Using NSBH Tidal Deformation for GW Cosmography with 3G Detectors

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under the guidance of
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[Satyaprakash, Schutz, and Van den Broeck, 2010]

Cosmography

Image Credit: David W. Hogg

- Cosmological Parameters:
  - H_0: Hubble constant
  - Ω_M: matter density parameter
  - Ω_Λ: dark energy density parameter
  - ω: determines dark matter equation of state
- Necessary tools: independent measures of luminosity distance (D_L) and redshift (z)

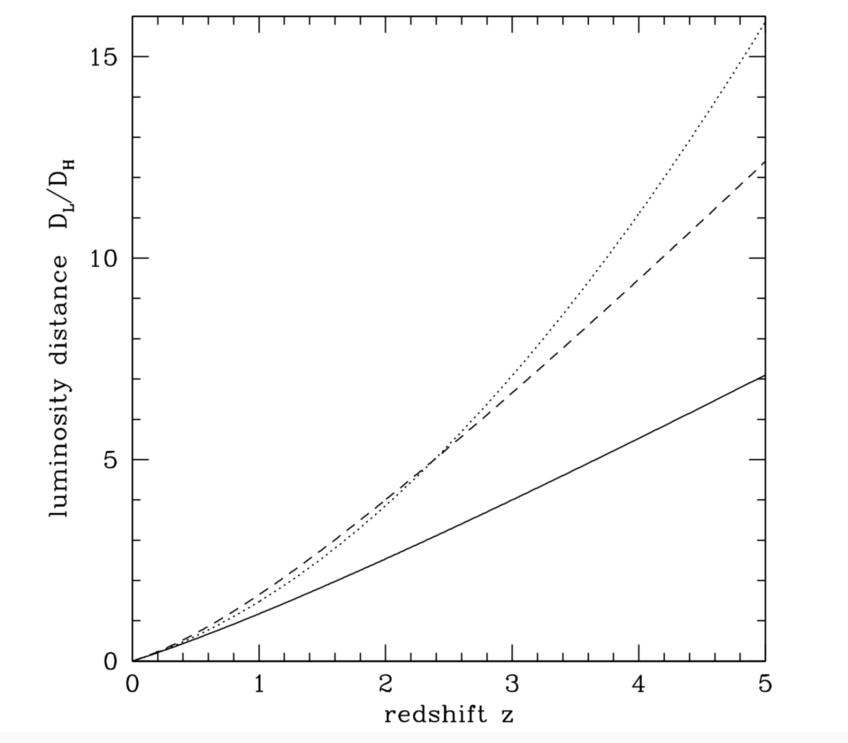
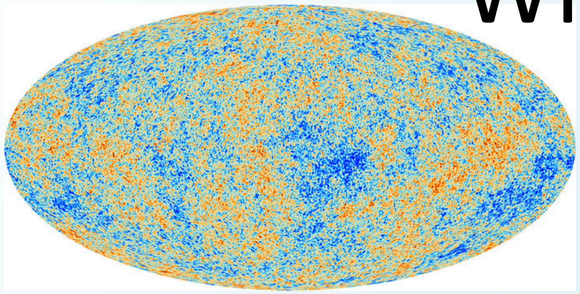


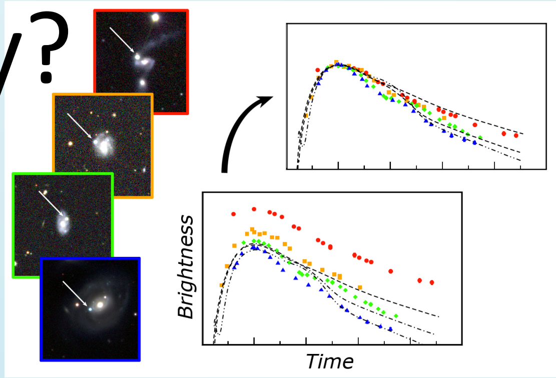
Figure 3: The dimensionless luminosity distance D_L/D_H. The three curves are for the three world models, $(\Omega_M, \Omega_\Lambda) = (1, 0)$, solid; $(0.05, 0)$, dotted; and $(0.2, 0.8)$, dashed.

$$D_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{[\Omega_M(1+z')^3 + \Omega_\Lambda(1+z')^{3(1+\omega)}]^{1/2}}$$

Why Cosmography?



Planck CMB image



Type Ia Supernovae lightcurves

- Disagreements between our best models:
  - Planck: H_0 = 67 ± 1.2 km/s/Mpc
  - Type Ia Supernovae: H_0 = 73 ± 0.7 km/s/Mpc
- Better constraints on cosmological parameters: Ω_M, Ω_{DE}, ω

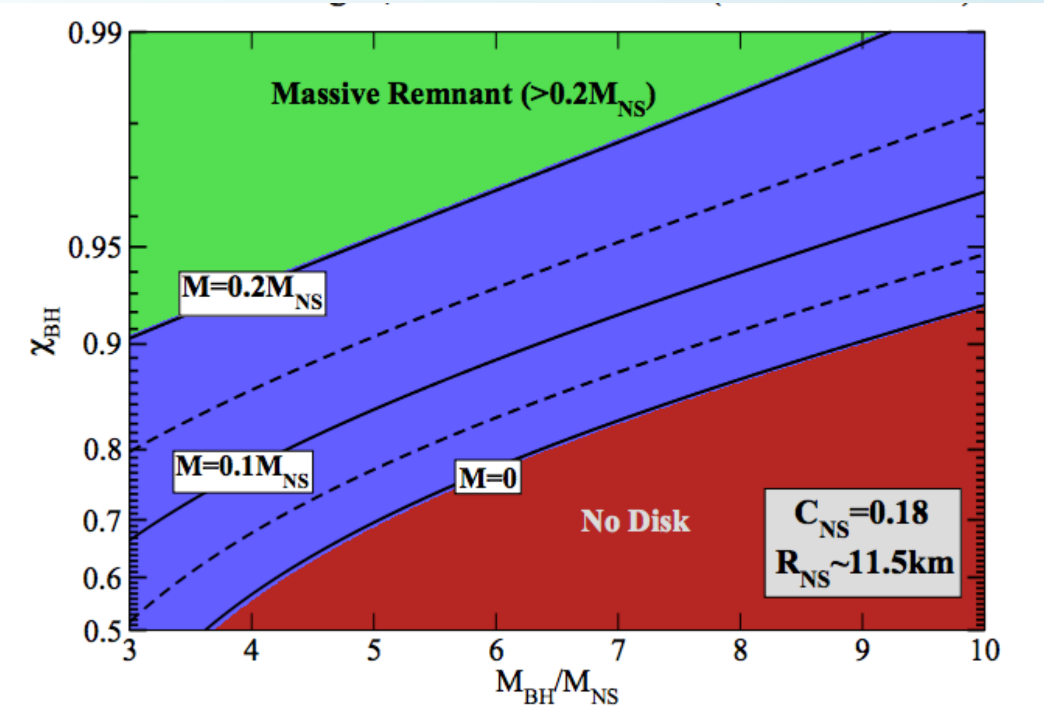
Standard Siren Cosmography

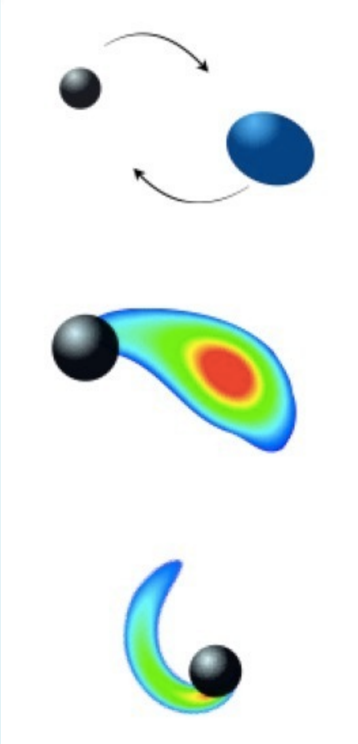
- Use GW as an independent measure of the luminosity distance to source
- Get redshift from one of these methods:
  - Method 1: Joint GW-EM observations (currently ongoing!) (Satyaprakash, Schutz, and Van den Broeck, 2010)
  - Method 2: host galaxy statistical averaging methods (Chen and Holz, 2016)
  - **Method 3: frequency of tidal deformation** (Messenger et al., 2013)
- How well can we determine the frequency of tidal deformation in GW using 3G detectors?

$$h(f) \propto \frac{1}{D} f^{-7/6}$$

$$\Phi \propto 2\pi f t_c + (M_c f)^{-5/3}$$

Conditions for Tidal Deformation





$0.00 \leq \chi_{NS} \leq 0.05$, $1\ M_{SUN} \leq M_{NS} \leq 2\ M_{SUN}$

$\chi = J / (GM / c^2)^2$

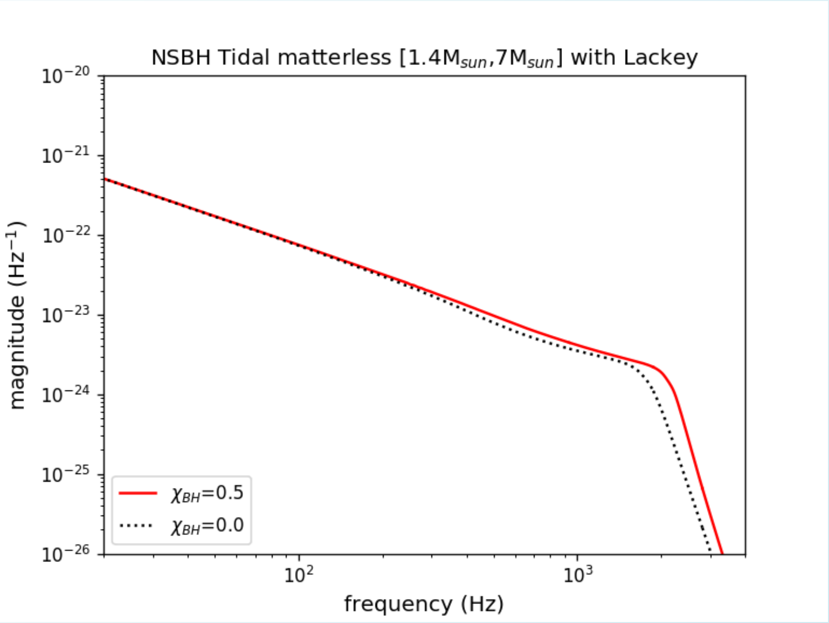
$0.00 \leq \chi_{BH} \leq 0.99$, $5\ M_{SUN} \leq M_{BH} \leq 15\ M_{SUN}$

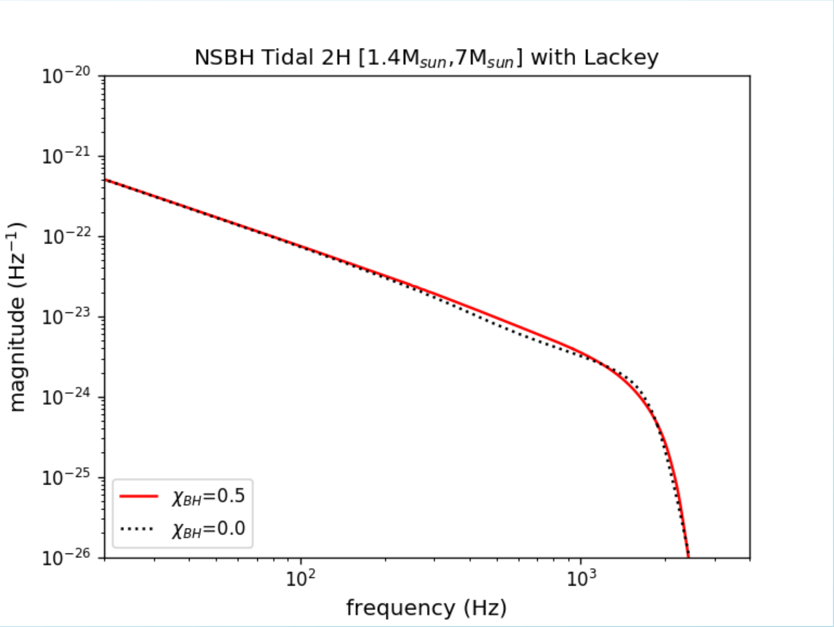
$3 \leq q = M_{BH} / M_{NS} \leq 5$

[Foucart, 2012]

Image Credit: T. Hinderer, F. Foucart

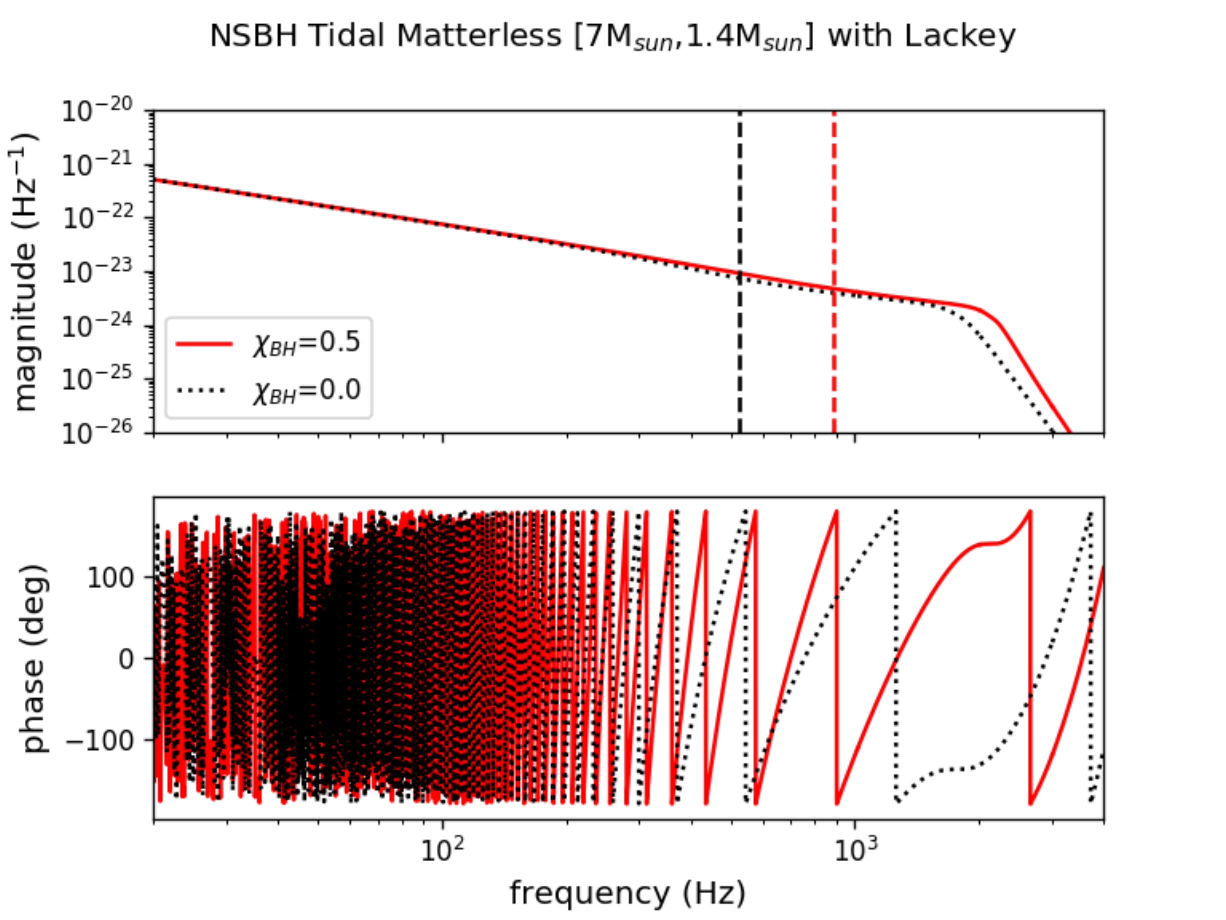
Tidal Deformation: breaking the mass-redshift degeneracy



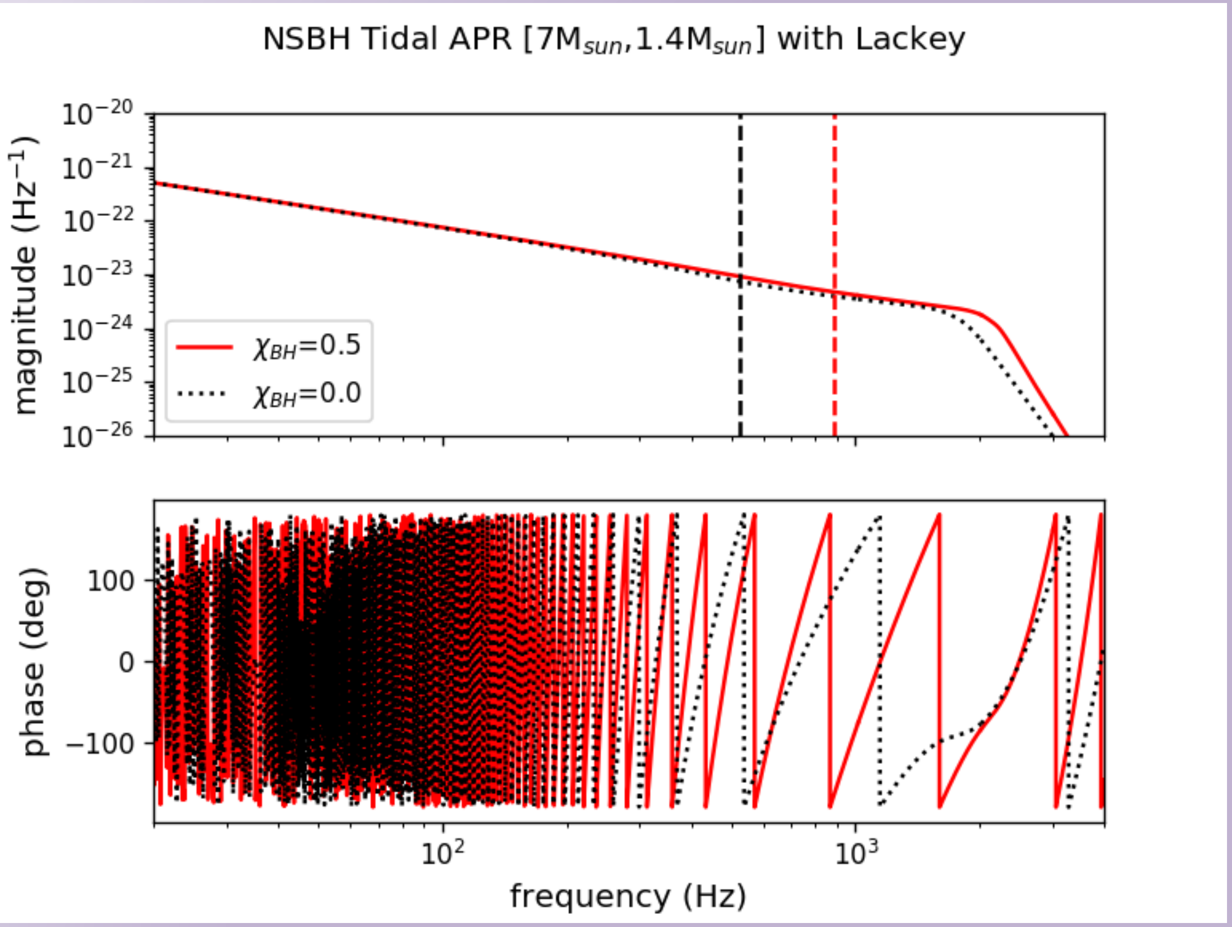


- Masses are redshifted: $m_z = m(1+z)$
- TD frequency redshifted: $f_{TD,\,z} = f_{TD} / (1+z)$
- Use EOS to relate TD frequency to mass

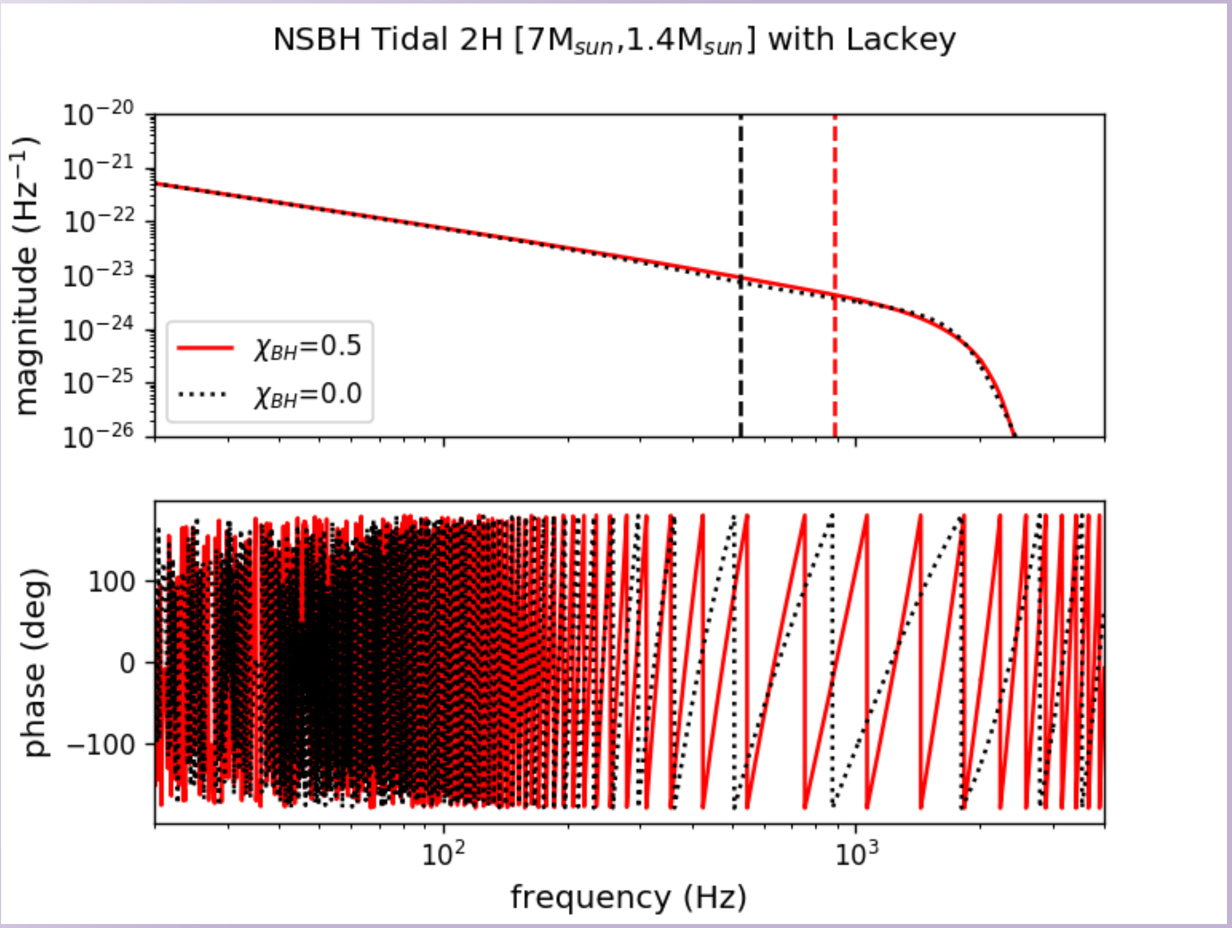
Waveform Visualization: No Matter Effects



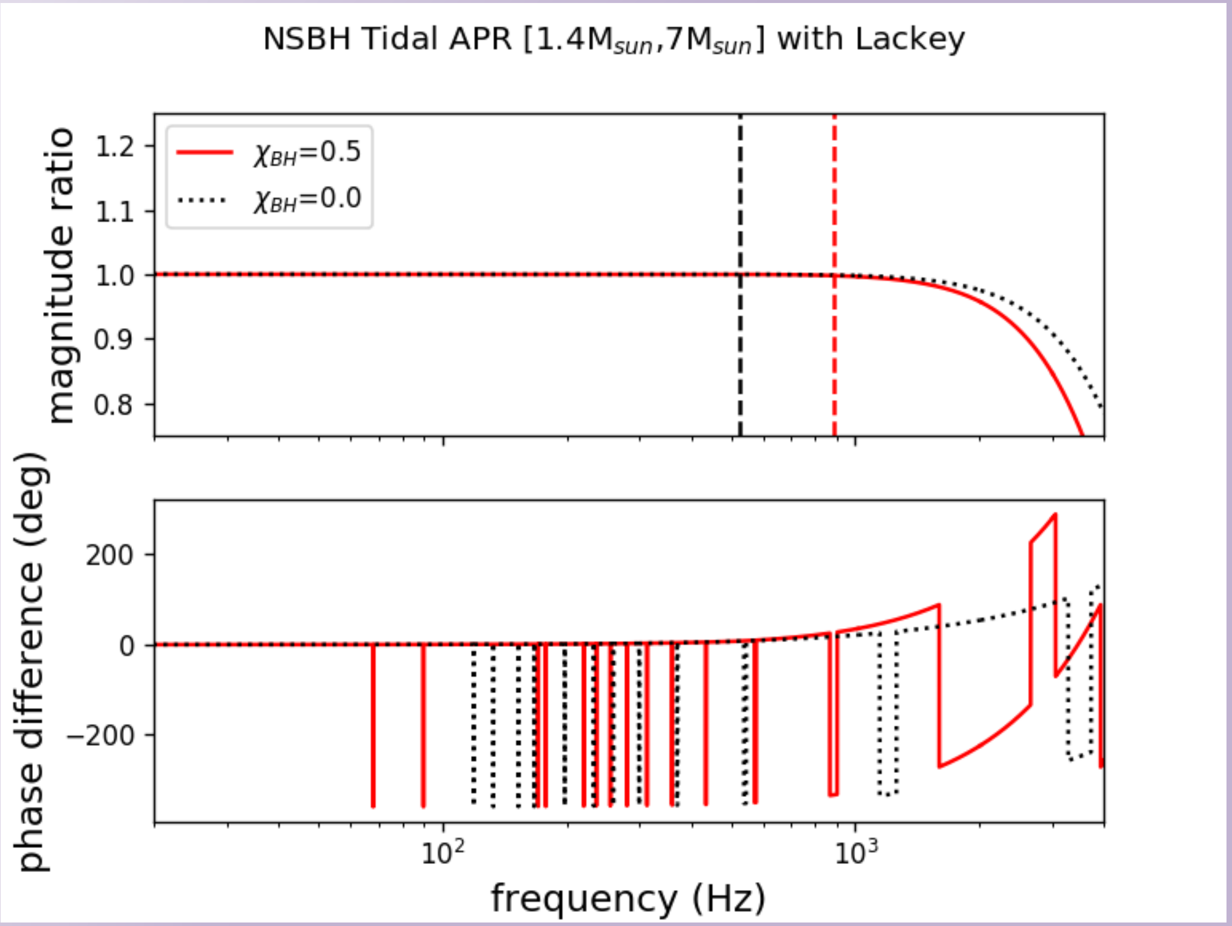
Waveform Visualization: APR Moderate Equation-of-State



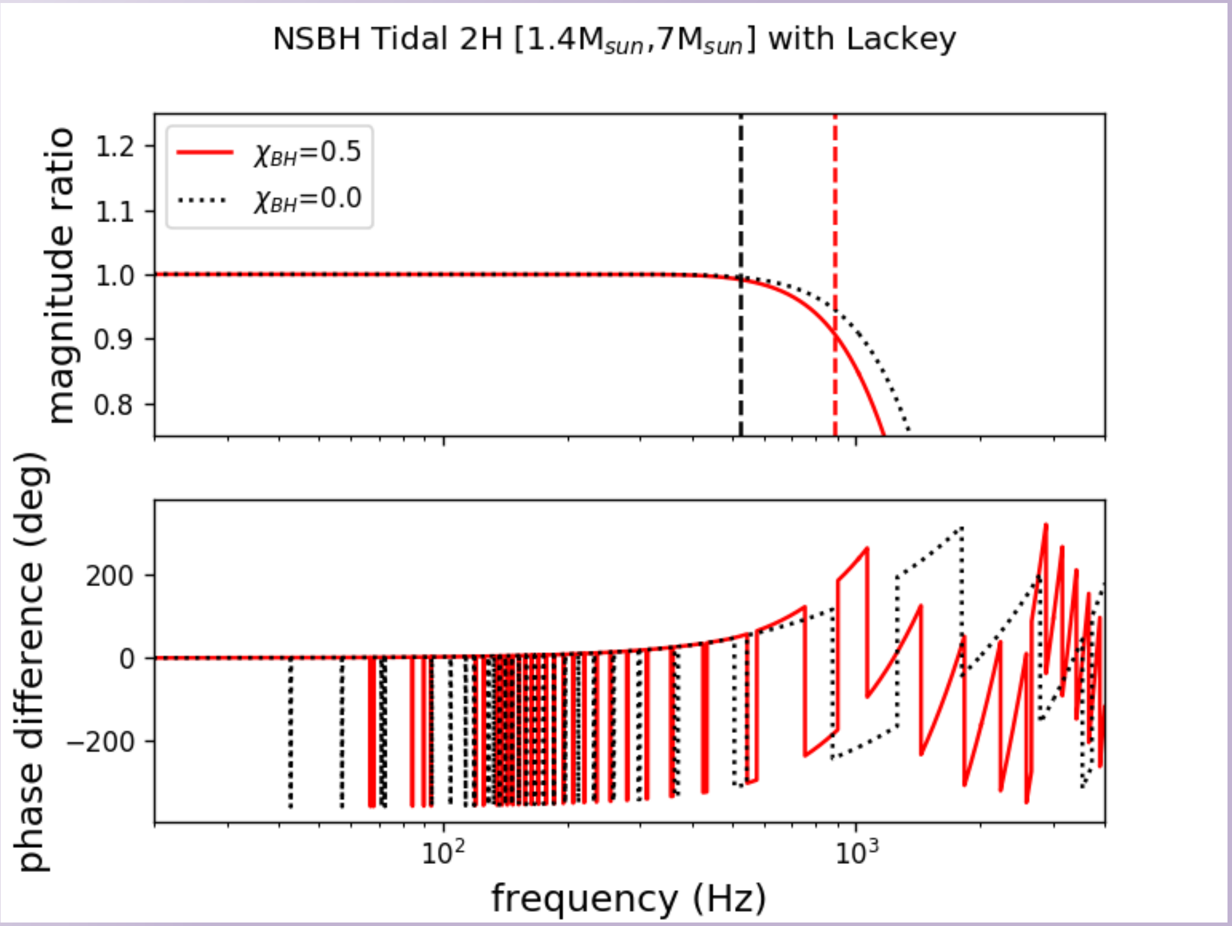
Waveform Visualization: 2H Extreme Equation-of-State



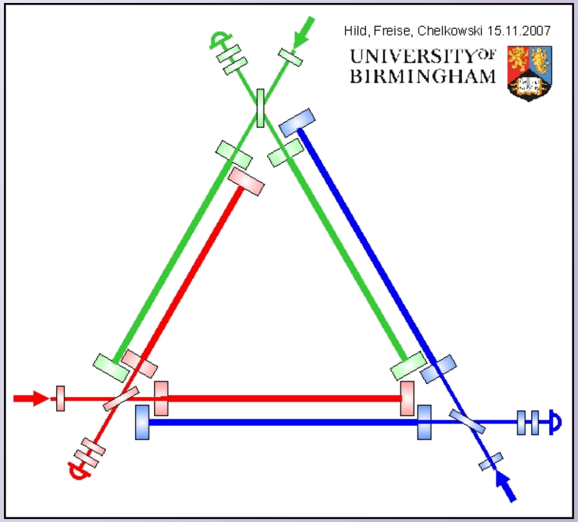
Tidal Deformation Signatures: Ratios Between Waveforms for APR



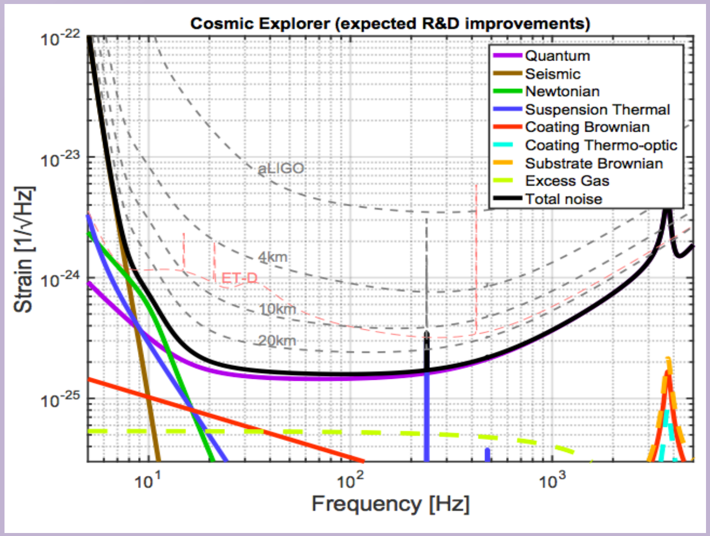
Tidal Deformation Signatures: Ratios Between Waveforms for 2H



Modeling the Next Generation



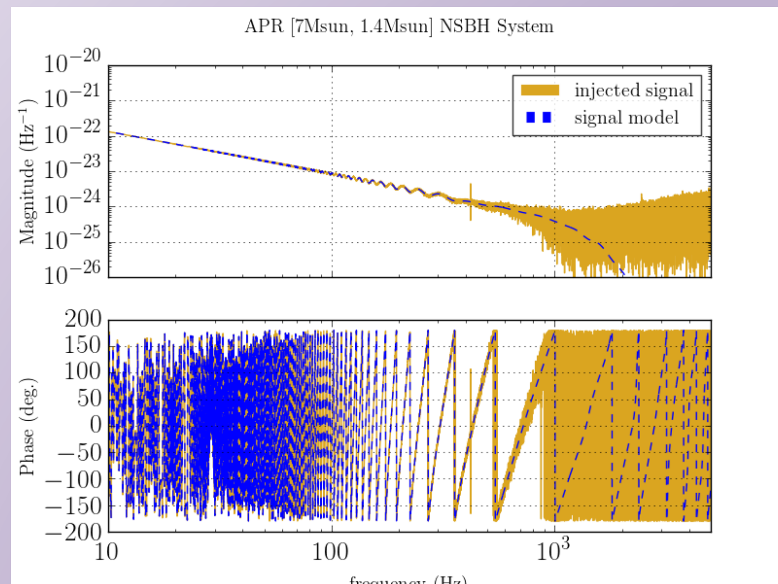
Einstein Telescope: 10 km arms
Three interferometers
Located in Europe

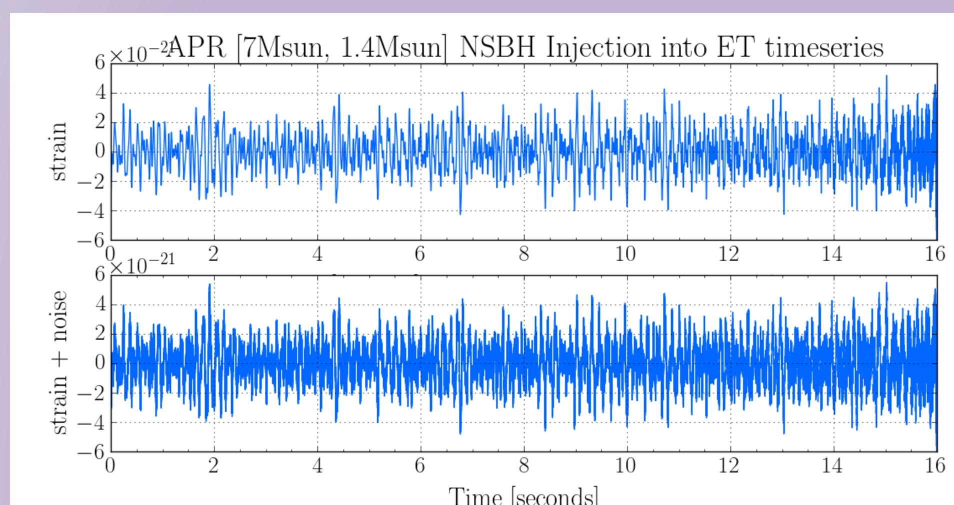


Cosmic Explorer: 40 km arms
Located in the United States

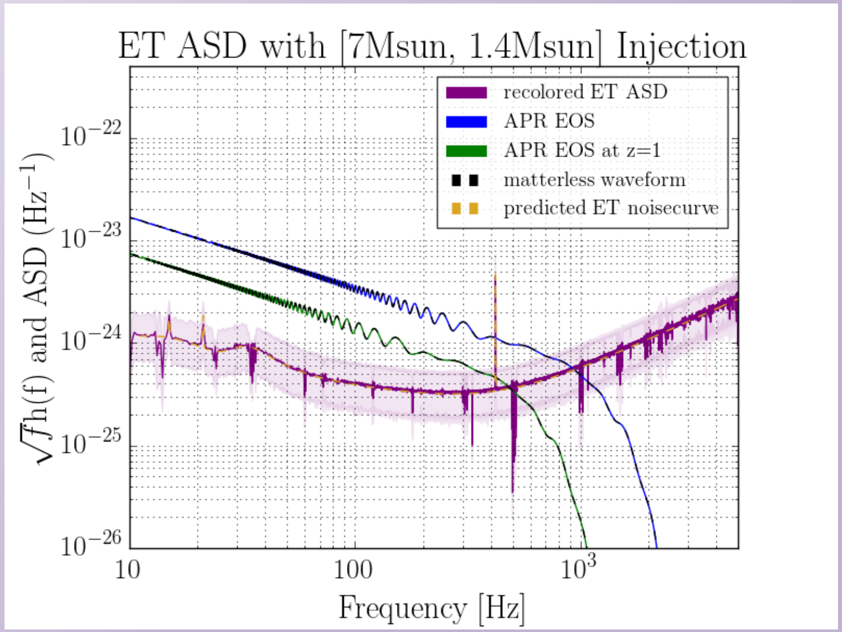
- Recolor the aLIGO datastream with ET and CE noisecurves
- Inject signals into datastreams to retrieve signatures

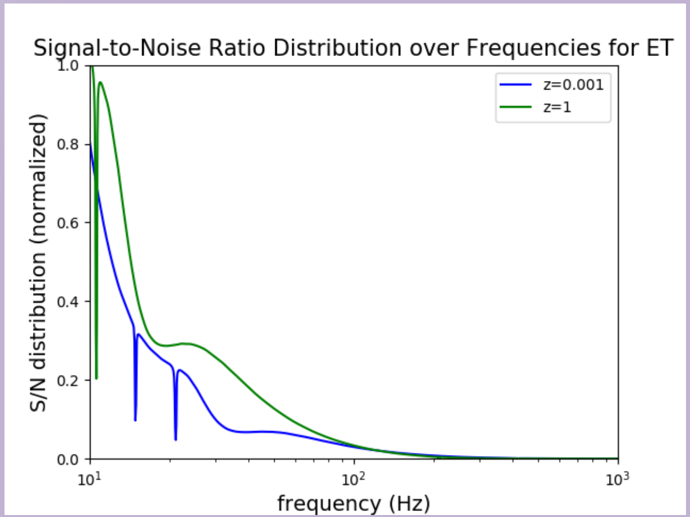
Signal Injection and Retrieval



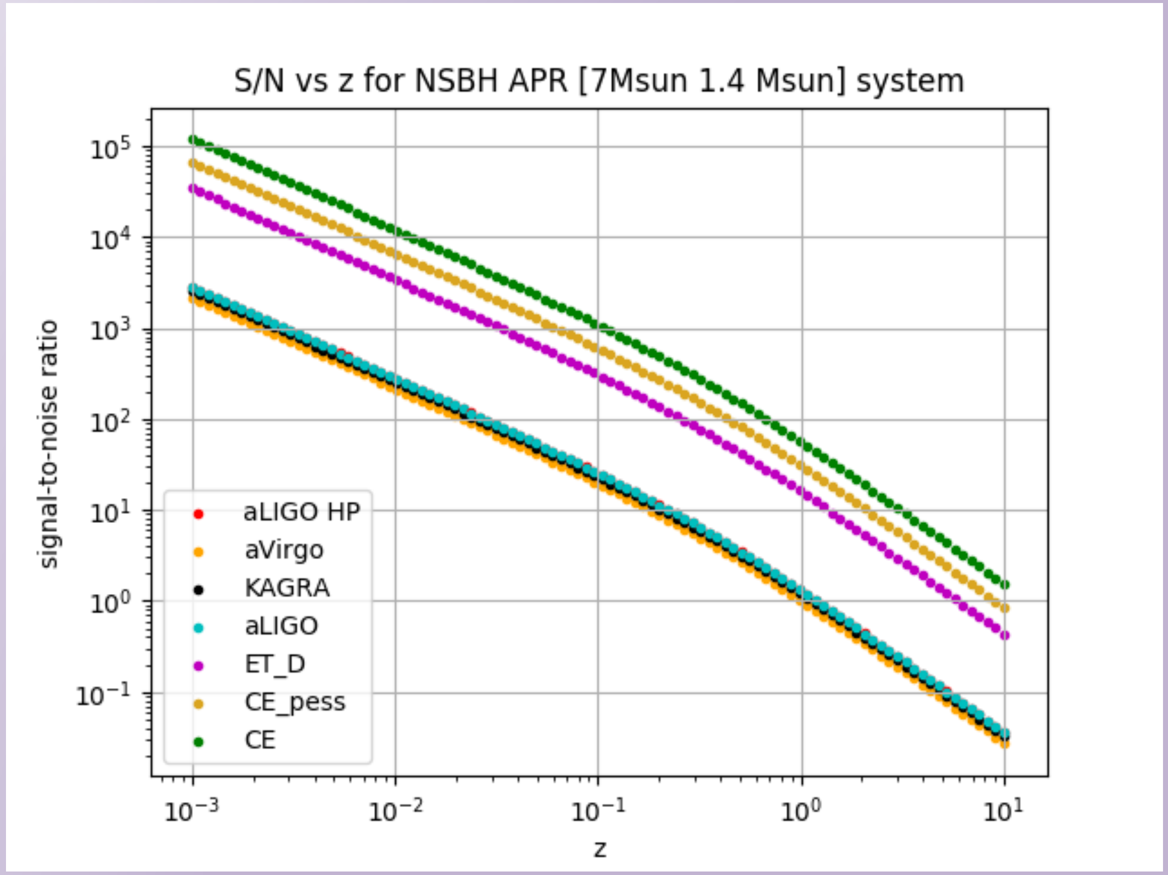


Detecting deformability signatures with ET for APR

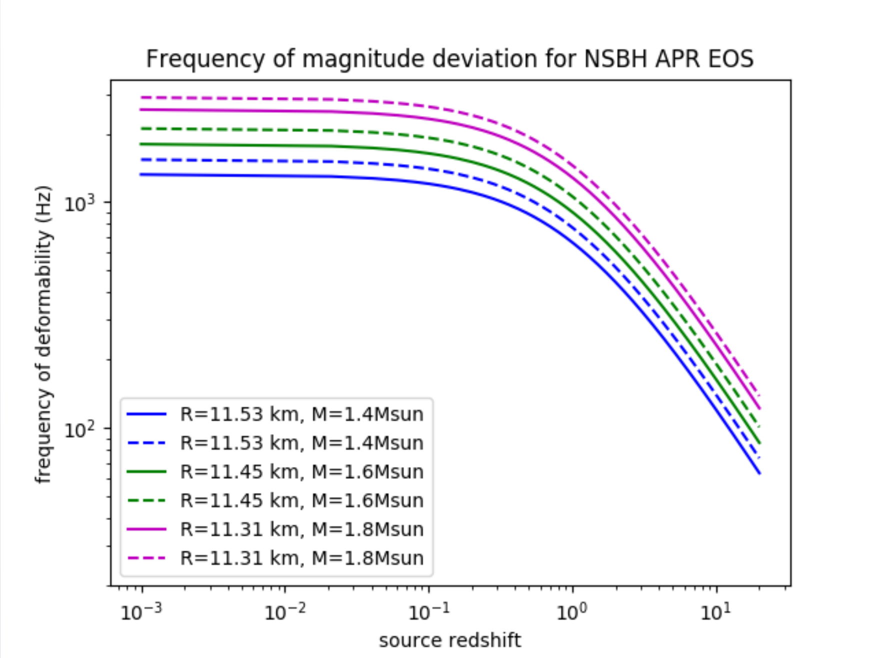


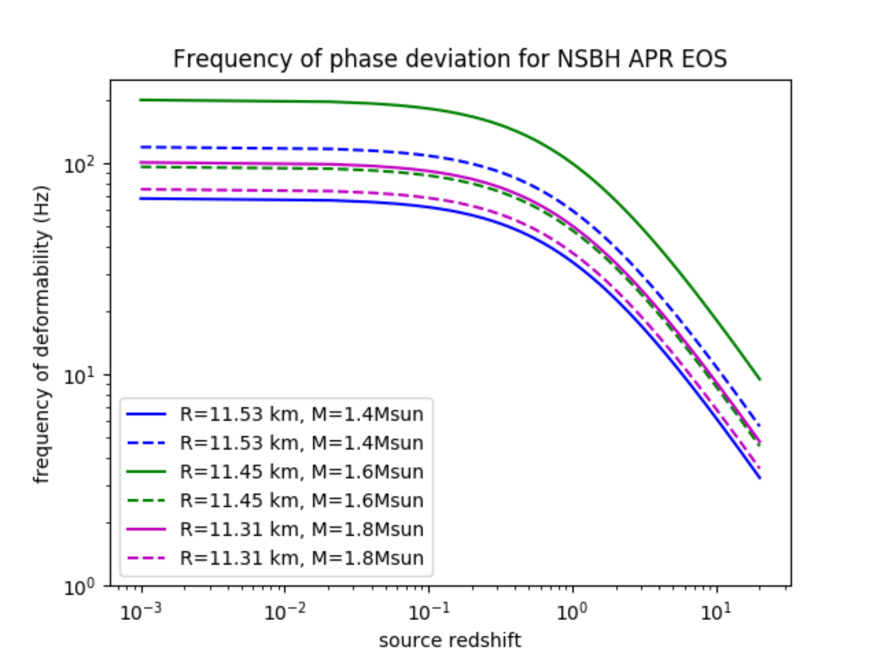


Signal-to-Noise Ratio Scaling with Redshift

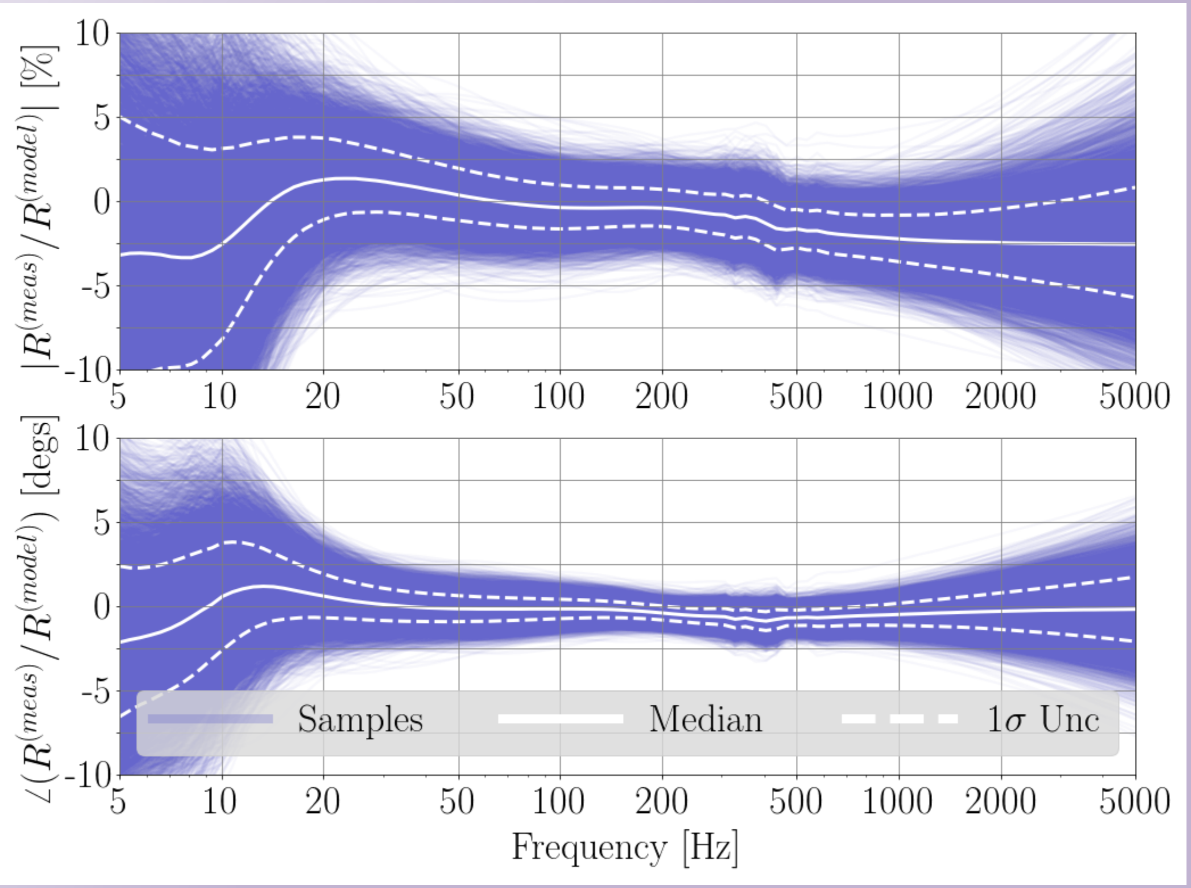


Deformation signatures as a function of redshift for APR EOS

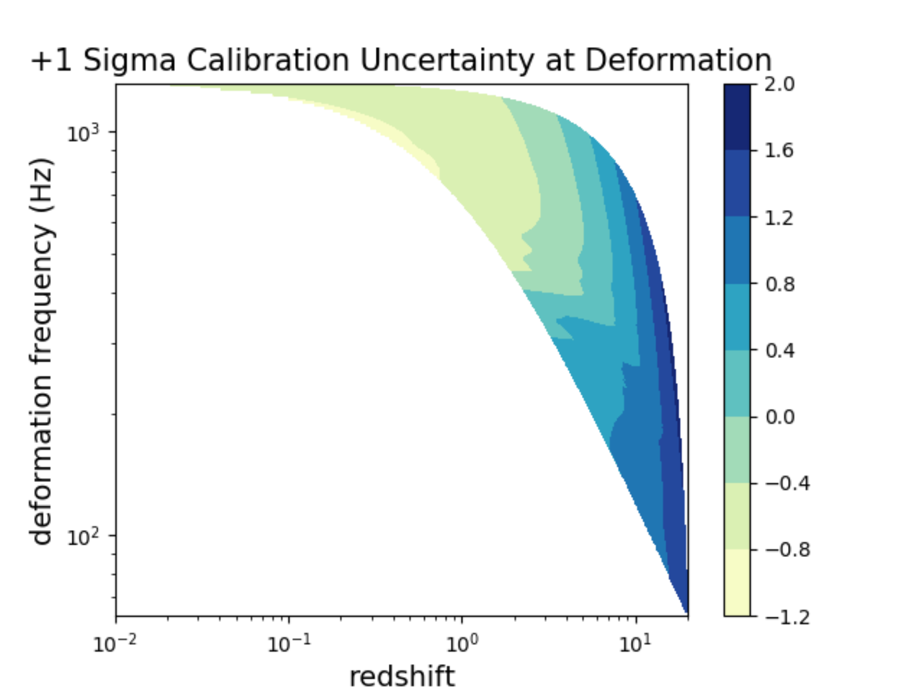


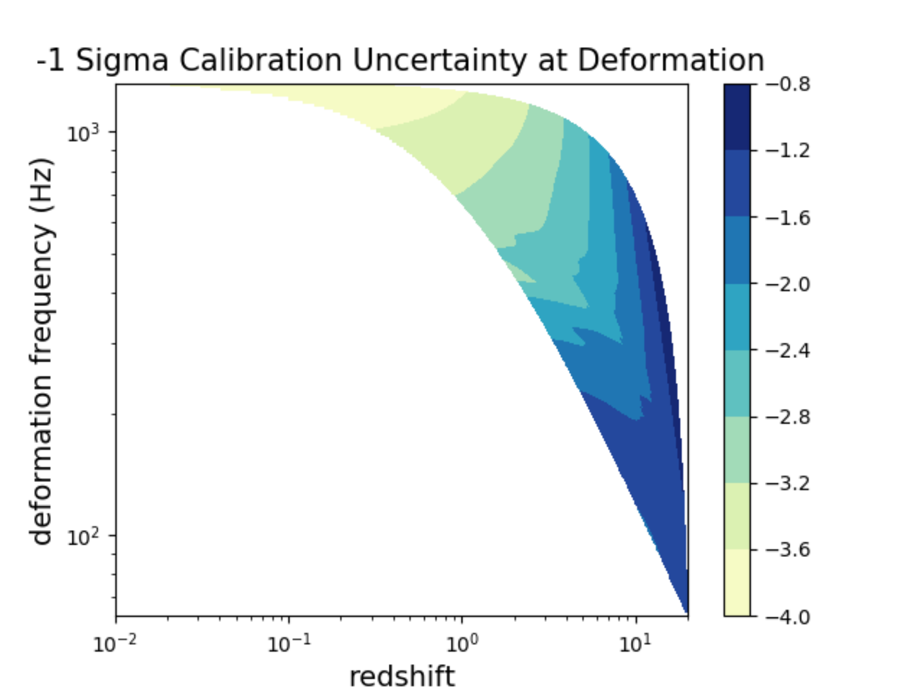


Calibration Uncertainty Budget for L1



Statistical Calibration Uncertainty at Deformation Signatures





Systematic biases

- Distance / inclination angle degeneracy will affect distance estimates to source
- Clearly, EOS *matters*, but we should know this by the 3G era!
- Waveform uncertainty: might be *greater* than calibration uncertainty
- We assume calibration uncertainty will be lower for ET than aLIGO

Future Work: Cosmography with 3G detectors

- Repeat signal injection for different cases:
  - BNS mergers
  - More realistic EOS models
  - CE recolored datastream
- Calculate luminosity distance to source using parameter estimation methods
- Address systematic biases*
- Mock calculation of H_0
- Fisher analysis to determine uncertainties on H_0
- Translate these to science requirements for 3G detectors

Thank You

- To Alex, for being such a fantastic mentor…
- To Alan, Craig, TJ and all the members and SURFs of LIGO Lab at Caltech for all your help…
- To Jocelyn and the Fullerton GWPAC group for collaborating with us…
- And to NSF and LIGO Scientific Collaboration for making the LIGO Caltech SURF program possible!

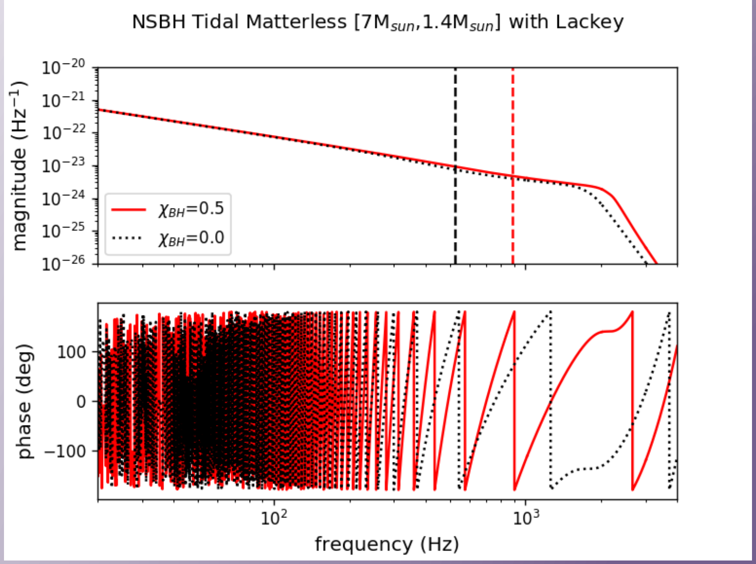
Observability of Tidal Signatures with APR EOS

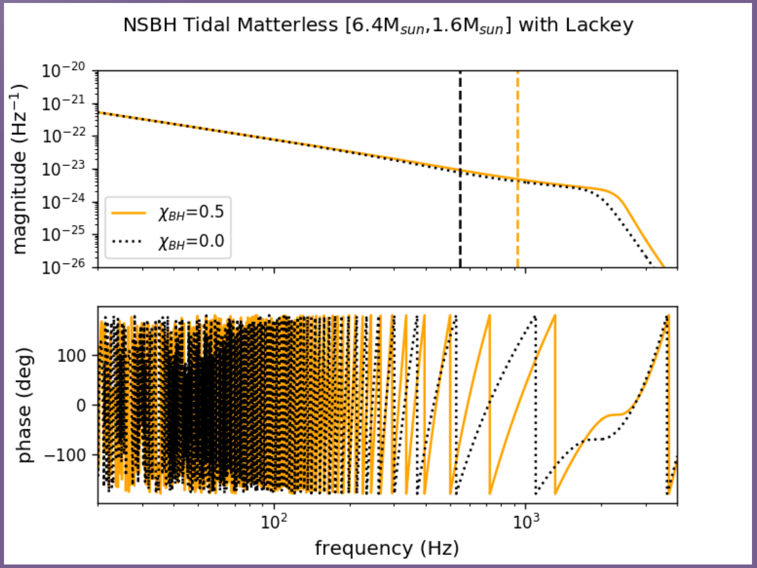
- Calibration uncertainty:
  - Magnitude: < 5% uncertainty at deformation frequency for sources with z < 2
  - Phase: < 2 deg. uncertainty at deformation frequency for sources with z < 2
- Injection:
  - NSBH waveforms clearly visible above ET noisecurve for a nearby source
  - NSBH waveforms with matter barely distinguishable from those without matter in magnitude (noise floor at f_{TD})
- SNR as a function of z:
  - ET can see NSBH sources out to z ~ 2 with SNR ~ 10

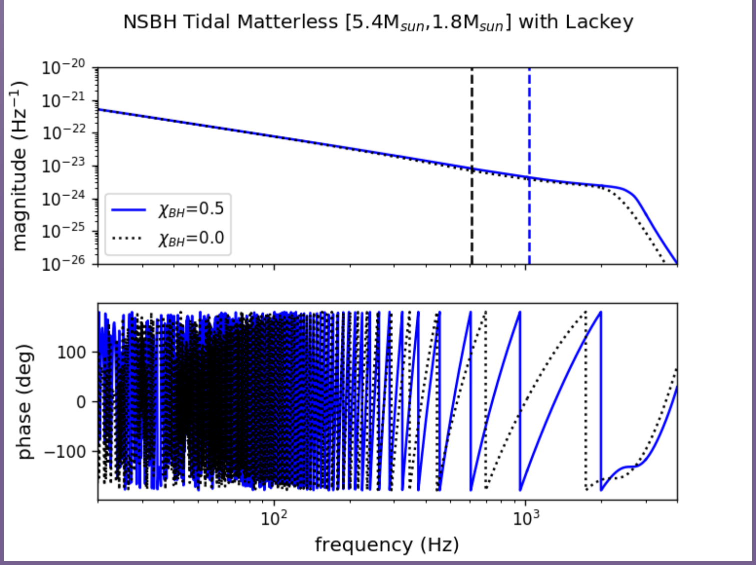
Observability of Tidal Signatures with 2H EOS

- Calibration uncertainty:
  - Magnitude: < 3.5 % uncertainty at deformation frequency for sources with z < 2
  - Phase: < 2 deg. uncertainty at deformation frequency for sources with z < 2
- Injection:
  - NSBH waveforms clearly visible above ET noisecurve for a nearby source
  - NSBH waveforms with matter barely distinguishable from those without matter in magnitude (noise floor)
- SNR as a function of z:
  - ET can see NSBH sources out to z ~ 2 with SNR ~ 10

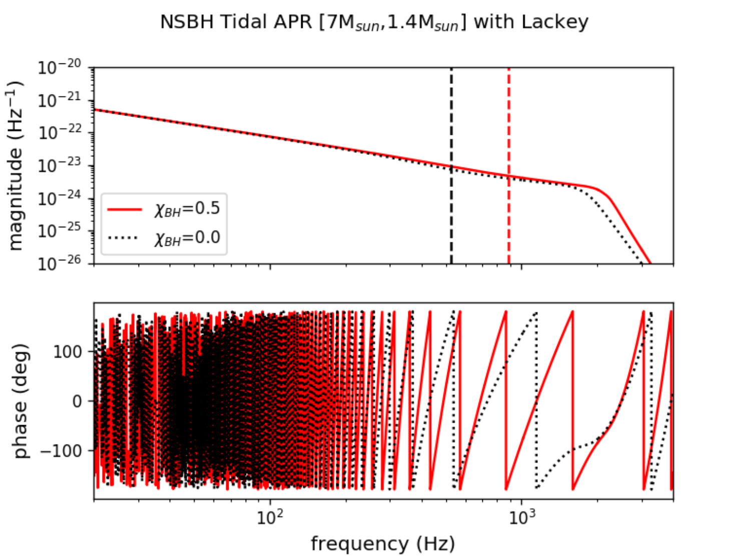
Waveform Visualization: No Matter Effects

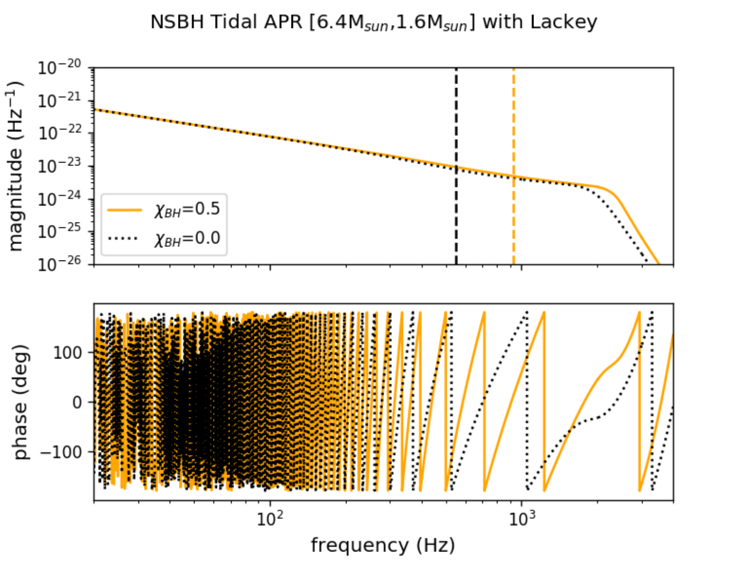


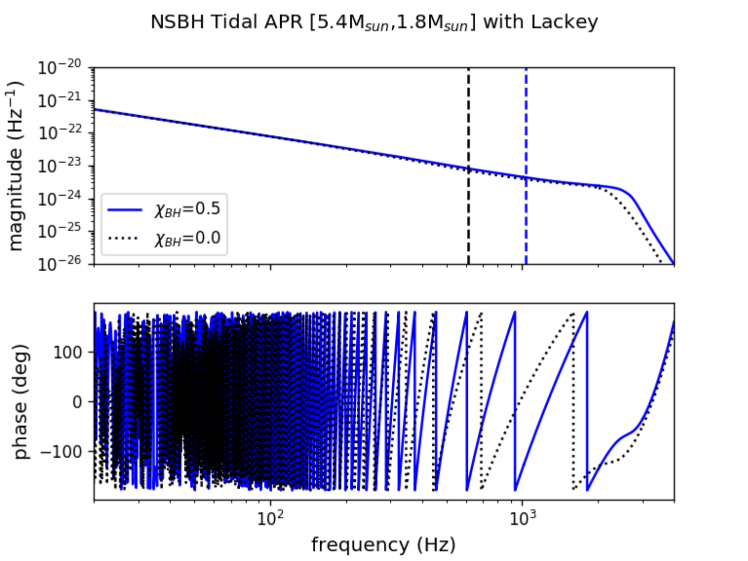




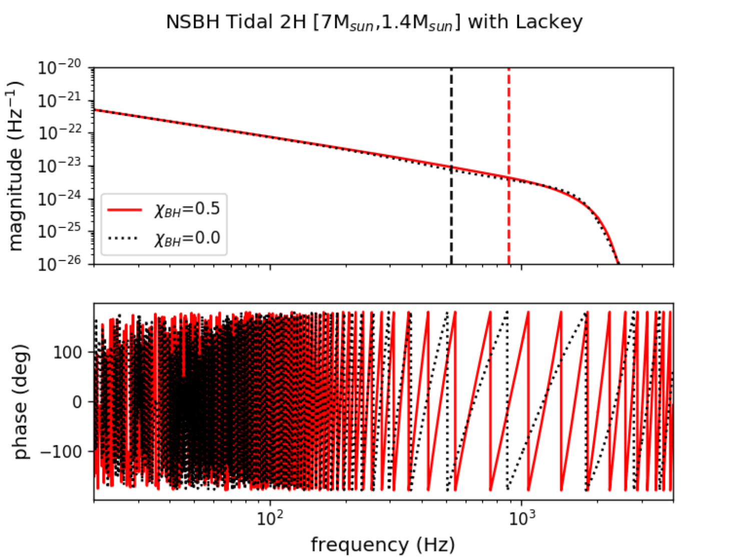
Waveform Visualization: APR Equation-of-State

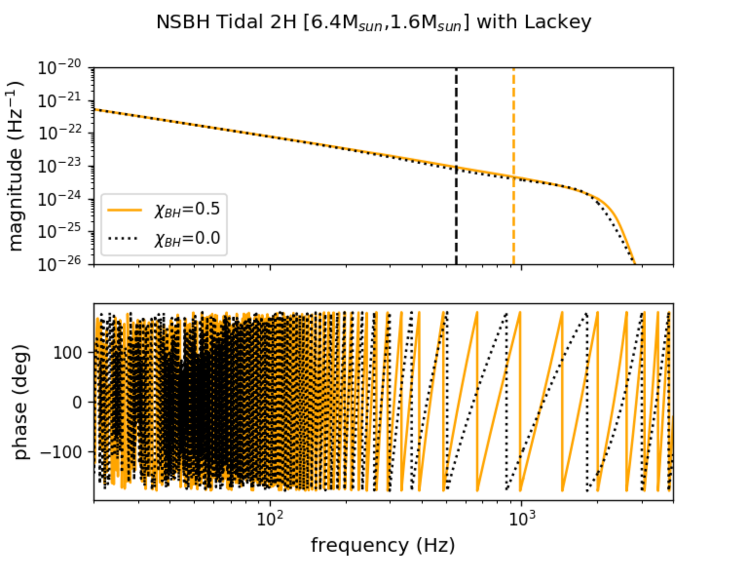


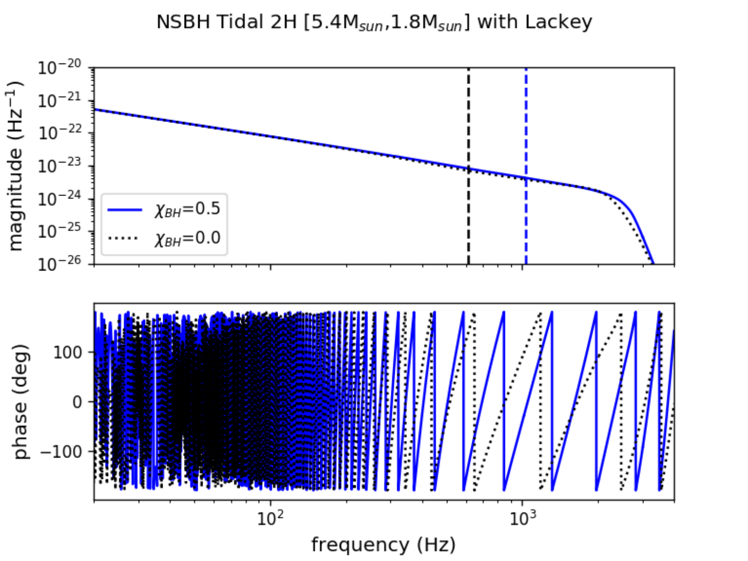




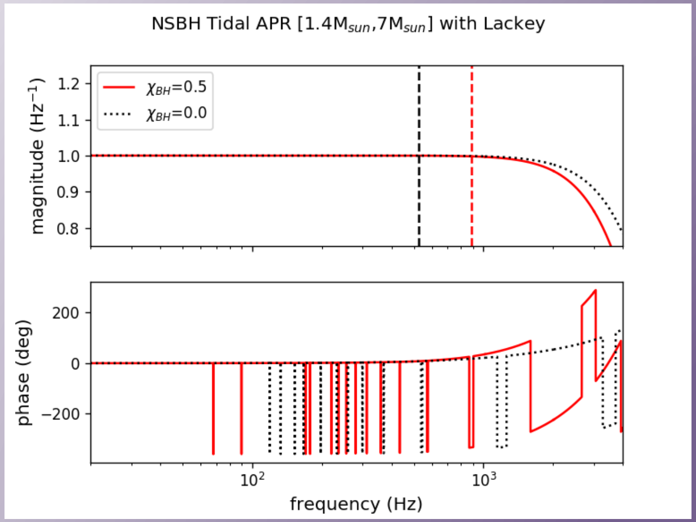
Waveform Visualization: Extreme 2H Equation-of-State

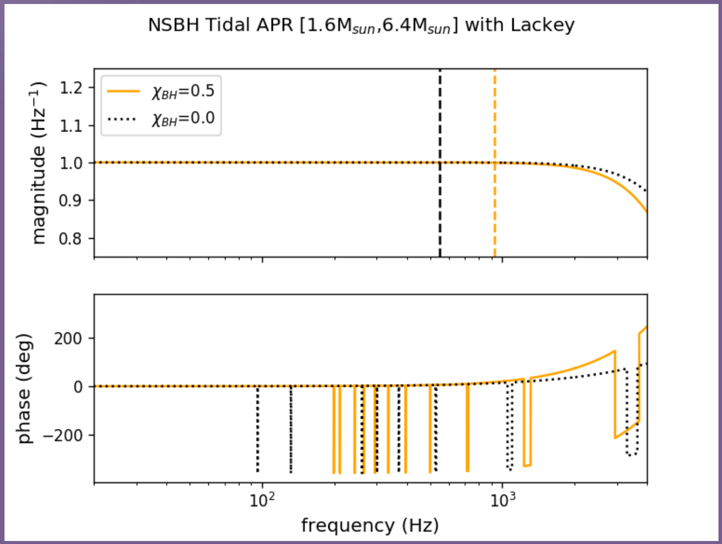


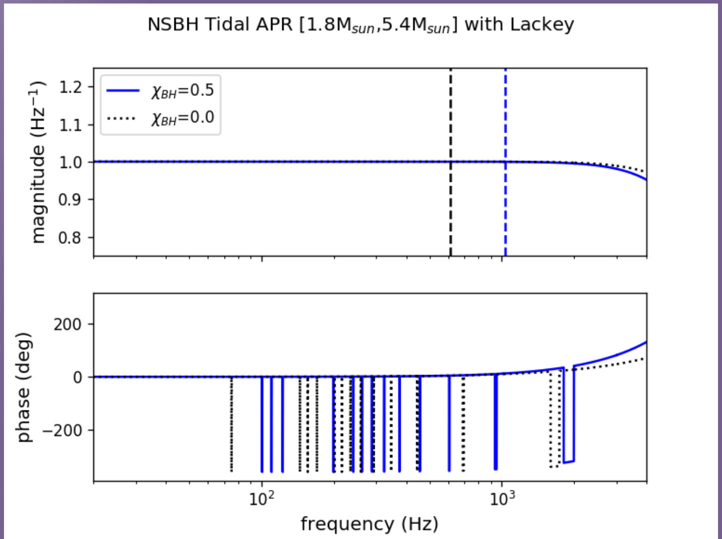




Tidal Deformability Signatures: Ratios Between Waveforms for APR







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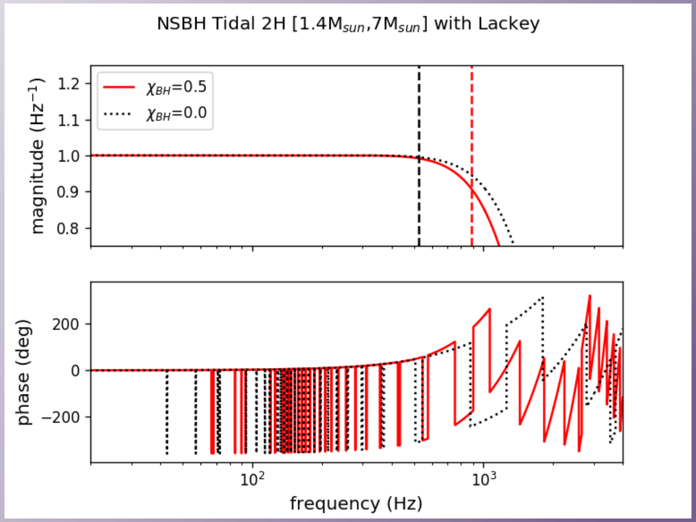
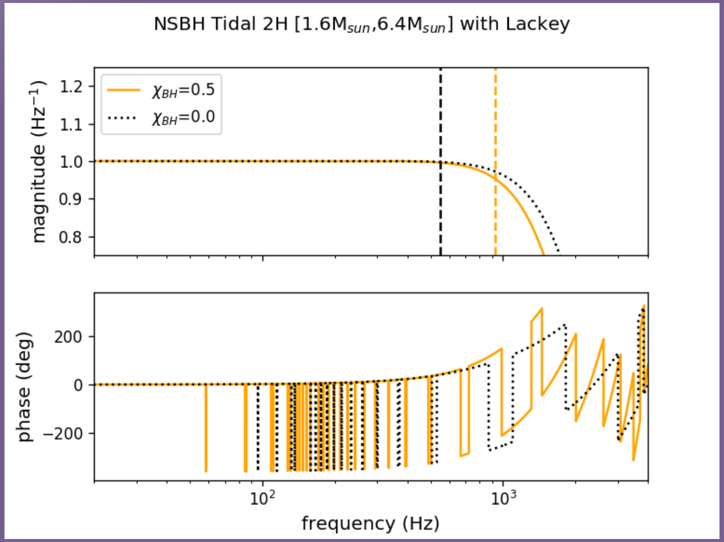
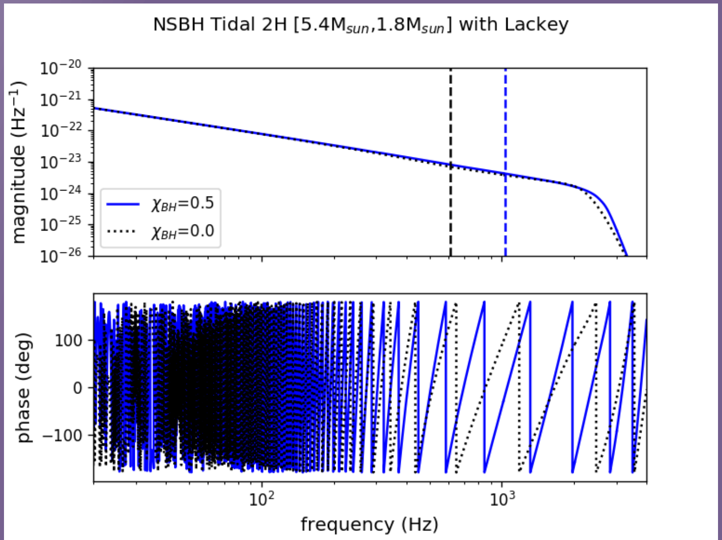
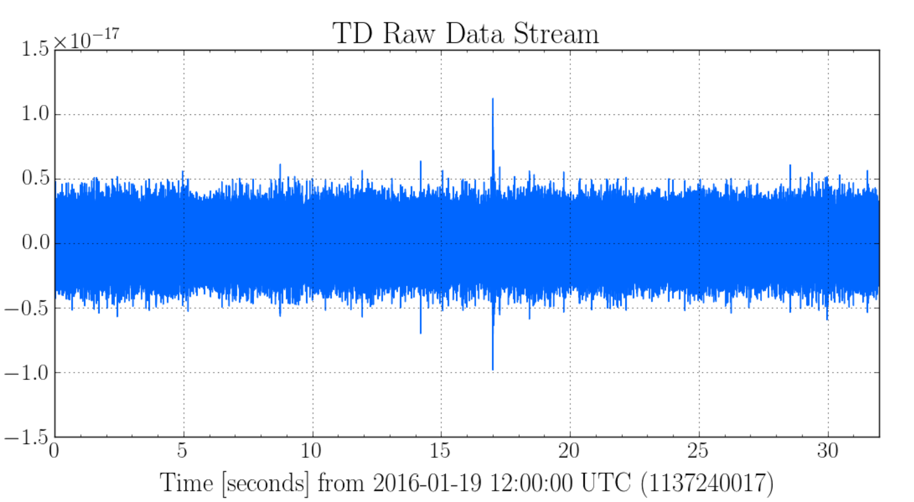
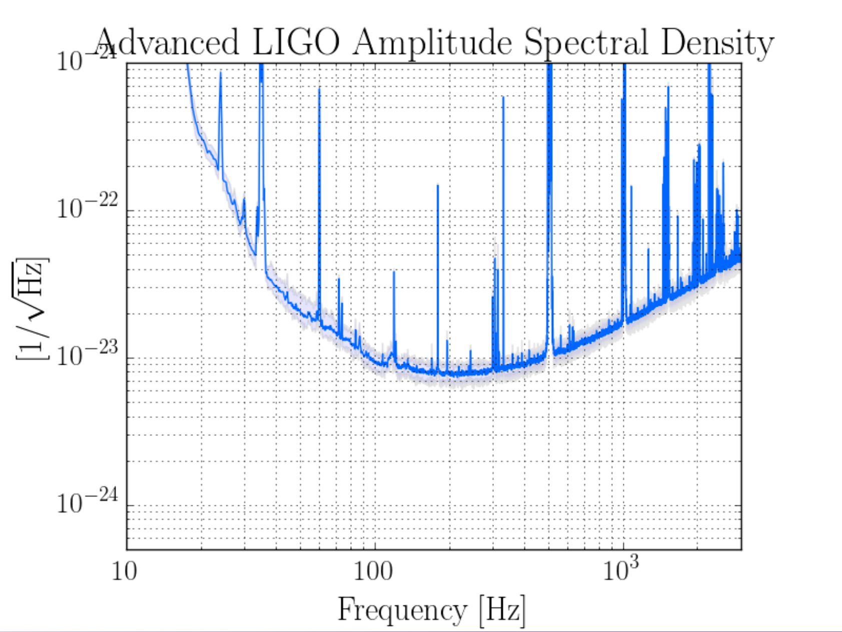


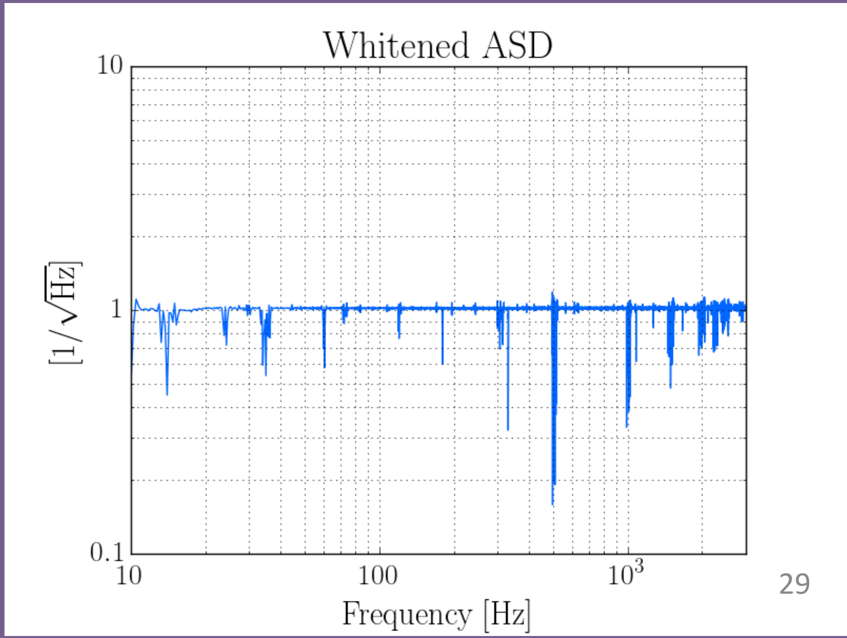




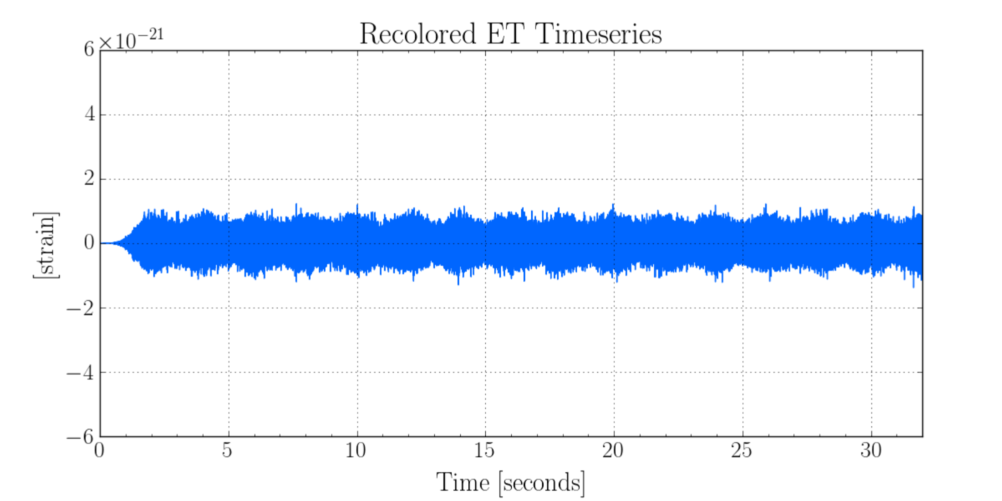
Whitening aLIGO datastream

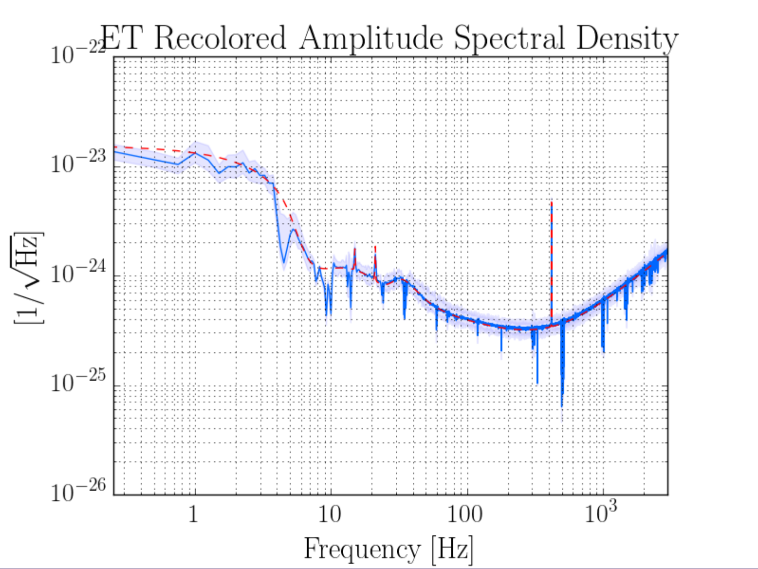


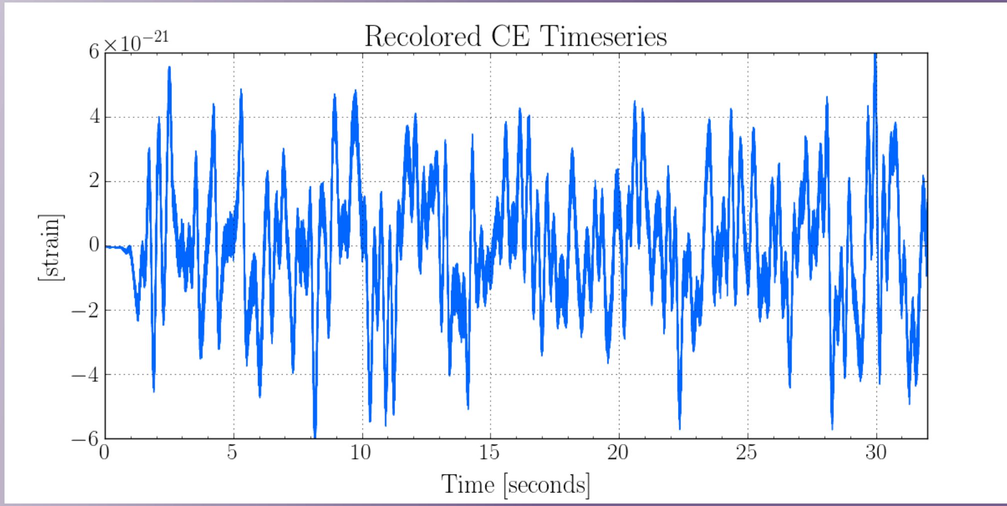


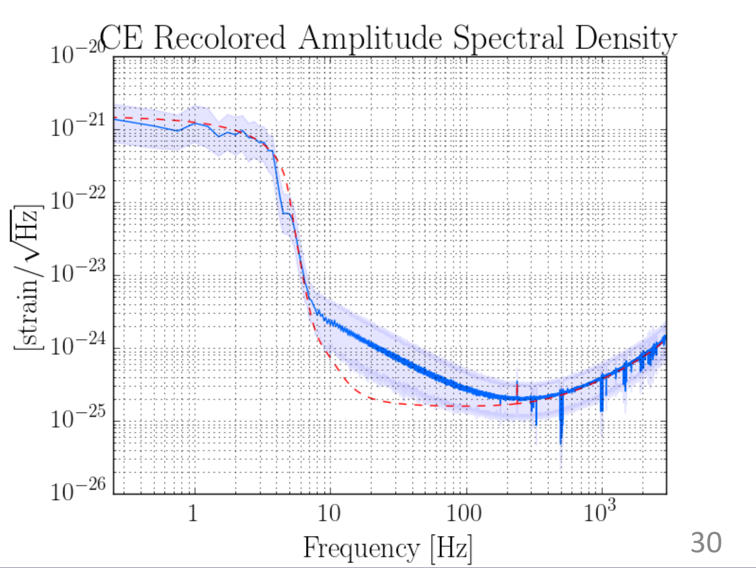


Recoloring datastream for ET-D and CE

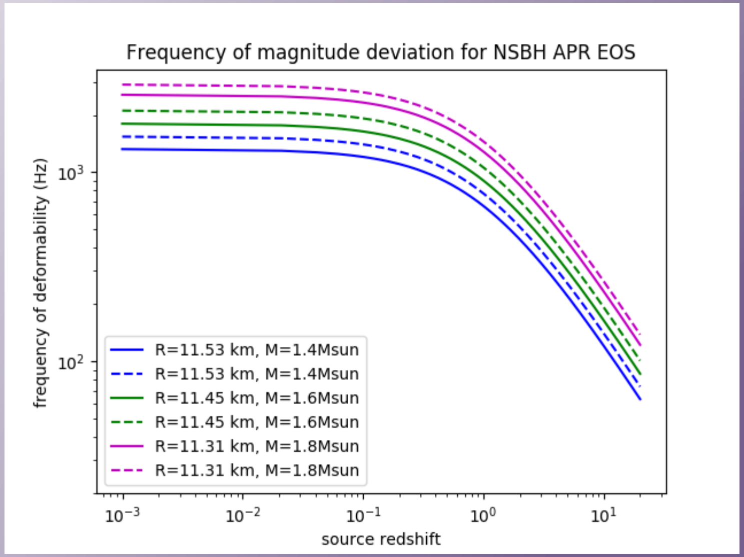


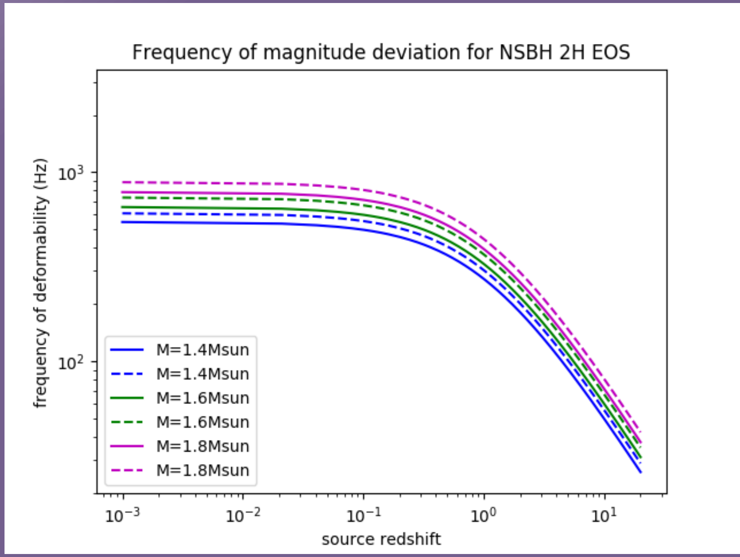


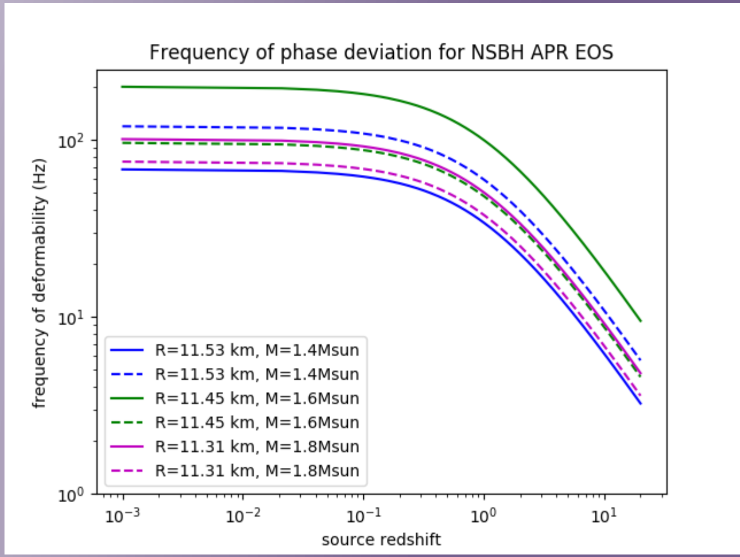


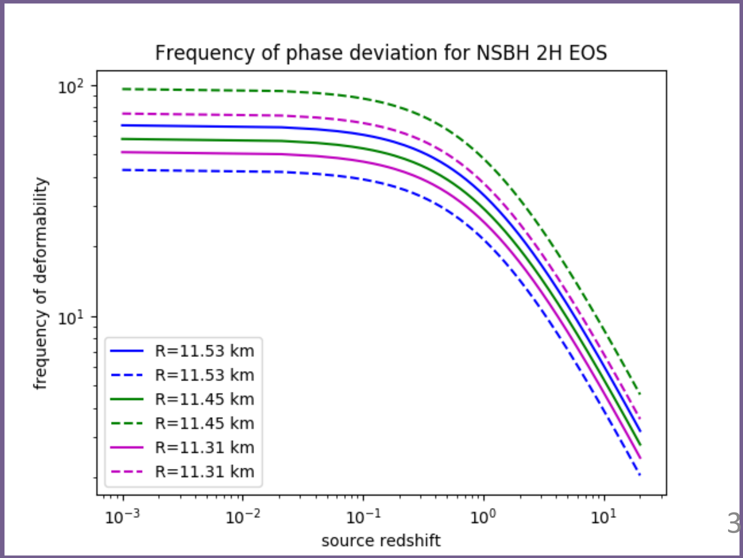


Deformation signatures as a function of redshift









Calibration Uncertainty at Deformation Signatures