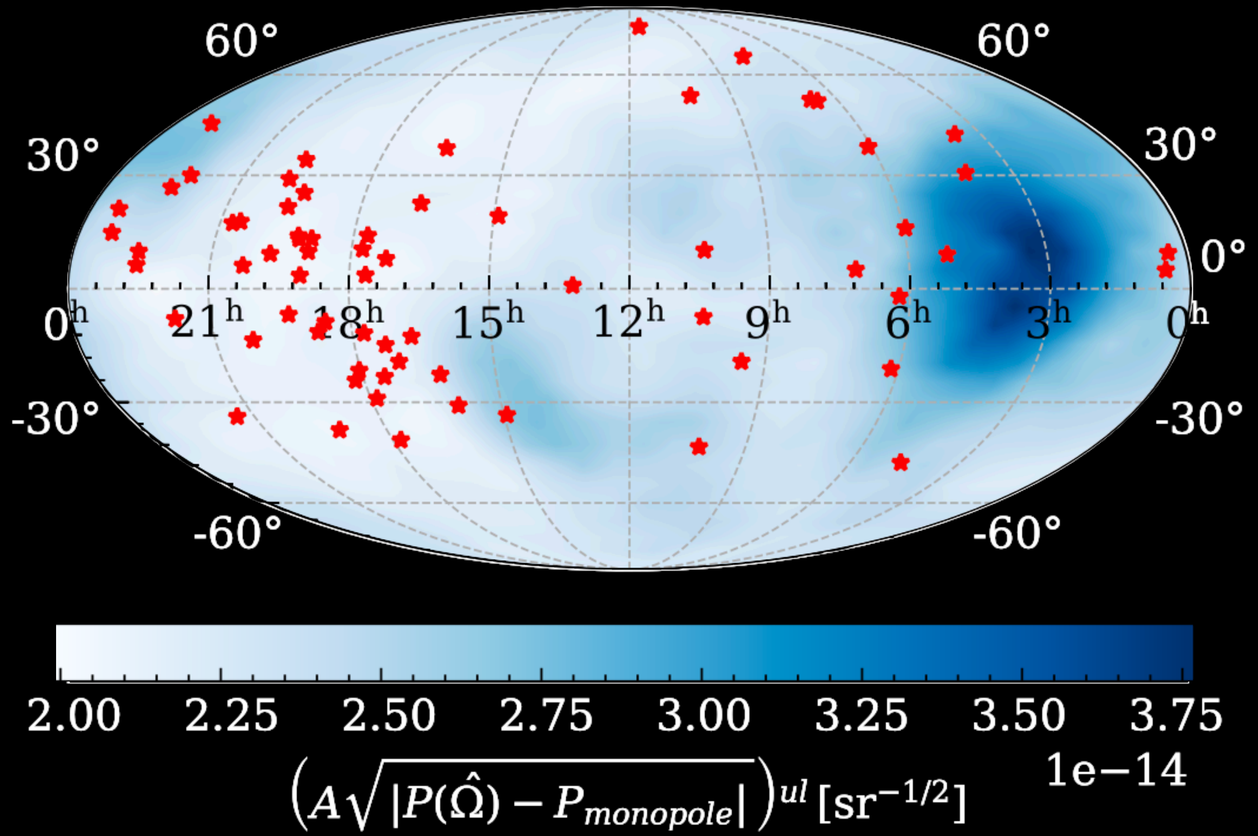
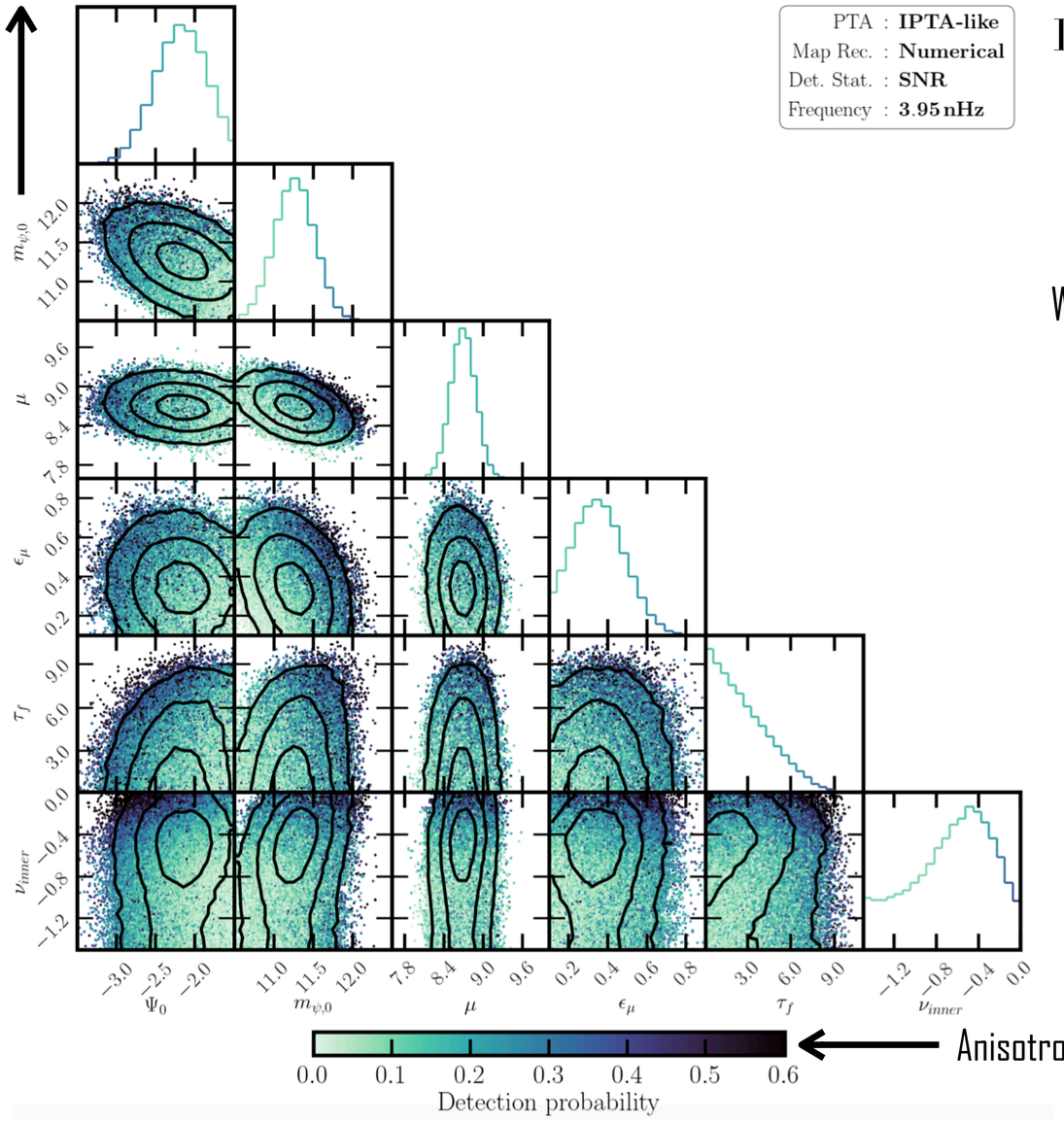


Deviations from isotropic GWB in terms of characteristic strain per steradian$^{1/2}$

No significant detection of anisotropies in the 15-yr NANOGrav dataset!

Malin-Lemke et al. [arxiv:2407.08705]

SMBHB population
parameters explaining GWB



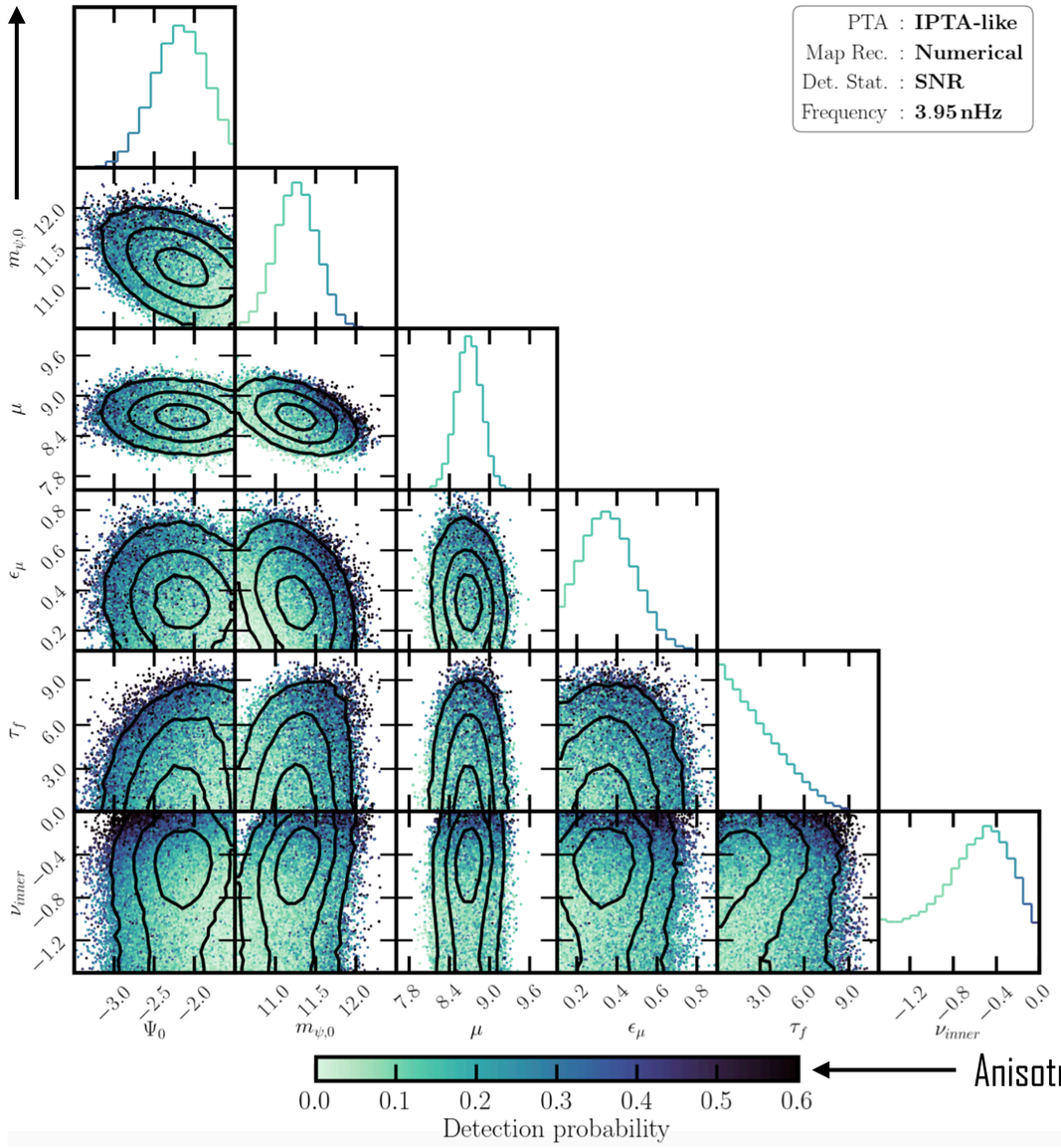
IPTA = NANOGrav + EPTA + InPTA + PPTA + MeerKAT

Will have improved sensitivity to anisotropies for SMBH-generated GWB

Anisotropy detection probability

Malin-Lemke et al. [arxiv:2407.08705]

SMBHB population
parameters explaining GWB



Anisotropy detection probability

$$\text{IPTA} = \text{NANOGrav} + \text{EPTA} + \text{InPTA} + \text{PPTA} + \text{MeerKAT}$$

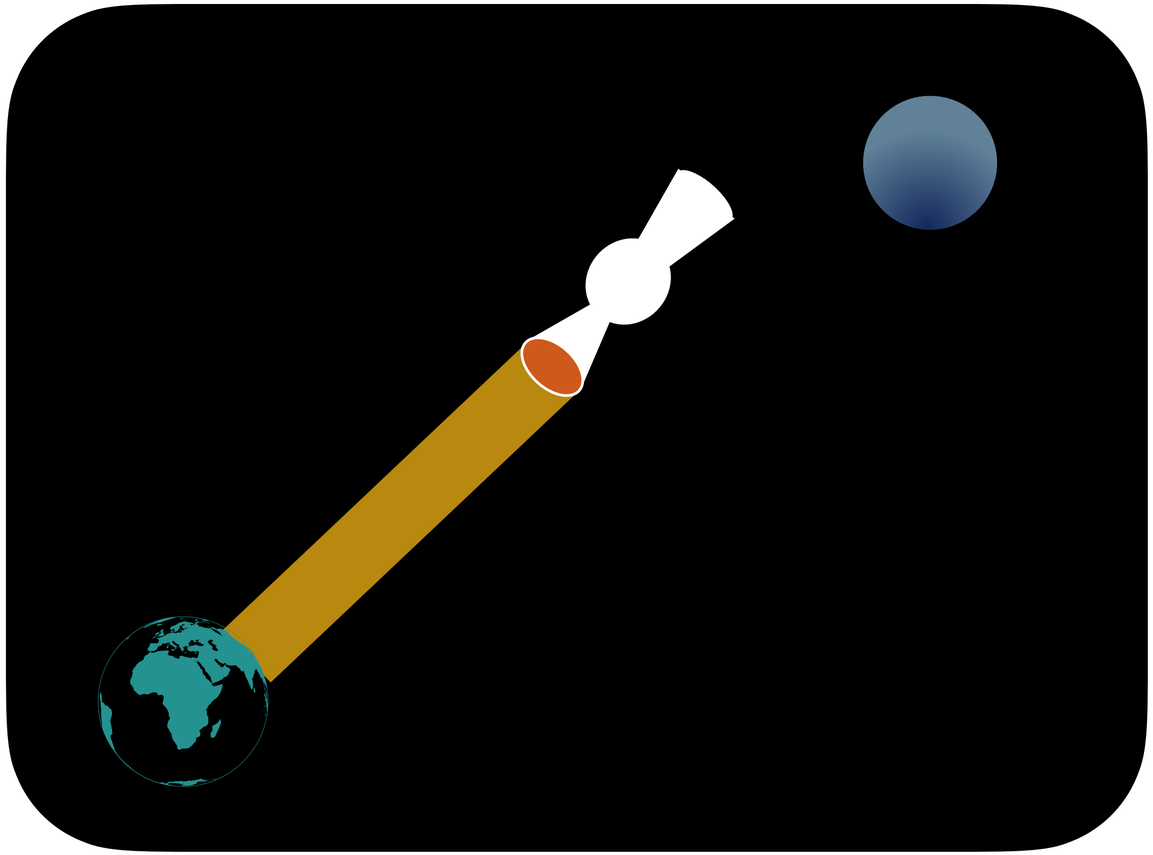
Will have improved sensitivity to anisotropies for SMBH-generated GWB

If still no anistropy? Even with improved sensitivity?

Exclude SMBHB interpretation?

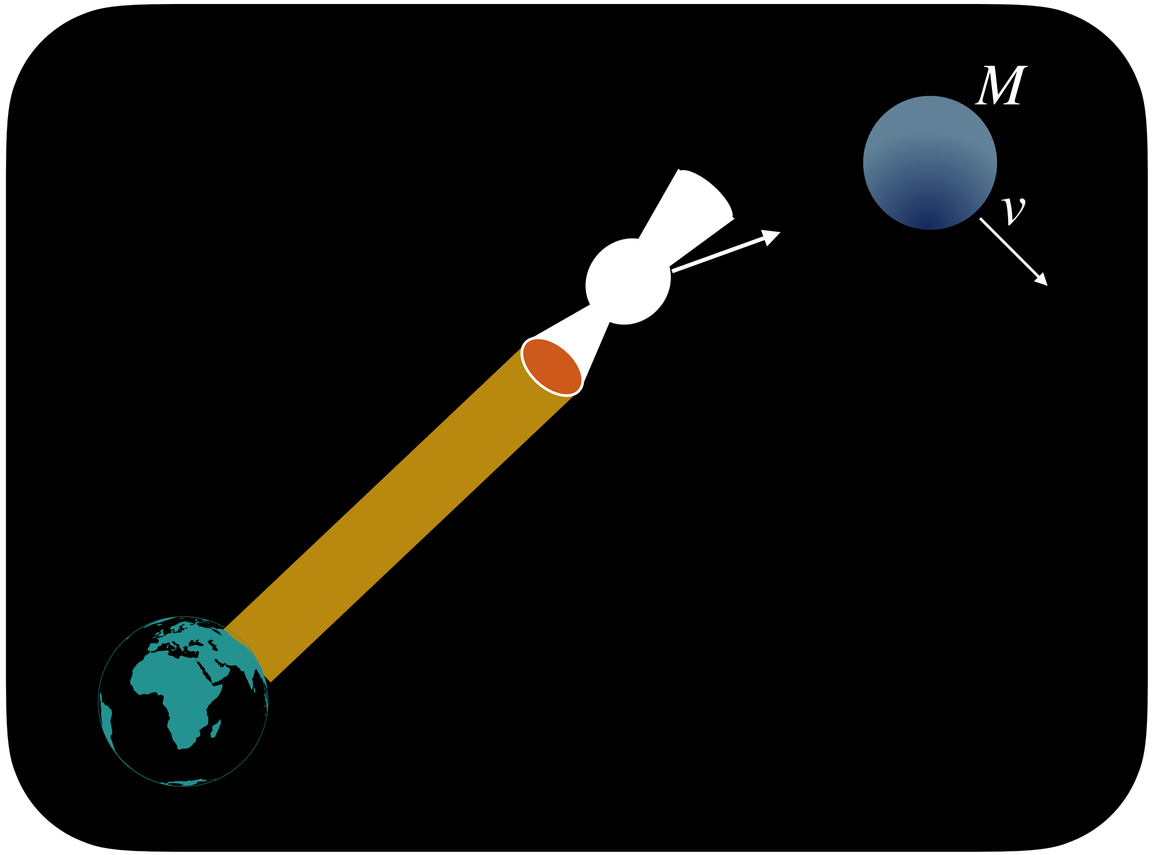
What more with PTAs?

Dark matter searches?



DOPPLER EFFECT

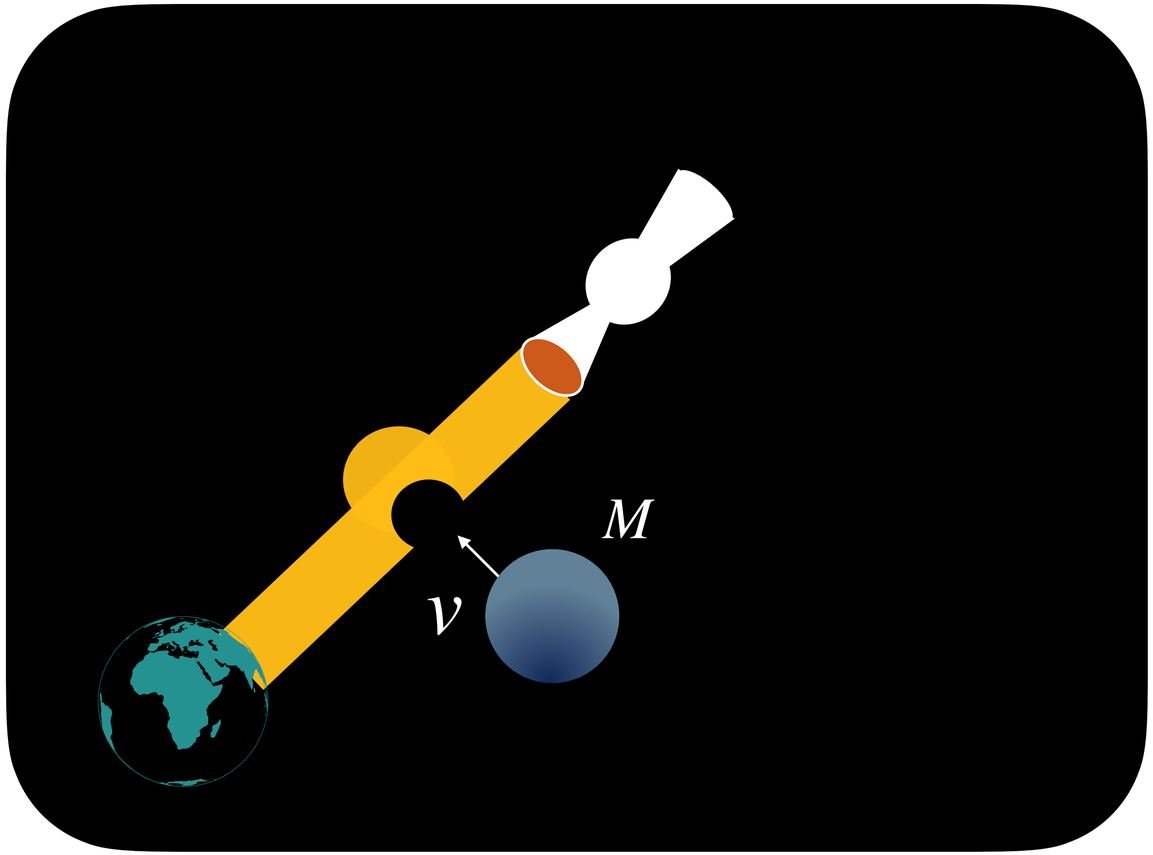
passing Primordial Black hole [PBH] will **pull the pulsar** due to gravitational acceleration, leading to a phase shift in pulse



See for e.g. [Lee, Taylor, Trickle, Zurek 2021]

SHAPIRO TIME DELAY

transiting PBH will **change light travel** time due to its gravitational potential



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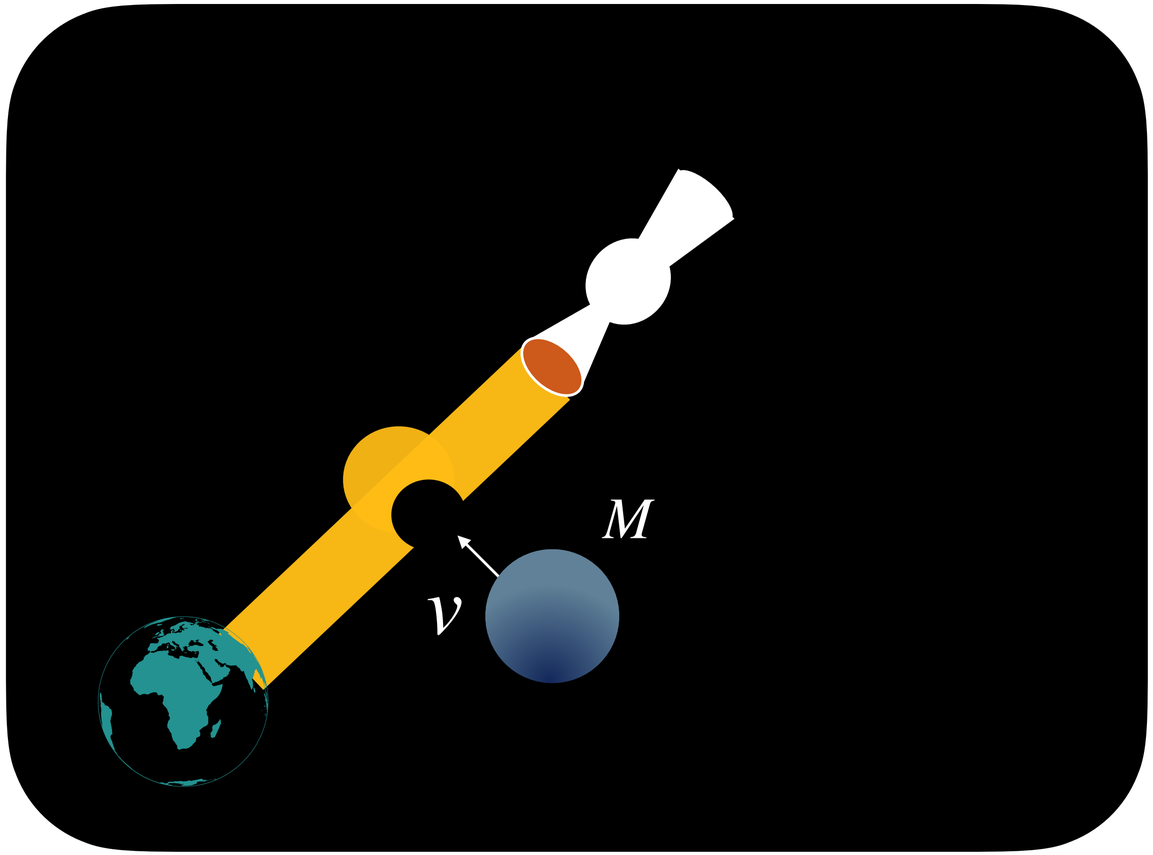
SHAPIRO TIME DELAY

transiting PBH will **change light travel** time due to its gravitational potential



phase shift parameterised as term $\propto t^3$

$$\frac{\delta\phi_S}{\nu} = \frac{A_S}{\mathrm{yr}^2} t^3$$

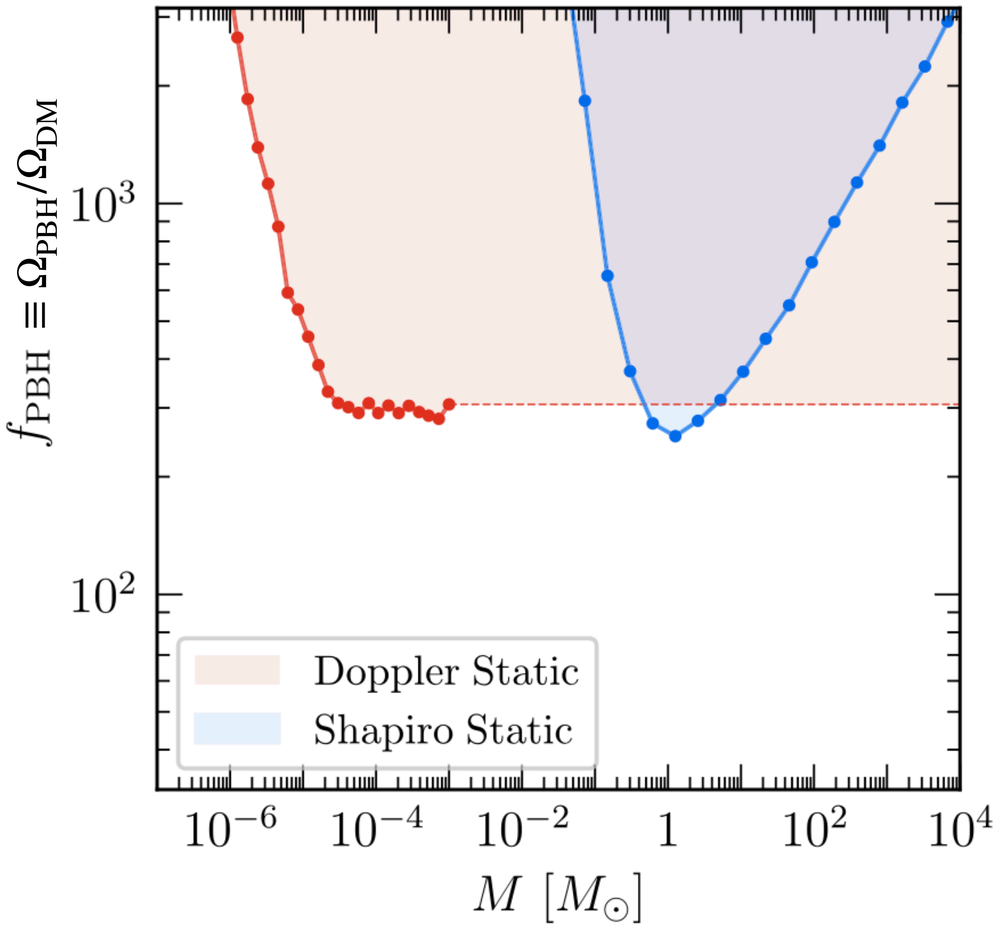
$$A_S = f(M, v, \tau, \dots)$$

dimensionless amplitude depending on the process kinematic parameters

See for e.g. [Lee, Taylor, Trickle, Zurek 2021]

[Afzal et. al. (NANOGrav) arxiv:2306.16219]

NANOGrav 15 yr dataset



SUMMARY

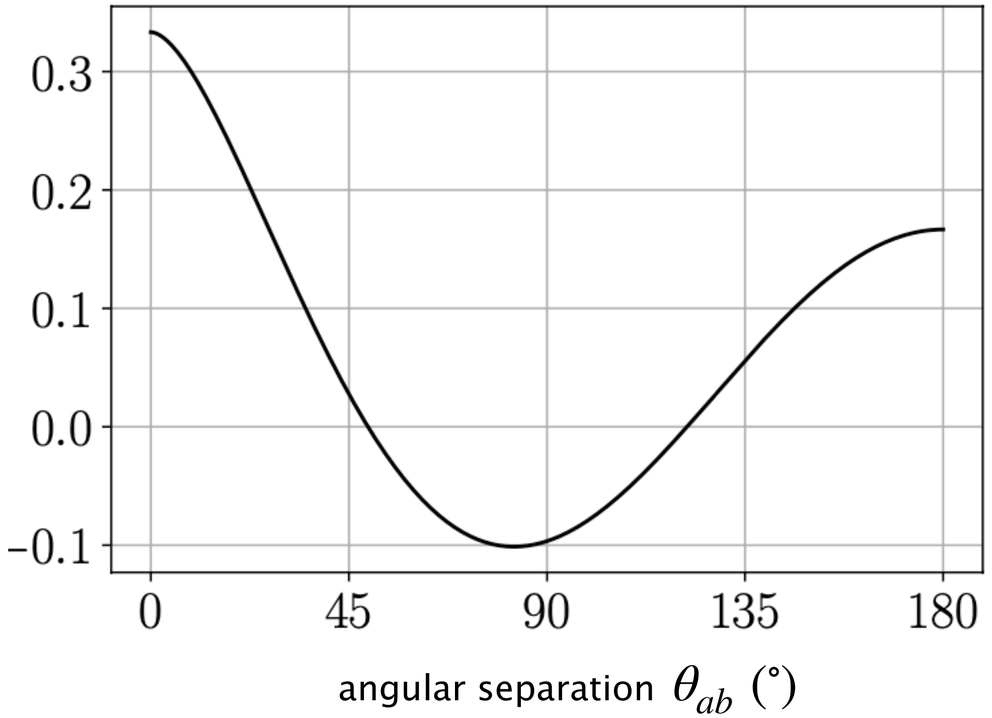
- PTAs show compelling evidence for a nHz GWB
- The origin of the GWB is not yet known
- Search for anisotropies in future datasets will help discriminate
- PTAs can be used for local dark matter searches

Expectation at PTAs for an isotropic, unpolarized gravitational wave background

Hellings and Downs Correlations

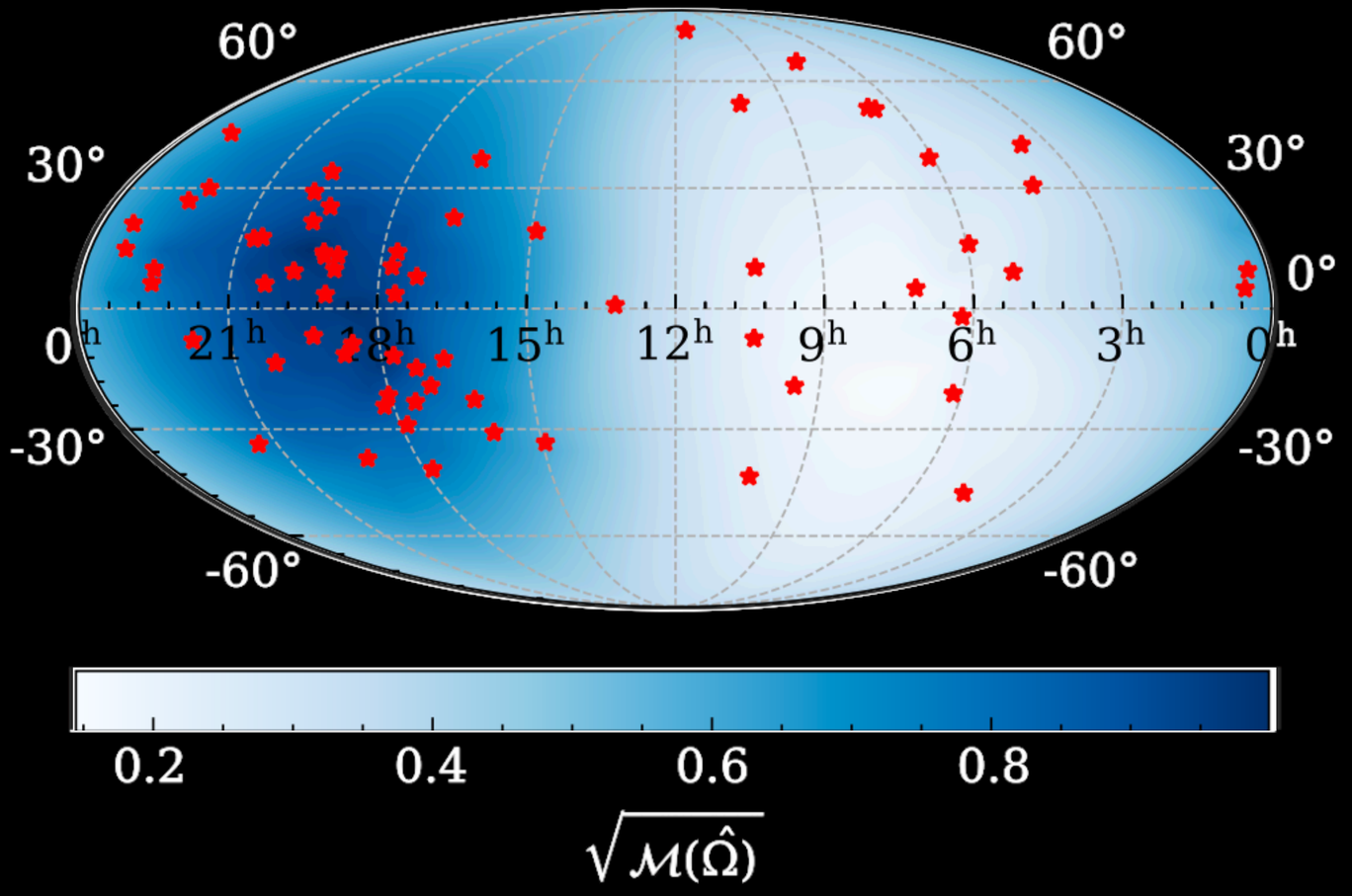
$$\Gamma_{ab}(\zeta_{ab})$$

$$\Gamma(\xi_{ab}) = \frac{3}{2}x\ln(x) - \frac{1}{4}x + \frac{1}{2} + \frac{1}{2}\delta_{ab},$$
$$x = \frac{1-\cos\xi_{ab}}{2}.$$

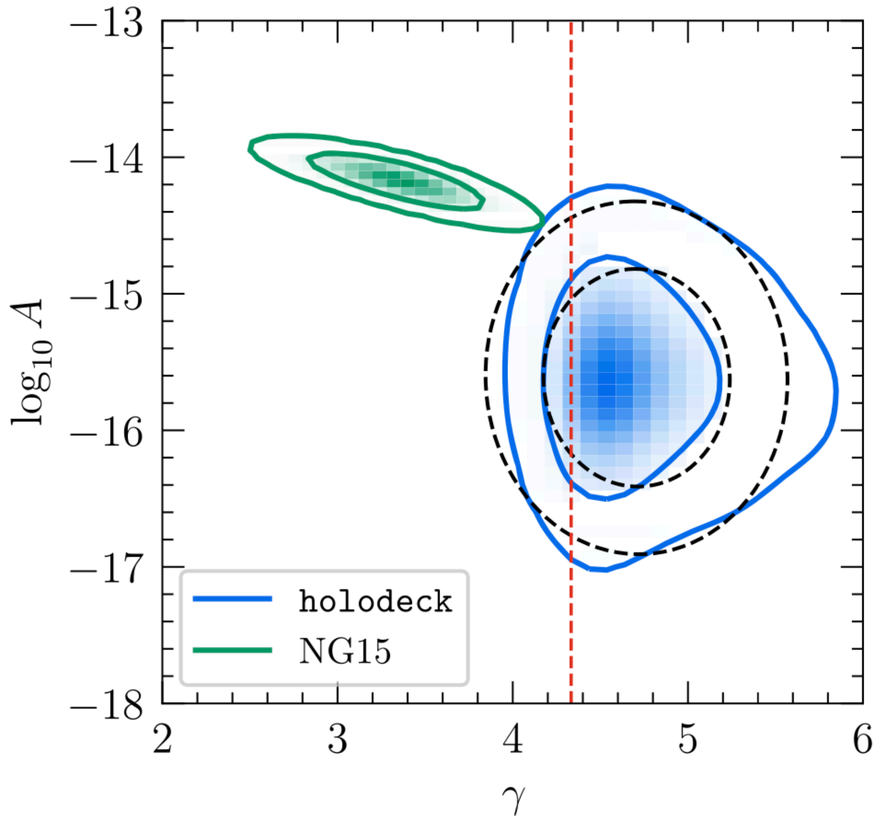


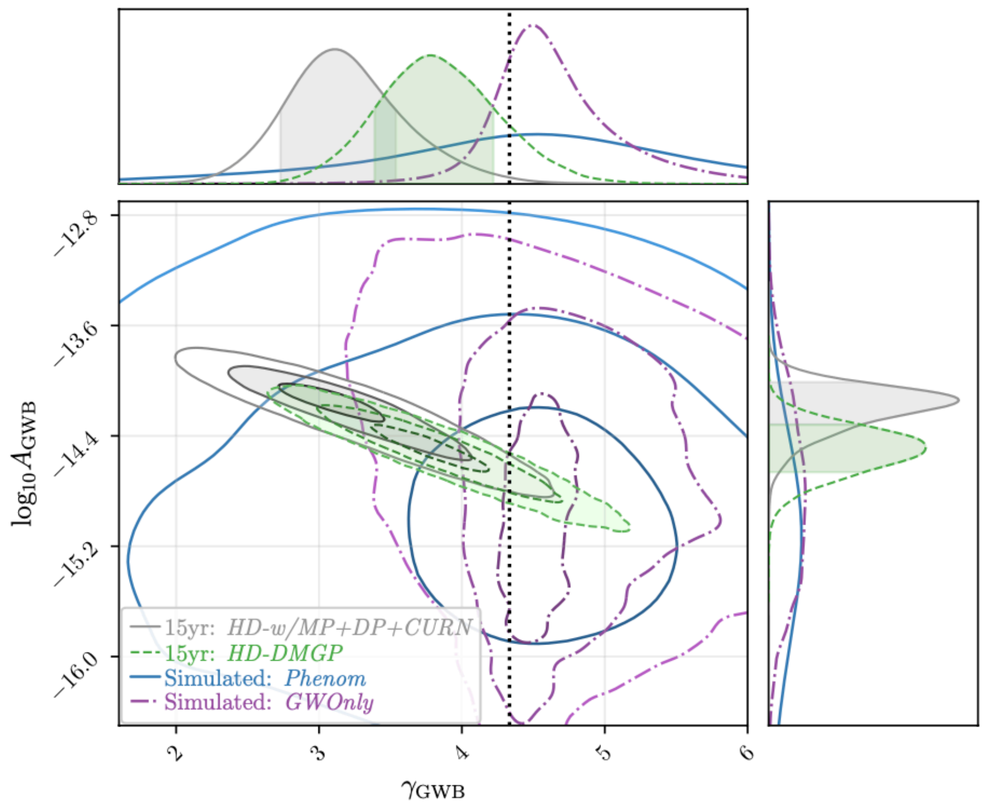
Agazie et al. [NANOGrav] arxiv:2306.16221

Current PTA sensitivity to anisotropies



Life is not that simple...





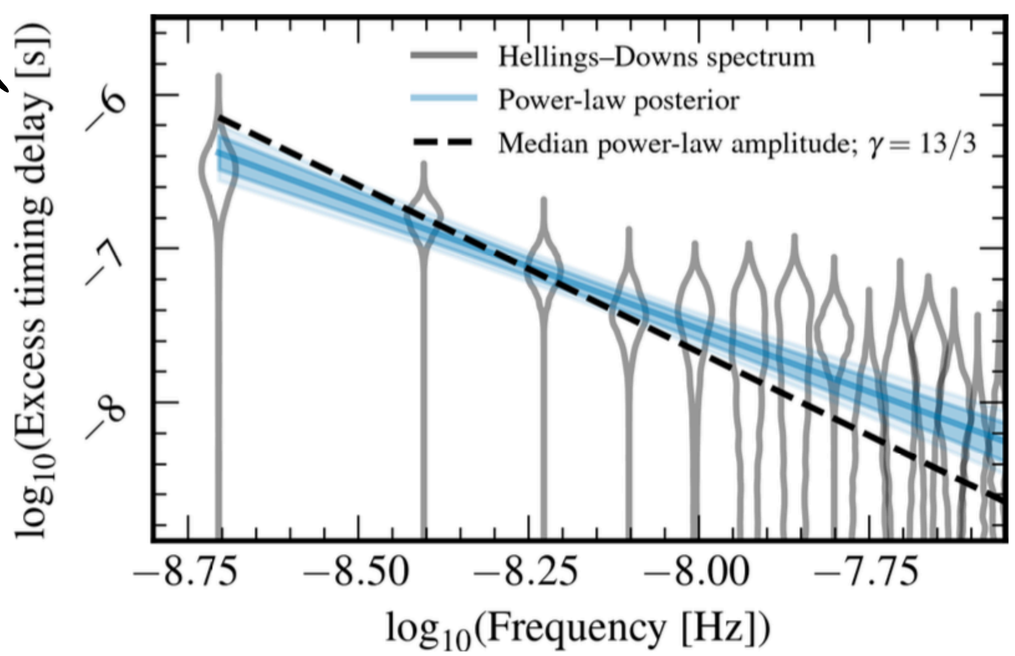
Useful conversions to understand the plots

$$\sqrt{\Phi_{CURN}} = \sqrt{\frac{1}{12\pi^2 f^3}\frac{1}{T}h_c(f)^2}$$

GW characteristic strain!

Parameterise:

$$h_c(f) = A\left(\frac{f}{f_{ref}}\right)^{-\alpha}$$



measured angular correlations

Agazie et al (NG) arxiv:2306.16213

Compelling evidence of Hellings-Downs correlations with false-alarm probability of $p = 10^{-3}$