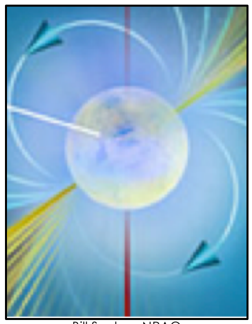
NANOGrav

Opening a New Frontier in Gravitational Wave Astronomy

WHAT IS NANOGRAV?

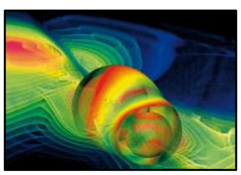
NANOGrav is a collaboration of scientists from over a dozen US and Canadian institutions whose goal is to detect gravitational waves using pulsars.

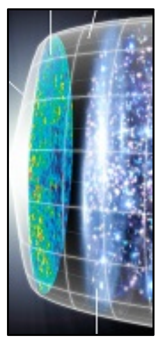
HOW WILL WE DETECT GRAVITATIONAL WAVES?


Bill Saxton, NRAO

We will detect gravitational waves by using an array of ultra-precise millisecond pulsars. The influence of gravitational waves on the Earth causes a unique signature in pulse times of arrival.

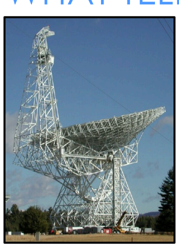
WHAT SOURCES WILL WE DETECT?


NPI for Gravitational Physics


NASA WNAP

We will detect sources with nanohertz frequency gravitational waves. These may include coalescing super black holes, relics from inflation, and cosmic strings. Pulsar timing probes a different frequency range than ground and space interferometers.

WHAT TELESCOPES DO WE USE?


NRAO

We use the most sensitive radio telescopes in the world: the Green Bank Telescope and the Arecibo Telescope. Both are vital to NANOGrav.


NRAO

WHEN WILL WE SUCCEED?

We are already providing unique constraints on the stochastic gravitational wave background. We believe a direct detection is feasible within five to ten years.

MEMBERS OF NANOGRAV

Senior Personnel

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NANOGrav

In Depth

PULSAR TIMING ARRAYS

Gravitational waves cause small deviations in the arrival time of pulsars at the tens of nanoseconds level. An array of millisecond pulsars is sensitive to this effect. We increase the sensitivity of timing arrays by observing longer and more frequently, finding more pulsars, understanding the pulsars and propagation effects on the signal, improving detection algorithms, and building improved instruments. All are active areas of work within NANOGrav.

WORLDWIDE EFFORT

NANOGrav is part of the International Pulsar Timing Array along with teams in Europe and Australia.

SPREADING THE WORD

NANOGrav is engaged in professional and public outreach and education at all levels. High school and undergraduate students play important roles in several NANOGrav projects.

JOIN US

Any scientist who believes they can make a valuable contribution to NANOGrav is encouraged to apply for membership. Please contact NANO-MT@NANOGrav.org for more information regarding membership.

NANOGRAV IS SUPPORTED BY THE NSF THROUGH THE PIRE PROGRAM AND BY THE NSERC.

MEMBERS OF NANOGRAV

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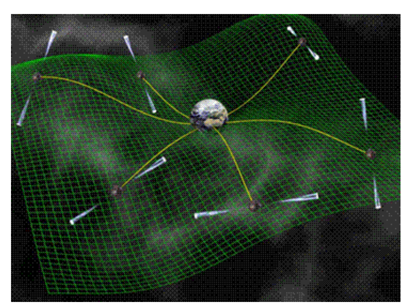


IPTA

The Importance of the Arecibo Observatory to Low-Frequency Gravitational Wave Astronomy

Einstein's Theory of General Relativity provides the foundation for our understanding of phenomena ranging from planetary motion to cosmic structure formation and the evolution of the Universe. One of the fundamental predictions of General Relativity is the existence of gravitational waves (GWs) as ripples in space-time. GW astronomy was highlighted by the *New Worlds, New Horizons* 2010 Decadal Survey as a science-frontier discovery area, capable of a transformational change in our understanding of the Universe. The goal of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration is to detect GWs through radio pulsar timing using the uniquely sensitive combination of the Arecibo Observatory and Green Bank Telescope and to use them to study supermassive black hole formation mechanisms and their implications for galaxy evolution, along with other possible GW sources.

Figure 1: The NANOGrav collaboration consists of 21 Senior Personnel, 13 postdoctoral scholars, 17 graduate students, two computing staff, and a large number of undergraduate students. These personnel are from 17 institutions, including 11 research universities, three liberal arts colleges, and three national facilities. The collaboration was formed in October 2007 and has grown rapidly since that time. More details about the collaboration, including membership and authorship policies, can be found at `http://nanograv.org`.

Pulsars are astrophysical clocks for precision metrology: These highly magnetized, rapidly rotating neutron stars have spin periods ranging from milliseconds to seconds. The timing stability of the most rapidly rotating subset, the millisecond pulsars (MSPs), rivals atomic clocks, enabling detection of perturbations of order tens of nanoseconds or smaller. The best *indirect* evidence for GWs comes from high-precision radio-pulsar timing measurements performed with the Arecibo Observatory of orbital decay in double neutron star binaries, resulting in the 1993 Nobel Prize in Physics [1]. In addition to carrying energy, propagating GWs cause the light-travel times between objects to change. These light-travel time variations produce characteristic direction-dependent signatures in pulse times of arrival with a quadrupolar angular correlation on the sky (see Fig. 2); these are the signals NANOGrav aims to detect and characterize in MSP timing data. Because observations over long time spans are needed to achieve the required sensitivity, pulsar timing is most responsive to GWs of nanohertz frequencies, complementary to the higher frequencies probed by other existing and planned detectors (Fig. 3). The most promising sources to which MSP timing is sensitive are supermassive binary black holes, which could be detectable individually or as a stochastic background produced by many sources. Other potential sources include cosmic strings, phase transitions in the early Universe, and relic GWs from inflation, all of which would provide unique windows into cosmology and galaxy formation and evolution.

A Galactic-scale GW detector: To achieve its goal of low-frequency GW detection, NANOGrav must observe an array of high-precision millisecond pulsars over multi-year timespans with the most sensitive telescopes in the world. Over the past decade, the collaboration has used both the Arecibo Observatory and the Green Bank Telescope (GBT) to carry out this experiment. Initially, only 20 millisecond pulsars were timed; this number has now risen to 43. Of these, 25 are timed using Arecibo, two in common with the GBT, once every three weeks for roughly 30 minutes each at each of two frequencies. Observing at multiple

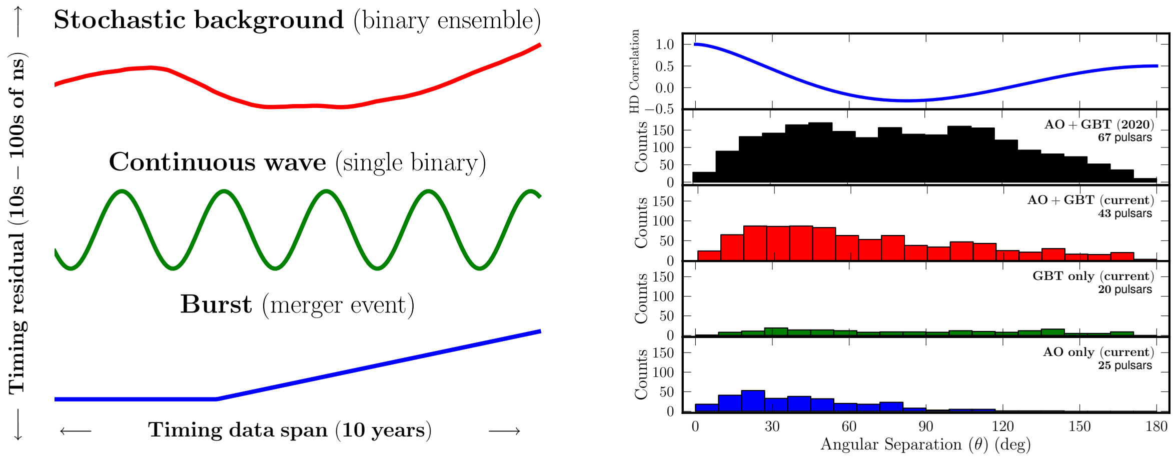


Figure 2: *Left:* Pulsar timing signatures expected for different types of GW signals. The vertical axis is timing residual, or the difference between measured and expected TOAs, and the horizontal axis is time. For reasonable supermassive binary black hole (SMBBH) parameters, the residual amplitudes expected for all three signal types range from tens to hundreds of nanoseconds. *Right:* The top panel shows the so-called "Hellings and Downs curve" [2], or the expected two-point correlation in the residuals as a function of angular separation assuming an isotropic stochastic GW background. The other panels show the number of MSP pairs as a function of separation for (from bottom to top) MSPs currently timed with Arecibo, the GBT, and both telescopes, and all MSPs that will be routinely timed by 2020. The two MSPs timed at both telescopes have been assigned to Arecibo for this plot. GW sensitivity to a stochastic background scales linearly with the number of MSPs in the array.

frequencies is crucial for removal of interstellar propagation effects. The combination of Arecibo's unrivaled collecting area and the 800-MHz bandwidth of PUPPI (the Puerto Rican Ultimate Pulsar Processing Instrument) provides the highest-precision time of arrival (TOA) data of any telescope in the world.

Detection of low frequency GWs is near: GW sensitivities are expressed in terms of characteristic strain h_c, or *amplitude*, the fractional change in path length induced by a GW. As the total time span of our observations grows, we become more sensitive to the lower GW frequencies that induce larger timing residuals. *A discovery is likely within the decade if the Universe evolves as current models and evidence suggest.* In this whitepaper, we concentrate our discussion on the detection of a stochastic background of GWs due to SMBBHs, but detections of single SMBBH systems as continuous wave or burst sources is also possible. In Fig. 4 we plot our projected sensitivity to a stochastic background as a function of time, assuming that our detection significance scales as $N\left(c/\sigma_{\rm RMS}^2\right)^{3/26}T^{1/2}$ where N is the number of MSPs, T the total data span, $\sigma_{\rm RMS}$ the RMS level of noise in TOA residuals, and c the cadence (number of observations per year) [3]. The dependence on the RMS and cadence is weak; increasing the number of pulsars N yields the greatest sensitivity improvement.

To create the projections shown in Fig. 4, we have added MSPs at a rate of four per year, conservatively assuming their RMS values to be the median of our existing sample (roughly 300 ns). Arecibo plays a critical role in this assumption, as roughly half of these discoveries are expected to come from the PALFA (Pulsar Arecibo L-band Feed Array) and 327-MHz drift-scan surveys. We have also assumed a doubling of the observing cadence in 2016/2018 for GBT/Arecibo sources, along with a modest 20% improvement in RMS through the use of new wideband receivers now in development (assuming they will first be deployed on the GBT). The current set of MSPs being monitored by NANOGrav does not show strong evidence for "red" spin noise but we conservatively include dashed lines for GW amplitudes assuming a red spin-noise RMS of 10 ns over 5 years. The different scaling between the upper-limit and detection amplitude limits arises because the upper limits assume that no GWs are present in the data (i.e., the spectrum is largely white).

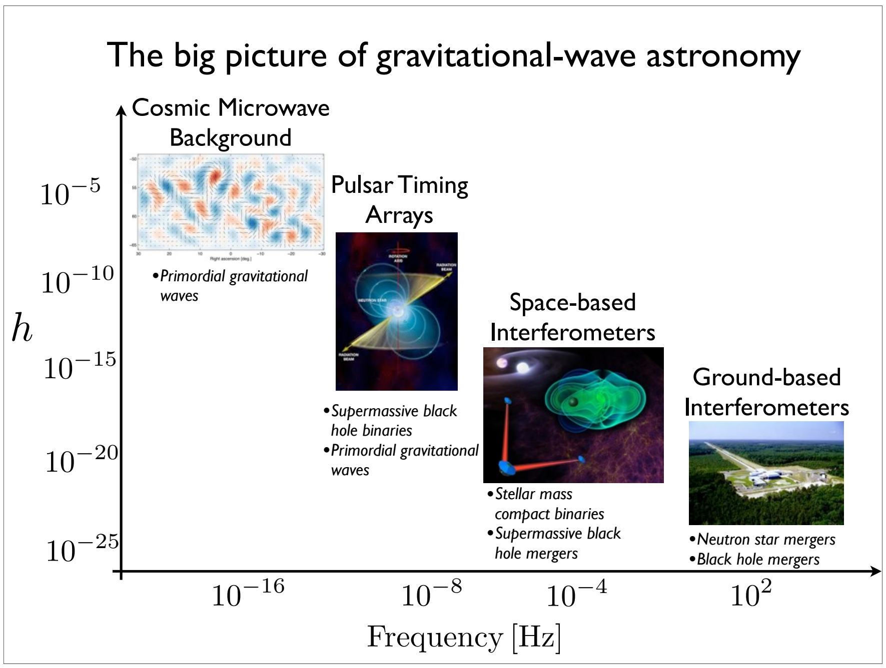


Figure 3: The range of amplitudes, measured by the gravitational-wave strain h, and frequencies to which the four essential detection techniques are sensitive, along with the expected kinds of sources that would produce gravitational waves at these amplitudes and frequencies are shown. Cosmic microwave background polarization experiments aim to confirm the recent B-mode polarization detection. At higher GW frequencies, experiments are targeting astrophysical sources. Pulsar timing efforts include NANOGrav, the European Pulsar Timing Array (EPTA), and the Australia Parkes Pulsar Timing Array (PPTA). These three collaborations together form the International Pulsar Timing Array. A space-based interferometer called eLISA (Evolved Laser Interferometer Space Antenna) is currently in the development phase, with a planned European Space Agency launch date of 2032. Ground-based GW interferometers include LIGO, which consists of two detectors (one in Louisiana and one in Washington) and is currently undergoing a sensitivity upgrade to become Advanced LIGO.

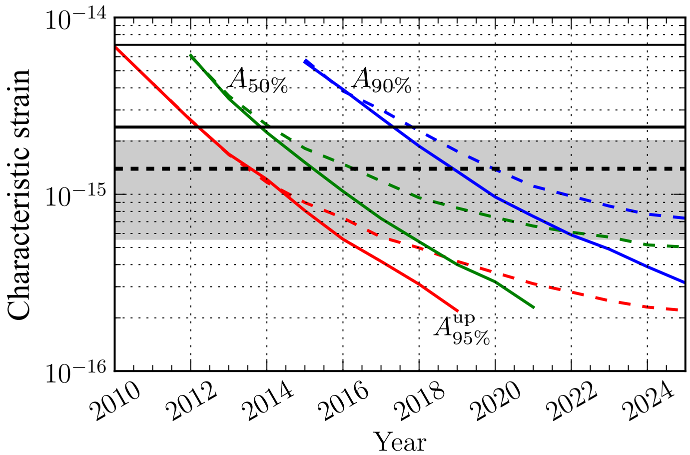


Figure 4: Sensitivity and detection projections for NANOGrav. The red curve corresponds to the 2σ upper limit we would set in the absence of a signal and the green and blue curves to the background amplitudes we will detect with 3σ significance with 50% and 90% probability, respectively. The dashed lines show the predictions if we include red spin-noise with an RMS of 10 ns at 5 years. The shaded region corresponds to the 1σ range of recent stochastic background estimates [4]. The top horizontal black line shows NANOGrav's upper limit based on 2005–2010 data [7] and the middle horizontal line shows the most recent PTA upper limit [8]. The dashed horizontal line is the preliminary upper limit from NANOGrav's upcoming 9-yr data release (in agreement with our projections based on simulated data), already ruling out viable regions of parameter space. All strains are scaled to a frequency of $1\,\mathrm{yr}^{-1}$.

The shaded region in Fig. 4 corresponds to the 1σ predicted range for the stochastic background due to SMBBHs from a recent model using a range of galaxy merger rates and empirical black hole-host relations from a survey of the literature [4]. This is a *conservative* model that provides a limit *lower* than those assuming either merger-driven or accretion-driven evolution of the galaxy mass function [5, 6]. The top horizontal line shows the upper limit from the 2005–2010 data release [7] and the dashed horizontal line is a preliminary upper limit from NANOGrav's upcoming 9-yr data release, which is very close to the projections based on simulated data. *This plot shows that a discovery is possible well before 2020 and very likely within a decade.*

Unique probes of fundamental physics: NANOGrav's pulsar timing program delivers significant ancillary science, in addition to the direct benefit of GW detection. Some of the other outcomes of our sustained pulsar timing program include:

– *Systemic motion of the pulsar (proper motion and parallax).* In some cases these are known from very long baseline interferometry (VLBI) [9], but often they must be derived from the timing data, leading to *improved understanding of neutron star kinematics and supernova dynamics* [10, 11].

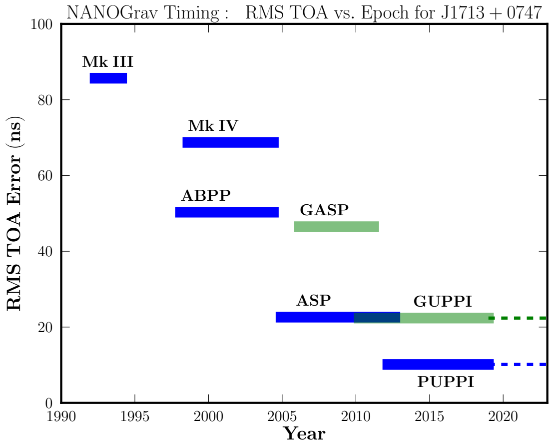
– *Motion of the Earth in the Solar System.* This is modeled using ephemerides of planetary motion that are generated independently from pulsar timing, such as the JPL DE421 ephemeris [12], but the process can be reversed and pulsar timing can be used to *refine the masses and ephemerides of solar system bodies* [13].

– *Orbital motion of the pulsar.* Many MSPs are in binary systems, usually with low-mass white dwarf companions, and show measurable relativistic phenomena. These present unique opportunities for *tests of relativistic gravity* in strong-field regimes not accessible to Solar System-based tests [14–16]. Measurement of relativistic parameters also provides *direct measurements of neutron star masses*, which provide unique constraints on the equation of state and behavior of matter at supra-nuclear densities [16–18].

– *Changes in dispersive and scattering delays.* These must be determined using multi-frequency timing data [7, 19] and provide *unique constraints on the small-scale structure of the ionized interstellar medium* [20, 21].

As we increase both the number of observed pulsars and the time span of the data sets, we will refine measurements in each of the above areas. Moreover, NANOGrav makes TOAs available to astronomers worldwide to ensure that they are exploited to the greatest extent possible for both GW and non-GW science.

The importance of Arecibo for NANOGrav: For the duration of the NANOGrav project, both Arecibo and the GBT have been operated as National Facilities, with access awarded solely on the basis of scientific merit. As a result of open access to these unique pulsar timing instruments, NANOGrav has been able to



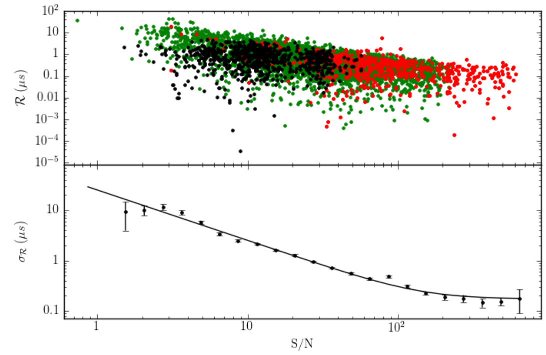


Figure 5: *Left:* RMS TOA error vs. time for different telescope backend combinations, for 120-s averages of PSR J1713+0747, NANOGrav's highest timing-precision pulsar. The PUPPI backend provides factors of two to three increased timing precision over previous generation instruments and a factor of two over its Green Bank clone GUPPI. *Right:* (Top) Residuals for PSR J1713+0747 vs. signal-to-noise for 120-s averages with Arecibo (red), the GBT (green), and all other telescopes (black). Arecibo has the lowest residuals and highest signal-to-noise of any telescope. (Bottom) The root-mean-square of residuals vs residual signal-to-noise, with a fitted line showing that the rms (σ) decreases linearly with signal-to-noise and then begins to flatter due to pulse-to-pulse jitter. Only with Arecibo do we reach this fundamental limit of timing precision.

generate the most sensitive pulsar timing data in the world. Our program would suffer dramatically if we lost access to either of these telescopes. In particular, Arecibo is the largest, and hence most sensitive, radio telescope in the world and therefore provides, of the two telescopes used by NANOGrav, the more precise TOAs. While all pulsars timed at Arecibo can be timed using the GBT, the precision is significantly reduced (see Fig. 5). Without access to Arecibo we would have to reduce the cadence of pulsars timed at GBT by a factor of at least two to accommodate Arecibo pulsars, given a fixed telescope time budget. This, and the reduced precision, would result in a significance 30–50% lower than with both telescopes combined, and a time-to-detection several (i.e. from one to five in best and worst case scenarios) years longer. The loss of Arecibo would more dramatically hinder our sensitivity to CWs and bursts, for which TOA RMS noise is critical, resulting in factors of two to three reduced significance for typical sources.

Broader Impacts: Our pulsar timing program is leading to strong links with communities that observe and study the electromagnetic counterparts of our potential GW source classes. Building on our three highly successful outreach programs for high-school and undergraduate students—based on experiential learning activities—we introduce students across the U.S. and Puerto Rico to astrophysics and technology. NANOGrav also trains a diverse group of participants at the graduate and postdoctoral levels not only in astrophysics and cosmology, but also in instrumentation, cyber-infrastructure, and the management of large datasets and scientific and technical campaigns, while providing them with substantive international experiences through our membership in the International Pulsar Timing Array. We hope to expand these efforts to include increasing numbers of Puerto Rican students. All of these efforts are supported by our website (http://nanograv.org), which hosts informational materials for scientists, students, and the general public and broadly highlights the importance of Arecibo.

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