Dark siren population analysis with modified gravity

Konstantin Leyde, Simone Mastrogiovanni, Danièle Steer, Eric Chassande-Mottin, Christos Karathanasis

Université Paris Cité

20.6.2022 "Cosmologie" et "Tests de la relativité générale et théories alternatives" du GdR Ondes Gravitationnelles

2202.00025

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, $\mathcal{H} = \dfrac{a'}{a}$ and δ the friction term

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

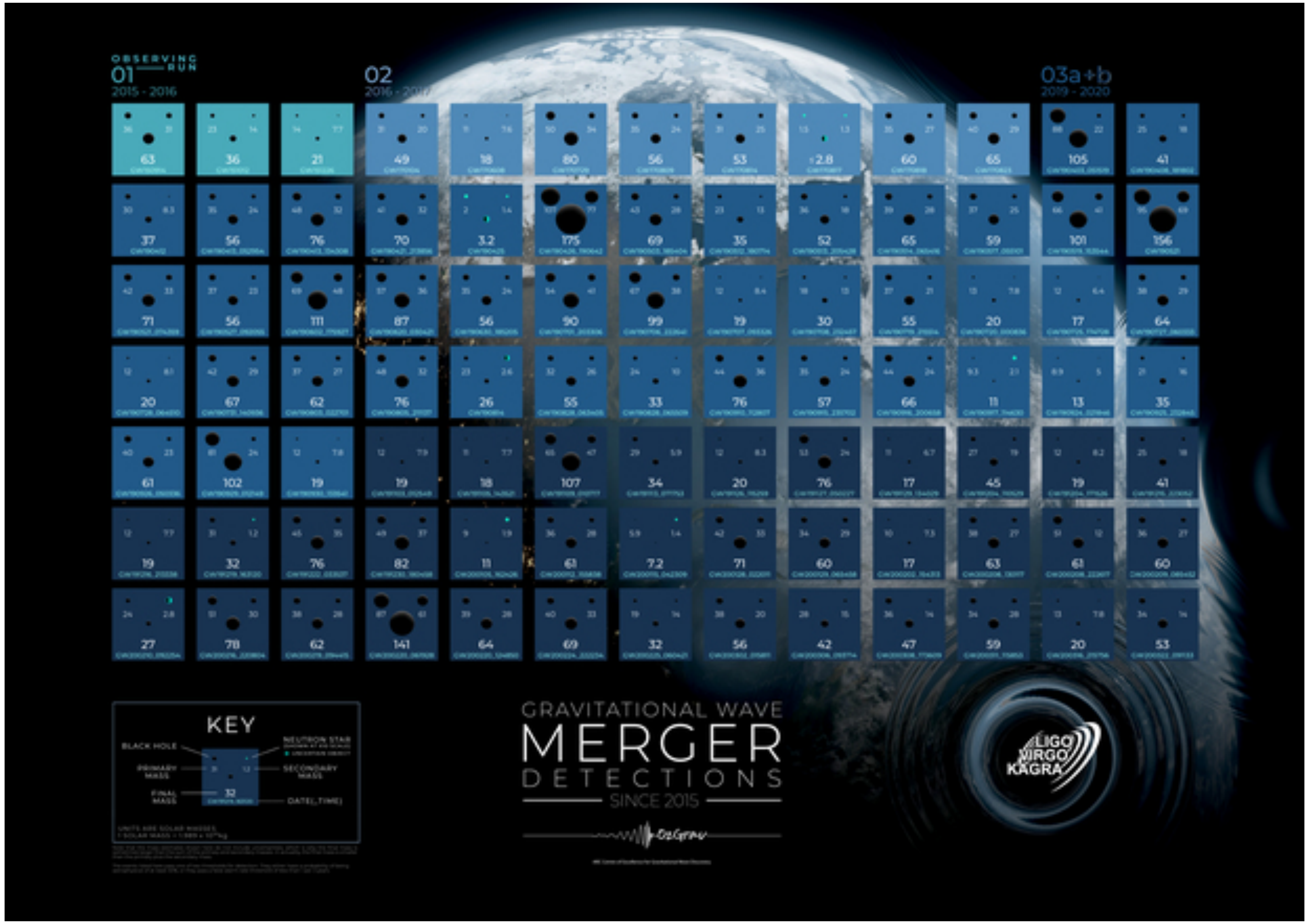
- Results in a modified gravitational wave distance (gravitational wave and electromagnetic distance do not coincide)

- **Testable** with gravitational wave observations

Observed events

2111.03606

- 90 compact binary coalescences
- Majority are BBH systems
- Deduce mass population
- Infer cosmological parameters



Carl Knox (OzGrav, Swinburne University of Technology)

Information carried by a gravitational wave

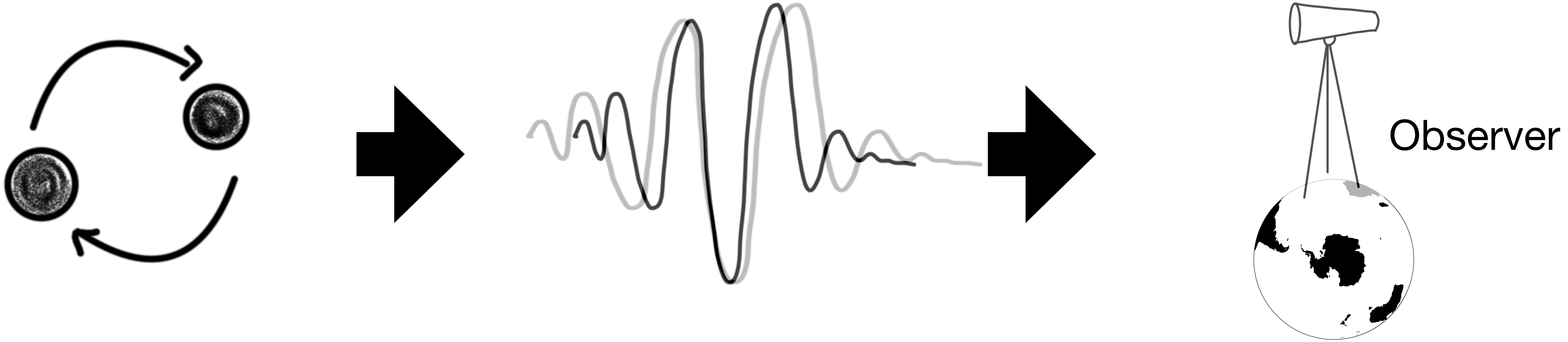
Source frame masses

$m_1^{(s)}, m_2^{(s)}$

Expansion

Detector frame masses

$m_1^{(d)}, m_2^{(d)}$



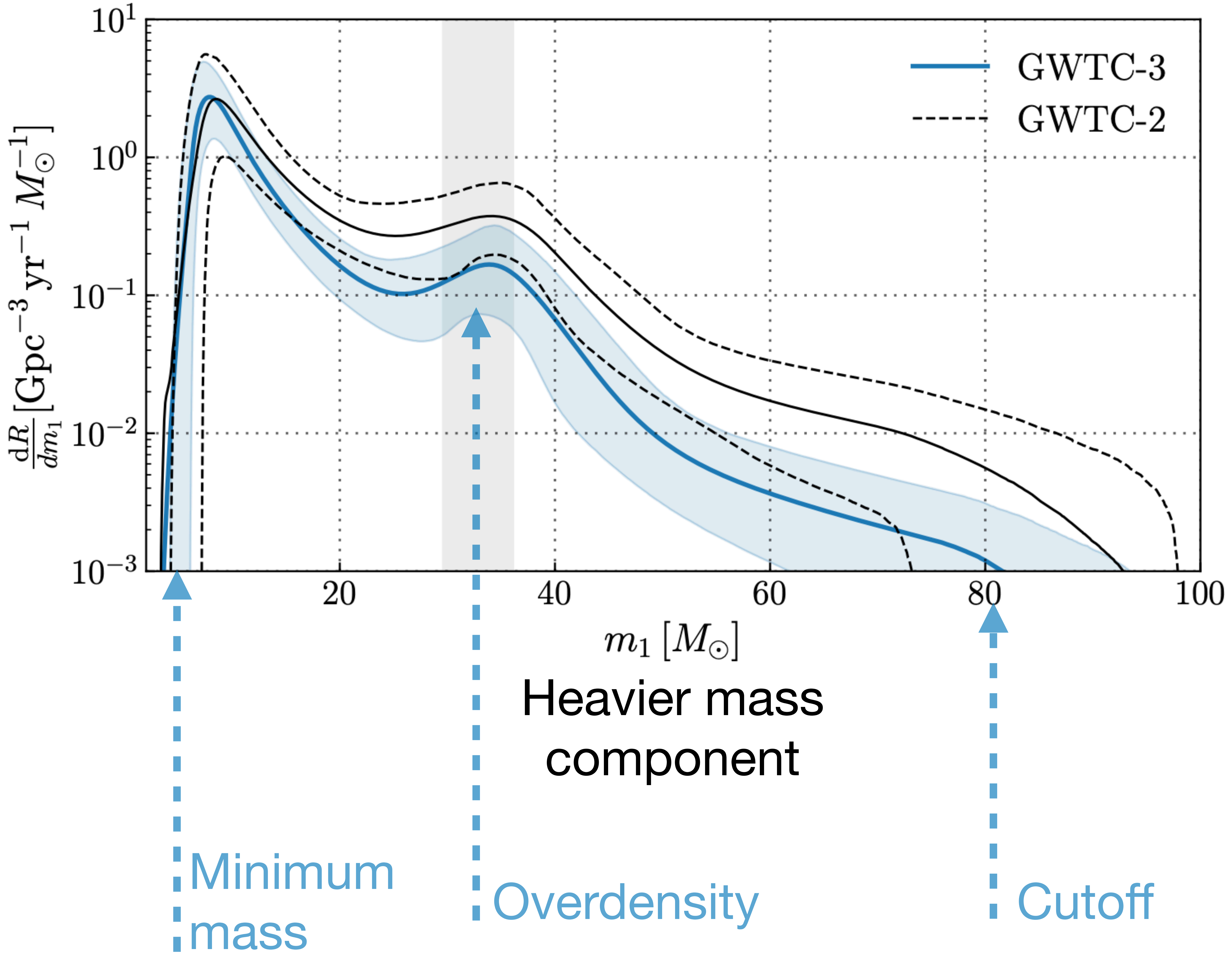
$$m^{(d)} = (1 + z)m^{(s)}$$

- GW frequency is shifted to lower values by the expansion
- Individual GW signal carries no redshift information

Population properties

2111.03634

- Collective event analysis
- Fix cosmological parameters
- Infer the distribution of BBH in
  - Source frame mass
  - Redshift



Cosmology with gravitational waves

2111.03604

- Need redshift information

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

- **Several approaches** to GW cosmology with EM information (*Schutz 1986*):
    - Electromagnetic counterpart (GW170817)
    - Statistical association of redshift from galaxy catalogs
- Current BBH horizon (1200 Mpc): Beyond the completeness of galaxy catalogs
- For many events, no EM information → Dark sirens

Source frame population and redshift measurement

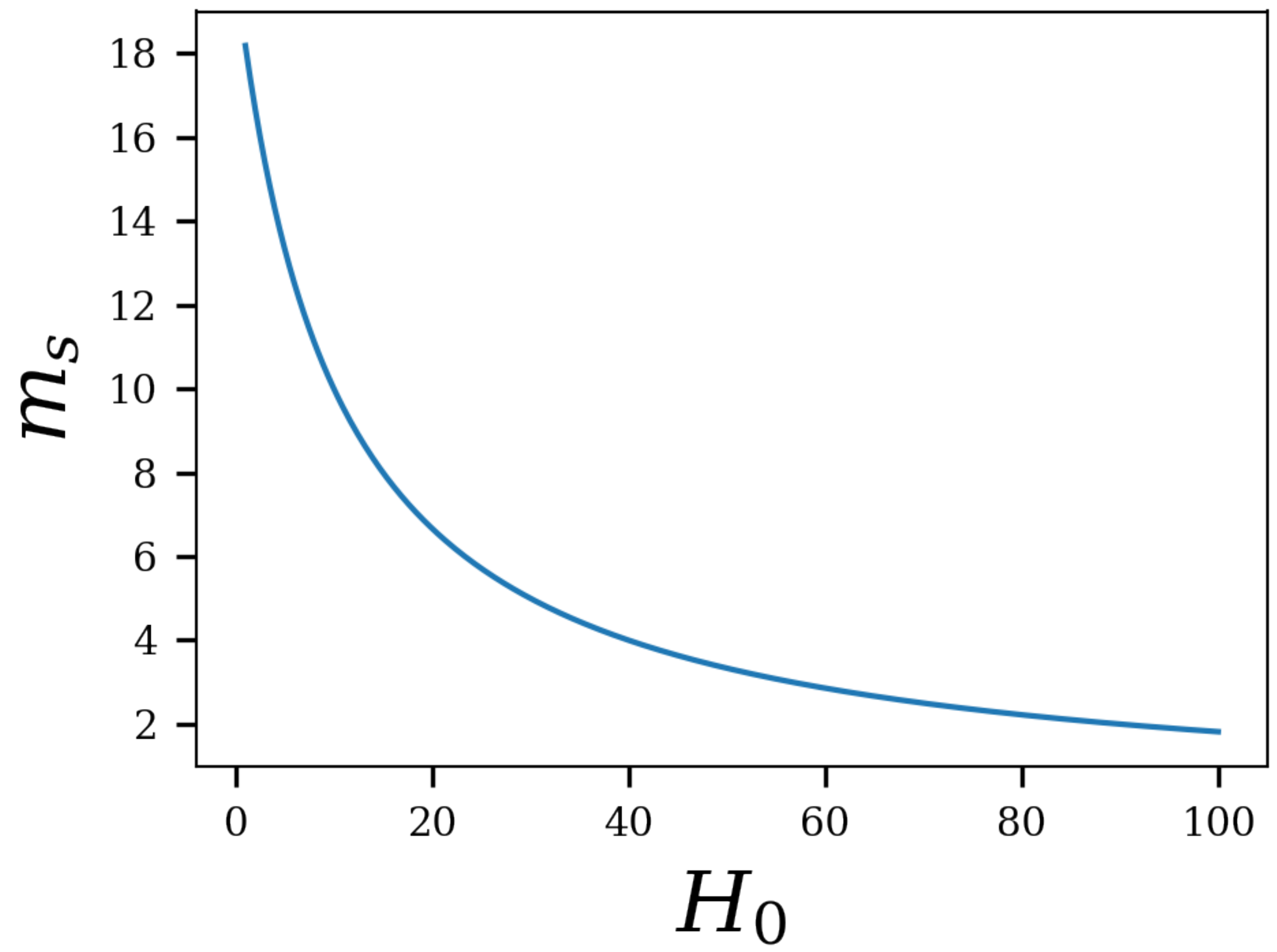
- Redshift information from a set of GW detections: assumption of mass model

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

- **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

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



Framework

Assumption on the modifications of GR

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

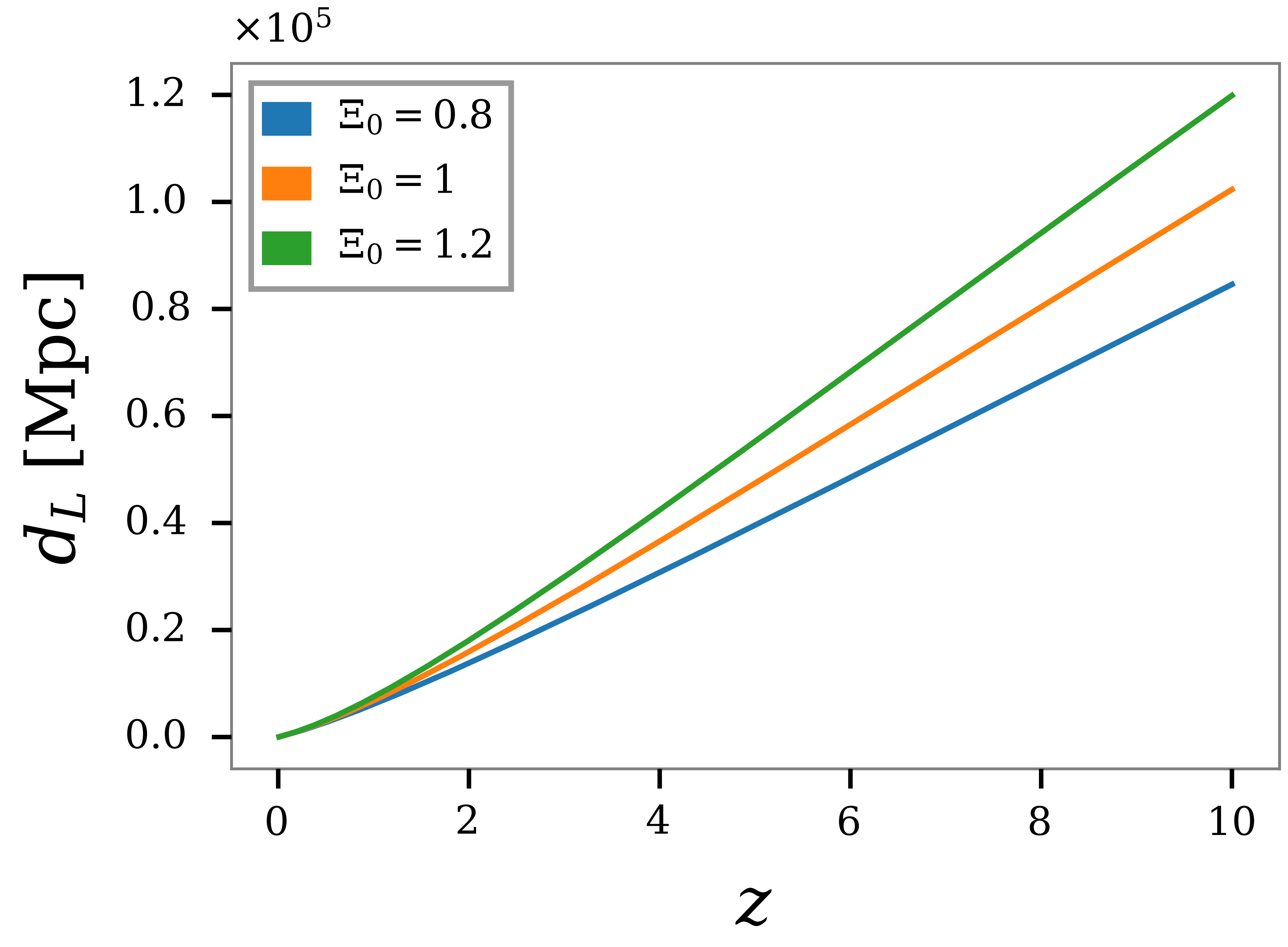
- Phenomenological model *1906.01593*

Ξ_0 characterises early time behaviour

GR: $\Xi_0 = 1$

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

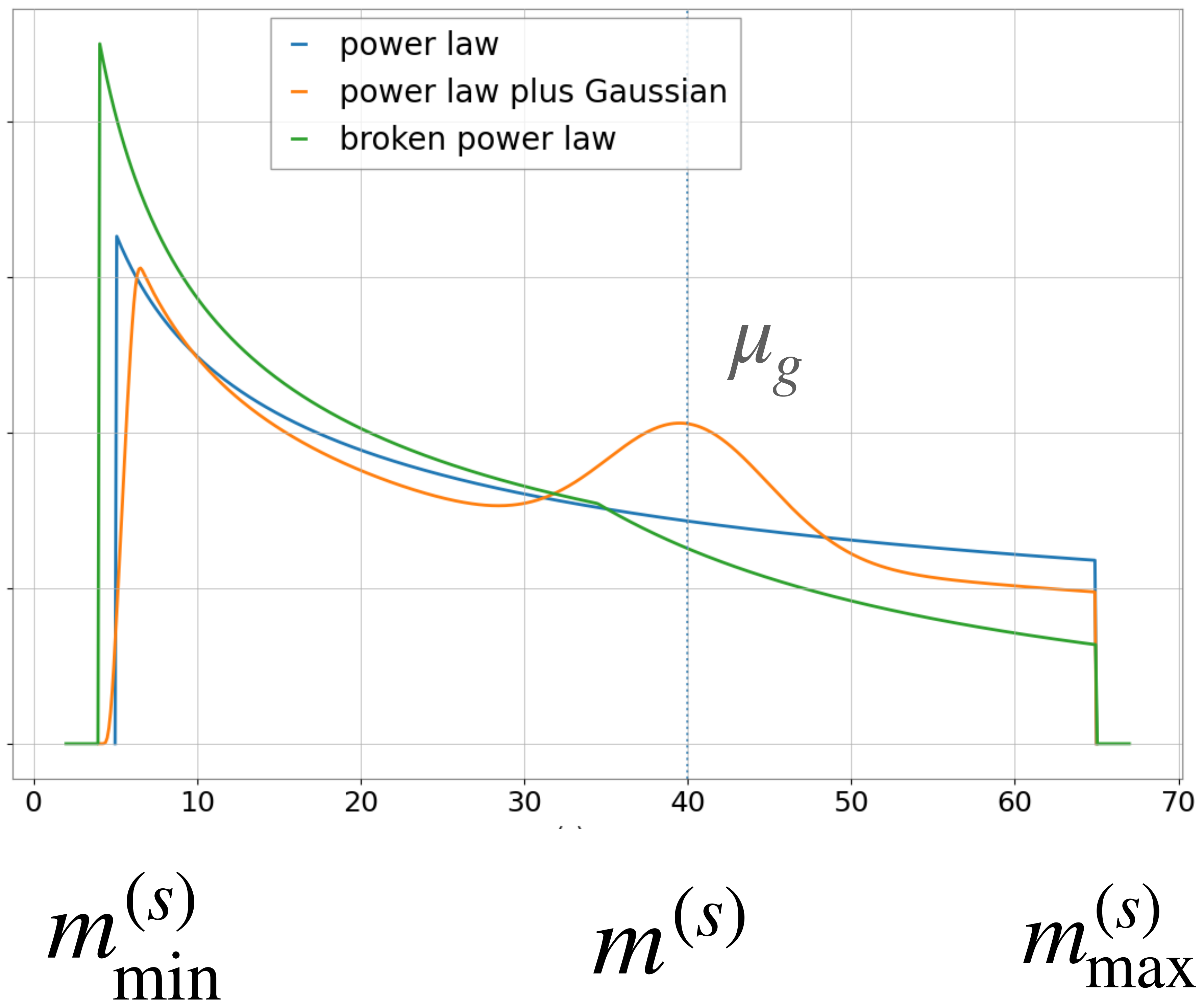
n characterises the transition from early to late times



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

The source mass population model

- **Various astrophysical mechanisms** shape the BH source mass distribution
  - **Pair instability supernova** (PISN, *J. R. Bond, W. D. Arnett, and B. J. Carr* 1984) → $m^{(s)}_{\rm max}$
  - **Pulsational PISN** (*Barkat et al. 1967; Woosley & Weaver 1986; Woosley 2017*) → Accumulation in a Gaussian peak μ_g
  - **X-ray observations** → No BHs < $m^{(s)}_{\rm min}$
- **Models** from *LVK Population properties: 2010.14533*
  - Power law: mass range and two power law slopes (PL)
  - Power law + Gaussian peak (PLG)
  - Broken power law
  - Power law + 2 Gaussians (Multi Peak)



Statistical framework

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

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

- Metaparameters Λ : population parameters, cosmological and modified gravity parameters, …
- GW data $\{x\}$
- Source parameters $\theta = \{m_{1,2}^{(d)}, d_L^{\rm GW}, \ldots\}$
- 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

Bayesian analysis with selection effects

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

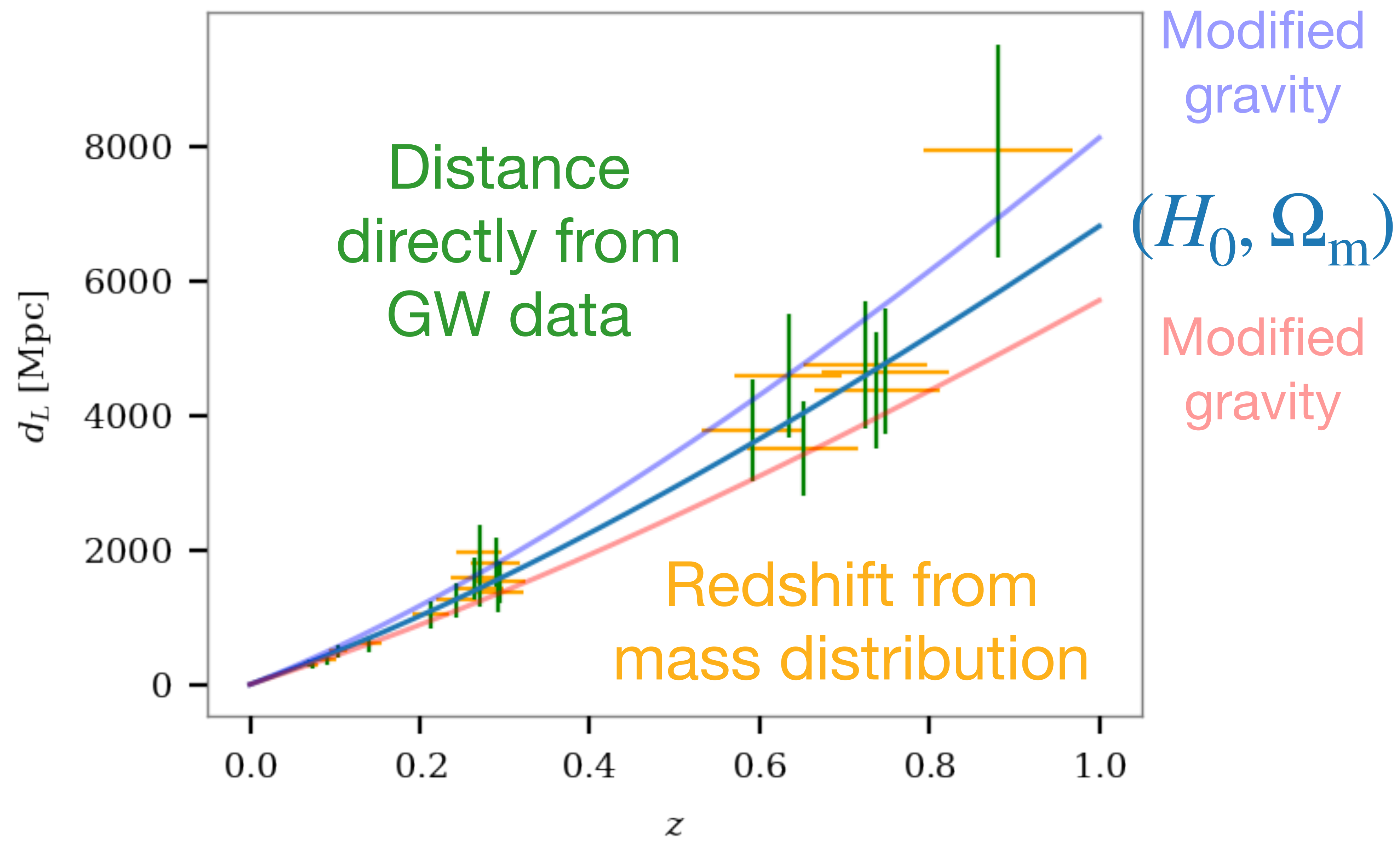
- Only events passing threshold (on signal to noise ratio or false alarm rate) are considered
- Numerical evaluation of $p_{\rm det}(\theta)$: produce a set of events and label them either "detected" or "undetected" (here: passing SNR threshold)

Aim of the analysis

- **Joint parameter estimation**
  - GW luminosity distance parametrization
  - Source mass parameters $(m^{(s)}_{\rm min}, m^{(s)}_{\rm max}, \ldots)$
  - Cosmological parameters $(H_0, \Omega_{\rm m})$
  - Rate evolution of sources

- Run this analysis for O3 data
- Identify factors that impact the uncertainties of the final Ξ_0 posterior for future observation runs (O4 and O4+O5). Precision?

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



- Based on Icarogw *2103.14663* (used for O3 in the last LVK cosmo paper)
- See also: *2104.05139, 2112.07650*

Results (with GWTC-3)

Results with O3 data

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

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

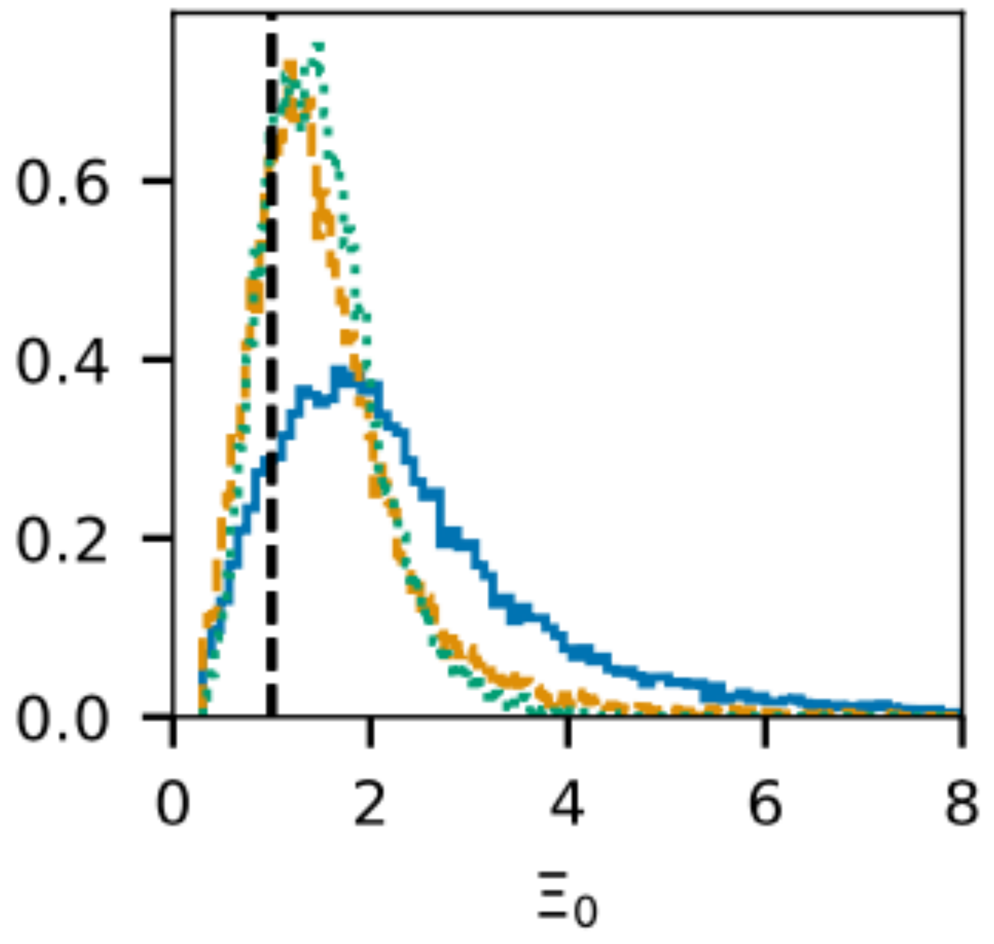
60 BBH events, SNR > 10, IFAR > 4 yr				
	Broken Power Law	**Multi Peak**	Power Law + Peak	Truncated
GR	−2.4	0.0	−1.2	−6.3
D	−2.0	−0.2	−1.7	−6.4
Ξ_0	−3.2	−0.9	−2.1	−6.8
c_M	−3.0	−1.0	−2.1	−6.5

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

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**)



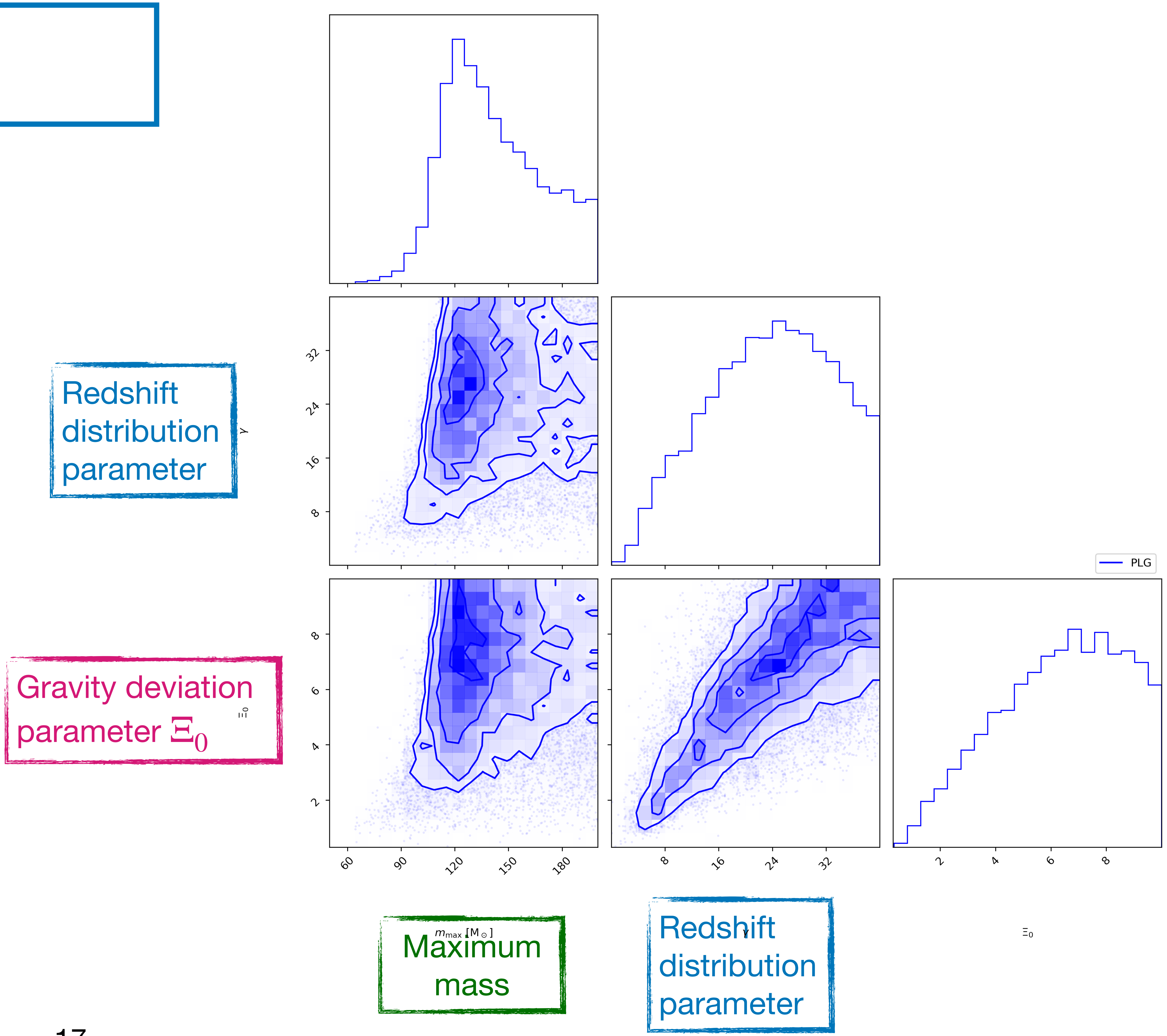
Multi peak mass model, varying SNR cut

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



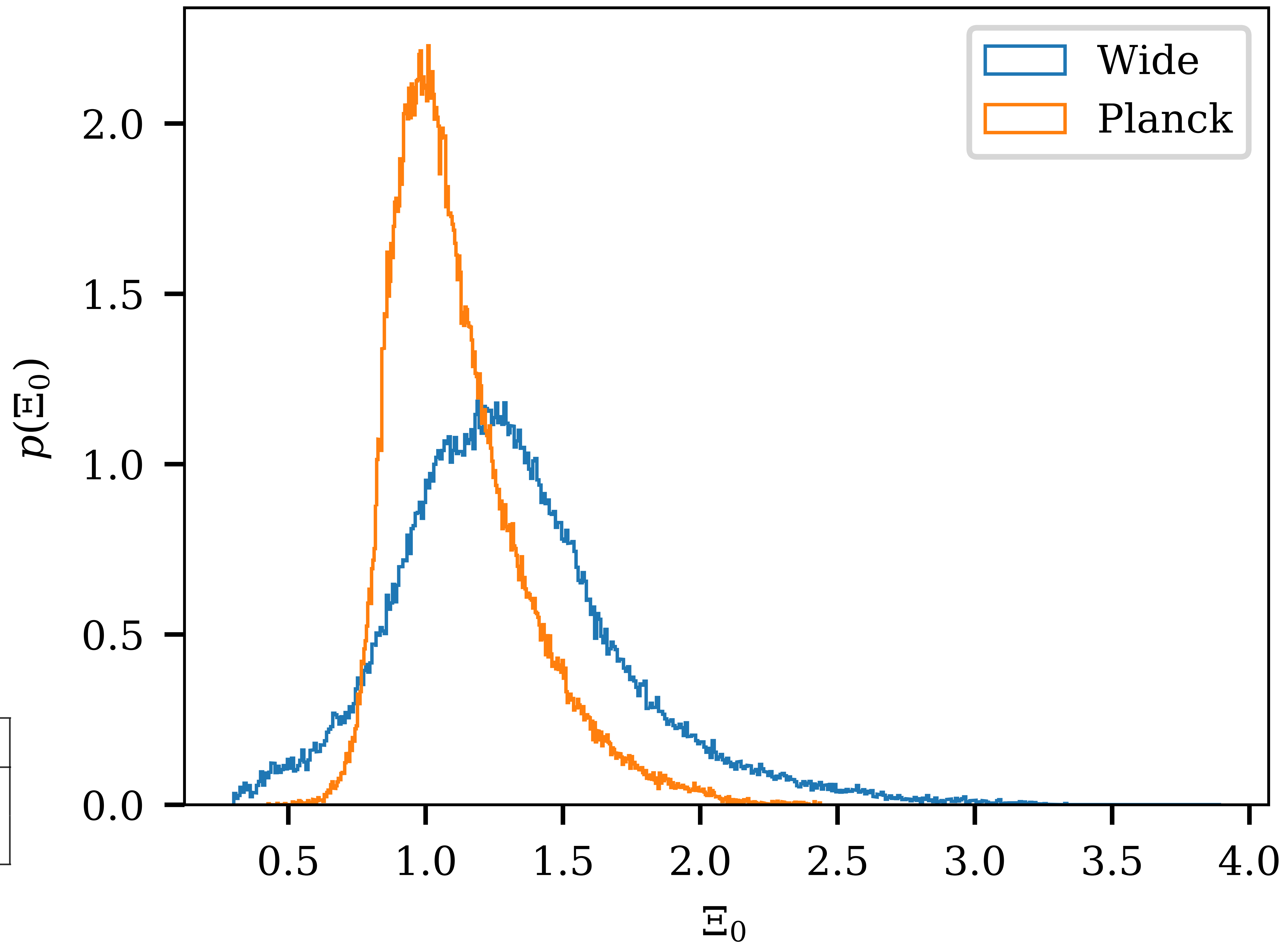
Forecast (with O4 + O5)

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	$\mathcal{U}(0.05, 0.4)$	$\mathcal{U}(0.3082, 0.3250)$



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