Speed of Gravity and Cosmology Constraints from Binary Neutron Stars using Time Delays between Gravitational Waves and Short Gamma-ray Bursts.

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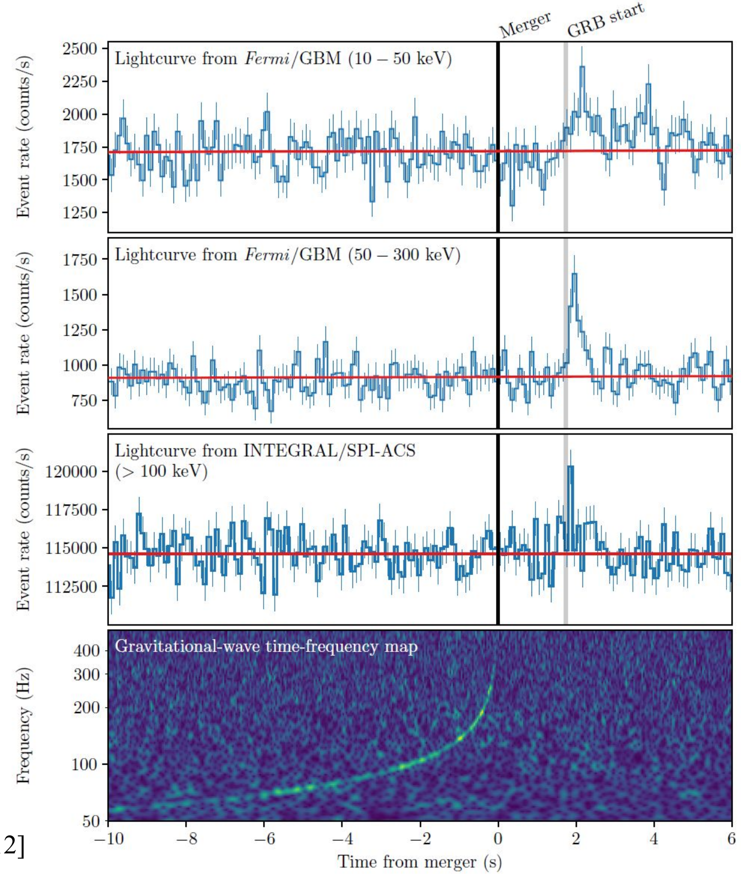
Multimessenger observations

17 August 2017: Joint detection of **gravitational waves** (GWs) and electromagnetic counterpart from coalescing binary neutron stars (BNS):

- **GW170817:** Consistent with the merger of a BNS at ~40 Mpc.
- **GRB170817A:** Detected by Fermi-GBM, **short Gamma-ray burst** (sGRB) arrived 1.74 s after the GW luminosity peak (merger). Luminosity of 10^{47} erg/s.
- **AT2017gfo**: **Kilonova**, observed from the X-ray to the radio for several days.



[B. P. Abbott et al 2017 ApJL 848 L12]

Speed of Gravity

- Multi-messenger observations of BNS mergers can be used to constrain both the speed of gravity and the Hubble constant.

- **The observed time delay** between GW and sGRB is given by:

$$\Delta t_d^{GW-EM} = (1+z_s)\Delta t_s^{GW-EM} + \frac{v_g - c}{2c} T_l$$

Observed Time Delay; Cosmological Redshift; Prompt Time Delay; Speed of Gravity; Lookback Time

- From GW170817, using the time delay measure, the following constraint was set on the **speed of gravity**:

$$-3 \cdot 10^{-15} < \frac{v_g - c}{c} < 7 \cdot 10^{-16}$$

[B. P. Abbott *et al* 2017 *ApJL* **848** L13]

Hubble Constant

- GW sources are standard sirens: we can derive the luminosity distance directly from the GW signal.

- **The luminosity distance** is given by:

Luminosity distance

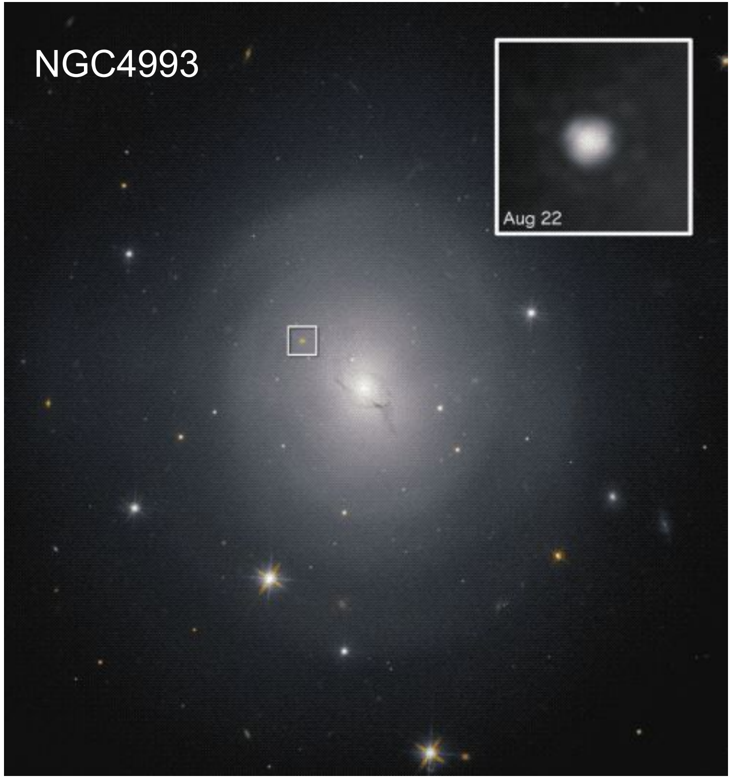
$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{E(z)}$$

Hubble constant

- For GW170817, **the redshift** is obtained from the host galaxy identification (NGC4993).

- These two observables were used to constrain the **Hubble Constant (H0)**:

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



[B. P. Abbott *et al* Nature volume 551 (2017)]

Summary and Goal

- During the two next observing runs of Ligo and Virgo, **O4 and O5**, we expect ~0-10 joint GW-sGRB detections per year [Patricelli+, MNRAS, Volume 513, Issue 3 2022].

- With Einstein Telescope (**ET**), we might expect ~100 joint GW-sGRB detections per year [Ronchini+, A&A 665, A97 (2022)].

Objectives: Exploit the hosteless (no single host identified) joint detections of GW-sGRB to:

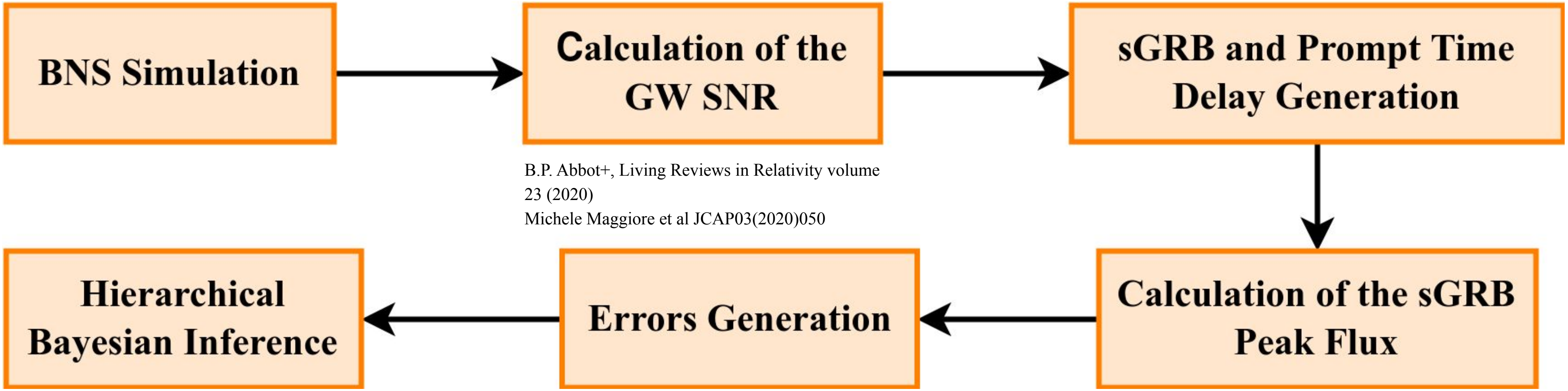
- Constrain speed of gravity and prompt time delay distribution. **! Never studied before !**

- Constrain H0 even in absence of redshift measure. **! New technique !**

Generation of the GW-sGRB Mock Catalog

I performed an end-to-end simulation of GW and sGRB detections from BNS mergers. I assumed several scenarios for the GW detector network and for the prompt time delay distribution.

- I generated 9 GW-sGRB Mock Catalogs for each detector network and prompt time delay model.



Ghirlanda+, A&A 594 (2016) A84

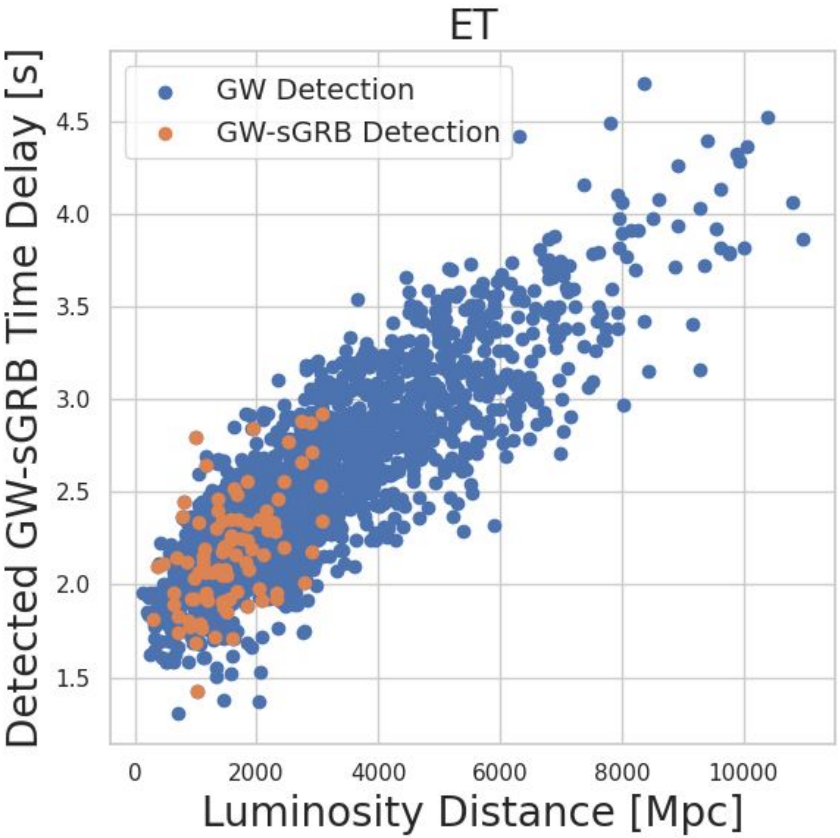
B.P. Abbot+, Living Reviews in Relativity volume 23 (2020)
Michele Maggiore et al JCAP03(2020)050

J. Gair+ The Astronomical Journal 166 (2023)

A. Farah+, ApJ 895 (2020) 108

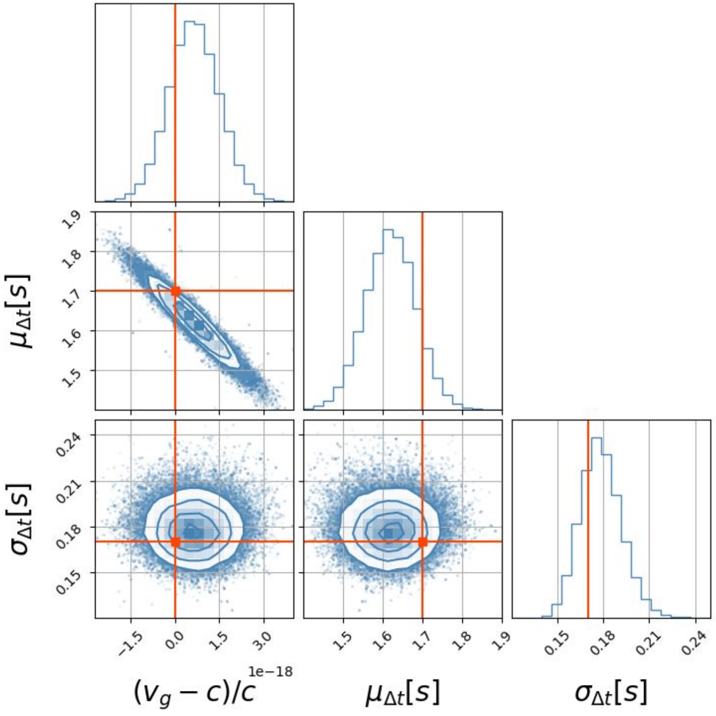
Catalog of Simulated GW-sGRB Detections

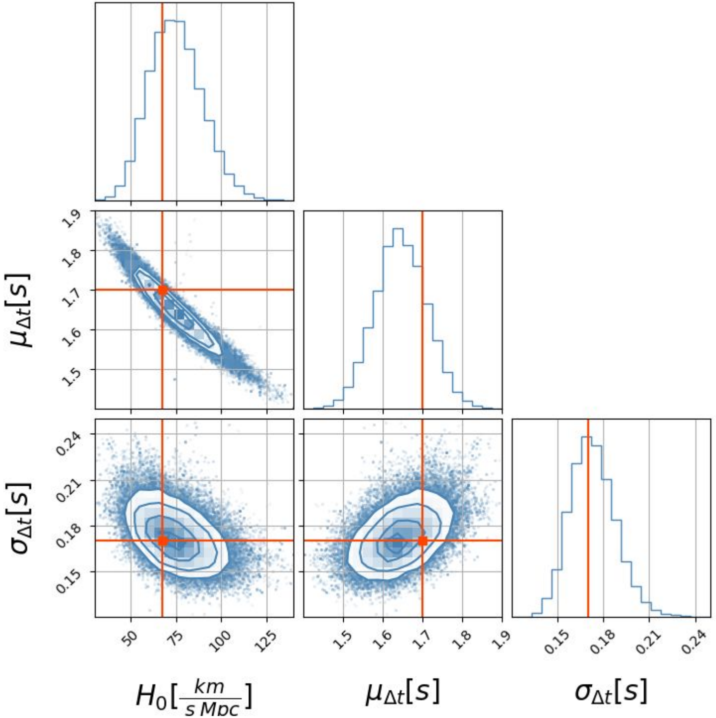
- $N = 10^6$ simulated BNS mergers.
- Prompt time delay model is a gaussian centered around 1.7 s.
- Detection Threshold: SNR > 12 for GW and Flux > 5 $\frac{\text{ph}}{s\ \text{cm}^2}$ for sGRB.



Forecast - 1

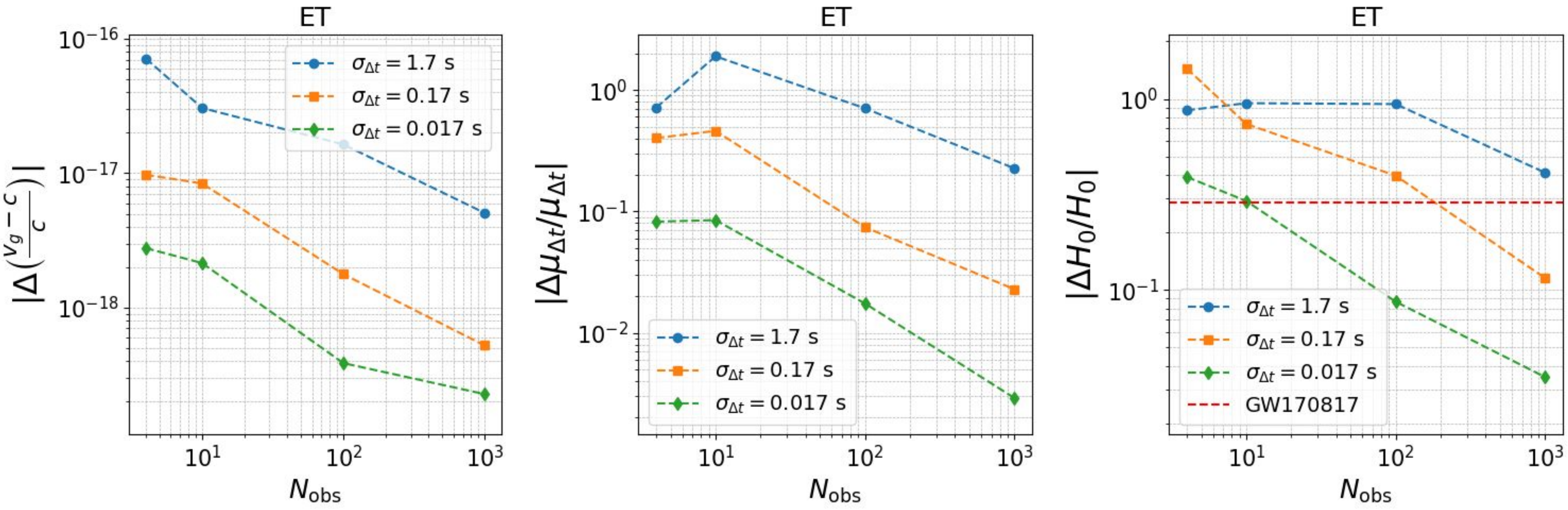
- Joint and marginalized posterior distributions in the case of 100 events detected by ET and true value of $\sigma_{\Delta t} = 0.17$ s.





Forecast - 2

- Precision on the population parameters as we combine more and more joint GW-sGRB detections.



Conclusions

- I performed 108 Hierarchical Bayesian Inference Analyses for each detector network, prompt time delay model and number of joint GW-sGRB detections.

- Speed of gravity and prompt time delay distribution can be jointly constrained with 10 observations for all detectors sensitivities.

- For a joint constraint on H0 and the prompt time delay distribution we need at least a 100 event and the sensitivity of the Einstein Telescope.

- This method of measuring the Hubble constant has different systematics with respect to both the Galaxy catalog method and the mass method and can thus be used to give an independent measure of H0.

Conclusions

Thanks for the attention

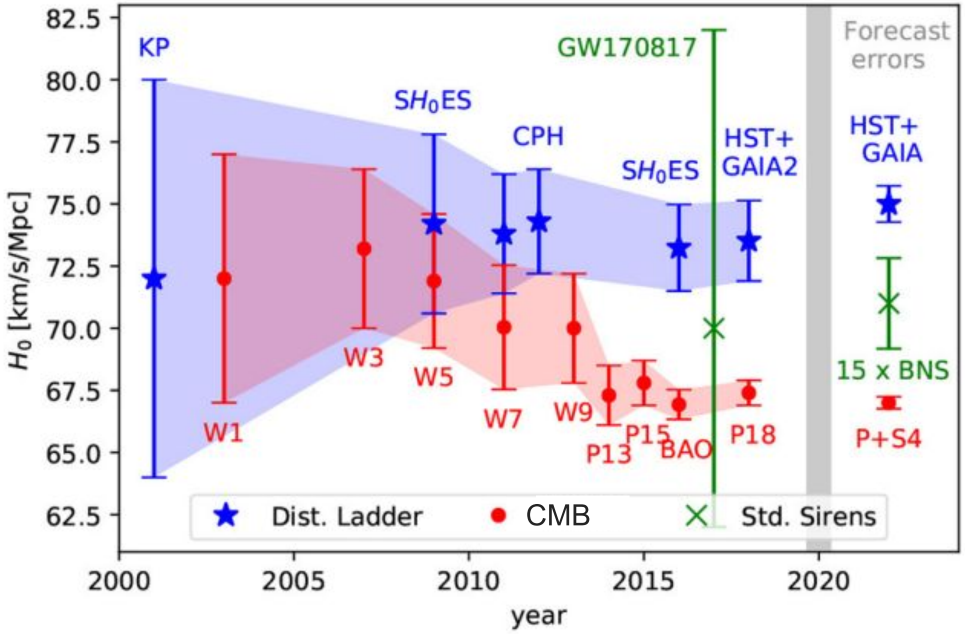
The Hubble tension

Discrepancy in the measured values of the **Hubble Constant (H0)**:

- Cosmic Microwave Background (early universe) - Planck experiment.
- Standard candles (late universe) - SH0ES experiment.

Proposed solutions to the Hubble tension:

- Unmodeled systematics in one of the experiments.
- New physics such as modified gravity: Can introduce a speed of gravity different from light.



[J. Ezquiaga+ Front. Astron. Space Sci., 21 December 2018]

Bayesian Hierarchical Inference and IcaroGW

- My objective is to reconstruct population properties from a set of noisy observation with selection biases.
- I use **Hierarchical Bayesian Inference** (HBI) to reconstruct posterior distribution for the population parameters.
- I implemented prompt time delay and merger rate models in **IcaroGW** (a package for HBI) to infer speed of gravity and Hubble constant.
- I performed 108 HBI Analyses.

GW Likelihood (errors measurement)

$$\mathcal{L}(\{\vec{d_i}\}|\vec{\lambda}) = \prod_{i=1}^{N_{\rm obs}} \frac{\int \mathcal{L}(\vec{d_i}|\vec{\theta},\vec{\lambda}) \frac{dN}{dt_d d\vec{\theta}}(\vec{\theta}|\vec{\lambda})\, d\vec{\theta}\, dt_d}{\int p_{\rm det}(\vec{\theta},\vec{\lambda}) \frac{dN}{dt_d d\vec{\theta}}(\vec{\theta}|\vec{\lambda})\, d\vec{\theta}\, dt_d}$$

Hierarchical Likelihood

Detection Probability

Prompt Time Delay and Merger Rate Model

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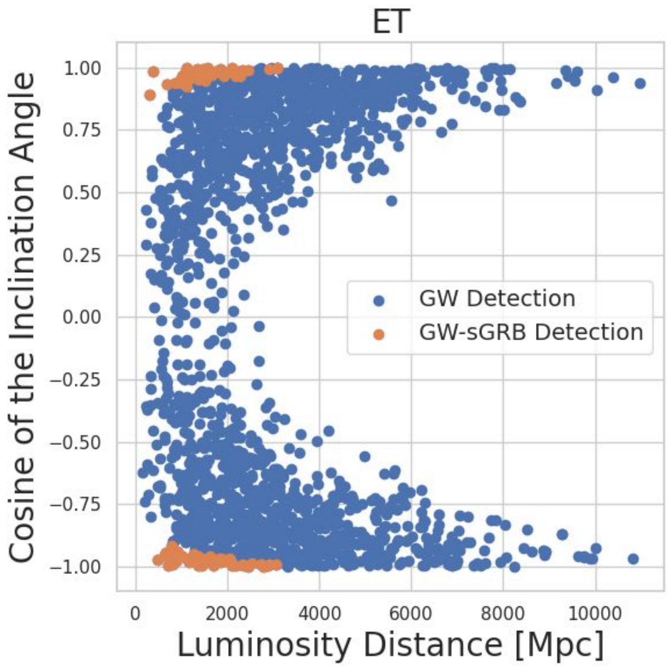
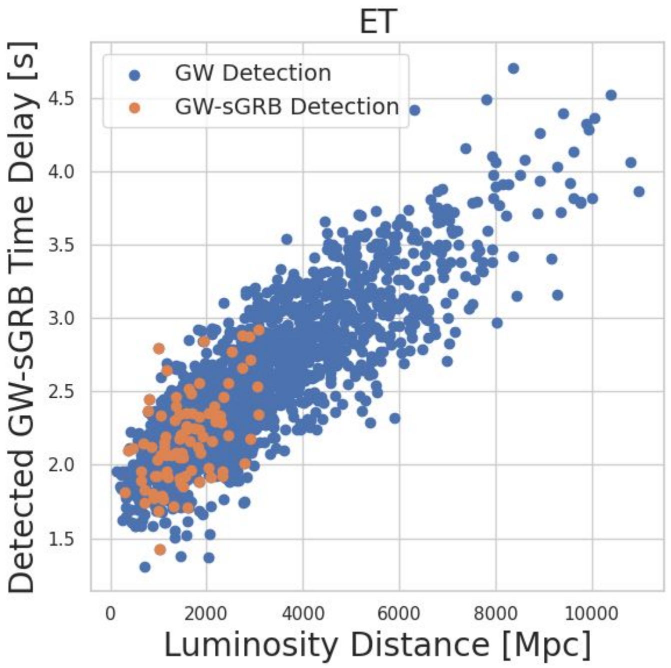




Summary and Goal - 2

To understand how to constrain H0 in the absence of a direct redshift measurement, consider the following **qualitative** discussion:

- At low redshift, the **observed GW-sGRB time delay** $\Delta t_d^{\text{GW-GRB}}$ is given by:

$$\Delta t_d^{\text{GW-GRB}} = (1 + z_s)\Delta t_s^{\text{GW-GRB}} + \frac{v_g - c}{2c^2} D_L$$

- From a joint GW-sGRB detection we can measure both the **luminosity distance** D_L and the **observed time delay** $\Delta t_d^{\text{GW-GRB}}$.

- If the values of the **prompt time delay** $\Delta t_s^{\text{GW-GRB}}$ and the **speed of gravity** v_g are known, we can obtain an implicit **redshift** z_s evaluation to use for cosmology.

- Since we do not know the distribution of $\Delta t_s^{\text{GW-GRB}}$ and the value of v_g we must fit for them.

Signal-to-Noise Ratio

- I used the 0-th post-Newtonian order approximation of the SNR:

$$\rho^2_{\text{opt}} = \frac{4A^2}{D_L^2}\left[F_+^2(t,\alpha,\rho,\psi)(1+\cos^2\iota) + 4F_\times^2(t,\alpha,\rho,\psi)\cos^2\iota\right] I$$

Inclination Angle

Luminosity Distance

Antenna Patterns

- Where A is given by:

Detected Chirp Mass

$$A = \sqrt{\frac{5}{96}}\left(\frac{G\mathcal{M}_{\text{obs}}}{c^3}\right)^{5/6} c\pi^{-2/3}$$

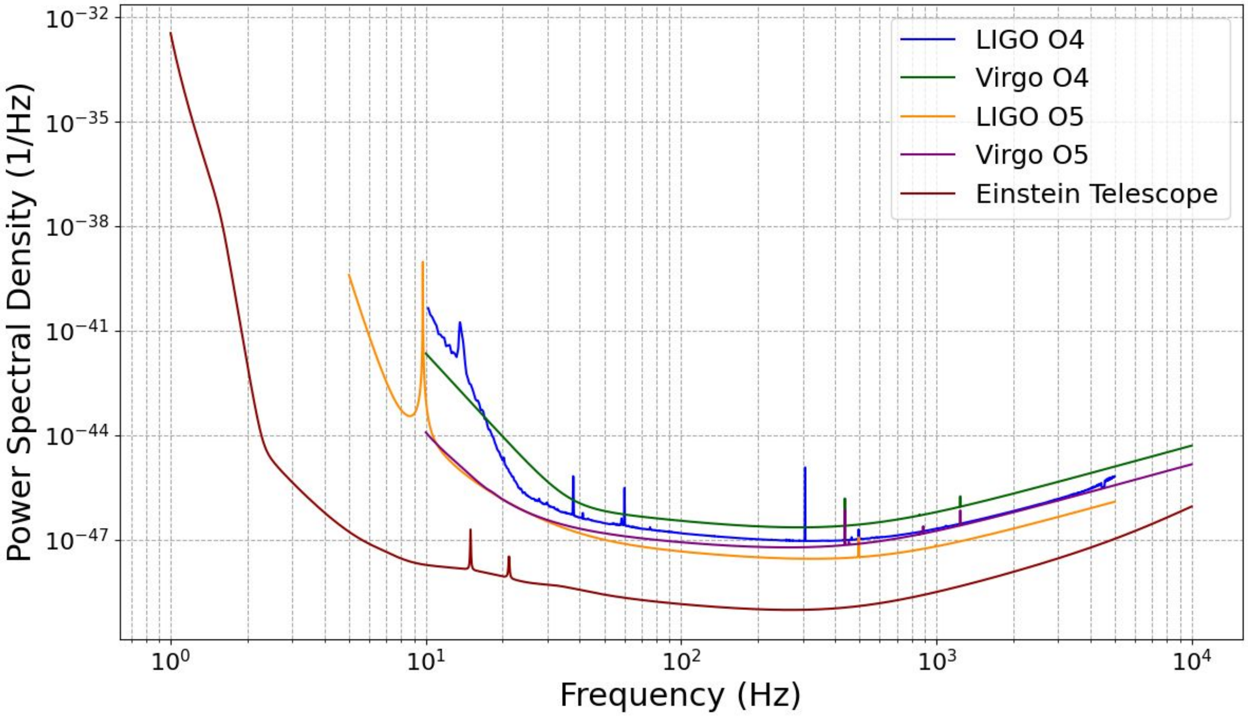
- While I, which encapsulates the noise curve of the detectors, is given by:

$$I = \int_{10\,\text{Hz}}^{f_{\text{isco}}} \frac{f^{-7/3}}{S_n(f)} df$$

Power Spectral Density

Power Spectral Density

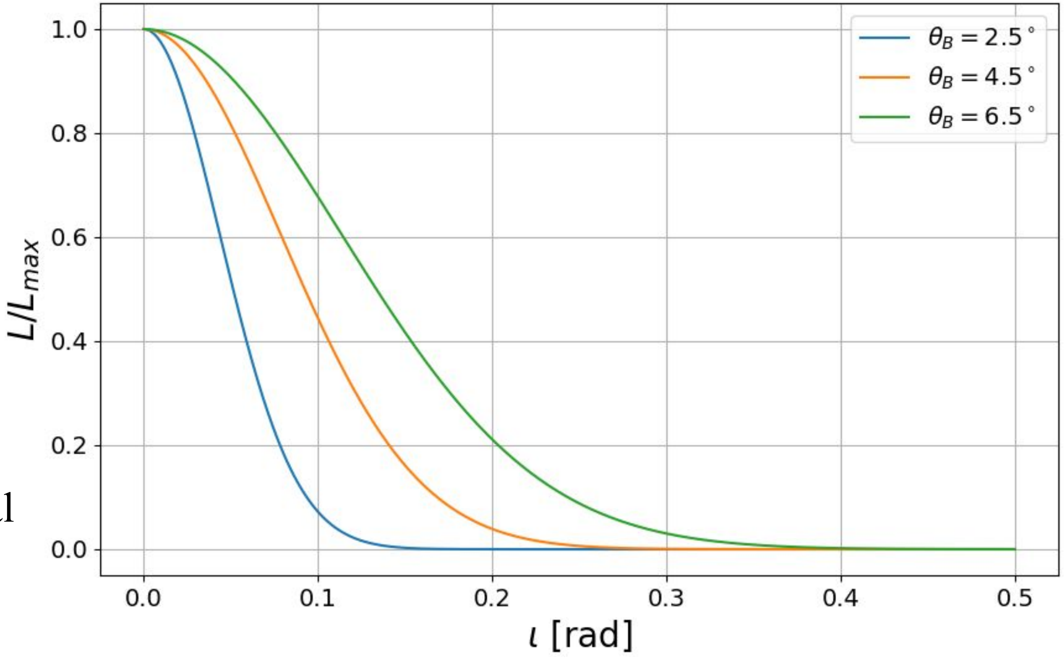
- **Power Spectral Density** as a function of frequency for current (O4) and future observational runs (O5, ET).



sGRBs Simulation

I chose the following simplified model to describe the **sGRB intrinsic luminosity**:

$$L(\iota; \theta_B, L_{\max}) = L_{\max} e^{-\frac{\iota^2}{2\theta_B^2}}$$



Where:

- ι is the viewing angle.
- $\theta_B = 4.5°$ is the width of the jet.
- $L_{\max}$ is the luminosity at the center of the jet. $L_{\max}$ is drawn from a log-normal distribution with a mean of 5×10^{51}erg s^{-1}and width of 0.56 dex.

Errors Generation

- I generated the noisy value of luminosity distances by using the following likelihood:

True Physical

$$\mathcal{L}_{\text{noise}}(D_L^{\text{obs}}|D_L^{\text{true}}) = \mathcal{N}(D_L^{\text{obs}}|\mu = D_L^{\text{true}}, \sigma = 0.2 \cdot D_L^{\text{true}})$$

Noisy Counterpart

- I sampled the noise of the detected time delays and the observed SNR from a Gaussian distribution:

$$\mathcal{L}_{\text{noise}}(\Delta t_d^{\text{obs}}|\Delta t_d^{\text{true}}) = \mathcal{N}(\Delta t_d^{\text{obs}}|\mu = \Delta t_d^{\text{true}}, \sigma = 0.05s)$$

$$\mathcal{L}_{\text{noise}}(\rho_{\text{obs}}|\rho_{\text{true}}) = \mathcal{N}(\rho_{\text{obs}}|\mu = \rho_{\text{true}}, \sigma = 1)$$

GW Likelihood

- The overall Gravitational Wave Likelihood is given by:

$$\mathcal{L}(\rho_{\rm obs}, D_L^{\rm obs}, \Delta t_d^{\rm obs} | \rho_{\rm true}, D_L^{\rm true}, \Delta t_d^{\rm true}) = \mathcal{L}(D_L^{\rm obs}|D_L^{\rm true})\mathcal{L}(\Delta t_d^{\rm obs}|\Delta t_d^{\rm true})\mathcal{L}(\rho_{\rm obs}|\rho_{\rm true})$$

- For each GW detection, I generated **Posterior Samples** (PEs), i.e. the possible values of ($D_L^{\rm true}$, $\Delta t_d^{\rm true}$) from which the observed ($D_L^{\rm obs}$, $\Delta t_d^{\rm obs}$) were generated.

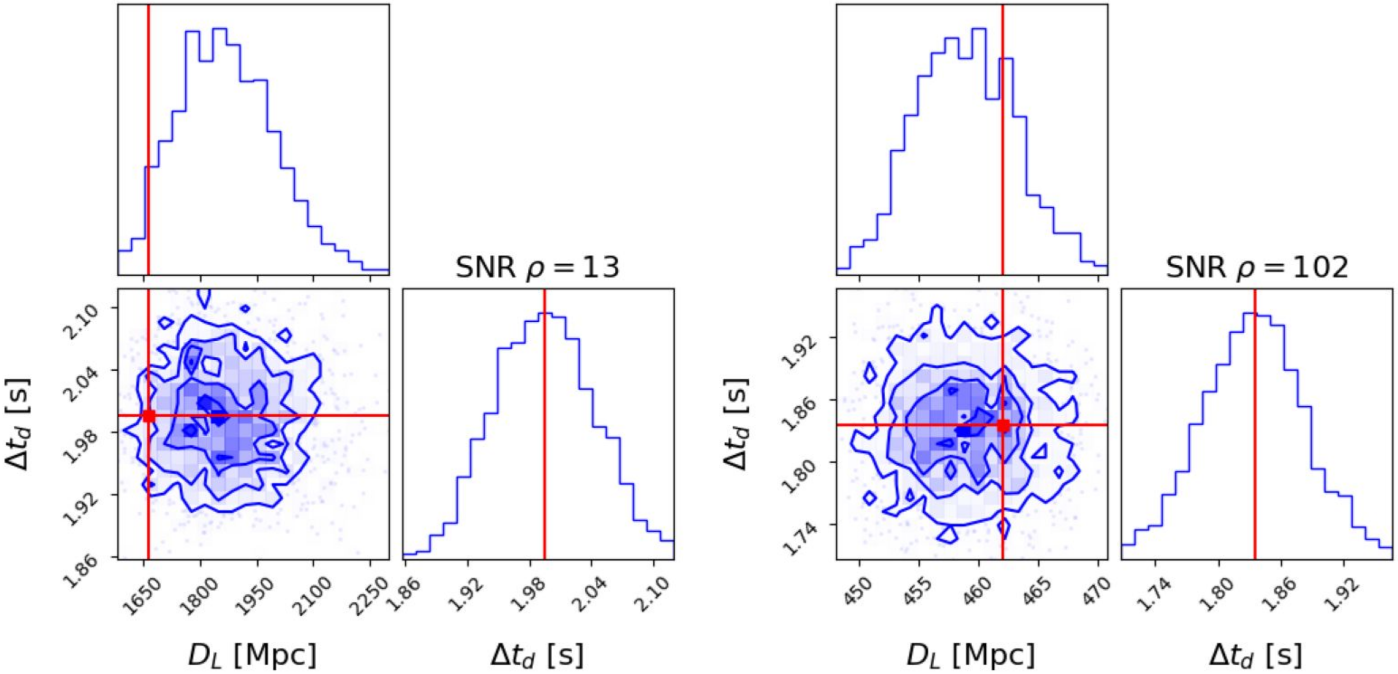
- PEs are sampled from the posterior:

$$p(D_L^{\rm true}, \Delta t_d^{\rm true}|D_L^{\rm obs}, \Delta t_d^{\rm obs}) = \mathcal{L}(D_L^{\rm obs}|D_L^{\rm true})\mathcal{L}(\Delta t_d^{\rm obs}|\Delta t_d^{\rm true})\mathcal{L}(\rho_{\rm obs}|\rho_{\rm true}(D_L^{\rm true}))\pi_{PE}(D_L^{\rm true}, \Delta t_d^{\rm true})$$

PE Prior

Posterior Samples

- Posterior samples of luminosity distance and detected time delay for a signal with SNR = 13 and one with SNR = 102. Both events have been detected by ET.



Hierarchical Likelihood Evaluation

- To evaluate the **numerator** in the **Hierarchical Likelihood** (HL) Expression I summed over the PE samples:

$$\int \mathcal{L}(\vec{d}_i|\theta)\frac{dN}{dtd\vec{\theta}}(\vec{\lambda})d\vec{\theta} \approx \frac{1}{N_{s,i}}\sum_{j=1}^{N_{s,i}}\frac{1}{\pi_{\rm PE}(\vec{\theta}_{i,j})}\frac{dN}{dtd\vec{\theta}}(\vec{\lambda})\Big|_{i,j} = \frac{1}{N_{s,i}}\sum_{j=1}^{N_{s,i}} w_{i,j}$$

- The second central quantity is the **denominator** of the HL Expression $\mathrm{I}_{\rm norm}$, which accounts for selection biases.
- In order to assess selection biases I used **"injections"**, i.e. Monte Carlo simulations of injected and detected events.
- I computed the integral in $\mathrm{I}_{\rm norm}$ through Monte Carlo integration over detected injections:

$$\mathrm{I}_{\rm norm} \approx \frac{1}{N_{\rm gen}}\sum_{j=1}^{N_{\rm det}}\frac{dN}{dtd\vec{\theta}_j}\frac{1}{\pi_{\rm inj}(\vec{\theta}_j)} = \frac{1}{N_{\rm gen}}\sum_{j=1}^{N_{\rm det}} s_j$$