How can we distinguish between high mass binary neutron star and binary black hole merger with gravitational waves?

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GW170817

First binary neutron star (BNS) merger detected by LIGO-Virgo on August 17, 2017

Why BNS?

- Total mass estimated: 2.73 and 3.29 M⊙ (Known BNS: 2.57 ~ 2.88)
- Gamma ray burst detected after the coalescence
- No known black holes have such low mass in our galaxy

Issue

- Equation of state of neutron star unclear; high mass neutron star ~ 2 $M_\odot$
- Low mass black holes could exist
- Current GW detectors: short range – known black holes
- Future GW detectors: more sensitive -- larger detection range – far away binary compact objects

Can we recognize BNS with GW detection?

Binary neutron stars

- Tidal effect:

- Tidal deformability λ

$$Q_{ij} = -k_2 \frac{2R^5}{3G} E_{ij} \equiv -\lambda E_{ij},$$

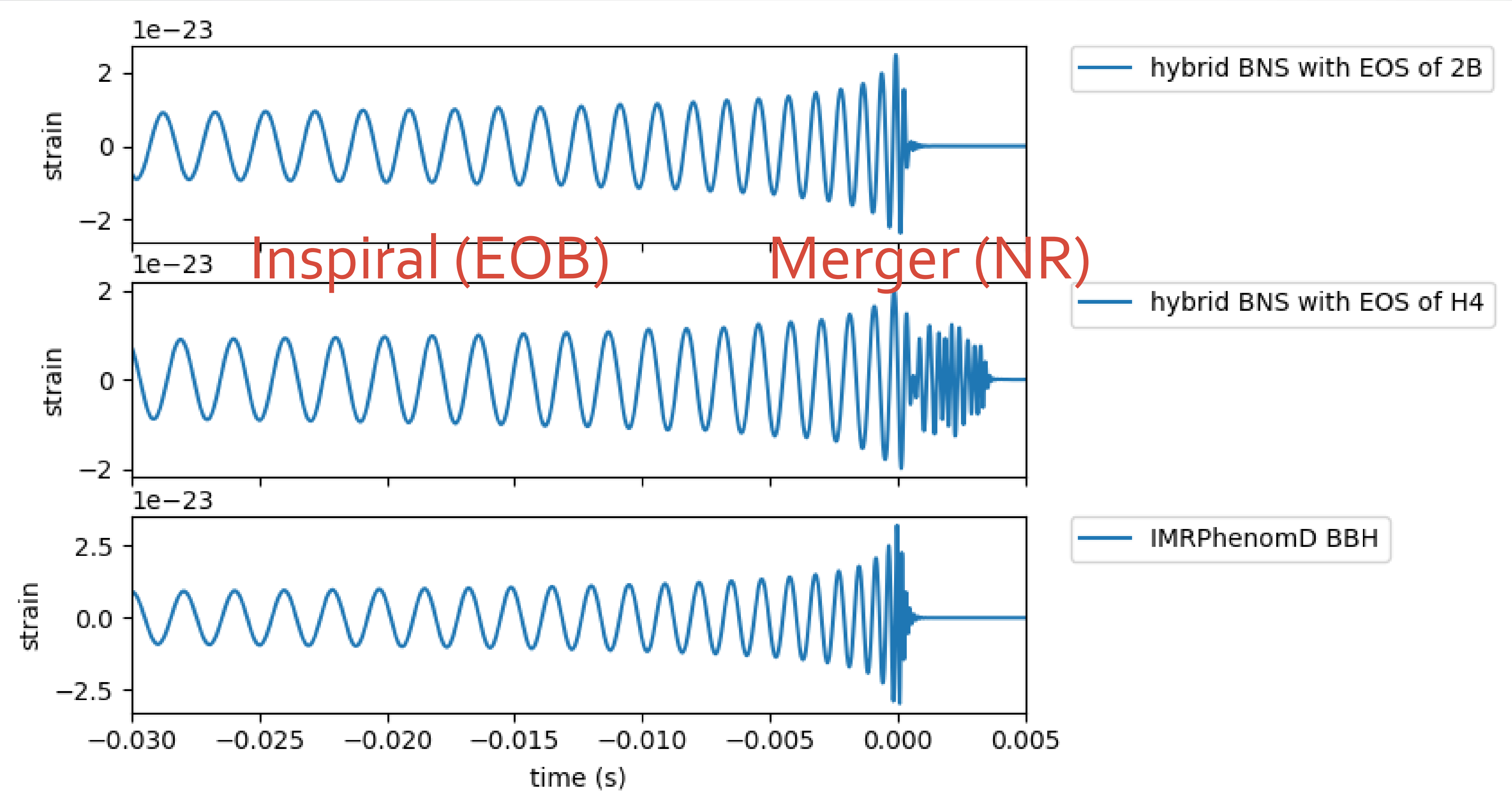
Q: quadrupole moment
E: tidal field
K2: Love number

- Quadrupole moments – different gravitational field – different GW waveforms
  - Different equation of state (EOS) – different tidal deformability – different quadrupole moments

  Tidal deformability of black hole is zero

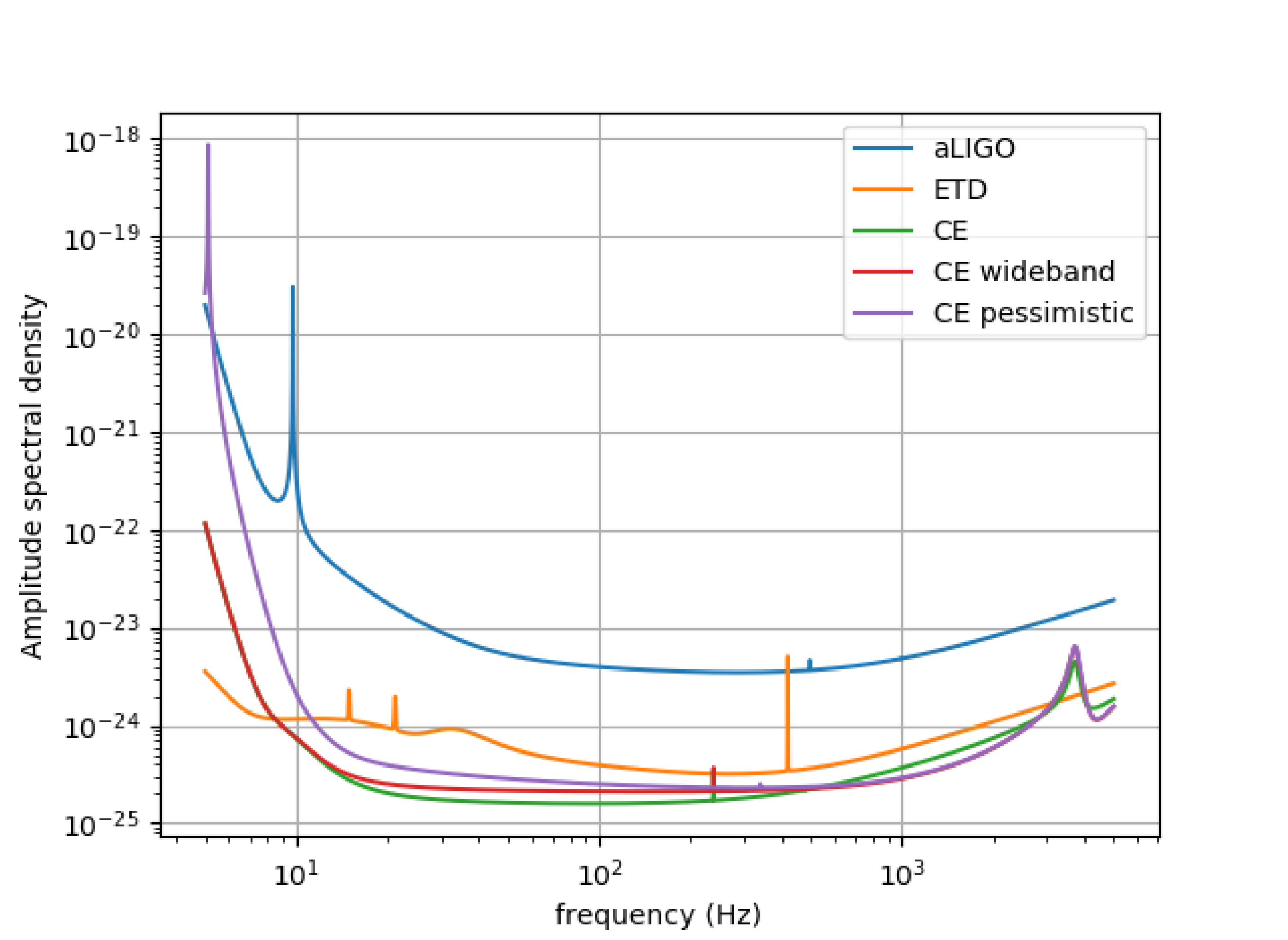
Simulated hybrid BNS waveform

Approximant: Effective-one-body model (EOB) + numerical relativity (NR)



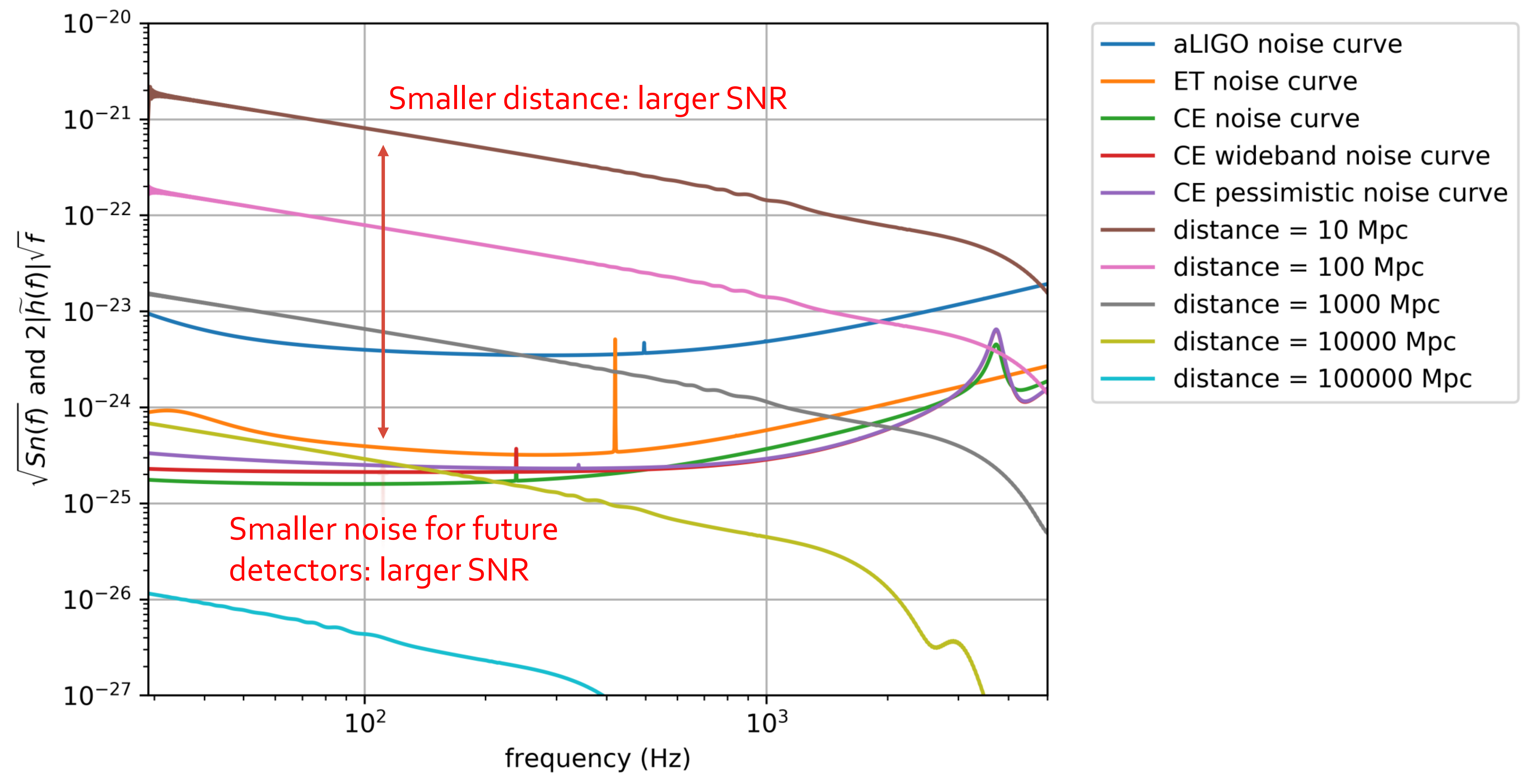
GW Detectors

- Advanced LIGO (aLIGO) and VIRGO
- Third generation detectors: Einstein Telescope (ET), Cosmic Explorer (CE)
- Noise curve:



Amplitude of GW waveform against noise curves

Signal-to-noise ratio (SNR): how clearly can we receive GW signals by detectors



Match between BNS and BBH waveform

$$\text{Match} = \max_{t_c, \phi_c} \frac{(h1|h2)}{\sqrt{(h1|h1)(h2|h2)}}$$

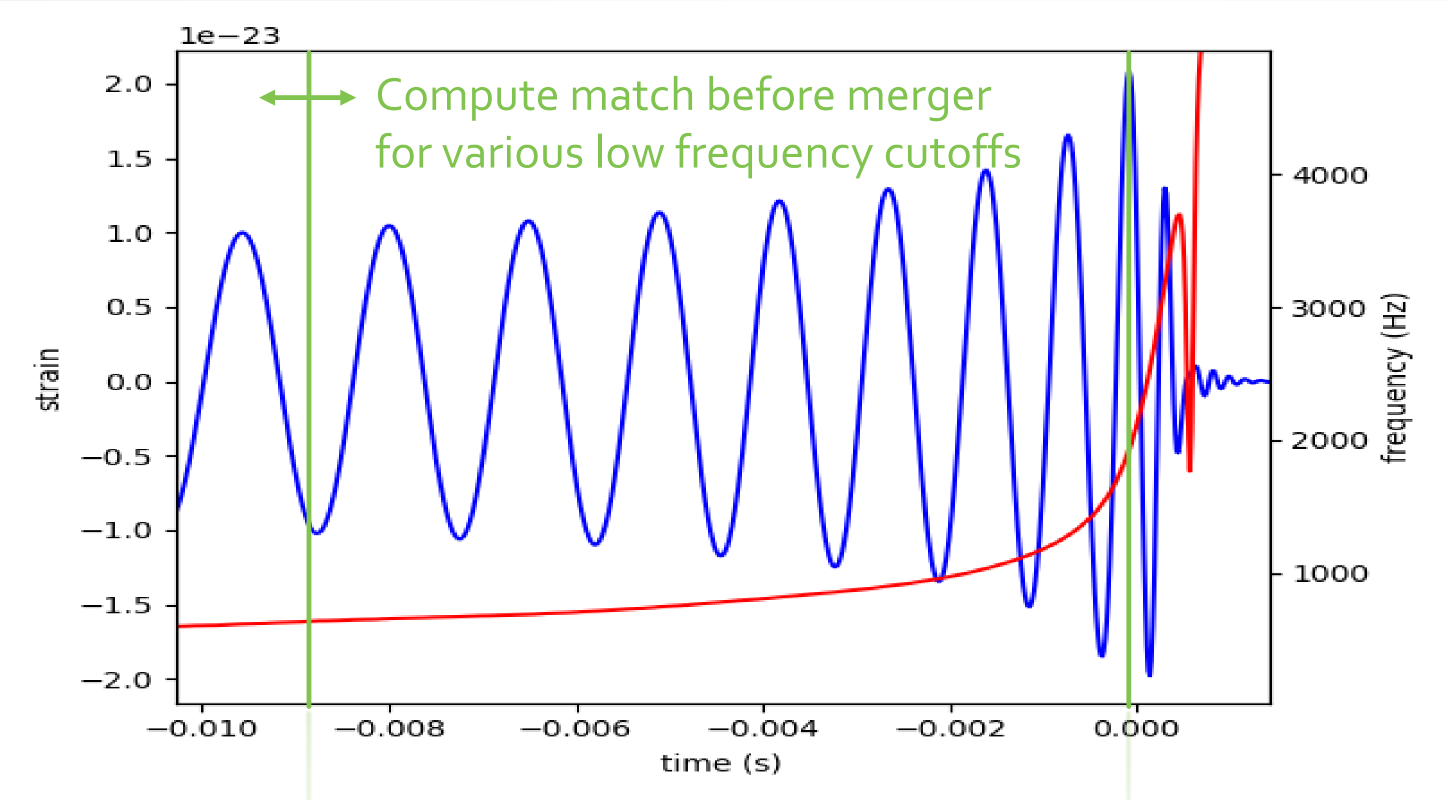
normalized between 0~1

t_c and ϕ_c : coalescence time and phase

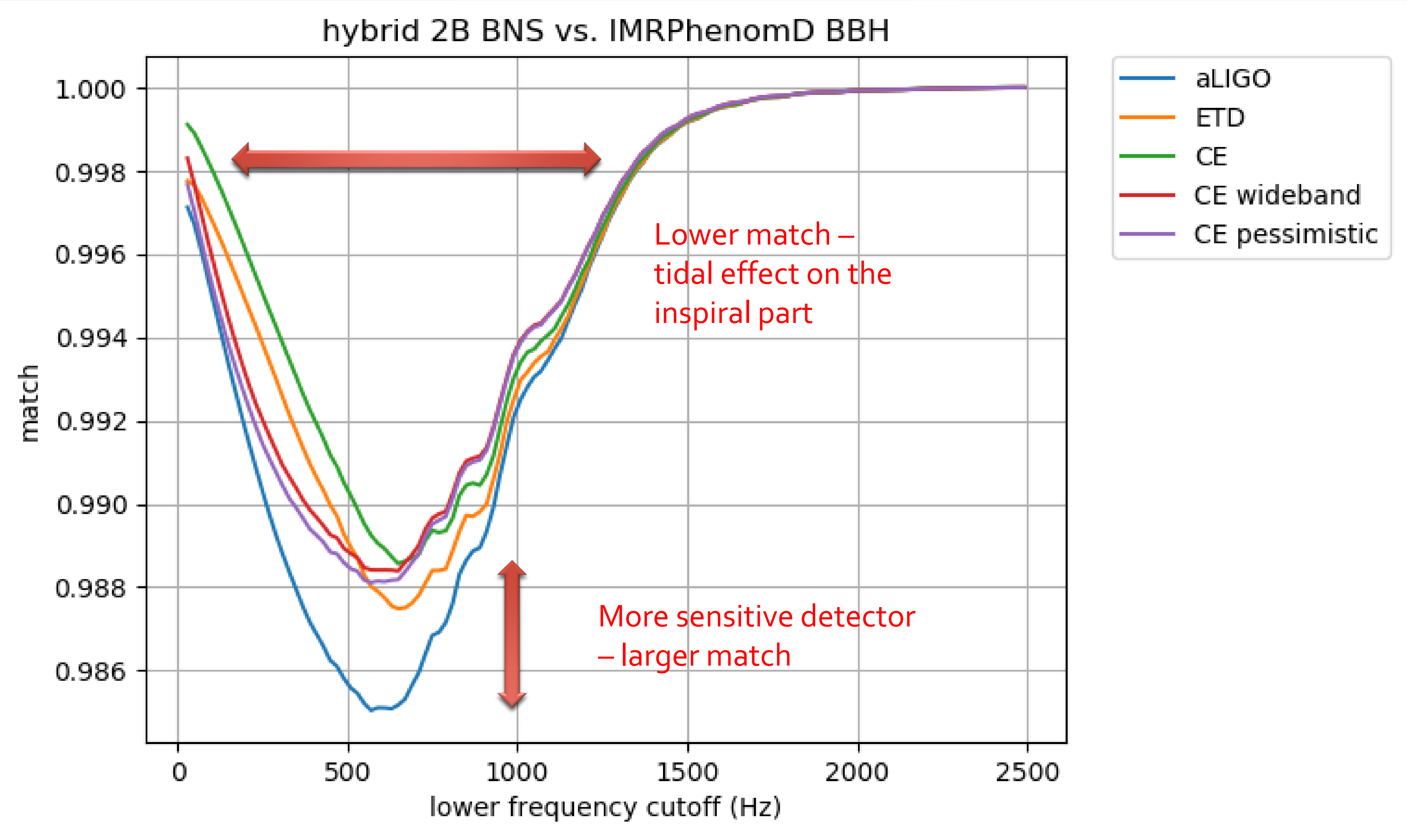
$$(h_1 \mid h_2) = 2 \int_0^\infty \frac{\tilde{h}_1^*(f)\tilde{h}_2(f) + \tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)}\, df$$

$\tilde{h}(f)$: Fourier transform of GW waveform

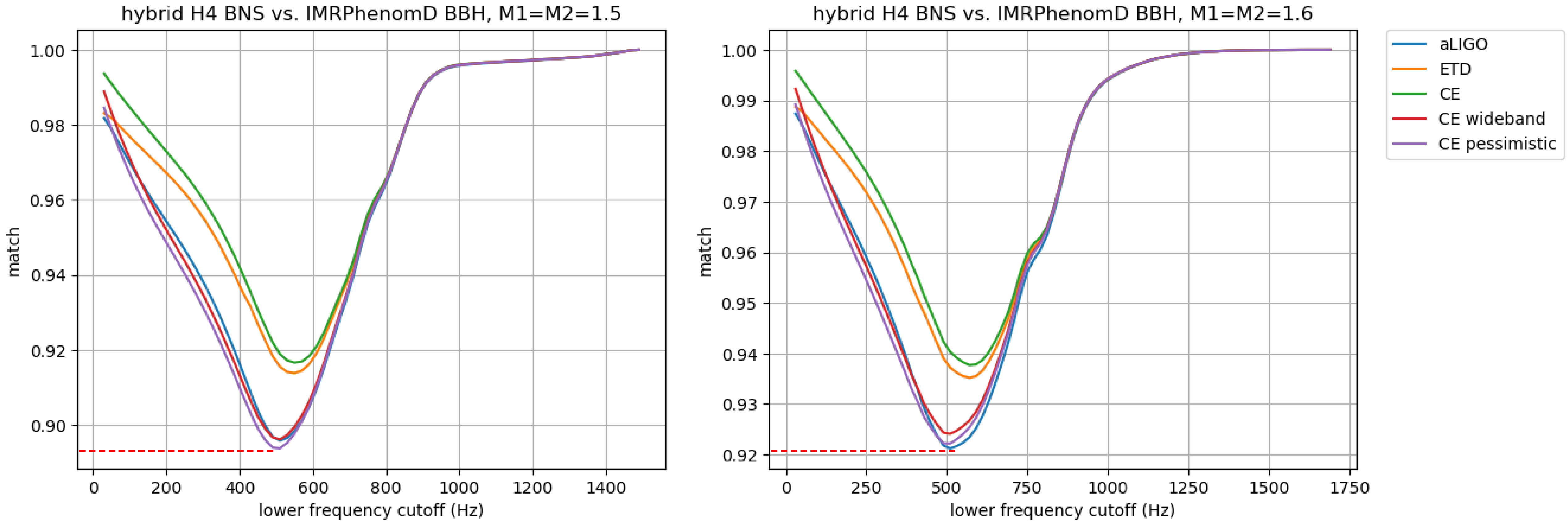
$S_n(f)$: noise curve



Frequency evolved with time in GW waveform

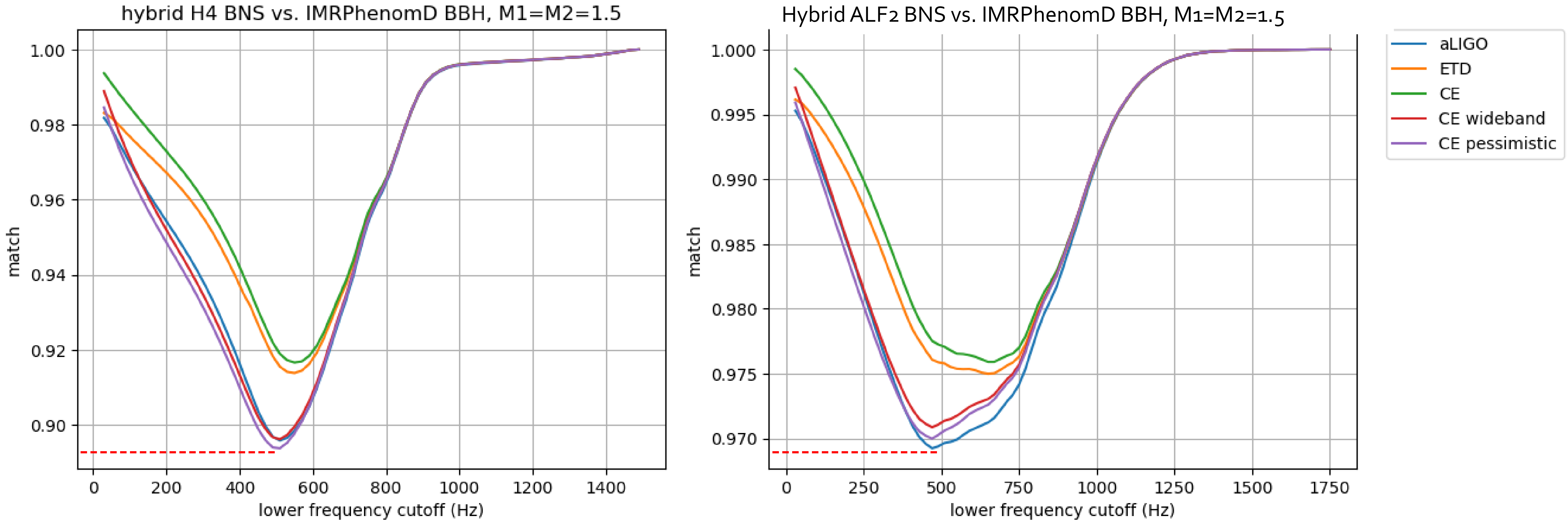

hybrid 2B BNS vs. IMRPhenomD BBH
match
lower frequency cutoff (Hz)
1.000
0.998
0.996
0.994
0.992
0.990
0.988
0.986
0
500
1000
1500
2000
2500
aLIGO
ETD
CE
CE wideband
CE pessimistic
Lower match – tidal effect on the inspiral part
More sensitive detector – larger match

Match with different masses



Higher masses – higher match – harder to distinguish between BNS and BBH

Match between different EOS



Different EOS – different tidal deformability – different match

Parameters estimation (PE) by LALInference

Parameters: masses, spins, tidal deformabilities, distance, sky location etc.

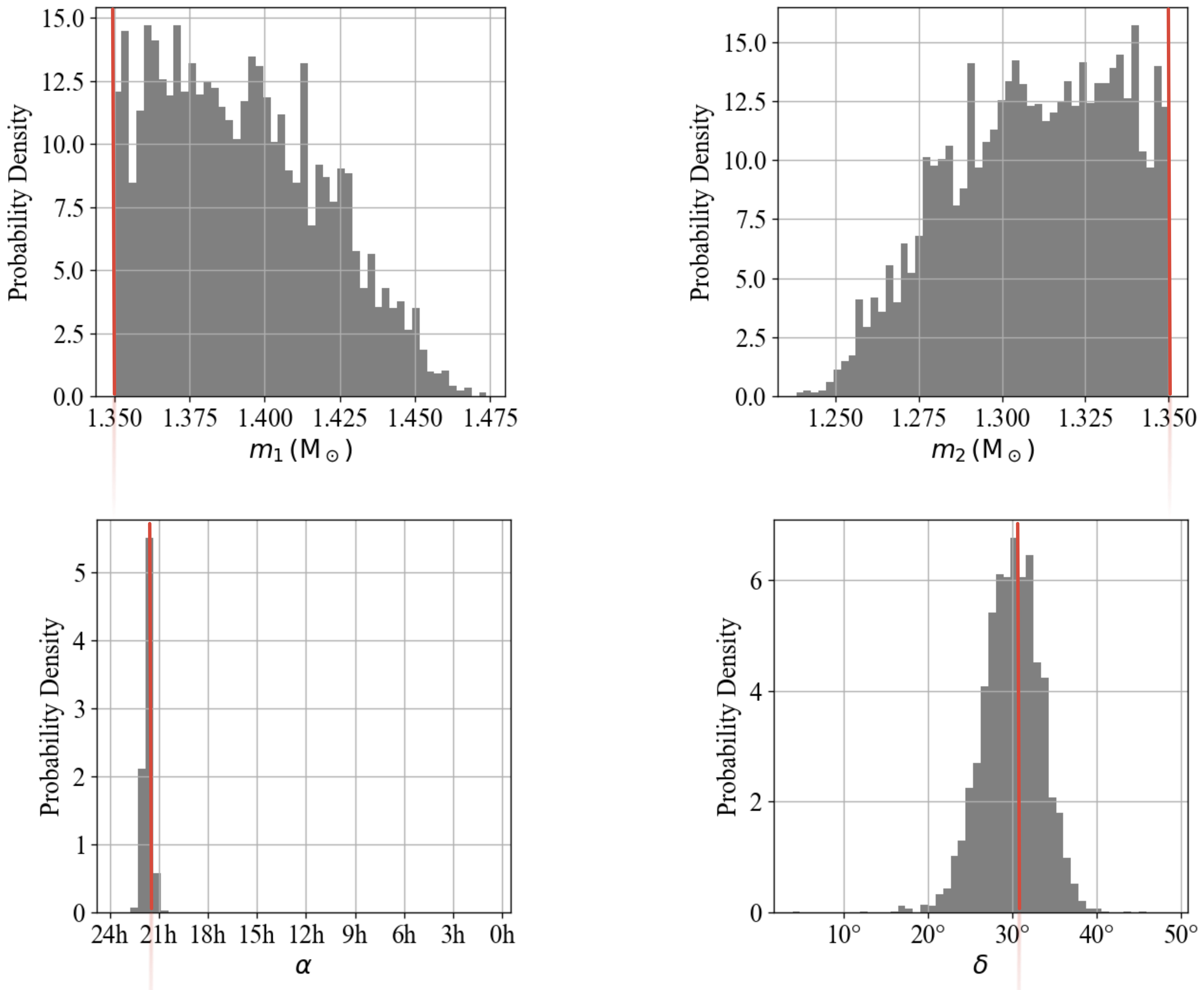
Theory: Bayesian theory

Method:

- Markov chain Monte Carlo (MCMC) – find the posterior probability distribution of parameters by stochastically wandering through the parameter space

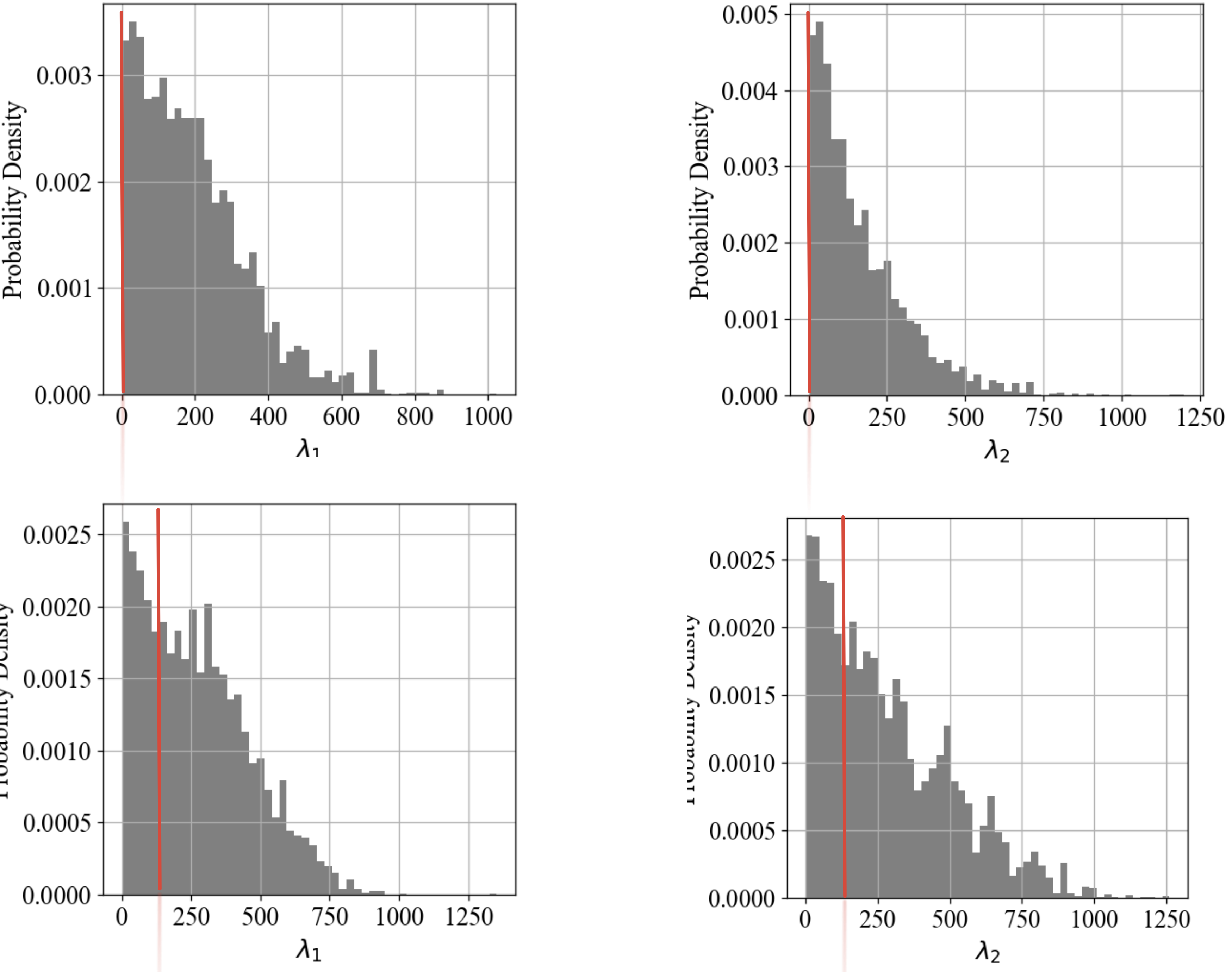
- Nested sampling – a Monte Carlo technique to find the posterior probability distribution of parameters through the computation of Bayesian evidence

PE for Hybrid 2B BNS by MCMC, with aLIGO noise curve



Right ascension
Declination

Estimation of tidal deformability



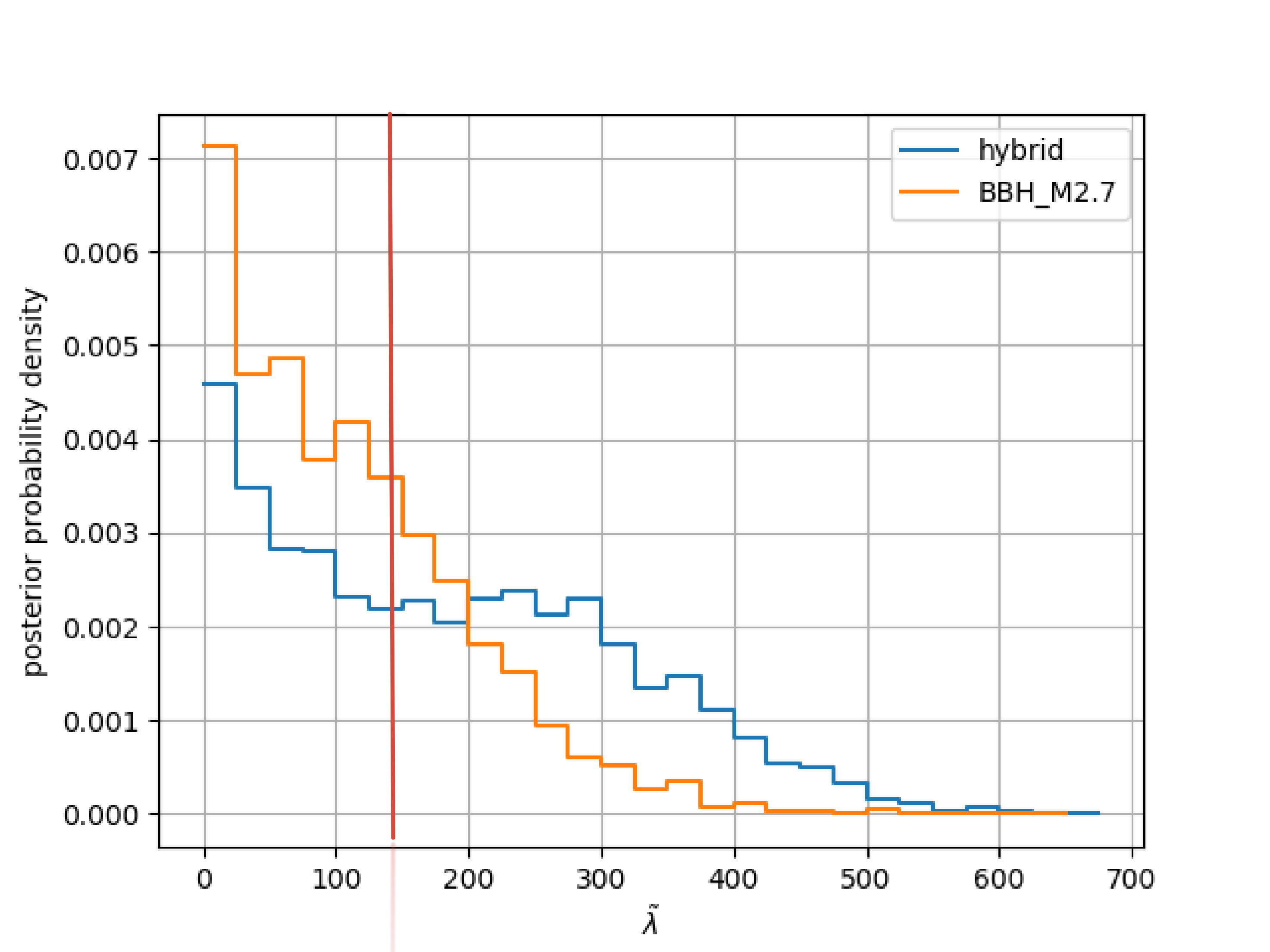
BBH

BNS ($\lambda_1 = \lambda_2 = 127.5$)

Useful parameter transformation

$$\tilde{\lambda} = \frac{8}{13}\left[(1 + 7\eta + 31\eta^2)(\lambda_1 + \lambda_2) + \sqrt{1 - 4\eta}(1 + 9\eta - 11\eta^2)(\lambda_1 - \lambda_2)\right]$$

$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$



Can see difference, but still not peak at the actual value for BNS

Future work

- Require larger SNR:

  Smaller distance

  New generation detectors: smaller noise

- Clearer difference in tidal deformability estimation of BNS and BBH:

  posterior probability density peaks around the actual value of BNS

Q & A