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INFN Istituto Nazionale di Fisica Nucleare

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Tagliolo di Monferrato

# FORECASTING THE SENSITIVITY OF PULSAR TIMING ARRAYS TO SCALAR-INDUCED GW

Chiara Cecchini, Gabriele Franciolini (CERN), Mauro Pieroni (CERN)

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## Chiara Cecchini

Department of Physics, University of Trento, Italy - TIFPA-INFN - CERN TH

September, 19th 2024

# OUTLINE

1. PULSAR TIMING ARRAYS
2. FORECASTS: INTRODUCING A NEW METHOD
3. SCALAR-INDUCED GW: CONSTRAINING A POTENTIAL SIGNAL

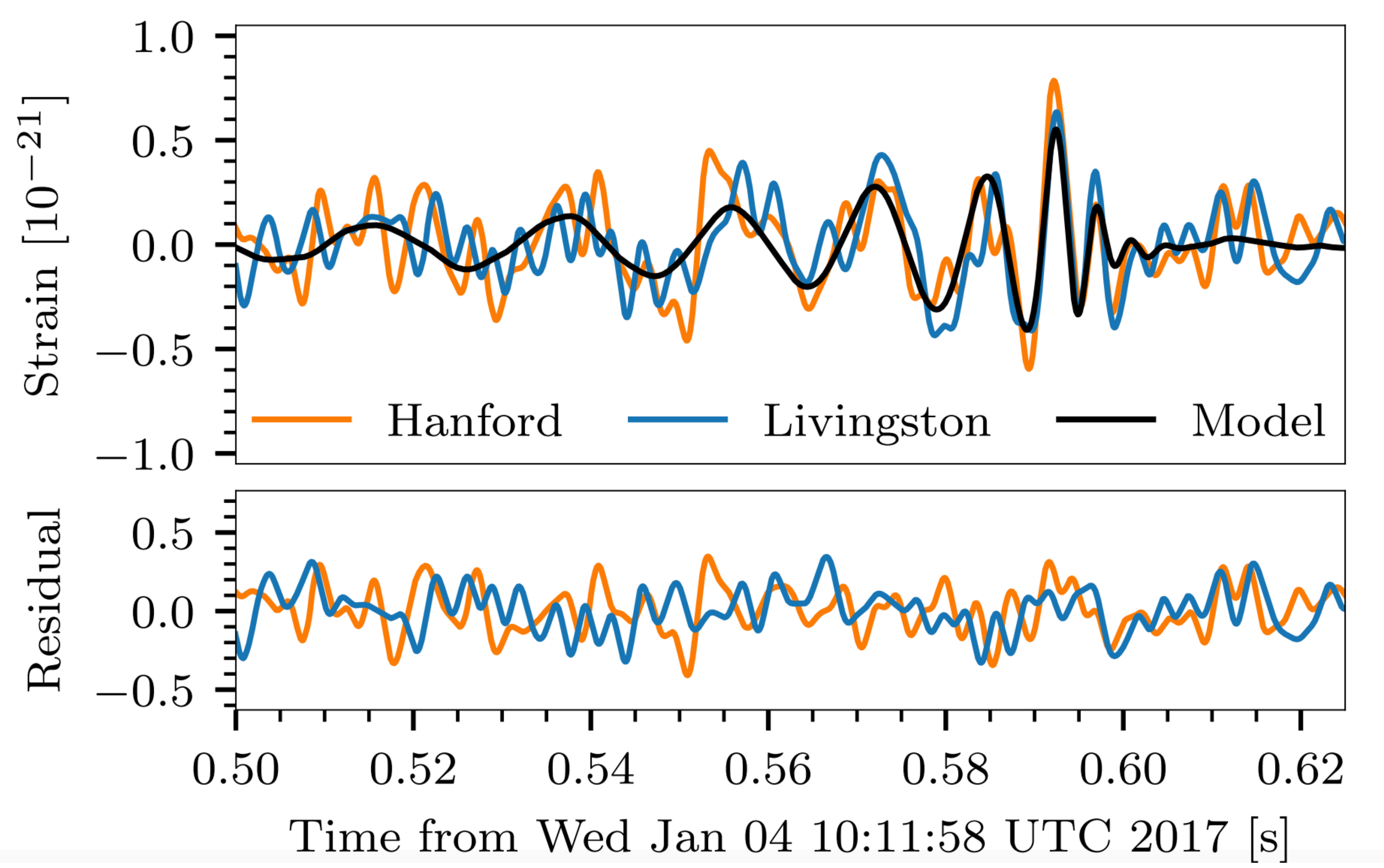
# MORPHOLOGY OF A GW SIGNAL

## DETERMINISTIC SIGNAL

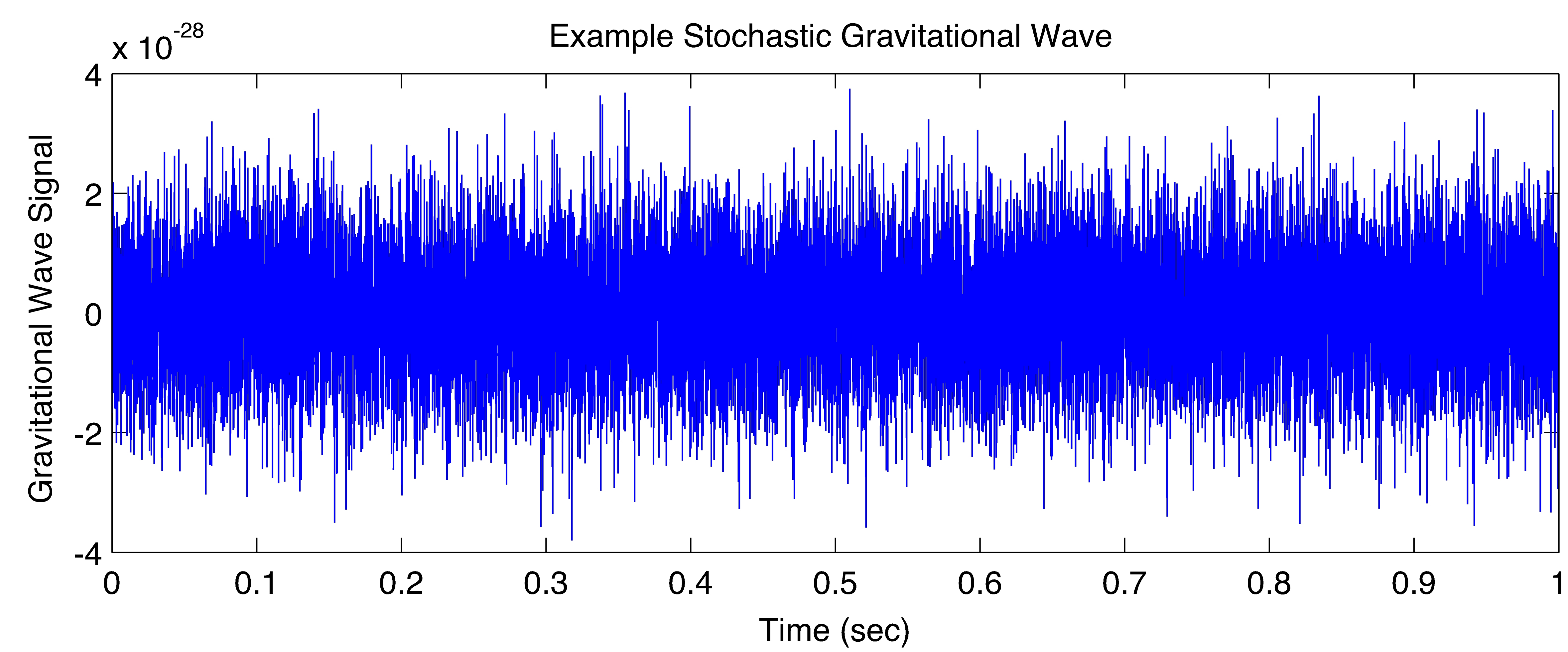
- Generated by binaries
- Time coherency
- Well localized in the sky

## STOCHASTIC BACKGROUND

- Superposition of many signals
- No time coherency
- Diffuse in the sky

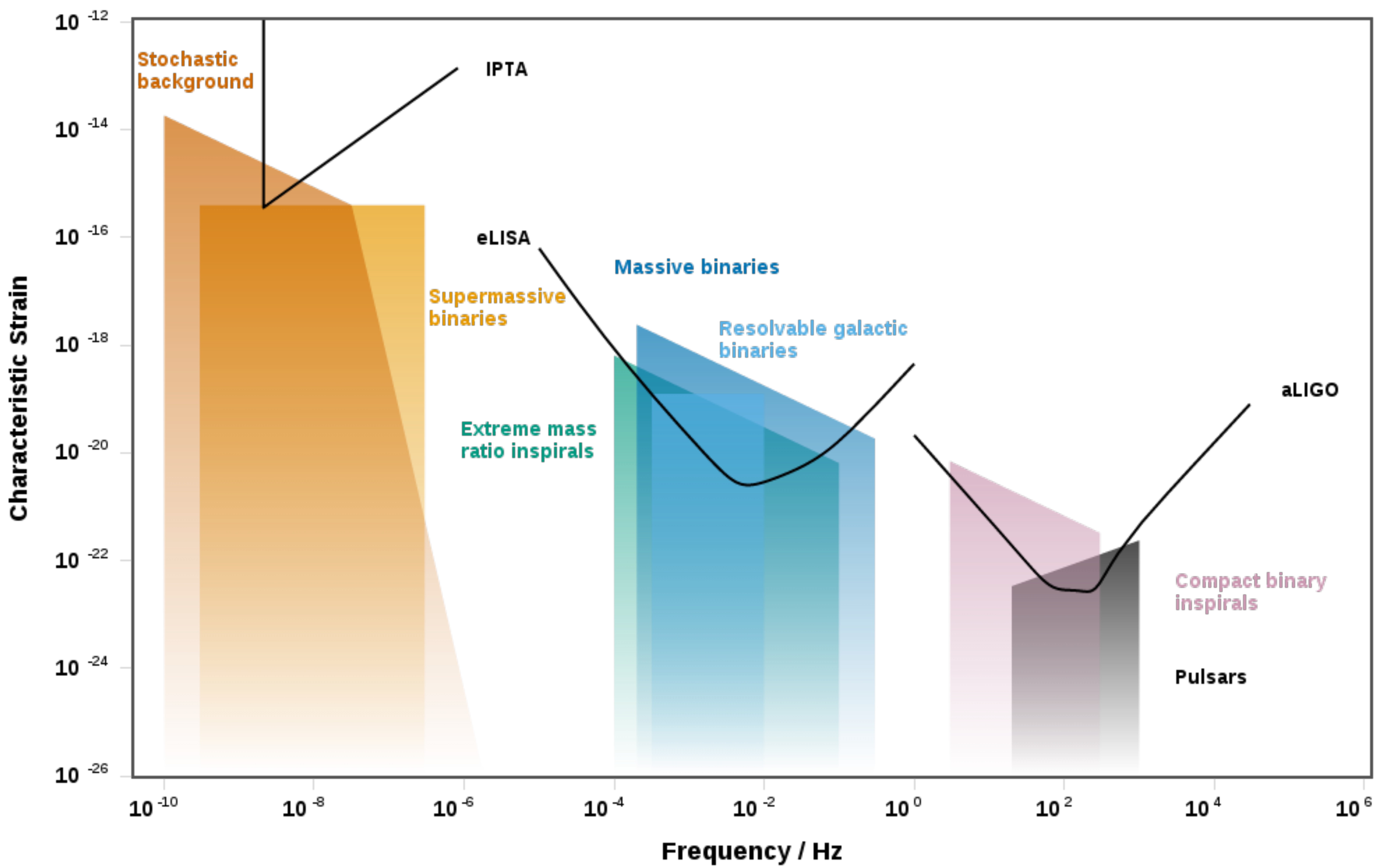



Strain data from Hanford and Livingston detectors at the time of GW170104. Credit: [1]




Example of a signal from a stochastic GW source. Credit: [2]

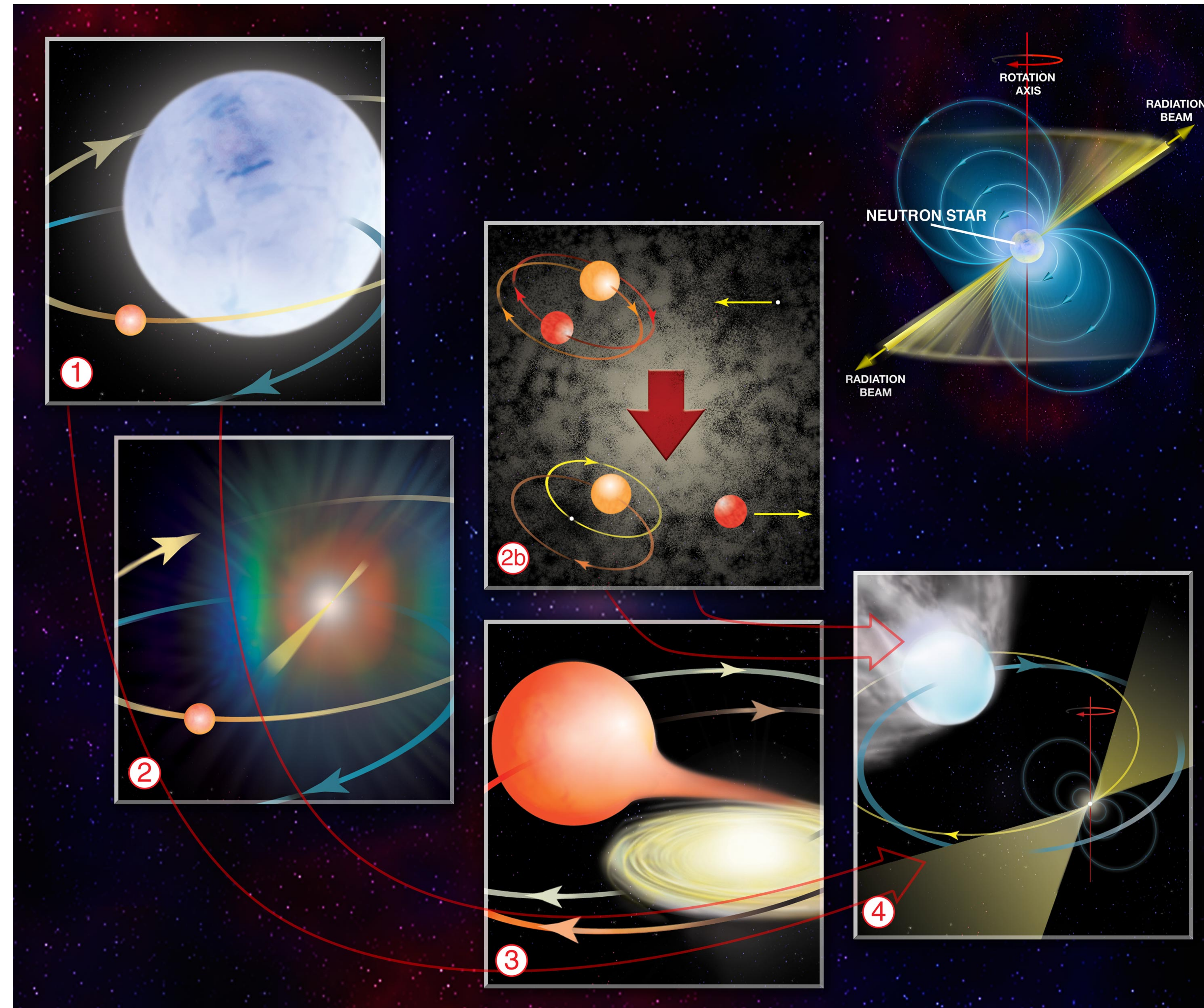
# PRESENT AND FUTURE DETECTORS




Gravitational-wave sensitivity-curve plot using characteristic strain. Credit: [3]

# MILLISECOND PULSARS

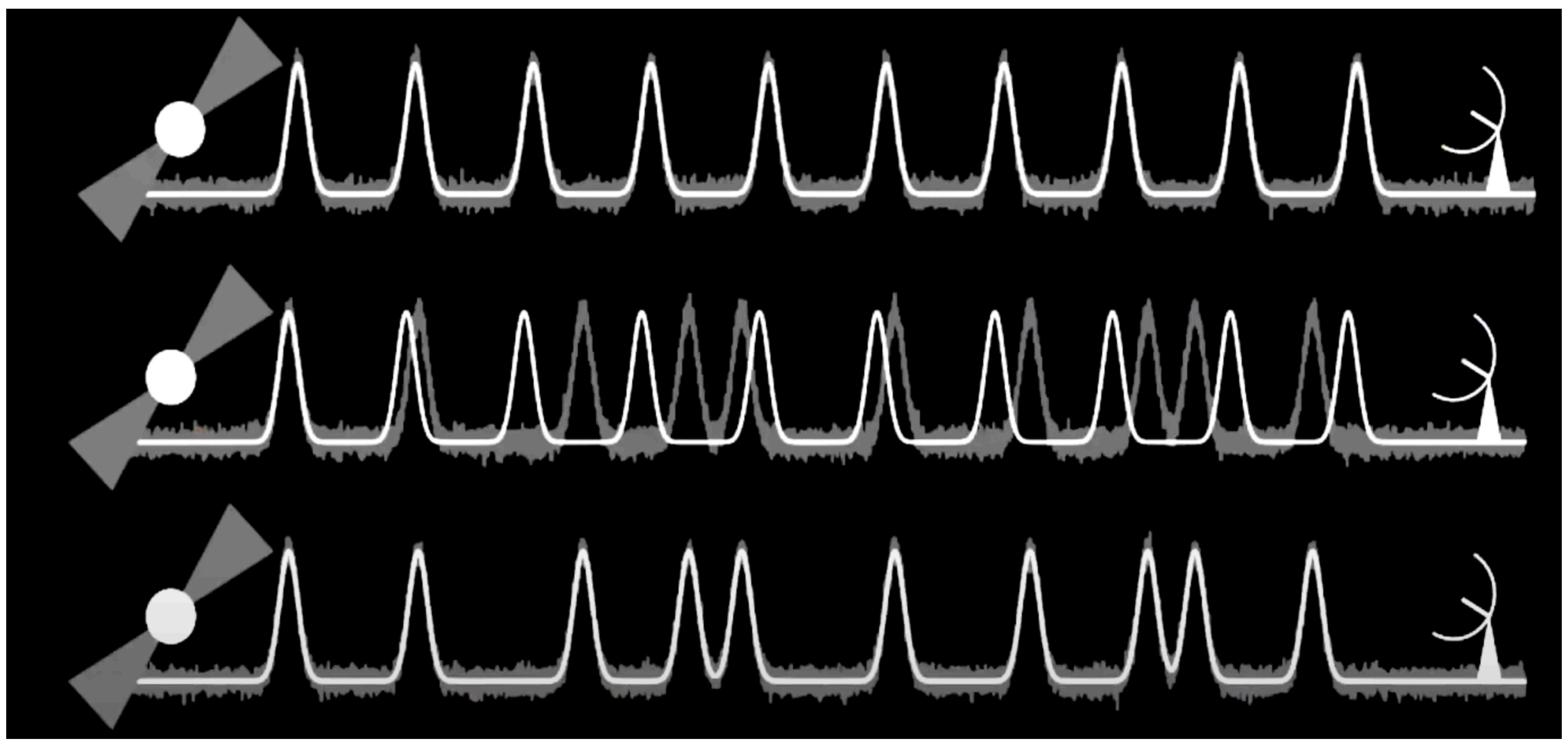
- Pulsars with a rotational period less then 10 ms
- Spun up through accretion of matter from a companion star in a close binary system
- Lighthouse effect: we observe the beam radiation
- $\sim$ 400 known pulsars
- Observed in the radio frequencies




Steps astronomers say are needed to create a pulsar with a superfast spin
Credit: [4]

# PULSAR TIMING

- Accounting for each pulse



Pulsar timing process. Credit: [5]

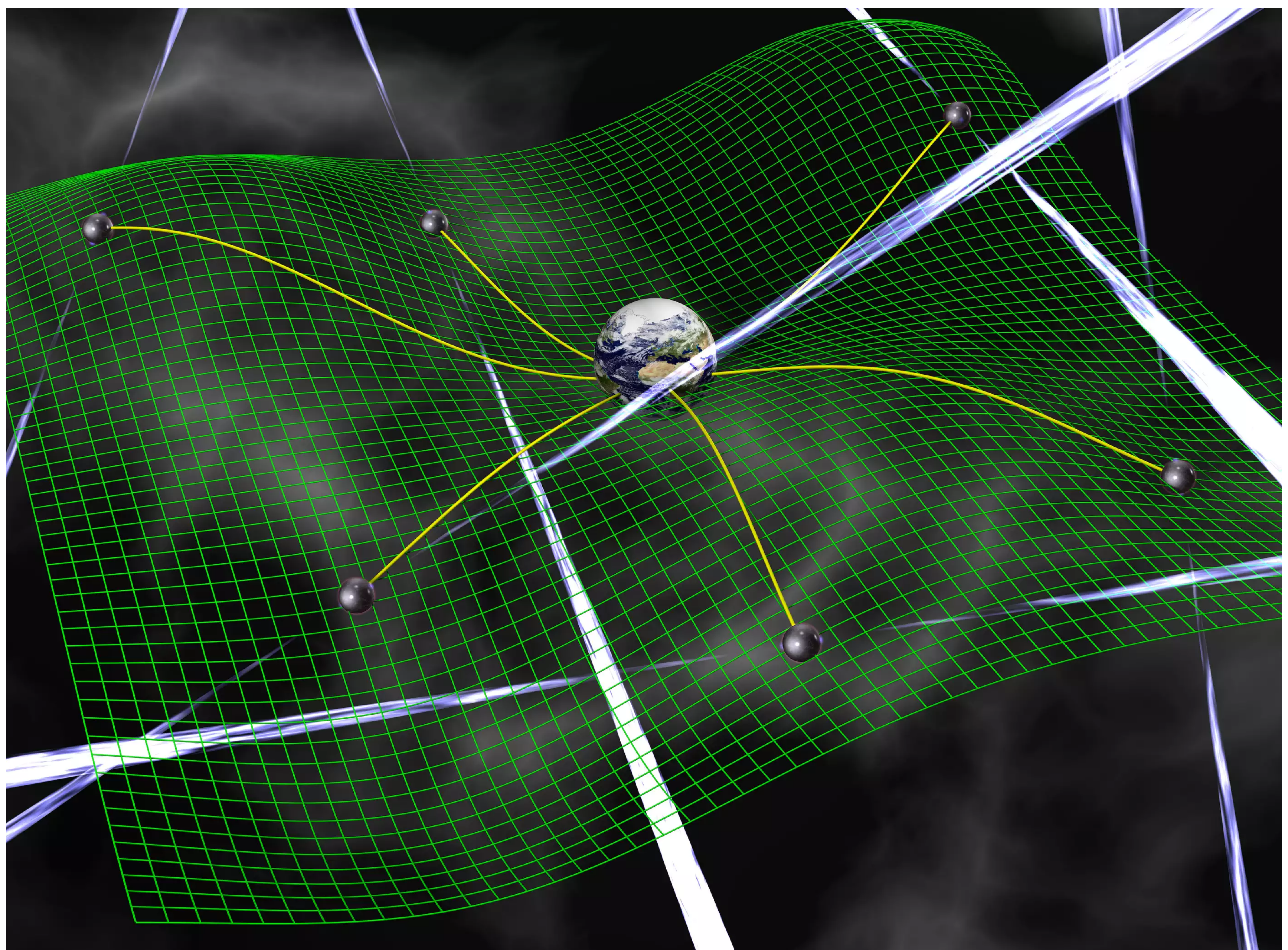
Many factors dictating the pulse arrival times:

- Pulse period, period derivatives, location on the sky
- GR effects, dispersion measure

- All these factors must be taken into account to build a pulsar timing model
- Time residuals: difference between the measured TOA and the model

# PULSAR TIMING ARRAYS

- Taking many pulsars reduces the noise contribution



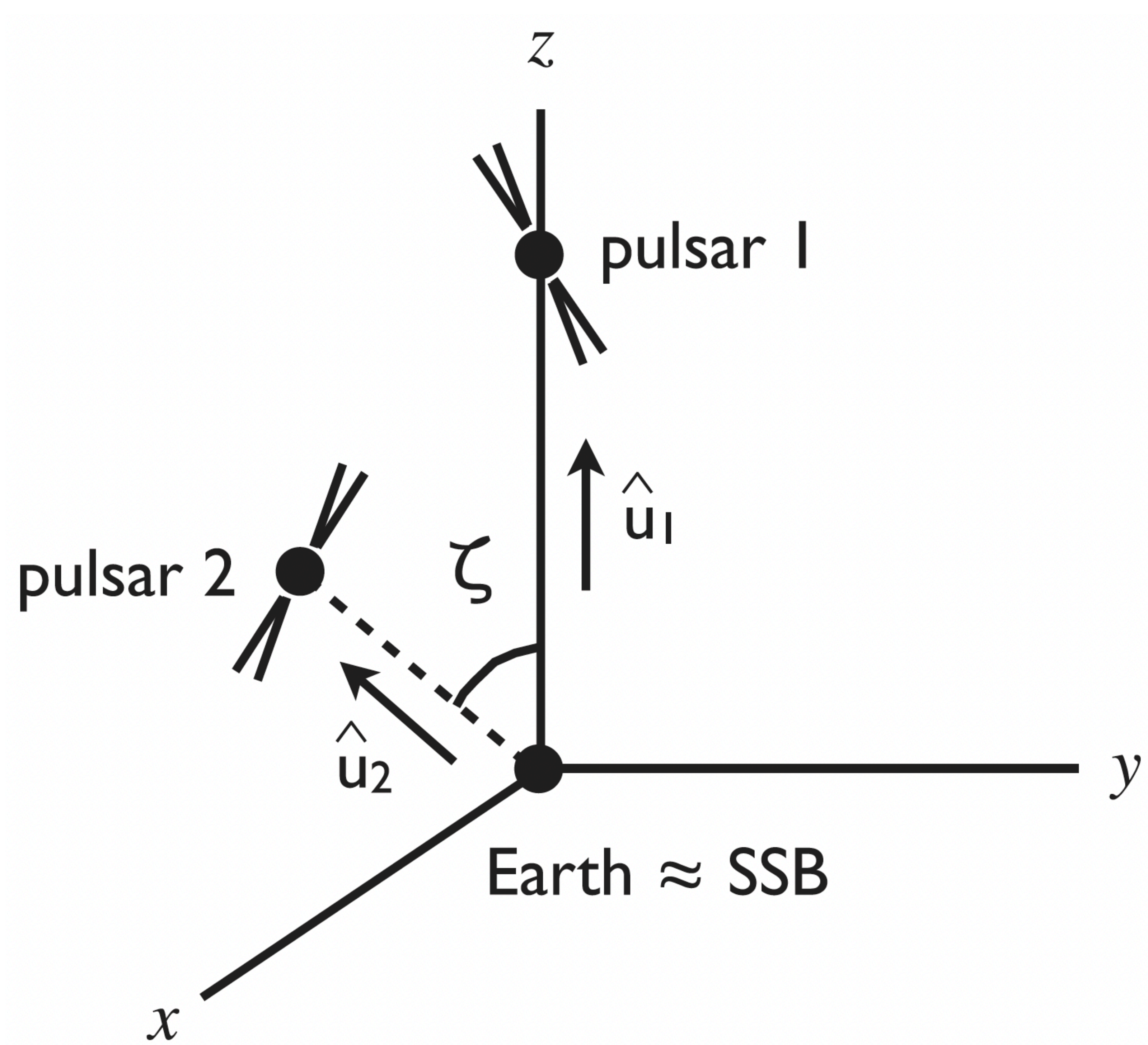
Pulsar timing arrays. Credit: [6]

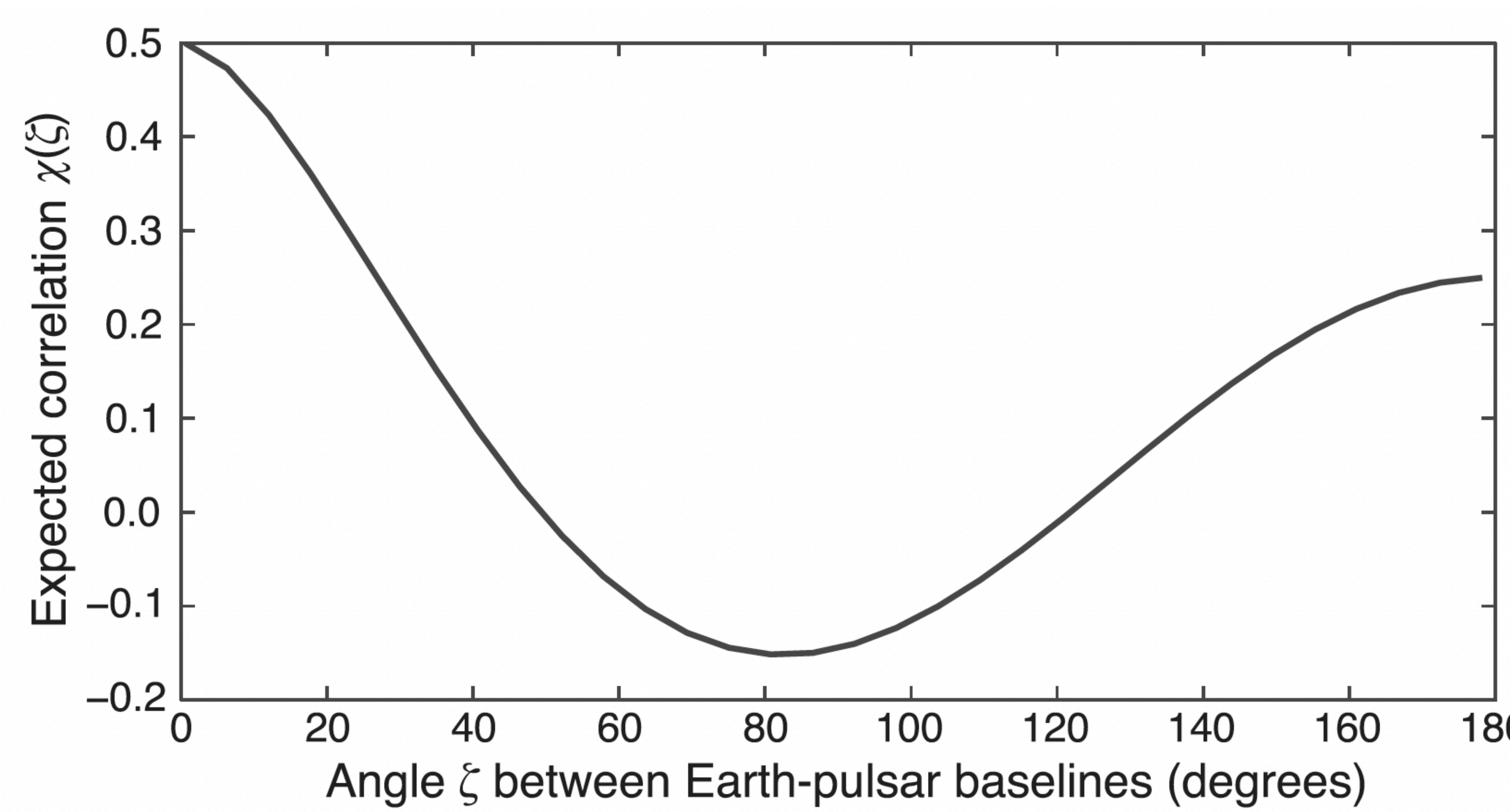
- Each pulsar is monitored by one or more telescopes
- Several frequencies are monitored
- Long acquisition time (> yrs) to go to very low frequencies

$$f_{yr} \sim 3.17 \times 10^{-8}\,\mathrm{Hz}$$

# THE MODEL: HELLINGS & DOWNS CURVE

- For an isotropic, unpolarized stochastic background of quadrupolar gravitational radiation with + and × polarisation modes, the expected correlated response of a pair of Earth-pulsar baseline follows the Hellings and Downs curve




Credit: [7]

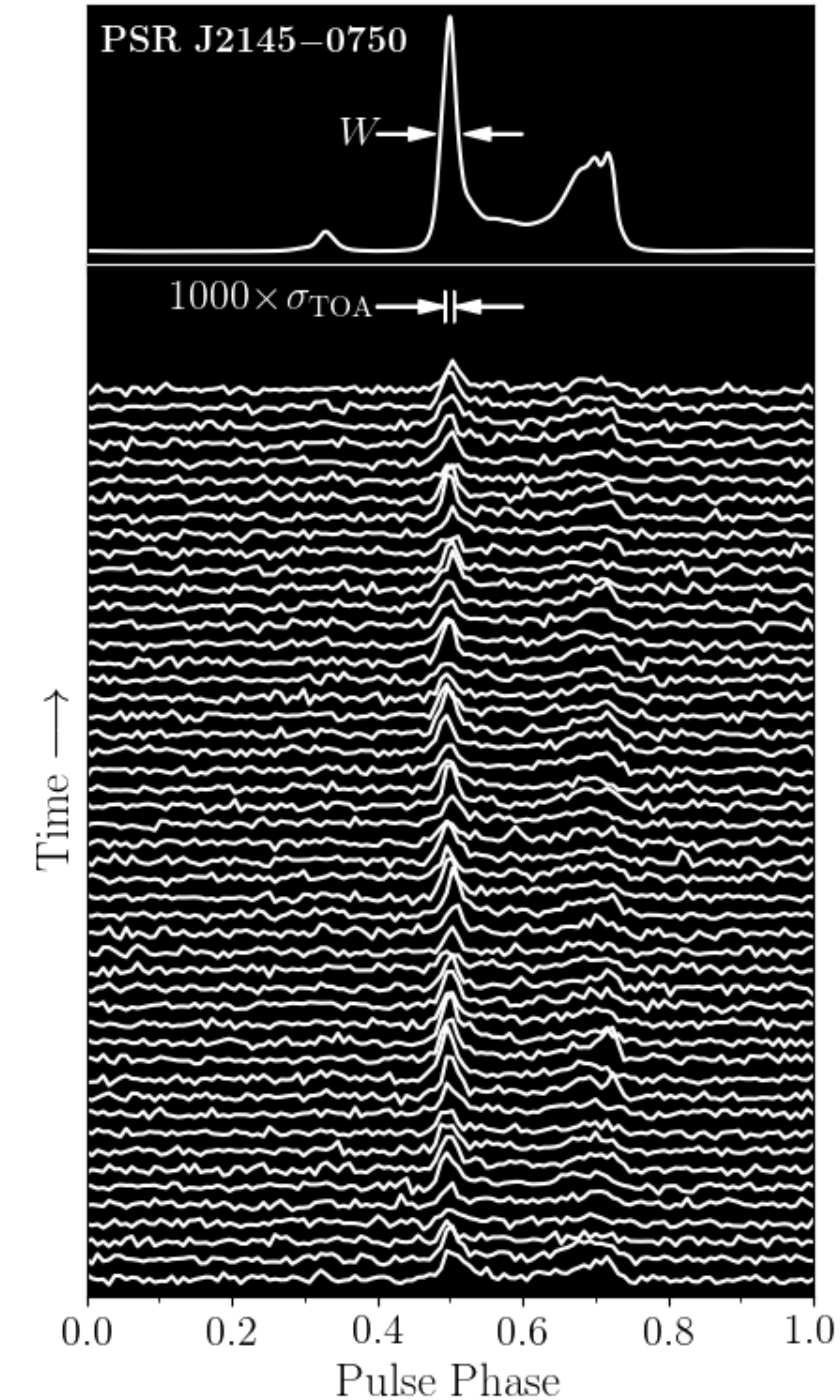
# NOISE SOURCES

- **White noise:** due to instrumental noise and change of shape of different pulses

- **Red noise:** due to the stochasticity in the rotation of pulsars

- **Chromatic noise components:** temporal variations in dispersion measure and scattering variations due to the time-varying electron column density along the line of sight

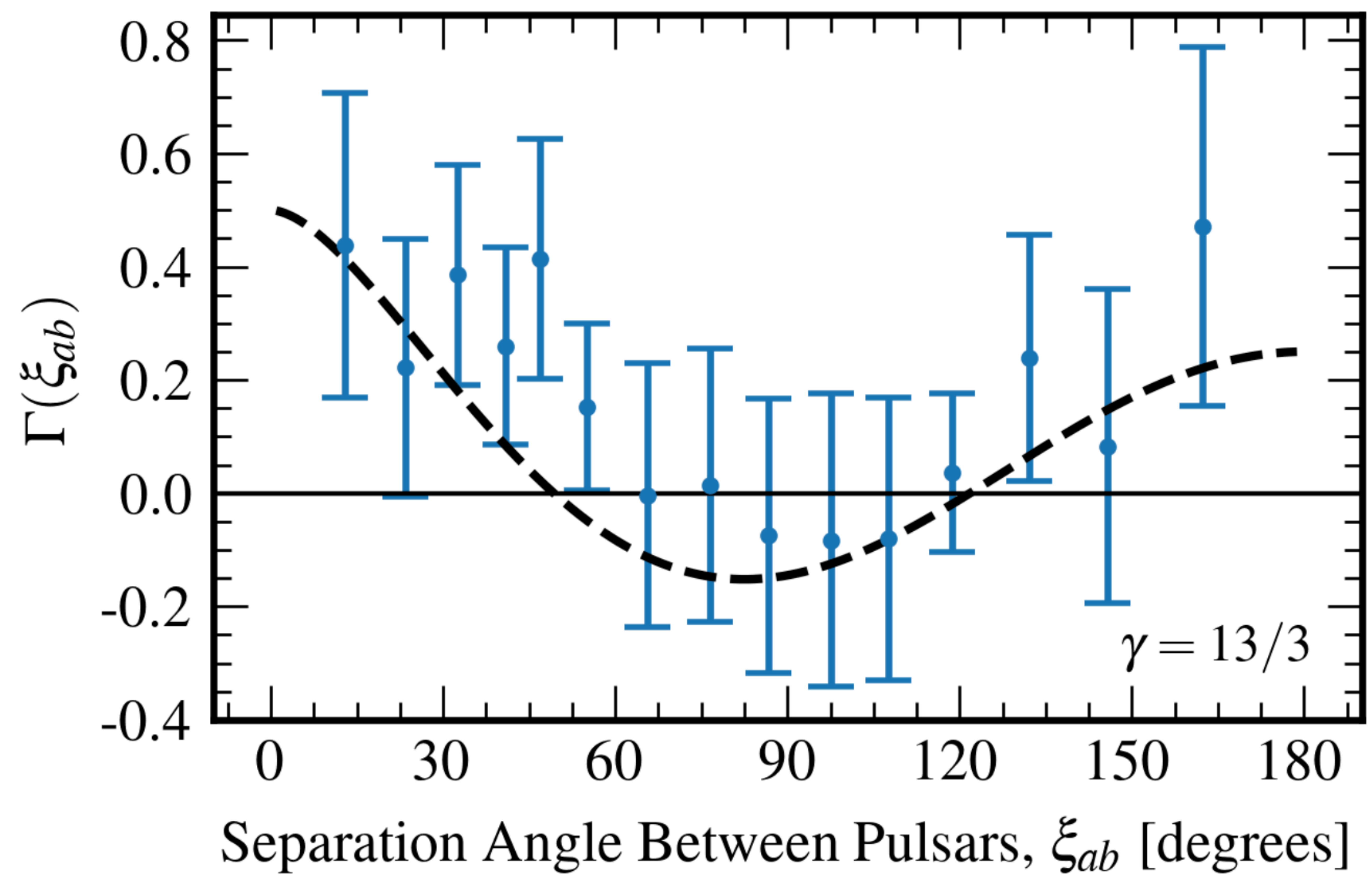
- Any of these is expected to behave as a quadrupole!




Jitter in the NANOGrav pulsar J2145-0750. Credit: [8]

# EVIDENCE FOR A STOCHASTIC GW BACKGROUND

- 67 pulsars
- Observation time: 16.03 yrs
- Not a $5\sigma$ evidence, but observation by independent collaborations



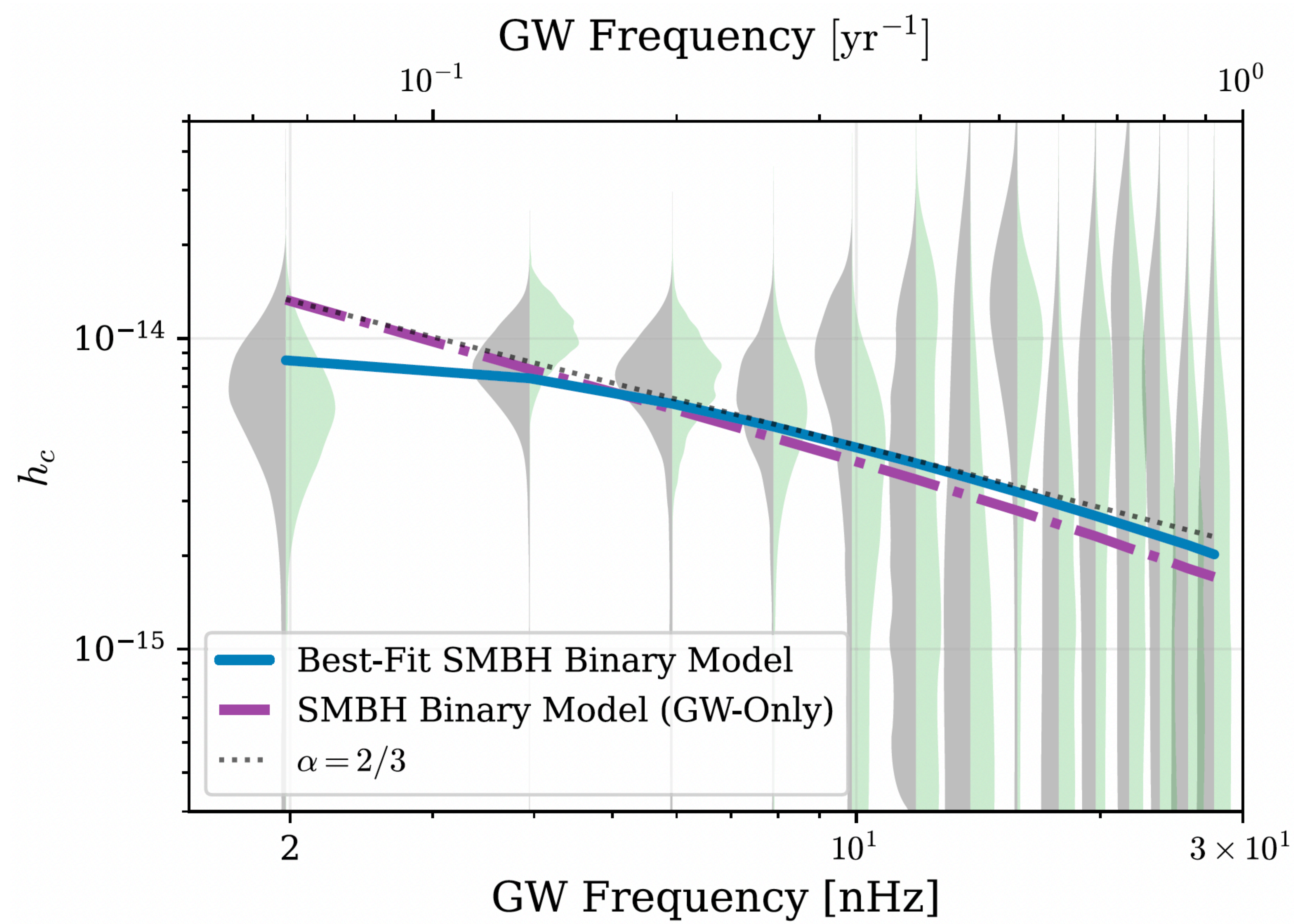

Credit: [9]

# ASTROPHYSICAL OR COSMOLOGICAL ORIGIN?

- The observed signal is consistent with SMBBHs

- GW strain is modelled with a power law

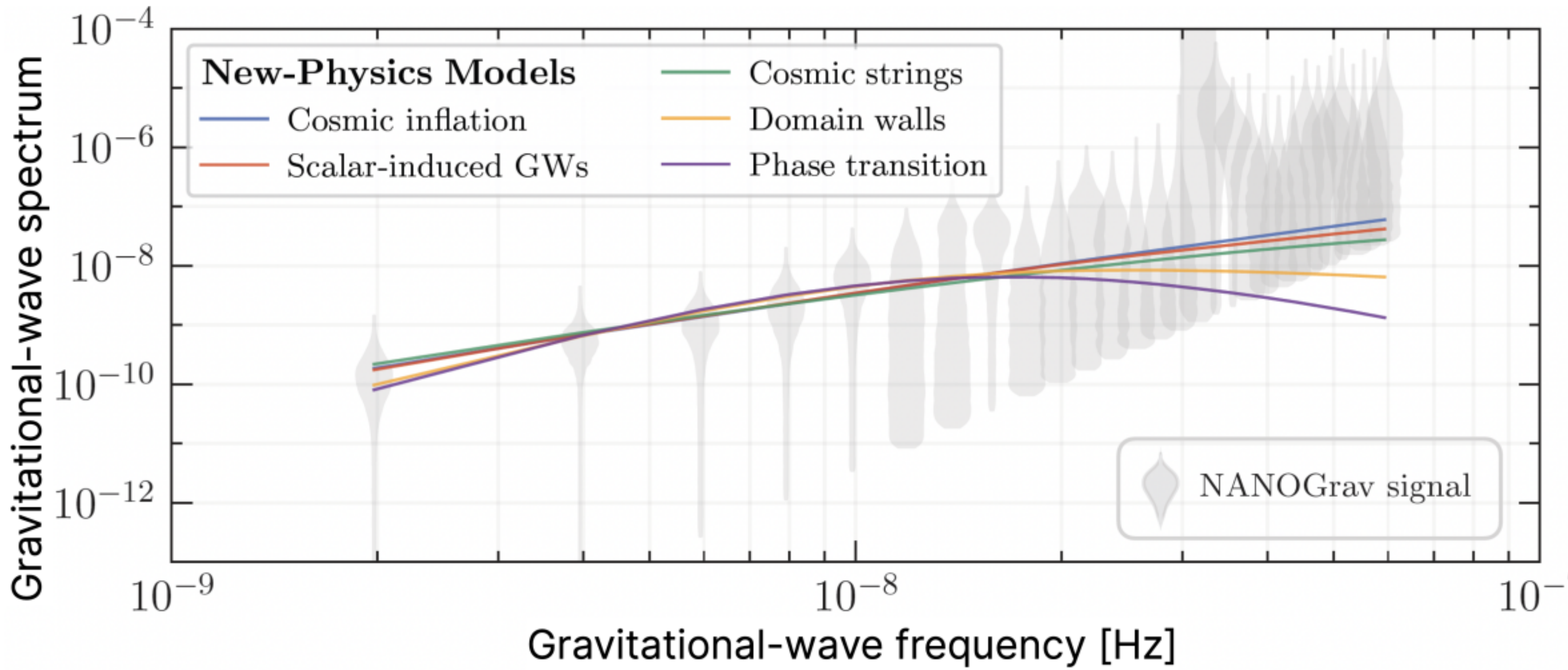
$$h_c(f) = A_{GWB}\left(\frac{f}{f_{yr}}\right)^{\alpha}$$




Credit: [10]

# ASTROPHYSICAL OR COSMOLOGICAL ORIGIN?

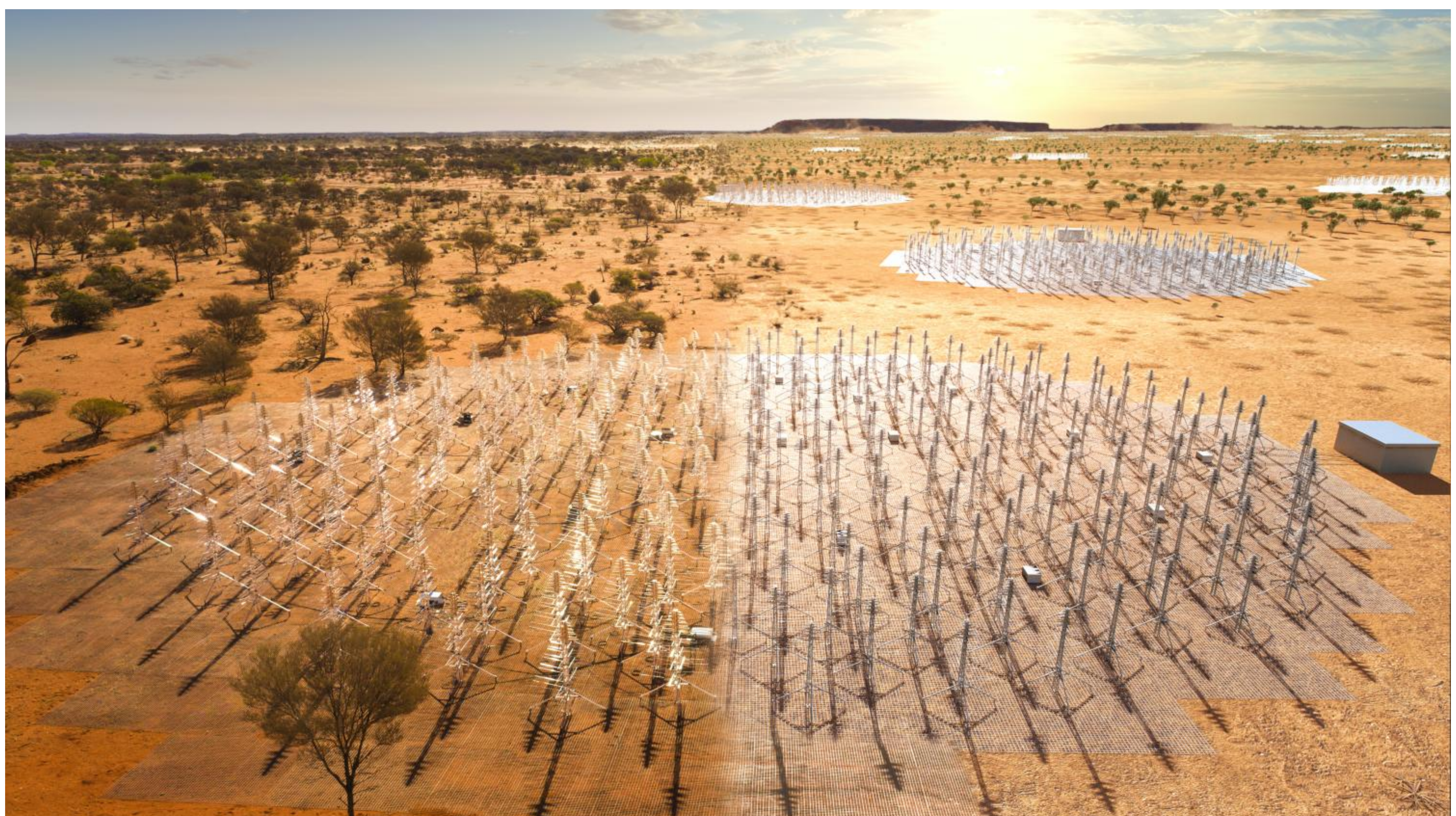
- The observed signal is also consistent with many other sources




Credit: [11]

# WHAT'S NEXT?

- More data: longer observation time, more pulsars and frequency points
- New generation telescopes: the Square Kilometer Array (SKA) will provide high-precision pulsar timing measurement with uncertainties below $\sim 100$ ns



Credit: [12]

# SPEED UP THE PRESENT ANALYSIS

S. Babak, M. Flaxa, G. Franciolini, & M. Pieroni *PR D* **110**, 063022 (2024)
P. F. Depta, V. Domcke, G. Franciolini, & M. Pieroni arXiv:2407.14460

- Data in the frequency domain:

$$\langle \tilde{s} \rangle = 0 \quad \text{for SGWB}$$
$$\langle \tilde{n} \rangle = 0 \quad \text{for noise}$$

- Information is in the variance: $\langle \tilde{d}^2 \rangle = \langle \tilde{s}^2 \rangle + \langle \tilde{n}^2 \rangle = RP_h + P_n$

- Simplifying assumptions: Gaussian, (isotropic) and stationary data for each pulsar

$$-\ln \mathscr{L}(\tilde{d}\,|\,\theta) \propto \sum_{k,IJ} \ln[C_{IJ}(f_k, \theta))] + \tilde{d}_I^k\, C_{IJ}^{-1}(f_k, \theta)\, \tilde{d}_J^{k*}$$

$$C_{IJ}(f) = P_{n,IJ}(f) + \chi_{IJ} R(f) P_h(f)$$

* I, J are pulsar indices

# SPEED UP THE PRESENT ANALYSIS

S. Babak, M. Flaxa, G. Franciolini, & M. Pieroni *PR D* **110**, 063022 (2024)

- Fisher matrix estimates on uncertainties

$$F_{\alpha\beta} \equiv -\frac{\partial^2 \log \mathscr{L}}{\partial\theta^\alpha \partial\theta^\beta} = T_{obs} \sum_{f_k} \frac{\partial \log C}{\partial\theta^\alpha} \frac{\partial \log C}{\partial\theta^\beta}$$

with $C(f_k, \theta_0) = \tilde{d}^k \tilde{d}^{k*}$ and $\theta_0$ is the maximum likelihood estimator of model parameters

- By inverting the FIM one can estimate the uncertainties as $\sigma_\alpha \equiv \sqrt{F^{-1}_{\alpha\alpha}}$

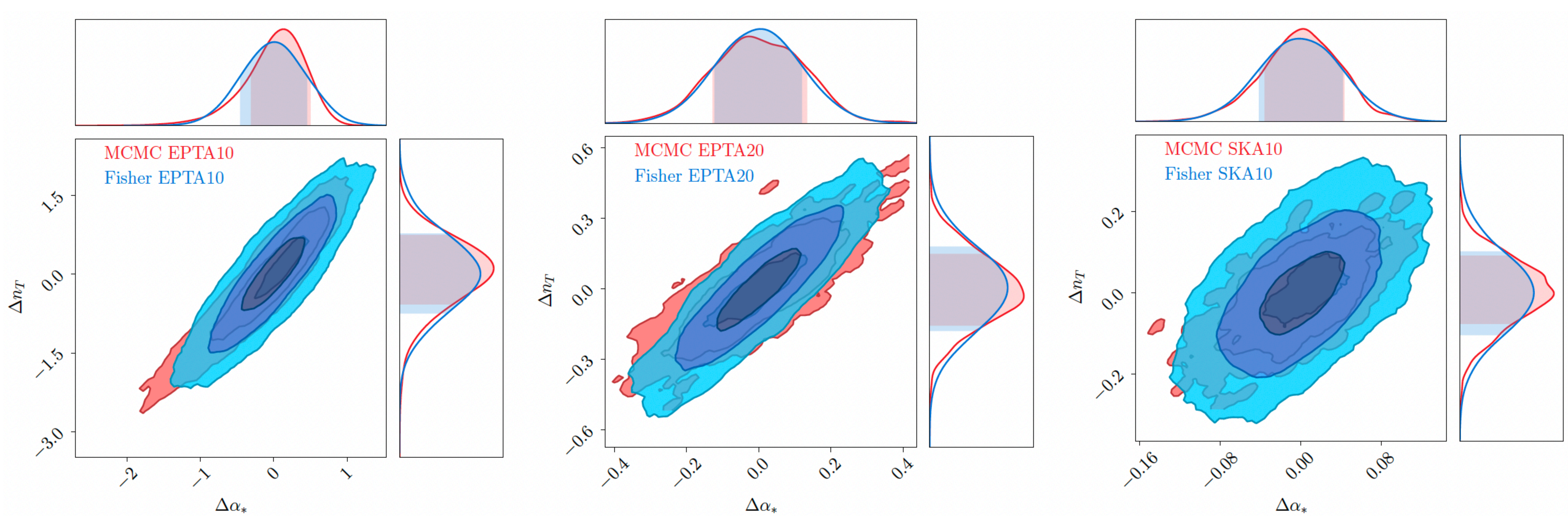
- The python code `fastPTA` is available: https://github.com/Mauropieroni/fastPTA/

# COMPARISON WITH FULL TIME DOMAIN BAYESIAN ANALYSIS

S. Babak, M. Flaxa, G. Franciolini, & M. Pieroni *PR D* **110**, 063022 (2024)

- Is this method consistent with the standard approach?
- Let's consider a power law signal and test against current data + simulated mock data for future configurations

$$h^2\Omega_{GW} = 10^{\alpha}\left(\frac{f}{f_{yr}}\right)^{n_T}$$




Fully consistent!

Computational time of a day vs few seconds

# SCALAR INDUCED GW

V. Dandoy, V. Domcke, & F. Rompineve *SciPost Phys. Core* **6**, 060 (2023)

- Aim: forecasting the sensitivity of PTAs to a primordial signal: scalar-induced gravitational waves (SIGW)

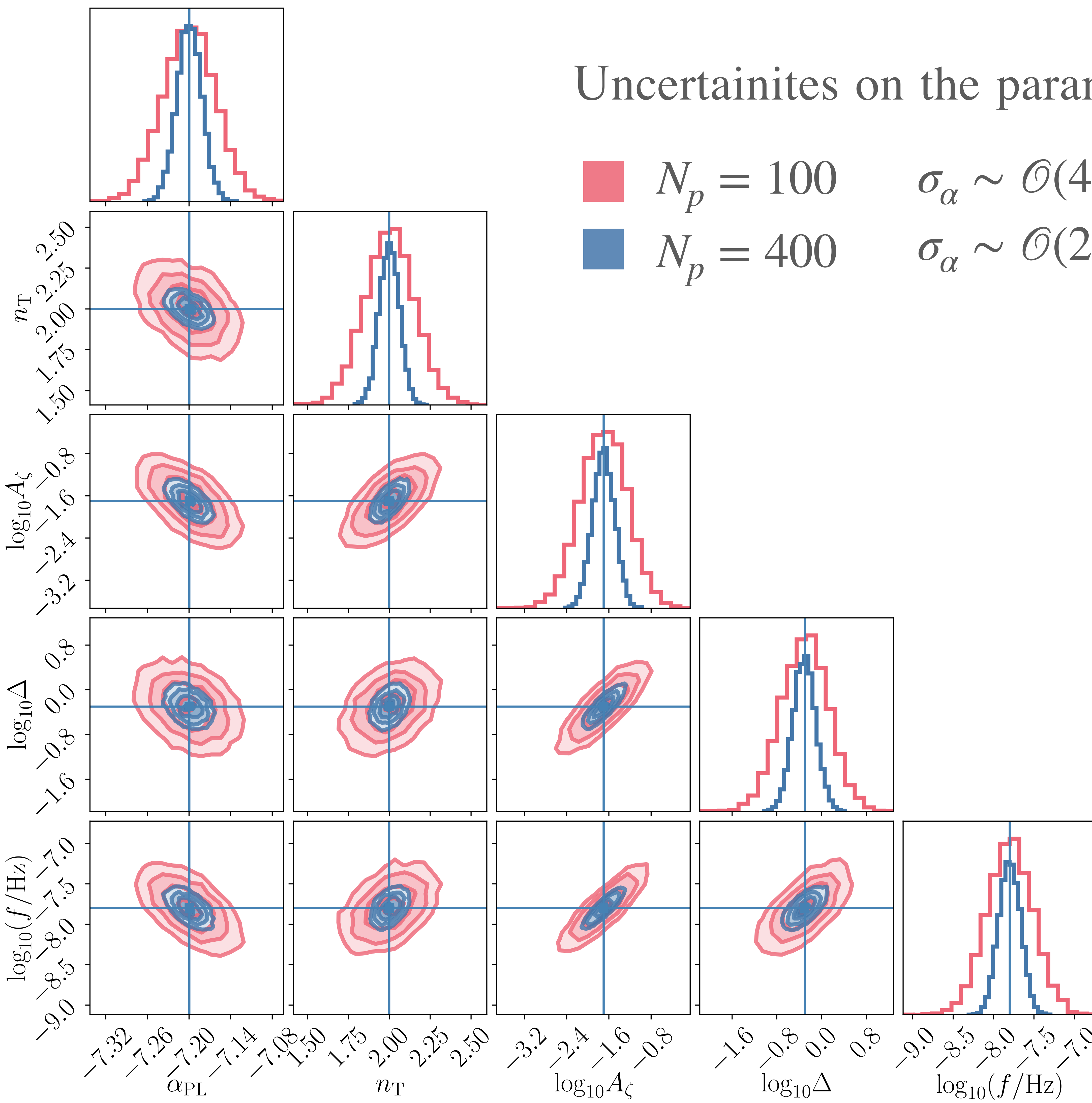
- Spectrum of GW induced at second order by scalar perturbations. We stay agnostic on the specific inflationary models and we adopt a log-normal parametrization

$$P_\zeta(k) = \frac{A_\zeta}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_*)}{2\Delta^2}\right]$$

- It captures the possibility of a peak in the power spectrum at small scales

# SCALAR INDUCED GW AND SMBBH

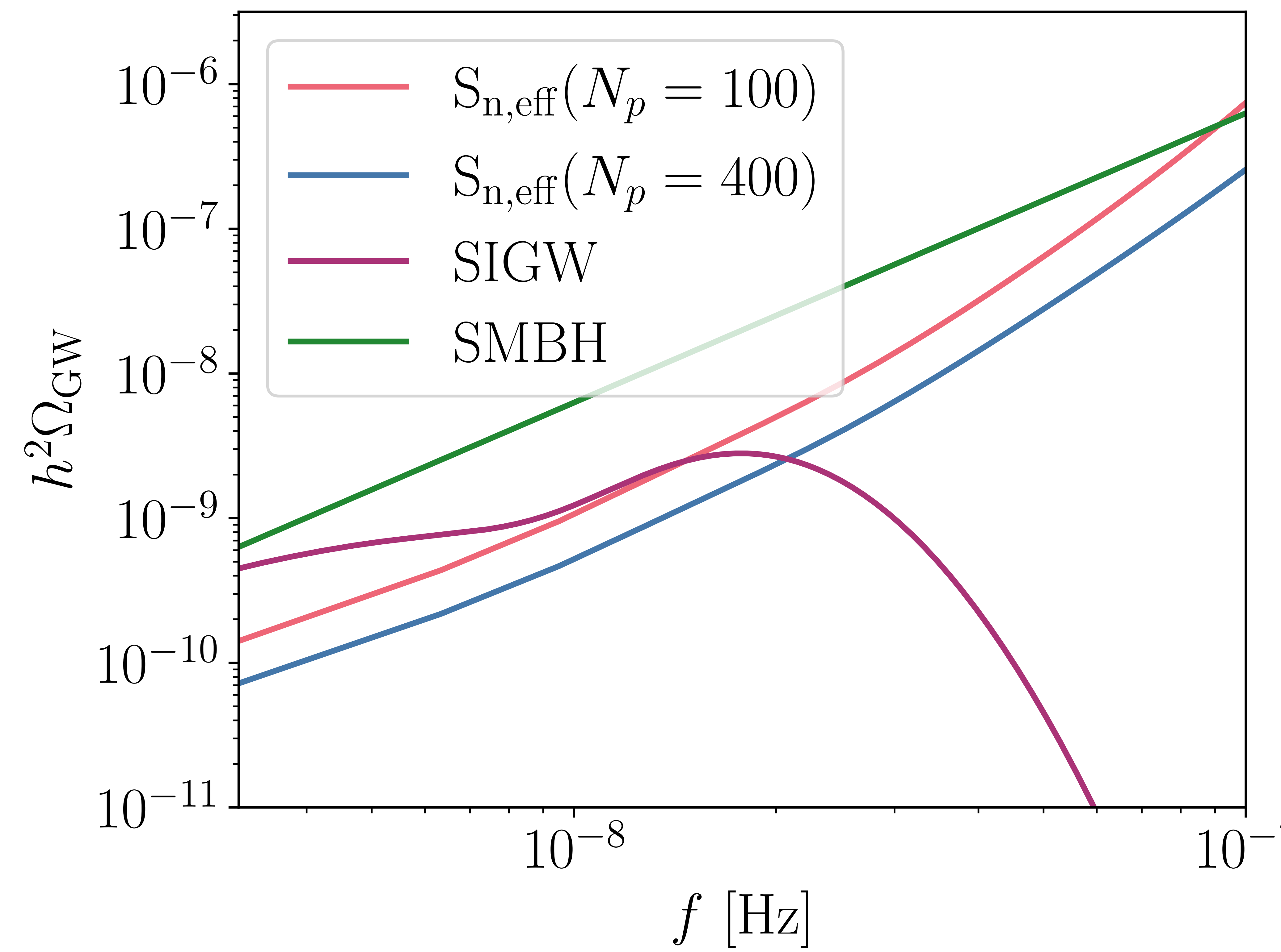
## POWER-LAW MODEL (SMBHs) + SIGWs (with maximal amplitude)




Uncertainites on the parameters:

$N_p = 100$ $\sigma_\alpha \sim \mathcal{O}(40\%)$

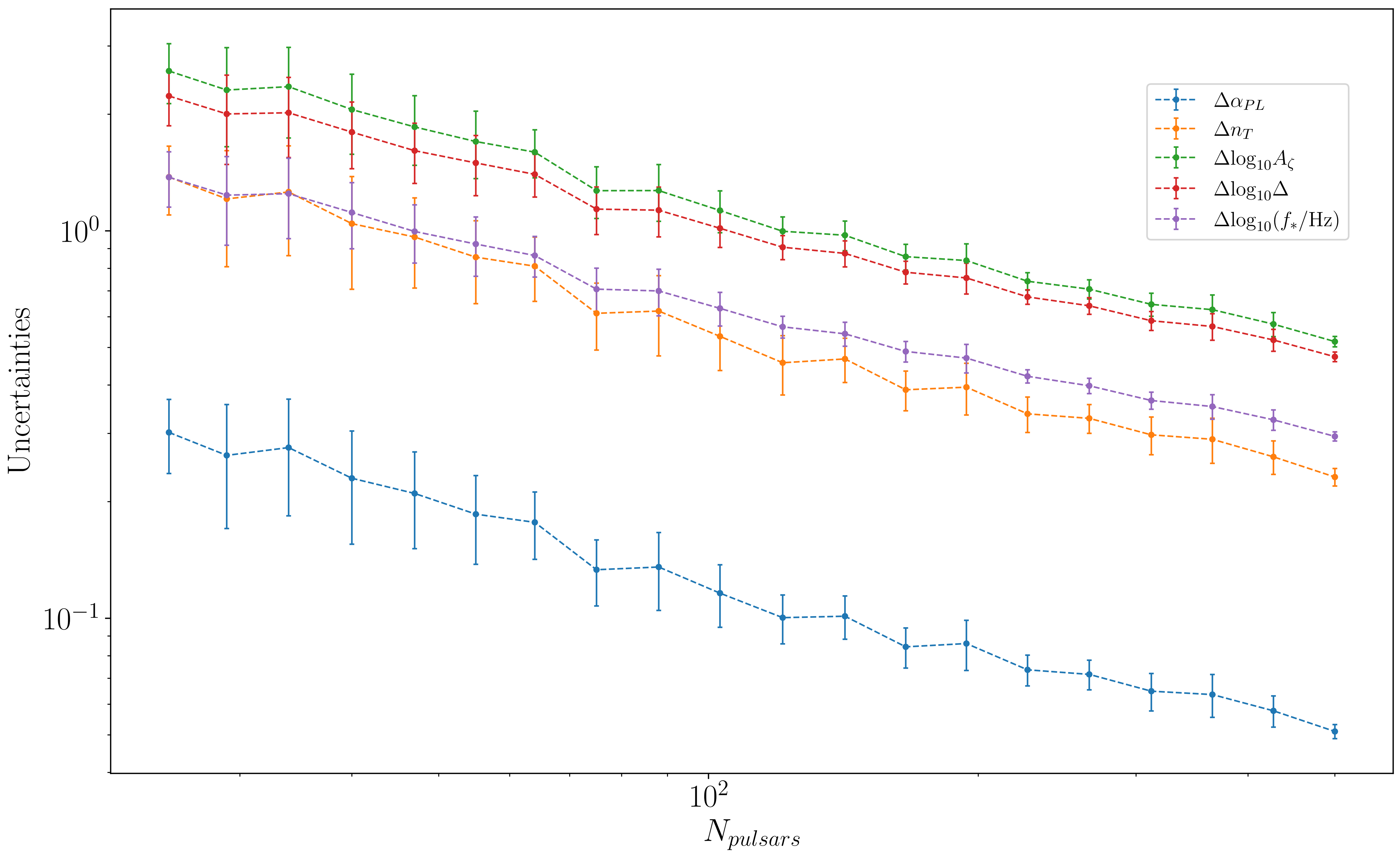
$N_p = 400$ $\sigma_\alpha \sim \mathcal{O}(20\%)$



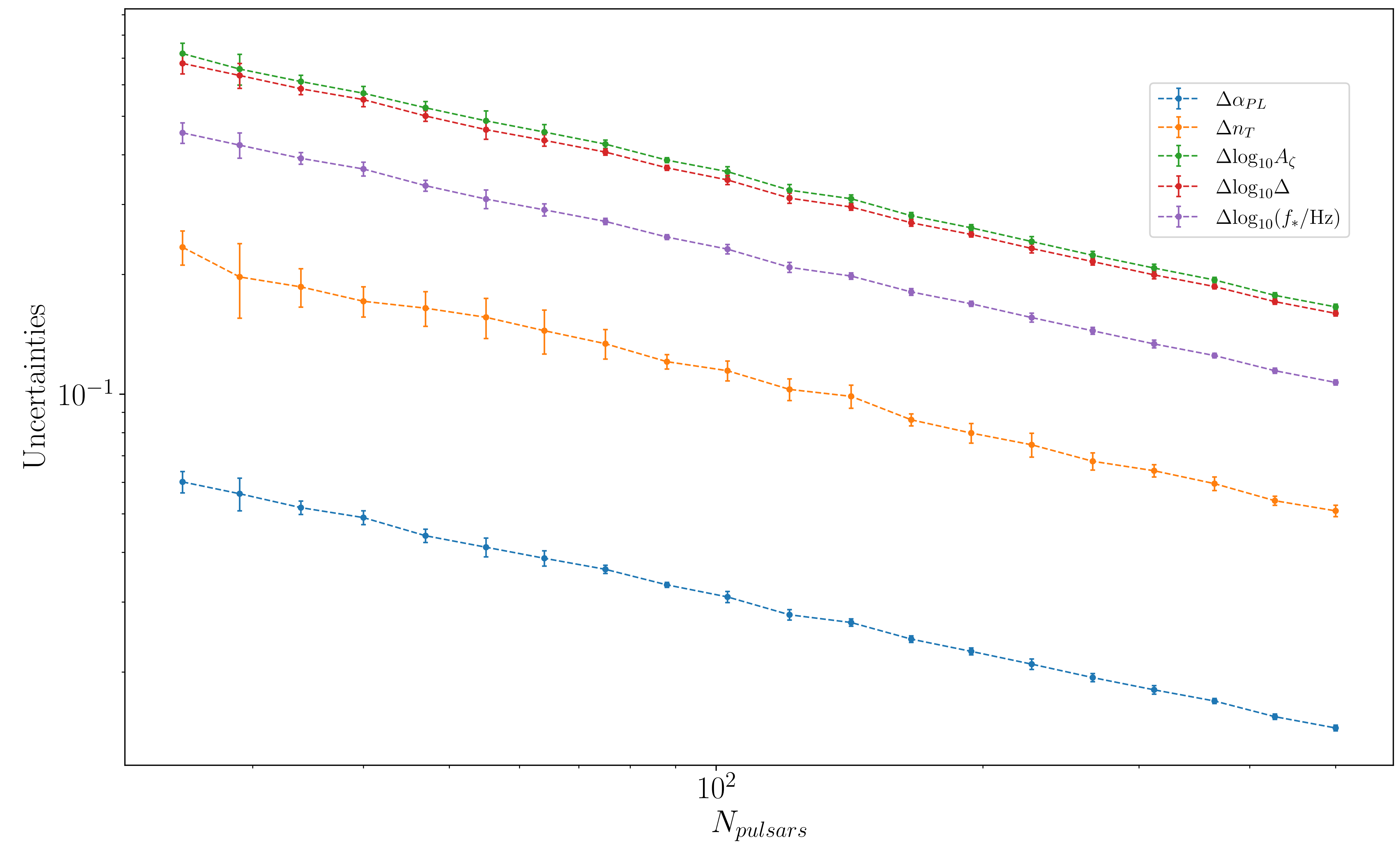

Future SKA-like: 10 yrs, $N_p$ pulsars

# SCALING OF THE UNCERTAINTIES WITH $N$

## EPTA

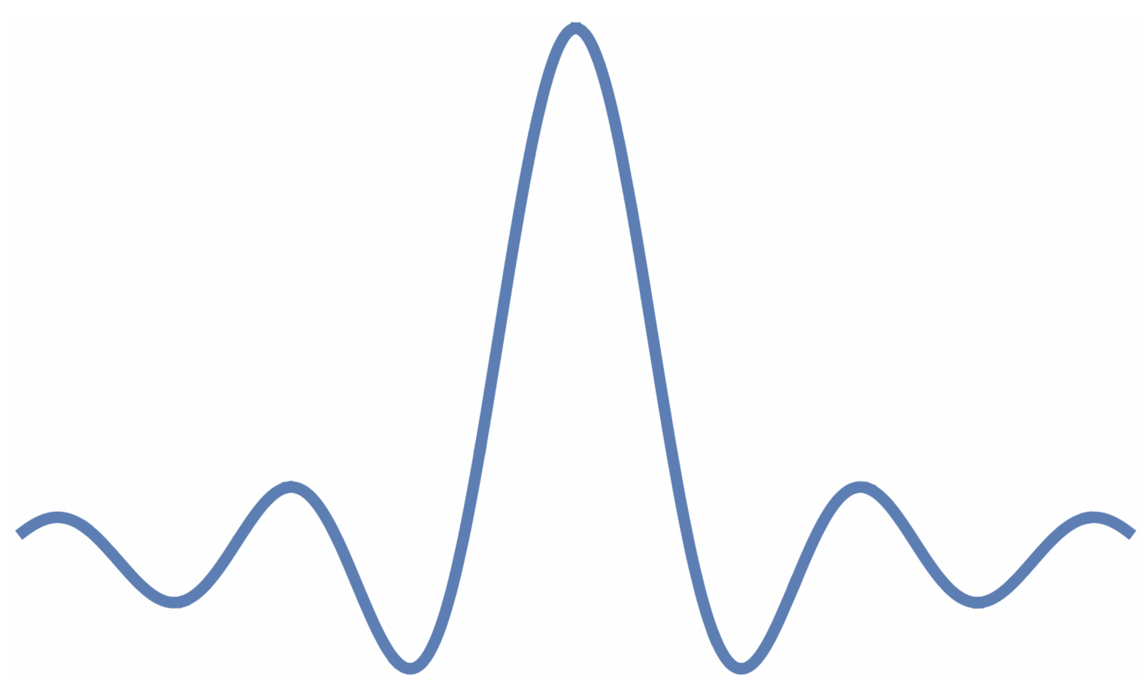



## SKA

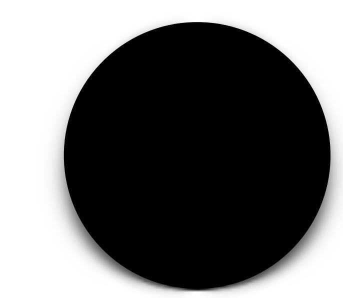



- Expected scaling $\propto 1/\sqrt{N}$
- Much better results for SKA

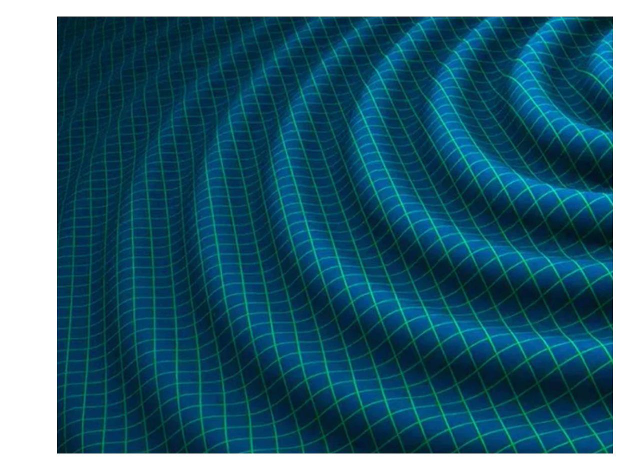
# PRIMORDIAL BLACK HOLES



PBH COLLAPSE



EMISSION OF II ORDER GWs



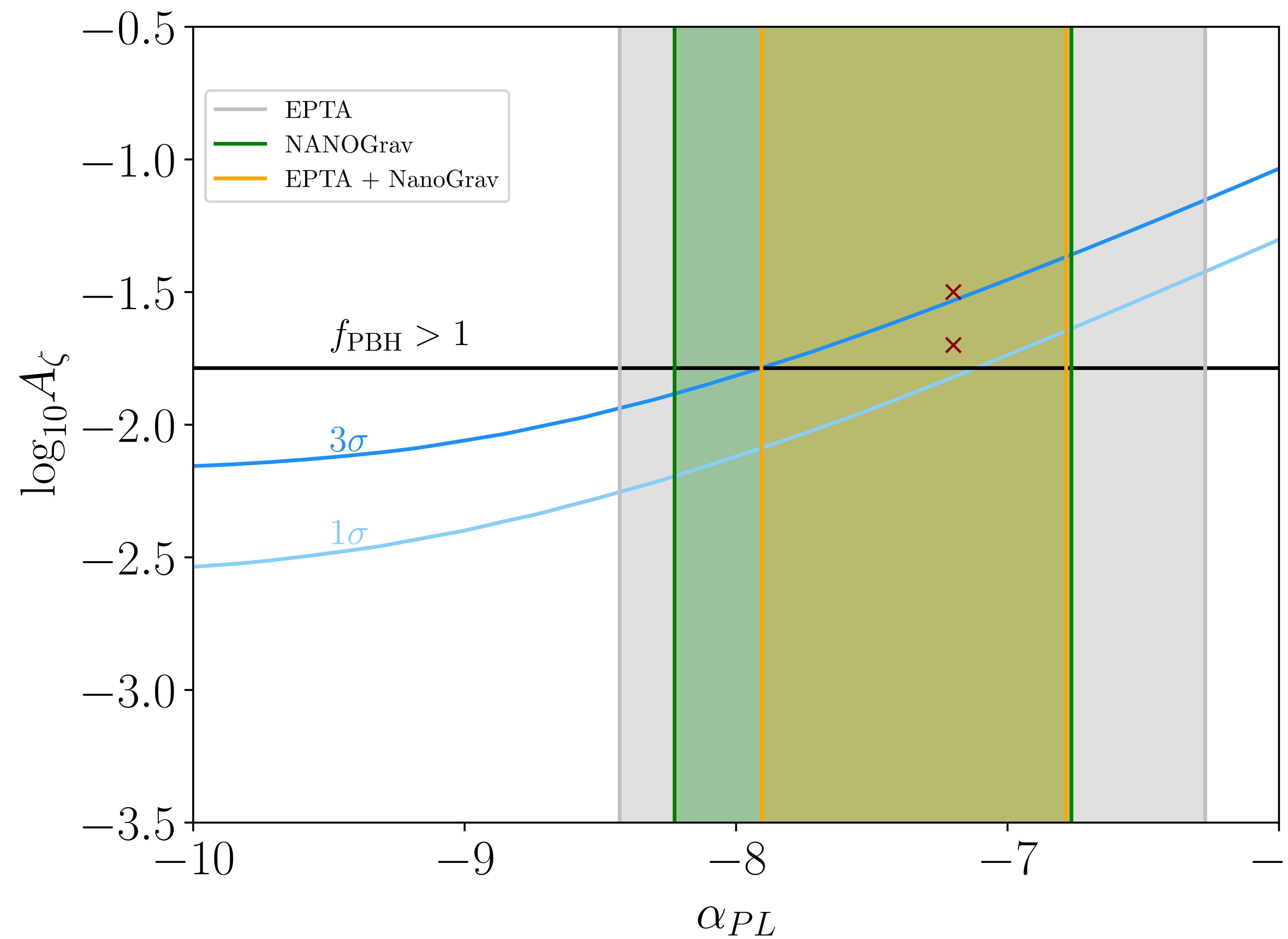
- Fraction $f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$ of the total dark matter today
- Avoid PBH overproduction!

$$f_{PBH} < 1$$

| Large signal amplitude is needed to better constrain SIGW | ⟷ | A too large amplitude overproduces PBH |
|---|---|---|

# CONSTRAINING THE PARAMETER SPACE

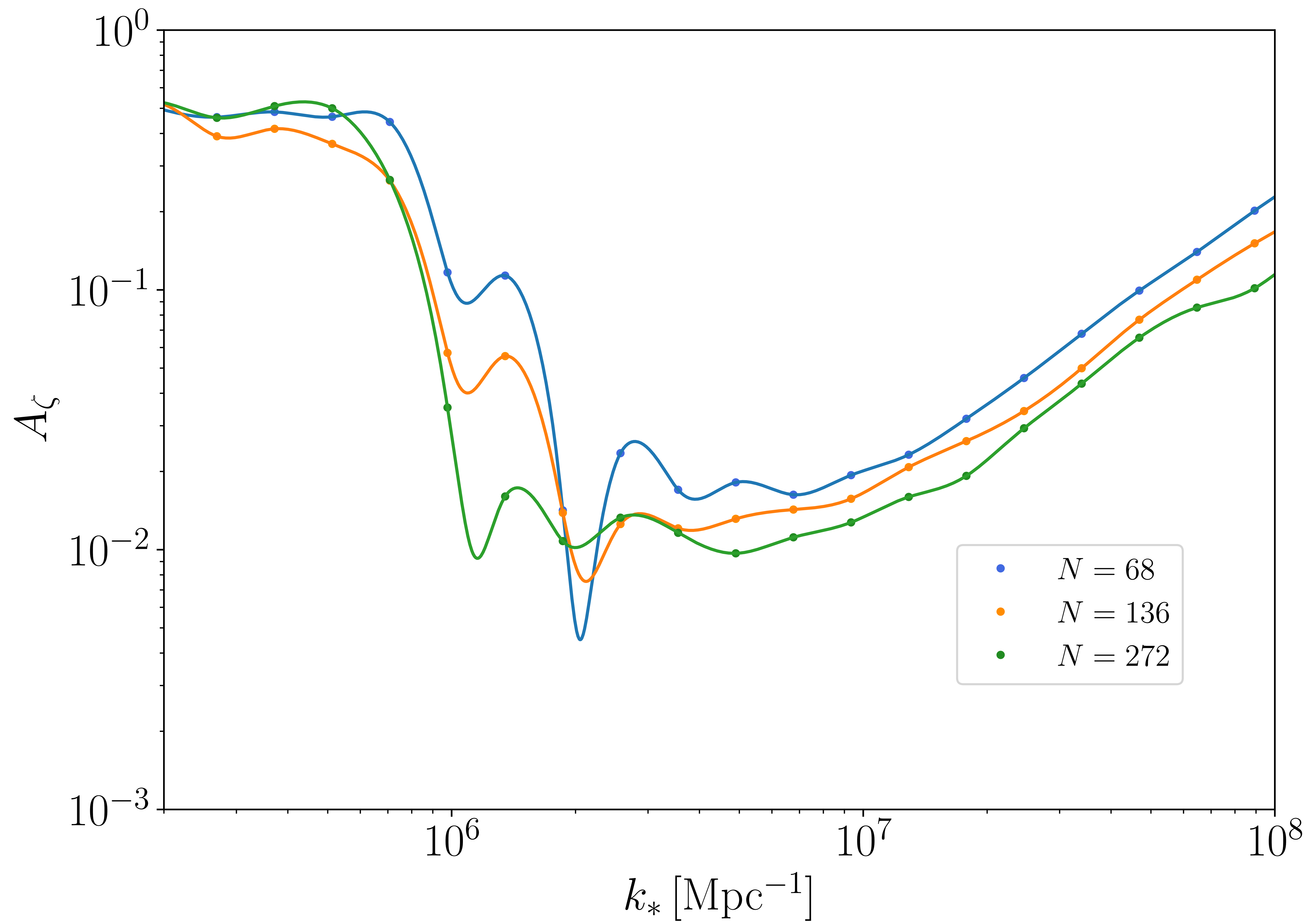
- Look for a region in the parameter space of signal amplitudes where we can:
  - Keep $f_{\rm PBH} < 1$
  - Measure $\log_{10} A_\zeta$ with $< 3\sigma$ uncertainties
  - Have a power-law amplitude within the inferred posteriors



# UPPER BOUND ON $A_\zeta$

See A. J. Iovino, G. Perna, A. Riotto, & H. Veermae arXiv: 2406.20089 for comparison

- Upper bound from NANOGrav15 ($N_p = 68$) and scaling with increasing number of pulsars



# SUMMARY

- Pulsar timing arrays (PTAs) provide an unprecedent opportunity to search for GWs in the nHz frequency range
- We expect to gain in sensitivity with next generation experiments
- Forecasting can be made faster
- Concrete possibility of measuring a scalar-induced GW signal and constrining primordial black holes (PBHs)

# IMAGE CREDITS


*[1]* B. P. Abbott et al, *PRL* **118**, 221101 (2017)

*[2]* A. Stuver/LIGO

*[3]* Christopher Berry blog

*[4]* B. Saxton, NRAO/AUI/NSF

*[5]* H. Thankful Cremartie, *Carnegie Colloquium, October 17, 2023*

*[6]* David Champion/Max Planck Institute for Radio Astronomy

*[7]* Fredrick A. Jenet, Joseph D. Romano, *Am. J. Phys.*, **83**, *635-645 (2015)*

*[8]* NANOGrav Collaboration, arXiv:1810.06594

*[9]* G. Agazie et al 2023 ApJL 951 L8

*[10]* G. Agazie et al 2023 ApJL 952 L37

*[11]* *https://nanograv.org/15yr/Summary/NewPhysics*

*[12]* *https://www.skao.int/en/explore/telescopes*

*[13] V*. Dandoy, V. Domcke, & F. Rompineve *SciPost Phys. Core* **6**, 060 (2023)

*[14]* B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, *Rept. Prog. Phys.* **84**, no.11, 116902 (2021)

# BACKUP SLIDES

# SCALAR INDUCED GW

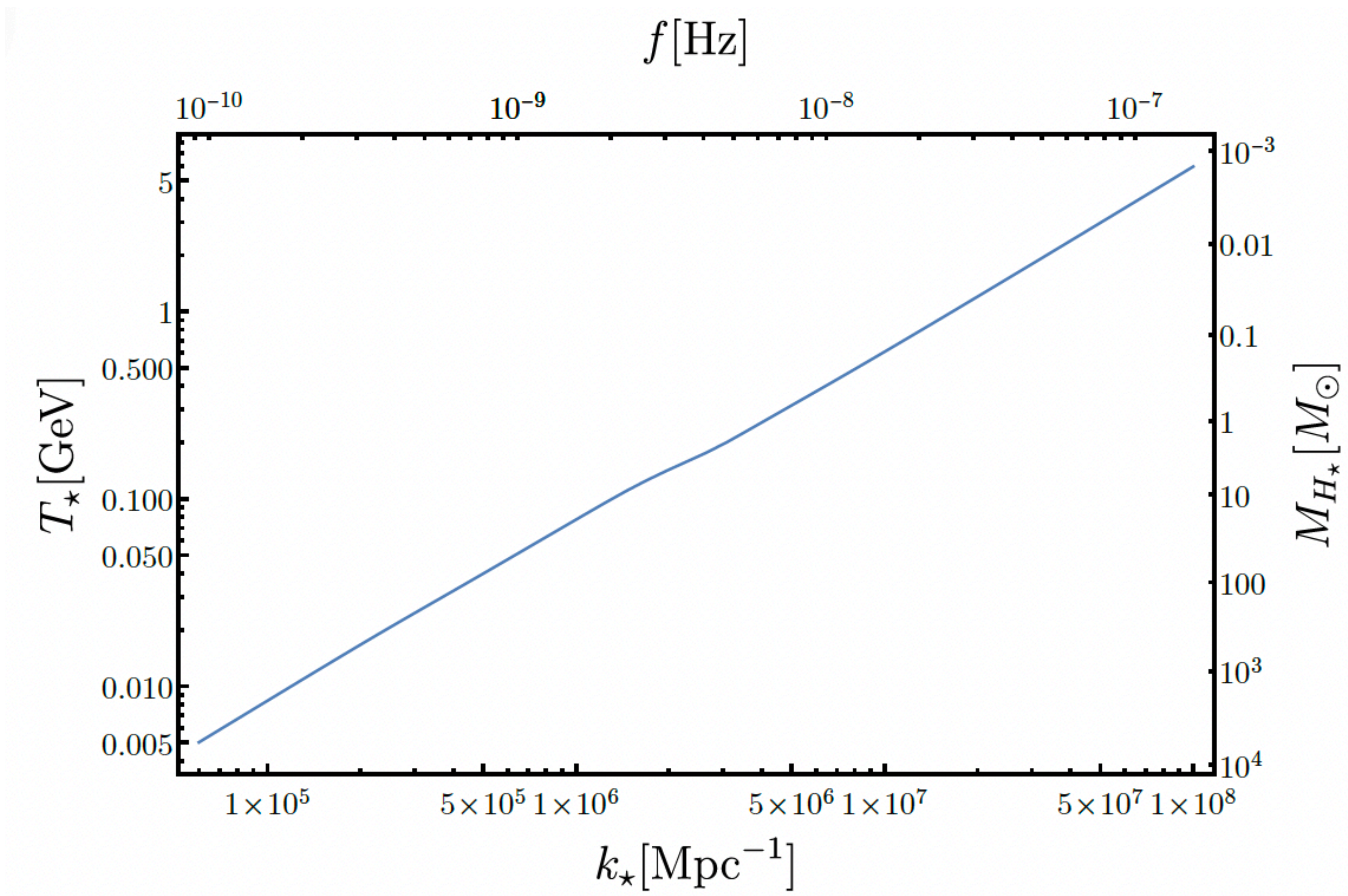
- The spectrum off GWs can be computed analytically

$$\Omega_{GW}\left(\frac{f}{f_*}, \Delta, A_\zeta\right) = \dots$$

- The spectrum today can be easily evaluated with a temperature-dependent modulation (GWs are decoupled from the thermal bath and they always evolve as radiation)

$$\Omega_{\rm GW}h^2 = \left[\frac{a(T)}{a_0}\right]^4 \left[\frac{H(T)}{H_0/h}\right]^2 \Omega_{\rm GW}(T)$$

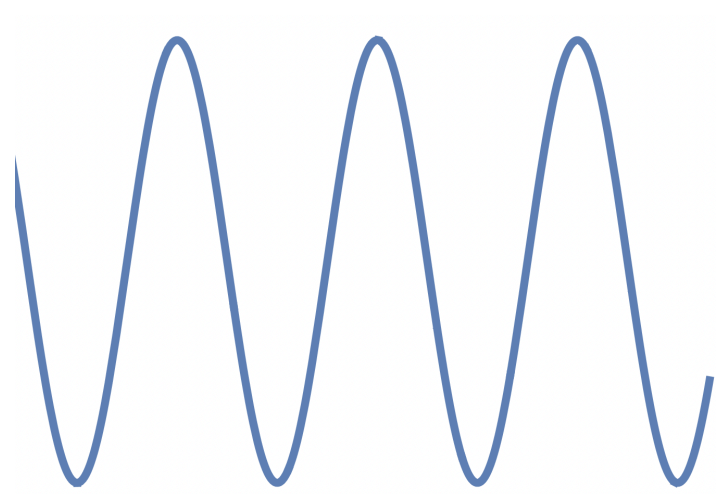
$$\approx 1.6\times 10^{-5}\left[\frac{g_*(T)}{100}\right]\left[\frac{g_{*s}(T)}{100}\right]^{-\frac{4}{3}}\Omega_{\rm GW}(T)$$



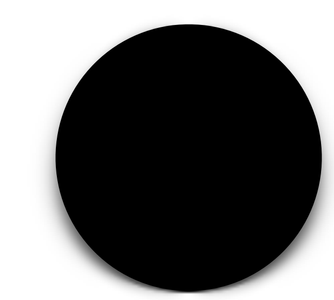

Credit: [13]

# PRIMORDIAL BLACK HOLES

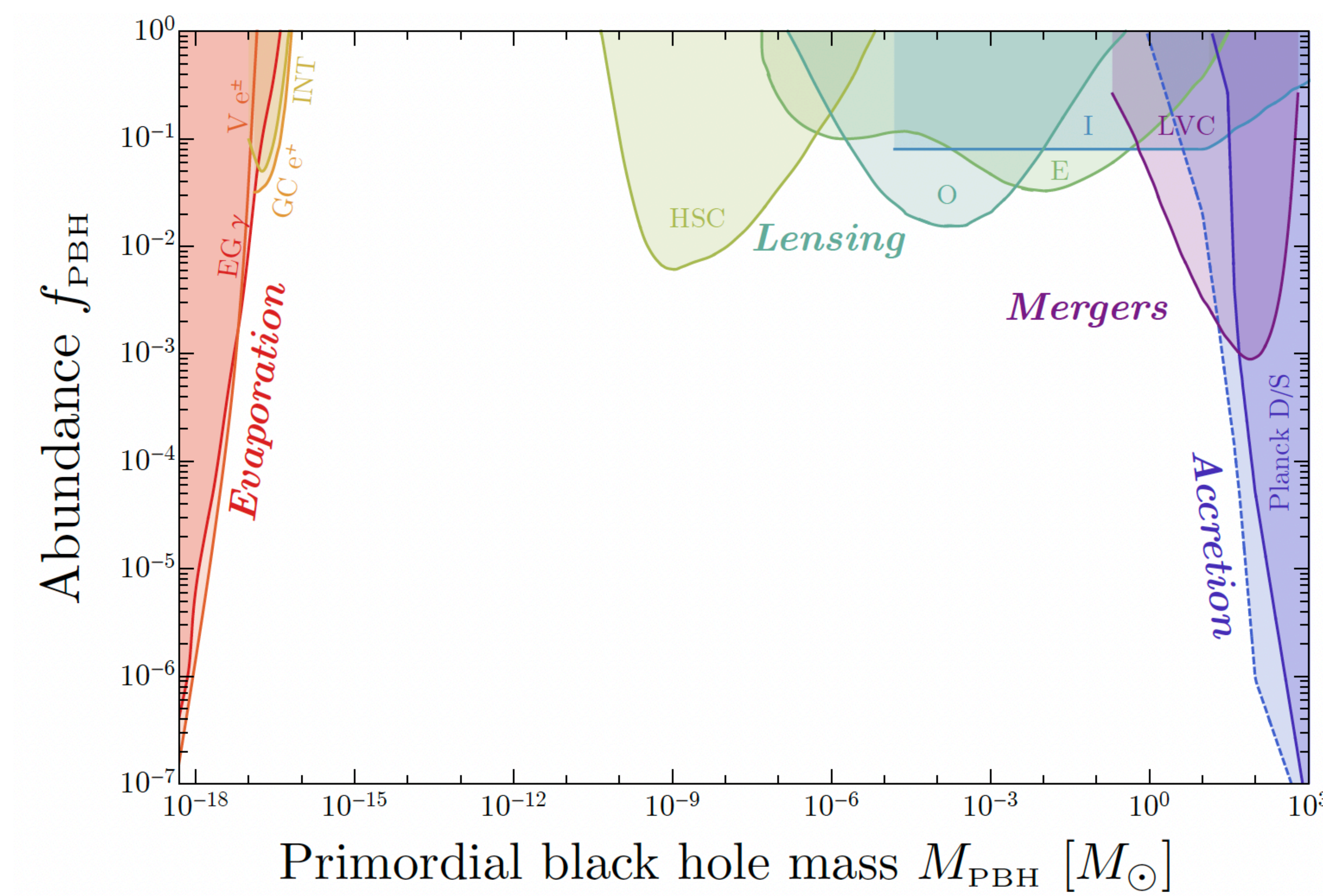
- Mass of the PBH and frequency of the GW are related by the Hubble scale at formation



$$f_{GW} \approx 3 \cdot 10^{-9}\,\mathrm{Hz} \left(\frac{m_{PBH}}{M_\odot}\right)^{-1/2}$$

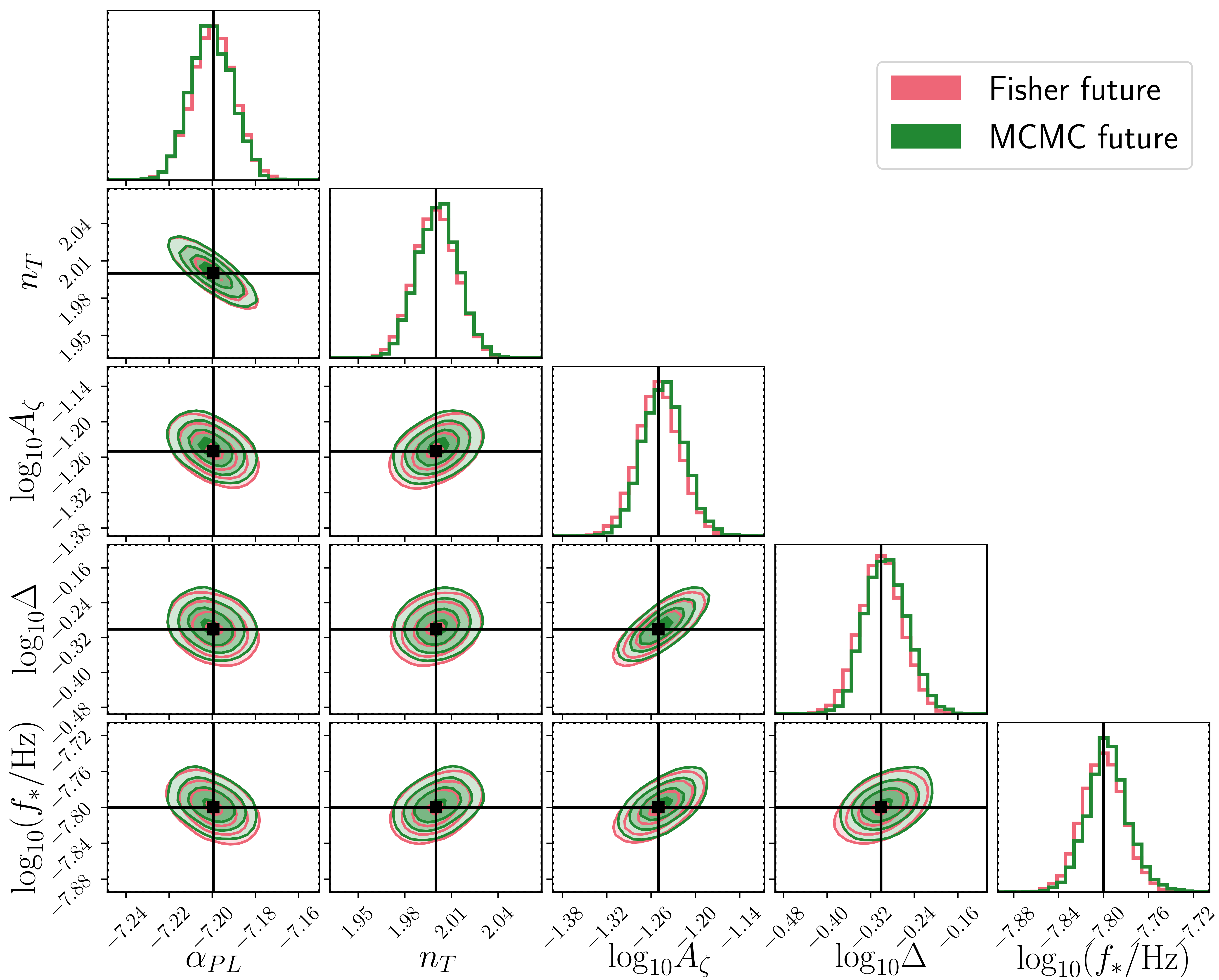


- Complementary constraints from PBH overproduction



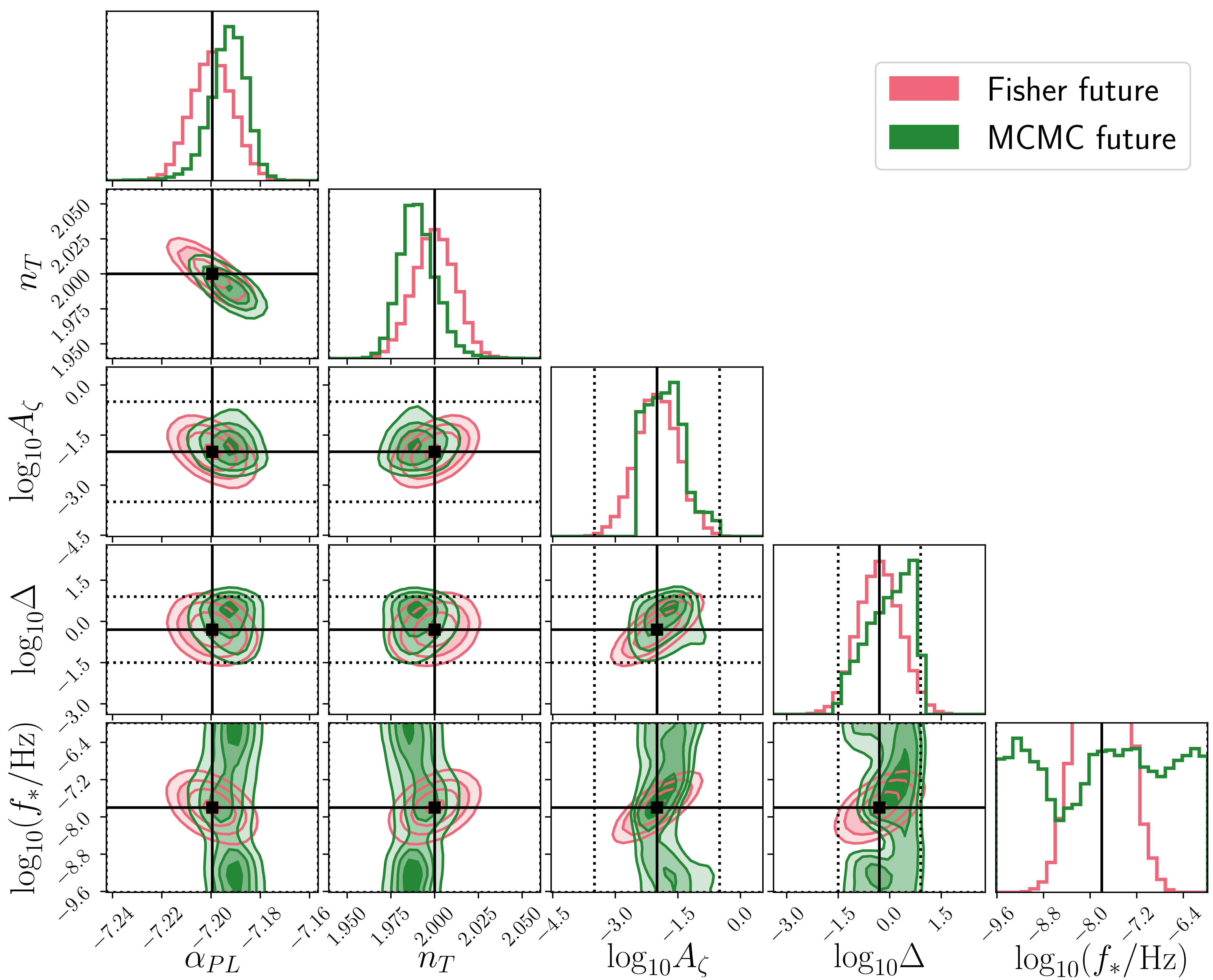

Credit: [14]

# FIM VS MCMC FOR NOISELESS DATA




- EPTA-like **noiseless** data
- Large SNR to see if the two methods agree ($\log_{10}A_\zeta = -1.25$)

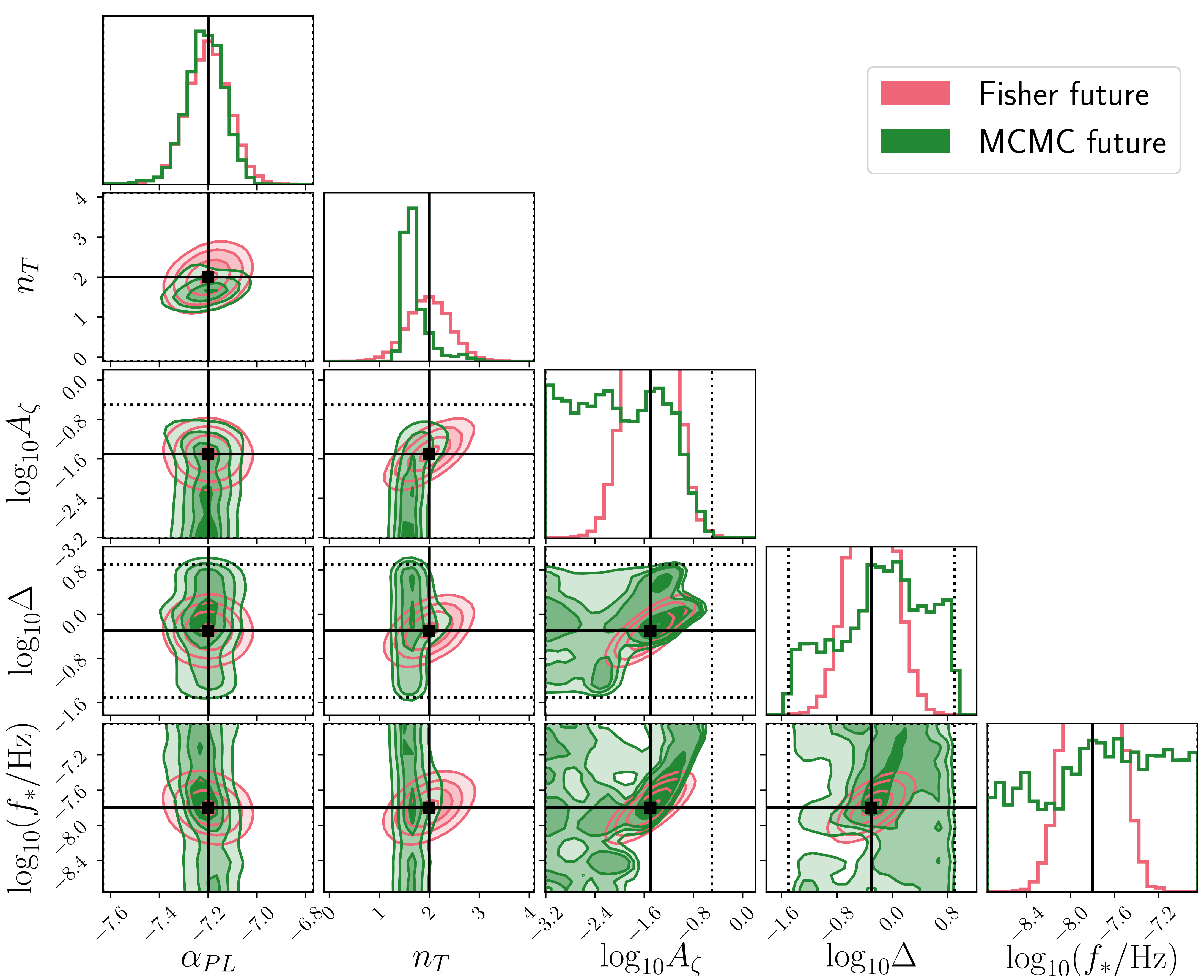
# FIM VS MCMC FOR NOISELESS DATA




- EPTA-like **noiseless** data
- Lowering the SNR ($\log_{10}A_\zeta = -2$)
- Degeneracy on $f_*$
- Visible effect of the priors

# COMPARISON BETWEEN EPTA AND SKA DATA

## EPTA




## SKA