중력파 우주론

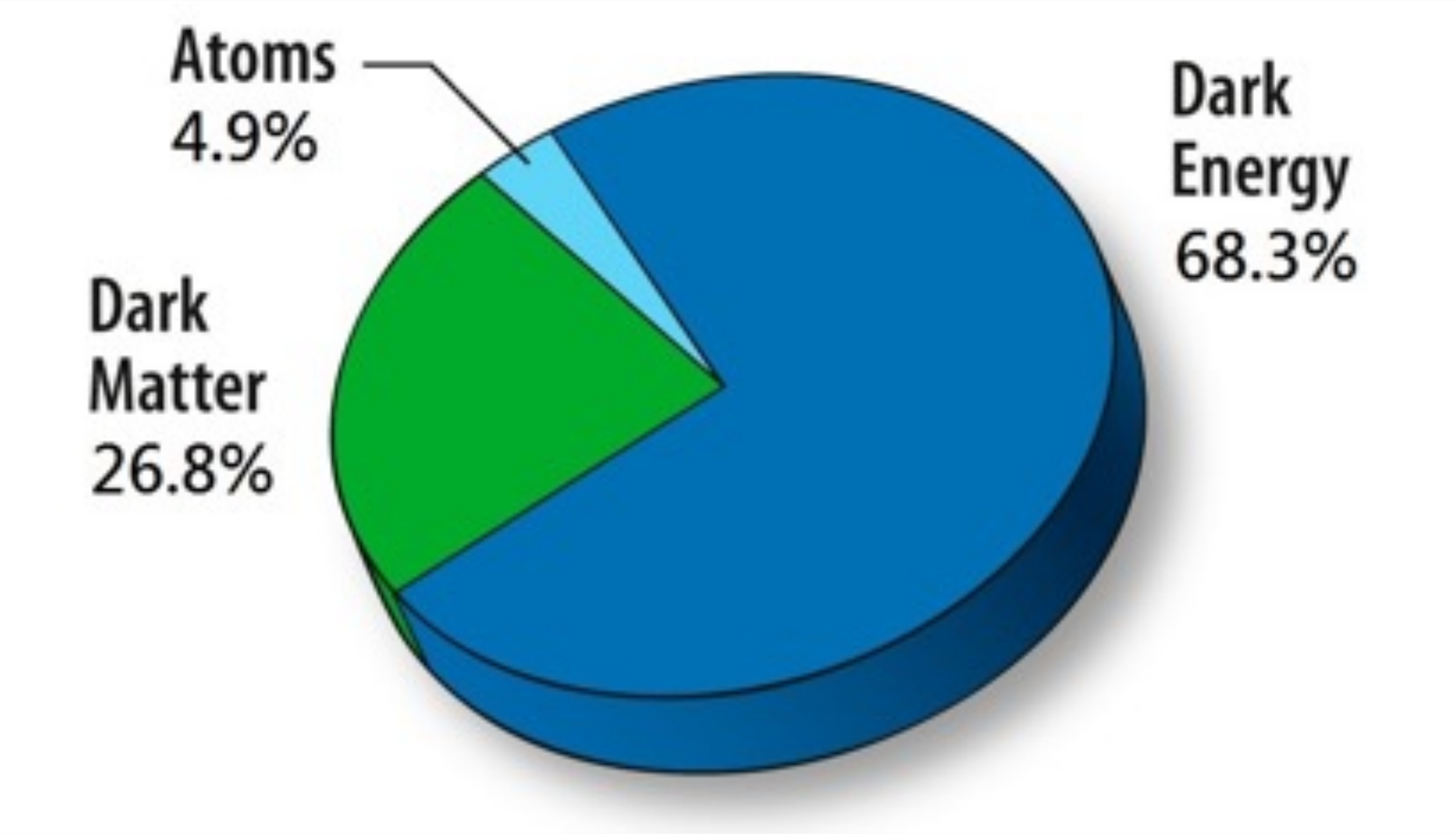
2022 중력파 및 수치 상대론 여름학교

7월 25-29, 2022

이형목 (서울대)

Standard cosmology

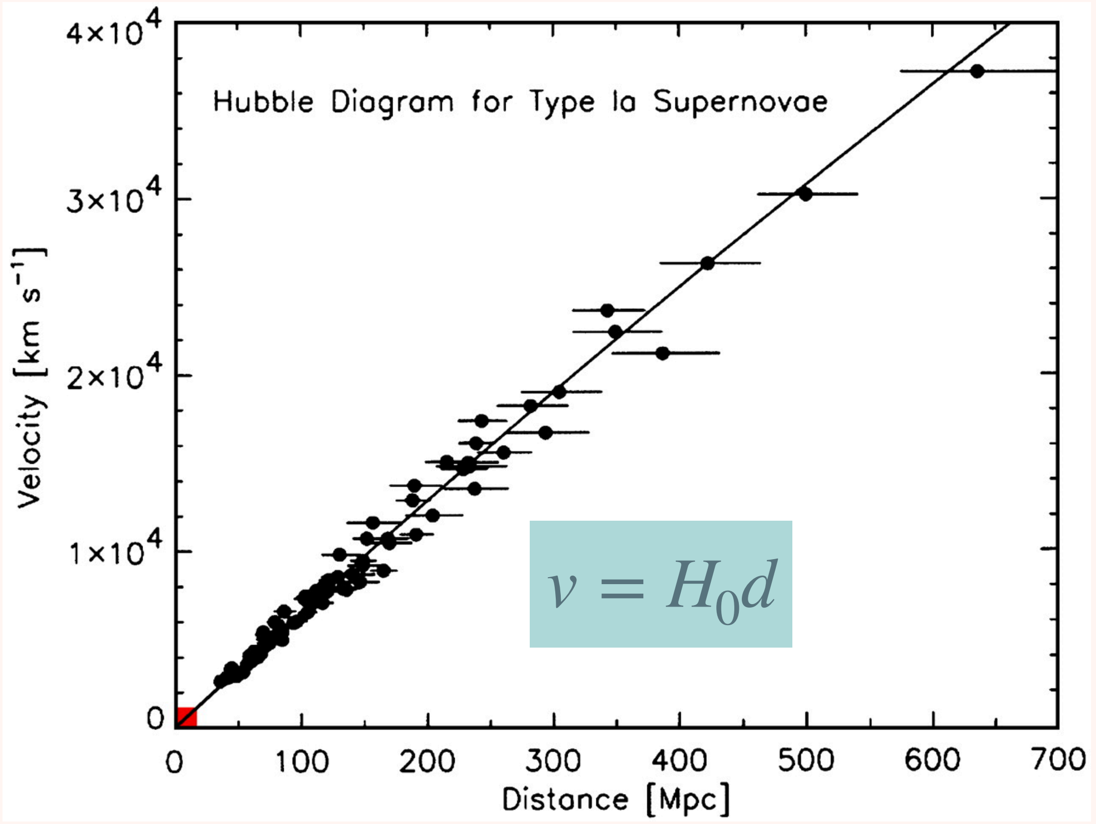
- Standard cosmology is based on general relativity, homogeneity, isotropy and the expansion of the universe.
- The shape of the expansion depends on the contents of the universe: matter, radiation and dark energy. Standard model is very successful in explaining many observed features of the universe.
- However, most of the energy is in the form of dark matter (~25%) and dark energy (~73%)

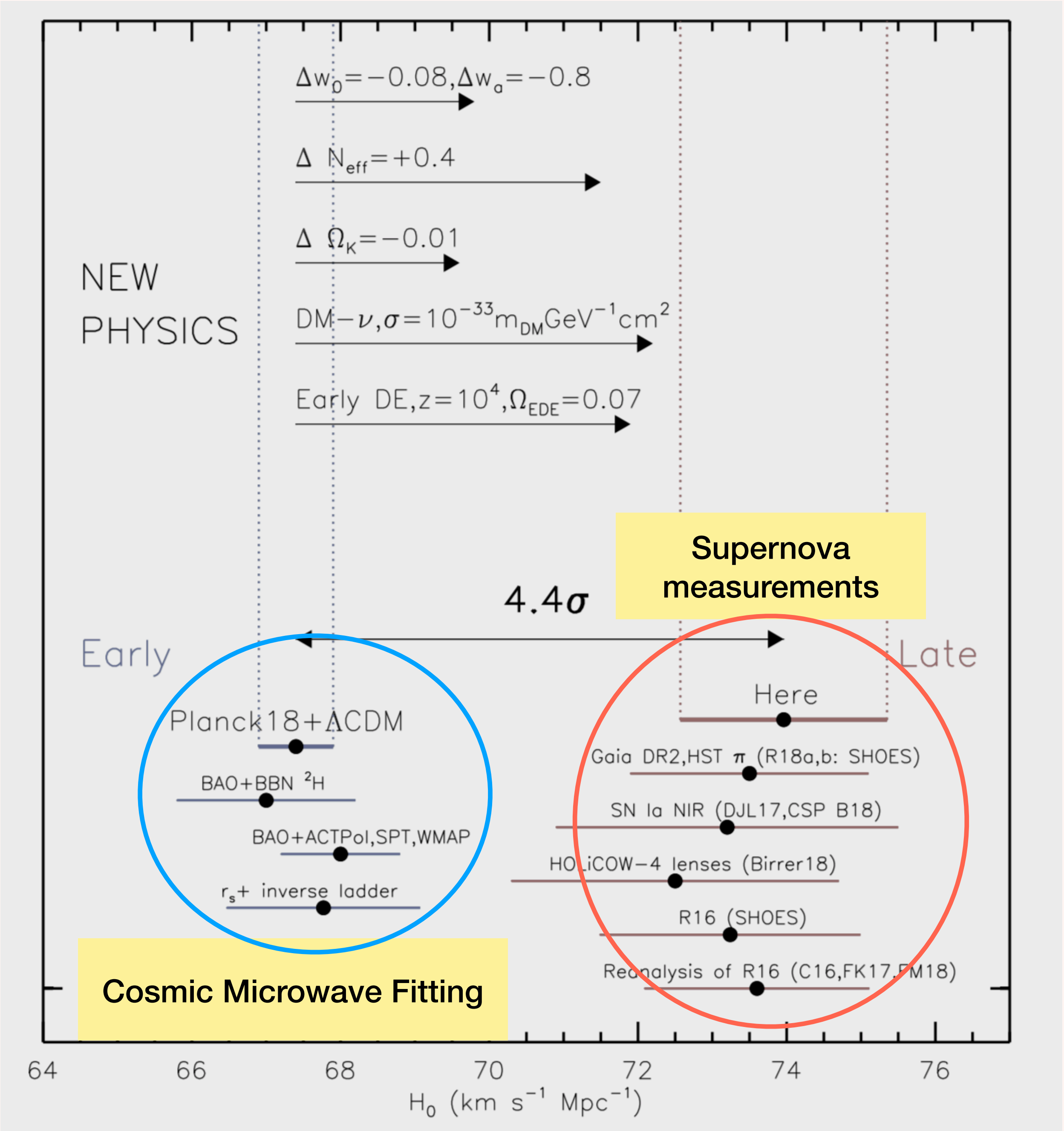


Energy contents in the Universe today. (Image credit: ESA and Planck Collaboration)

Hubble tension

- One of the key parameters for understanding the expansion of the Universe is the Hubble constant H_0.
  - It can be determined by measuring distances and receding velocities of galaxies in the local universe.
  - H_0 can also be inferred from the analysis of the Cosmic Microwave Background (CMB).
- H_0(local universe) and H_0 (CMB) are different with high statistical significance. It is called Hubble tension.
- Such a difference could be either due to systematic error in local measurement or the failure of the cosmological models.
- Hubble tension could be resolved by independent measurement of H_0.
  - GWs provide distances to the sources. If we can measure redshift of the GW sources, we can obtain Hubble constant independently.

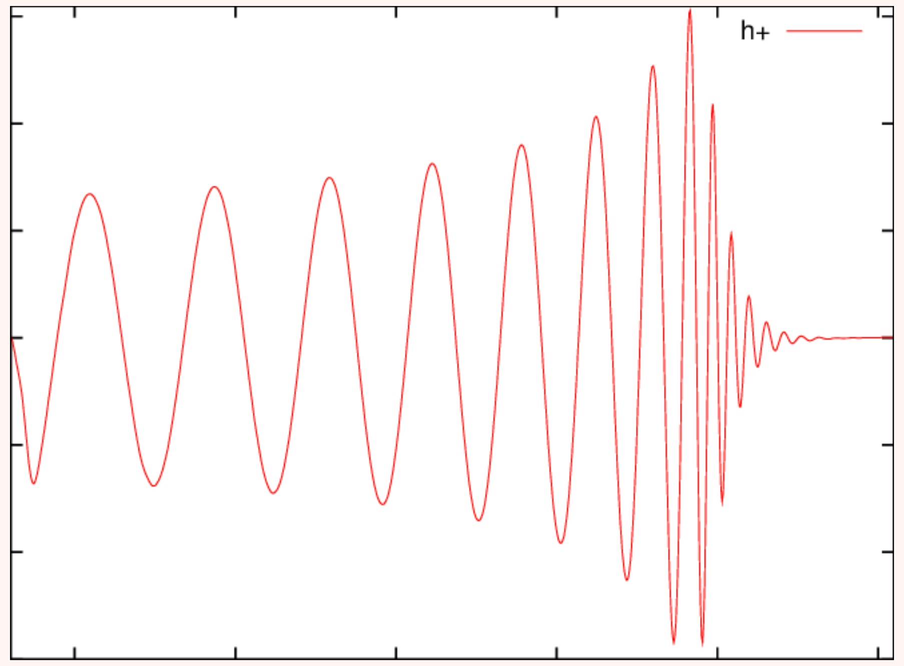




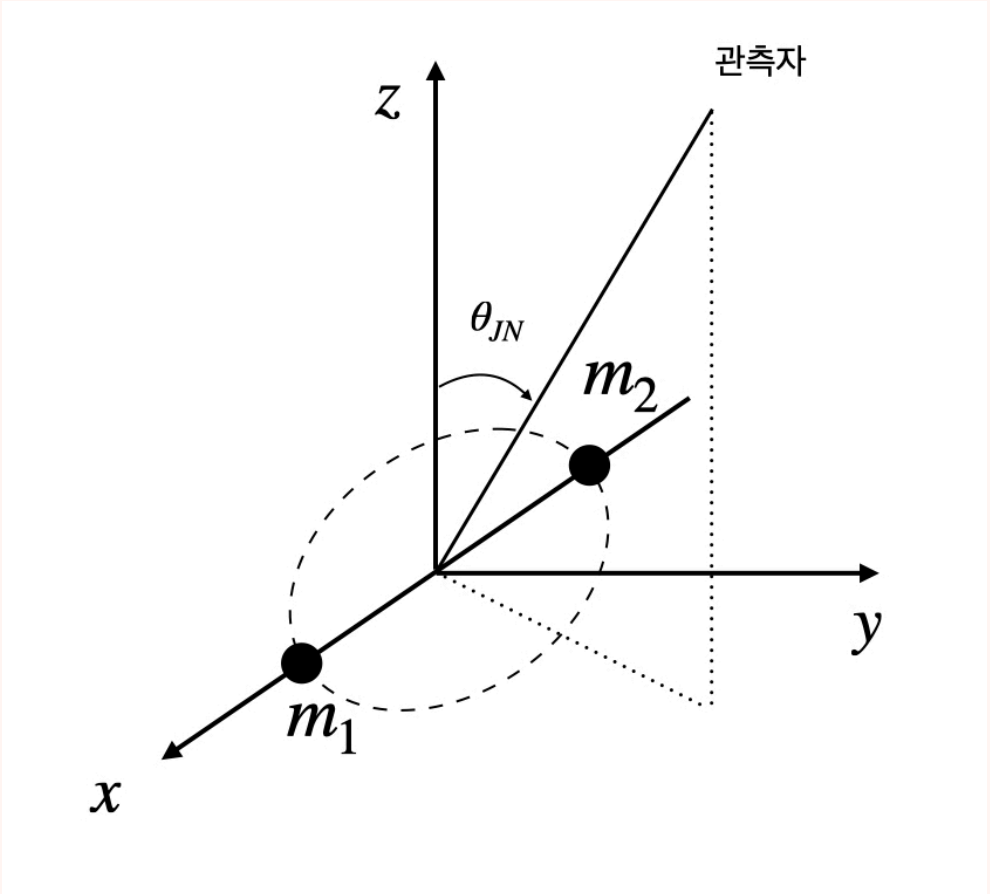
The Hubble constants measured by CMB and Supernovae are different by a large margin. (Figure from Riess et al. 2019, ApJ, 875, 85)

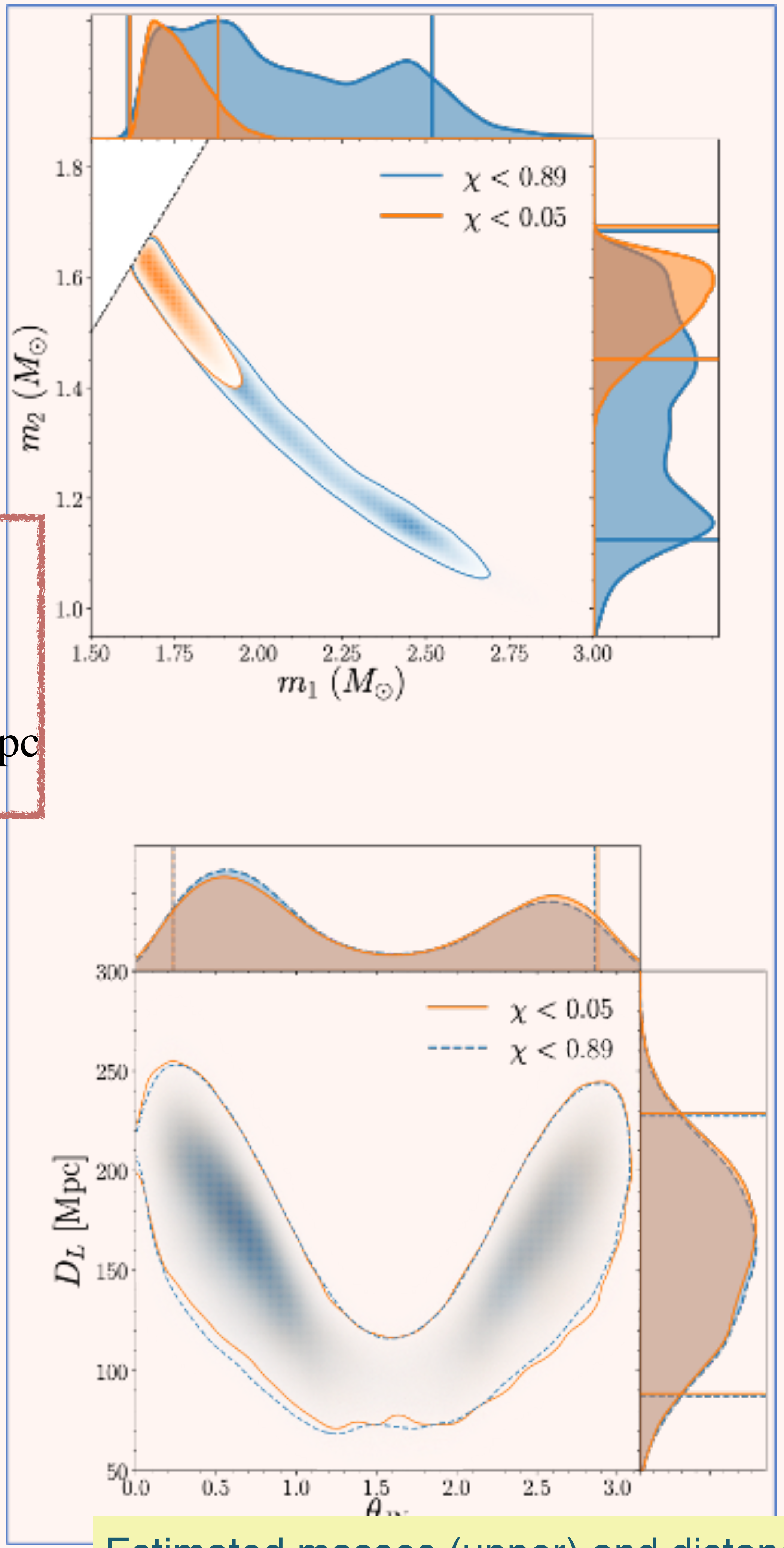
Distance measurement with GWs

- GW waveforms of binary merger depend on many parameters, with mass, eccentricity and spin being the most important ones.
- The amplitude of the GW signal is inversely proportional to the distance (luminosity distance d_L).
- Therefore, we can infer the distances to the GW signals from binary mergers.
- The distance estimation from GWs does not suffer from **systematic uncertainty**, unlike the use of variable stars as 'standard candles'.
- However, GW distance estimation suffers from large **statistical uncertainties** due to the lack of information on the angle between the line-of-sight and the orbital plane of the binary (inclination angle).



$$d_L = \frac{5}{96\pi^2}\frac{c}{h}\frac{\dot{f}_{GW}}{f_{GW}^3}$$
$$= 512\frac{1}{h_{21}}\left(\frac{0.01s}{\tau}\right)\left(\frac{100\text{Hz}}{f_{GW}}\right)^2 \text{Mpc}$$

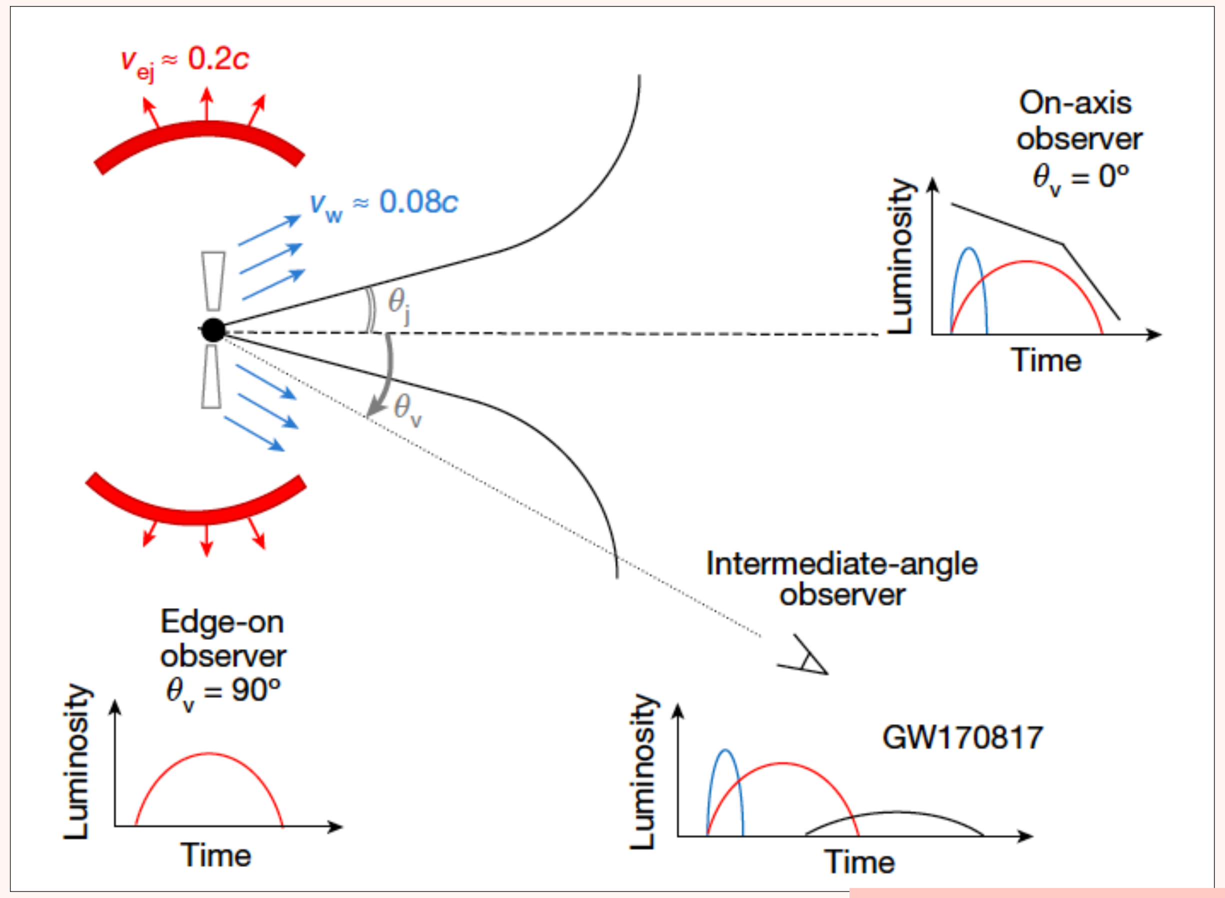




Estimated masses (upper) and distance (lower) to GW190425, a binary neutron star merger event.(Figure from Abbott et al. 2020, ApJL, 892, L3)

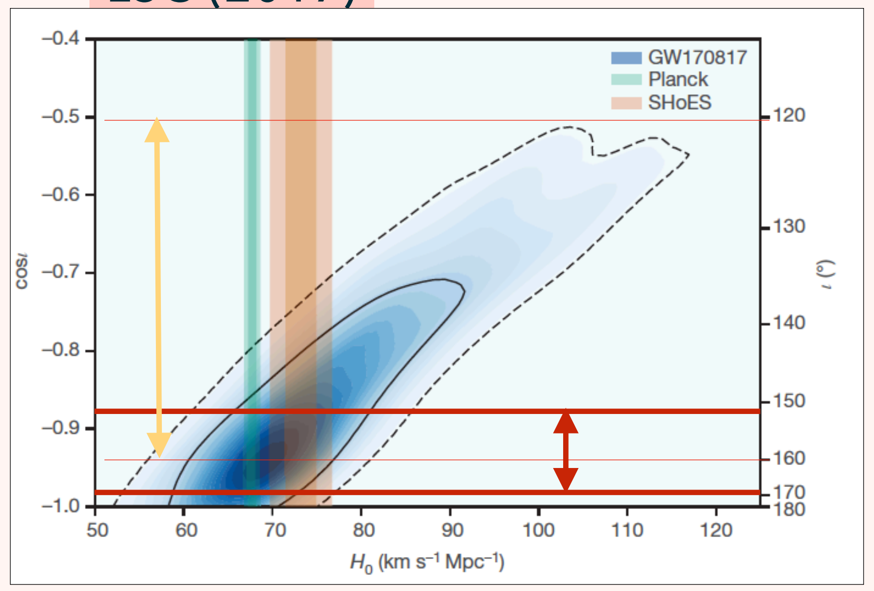
Can we constrain the inclination angle?

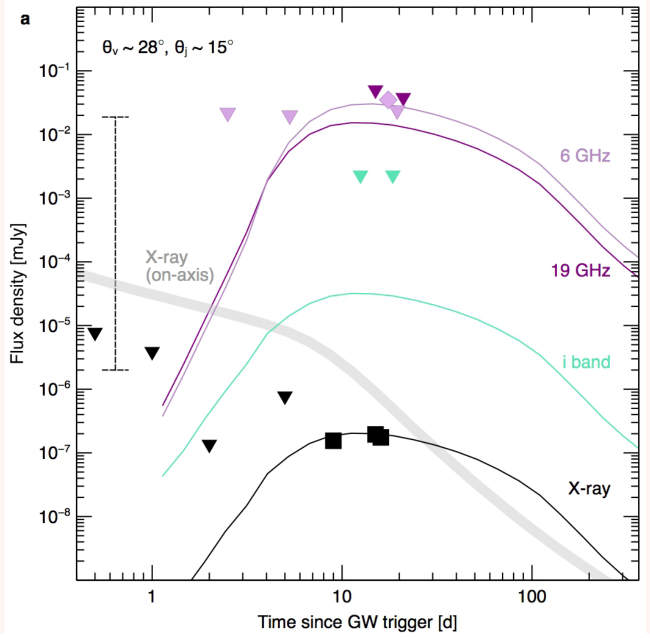
- Binary Neutron Star (BNS) merger will lead to the short Gamma-ray Burst (GRB) and Kilonova
- If the GRB is observed, together with the GWs, the line of sight should lie within the opening angle (θ_j) of the jet, which is perpendicular to the orbital plane (i.e., $\iota = \theta_{JN} = 0$), and the uncertainty in ι is smaller than θ_j
- Also synchrotron radiation in radio could constrain ι.
- On the other hand, kilonova lightcurve in optical/IR alone is not sensitive to ι.
- Example: GW170817. $20^\circ \lesssim \iota \lesssim 60^\circ$ mostly from radio data. Not enough to reduce the distance error significantly
- In addition discovery of the superluminal radio jet (Mooley et al. 2019) is claimed to give the range of the inclination angle more tightly ($14^\circ \lesssim \iota \lesssim 28^\circ$). Early detection of electro-magnetic (EM) counterpart is very important for adding more BNSs with optical counterpart: (eg. 7Dimensional Telescope)

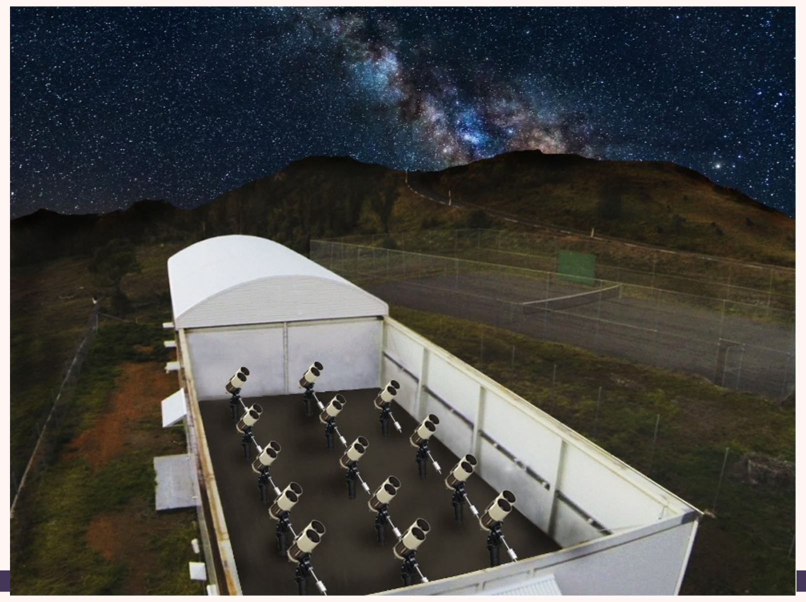


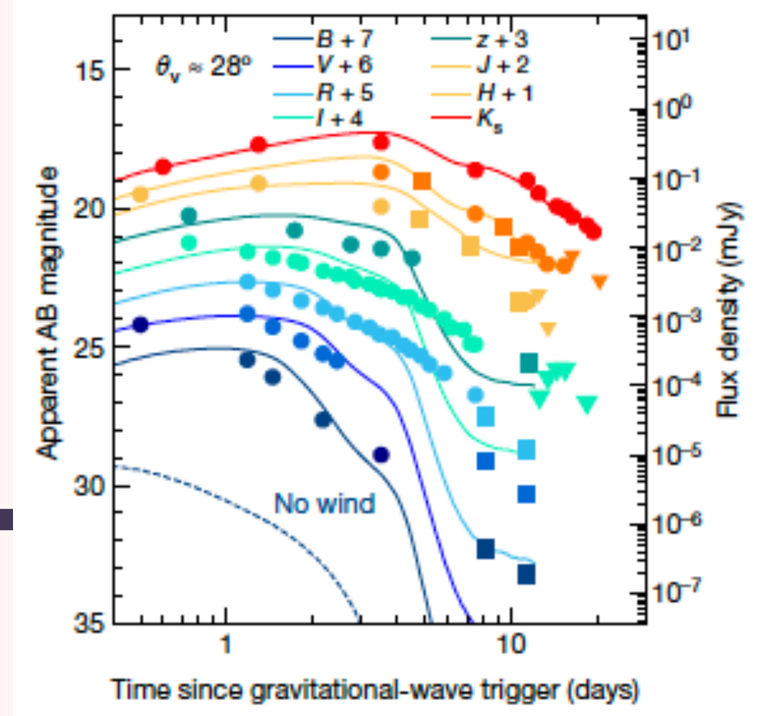
Troja et al. 2017

LSC (2017)







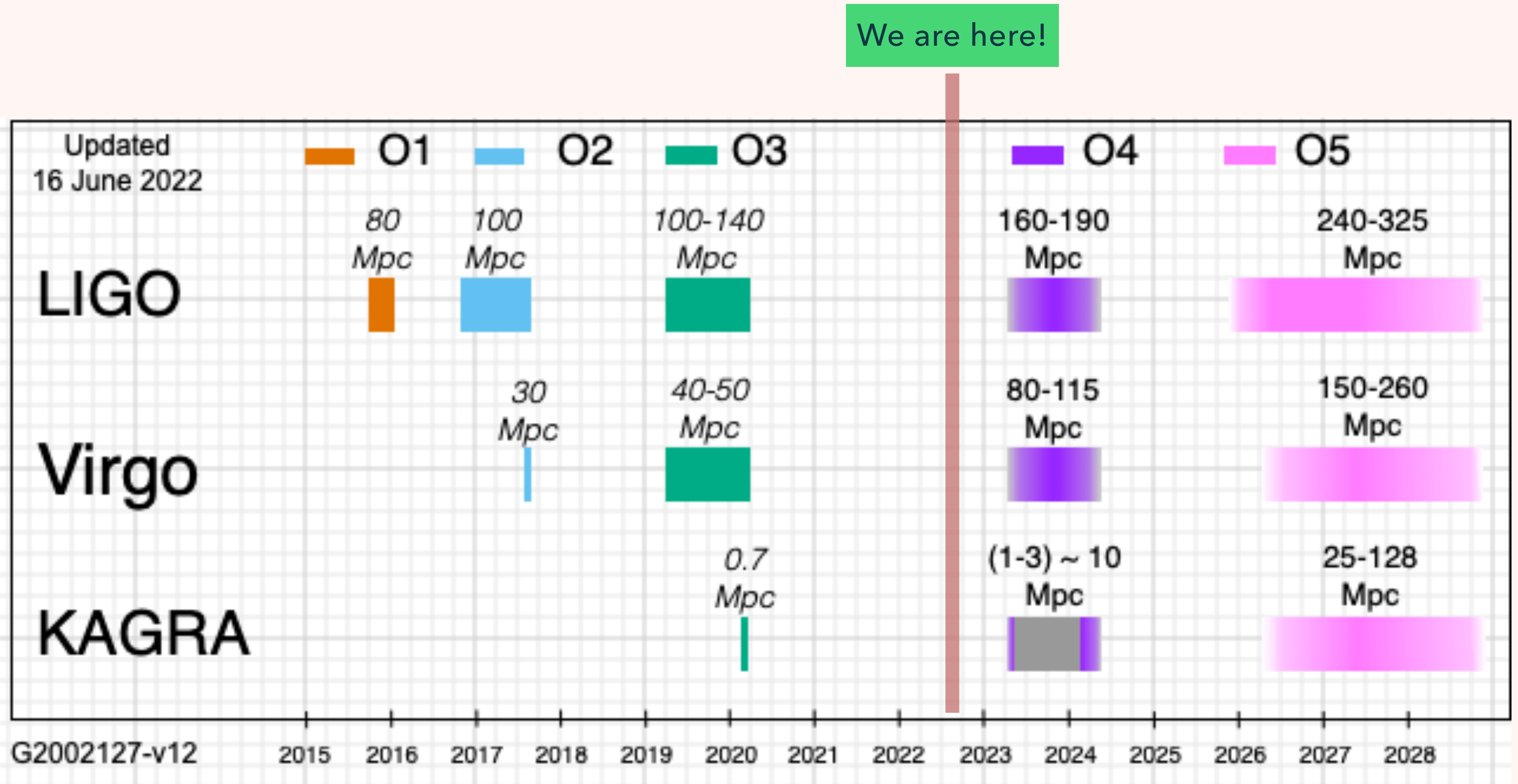


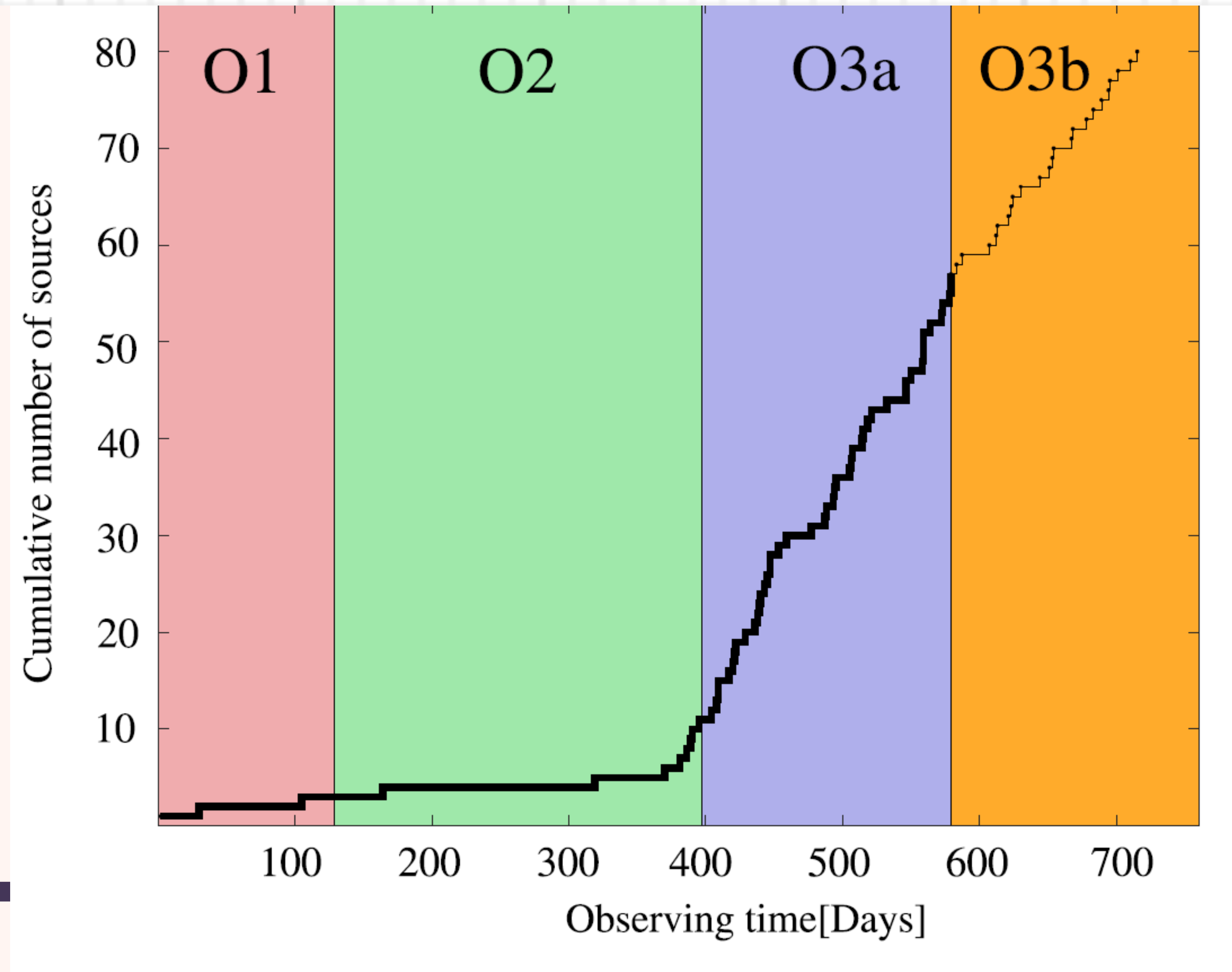
Determination of Hubble Constant

- GW data does not yield redshift.
- Redshift can be measured if either the source itself emits EM radiation or host galaxy can be identified in other ways.
  - **Bright Siren [NS-NS or NS-BH]**: GW sources with optical counterpart. Host galaxy can be identified if the EM emission after the merger is observed
    - Example: GW170817
    - Host identification is difficult even for bright sirens because of large uncertainties in set localization
    - The EM emission after the merger of BNS is not bright and fades away very quickly
  - **Dark Siren [BH-BH]:** GWs without optical counterpart. Host galaxy cannot be uniquely identified, but statistical analysis can be applied.
    - Example: most of the other GW sources.
    - Because of large uncertainties in sky localization, BBH events gives large uncertainties in Hubble constant even though the number is large.
  - Combination of BOTH.

Current Status of GW Observations

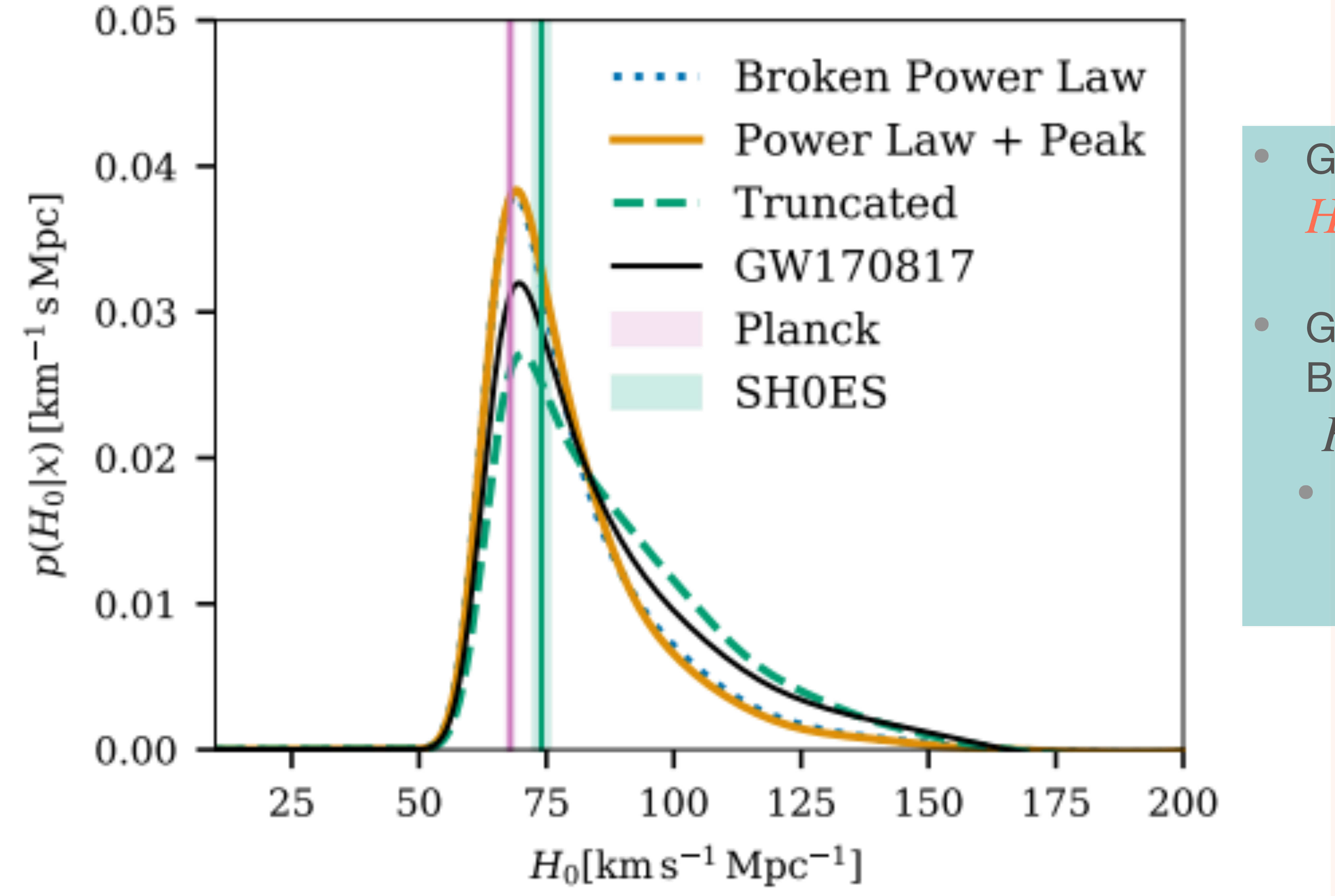
- LIGO-Virgo-KAGRA finished the third observing run (O3) at the end of March 2021
- Catalogue of the sources was released on November 5, 2021 (GWTC-3, arXiv:2111.03606)
- GWTC-3 contains 90 sources:
  - 2 Binary neutron stars (BNS)
  - 2 NS-BH binaries
  - 86 Black hole binaries (BBH)
- Next observing run will start in late 2022 with better sensitivities and more detectors (i.e., KAGRA)





Current status of H_0 measurement with GWs

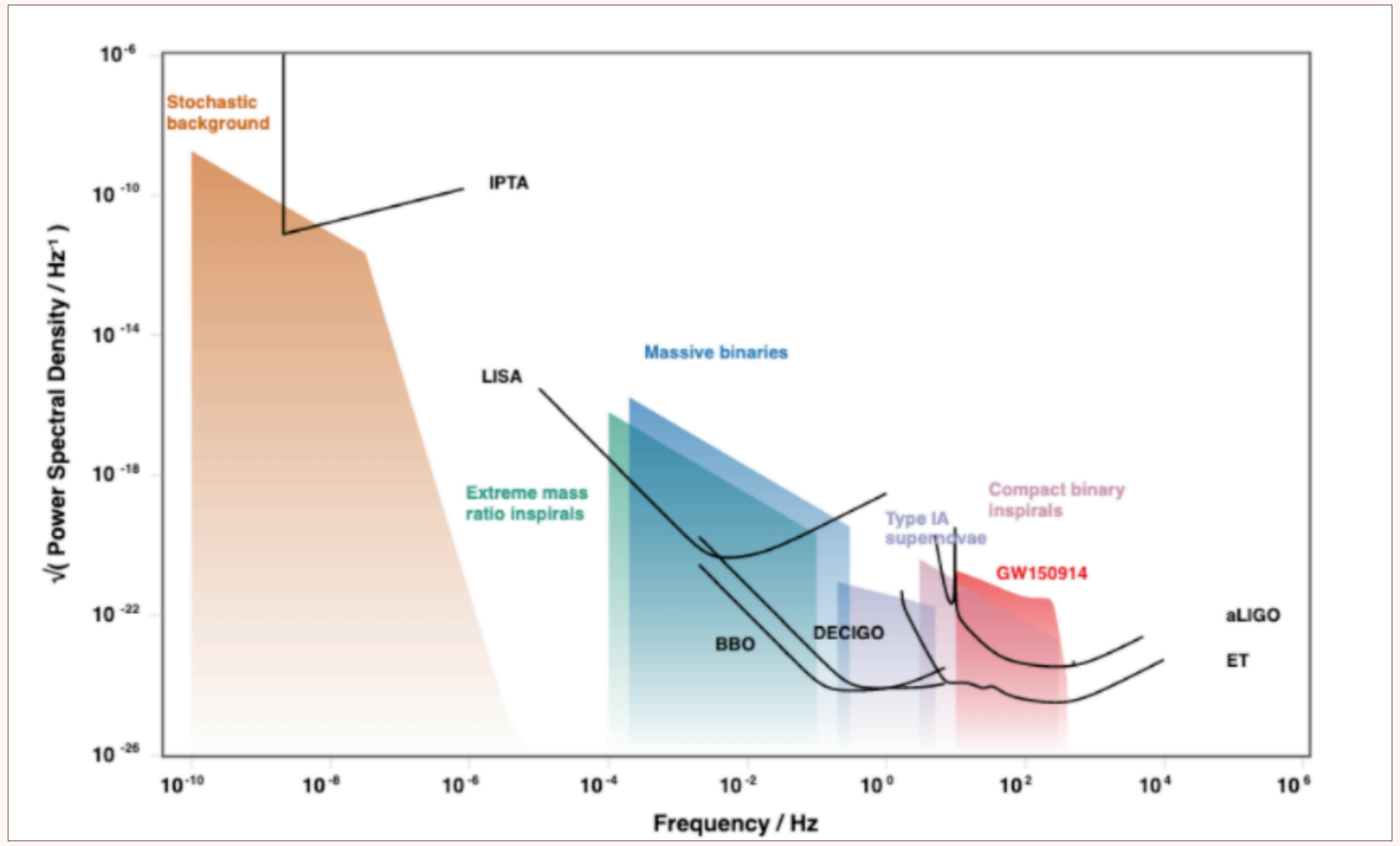
arXiv:2111.03604V1

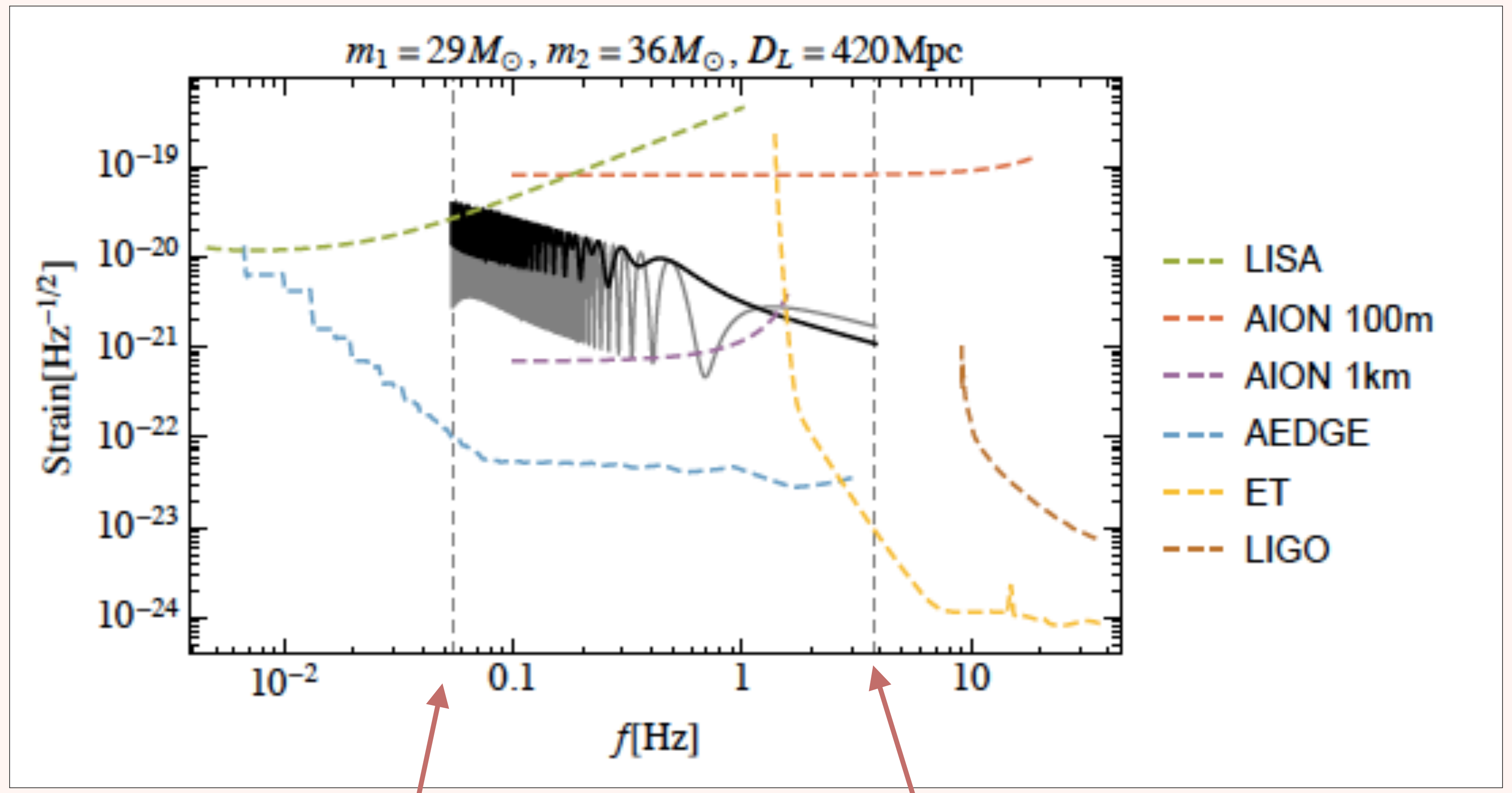


- GW170817 alone:
  $H_0 = 69^{+17}_{-8}$ km/sec/Mpc
- GW170817 (Bright Siren) + 42 BBH (Dark Sirens)
  $H_0 = 68^{+12}_{-7}$ km/sec/Mpc
  - Improvement of 13% compared to bright siren alone

Observations with mid-frequency detectors

- The frequency and amplitude of GWs from merging binaries increases toward the final merger.
- Detectors operating at lower frequencies can observe the merging binaries for a long time (days to years)
- Information about the source position and inclination angle are encoded in the measured signal through
  - Relative amplitudes and phases of the two polarization components,
  - Periodic Doppler shift imposed on the signal by the detector's motion around the Sun,
  - Further modulation of the signal caused by the detector's time-varying orientation.
- Accuracies of localization (Ω) and d_L can be significantly improved





60 days before merger

1 minute before merger

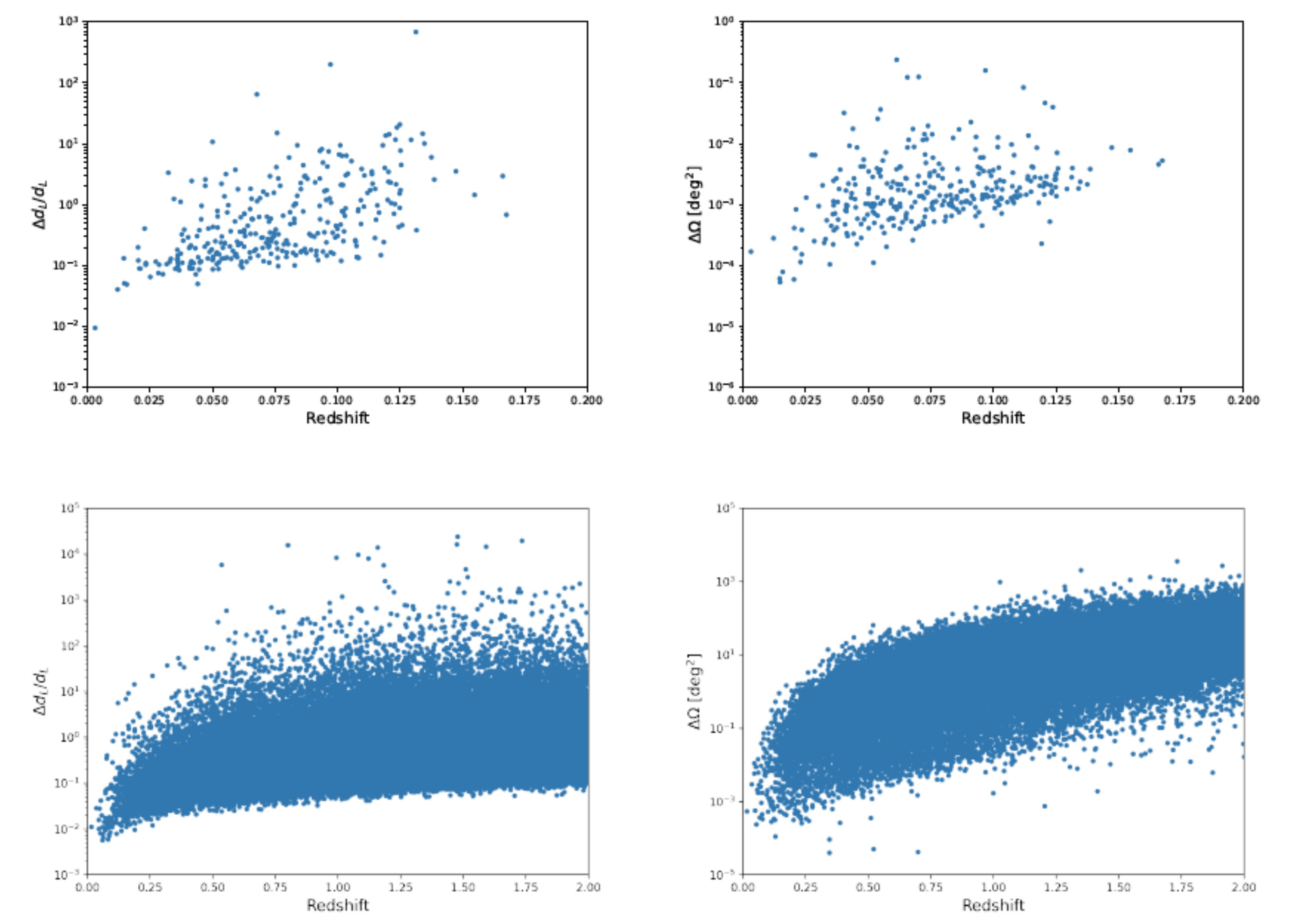
A case study: Simulation of BBH and BNS observations with AEDGE (Yang, Lee+, 2022)

- Sky localization error

$$\Delta\Omega = 2\pi|\sin\theta|\sqrt{\Gamma^{-1}_{\theta\theta}\Gamma^{-1}_{\phi\phi} - (\Gamma^{-1}_{\theta\phi})^2}$$

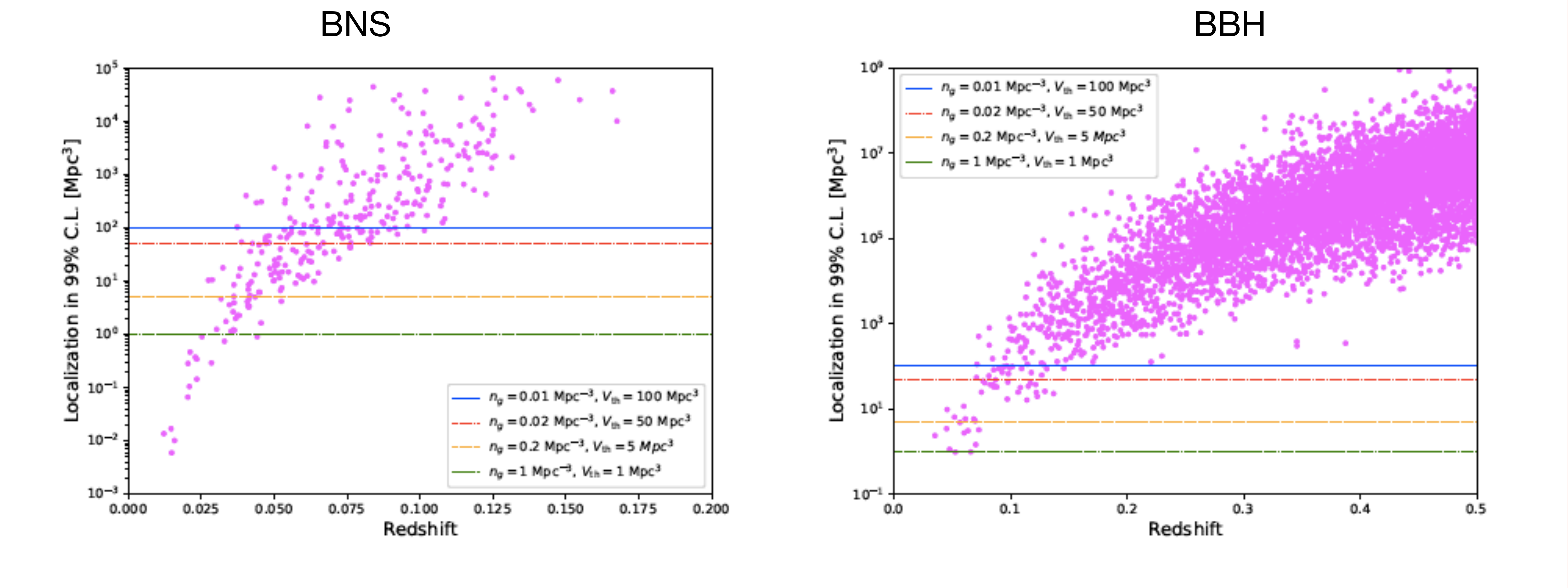
where $\Gamma_{ij} = \left(\frac{\partial h}{\partial \lambda_i}, \frac{\partial h}{\partial \lambda_j}\right)$ is Fisher matrix.

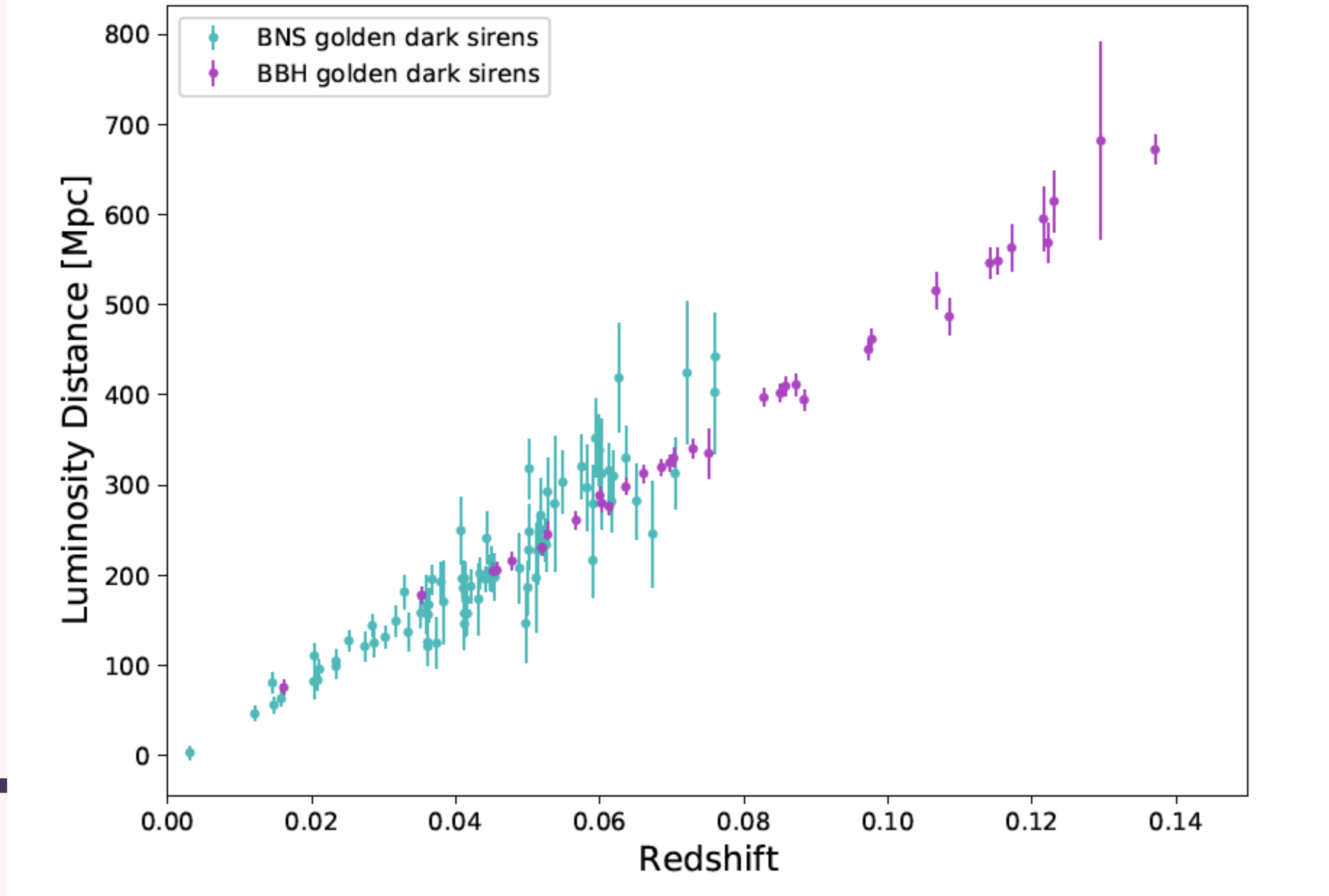
BNS BBH



Simulated results for 5 year run of AEDGE

Simulations of BBH mid-freq. detector

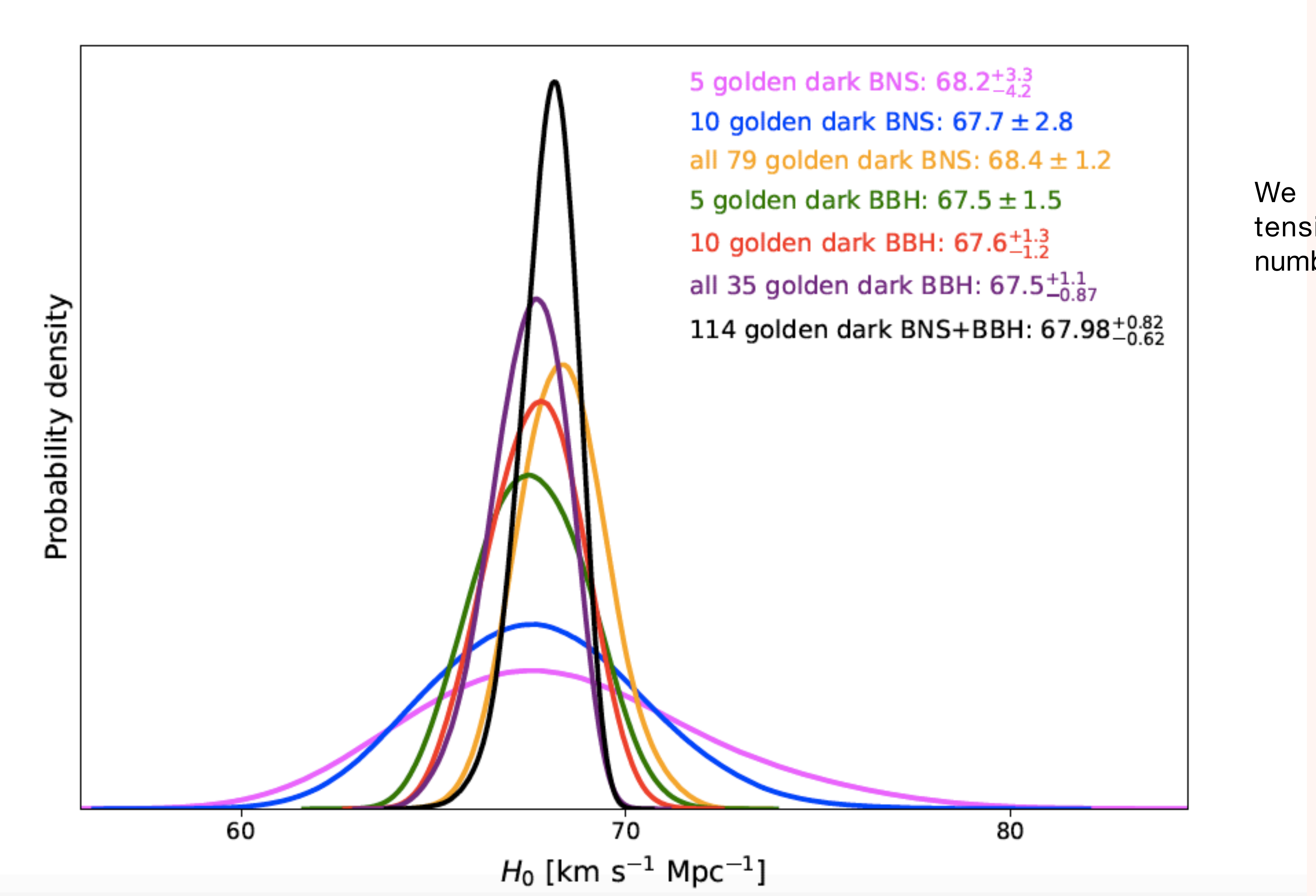




Golden Events: Various cuts are assumed galaxy number densities: below these lines, we can uniquely identify host galaxies within 5 year observation

Simulated Hubble Diagram

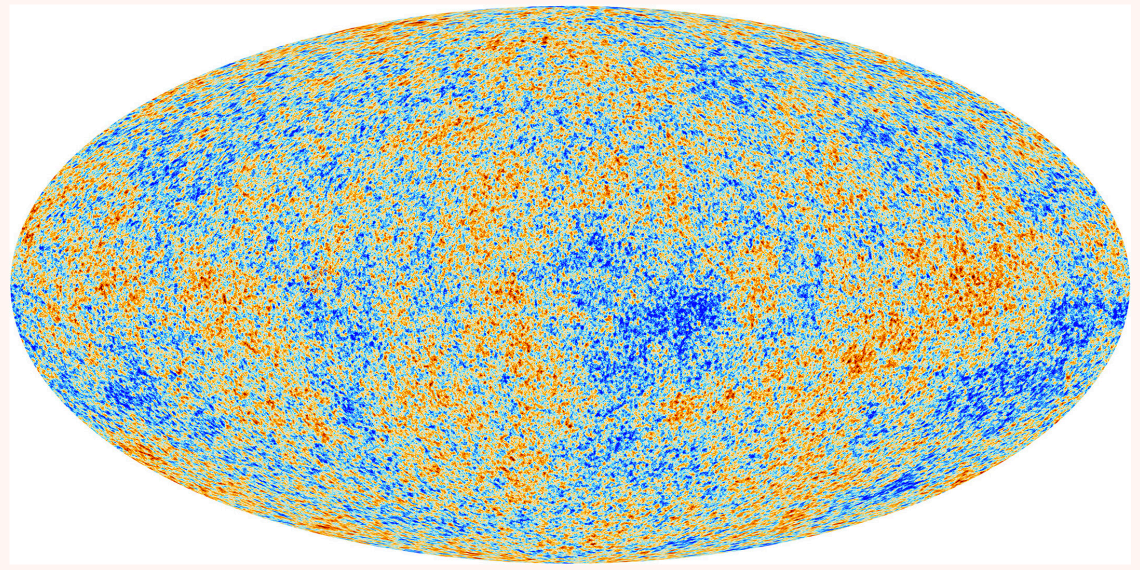
Hubble Constant Estimation from Dark Sirens

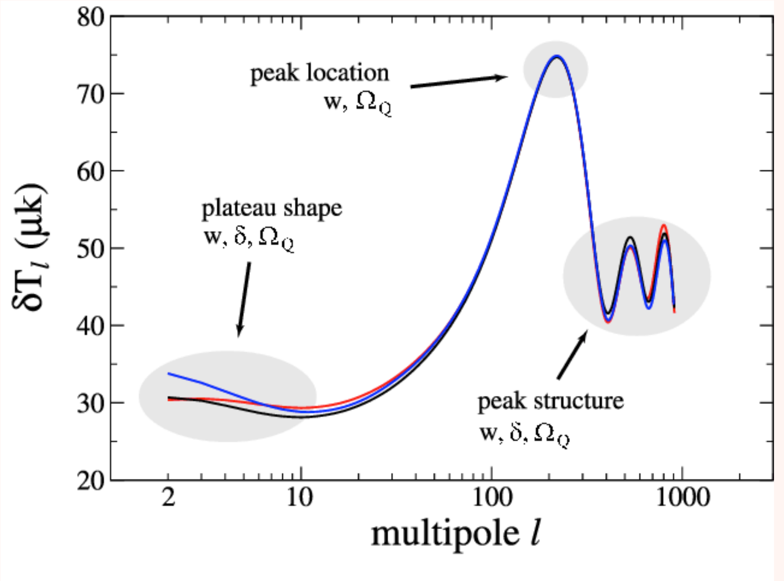


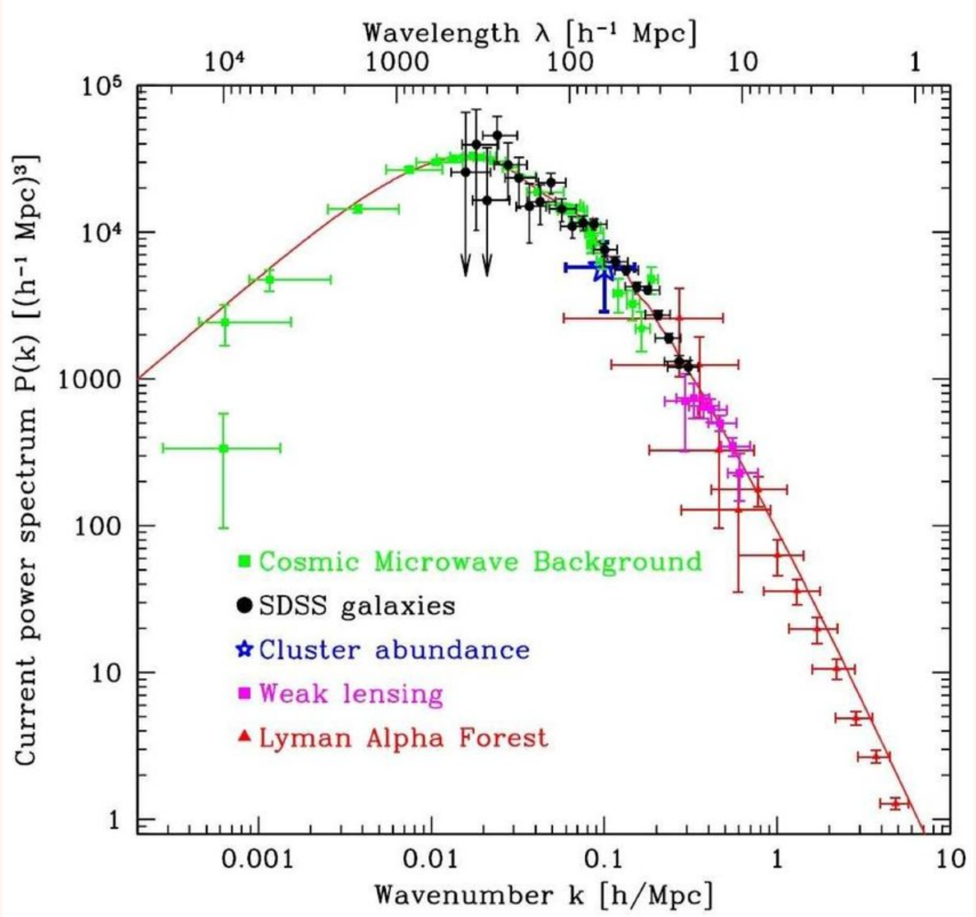
We can resolve Hubble tension even with small number of golden events

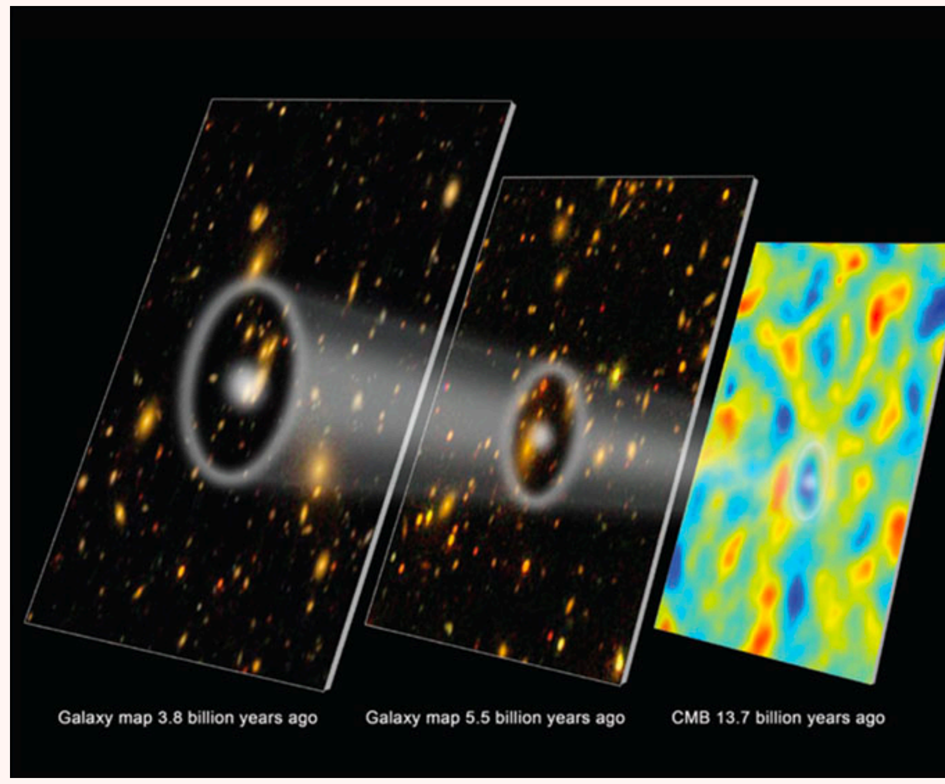
Large Scale Structure as Cosmological Probes

- Large scale structure depends on various parameters and physics, including cosmic expansion history
- Examples:
  - CMB Power spectrum
  - Galaxy power spectrum
  - Two-point correlation functions in redshift space and Baryonic Acoustic Oscillation (BAO)
  - Alcock-Pacyzinski Test
  - Genus statistics
  - Weak lensing
  - ....



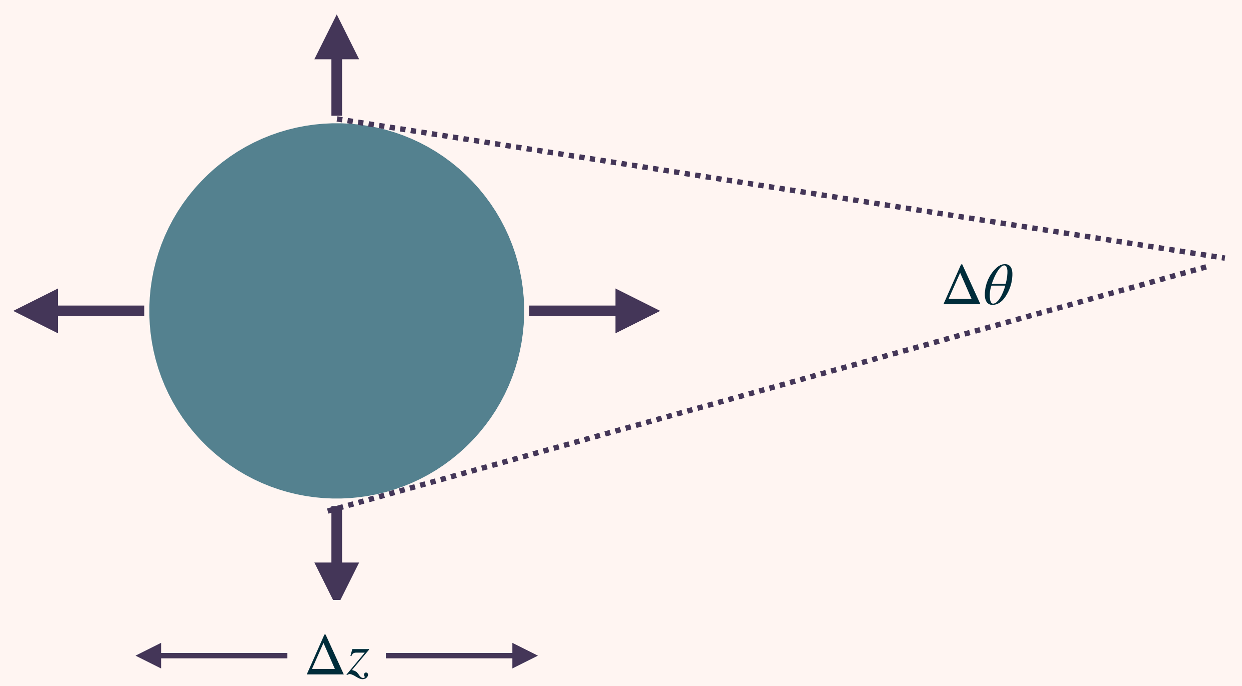






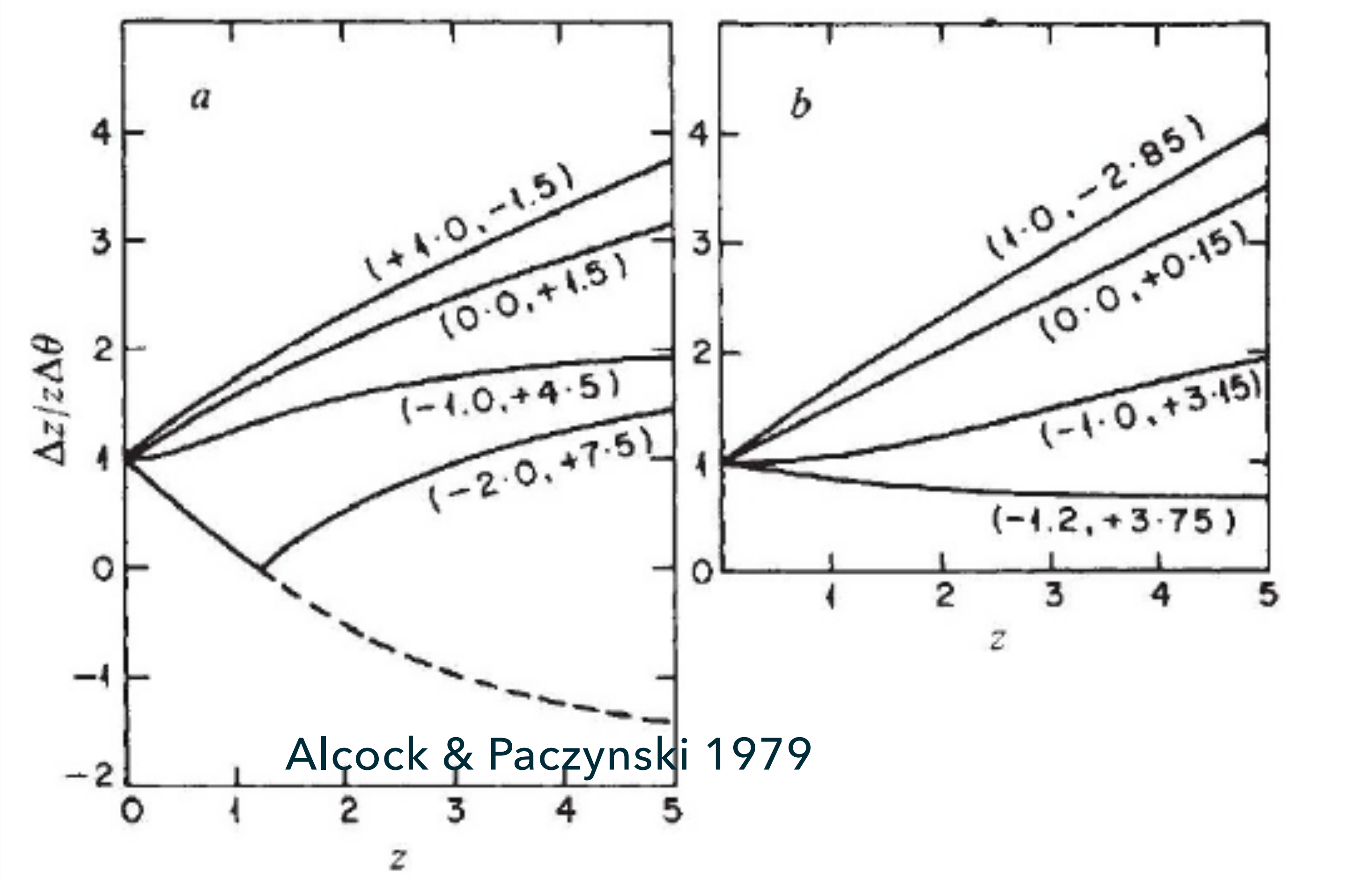
Alcock-Paczynski Test

- For any isotropic system, its extent must on average be the same both along the line of sight and across the line of sight.
- A spherical object will have different line-of-sight and angular sizes depending on cosmological parameters.
- This test is highly sensitive to the Cosmological Constant
- The cross-correlation of GWs and redshift surveys can give accurate estimation of cosmological parameters(Mukherjee & Wandelt 2018)



$\frac{\Delta z}{z\Delta\theta}$ is very sensitive to cosmological parameters

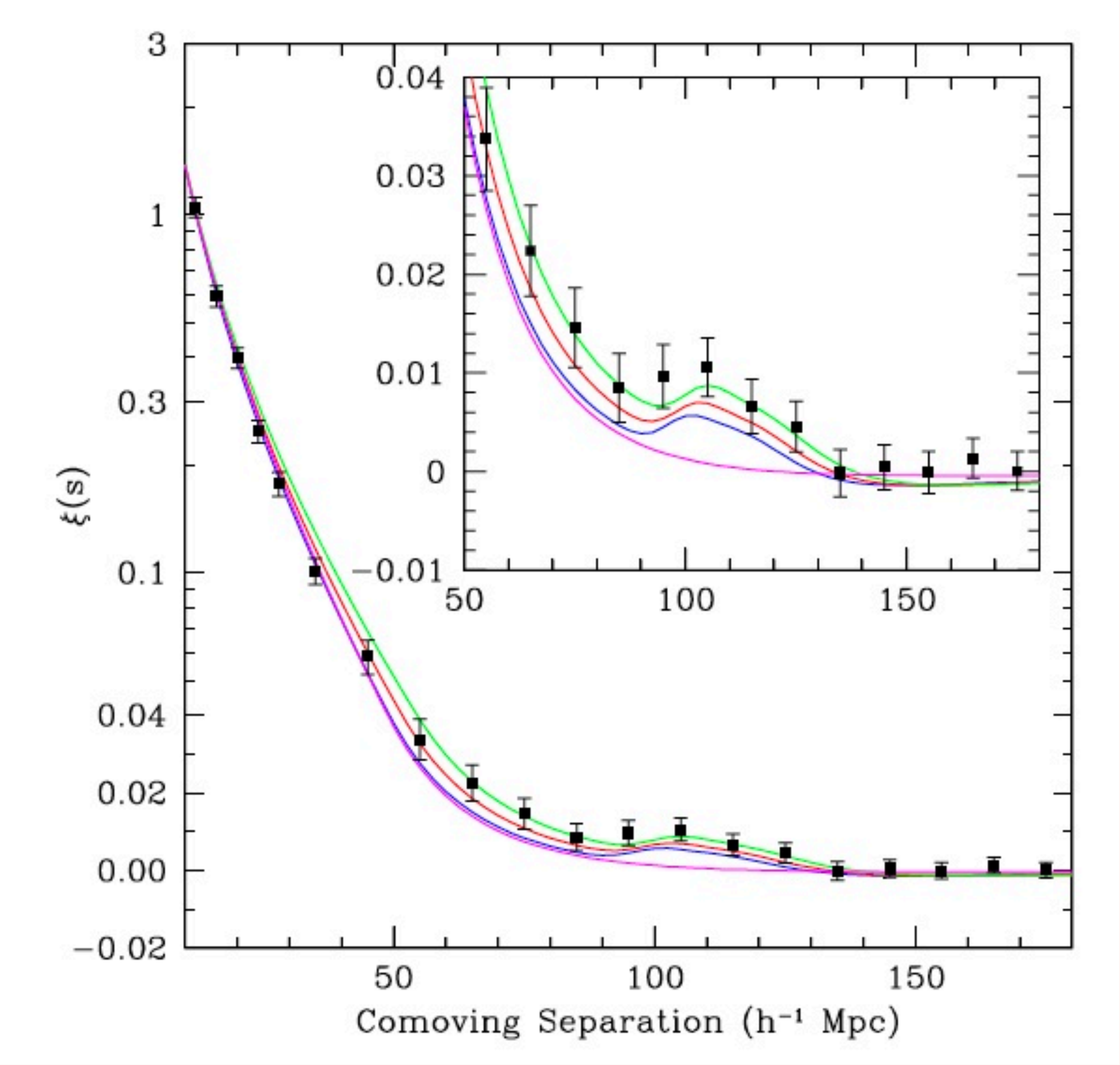
$(q_0,\ 1.5\Omega_0 - q_0)$



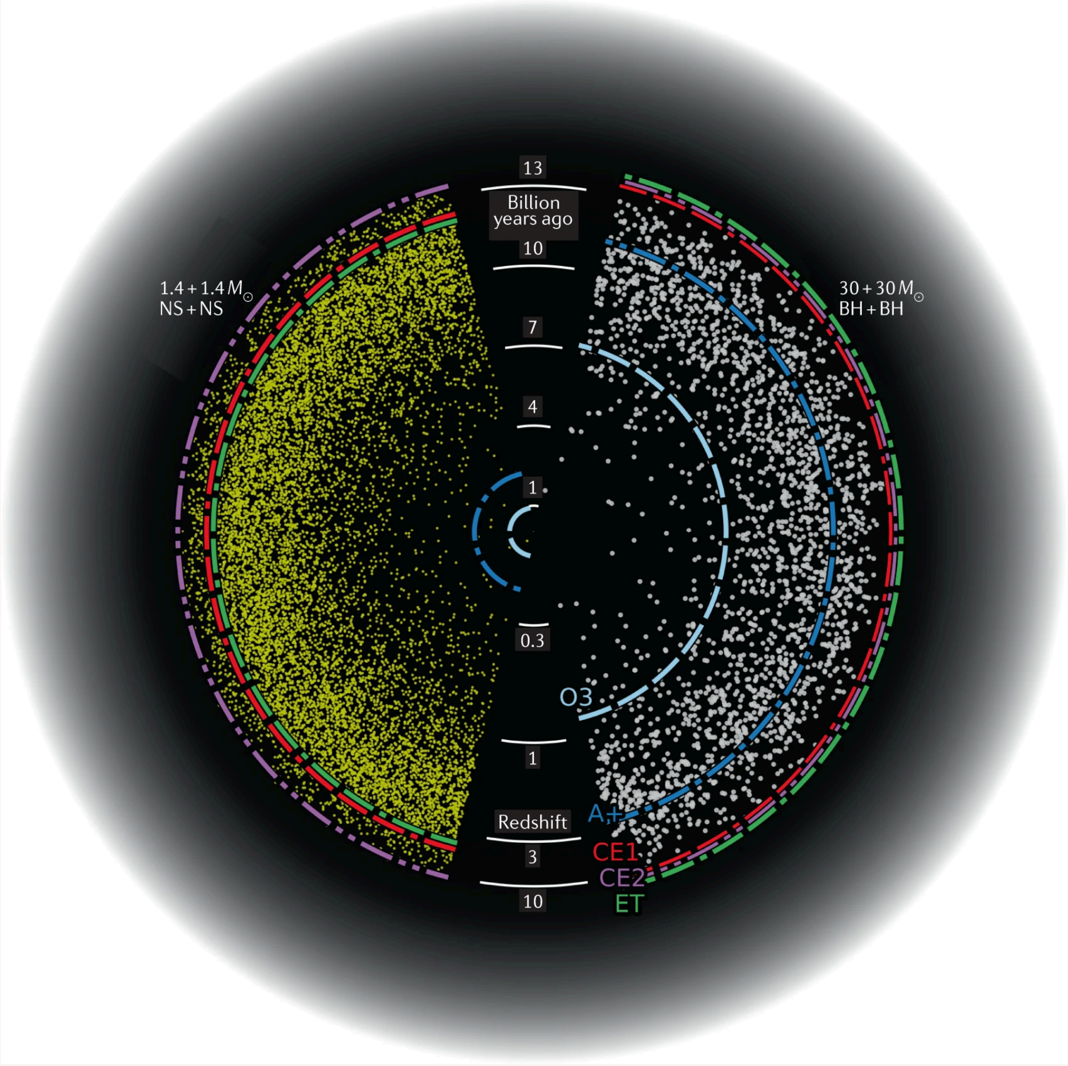
Alcock & Paczynski 1979

Cross-correlation of Redshift and Distance Surveys

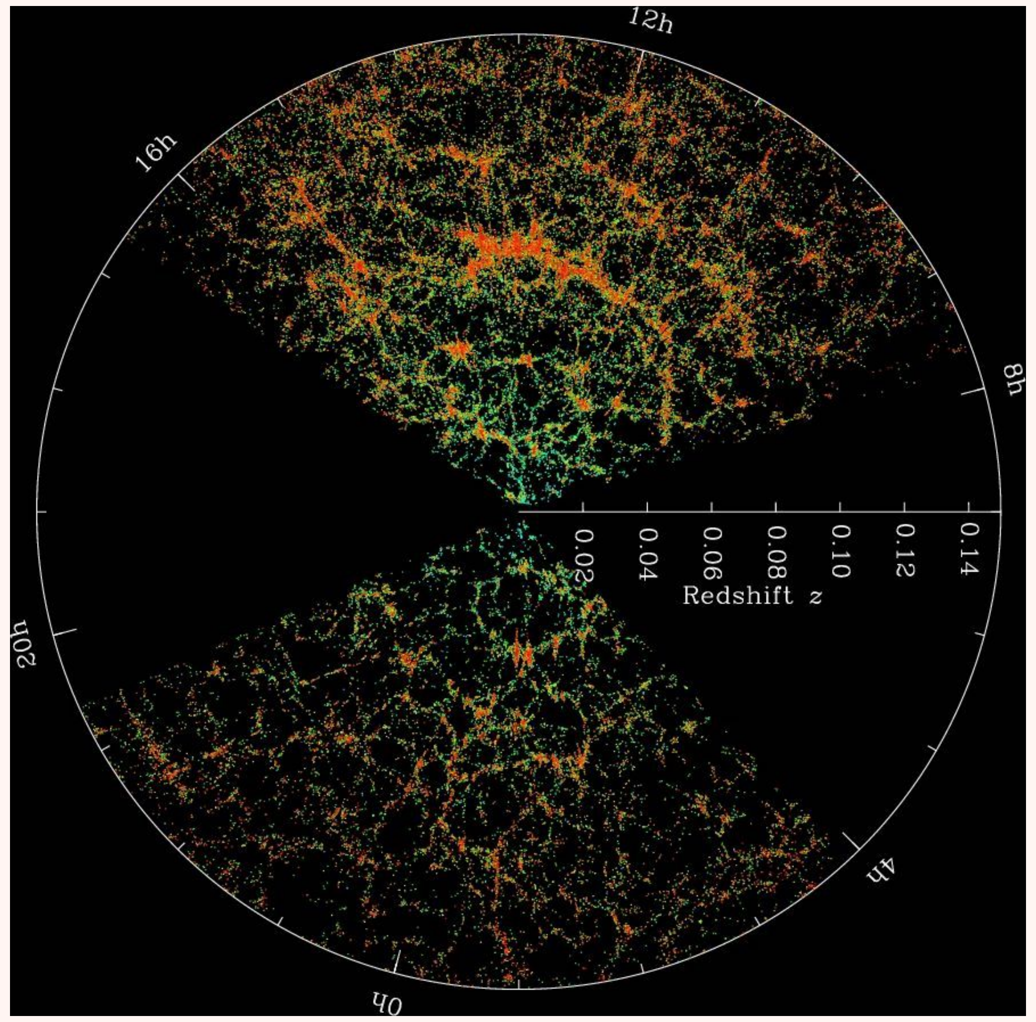
- If we assume that both GW sources and galaxies follow (isotropic) matter density field, we can make accurate estimation of cosmological parameters with high precision by cross correlating GW sources and galaxies in redshift surveys (Mukherjee et al., 2018, 2021)
- $dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$: Generalization of Alcock-Paczynski test



Eisenstein et al. 2005

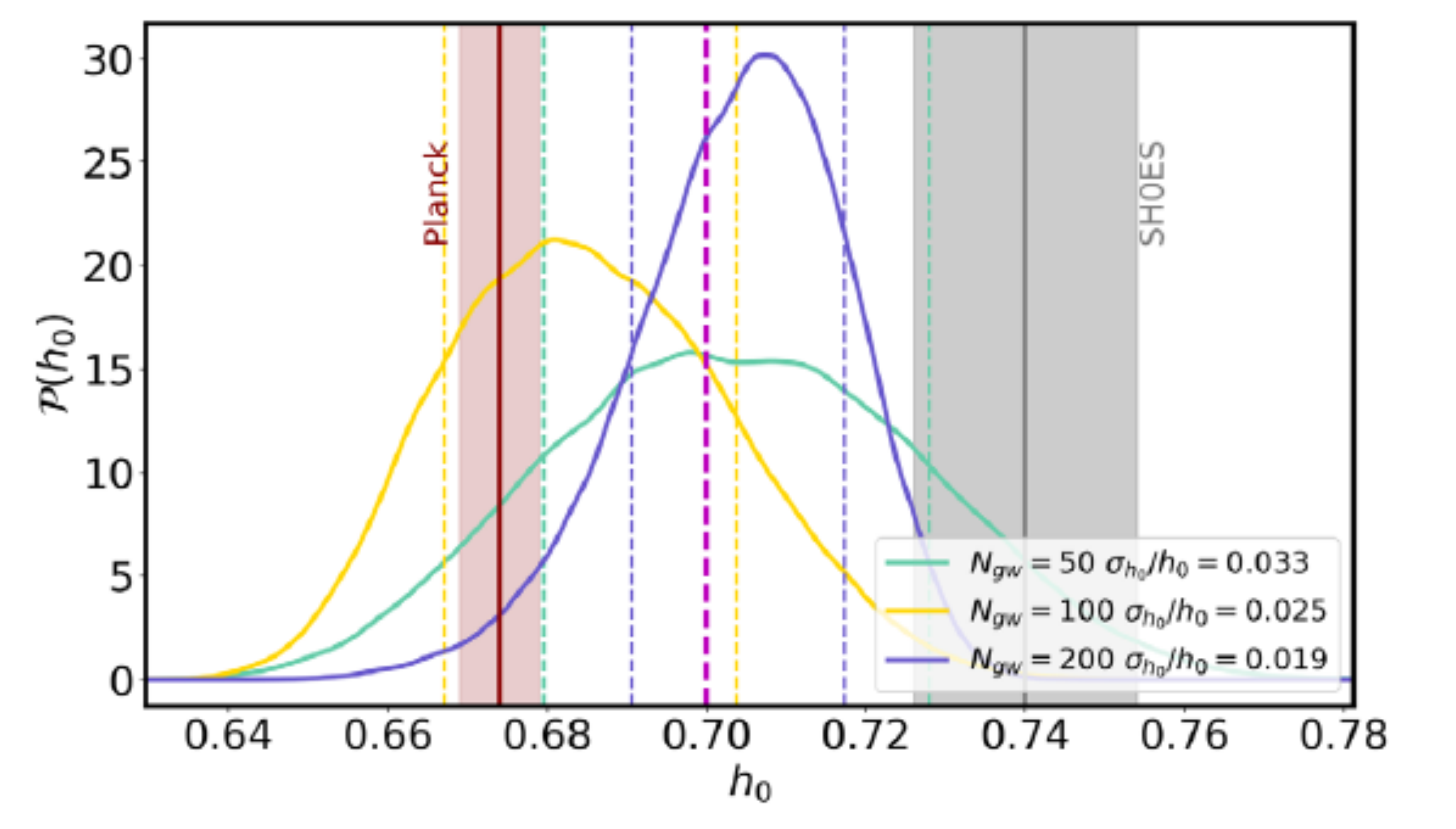


x



Simulated result (Mukherjee et al. 2021)

- Generation of mock galaxy sample of 1.5 $\times 10^4$ at $0 < z < 1.0$.
- Gravitational wave sources are sampled from the same density field.
- The luminosity distance errors (σ_{d_L}/d_L) and localization errors ($\Delta\Omega_{GW}$) depend on the signal-to-noise ratio of the GW detections.
- 200 BBH with $\Delta\Omega_{GW} < 10$ sq. degrees up to $z < 0.5$ would be able to determine H_0 within 2%, after marginalizing various cosmological parameters.

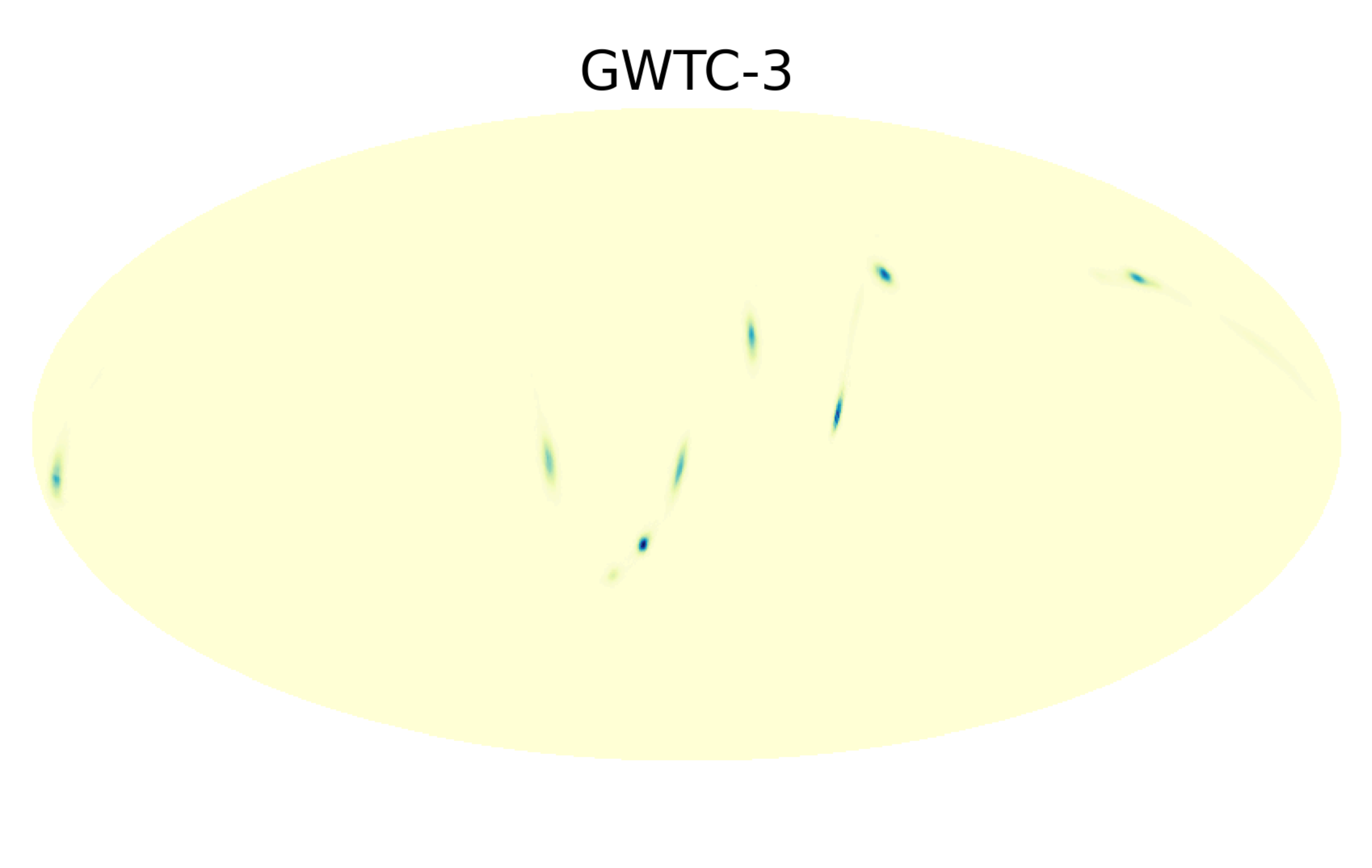


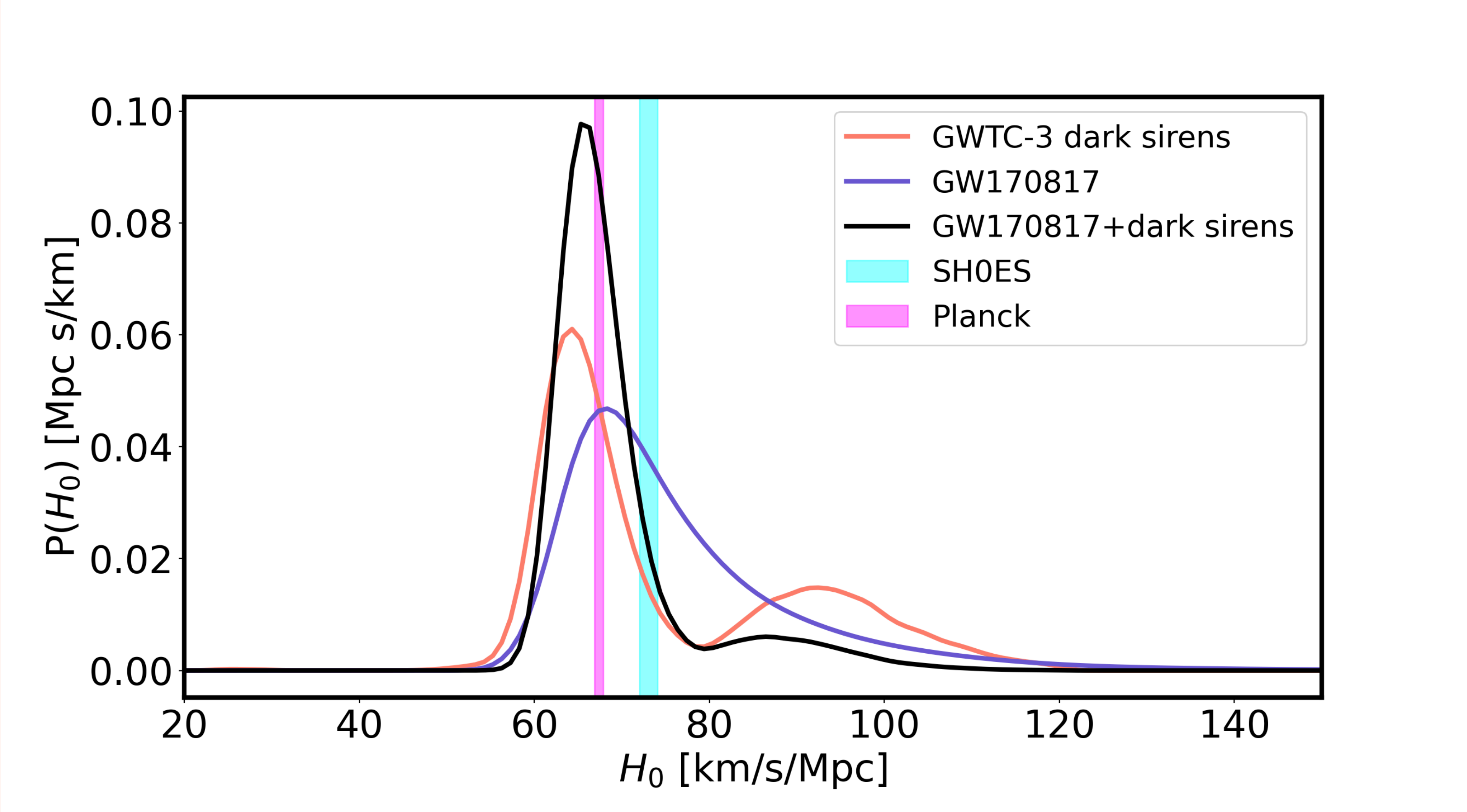
Mukherjee et al. 2021, PRD, 103, 043520

Injected $H_0 = 70$ km/sec/Mpc

Cross-correlation study of dark sirens with galaxies

- Mukherjee et al. (arXiv:2203.03643) carried out a cross-correlation study of selected dark sirens from GWTC-3 and photometric galaxy surveys.
- GW sources with SNR>11 and $\Delta\Omega \leq 30$ sq. degrees are selected from GWTC-3.
- As for correlating galaxies, they used 2MASS Photometric Redshift catalog [2MPZ] and WISE cross SuperCoSMOS Photometric Redshift catalogue [WSC]
- Results
  - Dark siren alone: $H_0 = 68.2^{+26.0}_{-6.2}$ km/s/Mpc ($H_0 = 67^{+13}_{-12}$ km/s/Mpc from dark siren measurement by LVK)
  - With GW170817: $H_0 = 67.0^{+6.3}_{-3.8}$ km/s/Mpc
- Still GW170817 plays very important role in constraining H_0.





Spectroscopic Survey Projects

- SPHEREx Mission (~2025)
  - A MIDex program for all-sky imaging spectroscopic survey in near infrared. KASI is the only international partner.
- A-Spec using K-Spec Multi-Object Spectrograph (MOS) (~2025)
  - A spectroscopic survey project currently pursued by the Korean group (KASI, KIAS, SNU….)
  - It will use one of the 1.5m KMTNet telescopes, and fiber-fed spectrometer.
  - It aims to make a complete redshift for ~770K galaxies (among which ~450 K galaxies without z)
  - Most of the galaxies are within z<0.15: very useful to cross-correlation analysis with GW sources
- 7 Dimensional Telescope (7DT, ~2023)

Figure by Jae-Woo Kim, SSG Workshop 2022

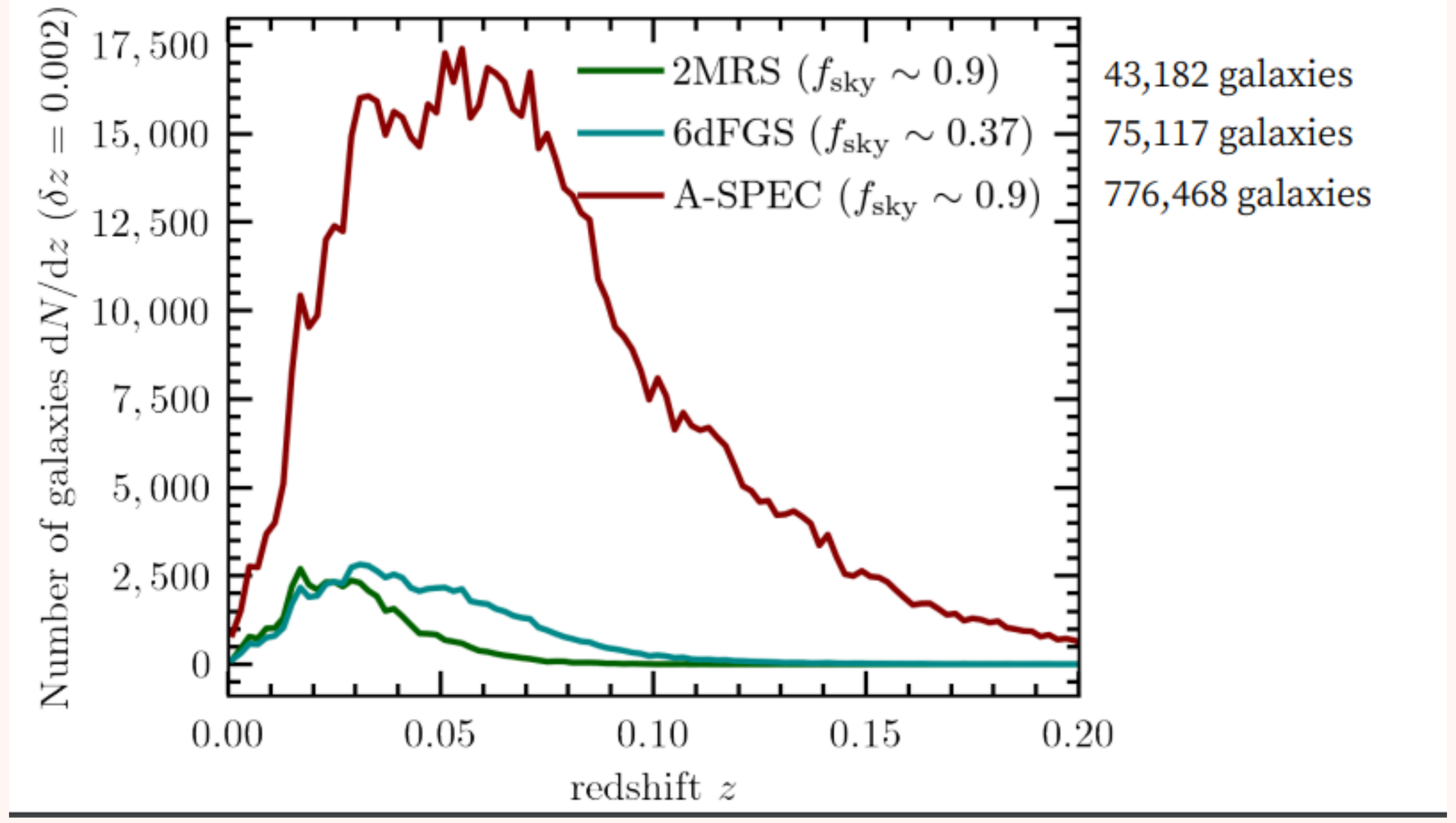


Figure by Donghui Jeong, SSG Workshop 2022

Summary

- GWs from compact binary coalescence allow us to determine distances without 'calibration' process.
- If distance estimation becomes accurate, and host galaxies can be identified, we can use GWs to reconstruct the cosmic expansion history completely independent of other methods.
- At the moment, estimated distances contain large (random) errors and host identification is difficult. There are various ways for the progress:
  - Significant improvement in distances can be achieved either through other astrophysical input from multi-messenger astronomy (~5 years) for neutron star merger with identified host galaxies
  - When mid-frequency detectors become operational, the improvements in distance and sky localization allow us to uniquely identify host galaxies of several black hole binaries out to $z \sim 0.2$ (~15 years)
  - Alternatively, the cross-correlation of GW sources and galaxies with redshifts can also allow us to determine various cosmological parameters accurately.