GWs Meets EFTs, Benasque, 22/08/23

Siren Tests of Gravity

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European Research Council

The Royal Society

Outline

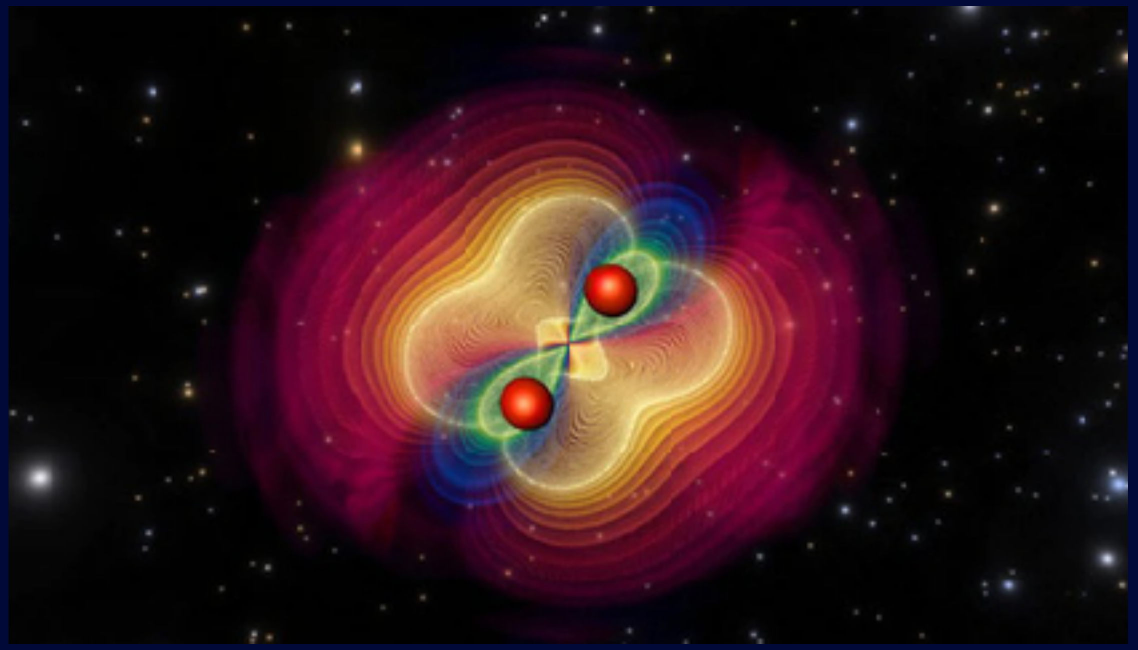
- GW propagation
- Sirens & GW friction
- Dark sirens —how it actually works
- Headline results

GW Propagation

Propagation vs generation

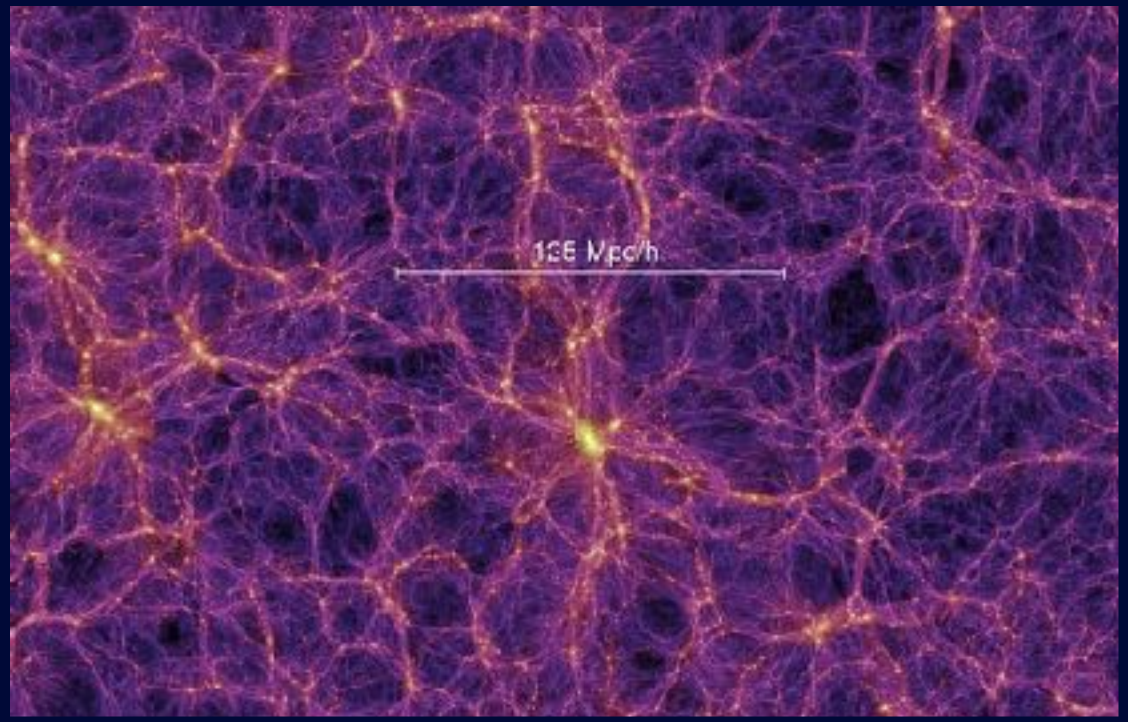
GWs can probe both:

Strong-field regime



GW generation

Weak-field regime



GW propagation

Today I will focus on *propagation* effects.

How cleanly can propagation & generation be separated? Difficult (but important) problem.

Propagation Beyond GR

GW propagating on FRW background in GR:

$$h''_{ij} \; + \; 2\,\mathcal{H}\,h'_{ij} \; + \; k^2\,h_{ij} \; = \; 0$$

Hubble `friction'

Contains +, X polarisation modes.

+ lensing corrections etc.

Propagation Beyond GR

GW propagating on FRW background in modified gravity:

$$h''_{ij} + 2\,(1+\nu(z))\,\mathcal{H}\,h'_{ij} + (c_T^2\,k^2 + a^2\,m_g^2)\,h_{ij} = a^2\,\Gamma_C\,\gamma_{ij}$$

Extra polarisation modes possible

Modified `friction' → changes GW amplitude

Modified propagation speed

Graviton mass

Non-zero source term

Least constrained

Most generic

Best constrained

Rare

Propagation Beyond GR

GW propagating on FRW background in modified gravity:

$$h''_{ij} + 2\,(\,1 + \nu(z)\,)\,\mathcal{H}\,h'_{ij} + c_T^2\,k^2\,h_{ij} = 0$$

Modified \`friction'
→ changes GW amplitude

Modified propagation speed

Most generic

Best constrained

Sirens: the bright, the dark & the spectral

(but mainly the dark)

((because they're the most fun))

Propagation Beyond GR

GW propagating on FRW background in modified gravity:

$$h''_{ij} + 2\,(\,1 + \nu(z)\,)\,\mathcal{H}\,h'_{ij} + k^2\,h_{ij} = 0$$

Modified `friction'
→ changes GW amplitude

Most generic

Luminosity distances

Deviations from GR affect GW luminosity distances:

$$\tilde{h}_{+,\times}(f) \;\propto\; \frac{\mathcal{M}_z^2}{\boxed{d_L}}\,(\pi\,\mathcal{M}_z\,f)^{-\frac{7}{6}} \;\times\; \text{(polarisation angles)} \;\times\; \text{(inclination factor)}$$

↓

Luminosity distance $$d_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})}$$

Luminosity distances

Deviations from GR affect GW luminosity distances:

$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{d_{\rm GW}} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

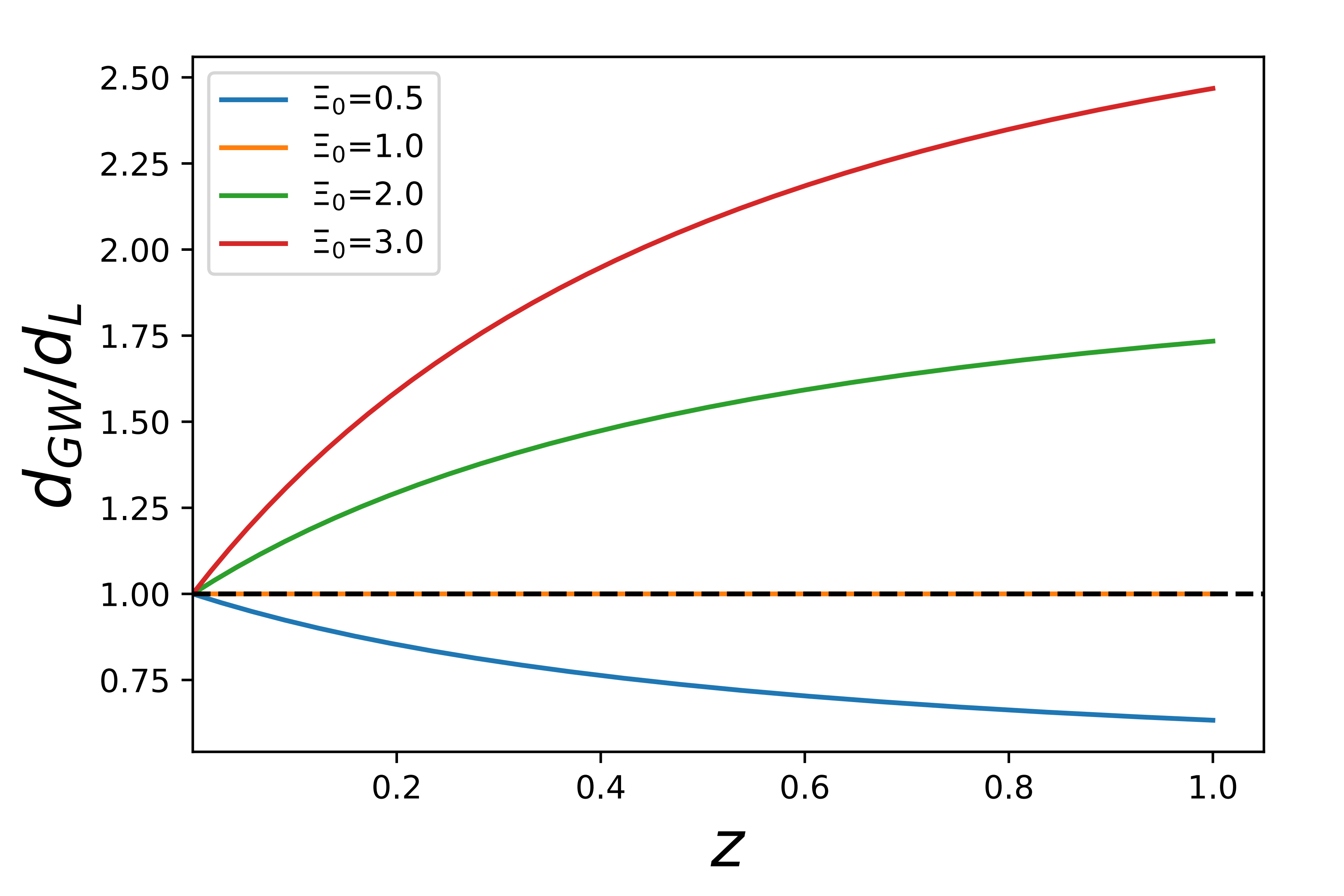
GW Luminosity distance parameterisation

Belgacem et al. (2018)

$$\frac{d_{\rm GW}}{d_L} \neq 1 \exp\left[\int_0^z \frac{\nu(\tilde{z})}{1+\tilde{z}}\, d\tilde{z}\right]$$

or

$$\frac{d_{\rm GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$



Bright & dark sirens

To obtain d_L we need a redshift & a cosmological model.

Bright sirens

EM counterpart → single redshift

Strong constraints from one event

Dark sirens

No EM counterpart

1. Galaxy catalogue → many possible hosts
2. Features in the mass spectrum contribute

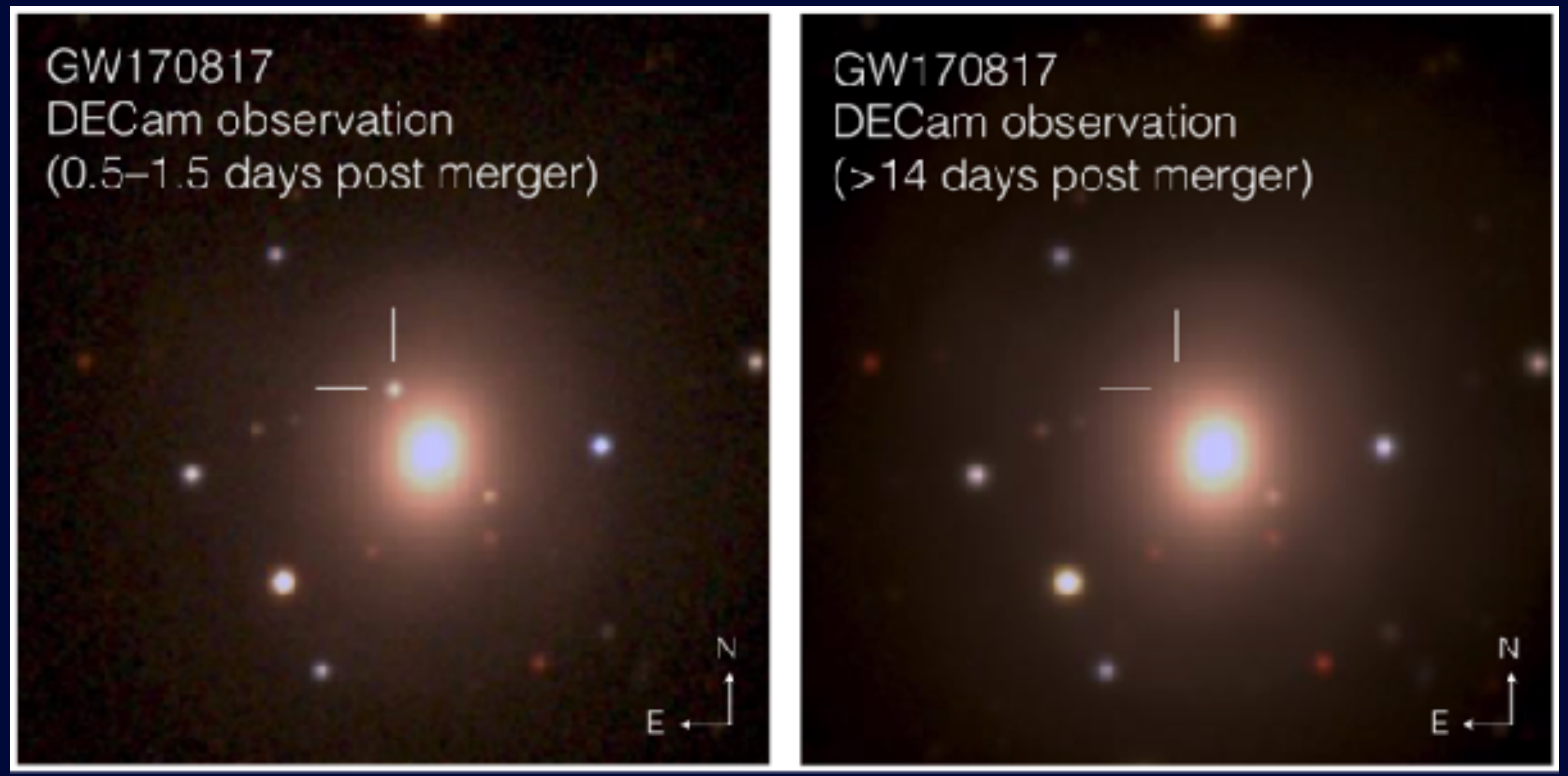
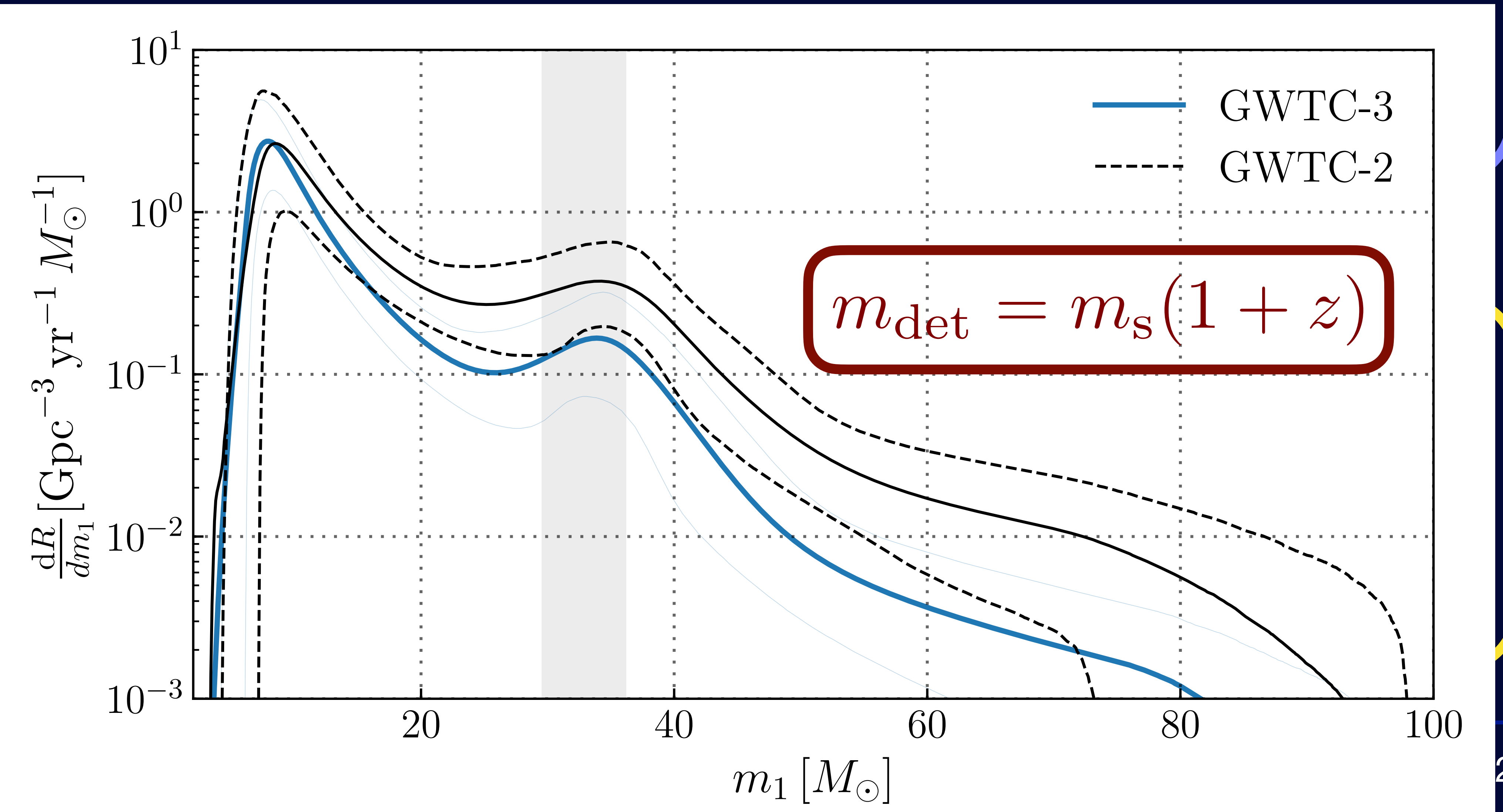


Image: Soares-Santos et al. 2017.

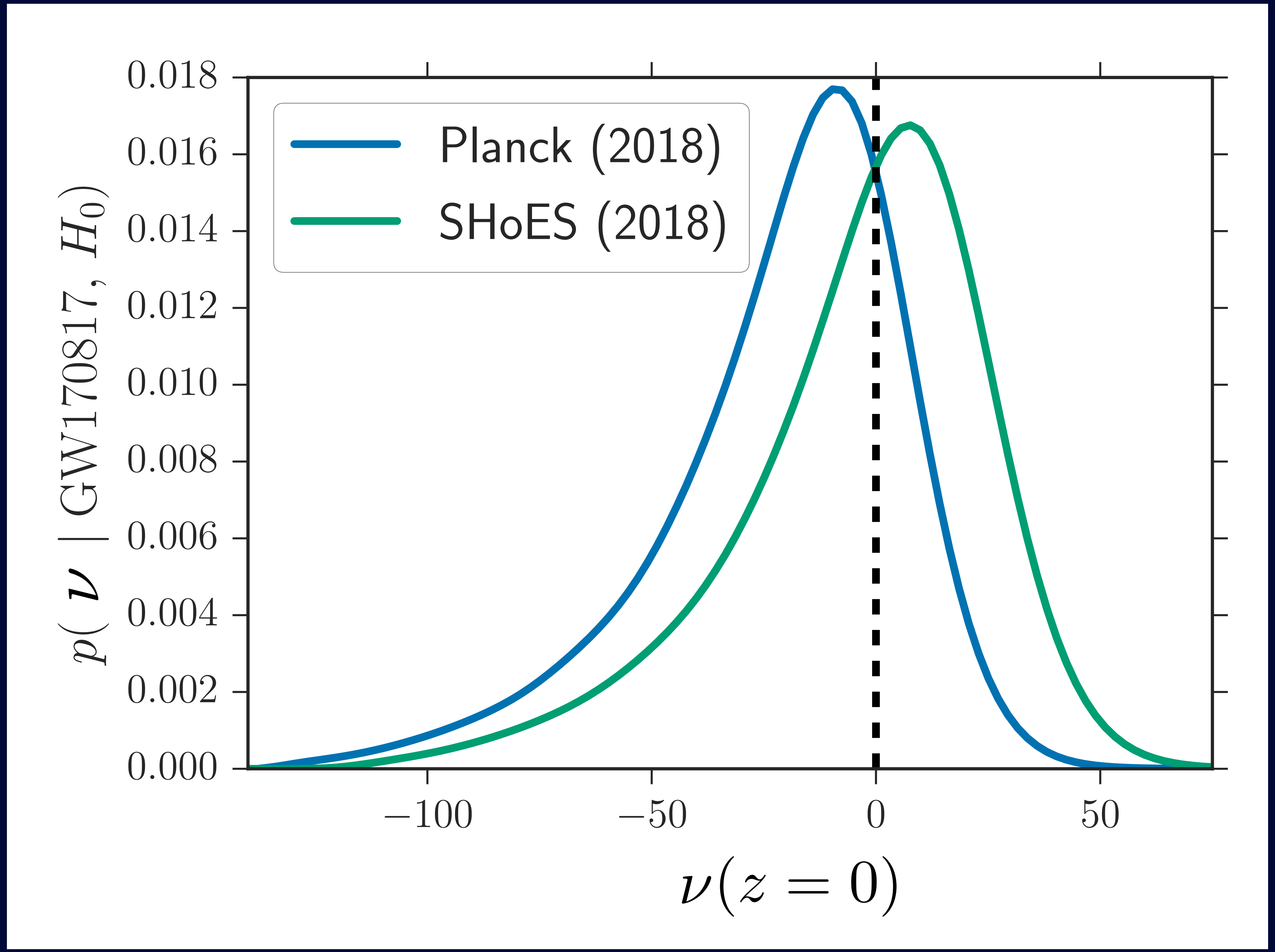


Bright sirens: constraints from GW170817

This would constrain GW friction, *but* it needs to be at a ‘reasonable’ distance to be useful.

$$\frac{d_{GW}}{d_L} = \exp\left[\int_0^z \frac{\nu(\tilde{z})}{1+\tilde{z}}\, d\tilde{z}\right]$$

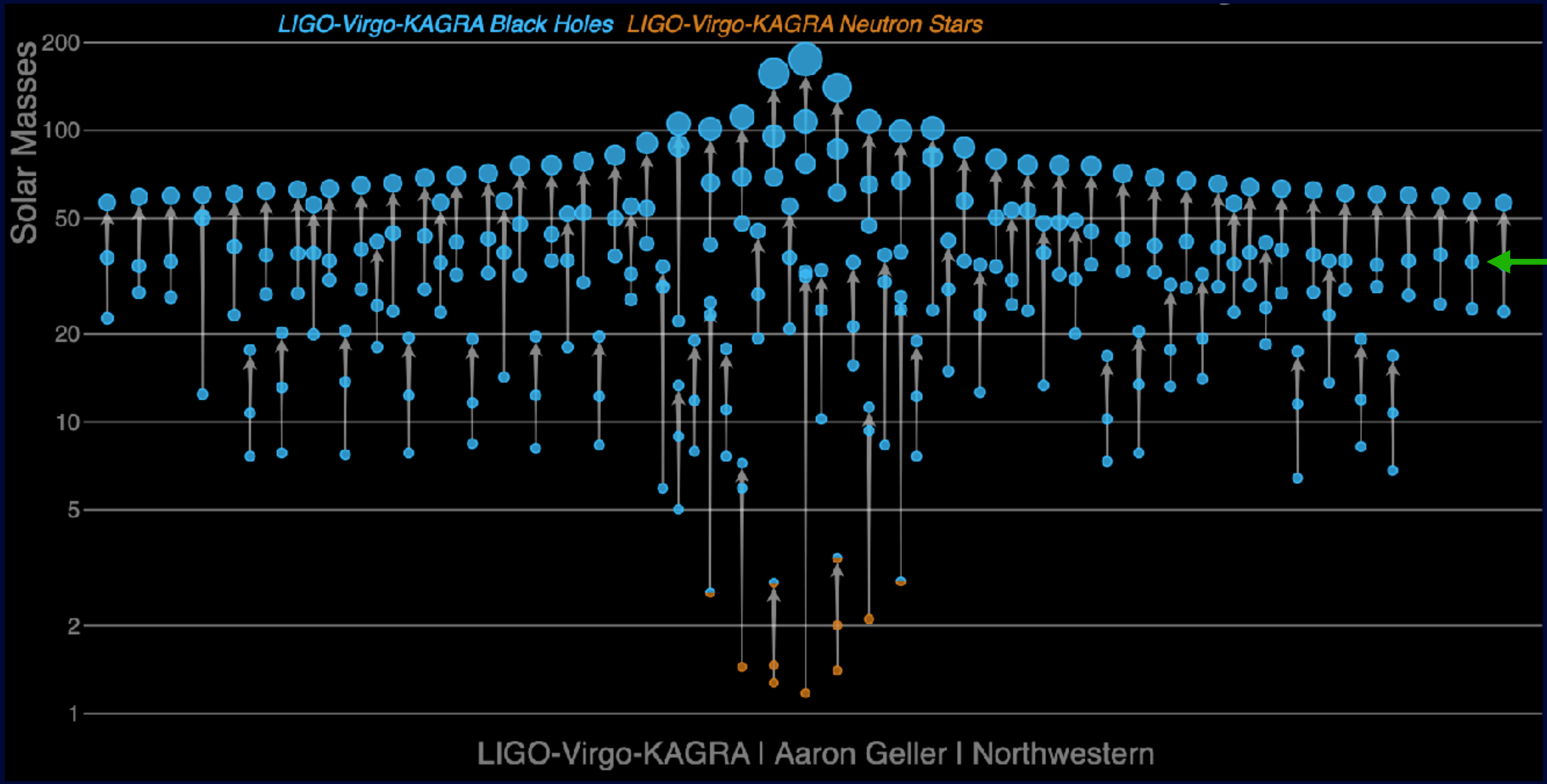
Lagos et al. (2018)



weak constraints only (GW170817 nearby)

The Trouble with Bright Sirens

…is that currently we have little idea how long it will take to get a useful number (say at least ~25).



Meanwhile, we have all these lovely black holes.

Here comes the technical part

Full calculation: Mandel et al. (2019)
Gray et al. (2019)
Finke et al. (2021)
Gray et al. (2023)

Dark Sirens Formalism

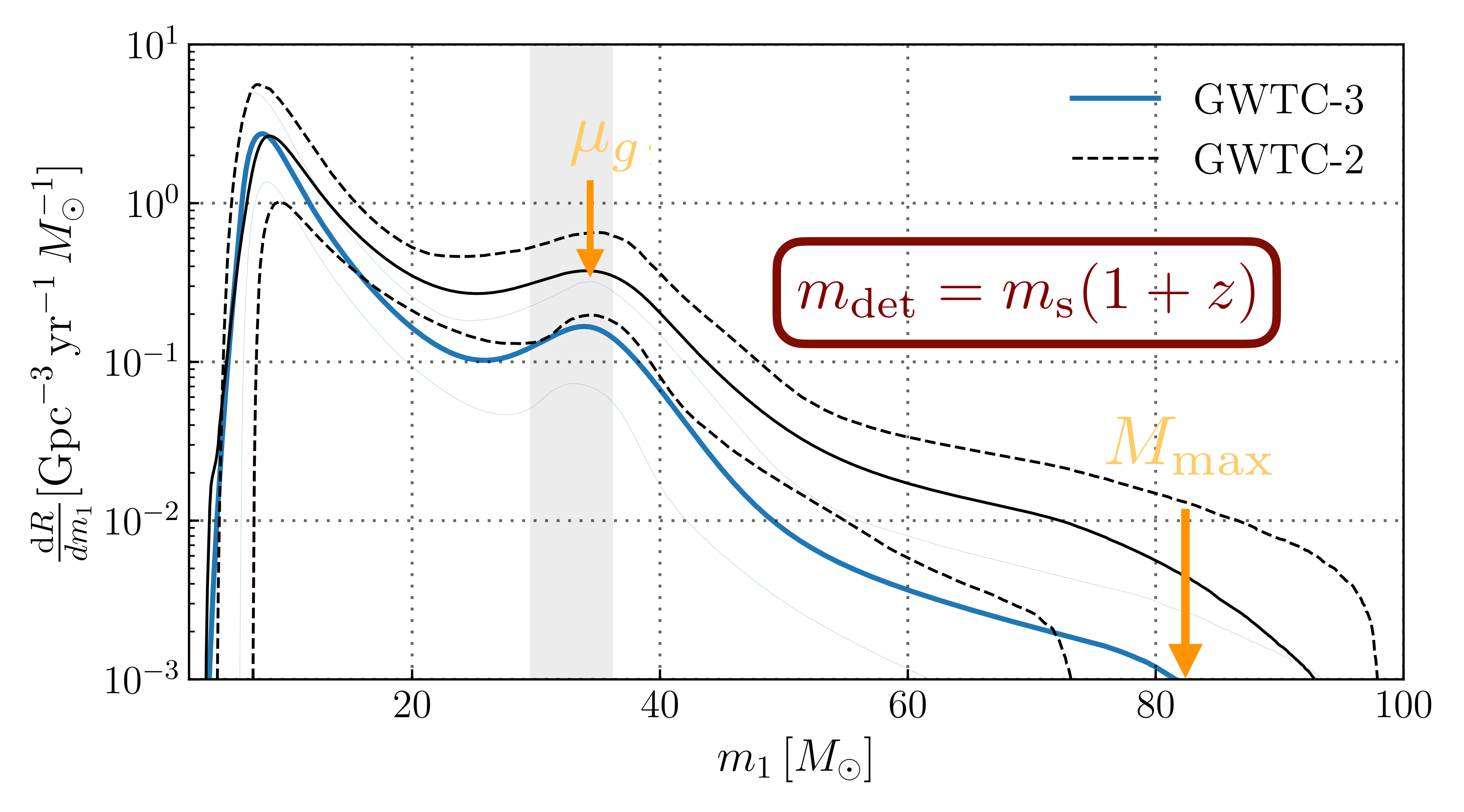
GW data set ↓ priors ↓

$$p\left(\Lambda\middle|\{x_{\rm GW}\}\right) \propto p(\Lambda)\, p(N_{\rm det}|\Lambda) \prod_i^{N_{\rm det}} p\left(x_{\rm GW,i}\middle|\Lambda\right)$$

where $\Lambda = \{\Lambda_{\rm cosmo},\ \Lambda_{\rm hyper}\}$

E.g. $H_0,\ \Xi_0$

E.g. $\mu_g,\ M_{\rm max}$



Abbott et al. 2022

Full calculation: Mandel et al. (2019)
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Dark Sirens Formalism

GW data set — priors

$$p\left(\Lambda \middle| \{x_{\rm GW}\}\right) \propto p(\Lambda)\, p(N_{\rm det}|\Lambda) \prod_i^{N_{\rm det}} p\left(x_{\rm GW,i}|\Lambda\right)$$

where $\Lambda = \{\Lambda_{\rm cosmo},\ \Lambda_{\rm hyper}\}$

No. of detections

Likelihood for one event

E.g. $H_0,\ \Xi_0$

E.g. $\mu_g,\ M_{\rm max}$

Complicated!

- merger rates
- mass distribution
- detector sensitivity
- parameter estimation

Full calculation: Mandel et al. (2019)
Gray et al. (2019)
Finke et al. (2021)
Gray et al. (2023)

Dark Sirens Formalism

Mass model

$$p\left(x_{\rm GW,i}|\Lambda\right) \quad \propto \quad \# \quad \int p\left(x_{\rm GW,i}|\Lambda,\theta\right)\; p\left(\theta|\Lambda\right)\; d\theta$$

Parameters of the binary
(mass, spin, etc)

`Selection effects'
→ which sources are detected
for a given detector network

Full calculation: Mandel et al. (2019)
Gray et al. (2019)
Finke et al. (2021)
Gray et al. (2023)

Dark Sirens Formalism

Mass model

$$p\left(x_{\mathrm{GW,i}}|\Lambda\right) \propto \# \iint p\left(x_{\mathrm{GW,i}}|\Lambda,\theta\right)\; p\left(z|\Lambda\right)\; p\left(\theta|\Lambda\right)\; d\theta\, dz$$

Parameters of the binary
(mass, spin, etc)

Redshift distribution of sources

G → galaxy in catalogue
$\bar{G}$ → galaxy not in catalogue

Dark Sirens Formalism

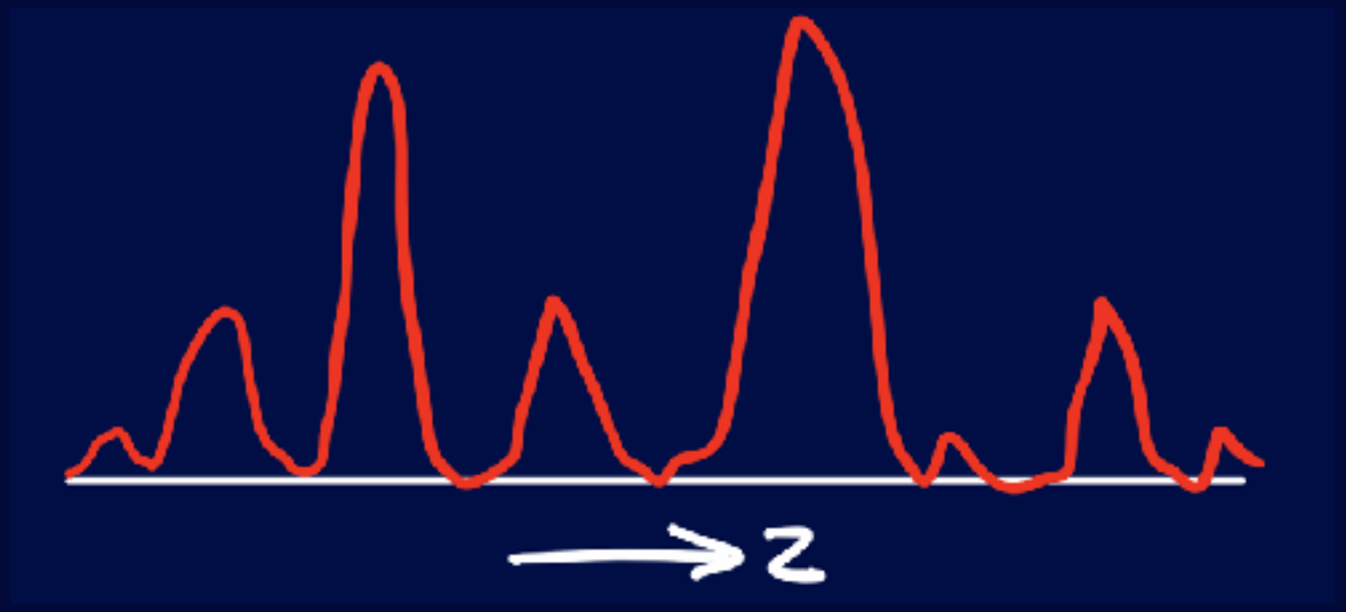
Where are the GW sources in redshift? 🤷‍♀️

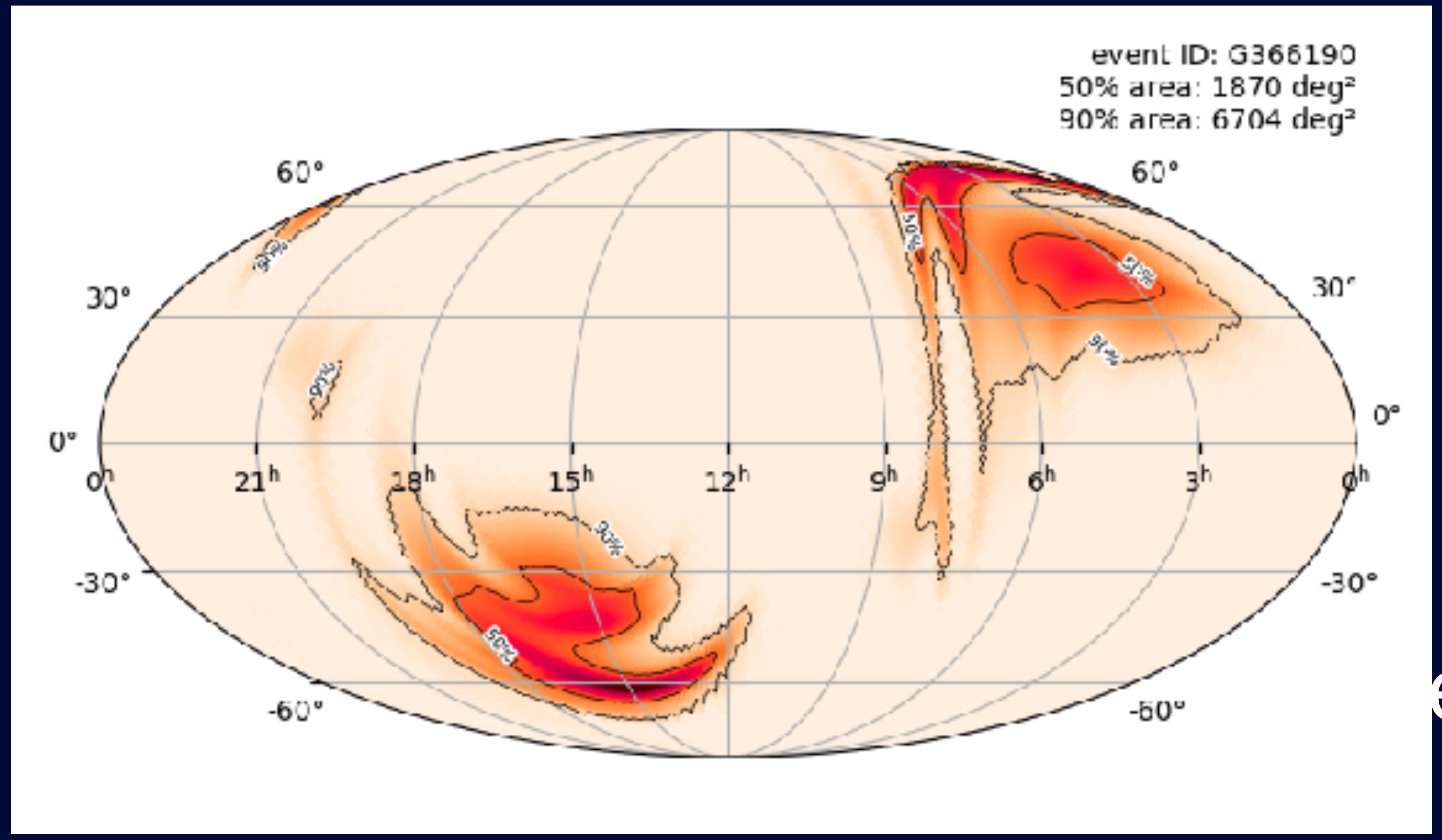
Galaxy catalogs tell us where (some) *potential* hosts are.

$$p(z|\Lambda)\,\Omega_j = p(G|\Lambda,\,\Omega_j)\sum^{\text{mag limit}} p(z|z_{\text{obs}}) + p(\bar{G}|\Lambda,\,\Omega_j)\int_{\text{mag limit}}^{\infty} p(z,M)\,dM$$

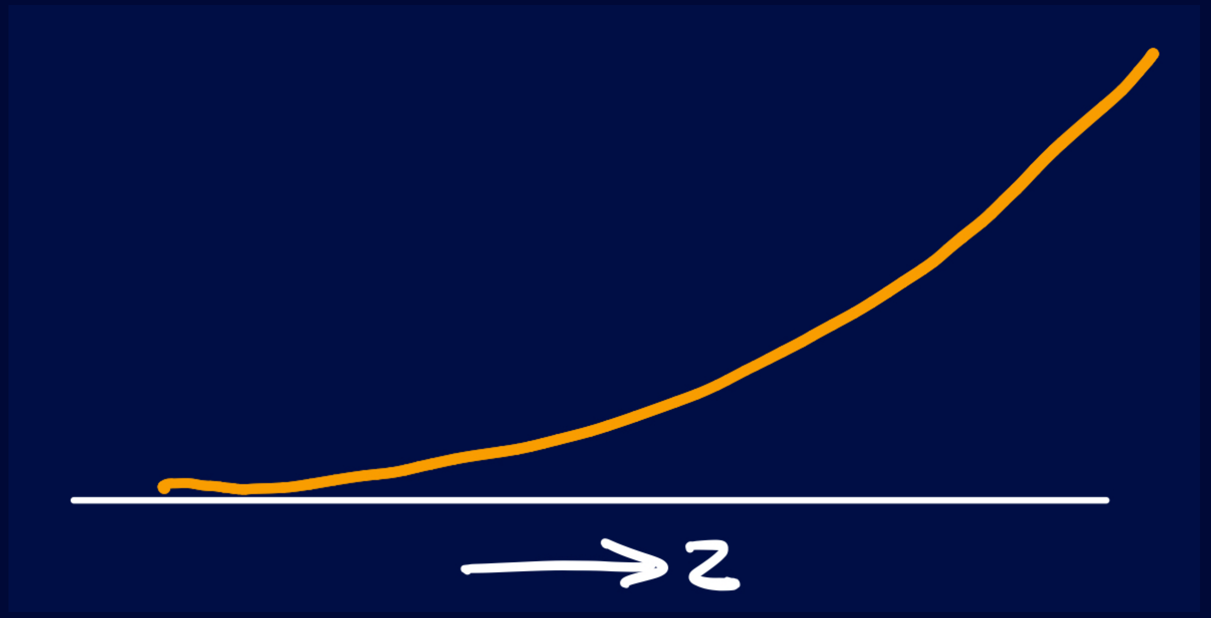
sky pixel

Galaxy catalog — measured redshifts

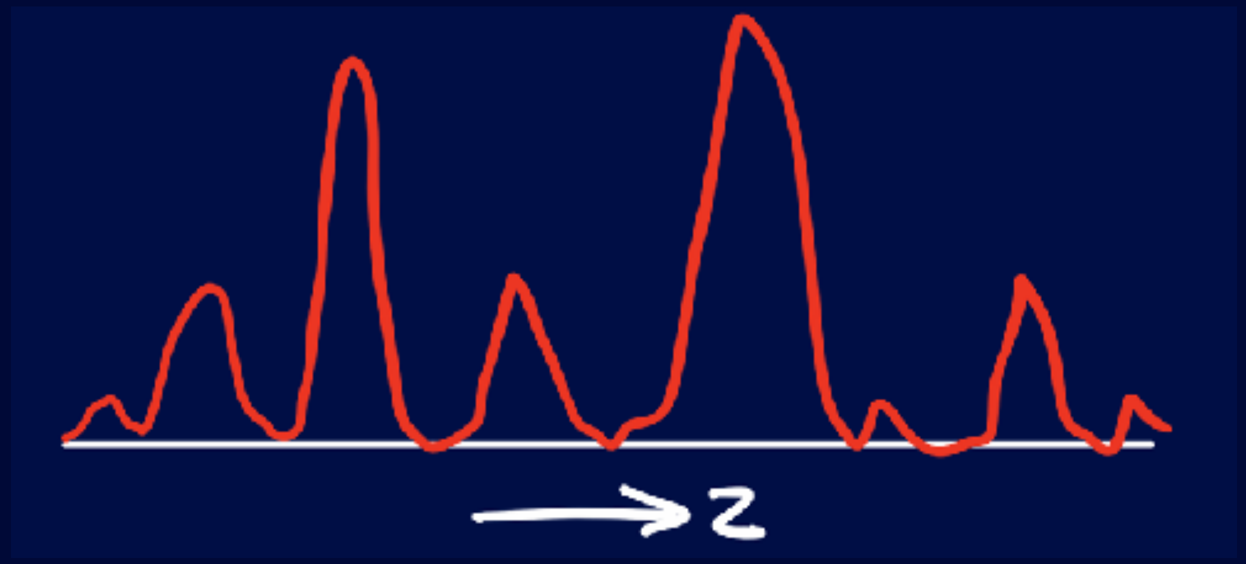




Assume distribution for missing galaxies:
efault is homogeneous in comoving volume

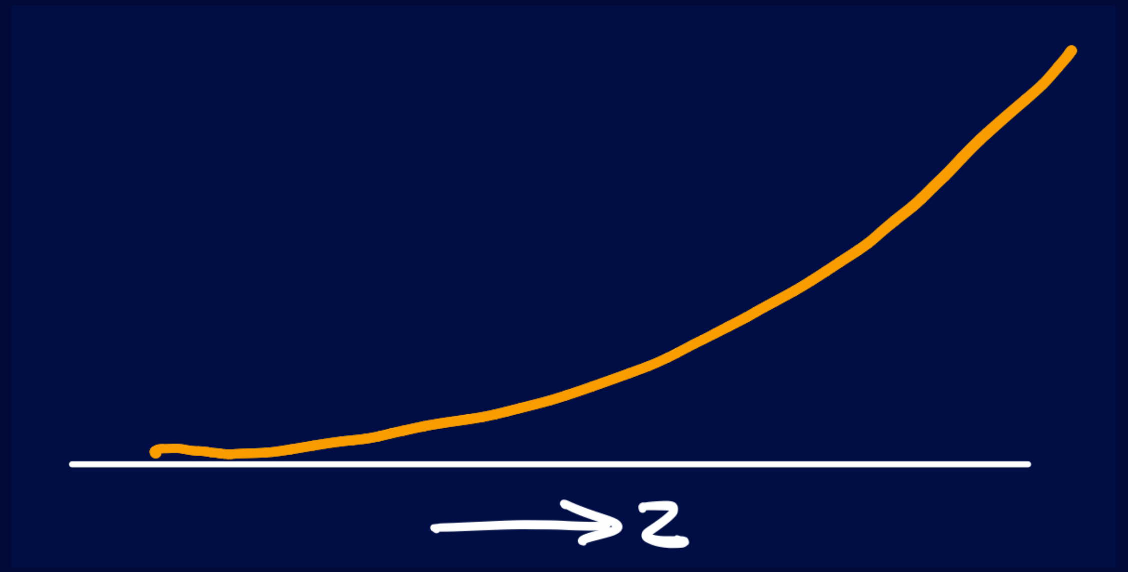


Dark Sirens Summary



galaxy catalogue

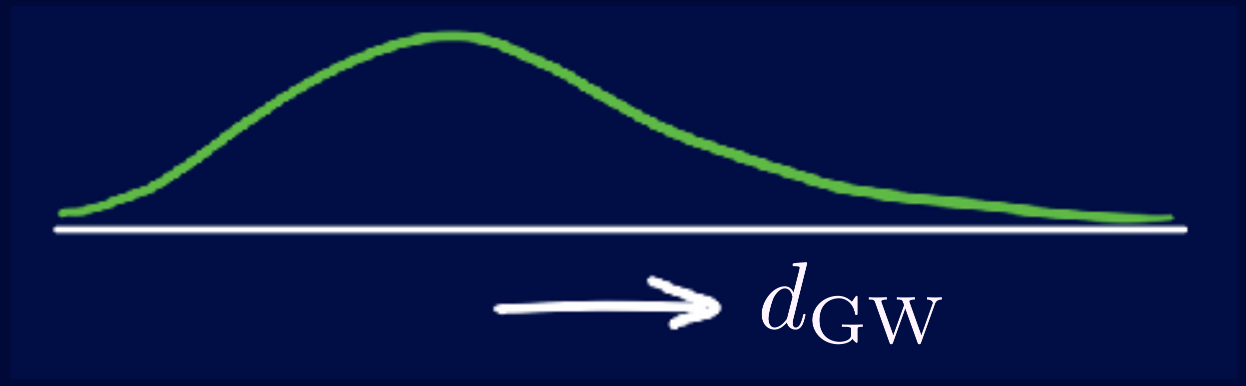
+



incompleteness

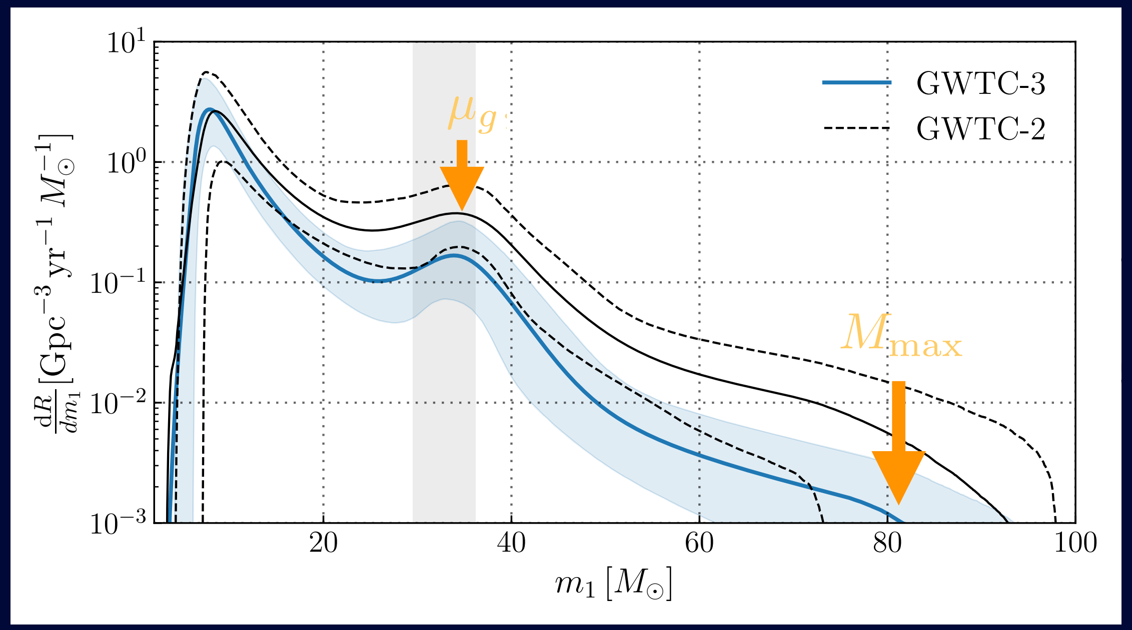
= line of sight redshift distribution

+



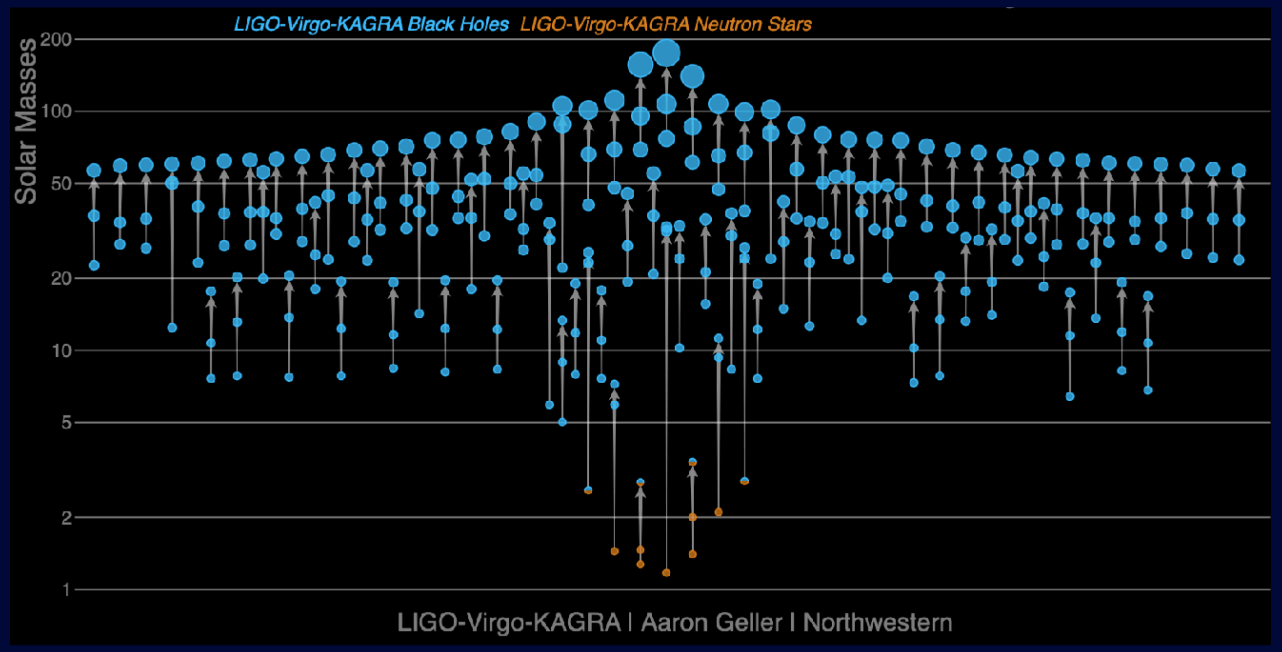
GW data

+



= likelihood for one event

+ mass distribution



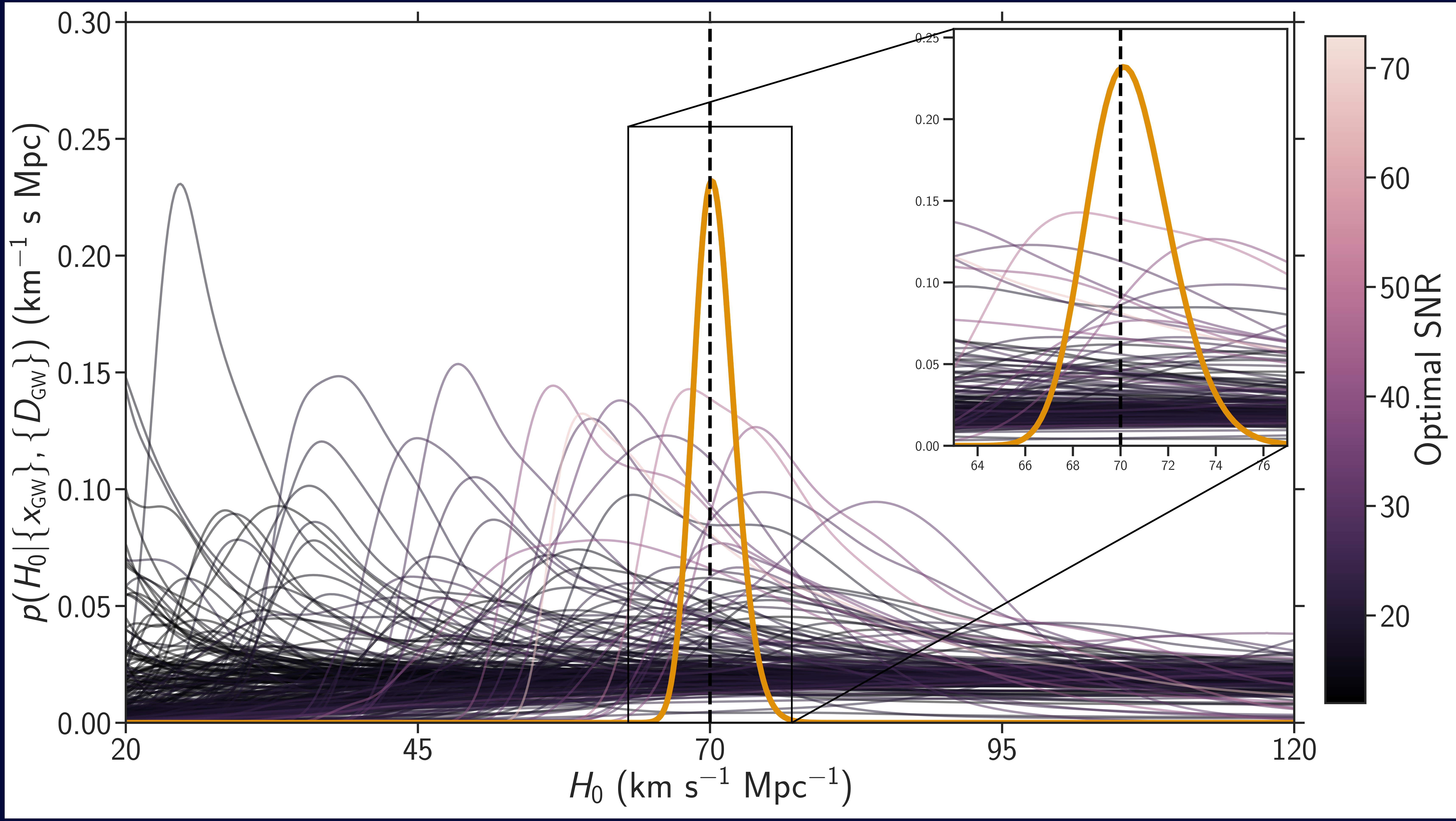
= joint posteriors for $\Lambda = \{\Lambda_{\rm cosmo}, \Lambda_{\rm hyper}\}$

NB: *must* jointly infer cosmo & astro params.

Dark sirens — current results

Dark Sirens Mock Data

Gray et al. 2019.

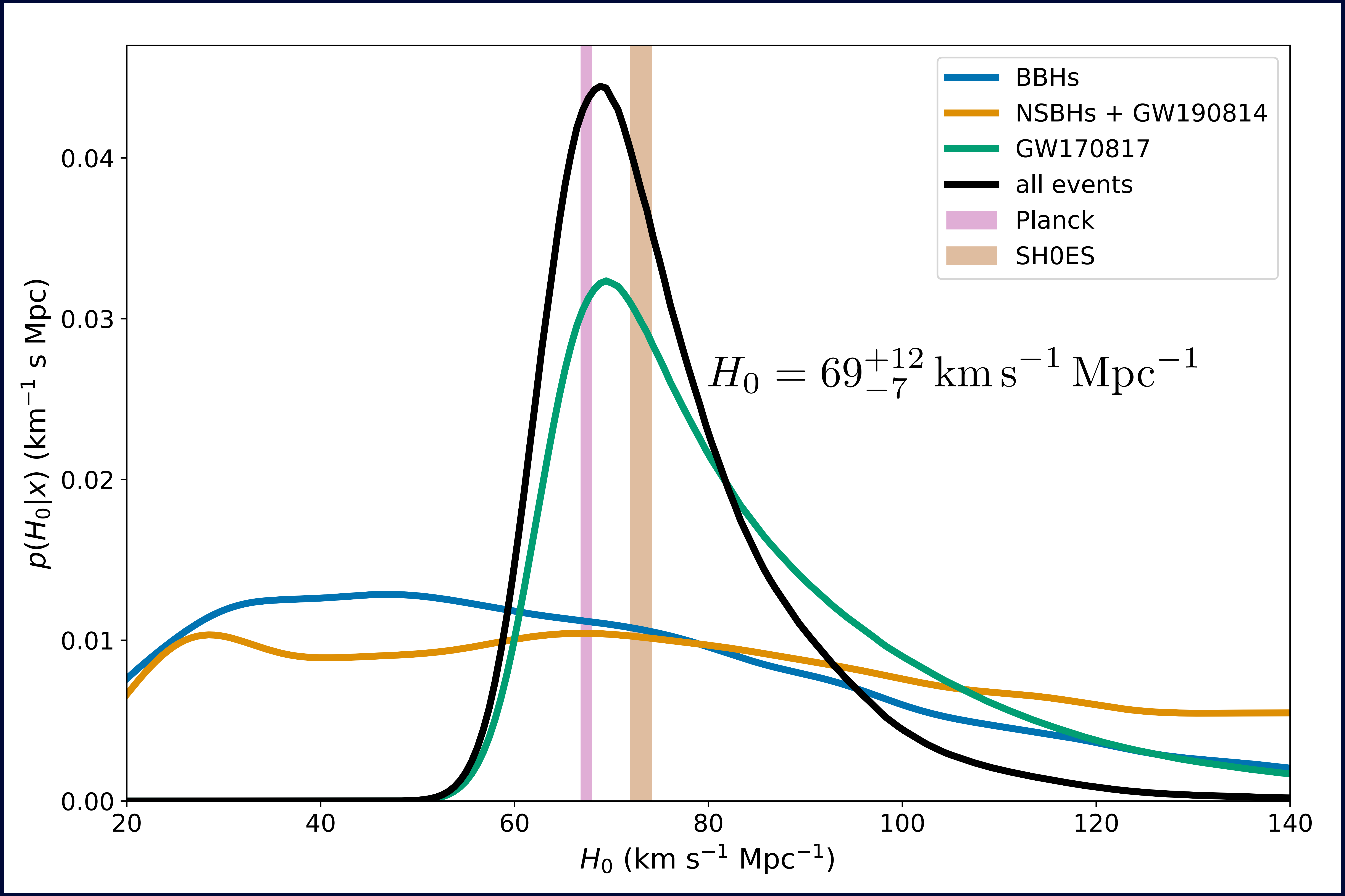


Using 249 mock BNS.

Dark Sirens Results: H_0

Rachel Gray
(U. Glasgow)

Gray et al. 2023.
arXiv 2308.02281



Using the

gwcosmo

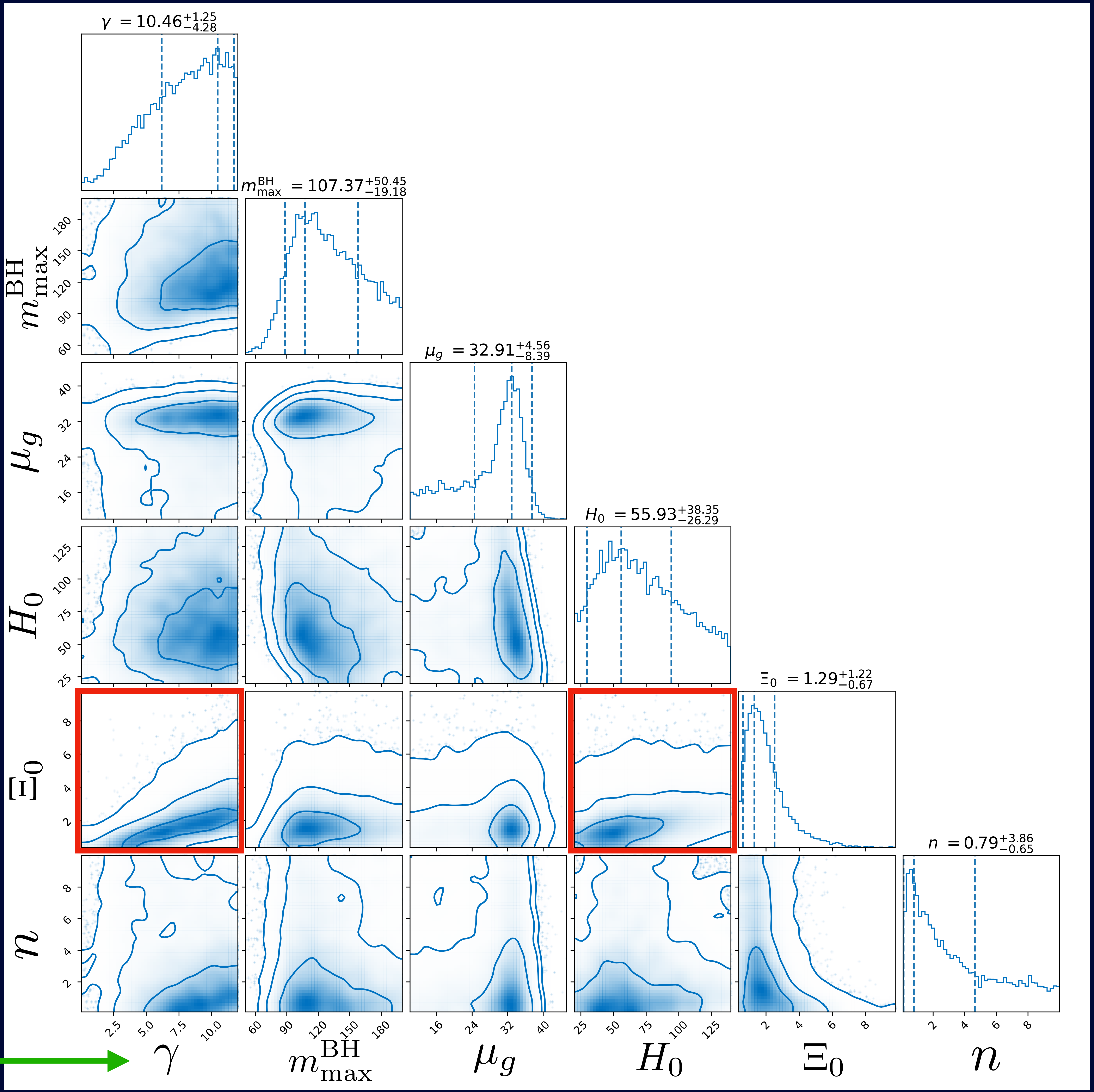
dark sirens code

(Public version on GitLab)

Dark Sirens Results: MG friction

$$\frac{d_{\rm GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$

Merger rate $\propto (1+z)^\gamma$

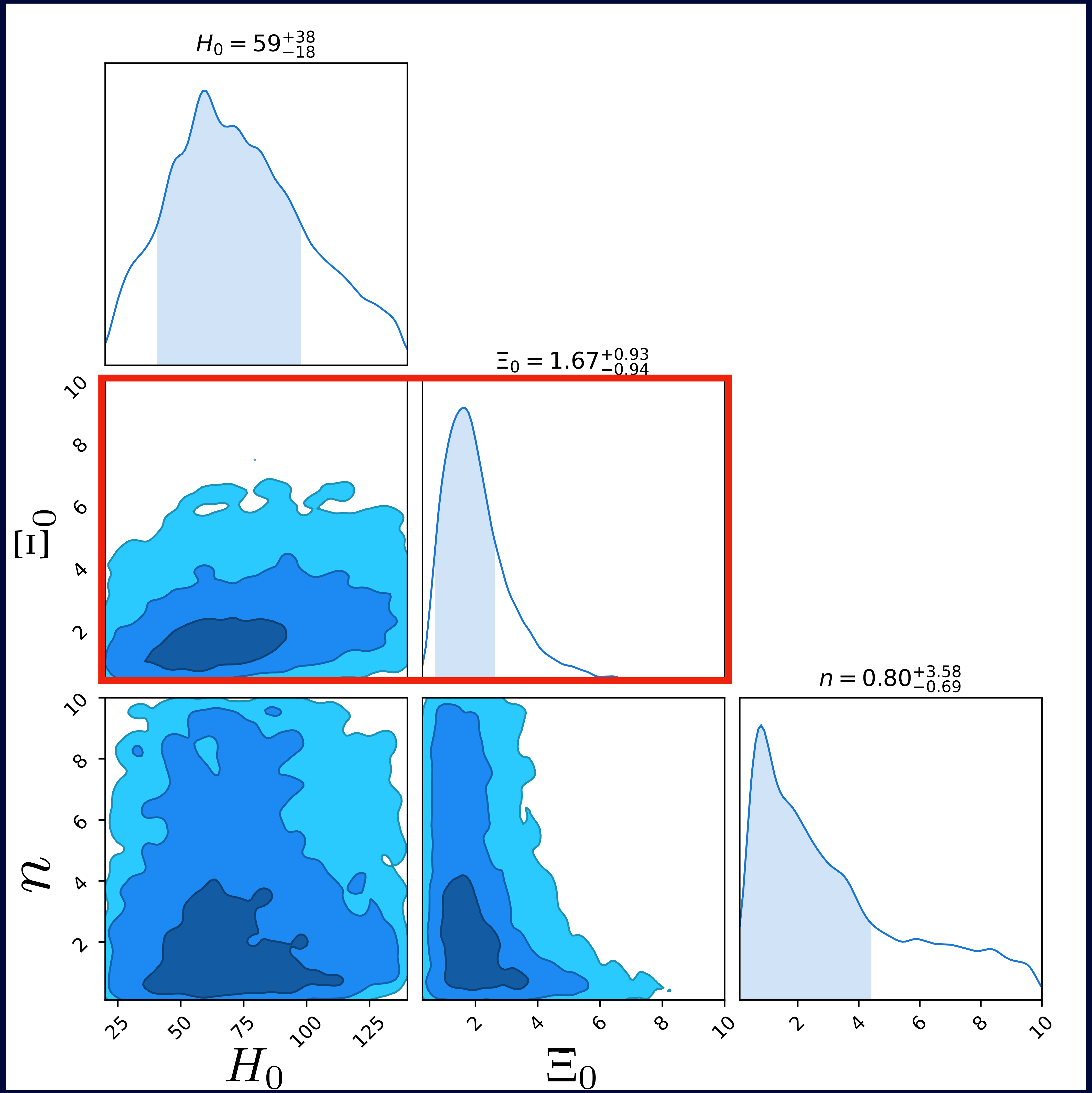


Anson Chen

Dark Sirens Results: MG friction

Anson Chen

$$\frac{d_{GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$



Chen et al. 2023.
(next week or two)

$$\Xi_0 = 1.67^{+0.93}_{-0.94}$$

(using 42 BBHs & 3 NSBHs from GWTC-3)

Stay tuned for O4 results, but H_0 and tests of gravity…

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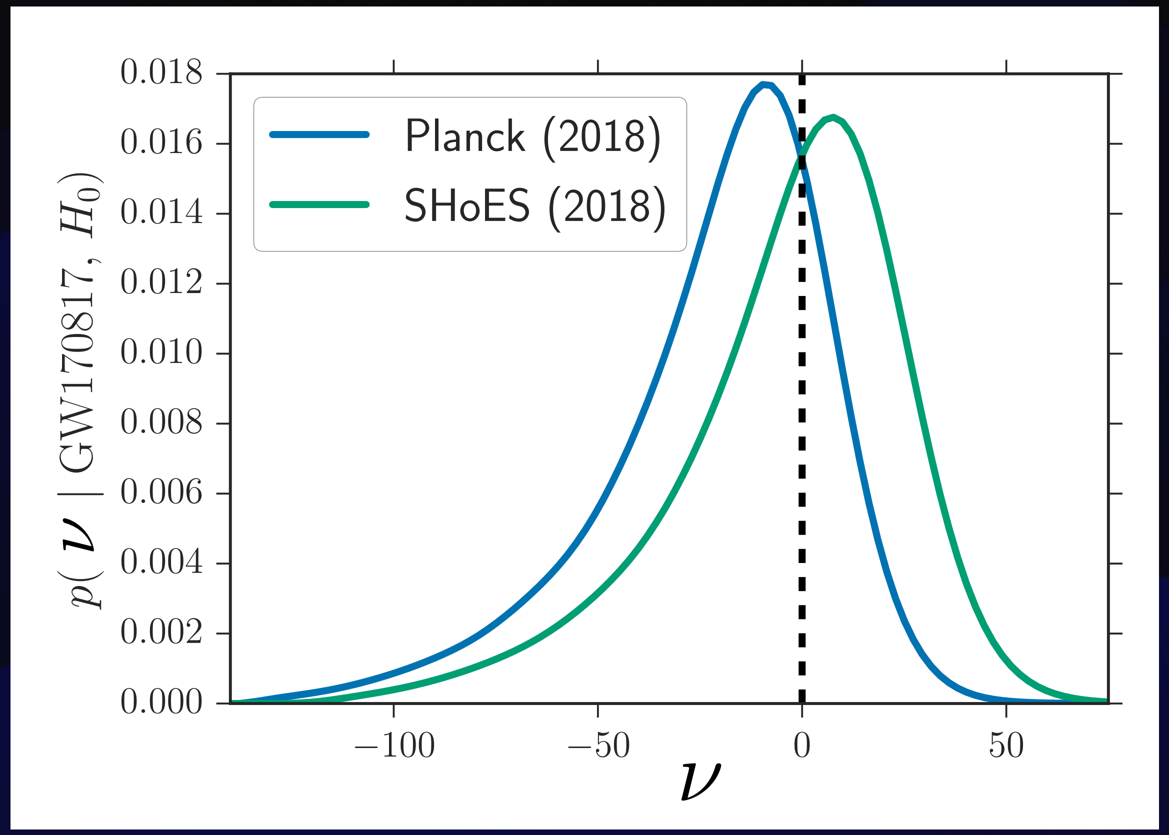
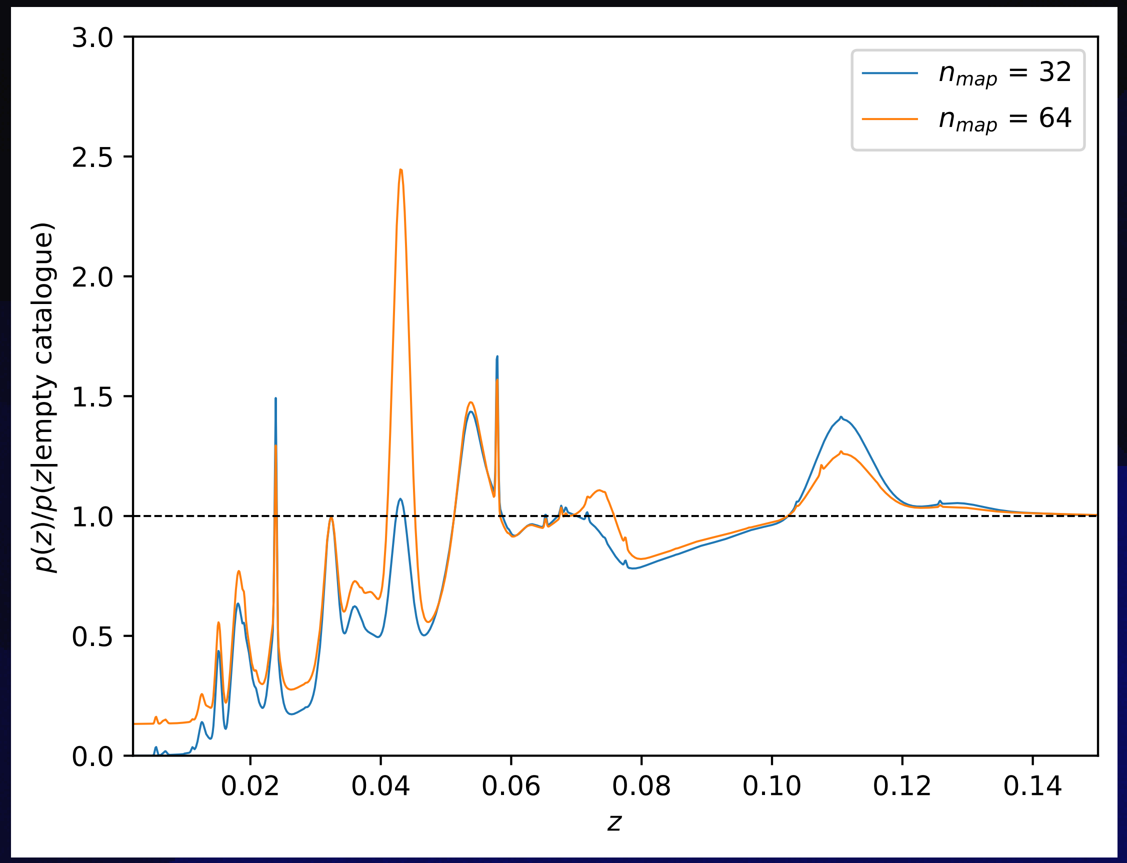
Conclusions

SIRENS

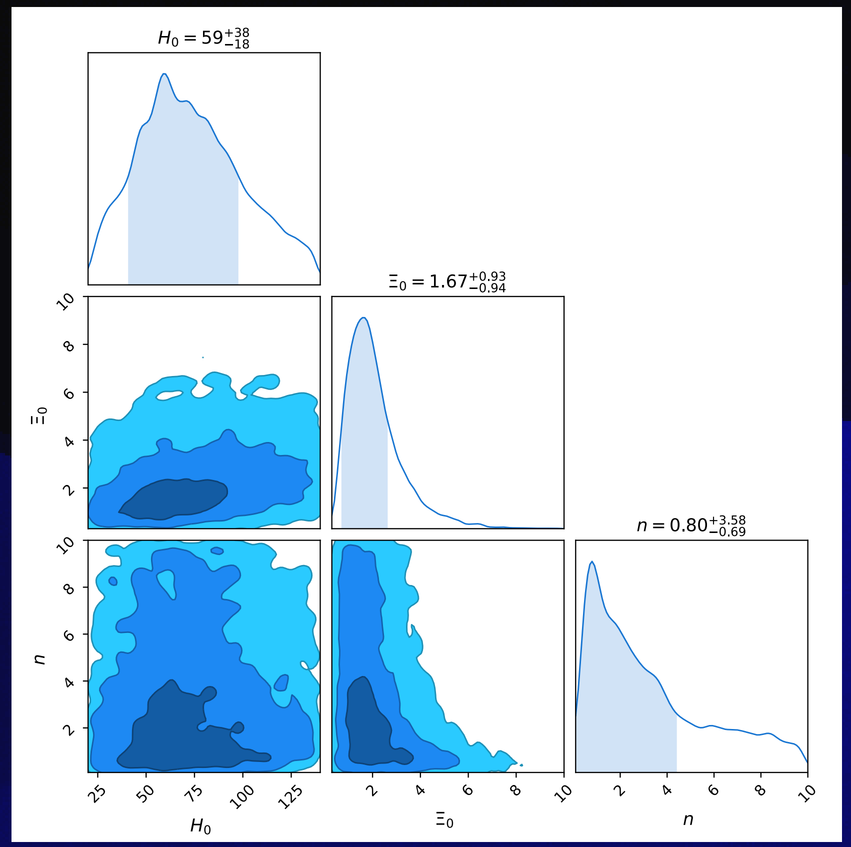
Bright Sirens



Galaxy completeness



Dark Siren tests of gravity



PARAMETERISATIONS

$$\frac{d_{\rm GW}}{d_L} = \exp\left[\int_0^z \frac{\nu(\tilde{z})}{1+\tilde{z}}\, d\tilde{z}\right]$$

$$\frac{d_{\rm GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$

TO-DO

- Some mass hyper-parameters still poorly constrained.
- Better galaxy catalogue completion.
- Stage 4 surveys → deeper catalogues.
- Weighting of host galaxies.