TESTING THE STRONG-FIELD DYNAMICS OF GENERAL RELATIVITY USING COMPACT BINARY SYSTEMS

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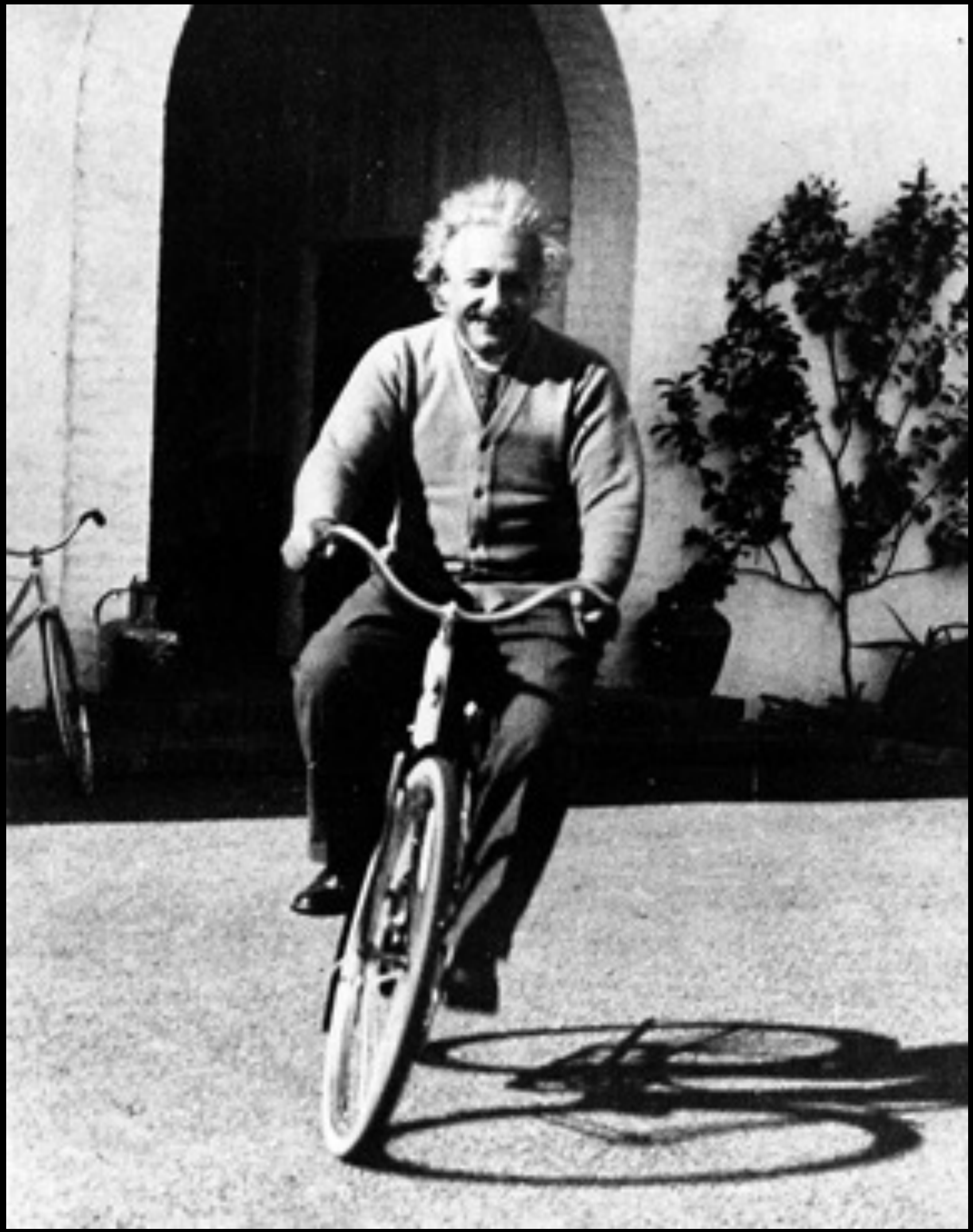
OBJECTIVE

This investigation aims to assess the ability to test and constrain deviations from GR by analyzing gravitational waves from detected binary black hole mergers in the presence of expected statistical and systematic errors.

OVERVIEW

- Introduction
  - GENERAL RELATIVITY
  - ALTERNATIVE THEORIES
  - COMPACT BINARIES
- Methods
  - IMRPHENOM-C APPROXIMANT
  - GENERIC MODIFICATIONS
  - MATCHED FILTERING
  - BAYESIAN INFERENCE
- Results
  - STANDARD GR WAVEFORMS
  - MODIFIED WAVEFORMS
  - OVERLAP STUDIES
  - PARAMETER ESTIMATION
- Conclusion
  - IMPLICATIONS FOR ADV. LIGO
  - FUTURE WORK



"ALBERT EINSTEIN RIDES HIS BIKE IN SANTA BARBARA, CALIFORNIA, IN 1933"

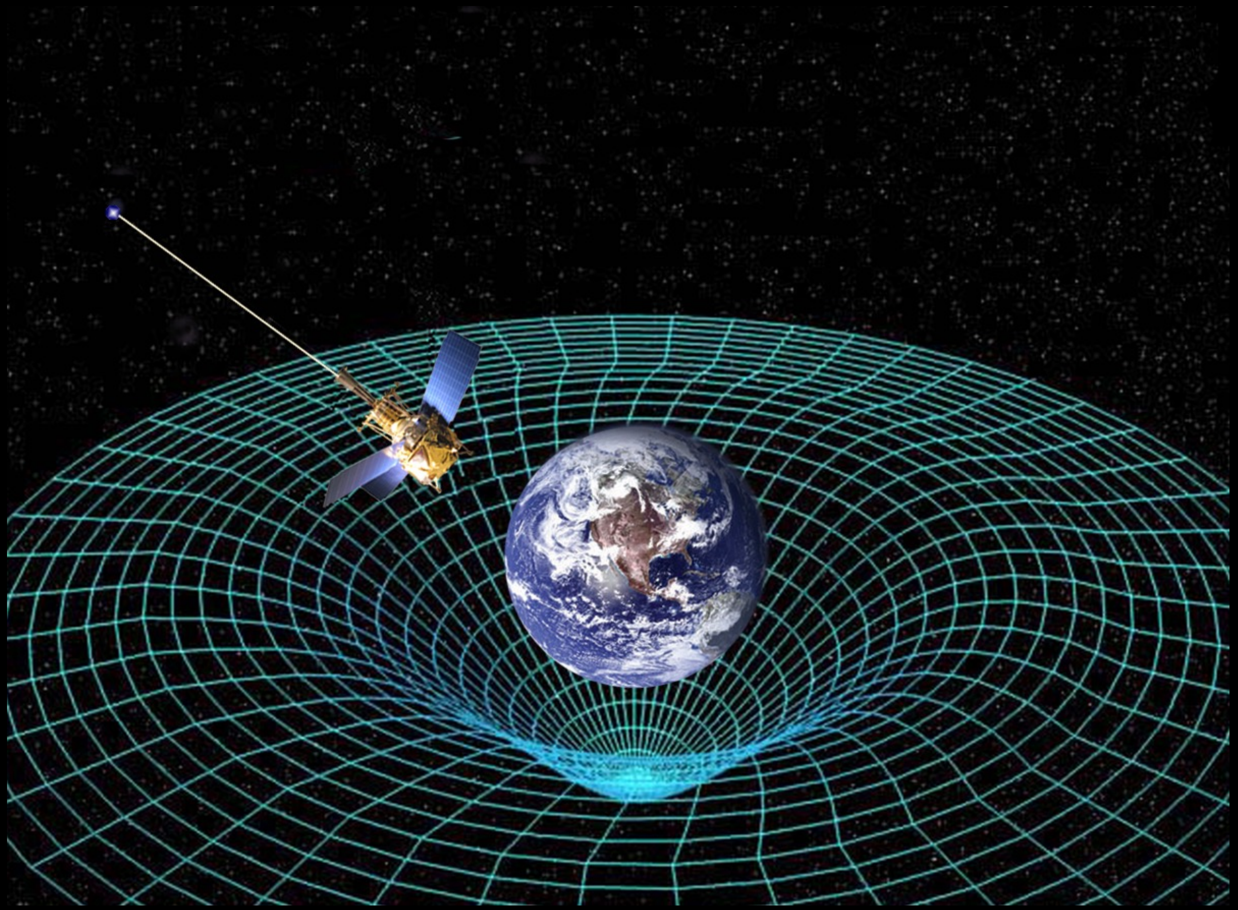
INTRODUCTION

- General Relativity (GR) is a theory of gravity originally proposed by Albert Einstein in 1915 to generalize special relativity and Newton's law of universal gravitation.

- Acceleration of massive bodies.

- Prediction of gravitational waves, lensing, time delay.

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Credit: NASA

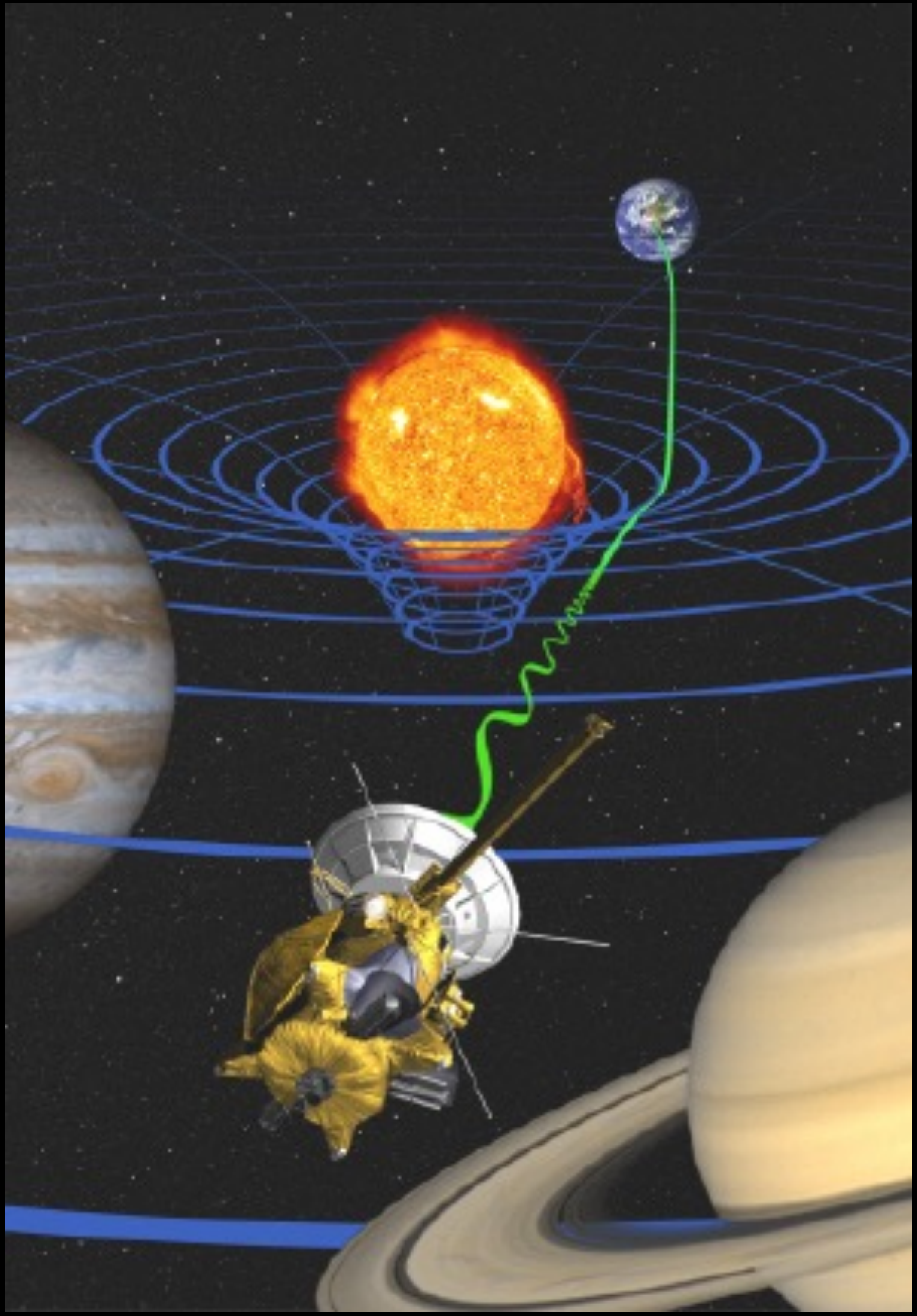
INTRODUCTION

- Alternative theories of gravity predict behavior that may differ from GR in strong-field. Constraints have been placed on plausible alternatives [1].

- Brans-Dicke scalar tensor theory predicts dipole radiation [2,3,4].

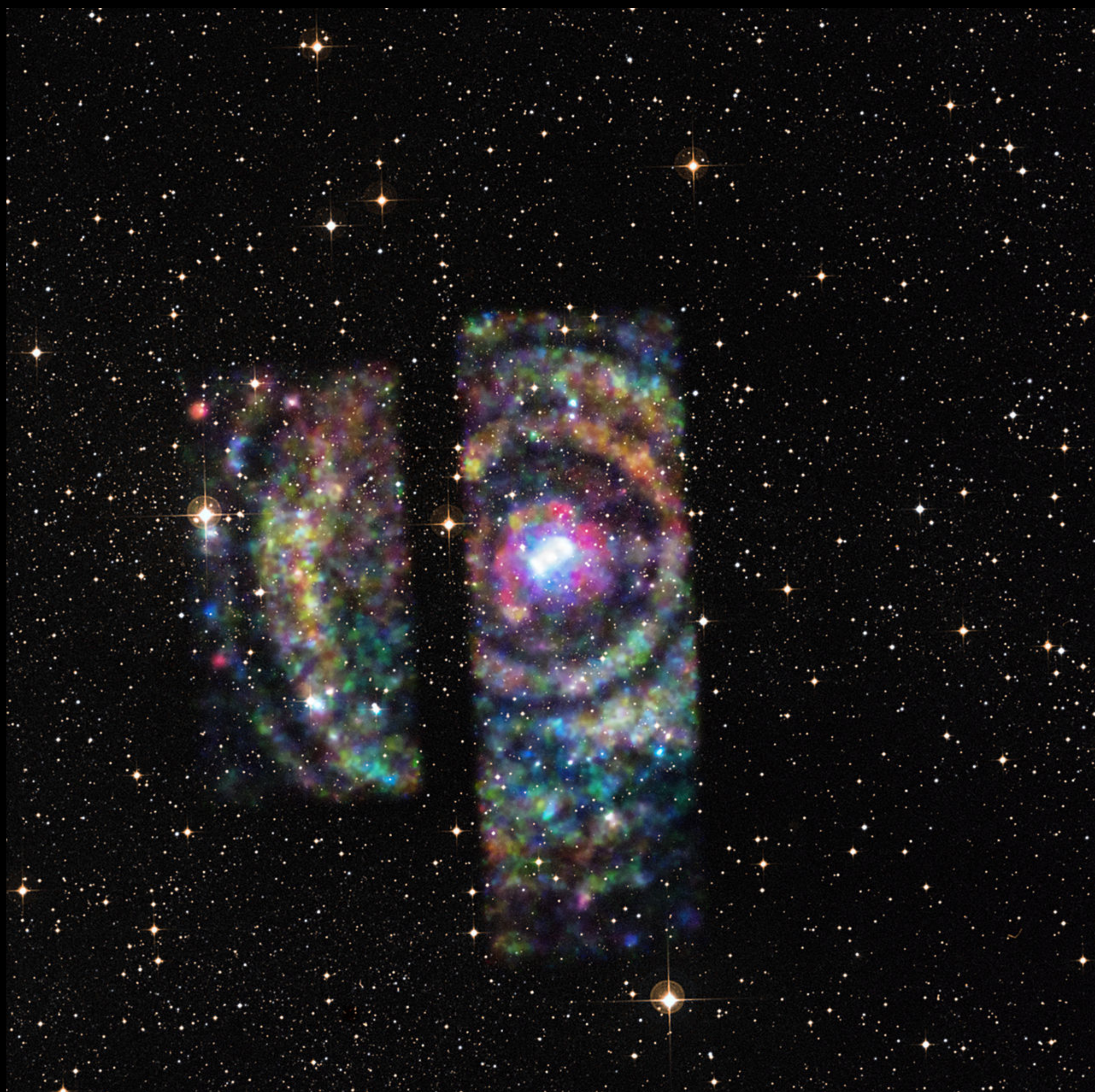
$$\dot{E} = \dot{E}_{\mathrm{GR}} + \dot{E}_{\mathrm{BD}}$$

- Alternatives agree with GR in weak-field (perihelion shift of Mercury, Hulse-Taylor binary pulsar, etc.).



Credit: NASA JPL 2003

INTRODUCTION



Circinus X-1: X-ray light rings from a binary neutron star

Credit: X-ray: NASA/CXC/Univ. of Wisconsin-Madison/S. Heinz, et al.; Optical: DSS

- Compact binaries consist of neutron star or black hole pairs provide direct tests of GR.

$$\epsilon \sim GM/Rc^2$$

$$\epsilon_{\text{weak}} \sim 10^{-6} \text{ (Solar system)}$$
$$\epsilon_{\text{strong}} \sim 0.2 \text{ (Neutron Stars)}$$

- Last seconds of coalescence are in strong-regime, contrary to all other tests carried out so far.

$$\bar{v}_{\text{Mercury}}/c \sim 10^{-4}$$
$$v_{\text{NS}}/c \sim 0.41$$

METHODS

- Simulate GW signals using a phenomenological waveform approximant IMRPhenomC [5].
  - Focus our study on binary black hole (BBH) mergers with total mass from 20 to 200 solar masses.
- Perform generic modifications to the waveform:

$$\psi_i^{\mathrm{nGR}} = \psi_i^{\mathrm{GR}}[1 + \alpha_{\mathrm{nGR}}] \ .$$

Credit: Bohn et al. 2015

- The physical parameters calculated in IMRPhenomC are modified such as: ringdown frequency, pre-merger amplitude etc.

METHODS

- Matched Filtering - How well does waveform ‘A’ *match* waveform ‘B’

$$\langle A|B\rangle = 4\Re \int_{-\infty}^{+\infty} \frac{\widetilde{A}(f)\widetilde{B}^*(f)}{S_n(f)} df \ ,$$

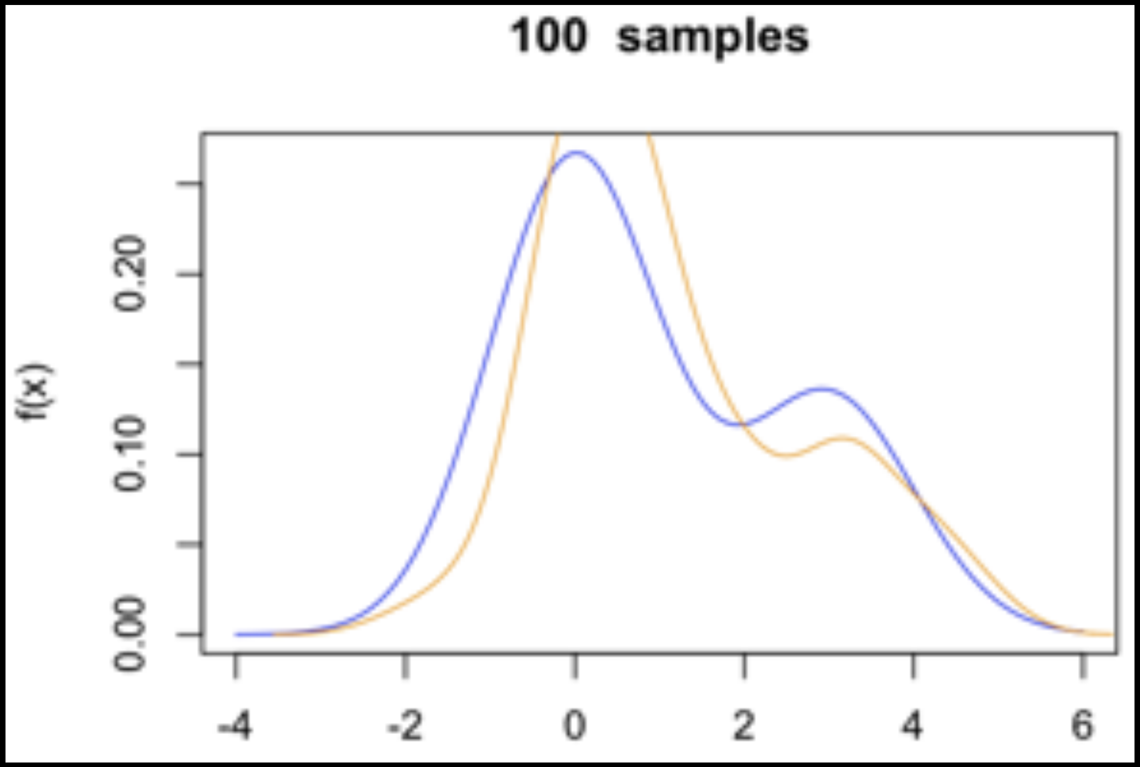
$$\mathrm{Match} = \mathrm{max}_{\{\phi_0, \mathrm{t}_0\}} \frac{\langle \mathrm{A}|\mathrm{B}\rangle}{\sqrt{\langle \mathrm{A}|\mathrm{A}\rangle \langle \mathrm{B}|\mathrm{B}\rangle}} \ .$$

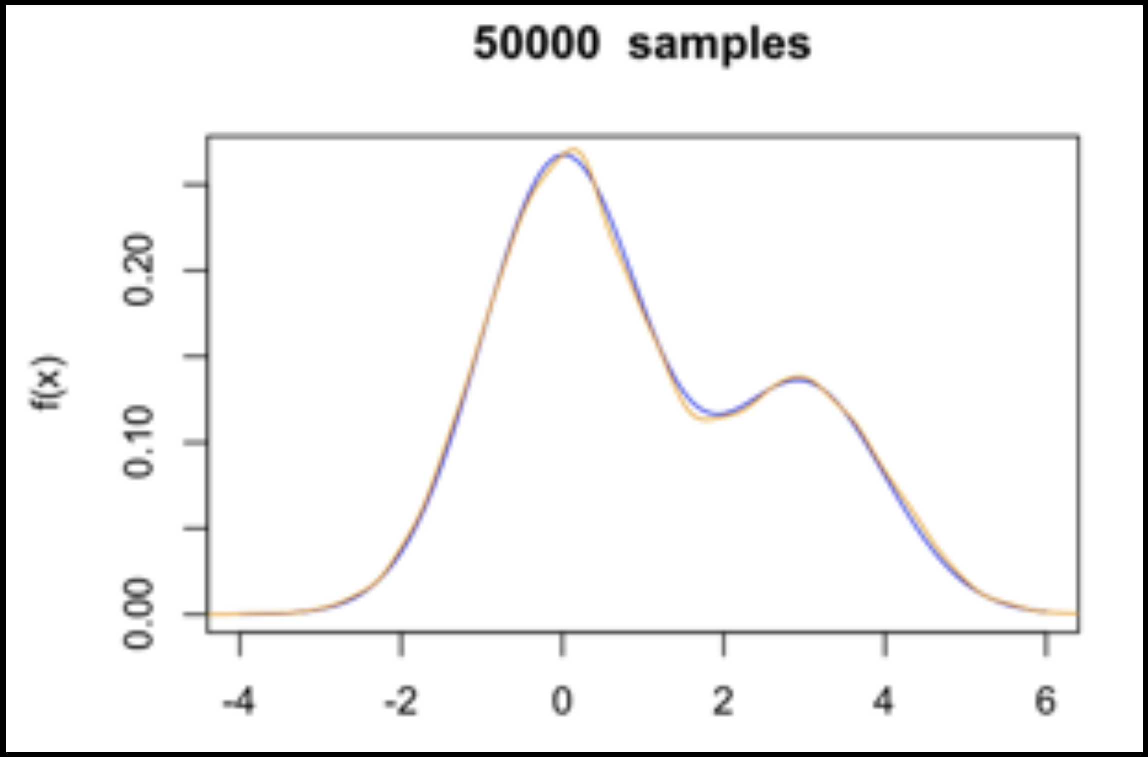
- Bayesian Inference - Based on the evidence, and in the context of a particular theory, how well can we estimate the parameters.

$$\mathrm{Posterior\ probability} \propto (\mathrm{Likelihood} \times \mathrm{Prior})$$

METHODS

- Markov chain Monte Carlo - estimate a posterior by stochastically wandering through the parameter space





Convergence of the Metropolis-Hastings algorithm. MCMC attempts to approximate the blue distribution with the orange distribution : Using R; FOSS statistical software.

RESULTS - STANDARD GR

- Non-Spinning equal mass ratio BBH systems, at a distance of D = 16Mpc.
- Largest amplitude with greater than 160 Msun at 100 (Hz).

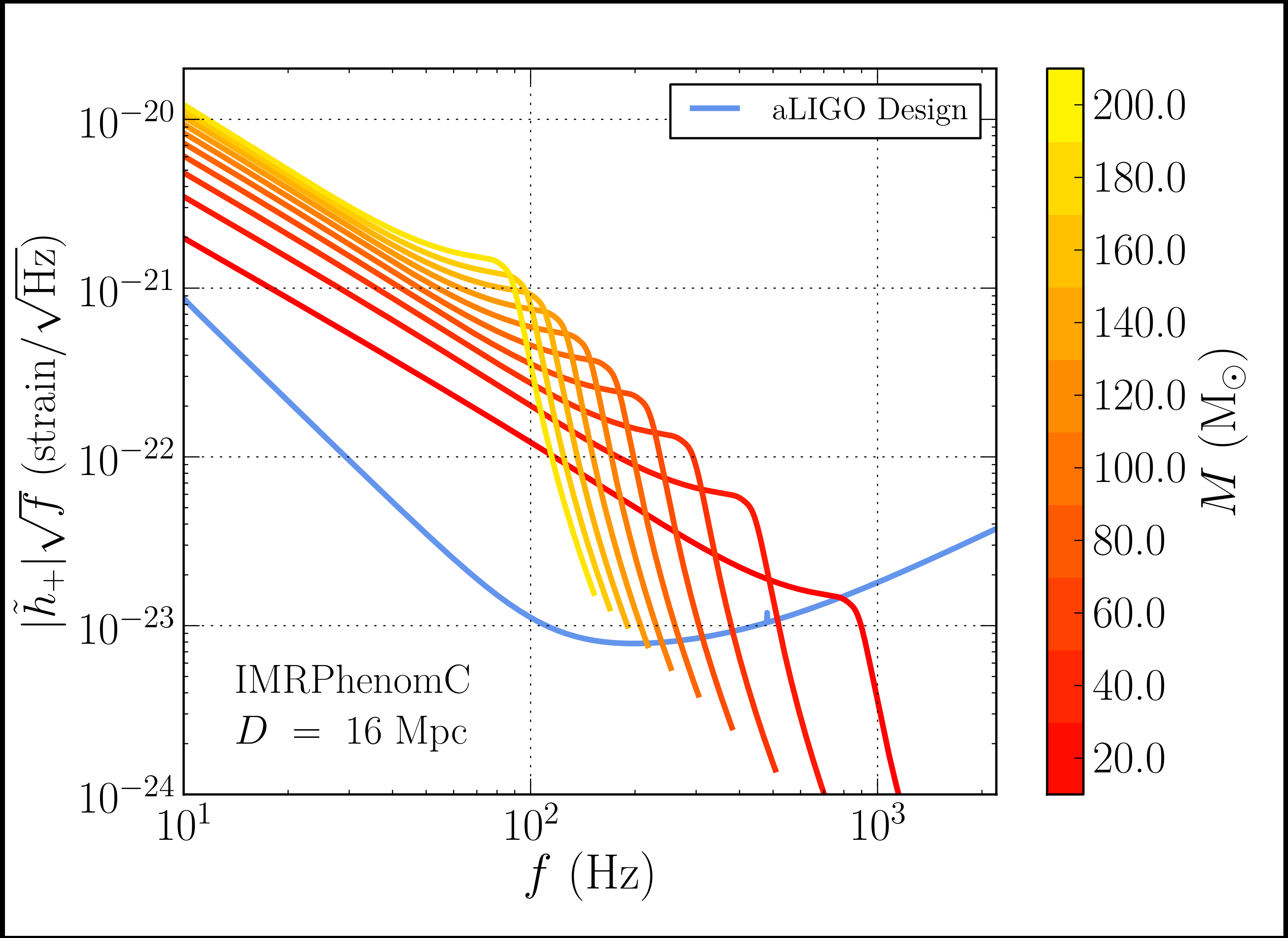


FIG1 - Diagram showing the inspiral, merger, and ringdown gravitational wave strain as a function of frequency for a set of different systems.

RESULTS - MODIFIED WAVEFORM

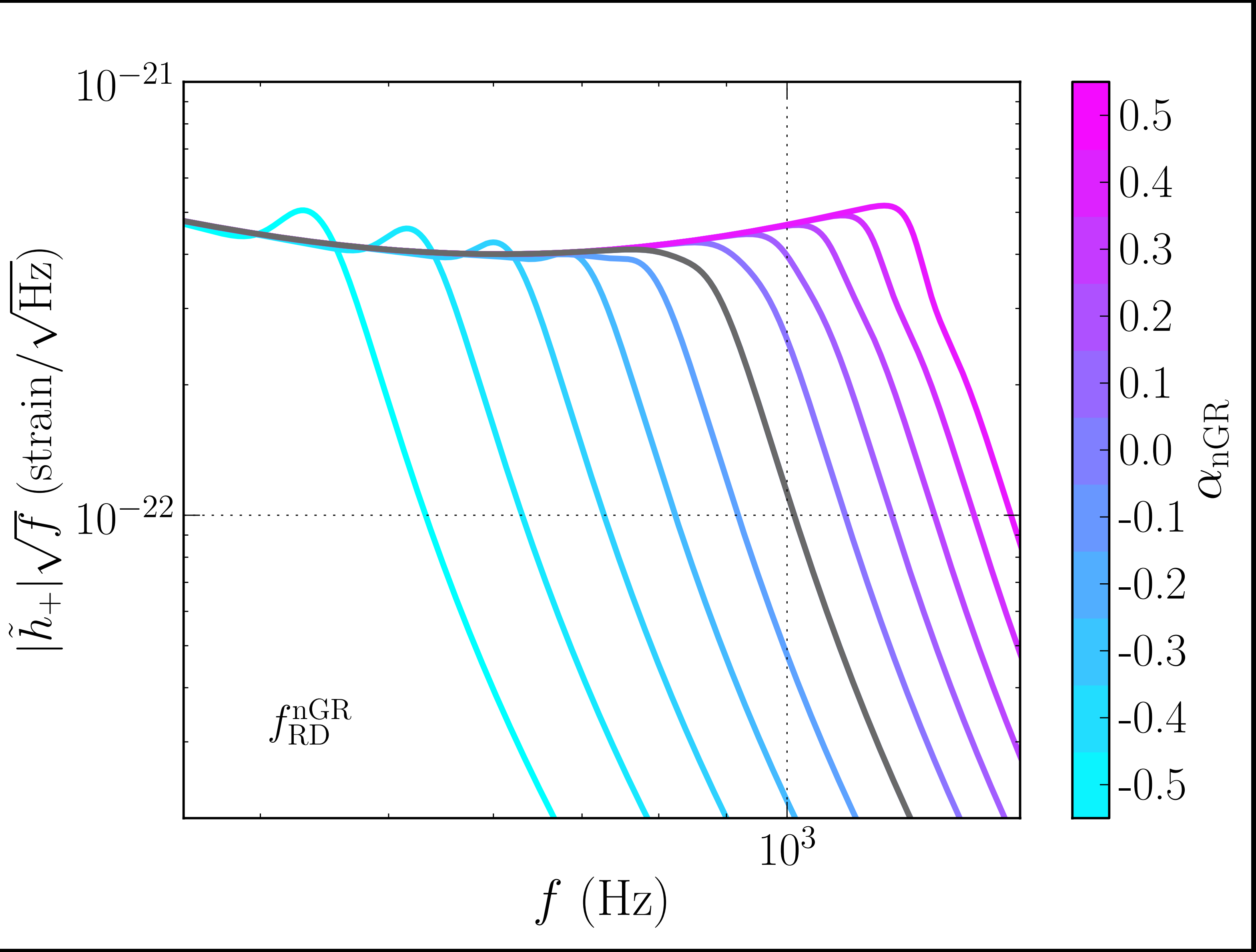


FIG.2 - A figure showing the modified strain as a function of frequency for a system with total mass, M = 20Msun. The gray line represents the GW for alpha_nonGR = 0.

- Modified ringdown frequency for a 20 solar mass non-spinning BBH using IMRPhenomC.

$$f_{\rm RD}^{\rm nGR} = f_{\rm RD}[1 + \alpha_{\rm nGR}] \ .$$

- Monotonic shift in ringdown frequency.

RESULTS - OVERLAP STUDIES

- Low mass systems can have small deviations and still match GR waveform well.

- Loss of SNR is greater for higher mass systems.

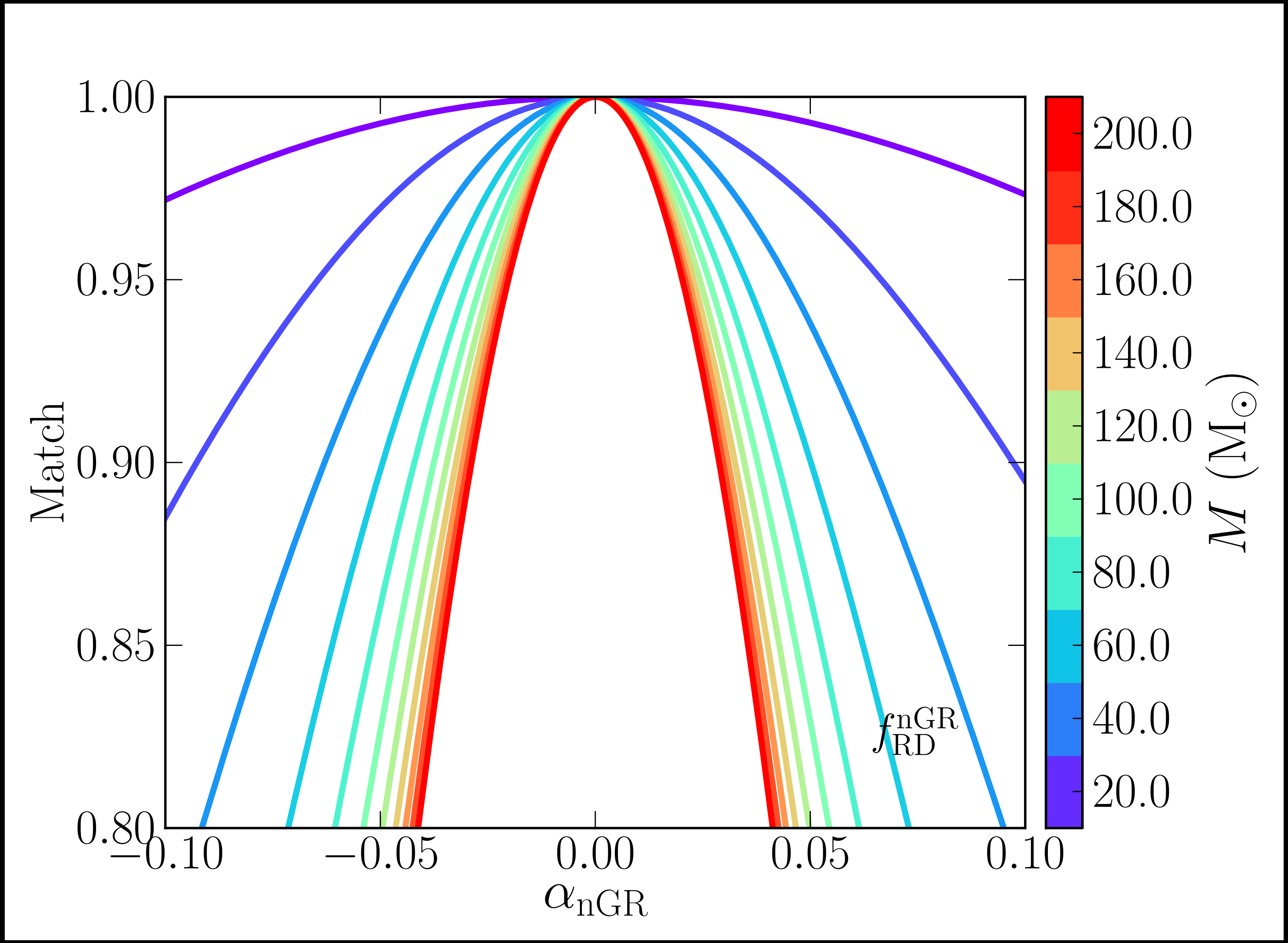


FIG.4 - Diagram showing the modification of the IMRPhenomC waveform for a system with total mass of M = 20Msun. The ringdown frequency was modified for a range of values from -0.5 to 0.5.

RESULTS - PARAMETER ESTIMATION

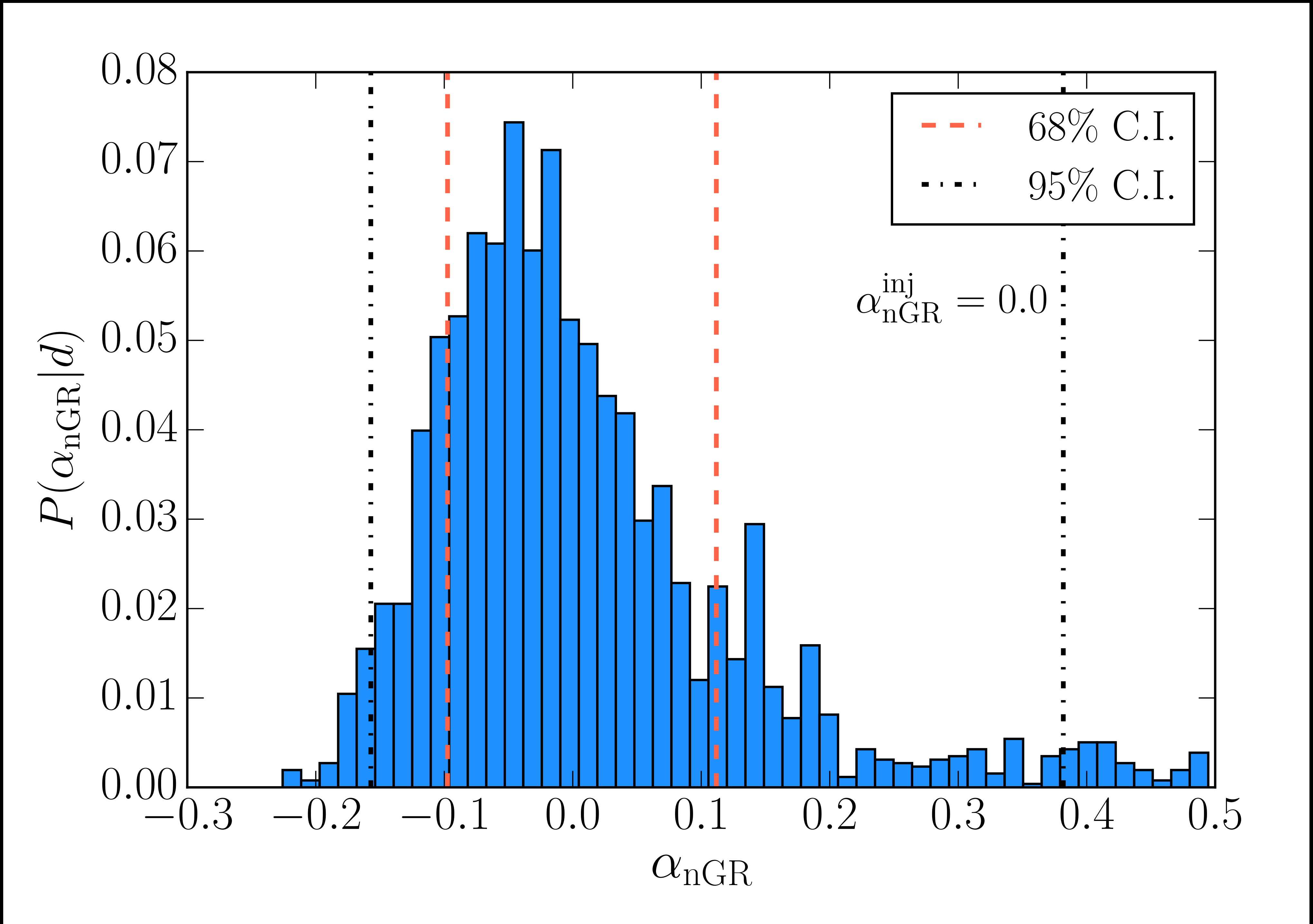


FIG. 6 - Diagram showing the posterior probability distribution of a lalsimulation mcmc calculation to estimate alpha_nonGR. SNR of 23.3 at D = ~ 100Mpc.

RESULTS - PARAMETER ESTIMATION

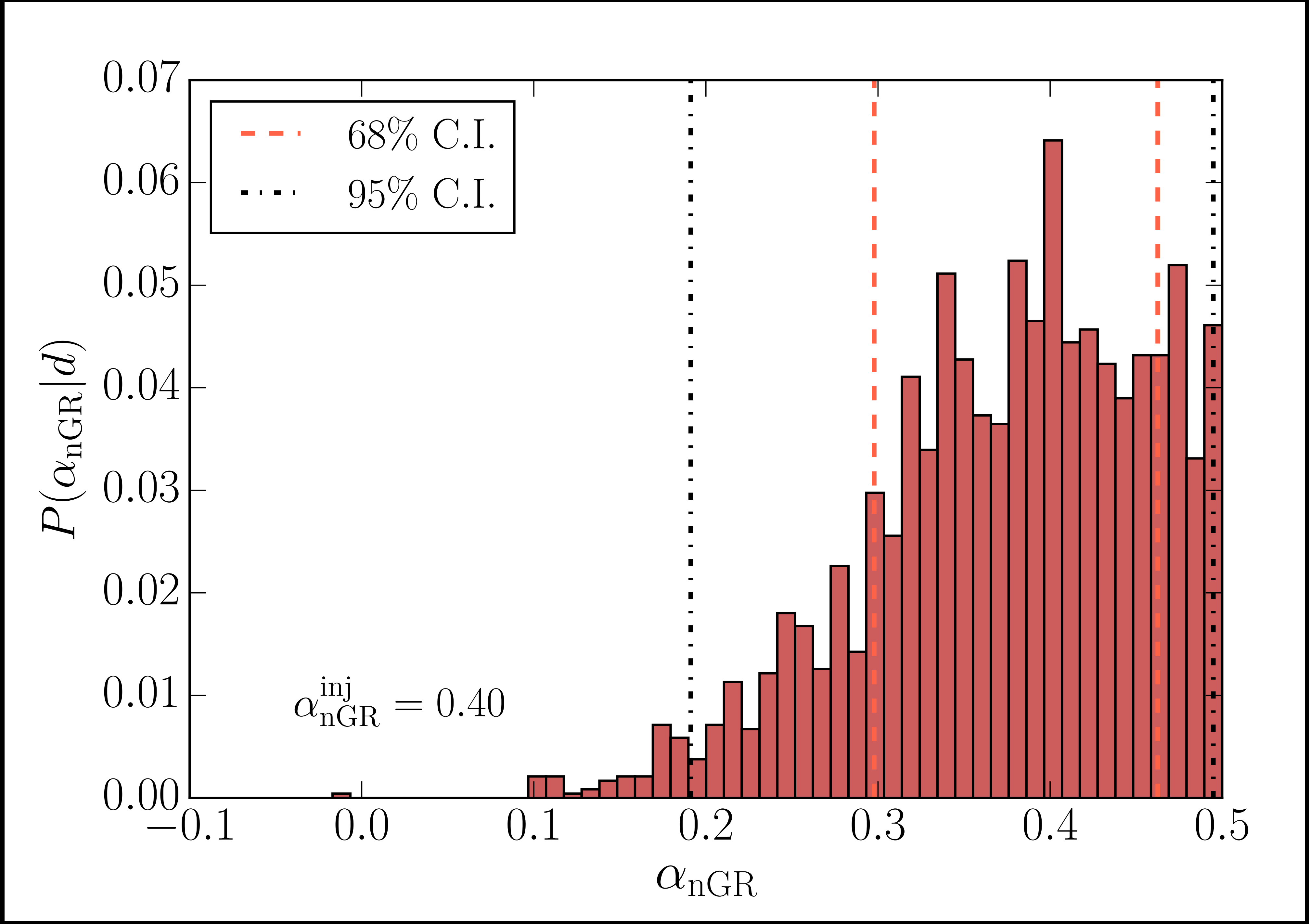


FIG. 7 - Diagram showing the posterior probability distribution of a lalsimulation mcmc calculation to estimate alpha_nonGR. SNR of 23.5 at D = ~ 100Mpc.

CONCLUSIONS

- Frequency at which ringdown occurs ***is sensitive*** to small deviations.
- Amplitude of the ringdown occurs ***is not sensitive*** to small deviations.
- With 95% confidence we can infer from the data that alpha is between -0.2 to 0.35. For an injected alpha of 0.0.
- With 95% confidence we can infer from the data that alpha is between 0.2 to 0.49. For an injected alpha of 0.4.

FUTURE WORK

- More Waveforms - IMRPhenomD, Taylor F2
- More Parameters - mass ratio, spin, distance, phase
- Degeneracies - shift in mass / spin degeneracies from modifications
- Integrate nonGR modifications into lalsuite.

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BACKUP - MODIFIED WAVEFORM

- Modified ringdown amplitude for a 20 solar mass non-spinning BBH using IMRPhenomC,

$$A_{\mathrm{RD}}^{\mathrm{nGR}} = A_{\mathrm{RD}}[1 + \alpha_{\mathrm{nGR}}] \ .$$

- Strong shift in amplitude of ringdown.

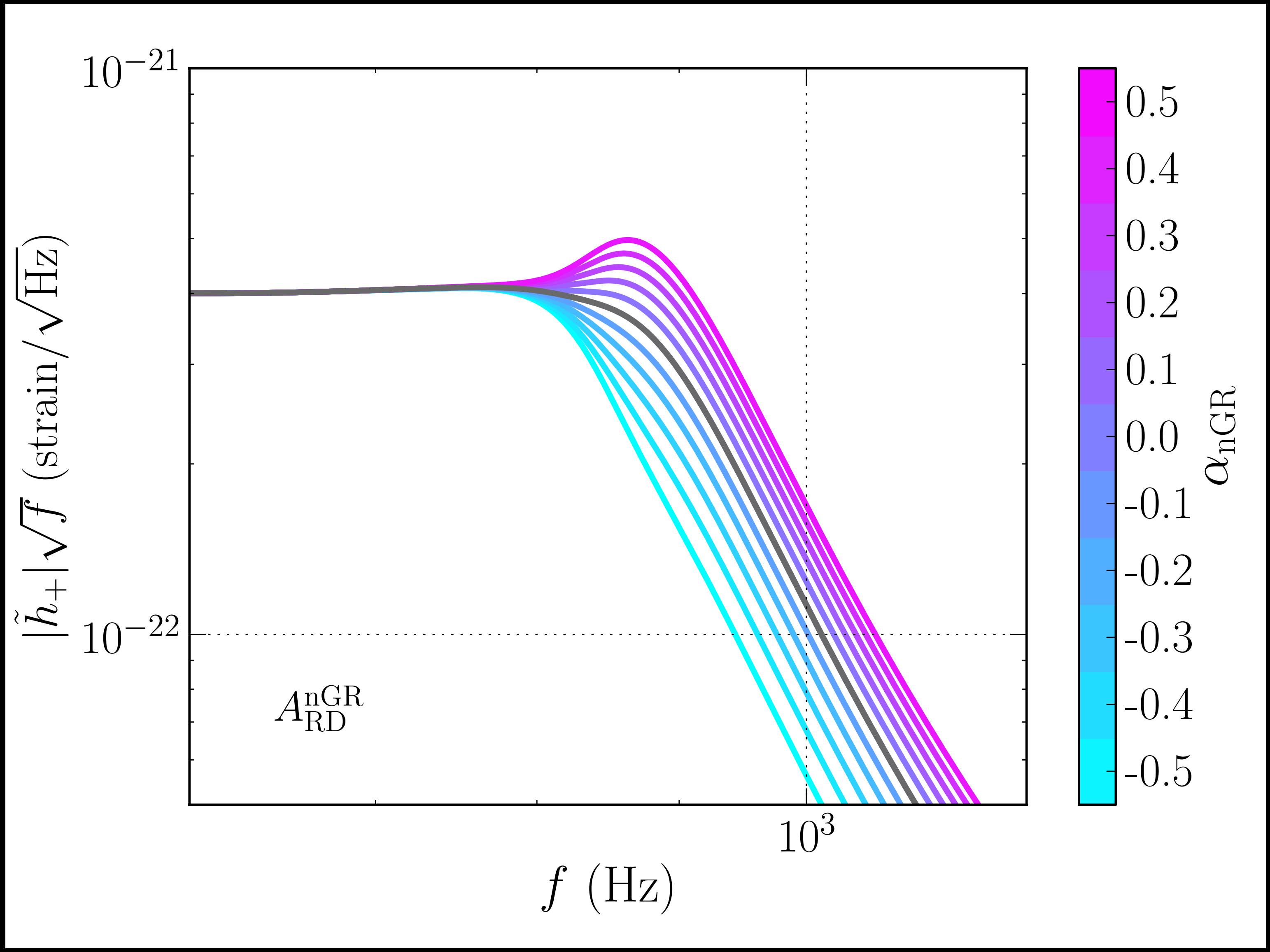

FIG.3 - A figure showing the modified strain as a function of frequency for a system with total mass, M = 20Msun. The gray line represents the GW for alpha_nonGR = 0.

BACKUP - OVERLAP STUDIES

- Match not as sensitive to deviations in amplitude.

- Loss of SNR is not significant for modifications to amplitude.

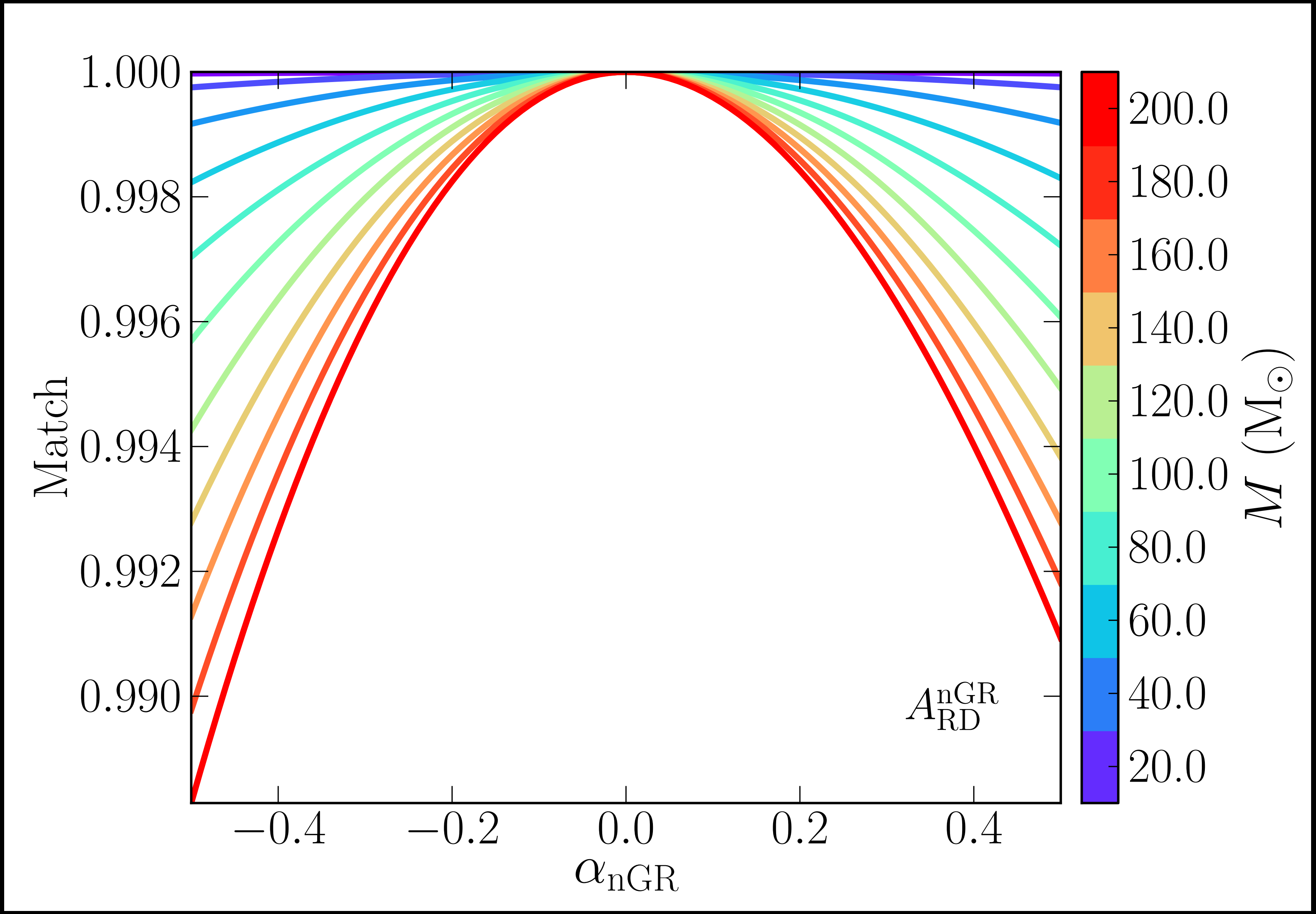

FIG.5 - Diagram showing the modification of the IMRPhenomC waveform for a system with total mass of M = 20Msun. The ringdown amplitude was modified for a range of values from -0.5 to 0.5.