OVERVIEW OF GRAVITATIONAL WAVE RESEARCH IN KOREA

Korea-Italy Workshop on Multi-Messenger Astrophysics and Cosmology

October 25, 2026

Hyung Mok Lee

About this meeting

- It is one of the Inter-Academy Workshop Series supported by the Korean Academy of Science and Technology (KAST, https://www.kast.or.kr)
  - To promote the achievements of Korean scientists and strengthen collaborations with scientists abroad.
  - Invitation-only meeting
- Additional Support was provided by Gran Sasso Science Institute (GSSI).

Center for the Gravitational-wave Universe

(https://gwuniverse.snu.ac.kr)

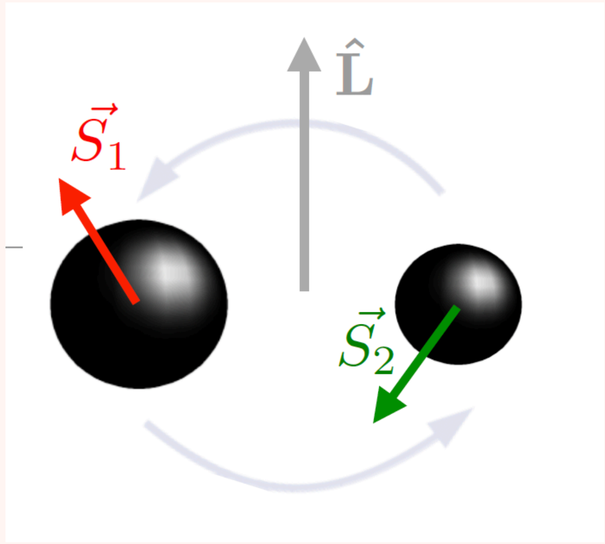
- One of the projects selected for 2021 National Science Challenge Initiative Program
  - Located at Seoul National University with additional members from
    - Ewha Woman's University
    - Korea Astronomy and Space Science Institute (KASI)
    - Pohang Institute of Science and Technology (POSTECH)
- Duration: July 1 2021 - December 31, 2025
- We do not have any dedicated funding from 2026, but we will continue to keep the research network active.

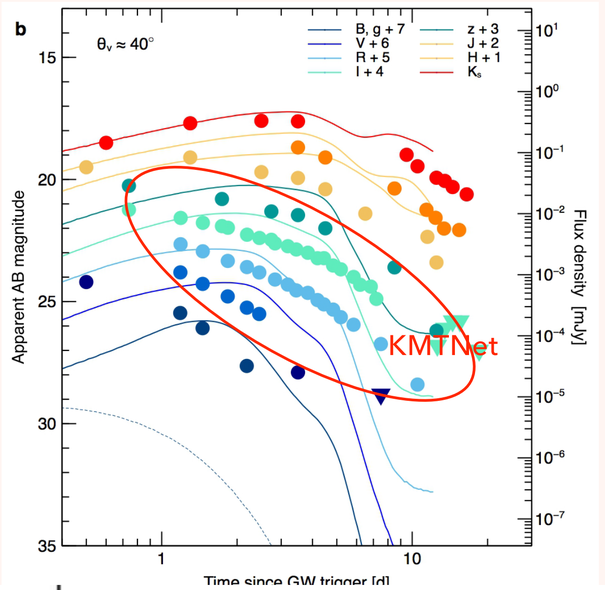
Members

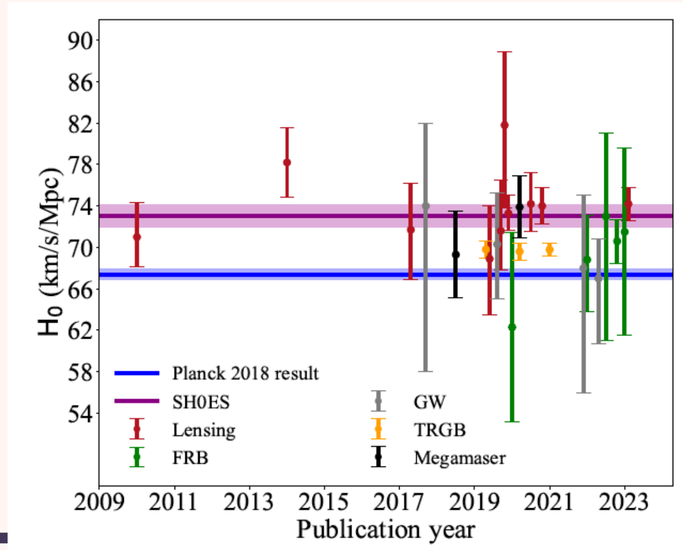
- **Core Members:**
  - **Hyung Mok Lee**, **Myungshin Im** (SNU), **Arman Shafieloo**, **Lucas Z. Uhm** (KASI), **Chunglee Kim** (Ewha), **Jae-Hun Jung** (POSTECH)
- **Research Associates:**
  - **Elahe Khalouei** (currently at KASI), **Tao Yang** (currently at Wuhan Univ.), **Christopher Bresten** (POSTECH), **Arif Shaikh** (currently at Vivekananda Satavarshiki Mahavidyalaya) , **Jeongcho Kim** (currently at NIMS), **Gihyuk Cho** (currently at a private company), **Ji Hoon Kim**, **Seo Won Chang**, **Sung Kook Lee**, **Hyunsung Jun** (currently at Northwester College), **Nicolas Chartier** (currently at RIKEN)
- **Associate Members:**
  - **Ho Song Hwang**(SNU), **Ryan Keeley**(UC Merced), **Kyung Min Kim**(KASI), **Hyung Won Lee** (Inje Univ), **Gopakumar Achamveedu**(TIFR), **Pau Amaro Seoane** (Universitat Politècnica de València), **Bing Zhang** (Hong Kong Univ.)

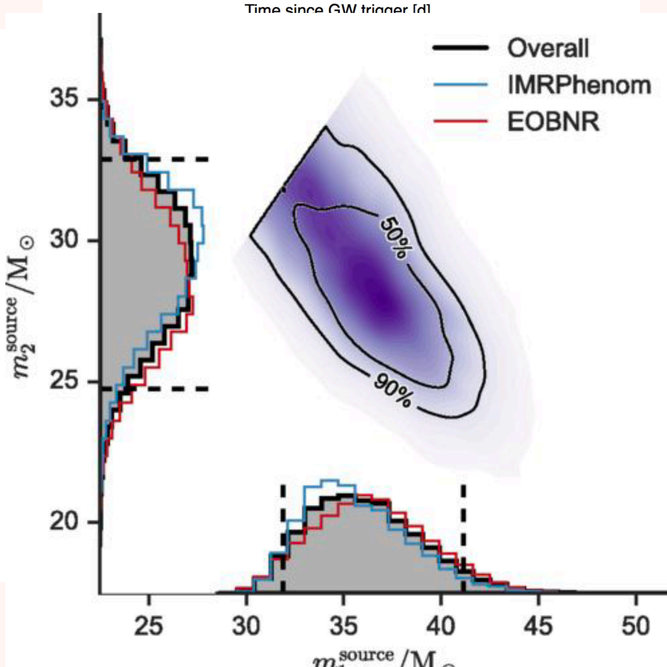
Keywords of GWUniverse

- **Gravitational Waves**
  - Sources
  - Waveforms
  - Identification of host galaxies
  - Future Detectors
- **Cosmology**
  - Tensions in Cosmology
  - Model-independent reconstruction of expansion history.
  - Dark Energy
- **Multi-Messenger Astronomy**
  - 7-dimensional Telescope (7DT)
  - EM Counterpart
  - Kilonovae/Gamma-Ray Burst Modeling



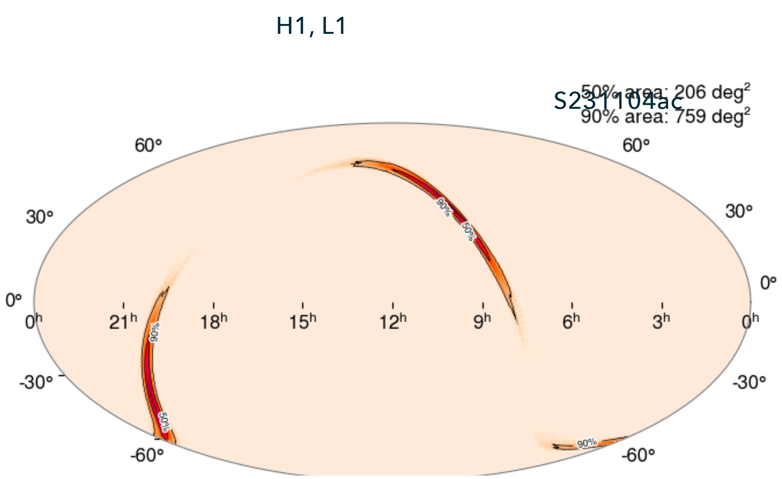


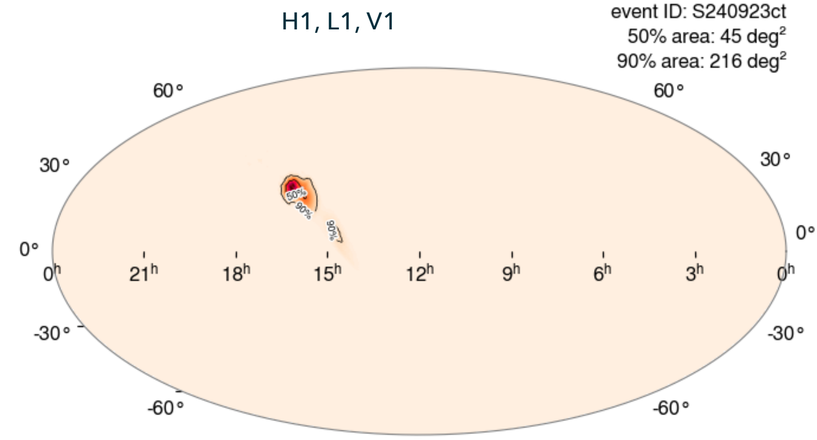




Dark Sirens

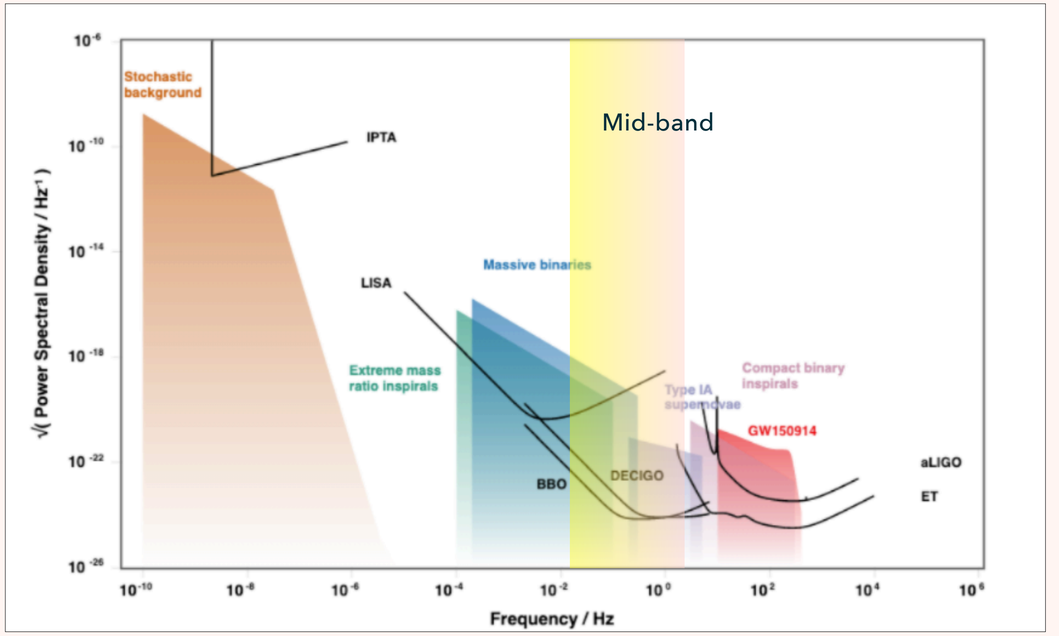
- BBH does not emit EM radiation, and distant BNS may emit EM radiation that is too faint to observe. Such objects are called **dark sirens**
  - One can still use dark sirens to constrain cosmological parameters using dark sirens statistically.
    - Prospects with ground-based detectors:
- Dark Siren prospects and issues with mid-frequency detectors
  - Yang, HMLee, Cai, Choi & Jung 2022, JCAP
  - Yang, Cai, & HMLee, 2022, JCAP
  - Yang, Cai, Cao & HMLee, 2023, PRD
  - Yang, Cai, Cao & HMLee, 2024, PRD

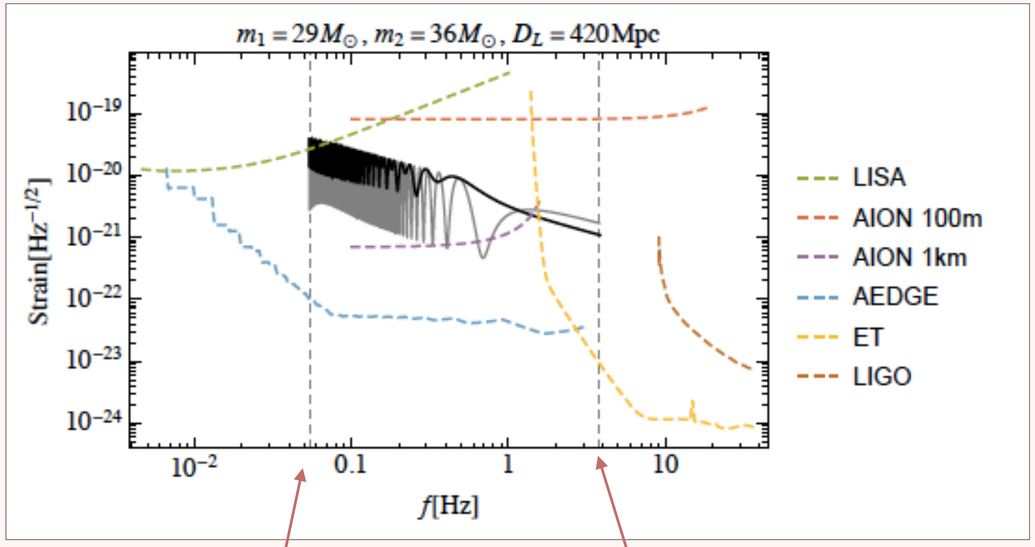




Improvement of localization in 3D volume with mid-band detectors

- 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
  - **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



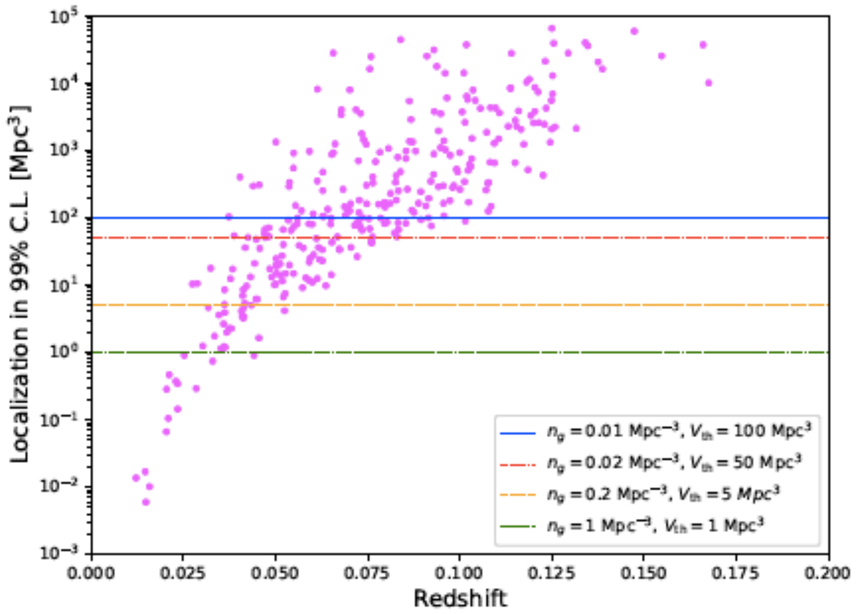


60 days before merger

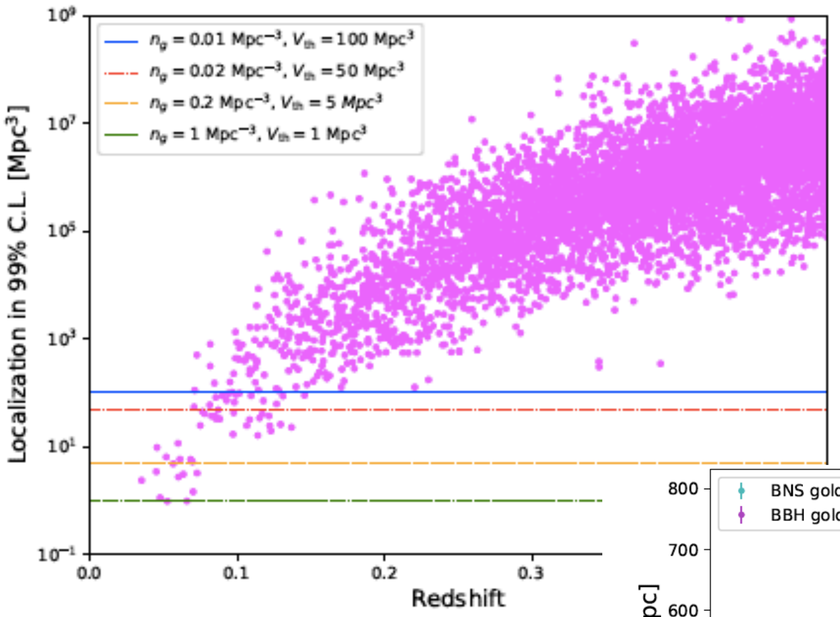
1 minute before merger

Localization volume and Hubble Diagram

BNS

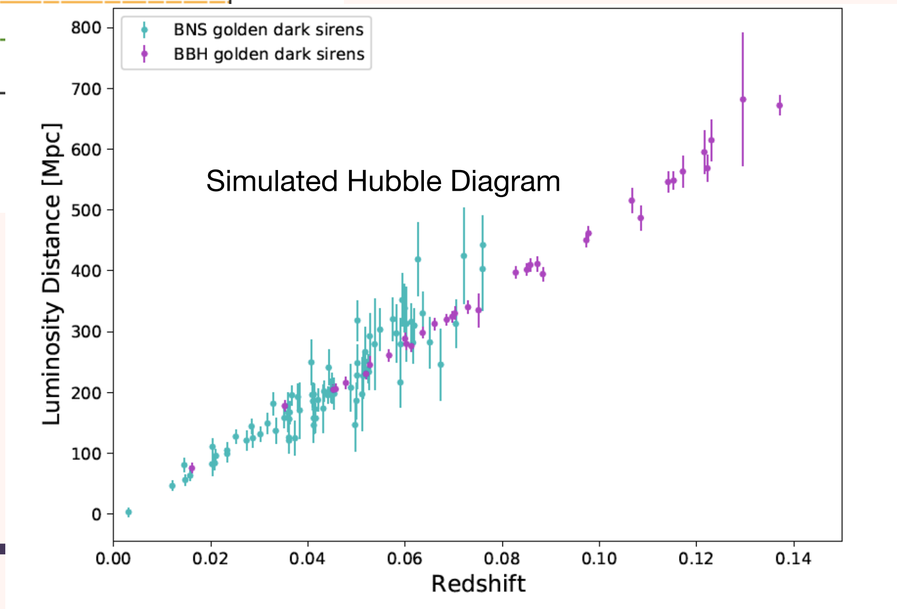


BBH

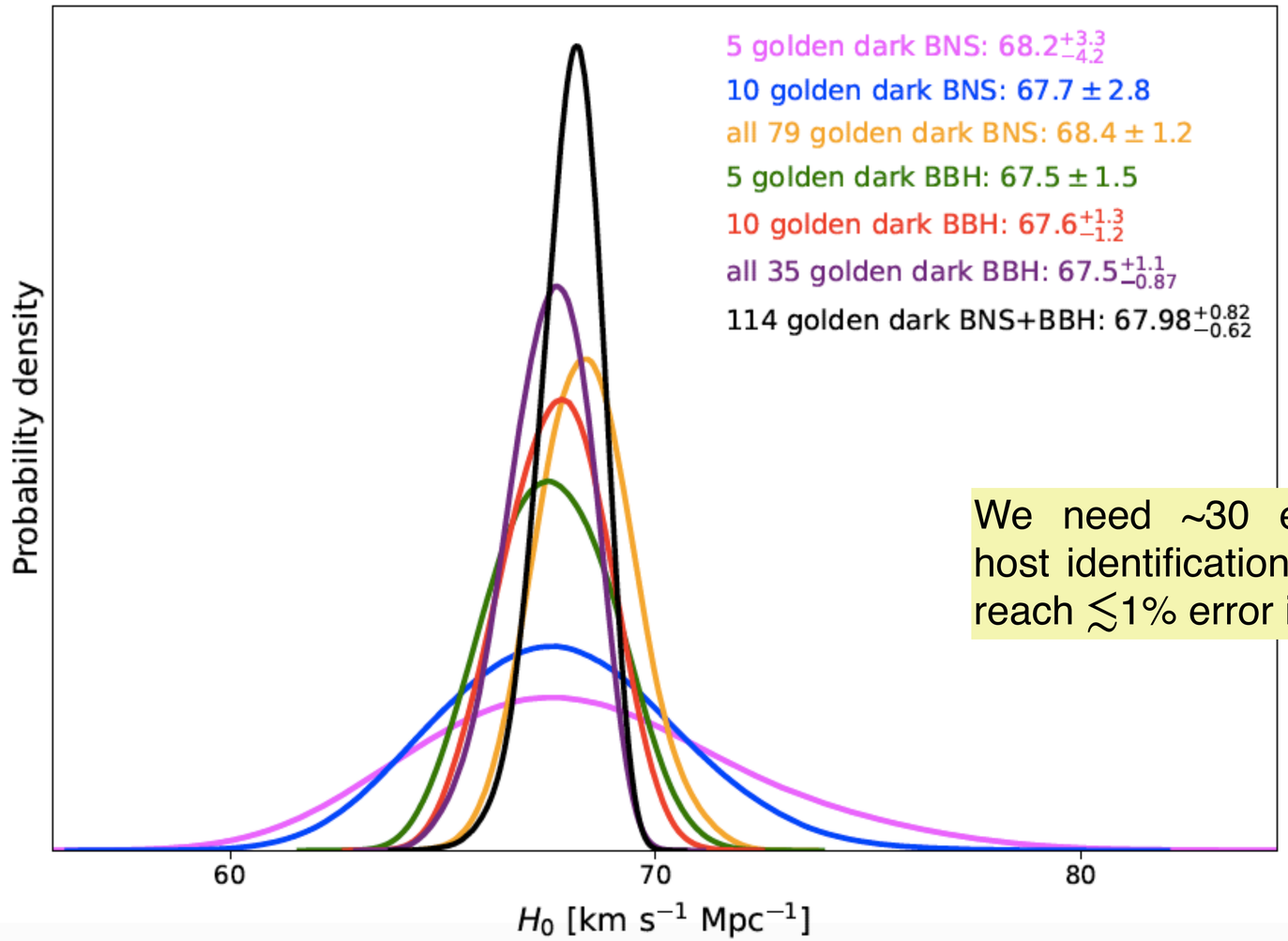


Yang, Lee, Cai + 2022, JCAP

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



Yang, Lee, Cai+ 2022, JCAP

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

Eccentricity Issues

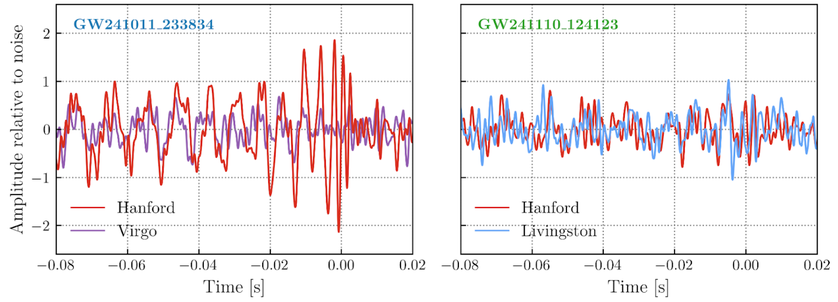
- **So far, most of the GW parameter estimations are based on the assumption of circular binaries**
  - However, some scenarios of BBH formation predicts substantial amount of eccentricities
  - Eccentricities leads to systematic errors in estimated parameters unless correct waveforms are used
- **Topics on eccentric binaries**
  - **Do we have unique definition of eccentricity?** (Shaikh et al., 2023, PRD; Chartier et al., 2025, PRD)
  - **Systematic Errors with incorrect waveforms** (Choi, Yang & HMLee, 2024, PRD)
  - **Long duration waveforms based on post-Newtonian dynamics** (Cho, Tanya Gopakumar & HMLee, 2022, PRD)
  - **Improvements on localization and and distances for eccentric binaries** (Yang, Cai, Cao & Lee, 2022, PRL)
  - **Higher order modes due to eccentricity effect** (Yang, Cai, Cao & HMLee, 2024, PRD)
  - **Machine learning for the detection of eccentricities** (Khalouei, Saibu, HMLee, Gopakumar, 2025, JCAP, also work in progress)

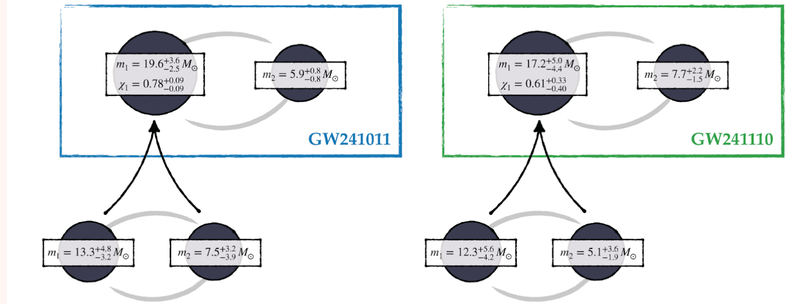
Compact Binaries from Binary Evolution

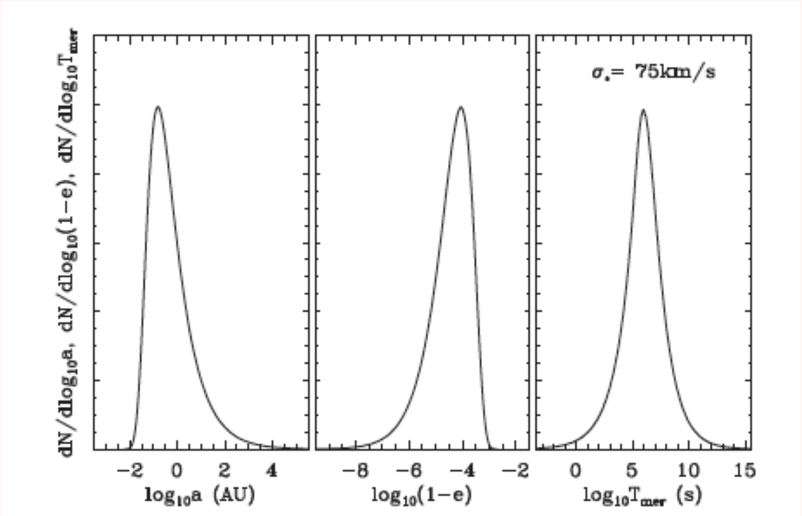
- Kowalska et al 2018 (arXiv:1010.0511)
- Investigated the properties of population of compact binaries in formation using StarTrack Code, and then studied the evolution of the orbits until they enter detector bands of DECIGO (0.3 Hz), Einstein Telescope (3 Hz) and LIGO/Virgo (30 Hz).
- Even in the case of the DECIGO detector, the typical eccentricities of BH-BH binaries are below 10^{-4} and the BH-NS eccentricities are smaller than 10^{-3}.
- They found that a fraction of between 0.2% and 2% NS-NS binaries will have an eccentricity above 0.01 for the Advanced LIGO/VIRGO detectors. For the ET detector, this fraction is between 0.4% and 4%, and for the DECIGO detector it lies between 2% and 27%.
- These results are not surprising, considering that the initial orbits are rather wide

Binaries of dynamical origin

- Some LVK BBHs may have been formed via dynamical scenario
- The fraction of dynamical binaries is very uncertain, but could be substantial (up to ~30%), if not the majority.
- Processes:
  - Direct capture
    - Very eccentric: $e \approx 1 - 1.62 \times 10^{-4} \eta^{3/7} \left(\frac{v_{rel}}{75\mathrm{km/s}} \right)^{10/7}$
    - Sometimes merge without further interactions
  - Three-body processes (Bae et al. 2014, Park et al. 2017)
    - Further hardening and ejection from the system
    - Eccentricity distribution is likely to be 'thermal', i.e., $f(e)de \propto ede$







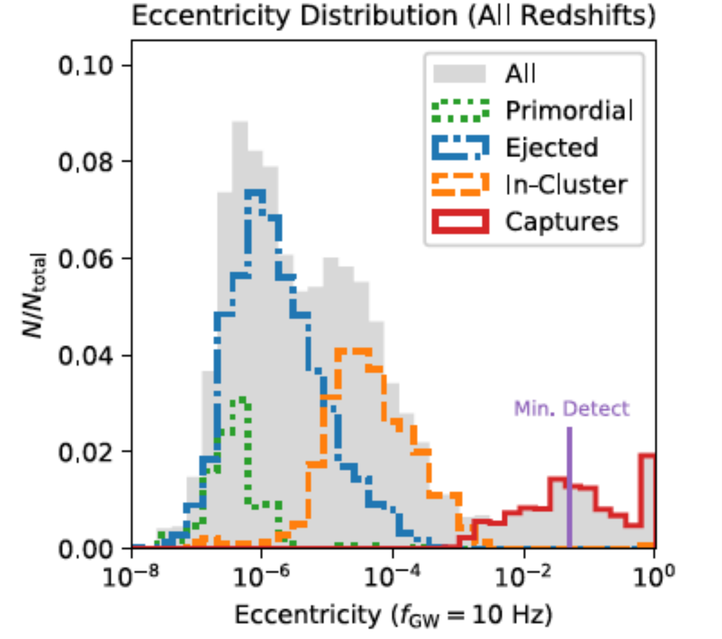
Hong & Lee 2015

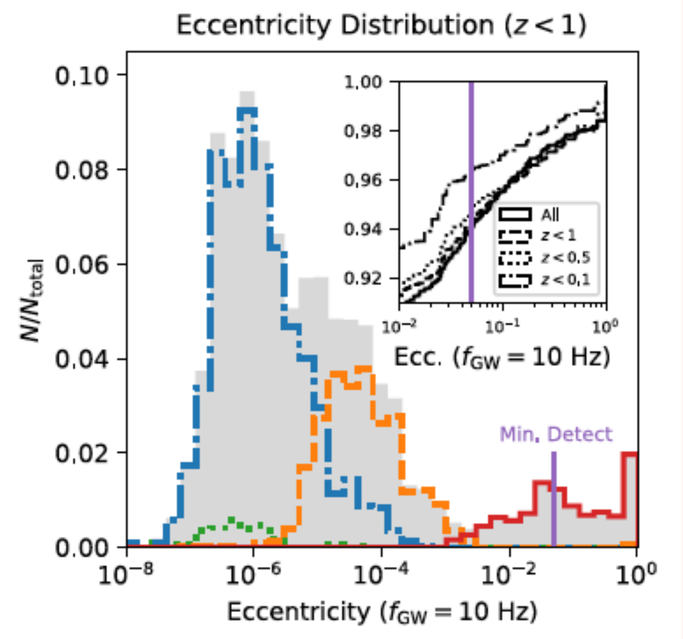
Estimation of Dynamical Binaries (Bae et al. 2014, Lee et al. 2015)

- We carried out large number of N-body simulations of globular clusters including neutron stars and black holes and derived merger rates as a function of cluster mass and velocity dispersion.
- We used 142 clusters in the catalogue by Harris (2010) with mass and velocity dispersion http://physwww.mcmaster.ca/~harris/Databases.html
  - We computed the number of binaries whose merging time is shorter than Hubble time for each cluster and add them up
- **Results for advanced detectors**
  - 0.1 - 1 yr^{-1} NS-NS merger
  - 15 – 60 yr^{-1} for BH-BH merger
  - Other works with different assumptions and methods give similar results (Banerjee et al., 2010, Downing et al. 2011)

BBHs from Comprehensive Simulations [Rodreguez et al. (2018), PRD, 98, 123005]

- Monte Carlo N-body simulations for globular clusters
- Only captured binaries would have significant eccentricities in mid-band
- This could be 10% of the dynamical binaries:
  - If 30% is dynamical origin, ~3 %
  - More precise eccentricity distribution has to be worked out
- Capture in the nuclear star cluster could add more eccentricity

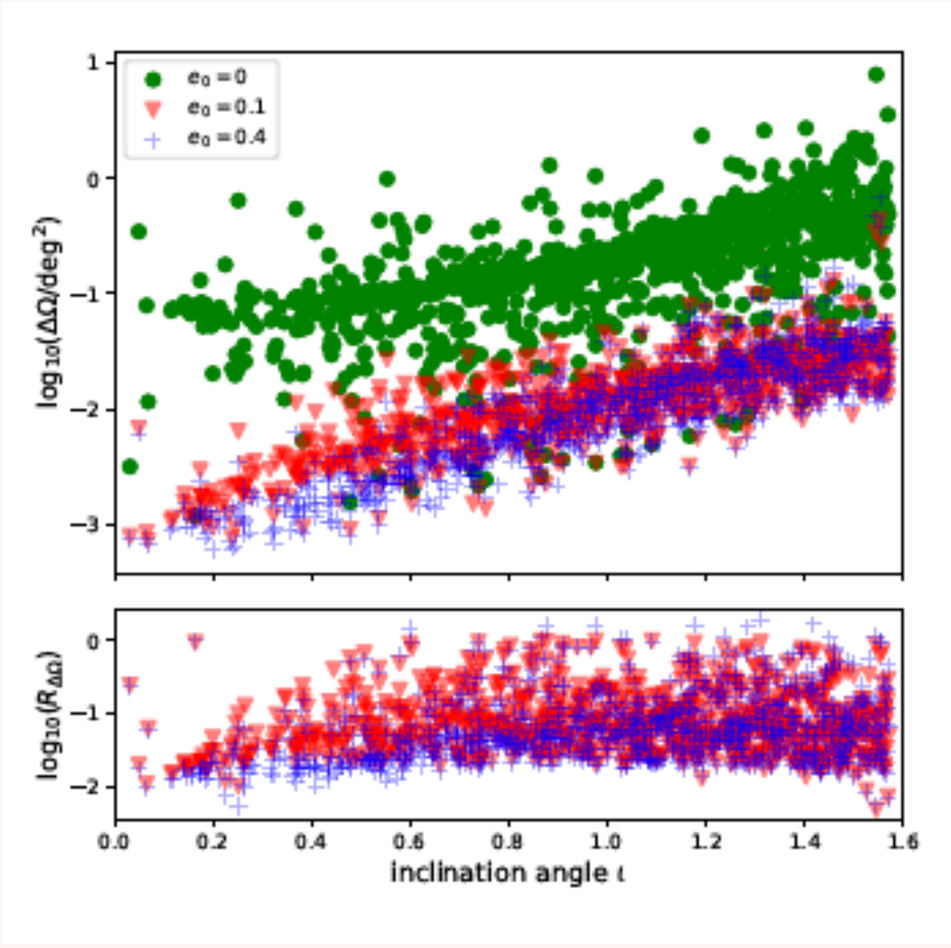




Improvements of estimated parameters for eccentric binaries

Yang, Cai. Cao & Lee, 2022, PRL

- 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
- For B-DECIGO:
  - $\Delta d_L/d_L$ can be improved near $\iota = 0$.
  - $(\Delta\Omega)_{e=0.1@0.1\mathrm{Hz}} \lesssim (\Delta\Omega)_{e=0}$
  - More improvement for larger e.



Definition of Eccentricity for Relativistic Binaries

- Eccentricity is uniquely defined in Keplerian orbits only.
- In PN theory, there are three eccentricities, e_r, e_ϕ and e_t with e_t being dependent on gauge.
- Different models may be using eccentricity that is defined differently.

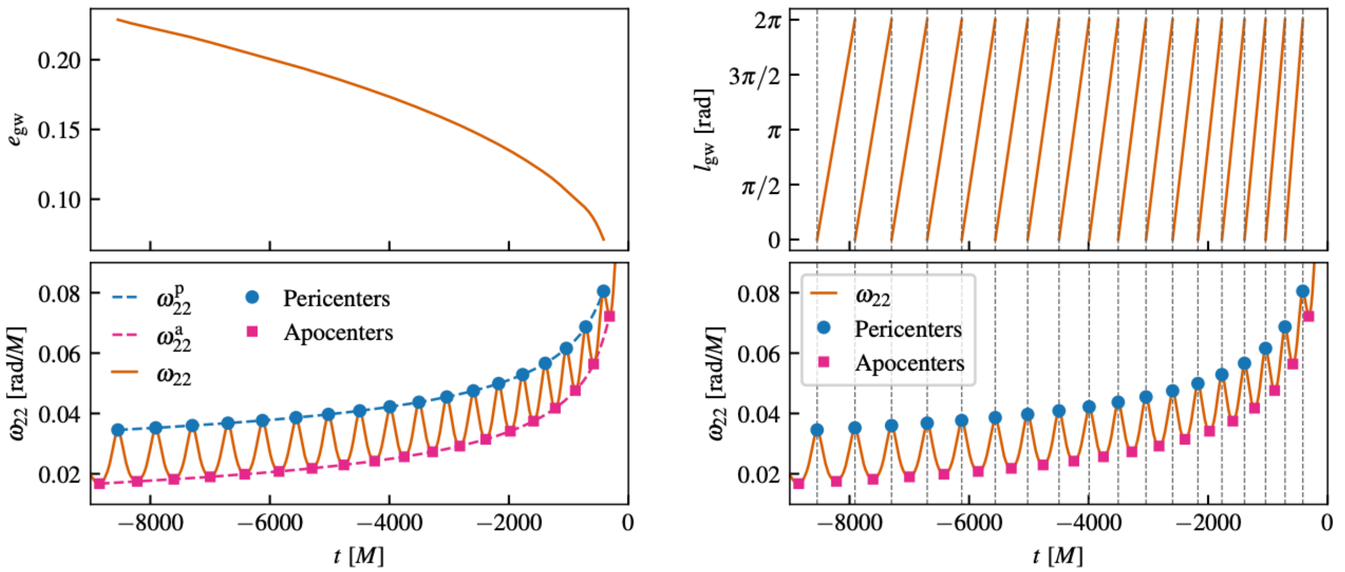
- Shaikh et al. (2023) proposed definition of guage independent eccentricity from the GW frequency evolution.

$$h_{22}(t) = A_{22}(t)e^{-i\phi_{22}(t)}, \quad \omega_{22}(t) = \frac{d\phi_{22}(t)}{dt}$$

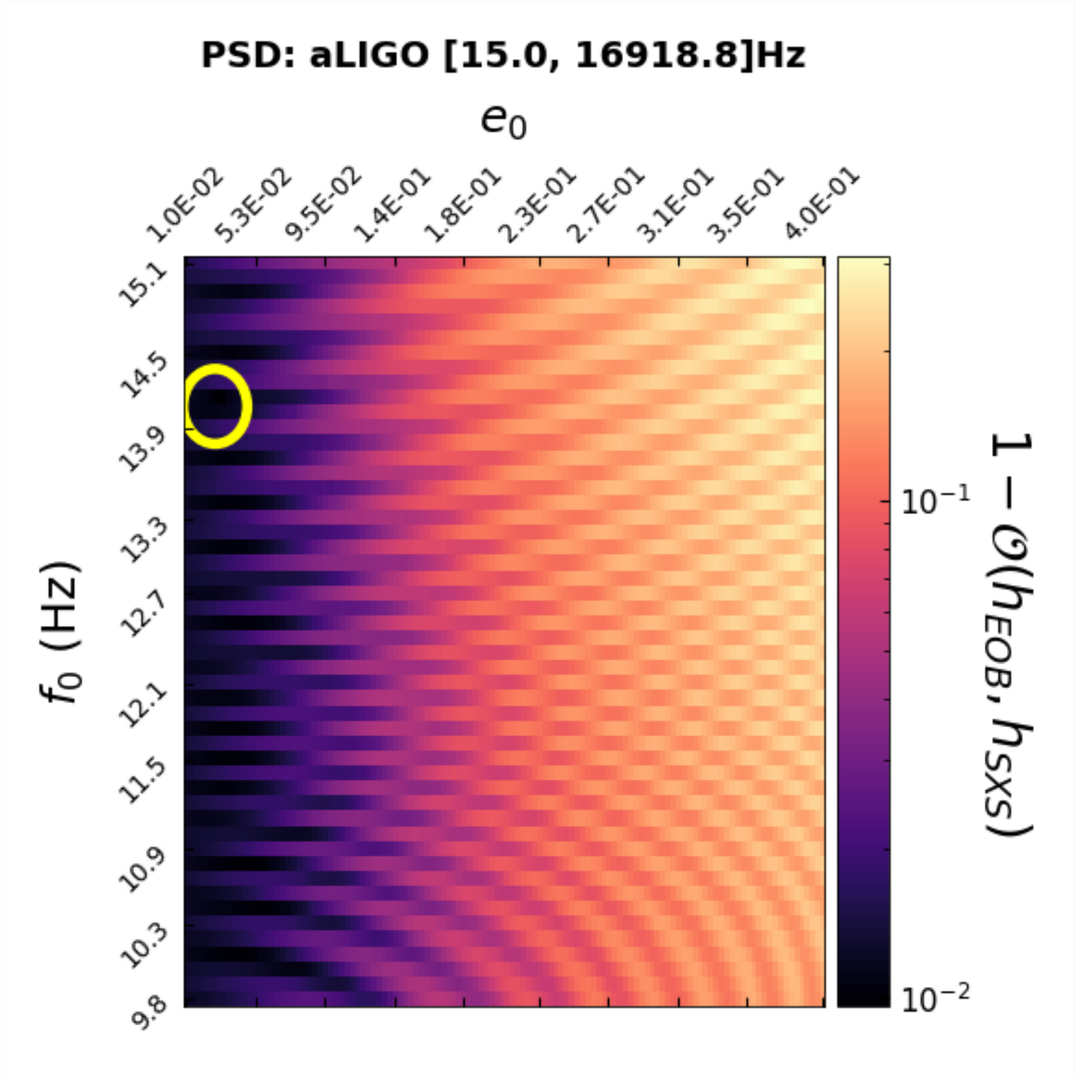
$$e_{\omega_{22}} = \frac{\omega_{22}^p - \omega_{22}^a}{\omega_{22}^p + \omega_{22}^a} \qquad \Psi = \arctan\left(\frac{1 - e_{\omega_{22}}^2}{2e_{\omega_{22}}}\right)$$

$$e_{gw} = \cos(\Psi/3) - \sqrt{3}\sin(\Psi/3)$$

Shaikh et al, 2023, PRD



Are eccentric models consistent each other (Chartier et al. 2025, PRD)

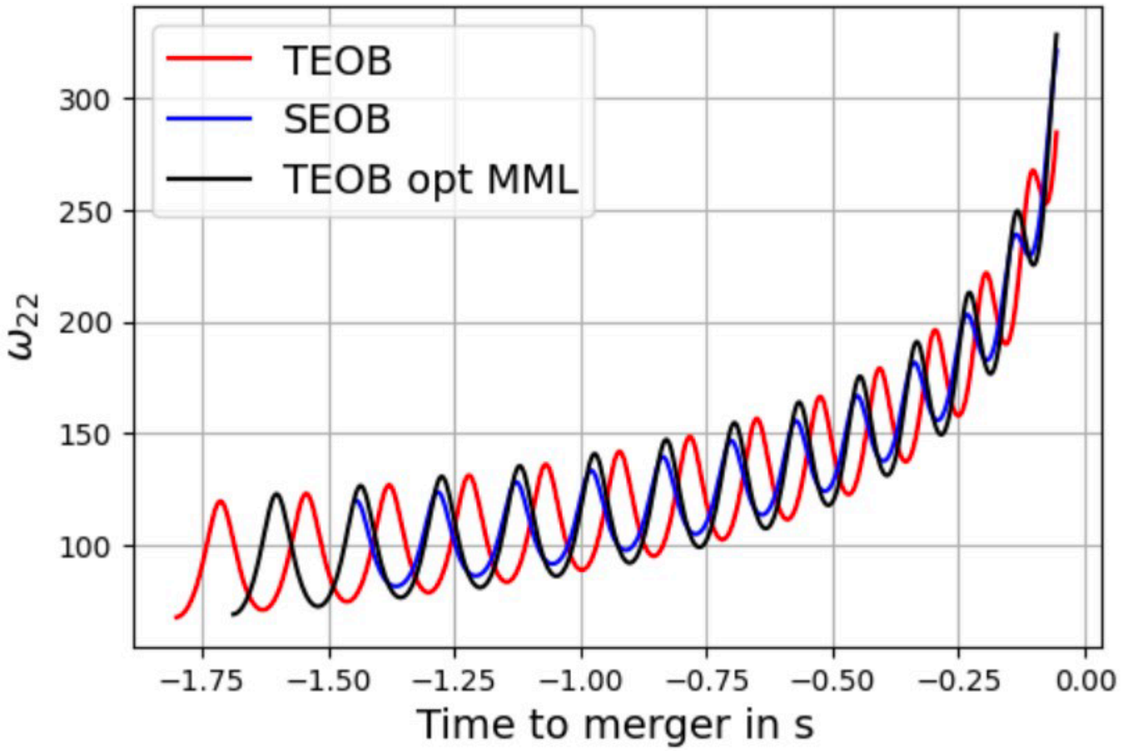


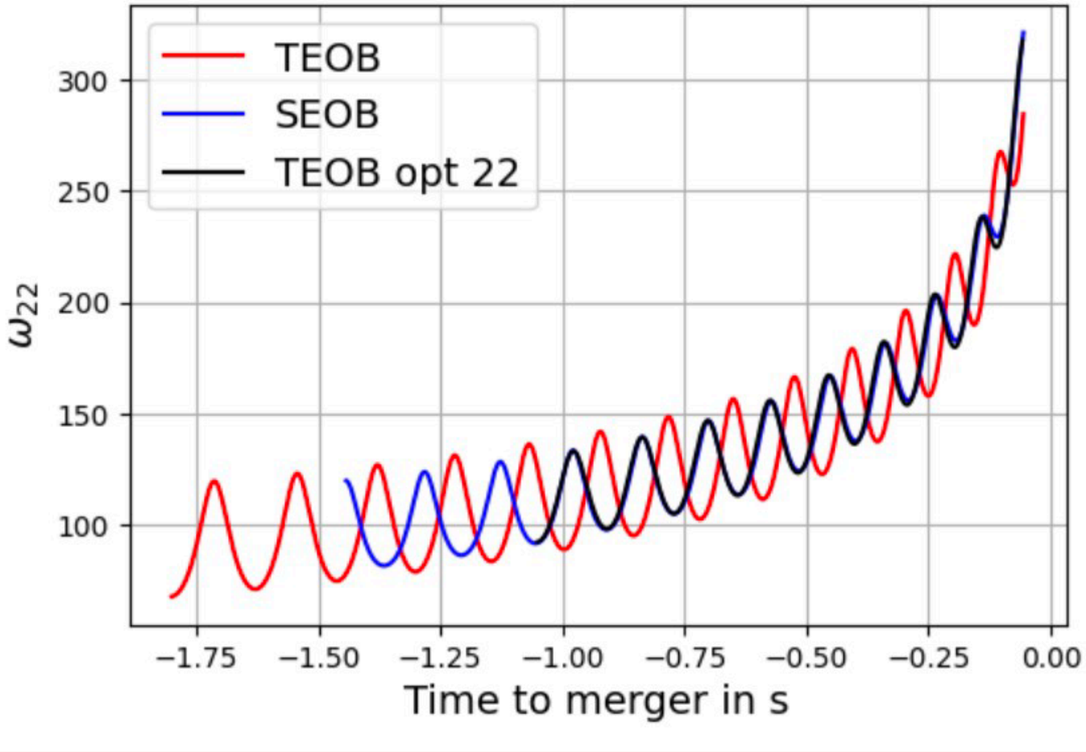
$$O(h_1, h_2) = \frac{< h_1 h_2 >}{|h_1||h_2|}$$

- Comparison between EOB model and NR shows that there is a significant mismatch for e>0.05 at f_0 ~ 10 Hz.
- Further, the mismatch seems to have oscillating behavior depending on the f_0 where e_0 is defined.
  - This indicates that the definition of eccentricity depends on the phase of the GW waves.

Optimize with the same e_{gw}

Chartier et al. 2025, PRD

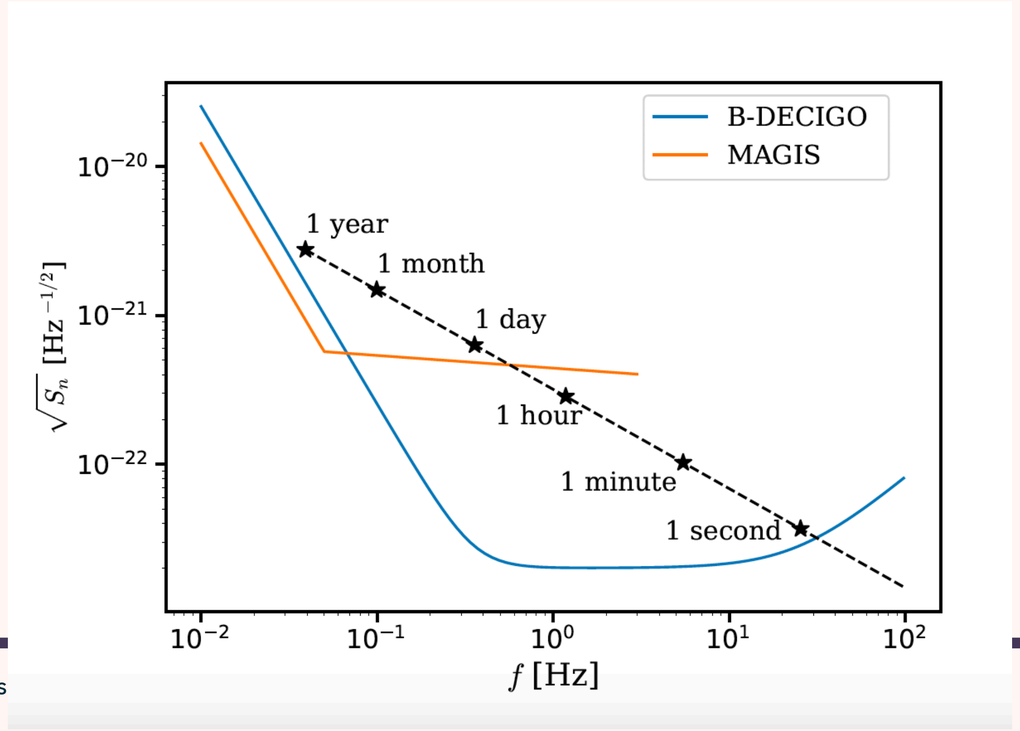


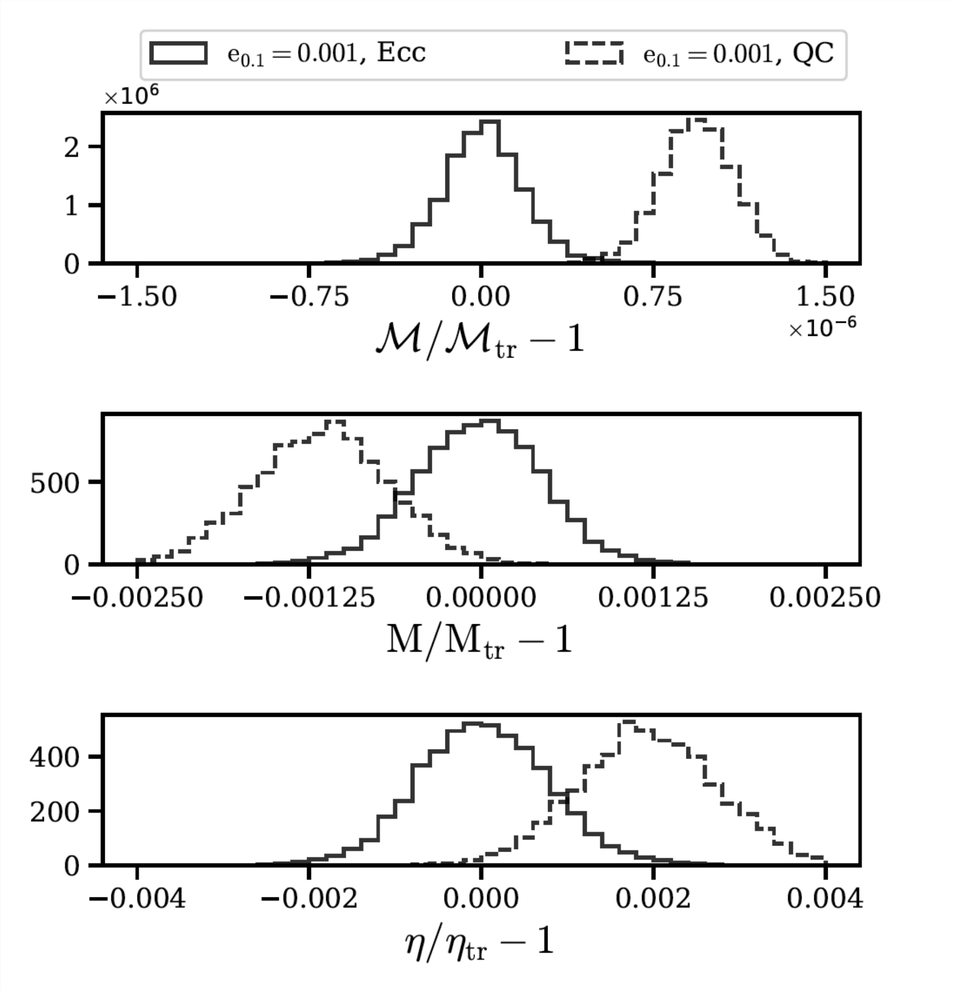


- If we require the same e_{gw} (t) behavior for different models, we sometimes end up with different phase evolution: that means significant mismatch.

Systematic Errors due to uncertain waveforms (Choi, Yang & Lee, PRD, 2024)

- We made detailed parameter estimation for assumed B-DECIGO and MAGIS Detectors for GW150914-like BBH
- The injected waveform is eccentric model (TaylorF2ECC) but analyzed with Quasi-circular model
- Systematic Errors in mass estimations (thus eventually distance) greater than statistical errors arise.



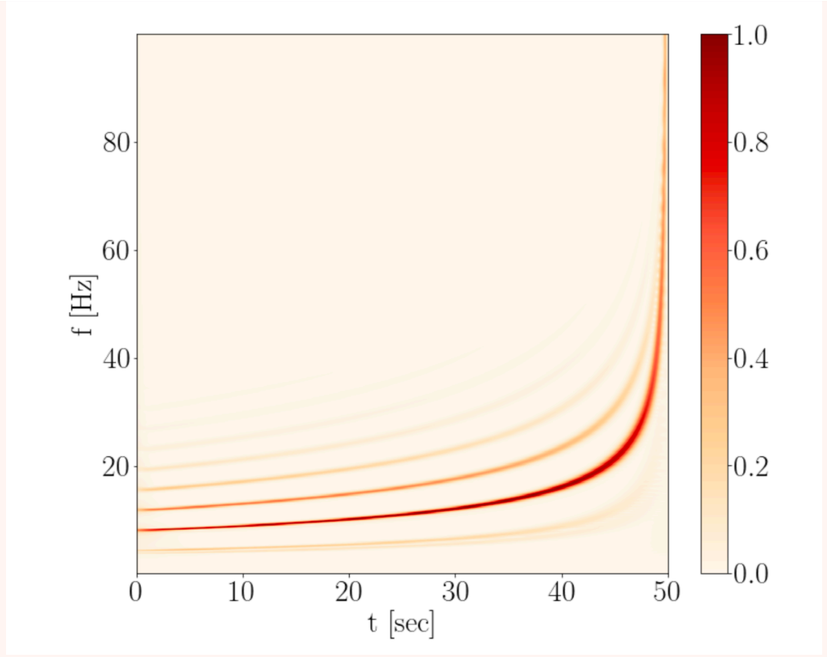


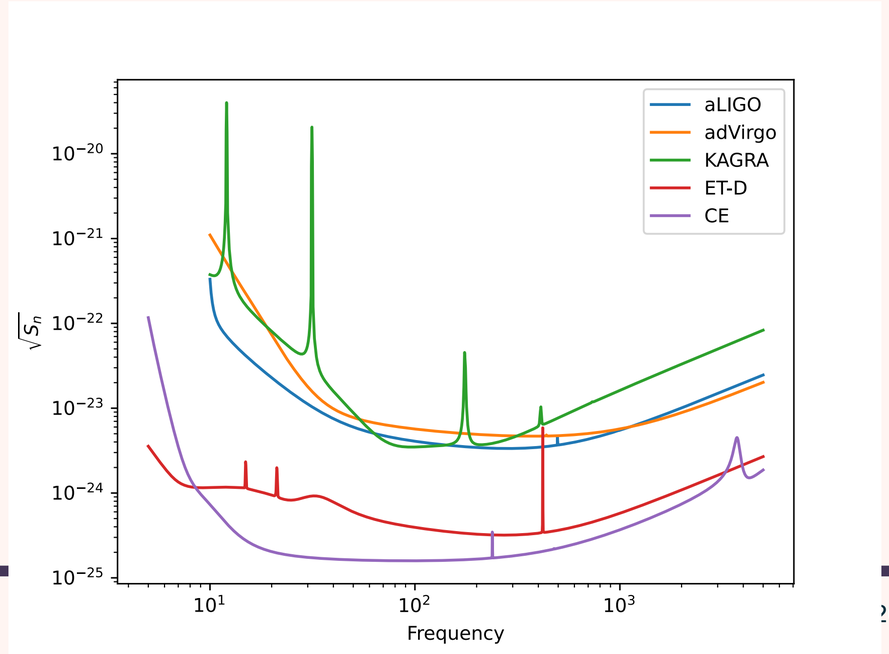
Effects if higher-order

- Eccentric binaries can emit various order modes: ($f_{GW} = l\, f_{orb}$, $l = 1,2,...$)

$$\tilde{h}(f) = Cf^{-7/6} \sum_{l=1}^{\infty} \xi_l \left(\frac{l}{2}\right)^{3/2} e^{-i\Psi_l}$$

- Quadruple mode ($l = 2$) produces strongest signal, but higher mode can enter the detector band before $l = 2$ mode enters
- They stay in the band for longer time
  - e.g., For Einstein Telescope (ET) $l = 10$ mode for BBH binary can enter a few month before $l = 2$

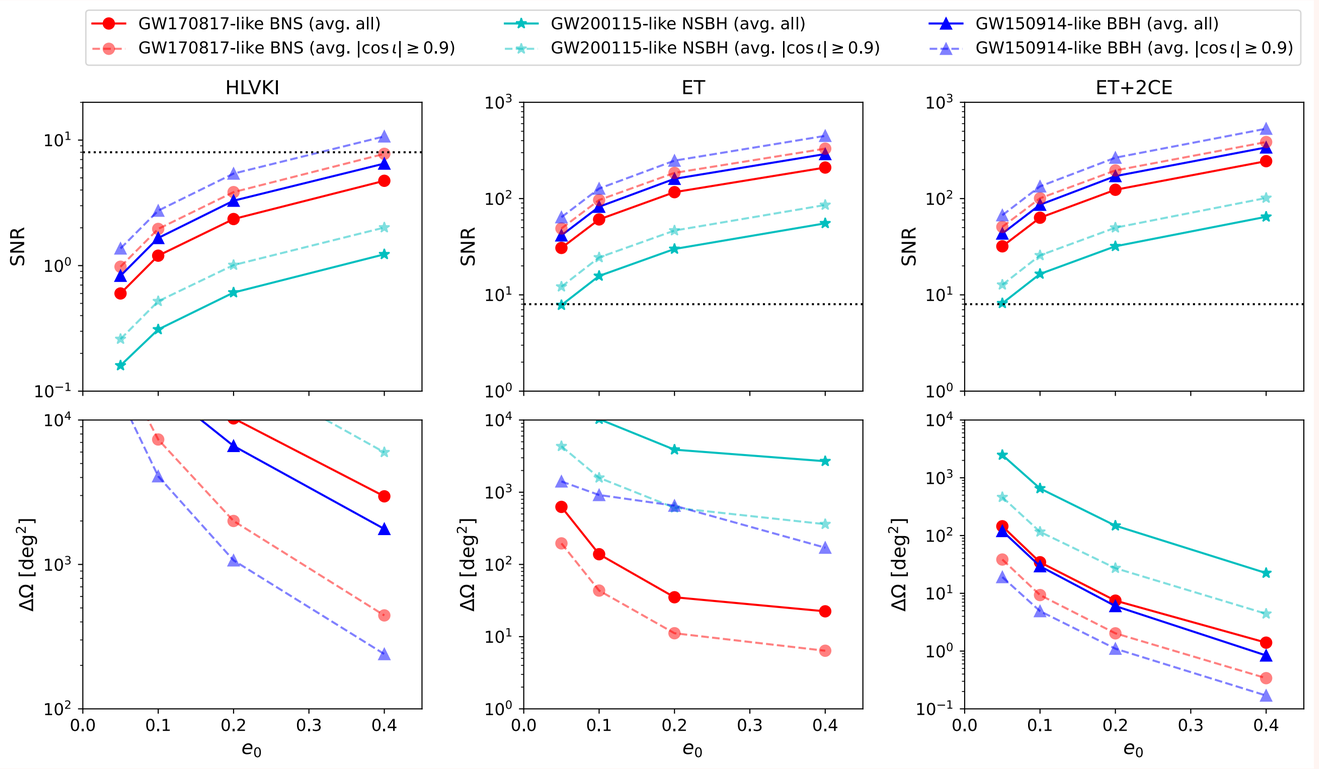




- ET: Einstein Telescope led by Europe
- CE: Cosmic Explorer led by US

Early Warning for Eccentric Binaries (Yang et al. 2024, PRD)

- Higher order mode can be used for early warning (negative latency).
- Three representative cases: BNS, NS-BH and BBH
- The higher-mode signal can be very significant for the 3G detectors.
  - ~10 sq. degrees localization can be possible at 1~1.8 hours before the merger for GW170817-like BNS
  - 10–1,000 sq. degrees approximately 18-30 minutes prior to the merger of a GW200115-like NSBH.



Accumulation of the SNR due to $l > 2$ modes until the $l = 2$ mode enters the detector band

Fast Estimation of Eccentricity

- Eccentricity in the LIGO band can help distinguish dynamical formation from isolated binary evolution.
- Most standard searches and parameter-estimation pipelines assume quasi-circular orbits.
- Eccentric waveform modeling and Bayesian inference are computationally expensive.

Can we infer infer eccentricity and chirp mass directly from gravitational-wave spectrograms using a fast AI model?

Khalouei, Sabiu, Lee & Gopakumar, JCAP 10 (2025) 028

External-attention transformer: data and method

SIMULATED SIGNALS

SEOBNRv5EHM
Non-spinning BBHs
15–60 $M_\odot$ chirp mass
$e_{15\mathrm{Hz}}$= 0.001–0.35

→

DETECTOR DATA

O4-like Gaussian noise
Hanford + Livingston
Network SNR > 10
30,000 total injections

→

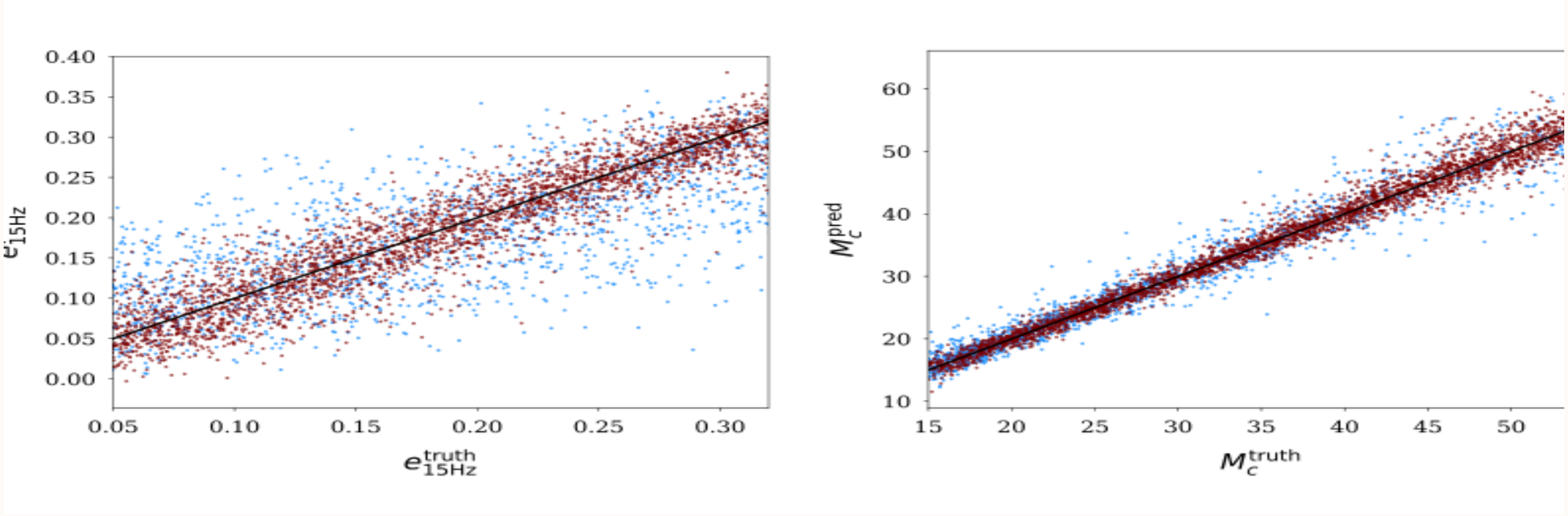
AI REGRESSION

256 × 256 × 2 spectrograms
16 × 16 image patches
8-head external attention
CNN → $e_{15\mathrm{Hz}}$ and chirp mass

1.84 million trainable parameters • Single GPU training < 1 hour • Joint estimation addresses mass–eccentricity degeneracy

Source: Khalouei et al. (2025),

Predicted vs. injected parameters



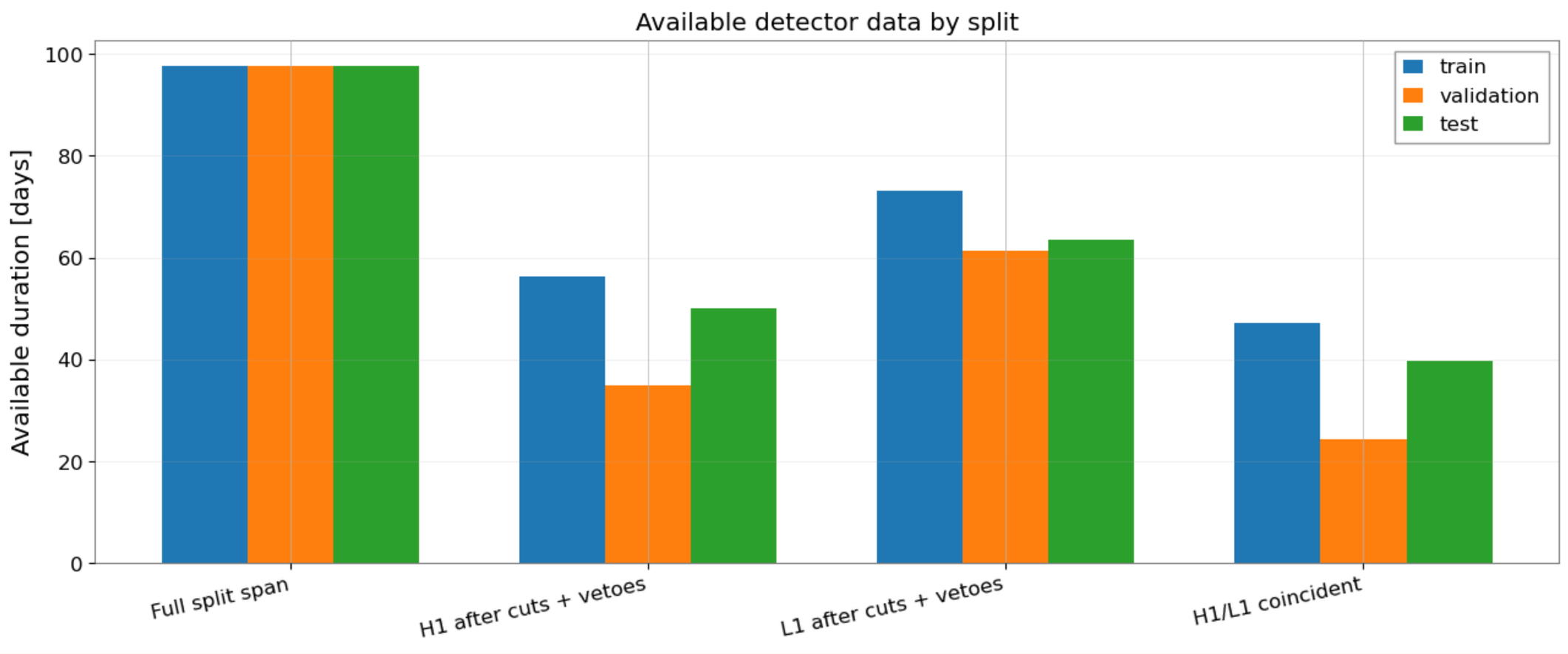
Blue: network SNR 10–20 • **Brown: network SNR 20–60**

Higher SNR gives tighter predictions; high chirp-mass events show increased scatter.

Adapted from Figure 2, Khalouei et al., JCAP 10 (2025) 028

Simulations with real data (O4b)

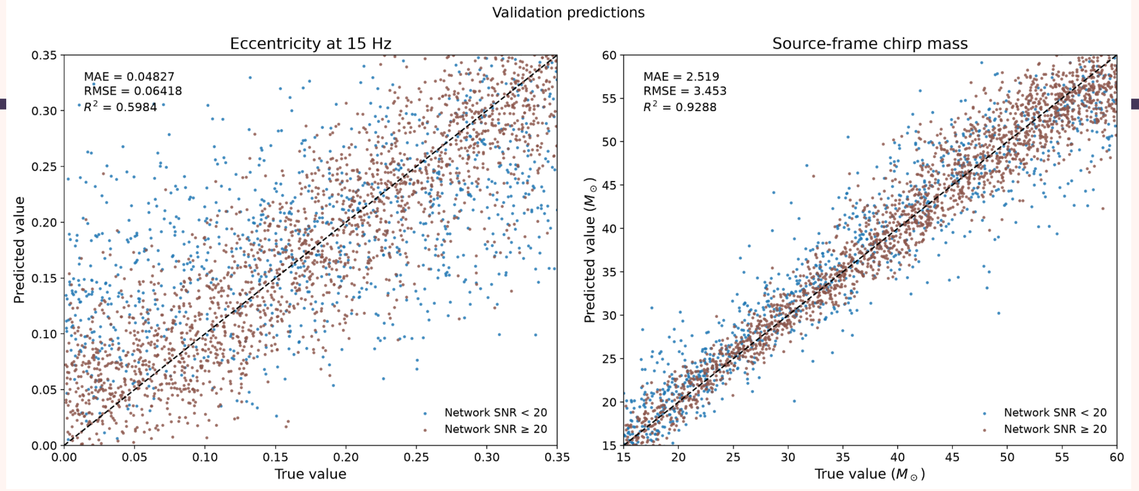
Simulations with O4b (preliminary, done mostly by an intern student,Tanush Medithe)



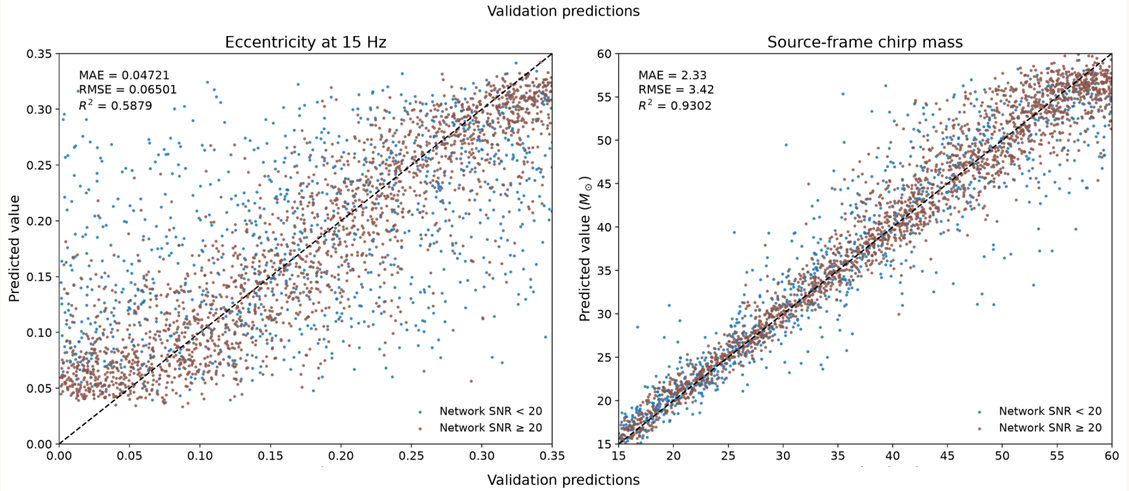
Additional Models

	Description	Precedent
ConvNeXt V2-Atto (2023) (emphasize local features)	CNN using transformer-inspired choices (patch-like downsampling, LayerNorm, GELU, large-kernel spatial mixing, MLP-style channel expansion, residual blocks) but replaces self-attention with depthwise convolutions	GW Data Glitch Classification Galaxy Morphology Classification
Mambavision-T (2025) (emphasize long-range features)	Hybrid vision architecture that combines convolutional layers for extracting local image features with Mamba state-space blocks and self-attention for modeling longer-range relationships.	Green Pea Galaxy Identification

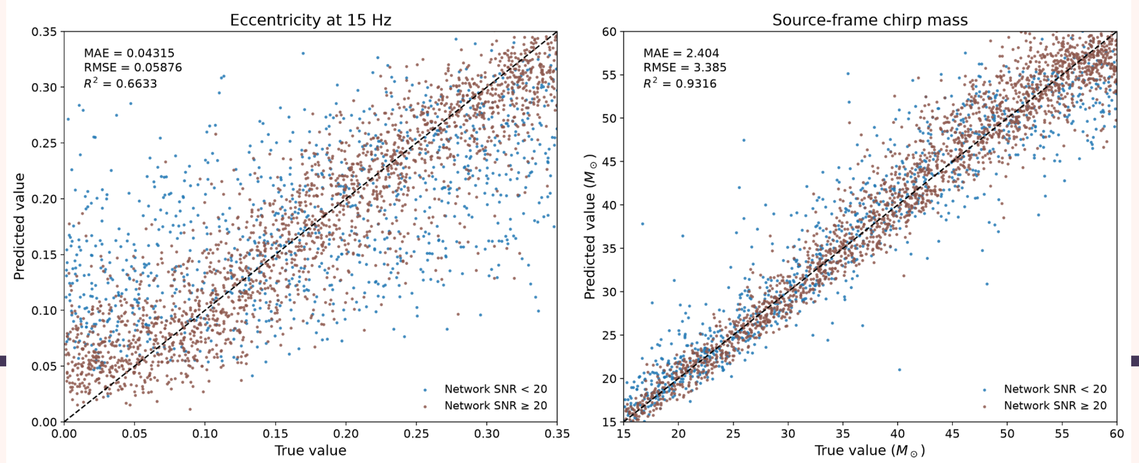
EANet + CNN (original)



ConvNeXt



Mambavision-T

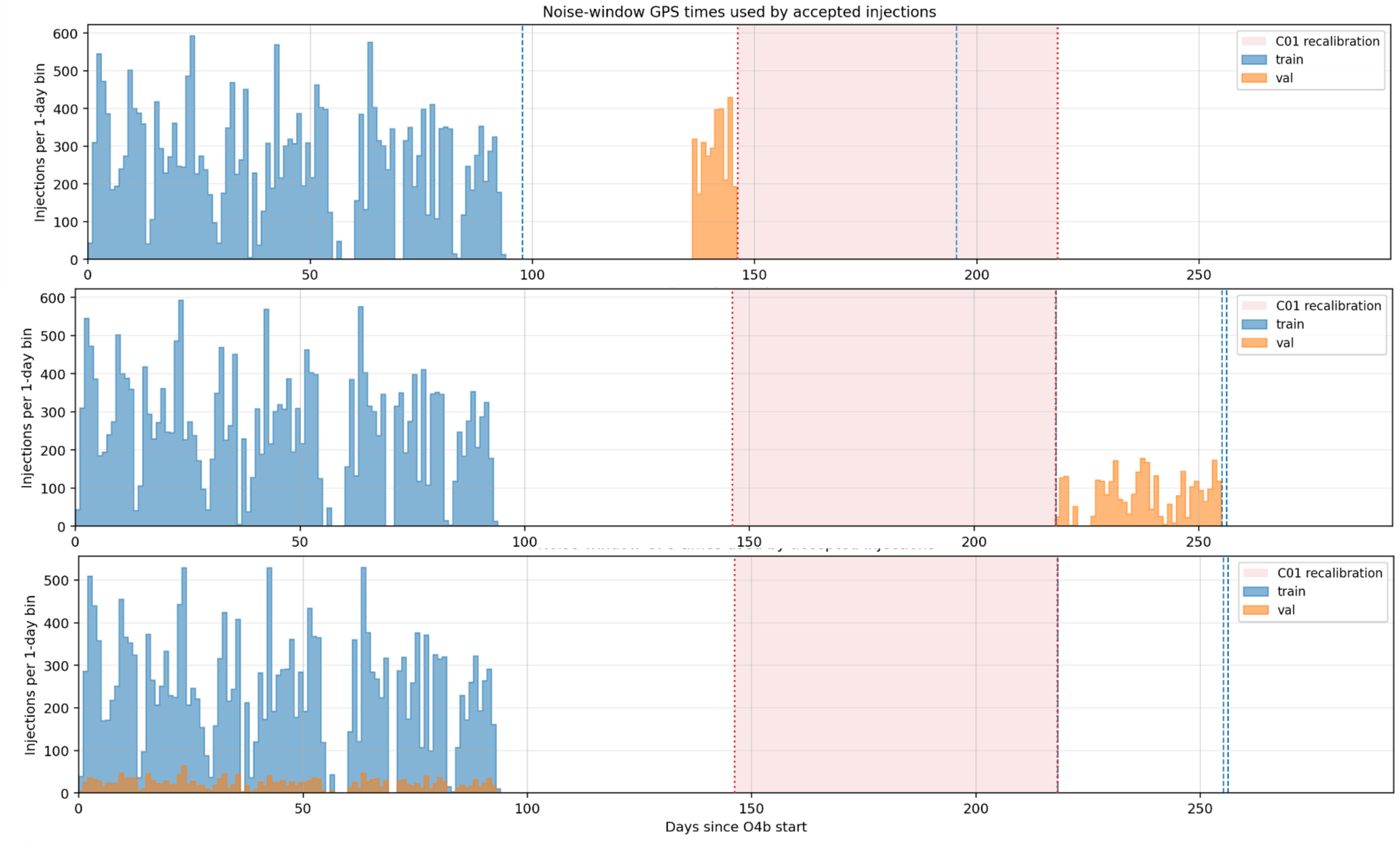


Also tried different regions for validation noise

Pre-C01

Post-C01

In-Distribution

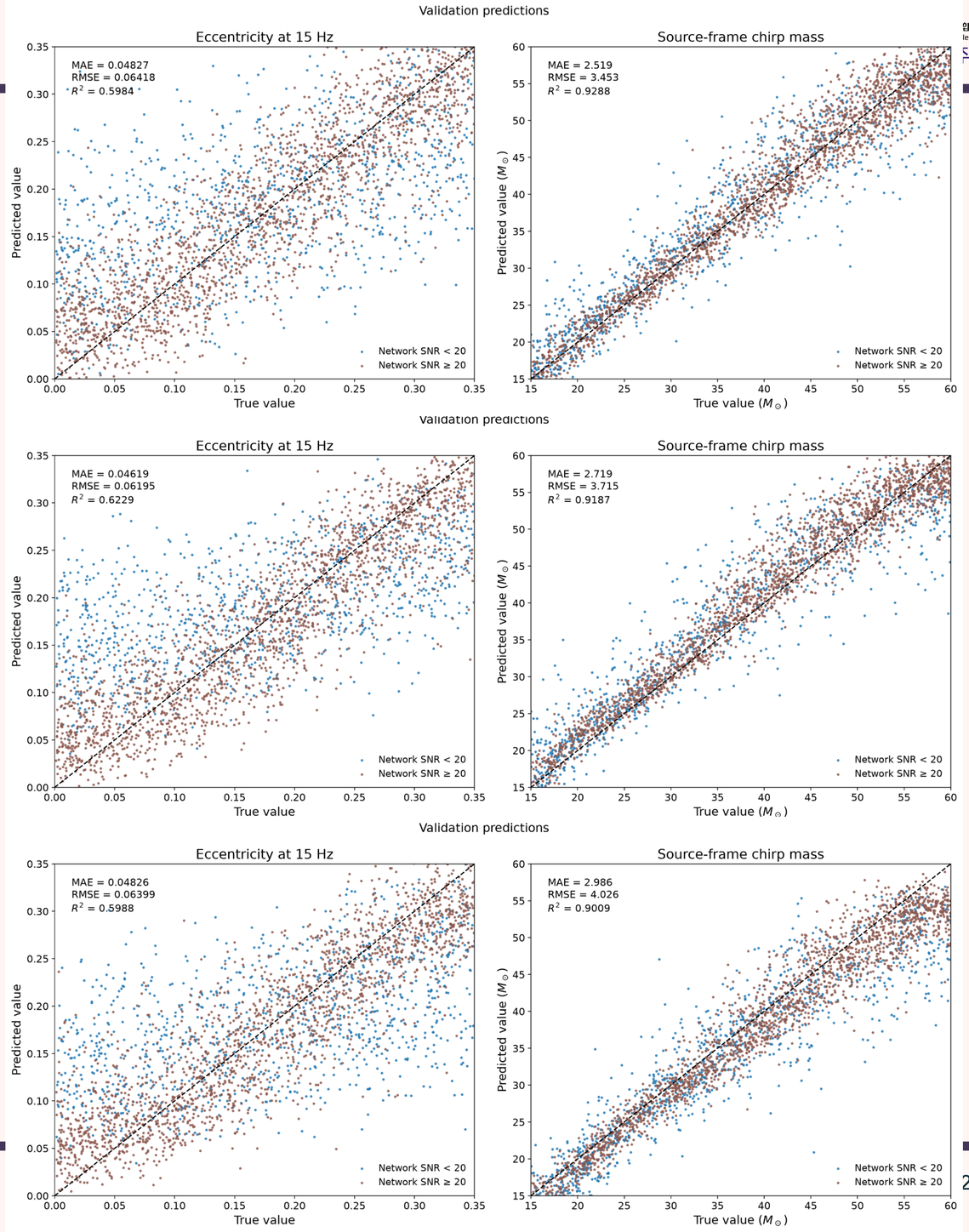


C00 versus C01

Pre-C00

Post-C01

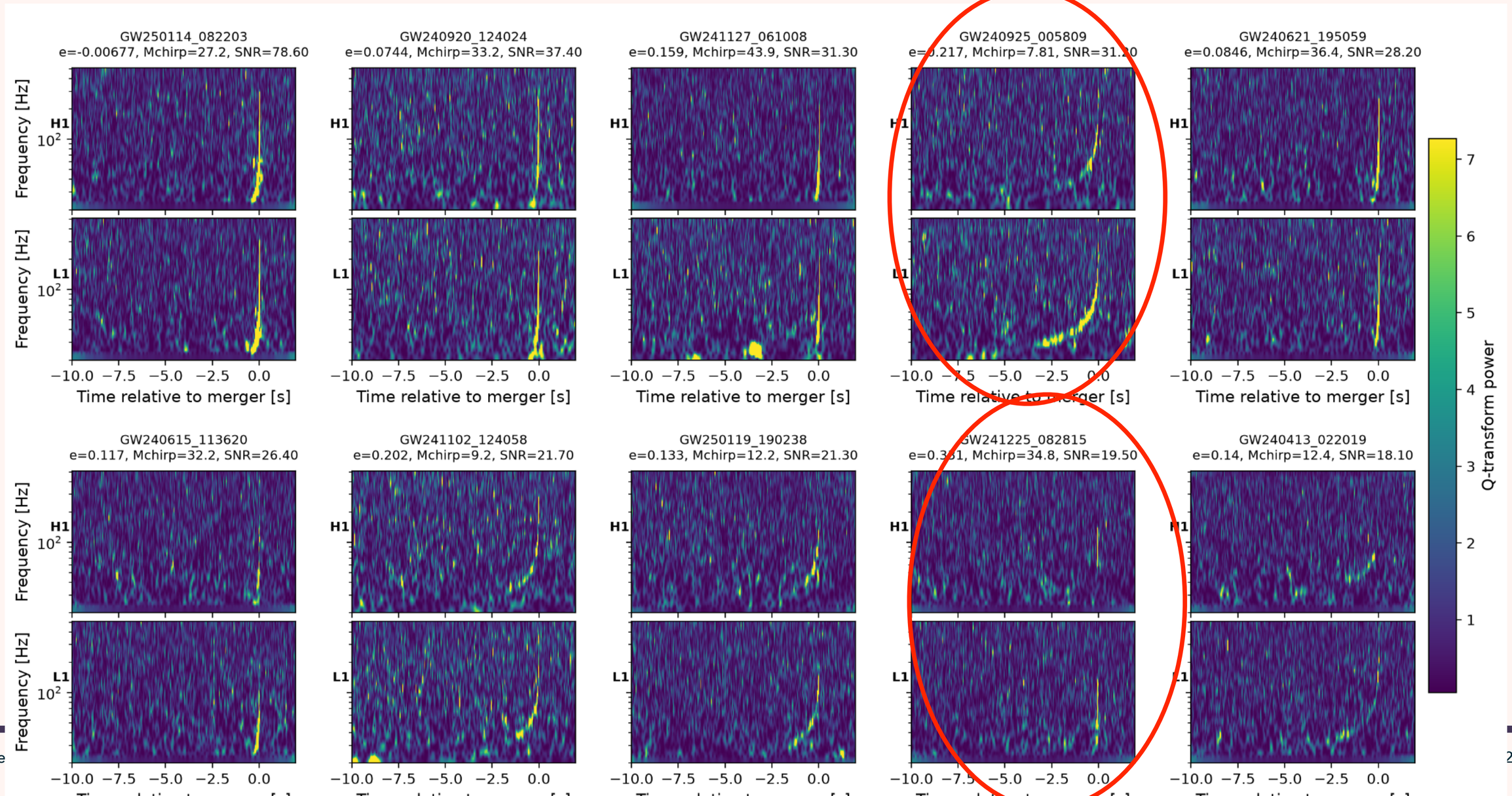
In-Distribution



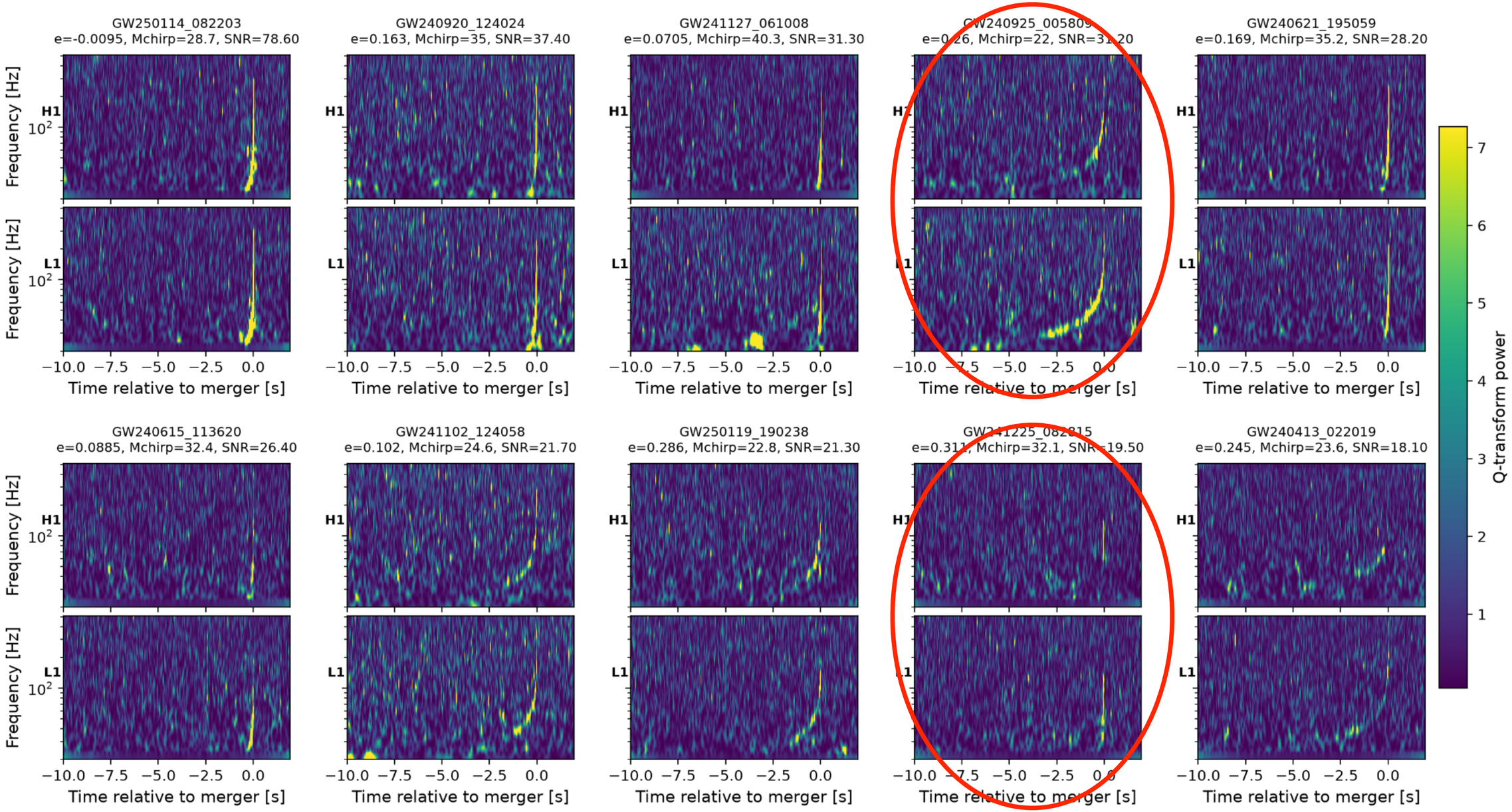
Real GW events

- Out of 161 detected O4b BBH events, 135 are used for prediction (available in both channels H1 L1)
- Prepared similarly to training samples (16 sec region whitened by 8 sec PSD, cropped to 12 sec)
- Include events from C01 region (which was excluded from training/ validation)

Highest SNR Events (MambaVisionT)



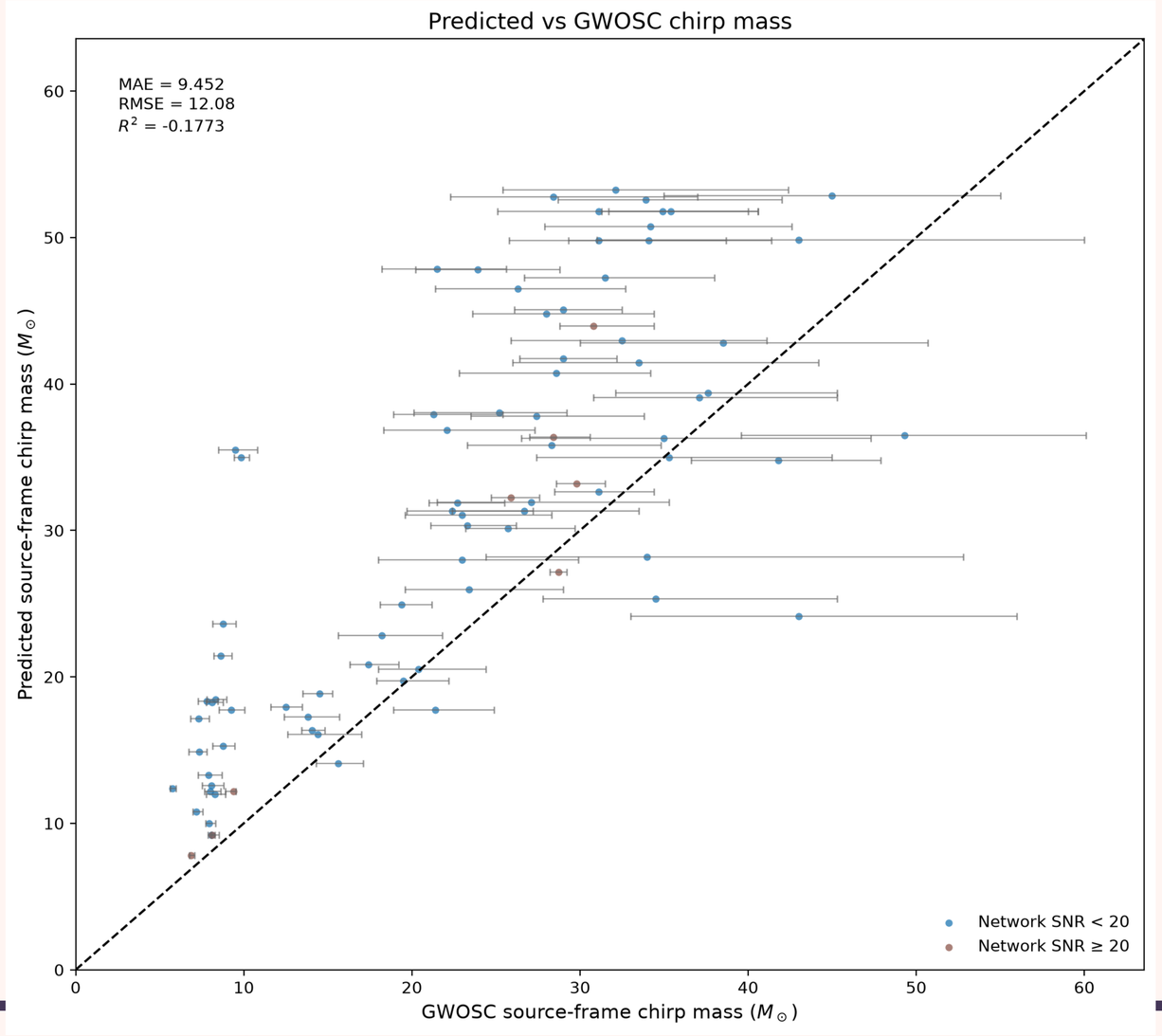
Highest SNR Events (EANet)



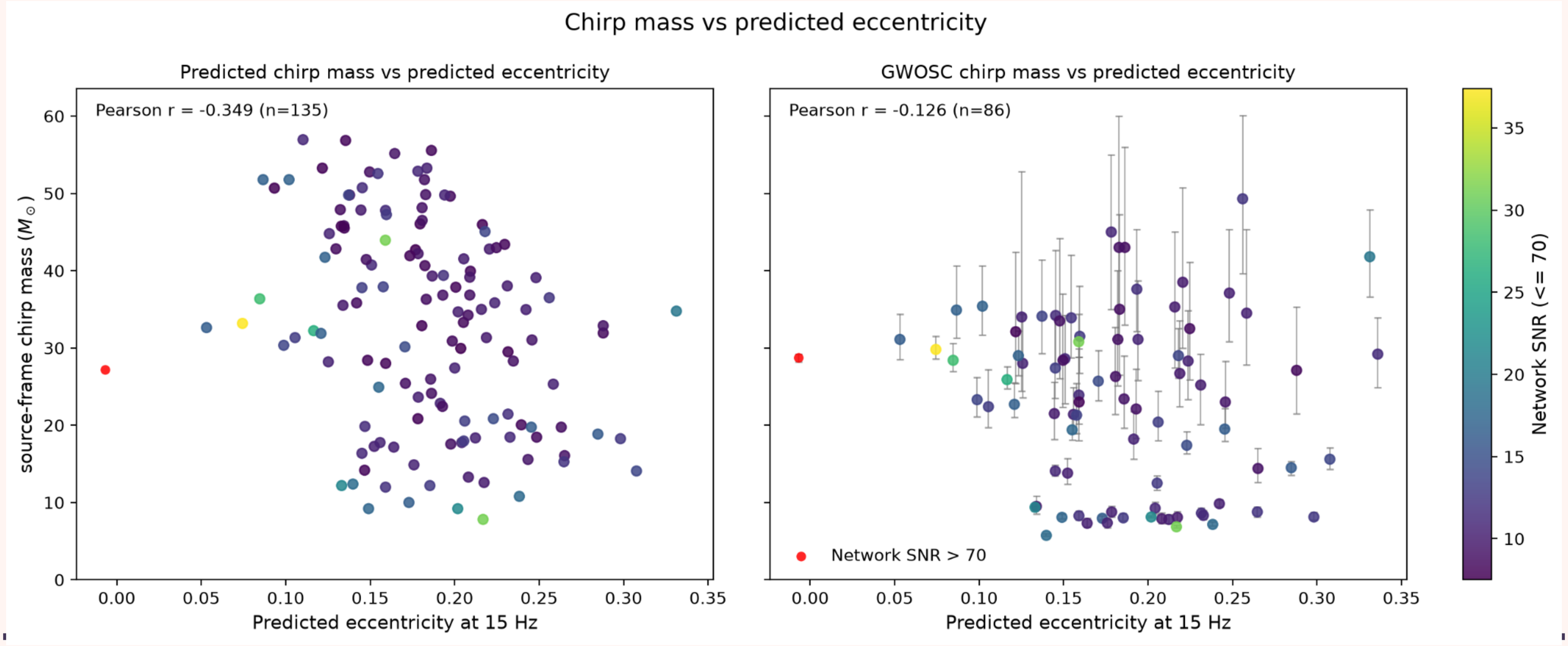
Chirp Mass Estimaiton Bias

Scatter (many low SNR events)

Overpredicts chirp mass

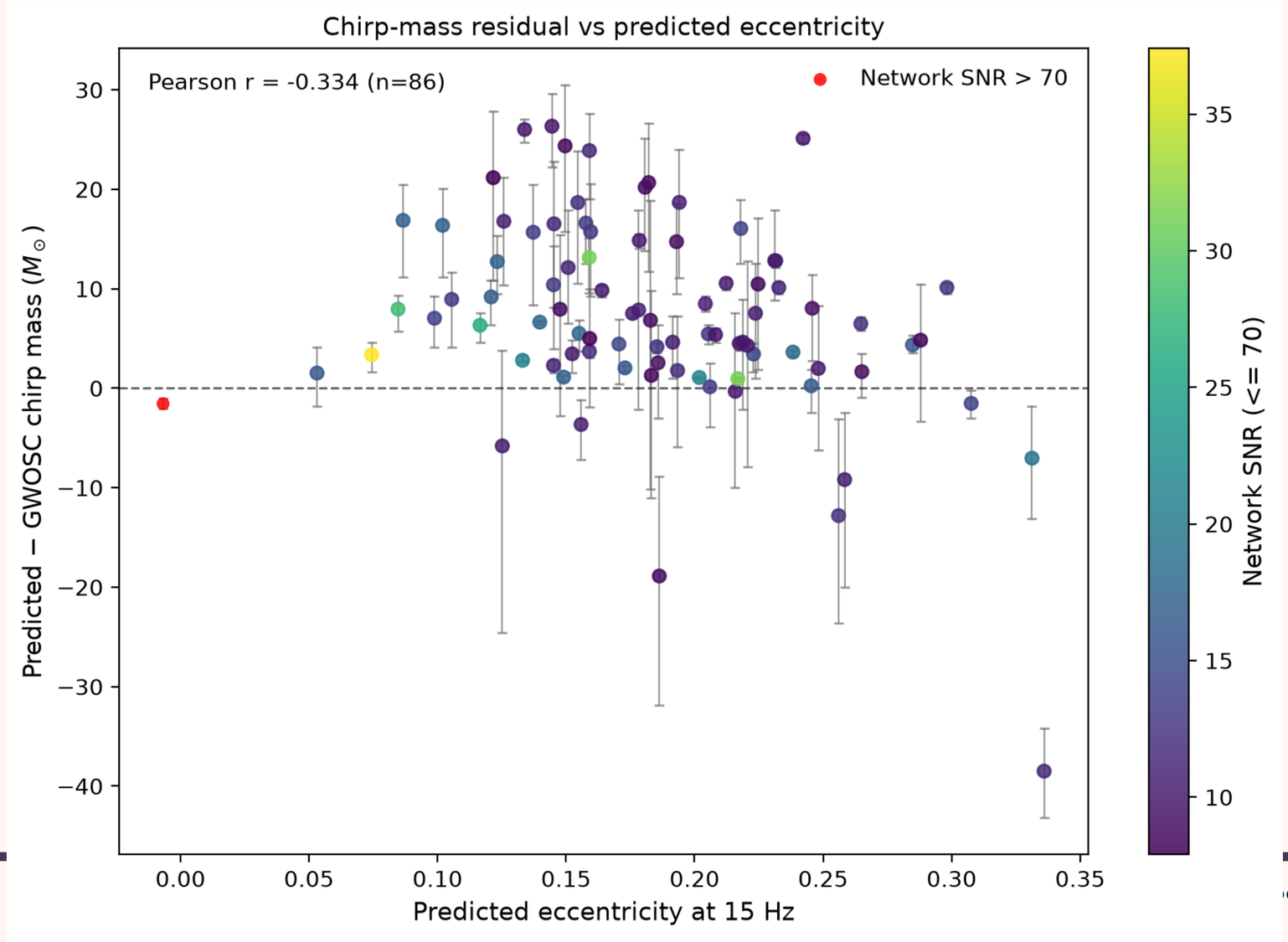


Eccentricity - Chirp Mass Correlation



Eccentricity - Chirp Mass Correlation

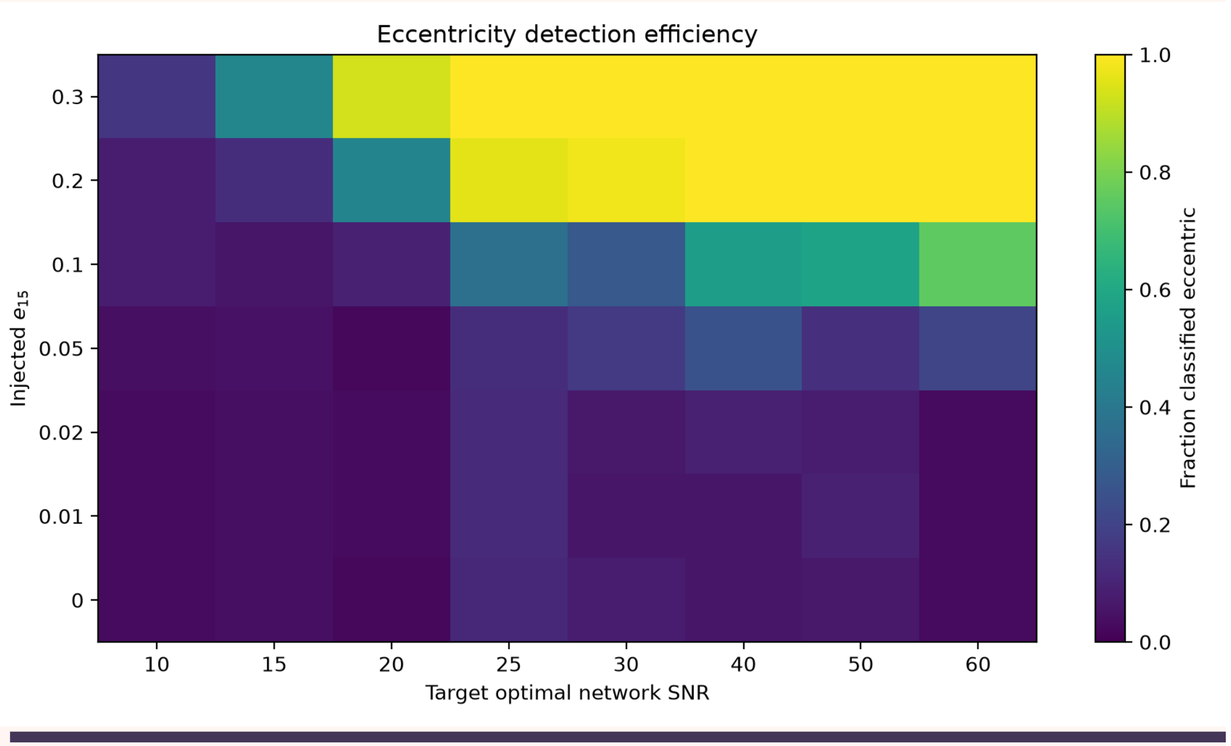
Negative correlation (more overprediction of chirp mass at lower predicted eccentricity)

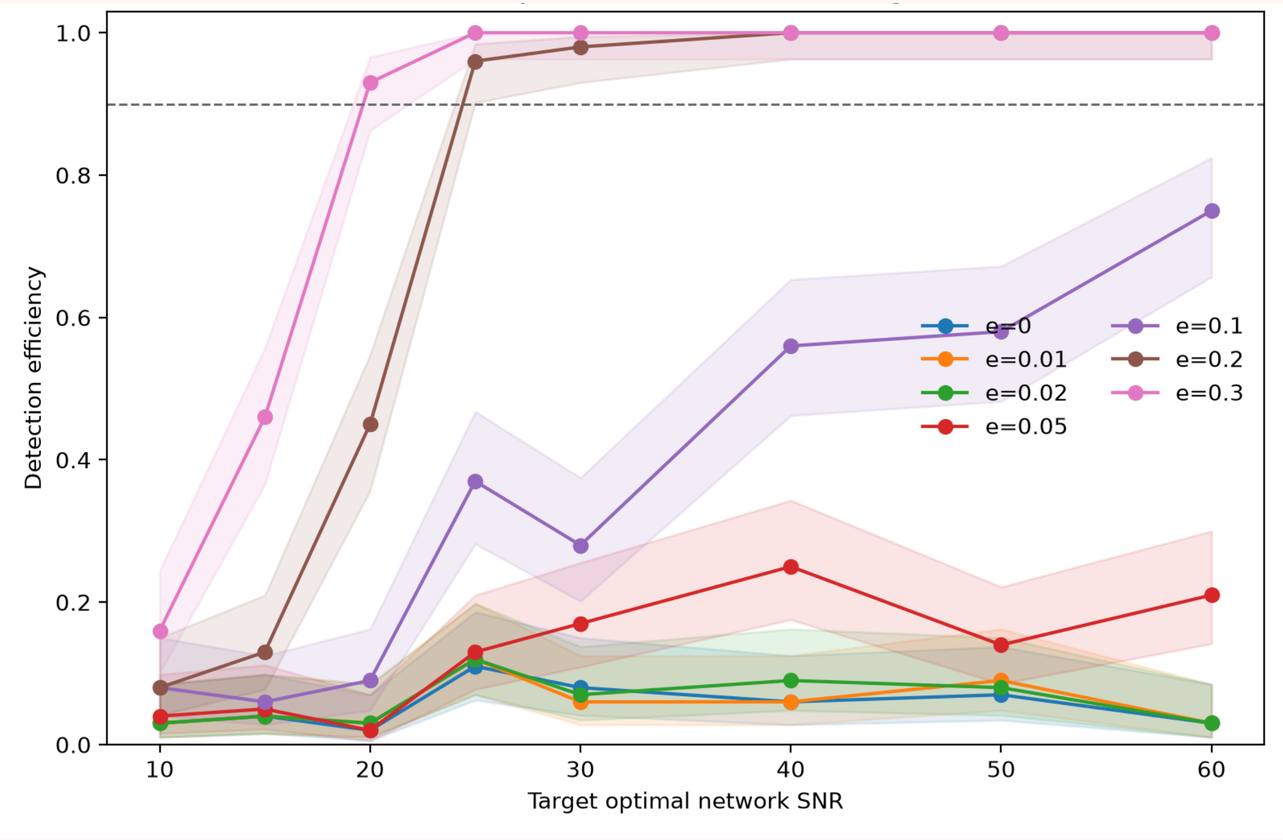


Eccentricity Detection Experiment

- Goal: Determine SNR/eccentricity threshold to distinguish between circular and eccentric binary
- I predict eccentricity for simulated waveforms + real noise for eccentricities e={0, 0.01, 0.02, 0.05, 0.1, 0.2, 0.3} and SNR = {10, 15, 20, 30, 40, 50, 60}
- Determine eccentricity threshold
  - find eccentricity e_cut at which 95% of e=0 fall
  - e_cut ≈ 0.2, which is quite high (model regression towards mean)
- Measure efficiency as fraction of correctly classified eccentricities
  - Correctly classified if predicted and true eccentricity both lie above or both below e_cut

- High efficiency for SNR > 20 and e= 0.2, e = 0.3, efficiency improves significantly with SNR
- Low eccentricities (e < 0.1) are not well classified even for high SNR





Summary of O4b Studies

- Model systematically overpredicts chirp mass
- Negative correlation between chirp mass and eccentricity (high chirp mass prediction → low eccentricity prediction)
- Eccentricity detection improves with SNR for $e \geq 0.2$, and is consistent for SNR > 20
- Eccentricity is not distinguished reliably for low eccentricity ($e < 0.1$), and does not improve significantly with SNR

Summary

- Center for the Gravitational wave Universe (GWUniverse in short) is the first research grant for a group dedicated for GW related research in Korea
- We carried out many research projects:
  - GW waveforms including eccentricity
  - Forecast studies for cosmology with dark sirens
  - DESI implications on dark energy
  - Multi-messenger studies
  - GRB modeling
- We will try to keep its activities, although the main funding has expired.