Gravitational Wave Cosmology

2023 Beyond the Standard Model Workshop

Feb. 20-24, 2023

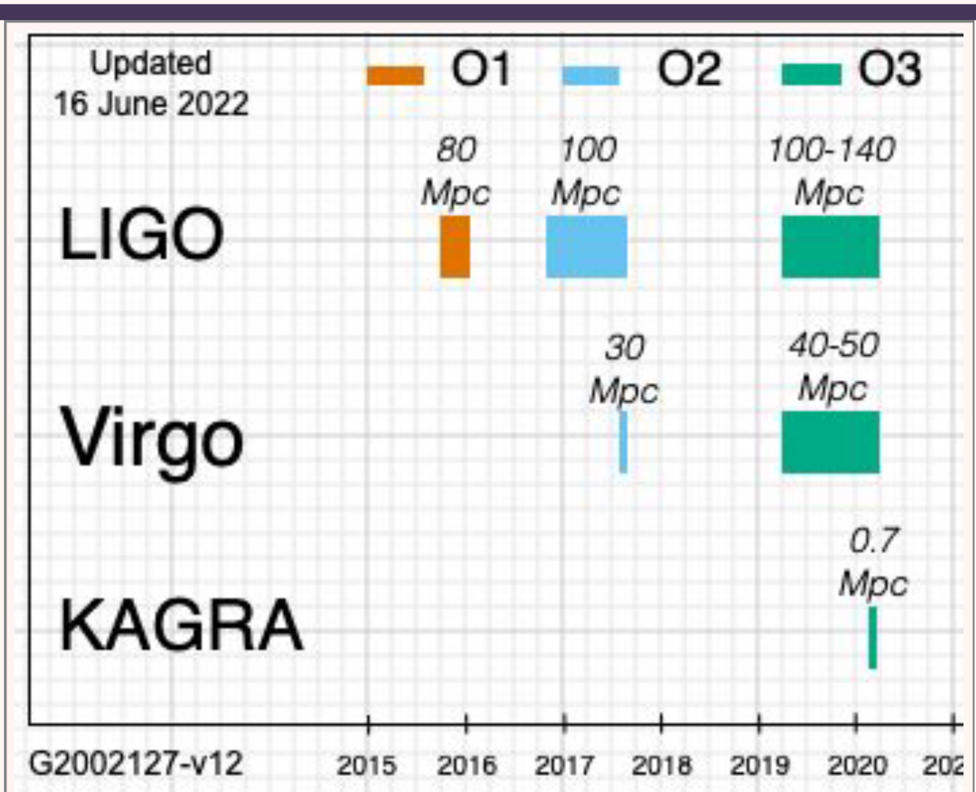
Hyung Mok Lee (SNU)

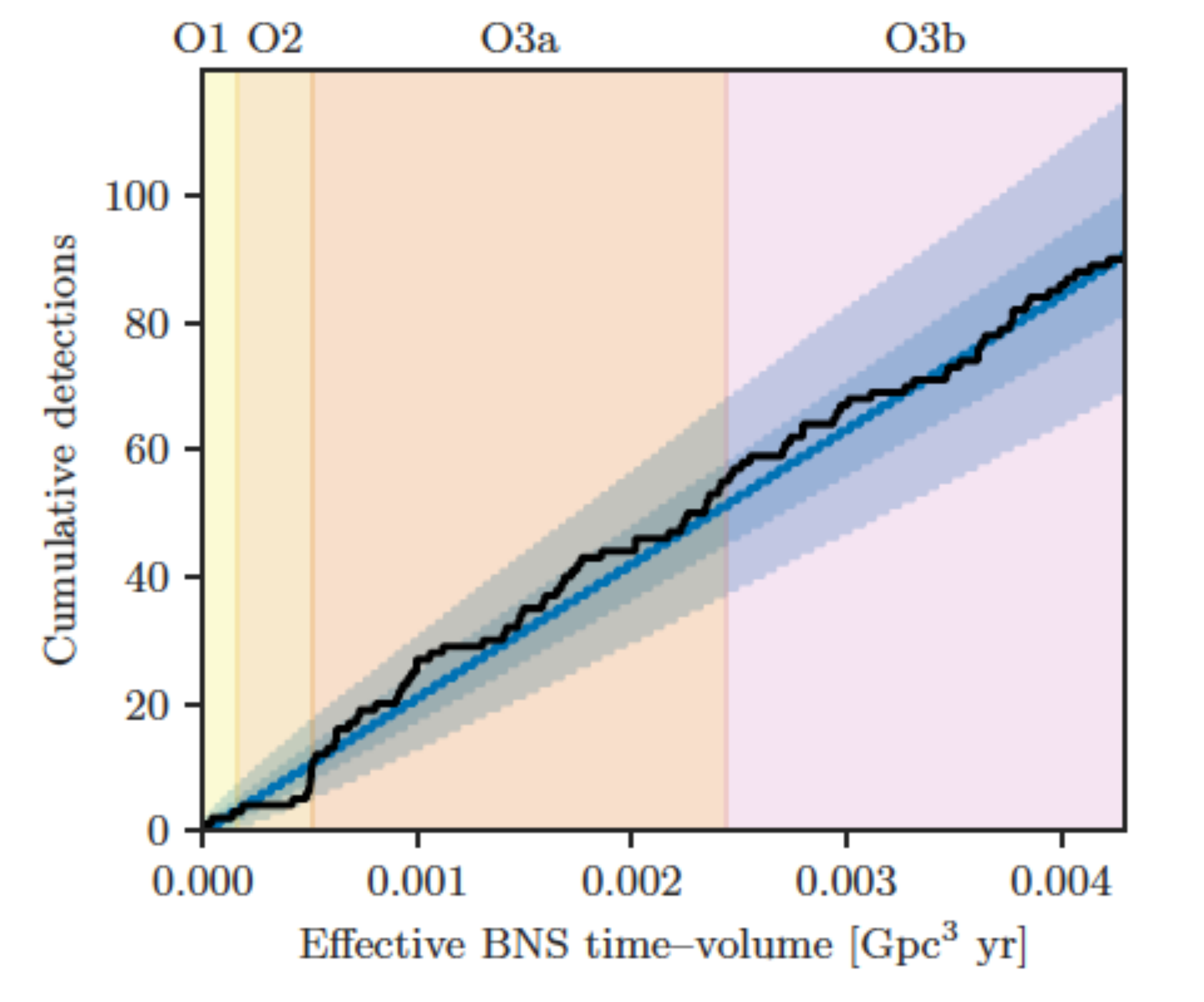
Topics

- Short Summary of the GW observations
- Cosmological Applications of the Gravitational Waves
- Current Status of Hubble Constant Measurements
- Dark Siren in Ground-based detectors
- Dark siren in Mid-band detectors
- Effects of Eccentricities in mid-band

GW Observations by LIGO/Virgo/KAGRA

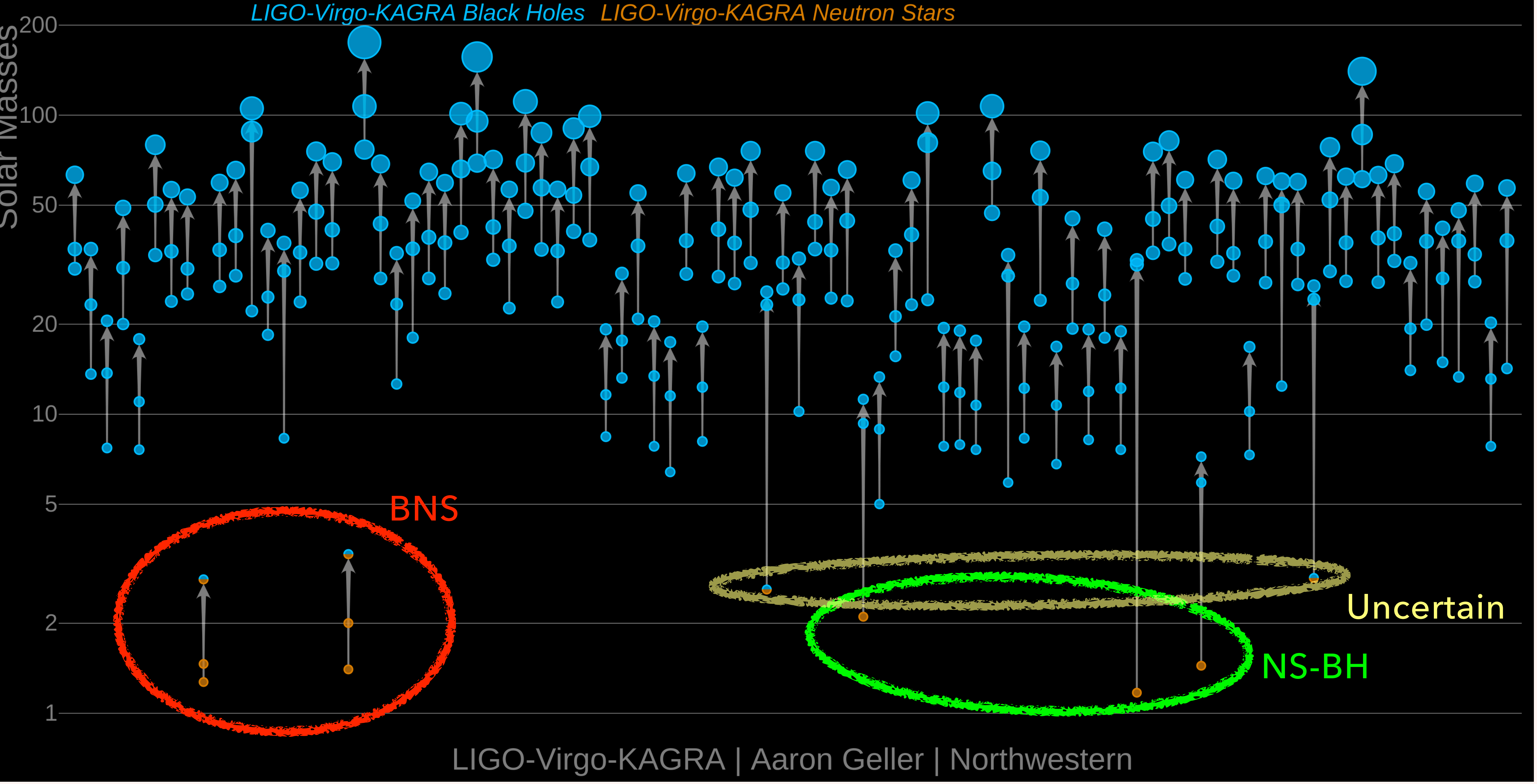
arXiv:2111.03606



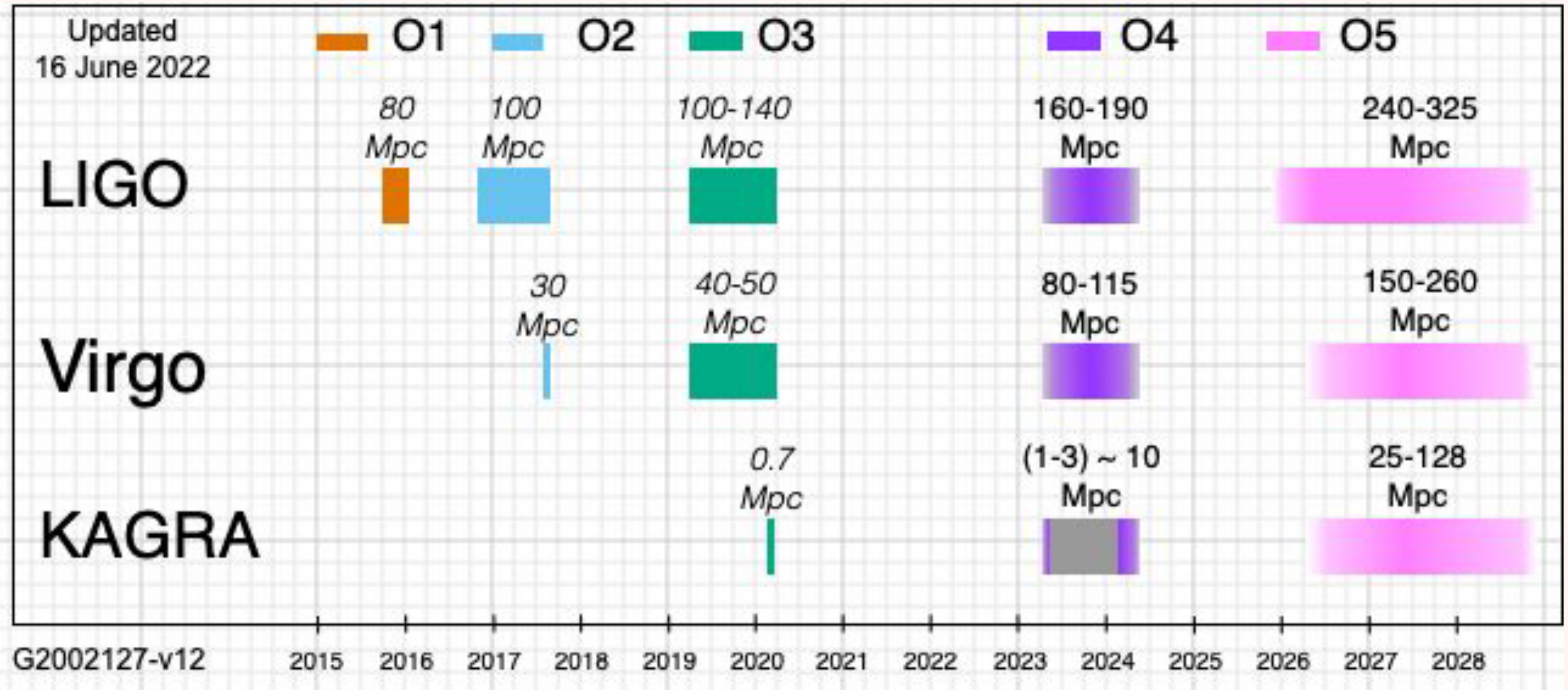


- O1-O2: Gravitational Wave Transient Catalogue (**GWTC-1**)
  - 11 events (including 1 BNS)
- Up to O3a: **GWTC-2.1**
  - 55 events (including GWTC-1)
  - 2 BNS, 2 BH-NS
- Up to O3b: **GWTC-3**
  - Total 90 events (2 BNS, 3 BH-NS, 2 uncertain, 83 BBH)

Masses in the Stellar Graveyard



Future runs: O4 and O5



- O4: 1 year run, split into
  - O4a and O4b (9 months each) with 1 month commissioning break in between.
- Start of O4a: scheduled to start on May 24 this year
- Data will be released 18 months after the end of each run

- Expect ~1 event per day:
  - ~ 300 BBH
  - ~ 9 events containing a neutron star
  - ~ 1 multimessenger BNS
  - + Nature's surprises:

GW Astrophysics

- We can determine many parameters from GW Observations
  - Distances (d_L)
  - Mass (m_1, m_2)
  - Spin (although very uncertain)
- It is important to identify host galaxies in order to carry out astrophysical research using GWs
  - Formation mechanisms
    - Isolated evolution/dynamical formation
  - Hubble constant, and other cosmological parameters)
- However, host galaxy has been identified for only one event (GW170818, a BNS event), through multi-messenger studies.

Cosmological Research with GWs

- Reconstruction of expansion history of the universe through direct measurements of distances
  - GWs from compact binaries are 'standard sirens' as the distances can be estimated from the detected waveforms and amplitudes
    - Bright sirens [optical counterparts] vs. Dark sirens [no optical counterparts]
  - Need to identify the host galaxies in order to measure the redshifts in order to construct Hubble diagram
- Cosmological parameters can also be constrained by doing cross-correlation analysis between GW sources (distance information) and galaxies with known redshifts
- Primordial gravitational waves
  - …

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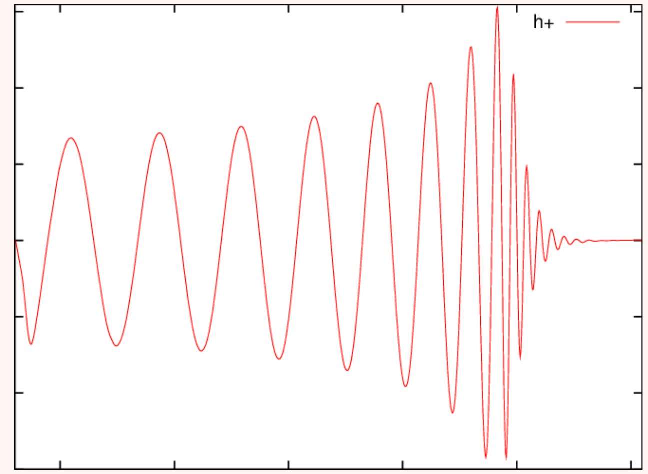
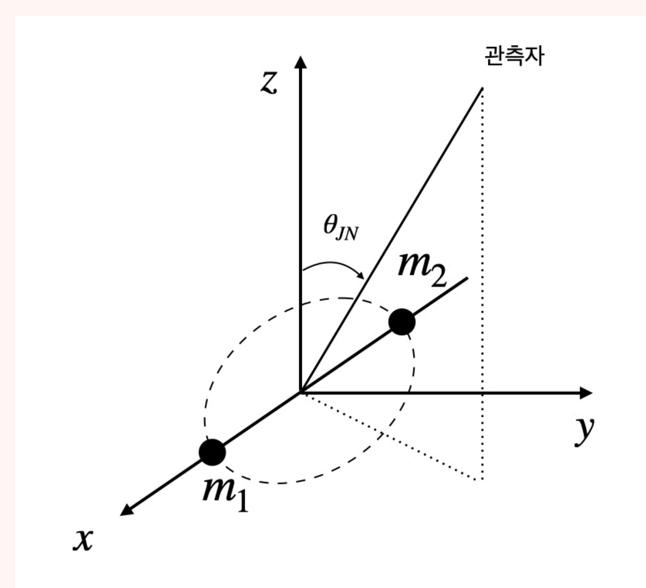
Not covered today

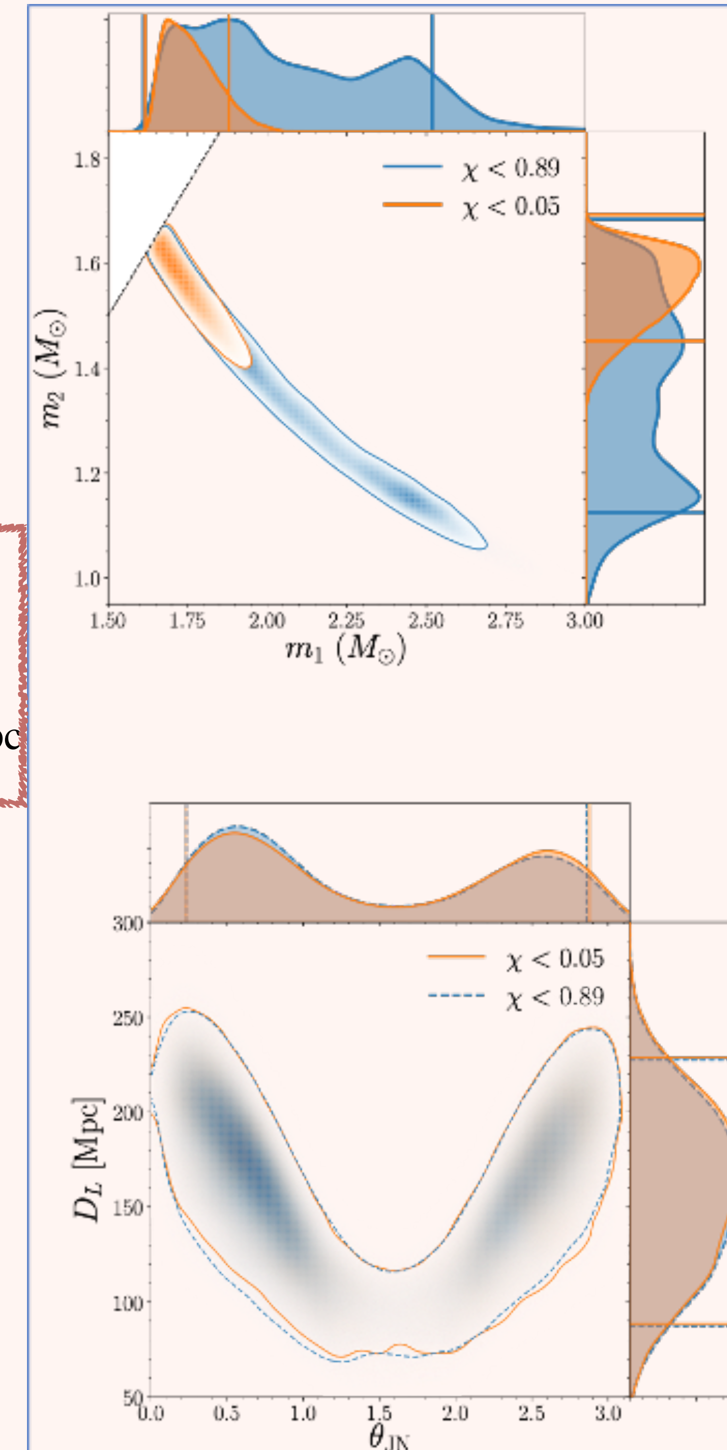
Distance measurement with GWs

- GW waveforms of binary merger depend on many parameters, with **masses** and **spins** being the most important ones. These parameters give GW luminosity.
- The amplitude of the GW signal is **inversely proportional** to the distance.
- 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 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).



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

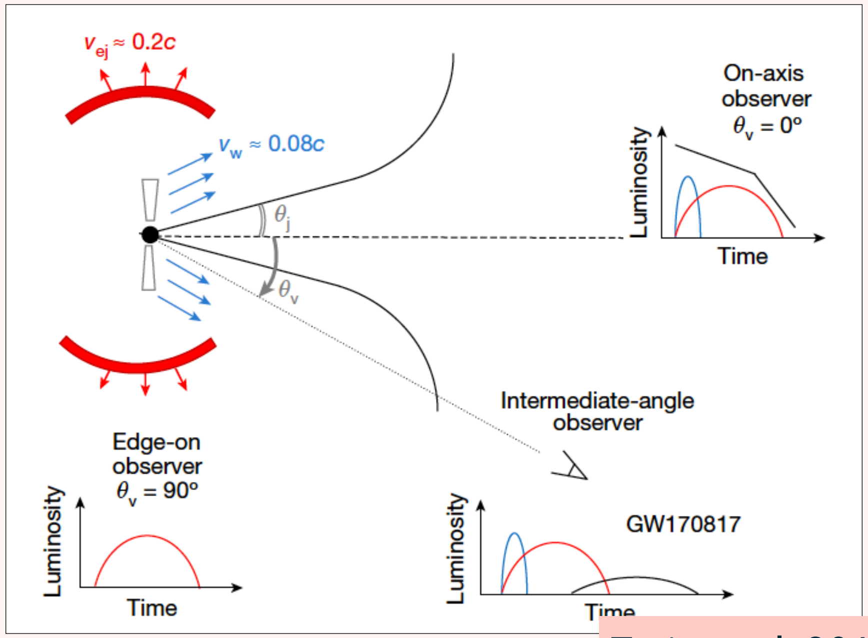




Estimated masses (upper) and distance (lower) to GW190425, a binary neutron star merger event. (Figure from Abbott et al. 2020, ApJL, 892, L3)

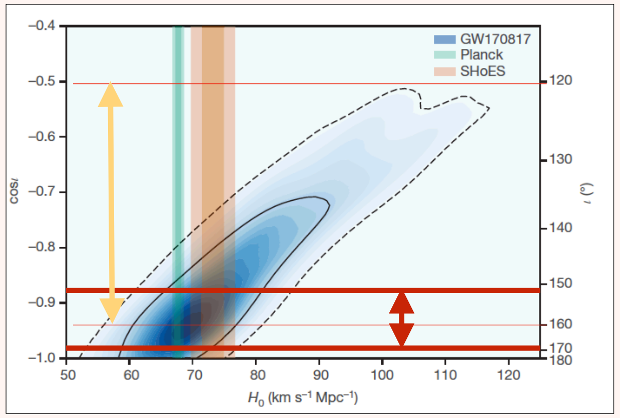
Can we constrain the viewing angle?

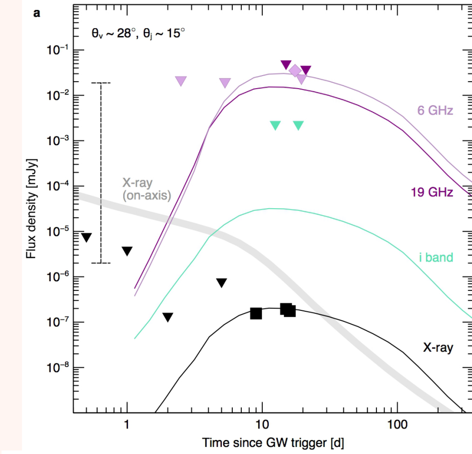
- BNS will lead to the short GRB and kilonova
- If the GRB is observed, together with the GWs, the line of sight should lie within the opening angle (θ_j) of the jet, which is perpendicular to the orbital plane (i.e., $\iota = \theta_{JN} = 0$), and the uncertainty in ι is smaller than θ_j
- Also synchrotron 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 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 ($19^\circ \lesssim \iota \lesssim 25^\circ$)
- Early detection of EM counterpart is very important for adding more BNSs with optical counterpart.

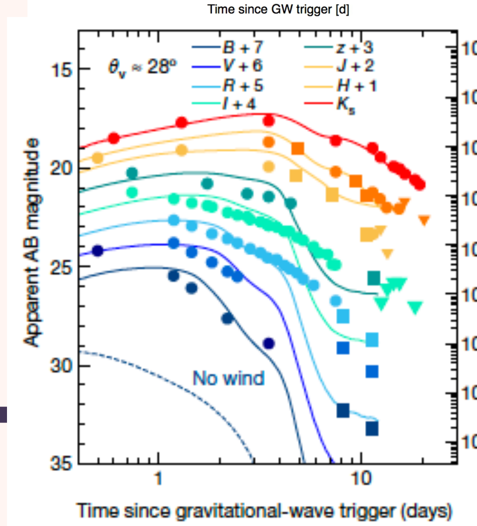


Troja et al. 2017

LSC (2017)

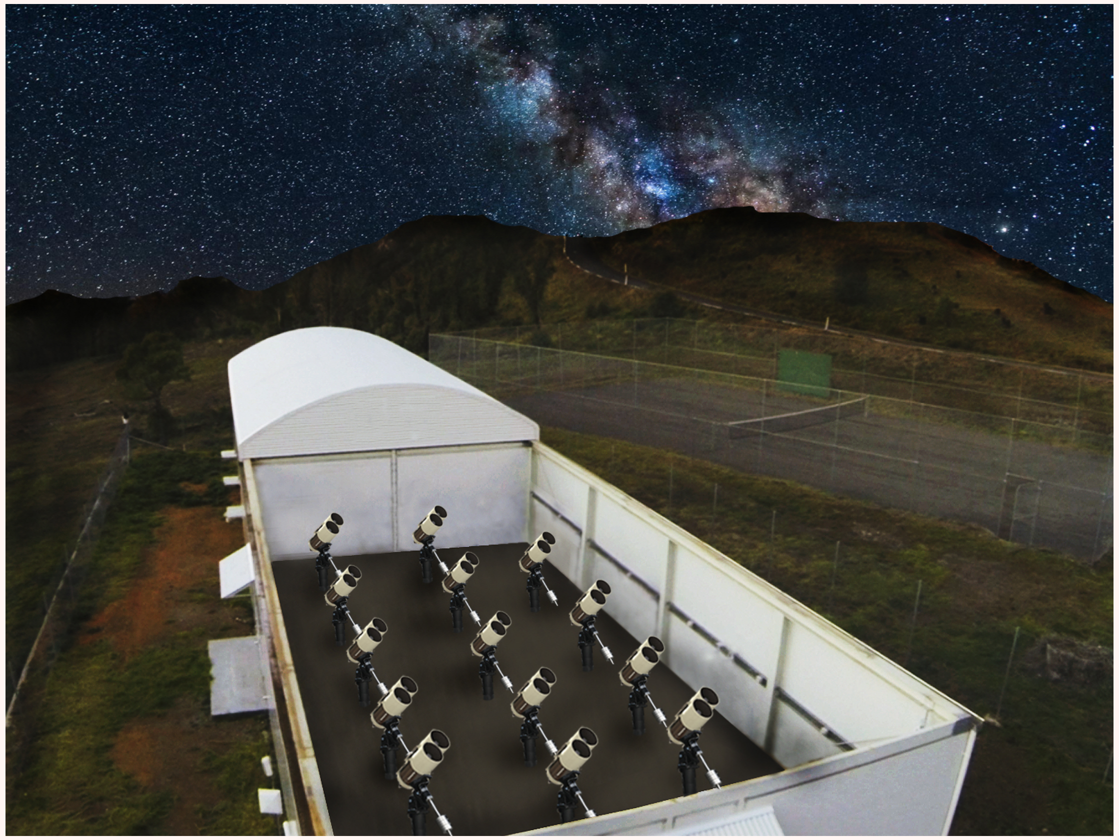


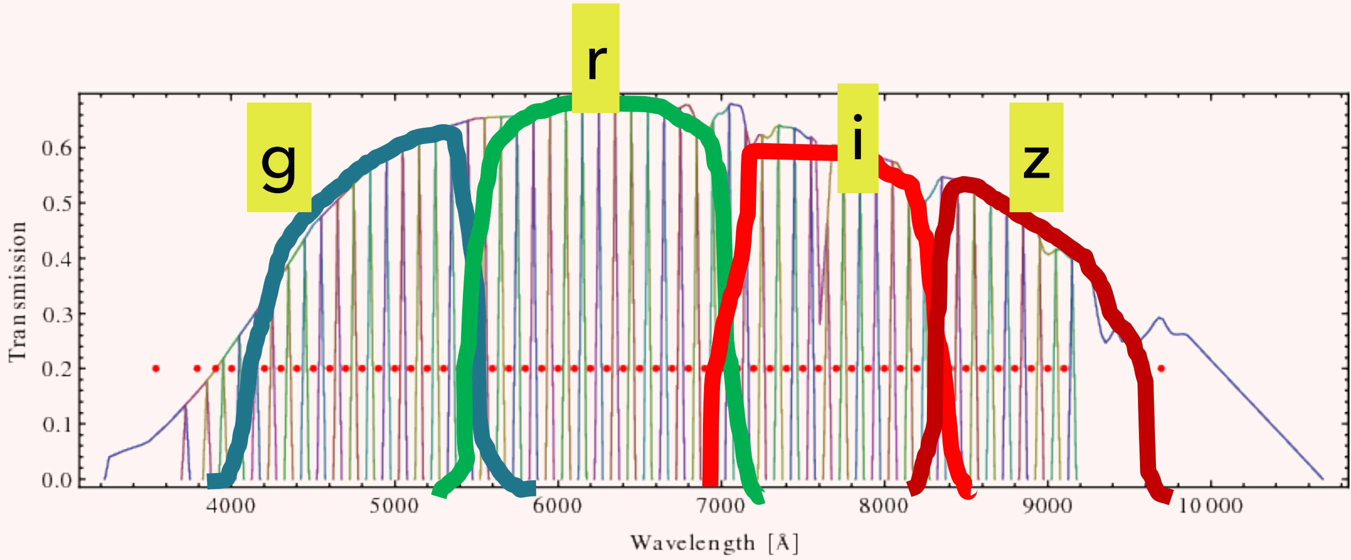




7-Dimensional Telescope, 7DT

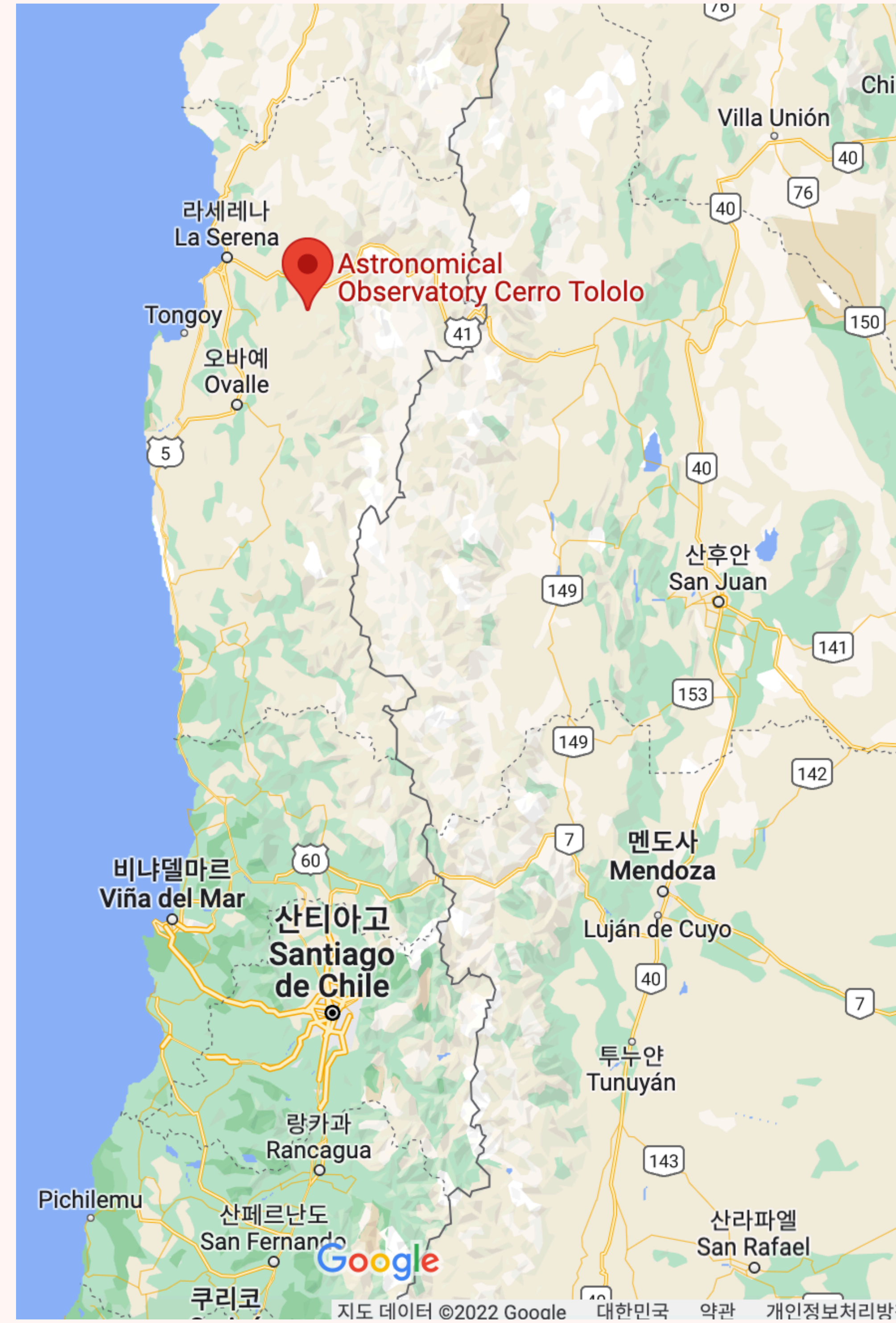
- We are building a system of telescope composed of 20 telescopes of 50 cm aperture
- Imaging wide field with 40 medium band filters (each telescope has 2) –> low resolution spectroscopy for every pixel in the field of view
- It can cover large area of sky repeatedly: wide-field, time domain, IFU-type spectroscopic telescope, suitable for the survey of transients such as GRB and Kilonovae





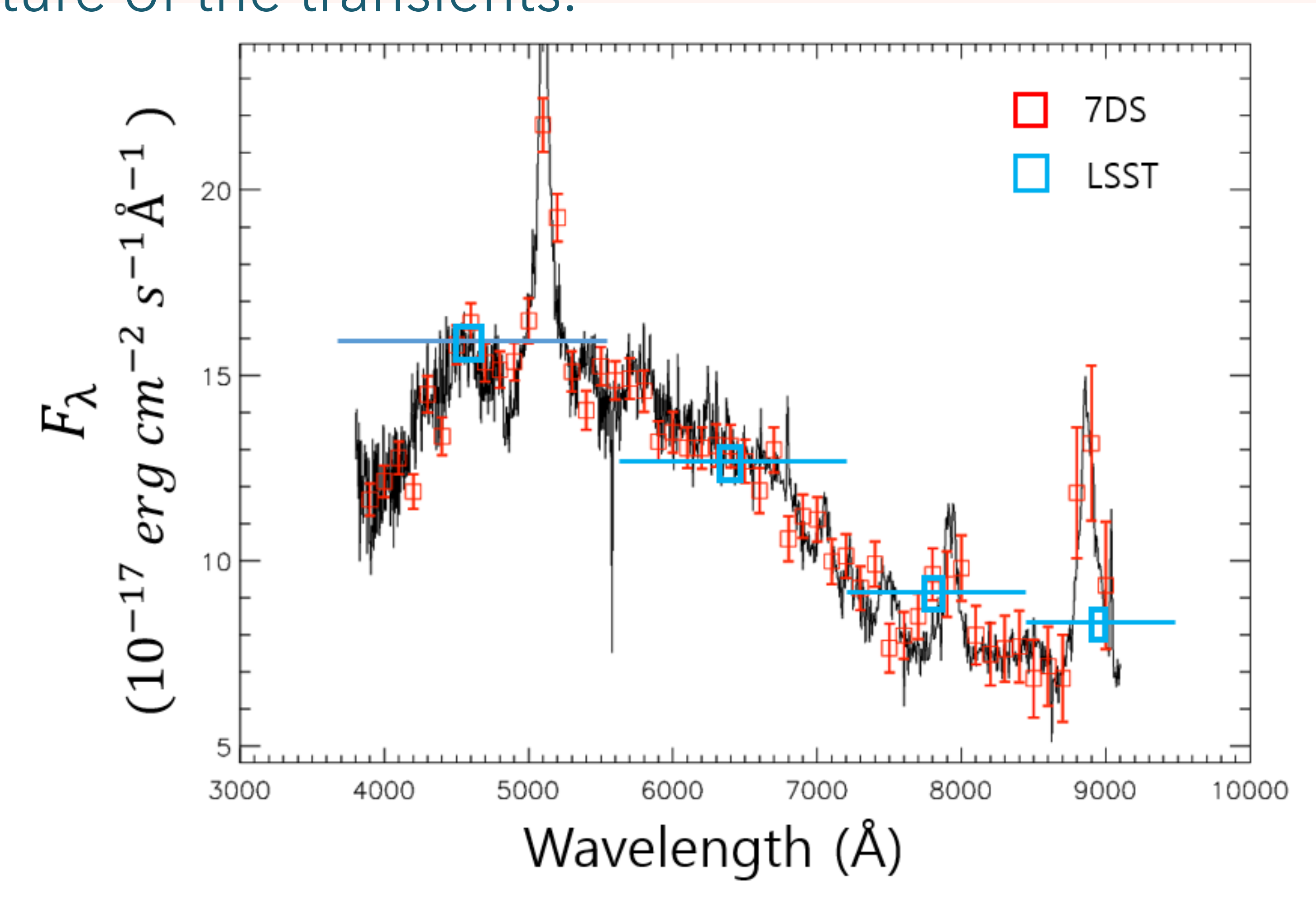
Telescope site

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



Advantage of Medium Band Spectrum

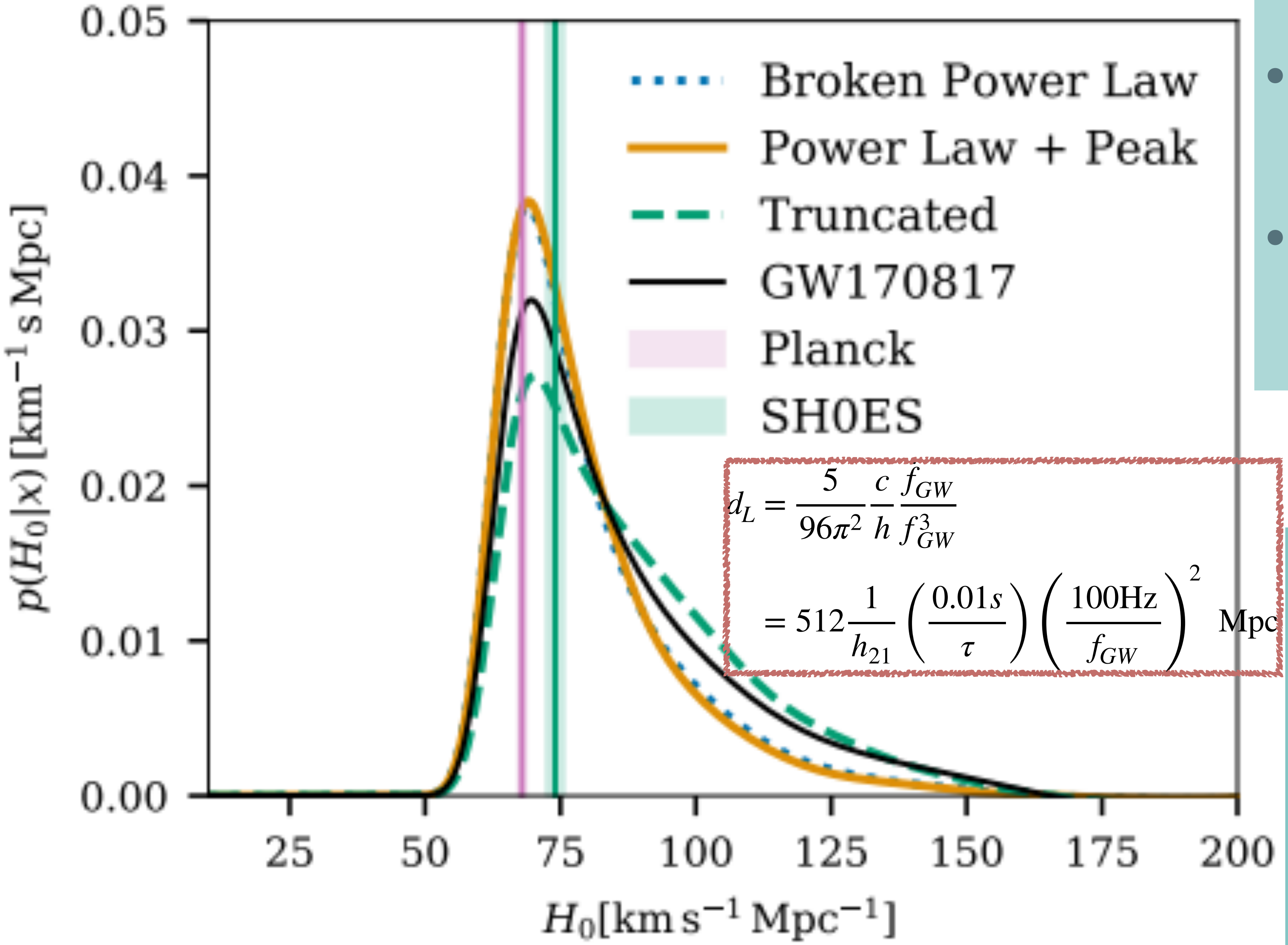
- Best suited for broad continuum features and broad emission lines continuum
- Photometric redshift: < 0.3% – 1% accuracy
- Emission line/continuum can be separated well, and thus characterize the nature of the transients.



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

Measurements of H_0 with Bright Siren: GW170817

arXiv:2111.03604V1



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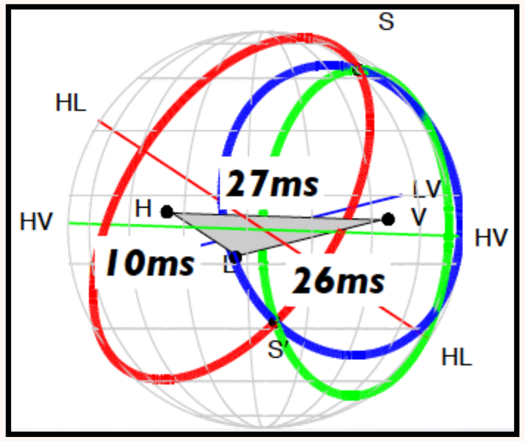
$$= 512\frac{1}{h_{21}}\left(\frac{0.01s}{\tau}\right)\left(\frac{100\text{Hz}}{f_{GW}}\right)^2 \text{Mpc}$$

- 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 upcoming O4, but may not be enough to resolve Hubble tension.
- Can we identify host galaxies of dark sirens?

Why host identification is so difficult?

- Most of the GW sources do not emit electromagnetic (EM) radiation (e.g., BBH)
  - BNS or NS-BH can emit EM radiation, but they are rare and generally rather faint.
- Sky localization is done by triangulation using differences in the arrival times to different detectors.
  - Accuracy depends on the signal-to-noise ratio



$$\sin\theta d\theta = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{\Delta t} \qquad \sigma_t = \frac{1}{2\pi\rho\sigma_f}$$

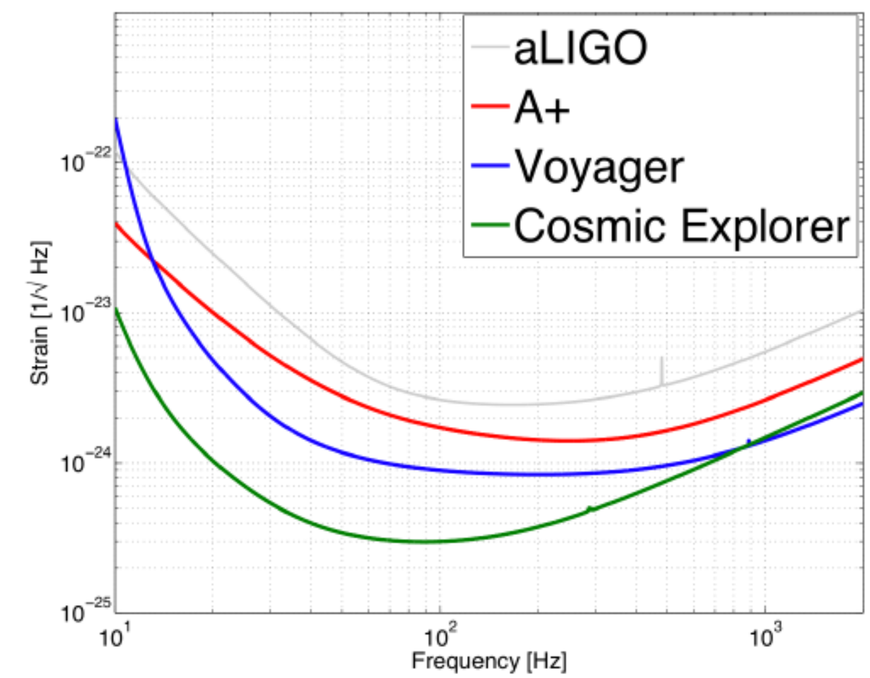
$d\theta$: width of the ring, Δt: baseline, ρ: signal-to-noise ratio, σ_f: effective **bandwidth of the source**, (~100 Hz for NS binaries, smaller for BH binaries)

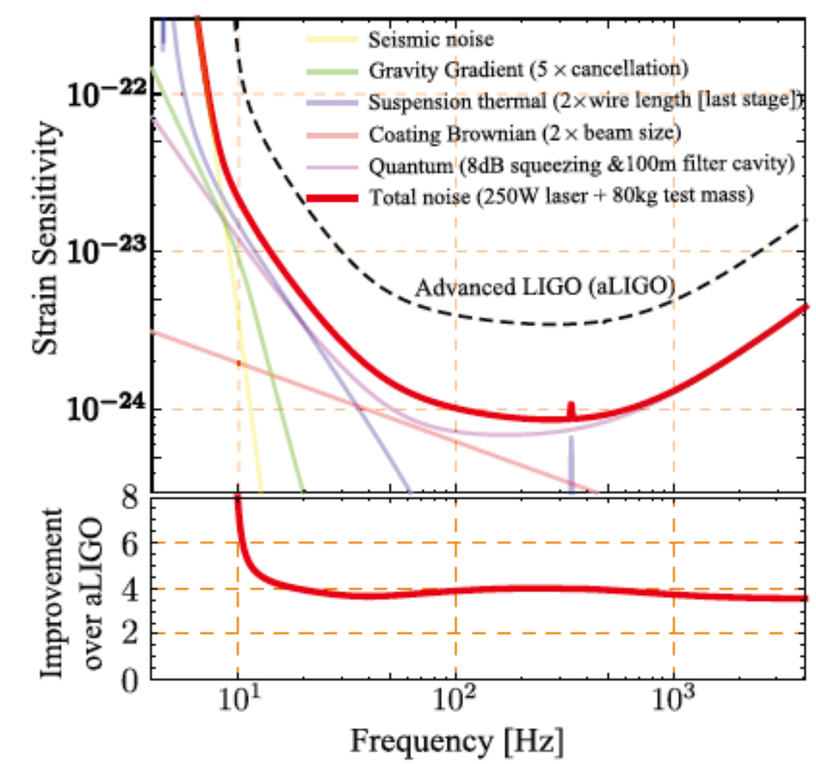
  - $\Delta\Omega$ is very large (100 - 1000 sq. deg.)
  - Localization accuracy improves with number and sensitivity of detectors

LIGO/Virgo Upgrades and near future detectors

- LIGO's upgrade plan
  - A+ (~50%)
  - Voyager (factor of 3)
  - Cosmic Explorer (order of magnitude)
- Additional Detectors
  - KAGRA (~2024), LIGO India (>2027)
  - Proposal for 8 km detectors in Australia (and possibly in China)
  - Einstein Telescope

LIGO Upgrade Plan white paper (LIGO-T1400316)

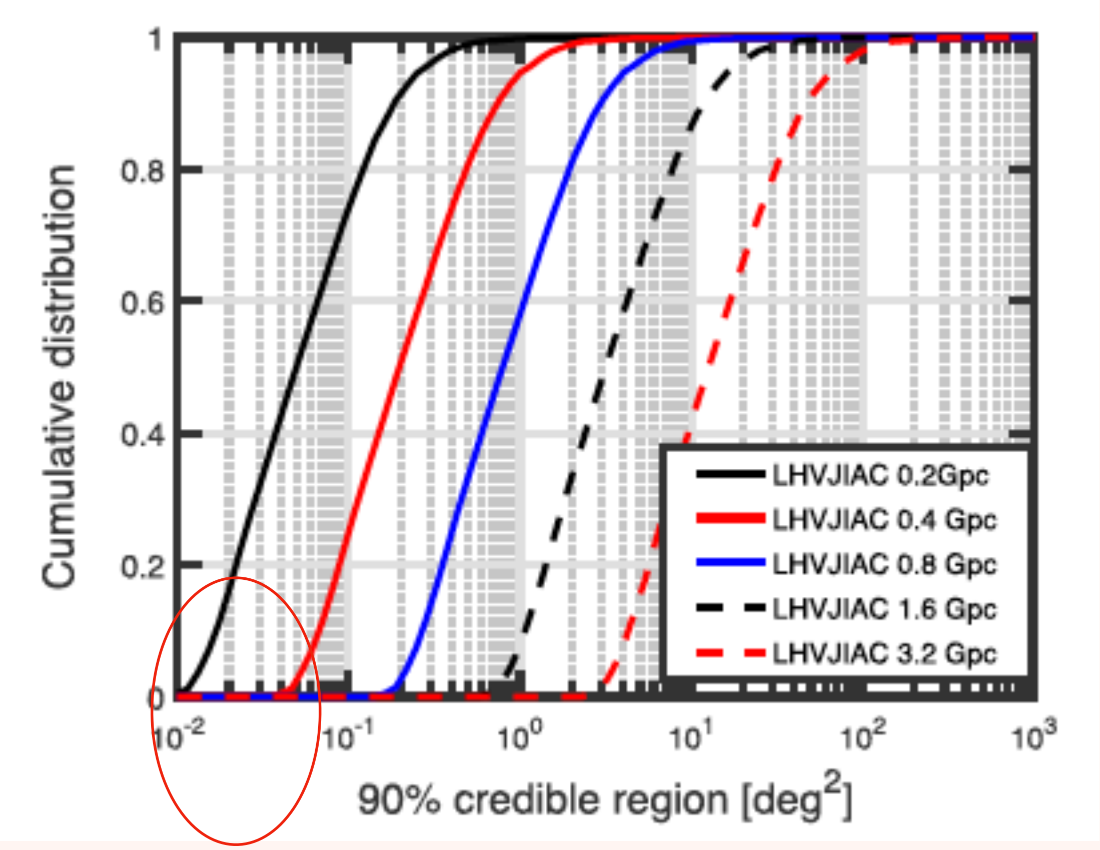


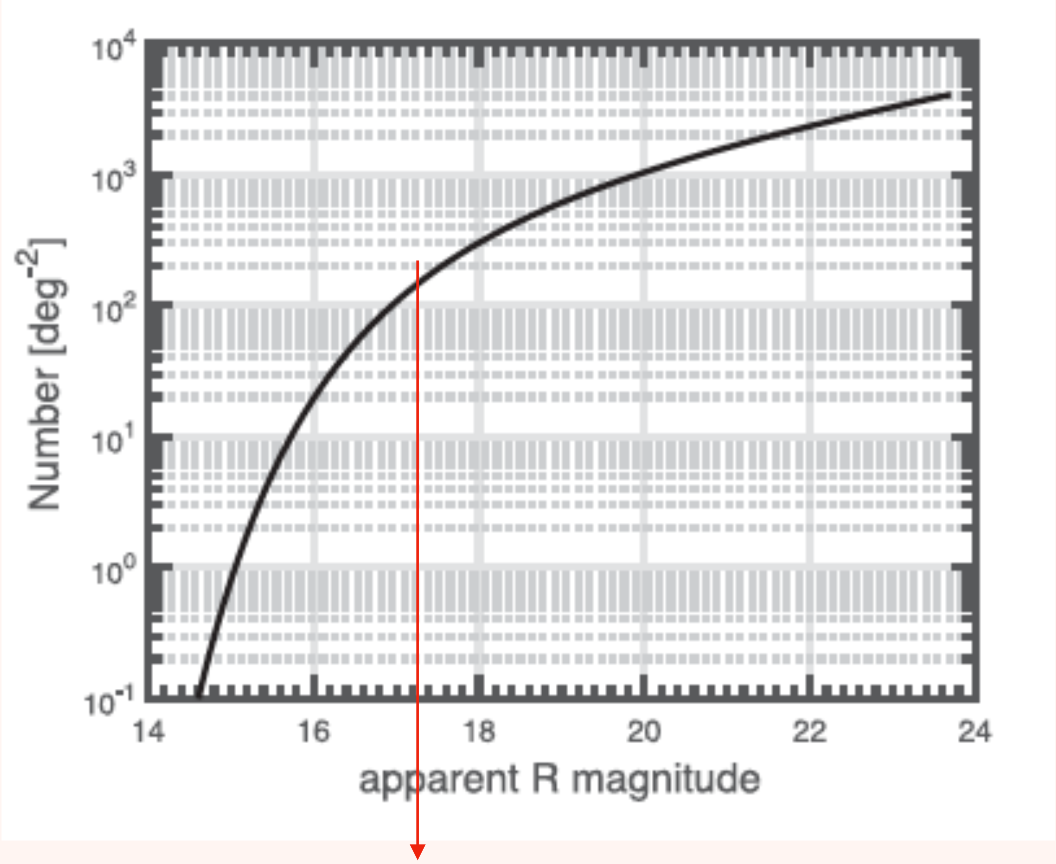


Blair et al. 2015, Science China Physics, Mechanics, and Astronomy, 58, 5747

Can BBH hosts be identified with ground based detectors?

Howell, … Lee, … et al. 2018



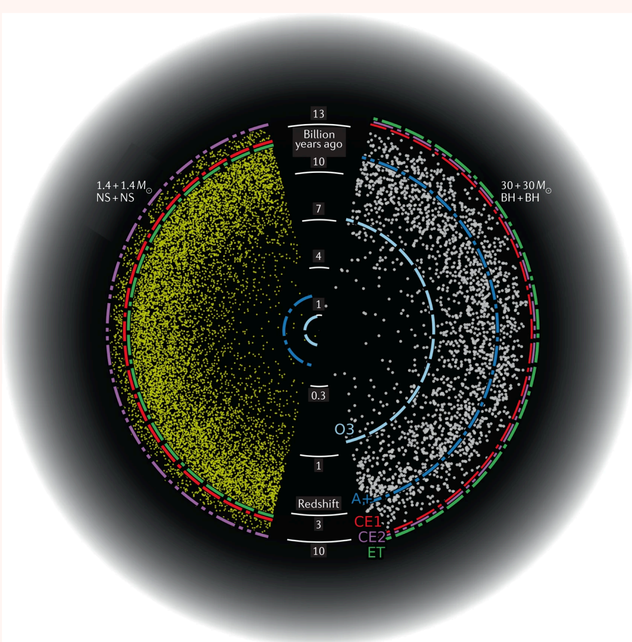


Milky Way Galaxy at 0.4 Gpc

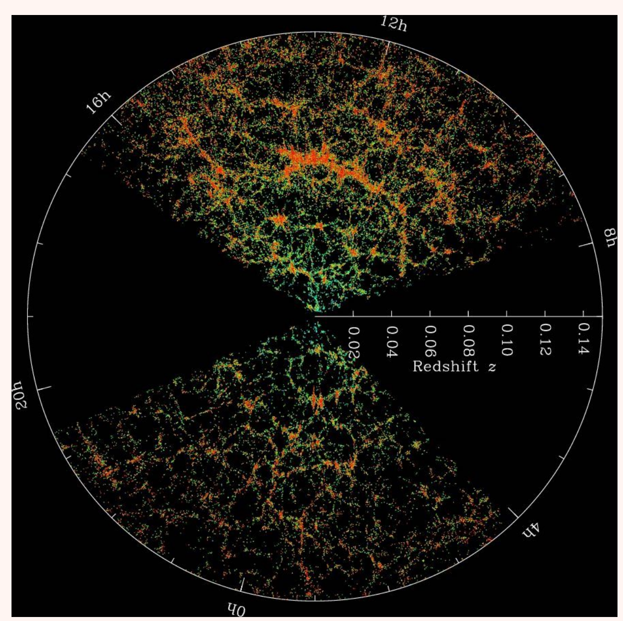
- With network of 5 advanced detectors and two additional detectors with better sensitivity, ~20% of the BBHs at 400 Mpc can be localized within 0.1 sq. deg.
- There could be 10-20 galaxies within the 0.1 sq. deg.
- **BBH host identification by ground based detectors is very challenging!**

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)



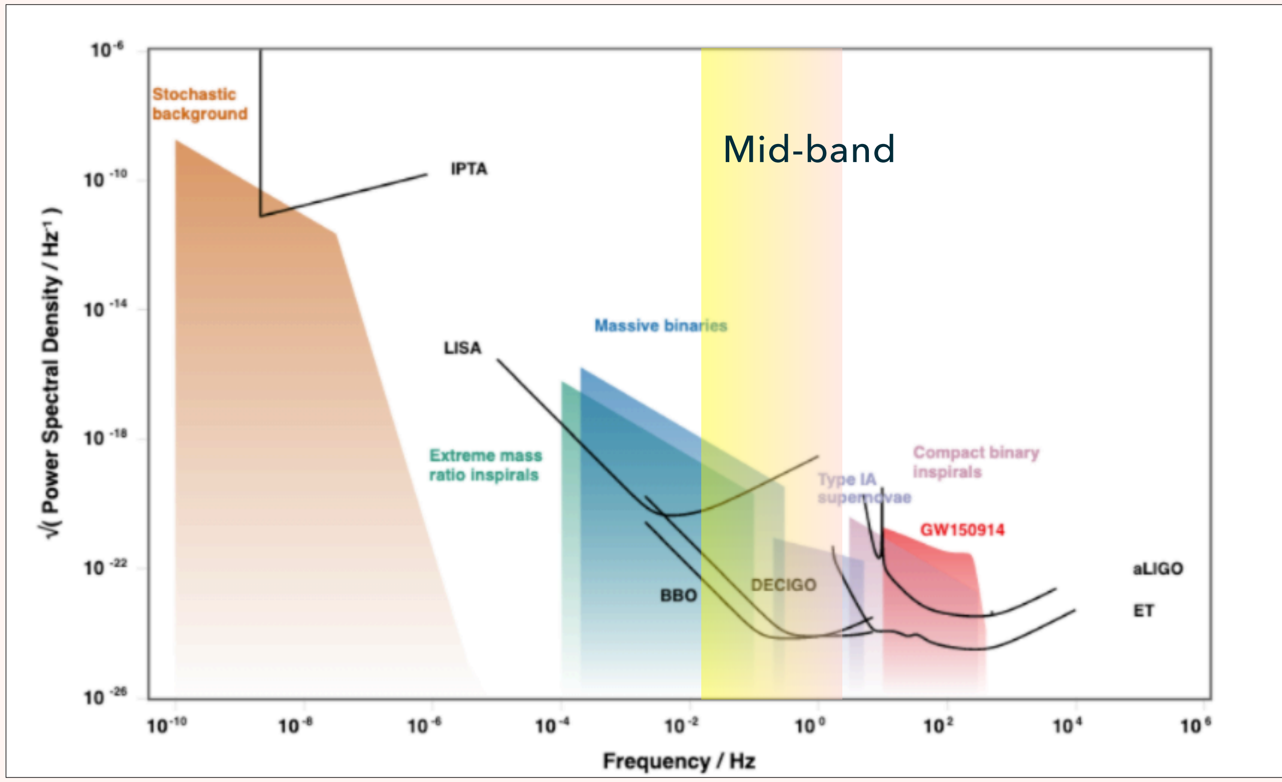
x

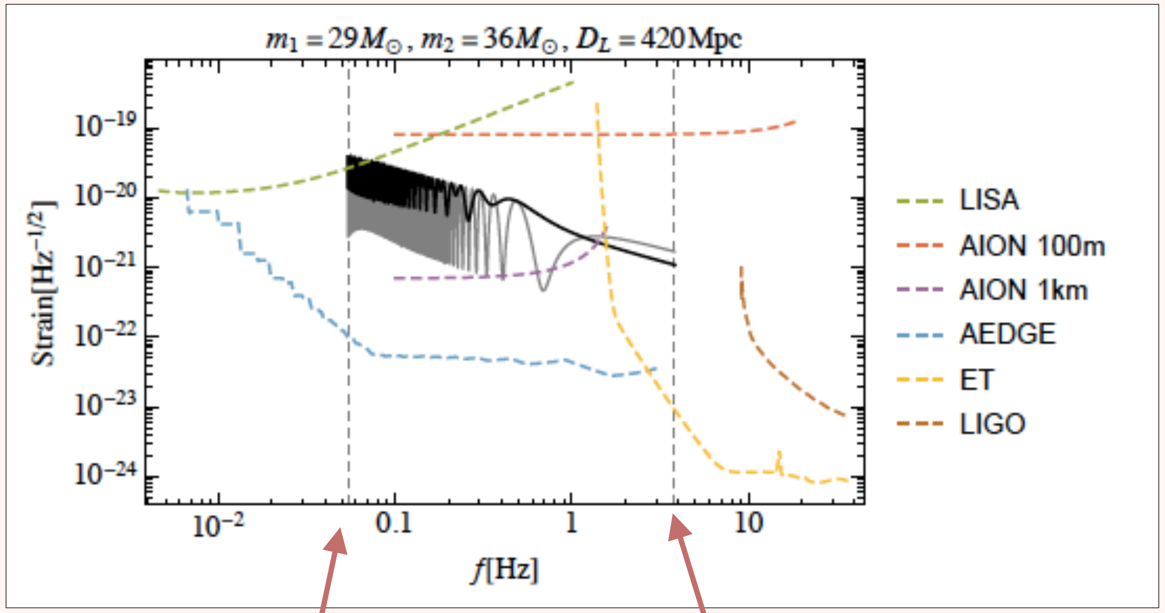


$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$

Observations with mid-frequency 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

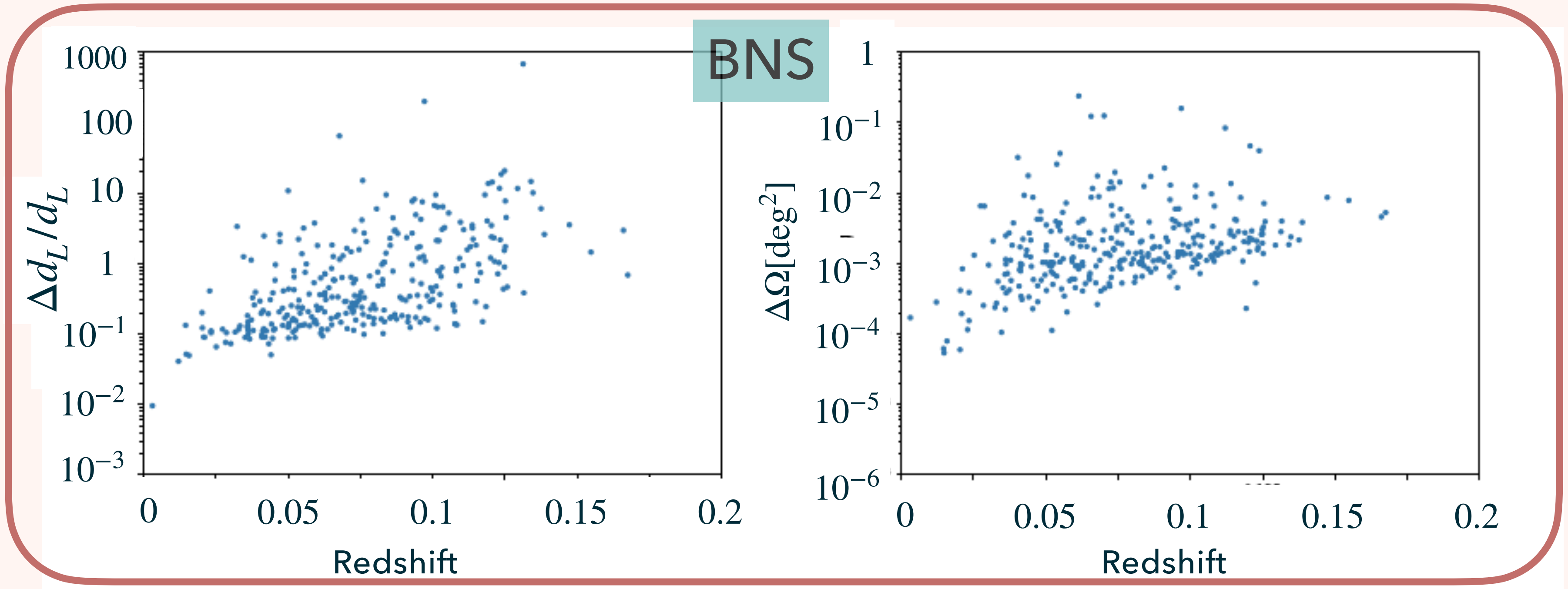


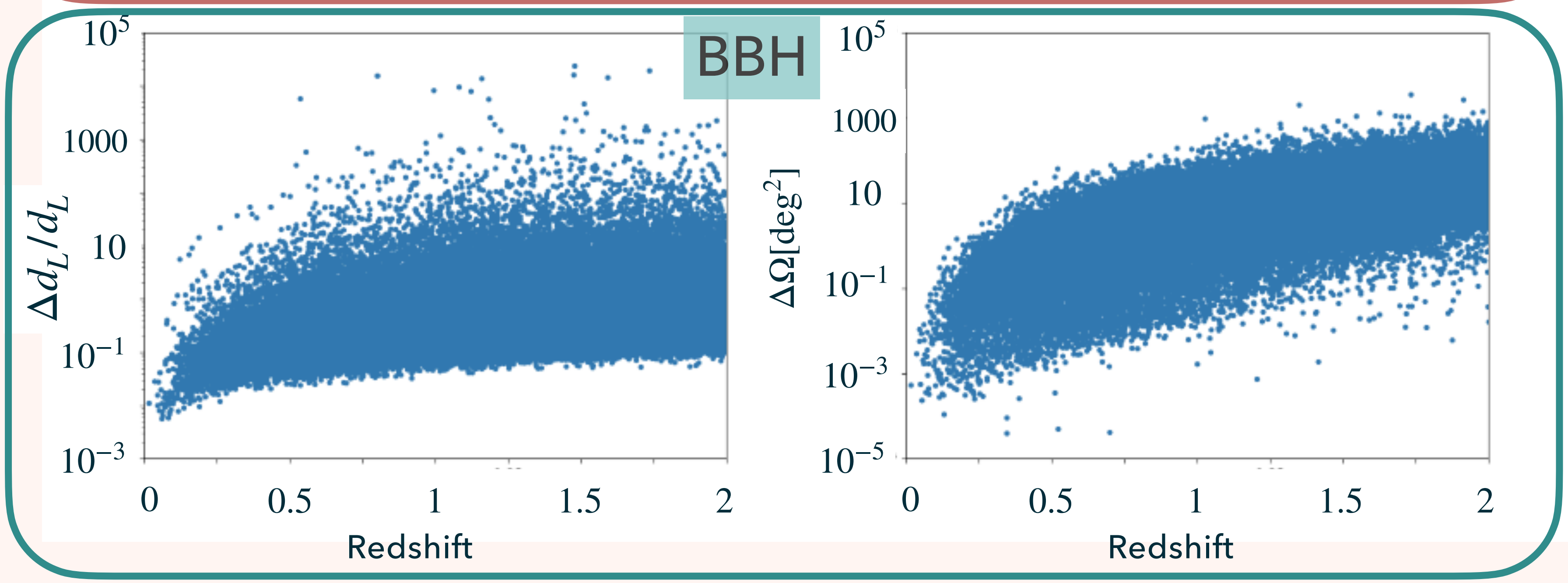


60 days before merger

1 minute before merger

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



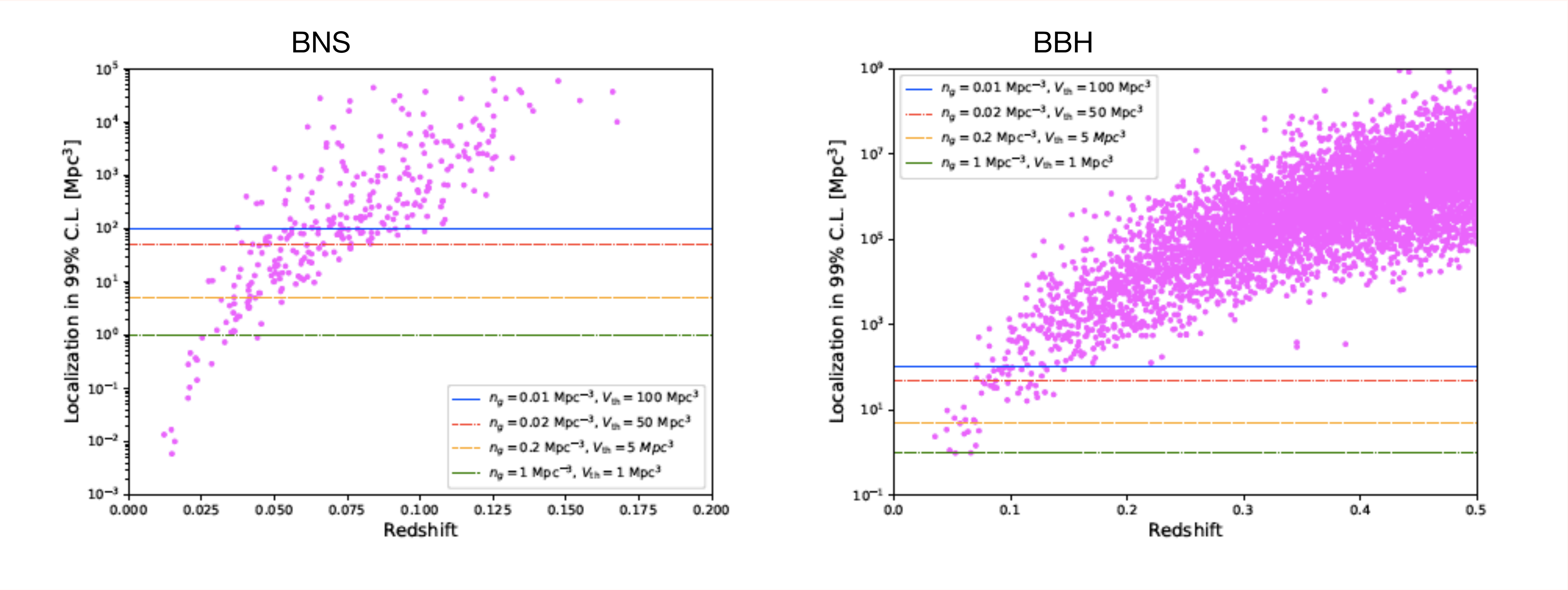


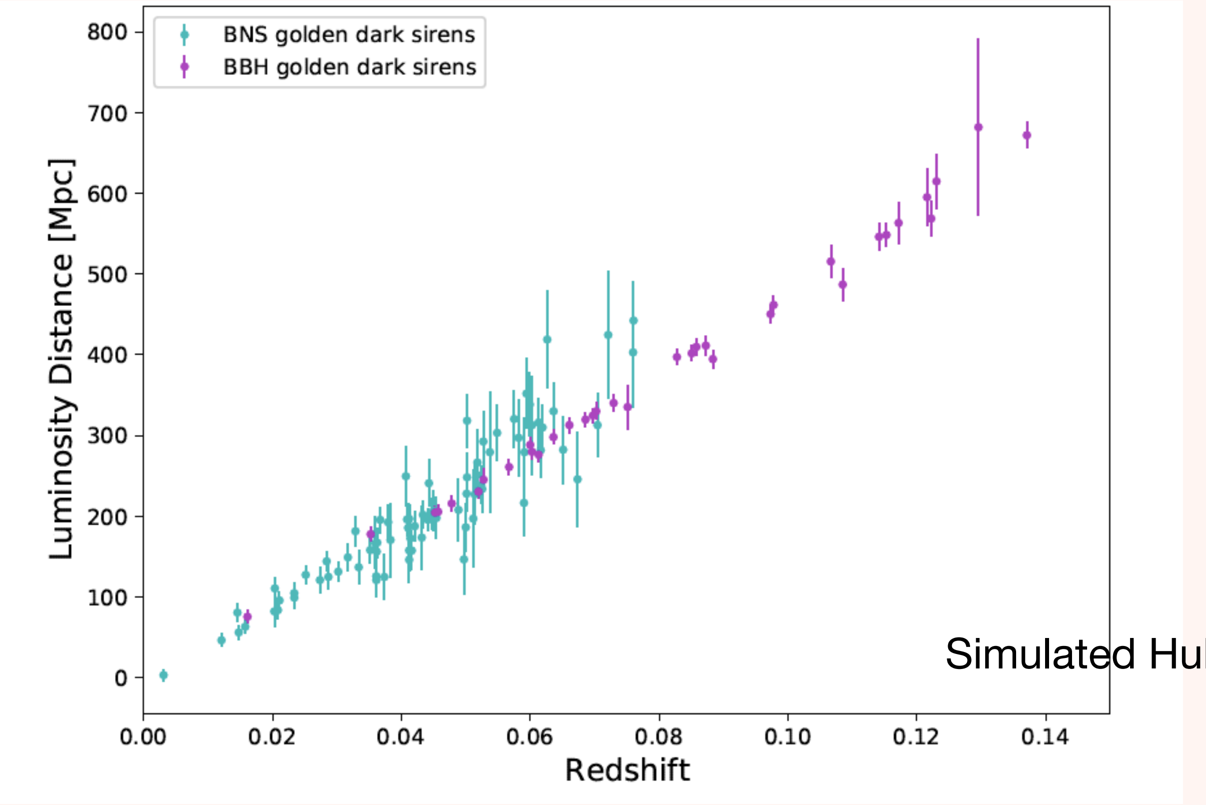
$$\Delta\Omega = 2\pi|\sin\theta|\sqrt{\Gamma^{-1}_{\theta\theta}\Gamma^{-1}_{\phi\phi} - (\Gamma^{-1}_{\theta\phi})^2}$$

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,

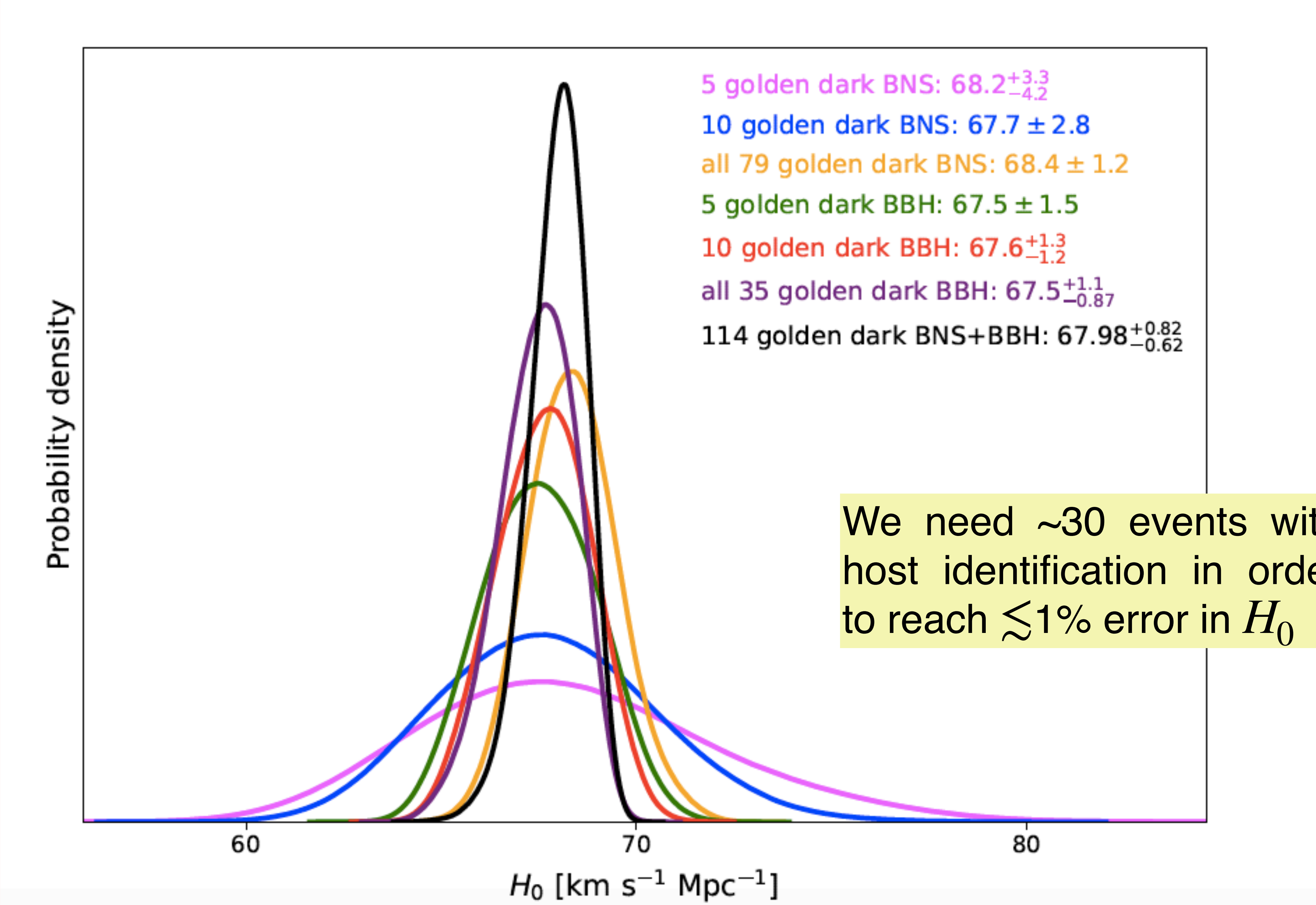




Simulated Hubble Diagram

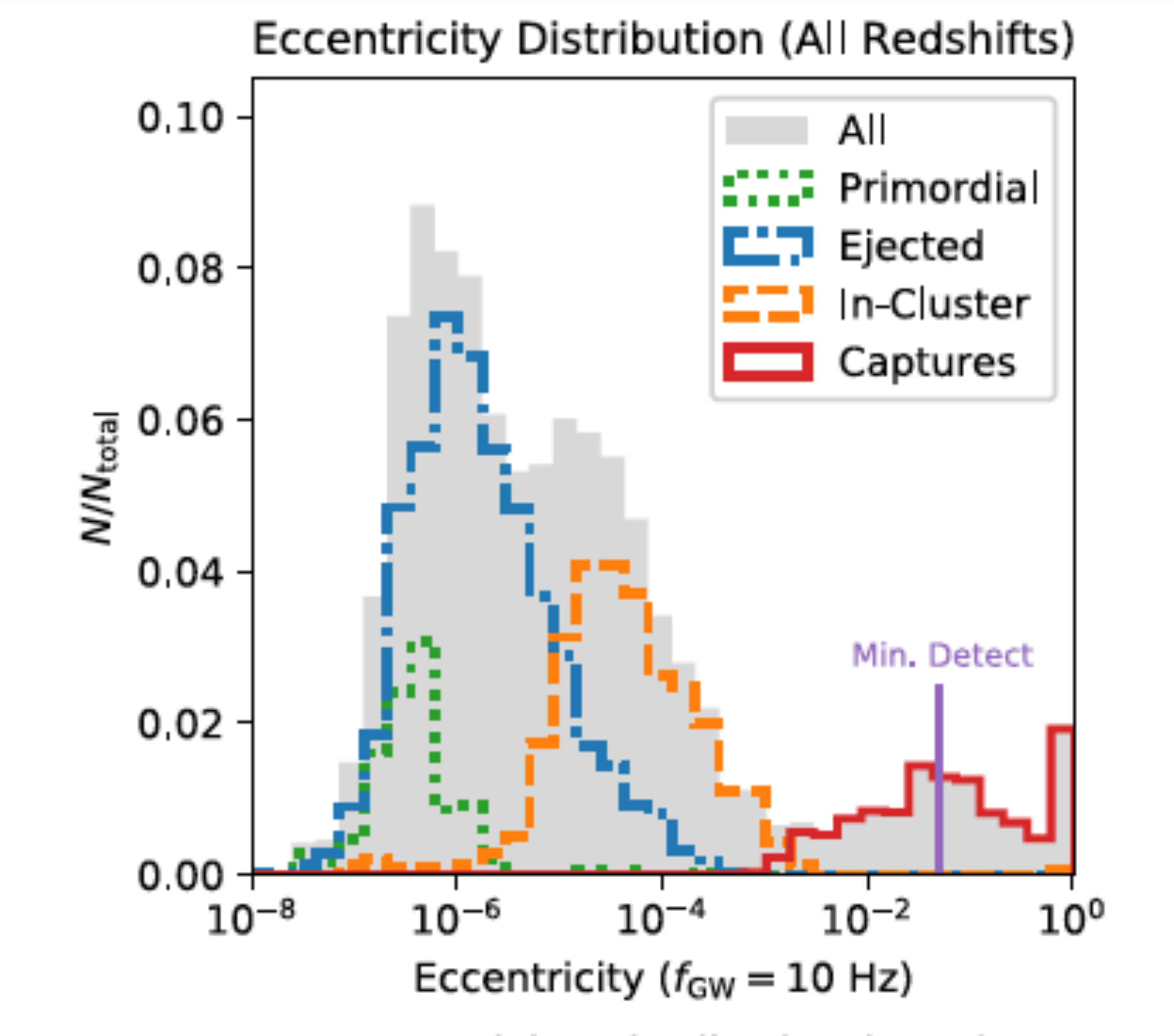
Various cuts are assumed galaxy number densities: below these lines, we can uniquely identify host galaxies within 5 year observation

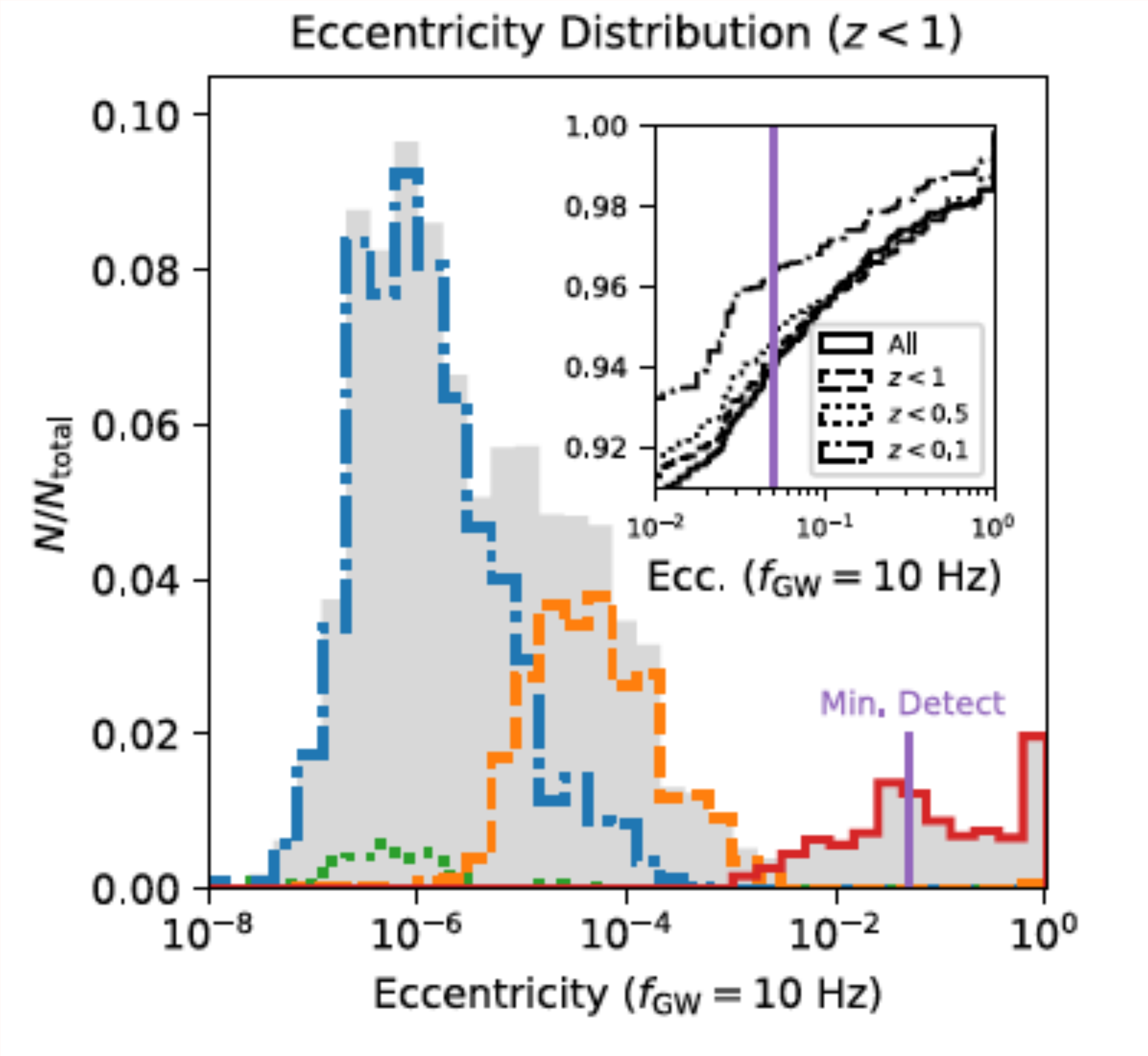
Simulation of Hubble Constant Estimation with Dark Sirens



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



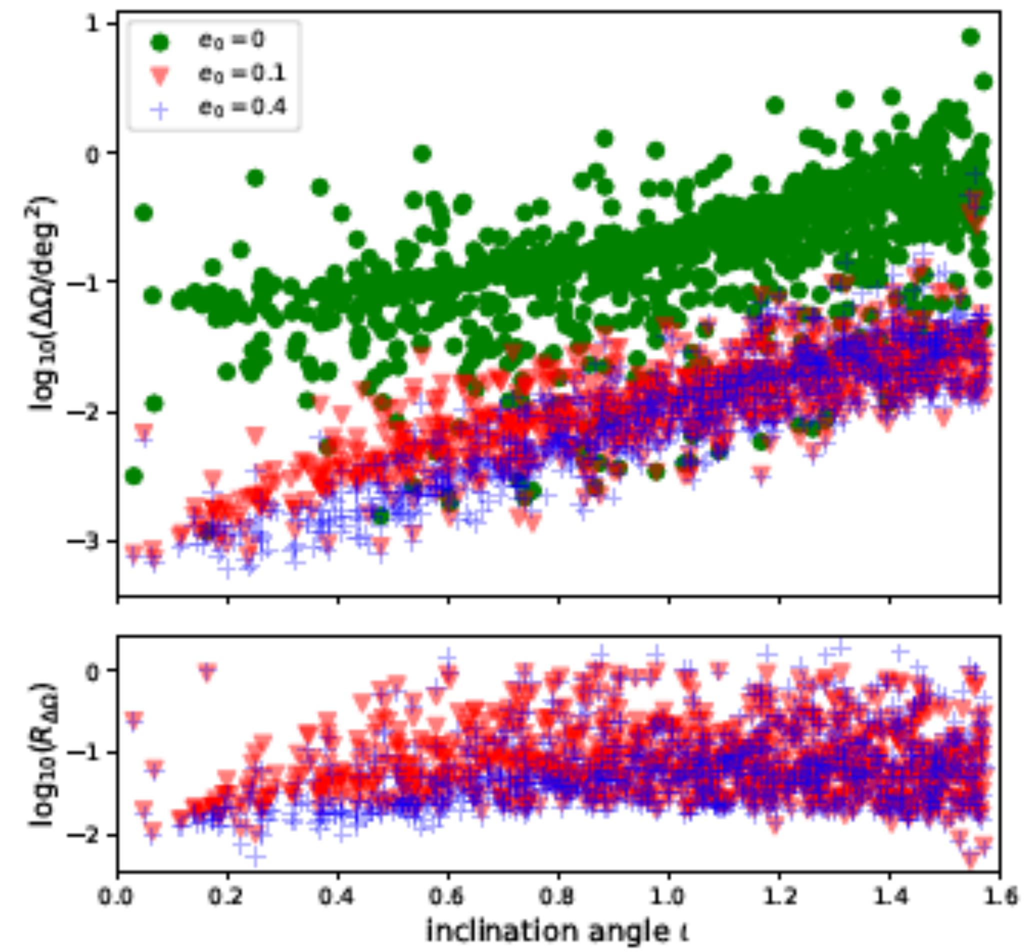


Rodriguez et al., PRD 98. 123005 (2018)

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.

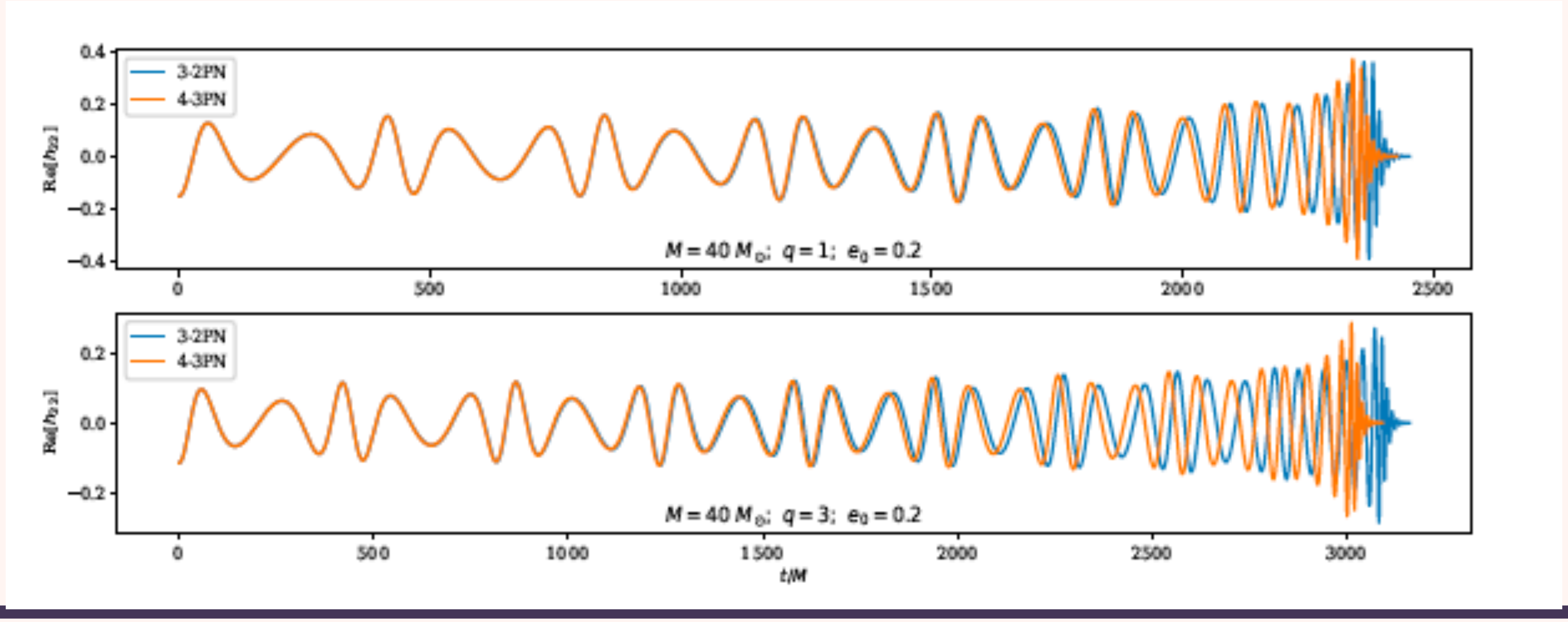
Yang,.. Lee, (2022), PRL, 129, 191102



Accurate Waveforms for longer 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 very 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.