FROM RINGDOWN BACK TO INSPIRAL

NO-HAIR TESTS FROM CONSISTENCY BETWEEN QUASI-NORMAL MODES AND INSPIRAL

B.S. Sathyaprakash

Penn State, University Park and Cardiff University, Cardiff

StronG BAD

Strong Gravity and Binary Dynamics, Ole Miss, Oxford, MS

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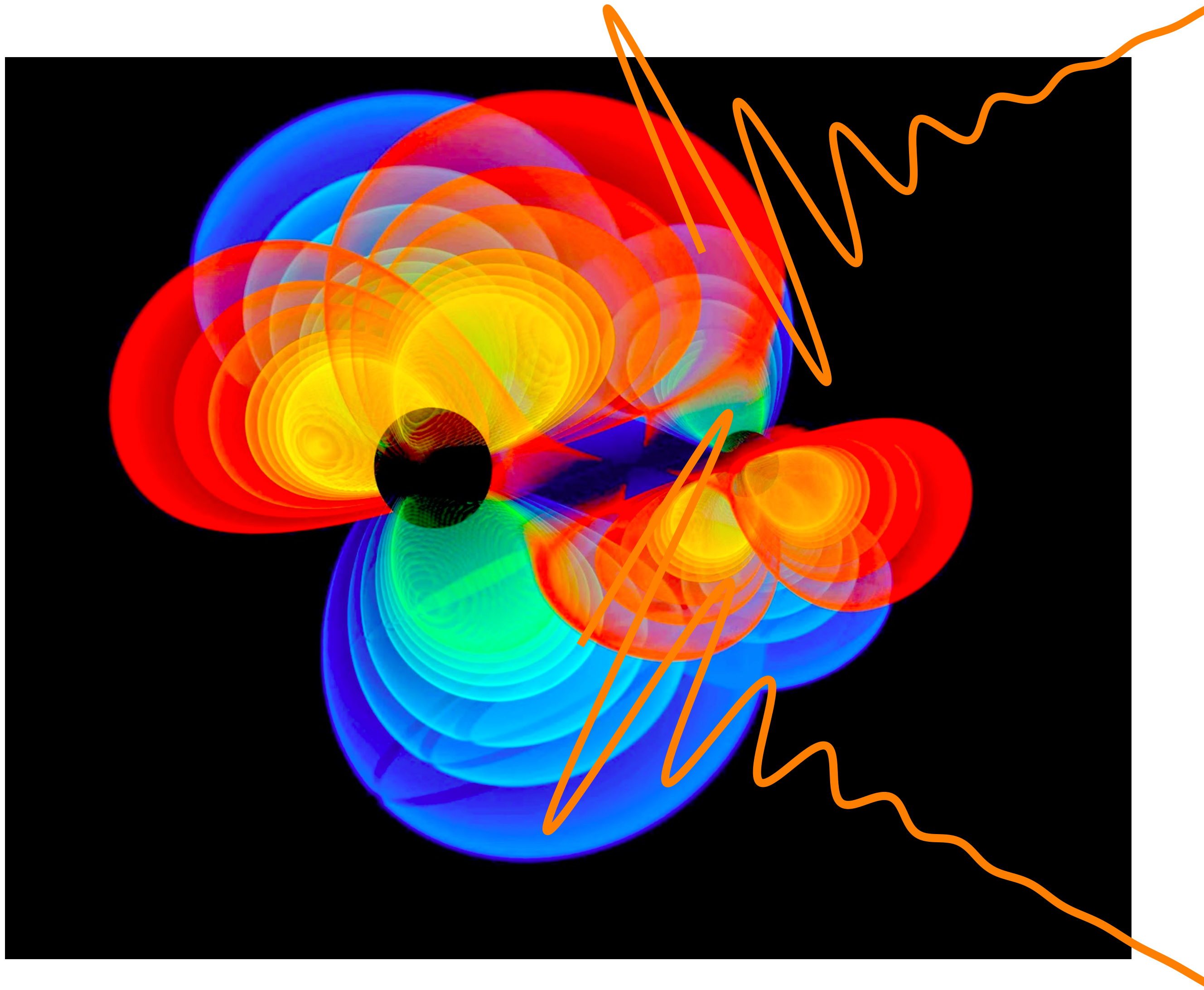
GW150914 IN FUTURE DETECTORS

Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800

LISA (2034)	10,000	2,400

CURRENT PROPOSAL FOR TESTING "BLACK HOLE" NO-HAIR THEOREM

- measure more than one quasi-normal complex frequency
    - are mass and spin inferred from different quasi-normal modes consistent with one another?
- a more powerful way of doing the same test
    - measure the Bayes factor between two alternative models: one in which all modes depend on just two parameters vs another that has extra hair
    - caveat: agreement b/w QNM from perturbation theory and NR sims



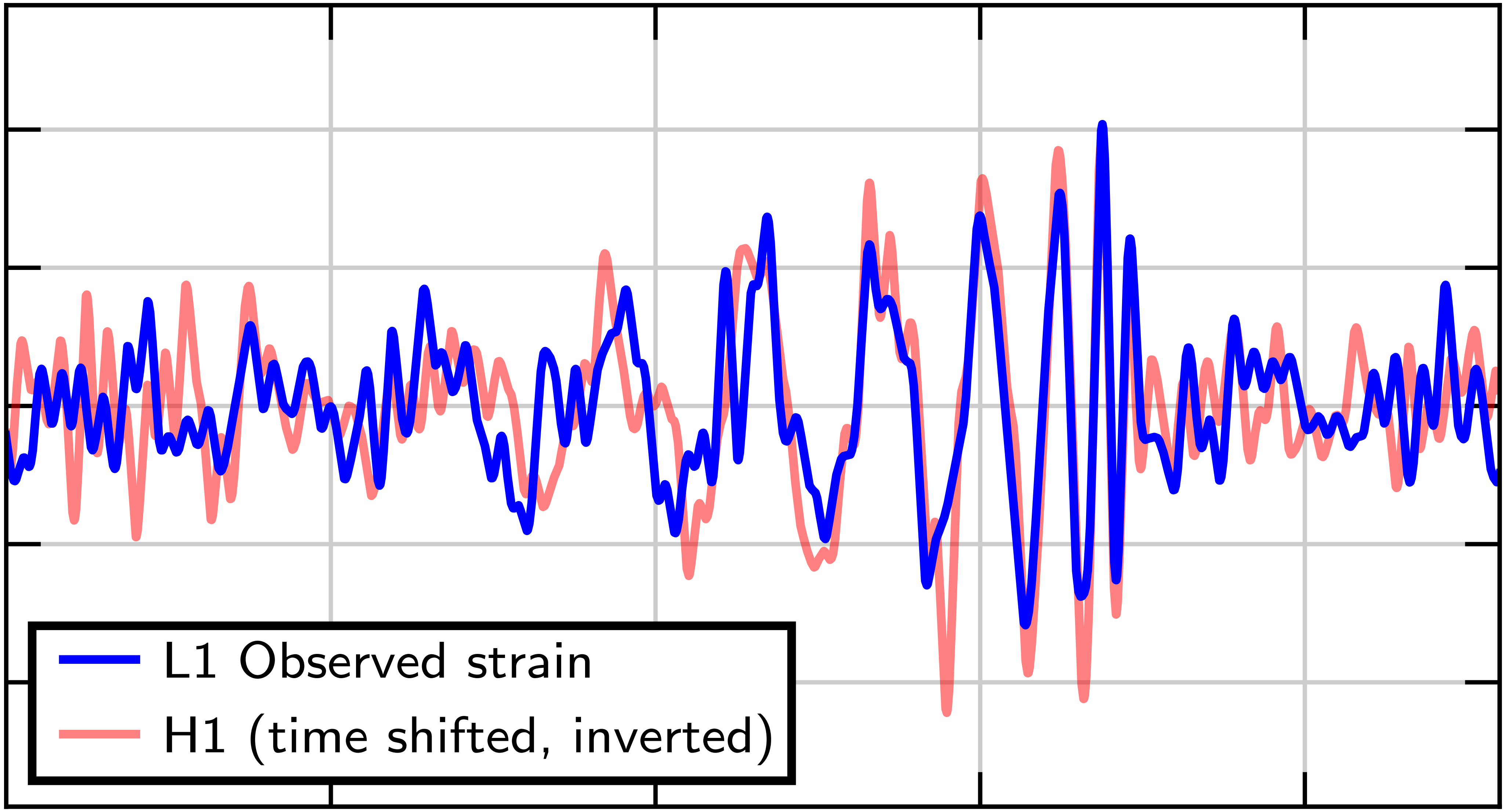
$$K = \frac{\Pr(D|M_1)}{\Pr(D|M_2)} = \frac{\int \Pr(\theta_1|M_1)\Pr(D|\theta_1, M_1)\, d\theta_1}{\int \Pr(\theta_2|M_2)\Pr(D|\theta_2, M_2)\, d\theta_2}.$$

on going: George+ 2017

SHORTCOMINGS OF THIS PROPOSAL

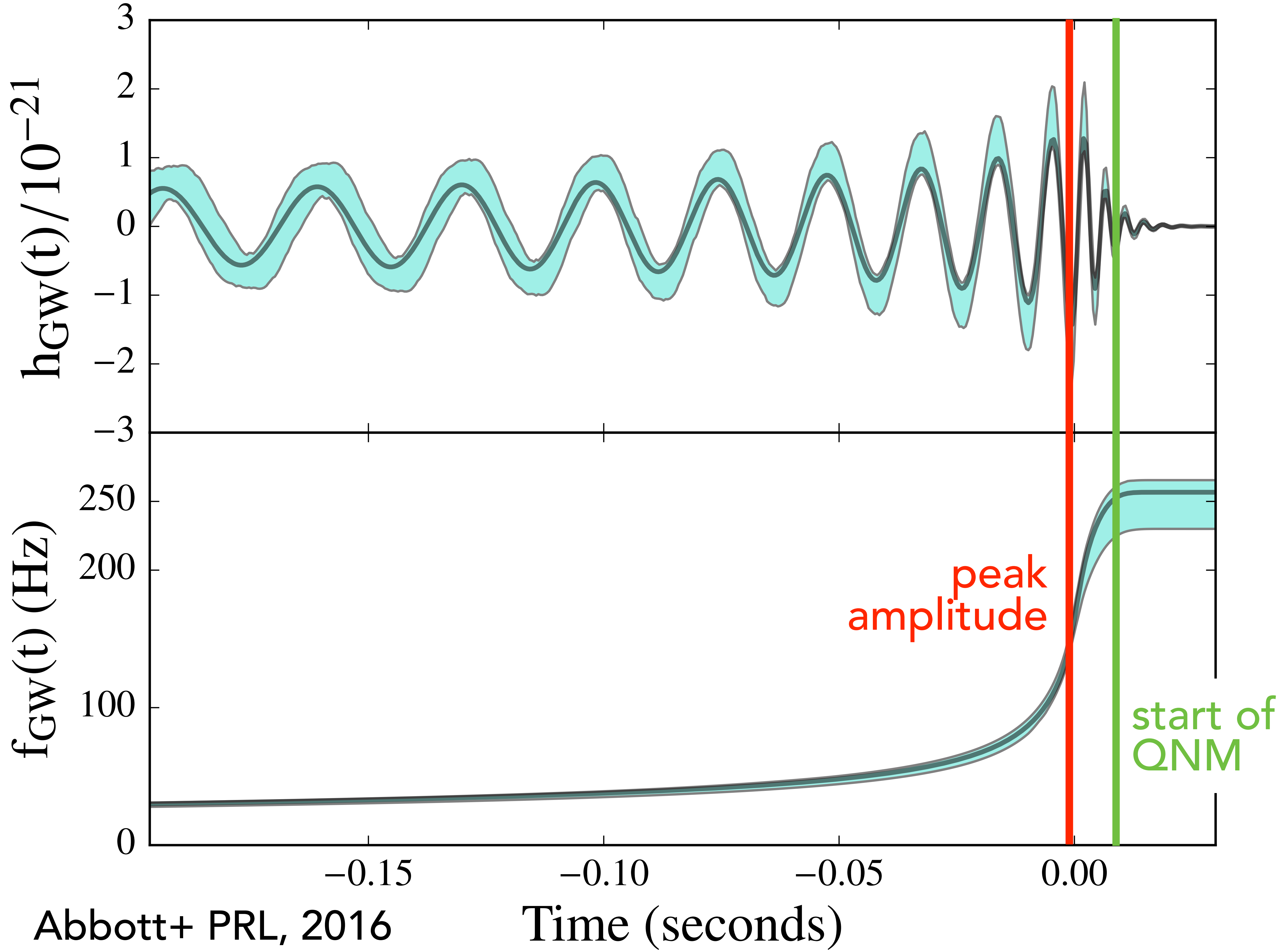
- Quasi-normal mode waveforms are derived in the perturbative approximation
  - need to wait for the signal to reach linear QNM regime
  - this could be 10 M to 20 M after the peak strain amplitude is reached
- most visible part of the signal will be trashed in this test

EXAMPLE: GW150914 ANALYSIS



Abbott+ PRL, 2016

WHEN DO QNM BEGIN?



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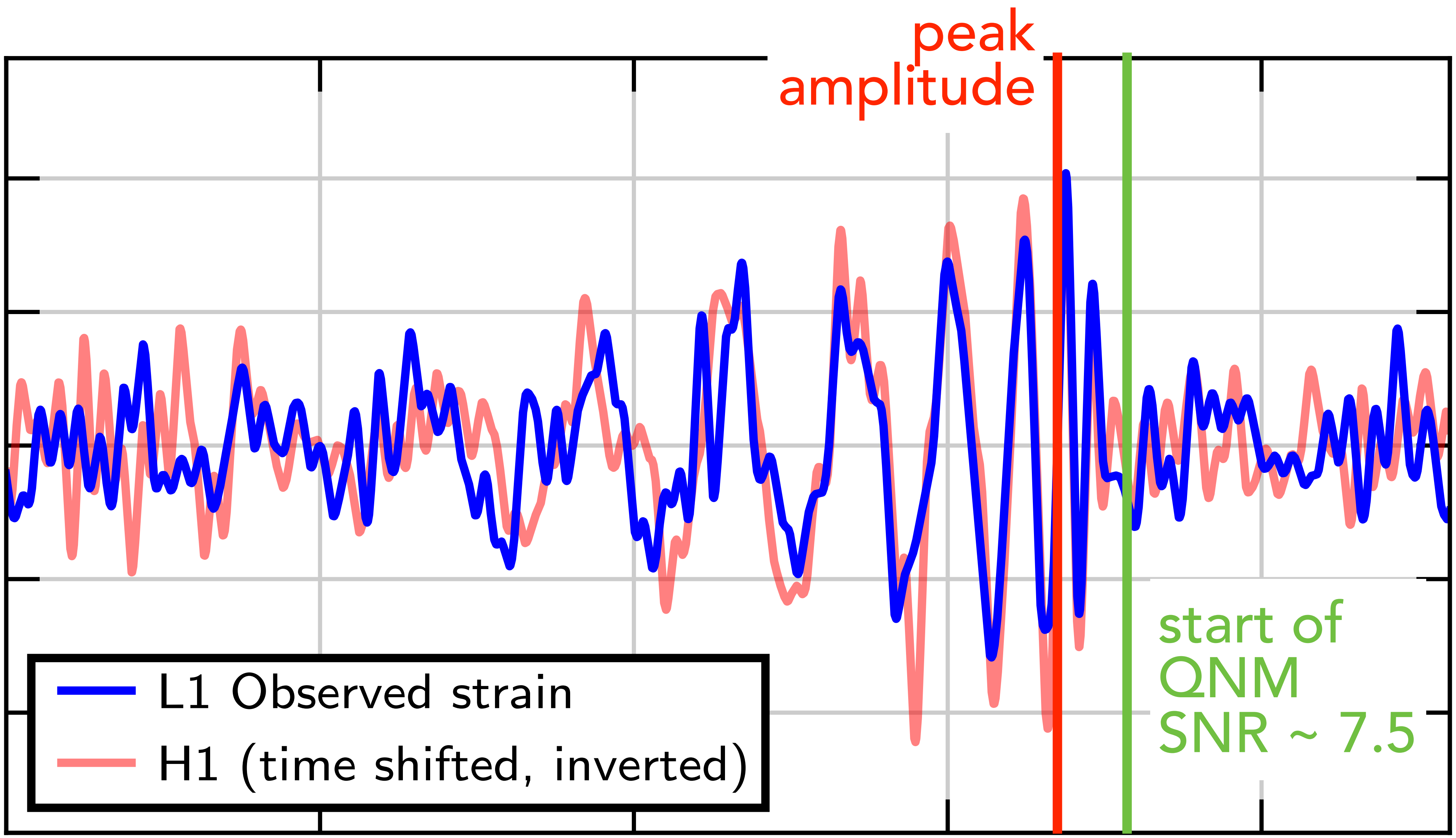
SO, DO WE SEE QNM?

YES BUT CAN'T TEST THE NO-HAIR THEOREM



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SO WHAT'S THE SOLUTION? FOUR PROPOSALS

- get a better model for post-merger
- compare the parameters of the remnant derived from inspiral waveform with those derived from QNM
  - from inspiral to ringdown
- compare the parameters of the binary derived from QNM to those derived from the inspiral
  - from ringdown back to inspiral
- search for a "binary black hole" no-hair theorem and test it

BETTER MODELS OF QNM

EOB MADE A FIRST ATTEMPT IN THIS DIRECTION

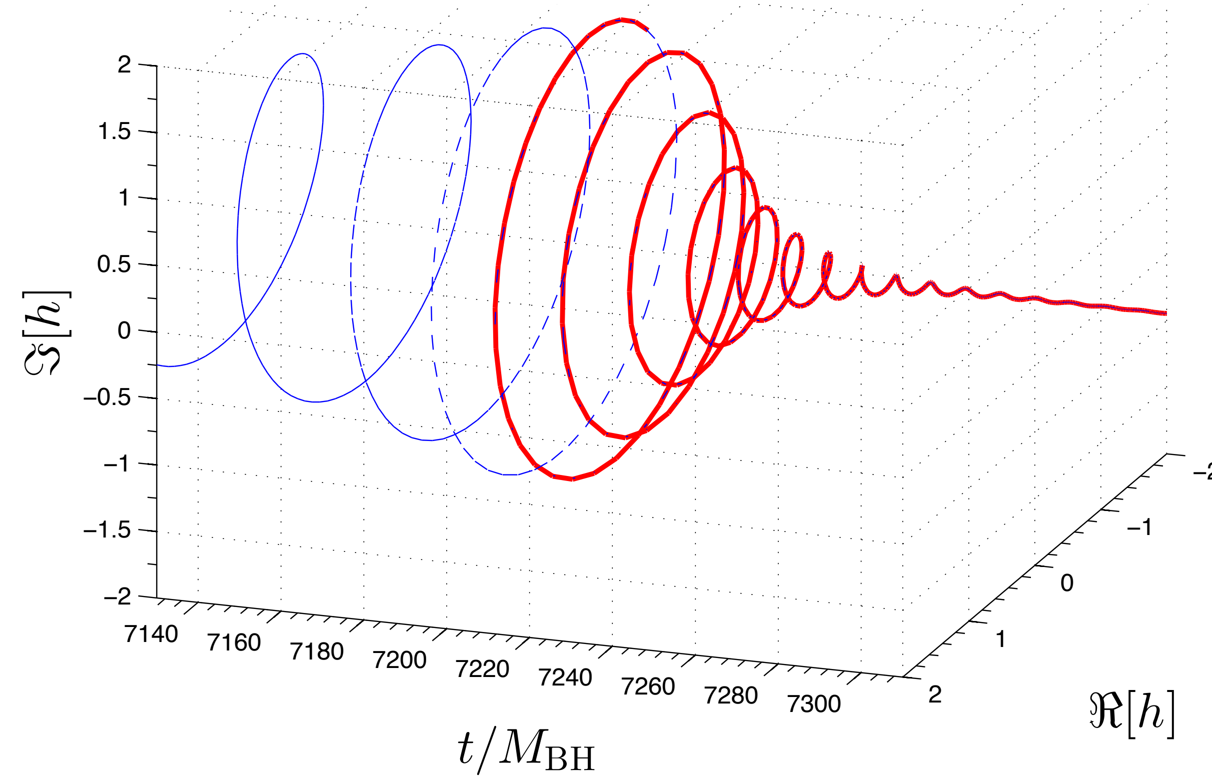
FACTORIZE QNM FROM POST-MERGER WAVEFORM

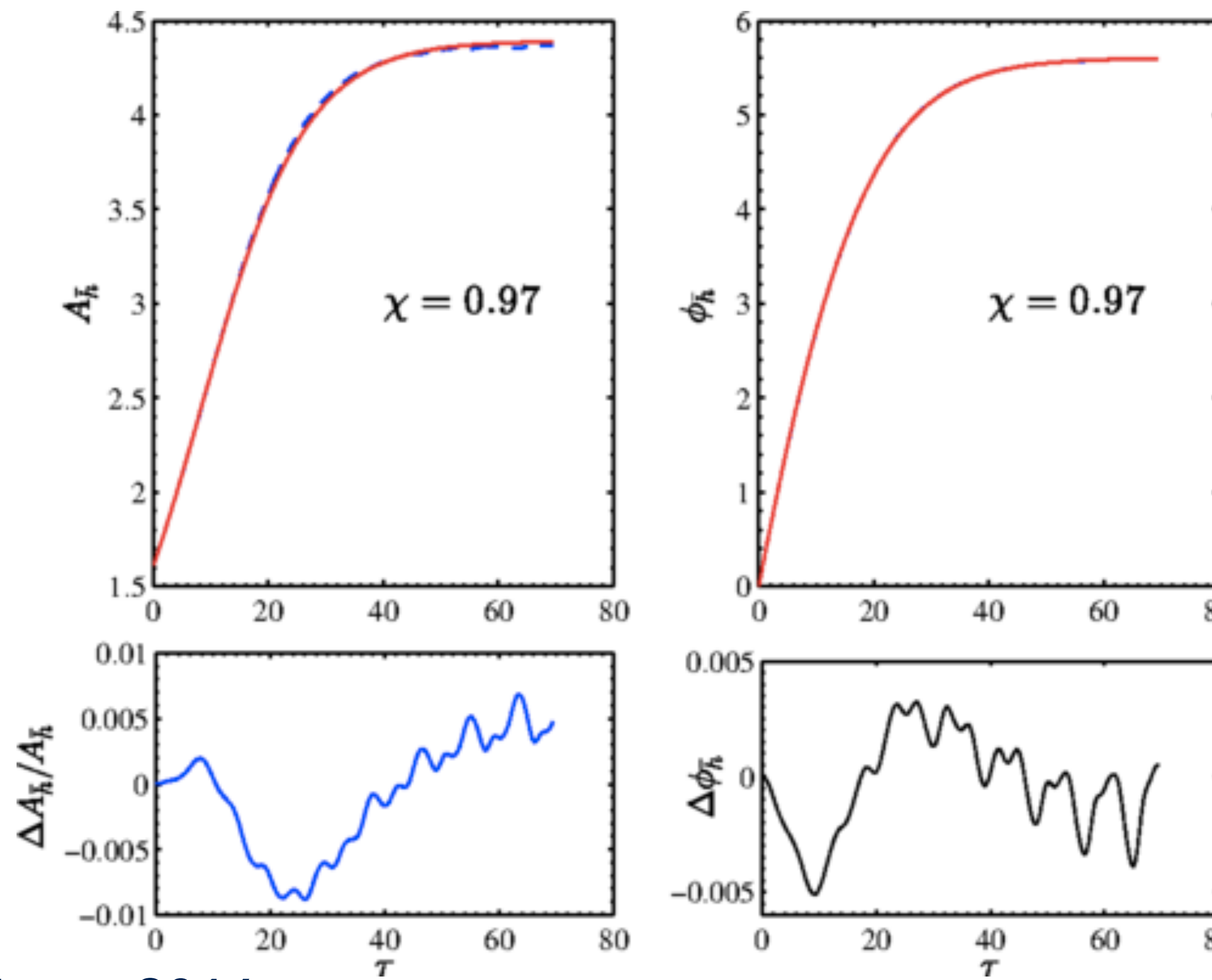
- represent QNM as "multiplicative decomposition" of h(t) in contrast to linear decomposition

  - residual time-dependent complex factor is fitted separately

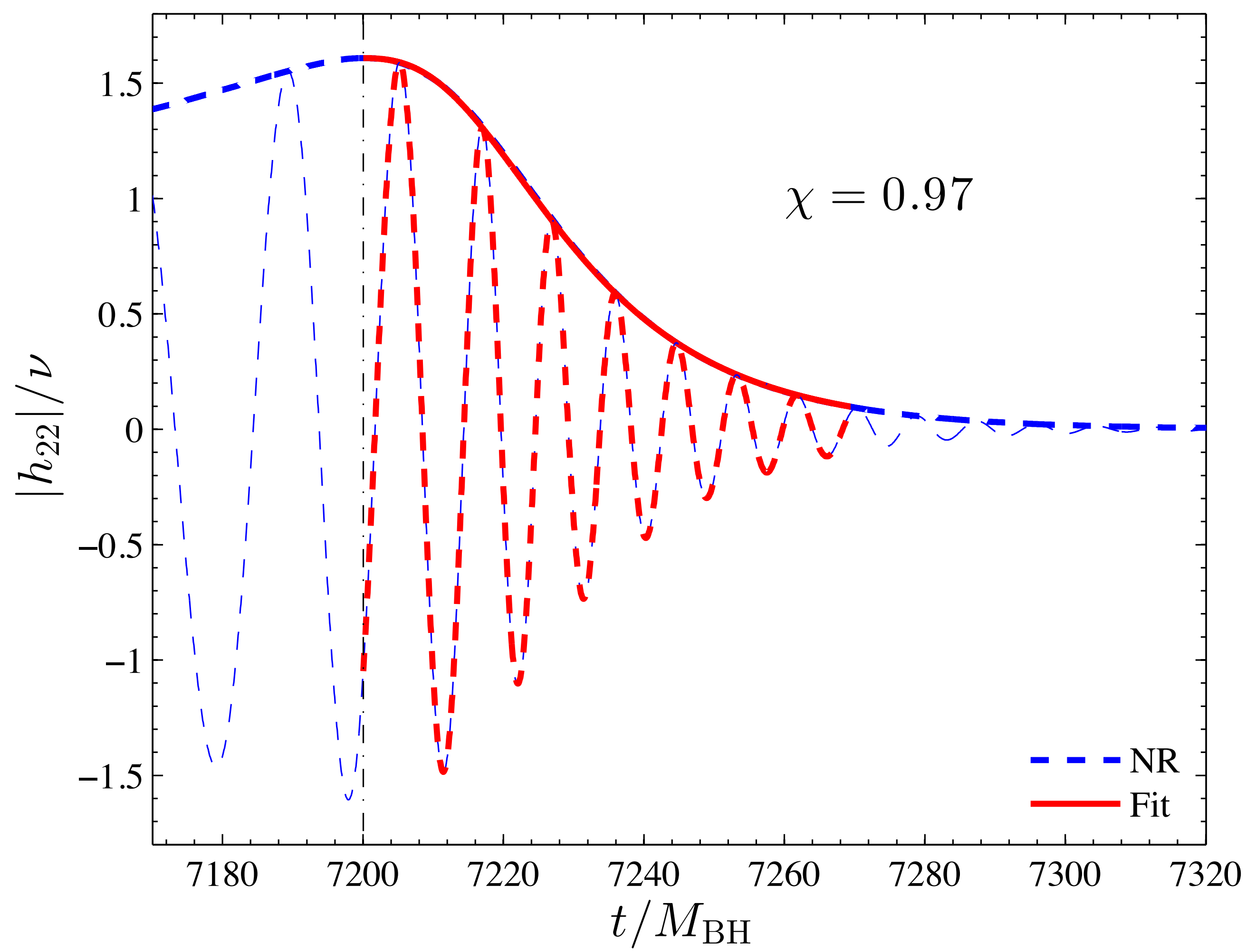
$$\bar{h}(\tau) \equiv e^{\sigma_1 \tau + \mathrm{i}\phi_{22}^{\mathrm{mrg}}} h(\tau),$$

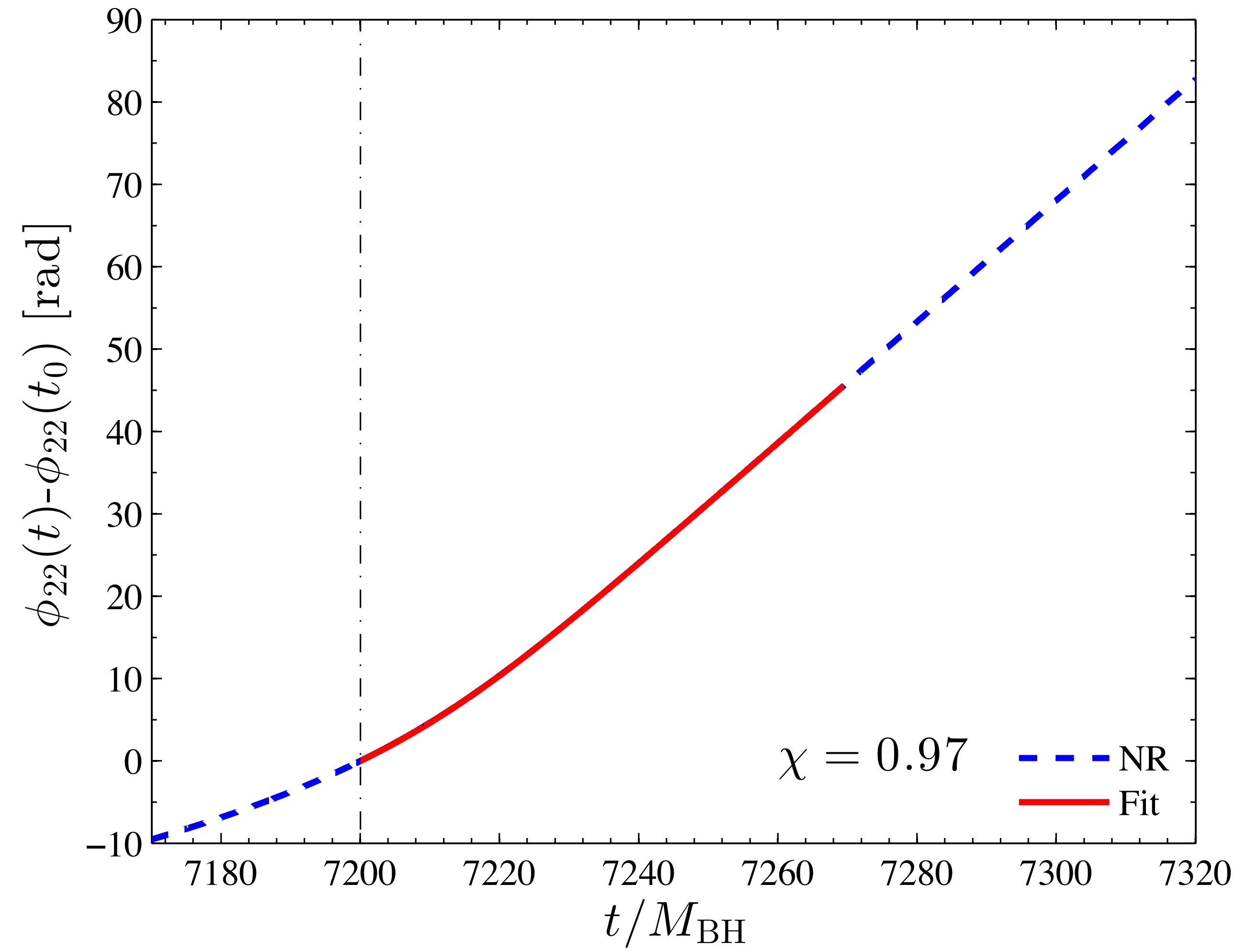
$$\bar{h}(\tau) \equiv A_{\bar{h}} e^{\mathrm{i}\phi_{\bar{h}}(\tau)}.$$



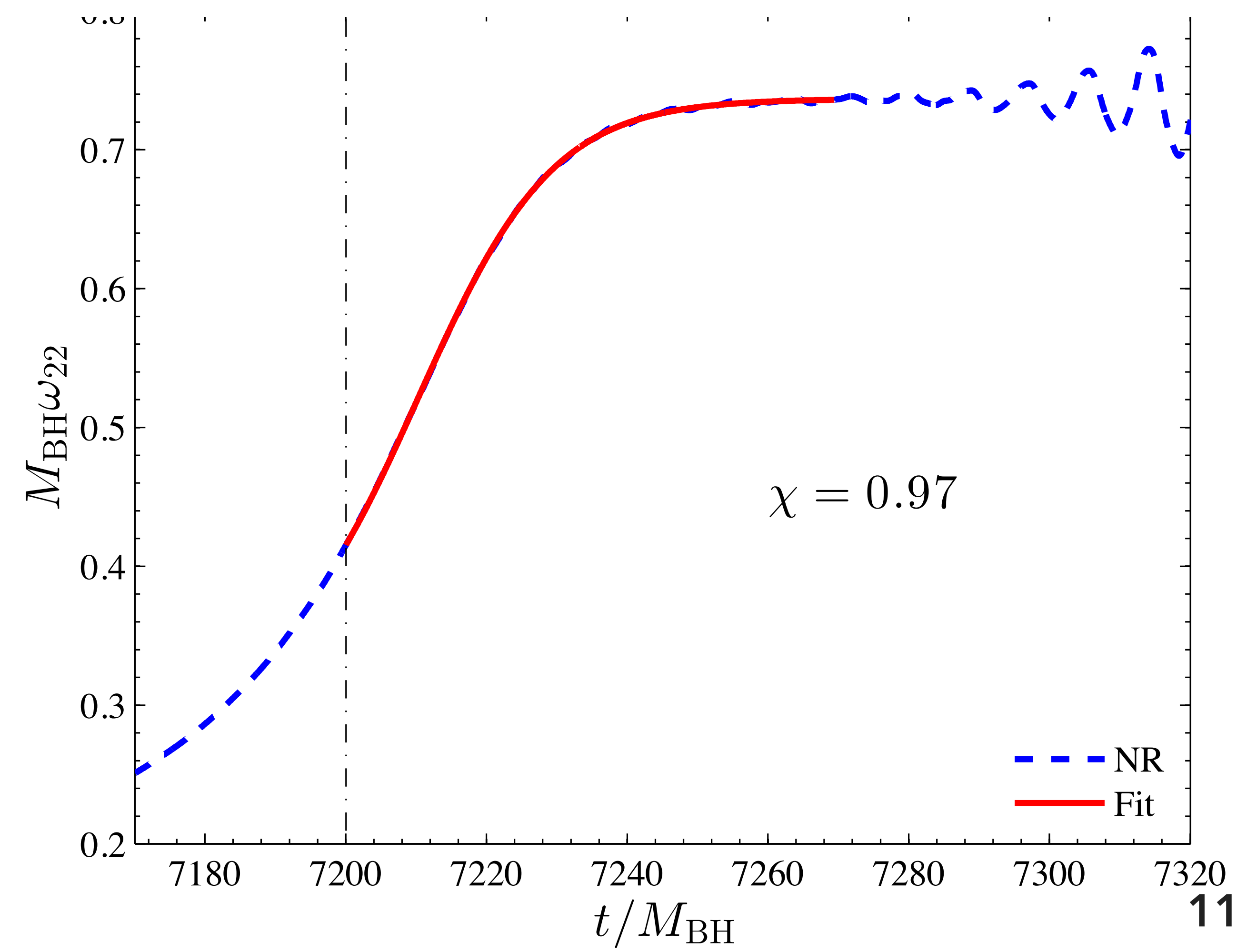


Damour and Nagar 2014; Del Pozzo and Nagar 2016



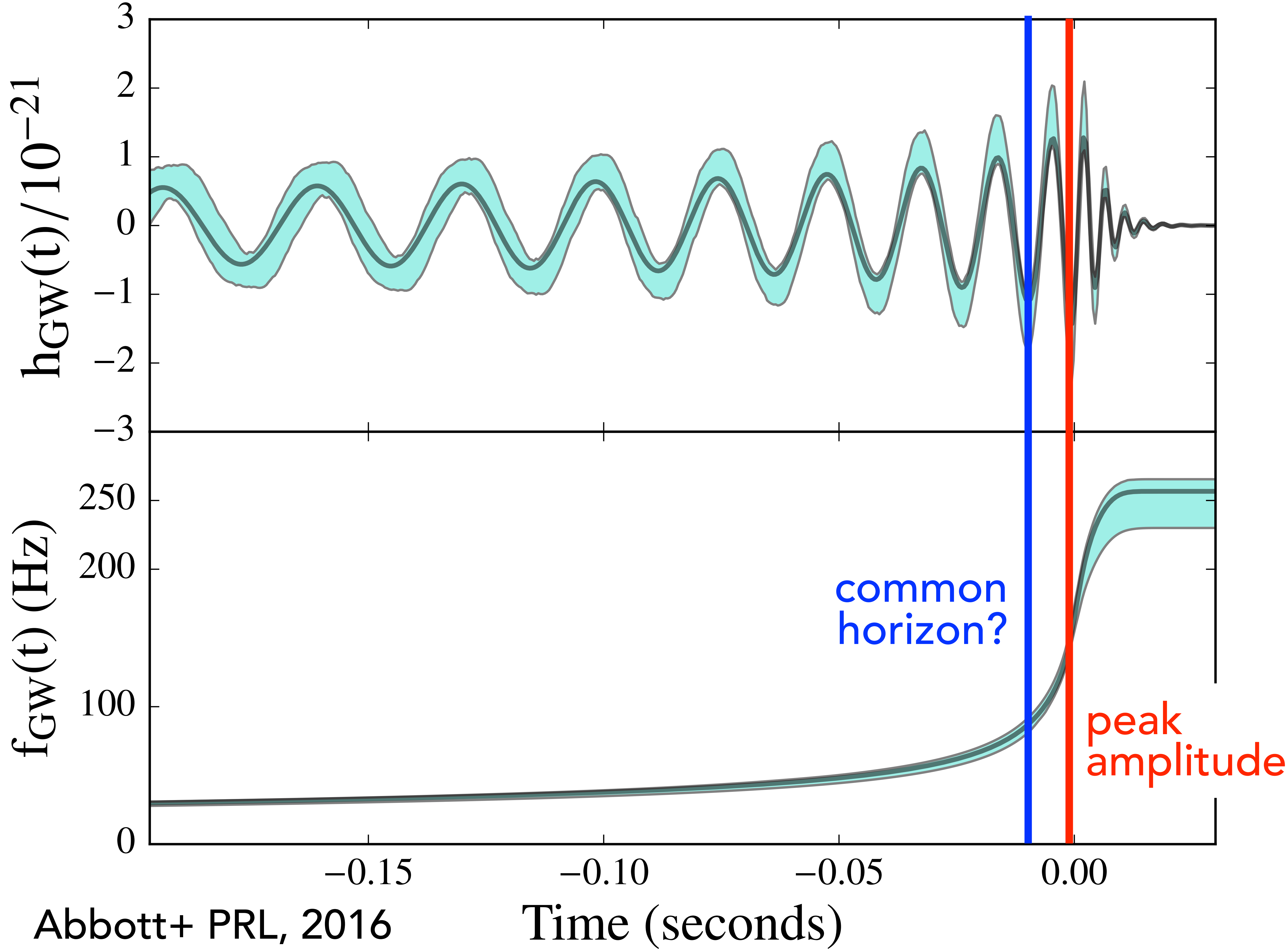


currently being generalized to precessing spins with SXS data by Pratten+



Damour and Nagar 2014

WHY NOT START BEFORE THE PEAK AMPLITUDE?



Abbott+ PRL, 2016

FROM INSPIRAL TO RINGDOWN

REMNANT MASS-SPIN CONSISTENCY

- estimate joint posterior probability for the intrinsic binary parameters (masses and spins) marginalized over all other parameters:

$$P_{\rm IMR}(m_1, m_2, \boldsymbol{S}_1, \boldsymbol{S}_2)$$

- infer the posterior on the final mass and dimensionless spin using fitting formulas: $M_f = M_f(m_1, m_2, \boldsymbol{S}_1, \boldsymbol{S}_2), \quad \chi_f = \chi_f(m_1, m_2, \boldsymbol{S}_1, \boldsymbol{S}_2).$

$$P_{\rm IMR}(M_f, \chi_f)$$

- split the waveform (in the Fourier domain) into inspiral part and merger-ringdown part and estimate the remnant mass and spin from each

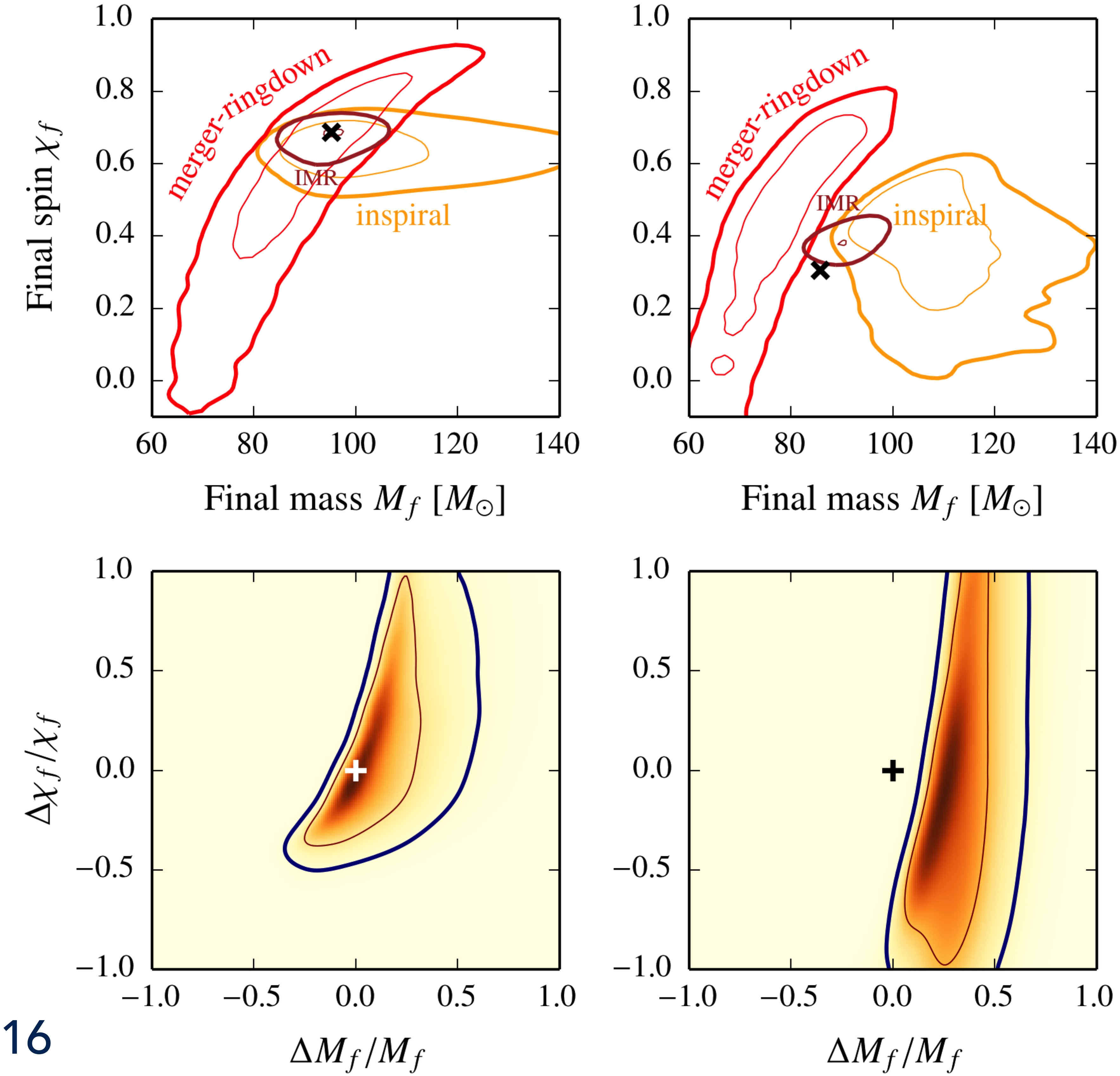
$$P_{\rm I}(M_f, \chi_f) \text{ and } P_{\rm MR}(M_f, \chi_f)$$

- look for consistency of the parameters of the remnant so derived

$$\Delta M_f := M_f^{\rm I} - M_f^{\rm MR}, \qquad \Delta\chi_f := \chi_f^{\rm I} - \chi_f^{\rm MR},$$

Abhirup+ 2016

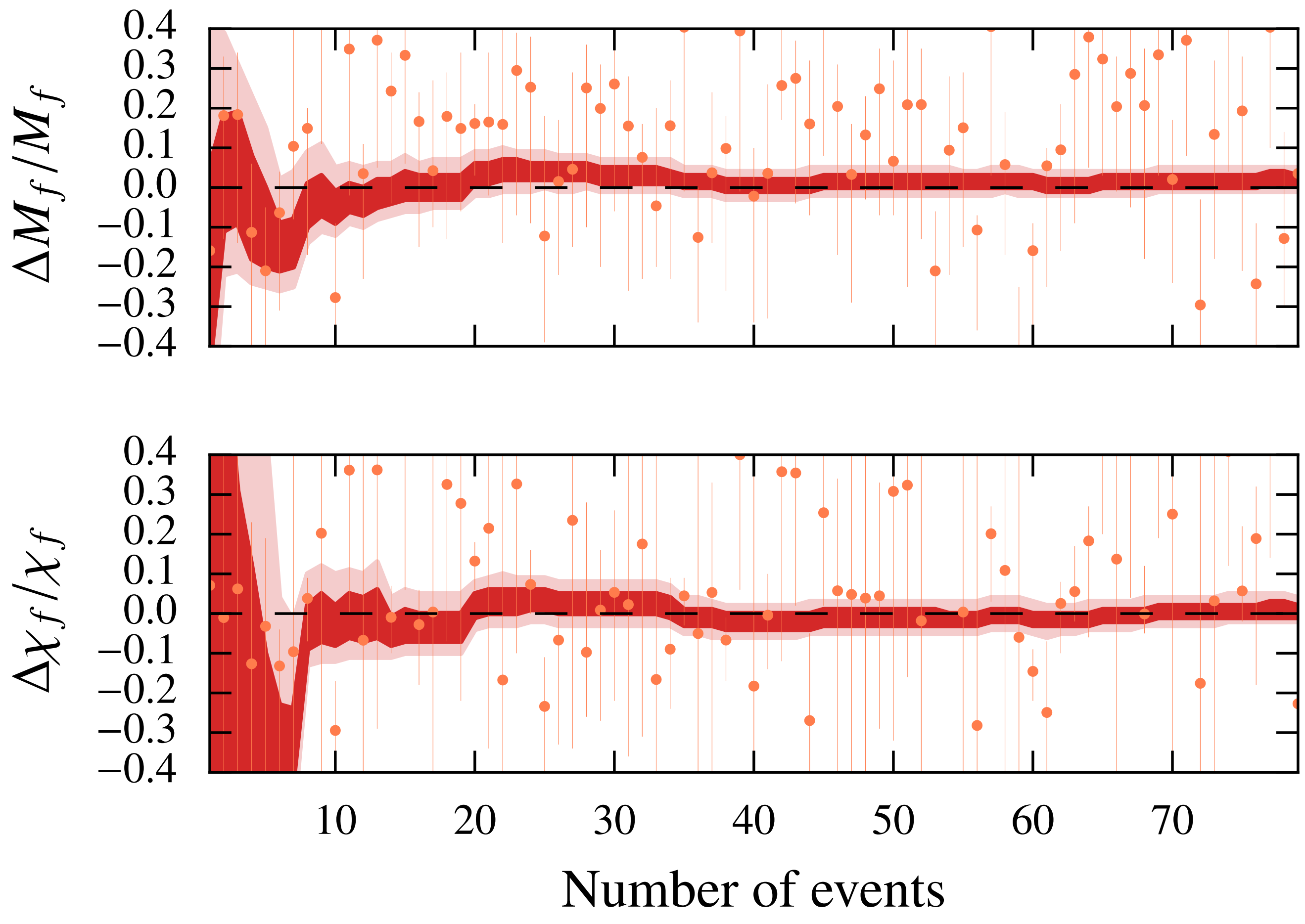
GR INJECTION (LEFT) NON-GR (RIGHT)

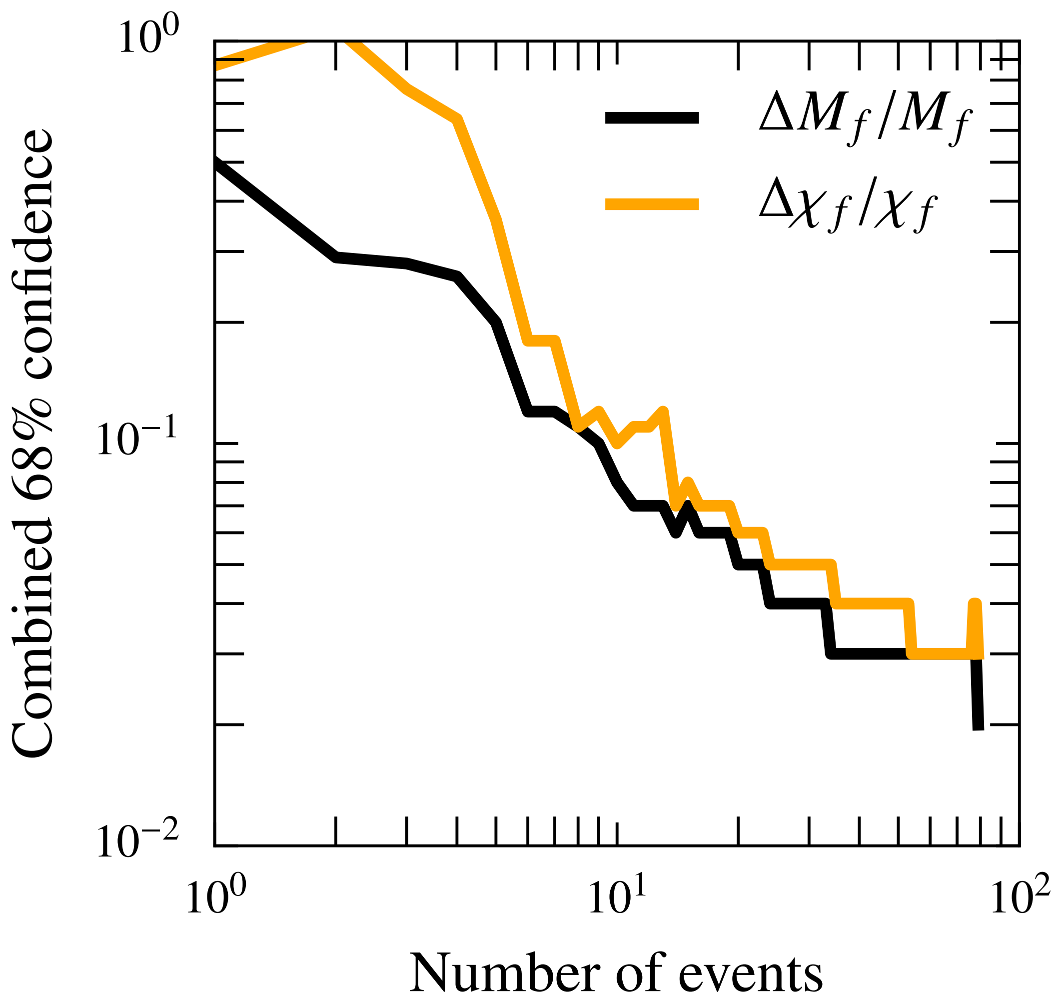


Abhirup+ 2016

COMBINING EVENTS

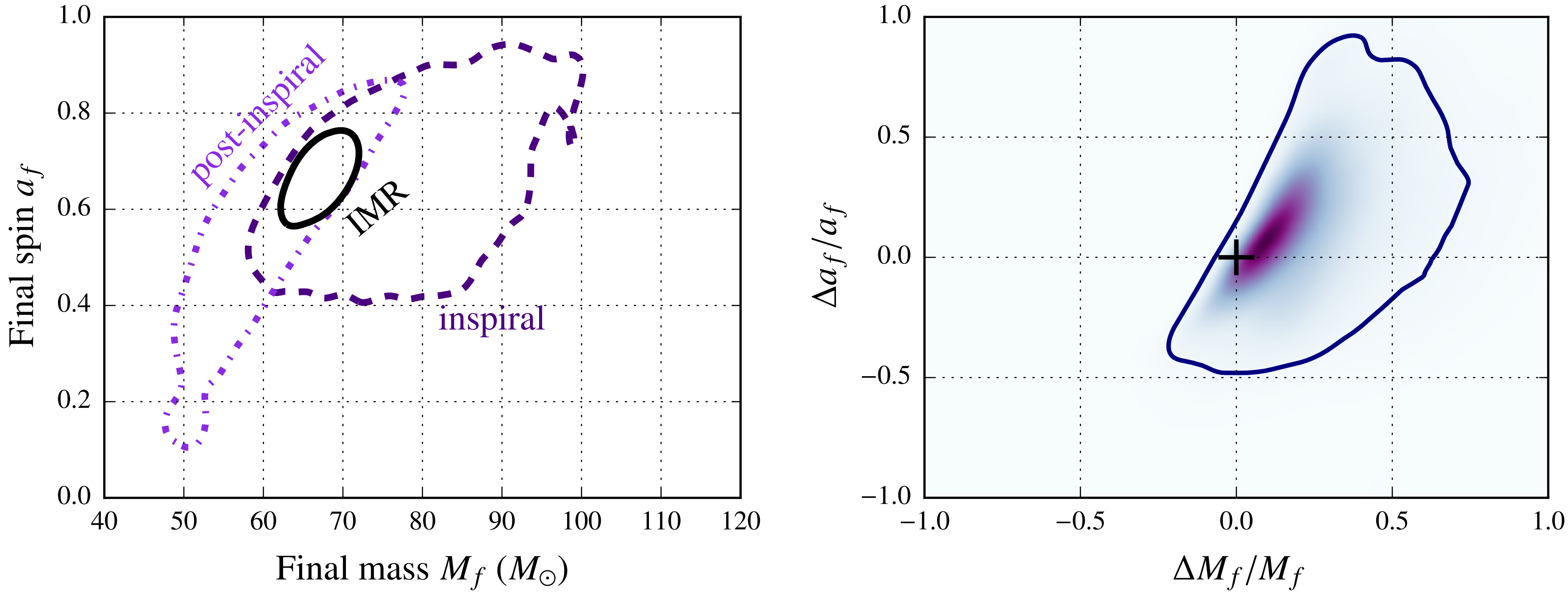
AFTER ~ 100 EVENTS WIDTH OF THE MARGINALIZED POSTERIOR IS BELOW 1%





Abhirup+ 2016

APPLICATION TO GW150914: FINAL BH MASS AND SPIN

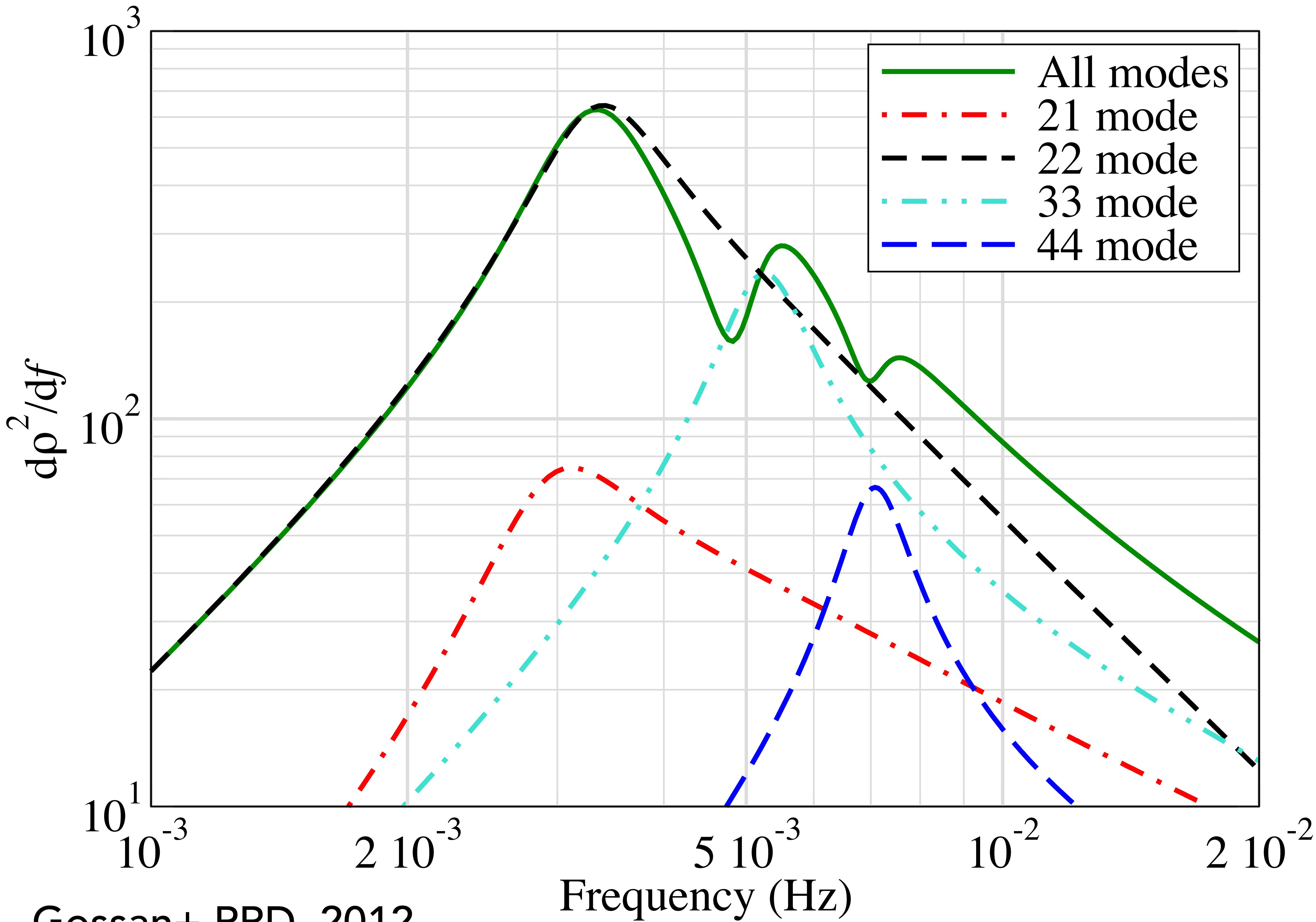


Abbott+ PRL, 2016

FROM RINGDOWN BACK TO INSPIRAL

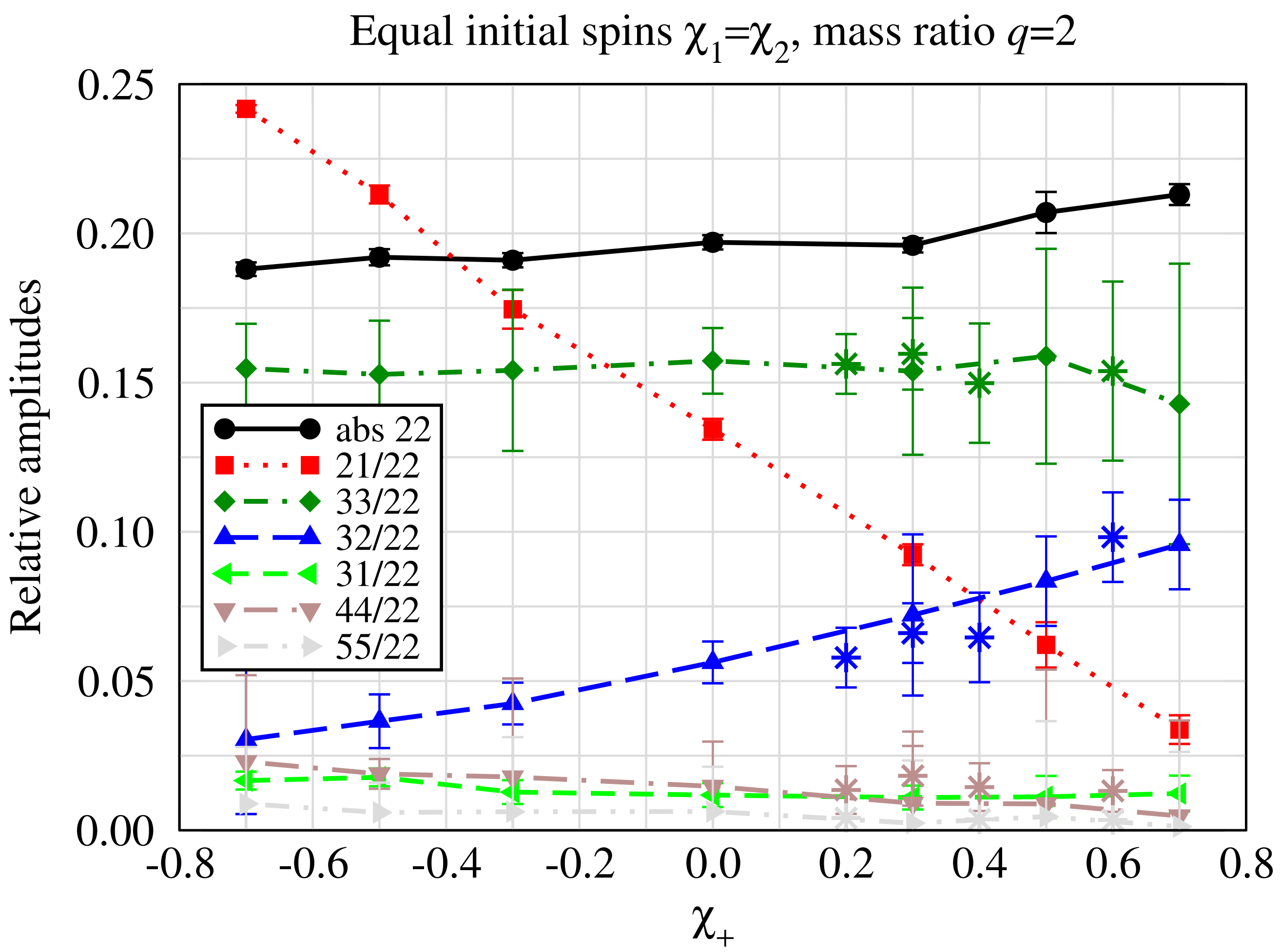
PROGENITOR BINARY PARAMETERS FROM RINGDOWNS

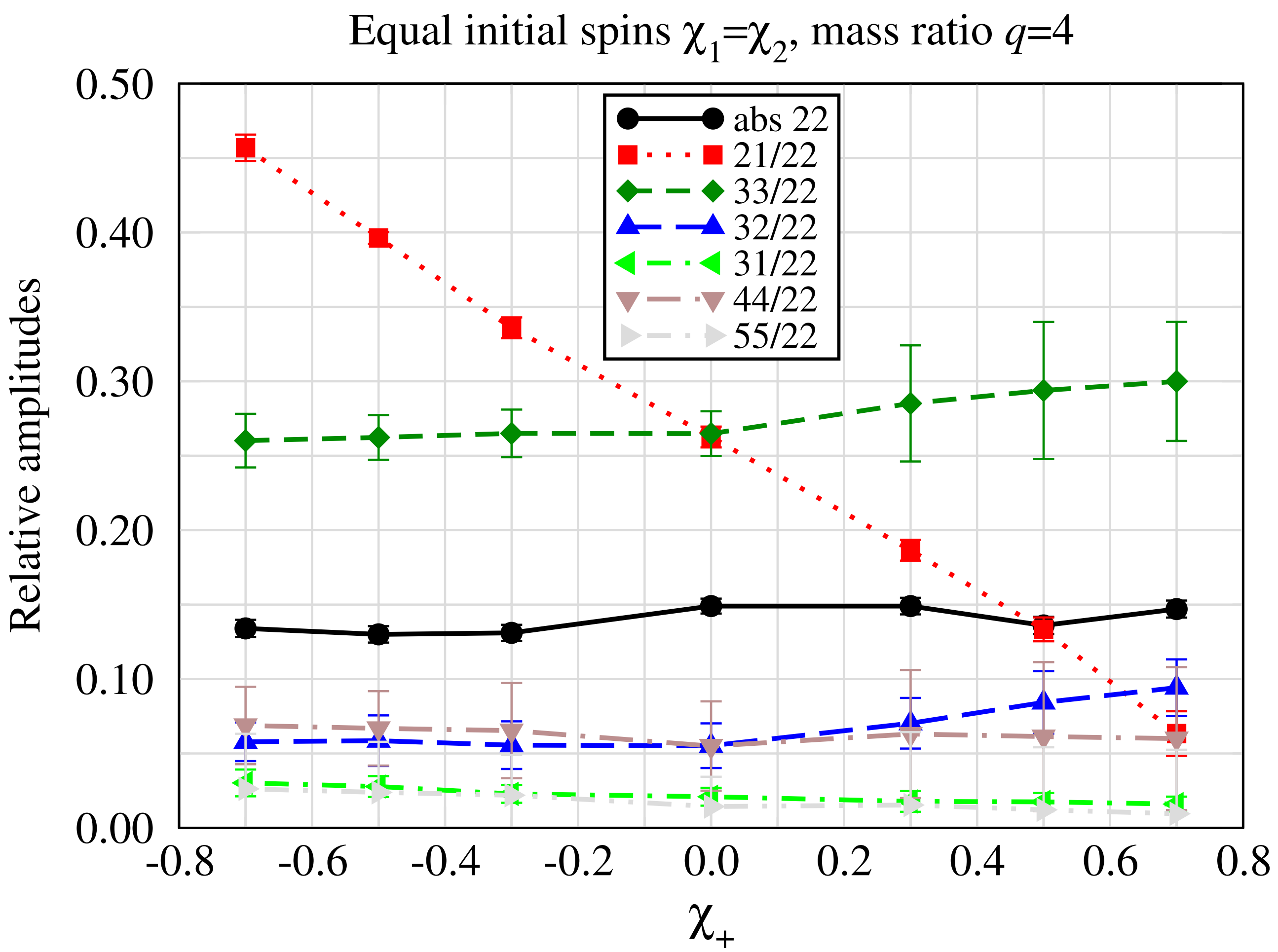
BLACK HOLE RAINBOWS



Gossan+ PRD, 2012

AMPLITUDES OF HIGHER MODE CARRY THE SIGNATURE OF INSPIRAL





Kamaratsos+ PRL, 2012

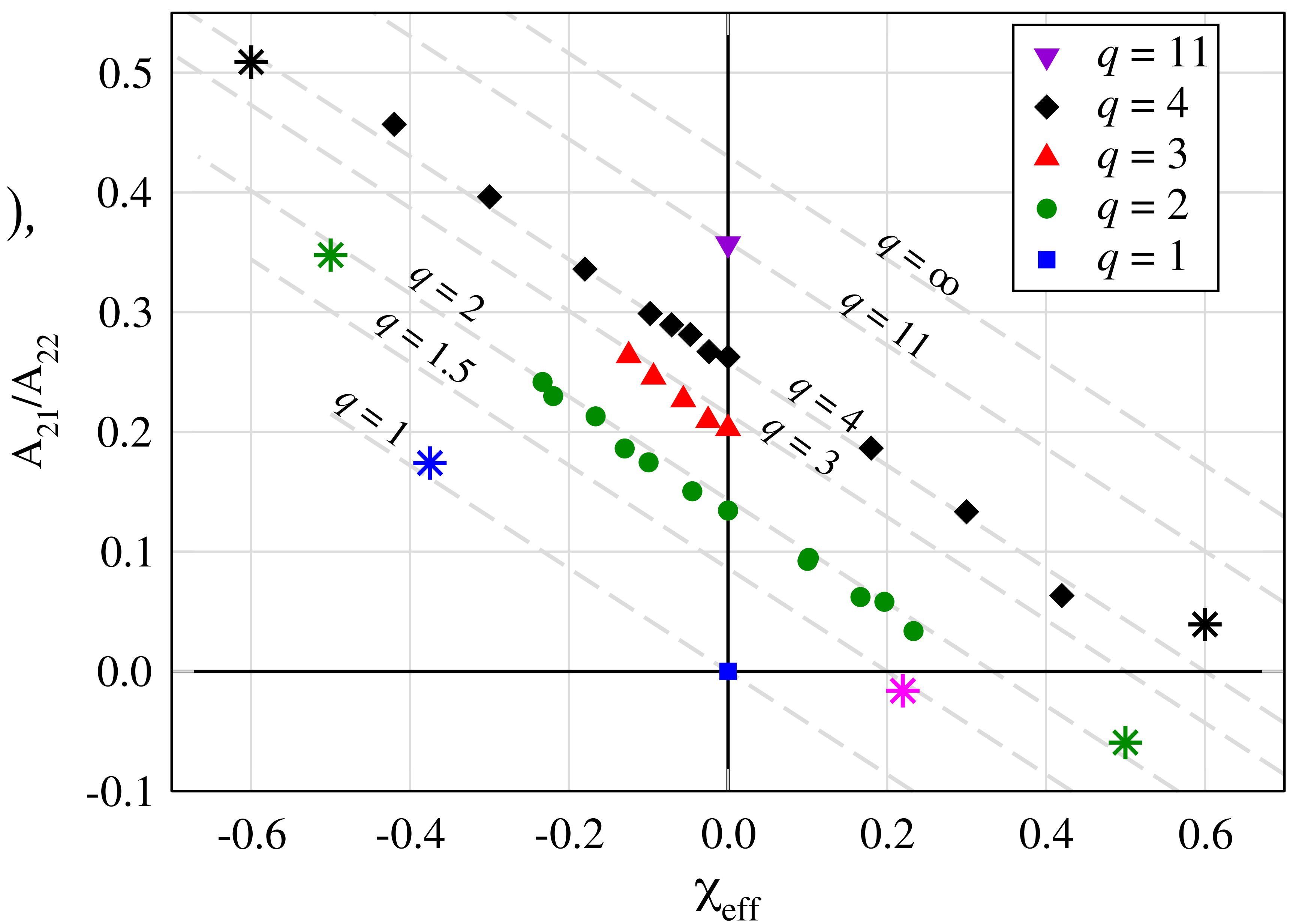
A21 AS A FUNCTION OF EFFECTIVE SPIN

CURRENTLY BEING GENERALIZED TO PRECESSING BINARIES AND IMPLEMENTATION OF THE TEST BY BORHANIAN+

$$\hat{A}_{21} \equiv A_{21}/A_{22} = 0.43[\sqrt{1-4\nu} - \chi_{\rm eff}],$$

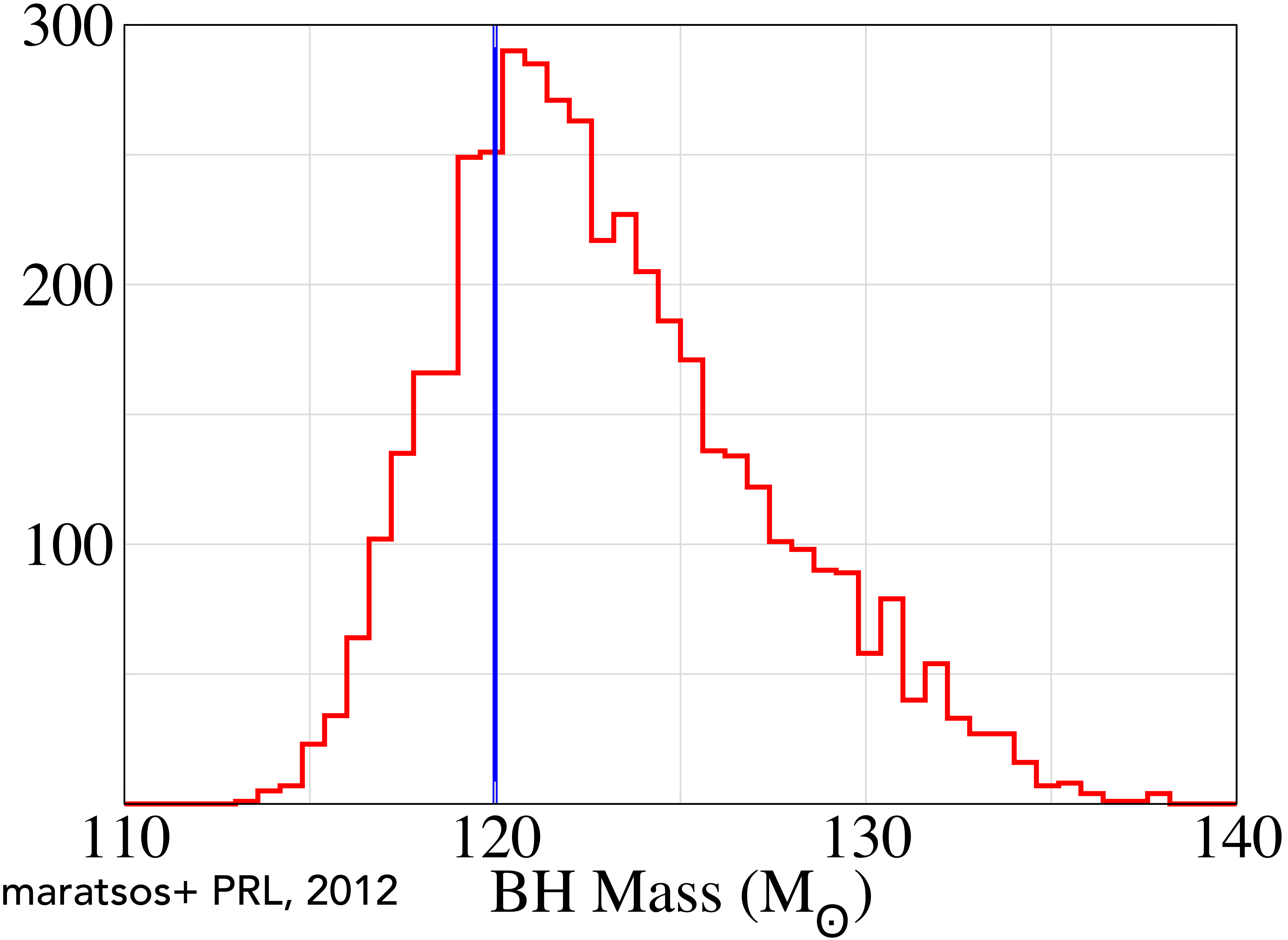
$$\chi_{\rm eff} = \frac{1}{2}(\sqrt{1-4\nu}\chi_1 + \chi_-),$$

$$\chi_- = \frac{m_1\chi_1 - m_2\chi_2}{M_{\rm in}}.$$



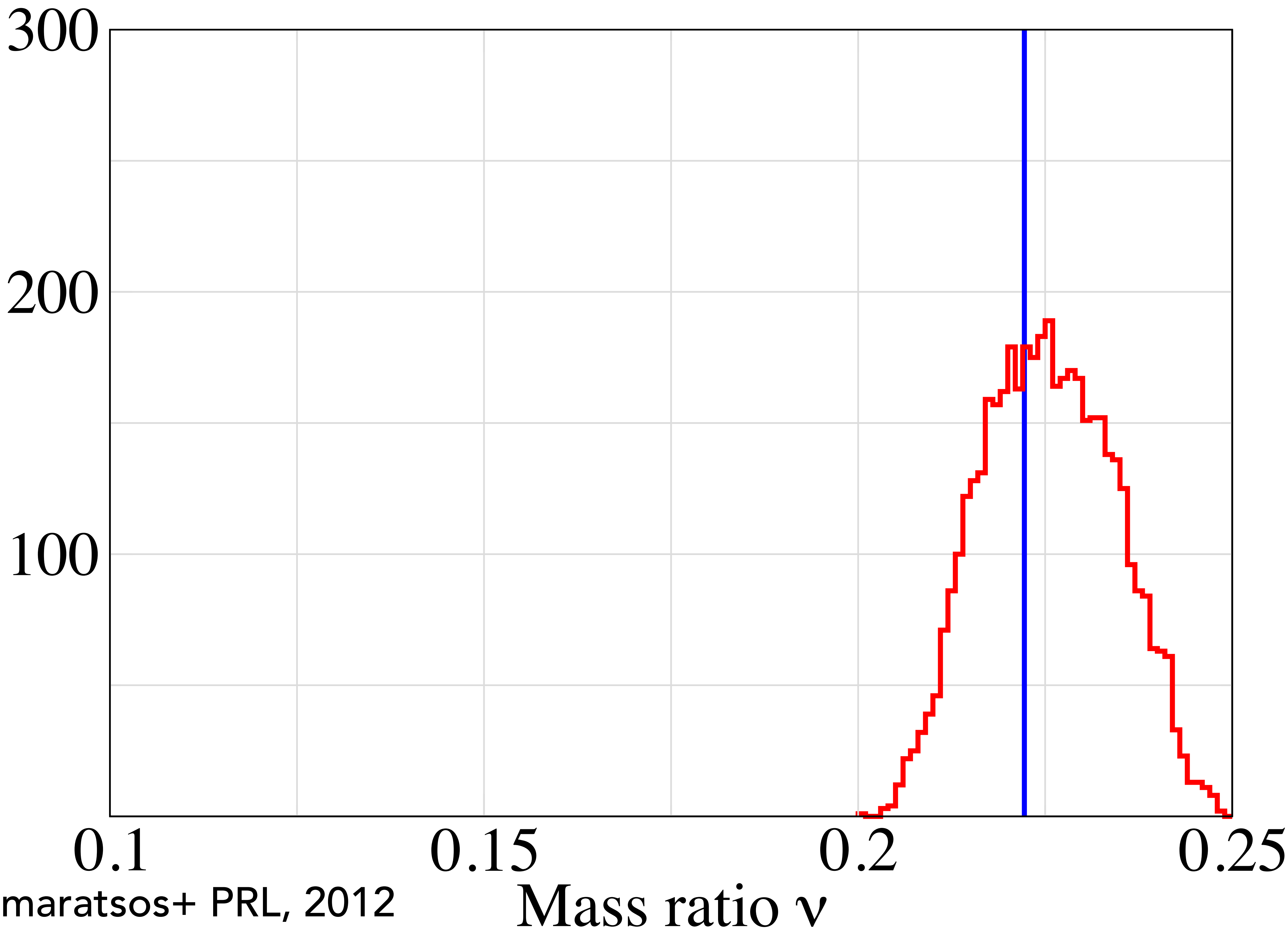
Kamaratsos+ PRL, 2012

POSTERIOR DENSITY OF BINARY BLACK HOLE MASS



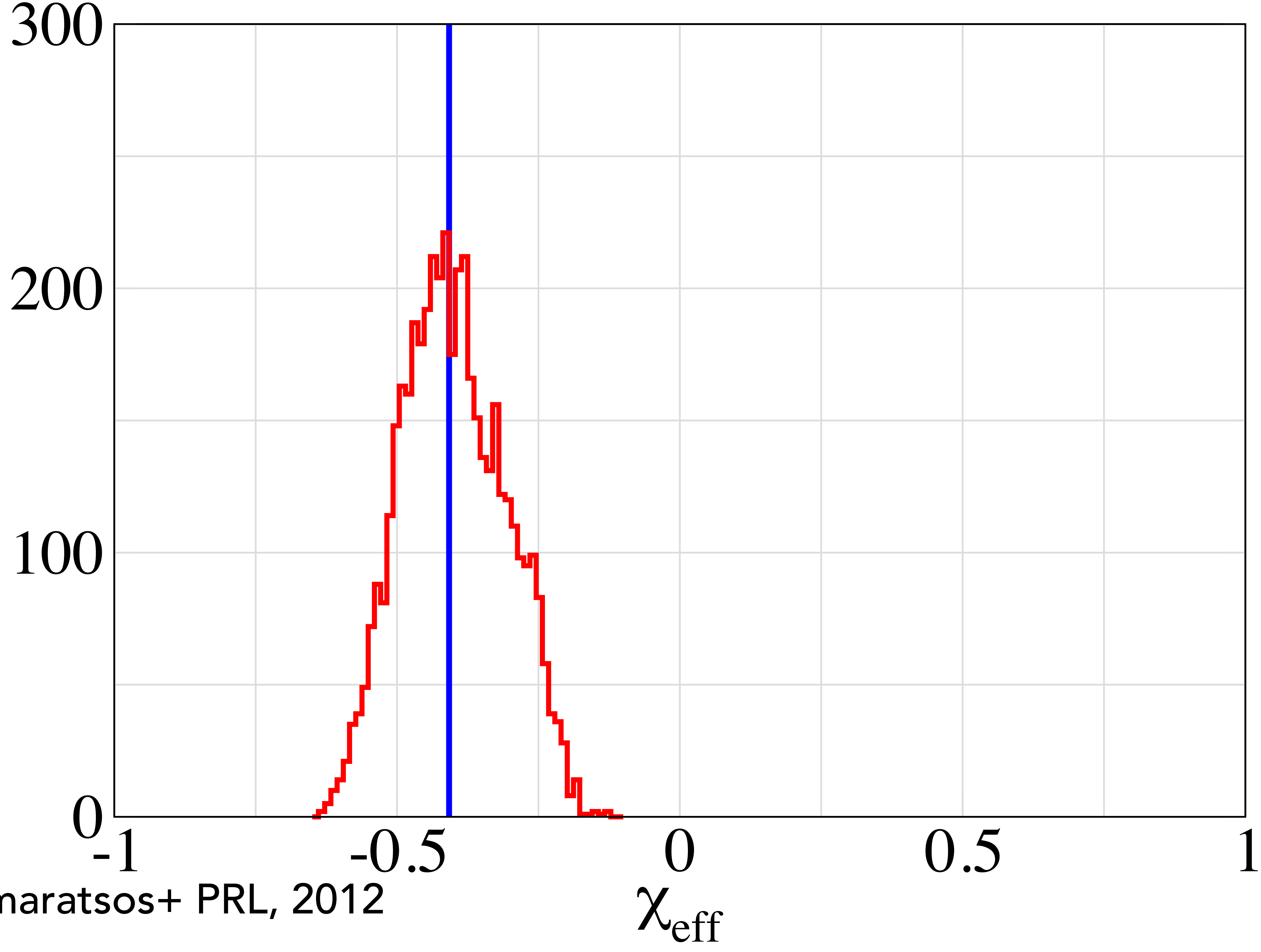
Kamaratsos+ PRL, 2012

POSTERIOR PDF OF BINARY MASS RATIO



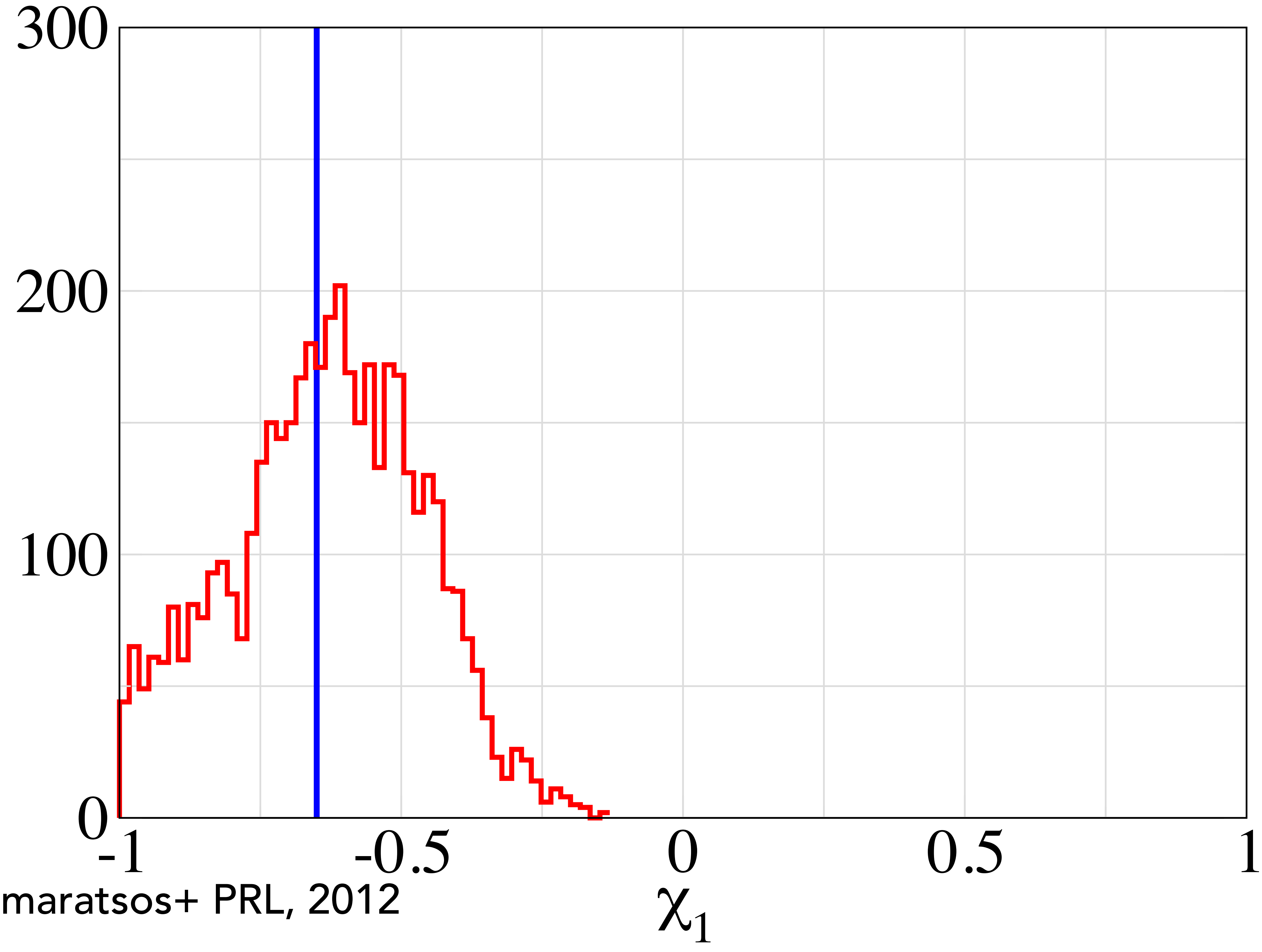
Kamaratsos+ PRL, 2012

POSTERIOR PDF OF EFFECTIVE SPIN



Kamaratsos+ PRL, 2012

POSTERIOR PDF OF COMPONENT SPIN



Kamaratsos+ PRL, 2012

GENERALIZING THE NO-HAIR THEOREM TO BINARY BLACK HOLES

CONSISTENCY BETWEEN DIFFERENT MULTIPOLES OR MODES

- originally proposed in the context of EMRI's for a single black hole by Ryan
  - in that case one avoids the problem of having to do with the spacetime of two black holes
  - the small black hole is a test body orbiting supermassive black hole under radiation reaction; primarily interested in measuring the multipoles of the big blackhole
- the current proposal is to measure the multipole structure of a binary black hole
  - identify a set of parameters that most accurately determined by higher modes
  - look for parameter-independent description - multipole structure of the binary
  - pose the test as consistency between different modes

Borhanian+ 2017