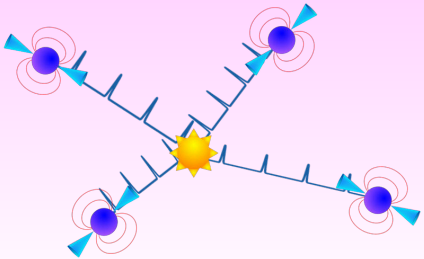
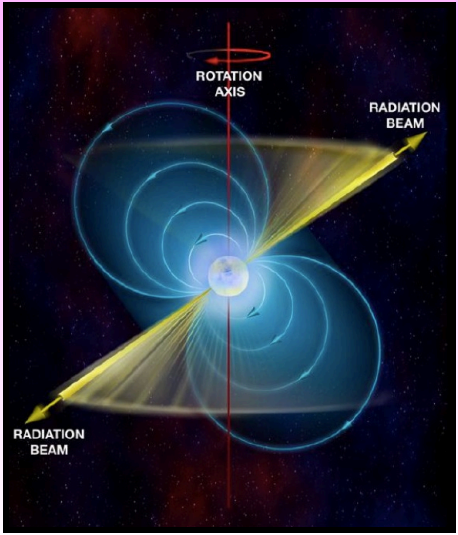
NANOGrav and IPTA Status Updates

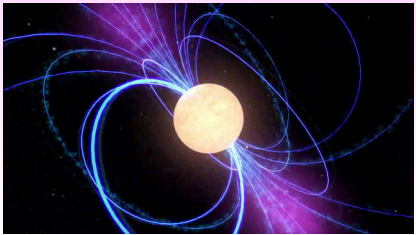
Jeffrey S. Hazboun,
University of Washington Bothell
Funded under NSF Award 1430284



Pulsar Timing Arrays



- Millisecond Pulsars are the remnants of stars, $\sim 20km$ 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: $P = 0.0057574519367125 9 \pm \mathbf{0.00000000000000000 2} s$!
- Period of pulsar known to $\mathbf{1/10^{15}}$



PTA: Galactic Scale Gravitational Wave Detector

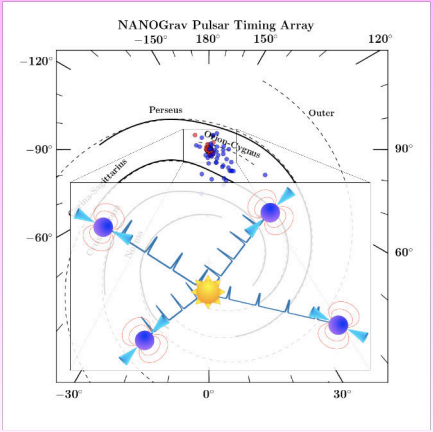


Image Credit: Jim Cordes, JSH

PTA: Galactic Scale Gravitational Wave Detector

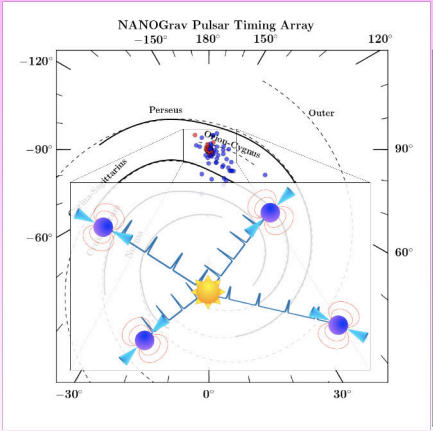


Image Credit: Jim Cordes, JSH

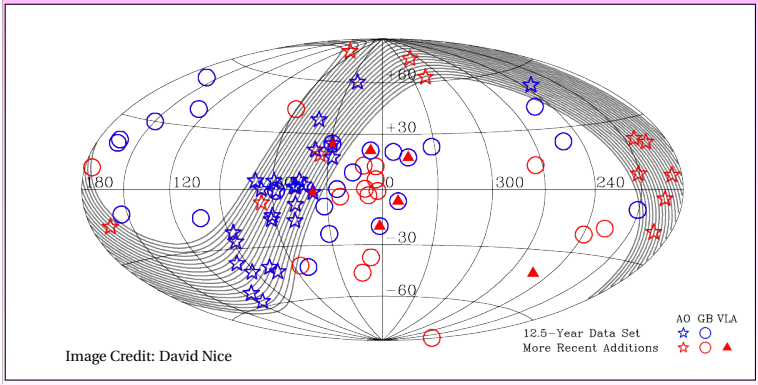


Image Credit: David Nice

PTA: Galactic Scale Gravitational Wave Detector

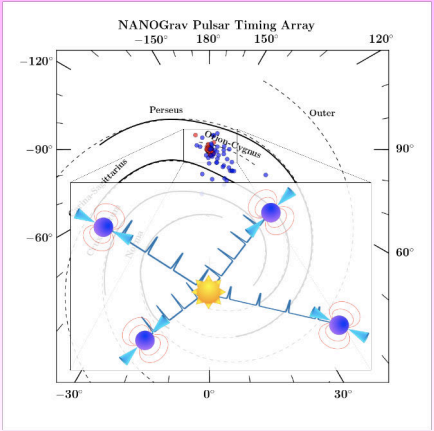


Image Credit: Jim Cordes, JSH

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

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

GW Interferometry vs Pulsar Timing Arrays

Similarities

- Use light to measure the passage of GWs
- Sensitive to changes in distance proportional to their respective "nuclei"
- Astronomy of Compact Objects
- Tests of Gravity/GR
- Seismic noise
- Shot noise / jitter
- Glitches

Differences

- Measure $\Delta L/L$ *vs.* $\Delta \nu/\nu$
- Strongest source: CBCs vs. Stochastic Background
- Evenly sampled data vs. Uneven PSR observing cadence
- 9 orders of magnitude in frequency
- 8 orders of magnitude in strain
- Physics of light source[†]

[†]Although recent progress in Philippov, Timokhin, and Spitkovsky, 2020. *Origin of Pulsar Radio Emission*, PRL

Search for Lumbering Giants

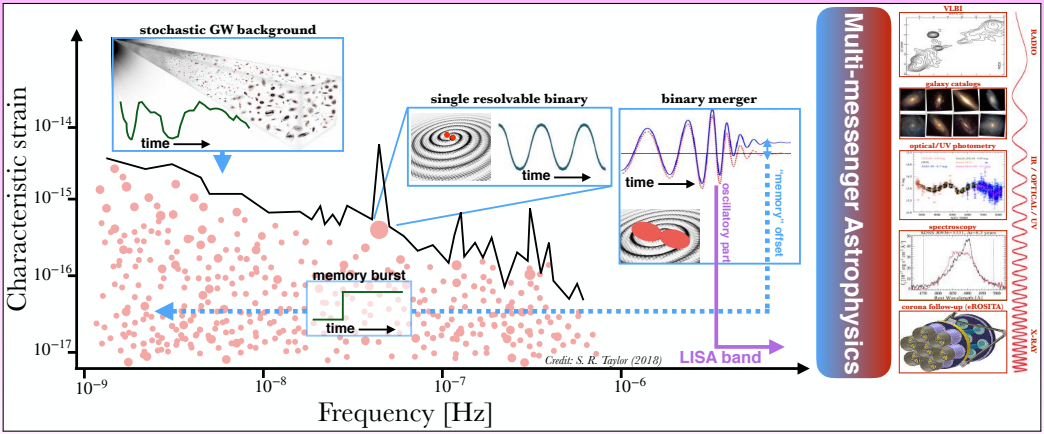
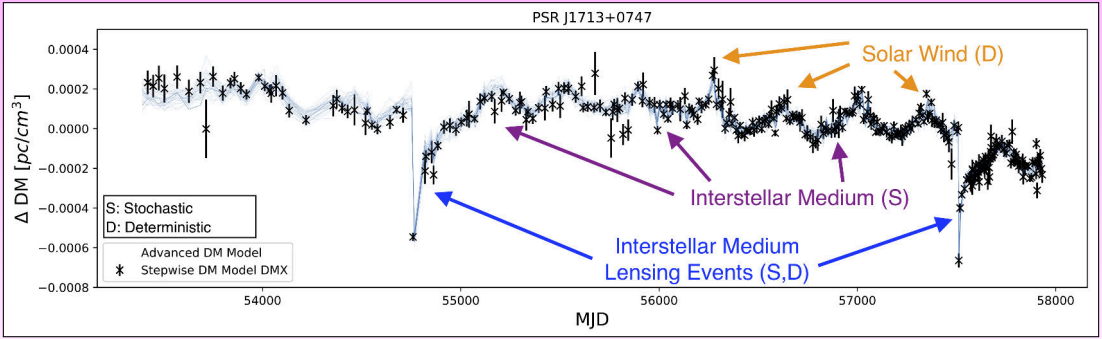


Image Credit: S.R. Taylor

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

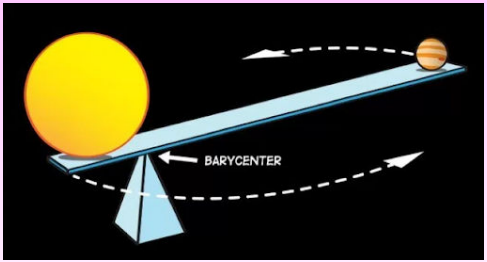
Bespoke noise models for each pulsar,
using a library of various Gaussian process kernels.

Correlated Noise **Solar-System Ephemeris Modeling**

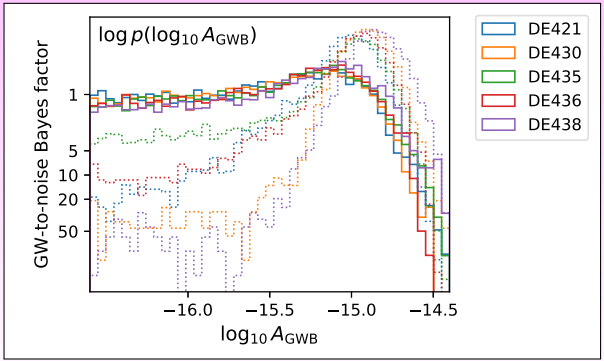
Michele Vallisneri, Joseph Simon, Steve Taylor

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

Perturbs the orbit of Jupiter ±100 km.

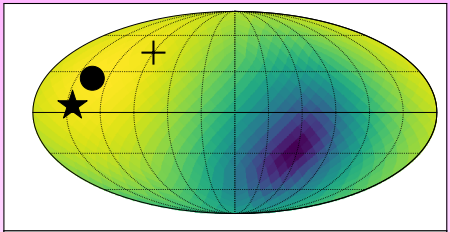


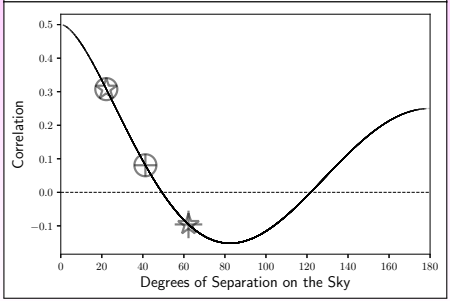
We are constraining the solar system barycenter with $\sim 100\,m$ accuracy.



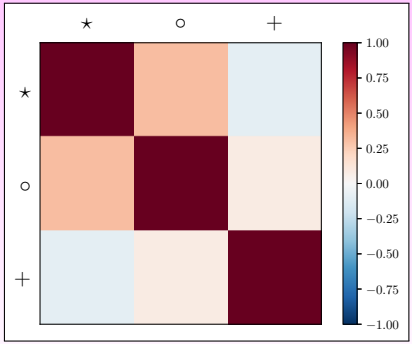
Vallisneri, et al., *Modeling the uncertainties of solar-system ephemerides for robust GW searches with PTAs*

PTAs and Spatial Correlations





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



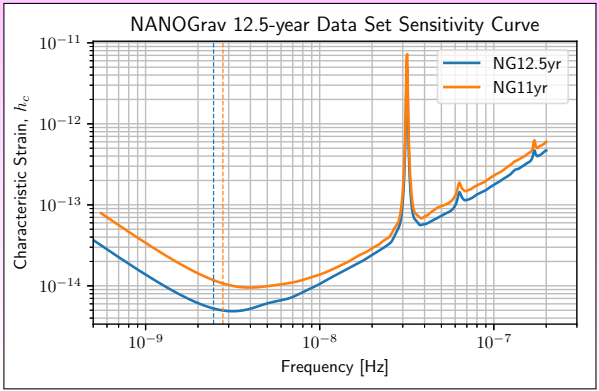
Cartoon Correlation Matrix

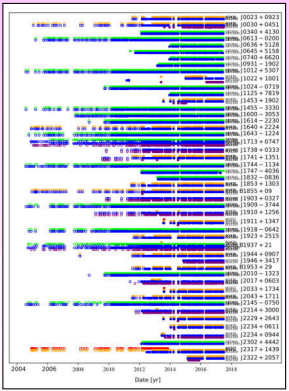
NANOGrav 12.5-Year Data Set

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.

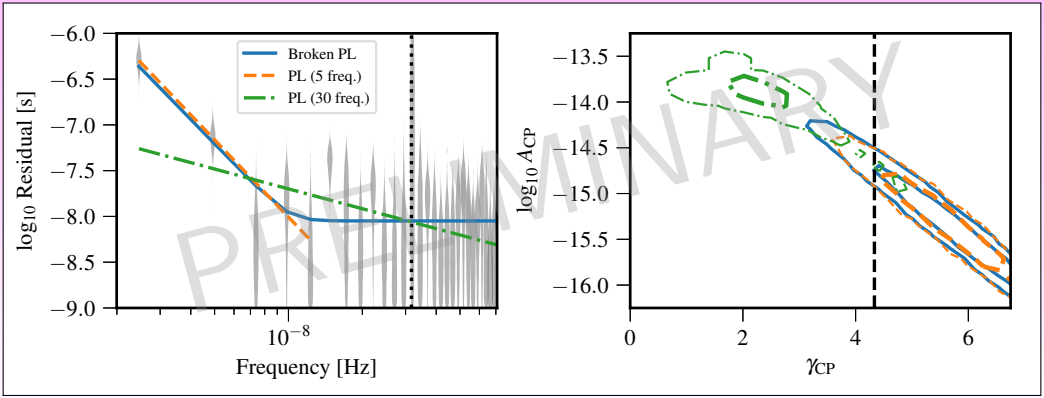




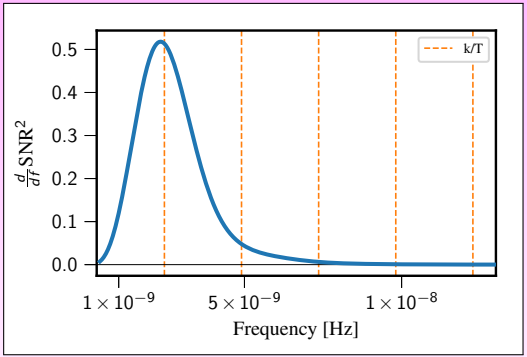
NANOGrav 12.5-Year Data Set: GW Background Search

Lead Joseph Simon

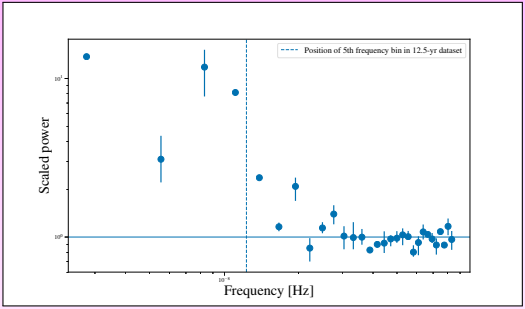
Varied Spectral Index Analyses show a strong common process across the PTA



NANOGrav 12.5-Year Data Set: GW Background Search



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

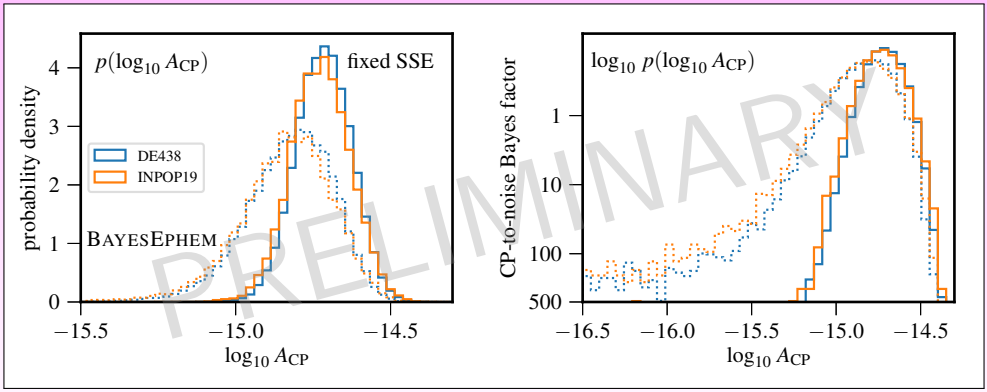


Injection analysis. Ratios of component power between injection amplitudes averaged across $A_{\mathrm{CP}} = 5 \times 10^{-15}$ and $A_{\mathrm{CP}} = 10^{-16}$.

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

Lead: Joseph Simon

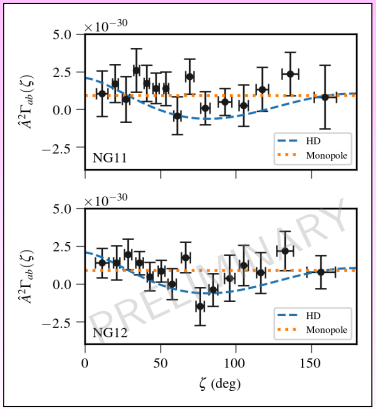
Bayesian Analyses. BF> 10,000 for Common Red Process, BF~ 4 for HD compared to CRP.



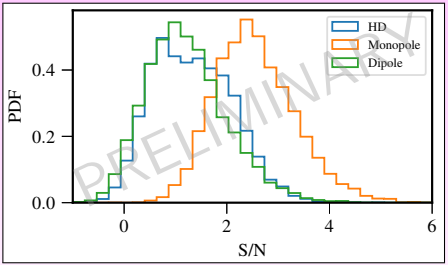
I'll discuss model dependence of GWB Stats, if there is time.

NANOGrav 12.5-Year Data Set: Spatial Correlations

Optimal Statistic Frequentist Analysis



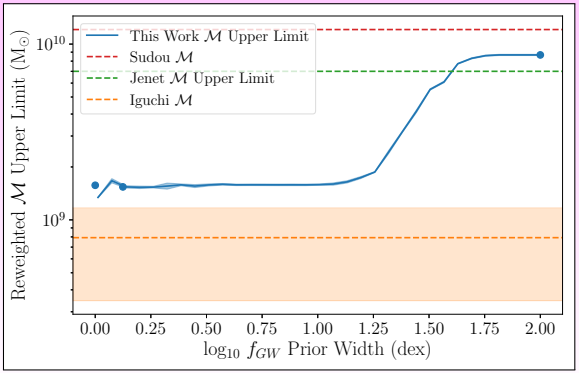
- Spatial Correlations for NG11(top) and NG12.5 (bottom).
- Noise-marginalized OS for monopole, dipole and quadrupole spatial correlations.

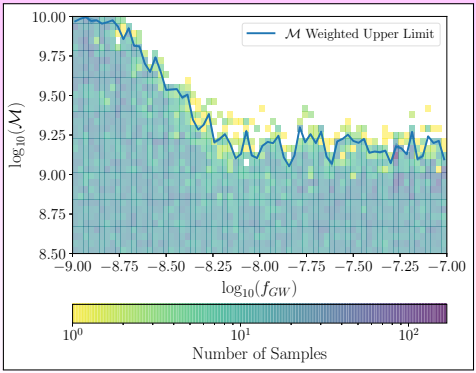


NANOGrav 11-Year Data Set Results: GW and Multimessenger Astrophysics

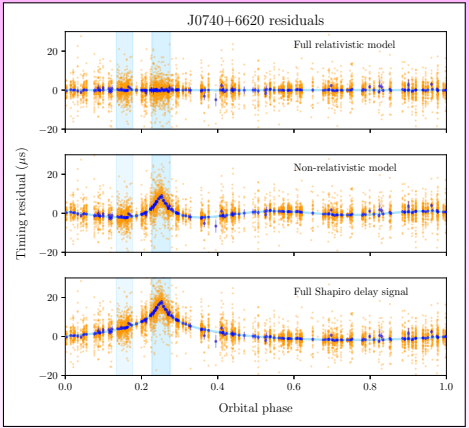
Aggarwal, et al. 2019, *The NANOGrav 11-Year Data Set: Limits on GWs from Individual SMBHBs*
Aggarwal, et al., 2019, *The NANOGrav 11-Year Data Set: Limits on Gravitational Wave Memory*

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**

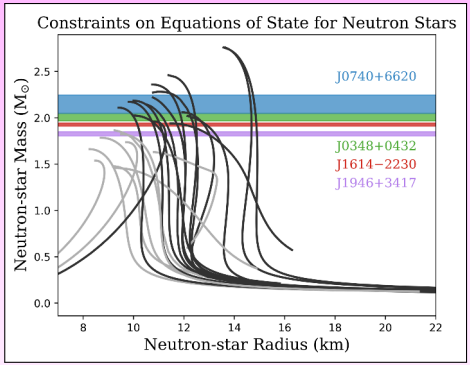




Synergistic Science: $2.15 M_\odot \pm 0.13$ Neutron Star



Shapiro Delay



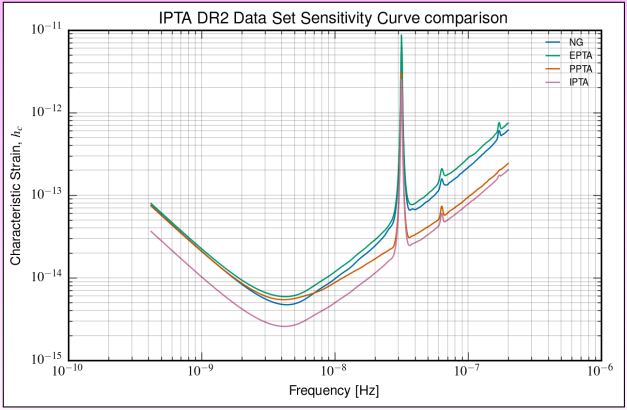
Neutron Star Equation of State

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

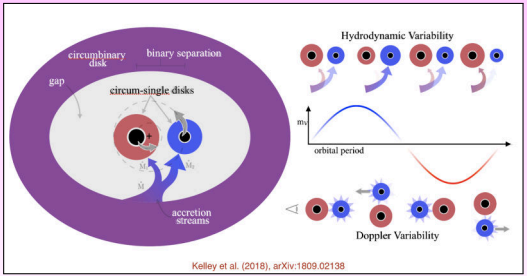
- 2nd mock data challenge submissions complete.
- 2nd data release published (Perera, et al., 2019).
- GW results from DR2 being finalized.
- 3rd data release officially under construction.



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

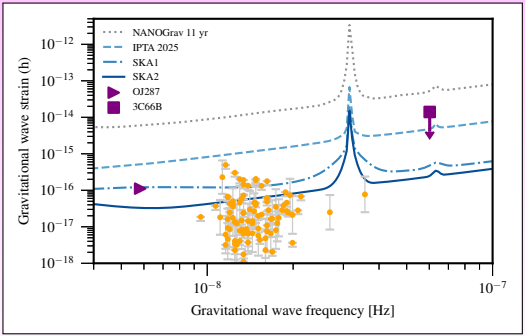
Future Prospects: Multimessenger Astrophysics

SMBBH Candidates with LSST
Luke Kelley NG11 and Neighboring Galaxy Catalogues *Maria Charisi*



"after 5 years of LSST observations, tens of true binaries will be detectable"

Catalina Rapid Transient Survey candidates
Chengcheng Xi, Chiara Mingarelli and JSH



CRTS candidates detectable by future PTAs

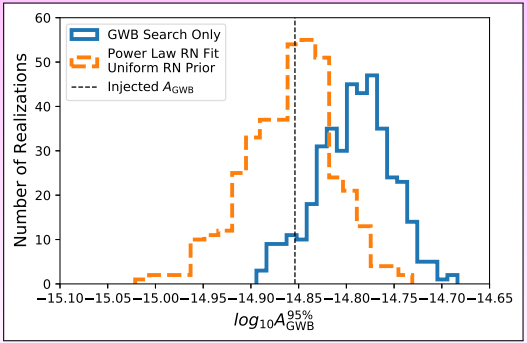
North American Nanohertz Observatory for Gravitational Waves

Thank You!

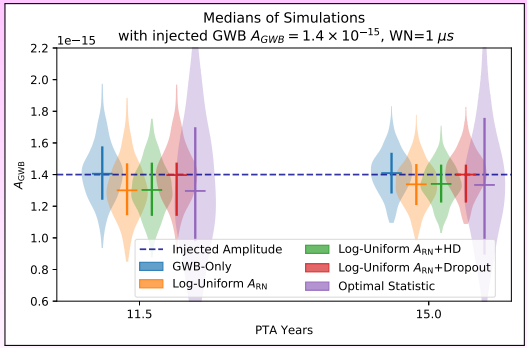
NANOGrav Members at the Green Bank Telescope, WVa. Image Credit: Tonia Klein

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, $A_{\rm GWB}$