Cosmological applications of GWs

Survey Science Group Workshop 2023

Jan. 16-18, 2023

Hyung Mok Lee (SNU)

Identification of Host Galaxies of GW Events

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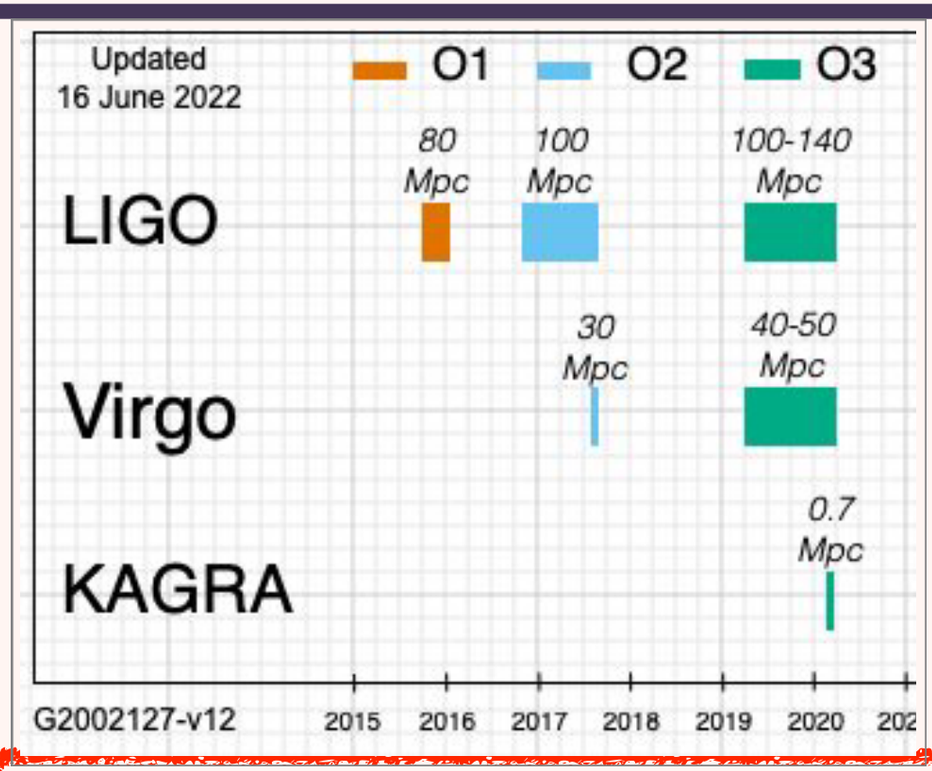
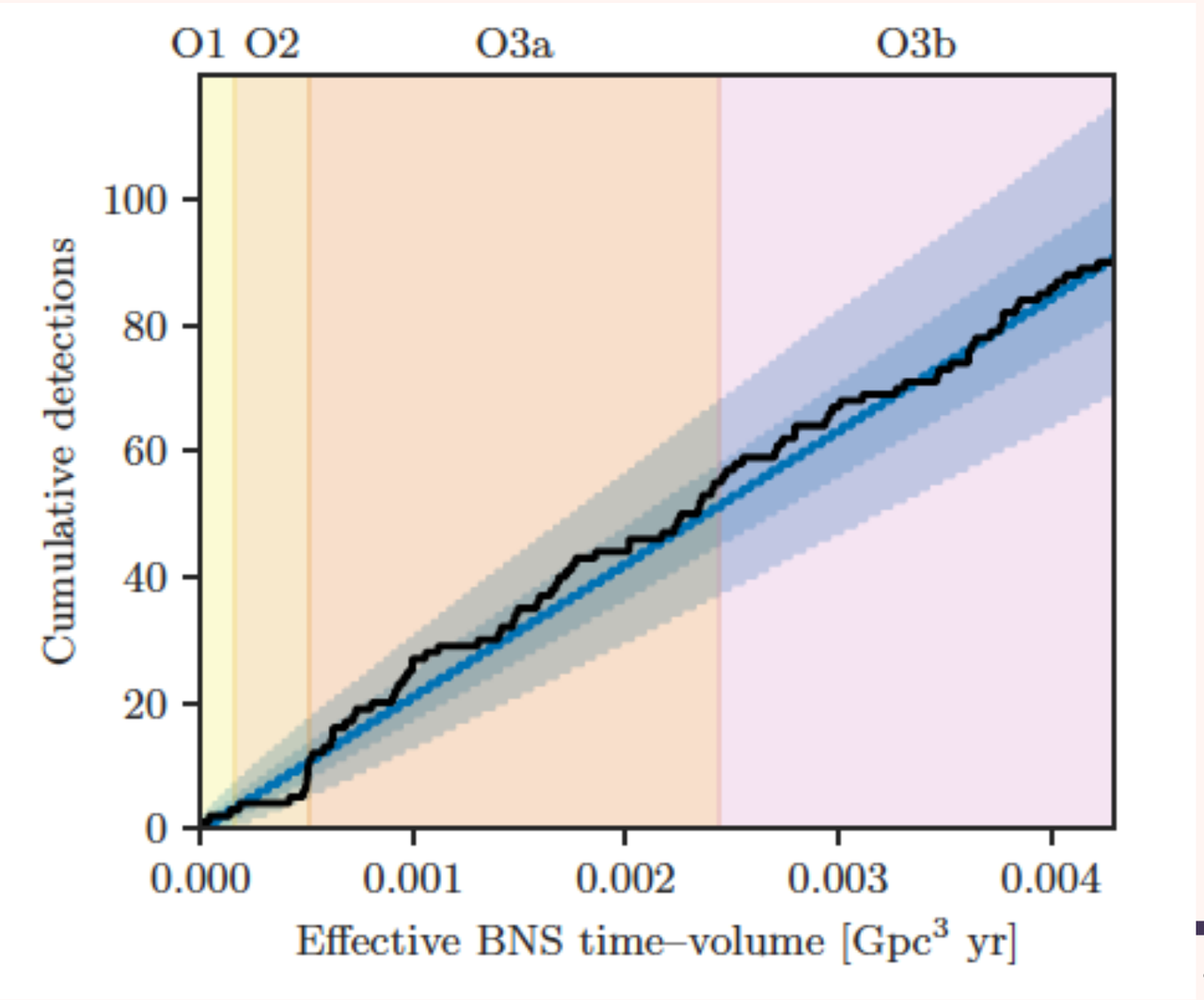
- Why do we need host identification?
- Dark Siren in Ground-based detectors
- Dark siren in Mid-band detectors
- Effects of Eccentricities in mid-band

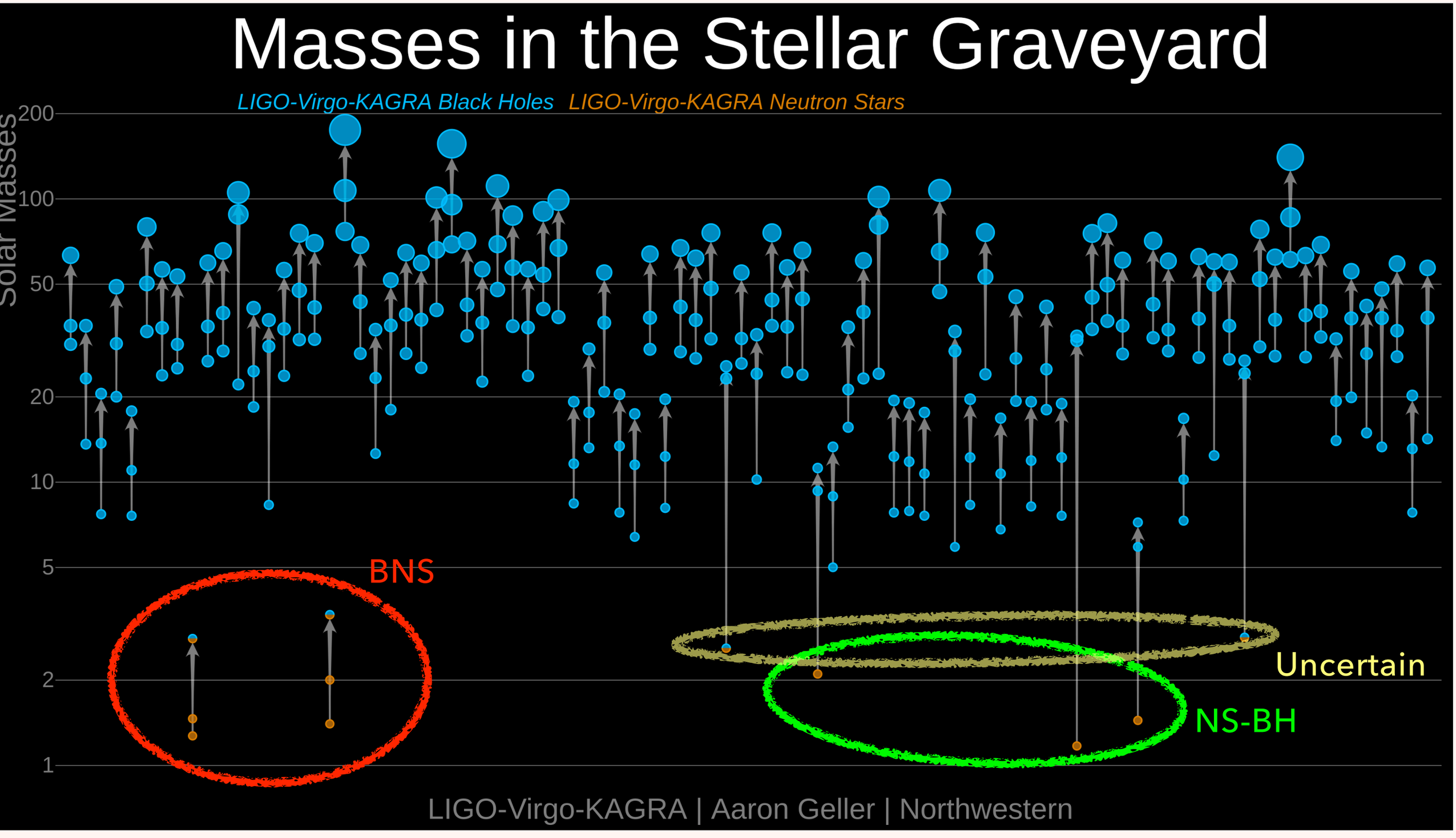
Results of LIGO/Virgo/ KAGRA Observing Runs in the past

arXiv:2111.03606

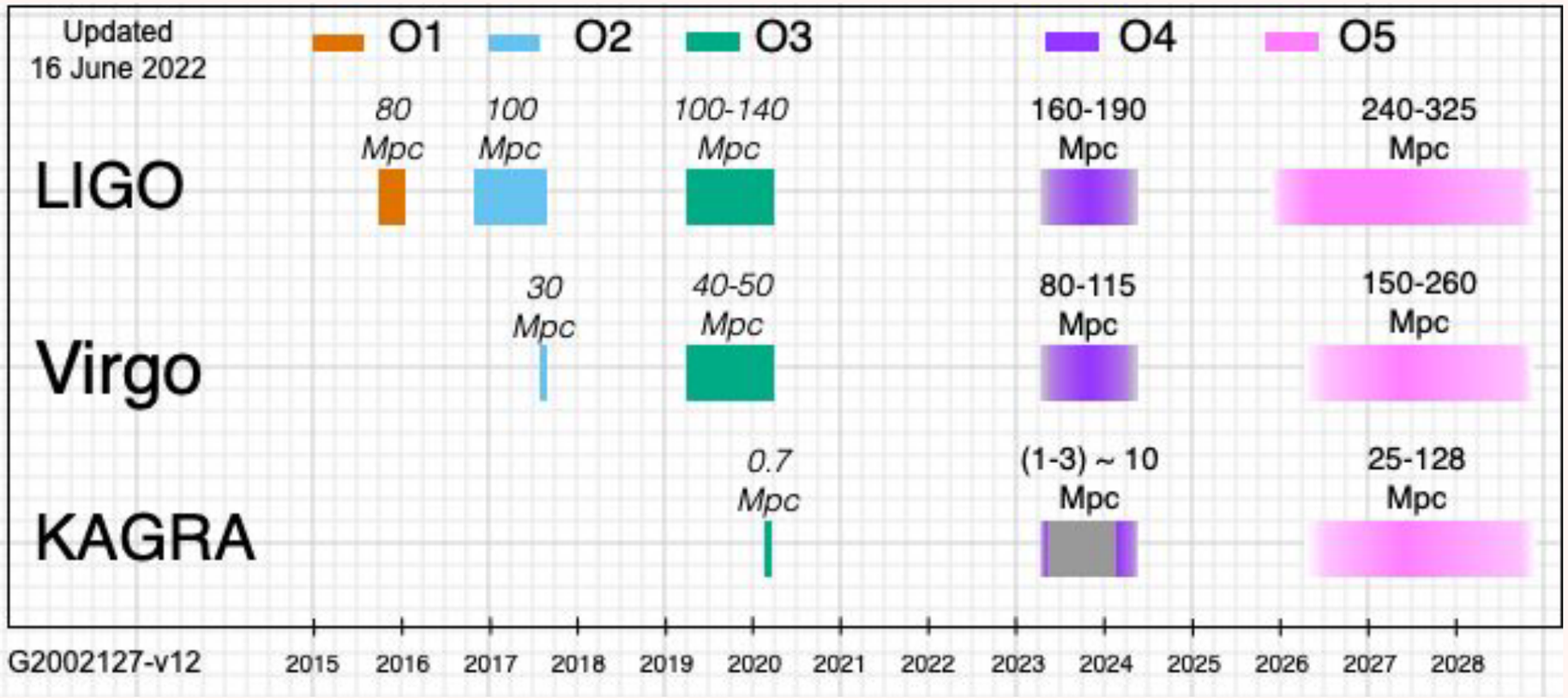




- O1-O2: Gravitational Wave Transient Catalogue (**GWTC-1**)
  - 11 events (including 1 BNS)
- Up to O3a: **GWTC-2.1**
  - 55 events (including GWTC-1)
  - 2 BNS, 2 BH-NS
- Up to O3b: **GWTC-3**
  - Total 90 events (2 BNS, 3 BH-NS, 2 uncertain, 83 BBH)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
BNS
Uncertain
NS-BH
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Future runs: O4 and O5



- O4: 1 year run, split into
  - O4a and O4b (6 months each) with 1 month commissioning break in between.
- Start of O4a: to be finalized on Jan. 19.
- Data will be released 18 months after the end of each run

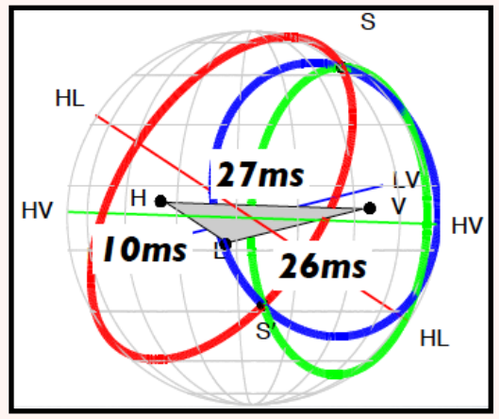
- Expect ~1 event per day:
  - ~ 300 BBH
  - ~ 9 events containing a neutron star
  - ~ 1 multimessenger BNS
  - + Nature's surprises:

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.

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



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

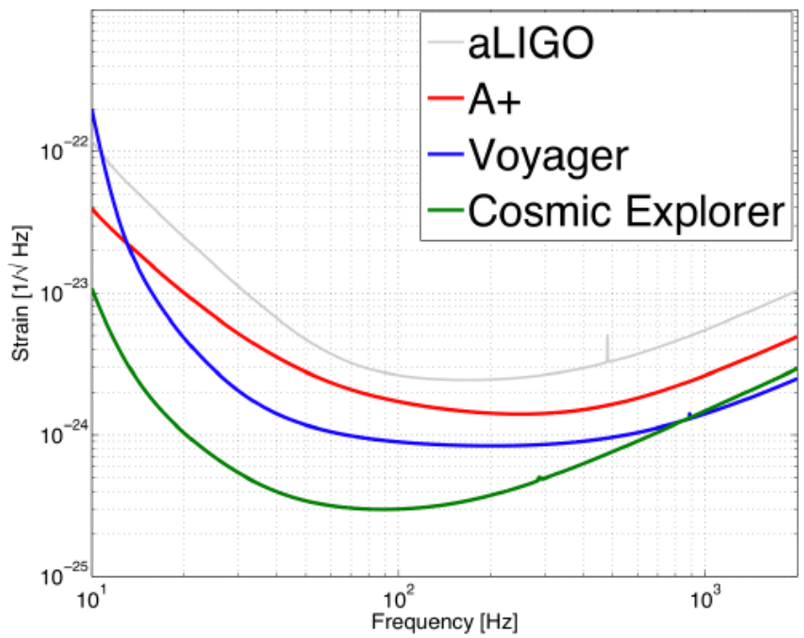
$d\theta$: width of the ring, Δt: baseline, ρ: signal-to-noise ratio, σ_f: effective bandwidth of the source, (~100 Hz for NS binaries, smaller for BH binaries)

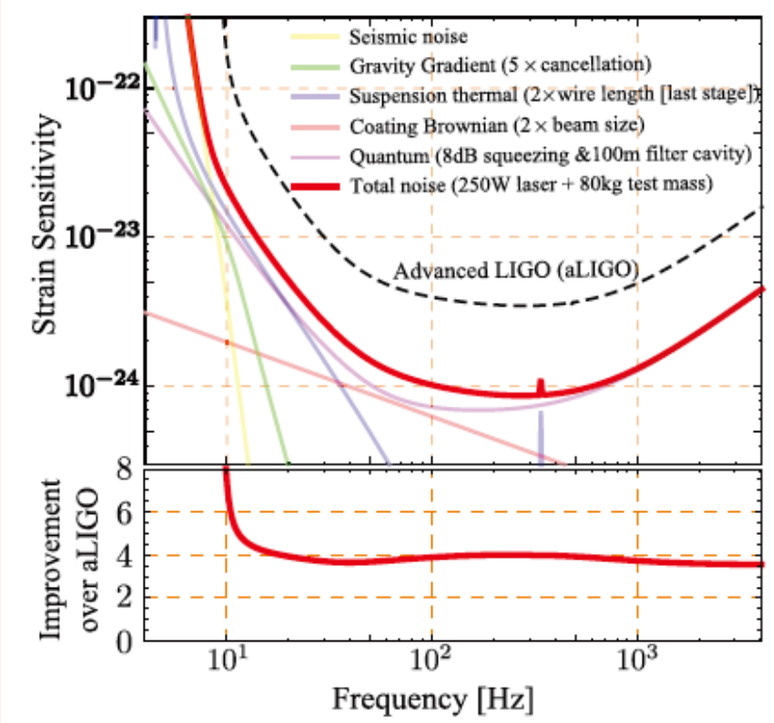
- $\Delta\Omega$ is very large (100 - 1000 sq. deg.)
- Localization accuracy improves with number and sensitivity of detectors

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)

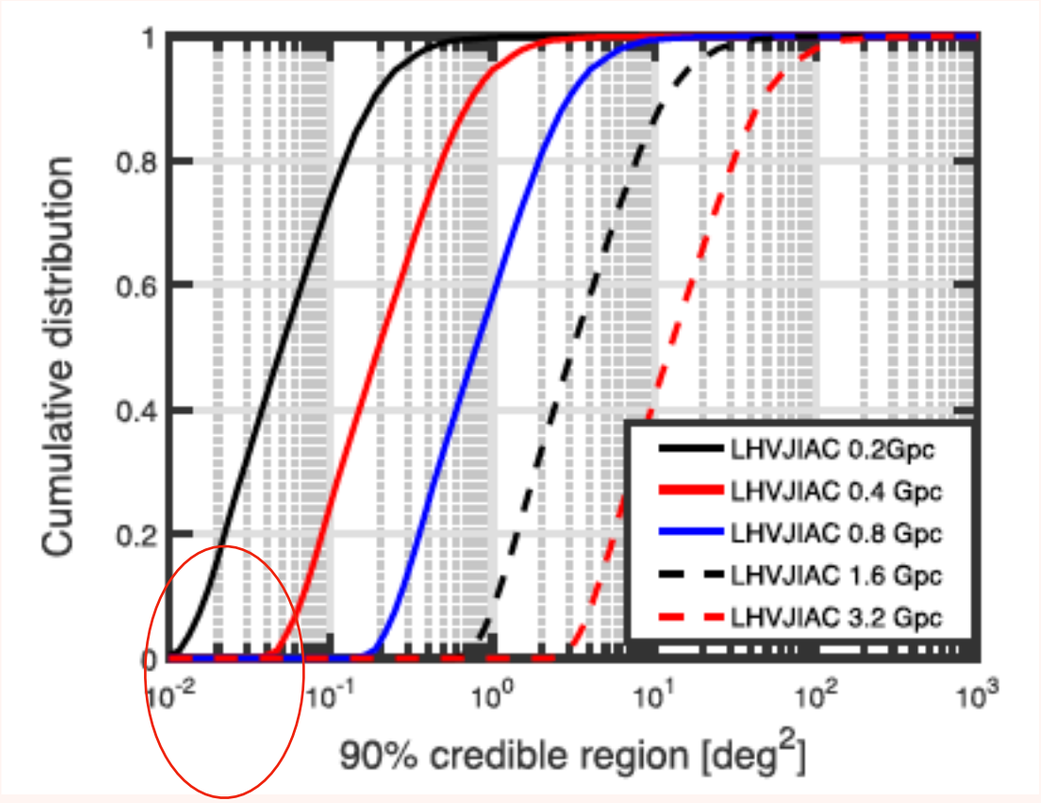


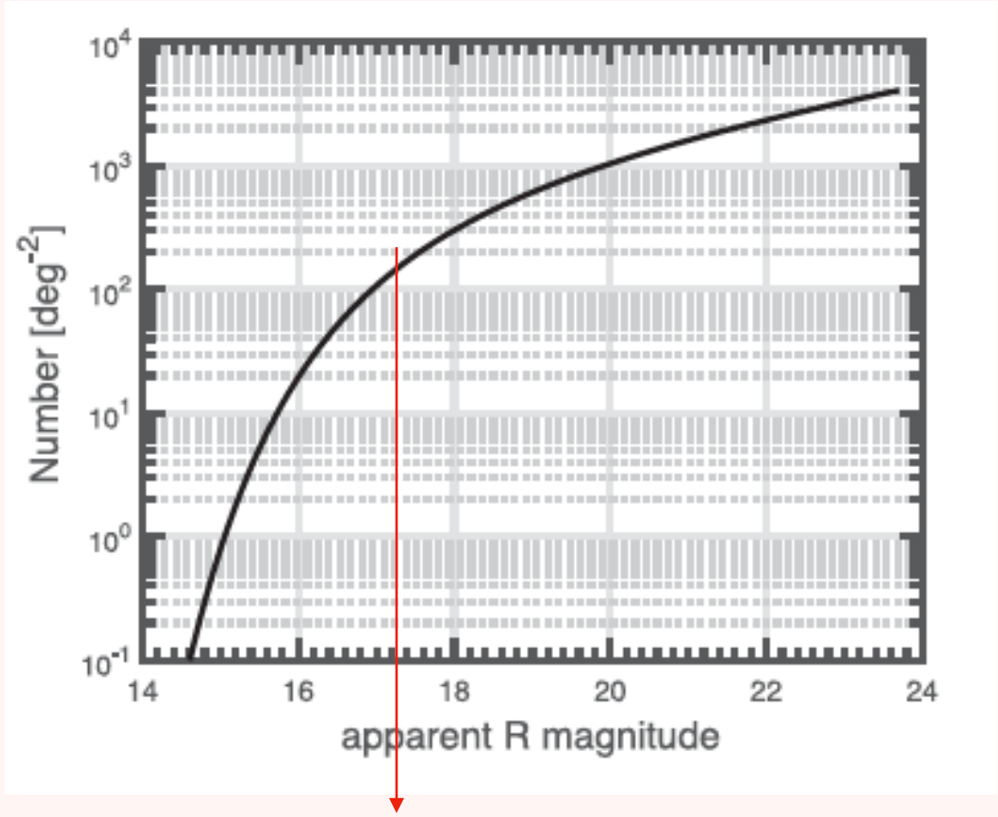


Blair et al. 2015, Science China Physics, Mechanics, and Astronomy, 58, 5747

Can BBH hosts be identified with ground based detectors?

Howell, … Lee, … et al. 2018



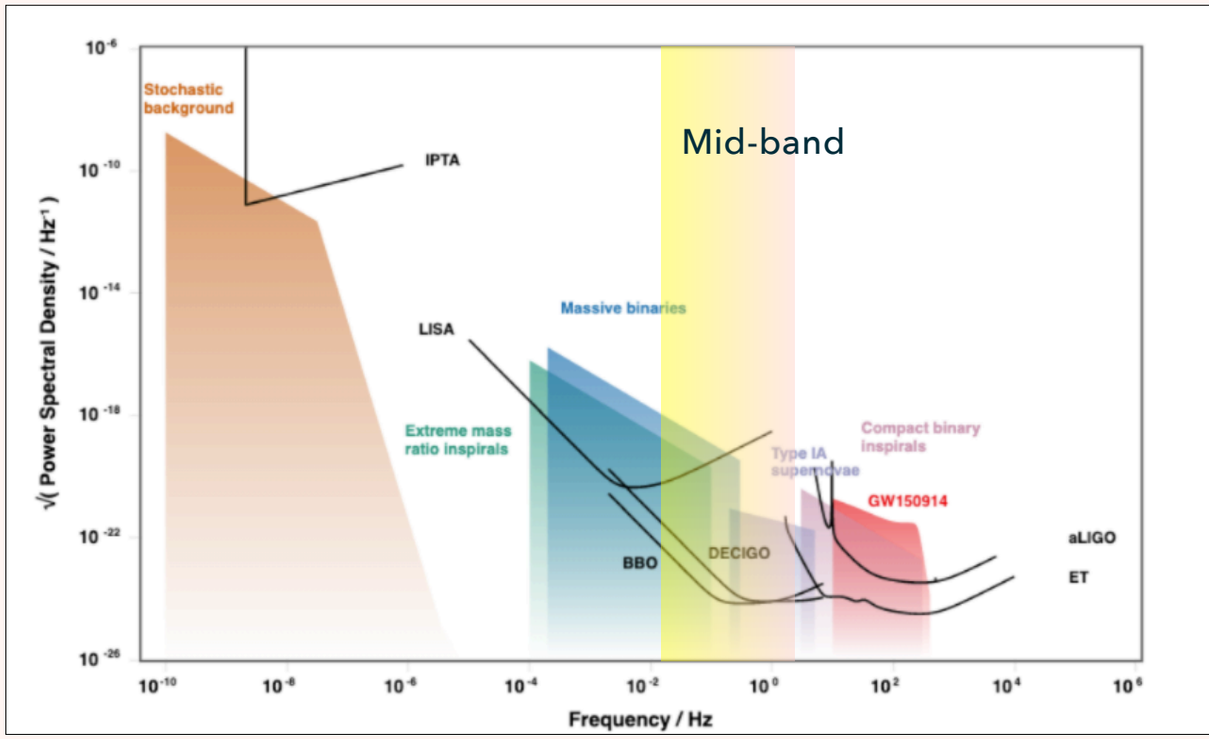


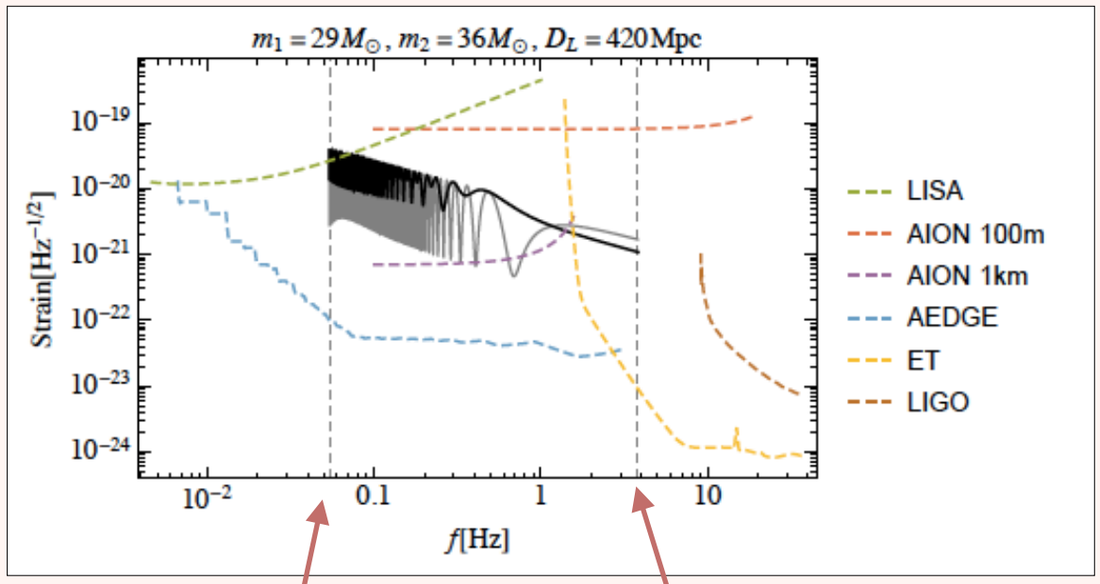
Milky Way Galaxy at 0.4 Gpc

- 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!**

Observations with mid-frequency detectors

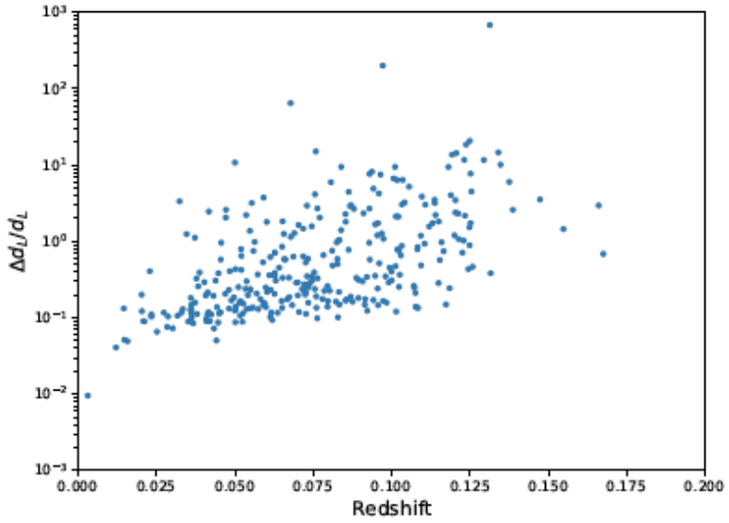
- Detectors operating at lower frequencies can observe the merging binaries for a long time (days to years)
- The source position and inclination angle are encoded in the measured signal through
  - Relative amplitudes and phases of the two polarization components,
  - Periodic Doppler shift imposed 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

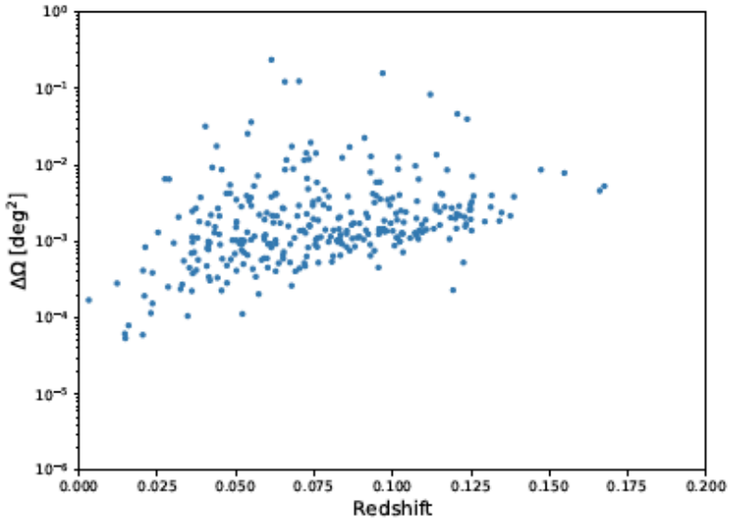




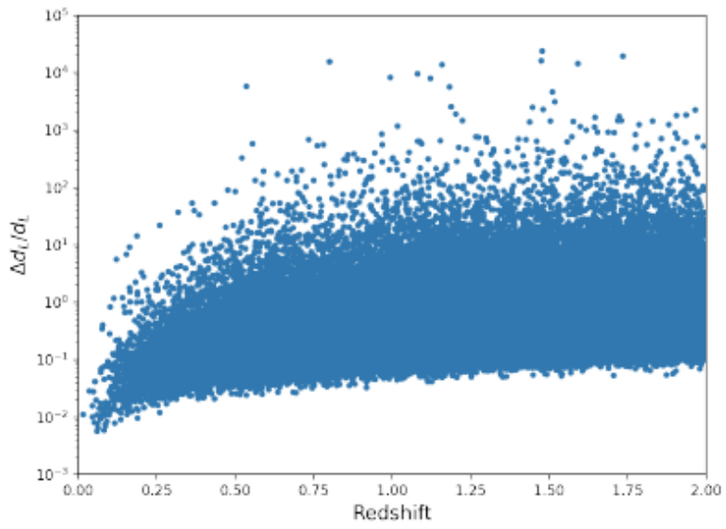
A case study: Simulation of BBH and BNS observations with AEDGE (Yang, Lee+, 2022, JCAP [arXiv:2110.9967v1])

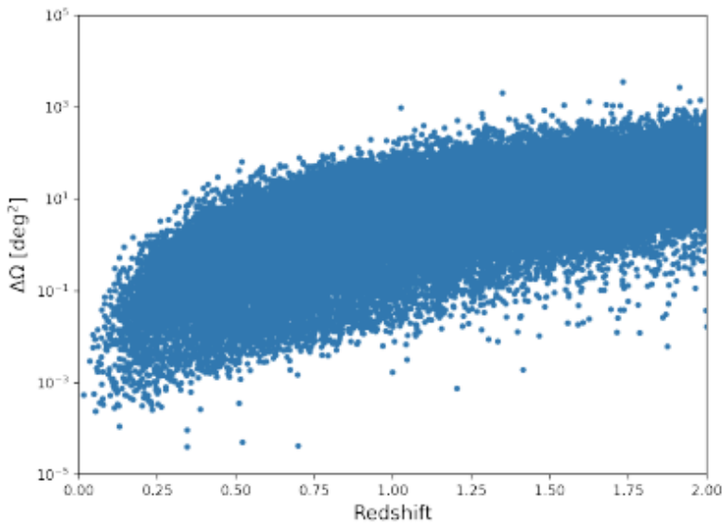
BNS





BBH





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

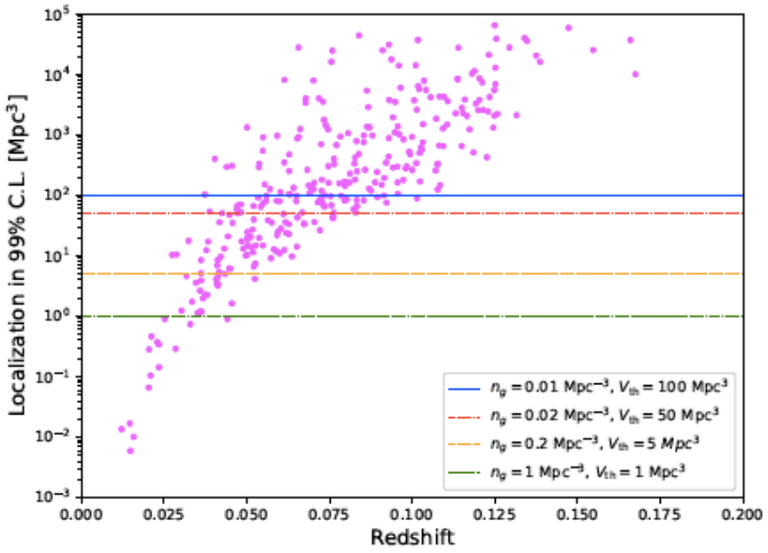
where $\Gamma_{ij} = \left(\frac{\partial h}{\partial\lambda_i}, \frac{\partial h}{\partial\lambda_j}\right)$ is Fisher matrix.

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

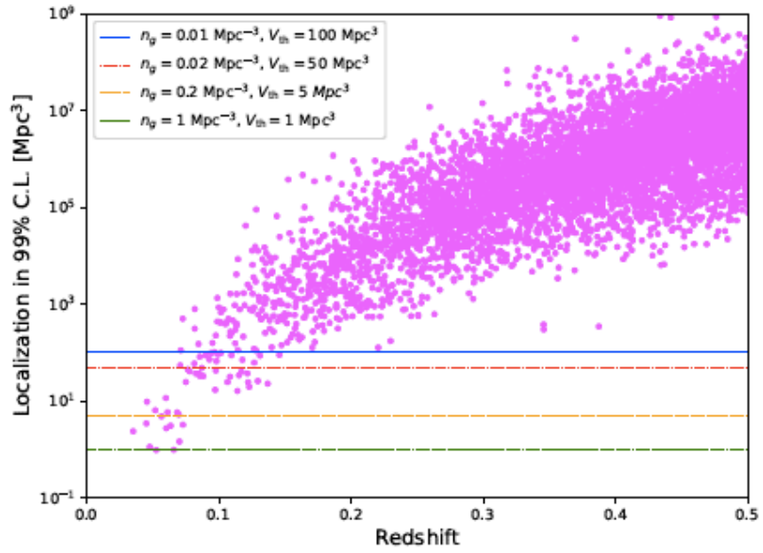
AEDGE is a proposed mid-band detector in space,

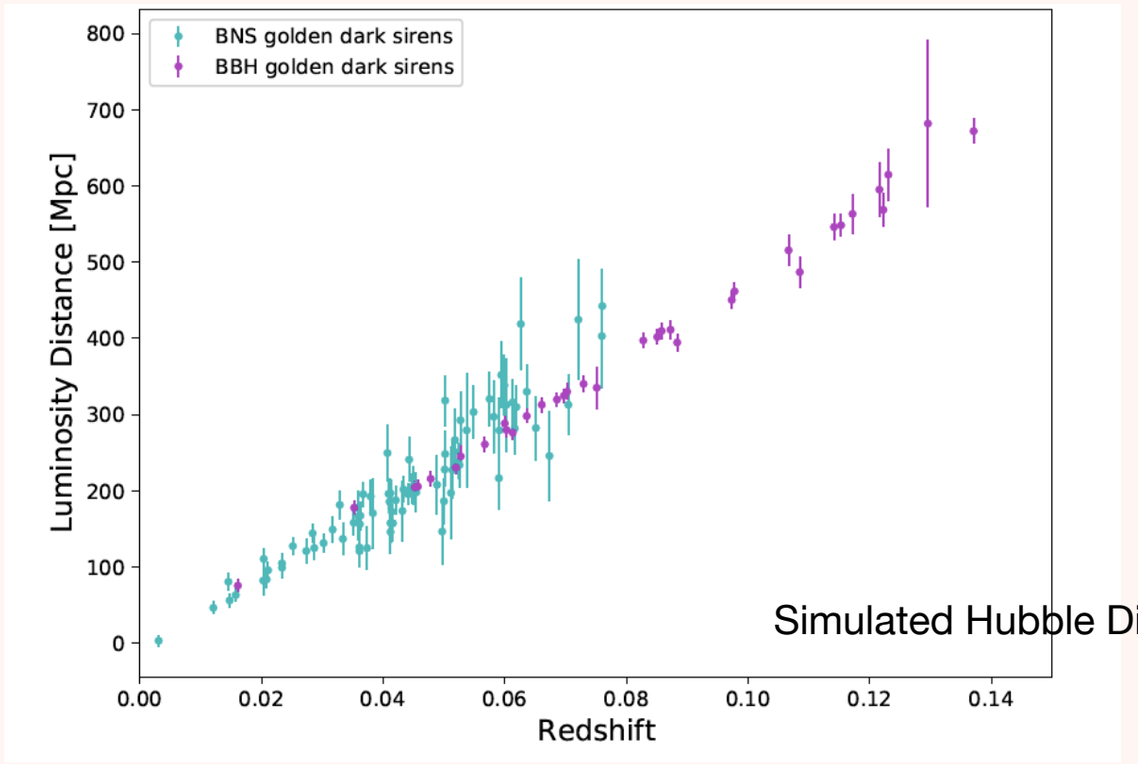
Simulations of BBH with mid-freq. detector

BNS



BBH

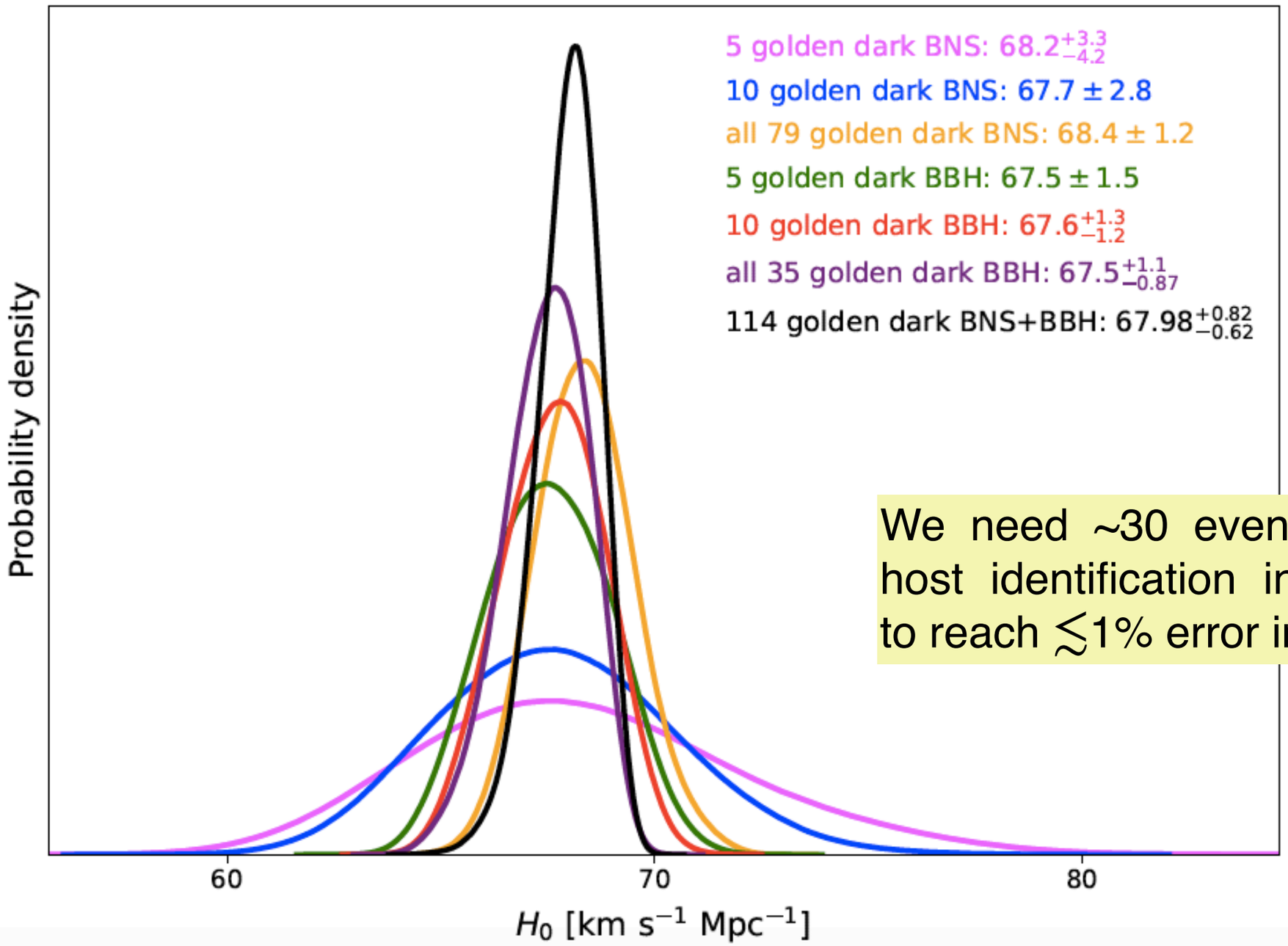




Simulated Hubble Diagram

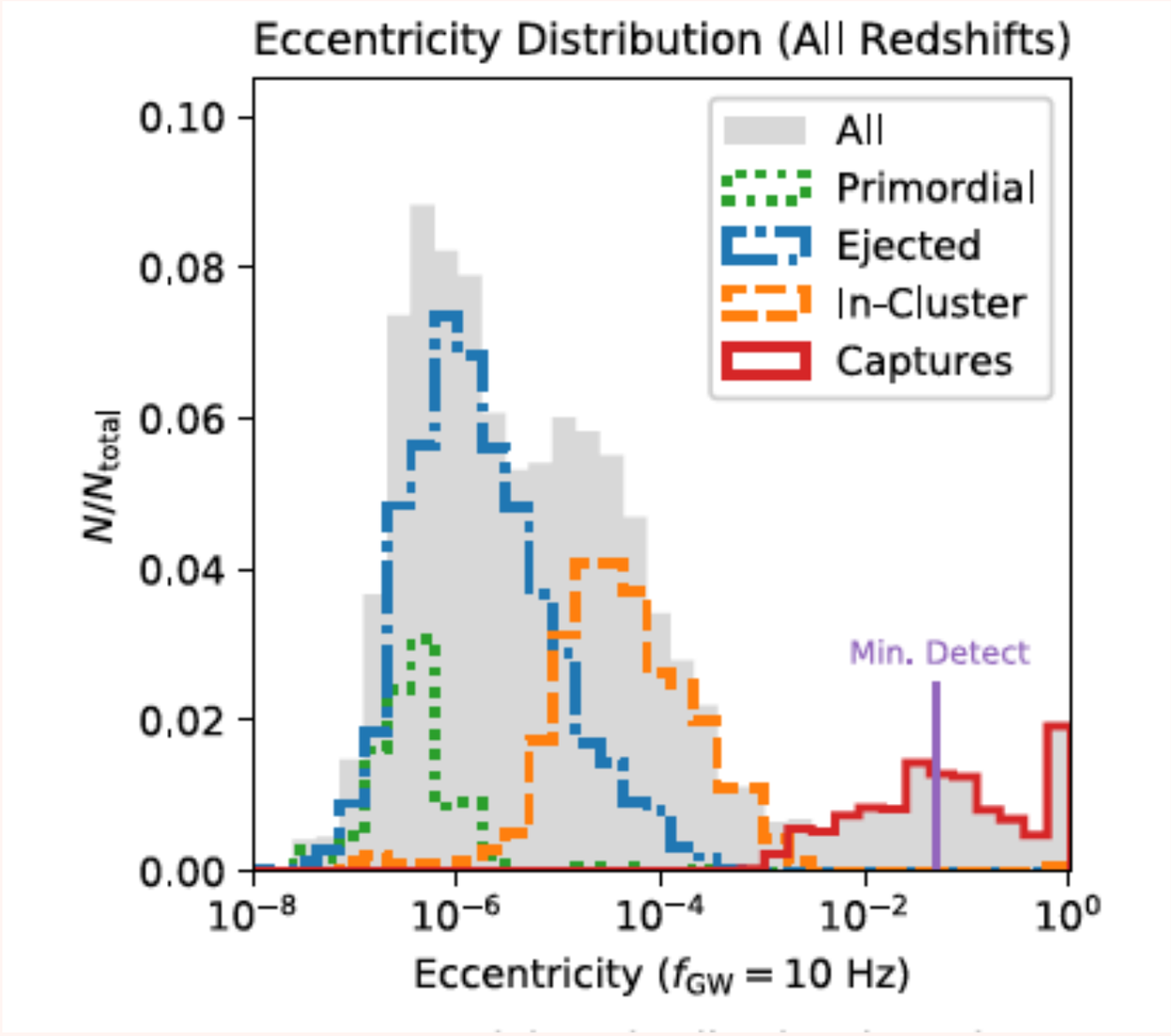
Various cuts are assumed galaxy number densities: below these lines, we can uniquely identify host galaxies within 5 year observation

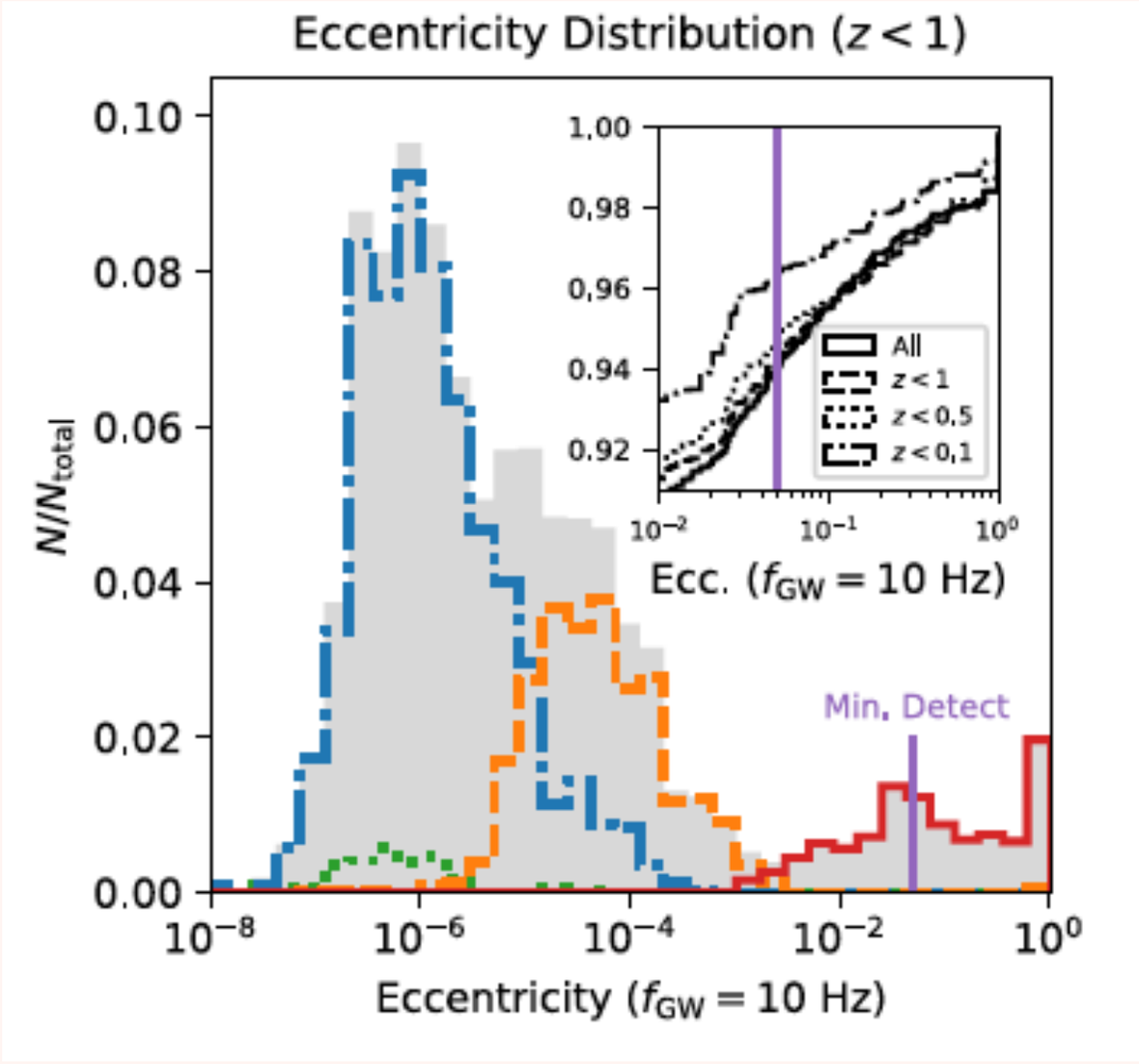
Hubble Constant Estimation from Dark Sirens



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

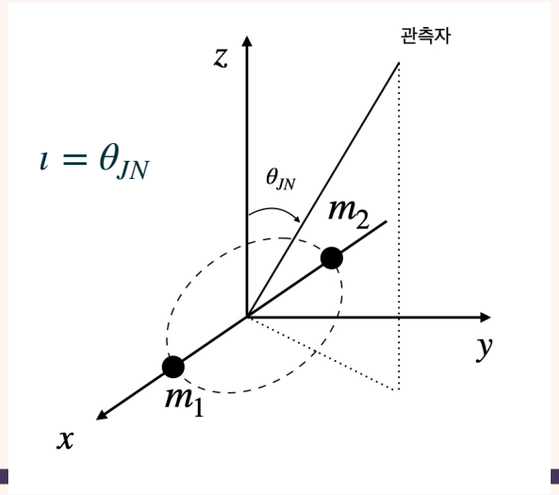


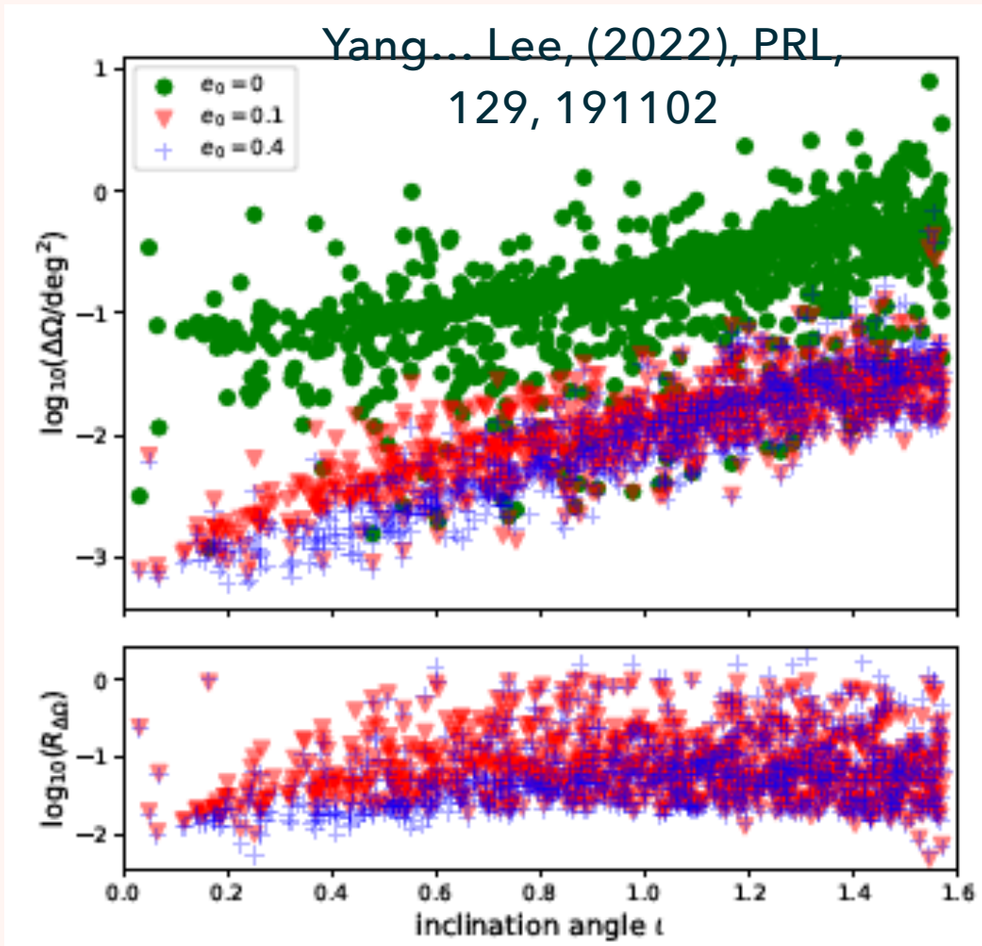


Rodriguez et al., PRD 98. 123005 (2018)

Further improvements of estimated parameters for eccentric binaries

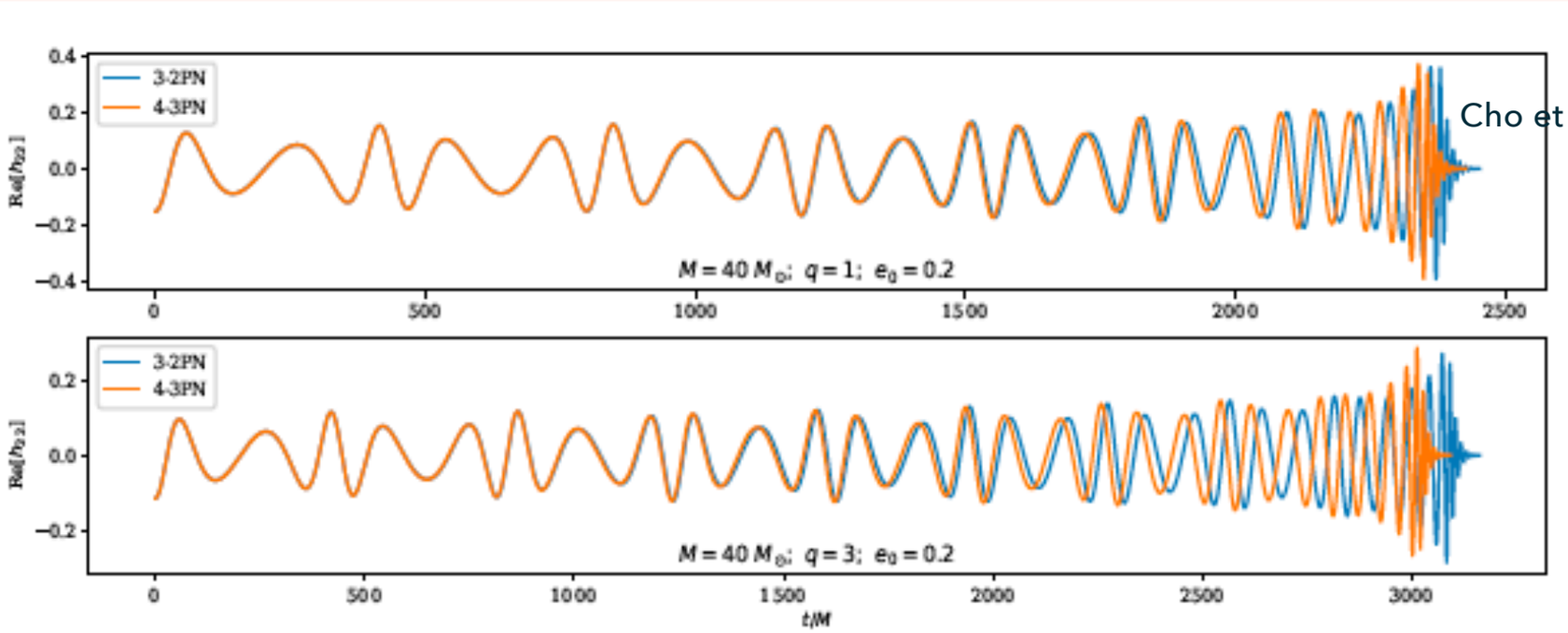
- In mid-frequency band, some binaries may have significant eccentricity (i.e., $e > 0.1$)
- The eccentric waveforms have more features than circular ones, and thus enable us to break some of the degeneracies during the inspiral phase → more accurate parameters can be inferred
- A case study with B-DECIGO: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





Accurate Waveforms for longer duration

- We developed accurate, easy to use waveforms in frequency domain covering 0.1~10 Hz for binaries with arbitrary eccentricity.
- Current status:
  - Time domain waveforms can be computed up to 4 PN. (Cho et al. 2022)
  - We need to transform the TD waveform into freq. domain.
- 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.