Influence of higher-order waveform multipoles for the detection of eccentric binary black hole mergers

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Outline

- Higher Order Modes
- Past Studies
- Motivations
- Gravitational Waveform Results
- Signal-to-Noise Ratio Results

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Higher Order Modes

$$h(t) = h_+ - ih_\times = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} h^{lm} Y_{-2}^{lm}(\theta, \varphi)$$

+ einstein toolkit $\longrightarrow$ $\psi_4 = \ddot{h}_+ - i\ddot{h}_\times$

Python Open Source Waveform Extractor (POWER): An open source, Python package to monitor and post-process numerical relativity simulations (Johnson, Huerta, Haas Class. Quantum Grav. Volume 35, 2018)

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Past Studies

Focus on quasi-circular binary black hole systems that are both spinning and non-spinning

- Highest fitting factors are observed for equal mass systems, since the amplitude of the higher order modes is around 2 magnitudes smaller than the amplitude of the dominant mode, (2,2).

- As the mass ratio increases, the relative amplitude of the higher order modes increase and the fitting factor decreases (Pan et. al Phys. Rev. D 84, 2011)

- 3M≤ m1, m2 ≤ 25 M, For binaries with high mass-ratios and inclination 0.31 ≤ θ ≤ 2.68, including higher order modes could increase the signal-to-noise ratio by as much as 8% (Brown, Kumar, and Nitz Phys. Rev. D 87, 2013)

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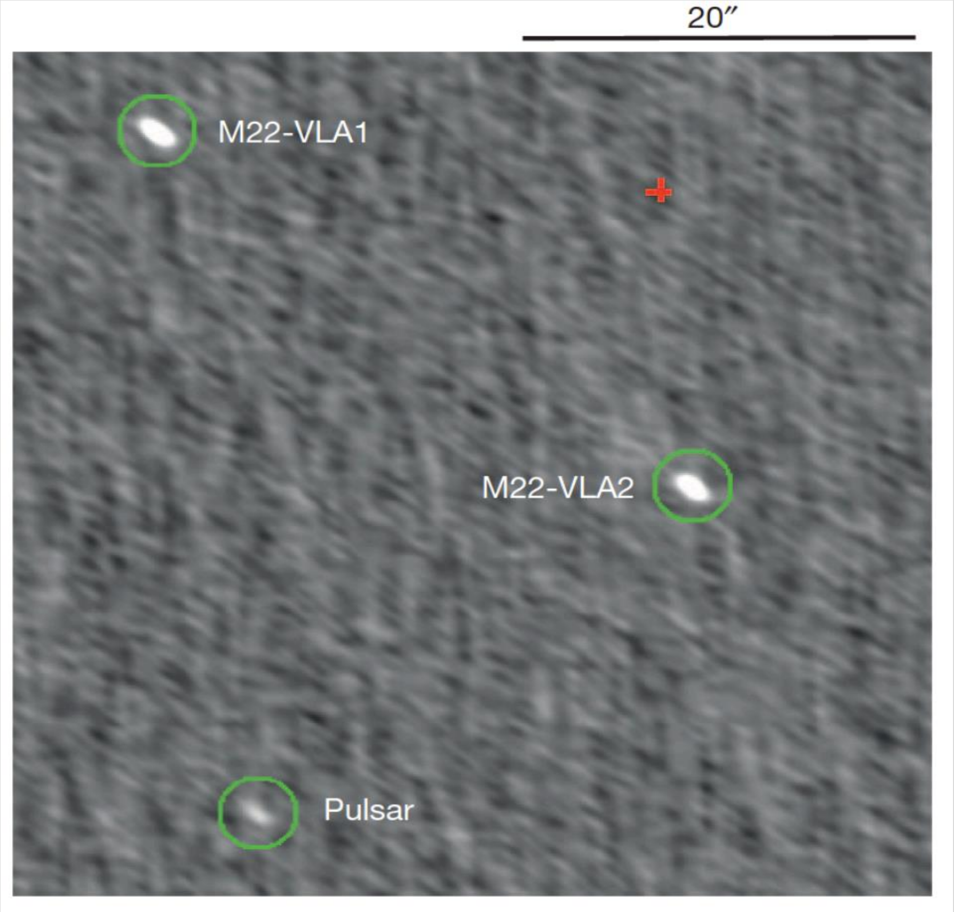
Motivations



Detection of black holes in M22
(Strader et al, Nature, 2012)

- Gravitational-wave observations of binary black holes currently rely on theoretical models that use only the dominant multipoles (l = 2, |m| = 2) to predict the gravitational radiation during inspiral, merger and ringdown.

- No study in the literature that has shed light on the importance of higher-order modes in the context of eccentric binary mergers

- Merger rate of eccentric black hole mergers underpredicted by a factor of 100 (previous predicted rate: 5 $Gpc^{-3}\ yr^{-1}$) (Samsing, Askar, and Giersz ApJ, 2018)

- C Rodriguez corrects previous rate estimates for LIGO's eccentric mergers (Rodriguez et al, 2017)

- State-of-the-art waveform model for eccentric black hole mergers. Recent detections may have eccentricity content (Huerta et al, PRD, 2018)

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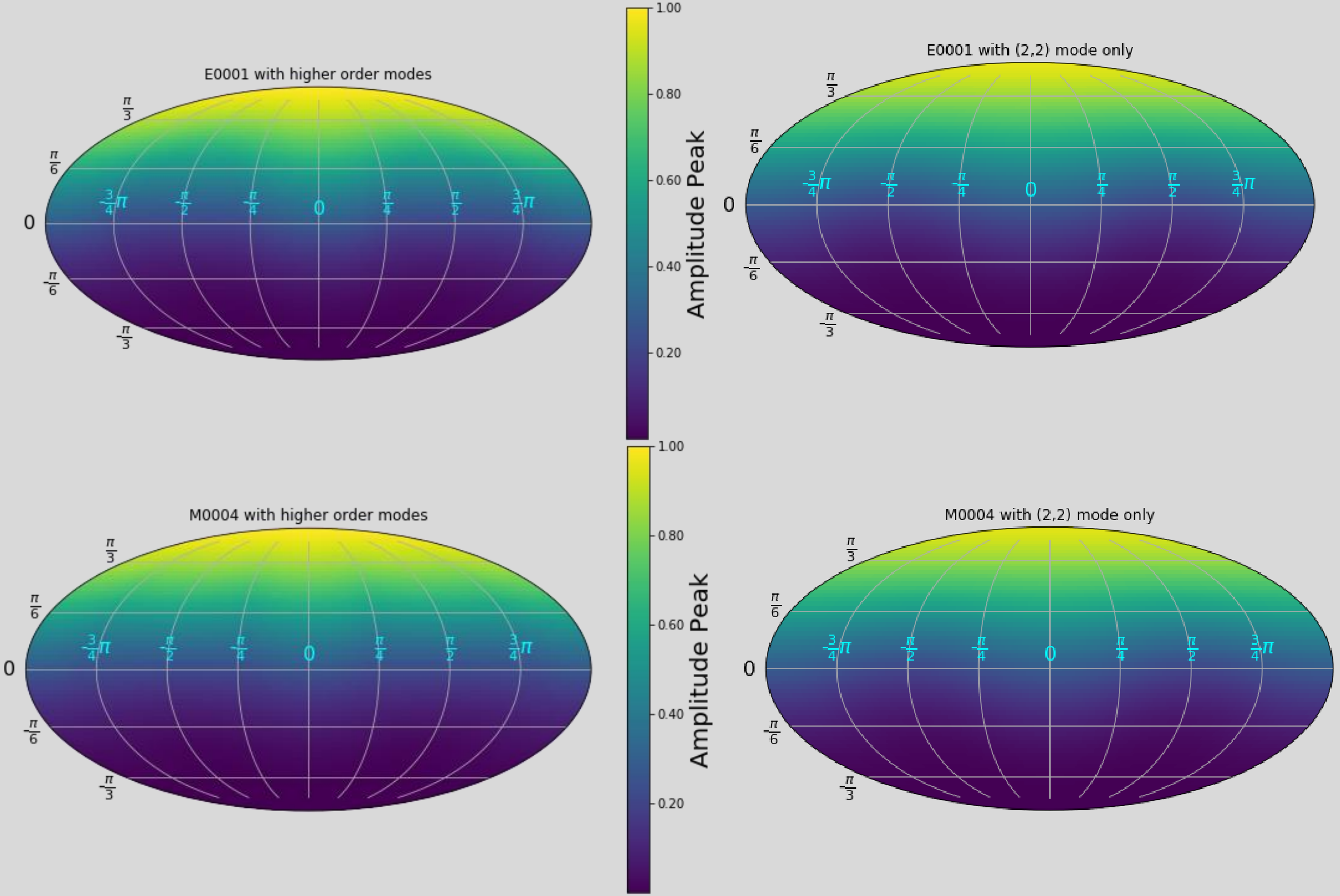
Equal Mass Binaries

$$(\ell,\ |m|) = \{(2,\ 2),\ (3,\ 3),\ (4,\ 4),\ (2,\ 1), (3,\ 2)\}$$

Low Eccentricity

High Eccentricity



q=8 Black Hole Binaries

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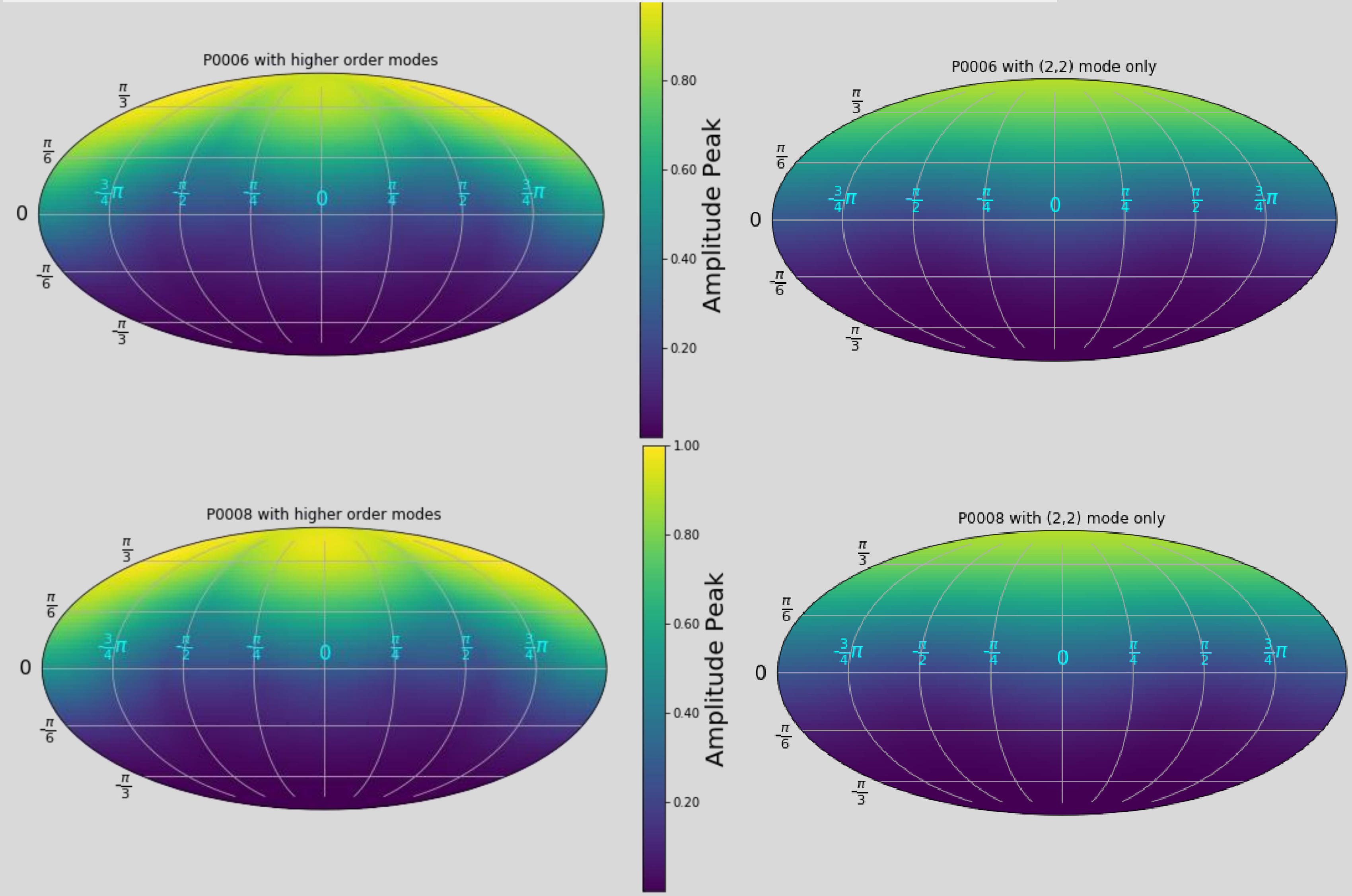
$$(\ell,\ |m|) = \{(2,\ 2),\ (3,\ 3),\ (4,\ 4),\ (2,\ 1), (3,\ 2)\}$$

Low Eccentricity

High Eccentricity



Effects of Eccentricity

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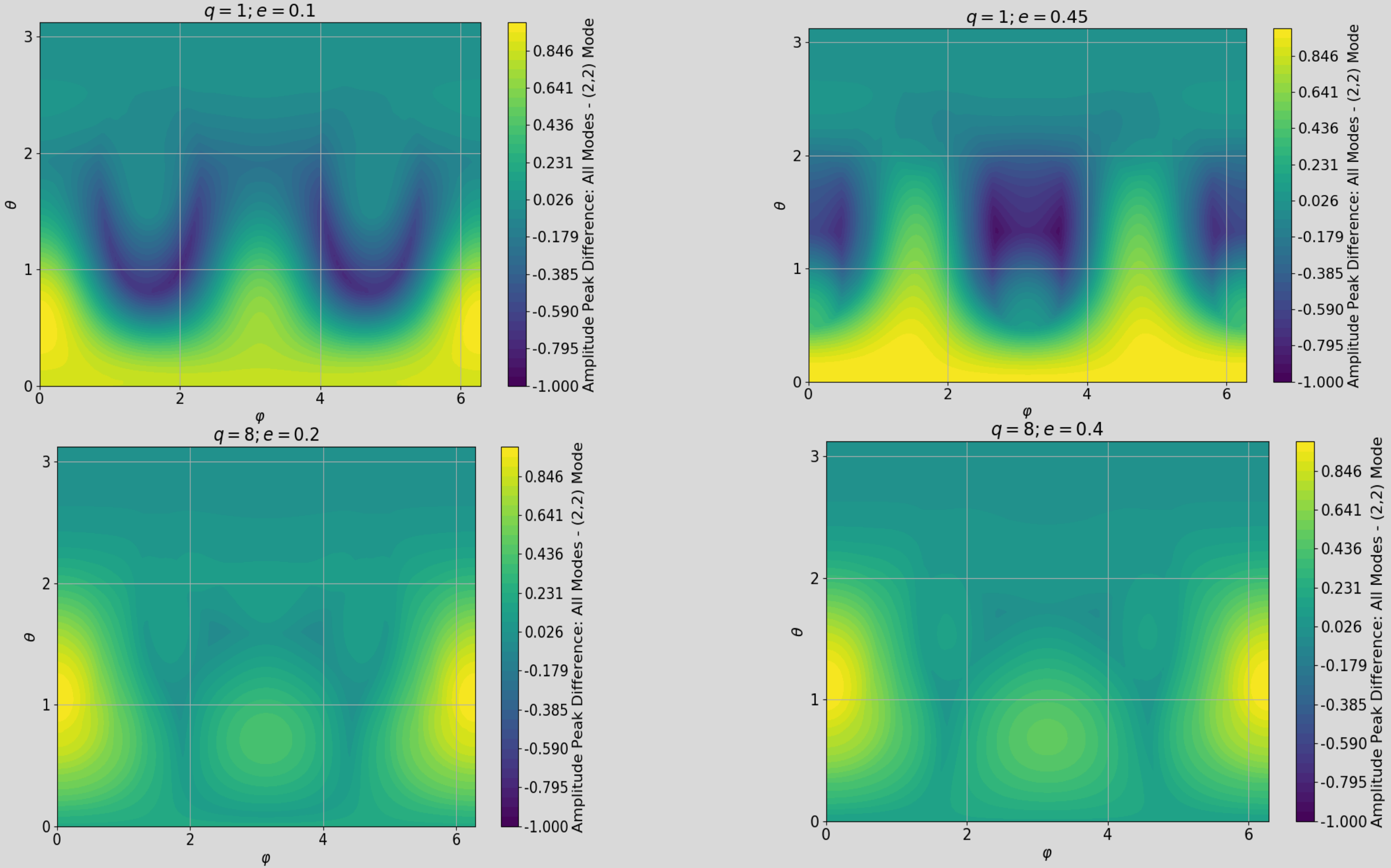

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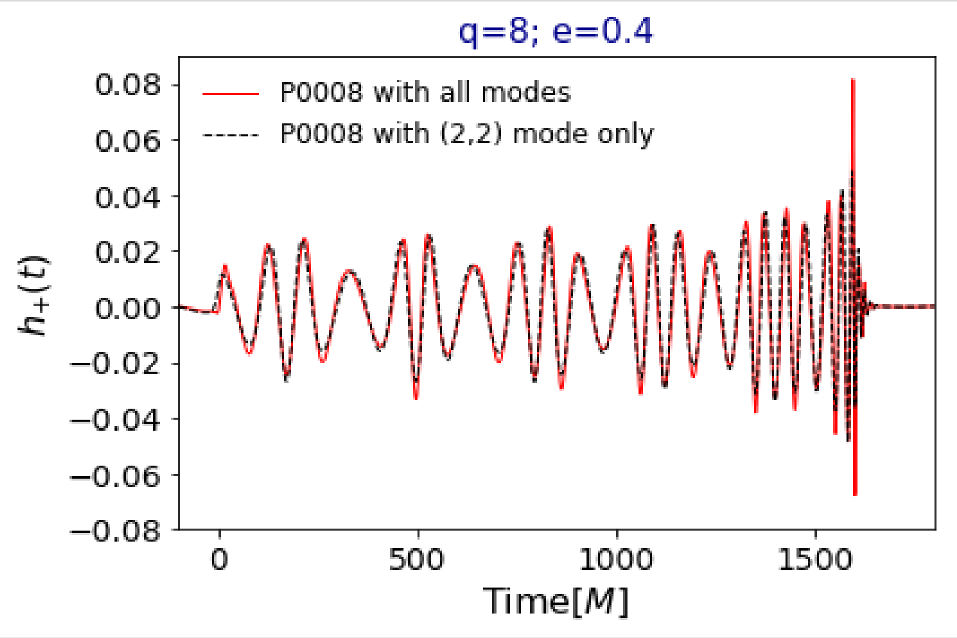

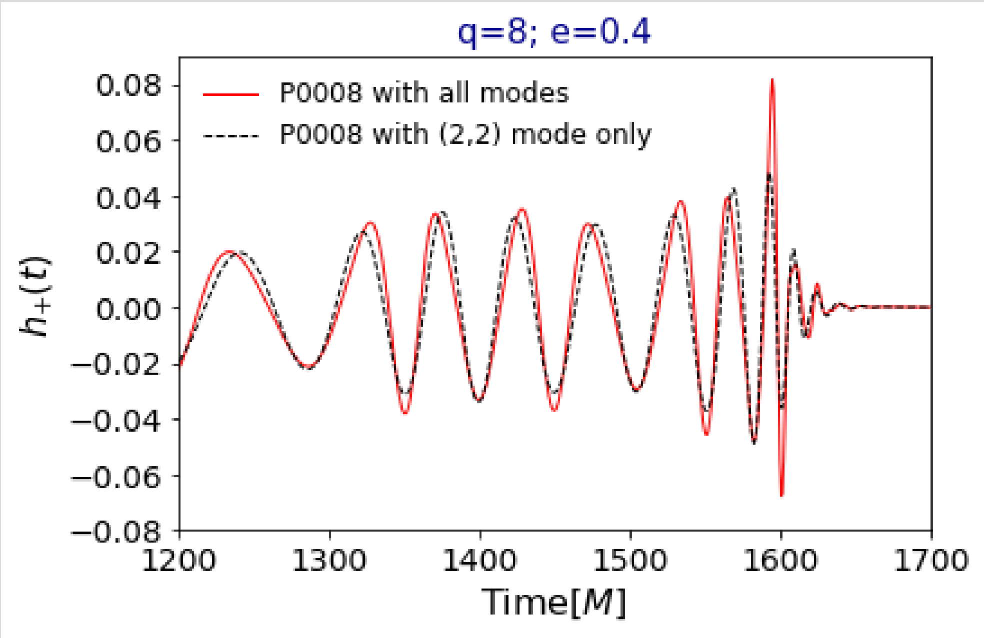

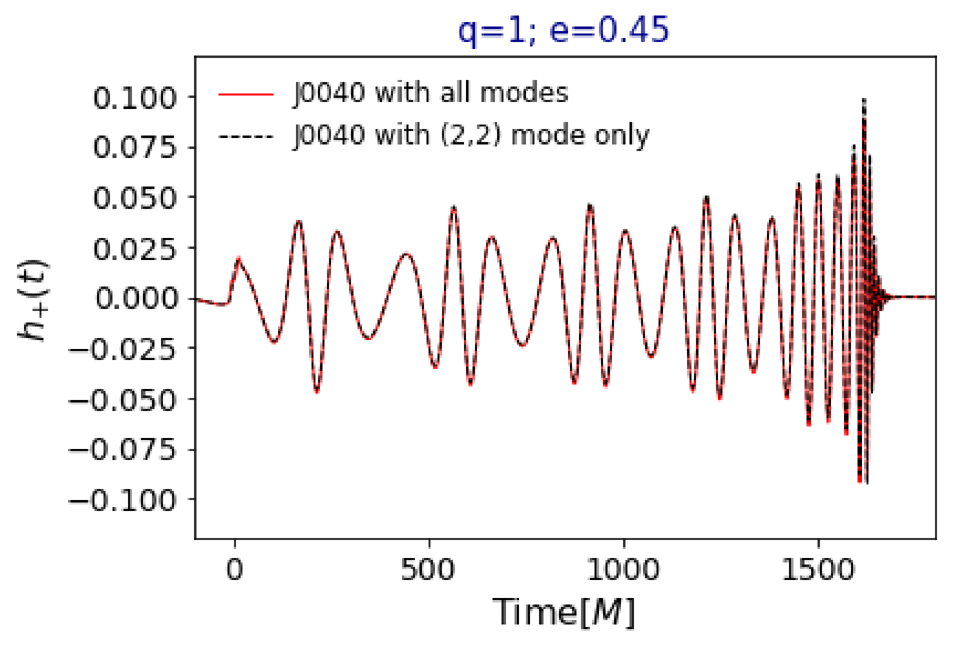

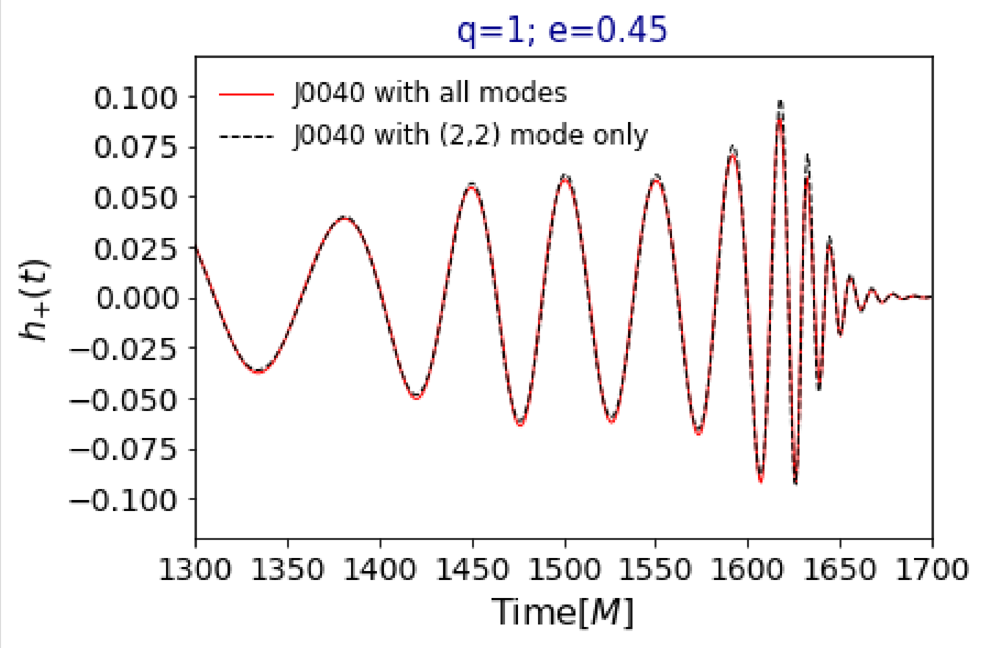

Signal-to-Noise Ratio

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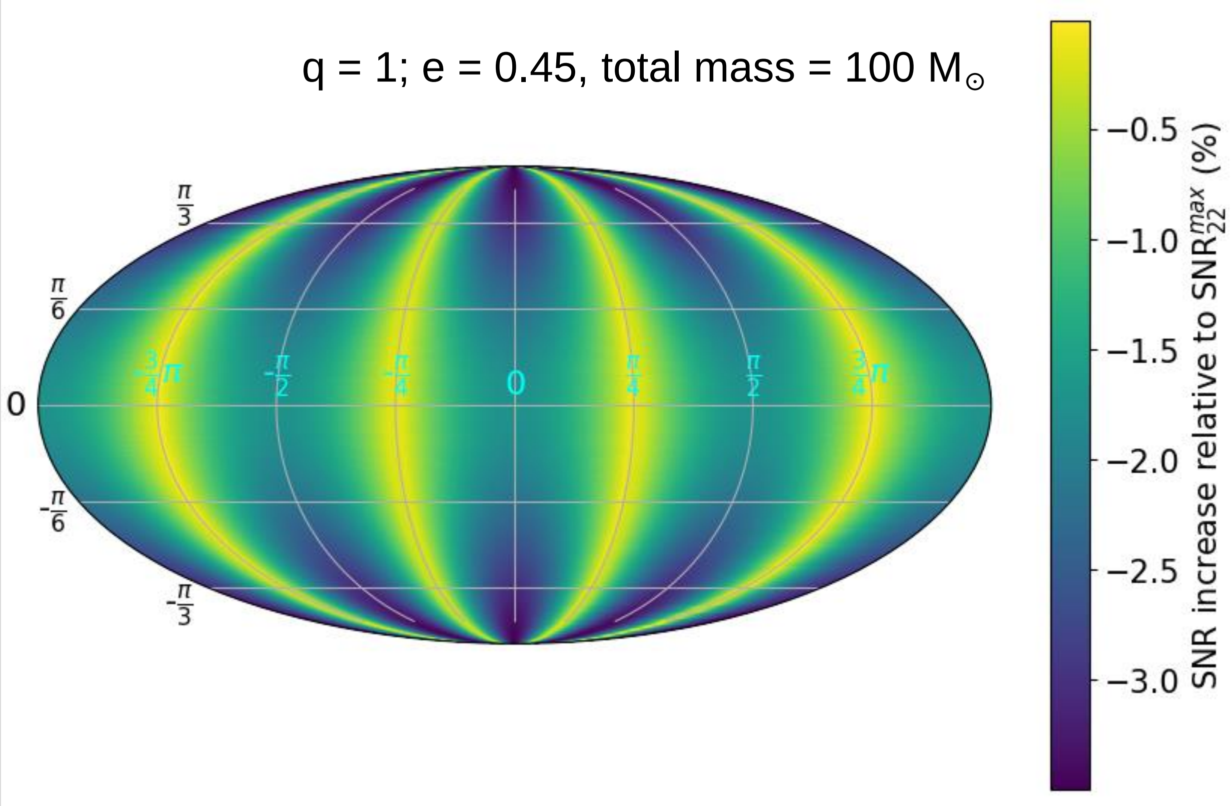
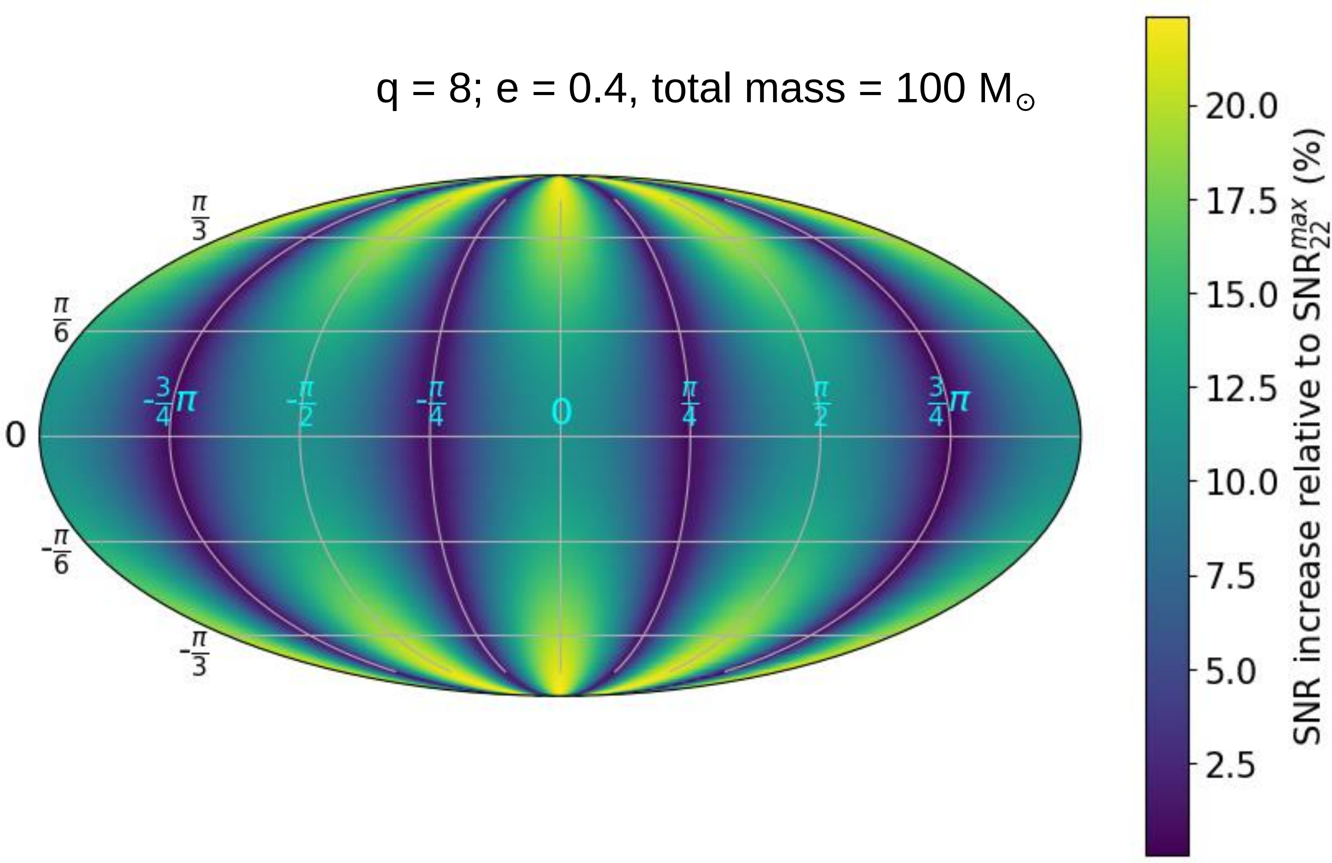
$$\left(\frac{S}{N}\right)^2 = \int_{-\infty}^{\infty} \frac{|h(f)|^2}{S_n(f)} df$$

Assuming LIGO design sensitivity





Using Numerical Relativity Waveforms at least 1500M long

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Summary

- Higher order modes in higher mass-ratio binaries → Access to wider range of (θ, φ) combinations
- Including higher order modes isn't always better than using only the (2,2) mode
- SNR can increase by as much as 20% when higher order modes are used for asymmetric mass-ratio binaries
- In the future:
  - Finish simulations with mass-ratio 10 to complete analysis
  - Explore spinning and eccentric binaries

NCSA Gravity Group at the 2018 APS April Meeting

1. Ed Seidel: Numerical Relativity 1980-2000s: The era of sharpening our tools and exploring Einstein's physics
2. Daniel George: Deep Learning for Real-time Gravitational Wave Detection and Parameter Estimation: Results with Advanced LIGO Data
3. Adam Rebei: Influence of higher-order waveform multipoles for the detection of eccentric binary black hole mergers
4. Roland Haas: Assessing confidence in numerical relativity waveforms of binary neutron star mergers
5. Hongyu Shen: Glitch Classification and Clustering for LIGO with Deep Transfer Learning (poster)
6. Eliu Huerta: Detection and characterization of eccentric compact binary coalescence at the interface of numerical relativity, analytical relativity and machine learning
7. Hongyu Shen: Denoising Gravitational Waves using Deep Learning with Recurrent Denoising Autoencoders
8. Roland Haas: BOSS-LDG using Blue Waters for LIGO data analysis (poster)
9. Vedant Puri: Scheduled Relaxation Jacobi Method for Initial Data Problems
10. Shawn Rosofsky: Study of f-mode Oscillations in Numerical Relativity Simulations of Perturbed Neutron Stars and Highly Eccentric Binary Neutron Star Mergers
11. Pablo Brubeck: On the Schur complement of the nearest Kronecker product preconditioner for elliptic boundary value problems
12. Haris Markakis: Helmholtz's third theorem in numerical general relativity
13. Miguel Holgado: Pulsar Timing Constraints on the Fermi Massive Black-Hole Binary Blazar Population