Proposed Research

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has the primary goal of detecting low-frequency gravitational waves (GWs) using high precision pulsar timing of millisecond pulsars (MSPs). Pulsar timing arrays (PTAs) are already probing the region of strain amplitude phase space where we expect GWs to exist and placing constraints on supermassive black hole (SMBH) binary environments, like gas/stellar content and orbital eccentricity. NANOGrav has also put limits on cosmic string tension that are the highest precision by far [2]. As NANOGrav improves techniques and instrumentation for high-precision pulsar timing with the goal of nHz GW detection, more conventional tests of general relativity, like those made possible through study of the Hulse-Taylor or double-pulsar binaries, are made more precise as well. PTAs will continue to increase sensitivity and improve limits, and by doing so will explore a new frontier in the GW universe not accessible by other experiments.

The majority of pulsar timing has been done with large single dishes; the next generation of pulsar timing will be done using interferometric instruments, like the VLA and SKA. My expertise with the VLA and GMRT makes me uniquely poised among young pulsar astronomers to facilitate this transition and maximize its potential. As a postdoc at LOCATION, I will search for pulsars and black holes via hybrid imaging, and characterize frequency-dependent interstellar effects in timing data that will be more influential for sources that are distant or located in the Galactic center.

Hybrid imaging searching. The sensitivity of a PTA increases linearly with the numbers of MSPs. It is therefore essential to add as many well-timed MSPs as possible. PTAs will have varying sensitivity to continuous GW sources depending on their location on the sky, illustrated in Figure 1. It is therefore not only important to find new pulsars to add to the array but to also conduct strategic searches in the Galaxy, which will heighten the GW sensitivity across the sky in an informed way. Standard time-domain pulsar surveys have succeeded in finding many radio pulsars, however these surveys are time intensive and many systems will not be detectable by this method of searching [7].

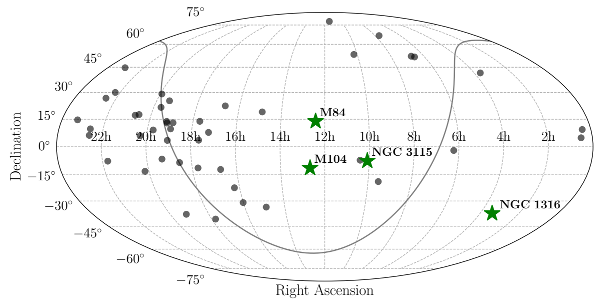

Figure 1: PTAs are more sensitive to individual GW sources that are located near pulsars in the array. The dots represent pulsars timed by NANOGrav in the 11-year data set and starred sources represent potential GW sources; it can be seen that they are located in less sensitive regions on the sky.

The large population of high mass stars in the Galactic center should guarantee a much higher number density of neutron stars and stellar mass black holes (BHs) than in the Galactic disk. Timing a pulsar in the Galactic center would probe the spacetime around the central SMBH in our Milky Way. It is also a likely location to host a pulsar-BH binary. However, due to the ionized interstellar medium (ISM), the pulsar emission will experience large amounts of scattering, which will completely smear out the pulse, shown in Figure 2. This effect cannot be corrected for in time-domain surveys and dramatically reduces sensitivity, to the point that short period pulsars will be undetectable [7]. This effect can be avoided by going to higher frequencies, but with the caveats of much lower pulse fluxes at high frequencies and smaller beam sizes, making large scale searches infeasible.

Hybrid imaging provides both survey efficiency as well as the sensitivity to detect objects missed in time-domain surveys, discussed in Figure 3. Using hybrid imaging searching, candidates can be identified in interferometric images by their radio compactness. After this initial identification of candidates, pointed time-domain searching can be applied. Hybrid imaging searching will be a critical strategy for current and future radio arrays like the VLA and ngVLA, as well as other instruments around the globe like the GMRT, MeerKAT and the SKA. *I will contribute to and streamline current pipelines for hybrid method searching for pulsars.* My combination of experience with interferometers along with chromatic timing effects makes me the ideal person to further develop hybrid-imaging and high-frequency periodicity searches. I will optimize pulsar searches in portions of the Galaxy that would be more beneficial in improving our GW sensitivity map, particularly in areas where pulsars might be widely separated or with high scattering. I will also predict expected sensitivities for searching with the future ngVLA.

Searching for a pulsar-BH binary. As mentioned in my epxerience statement, I am currently working on simulating the timing residuals resulting from long period pulsar-BH binaries in PTA data. The goal is to constrain the properties of systems that may remain undetected in current data, and that may be detectable with more observation

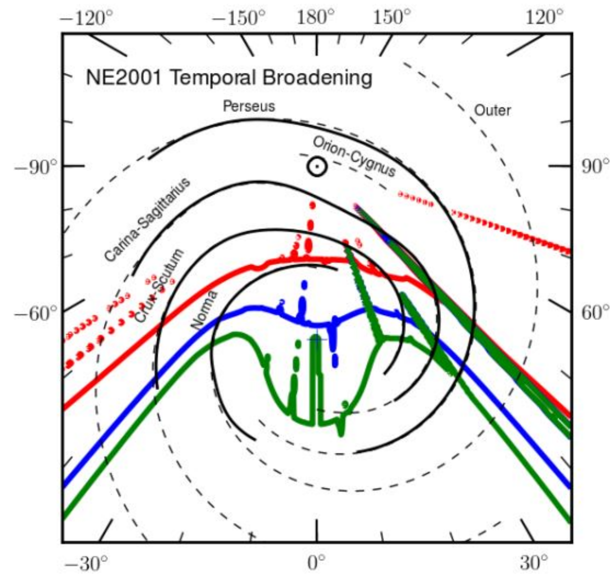

Figure 2: Temporal broadening due to free electrons in the Milky Way at a frequency of 1.5 GHz [3]. The Earth is represented by the black circle. Pulsars located near the red, blue, and green contours will experience 1, 10, and 20 ms respectively of pulse smearing from scattering. MSPs with periods shorter than this will be undetectable by time-domain surveys at these radio frequencies or lower.

time or more sensitive algorithms. *After the determination of pulsar-BH binary candidates through timing data, I will investigate candidates using data from the VLA Sky Survey (VLASS) to facilitate detection.* This work would inform on populations of long period binaries, which could be used in the actual discovery of a binary, put constraints on LIGO merger rates, probing the physical mechanisms for neutron star-back hole binaries, and investigating merger timescales. The discovery of the first pulsar-BH system using the VLA will be monumentally important for pulsar timing studies and for constraining the as yet unconstrained LIGO event rate for such systems. The techniques used here will be honed using the VLA and be applicable for the future ngVLA as well as other interferometers around the globe.

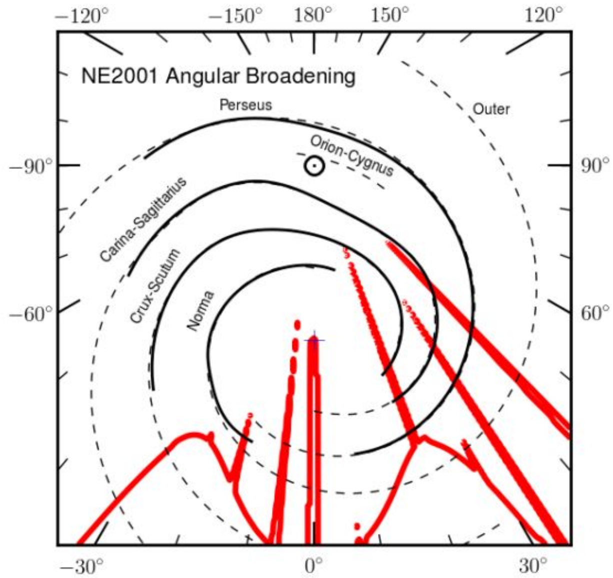

Figure 3: Angular broadening due to free electrons in the Milky Way at a frequency of 1.5 GHz [3]. The Earth is represented by the black circle. Pulsars located near the red contour will experience 100 mas of angular broadening due to scattering. As can be seen from a comparison of Figure 2, scattering has a much less deleterious effect on imaging surveys to find compact sources like pulsars within the Galaxy. Hybrid imaging can provide a road map of potential sources that can be followed up with targeted time-domain observations at higher radio frequencies.

Optimizing multi-frequency timing. All contributions to noise in pulsar timing data need to be characterized to achieve the sensitivity needed to detect GWs. Our PTA must be as sensitive as possible, requiring the mitigation of all other astrophysical delays, including those from the ISM. As other forms of noise in timing data are modeled and accounted for, PTAs will become more sensitive to chromatic (i.e. radio frequency-dependent) effects, like time delays due to interstellar effects [4, 5]. For example, low frequency data had to be excluded in the analysis of the pulsar located in a hierarchical triple system [1]. Many of the pulsars found via hybrid imaging will have avoided detection by other surveys; while large amounts of scattering and dispersion do not present an issue for imaging, they will still need to be mitigated in timing data. In addition, chromatic interstellar propagation effects occur as red noise when not properly mitigated, making GW detection more difficult.

Properly understanding and correcting for chromatic effects in timing data is therefore paramount. *Because chromatic noise sources will dominate over time, I will improve our characterization of the ISM by investigating how scattering varies with time.* I will use the corresponding results to understand how to use these multi-frequency data properly to remove chromatic effects.

excess chromatic noise?

update to ne2001?

[1] Archibald et al., Nature, 559, 73, 2018.
[2] Arzoumanian et al., ApJ, 859, 47, 2018
[3] Chatterjee et al., *Discovering Exotic Pulsars and Transients with VLASS and Time Domain Surveys*, 2013.
[4] Cordes et al., ApJ, 817, 16, 2016.
[5] Lam et al., ApJ, 861, 12, 2018.
[6] Liu et al., ApJ, 747, 1, 2014.
[7] Lorimer & Kramer, *Handbook of Pulsar Astronomy*, 2012.
[8] Seymour et al., arXiv:1808.00080, 2018.
[9] Taylor et al., ApJL, 819, L6, 2016.