LIGO-Virgo-KAGRA O3 cosmology results

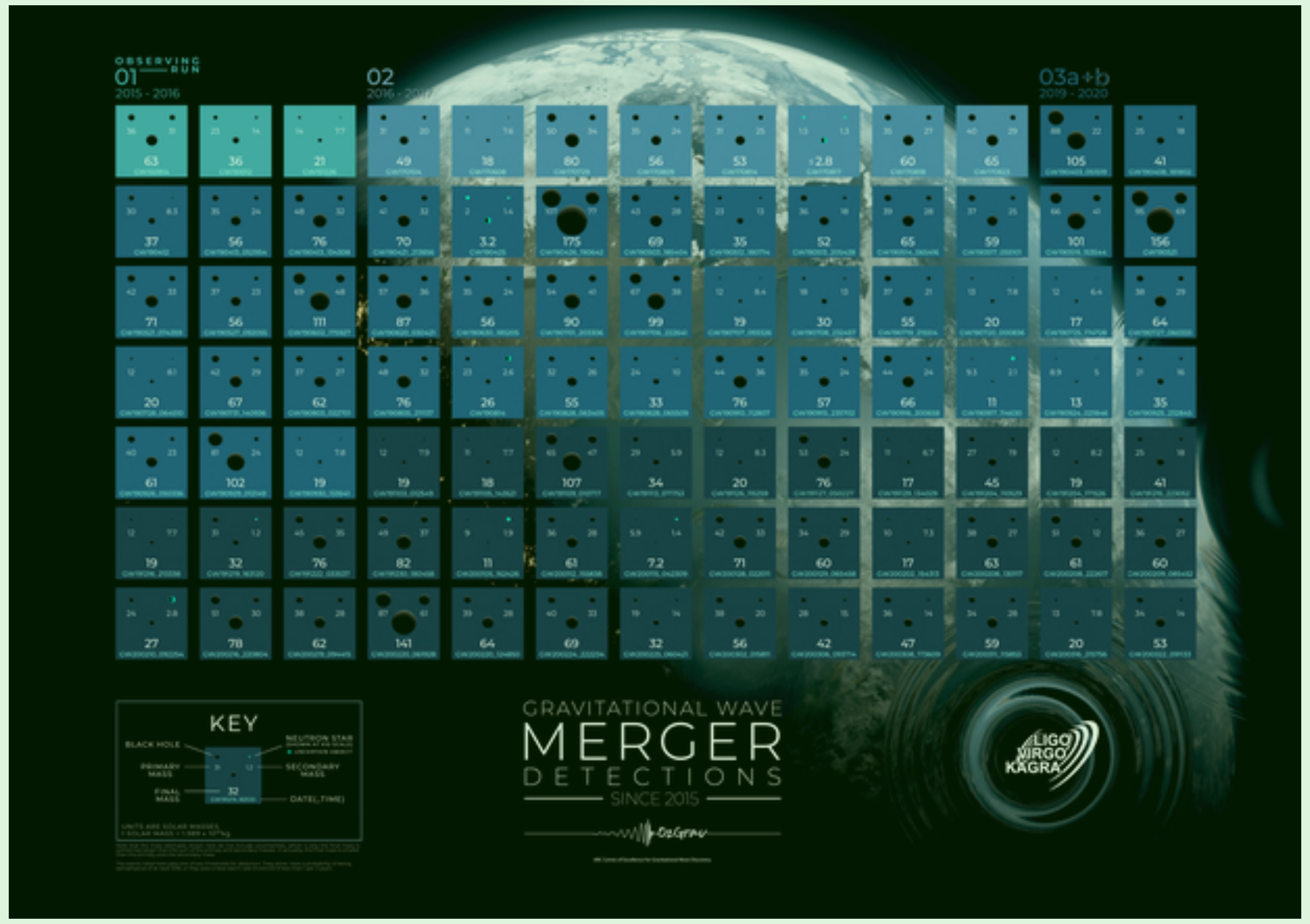
Konstantin Leyde

11.10.2022 GdR France Ondes Gravitationelles

2111.03604

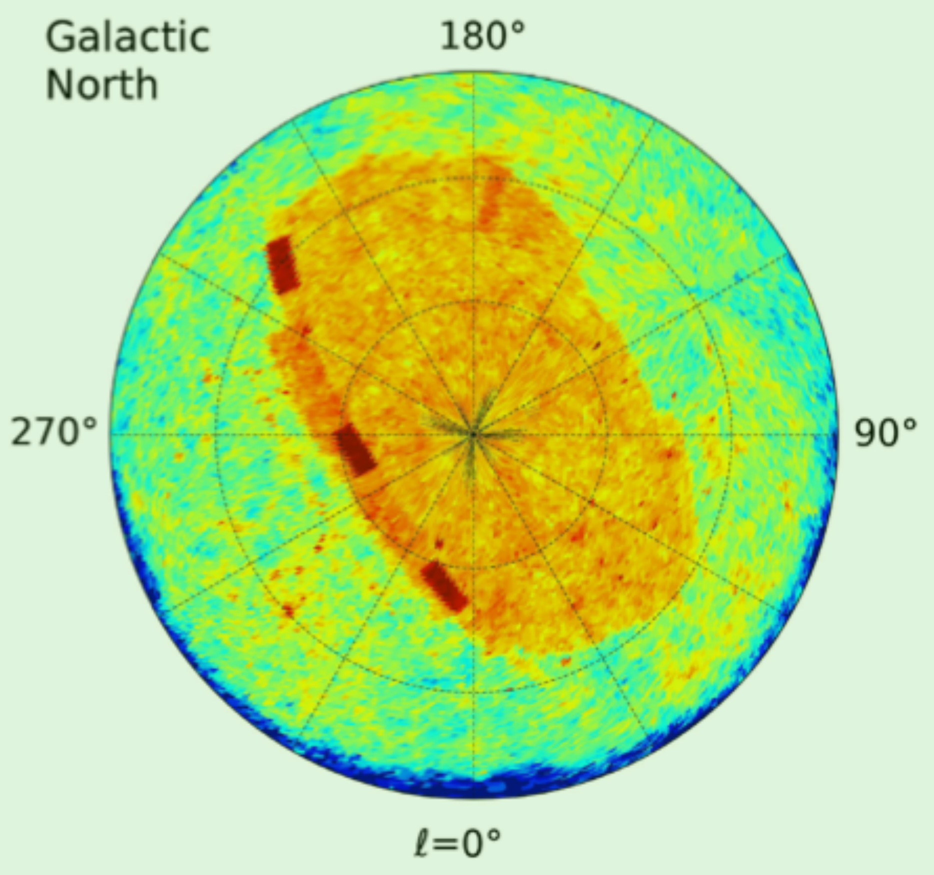
From data to the H_0 posterior

GW data



Carl Knox (OzGrav, Swinburne University of Technology)

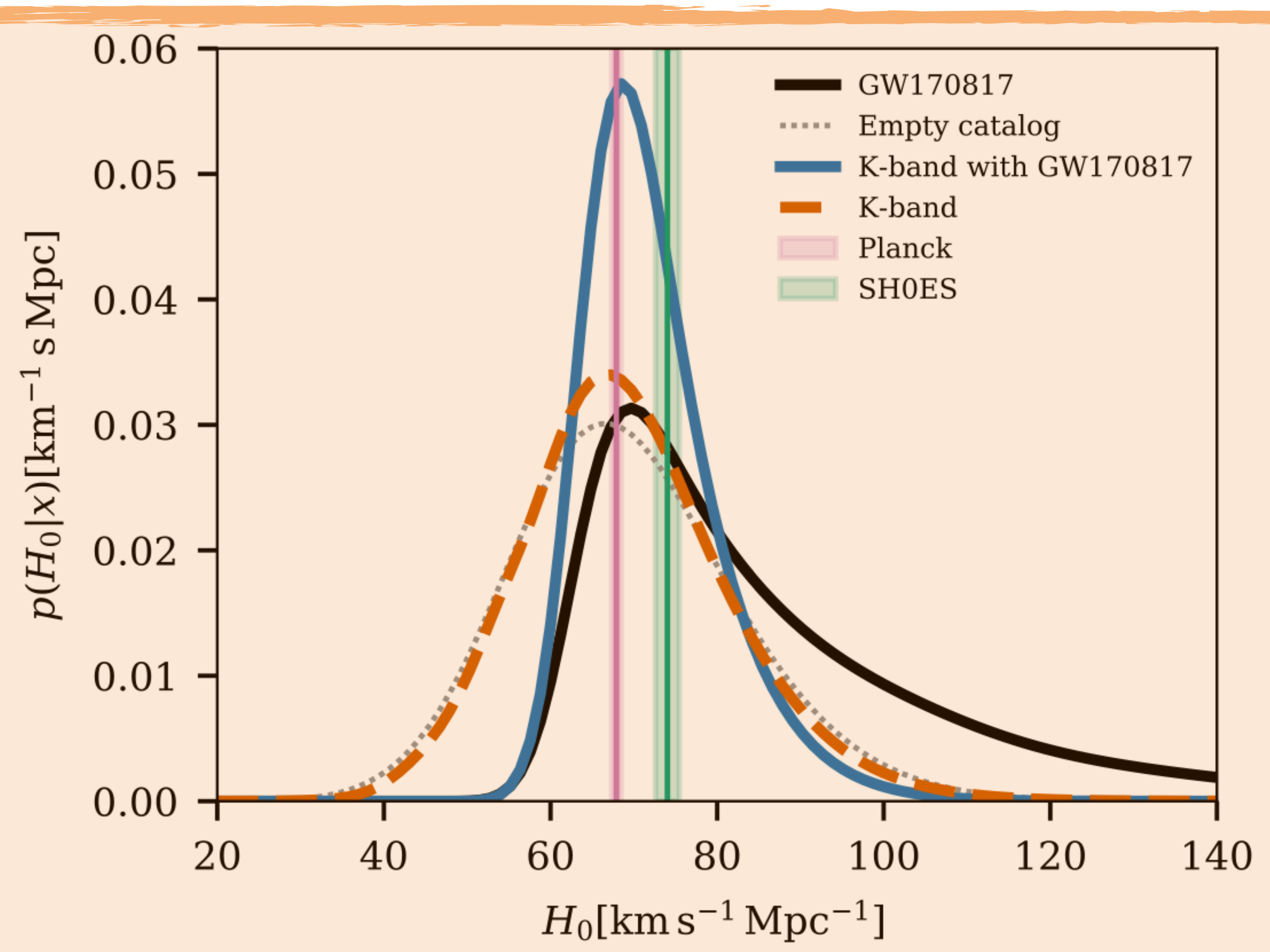
Galaxy Catalog Data

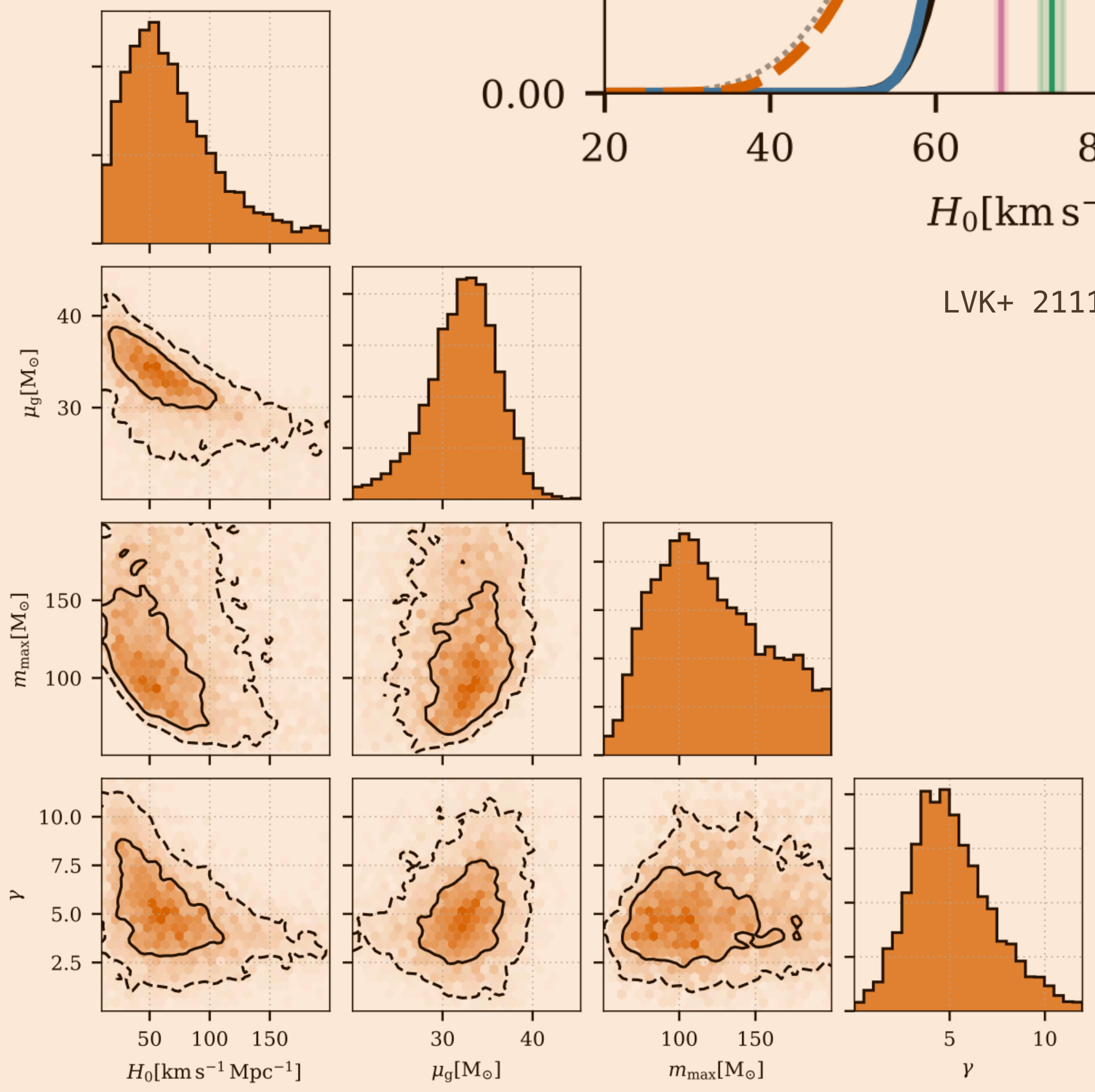


Dálya et al. 1804.05709

Pipelines

GWcosmo
IcaroGW





LVK+ 2111.03604

Cosmology with gravitational waves

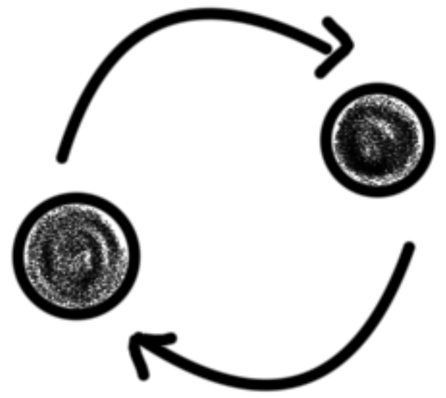
- [IcaroGW]
  - Deduce redshift from joint fit of the source frame mass and cosmological parameters
  - Marginalize over mass population

- [GWcosmo]
  - Assumption: GW sources in galaxies
  - Statistical redshift association from galaxy catalogs
  - Fixed mass distribution

Redshift information

GW data

$$d_L(z) = \frac{(1+z)c}{H_0} \int_0^z \frac{\mathrm{d}z'}{[\Omega_\mathrm{m}(1+z')^3 + \Omega_\Lambda]^{1/2}}$$



Gravitational wave parameters

Source frame masses
$m_1^{(s)}, m_2^{(s)}$

Expansion $(H_0, \Omega_\mathrm{m}, \ldots)$

Detector frame masses
$m_1^{(d)}, m_2^{(d)}$

- GW frequency is shifted to lower values by the expansion
- Redshift information is degenerate with other variables

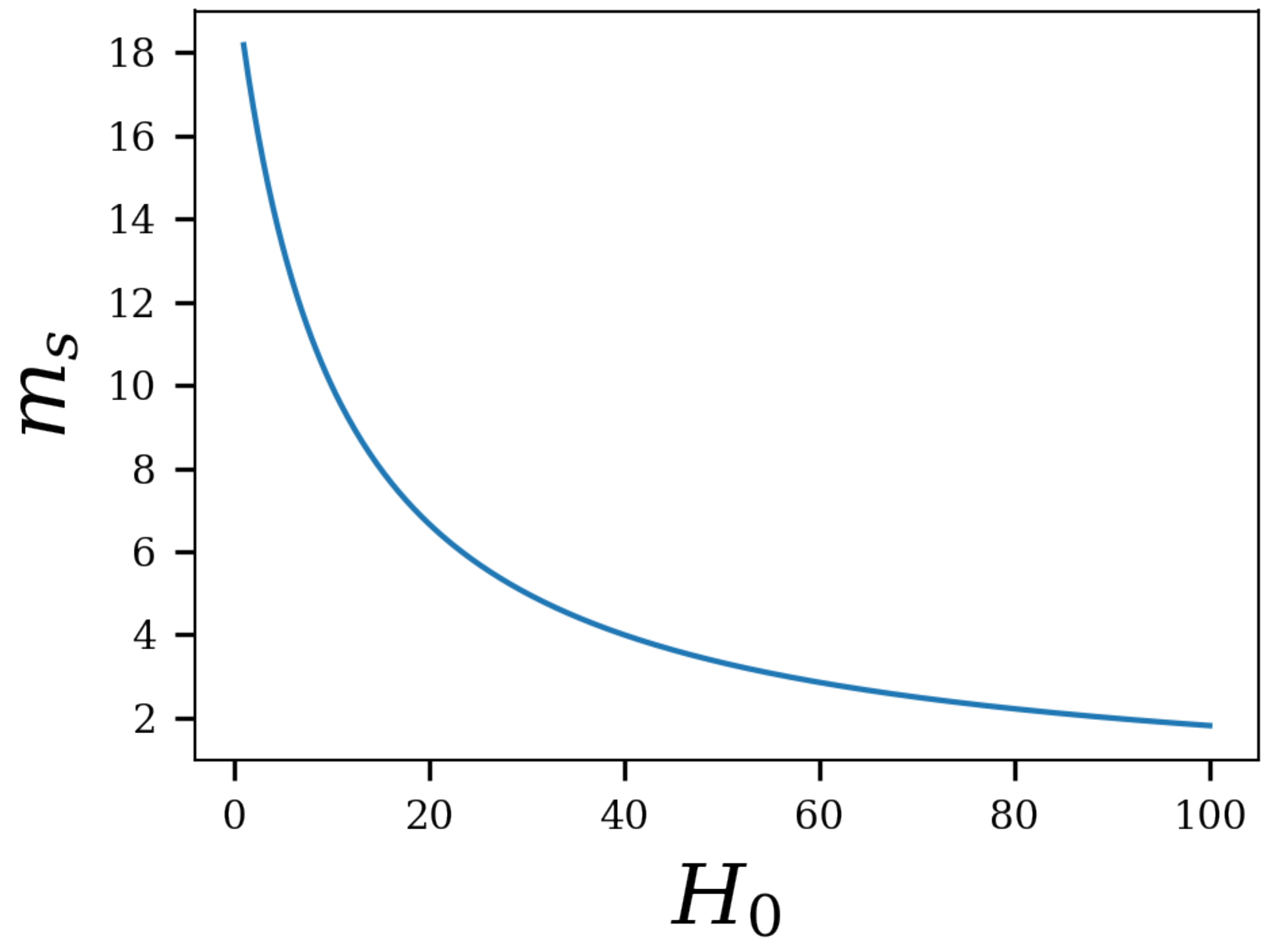
$$m^{(d)} = (1+z)m^{(s)}$$

Source frame population

- Assumption of mass model → statistical measurement of redshift

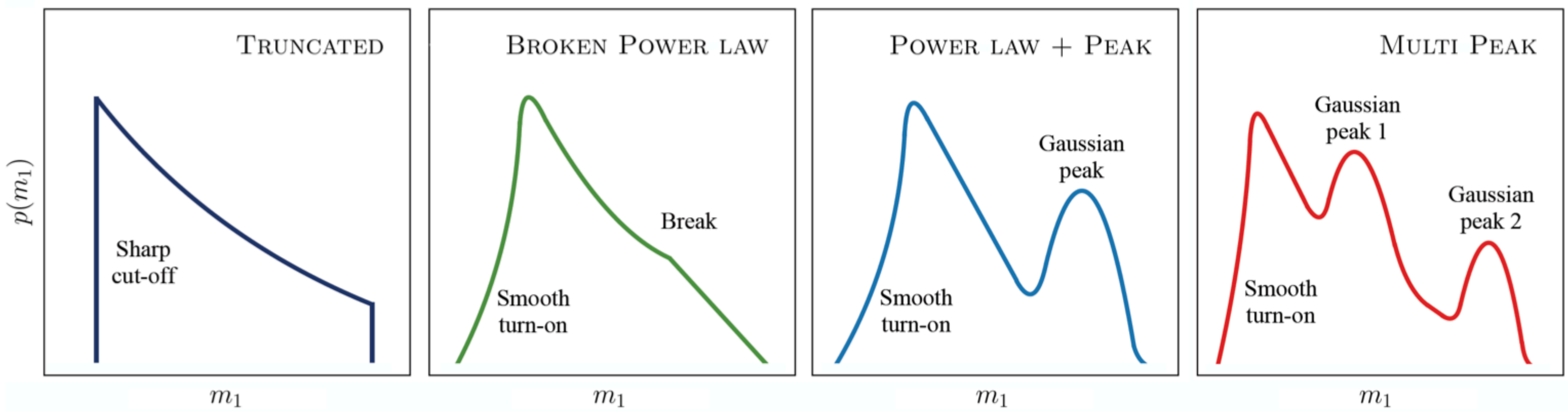
$$m^{(d)} = (1+z)m^{(s)} \quad \rightarrow \quad z = \frac{m^{(d)}}{m^{(s)}} - 1$$

- Joint fit of cosmological parameters and mass population models (*Taylor et al. 2012, Taylor and Gair 2012, Farr et al. 2019, You et al. 2020*)
- Strong correlation between H_0 and the characteristic mass scales



$$m^{(s)} = \frac{m^{(d)}}{1 + d_L H_0 / c} \qquad\qquad z \approx \frac{d_L H_0}{c}$$

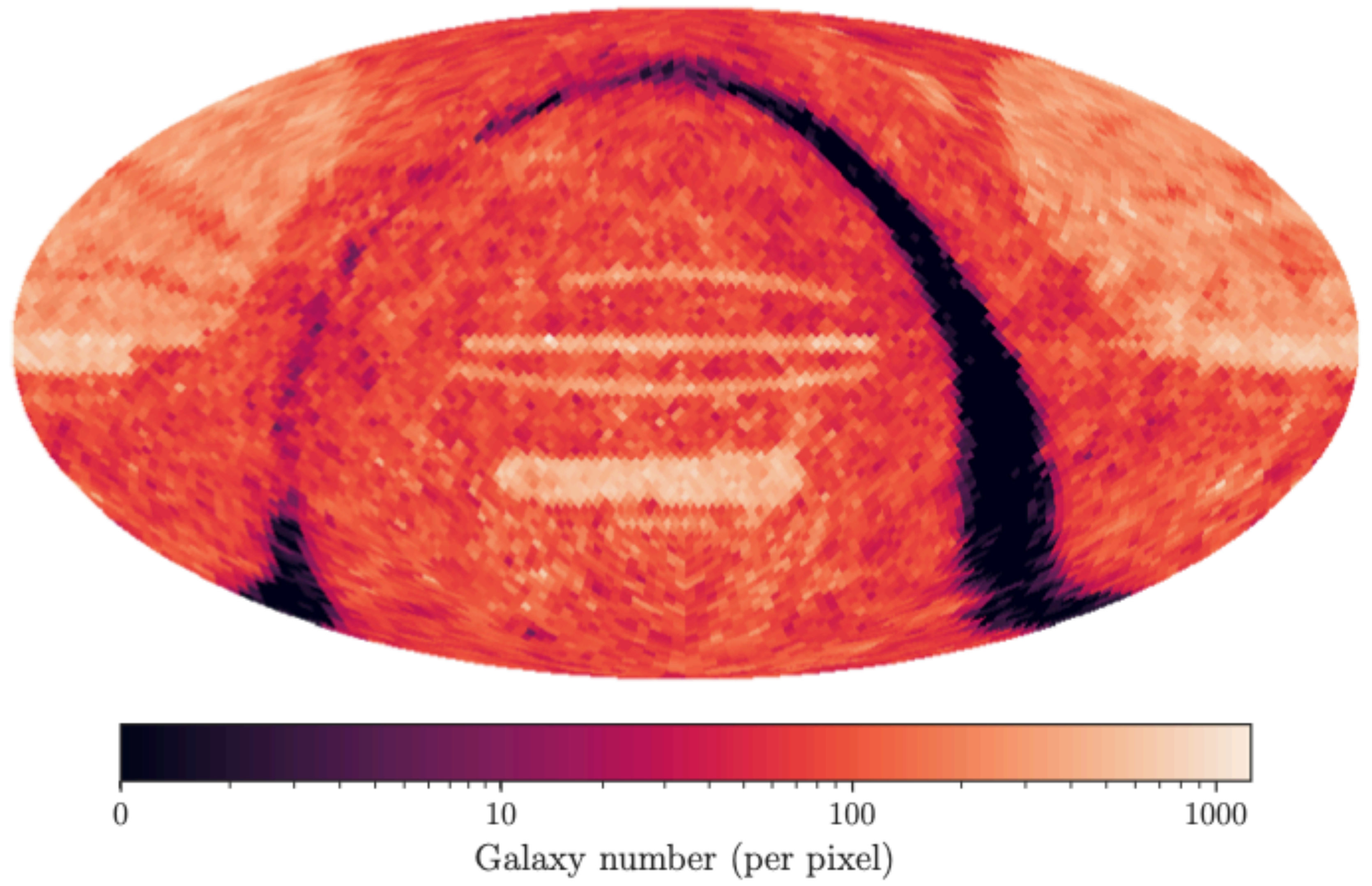
The source mass population model $p_{\mathrm{pop}}(\theta\,|\,\Lambda)$



LVK+ 2010.14533

GWcosmo *(Gray et al. 1908.06050)*

- Assumption: GW sources are found in galaxies
  - Possible GW hosts from galaxy catalogs *(Schutz 1986)*
  - *Give importance to galaxy according to luminosity*
- **Input from GW side:**
  - **Sky position**
  - Luminosity distance
  - Detector frame masses
- **Input from galaxy catalog:**
  - Sky position
  - Luminosity
  - Redshift
- **Challenge:** Galaxy catalogs incompleteness
  - Calculate selection effects:
    - Host galaxy is observed (in catalog) or not

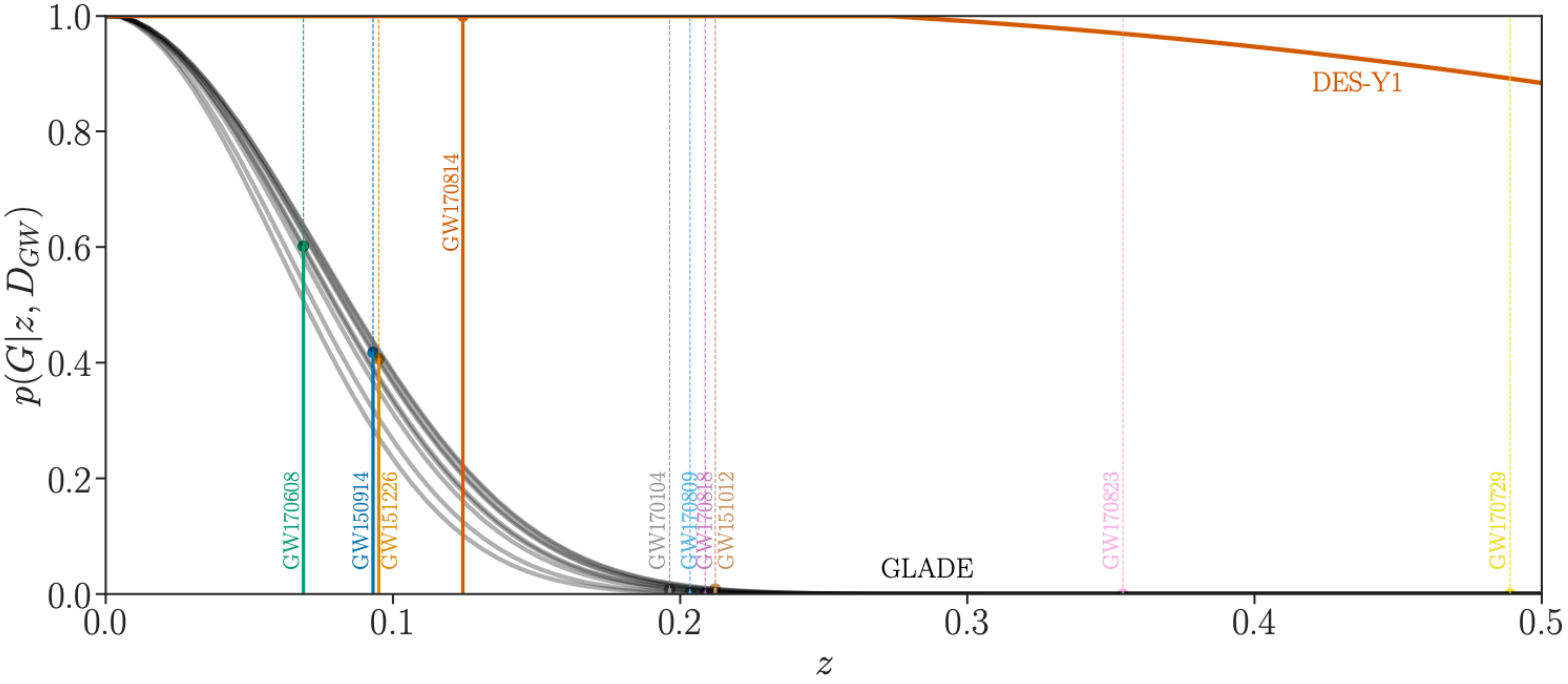


Gray et al. 2111.04629

Galaxy catalog used for GWcosmo

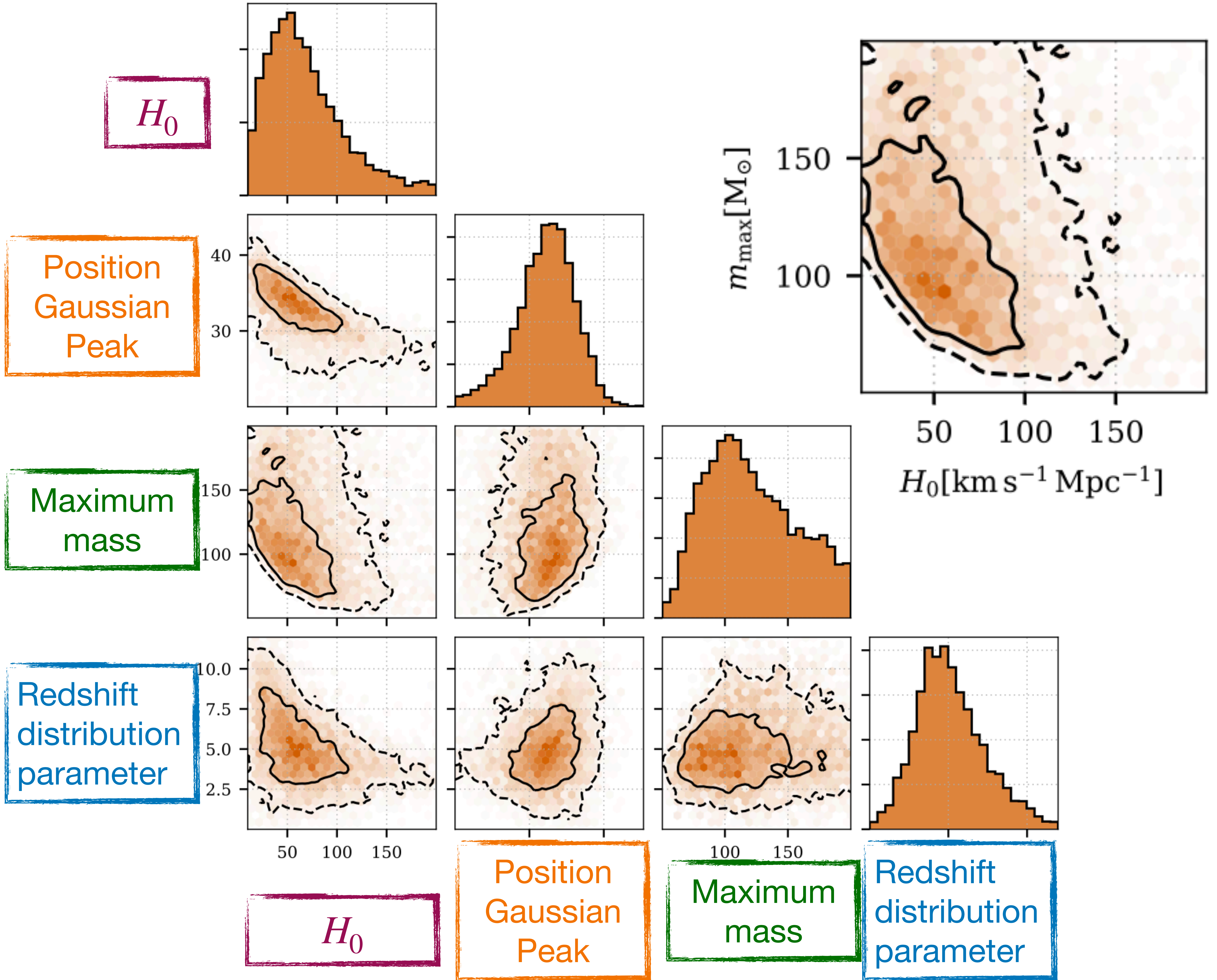
- All-sky catalog: Glade *(Dálya et al. 2018)*
- Partial coverage, but deeper in redshift: DES *(Drlica-Wagner et al. 2018)*

Probability of being in the catalog



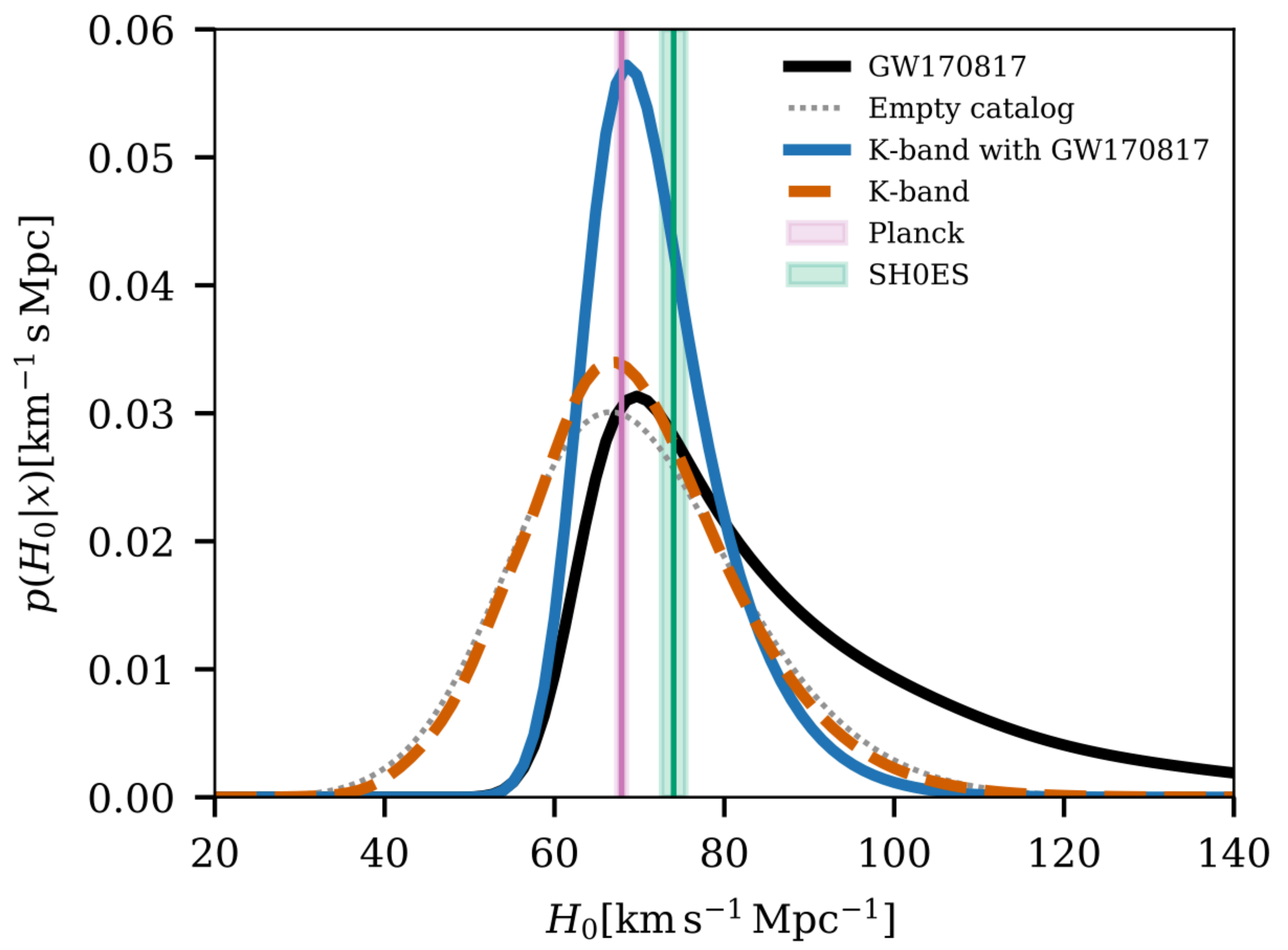
Results IcaroGW

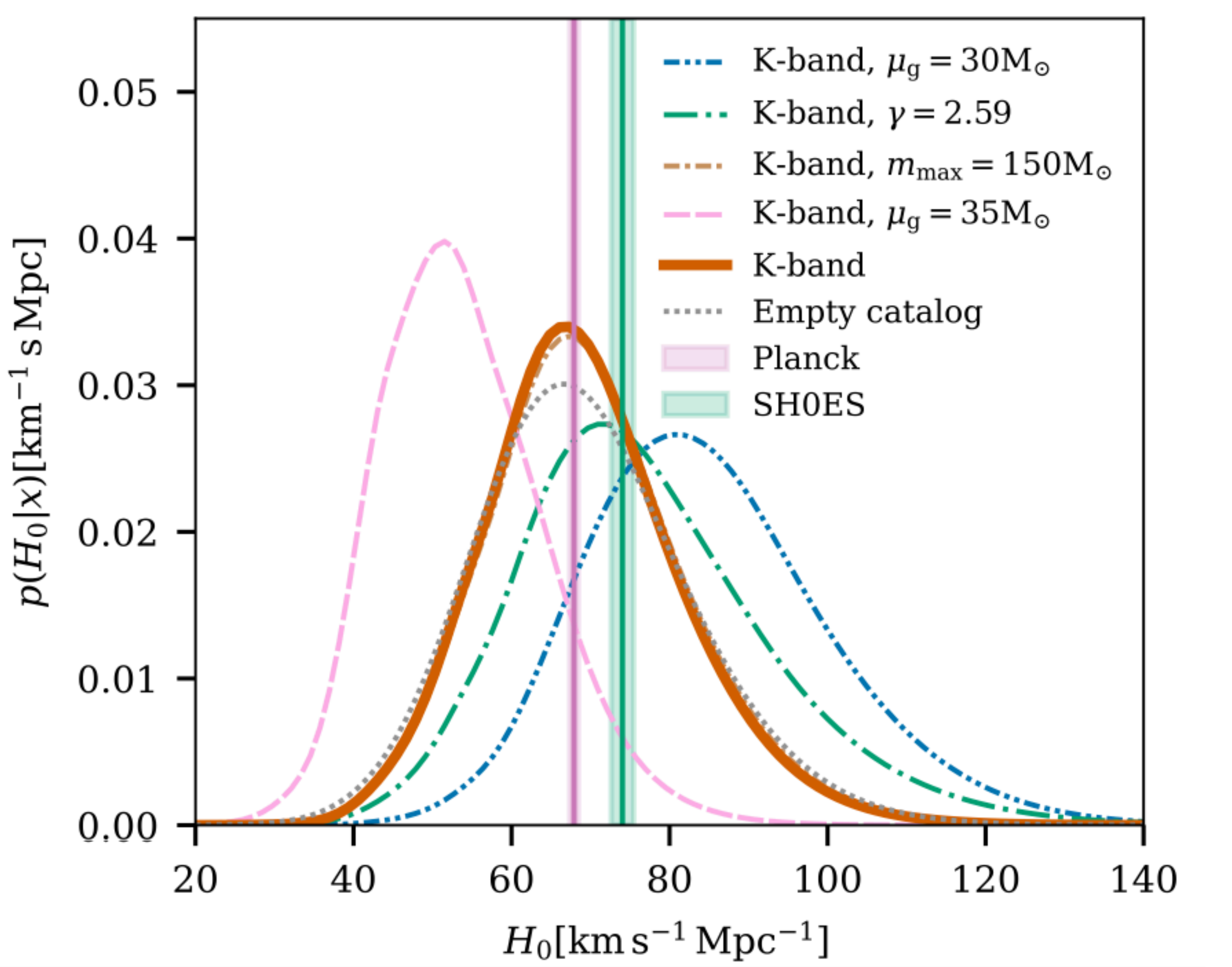
- Strong correlation between H_0 and the maximum mass
- Hubble constant not strongly constrained



Results GWcosmo

- Fix the mass distribution to the values obtained by Icarogw
- Result is strongly dependent on population assumption





$$H_0 = 67^{+13}_{-12}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Glade+
K-band

$$H_0 = 67^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Glade+, K-band
With GW170817

Conclusions

- IcaroGW (no EM information) method allows to simultaneously constrain cosmological and population parameters

- GWcosmo uses galaxy catalog information to constrain H_0 $\rightarrow$ Better constraint on H_0

- Main result from O3

$$H_0 = 67^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \text{ with Glade+, K-band and GW170817}$$

- Strong degeneracies between the rate evolution γ, the overall rate of events R_0, the Hubble constant H_0
    - $\rightarrow$ Marginalize over population assumptions

Relaxing an assumption:

Modified propagation equation for gravitational waves

$$h_A'' + 2\mathcal{H}(1 - \delta(\eta))h_A' + k^2 h_A = 0$$

- k the wave vector, A the GW polarisation, η the conformal time, $\mathcal{H} = \frac{a'}{a}$ and δ the friction term

- Appears in some modified gravity theories (e.g. beyond Horndeski *1404.6495,* DHOST, *1510.06930, 1703.03797, 1707.03625*)

- Results in a modified gravitational wave distance (gravitational wave and electromagnetic distance do not coincide)

- **Testable** with gravitational wave observations

Binary black hole dark siren population analysis with modified gravity

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ÉCOLE DOCTORALE STEP'UP

11.10.2022 Session Cosmologie du GdR Ondes Gravitationnelles

2202.00025

Assumption on the modifications of GR

$$h_A'' + 2\mathcal{H}(1 - \delta(\eta))h_A' + k^2 h_A = 0$$

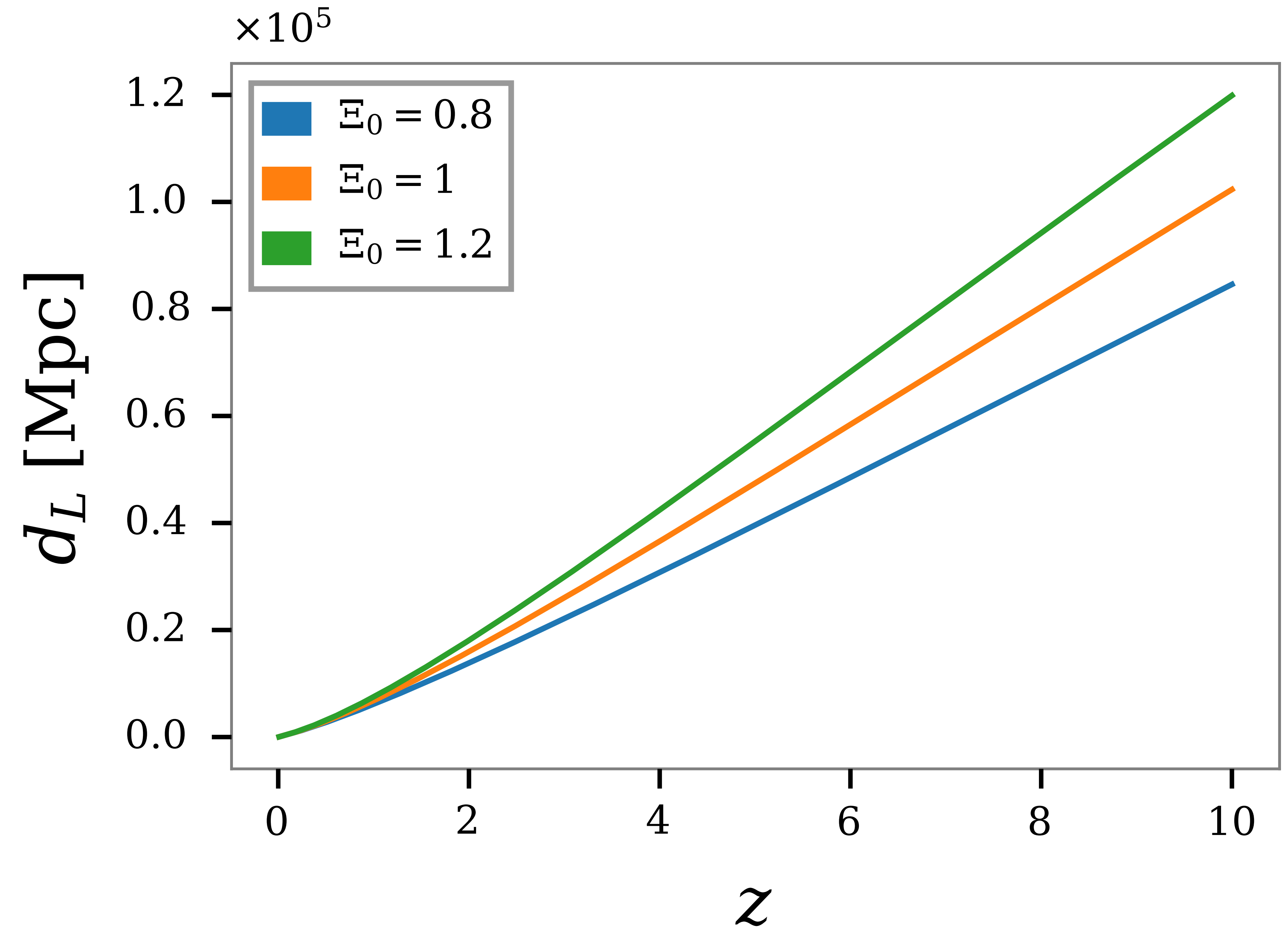
- Phenomenological model *1906.01593*

Ξ_0 characterises early time behaviour

GR: $\Xi_0 = 1$

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

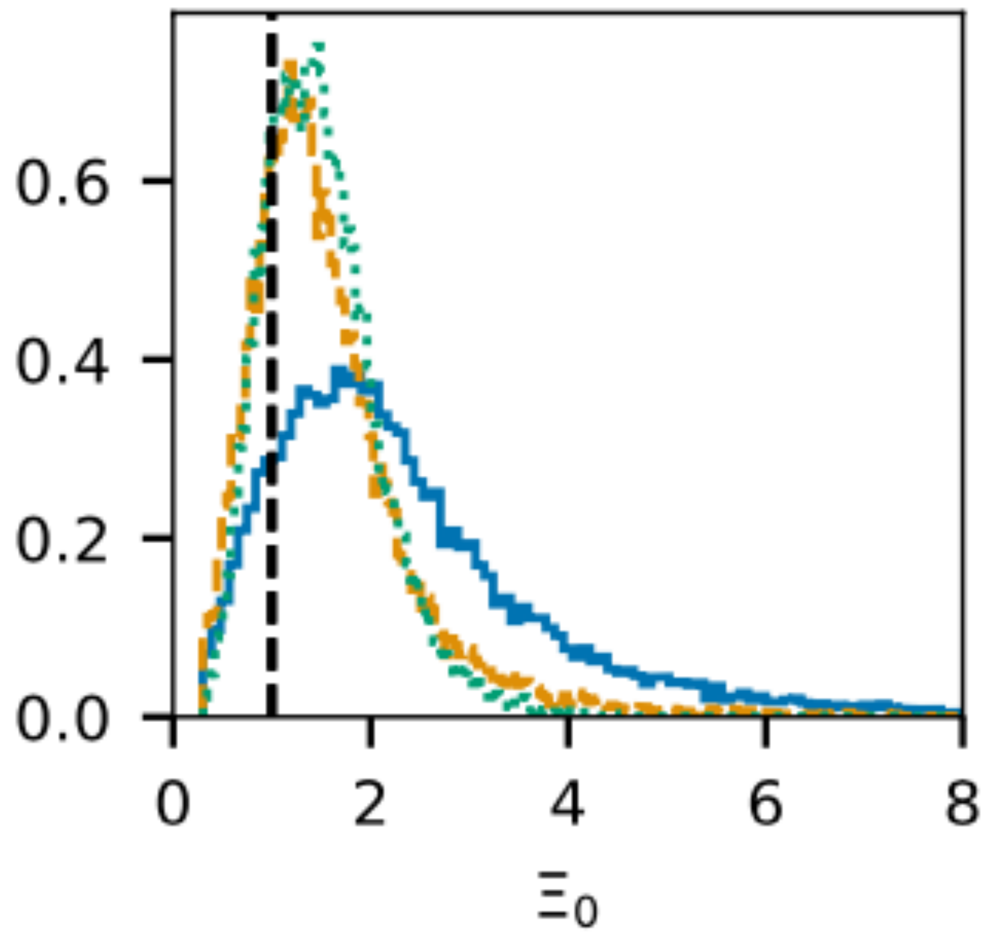
n characterises the transition from early to late times



- Assumptions: No modifications of the waveform during the inspiral phase and cosmological background is unchanged

Results with O3 data

- GR: $\Xi_0 = 1$
- For all modified gravity models: **compatible with their GR values** at 90% confidence level (for **Multi Peak**)



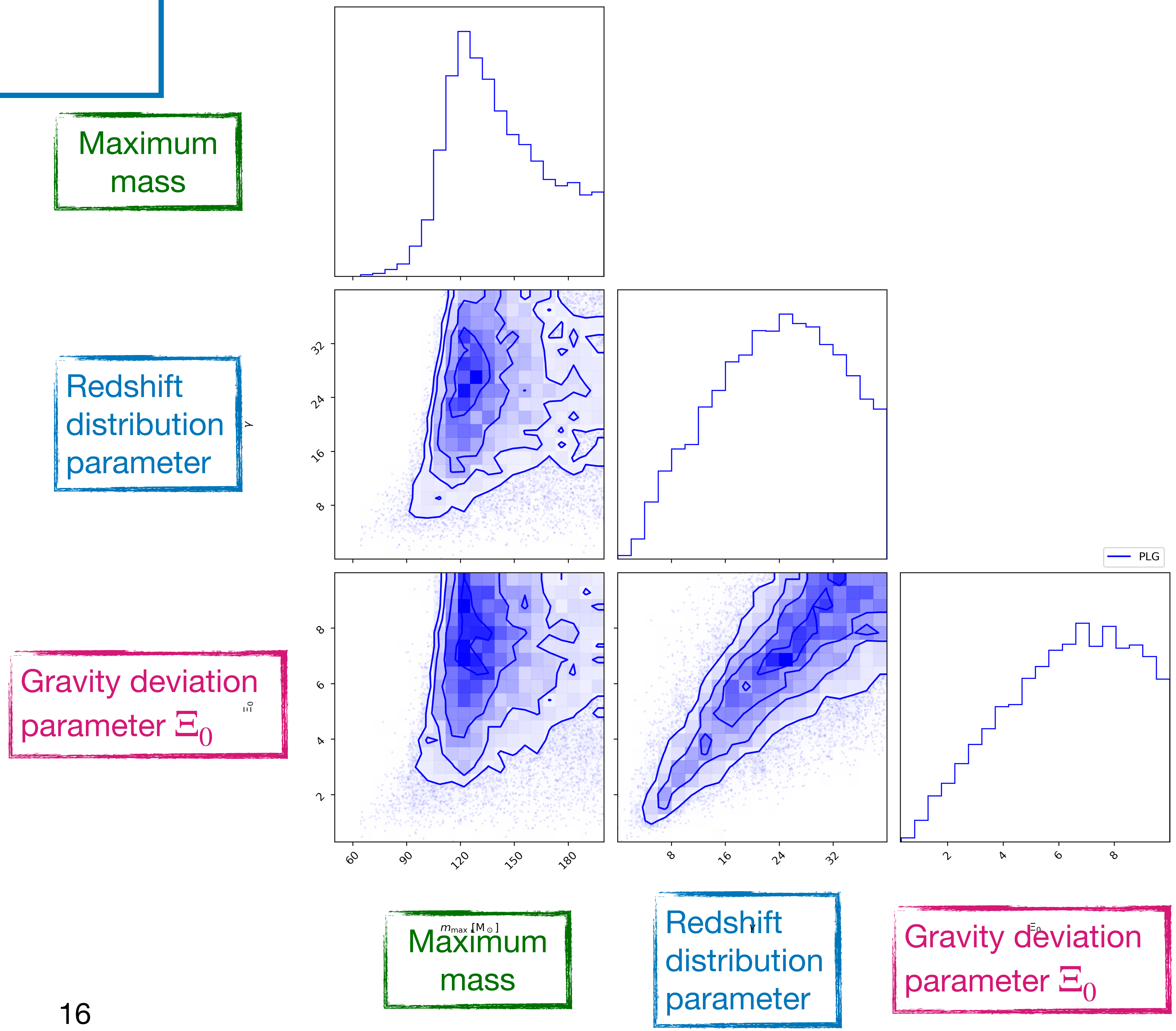
Multi peak mass model, varying SNR cut

60 BBH events, SNR > 10, IFAR > 4 yr				
	Broken Power Law	Multi Peak	Power Law + Peak	Truncated
D	6^{+2}_{-2}	5^{+3}_{-1}	5^{+3}_{-1}	$4.5^{+3.1}_{-0.8}$
Ξ_0	$1.6^{+1.3}_{-0.8}$	$1.4^{+1.1}_{-0.7}$	$1.3^{+1.2}_{-0.7}$	$0.6^{+1.4}_{-0.2}$
c_M	$1.0^{+2.3}_{-2.6}$	$0.5^{+2.5}_{-2.4}$	$0.1^{+2.7}_{-2.1}$	-2^{+3}_{-1}
42 BBH events, SNR > 11, IFAR > 4 yr				
	Broken Power Law	Multi Peak	Power Law + Peak	Truncated
D	$4.7^{+2.9}_{-0.9}$	$4.6^{+2.6}_{-0.8}$	$4.7^{+2.7}_{-0.9}$	5^{+3}_{-1}
Ξ_0	2^{+3}_{-1}	2^{+4}_{-1}	2^{+3}_{-1}	$0.7^{+3.0}_{-0.4}$
c_M	$0.5^{+4.1}_{-4.2}$	1^{+4}_{-5}	1^{+4}_{-4}	-3^{+5}_{-2}
35 BBH events, SNR > 12, IFAR > 4 yr				
	Broken Power Law	Multi Peak	Power Law + Peak	Truncated
D	5^{+3}_{-1}	$4.6^{+2.9}_{-0.9}$	$4.8^{+2.9}_{-1.0}$	5^{+3}_{-1}
Ξ_0	$1.2^{+1.4}_{-0.7}$	$1.4^{+1.8}_{-0.8}$	$1.4^{+1.8}_{-0.8}$	$0.8^{+2.0}_{-0.5}$
c_M	$-0.1^{+2.8}_{-3.0}$	$0.3^{+3.2}_{-3.3}$	$0.4^{+3.2}_{-3.0}$	-2^{+5}_{-3}

See also: *Mancarella et al. 2112.05728*

Degeneracies

- GR: $\Xi_0 = 1$
- Gravity deviation parameter Ξ_0 strongly degenerate with the redshift distribution parameter γ



Conclusions

- Method allows to simultaneously constrain modified gravity, cosmological and population parameters
  - Implication of O3 : bright sirens are rare
- O3 data favours GR over all modified gravity models investigated
- Study impact of mass models on the measurement of Ξ_0 and on H_0
- Strong degeneracies between the rate evolution γ, the overall rate of events R_0, the Hubble constant H_0 and friction amplitude Ξ_0
  - Assumptions on astrophysics can bias this measurement
  - $\rightarrow$ Marginalize over population assumptions
- Constrain Ξ_0 to $50\,\%$ with O4 and $20\,\%$ with O4+O5

Thank you!

Questions?

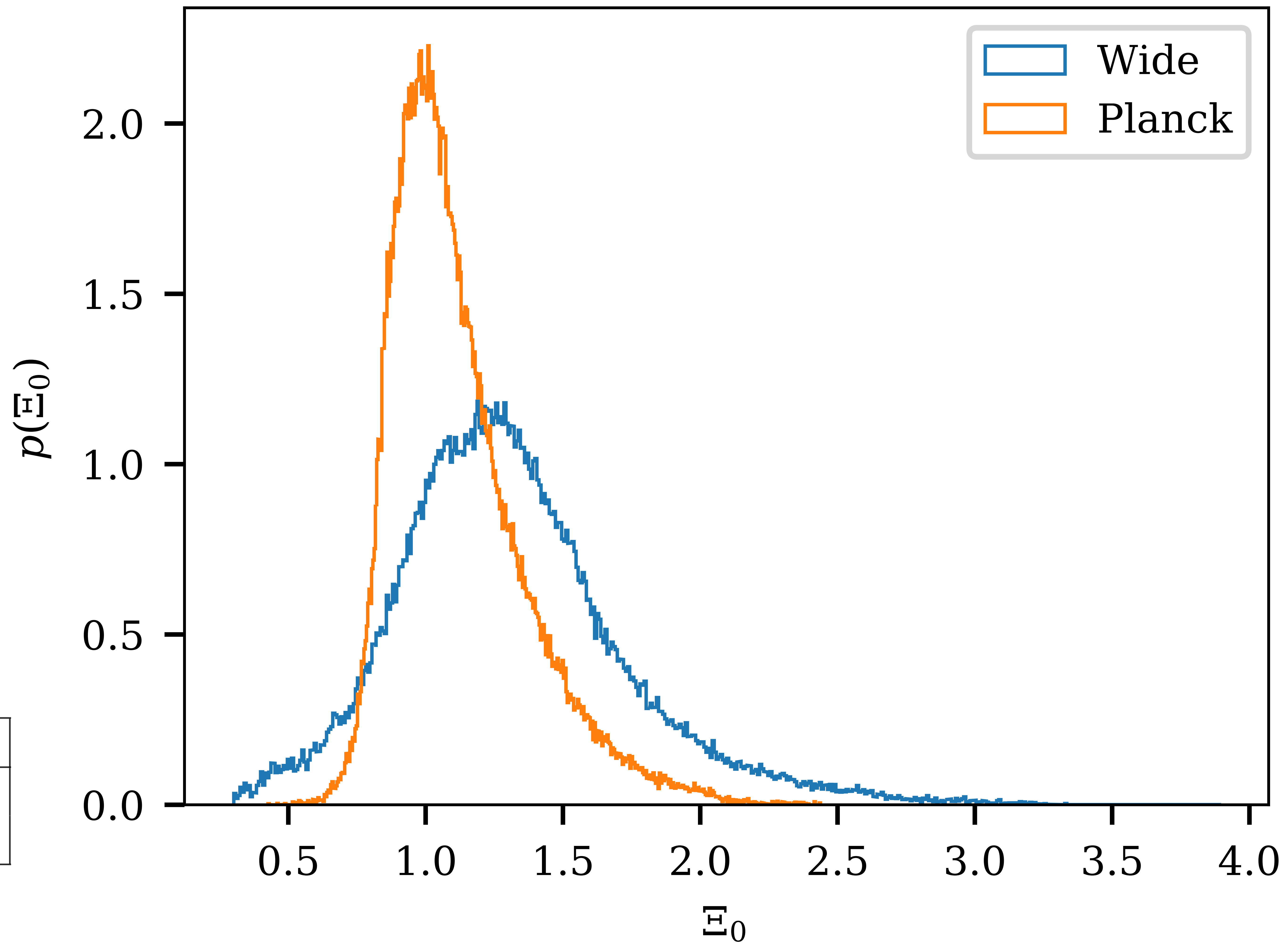
Forecast (with O4 + O5)

The effect of a prior on the cosmological values

Wide: Agnostic priors for the cosmological parameters

Planck: Priors from the Planck estimate for the cosmological parameters

	Agnostic	*From Planck*
H_0	$\mathcal{U}(30, 130)$	$\mathcal{U}(66.07, 68.47)$
Ω_M	$\mathcal{U}(0.05, 0.4)$	$\mathcal{U}(0.3082, 0.3250)$



Back up slides

Statistical framework of IcaroGW *(Mastrogiovanni et al. 2103.14663)*

- Bayesian analysis with selection effects *(Mandel et al. 1809.02063, Thrane and Talbot 1809.02293, Vitale et al. 2007.05579)*

$$p(\Lambda|\{x\}) \propto p(\Lambda) \prod_{j=1}^{N_{\rm obs}} \frac{\int p(x_j|\theta_j)\, p_{\rm pop}(\theta_j|\Lambda) \mathrm{d}\theta_j}{\int p_{\rm det}(\theta_j)\, p_{\rm pop}(\theta_j|\Lambda) \mathrm{d}\theta_j}$$

- Metaparameters Λ : population parameters, cosmological parameters, …
- GW data $\{x\}$
- Source parameters $\theta = \{m_{1,2}^{(d)}, d_L^{\rm GW}, \dots\}$
- GW likelihood $p(x_i \,|\, \Lambda, \theta)$, obtained from posterior samples
- Population assumption $p_{\rm pop}(\theta \,|\, \Lambda)$
- Detection probability $p_{\rm det}(\theta)$

Statistical framework of IcaroGW *(Mastrogiovanni et al. 2103.14663)*

Bayesian analysis with selection effects

$$p(\Lambda|\{x\}) \propto p(\Lambda) \prod_{j=1}^{N_{\rm obs}} \frac{\int p(x_j|\theta_j)\, p_{\rm pop}(\theta_j|\Lambda) {\rm d}\theta_j}{\int p_{\rm det}(\theta_j)\, p_{\rm pop}(\theta_j|\Lambda) {\rm d}\theta_j}$$

- Only events passing threshold (on signal to noise ratio or false alarm rate) are considered
- Numerical evaluation of $p_{\rm det}(\theta)$: produce a set of events and label them either "detected" or "undetected" (passing SNR threshold and IFAR threshold)

Statistical framework of GWcosmo *(Gray et al. 1908.06050)*

Bayesian analysis with selection effects

Prior H_0

Observed events

$$p(H_0 \,|\, x_{\rm GW}, N_{\rm obs}, \Lambda_m, \Lambda_z) = p(H_0) \prod_{i=1}^{N_{\rm obs}} \sum_{g \in [G, \bar{G}]} p(x_{\rm GW,i} \,|\, H_0, \Lambda_m, g)\, p(g \,|\, H_0, \Lambda_m, \Lambda_z, \hat{d})$$

Posterior on H_0

Host galaxy in catalog?

One event posterior

Hidden here are the selection effects

- Assumes a fixed mass and redshift distribution
- $\hat{d}$: “event is detected”
- $N_{\rm obs}$ number of observed events

Statistical framework of GWcosmo *(Gray et al. 1908.06050)*

Host galaxy in catalog?

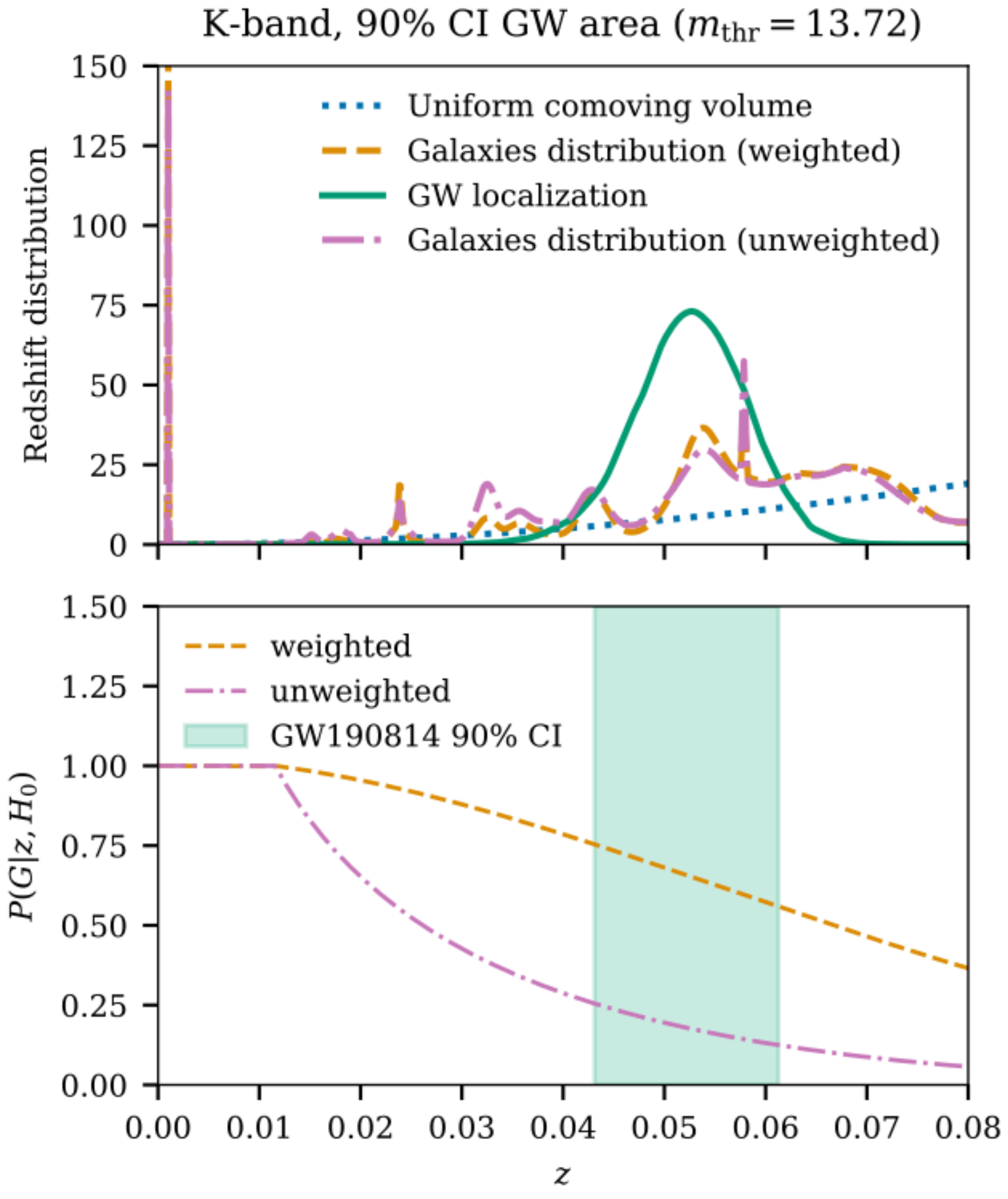
Probability of being in catalog

Probability of **not** being in catalog

$$\sum_{g\in[G,\bar{G}]} p(x_{\rm GW,i}\,|\,H_0,\Lambda_{m,z},g)p(g\,|\,H_0,\Lambda_{m,z},\hat{d}) = p(x_{\rm GW,i}\,|\,H_0,\Lambda_{m,z},G)p(G\,|\,H_0,\Lambda_{m,z},\hat{d}) + p(x_{\rm GW,i}\,|\,H_0,\Lambda_{m,z},\bar{G})p(\bar{G}\,|\,H_0,\Lambda_{m,z},\hat{d})$$

One event posterior

- Assumptions for selection effects
    - Apparent magnitude threshold of the galaxy catalog
    - Redshift distribution of galaxies
    - Luminosity distribution of galaxies (e.g. Schechter function)
- Pixelated approach: Treat selection effects as non-uniform in the sky



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Results with O3 data

Bayes factor: $\dfrac{p(\text{data}\,|\,\text{model}_1)}{p(\text{data}\,|\,\text{model}_2)}$

- GR: $\Xi_0 = 1$
- Compare Bayes factors
  → Multi Peak + General Relativity is preferred
- Consistent results for all 3 SNR cuts

60 BBH events, SNR > 10, IFAR > 4 yr

	Broken Power Law	**Multi Peak**	Power Law + Peak	Truncated
GR	−2.4	0.0	−1.2	−6.3
D	−2.0	−0.2	−1.7	−6.4
Ξ_0	−3.2	−0.9	−2.1	−6.8
c_M	−3.0	−1.0	−2.1	−6.5

42 BBH events, SNR > 11, IFAR > 4 yr

	Broken Power Law	**Multi Peak**	Power Law + Peak	Truncated
GR	−1.5	0.0	−0.8	−3.2
D	−1.5	−0.0	−0.9	−3.4
Ξ_0	−1.9	−0.6	−1.4	−3.9
c_M	−1.9	−0.9	−1.7	−3.4

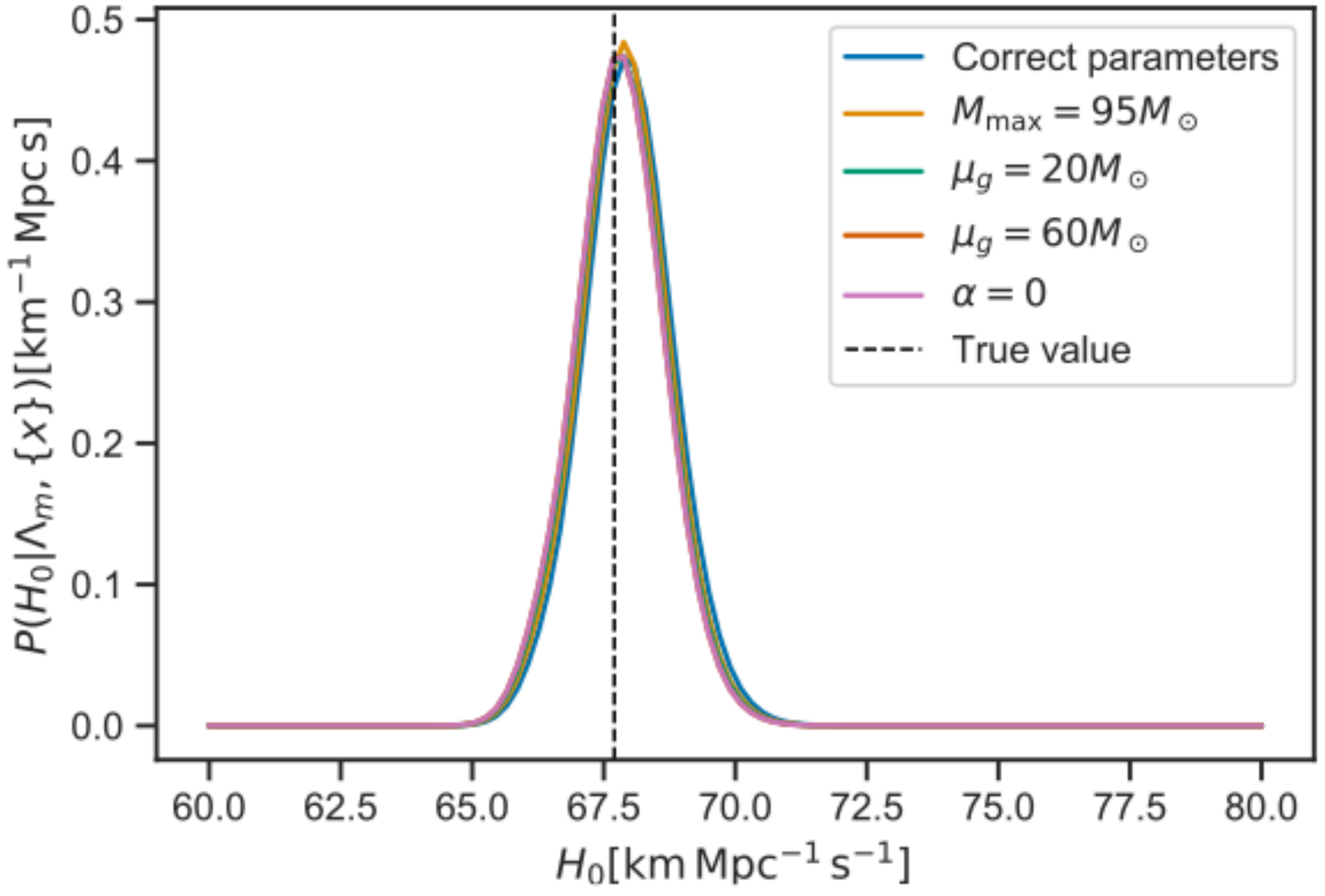
35 BBH events, SNR > 12, IFAR > 4 yr

	Broken Power Law	**Multi Peak**	Power Law + Peak	Truncated
GR	−1.2	0.0	−1.1	−2.6
D	−1.1	−0.4	−1.2	−2.8
Ξ_0	−2.1	−1.0	−1.9	−3.3
c_M	−1.9	−1.2	−1.9	−3.1

Two limits…

[“GWcosmo”]

- Close-by signals, well-localised (very few compatible galaxies)
  - H_0 posterior is independent of the mass distribution assumed



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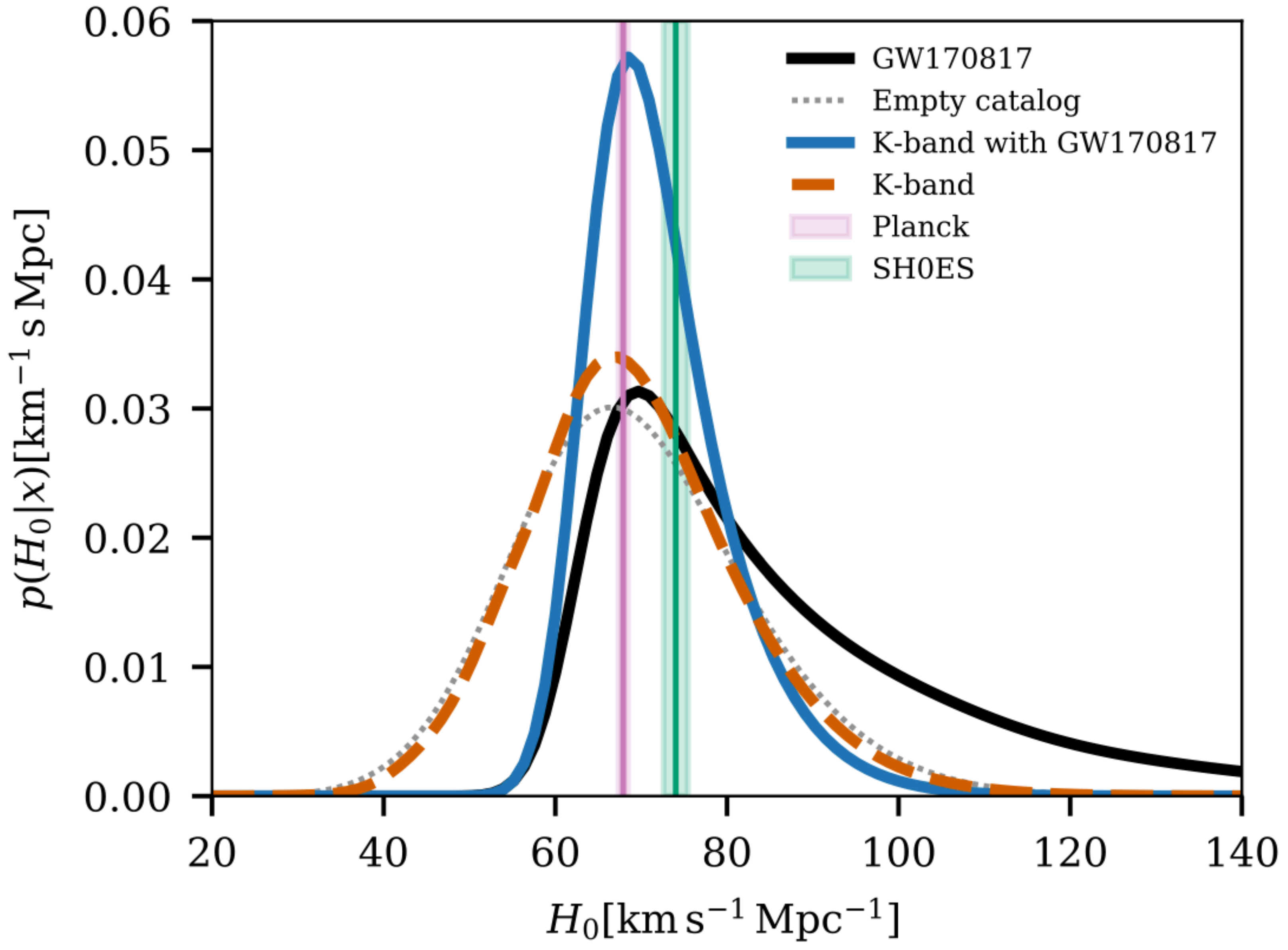
[“IcaroGW”]

- Far signals, not well-localised
  - Redshift information from source frame mass distribution



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The Ξ_0 paramatrization

Table 1 of 1906.01593

Model	$\Xi_0 - 1$	n	Refs.
HS $f(R)$ gravity	$\frac{1}{2} f_{R0}$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[68]
Designer $f(R)$ gravity	$-0.24\Omega_m^{0.76} B_0$	$3.1\Omega_m^{0.24}$	[69]
Jordan–Brans–Dicke	$\frac{1}{2}\delta\phi_0$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[70]
Galileon cosmology	$\frac{\beta\phi_0}{2M_{\rm Pl}}$	$\frac{\dot{\phi}_0}{H_0\phi}$	[71]
$\alpha_M = \alpha_{M0} a^{\tilde{n}}$	$\frac{\alpha_{M0}}{2\tilde{n}}$	$\tilde{n}$	[67]
$\alpha_M = \alpha_{M0} \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$	$-\frac{\alpha_{M0}}{6\Omega_\Lambda} \ln \Omega_m$	$-\frac{3\Omega_\Lambda}{\ln \Omega_m}$	[67, 72]
$\Omega = 1 + \Omega_+ a^{\tilde{n}}$	$\frac{1}{2}\Omega_+$	$\tilde{n}$	[6]
Minimal self-acceleration	$\lambda \left(\ln a_{acc} + \frac{C}{2}\chi_{acc} \right)$	$\frac{C/H_0 - 2}{\ln a_{acc}^2 - C\chi_{acc}}$	[66]

Table 1. Mapping of the parametrisation in Eq. (2.31) to a number of frequently studied, representative modified gravity models embedded in the Horndeski action (3.1) with luminal speed of gravitational waves. For simplicity, we have employed the approximations $\alpha_{M0} \ll 1$ (and $n \sim 1$).

DHOST Lagrangian

1810.12070

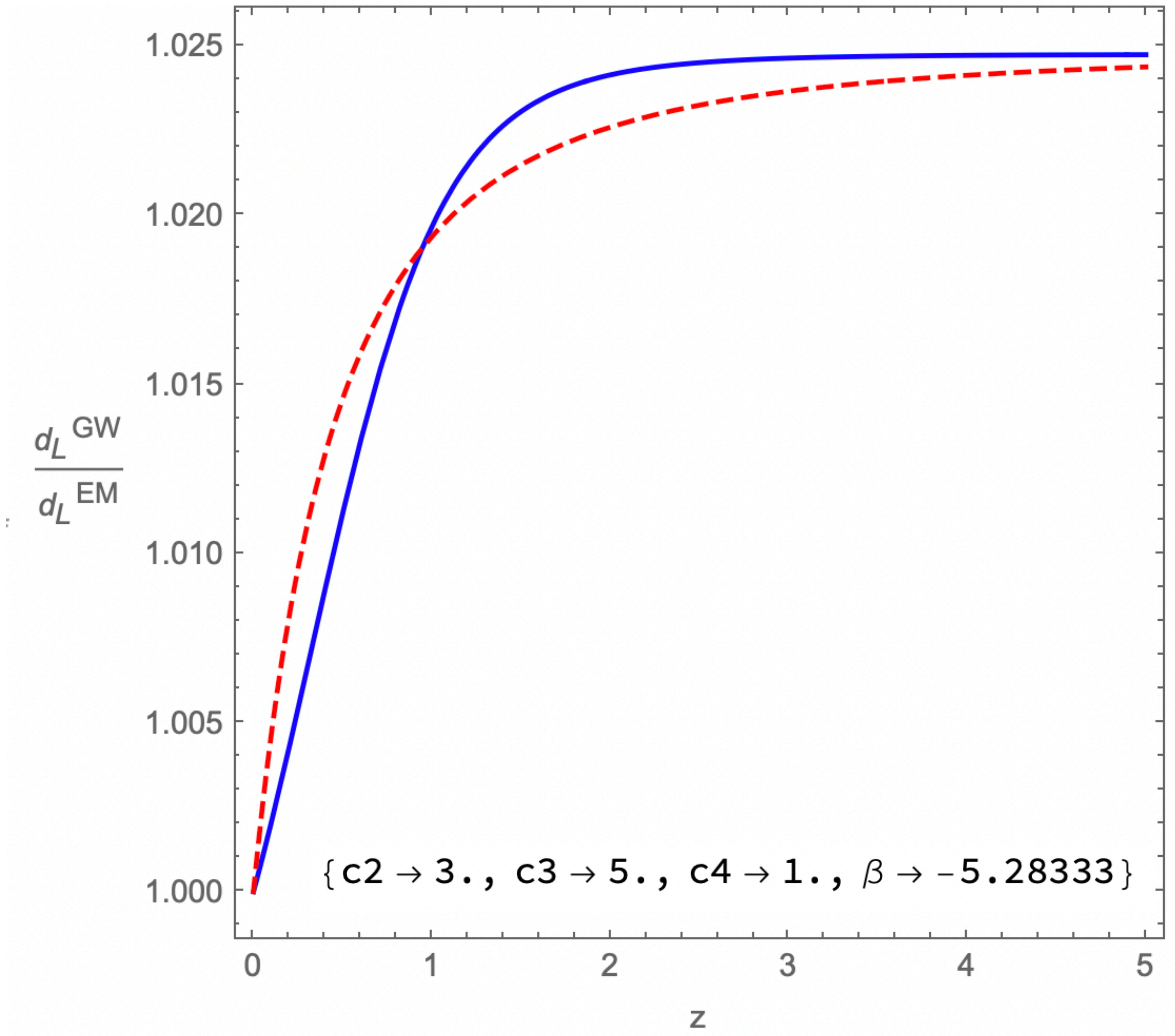
$$S[g_{\mu\nu},\phi] = \int d^4x\sqrt{-g}\left[F_0(\phi,X) + F_1(\phi,X)\Box\phi + F_2(\phi,X)R + \sum_{I=1}^{5} A_I(\phi,X)L_I^{(2)}\right]$$

$$L_1^{(2)} \equiv \phi^{\mu\nu}\phi_{\mu\nu}, \qquad L_2^{(2)} \equiv (\phi_\nu{}^\nu)^2, \qquad L_3^{(2)} \equiv \phi_\nu{}^\nu\phi^\rho\phi_{\rho\sigma}\phi^\sigma\,,$$
$$L_4^{(2)} \equiv \phi^\mu\phi_{\mu\nu}\phi^{\nu\rho}\phi_\rho, \qquad L_5^{(2)} \equiv (\phi^\rho\phi_{\rho\sigma}\phi^\sigma)^2\,,$$

where $\phi_{\mu\nu} = \nabla_\nu\nabla_\mu\phi$, and $\phi_\mu = \nabla_\mu\phi$.

An example:

$$F_0 = c_2X\,, \qquad F_1 = 0\,, \qquad F_2 = \frac{M_0^2}{2} + c_4X^2\,, \qquad A_3 = -8c_4 - \beta.$$



Future prospects

2202.08240

Spectral Sirens: Cosmology from the Full Mass Distribution of Compact Binaries

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(Dated: August 15, 2022)

We explore the use of the mass spectrum of neutron stars and black holes in gravitational-wave compact binary sources as a cosmological probe. These standard siren sources provide direct measurements of luminosity distance. In addition, features in the mass distribution, such as mass gaps or peaks, will redshift, and thus provide independent constraints on their redshift distribution. We argue that the entire mass spectrum should be utilized to provide cosmological constraints. For example, we find that the mass spectrum of LIGO–Virgo–KAGRA events introduces at least five independent mass "features": the upper and lower edges of the pair instability supernova (PISN) gap, the upper and lower edges of the neutron star–black hole gap, and the minimum neutron star mass. We find that although the PISN gap dominates the cosmological inference with current detectors (2G), as shown in previous work, it is the lower mass gap that will provide the most powerful constraints in the era of Cosmic Explorer and Einstein Telescope (3G). By using the full mass distribution, we demonstrate that degeneracies between mass evolution and cosmological evolution can be broken, unless an astrophysical conspiracy shifts all features of the full mass distribution simultaneously following the (non-trivial) Hubble diagram evolution. We find that this self-calibrating "spectral siren" method has the potential to provide precision constraints of both cosmology and the evolution of the mass distribution, with 2G achieving better than 10% precision on $H(z)$ at $z \lesssim 1$ within a year, and 3G reaching $\lesssim 1\%$ at $z \gtrsim 2$ within one month.

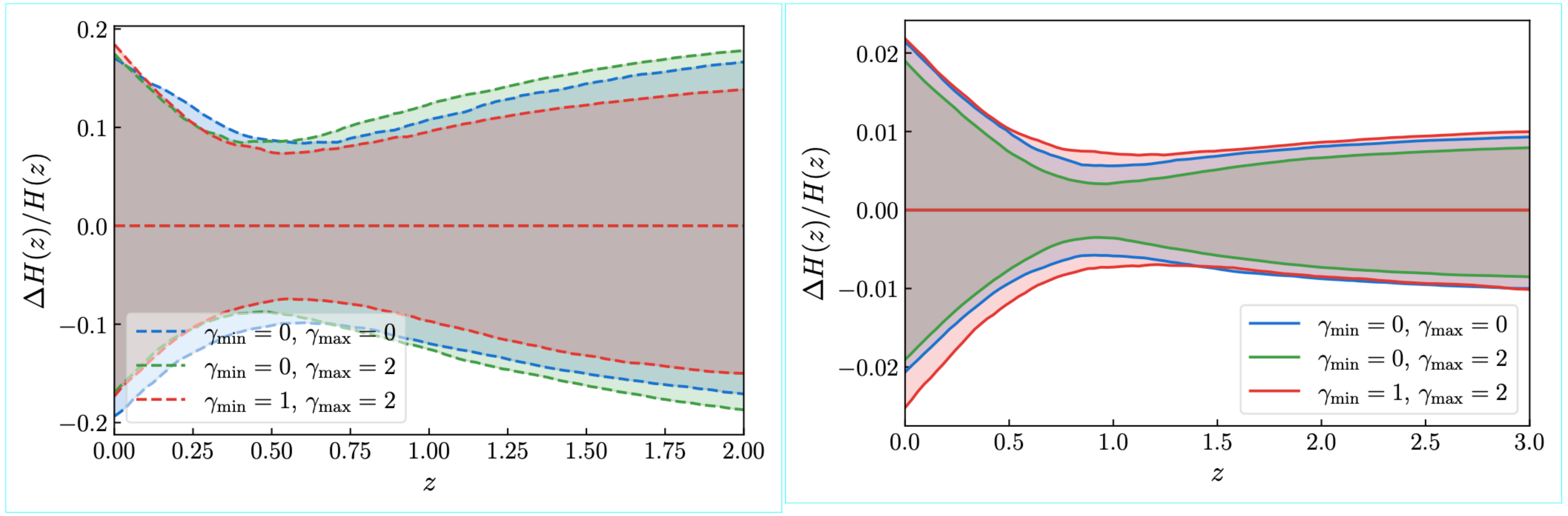

FIG. 10. 1σ relative errors in the Hubble parameter with 1,000 2G (left) and 10,000 3G (right) detections when the fitting model *does* account for a possible evolution of the mass distribution. 2G in 1 year could achieve $< 10\%$ at $z \sim 0.7$, while sub-percent precision is possible with 1 month of observations.

Future prospects: evolving mass distribution

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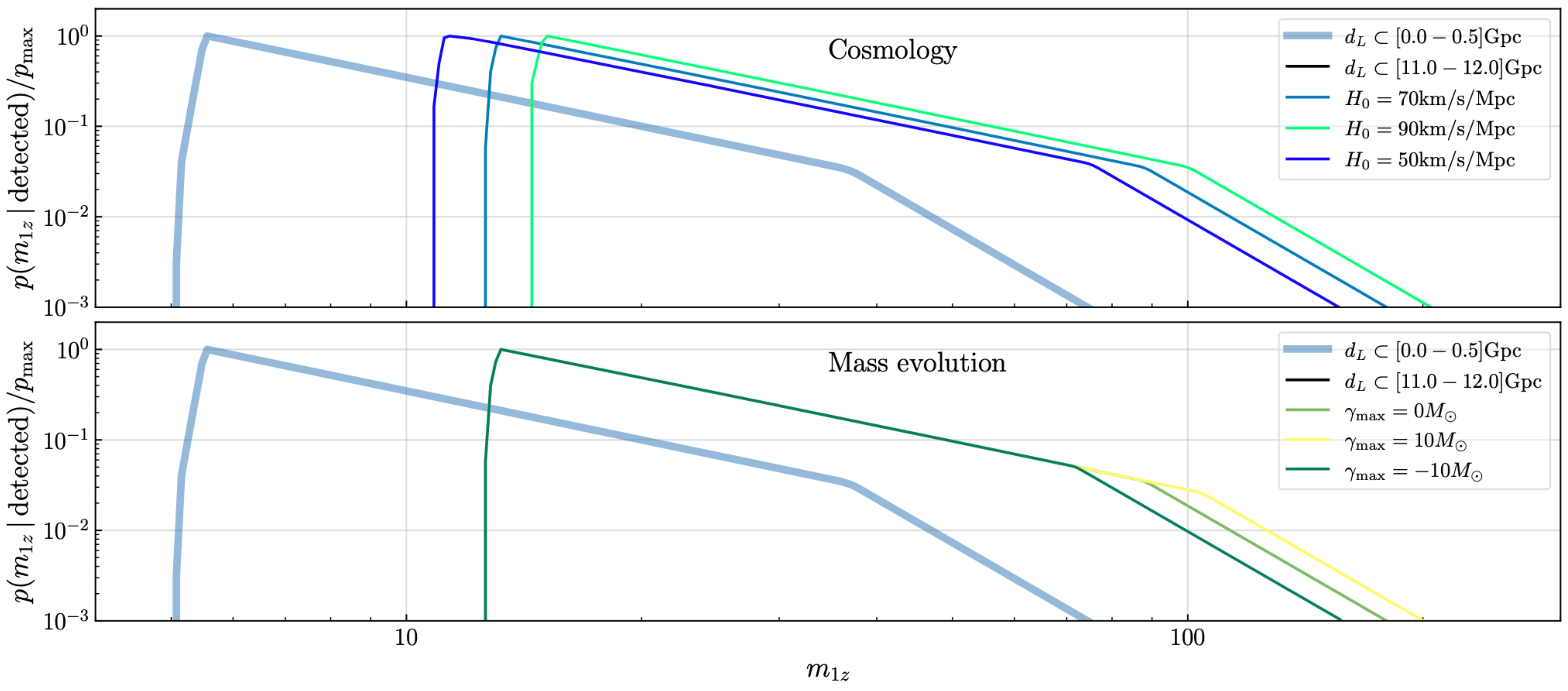
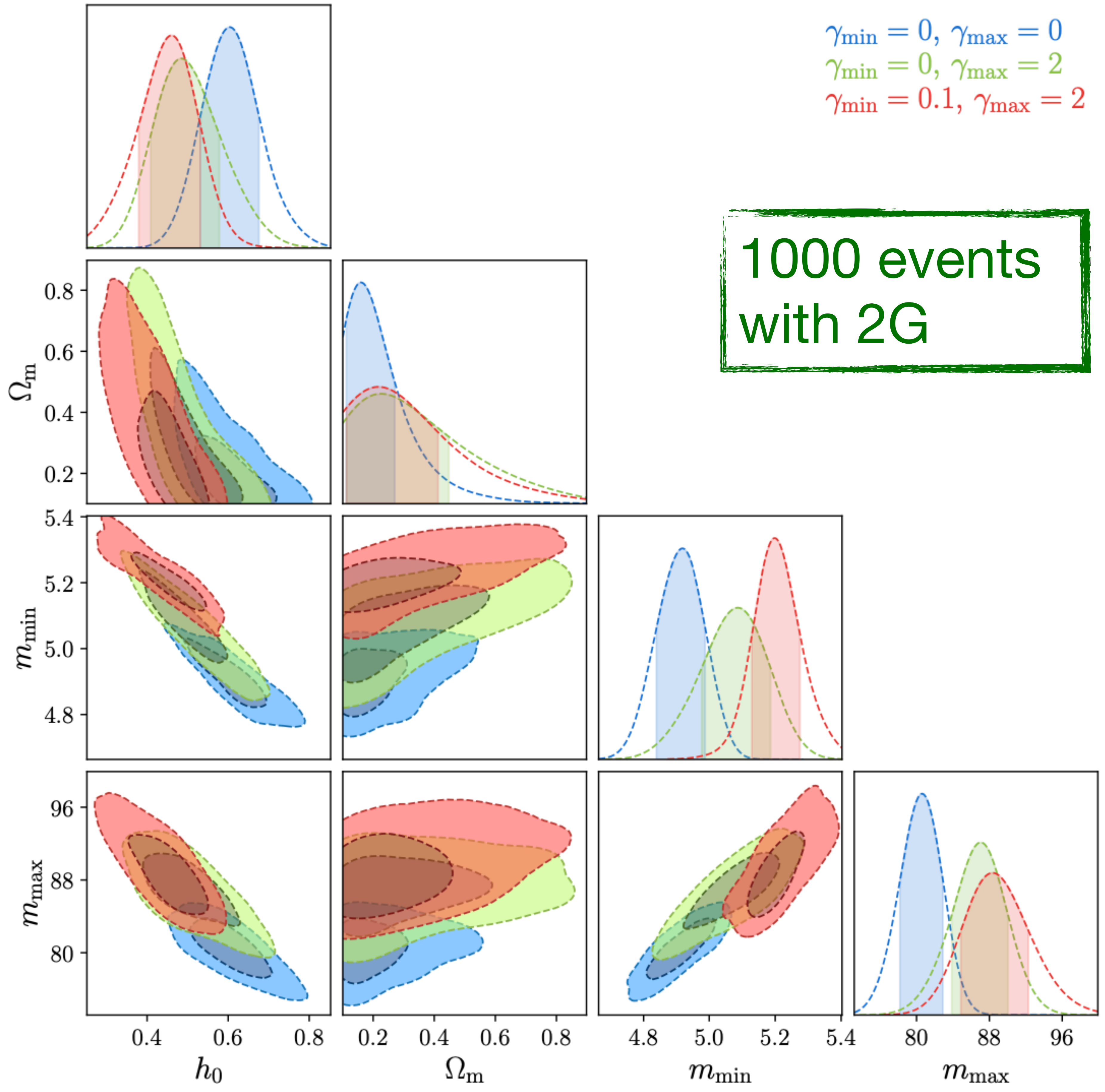


$$m_{\text{edge,ev}}(z) = m_{\text{edge}} + \gamma \cdot z$$



1000 events with 2G