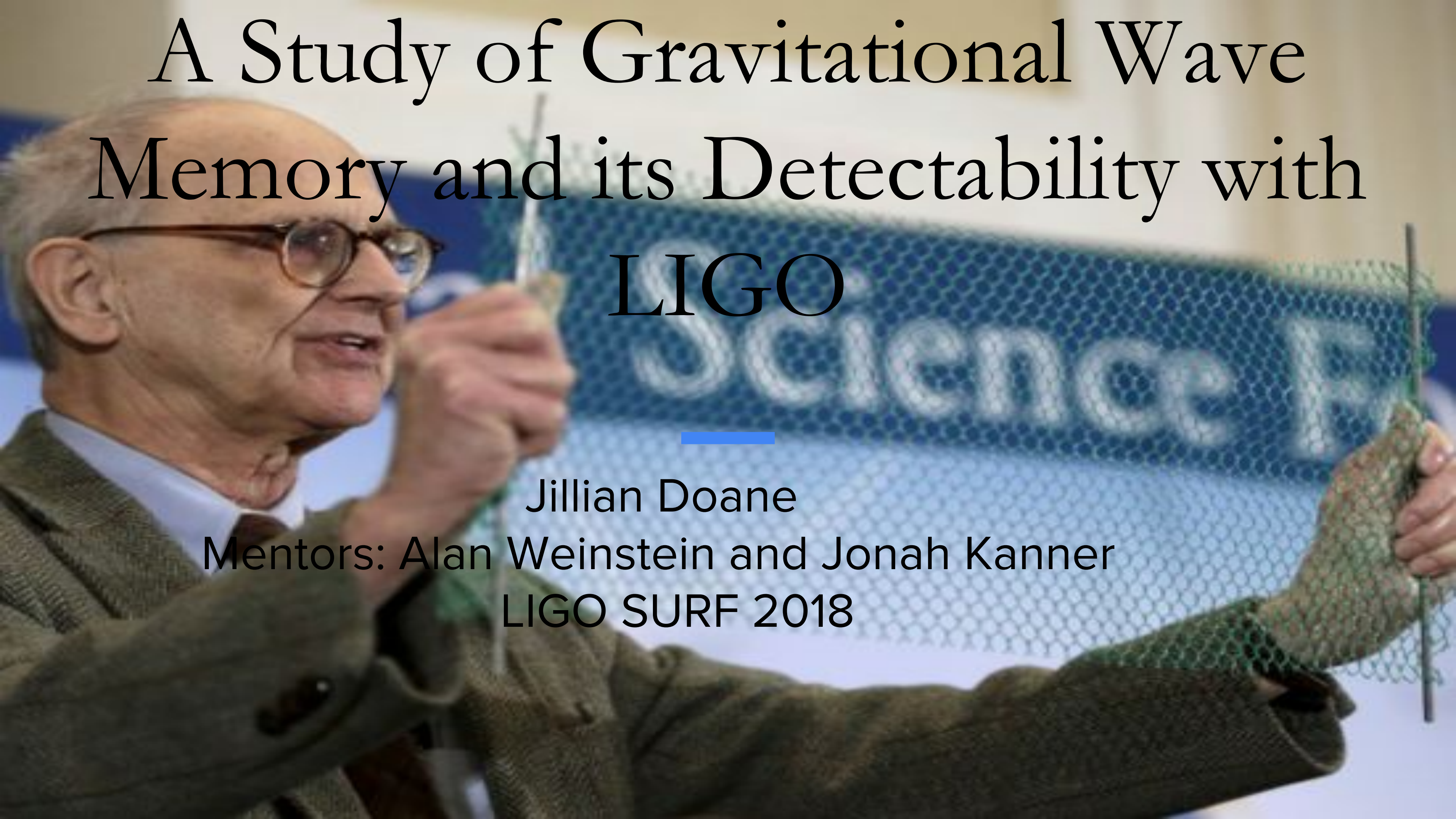

A Study of Gravitational Wave Memory and its Detectability with LIGO

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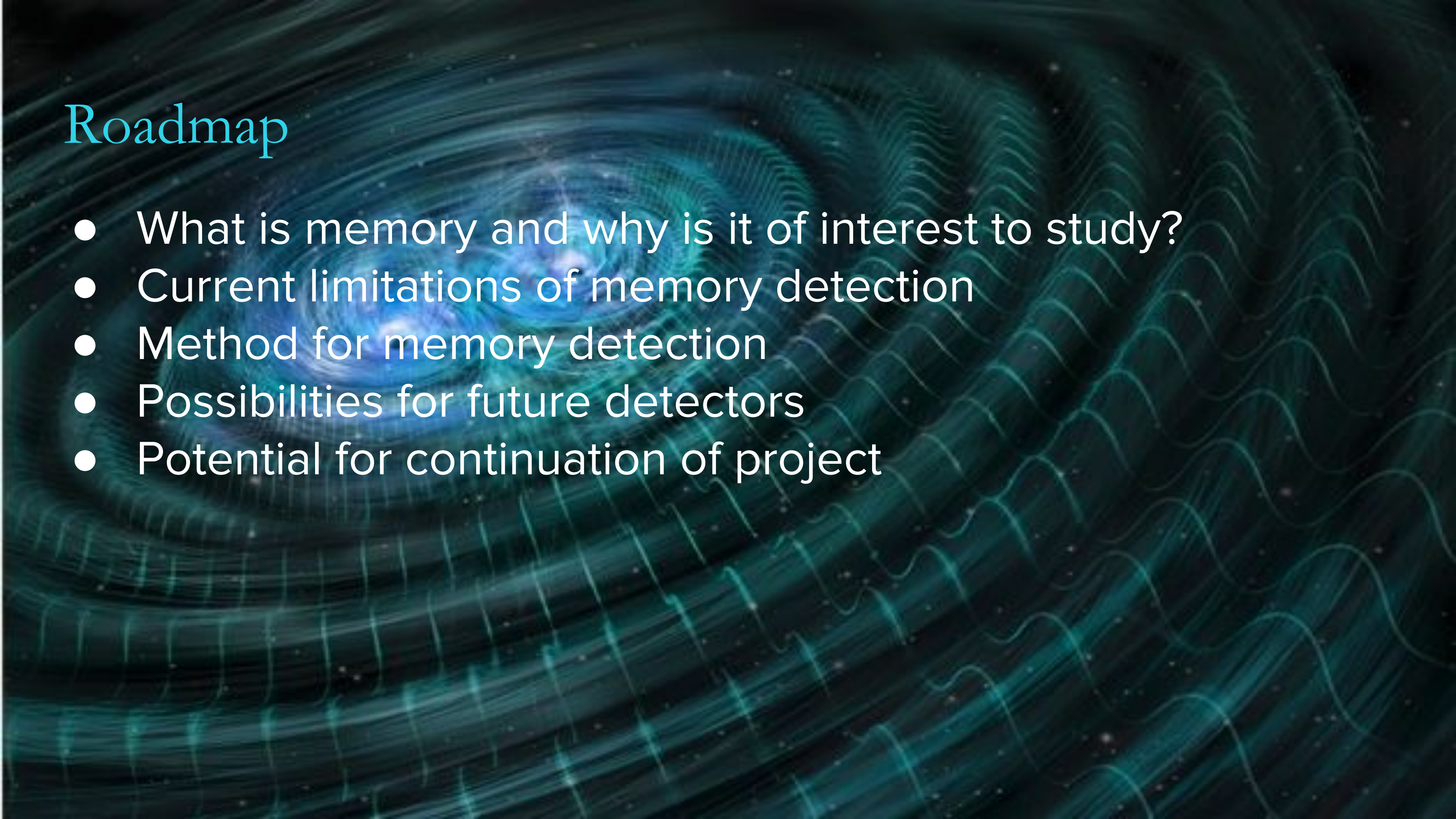
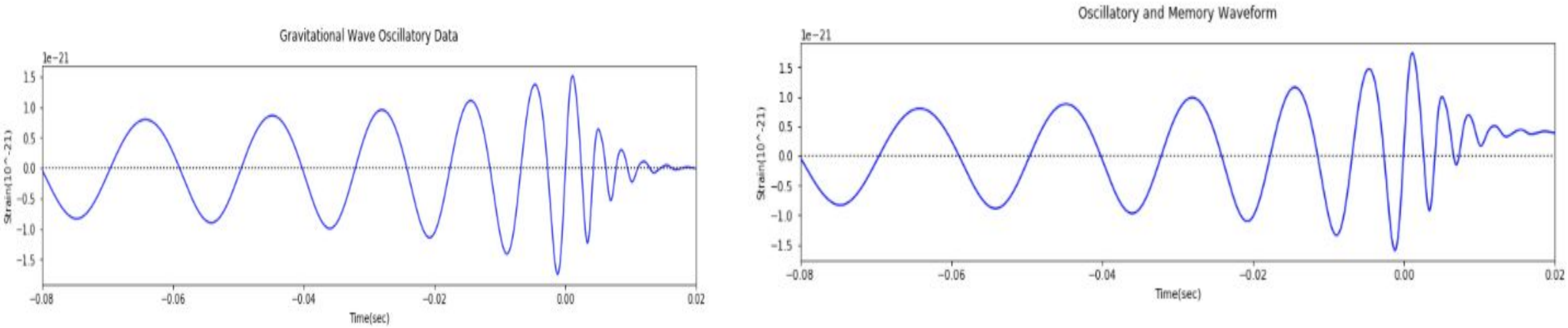
Mentors: Alan Weinstein and Jonah Kanner
LIGO SURF 2018



Roadmap

- What is memory and why is it of interest to study?
- Current limitations of memory detection
- Method for memory detection
- Possibilities for future detectors
- Potential for continuation of project

What is Memory?



Waveform showing oscillatory binary black hole merger waveform with memory (solid blue line) and without memory (--line). Made with package GWMemory from “Gravitational-wave Memory: Waveforms and Phenomenology”

-A gravitational wave contains an oscillatory and memory component.
-Post ringdown values of one of the polarizations is non-zero.
-Permanent warping of spacetime left behind by a passing oscillatory wave.
-Christodoulou memory

Why Is Memory Of Interest to Study?

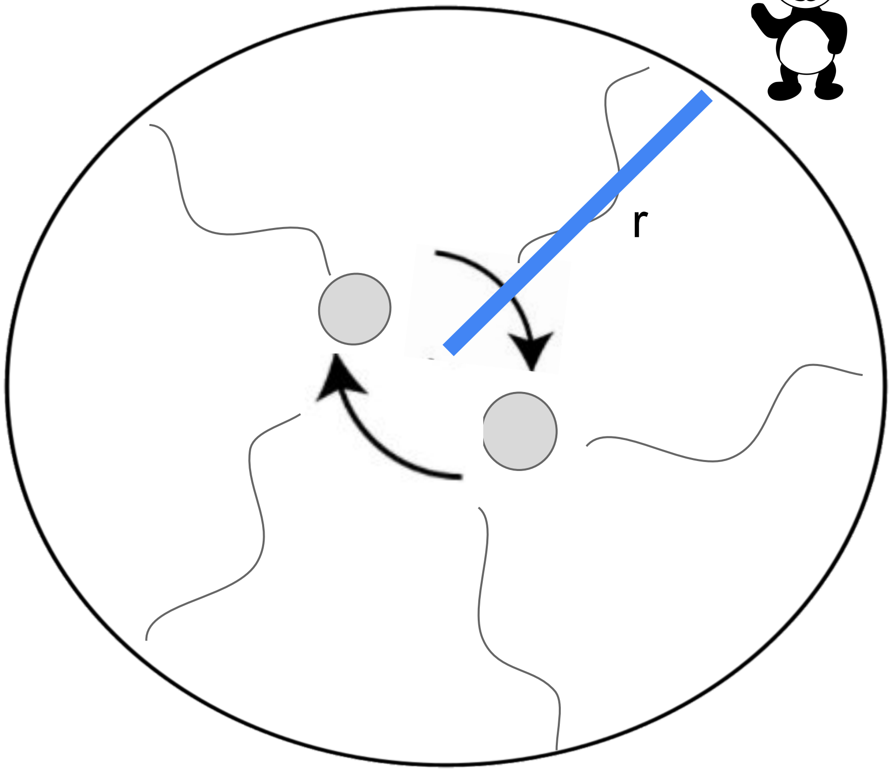
- Opportunity to test a firm prediction of General Relativity.
- Enters the waveform at a non-negligible order.
- Adds a unique signature to the GW waveform.
- Warping of space sourced by the warping of space.
- Has potential to give us a clearer picture of objects in our universe, specifically black holes.

How Can We Picture Memory?

$$\Delta h_{jk}^{TT} = \Delta \sum_{A=1}^{N} \frac{4M_A}{r\sqrt{1-v_A^2}} \left[\frac{v_A^j v_A^k}{1 - v_A \cos\theta_A} \right]^{TT}$$

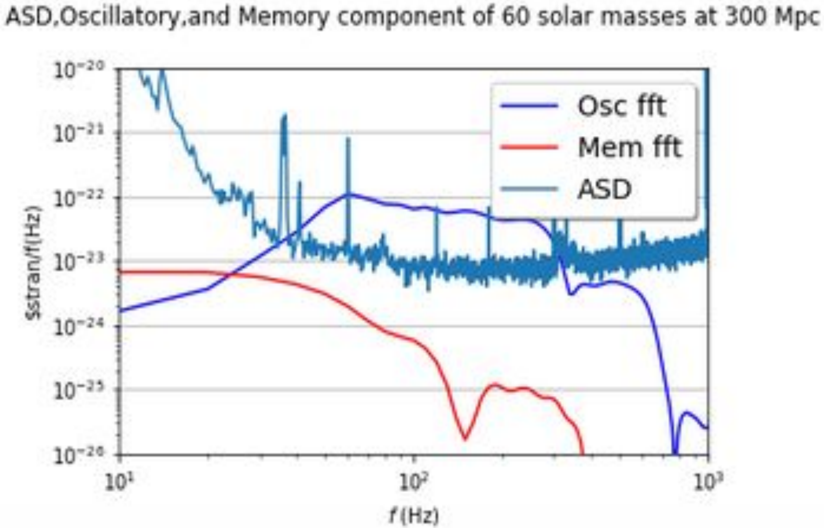
- $\Delta h \sim \frac{\Delta E_{gw}}{r} \longrightarrow e = mc^2$

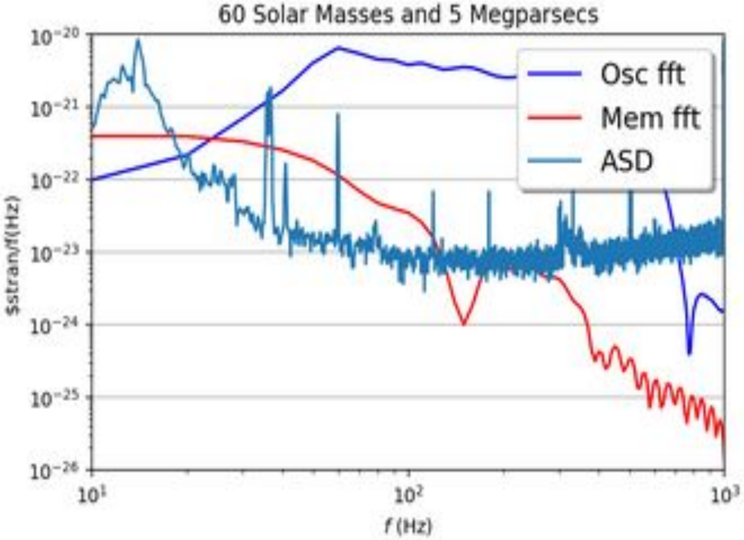
- Mass and energy have left the system
- Curvature of spacetime has changed



Why is Memory Difficult to Detect?

- Smaller than the oscillatory component of gravitational waves
- Significantly lower frequency.
- Low frequency detector noise.
- Detector sensitivity improvements needed


ASD,Oscillatory,and Memory component of 60 solar masses at 300 Mpc


60 Solar Masses and 5 Megparsecs

Method of Detection

- Surrogate Model - composed of numerical relativity models.
- Set of data
  - S = Oscillatory + Memory
- Create a template
  - Multiply memory by parameter
  - H = Oscillatory + λMemory
  - Goal: Test the value of lambda

$P(\lambda)$ Prior : Probability distribution of the parameters

- [-10, 10, 0.1]

$$P(d|\lambda) = e^{-1/2(s-h(\lambda)|s-h(\lambda))}$$

Normalization: $\int P(d|\lambda)P(\lambda)$

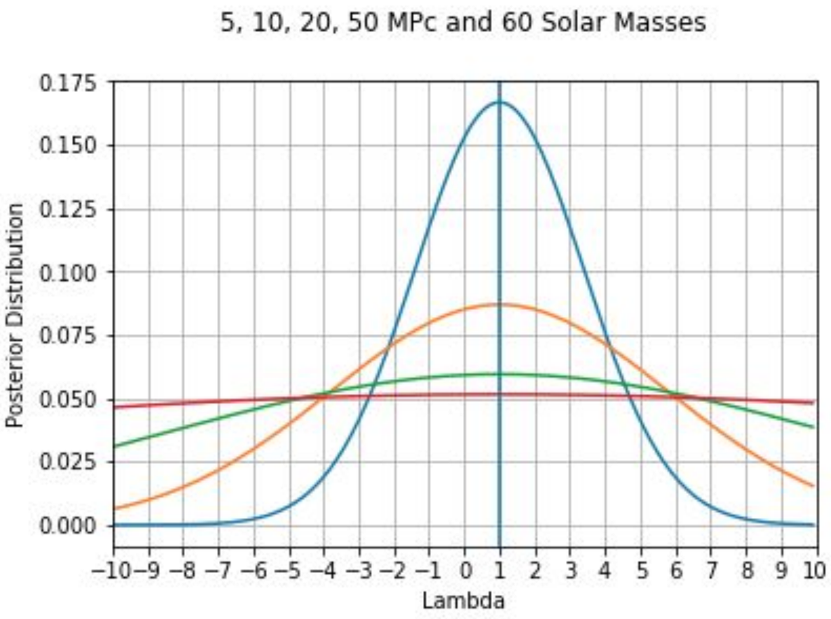
$P(\lambda|d)$ Probability of a certain parameter given data with a certain model

Bayes Theorem: $$P(\lambda|d) = \frac{P(d|\lambda)\,P(\lambda)}{\int P(d|\lambda)P(\lambda)}$$

Noise weighted inner product

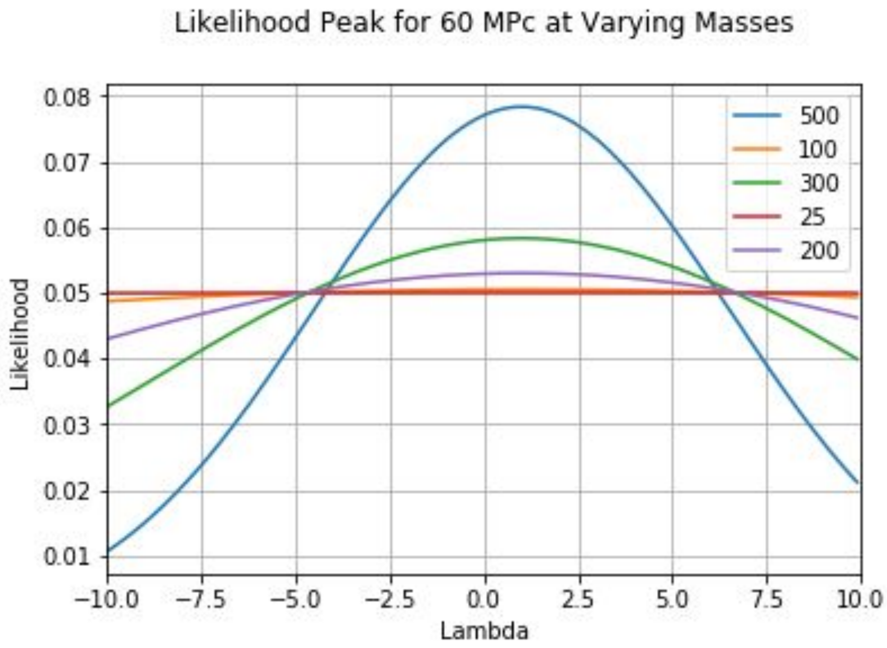
Posterior Probability Distribution Function (Varying Distances)

- The lower the distance, the higher the SNR
- The higher the SNR, the narrower the peak



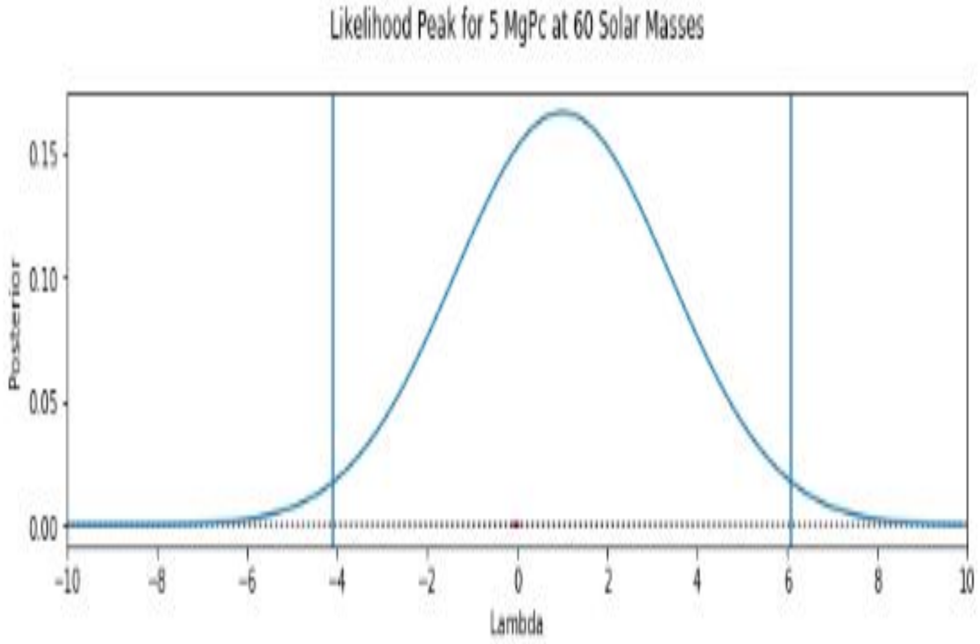
Likelihood Peak (Varying Masses)

- Larger the mass, larger the amplitude of the signal.
- However smaller mass binaries merge at a higher frequency. Also rate per unit volume is higher for neutron star mergers.
- Higher amplitude is more important in memory detection than closer, smaller mass systems.



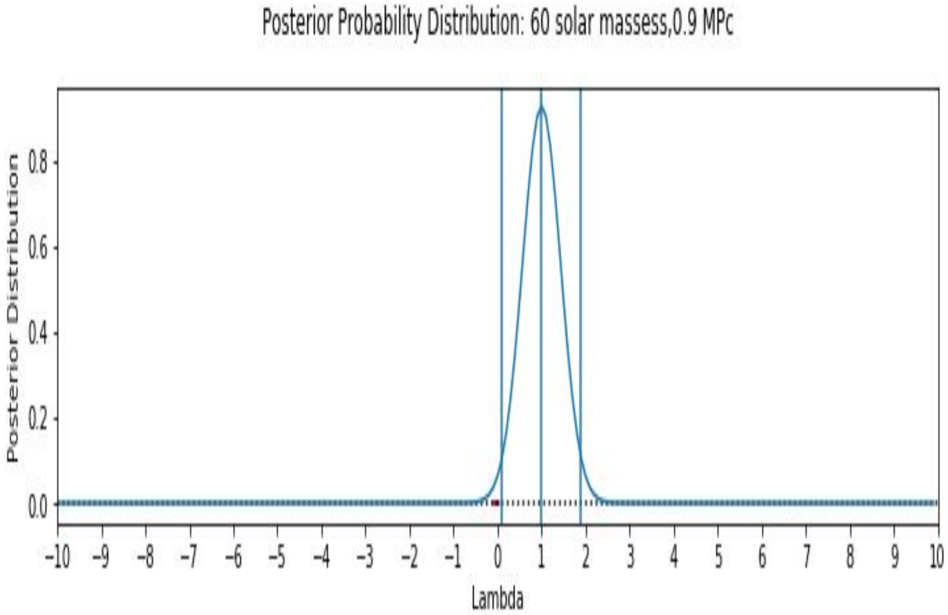
90% Confidence Interval - 5 Megaparsecs

- Confidence interval: -4.1 to 6.1
- Unfortunately, zero is included in this specific confidence interval.

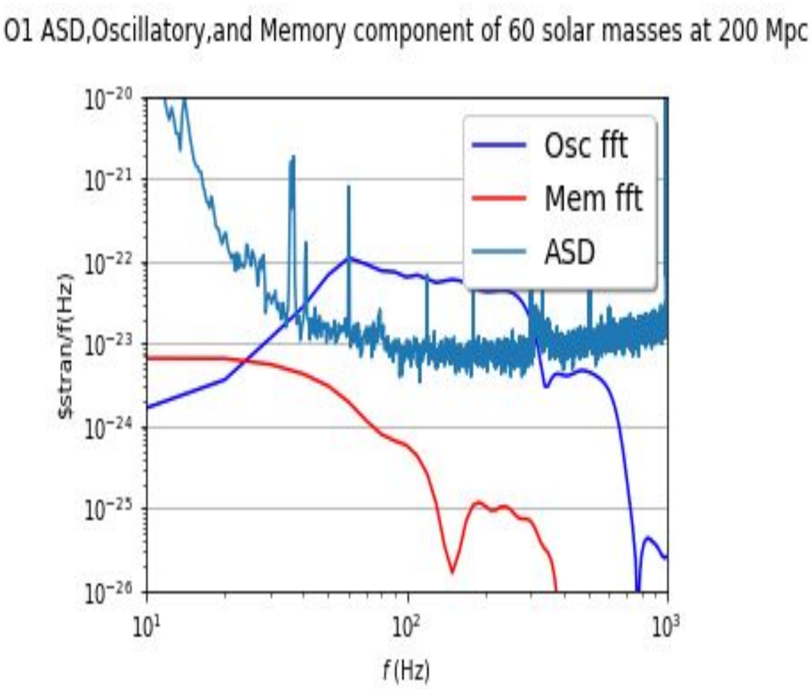


90% Confidence Interval - 0.8 Megaparsecs

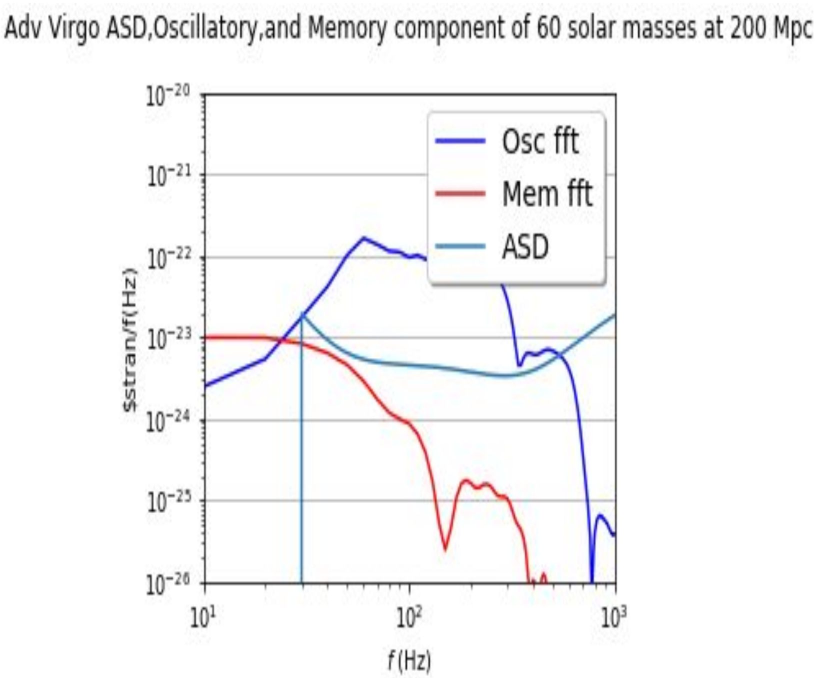
- Confidence Interval: 0.1 to 1.9
- Zero is not included!
- While 0.8 megaparsecs is not very far, more sensitive detectors can extend this distance.



Future Detectors



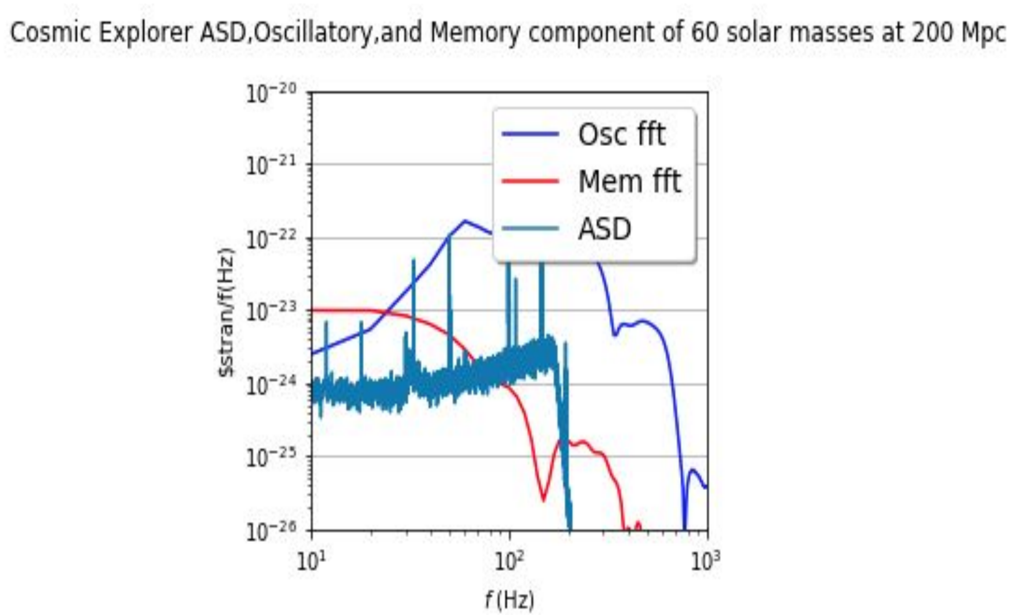
O1 ASD,Oscillatory,and Memory component of 60 solar masses at 200 Mpc



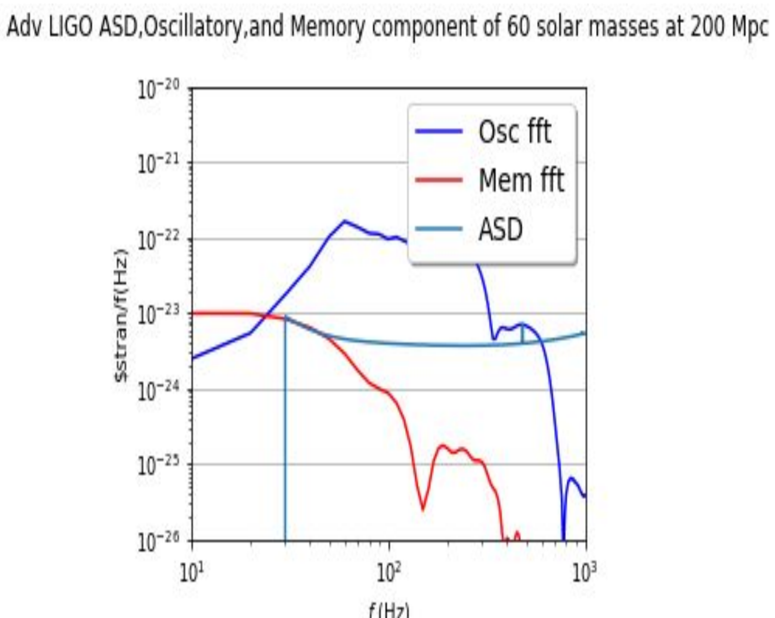
Adv Virgo ASD,Oscillatory,and Memory component of 60 solar masses at 200 Mpc

Future Detectors

- SNR scales with distance
- Cosmic Explorer is ten times more sensitive than Advanced LIGO; can detect events ten times farther.

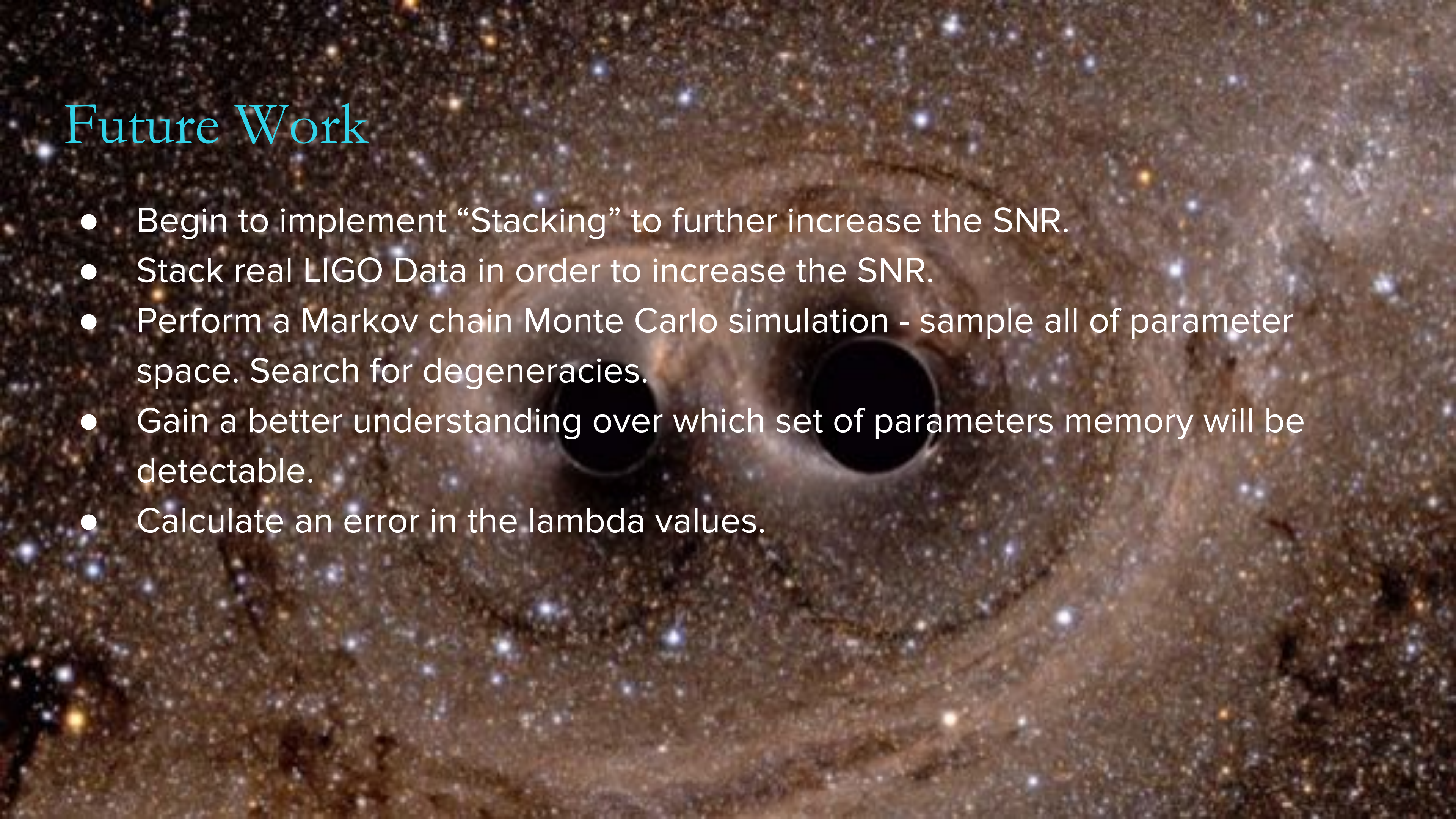


Cosmic Explorer ASD,Oscillatory,and Memory component of 60 solar masses at 200 Mpc

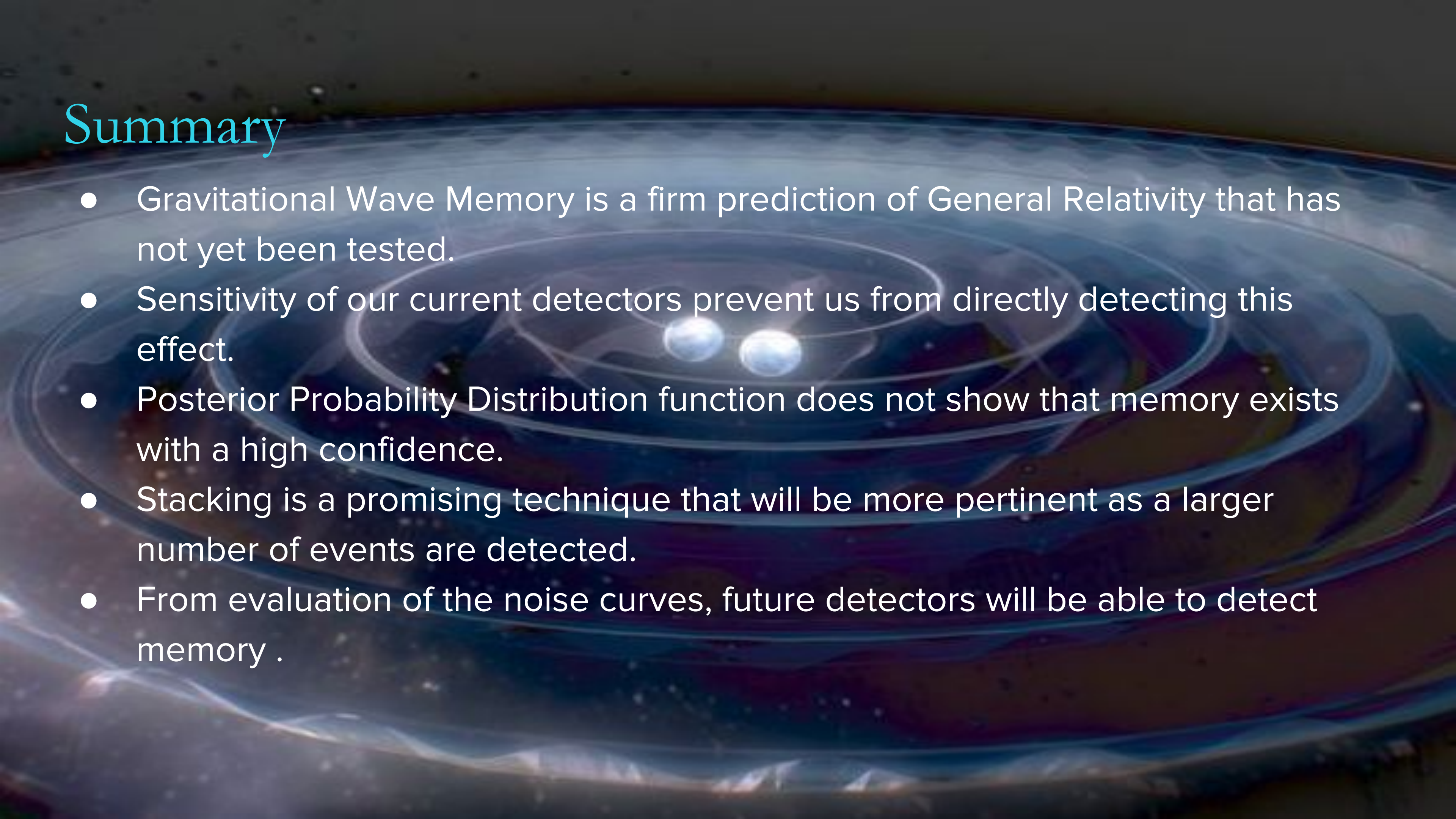


Adv LIGO ASD,Oscillatory,and Memory component of 60 solar masses at 200 Mpc

Future Work



- Begin to implement “Stacking” to further increase the SNR.
- Stack real LIGO Data in order to increase the SNR.
- Perform a Markov chain Monte Carlo simulation - sample all of parameter space. Search for degeneracies.
- Gain a better understanding over which set of parameters memory will be detectable.
- Calculate an error in the lambda values.



Summary

- Gravitational Wave Memory is a firm prediction of General Relativity that has not yet been tested.
- Sensitivity of our current detectors prevent us from directly detecting this effect.
- Posterior Probability Distribution function does not show that memory exists with a high confidence.
- Stacking is a promising technique that will be more pertinent as a larger number of events are detected.
- From evaluation of the noise curves, future detectors will be able to detect memory .

Acknowledgments

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