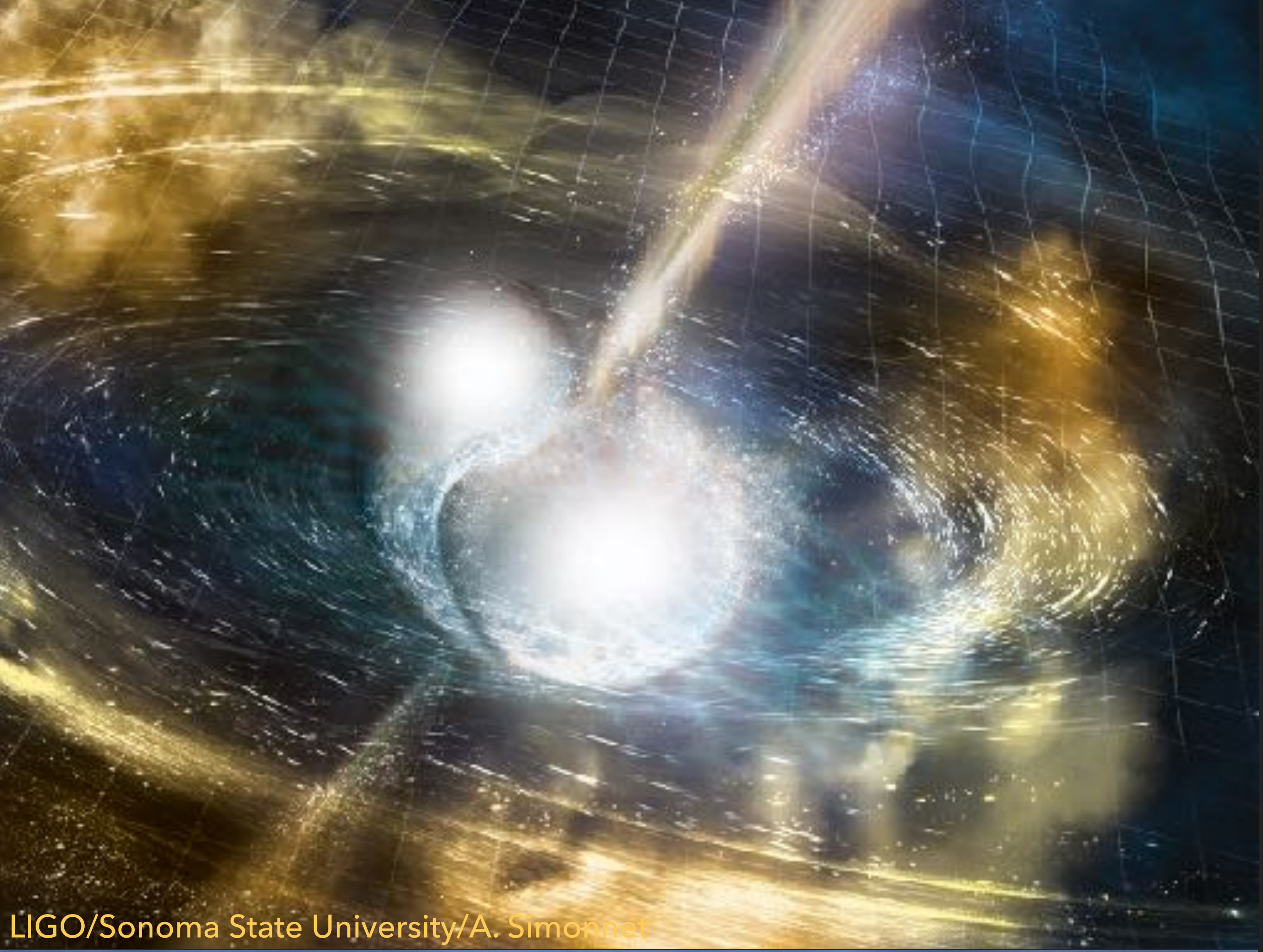


LIGO/Sonoma State University/A. Simonnet

LIGO

Update on Gravitational-Wave Standard Siren Cosmology

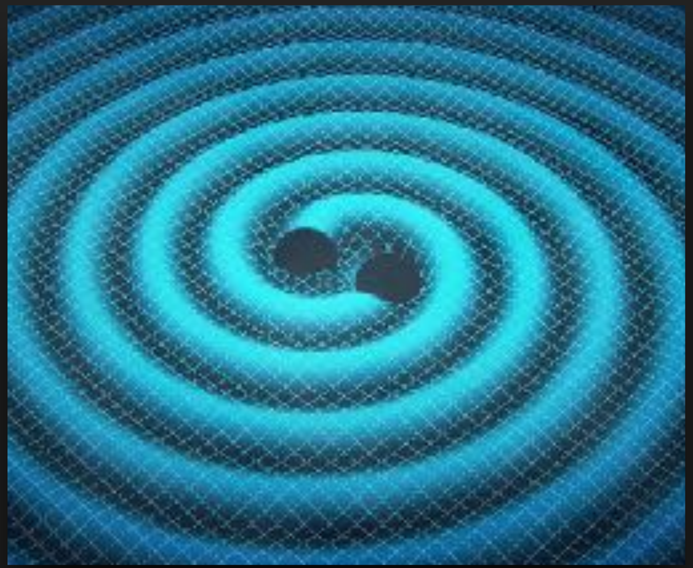
Daniel Holz
University of Chicago

Gravitational-wave standard siren

- Black holes are the simplest macroscopic objects in the Universe
- Binary coalescence is understood from first principles; provides direct absolute measurement of luminosity distance (Schutz 1986)
- Calibration is provided by General Relativity
- Need independent measurement of redshift to do cosmology*

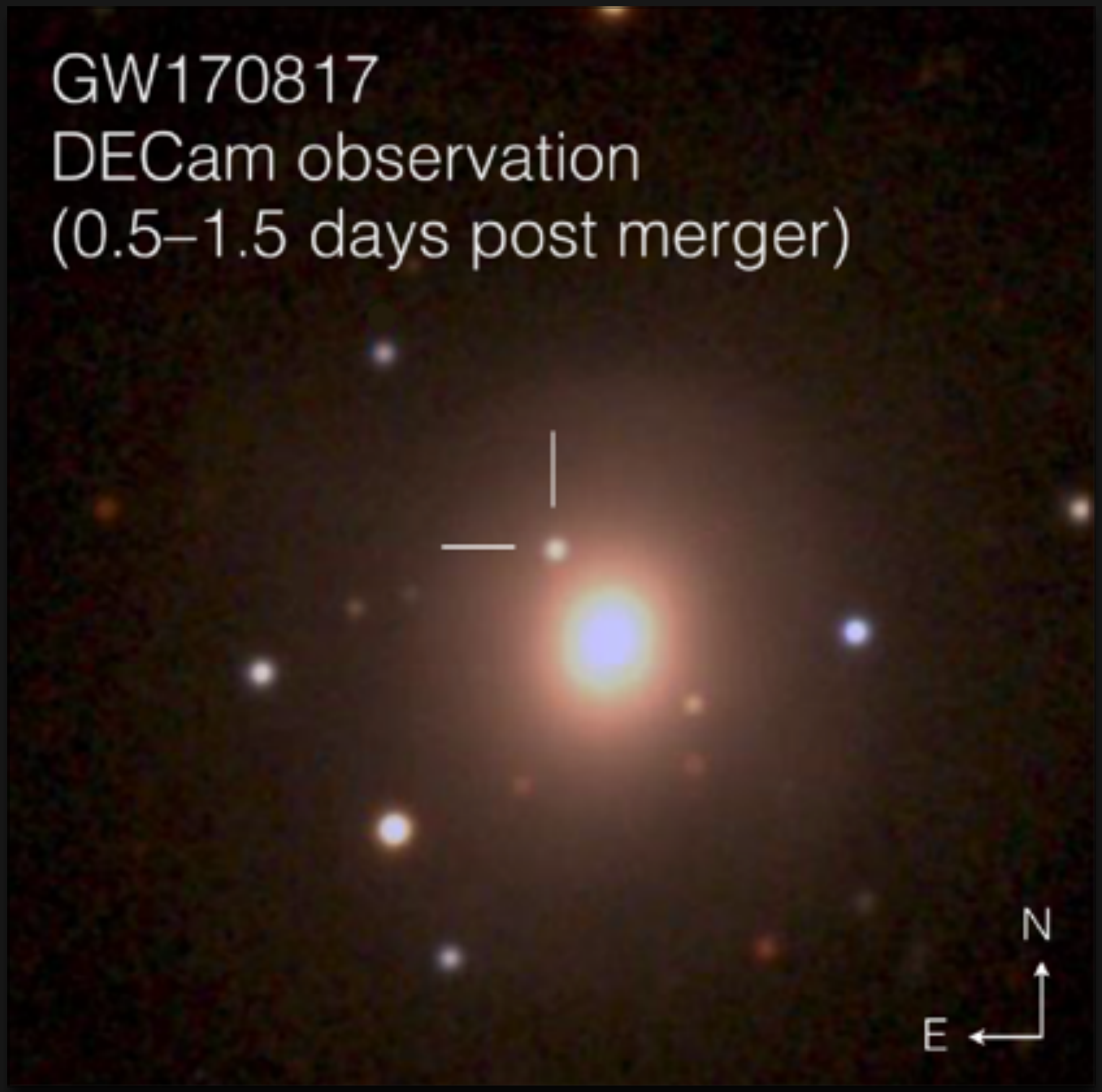
* Proposals to use mass distribution, EOS, etc.

Finn 1996; Taylor, Gair, & Mandel 2012; Messenger & Read 2012; Del Pozzo, Li, & Messenger 2017; Farr+ 2020; Ezquiaga & DH 2021; Chatterjee+ 2021



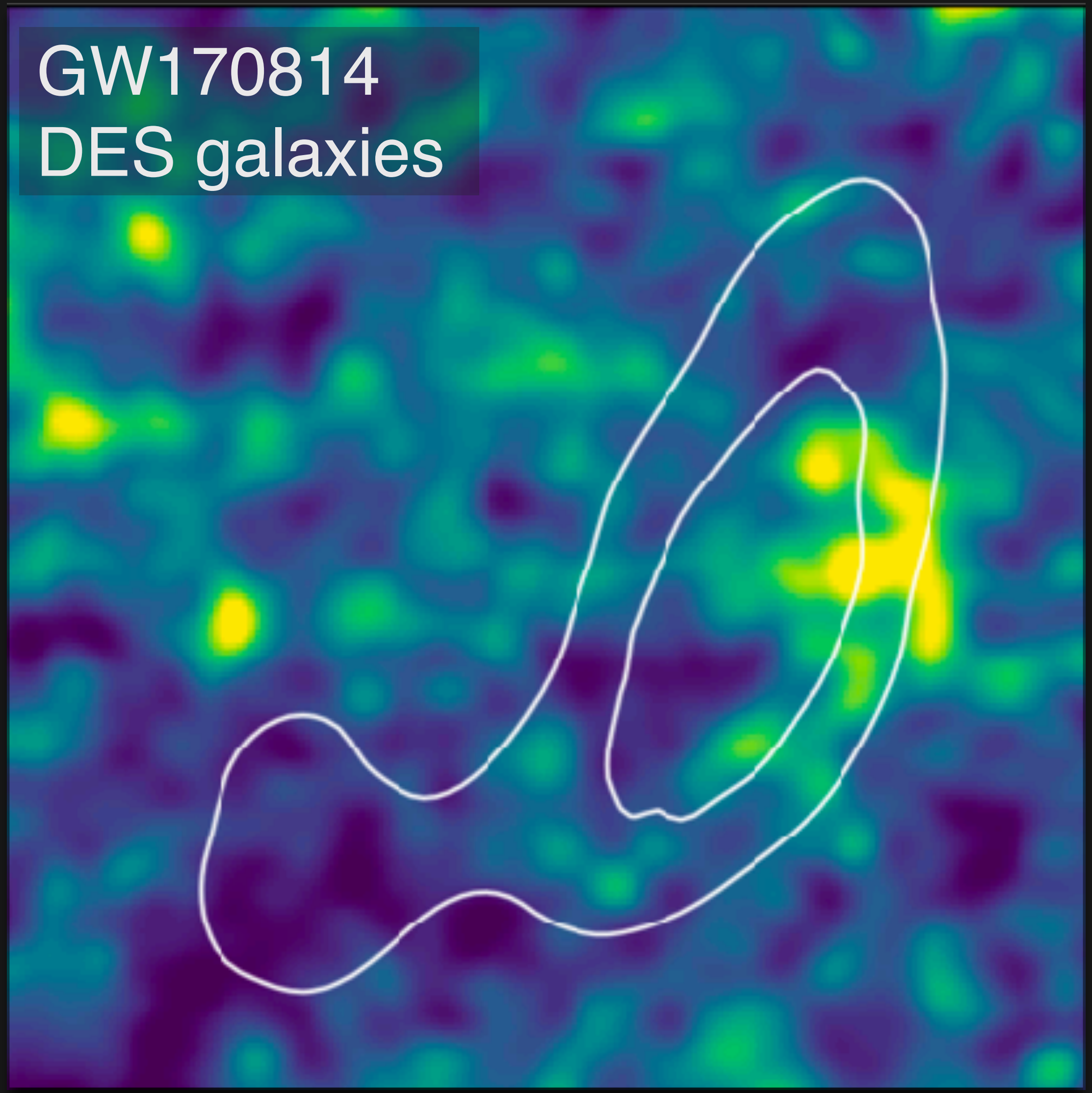
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

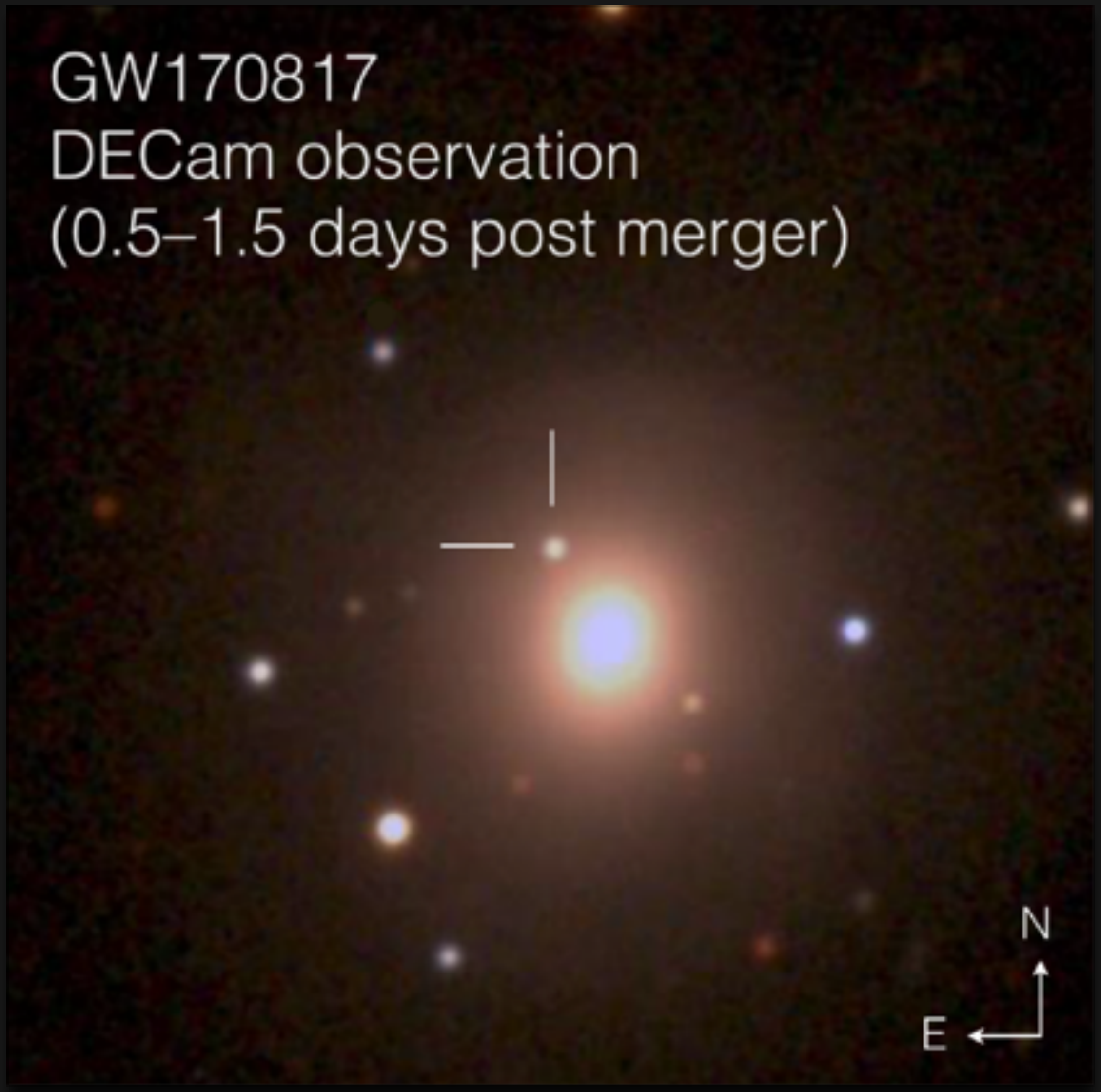
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

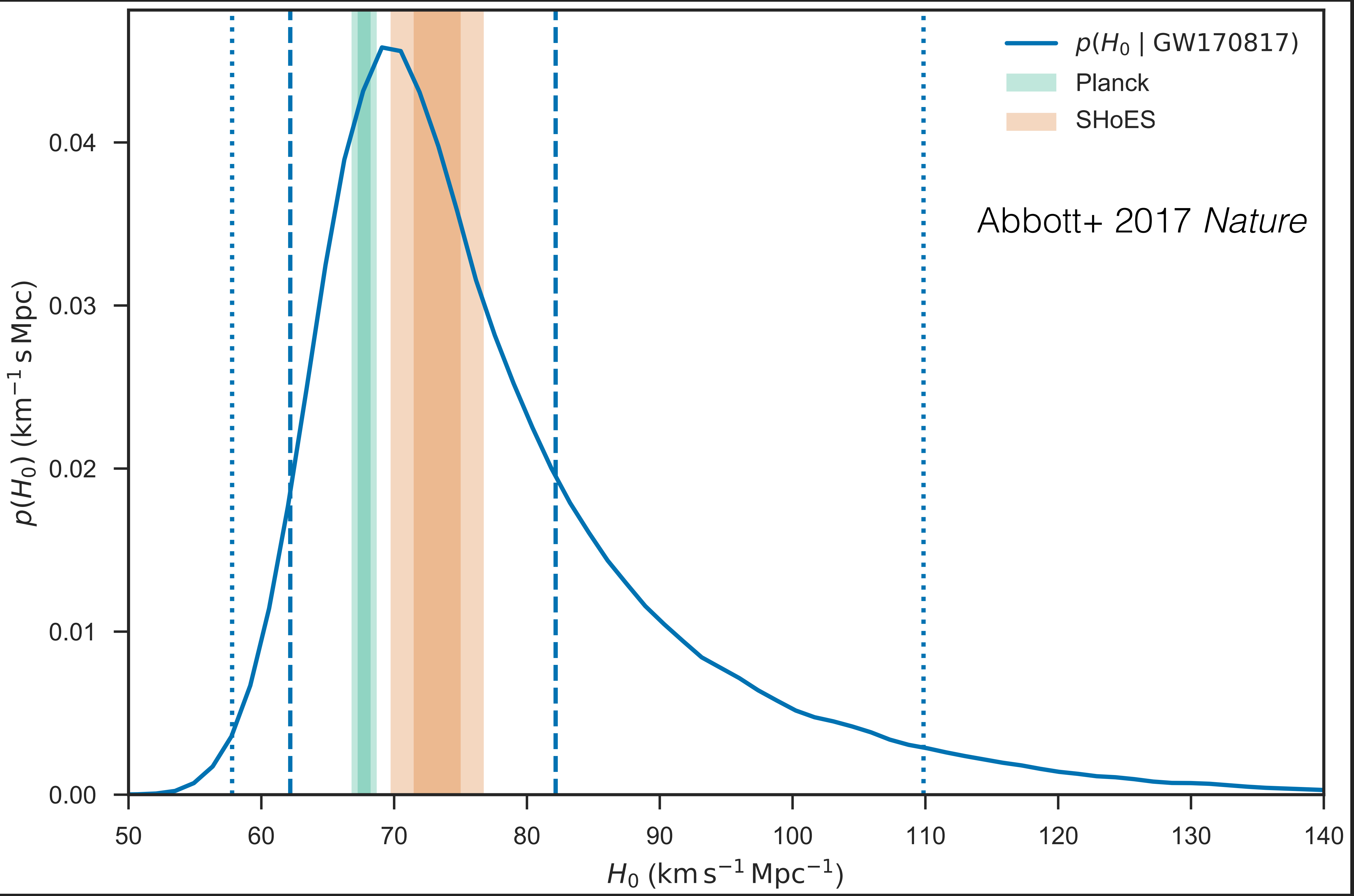
Counterpart/Bright



Unique host galaxy

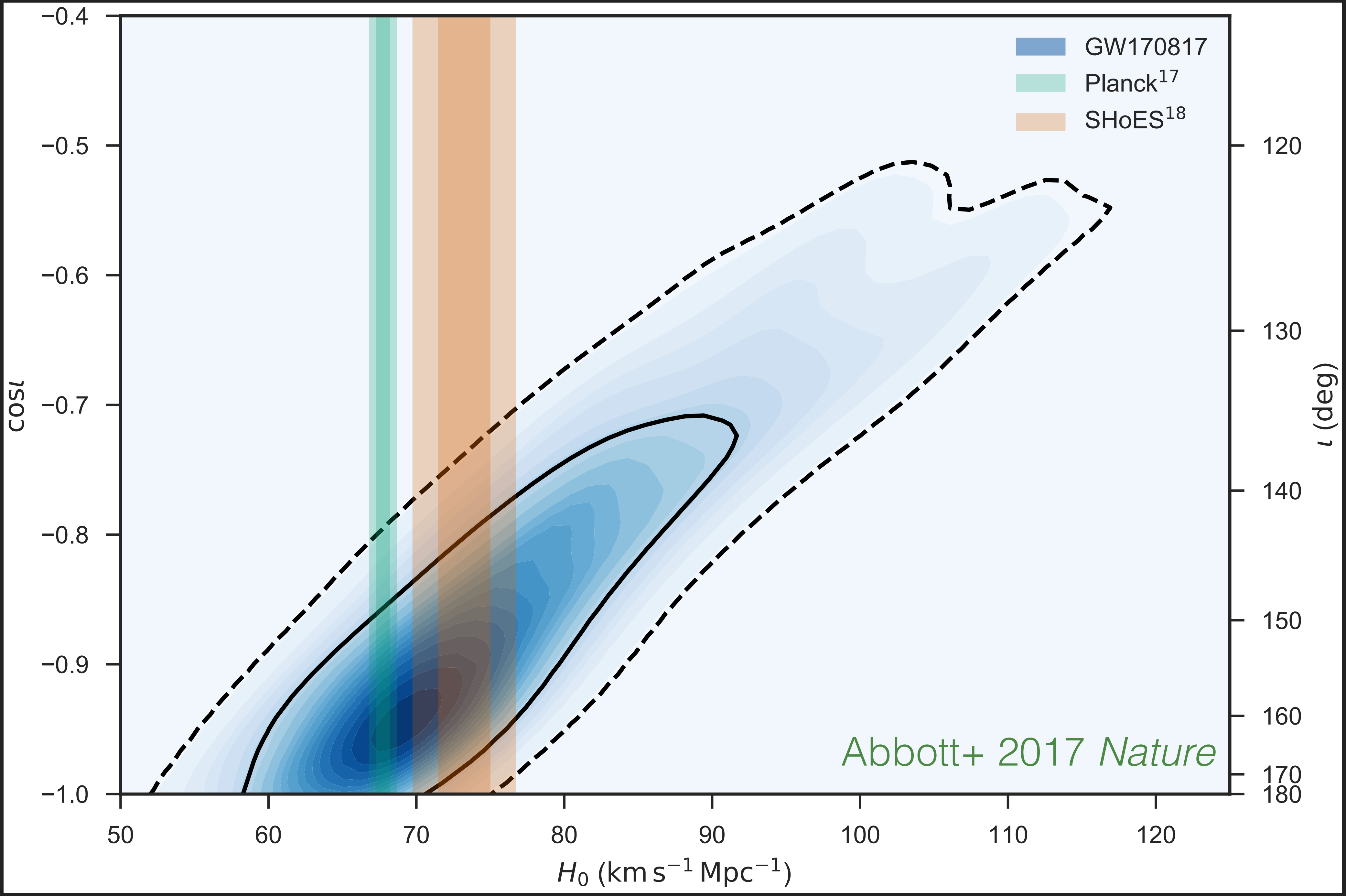
- Gravitational waves provide distance and photons provide redshift
- Pros: clean and direct way to put a point on the luminosity distance-redshift curve
- Cons: need an EM counterpart and associated redshift

Standard siren measurement of the Hubble constant



$$H_0 = 70.0^{+12}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

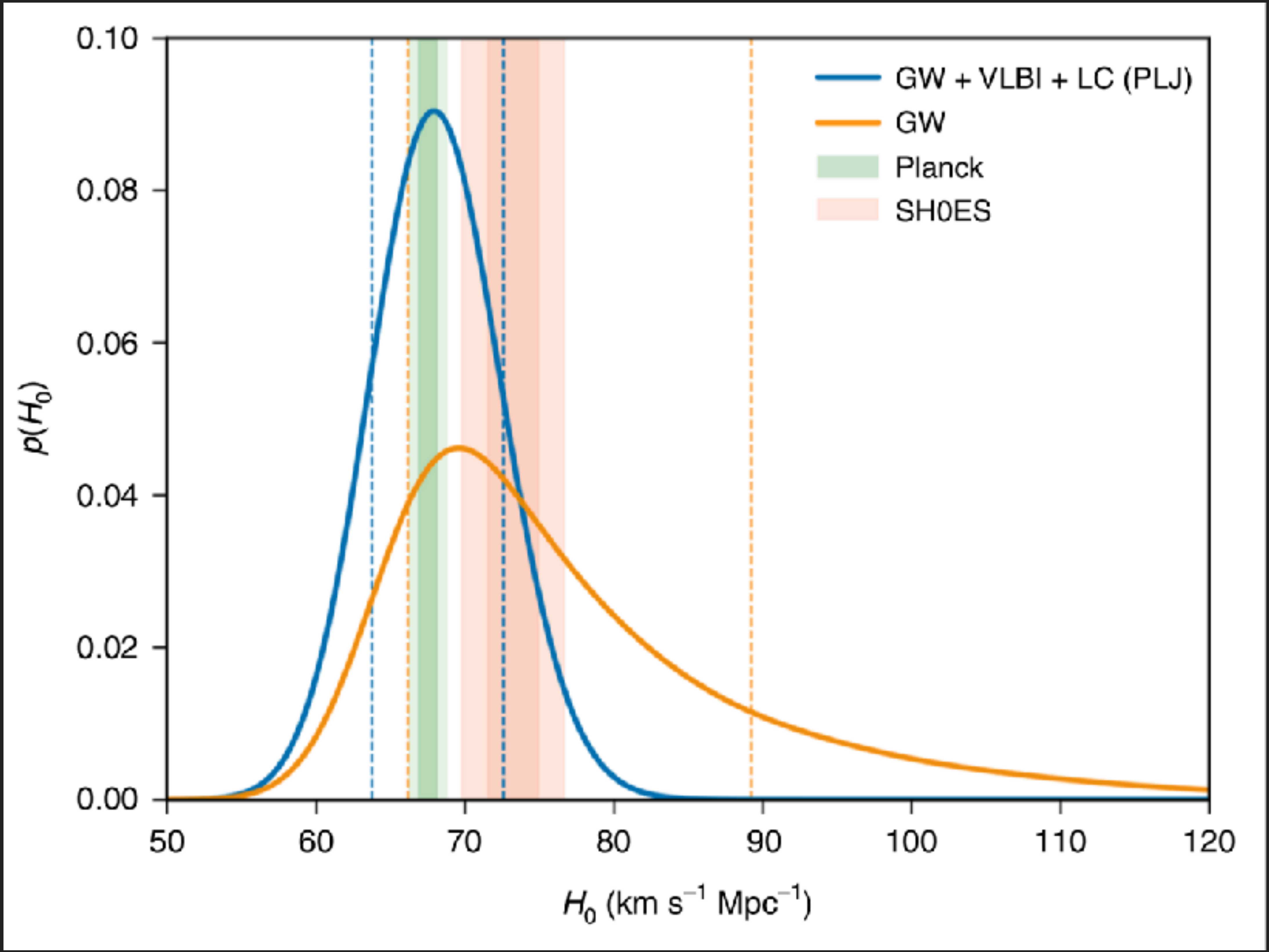
Distance is correlated with inclination



- If you know cosmology, can improve measurement of inclination
- If you know inclination, can improve measurement of cosmology

Dalal, DH, Hughes, & Jain 2006; Schutz 2011; Abbott+ 2017

If you know inclination, can improve cosmology

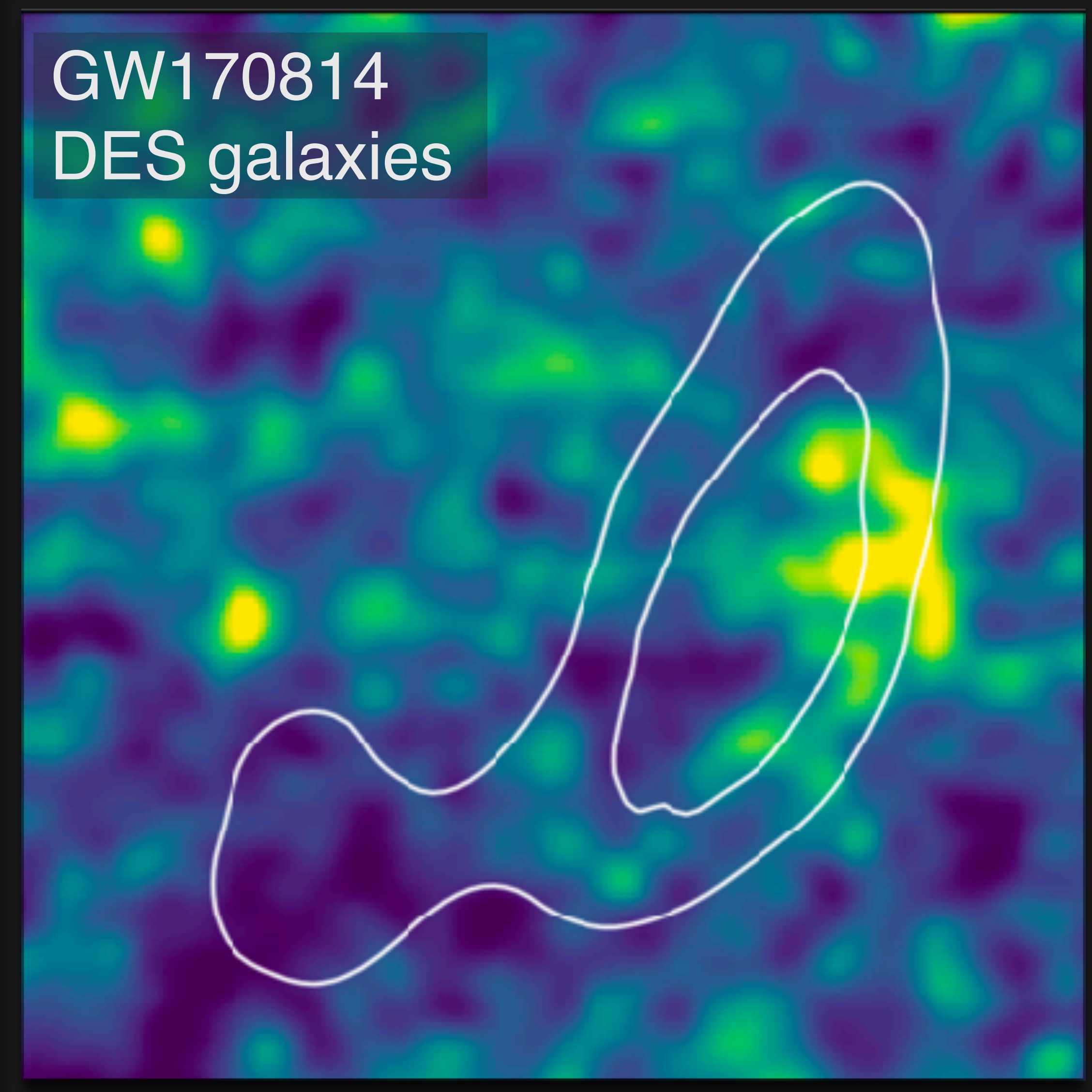


Hotokezaka+ 2018 based on radio observations from Mooley+ 2018
Also Abbott+ 2017; Guidorzi+ 2017

Two standard siren approaches

Statistical/Dark

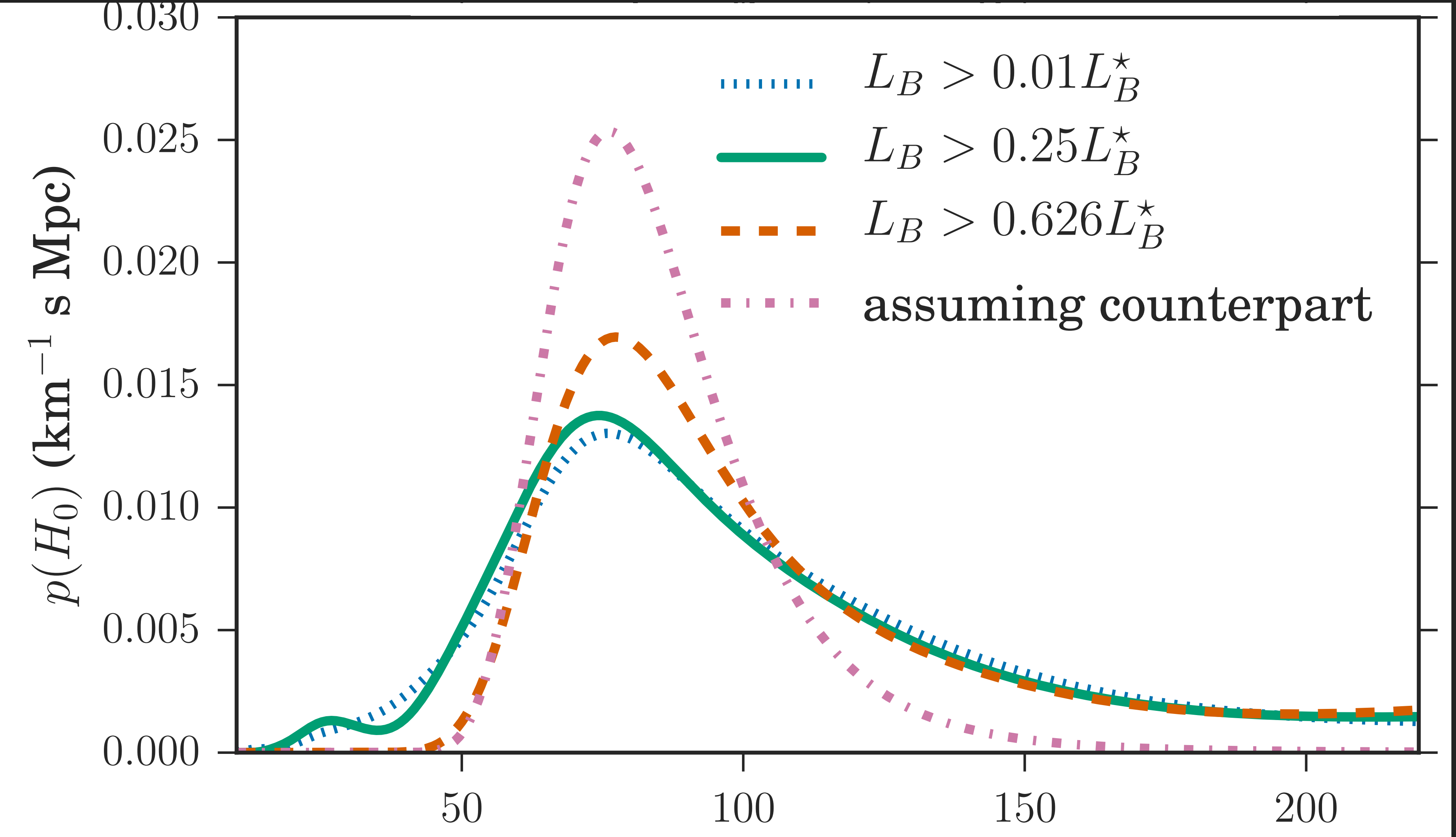
- "Schutz method" (Schutz 1986)
- If you can't identify the unique host galaxy, then use all galaxies in the 3D localization volume
- Pros: can be done for all GW sources, including BBH mergers
- Cons: there are many, many galaxies in the Universe



Use all galaxies in localization volume

GW170817 as a dark standard siren

- Apply statistical standard siren method to GW170817
  - Ignore the electromagnetic counterpart and associated host galaxy
  - Instead, consider every galaxy in localization volume as a potential host, calculate H_0 for each one, and combine

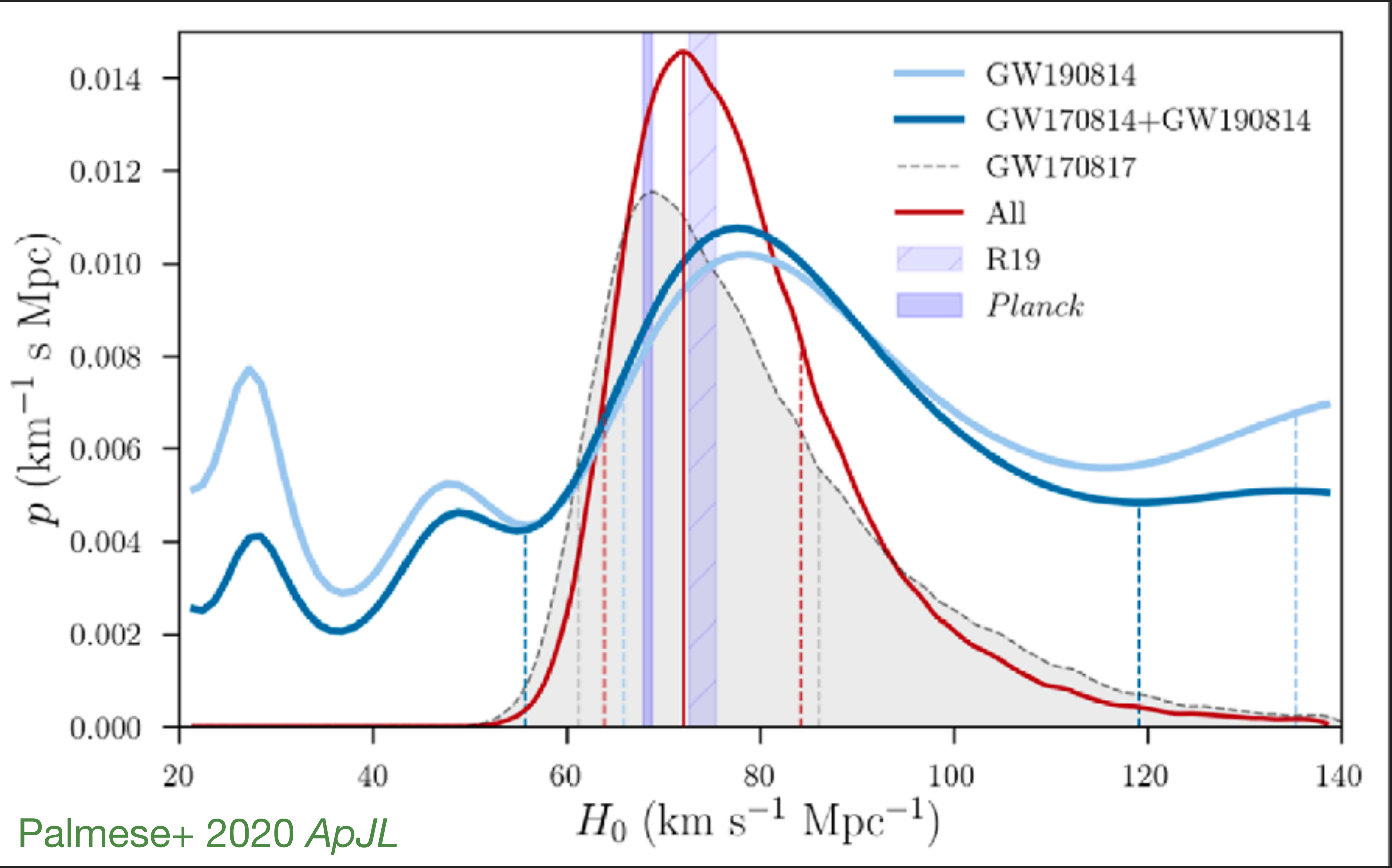


Fishbach+ 2019 *ApJL*

$$H_0 = 77^{+37}_{-18}\,\mathrm{km/sec/Mpc}$$

Dark sirens

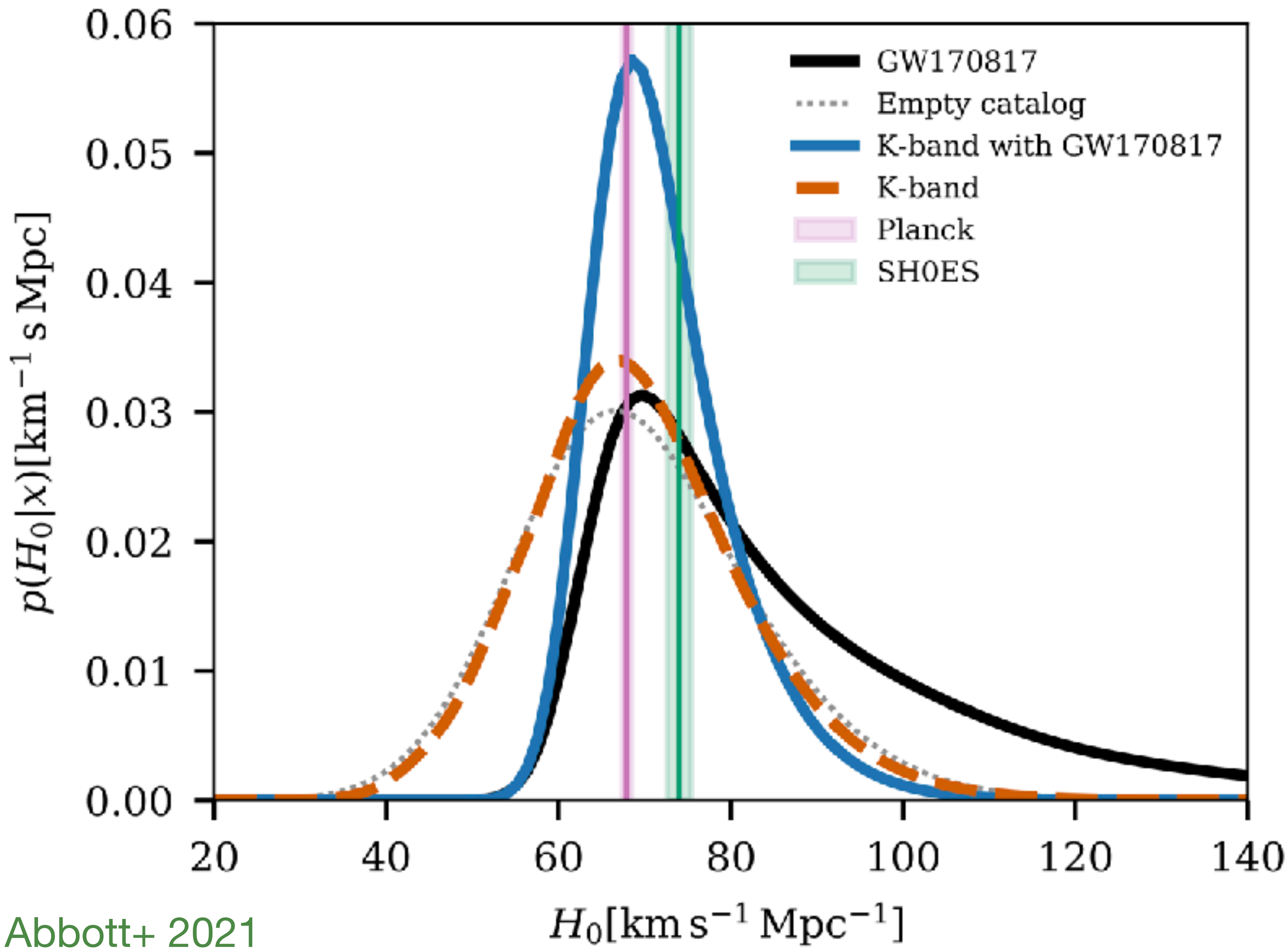
- Statistical standard siren applied to GW190814



Palmese+ 2020 *ApJL*

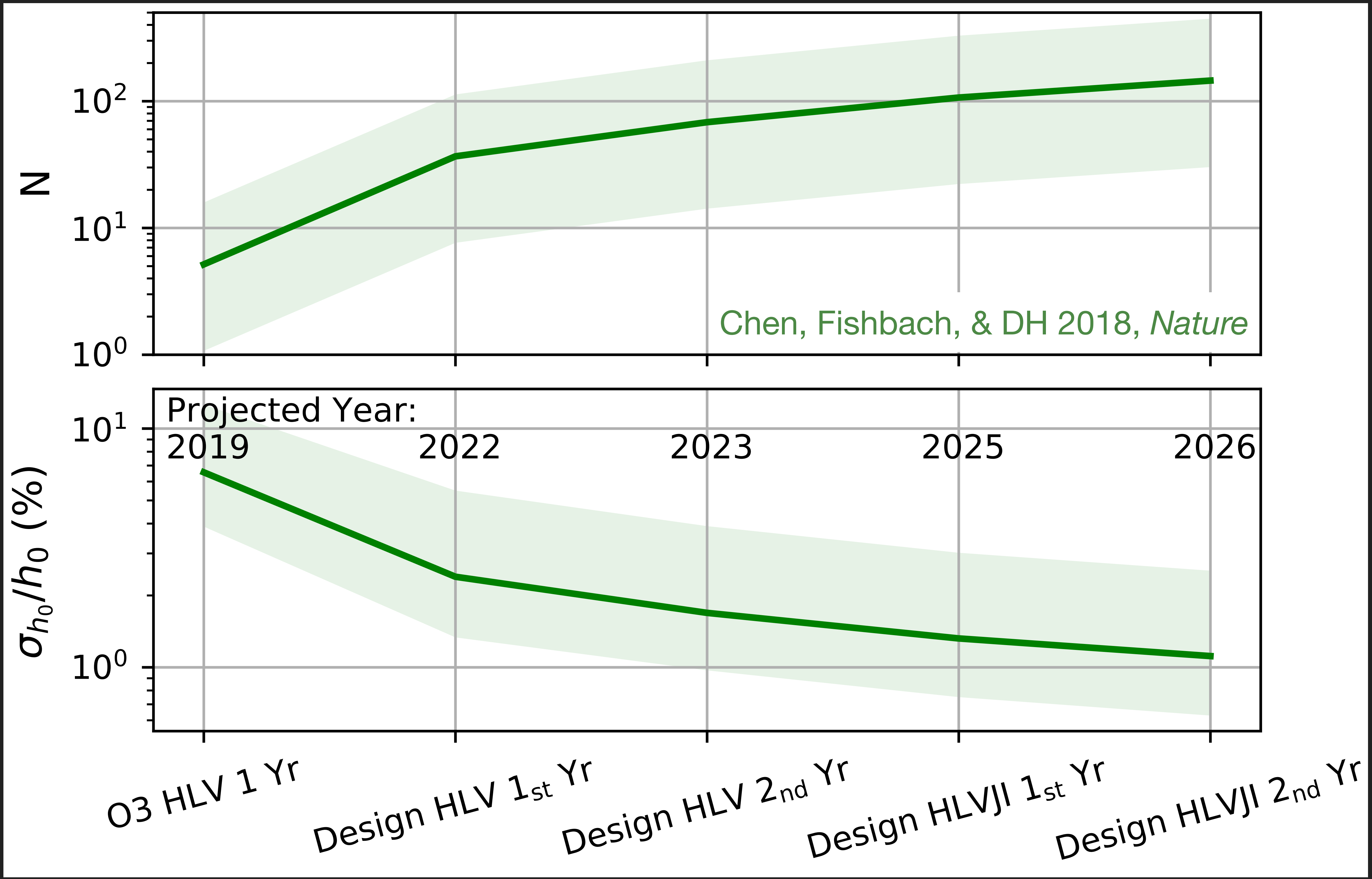
Dark sirens

- Statistical standard siren approach, for BBHs through O3



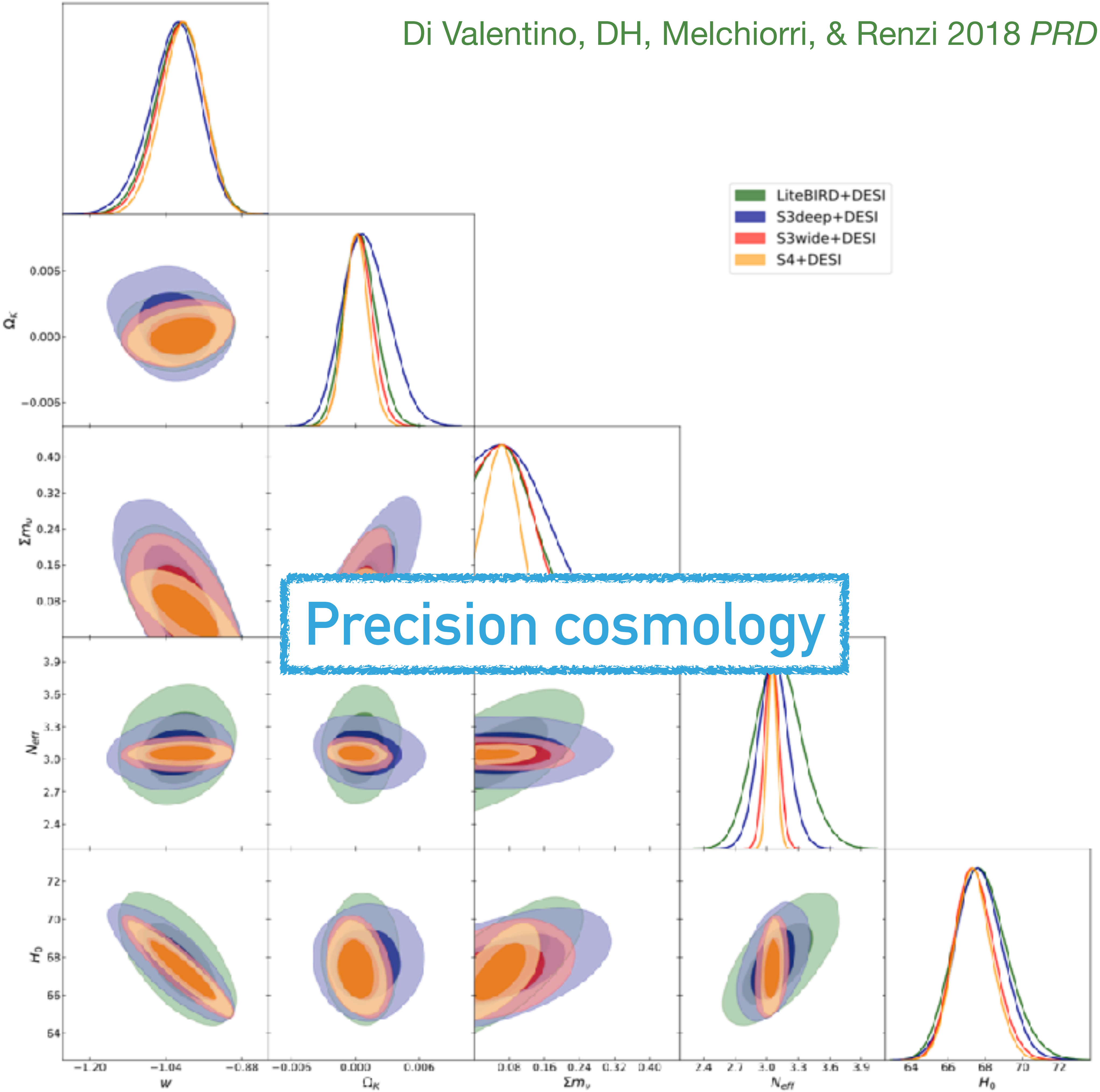
Abbott+ 2021

Precision standard siren cosmology (eventually)



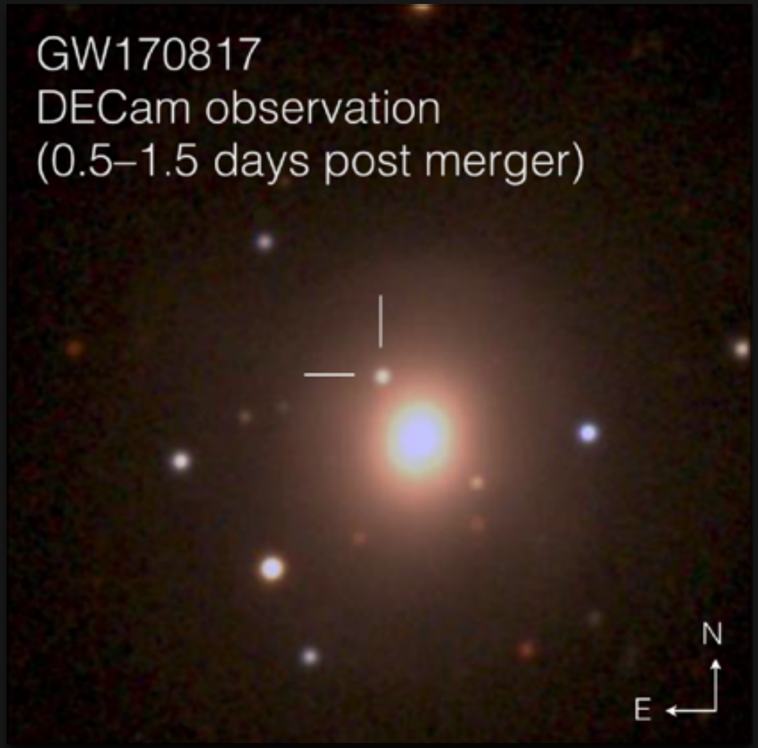
Interesting constraints with ~40 bright sirens

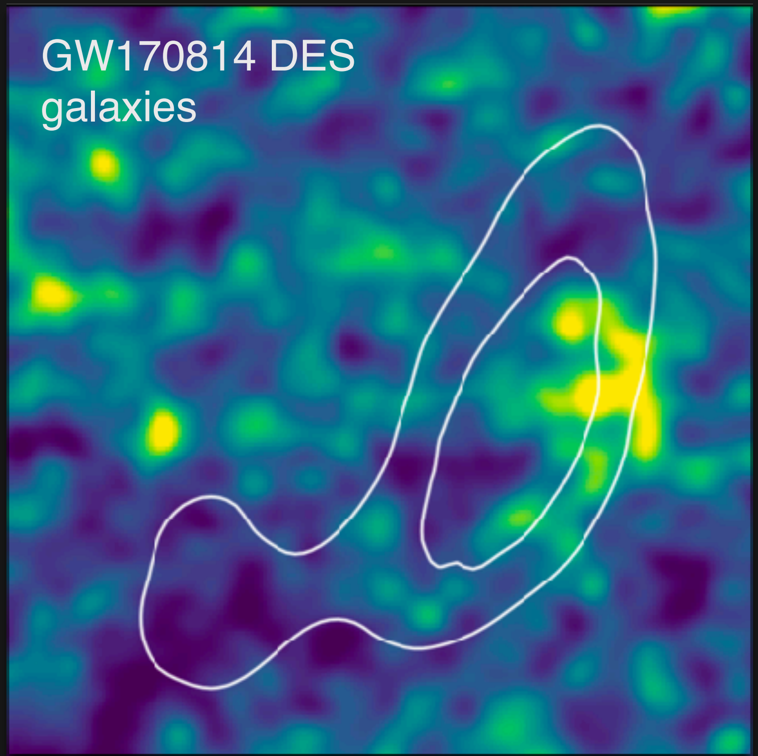
Di Valentino, DH, Melchiorri, & Renzi 2018 *PRD*



Finding EM counterparts will be difficult

- Complete galaxy catalogs to requisite depth will be unlikely/impossible. Statistical method won't work for most sources
- Finding kilonovae to requisite depth will be almost impossible
- Finding short GRBs to requisite depth will be difficult. Identifying host galaxies will be very difficult
- "Traditional" standard siren approaches probably won't scale





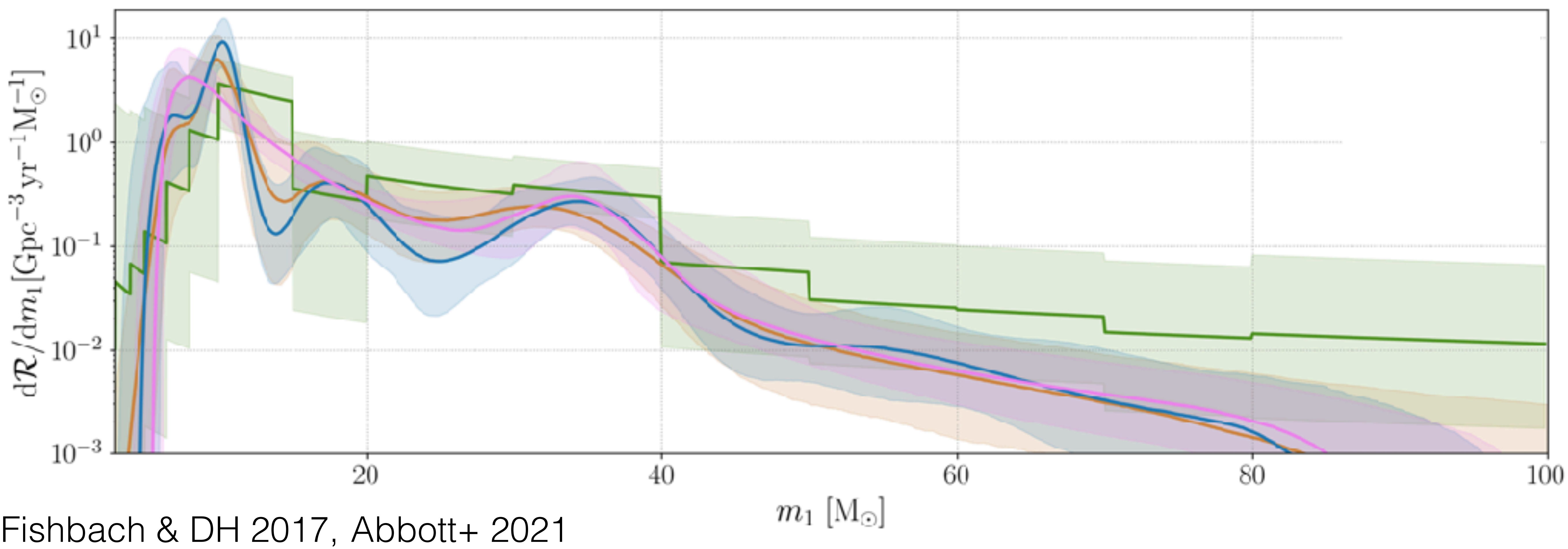
Standard siren systematics

- Peculiar velocities (Howlett & Davis 2019; should become negligible)
- Model selection (priors over GW population impact final results [e.g. rate evolution, mass distribution]; Abbot+ 2017; Chen, Fishbach, & DH 2018; Fishbach, DH+ 2018; Feeney+ 2018; Mortlock+ 2019)
- Inclination distribution (can be fit out). EM constraints on inclination (Chen 2020)
- Statistical standard sirens: Galaxy mis-identification? Galaxy catalog incompleteness? Redshift systematics?
- Failure of general relativity (Keeley+ 2019)?

- Absolute calibration of GW detectors: amplitude response as a function of frequency (Cahillane+ 2017; Payne+ 2020; Sun+ 2020, 2021; Vitale+ 2021…)
    - 1% measurement of H_0 requires 1% calibration of amplitude response

Non-standard standard siren approaches

There are features in the mass distribution!

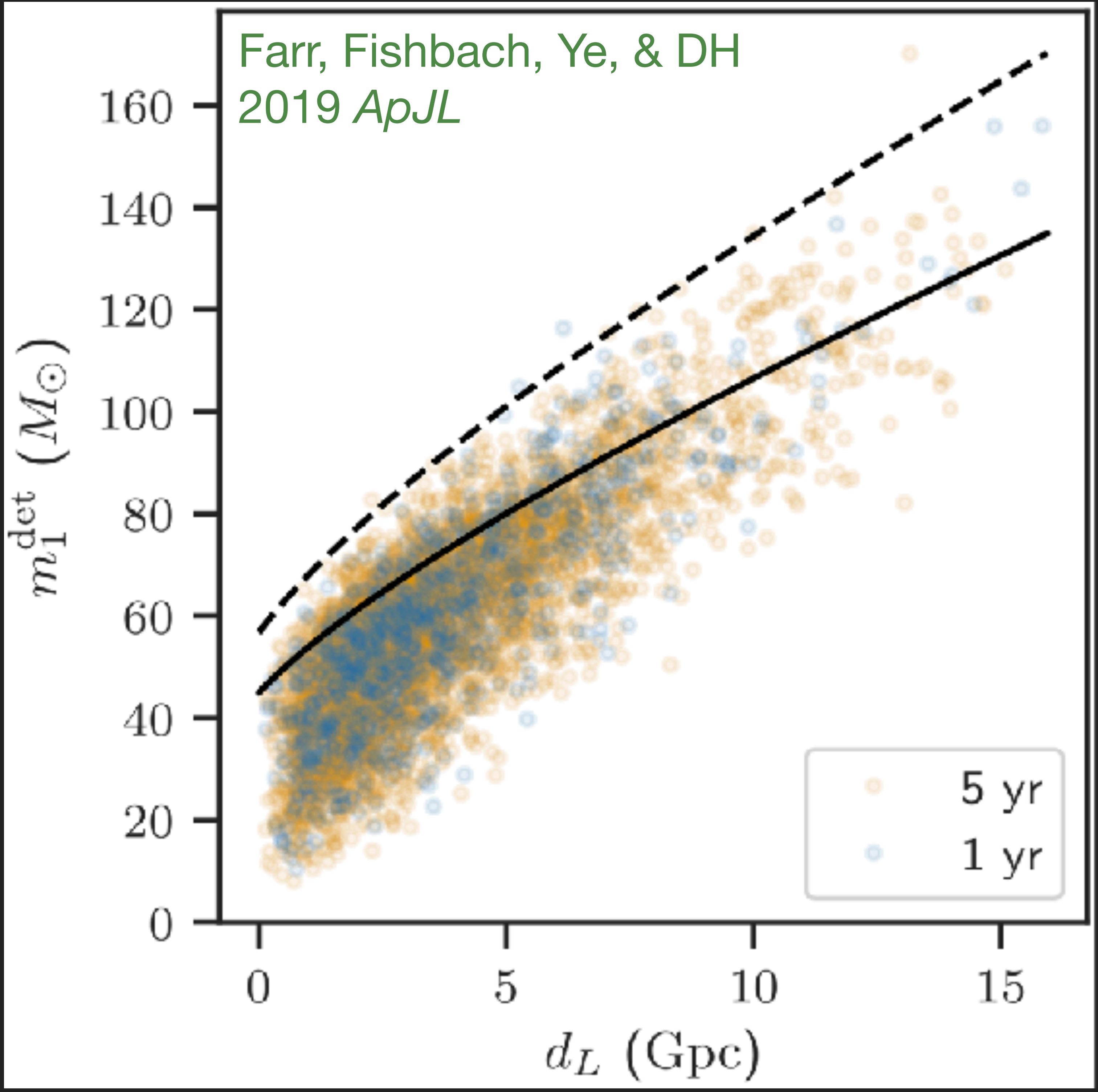


Fishbach & DH 2017, Abbott+ 2021

- The rate of BBHs with component BBHs above $\sim 45\, M_\odot$ drops precipitously
- This is roughly consistent with expectations from the existence of pair-instability supernovae
- Can use this “feature” to do cosmology!

A new method for standard siren cosmology

- LIGO/Virgo is missing big black holes (Fishbach & DH 2017, Abbott+ 2019)
- Existence of upper mass gap, as expected from pulsational/pair instability supernovae
- The edge of the mass gap imprints an "absorption" feature in the mass distribution of binary black holes
- Five years of observation of binary black holes with Advanced LIGO/Virgo would constrain $H(z)$ at pivot redshift of $z \sim 0.75$ to 2%



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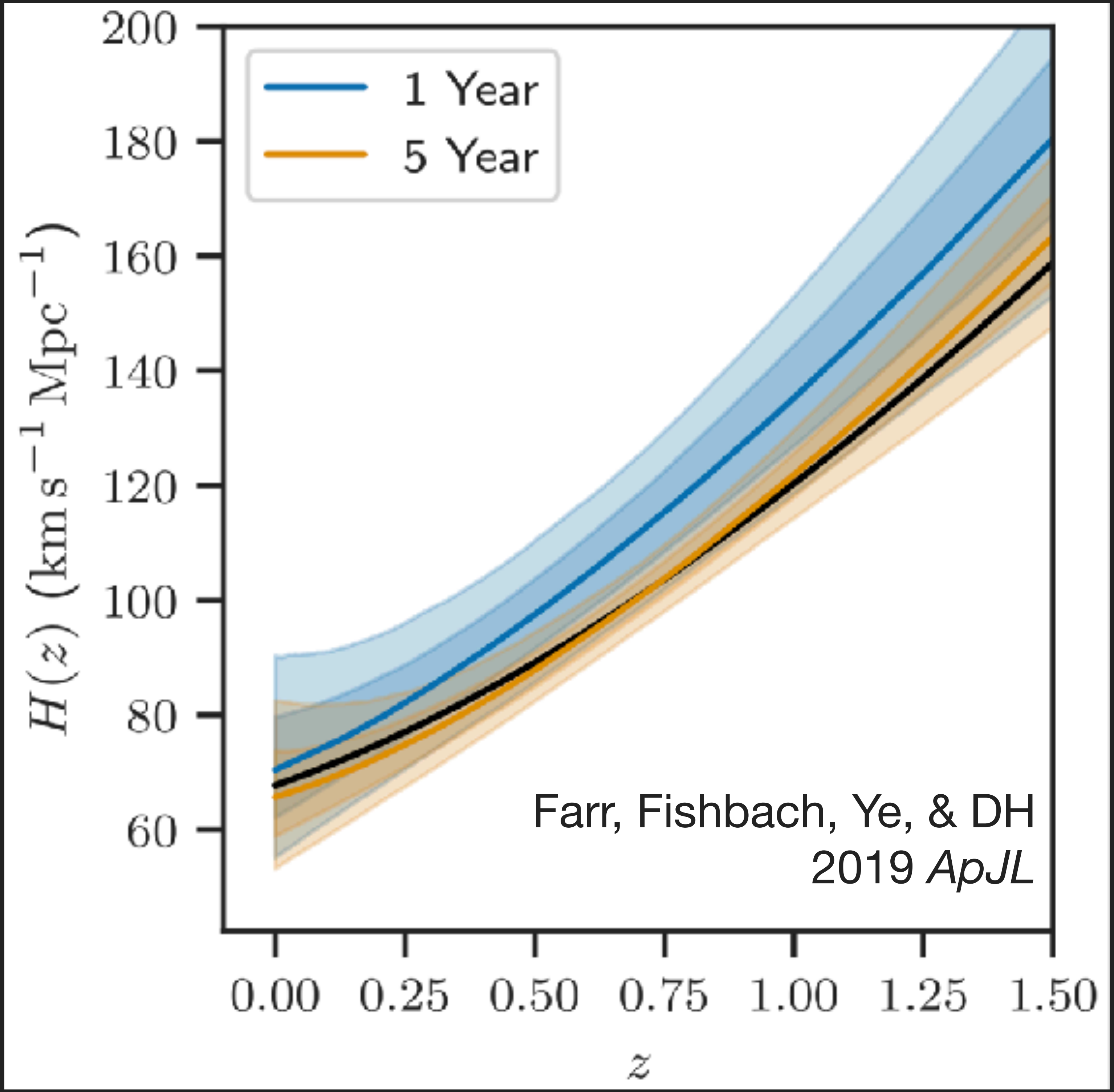
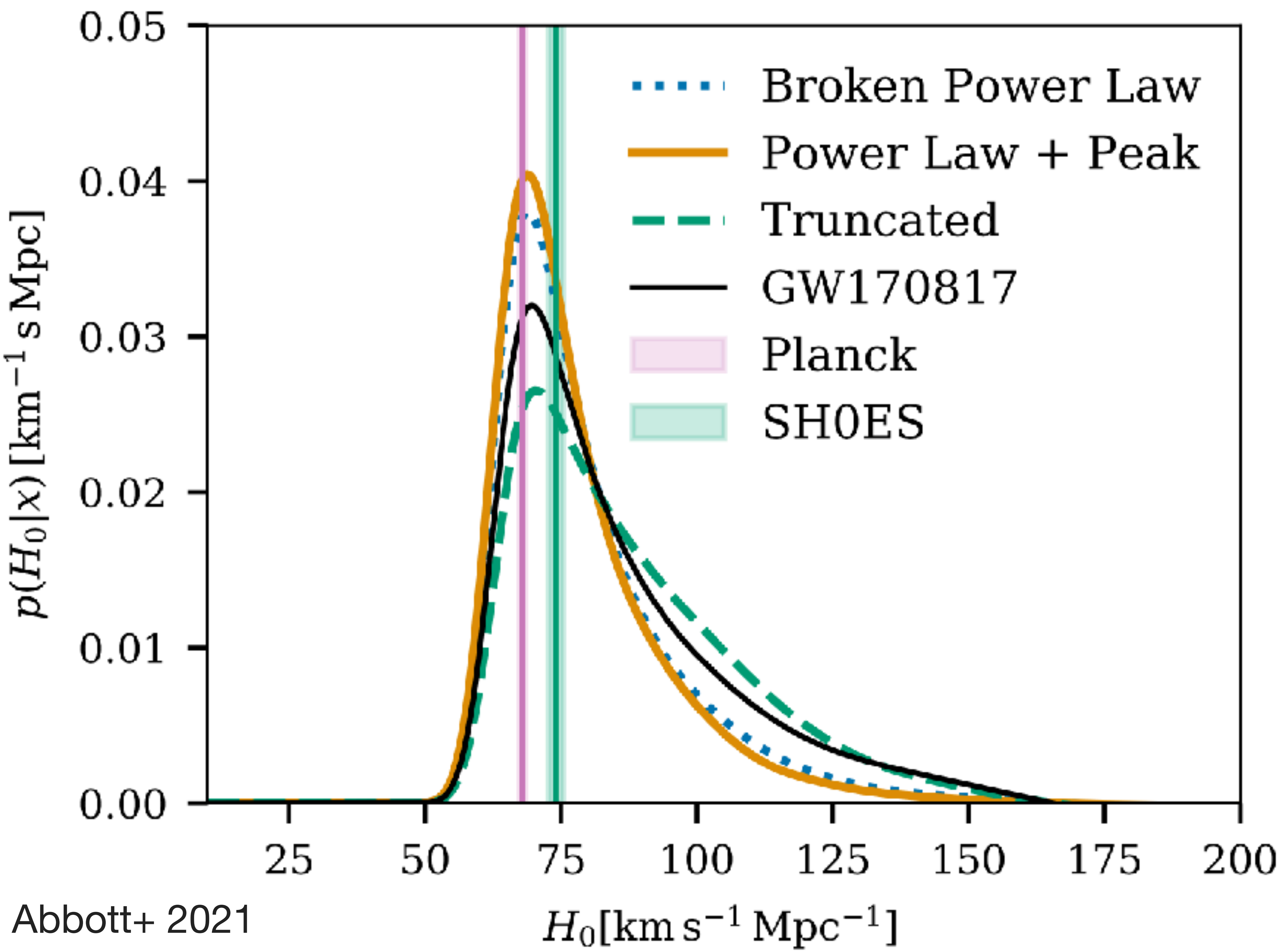
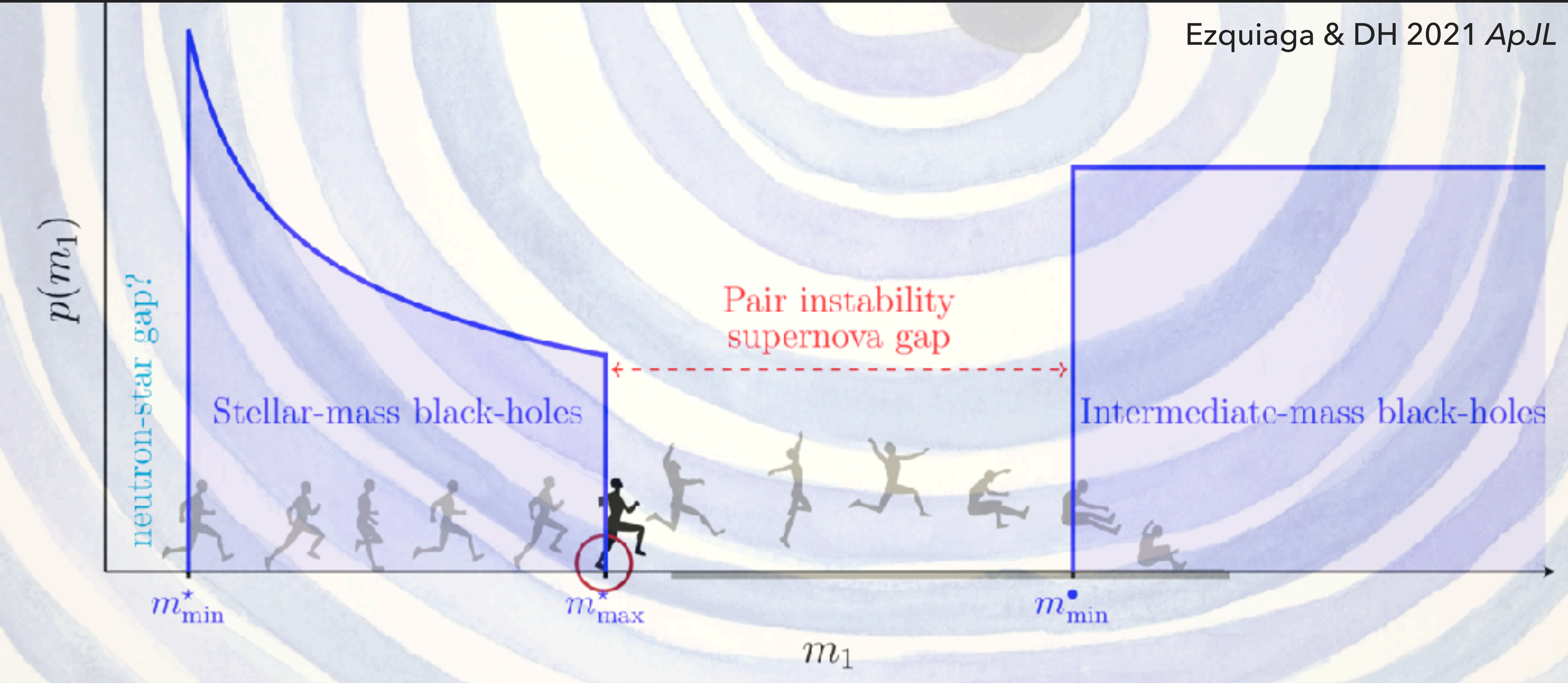


Implementation of mass gap cosmology in O3!



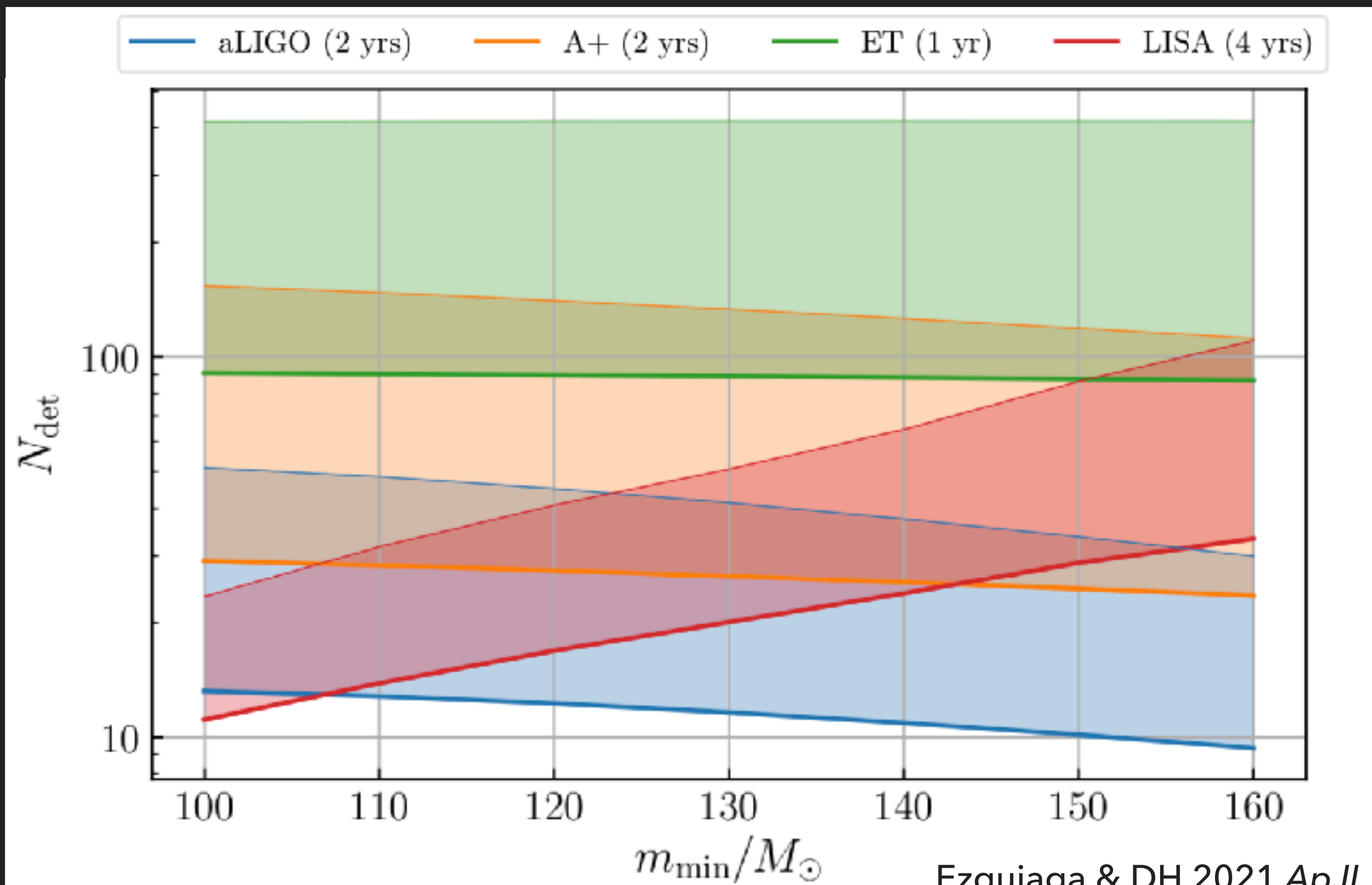
Abbott+ 2021

Jumping the gap



Jumping the gap

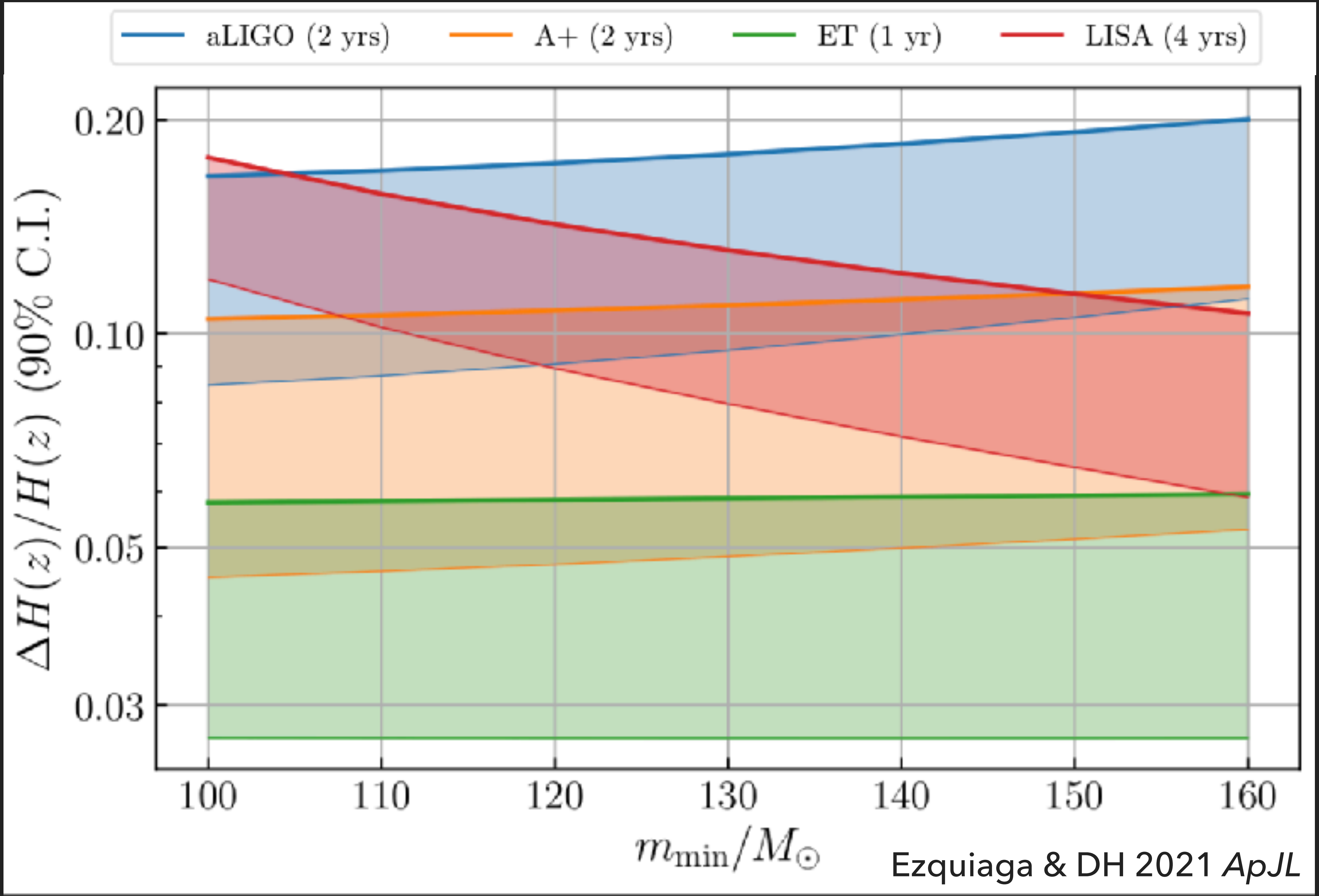
- We expect BHs to exist on the other side of the PISN gap
- These "far side" black holes can be detected by LIGO and *LISA*



Ezquiaga & DH 2021 *ApJL*

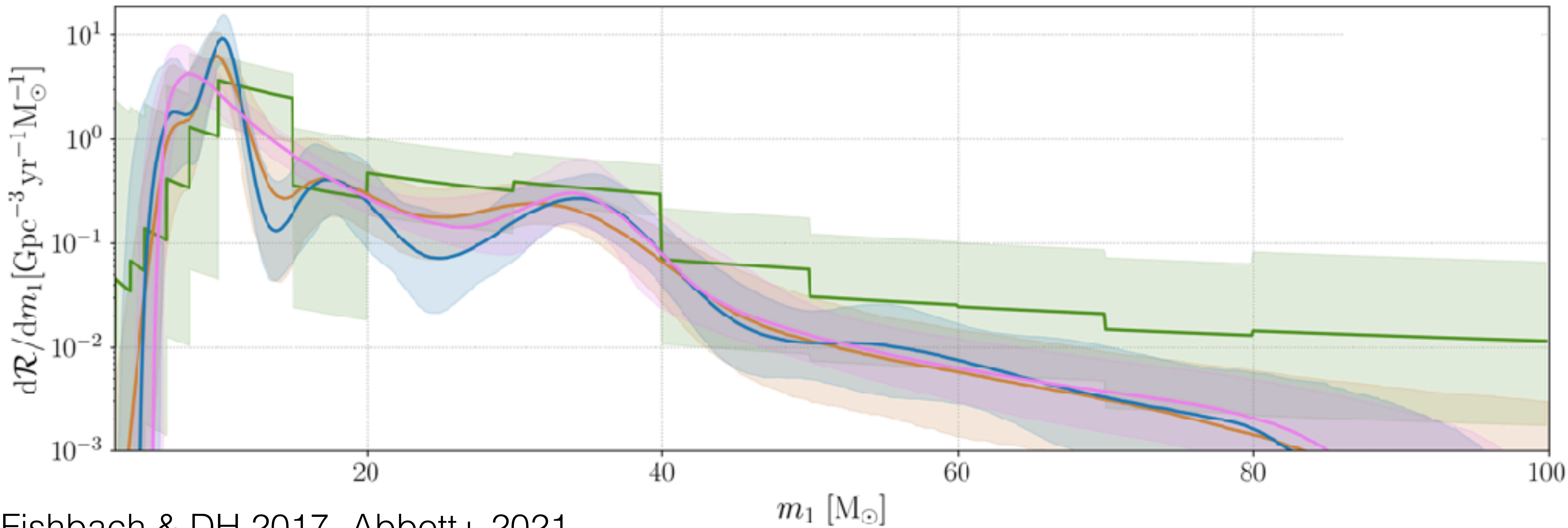
Jumping the gap

- Some of these binaries can be seen by both LIGO and *LISA*
- Can do standard siren science with the **upper** edge of the gap



Ezquiaga & DH 2021 *ApJL*

Can use all the features to estimate redshift

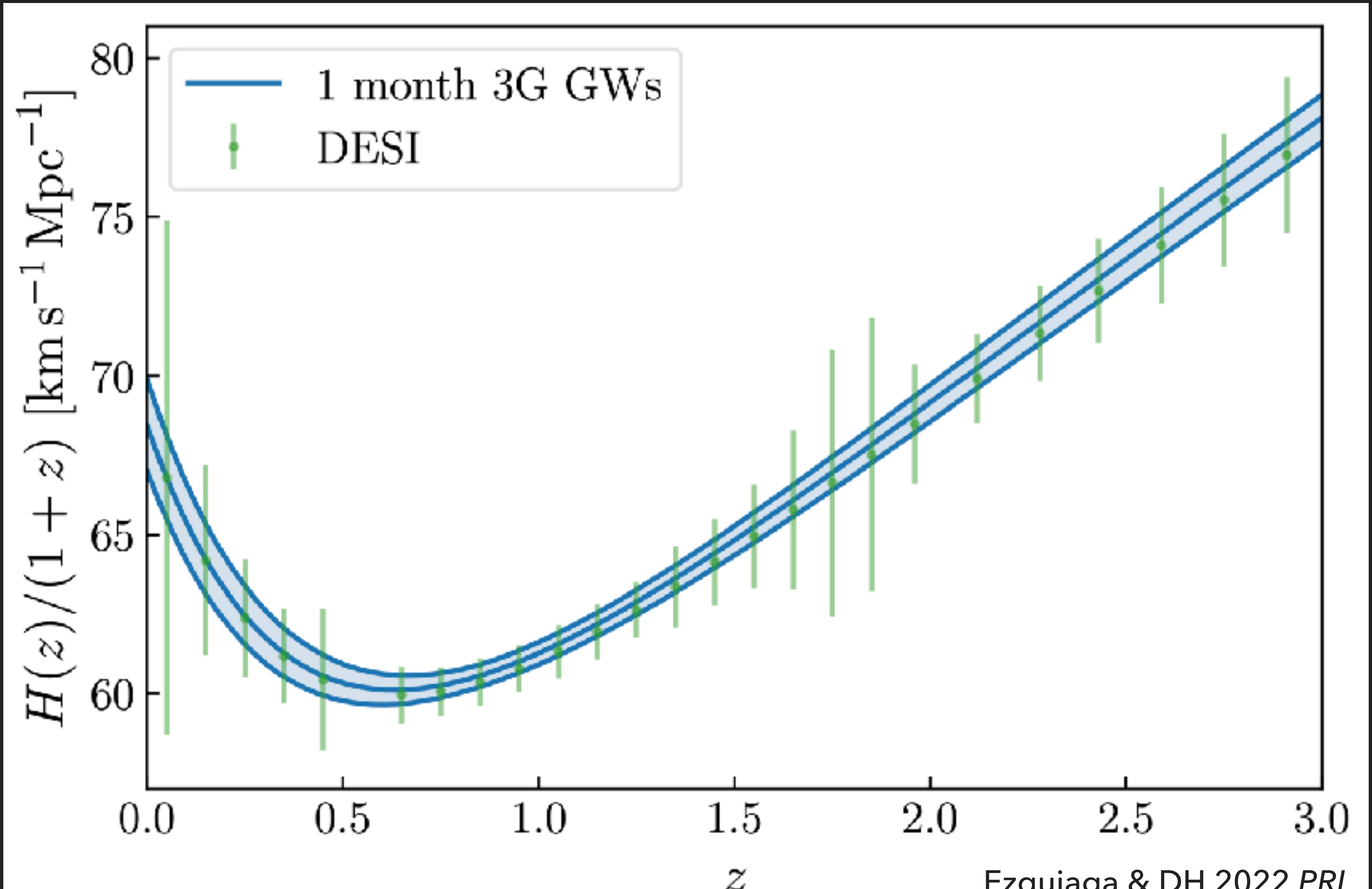


Fishbach & DH 2017, Abbott+ 2021

- There is lots of structure in the mass distribution
- The entire distribution can be used to calibrate the redshift

Spectral sirens

- The entire mass distribution offers "features" to calibrate the standard sirens
- Can distinguish redshift evolution from cosmology!



Ezquiaga & DH 2022 *PRL*

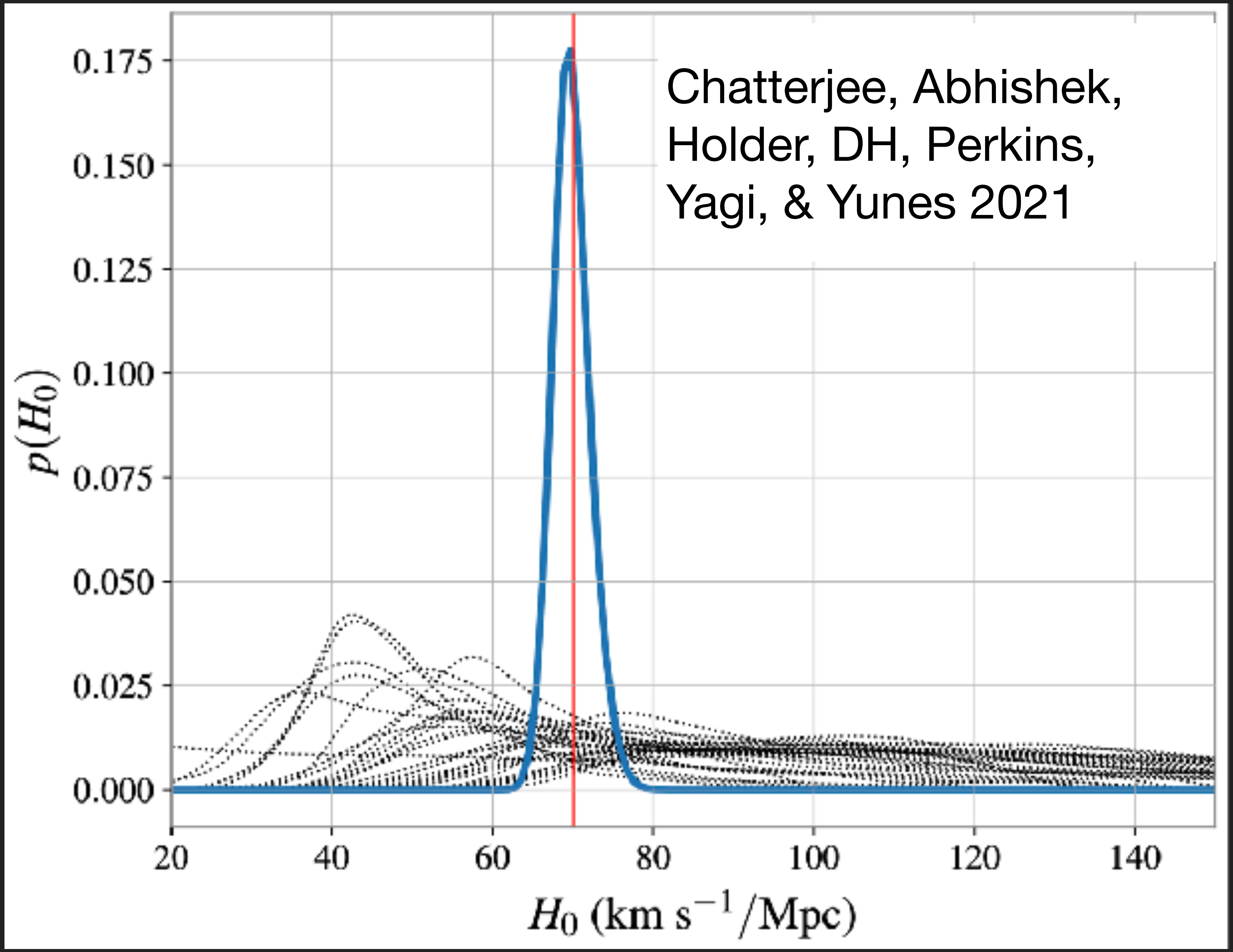
Cosmology with Love

- Can use the equation-of-state of neutron stars to calibrate the absolute mass of the binary, and thereby directly infer the redshift of the source. Combined with distance from gravitational waves, have a standard siren! (Messenger & Read 2012)

- Binary Love relations relate the tidal deformabilities of neutron stars in an equation-of-state insensitive way

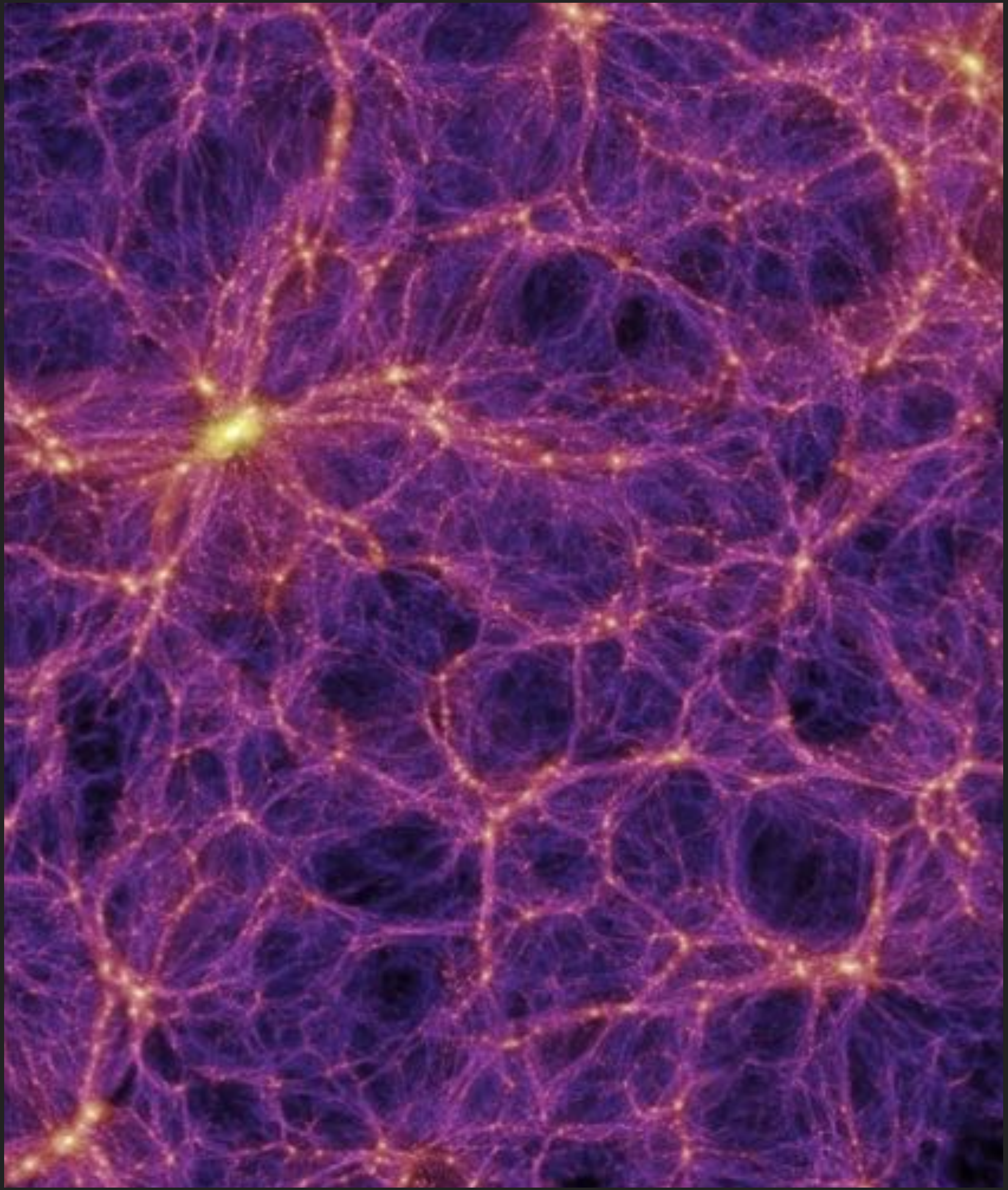
- 10% measurement of H_0 with LIGO Voyager

- 2% measurement of H_0 with Cosmic Explorer



Correlations with large-scale structure

- Cross correlation with weak lensing (Congedo & Taylor 2019 *PRD*)
- Cross correlation with galaxy surveys (Oguri 2016; Scelfo+ 2018; Nair, Bose, & Saini 2019; Nakama 2020; Vijaykumar+ 2021; Mukherjee+ 2021)
- Cosmic explorer produces GW source catalogs comparable to galaxy catalogs



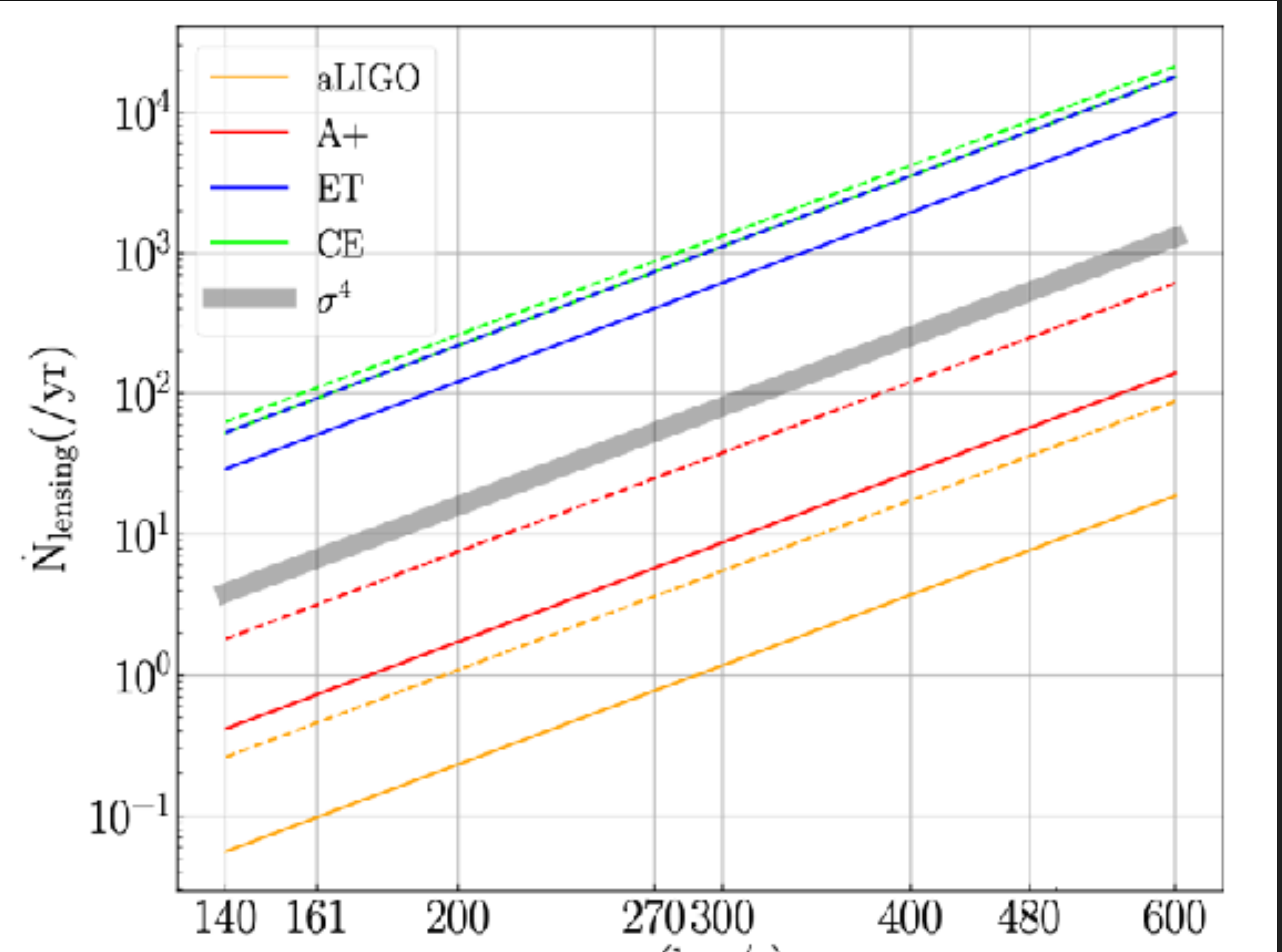
Gravitational lensing of gravitational waves

- We **will** detect strong lensing of GW sources (eventually)
- These are probes of both source population and lensing population

Ezquiaga, DH, Hu, Lagos, and Wald 2021 ("Breaking GR from lensing")

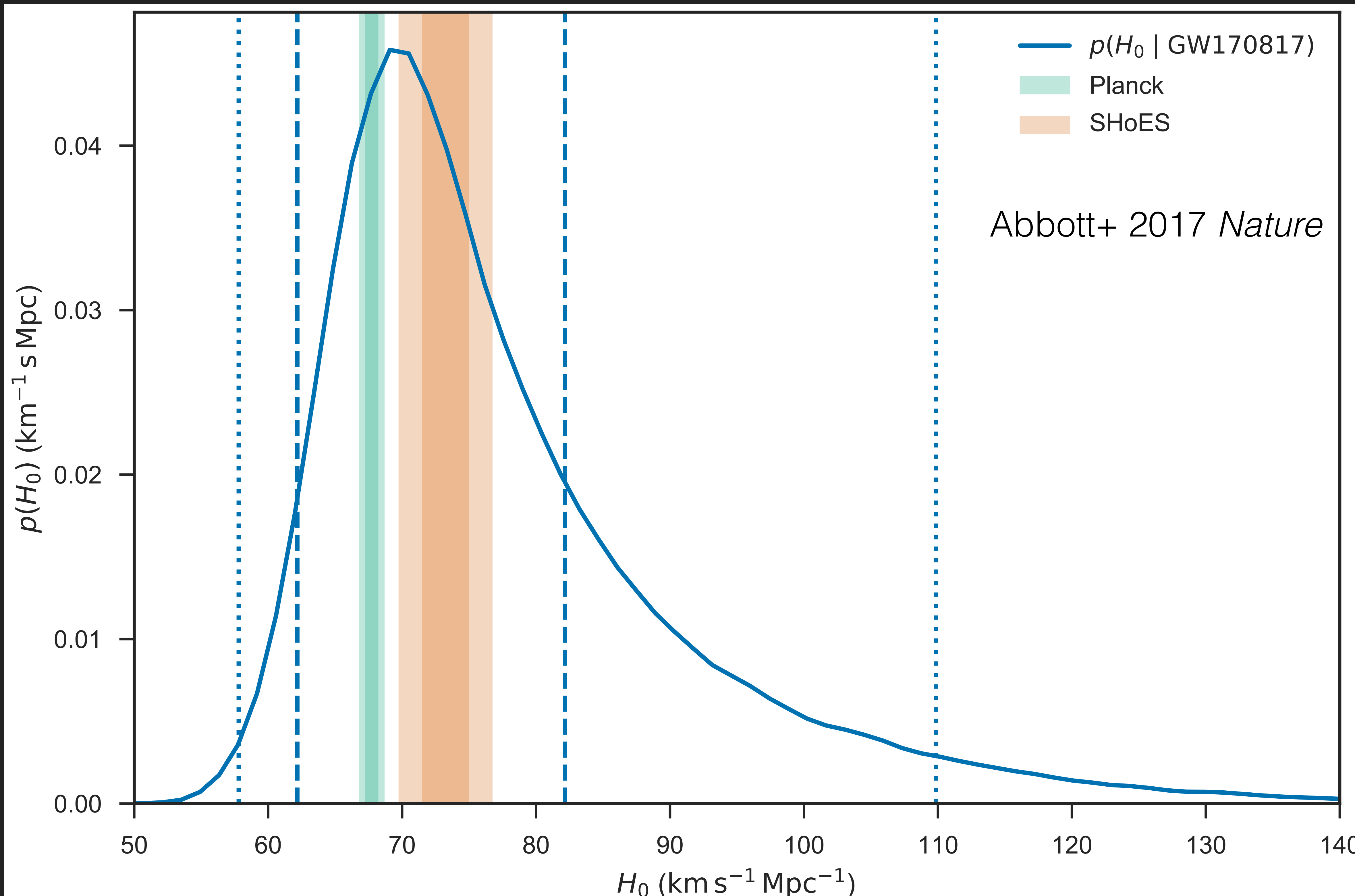
Xu, Ezquiaga, & DH 2021 ("Please repeat")

Çalışkan, Ezquiaga, Hannuksela, & DH 2022 ("Lensing or Luck?")



Xu, Ezquiaga, & DH 2021

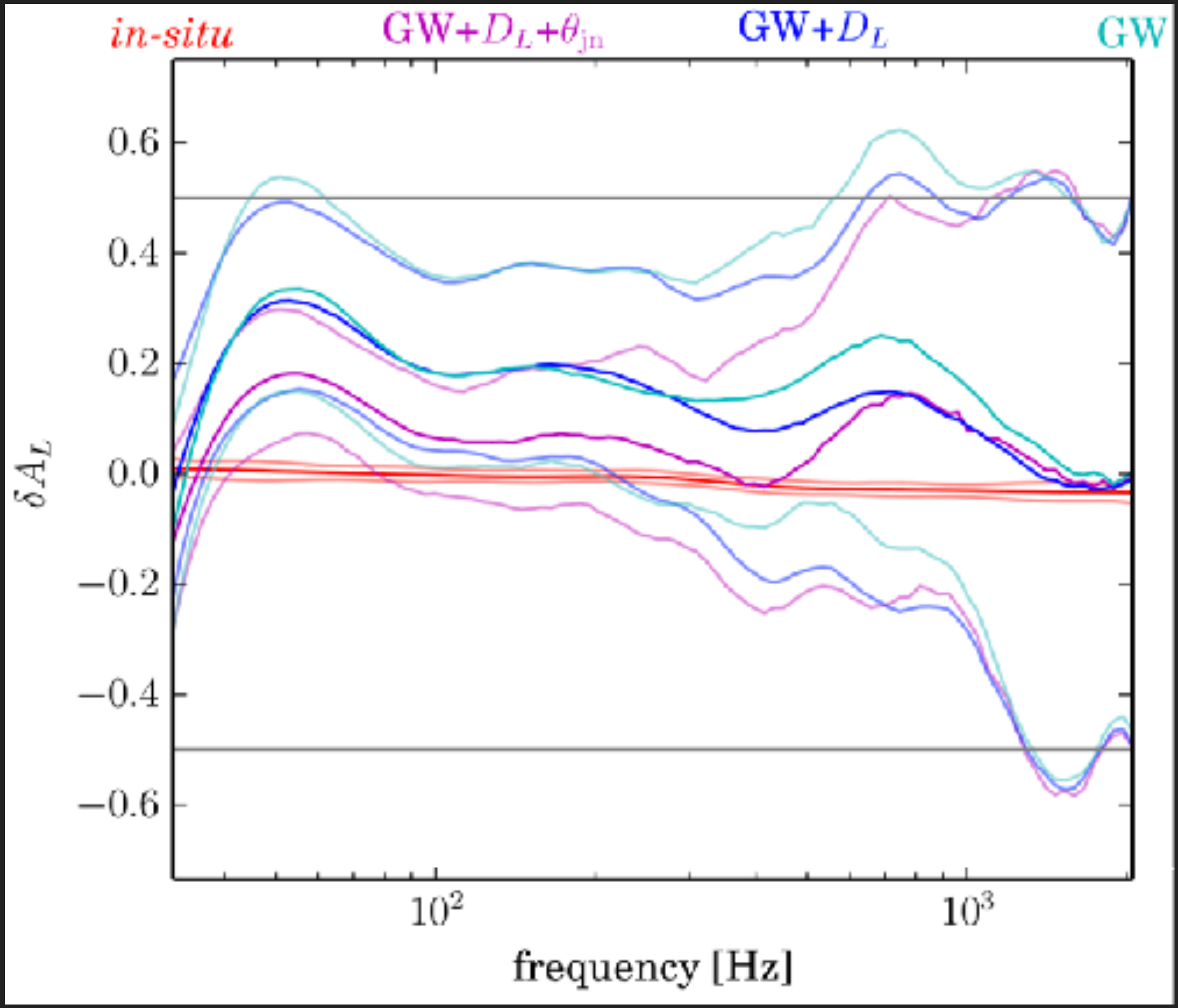
The era of GW cosmology has begun…



…the best is yet to come

Use GW170817 to calibrate LIGO!

- If we assume general relativity is correct, then the waveform of a binary merger is known from first principles
    - Phase and amplitude evolution are fixed by general relativity
    - Absolute amplitude calibration is not fixed: degenerate with distance



Essick & DH 2019 *PRD*

- From GW170817:
    - relative amplitude calibration to approximately ± 20%
    - relative phase calibration to approximately ± 15%