Spectral Siren Cosmology with GWs using a Combined-Population Mass Distribution

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Motivation

- As mentioned before - Hubble tension between early- and late-time measurements
- Use GWs to constrain the Hubble constant

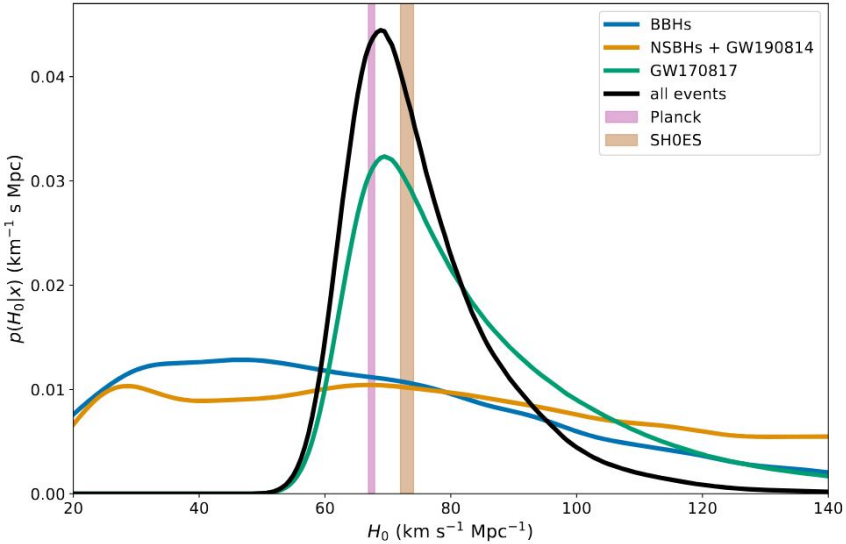
$$A = \frac{\mathcal{M}_z}{d_L} f(\mathcal{M}_z, t) \qquad d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_M + \Omega_\Lambda}}$$

- Use spectral sirens to extract as much information from population of events on this (+other things) as possible using

gwcosmo

- Cosmological inference pipeline for GW data
- Constrain cosmological and GW population parameters (H_0 and others)
- Uses spectral siren method and/or galaxy catalogs to find GW event redshift

Separate analysis by binary type (BBH, NSBH,BNS)!

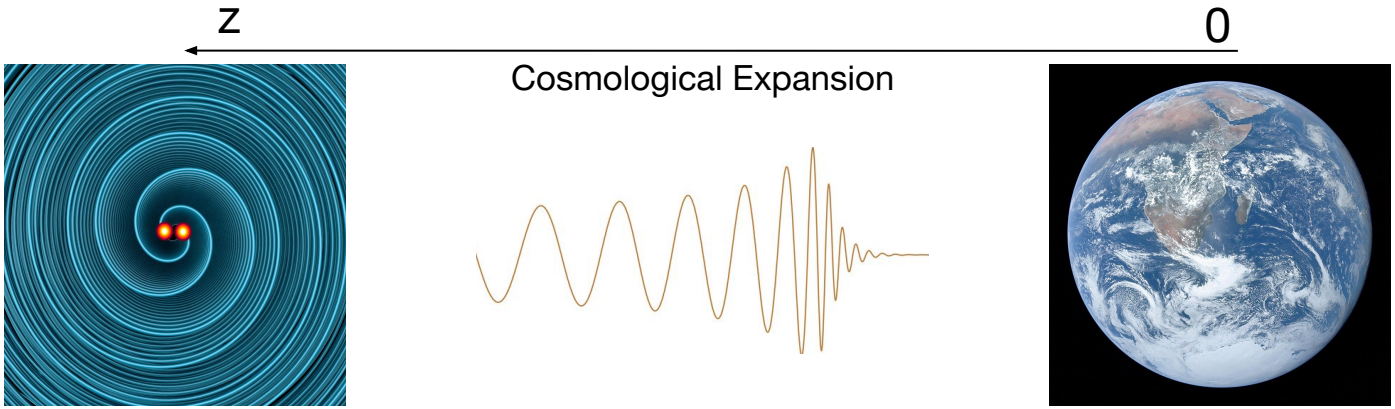


R. Gray *et al* JCAP12(2023)023

What are spectral sirens?

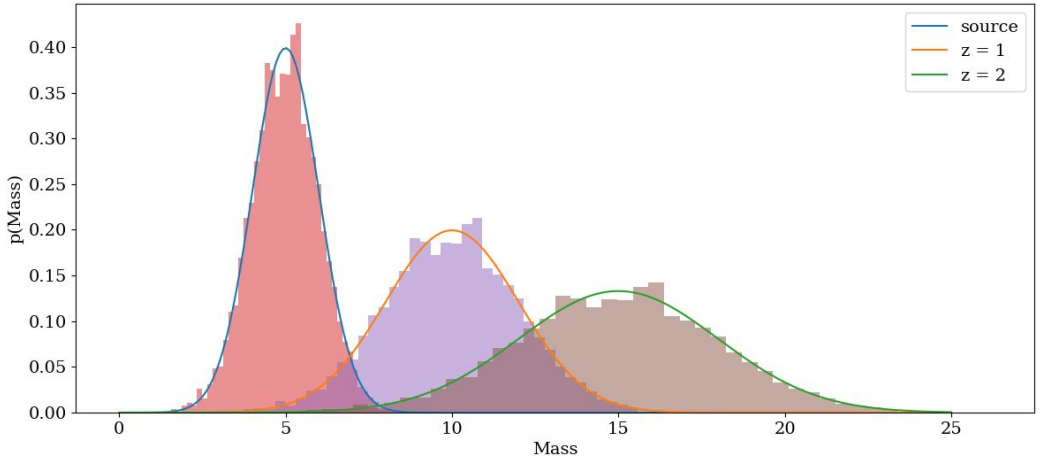
- Calculate redshift of event without EM counterpart or galaxy catalog

$$\mathcal{M}_z = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$



What are spectral sirens?

- Use features in the mass spectrum of GW sources to break mass-redshift degeneracy $m_d = (1+z)m_s$ (Taylor+ 2012)
- Sharper features in mass distribution -> better redshift determination
- Additionally, allows for constraints on mass distribution parameters



What are spectral sirens?

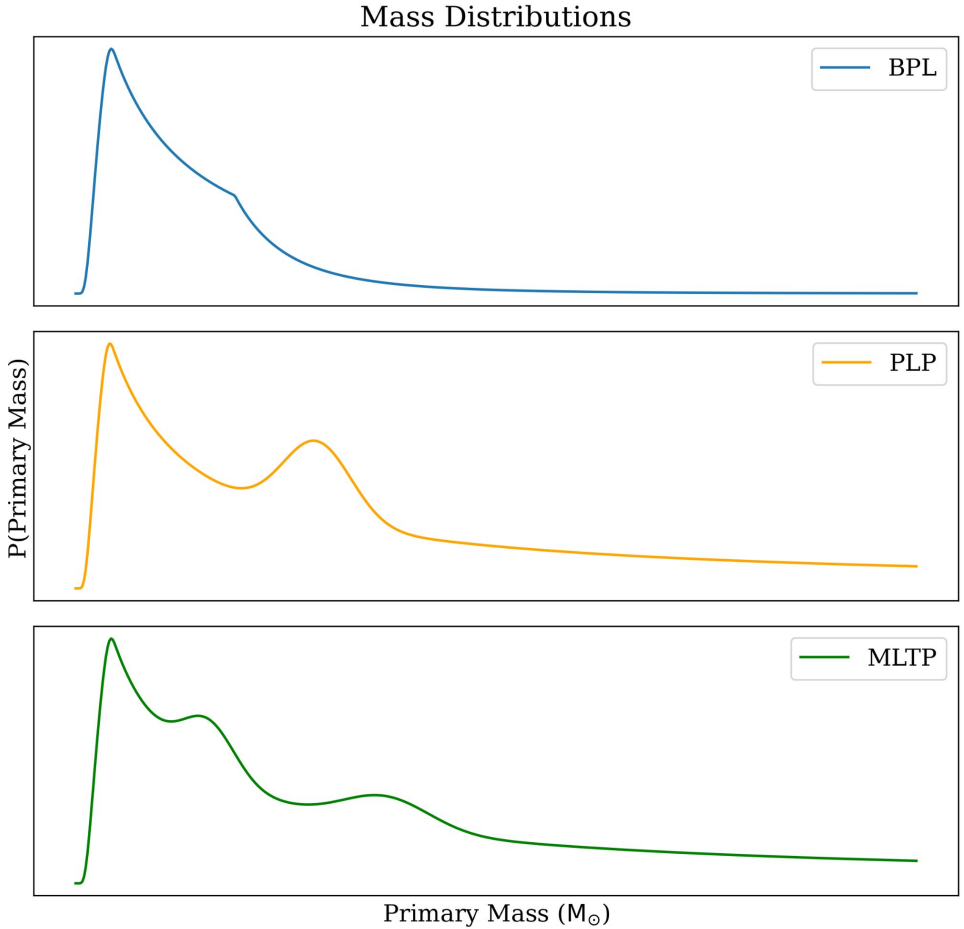
Strengths:	Weaknesses:

• Allows calculation of redshift information for GW events, without reliance on other factors (presence of an EM counterpart, completeness of a galaxy catalog/large localisation area)
• Features of the distribution can be **very** cosmologically informative
	• If features of mass model do not mimic true distribution, this can cause a large bias in estimates of cosmology e.g:
	  ○ No evolution with redshift when this is present in data
	  ○ Missing peaks, gaps etc that exist in true distribution which are not in model

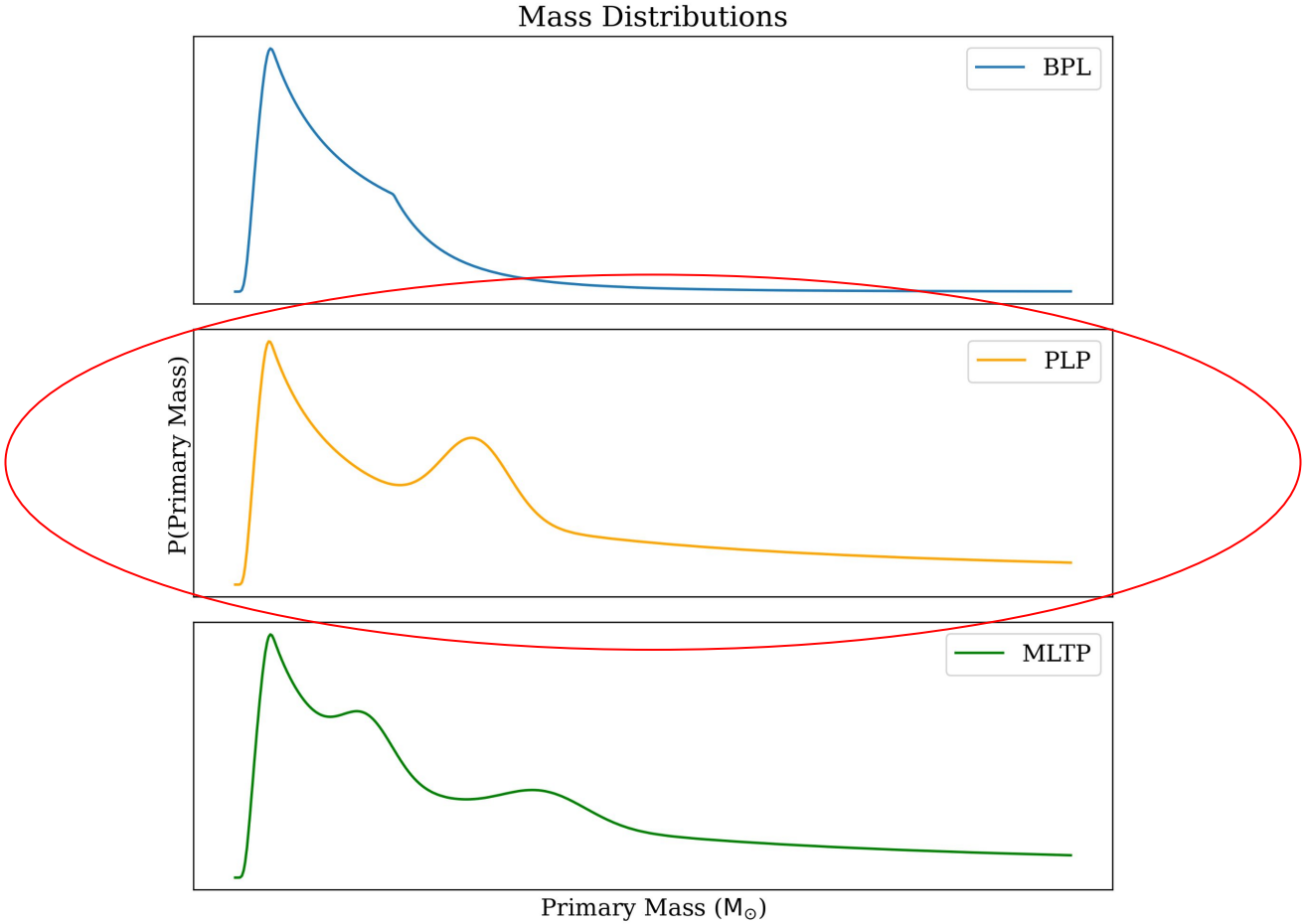
What's new?

Current:	Updated:
• Fiducial models for mass distribution based on some combination of powerlaw and Gaussian peaks • Analysis run separately for CBC events of different binary classification (e.g. BBHs, NSBHs, BNSs)	• Combined-population model with three components • Analysis on all events can be run at same time • '*Uninformative prior*' on the classification of individual events • Particularly useful for events with uncertain classification (e.g. mass-gap events)

BH Mass Models



BH Mass Models



Combined-population prior expression

Powerlaw + Peak with smoothing

Powerlaw

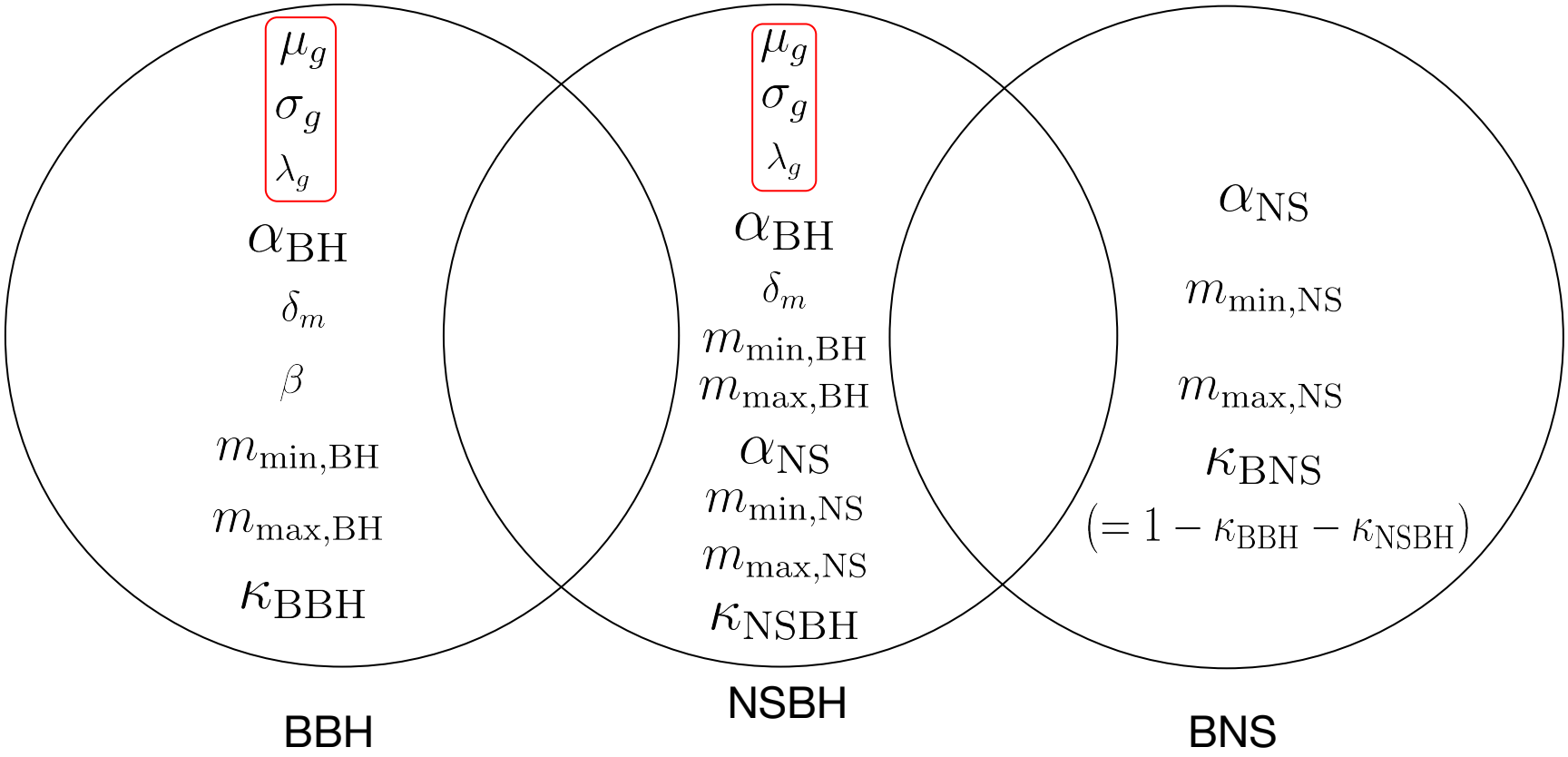
$$p(m_1) \propto \kappa_{\rm BBH} \overbrace{(\mathcal{G}_{\rm BBH} + \mathcal{P}_{\rm BBH})\mathcal{S}_{\rm BBH}} + \kappa_{\rm NSBH} \overbrace{(\mathcal{G}_{\rm NSBH} + \mathcal{P}_{\rm NSBH})\mathcal{S}_{\rm NSBH}} + \kappa_{\rm BNS} \overbrace{\mathcal{P}_{\rm BNS}}$$

$$\kappa_{\rm BBH} + \kappa_{\rm NSBH} + \kappa_{\rm BNS} = 1$$

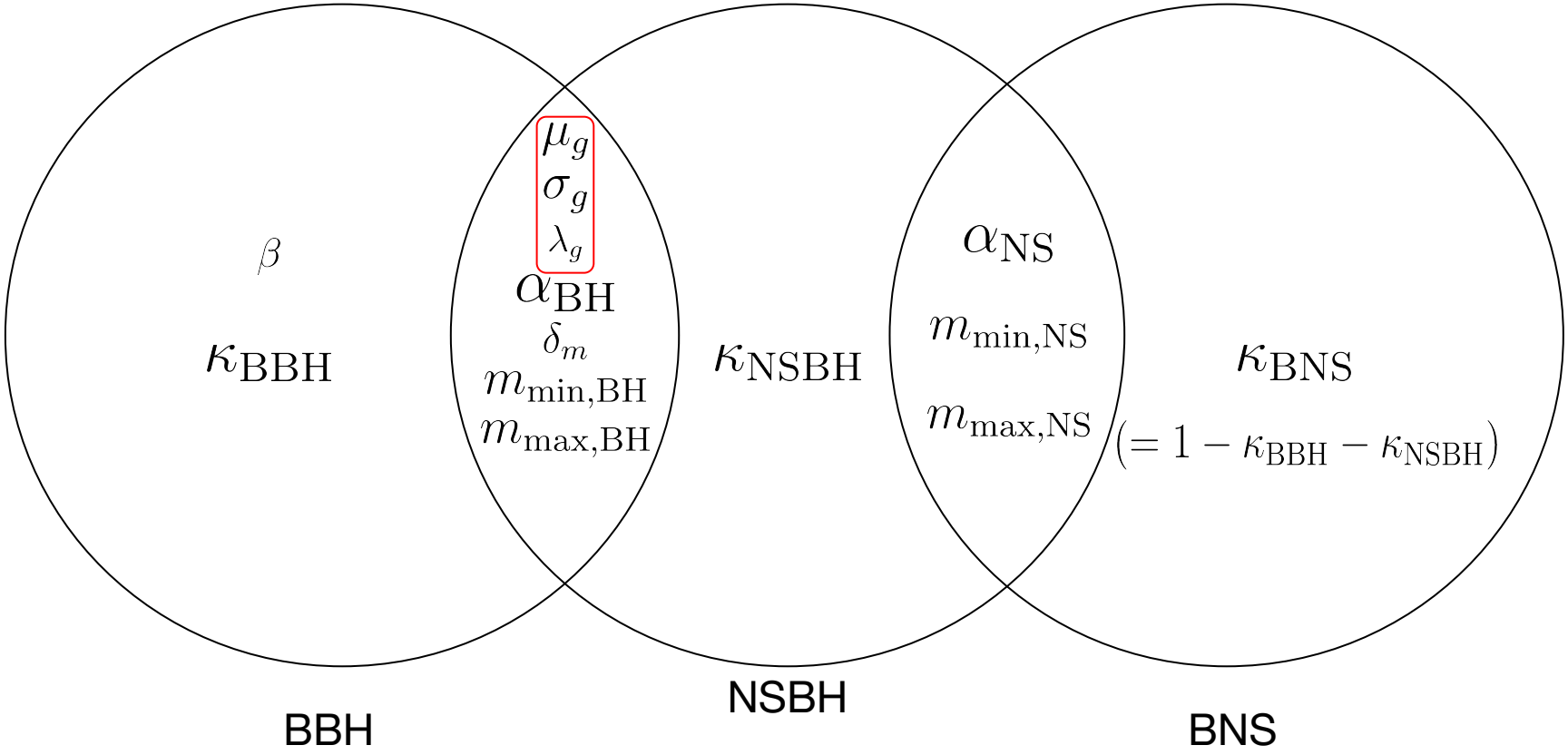
Powerlaw

$$p(m_2) \propto \kappa_{\rm BBH} \overbrace{\mathcal{P}_{\rm BBH}\mathcal{S}_{\rm BBH}} + \kappa_{\rm NSBH} \overbrace{\mathcal{P}_{\rm NSBH}} + \kappa_{\rm BNS} \overbrace{\mathcal{P}_{\rm BNS}}$$

Unshared case - 24 population parameters



Shared case - 14 population parameters



Analysis setup

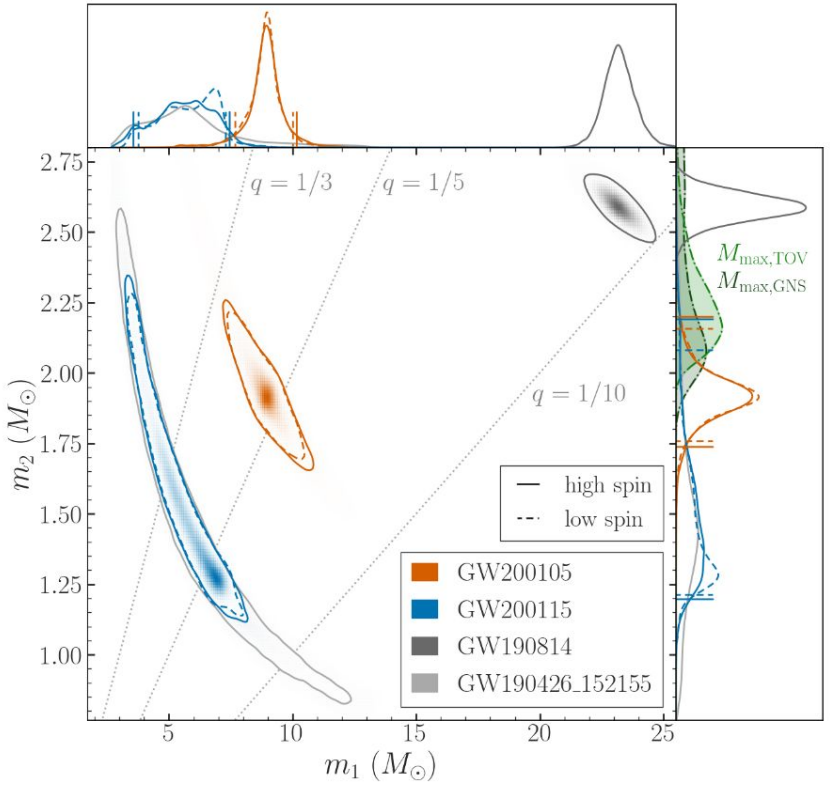
- Applied to analysis of GWTC-3 catalog (The LIGO, Virgo and KAGRA collaborations, Phys. Rev. X; **13**(4):041039)

- Events with threshold SNR > 11 consists of 42 BBHs, 2 NSBHs and 2 BNS (including GW170817 as a dark siren) + mass-gap event GW190814

- Uses priors consistent with GWTC-3 cosmology paper (R. Abbott et al. 2023 ApJ **949** 76)

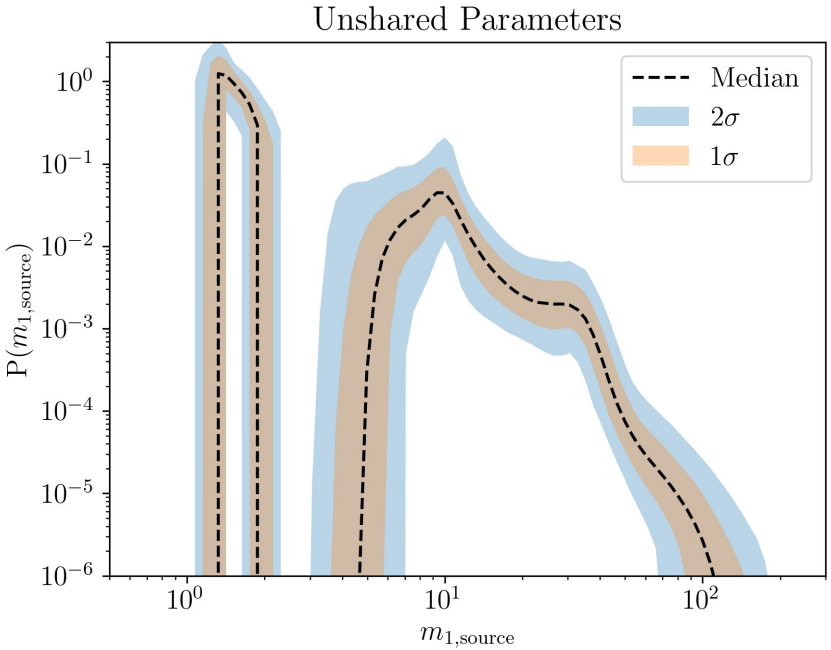
GW190814 - mass gap event

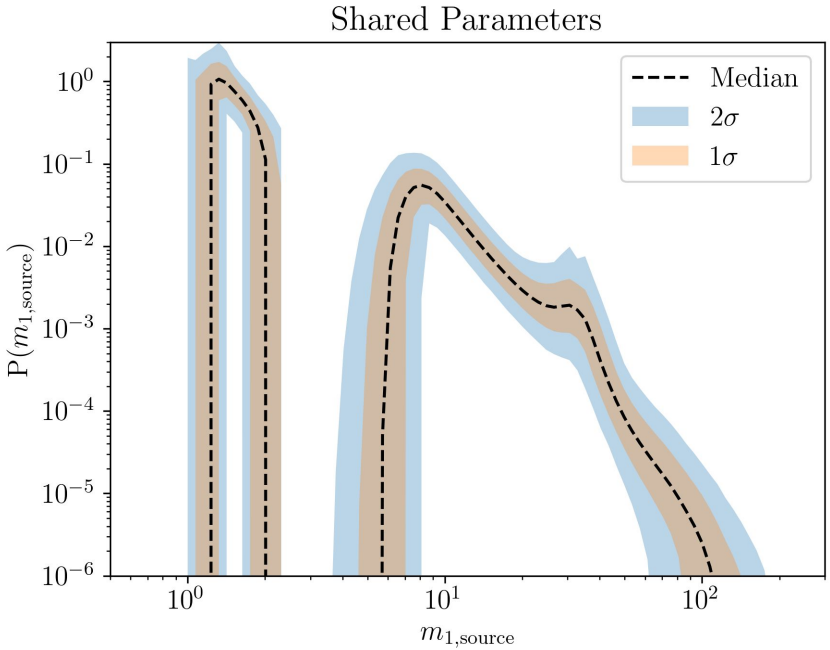
- Event observed during O3 observing run with secondary mass ~2.6 Solar masses
- Most unequal observed mass ratio of 0.122
- Unclear if the secondary component is very heavy NS or very light BH



The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, ApJL, 915, L5 (2021)

Primary distributions

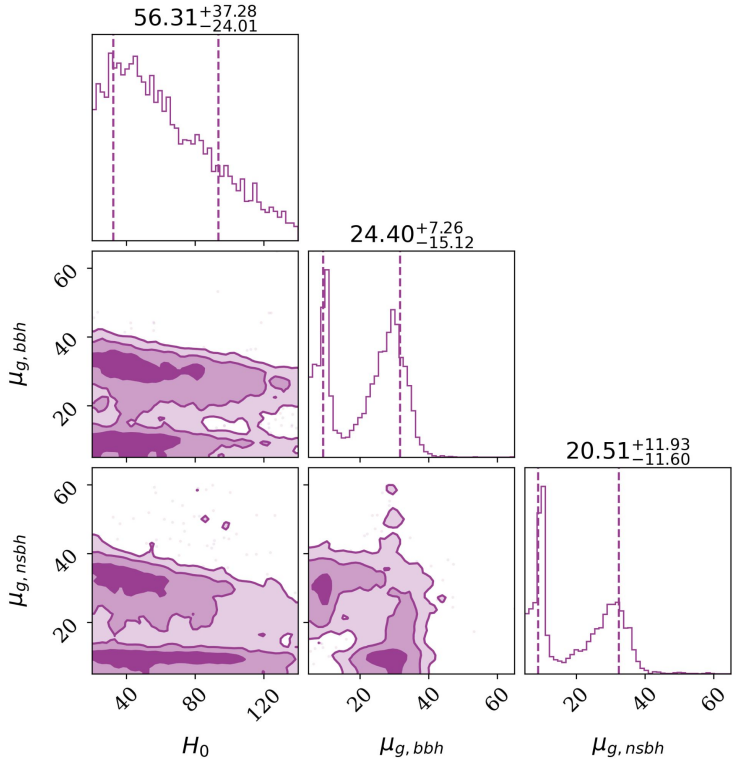




$$\mathcal{B} = 3.53$$

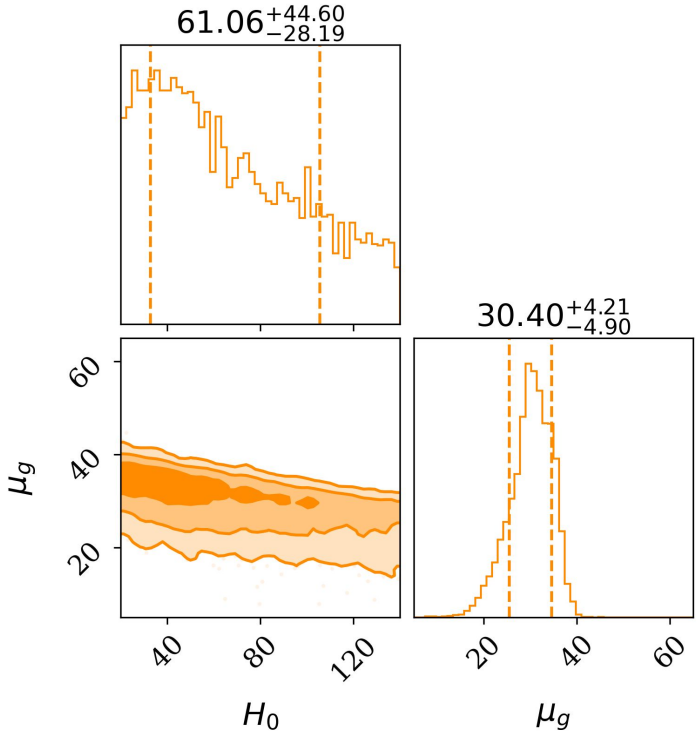
Unshared vs shared

Features - Unshared case



- Multimodal support for peak location in BH population for both NSBHs and BBHs
- Evidence for more structure in underlying distribution than model currently allows

Features - Shared case



- No multimodal support in peak location
- Consistent with results from GWTC-3 cosmology

Rates comparison

- Population weights are fractions of a total - therefore can be compared to merger rates

$$\mathcal{R}_{\rm total} = \mathcal{R}_{\rm BBH} + \mathcal{R}_{\rm NSBH} + \mathcal{R}_{\rm BNS}$$

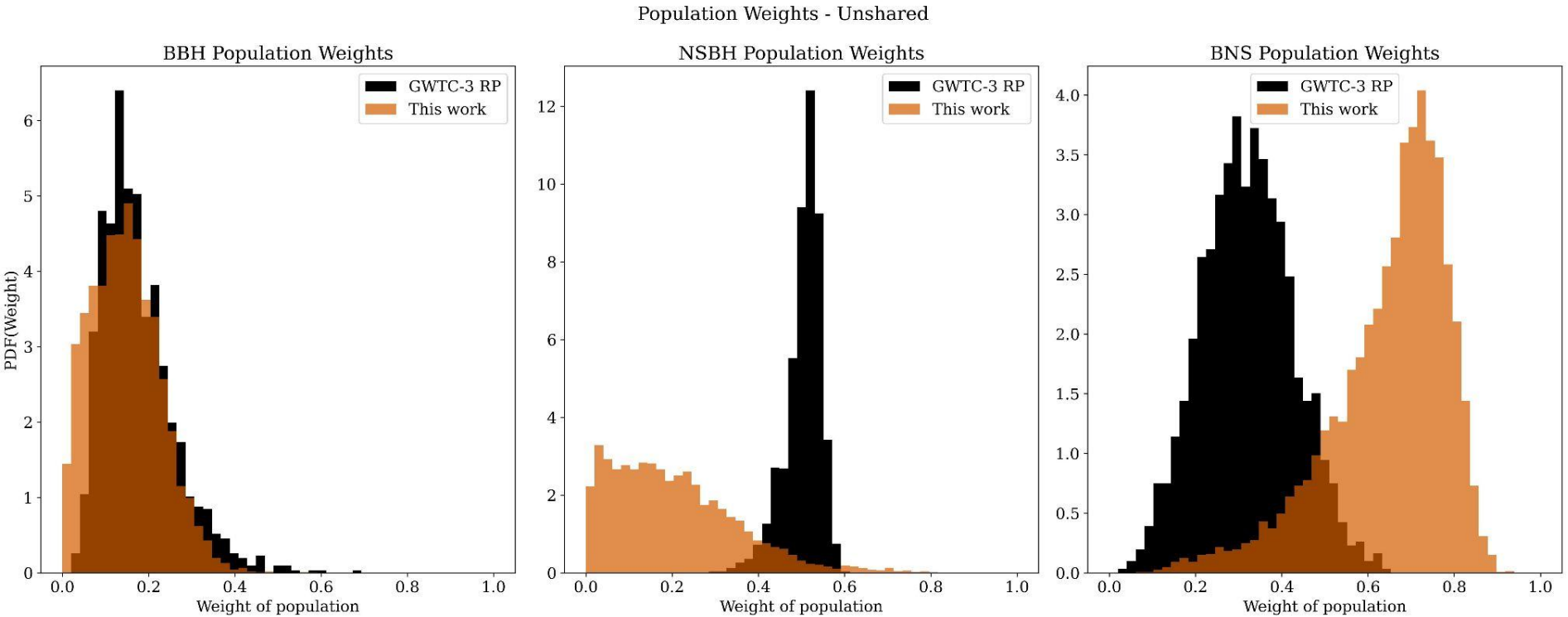
$$\kappa_i = \frac{\mathcal{R}_{\rm i}}{\mathcal{R}_{\rm total}} \qquad i = \rm BBH, NSBH, BNS$$

- Compare to PDB rate bounds from GWTC-3 R&P

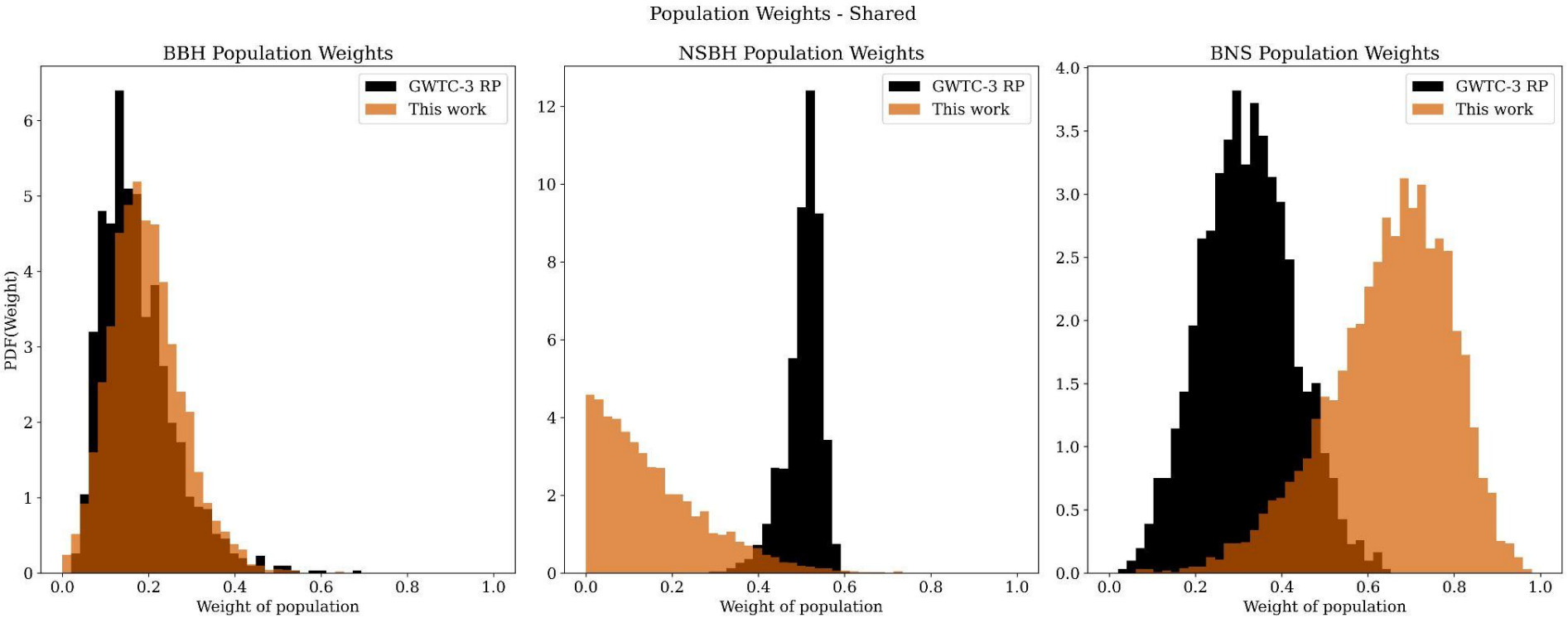
	BNS	NSBH	BBH
	$m_1 \in [1, 2.5] M_\odot$	$m_1 \in [2.5, 50] M_\odot$	$m_1 \in [2.5, 100] M_\odot$
	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 100] M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$
MERGED	$10 - 1700$	$7.8 - 140$	$16 - 61$

Table II, R. Abbott et al. Phys. Rev. X **13**, 011048

Weights - Unshared case



Weights - Shared case



Mock Data Challenge

- Create mock event posteriors using Fisher matrices with GWFish (Dupletsa+ 2022)
- Population fixed at GWTC-3 cosmology values + component weights fixed at ⅓
- 200 events with SNR > 11 at O5 sensitivity on an LHV network
- Currently ongoing!

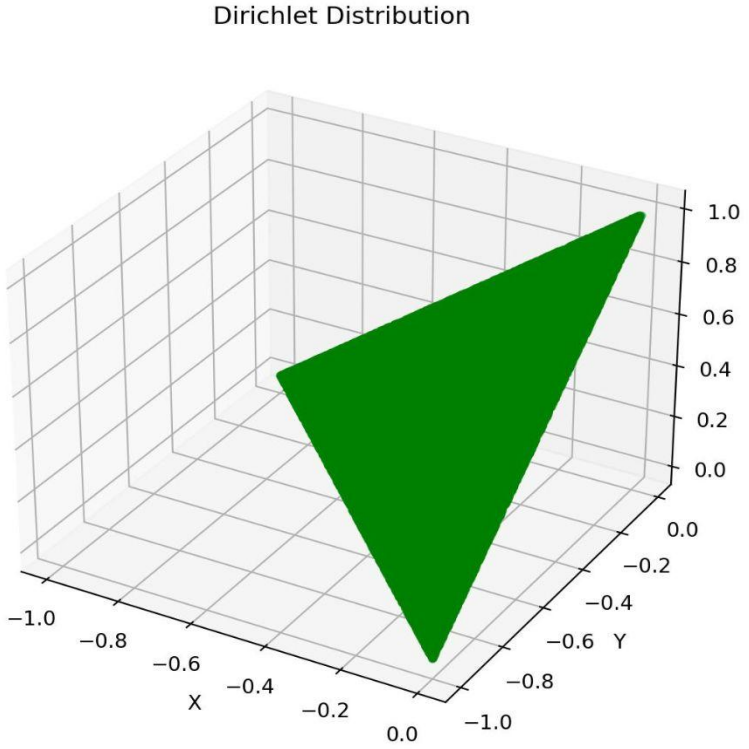
Going forwards

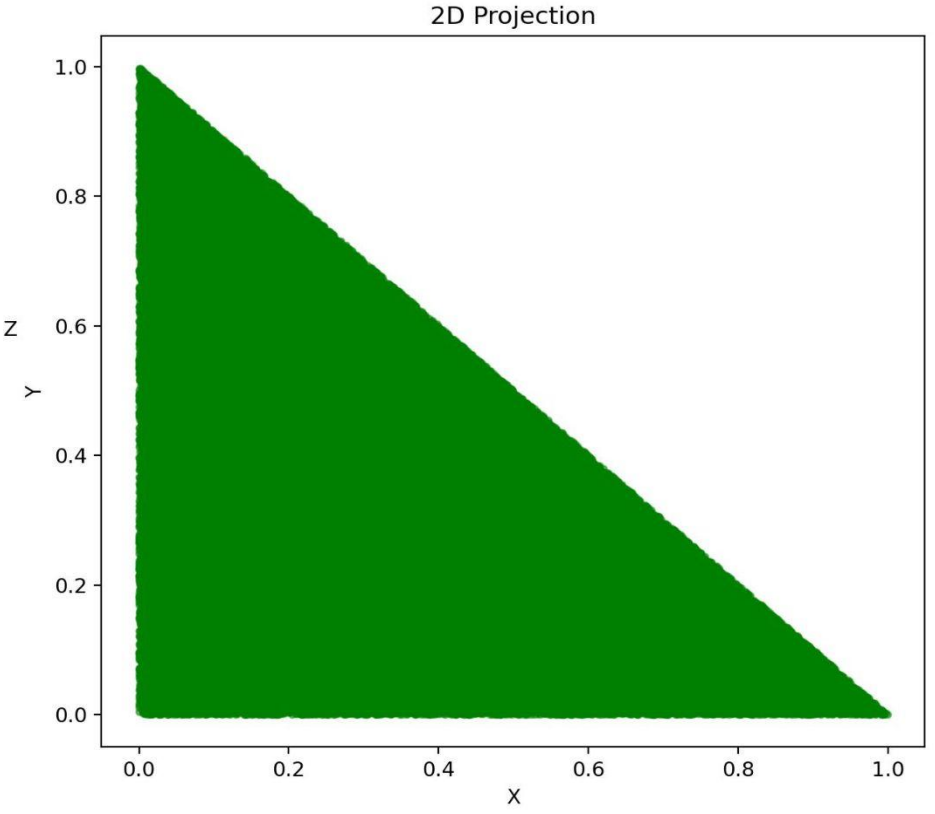
- Complete mock data challenge
- Use in analysis of O4b observing run
- Output likelihood of event being a particular type of CBC
- Consider astrophysical motivation for shared parameters
- Potentially extend to Multipeak model for BBH+NSBH components
- Consider evolution of mass distribution components with redshift

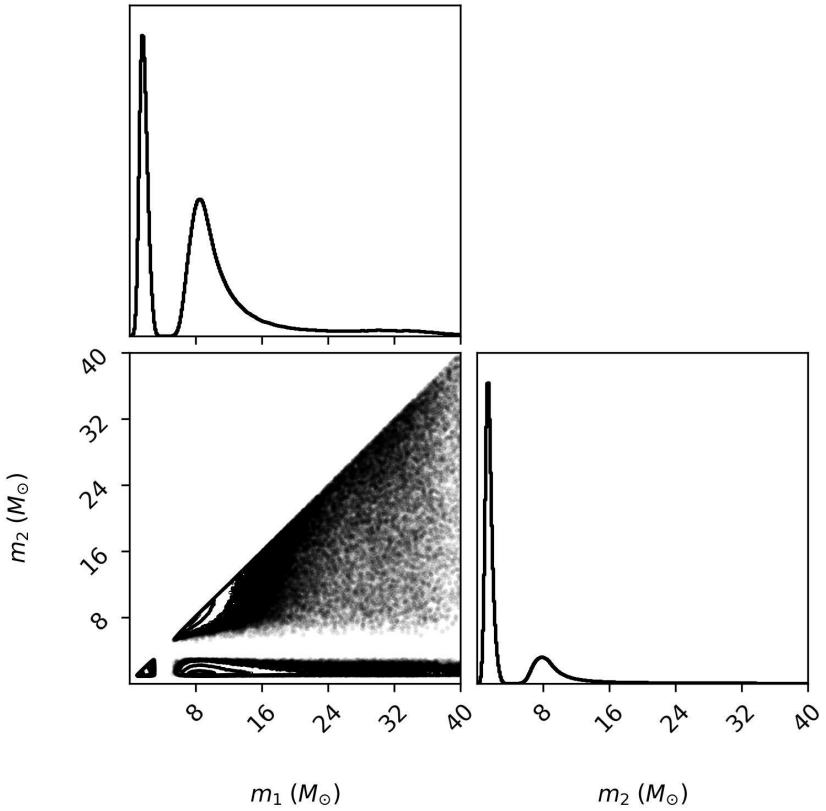
Summary

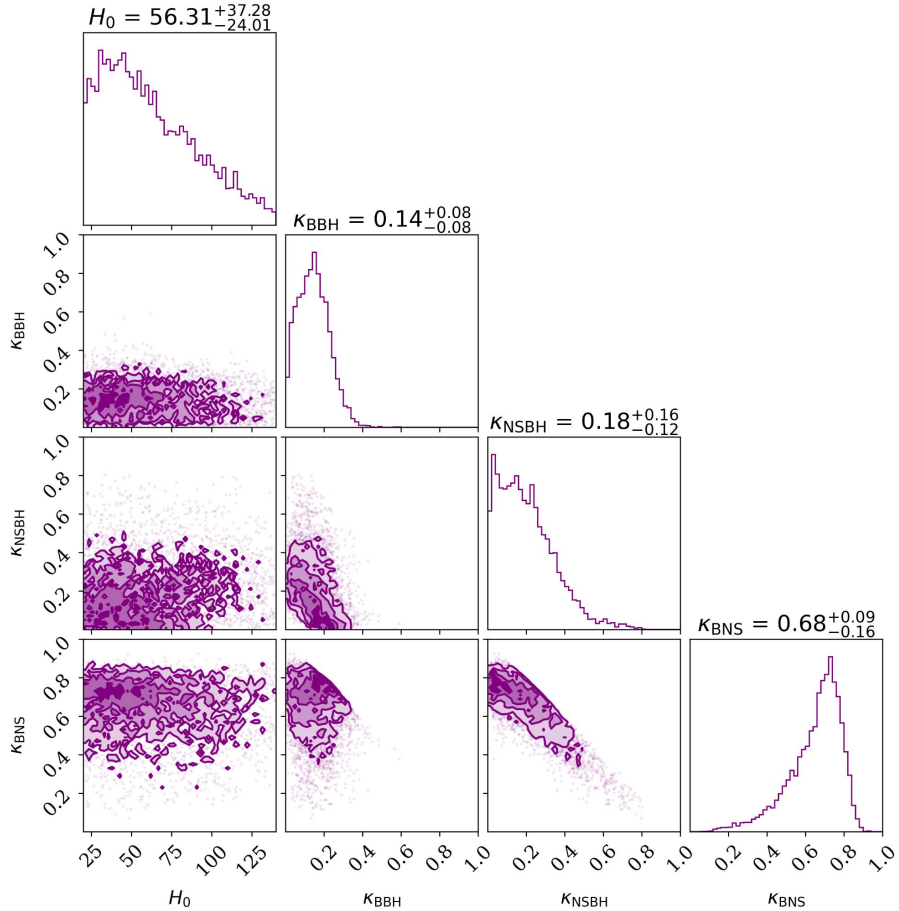
- Want to use the spectral siren method to constrain the Hubble constant
- Combined-population mass model allows for all GW events to be in same analysis
- Flexible to inclusion of events of uncertain binary classification (GW190814)
- Can infer astrophysical information about CBC population fractions alongside this, and compare with merger rate calculations

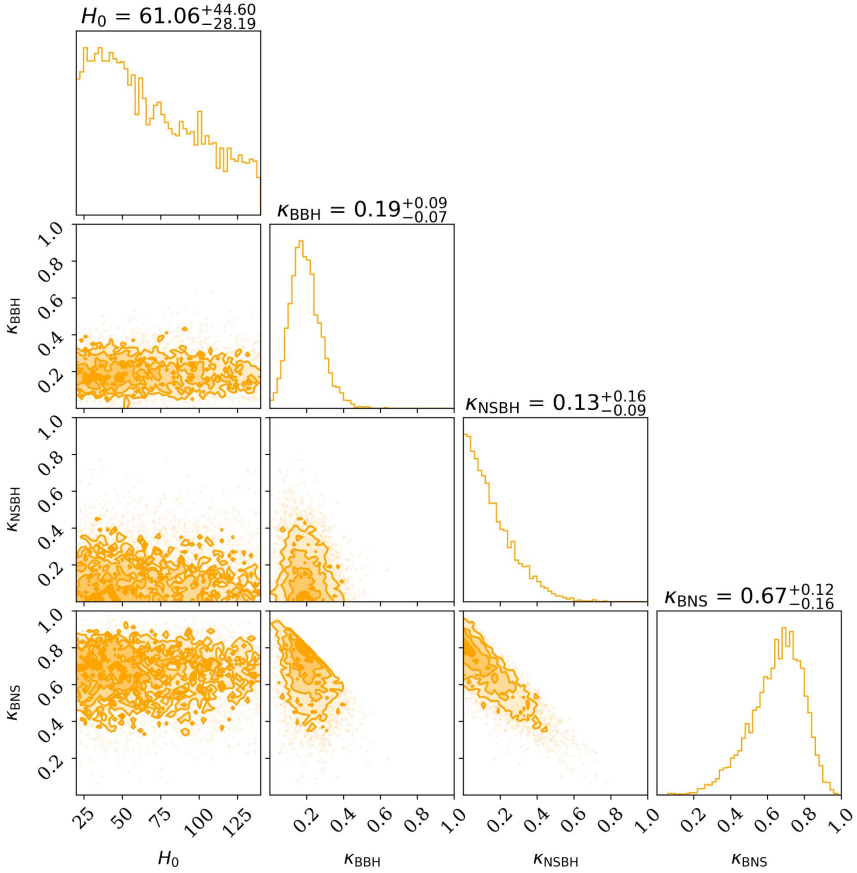
Auxiliary plots

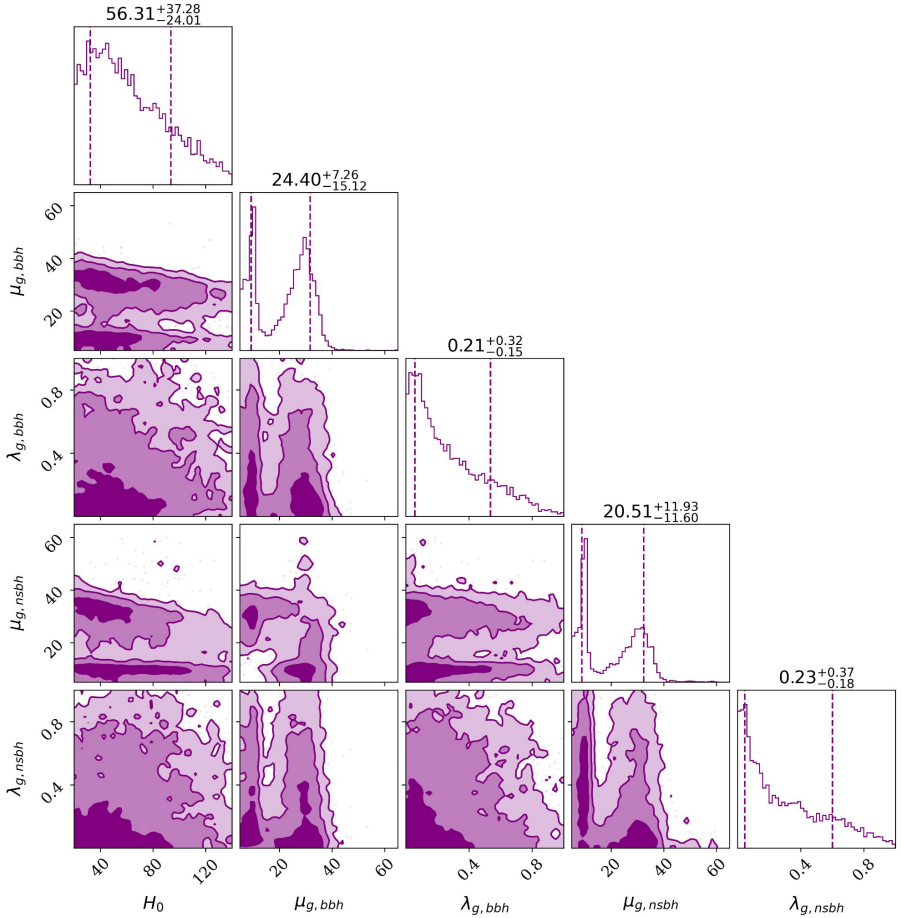


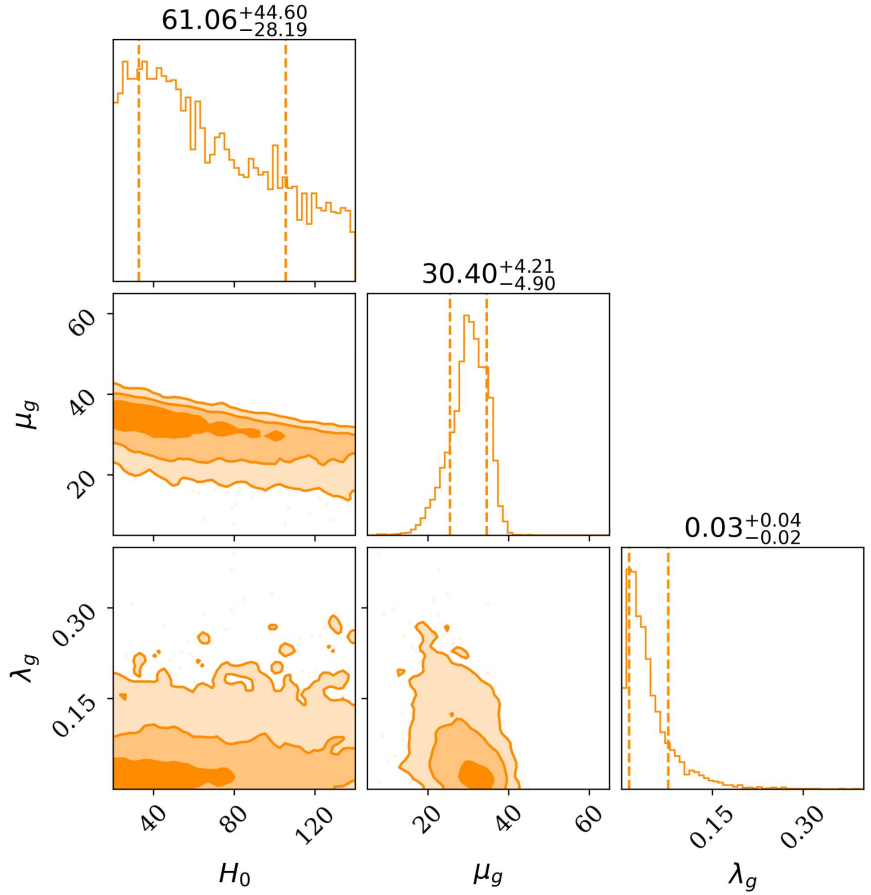


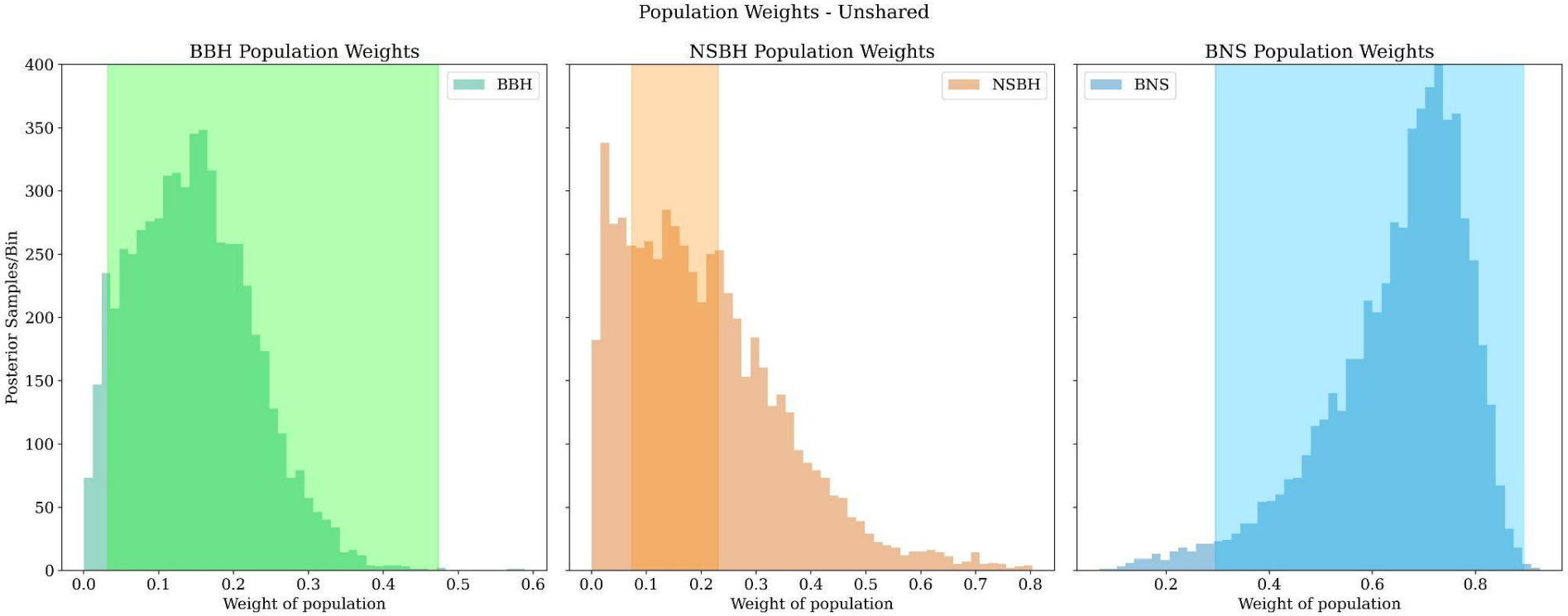

40
32
24
16
8
$m_2\ (M_\odot)$
8
16
24
32
40
$m_1\ (M_\odot)$
8
16
24
32
40
$m_2\ (M_\odot)$

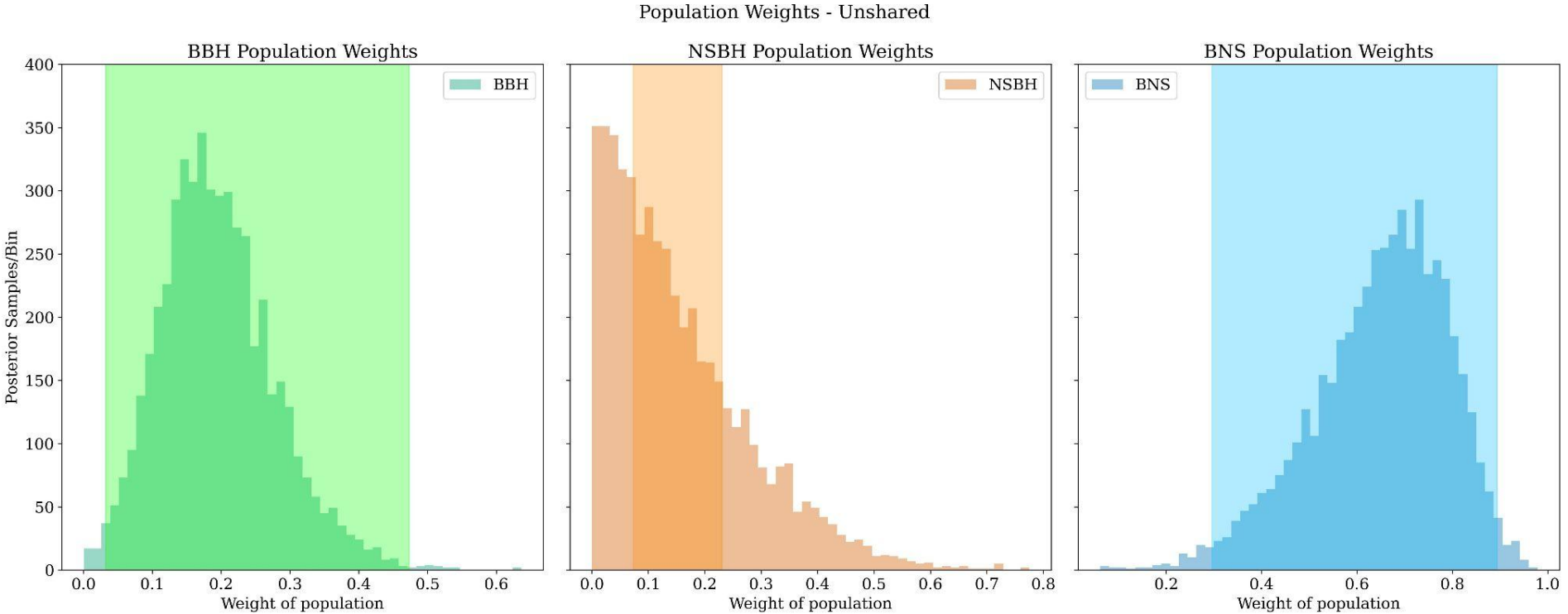

$H_0 = 56.31^{+37.28}_{-24.01}$
$\kappa_{BBH} = 0.14^{+0.08}_{-0.08}$
$\kappa_{NSBH} = 0.18^{+0.16}_{-0.12}$
$\kappa_{BNS} = 0.68^{+0.09}_{-0.16}$
H_0
κ_{BBH}
κ_{NSBH}
κ_{BNS}


$H_0 = 61.06^{+44.60}_{-28.19}$
$\kappa_{BBH} = 0.19^{+0.09}_{-0.07}$
$\kappa_{NSBH} = 0.13^{+0.16}_{-0.09}$
$\kappa_{BNS} = 0.67^{+0.12}_{-0.16}$
H_0
κ_{BBH}
κ_{NSBH}
κ_{BNS}


$56.31^{+37.28}_{-24.01}$
$24.40^{+7.26}_{-15.12}$
$0.21^{+0.32}_{-0.15}$
$20.51^{+11.93}_{-11.60}$
$0.23^{+0.37}_{-0.18}$
H_0
$\mu_{g,bbh}$
$\lambda_{g,bbh}$
$\mu_{g,nsbh}$
$\lambda_{g,nsbh}$


$61.06^{+44.60}_{-28.19}$
$30.40^{+4.21}_{-4.90}$
$0.03^{+0.04}_{-0.02}$
μ_g
λ_g
H_0
μ_g
λ_g
60
40
20
0.30
0.15
40
80
120
20
40
60
0.15
0.30


Population Weights - Unshared
BBH Population Weights
NSBH Population Weights
BNS Population Weights
BBH
NSBH
BNS
Posterior Samples/Bin
Weight of population
Weight of population
Weight of population


Population Weights - Unshared
BBH Population Weights
NSBH Population Weights
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BBH
NSBH
BNS
Posterior Samples/Bin
Weight of population
Weight of population
Weight of population