The Role of The Arecibo Observatory on the Detection of Low-Frequency Gravitational Waves.

F. Jenet, S. Finn, A. Lommen, R. Shannon, D. Stinebring, X. Siemens

The Arecibo Observatory is an ideal instrument for the discovery and further studies of exotic stars known as radio pulsars. The unique properties of radio pulsars make it possible to detect and characterize low-frequency gravitational waves (GWs). The existence of GWs is a direct consequence of the general theory of relativity, and there is a world-wide effort to detect these waves using various different techniques. By observing radio pulsars, Arecibo has the potential to play a major role in the detection of GWs. This will simultaneously confirm General Relativity and give us a new tool to study the universe.

The ability to detect gravitational waves using radio pulsars depends on our ability to measure the arrival times of pulses from radio pulsars with high precision. Measuring these times of arrival is known as pulsar timing. Once systematics are removed, the root-mean-square error in measuring the arrival times is proportional to the receiver system temperature and inversely proportional to the effective collecting area of the telescope. Putting it all together, Arecibo can measure the arrival times of pulses five times more accurately than any telescope in existence or likely to be in operation in the next five years.

In order to quantify the effect that Arecibo will have on the detection of low-frequency gravitational waves, we investigated two different quantities. First, we calculated the probability of detecting an ensemble of supermassive black holes (i.e. a stochastic background) using five years of data both with and without using Arecibo. Second, we calculated how quickly one could detect such a stochastic background of GWs both with and without Arecibo. Note that the amplitude of the stochastic background, A, is defined as the magnitude of the GW characteristic strain at a frequency of one cycle per year. In order to definitely detect this background, one needs to observe about 20 pulsars. We therefore considered four observing scenarios. This first uses Arecibo to observe 8 pulsars and a 100 m class telescope to observe the remaining 12. All pulsars are observed once a month. This scenario is consistent with the current observing strategy of the NANOGrav consortium (http:nanograv.org). We assume that we can time 12 pulsars with 200 ns accuracy with the 100 m class telescope and 8 pulsars with 40 ns accuracy at Arecibo.. The second scenario observes the 20 pulsars in exactly the same way but once every week. In the third scenario, we observe all 20 pulsars once a month at the 100 m telescope and time all of them to an accuracy of 200 ns. The fourth scenario is the same as the third but the observations are made once a week.

Figure 1 plots the probability of detecting the background in five years of time as a function of the amplitude of the background for each of the scenarios described above. From Figure 1, we see that the scenarios that include Arecibo are a factor of three more sensitive than those that do not include this observatory. In other words, when Arecibo is removed, the background level needs to be increased by a factor of three in order to have the same probability of detecting it. This conclusion is insensitive to the observing cadence. Since the energy density parameter scales as A^2, this corresponds to a factor of 9 in Ω_g.

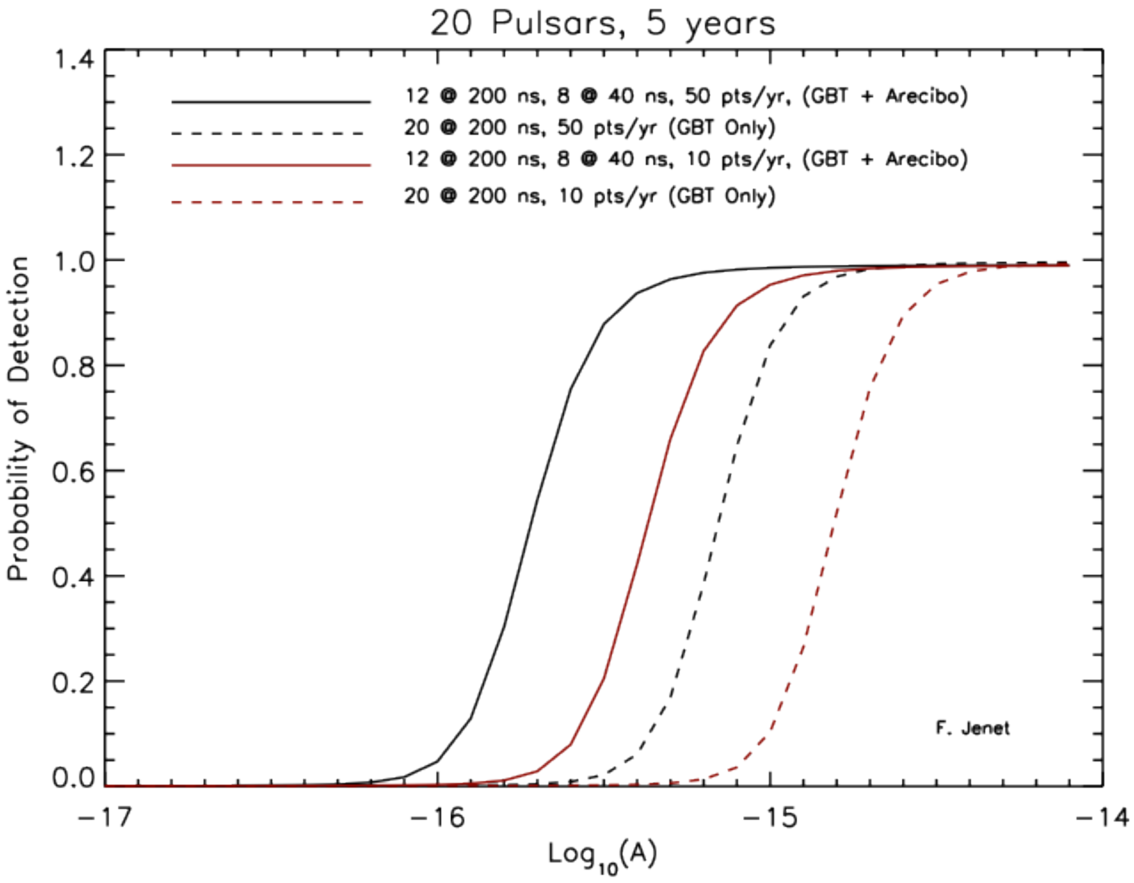

Figure 1: The probability of detecting a stochastic background generated by an ensemble of supermassive black hole binaries as a function of the amplitude of the background. The amplitude is defined as the magnitude of the characteristic strain of the background at a frequency of one cycle per year. The solid lines were calculated assuming five years of observations and using 20 pulsars, 12 observed at a 100 m telescope (i.e. the Green Bank Telescope), and 8 observed at Arecibo. The dashed lines were calculated using the 100 m telescope alone. The black lines were calculated assuming 50 observations per year (about 1 per week), while the red lines were calculated assuming 10 observations per year (about 1 per month). Note, the black lines are the first and third lines counting from the left.

Figures 2 and 3 plot the probability of detecting the background as a function of time for each of these scenarios. Figure 1 assumes that the background is at the level expected by current astrophysical models. Figure 2 assumes that the background is a factor of ten lower than these estimates.

From the figures, we see that Arecibo increases our sensitivity to a stochastic background by a factor of three. In terms of time to a detection, this increase in sensitivity translates into a saving of somewhere between 2 to 7 years, depending on the observing cadence and the level of the background. In the optimistic case where the background is at the expected level and with observations once a week, we would detect the background two years earlier with Arecibo than without. Note that this observing scenario would require a substantial amount of telescope time. Arecibo would save us four years using the more realistic once-per-month observing strategy. In the pessimistic case where the background is ten times lower than expected and we only observe once every week, we would detect the background 7 years earlier with Arecibo than without.

Given the arguments above, Arecibo is crucial to ensure the timely detection of gravitational waves. Arecibo also plays an important role through the very sensitive surveys that are being carried out with the multi-beam receiver. These are revealing more millisecond pulsars which can be added to the array, increasing its sensitivity dramatically. Furthermore, once GWs are detected, the unparalleled sensitivity of Arecibo will be essential in order for us to study GW sources and constrain their properties.

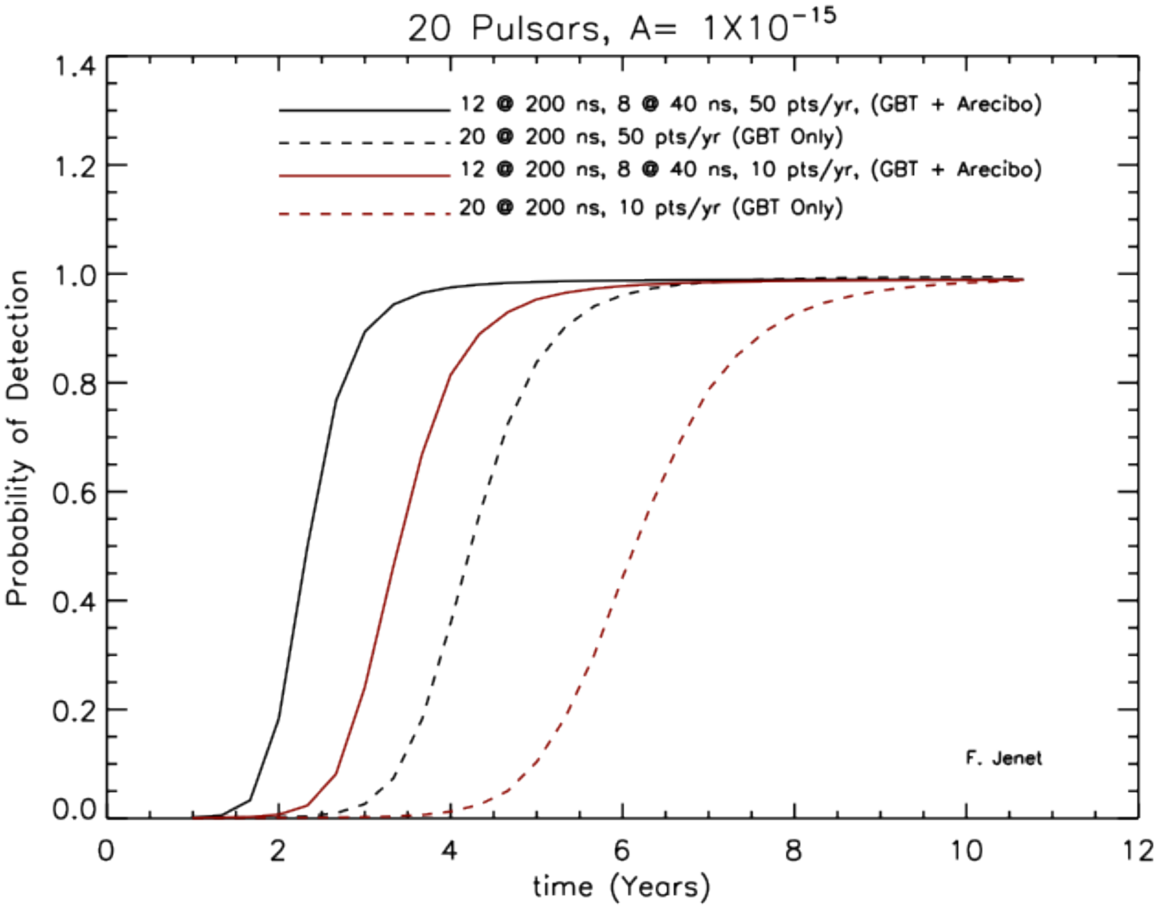

Figure 2: The probability of detecting a stochastic background of gravitational waves generated by an ensemble of super massive black hole binaries. The level of the background is assumed to be at the theoretically expected level. The solid lines were calculated using 20 pulsars, 12 observed at a 100 m telescope (i.e. the Green Bank Telescope), and 8 observed at Arecibo. The dashed lines were calculated using the 100 m telescope alone. The black lines were calculated assuming 50 observations per year (about 1 per week), while the red lines were calculated assuming 10 observations per year (about 1 per month). Note, the black lines are the first and third lines counting from the left.

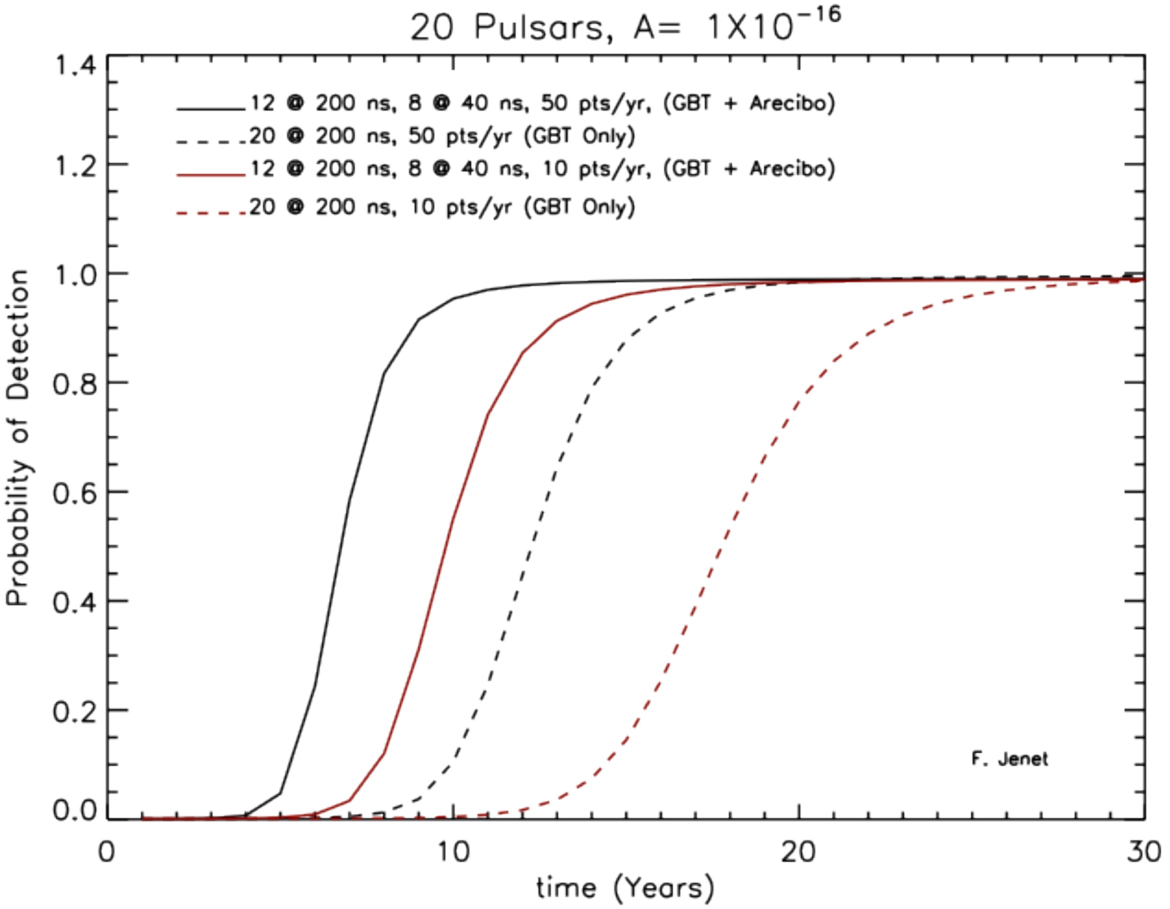

Figure 3: The probability of detecting a stochastic background of gravitational waves generated by an ensemble of super massive black hole binaries. The level of the background is assumed to be 10 times less than theoretically expected level. The solid lines were calculated using 20 pulsars, 12 observed at a 100 m telescope (i.e. the Green Bank Telescope), and 8 observed at Arecibo. The dashed lines were calculated using the 100 m telescope alone. The black lines were calculated assuming 50 observations per year (about 1 per week), while the red lines were calculated assuming 10 observations per year (about 1 per month). Note, the black lines are the first and third lines counting from the left.