North American Nanohertz Observatory for Gravitational Waves

15-year effort yields evidence for universal background of gravitational waves

In a series of papers published on June 28th in The Astrophysical Journal Letters, NANOGrav reported an analysis pointing to the existence of low-frequency gravitational waves permeating our Universe.

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The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is an international collaboration dedicated to exploring the low-frequency gravitational wave universe through radio pulsar timing.

NANOGrav was founded in October 2007 and has grown to more than 190 members at more than 70 institutions. In 2015 it was designated a National Science Foundation Physics Frontiers Center.

The materials in this kit address a series of five scientific articles published in The Astrophysical Journal Letters.
These papers were released at 8:00 pm Eastern Time on June 28, 2023.

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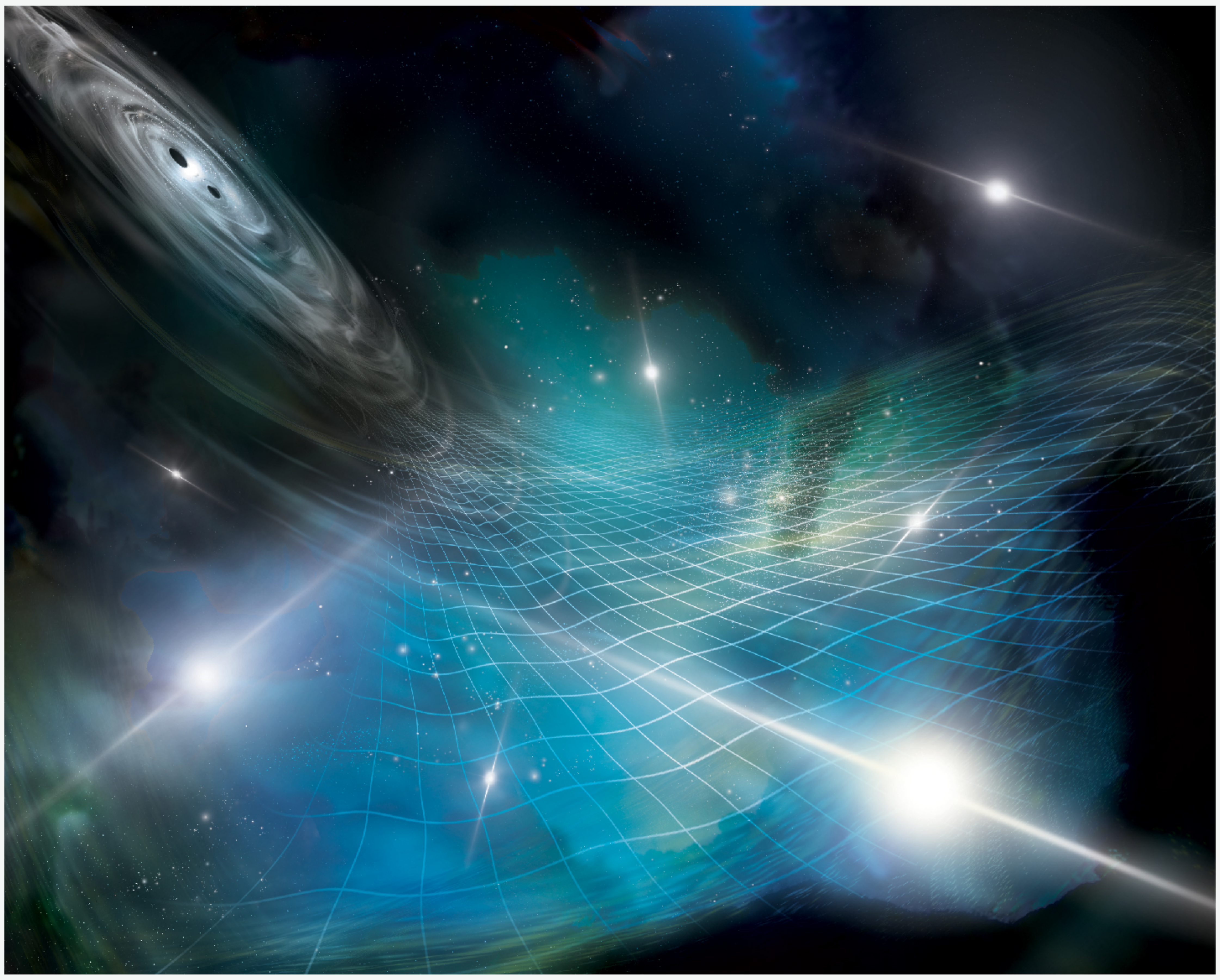
The NANOGrav 15-year Results: Press Release Summary

The NANOGrav Collaboration has found the first evidence for low-frequency gravitational waves permeating the cosmos. This finding was made possible with 15 years of pulsar observations that turn the Milky Way into a galaxy-sized gravitational-wave detector.



Credit: NANOGrav/Sonoma State University/Aurore Simonnet

Scientists use Exotic Stars to Tune into Hum from Cosmic Symphony

For the last 15 years, the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Physics Frontiers Center has been using radio telescopes supported by the National Science Foundation to turn a suite of millisecond pulsars into a galaxy-scale gravitational-wave detector. Millisecond pulsars are remnants of extinguished massive stars; as they spin hundreds of times each second, their “lighthouse-like" radio beams are seen as highly regular pulses. Gravitational waves stretch and squeeze space and time in a characteristic pattern, causing changes in the intervals between these pulses that are correlated across all the pulsars being observed. These correlated changes are the specific signal that NANOGrav has been working to detect.

NANOGrav’s most recent dataset offers compelling evidence for gravitational waves with oscillations of years to decades. These waves are thought to arise from orbiting pairs of the most massive black holes throughout the Universe: billions of times more massive than the Sun, with sizes larger than the distance between the Earth and the Sun. Future studies of this signal will enable us to view the gravitational-wave universe through a new window, providing insight into titanic black holes merging in the hearts of distant galaxies and potentially other exotic sources of low-frequency gravitational waves.

The NANOGrav 15-year Results: Short Press Release for Institutional Partners

This short version of the press release is intended for our institutional partners and includes direction for where in the text institution-specific details should be included.

Scientists use Exotic Stars to Tune into Hum from Cosmic Symphony

Astrophysicists using large radio telescopes to observe a collection of cosmic clocks in our Galaxy have found evidence for gravitational waves that oscillate with periods of years to decades, according to a set of papers published today in The Astrophysical Journal Letters. The gravitational-wave signal was observed in 15 years of data acquired by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Physics Frontiers Center (PFC), a collaboration of more than 190 scientists from the US and Canada who use pulsars to search for gravitational waves. International collaborations using telescopes in Europe, India, Australia and China have independently reported similar results.

While earlier results from NANOGrav uncovered an enigmatic timing signal common to all the pulsars they observed, it was too faint to reveal its origin. The 15-year data release demonstrates that the signal is consistent with slowly undulating gravitational waves passing through our Galaxy.

“This is key evidence for gravitational waves at very low frequencies,” says Vanderbilt University’s Dr. Stephen Taylor, who co-led the search and is the current Chair of the collaboration. “After years of work, NANOGrav is opening an entirely new window on the gravitational-wave universe."

Unlike the fleeting high-frequency gravitational waves seen by ground-based instruments like LIGO (the Laser Interferometer Gravitational-wave Observatory), this continuous low-frequency signal could be perceived only with a detector much larger than the Earth. To meet this need, astronomers turned our sector of the Milky Way Galaxy into a huge gravitational-wave antenna by making use of exotic stars called pulsars. NANOGrav’s 15-year effort collected data from 68 pulsars to form a type of detector called a pulsar timing array.

A pulsar is the ultra-dense remnant of a massive star's core following its demise in a supernova explosion. Pulsars spin rapidly, sweeping beams of radio waves through space so that they appear to “pulse” when seen from the Earth. The fastest of these objects, called millisecond pulsars, spin hundreds of times each second. Their pulses are very stable, making them useful as precise cosmic timepieces.

Over 15 years of observations with the Arecibo Observatory in Puerto Rico, the Green Bank Telescope in West Virginia, and the Very Large Array in New Mexico, NANOGrav has gradually expanded the number of pulsars they observe. “Pulsars are actually very faint radio sources, so we require thousands of hours a year on the world’s largest telescopes to carry out this experiment,” Dr. Maura McLaughlin of West Virginia University and co-Director of the NANOGrav PFC explains. “These results are made possible through the National Science Foundation’s (NSF’s) continued commitment to these exceptionally sensitive radio observatories.”

Einstein’s theory of general relativity predicts precisely how gravitational waves should affect pulsar signals. By stretching and squeezing the fabric of space, gravitational waves affect the timing of each pulse in a small but predictable way, delaying some while advancing others. These shifts are correlated for all pairs of pulsars in a way that depends on how far apart the two stars appear in the sky.

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The NANOGrav 15-year Results: Short Press Release for Institutional Partners

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“The large number of pulsars used in the NANOGrav analysis has enabled us to see what we think are the first signs of the correlation pattern predicted by general relativity,” says Oregon State University’s Dr. Xavier Siemens, co-Director of the NANOGrav PFC.

NANOGrav’s most recent dataset shows growing evidence for gravitational waves with periods of years to decades. These waves could arise from orbiting pairs of the most massive black holes in the entire Universe: billions of times more massive than the Sun, with sizes larger than the distance between the Earth and the Sun. Future studies of this signal will open a new window on the gravitational-wave universe, providing insight into titanic black holes merging in the hearts of distant galaxies, among other exotic sources.

Add Institution-specific Contributions Here

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Support from the National Science Foundation (NSF) has been critical to NANOGrav’s success by providing support for scientific work through the Physics Frontiers Center program and through access to multiple world-class radio telescopes. Future NANOGrav results will incorporate data from Canada’s CHIME telescope, added to the project in 2019.

"The NSF NANOGrav team created, in essence, a galaxy-wide detector revealing the gravitational waves that permeate our universe," says NSF Director Sethuraman Panchanathan. "The collaboration involving research institutions across the U.S. shows that world-class scientific innovation can, should and does reach every part of our nation.”

Astrophysicists around the globe have been busy chasing this gravitational-wave signal. Several papers released today by the Parkes Pulsar Timing Array in Australia, the Chinese Pulsar Timing Array, and the European Pulsar Timing Array/Indian Pulsar Timing Array report hints of the same signal in their data. Through the International Pulsar Timing Array consortium, regional collaborations are working together to combine their data in order to better characterize the signal and search for new types of sources. “Our combined data will be much more powerful,” says Taylor. “We’re excited to discover what secrets they will reveal about our Universe.”

The NANOGrav collaboration receives support from National Science Foundation Physics Frontiers Center award numbers 1430284 and 2020265, the Gordon and Betty Moore Foundation, NSF AccelNet award number 2114721, a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant, and the Canadian Institute for Advanced Research (CIFAR). The Arecibo Observatory is a facility of the National Science Foundation operated under cooperative agreement (#AST-1744119) by the University of Central Florida (UCF) in alliance with Universidad Ana G. Méndez (UAGM) and Yang Enterprises (YEI), Inc. The Green Bank Observatory and The National Radio Astronomy Observatory are facilities of the National Science Foundation operated under cooperative agreements by Associated Universities, Inc.

>>> End Short Version of Press Release <<<

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The NANOGrav 15-year Results: Press Release Full Text

This is the full text of the press release describing the analysis and interpretation of NANOGrav's 15-year data set.

Scientists use Exotic Stars to Tune into Hum from Cosmic Symphony

Astrophysicists using large radio telescopes to observe a collection of cosmic clocks in our Galaxy have found evidence for gravitational waves that oscillate with periods of years to decades, according to a set of papers published today in The Astrophysical Journal Letters. The gravitational-wave signal was observed in 15 years of data acquired by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Physics Frontiers Center (PFC), a collaboration of more than 190 scientists from the US and Canada who use pulsars to search for gravitational waves. International collaborations using telescopes in Europe, India, Australia and China have independently reported similar results.

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Observing so many pulsars requires a huge investment in people, infrastructure, and time. In 2004, a small group of astronomers carried out the first set of pulsar observations that would form the foundation for this work. For nearly two decades, the group has been growing in the number of people and diversity of expertise needed to perform this complex gravitational-wave search. Along the way, the NANOGrav collaboration took form, using the members' combined knowledge and skills to expand the data collection and improve the analysis.

Initially, pulsar instrumentation was not precise enough to achieve the sensitivity needed for this experiment. The team worked to develop next-generation instrumentation for both the Arecibo and Green Bank telescopes. They scoured known pulsars to find those precise enough to enable the search for low-frequency gravitational waves and added them to the pulsar timing array. In parallel, there were advances in theory and breakthroughs in data-analysis techniques that are tuned and optimized for modern computing architectures.

Along the way, NANOGrav found many uses for their rich pulsar timing data, addressing a wide range of intriguing astrophysical puzzles. The data and NANOGrav's methodologies are described in companion papers. “This marks the first time we’ve released the software used to produce our data set alongside the data products themselves,” Dr. Joseph Swiggum of Lafayette College, who led the pulsar timing paper explains. “All the tools necessary to reproduce our results are now public, making it easier for other scientists to get involved. This will foster improvements to the code, grow our interactions with the community, and provide educational opportunities for students.”

In 2020, with just over twelve years of data, NANOGrav scientists began to see hints of a signal, an extra “hum” that was common to the timing behavior of all pulsars in the array, and that careful consideration of possible alternative explanations could not eliminate. The collaboration felt confident that this signal was real, and becoming easier to detect as more observations were included. But it was still too faint to show the gravitational-wave signature predicted by general relativity. Now, their 15 years of pulsar observations are showing the first evidence for the presence of gravitational waves, with periods of years to decades.

University of Wisconsin-Milwaukee’s Dr. Sarah Vigeland who, with Taylor, is spearheading NANOGrav’s effort to determine the source of the signal, says, “Now that we have evidence for gravitational waves, the next step is to use our observations to study the sources producing this hum. One possibility is that the signal is coming from pairs of supermassive black holes, with masses millions or billions of times the mass of our Sun. As these gigantic black holes orbit each other, they produce low-frequency gravitational waves.”

Supermassive black holes are believed to reside at the centers of the largest galaxies in the Universe. When two galaxies merge, the black holes from each wind up sinking to the center of the newly-combined galaxy, orbiting each other as a binary system long after the initial galaxy merger. Eventually, the two black holes will coalesce. In the meantime, their slow inspiral stretches and squeezes the fabric of space-time, generating gravitational waves that propagate away from their origin galaxy like ripples in a pond, eventually reaching our own.

Gravitational-wave signals from these gigantic binaries are expected to overlap, like voices in a crowd or instruments in an orchestra, producing an overall background “hum” that imprints a unique pattern in pulsar timing data. This pattern is what NANOGrav scientists have been seeking for almost 20 years. In its suite of newly published papers, NANOGrav demonstrates evidence for this gravitational-wave background.

Detailed analysis of the background hum is already providing insights into how supermassive black holes grow and merge. Given the strength of the signal NANOGrav sees, the population of extremely massive black hole binaries in the Universe must number in the hundreds of thousands, perhaps even millions.

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“At one point, scientists were concerned that supermassive black holes in binaries would orbit each other forever, never coming close enough together to generate a signal like this,” says Dr. Luke Kelley, of University of California, Berkeley, and chair of NANOGrav’s astrophysics group. “But now we finally have strong evidence that many of these extremely massive and close binaries do exist. Once the two black holes get close enough to be seen by pulsar timing arrays, nothing can stop them from merging within just a few million years.”

Future investigation of this signal will feed into scientists' understanding of how the Universe evolved on the largest scales, providing information about how often galaxies collide, and what drives black holes to merge. In addition, gravitational ripples of the Big Bang itself may make up some fraction of the signal, offering insight into how the Universe itself was formed. These results even have implications at the smallest scales, placing limits on what kind of exotic particles may exist in our Universe. "This is an important milestone in NSF's multifaceted effort to leverage gravitational wave signals to gain a clearer understanding of phenomena at the astrophysical frontier," says NSF's Physics Frontiers Centers Program Director Michael Cavagnero.

Over time, NANOGrav expects to be able to pick out the contributions of relatively nearby, individual supermassive black hole binaries. "We’re using a gravitational-wave detector the size of the galaxy that’s made out of exotic stars, which just blows my mind,” exclaims National Radio Astronomy Observatory’s Dr. Scott Ransom. “Our earlier data told us that we were hearing something, but we didn't know what. Now we know that it’s music coming from the gravitational universe. As we keep listening, we'll likely be able to pick out notes from the instruments playing in this cosmic orchestra. Combining these gravitational-wave results with studies of galaxy structure and evolution will revolutionize our understanding of the history of our Universe.”

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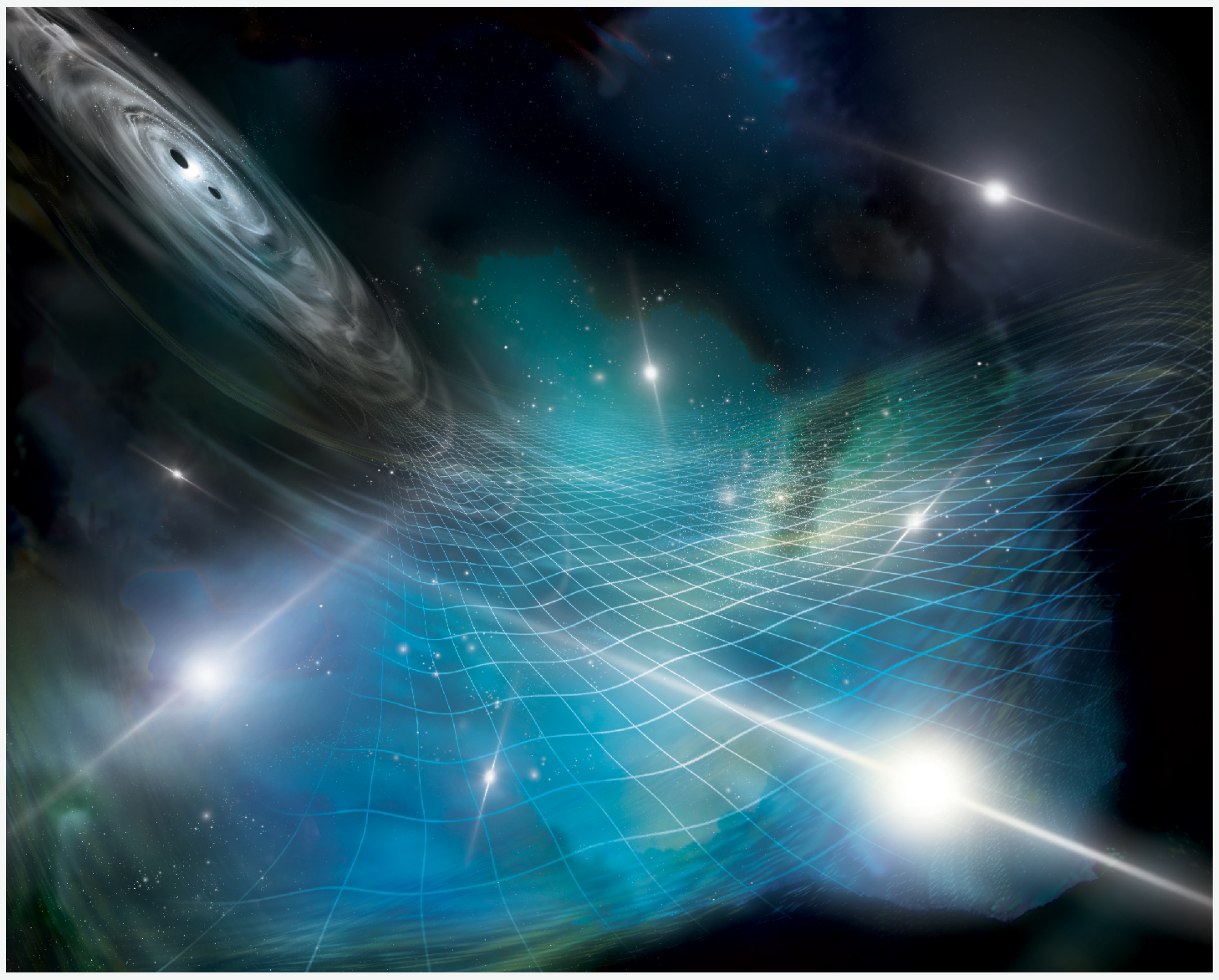
The NANOGrav 15-year Results:
Accompanying Files, Images, Graphics, and Attributions

Cover Image:



Caption: Artist's interpretation of an array of pulsars being affected by gravitational ripples produced by a supermassive black hole binary in a distant galaxy.

Filename: NANOGrav_PTA_GWB_15yr.jpg
NANOGrav_PTA_GWB_15yr_wide.jpg

Credit: NANOGrav/Sonoma State University/Aurore Simonnet

Press Release Text:

Summary text:
NG15-press_release_summary.txt

Short version:
NG15-press_release_short.txt

Full text:
NG15-press_release_full.txt

Publications and Preprints:

Published in ApJL Focus Issue:

Paper 1: Agazie_2023_ApJL_951_L9.pdf
DOI: 10.3847/2041-8213/acda9a

Paper 2: Agazie_2023_ApJL_951_L10.pdf
DOI: 10.3847/2041-8213/acda88

Paper 3: Agazie_2023_ApJL_951_L8.pdf
DOI: 10.3847/2041-8213/acdac6

Paper 5: Afzal_2023_ApJL_951_L11.pdf
DOI: 10.3847/2041-8213/acdc91

Paper 6: Agazie_2023_ApJL_951_L50.pdf
DOI: 10.3847/2041-8213/ace18a

Accepted for publication in ApJL:

Paper 4: NG15-Astrophysical_Interpretation.pdf

Paper 6: NG15-Search for Anisotropy in the Gravitational-Wave Background.pdf

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The NANOGrav 15-year Results: Publications

Five publications detailing the NANOGrav 15-year data set and the resulting search for gravitational waves have been submitted for publication in The Astrophysical Journal Letters.

Paper 1: Observations and Timing of 68 Millisecond Pulsars

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is a pulsar timing array experiment that monitors a growing array of millisecond pulsars (MSPs) with some of the largest radio telescopes in the world. These observations enable high-precision timing over decades-long timescales with the aim of directly detecting gravitational waves from merging supermassive black hole binary systems. This is a multifaceted project that requires expertise in many areas, each of which is covered in five companion papers detailing findings in NANOGrav's latest "15-year" data set.

In the first paper of this series, we present observations and analyses of 68 millisecond pulsars, each of which is observed roughly monthly, some for more than 15 years. We made observations using the Arecibo Observatory, in Puerto Rico, the Green Bank Telescope, in West Virginia, and the Very Large Array, in New Mexico.

This is NANOGrav's fifth public data release, containing 21 more pulsars than our previous data set – the largest expansion of our array to date. Most of these were pulsars that were newly discovered in recent sky surveys with radio and gamma-ray telescopes. Millisecond pulsars are scattered throughout the Milky Way Galaxy; those observed by NANOGrav are within a few thousand light years of Earth. They emit beams of radio waves while spinning hundreds of times per second. Like the flashes of a lighthouse beacon, the pulsar signals are a series of pulses of radio waves. These pulses act as the very precise "ticks'' of cosmic clocks. The times at which these pulses are detected by radio telescopes can be measured to within a millionth of a second.

Gravitational waves stretch and compress the space between a pulsar and the Earth ... we aim to detect this stretching and shrinking by its effect on pulse time-of-arrival measurements.

Anything that changes the distance between the pulsar and the Earth will make the pulses arrive a little earlier or a little later at a telescope. Gravitational waves stretch and compress the space between a pulsar and the Earth, and we aim to detect this stretching and shrinking by its effect on pulse time-of-arrival measurements. In order to do this, we need to model and remove from the data anything else that affects the distance between the pulsar and the Earth, such as binary motion of some pulsars, their motion through our Galaxy, and the Earth's motion as it moves through the Solar System. As a byproduct of this process, we have refined orbital models for the fifty binary pulsars in our sample, allowing us to precisely measure the masses of several pulsars.

After the data in this paper were collected, the Arecibo Observatory experienced a catastrophic cable failure, leading to its collapse in August 2020. NANOGrav is continuing its millisecond pulsar observing program using the Green Bank Telescope, the Very Large Array, and the CHIME telescope in Penticton, British Columbia, Canada.

Paper 1: Observations and Timing of 68 Millisecond Pulsars

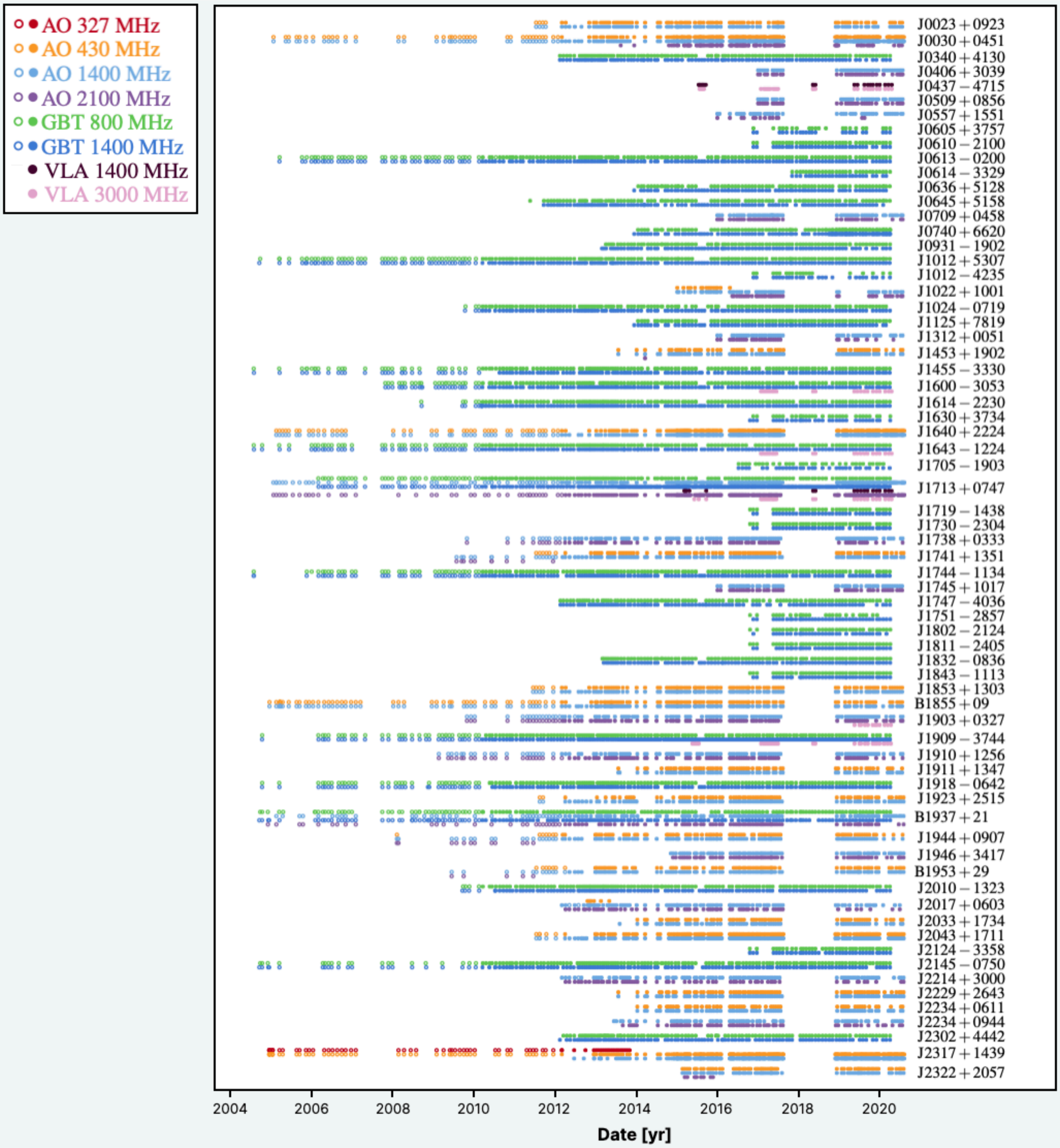


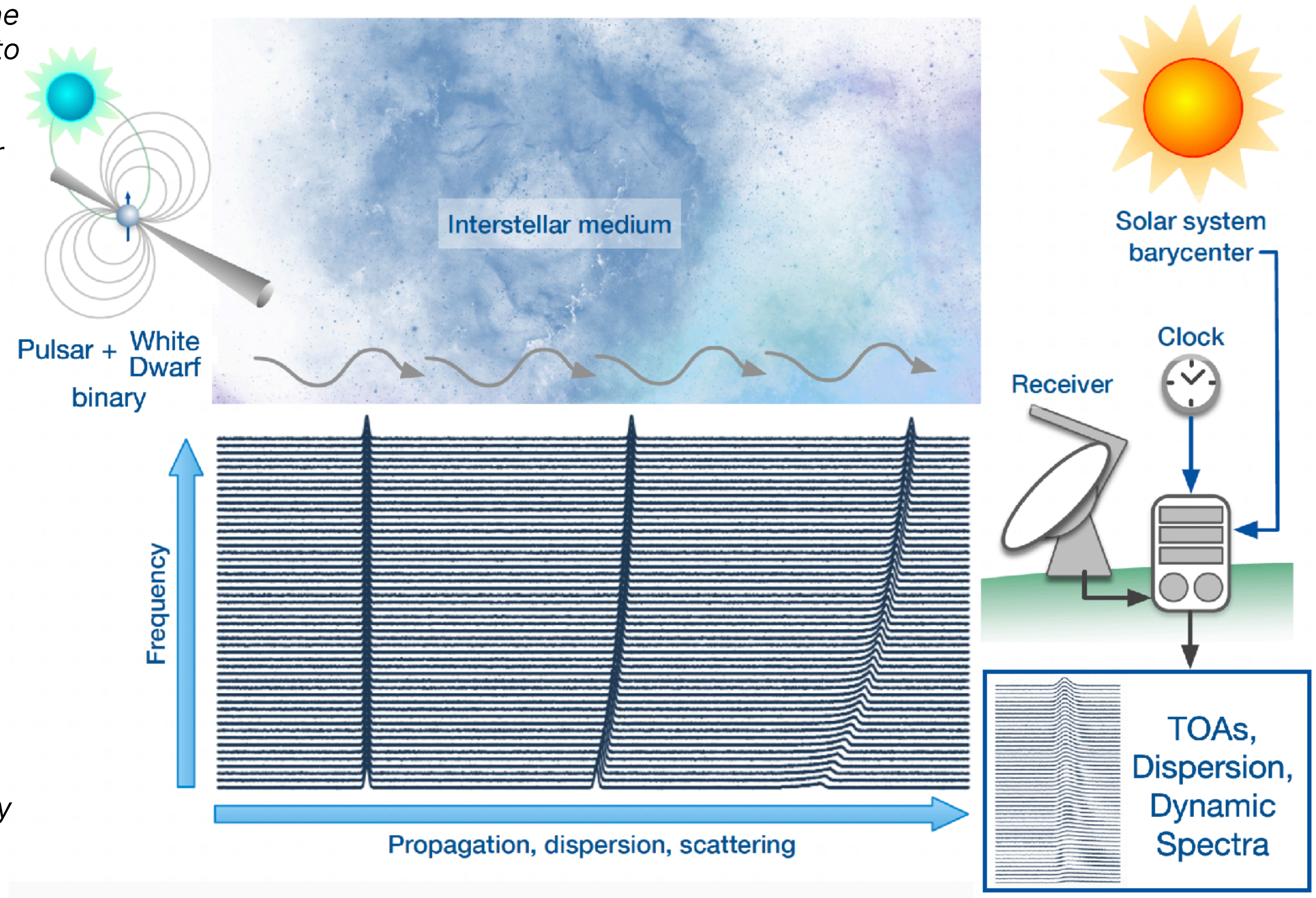
***Figure:** All timing measurements in the data set. Most pulsars are observed once per month. The observatory and radio frequency used are indicated by color (see legend). Data acquisition systems are indicated by symbols: open circles are first-generation pulsar timing instruments, while closed circles indicate that upgraded instrumentation was used for the observation. Improvements in instrumentation and a significant increase in the number of pulsars being monitored have greatly increased the sensitivity of the pulsar timing array to gravitational waves.*

Paper 2: Detector Characterization and Noise Budget

A Pulsar Timing Array (PTA), such as the one that NANOGrav has constructed, is designed to detect and study long-wavelength gravitational waves. The LIGO detector, which detected gravitational waves from merging black holes in 2015, has similarities and differences with the NANOGrav PTA. In both experiments, however, it is vital to characterize the detector noise that could give rise to a false signal. This is even more important for the NANOGrav PTA because our expected signal is similar to some features of the detector noise. In this paper, we detail how NANOGrav characterizes the detector noise – both its likely causes and its properties – and spell out how we account for that in our search for a gravitational-wave signal in the data.

The NANOGrav PTA consists of 68 arms, each one of which extends from the Earth to a pulsar situated hundreds to thousands of light years distant in our Milky Way Galaxy. As sketched in Figure 1, radio waves from each of the 68 pulsars travel a distinct path through the interstellar medium (ISM). Radio waves are slowed down slightly by the ionized gas in the ISM, by an amount that depends on the radio frequency, as is shown by the increasingly delayed signal at lower radio frequencies in Figure 1. The motion of the pulsars through the ISM at hundreds of kilometers per second (and, to a lesser extent, the motion of the Earth and the ISM), causes this dispersion delay to change with time, an effect that we carefully correct for by observing each pulsar at multiple radio frequencies at each epoch. This is but one of more than a dozen such subtle effects that we need to carefully monitor and, where possible, mitigate their effect on the pulse arrival times, which are the essential measurements for our experiment. To achieve the necessary precision, we must predict the arrival of a pulse to within about 1 microsecond over a period of 15 years. This is a fractional precision of 2 parts in 10^{15}, comparable to measuring the distance to the Moon to within a thousandth of a millimeter!

__Figure 1:__ An illustration of the signal path from the pulsar to the data products, highlighting a few relevant sources of noise. The pulsar emission itself is subject to jitter (and in rare cases, glitches), and our model accounts for spin and spindown, the pulsar's sky location, and a binary orbit where needed. Propagation through the interstellar medium imposes pulse dispersion and scattering, which are both frequency- and time-dependent. At the receiver, along with thermal noise, there are effects related to clock corrections and the solar system barycenter, among others, that must be modeled to produce the most accurately measured pulse times of arrival (TOAs) possible.



Paper 3: Evidence for a Gravitational-Wave Background

Gravitational waves are a fundamental prediction of Einstein's theory of general relativity, appearing as a byproduct of the dynamic nature of space-time. From their first mention in the scientific literature in 1916, nearly a full century elapsed before humans developed the technology to measure them. When the LIGO detector did measure gravitational waves, it was from the inspiral and coalescence of two black holes, each approximately thirty times as massive as the Sun. Yet there had already been signs of gravitational waves from precision timing campaigns of the Hulse-Taylor pulsar, showing that its orbit with another star was tightening due to the emission of gravitational waves. These observations aligned beautifully with general relativity. Now NANOGrav has constructed a measuring technique that employs pulsars to find gravitational waves from all over the Universe.

> *...the spectral characteristics broadly agree with expectations for a population of inspiraling supermassive black hole binaries... in the mass range of ~100 million to ~10 billion Solar masses*

By tracking exact arrival times of radio pulses from 68 pulsars in the Milky Way over 15 years, NANOGrav has found evidence for a distinctive pattern of correlated timing deviations, agreeing with the predictions of general relativity. The source of these gravitational waves is an all-sky background, rather than just one single source. NANOGrav has found that the spectral characteristics broadly agree with expectations for a population of inspiraling (but not yet coalescing) super-massive black hole binaries. These binaries are expected to be in the mass range of approximately 100 million to 10 billion Solar masses. However, the source population is still in question, and alternative cosmological hypotheses have been explored.

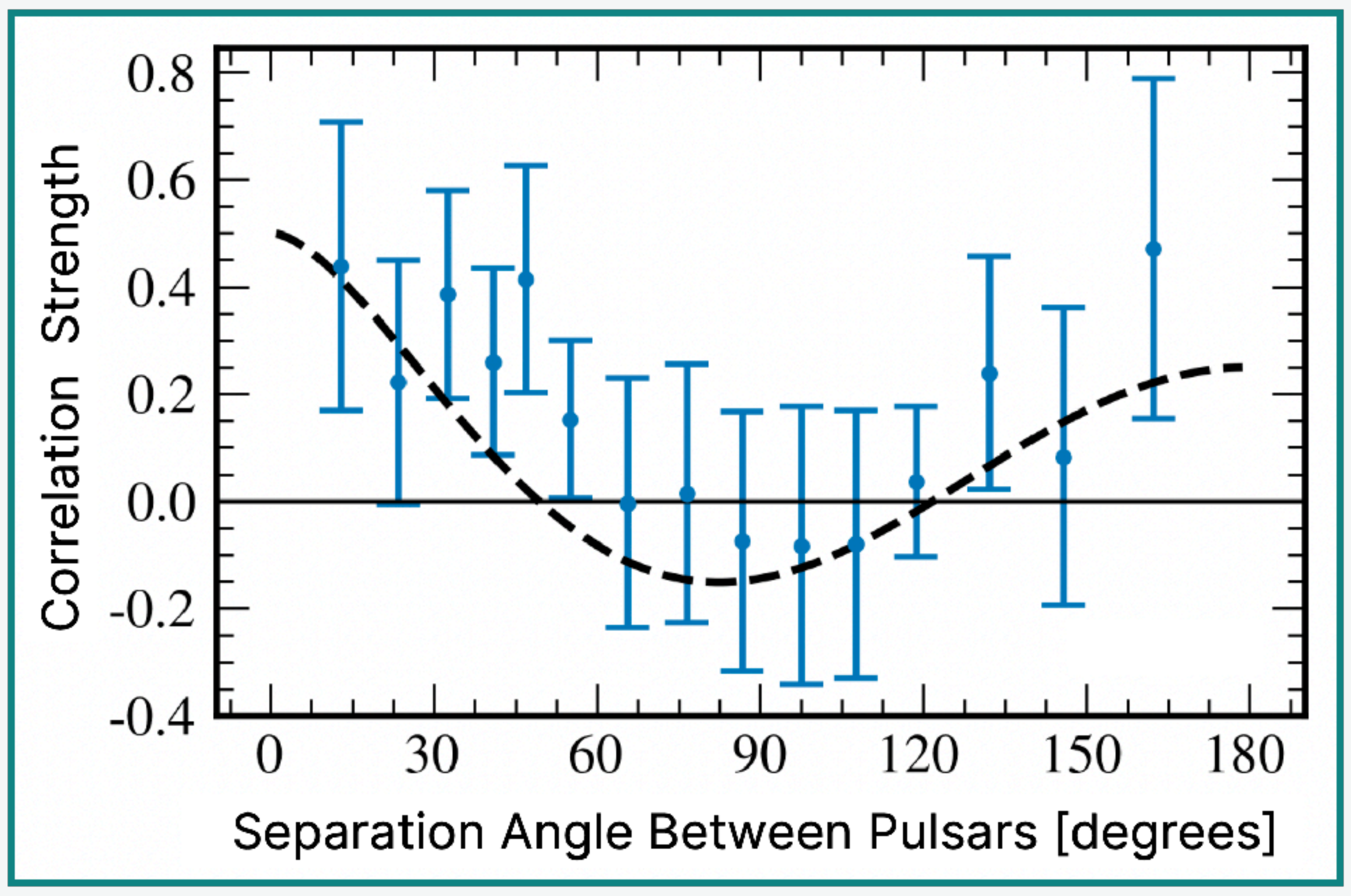


Figure: *Einstein's theory of general relativity predicts that a background of gravitational waves should imprint a distinctive pattern of correlated timing variations on pulsars, indicated by the black dashed line. By binning and averaging the correlation measurements of all our pulsar pairs, NANOGrav finds the points in blue with uncertainties shown by the error bars. We now have multiple lines of evidence for a gravitational wave background, producing a pattern of correlated timing offsets that is consistent with general relativity.*

The correlations between pulsars are key to identifying the signal as being produced by gravitational waves. Both Bayesian and frequentist analyses find that the so-called "Hellings & Downs" pattern, which is predicted for a gravitational-wave background, is preferred over other correlation patterns, which could be caused by systematic effects. We have also performed numerous consistency checks, which confirm that the signal is present in many of our pulsars, and that the signal is growing time, as we expect for a gravitational-wave background.

Analyses of future data sets, such as the upcoming IPTA data set that will combine measurements from many telescopes worldwide, will enable us to better constrain the correlation pattern and learn about the astrophysical and/or cosmological sources producing this signal.

Dedication. This paper is dedicated to the memory of Donald Backer (1943-2010): a pioneer in pulsar timing arrays, a term he coined; a discoverer of the first millisecond pulsar; a master developer of pulsar timing instrumentation; a founding member of NANOGrav; and a friend and mentor to many of us.

Paper 4: Astrophysical Interpretation of a Gravitational-Wave Background from Massive Black Hole Binaries

Supermassive black holes (SMBHs) lie at the centers of massive galaxies, with masses sometimes billions of times greater than our Sun, and as large as our own Solar System. Galaxies grow through successive mergers, providing the opportunity for two of these behemoths to find each other and form an SMBH binary. For decades, such binaries have been hypothesized to exist, but not a single example has been confirmed. For just as long, theorists have been debating whether or not such monstrous systems could actually form—can two SMBHs find each other after the violence of galaxy merger? If so, what physical mechanisms could bring them so close together that they are able to produce detectable gravitational waves (GWs)?

In this study, we produce simulations of SMBH binary populations that contain billions of sources, and compare their predicted GW signatures with NANOGrav's most recent observations. We find that a number of different models are accurately able to reproduce the observed 15yr GW spectrum (see figure). While we can't yet pin down the source of the NANOGrav signal uniquely, the measurements are consistent with expectations for SMBH binaries.

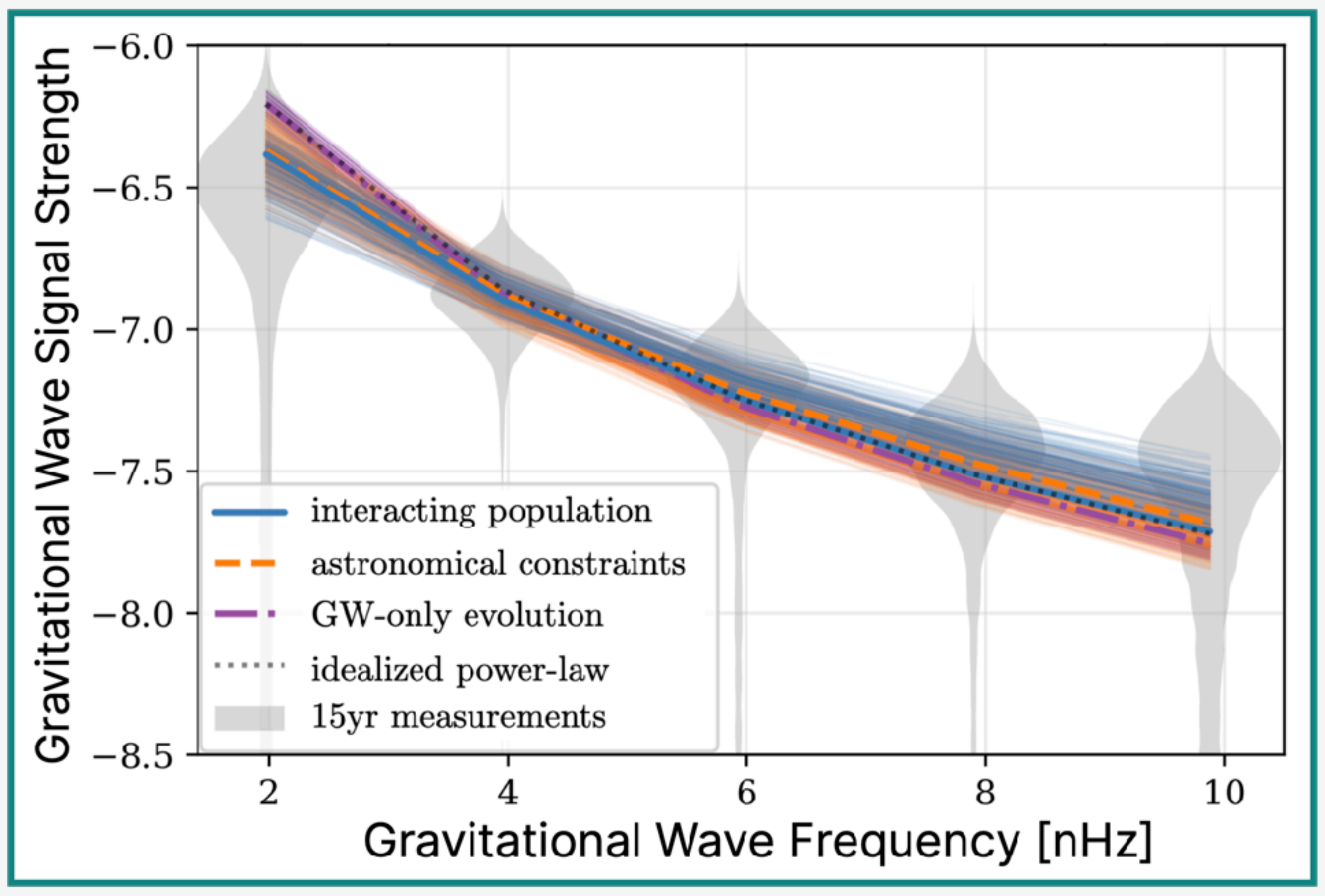


Figure: *Simulated populations of supermassive black hole binaries accurately reproduce the signal detected by NANOGrav. We compare the observed characteristics of the gravitational-wave (GW) background detected by NANOGrav, shown as grey "violins," with the best-fitting theoretical GW spectra from SMBH binary population models (colored lines). We show three different types of simulated populations, all of which are able to accurately match the data. The bestfitting populations (blue) require more than just gravitational waves: the binaries must be interacting with their host galaxies at higher frequencies than typically expected.*

> *Based on current measurements, the ... signal suggests that SMBHs may be more common or more massive than previously thought.*

In our simulations, we find that information about SMBHs is encoded in the precise shape of the GW spectrum. If the signal is produced by binaries, we are already able to place constraints on their properties, such as their typical masses and distances. Based on current measurements, the amplitude of the signal suggests that SMBHs may be more common or more massive than previously thought.

Excitingly, the amplitude of the signal in the lowest frequency bin provides a tantalizing hint that SMBH binaries may not evolve in isolation—they may require interactions with the stars and gas of their host galaxies to produce the signal that we've detected.

NANOGrav's sensitivity will continue to improve as observations continue, allowing us to improve our constraints. We will also seek out variations in the GW amplitude at different positions on the sky, which could be a hallmark of SMBH binaries as opposed to alternative sources that have been proposed. Eventually we will be sensitive enough to pick out individual binaries from the background. These sources would then represent a golden opportunity for observation with not only GWs, but also traditional electromagnetic surveys, allowing for unprecedented measurements with both light and gravity.

Paper 5: Search for Signals from New Physics

Our current understanding of the subatomic world is based on the Standard Model of particle physics, whose last missing particle, the Higgs boson, was triumphantly discovered in 2012. However, while being incredibly successful in describing all known subatomic particles, the Standard Model still fails to explain several key properties of our Universe: it cannot explain the origin of the observed asymmetry between matter and antimatter, it does not contain a good particle candidate for dark matter, and it fails to describe the properties of dark energy — three observations that point to the existence of new physics beyond the Standard Model (BSM). Therefore, after the development of the Standard Model in the 20th century, 21st-century particle physics now faces the challenge of venturing into BSM territory and identify the correct successor to the Standard Model.

Over the years, theorists have proposed countless BSM models, many of which are currently being tested in high-energy laboratories around the world, notably at particle accelerators such as CERN's Large Hadron Collider (LHC). Current efforts in particle physics focus on several frontiers that are characterized by, for instance, ever higher energies (the "energy frontier") or ever larger statistics (the "intensity frontier"). A new emerging frontier in this context is the gravitational-wave frontier, which capitalizes on the fact that many BSM models also predict the generation of gravitational waves in the early Universe. In the present paper, we open a new chapter in the exploration of this frontier and establish the search for new physics at what we call the "PTA frontier."

In our work, we consider a suite of BSM models that predict the generation of a gravitational-wave background (GWB) only fractions of a second after the Big Bang. Our goal is to assess to what degree this primordial GWB, which has propagated more

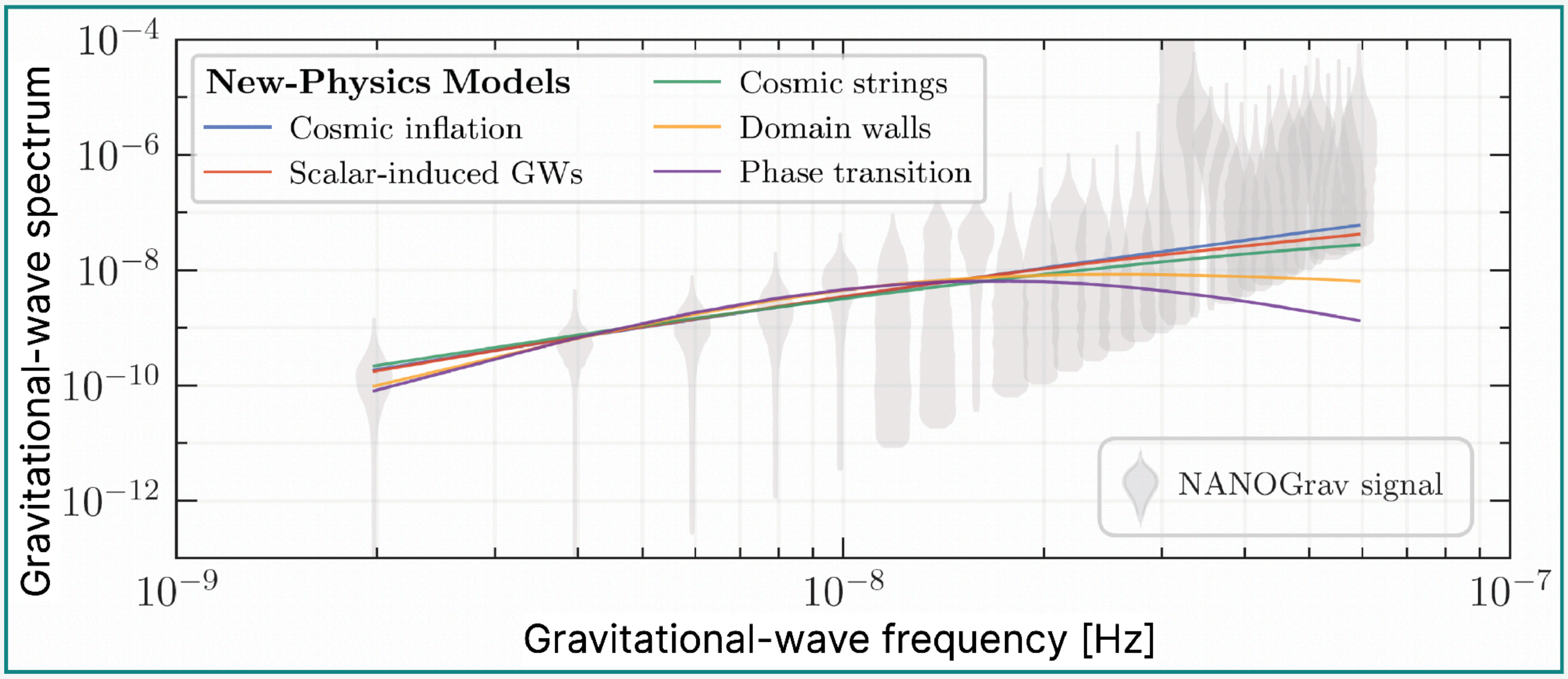


Figure: *The NANOGrav signal might also contain a contribution from gravitational waves (GWs) produced in the early Universe right after the Big Bang. Here we compare the GW spectrum of potential primordial signals with the strength of the observed signal (gray contours). Each model ties to an extension of the Standard Model of particle physics; cosmic inflation (blue - exponential expansion of the Universe), scalar-induced GWs (red - large density fluctuations in the primordial plasma), cosmological phase transitions (purple - changes in the vacuum state of the Universe, similar to the phase transition from liquid water to steam). Cosmic strings and domain walls (green and orange lines, respectively) are cosmic defects, like cracks in an ice cube that occur as water freezes.*

Paper 5: Search for Signals from New Physics

or less freely through the Universe since its production, could explain the signal observed in the NANOGrav 15-year data set. Such a GWB should be thought of as the gravitational analog of the well-known cosmic microwave background (CMB), which denotes the relic electromagnetic radiation produced when the Universe was as young as 380,000 years. A crucial difference from the CMB, however, is that a cosmological GWB is expected to be generated at even earlier times, much closer to the Big Bang. Detecting a primordial GWB would therefore provide a direct glimpse of the dynamics of the Universe at times that are not accessible by other means, and probe particle interactions at energies that cannot be attained in laboratory experiments. In this way, our search for primordial gravitational waves in the NANOGrav 15-year data allows us to test ideas such as grand unification (the unification of all subatomic forces in one common super force at extremely high energies) or even string theory, a proposal for a consistent theory of quantum gravity.

Such a GWB should be thought of as the gravitational analog of the cosmic microwave background ... generated at even earlier times, much closer to the Big Bang.

Many of the models that we consider can fit the data equally well or even better than the expected signal from supermassive black holes. However, there are still large uncertainties related to the modeling of the supermassive black holes signal, and more work is needed before we can conclusively establish whether the NANOGrav signal is of cosmological or astrophysical origin.

Paper 6: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries

The gravitational wave background signature in the NANOGrav 15-year data set raises the question of what might be producing this signal. The mostly likely source is generally thought to be a chorus of massive black hole binaries, but other more exotic possibilities include signatures from physics beyond the standard model of particle physics. One way to decide between these possibilities and provide definite evidence that the background comes from a chorus of binary black holes is to detect the signal from an individual soloist that stands out from the background.

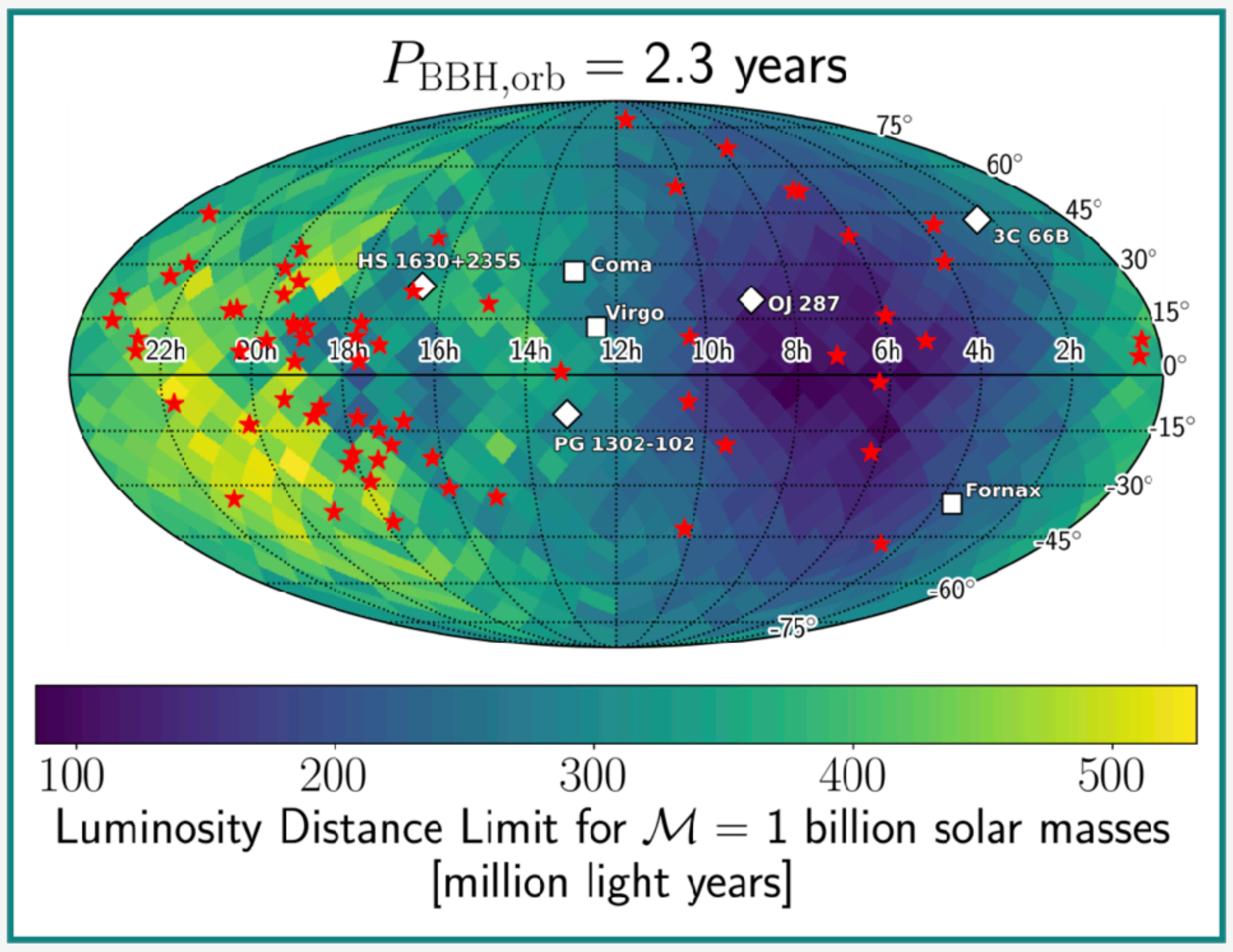


Figure: *An all-sky map showing the reach of the search for supermassive black hole binaries with orbital periods of 2.3 years, with the distance limit scaled for systems with a mass of one billion suns. The red stars indicate the sky locations of the pulsars used in the analysis. White squares show the location of nearby galaxy clusters, while the white diamonds indicate the locations of galaxies where light curve variations suggest binaries might be found. The search is most sensitive in the region of the sky with the most pulsars.*

The super massive black hole binaries that NANOGrav is searching for will be sedately orbiting one another, with orbital periods similar to those of planets in our solar system. Unlike the frenzied mergers of stellar remnants detected by the ground based interferometers such as LIGO and Virgo, the NANOGrav black holes evolve very slowly over hundreds of thousands of years. The black hole binaries detected by LIGO emit "chirps" - signals with rapidly changing pitch and volume, while the supermassive black hole binaries targeted by NANOGrav produce almost perfect sine waves. Using a new rapid analysis technique, a Bayesian search for individual black hole binaries was performed using the 15-year NANOGrav data set. The search did not find any strong candidate signals, though there was an intriguing hint of a signal corresponding to a binary period of around 16 years.

Absent a clear detection, upper limits on the amplitude of individual binary black hole systems were placed as a function of orbital period and sky location. The analysis has its greatest reach for systems with orbital periods of 2.3 years, and at the most sensitive sky location it was possible to rule out the presence of a billion solar mass binary out to a distance of 500 million light years. Looking towards the future, if the background signal is from a chorus of black holes we will eventually be able to locate the loudest sources, which might also be picked up in the time varying brightness from the gas swirling around these systems. With luck, the first soloists might be found in the next NANOGrav data set, or from the combined datasets from the International Pulsar Timing Array.

Paper 7: Search for Anisotropy in the Gravitational-Wave Background

The evidence for a gravitational wave background (GWB) reported in NG15gwb and other pulsar timing array (PTA) publications makes the assumption that the GWB is *isotropic*, i.e. the background looks the same in all directions on the sky.

This is a robust assumption when our main goal is to make the first detection of the GWB. However, if the GWB is produced by a population of inspiraling supermassive black hole binary (SMBHB) systems, then the GWB will be different in different directions on the sky, depending on how these systems are distributed in the local Universe. This effect is known as *anisotropy*, and in this analysis, we search for evidence of anisotropy in the GWB reported in the NANOGrav 15 yr dataset. or less freely through the universe since its production, could explain the signal ob-served in the NANOGrav 15-year data set. Such a GWB should be thought of as the gravitational analog of the well-known cosmic microwave background (CMB), which denotes the relic electromagnetic radiation produced when the Universe was as young as 380,000 years. A crucial difference to the CMB, however, is that the GWB is expected to be generated at even earlier times, much closer to the Big Bang. This means that detecting a primordial GWB would provide a direct glimpse into the dynamics of the Universe at times that are not accessible by other means, and probe particle interactions at energies that cannot be attained in laboratory experiments. In this way, our search for primordial gravitational waves in the NANOGrav 15-year data allows us to test ideas such as grand unification (the unification of all subatomic forces in one common super force at extremely high energies) or even string theory, a proposal for a consistent theory of quantum gravity.

We search for anisotropy on both large and small angular scales. The former kind of anisotropy could be produced if there was an overdensity of SMBHB systems in one part of the sky, as might happen in large galaxy clusters like Virgo or Fornax. The latter kind of anisotropy could be produced from individual inspiraling SMBHB systems, offering us the opportunity to target these parts of the sky with our single source search pipeline, as well as electromagnetic surveys.

In the 15 yr dataset, we do not find evidence for the presence of anisotropy in the GWB, either on large or small angular scales. However, we do see some interesting features in the deviations away from isotropy, which might be the first hints of emerging anisotropy in the nanohertz GWB. We also estimate what level of anisotropy we would expect given the isotropic background that we see in the 15 yr dataset and we show that we already have sufficient sensitivity to start probing anisotropy at these levels.

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As PTA datasets grow in time and add more

Paper 7: Search for Anisotropy in the Gravitational-Wave Background

pulsars, leading to improved sensitivity to the GWB, we might expect our searches for anisotropy to follow the same path that we did for the cosmic microwave background (CMB), which is another background signal discovered in the electromagnetic spectrum at microwave frequencies by Penzias and Wilson. The first detection of the CMB was as an isotropic background, and then as we built more sensitive telescopes (COBE, WMAP, Plank), we were able to start seeing anisotropy in the CMB, which unveiled a tremendous amount of knowledge about our early universe.

With an eye towards a similar trajectory for the nanohertz GWB, we conclude our analysis by highlighting the developments that would need to be made in order to allow us to efficiently search for anisotropies, as well as highlighting the potential discoveries that stand to be made by *both* a detection and non-detection of anisotropy in the GWB.

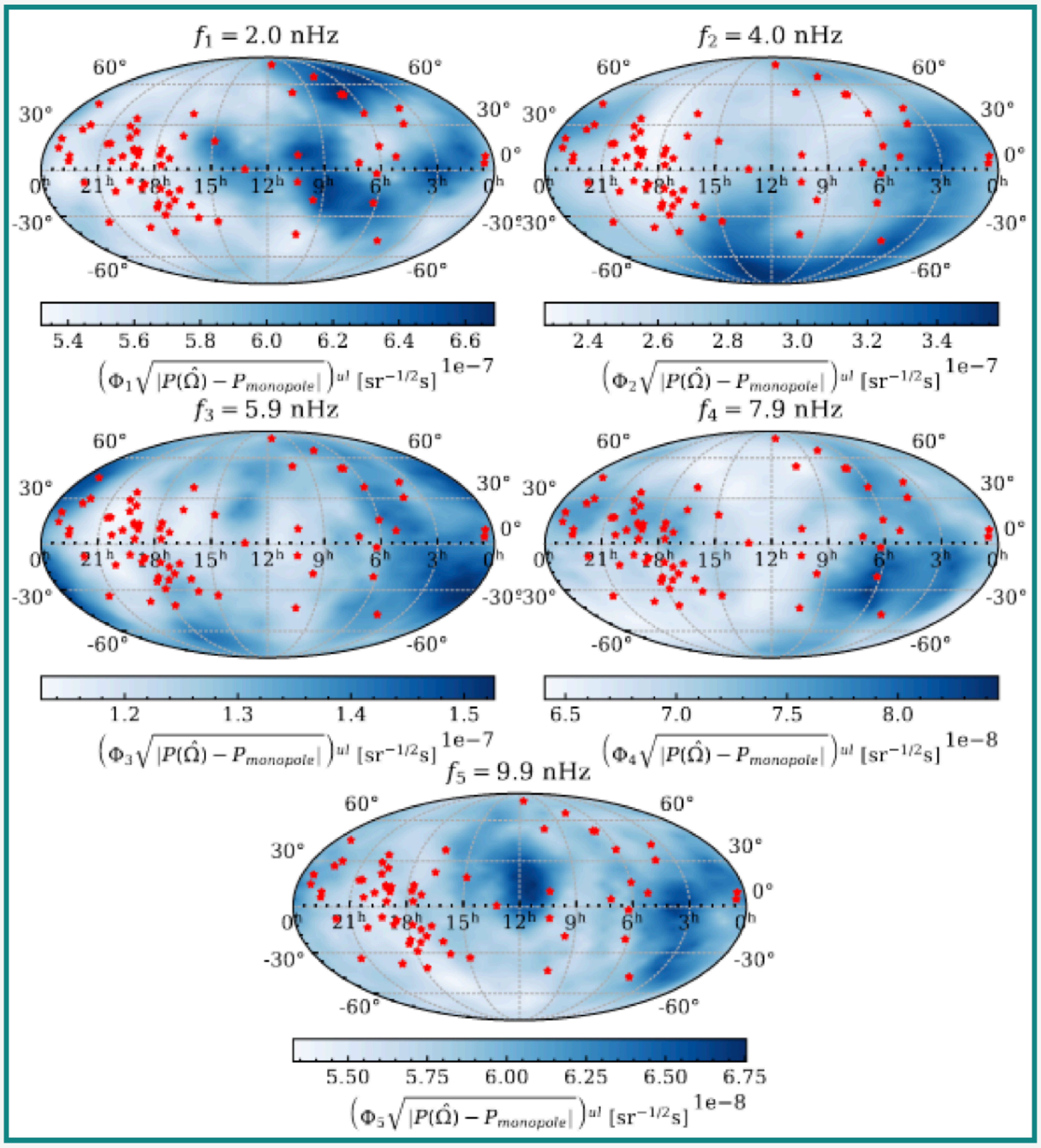

***Figure:** Reconstructed frequency-resolved sky maps showing the 95% upper limit on deviations away from isotropy in GWB power for the lowest five frequency bins from the NANOGrav 15 yr dataset. The red stars represent the positions of the pulsars in the NANOGrav 15 yr dataset. The units on the colorbar represent the timing delay (in seconds) induced by the GWB from different parts of the sky, which we can see ranges from a few hundreds of nanoseconds at 2 nHz to tens of nanoseconds at 10 nHz.*

We do not find significant evidence for the presence of anisotropy at any of these frequencies. Since different SMBHBs contribute to the GWB at different frequencies, we would expect to see unique anisotropy signatures at each of these frequencies. We do see some interesting features in these skymaps, which might be the first signs of emerging anisotropy in the GWB.

The North American Nanohertz Observatory for Gravitational Waves

Press / Media Kit

Questions and comments should be directed to:

Dr. Elizabeth Ferrara
NANOGrav Press Officer
press@nanograv.org

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Physics Frontiers Center

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NANOGrav and Pulsar Timing Array Science

What is NANOGrav?

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is an international collaboration of astronomers dedicated to exploring the low-frequency gravitational wave universe through radio pulsar timing. NANOGrav is an NSF-funded Physics Frontiers Center, with additional funding from Canada's NSERC and CIFAR, plus the Gordon and Betty Moore Foundation.

NANOGrav has more than 190 members at over 70 partner institutions including four-year colleges, research universities, national laboratories, and radio observatories throughout North America and around the globe.

NANOGrav observes an ensemble of ultra-stable millisecond pulsars known as a pulsar timing array with the world's largest telescopes, including the Green Bank Telescope, the CHIME telescope, the Very Large Array, and (formerly) the Arecibo Telescope. NANOGrav is also a member of the International Pulsar Timing Array, which also includes the Parkes Pulsar Timing Array in Australia, the European Pulsar Timing Array, and the Indian Pulsar Timing Array.

NANOGrav uses millisecond pulsars as a network of cosmic clocks to measure invisible ripples in spacetime produced by extremely massive black holes. This transformative experiment will produce unique insights into how galaxies have grown over cosmic timescales. Our pulsar timing observations also enable many additional astrophysical experiments and applications, from stellar evolution to particle physics.

The NANOGrav website offers a wealth of information about the experiment, the science, and the collaboration. To further explore the pulsar timing array and the science it enables, we recommend the following links.

NANOGrav Website

Radio Astronomy

We observe with the largest telescopes in the world in order to probe energetic processes that are invisible to optical telescopes.

Pulsars as Cosmic Clocks

Pulsars are rapidly rotating, highly magnetic neutron stars that emit beams of radio emission, like cosmic lighthouses. They are unique laboratories for a variety of fundamental physics experiments.

Multimessenger Astrophysics

We can gain unique insights about our Universe through observations with both gravitational waves and electromagnetic waves, using telescopes on Earth and in space.

Galaxies & Supermassive Black Holes

We will gain unique insights into the history of galaxy mergers and evolution by detecting the gravitational waves produced by extremely massive pairs of black holes at the cores of merged galaxies.

Low-Frequency Gravitational Waves

Gravitational waves were predicted by general relativity and are produced by accelerating masses like black holes in binaries. Our experiment is sensitive to low-frequency gravitational waves with periods of years to decades.

Data and Software (after release)

Anyone can download the data and software used for this analysis from our website.

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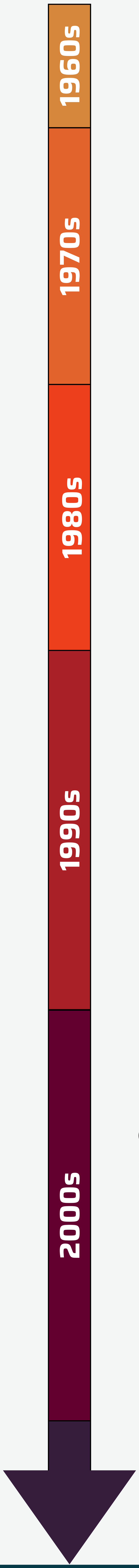
A Brief History of PTAs and NANOGrav



1967	✦ The first radio pulsar was discovered by a team led by graduate student Jocelyn Bell-Burnell.
1975	✦ Estabrook and Wahlquist had the idea of using spacecraft to detect low-frequency GWs, “Response of Doppler spacecraft tracking to gravitational radiation,” sparking a new way of searching for GWs.
	✦ Hankins and Rickett proposed “coherent dedispersion” instrumentation to make the most precise possible TOA measurements.
1978-1979	✦ Sazhin (1978) and Detweiler (1979) proposed the idea of using pulsars instead of spacecraft. Detweiler set the first upper limits on the amplitude of the gravitational-wave background (GWB).
1982	✦ Backer discovered the first millisecond pulsar, PSR B1937+21.
1983	✦ Hellings and Downs first developed the concept of a pulsar timing array (PTA) when they proposed that the cross-correlation of pulsar timing residuals could be used to search for the GWB signal. Only four pulsars were used for their first limit on the GWB.
1984	✦ The first MSP timing program was begun at Arecibo by Taylor et al.
1990	✦ Foster and Backer first coined the term “pulsar timing array (PTA)” and described the first PTA timing program using MSPs with the 140-ft telescope at Green Bank.
1990s	✦ Computing became fast enough to allow coherent dedispersion over ~10 MHz bandwidth. Early instruments were built for Arecibo by Berkeley, Caltech, and Princeton.
	✦ Multiple upper limits were set on the GWB using small numbers of MSPs — e.g., Stinebring, Ryba, and Taylor (1990) and Kaspi, Ryba, and Taylor (1994).
1997	✦ The Arecibo Gregorian dome upgrade was completed.
2000	✦ The Green Bank Telescope came online.
2003	✦ Jaffe and Backer demonstrated that detection of GWs from super-massive black hole binaries through PTAs was a worthwhile and achievable goal.
early 2000s	✦ Various groups around the world began PTA timing programs in earnest, with the Parkes PTA established in 2006, the European PTA in 2006, and NANOGrav in 2007. NANOGrav was formed at a meeting at NRAO in Charlottesville, VA, with strong encouragement from then-NRAO-director Fred Lo.
2004	✦ Berkeley, Bryn Mawr and UBC built the 100-MHz ASP and GASP coherent-dedispersion instruments for Arecibo and Green Bank, respectively, allowing high enough timing precision to enable a truly sensitive search for gravitational waves.
2008	✦ At a meeting at Arecibo, Andrea Lommen first coined the term “International Pulsar Timing Array (IPTA)”, and the IPTA collaboration was born.

A Brief History of PTAs and NANOGrav - Continued

2010s

2010 ✦ NANOGrav received its first award as a collaboration from the NSF from the PIRE (Partnerships for International Research and Education) program for $6.5M.

✦ NANOGrav began using the advanced GUPPI pulsar timing instrument at the Green Bank Telescope.

2012 ✦ NANOGrav began using the advanced PUPPI pulsar timing instrument at Arecibo.

2013 ✦ NANOGrav released its first dataset and GWB limit, based on five years of data on 17 pulsars.

2015 ✦ NANOGrav became a Physics Frontiers Center with a $17.3M award from the NSF. This award was co-funded by the PHYS and AST divisions.

2015-2016 ✦ NANOGrav released its nine-year dataset, with 37 pulsars, and the associated GWB upper limit, along with other papers.

2016 ✦ The IPTA released its first dataset, with 48 MSPs, along with the first upper limit on the GWB set using IPTA data.

2018 ✦ NANOGrav released its 11-year dataset, with 45 pulsars, and the associated upper limit on the GWB, along with other papers.

2019 ✦ The IPTA published its second data release, with 65 pulsars.

✦ CHIME began collecting data to include with NANOGrav observations.

2020s

2020 ✦ NANOGrav released its 12.5-yr dataset, with 47 pulsars, and the associated upper limit on the GWB, along with other papers. The collaboration reported the detection of a common noise process consistent with a GWB.

✦ Preliminary analysis showed the first sign of the spatial correlations expected from a GWB in NANOGrav data.

✦ The Arecibo Telescope collapsed.

2021 ✦ Both the EPTA and the PPTA reported the detection of a common process consistent with that detected by NANOGrav in their most recent datasets.

✦ NANOGrav received another $17M award from the Physics Frontiers Center program, again co-funded by the PHYS and AST divisions.

2022 ✦ The IPTA reported the detection of a similar common process as seen in the NANOGrav 12.5-yr data in combined PTA data.

2023 ✦ NANOGrav releases its 15-yr dataset, with 68 pulsars, and associated GWB and other papers. NANOGrav reports evidence for the spatial correlations that are the hallmark of an astrophysical GWB.

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About NANOGrav: The Telescopes

NANOGrav uses world-class radio telescopes to observe a suite of pulsars using precise timing. Three major observatories have provided data for NANOGrav's 15-year data set.

The Arecibo Telescope - Puerto Rico

For decades, the NSF's iconic 305-m diameter Arecibo telescope in Puerto Rico was the largest and most sensitive radio telescope in the world. That sensitivity, from 300 MHz to over 2 GHz, made it one of the very best instruments for pulsar science, as evidenced by the hundreds of pulsars discovered with Arecibo data, and the amazing scientific results, including a Nobel Prize in Physics for the discovery of binary pulsars which allowed for the study of gravitational wave emission. Nineteen of the pulsars that NANOGrav currently monitors were initially found with Arecibo. While Arecibo was limited to seeing only about 30% of the total sky, its unparalleled sensitivity meant that for those pulsars that it could see, nothing could measure them better. The Arecibo telescope collapsed on December 1, 2020. Its legacy lives on in NANOGrav's data, as approximately one half of our gravitational wave sensitivity comes from our Arecibo observations.

Credit: Arecibo Observatory, a facility of the NSF

Arecibo Observatory Website

The Green Bank Telescope (GBT) - West Virginia

The NSF's 100-m diameter GBT, in West Virginia, is the largest human-made movable object on land. And that huge size plus its steerability is why it has been so important for pulsar observations over the past two decades. Because it can see more than 80% of the total sky, the GBT provided the best data possible on dozens of millisecond pulsars that Arecibo couldn't observe. The combination of fantastic sky coverage and excellent sensitivity, enhanced by the surrounding National Radio Quiet Zone, lets the GBT contribute about half of our gravitational wave sensitivity. 16 of the pulsars that NANOGrav currently monitors were discovered there, through a series of sensitive pulsar surveys over the years.

Currently, the Gordon and Betty Moore Foundation funds most of NANOGrav's ongoing observations of 72 pulsars with the GBT.

Photo Credit: Jay Young for Green Bank Observatory

Green Bank Observatory Website

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About NANOGrav: The Telescopes

NANOGrav uses world-class radio telescopes to observe a suite of pulsars using precise timing. Three major observatories have provided data for NANOGrav's 15-year data set.

The Very Large Array (VLA) - New Mexico

The NSF also funds the iconic Y-shaped array of 27 25-meter diameter dishes in New Mexico. The VLA is usually used to make radio images via interferometry, but the combined collecting area of its dishes, its broad radio frequency coverage, and its ability to see far into the Southern sky, make it a key instrument for NANOGrav pulsar timing, as 15 pulsars need those capabilities. The 15-year data release is the first to include VLA measurements, but it will not be the last. In combination with the CHIME telescope in Canada, the VLA is helping to offset the loss of the Arecibo telescope in our regular observations.

Photo Credit: NRAO/AUI/NSF

Very Large Array Website

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) - British Columbia

CHIME, a set of 4 fixed cylindrical reflectors that operates as a transit telescope, is run by a consortium of universities led by the University of British Columbia, McGill University, and the University of Toronto. CHIME operates at low radio frequencies and was originally designed to map the distribution of Hydrogen gas in the early Universe. Software manipulation of the incoming data stream can allow the telescope to "point" anywhere within its large field of view; this feature is used to detect the still-mysterious Fast Radio Bursts and also to time up to 10 pulsars simultaneously. CHIME provides daily observations of all the Northern NANOGrav pulsars, and, along with the VLA, is helping to offset the loss of the Arecibo telescope in our regular observations. CHIME/Pulsar data will be included in future NANOGrav data releases.

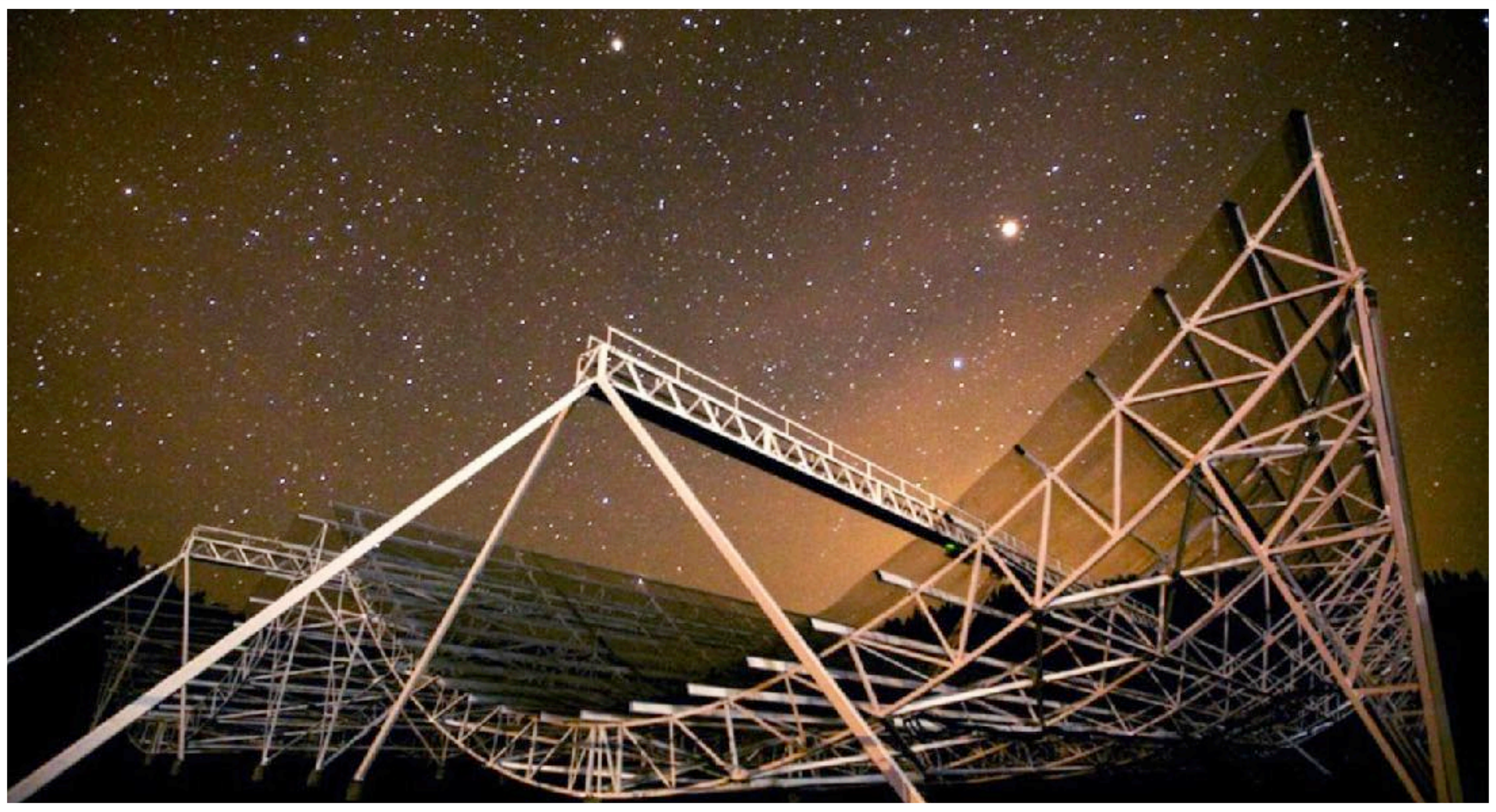

Photo: Courtesy of CHIME

CHIME Website

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About NANOGrav: The Pulsar Timing Array

Over the last two decades, NANOGrav has regularly added more pulsars to the array. We have shown that our sensitivity to gravitational waves increases as the number of pulsars grows, expanding our detector.

Pulsar Searches

Finding pulsars, like finding a needle in a haystack, requires painstaking and methodical work. Many of the pulsars that have been added to the array over the last decade were discovered through the Green Bank telescope, as well as the Pulsar Arecibo L-band Feed Array survey at Arecibo and other pulsar search programs.

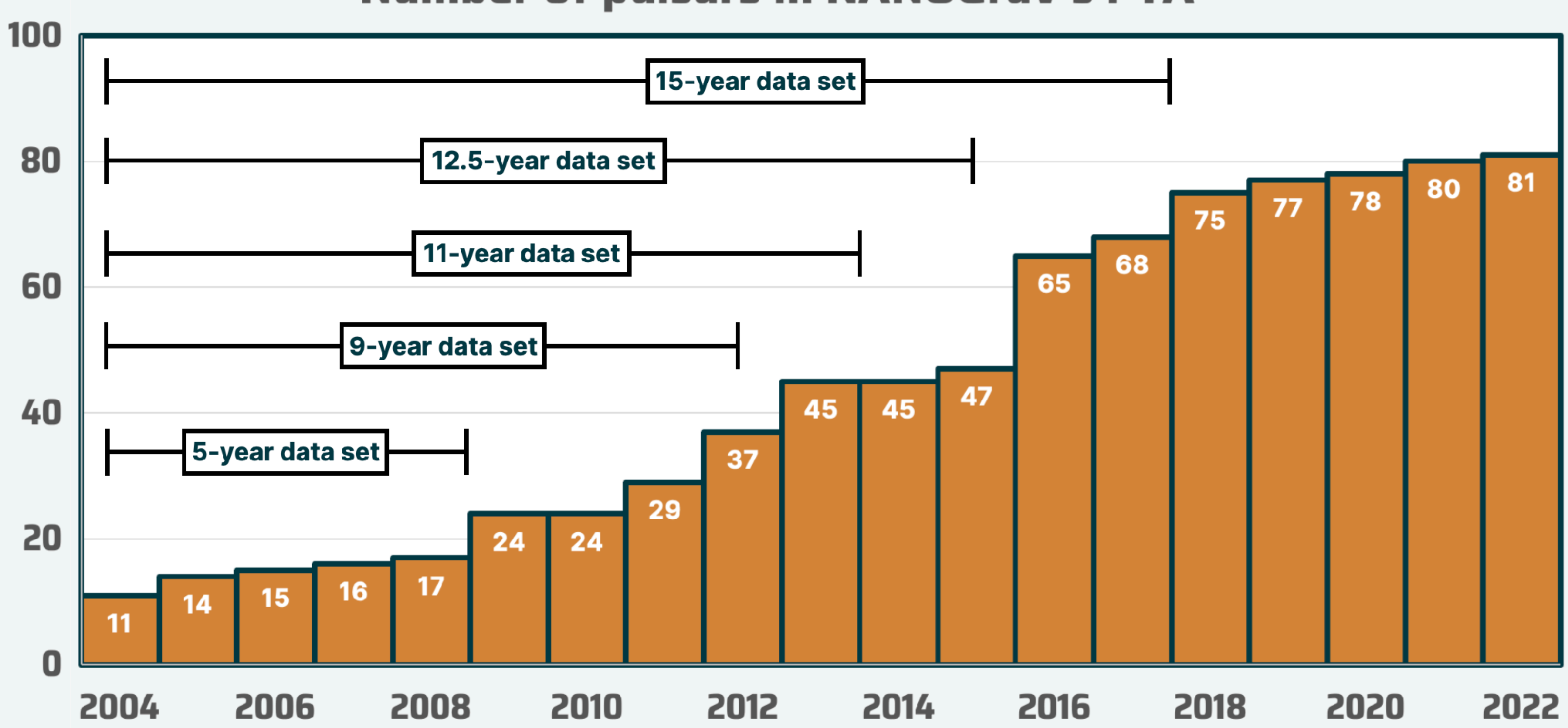
In some cases, information from other wavebands makes finding pulsars easier. Many new sources from NASA's Fermi Gamma-ray Space Telesope have been revealed to be millisecond radio pulsars. These discoveries make up more than a third of the new pulsars added to NANOGrav's pulsar timing array since 2010.

Instrument Upgrades

Improving radio instrumentation makes it possible to observe fainter pulsars with more precision. In 2010 and 2012, the instruments used to record pulsar observations were upgraded at Green Bank and Arecibo, respectively. These changes alone enabled NANOGrav to add a dozen previously-discovered pulsars to the pulsar timing array.

The new instruments also widened the range of radio frequencies that could be collected at one time. This change improved the team's ability to compensate for the effects of interstellar gas on pulse arrival times.

Number of pulsars in NANOGrav's PTA



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The NANOGrav Collaboration: Membership Information

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is a collaboration of faculty, researchers, and students from institutions around the globe.

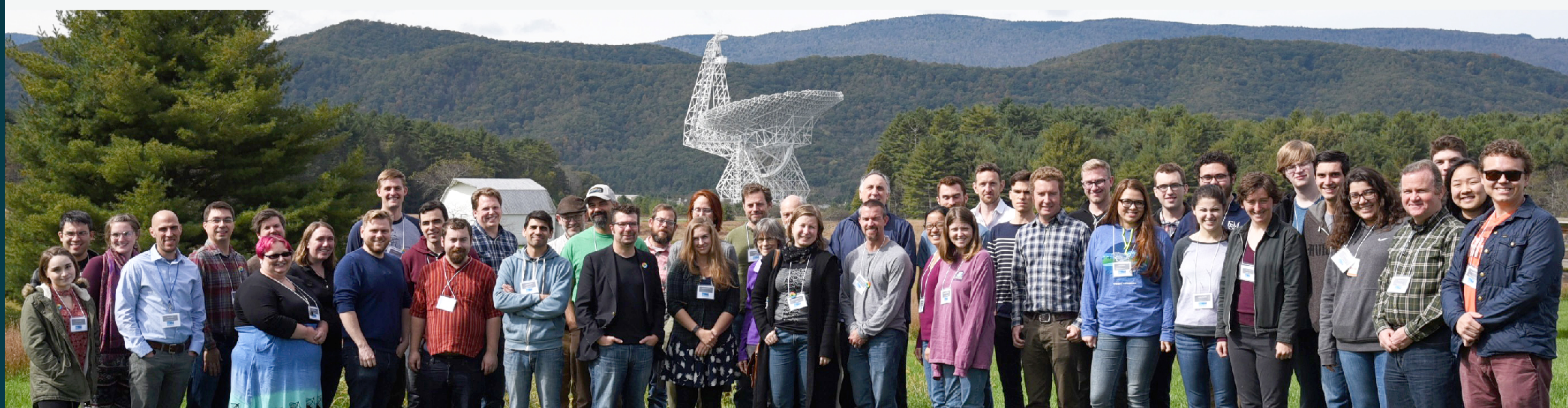


Photo Credit: Tonia Klein for the NANOGrav Collaboration

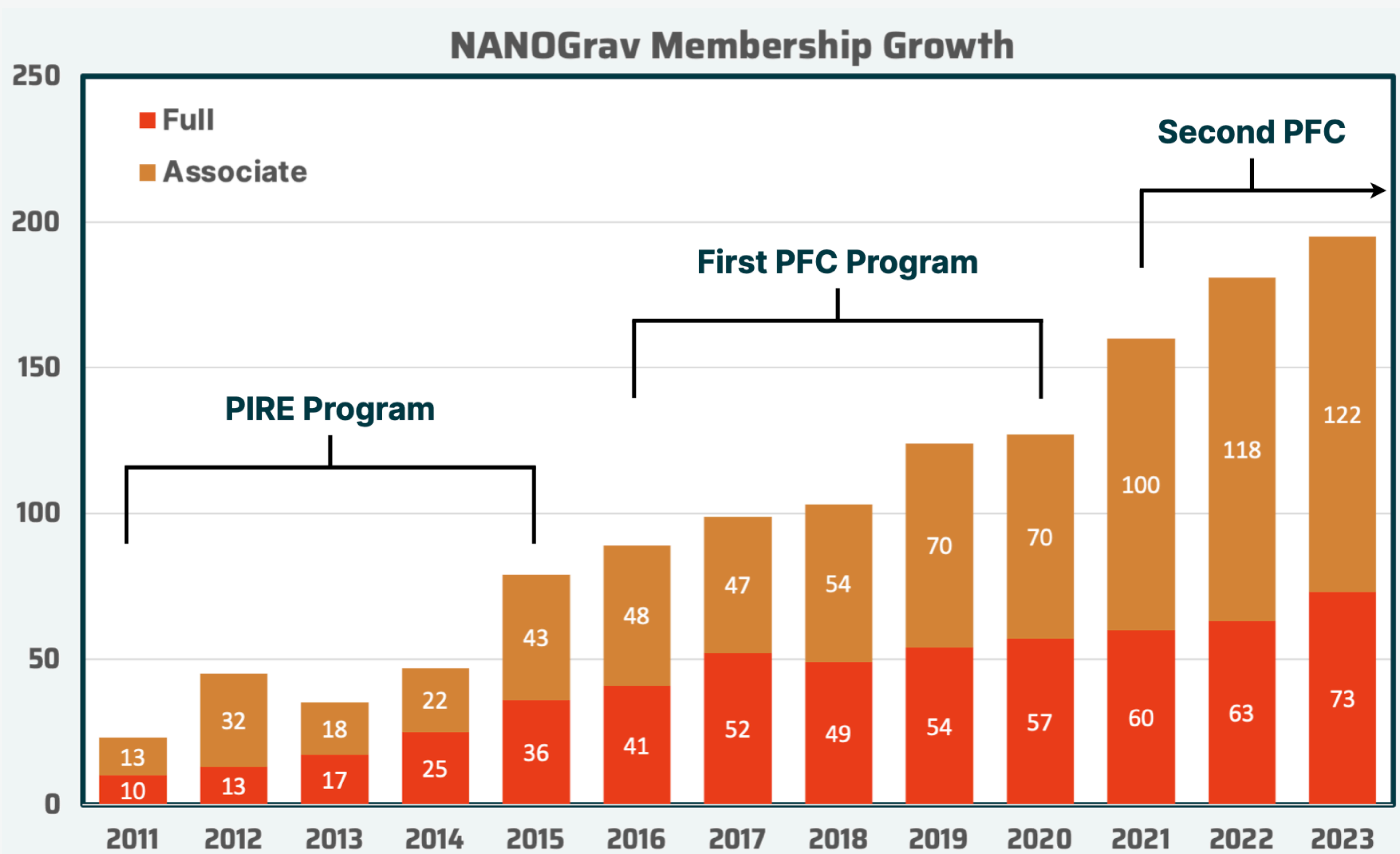
Member roles:

- 56 University faculty
- 26 Research scientists
- 38 Postdoctoral researchers
- 75 Graduate students
- 125 Undergraduate students**

** Not all undergraduates working with NANOGrav have joined the collaboration officially.

Current membership:

- 73 Full members
- 122 Associate members
- 25 Junior members
- 1 Legacy member



NANOGrav membership by year. Undergraduate members are not included in these totals.

NANOGrav
Physics Frontiers Center

The NANOGrav Collaboration: Key Members

The full collaboration has contributed to the results being reported here.
A number of the members critical to this effort have been highlighted below.

Dr. Joe Swiggum:

Lead for Observations and Timing Paper
Lafayette College

Dr. Joe Swiggum has been an active member of NANOGrav for more than a decade and is currently a PFC Senior Postdoctoral Fellow and 15-year data set development lead. In addition to expertise in pulsar population studies and discovery and timing of new MSPs, he has fostered growth in the PTA community, through outreach to high school students and the general public locally, and by building bridges with international collaborators.

Dr. Jeffrey Hazboun:

Lead for Detector Characterization Paper
Oregon State University

Dr. Jeffrey Hazboun has been studying gravity and gravitational waves for 18 years. He joined NANOGrav as a postdoctoral scholar in 2016 and develops gravitational-wave search algorithms and noise mitigation strategies. He also works on characterizing the PTA as a Galaxy-scale gravitational-wave detector.

Dr. Sarah Vigeland:

Co-Lead for Gravitational-Wave Background Paper
University of Wisconsin Milwaukee

Dr. Sarah Vigeland is an astrophysicist who develops methods to search for gravitational waves and performs these searches on the NANOGrav data set. She has been a member of NANOGrav since 2013, and is currently Chair of the Gravitational Wave Detection Working Group.

Dr. Stephen Taylor:

Co-Lead for Gravitational-Wave Background Paper
Vanderbilt University

Dr. Stephen Taylor joined NANOGrav as a postdoctoral fellow at JPL in 2014. He developed many of the methods and analysis techniques that are the foundation of current PTA gravitational-wave searches. Dr. Taylor leads a research group specializing in PTA science and has authored a textbook on nanohertz-frequency gravitational-wave astronomy.

NANOGrav
Physics Frontiers Center

The NANOGrav Collaboration: Key Members

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A number of the members critical to this effort have been highlighted below.

Dr. Thankful Cromartie:

Timing Working Group Chair
Cornell University

Dr. Thankful Cromartie joined NANOGrav in 2015 and is the current chair of the collaboration's Timing Working Group. She helped develop the NANOGrav pulsar timing pipeline, was a leader in the 15-year data release effort, and uses the data set to precisely measure neutron star masses in order to constrain the dense matter equation of state.

Dr. Luke Zoltan Kelley:

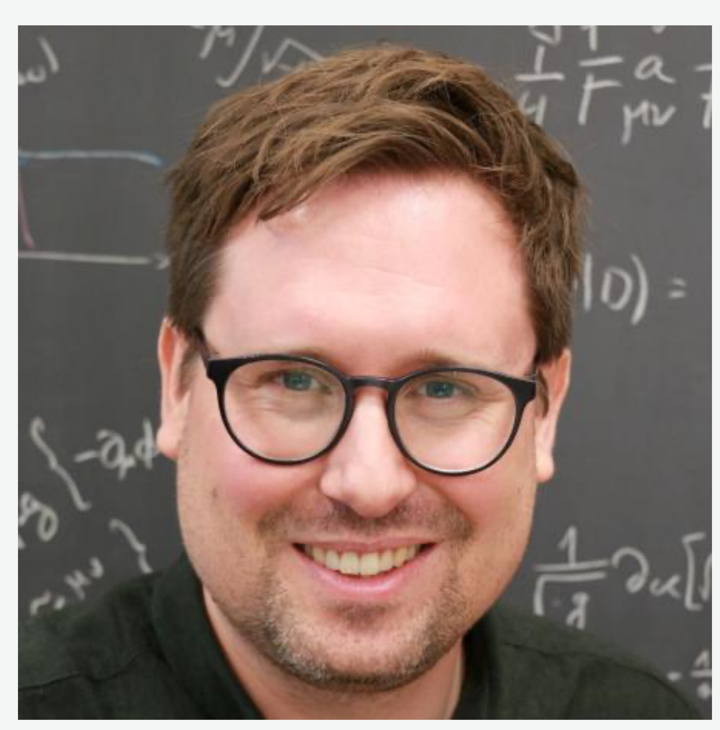
Lead for Astrophysics Interpretation Paper
University of California, Berkeley

Dr. Luke Kelley joined NANOGrav in 2016, and began contributing simulated populations of massive black holes (MBHs) from cosmological simulations. Since then, he has developed an array of methods for predicting and analyzing the gravitational-wave signals and electromagnetic counterparts of MBHs. Dr. Kelley currently serves as chair of the Astrophysics Working Group, where he has led the development of the Holodeck simulation framework and the 15-year astrophysical analysis.

Dr. Andrea Mitridate:

Co-Lead for Signals from New Physics Paper
DESY Hamburg

Dr. Andrea Mitridate is a particle physicist interested in searching for gravitational waves produced in the primordial Universe. He joined the NANOGrav collaboration in late 2020 and has been co-leading the search for signatures of physics beyond the Standard Model in the NANOGrav 15-year data set.



Dr. Kai Schmitz:

Co-Lead for Signals from New Physics Paper
University of Münster

Dr. Kai Schmitz has been an associate NANOGrav member for nearly two years and a full member since April 2023. He is a particle physicist interested in gravitational waves from the Big Bang and has been co-leading the search for signals from new physics in the NANOGrav 15-year data set.

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The NANOGrav Collaboration: Key Members

The full collaboration has contributed to the results being reported here.
A number of the members critical to this effort have been highlighted below.

Working Group Leadership

The production of groundbreaking science requires contributions from members in a wide variety of areas. The NANOGrav collaboration contains a diverse array of Working Groups whose leaders help the group's members innovate in each of these areas.

Working Group	Chair(s)
Astrophysics & Sources	Luke Zoltan Kelley *University of California, Berkeley*
Cyber-Infrastructure	Adam Brazier *Cornell University* Nate Garver-Daniels *West Virginia University*
Education & Outreach	Tim Dolch *Hillsdale College / Eureka Scientific* Natalia Lewandowska *SUNY Oswego*
Equity & Climate	Laura Blecha *University of Florida* Dustin Madison *University of the Pacific*
Gravitational Wave Detection	Sarah Vigeland *University of Wisconsin - Milwaukee*
Interstellar Medium Mitigation & Noise Budget	Michael Lam *SETI Institute* Natalia Lewandowska *SUNY Oswego*
Pulsar Searching	Shami Chatterjee *Cornell University*
Pulsar Timing	Thankful Cromartie *Cornell University*

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The NANOGrav Collaboration: Management Team

The Management Team oversees all NANOGrav activities and consists of an elected chair, four elected members, and the Principal Investigators of our funding grants.

Dr. Stephen Taylor:

NANOGrav Collaboration Chair
Vanderbilt University

Dr. Stephen Taylor joined NANOGrav as a postdoctoral fellow at JPL in 2014. He developed many of the methods and analysis techniques that are the foundation of current PTA gravitational-wave searches. Dr. Taylor leads a research group specializing in PTA science and has authored a textbook on nanohertz-frequency gravitational-wave astronomy.

Dr. Maura McLaughlin:

Physics Frontiers Center Co-Director
West Virginia University

Dr. Maura McLaughlin is one of the founding members of NANOGrav and serves as Co-Director of the NANOGrav PFC. She was PI of the PIRE award, is PI on the AccelNet award, and is a member of the IPTA Steering Committee. She works primarily on searches for millisecond pulsars, timing, and understanding and mitigating noise in pulsar timing data. She also contributes to education and outreach, in particular through the Pulsar Science Collaboratory.

Dr. Xavier Siemens:

Physics Frontiers Center Co-Director
Oregon State University

Dr. Xavier Siemens is the Principal Investigator of the NANOGrav Physics Frontiers Center and serves as co-Director. A member of NANOGrav for 14 years, he was the first to codify the requirements for detecting a gravitational-wave background with pulsars. He developed statistical techniques essential to the current results, and catalyzed the development of modern PTA gravitational-wave search pipelines.

Dr. Michael Lam:

Noise Budget Working Group Co-Chair
SETI Institute

Dr. Michael Lam started in NANOGrav as an undergraduate summer student and has been deeply involved for the last eleven years. He is currently a member of the Management Team, co-chair of the Noise Budget Working Group, and works to characterize the pulsar timing array as a detector and optimize its performance.

The NANOGrav Collaboration: Management Team

The Management Team oversees all NANOGrav activities and consists of an elected chair, four elected members, and the Principal Investigators of our funding grants.

Dr. Dustin Madison:

University of the Pacific

Dr. Dustin Madison joined NANOGrav in 2012 as a graduate student. He led NANOGrav's first searches for signals called "bursts with memory" and has been involved in these searches ever since. He works to improve the way NANOGrav handles the solar wind, an important source of noise that is interesting in its own right. Dr. Madison was elected to the NANOGrav Management Team at the start of 2023.

Dr. Adam Brazier:

Cyber-Infrastructure Working Group Co-Chair
Cornell University

Dr. Adam Brazier has been a member of NANOGrav for 15 years, during which he has been Chair of the NANOGrav Cyber-Infrastructure Working Group, co-chaired the NANOGrav Equity and Inclusion Committee, and has been an elected member of the NANOGrav Management Team since 2019.

Dr. David Nice:

Lafayette College

Dr. David Nice has thirty years of experience using radio telescopes for high precision pulsar timing experiments, with a particular focus on using these observations to measure relativistic phenomena. More than 15 years ago, NANOGrav evolved out of pre-existing long-term observing programs at the Arecibo and Green Bank telescopes led by him and others.

Dr. Scott Ransom:

Ex-Officio Chair
National Radio Astronomy Observatory

Dr. Scott Ransom is one of the founding members of NANOGrav and was the previous Chair of the collaboration (2016-2022). He specializes in searches for new millisecond pulsars, high-precision timing techniques, and improving our pulsar instruments and processing software.

The NANOGrav Collaboration: Member Institutions

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is a collaboration of faculty, researchers, and students from institutions around the globe.

Institutions:

- 66 in United States and Canada
- 22 in other nations

Canada:

British Columbia	University of British Columbia
Ontario	University of Toronto

United States:

Alabama	University of Alabama, Huntsville NASA Marshall Space Flight Center
Arkansas	University of Arkansas
California	California Institute of Technology Eureka Scientific Jet Propulsion Laboratory SETI Institute University of California, Berkeley University of the Pacific
Colorado	University of Colorado, Boulder
Connecticut	University of Connecticut Yale University
District of Columbia	Naval Research Laboratory
Florida	Florida Atlantic University Florida Space Institute University of Central Florida University of Florida
Illinois	Adler Planetarium Argonne National Laboratory Fermilab Northwestern University University of Chicago
Indiana	Indiana University Bloomington
Massachusetts	Harvard University Harvard & Smithsonian Center for Astrophysics Tufts University
Maryland	Johns Hopkins University NASA Goddard Space Flight Center Notre Dame of Maryland University University of Maryland University of Maryland, Baltimore County
Michigan	Hillsdale College University of Michigan
Montana	Montana State University
New Hampshire	Dartmouth College
New Mexico	New Mexico Institute of Technology University of New Mexico
New York	Cornell University Flatiron Institute Rochester Institute of Technology Skidmore College State University of New York at Oswego
Ohio	Kenyon College Oberlin College
Oregon	Oregon State University
Pennsylvania	Carnegie Mellon University Franklin & Marshall College Haverford College Lafayette College Penn State University Abington Swarthmore College Widener University
Tennessee	Vanderbilt University
Texas	Texas Tech University University of Texas at Austin
Virginia	George Mason University National Radio Astronomy Observatory University of Virginia
Washington	University of Washington Bothell
Wisconsin	University of Wisconsin Milwaukee
West Virginia	Green Bank Observatory West Virginia University
Puerto Rico	Arecibo Observatory University of Puerto Rico at Mayaguez

Other Nations:

Australia	Curtin University
Brazil	Observatório Nacional
China	Chinese Academy of Sciences National Astronomical Observatories Peking University
Denmark	University of Copenhagen University of Southern Denmark
Germany	DESY, Hamburg Mainz University Max Planck Institute for Gravitational Physics University of Münster
Hungary	Eötvös Loránd University
Israel	Ben-Gurion University Weizmann Institute
Italy	Scuola Normale Superiore, Pisa
Japan	Kumamoto University Osaka Metropolitan University
Singapore	National University of Singapore
Spain	Basque Foundation for Science
United Kingdom	Newcastle University University of Birmingham University of Hertfordshire University of Hull

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The NANOGrav Collaboration: Funding Sources

Various federal agencies, universities, and private entities have contributed to NANOGrav – providing funding for instrumentation, data acquisition, analysis, and scientific investigations. Below is a non-exhaustive list of our backers.

National Science Foundation

The National Science Foundation (NSF) is an independent agency of the United States government that supports fundamental research and education in all the non-medical fields of science and engineering.

Physics Frontiers Center

The NSF's Physics Frontiers Centers (PFC) program supports university-based centers and institutes where the collective efforts of a larger group of individuals can enable transformational advances in the most promising research areas.

PFC Website

Partnerships for International Research and Education

The NSF's PIRE (Partnerships for International Research and Education) is a funding mechanism that supports multi-stakeholder and international partnerships that are essential to address challenges of critical societal importance at a regional or global scale.

PIRE Website

AccelNet

The NSF's Accelerating Research through International Network-to-Network Collaborations (AccelNet) program is a mechanism that accelerates the process of scientific discovery and prepares the next generation of U.S. researchers for multi-team international collaborations. The AccelNet program supports strategic linkages among U.S. research networks and complementary networks abroad that will leverage research and educational resources to tackle grand research challenges that require significant coordinated international efforts. The program seeks to foster high-impact science and engineering by providing opportunities to cooperatively identify and coordinate efforts to address knowledge gaps and research needs.

AccelNet Website

Radio Telescope Facilities

The NSF has been the primary source of funding for three of the radio telescopes used by NANOGrav.

Other NSF Support

Astronomy & Astrophysics Program Grants
Physics Program Grants
Graduate Research Fellowship Program
Astronomy & Astrophysics Fellowship Program
Major Research Implementation Award
CAREER Awards
Grote Reber Fellowship Program
Research Experience for Undergraduates
Established Program to Stimulate Competitive Research: Track 1

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The NANOGrav Collaboration: Funding Sources

Natural Sciences and Engineering Research Council of Canada

The Natural Sciences and Engineering Research Council of Canada (NSERC) is the major federal agency responsible for funding natural sciences and engineering research in Canada. NSERC directly funds university professors and students as well as Canadian companies to perform research and training.

NSERC Website

Canadian Institute for Advanced Research

The Canadian Institute for Advanced Research (CIFAR) is a Canada-based global research organization that brings together teams of top researchers from around the world to address important and complex questions. It was founded in 1982 and is supported by individuals, foundations and corporations, as well as by the Government of Canada and the provinces of Alberta, British Columbia, Ontario and Quebec.

CIFAR Website

Gordon and Betty Moore Foundation

The Moore Foundation is an American foundation established by Intel co-founder Gordon E. Moore and his wife Betty I. Moore in September 2000 to support scientific discovery, environmental conservation, patient care improvements and preservation of the character of the Bay Area. The foundation's aim is to tackle large, important issues at a scale where it can achieve significant and measurable impacts.

Moore Foundation

Other Grants and Support

- Associated Universities, Inc.
- Association of Universities for Research in Astronomy, Inc.
- Ben-Gurion University Kreitman Fellowship Program
- Brinson Foundation
- California Institute of Technology
- Caltech & JPL's President's and Director's Research and Development Fund
- Center for Interdisciplinary Exploration & Research in Astrophysics and Adler Planetarium Post-doctoral Fellowships
- Council for Higher Education and Israel Academy of Sciences & Humanities Excellence Fellowship Program
- The Dunlap Institute
- Eötvös Loránd Research Network
- Flatiron Institute
- George and Hannah Bolinger Memorial Fund at OSU
- The German Research Foundation
- Jet Propulsion Laboratory
- Larry W. Martin & Joyce B. O'Neill Endowed Fellowship at OSU
- National Aeronautics and Space Administration
- NASA Hubble Fellowship Program
- National Radio Astronomy Observatory
- Naval Research Laboratory
- Research Corporation for Science Advancement
- Science and Technology Facilities Council
- Simons Foundation
- Sloan Foundation Fellowship Program
- Space Telescope Science Institute
- University of British Columbia Fellowships
- Vanderbilt Initiative in Data Intensive Astrophysics Fellowship Program
- WVU Center for Gravitational Waves & Cosmology
- WVU Research Corporation

The NANOGrav Collaboration:
Files, Images, Graphics, and Attributions

Caption: Aerial view of the Arecibo Telescope before its collapse in December 2020.

Filename: Arecibo_Telescope.jpg

Credit: Arecibo Observatory, a facility of the NSF

Caption: Flowers accompanying the Very Large Array on the Plains of San Agustin, NM.

Filename: VeryLargeArray.jpg

Credit: NRAO/AUI/NSF

Caption: The radio frequency receiver platform for the Green Bank Telescope rises above the dish.

Filename: GreenBank_Telescope.jpg

Credit: Jay Young for Green Bank Observatory

Caption: Photo of NANOGrav Collaboration members at a scientific conference held at the Green Bank Observatory in West Virginia in 2018.

Filename: NANOGrav_GBMeeting_2018.jpg

Credit: Tonia Klein for the NANOGrav Collaboration

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Physics Frontiers Center

Suggested Non-NANOGrav Expert Contacts

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Physics Frontiers Center

NSF | VANDERBILT UNIVERSITY | UNIVERSITY of VIRGINIA | UBC | Oregon State University | UWM | U.S. NAVAL RESEARCH LABORATORY

NSERC CRSNG | HAVERFORD | LAFAYETTE COLLEGE | UNIVERSITY OF TORONTO | Tufts UNIVERSITY | RECINTO UNIVERSITARIO DE MAYAGÜEZ UNIVERSIDAD DE PUERTO RICO | Widener University | JPL Jet Propulsion Laboratory

CIFAR | MONTANA STATE UNIVERSITY | University of Connecticut | CALIFORNIA INSTITUTE OF TECHNOLOGY 1891 | HILLSDALE COLLEGE | OBERLIN COLLEGE & CONSERVATORY | RIT Rochester Institute of Technology | NASA Goddard

GORDON AND BETTY MOORE FOUNDATION | NORTHWESTERN UNIVERSITY | CORNELL UNIVERSITY FOUNDED A.D. 1865 | UAH THE UNIVERSITY OF ALABAMA IN HUNTSVILLE | GEORGE MASON UNIVERSITY | THE UNIVERSITY of NEW MEXICO | TEXAS TECH UNIVERSITY | NASA Marshall Space Flight Center

AO | Berkeley UNIVERSITY OF CALIFORNIA | W BOTHELL | THE UNIVERSITY OF CHICAGO | UNIVERSITY OF MARYLAND 1856 | Yale | OSWEGO STATE UNIVERSITY OF NEW YORK | Adler PLANETARIUM

GREEN BANK OBSERVATORY | UNIVERSITY OF ARKANSAS | CU Boulder | Argonne NATIONAL LABORATORY

chime | UF UNIVERSITY of FLORIDA | FLORIDA ATLANTIC UNIVERSITY EST. 1961 | F&M | SWARTHMORE | BLOOMINGTON | PennState Abington | Smithsonian Astrophysical Observatory

NRAO | CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN | UNIVERSITY OF CENTRAL FLORIDA | NOTRE DAME OF MARYLAND UNIVERSITY | D | UNIVERSITY OF THE PACIFIC | NEW MEXICO TECH SCIENCE • ENGINEERING • RESEARCH UNIVERSITY | MPE

FLORIDA SPACE INSTITUTE | JOHNS HOPKINS UNIVERSITY | SKIDMORE COLLEGE | Carnegie Mellon University | THE UNIVERSITY OF TEXAS AT AUSTIN | Kenyon | UMBC UNIVERSITY OF MARYLAND BALTIMORE COUNTY 1966 | Fermilab

Eureka Scientific | UNIVERSITY OF BIRMINGHAM | WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER | UNIVERSITY OF COPENHAGEN | EÖTVÖS LORÁND UNIVERSITY | SCUOLA NORMALE SUPERIORE | Curtin University | SETI INSTITUTE

FLATIRON INSTITUTE | University of Hertfordshire UH | Newcastle University | OSAKA METROPOLITAN UNIVERSITY 1880 | Kumamoto University | University of the Basque Country | מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE | DESY.

JG|U | Observatório Nacional | SDU University of Southern Denmark | NUS National University of Singapore | UNIVERSITY OF HULL | 北京大學 PEKING UNIVERSITY | Ben-Gurion University of the Negev | NAOC