

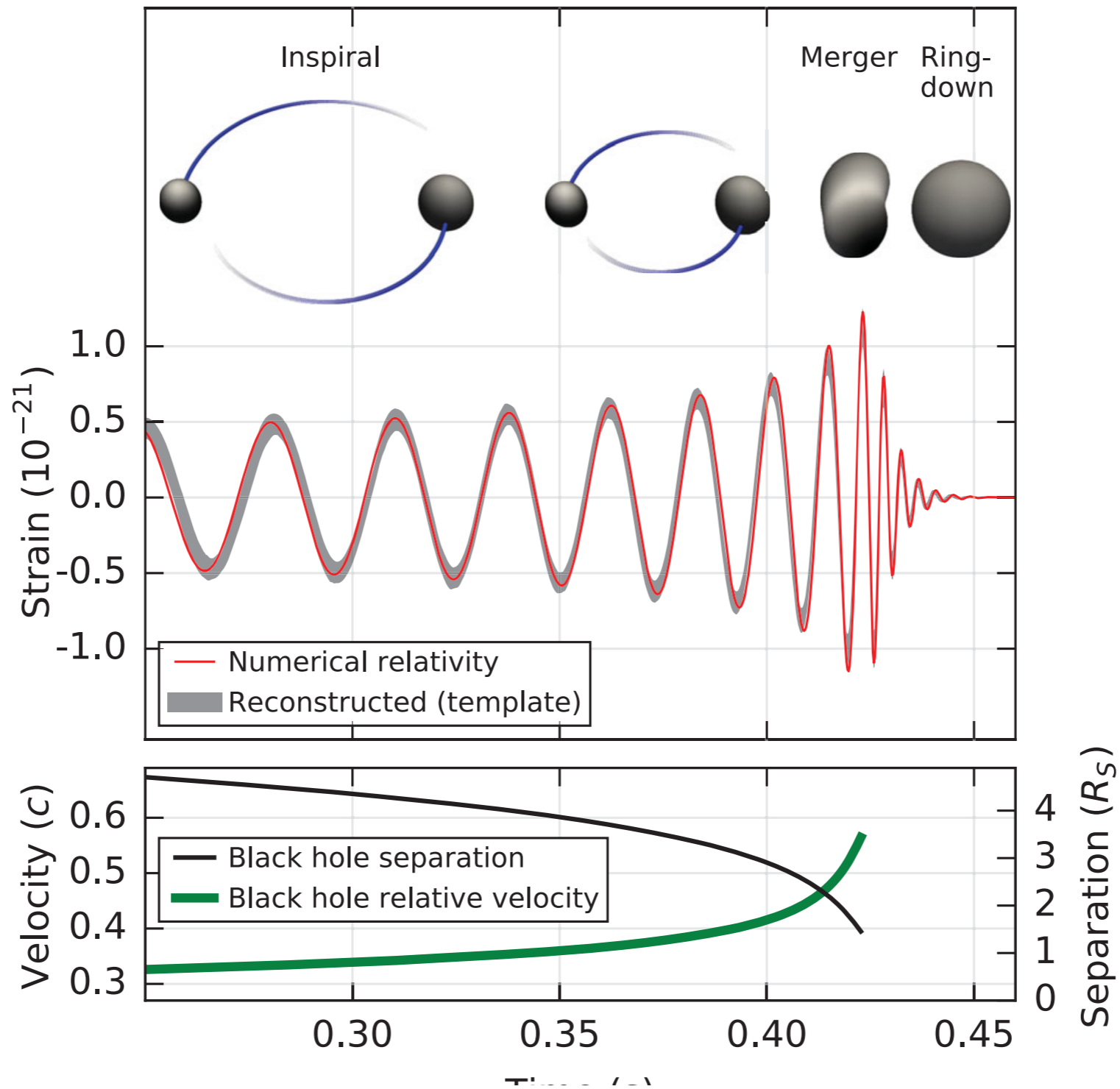
# Numerical relativity and GW data

---

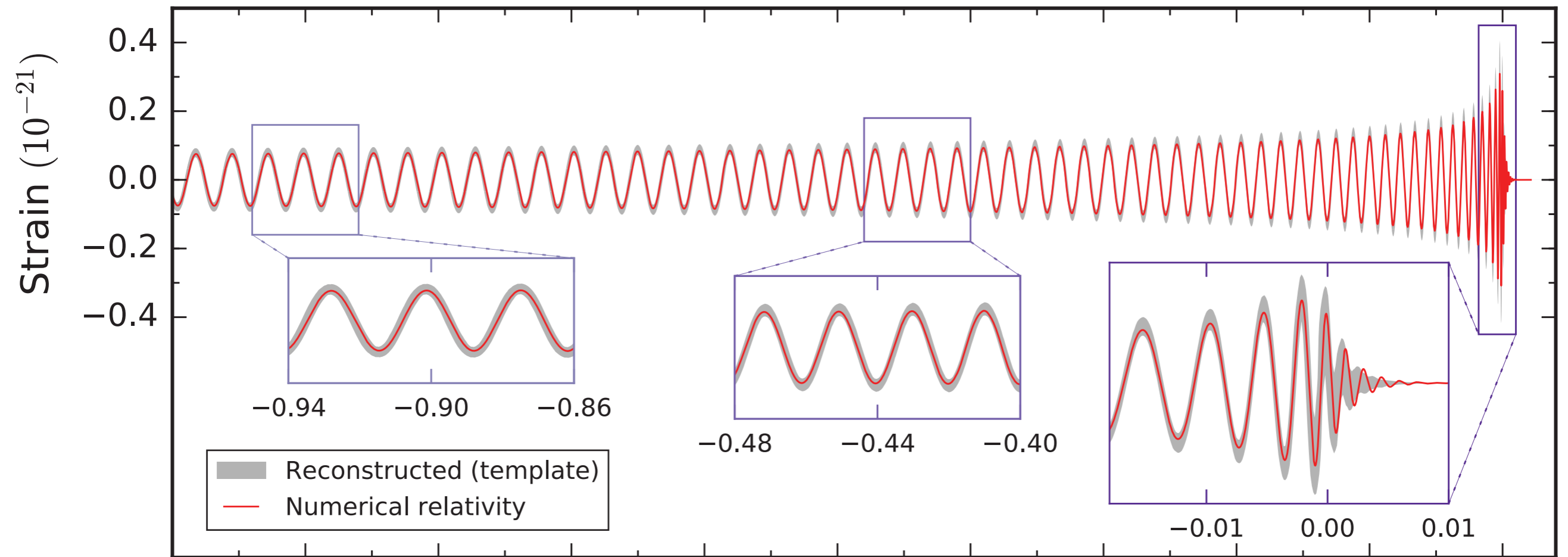
Richard O'Shaughnessy

Aspen, 2017-02-06

# GW150914: Short signal, in agreement with NR



# GW151226: Long signal, still in agreement with NR



# Outline

---

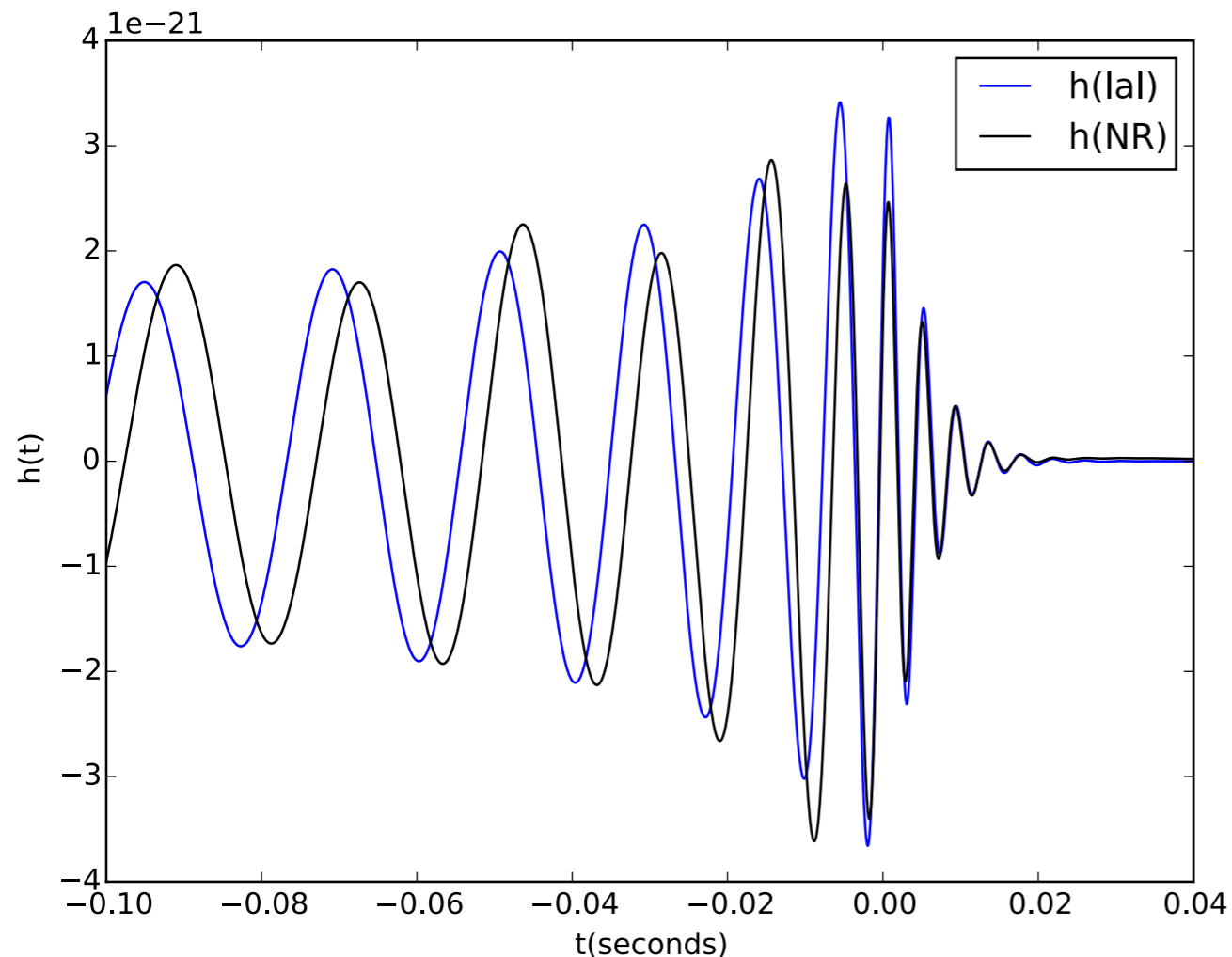
- NR is the best solution to GR, and differences matter
  - Illustration 1: Waveforms
  - Illustration 2: Posteriors
- Using NR directly with GW data
  - A strategy
  - Finite duration & hybrids
  - Sparse density & interpolation, placement
  - NR-calibrated surrogate (or GP) models



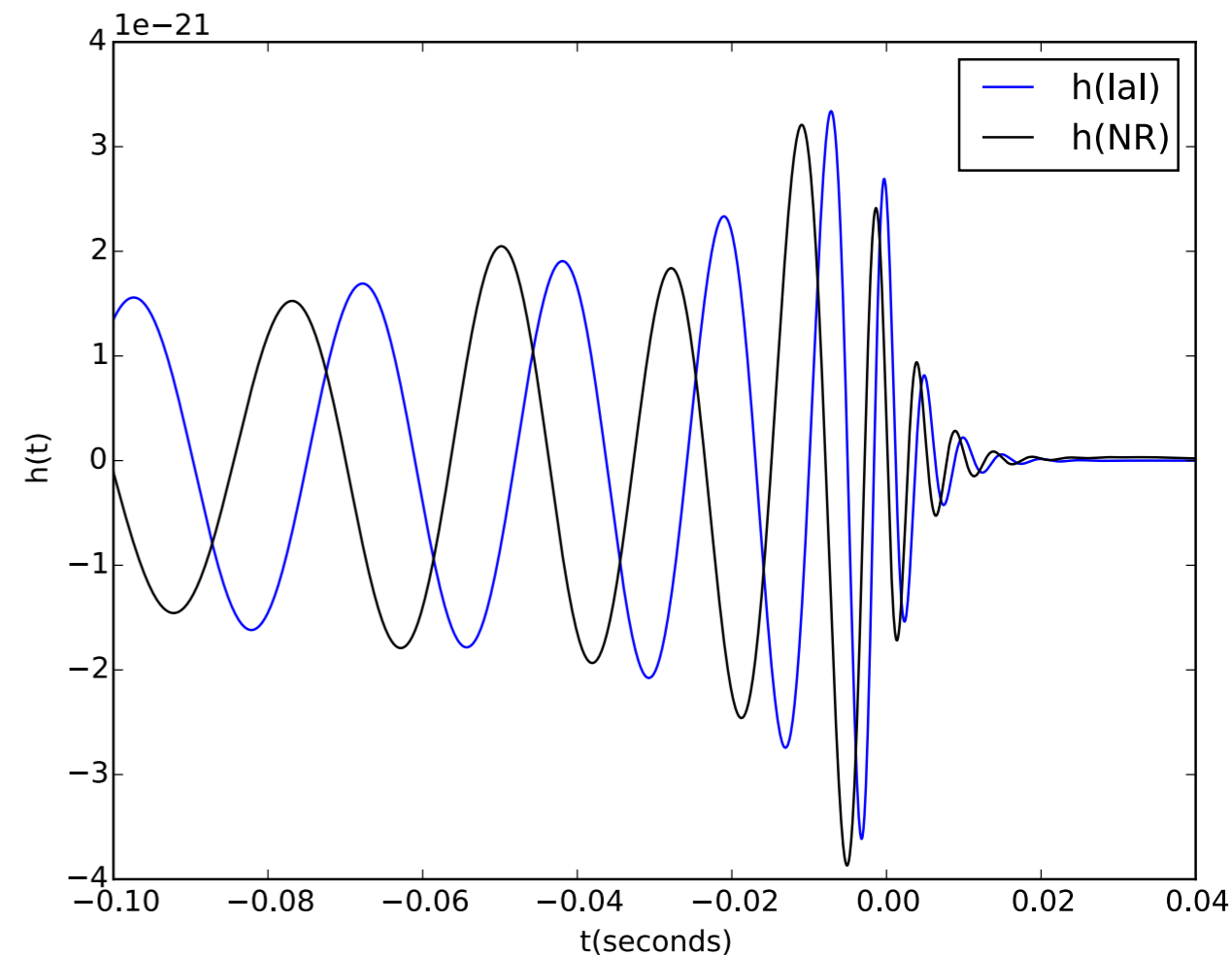
# NR solves GR more completely, accurately

- Analytic models are good first approximations **but not perfect**
- **Example:** Edge-on line of sight

$$q = 2.0, a = 0.0, M = 70M_{\odot}$$



$$q = 2.0, a = -0.8, M = 70M_{\odot}$$



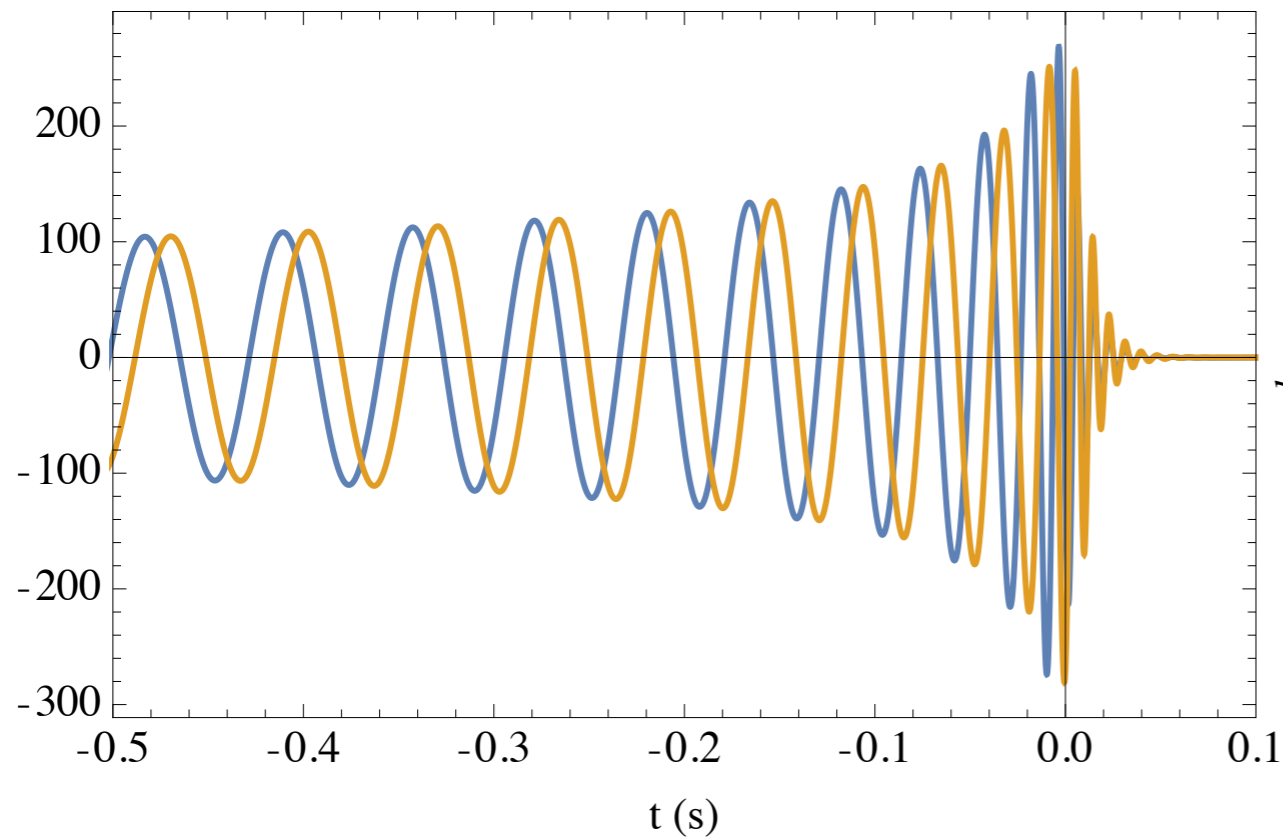
# NR solves GR more completely, accurately

- One reason: “higher modes” are missing or not calibrated

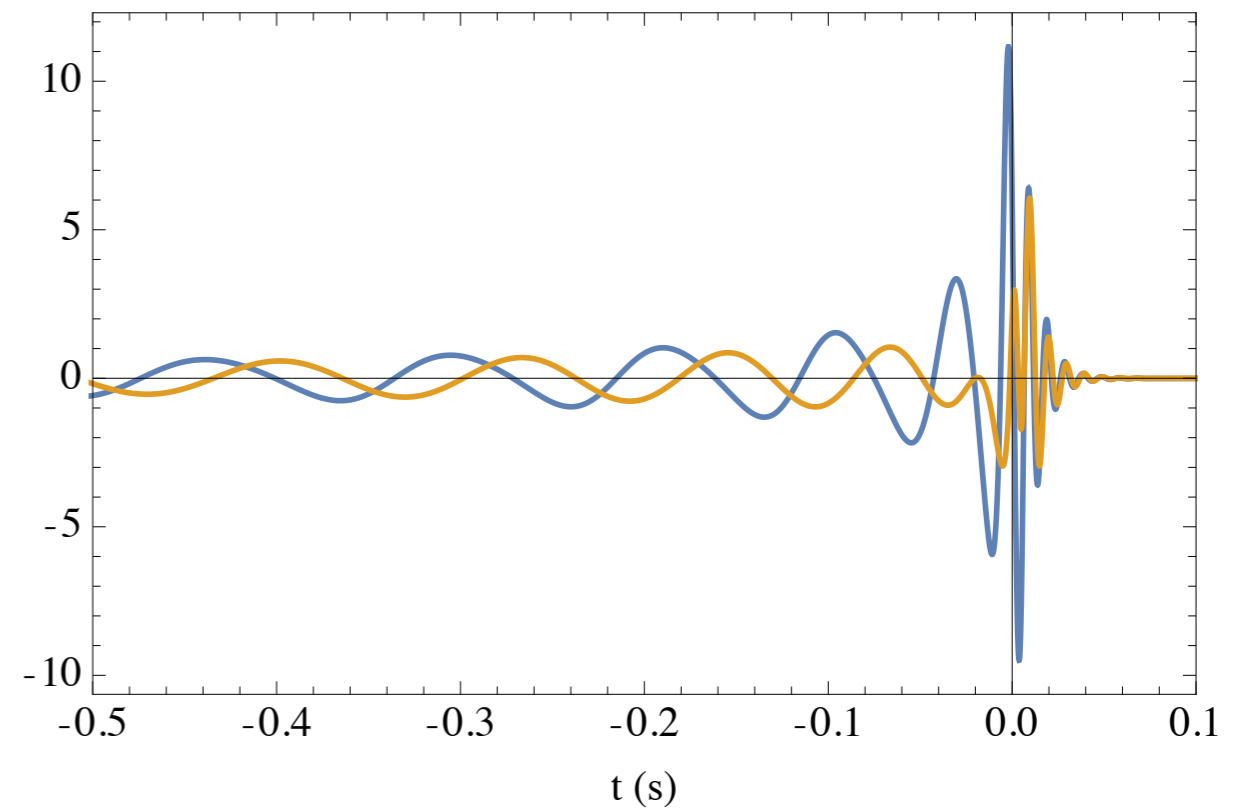
$$h(t|\hat{n}) = \sum_{lm} {}_{-2}Y_{lm}(\hat{n})h_{lm}(t)$$
$$\simeq h_{22}(t) {}_{-2}Y_{22} + h_{2,-2}(t) {}_{-2}Y_{2,-2} + 0$$

NR  
Model (SEOBNRv3)

GW150914-like

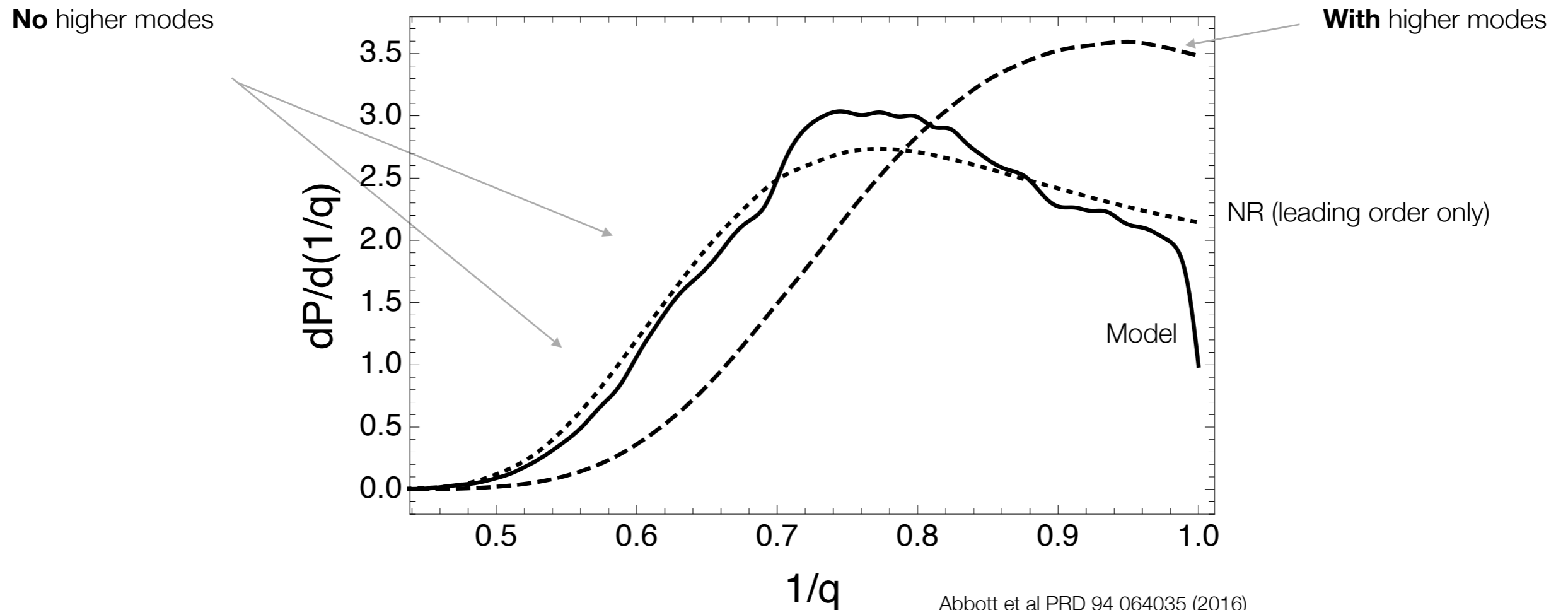


GW150914-like



# Differences matter

- Conclusions about BBH derived from NR are often slightly different
  - Even where models are “well-calibrated”

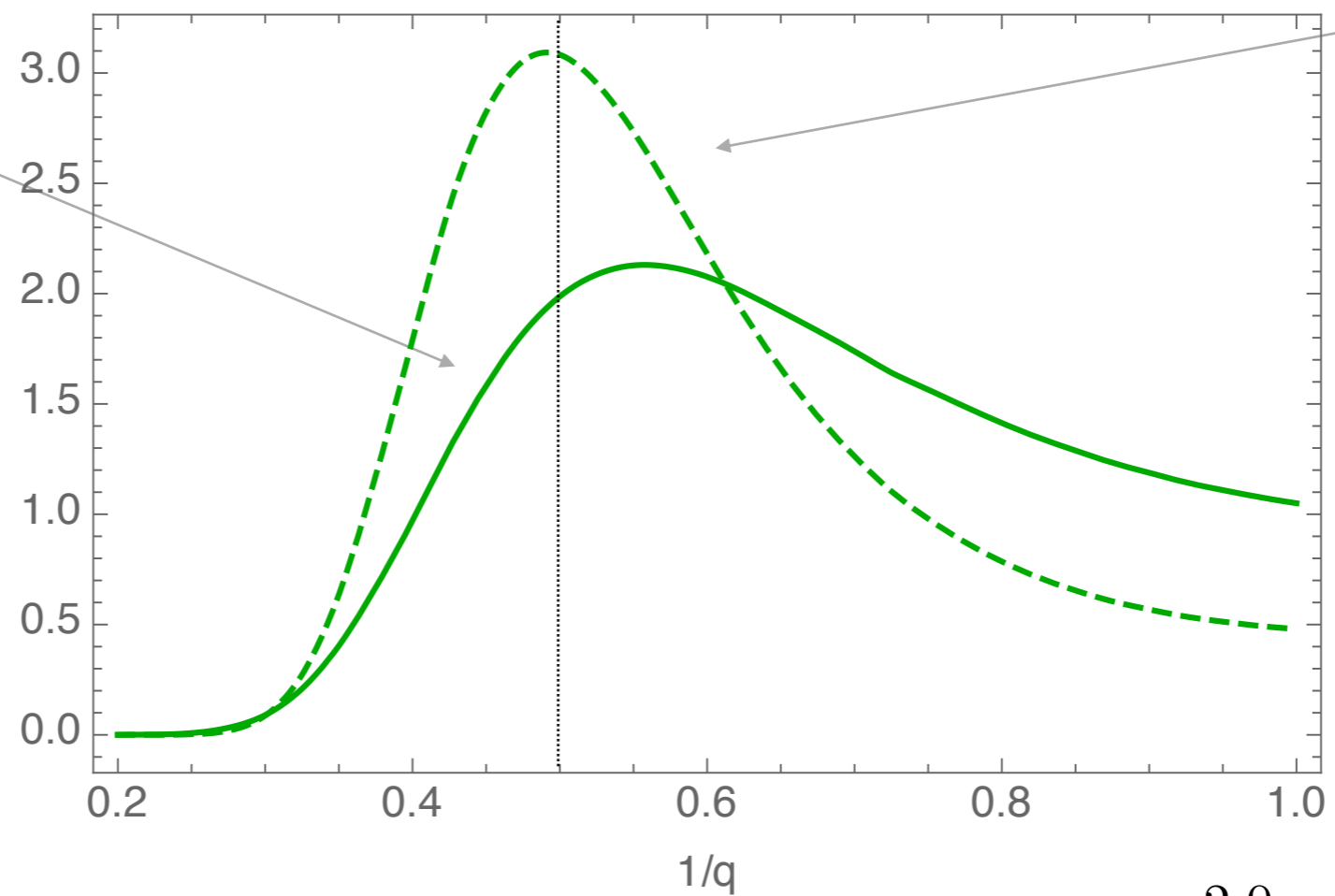


Abbott et al PRD 94 064035 (2016)  
GW150914: directly comparing to NR (=with higher modes)  
Nonprecessing analysis

# Differences matter

**No** higher modes

**With** higher modes

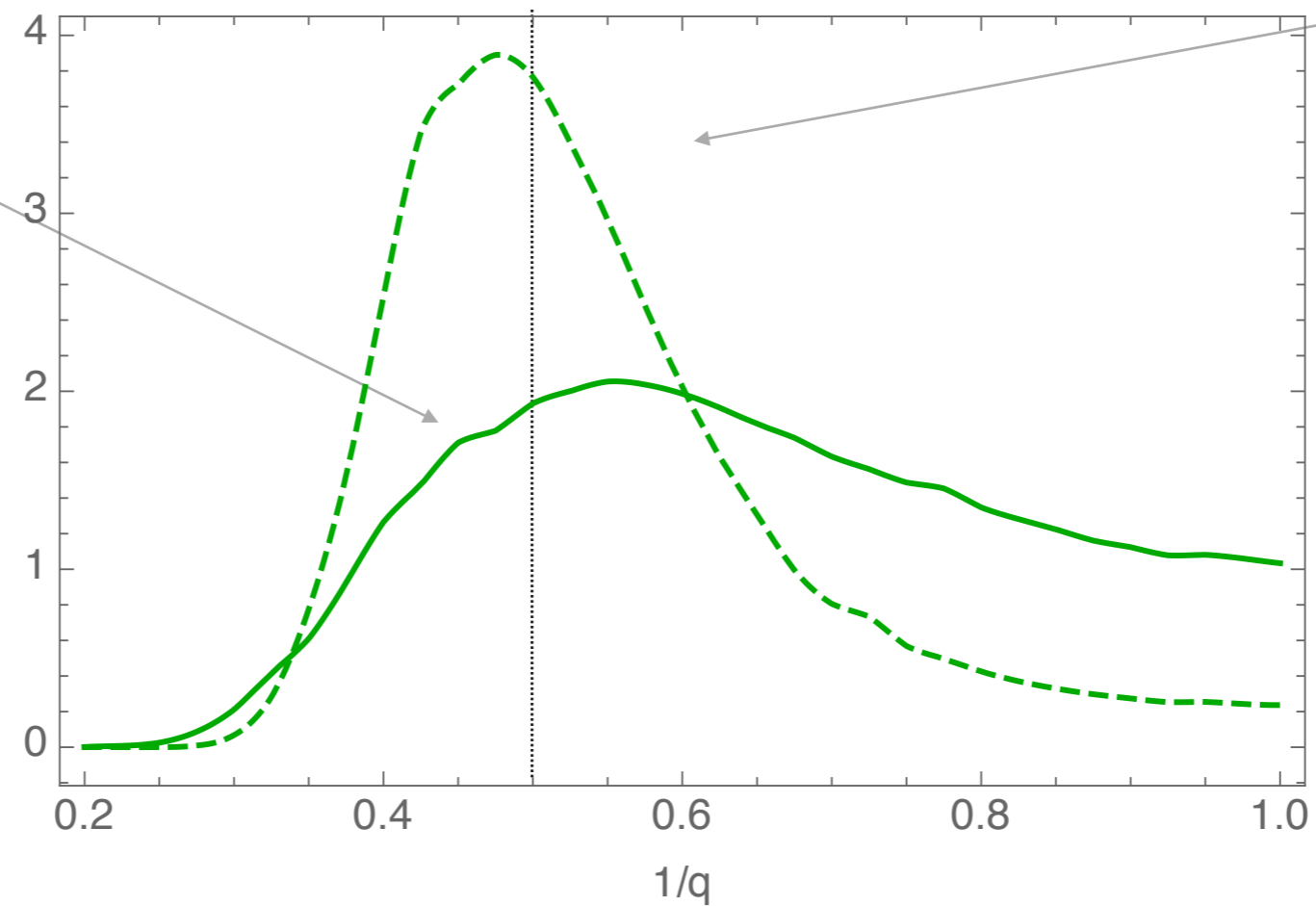


Synthetic data  $q = 2.0, a = 0.0, M = 70M_{\odot}$   
PSD similar to GW150914-like sensitivity  
Inclination  $\sim \pi/4$ , SNR=20  
Nonprecessing analysis

# Differences matter

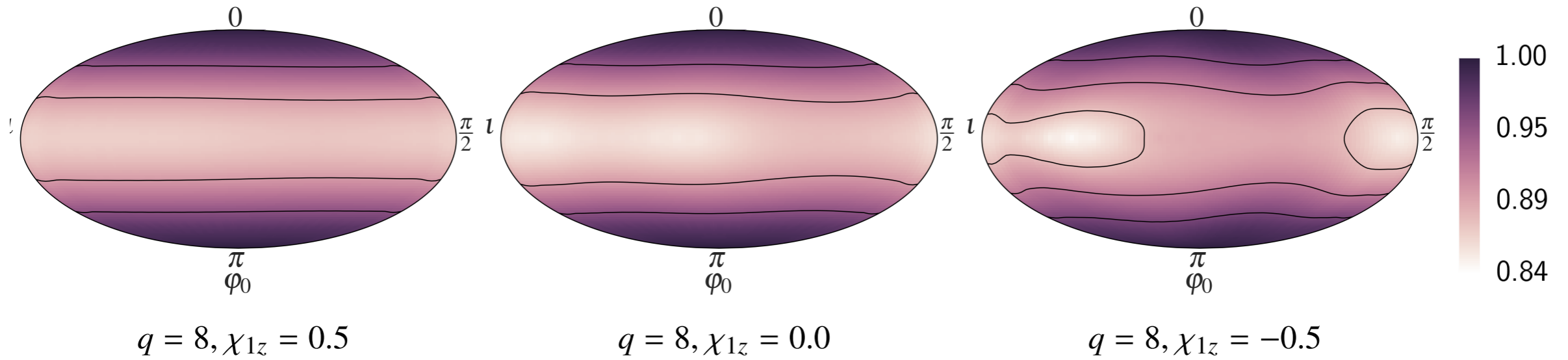
**No** higher modes

**With** higher modes

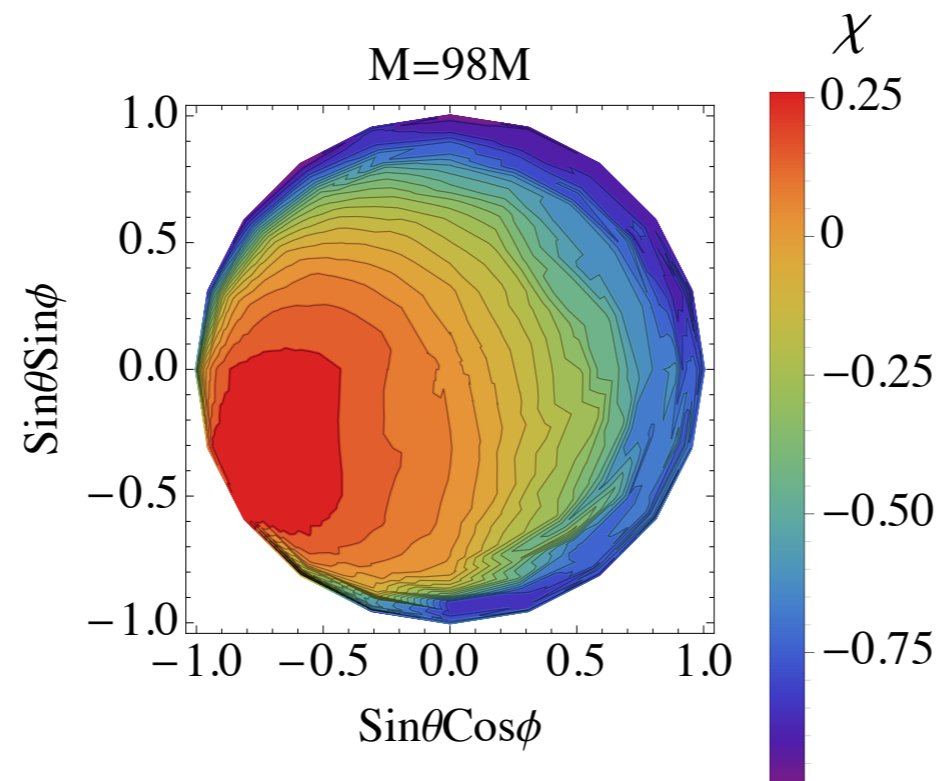


Synthetic data  $q = 2.0, a = -0.8, M = 70M_{\odot}$   
PSD similar to GW150914-like sensitivity  
Inclination  $\sim \pi/4$ , SNR=20  
Nonprecessing analysis

# Omission introduces orientation-dependent error



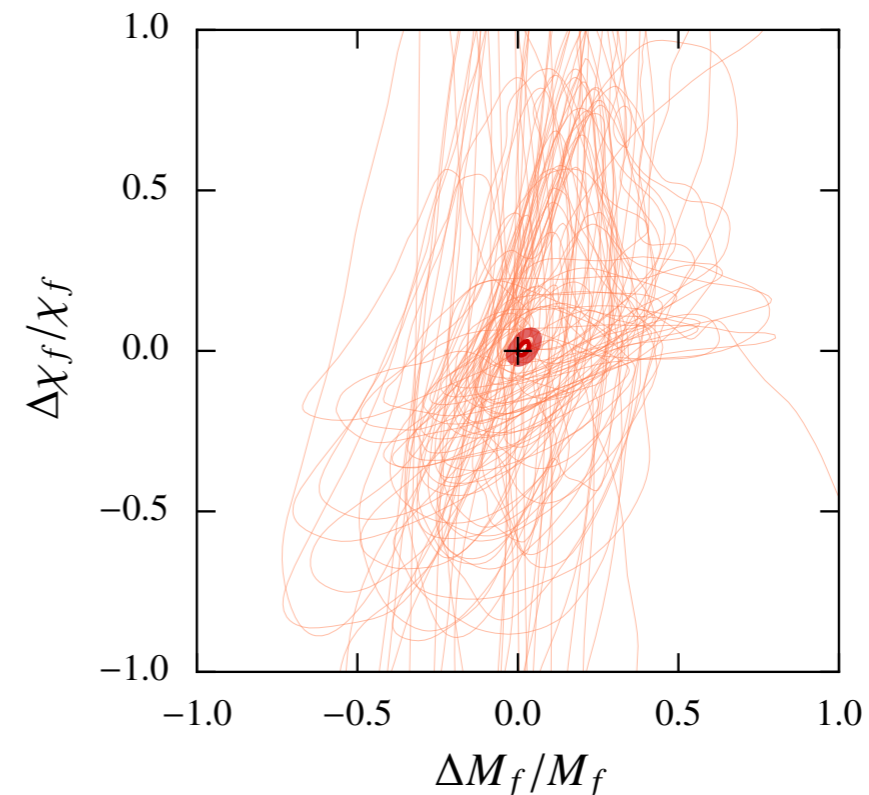
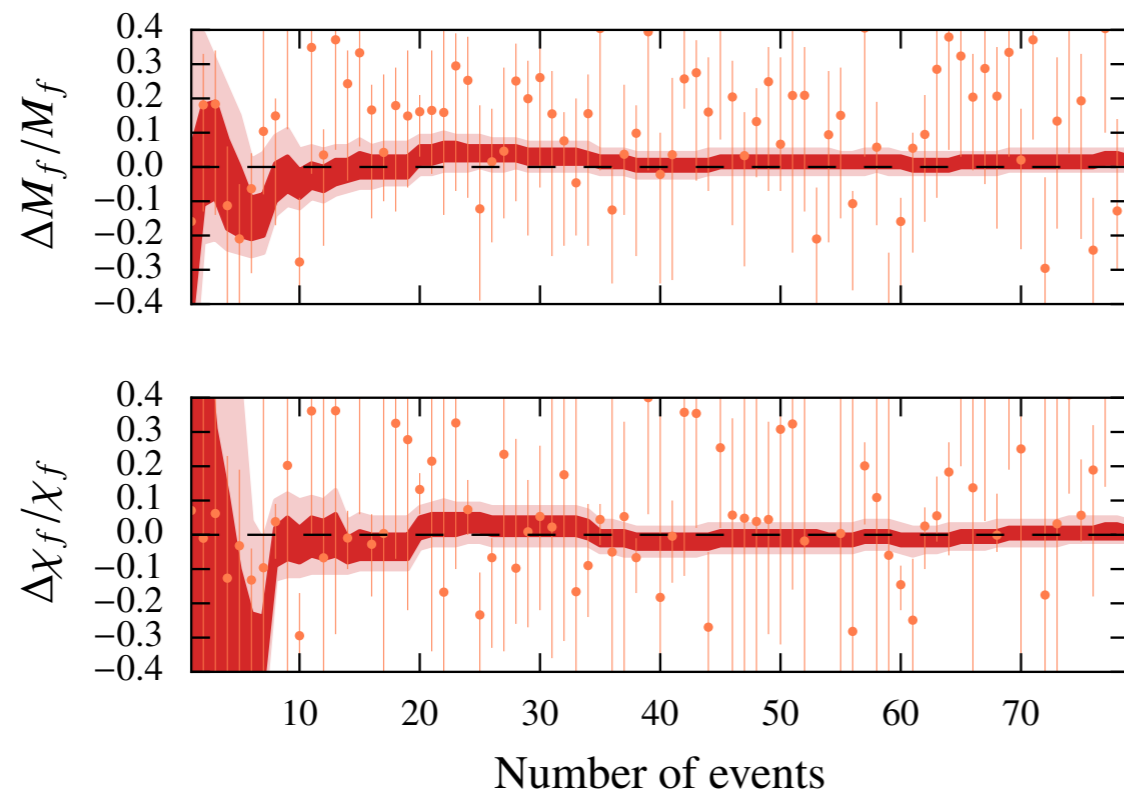
Varma and Ajith, 1612.05608



J. Calderon-Bustillo et al 1511.02060  
(early aLIGO)

# Should you care?

- Even if biases tolerable on event-by-event basis, they are systematic
- Some conclusions may require **stacking** and/or **weak effect**
  - Mass of small companion [NS; mass gaps]
  - Evidence for precessing binary population [clusters; kicks]
  - Tests of GR **[example below]**



# NR for parameter estimation I: Framework

- **Parameter estimation for GW sources:** Compare models and data, using gaussian statistics

$$\ln \mathcal{L}(\lambda; \theta) = -\frac{1}{2} \sum_k \langle h_k(\lambda, \theta) - d_k | h_k(\lambda, \theta) - d_k \rangle_k - \langle d_k | d_k \rangle_k$$

- **Idea:** [e.g., Pankow et al 2015 (1502.04370)]

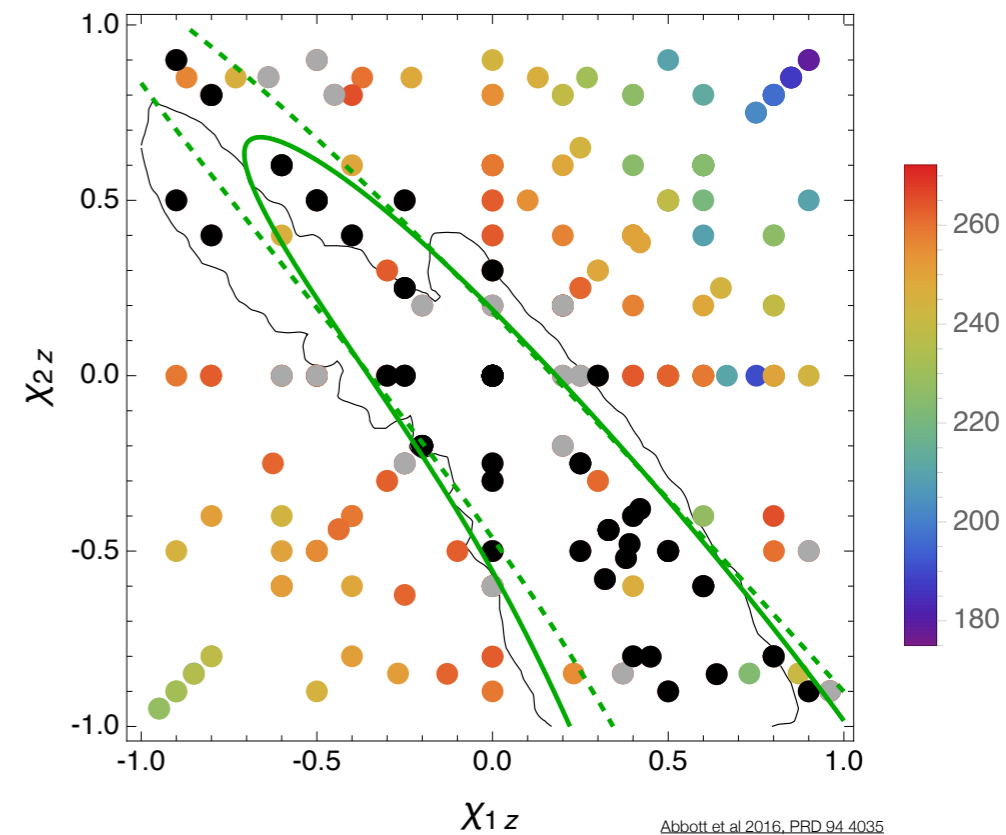
- Integrate over extrinsic parameter space [**NR can't vary intrinsic params**]

$$\mathcal{L}_{\text{marg}}(\lambda) \equiv \int \mathcal{L}(\lambda, \theta) p(\theta) d\theta$$

- Stitch likelihood from discrete evaluations  $\mathcal{L}_{\text{marg}}(\lambda_k)$ 
  - **Currently:** Aligned spin via fit (or GP)

- Posterior via Bayes

$$p_{\text{post}}(\lambda) = \frac{\mathcal{L}_{\text{marg}}(\lambda) p(\lambda)}{\int d\lambda \mathcal{L}_{\text{marg}}(\lambda) p(\lambda)}$$

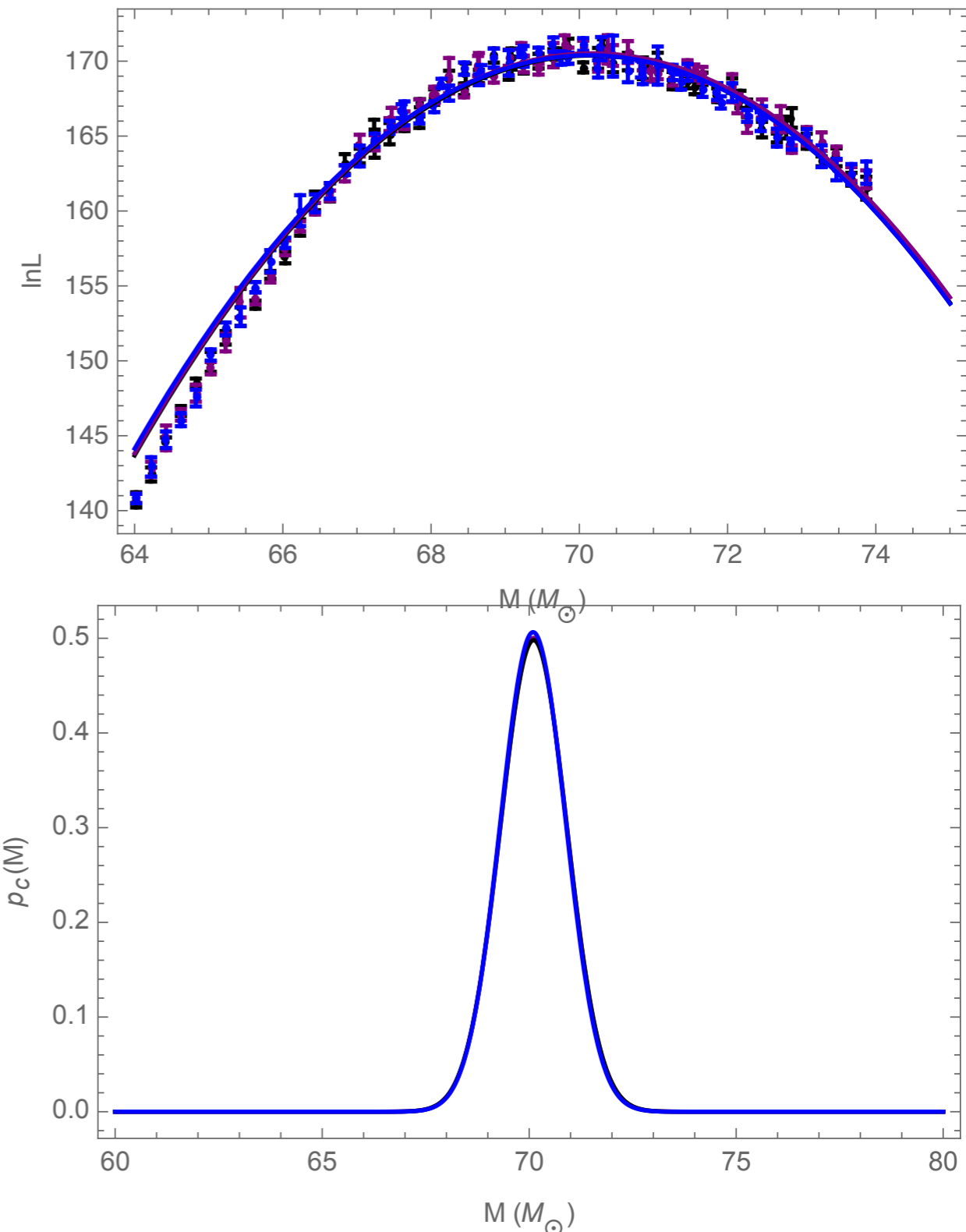




# NR for parameter estimation II: Checks

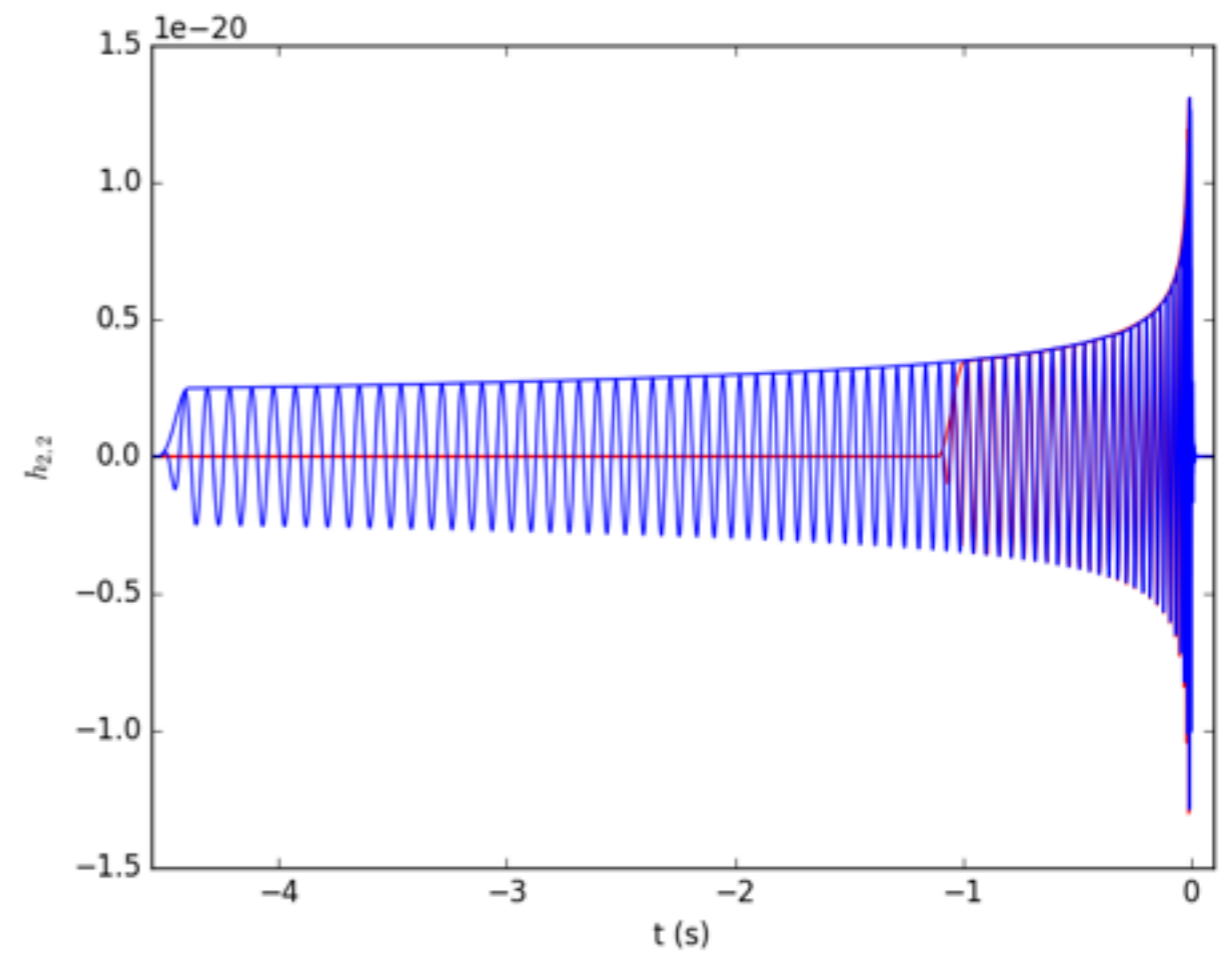
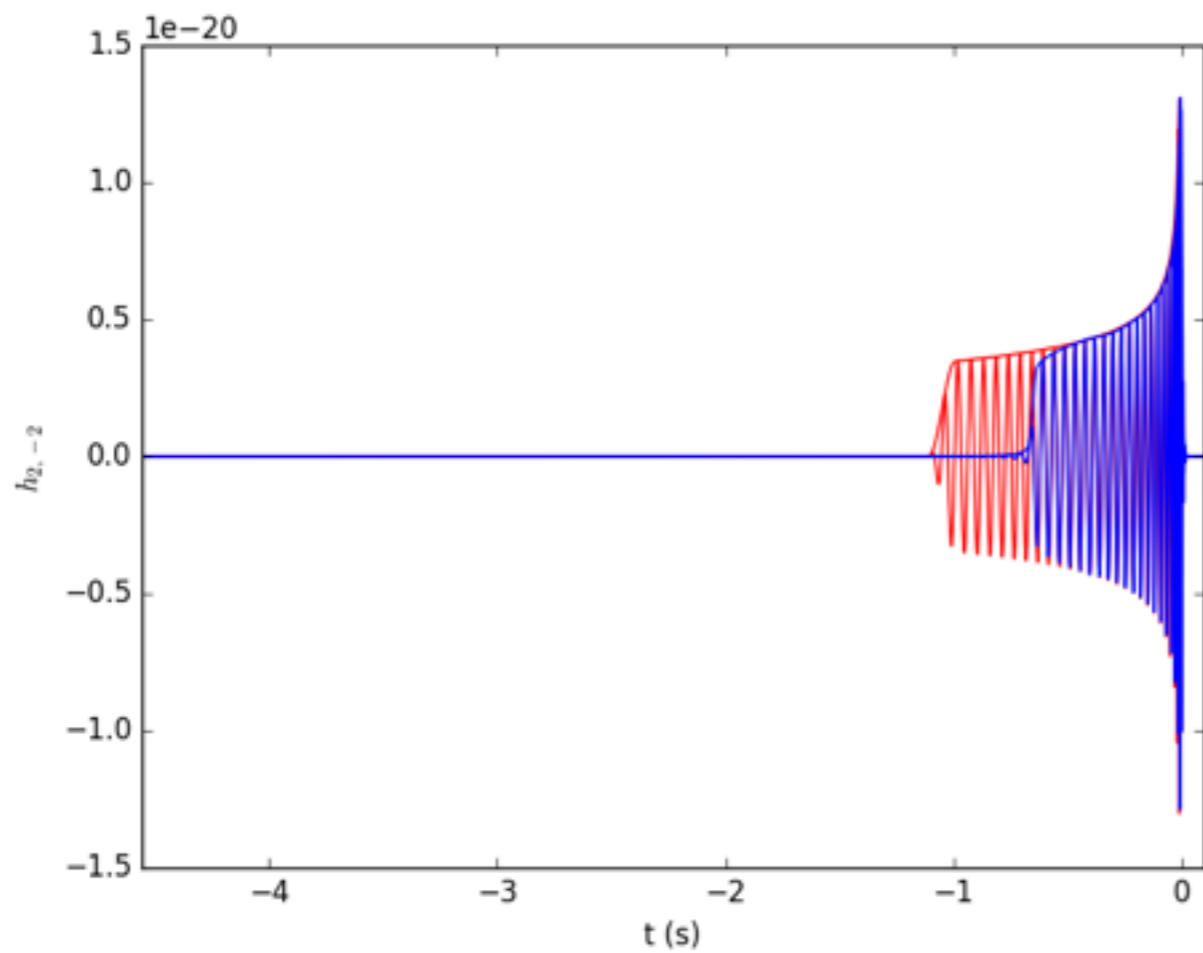
- Interpolation or fitting error
- Monte Carlo error
- Extraction error
- NR simulation resolution error
- Consistency between groups

## Simulation Resolution Test



Source/Template Resolution	KL Divergence
n120/n120	0
n120/n110	2.0E-04
n120/n100	6.5E-04

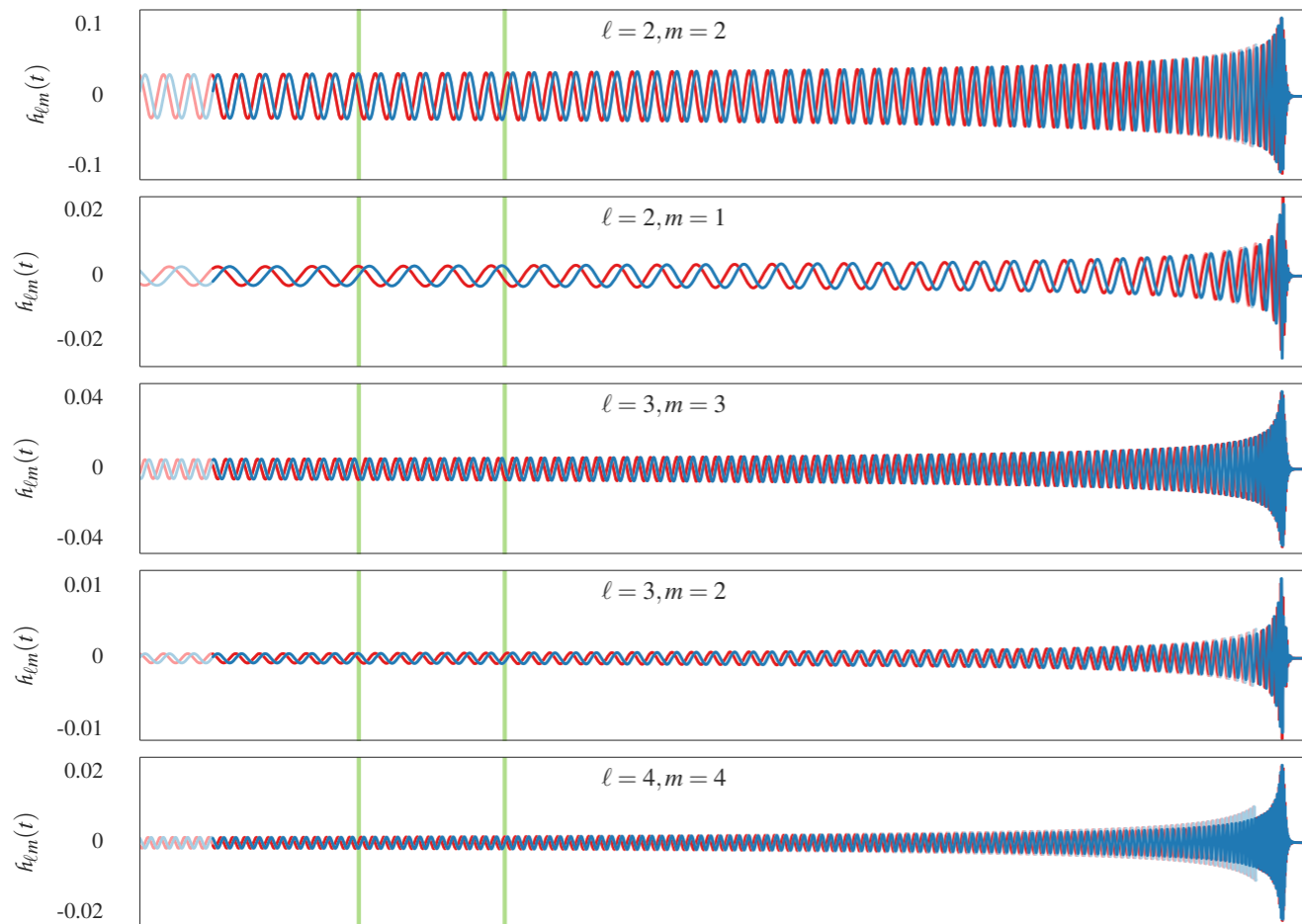
# Finite duration & Hybrids



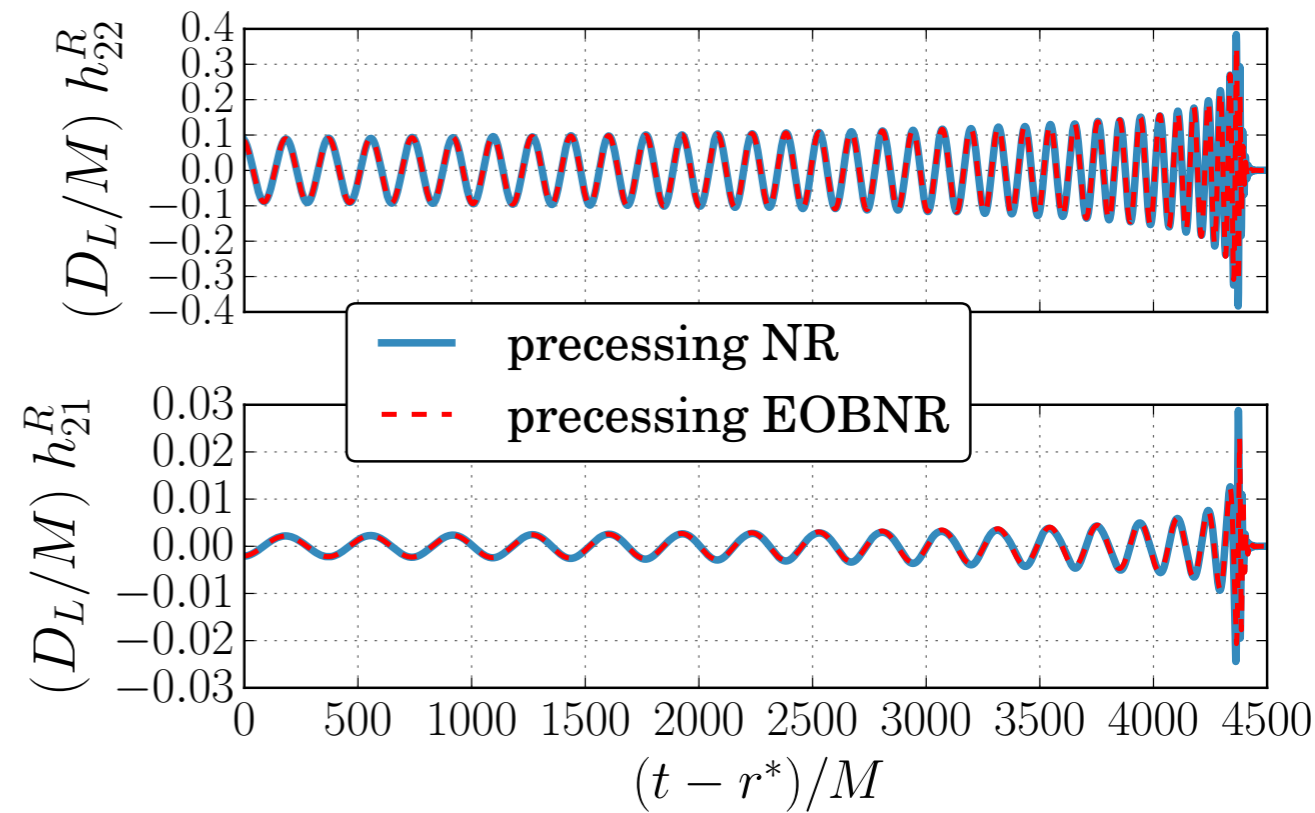
**Original RIT GW150914-like**  
**SXS event-like**

# Finite duration & Hybrids

- Familiar, well-used techniques for aligned (& precessing) spin



Varma and Ajith, 1612.05608

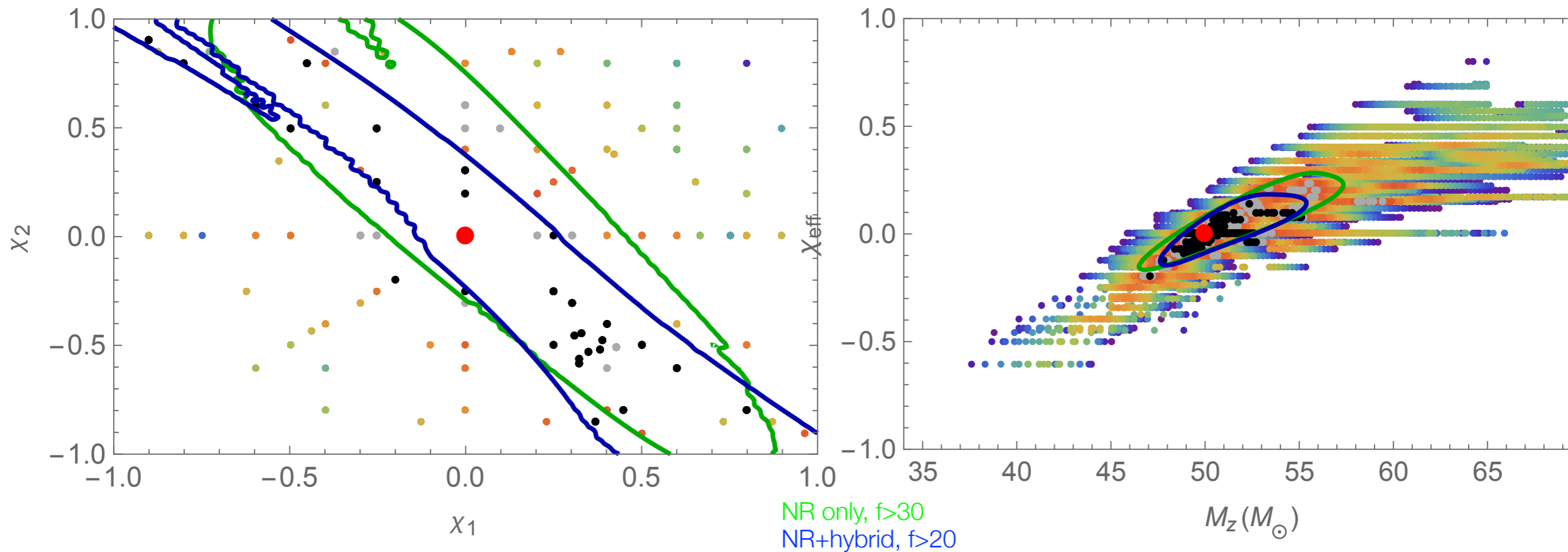


Babak, Taracchini, Buonanno 1607.05661  
[comparison paper, not a hybrid paper..same ideas]

# Finite duration & Hybrids

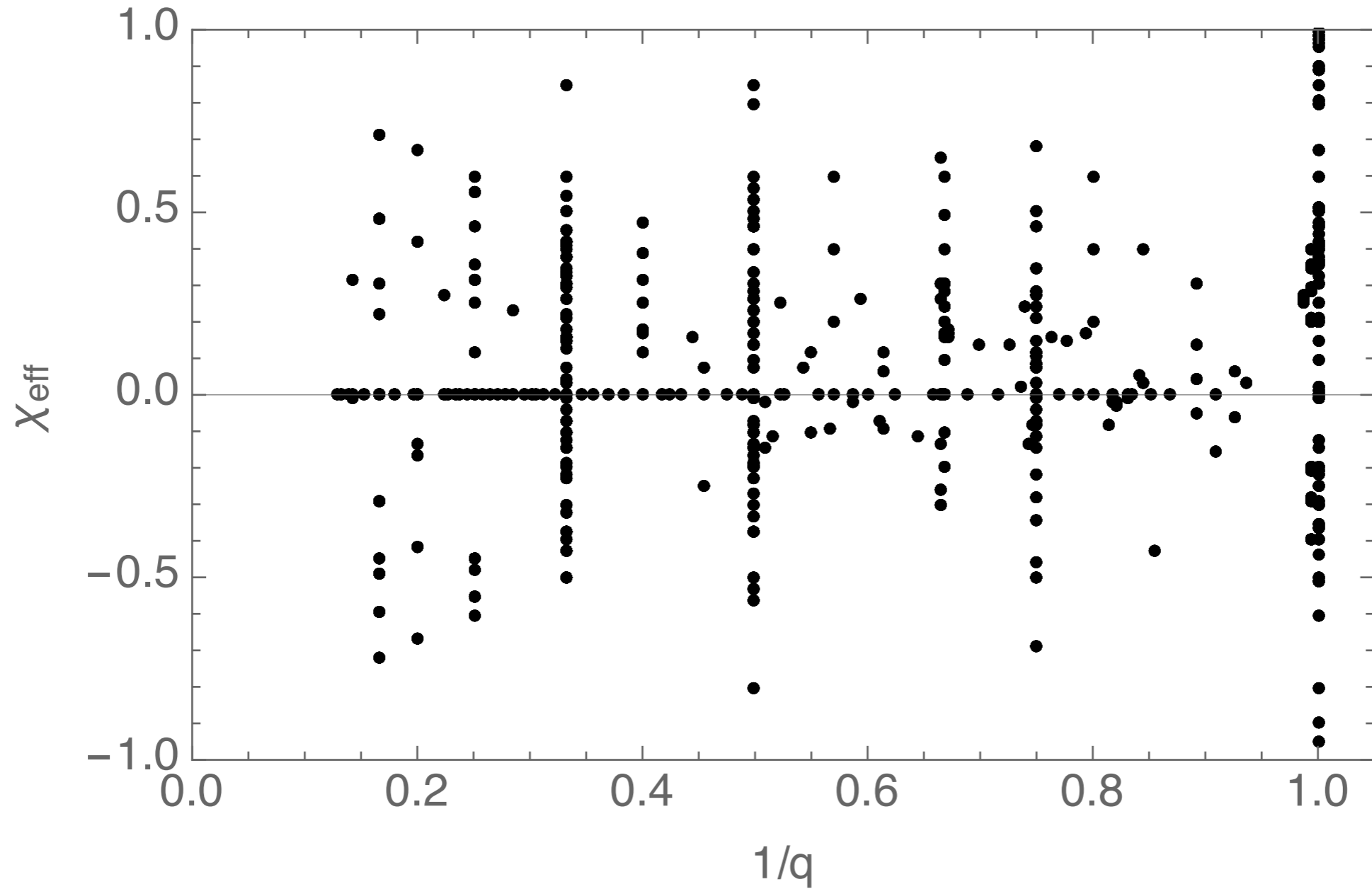
- Impacts PE

$$q = 1.0, a = 0.0, M = 50M_{\odot}$$



# Interpolation and placement

---

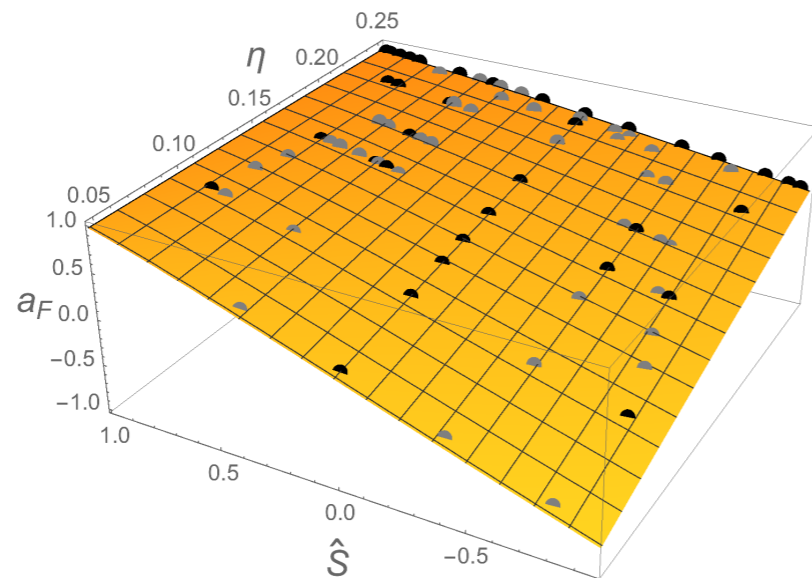


# Interpolation and placement

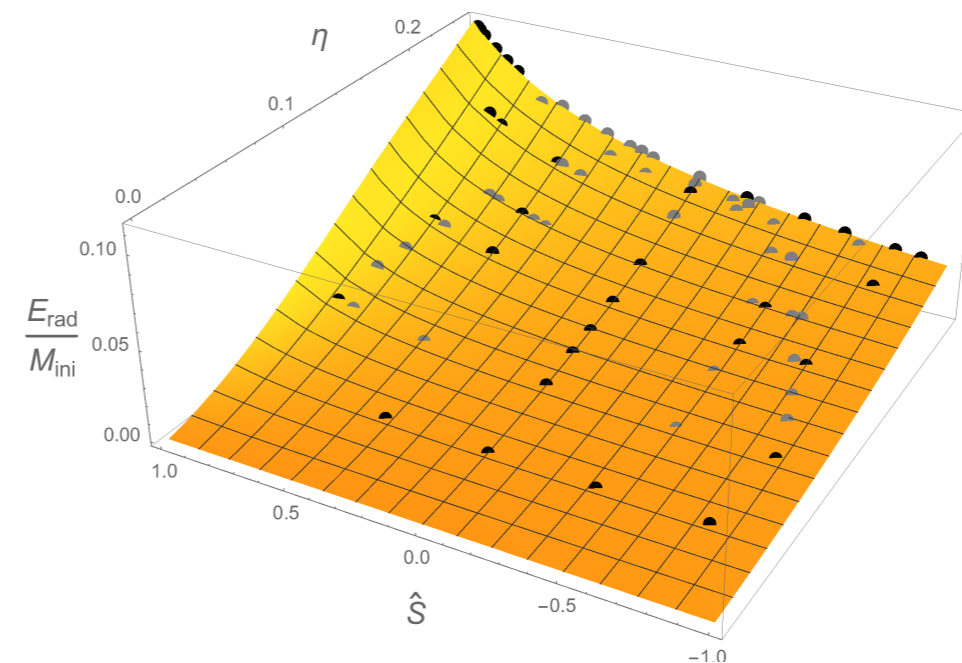
- Familiar problem:
  - Model-based: Similar to final mass, spin, recoil formulae
    - Form set by physics, symmetry principles
    - BIC for model selection

## Long history

Boyle, Kesden, Nissanke  
Healy; Lousto; Zlochower 2014  
Rezzolla et al  
UIB



Husa et al 2016

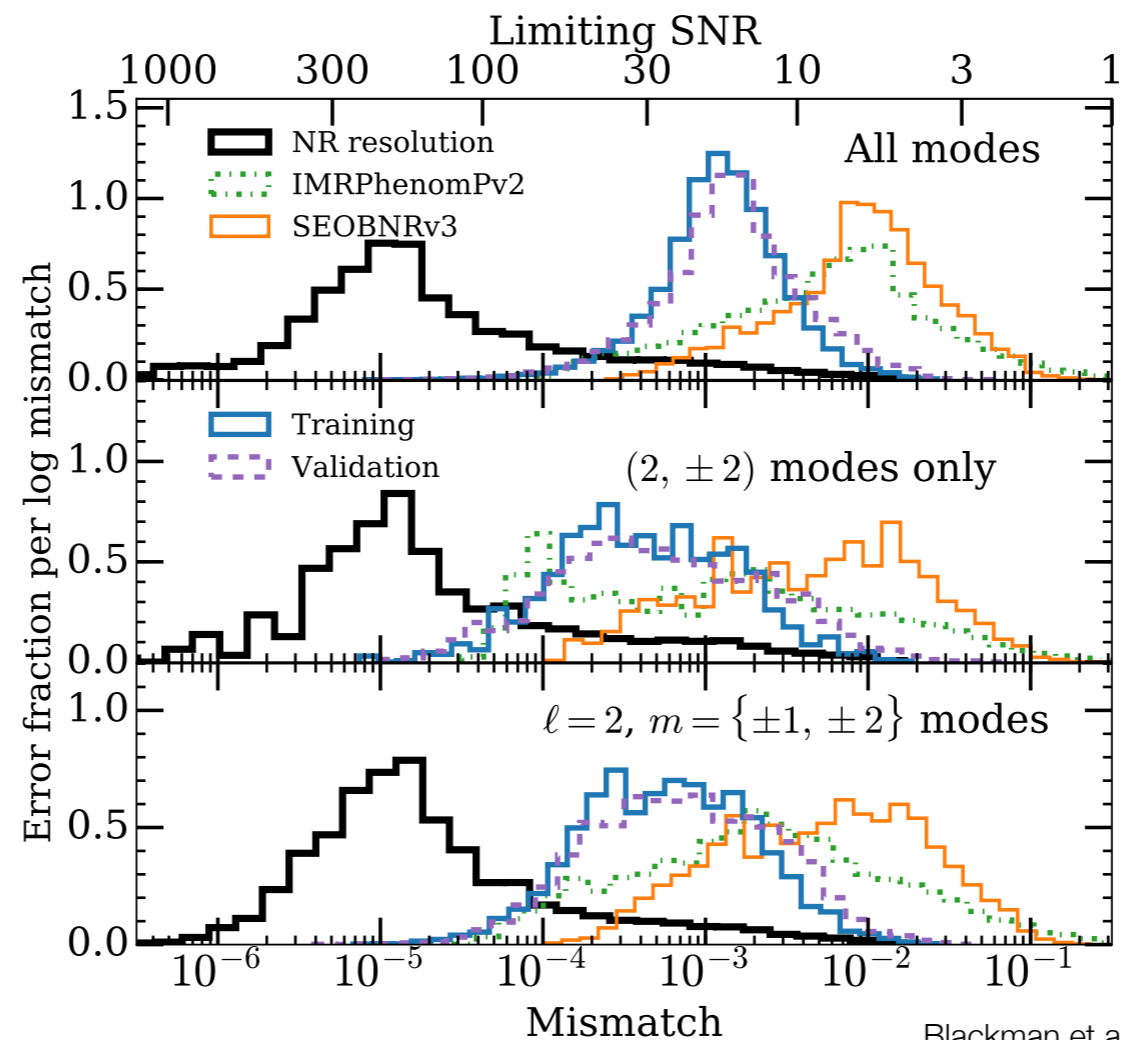


- Nonparametric methods: gaussian processes & others
- Followup: greedy, via natural distance (incl. systematics); or target model error

# NR-calibrated surrogate models

- Surrogate models can
  - interpolate between NR simulations directly
  - include most higher modes; precession

Blackman et al [2015,2017](#)  
[ROS et al 2017](#)



Blackman et al 2017

- Limitations so far
  - Placement (exploration in 'q'; spins), **duration**

# Final remarks

---

- NR is being used to interpret GW data
  - LSC has active NR involvement, including followup program & efforts to assess model systematics
  - Several groups developing strategies to use NR creatively
    - Search selection biases
    - Burst searches
    - Waveform systematics
- NR (+hybrids+surrogates) are valuable!
  - Confront data with best solution of Einstein's equations
  - Should provide best estimates of generic binary parameters
  - Valuable cross-check for model-based analysis



# Simulations of binary black hole coalescence

---



Manuela Campanaelli

Jim Healy

Carlos Lousto

Yosef Zlochower

Mike Boyle

Tony Chu

Heather Fong

Daniel Hemberger

Larry Kidder

Geoffrey Lovelace

Serguei Ossokine

Harald Pfeiffer

Mark Scheel

Bela Szilagyi

Saul Teukolsky

Michael Clark

Matt Kinsey

Jim Healy

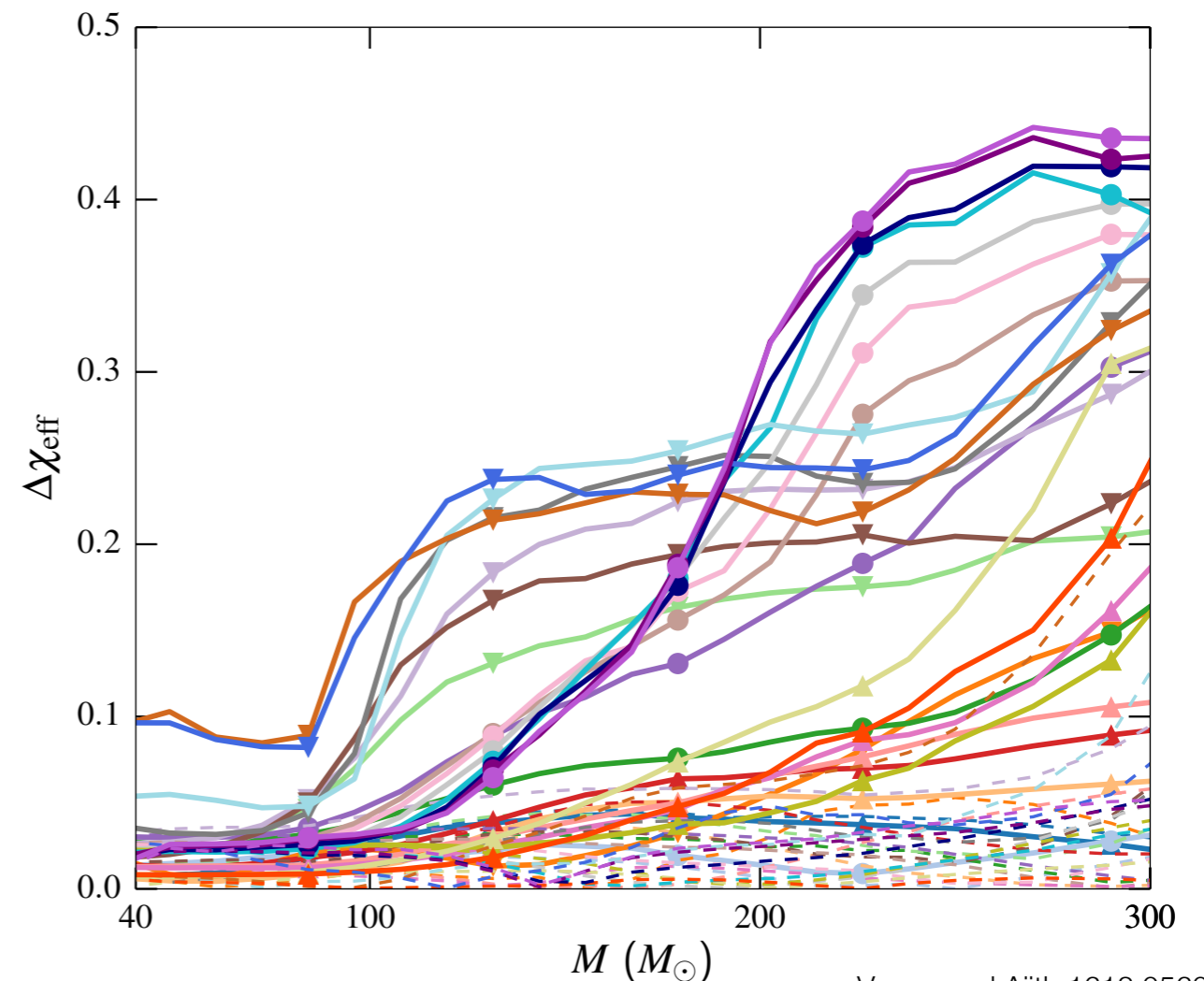
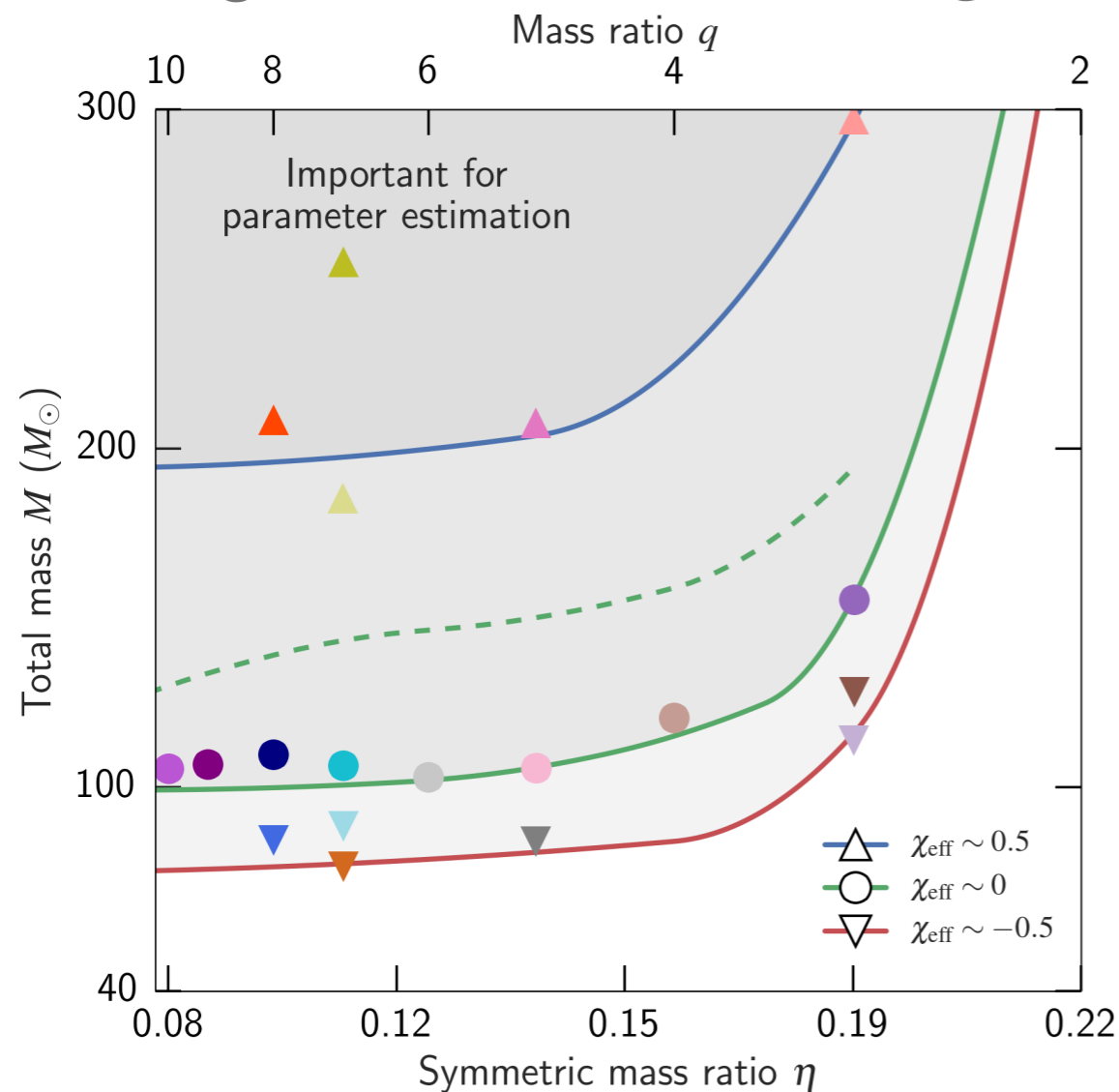
Ian Hinder

Pablo Laguna

Deirdre Shoemaker

# Literature review I: Varma et al

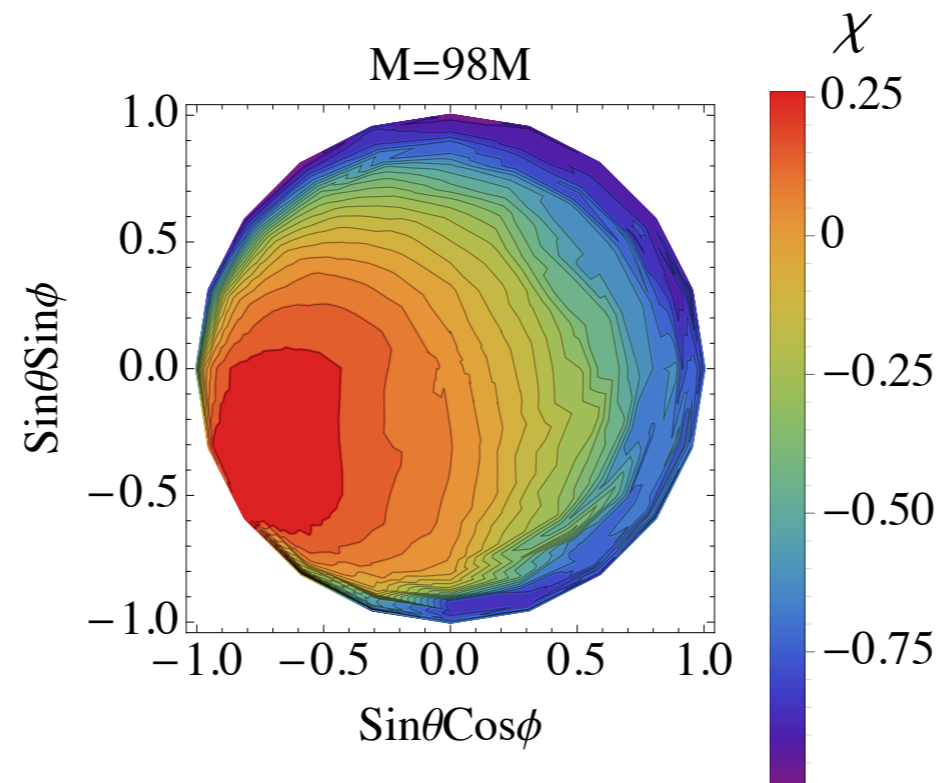
- Aligned-spin hybrid match-based calculation, to estimate PE biases
- Result: Higher modes matter
- **MLE** estimator bias with just 22 is modest [offset  $\geq$  statistical error]
  - Figures illustrate it is **significant**, & **MLE is not posterior**



# Literature review 2: JCB

---

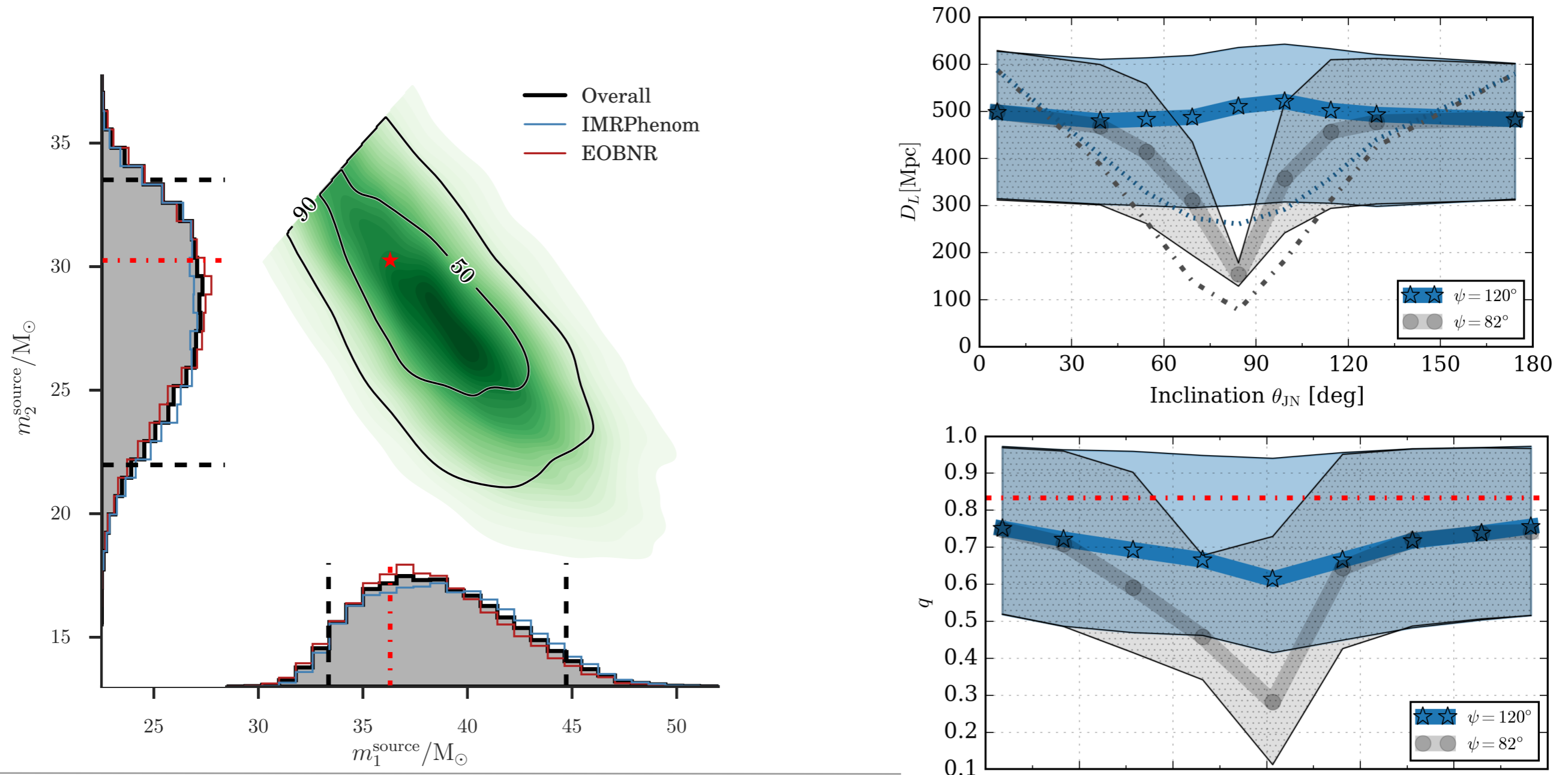
- Orientation-dependent biases



J. Calderon-Bustillo et al 1511.02060  
(early aLIGO)

# Literature review 3: LVC NR systematics paper

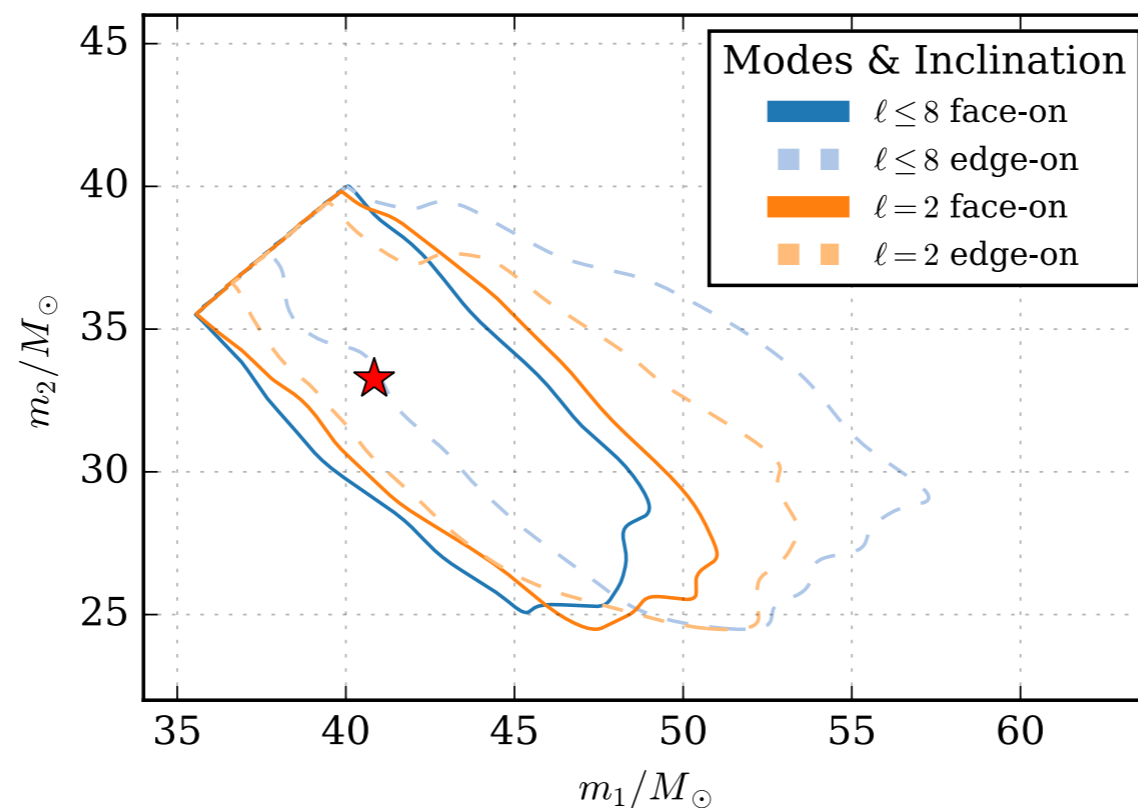
- NR injection study, but recovery with existing models
  - Orientation-dependent biases using quadrupole-only templates
  - What would the posterior be, with a better model?



# Literature review 3: LVC NR systematics paper

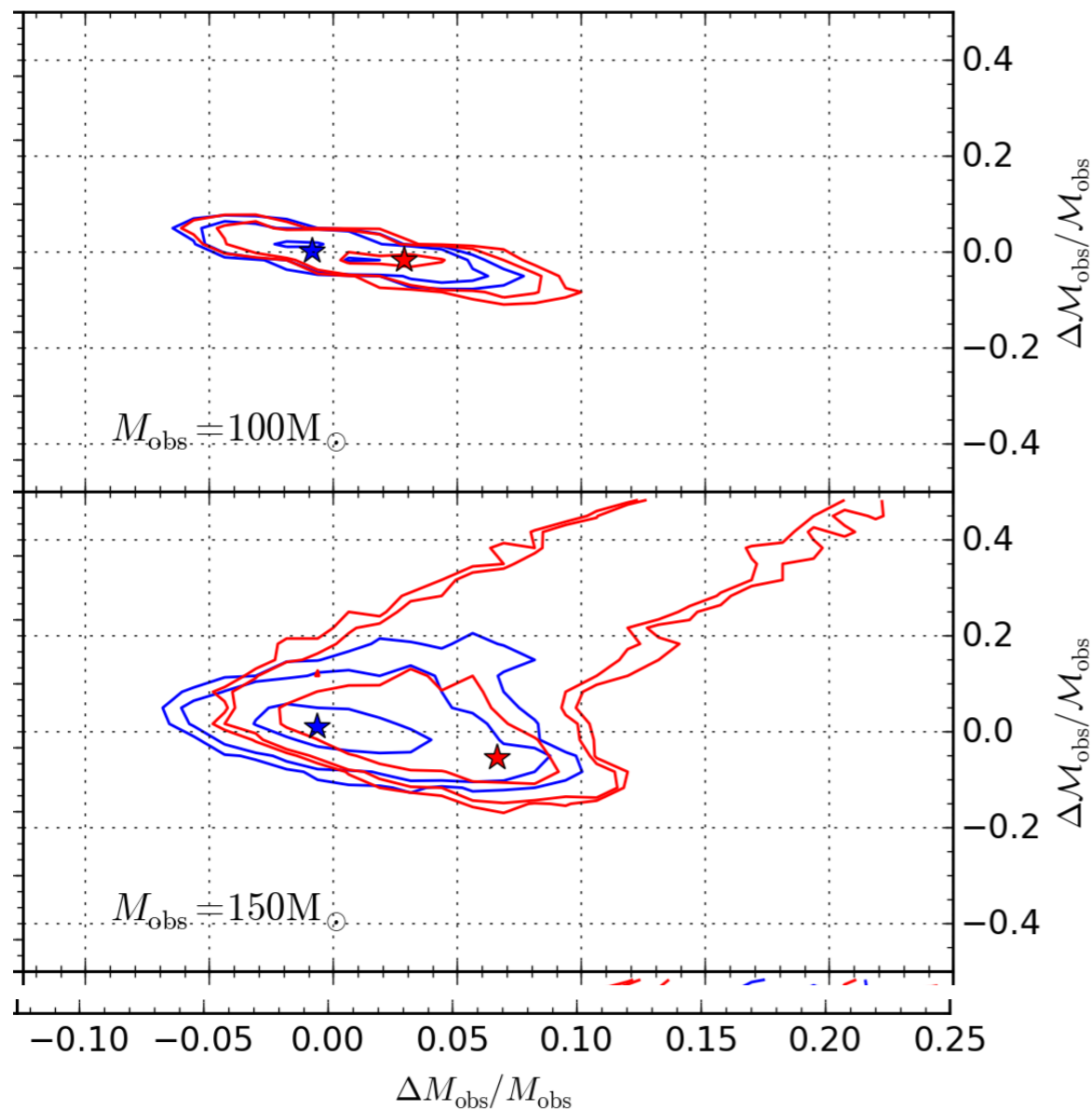
---

- NR injection study, but recovery with existing models
  - Orientation-dependent biases using quadrupole-only templates
  - What would the posterior be, with a better model?

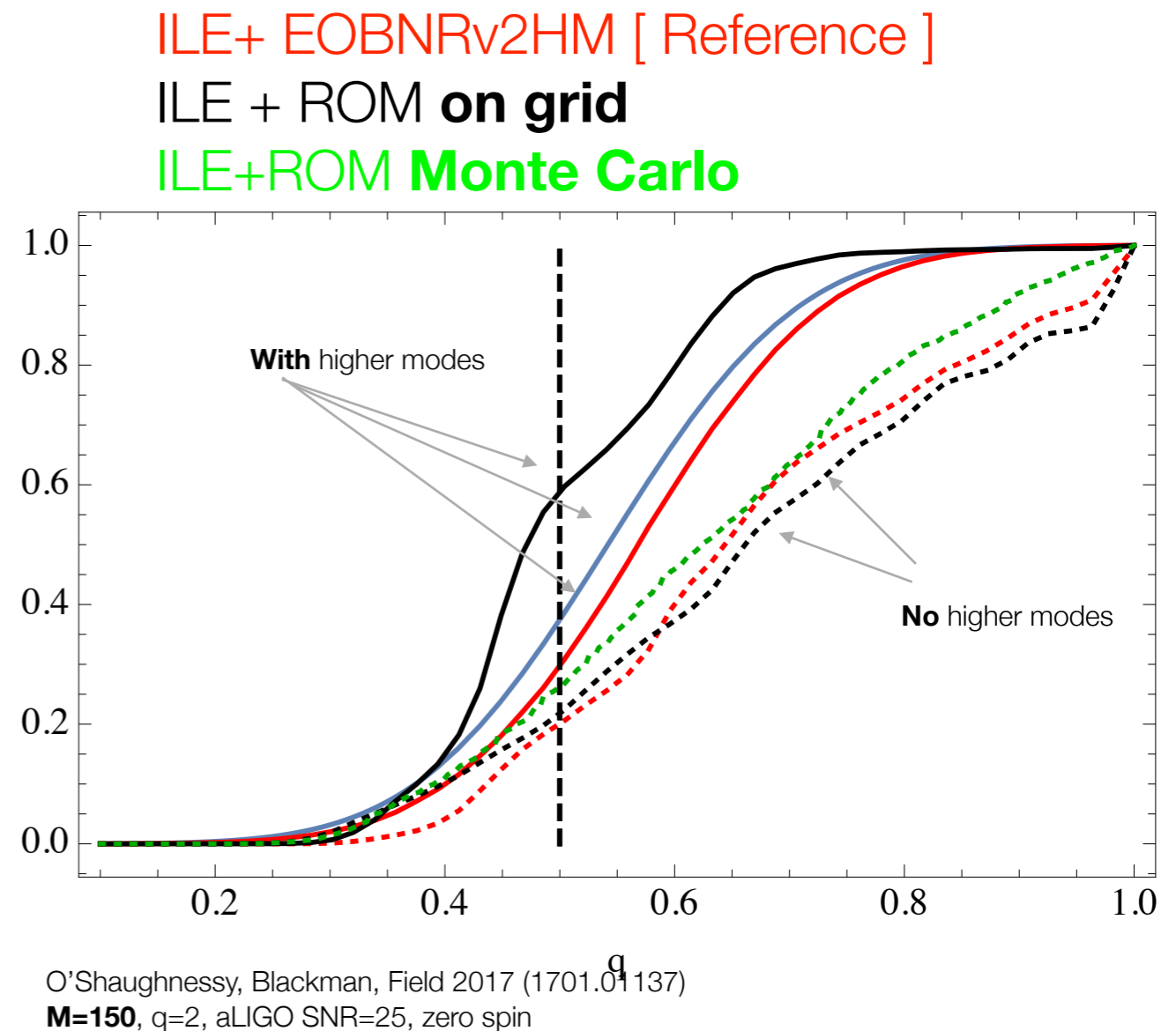


# Literature review 4: Graff et al / ROS, JB, Field

- **Zero-spin PE** calculations with higher modes (EOB; NR surrogate)
- Higher modes matter. NR surrogate differs from EOB

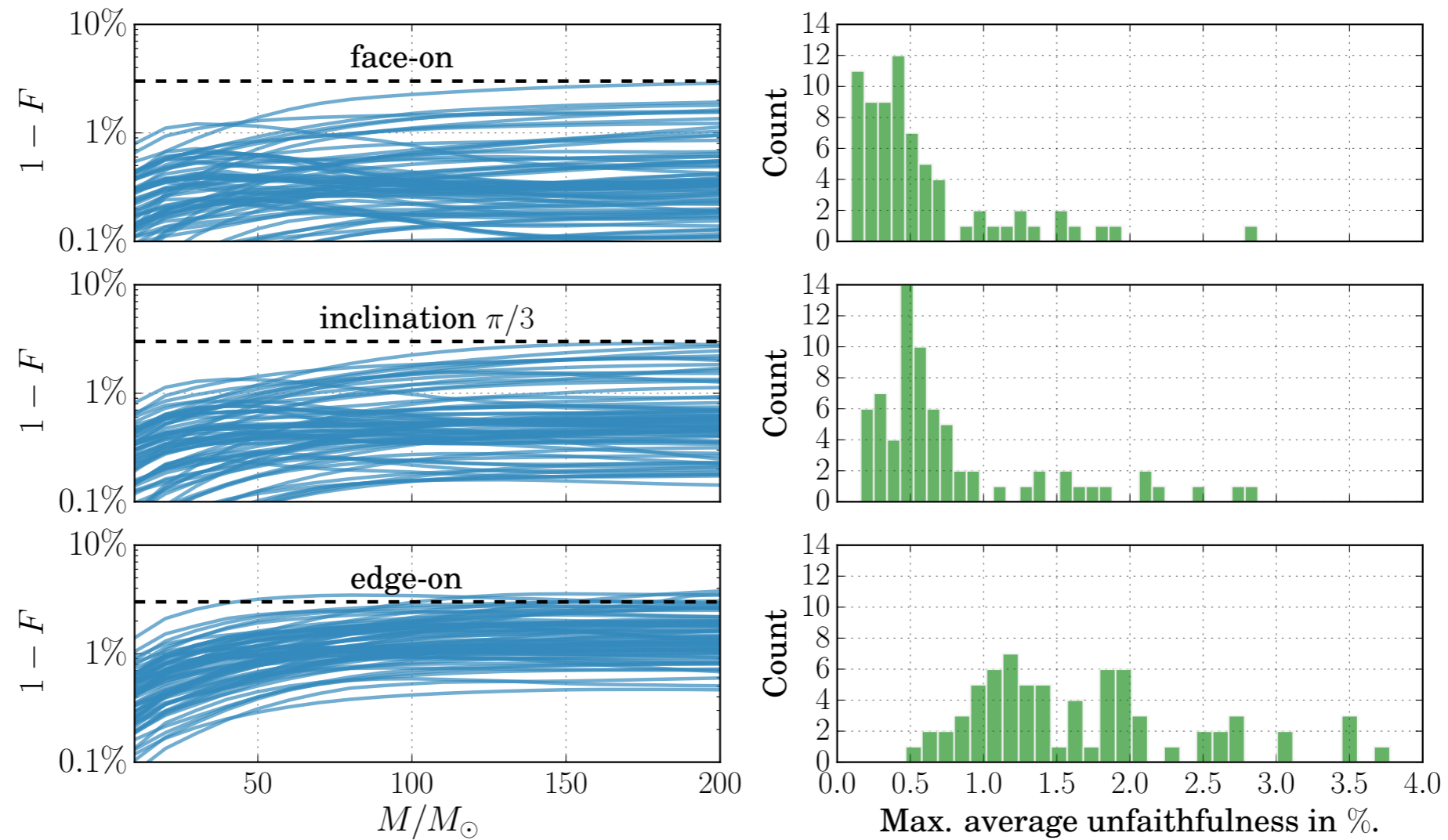


Graff et al 2015  
q=4, SNR=12, zero spin



# Literature review 5: Babak, Taracchini, Buonanno

- **Large mismatches** with SEOBNRv3



Babak, Taracchini, Buonanno 1607.05661

# Bonus: Event loss from lacking higher modes

---