Pulsar Timing Arrays:

The Observation Era

Patrick Meyers, Caltech and NANOGrav

10 years to LISA

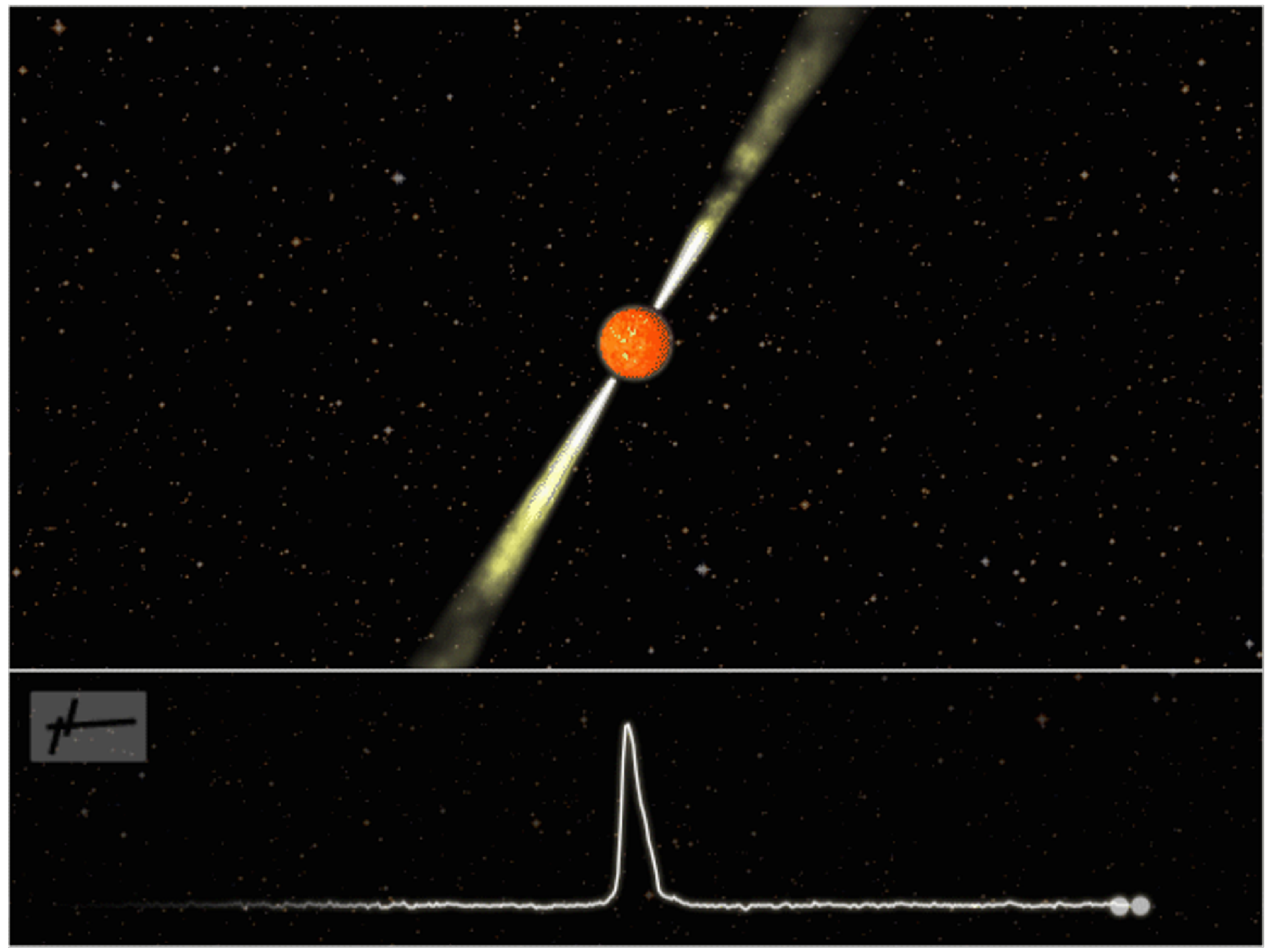
April 1st, 2025

Caltech

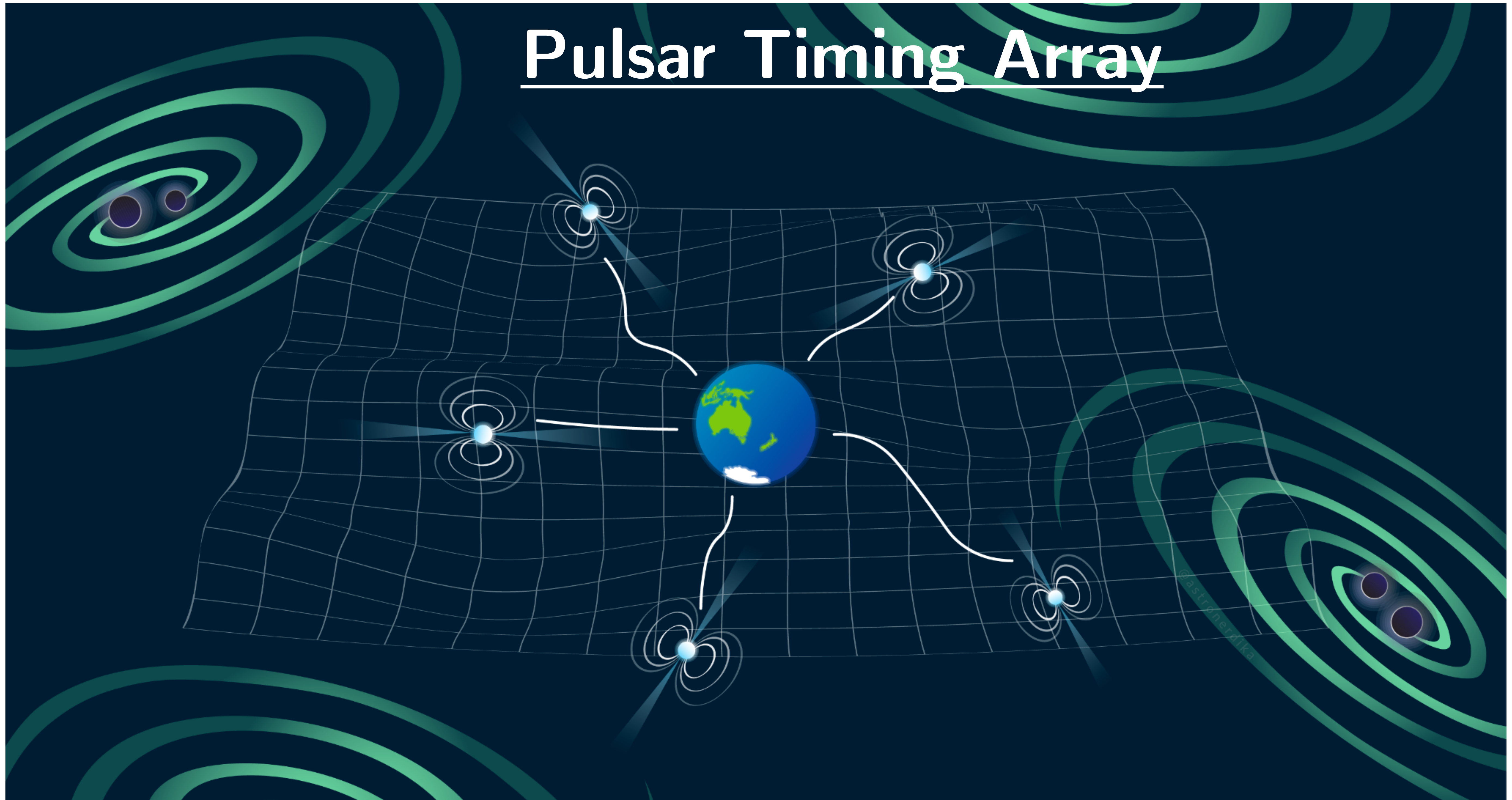
NANOGrav

Pulsar Timing

- GWs change the arrival time of pulses
- Those changes are **correlated across pulsars**
- Target **persistent, stochastic** signals, like due to unresolved SMBHB mergers
  - Plenty of other possible explanations



Credit: Joeri van Leeuwen



Pulsar Timing Array; @astronerdika

Caltech

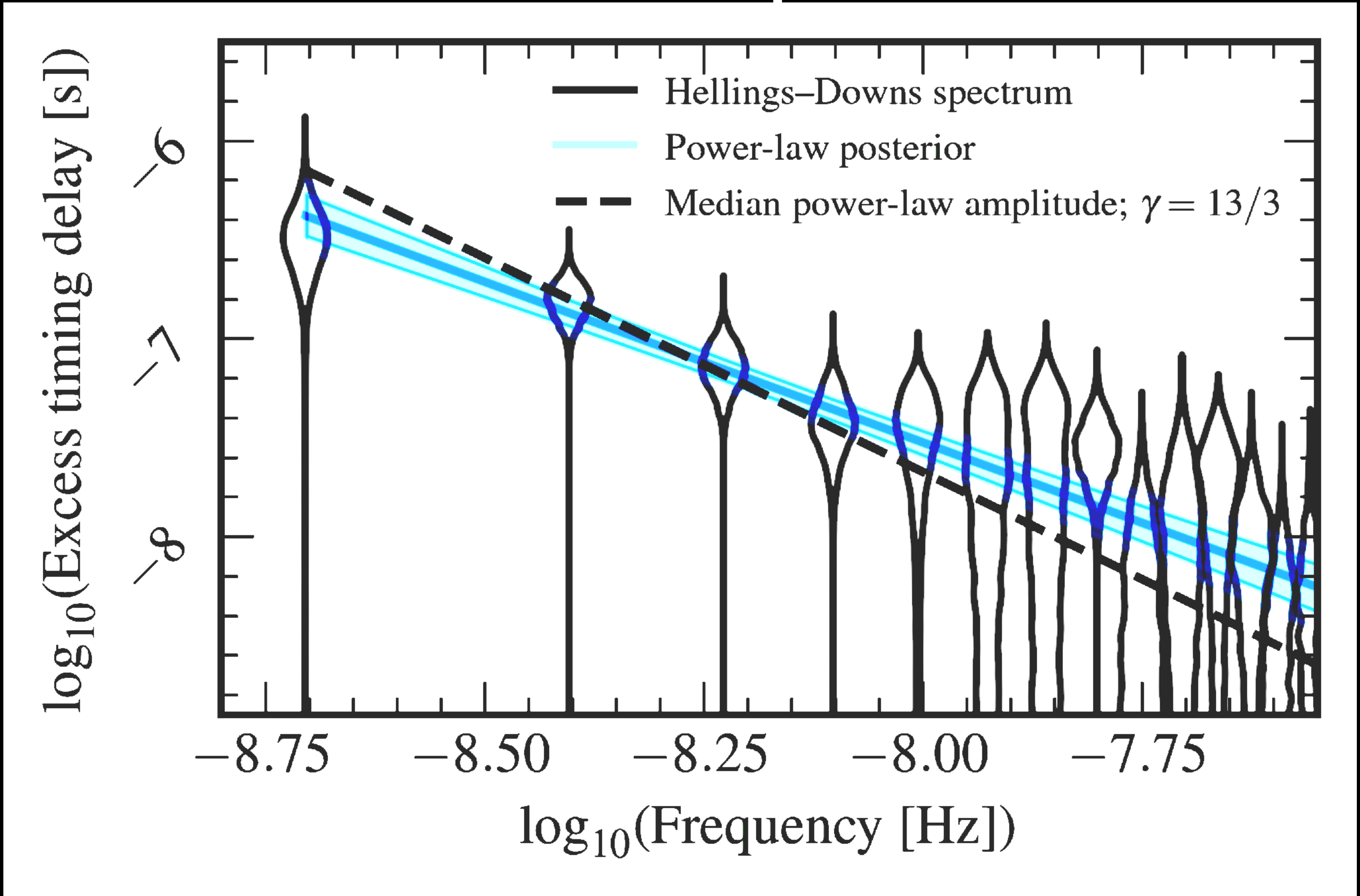
NANOGrav

Without
Gravitational Waves
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)
Animation concept by Olivia Young

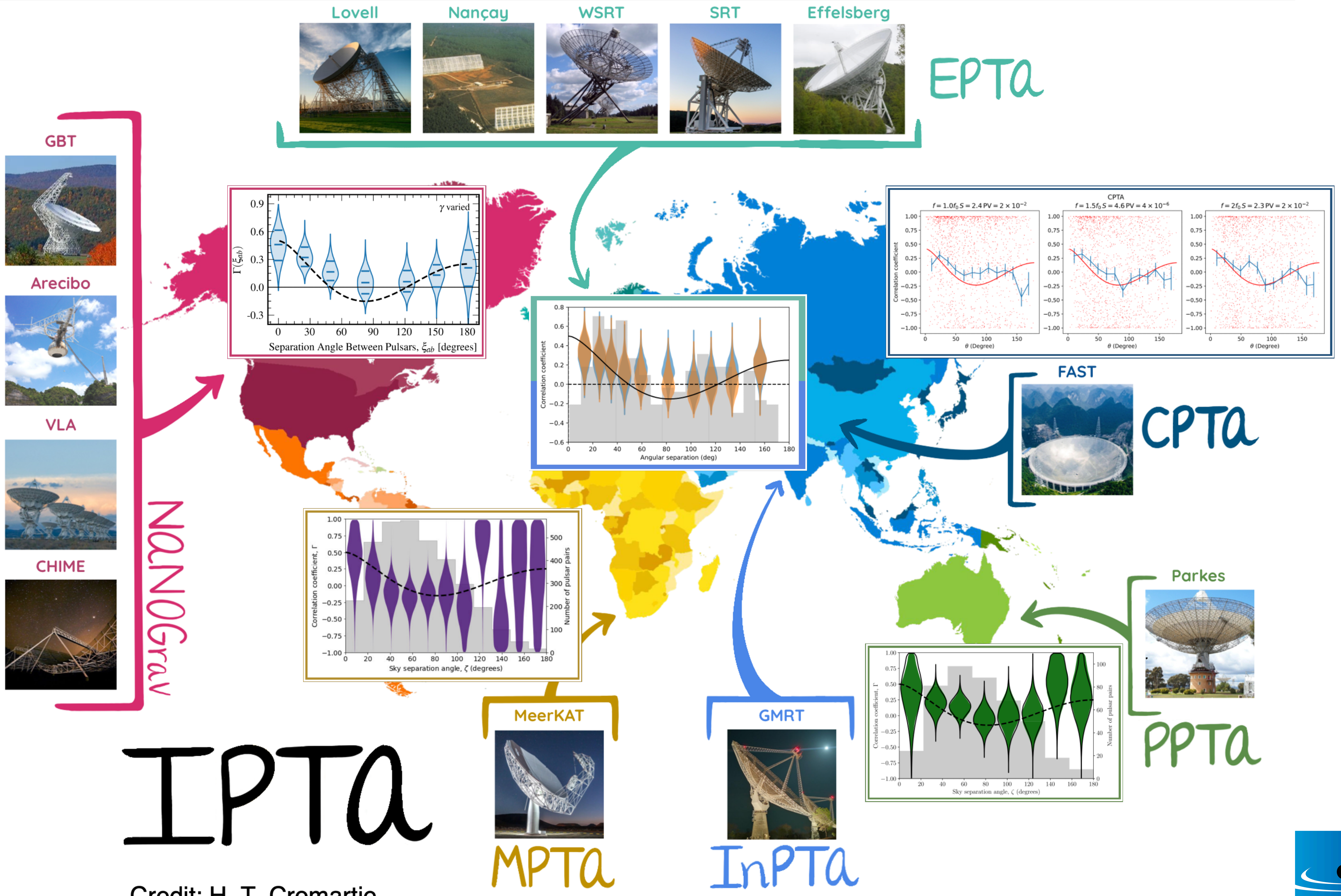
NANOGrav 15 yr dataset results

NANOGrav 2023, **ApJL, 951:L8**

Recovered spectrum



Credit: H. T. Cromartie



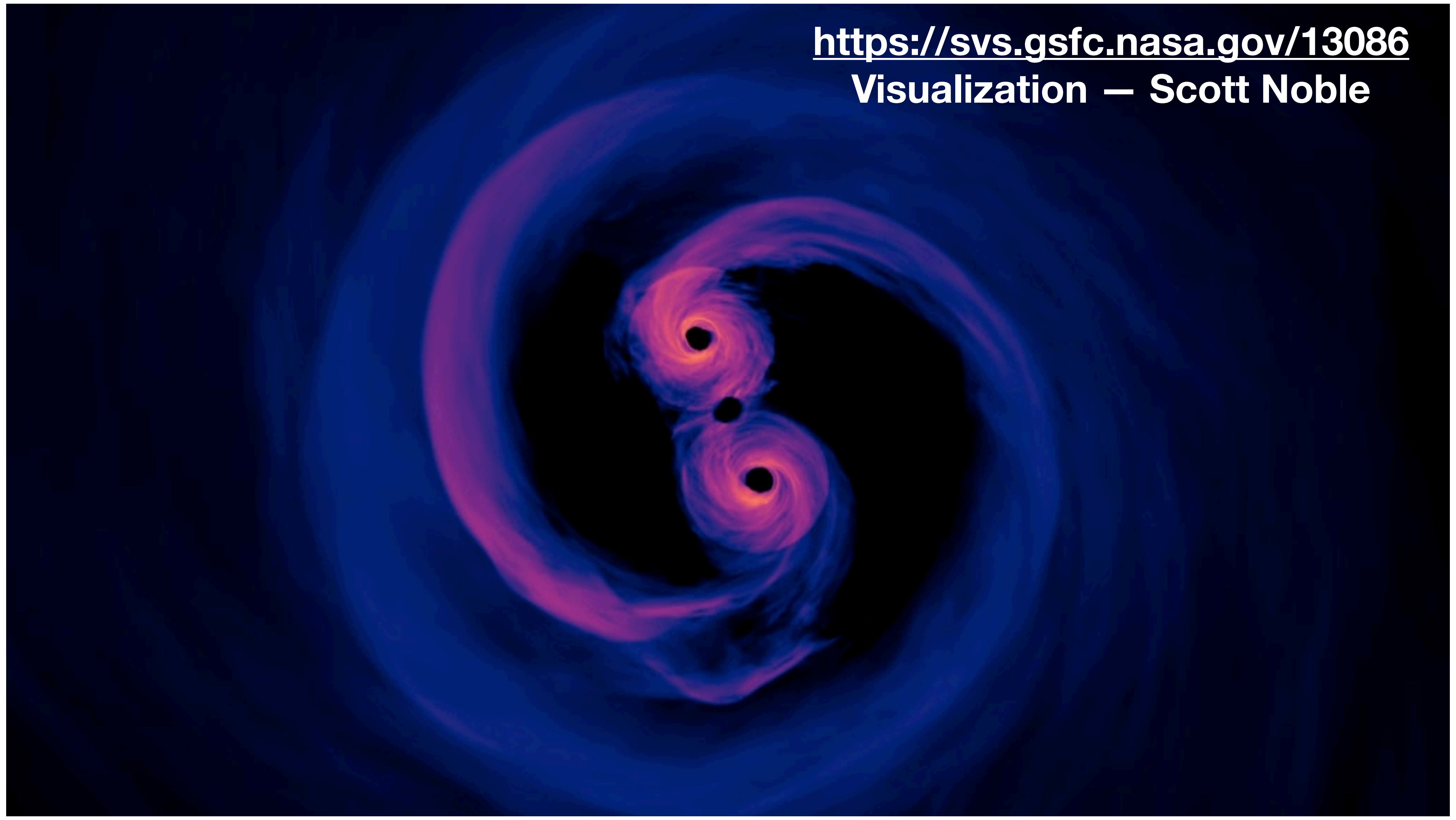
Credit: H. T. Cromartie

Caltech

NANOGrav

What are we targeting long term?

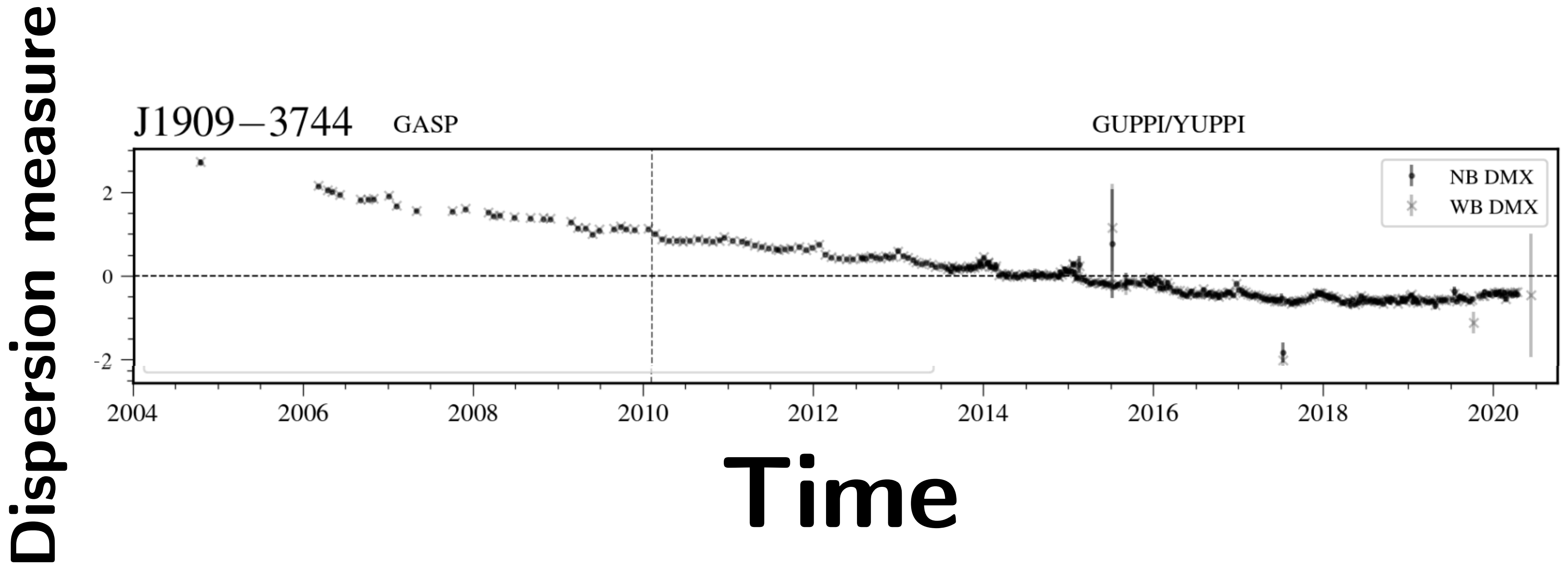
- Identifying source of GWB
- Improved constraints on SMBHB population
- Signals from individual SMBHB systems (GW and EM)
- Constraints on new physics, tests of general relativity
- Pulsar masses, nuclear physics
- IISM physics

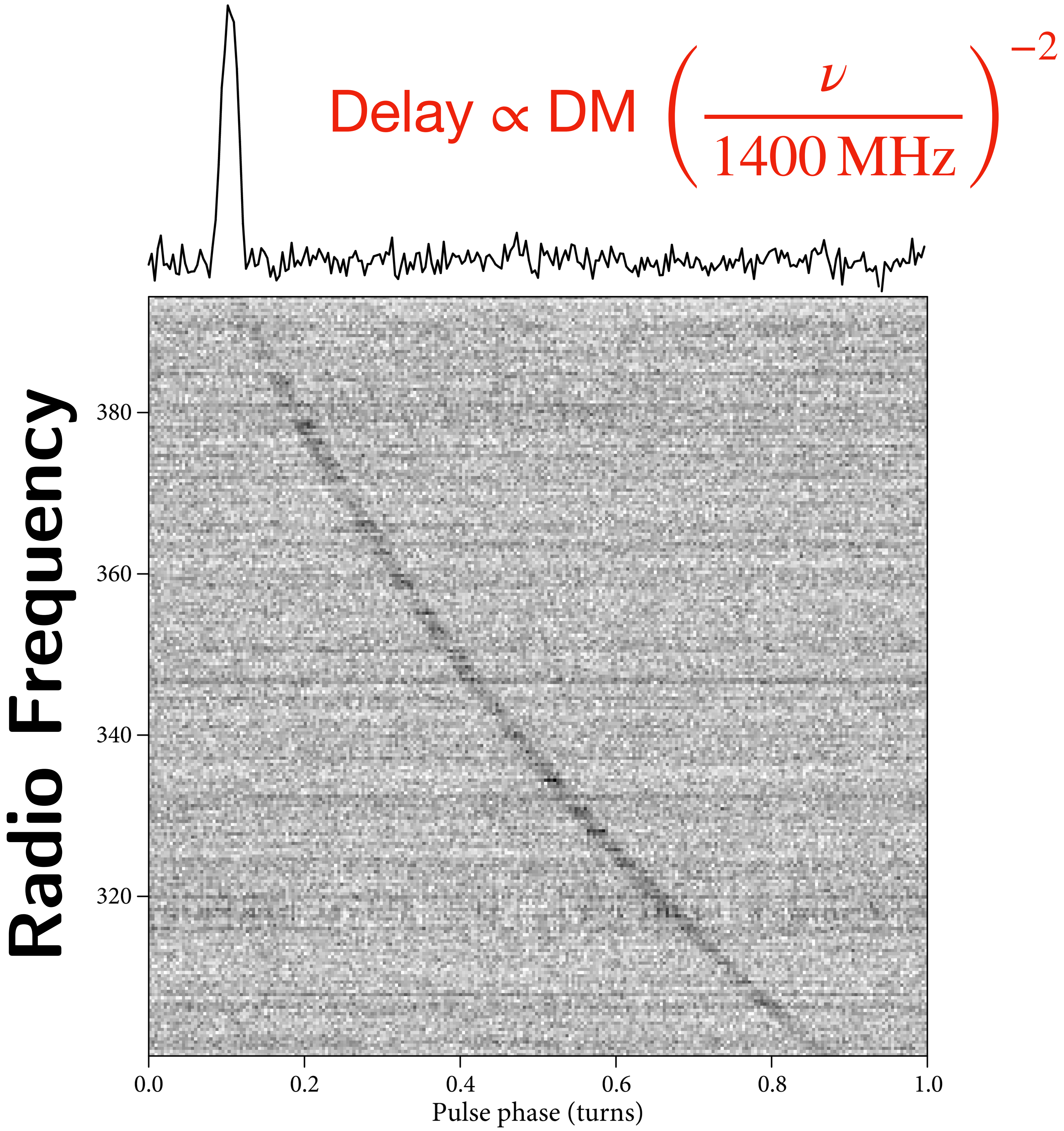


Caltech

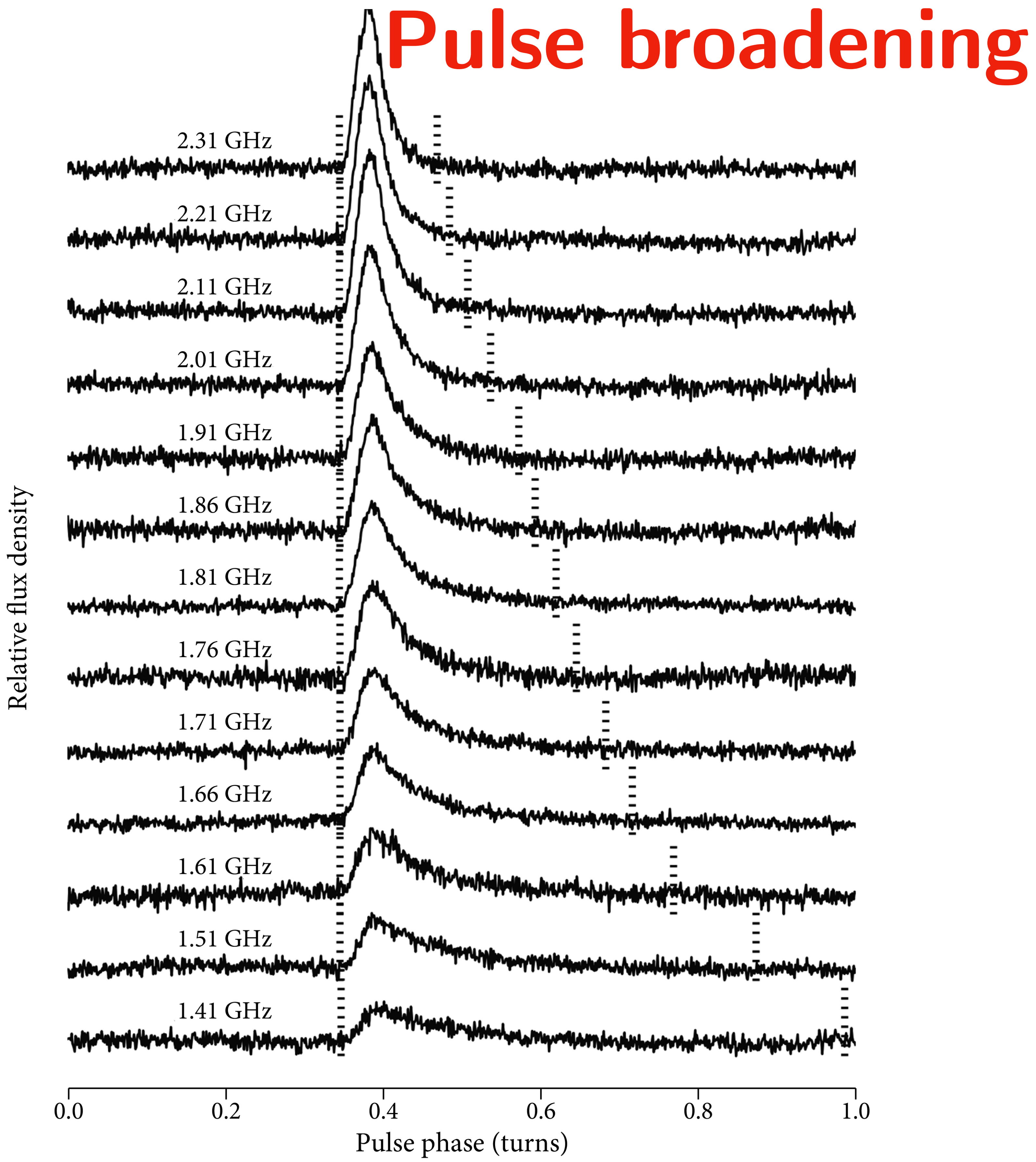
NANOGrav

- **Chromatic noise**: noise that is different at different radio frequencies





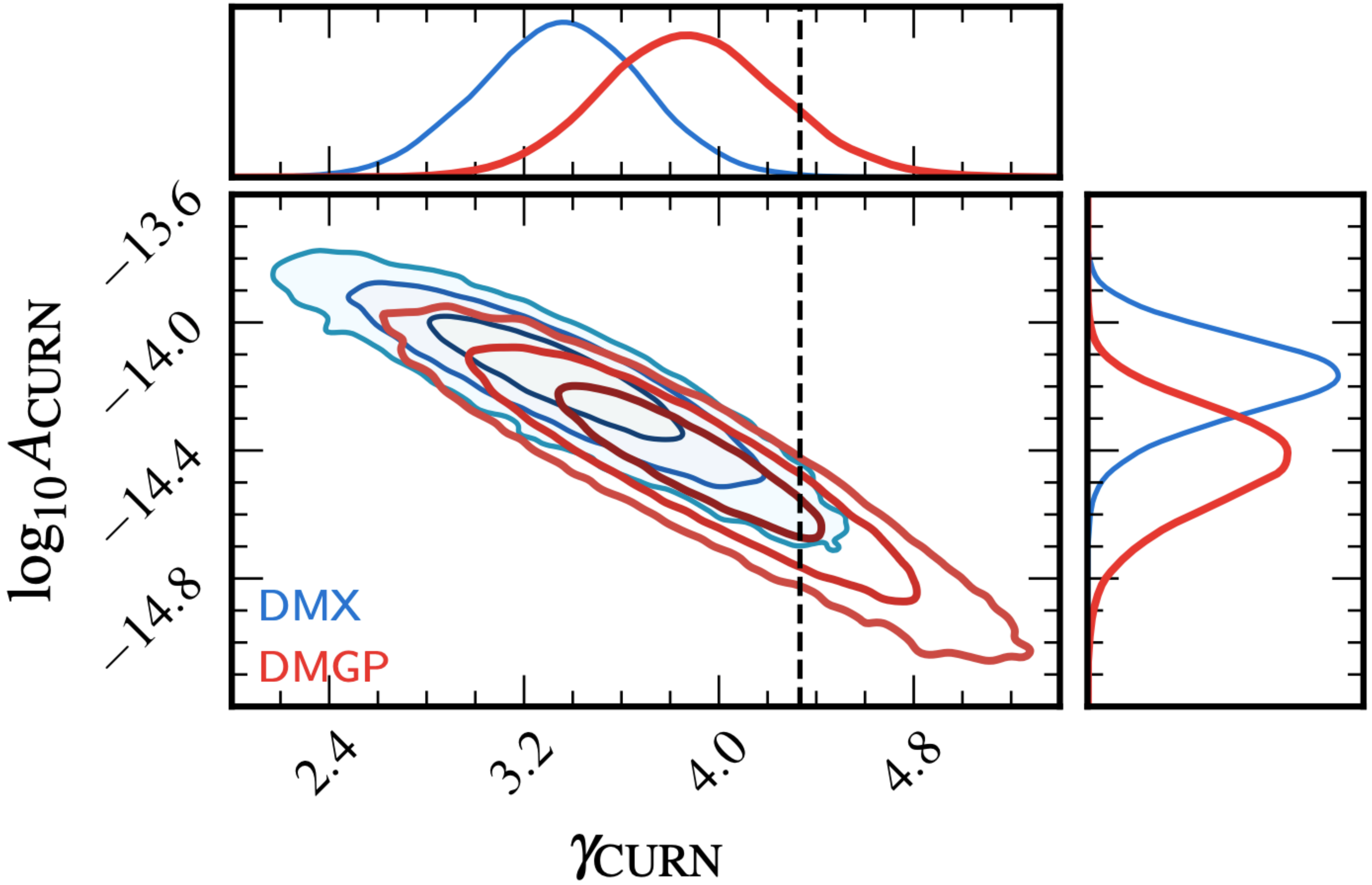
$$\text{Delay} \propto \text{DM}\left(\frac{\nu}{1400\,\text{MHz}}\right)^{-2}$$



Caltech

NANOGrav

- **Chromatic noise**: noise that is different at different radio frequencies



Caltech

NANOGrav

How do we optimize a PTA?

Signal-to-noise for correlations

Observation time

$$\mathrm{SNR} \propto N_{\mathsf{psr}} \left(\frac{T_{\mathsf{obs}}^{1/2}}{\sigma^{3/13}} \right)$$

Number of pulsars

Timing uncertainty

Caltech

Siemens+2013, 1305.3196

NANOGrav

Observatories of the future

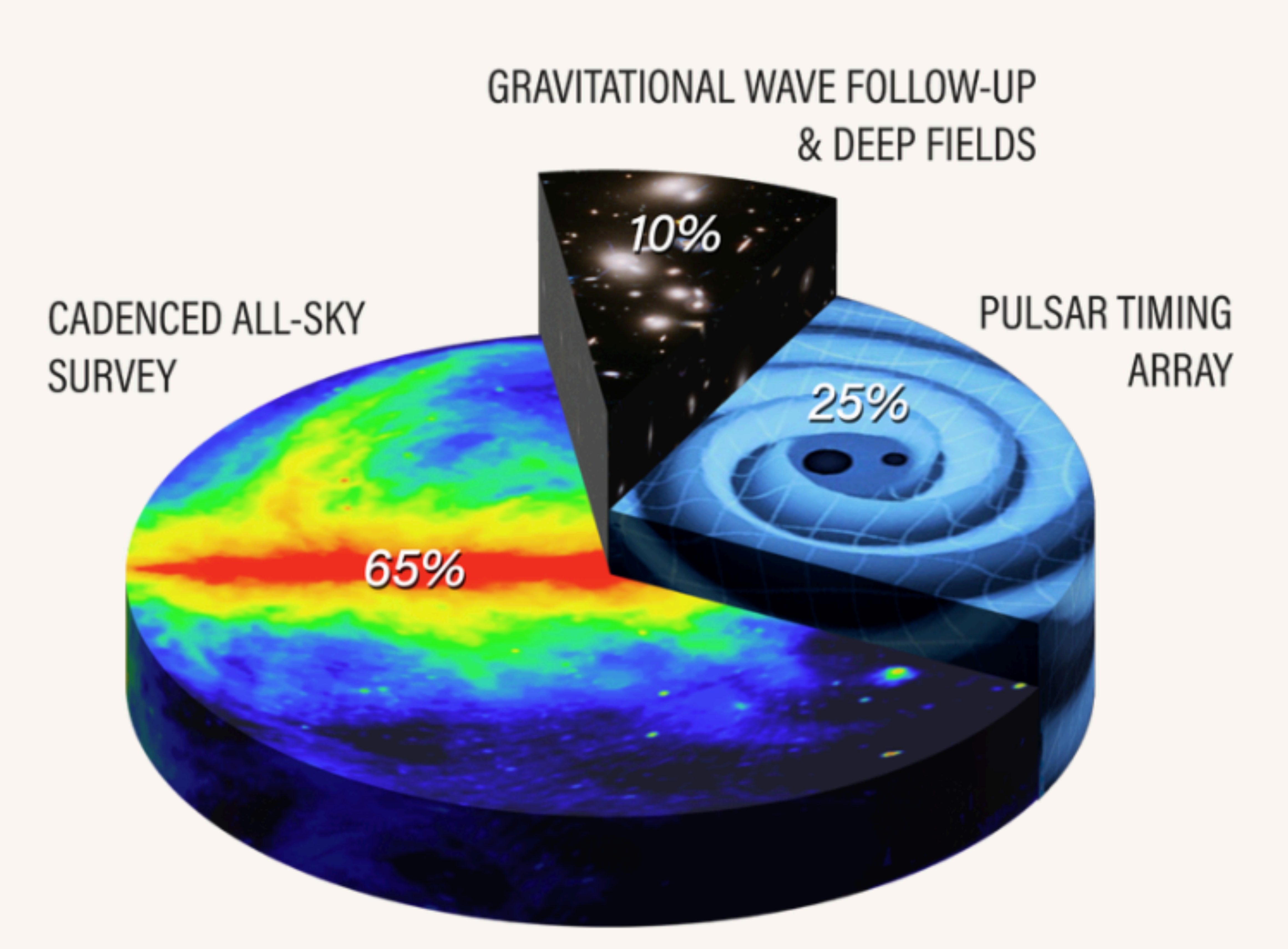
Next up:

- NANOGrav: **20** yrs, **77** pulsars
- IPTA: **121** pulsars, **25** yrs

Credit: H. T. Cromartie

DSA-2000

- Survey telescope, 2000 5m dishes, **0.7-2 GHz**
- ~25% of its time dedicated to PTAs, **Could monitor 200 pulsars monthly**
- Estimated 22,000 new pulsars (not necessarily millisecond pulsars)



Caltech

NANOGrav

Square Kilometer Array

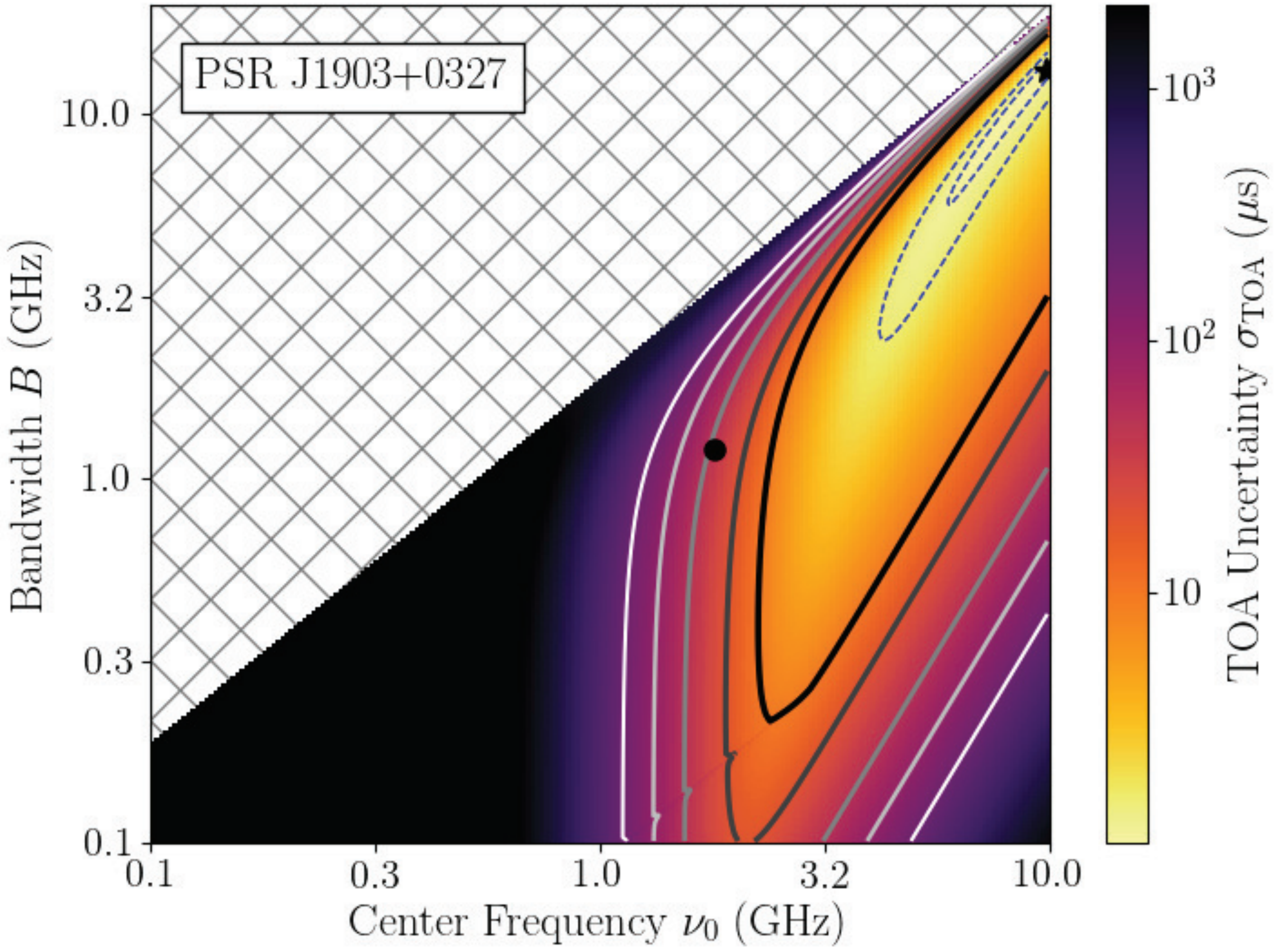
- SKA-mid will be 197 separate 13.5 m dishes, 0.35 - 15 GHz
  - Central core (~1km across) + 3 spiral arms extending out $\mathcal{O}(100\text{ km})$
  - 5 ns timing precision
- SKA-low 131,072 antennae, 74km baseline, 512 stations, $5 - 350$ MHz
  - 10 ns timing precision

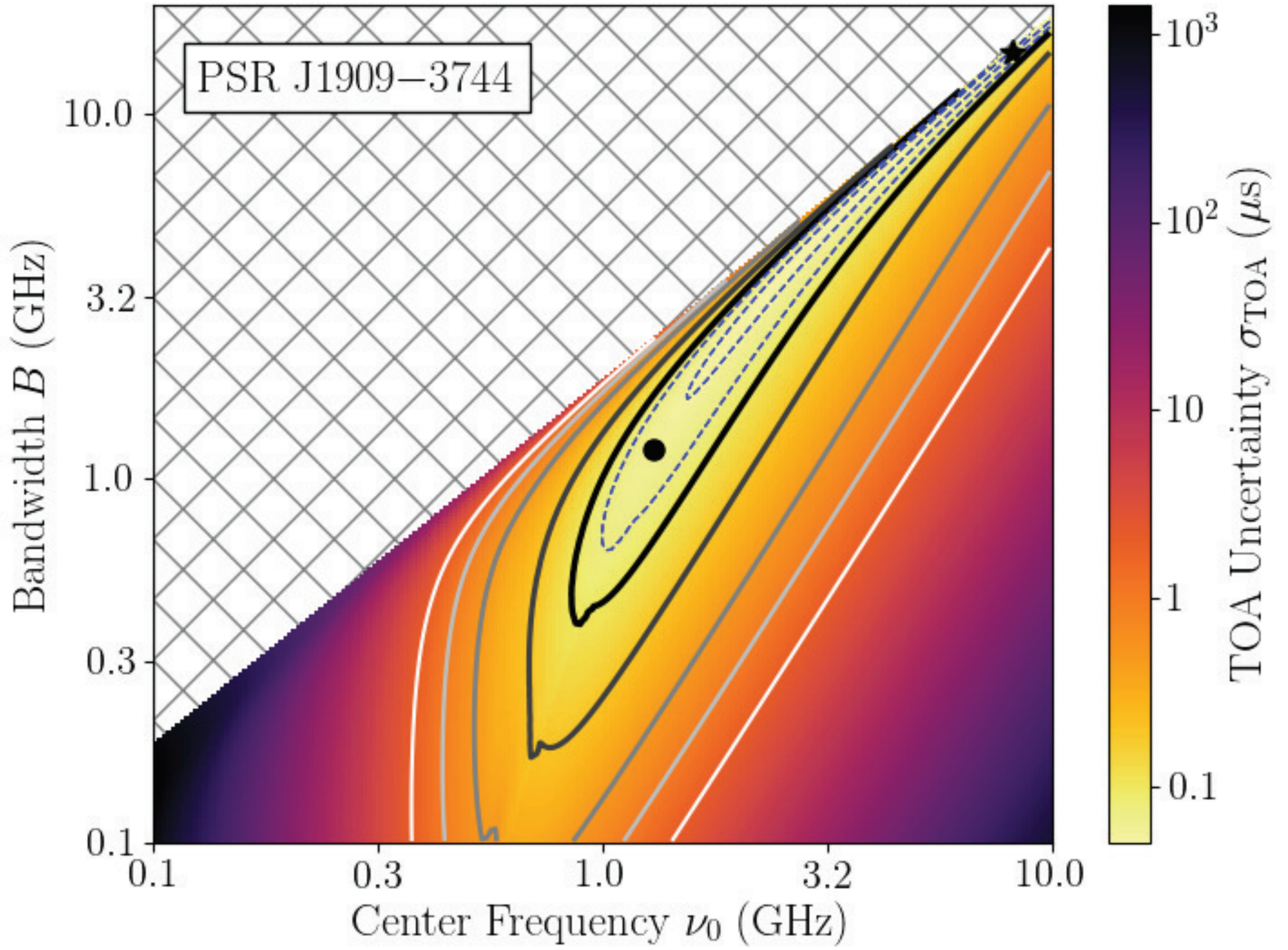
Caltech

NANOGrav

ngVLA

- First light, late 2030's
- Interferometric instrument with 18m dishes (244), and 6m dishes (19)
  - 1.2 - 116 GHz — bridge gap between SKA1 and ALMA
  - Core array + extensions to 1000 km
- Higher frequencies + larger bandwidth = easier to deal with scattering/dispersion

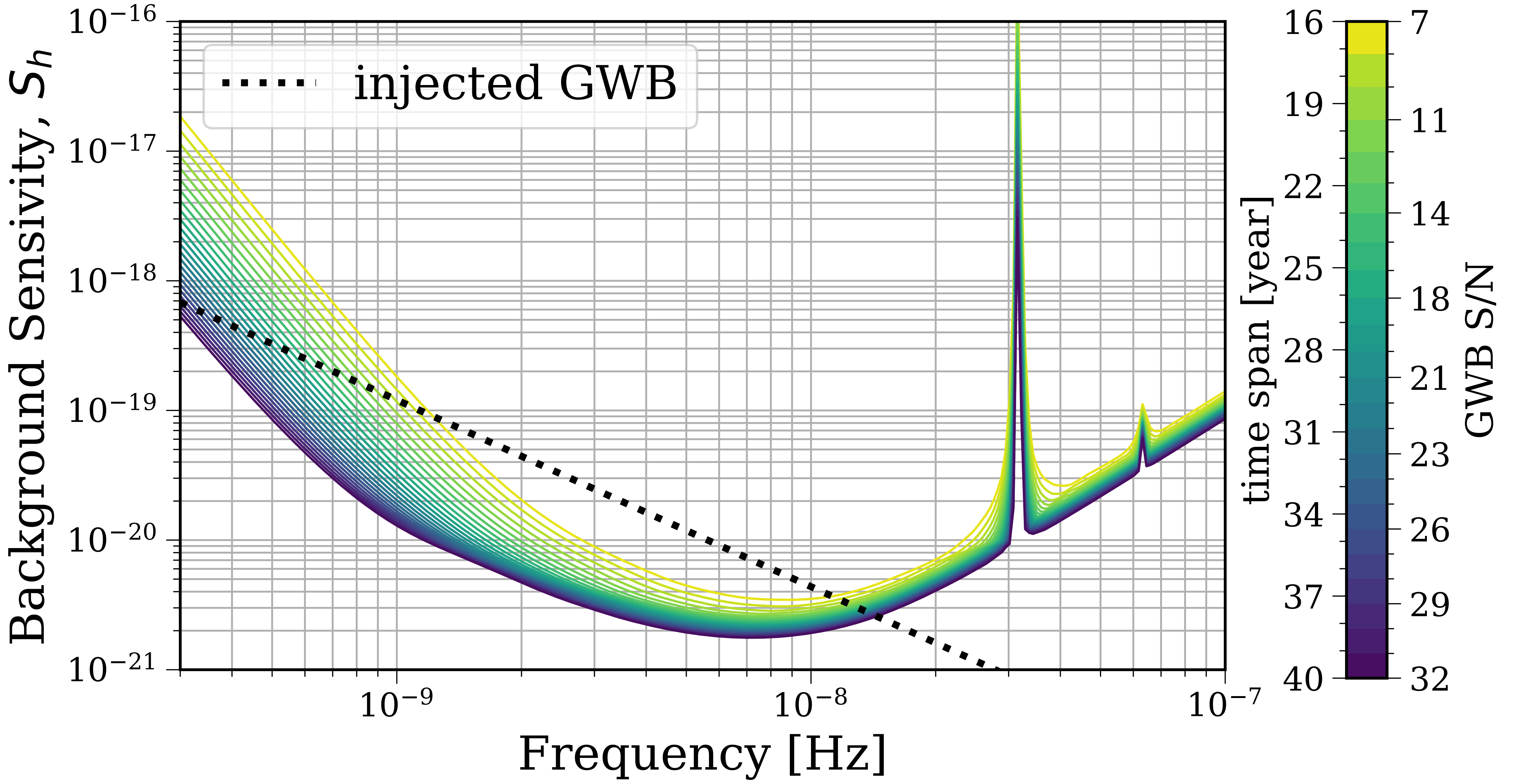




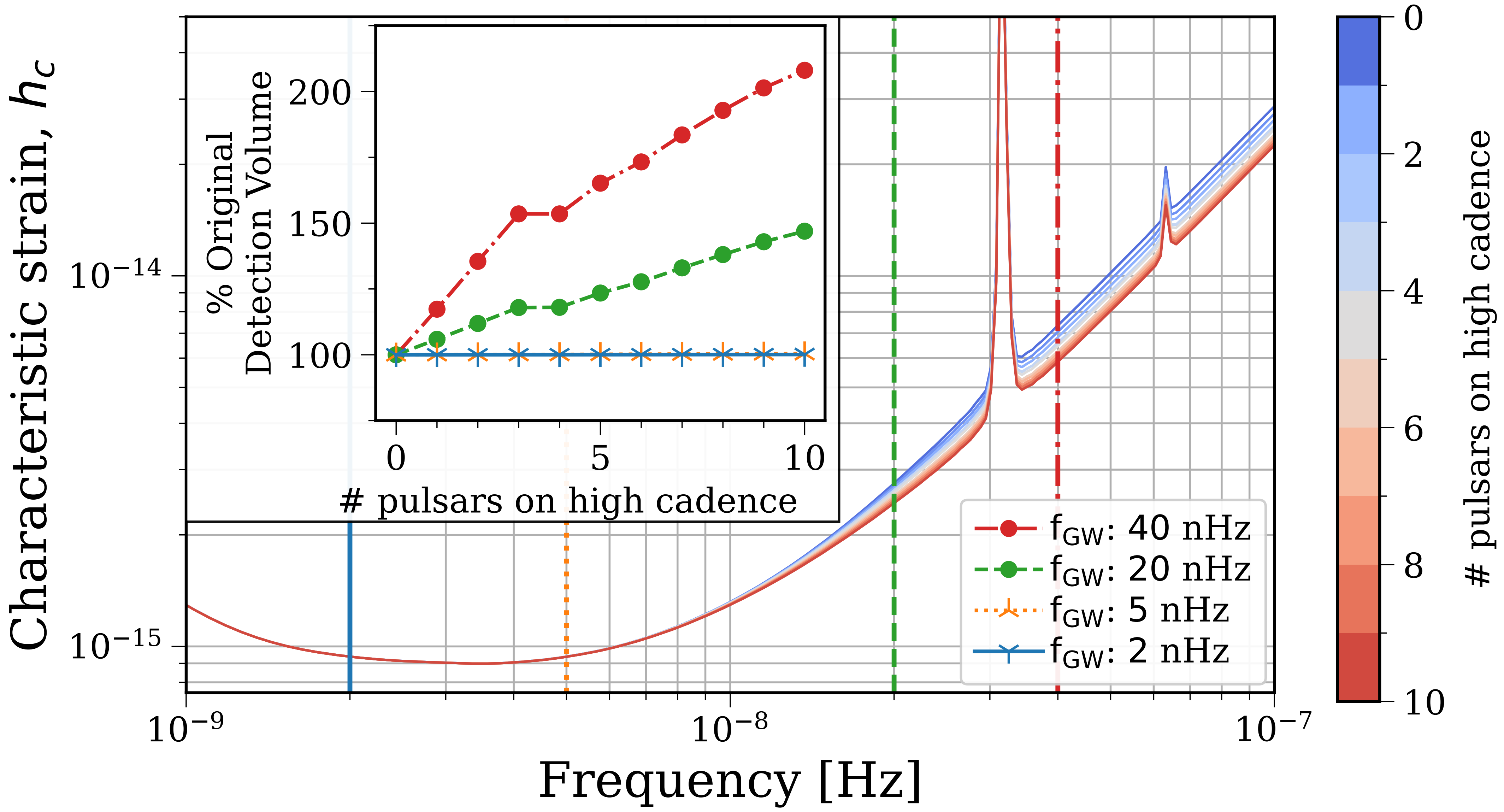
Caltech

Modeling improvements, PTA optimization

- 115 pulsars (IPTA-like) + 2 pulsars per year.
- Sky location, noise properties similar to NANOGrav 15 yr dataset.



- Dropping pulsars from the array in favor of timing some pulsars more frequently
  - Enhances single-source sensitivity at high frequency!

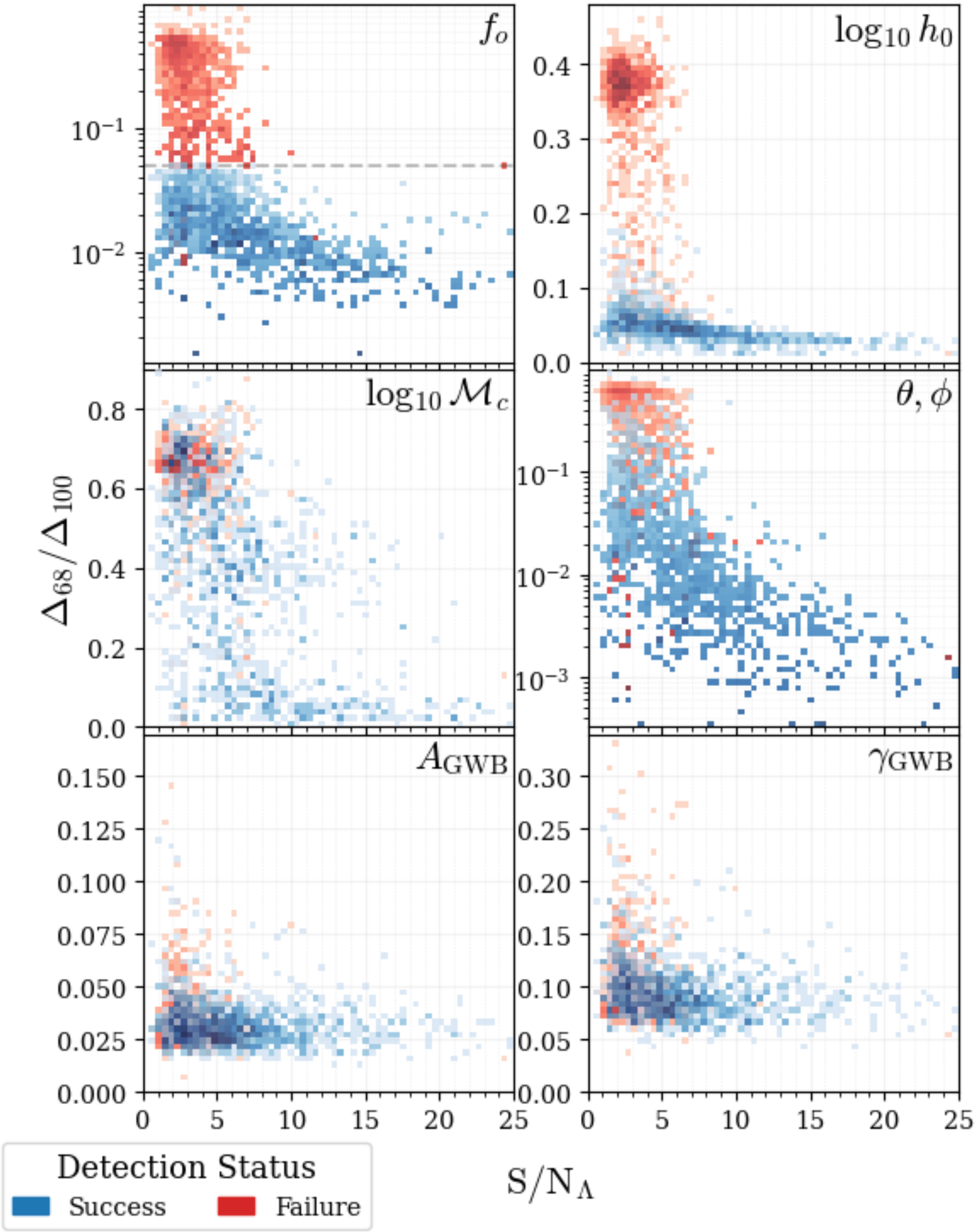


Caltech

Baier+2024, 2409.00336

Projections for single source detection

- Realistic populations of SMBHBs based on amplitude of NANOGrav results.
- ~50% probability of a detectable continuous wave in the 15 yr dataset
  - Limited ability to constrain parameters
- Projecting when a detection could be made is difficult.
  - Need to combine this work with work of Baier for realistic simulations + detection probability projections



Caltech

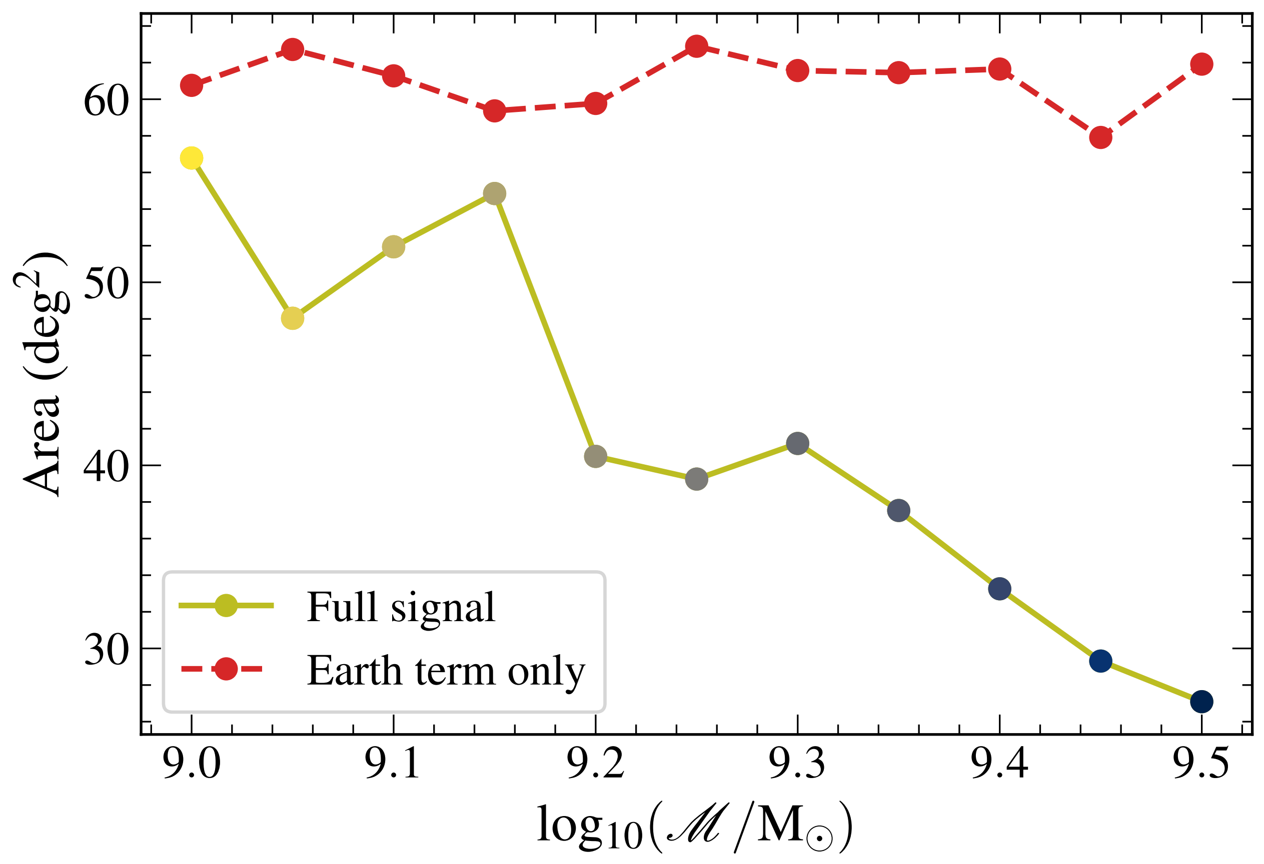
Gardiner+2025, arXiv:2502.16016

NANOGrav

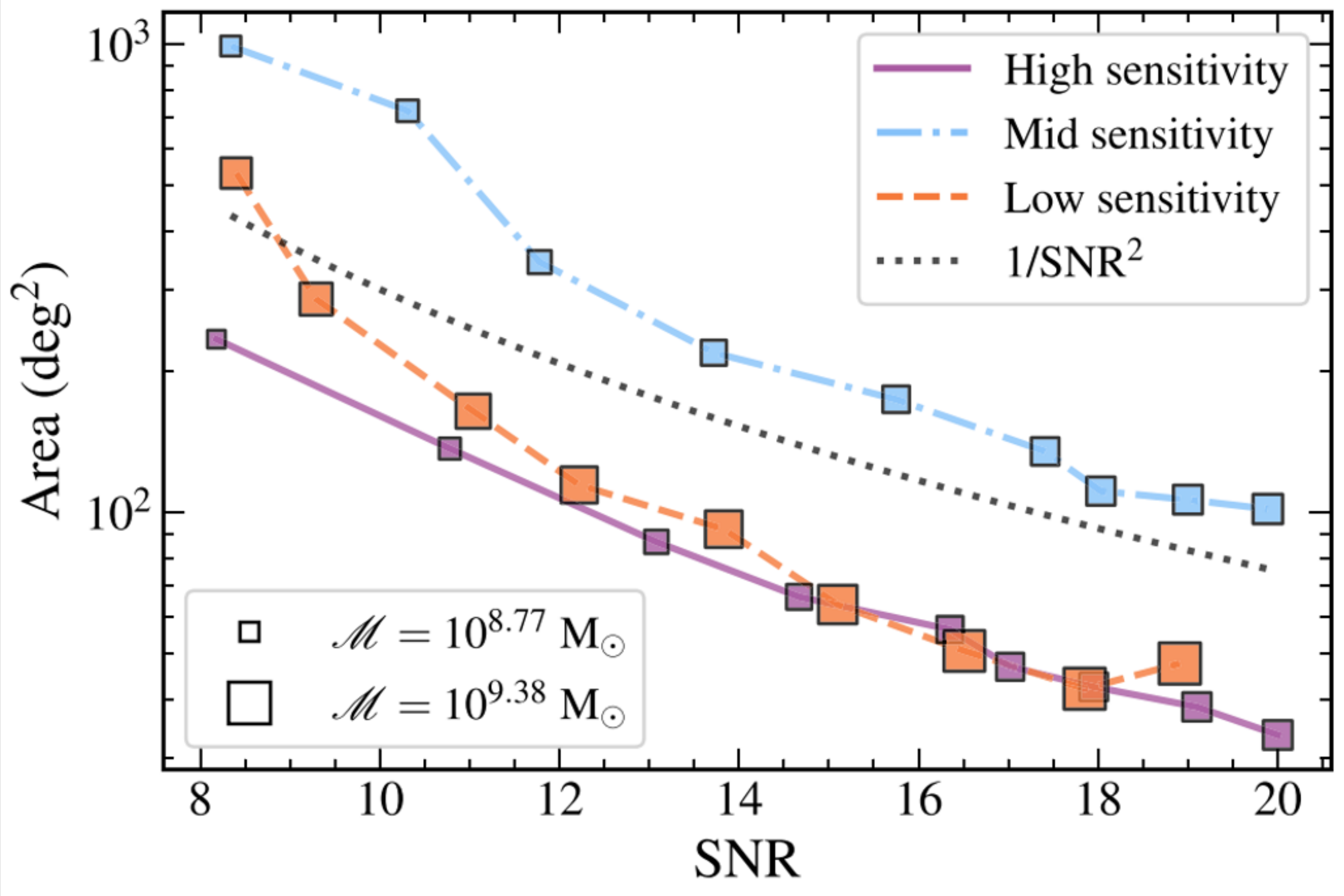
Host Identification

- If a CW detection is made, the goal would be to identify the host galaxy
- Petrov+2024 (arXiv: 2406.04409) build a realistic pipeline for follow up using galaxy catalogues to make mass/distance cuts.

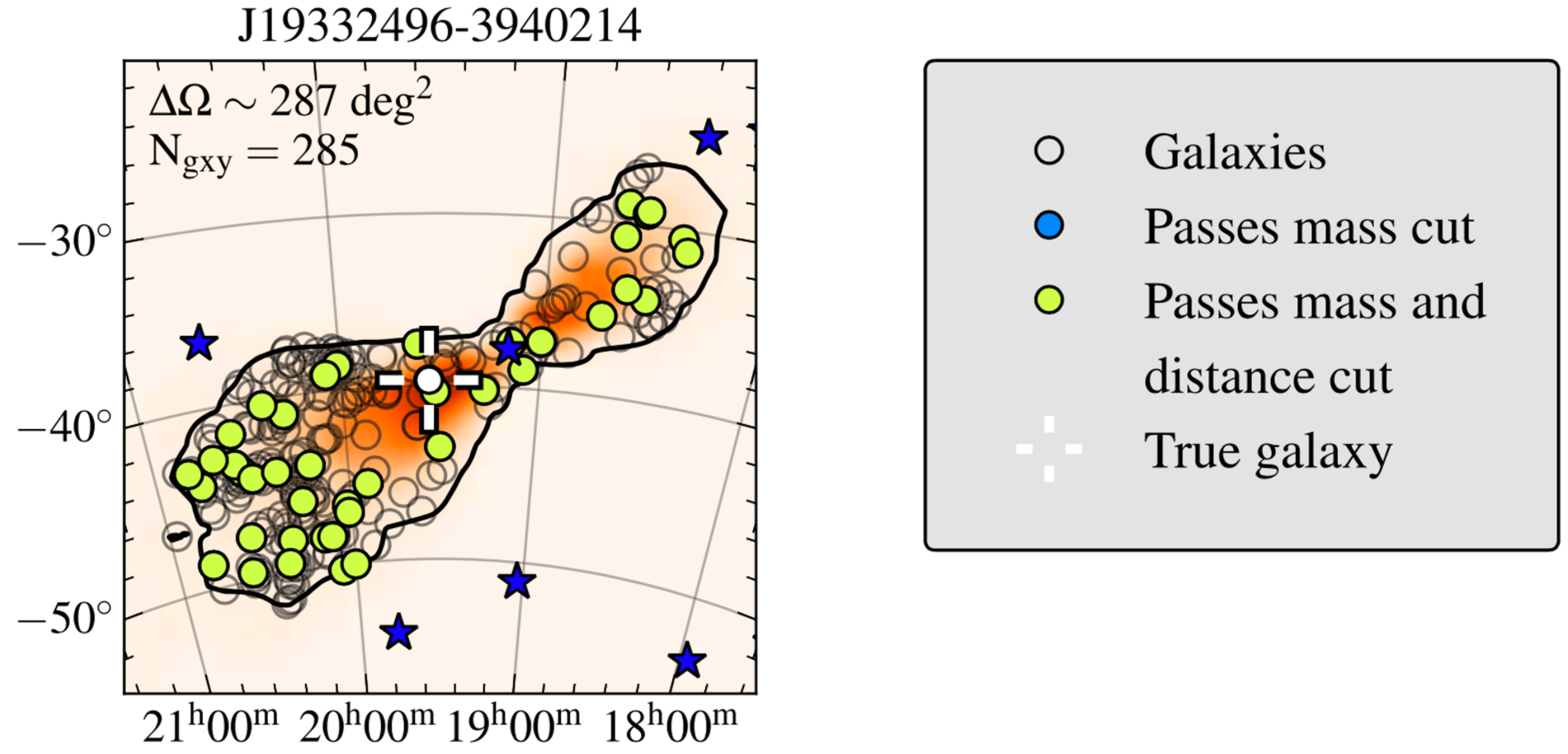
Loc. area vs. Chirp Mass



Loc. area vs. SNR



Follow up process

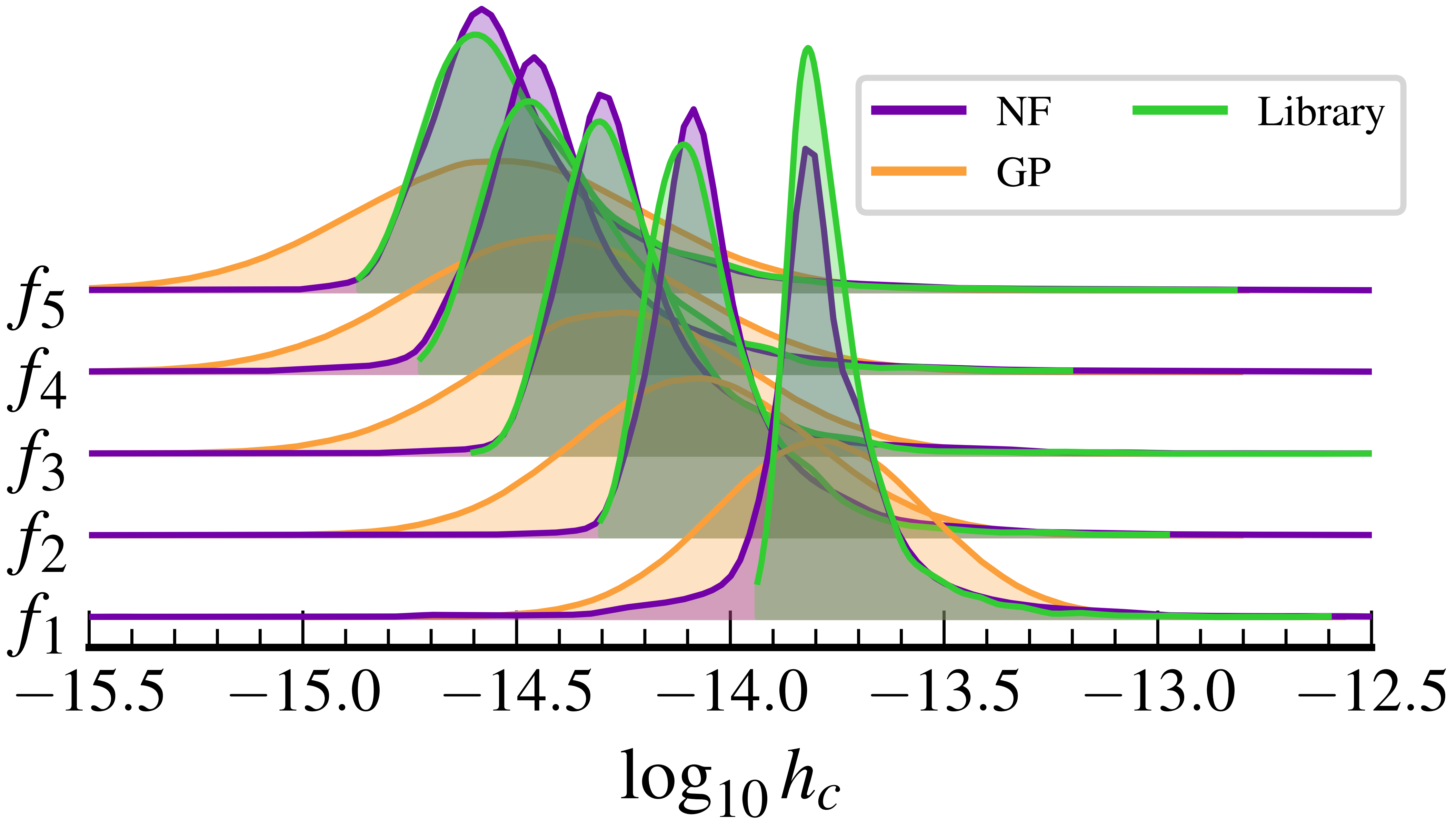


Caltech

NANOGrav

Improved methods

- Direct astrophysical inference from population synthesis using Normalizing Flows
- More complex noise models (of all kinds)
- Detailed model checking
- Hierarchical modelling for noise



- Being made possible by software and modeling improvements

https://github.com/NimaLaal/pandora

https://github.com/nanograv/discovery

Caltech

NANOGrav

PTAs into the future

- There's a fairly clear roadmap, in some ways:
  - More sensitive observatories
  - Continue to take more data, find new, quiet pulsars and optimize observing
  - Leverage software and hardware improvements to include more complete noise models, potentially end-to-end analyses