중력파 실험의 현황과 전망

고에너지 물리학회 2022년 가을 정기학술대회

November 17-19, 2022

Hyung Mok Lee (SNU)

Plan

- Korean Gravitational Wave Group (KGWG)
- LIGO/Virgo/KAGRA (LVK)Observing runs 1-3 (O1-O3)
- Highlights of Gravitational Wave Astrophysics Upcoming Runs (O4)
- Future detectors and science promises

Korean Gravitational-Wave Group

- Purpose: Promote Gravitational Research in Korea
  - Kick-off meeting of working group: November 2003
  - Voluntary Study Group composed of ~ 20 members
- Early Activities:
  - Numerical Relativity led by Gungwon Kang (KISTI, Currently at ChungAng Univ.)
  - Organizing Summer Schools (supported by APCTP & KISTI)
- Sept. 2009 : Presentation in LSC meeting at Budapest. LSC Council approved our proposal
  - MOU was signed during the LSC Meeting in March 2010

Summer School 2008

Signing of the first MOU 2010

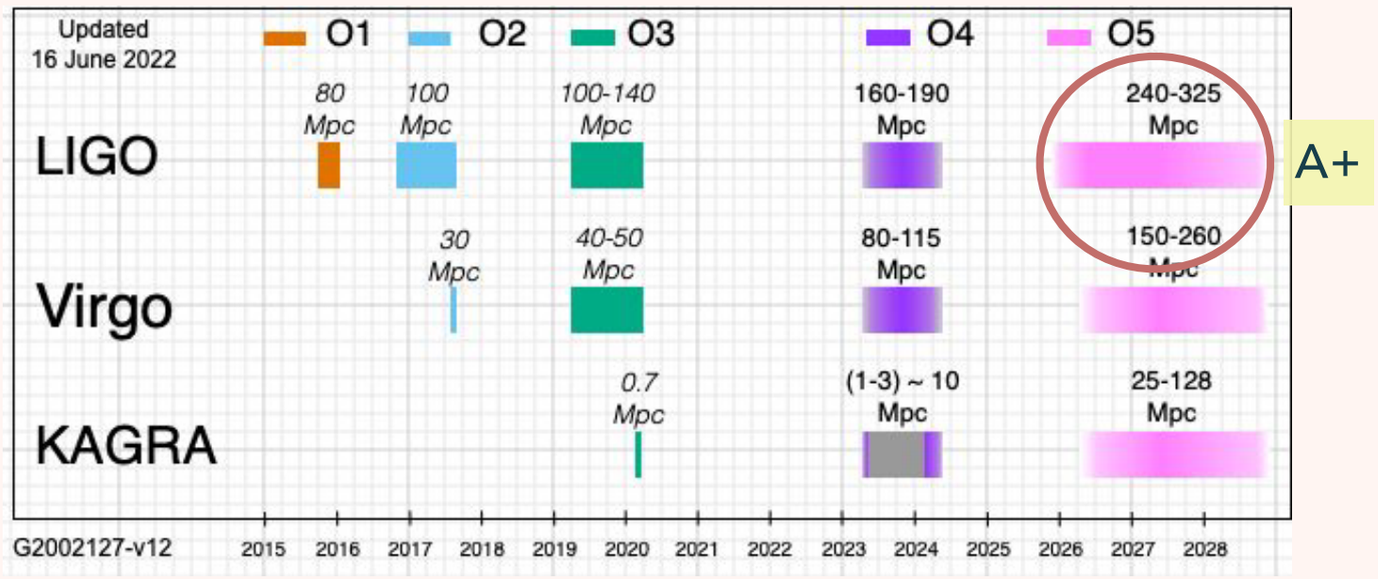
Fist International GW Meeting in Korea 2013

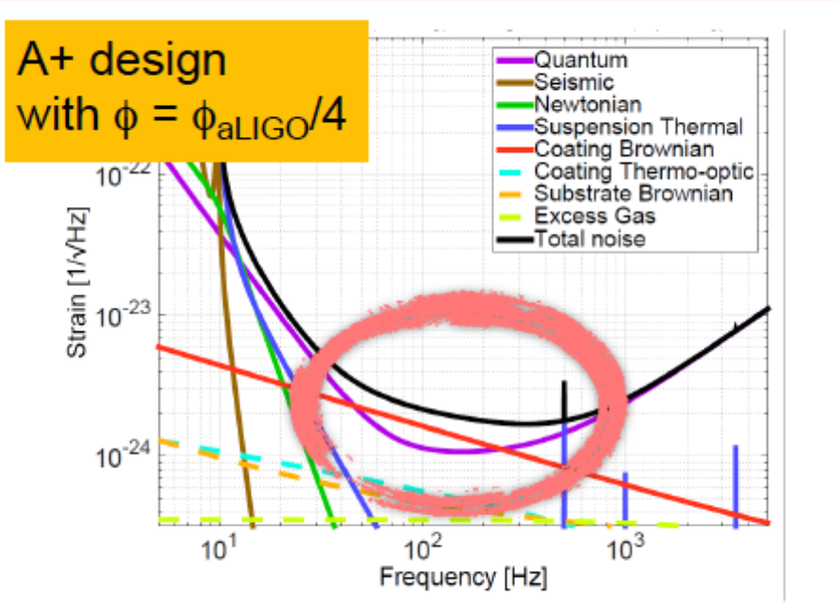
LIGO/KAGRA/ET Members

- LIGO Scientific Collaboration
  - 전체 14명
    - 8 Permanent Members (서울대, 이화여대, NIMS, KASI, KISTI, UNIST, 인제대)
    - 4 Researchers
    - 2 Students
  - 박사학위 배출: 4 (부산대 2, 한양대 1, 인제대 1)
- KAGRA
  - 저자수: 10/(720) [학생 2명 포함] (세종대, 인제대, 충남대, KASI, NIMS, KISTI, UNIST)
- Einstein Telescope
    - KASI GW R&D Research Unit
    - 천문연 등 5개 기관 14명 멤버
    - Squeezed-light Working Group 참여

Recent Activities of KGWG in LSC (2022 MOU)

- Softwares
  - Development of deep learning-based weak lensing events search pipeline
  - Optimization of parameter estimation for Compact Binary Coalescences with low-eccentricity
  - Development of the code for Bayesian inference on GW data with hadronic/hyperonic equation of state
- Detector Characterization
  - Development of machine learning model to classify and trace the responsible channels of known noise
- Search for Coating Materials
  - Utilizing Transmission Electron Microscope (TEM), KGWG members collect electron diffraction data to get electron Pair Distribution Function(PDF), which is essential for understanding and predicting mechanical losses of different potential coating materials



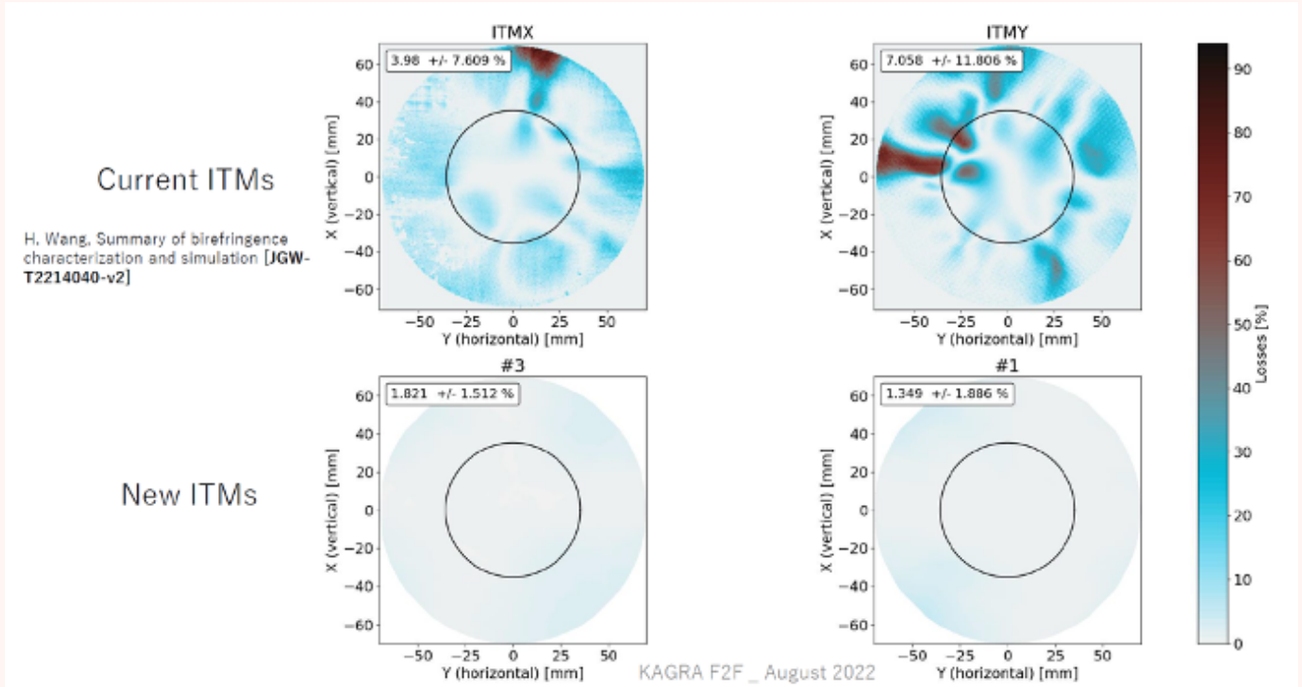


Barsotti et al. LIGO-T18042

Contributions to KAGRA

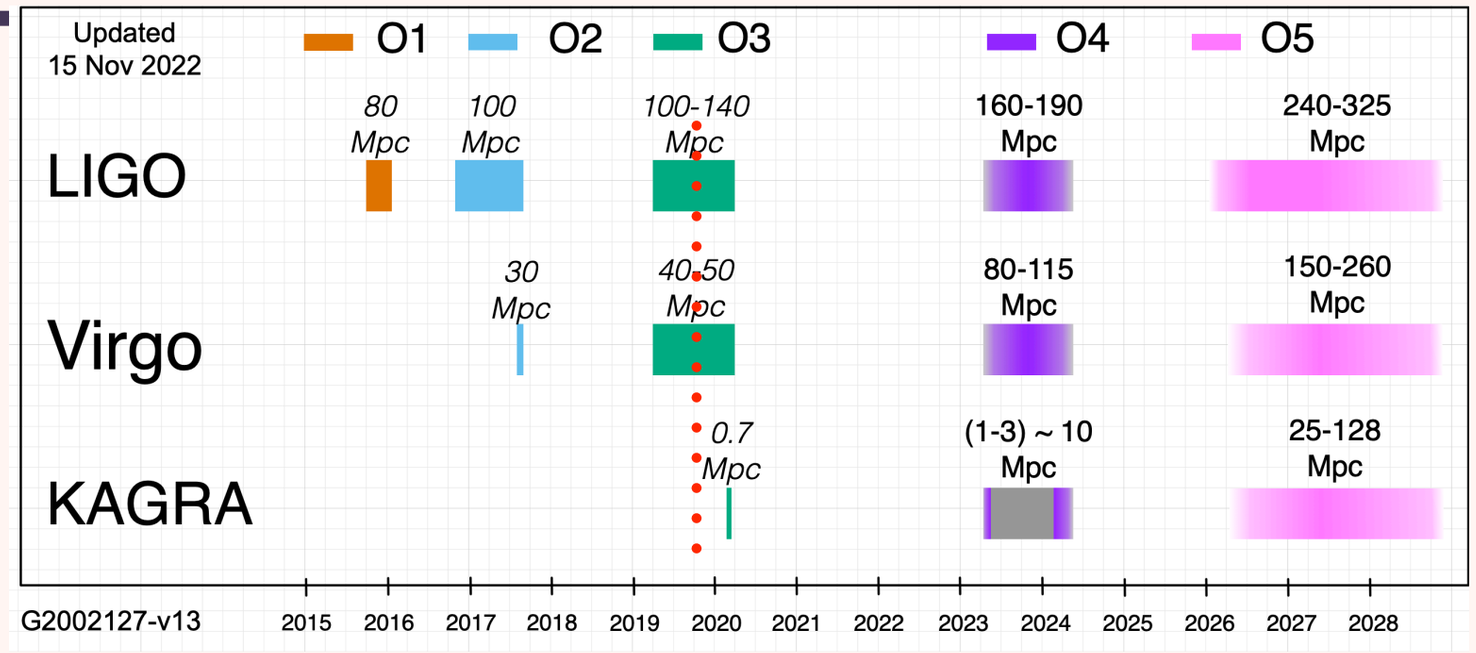
- **Detector Characterization**
  - Glitch Classification using Machine Learning Algorithms
  - Development of Detchar tool using correlation between main and auxiliary channels
- **Experimental Support**
  - High frequency squeezing for 1060 and 1550 nm lasers
  - Development of Filter Cavity system for frequency dependent squeezing
- Supply of Hardware
  - High quality Sapphire Input Test Mass (developed by Aztec, and provided by KASI)

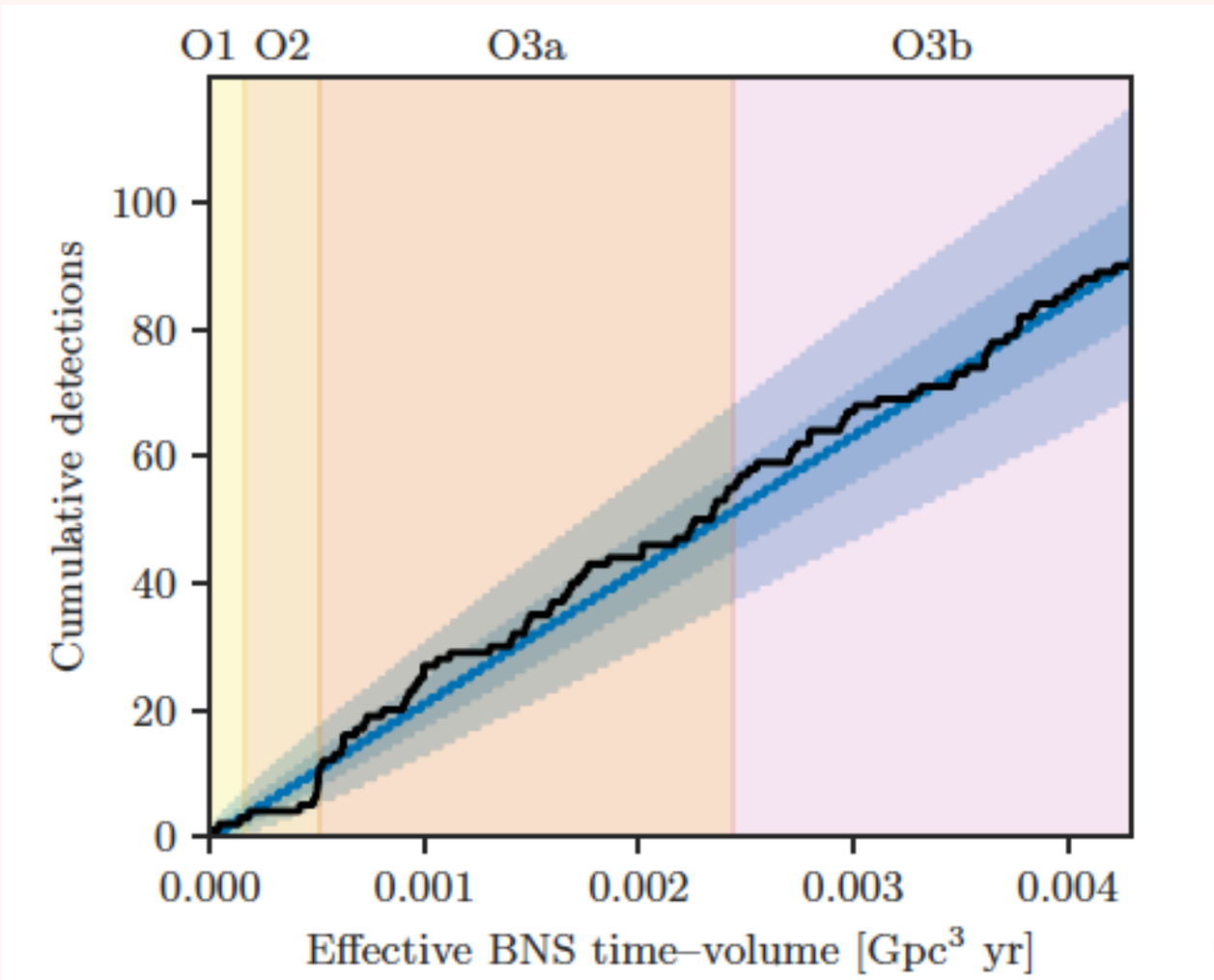
M. Eisenmann @ KAGRA F2F 2022



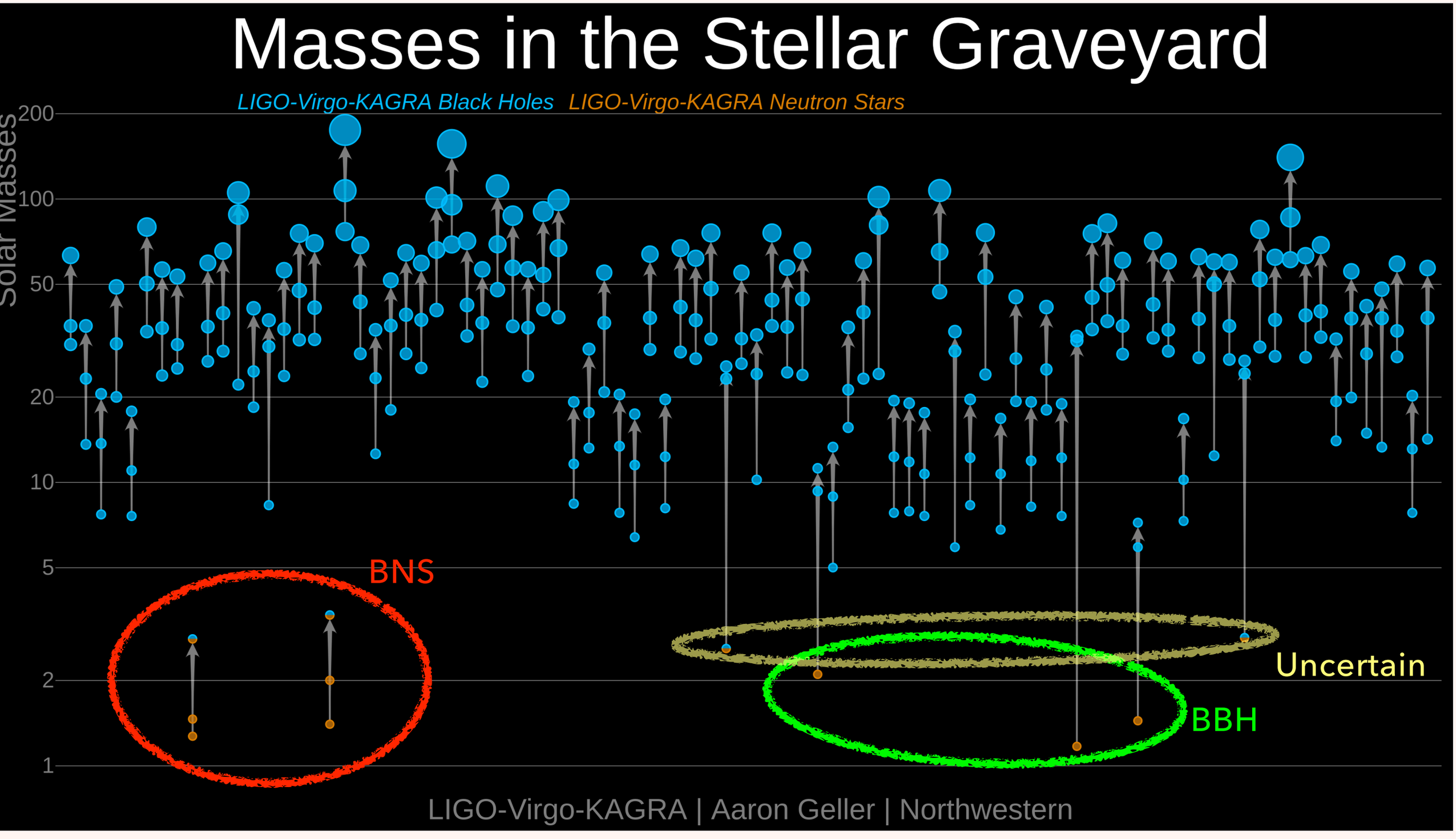
Results of LIGO/ Virgo/KAGRA Observing Runs

arXiv:2111.03606



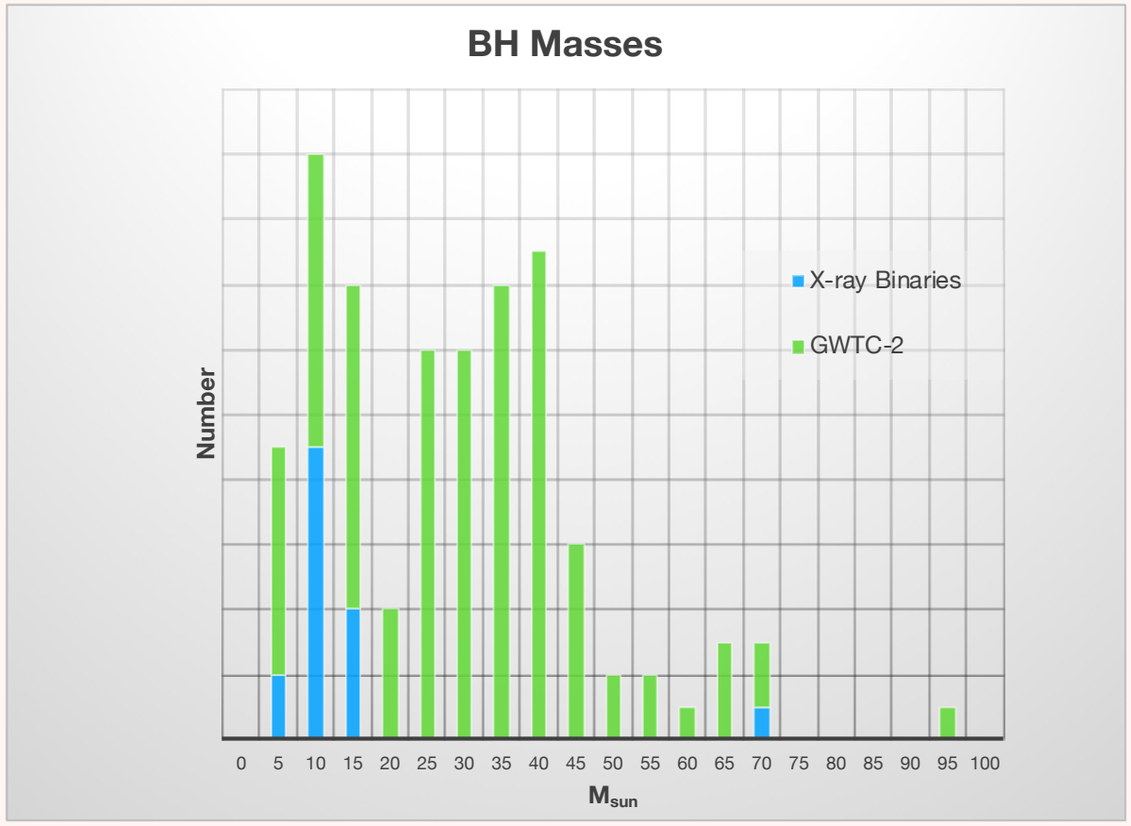


- O1-O2: Gravitational Wave Transient Catalogue (**GWTC-1**)
  - 11 events (including 1 BNS)
- Up to O3a: **GWTC-2.1**
  - 55 events (including GWTC-1)
  - 2 BNS, 2 BH-NS
- Up to O3b: **GWTC-3**
  - Total 90 events (2 BNS, 3 BH-NS, 2 uncertain, 83 BBH)

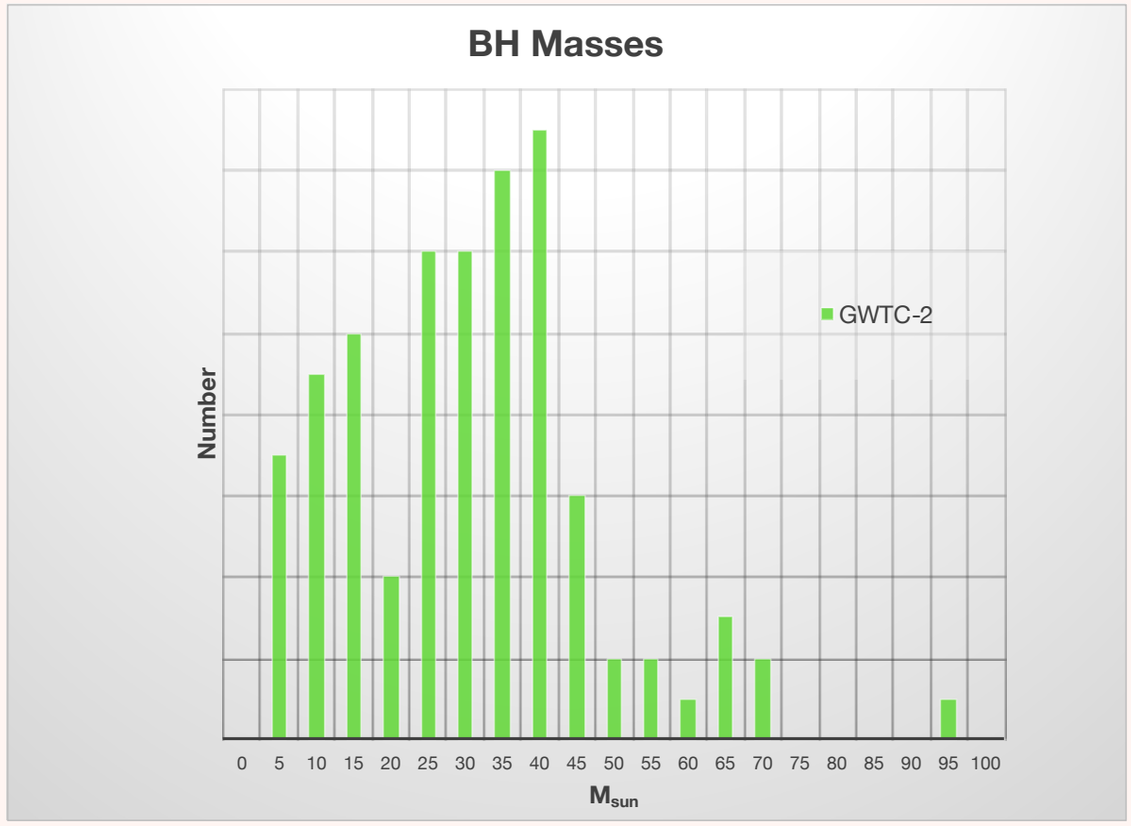

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
BNS
Uncertain
BBH
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses of Black Holes (sources)

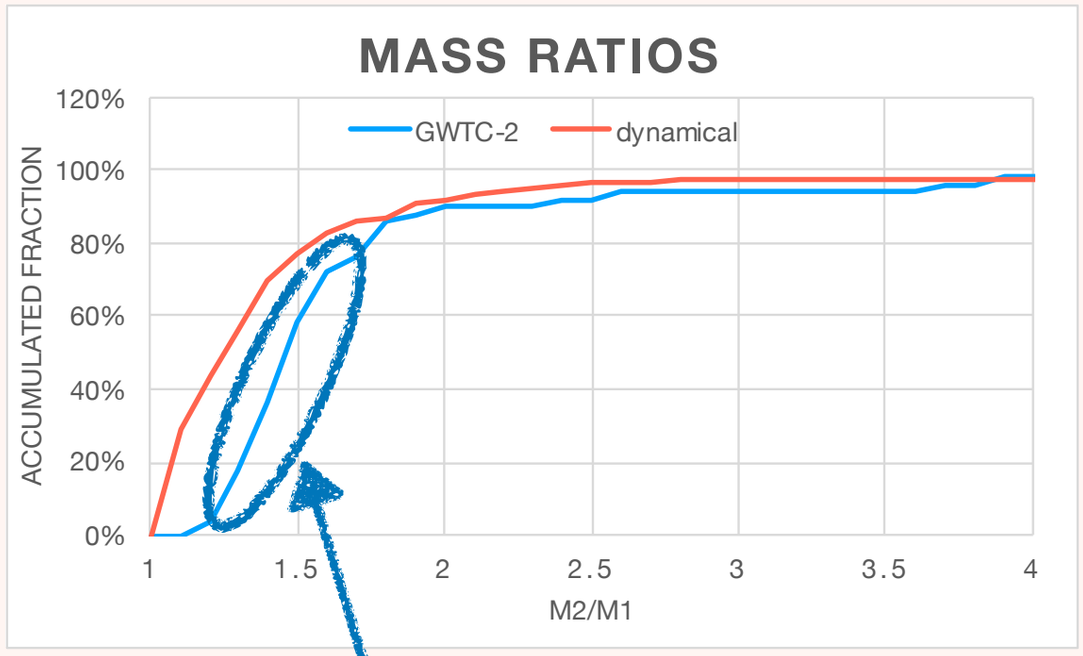
- GW BH mass range is much larger than X-ray binary BH
- Most of the Black holes (~95%) have masses smaller than 45 $\mathrm{M}_{\odot}$.
  - There are a few cases with $M_{BH} > 65\mathrm{M}_{\odot}$, a theoretical lower limit for pair instability
- Many newly formed binaries with $M_{BH} > 100\mathrm{M}_{\odot}$, intermediate mass black holes



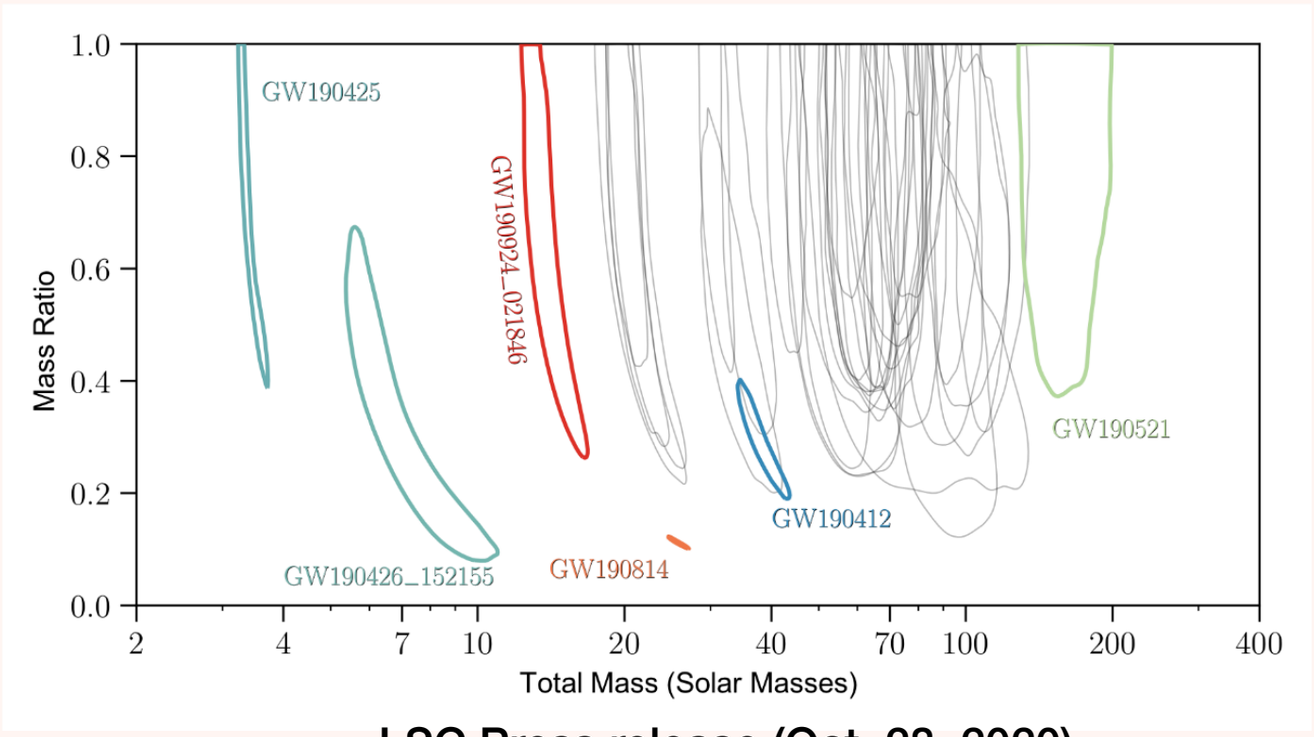
Caution: Not a fair mass function



Mass Ratios



Not well constrained



LSC Press release (Oct. 28, 2020)
https://www.ligo.org/detections/O3acatalog.php

- Dynamical Scenario prefers equal mass
- GWTC-2 shows broader distribution, but >90% of the detected binaries have $m_1/m_2 < 2$
  - Individual masses are not well constrained and the small mass ratio cannot be precisely determined
- GWTC-2 has a few clear cases of large mass ratio

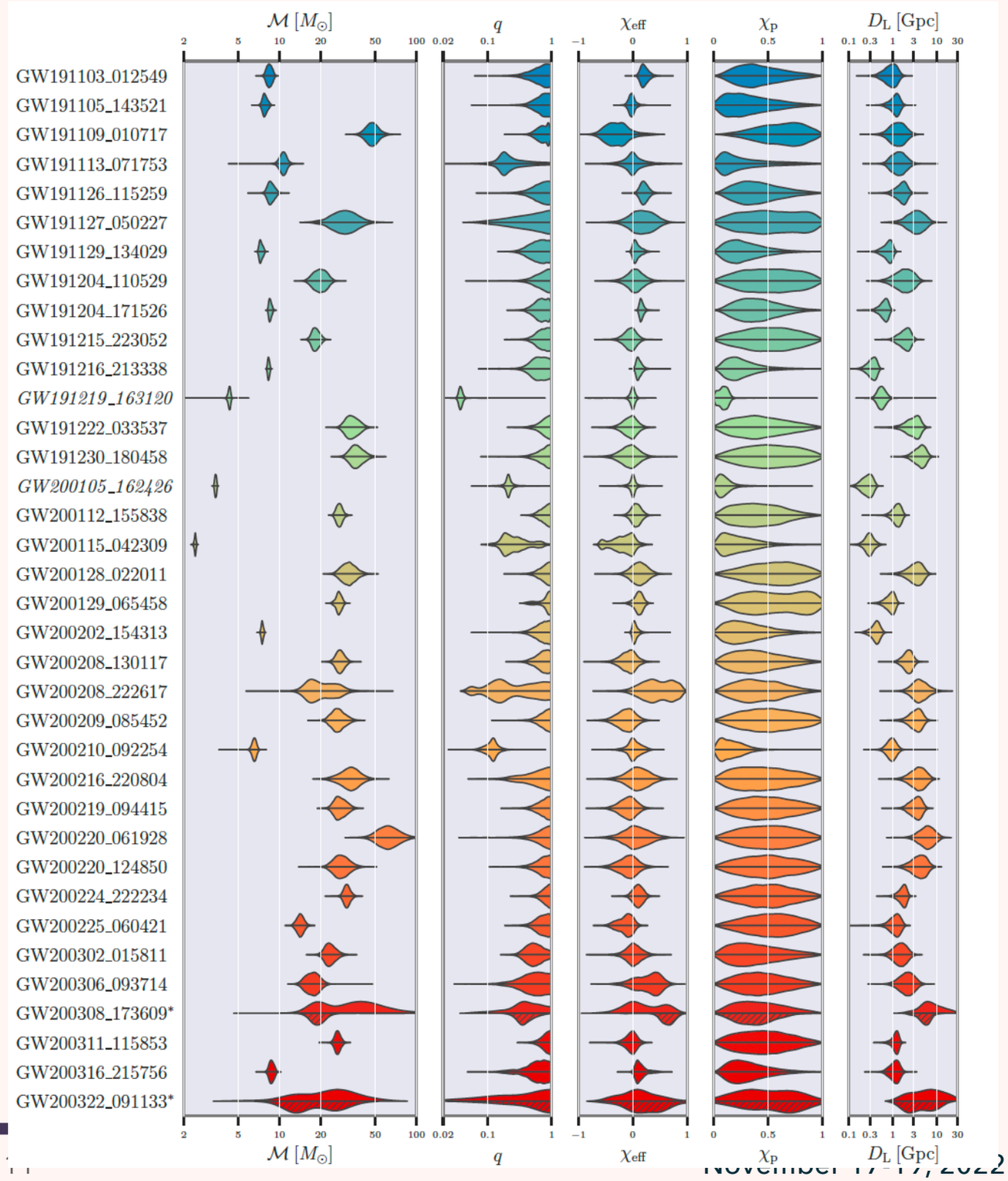
Spin

- Effective Spin:

$$\chi_{eff} = \frac{\left(m_1\vec{\chi}_1 + m_2\vec{\chi}_2\right)\cdot\hat{L}_N}{m_1 + m_2}$$

- If $\chi_{eff} < 0$, BH spin and orbital axis are anti-aligned
  - Only possible if the BBH is formed by dynamical processes.
- In most cases, BH spins are very small
- There are a few cases of high probability of $\chi_{eff} < 0$ →existence of dynamically formed binaries

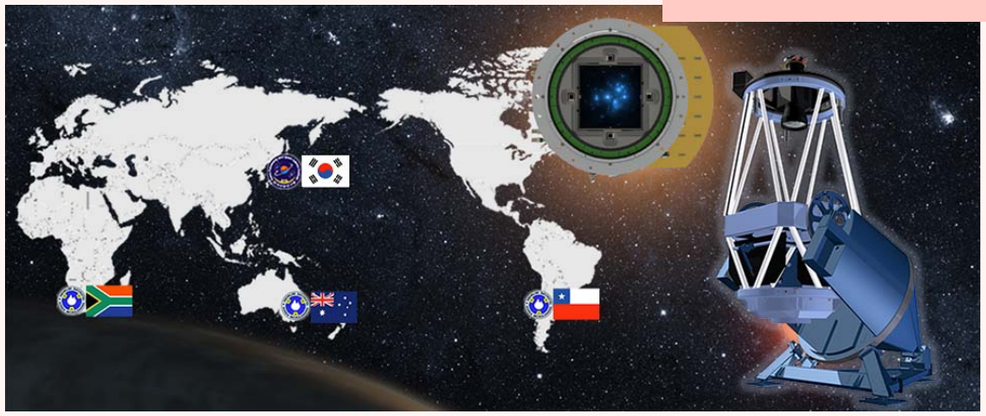
35 sources during O3b (arXiv:2111.03606)

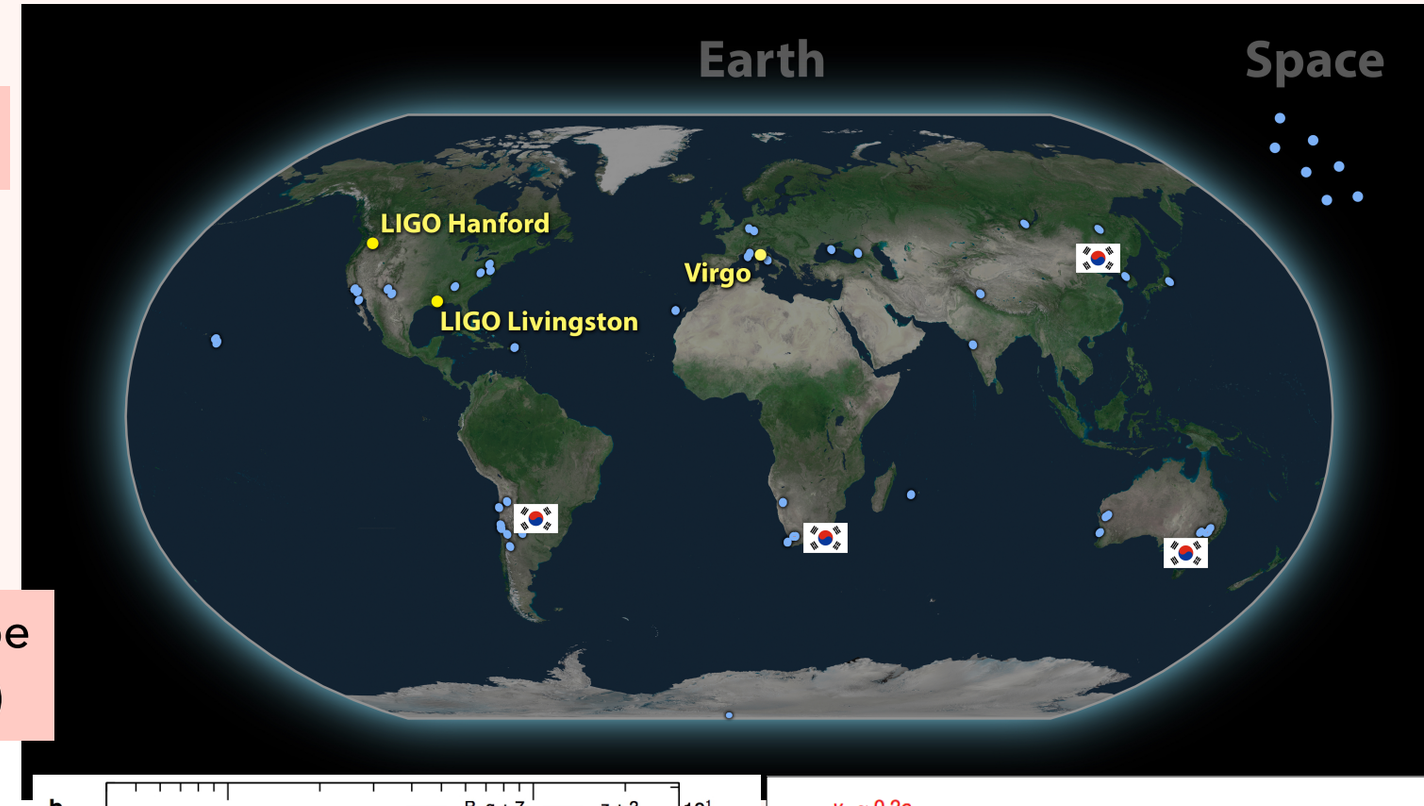


Multi-Messenger Astronomy: GW170817

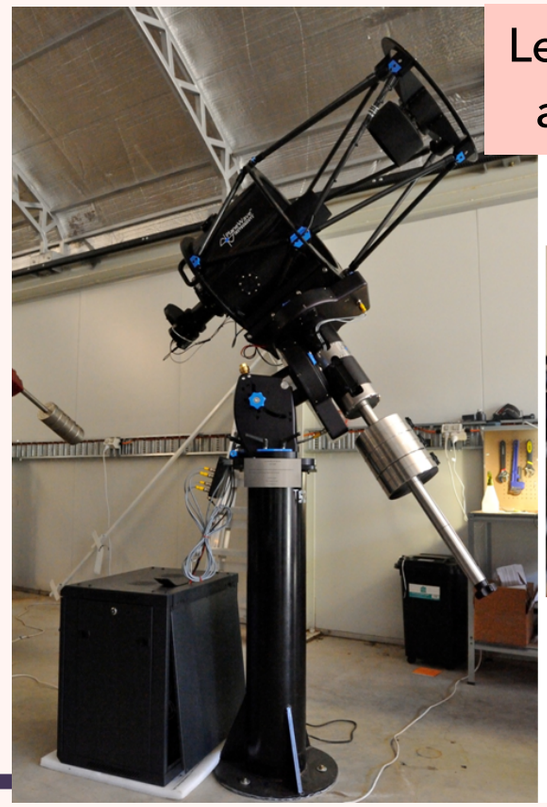
- Korean facilities made significant contribution to the EM followup of GW170817

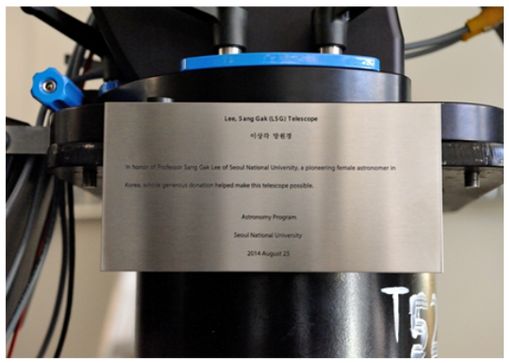
KMTNet (KASI)

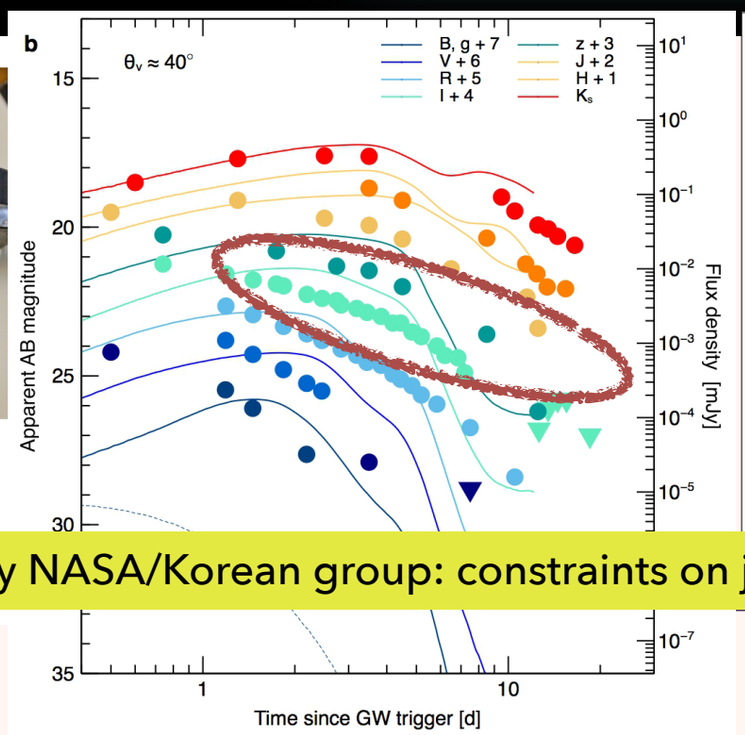


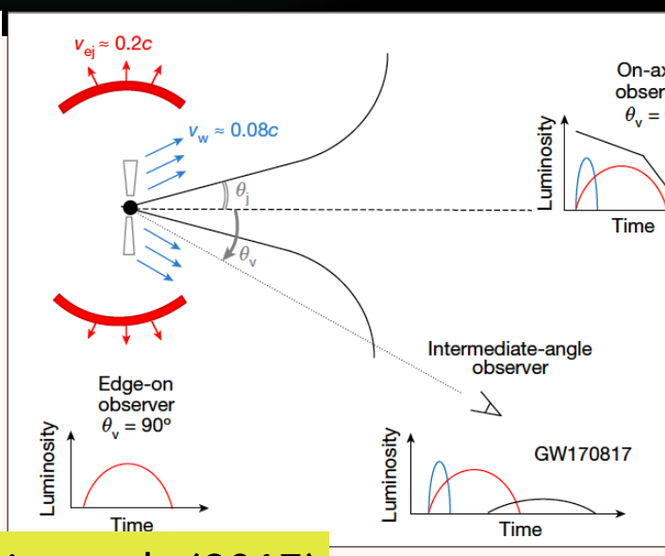


Lee Sang Gak Telescope at Siding Spring(SNU)





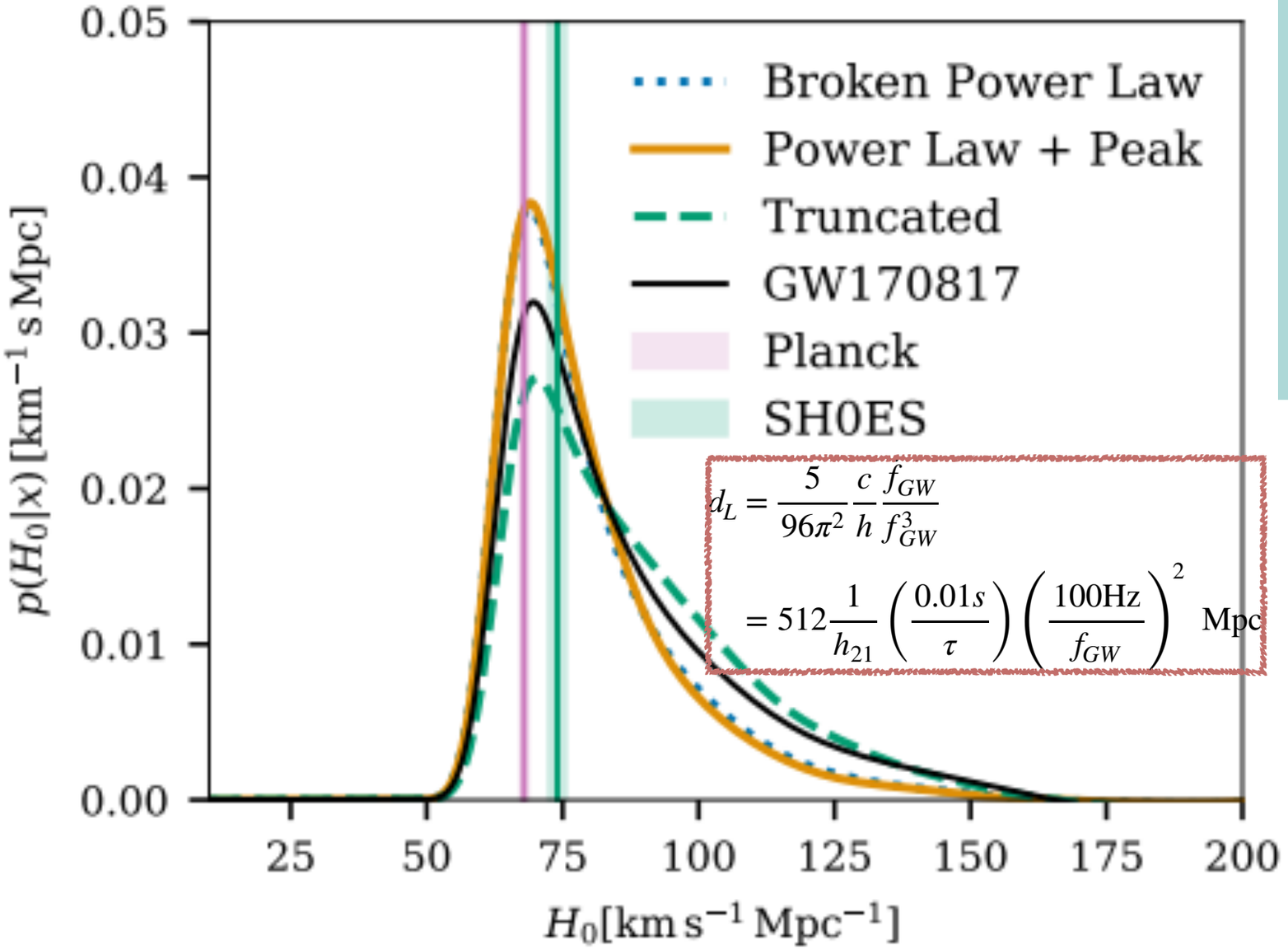




Nature article by NASA/Korean group: constraints on jet angle (2017)

Measurements of H_0 with GWs

arXiv:2111.03604V1

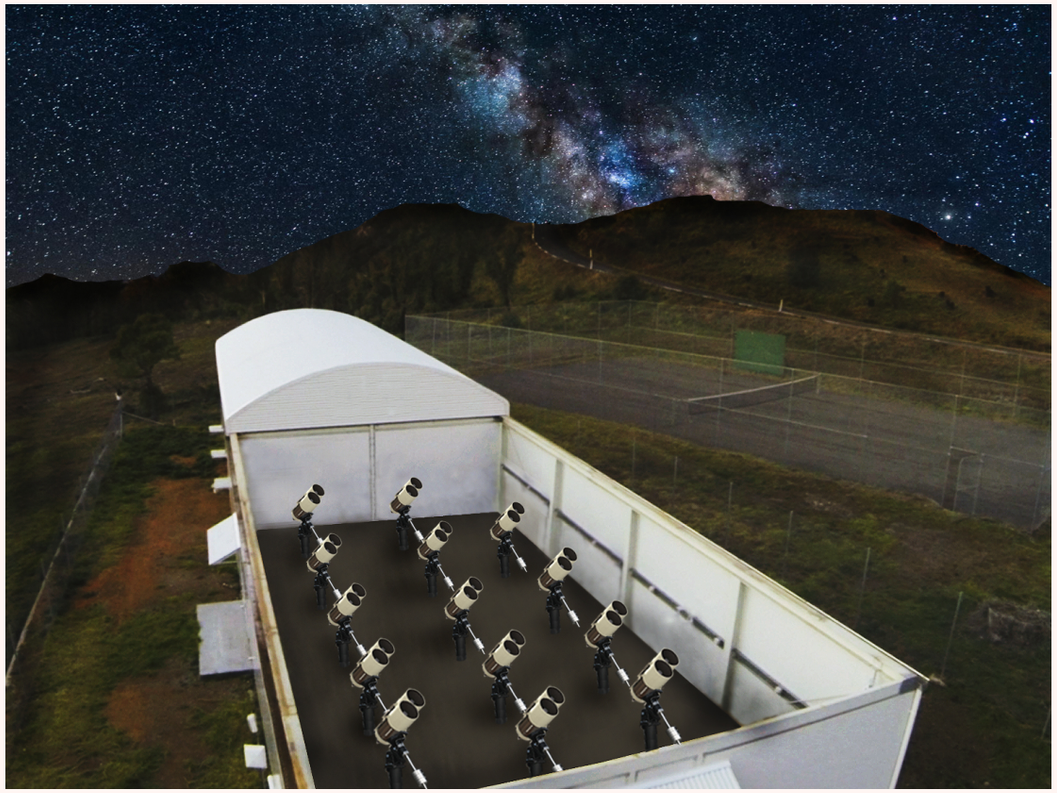


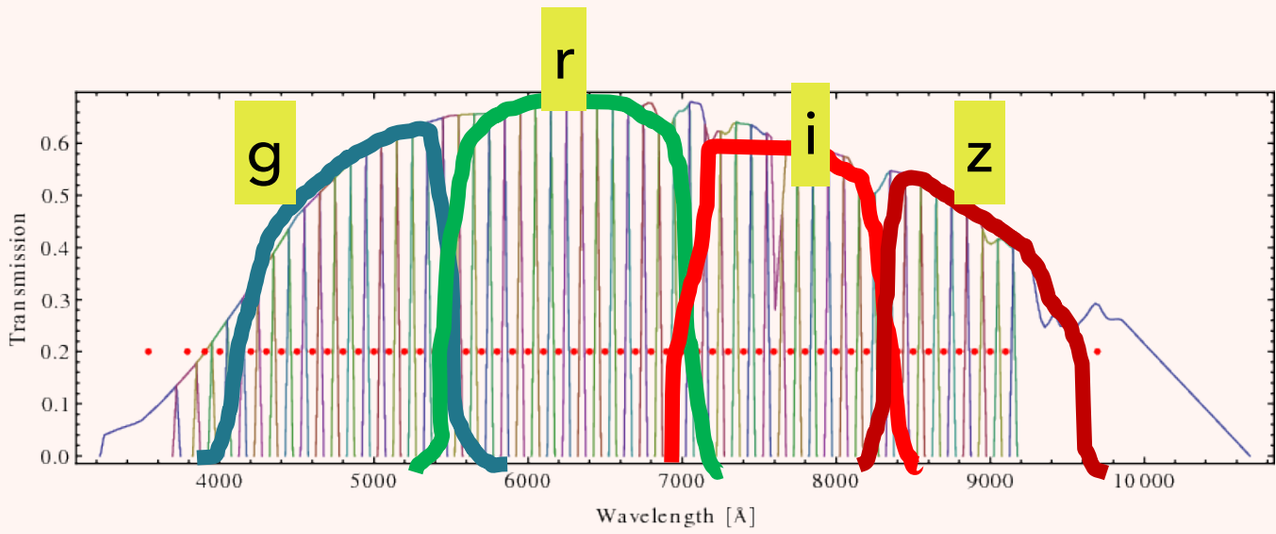
- GW170817 alone:
  $H_0 = 69^{+17}_{-8}$ km/sec/Mpc
- GW170817 (Bright Siren) + 42 BBH (Dark Sirens)
  $H_0 = 68^{+12}_{-7}$ km/sec/Mpc
  - Improvement of 13% compared to bright siren alone

- 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 O5, but may not be enough to resolve Hubble tension.
- Can we identify host galaxies of dark sirens?

7-Dimensional Telescope, 7DT

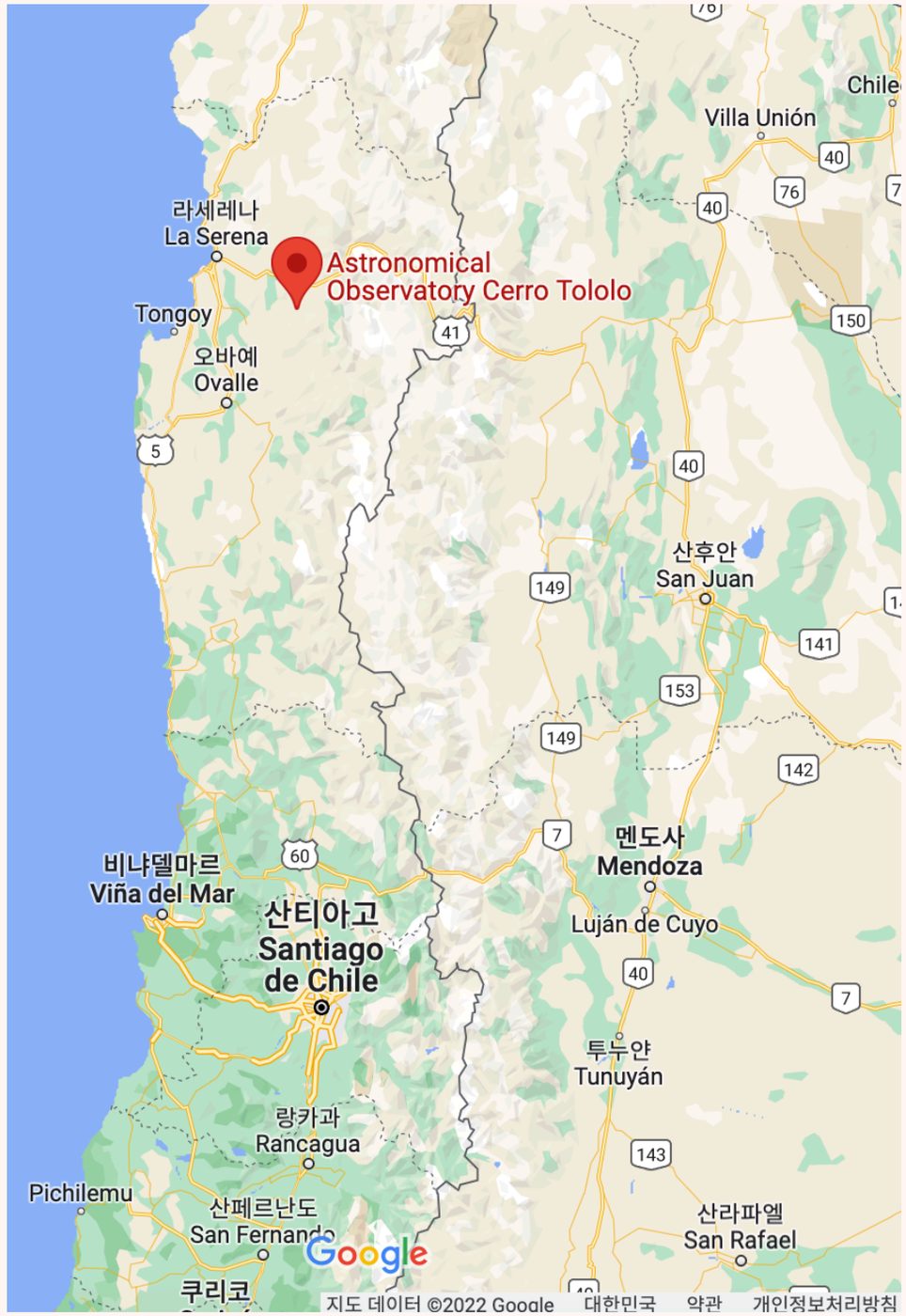
- We are building a system of telescope composed of 20 telescopes of 50 cm aperture
- Imaging wide field with 40 medium band filters (each telescope has 2) –> low resolution spectroscopy for every pixel in the field of view
- It can cover large area of sky repeatedly: wide-field, time domain, IFU-type spectroscopic telescope
- Why it is called 7DT?
  - X, Y, Z (3D), Time (1D), Flux (1D) at a wavelength (1D), Radial velocity (1D)
  - The telescope explore the universe in 7-dimensional parameter space





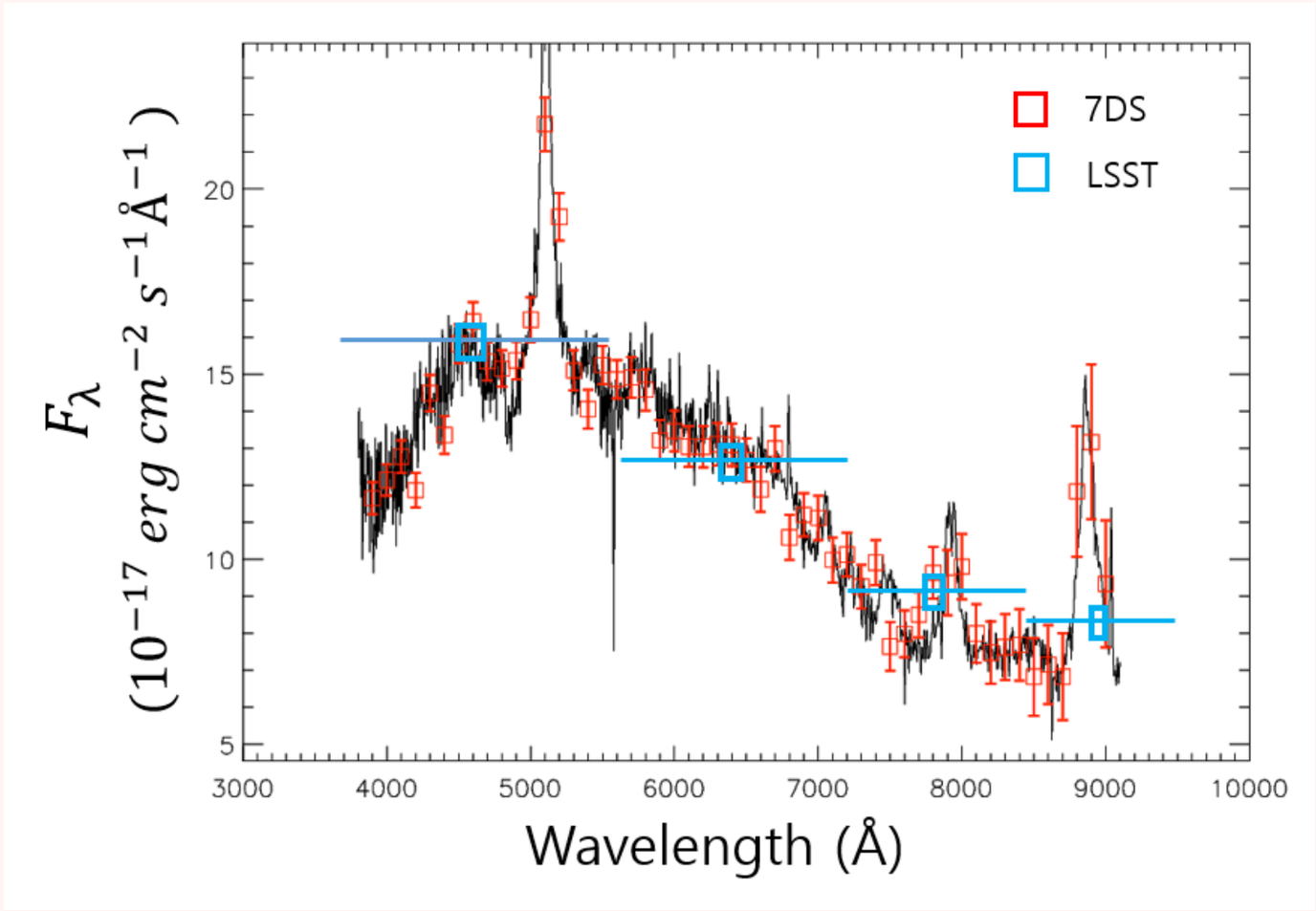
Telescope site

- 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 (vs broad-band)



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

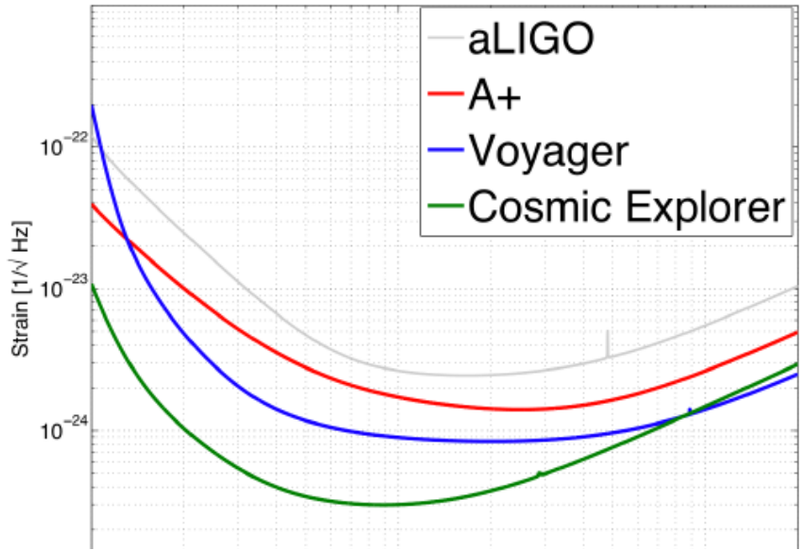
What do we expect from O4?

- O4 will start in March 2023 for about one year (with a one-month break for maintenance)
- KAGRA will join the observations and then at some point, step away for commissioning and return to observing with a greater sensitivity toward the end of O4
- Based on the improved sensitivity, we expect
  - ~ 300 BBH
  - ~ 9 events containing a neutron star
  - ~ 1 multimessenger BNS
  - + Nature's surprises

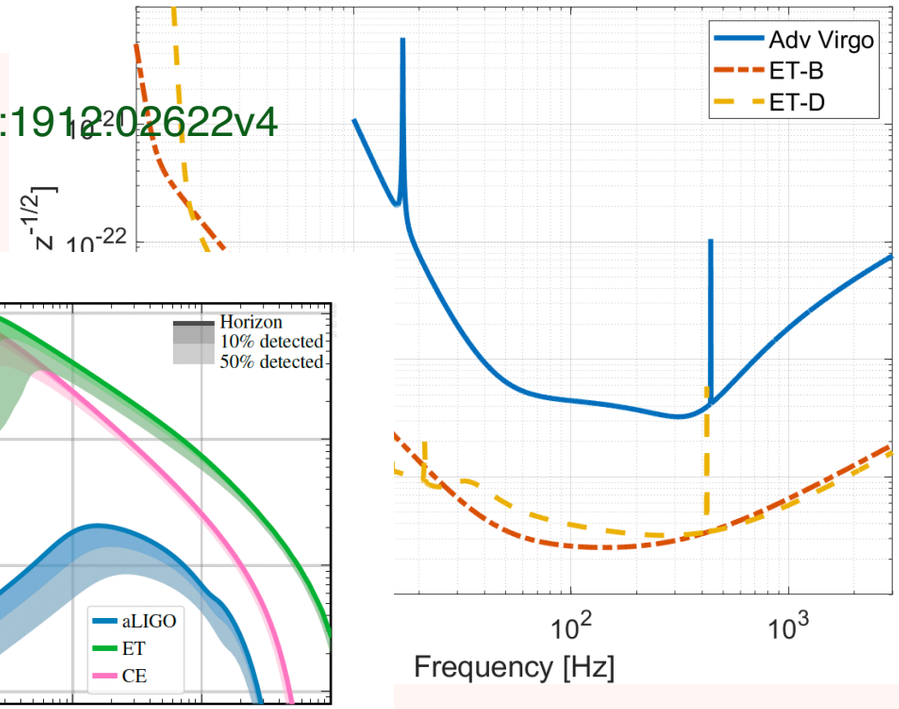
LIGO/Virgo Upgrades and near future detectors

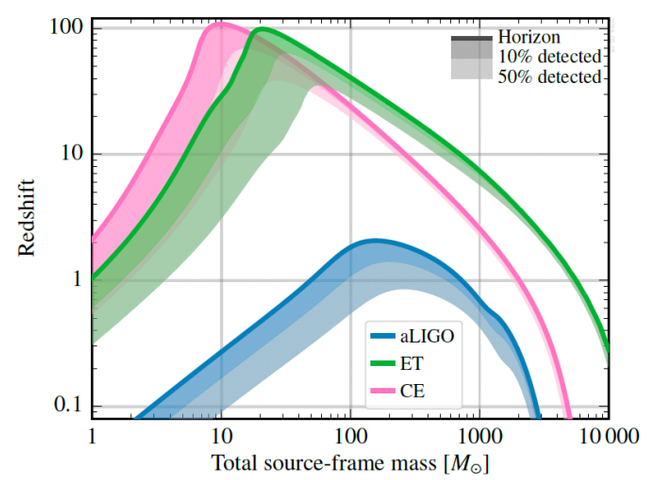
- Accuracy of the sky localization could be improved by additional detectors and better sensitivity
- LIGO's upgrade plan
  - A+ (~50%)
  - Voyager (factor of 3)
  - Cosmic Explorer (order of magnitude)
- Virgo has similar upgrade path (except for Cosmic Explorer)
  - Virgo's next generation detector is **Einstein Telescope**
- Additional Detectors
  - LIGO India

LIGO Upgrade Plan white paper (LIGO-T1400316)



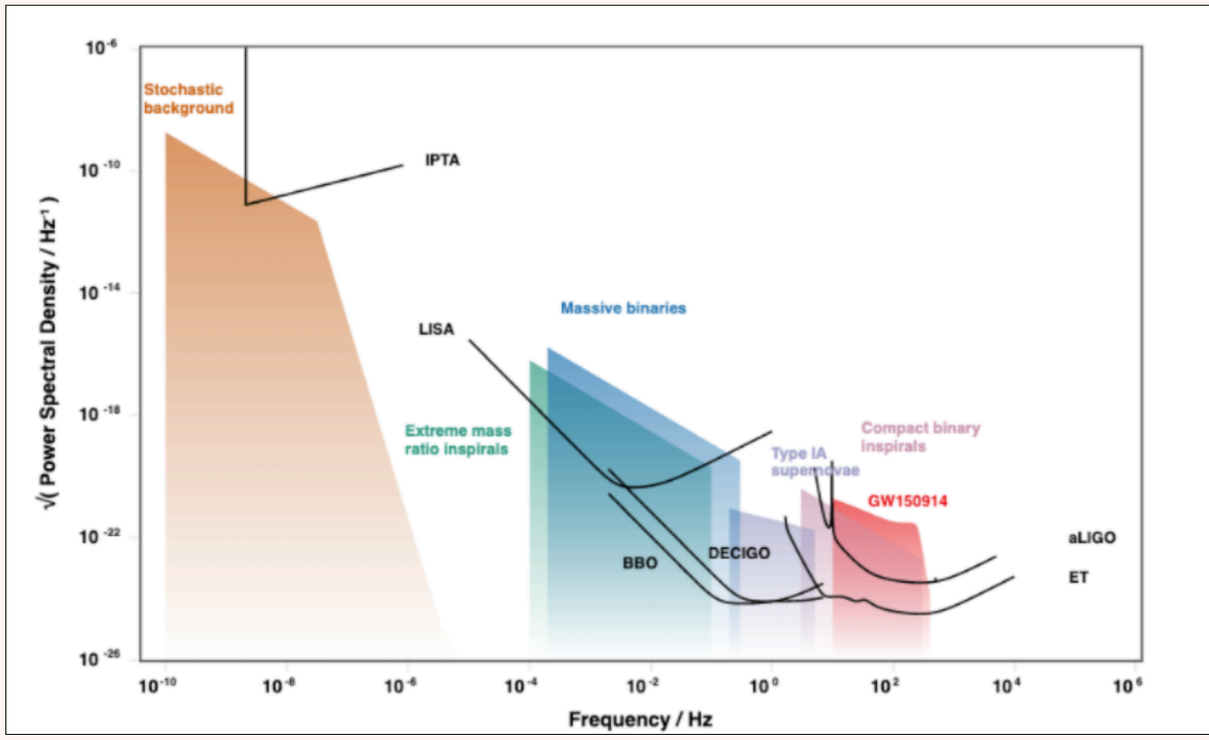
arXiv:1912.02622v4

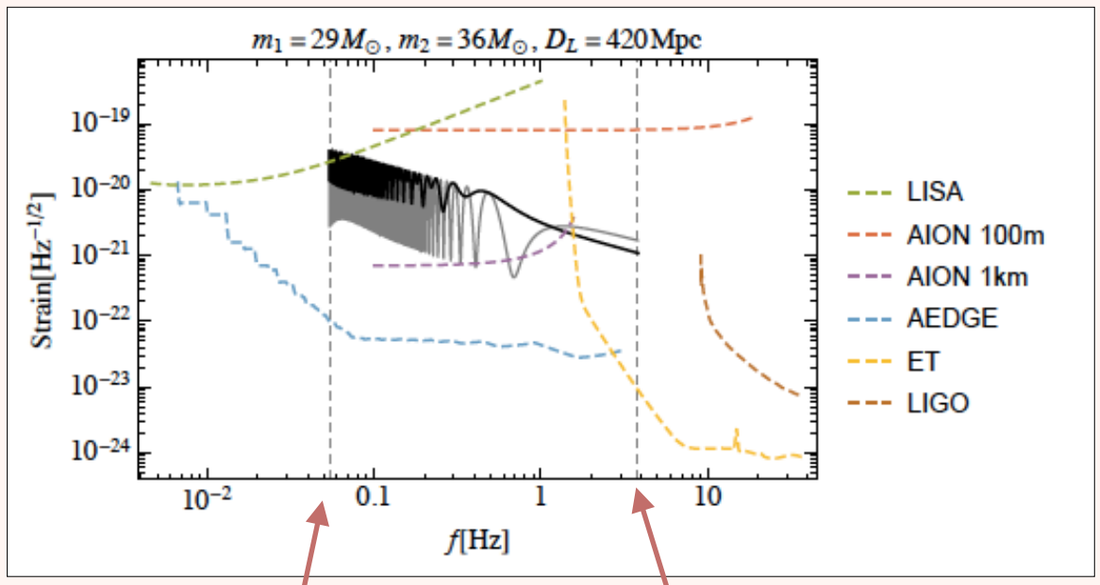




Observations with mid-frequency detectors

- 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



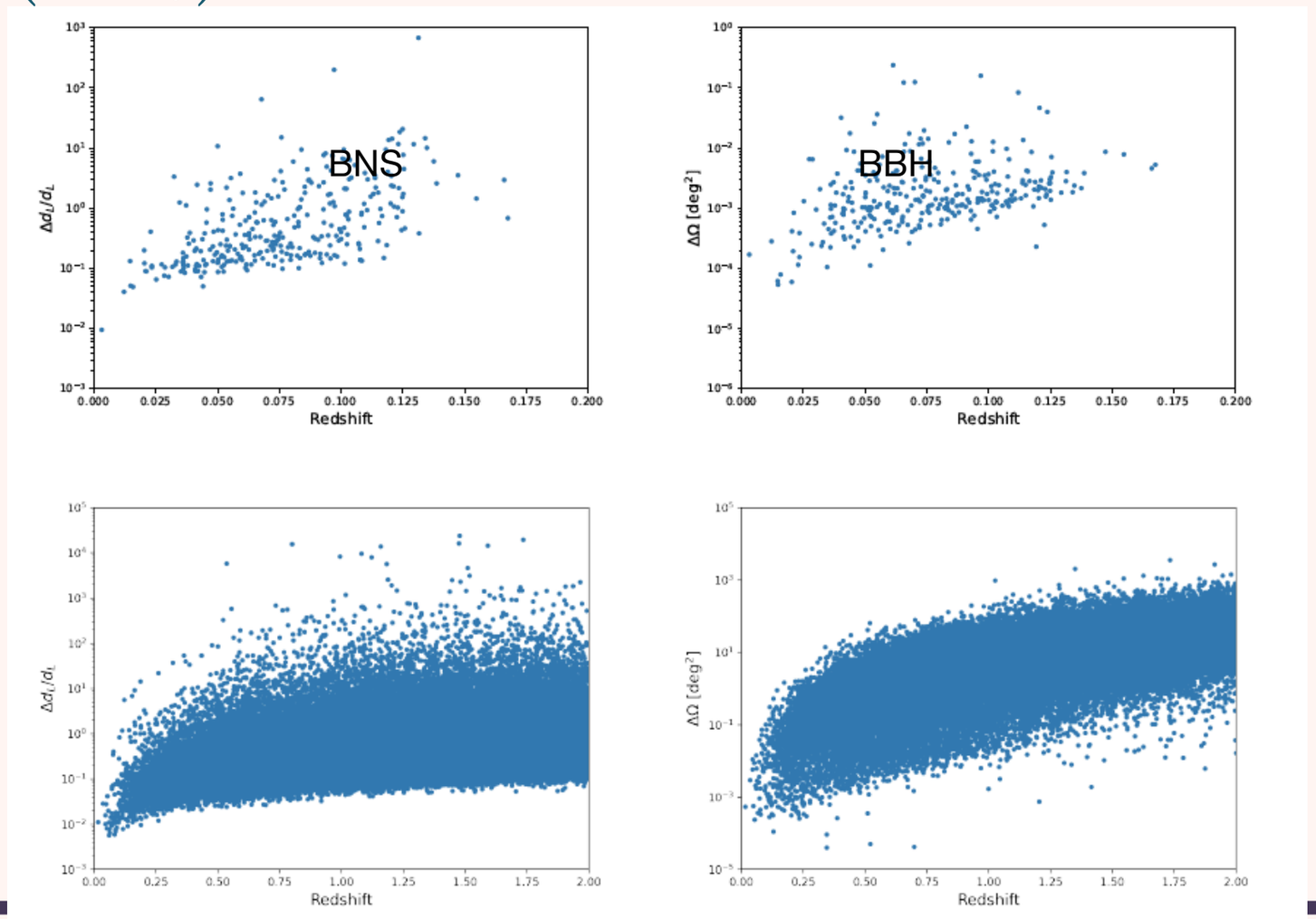


A case study: Simulation of BBH and BNS observations with AEDGE (Yang, Lee+, 2022, JCAP [arXiv:2110.9967v1])

- Sky localization error

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

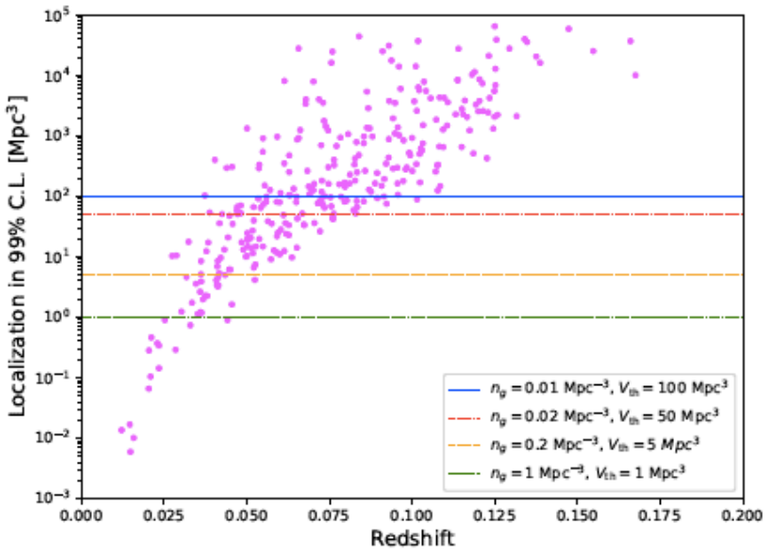
where $\Gamma_{ij} = \left(\frac{\partial h}{\partial \lambda_i}, \frac{\partial h}{\partial \lambda_j} \right)$ is Fisher matrix.



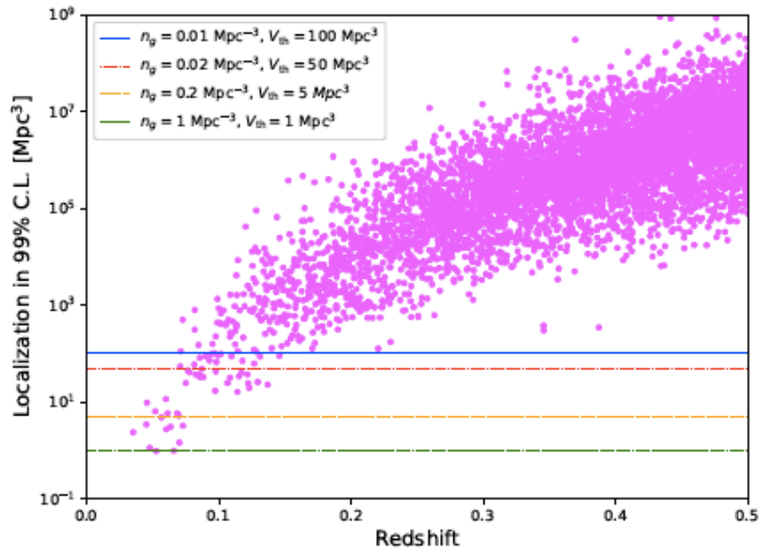
Simulated results for 5 year run of AEDGE, assuming GWTC-3 population

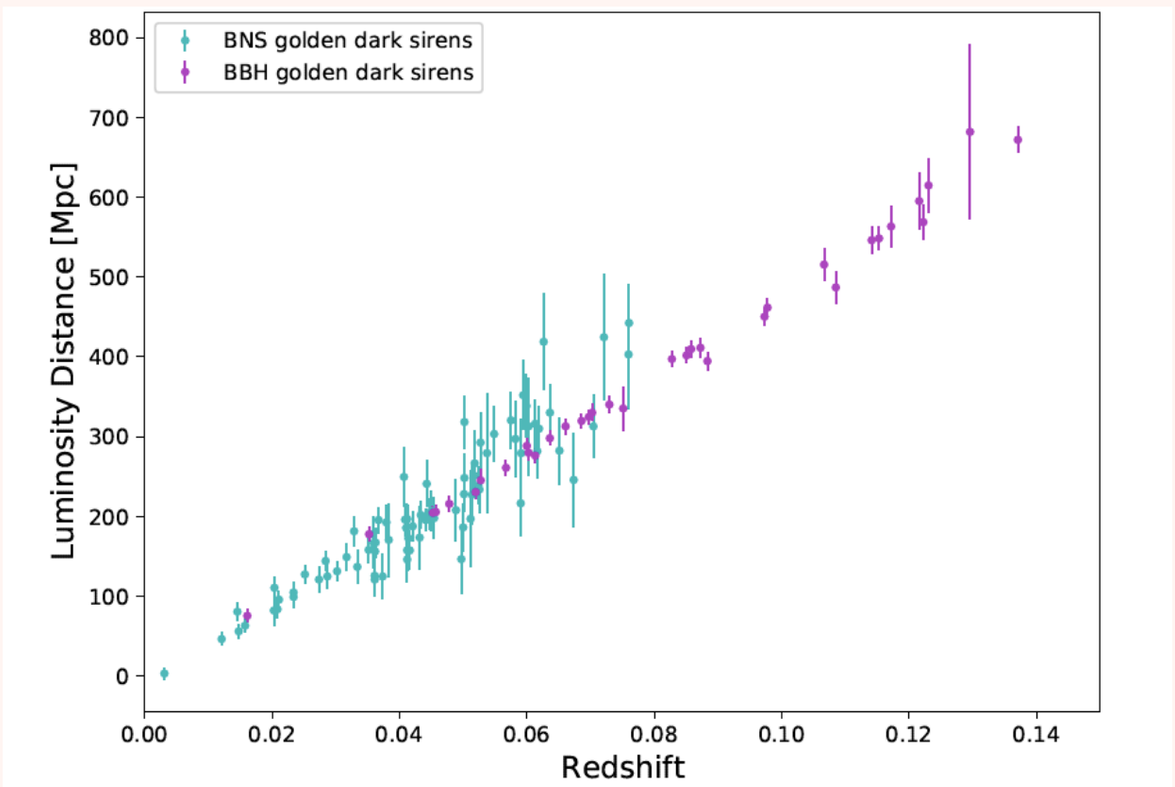
Simulations of BBH with mid-freq. detector

BNS



BBH

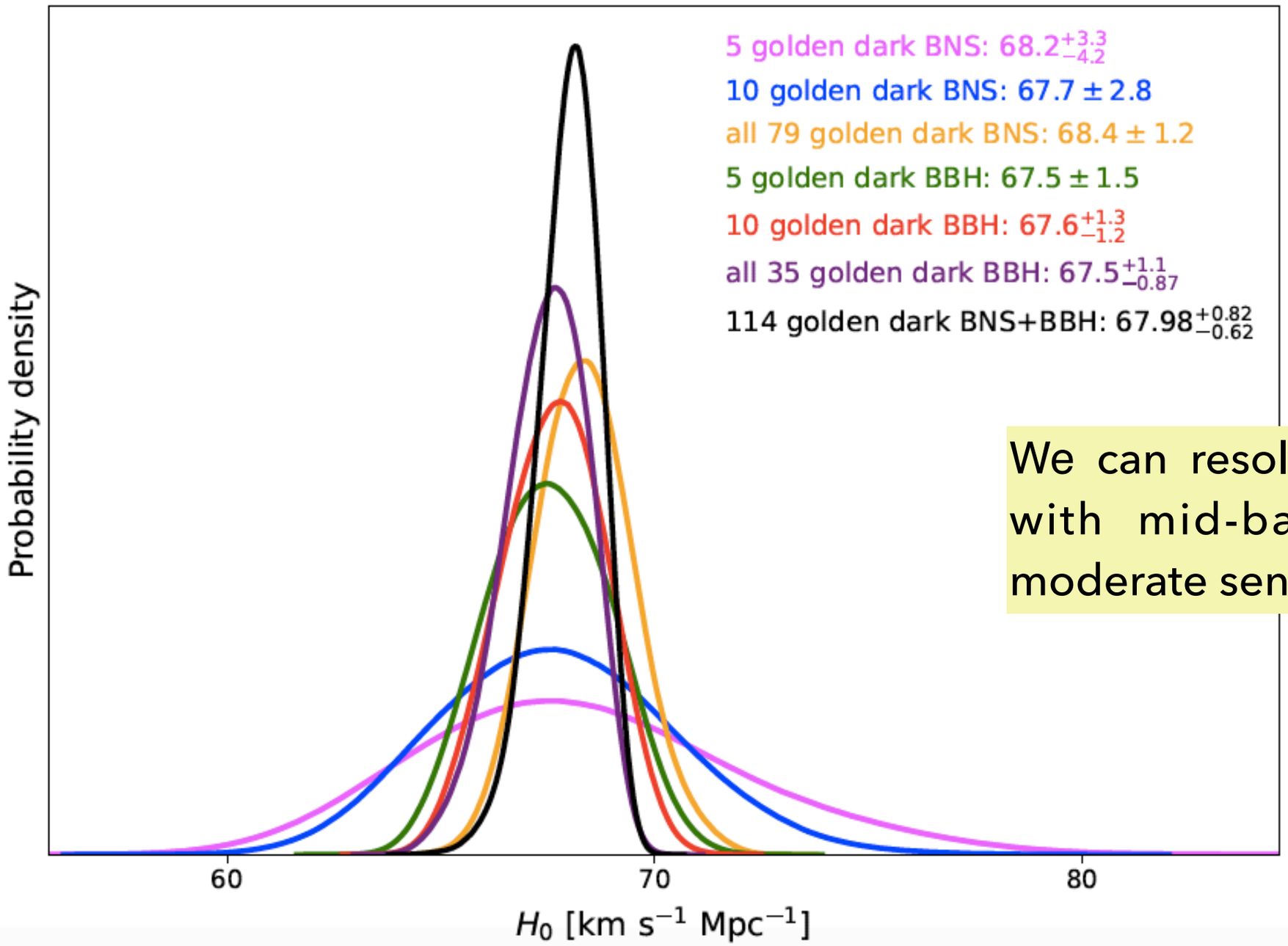




Golden Events: Various cuts are assumed galaxy number densities: below these lines, we can uniquely identify host galaxies within 5 year observation

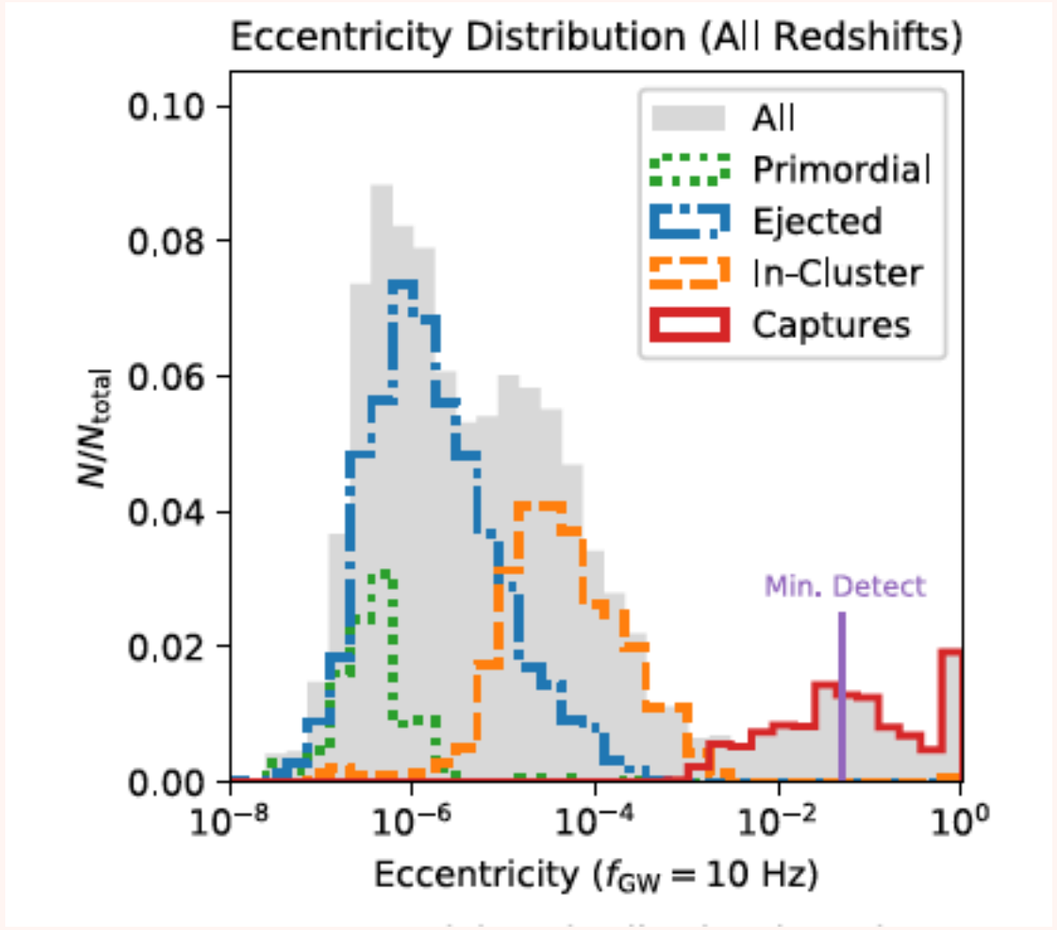
Simulated Hubble Diagram

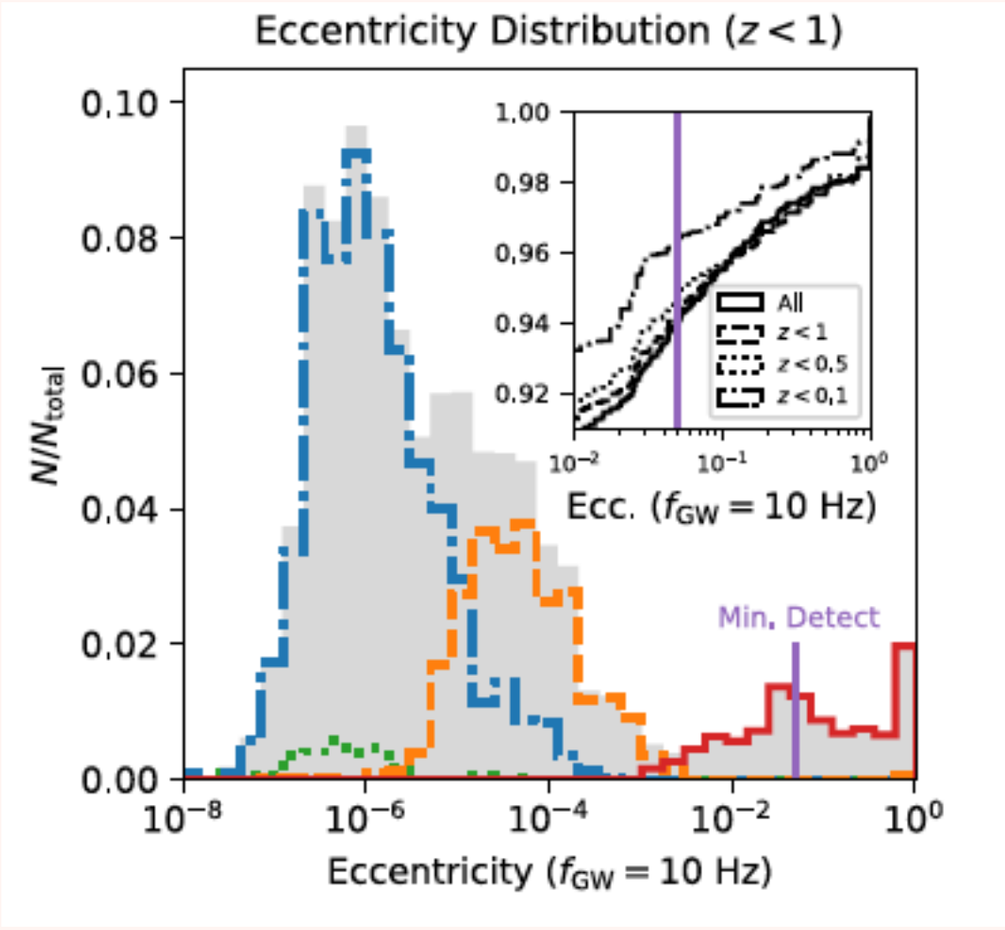
Hubble Constant Estimation from Dark Sirens



We can resolve Hubble tension with mid-band detectors of moderate sensitivity

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





- ~12% formed by capture

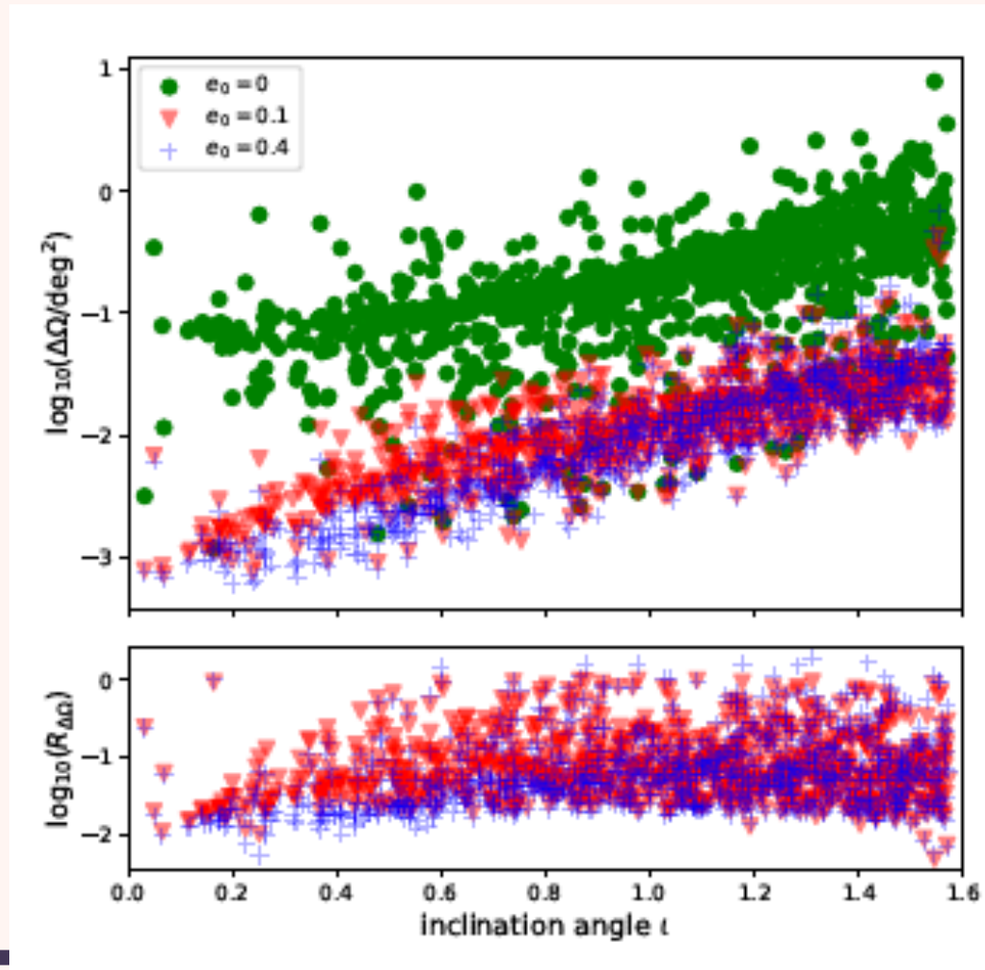
Rodriguez et al., PRD 98. 123005 (2018)

- ~4% of all mergers from GCs have e>0.1 at 10 Hz: If the dynamical binaries comprise ~10% of entire observed BBH, the fraction becomes 0.4%

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



Summary

- The Korean GW community is closely collaborating with LSC and KAGRA
- So far 90 GW sources are detected through three observing runs
  - Implications on formation scenarios
  - Spins are generally small
  - Multi-messenger astronomy
- Distances to merging binaries can be measured from GW observations only, although the statistical uncertainty of individual sources is very large.
  - Improvements on Hubble constant can be possible when many (~20) BNSs with optical counterparts are observed
- Some black hole binary host galaxies can be also identified when mid-band detectors become available.
  - Cosmological parameters could be precisely constrained with dark sirens alone in the future.