Gravitational Waves and the Galactic Center Excess: Using Millisecond Pulsars to Probe Physics Beyond the Standard Model

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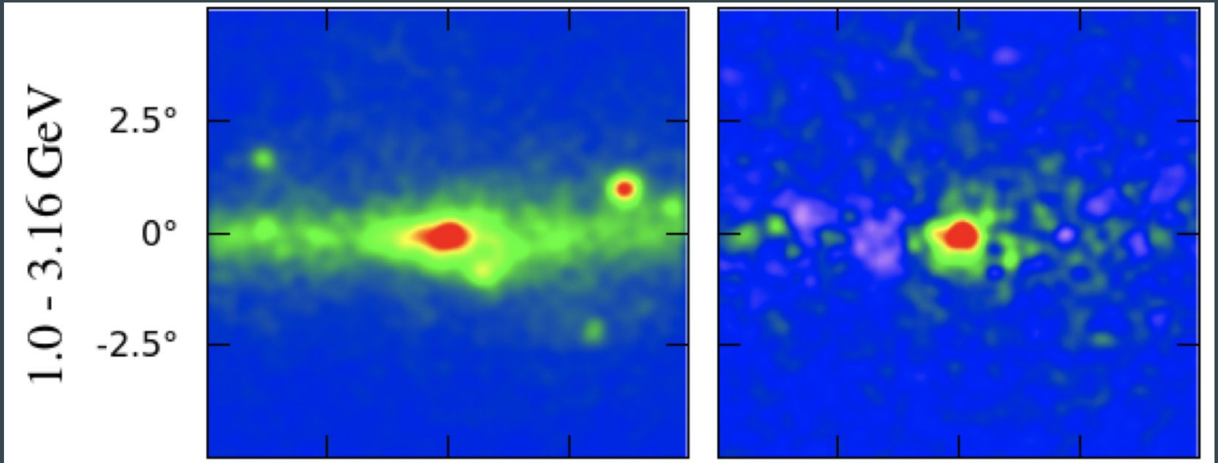
The Galactic Center Excess (GCE)

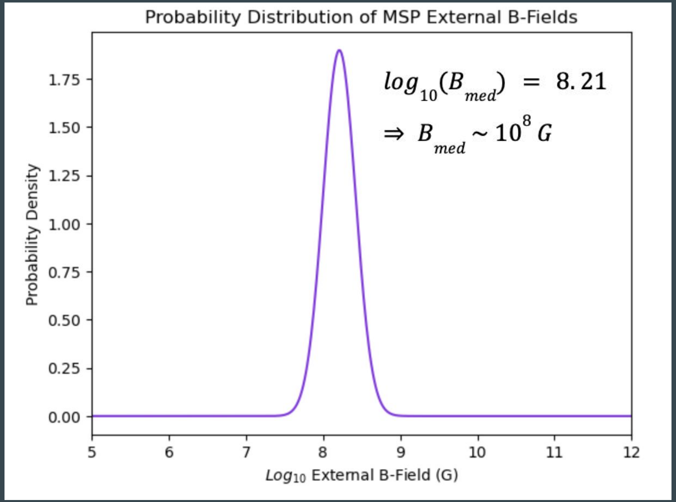


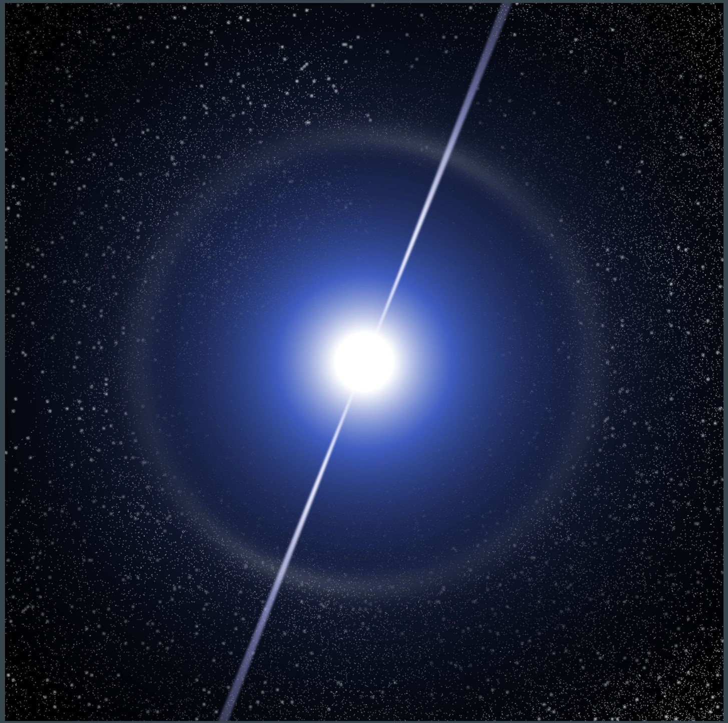
Daylan, et al. (2014)

- Source of high energy gamma rays (1-3 GeV) (Holst, 2024)
- Two potential causes: annihilating DM or unresolved population of MSPs (Slatyer, 2022)

Millisecond Pulsars (MSPs)

- Rapidly rotating (periods of milliseconds) neutron stars
- Emit gamma rays
- Have strong magnetic fields (Ploeg, 2021):





https://commons.wikimedia.org/wiki/File:Pulsar_2.jpg

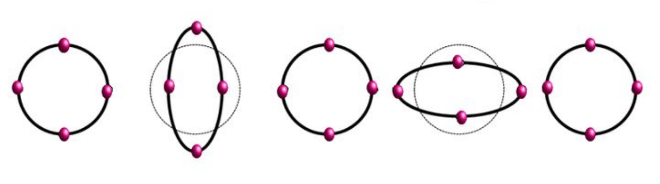
Gravitational Waves (GWs)

- Caused by rotating objects with axial asymmetry (Agarwal, 2022)
- Characterized by ellipticity, which can be found from an MSP's internal magnetic field (Miller, 2023):

$$\epsilon \approx 10^{-8} \frac{B_{int}}{10^{12}}$$

- Amplitude of (Miller, 2023):

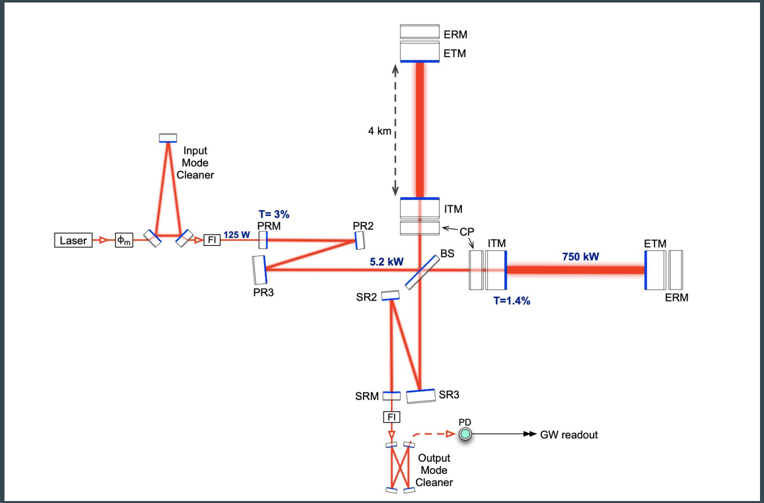
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{rot}^2}{d}$$



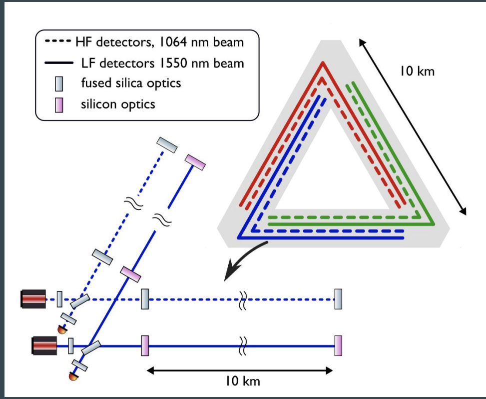
Belahcene, 2019

Gravitational Wave Detectors

- Use laser interferometry to detect gravitational waves (Abbott, 2009)
- Current detectors: aLIGO (Abbott, 2009), aVIRGO (Acernese, 2014), KAGRA (Aso, 2013)
- Future detector: Einstein Telescope (Rowlinson, 2021)



Advanced LIGO, 2015



Rowlinson, 2021

How do we generate a population of MSPs and the corresponding the GW signal?

Sample the MSP density distribution to get population

Find the ellipticity distribution from the internal B-fields

Calculate the GW signal using $h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_{rot}^2}{d}$

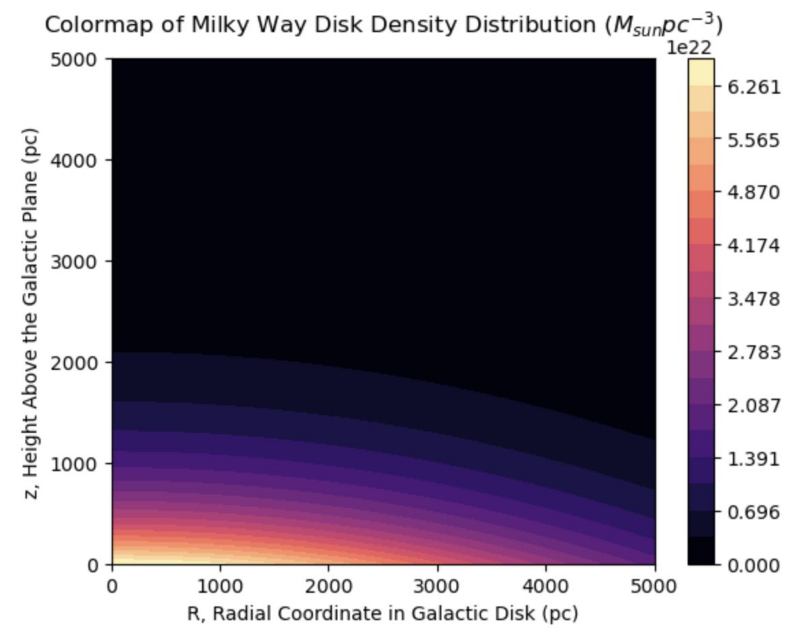
and the GW frequency usi

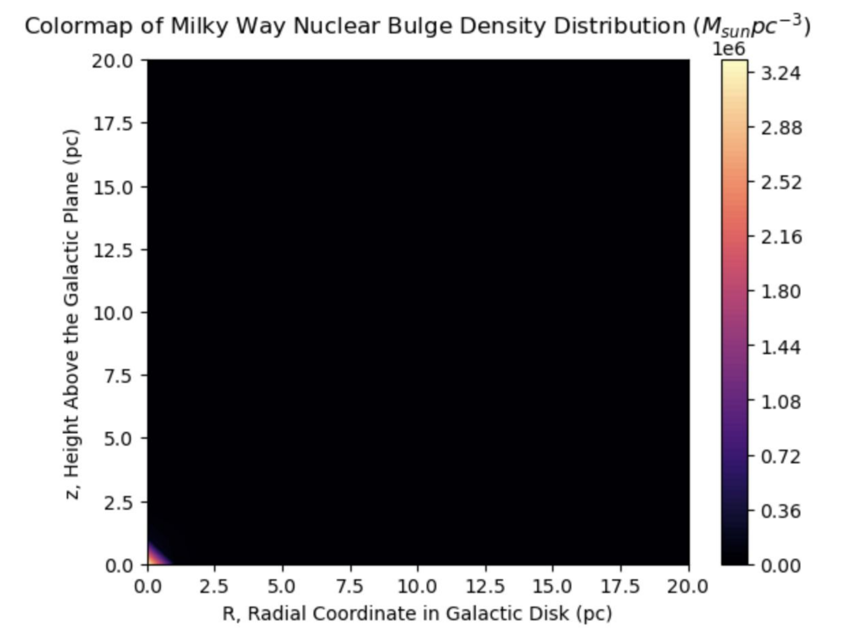
$$f_{GW} = 2 f_{rot}$$

Constrain the signal using GW detector sensitivities

Millisecond Pulsar Densities in the Milky Way

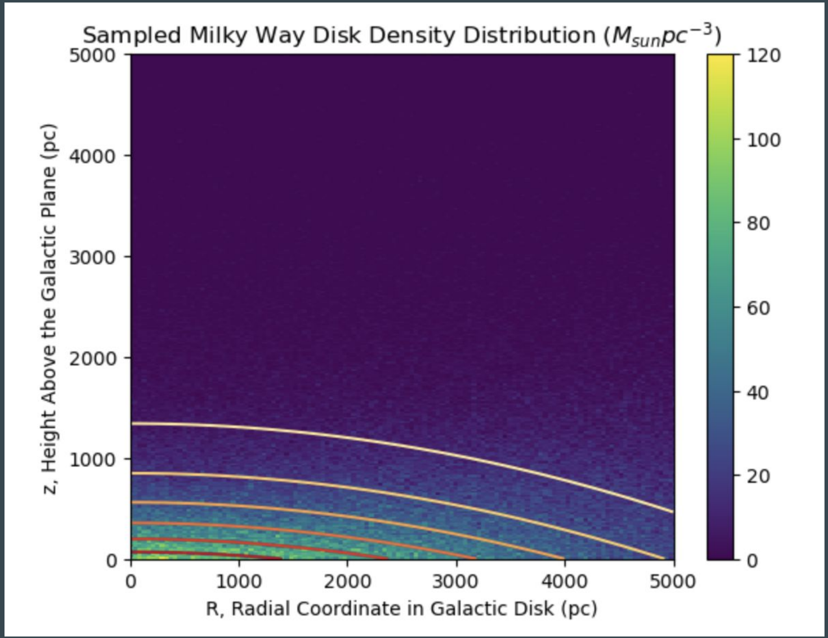
- 2 populations: the Milky Way Disk and the Milky Way Nuclear Bulge



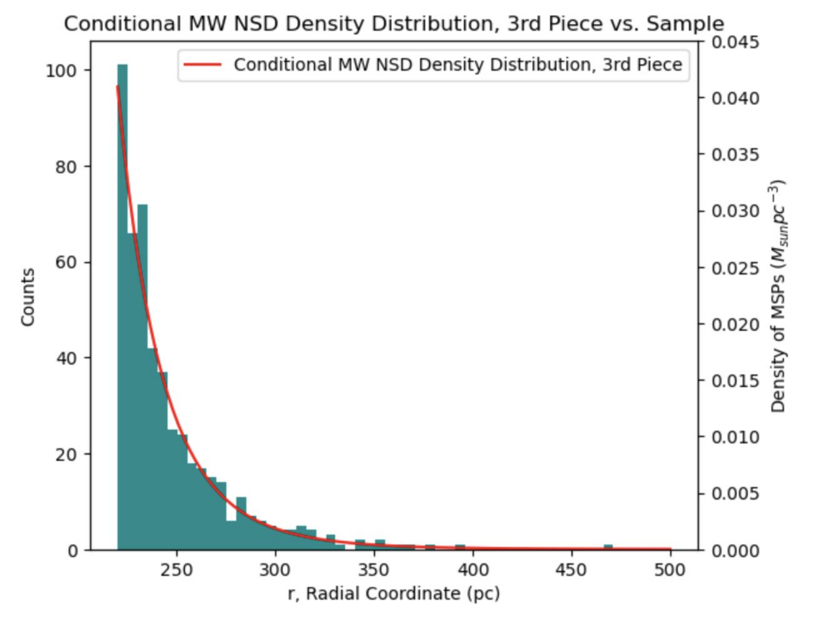


Sampling the MSP Population

MCMC Method

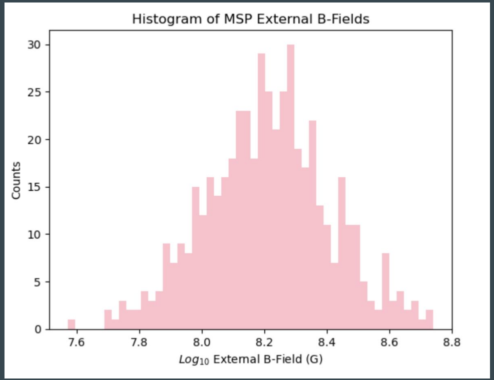


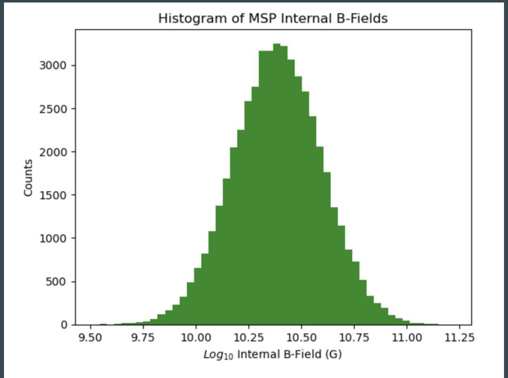
Inverse Transform Method

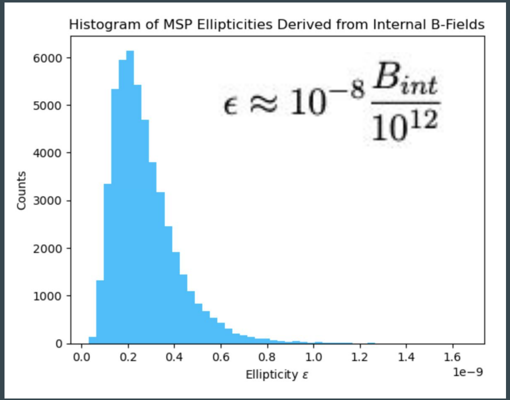


Ellipticity Distribution of MSPs

- External B-field → internal B-field → ellipticity (Miller, 2023)

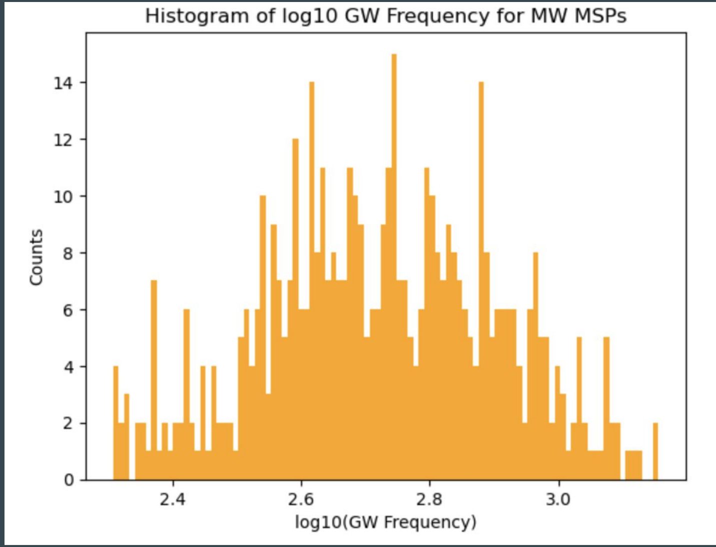


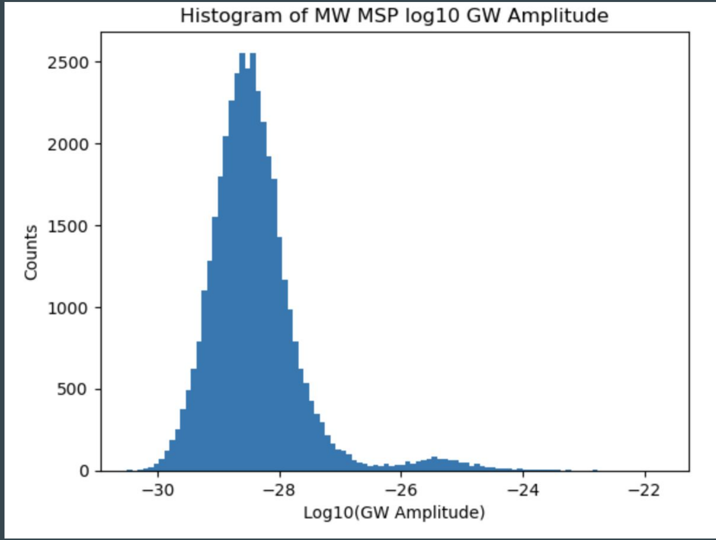




- Ellipticity minimums are ~ 10^{-9} (Woan, 2018)

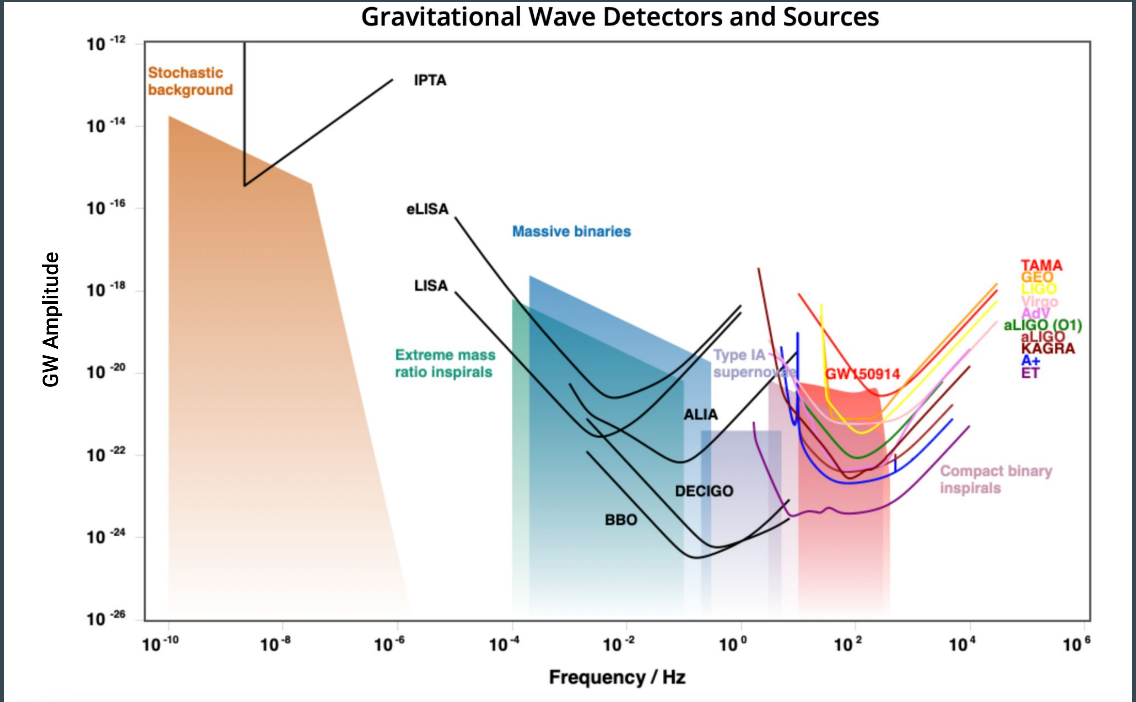
Generating the GW Signal

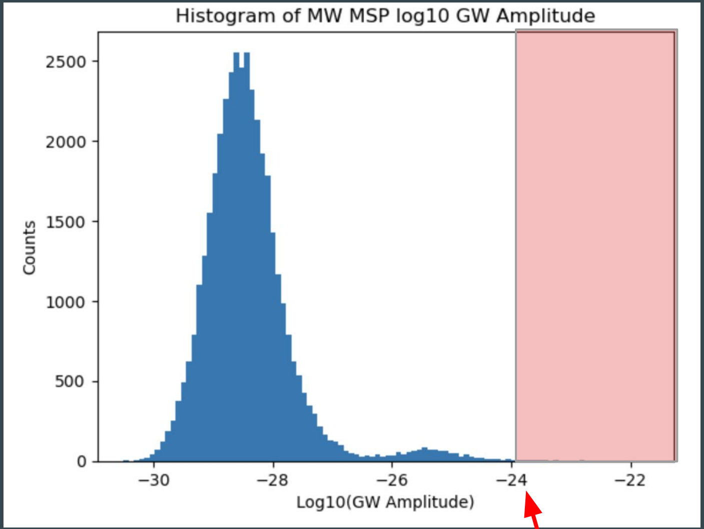




Analysis and Possibility of Detection Pt. I

- GW amplitudes on the order of $10^{-24} - 10^{-20}$





Max. Sensitivity

Analysis and Possibility of Detection Pt. II

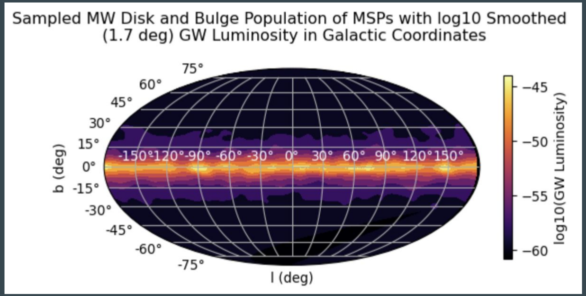
No Detector Constraints

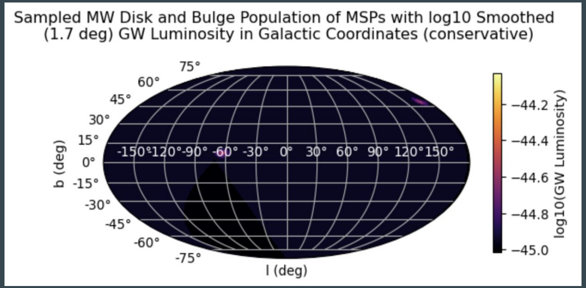
Conservative Constraints

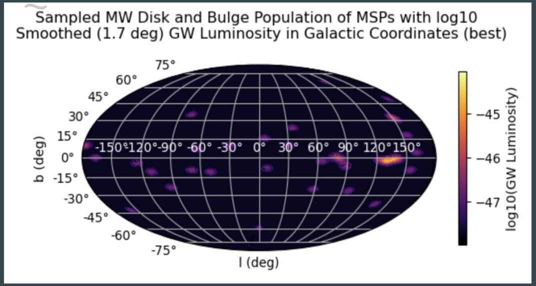
$> \sim 10^{-23}$ (aVIRGO, aLIGO, Kagra)

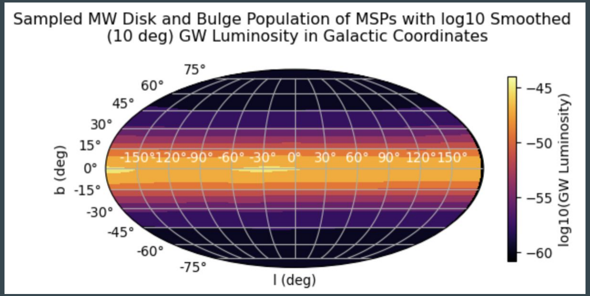
Optimal Constraints

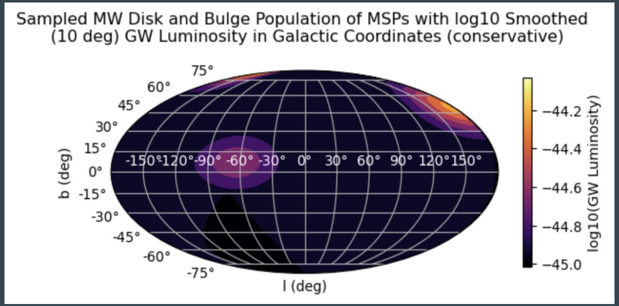
$> \sim 10^{-24}$ (ET)

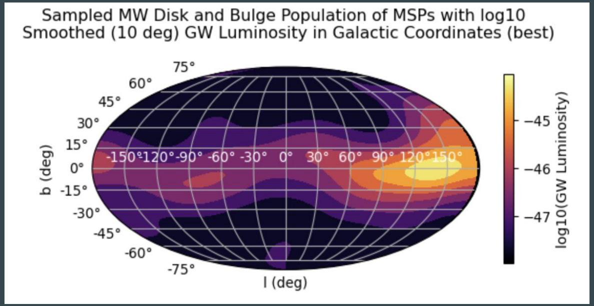




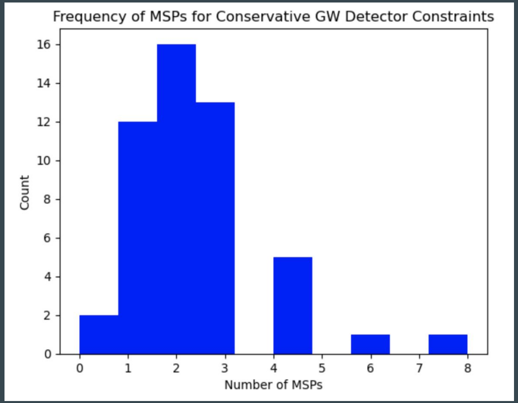


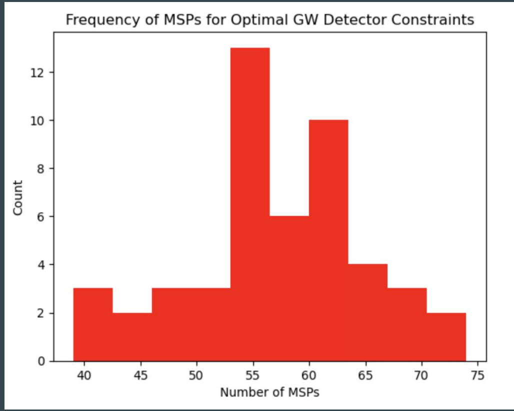






Analysis and Possibility of Detection Pt. III

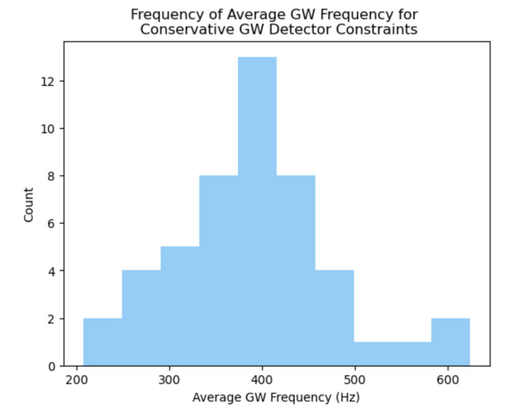


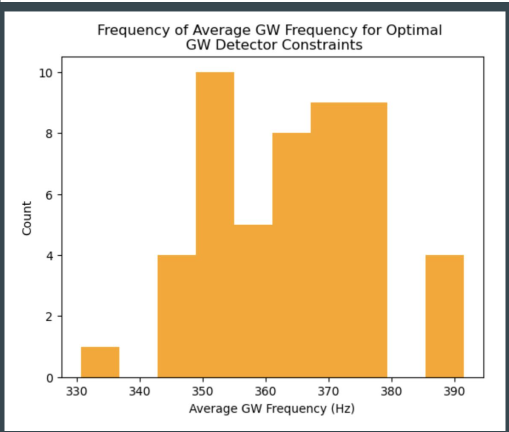


Ave. Number of MSPs detectable:

Conservative: 2

Optimal: 57





Ave. GW Frequency detectable:

Conservative: 390 Hz

Optimal: 360 Hz

Conclusion

- Only Advanced LIGO/Virgo (with sensitivities above ~$3 \cdot 10^{-23}$), Kagra (with sensitivities above ~ 10^{-23}), and ET (with sensitivities above ~ 10^{-24}) would be capable of detecting the GW signal
- if MSPs are responsible for the GCE, then between ~2–57 pulsars should be detectable on average with a corresponding GW frequency range of 360-390 Hz
- GW detectors sensitive to frequencies in the hundreds of hertz, sensitive to gravitational waves from MSPs, must see at least a few MSPs, otherwise there are strong constraints placed on MSP's contribution to the GCE
- Future work: get a more robust statistical picture of our population of MSPs and the corresponding detectability

References

Sources:

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Yoichi Aso et al. “Interferometer design of the KAGRA gravitational wave detector”. In: Physical Review D 88.4 (Aug. 2013). issn: 1550-2368. doi:10.1103/physrevd.88.043007. url:http://dx.doi.org/10.1103/PhysRevD.88.043007.
Samuel Rowlinson et al. “Feasibility study of beam-expanding telescopes in the interferometer arms for the Einstein Telescope”. In: Physical Review D 103.2 (Jan. 2021). issn: 2470-0029. doi:10.1103/physrevd.103.023004. url:http://dx.doi.org/10.1103/PhysRevD.103.023004

Images (slides 1–5):

https://arxiv.org/abs/1402.6703

https://commons.wikimedia.org/wiki/File:Pulsar_2.jpg

Searching for gravitational waves produced by cosmic strings in LIGO-Virgo data - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Effect-of-a-passing-gravitational-wave-propagating-in-the-z0-plan-with-plus_fig4_342436340 [accessed 14 May, 2024]

https://upload.wikimedia.org/wikipedia/commons/f/f5/LISA-waves.jpg

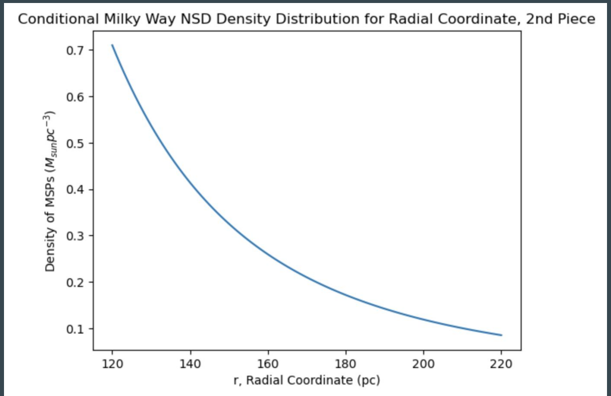
Methods of Sampling

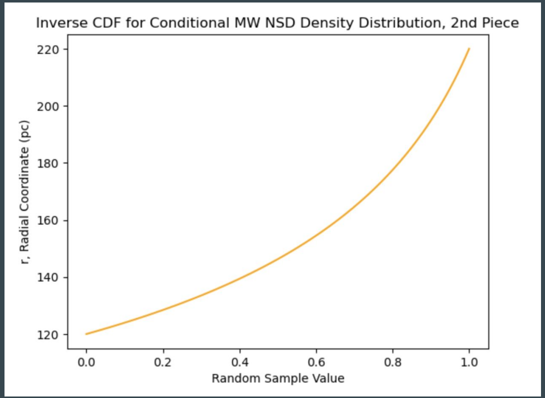
Monte Carlo Markov Chain (MCMC) Sampling

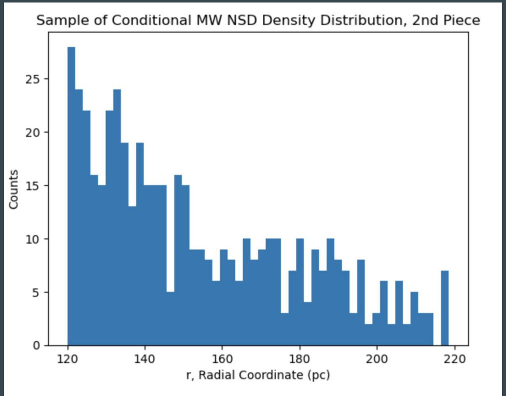
- Method for generating a sample from a given distribution using a number of random walkers

Inverse Transform Sampling

- Method for generating a sample from a given distribution using the inverse CDF of a function







Sampling a 2D Distribution

- 2-variable functions are hard to sample → we need a way to hold one variable constant while sampling the other
- Split the function to be sampled into 2 conditional functions f(x|y) and f(y|x)