Cosmology with Dark-Sirens : The pure population method and O3 results

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Overview of today's talk

- Cosmology with gravitational waves (Dark-Sirens) ?
- IcaroGW : a python based pipeline for GWs cosmology
- O3 cosmology results and interpretation

Dark-Sirens method

How to access H0 with GWs ?

- The redshift z and the luminosity distance d_L of a GW source are related through cosmology

$$d_L \simeq \frac{c}{H_0} z$$

(low redshift approximation)

d_L : Directly measurable the GW signal

z : Need to be found through other methods

- Access H0 by breaking this degeneracy

Dark-Sirens method

ICAROGW : **I**nferring **C**osmology and **A**st**R**ophysics with **O**bservations of **G**ravitational **W**aves *(Mastrogiovanni et al. 2103.14663)*

- One of the two official pipelines in LVK for cosmology analysis.
  (main dev : S. Mastrogiovanni, G. Pierra et al.)
- Jointly infer the population parameters (masses, redshift, rate, spins) and the cosmological parameters (H0, Ω_m, w0)
- Hierarchical Bayesian inference method with Dark-Sirens events (no e.m. counterpart)
- Based on the mass-redshift degeneracy : $m_i^{\rm det} = (1+z) m_i^{\rm source}$

Hierarchical inference

- Bayesian analysis in presence of selection effect (*Mandel et al. 1809.02063, Thrane and Talbot 1809.02293, Vitale et al. 2007.05579*)

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

- Hyper-parameters $\boldsymbol{\Lambda}$: population and cosmological parameters
- GW data $\{x\}$
- Source parameters $\boldsymbol{\theta}$: masses and luminosity distance
- GW likelihood : from GW posterior samples
- Population assumptions : (source mass model etc ...)
- Detection probability

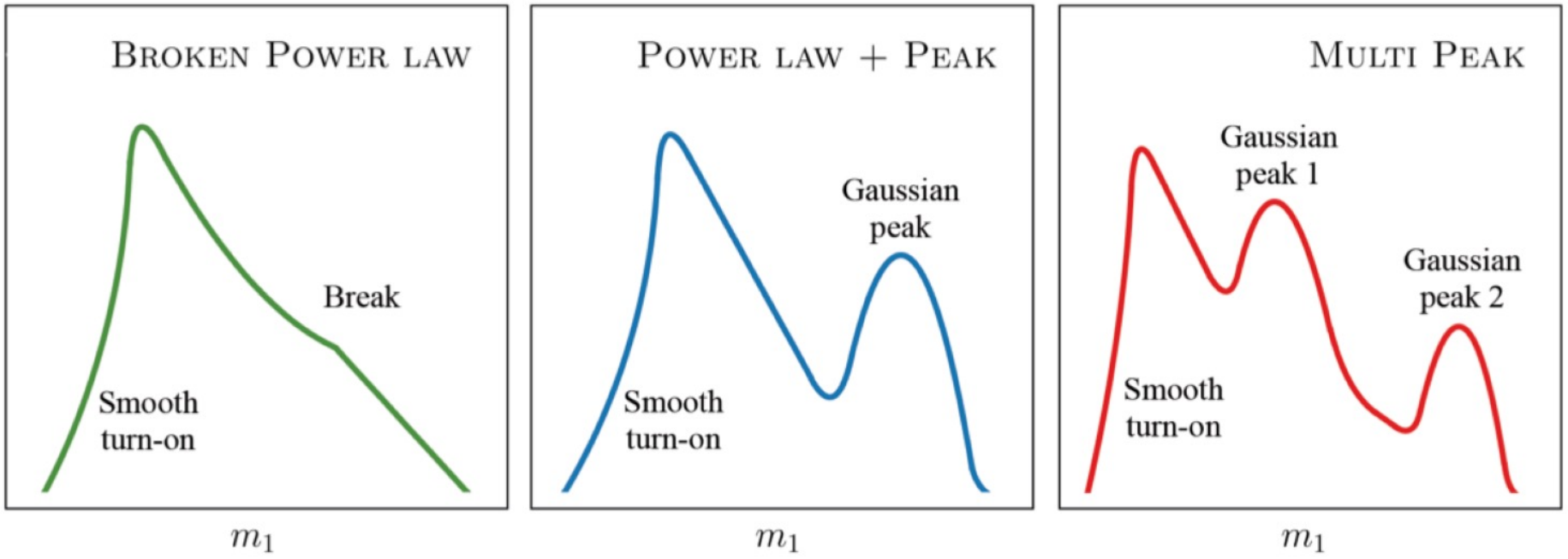
Dark-Sirens method

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

ICAROGW : **I**nferring **C**osmology and **A**st**R**ophysics with **O**bservations of **G**ravitational **W**aves

LVK+ 2010.14533

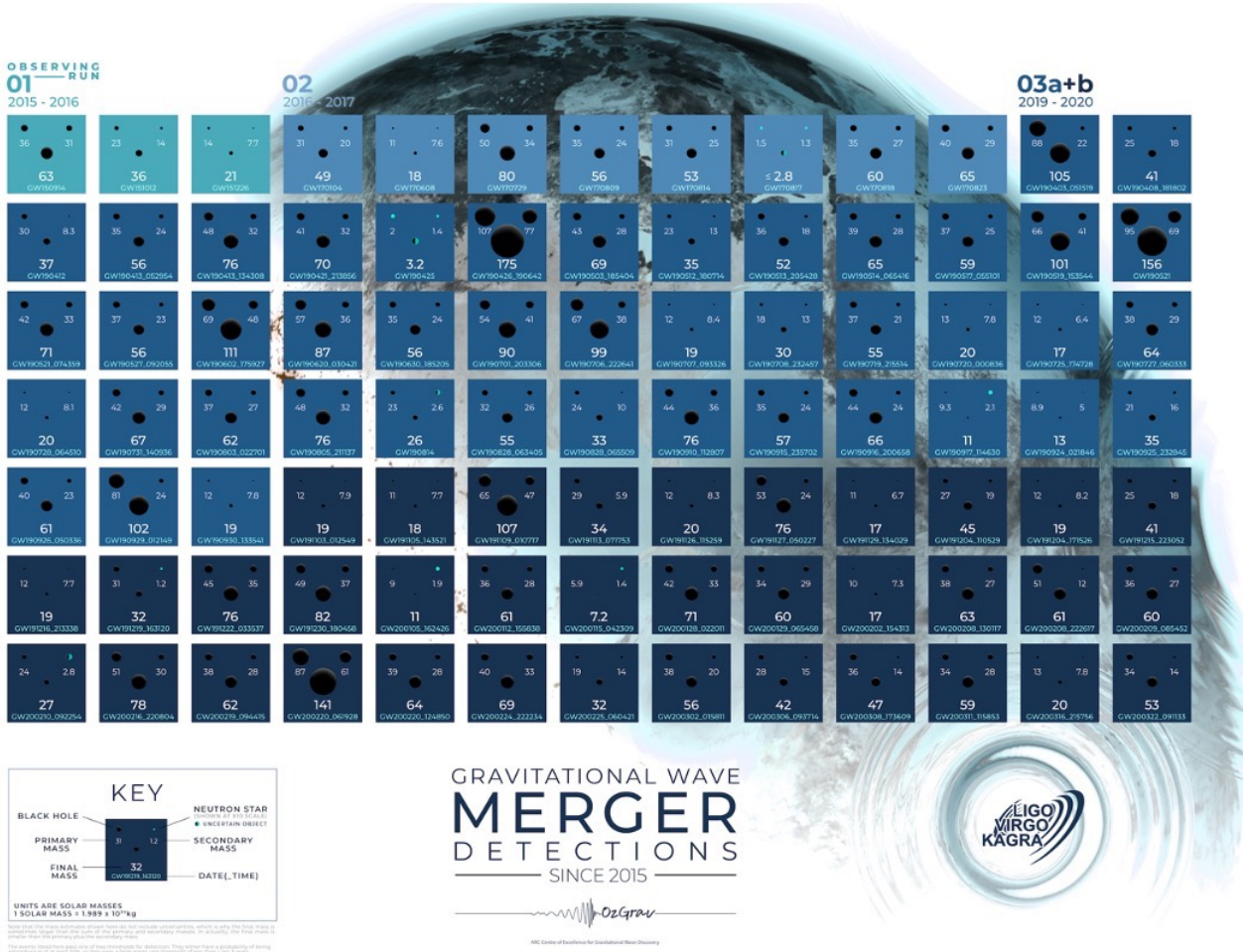
LVK Source frame mass models



LVK detection : state of the art

Since 2015, the LVK collaboration had 3 observing runs :

- 90 compact binary coalescences
- 89 of them are Dark-Sirens (no e.m. counterpart)

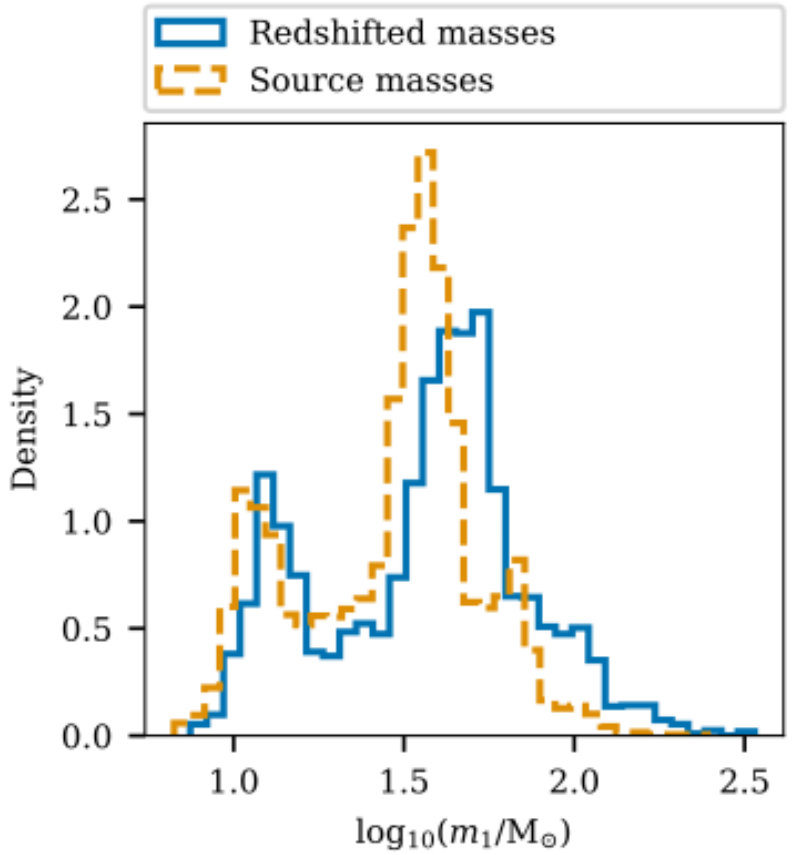


O3 Pure population analysis

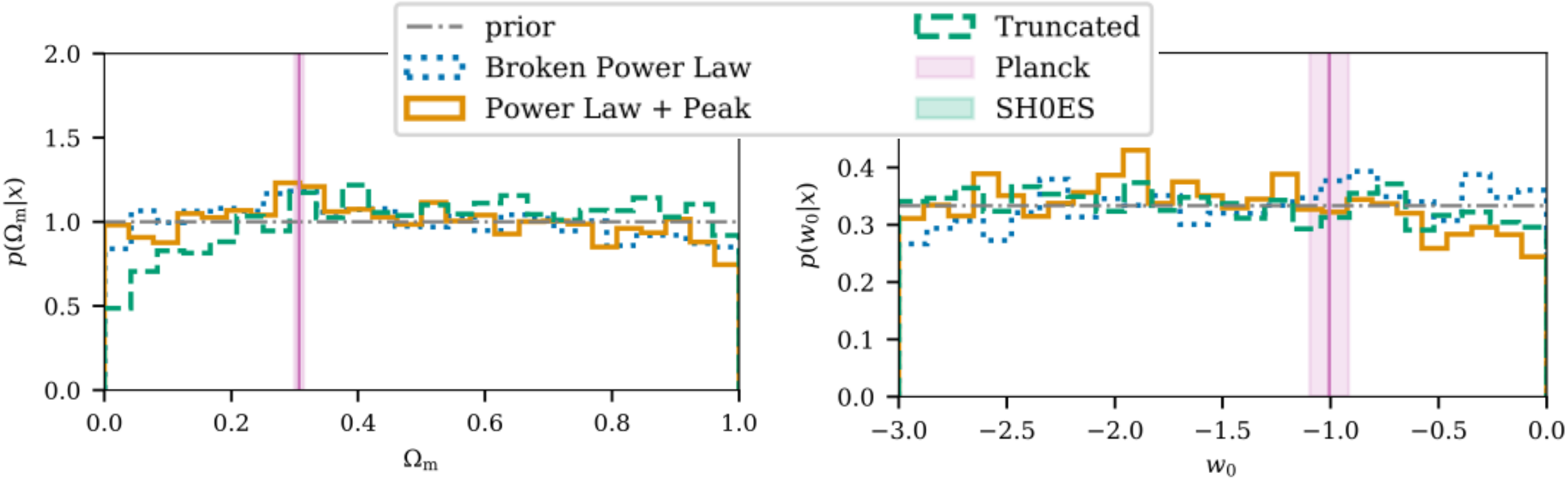
- LVK cosmology paper O3 : Constraints on the cosmic expansion history from GWTC-3

- Analysis set-up :
  - 42 binary black hole detections
  - Cut-off to ensure astrophysical signals :
    SNR > 11 & IFAR > 4yr
  - Madau & Dickinson rate model
  - 2 cosmological models
  - 3 mass models (sources frame)

- GW190814 excluded (NSBH)

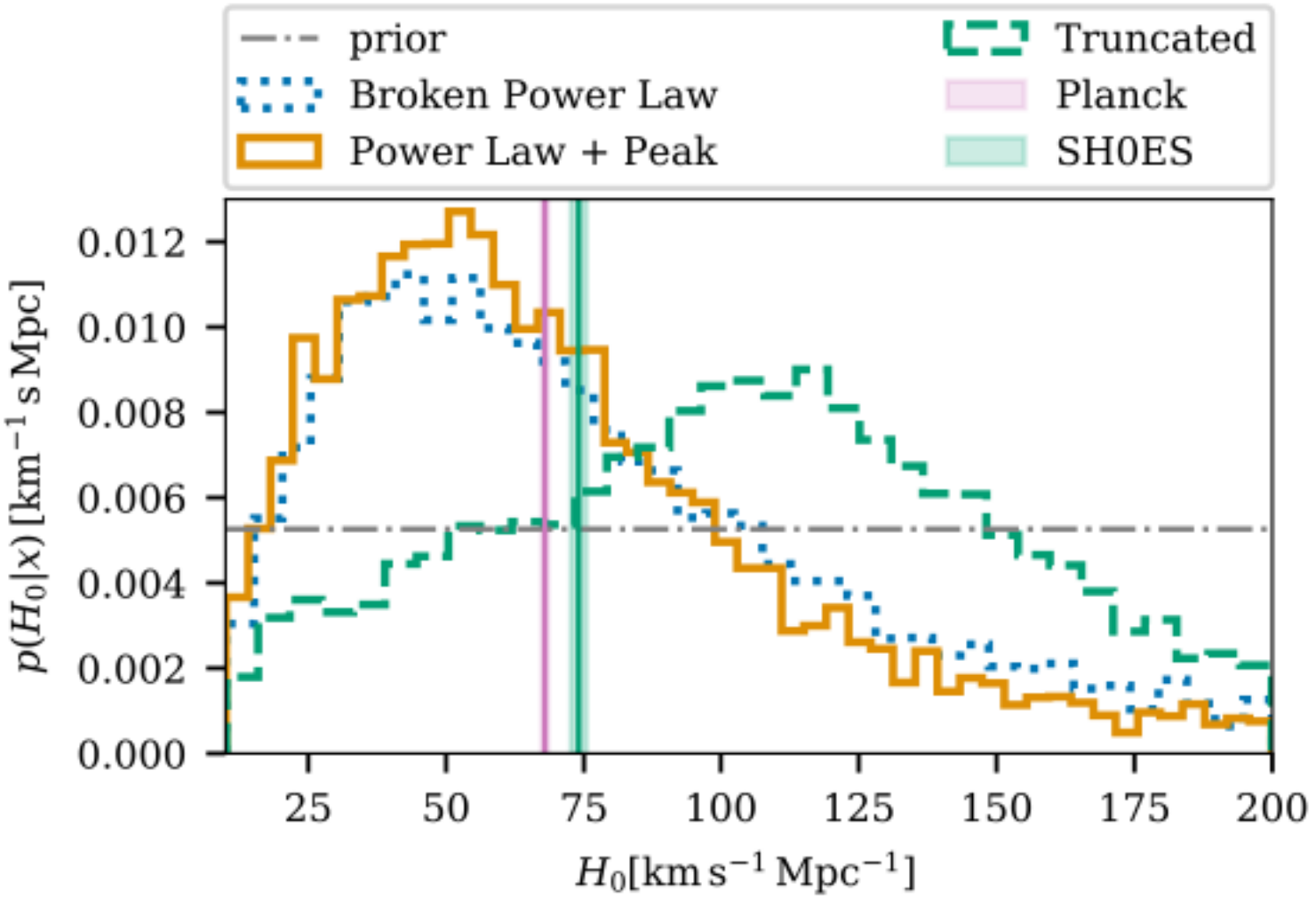


IcaroGW results : Ωm, w0



- No constraint with the current GW detections on w_0, Ω_m
- Uninformative about the two cosmological model studied

IcaroGW results : H0



Best constraint with IcaroGW

- Power-Law + Peak

$$H_0 = 50^{+37}_{-30} \ \mathrm{km.s^{-1}.Mpc^{-1}}$$

- Broken Power-Law

$$H_0 = 44^{+52}_{-24} \ \mathrm{km.s^{-1}.Mpc^{-1}}$$

Interpretation of IcaroGW results

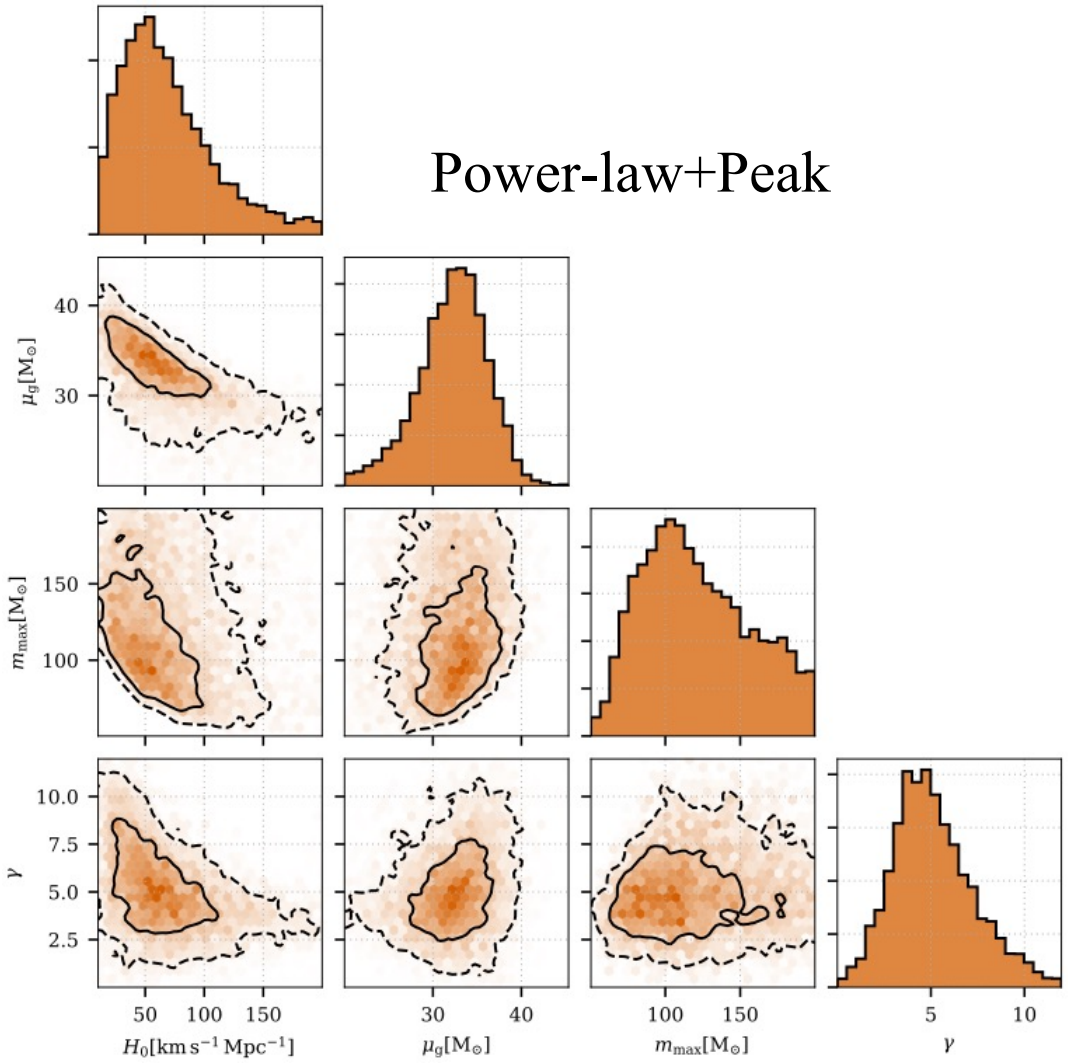
- No evidence in the data to support one cosmological model
  - Uninformative on Ωm and w0
  - Error on H0 too large

Mass model	$\log_{10} \mathcal{B}$
TRUNCATED	−1.9
POWER LAW + PEAK	0.0
BROKEN POWER LAW	−0.5

- Truncated model strongly disfavoured
  - By a factor ~100
  - Too much structure in the mass spectrum
  - Impossibility to capture the fraction of high mass events ~35 Msol

- For the PLP and the BPL models :
  - Ability to fit the excess of BBHs at higher masses
  - Set a scale for the redshift distribution of BBHs

Population/cosmology correlations



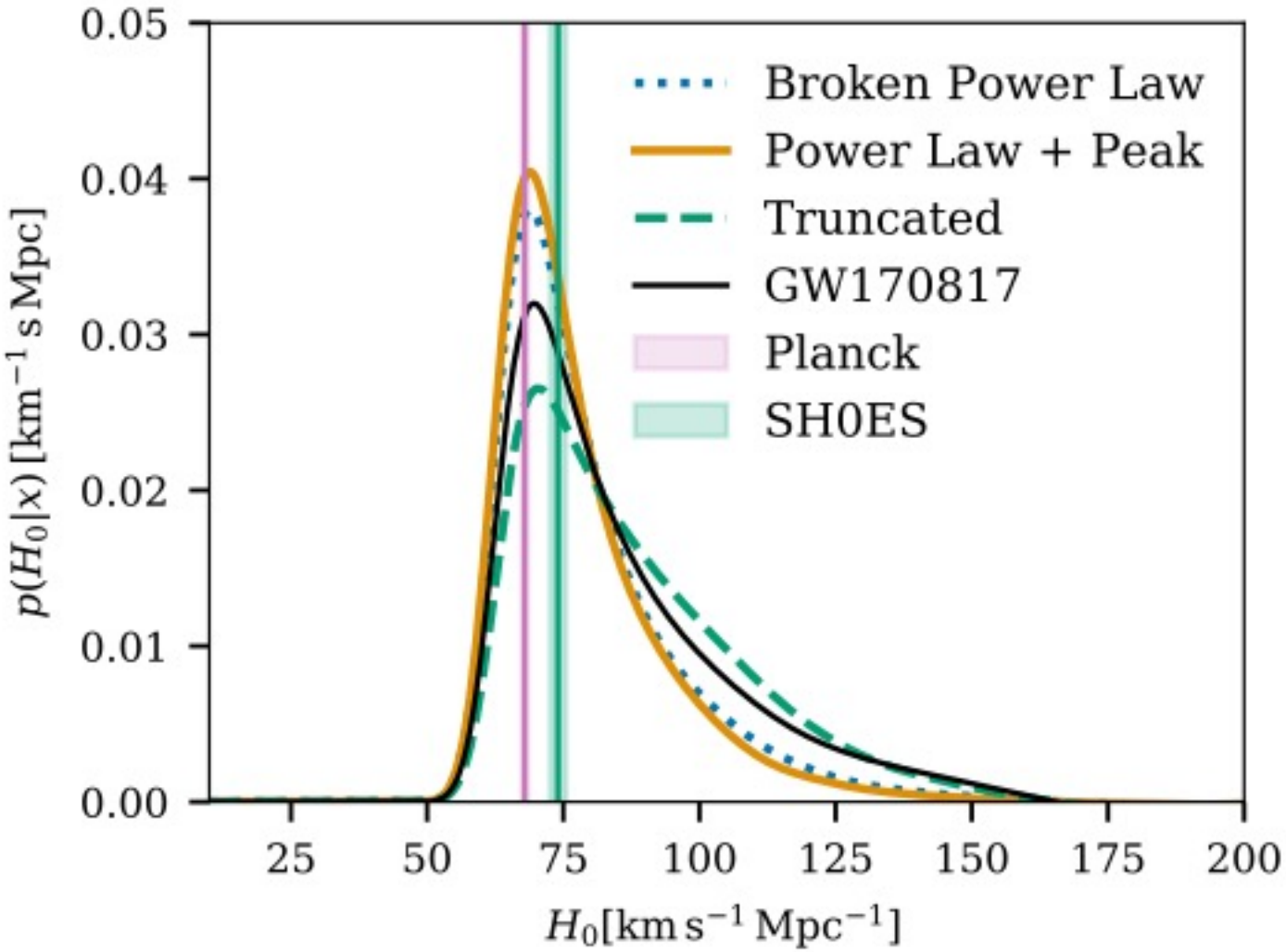
- Significant correlation between the position of the peak in the source mass distribution and H0
- Constraints on H0 arise from the ability of our model to catch those sharp features in the mass spectrum
- With the PL+Peak : Exclusion of high H0 values
- With the Truncated : Support for higher values of H0, due to the impossibility to account for the structures around ~35Msol
- Results consistent with independent studies *(Mancarella et al 2022)*

IcaroGW result with GW170817

GWTC-3 combined with GW170817

$$H_0 = 68^{+12}_{-8} \ \mathrm{km.s^{-1}.Mpc^{-1}}$$

- 17% improvement compared to GW170817 alone
- 12% improvement compared to GWTC-2 + GW170817



Conclusion

- Using 42 BBH events : We inferred constraints on the cosmological parameters using IcaroGW
- First time analysis to jointly estimate population properties and cosmology (showing crucial correlations)
- The choice of the source mass model can impact the inferred value of the cosmological parameters
- Improved constraints on the Hubble constant :
  - Pure population : $H_0 = 50^{+37}_{-30}\ \mathrm{km.s^{-1}.Mpc^{-1}}$
  - Pure population + GW170817 : $H_0 = 68^{+12}_{-8}\ \mathrm{km.s^{-1}.Mpc^{-1}}$

Prospective O4

- O4 observation run starting next month (24th of may) !
- Probably ~ few hundreds BBHs detections (very nice for cosmology studies)
- New version of IcaroGW2.0 + official review almost done
    - Spins
    - Galaxy catalog
    - NSBH, e.m.c method
- Local project : On the H0 bias using Dark-Sirens methods (G. Pierra, S. Perries, S. Mastrogiovanni, M. Mapelli)

Thank you