Astrophysics with NANOGrav's 15yr Data Set:
What can we learn from the nHz Gravitational Wave Background?

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AAS 243: NASA GW Special Interest Group

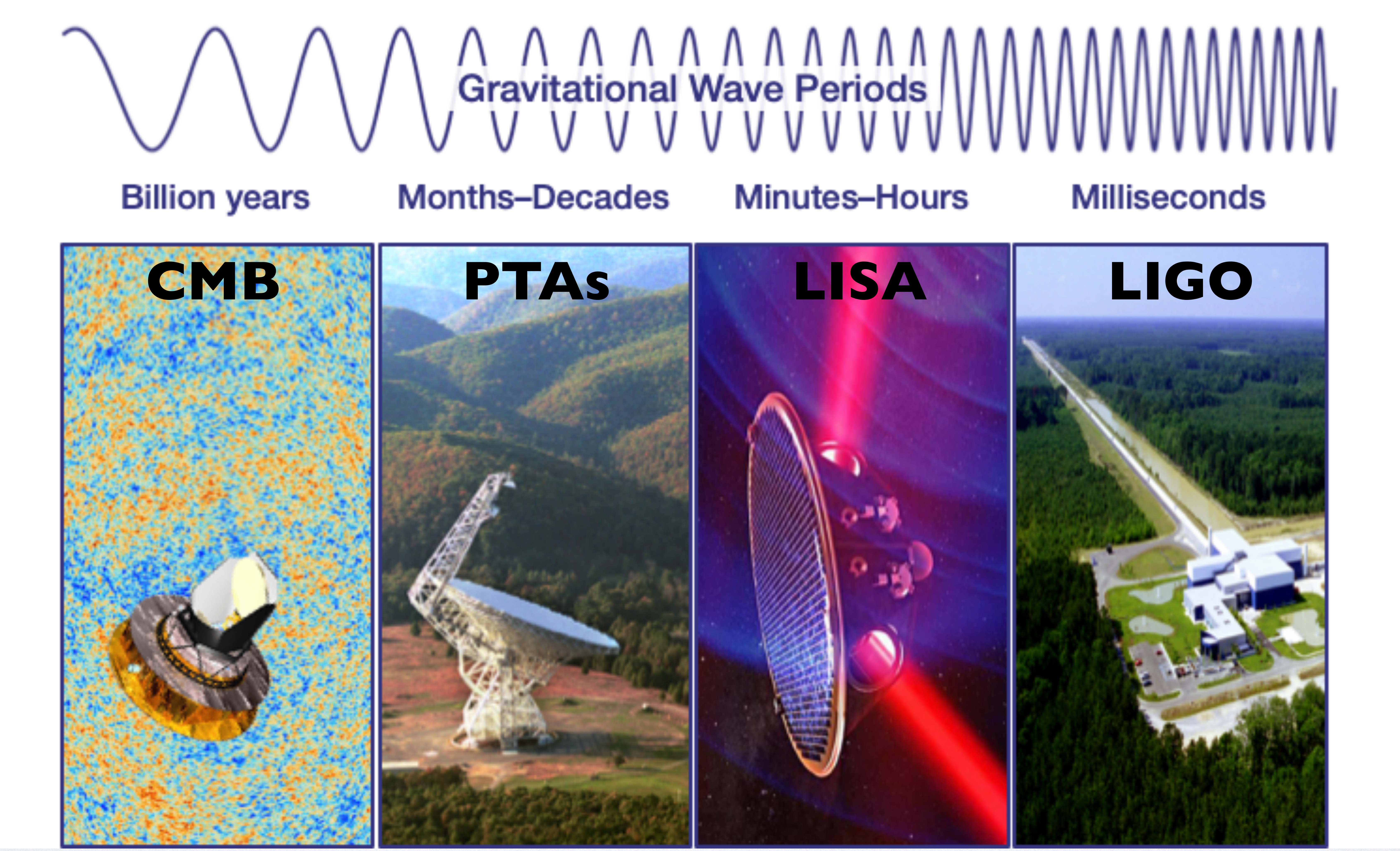
Talk Outline

- **A Brief Introduction to Pulsar Timing Arrays**
  NANOGrav's Evidence for a GW Background

- **Astrophysical Inference**
  Understanding the GWB

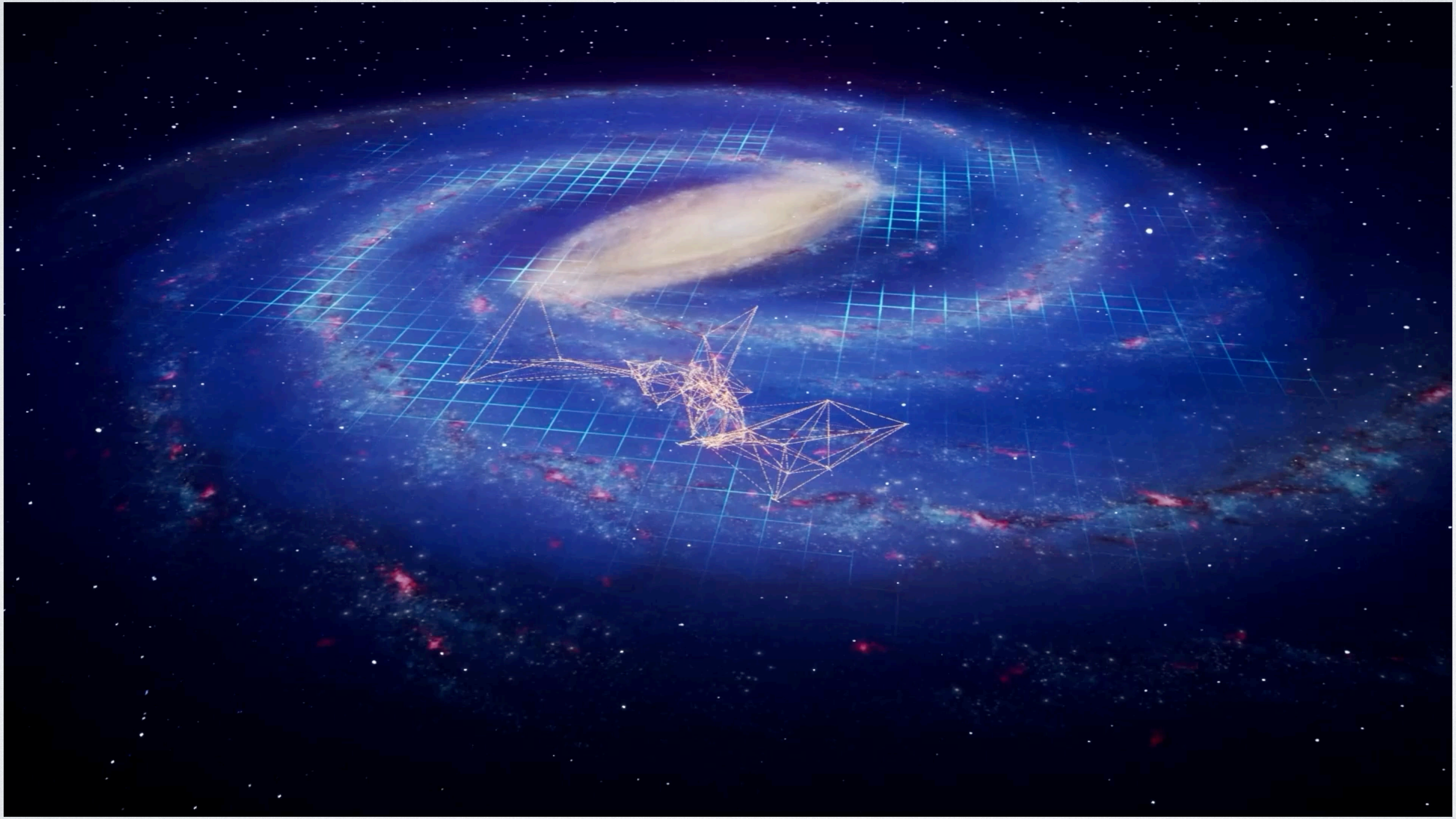
- **The Road Ahead**
  The nHz GW Multi-Messenger Landscape

Gravitational Wave Spectrum



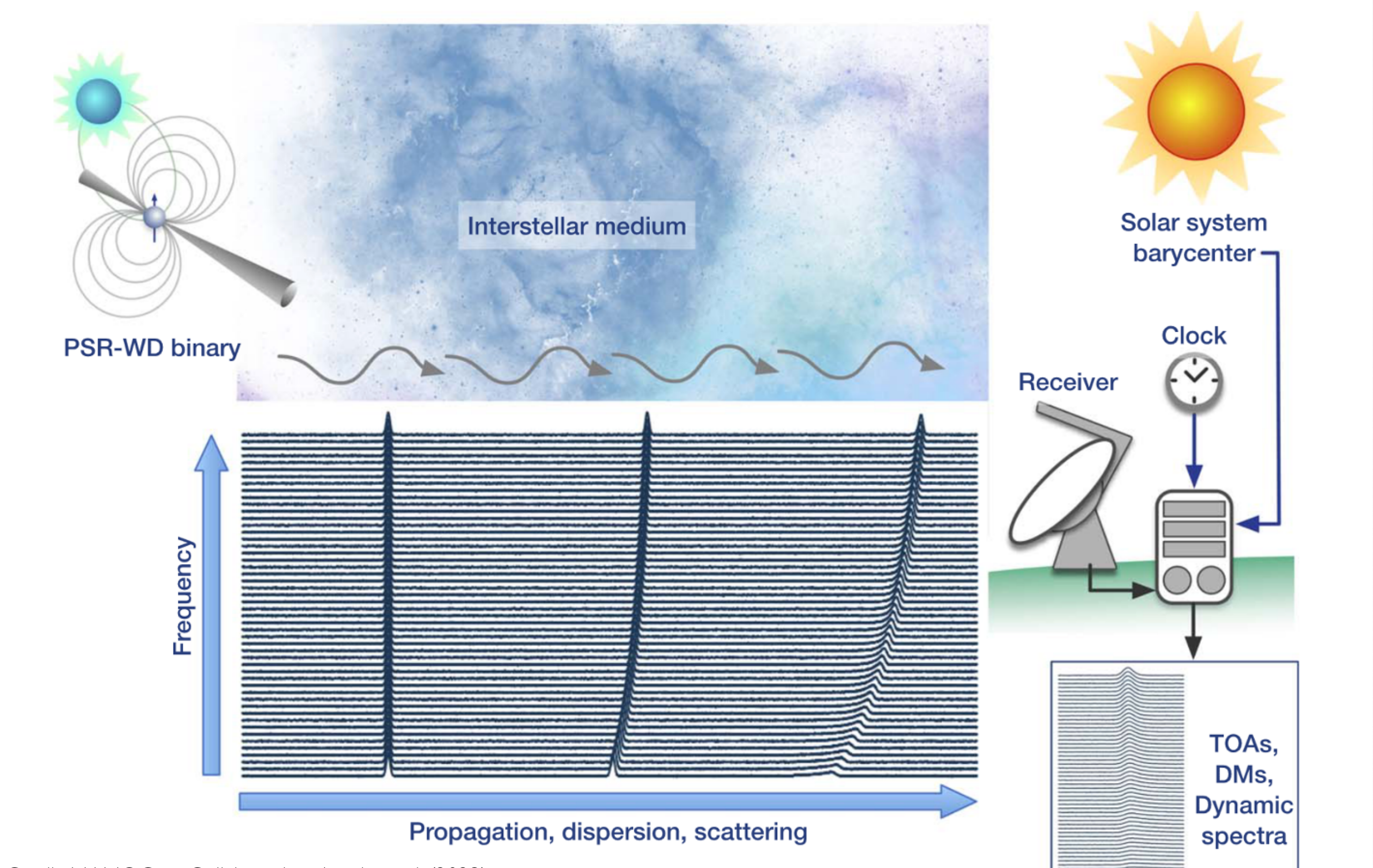
Primordial GWs | Supermassive Black Hole Binaries | Massive Black Hole Binaries | Stellar Mass Binaries

Building NANOGrav's Pulsar Timing Array



Pulsar Timing Array Data Analysis

Simultaneous Search For GWB & Noise

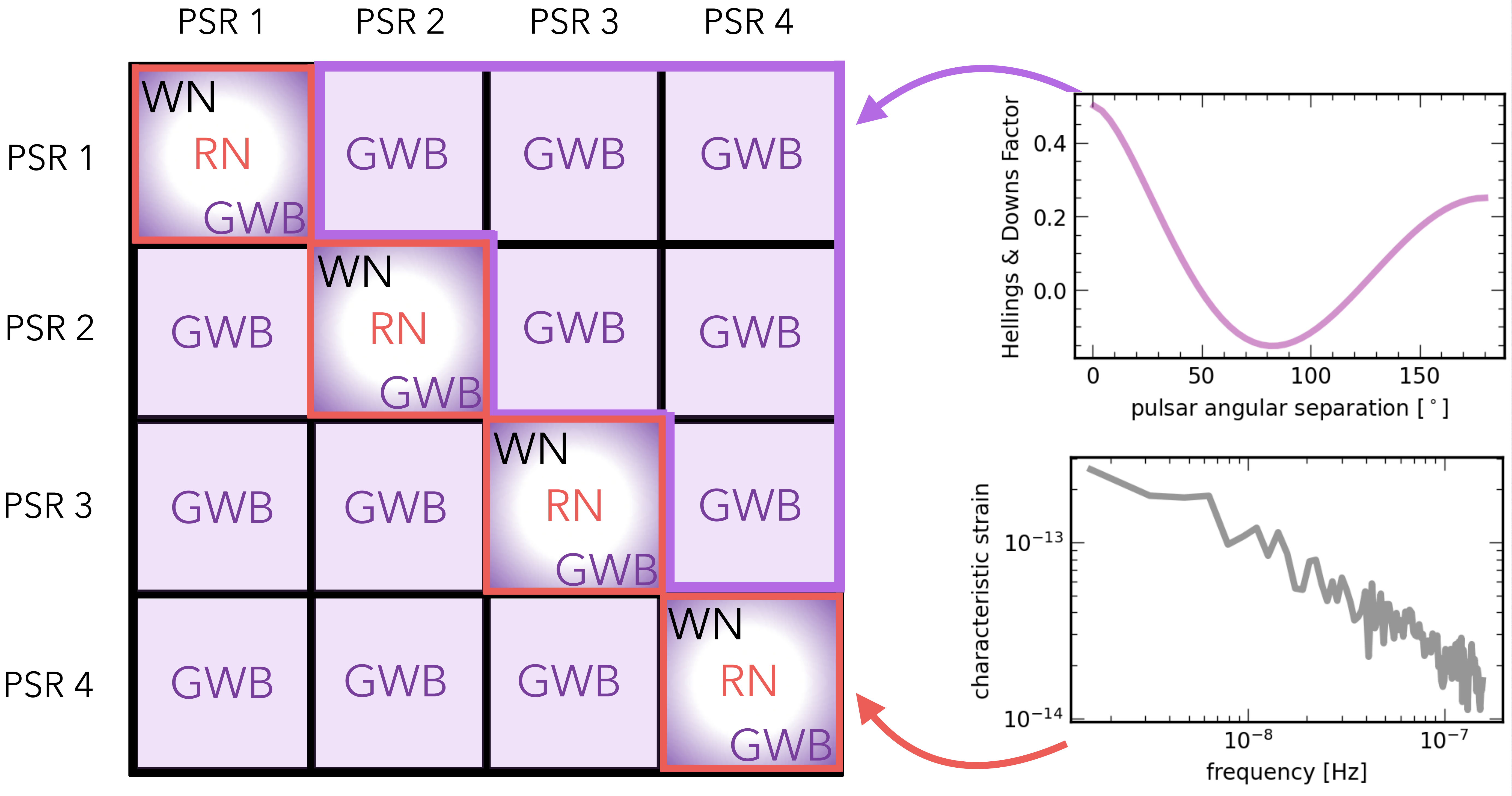


Credit: NANOGrav Collaboration, Agazie et al. (2023)

Searching For A GW Background

Results From NANOGrav's 15yr Data Set

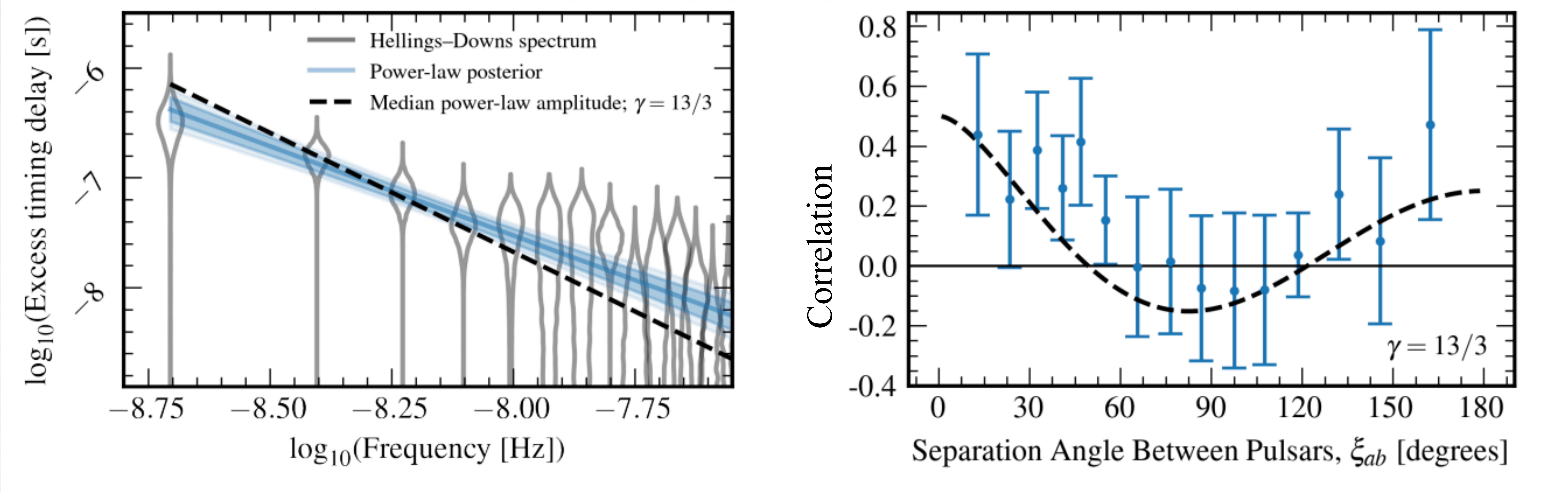
First, we searched for an *uncorrelated* signal,
followed by searching for evidence of spatial correlations.



Credit: S. Taylor, **JS**, et al. (2022)

NANOGrav's 15yr Pulsar Timing Data

Evidence for a nHz Gravitational Wave Background

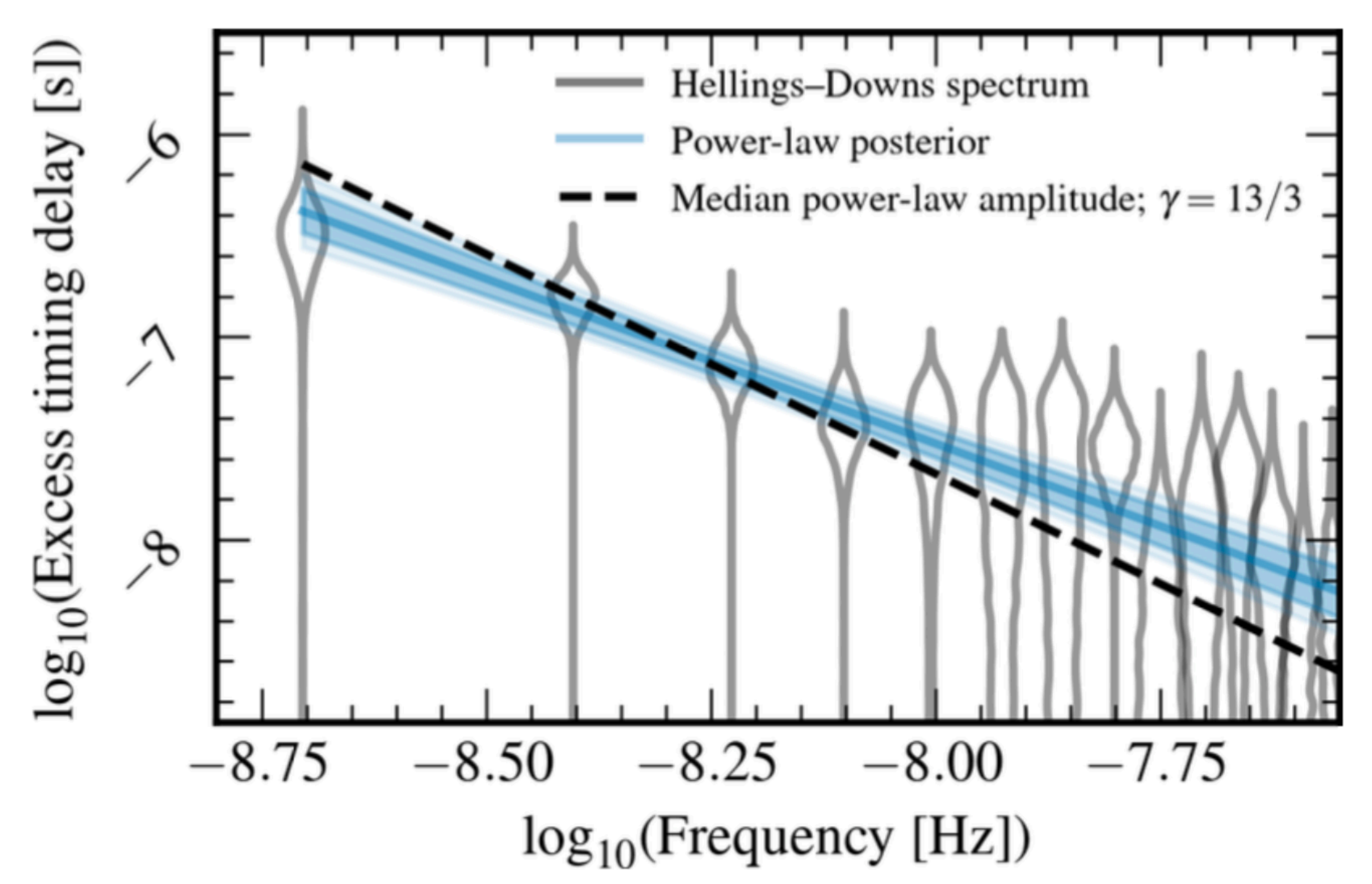


Credit: NANOGrav Collaboration, Agazie et al. (2023)

NANOGrav's 15yr Pulsar Timing Data

Evidence for a nHz Gravitational Wave Background

NANOGrav's Observed Power Spectrum



Credit: NANOGrav Collaboration, Agazie et al. (2023)

Data contain *no clear indication about the source of this signal!*

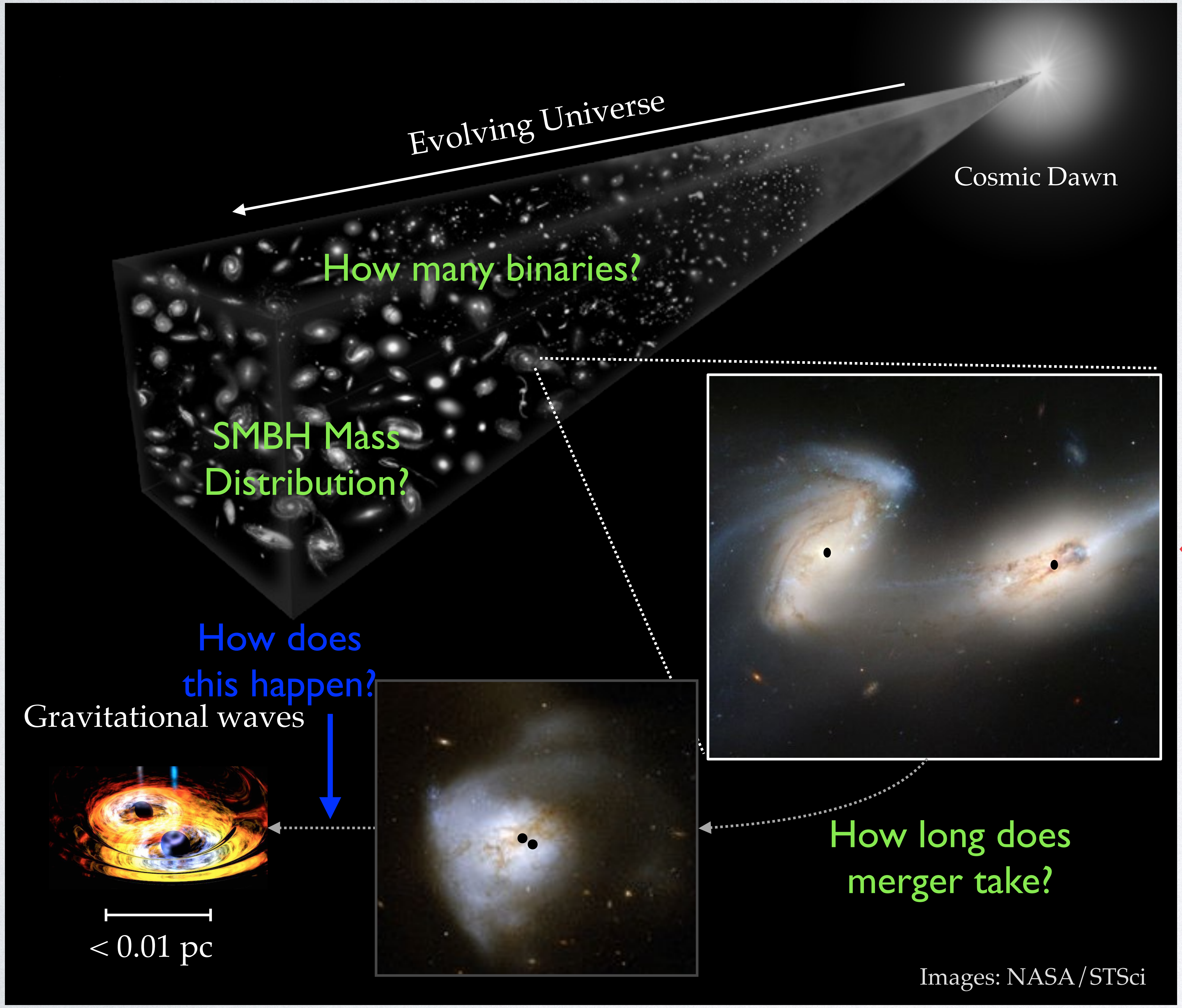
Sources of nHz Gravitational Waves

Binary Supermassive Black Holes ($10^6 - 10^9$ M_{sun})

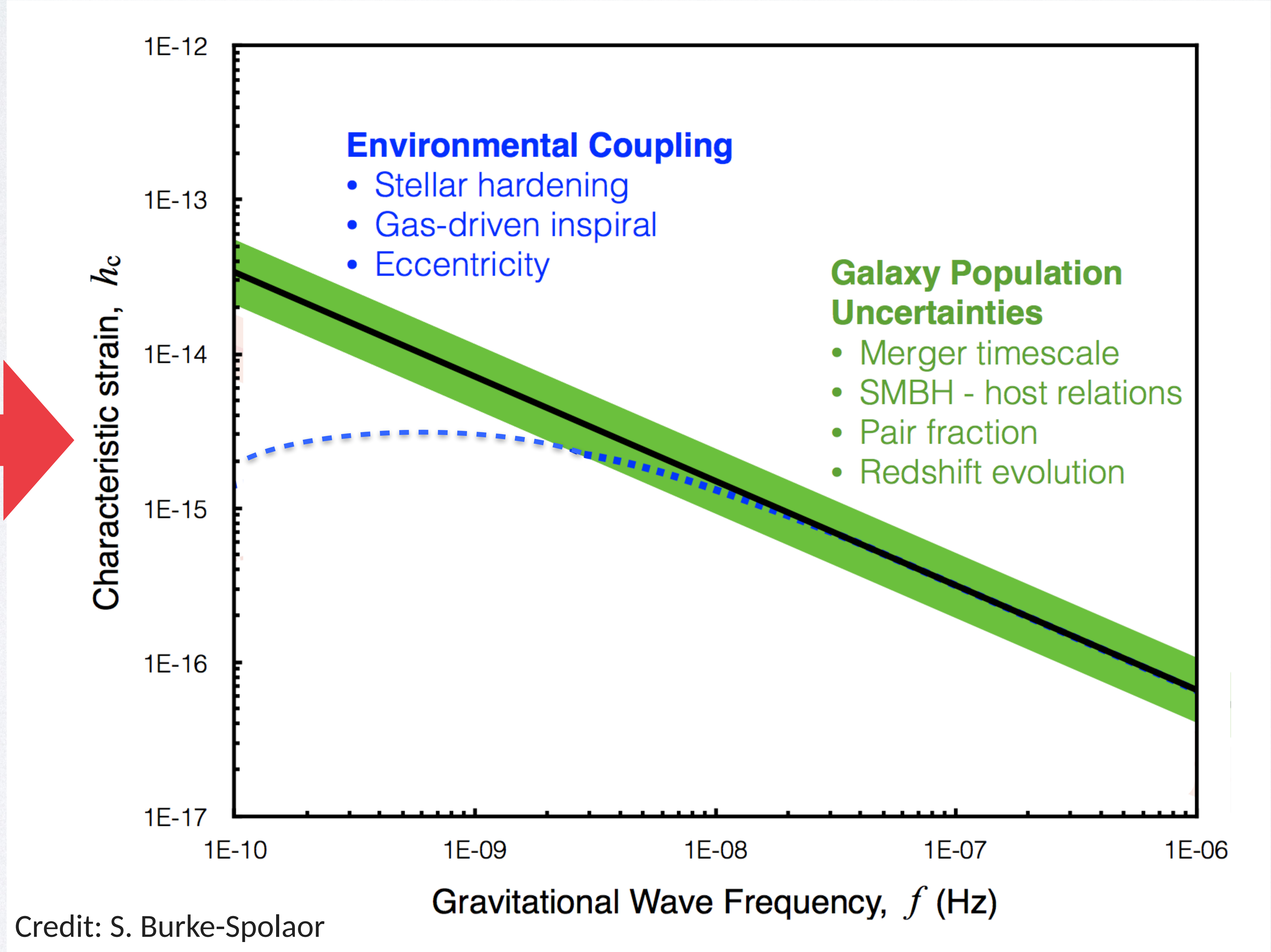
1. Dynamical friction drives galaxy merger.
2. Binary SMBH forms in core of merged galaxy.
3. Gravitational Radiation provides efficient inspiral.

Sources of nHz Gravitational Waves

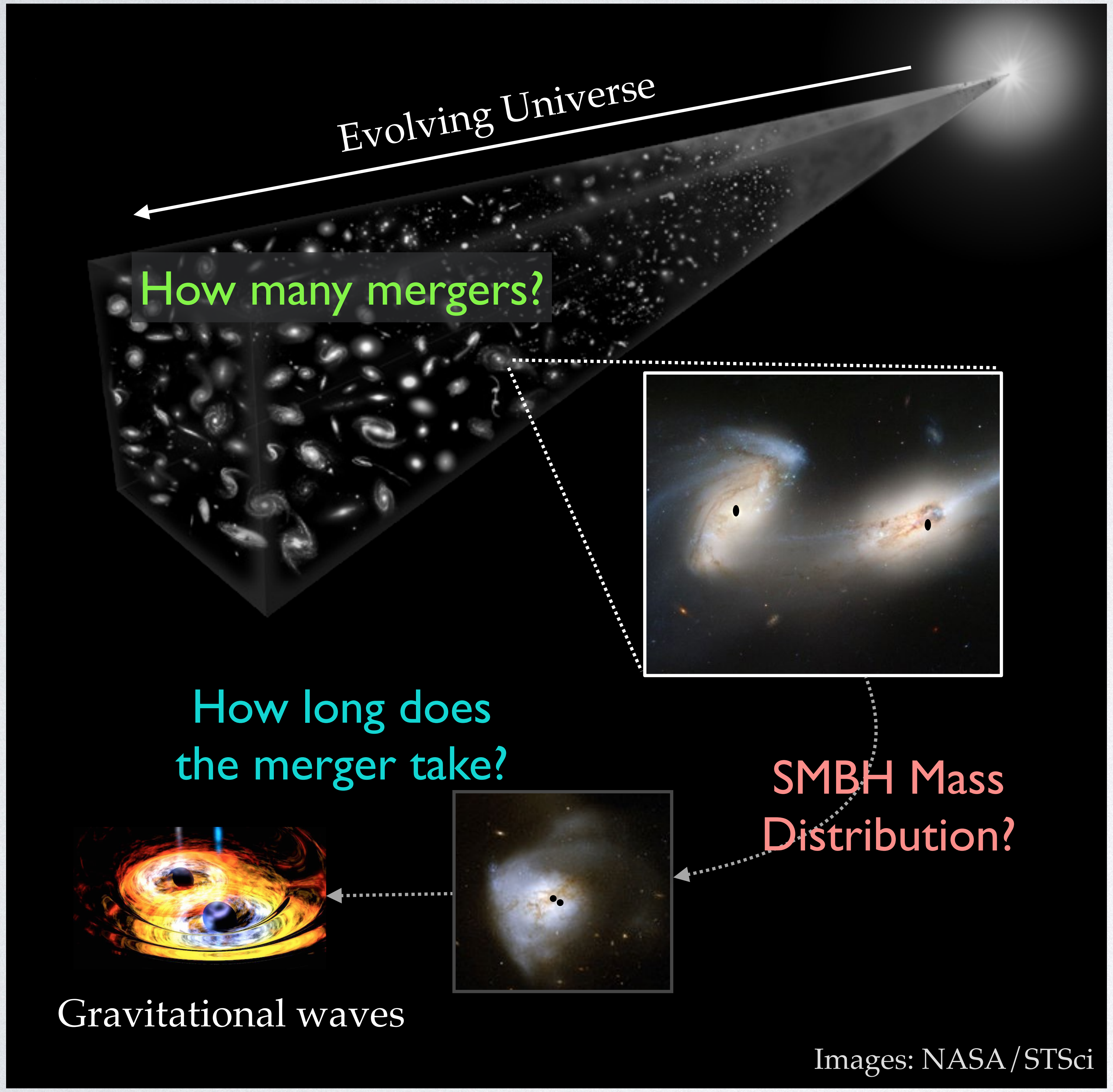
Binary Supermassive Black Holes ($10^6 - 10^9$ M_{sun})

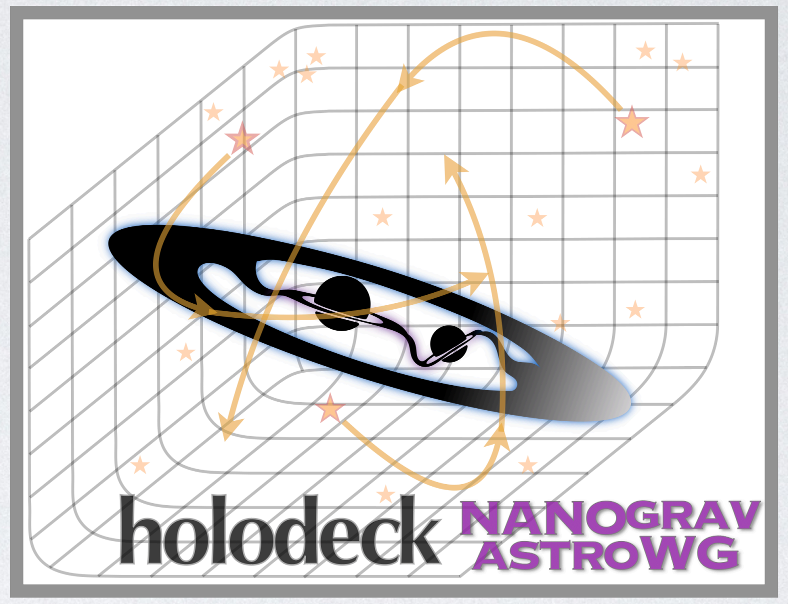


Entire GW Spectrum contains information about the SMBH Binary Population



Modeling the Binary SMBH Population



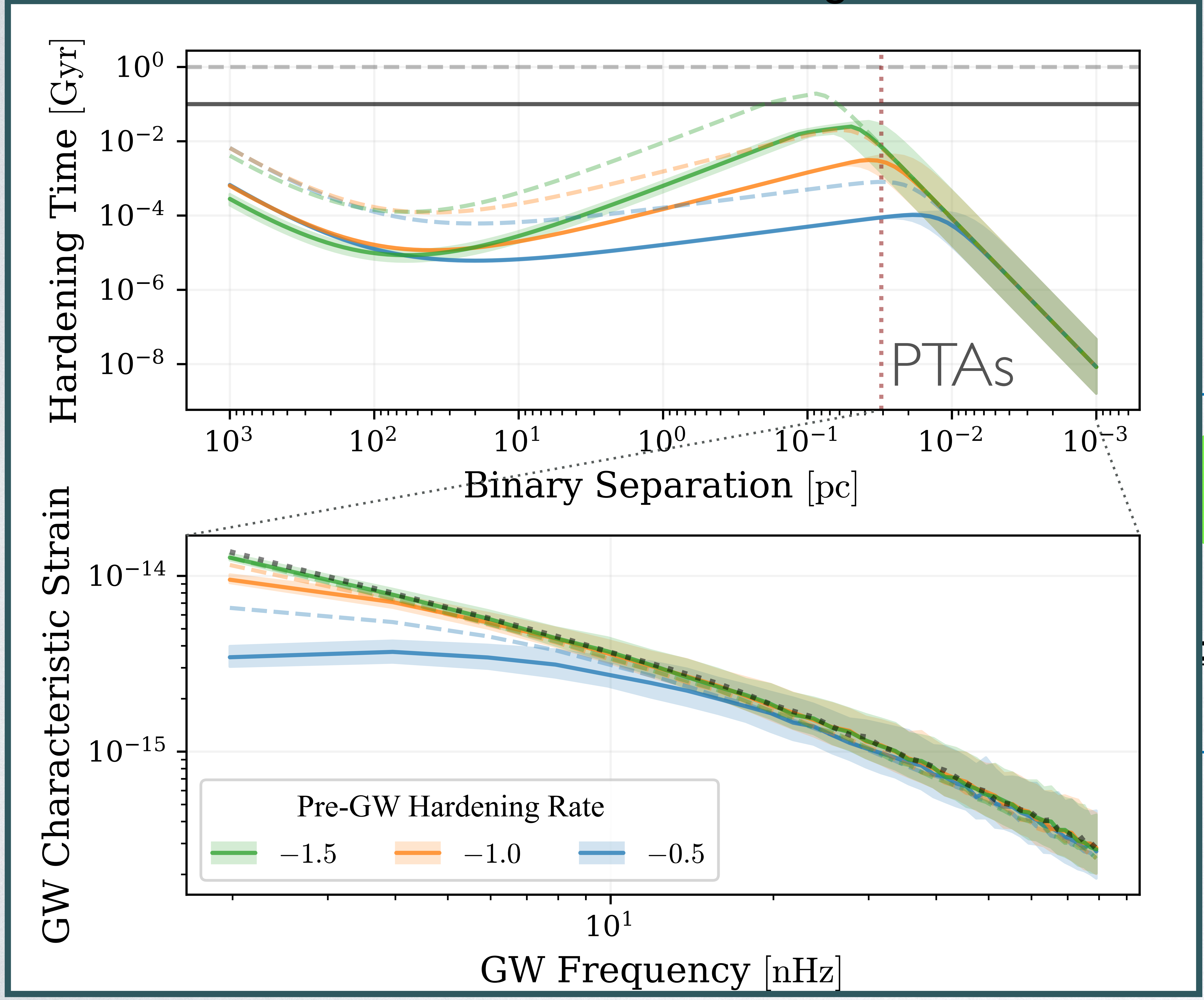


Binary SMBH Population Synthesis Framework

Key Factors:	Galaxy Mergers	SMBH Masses	Binary Evolution
Varied Parameters:	Galaxy Stellar Mass Function	M_{BH}-M_{bulge} (MMB) Relation	Phenomenological
Fixed Parameters:	Galaxy Merger Rate	Galaxy Mass Bulge Fraction	

Modeling the Binary SMBH Population

formation ⟶ evolution/“hardening” ⟶ coalescence



SMBH Population Synthesis Framework

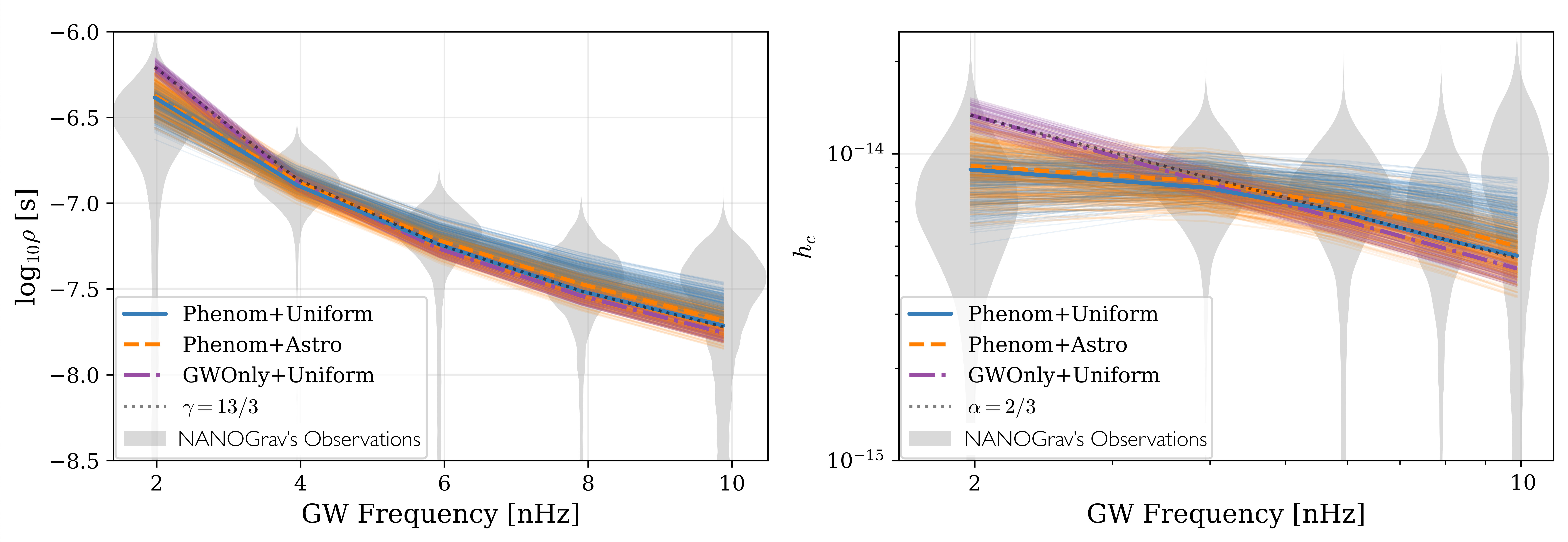
Galaxy Mergers — Galaxy Stellar Mass Function; Galaxy Merger Rate

SMBH Masses — M_{BH}-M_{bulge} (MMB) Relation; Galaxy Mass Bulge Fraction

Binary Evolution — Phenomenological

NANOGrav's 15yr Data Set

Constraining the Binary SMBH Population



Credit: NANOGrav Collaboration, Agazie et al. (2023)

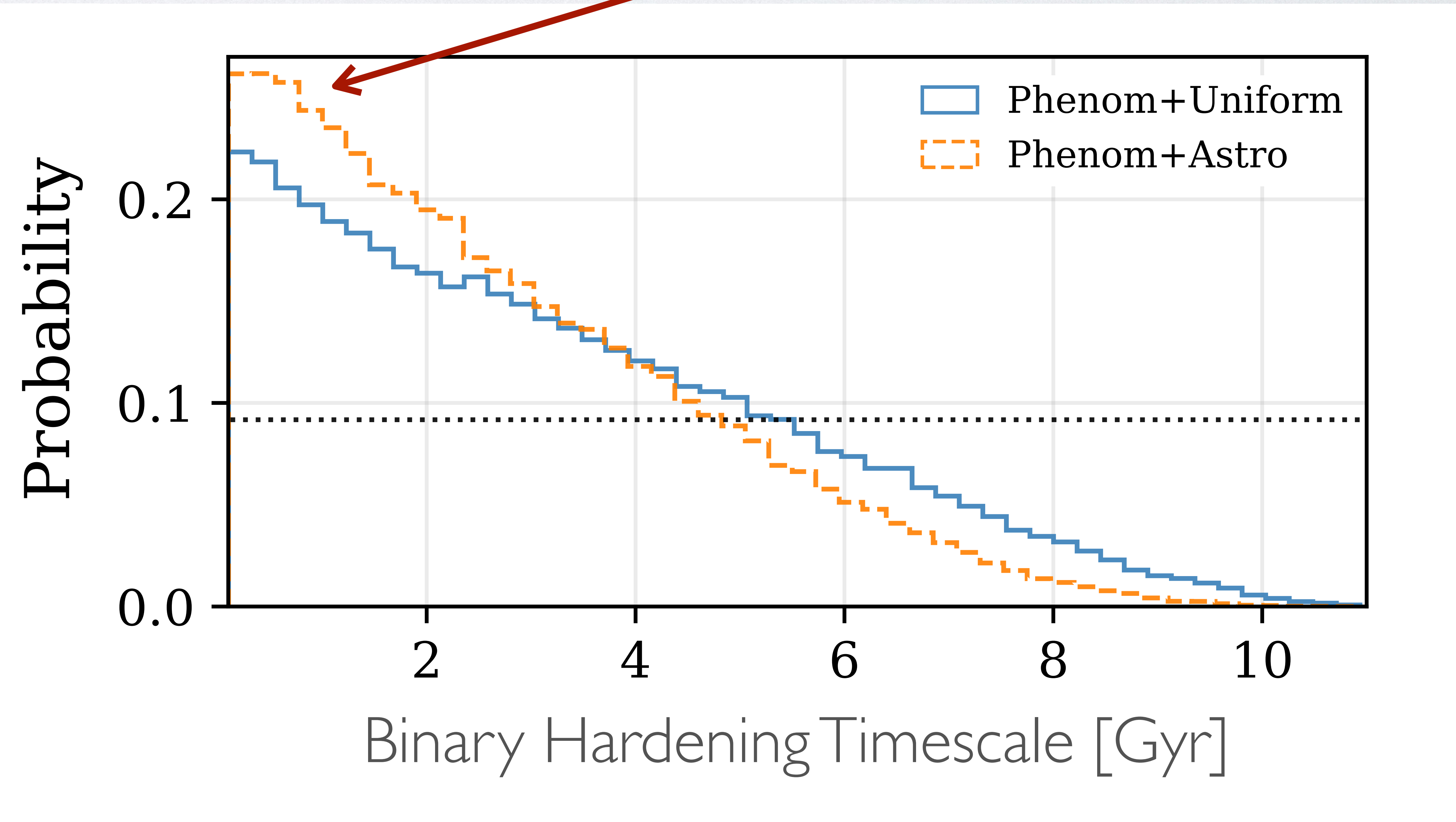
NANOGrav's 15yr Data Set

Constraining the Binary SMBH Population

What do we learn about the population?

- Shorter Binary Evolution Timescales
  No Final Parsec Problem!

Many systems coalesce in < 1 Gyr



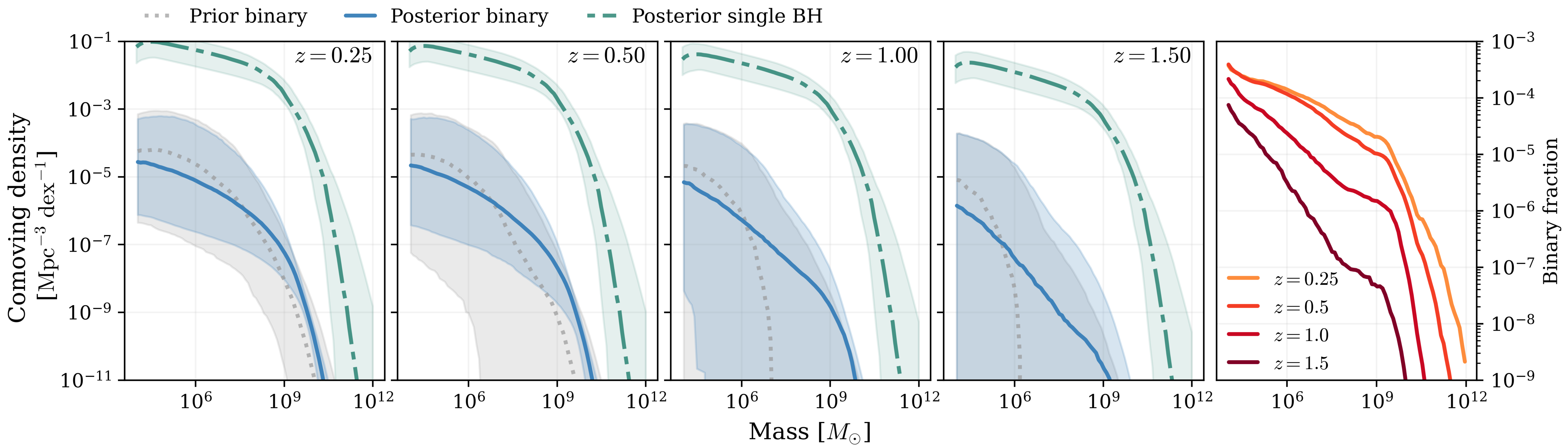
Credit: NANOGrav Collaboration, Agazie et al. (2023)

NANOGrav's 15yr Data Set

Constraining the Binary SMBH Population

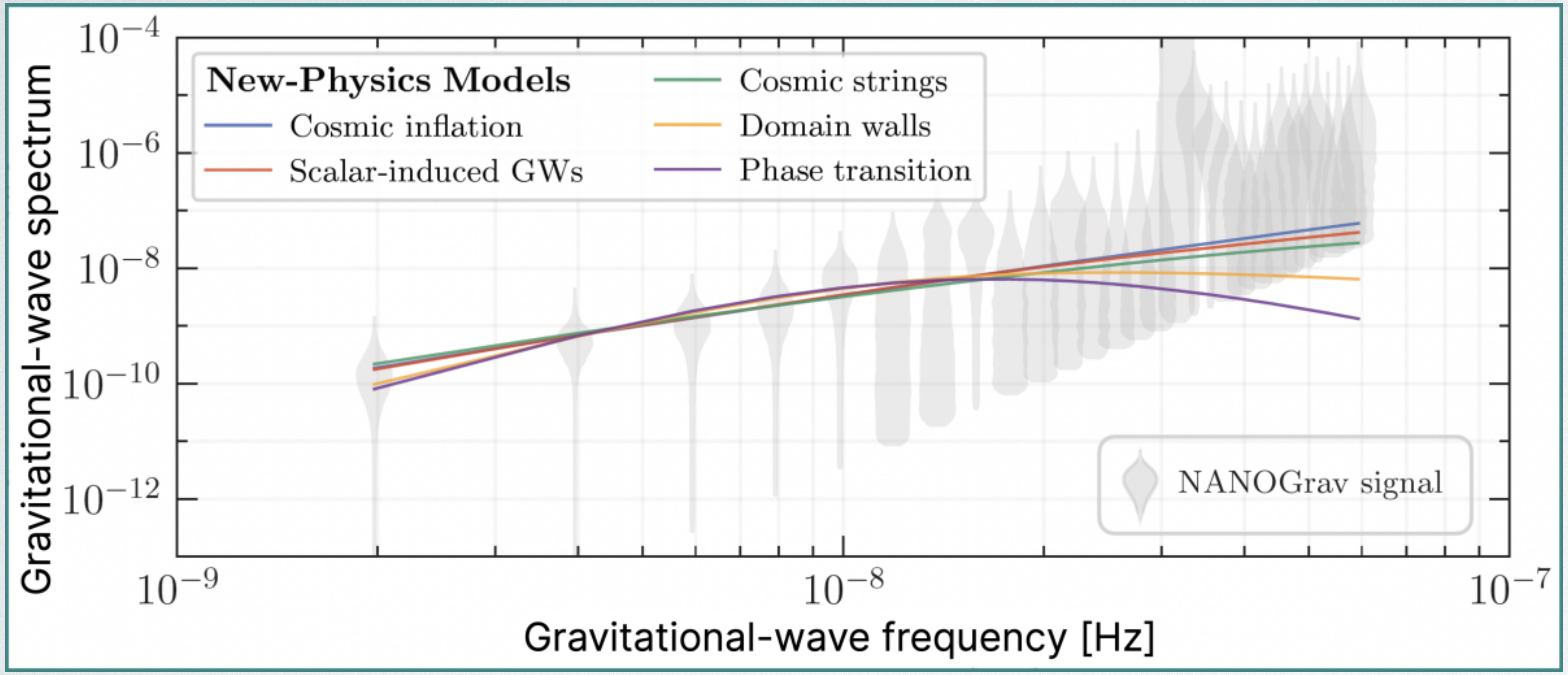
What do we learn about the population?

- Binary Population Is More Numerous / More Massive
  Consistent with emerging picture from JWST?



NANOGrav's 15yr Data Set:

Constraining Signals from New Physics



Credit: NANOGrav Collaboration, Afzal et al. (2023)

- **Cosmological Models**
  Inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, domain walls.
- No evidence of New-Physics.
  - But can't be ruled out either!
- No evidence of ultralight dark matter.
  - But constraints outperform torsion balance and atomic clock tests.

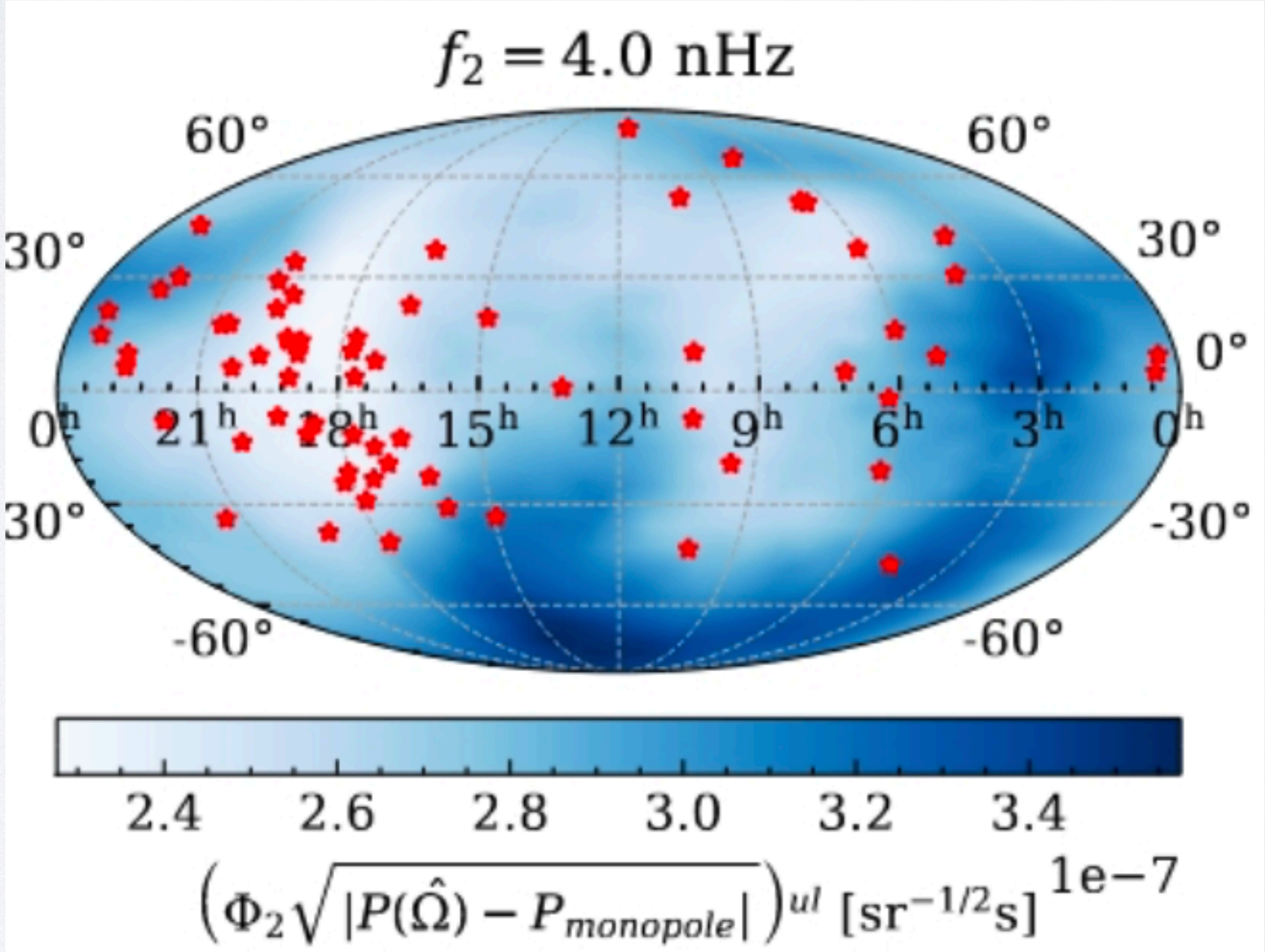
Next Steps:

What can we do to distinguish the source of the signal?

GWB from discrete population tends to have anisotropies at a much higher level than a GWB from a cosmological source.

No evidence of anisotropy found (yet), but recent predictions say it may be detectable in ~ 5 years (see Pol, Taylor, Romano 2022 and others)

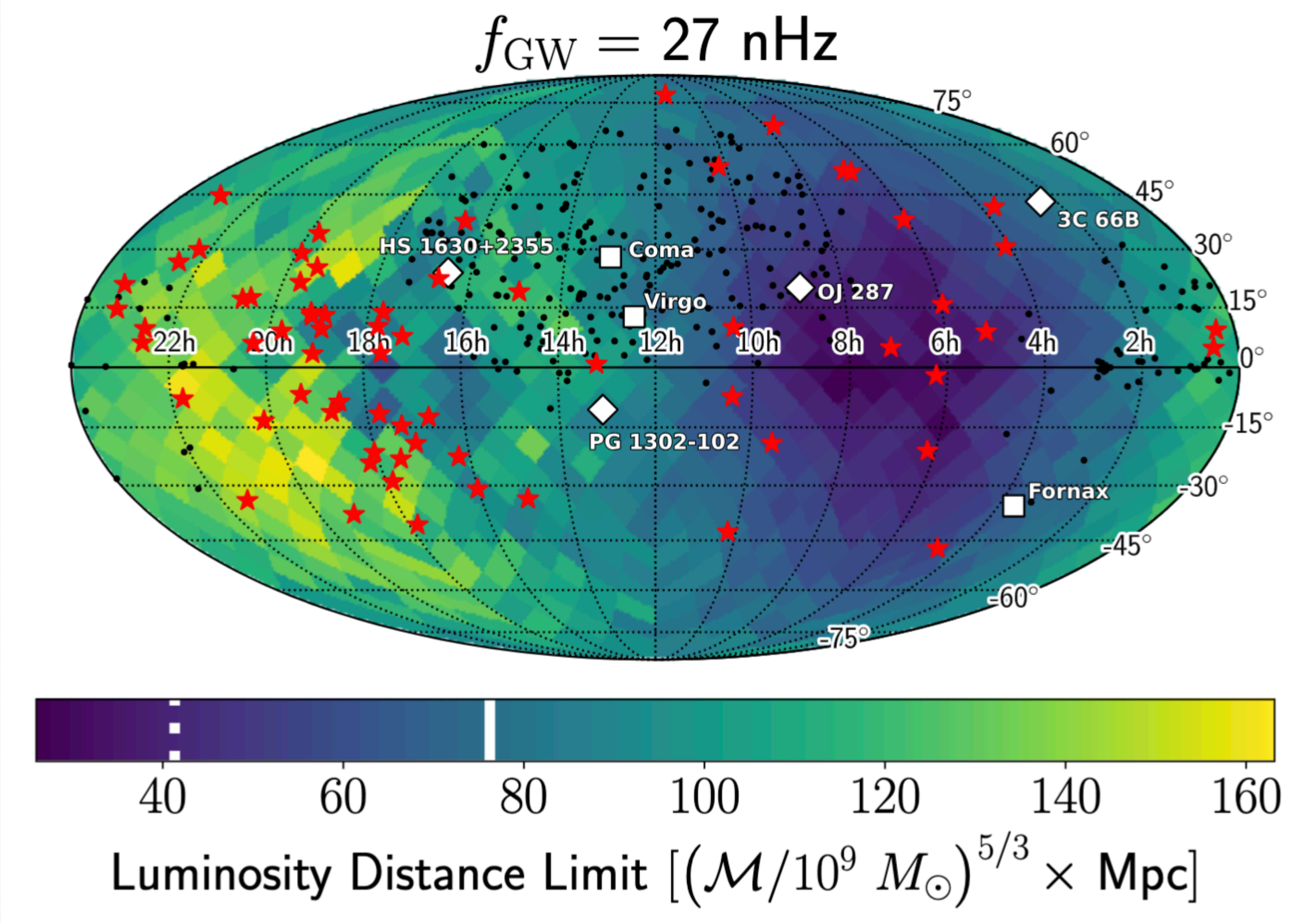
Note: Upper limits are best where there is the greatest density of pulsars.

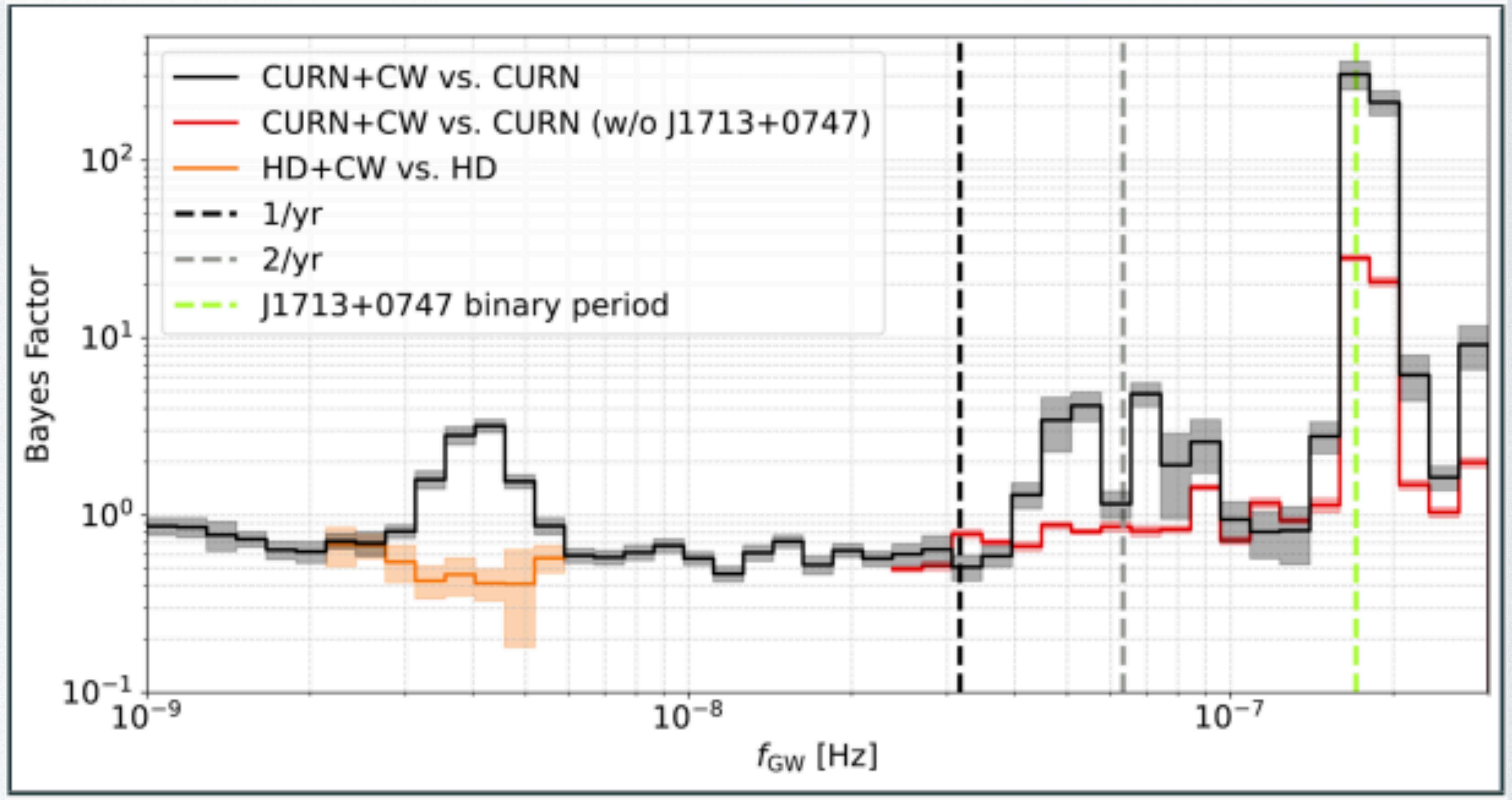


Next Steps:

What can we do to distinguish the source of the signal?

GWB from discrete population (e.g., SMBH Binaries) will have individual resolvable systems (i.e., continuous wave [CW] sources).





No evidence for single sources (yet)

The Next Multi-messenger Frontier

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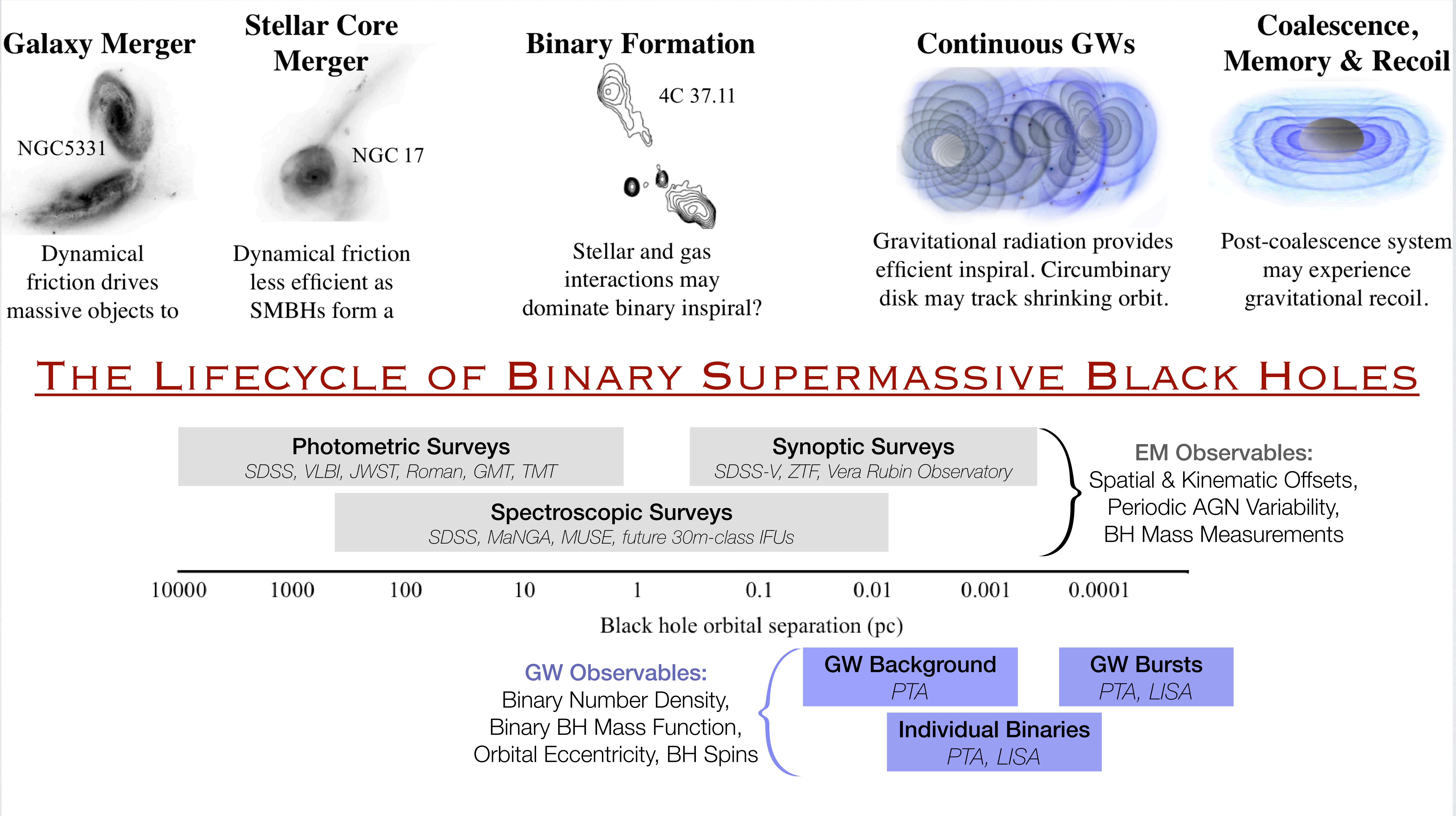
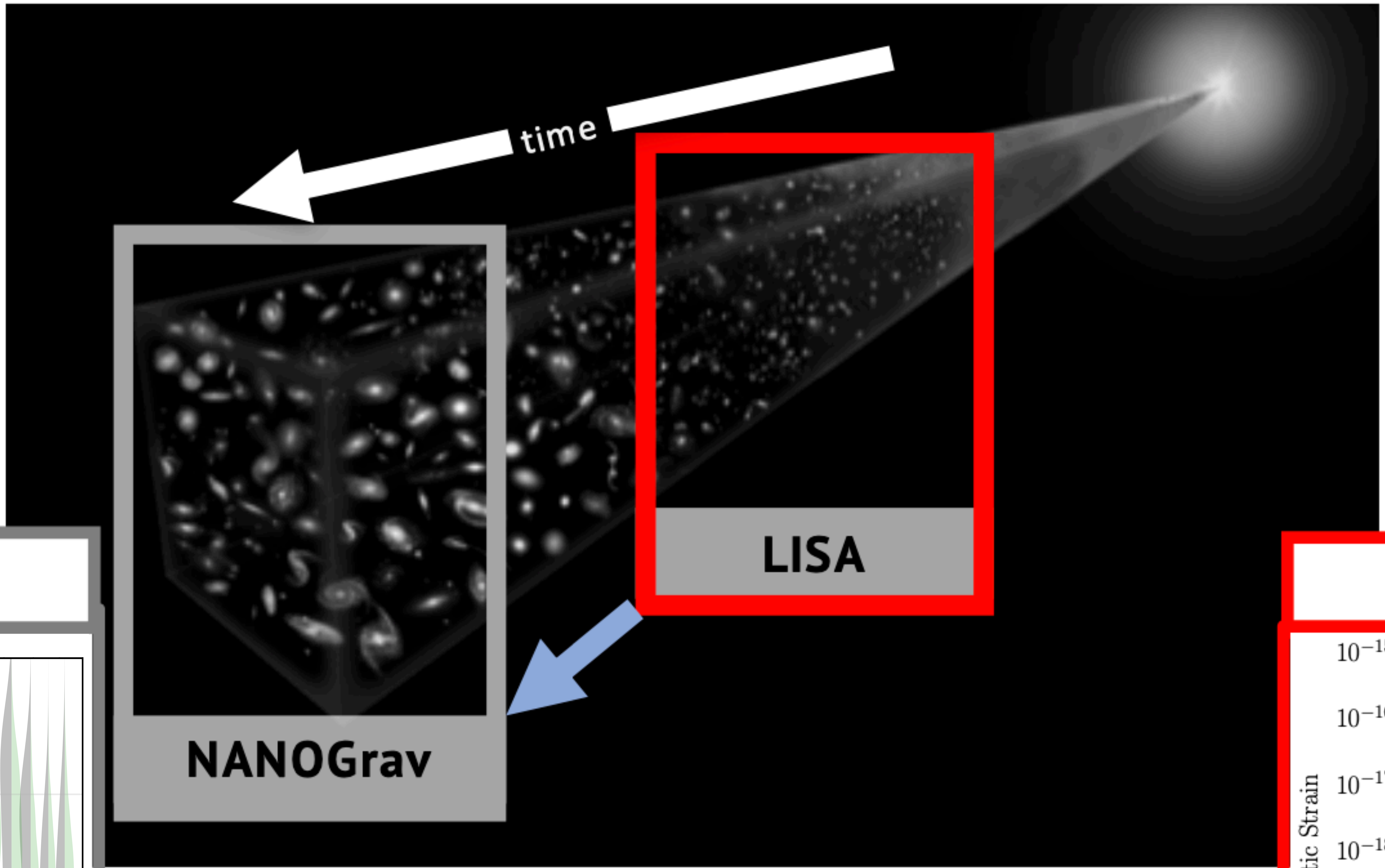
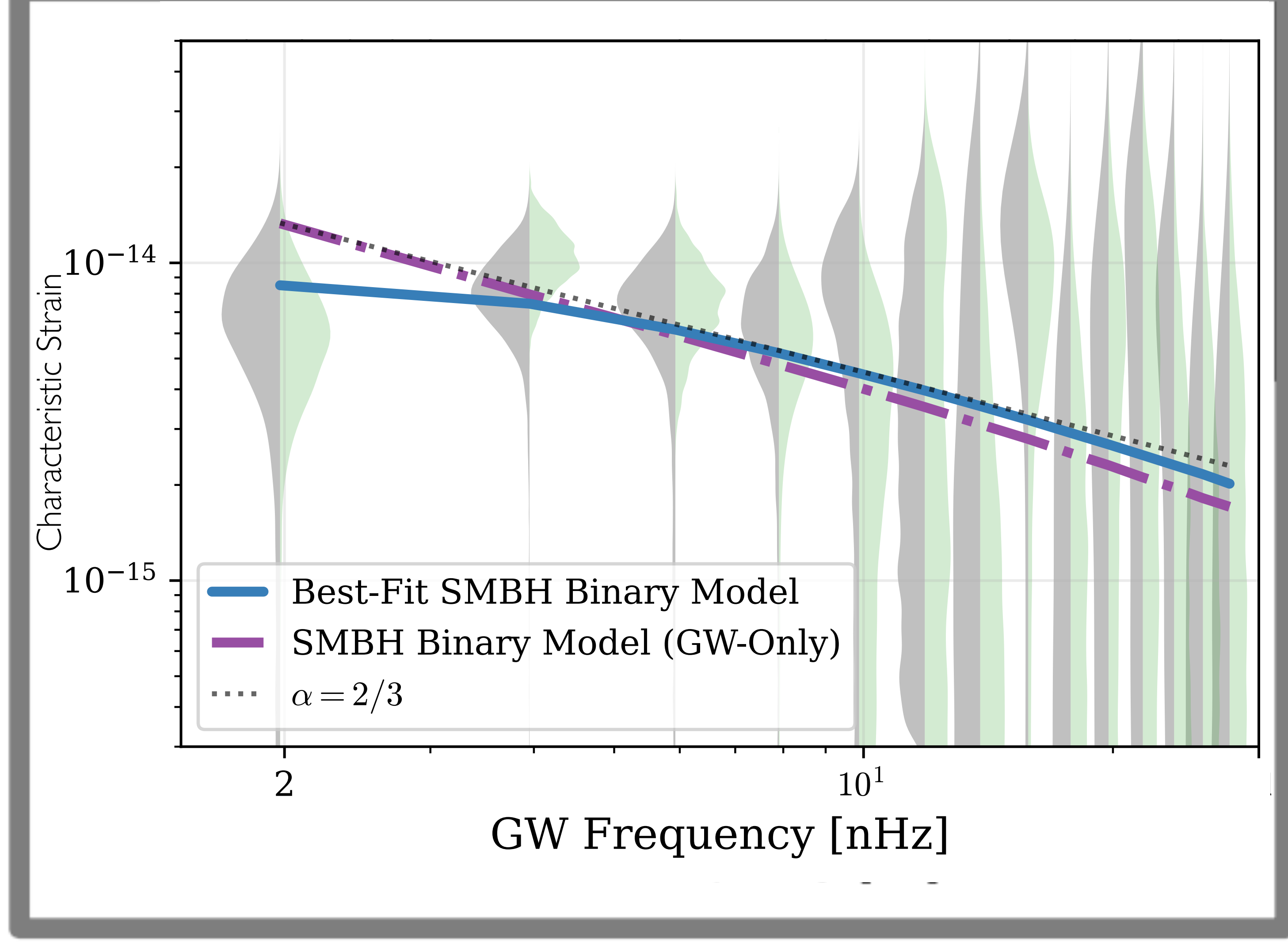


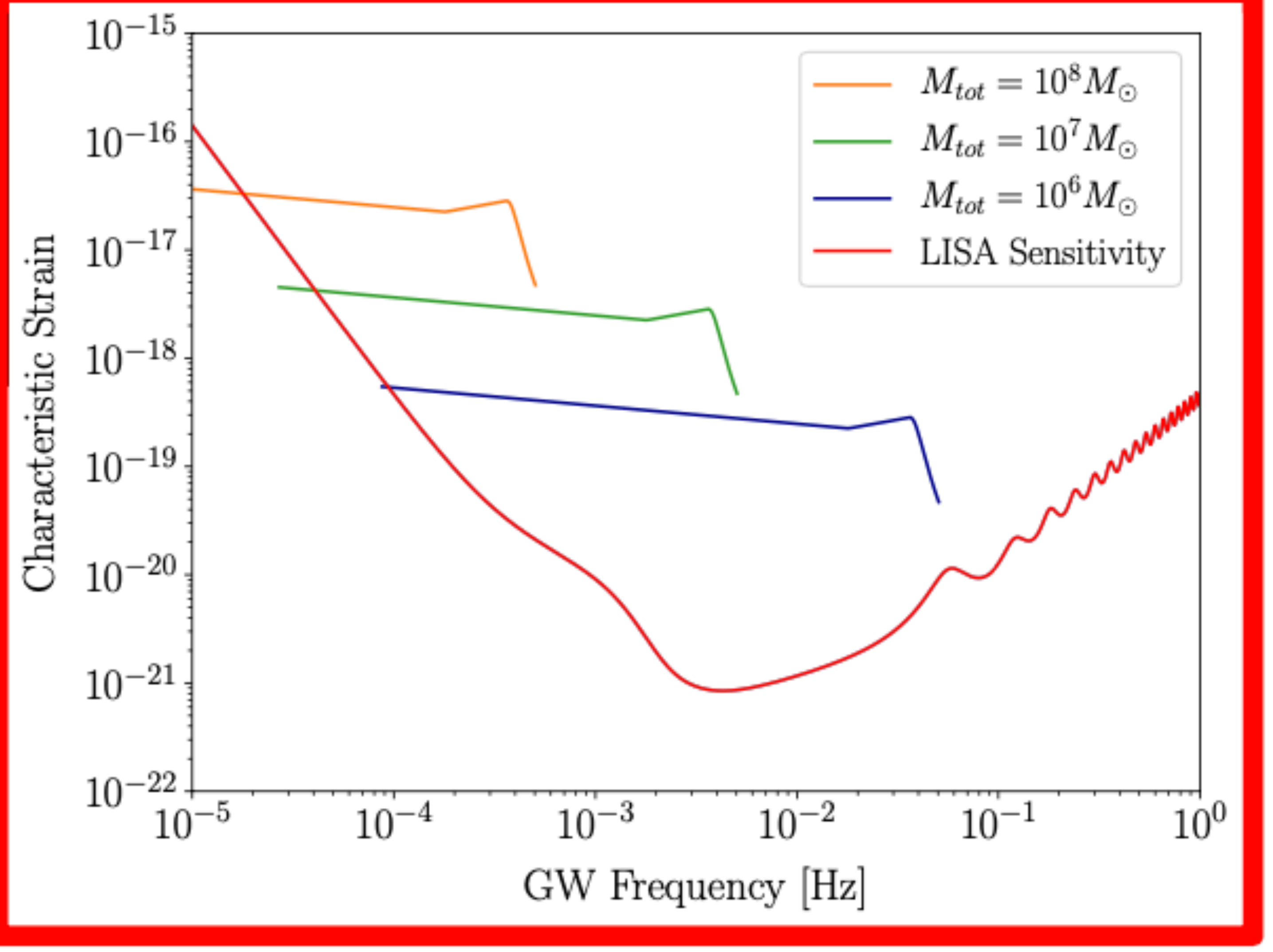
Multi-band Gravitational Wave Astrophysics with PTAs and LISA



NANOGrav



LISA



The massive black hole binaries detected by LISA are the progenitors to the supermassive black hole binaries that form the stochastic background detected by pulsar timing arrays

Summary

Analysis of the NANOGrav 15-yr Data Set reveals evidence for a Nanohertz Gravitational Wave Background, which contains unique insights about the Universe.

While pulsar timing data contain *no clear indication about the source of this signal*, we can start to constrain a variety of models.

For Binary Supermassive Black Holes: A more numerous and more massive population, with shorter binary hardening timescales (no "final parsec problem").

For New Physics: A window into the Universe before the emission of the CMB, where GWs are the only data we have to test and constrain models.

Next Steps: Multimessenger science studying individual systems as well as entire population, and potential for multi-band population studies with future GW observatories!