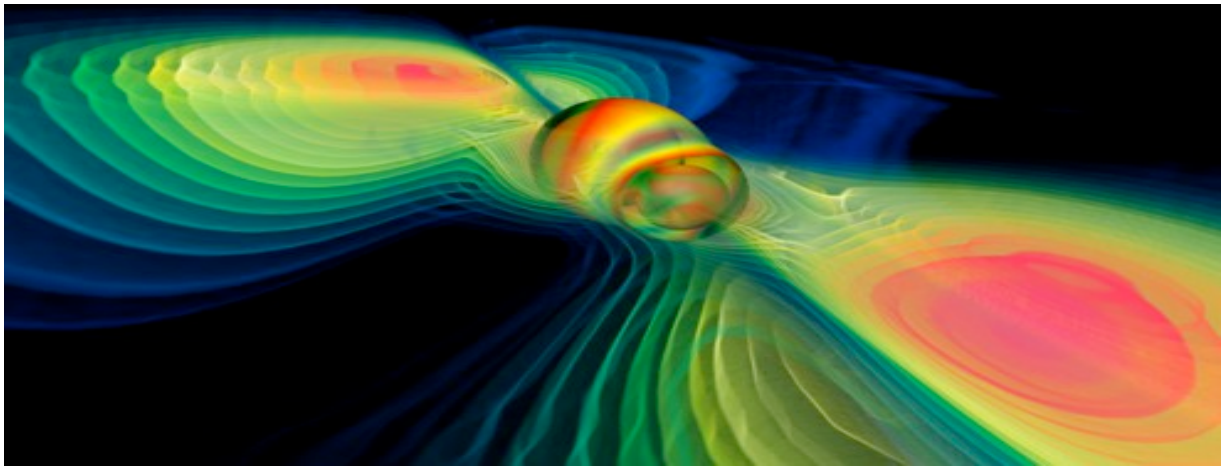
Understanding black hole rainbows

is the ringdown a memory of the progenitor binary?



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in collaboration with

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➢ Preliminaries..

➢ Perturbed BHs that reach equilibrium emit gravitational radiation in a very characteristic manner usually termed the 'ringdown' phase

$$h_+(t) = \sum_{\ell,m>0} \frac{\alpha_{\ell m} M}{D_{\rm L}} Y_+^{\ell m}(\iota)\, e^{-t/\tau_{\ell m}} \cos\left(\omega_{\ell m} t - m\phi\right)$$

$$h_\times(t) = \sum_{\ell,m>0} \frac{\alpha_{\ell m} M}{D_{\rm L}} Y_\times^{\ell m}(\iota)\, e^{-t/\tau_{\ell m}} \sin\left(\omega_{\ell m} t - m\phi\right)$$

$$\omega_{\ell mn} = \frac{F_{\ell mn}(j)}{M}, \quad \tau_{\ell mn} = M G_{\ell mn}(j)$$

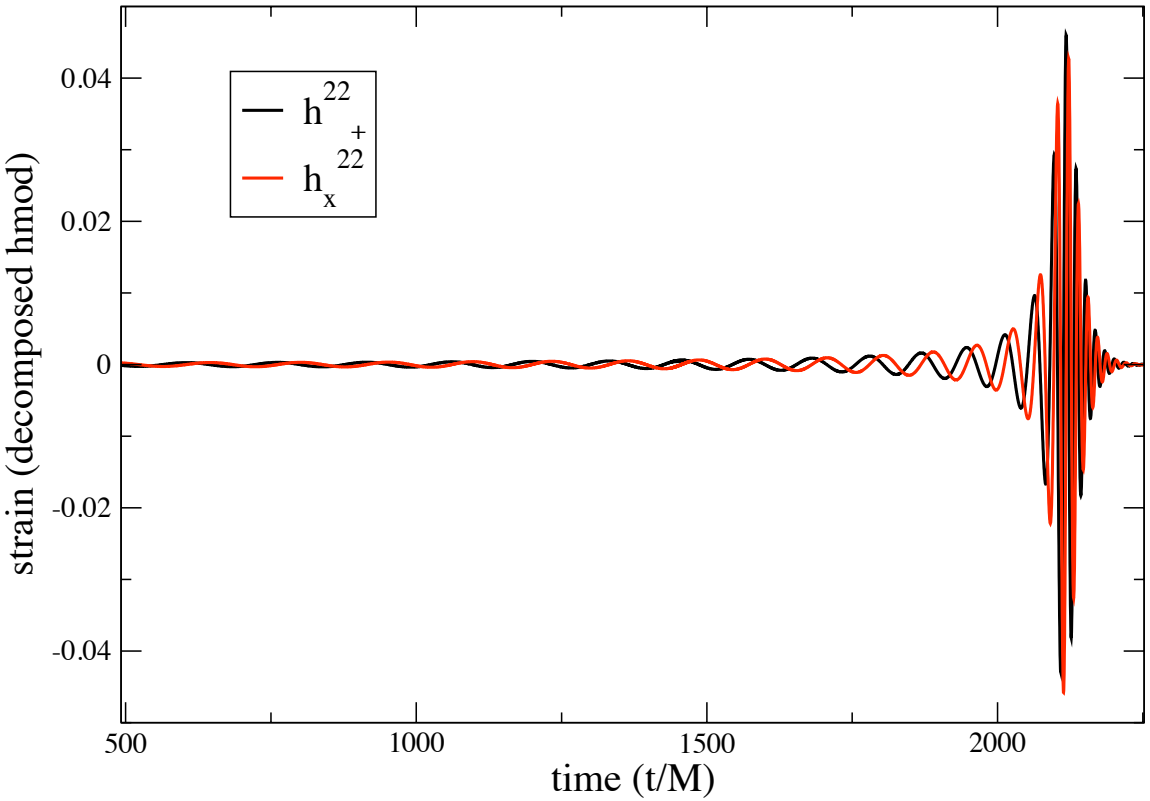
➢ We take the nature of the perturbation to be the merging of two inspiralling BHs with low mass ratios, ***initial aligned/ anti-aligned spins*** and very small initial eccentricity (~1e-03)

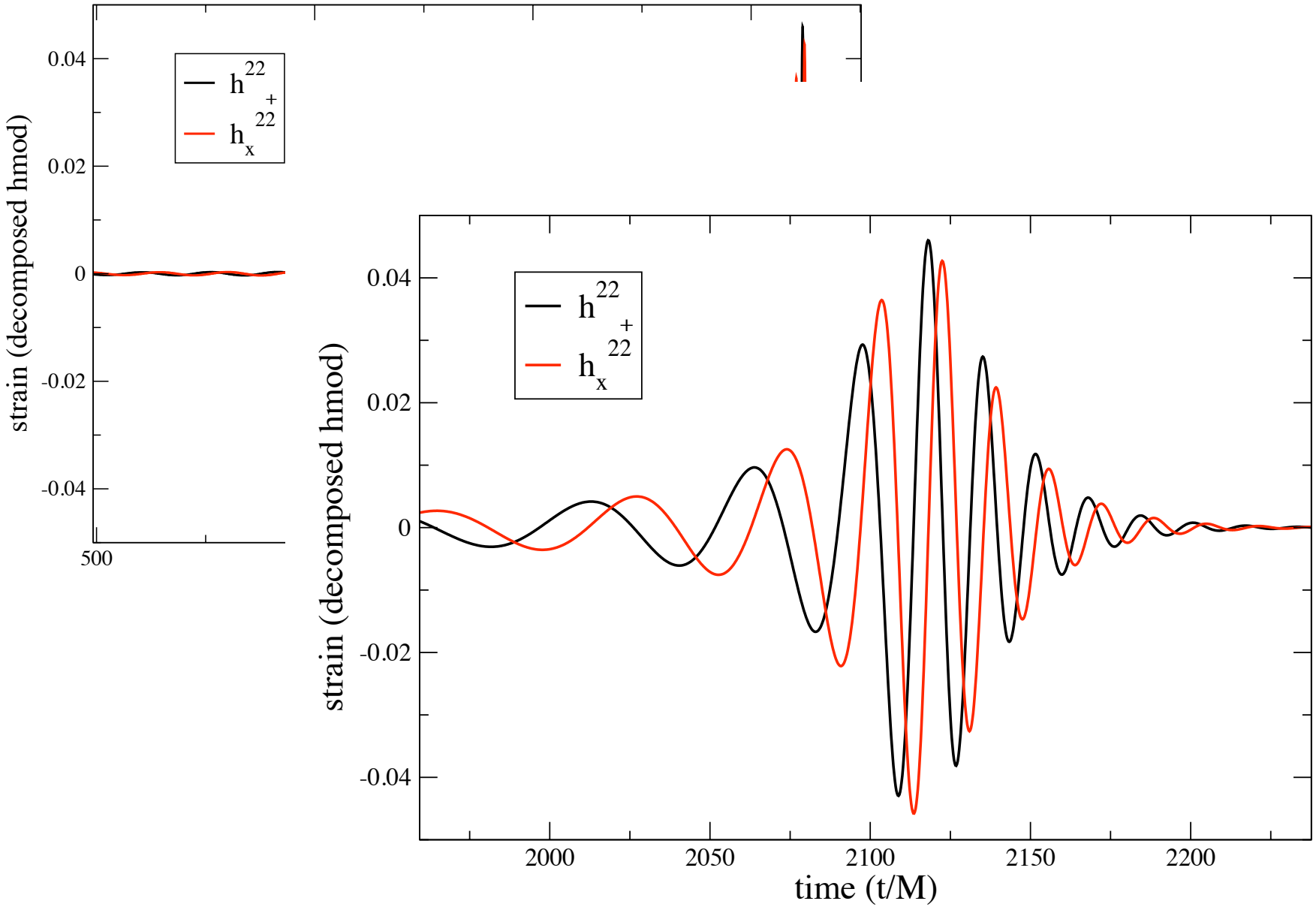
➢ Preliminaries..

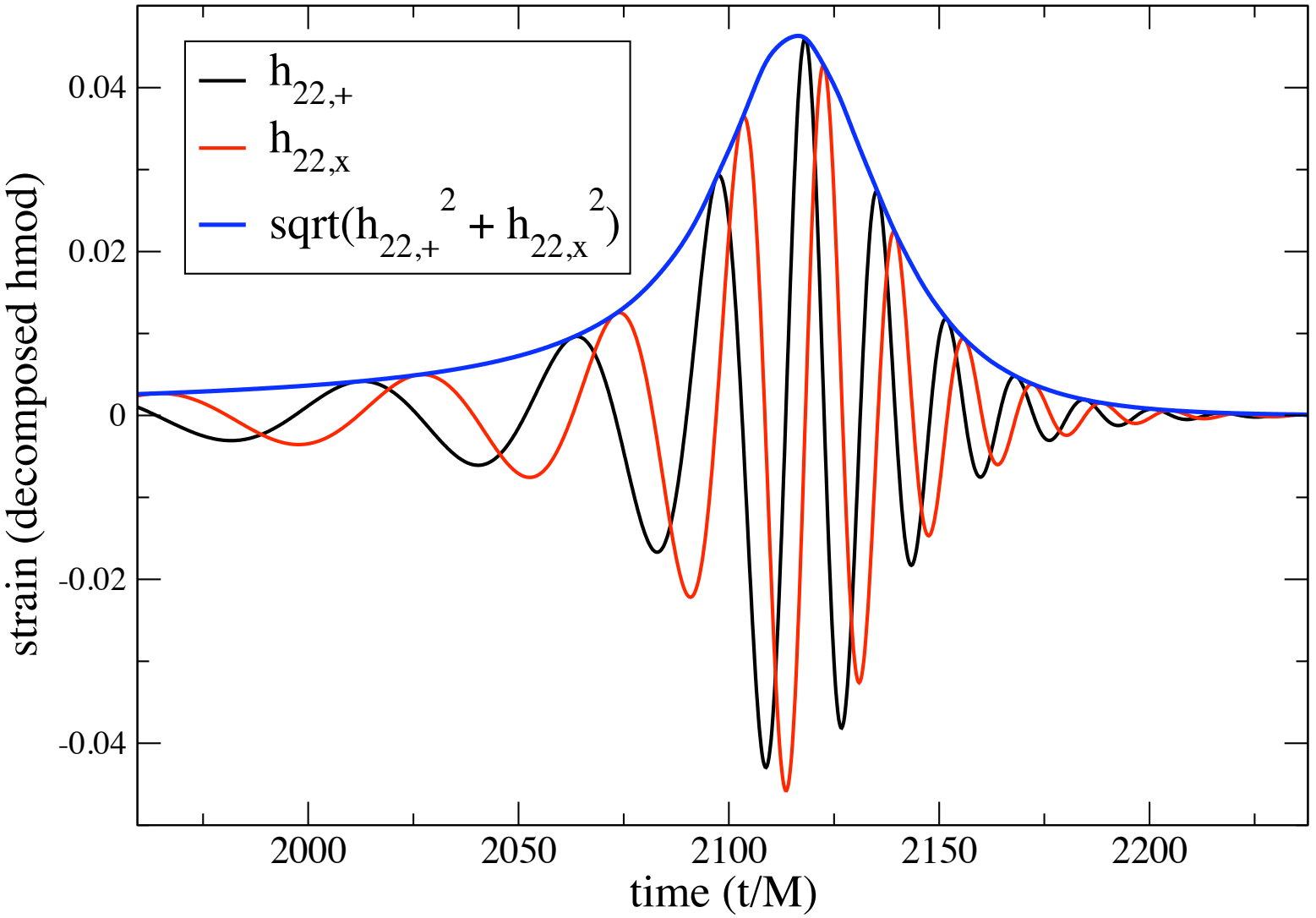
➢ we are using the BAM code for performing the numerical simulations of BH binaries (Bernd Brugmann, developed by Sascha Husa, Mark Hannam and others)

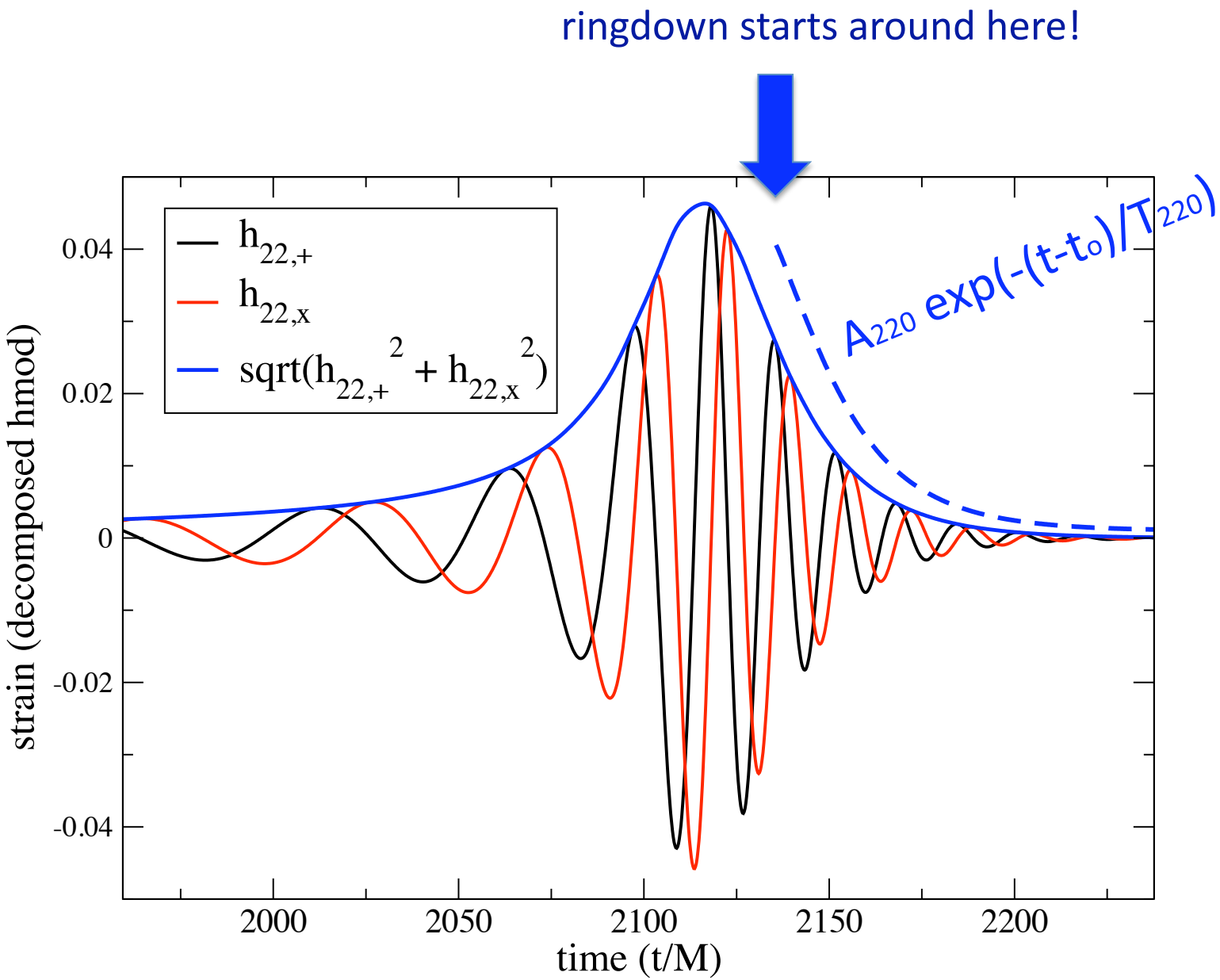
- $q = m_1/m_2, \ m_1 > m_2$
- $\chi_k = |S_k|/m_k^2, k=1, 2$
- $\nu = q/(1+q)^2$
  - $q = 1, \ \nu = 0.25,$
  - $q = 2, \ \nu = 0.222..$
  - $q = 3, \ \nu = 0.1875,$
  - $q = 4, \ \nu = 0.16.$

➢ Preliminaries..

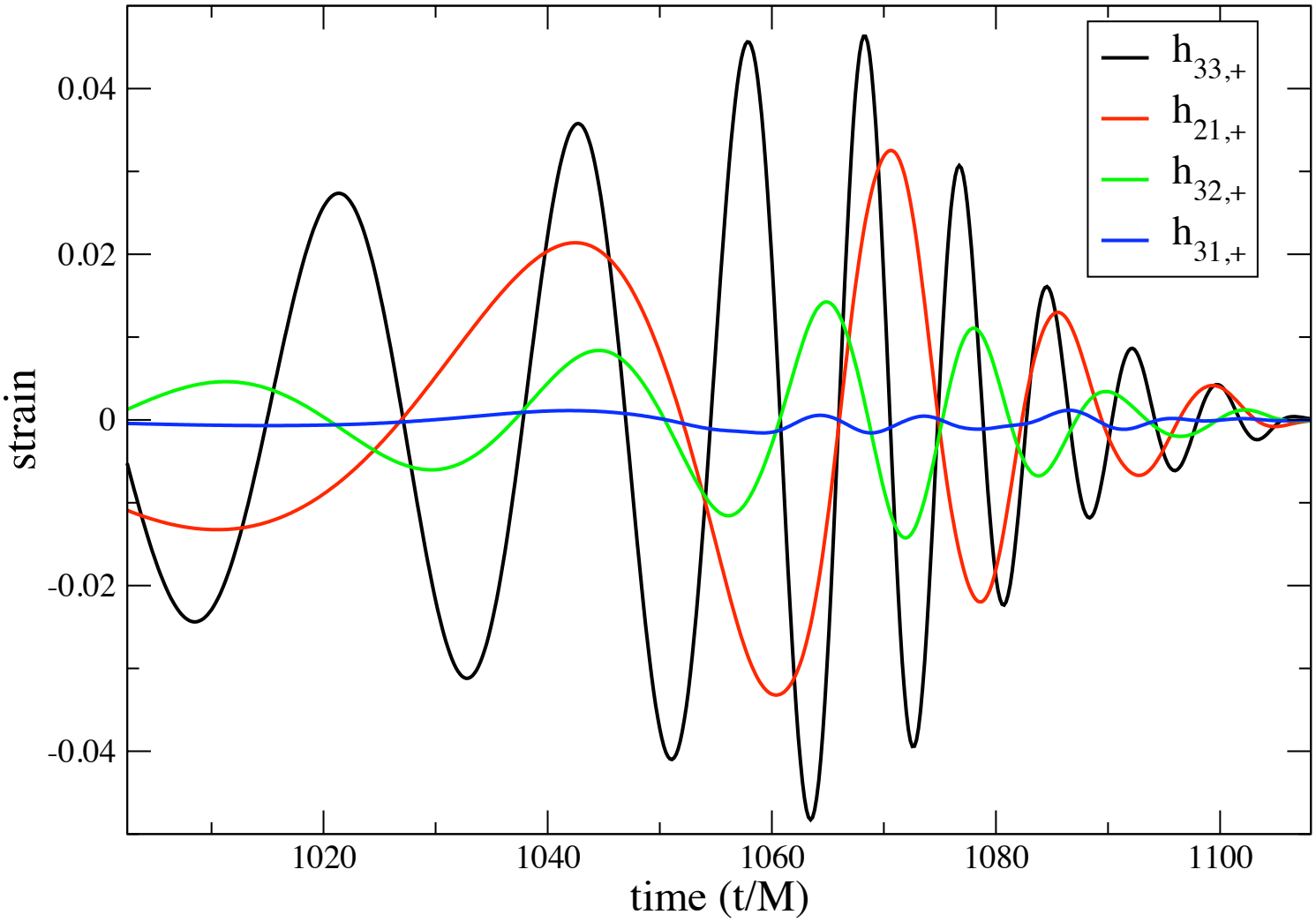



0.04
0.02
0
-0.02
-0.04
500
strain (decomposed hmod)
h+22
hx22
2000
2050
2100
2150
2200
time (t/M)


h22,+
h22,x
sqrt(h22,+^2 + h22,x^2)
0.04
0.02
0
-0.02
-0.04
2000
2050
2100
2150
2200
strain (decomposed hmod)
time (t/M)


ringdown starts around here!
$h_{22,+}$
$h_{22,x}$
$\mathrm{sqrt}(h_{22,+}^2 + h_{22,x}^2)$
$A_{220}\exp(-(t-t_0)/T_{220})$
strain (decomposed hmod)
0.04
0.02
0
-0.02
-0.04
2000
2050
2100
2150
2200
time (t/M)

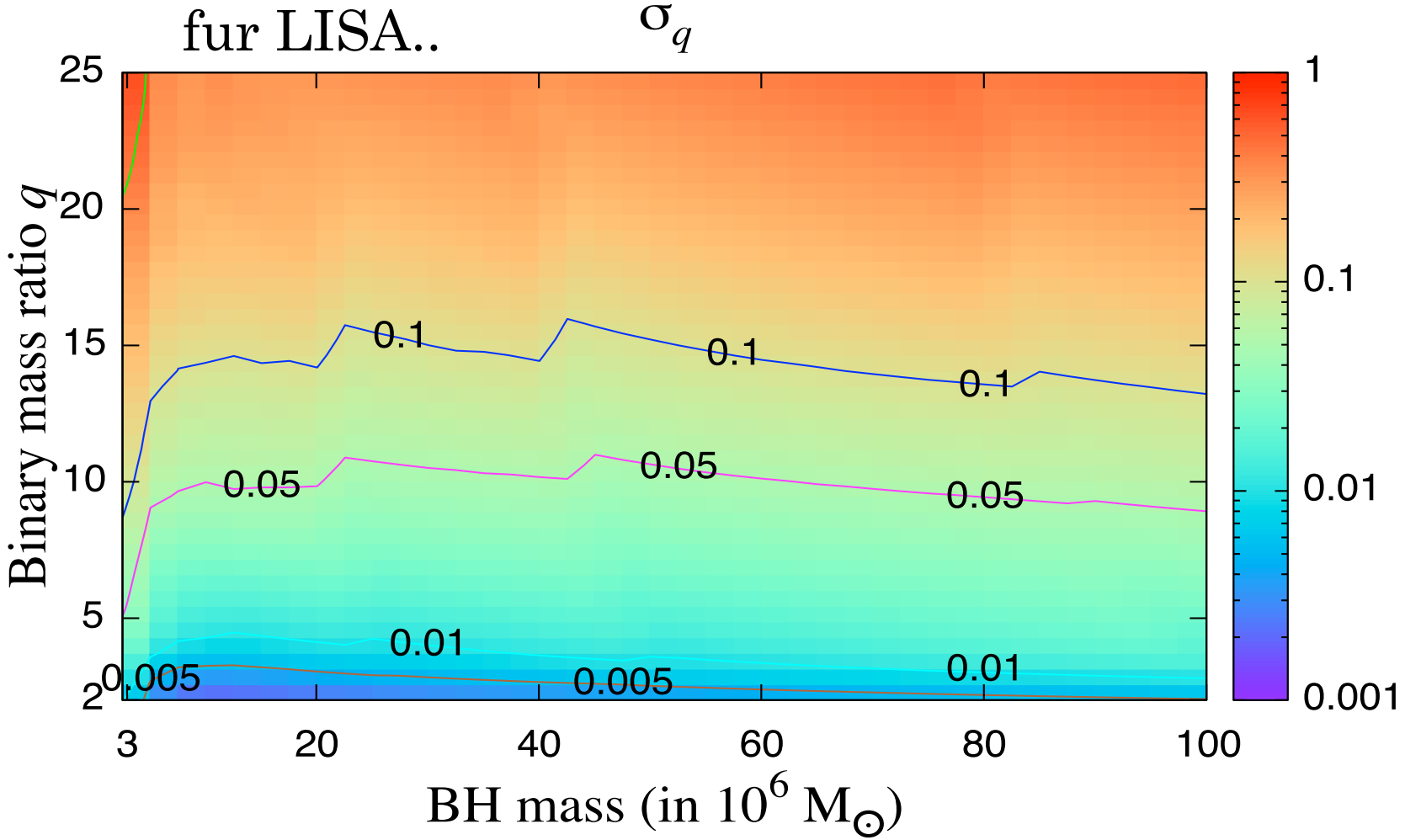
- Do the same for several subdominant modes..



A_{33}/A_{22} -> “33/22”, A_{21}/A_{22} -> “21/22, A_{44}/A_{22} -> “44/22” etc..

main result for non-spinning binaries

- the ringdown phase alone allows us to measure the mass ratio of the progenitor binary and test the no-hair theorem [1]



[1] Kamaretsos et al. Phys. Rev. D85, 024018, arXiv: 1107.0854, 2011

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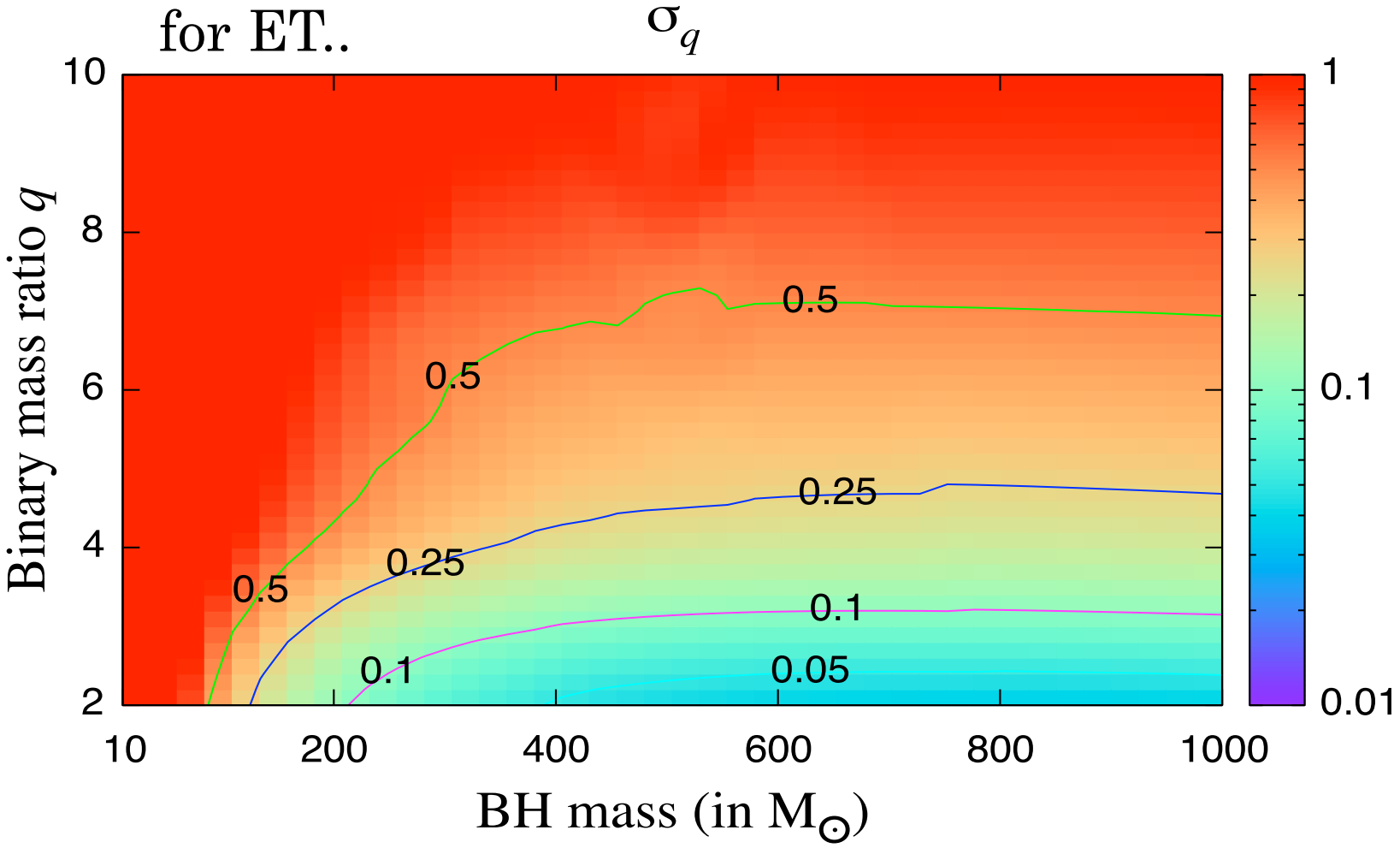

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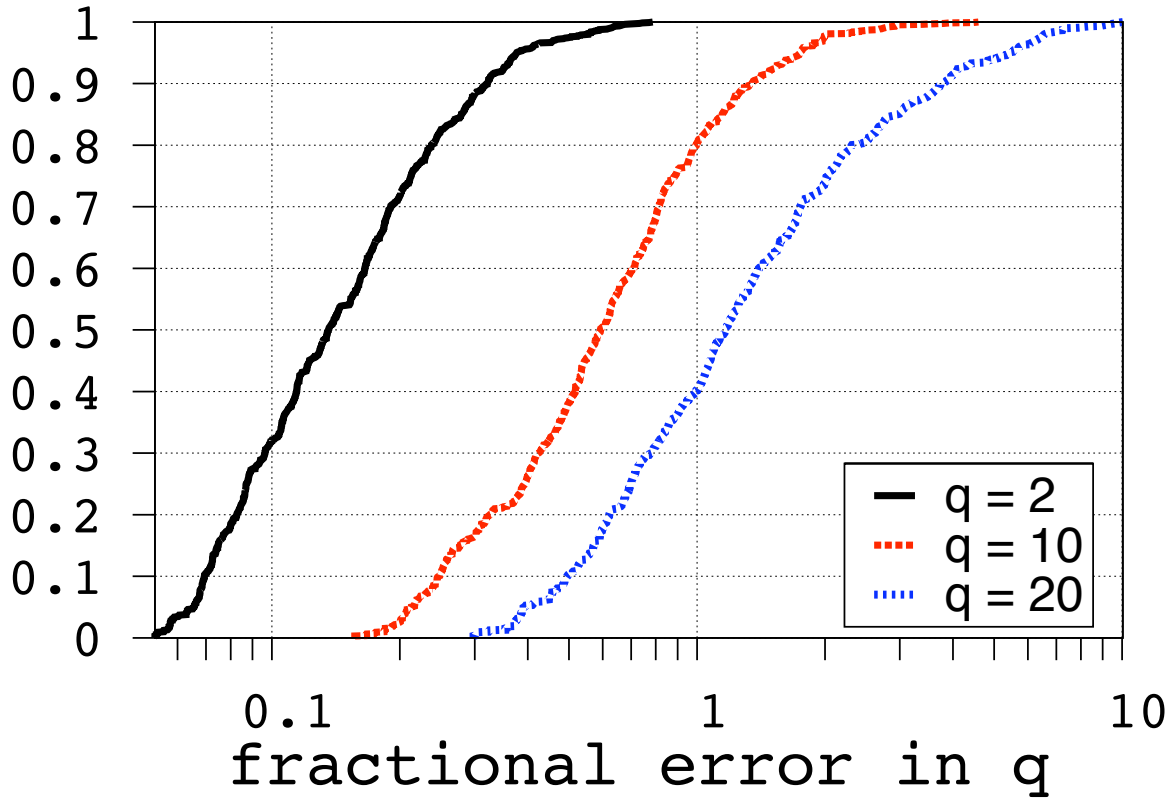
main result for non-spinning binaries

➢ Even in the case where the angular parameters: sky position θ and ϕ, polarization angle and orientation of the binary are not known, there is a high chance for an accurate measurement of the mass ratio and other parameters [2]



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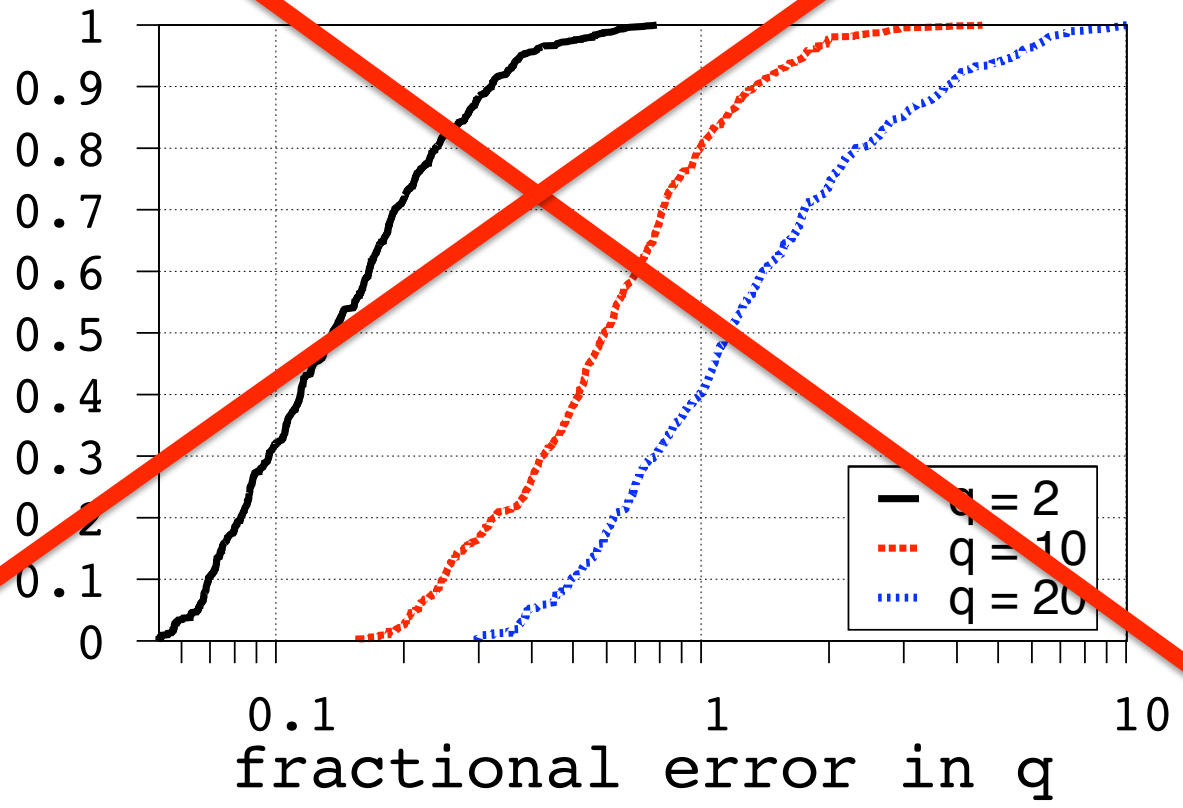

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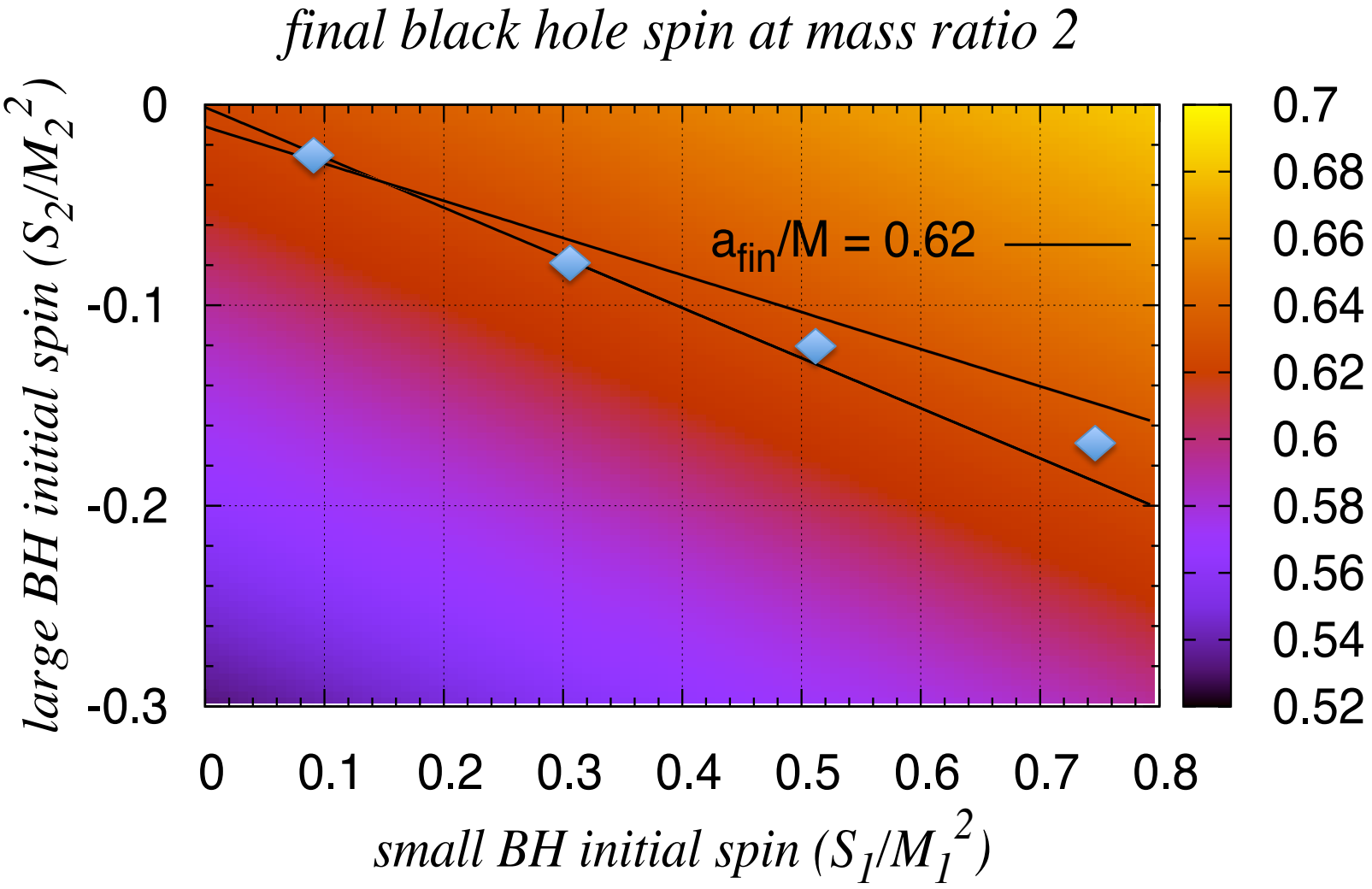
Synopsis of the simulation sets

- progenitor spins such that the final BH spin is the same as in the non-spinning case
- q = 2, χ_{final} ~ 0.62



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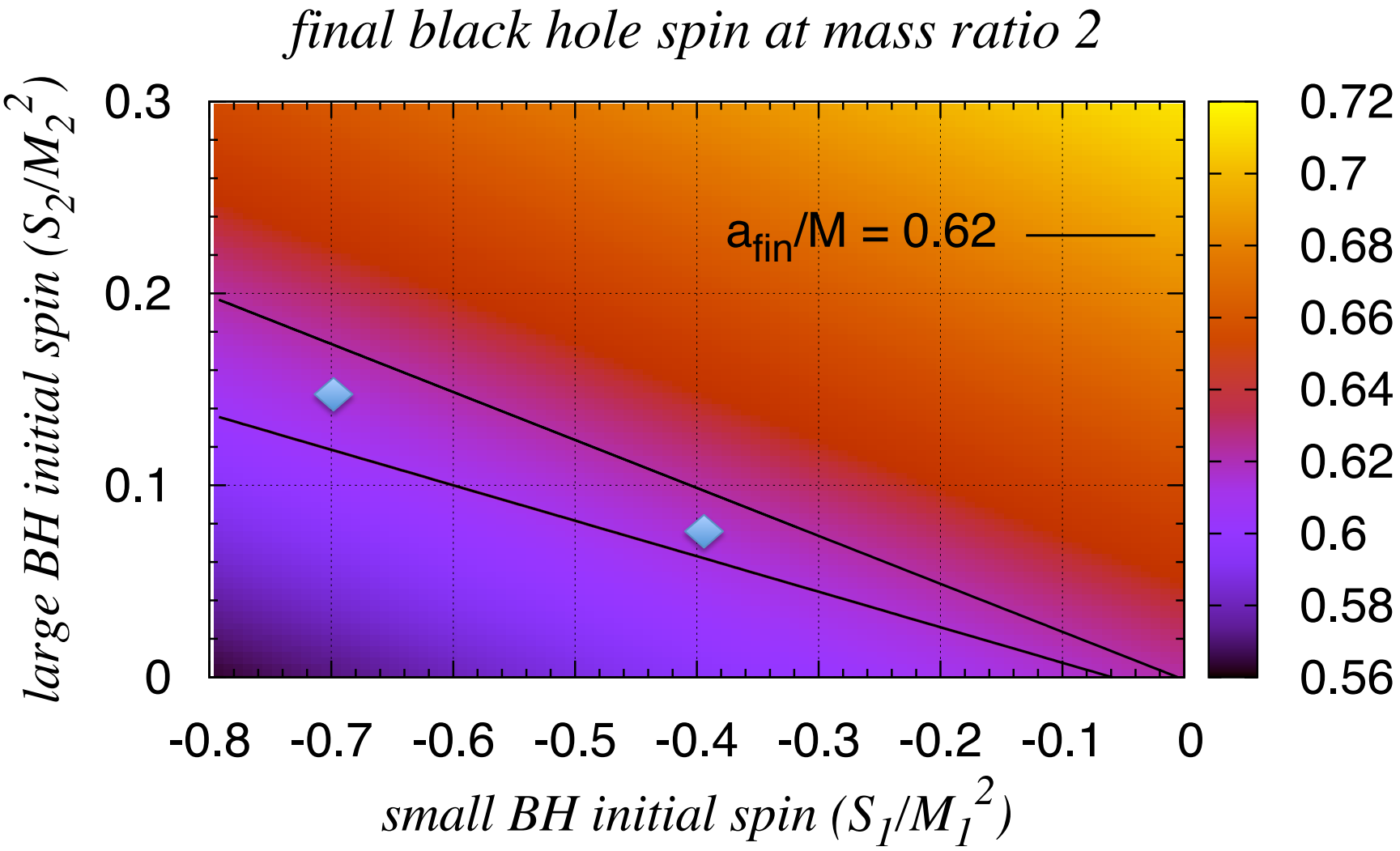
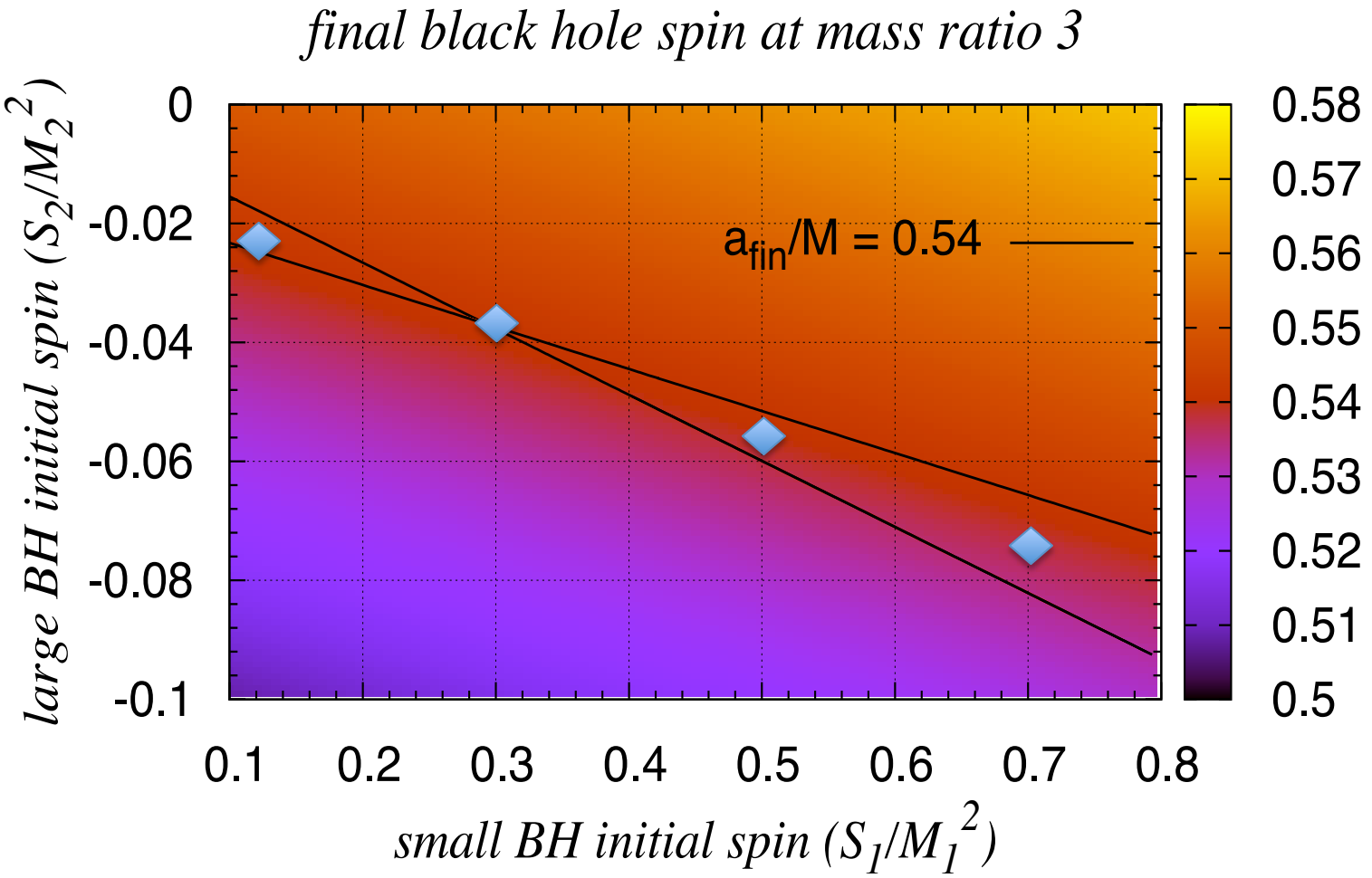


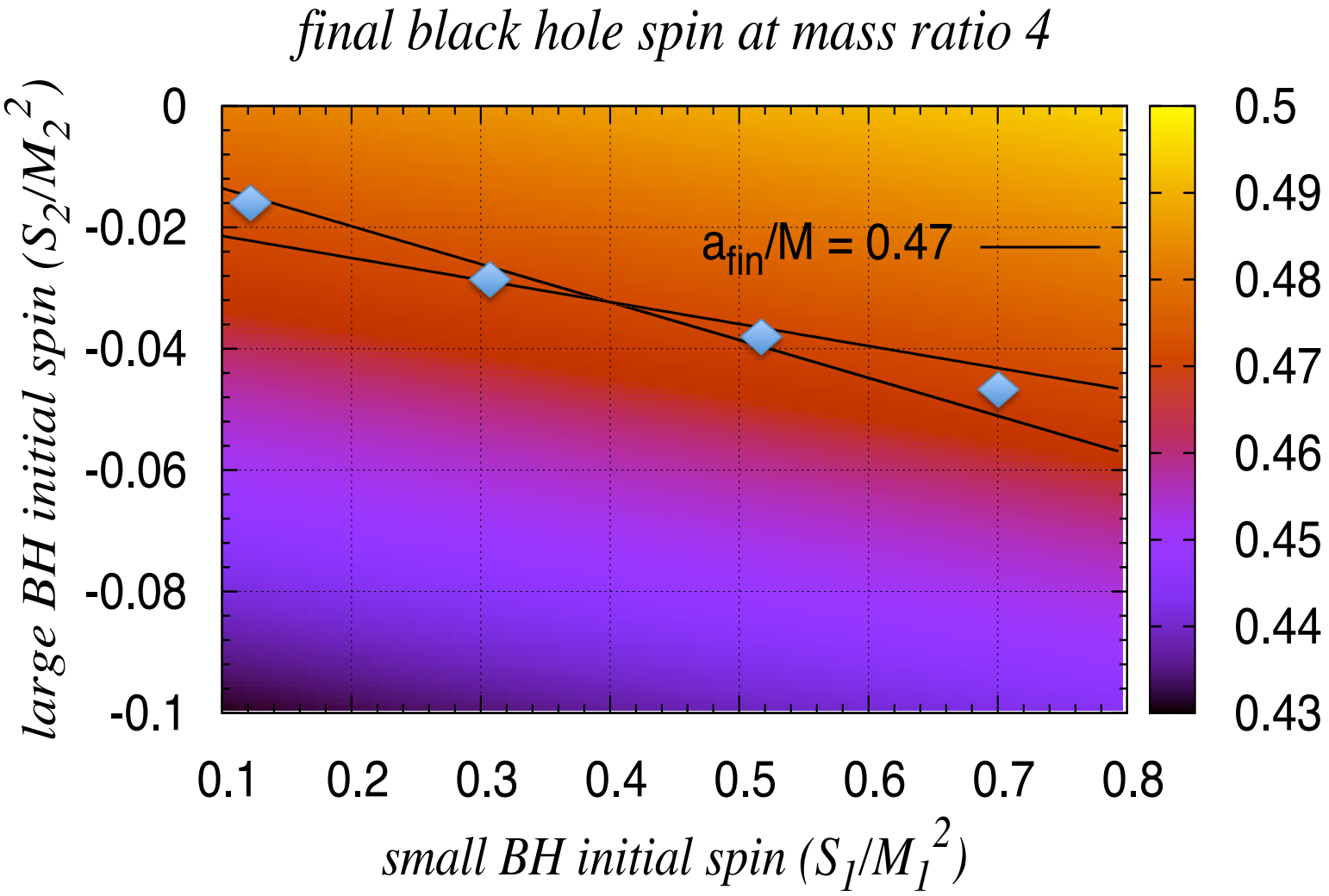
Synopsis of the simulation sets

- progenitor spins such that the final BH spin is the same as in the non-spinning case
- q = 3, $\chi_{final} \sim 0.54$



Synopsis of the simulation sets

- progenitor spins such that the final BH spin is the same as in the non-spinning case
- q = 4, χ_{final} ~ 0.47



Synopsis of the simulation sets

- progenitor spins such that the final BH spin is the same as in the non-spinning case
- q = 2, χ_{final} ~ 0.62
- q = 3, χ_{final} ~ 0.54
- q = 4, χ_{final} ~ 0.47

- equal binary progenitor spins χ_i
- q = 2, equal progenitor spins χ_i = -0.7,-0.5,-0.3, +0.3,+0.5,+0.7
- q = 4, equal progenitor spins χ_i = -0.7,-0.5,-0.3, +0.3,+0.5,+0.7

Synopsis of the simulation sets

- progenitor spins such that the final BH spin is the same as in the non-spinning case
- q = 2, $\chi_{final} \sim 0.62$
- q = 3, $\chi_{final} \sim 0.54$
- q = 4, $\chi_{final} \sim 0.47$

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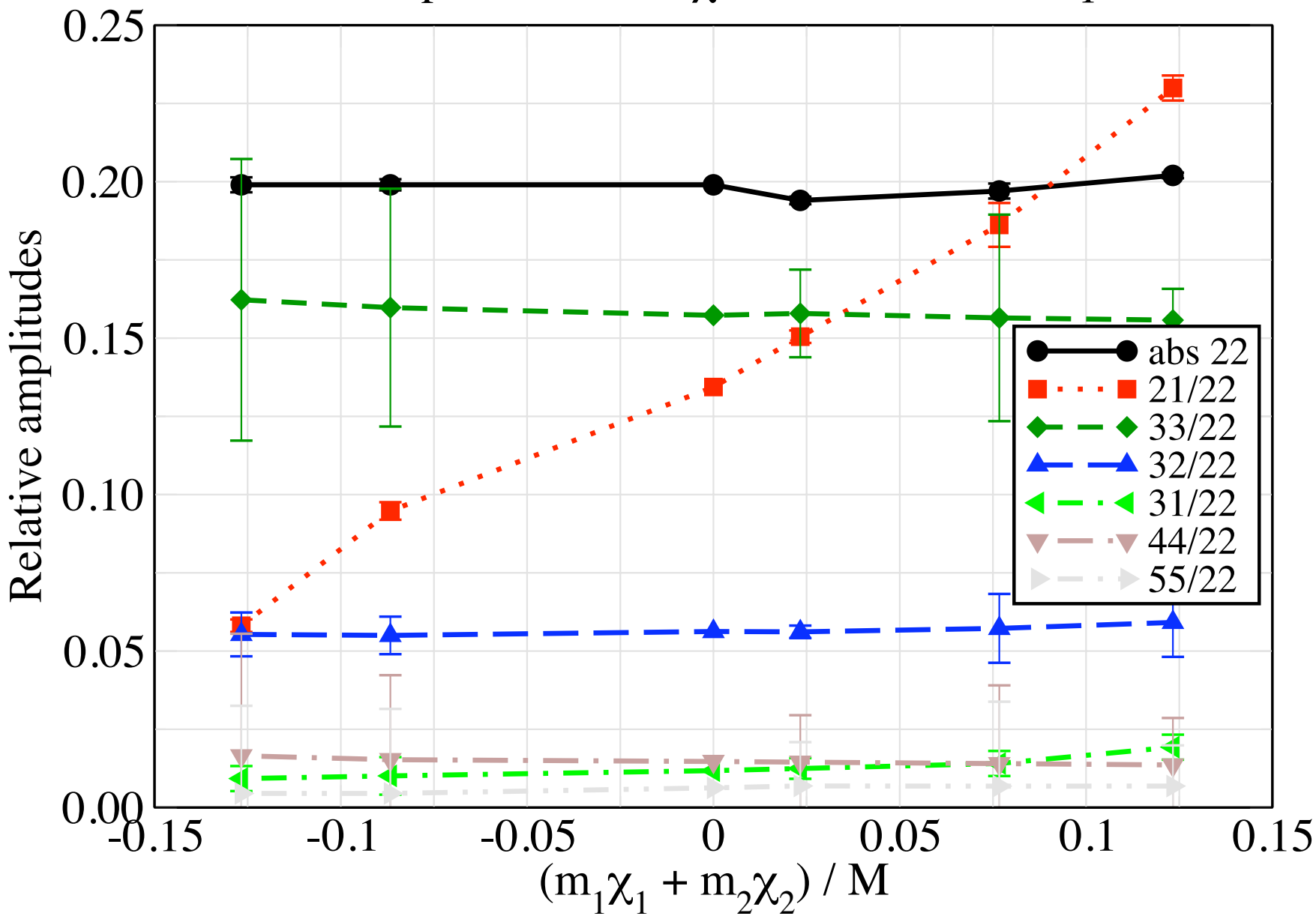
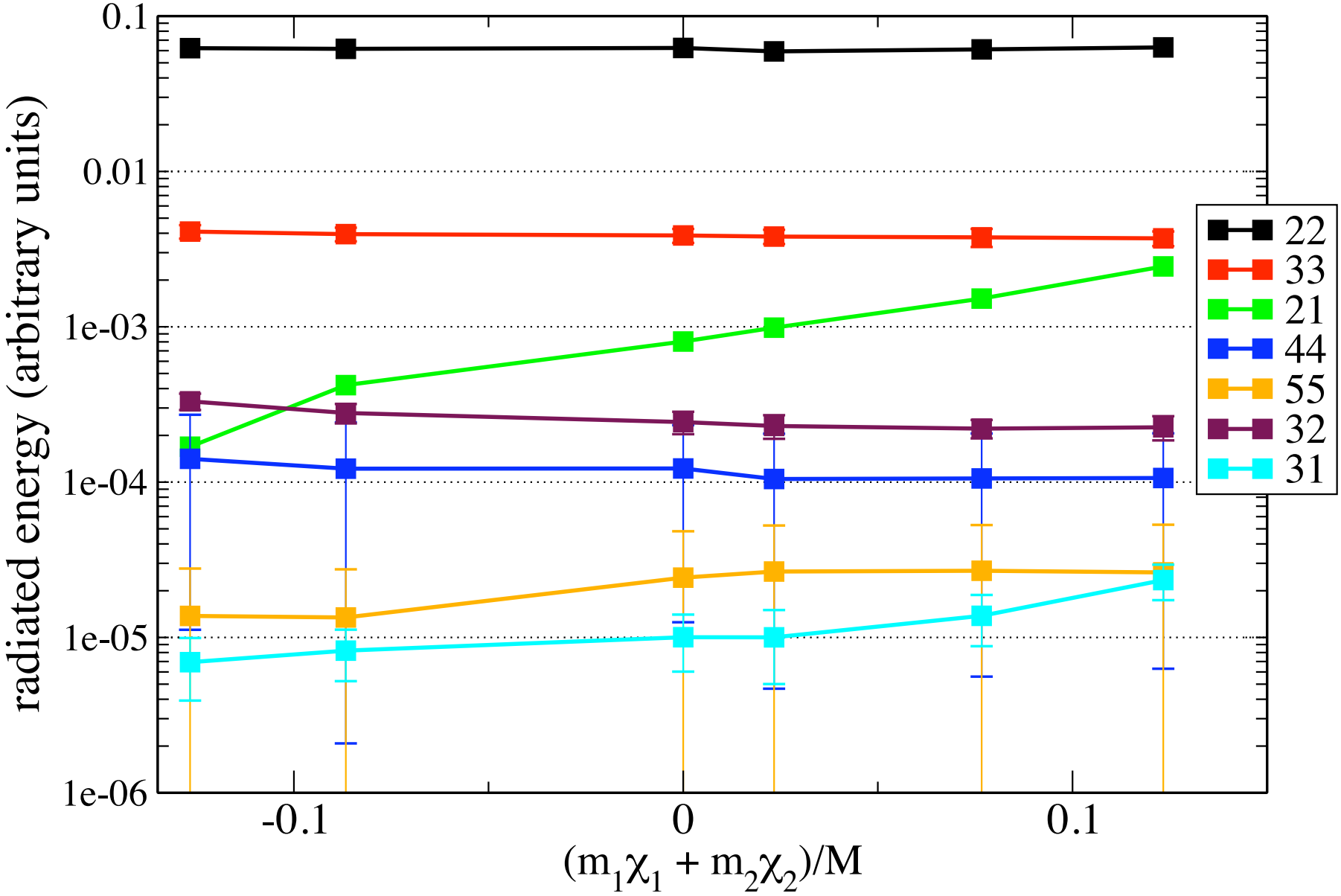
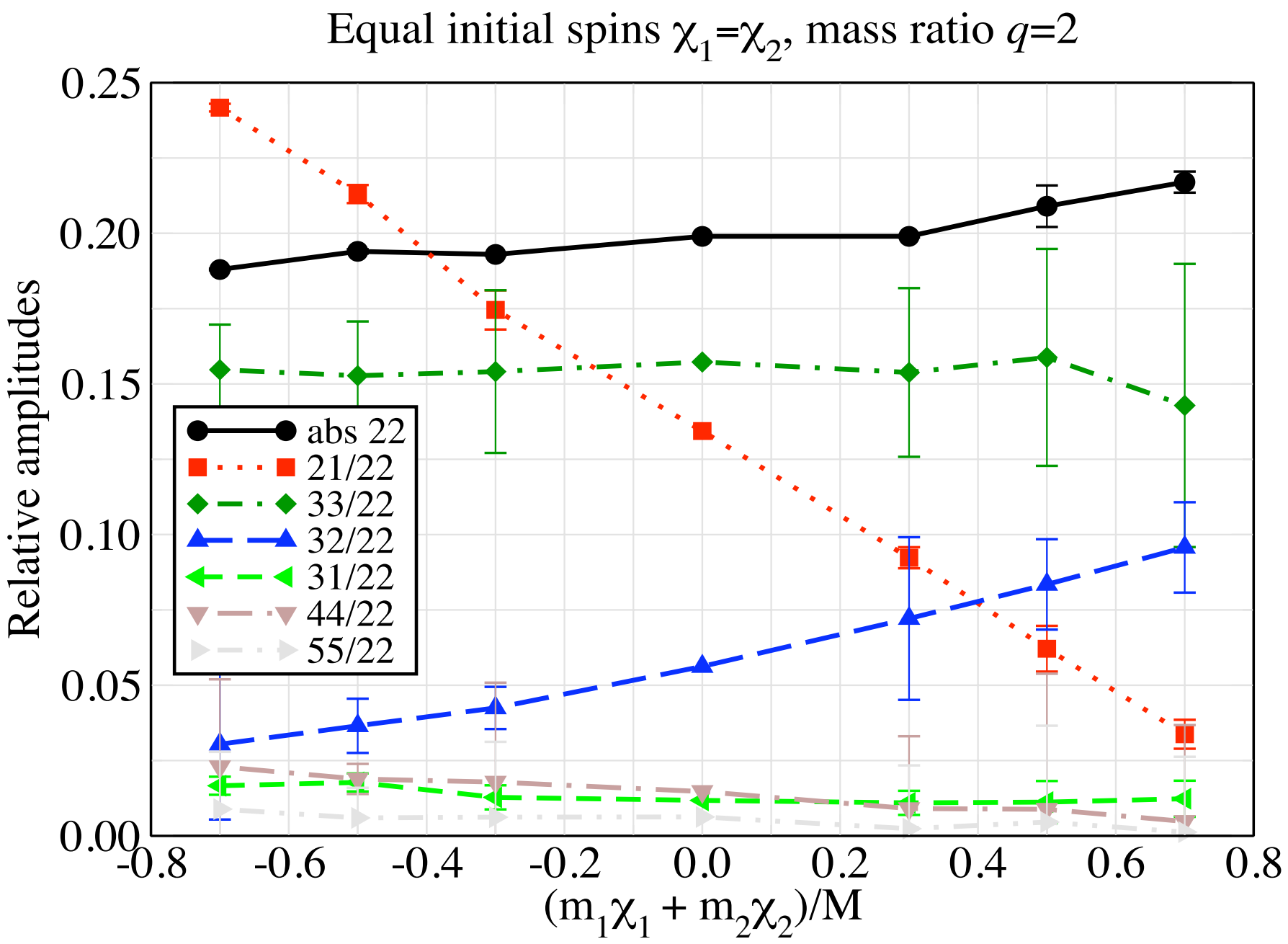
- q = 4, equal progenitor spins χ_i = -0.7,-0.5,-0.3, +0.3,+0.5,+0.7

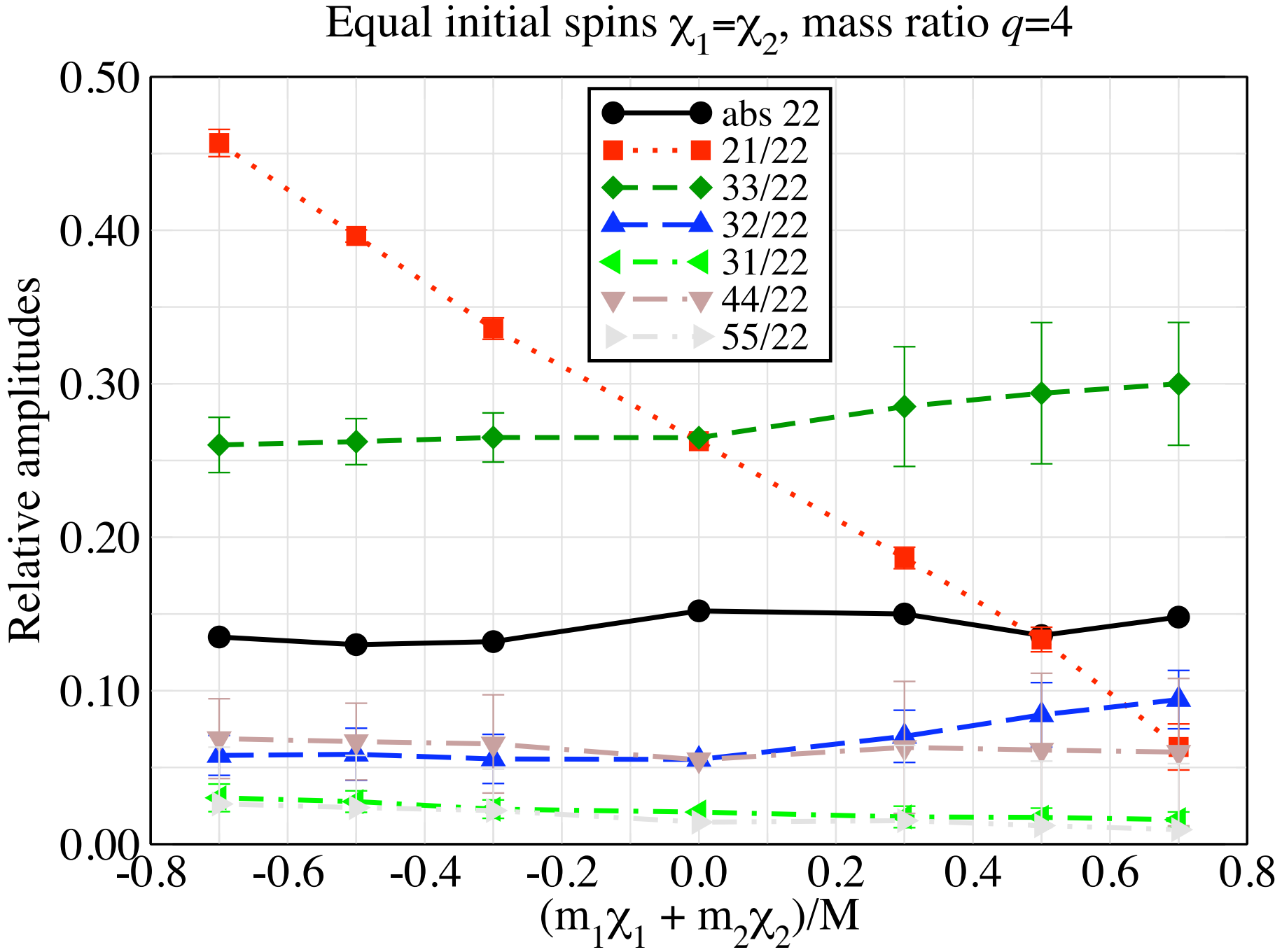
- 'extra' (bonus) simulations

- precessing simulations

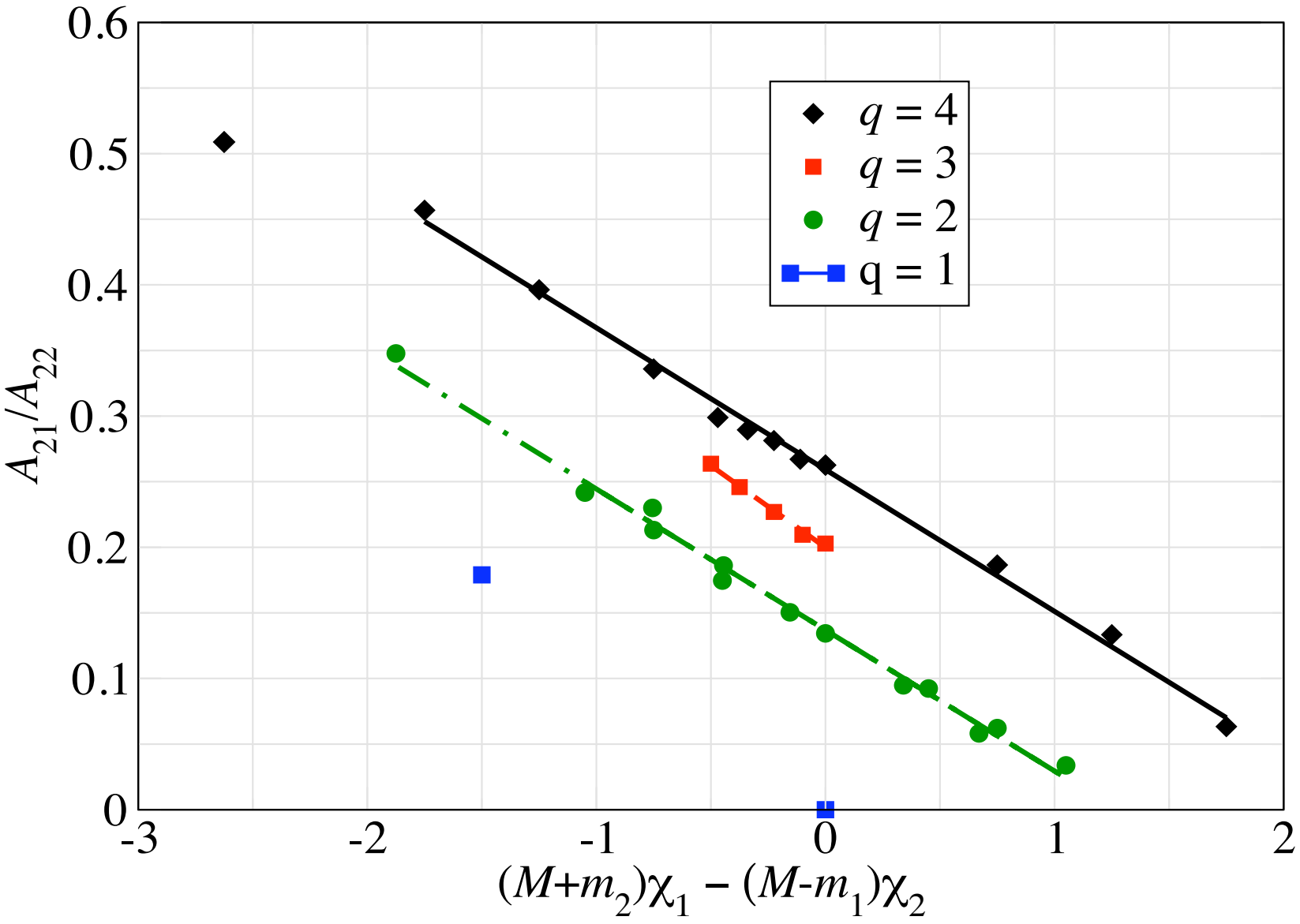

Initial spins such that χ ~ 0.62, mass ratio q=2
Relative amplitudes
0.25
0.20
0.15
0.10
0.05
0.00
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
(m1χ1 + m2χ2) / M
abs 22
21/22
33/22
32/22
31/22
44/22
55/22


modes' radiated energies for ν=0.222 when χ_{final}~0.62
radiated energy (arbitrary units)
0.1
0.01
1e-03
1e-04
1e-05
1e-06
-0.1
0
0.1
$(m_1\chi_1 + m_2\chi_2)/M$
22
33
21
44
55
32
31


Equal initial spins $\chi_1=\chi_2$, mass ratio q=2
Relative amplitudes
0.25
0.20
0.15
0.10
0.05
0.00
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
$(m_1\chi_1 + m_2\chi_2)/M$
abs 22
21/22
33/22
32/22
31/22
44/22
55/22


Equal initial spins $\chi_1=\chi_2$, mass ratio q=4
Relative amplitudes
0.50
0.40
0.30
0.20
0.10
0.00
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
$(m_1\chi_1 + m_2\chi_2)/M$
abs 22
21/22
33/22
32/22
31/22
44/22
55/22

21/22 for *all five simulation sets* plus *more points*



Parameter estimation on the progenitor binary

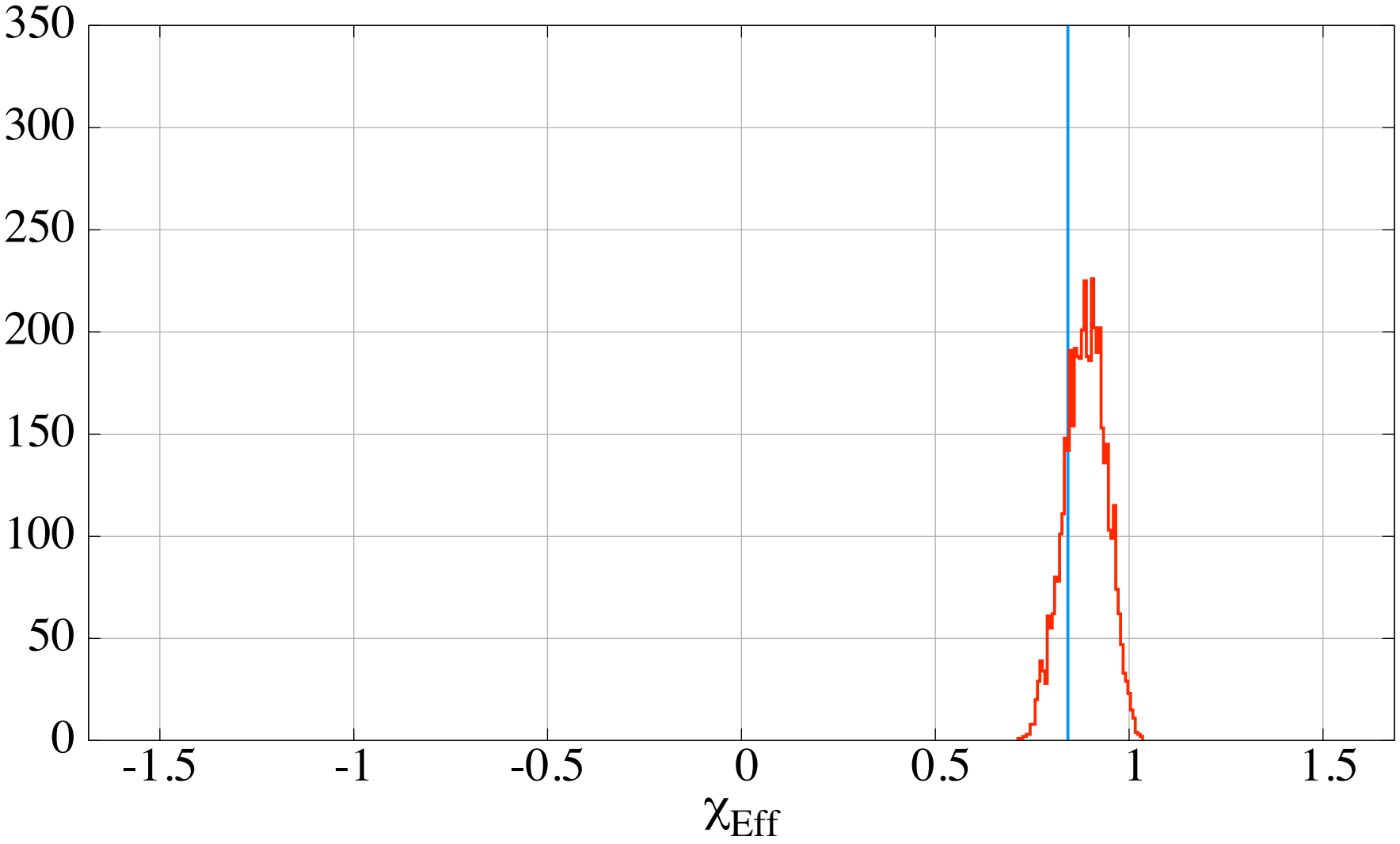
signal model:

- 22, 33 and 44 remain independent of spins and depend only on the mass ratio of the binary; thus we can use the known fitting functions for non-spinning binaries (our previous work)

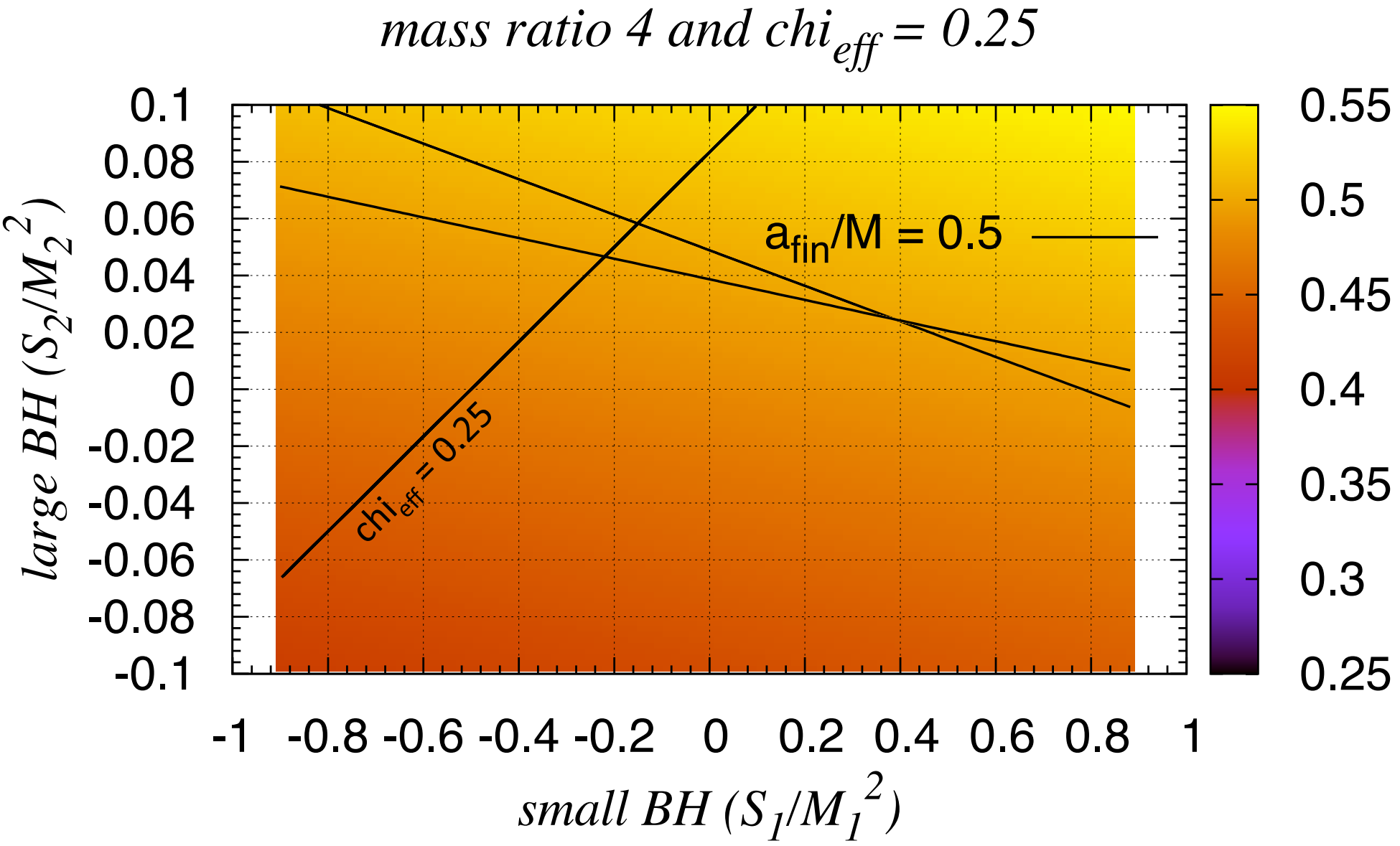
- 21 becomes a function of the mass ratio, as well as the chi_{eff} that fits all the data so far: $(M+m_2)\chi_1 - (M-m_1)\chi_2$

- frequencies and damping times of all modes depend on the final BH mass and spin according to formulas given by Berti, Cardoso, Will (2006)

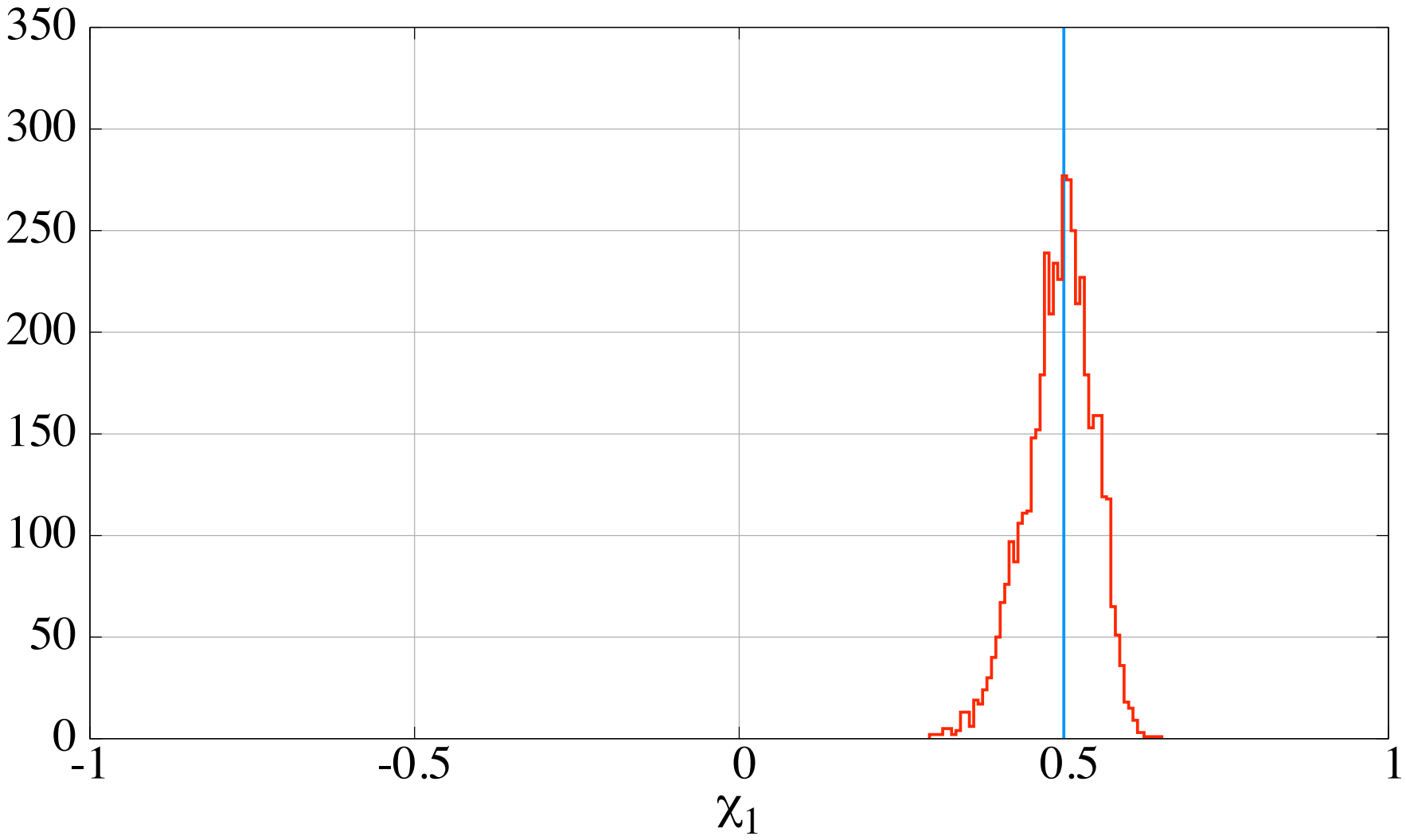
Parameter estimation on the progenitor binary



Determining individual progenitor spins from ringdown?



Parameter estimation on the progenitor binary



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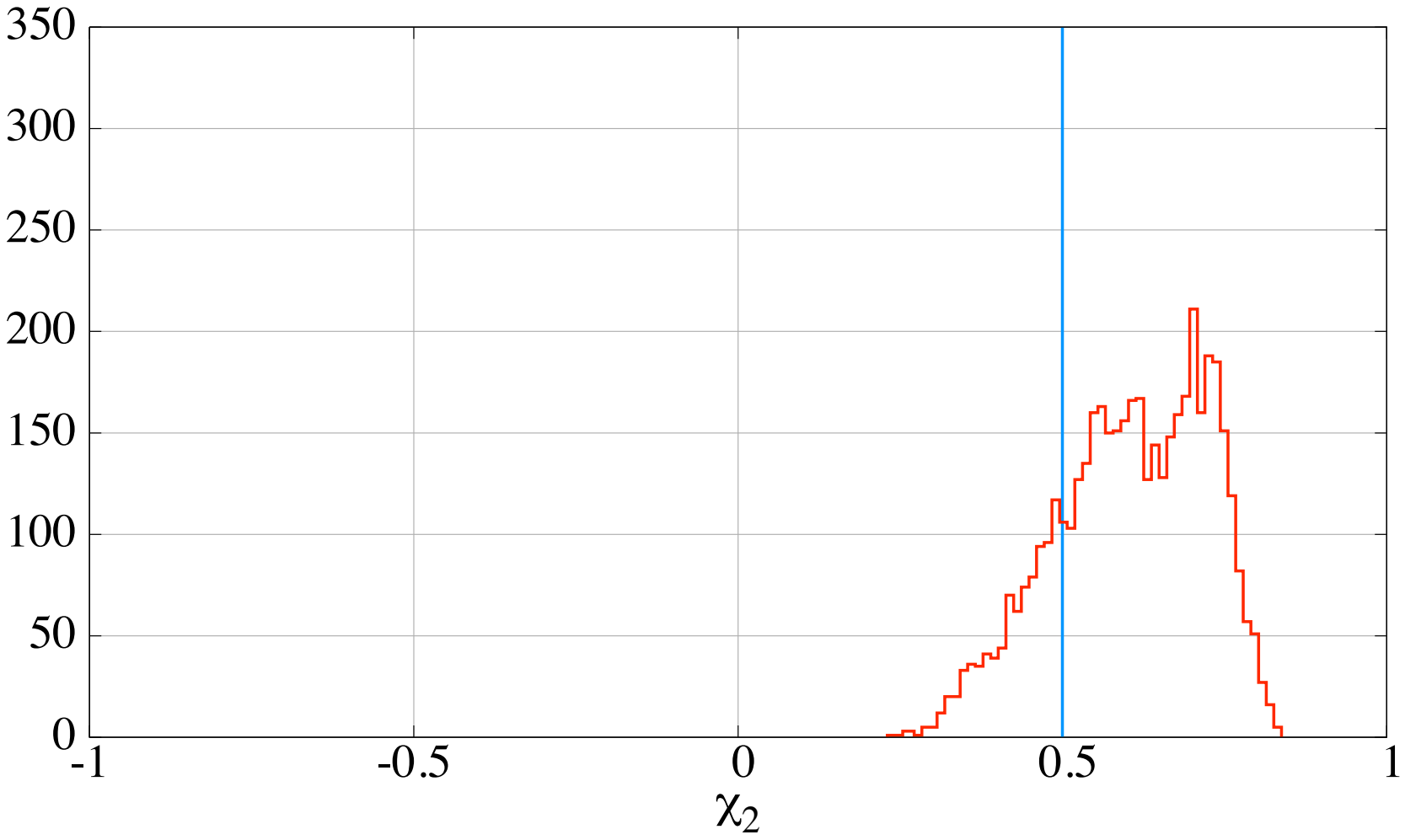

synopsis and future prospects

- the most dominant mode amplitudes: 22 and 33 vary with respect to the progenitor mass ratio, BUT are largely independent on the progenitor spins

- 21 carries the signature of the progenitor spins, with modes 32 and 31 also showing a small dependence

- 22, 33 and 21 behave such that we can still measure the progenitor mass ratio for binaries with aligned/anti-aligned spins, as well as perform PE on a combination of the progenitor spins or even the individual spins

- all these suggest the ringdown has a clear memory of its progenitor!

- take into account the phase evolution
- precessing simulations ... TOP SECRET
- interpret the observed effects!