Observing upper-stellar-mass gap with LIGO and Virgo

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Mehta et al. 2105.06366

Upper-stellar-mass gap ?

- Single stars with masses, $20\,M_\odot \lesssim M_{\rm ZAMS} \lesssim 100\,M_\odot$, end their lives in core collapse supernovae and forms black holes (BHs).

- Stars with masses $M_{\rm ZAMS} \gtrsim 100\,M_\odot$ ⇨ Electron-positron pair production

  - $100\,M_\odot \lesssim M_{\rm ZAMS} \lesssim 130\,M_\odot$ ⇨ Pulsational pair-instability supernova (PPISN)
  - $130\,M_\odot \lesssim M_{\rm ZAMS} \lesssim 250\,M_\odot$ ⇨ Pair-instability supernova (PISN)
    ↓
    Completely destroys the star

- $M_{\rm ZAMS} \gtrsim 250\,M_\odot$ ⇨ Photodisintegration ⇨ Core collapse supernovae

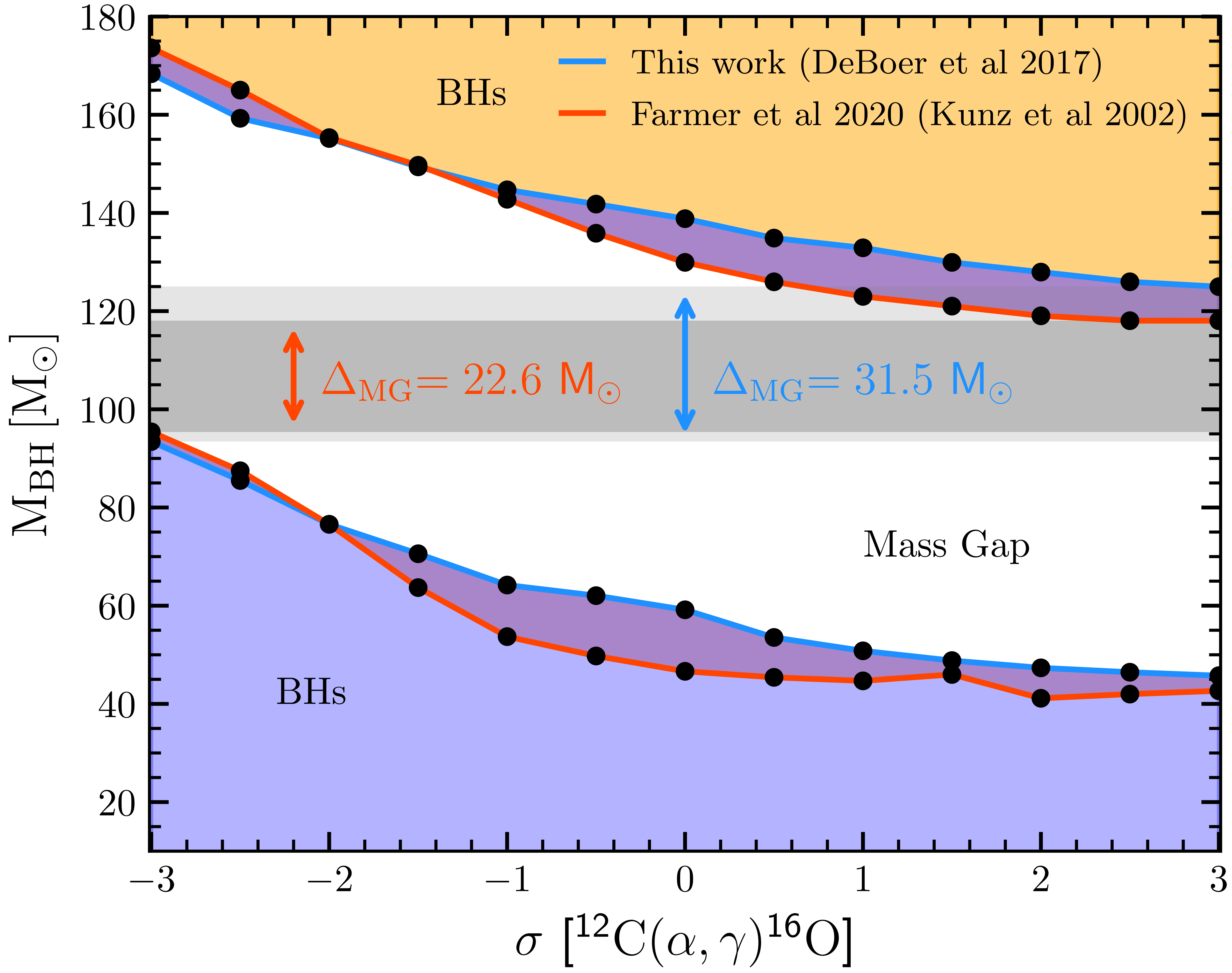
Mass-gap (PISN and $M_{\rm ZAMS} \gtrsim 250\,M_\odot$ ranges)

Boundaries of mass-gap ??

- The final fate of the stars also depend heavily on $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, i.e., C/O ration in the core after helium burning.

- Depending on C/O ratio, the cores can undergo or skip the carbon burning, and set explosive oxygen burning.

- The plot uses the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate provided in deBoer et. al. (2017) which considered the entirety of existing experimental data, aggregating 60 year of experimental data consisting of more than 50 independent experimental studies.



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$^{12}C(\alpha,\gamma)^{16}O$ reaction rate

- The reaction rate per particle pair is given by,

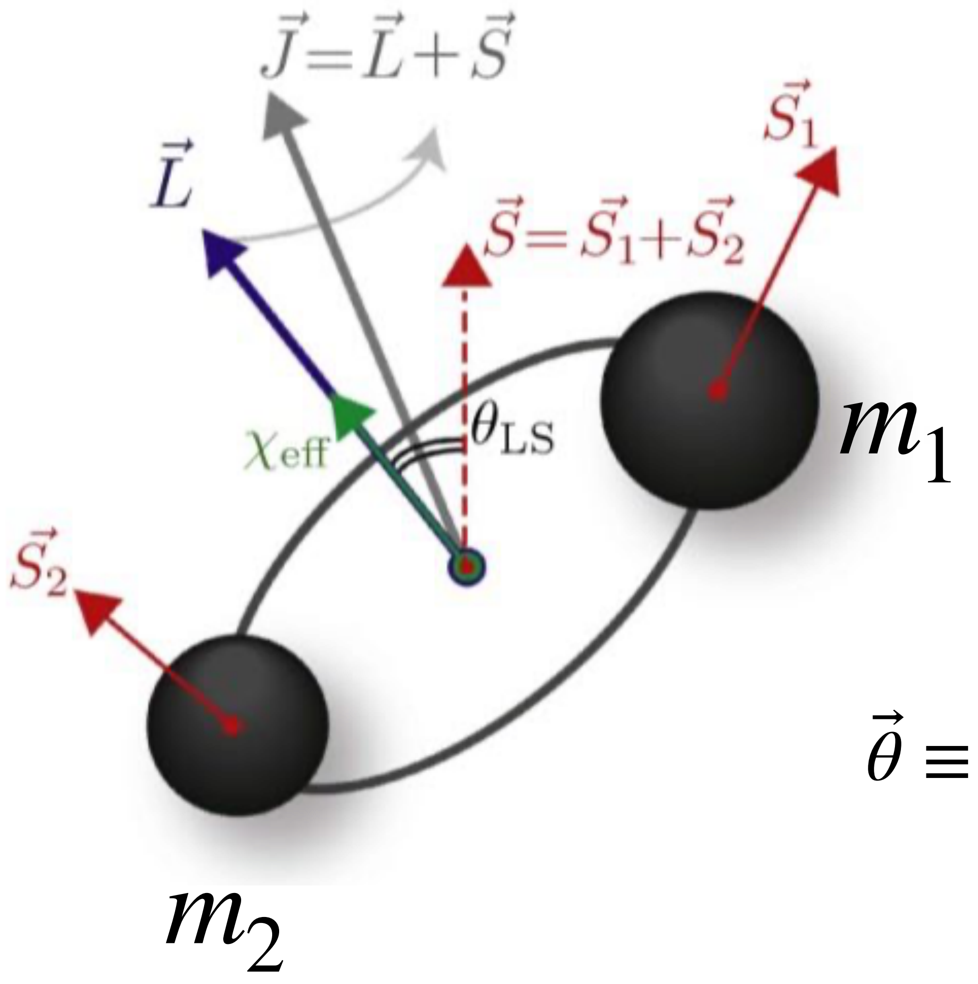
$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(k_B T)^{3/2}} \int_0^\infty \sigma(E)\, E\, e^{-E/k_B T}\, dE$$

$$= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(k_B T)^{3/2}} \int_0^\infty S(E)\, e^{-E/k_B T - 2\pi\eta}\, dE$$

- Where $S(E) = \sigma(E)\, E\, e^{2\pi\eta(E)}$ and, $\eta = \sqrt{\frac{\mu}{2E}}\, Z_1 Z_2 \frac{e^2}{\hbar}$

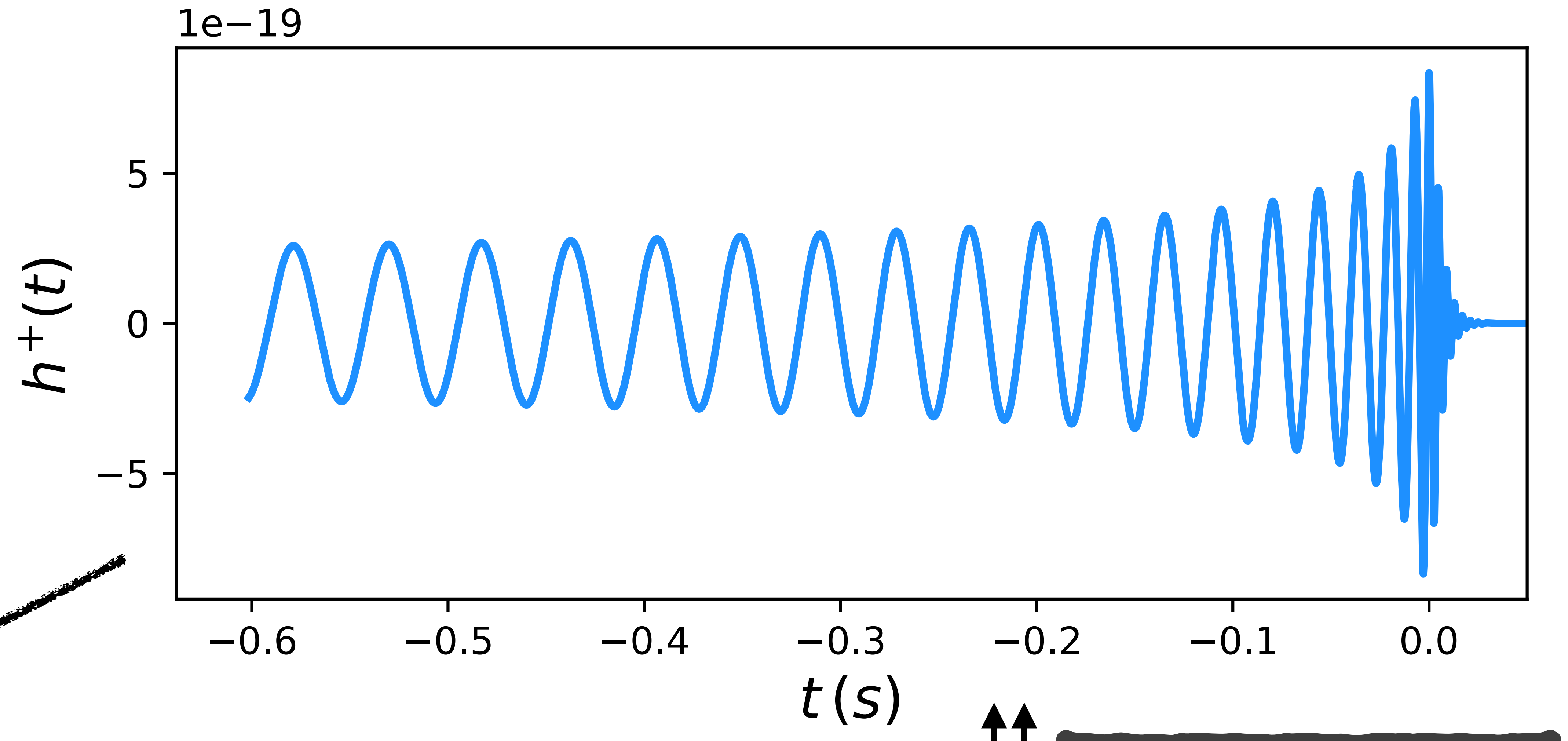
From GW, we can measure M_{BH}^{gap} $\Longrightarrow$ $\langle \sigma v \rangle$ $\Longrightarrow$ $S(E)|_{E=E_0}$

Observations of GWs from BBHs



$$h^{+,\times}(t;\vec{\theta})$$

$$\vec{\theta} \equiv \{m_1, m_2, \vec{S}_1, \vec{S}_2, D_L, \iota, t_c, \phi_c, \psi, \alpha, \delta\}$$

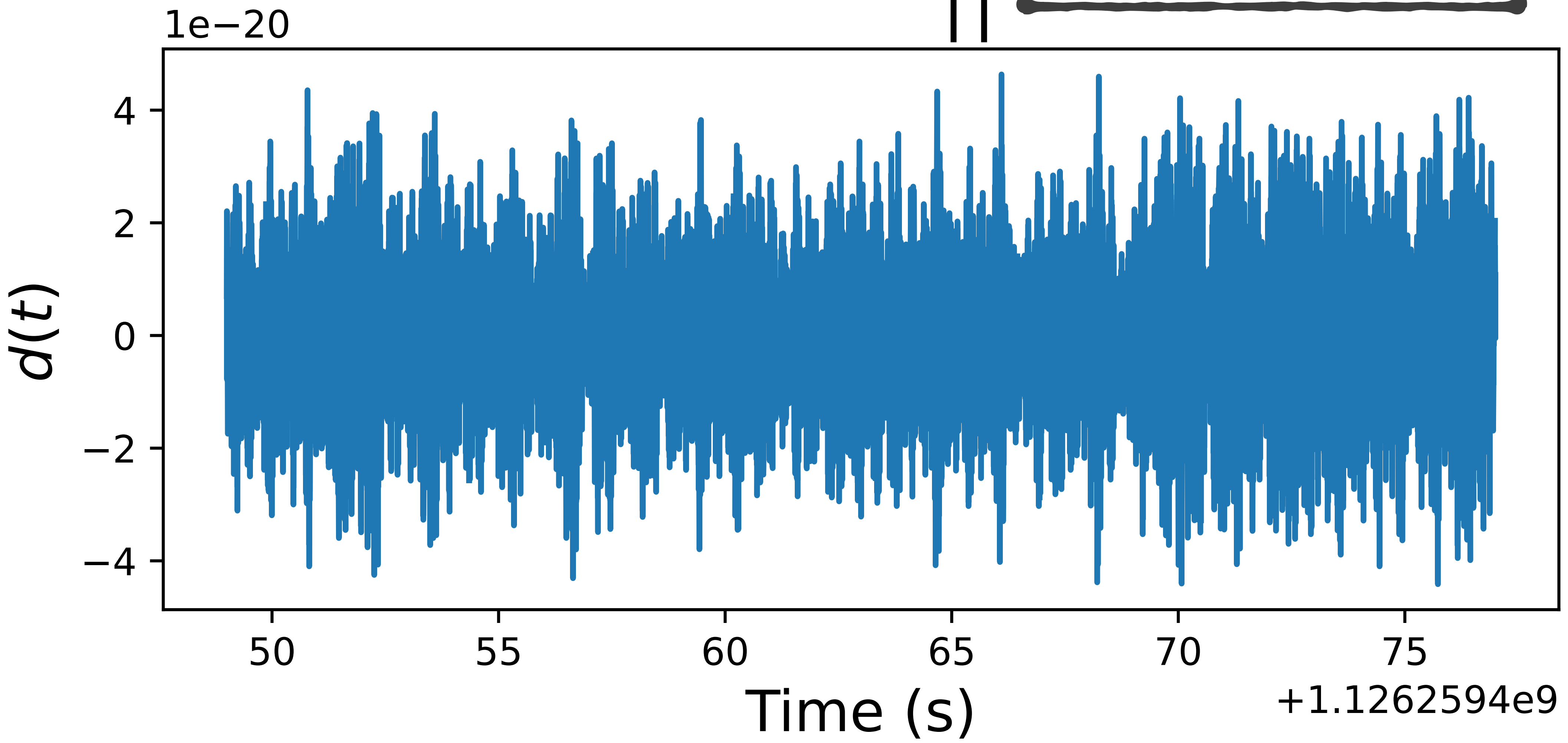


Search Pipelines

Detector noise

$$d(t) = h(t) + n(t)$$

Expected strain



Parameter Inference: Bayes' Theorem

- Let's say we know that the data segment *d* contains a GW signal. Then the distribution of the parameters can be reconstructed using Bayes' theorem as follows:

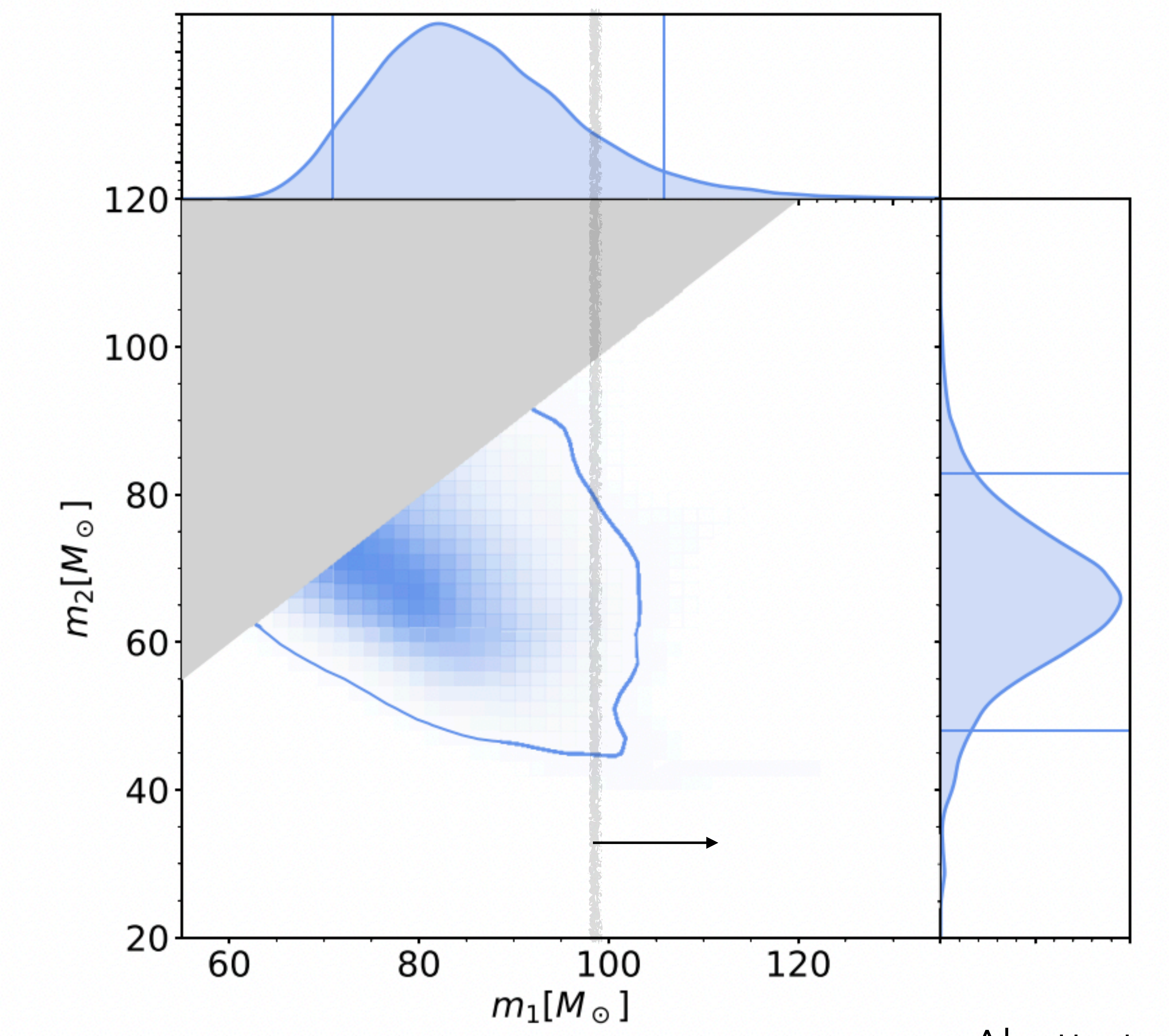
Likelihood

Prior

Posterior → $$P(\boldsymbol{\theta}|d,\mathcal{H}) = \frac{P(d|\boldsymbol{\theta},\mathcal{H})P(\boldsymbol{\theta}|\mathcal{H})}{P(d|\mathcal{H})} \, ,$$

Evidence

Example: GW190521



Abott et al. 2020

$$m_1 = 85^{+21}_{-14}\, M_\odot$$

$$m_2 = 66^{+17}_{-18}\, M_\odot$$

⇊

$$\sigma_{C12} = -2.4^{+0.6}$$

⇊

$$S(300\,\mathrm{keV}) = 73^{+11}\,\mathrm{keV\,b}$$

Farmer et al. 2019

GW population analysis

- Detection of BBHs allows us to measure/constrain the (hyper-) parameters which characterise the properties of BBHs from a formation channel.
- Let's denote by Λ the set of parameters which give you the shape of BBH mass function.

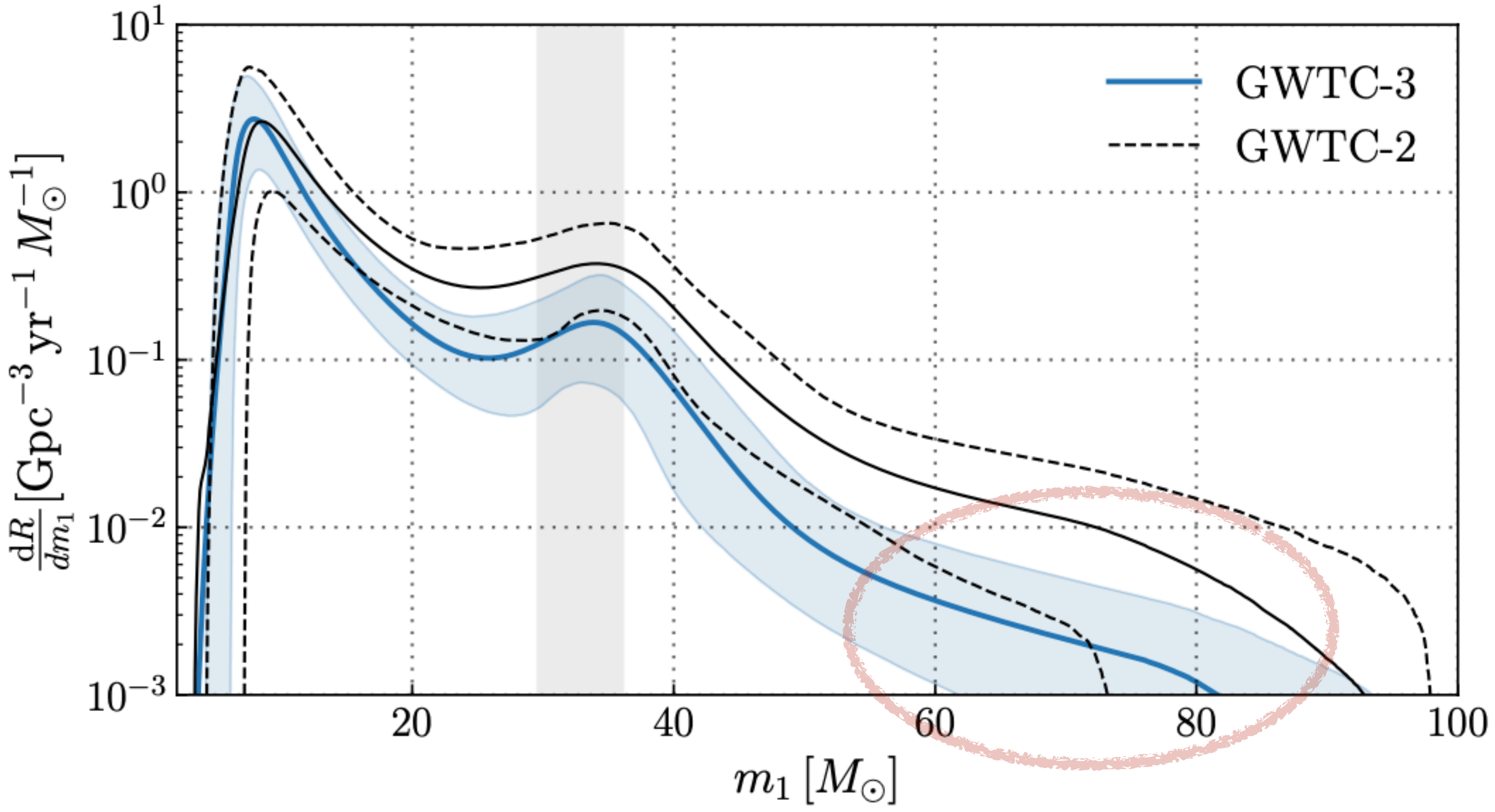
$P(m_1) \propto m_1^{-\alpha}$

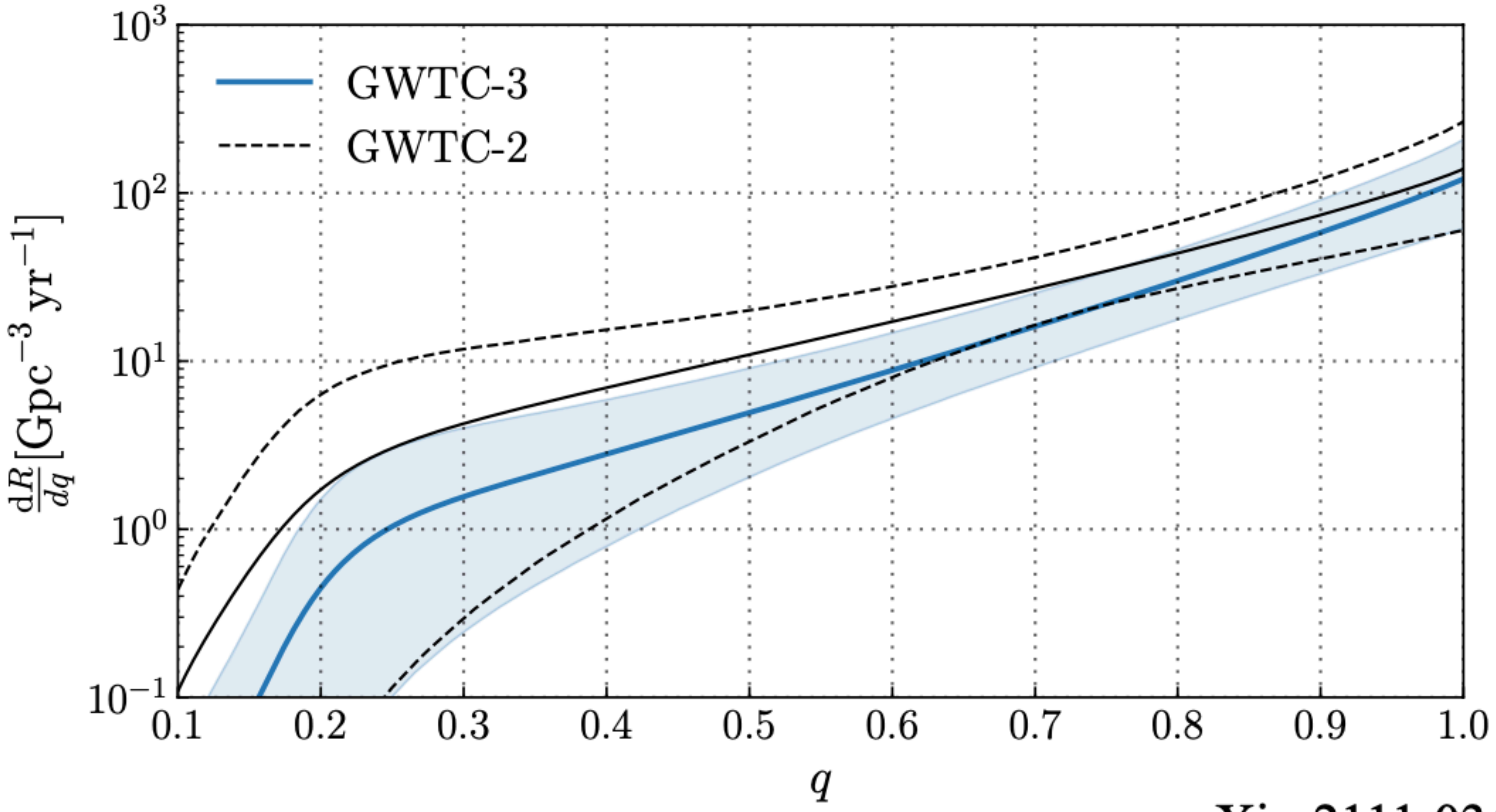
$P(q) \propto q^{\beta}$

For given parameter set Λ, this quatifies the fraction of binaries that are detectable.

Hierarchical Bayesian approach $\Longrightarrow$ $\mathcal{L}(\{d\}|\Lambda) \propto \prod_{i=1}^{N_{\rm det}} \frac{\int \mathcal{L}(d_i|\theta)\pi(\theta|\Lambda)d\theta}{\xi(\Lambda)}.$

Once Λ is measured, we can predict BBH mss function, as shown below.





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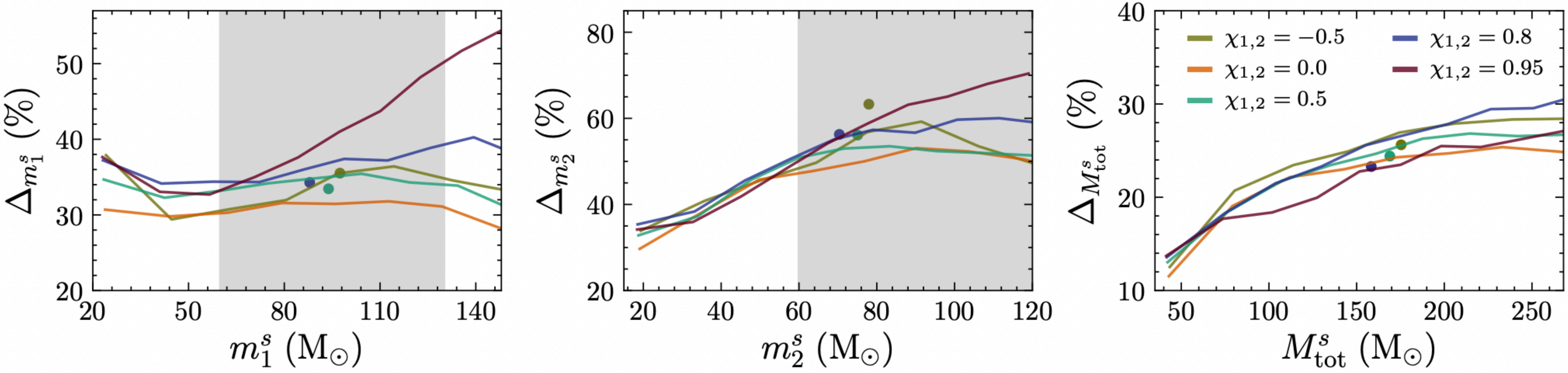
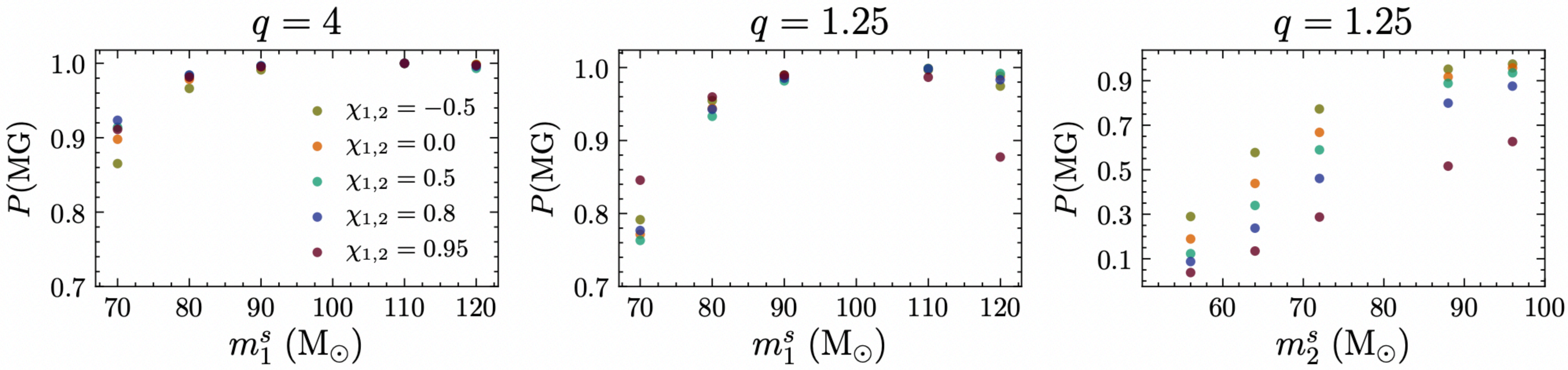
arXiv:2111.03634

Injection study at O4/O5 sensitivity



- The primary mass can be measured with precision better than $< 40\,\%$ in the mass gap.

Injection study at O4/O5 sensitivity



- Most of the BBH signals whose primary mass lie in the mass gap will be faithfully placed in the mass gap from GW observations during O4/O5.

Summary

- GW observations from upcoming LIGO-Virgo-KAGRA runs (e.g., O4) are expected to provide much better measurement of primary mass of the BBH signals.

- This, in turn, should lead to much better estimation of lower edge of mass-gap.

- This will further tighten the constraints on the astrophysical S-factor.