Advanced LIGO's ability to detect apparent violations of cosmic censorship and the no-hair theorem through CBC detections

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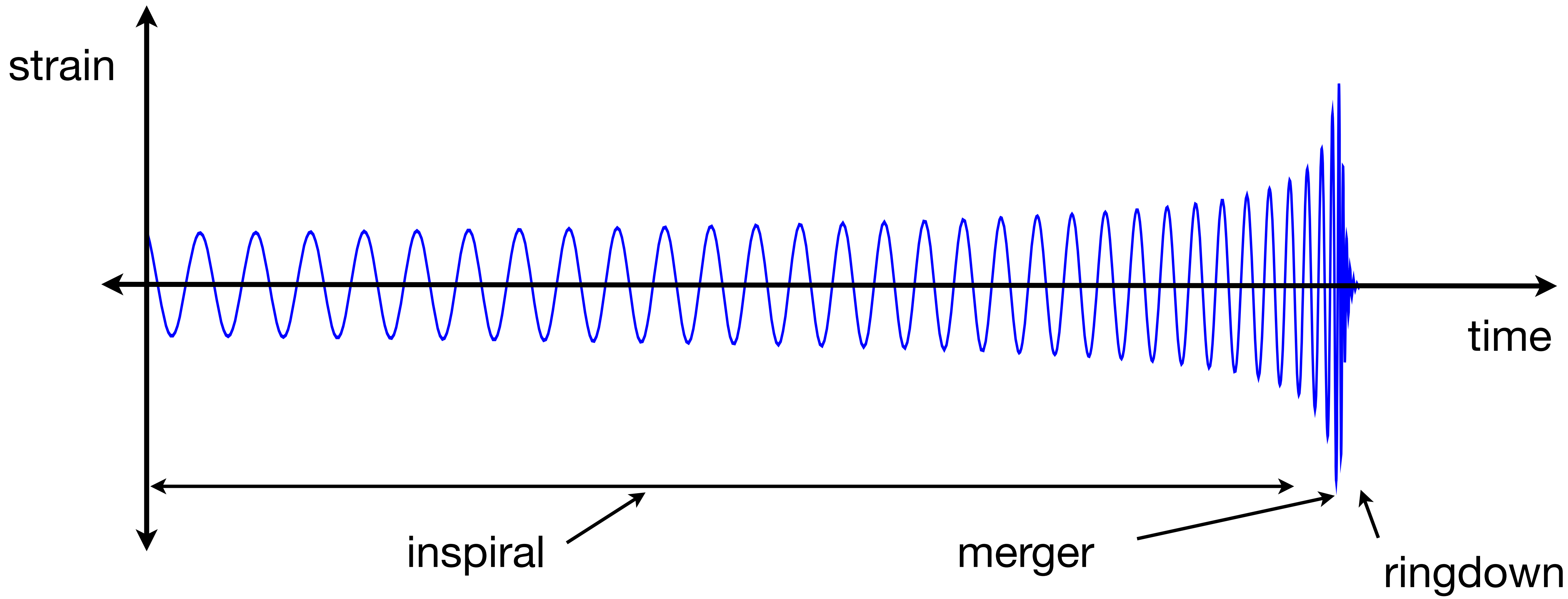
Outline

- Gravitational waves (GWs) from CBC events
- Possible tests of GR from a CBC GW detection involving a black hole (BH)
    - Cosmic censorship conjecture
    - No-hair theorem
- Results for improving tests of GR through parameter measurability

Compact Binary Coalescence (CBC)

- Stellar mass black hole and/or neutron star CBC events are among some of the most promising sources for ground-based interferometers, such as aLIGO



Plot from Aylott et al. (arXiv:0901.4399v2)

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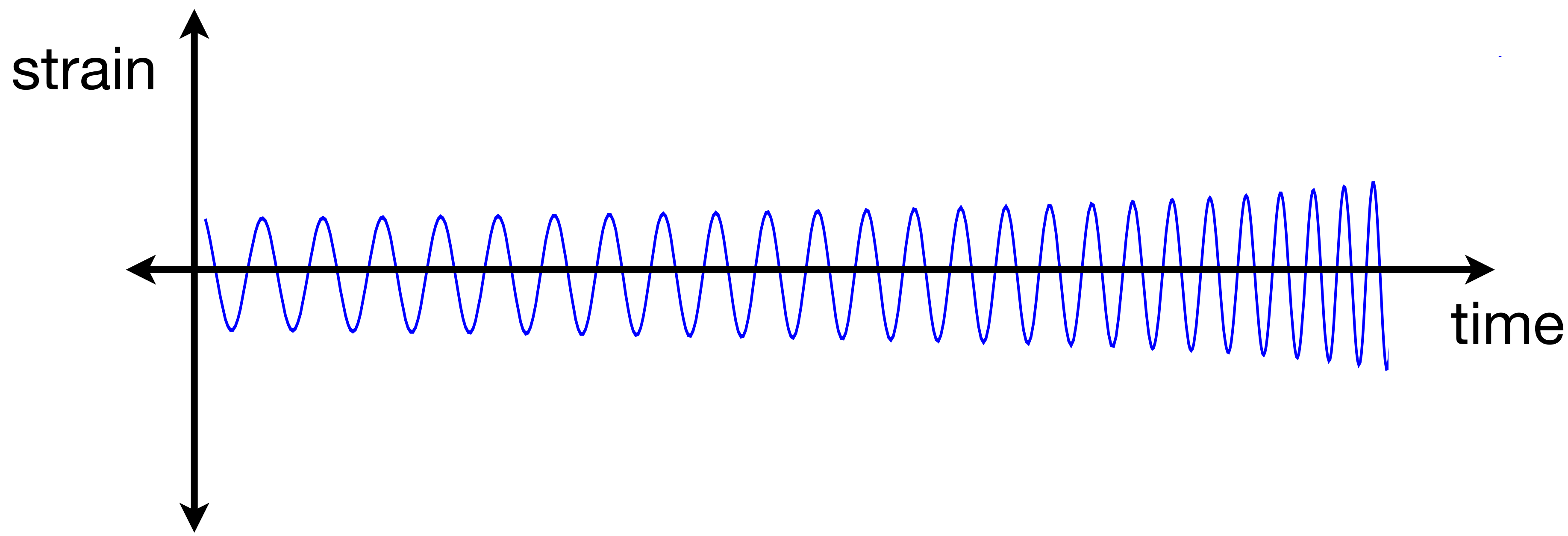

- Inspiral is well-modeled with post-Newtonian (PN) waveforms

- PN waveforms depend on system parameters:

$$m_1,\ m_2,\ \chi_1 = \frac{j_1}{m_1},\ \chi_2 = \frac{j_2}{m_2},\ \lambda_1 \propto k_2 r_1^5,\ \lambda_2 \propto k_2 r_2^5$$

Plot from Aylott et al. (arXiv:0901.4399v2)

Tests of General Relativity with Black Holes

Cosmic Censorship	No-Hair Theorem
For a Kerr BH:	For a non-spinning Kerr BH:
$\chi \equiv \frac{j}{m^2} \leq 1$	$\lambda \equiv \frac{2}{3} k_2 R^5 = 0$
⇓	⇓
In a CBC event:	In a CBC event:
$\chi_1 \leq 1$ and/or $\chi_2 \leq 1$	$\lambda_1 = 0$ and $\lambda_2 = 0$
↙ BBH ↘ NS-BH	↓ BBH

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In a CBC event:	In a CBC event:
$\chi_1 \nleq 1$ and/or $\chi_2 \nleq 1$	$\lambda_1 \neq 0$ and $\lambda_2 \neq 0$

Not a Kerr BH in PN formalism!
Exotic object?
Waveform inaccuracy?

Relevant Parameters and Parameter Space Bounds

	Measured Parameters	Parameter Space Bounds
Mass	$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$ $\mathcal{M} = (m_1 + m_2)\eta^{3/5}$	$0 \leq \eta \leq \frac{1}{4}$
Spin	$\chi_s = \frac{1}{2}(\chi_1 + \chi_2)$ $\chi_a = \frac{1}{2}(\chi_1 - \chi_2)$	$-1 \leq \chi_s, \chi_a, \leq 1$
Tidal	$\tilde{\Lambda} = \frac{\tilde{\lambda}(\lambda_1, \lambda_2)}{(m_1 + m_2)^5}$	$\lambda_{\rm BH} = 0 \rightarrow \tilde{\Lambda}_{\rm BBH} = 0$

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Tidal	$\tilde{\Lambda} = \frac{\tilde{\lambda}(\lambda_1,\lambda_2)}{(m_1+m_2)^5}$	$\lambda_{\mathrm{BH}} = 0 \rightarrow \tilde{\Lambda}_{\mathrm{BBH}} = 0$

physical bound

Relevant Parameters and Parameter Space Bounds

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Spin	$\chi_s = \dfrac{1}{2}(\chi_1 + \chi_2)$ $\chi_a = \dfrac{1}{2}(\chi_1 - \chi_2)$	$-1 \leq \chi_s, \chi_a, \leq 1$	cosmic censorship
Tidal	$\tilde{\Lambda} = \dfrac{\tilde{\lambda}(\lambda_1, \lambda_2)}{(m_1 + m_2)^5}$	$\lambda_{\mathrm{BH}} = 0 \rightarrow \tilde{\Lambda}_{\mathrm{BBH}} = 0$	

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Tidal	$\tilde{\Lambda} = \frac{\tilde{\lambda}(\lambda_1, \lambda_2)}{(m_1 + m_2)^5}$	$\lambda_{\rm BH} = 0 \rightarrow \tilde{\Lambda}_{\rm BBH} = 0$	no-hair theorem

Improving aLIGO's Ability to Test Cosmic Censorship and the No-Hair Theorem

Limiting Factor: Parameter Measurability

Cosmic Censorship: Spin

No-Hair Theorem: Tides

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improved by?

prior knowledge of parameter space

$$0 \leq \eta \leq \frac{1}{4}$$

Improving aLIGO's Ability to Test Cosmic Censorship and the No-Hair Theorem

Limiting Factor: Parameter Measurability

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improved by?

prior knowledge of parameter space

$$0 \leq \eta \leq \frac{1}{4}$$

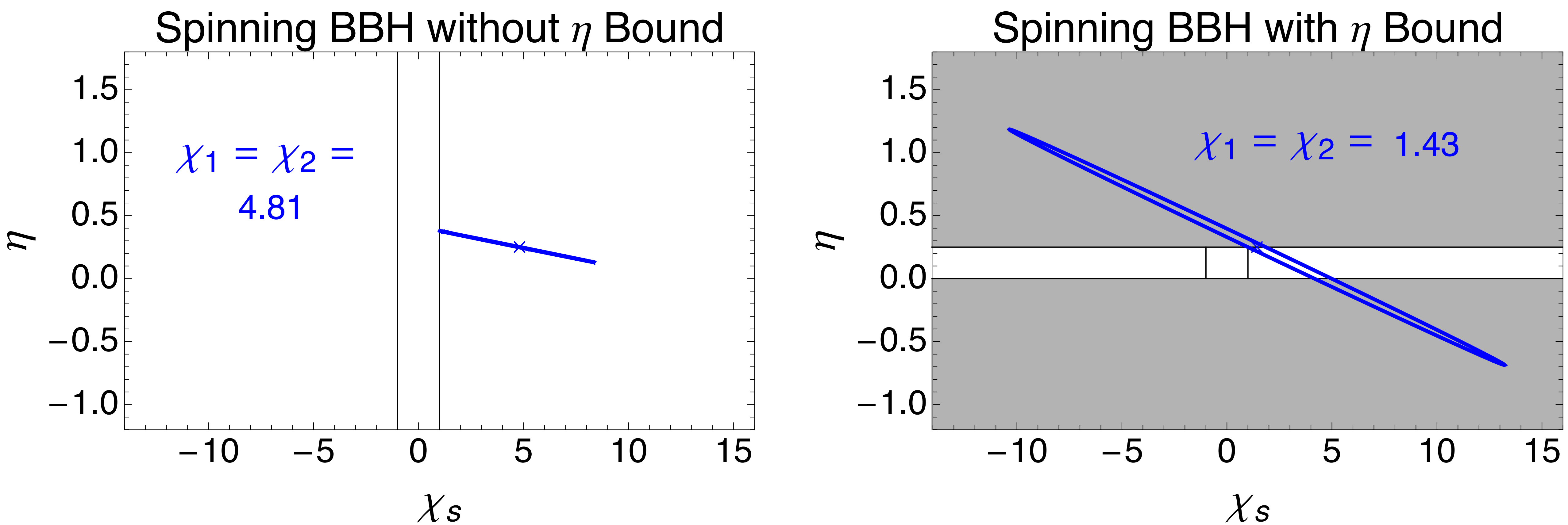
accuracy of PN waveform

$$h = A(f;\vec{\theta})e^{i\psi(f;\vec{\theta})}$$

vary from 0-2.5 PN,
with and without spin in amp.

Improving Measurability of Spin for a Near-Equal Mass BBH system (10, 11) M_{sun}

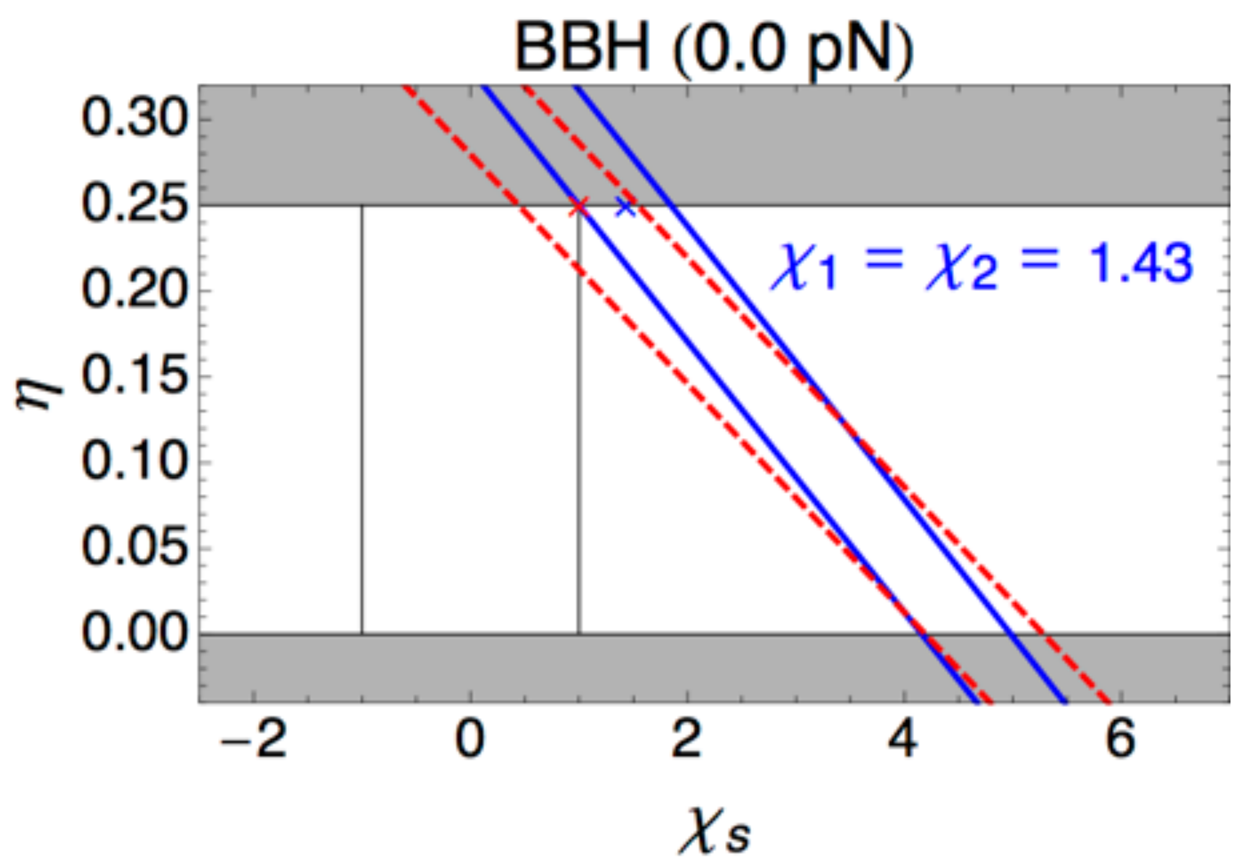
Physical prior on symmetric mass ratio important for near-equal mass BBH systems when using Newtonian amplitude waveform

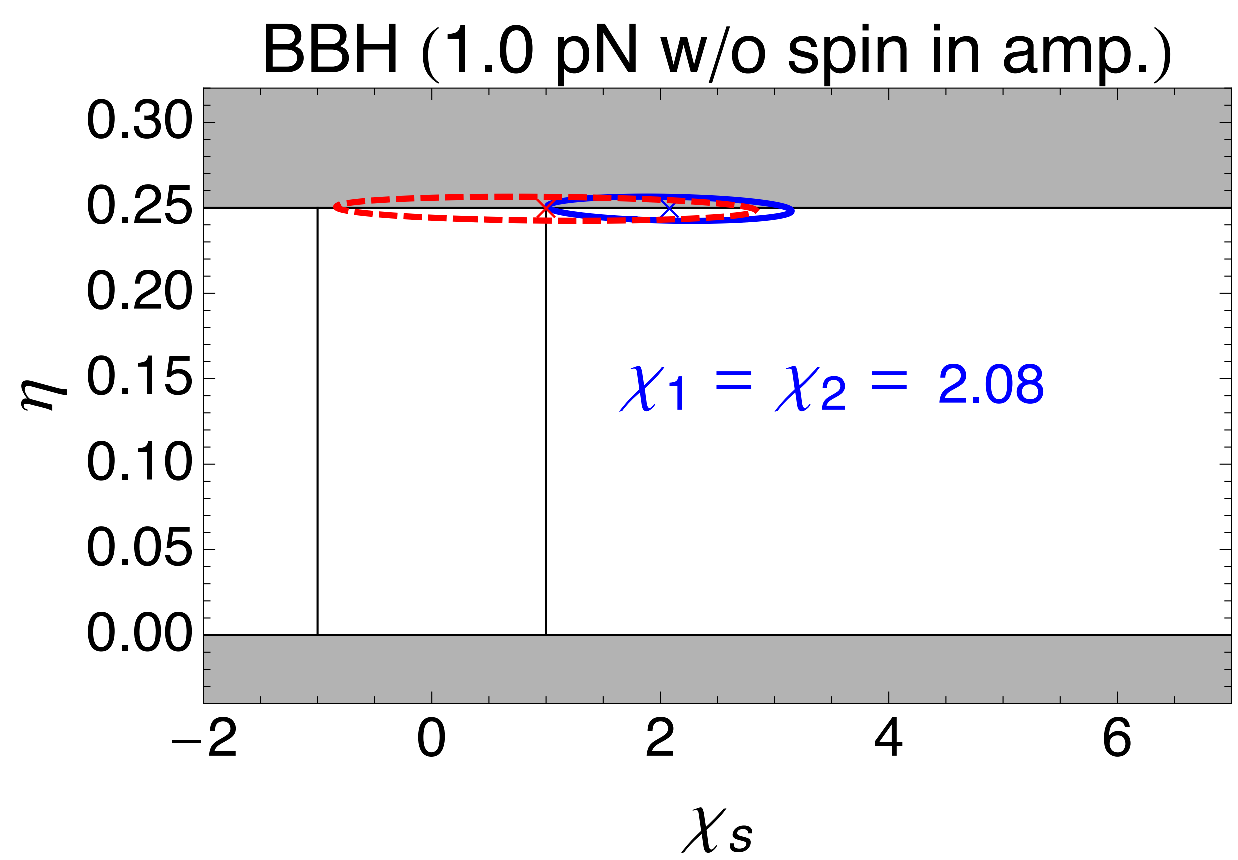


Blue: minimal detectable violation at 1-sigma for an SNR of 10

Improving Measurability of Spin for a Near-Equal Mass BBH system (10, 11) M_{sun}

Non-spinning amplitude corrections important for near-equal mass BBH system (*degeneracy breaking between spin and symmetric mass ratio)*, but about equivalent effect as symmetric mass ratio prior





Blue: minimal detectable violation at 1-sigma for an SNR of 10

Red: 1-sigma error ellipse for fiducial spins at SNR of 10

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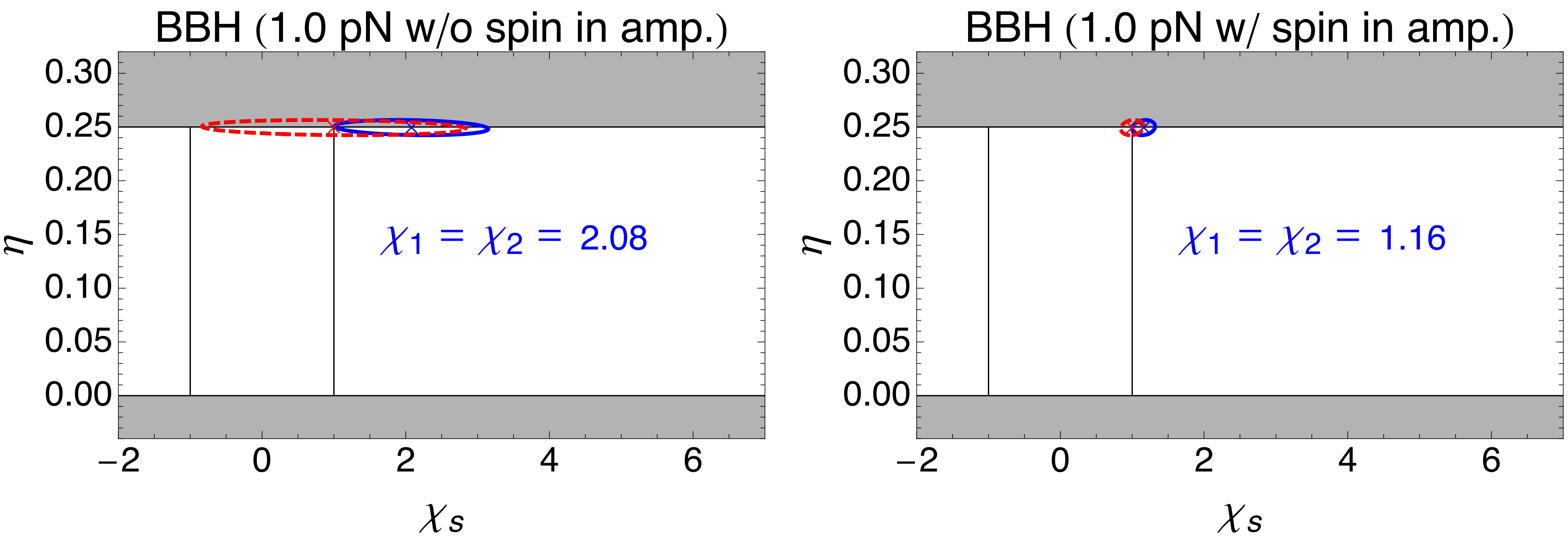
Improving Measurability of Spin for a Near-Equal Mass BBH system (10, 11) M_{sun}

Additional improvement in spin measurability seen when spin corrections are included in the amplitude *(degeneracy breaking between spin and chirp mass)*

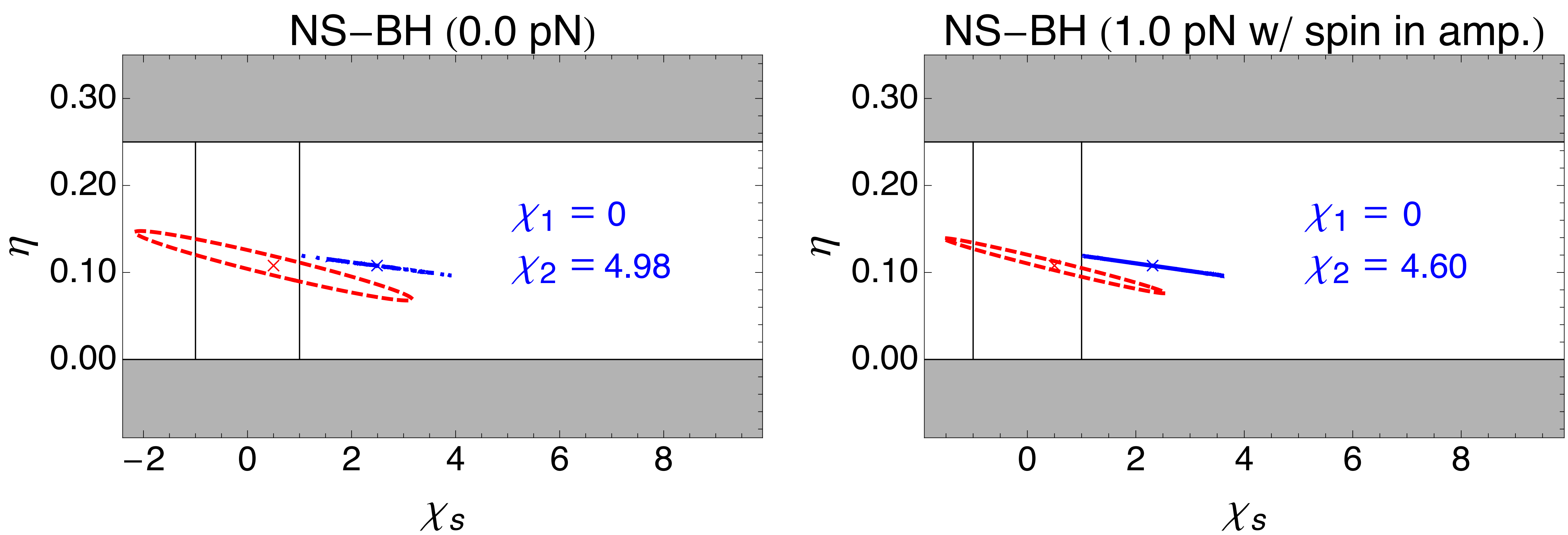


Blue: minimal detectable violation at 1-sigma for an SNR of 10

Red: 1-sigma error ellipse for fiducial spins at SNR of 10

No Improvement in Measurability of Spin for an NS-BH system (1.4, 10) M_{sun}

No effect from physical prior on symmetric mass ratio or amplitude corrections, with or without spin.



Blue: minimal detectable violation at 1-sigma for an SNR of 10

Red: 1-sigma error ellipse for fiducial spins at SNR of 10

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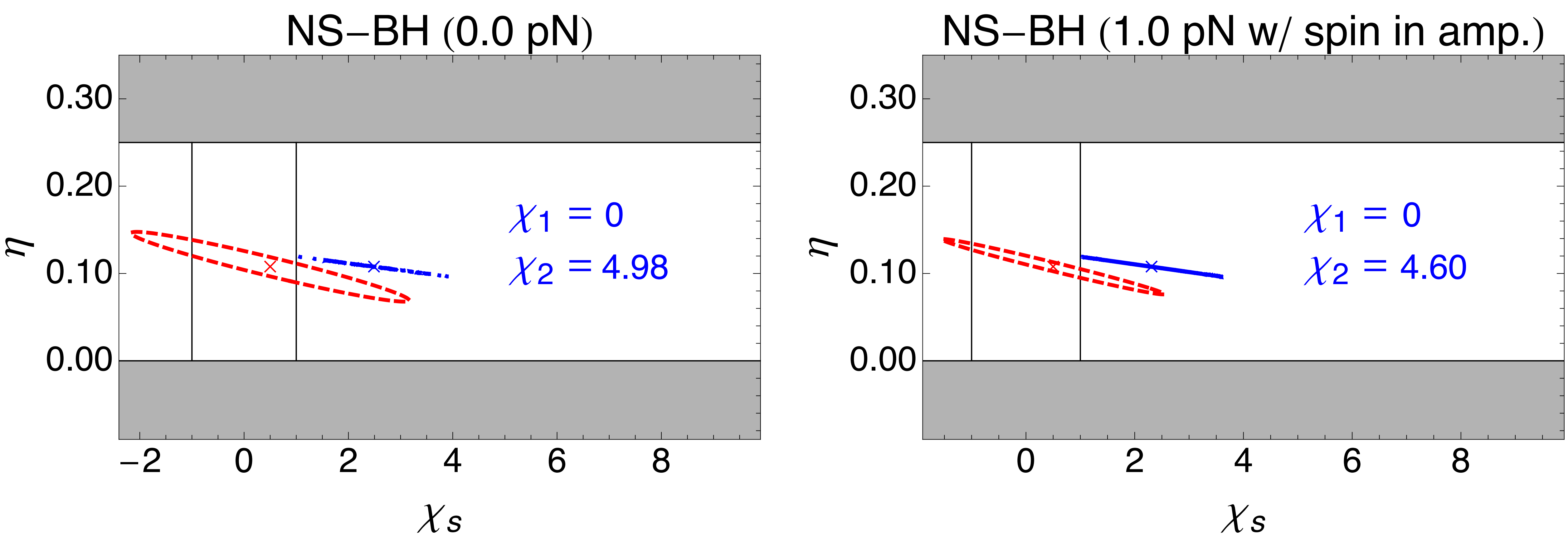
Improvement in Measurability of Tides for a Near-Equal Mass BBH system (10, 11) M_{sun}

Amplitude corrections improve the measurability of the tidal deformability parameter *(degeneracy decreases between chirp mass and tides and symmetric mass ratio and tides)*



Blue: minimal detectable violation at 1-sigma for an SNR of 10

Red: 1-sigma error ellipse for fiducial spins at SNR of 10

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Summary of Results

	restricting parameter space	including higher harmonics	including spin in amplitude
spinning BBH	yes, only at 0.0 pN in amplitude	yes, starting at 0.5 pN in amplitude	yes, starting at 1.0 pN in amplitude
spinning NS-BH	no	no	no
tidal BBH	no	yes, starting at 1.0 pN in amplitude	N/A

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Conclusions

- Consider physical parameter space bounds (already done in LAL's Bayesian parameter estimation)
- Use more accurate approximations to the amplitude of the waveform, since this can break parameter degeneracies
- These effects are most important for near-equal mass systems