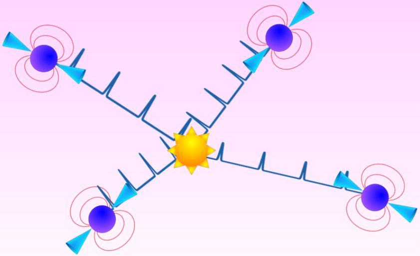
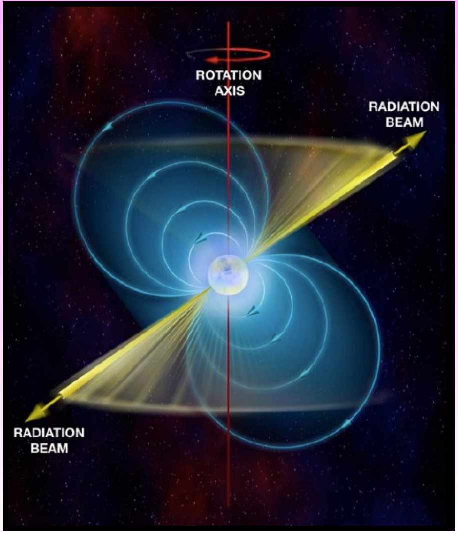
The Search for Lumbering Giants

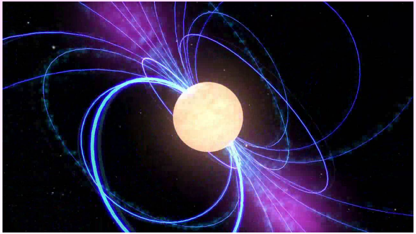
Jeffrey S. Hazboun,
University of Washington Bothell
Funded under NSF Award 1430284



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: $P = 0.00575745193671259 \pm \mathbf{0.00000000000000002} s$!
- Period of pulsar known to $\mathbf{1/10^{15}}$



PTA: Galactic Scale Gravitational Wave Detector

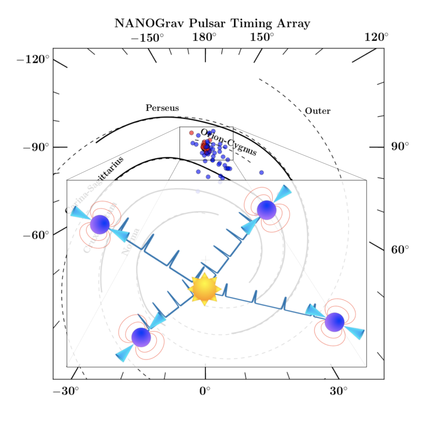
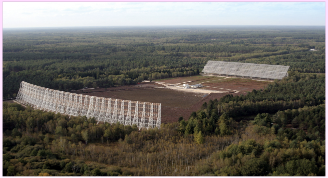


Image Credit: Jim Cordes, JSH



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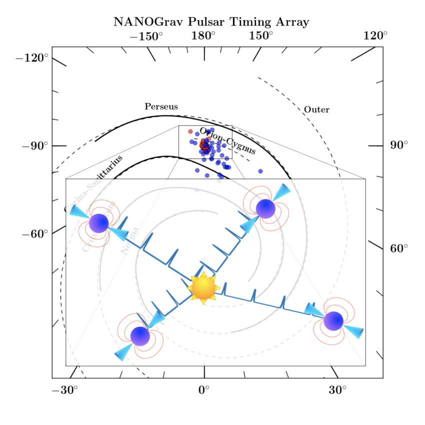

Image Credit: Jim Cordes, JSH

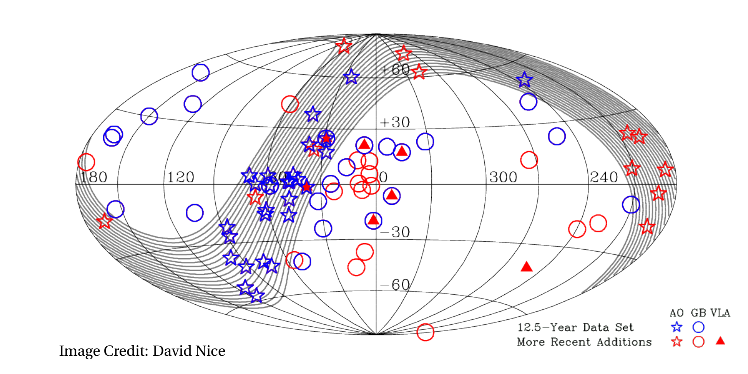

Image Credit: David Nice

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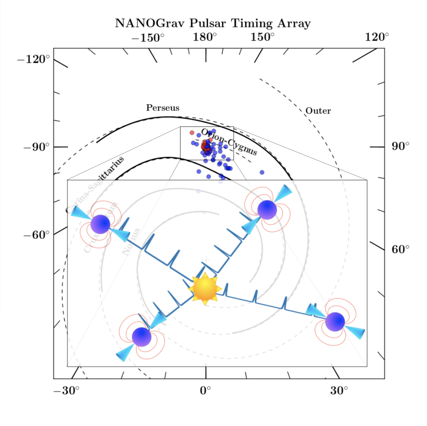
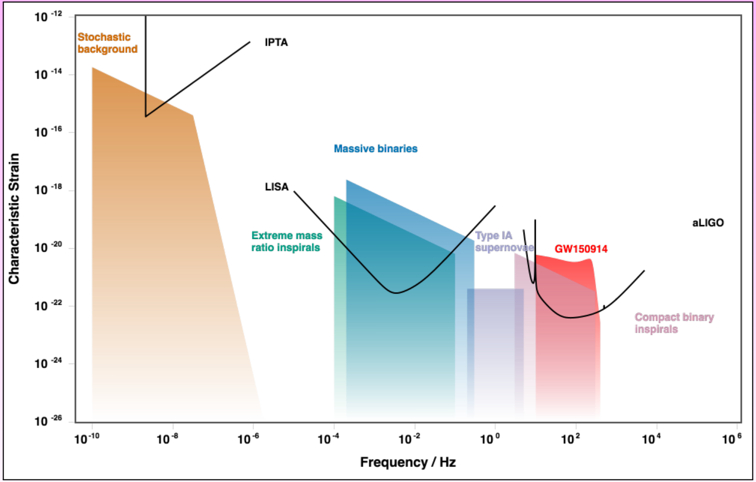


Image Credit: Jim Cordes, JSH

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

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

PTA: Galactic Scale Gravitational Wave Detector



Moore, Cole and Berry, *Gravitational-wave Sensitivity Curves*

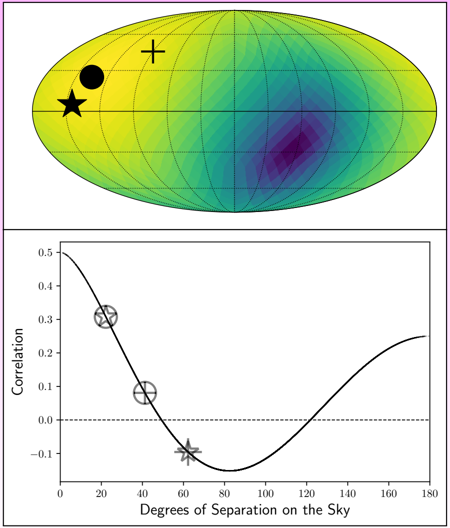
GW Interferometry vs Pulsar Timing Arrays

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	

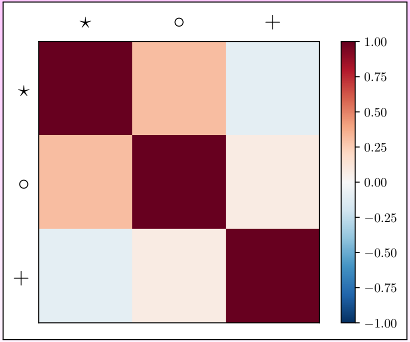
Sources of Noise and their Characteristics

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	✓	✓	✓	✓

PTAs and Spatial Correlations

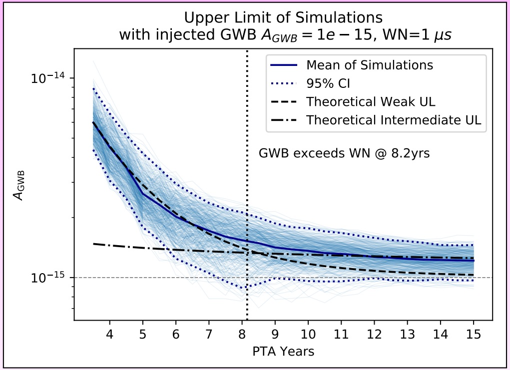


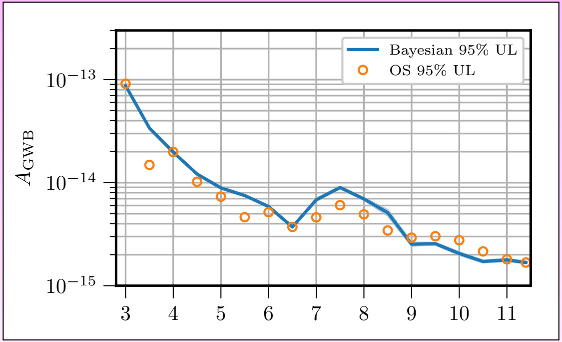
The sky positions of our pulsars translate to a correlation factor in the correlation matrix of our analyses.



Cartoon Correlation Matrix

Evolution of GWB Statistics



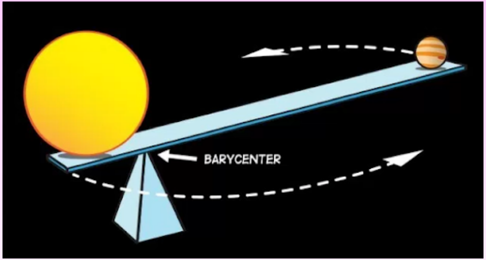


Hazboun, et al., 2019, *The NANOGrav 11-Year Data Set: Evolution of Gravitational Wave Background Statistics*

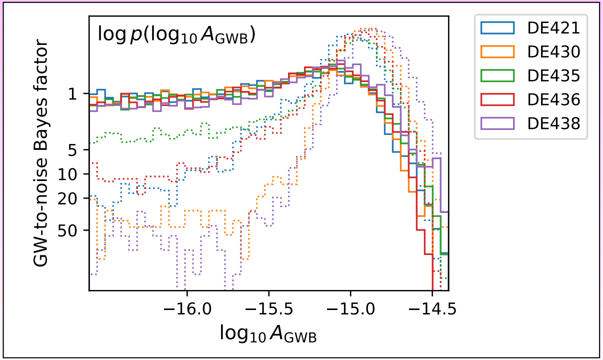
Michele Vallisneri, Joseph Simon, Steve Taylor

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

Perturbs the orbit of Jupiter ±100 km.

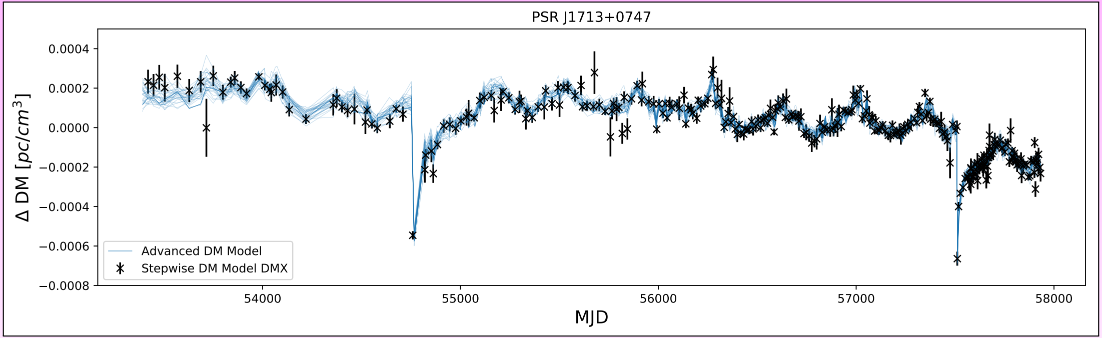


We are constraining the solar system barycenter with ~ $100m$ accuracy.



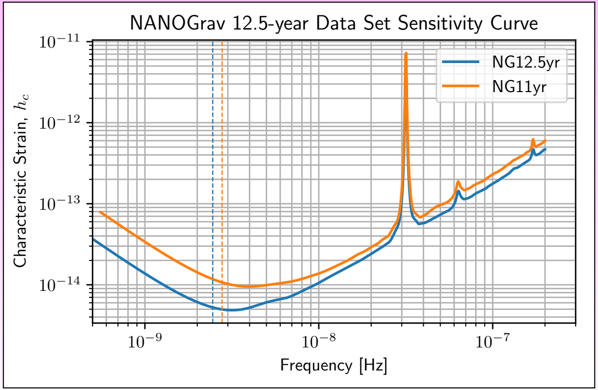
Vallisneri, et al., *Modeling the uncertainties of solar-system ephemerides for robust gravitational-wave searches with pulsar timing arrays*

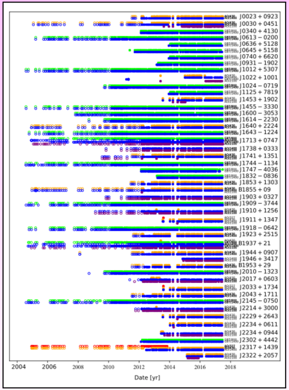
Ongoing Pulsar Noise Modeling



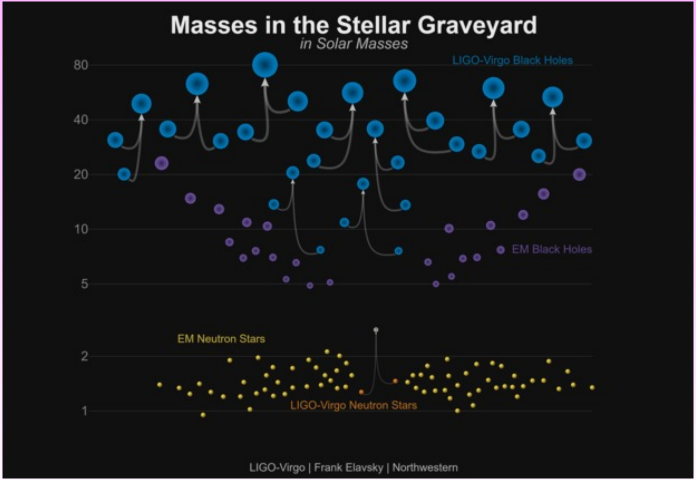
Advanced Noise Modeling/ Bayesian Solar Wind Model, JSH and Joseph Simon

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.





Searching for Lumbering Giants



- It's been a good few years for people interested in black holes.
- Binary black holes are the bread & butter signals for LIGO.
- The silhouette of the SMBH at the center of M87 was captured by the Event Horizon Telescope.
- Mass calculated from this image is 6.5 billion $M_{\odot}$.
- Most galaxies have a black hole at their center.

Searching for Lumbering Giants

Image Credit: Event Horizon Telescope Collaboration

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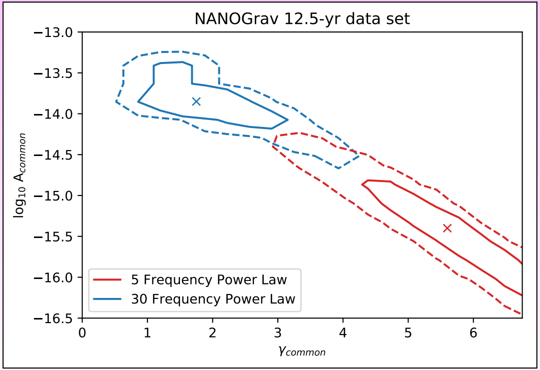
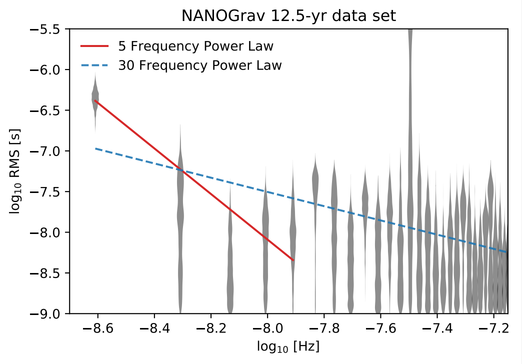
NANOGrav 12.5-Year Data Set: **GW Background Search**

Joseph Simon, Sarah Vigeland, Steve Taylor, JSH, Detection Working Group

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





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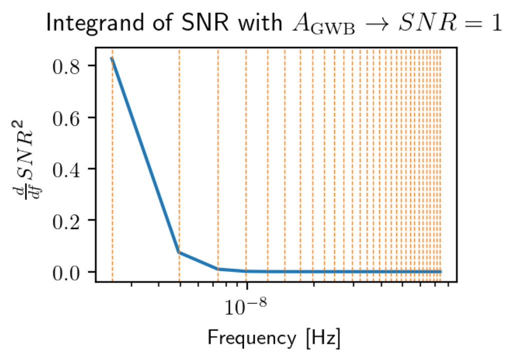
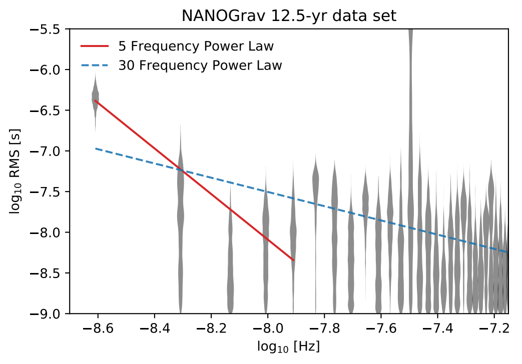
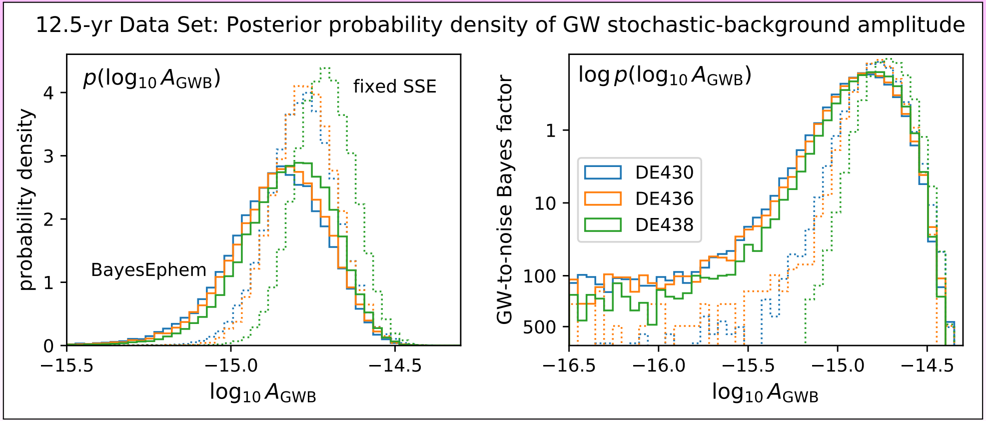


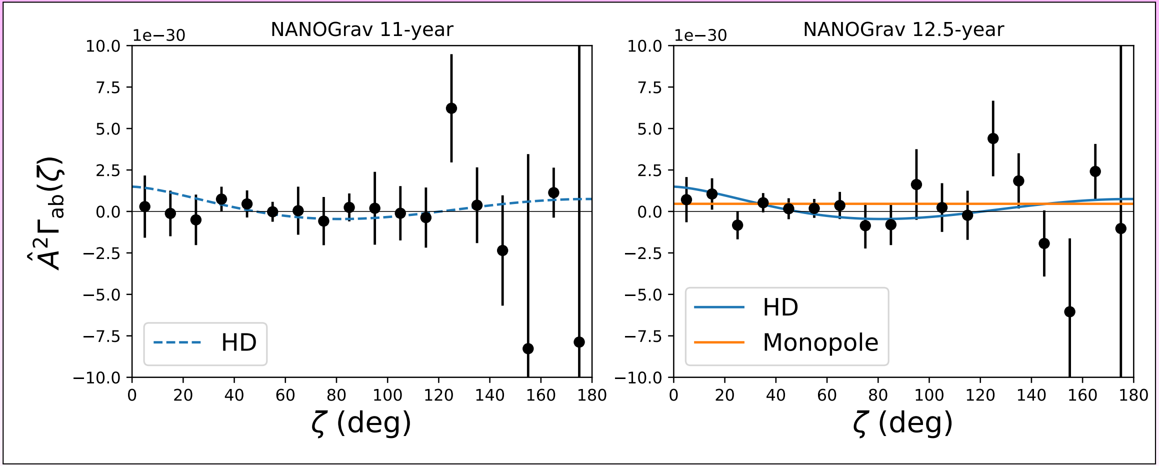


Joseph Simon, Sarah Vigeland, Steve Taylor, JSH, Detection Working Group

Preliminary and Bayesian Analyses. BF~ 100 for Common Red Process, BF~ 2 for HD.



NANOGrav 12.5-Year Data Set: Spatial Correlations



NANOGrav 11-Year Data Set Results: Astrophysical Inference

$M - M_{\mathrm{Bulge}}$ **Relation,** *Joseph Simon, Steve Taylor, Sarah Burke-Spolaor*

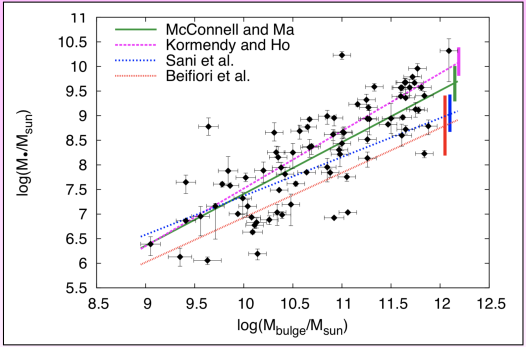
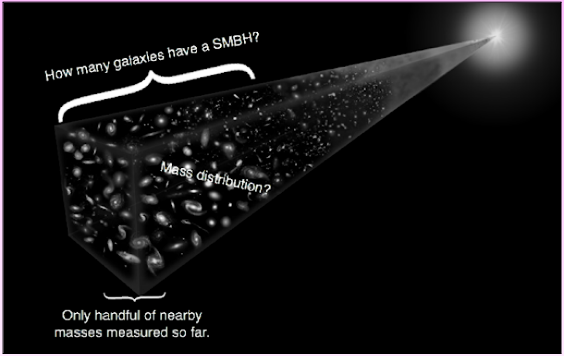


Image Credit: J. Simon and S. Burke-Spolaor



$$\log_{10} M_{\mathrm{BH}} = \alpha + \beta \log_{10}\left(\frac{M_{\mathrm{bulge}}}{10^{11} M_{\odot}}\right)$$

Simon and Burke-Spolaor, 2016, *Constraints on black hole/host galaxy co-evolution and binary stalling*

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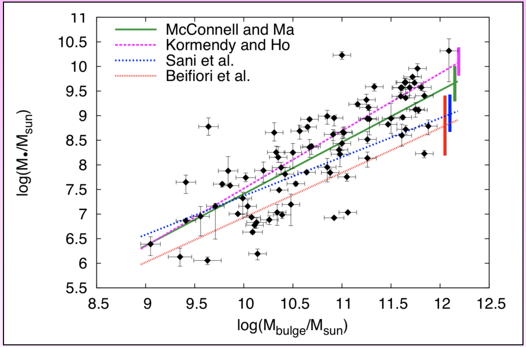

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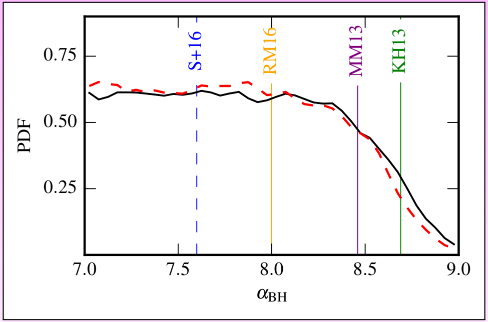

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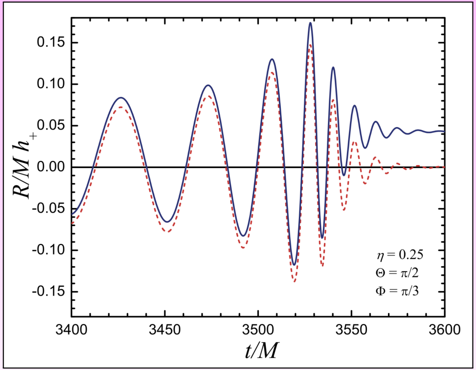
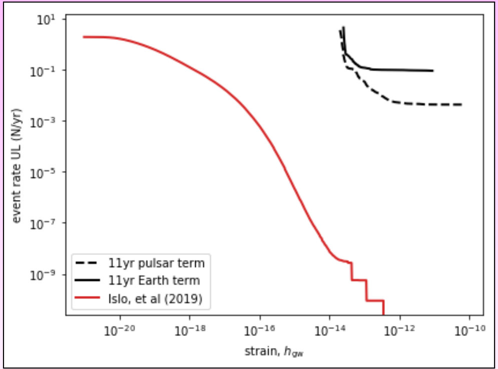
Simon and Burke-Spolaor, 2016, *Constraints on black hole/host galaxy co-evolution and binary stalling using pulsar timing arrays*

NANOGrav 11-Year Data Set Results: Single Sources

Burst with Memory Search, *Paul Baker, Kristina Islo*

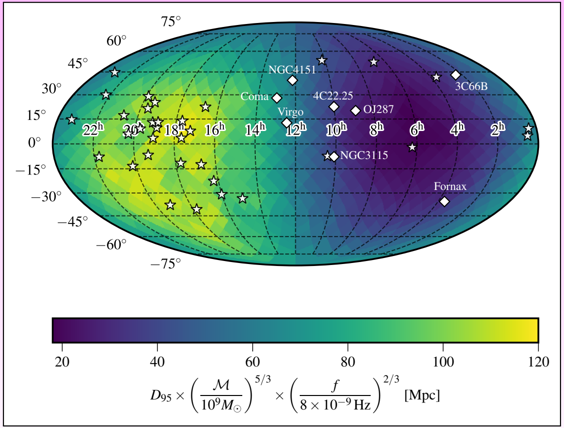


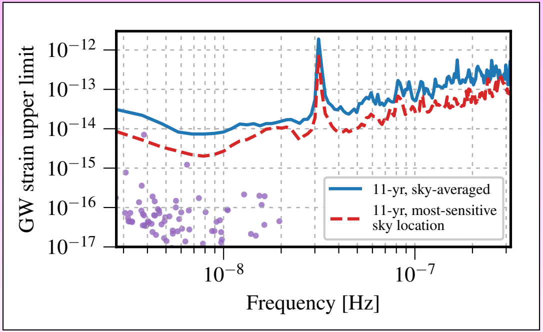


Favata, 2010, *The gravitational-wave memory effect*
Aggarwal, et al., 2019, *The NANOGrav 11-Year Data Set: Limits on Gravitational Wave Memory*
Islo, et al., 2019, *Prospects for Memory Detection with Low-Frequency Gravitational Wave Detectors*

NANOGrav 11-Year Data Set Results: Single Sources

Single-Source Search, *Sarah Vigeland, Kristina Islo*

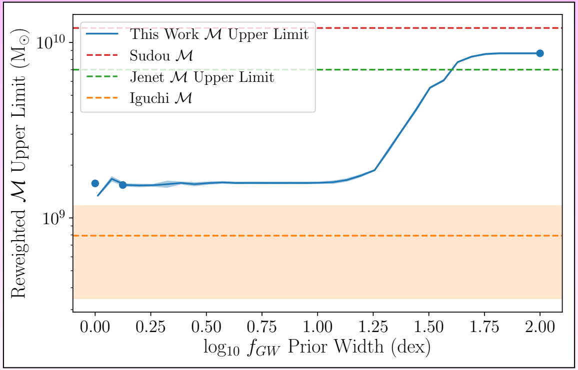


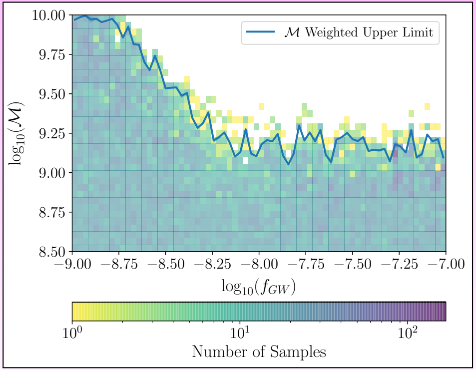


Aggarwal, et al. 2019, *The NANOGrav 11-Year Data Set: Limits on GWs from Individual Supermassive Black Hole*

NANOGrav 11-Year Data Set Results: Multimessenger Astrophysics

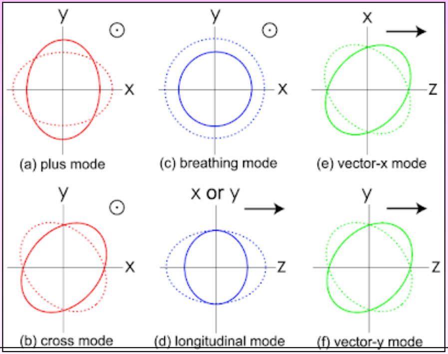
Directed Searches (3C66B), *Caitlin Witt*

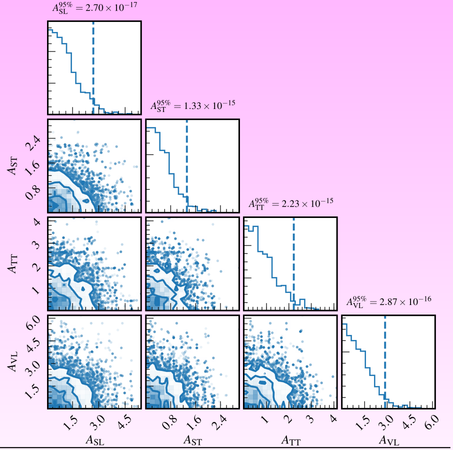




Alternative-Polarization Limits,

Neil Cornish, Logan O'Beirne, Steve Taylor, Sarah Vigeland

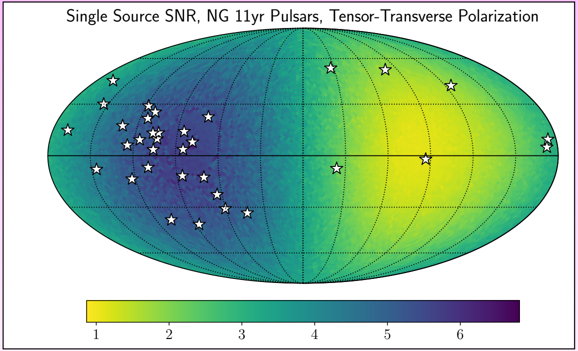


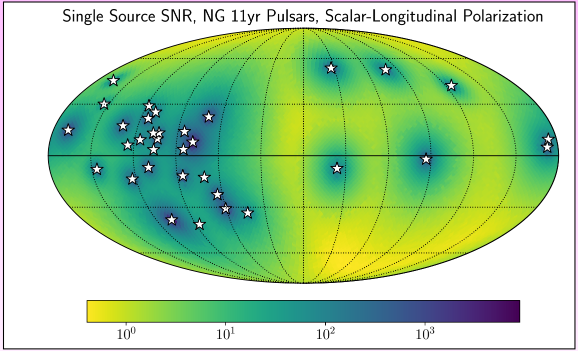


Cornish, et al., 2018, *Constraining alternative theories of gravity using pulsar timing arrays*
O'Beirne, et al., 2019, *Constraining alternative polarization states of gravitational waves from individual black hole binaries using pulsar timing arrays*

Longitudinal-Transverse Polarization Single-Source

$\mathscr{M}_{\mathrm{chirp}} = 10^9 M_\odot, \quad f_{\mathrm{gw}} = 10nHz, \quad \mathscr{D}_L = 120Mpc$

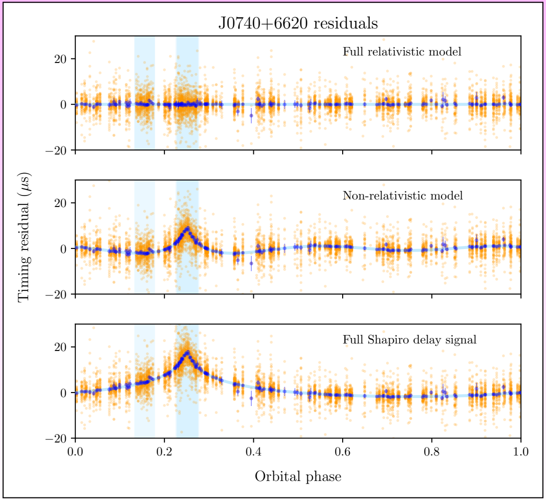




Note the scale difference between the two images!!

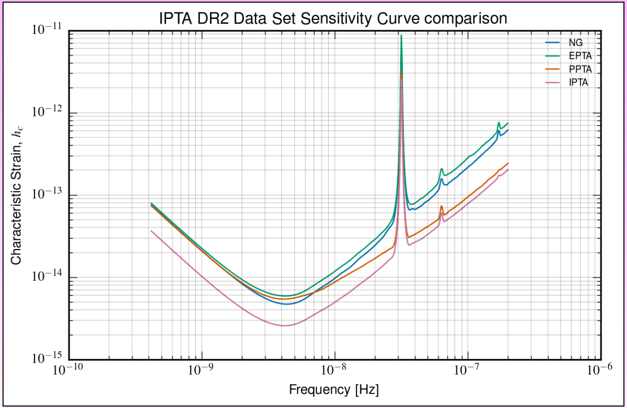
Synergistic Science: $2.15 M_\odot \pm 0.13$ Neutron Star

Shapiro Delay



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.

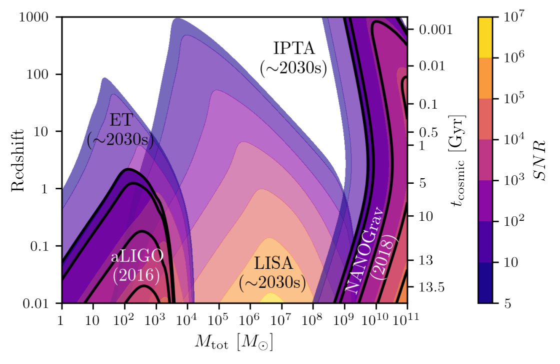


Ben Perera, *The International Pulsar Timing Array: Second data release*

Future Prospects: Multimessenger Astrophysics

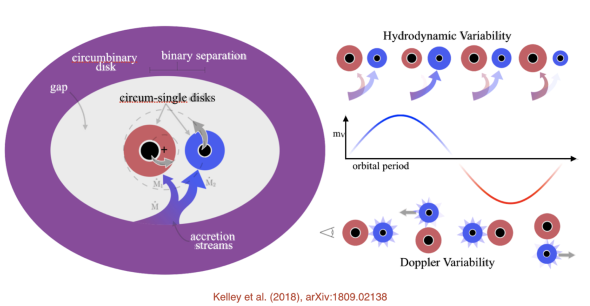
Black Hole SNR with Distance

Andrew Kaiser, Sean McWilliams



SMBBH Candidates with LSST

Luke Kelley, Maria Charisi



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

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

Detection Prospects