Gravitational Waves as Cosmological Probes

WINDOWS ON THE UNIVERSE

30TH ANNIVERSARY OF RENCONTRES DU VIETNAM

August 6-12, 2023

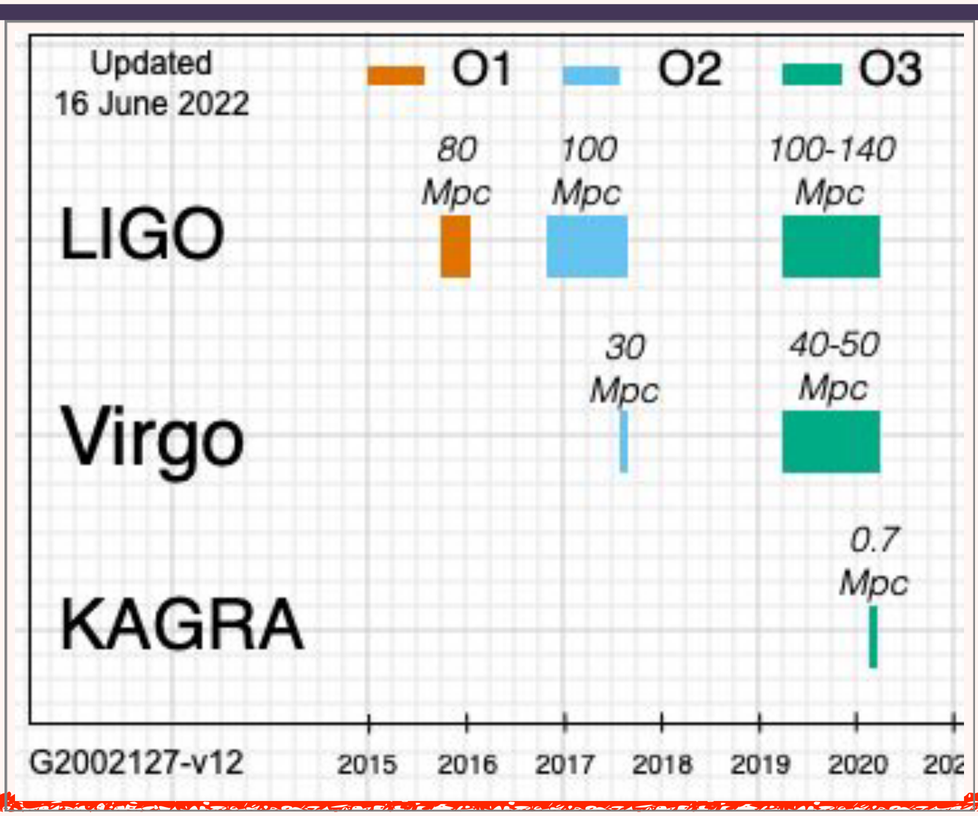
Hyung Mok Lee (Seoul National University)

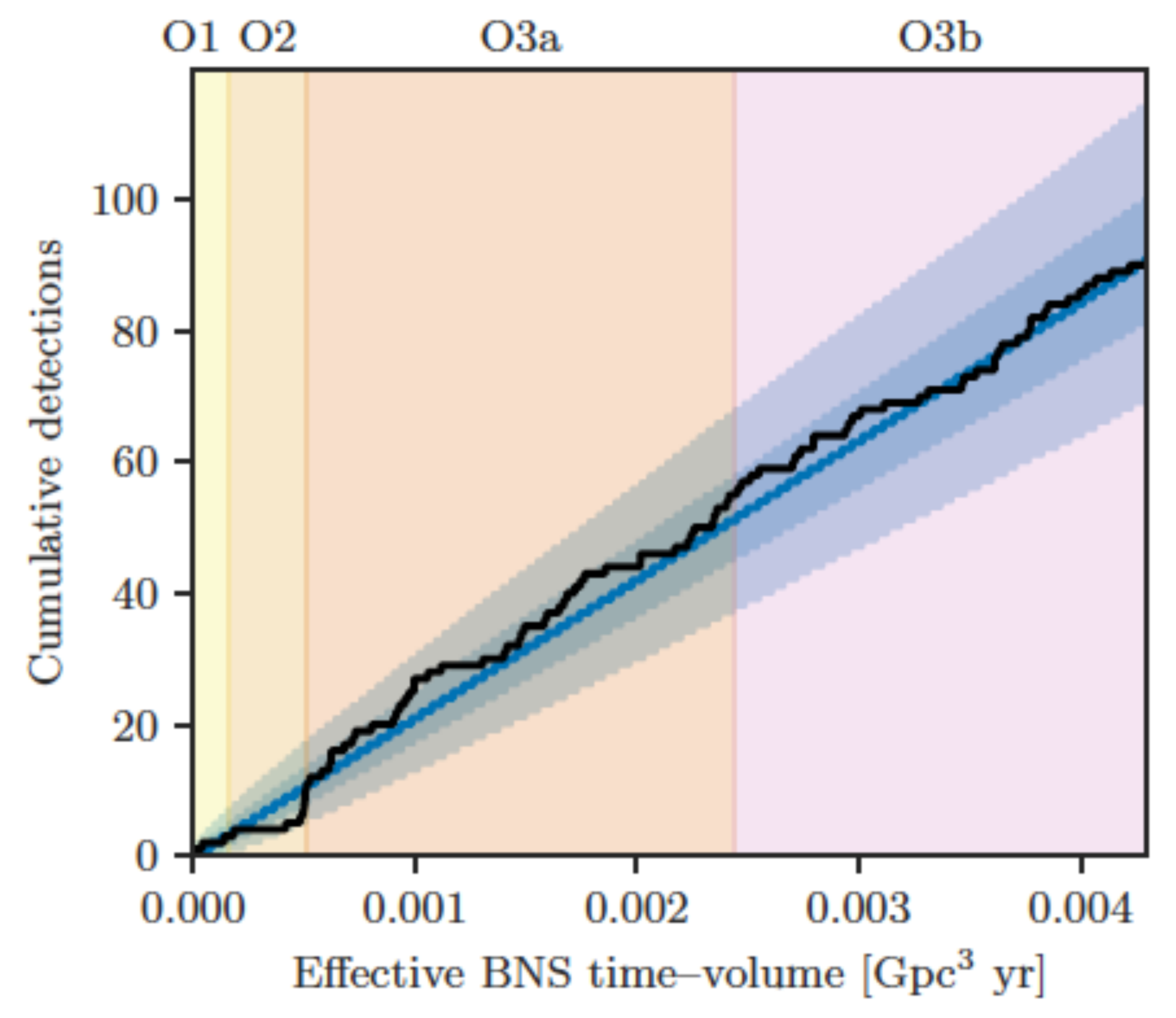
Topics

- Short Summary of the GW observations
- Estimation of Source Parameters
- Bright siren measurement of H_0 and search for EM counterpart
- 7DT: A New Multi-messenger Facility
- Prospects of Dark Siren Measurements

GW Observations by LIGO/Virgo/KAGRA

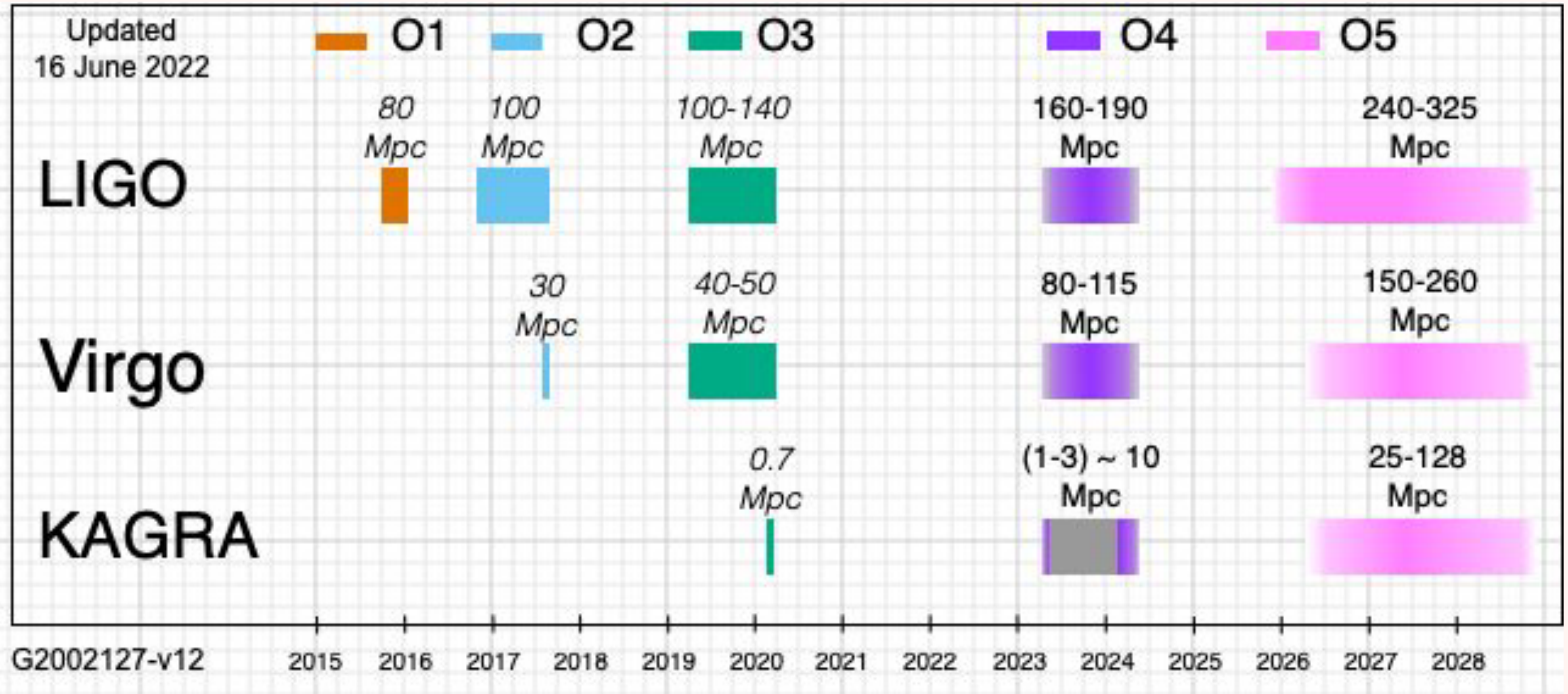
arXiv:2111.03606





- O1-O2: Gravitational Wave Transient Catalogue (**GWTC-1**)
  - 11 events (including 1 BNS)
- Up to O3a: **GWTC-2.1**
  - 55 events (including GWTC-1)
  - 2 BNS, 2 BH-NS
- Up to O3b: **GWTC-3**
  - Total 90 events (2 BNS, 3 BH-NS, 2 uncertain, 83 BBH)

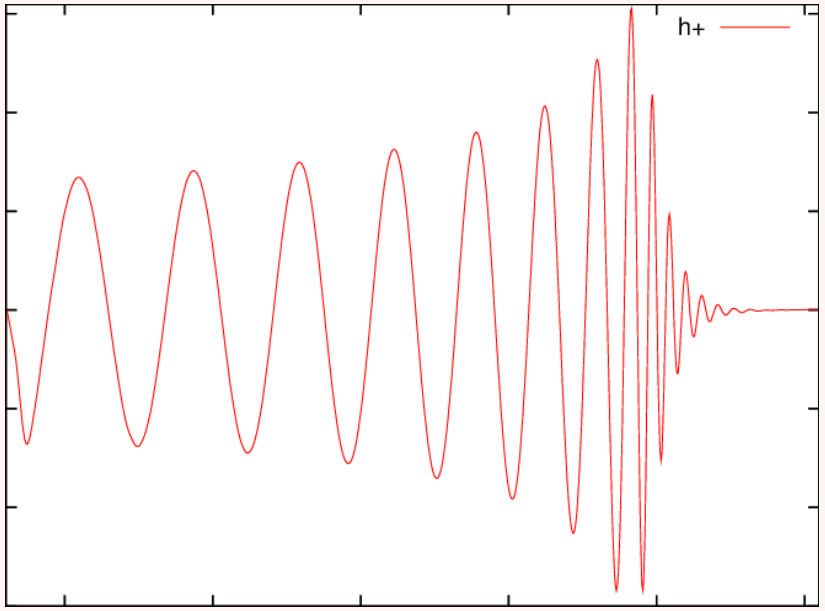
Present and Future Runs: O4 and O5



- O4: 1 year run, split into
  - O4a and O4b (9 months each) with 1 month commissioning break in between.
- O4a: Started on May 24 this year (After ~ 1 month Engineering from April 26)
- Data will be released 18 months after the end of each run

- Expect ~1 event per day:
  - ~ 450 BBH
  - ~ 15 events containing a neutron star
  - ~ 1 multi-messenger BNS
  - + Nature's surprises:

Estimation of Parameters from GW Observations



- What we measure is the waveforms form for certain duration

$$h(t) = F_+(\alpha, \delta, \psi, t_c)h_+(t) + F_\times(\alpha, \delta, \psi, t_c)h_\times(t)$$

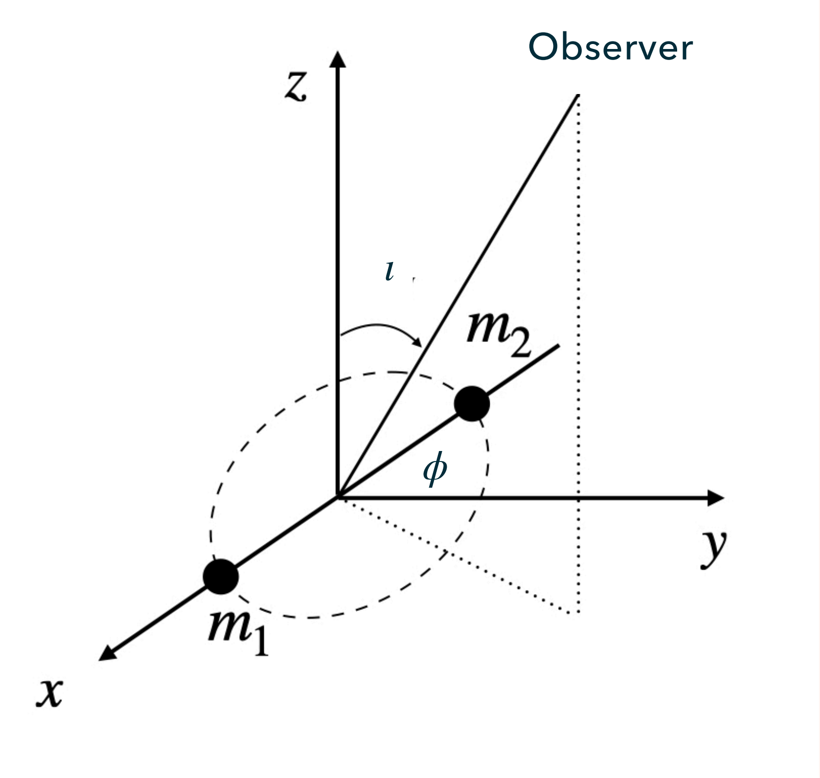
- For circular binaries, 15 parameters are imprinted on the waveforms
  - Intrinsic: m_1, m_2, $\mathbf{s_1}$, $\mathbf{s_2}$ (8)
  - Extrinsic: $\mathbf{\Omega} = (\alpha, \delta)$, ι, d, ψ, t_c, ϕ_c (7)
  - If we ignore spins, the number of parameters reduces to 9.

Polarization angle

Coleascence Phase

- Duration of the observations from frequency f until merger ($f_{merge} \gg f$)

$$T = \frac{f}{\dot{f}} = \frac{5}{96}\pi^{-8/3}\frac{c^5}{\eta(GM)^{5/3}}f^{-8/3}$$



Estimation of Parameters from GW Observations

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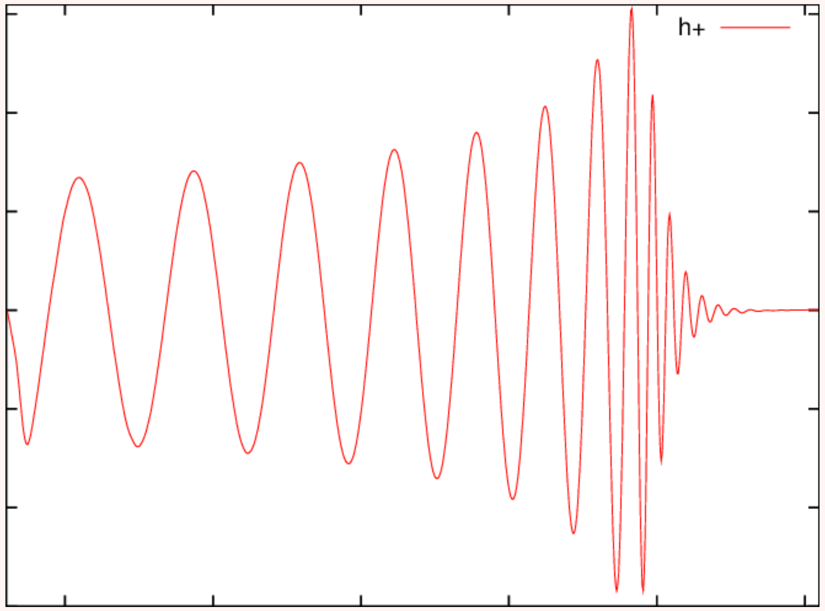
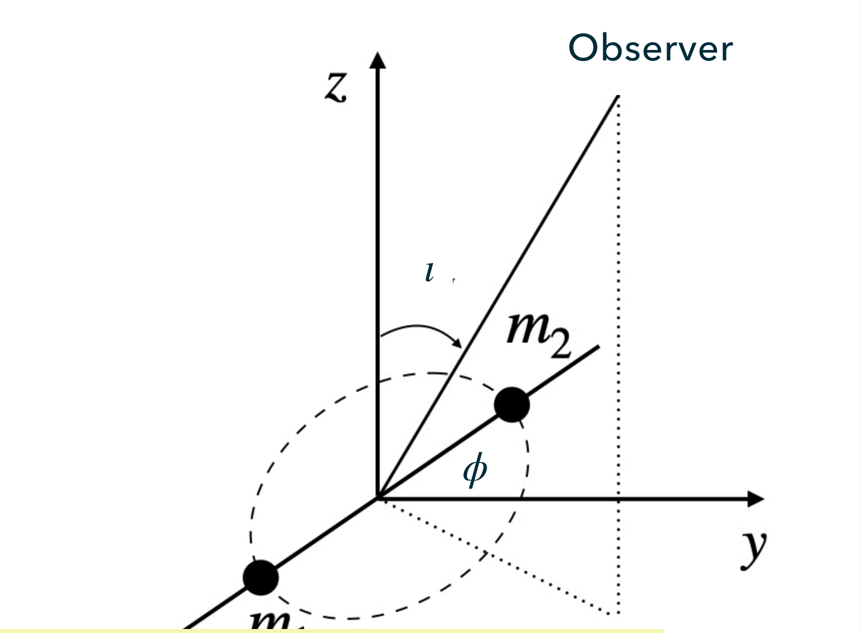




For ground based detectors, $f_0 \sim$ 30 Hz
- $T < 1$ second for BBH
- $T \sim$ minute for BNS

For lower frequency detectors, T could become very long (weeks to years)

Estimation of Distances

- The shape of the waveforms does not depend on distances →masses & spins
- Luminosity distances can be estimated because the amplitude of the GW signal is **inversely proportional** to the distance.

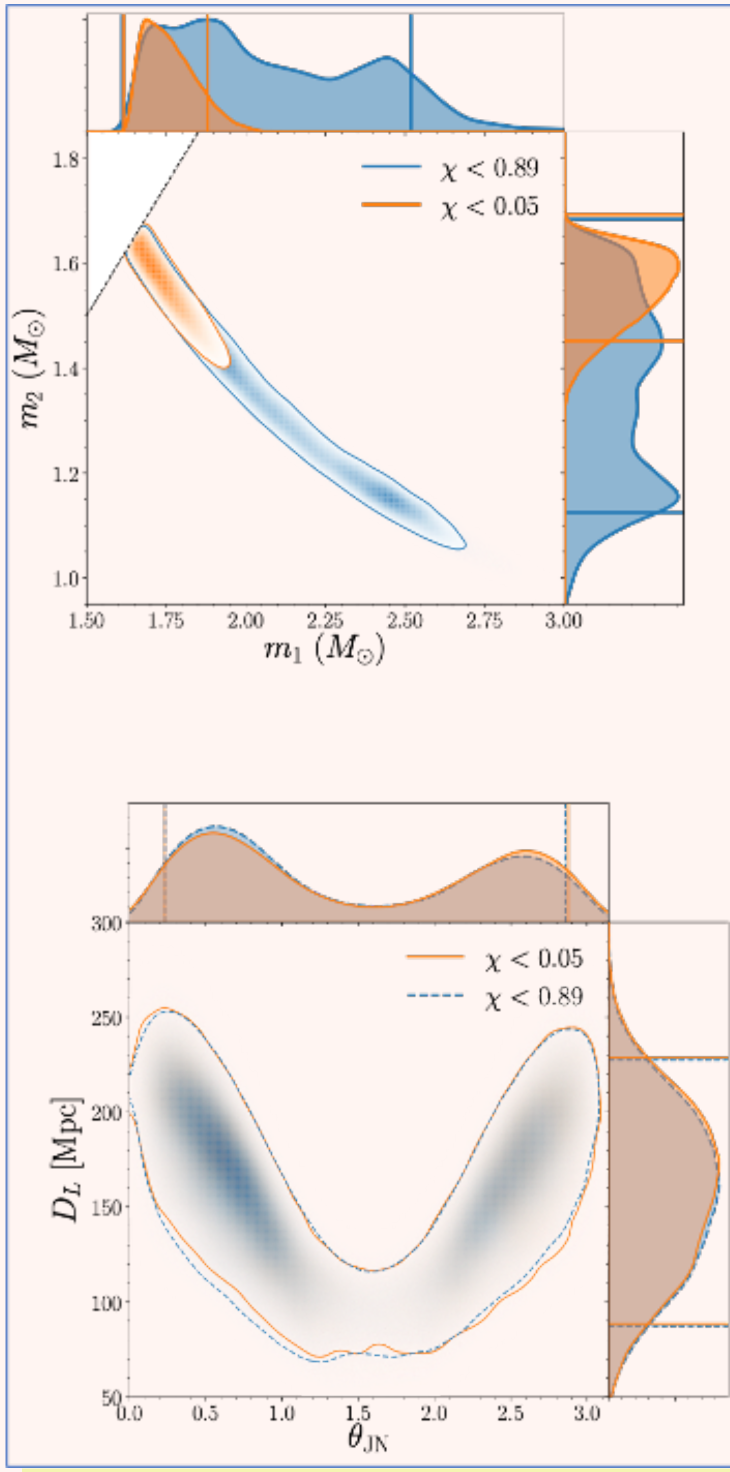
$$\boxed{\begin{aligned} d_L &= \frac{5}{96\pi^2}\frac{c}{h}\frac{f_{GW}}{f_{GW}^3} \\ &= 512\frac{1}{h_{21}}\left(\frac{0.01s}{\tau}\right)\left(\frac{100\text{Hz}}{f_{GW}}\right)^2 \ \text{Mpc}\end{aligned}}$$

- The distance estimation from GWs does not suffer from **systematic uncertainty**, unlike the use of variable stars as 'standard candles'.
- However, individual GW distance estimation is subject to large **statistical uncertainty** due to the lack of information on the angle between the line-of-sight and the orbital plane of the binary (viewing angle).

$$h_+ = \frac{h_c}{d}(1+\cos^2\iota),\ h_c \equiv 2\mu(M\Omega^{2/3})\cos(2[\Omega t - \phi_0])$$

$$h_\times = \frac{h_s}{d}\cos\iota,\ h_s \equiv 2\mu(M\Omega^{2/3})\sin(2[\Omega t - \phi_0])$$

Ω : Orbital frequency

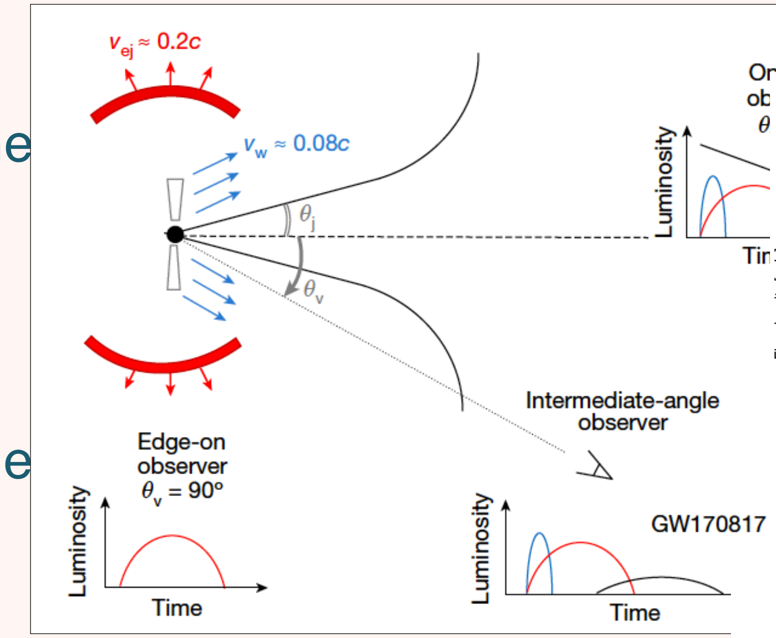


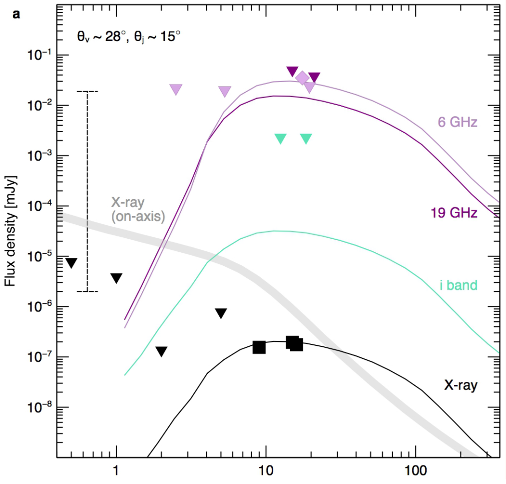
Estimated masses (upper) and distance (lower) to GW190425, a binary neutron star merger event. (Figure from Abbott et al. 2020, ApJL, 892, L3)

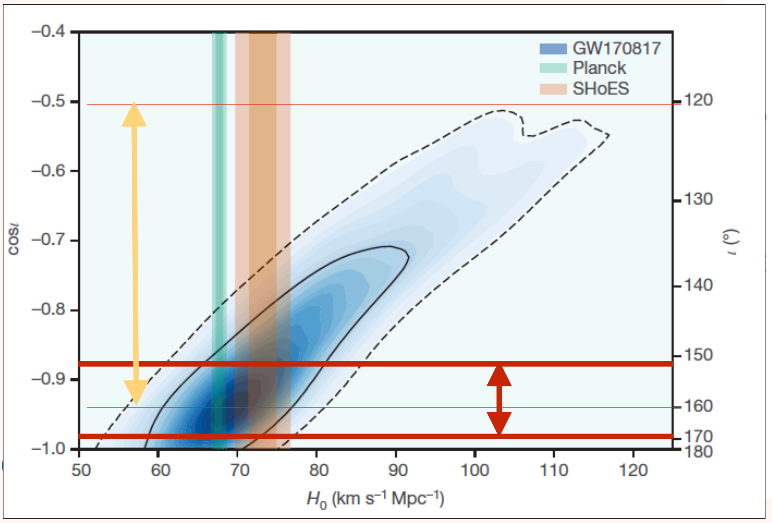
Can we constrain the viewing angle?

Troja et al. 2017, Nature

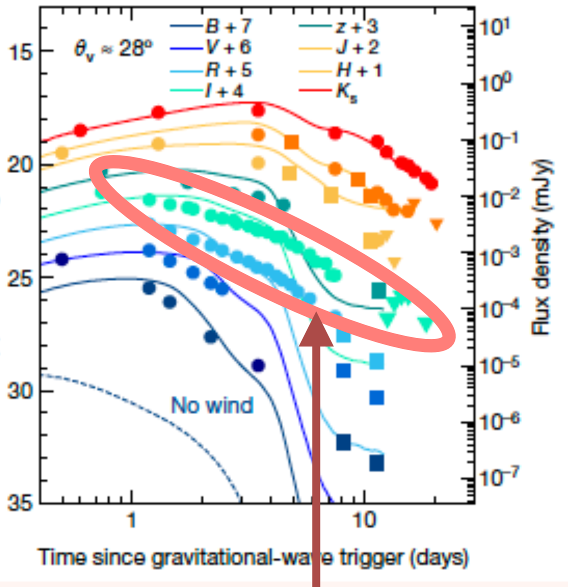
- BNS will lead to the short GRB and kilonova
- If the GRB is observed, together with the GWs, the line of sight should lie within the opening angle (θ_j) of the jet which is perpendicular to the orbital plane → $\iota < \theta_j$
- Also emerging radio synchrotron emission contains the information on ι
- On the other hand kilonova lightcurve in optical/IR alone is not sensitive to ι.
- GW170817:
  - Early constraint: $20^\circ \lesssim \iota \lesssim 60^\circ$ mostly from radio data (Troja et al. 2017)
  - Discovery of the superluminal radio jet (Mooley et al. 2019) is claimed to give the range of the viewing angle more tightly ($14^\circ \lesssim \iota \lesssim 28^\circ$).
  - More recently, optical superluminal jet (Mooley et al. 2022) gave even tighter constraints the viewing angle ($19^\circ \lesssim \iota \lesssim 25^\circ$)







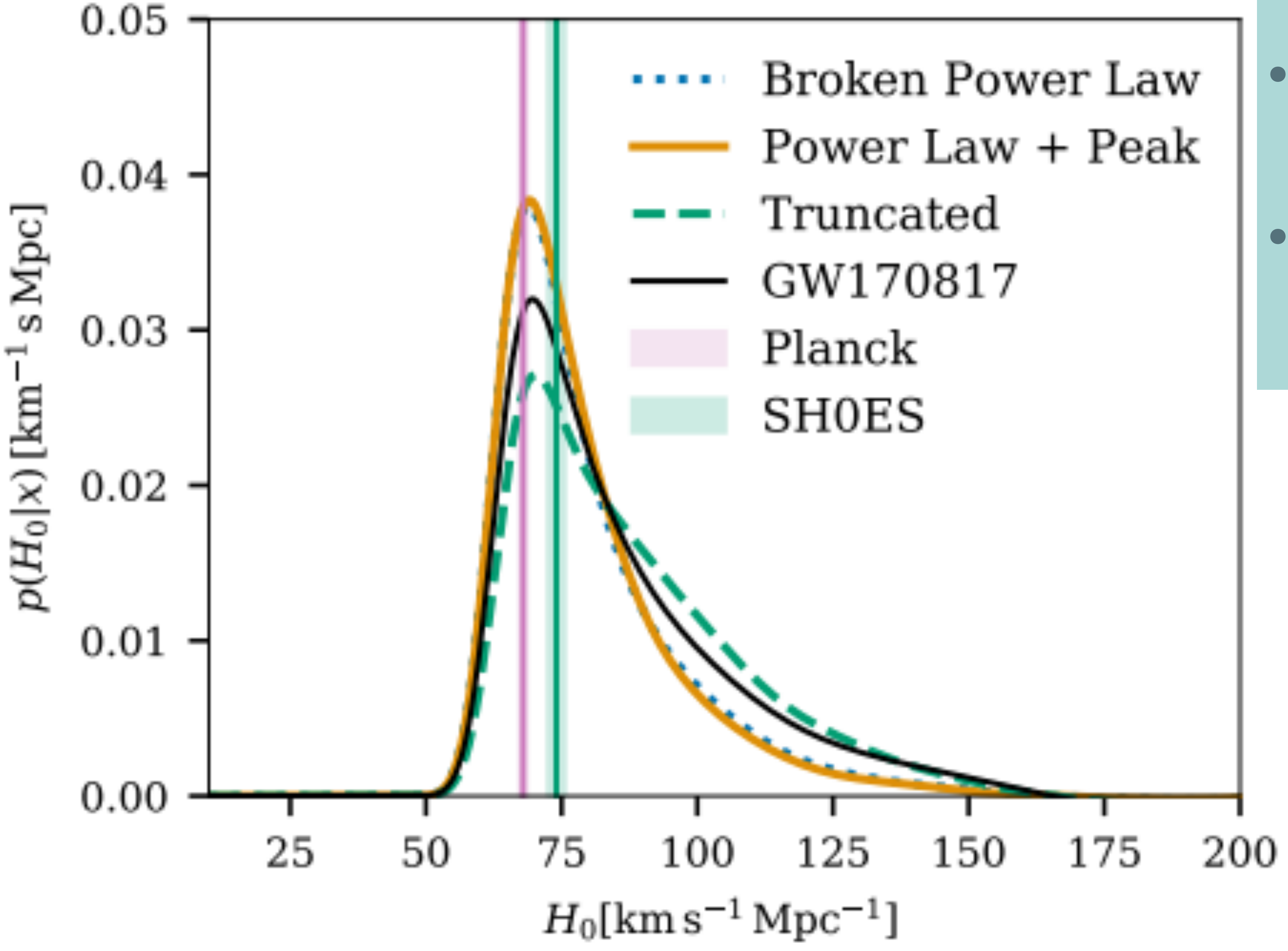
LSC (2017)



KMTNet

Measurements of H_0 with GW170817

arXiv:2111.03604V1

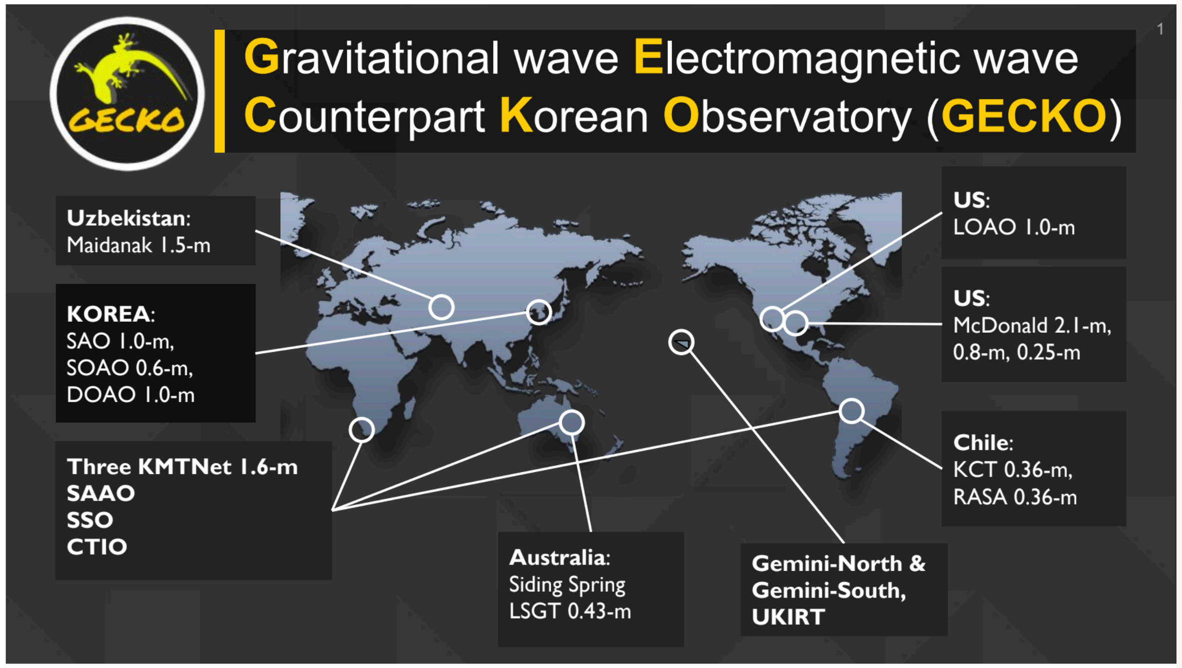


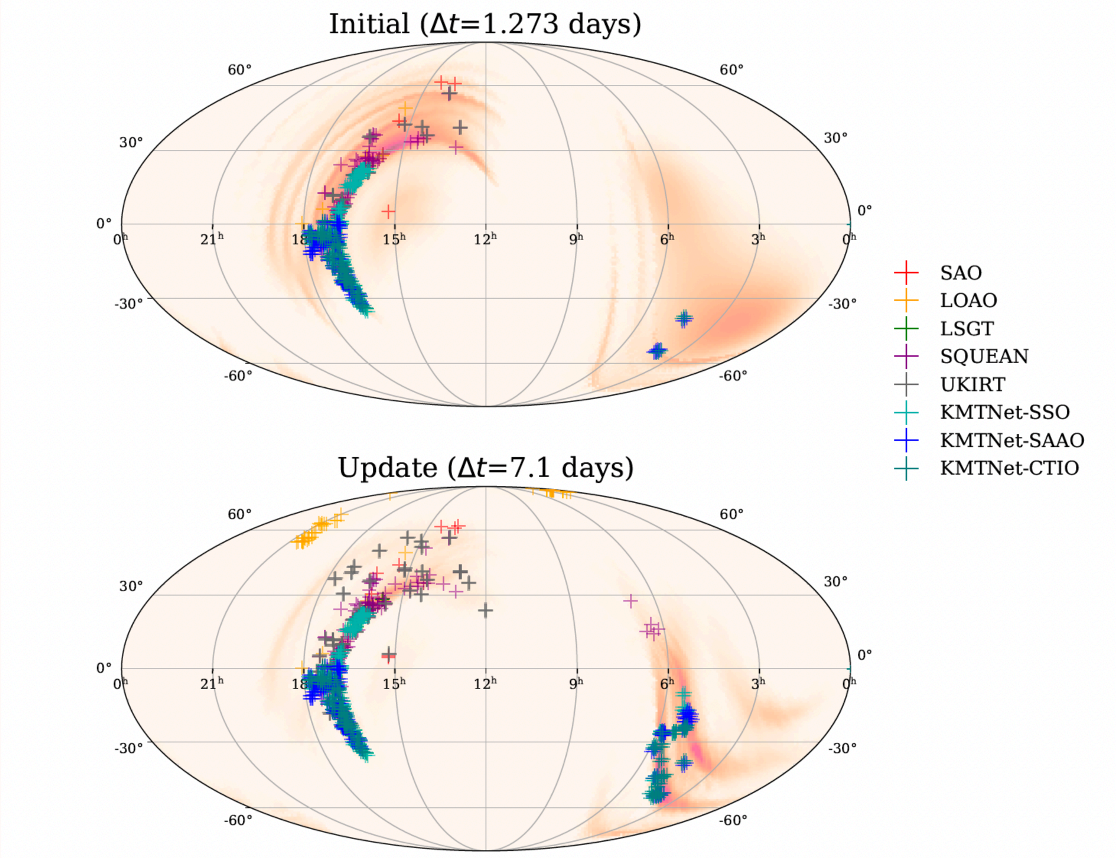
- GW170817 alone:
  $H_0 = 69^{+17}_{-8}$ km/sec/Mpc (LSC, 2017)
- GW170817 (Bright Siren) + 42 BBH (Dark Sirens) $H_0 = 68^{+12}_{-7}$ km/sec/Mpc (LSC, 2021, arXiv:2111.03604V1)
- With radio and optical superluminal jets
  $H_0 = 72.5 \pm 4.6$ km/s/Mpc (Mooley et a. 2022)

- Accuracy of Hubble constant can be improved if we have many BNS events with EM counterparts.
- There will be a few more such events in during O4.
- Since the EM emission fades away very quickly, we need to identify the EM counterpart rather quickly.

GW190425: Another BNS Candidate

- Network status:
  - Hanford: Offline
  - Livingstone: Online, BNS Range: 135 Mpc, SNR=12.9
  - Virgo: Online, BNS Range: 48 Mpc, SNR=2.5.
  - Poor localization (~7500 deg^2)
- SNU group tried to observe the EM counterpart very hard for the first few days with GECKO (Paek et al. 2023, submitted)
  - Instead of tiling, we observed individual galaxies in the localization area
  - We gave privatization ranking based on localization probability and stellar mass.
  - No candidate for GW190425 has been found
  - However, we found a new transient, together with its host galaxy at $z \approx 0.15$ has been discovered on April 27 (GECKO190427a)

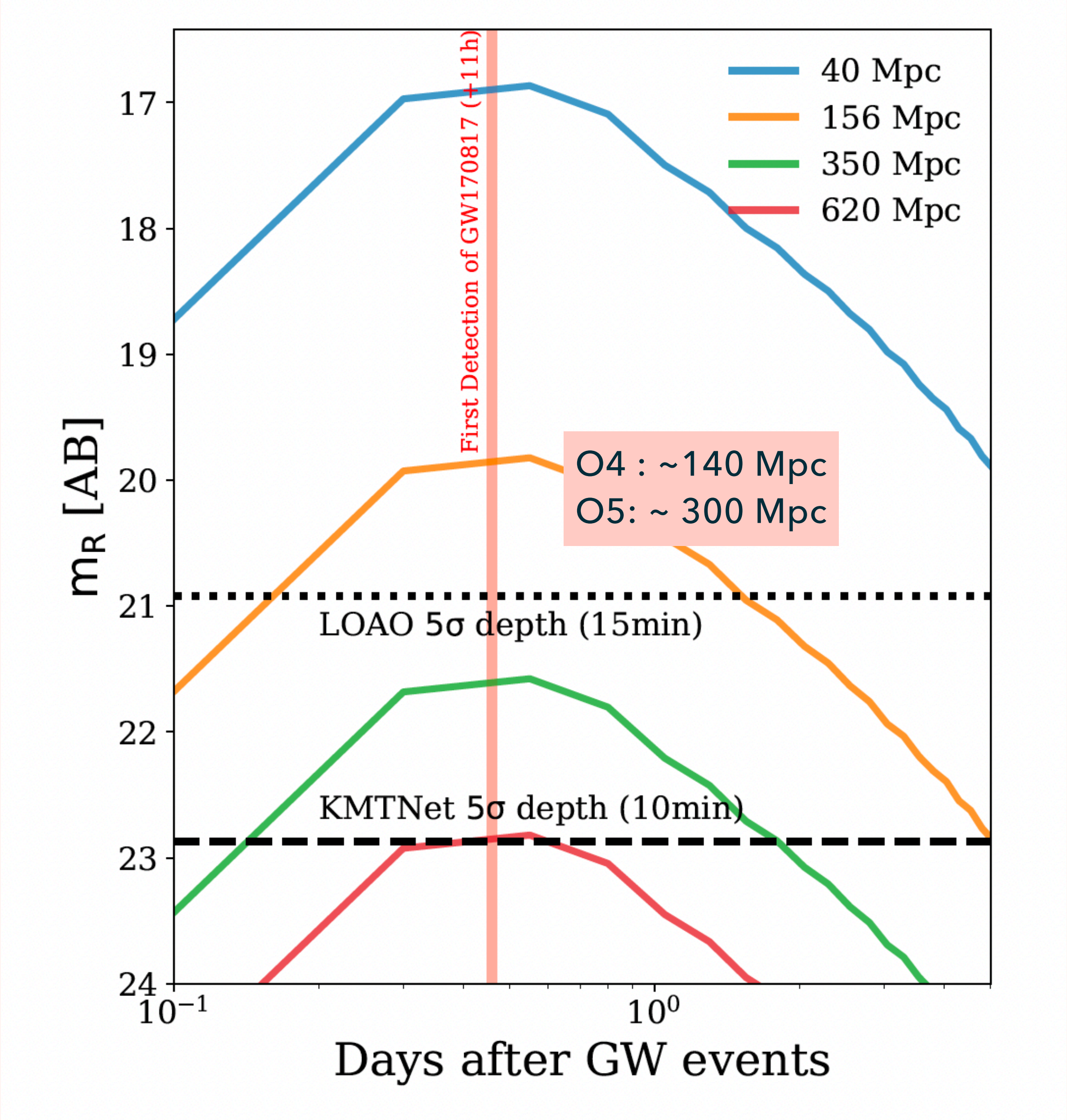



Initial (Δt=1.273 days)

Update (Δt=7.1 days)

Lessons from GW190425

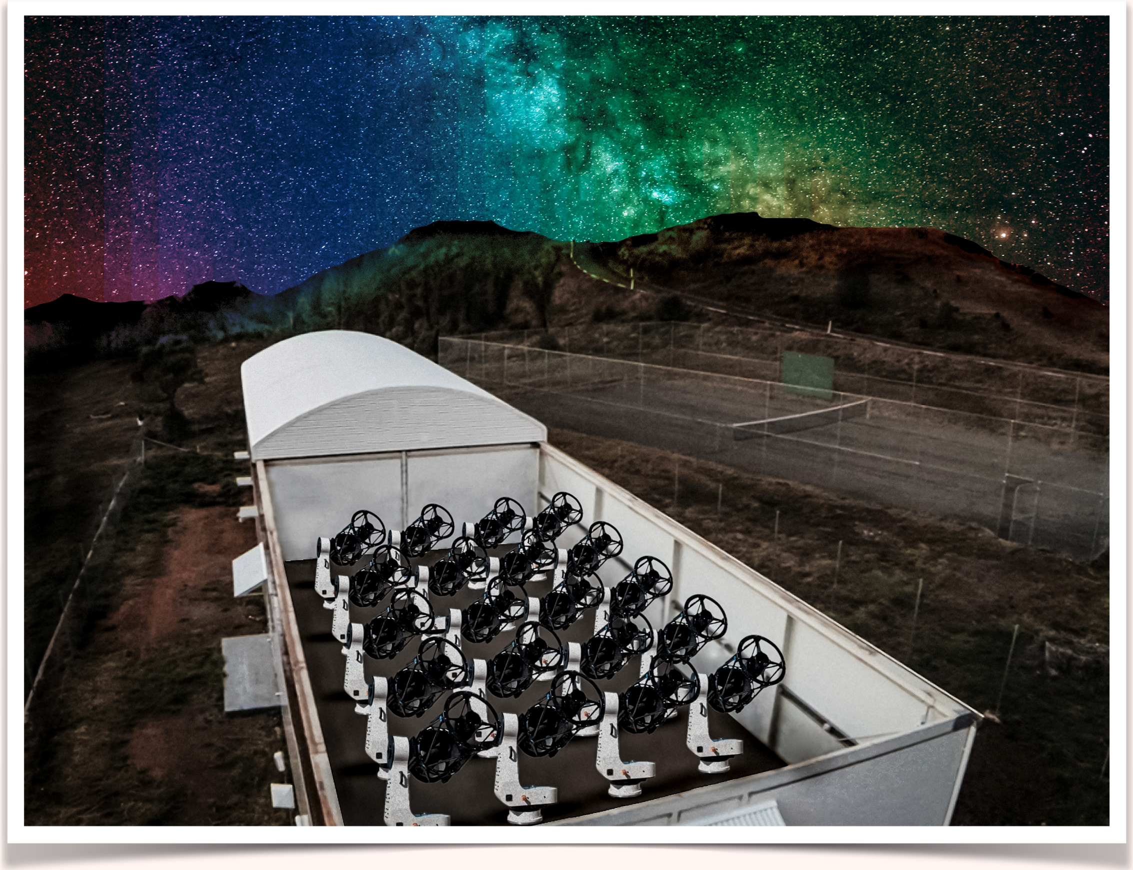
- It is not easy to observe the entire localization area, but large fraction of very likely host galaxies can be observed in short time.
    - When applied to GW170817, the actual galaxy NGC4993 stands out as a top priority without rivalry.
    - We covered only ~10 % of the localization area, but we were able to cover 30% of score coverage within 3 days.
    - There were many transients in the FoV: rapid classification would be very useful in identifying the nature of those transients.
    - GECKO can possibly uncover a GW170817-like KN at a distance < 200 Mpc if the localization area is of the order of 100 deg^2

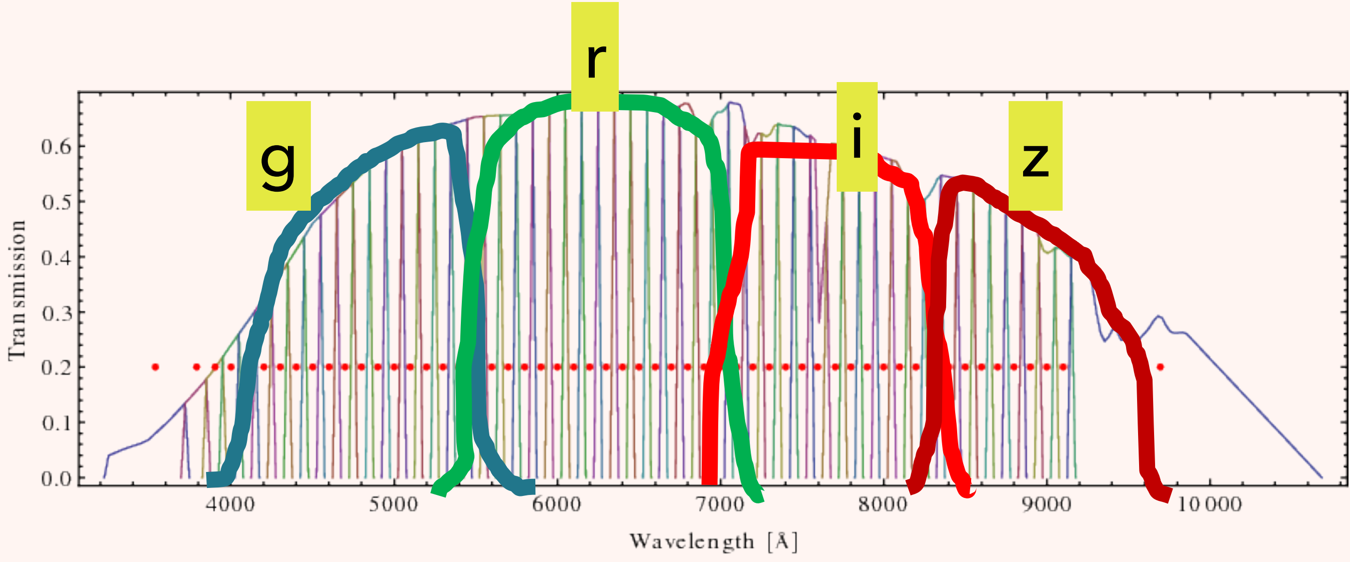


O4 : ~140 Mpc
O5: ~ 300 Mpc

A new facility (7DT) for rapid followup of transients

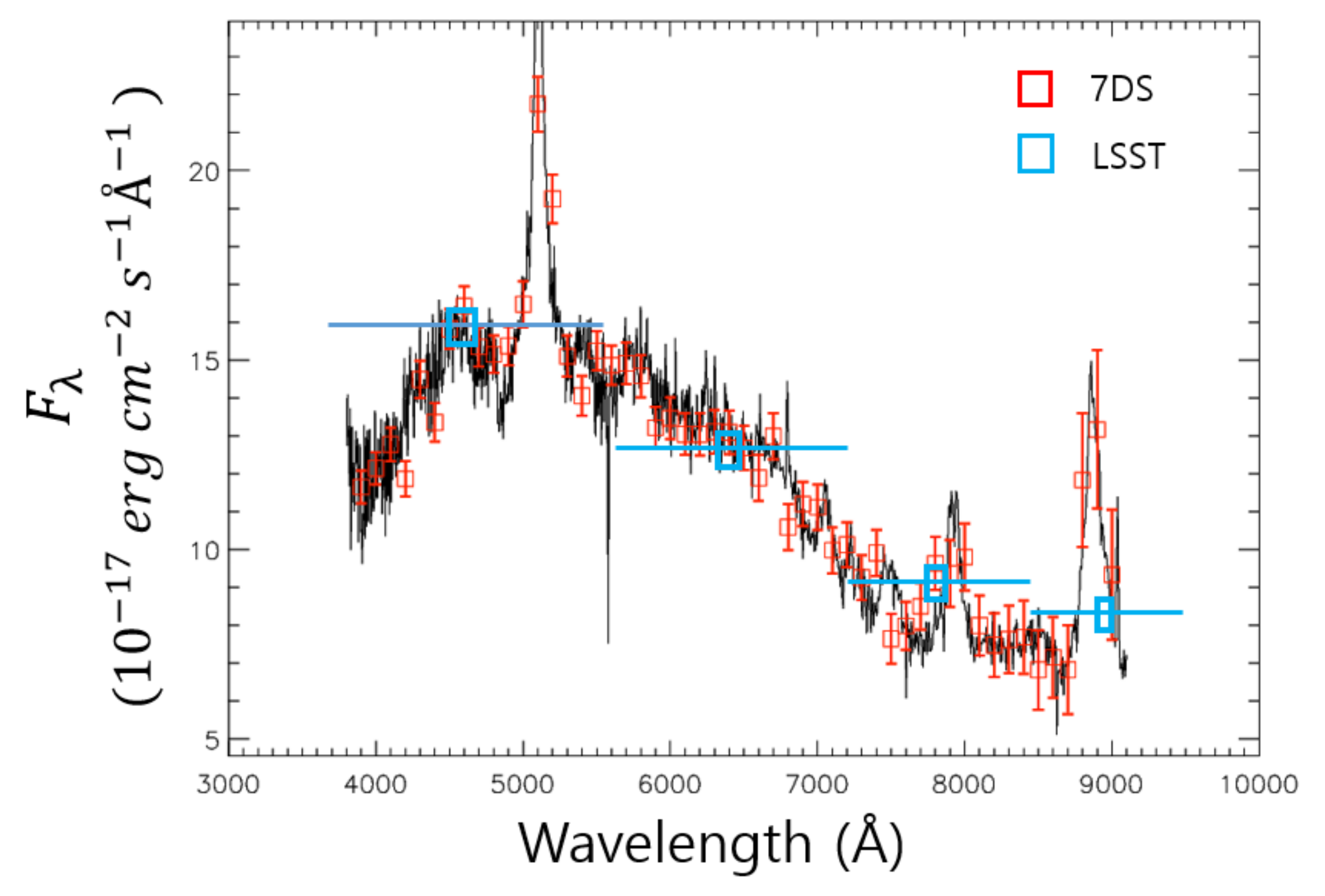
- We are building a system of telescope composed of 20 telescopes of 50 cm aperture (~Effective D~2.2 m if all telescopes are combined)
- Imaging wide field with 40 medium band filters (each telescope has 2) –> medium resolution spectroscopy for every pixel in the field of view
- It can cover large area of sky repeatedly:
  - Wide-field, time domain, IFU-type spectroscopic telescope
  - Suitable for the survey of transients such as GRB and Kilonovae
- It can be regarded as an optical version of SPHEREx, an all sky spectroscopic imaging surveyor in near infrared, to be launched in early 2025, with KASI’s involvement





Advantage of Medium Band Spectrum

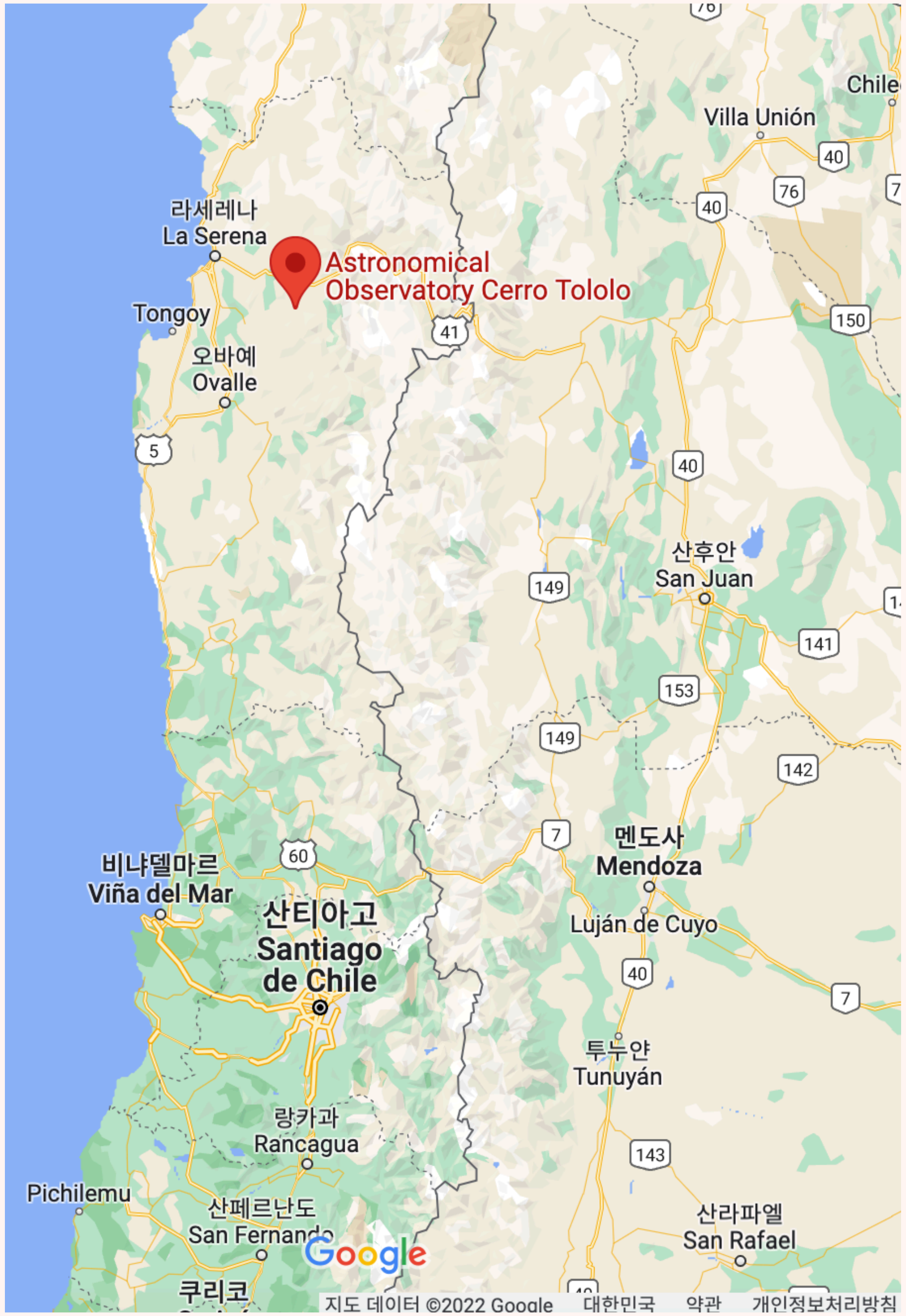
- Best suited for broad continuum features and broad emission lines continuum
- Photometric redshift: < 0.3% – 1% accuracy
- Emission line/continuum can be separated well, and thus characterize the nature of the transients.



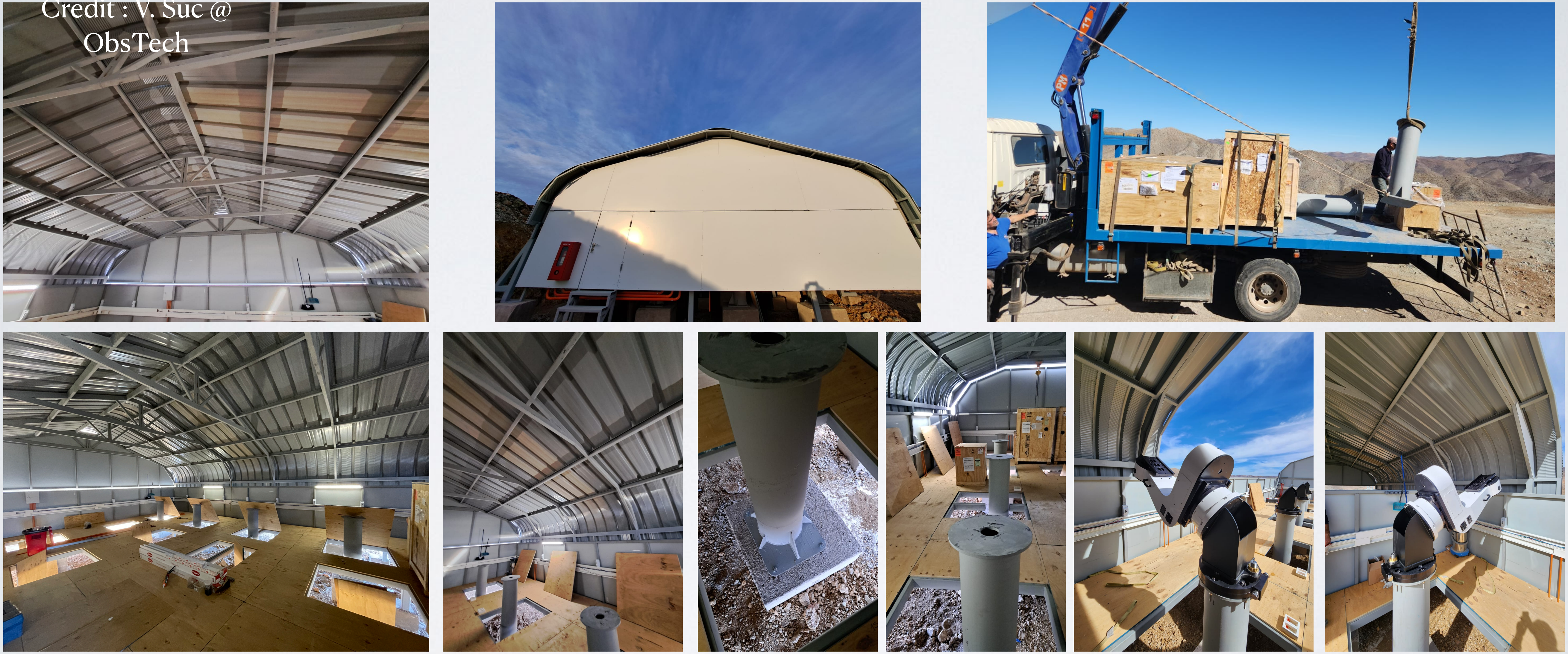
z = 0.822,
i = 18.3 quasar spectrum
(black: SDSS
red: 7DS
blue: LSST)

Telescope site

- Chile, Rio Hurtado (near CTIO/Cerro Pachon)
- Altitude: 1700 m
- 320 clear nights
- <1″ Seeing



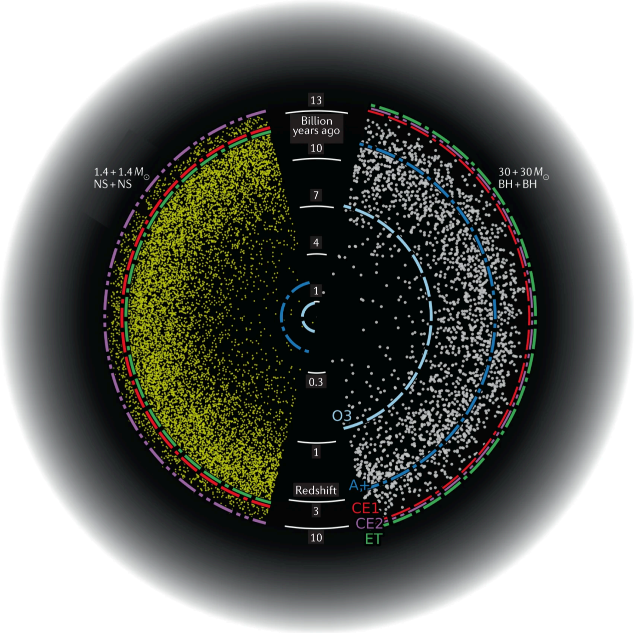
Site: Current Status ~ last week of July



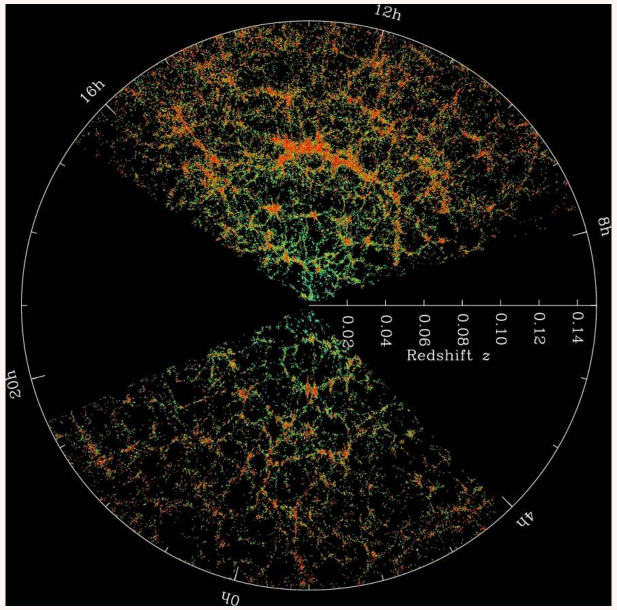
Credit : V. Suc @ ObsTech

Dark sirens

- BBH does not emit EM radiation, and distant BNS may emit EM radiation that is too faint to observe. Such objects are called **dark sirens**
- Unless the angular resolution of the dark sirens becomes very good, it would be very difficult to uniquely identify their host galaxies with ground-based detectors.
- One can still use dark sirens to constrain cosmological parameters (Hubble constant, DE equation of state, etc.) using dark sirens statistically.
  - Photometric redshifts of galaxies within Ω and d_L range (e.g., Soares-Santos et al. 2021)
  - Cross-correlation with galaxies (Mukherjee et al. 2018, 2021)



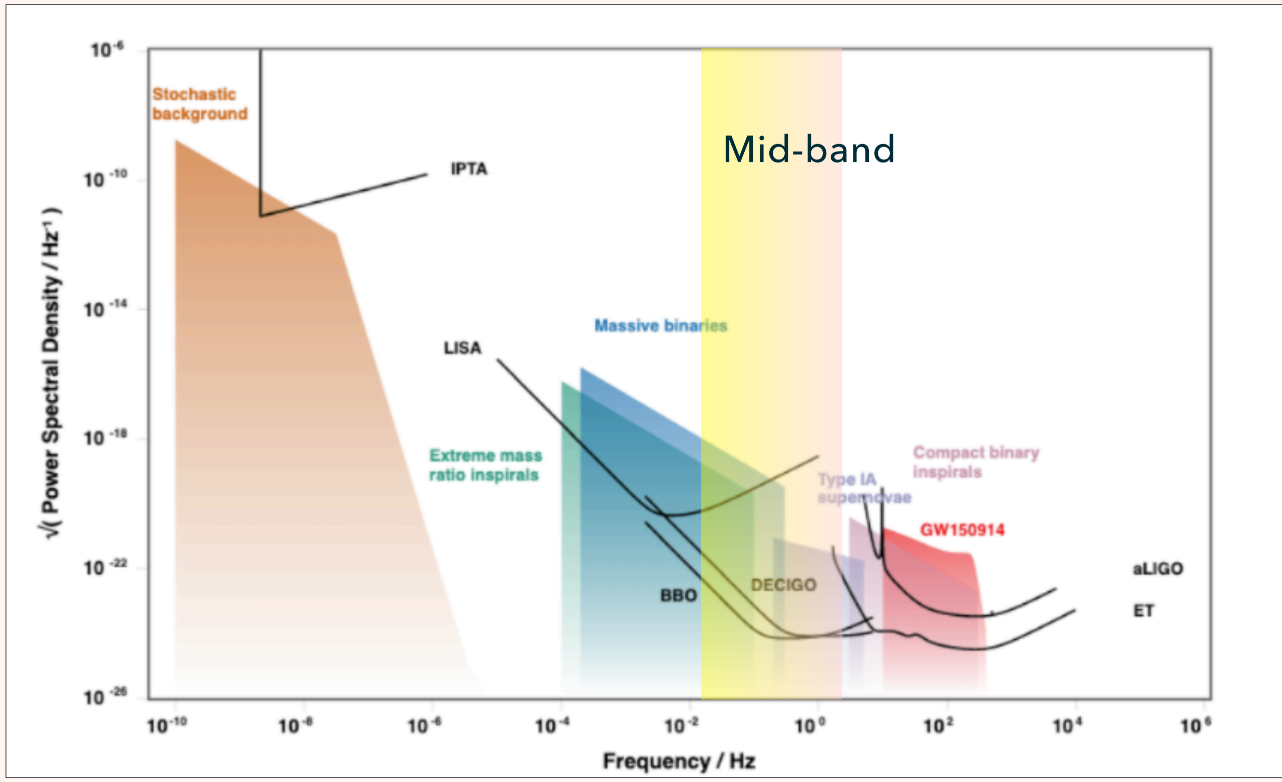
x

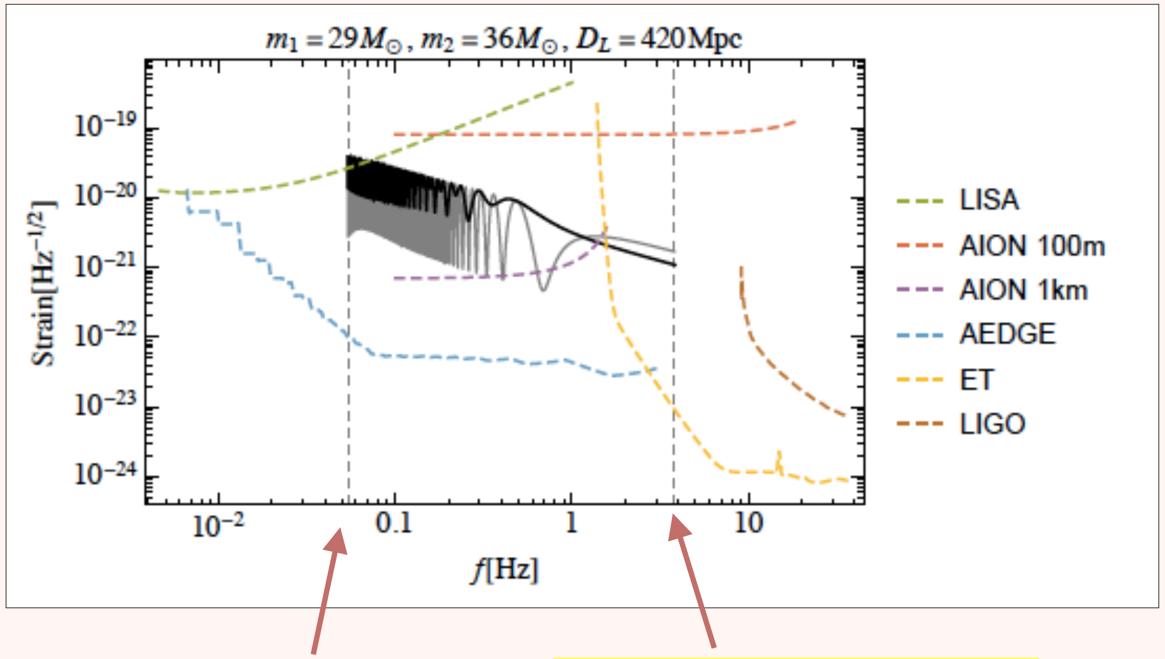


$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$

Improvement of localization with mid-band detectors

- Detectors operating at lower frequencies can observe the merging binaries for a long time (**days to years**)
- 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 Ω and d_L can be significantly improved

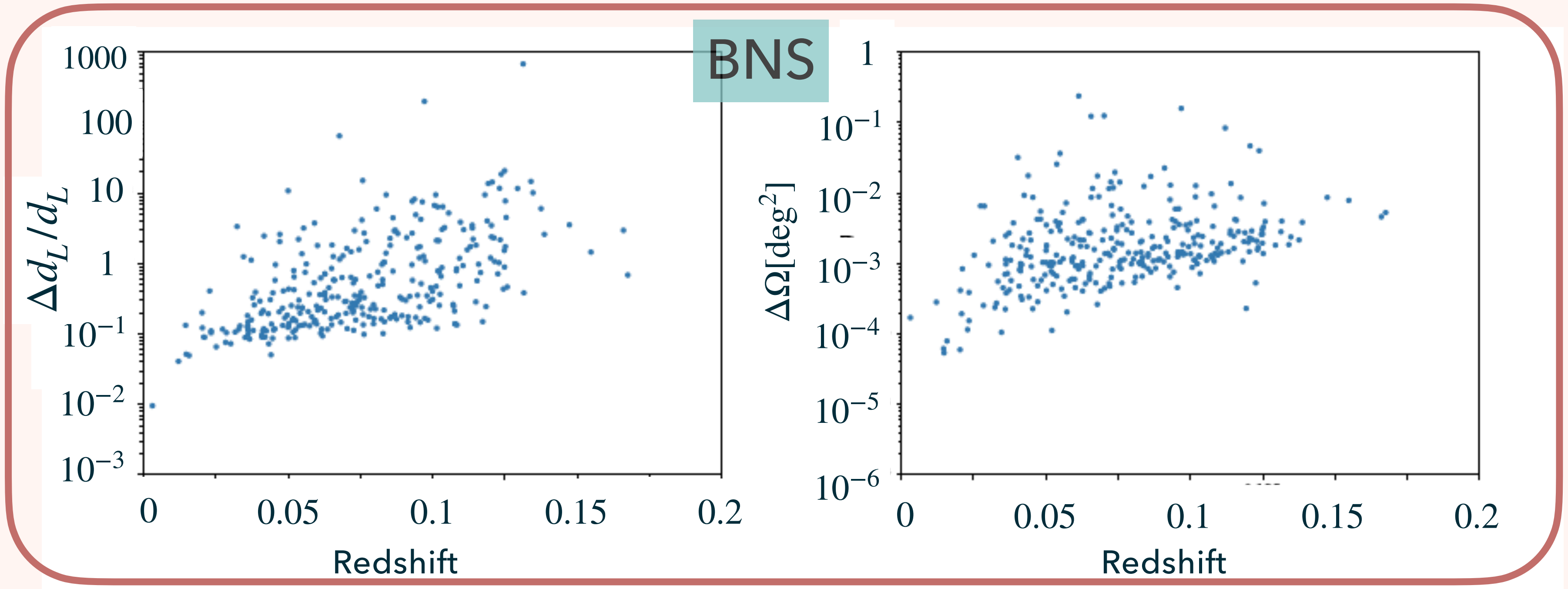


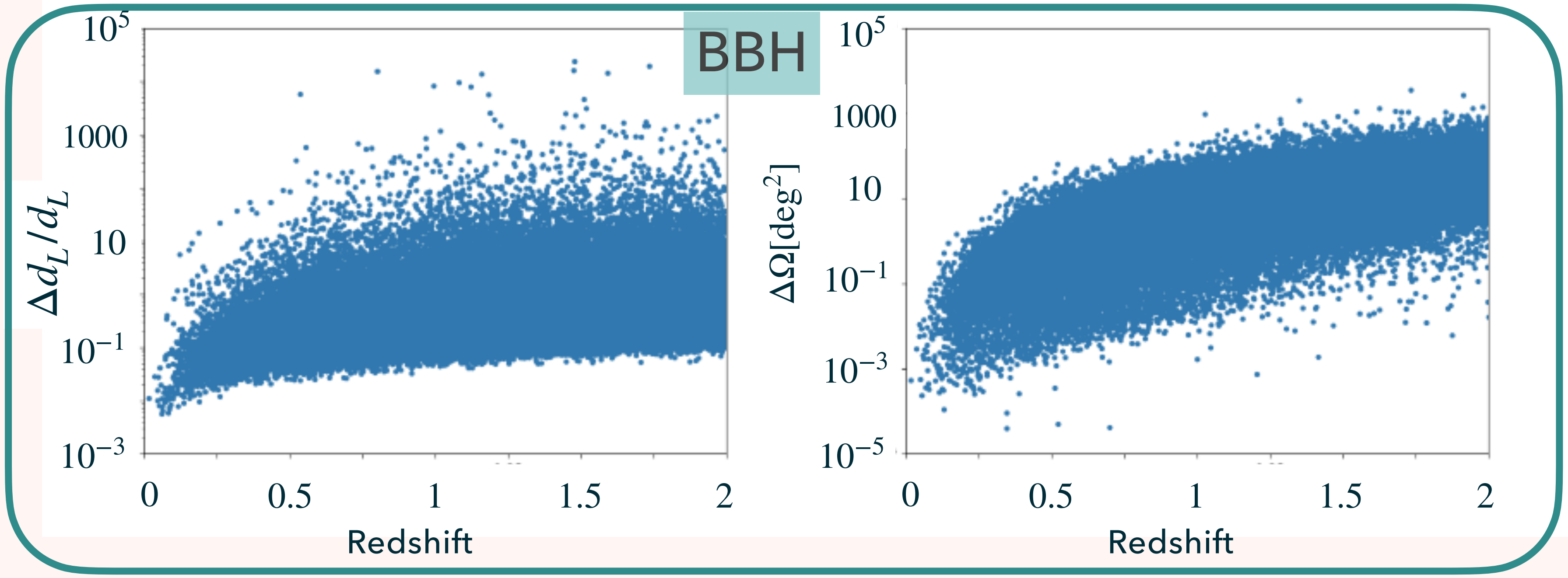


60 days before merger

1 minute before merger

A case study: Simulation of BBH and BNS observations with AEDGE (Yang, Lee+, 2022, JCAP [arXiv:2110.9967v1])





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

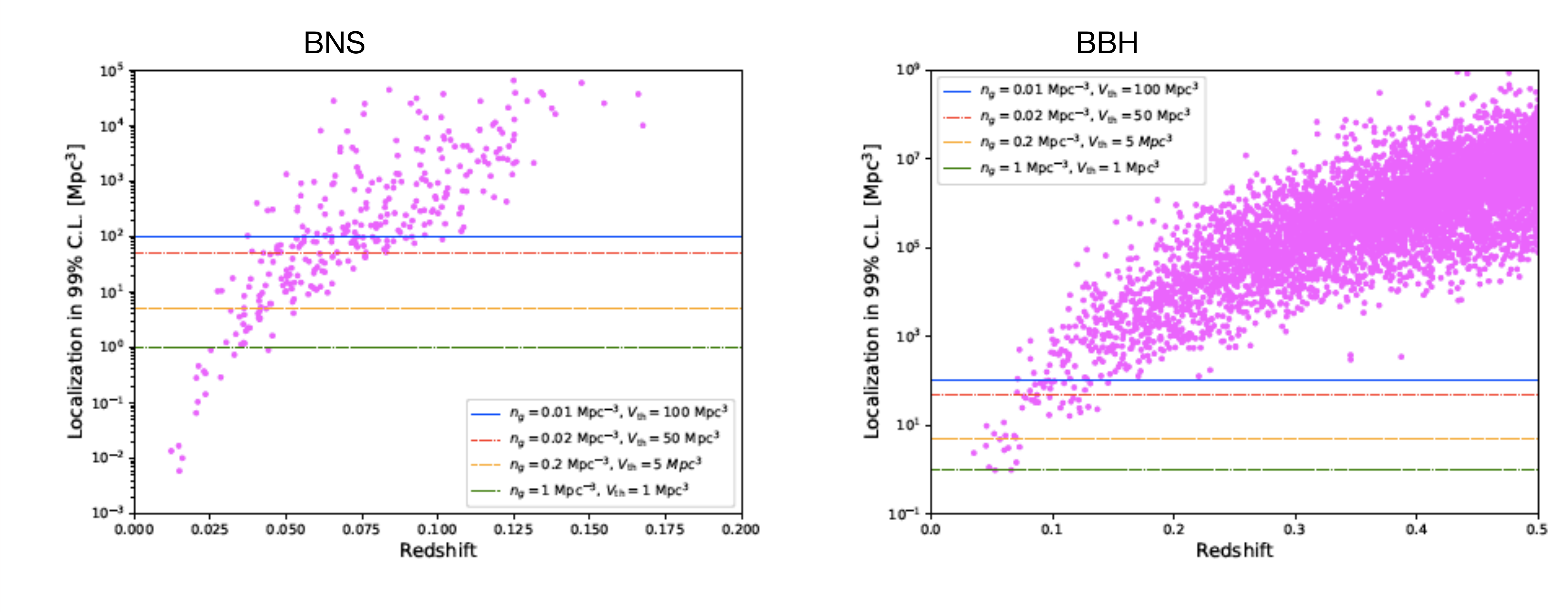
where $\Gamma_{ij} = \left(\frac{\partial h}{\partial \lambda_i}, \frac{\partial h}{\partial \lambda_j}\right)$ is

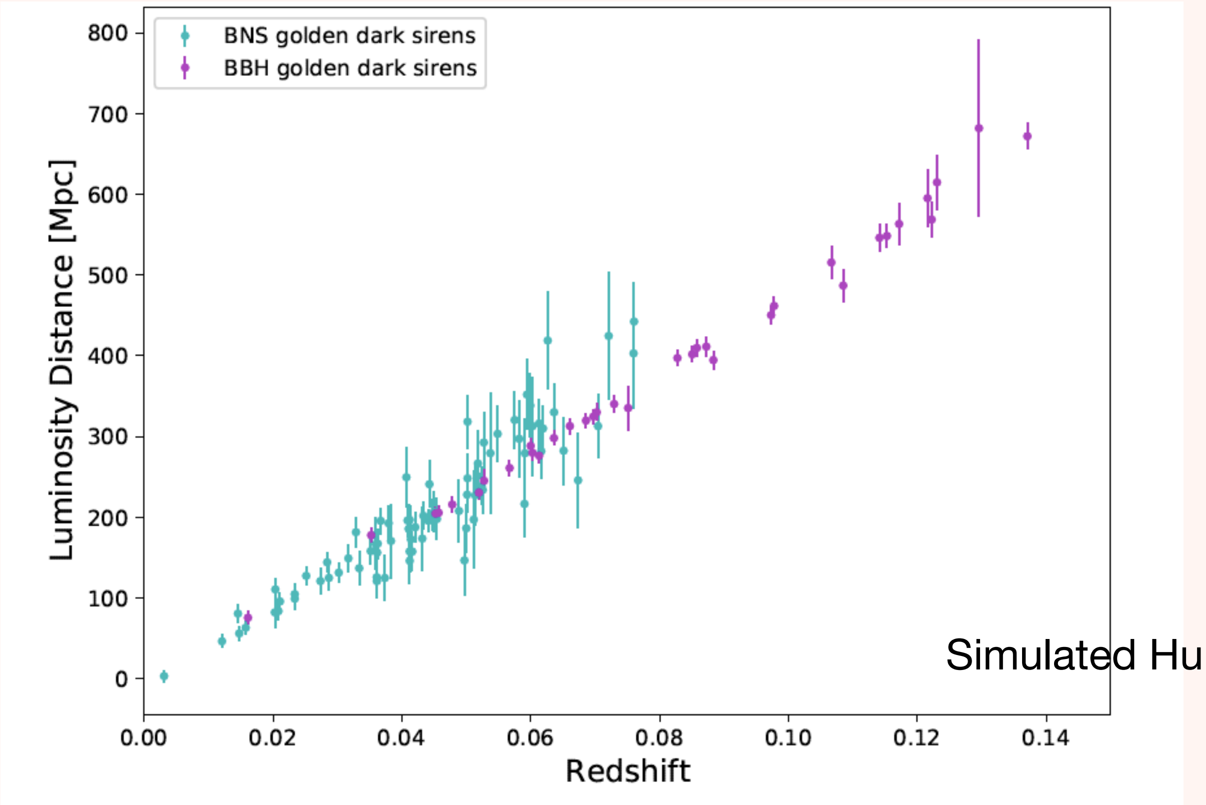
Fisher matrix.

Simulated results for 5 year run of AEDGE assuming GWTC-3 population

AEDGE is a proposed mid-band detector in space,

Localization volume and Hubble Diagram

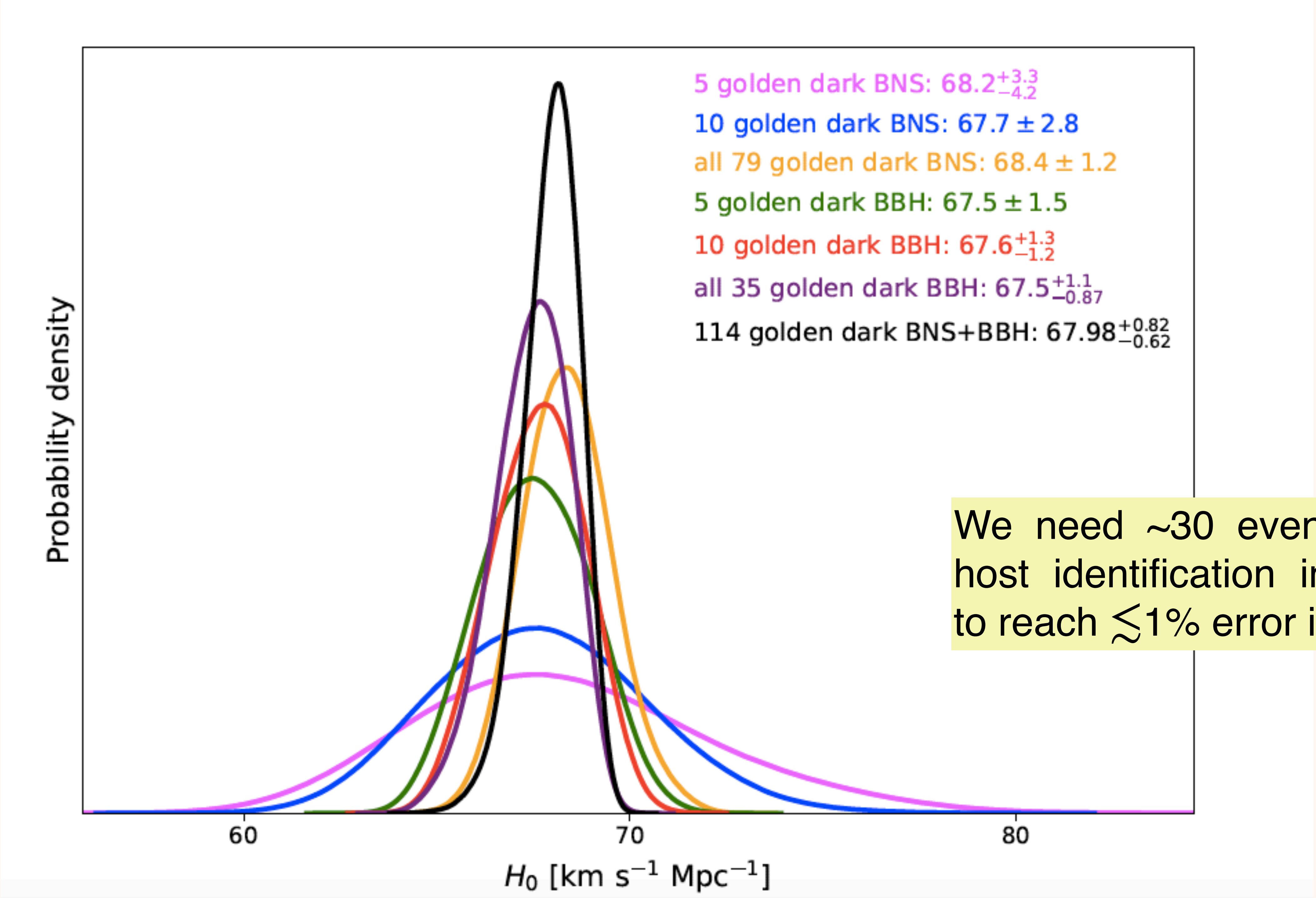




Simulated Hubble Diagram

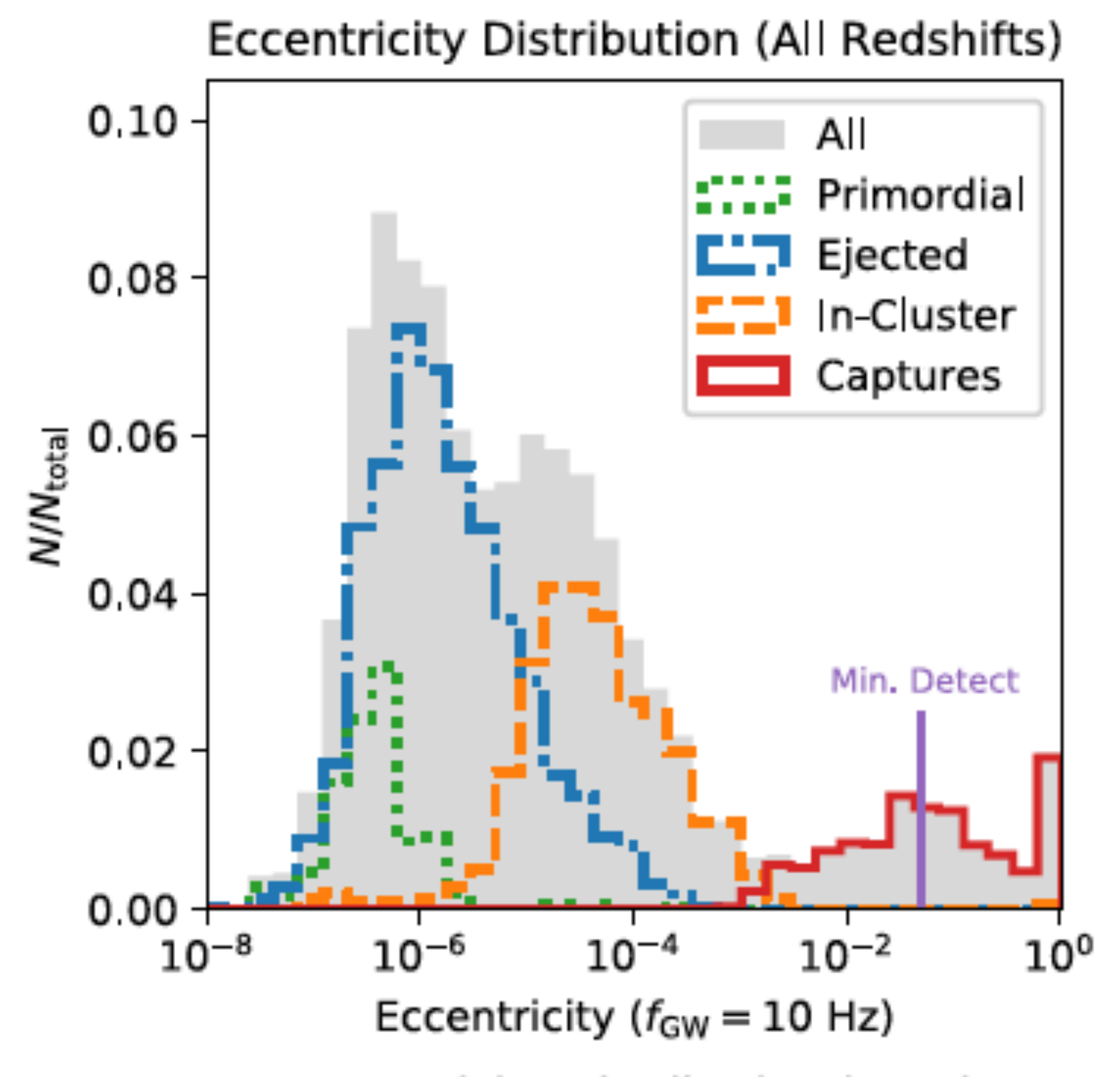
Various cuts are assumed galaxy number densities: below these lines, we can uniquely identify host galaxies within 5 year observation

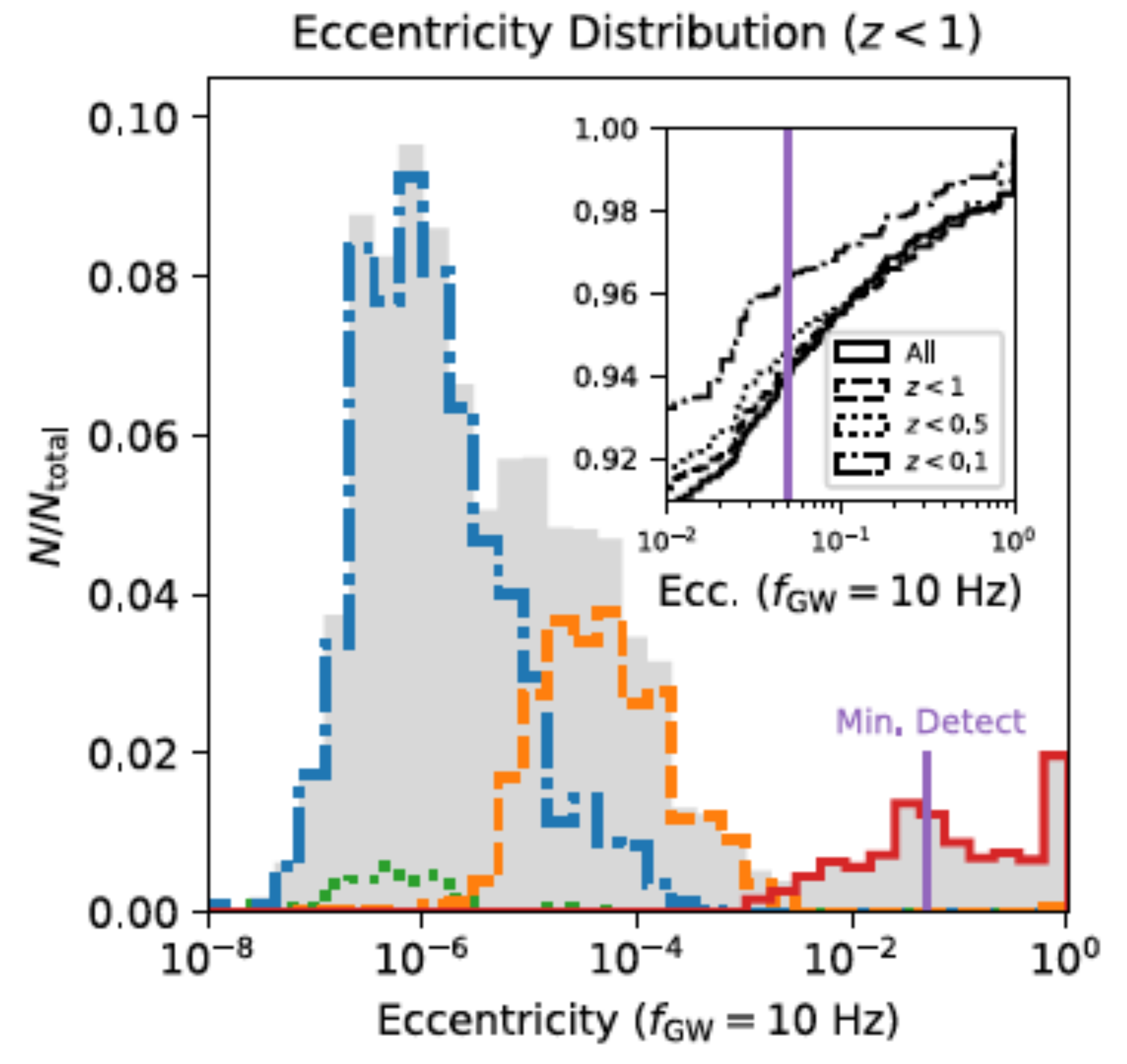
Simulation of Hubble Constant Estimation with Dark Sirens



We need ~30 events with host identification in order to reach $\lesssim$1% error in H_0

So far we assumed circular binaries, but dynamical processes produce eccentric binaries



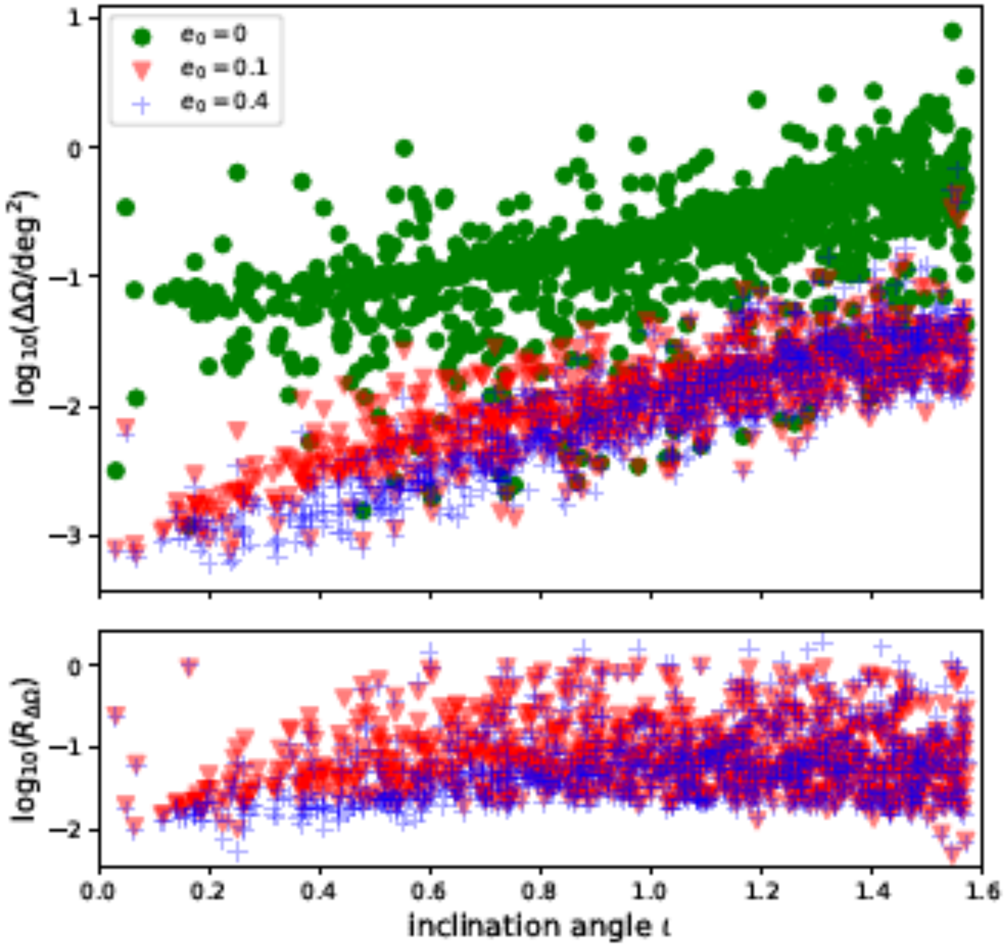


Rodriguez et al., PRD 98. 123005 (2018)

Further improvements of estimated parameters for eccentric binaries

- In mid-frequency band, some binaries may have significant eccentricity (i.e., $e > 0.1$)
- The eccentric waveforms have more features than circular ones, and thus enable us to break some of the degeneracies during the inspiral phase → more accurate parameters can be inferred
- A case study with B-DECIGO:
  - $\Delta d_L / d_L$ can be improved near $\iota = 0$.
  - $(\Delta\Omega)_{e=0.1} \lesssim (\Delta\Omega)_{e=0}$
  - More improvement for larger e.

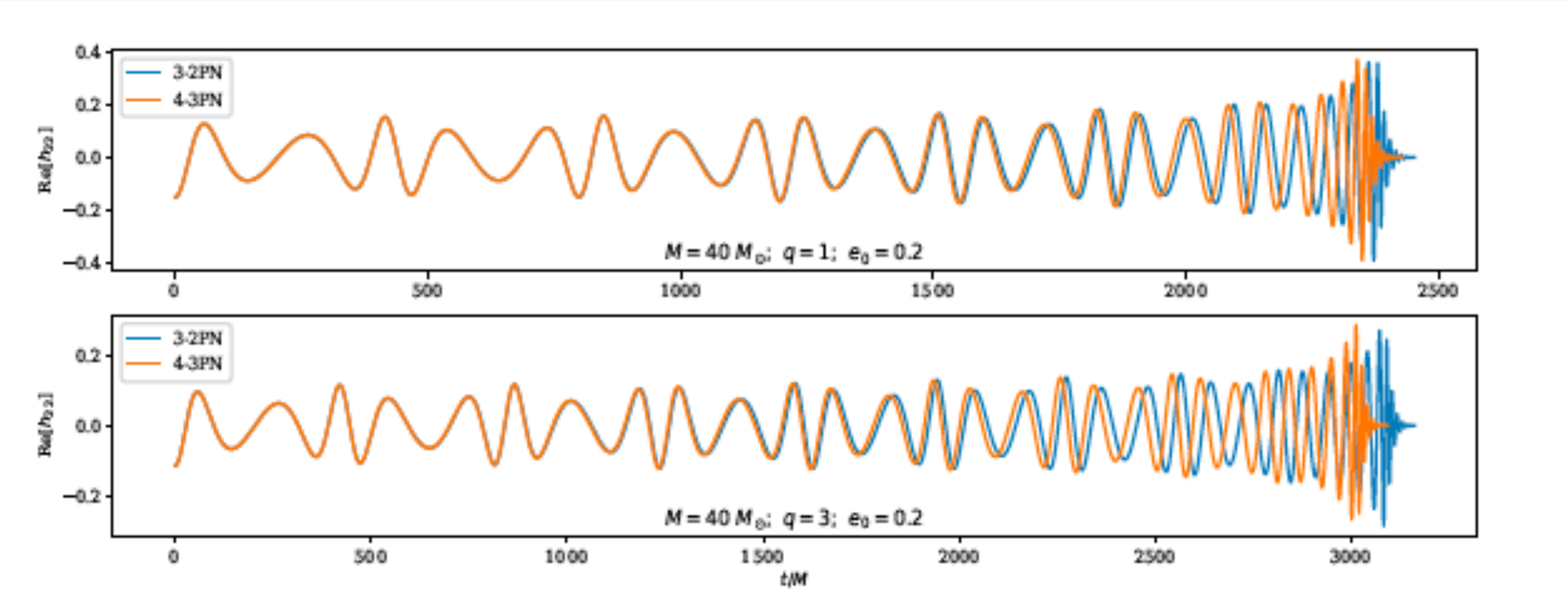
Yang,.. Lee, (2022), PRL, 129, 191102



Challenges: Accurate Waveforms for long duration

- In order to fully utilize the long duration observation data with mid-frequency, we need accurate waveforms from binaries with eccentricity and spins.
- Current status:
  - Time domain waveforms can be computed up to 4 PN. (Cho et al. 2022) for binaries with arbitrary eccentricity.
  - We need to transform the TD waveform into freq. domain: issue of higher modes.
- Spin:
  - Machinery for the inclusion of spin has been developed by Cho & Lee (2019), but has not been incorporated in the high order PN dynamics.
  - We are now improving the precessing waveforms

Cho et al. 2022, PRD, 105, 064010



Summary

- Identification of the host galaxies is very important for the understanding of the the formation mechanisms and cosmological applications.
    - Followup observations in EM radiation is the obvious way, but such sources are very rare and limited to those containing neutrons stars
- BBH do not emit EM radiation. The pointing accuracy of the ground-based detectors (including the future ones) is too poor for host identification.
    - However, some black hole binary host galaxies can be identified when mid-band detectors become available, through long duration observations.
    - If some binaries are eccentric, accuracies of directions and distances can be further improved.
    - Cosmological parameters could be precisely constrained with dark sirens alone with mid-band detectors.