Pulsar Timing Array
GW Astronomy Update

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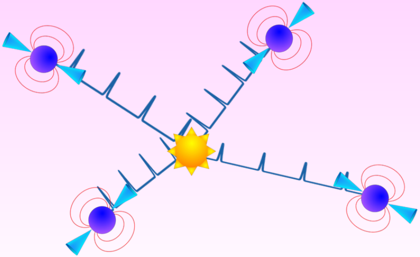
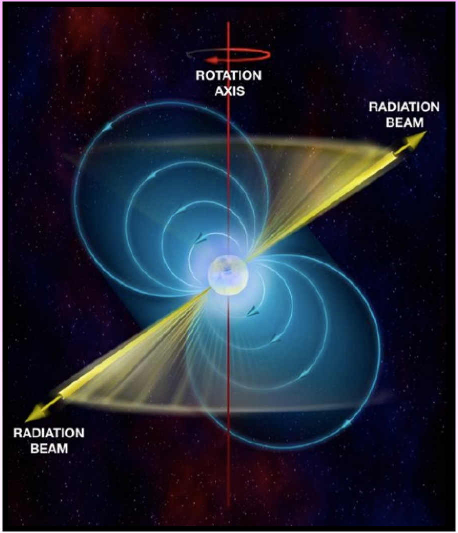
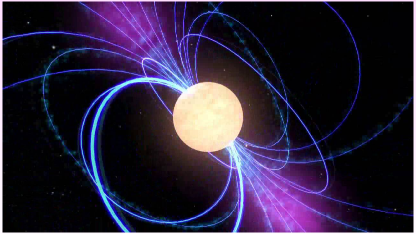
University of Washington Bothell
Funded under NSF Award 1430284



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: $P = 0.005757451936712\mathbf{59} \pm \mathbf{0.000000000000000002}s$!
- Period of pulsar known to $\mathbf{1/10^{15}}$



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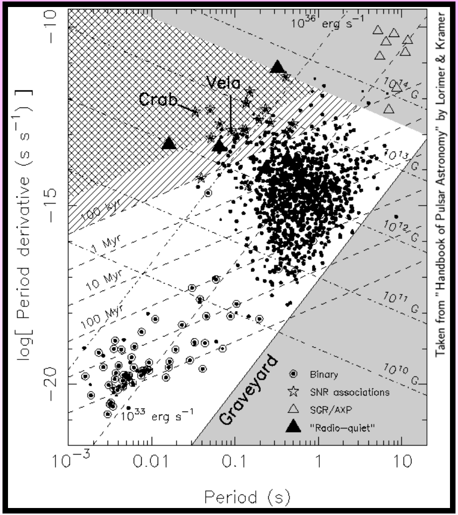

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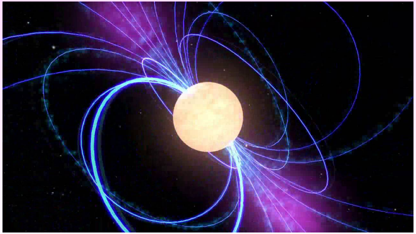
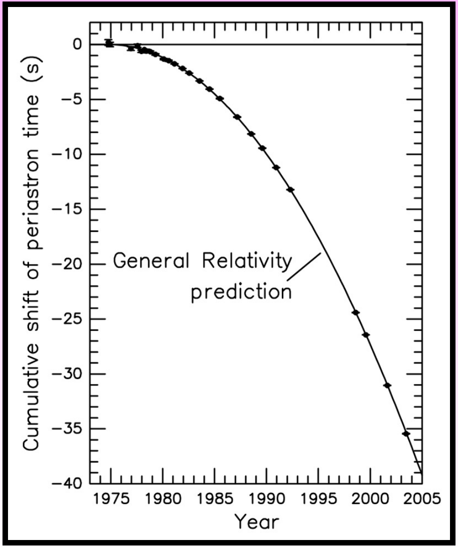


Pulsar Timing Arrays



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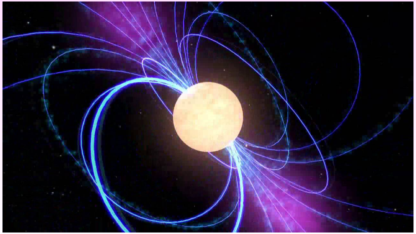
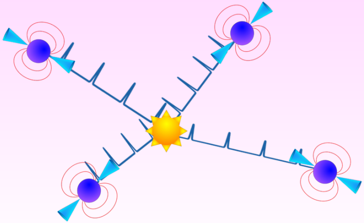


PTA: Galactic Scale Gravitational Wave Detector

Image Credit: Tonia Klein

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

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



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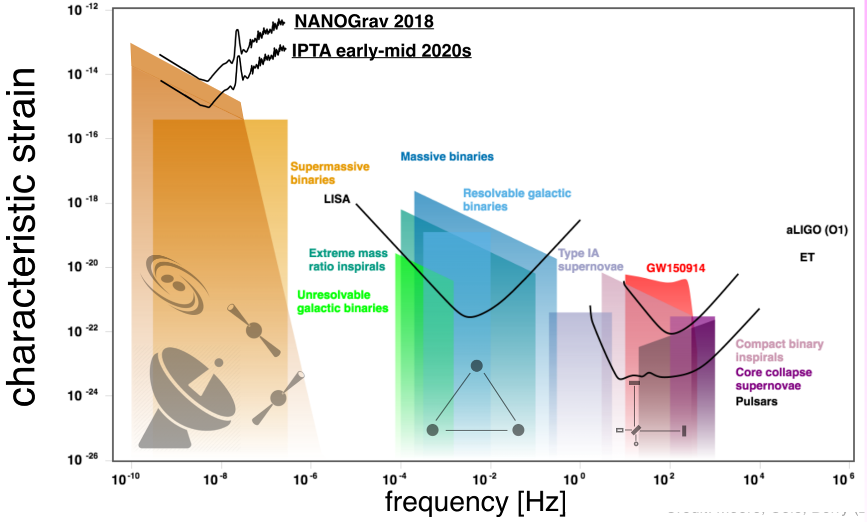

Moore, Berry, Cole (http://gwplotter.com/) [modified by Taylor]

Continuous, Burst and Stochastic Signals

Continuous Wave Signal:

- Low to medium strength signal.
- Long lived.
- Few Fourier modes.

Burst Signal:

- Strong to medium strength signal.
- Short lived
- Many Fourier modes.

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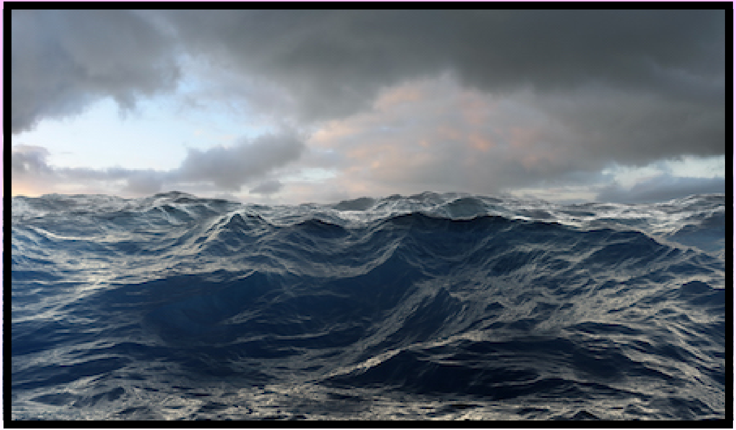
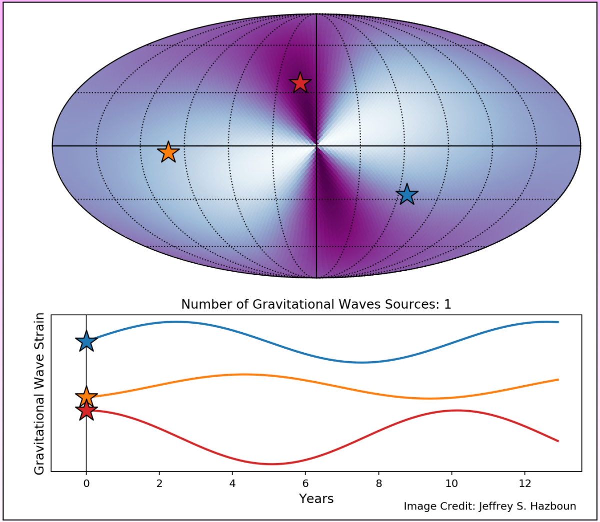
Continuous, Burst and Stochastic Signals

Stochastic Background:

- Individual sources weak, but the sum is detectable.
- Long lived.
- Many Fourier modes. Often following a power-law, or turnover power spectral model.
- Gerhard Mantz, *Rough Seas*



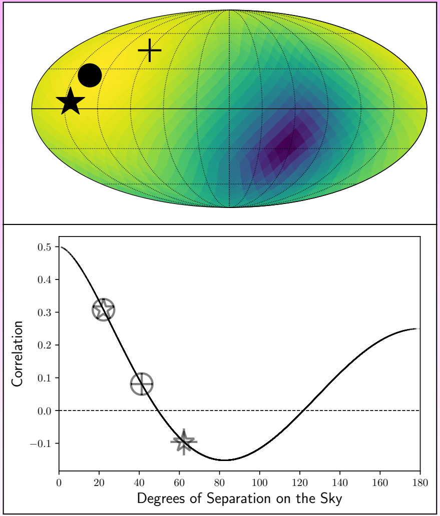
Stochastic Gravitational Wave Backgrounds



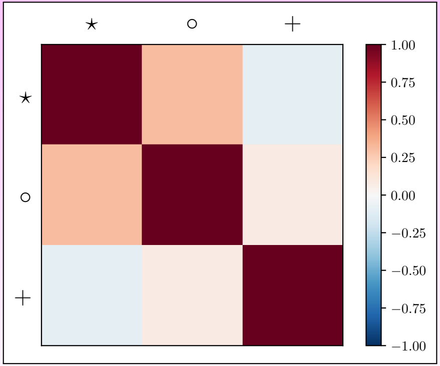
- Single gravitational wave sources are seen as “rotating hourglasses”.
- Individual pulsars see sinusoidal signals in the times-of-arrival of pulses.
- Single sources can be searched for using a deterministic “matched-filter” analysis.
- Many individual sources add up to a stochastic gravitational wave background (GWB).
- The characteristic strain from the GWB follows a power law dependent on the population of supermassive binary black holes.

$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{f_{\mathrm{yr}}} \right)^{-\frac{2}{3}}$$

Spatial Correlations

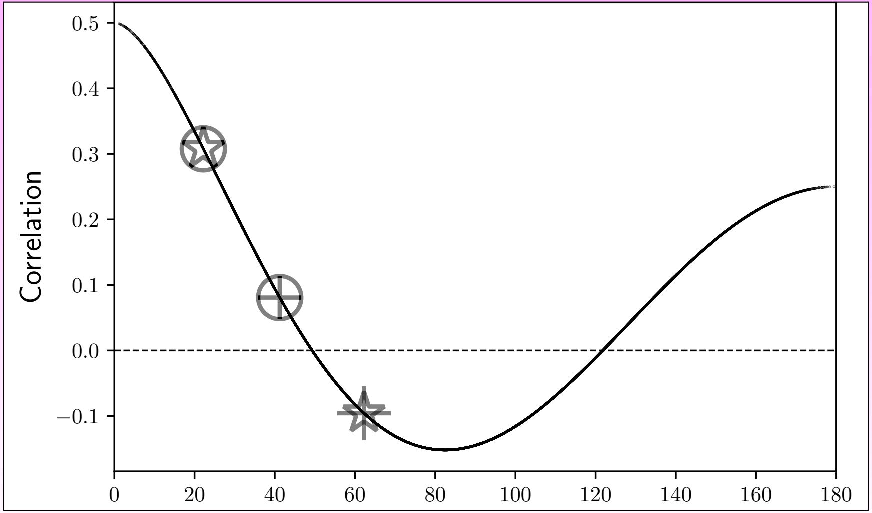


The sky positions of our pulsars translate to a correlation factor in the correlation matrix of our analyses.



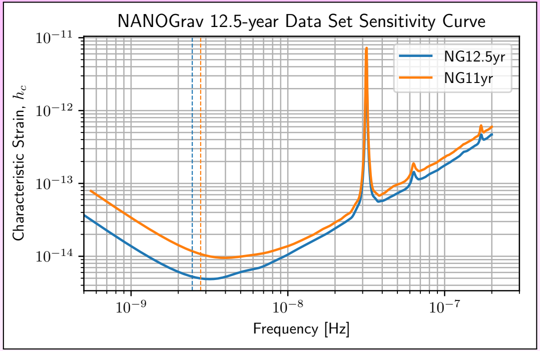
Cartoon Correlation Matrix

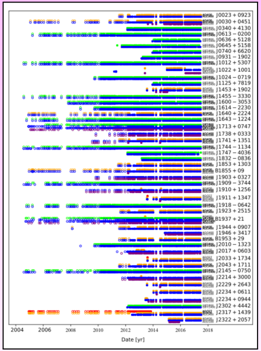
Spatial Correlations



NANOGrav 12.5-Year Data Set

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.

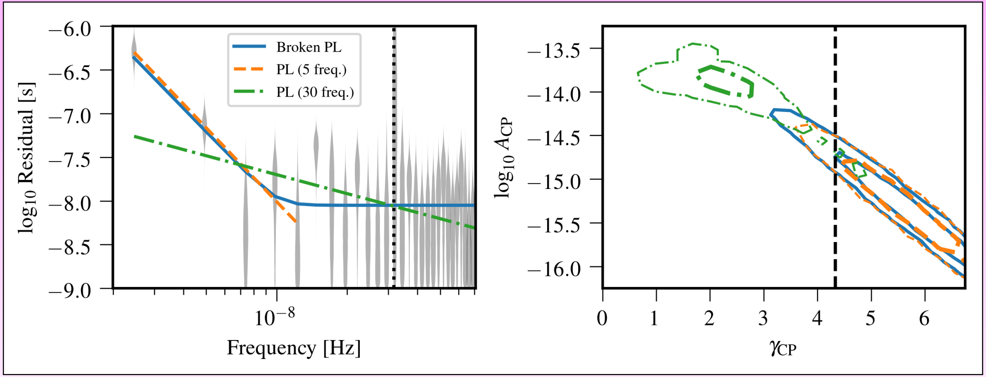




Alam, et al., [DeCesar] 2021. *The NANOGrav 12.5 yr Data Set: Observations and Narrowband Timing of 47 Millisecond Pulsars*

Alam, et al., [Pennucci] 2021. *The NANOGrav 12.5 yr Data Set: Wideband Timing of 47 Millisecond Pulsars*

NANOGrav 12.5-Year Data Set: Common “Red” Process

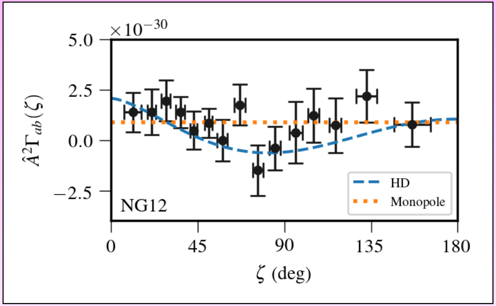


Spectral analysis shows strong evidence for power at lowest frequencies.

Arzoumanian, et al., [Simon] 2021. *The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background*

NANOGrav 12.5-Year Data Set: Spatial Correlations

- NG12.5 yr spatial correlations
- Note that, while the fit to the Hellings-Downs curve is getting better, fits to other curves are also reasonable.
- As individual pulsar become more sensitive at lower frequencies we will get more information about the spatial correlations.



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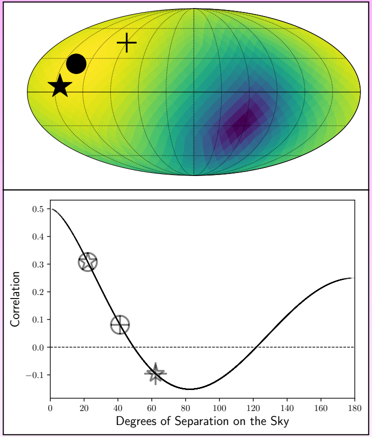
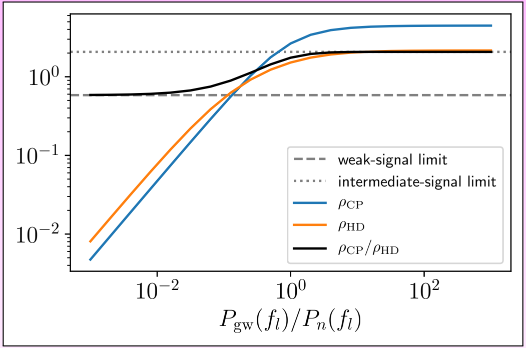
Auto vs. Cross Correlations

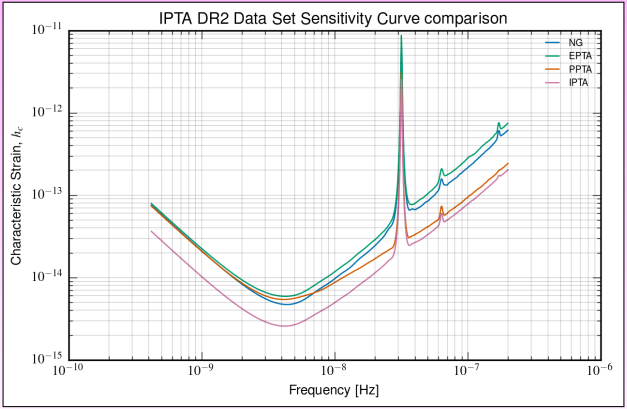




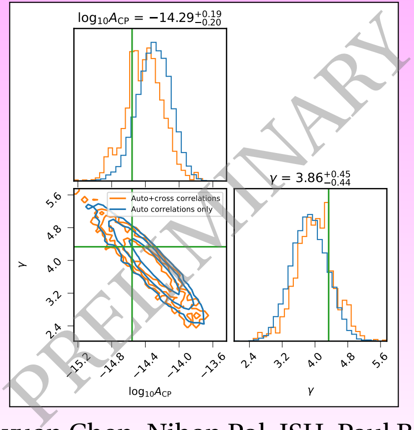
Romano, Hazboun, Siemens and Archibald, 2020. *Common-spectrum process versus cross-correlation for gravitational-wave searches using pulsar timing arrays*

International Pulsar Timing Array/ European PTA/ Parkes PTA

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



International Pulsar Timing Array/ European PTA/ Parkes PTA

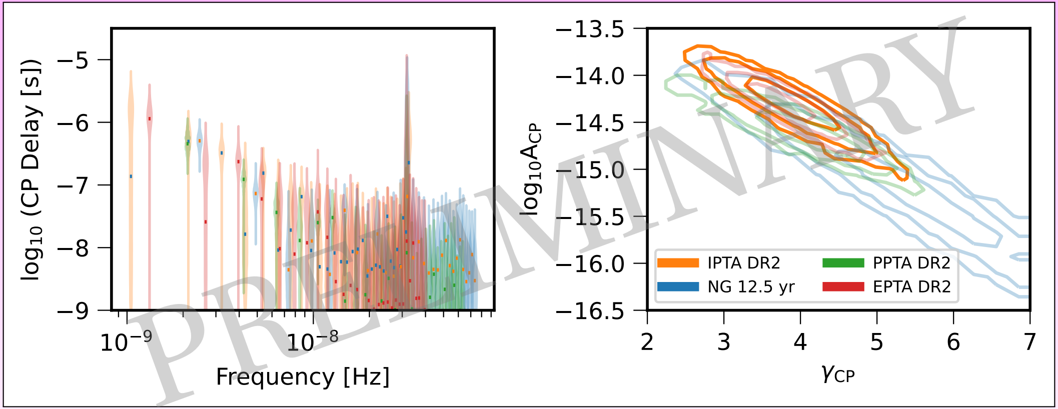


IPTA: Siyuan Chen, Nihan Pol, JSH, Paul Baker, ...

PPTA: Boris Goncharov, Daniel Reardon, Ryan Shannon, ...

EPTA: Siyuan Chen, Nicolas Caballero, ...

International Pulsar Timing Array/ European PTA/ Parkes PTA



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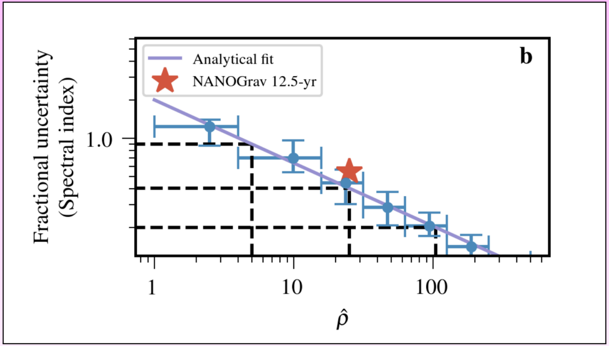
Detection Prospects, Spectral Characterization

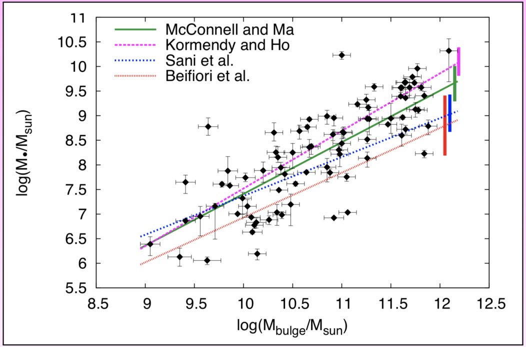
- We have the next 15 year dataset in hand!!
- Our simulations show that if we are seeing the GWB our next dataset will cross the detection threshold
- When we detect the GWB we will be able to ascertain the spectral index to within 40% fractional uncertainty.
- This is enough to disfavor at 95% credible intervals $\alpha = -2$ and $\alpha = -1$.
- Possibly able to distinguish from some cosmic string models with $\alpha = -7/6$



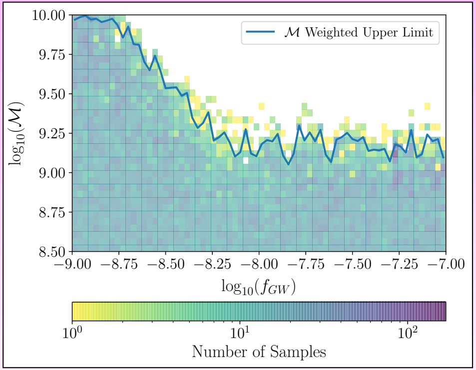
Pol, et al., [Nihan Pol], 2020 *Astrophysics Milestones For Pulsar Timing Array Gravitational Wave Detection*

Super Massive Binary Black Hole Astrophysics

Black Hole / Host Galaxy Relationships



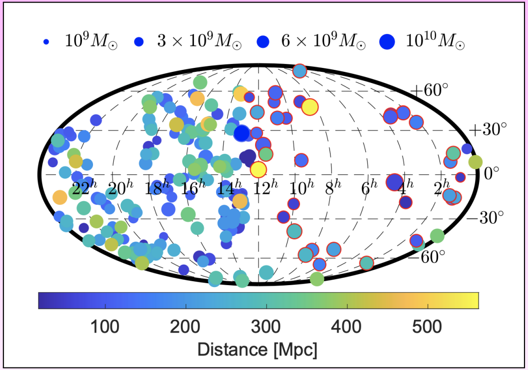
Directed Searches (3C66B), *Caitlin Witt*



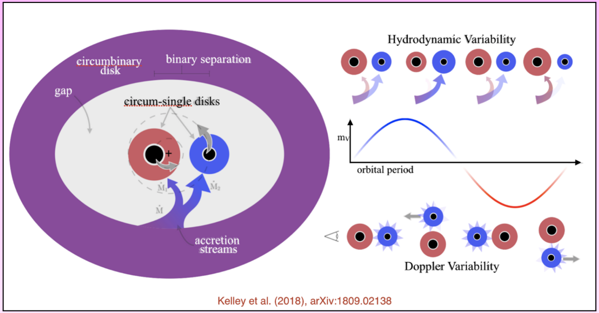
Middleton, et al., 2020. *Massive black hole binary systems and the NANOGrav 12.5 year results*
Aggarwal, et al., [Vigeland] 2019. *NG11: limits on gravitational waves from individual supermassive black hole binaries*
Simon and Burke-Spolaor, 2016, *Constraints on black hole/host galaxy co-evolution and binary stalling using pulsar timing arrays*

Multimessenger Astrophysics

Targeted Searches for Candidates



SMBBH Candidates with LSST



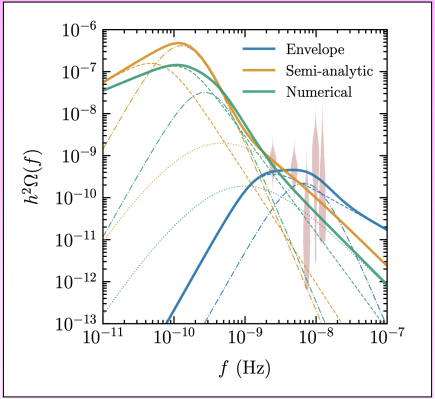
"after 5 years of LSST observations, tens of true binaries will be detectable"

Arzoumanian, et al., [Charisi] 2021 *The NANOGrav 11yr Data Set: Limits on Supermassive Black Hole Binaries in Galaxies within 500Mpc*

Kelley, et al., 2019 *Massive BH binaries as periodically variable AGN*

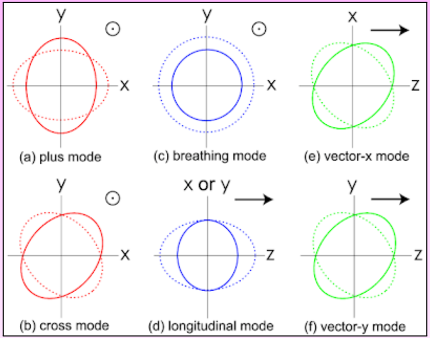
Cosmological Phase Transitions

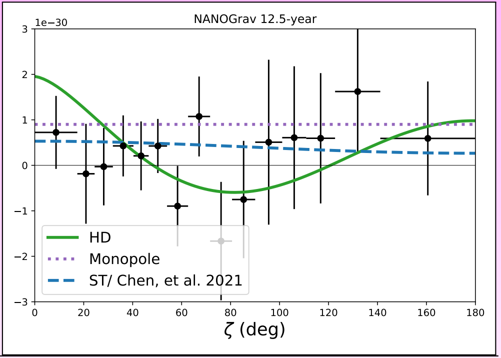
- First order phase transitions in early universe.
- Various models for bubble spectral shape.
- Strong phase transition at temp below the electroweak scale.
- Includes version of search with a GWB from SMBBHs.
- Currently signal is degenerate with GWB from SMBBHS.



Arzoumanian, [Zurek, Taylor] et al, 2021 *Searching For Gravitational Waves From Cosmological Phase Transitions With The NANOGrav 12.5-year dataset*

Alternative Polarizations

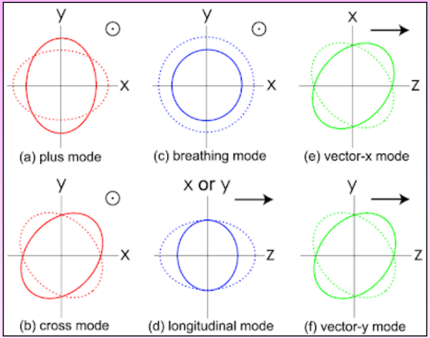


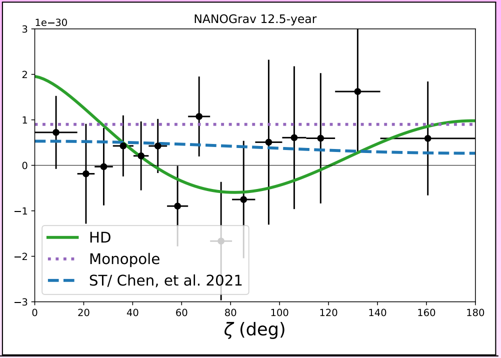


Cornish, et al., 2018, *Constraining alternative theories of gravity using pulsar timing arrays*
O'Beirne, et al., 2019, *Constraining alternative polarization states of gravitational waves from individual black hole binaries using pulsar timing arrays*
Chen, Yuan and Huang, 2021, *Non-tensorial Gravitational Wave Background in NANOGrav 12.5-Year Data Set*

Alternative Polarizations

See Xavi's talk for NG results by Nima Laal !!





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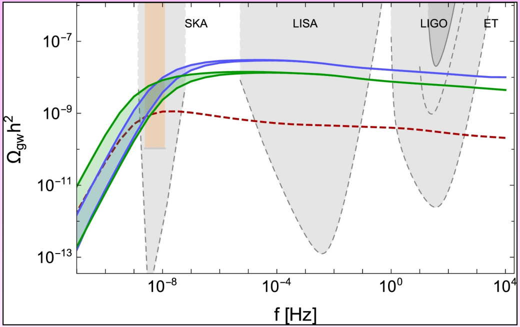
Any Signal in the nanohertz band

- Cosmic strings
- QCD matter confinement phase transition GWB
- Clumps of Dark Matter (Shapiro Delay, Doppler Shifts)*
- Primordial Black Holes
- Limits on mass of graviton
- Ultralight Scalar Field (Fuzzy) Dark Matter*
  Brendan Drachler at RIT working on dual signal recovery.
- The Astrophysics of Nanohertz Gravitational Waves, arxiv:1811.08826
- Physics Beyond the Standard Model With Pulsar Timing Arrays, arxiv:1907.04960



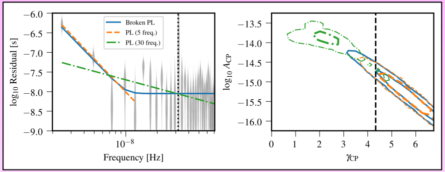
Buchmuller, Domcke and Schmitz, 2020. *From NANOGrav to LIGO with metastable cosmic strings.*

Motivation for Reconsidering PTA Observing Strategies

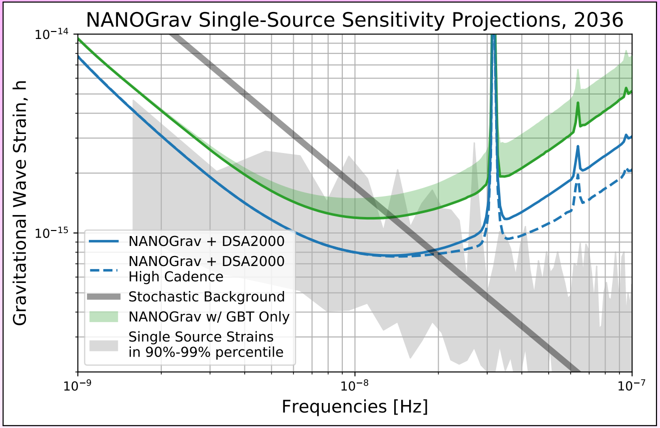
1. Early signs of a stochastic GWB

   $\Downarrow$

   "Are any of these sources resolvable"?
2. Tragic loss of Arecibo in December has forced many of us to reconsider PTA observing strategies. An opportunity to investigate how to tune our observation campaigns for multimessenger astronomy.
3. Given the many *heterogeneous* pulsars we observe, there is already quite a bit of latitude in our observing campaign...



Metrics for evaluating a PTA's observing strategy for resolvable sources.



- Sky-averaged sensitivity
- Detection volume
- Directional sensitivity

Luke Z. Kelley, Xavier Siemens, JSH, Paul Demorest, Tyler Cohen, Michael Lam, ...

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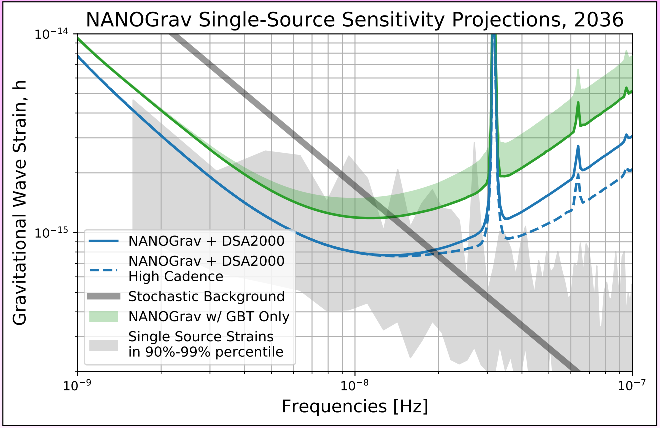

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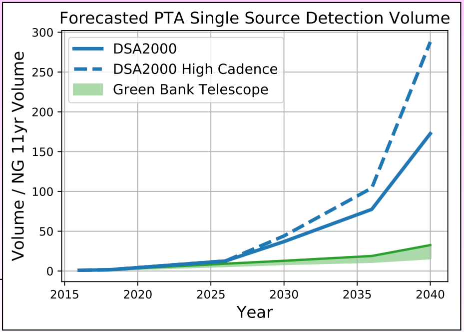

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North American Nanohertz Observatory for Gravitational Waves

Thank You!

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