Snowmass2021 - Letter of Interest

Fundamental Physics with Pulsar Timing Arrays

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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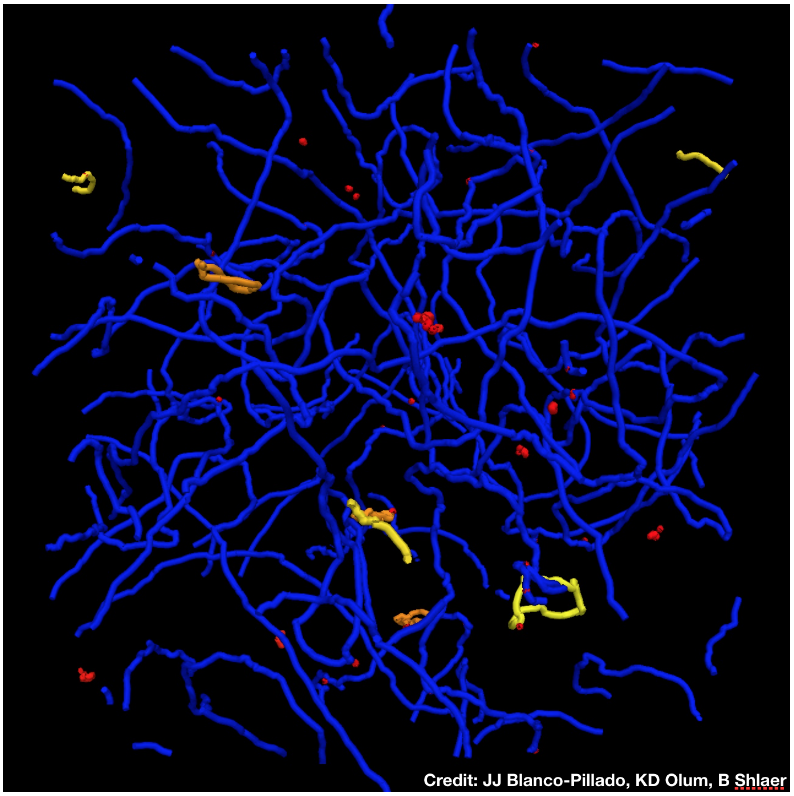

Pulsar timing arrays (PTAs) will enable the detection an characterization of nanohertz gravitational waves (GWs) from a population of supermassive binary black holes (SMBBHs) in the next few years. Additionally, PTAs provide a rare opportunity to probe fundamental physics. Potential sources of GWs in the nanohertz band include *cosmic strings and cosmic superstrings*, *inflation*, and *phase transitions in the early universe*.

GW observations will also make possible *tests of gravitational theories* that, by modifying Einstein's theory of general relativity, attempt to explain the origin of cosmic acceleration and reconcile quantum mechanics and gravity, two critical challenges facing fundamental physics today. Finally, PTAs also provide a new means to probe certain *dark matter* models. Clearly, *a positive detection of any of these observational signatures would have profound consequences for cosmology and fundamental physics*. In this letter of intent we briefly discuss these potential signatures.

Cosmic strings and cosmic superstrings: Cosmic strings are topological defects that can form during phase transitions in the early Universe [1, 2], and cosmic superstrings are the fundamental strings of string theory stretched to cosmological scales due to the expansion of the Universe [3–8]. Once formed, cosmic string and superstring networks both evolve in a similar way [9], producing a GW stochastic background along with bursts of GWs that stand out above the background [10–17].

The detection of a stochastic background from cosmic (super)strings, or GWs from individual cosmic (super)string loops, would be transformative for fundamental physics. PTAs are currently the most sensitive experiment for the detection of cosmic (super)strings [18], and will remain so for at least the next decade and a half; PTA sensitivity to cosmic (super)strings will not be superseded until the LISA mission which is scheduled for launch in 2034 [17].

Primordial GWs from inflation: The evolution of the very early Universe is thought to include a period of exponential expansion that accounts for the observed homogeneity, isotropy, and flatness of the Universe [19–25]. Additionally, by expanding quantum fluctuations present in the pre-inflationary epoch, inflation seeds the density fluctuations that evolve into the large scale structures we see in the Universe today [26–30], and produces a stochastic background of GWs [31–33].

The inflationary GW background is broad-band, like the one produced by cosmic strings, and potentially detectable by multiple experiments. For standard inflation models the GW background in the PTA band is likely to be fainter than that of SMBBHs; this, however, depends on the character of the SMBBH spectrum at the lowest frequencies where environmental effects like accretion from a circumbinary disk or stellar scattering can reduce SMBBH GW emission [34]. Additionally, some inflationary models have a spectrum that rises with frequency and could be tested with PTAs, and higher frequency GW experiments such as LISA and LIGO. Indeed, PTA, GW interferometer, and CMB data, combined across 29 decades in frequency, have already begun to place stringent limits on such models [35].

Phase transitions in the early universe: The early Universe may have experienced multiple phase transitions as it expanded and cooled. Phase transitions can produce GWs with wavelengths of order the Hubble length at the time of the phase transition. The nanohertz frequency band accessible to PTAs maps onto the era in the early universe when the quantum chromodynamics (QCD) phase transition took place, about 10^{-5} s after the Big Bang. The horizon at that time was on the order of 10 km, and any GWs generated at that length scale at that time would today be stretched to about 1 pc (or 3 light-years), which corresponds to GW frequencies of about 10 nHz, and lie within the PTA sensitivity band. The possibility that interesting QCD physics can result in a GW signal detectable by PTAs was first pointed out by Witten in the 1980s [36]. PTAs provide a window onto GW-producing physical processes occurring in the universe at the time of the QCD phase transition, and, for example, could detect GWs from a first order phase transition at that time [37].

Gravitational-wave tests of general relativity: Attempts to explain the origins of cosmic acceleration and to reconcile gravity and quantum mechanics, two outstanding fundamental physics problems, often involve modifications to Einstein's theory of general relativity. Testing general relativity as a theory of gravity is therefore a crucial goal for PTAs [38]. Here we focus on tests of general relativity made possible by PTA detections of gravitational waves; strong-field tests of GR based on binary neutron star orbits are also possible with PTA data and are discussed in a separate LOI. General relativity predicts the existence of GWs which travel at the speed of light, are transverse, and have two polarizations. Other metric theories of gravity generically predict the existence of GWs with different properties: up to six polarizations and modified dispersion relations [39, 40].

PTAs offer significant advantages over interferometers like LIGO for detecting new polarizations or constraining the polarization content of GWs. Each line of sight to a pulsar can be used to construct an independent projection of the various GW polarizations, and since PTAs typically observe tens of pulsars, linear combinations of the data can be formed to measure or constrain each of the six polarizations many times over [38]. Additionally, PTAs have an enhanced response to the longitudinal polarization [41]. Finding experimental evidence in favor of additional polarizations and/or non-standard dispersion properties for GWs would immediately rule out general relativity.

Dark matter: Dark matter is an essential component of the universe, accounting for about a quarter of its energy density. It explains a wide range of cosmological phenomena, from galaxy rotation curves to the detailed characteristics of the CMB and large-scale structure formation. Despite the enormous success of dark matter its nature remains an open question in fundamental physics.

Certain classes of dark matter models produce observable signatures at nanohertz frequencies. Scalar fields with masses around 10^{-23} eV, for example, can produce periodic oscillations in the gravitational potential with frequencies in the nanohertz range, well within the detectable range of PTAs in the coming decade [42, 43]. Finally, standard cold dark matter (CDM) models naturally produce small scale clumps which may also be detectable by PTAs. A CDM clump moving near the Earth or a pulsar produces an acceleration that could be measurable in PTA data, providing an opportunity to test the CDM paradigm [44–50].

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