PTAs Beyond the Stochastic Background

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Our Sources
A Stochastic GW Background

Circular GW-driven binaries assuming isotropy and homogeneity of population

\[ h_c^2(f) = \frac{4 f^{-4/3}}{3 \pi^{1/3}} \int \int dz dM \frac{d^2 n}{dz dM} \frac{M^{5/3}}{(1 + z)^{1/3}} \]

Sesana (2013)
We Haven’t Made a Detection Yet???

Shannon et al. (2013)
Realities of the Background

Figure 2. Influence of the binary–environment coupling on the GW signal. The black dotted line denotes the standard $f^{-2/3}$ spectrum for a population of circular GW-driven systems. Red lines are for star-driven binaries with eccentricity of 0 (solid) and 0.7 (long-dashed) at pairing; the green dot–dashed line is for circular gas-driven binaries. A sketch of the current PTA sensitivity is given by the solid blue line, which is then extrapolated to the limit at $1 \text{ yr}^{-1}$. Also shown in blue are the extrapolation of the current sensitivity to include 8 and 30 more years of observations (here, we assume no improvement in the timing of the pulsars; the mild improvement in the sensitivity floor is given by the $T_1/4$ gain that comes from the longer integration time), as well as the sensitivity given by putative arrays with four and six times better timing precision. We stress that the sensitivity curves are sketchy and only illustrative, but capture the trends relevant to the discussion in the text.

5. Conclusions

Pulsar timing arrays are achieving sensitivities that might allow the detection of the predicted GW background produced by a cosmological population of SMBH binaries. Beyond the obvious excitement of a direct GW observation, the detection of such signal, together with the determination of its amplitude and spectral slope, will provide an enormous wealth of information about these fascinating astrophysical systems, in particular:

(i) it will give direct unquestionable evidence of the existence of a large population of sub-parsec SMBH binaries, proving another crucial prediction of the hierarchical model of structure formation;

(ii) it will demonstrate that the 'final parsec problem' is solved by nature;

(iii) it will provide important information about the global properties of the SMBH binary population, giving, for example, insights into the relation between SMBH binaries and their hosts;

Sesana (2013)
Environmental Attenuation

Figure 5. Probability density plots of the recovered GWB spectra for models A and B using the broken-power-law model parameterized by $(A_{gw}, f_{bend}, \alpha)$ as discussed in the text. The thick black lines indicate the 95% credible region and median of the GWB spectrum. The dashed line shows the 95% upper limit on the amplitude of purely GW-driven spectrum using the Gaussian priors on the amplitude from models A and B, respectively. The thin black curve shows the 95% upper limit on the GWB spectrum from the spectral analysis.

Figure 6. One- and two-dimensional posterior probability density plots of the spectrum model parameters $A_{gw}, f_{bend}, \alpha$. In the one-dimensional plots, we show the posterior probability from the 9-year data set (blue), the 5-year dataset (dashed red) and the prior distribution used in both analyses (green). In the two-dimensional plots we show a heat map along with the one (solid), two (dashed), and three (dash-dotted) sigma credible regions. model A is on the left and model B is on the right.

Specifically, we constrain the $M_\bullet - M_{\text{bulge}}$ relation:

$$\log_{10} M_\bullet = \alpha + \log_{10} M_{\text{bulge}} / 10^{11} M_\odot.$$

In addition to $\alpha$ and $\epsilon$, observational measurements of this relation also fit for $\epsilon$, the intrinsic scatter of individual galaxy measurements around the common $\alpha$ trend line. In practice, $\alpha$ and $\epsilon$ have the greatest impact on predictions of $A_{gw}$, and all observational measurements agree with $\alpha \approx 1$.

PTAs are most sensitive to binary SMBHs where both black holes are $\approx 10^8 M_\odot$ (e.g. Sesana et al. (2008)). Therefore $M_\bullet - M_{\text{bulge}}$ relations that are derived including the most massive systems are the most relevant to understanding the population in the PTA band. Several recent measurements of the $M_\bullet - M_{\text{bulge}}$ relation specifically include high-galaxy-mass measurements, e.g. those from Brightest Cluster Galaxies (BCGs). As these fits include the high-mass black holes that we expect to dominate the PTA signals, we take these as the "gold standard" for comparison with PTA limits (Kormendy Arzoumanian et al. (2016)).
Realities of the Background

Let us assume that we have a large set of realisations of the Universe, and that the optimal way to cross-correlate many detectors is to combine them in pairs (Allen & Romano 1999). Throughout this section, by 'realisations' we do not refer to the outputs of the computer simulations analysed in other sections of this paper, but to a hypothetical set of copies of the same Universe.

We assume that the collection of sources via time an ensemble of millisecond pulsars for a period of 15 yr can be described in terms of a characteristic GW strain at each frequency

\[
\log_{10}(S) = \sum_{k=1}^{n} h_{k} c T_{k}
\]

where

\[
S = \sum_{k=1}^{n} h_{k} c T_{k}
\]

is an index running over all sources in a given frequency bin, which is consistent with previous predictions for the amplitude of the GWB (Rajagopal & Romani 1995; Wyithe & Loeb 2003; Rosado 2011; Ravi et al. 2015). One example of the GWB is presented in Figure 1, in which we show the 5th and 95th percentiles of the

\[
Z = \int_{0}^{T} dw f(w) \exp(-w)
\]

where

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is the probability of claiming a spurious detection in the absence of a GWB. Alternatively, the integral of

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Z = \int_{0}^{T} dw f(w) \exp(-w)
\]

when it is indeed present. We now turn to the several SBHBs, each contributing a sizeable share of the GW strain. However, such high strain values can be realised only a minor impact on our results.

In the absence of a GWB, the cross-correlation output reflects the size of the frequency bin is

\[
\log_{10}(S)
\]

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\[
S
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is independent of the binaries' exact sky location and polarizability density function (PDF) defined by a mean

\[
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\]

and a standard deviation

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Eccentric Binaries

Taylor, Huerta, et al. (2016)
Anisotropic Background

Taylor, Mingarelli, et al. (2016)
**Bonus: Cosmic Strings**

**Stochastic Background Redux**

![Graph 1](image1.png)

![Graph 2](image2.png)

**Arzoumanian et al. (2016)**