GRAVITATIONAL WAVE RESEARCH AT THE CENTER FOR THE GRAVITATIONAL-WAVE UNIVERSE

고에너지 물리학 워크숍

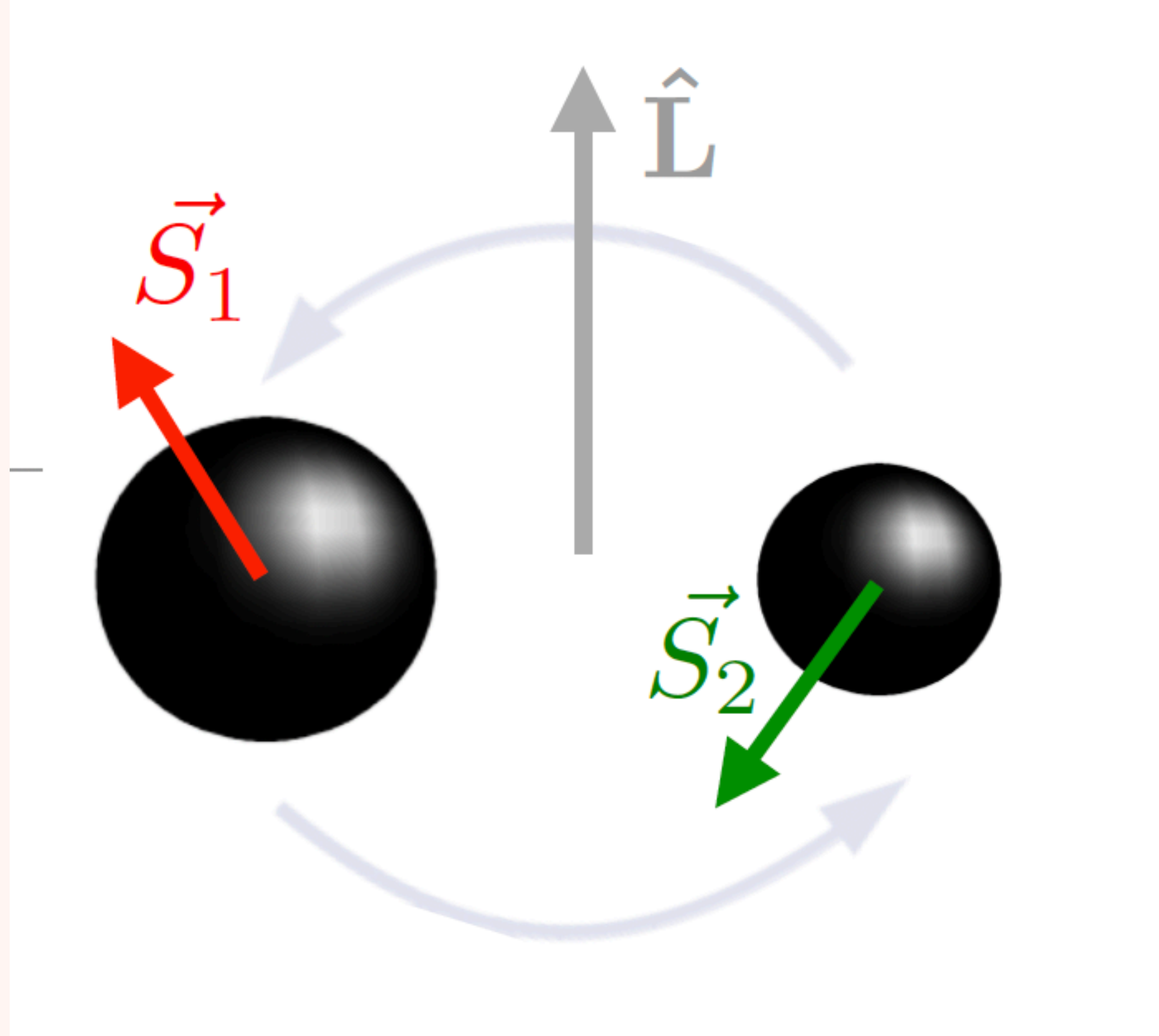
2025년 11월 19일

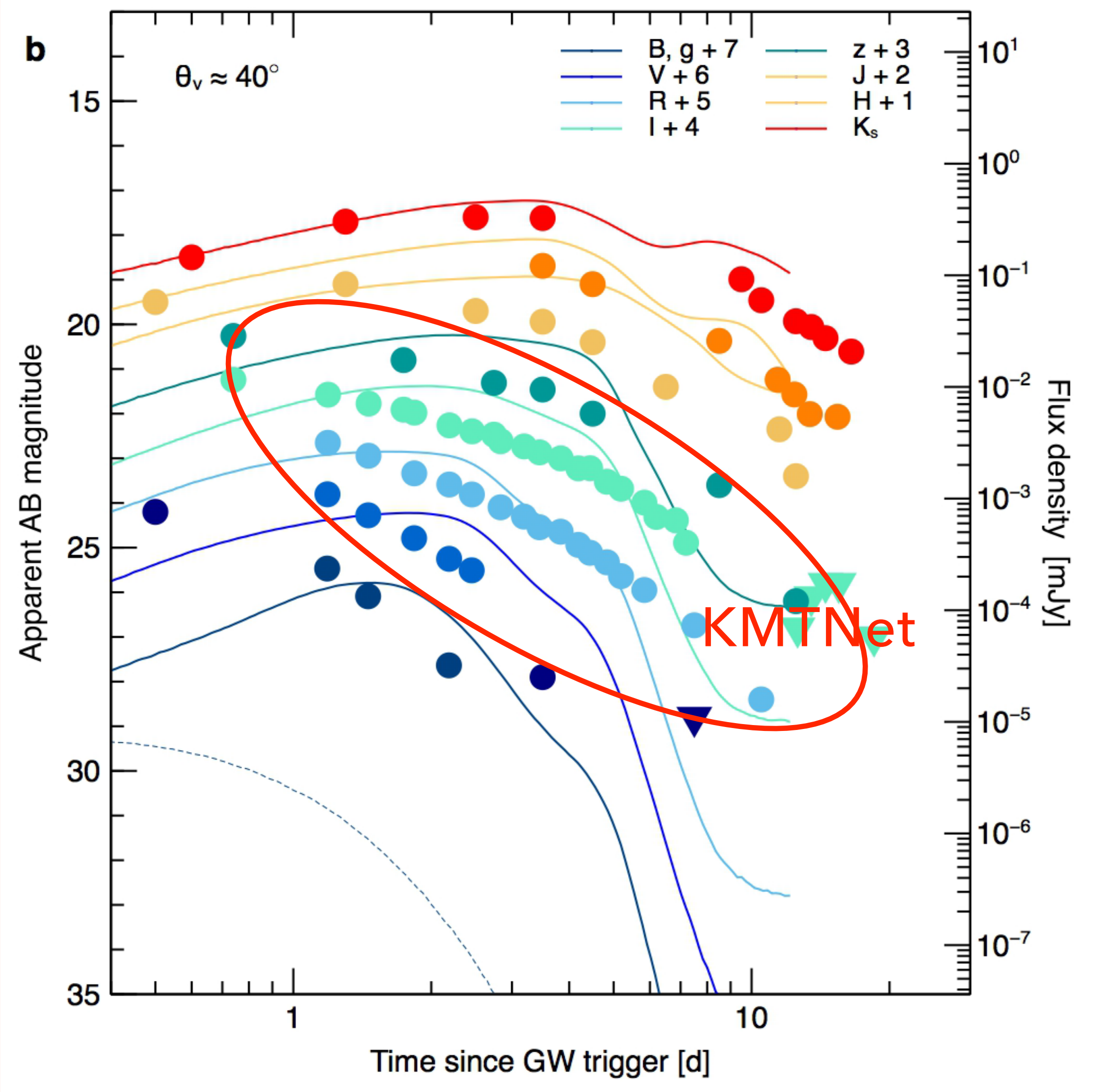
Hyung Mok Lee

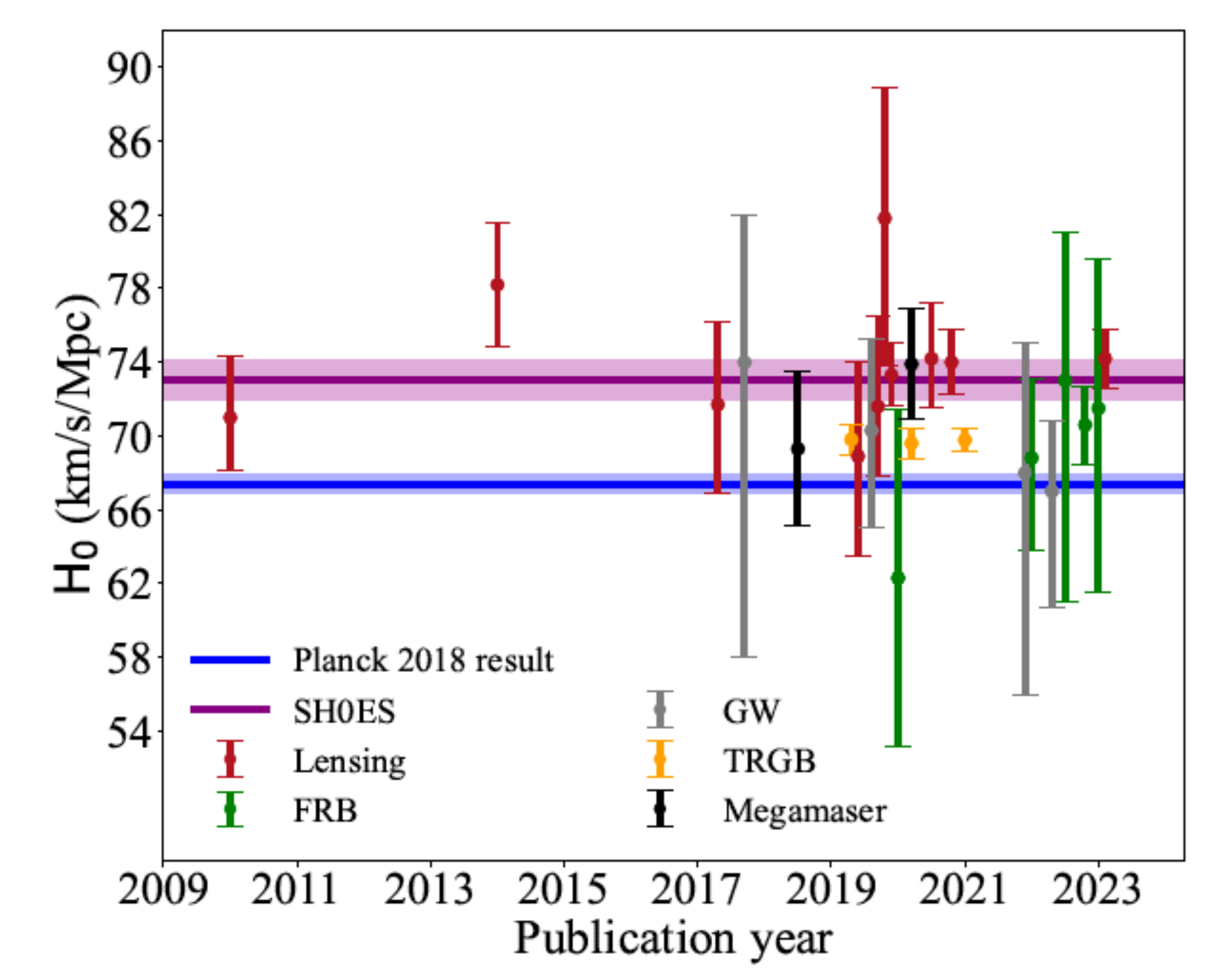
Keywords of GWUniverse

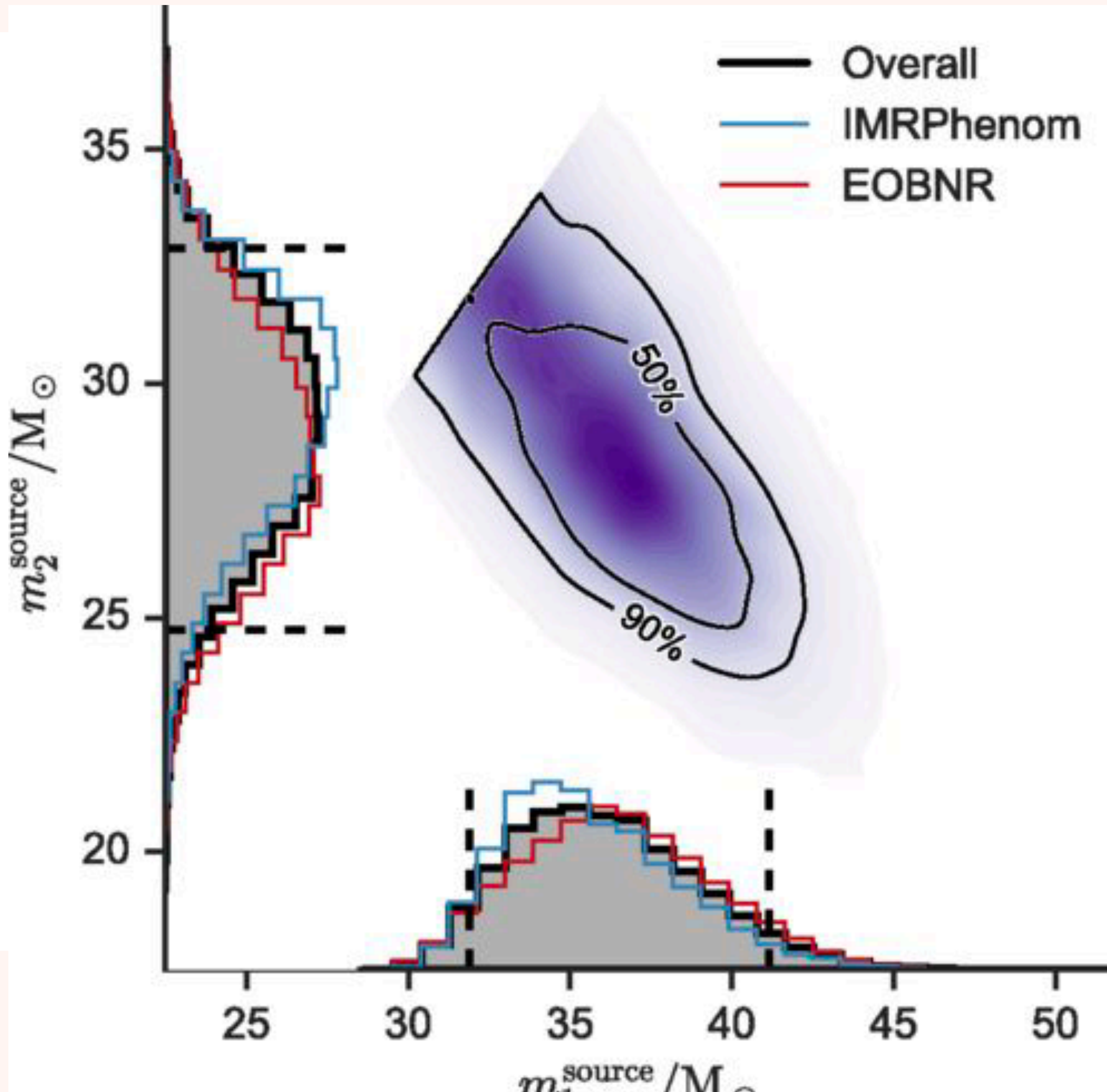
- **Gravitational Waves**
  - Sources
  - Waveforms
  - Parameter Estimation
  - Future Detectors
- **Cosmology**
  - Hubble Tension
    - Distance Measurements
    - Alternative Cosmology
  - Dark Energy
- **Multi-Messenger Astronomy**
  - 7-dimensional Telescope (7DT)
  - EM Counterpart
  - Kilonovae/Gamma-Ray Burst Modeling

Not covered in this talk









Members

- **Core Members**: **Hyung Mok Lee** (SNU, PI), **Myungshin Im** (SNU, Co-PI), **Arman Shafieloo** (KASI), **Z. Lucas Uhm** (KASI), **Chunglee Kim** (Ewha), **Jae Hun Jeong** (Postech)
- **Researchers**: **Seo-won Chang**, **Elahe Khalouei. Seong-Kook Lee, Donggeun Tak, Nicolas Chartier, Ji Hoon Kim**
- **Students**: **최현호, 최윤의, 현동환, 이원형, 배장호, 이동진, 이성헌, 백인수, 박보미, 정만근, 김창완, Clea Millard** (Sejong Univ.)
- **Associate Members**: **Ho Seong Hwang** (SNU), **Ryan Keeley** (UC Merced), **Hyung Won Lee** (Inje Univ.), **Kyungmin Kim** (KASI), **Benjamin L'Huiller** (Sejong University.), **Bing Zhang** (University of Nevada), **A. Gopakumar** (TIFR), **Pau Amaro Seoane** (University of Valencia)
- **Alumni**: **Arif Shaikh** (Vidyasagar University, India), **Tao Yang** (Wuhan University), **김정초** (국가수리과학연구소), **박찬** (Henan Academy of Sciences), **조기혁** (기업), **최한길** (IBS)

The Gravitational Wave Spectrum

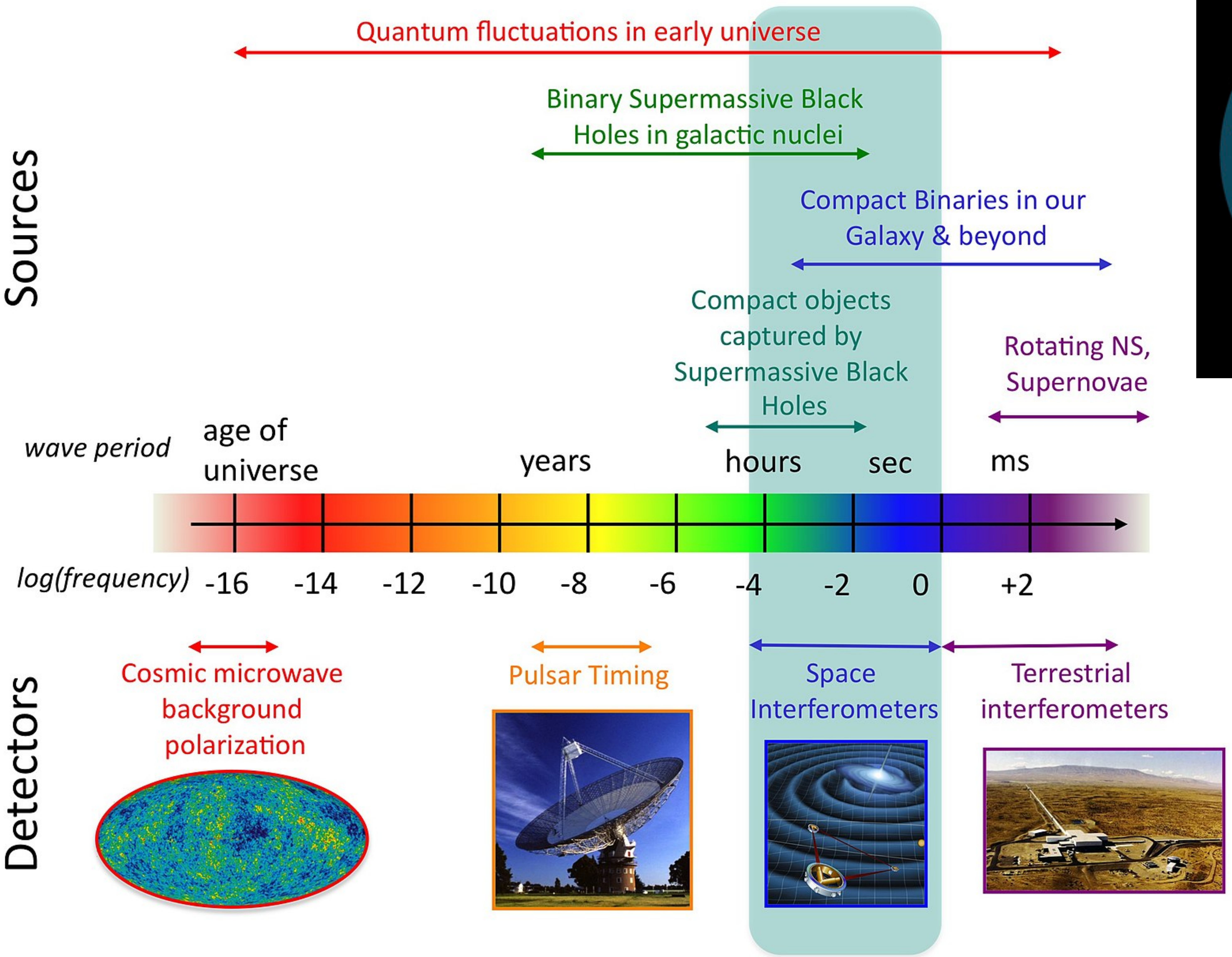
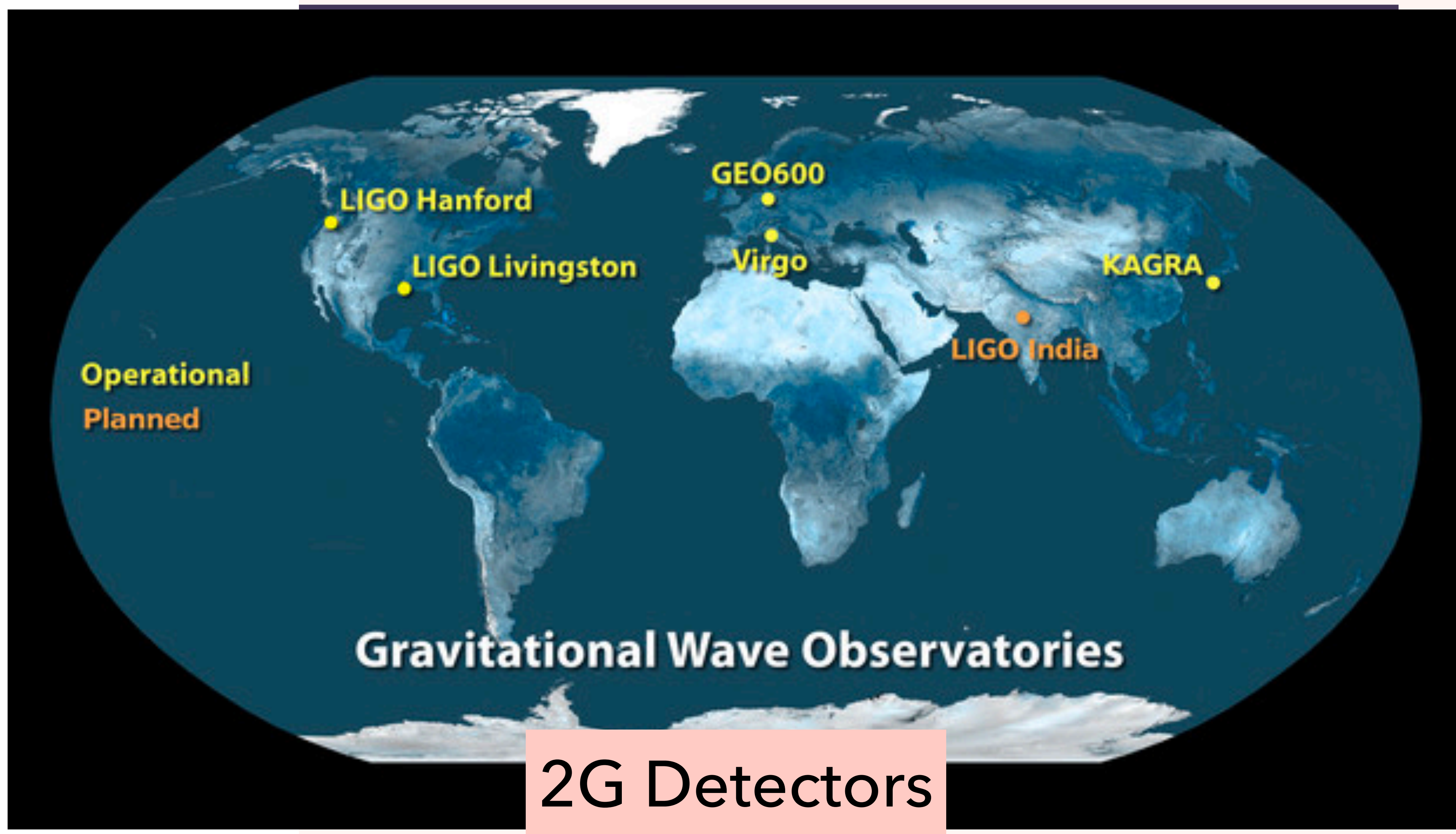
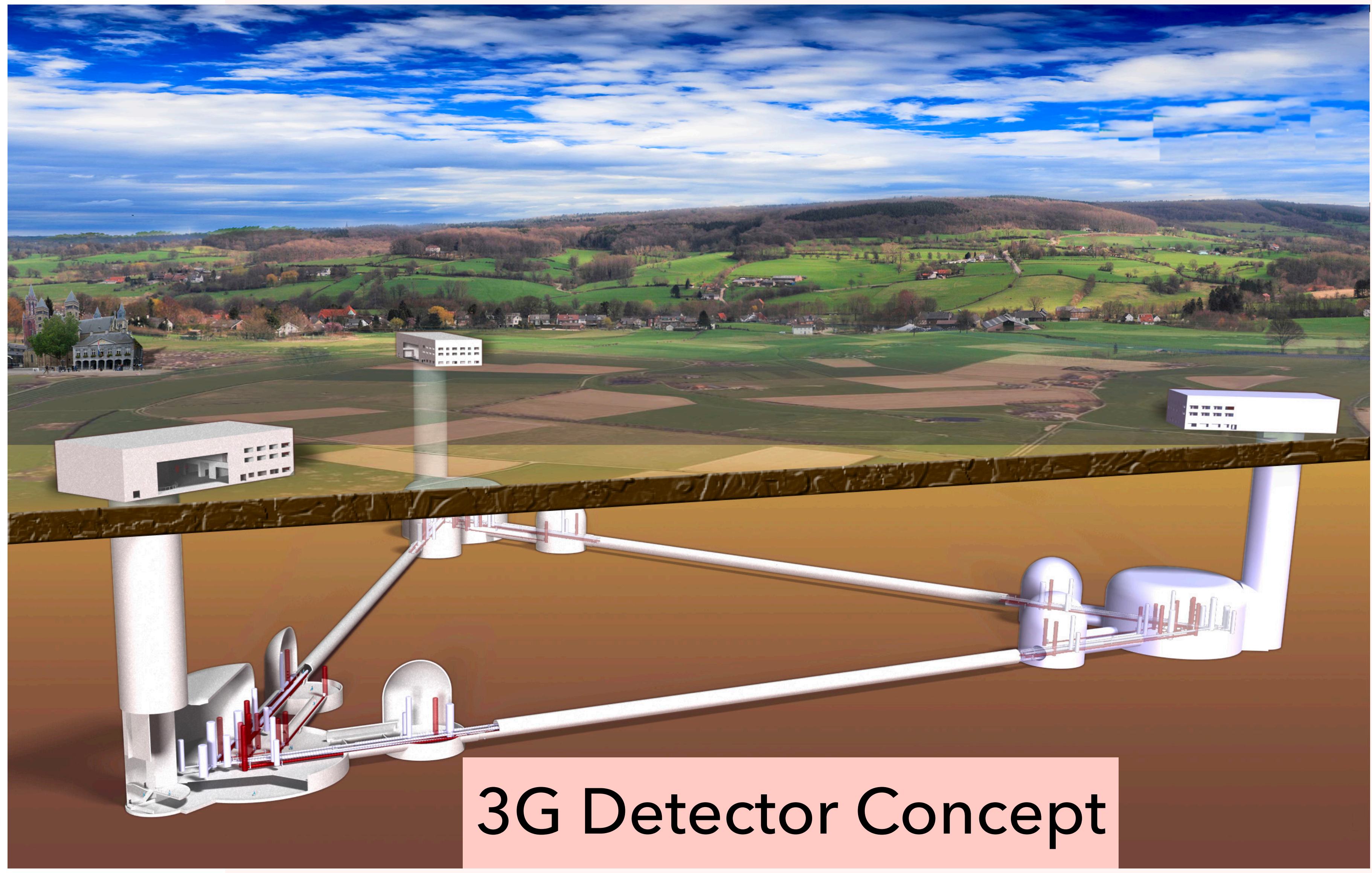


Image Credit: NASA/GSFC



2G Detectors



3G Detector Concept

The Gravitational Wave Spectrum

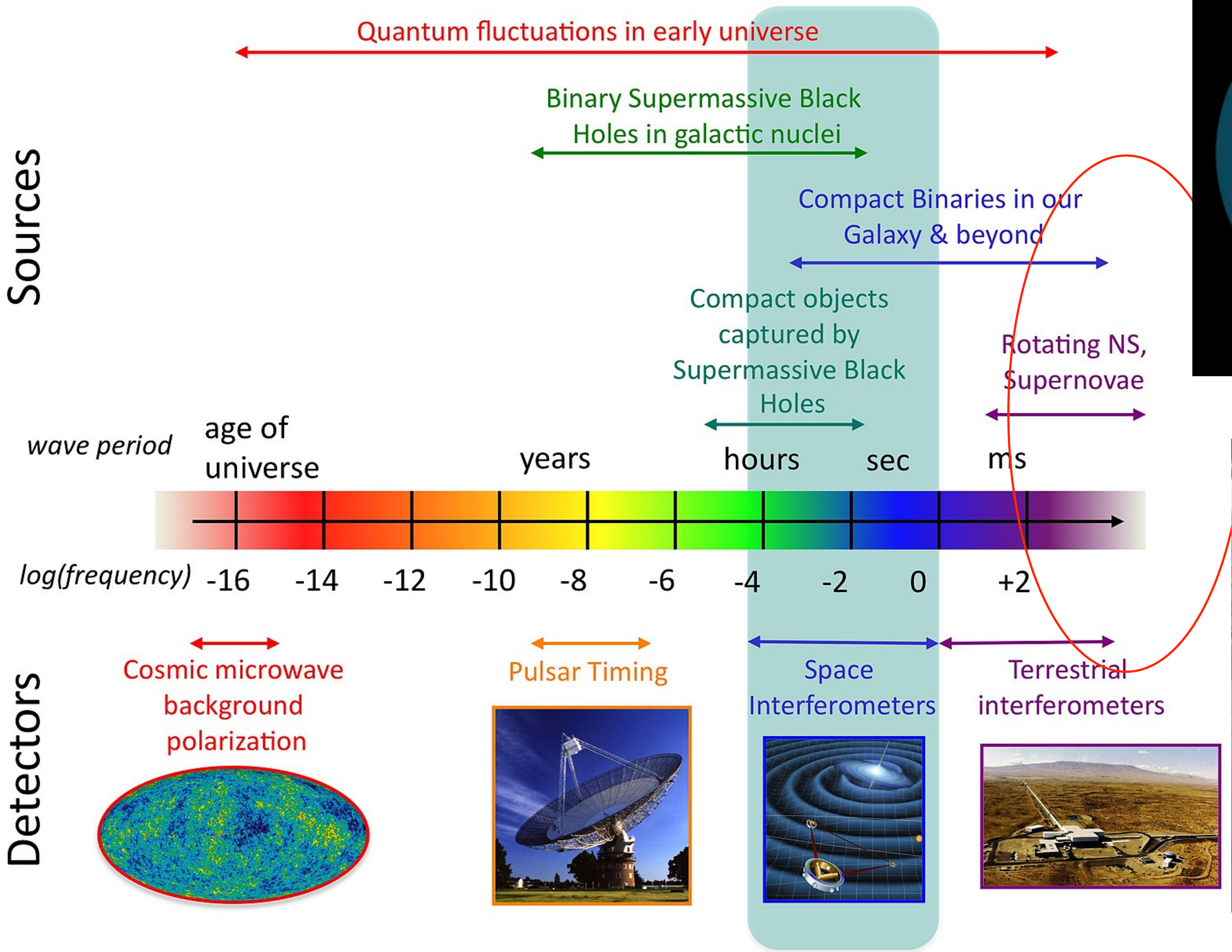
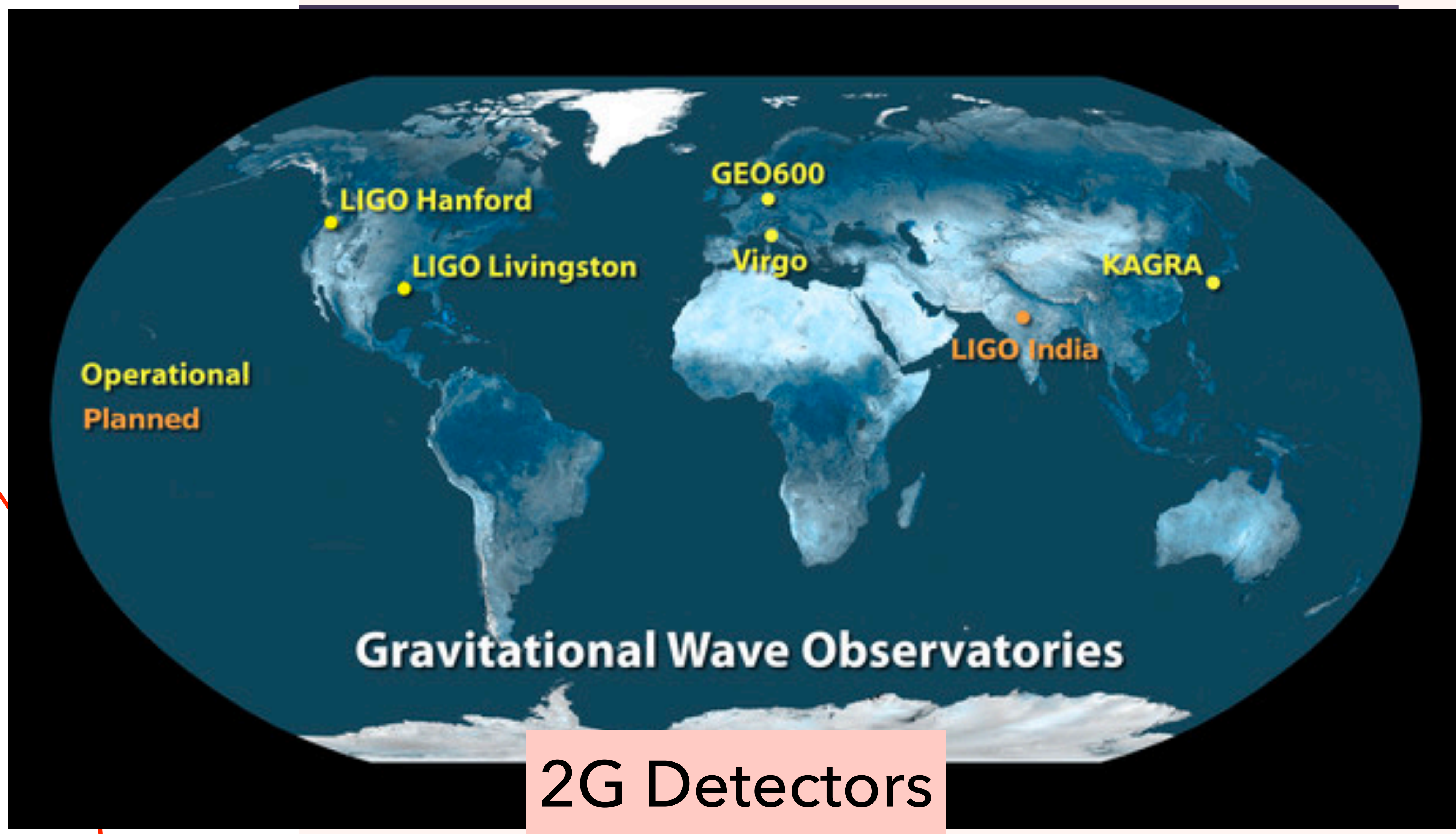
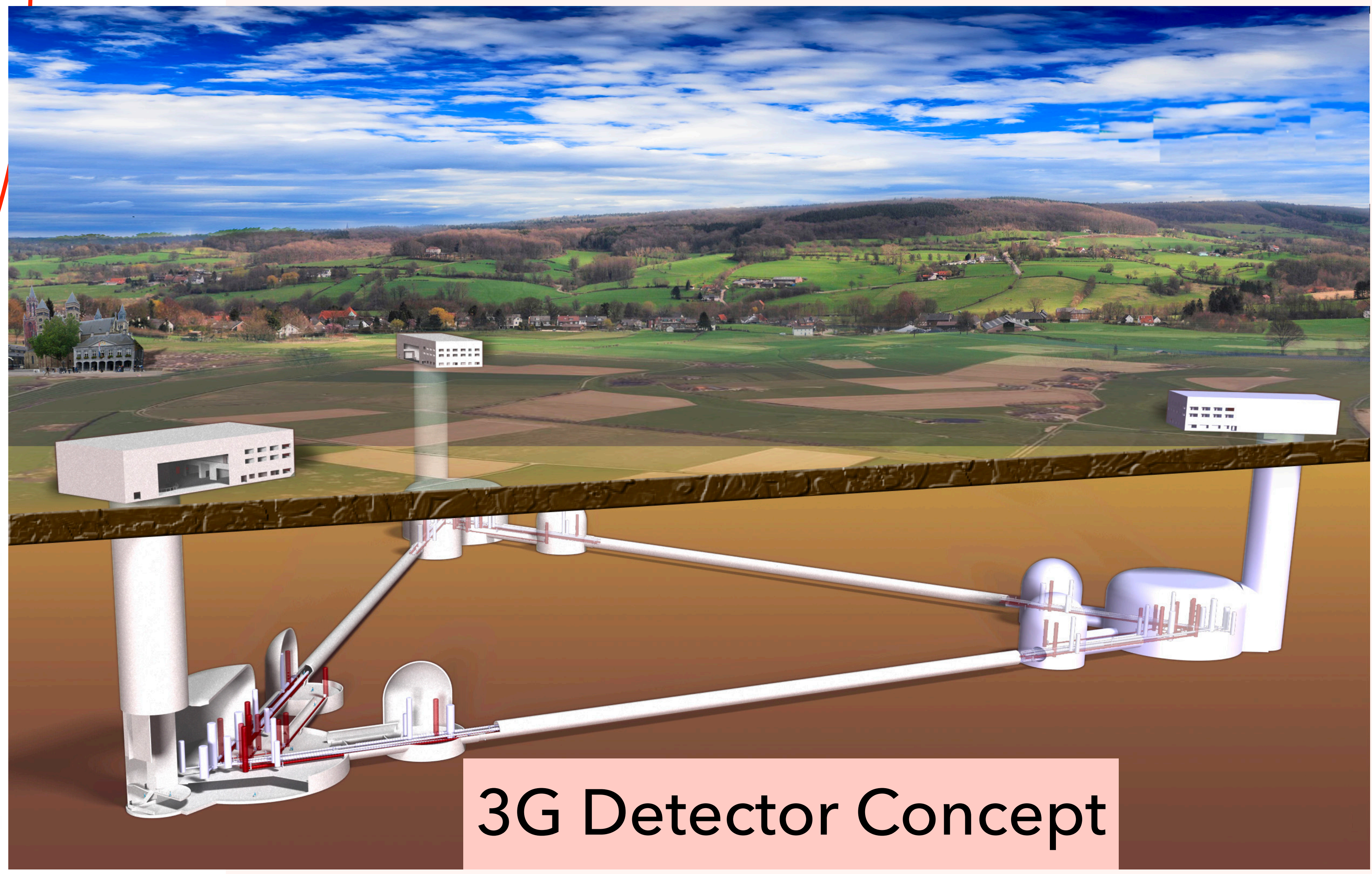


Image Credit: NASA/GSFC





The Gravitational Wave Spectrum

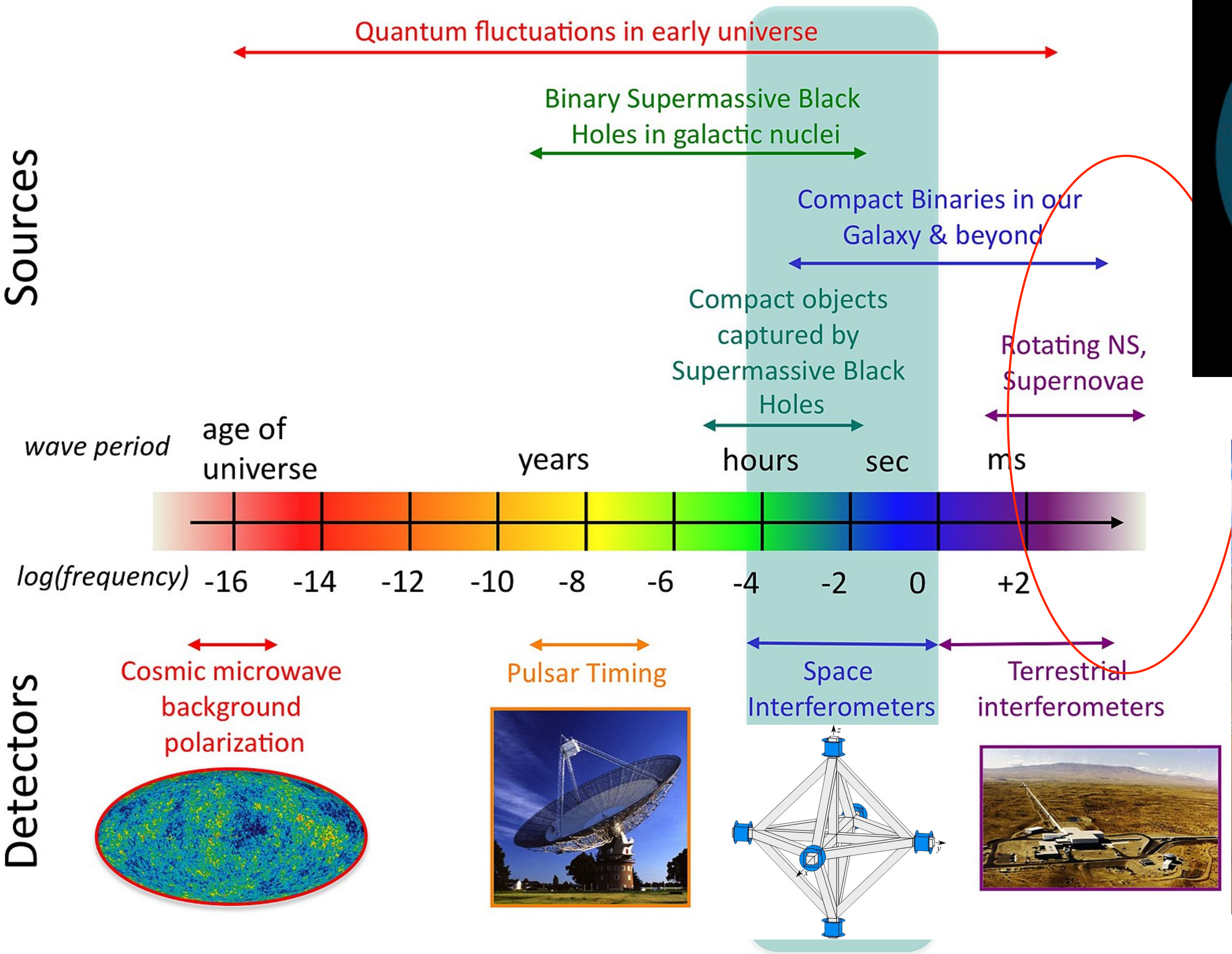
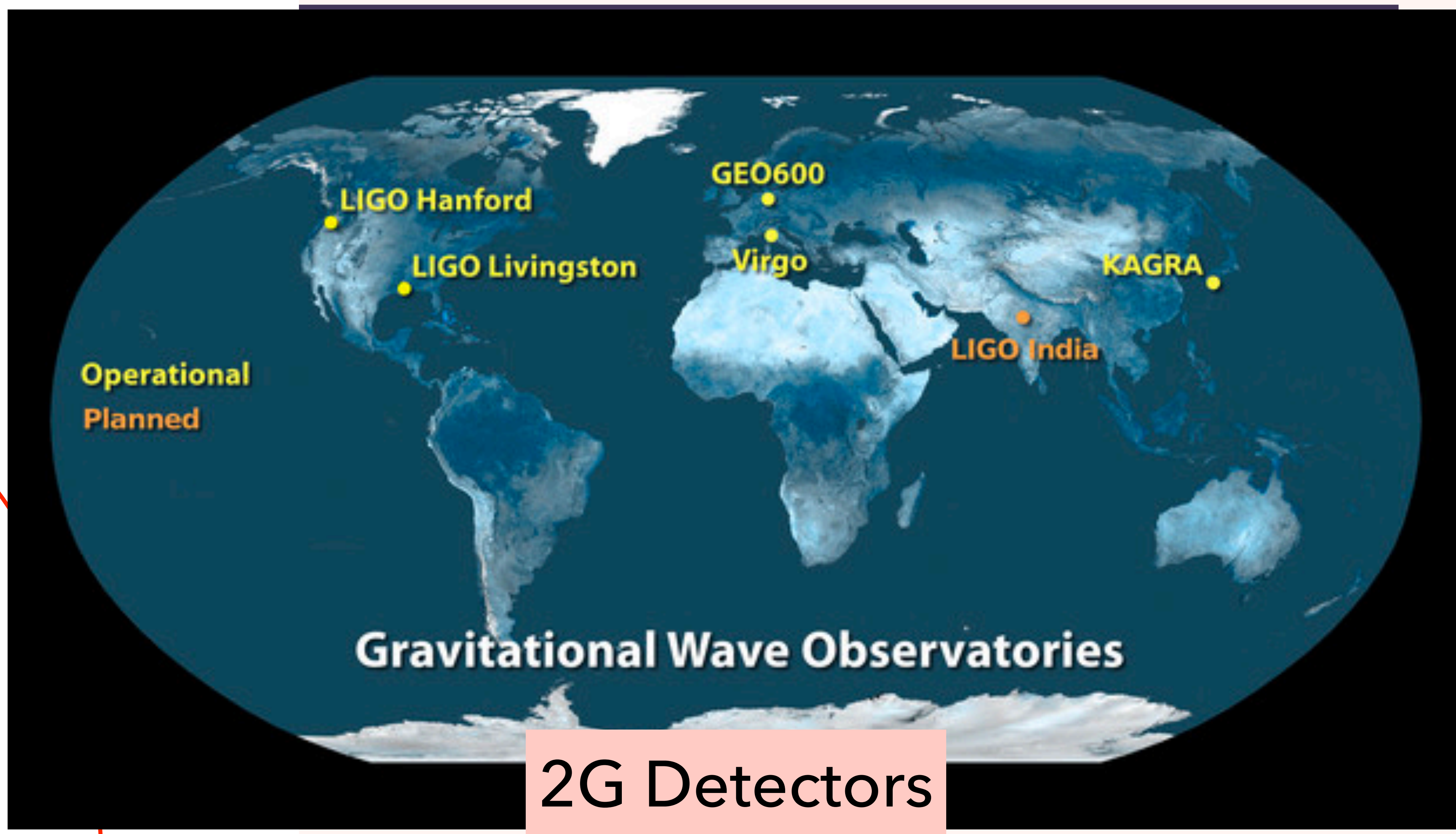
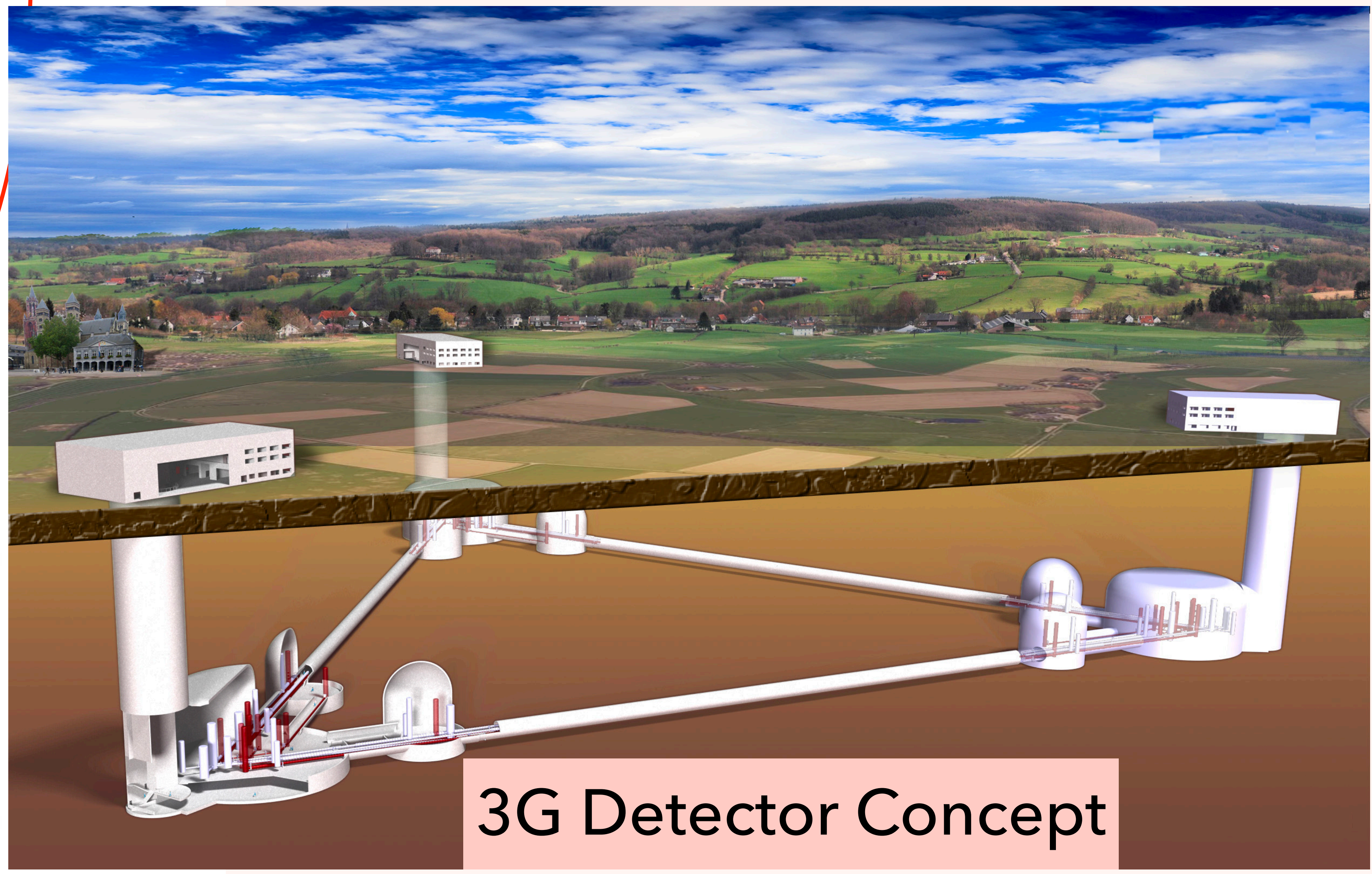


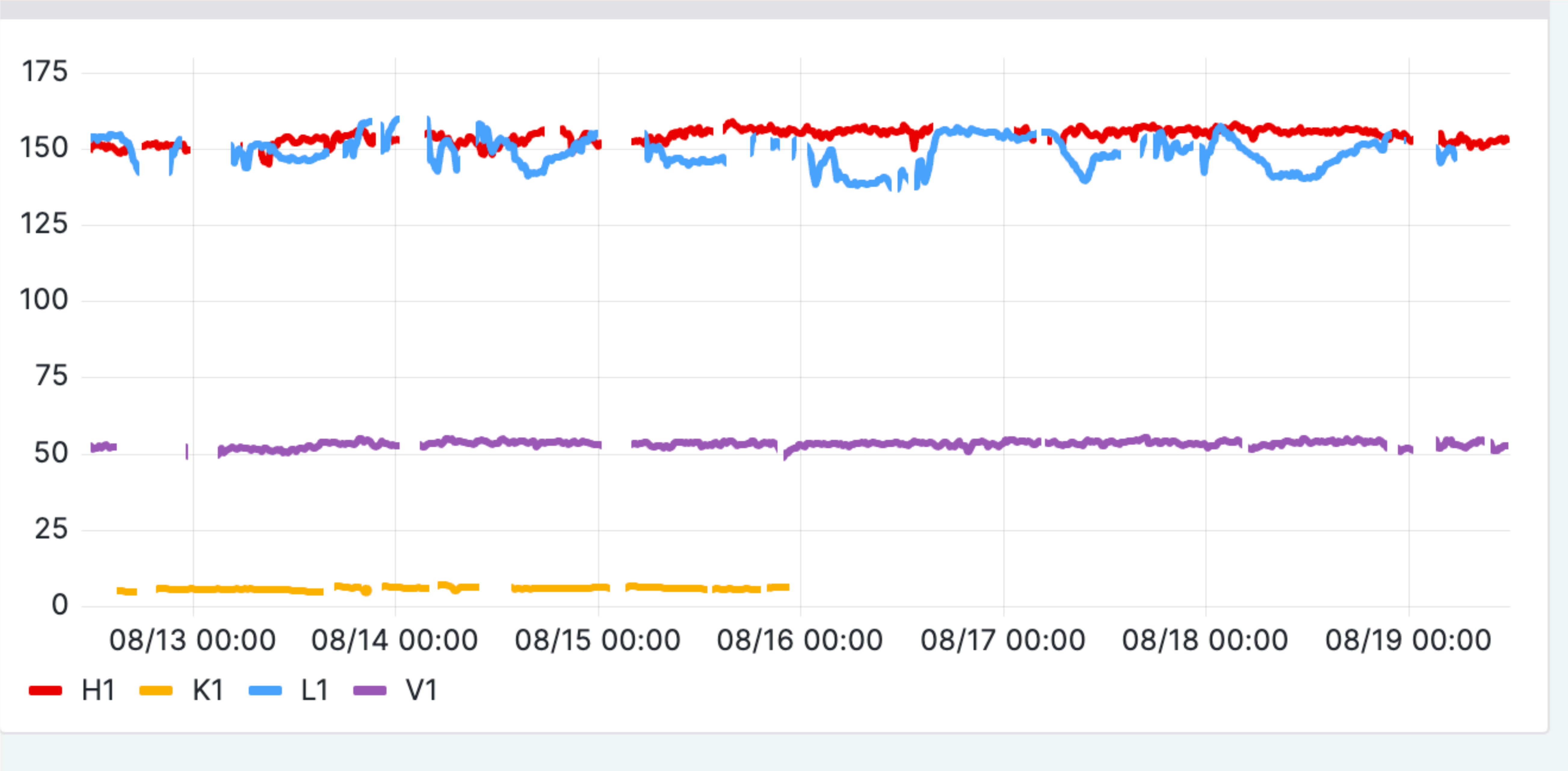
Image Credit: NASA/GSFC

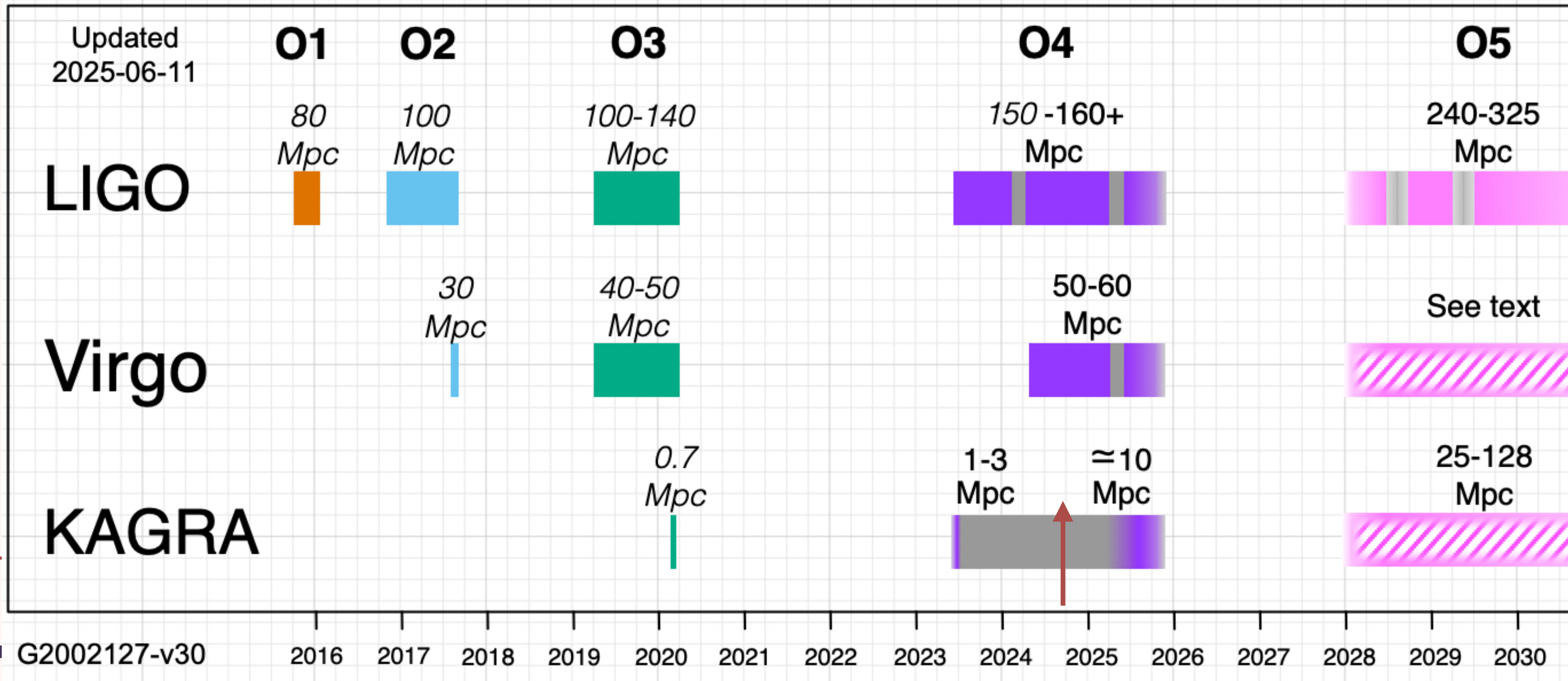




Observing Runs of LIGO/Virgo/KAGRA

- O1 - O3: 2015 ~ 2020, 90 detections
- O4: 2023 ~ 2025
  - O4a (2 detectors): May 24, 2023 – Jan 16, 2024
  - O4b (>= 3 detectors) : May 24 2024 - April 1, 2025
  - O4c (3 Detectors): June 11, 2025 - November 18, 2025
  - O4d in second half of 2026
- Schedule for O5 is uncertain

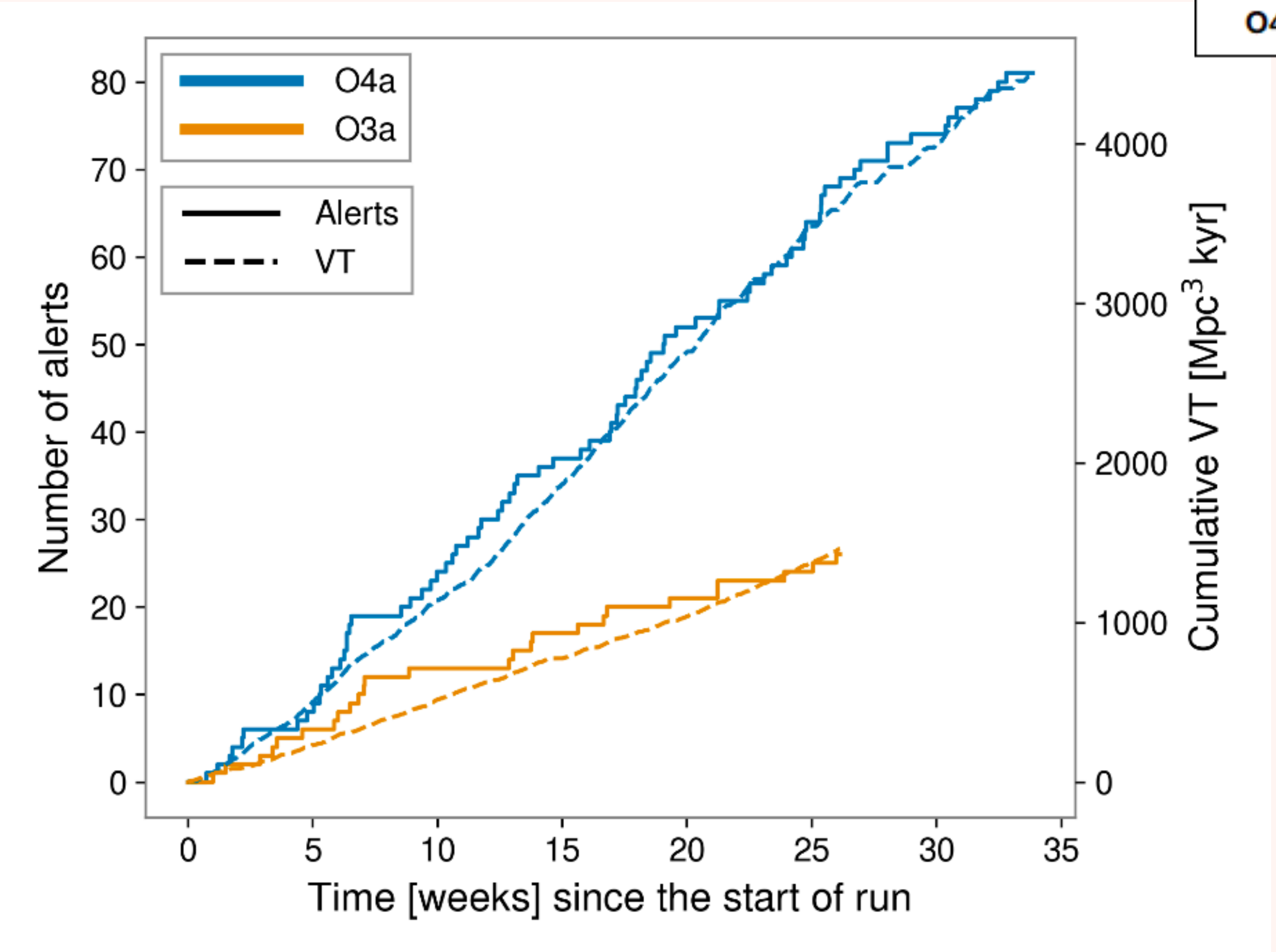




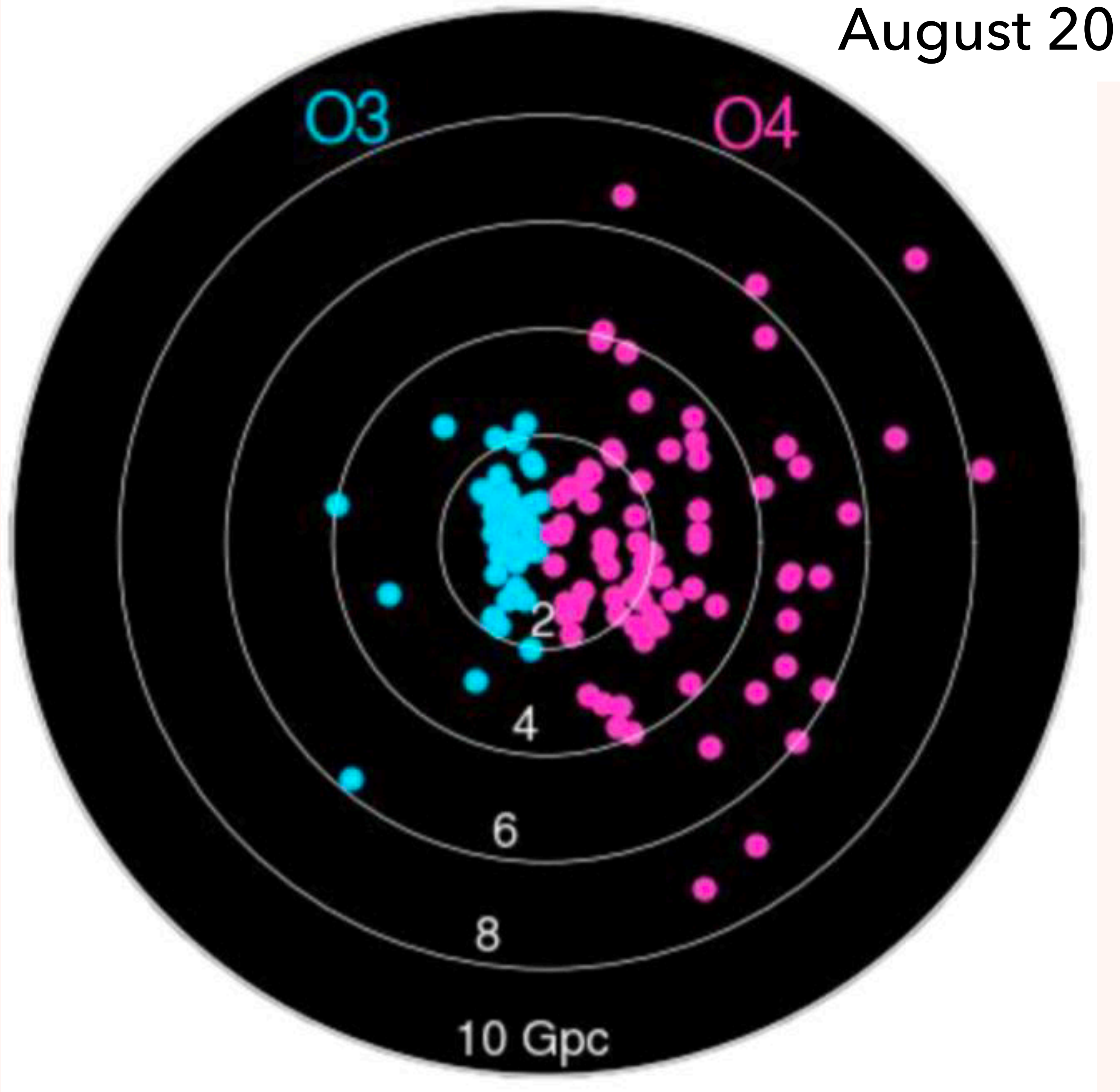
O3 versus O4

- Better sensitivity → More detections, further distances
- Lower retraction

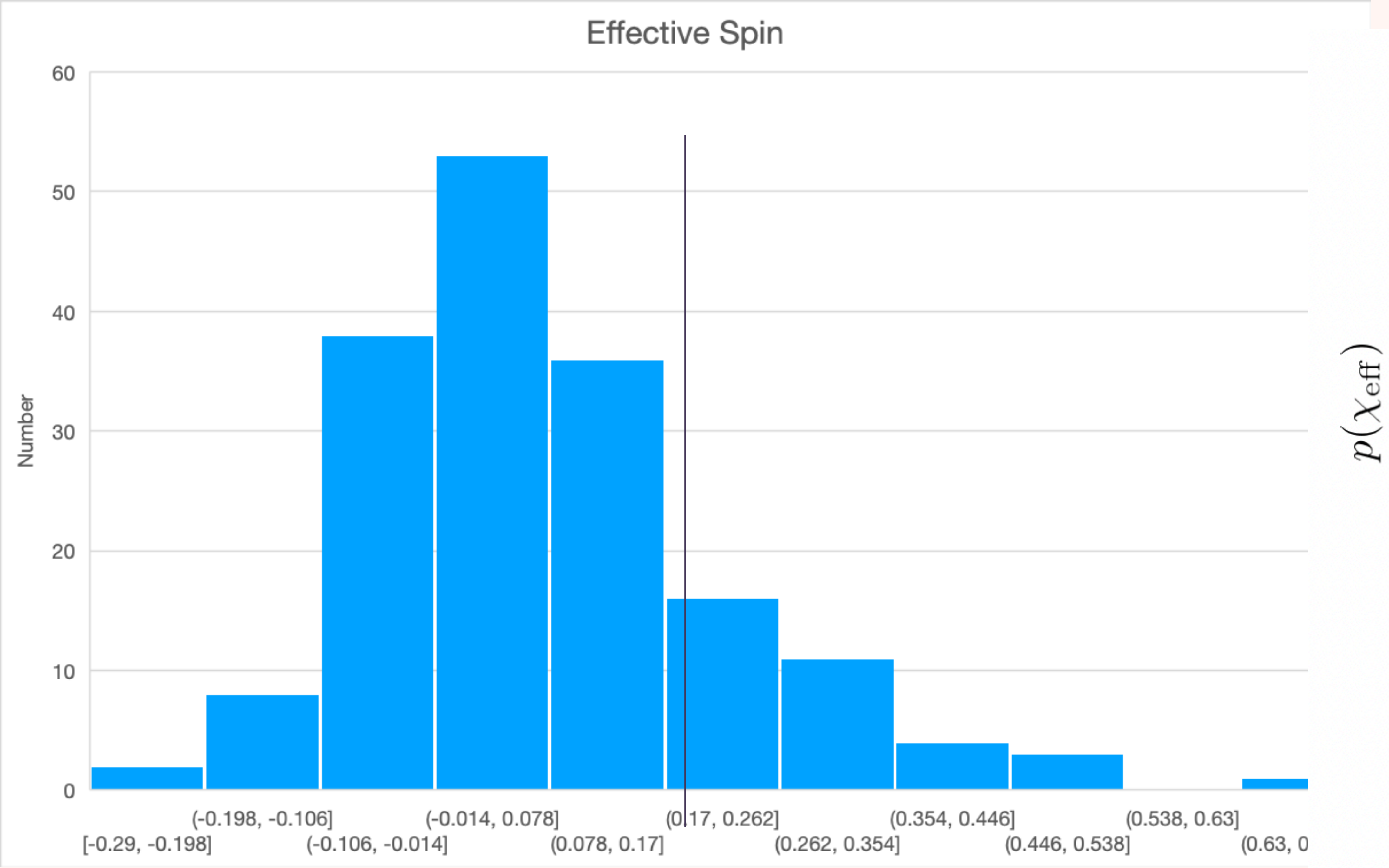
Run	Dates	Duration (months)	Detections
O1	September 18, 2015 to January 12, 2016	3	3
O2	November 30, 2016 to August 25, 2017	9	8
O3	April 1, 2019 to March 26, 2020	11	79
			Candidates
O4	May 24, 2023 to March 19, 2025	23	200

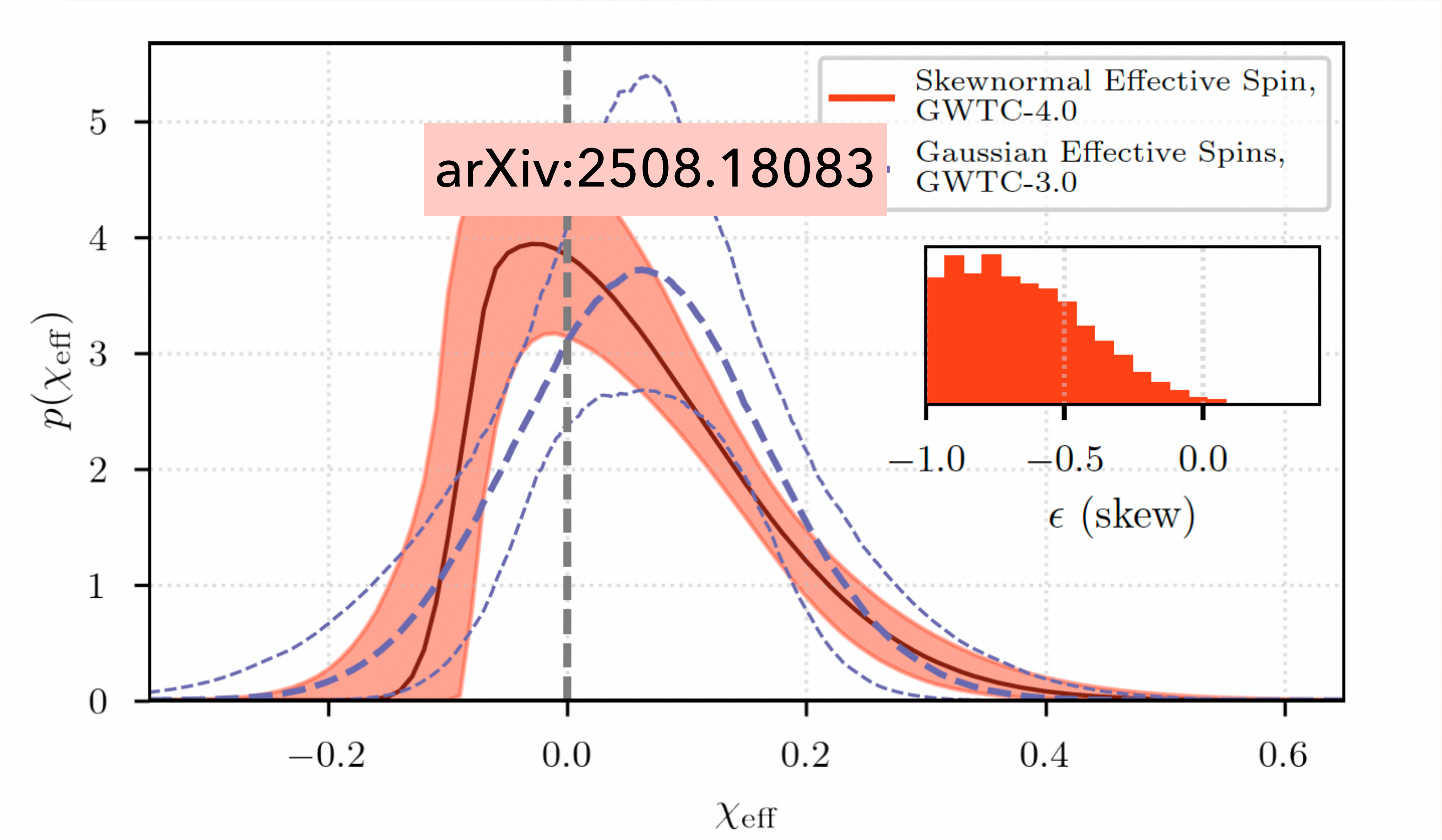


August 20: 223 candidates



Spins





GWTC-4

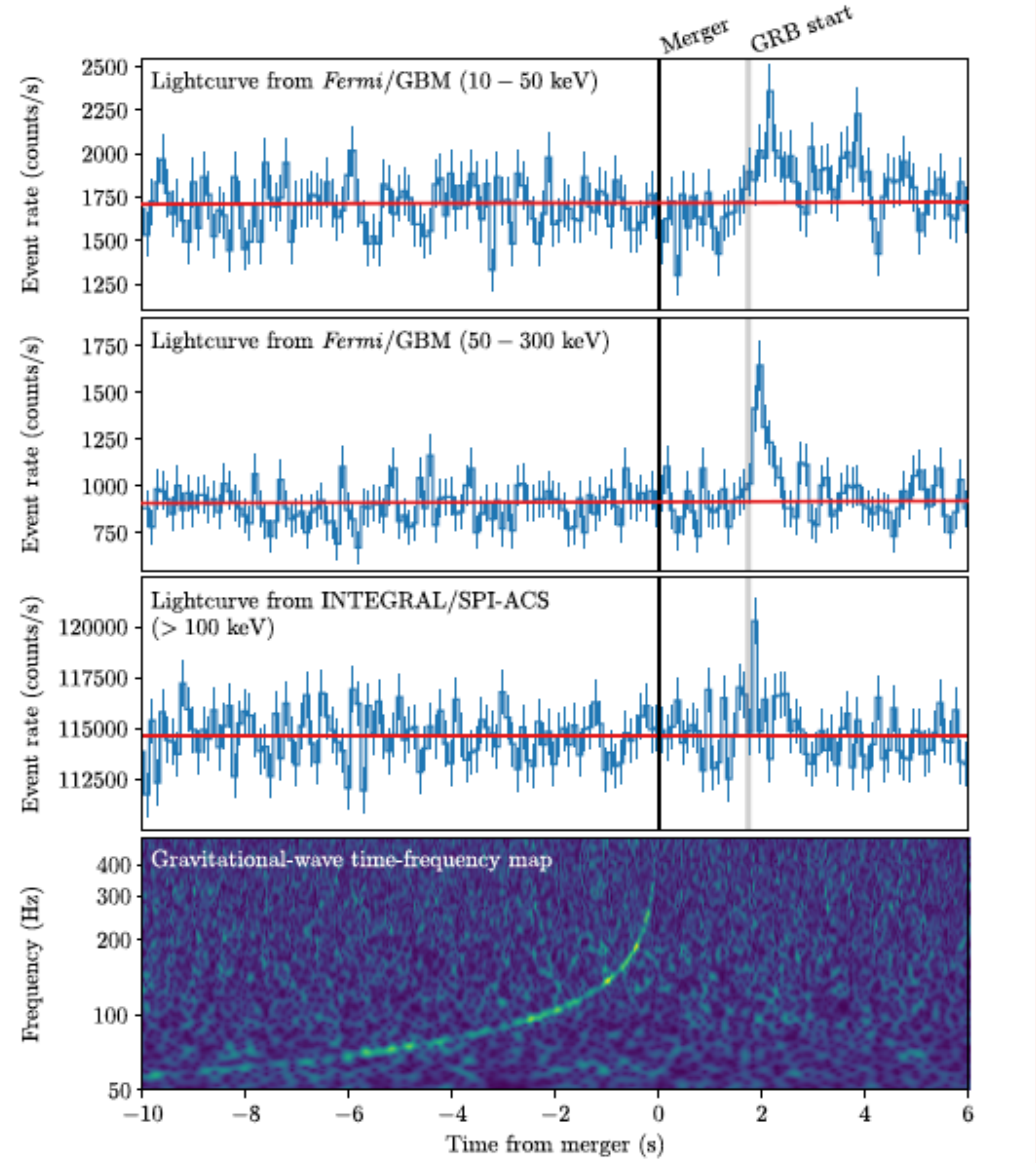
marginal χ_{eff}

- Effective spin, $\chi_{eff} = \dfrac{m_1\chi_1 + m_2\chi_2}{m_1 + M_2}$, is expected to be positive for field population of binaries.
- There could be a substantial population of dynamical binaries

Multi-messenger source: GW170817

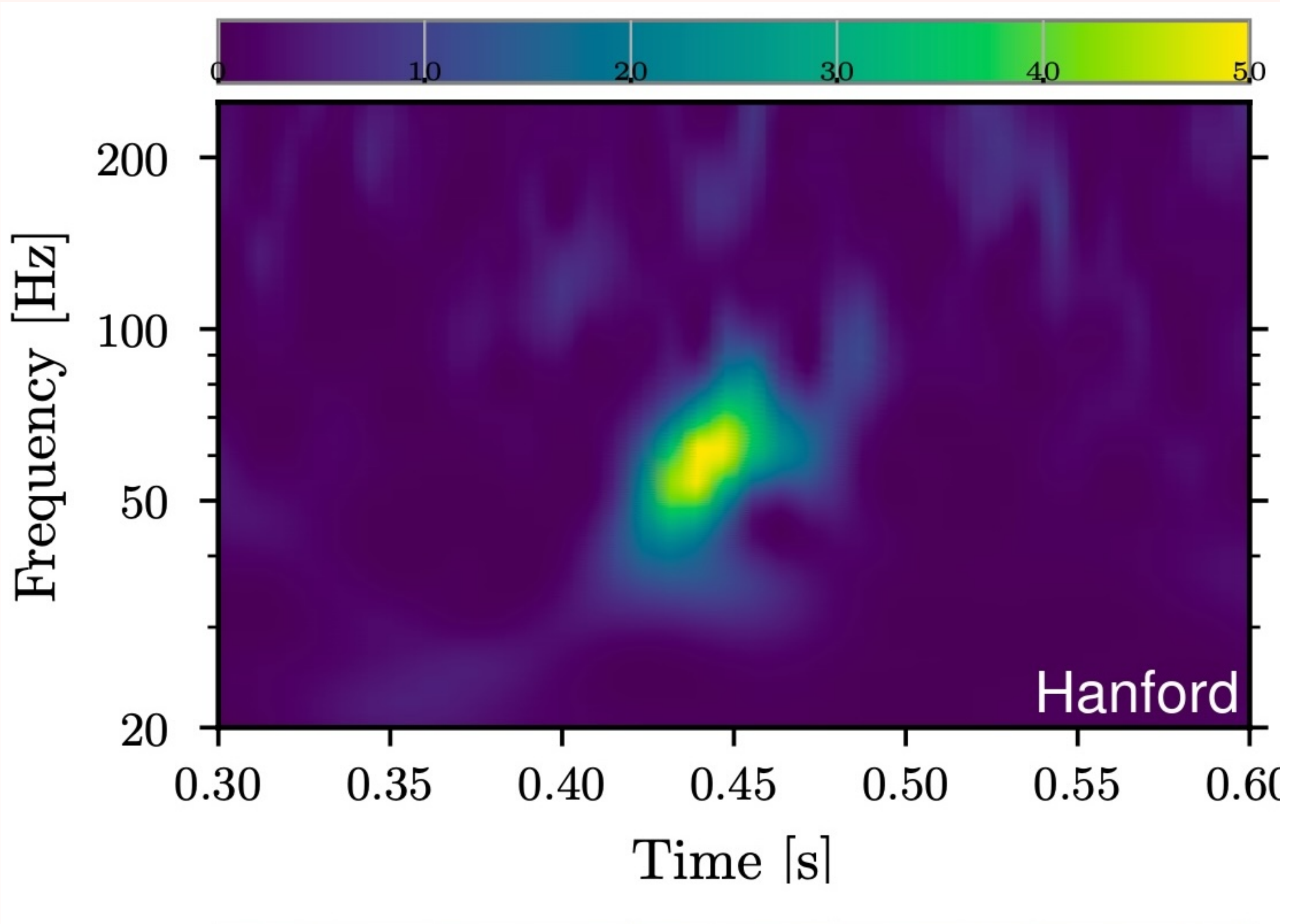
ApJL, 2017, 848

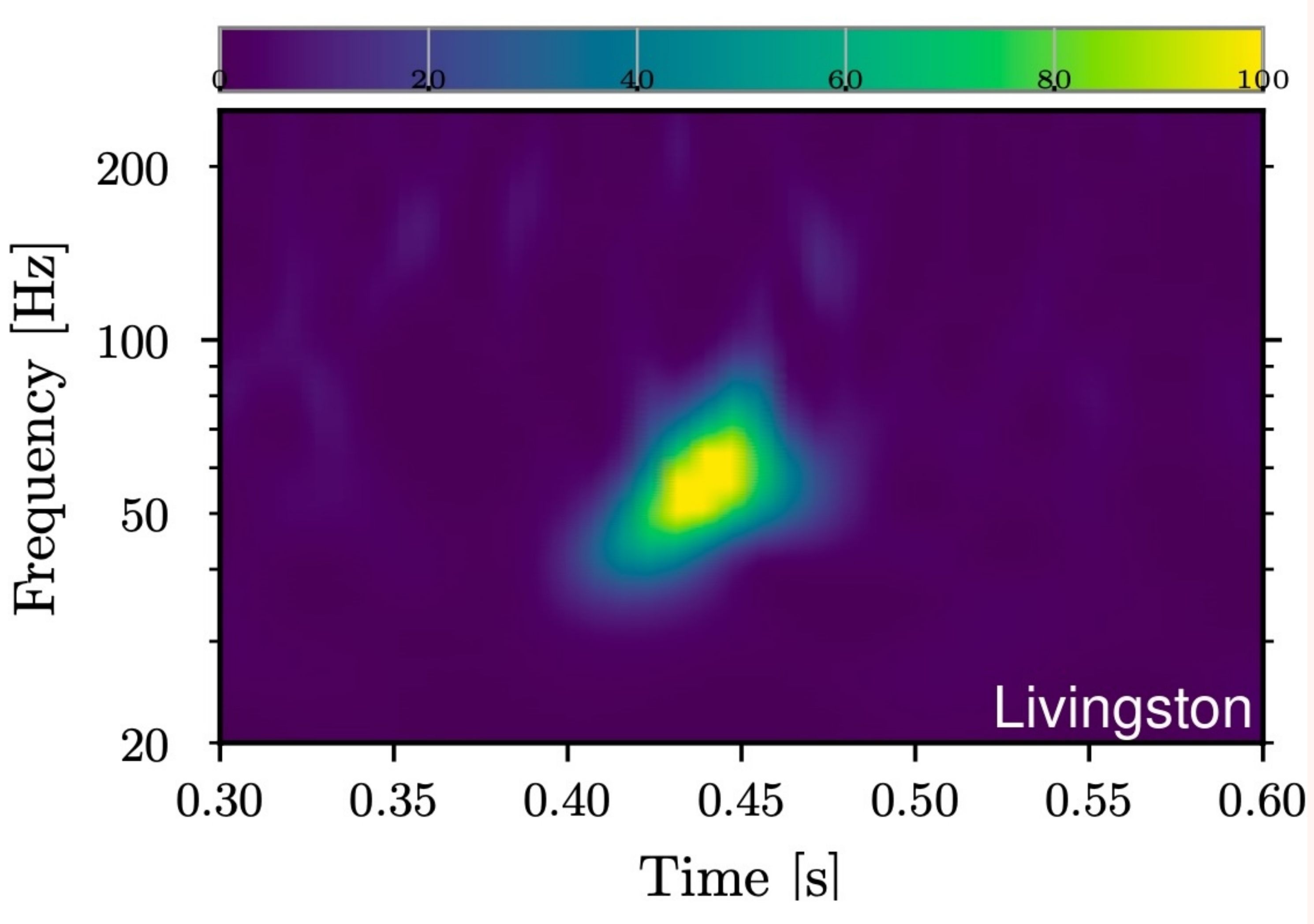
- Binary neutron star merger
- GRB: 1.7 seconds after the merger
- Host galaxy NGC 4993 was identified soon after the GW/GRB detections
- KASI/SNU group actively participated the followup campaign with many facilities
- Estimated parameters are generally consistent with all multi-messenger observations
  - EM and GW distances
  - Neutron star mass
  - Emergence of X-ray and radio emission ~ week
- GW and EM estimations of distance were consistent

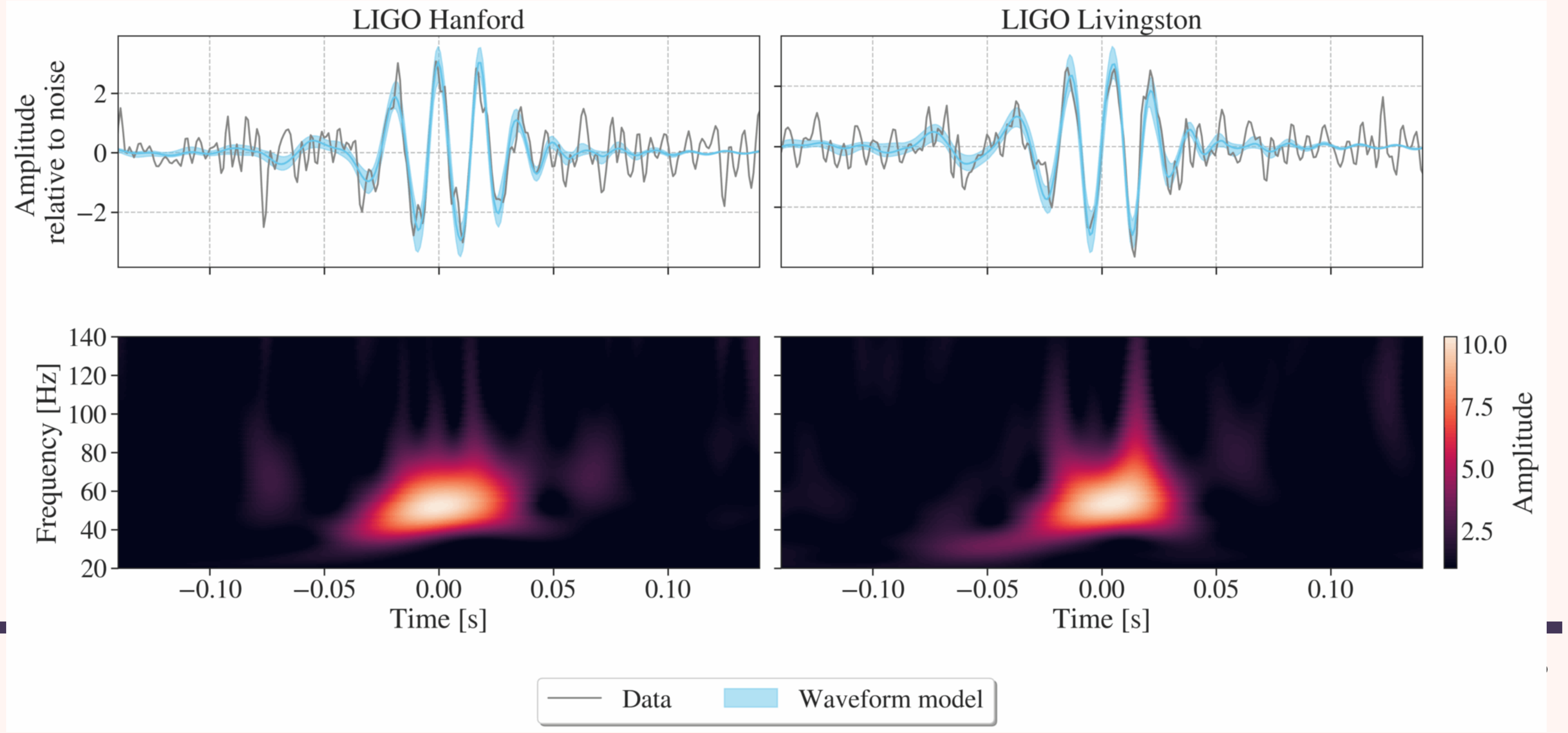


Sources of Interests: BH in the mass gap

- Black Holes in the mass gap:
  - Upper mass gap:
    - GW 190521 (PRL, 2020, 125)
      - $M_1 \sim 85\ \mathrm{M}_\odot \quad M_2 \sim 66\ \mathrm{M}_\odot$
    - GW231123 (Submitted to ApJ)
      $M_1 \sim 137\ \mathrm{M}_\odot \quad M_2 \sim 103\ \mathrm{M}_\odot$.
  - Lower Mass Gap (GW230929, ApJL, 2024, 970)
    $M_1 \sim 3.6\ \mathrm{M}_\odot \quad M_2 \sim 1.4\ \mathrm{M}_\odot$

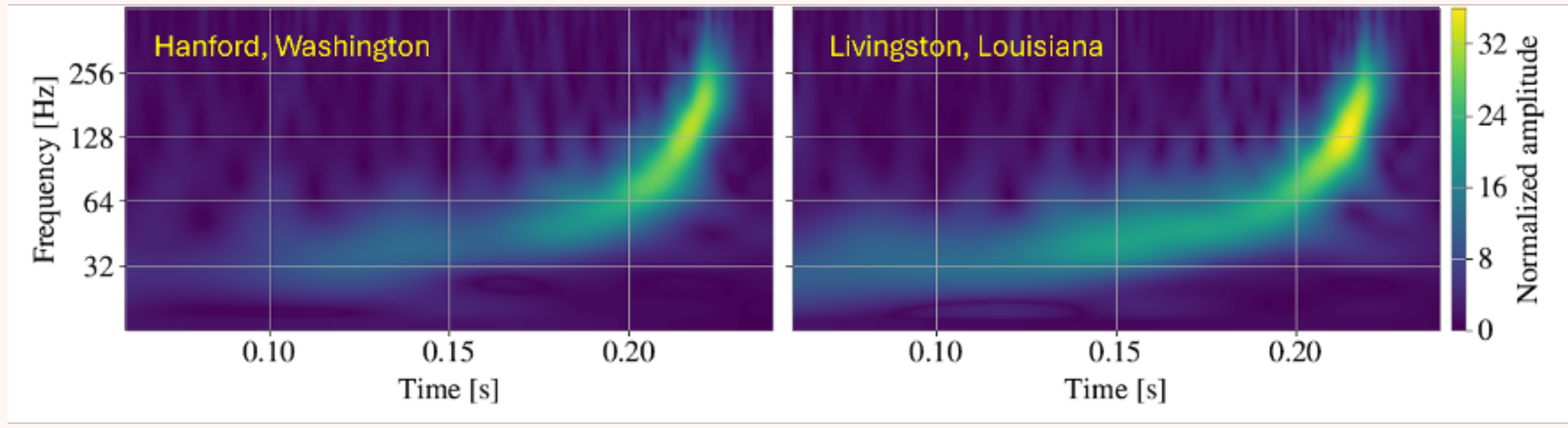


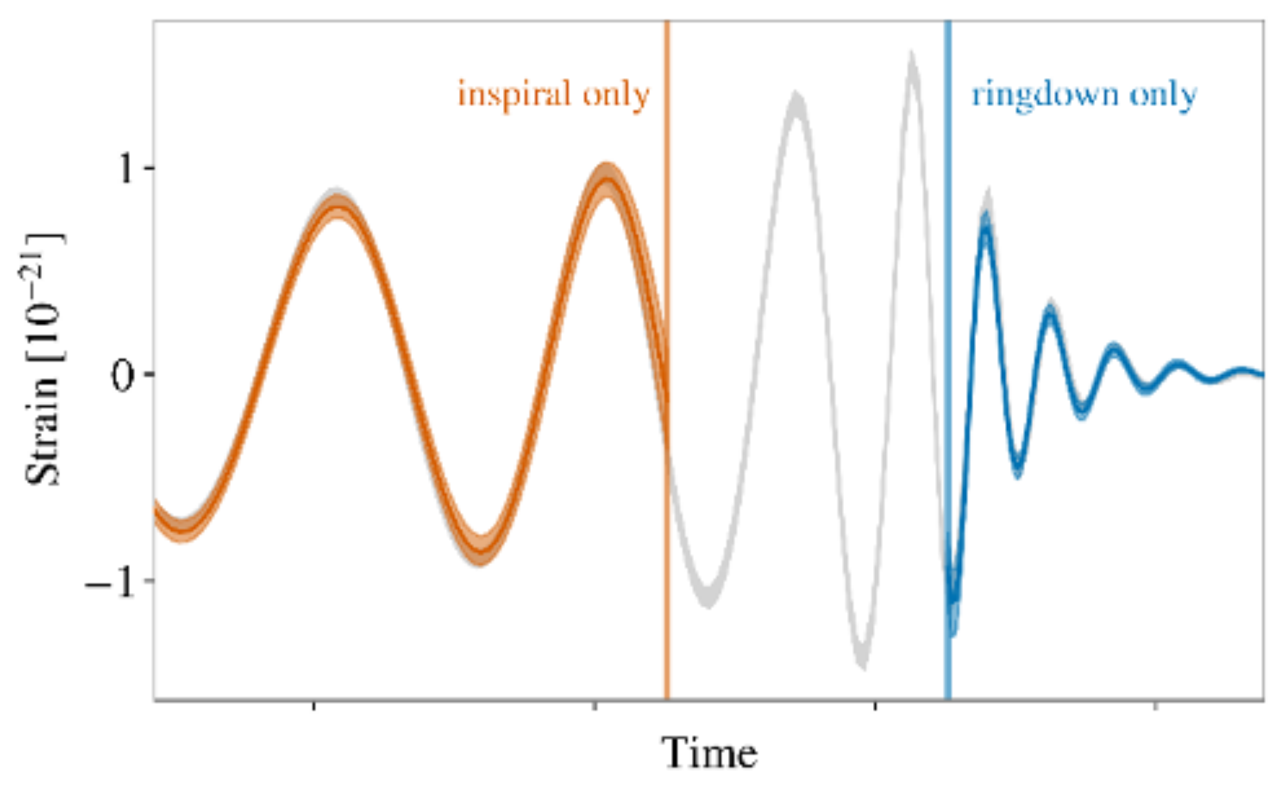


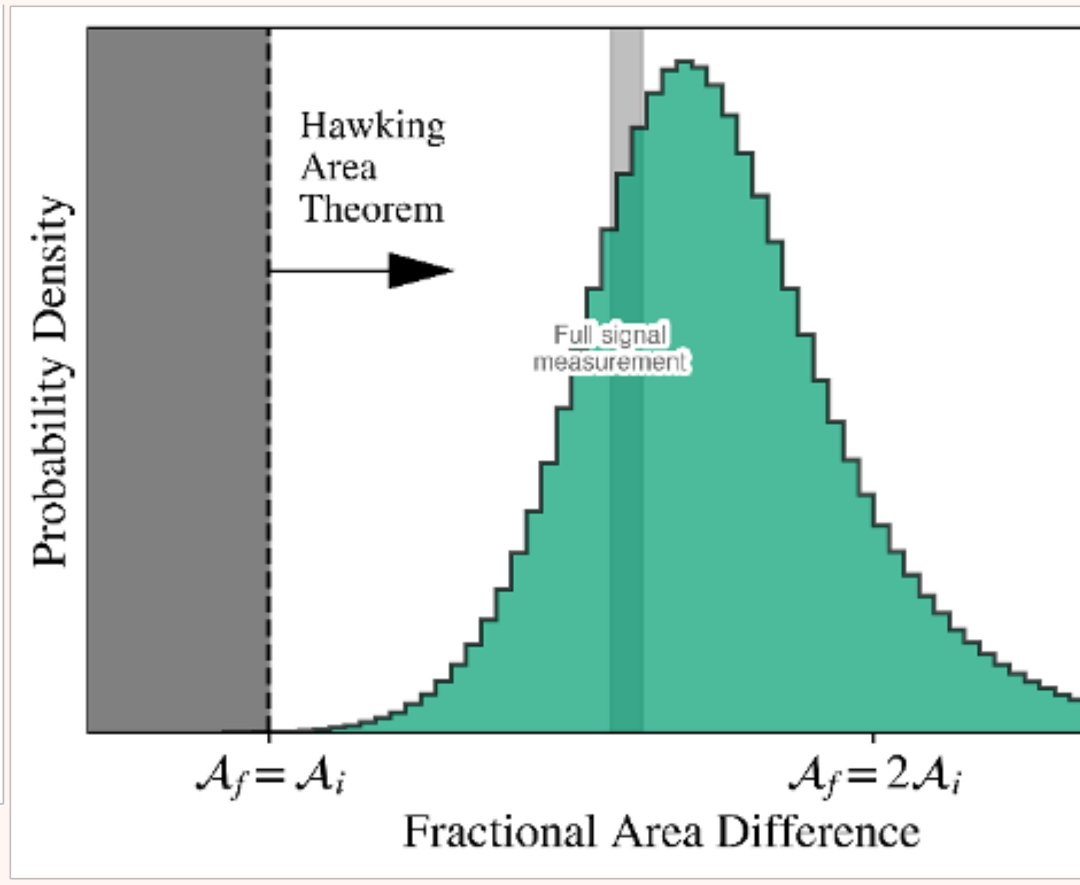


Sources of Interests: ringdown and final Product

- Ringdown Sigal
  - GW250114
    - Very similar to GW150914 in mass, with 3 times stronger signal
    - Signal is 3 times stronger
      - Clear ring-down signal after the merger
      - We can study the properties of the merger remnant
      - More stringent test of GR





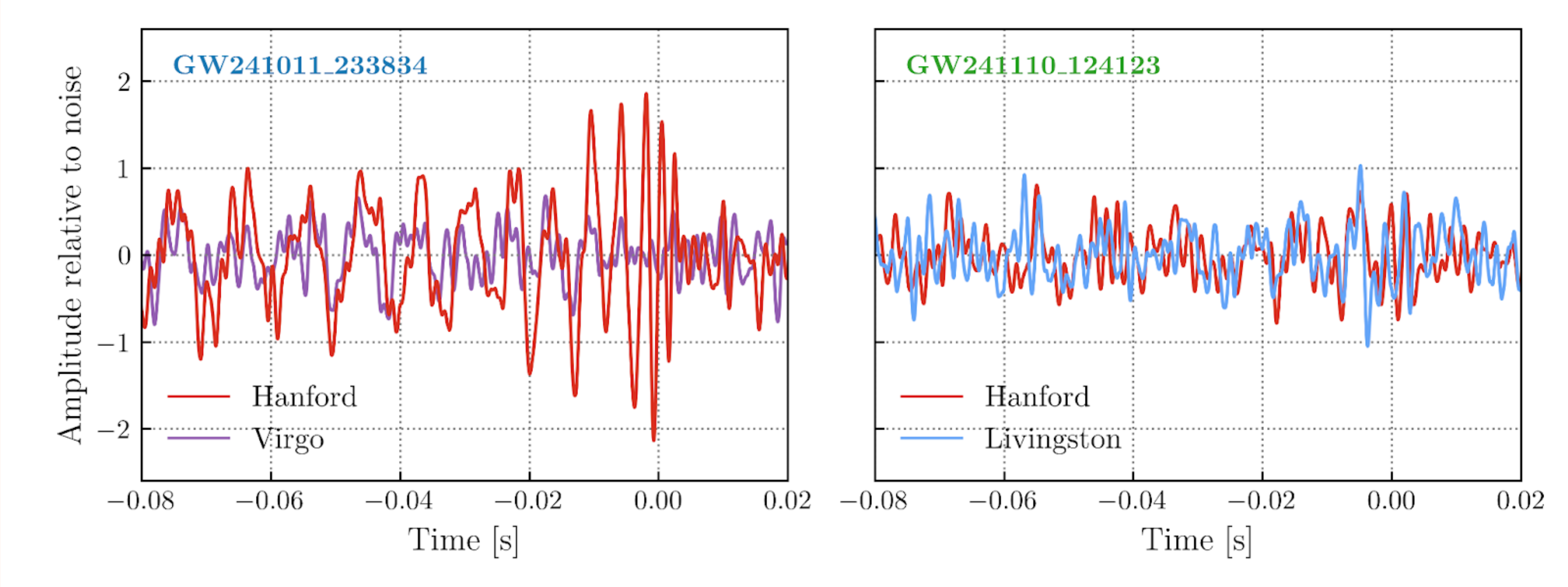


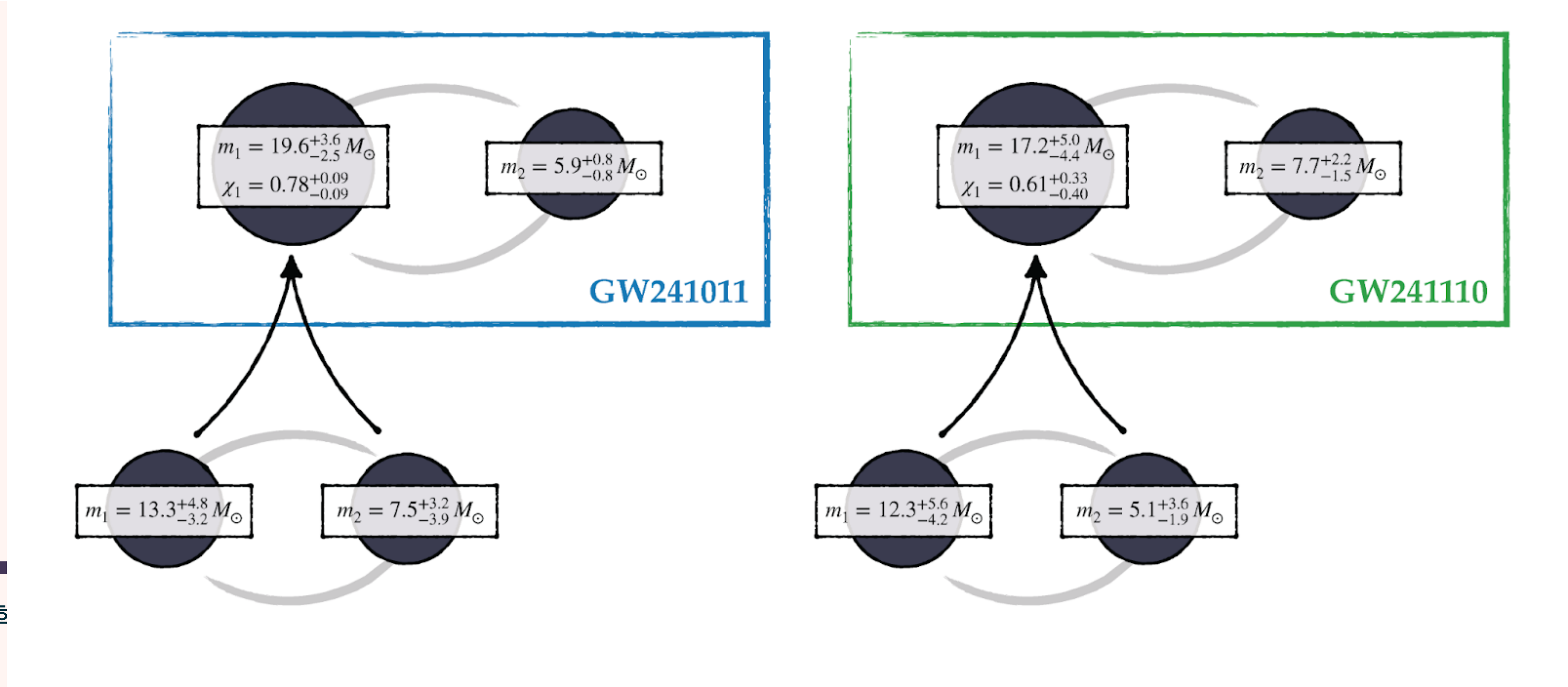
Suface area of the
BH has increased

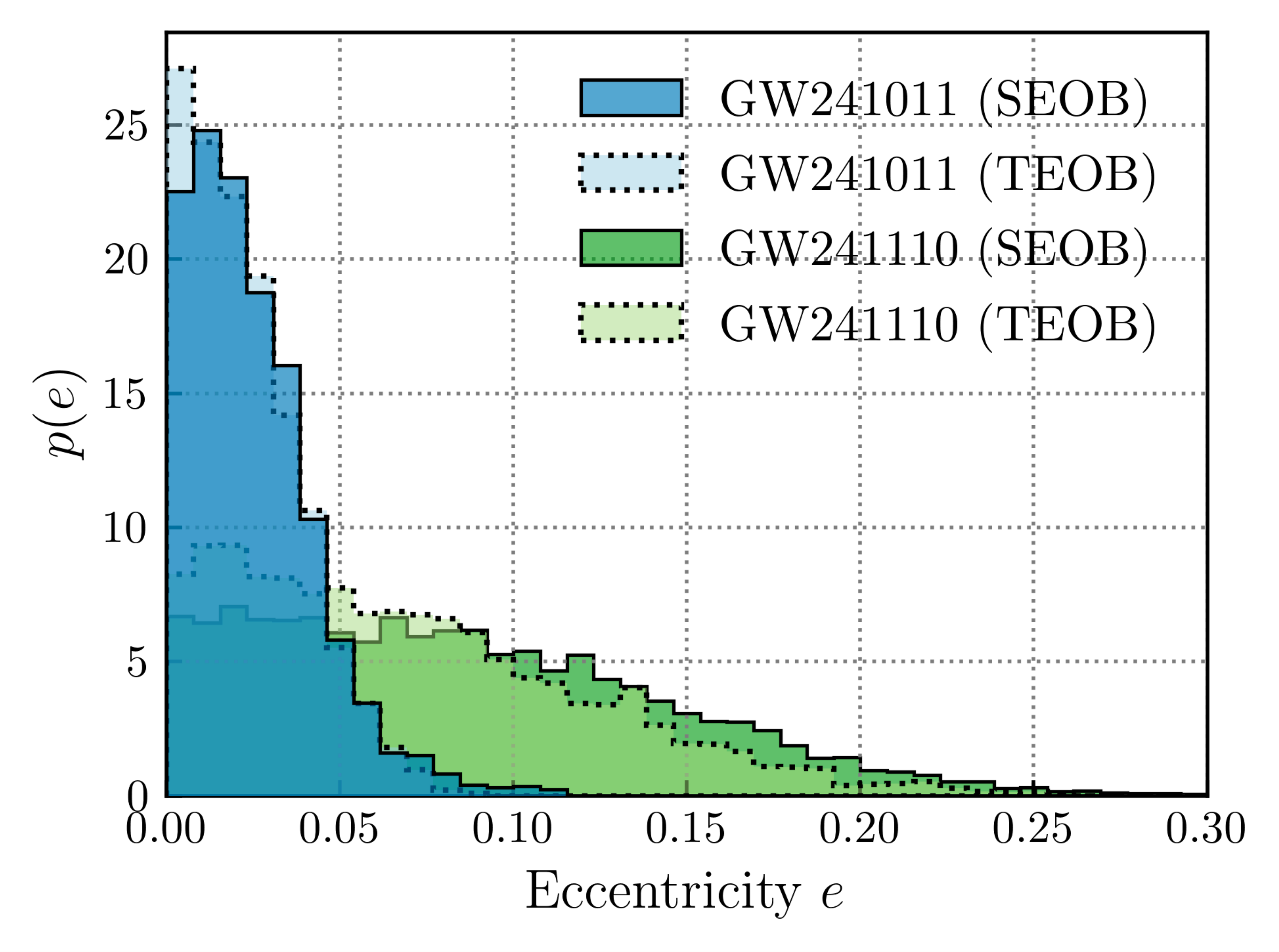
Tale of two mergers: GW241011 and GW241110

Positive spin

Negative spin





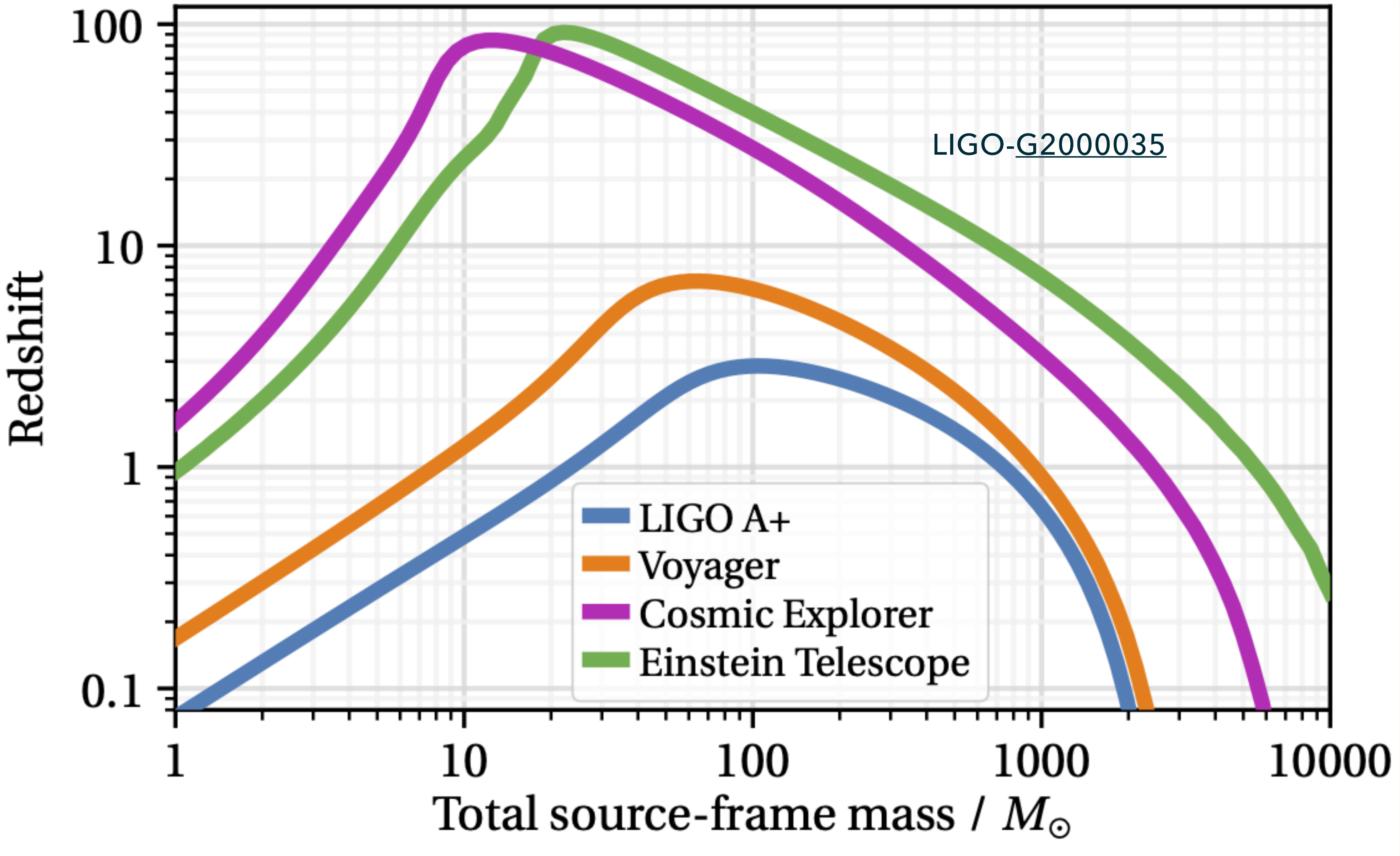


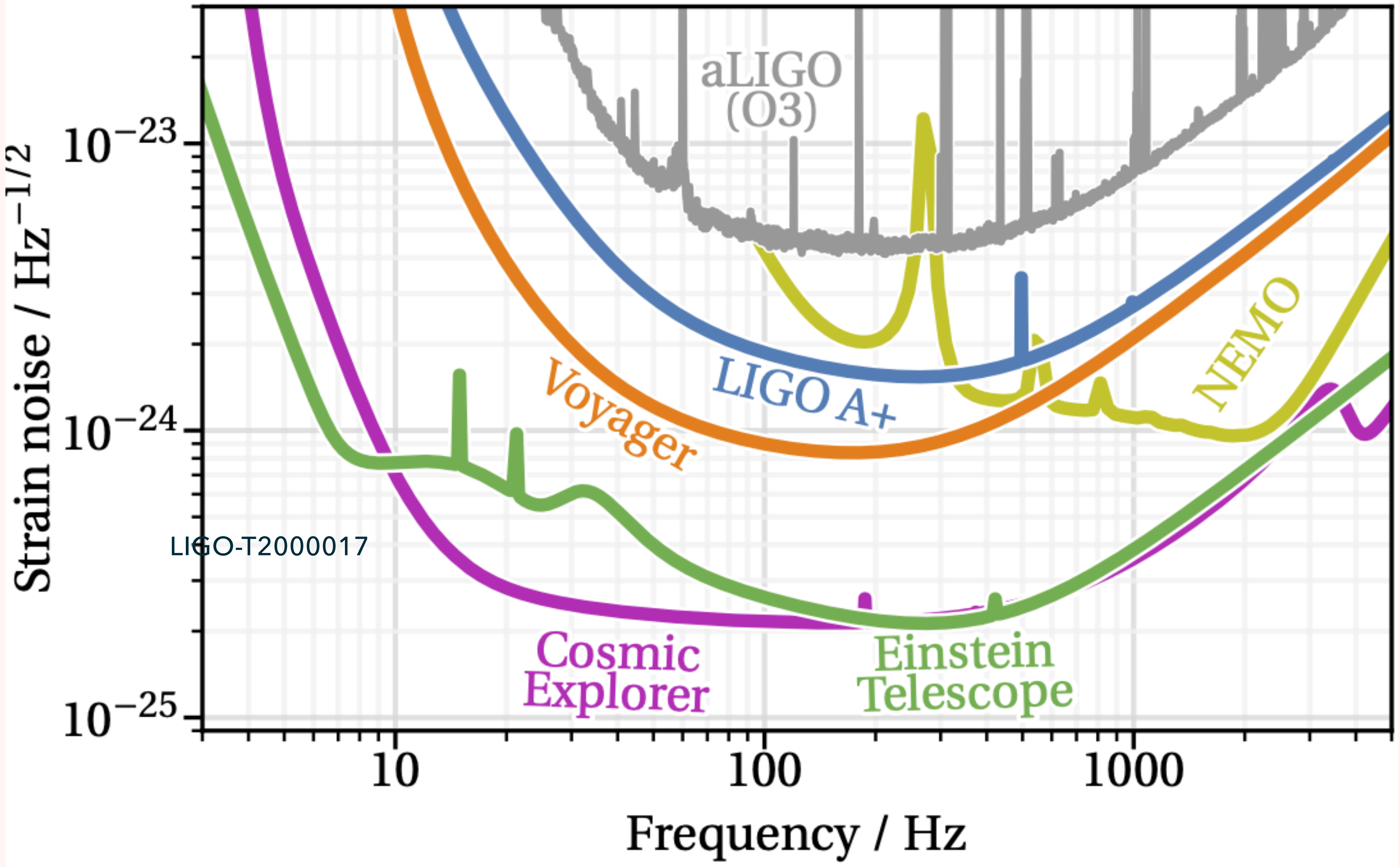
Eccentricity posterior of GW241110 is broader

Summary of Fundamental Physics from GWs

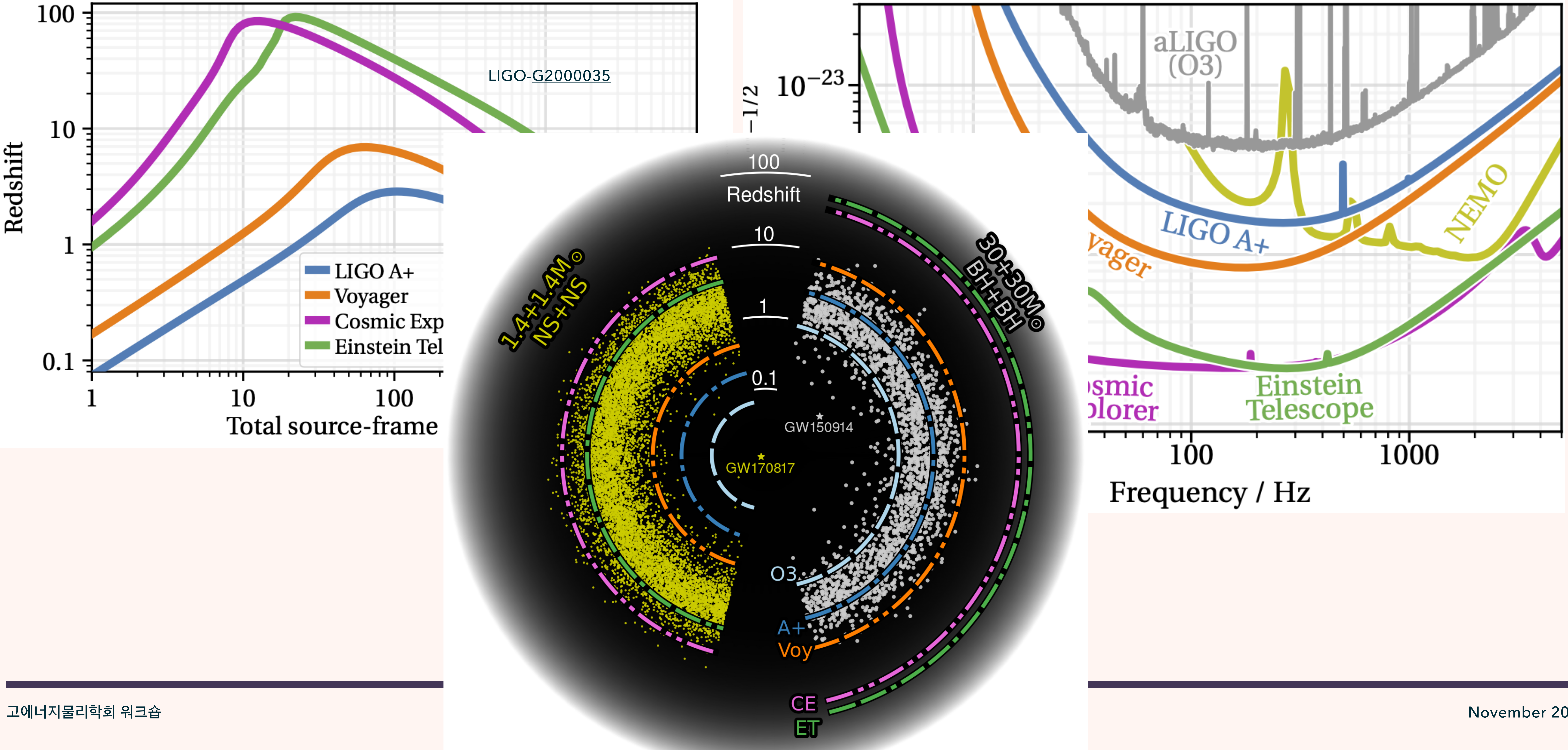
Test / Quantity	Physical Meaning	Best Constraint (as of O3–O4 / 2025)	Main Events / Datasets
Speed of gravitational waves	Checks Lorentz invariance & graviton dispersion	**$(v_{gw} - c)/c < 3 \times 10^{-15}$**	The joint detection of GW170817 and its electromagnetic counterpart
Graviton mass (m_g)	Massive graviton → frequency-dependent GW speed	**m_g < 1.27×10^{-23} eV / c^2 (90% C.L.)**	Population of BBH mergers , GWTC-3)
Polarization content	Extra scalar/vector modes beyond GR	**Pure tensor modes favored (> 99%)**	GW170814, GW170817, catalog O3b
Ringdown (Kerr test)	Are remnant BHs described by Kerr metric?	**No deviation > few % in mode freqs/ Q**	GW150914, GW190521 + stacked tests
Post-Newtonian coefficients	Deviations in inspiral phase evolution	**All coefficients consistent with 0 within 1–2 σ**	GWTC-3 catalog
GW energy loss vs GR	Checks radiation damping law	**Consistent to within 10%**	BNS and BBH events
Equation of State (Neutron Stars)	Tidal deformability $\Lambda(1.4\,M_\odot) \approx 190–580$	**Radius ≈ 11.9 ± 0.9 km**	GW170817, GW190425
Hubble constant (H_0)	Cosmology via “standard sirens”	**H_0 = 68 ± 8 km $s^{-1}Mpc^{-1}$**	GW170817 + galaxy catalogs (O3)
Stochastic GW background	Early-Universe relics or unresolved sources	**$\Omega(f)$ (f = 25 Hz) < 5.8×10^{-9}**	O1-O4a LVK stochastic search
Cosmic-string tension ($G\mu/c^2$)	Fundamental-string remnants	**$G\mu < 1.4 \times 10^{-7}$**	O3 stochastic analysis
Black-hole area theorem test	$\Delta A \geq 0$ (expected in GR)	**Consistent within 5 sigma**	GW250114

Near Future Upgrade Path



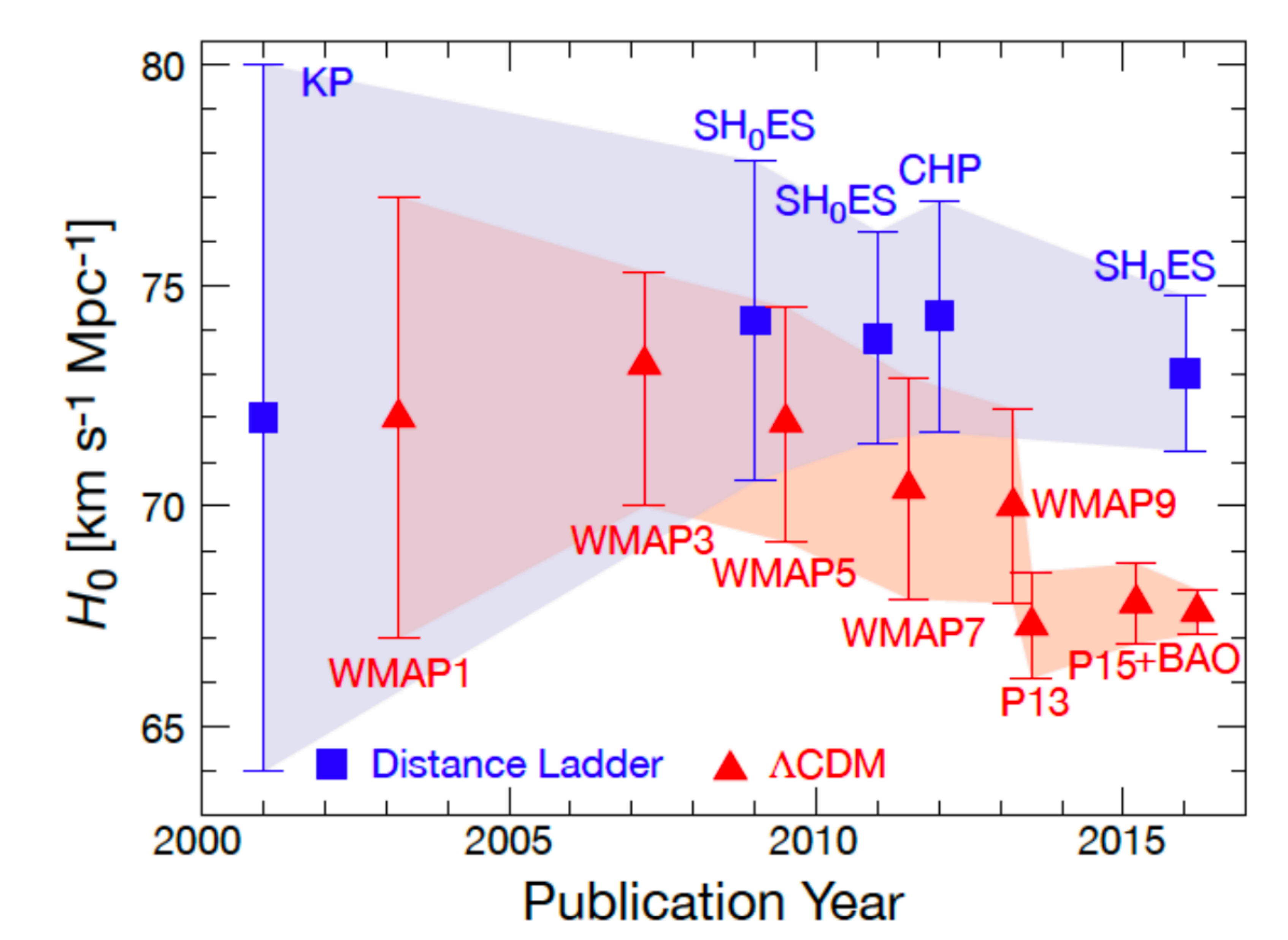


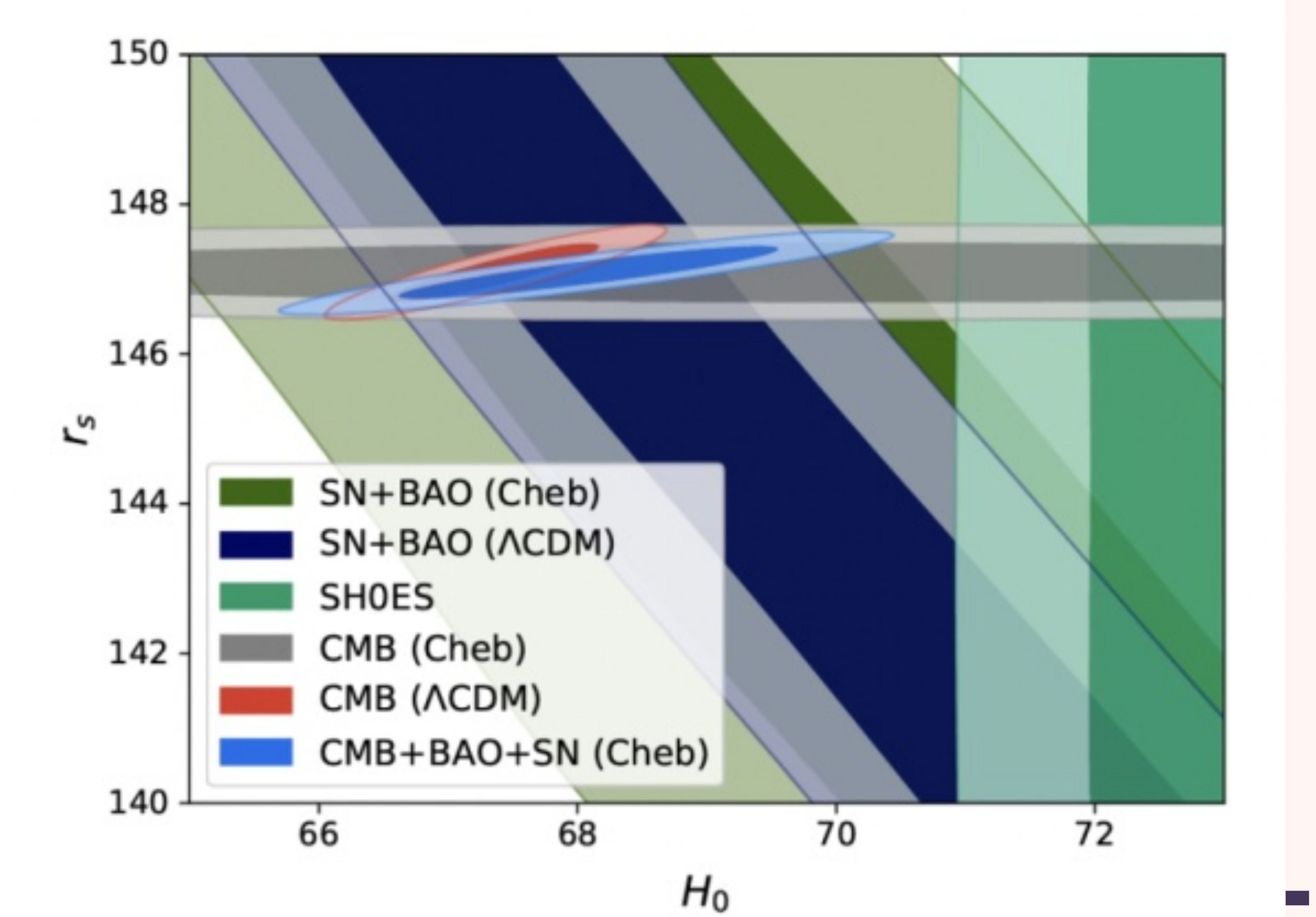
Near Future Upgrade Path



Tensions in Cosmology

- **Hubble Tension:** Hubble constant based on Cepheids/SN Ia does not agree with the value inferred from the Planck CMB fitting
  - Failure of ΛCDM Model?
  - CMB small scale data is not consistent with large scale data?
  - Does the local measurement of Cepheid and SN Ia distance suffer from systematic error
- **What is Dark Energy?**:
  - Any allowed modification of wCDM is compatible with Planck data?
  - Either local measurement is wrong or we need to modify physics of the early universe (Keeley & Shafieloo 2023, PRL)

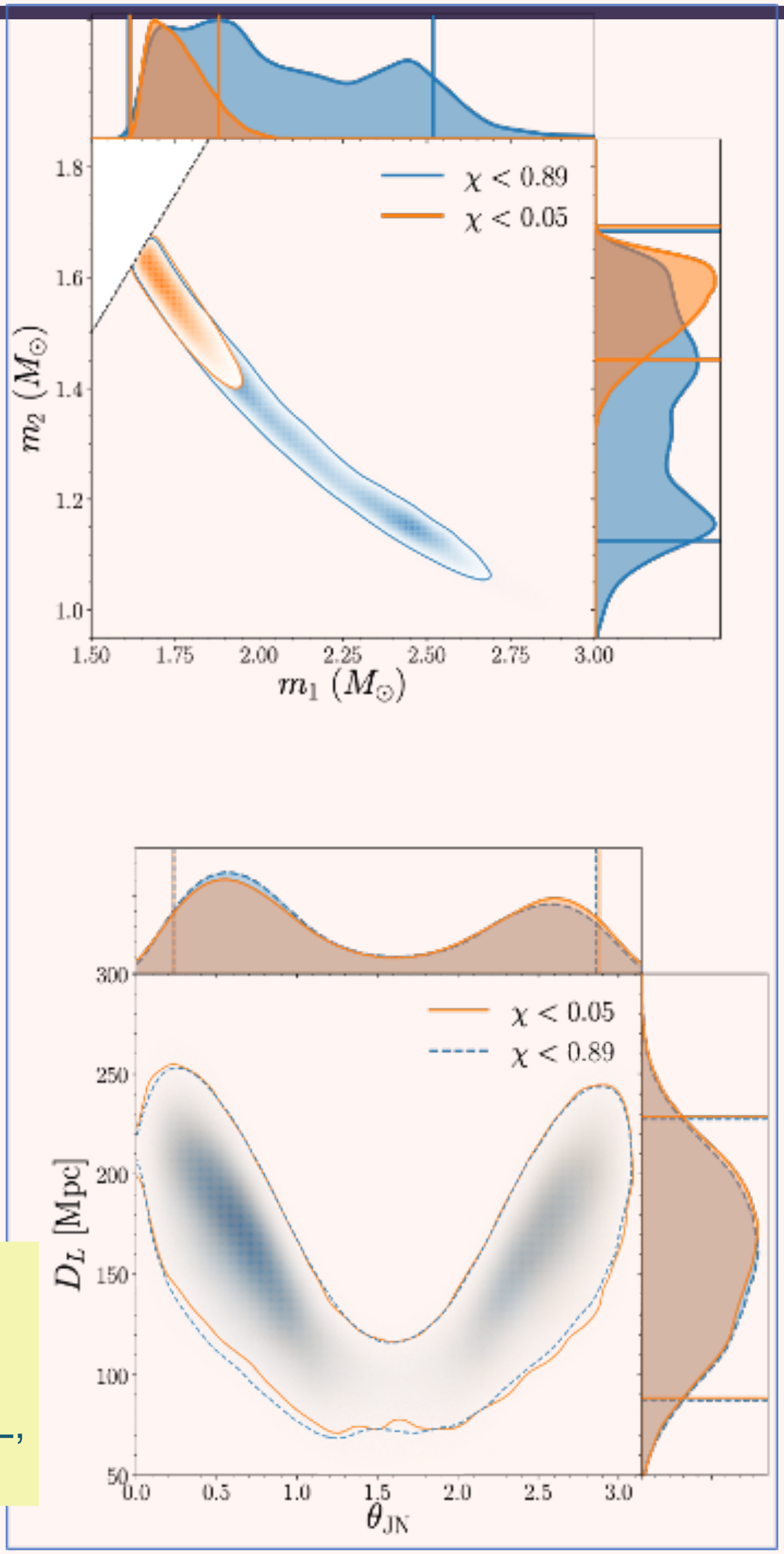




Keeley & Shafieloo 2023

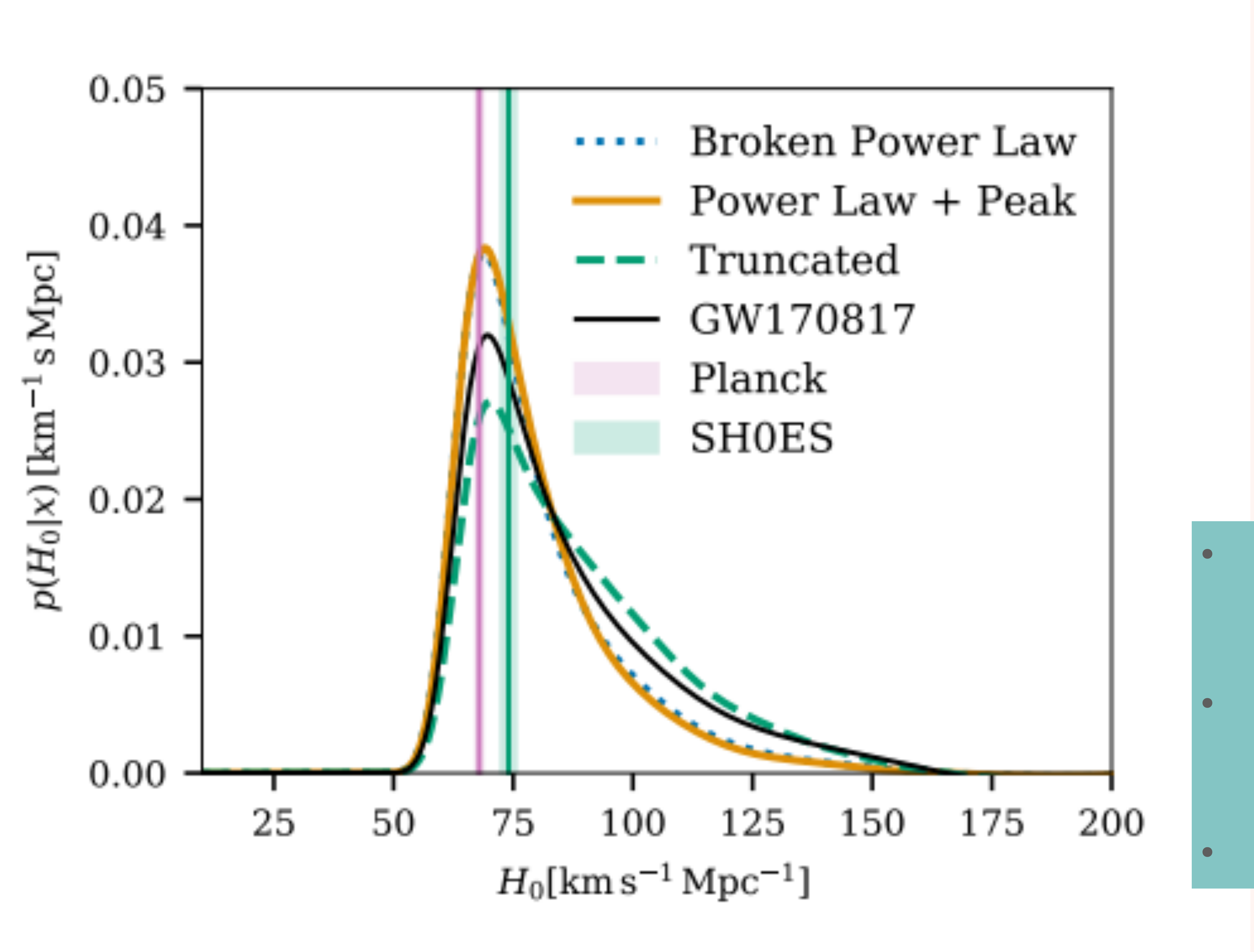
Challenges of GW measurement of H_0: Distance and Localization

- We need to know distance and redshift to determine $H_0(=v/d)$
  - GW observation allows to determine d_L, but uncertainty is large.
  - Redshift cannot be estimated from GW: we need to identify host galaxy
- Host galaxy identification
  - Accurate localization
  - Optical counterpart: Rare



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

Measurements of H_0 with Bright Siren: GW170817



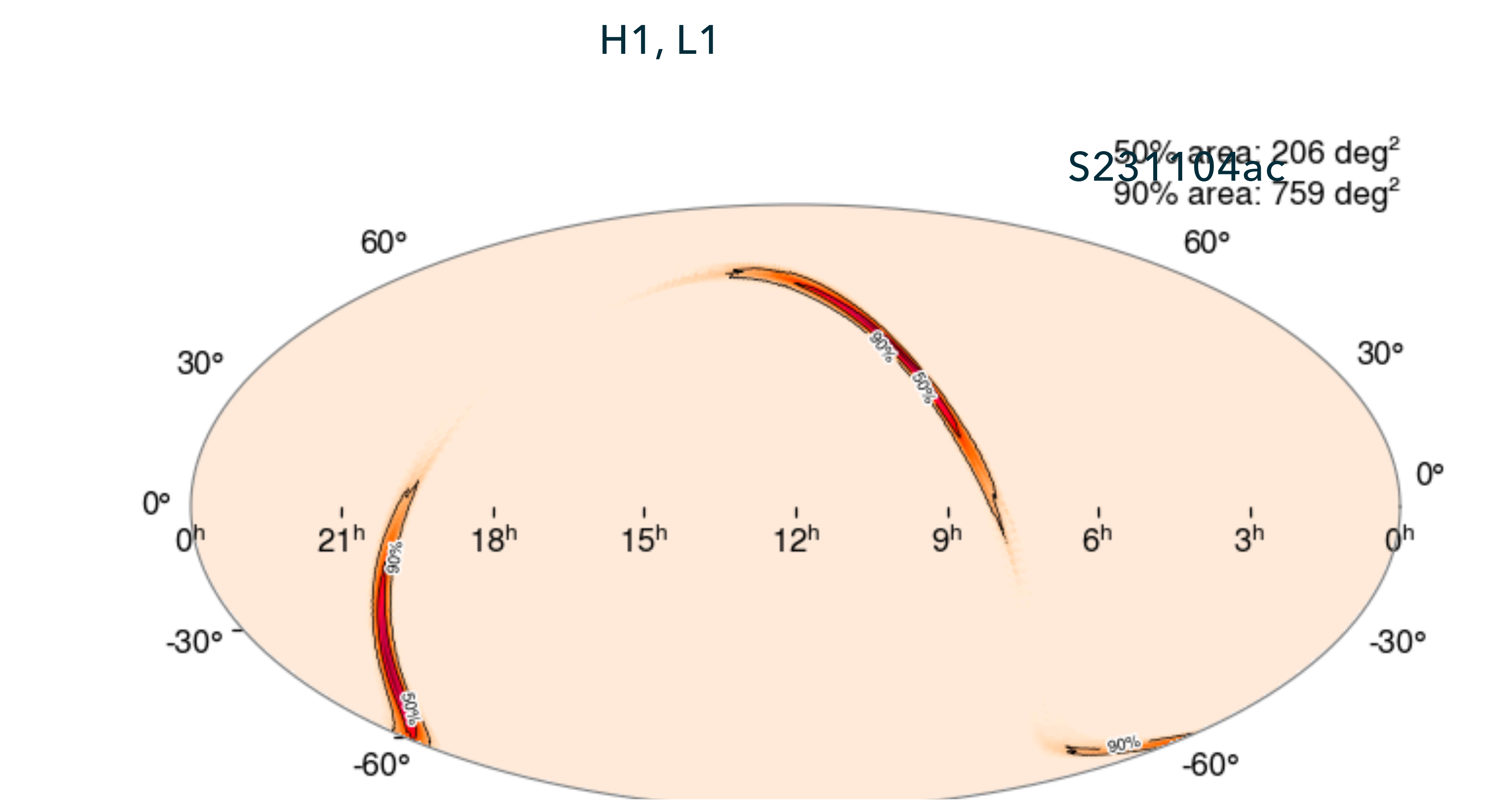
- Accuracy of Hubble constant can be improved if we have many BNS events with EM counterparts.
- There will be a few more such events in O4 & O5, but may not be enough to resolve Hubble tension.
- Can we identify host galaxies of dark sirens?

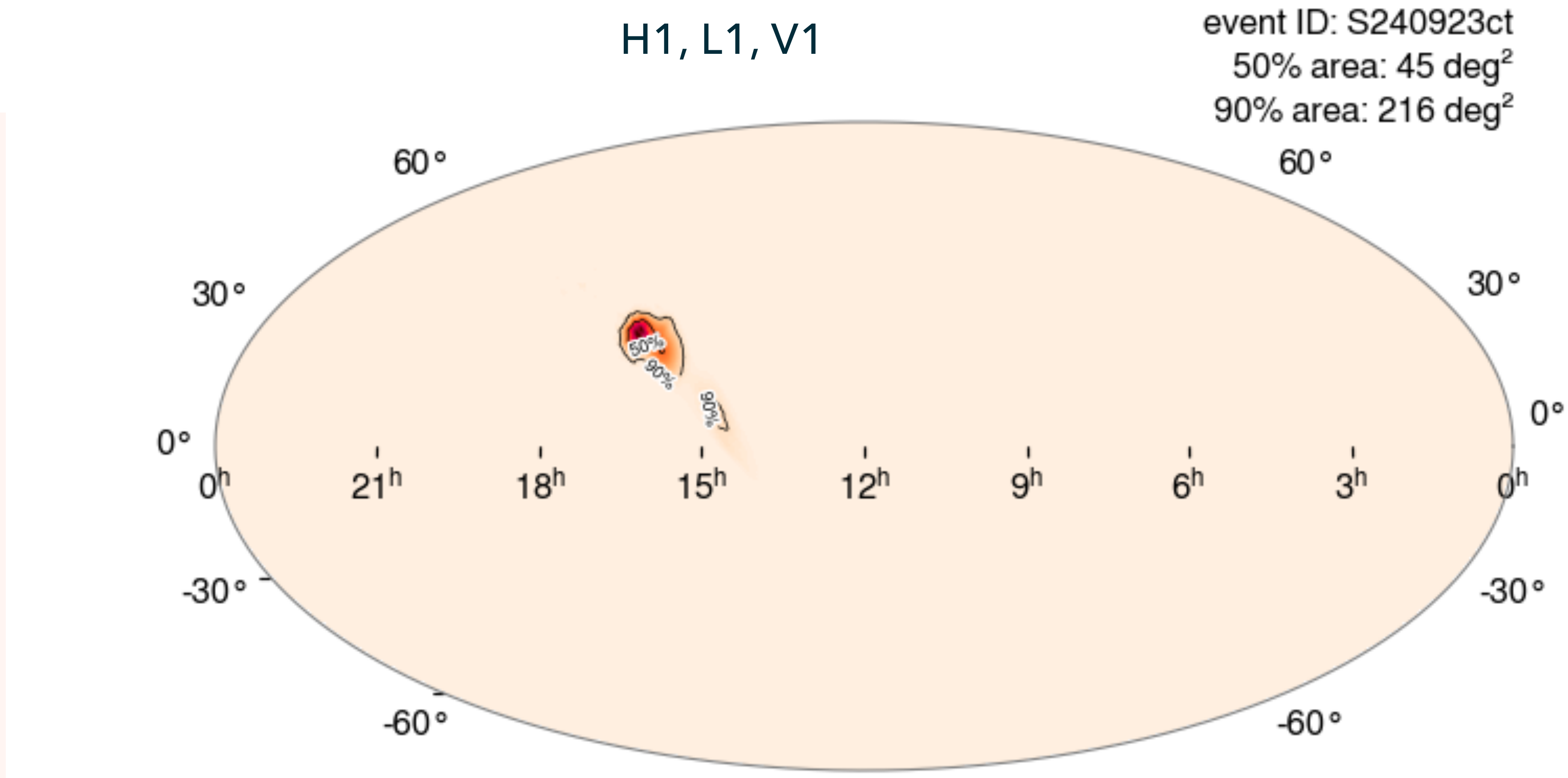
Cosmology/Dark Energy

- **Compatibility of Hubble tension with modified LCDM?** (Keeley & Shafieloo, 2023, PRL; Calderon, Shafieloo et al. 2023, JCAP)
- **Model independent approaches for dark energy/cosmology** (Shafieloo et al, 2023, PRD; Li, Keeley, Shafieloo & Liao, 2024, ApJ; L'Hilller, Keeley & Shafieloo, 2025, JCAP; Shafieloo et al., 2023, PRD)
- **Constraints on dark energy with DESI 2024** (Lodha, Shafieloo, et al. 2024, PRD)
- **Cosmology with strongly lensed qusars/Superonovae** (Shafieloo et al. 2022; Mathewson & Shafieloo, 2025, JCAP)
- **Search for lensed supernovae** (Khalouei et al. 2025, A&Ap)
- **Forecast of Cosmologcal constraints with Stage-IV surveys** (Calderon, L'Huiller, Polarski, Shafieloo et al., 2022, PRD; 2023, PRD)

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





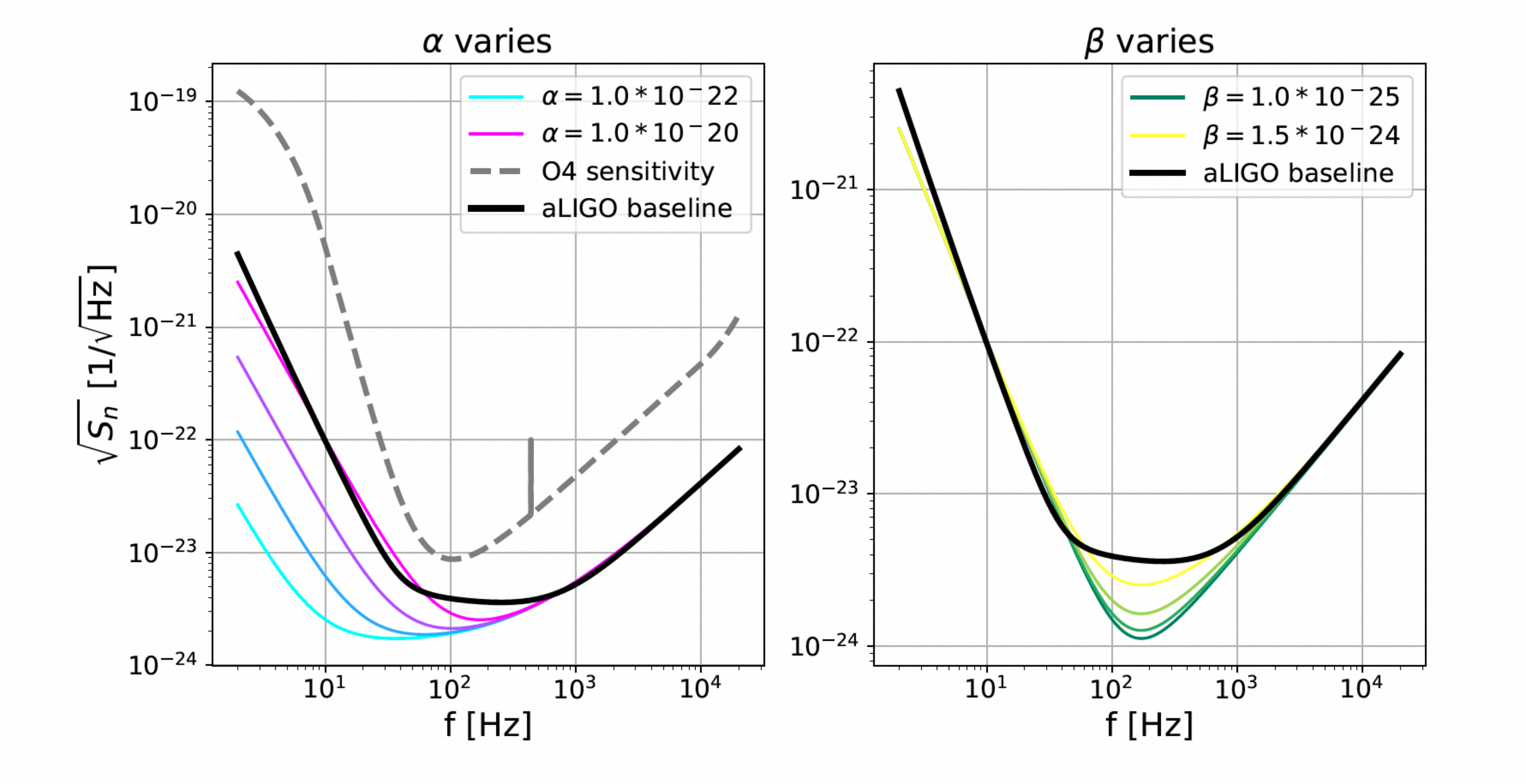
Effects of Detector Sensitivity on Science (Chartier, Keeley, L'Huiller, Shafieloo, Lee , in prep.)

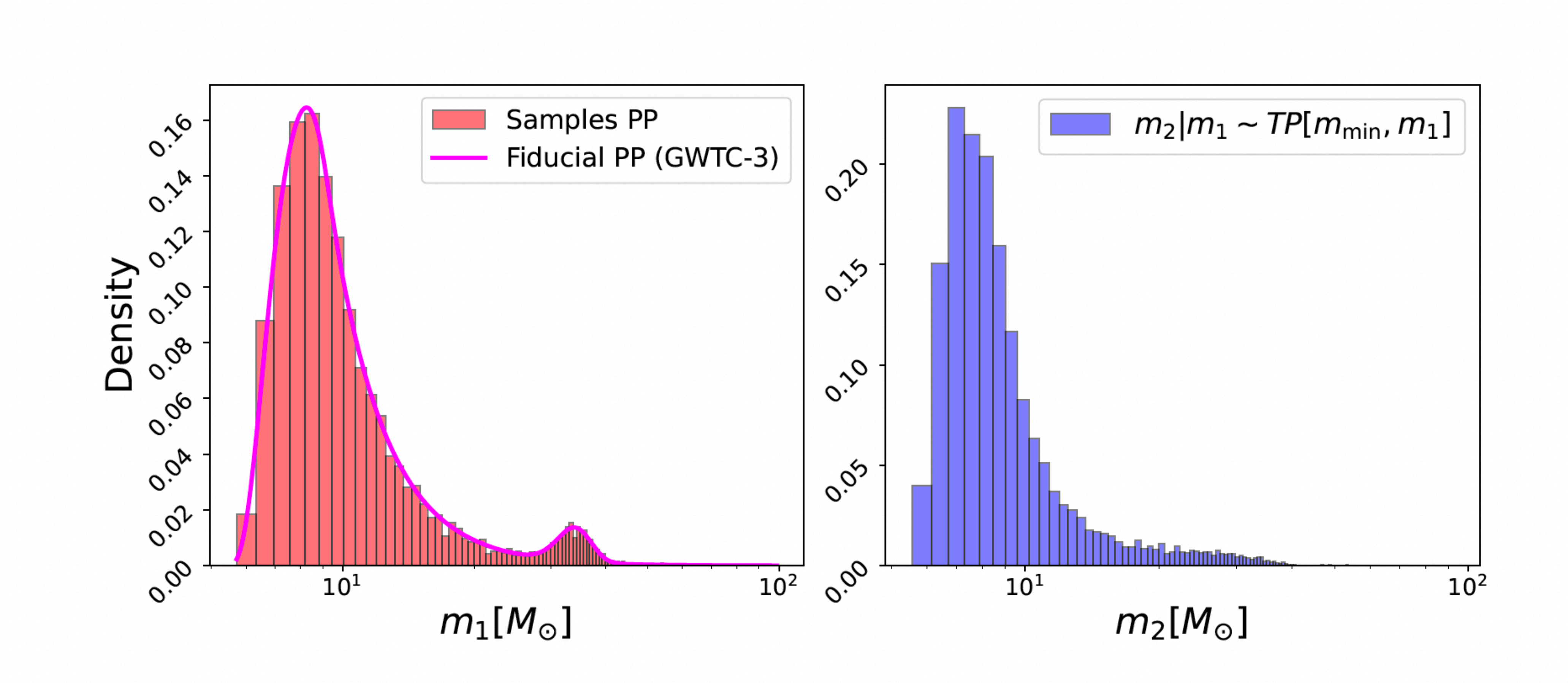
- Parametric model for detector sensitivity
  - $S_n(f) = \alpha f^{-2} + \beta + \gamma f$
- Merger Events in the universe

$$\mathcal{R}(z_m) \propto \int_{z_m}^{+\infty} dz_f \frac{d\tau}{dz_f} \mathcal{P}(\tau) \Psi(z_f) \; [\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}]$$

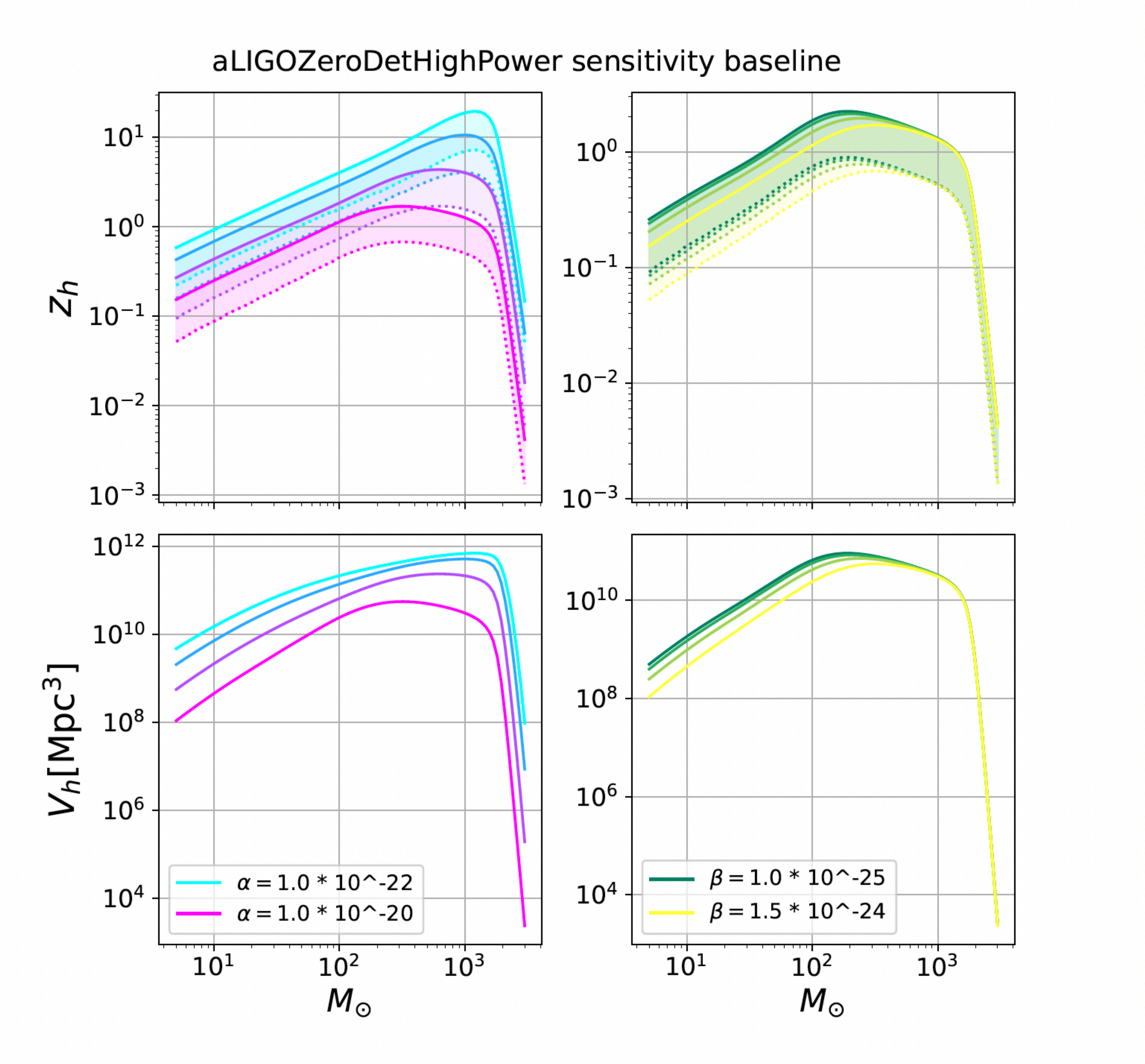
$\tau \equiv t_m - t_f$: Cosmic time delay between formation. and merger
$P(\tau)$: distribution of τ
Ψ: star formation rate

- Generation of Mock catalogue
- Simulation of observations with hypothetical detectors

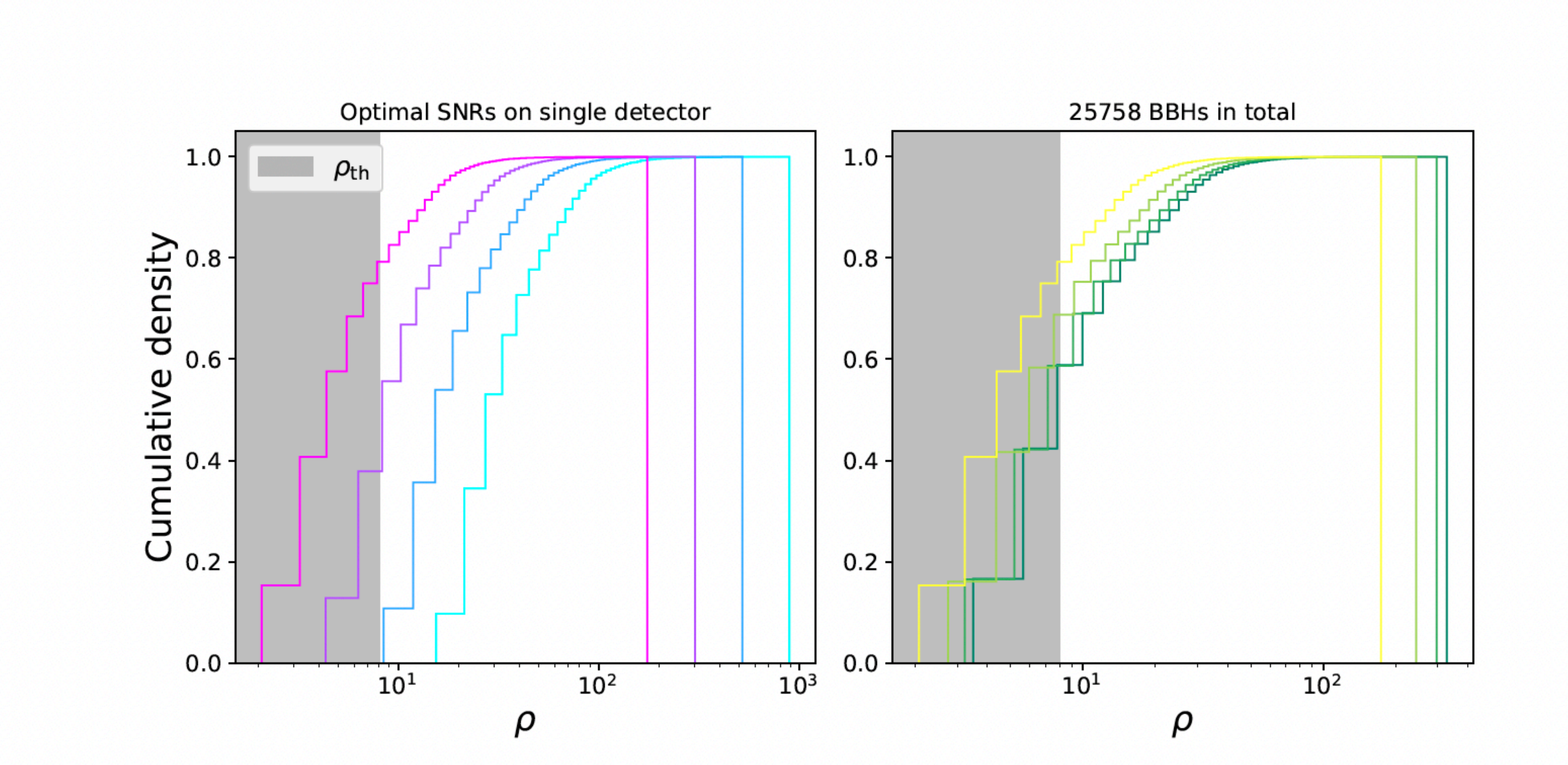




How far we can see?



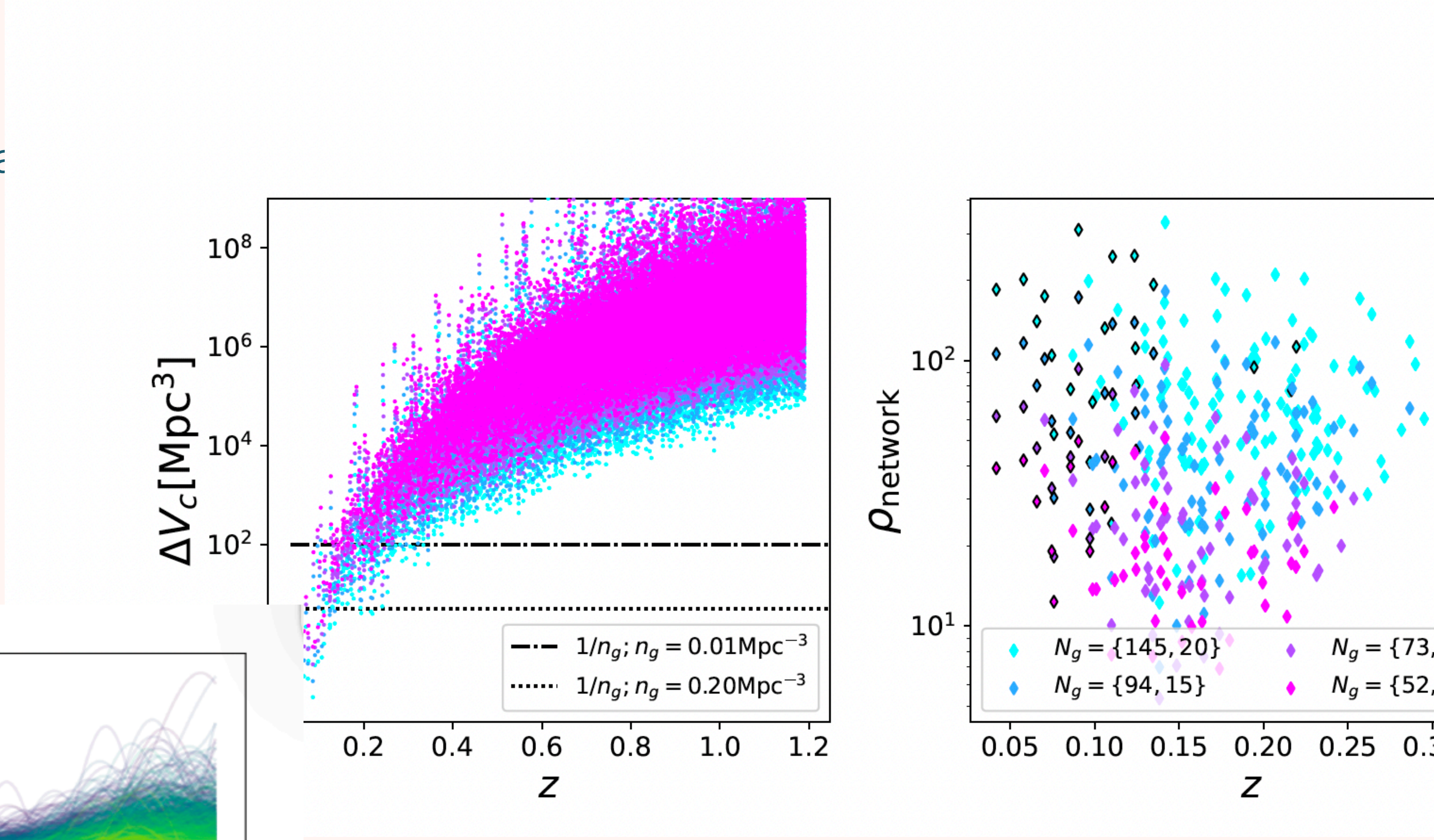
Equal Mass BBH

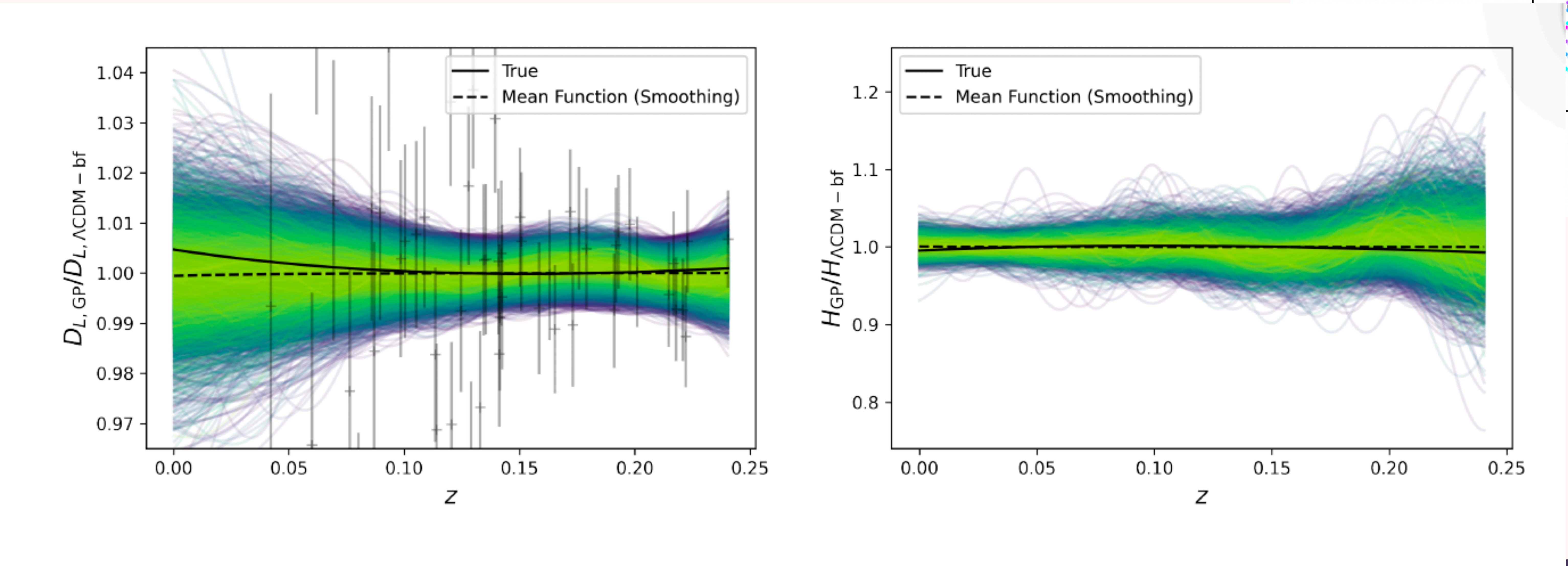


Distribution of SNR

Accuracy of the localization

- Large number of BBH with sufficiently accurate localization can be observed with detectors sensitive a lower frequencies.
- Technically feasible for ground-based detectors?





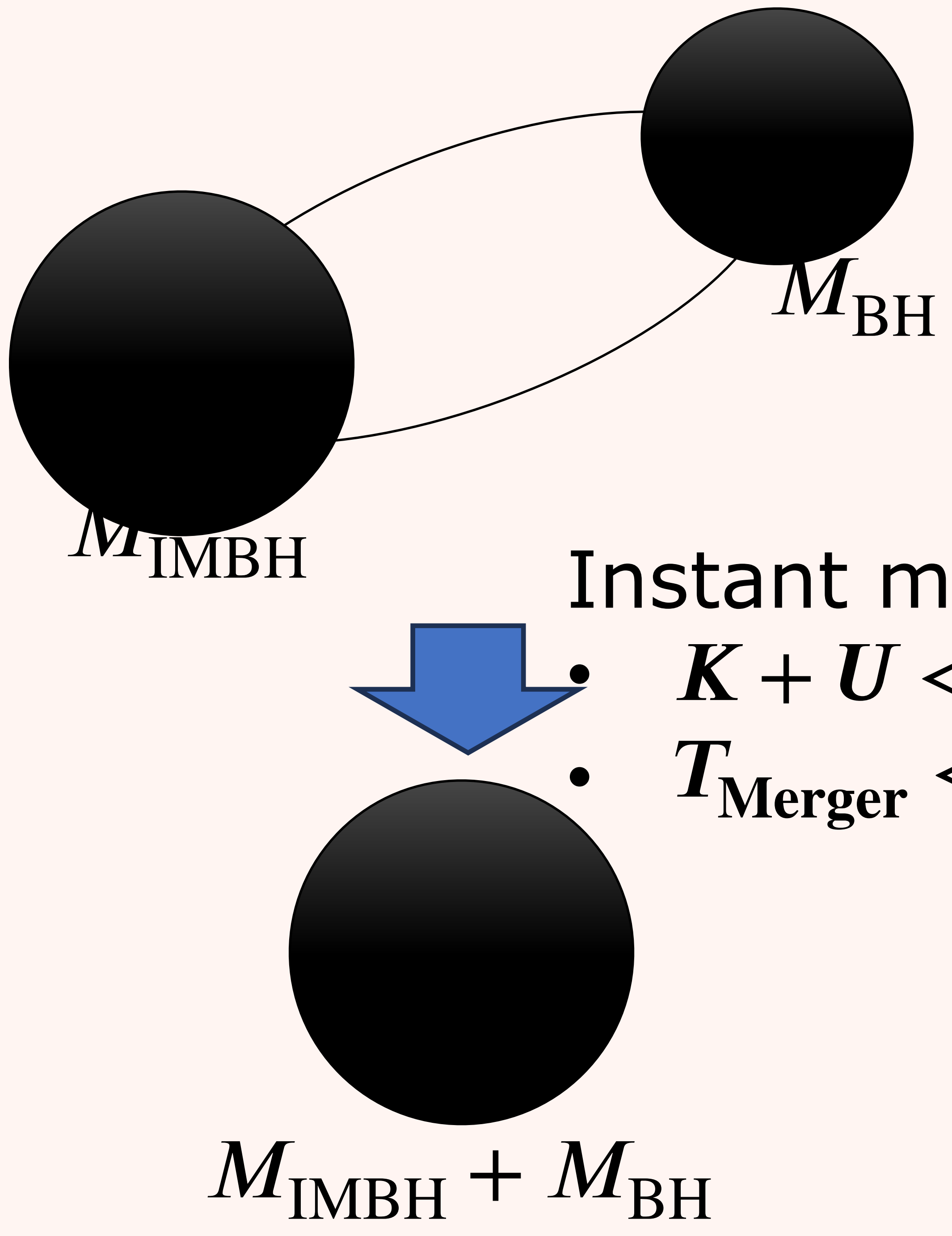
Intermediate-mass black holes (IMBHs)

- Black holes with mass $\sim 10^2 - 10^5 M_\odot$.
- They fill the mass gap between stellar-mass black holes (SBHs) and supermassive black holes (SMBH).
- They are critical in understanding massive black hole (MBH) evolution history.
- There is no conclusive evidence of IMBH so far.
- Globular clusters are good place for IMBH
- IMBH can form a binary stellar mass BH occasionally
  - We carries out dynamical evolution simulations of globular clusters with IMBH, stellar mass BH, and ordinary long-lived stars
- Can we prove that they exist by GW observation?
- They can also be precisely localized.

Modeling IMRIs and Their Signals

$h_{c,n}$: amplitude of n-th harmonics
S_{det}: detector's sensitivity

Simulation

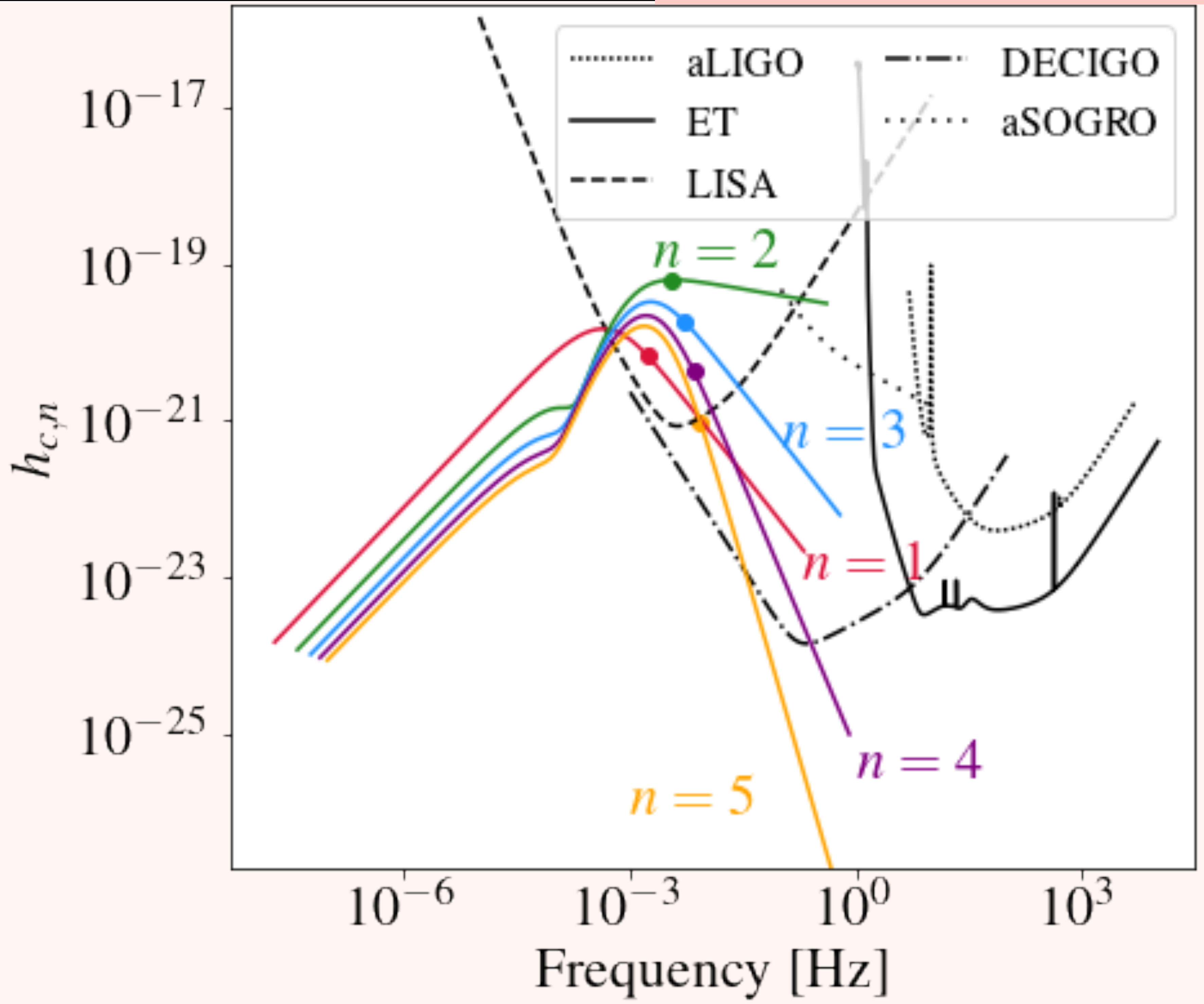


Instant merger if
- $K + U < 0$
- $T_{\mathrm{Merger}} < 1\ \mathrm{Myr}$

$$T_{\mathrm{Merger}} \equiv \frac{5}{256} \frac{c^5 a^4 (1-e^2)^{3.5}}{G^3 M_{\mathrm{IMBH}} M_{\mathrm{BH}} (M_{\mathrm{IMBH}} + M_{\mathrm{BH}})}$$

Binary properties
M: Mass
a: Semimajor axis
e: Eccentricity

GW Signal



S/N ratio from luminosity distance D_{L}:

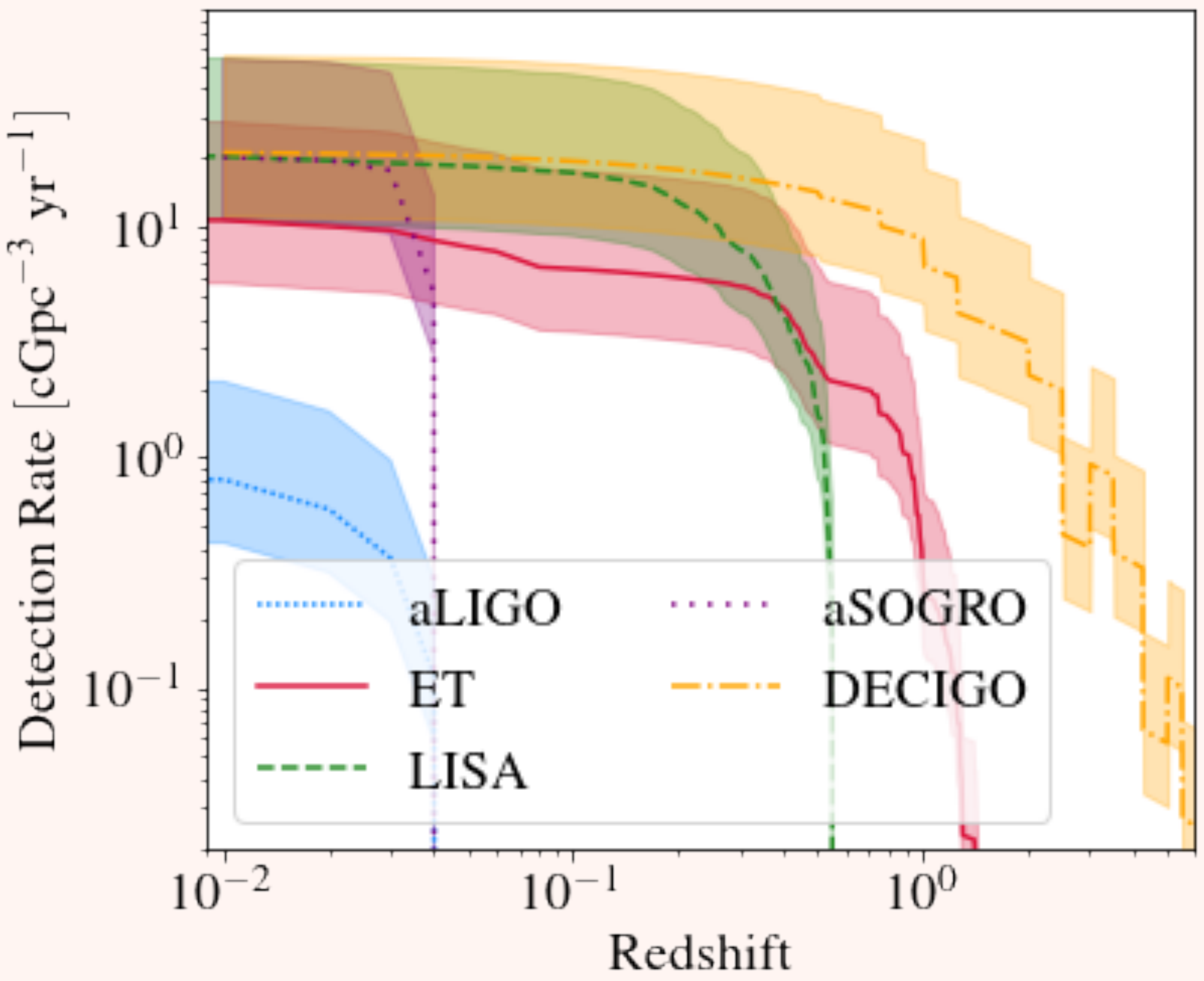
$$\left(\frac{S}{N}\right)^2 \sim \int \frac{h_c^2(f)}{S_{\mathrm{det}}^2(f)} \frac{d \ln f}{f}$$

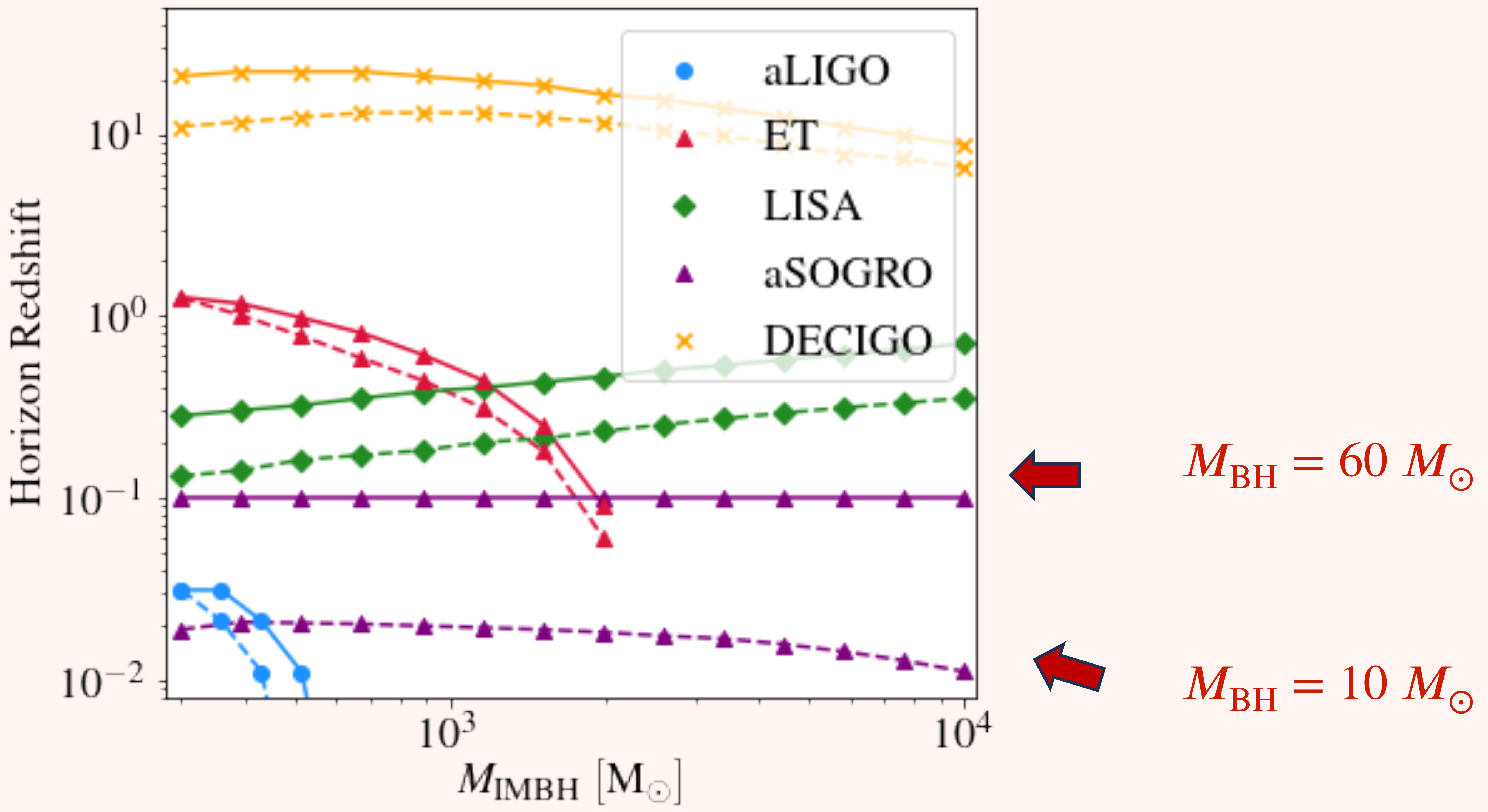
where

$$h_c \propto \frac{M_{\mathrm{IMBH}} M_{\mathrm{BH}}}{D_L (M_{\mathrm{IMBH}} + M_{\mathrm{BH}})^{1/3}} f^{2/3}$$

Horizon of the GW Telescopes ($300\ M_\odot \leq M_{\rm IMBH} \leq 5000\ M_\odot$)

S. Lee , H. M. Lee et al. 2025, ApJ





- Each GW observatory can offer unique capabilities, making them complementary to one another.
- E.g.) ET has a longer detection range, but LISA and aSOGRO have a broader mass spectrum.

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)

Eccentricities

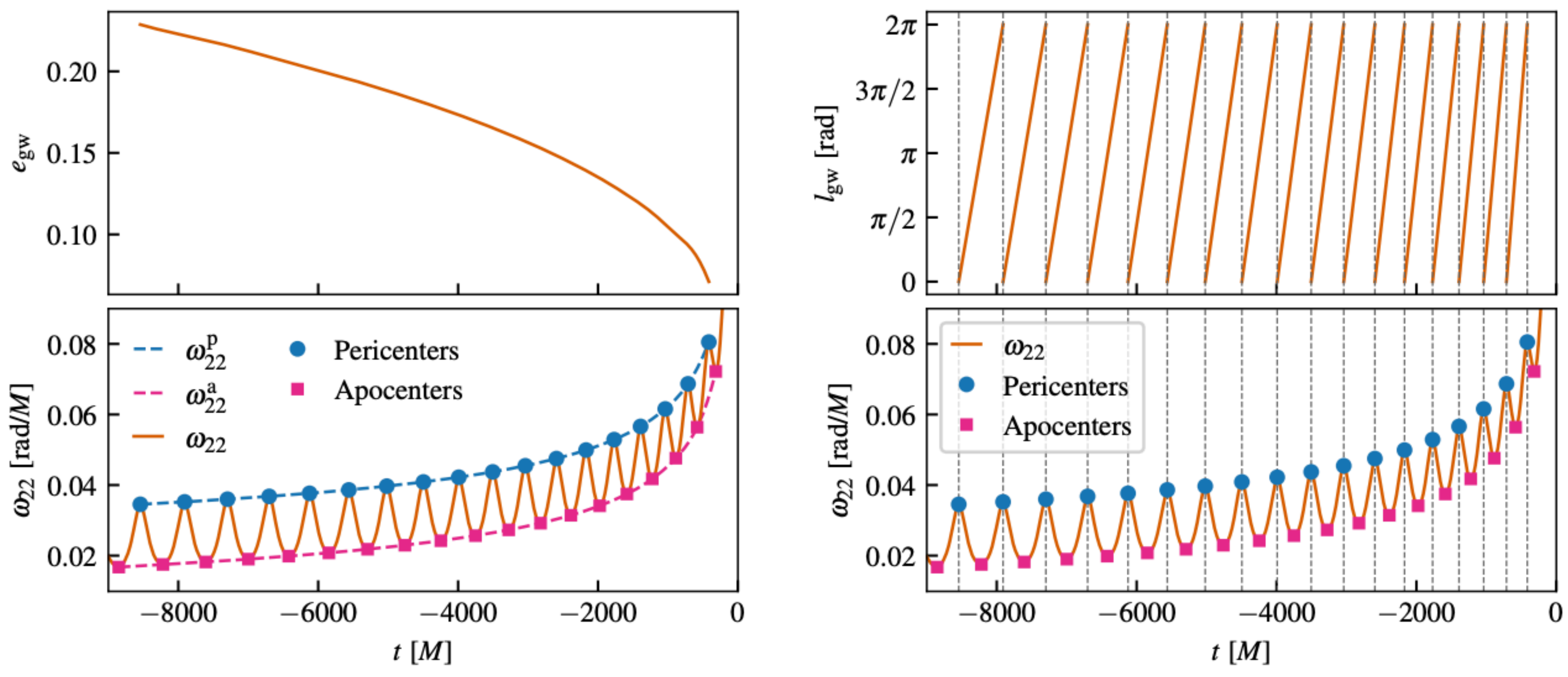
- What is the eccentricity?
  - It is uniquely defined in Keplerian orbits only.
  - In PN theory, there are three eccentricities, e_r, e_ϕ and e_t with e_t being dependent on gauge.
  - Different models may be using eccentricity that is defined differently.
- Recently, Shaikh et al. (2023) proposed definition of guage independent eccentricity from the GW frequency evolution.

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

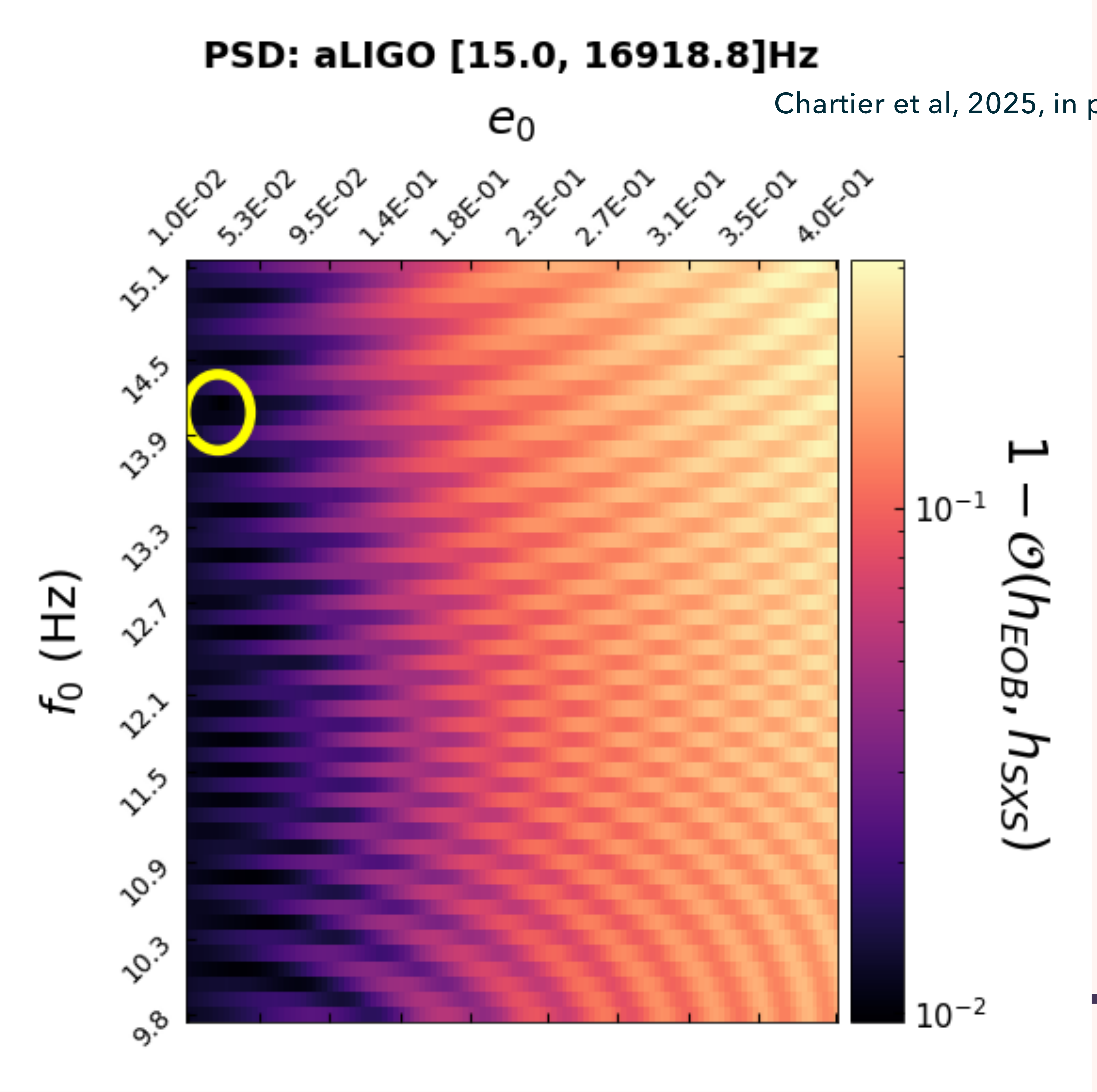
$$e_{\omega_{22}} = \frac{\omega_{22}^p - \omega_{22}^a}{\omega_{22}^p + \omega_{22}^a} \quad \Psi = \arctan\left(\frac{1 - e_{\omega_{22}}^2}{2e_{\omega_{22}}}\right)$$

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

Shaikh et al, 2023, PRD



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



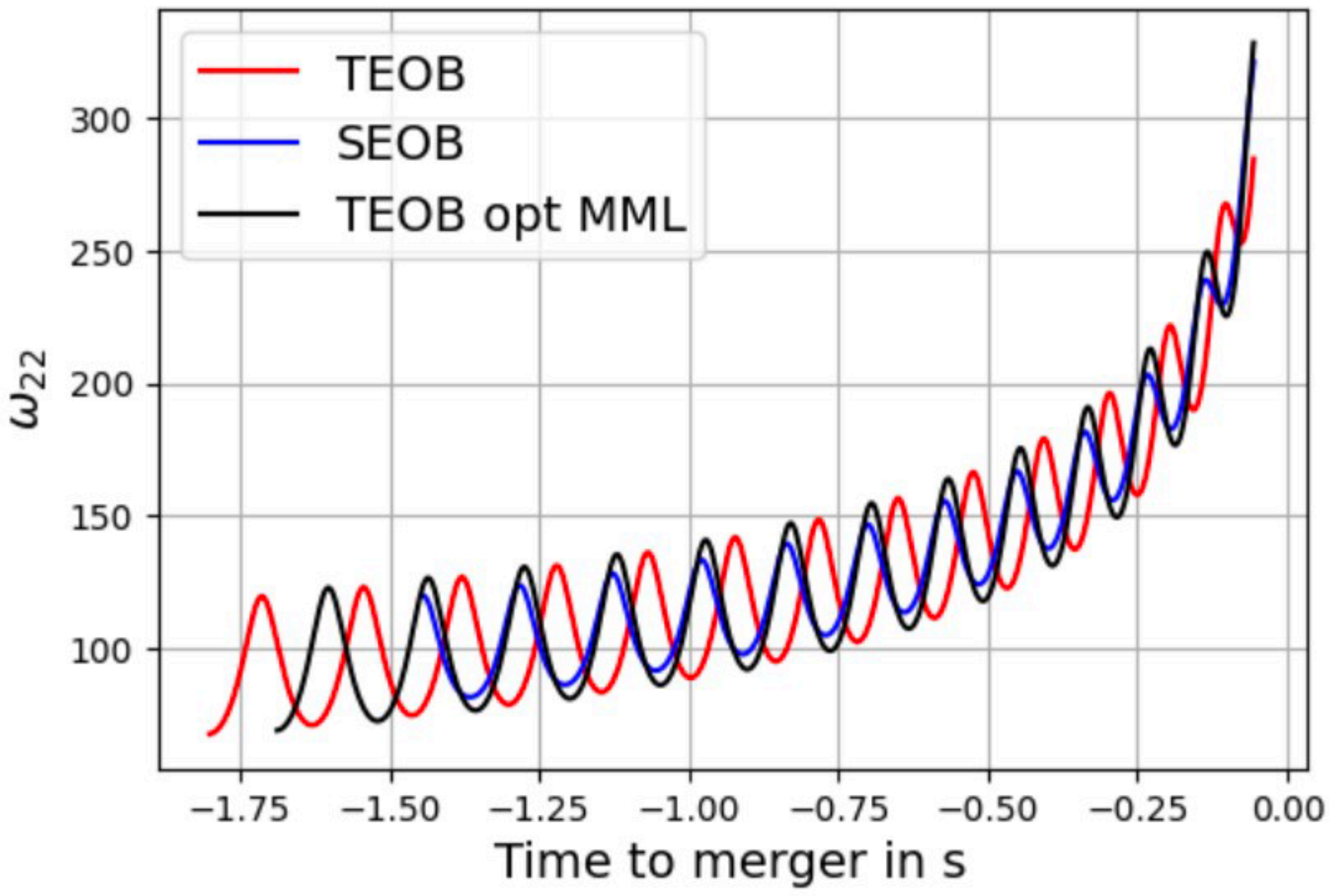
Chartier et al, 2025, in press

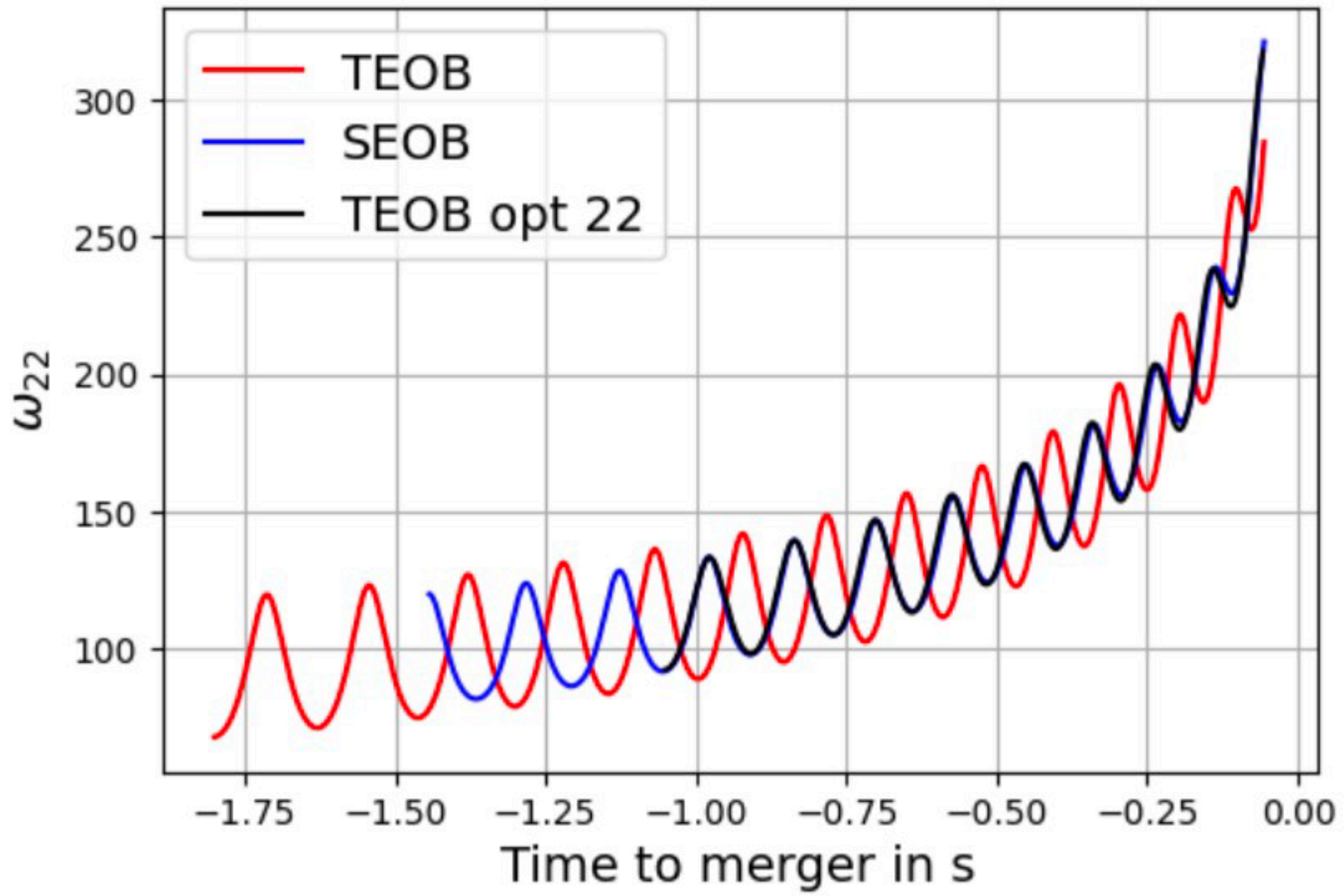
$$O(h_1, h_2) = \frac{< h_1 h_2 >}{|h_1||h_2|}$$

- 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, in press



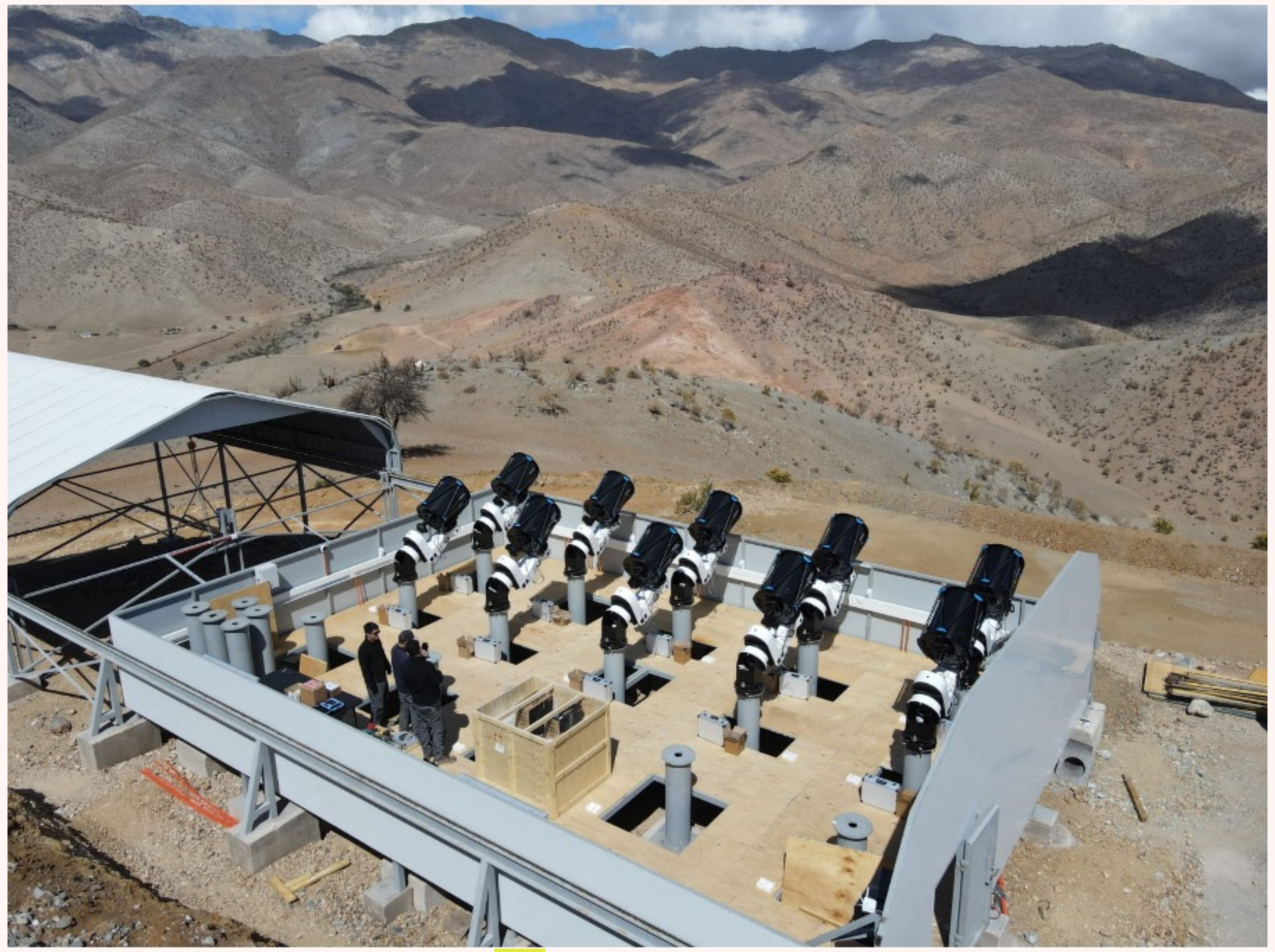


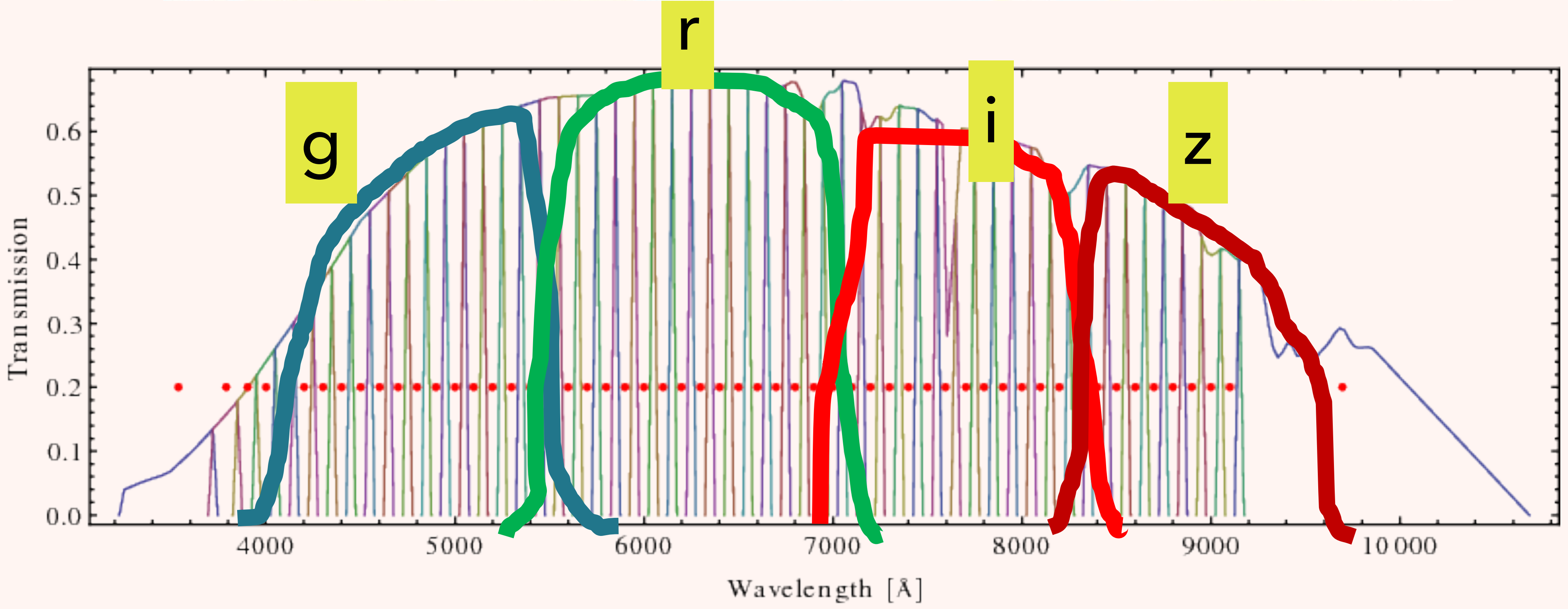
- If we require the same e_{gw} (t) behavior for different models, we sometimes end up with different phase evolution that means significant mismatch.

A new facility: 7Dimentional Telescope (김지훈, 11월 20일 오후 3:00)

- 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) —> **low resolution spectroscopy** for every pixel in the field of view
- It can cover **large area** of sky repeatedly:
  - Wide-field, time domain, spectroscopic telescope
  - Suitable for the survey of transients such as GRB and Kilonovae and other surveys require large FOV and spectroscopic information
- 16 telescopes are installed

Photo courtesy of Myungshin Im





GRB Modeling/ GW Data Analysis

- **GRB/Kilonova Theory and Modeling**
  - **Identification of High Latitude Emission in the Prompt Emission** (Tak, Uhm et al. 2023, ApJ; Uhm, Tak et al., 2024, ApJL)
  - **Ejecta Velocity Profile and Diversity of Kilonova Lightcurves** (Tak, Uhm & Gillanders 2023, ApJ)
  - **Effect of Ejecta Temperature and Mass on Strength of Heavy Element Signature in Kilonova** (Tak, Uhm & Gillanders, 2024, ApJ
- **GW Data Analysis and Parameter Estimation**
  - **Effects of Eccentricity and Spin** (Chunglee Kim, Jeongcho Kim & HWLee, 2025)
  - **Enhancement of Parameter Estimation for Lensed GW events** (Kyungmin Kim, Eunkwang Seo & Chunglee Kim, 2024, PRD)

Summary

- Since the first detection of GW in 2015, large number of binary merger events have been observed through four observing runs.
- O4 completed on November 18, and next run will take place in the second half of 2026
- Gravitational-waves can provide information on many parameters, including distances to the sources, allowing us to reconstruct the expansion history of the universe, independently.
  - However, we need to identify the host galaxies in order to probe cosmology.
    - 7DT is a unique telescope system that allows us to indentify Kilonova candidates rapidly.
  - BBHs are much more abundant among GW sources, but host identification is difficult.
    - We are working on fundamental studies for the understanding and utilization of dark sirens for cosmological research: long duration waveforms, potential of future detectors, statistical methods.