パルサータイミングアレイによる重力波観測とその最新結果

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InPTA
Indian Pulsar Timing Array

NANOGrav
Physics Frontiers Center

credit: Danielle Futselaar, MPIfR

～中性子星の観測と理論～研究活性化ワークショップ2023

1. Pulsar Timing Array

2. Timing Analysis

3. Results

4. Summary

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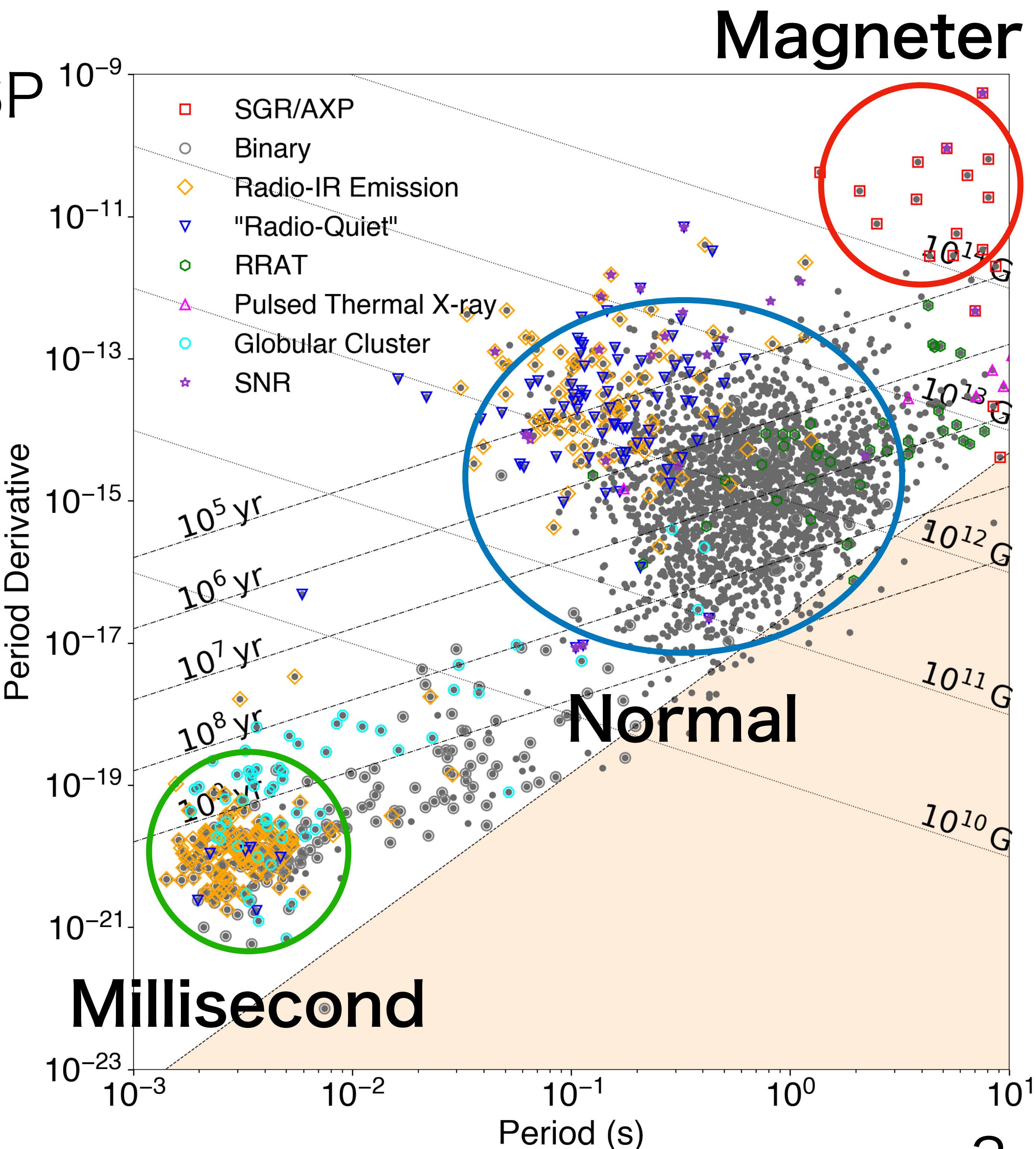
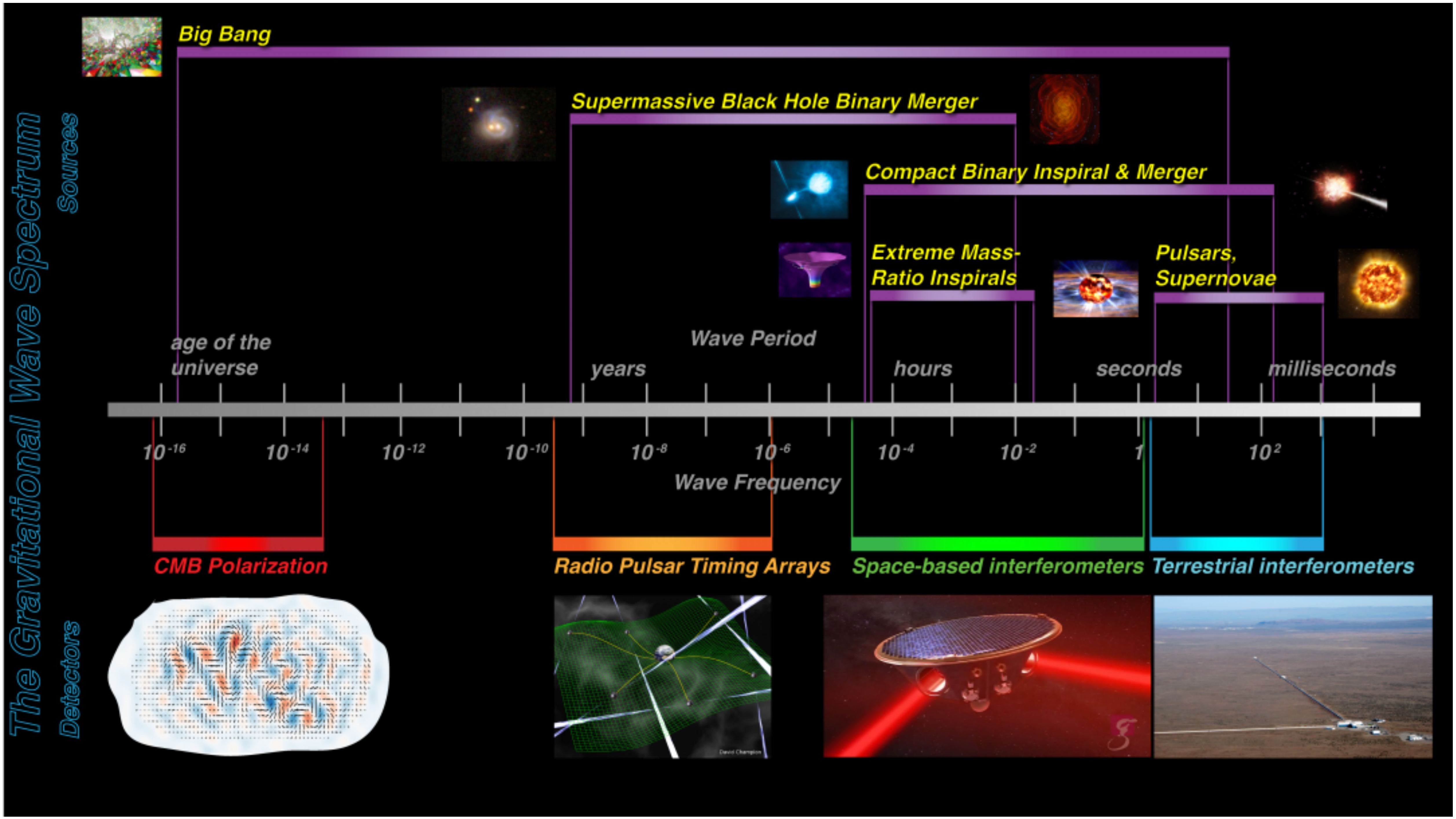
Pulsar

- Period: 1ms - 20s
- Very stable, especially for MSP
- Radio ~ Gamma-ray
- ~3300 discoveries
- Pulsar Zoo



Gravitational Waves



Credit: NASA/J. I. Thrope

Gravitational Wave Background (GWB)

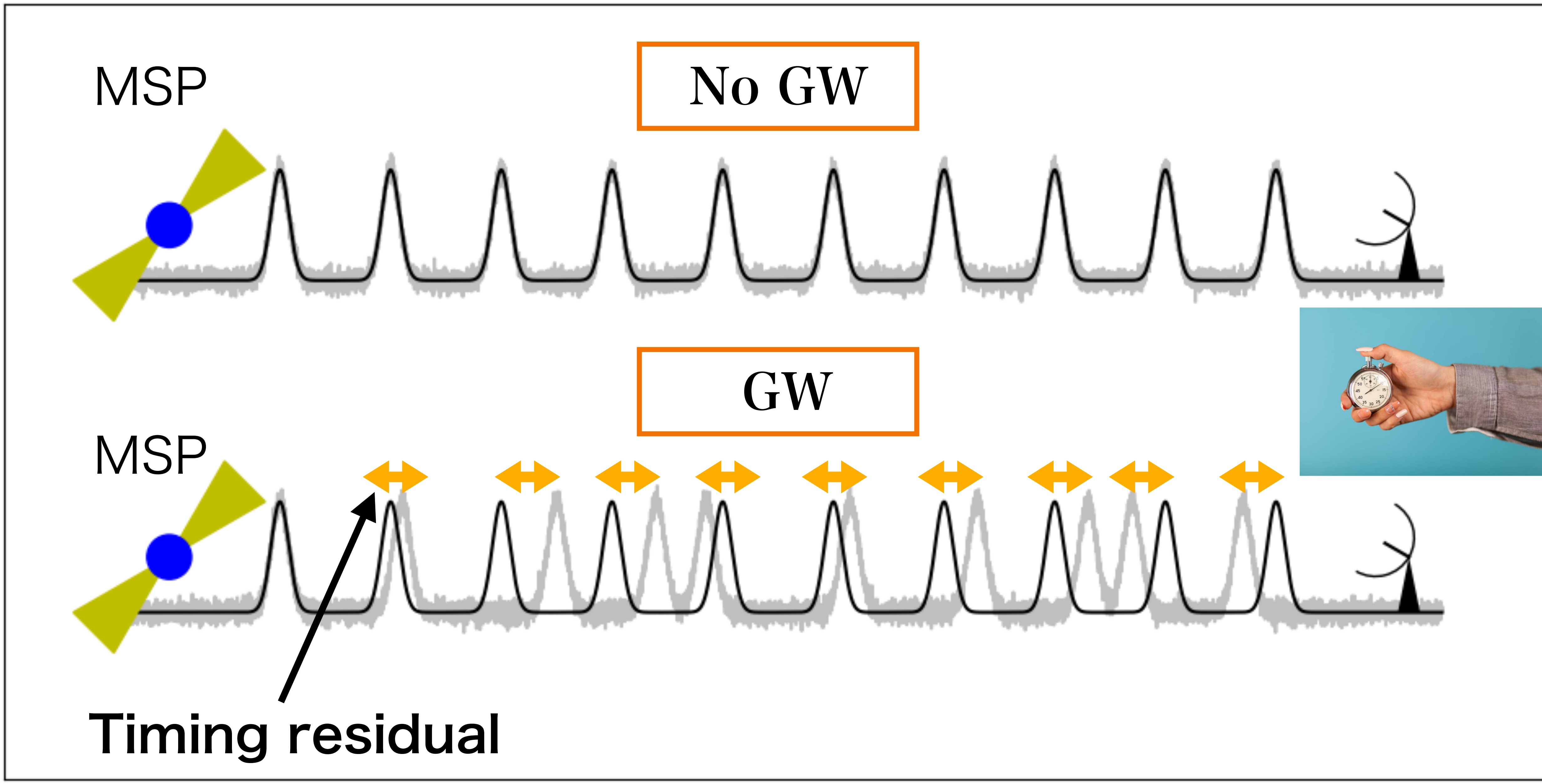
- ensemble of GWs (SMBHB, cosmic strings, etc)
- expected target signal is from SMBHBs

$$P(f) \propto A^2 \left(\frac{f}{f_{\rm ref}} \right)^{-\gamma}$$

$$\gamma = \frac{13}{3}$$ for the GWB from SMBHBs

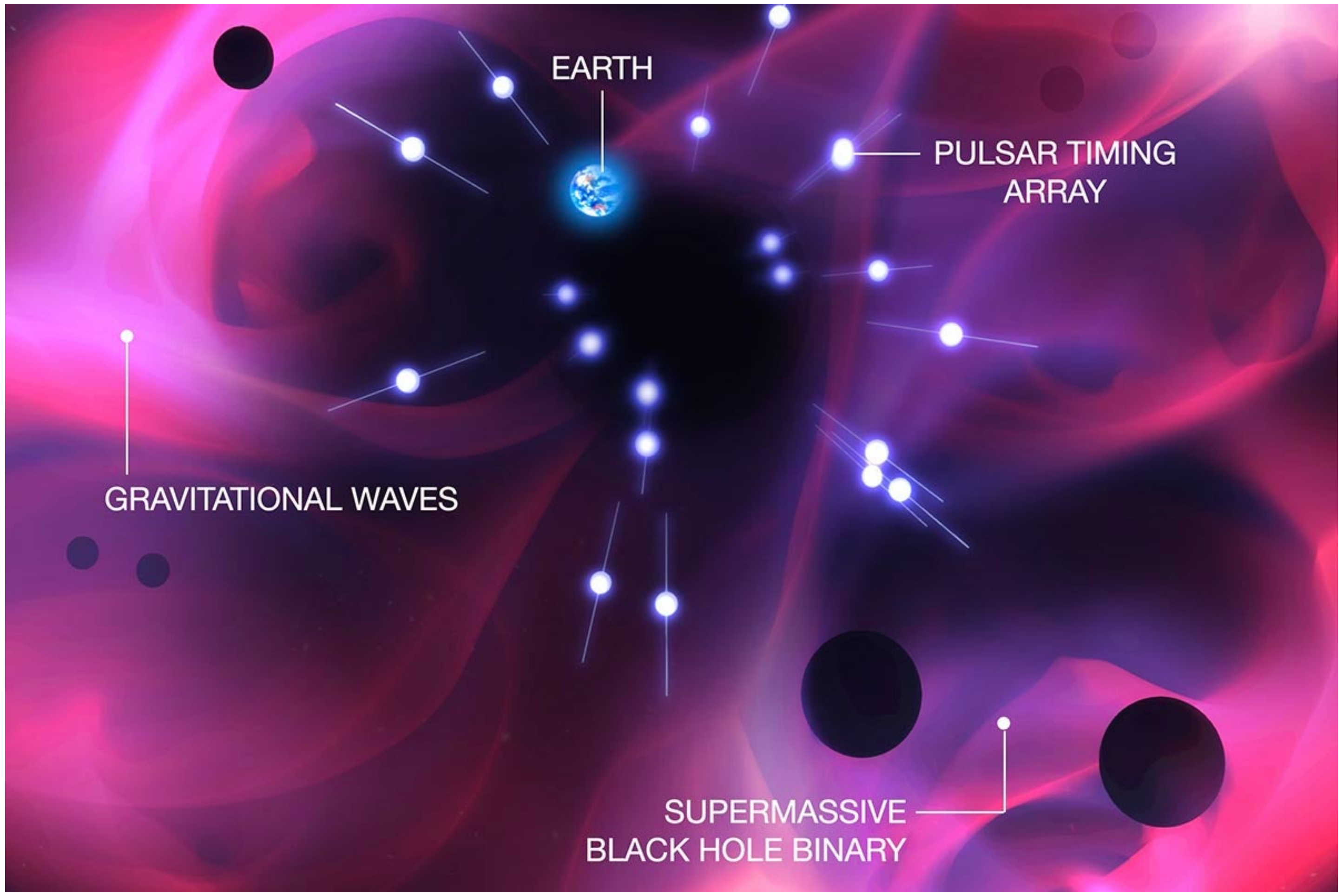
Credit: OzGrav

Pulsar Timing Array (PTA)



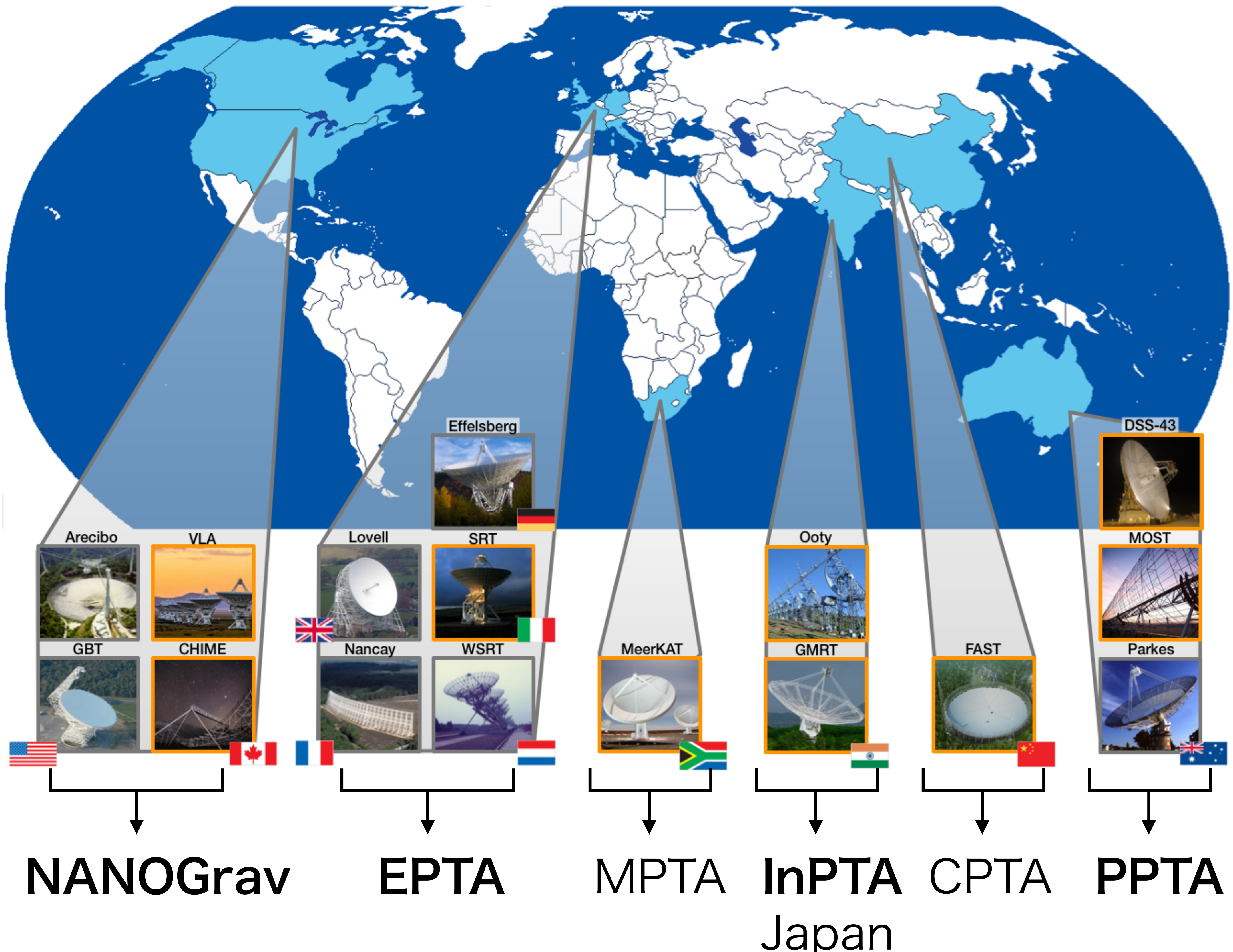
Pulsar Timing Array (PTA)

- array of very stable MSPs
- accurate timing observation, O(10y)
- GW frequency
  - cadence and period
  - $O(\text{week})^{-1} \sim O(10\text{y})^{-1}$
  - μHz ~ nHZ



Credit: Carl Knox at OzGrav

Pulsar Timing Array (PTA)



Credit: radio telescopes of the International Pulsar Timing Array (IPTA)

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Timing Model

Deterministic timing model

- Spin : phase, period, period derivative
- Astrometry : position, proper motion, parallax
- Binary : more than 5 Keplerian parameters
- Dispersion measure : dispersive delay $\propto \nu^{-2}$
- Ephemeris : JPL DE440 model
- Earth's motion
- Gravitational potential in the solar system

Noise components

- **White noise**
  - EFAC : a linear scaling of TOA uncertainties
  - EQUAD : added to the TOA uncertainties in quadrature
  - ECORR : common to all subbands at the same epoch

$$\sigma^2_{\mathrm{scaled}} = \mathrm{EFAC}^2 \times (\sigma^2_{\mathrm{original}} + \mathrm{EQUAD}^2) + \mathrm{ECORR}^2$$

- **Red noise**
  - achromatic : include GWs
  - chromatic : Interstellar medium effects

    dispersion measure ($\propto \nu^{-2}$), scattering ($\propto \nu^{-4}$)

Noise components

- **Red noise**

$$\Phi_{ab} = \Gamma_{ab}\Phi$$

describes the correlations between pulsar pairs (Γ_{ab})

power law spectrum (Φ)

CURN : $\Gamma = \delta_{ab}$

monopole : $\Gamma = 1$

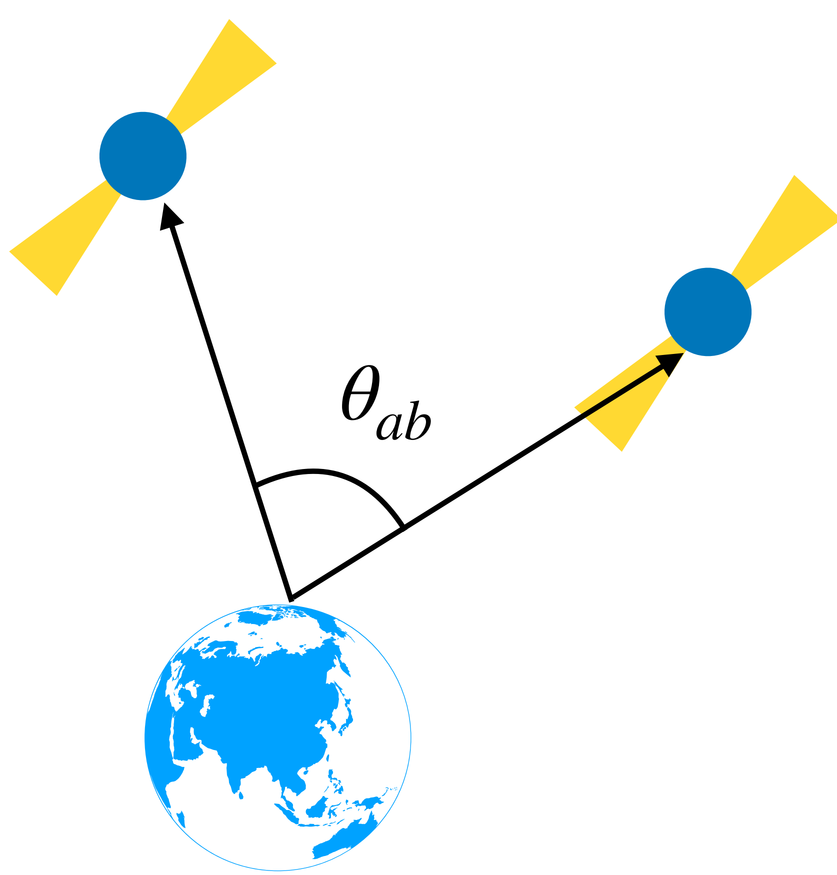
dipole : $\Gamma(\theta_{ab}) = \cos(\theta_{\mathrm{ab}})$

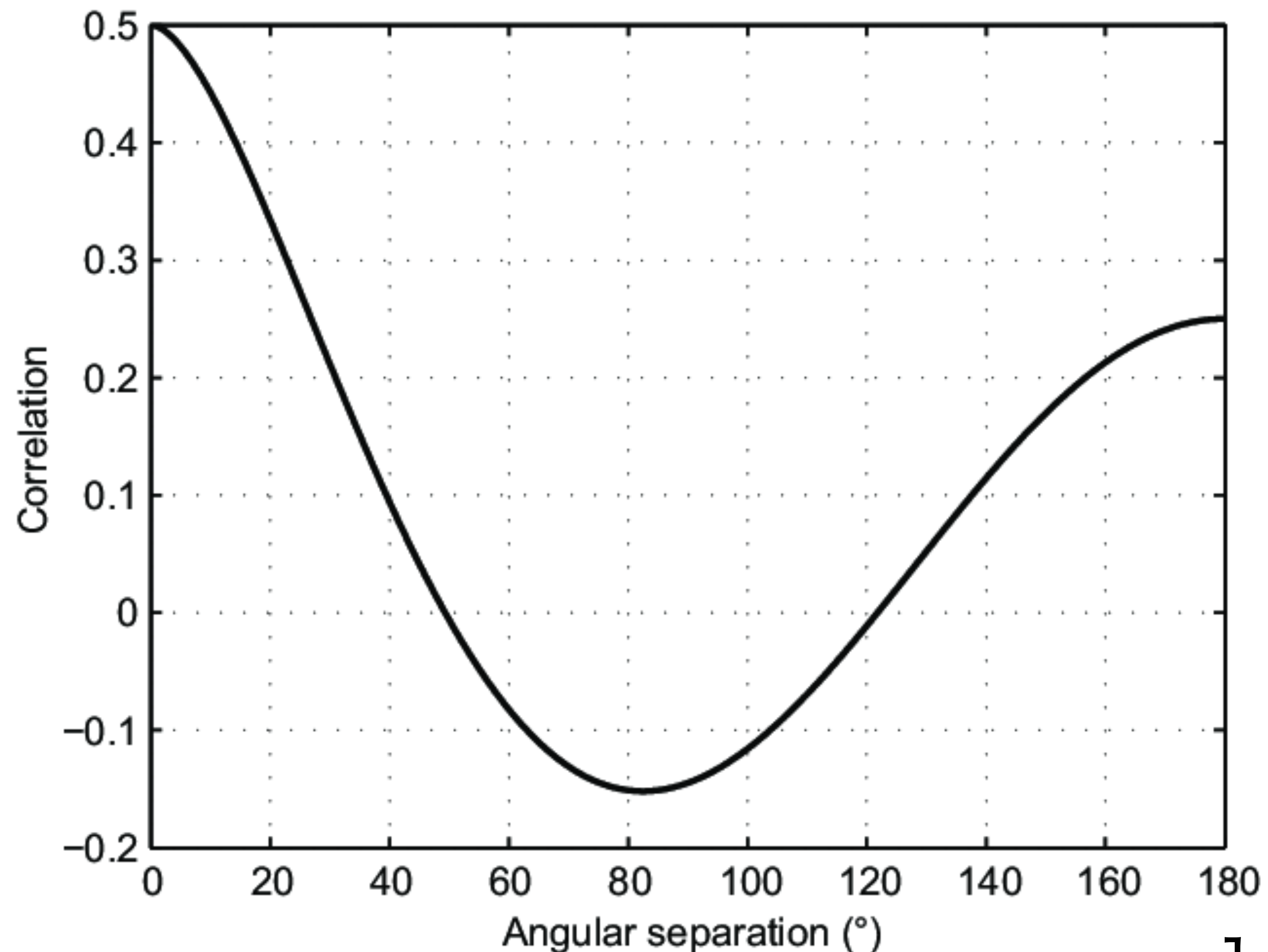
HD : $\Gamma(\theta_{ab}) = \frac{3}{2}x\ln(x) - \frac{1}{4}x + \frac{1}{2}(1 + \delta_{ab})\ ,\ x = \frac{1 - \cos\theta_{ab}}{2}$

Hellings-Downs curve

- Spacial correlation between two pulsars
- ”quadrupolar” trend

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





Bayesian analysis

Bayesian method

prior **likelihood**

$$p(\boldsymbol{\theta} \,|\, \boldsymbol{y}) = \frac{p(\boldsymbol{\theta})p(\boldsymbol{y} \,|\, \boldsymbol{\theta})}{p(\boldsymbol{y})}$$

posterior **evidence**

Model selection

Bayes factor $$BF_{\boldsymbol{\theta}_2}^{\boldsymbol{\theta}_1} = \frac{p(\boldsymbol{y} \,|\, \boldsymbol{\theta}_1)}{p(\boldsymbol{y} \,|\, \boldsymbol{\theta}_2)}$$

If BF > 1, model1 is preferred over model2

Likelihood

Likelihood : $L \propto \exp\left(-\frac{1}{2}\boldsymbol{\delta t}^{\mathrm{T}}\boldsymbol{C}^{-1}\boldsymbol{\delta t}\right)$

Covariance matrix : $\boldsymbol{C} = \boldsymbol{N} + \boldsymbol{TBT}^{\boldsymbol{T}}$

White noise covariance matrix
- EFAC, EQUAD, ECORR

Red noise
- include GWs

Data set

PTA	Data span (yr)	Pulsars	Telescopes
NANOGrav	15	68	3
EPTA	25	25	6
InPTA	3.5	10	1
PPTA	18	32	1

- Each group has reported their results independently (EPTA and InPTA are combined)
- International PTA (IPTA) is combining all the PTA data

\- most sensitive data set

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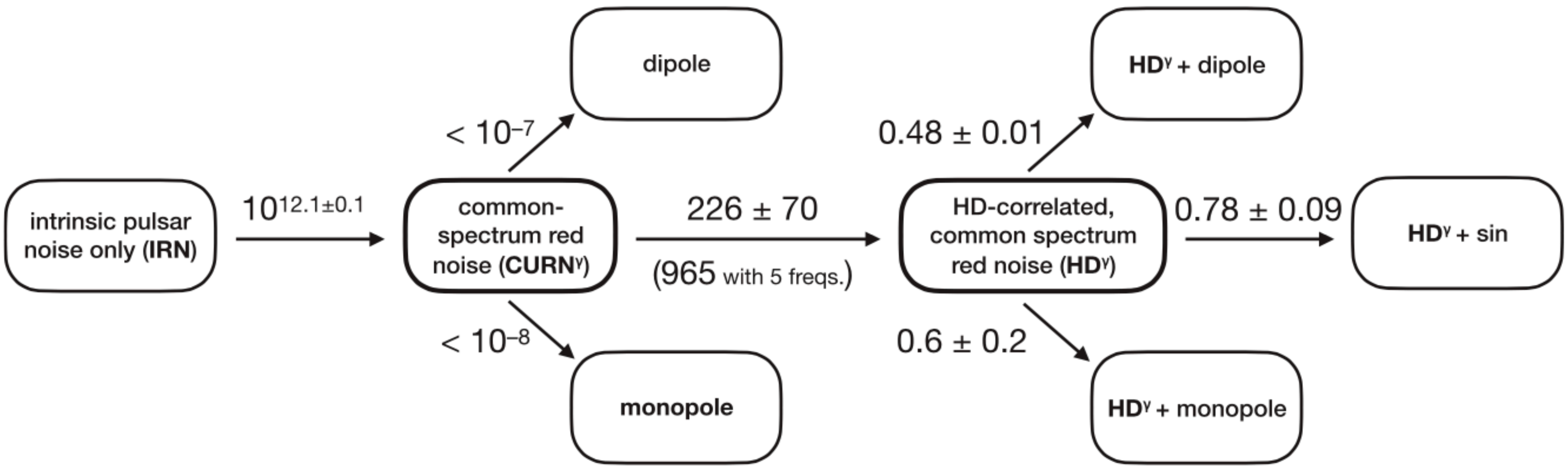
Bayes factors comparison

Bayes factors between models (NANOGrav)



・HD is favored over CURN

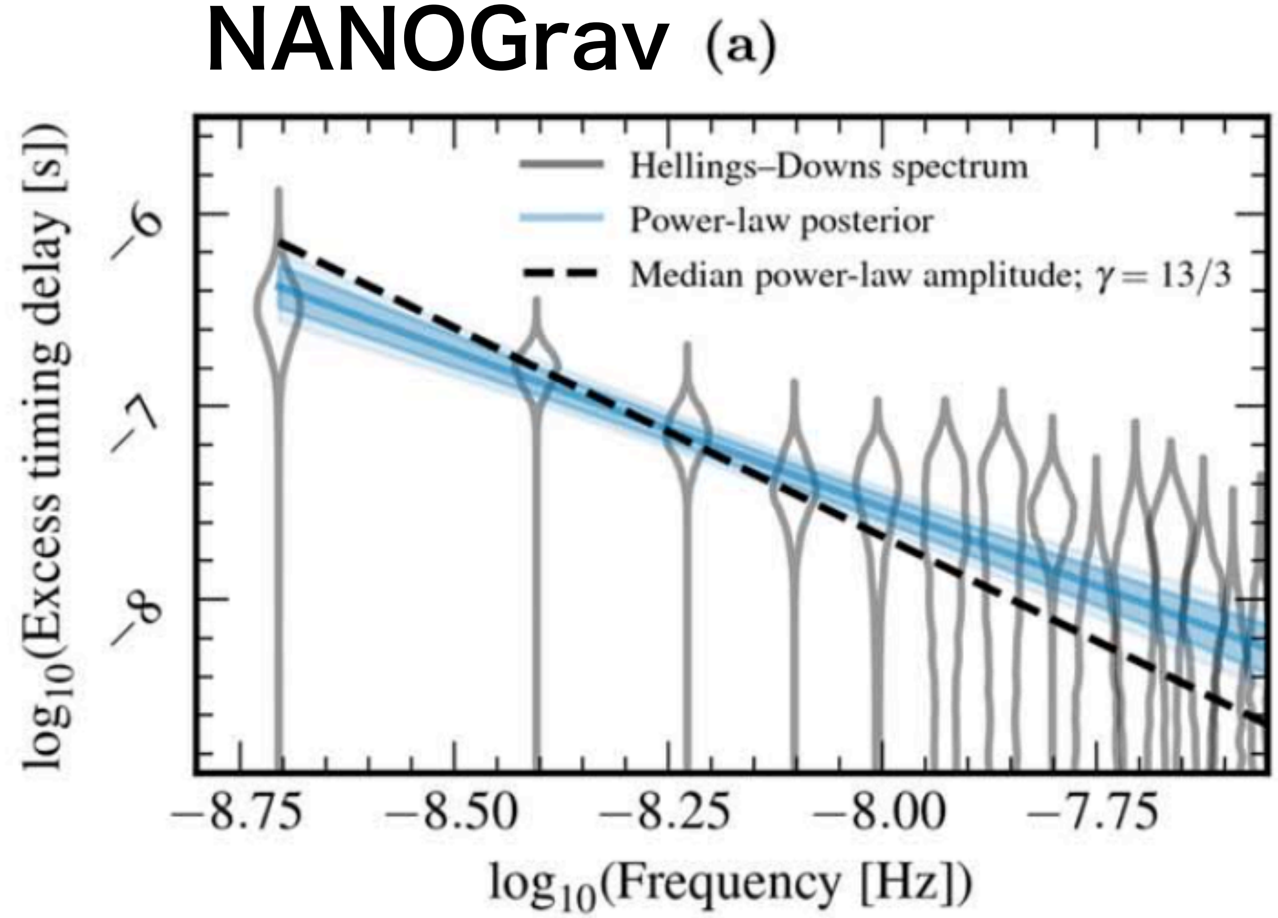
-> spatially correlated

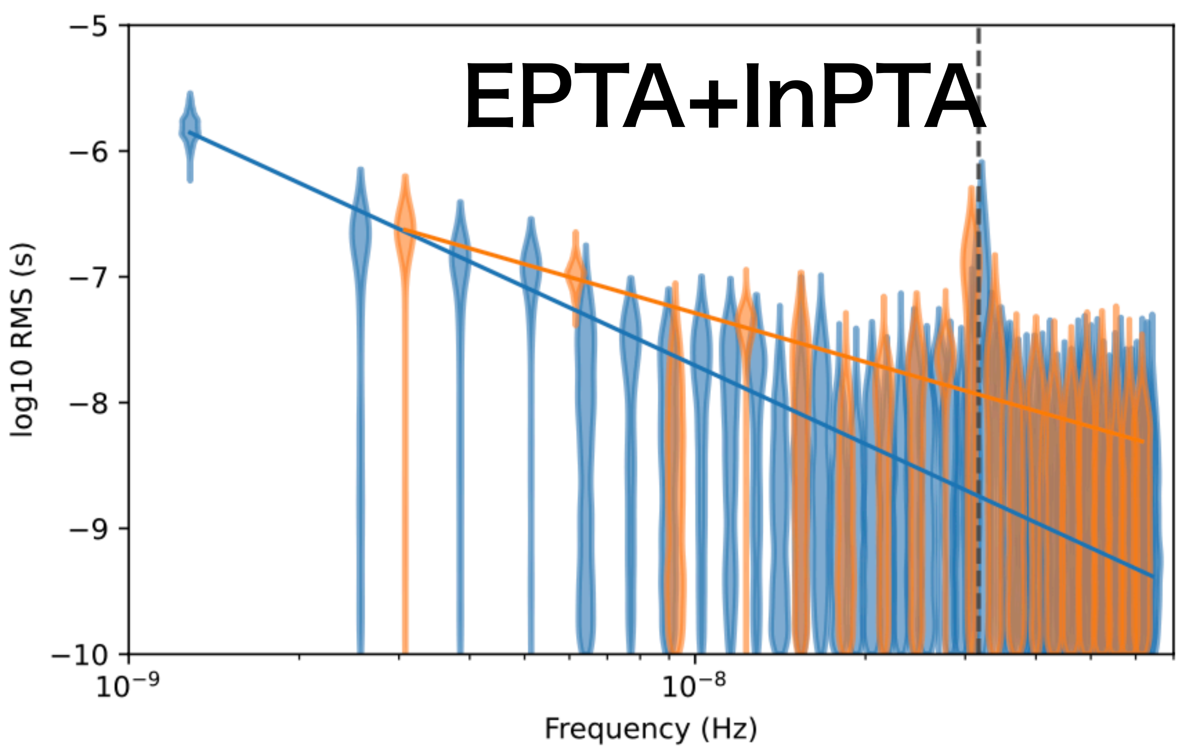
・dipole and monopole processes are strongly disfavored

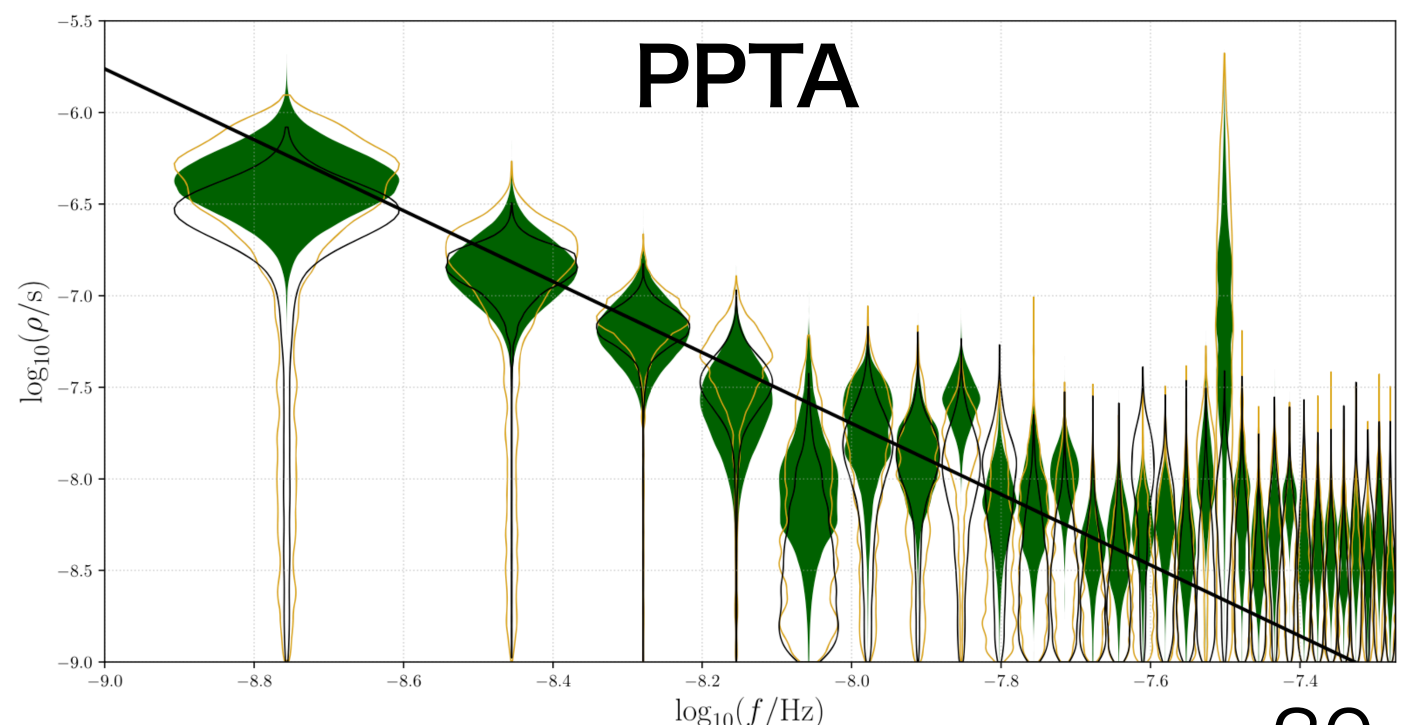
HD power spectrum

- HD power spectrum for each PTA
- excess power at low frequency

NANOGrav (a)



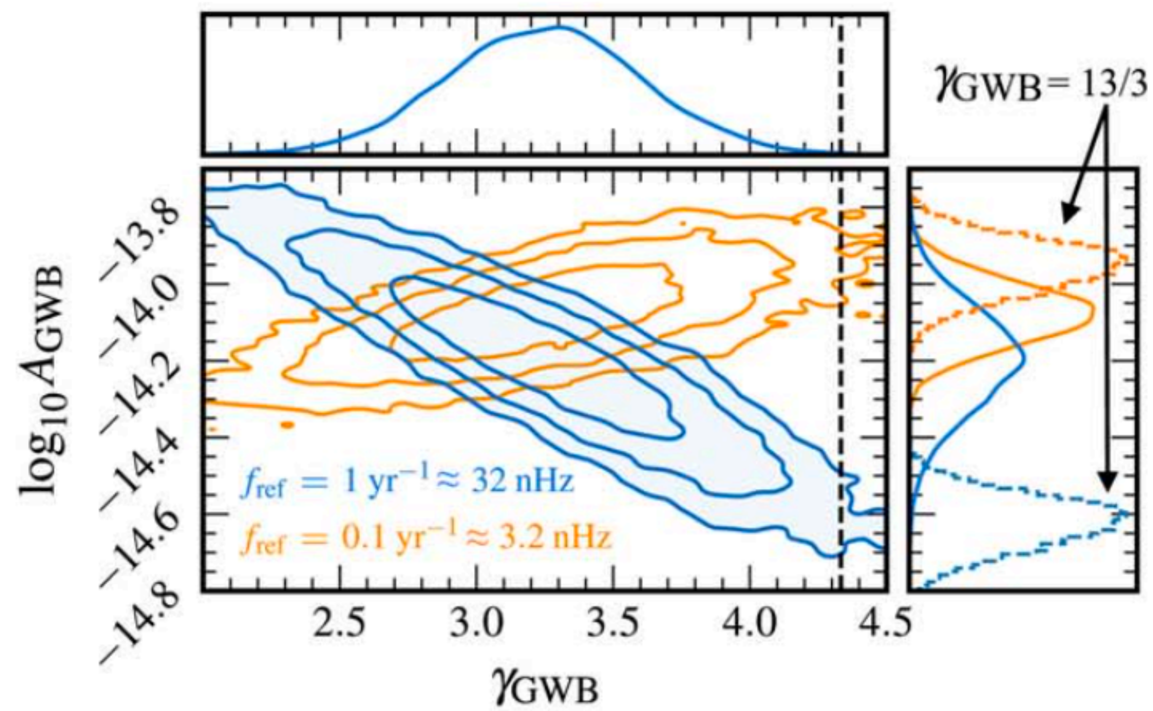




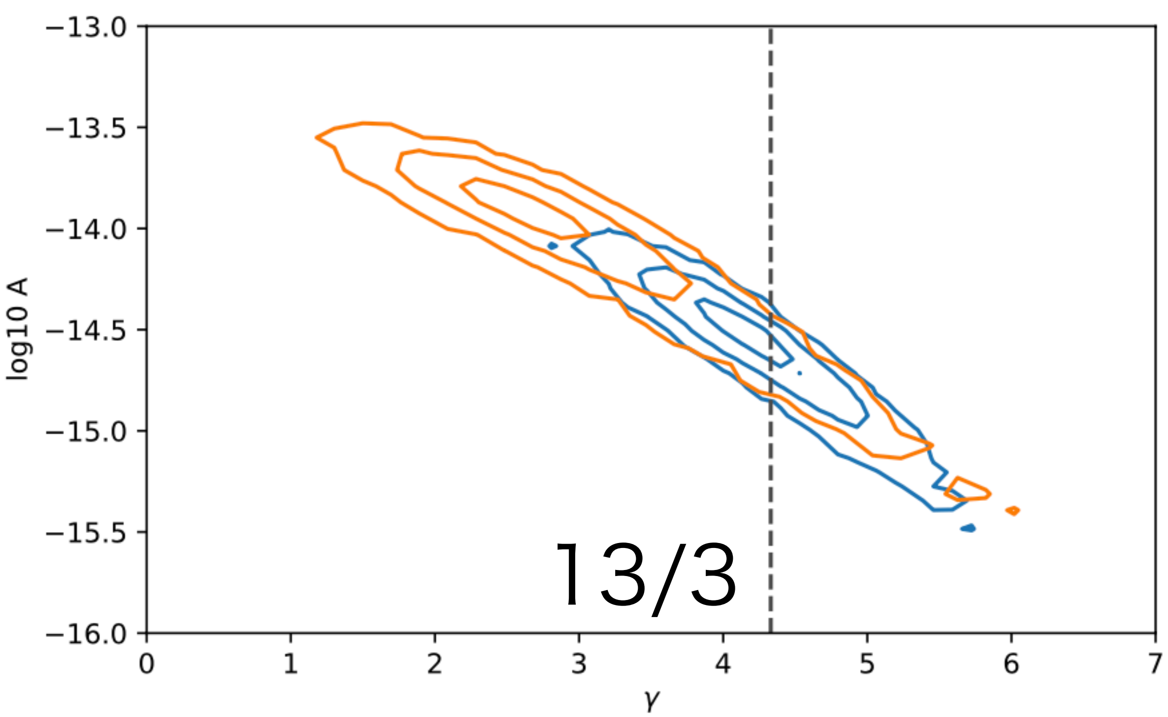
HD power spectrum

- posteriors of GWB amplitude and index
- they are within 3σ for each PTA

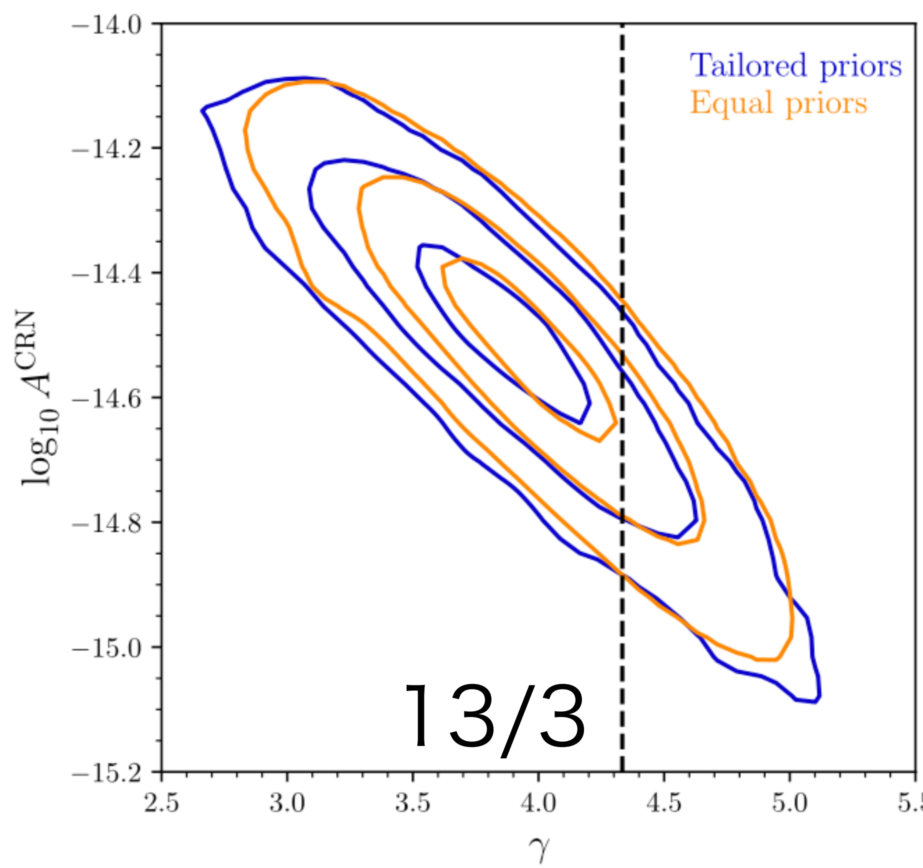
NANOGrav (b)



EPTA+InPTA



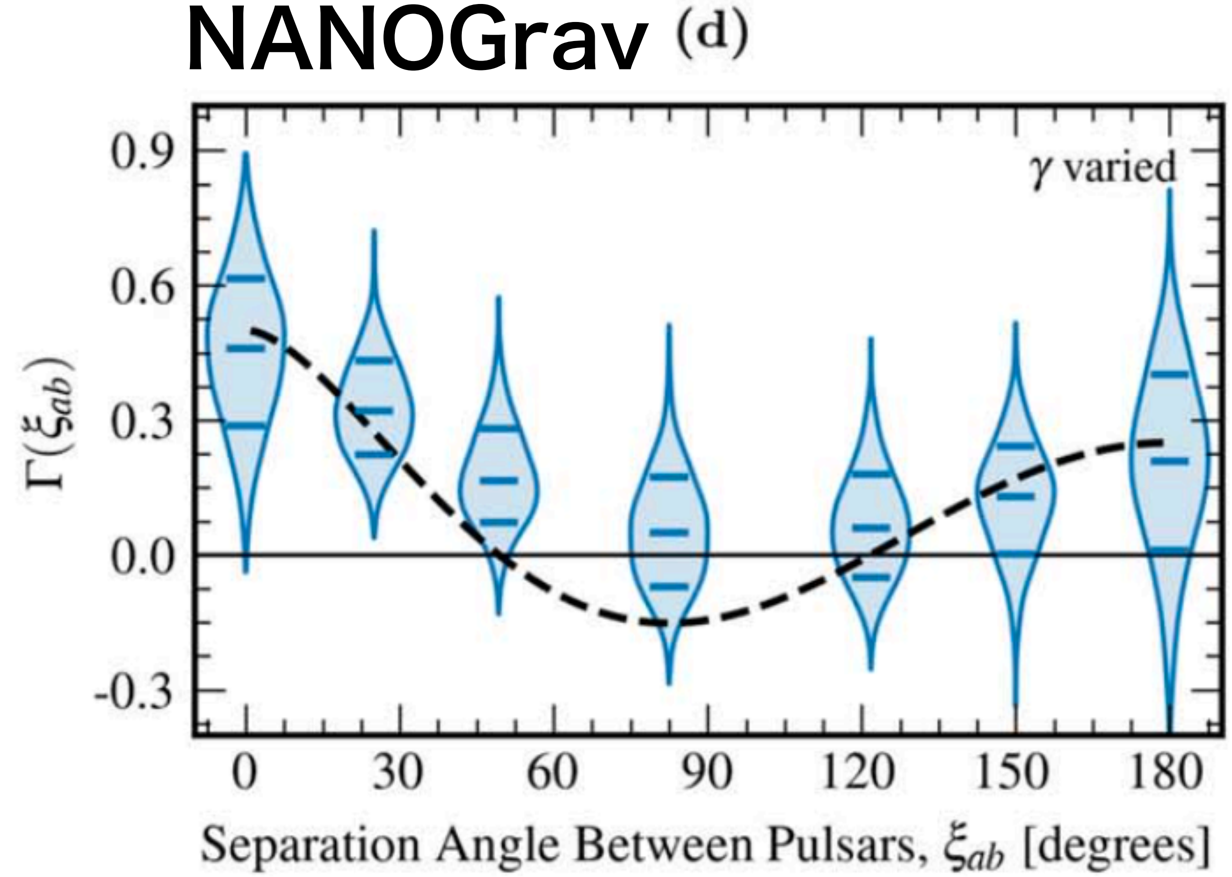
PPTA



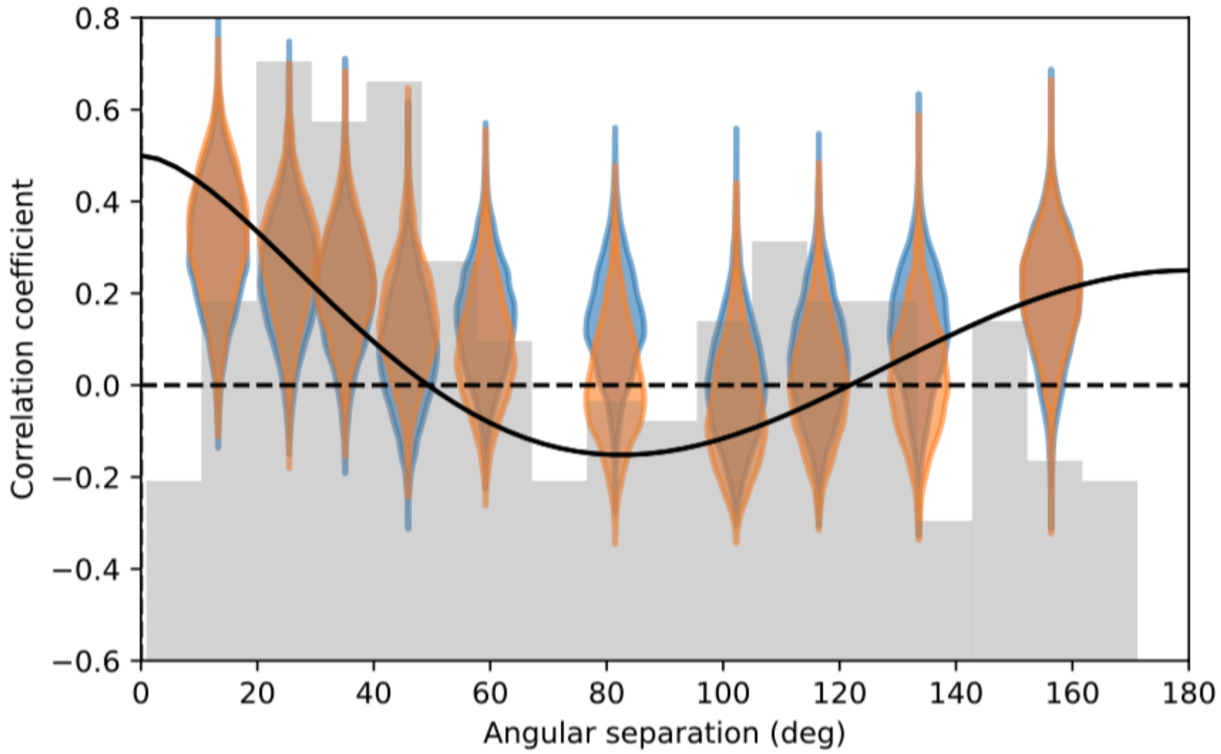
HD correlation

- HD correlation for each PTA
- offset around 90deg?

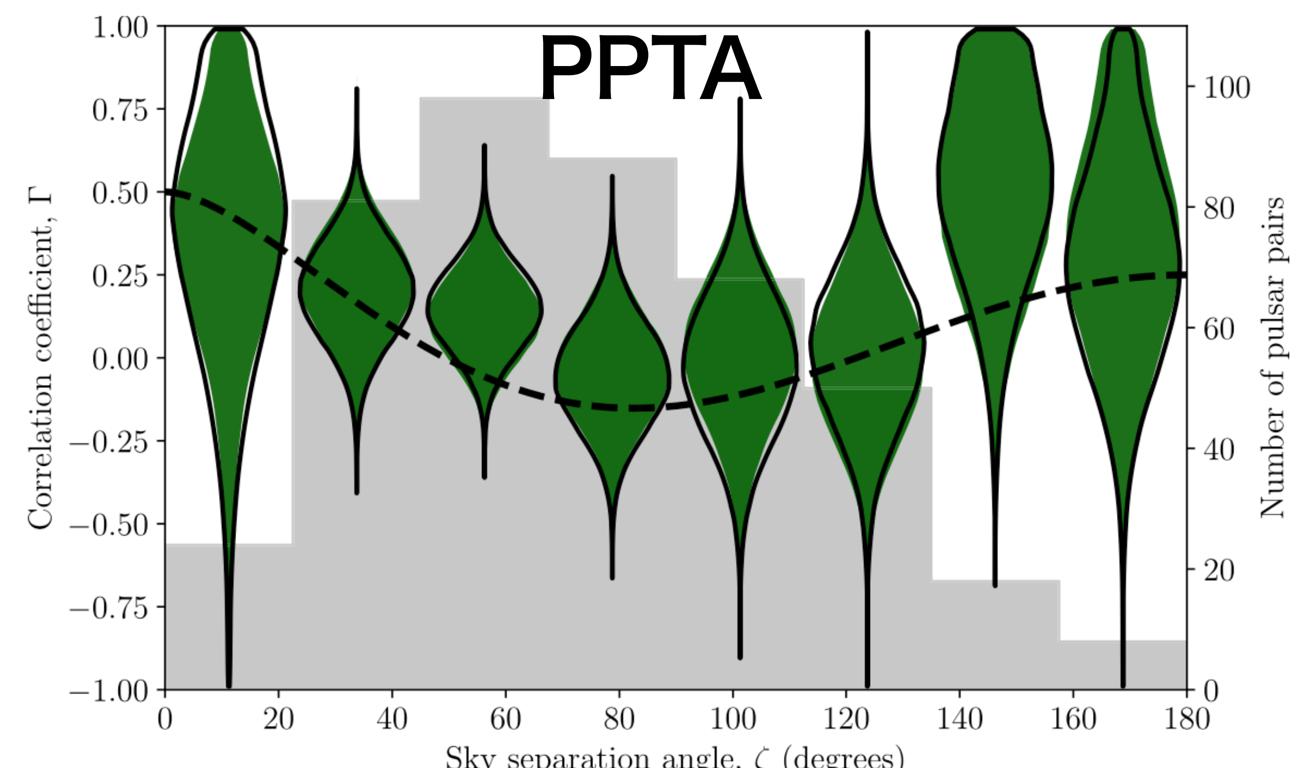
NANOGrav



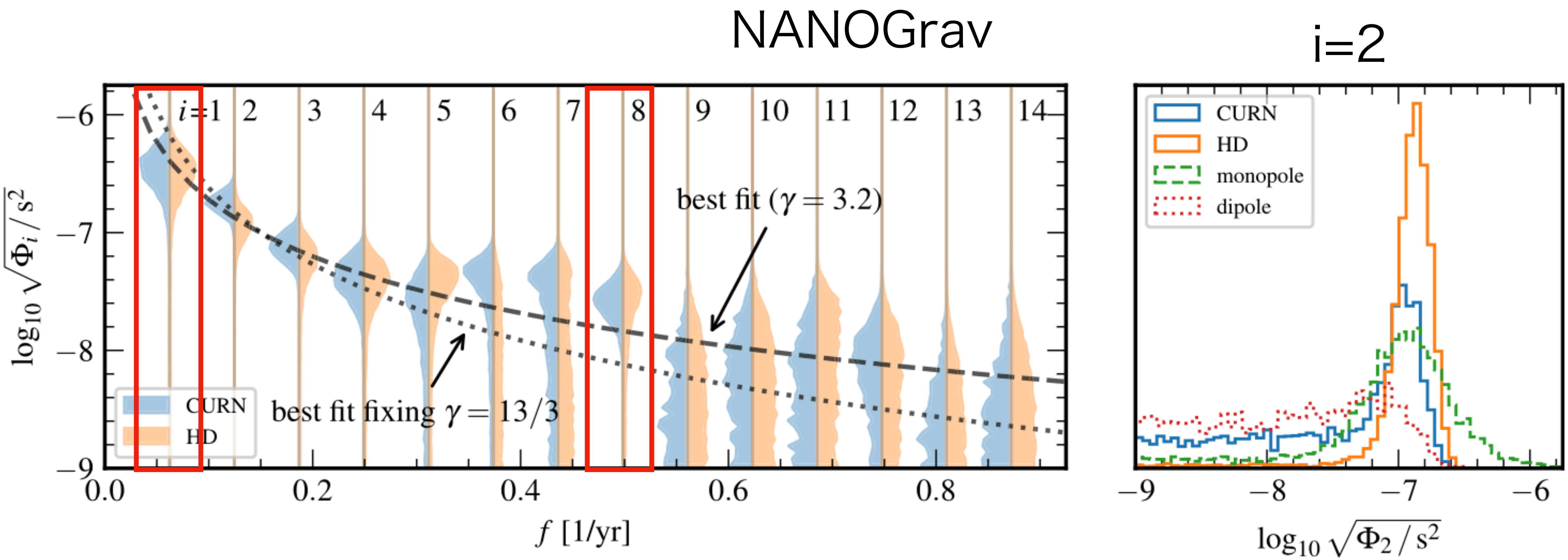
EPTA+InPTA



PPTA



Fourier component



- posteriors of Fourier component
- the fit is pushed to lower γ by bins 1 and 8
- statistical fluctuations of the astrophysical background or from unmodeled systematics?

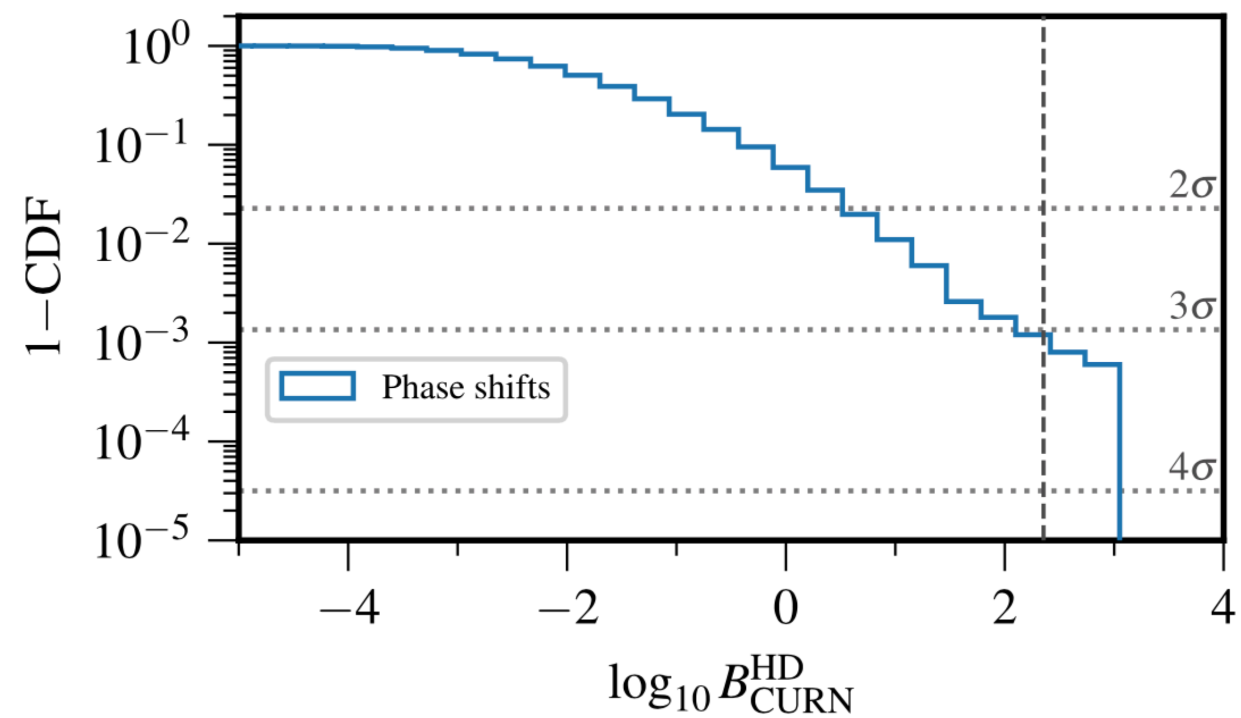
Statistical significance

・test 2 null hypotheses

1. **no interpulsar correlations** are present

・phase shift method

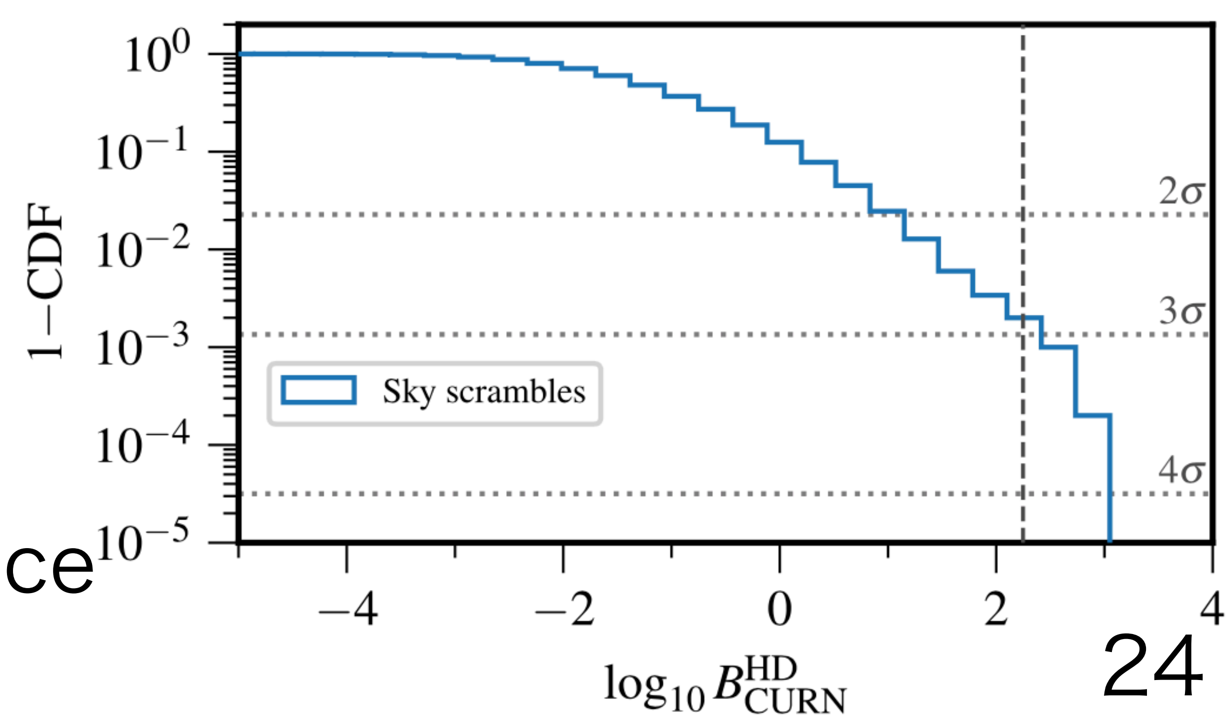
randomly change the phase of Fourier components



2. interpulsar correlations have **no dependence on angular separation**

・Sky scramble method

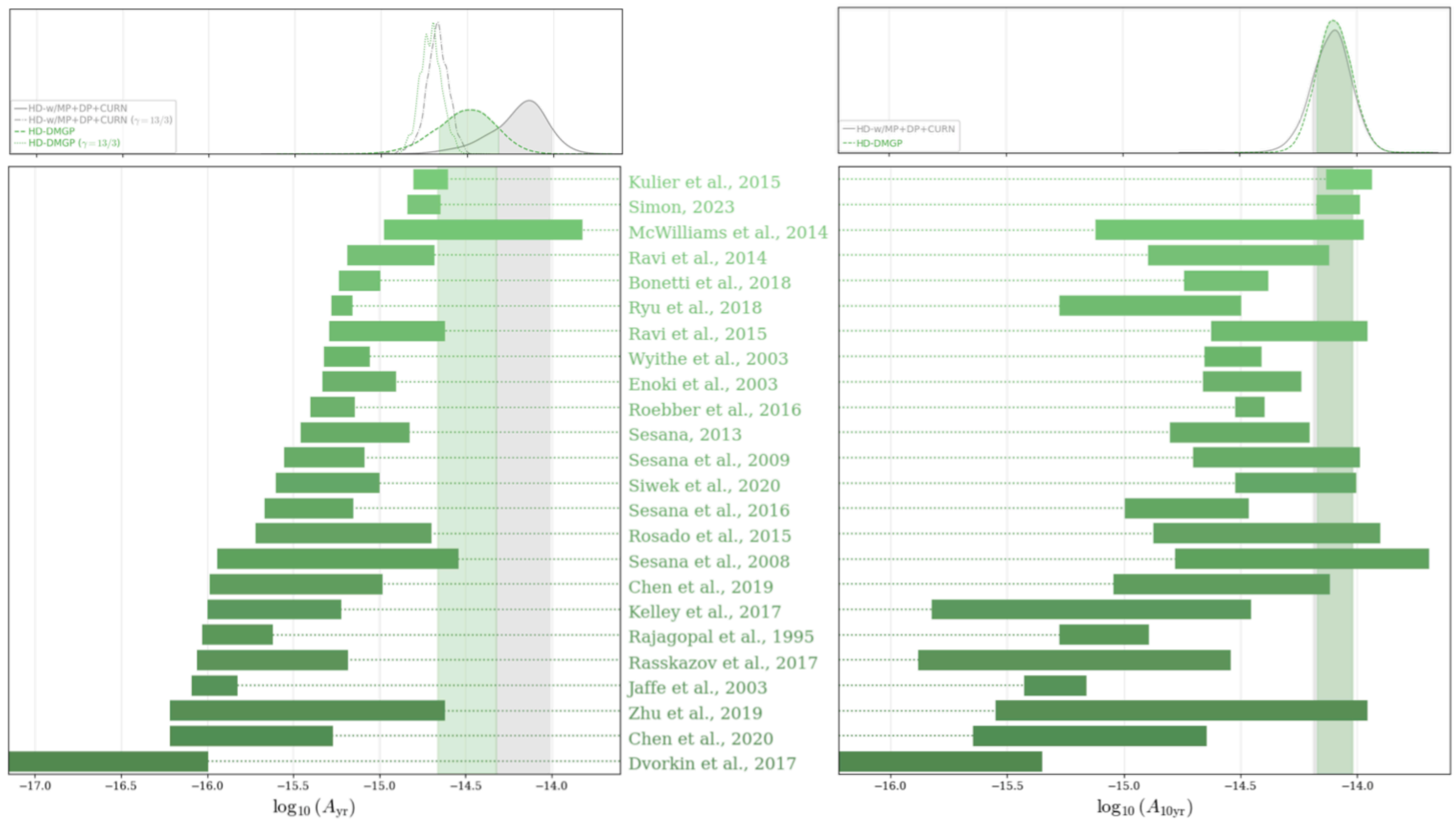
randomly change the pulsar position



Both methods show ~3σ significance

Interpretation

Model comparison (NANOGrav)

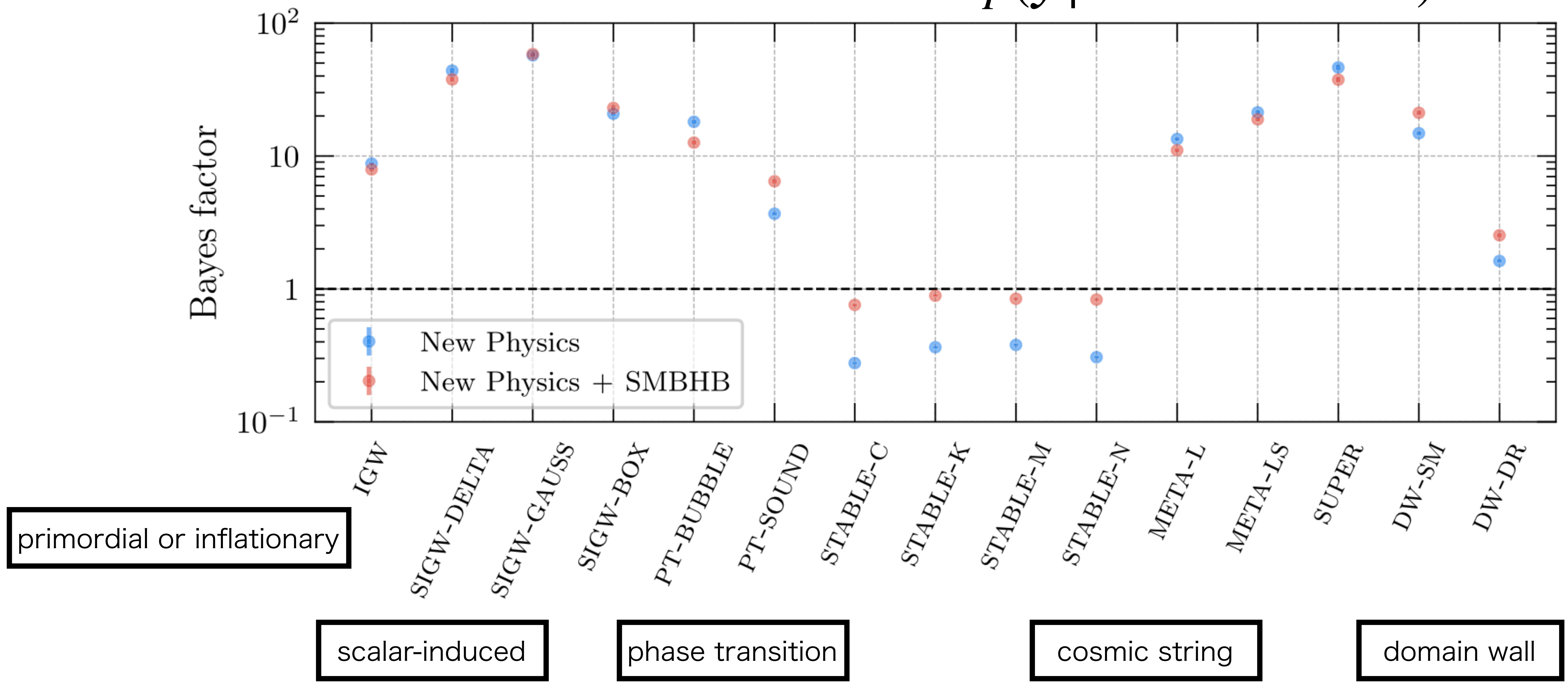


- higher amplitude than model predictions

-> short binary hardening timescales, higher galaxy merger rates, or higher normalization of the M_{BH}-M_{bulge} relation?

New physics

$$BF = \frac{p(\boldsymbol{y}\,|\,\text{New Physics})}{p(\boldsymbol{y}\,|\,\text{SMBHBs alone})}$$



・Many models provide a better fit (10 < BF < 100)

・However, strongly depends on modeling assumptions

-> should **not** be regarded as evidence for new physics

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Summary

- PTA groups have announced the “**evidence**” for the GWB
  - 2~4 sigma

- The signal is consistent with the GWB from SMBHBs, but we can not exclude other sources

- IPTA is now combining all the PTA data for the most sensitive data set
  - detection is coming soon(?)

- New members are very welcome!