

Challenges in GW Detection & Inference

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Challenges



Computational

- ▶ Today: Source characterisation takes hours to $\mathcal{O}(\text{week})$
- ▶ Future: More, longer, louder, overlapping signals
- ▶ Exploration of a wide parameter space (eccentric, precessing, compact objects in non-trivial environment, calibration, glitches, ...)
- ▶ Time/frequency-dependent detector response

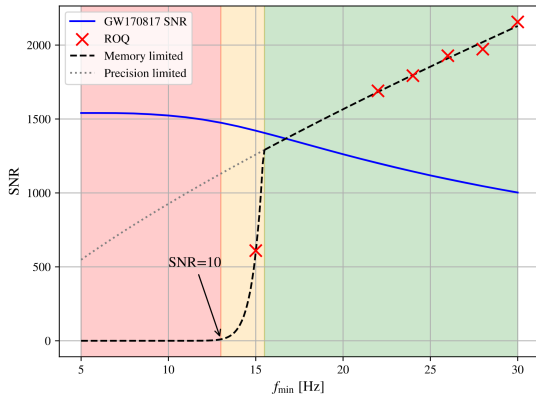
Accuracy

- ▶ Models remarkably accurate, but subject to numerous uncertainties: NR resolution, analytical approx., inter-/extrapolation, missing physics, ...
- ▶ Accuracy requirements scale with SNR^κ
- ▶ Future: More, longer, louder, overlapping signals
- ▶ Systematics may become dominant source of uncertainty

Computational Challenges

Some simple estimates:

- ▶ Rate $\sim V \sim D_h^3 \sim (\rho/\rho_0)^3$
- ▶ Duration $T \approx 5M_c^{-5/3}(\pi f_0)^{-8/3}/256$
factor > 400 from 30 Hz \rightarrow 3 Hz
- ▶ Detector moves while signal in band;
long-wavelength approx. not always valid
 $\Rightarrow t/f$ -dependent detector response
- ▶ [Baker, Lasky, Thrane, Golomb 2025]: “...*standard data compression techniques become impractical, and the full problem becomes computationally infeasible*...”
- ▶ New techniques needed (ML?)



Accuracy Requirements

Likelihood $\log \Lambda \sim \|d - h(\theta)\|^2/2$

Neglecting noise $\|h_0 - h(\theta)\|^2 \approx 2\rho^2 \underbrace{(1 - \langle \hat{h}_0, \hat{h}(\theta) \rangle)}_{=\mathcal{M}}$

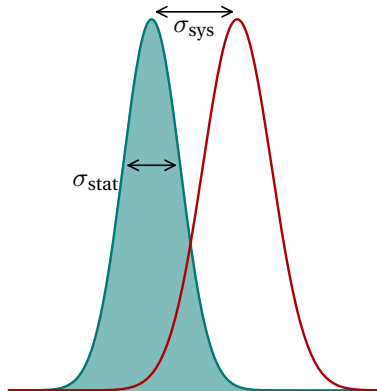
Linearization $\|h_0 - h(\theta)\|^2 \approx \Gamma_{ij} \Delta\theta^i \Delta\theta_j$

Credible interval $\|h_0 - h(\theta)\|^2 < \chi_k^2(p)$

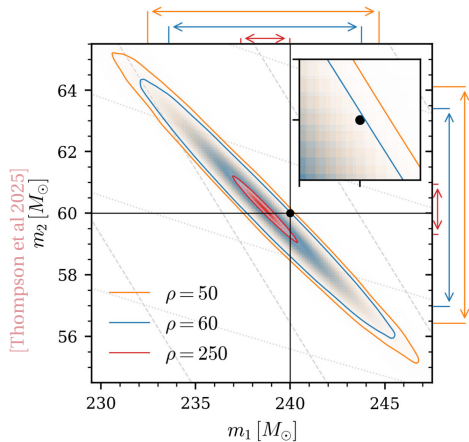
Criterion $\mathcal{M} < \chi_k^2(p)/(2\rho^2)$

- This is very conservative, does not take *direction* of difference into account. See [Thompson et al 2025]

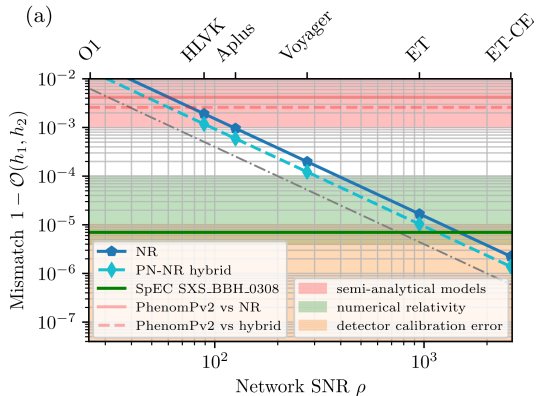
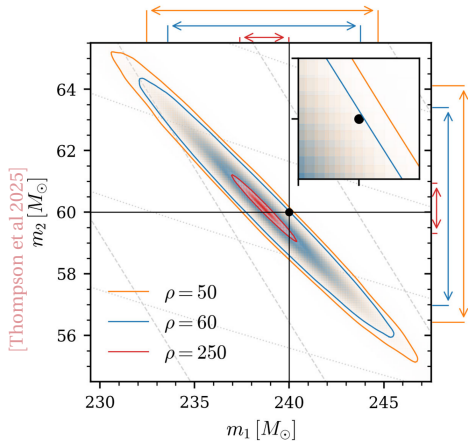
System. Error $\sigma_{\text{sys}}^i = \Gamma^{ij} \langle \partial_j h, \Delta h \rangle$



Accuracy Requirements



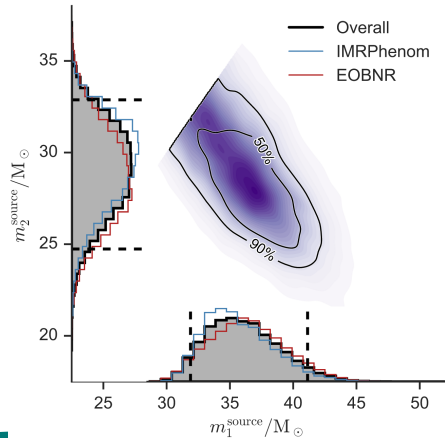
Accuracy Requirements



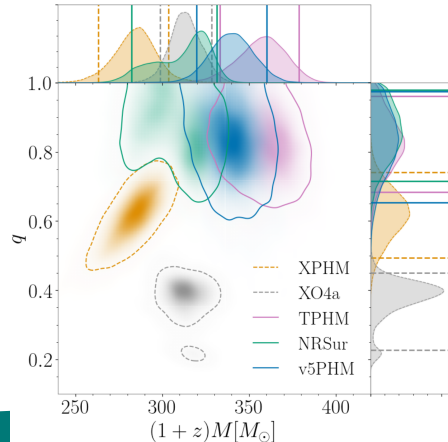
[Pürrer & Haster 2020]

Examples

GW150914

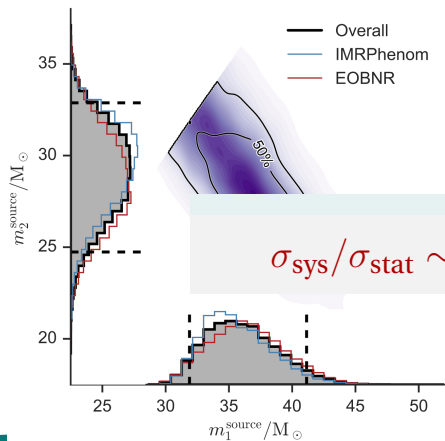


GW231123

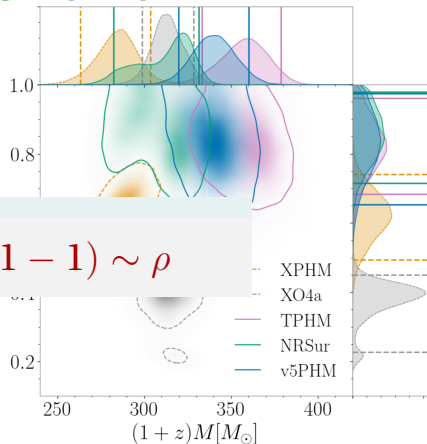


Examples

GW150914



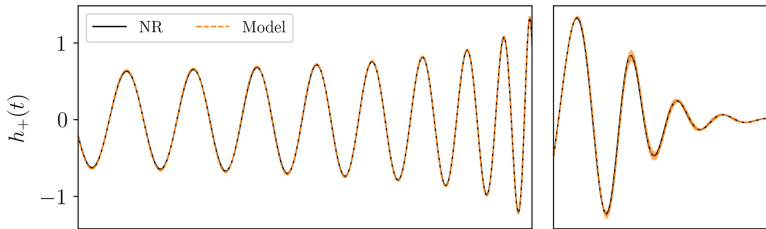
GW231123



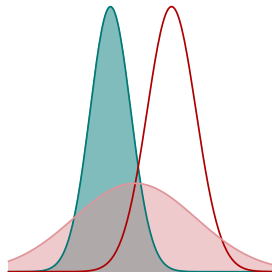
$$\sigma_{\text{sys}}/\sigma_{\text{stat}} \sim \mathcal{O}(0.01 - 1) \sim \rho$$

Accounting for Systematics

- ▶ Waveform models will continue to improve, but we need a paradigm shift
- ▶ Complete signal models should not only provide a “best guess”, but a waveform “bundle”



[Khan 2024]

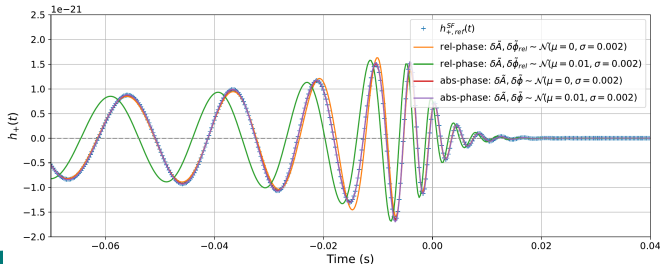


Proposed Ideas

- ▶ Analyse using a discrete set of models, combine their results (uniform prior, evidence based prior, NR mismatch informed prior) [LVK, Hoy et al 2025, Ashton & Khan 2020, Jan et al 2020, Ashton & Dietrich 2022, Hoy 2022]
→ Limited by inaccuracy of most accurate model
- ▶ Provide uncertainty in tuning coefficients [Mezzasoma et al 2025, Pompili et al 2025]
- ▶ Provide error envelopes for waveforms [Khan 2024, Bachhar et al 2025, Kumar & Melching & FO 2025]

Proposed Ideas

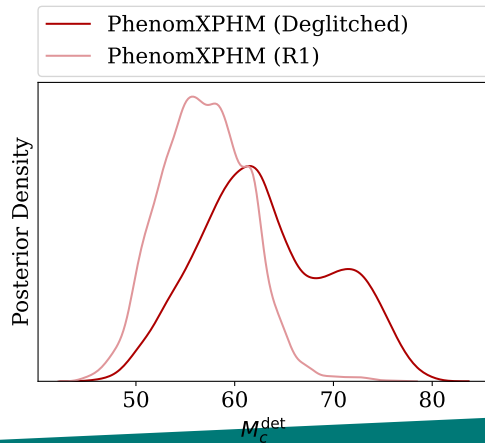
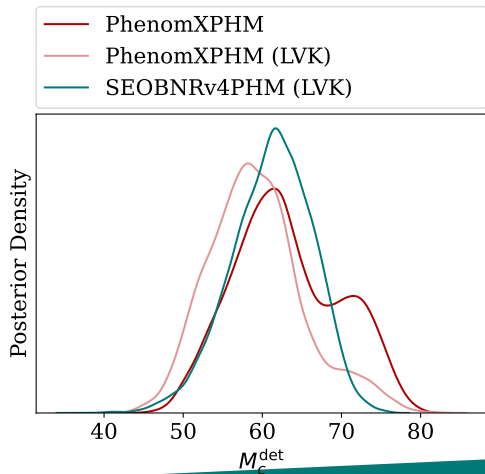
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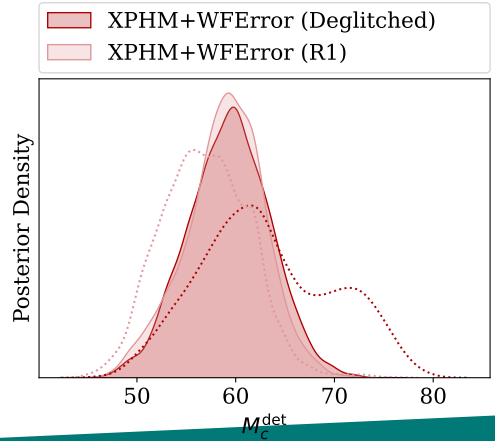
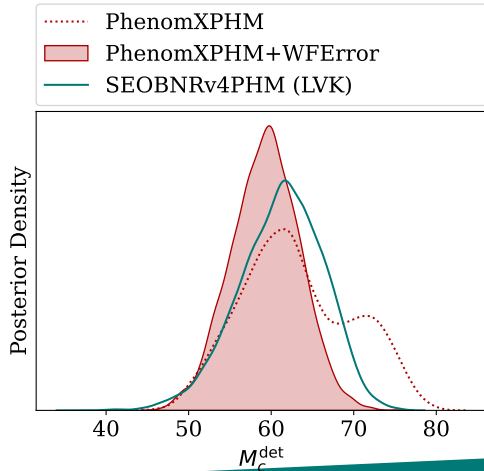
$$\tilde{h} = \tilde{A}_0 (1 + \delta \tilde{A}) e^{i\tilde{\phi}_0(1+\delta\tilde{\phi})}$$



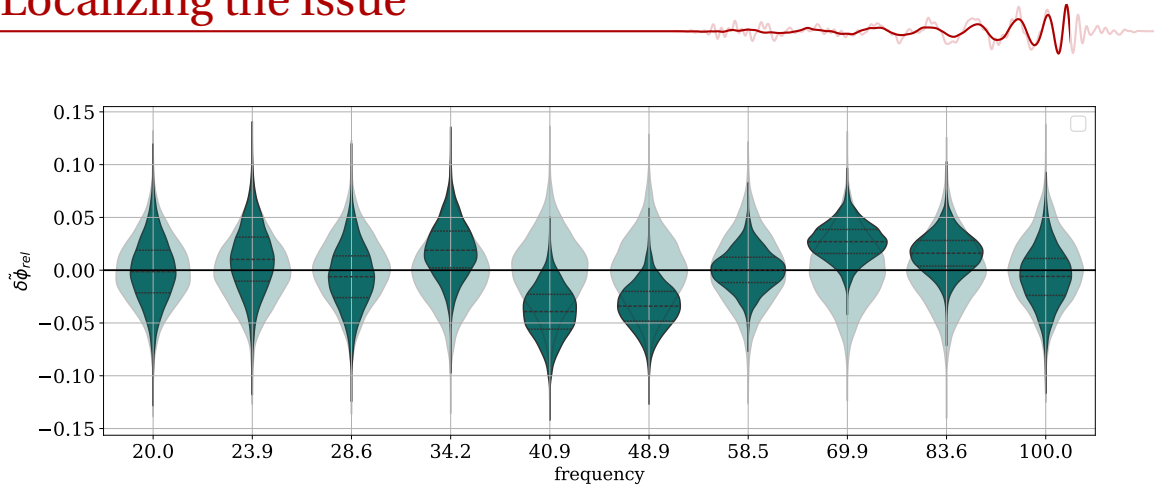
Example: GW191109



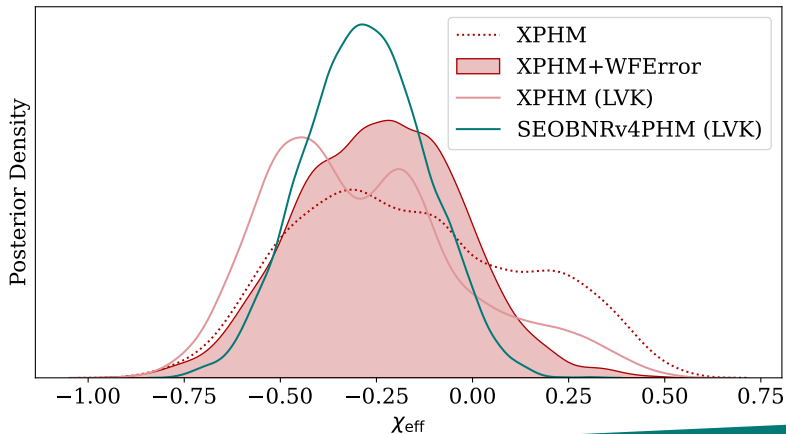
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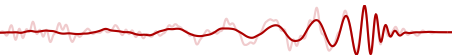
Localizing the Issue



The Spin of GW191109



Summary



- ▶ **Computational demands** will grow rapidly
→ new methods for compression & efficient analysis
- ▶ **Accuracy requirements** just satisfied at the moment; becoming more demanding with growing SNR and more observations
→ further waveform refinements, more and longer NR simulations, new methods for building accurate models
- ▶ **Waveform systematics** need to be quantified and included in analyses
→ Promising first approaches available. Need to re-evaluate science potential under potentially dominating systematics