Impact of calibration uncertainties on cosmological measurements from gravitational wave sources

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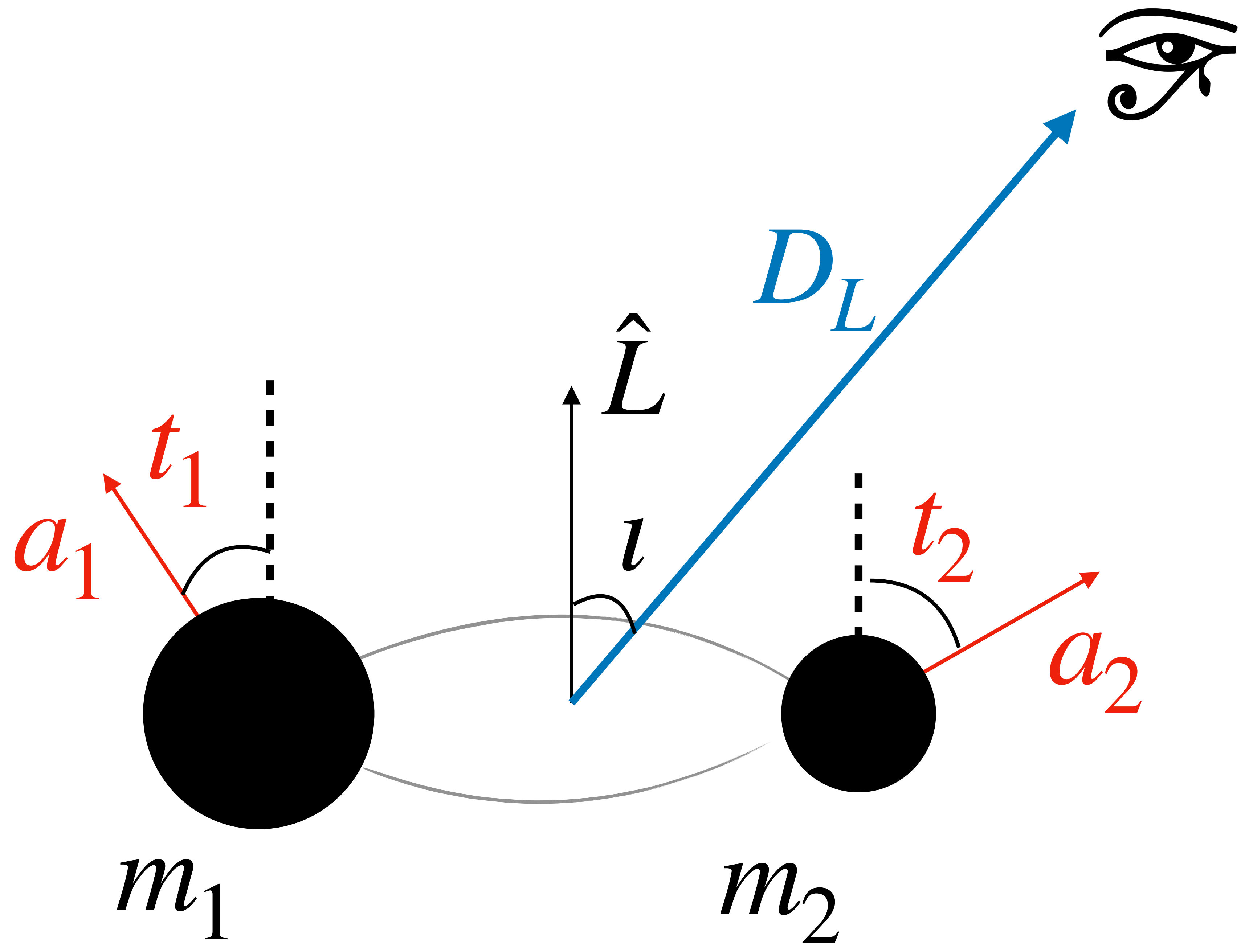
Outline

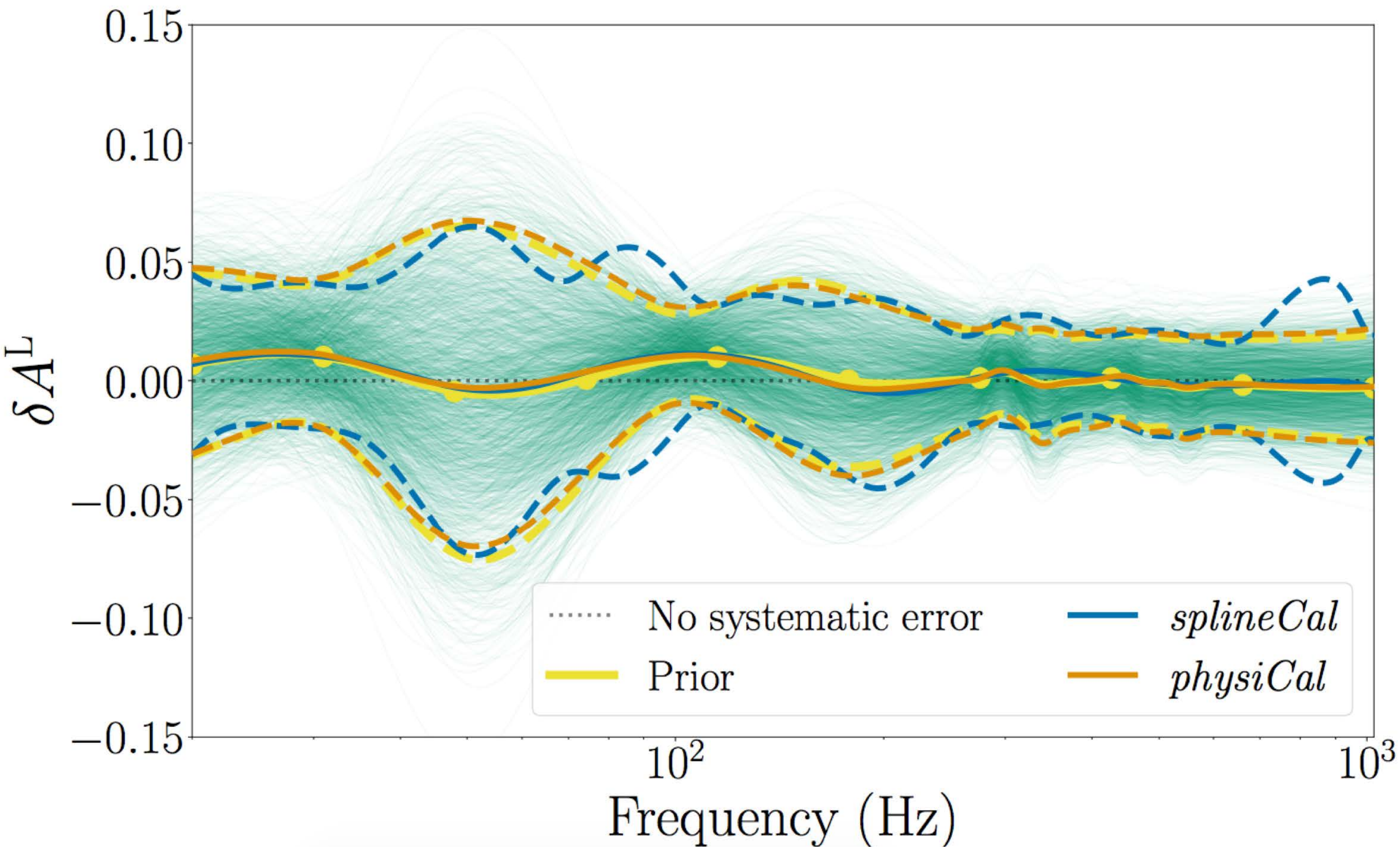
- Goal: understand the impact of calibration errors and uncertainties on astrophysical parameter estimation(PE) and cosmology
  - Calibration: produce response functions that convert the photodetector output in the interferometers to the strain data from which we can extract gravitational wave signals
- Method: add artificial calibration errors, motivated by detector behavior of Hanford and Livingston in the third observing run (O3) of aLIGO-VIRGO
- **PE results** for individual events
- Plans to combine events for Hubble constant (H_0) measurements

Background



- We need **luminosity distances** D_L for Hubble constant H_0 measurement
  - $v_H = H_0 D_L$ at small redshifts, v_H is local Hubble flow velocity
  - Biases in luminosity distance can lead to bias in Hubble constant, more significant when we combine multiple events
- We assume there are electromagnetic (EM) counterparts for binary neutron stars(BNSs) and neutron star-black holes(NSBHs) in our study

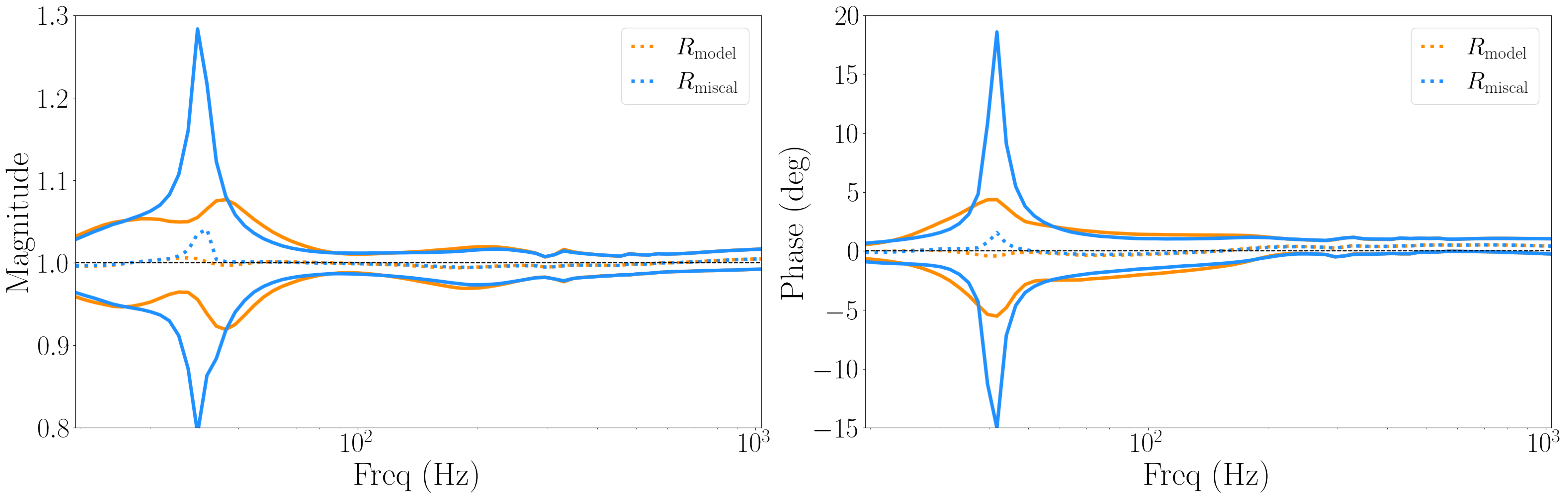
Calibration uncertainties in PE



- **Spline interpolation**
  - Fits the response function using a cubic spline polynomial
  - Determines errors at each nodes of the polynomial in frequency
- **physiCal**[2009.10192]
  - Uses a distribution of response function curves
  - Each curve is a possible posterior sample

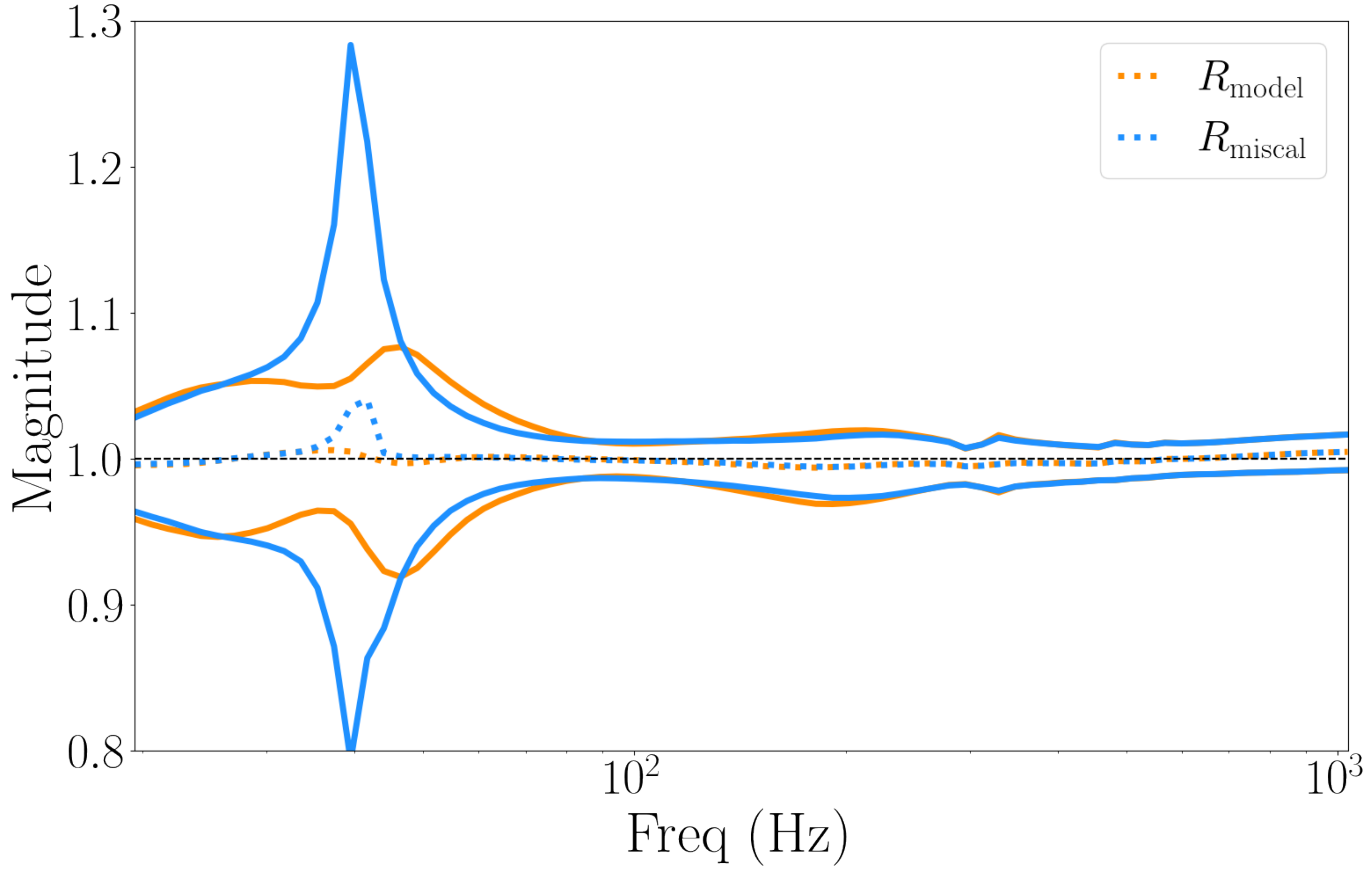
Simulation Set-up

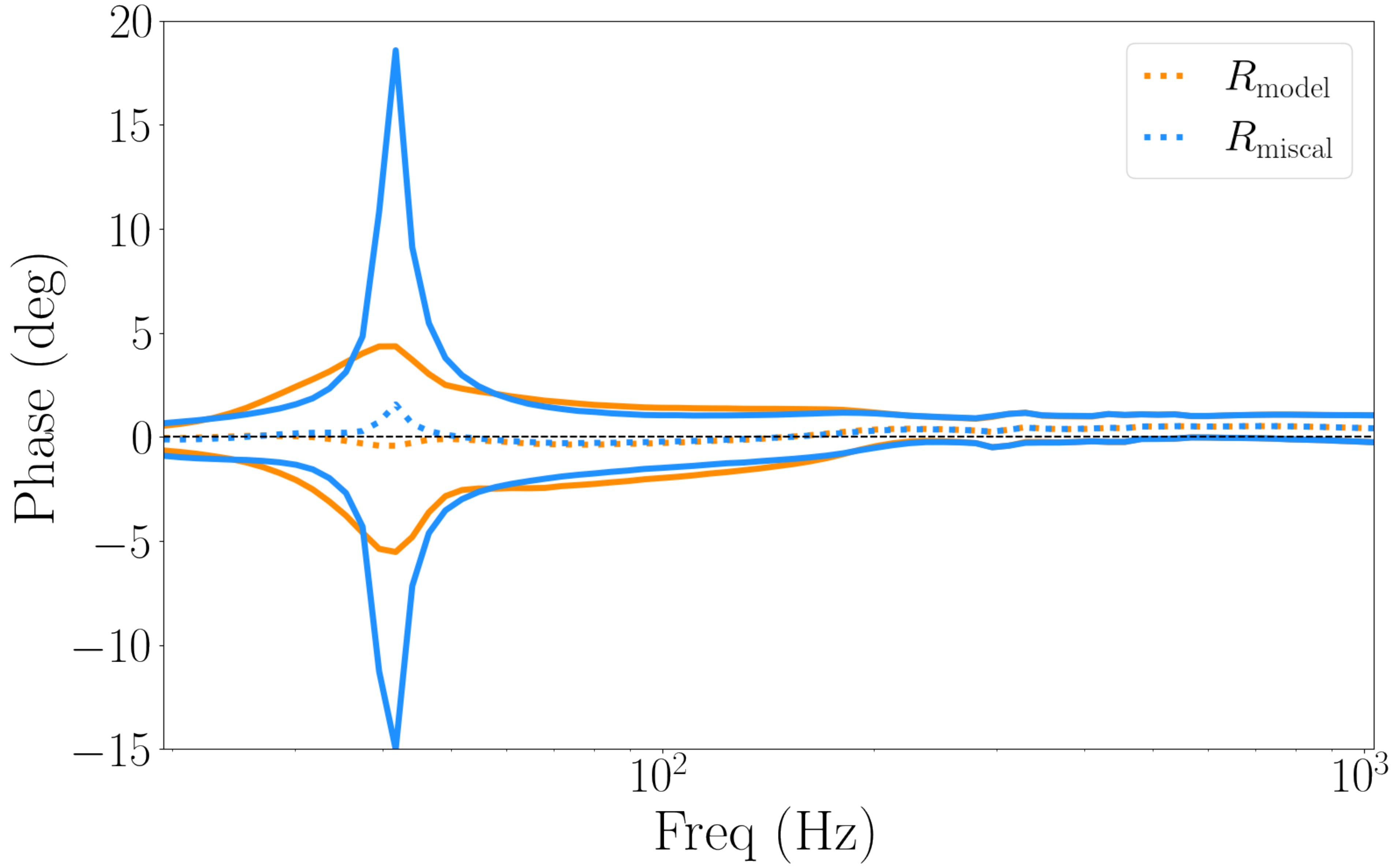
- From calibration team: model response functions R_{model} used in parameter estimation and the response functions R_{miscal} used for miscalibration



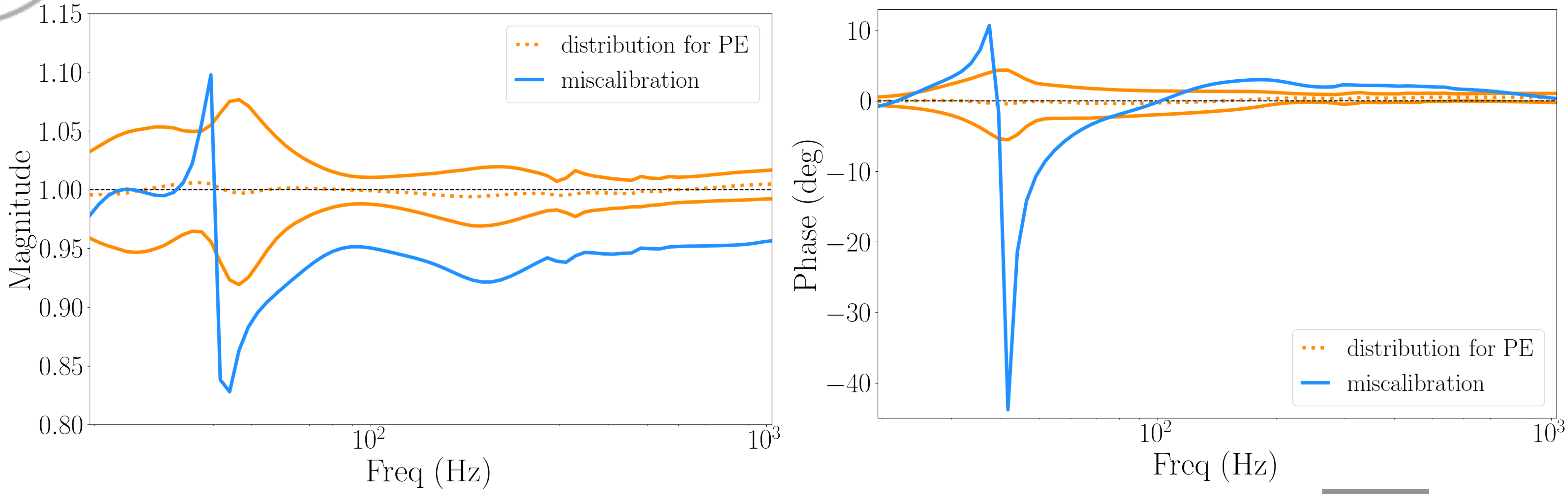
Simulation Set-up

- From calibration team: model response functions R_{model} used in parameter estimation and the response functions R_{miscal} used for miscalibration
- Run parameter estimation with R_{model}
  - Experiment runs: add artificial calibration errors using one curve from R_{miscal} to mimic "bad scenarios" where we do not manage to capture all the features when modeling the response function
  - Control runs: no calibration error, to disentangle other causes for bias





Simulation Set-up



- **A curve for the misbehaving detector, picked by minimizing:** $$\int_{f_{\min}}^{f_{\max}} \frac{A_{\mathrm{i,miscal}}(f) - A_{\mathrm{model}}(f)}{S(f)} df$$

(Median)

Weighted by PSD(sensitivity)

- A curve within the 68% of the **model response function distribution used for PE (physiCal)**, for the other detector

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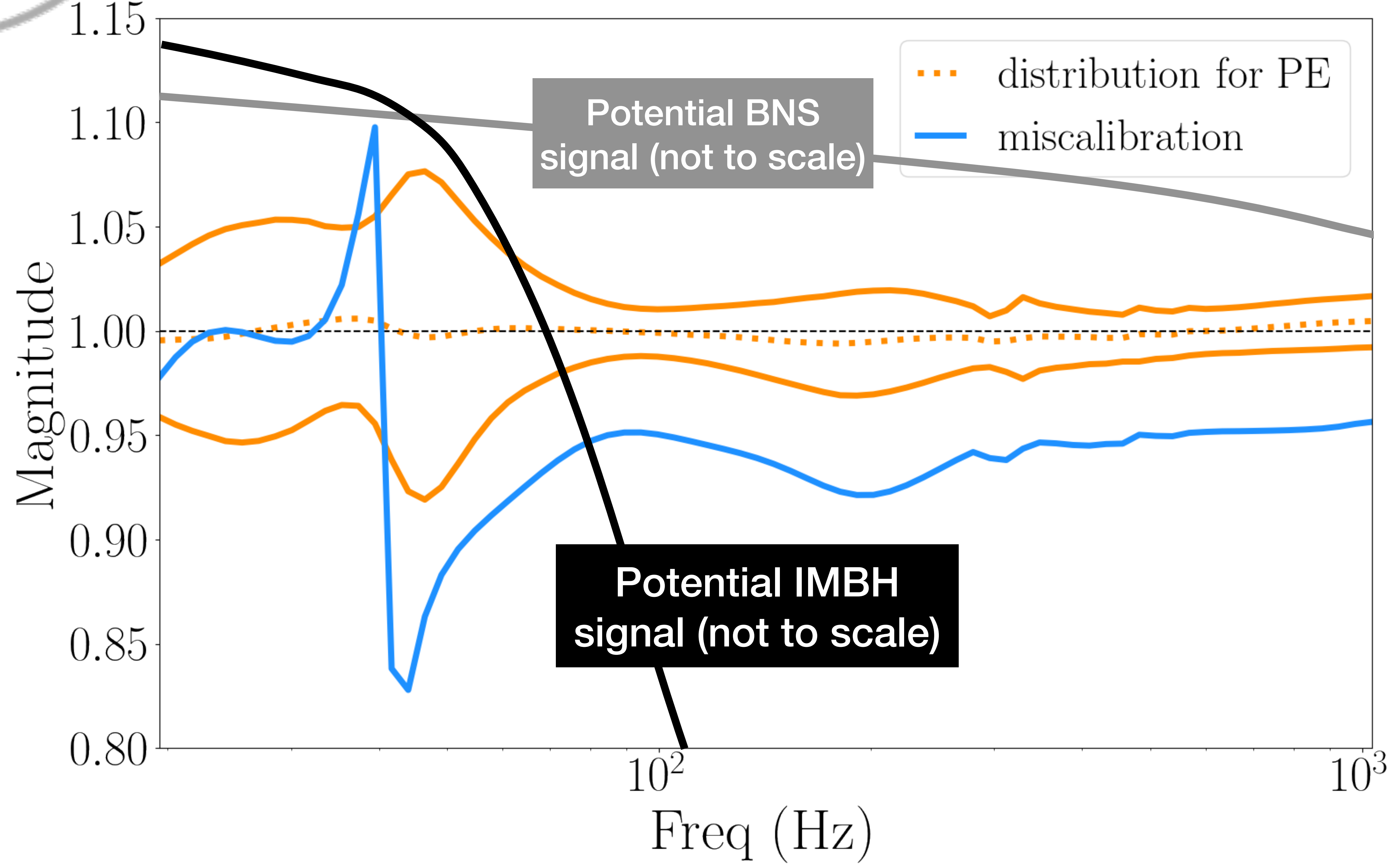

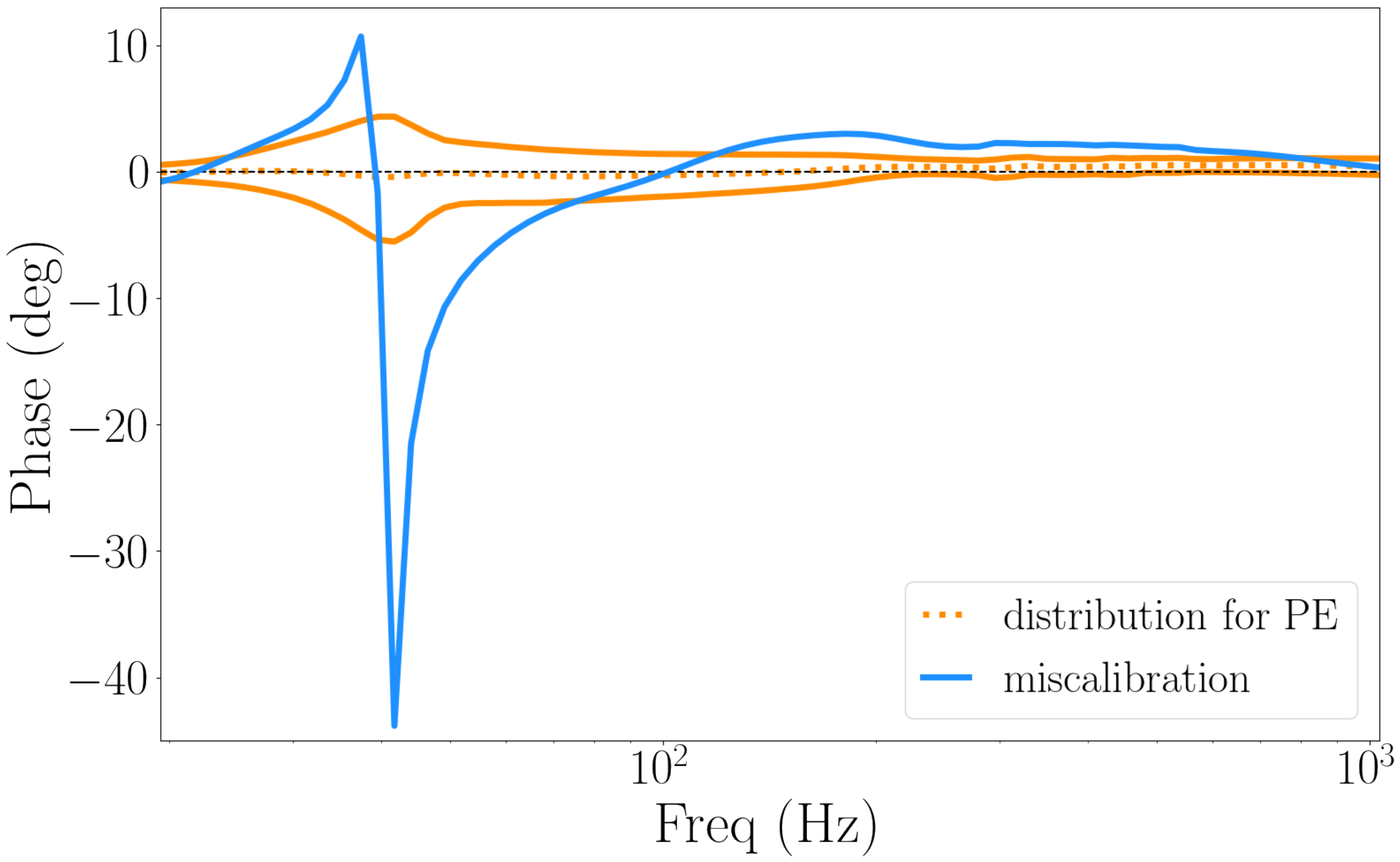

- **A curve for the misbehaving detector, picked by minimizing:** $$\int_{f_{\min}}^{f_{\max}} \frac{A_{\mathrm{i,miscal}}(f) - A_{\mathrm{model}}(f)}{S(f)} df$$ (Median) Weighted by PSD(sensitivity)
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- From calibration team: model response functions R_{model} used in parameter estimation and the response functions R_{miscal} used for miscalibration
- Run parameter estimation with R_{model}
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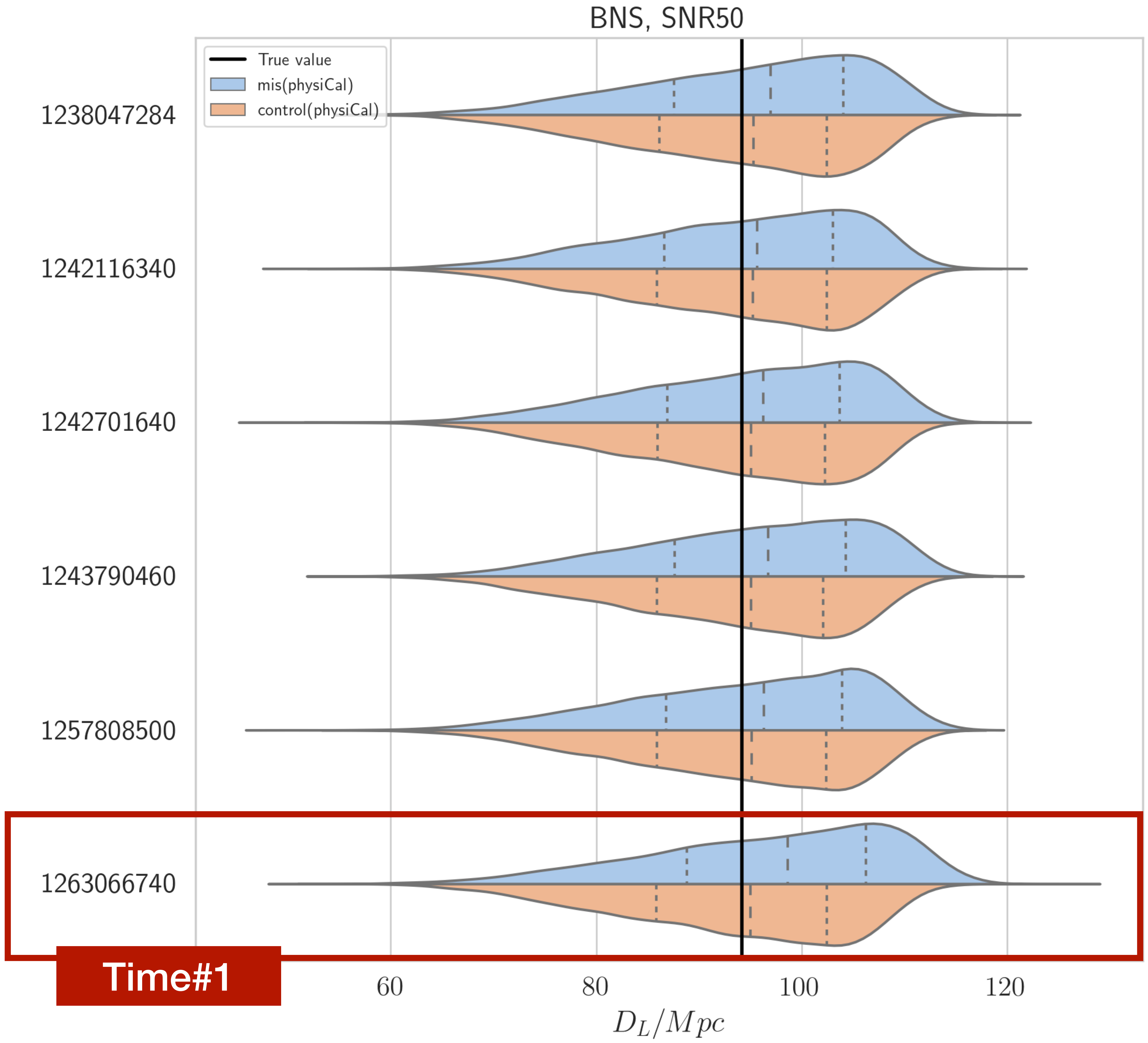
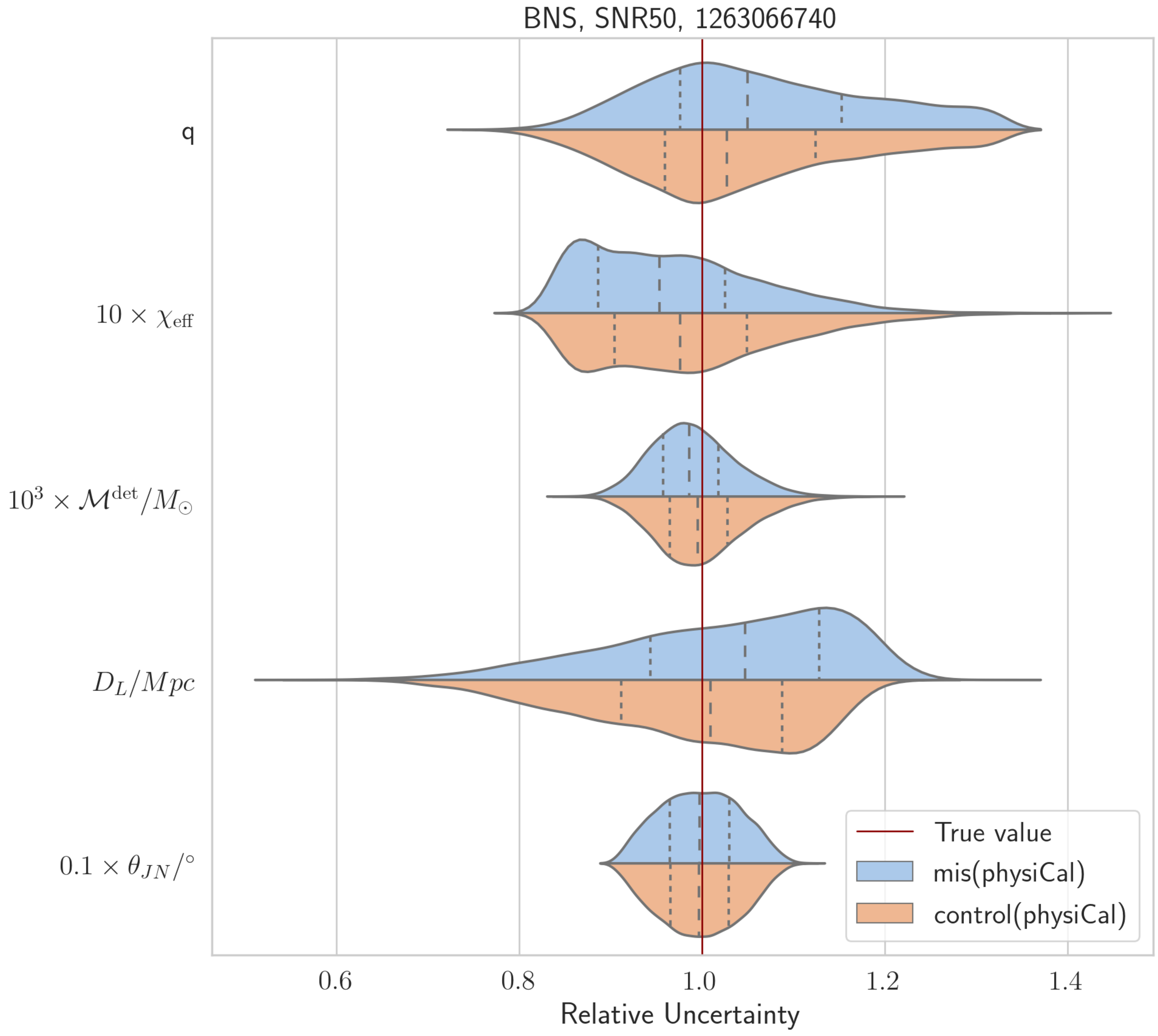
  - Control runs: no calibration error, to disentangle other causes for bias
- 4 typical compact binary coalescence signals $h(t, \theta)$
  - Assume we know the sky localization (ra, dec) of potentially EM bright coalescences that include a neutron star
- Add miscalibration $S_{\text{miscal}} = (\text{noise(t)} + h(t, \theta)) \times R_{\text{miscal,i}}$
- Worst-case scenario: the same calibration error is not accounted for but present for all events

PE Results - BNS



- BNS
  - $m_1 = 2M_\odot$, non spinning
  - $m_2 = 1.5M_\odot$, non-spinning
  - Sky localization known
- SNR 50, physiCal*, **Large calibration error ("mis")** vs **No calibration error ("control")**
  - Lines are quartiles (25%, 50% and 75%)
  - *Spline results are very similar to physiCal, thus not shown here

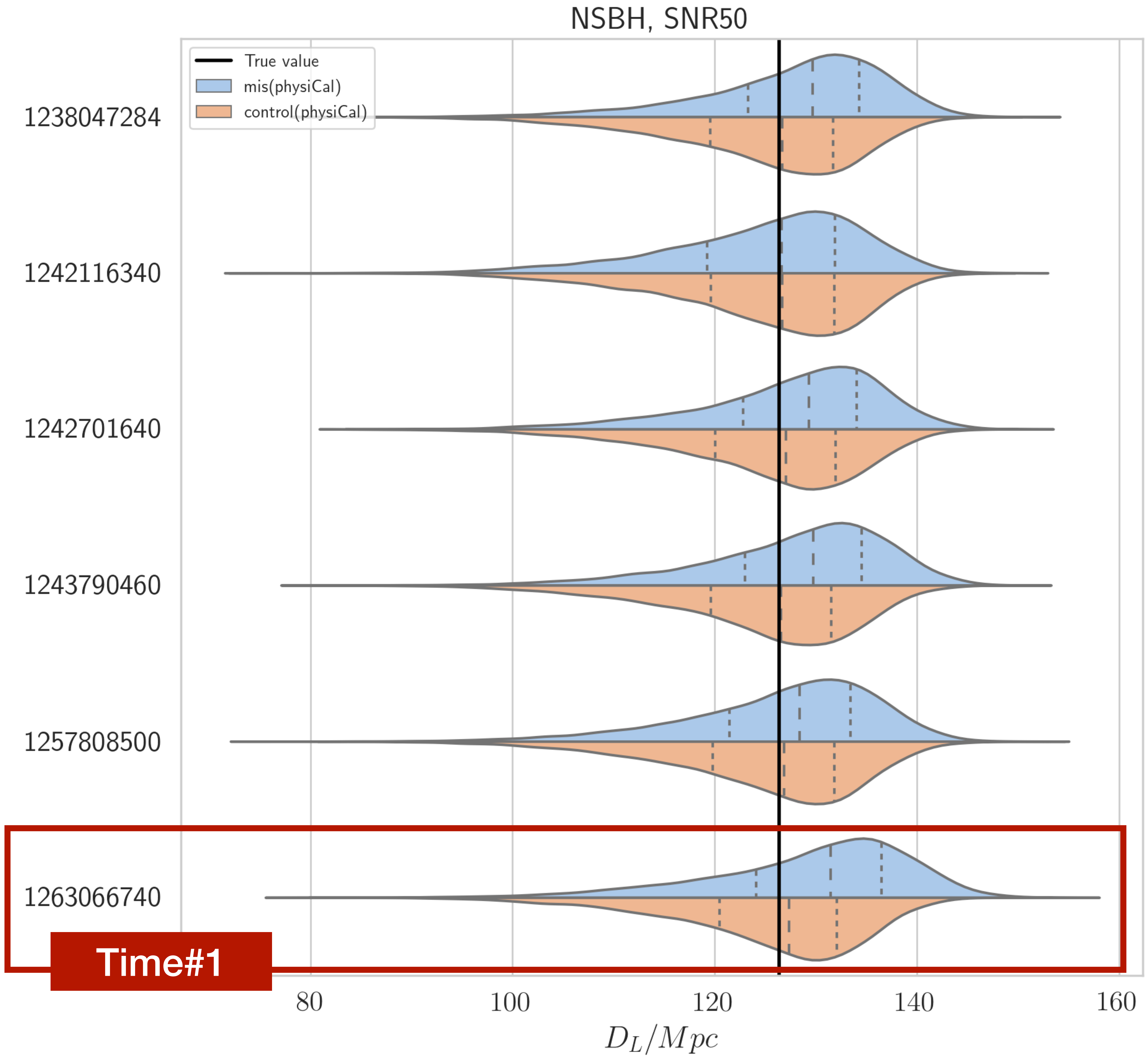
PE Results - BNS



Normalized by the true value

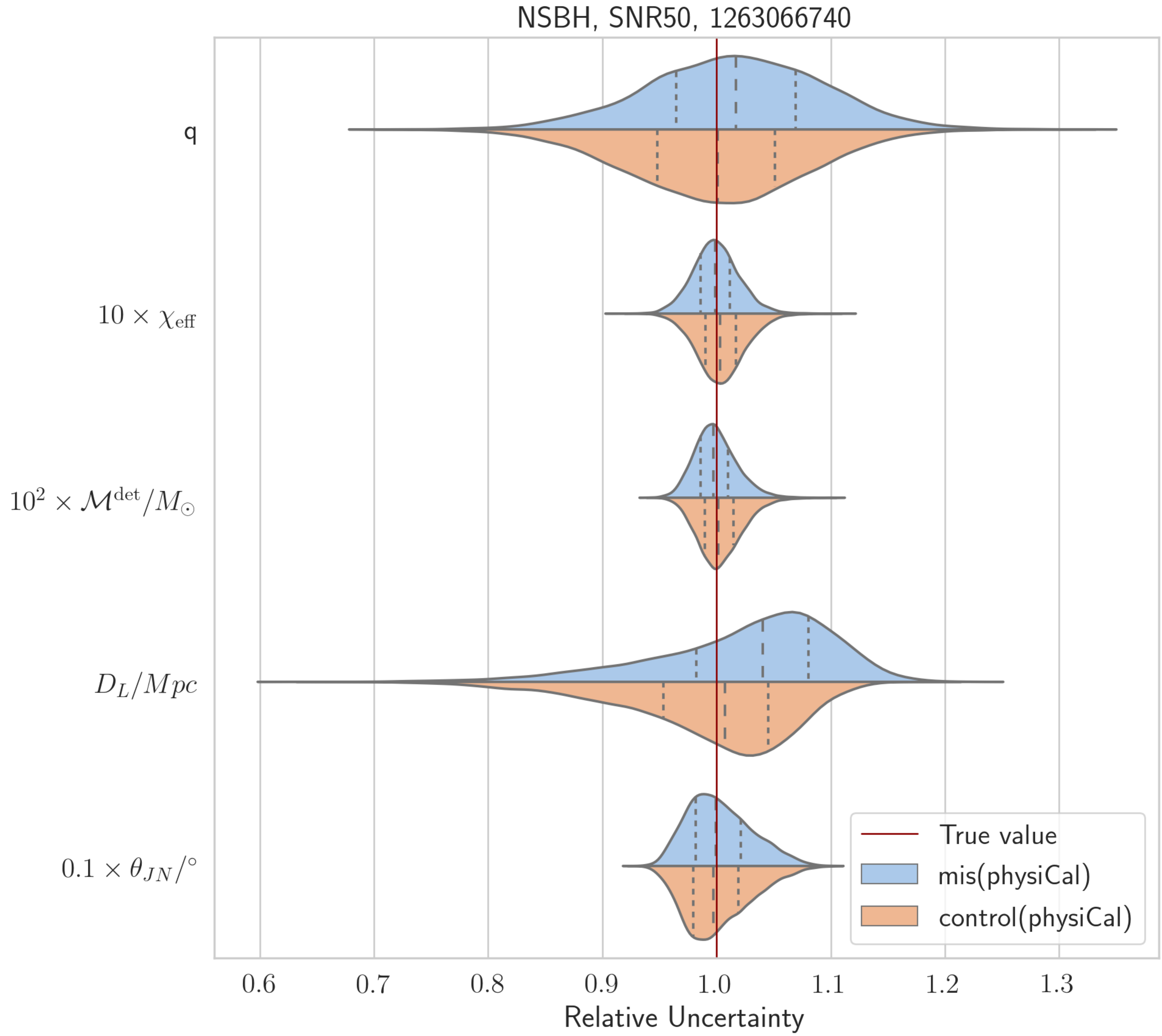
- BNS
  - $m_1 = 2M_\odot$, non spinning
  - $m_2 = 1.5M_\odot$, non-spinning
  - Sky localization known
- SNR 50, PhysiCal with unif $\eta_{\rm NIST}$ prior, **Large calibration error ("mis")** vs **No calibration error ("control")**
  - Relative biases on distance ($\Delta D_{L,\rm med}/D_{L,\rm true}$) for mis (control)
  - **4.7%(0.9%) for SNR50**
  - 4.1%(0.2%) for SNR35

PE Results - Neutron Star Black Hole



- NSBH
  - $m_1 = 5M_\odot, a_1 = 0.8, t_1 = 40°$
  - $m_2 = 1.4M_\odot$, non-spinning
  - Sky localization known
- SNR 50, PhysiCal* with unif η_{NIST} prior, **Large calibration error ("mis")** vs **No calibration error ("control")**
  - Lines are quartiles (25%, 50% and 75%)
  - *Spline results are very similar to physiCal, thus not shown here

PE Results - NSBH



Normalized by the true value

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  - $m_1 = 5M_\odot, a_1 = 0.8, t_1 = 40^\circ$
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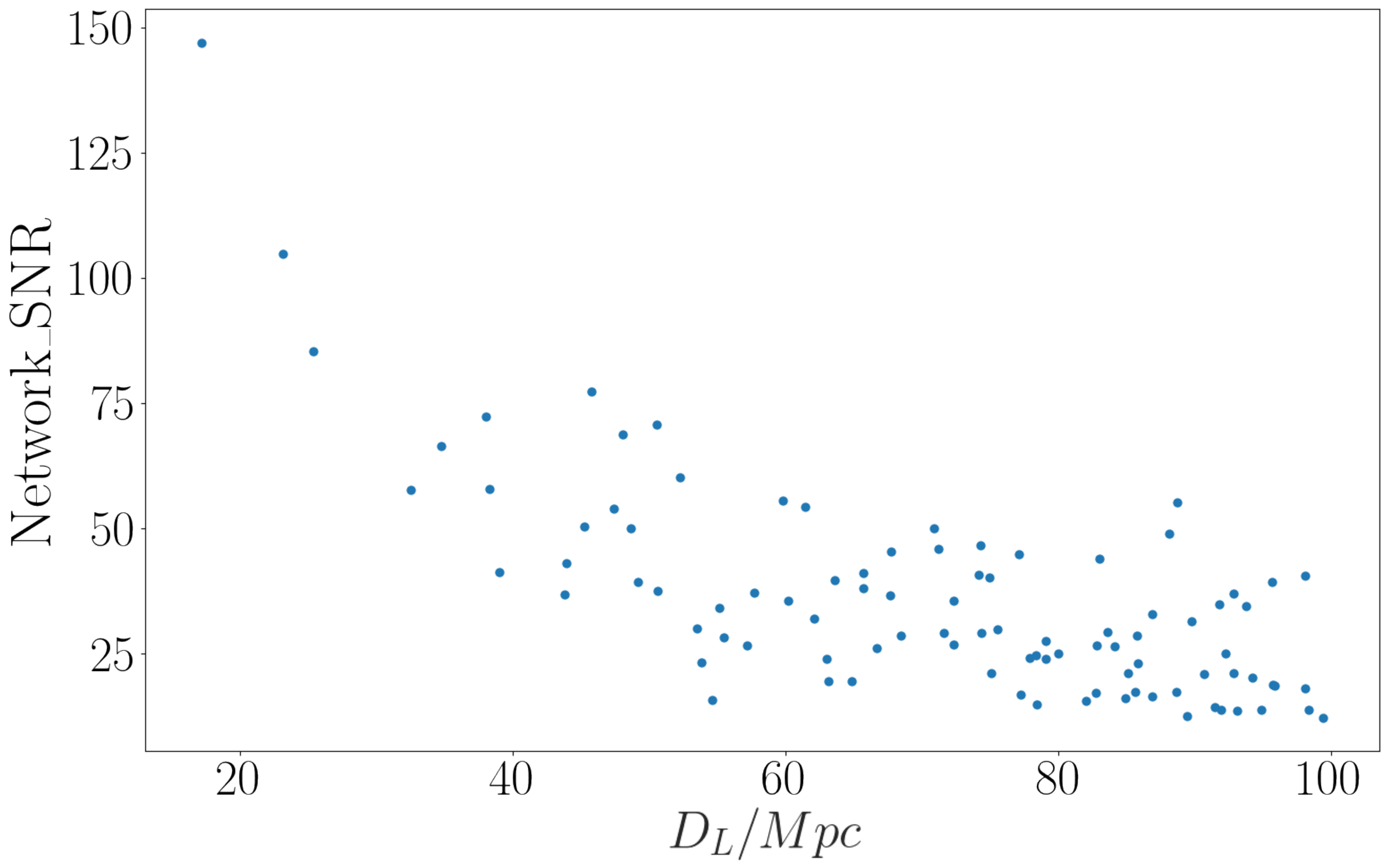
  - Sky localization known
- SNR 50, PhysiCal* with unif $\eta_{\rm NIST}$ prior, **Large calibration error ("mis")** vs **No calibration error ("control")**
  - Relative biases on distance ($\Delta D_{L,\rm med}/D_{L,\rm true}$) for mis (control)
  - **4.1%(0.8%) for SNR50**
  - 4.6%(1.0%) for SNR35

Summary

- Single event level
  - Systematic bias ~4-5% in luminosity distances, smaller than statistical uncertainties for all individual events here
- If the same effect is present in **multiple events**, the bias on combined PE will become more significant

Next Steps



- 100 BNS coalescences
  - Random luminosity distances uniform-in-volume $\sim D_L^2$
  - Random inclinations and sky localizations (ra, dec) uniformly distributed
  - Assume we know the sky localization (ra, dec)
- Use time #1 for “worst” calibration error realization
  - Most significant biases in distance, etc
  - Worst-case scenario: same calibration error is not accounted for but present for all events

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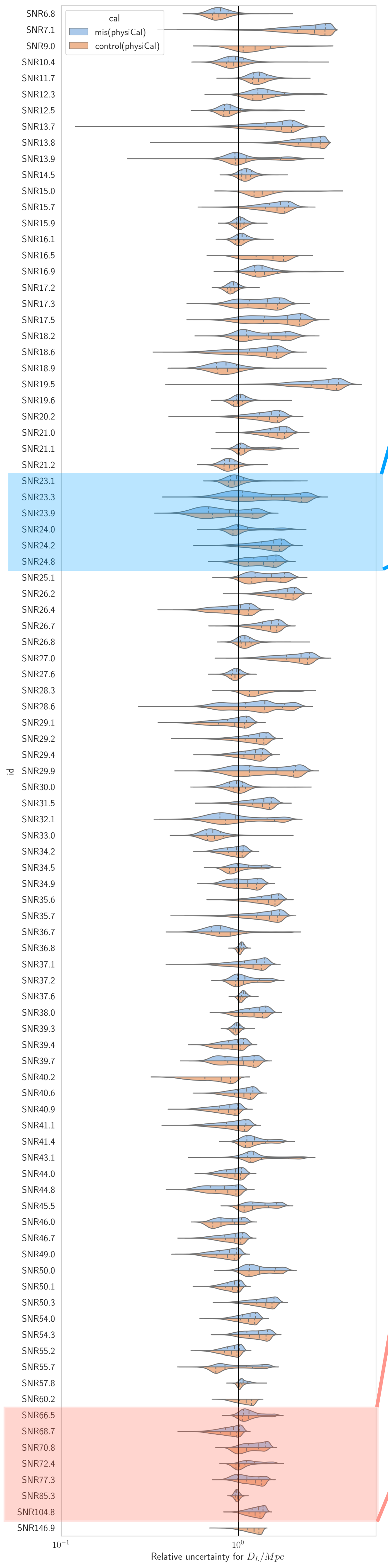
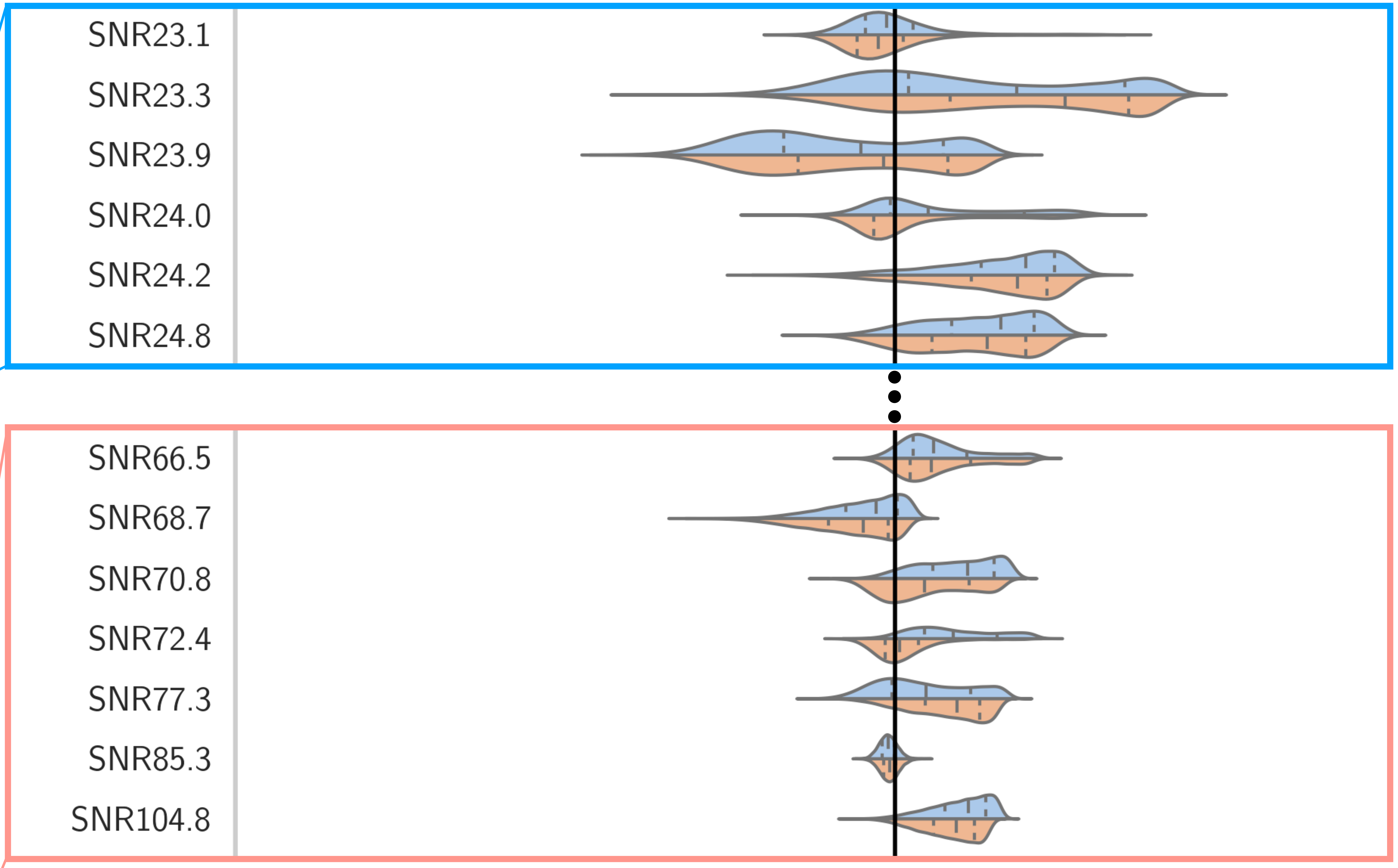
Preliminary results

Low SNR



High SNR



At SNRs of potential O4 events

- Relative uncertainties on luminosity distances (sorted by SNR) show a big spread among events
- Systematic biases become more comparable to statistical uncertainties at higher SNRs