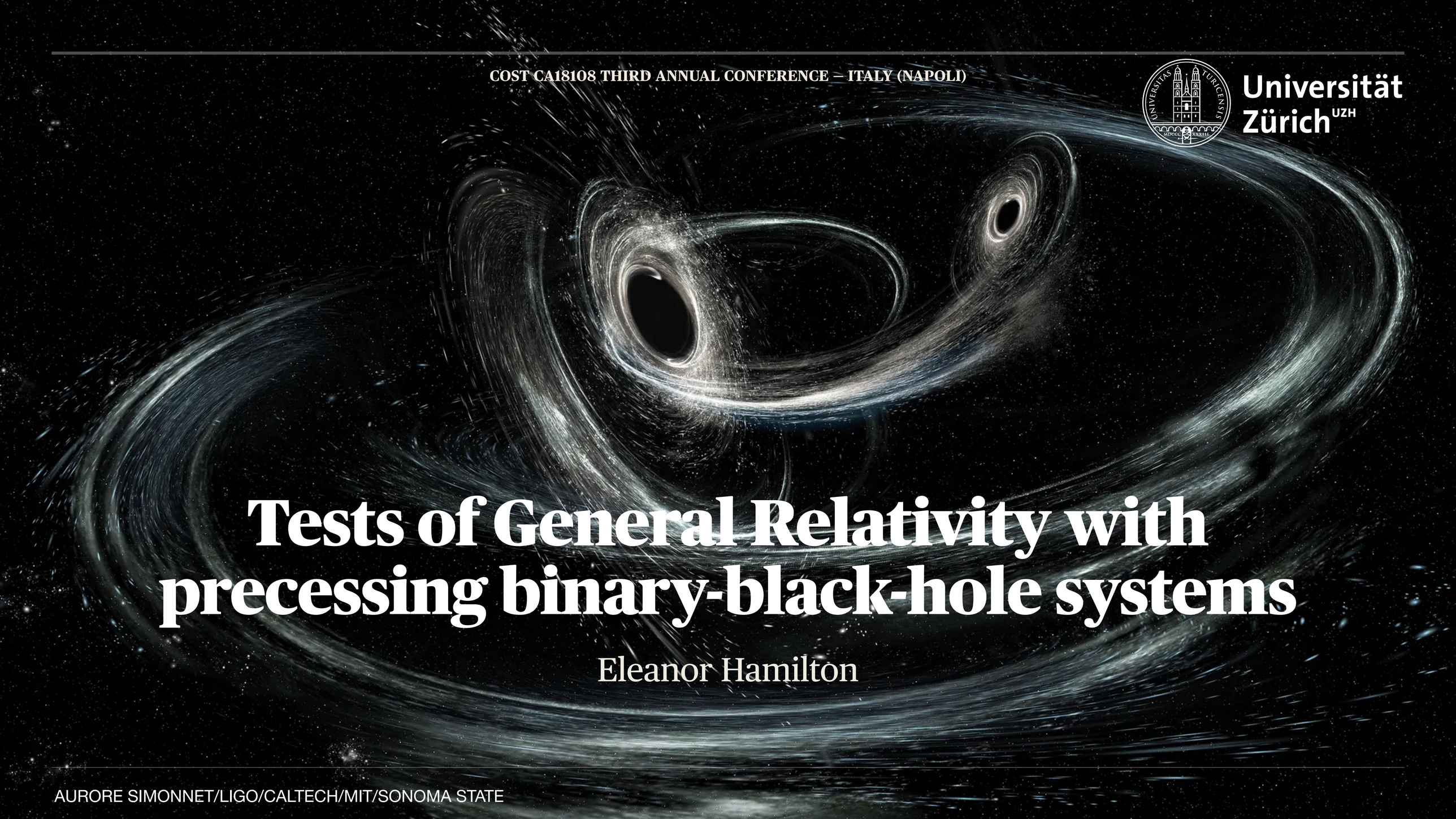

Tests of General Relativity with precessing binary-black-hole systems

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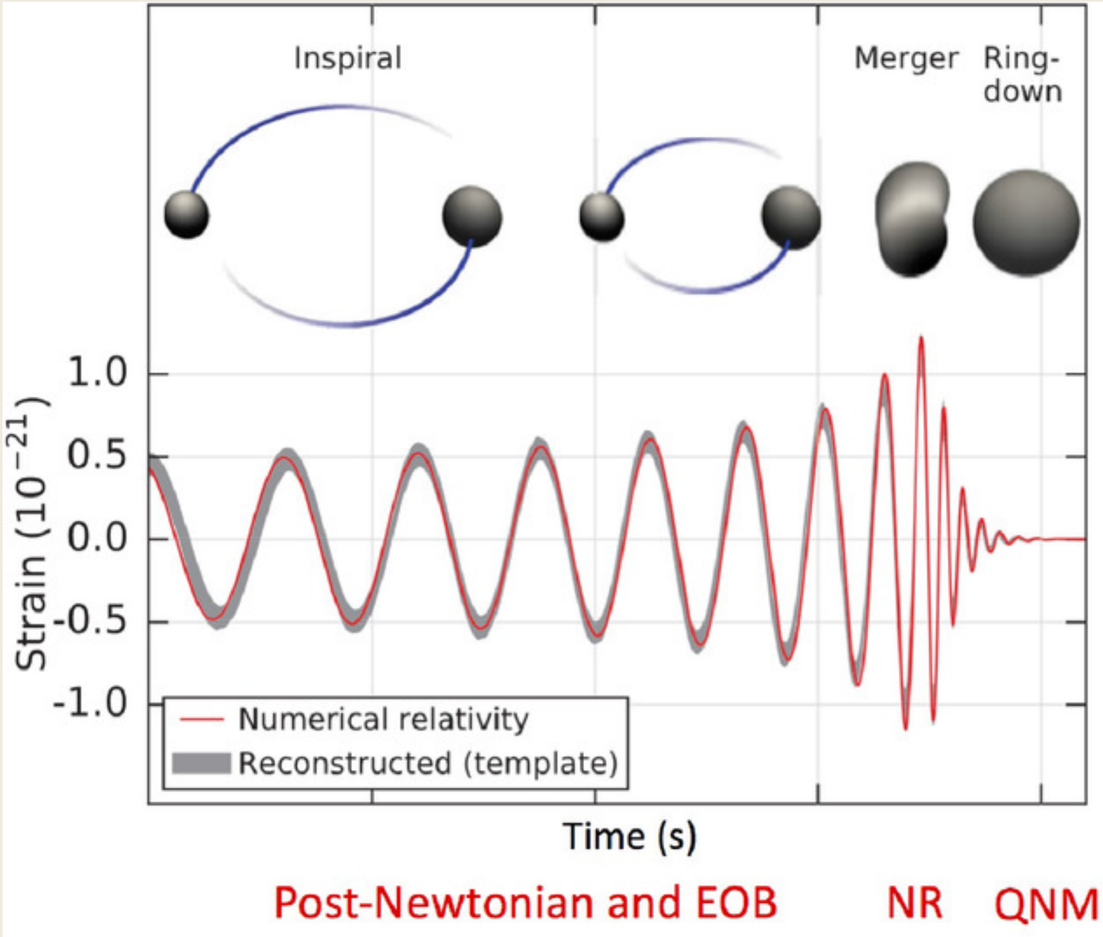
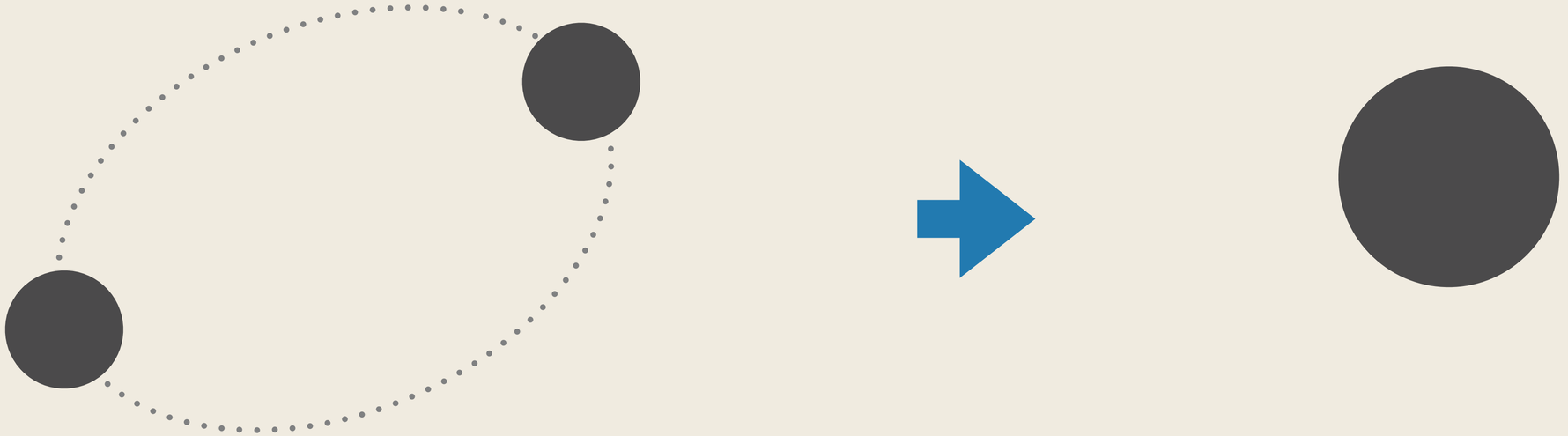
Gravitational wave signals



Abbott, Benjamin P., et al. "Observation of gravitational waves from a binary black hole merger." *Physical review letters* 116.6 (2016): 061102.

Binary parameters



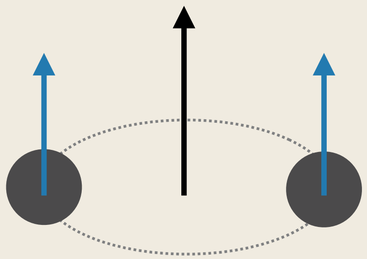
Total mass M and mass ratio q

Spins $\mathbf{S}_1$ and $\mathbf{S}_2$

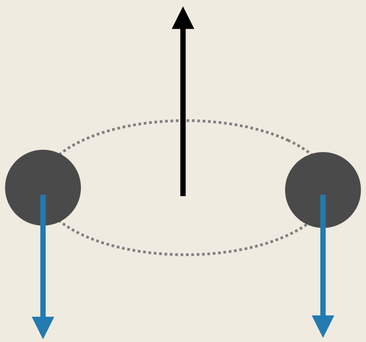
Final mass M_f

Final spin $\mathbf{S}_f$

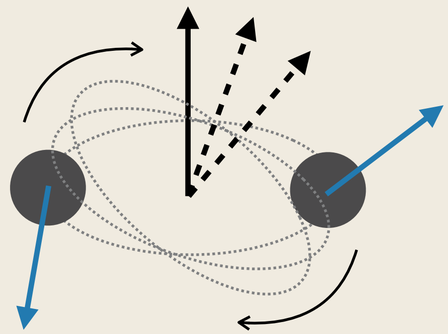
Effect on waveform



If the black holes' spin is aligned with the orbital angular momentum, the two black holes will take longer to coalesce



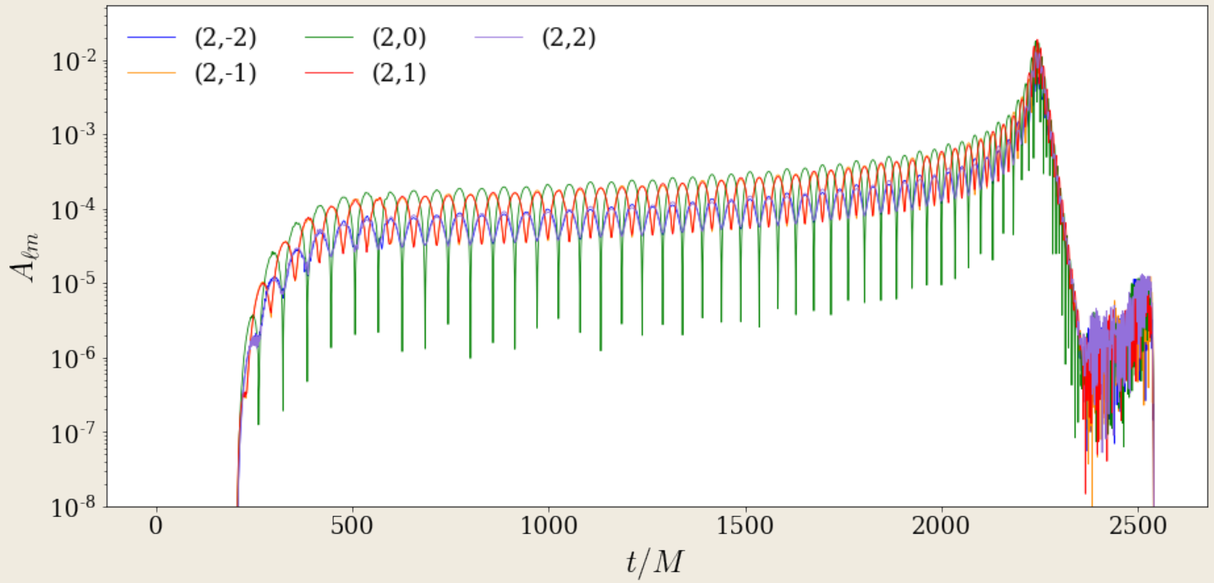
If the black holes' spin is anti-aligned with the orbital angular momentum, the two black holes will take less time to coalesce



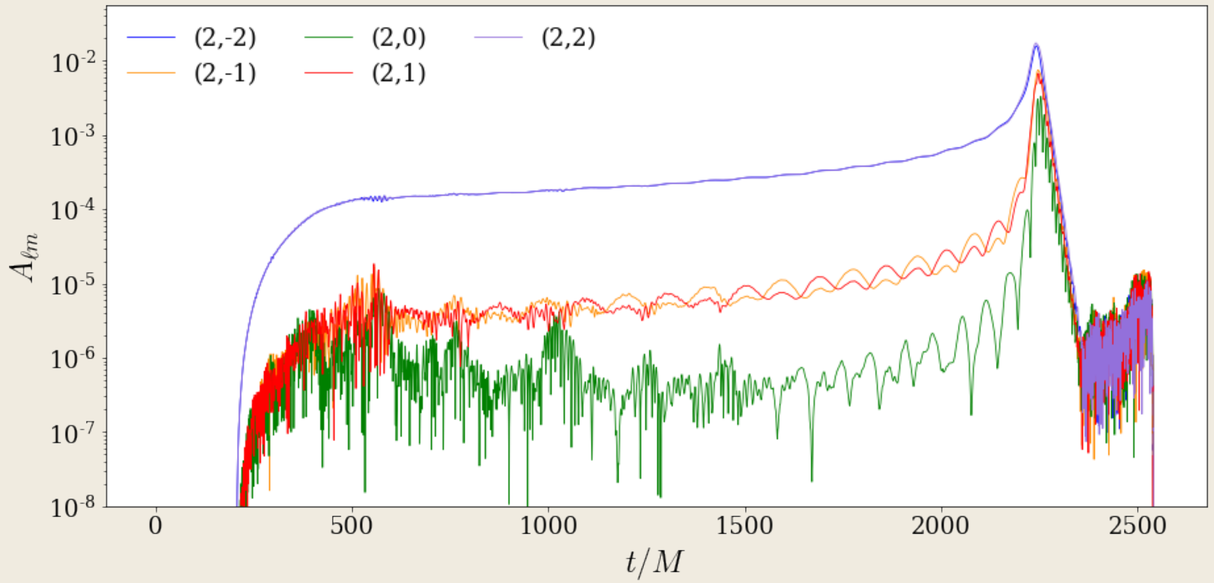
If the black holes' spin is not aligned with the orbital angular momentum, the orbital plane will precess

Precessing waveforms

- Precessing binaries: one or both spins are not aligned with the orbital angular momentum



Inertial frame (with J || z) waveform

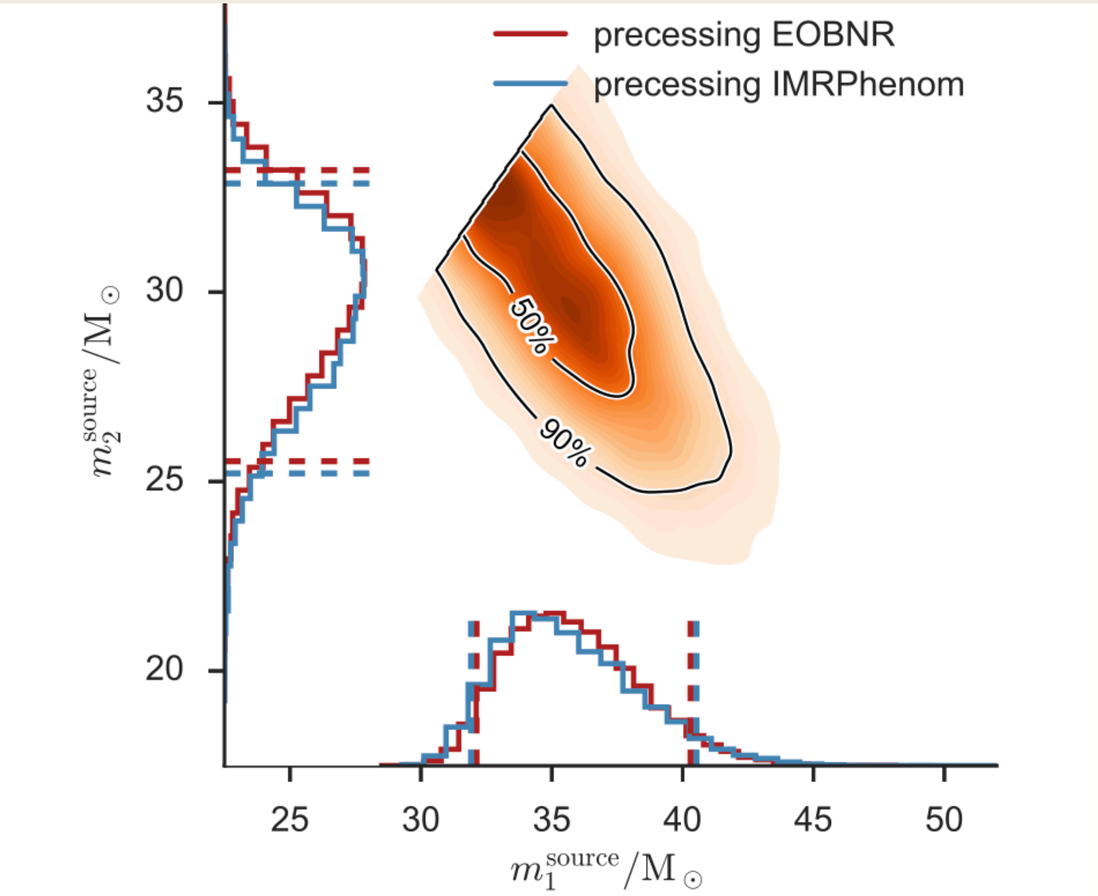


Co-precessing frame waveform

$$q = 8, \chi = 0.8, \theta_{LS} = 120^{\circ}$$

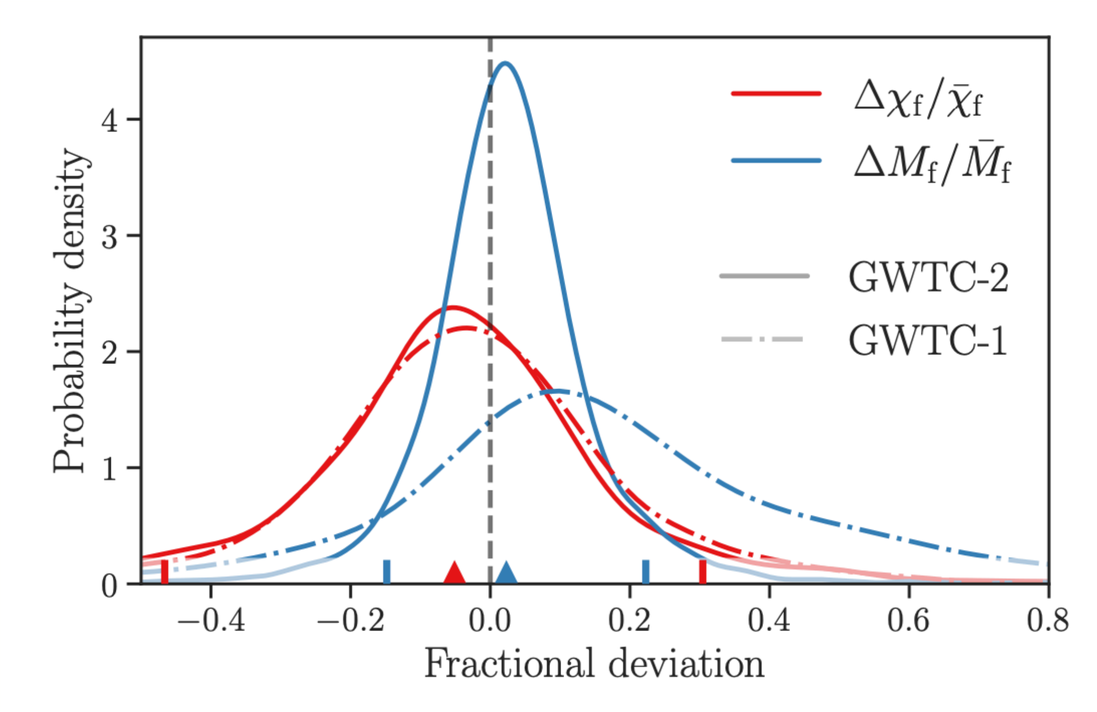
Parameter Estimation

- We can infer the binary's properties from the signal
- Some effects are more distinctive than others
- Accurate waveform models are required for accurate inference



Abbott, Benjamin P., et al. "Improved analysis of GW150914 using a fully spin-precessing waveform model." Physical Review X 6.4 (2016): 041014.

IMR consistency tests

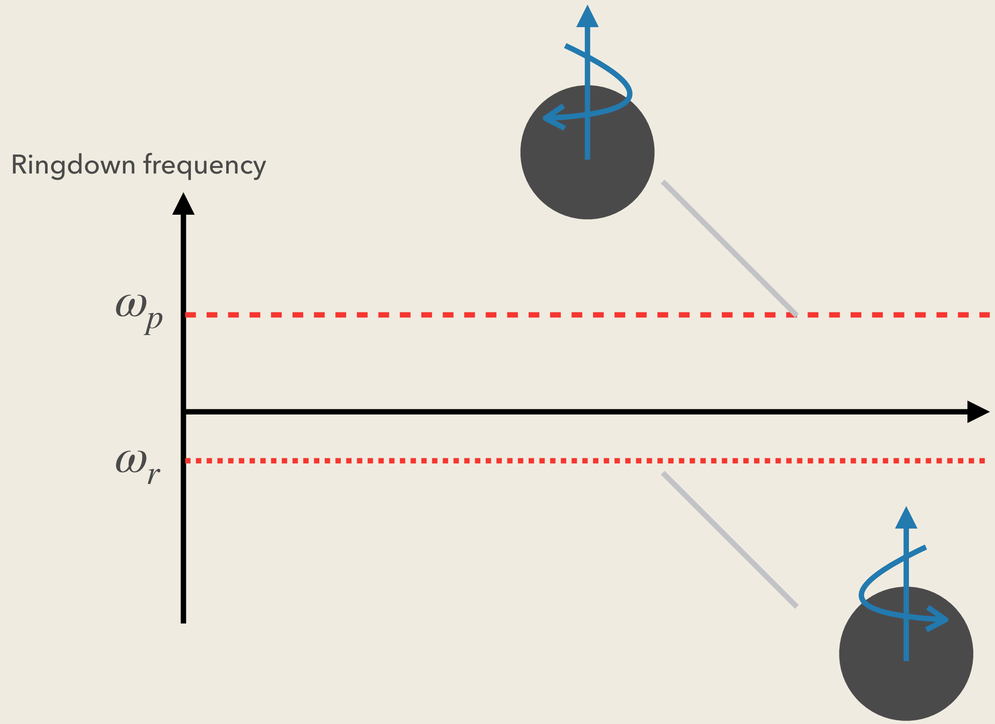


Deviation in final mass and spin as measured from GWTC-1 and GWTC-2.
Abbott, R., et al. "Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog." Physical review D 103.12 (2021): 122002.

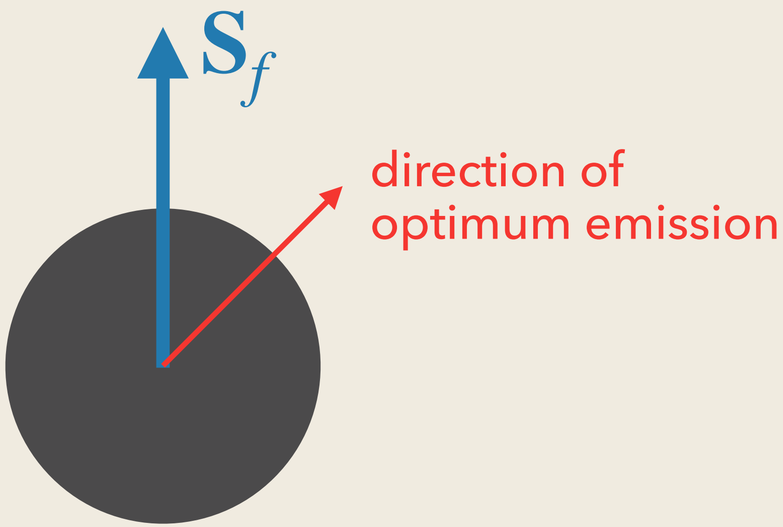
- We can test whether the black holes are merging as predicted by general relativity
- We perform parameter estimation on the inspiral and merger-ringdown parts of the signal separately

Ringdown

The remnant black hole “rings down” emitting gravitational waves at characteristic frequencies, known as **Quasi-Normal Modes**



Precession in ringdown



After merger, the direction of maximum emission continues to precess about the total angular momentum

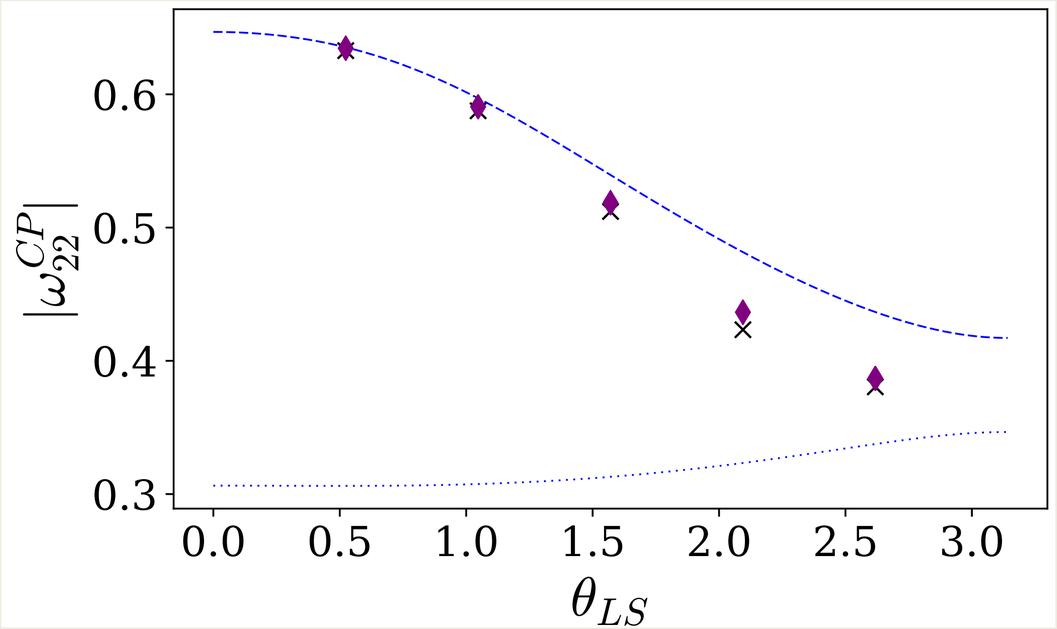
Effective ringdown frequency

The prograde and retrograde frequencies are shown in blue

The black crosses show data from NR simulations

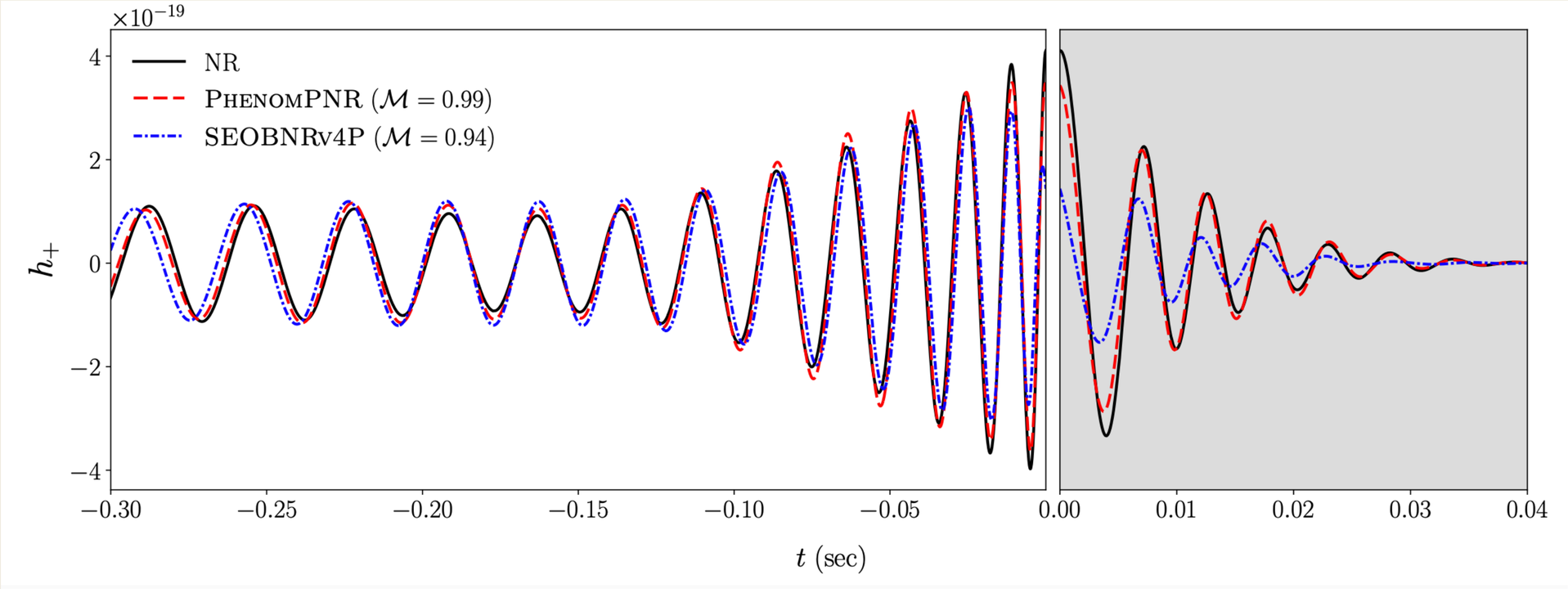
The purple diamonds show an analytic prediction

$(q,\chi) = (8,0.8)$



Effective ringdown frequency for the (2,2) multipole moment

Effect on the waveform



Comparison of two models with NR waveform with mass ratio 8, dimensionless spin 0.8 and spin inclination angle 60.

SEOBNRv4P: has not accounted for effective ringdown frequency

PhenomPNR: accounted for effective ringdown frequency

Conclusions

- Before we can begin to perform reliable **tests of General Relativity** with gravitational waves, we need to have **accurate gravitational waveforms** which incorporate **all known physical effects** of the system
- We may see signals where neglecting these physical effects potentially **biases our tests of General Relativity** in the LVK's **next observing run**