

1. Final publishable summary report

- Introduction:

Supermassive black hole binaries (SMBHBs) in the million to 10 billion solar mass range form in galaxy mergers, and live in galactic nuclei with large and poorly constrained concentrations of gas and stars. There are currently no observations of merging SMBHBs— it is in fact possible that they stall at their final parsec (3.3 light years) of separation and never merge, called the final parsec problem. While LIGO has detected high frequency GWs, SMBHBs emit GWs in the nanohertz to millihertz band. This is inaccessible to ground-based interferometers such as LIGO, but possible with Pulsar Timing Arrays (PTAs).

PTAs can detect nanohertz GWs from both individual SMBHB systems, and from the GW background (GWB) formed by the cosmic merger history of SMBHBs. This is achieved by monitoring millisecond pulsars, which are highly stable clocks. GWs change the proper distance between the pulsars and the Earth, thus inducing a delay or advance of the pulse arrival times. The difference between the expected and actual pulse arrival times -- the timing residuals -- carries information about the GWs that is extracted by cross-correlating the pulsar residuals.

The aim of “Gravitational Wave Astrophysics and Analysis with Pulsars” (GW ASAP) was to find the first ever direct evidence for nanohertz GWs with PTAs by means of a new interdisciplinary collaboration in radio and infrared astronomy, data analysis, and astrophysics. The main Objectives were (a) to identify SMBHB candidates using galaxy catalogues to create multiple realizations of realistic GW backgrounds (GWBs), assessing and mapping the degree of GW anisotropy in the local universe; (b) to integrate anisotropic searches into PTA data analysis libraries; and (c) use the anisotropy method to search for resolvable GW sources.

In Objective (a), it became clear that the methods I developed had broad applications. As such, I applied them to continuous GW (CGW) sources in addition to GWB anisotropy. By introducing galaxy merger rates from the Illustris simulation, and adding pulsars to the IPTA with realistic noise properties in sky locations accessible by IPTA telescopes, not only was I able to create local GW skies based on real galaxies, but also realistic IPTA detection curves with which to estimate the time to detection of nearby SMBHBs (see Figure 1). Results from this objective have led to several firsts in the field: the first time a galaxy survey has been used to predict the likeliest galaxies hosting SMBHBs in the PTA band; the first time that a real galaxy sample has been used to estimate GWB anisotropy; and the first estimates of the time to detection of nanohertz CGW sources. These results were published in Mingarelli et al. (2017), marking the first time a PTA paper was published in a Nature research journal.

To achieve my goals in objective (b), I started with a rigorous analysis of the assumptions made in GWB searches (Mingarelli & Sidery 2014), and looked to the future to understand what PTA science could be done with the Square Kilometre Array (Janssen et al. 2015). Following this analysis, I co-led the first search for GWB anisotropy using EPTA data (Taylor, Mingarelli, Sesana et al. 2015) — published in Physical Review Letters — and found that the strain

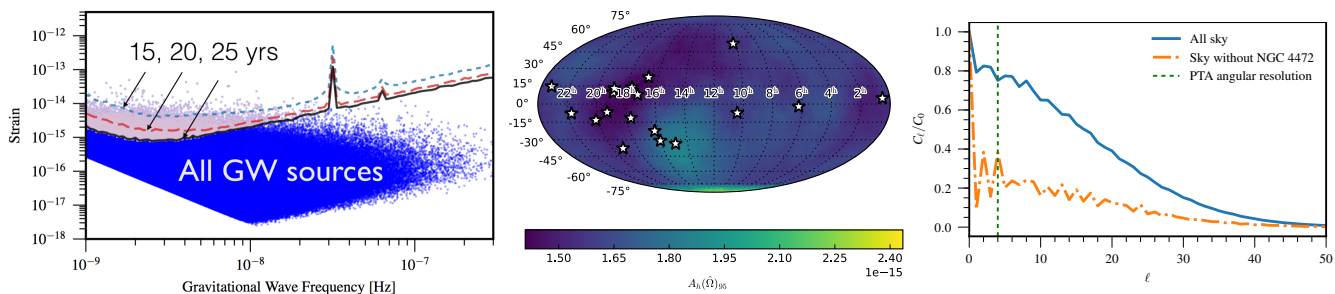


Figure 1 (left): IPTA time to detection of continuous GW sources within 225 Mpc (Mingarelli et al. 2017) with 15, 20 and 25 year datasets. Current PTAs have 10-15 year datasets. (center) Limit on GWB anisotropy in NANOGrav 9-yr data (Mingarelli for NANOGrav, in prep). (right) Angular power spectrum of a GW sky with a strong CGW source (blue), and the background from local unresolved sources with the loud source removed (Mingarelli et al. 2017).

amplitude in $l > 0$ spherical harmonic multipoles was $< 40\%$ of the isotropic (monopole) value. Before analyzing NANOGrav data, I wanted to better understand the expected astrophysical contribution from local CGW sources. My results in Objective (a) indicated that local CGW sources induce a 20% level of anisotropy (Mingarelli et al. 2017, Figure 1). I then analyzed the NANOGrav 9-yr data, and found that the strain amplitude in $l > 0$ multipoles was $< 32\%$ of the isotropic value (Mingarelli for NANOGrav, in prep).

Objective (c) was also achieved in Mingarelli et al. (2017). Using methods developed specifically for this research, it was possible to create a GWB from the superposition of many faint CGW sources, and examine the angular power spectrum of this GWB. The spectra with loud CGW sources are easily distinguishable from ones with many unresolved sources (see attached document, Figure 1). Moreover, we find that when two GW sources are close to each other on the sky, the GWs create a beat in the angular power spectrum, providing additional clues to the GW landscape.

- Additional Research:

The research independence granted by the MC IOF enabled me to explore new research paths — in addition to the ones laid in GW ASAP — resulting in significant contributions to each individual PTA. Concretely, in Lentati et al. (2015), I helped analyze the European PTA 18 year dataset, searching for an isotropic GWB, and also placing limits on primordial GWs from inflation, which had previously been overlooked. This primordial limit garnered much interest, and led to a new collaboration with the Parkes PTA (Lasky, Mingarelli, Smith et al. 2016), where we combined GW limits from across the entire frequency spectrum to constrain primordial GWB parameters. This work was published in Physical Review X — a highly selective and fully open-access journal. In the NANOGrav 9-yr isotropic GWB paper (Arzoumanian et al. 2016), I led the initial development of the astrophysical interpretation of the GWB limit, describing a turnover in the GWB strain spectrum at a transition frequency where SMBHB evolution is driven by GWs instead of environmental interactions. Moreover, I re-interpreted the NANOGrav 9-yr GWB limit in terms of the primordial GWB, and contributed to the cosmic string analysis. Other collaboration papers I co-authored include Desvignes et al. (2016), Lentati et al. (2016), Verbiest et al. (2016), Babak et al. (2016), and Caballero et al. (2015). In terms of additional short-author papers, I developed a model where a stellar mass black hole — neutron star merger produces a fast radio burst (FRB) which is characterized by a double peak (Mingarelli, Levin, Lazio 2015), and I co-authored new research predicting the time to detection of the GWB as a function of the underlying astrophysics (Taylor et al. 2016). Both these papers were published in the prestigious Astrophysical Journal Letters. Finally, I aided the establishment of a new formalism to map the GWB using Cosmic Microwave Background methods, in order to retain the polarization information (Gair et al. 2014). We then applied this method to ground-based interferometers (Romano et al. 2015), which is the first time PTA methods have informed ground-based interferometer (e.g. LIGO) GW searches.

- Dissemination of Research and Prizes:

Over the last 3 years, I gave 21 invited talks at world-class universities and research centers, including Princeton University, Caltech, and NASA Headquarters, and at large international meetings such as the 11th International LISA Symposium, the 229th American Astronomical Society Meeting, and International PTA meetings. I further disseminated my research by teaching at the Caltech GW Astrophysics School in 2015, writing an invited article for Scientific American, and giving interviews to the Wall Street Journal, Popular Mechanics, Sky & Telescope, Wired, New Scientist and Nautilus Magazine. Moreover, I was awarded “APS Woman Physicist of the Month” November 2016, MSCA “Fellow of the Week” (February 2017), and the MSCA 2017 “Communicating Science” Prize, 1st place.

- Conclusions:

While nanohertz GWs have not yet been detected, my interdisciplinary research efforts made possible by GW ASAP have led to milestone achievements in nanohertz GW astronomy,

including a completely new approach to predicting the local nanohertz GW landscape from SMBHBs (Mingarelli et al. 2017), searching for manifestations of final parsec physics in the GWB (Arzoumanian et al. 2016), and the first searches for GWB anisotropy (Mingarelli for NANOGrav (in prep); Taylor, Mingarelli, Sesana et al. 2015). Moreover, I explored novel ideas pertaining to fast radio bursts (Mingarelli, Levin, Lazio 2015), time to detection of the GWB (Taylor et al. 2016), and GW cosmology (Lasky, Mingarelli, Smith et al. 2016; Arzoumanian et al. 2016; Lentati et al. 2015). All codes used to generate results in Mingarelli et al. papers are publicly available on my github account, <https://github.com/ChiaraMingarelli>.