Detectability of intermediate mass binary black holes

Juan Calderón Bustillo

Center for Relativistic Astrophysics

Georgia Institute of Technology

in collaboration with: P. Laguna, D.Shoemaker, Karan P. Jani, Tito dal Canton, Francesco Salemi & Ian Harry.

7th Iberian Gravitational Waves Meeting **Bilbao, Spain, May 2017**

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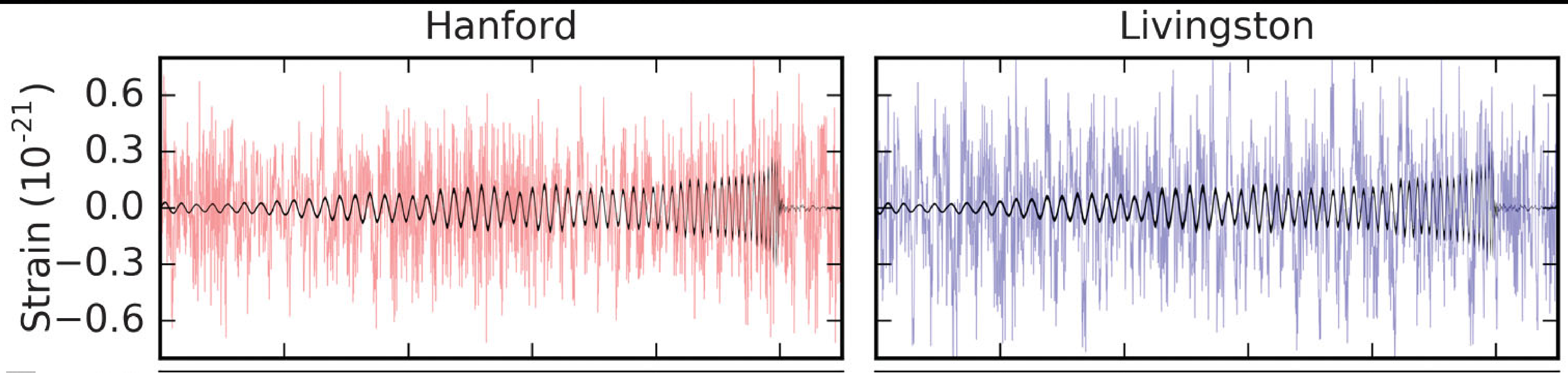
Introduction: matched filter searches (or modelled searches)



GW151226 (or Boxing Day event)

LSC+ Virgo, PRL 116, 141103 (2016)

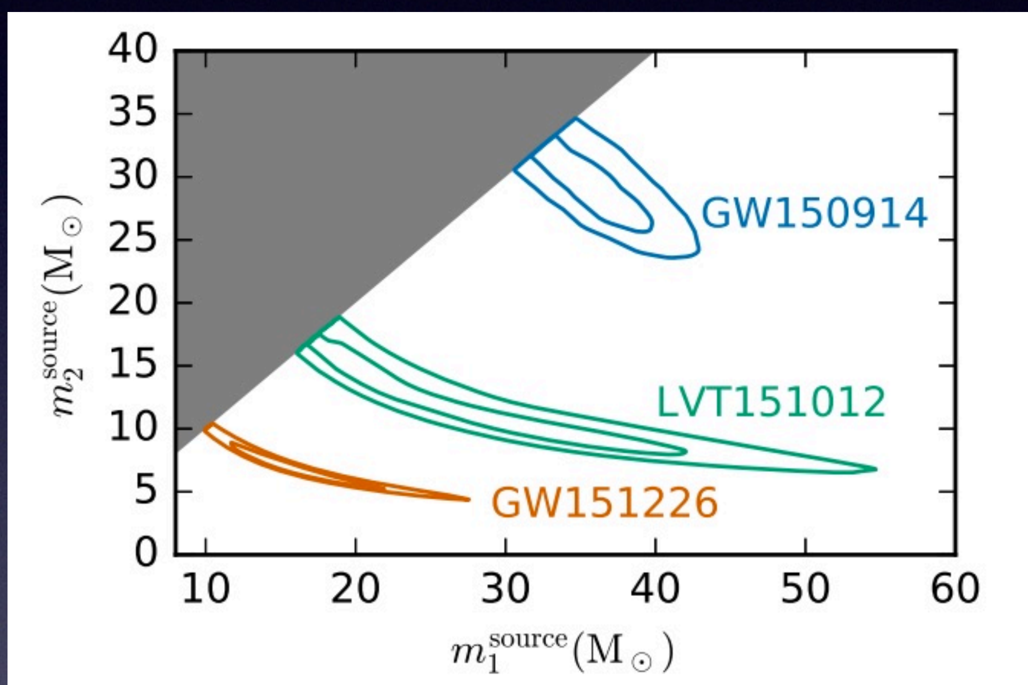
Key facts of modelled searches.

- GW signals are normally weaker than the detector background noise.
- Compare (via matched filter) the detector output with waveform models (or templates) —> Signal-to-noise ratio.
- <u>Templates need to be accurate representations</u> of the GW signal.
- Wrong modelling leads to loss in SNR and damages the detection process.

Introduction: Detections so far have a low mass ratio and no clear precession.

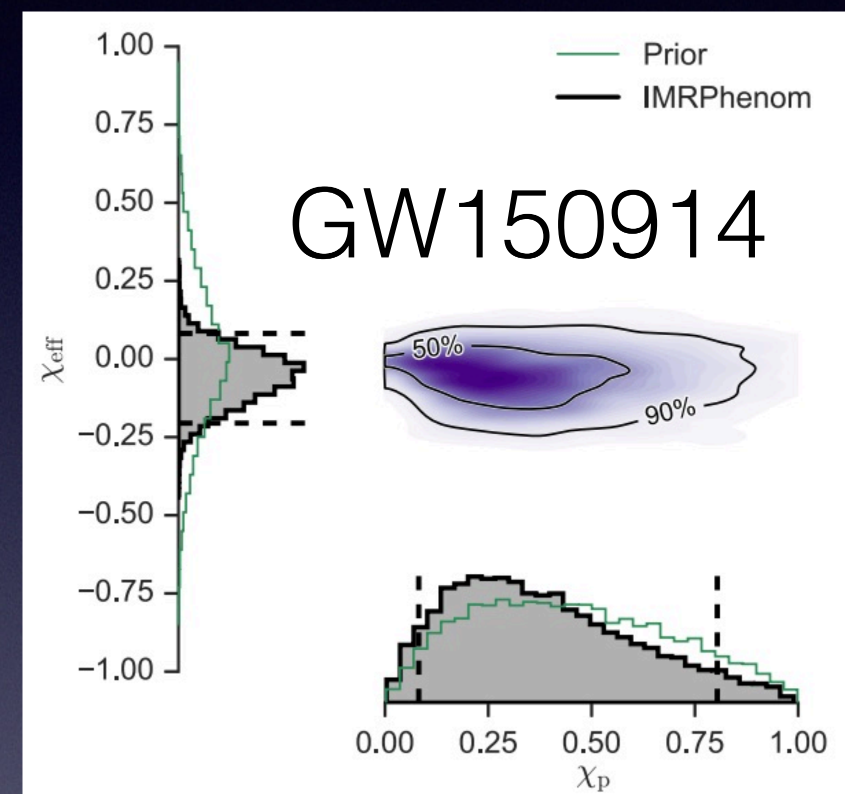
$$\chi_{eff} = \frac{\chi_1 m_1 + \chi_2 m_2}{m_1 + m_2}$$

GW150914



LSC + Virgo, PhysRevX.6.041015

Low mass ratio q=m1/m2 and total mass below M=m1+m2=100Msun



LSC + Virgo, PhysRevLett.116.241102

Data is uninformative about precession as the posterior is almost equal to the prior

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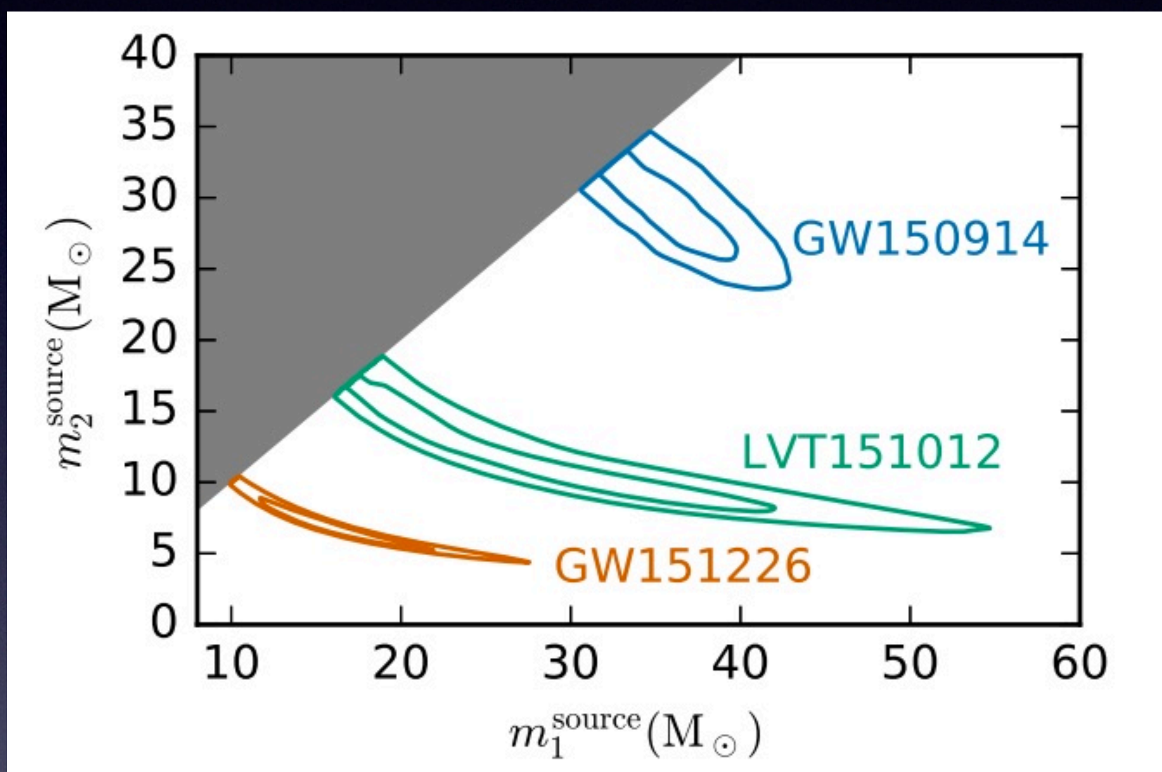

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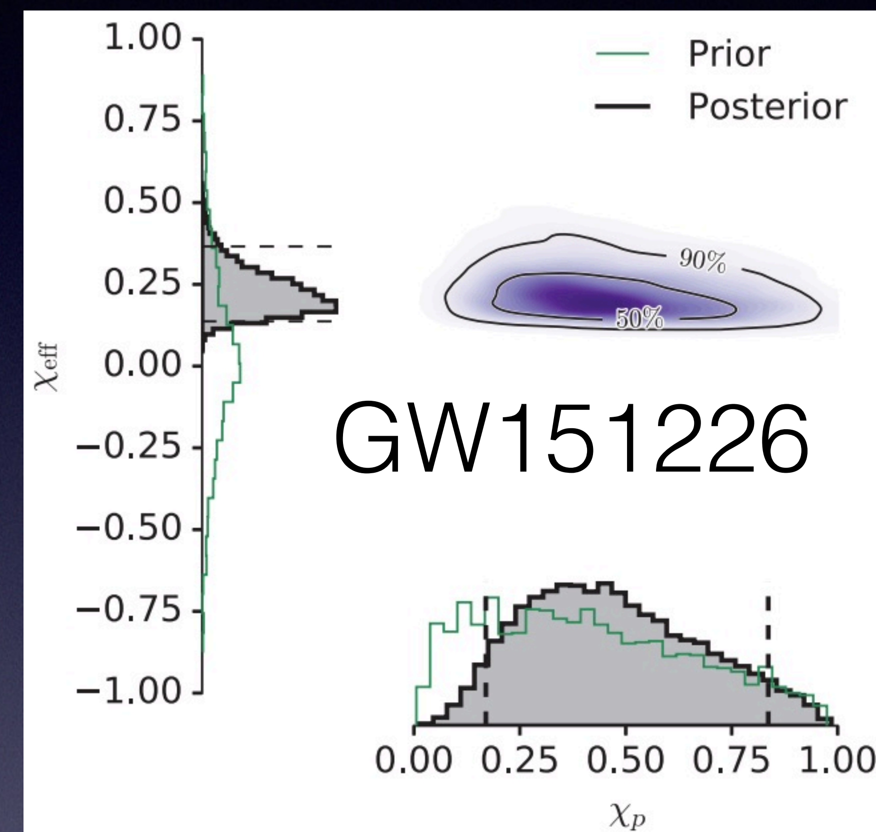


LSC + Virgo, Phys. Rev. Lett. 116, 241103

Data is uninformative about precession as the posterior is almost equal to the prior

Introduction: results from the search for intermediate mass black holes

Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO

During their first observational run, the two Advanced LIGO detectors attained an unprecedented sensitivity, resulting in the first direct detections of gravitational-wave signals produced by stellar-mass binary black hole systems. This paper reports on an all-sky search for gravitational waves (GWs) from merging intermediate mass black hole binaries (IMBHBs). The combined results from two independent search techniques were used in this study: the first employs a matched-filter algorithm that uses a bank of filters covering [illegible] the second is a generic search for GW transients (bursts). No GWs from IMBHBs were detected; therefore, we constrain the rate of several classes of IMB[illegible] obtained for black holes of individual mass 100 $M_\odot$, with spins aligned with the binary orbital angular momentum. For such systems, the merger rate is constrained to be less than 0.93 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ in comoving units at the 90% confidence level, an improvement of nearly two orders of magnitude over previous upper limits.

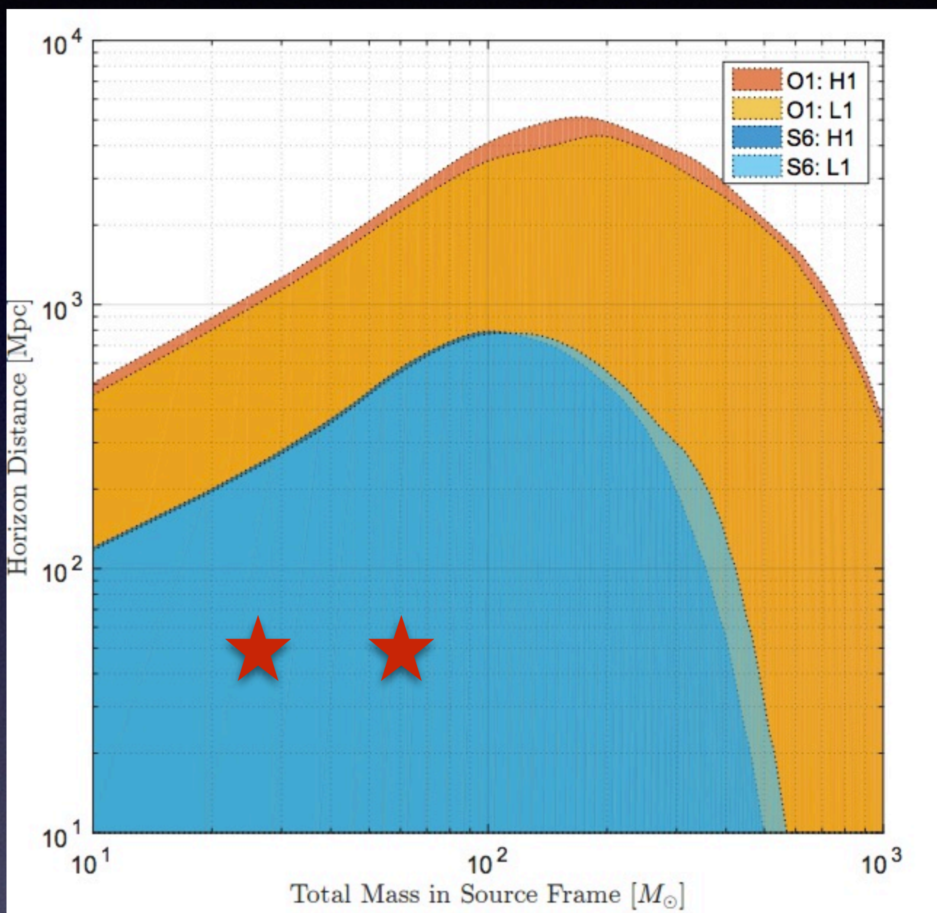
LSC + Virgo,arXiv 1704.04628

Motivations summary:

- No detections with total mass above 100Msun.
- All of them showed mass ratios below ~3.5
- No clear signs of precession.

Introduction: Intermediate mass black holes

- Black holes with total mass M > 100Msun.
- If they exist, these would be the strongest CBC-like source for gravitational waves.



LSC + Virgo,arXiv 1704.04628

GW151226

Challenges:

- Signal dominated by its merger and ringdown parts.
- Higher modes impact the signal (coming later)
- Templates not as accurate as for the case of lower mass systems.
- Background noise can reproduce easily these signals (Sine gaussian glitches, A.Torres' talk)

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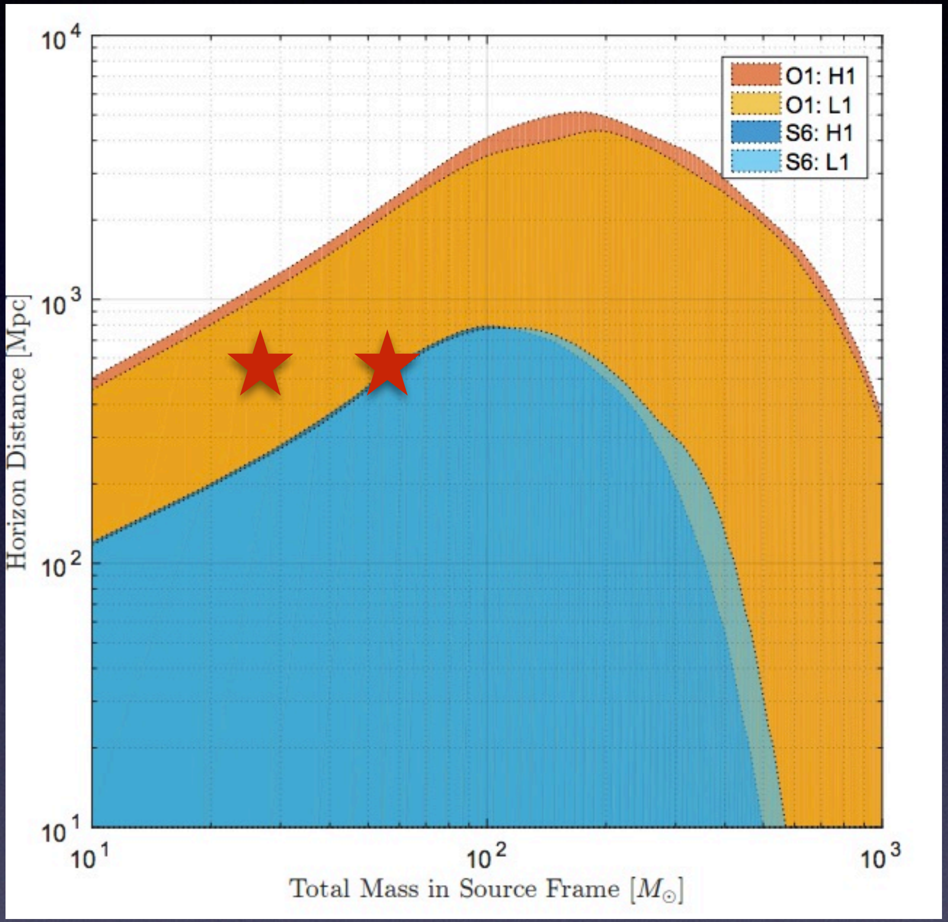
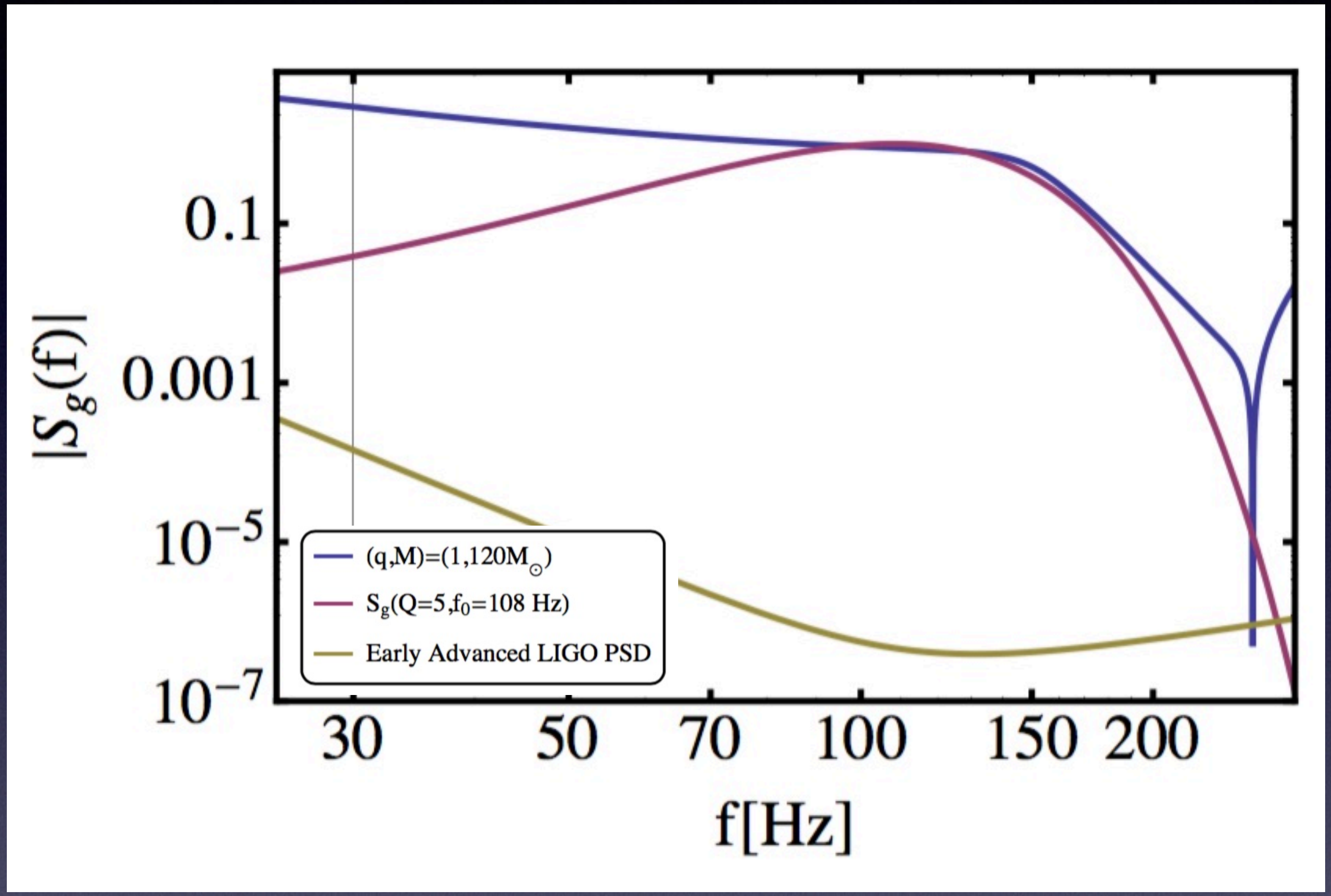


LSC + Virgo,arXiv 1704.04628



JCB, PhD Thesis

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- Templates not as accurate as for the case of lower mass systems.
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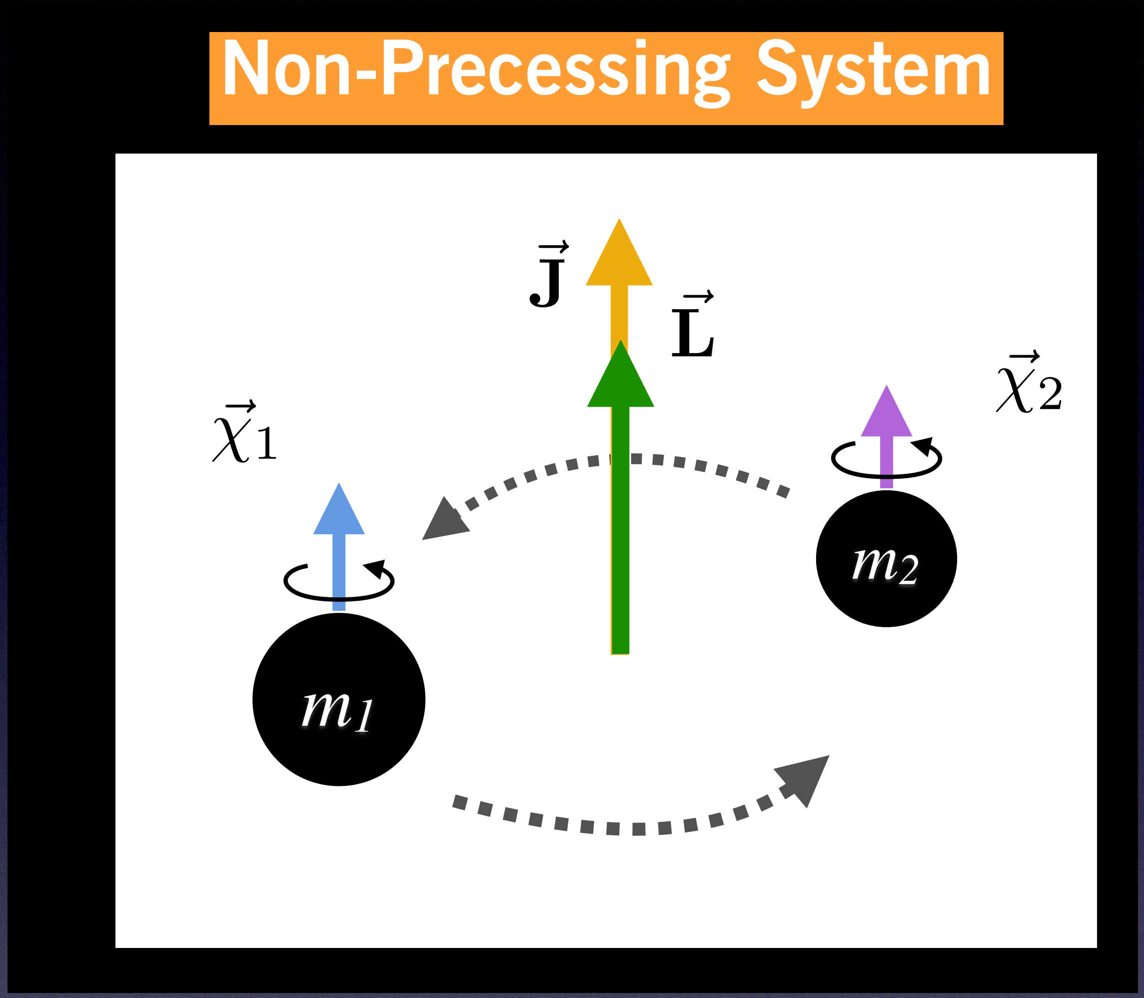
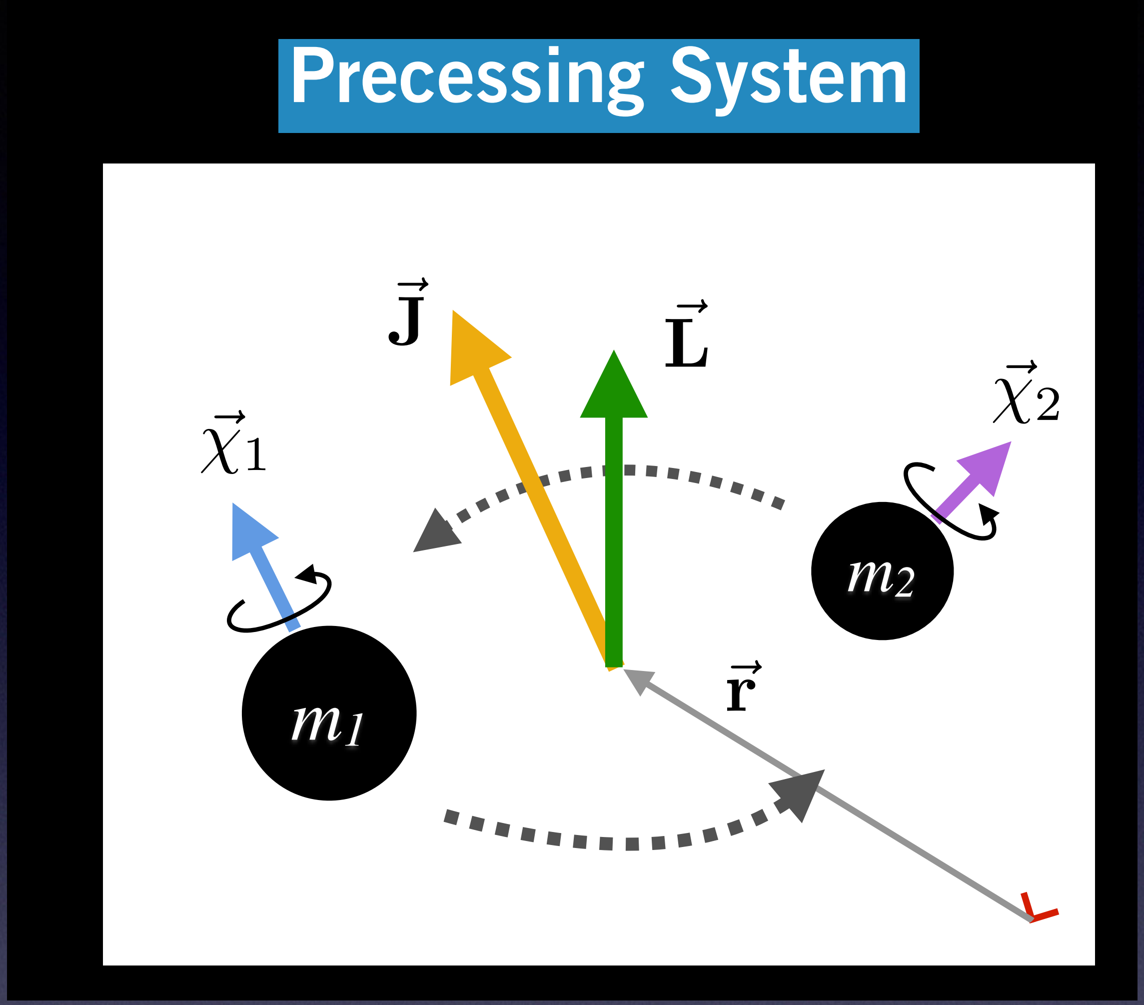
What our (modelled) searches lack: Higher modes & Precession.

Introduction: Precession

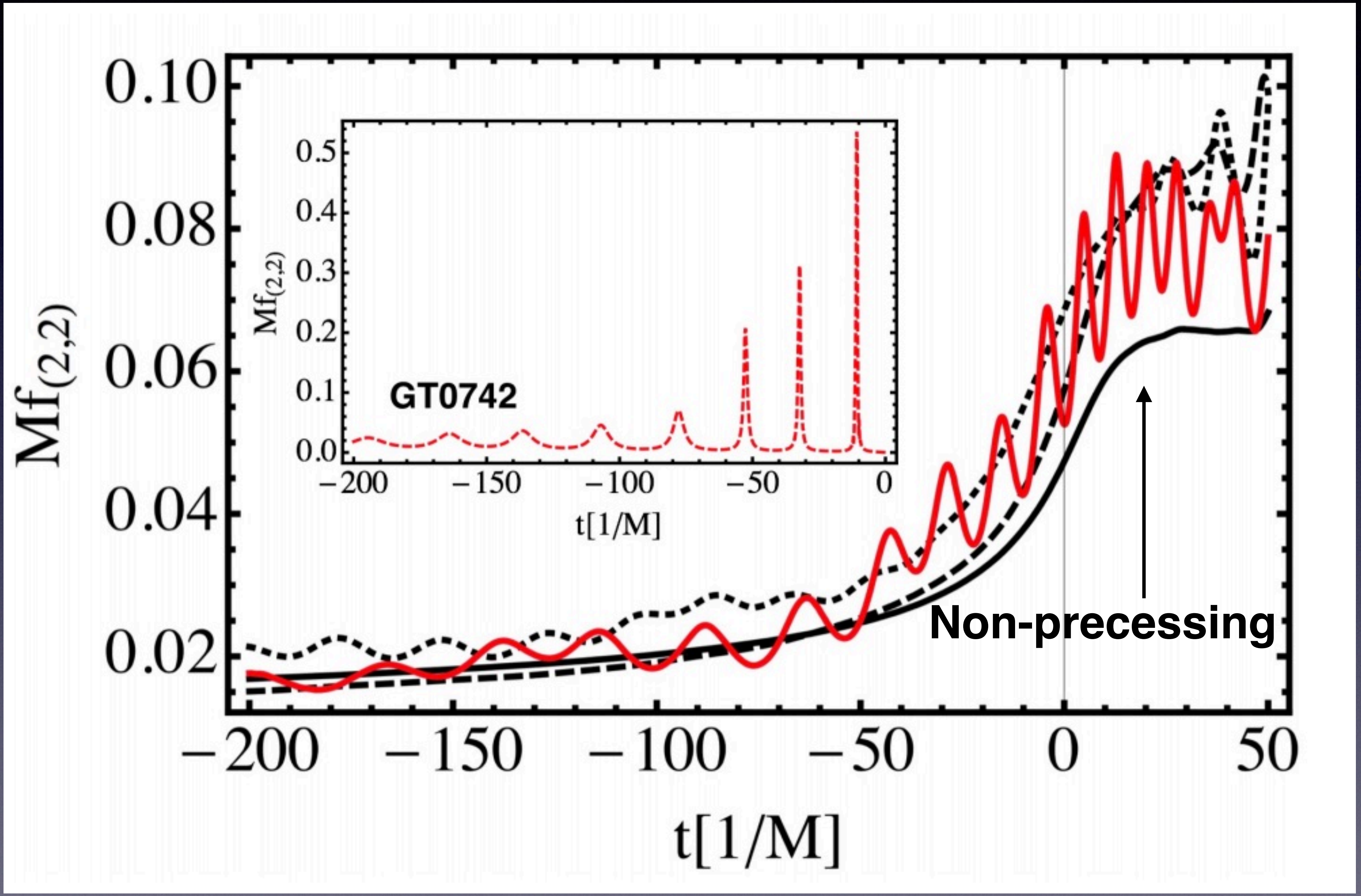




C.Capano, LIGO-G1601021, GR21 conference.

- Presence of <u>in-plane spin components</u> causes the orbital plane to precess.
- This causes <u>modulations in the amplitude and frequency</u> of the signal.
- The <u>longer the signal</u> the more precession will hurt (similar to eccentricity).
- Currently used for parameter estimation (SEOBNRv3, PhenomP) but <u>not for searches</u>.

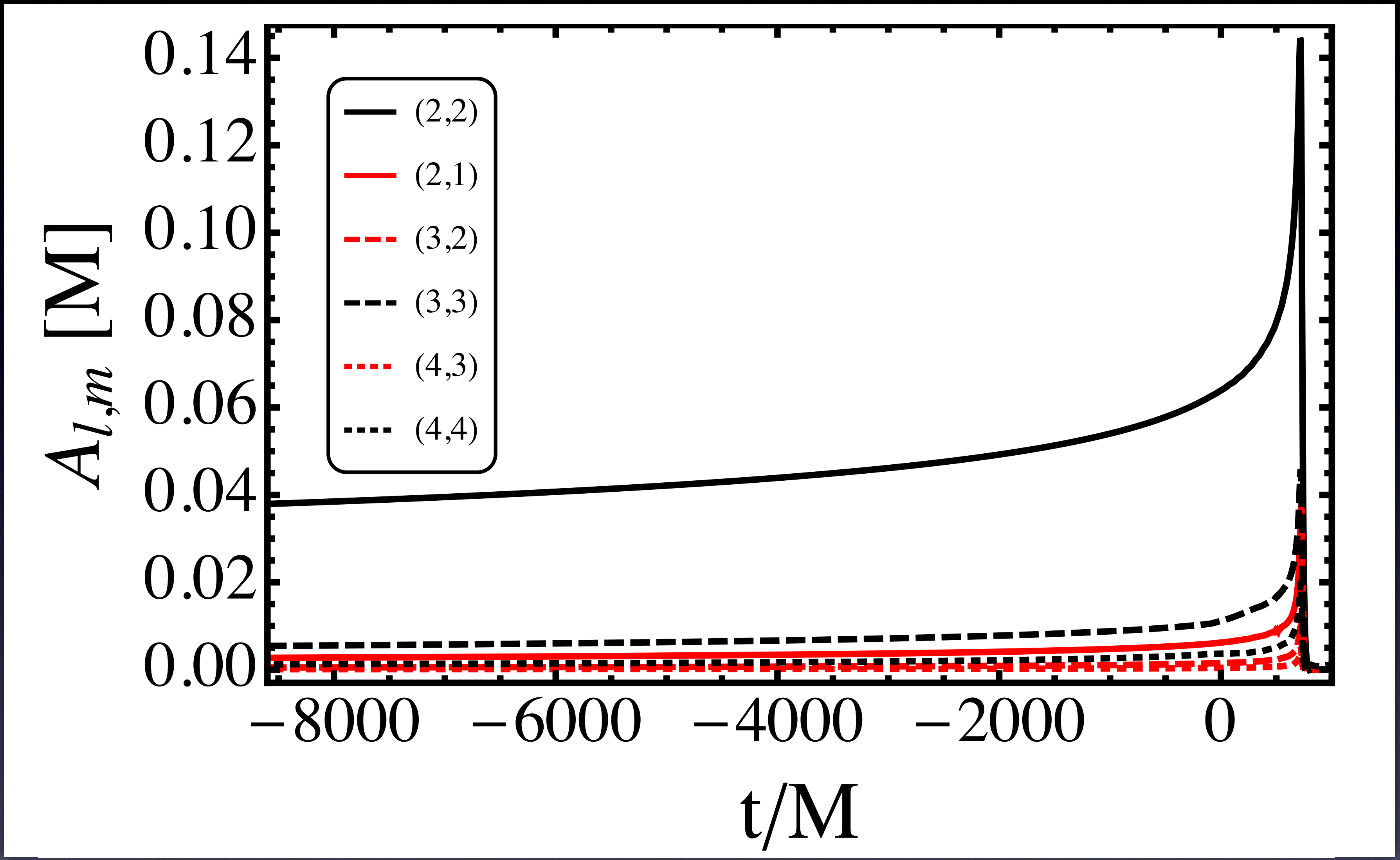
Impact of precession



JCB, Laguna, Shoemaker, PRD , ArXiv1612.02340v2

Introduction: Higher order modes

JCB+, Phys. Rev. D 93, 084019

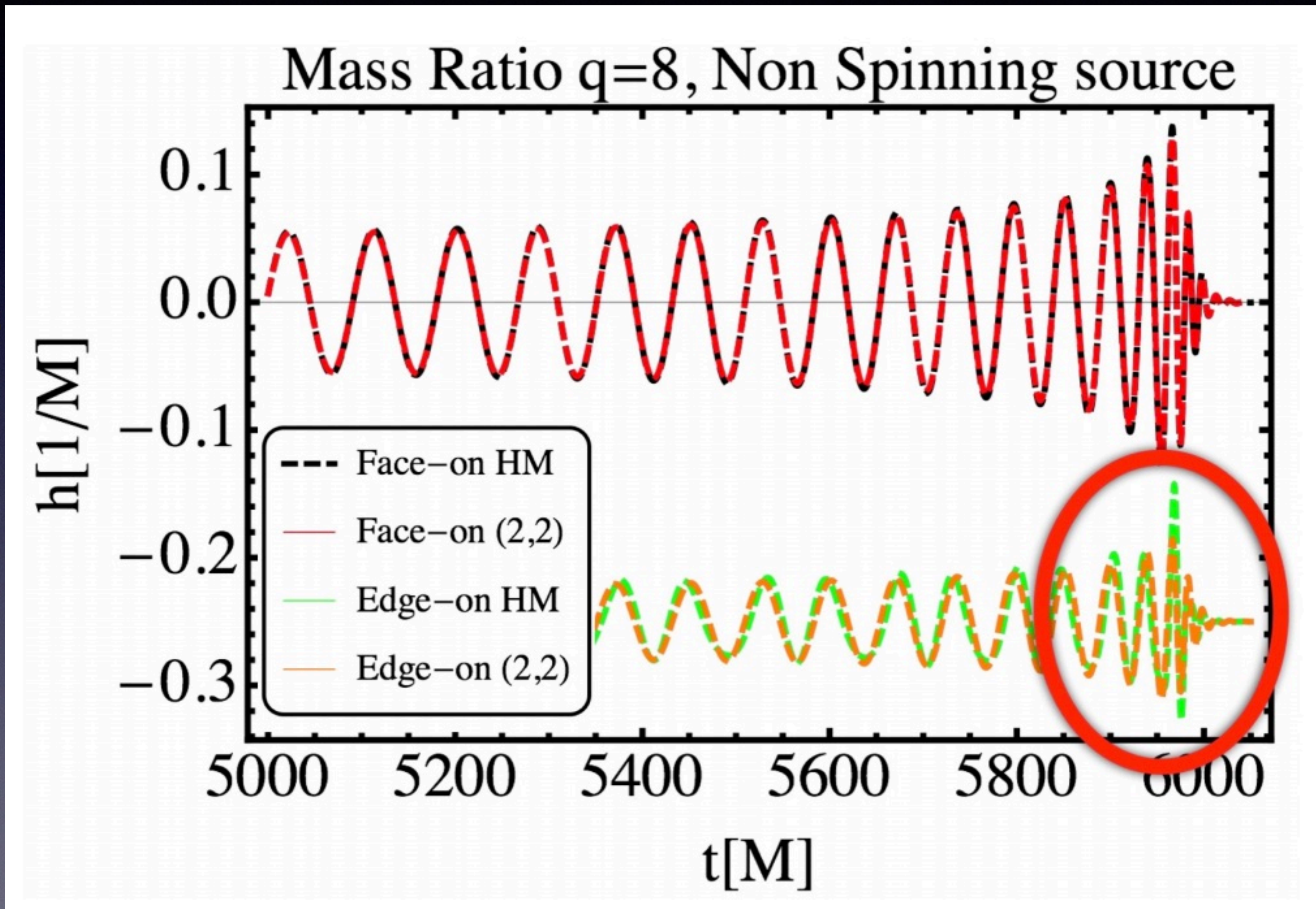


Harmonics: Depend on orientation

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

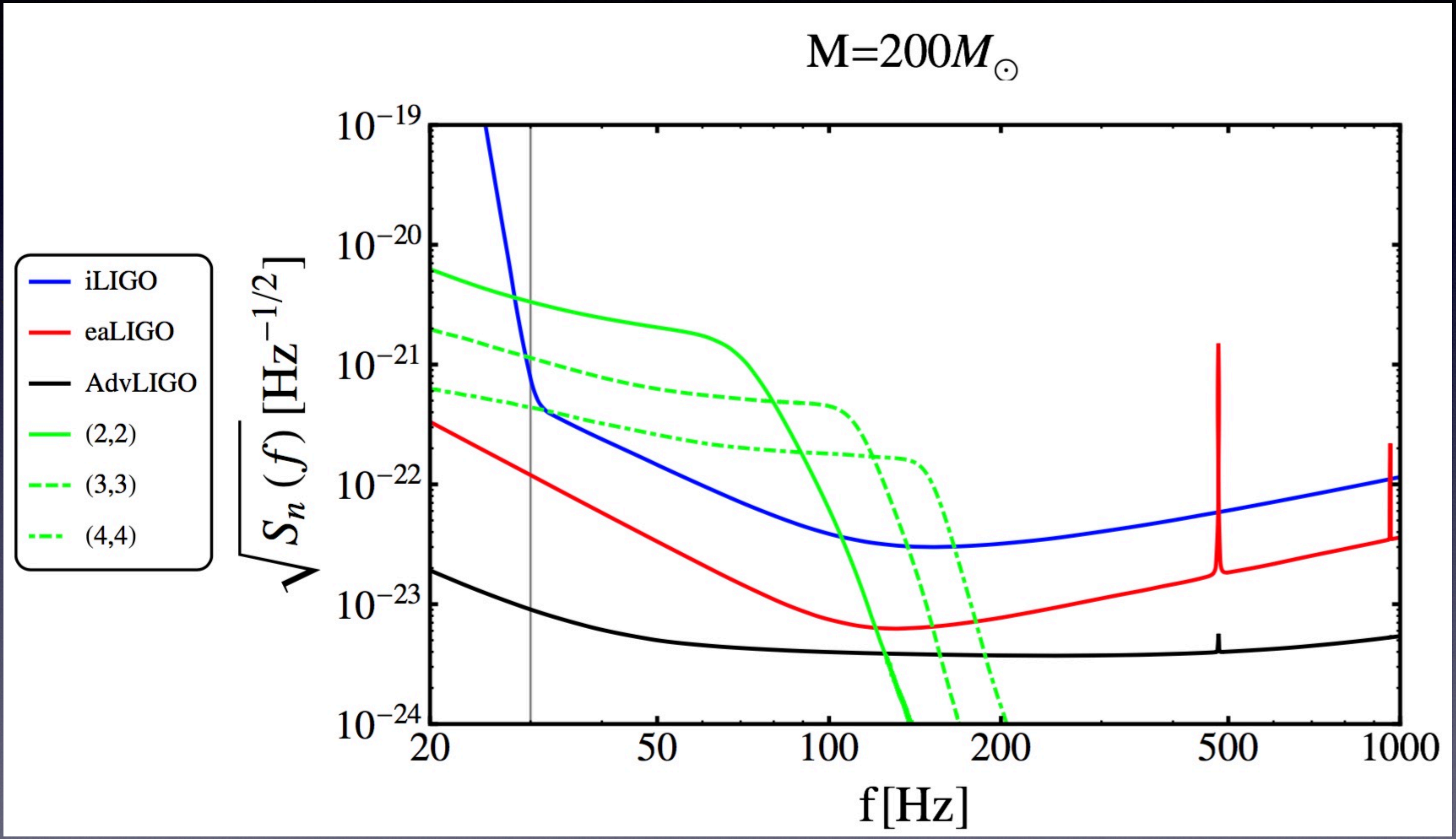
Modes: Depend on source parameters

Impact of higher order modes



JCB, Dal Canton +, In prep. LIGO-G1700062-v6

Impact of higher order modes

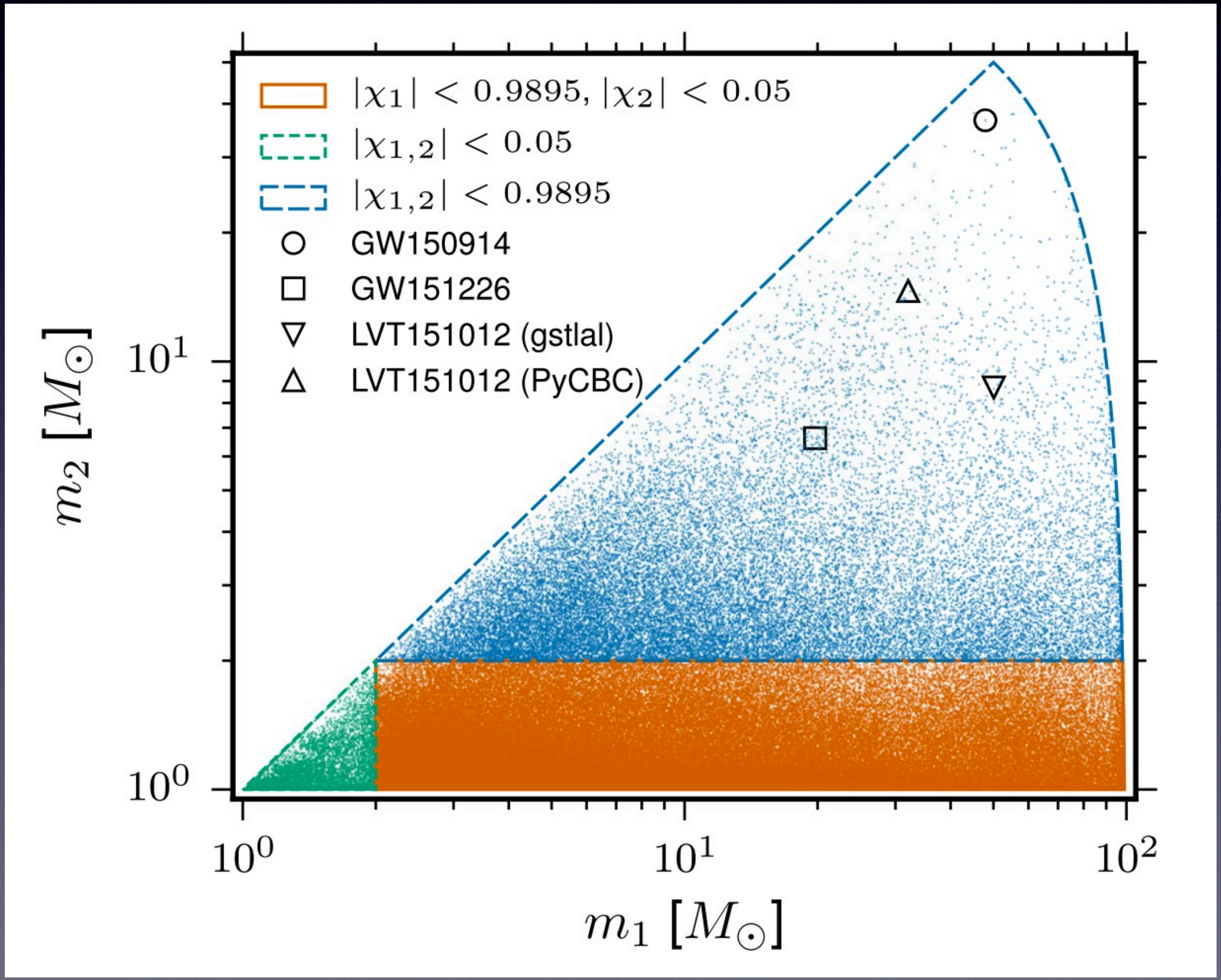


JCB, Husa, Sintes, Puerrer PRD 93.084019 (2016)

What do we pay?

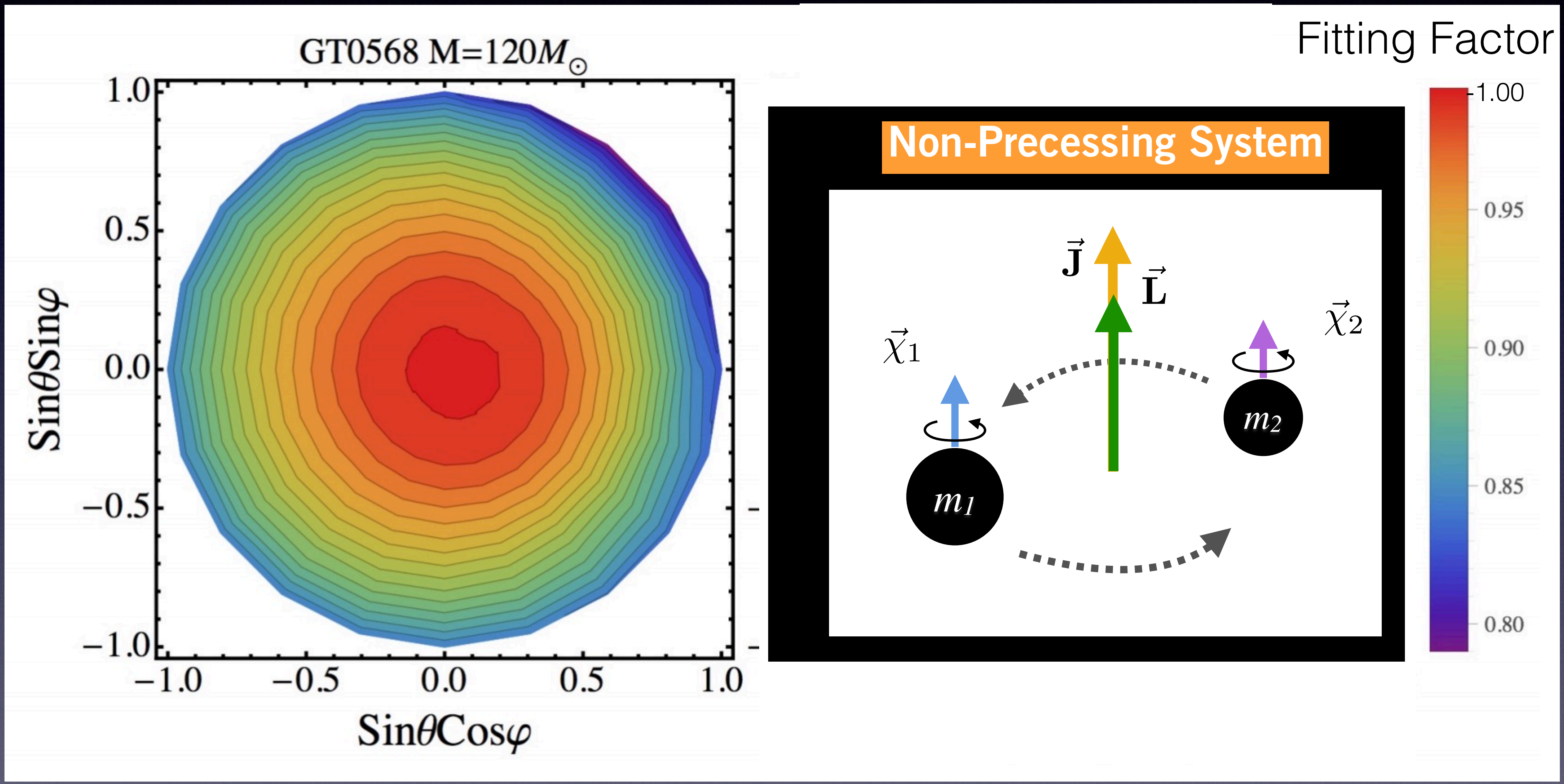
Impact of omission of higher modes and precession

- Template banks are designed such that not more than **10% of signals are missed** (at a given SNR), this requires a **minimum overlap of 0.965** to targeted signals.



Impact of omission of higher modes and precession

- Precession vs. higher modes: SEOBNRv2 (Taracchini +'12,'14, Pürrer 16) trying to recover Georgia Tech Numerical Relativity waveforms (Jani+ 16).



q=10, non-spinning
only higher modes

JCB, Laguna, Shoemaker, Accepted in PRD , ArXiv1612.02340v2

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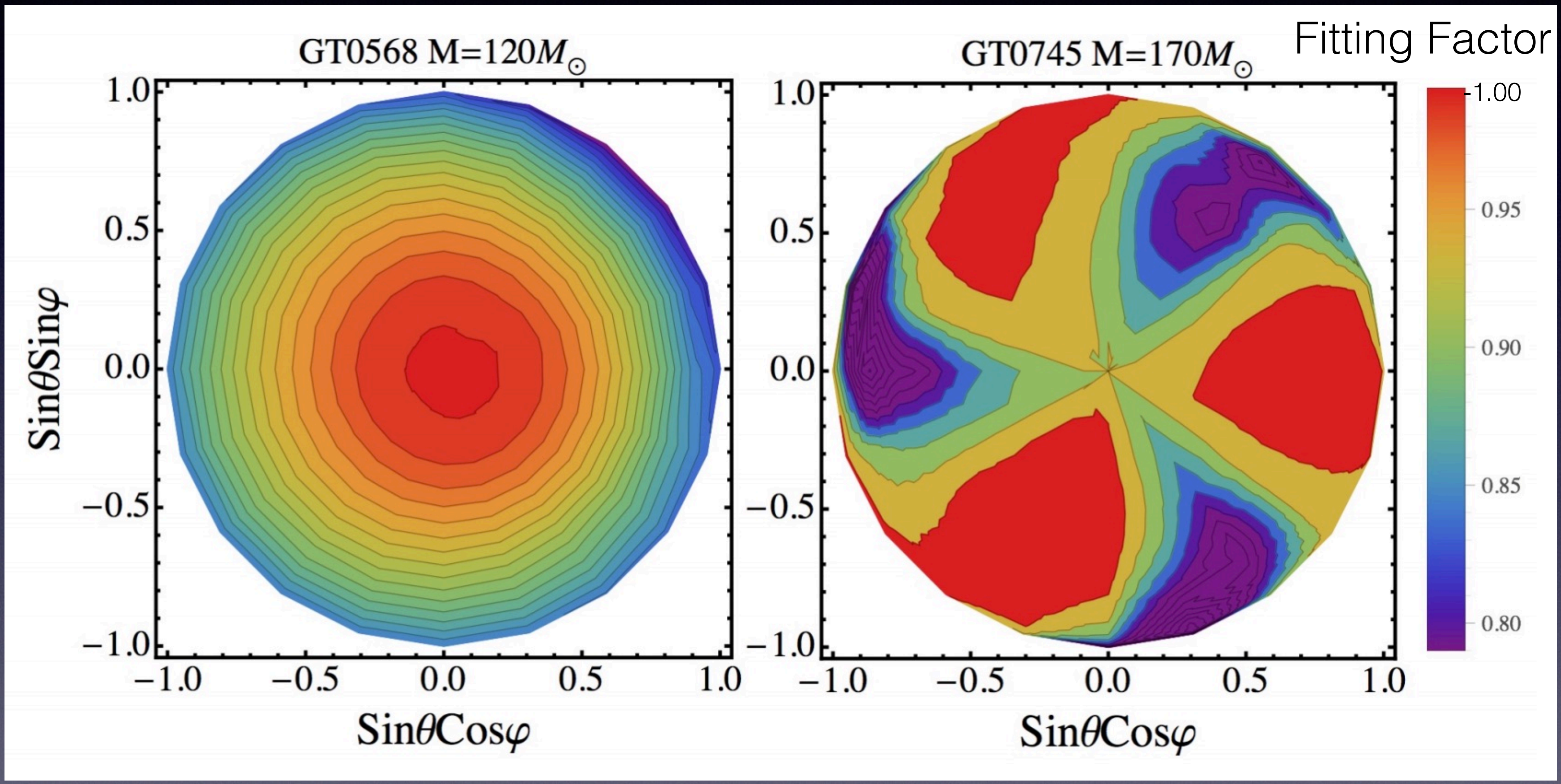


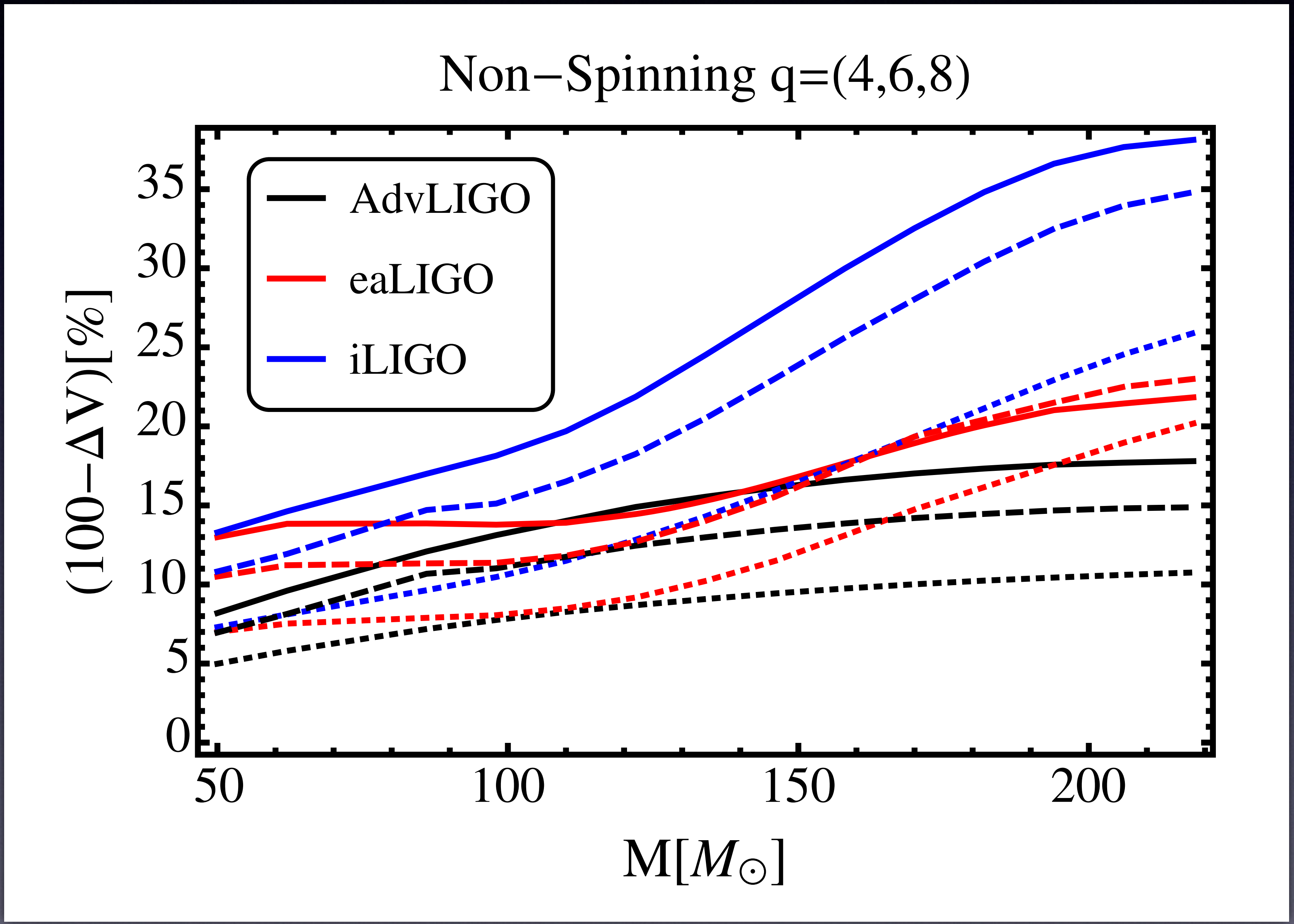
q=10, non-spinning
only higher modes

q=7, precessing
+ higher modes

JCB, Laguna, Shoemaker, Accepted in PRD , ArXiv1612.02340v2

Impact of omission of higher modes and precession

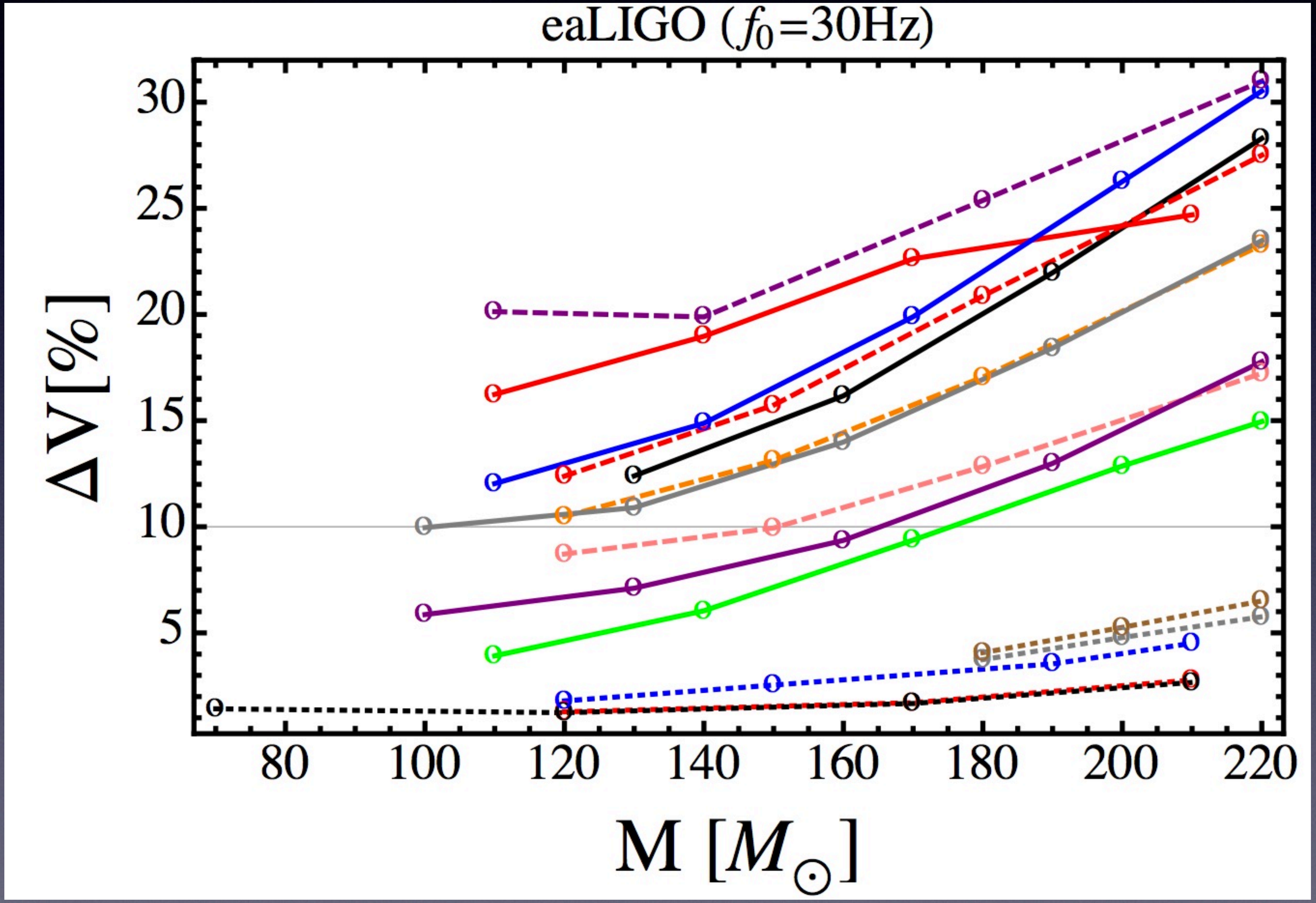
- This will cause **losses larger than 10%** for q > 4 sources when M > 100 Msun for aligned spin cases. (Varma + 14, JCB + 15, JCB +16).



JCB, Husa, Sintes, Puerrer PRD 93.084019 (2016)

Impact of omission of higher modes and precession

- Losses when both effects combine: orientation averaged losses.



q > 3 sources precessing

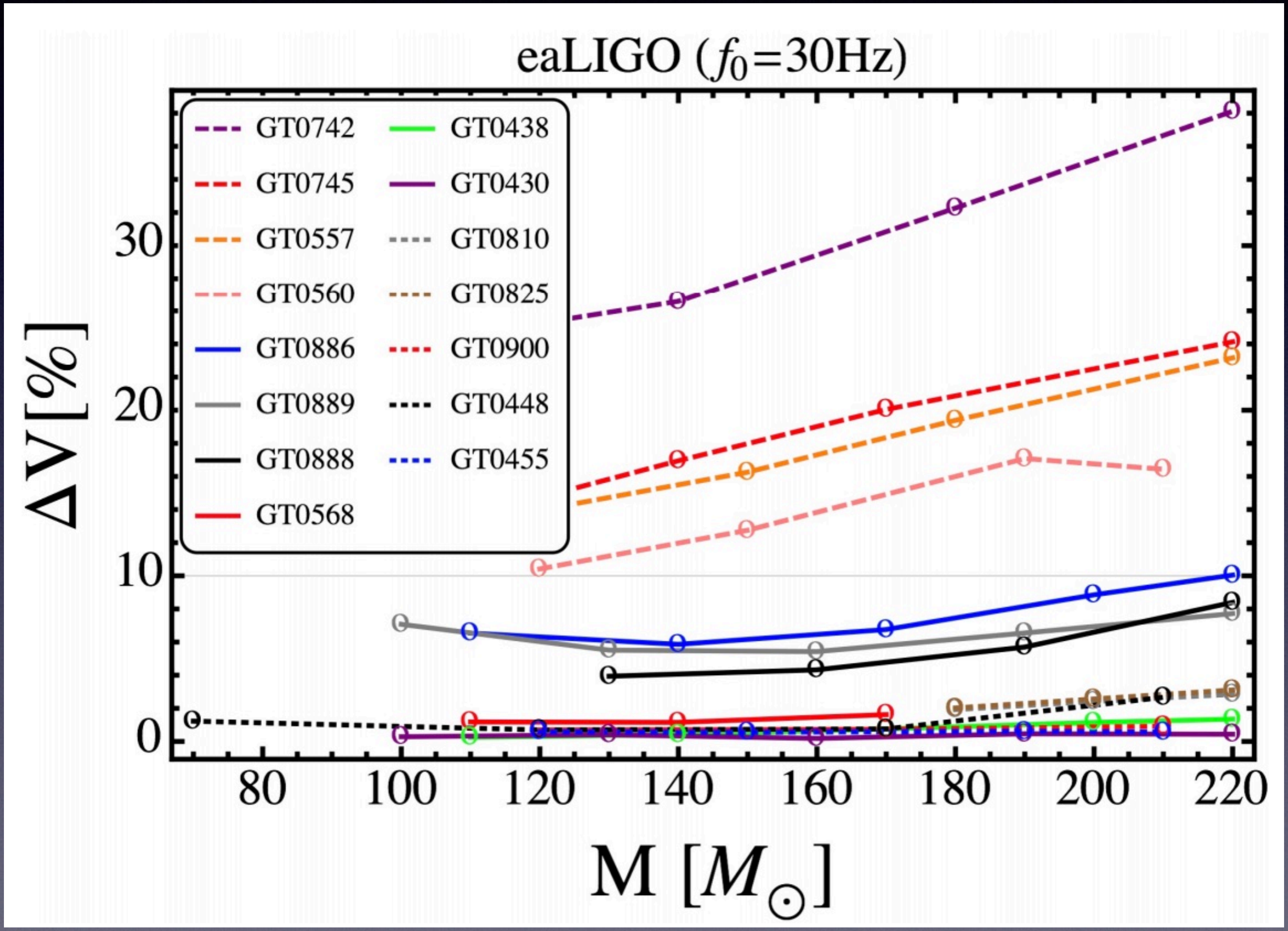
Dashed: strong precession (chi_p > 0.5)

GW150914 - like sources

JCB, Laguna, Shoemaker, PRD , ArXiv1612.02340v2

Impact of omission of higher modes and precession

- Isolating precession: face-on losses.



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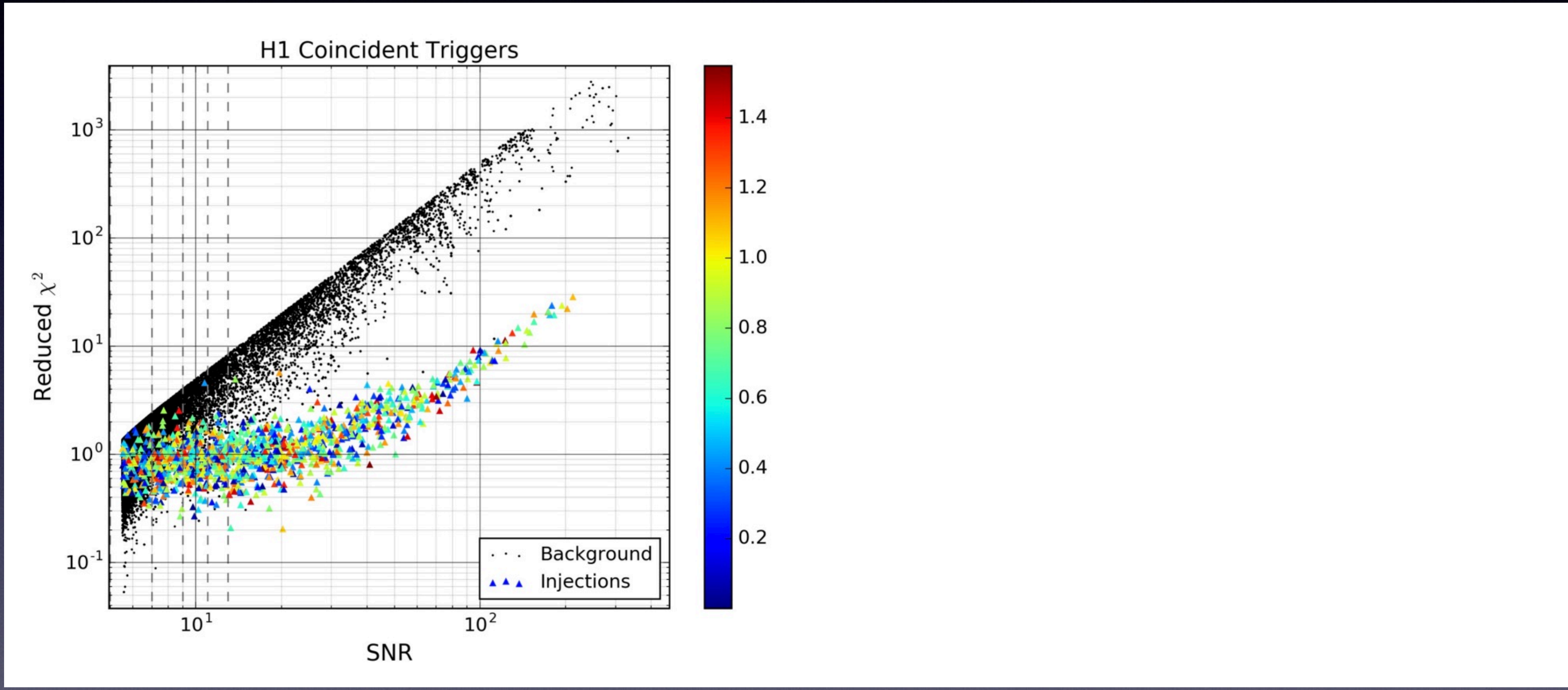
GW150914 - like sources

JCB, Laguna, Shoemaker, PRD , ArXiv1612.02340v2

Further impact: growth of the chi-square value

Signals omit higher modes:
GOOD separation from background triggers

Signals include higher modes:
POOR separation from background triggers



JCB, Dal Canton +, In prep. LIGO-G1700062-v6

- The signal-to-noise ratio is the reference value for estimating the significance of triggers.
- However, we must discriminate terrestrial glitches from real GW.
- One of the main ways of doing this is the so called chi-square value
- Mismatch between GW and template, will reduce SNR *and* increase chi-square.

Further impact: growth of the chi-square value

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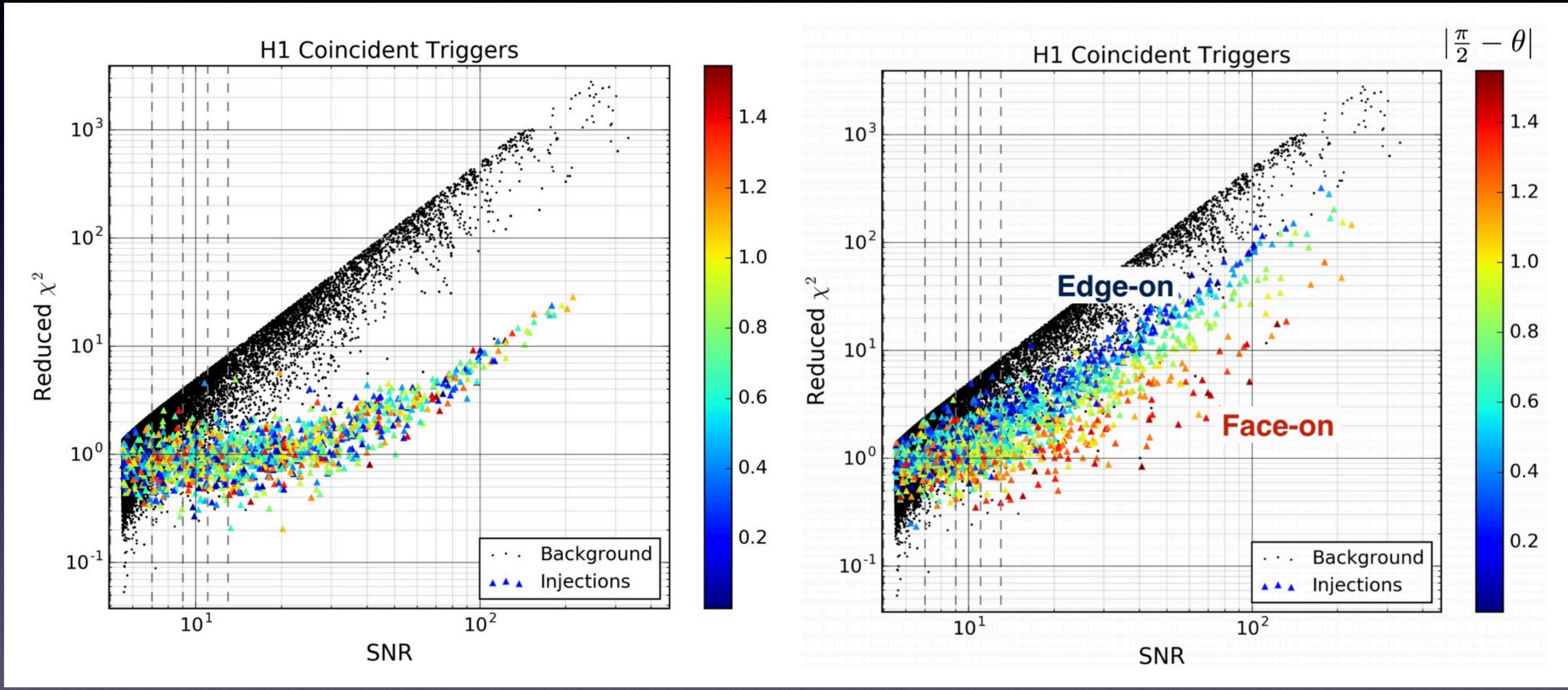

JCB, Dal Canton +, In prep. LIGO-G1700062-v6

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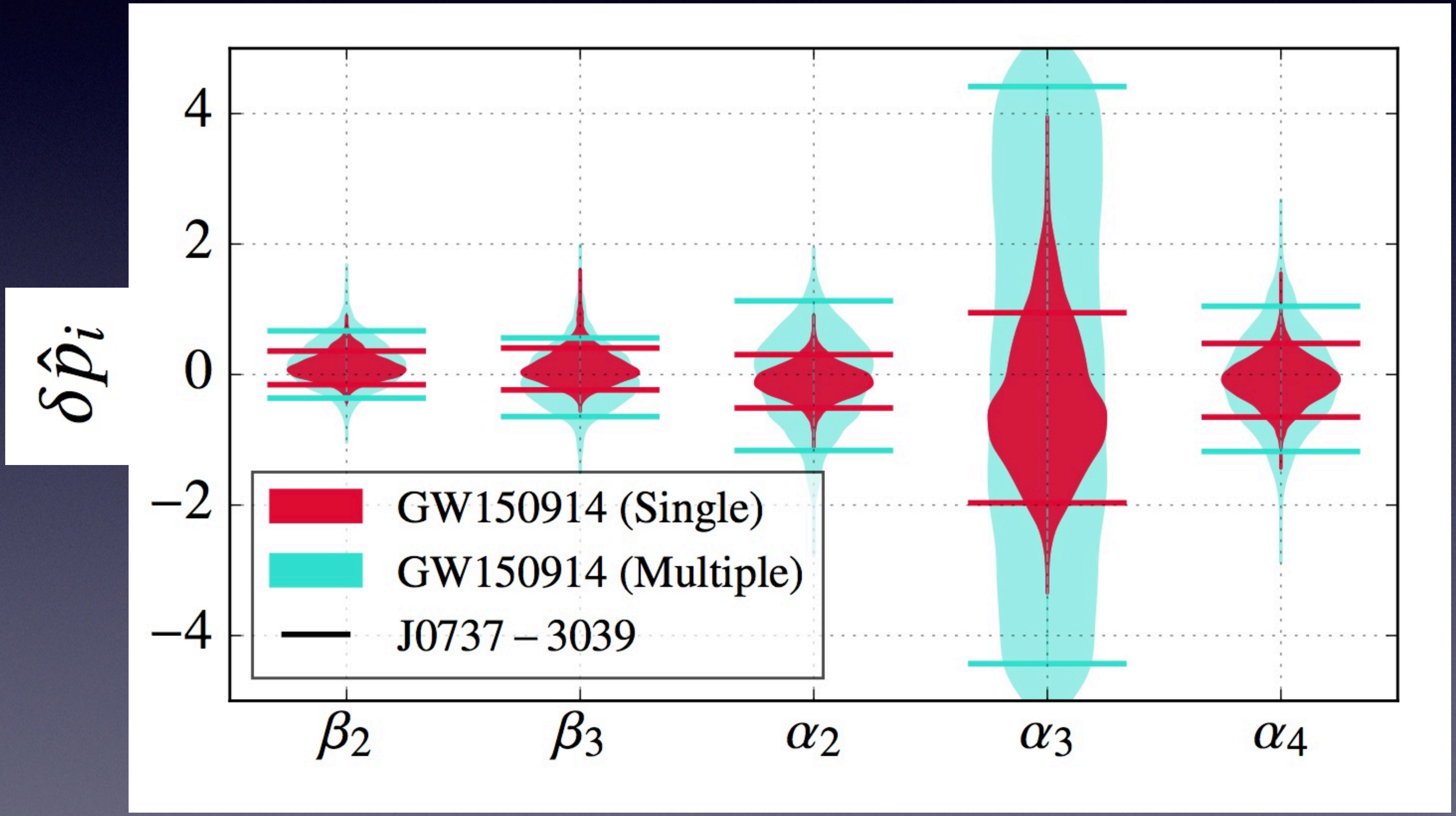
Testing GR: fake violations of GR

In Collaboration with TGF Li, Peter Tsung, Wang Yifan, T. Carter

$$\Phi_{\rm IMR} \sim \begin{cases} \frac{3}{128\eta} \sum_{j=0}^{7} \varphi_j(\Xi)(\pi M f)^{(j-5)/3} + \ldots & f < f_1, \\ \frac{1}{\eta}\left(\ldots + \beta_2 \log(f) - \frac{1}{3}\beta_3 f^{-3}\right) & f_1 \leq f < f_2 \\ \frac{1}{\eta}\left(\ldots + \alpha_2 f^{-1} + \frac{4}{3}\alpha_3 f^{3/4} + \alpha_4 \tan^{-1}(af+b)\right) & f \geq f_2 \end{cases}$$



LSC+Virgo, PhysRevLett.116.221101
GW150914 TestingGR paper

Testing GR: fake violations of GR

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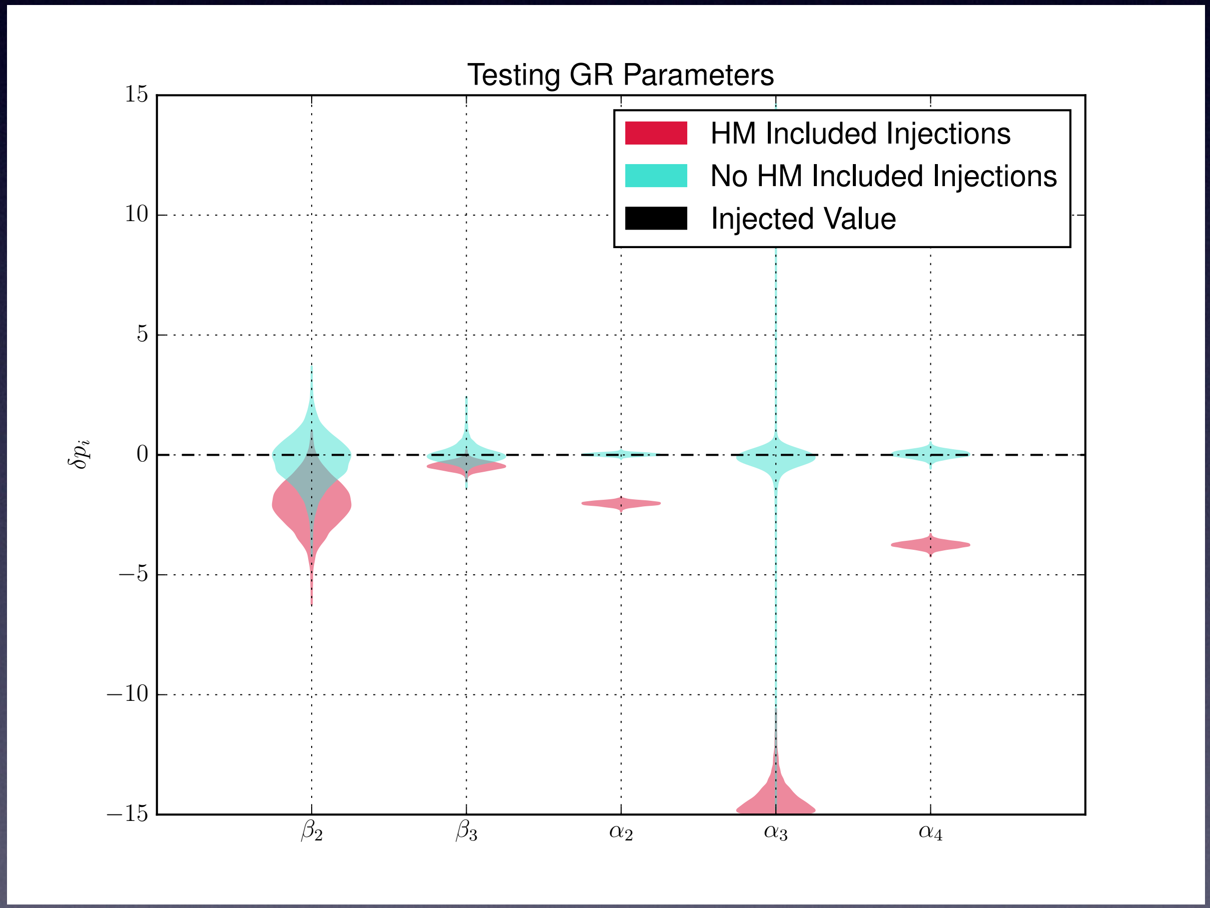
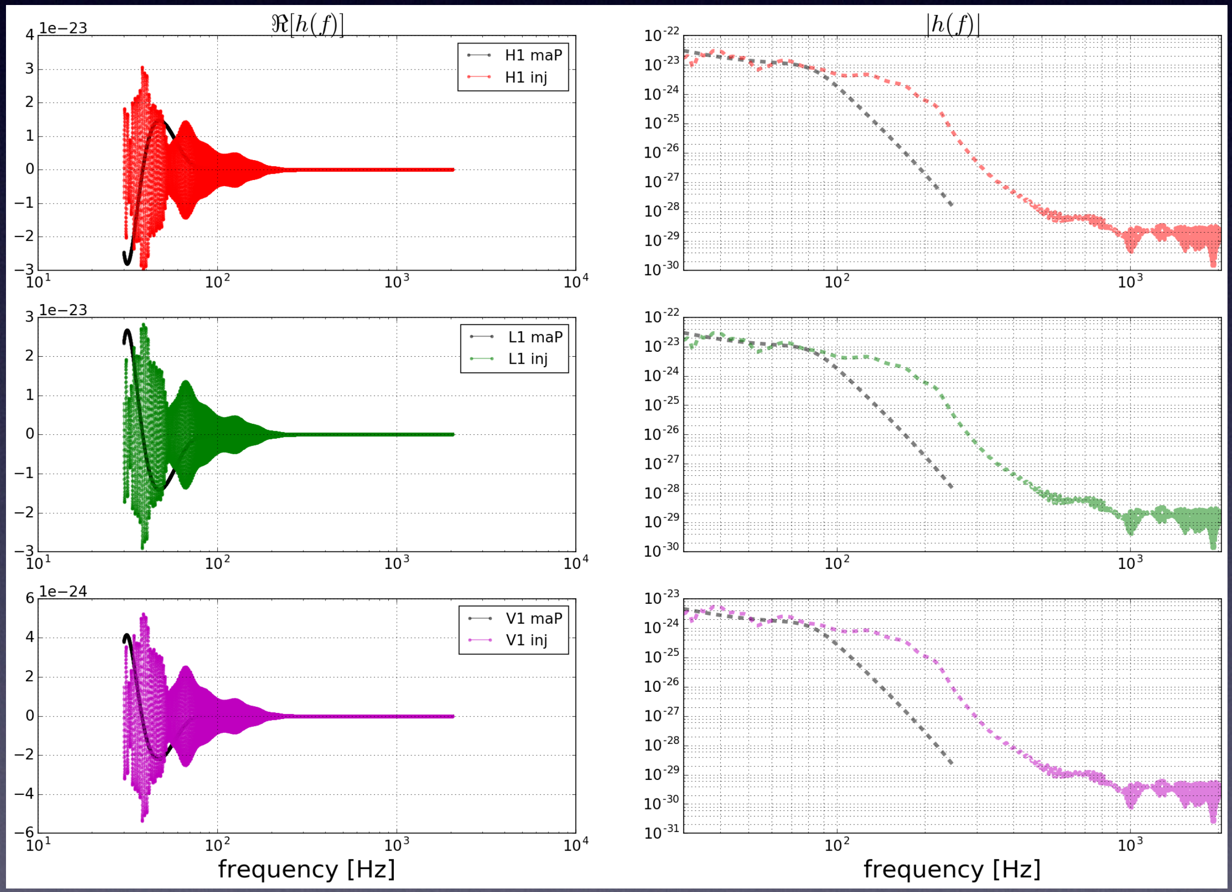
Test Case: q=8, M=170Msun BBH, edge-on, SNR=50





- Absence of higher modes can lead to **apparent fake violations of GR**
- The effect of higher modes is accounted by the alpha and beta corrections to GR.
- Larger impact at large post-Newtonian orders
- Wrong signal recovery when GR corrections are switched off.

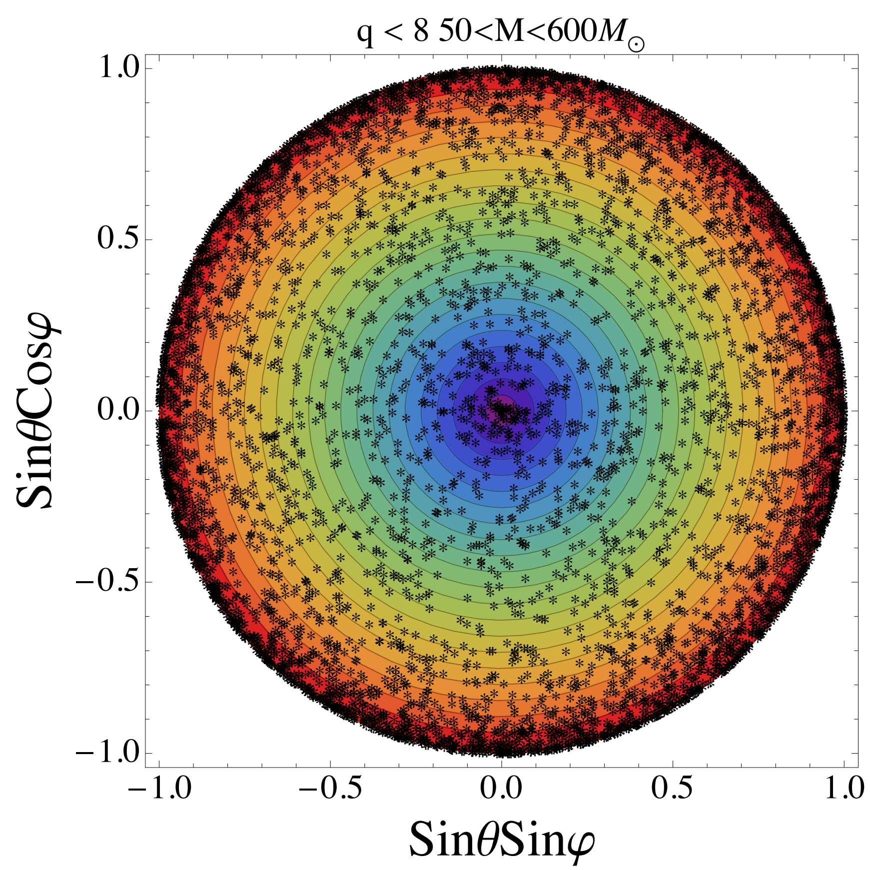
On its way: implementing a search including higher order modes

Search including higher order modes:

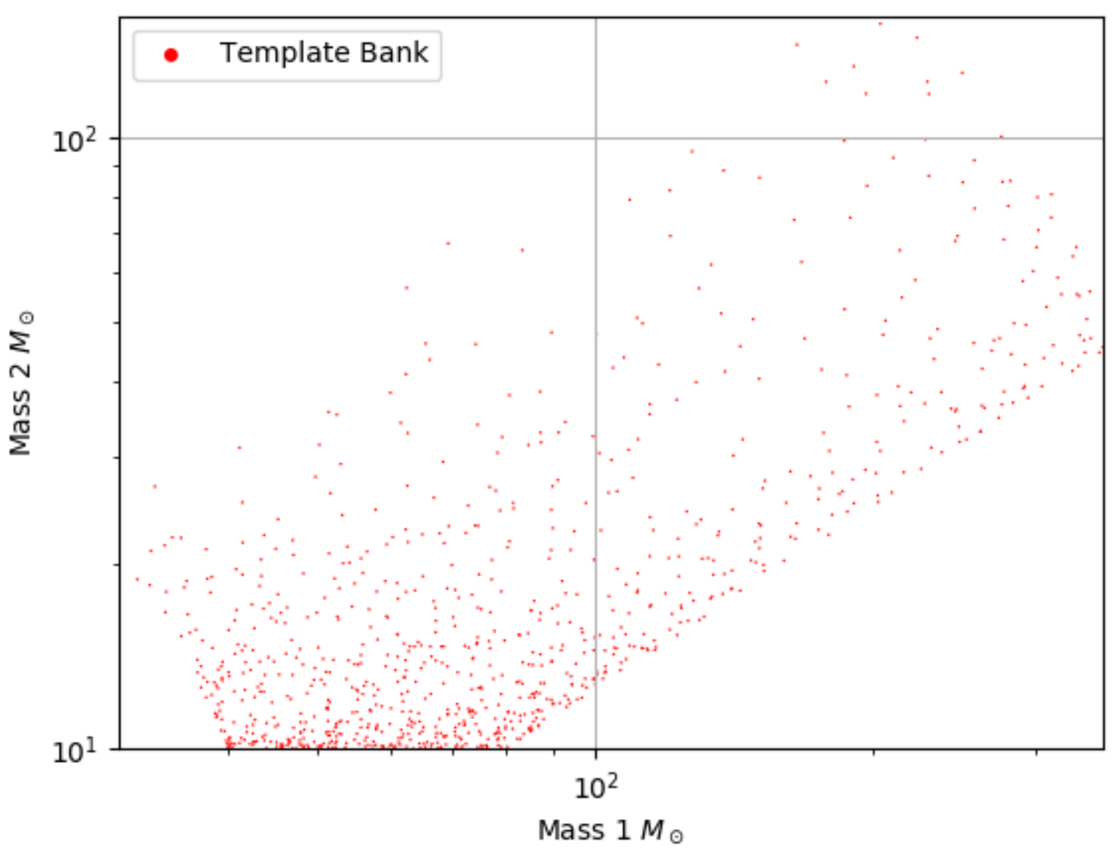
- We build on the existing pyCBC search algorithm.
- Higher modes force us to include two extra parameters: the **<u>orientation angles</u>** of the source.
- Polarisation can be analytically maximised over.
- Growth of the number of required templates.

Template bank including higher modes: used EOBNRv2HM model (Pan +, PhysRevD.81.084041)

Templates vs. orientations



Templates vs. masses



Conclusions:

- All LIGO detections so far are characterised by a low mass ratio, total mass ≤ 100Msun, and no clear evidence for a precessing orbital plane.
- Omission of physical effects like higher modes or precession damages our ability to detect binary black holes, specially those not satisfying the above conditions.
- Precession can have a large impact even for large total masses.
- Losses up to 30% occur for the current version of Advanced LIGO.
- Need for waveform models including the effects of both precession and higher order modes (Ongoing work by Khan, Mishra, Cotesta, UIB group +).

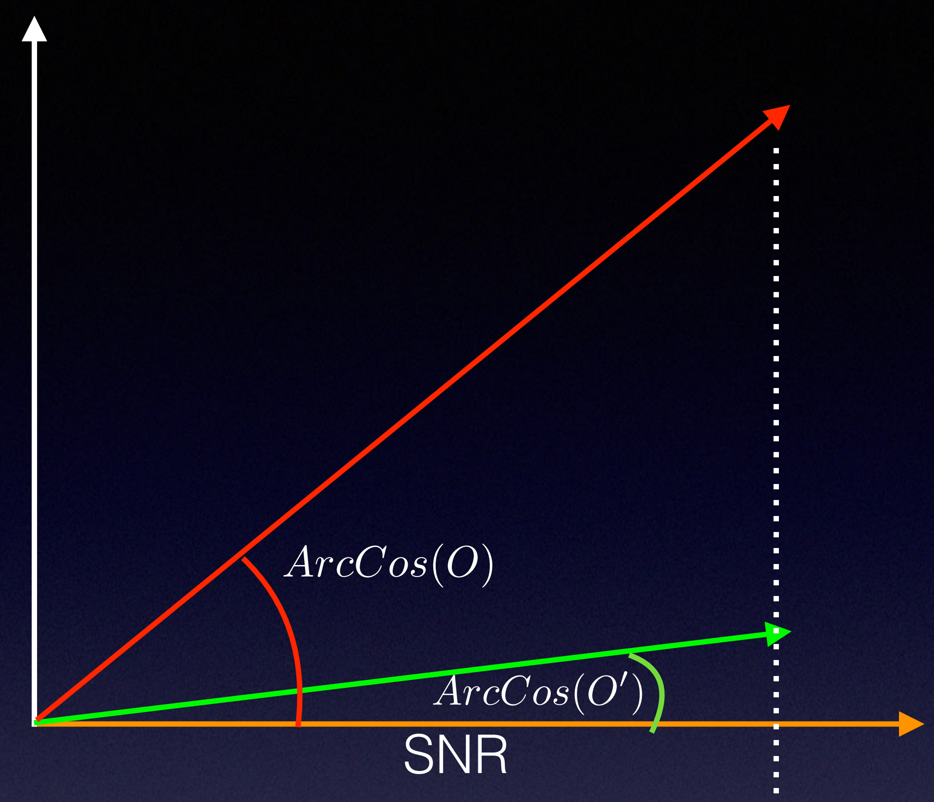
Ongoing work:

- Development of a search using such waveform model, and hopefully discover IMBBH's?.
- We need a waveform model including both precession and higher order modes.

Bonus: Key aspects of GW detection.

$$\rho = \frac{|\langle h|s\rangle|}{\sqrt{\langle h|h\rangle}} \qquad \langle a|b\rangle \equiv 4\int_0^\infty \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}\mathrm{d}f$$

- SNR is just the projection of the signal s onto the template h.
- If h does not accurately represent the GW contained in s, SNR will be suboptimal.



$$O(a|b) = \frac{\langle a|b\rangle}{\sqrt{\langle a|a\rangle\langle b|b\rangle}} \in [0,1]$$

$$\rho(a|b) \sim O(a|b)$$

$$\rho \sim 1/D_{Hor}$$

$$\Rightarrow$$

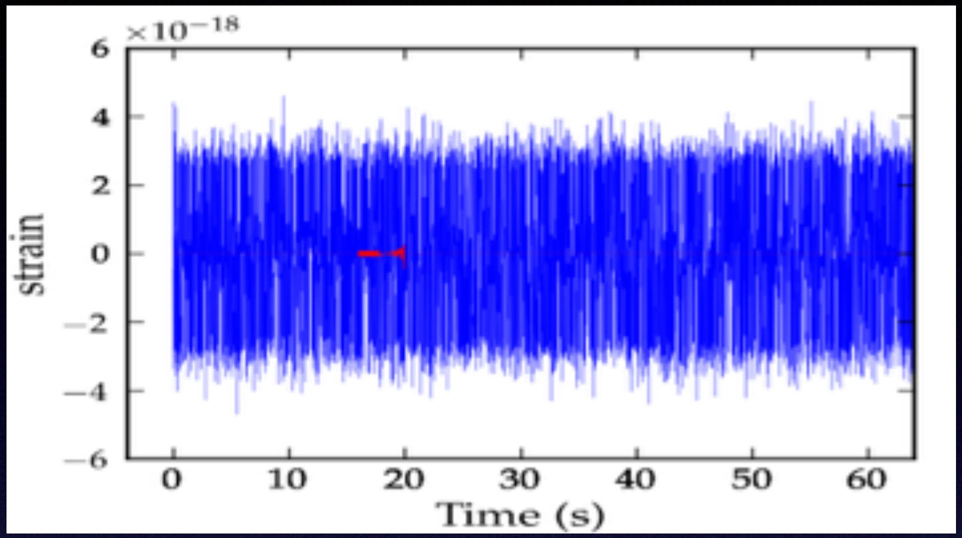
$$D_{Hor} \sim O(a|b)$$

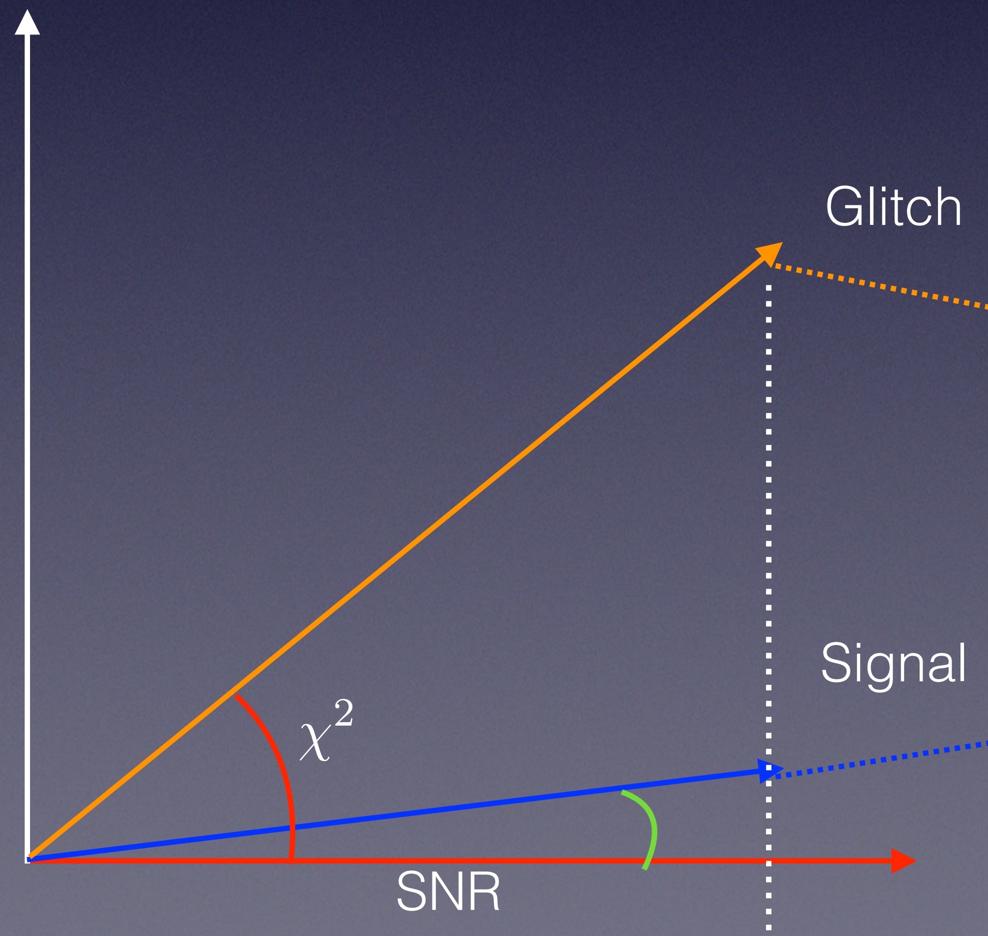
$$V_{Hor} \sim O(a|b)^3$$

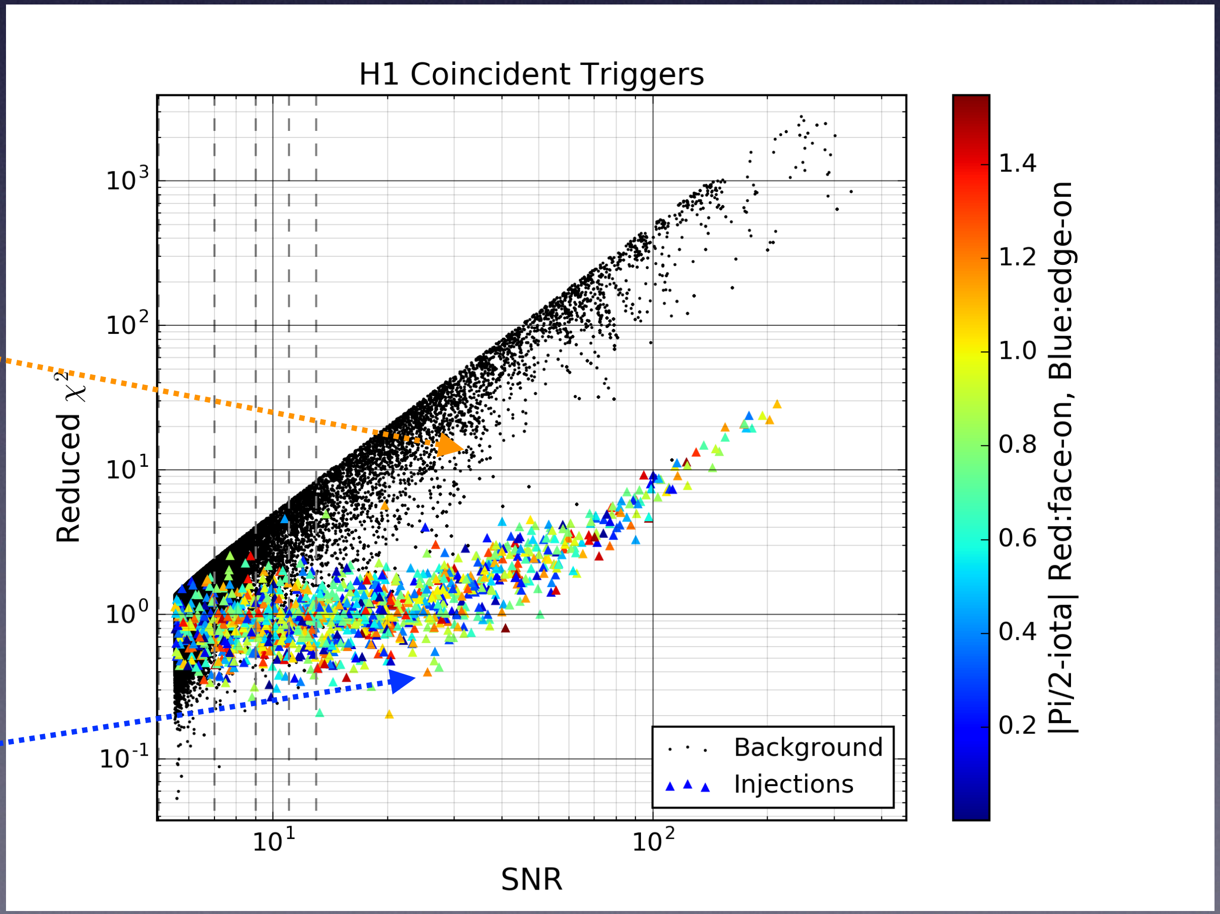
- Inaccurate templates lead to a loss of SNR and sensitive volume.
- Omission of physical effects causes templates to be inaccurate: event loss and parameter bias

Bonus: Key aspects of GW detection.

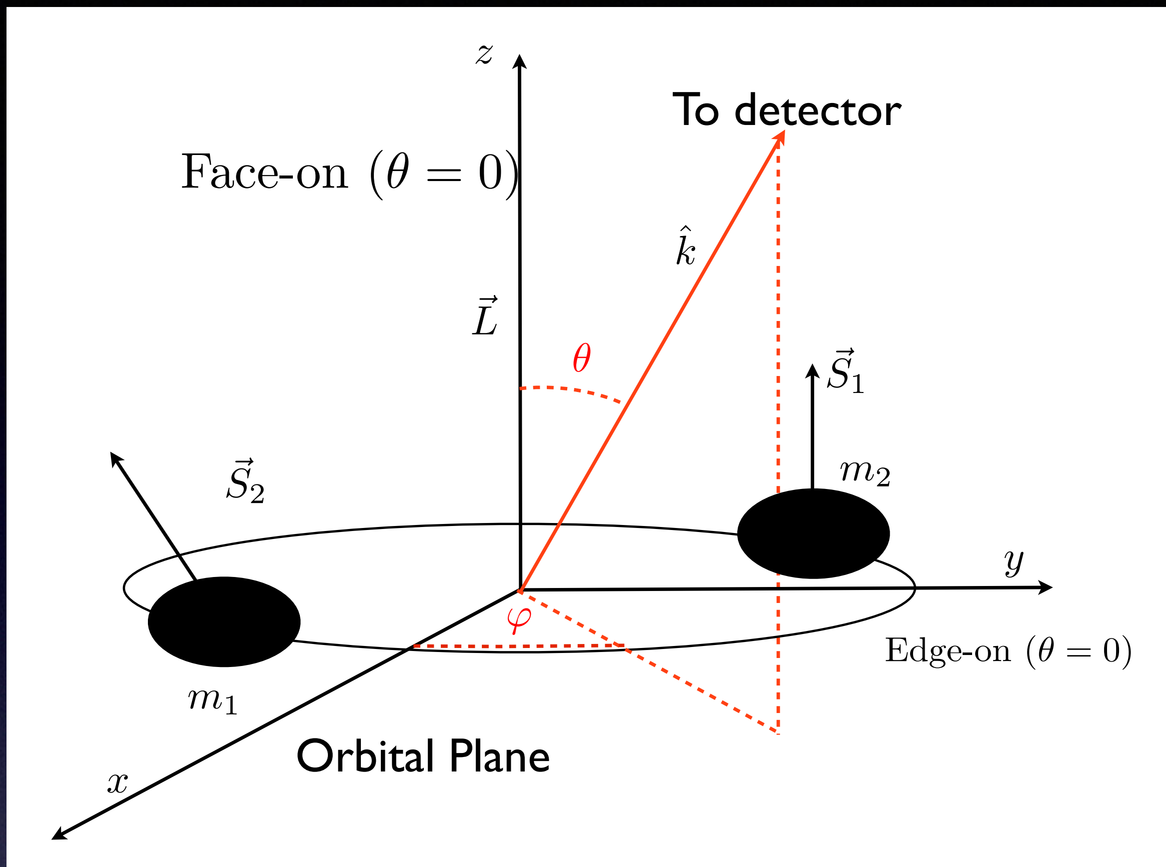
- We look for weak signals in strong noise: usage of matched filter technique.
- We use templates as filters for the incoming signal, and compute its signal-to noise ratio (SNR).
- Noise is non-Gaussian: we need to discriminate noise transients from real GW's.







Bonus: Parameters of Binary Black Holes' signals



- 2 Masses:

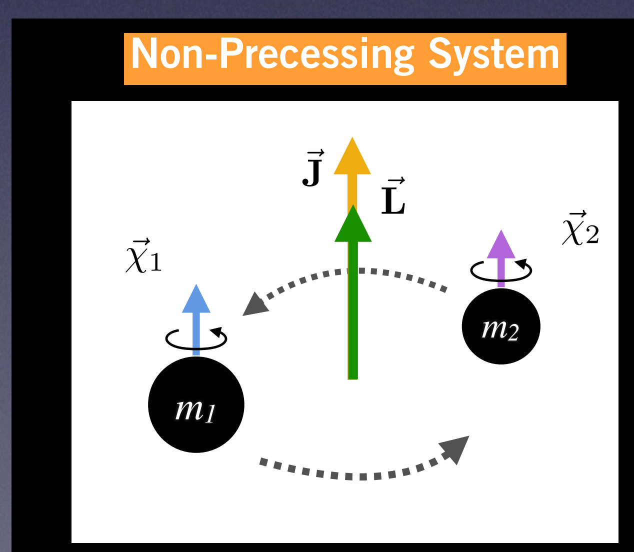
$$M = m_1 + m_2 \qquad q = \frac{m_1}{m_2} \geq 1$$

- ~~6 Spin Components:~~

$$\chi_{eff} = \frac{s_1^z m_1 + s_2^z m_2}{m_1 + m_2}$$ 2 Spin Components

- ~~Orientation of the Binary (2 angles)~~
- ~~Orientation of the Detector (3 angles)~~
- ~~Distance~~
- ~~Time of arrival~~ +

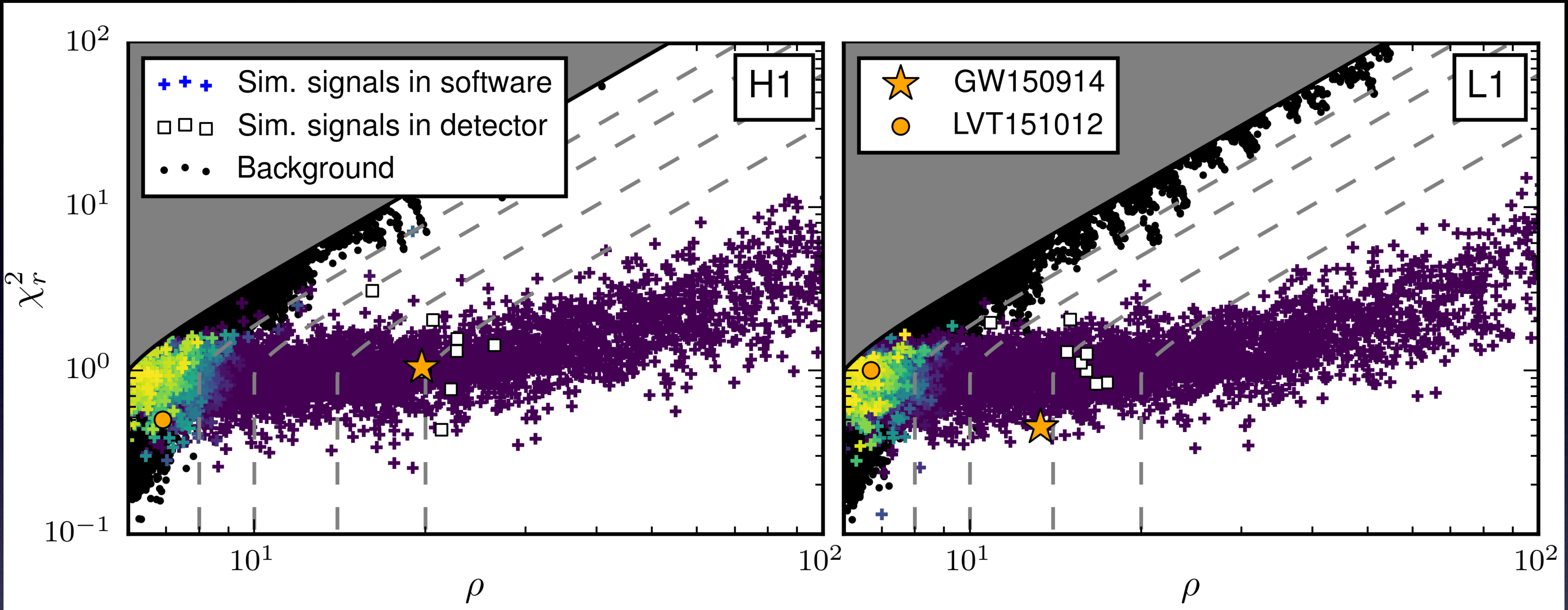
4 Physical Parameters



No in-plane spins

No Higher Modes → Analytical Maximisation over angles

Bonus: Significance of GW150914

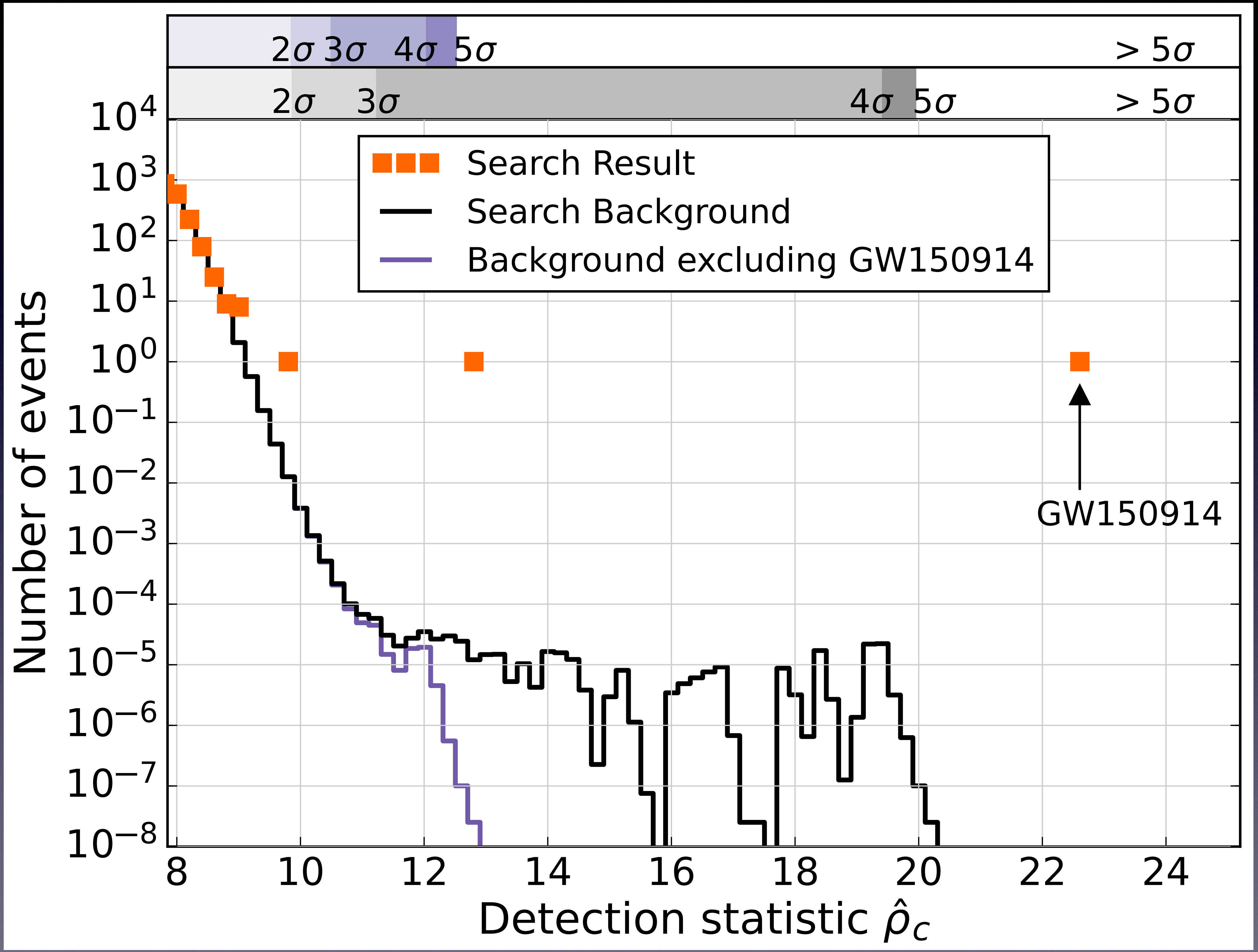


LSC + Virgo, Phys. Rev. D 93, 122003

- Need to define some ranking statistic.
- Compute the distribution of the ranking statistic in background: time-slides method.

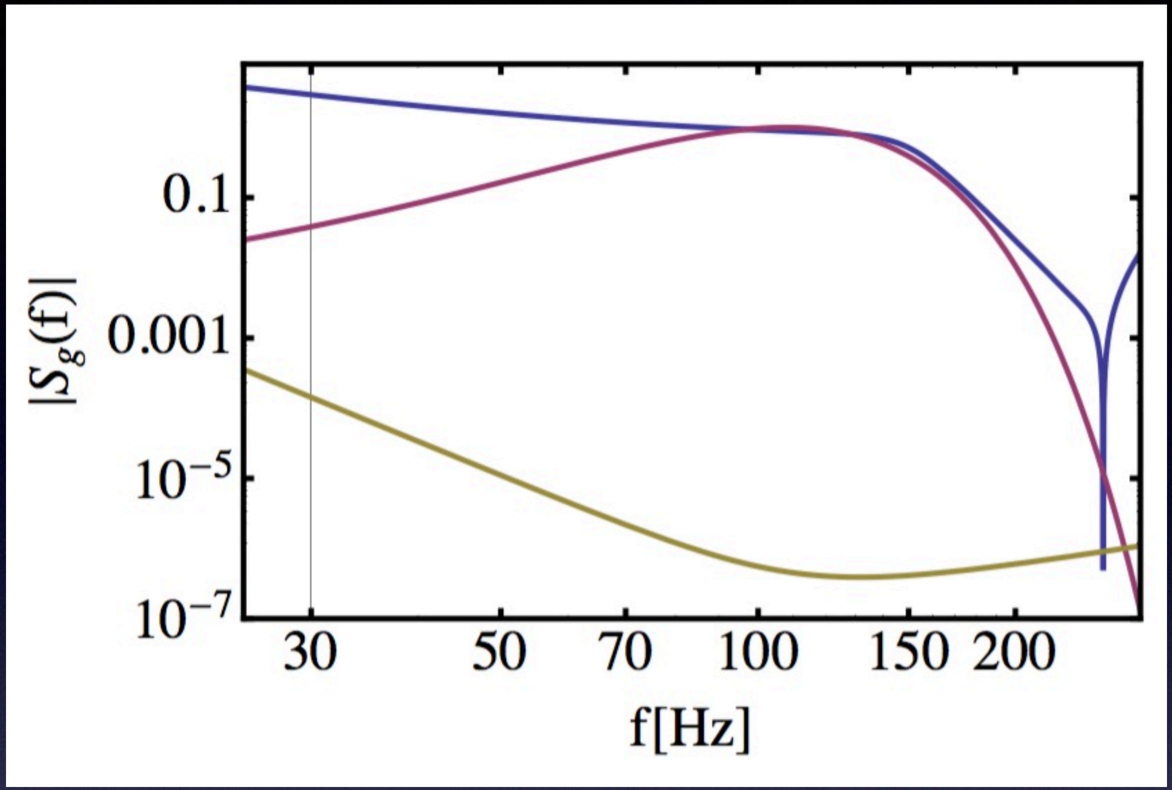
$$\hat{\rho} = \begin{cases} \rho\left[(1+(\chi_r^2)^3)/2\right]^{-\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$

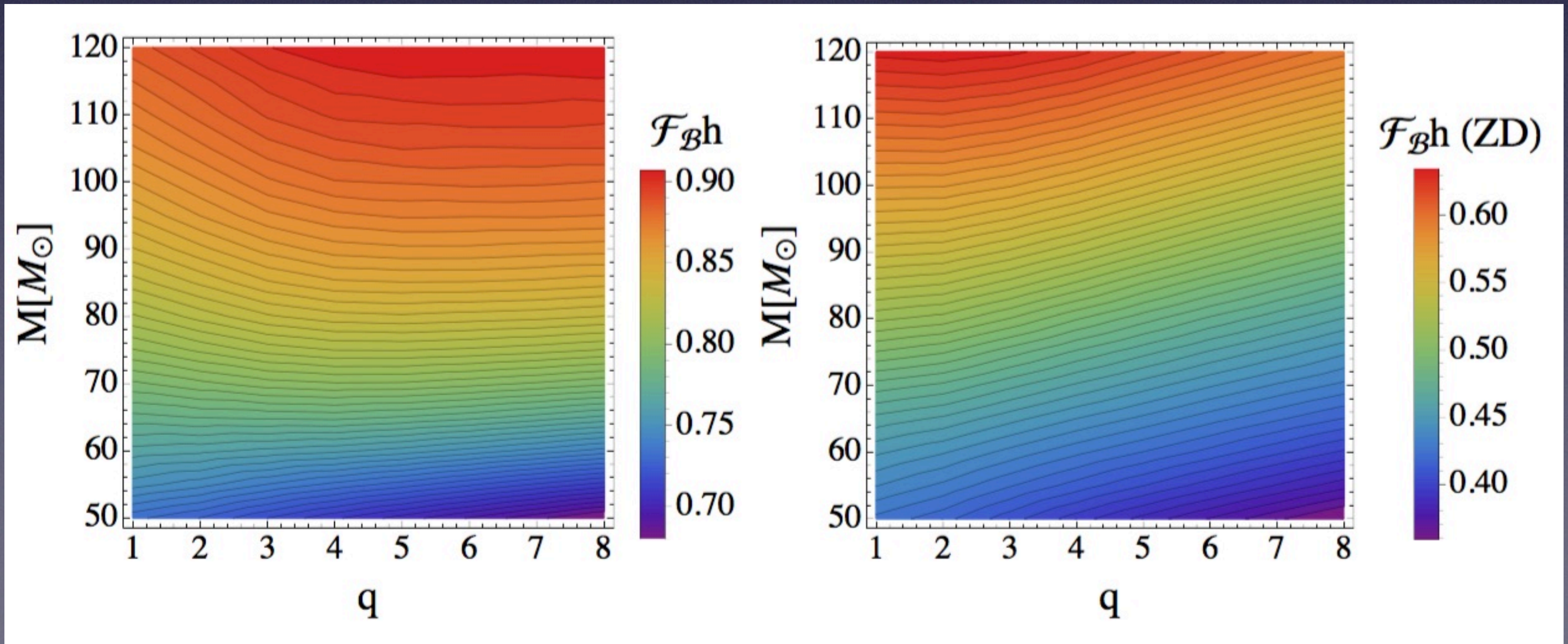
Bonus: Significance of GW150914



LSC + Virgo, Phys. Rev. X 6, 041015 (2016)

Bonus: How similar are sine-gaussian glitches to IMBH signals?



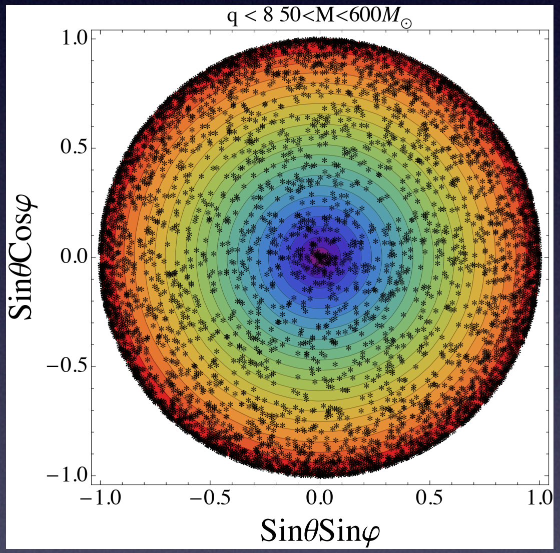


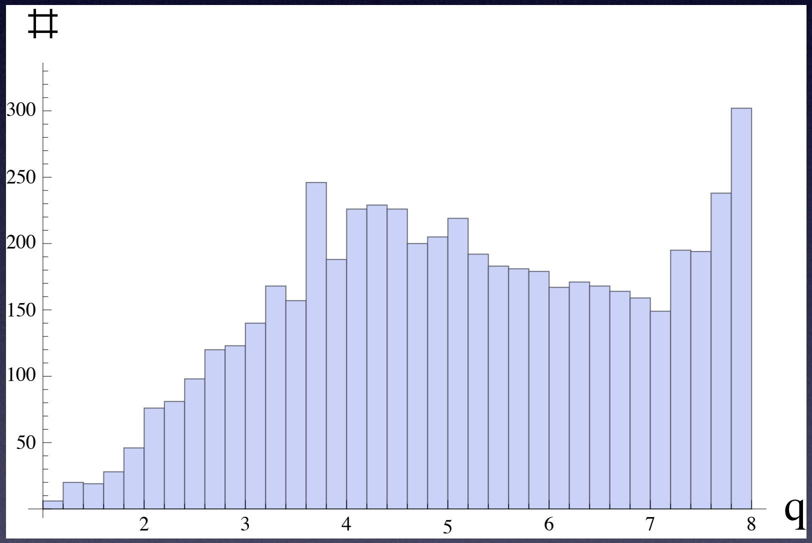
JCB, PhD Thesis

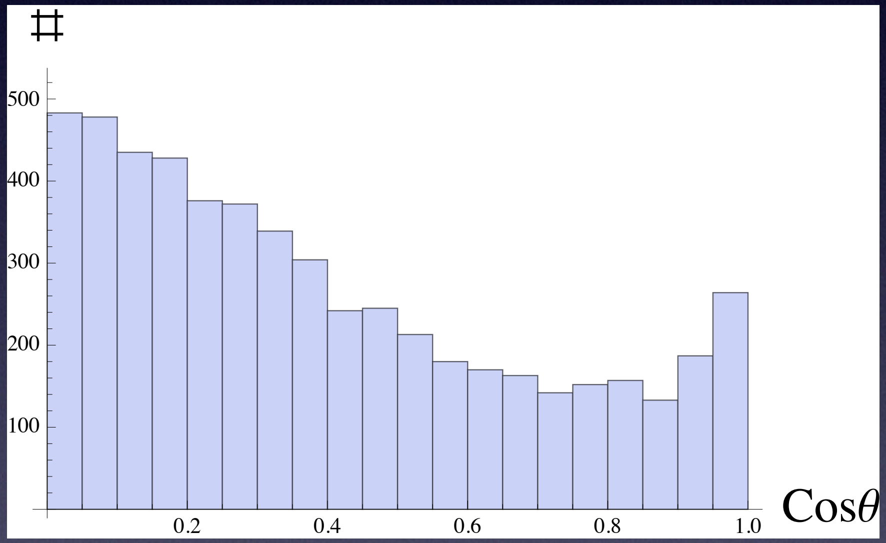
Bonus:Template bank including higher order modes:

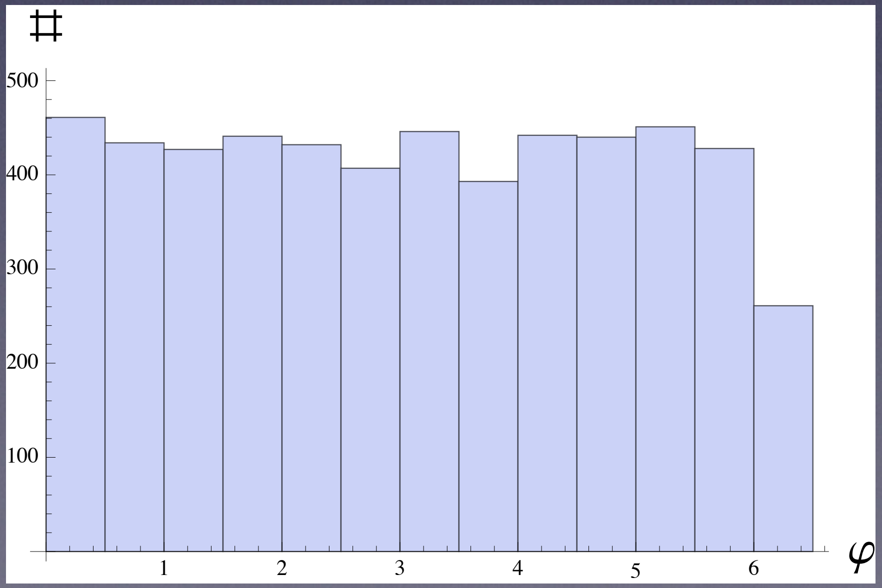
Key facts:

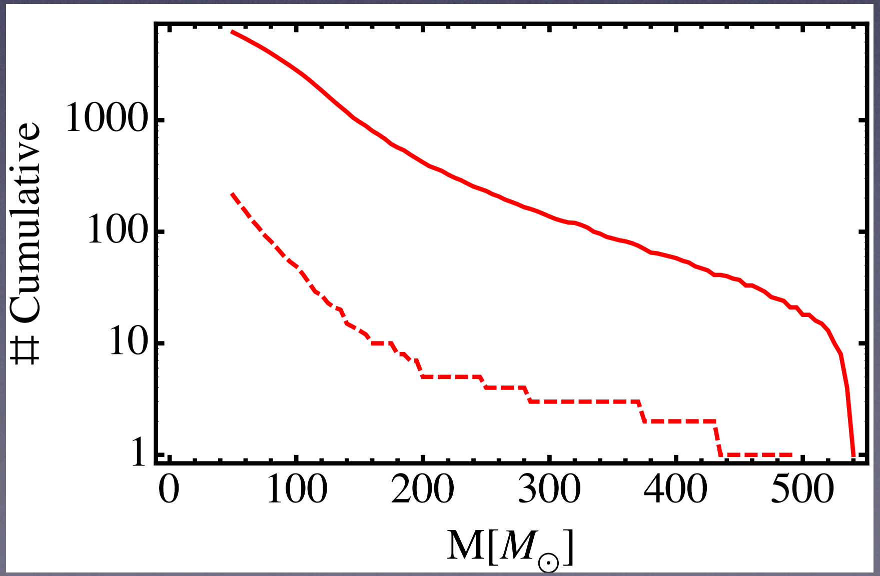
- EOBNRv2HM (non-spinning).
- Inclination and azimuth (theta and phi below) are now template parameters (polarisation is maximised over)
- Size ~6000 templates. Modifying now pycbc_inspiral_skymax to use this.



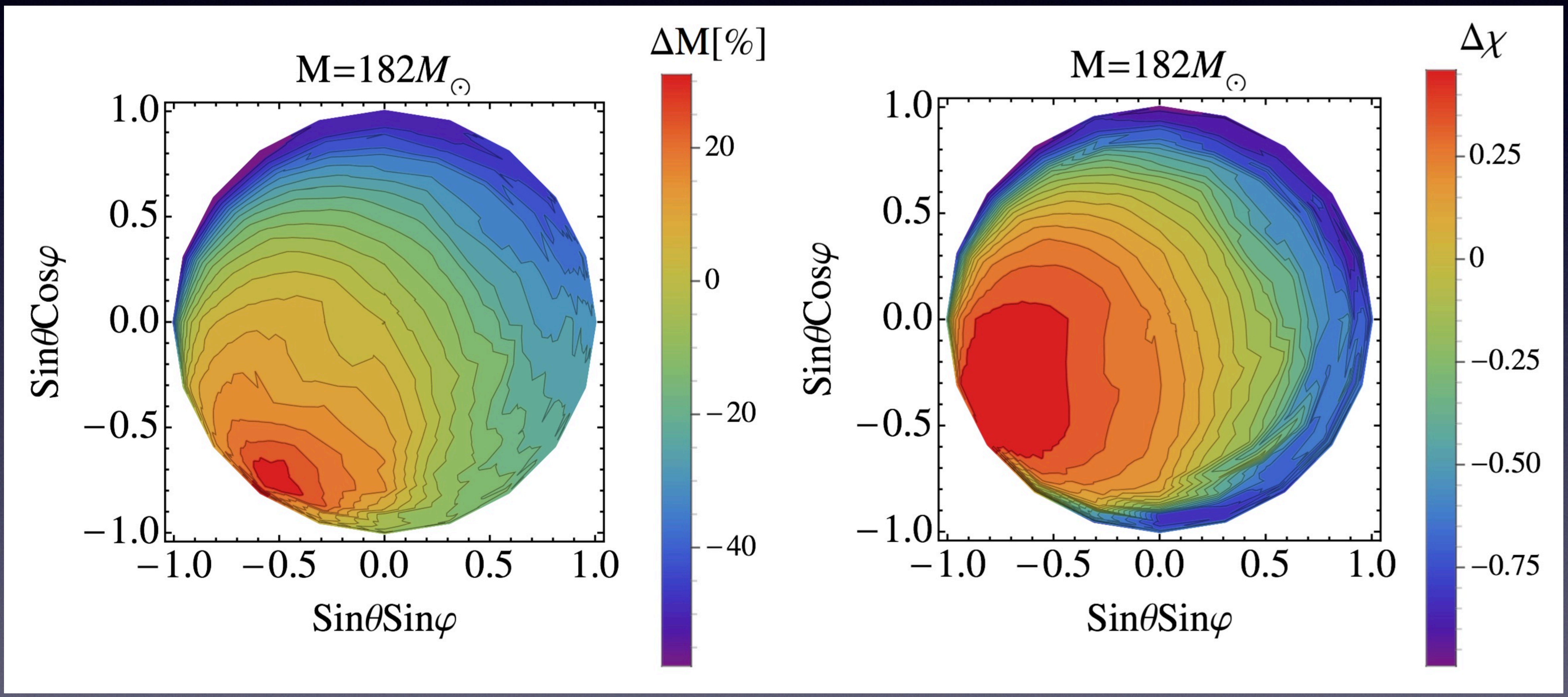




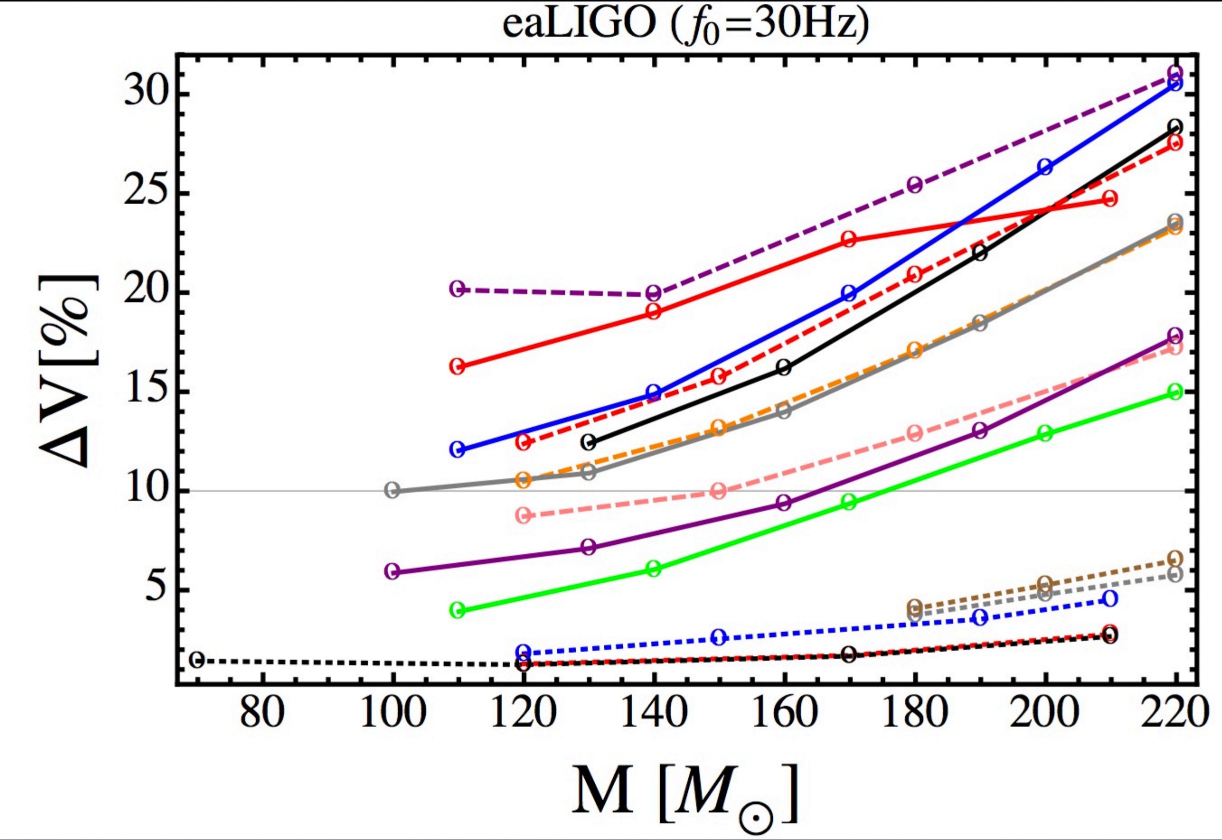


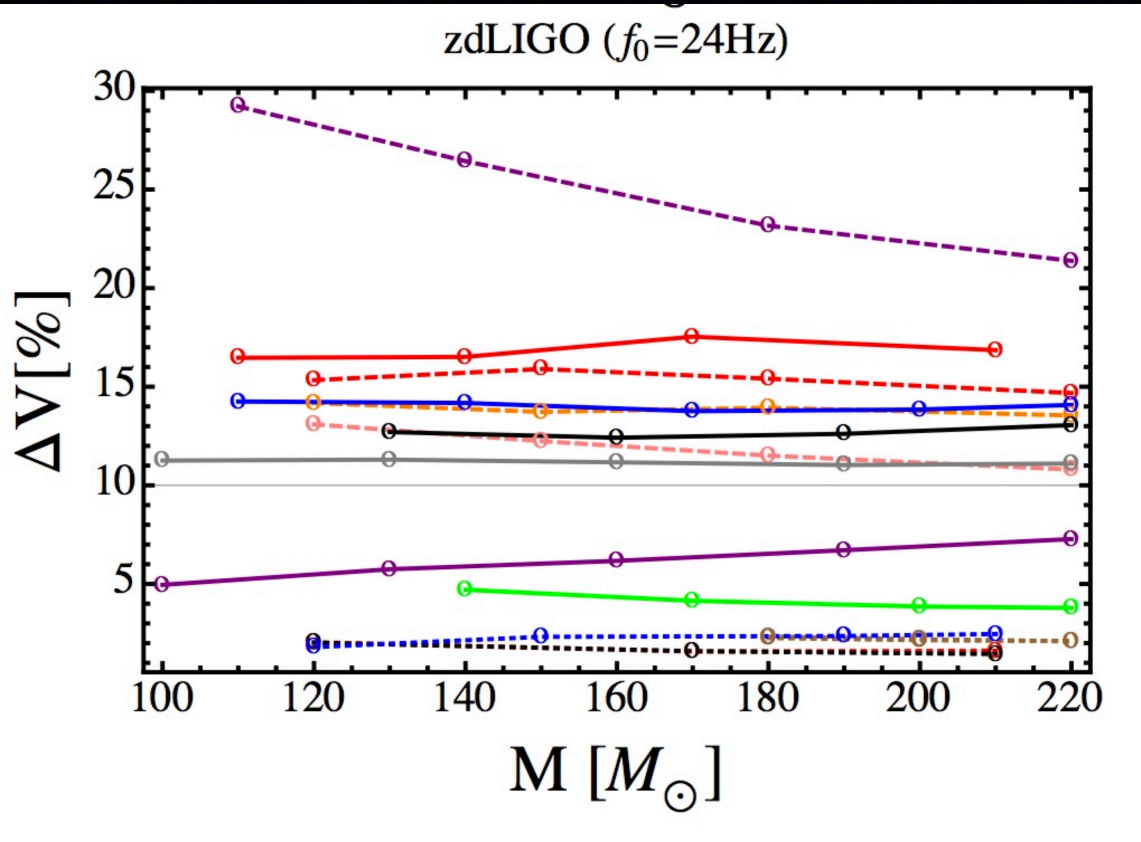


Bonus: Parameter bias due to omission of higher modes:



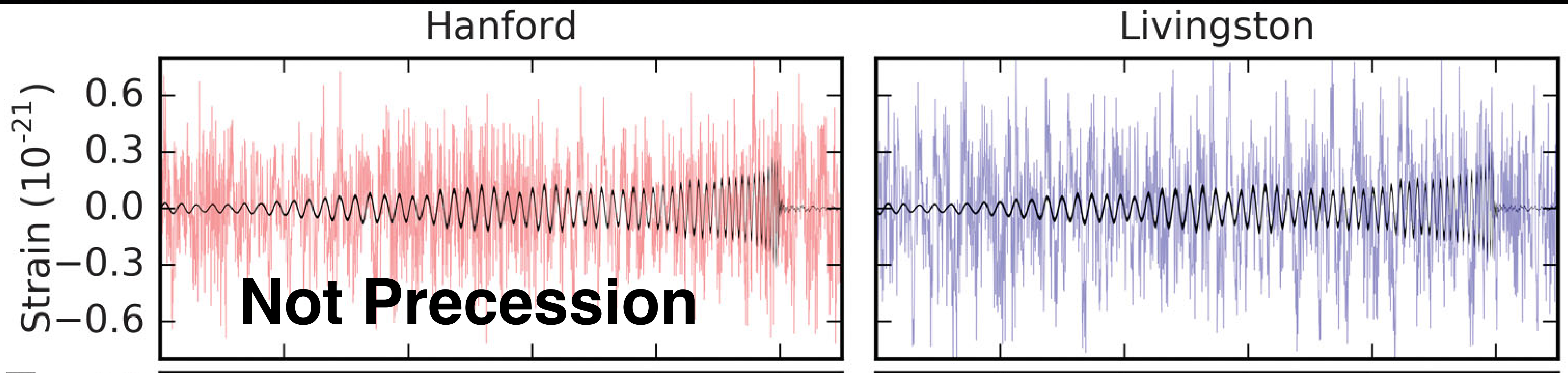
Bonus: The case of 2018 Advanced LIGO:





- Lower impact of higher modes due to signals lasting longer in band.
- Rather constant impact of both precession and HM as a function of total mass.
- Slightly larger impact of precession due to waveforms being longer

Introduction: matched filter searches (or modelled searches)



GW151226 (or Boxing Day event)

LSC+ Virgo, PRL 116, 141103 (2016)

Key facts of modelled searches.

- GW signals are normally weaker than the detector background noise.
- Compare (via matched filter) the detector output with waveform models (or templates) —> Signal-to-noise ratio.
- Templates need to be accurate representations of the GW signal.
- Wrong modelling leads to loss in SNR and damages the detection process.