Impact of higher order modes in aligned spin searches for Binary Black Holes

PHYSICAL REVIEW D **93,** 084019 (2016)

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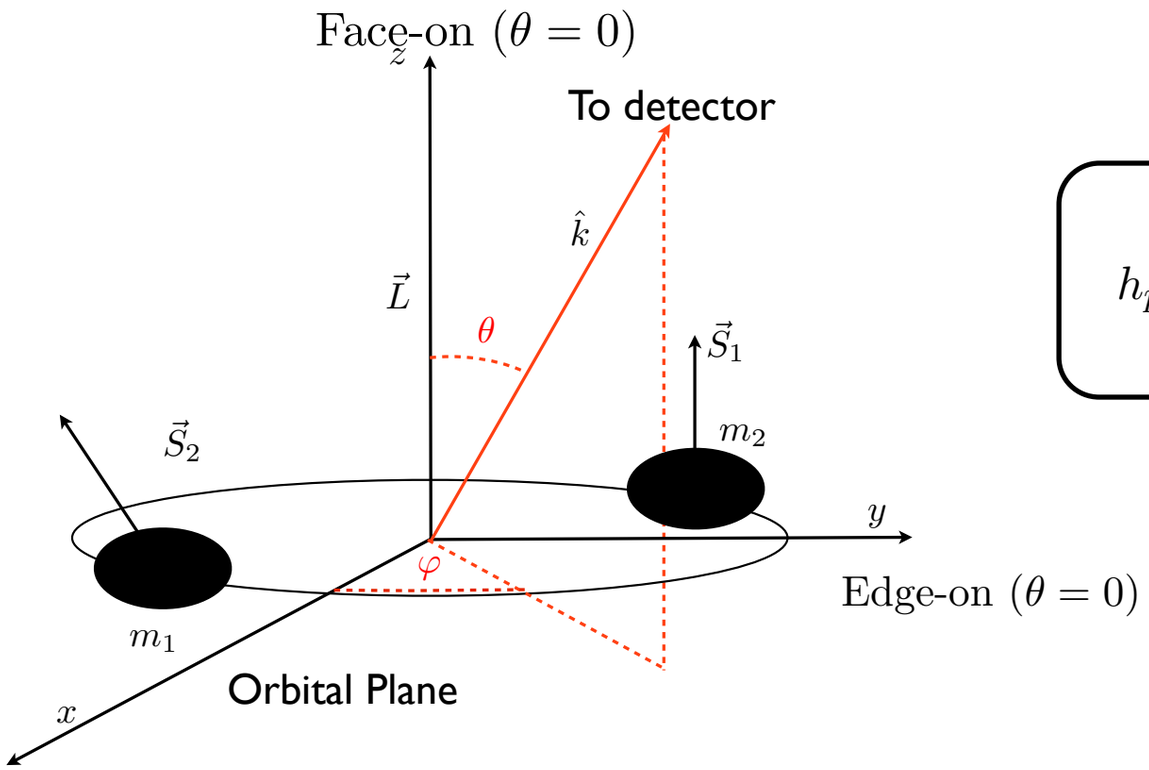
GR21 Conference, Columbia University, NewYork, July 2016

Higher modes of BBH radiation

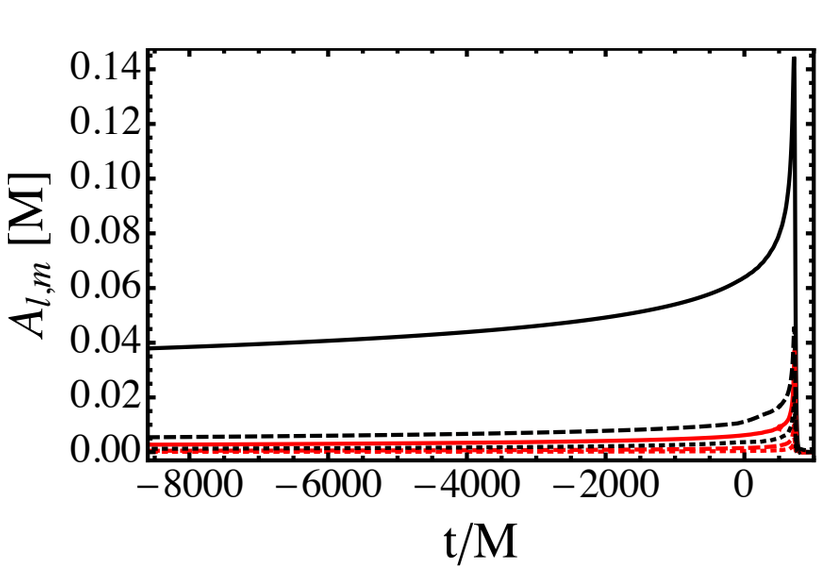


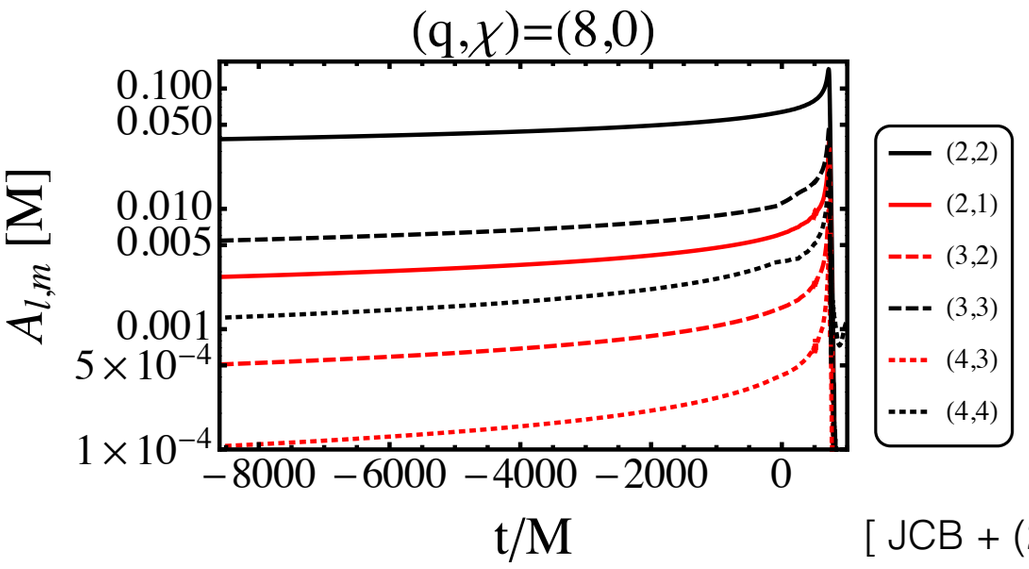
Modes: source info.

$$h_p(\Xi; r, \theta, \varphi; t) = h_+ - i h_\times = \frac{1}{d_L} \sum_{\ell \geq 2} \sum_{m=-\ell}^{m=\ell} Y^{-2}_{\ell,m}(\theta, \varphi)\, h_{\ell,m}(\Xi; t)$$

Harmonics: orientation info.

Searches do only include the (l,|m|)=(2,2) modes

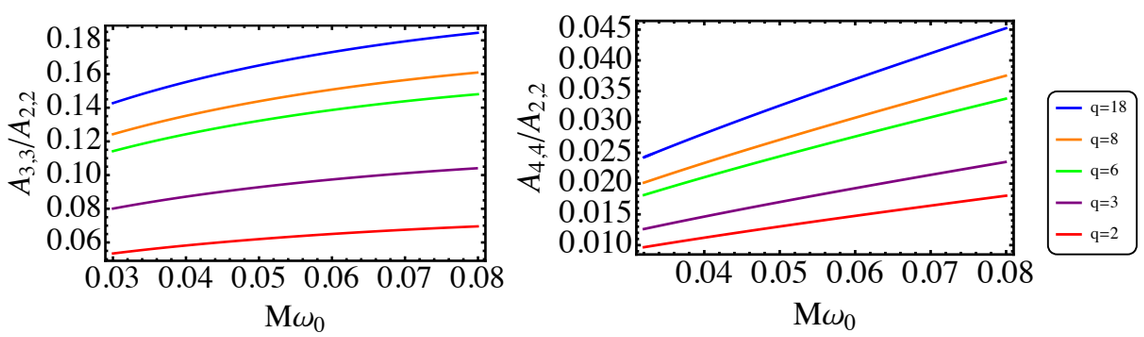


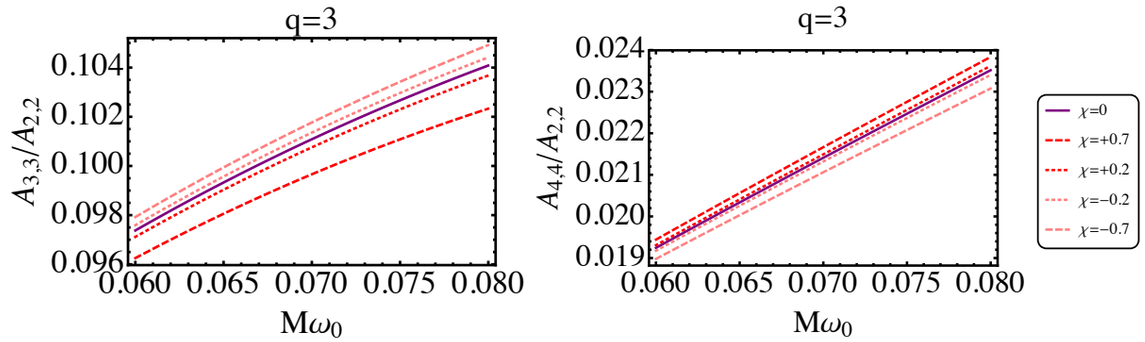


[JCB + (2016)]

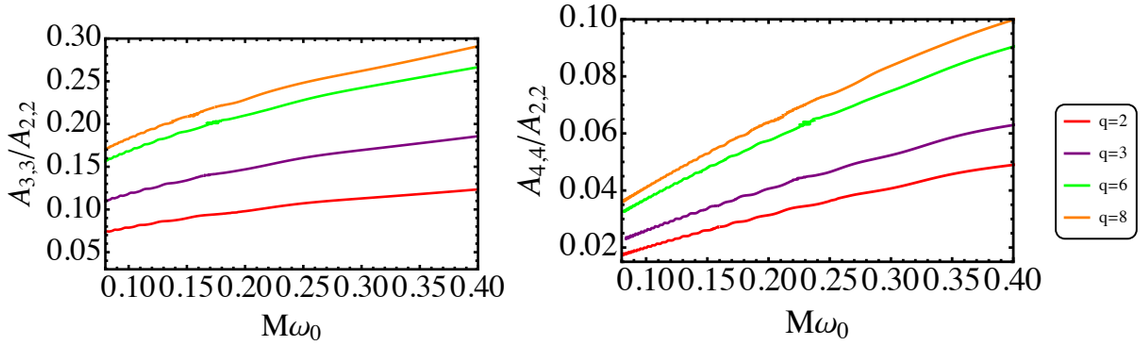
Higher Modes are strong for…..

PN





NR (SXS)



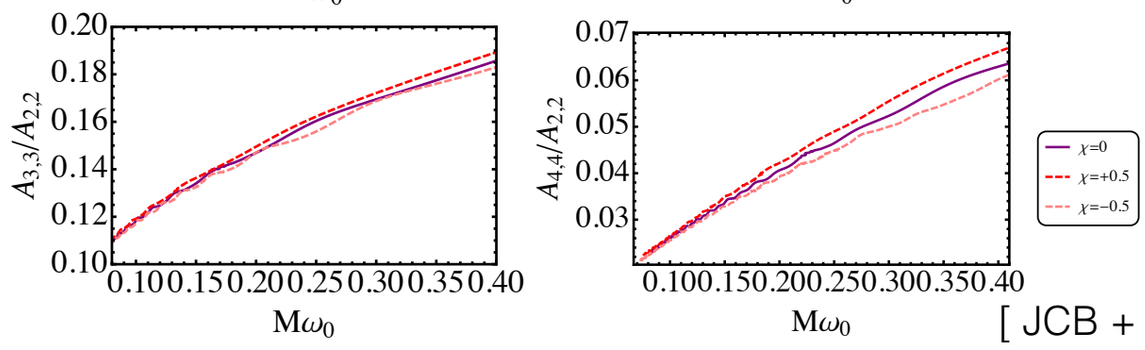


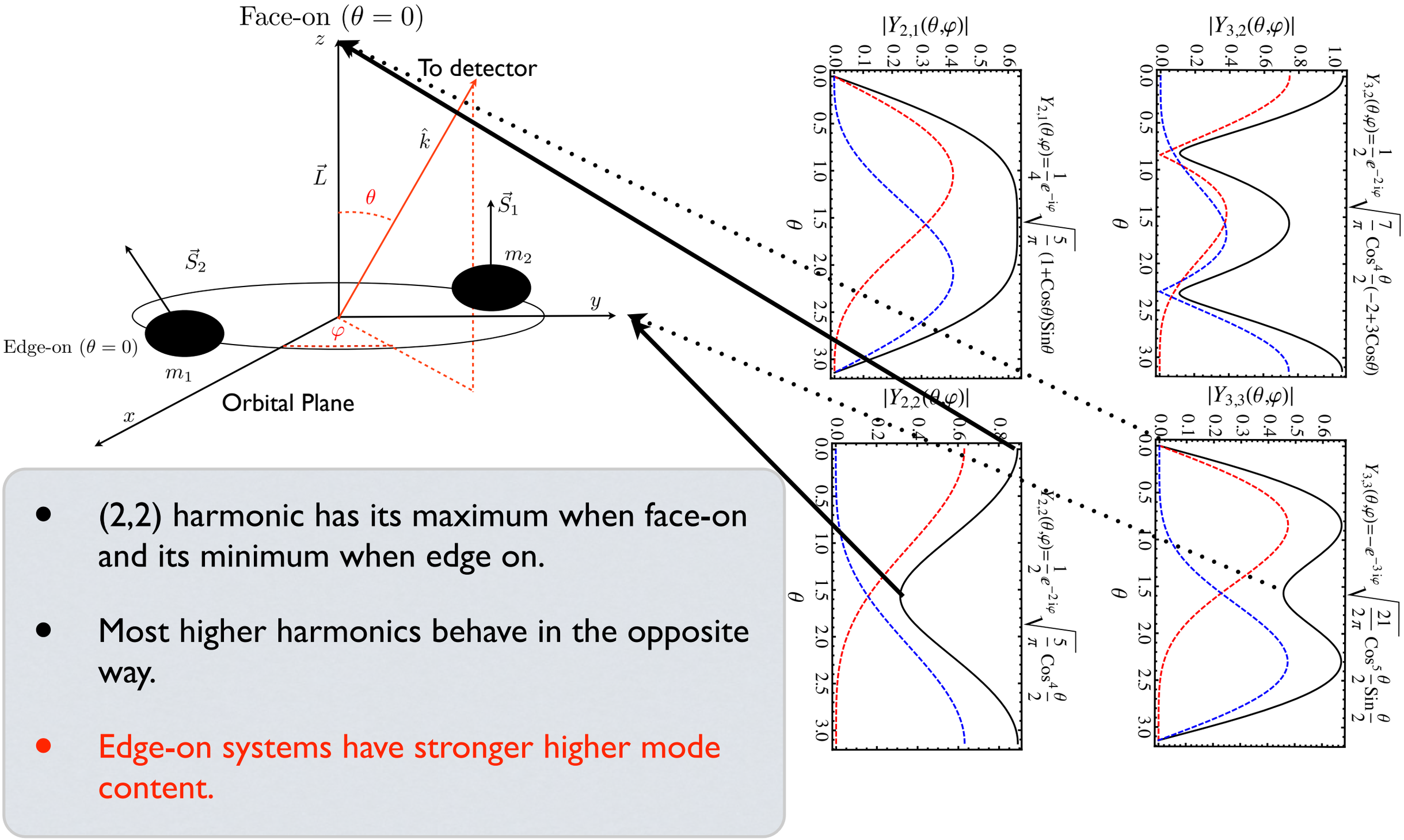
FIGURE 2.5: Relative T1 (Top) and NR (Bottom) amplitude of the higher modes $(3,3)$ and $(4,4)$ relative to the dominant $(2,2)$ mode as a function of the frequency for several non-spinning systems. Note how the higher the mass ratio q, the larger the contribution from higher order modes.

FIGURE 2.6: Relative T1(Top) and NR (Bottom) amplitude of several higher modes relative to the dominant $(2,2)$ mode as a function of the frequency for several $q = 3$ spinning systems. Note that the influence of the spin is much lower than that due to the mass ratio.

[JCB + (2016)]

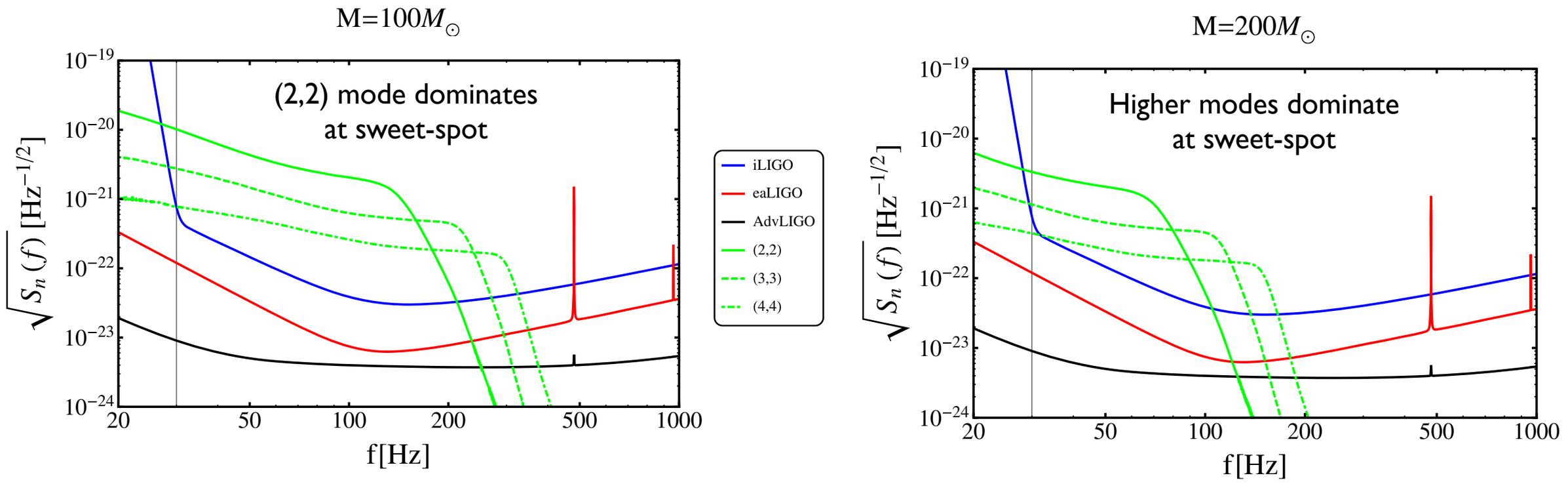
- Large mass ratio (q) BBH show stronger higher modes.
- Spin has a secondary effect.

Harmonics Impact (Orientation)



- (2,2) harmonic has its maximum when face-on and its minimum when edge on.
- Most higher harmonics behave in the opposite way.
- Edge-on systems have stronger higher mode content.

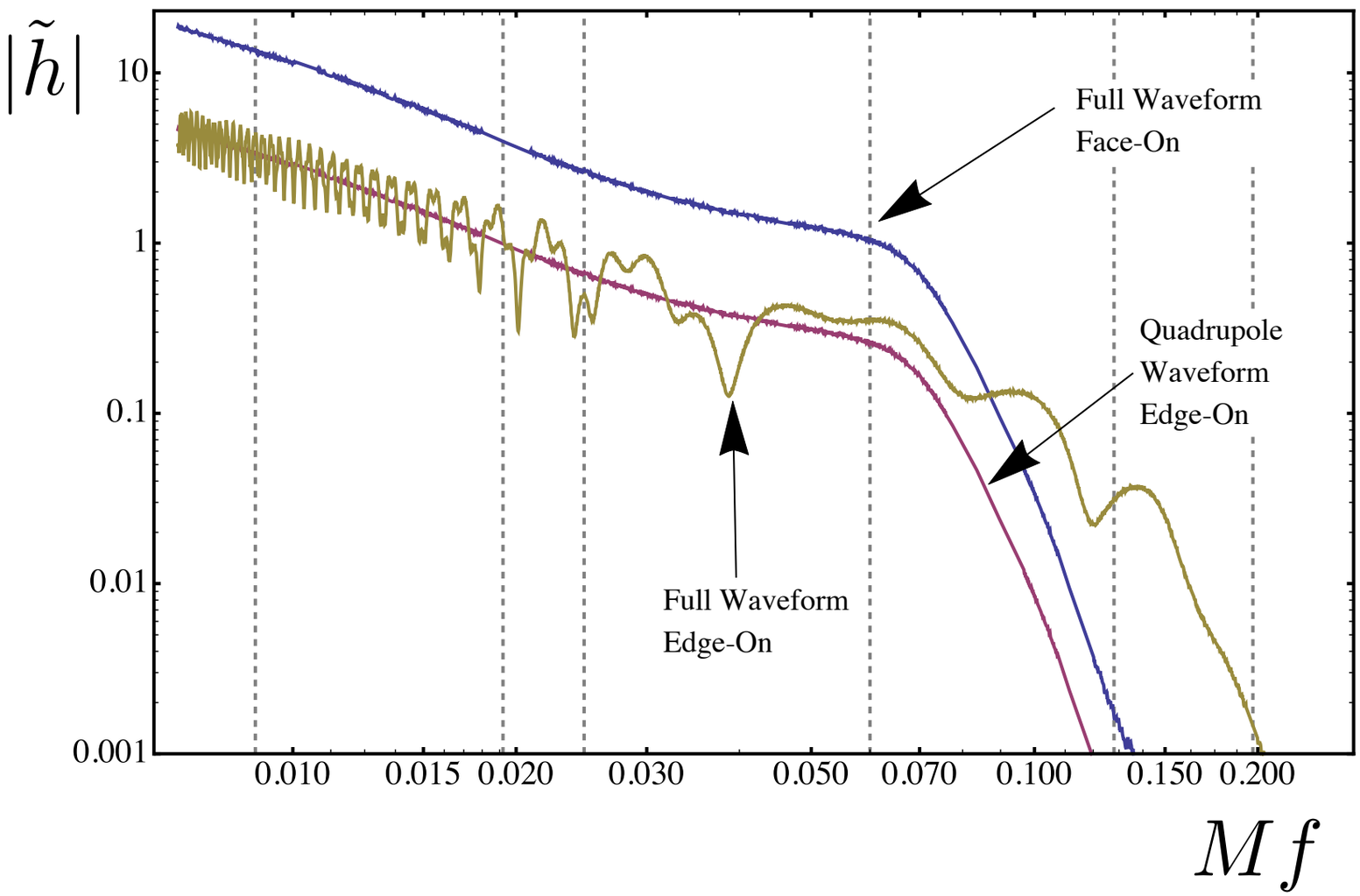
Total mass (M) and detector noise curve



[JCB + (2016)]

Higher modes important for high mass sources
(+ high mass ratio, + edge-on)

Getting some intuition



Waveforms: Hybrid NR (SXS collaboration) + post Newtonian Taylor T1

Hybridisation procedure: [JCB + (2015), arXiv:1501.00918]

Data analysis tools

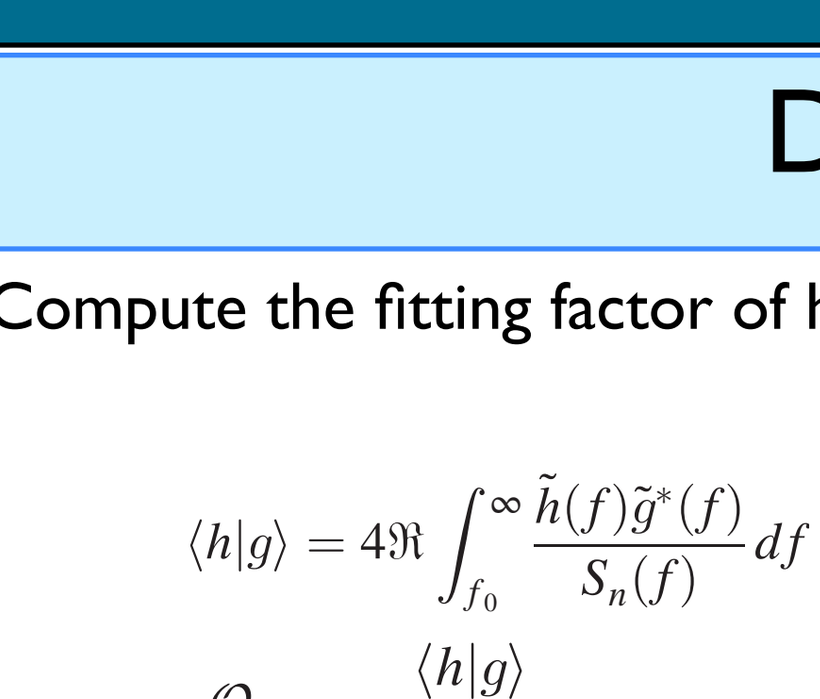
Compute the fitting factor of hybrid PN+NR waveforms towards SEOBNRv1_ROM (only 2,2 mode)

$$\langle h|g\rangle = 4\Re \int_{f_0}^{\infty} \frac{\tilde{h}(f)\tilde{g}^*(f)}{S_n(f)} df$$

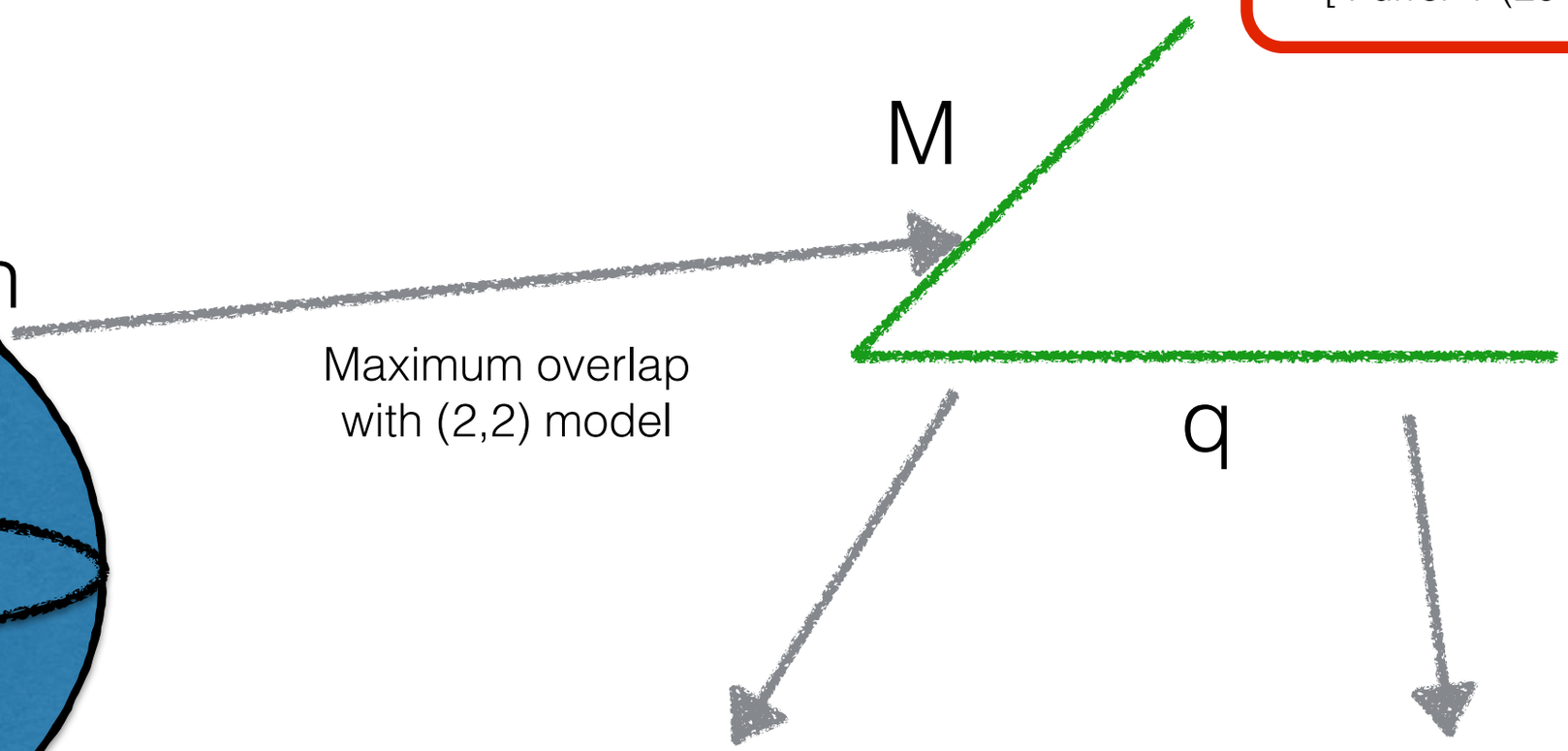
$$\mathcal{O} = \frac{\langle h|g\rangle}{\sqrt{\langle h|h\rangle\langle g|g\rangle}}$$

(2,2)-model: SEOBNRv1_ROM

[Pürrer + (2014)]



Average results weighting by optimal SNR



% Event loss

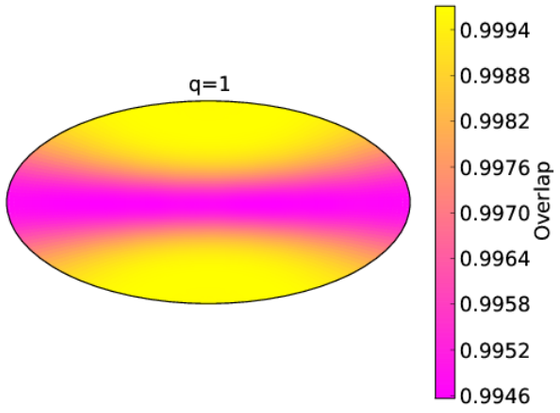
$$R_i = \sum_j \left(\frac{\rho_{i,j}\mathcal{F}_{i,j}}{\rho_{i,j}}\right)^3$$

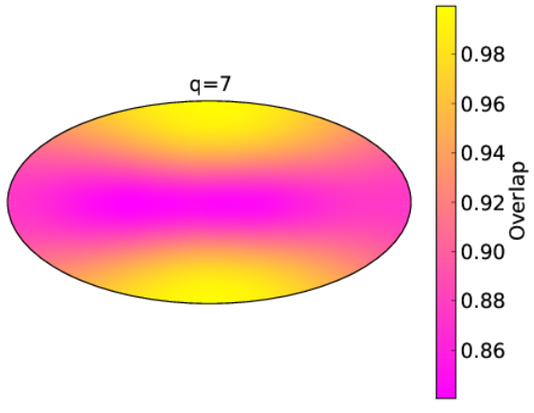
Parameter bias

$$\Xi_i^{\mathcal{B}} = \sum_j \Xi_{i,j}^{\mathcal{B}} \left(\frac{\rho_{i,j}\mathcal{F}_{i,j}}{\rho_{i,j}}\right)^3$$

$$\Delta\Xi_i = \Xi_{i,0} - \Xi_i^{\mathcal{B}}$$

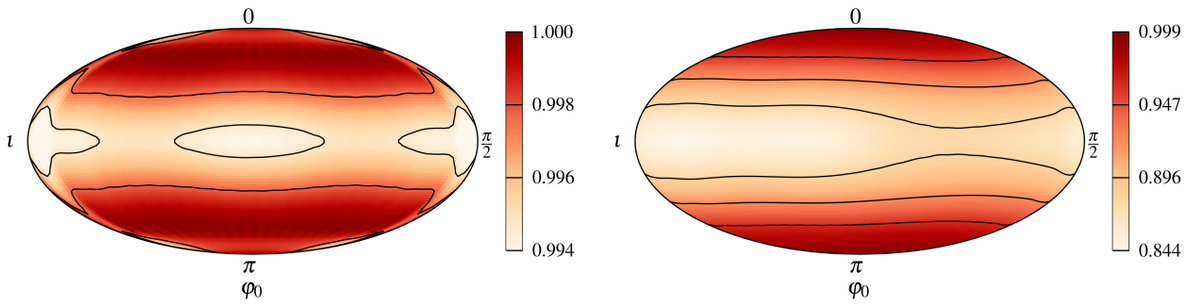
Previous studies I



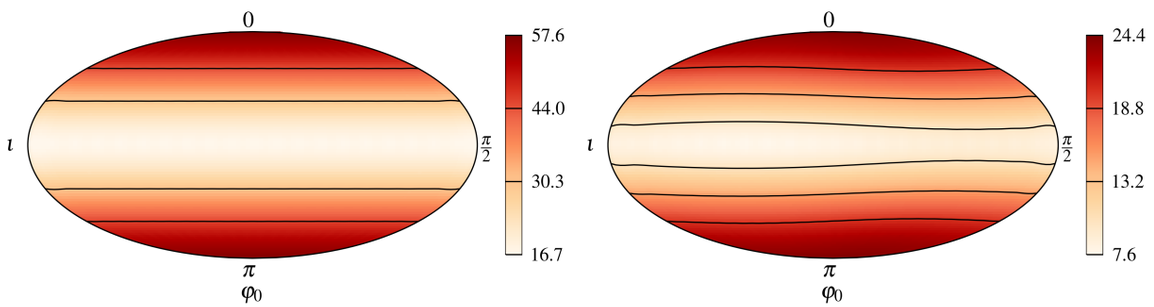


-Low match for edge-on orientations.
-These produce however the lowest SNR (for suitable low masses)

[L. Pekowsky + (2012)]

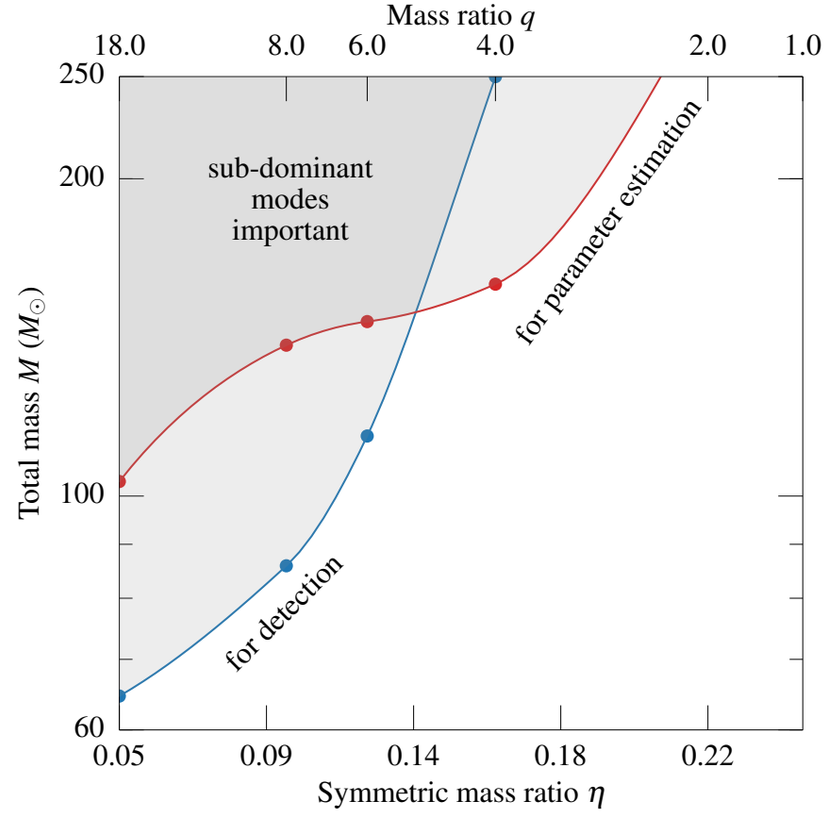


(a) $q = 1$, $M = 100M_\odot$ (b) $q = 8$, $M = 100M_\odot$

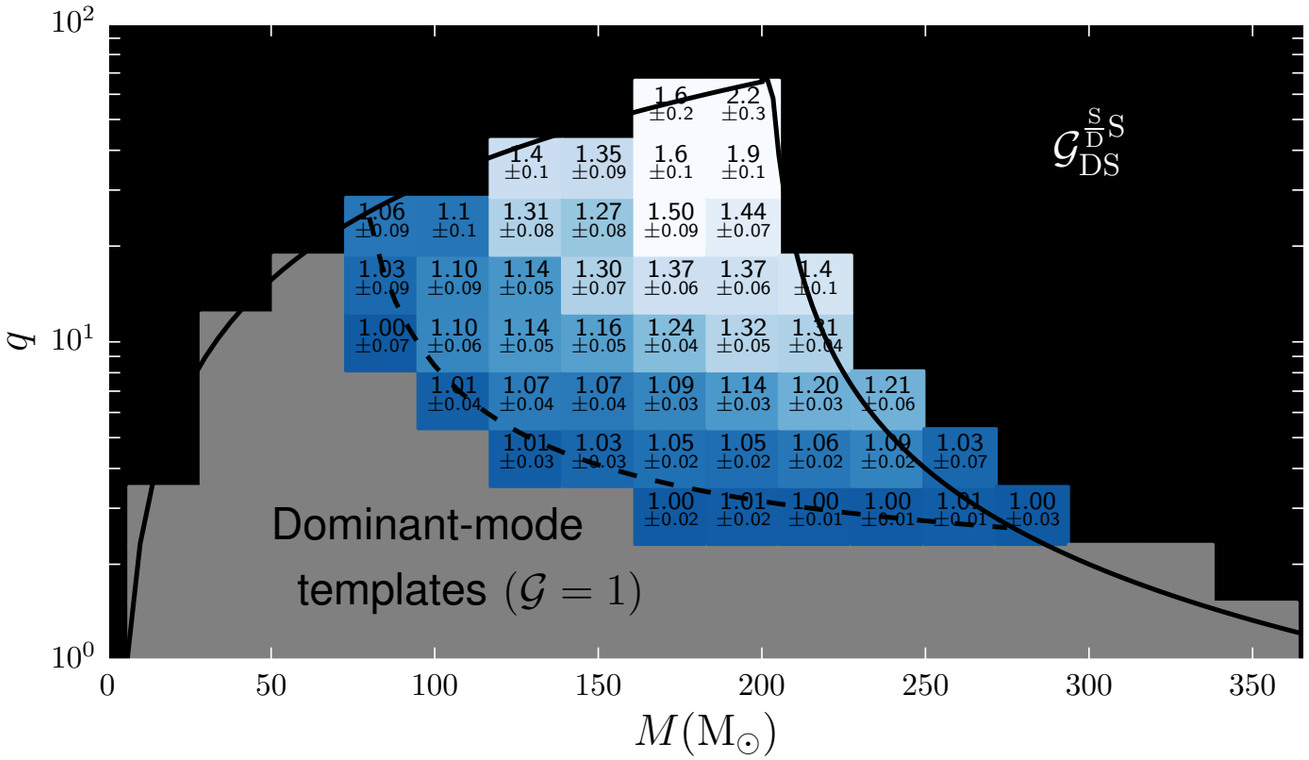


(a) $q = 1$, $M = 100M_\odot$ (b) $q = 8$, $M = 100M_\odot$

[Varma + (2014)]



Previous studies II



Reduction of sensitivity due to the larger number of templates.

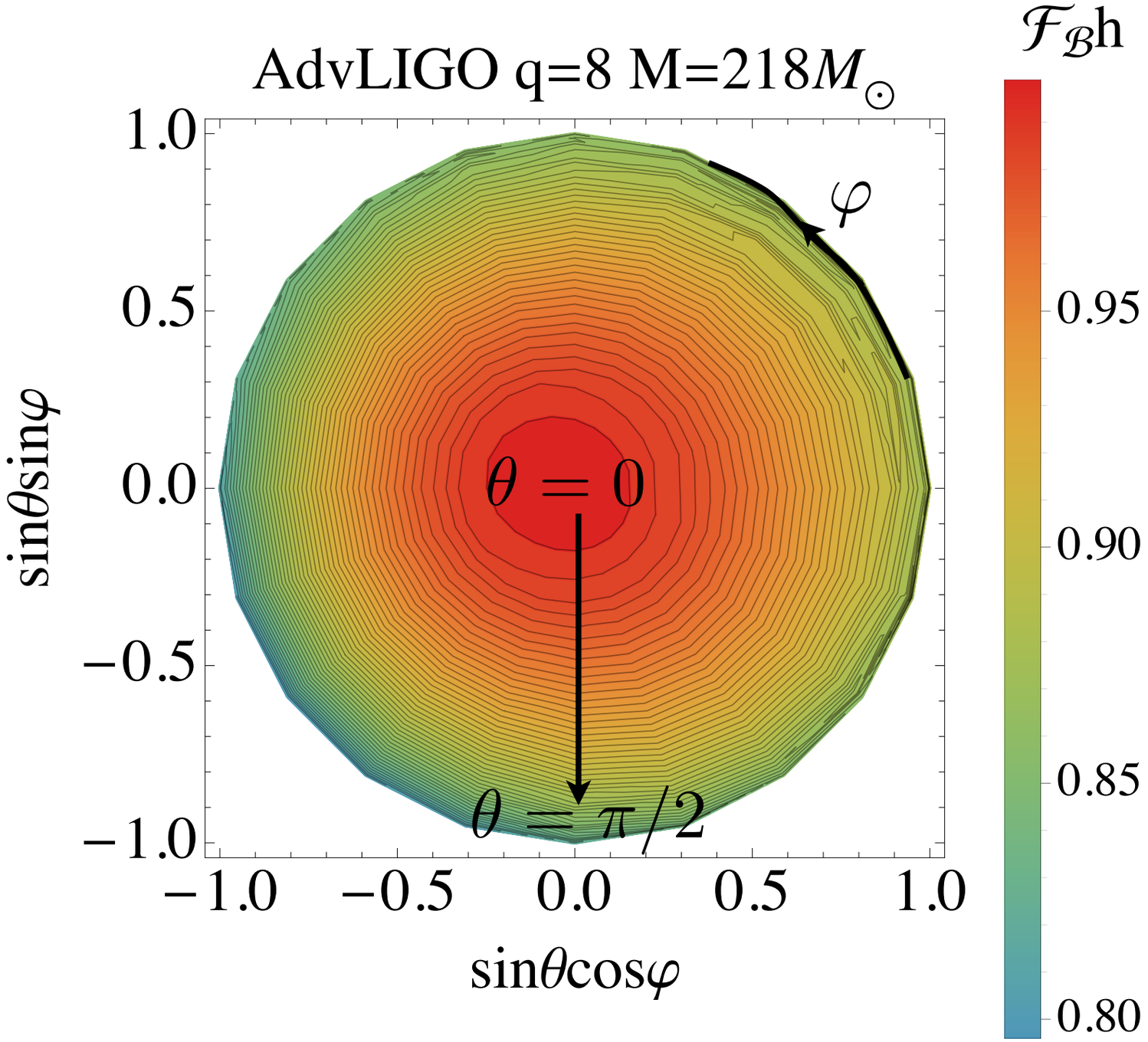
Worth to include higher modes for certain part of the parameter space.

[Capano + (2013)]

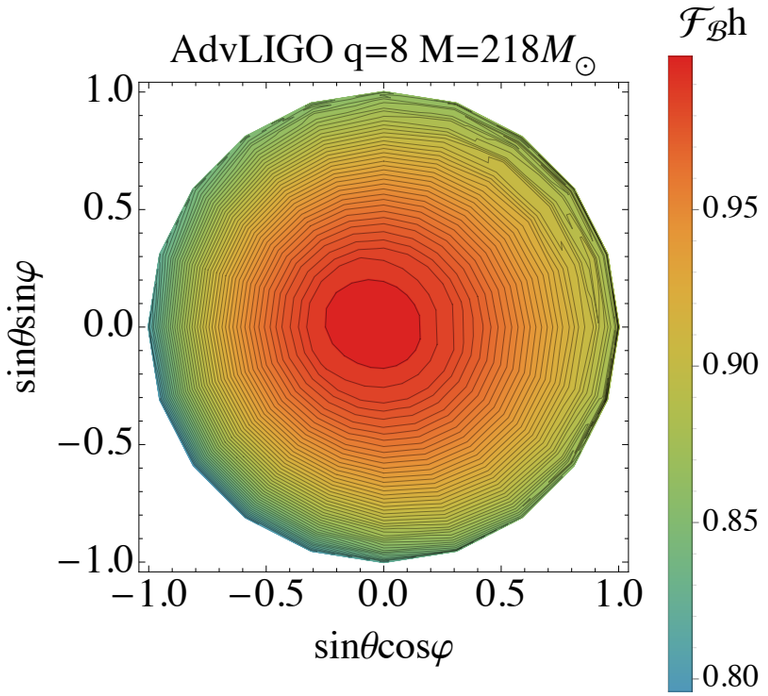
- All considered the design Advanced LIGO curve (f0=10Hz).
- Restricted to non-spinning targets and template banks
- We extend to aligned-spin searches and early Advanced LIGO (f0=30Hz).

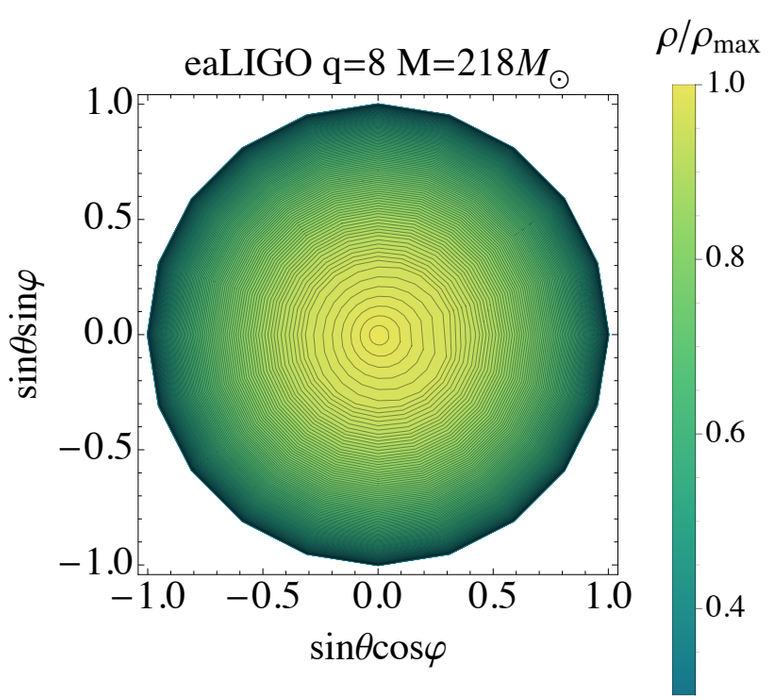
Warning: how to read sky-plots

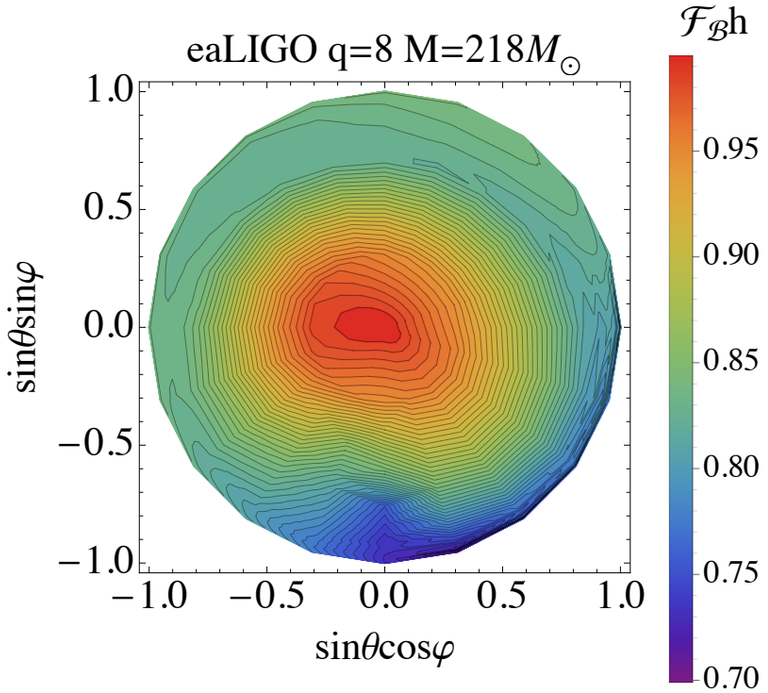
- Sky around source projected onto the (x,y) orbital plane.
- Center corresponds to face-on.
- Perimeter corresponds to edge-on.
- The color code indicates the value of the measured magnitude.

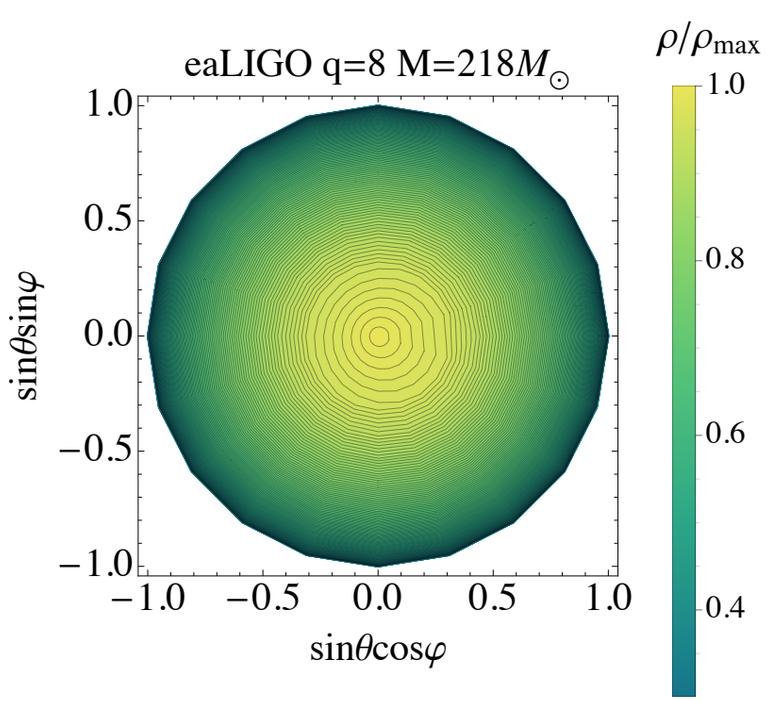


Results: fitting factors vs. SNR



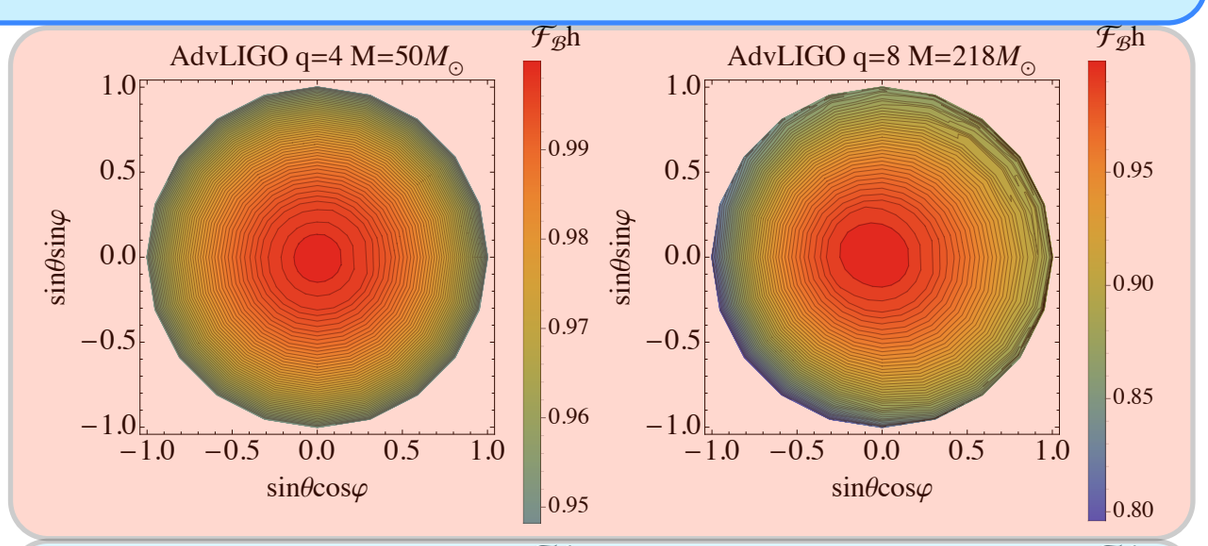






Results: fitting factors

- Fitting factors are lower the larger q and M are.
- Lower for edge-on cases.
- Lowest for iLIGO (f=30Hz & non-spinning templates.)
- Larger for eaLIGO (spinning templates)
- Largest for aLIGO (f=10Hz.)



Results: averaged event loss

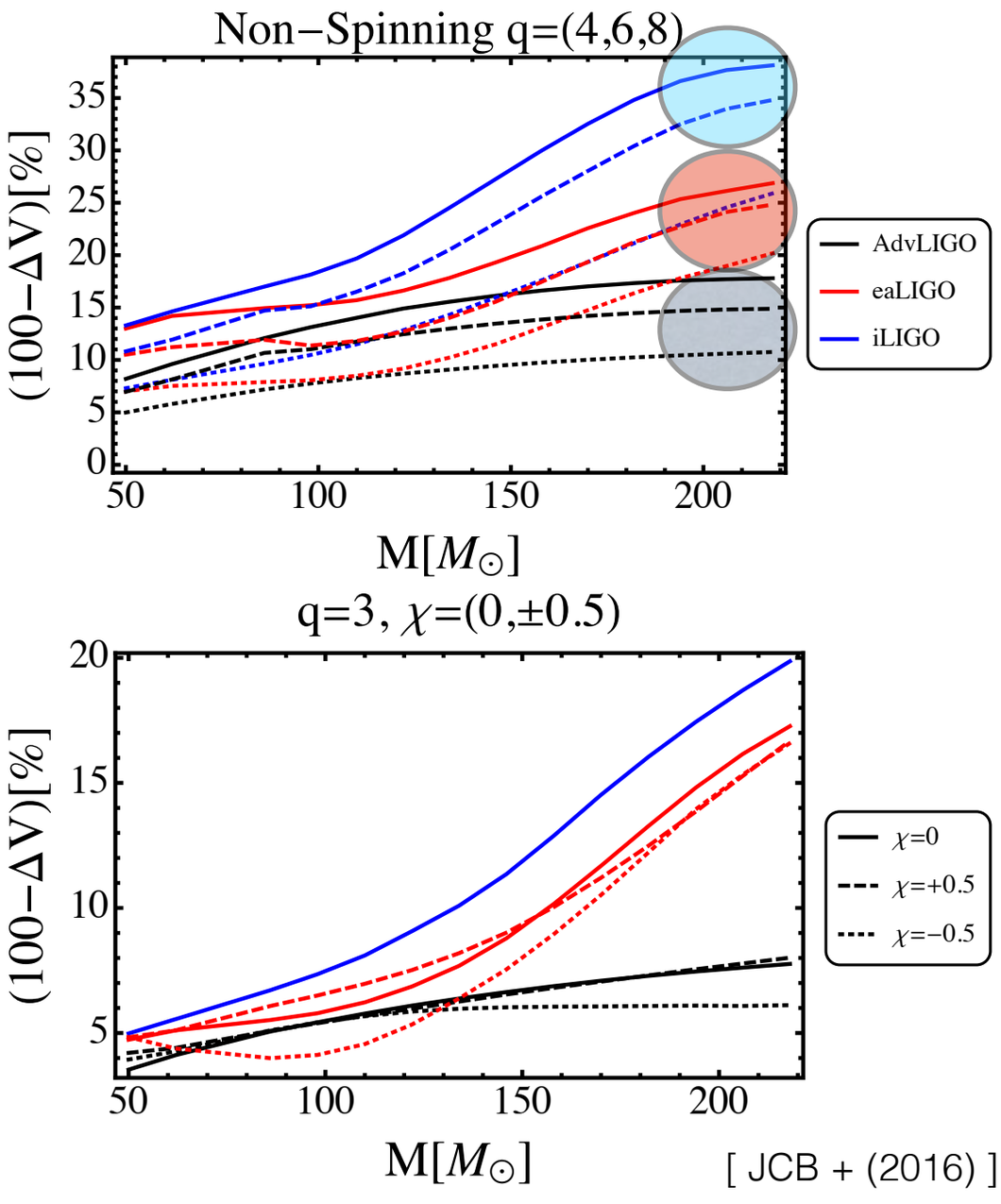
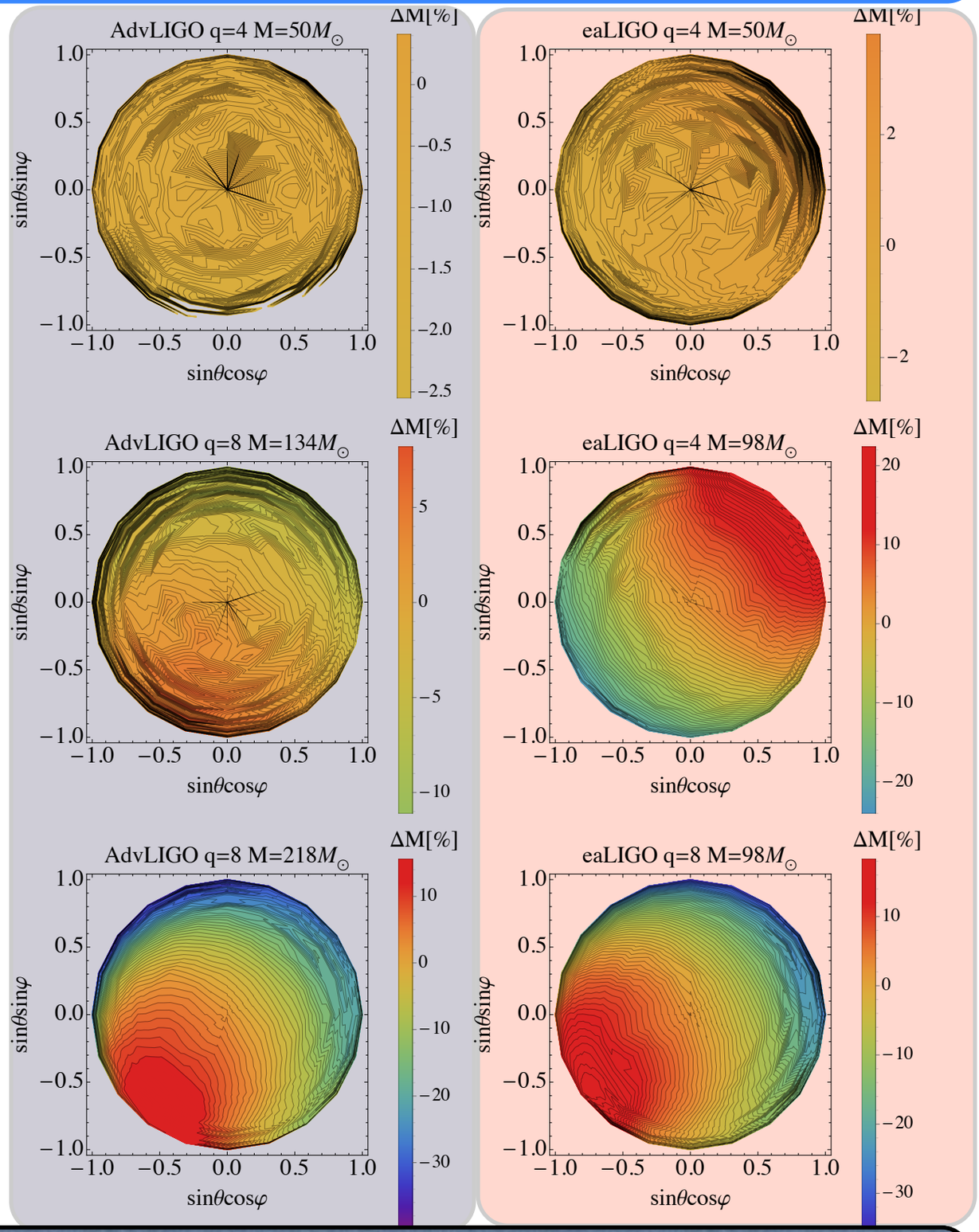


FIGURE 6.6: Top: Fractional volume loss in % for non-spinning $q = (4, 6, 8)$ systems in (dotted, dashed, solid). Bottom: same for $(q, \chi) = (3; 0, \pm 0.5)$ with the style code indicated in the corresponding caption. Note that since we used a non-spinning template bank for iLIGO, we did not consider spinning targets.

- 10% loss for q>4 (M>100 solar masses.) for AdvLIGO (note: M=100 solar masses for non-spinning bank).
- 10% loss for q>4 (M>100 solar masses.) and q>6 for all mass range for eaLIGO.
- Losses up to 25% for eaLIGO
- Very similar losses for spinning and non-spinning targets (spin is subdominant).

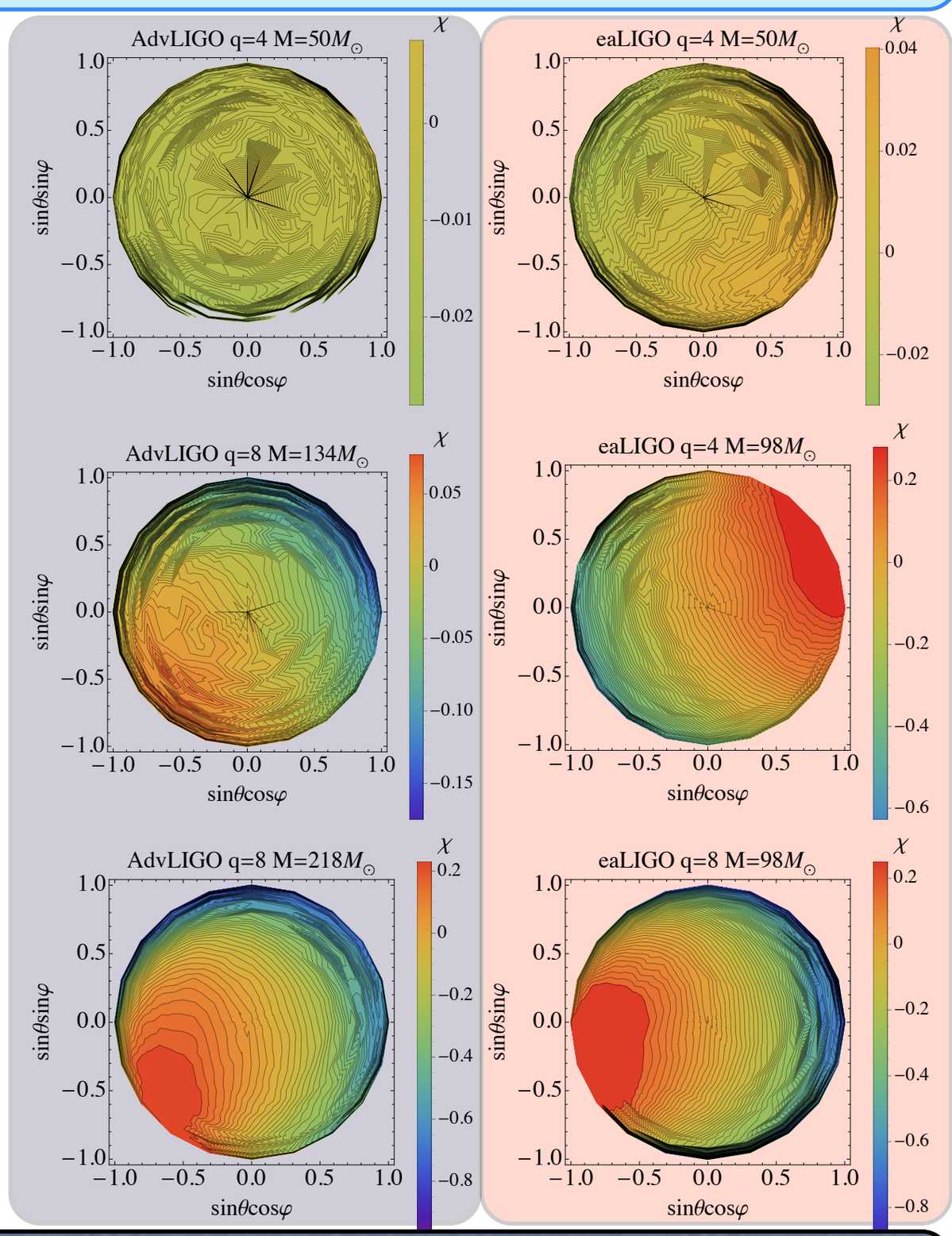
Results: Parameter Bias (total mass)

- Biases larger for edge-on systems and eaLIGO.
- Larger the larger q and M.
- Largest biases are towards lower total masses, as this increments the frequency of the bank waveform.
- When the mass is over-estimated, the mass ratio is underestimated and viceversa.



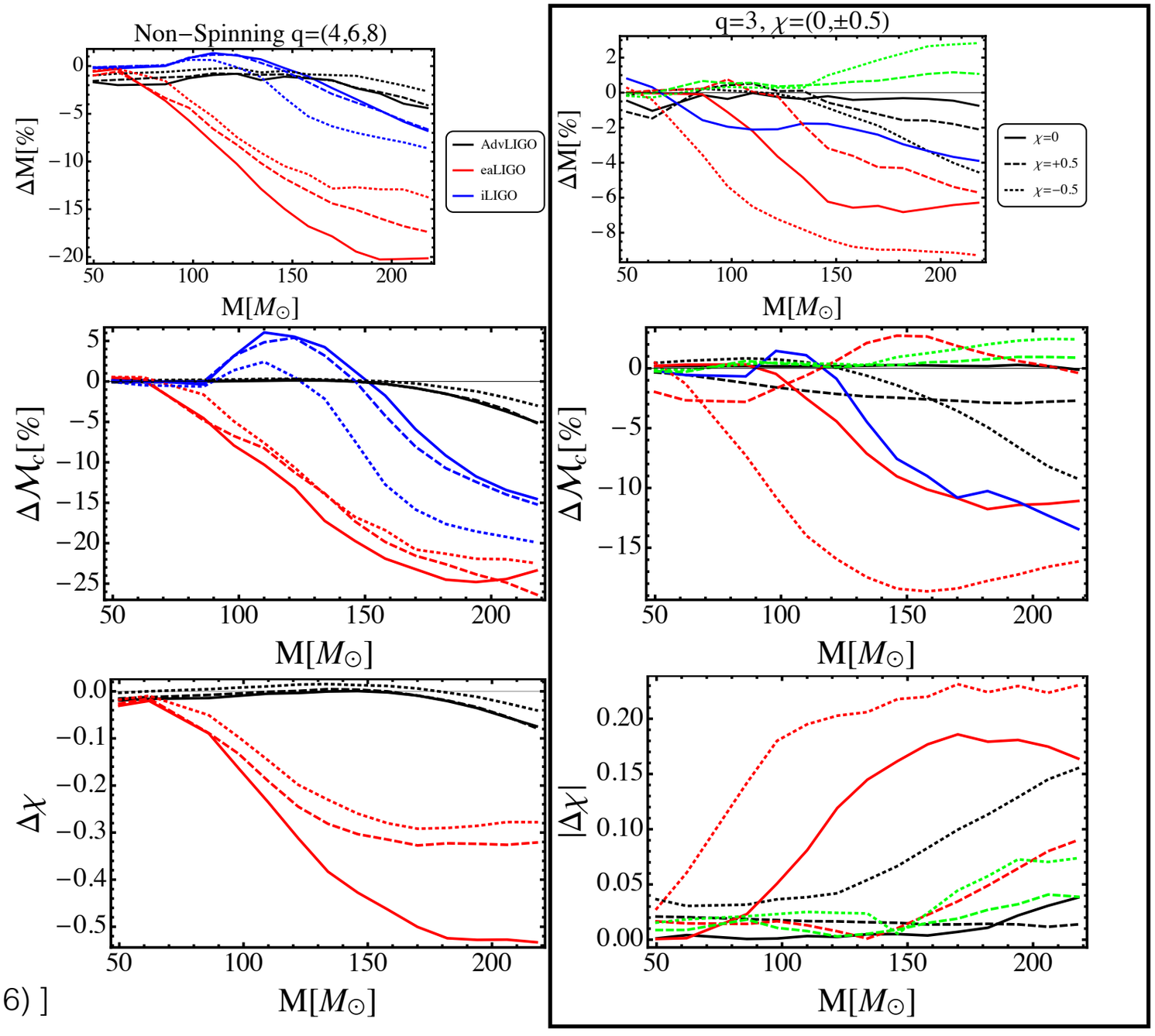
Results: Parameter Bias (spin)

- Biases larger for edge-on systems and eaLIGO.
- Larger the larger q and M.
- Largest biases are towards lower spins.
- Biases can get to -1 for non-spinning edge-on systems.



Results: averaged parameter bias

- Biases are larger the larger q and M are.
- Larger for eaLIGO (f=30Hz).
- Large spin biases for eaLIGO.
- Larger biases for negative spin systems.



[JCB + (2016)]

FIGURE 6.9: Top: M, $\mathcal{M}_c$, and χ systematic bias for the $q = (3, 4, 6, 8)$ (from solid to dot-dashed) nS cases. We use the same color-detector code as in Fig.2. Bottom: Same for the $(q; \chi) = (3; 0, \pm 0.5)$. We use dashed (dotted) for - (+) spin and add $(q, \chi) = (1, -0.2)$ case in solid green for eaLIGO.

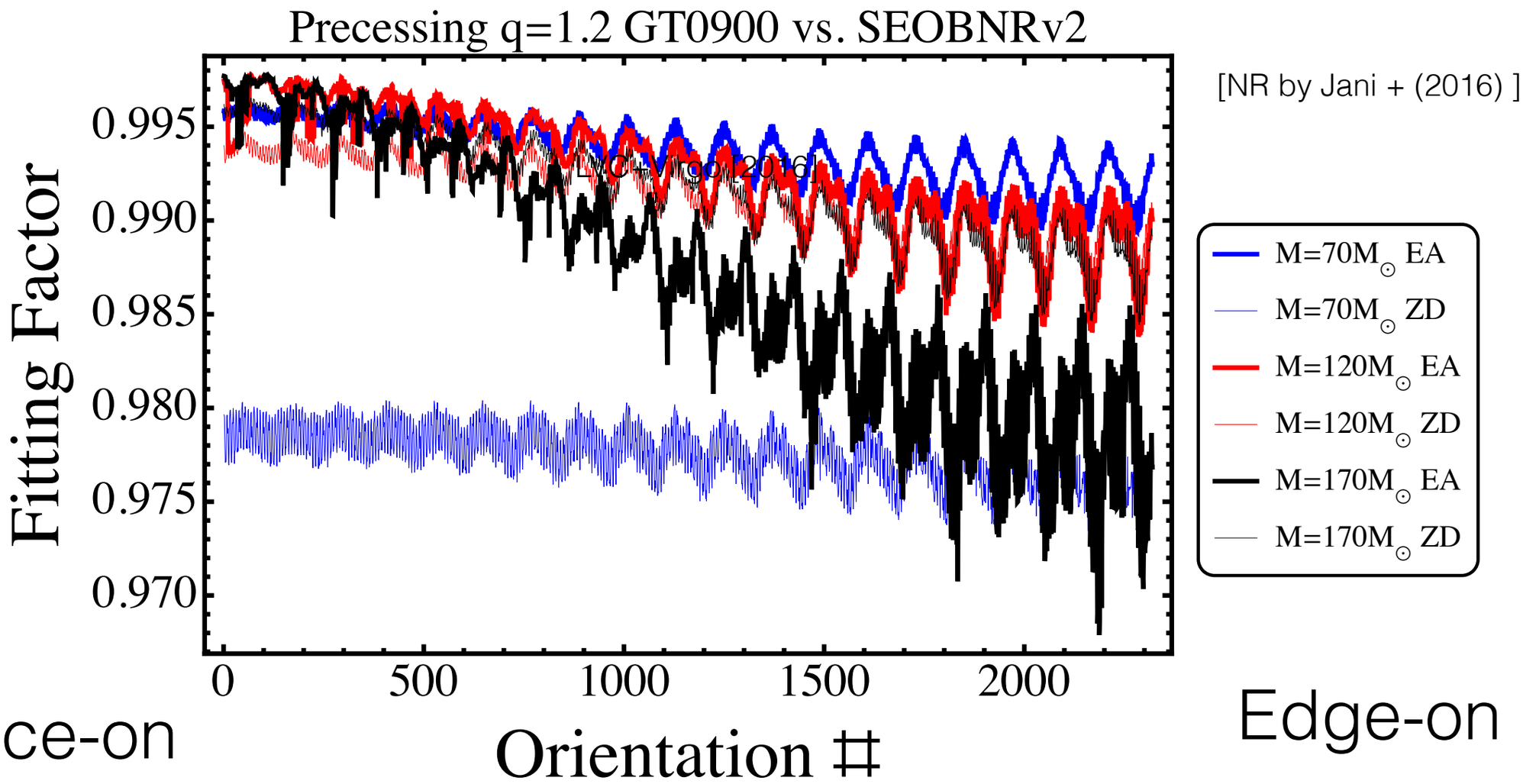
Conclusions & further work

- Higher modes have a large impact in systems with large mass ratio and total mass, specially if edge-on.
- Including a spin parameter in the template bank, reduces losses for the case of non-spinning targets (before applying signal based vetoes) at the cost of large spin bias.
- Losses of events (up to 26%) are larger for the case of early Advanced LIGO.
- Including higher modes is (in principle) worth for a larger portion of the parameter space for early advanced LIGO.

- Include precessing sources (in prep. with D. Shoemaker, P. Laguna K. Jani)
- Impact for chi-squared in gravitational wave search pipelines (in prep. with K.Jani)
- Build template bank including higher modes and run a search (addressing it…)

Precessing Targets I

- Precession dominates for low mass systems, and Design Advanced LIGO.
- Higher modes dominate for large total mass.

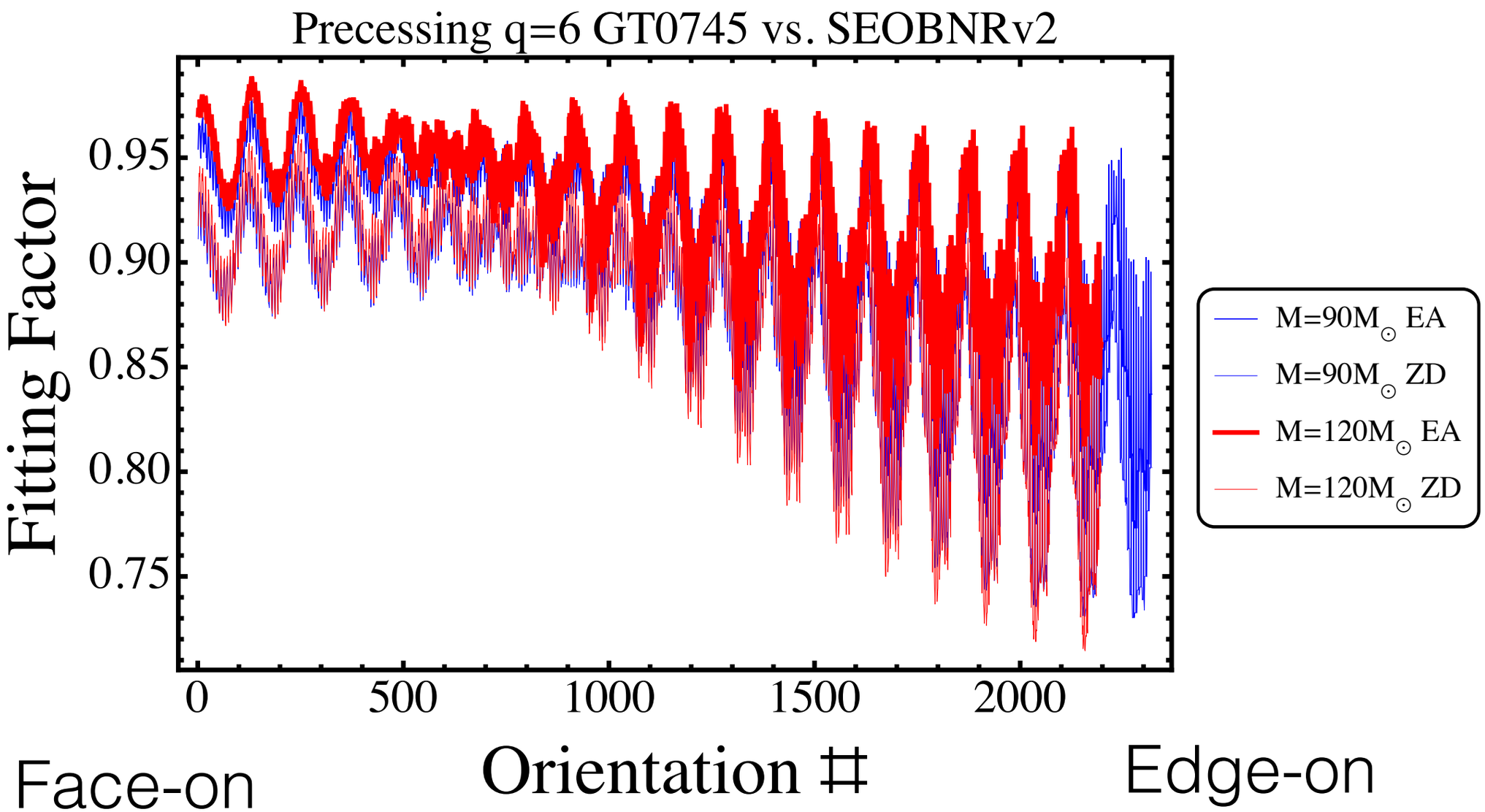


[NR by Jani + (2016)]

Face-on

Edge-on

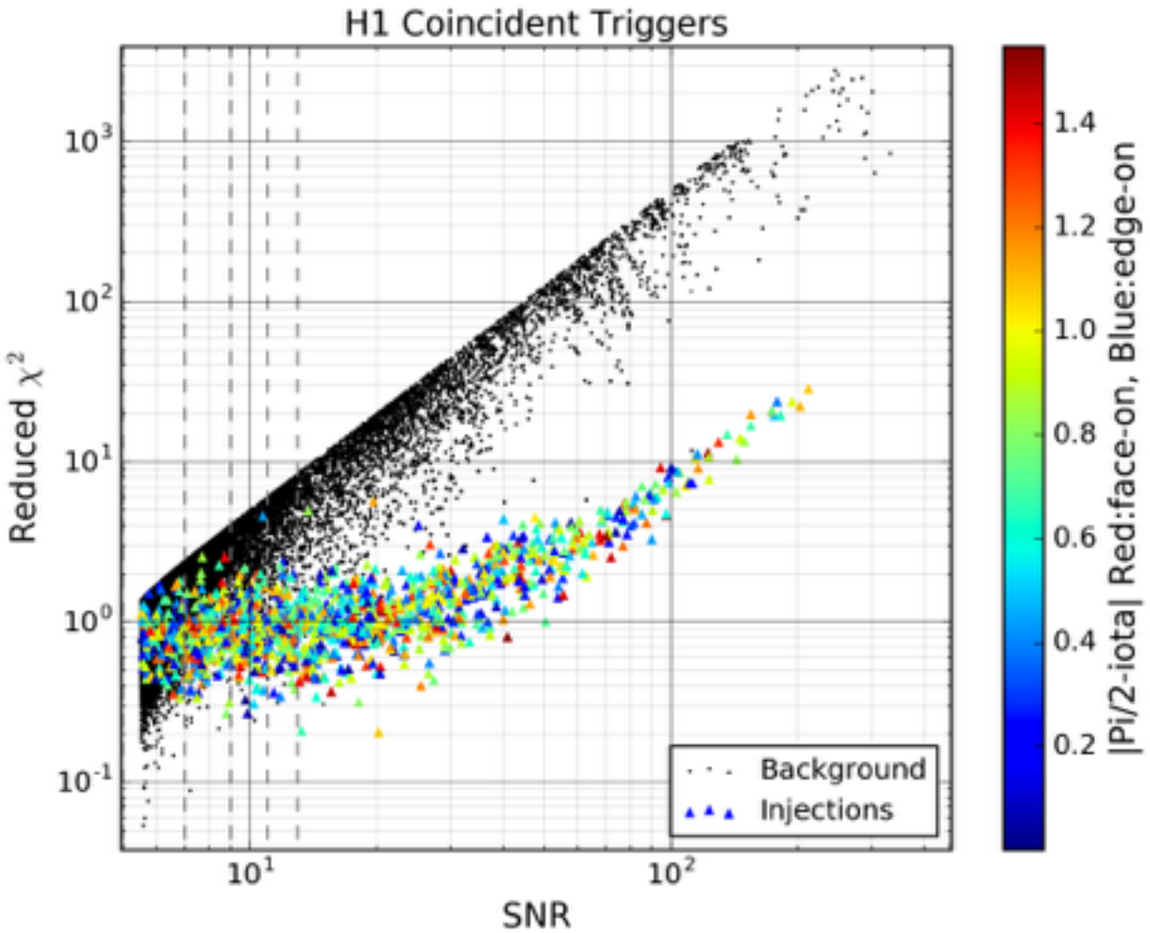
Precessing Targets II



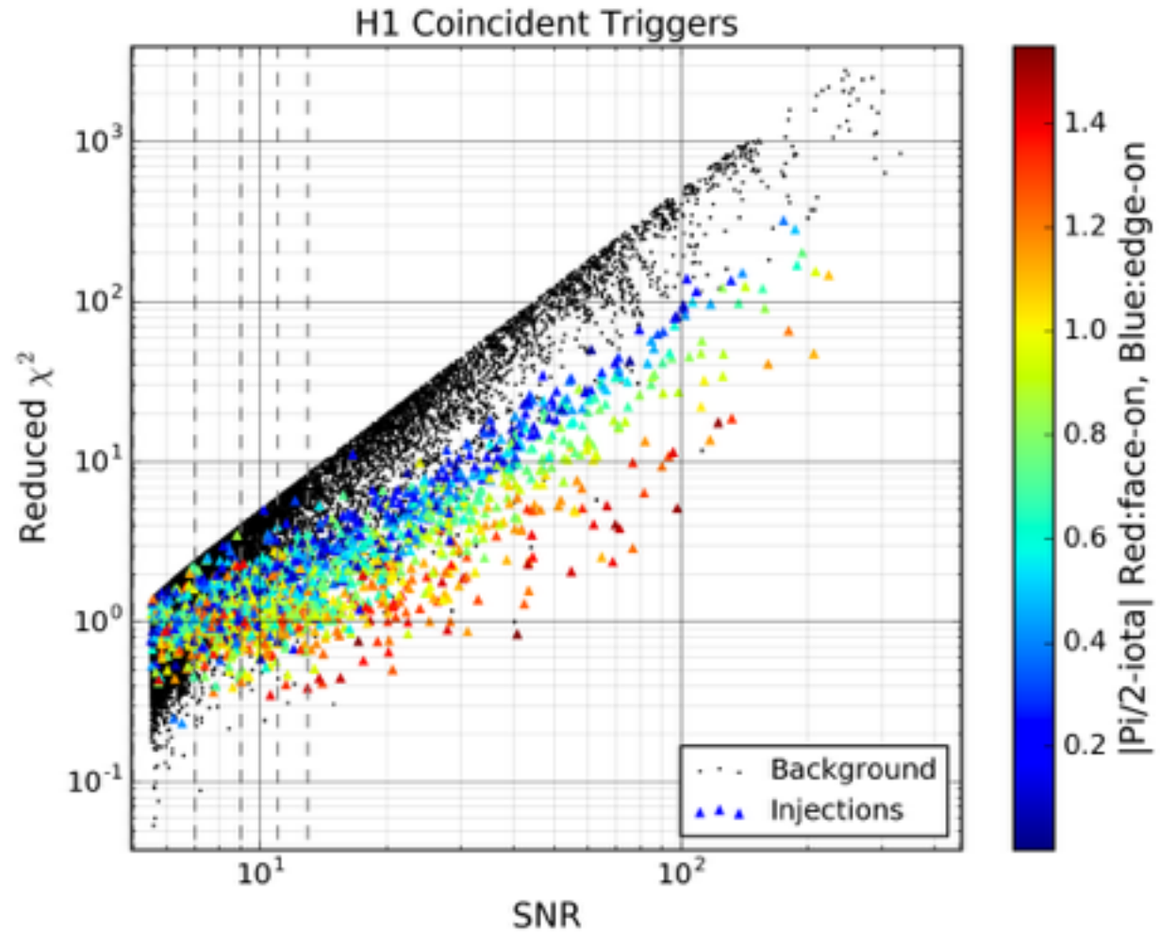
Searches and chi-squared

Separation of injections and background via chi-squared

Injections do not contain higher modes



Injections contain higher modes



Injected signals: EOBNRv2 and EOBNRv2HM. q=6 M=200

Matched Filtering

Inner product

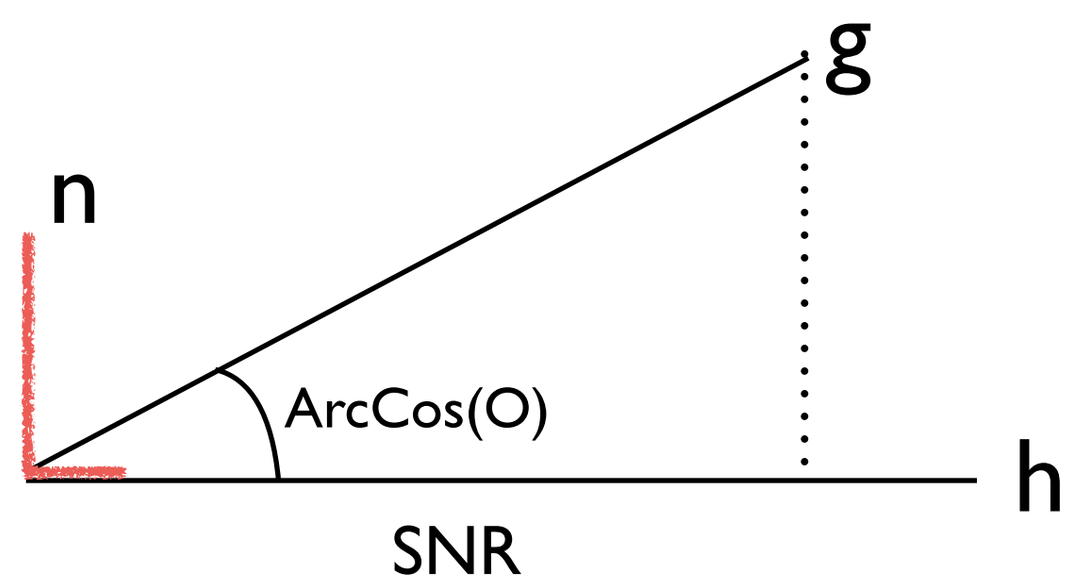
$$\langle h|g\rangle = 4\Re \int_{f_0}^{\infty} \frac{\tilde{h}(f)\tilde{g}^*(f)}{S_n(f)}\, df$$

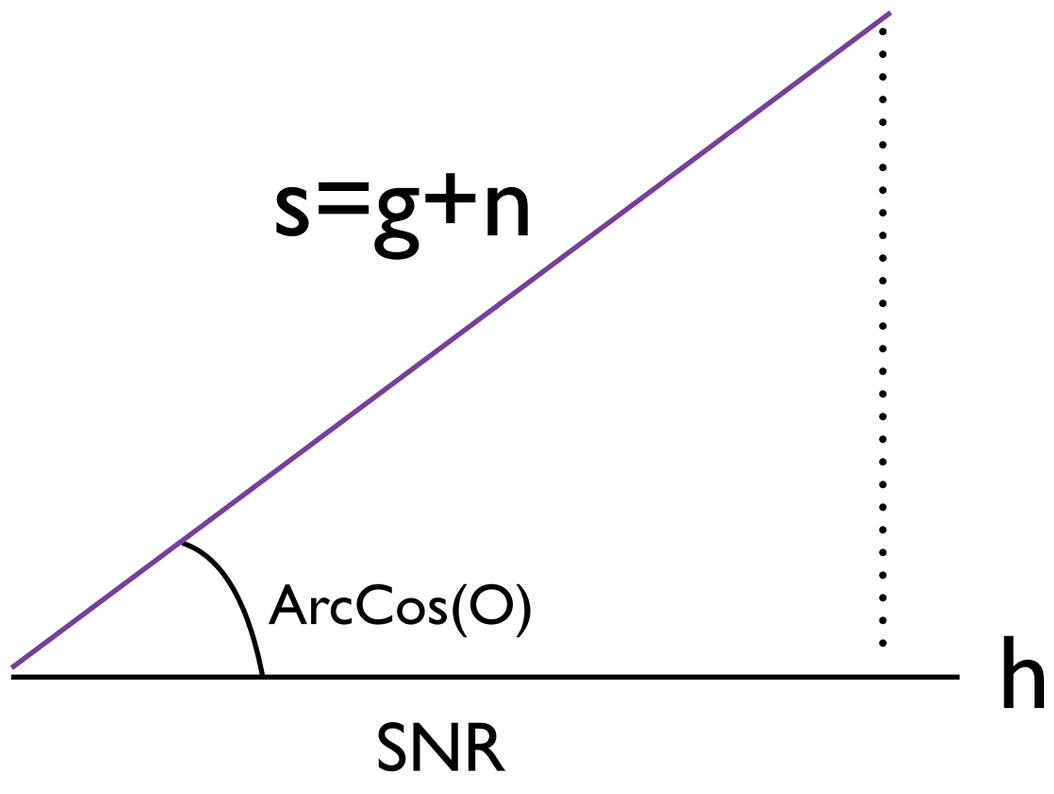
SNR

$$\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}}$$

Overlap

$$\mathcal{O} = \frac{\langle h|g\rangle}{\sqrt{\langle h|h\rangle\langle g|g\rangle}}$$





Fitting Factor

Searches compare the incoming signal to a full bank B of templates h_i

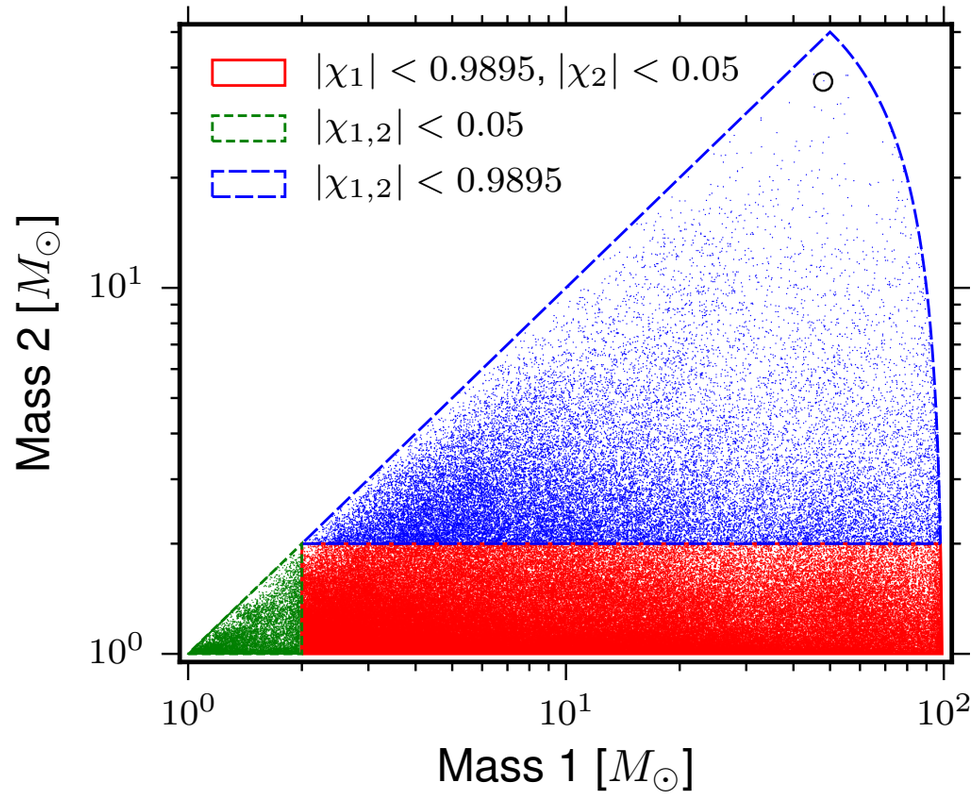
Fitting Factor

$$FF = Max_i \mathcal{O}(h|h_i^B)$$

$$d \sim \rho(h|B) = FF \times \rho(h|h)$$

$$d \sim FF$$

$$V \sim FF^3$$



Accesible volume proportional to FF^3

LVC+Virgo [2016]

Note: There will be a bias on the recovered parameters

Results: comparison to statistical errors