# COSMOLOGY WITH GRAVITATIONAL WAVES

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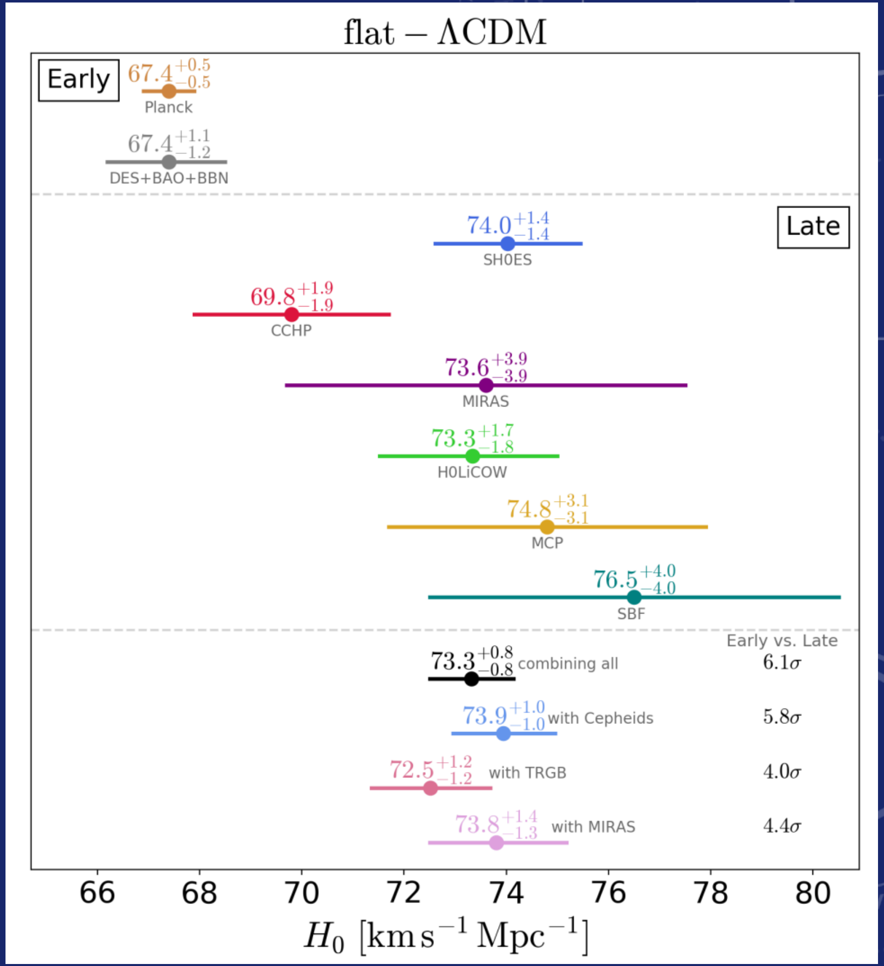
# CURRENT CRISIS IN COSMOLOGY

- Early-universe data, Planck (CMB): $H_0 = 67.4 \pm 0.5$ km/s/Mpc
- Late-universe data, SH0ES (Type Ia Supernovae): $H_0 = 74 \pm 1.4$ km/s/Mpc
- $4 - 5\sigma$ discrepancy => Systematics OR new physics ??
- Need for 3rd independent method => GWs!!




Source: *Tensions between the Early and the Late Universe, Verde Licia & al. Nature Astronomy 2019*

# GRAVITATIONAL WAVES & $H_0$

- 90 detections so far by LIGO-VIRGO : 87 BBH, 2 BNS, 1 BHBN
- Parameter estimation pipelines (Bilby, LALInference..) provide posteriors (pdf) on binary system parameters ($d_L$, spins, masses..) through Bayesian inference
- Doppler shift : $m_{source} = \frac{m_{\text{det}}}{1+z}$ => degeneracy

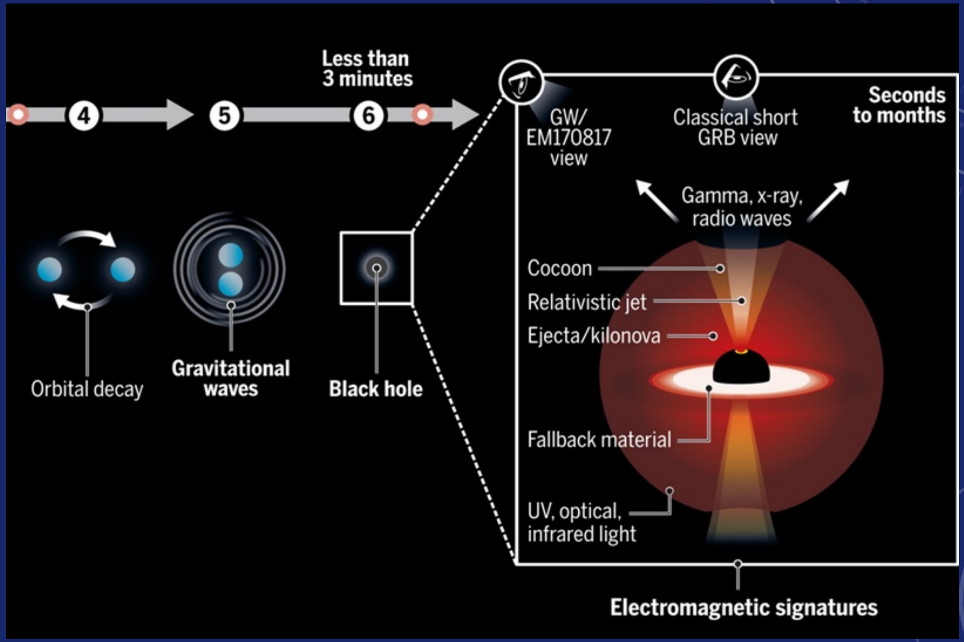
- To estimate $H_0$, one needs both distance and redshift
- For nearby events (z <1), we can consider $H_0 = \frac{cz}{d_L}$

$\Rightarrow$ **How can we break this degeneracy ??**

Differents methods to be processed through GWCosmo

# METHOD 1 : EM COUNTERPART

- In case of binary neutron stars (BNS) detections, electromagnetic counterpart detection is possible if luminosity is high enough
- EM spectrum provides redshift by photometry
- Potential GRB detection helps in sky localization



# METHOD 1 : EM COUNTERPART

- In case of binary neutron stars (BNS) detections, electromagnetic counterpart detection is possible if luminosity is high enough
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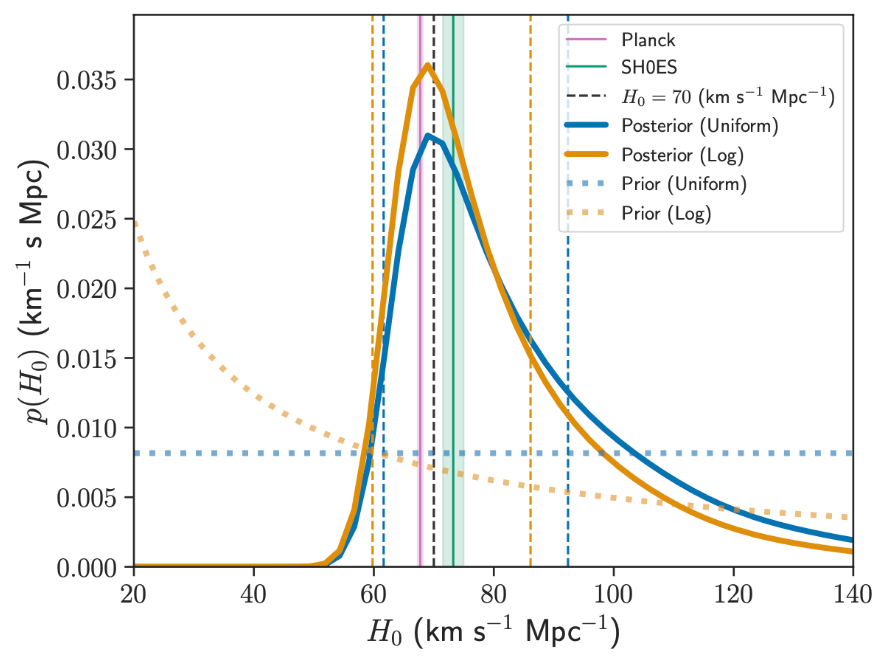
- For GW170817: $H_0 = 70^{+23}_{-8}$ km/s/Mpc



# METHOD 1 : REACHING ~4% PRECISION

1) Injections (simulated GW data) using Bilby:

- GW170817-like events at 40, 70, 100 Mpc
- Considering O4 design PSD

2) Run parameter estimation process (Bilby)

$\Rightarrow$ Posterior on luminosity distance $d_L$

3) Run GWCosmo bayesian inference code

$\Rightarrow$ Posterior on $H_0$

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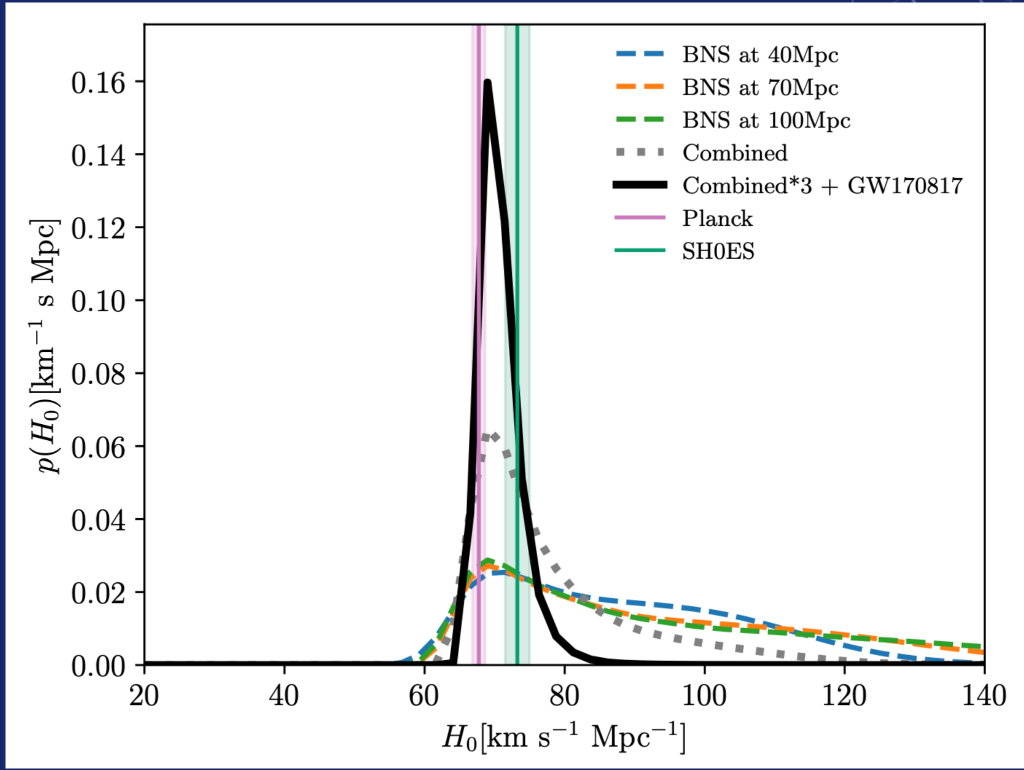



$\mathrm{H_0} = 70 \pm 3$ km/s/Mpc

# METHOD 2 : STATISTICAL GALAXY CATALOG

- GWCosmo code is compatible with GLADE and GLADE+ catalogs which contain galaxy information (luminosities, positions in radec, redshift…)
- Parameter estimation pipelines provide sky localizations of GW events
- GWCosmo crossmatches skymap and galaxy catalog

  $\Rightarrow$ **Potential host galaxies of GW event**

- Probability of a galaxy being the host $\propto$ galaxy luminosity
- Galaxies fainter than $m_{thresh}$ (apparent magnitude) are ignored

⚠ Possibility of the host not being in the galaxy catalog : **empty catalog (population) method** !

$$p(H_0|x, N_{\mathrm{obs}}, \Phi_m) = p(H_0)p(N_{\mathrm{obs}}|H_0, \Phi_m) \times \prod_{i=1}^{N_{\mathrm{obs}}} \sum_{g\in[G,\bar{G}]} p(x_i|\hat{d}, H_0, \Phi_m, g)p(g|H_0, \Phi_m, \hat{d}),$$

# METHOD 2 : STATISTICAL GALAXY CATALOG (PIXELATED)

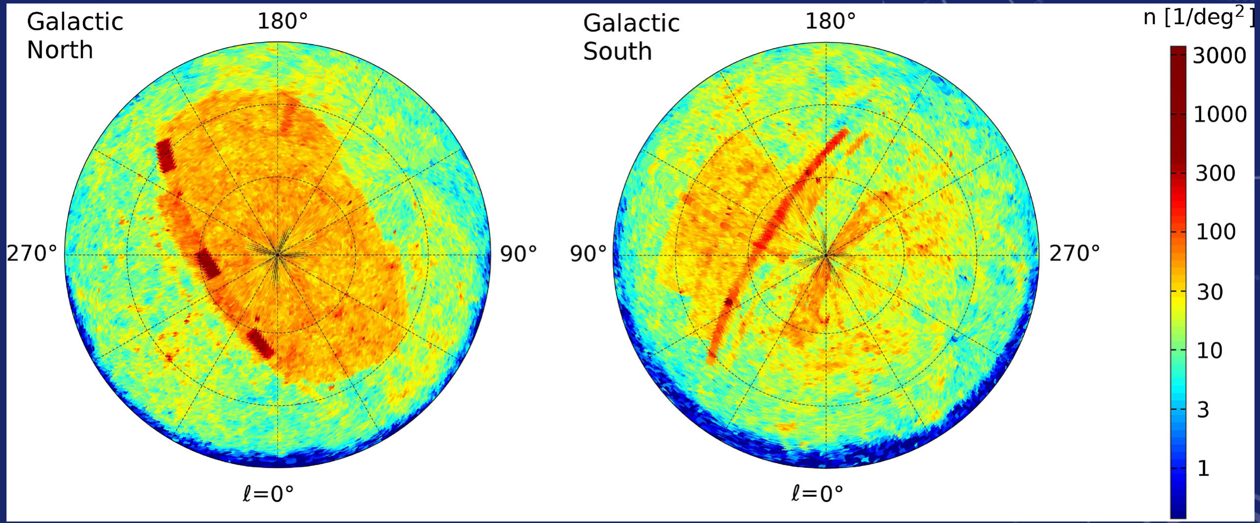
- In standard method we applied a unique magnitude threshold
- But in reality: catalog completeness depend on sky localization (different sensitivities)

Q: How to take into account this effect ?

R: **Pixelated method**

⇒ Divide sky into pixels

⇒ Apply different magnitude threshold : median magnitude of the pixel




The number density (n) of objects in GLADE, using azimuthal projection with galactic coordinates.



Source : *Mon Not R Astron Soc*, Volume 479, Issue 2, September 2018, Pages 2374–2381, https://doi.org/10.1093/mnras/sty1703

# METHOD 3 : EMPTY CATALOG/POPULATION

- We assume a specific :

1) Mass distribution for BBH/BNS (independent of redshift)
2) Merger rate evolution with redshift

- Posterior on redshifted mass of GW data by parameter estimation pipelines

$\Rightarrow$ Breaking the degeneracy between redshift and mass

$\Rightarrow$ After taking detection probability, GWCosmo estimates posterior on $\boldsymbol{H_0}$

**Posterior on $\boldsymbol{\phi}$ ($\boldsymbol{H_0}$ only in our case) can be obtained from :**

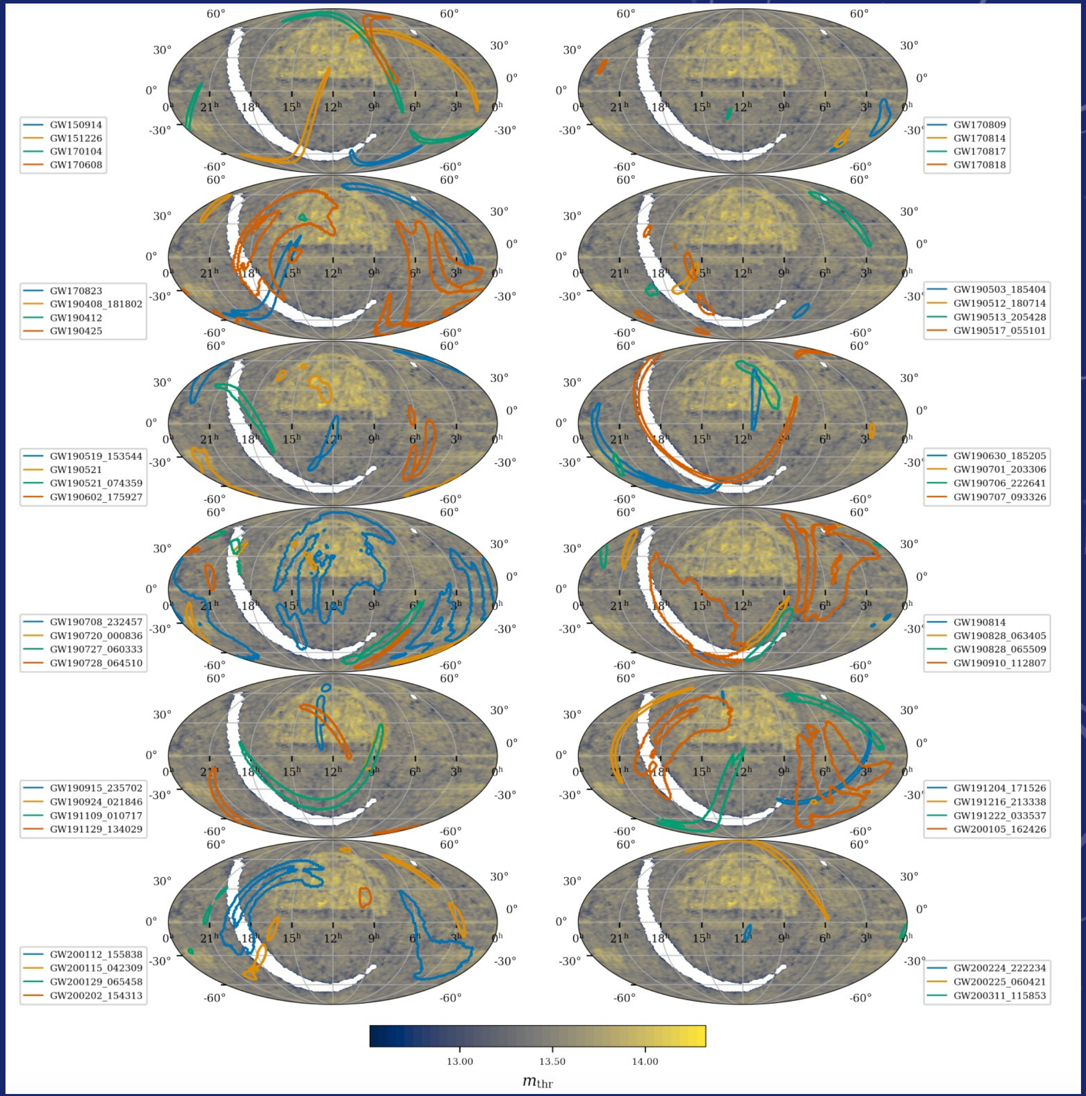
$$p_{\rm pop}(\theta|\Phi_m, H_0, \Omega_{\rm m}, w_0) = C\, p(m_1, m_2|\Phi_m)\psi(z|\gamma, k, z_{\rm p}) \times \frac{p(z|H_0, w_0, \Omega_{\rm m})}{1+z}, \quad (3)$$

$$p(\Phi|\{x\}, N_{\rm obs}) = p(\Phi) \prod_{i=1}^{N_{\rm obs}} \frac{\int p(x_i|\Phi, \theta) p_{\rm pop}(\theta|\Phi) {\rm d}\theta}{\int p_{\rm det}(\theta, \Phi) p_{\rm pop}(\theta|\Phi) {\rm d}\theta},$$

# DATA ANALYSIS EXAMPLE

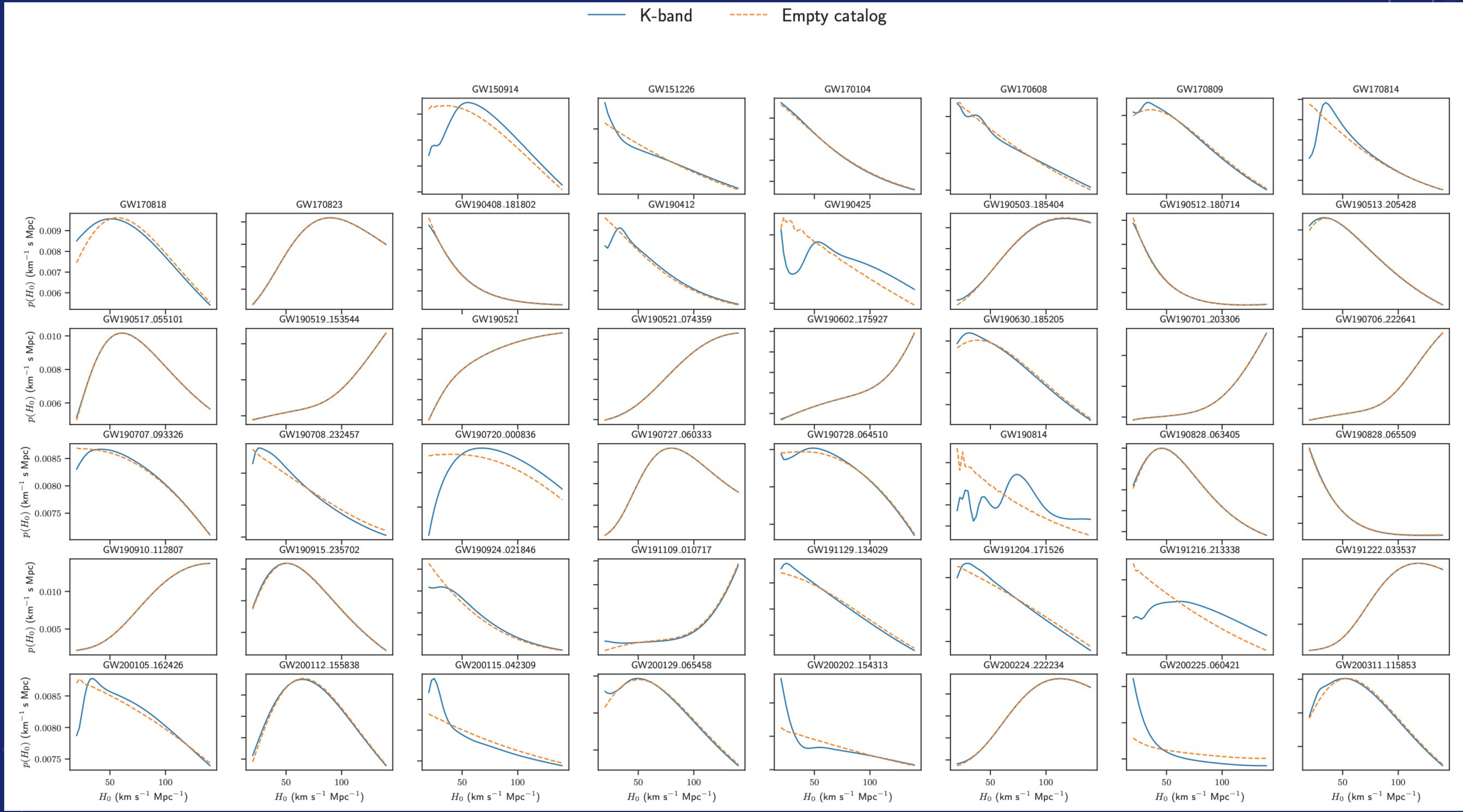
- 47 GW events in GWTC-3 catalog with SNR > 11 and IFAR > 4 yr
- Merger rate with redshift as described in Madau & Dickinson (2014) : power law + peak
- Population mass distribution as prefered in GWTC-3 data : power law + peak (gaussian) for BBH, uniform for BNS
- GLADE+ as the galaxy catalog for GWCosmo, K-band

- We use posterior samples infered using cosmological-agnostic priors (prop. to $D_L^2$)



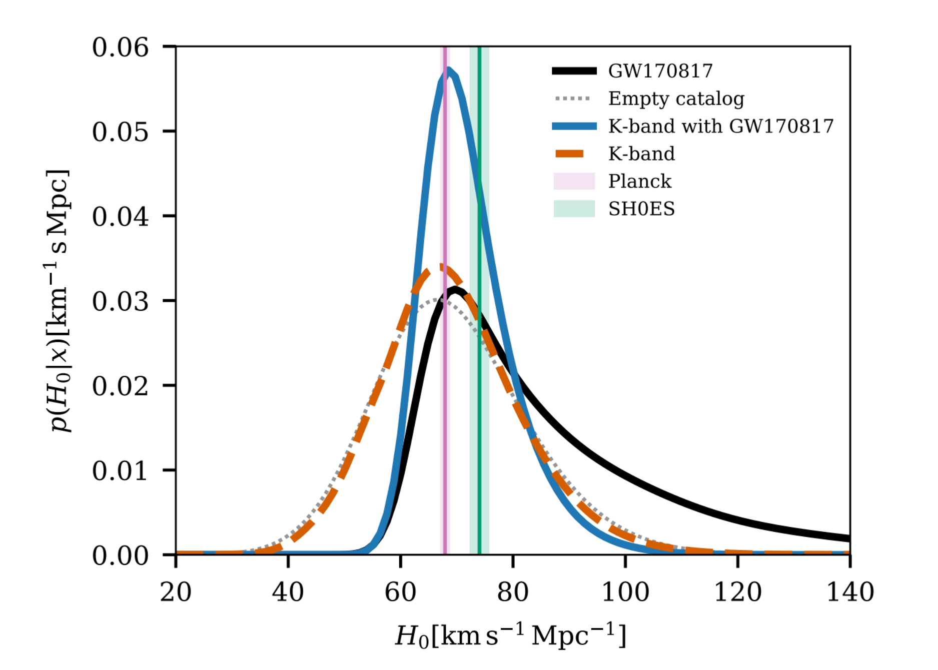

Source : P. Abbott et al. Constraints on the cosmic expansion history from GWTC-3, 2021. https://doi.org/10.48550/arXiv.2111.03604

# DATA ANALYSIS : EVENT BY EVENT (CATALOG VS POP)



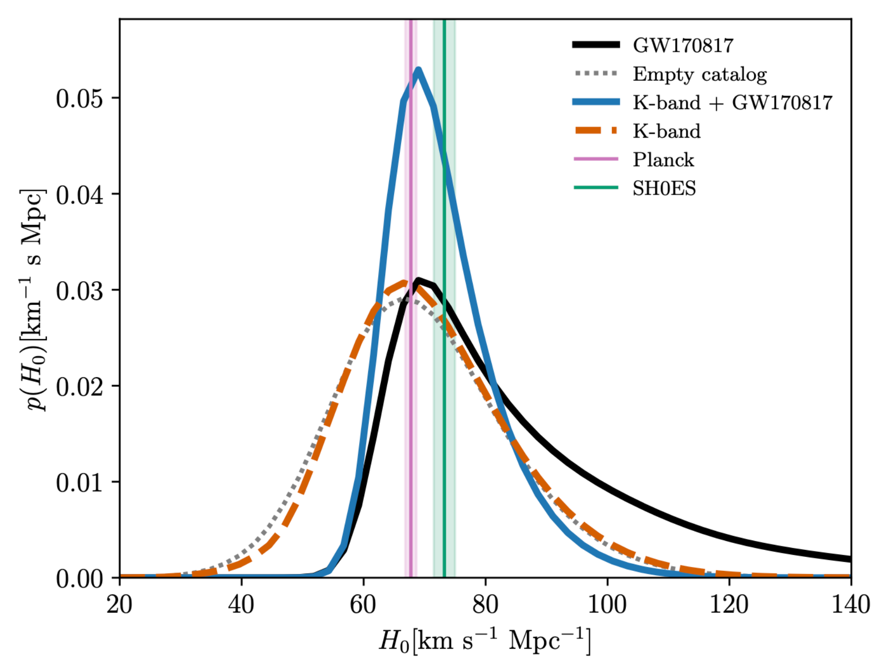
# DATA ANAYSIS : GLADE+ CATALOG

*GWTC-3 cosmology paper*




$H_0 = 69^{+8}_{-6}$ km/s/Mpc

*Our data analysis results*




$H_0 = 70^{+9}_{-7}$ km/s/Mpc



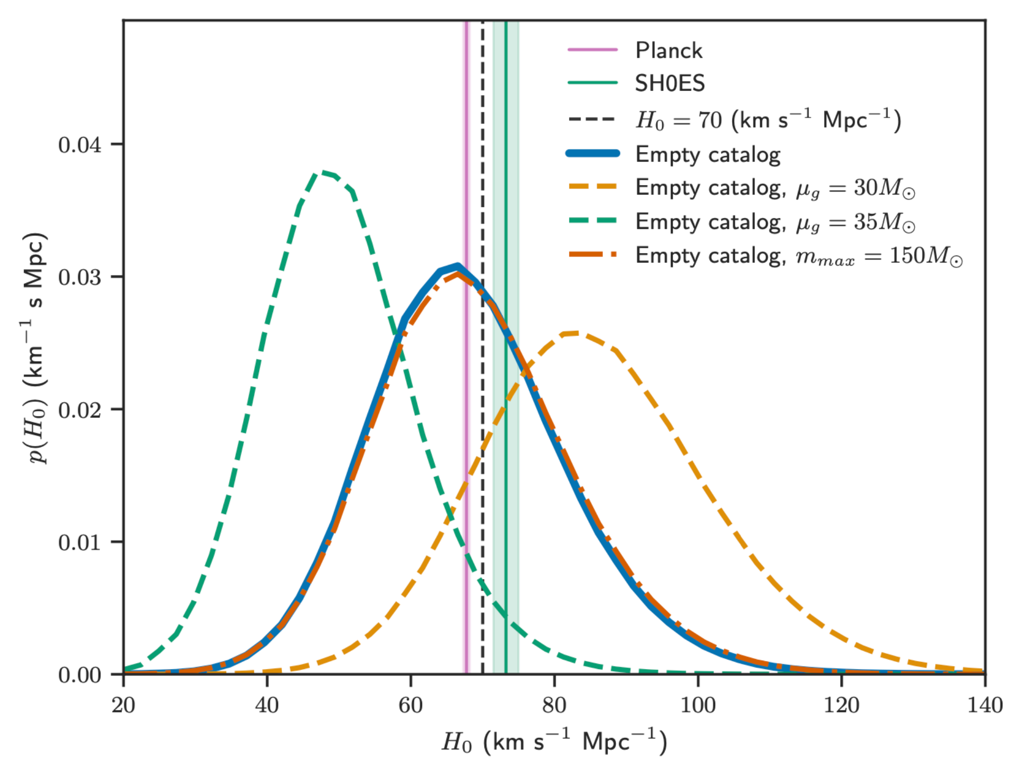
Results are very similar. Main conclusion is : **population method contribution dominates**

# DATA ANAYSIS : POPULATION ASSUMPTIONS

- Default parameter values :

$$\mu_g = 32.27, \qquad m_{\max} = 112.5$$

- Infered $H_0 = 66^{+15}_{-12}$ km/s/Mpc
- Varying $m_{\max}$ negligibly changes posterior
- Mean value of gaussian peak $\mu_g$ is crucial, $H_0$ decreases as $\mu_g$ increases

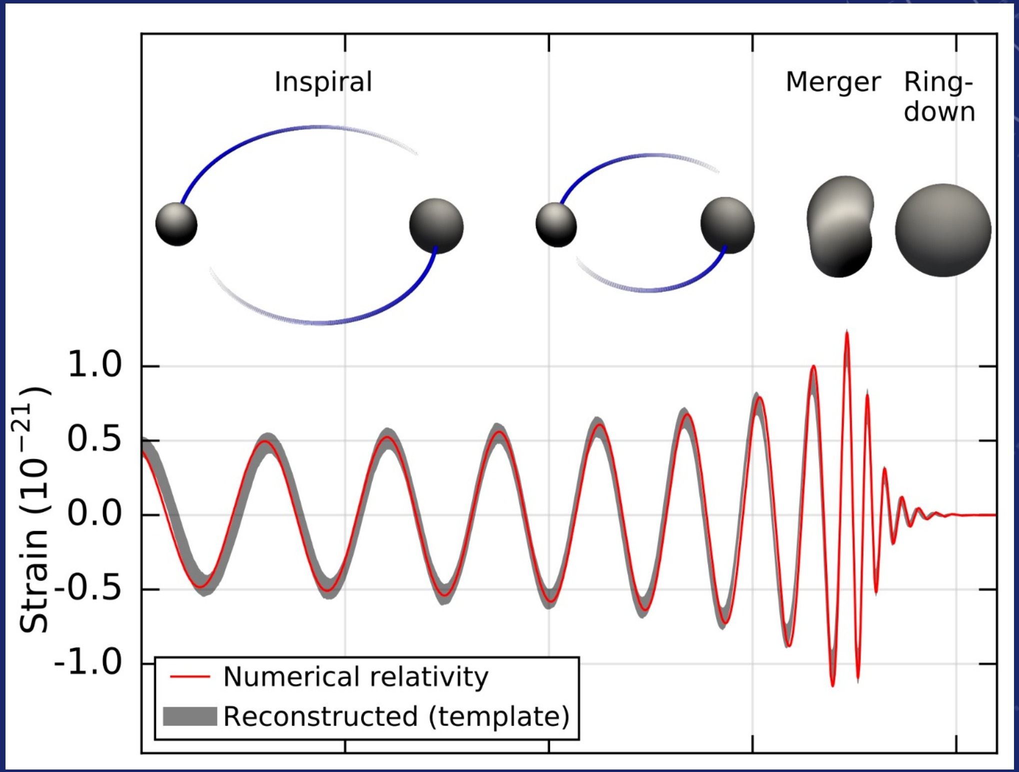


# METHOD 4 : BNS TIDAL COUPLINGS

- The GW signal of a merger can be decomposed into 3 parts : inspiral, merger, ringdown
- Inspiral waveform using 3.5 PN perturbation calculations :

$$\tilde{h}(f) = \sqrt{\frac{5}{24}} \pi^{-2/3} Q(\varphi)(M\eta)^{3/5} f^{-7/6} \frac{e^{-i\Psi(f)}}{r}$$

- The phase $\psi = \psi_{PP} + \psi_{tidal}$
- $\psi_{tidal}$ is relevant in high frequencies during the merge, detectable in next-gen detectors (ET, CE)



# METHOD 4 : BNS TIDAL COUPLINGS

- The waveform is redshifted due to Doppler effect, $f \to \frac{f}{1+z}$ which is equivalent to :

$$r \to r(1+z) = d_L, \qquad M \to M(1+z)$$

- h(f) $\propto d_L^{-1}$, the lumonisity distance can be infered using parameter estimation pipelines
- $\psi_{PP}$ is invariant under doppler shift

$\Rightarrow$ We detected redshifted mass and not source mass

$$\Psi^{tidal}(f) = \sum_{a=1,2} \frac{3\lambda}{128\eta M^5}\left[-\frac{24}{\chi_a}(1+\frac{11\eta}{\chi_a})x^{5/2} - \frac{5}{28\chi_a}(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3)x^{7/2}\right]$$

- Using NS EoS, we can establish a $m - \lambda$ relation

$\Rightarrow$ Tidal contribution involves only masses and redshifted masses

$\Rightarrow$ Estimation of both contributions leads to degeneracy breaking, implementation of bayesian inference is possible