TeVPA 2024
University of Chicago, 29 August 2024

NANOGRAV AND GRAVITATIONAL WAVES FROM THE EARLY UNIVERSE

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on behalf of the NANOGrav collaboration

Supermassive Black Hole Binaries

Gravitational Wave Landscape

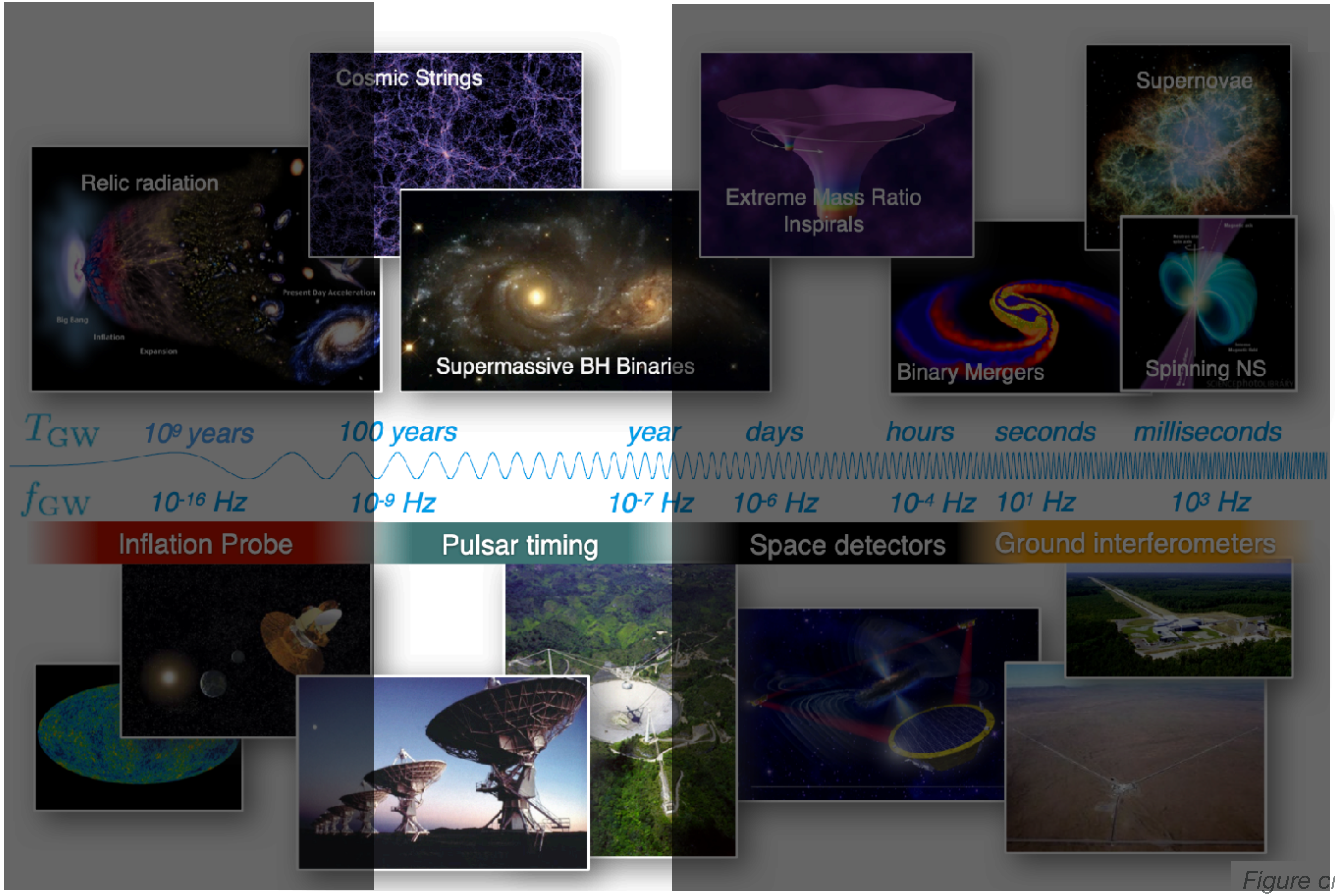


Figure credit: K. Chatziioannou

Worldwide Pulsar Timing Array (PTA) Experiments

Figure credit: T. Cromartie

Announcement in June 2023

Multiple pulsar timing array experiments reported evidence for background of nHz gravitational waves

NANOGrav

- SGWB search (2306.16213)
- Observation & Timing (2306.16217)
- Detector & Noise (2306.16218)
- New physics (2306.16219)
- SMBHB (2306.16220)
- Anisotropy (2306.16221)
- Continuous waves (2306.16222)
- Pipeline (2306.16223)

EPTA / InPTA

- SGWB search (2306.16214)
- Data & Timing (2306.16224)
- Noise (2306.16225)
- Continuous waves (2306.16226)
- Signal sources (2306.16227)
- ULDM (2306.16228)

PPTA

- SGWB search (2306.16215)
- Noise (2306.16229)
- Data (2306.16230)

CPTA

- SGWB search (2306.16216)

High-Precision Timing of Millisecond Pulsars

Animation by NSF

Pulsar Timing Measurements

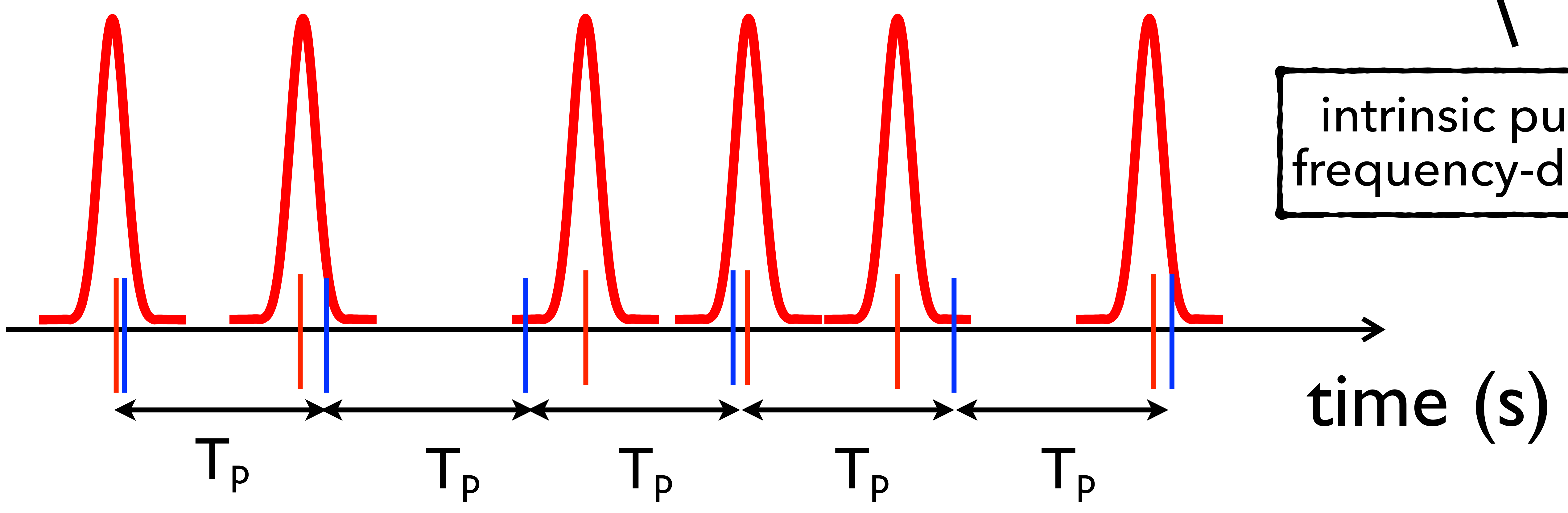
pulsar spin period (and derivative), position in sky, proper motion, distance from Earth, etc.

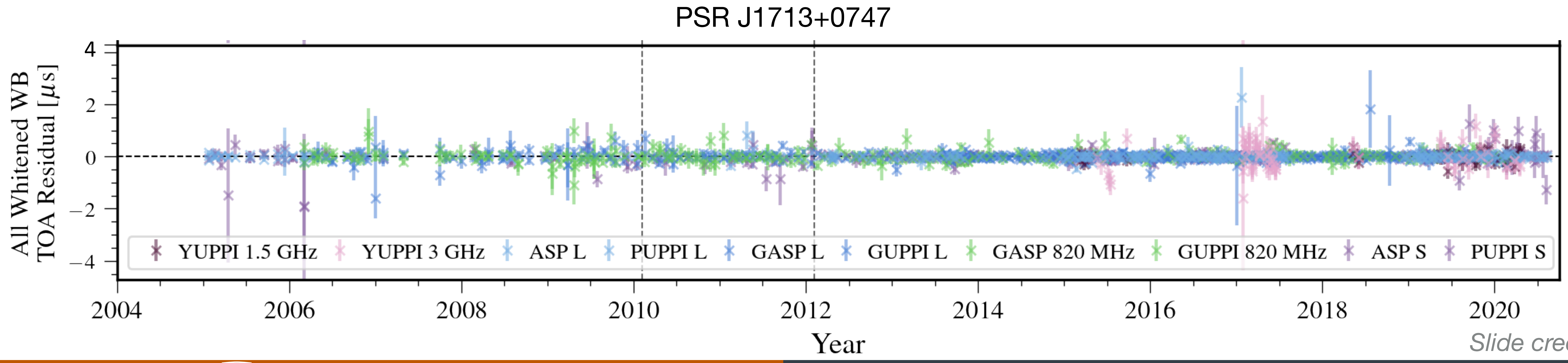
timing residual = observed arrival time — predicted arrival time

= unmodeled deterministic processes + noise + GWs

red noise

intrinsic pulsar and measurement noise, frequency-dependent dispersion measure





Slide credit: J. Romano

NANOGrav Timing Data Summary: 15-Year Data Set, 68 Pulsars

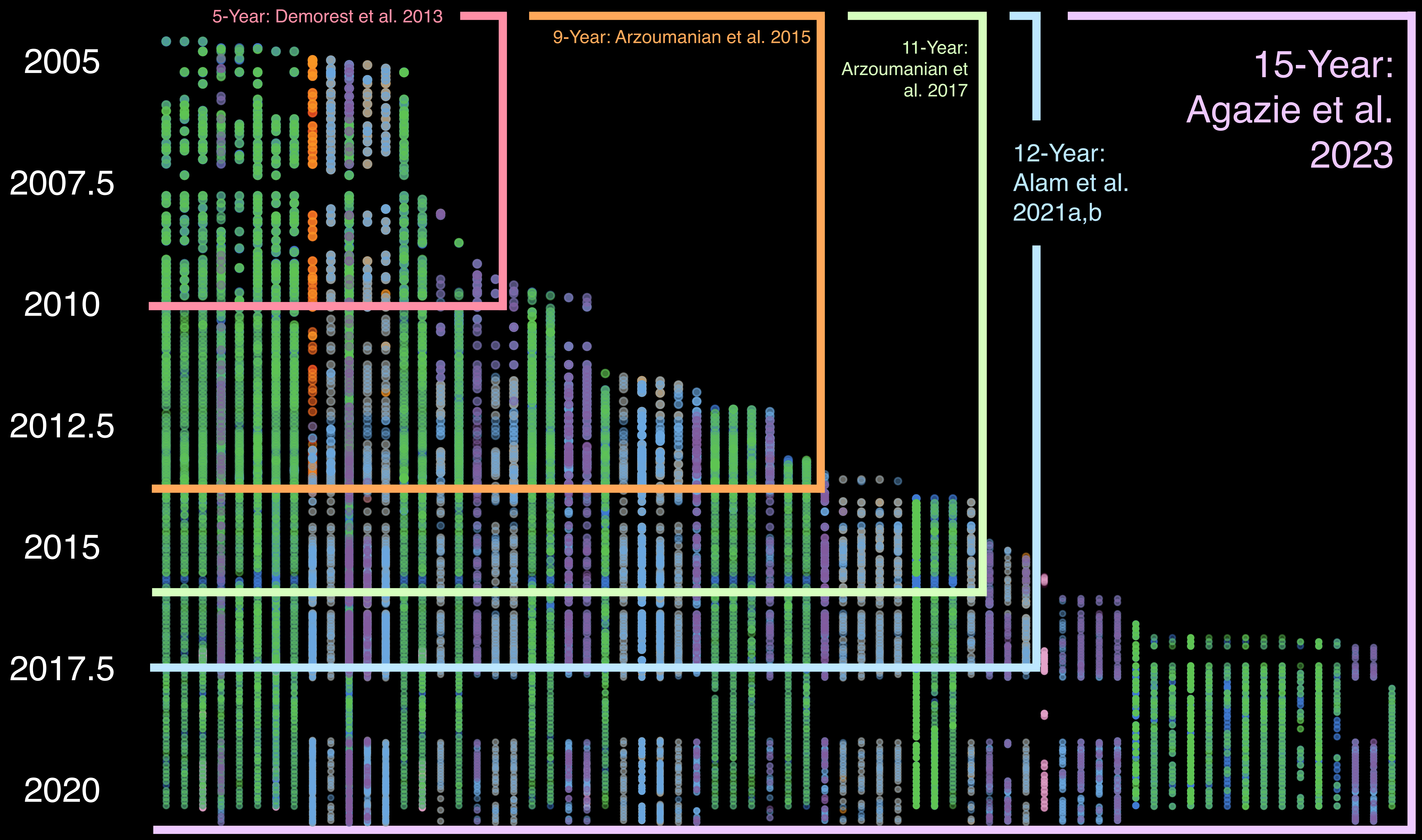
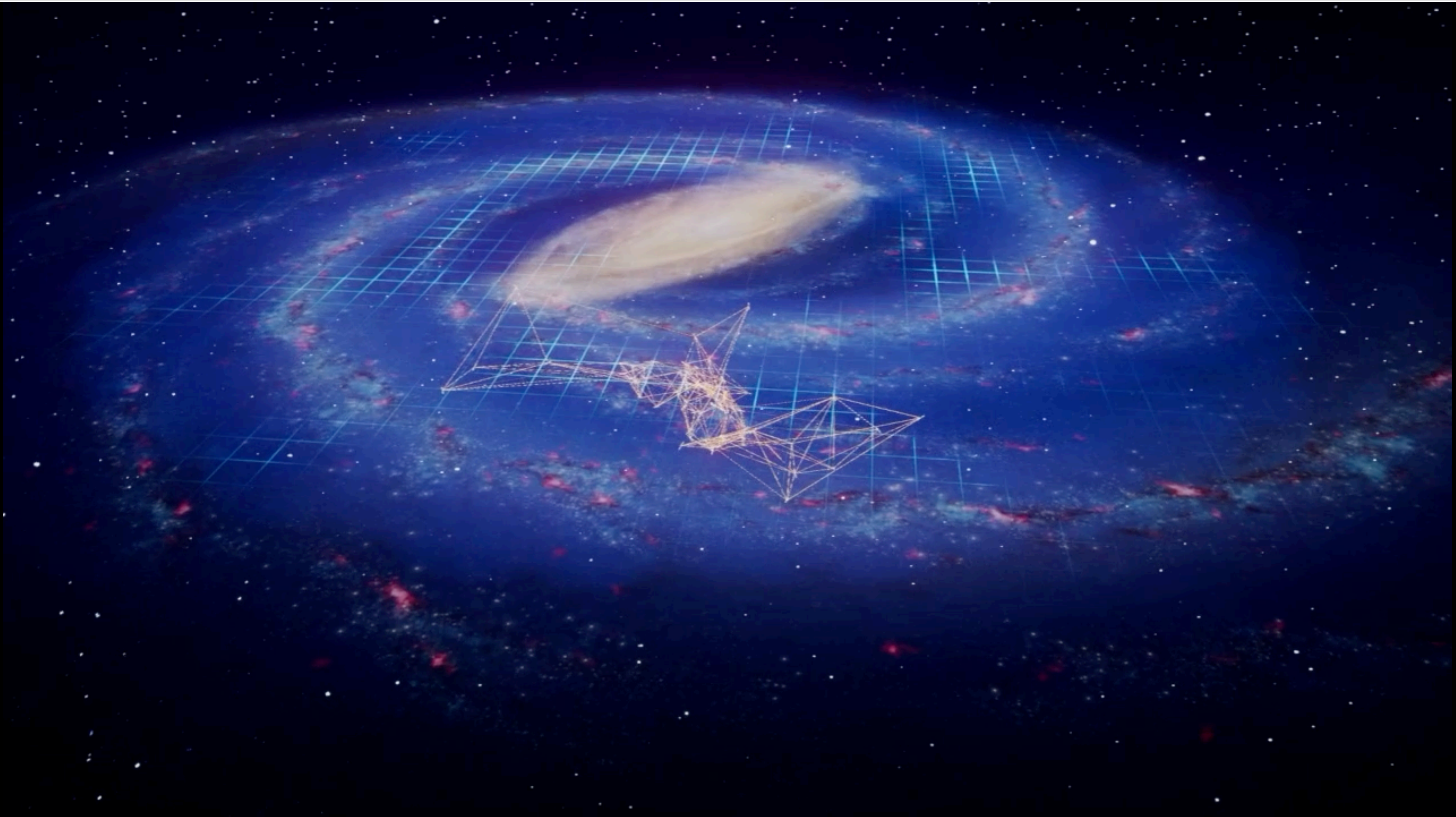


Figure credit: T. Cromartie

Pulsar Timing Array

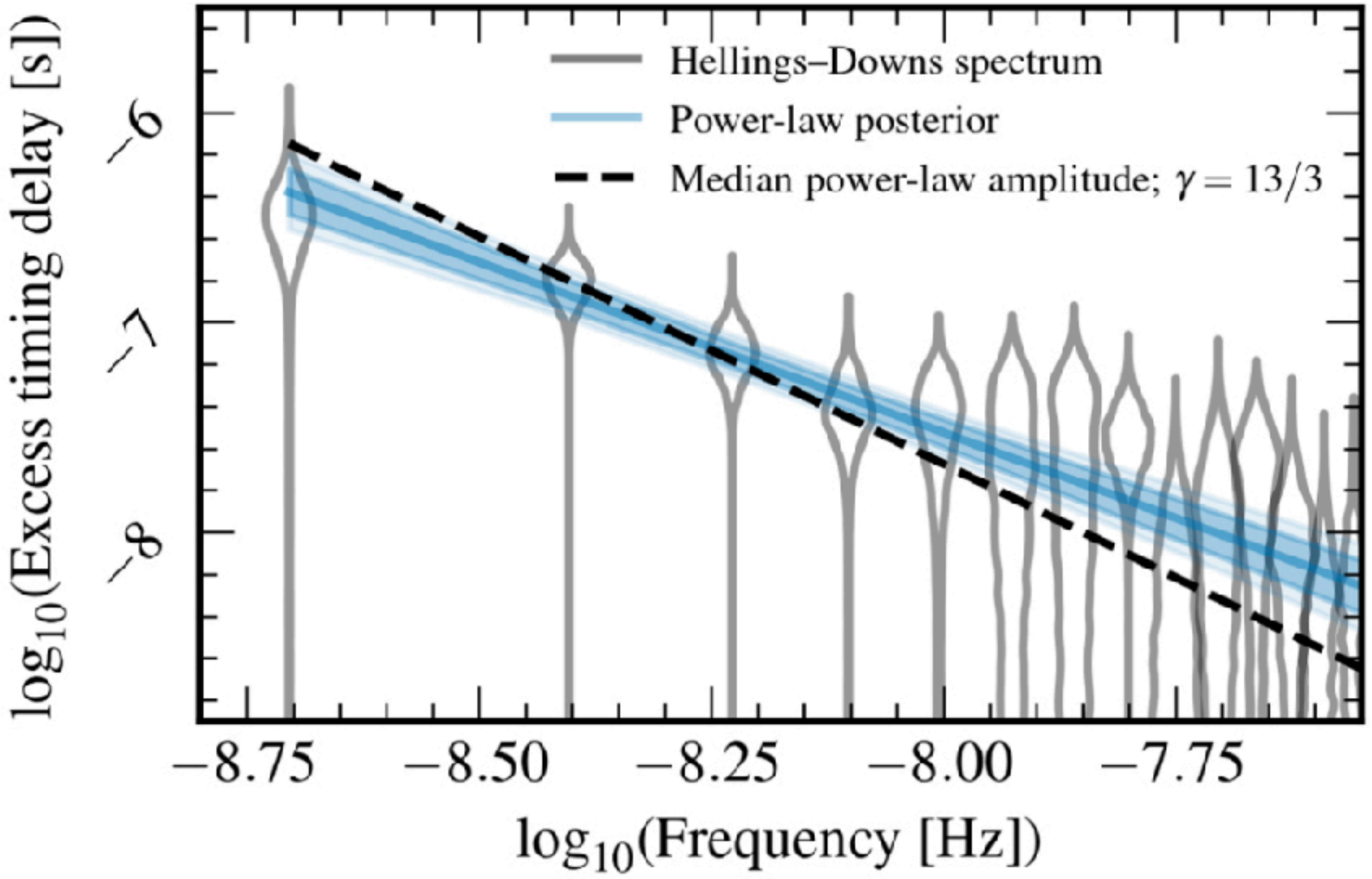


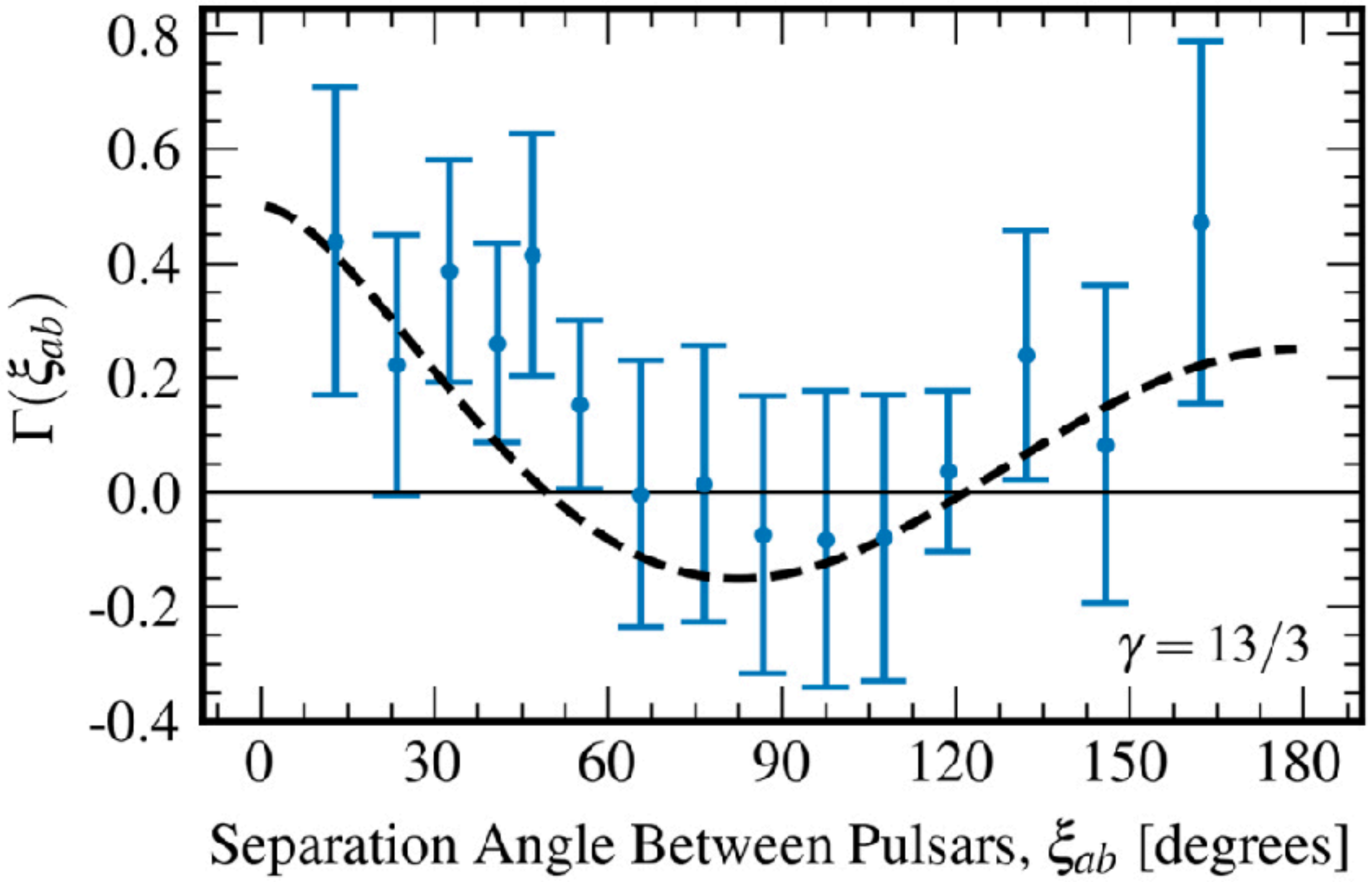
Background by Little Shadow

Animation concept by Olivia Young


15-year
results
Correlation Strength
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0
20
40
60
80
100
120
140
160
180
Pulsar Sky Separation (degrees)
Background by Little Shadow
Animation concept by Olivia Young

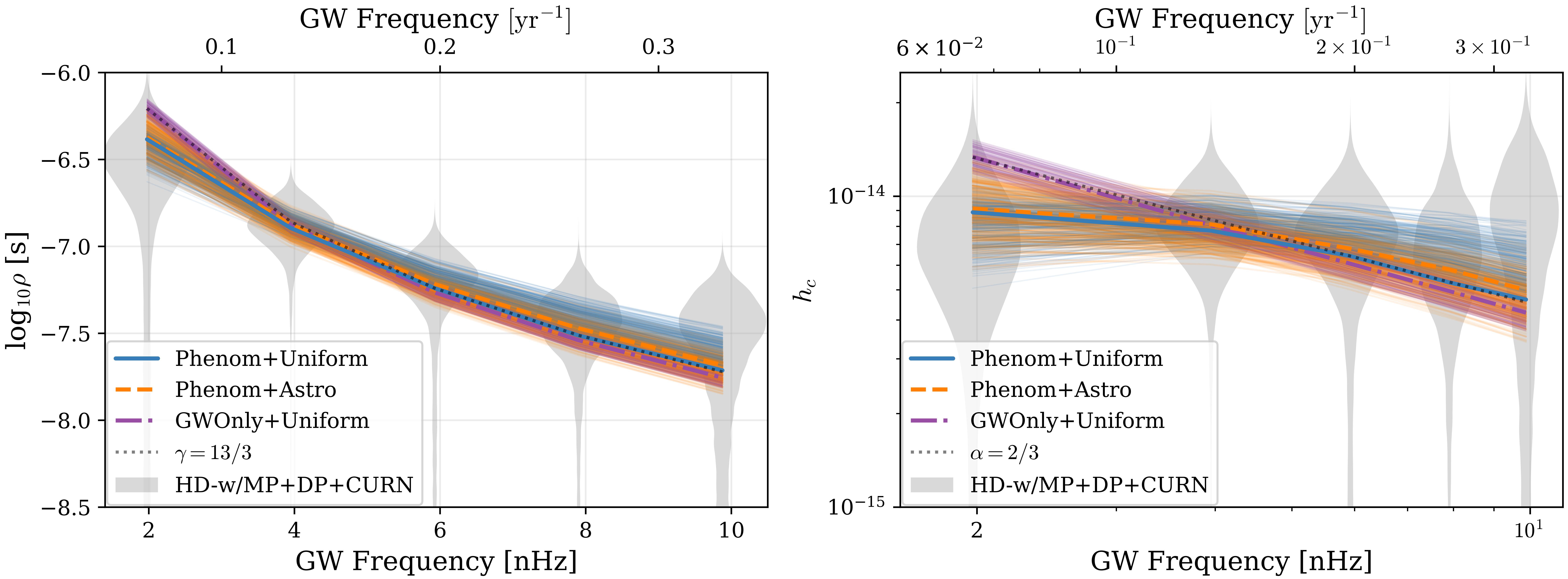
NANOGrav 15-year Results





NANOGrav (2306.16213)

Astrophysical Interpretation: Supermassive Black Hole Binaries



NANOGrav (2306.16220)

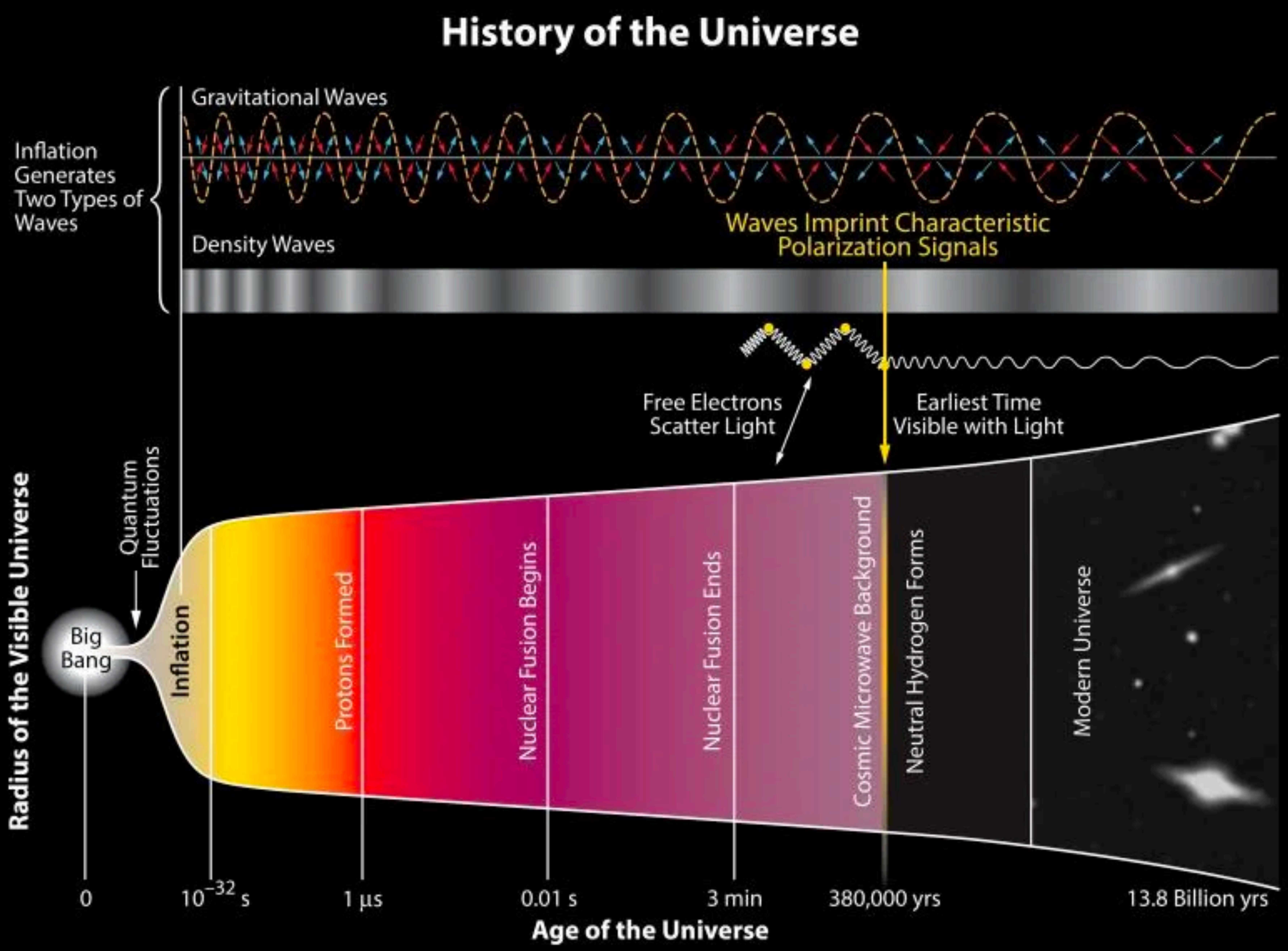
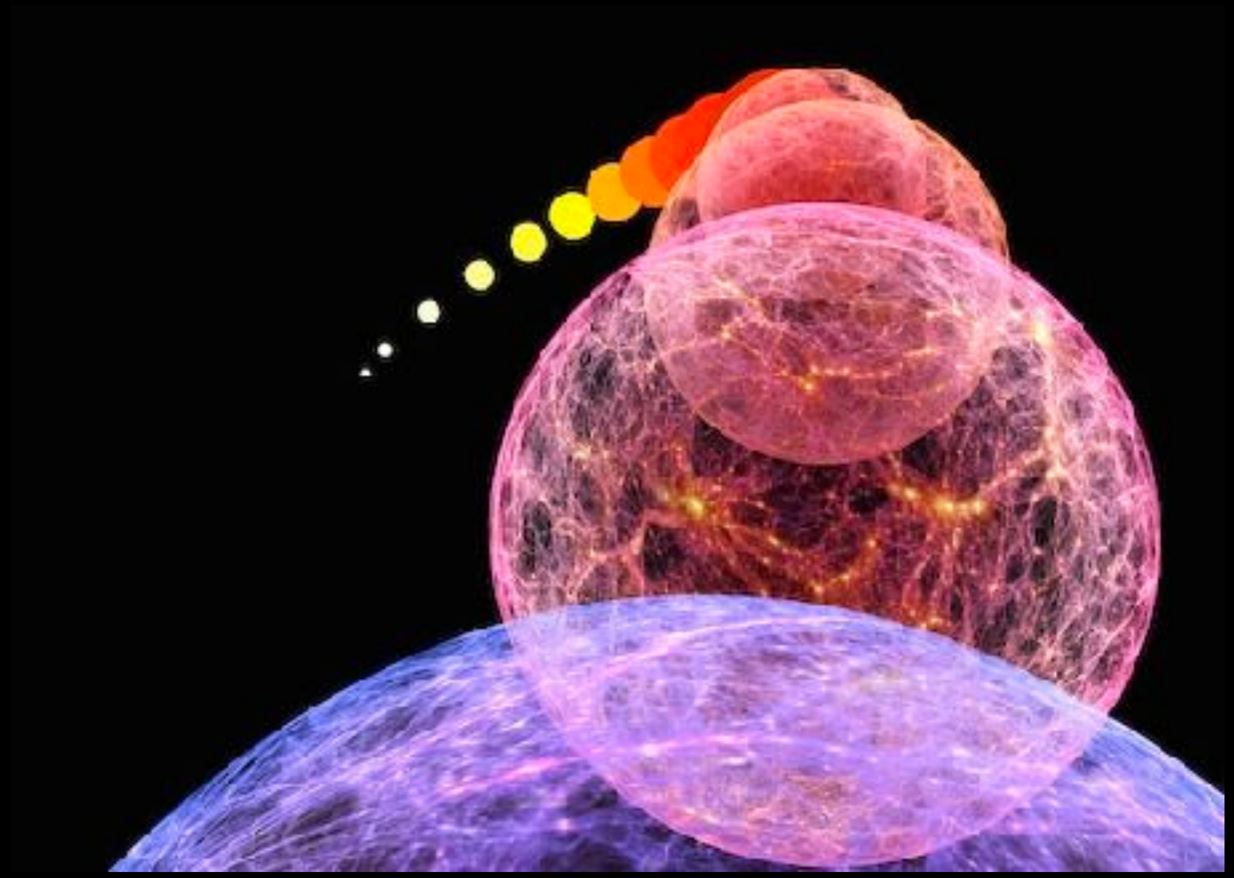


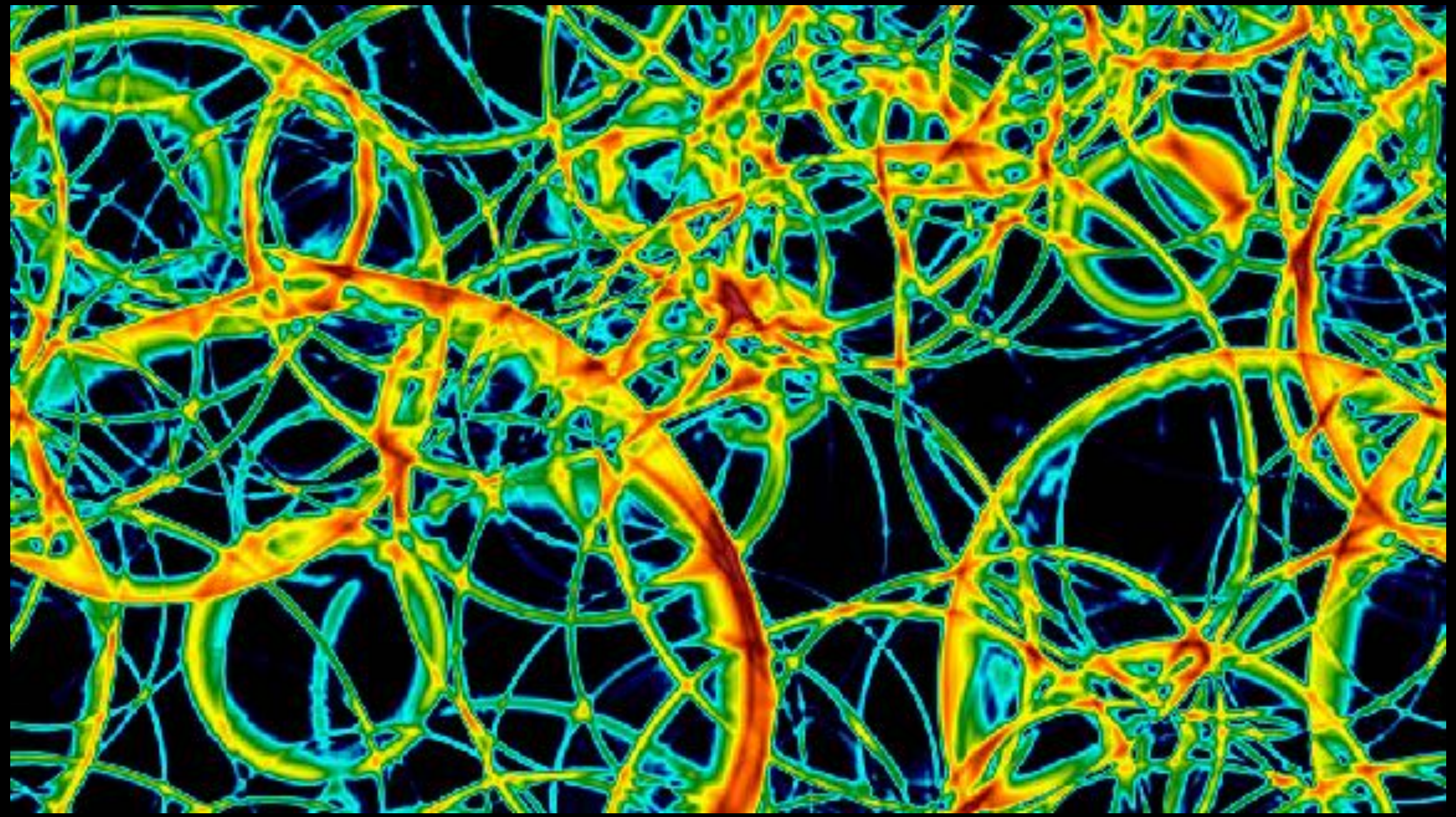
Figure credit: BICEP2

New Physics Models

Inflation
- Non-minimal blue-tilted models

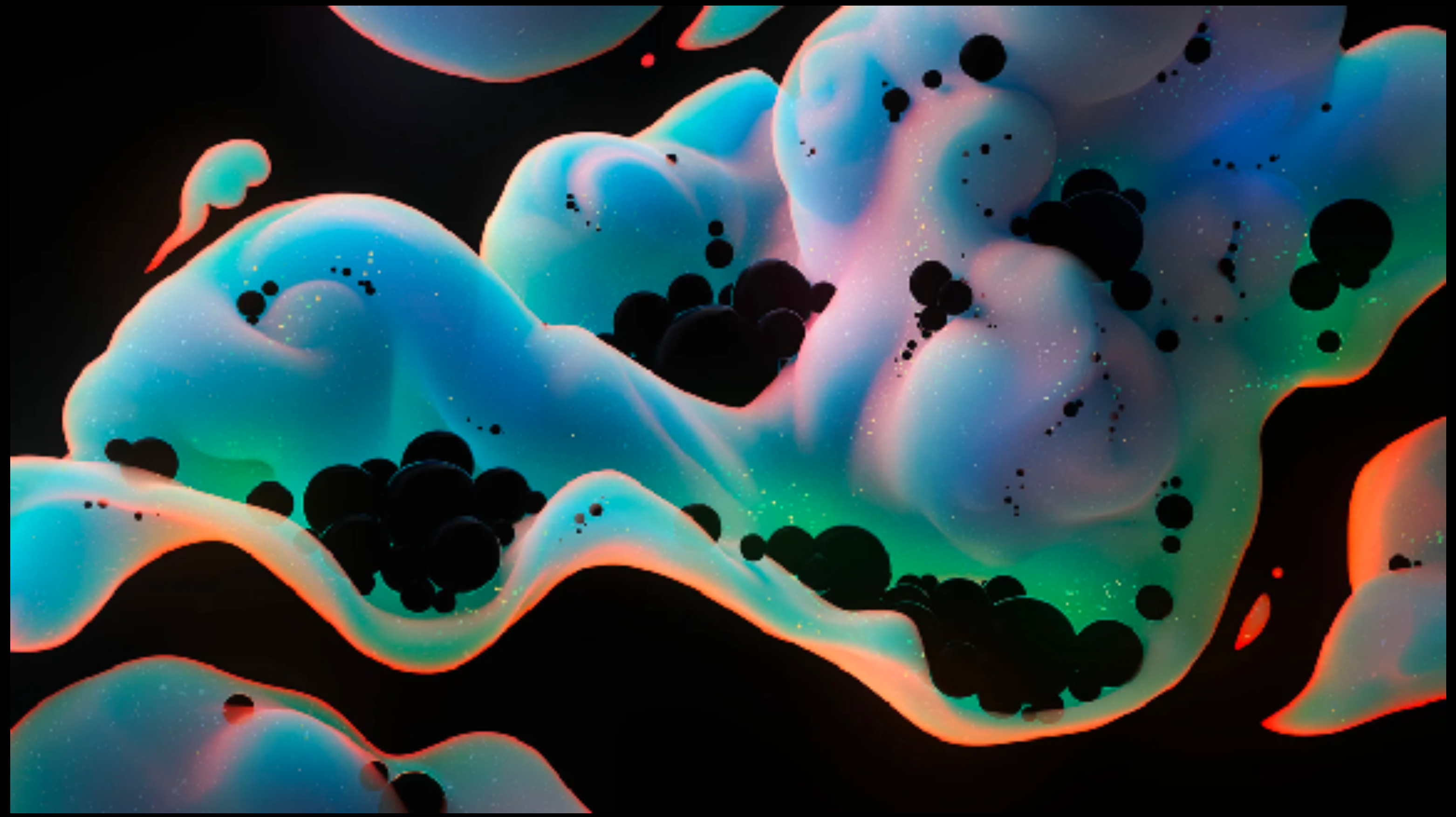


Phase transitions
- QCD transition in BSM, dark sector



Topological defects
- Cosmic strings, domain walls

Enhanced scalar perturbations
- Primordial black hole production



The NANOGrav 15-year Data Set: Search for Signals from New Physics

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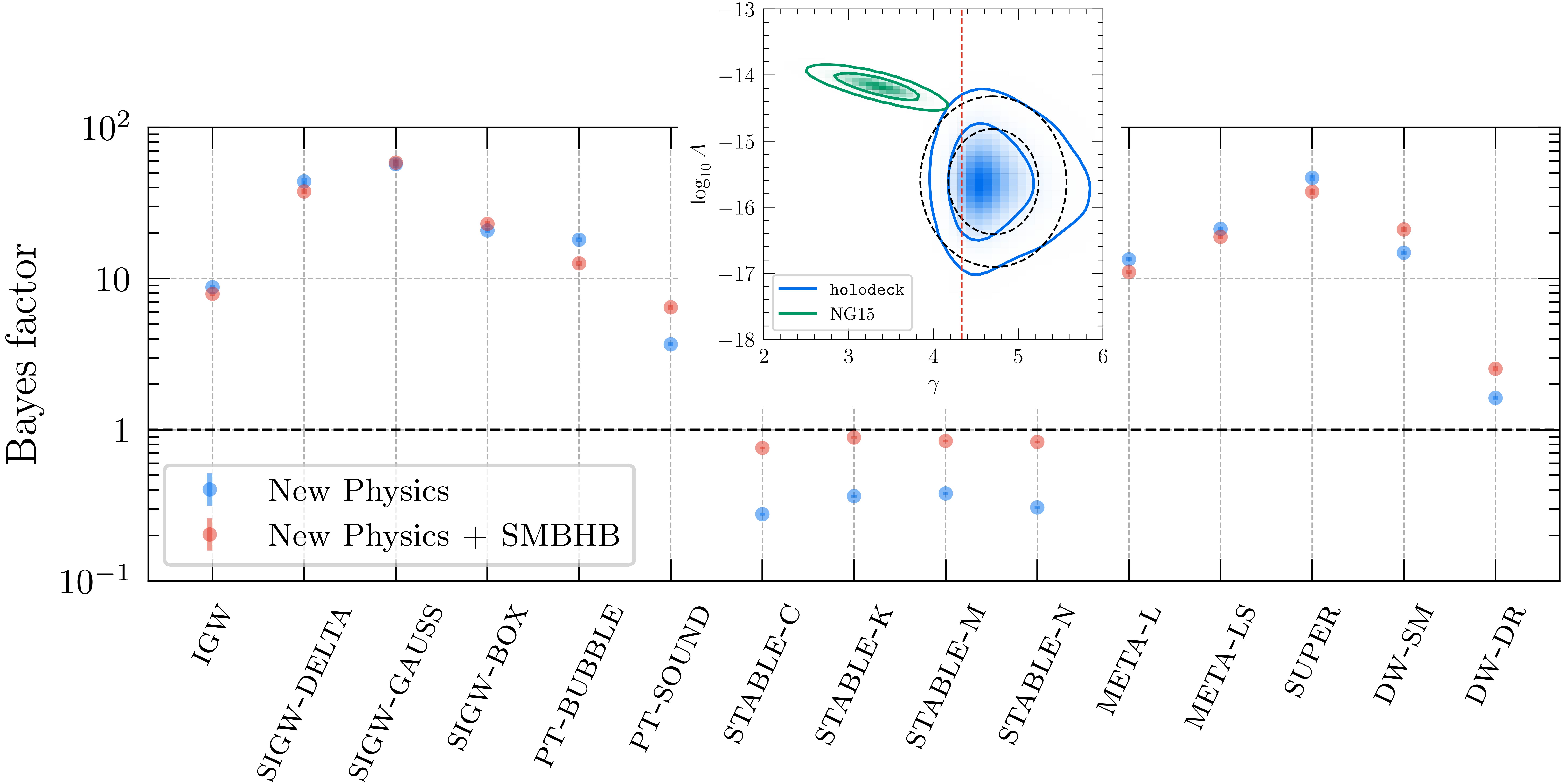
NANOGrav (2306.16219)

New Physics Models: Summary

amplitude
spectral features
both

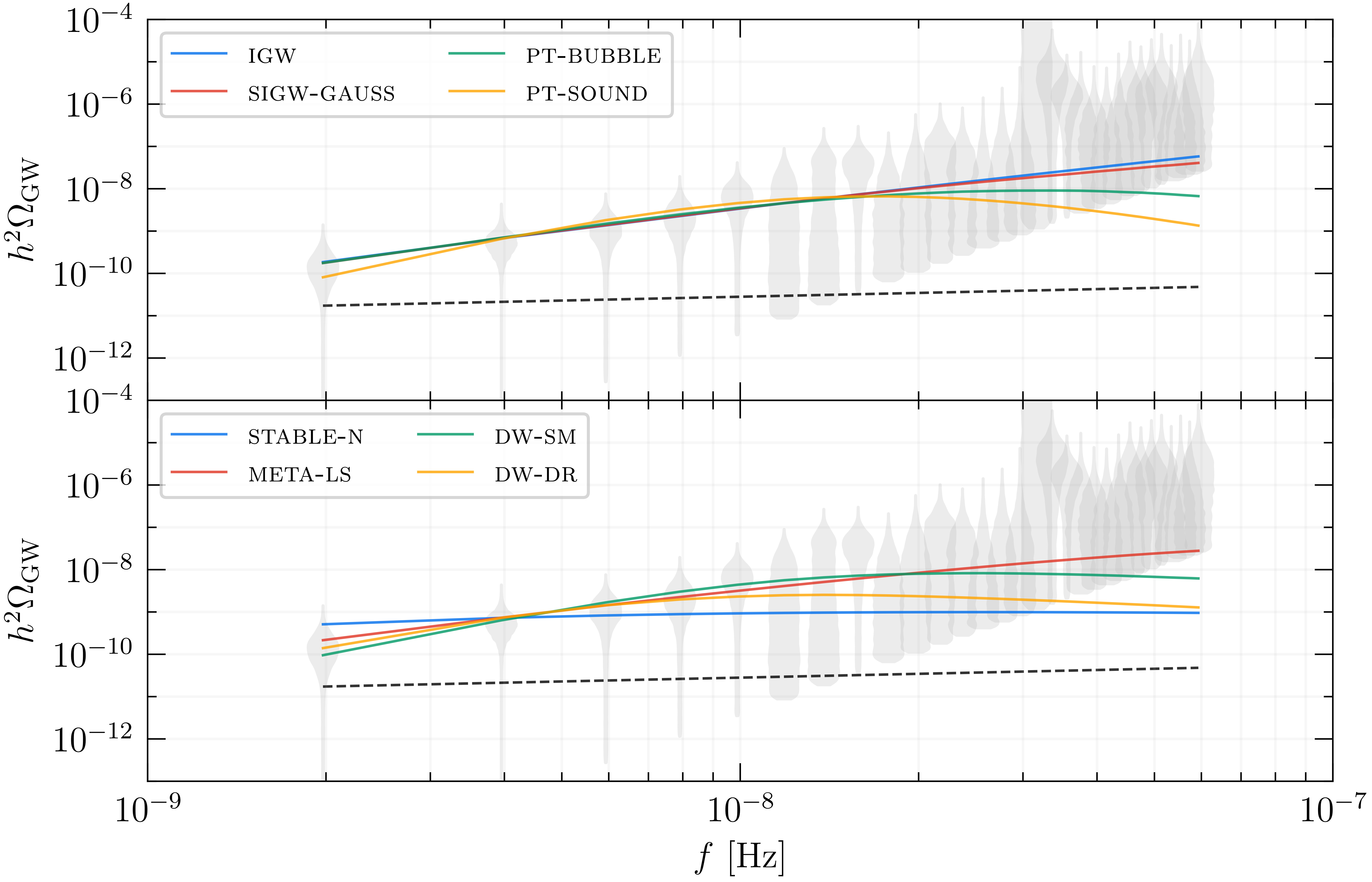
- IGW: Inflationary Gravitational Waves
  tensor-to-scalar ratio, tensor spectral index, reheating temperature
- SIGW: Scalar-Induced Gravitational Waves
  scalar amplitude, frequency shape parameters (delta, gauss, box)
- PT: Phase Transitions (sound-wave analysis & bubble-collisions only)
  transition temperature and strength, bubble separation, low/high-frequency slope, spectral-shape width
- STABLE: Stable Cosmic Strings (cusps, kinks, monochromatic, numerical)
  string tension
- META: Metastable Cosmic Strings (loops only, loops and segments)
  string tension, decay parameter
- SUPER: Cosmic Superstrings
  string tension, intercommutation probability
- DW: Domain Walls
  transition temperature, energy fraction, high-frequency slope, spectral-shape width

Summary of Results



NANOGrav (2306.16219)

Median GWB Frequency Spectra



NANOGrav (2306.16219)

New Physics Models: Deterministic Signatures

- Ultralight dark matter with gravitational coupling only
  - Substructure exhibits pressure oscillations
- Ultralight dark matter coupled to Standard Model
  - Doppler signal – vector ULDM accelerates pulsar
  - Pulsar spin fluctuations – scalar ULDM causes particle mass fluctuations
  - Reference clock shifts – scalar ULDM alters reference atomic clocks

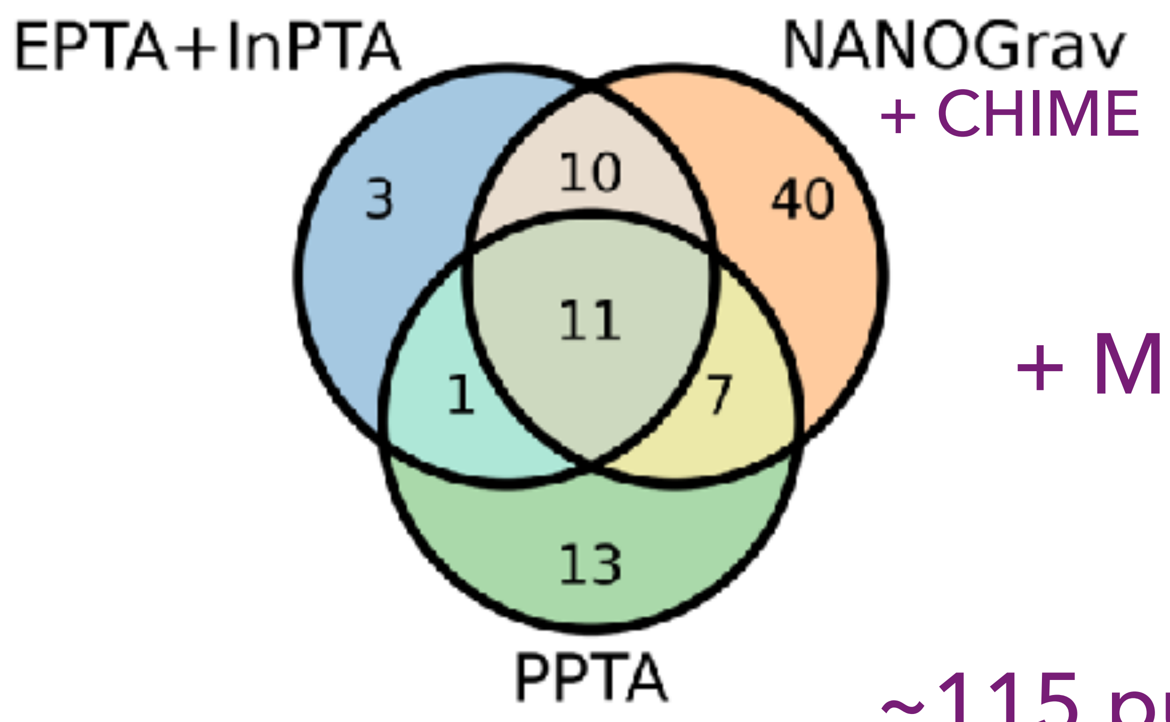
$$\mathscr{L} \supset \frac{\phi}{\Lambda}\left[\frac{d_\gamma}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum_{f=e,\mu} d_f m_f \bar{f}f - \sum_{q=u,d}(d_q + \gamma_q d_g)m_q\bar{q}q\right]$$

Ultralight Dark Matter Results

NANOGrav (2306.16219)

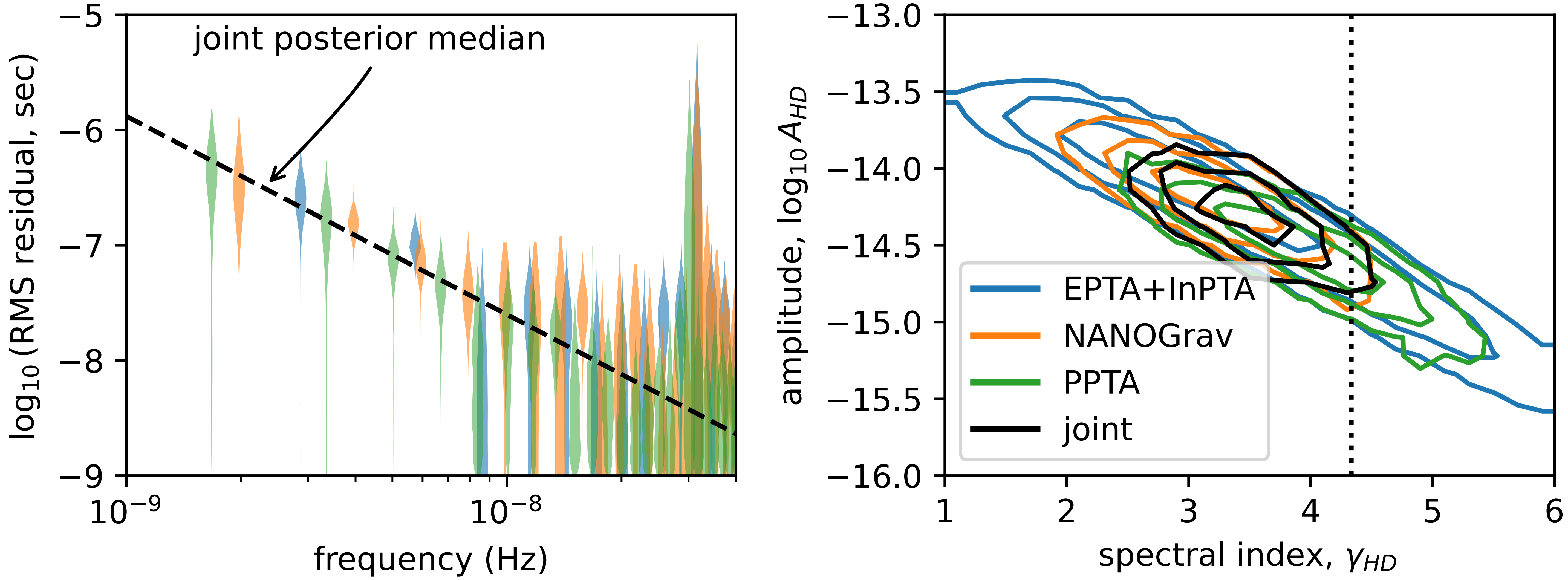
Upcoming Prospects

- IPTA is assembling DR3



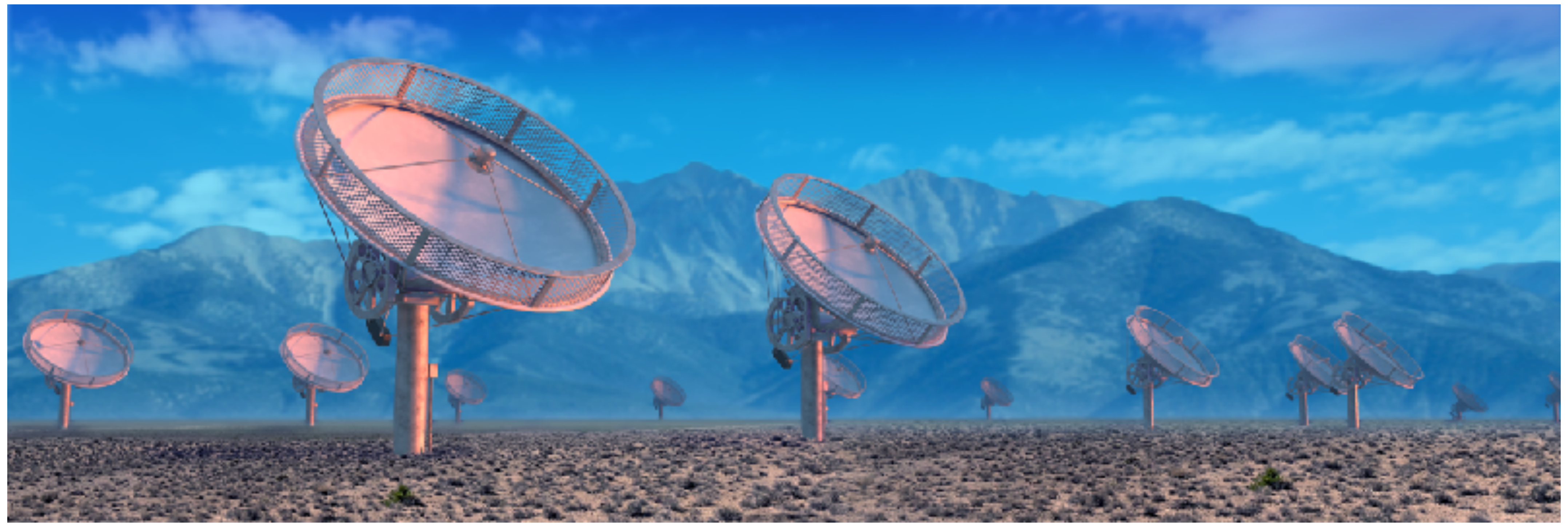
+ MPTA

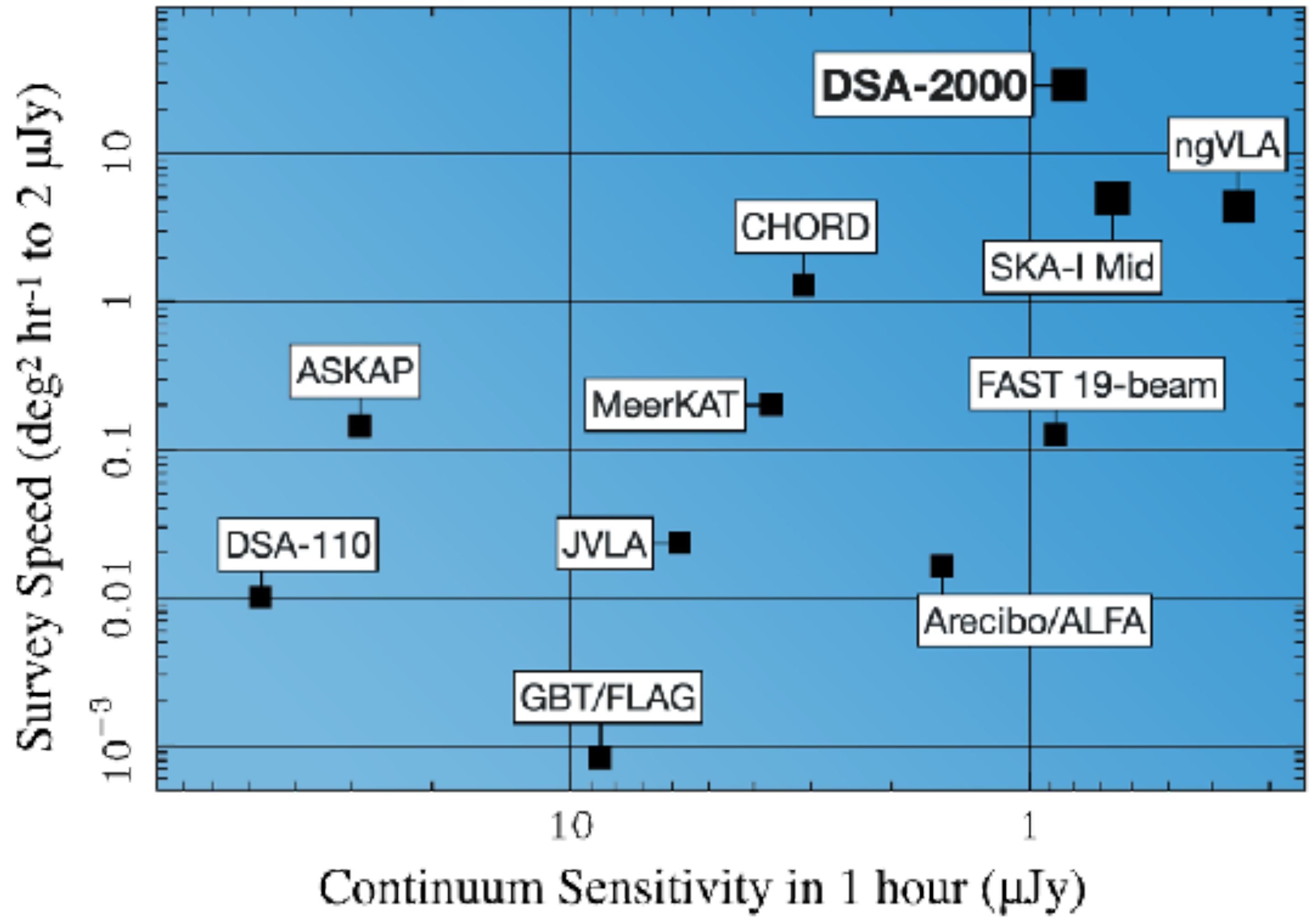
~115 pulsars



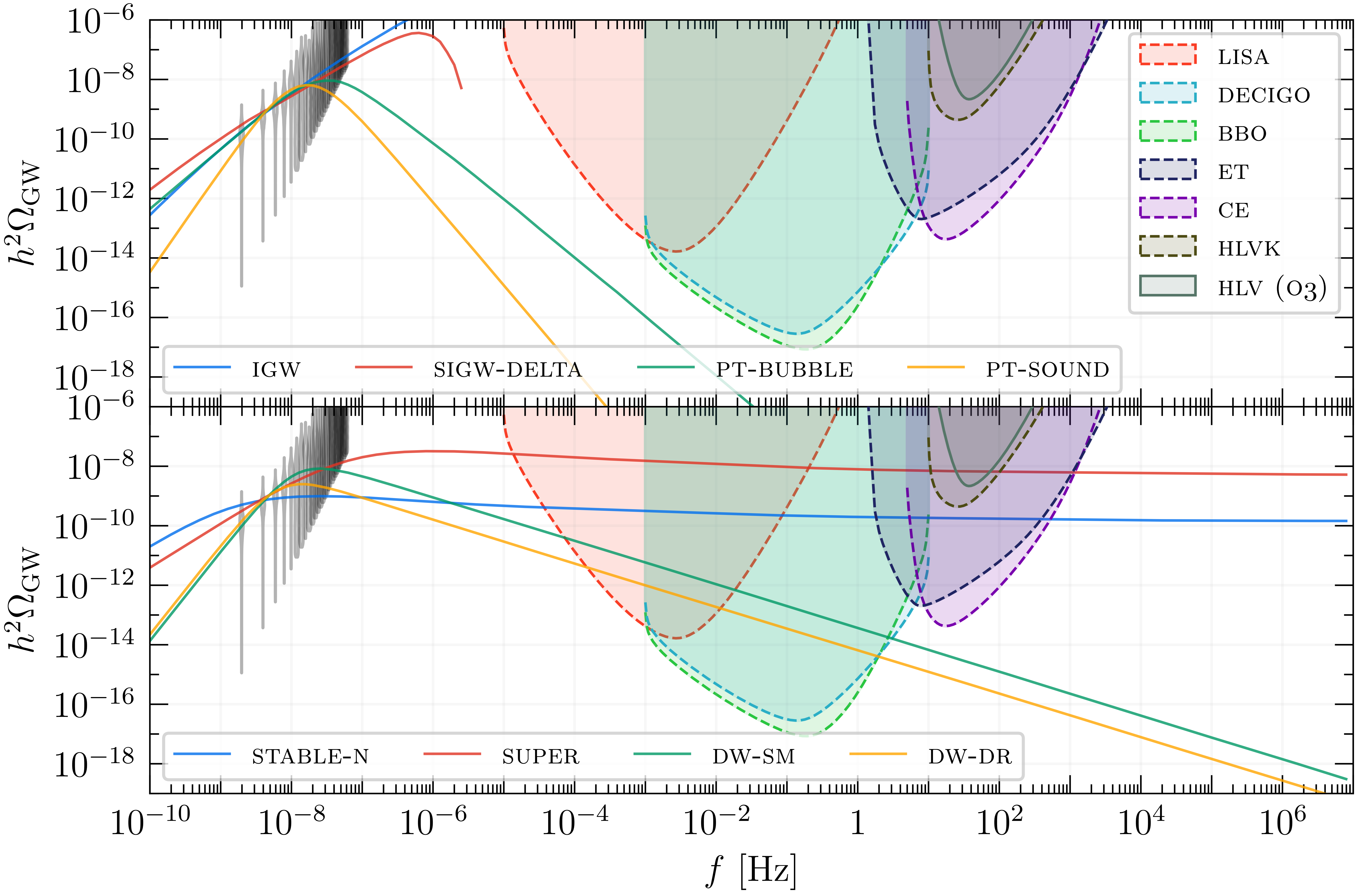
IPTA (2309.00693)

- Possible future of US pulsar timing: Deep Synoptic Array (DSA-2000)





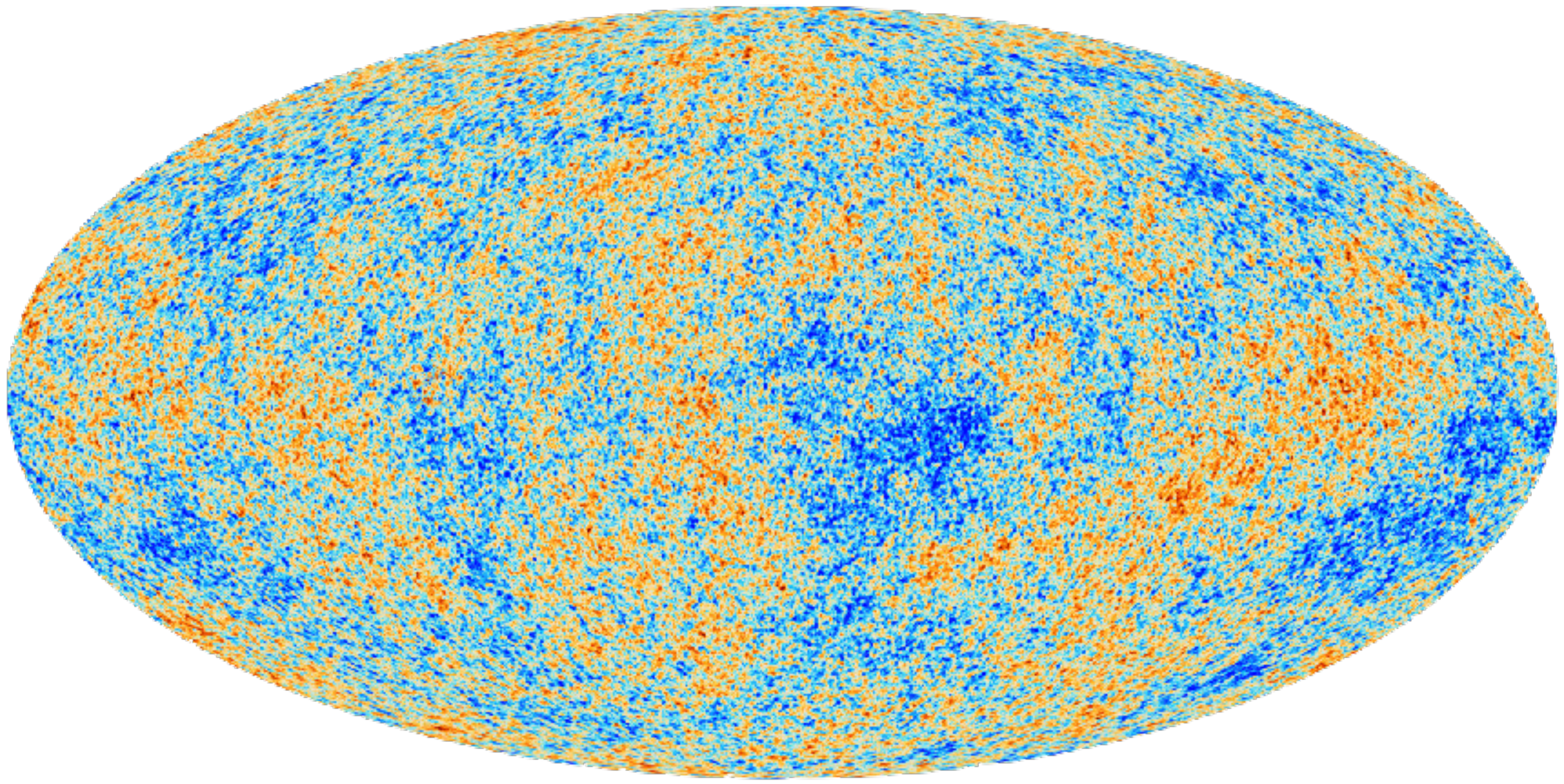
How can we understand sources? Spectral features?



NANOGrav (2306.16219)

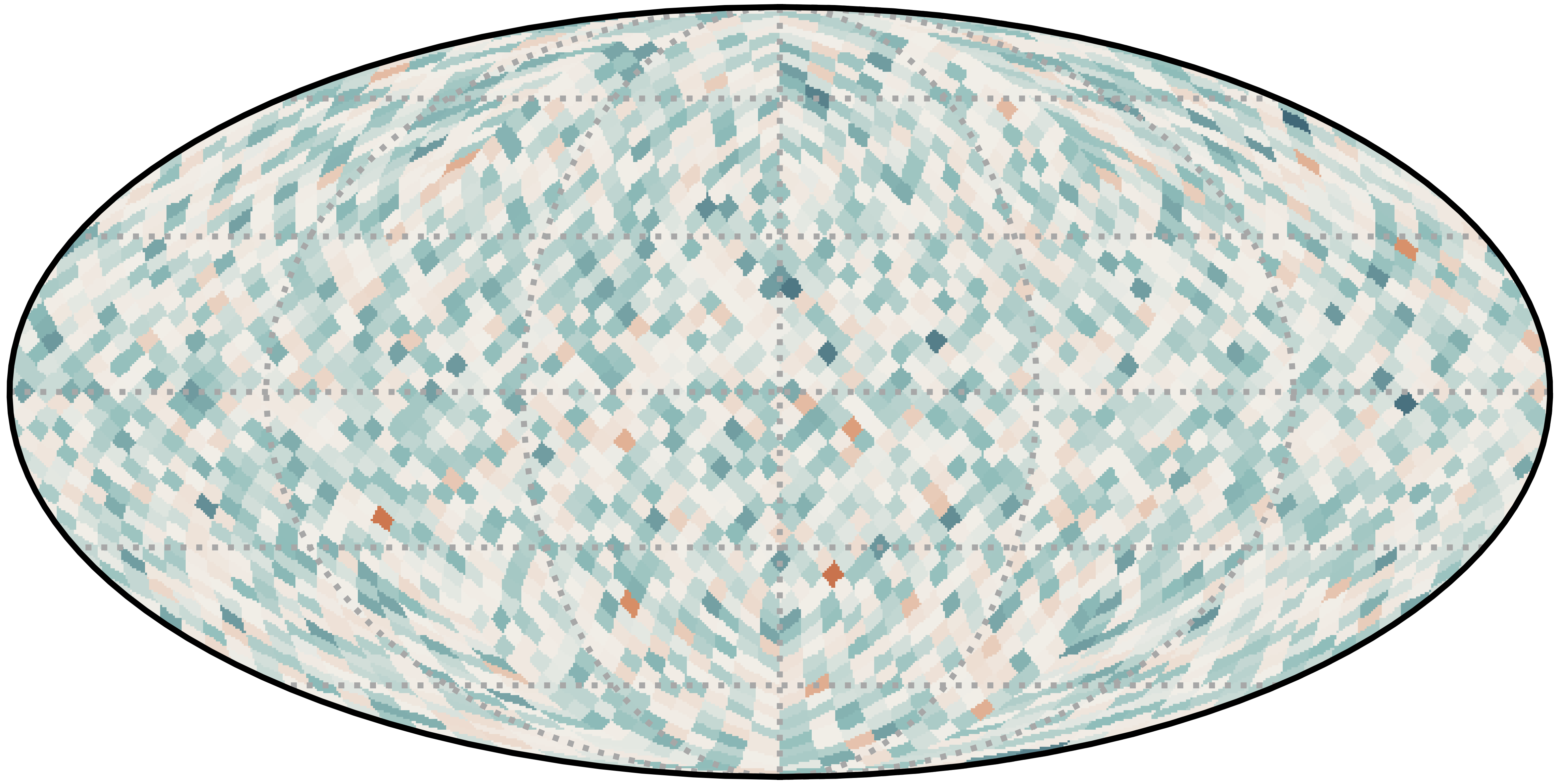
How can we understand sources? Anisotropies?

Cosmic Microwave Background



(observed)

Gravitational Wave Background



(simulated)

ESA and Planck Collaboration

Sato-Polito and Kamionkowski (2305.05690)

Just the beginning!

We have a new window into astrophysics and early Universe cosmology!

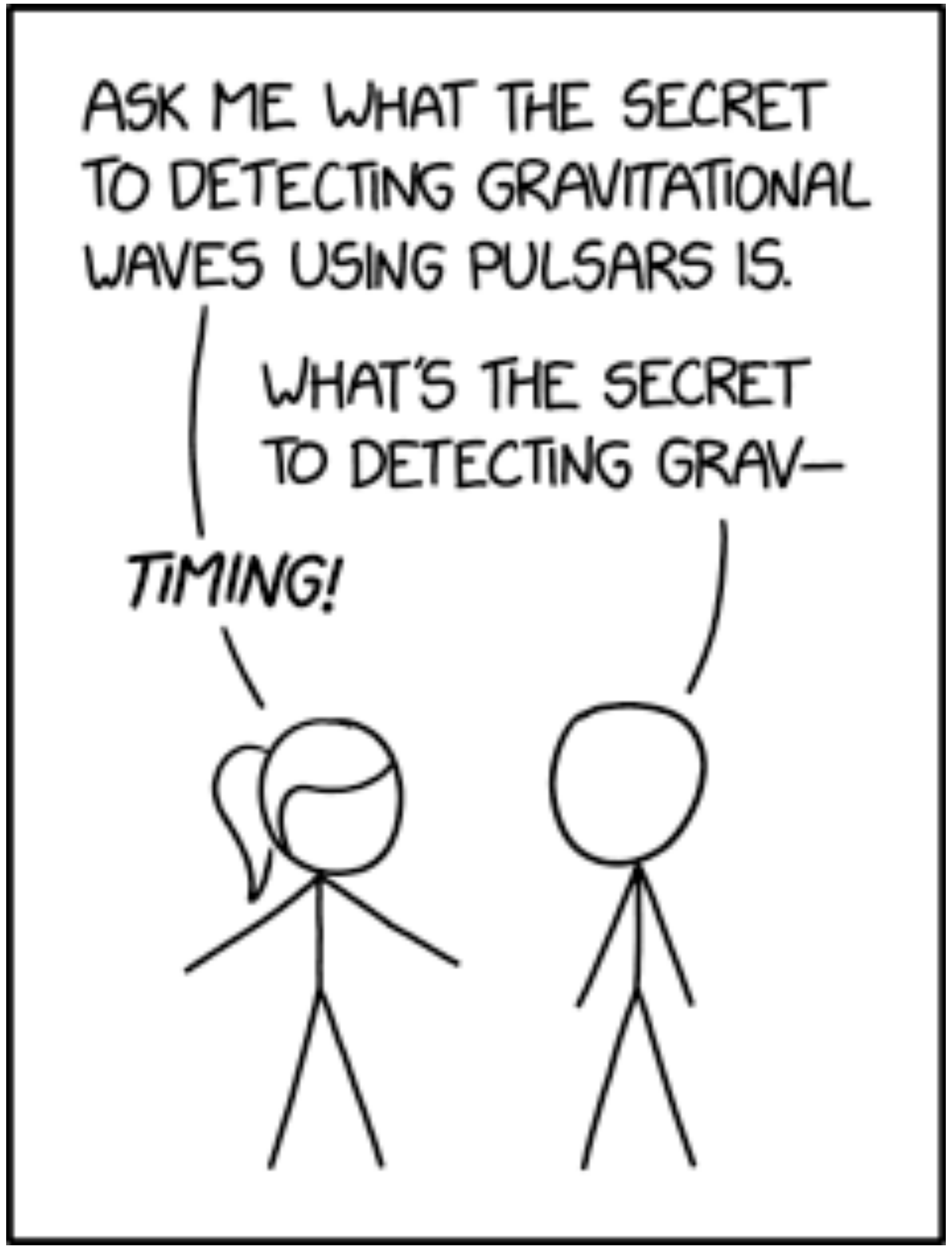
More data is incoming and more work needs to be done to extract possible primordial signals.

Natural Sciences and Engineering Research Council of Canada

Canadian Institute for Advanced Research

Gordon and Betty Moore Foundation

https://xkcd.com/2358/



The most important attributes of a vector in 3-space are {Location, Location, Location}