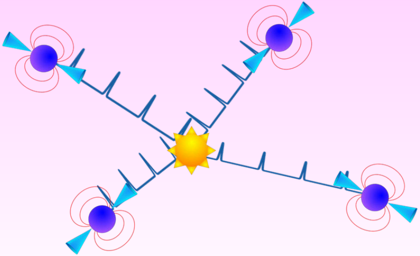
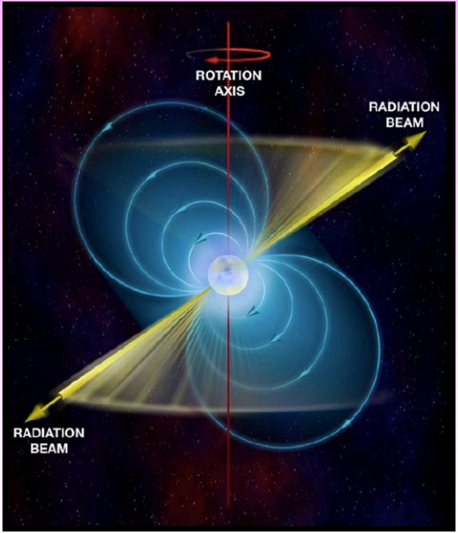
# NANOGrav and IPTA Status Updates

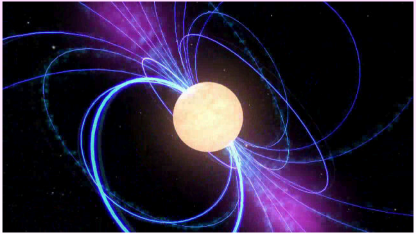
Jeffrey S. Hazboun,
University of Washington Bothell
*Funded under NSF Award 1430284*



# Pulsar Timing Arrays




- Millisecond Pulsars are the remnants of stars, $\sim 20 km$ across, spinning a thousand times per second.
- They are neutron stars that are inclined such that we can see emission.
- Very stable clocks. Spin period of PSR J0437-4715: $P = 0.005757451936712 59 \pm \mathbf{0.000000000000000002} s$!
- Period of pulsar known to $\mathbf{1/10^{15}}$



# PTA: Galactic Scale Gravitational Wave Detector

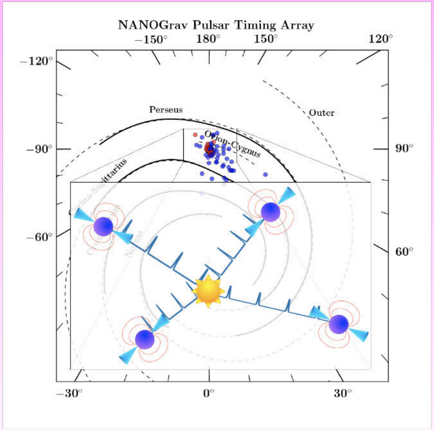
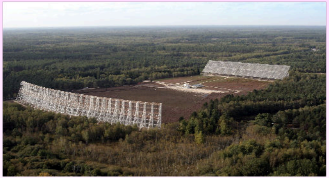



Image Credit: Jim Cordes, JSH



# PTA: Galactic Scale Gravitational Wave Detector

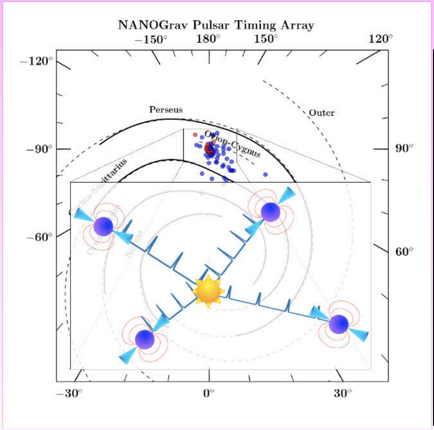



Image Credit: Jim Cordes, JSH

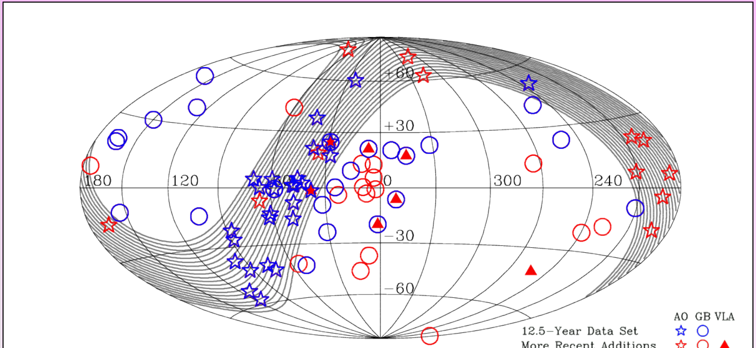



Image Credit: David Nice

# PTA: Galactic Scale Gravitational Wave Detector

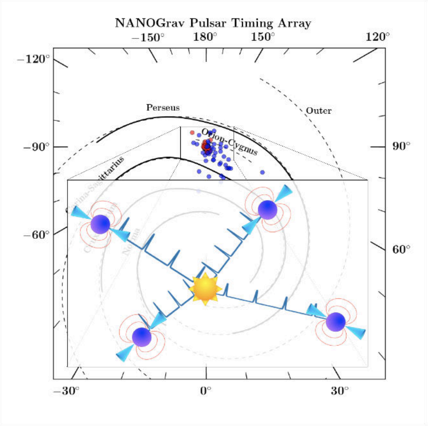



Image Credit: Jim Cordes, JSH

$$\frac{\Delta\nu}{\nu} = -F^{ij}\left[h_{ij}\left(t_E, x_E^i\right) - h_{ij}\left(t_E - \frac{D_P}{c}, x_P^i\right)\right]$$

$$R(t) = \int_{t_0}^{t} \frac{\Delta\nu}{\nu} dt$$

# GW Interferometry vs Pulsar Timing Arrays

| Similarities | Differences |
| --- | --- |
| - Use light to measure the passage of GWs | - Measure $\Delta L/L$ *vs.* $\Delta\nu/\nu$ |
| - Sensitive to changes in distance proportional to their respective "nuclei" | - Strongest source: CBCs vs. Stochastic Background |
| - Astronomy of Compact Objects | - Evenly sampled data vs. Uneven PSR observing cadence |
| - Tests of Gravity/GR | - 9 orders of magnitude in frequency |
| - Seismic noise | - 8 orders of magnitude in strain |
| - Shot noise / jitter | - (Knowledge of) Physics of light source |
| - Glitches | |

# Search for Lumbering Giants

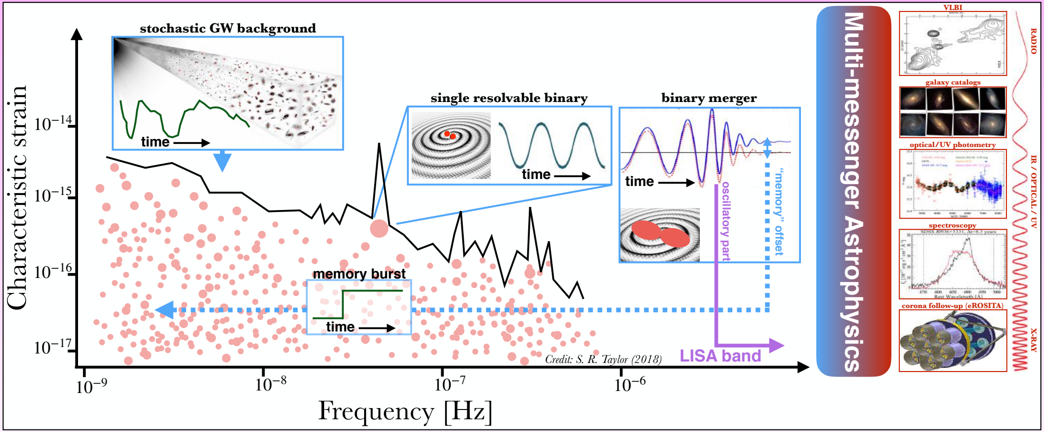
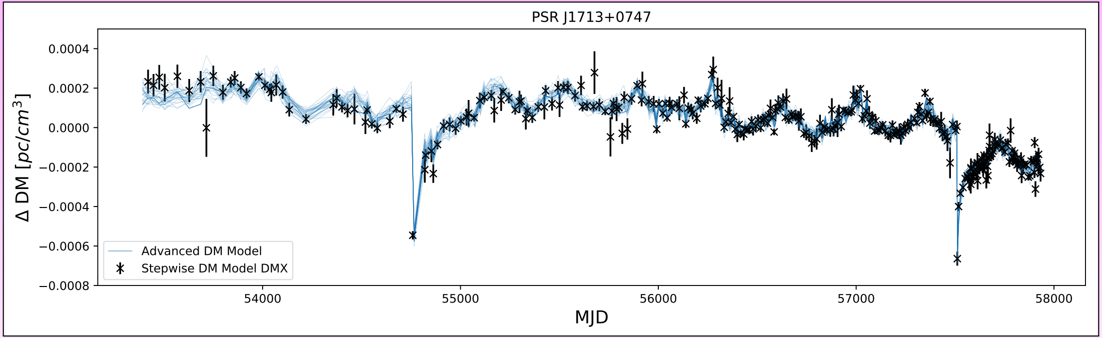



Image Credit: S.R. Taylor

# Sources of Noise and their Characteristics

| Noise source | Achromatic? | Correlated in time? | Correlated in space? | Quadrupolar? |
|---|---|---|---|---|
| Pulsar Rotational Irregularities | ✓ | ✓ | ✗ | ✗ |
| Pulse Jitter | ✓ | ✗ | ✗ | ✗ |
| Scattering and dispersion measure variations | ✗ | ✓ | ✗ | ✗ |
| Solar System Ephemerides | ✓ | ✓ | ✓ | ✗ |
| Clock Errors/ Offsets | ✓ | ✓ | ✗ | ✗ |
| **GW Background** | ✓ | ✓ | ✓ | ✓ |

# Ongoing Pulsar Noise Modeling



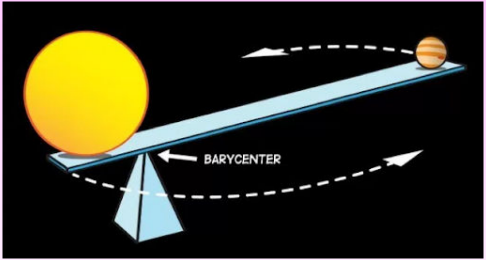

Advanced Noise Modeling/ Bayesian Solar Wind Model, JSH and Joseph Simon

# Correlated Noise **Solar-System Ephemeris Modeling**

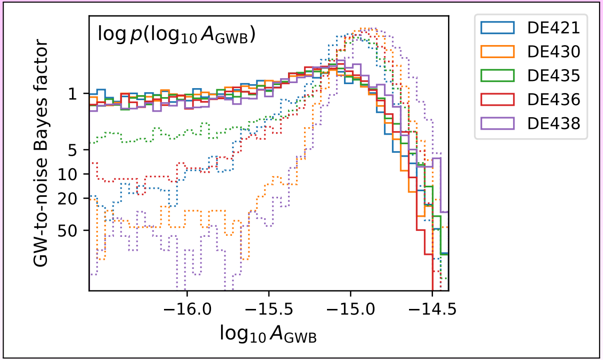
*Michele Vallisneri, Joseph Simon, Steve Taylor*

Perturbs the masses of the outer planets and the orbital elements of Jupiter.

Perturbs the orbit of Jupiter $\pm 100$ km.

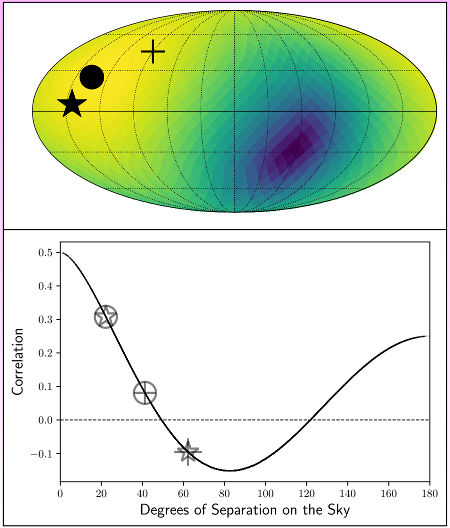



We are constraining the solar system barycenter with $\sim 100m$ accuracy.

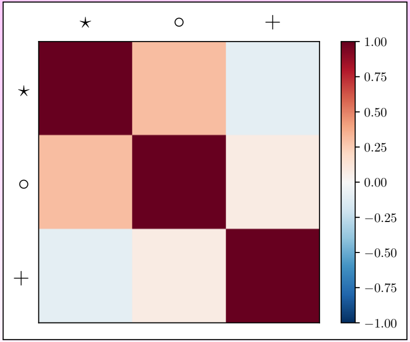



Vallisneri, et al., *Modeling the uncertainties of solar-system ephemerides for robust GW searches with PTAs*

# PTAs and Spatial Correlations




The sky positions of our pulsars translate to a correlation factor in the correlation matrix of our analyses.



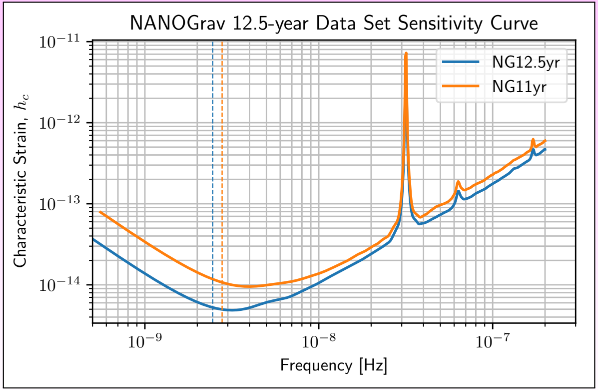

Cartoon Correlation Matrix

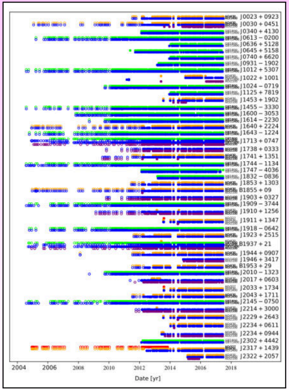
# NANOGrav 12.5-Year Data Set

Alam, et al., 2020. *The NANOGrav 12.5-year Data Set: Observations and Narrowband Timing of 47 Millisecond Pulsars*

Alam, et al., 2020. *The NANOGrav 12.5-year Data Set: Wideband Timing of 47 Millisecond Pulsars*

The 12.5 year data set, not only includes more data, but a battery of new data processing techniques have removed a significant amount white noise.

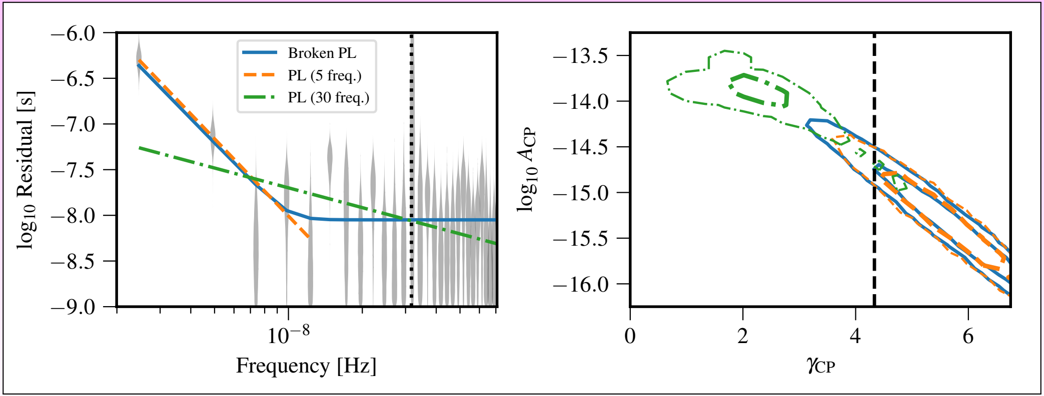


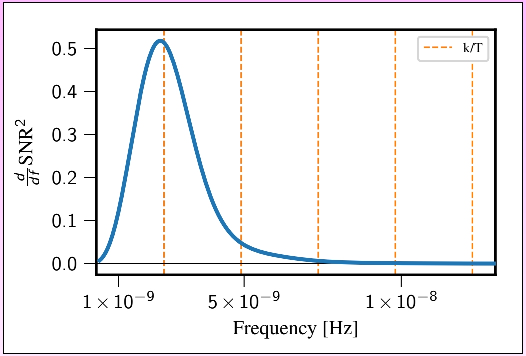
# NANOGrav 12.5-Year Data Set: GW Background Search

*Lead Joseph Simon, Detection Working Group*

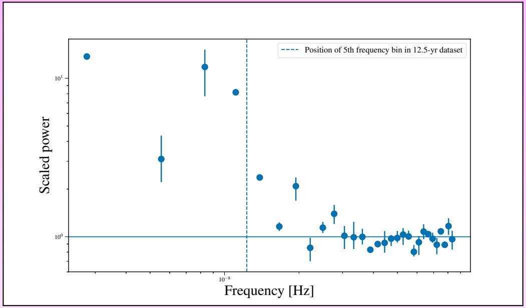
Varied Spectral Index Analyses show a strong common process across the PTA



# NANOGrav 12.5-Year Data Set: GW Background Search




Signal to noise integrand from sensitivity analysis of pulsars using **`hasasia`**.

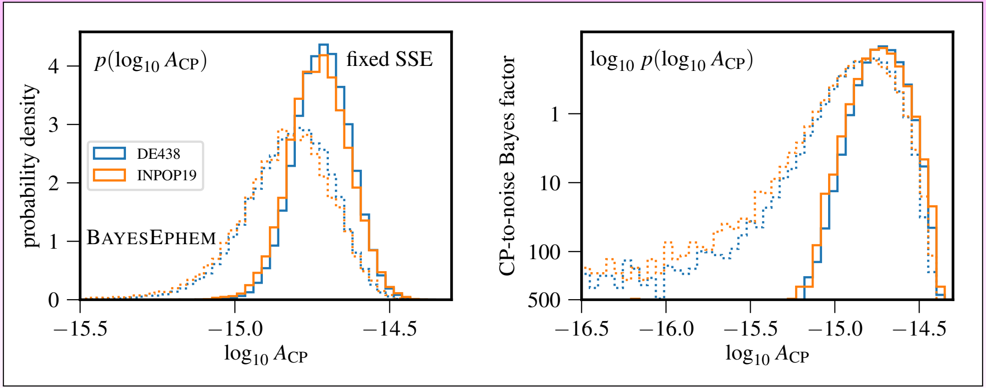



Injection analysis. Ratios of component power between injection amplitudes averaged across $A_{\mathrm{CP}} = 5\times10^{-15}$ and $A_{\mathrm{CP}} = 10^{-16}$.

# NANOGrav 12.5-Year Data Set: **GW Background Search**

*Lead: Joseph Simon*

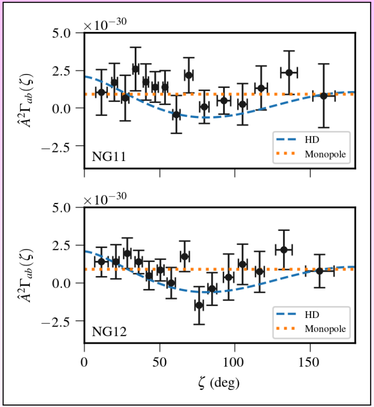
Bayesian Analyses. BF> 10,000 for Common Red Process, BF∼ 4 for HD compared to CRP.



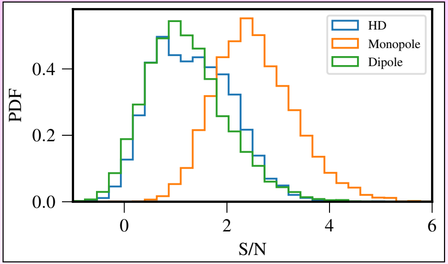

I'll discuss model dependence of GWB Stats, if there is time.

# NANOGrav 12.5-Year Data Set: Spatial Correlations

## Optimal Statistic Frequentist Analysis



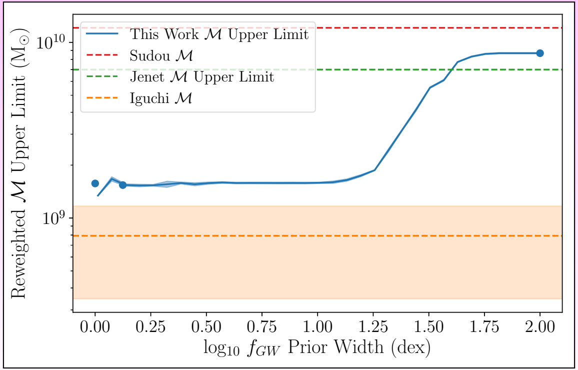

- Spatial Correlations for NG11(top) and NG12.5 (bottom).
- Noise-marginalized OS for monopole, dipole and quadrupole spatial correlations.

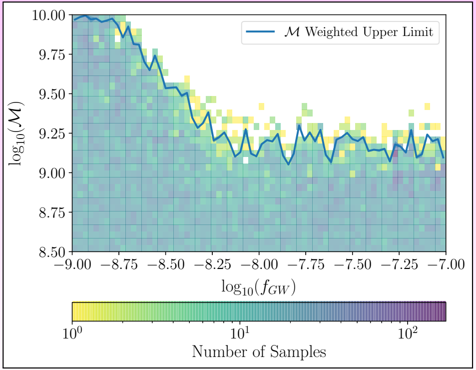


# NANOGrav 11-Year Data Set Results: GW and Multimessenger Astrophysics

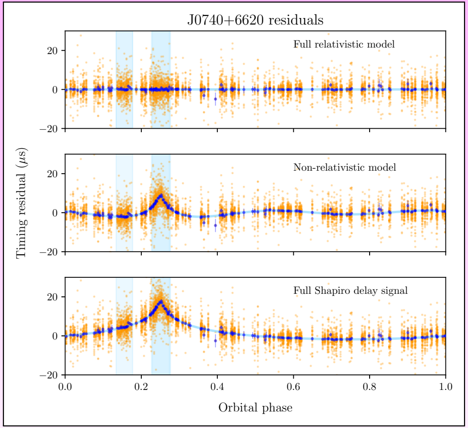
Aggarwal, et al. 2019, *The NANOGrav 11-Year Data Set: Limits on GWs from Individual SMBHBs*
Aggarwal, et al., 2019, *The NANOGrav 11-Year Data Set: Limits on Gravitational Wave Memory*

Arzoumanian, et al., 2020, *Multi-Messenger Gravitational Wave Searches with Pulsar Timing Arrays: Application to 3C66B Using the NANOGrav 11-year Data Set* **Corresponding Author: Caitlin Witt**

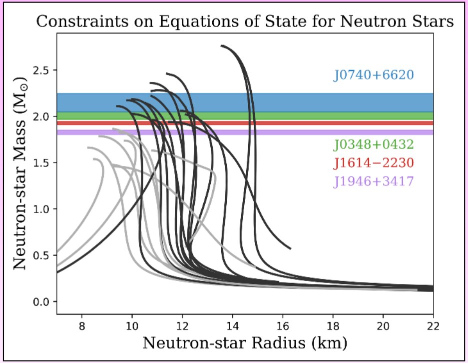


# Synergistic Science: $2.15 M_\odot \pm 0.13$ Neutron Star




Shapiro Delay



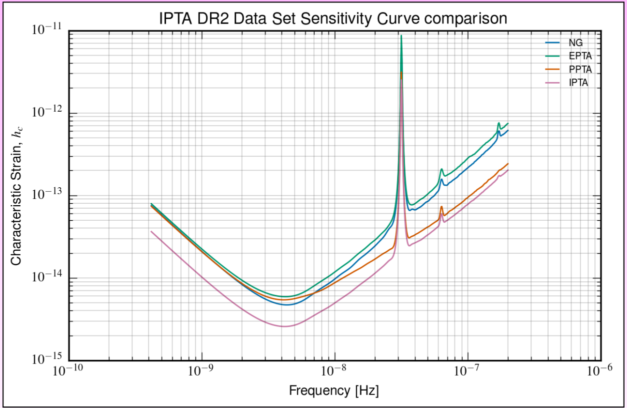

Neutron Star Equation of State

Cromartie, et al., 2019, *Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar*

Also a LOT of other pulsar and interstellar medium astronomy happening!!

# International Pulsar Timing Array

- 2nd mock data challenge submissions complete.
- 2nd data release published (Perera, et al., 2019).
- GW results from DR2 being finalized.
- 3rd data release officially under construction.




Ben Perera, *The International Pulsar Timing Array: Second data release*

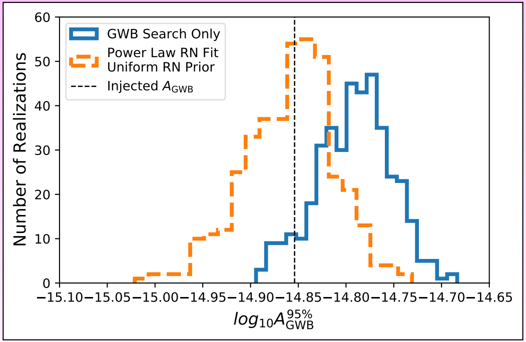
# North American Nanohertz Observatory for Gravitational Waves

# Thank You!

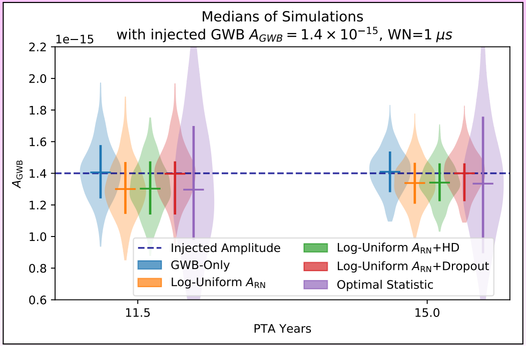
NANOGrav Members at the Green Bank Telescope, WVa. Image Credit: Tonia Klein

# Model Dependence of GWB Stats

The presence of individual intrinsic red noise models for pulsars, and the priors on those amplitudes, has significant consequences for the outcome of the Bayesian GWB searches.




95% Upper Limits




Parameter Estimation, $A_{GWB}$