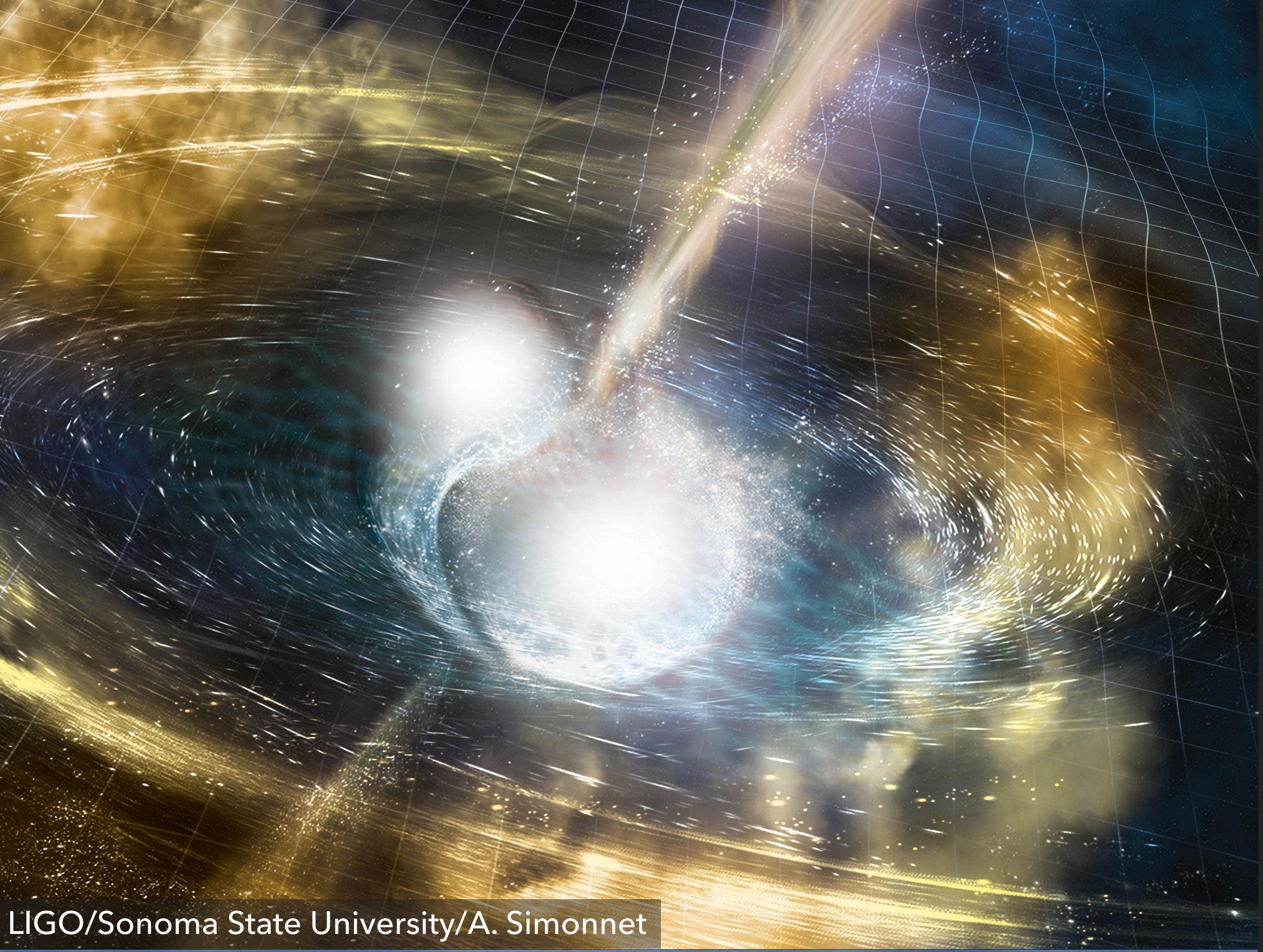


LIGO/Sonoma State University/A. Simonnet

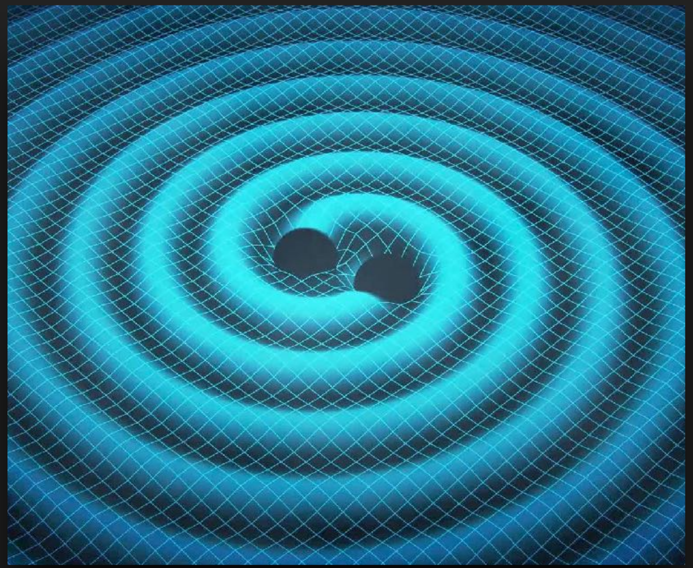
LIGO

Standard sirens and H_0

Daniel Holz
University of Chicago

What is a gravitational-wave standard siren?

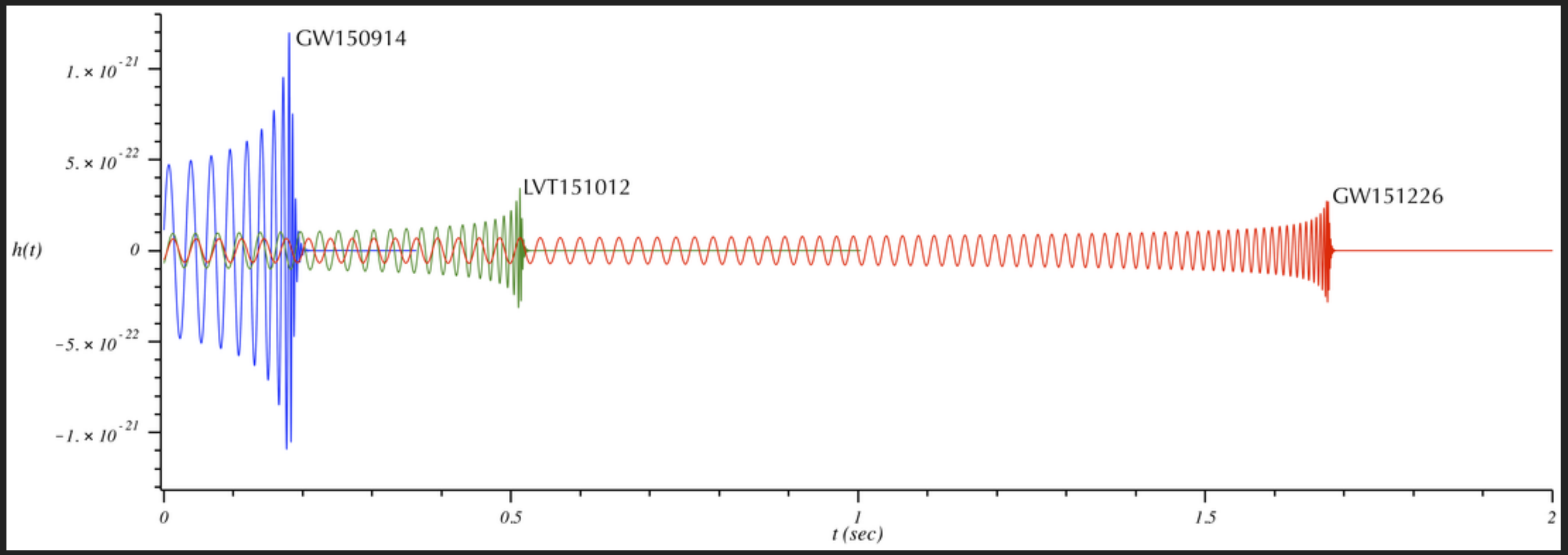
- Black holes are the simplest macroscopic objects in the Universe
- Binary coalescence is understood from first principles; provides direct absolute measurement of luminosity distance (Schutz 1986)
- Distance calibration provided by General Relativity



Calibration is provided by General Relativity

- GW waveform can be derived
    - Quadrupole formula for GW emission + Kepler's Laws + Energy Conservation
- Frequency evolution provides fundamental scale of the binary, called the chirp mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$



Calibration is provided by General Relativity

- Strongest harmonic (widely separated):

$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$

- dimensionless strain $h(t)$
- luminosity distance D_L
- accumulated GW phase $\Phi(t)$
- GW frequency $f(t) = (1/2\pi) d\Phi/dt$
- position & orientation dependence $F(\text{angles})$
- (redshifted) chirp mass:

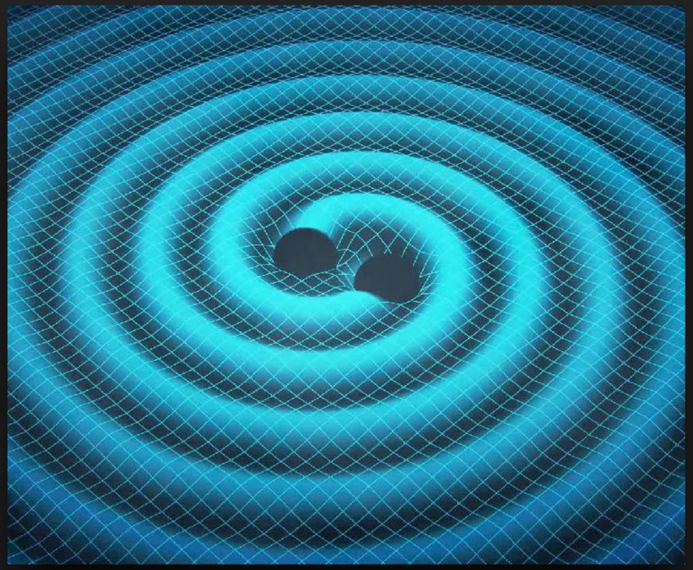
$$M_z = (1+z)(m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$$

What is a 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)
- Distance calibration provided by General Relativity
- Need independent measurement of redshift to do cosmology*

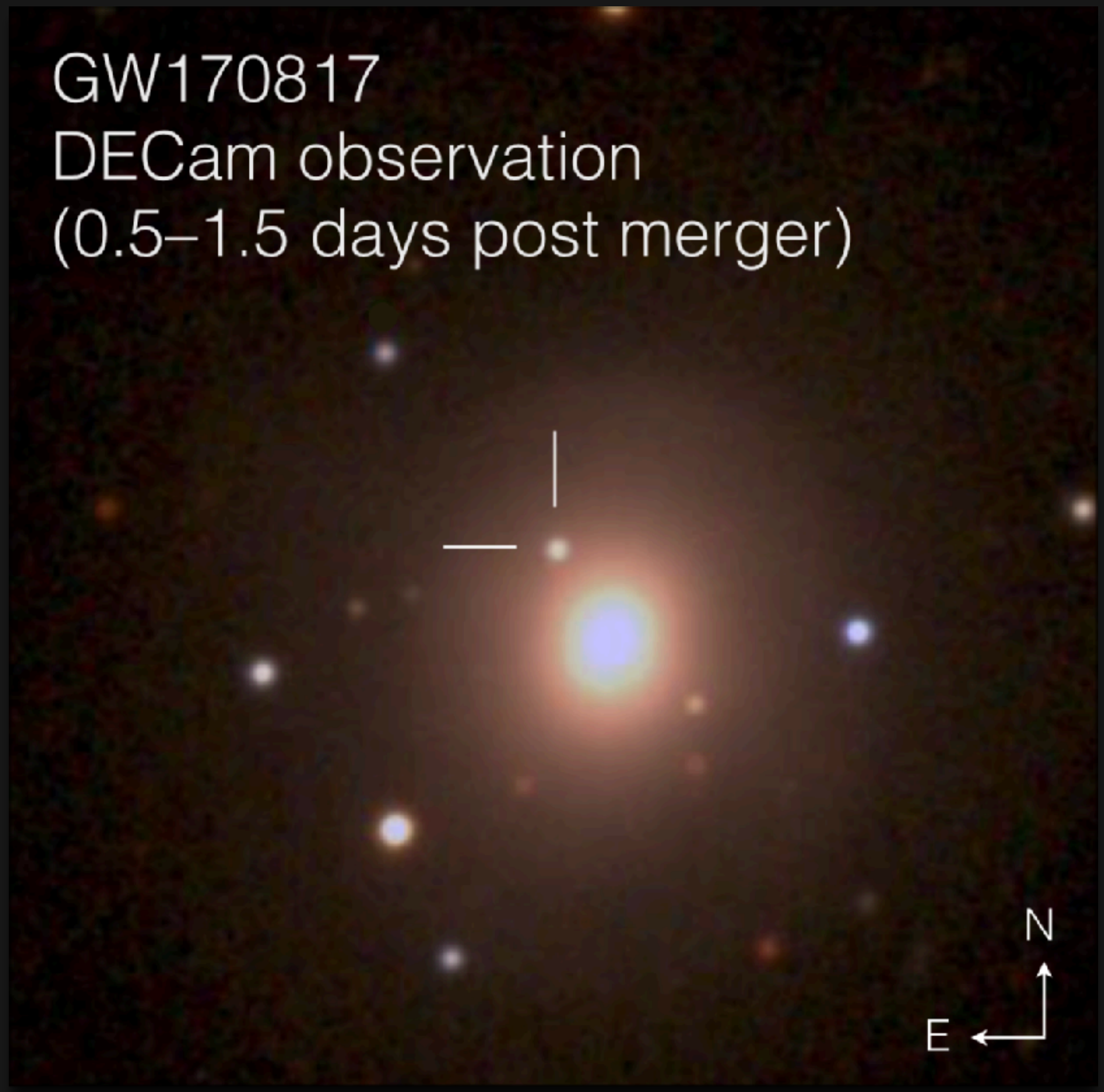
  * Proposals to use mass distribution, EOS, etc.

  Finn 1996; Taylor, Gair, & Mandel 2012; Messenger & Read 2012; Del Pozzo, Li, & Messenger 2017



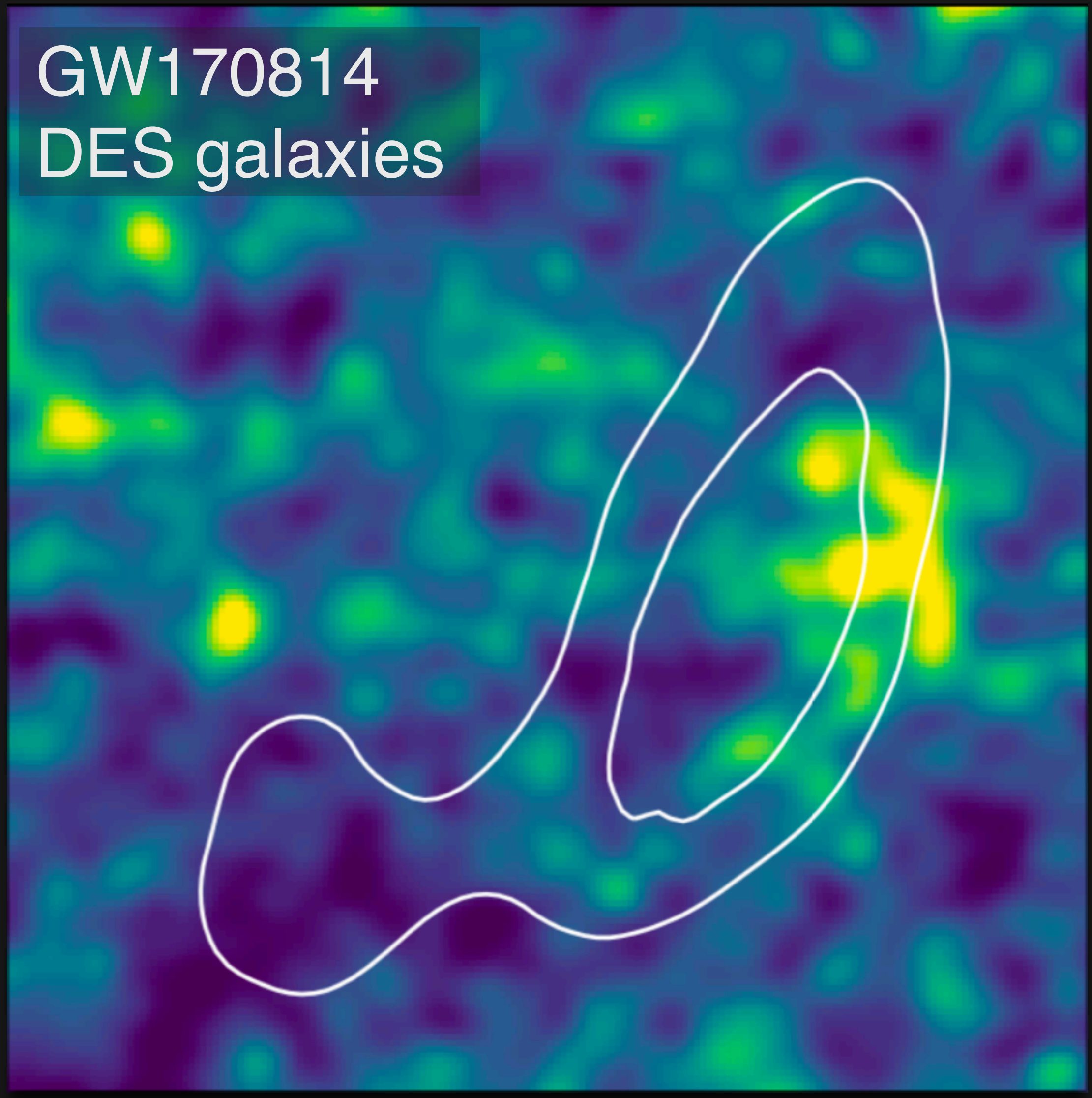
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

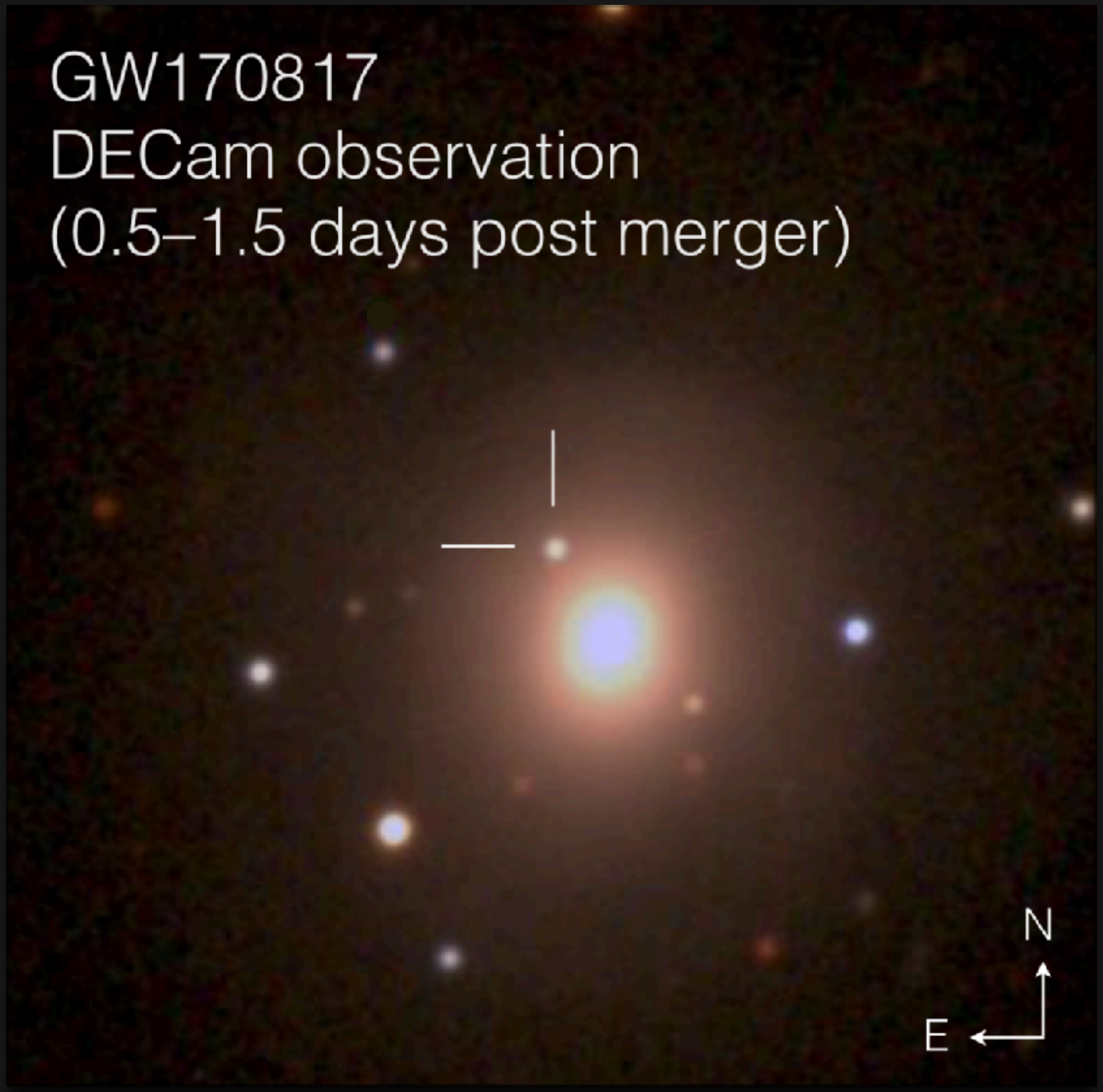
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

Counterpart/Bright



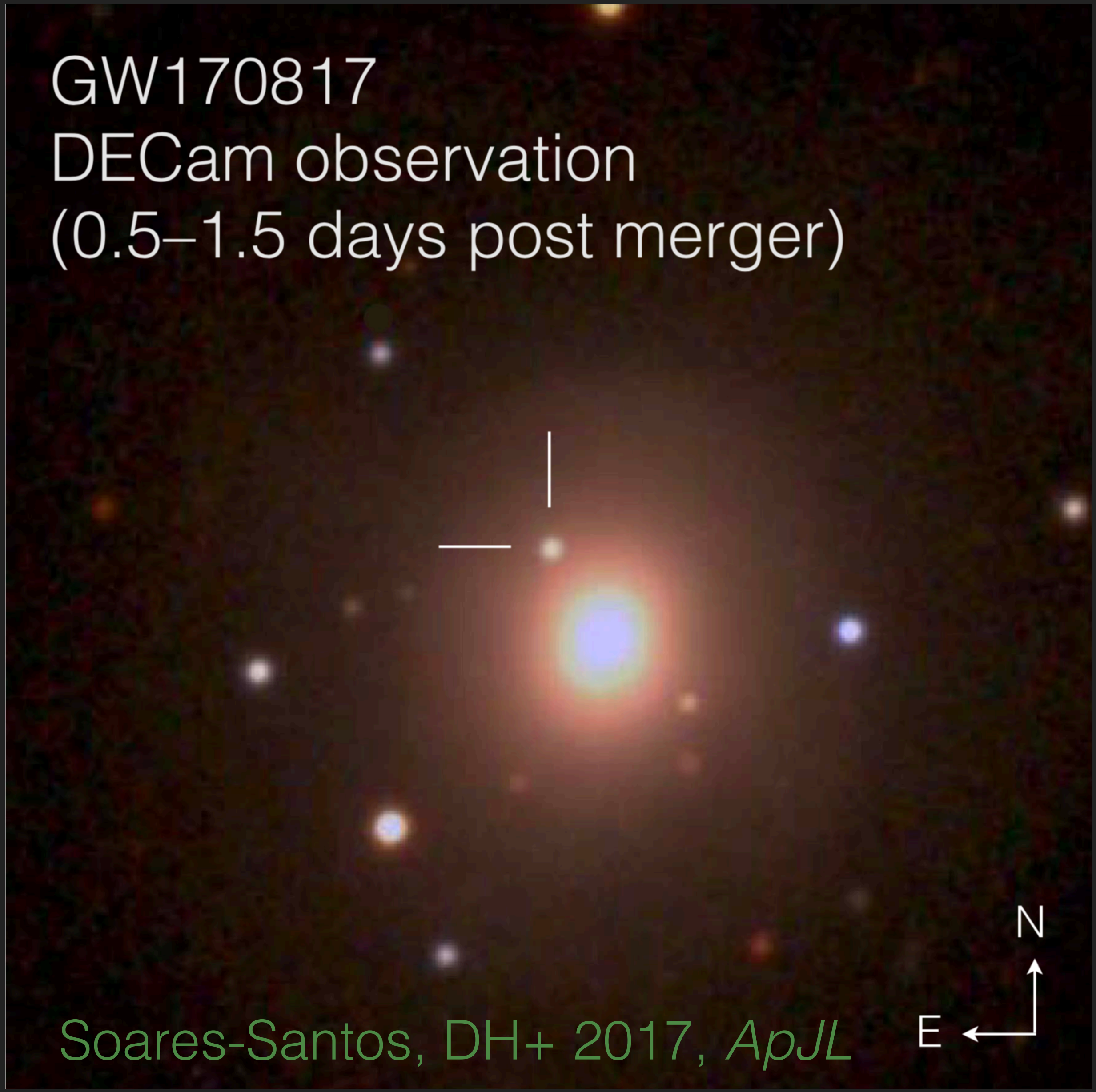
Unique host galaxy

- 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

DH & Hughes 2005; Dalal, DH, Hughes, & Jain 2006; Nissanke, DH+ 2010, 2013; Kasliwal & Nissanke 2014

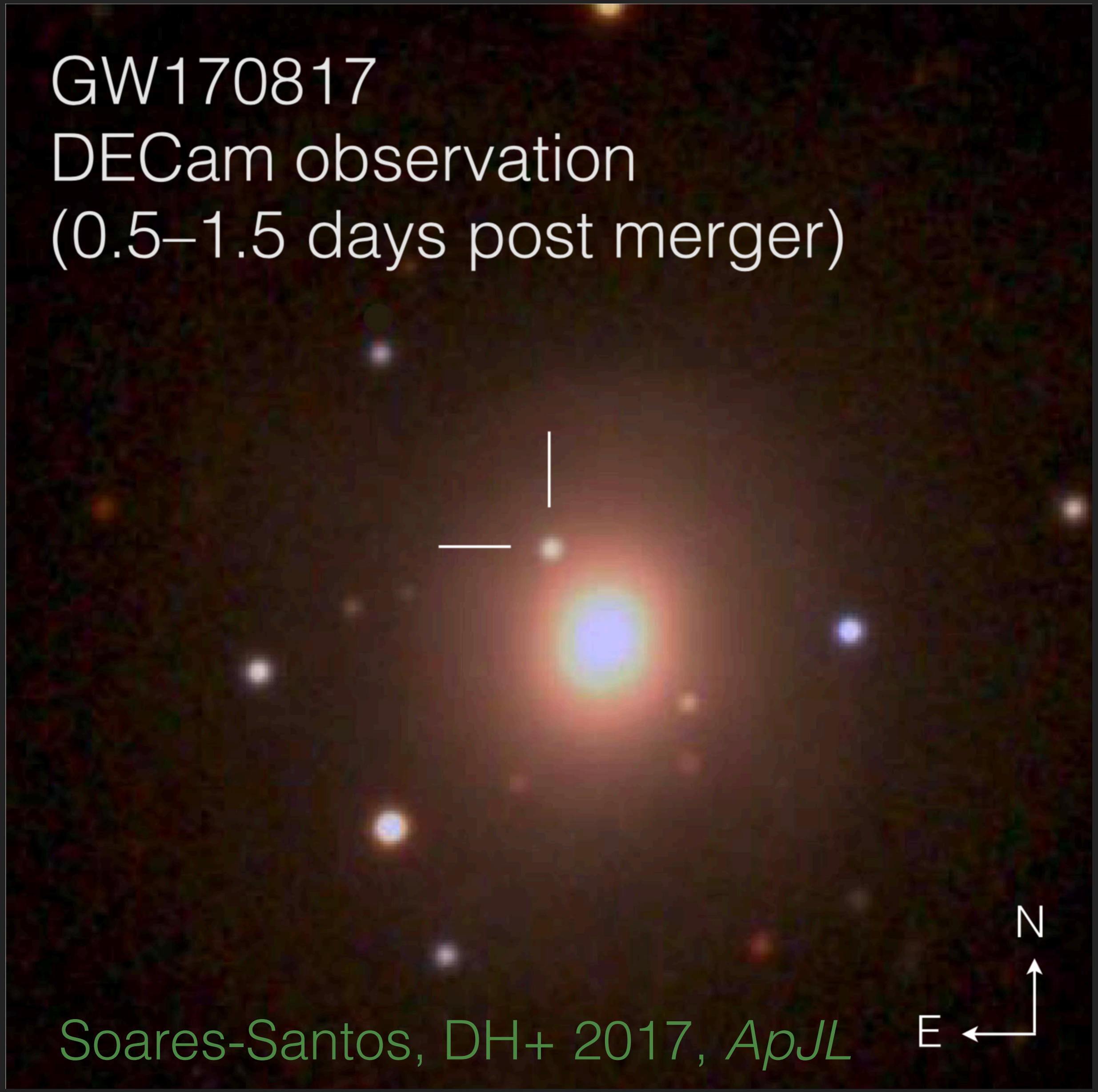
GW170817 is an ideal standard siren

- GW170817 was detected in gravitational waves
  - Very high SNR
  - Excellent measurement of distance
- GW170817 had an optical counterpart
  - Host galaxy is NGC 4993
  - Measurement of redshift
- Poster child for the standard siren method….

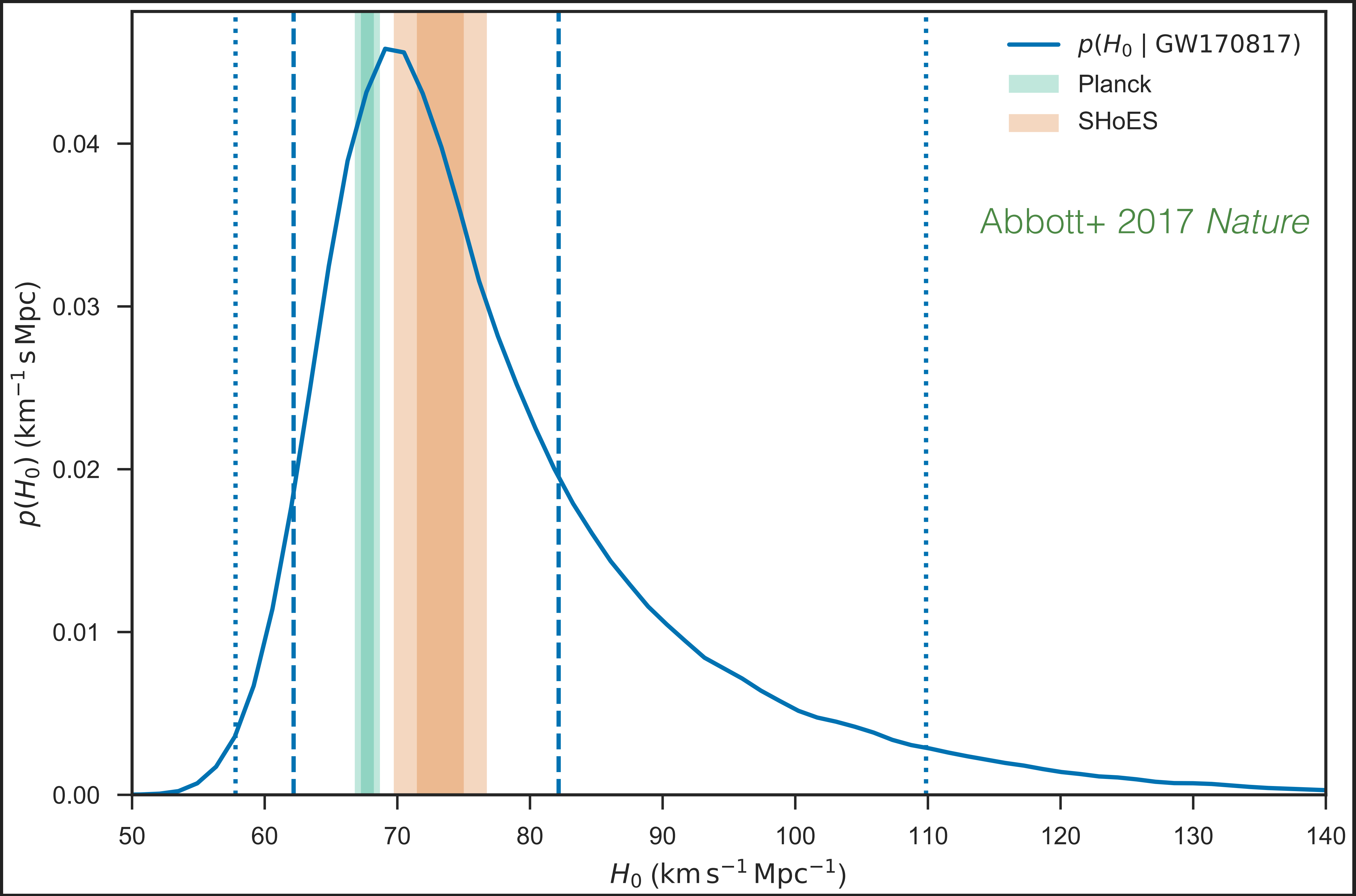


Caveat: GW17081 is too good!

- Host galaxy is so close (40 Mpc) that peculiar motions are important
- NGC 4993 belongs to a group of galaxies with center-of-mass velocity 3327 ± 72 km/s in the CMB frame (Crook+ 2007)
- Correct for coherent bulk flow of 310 ± 150 km/s (Springob+ 2014)

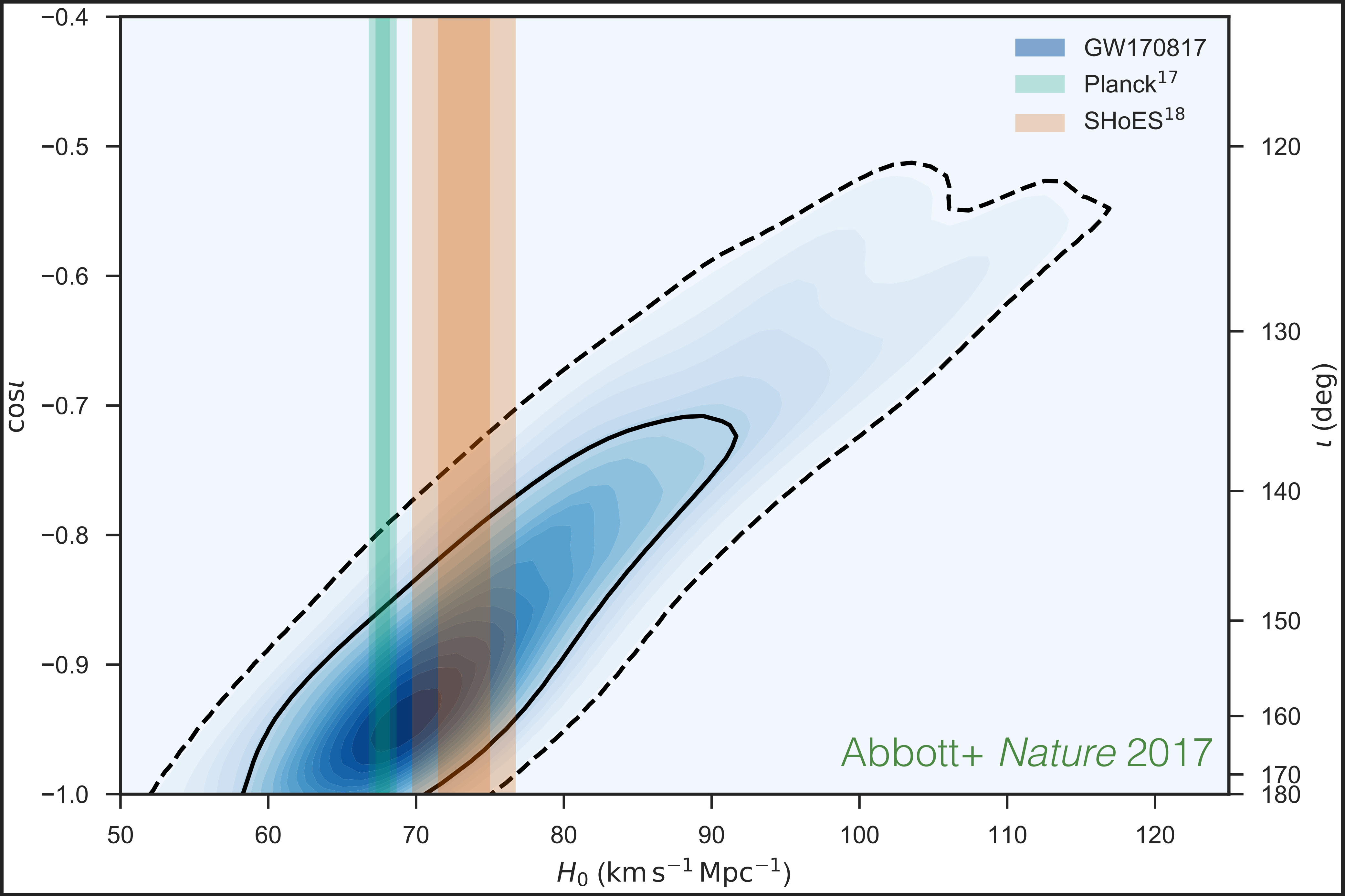


Standard siren measurement of the Hubble constant



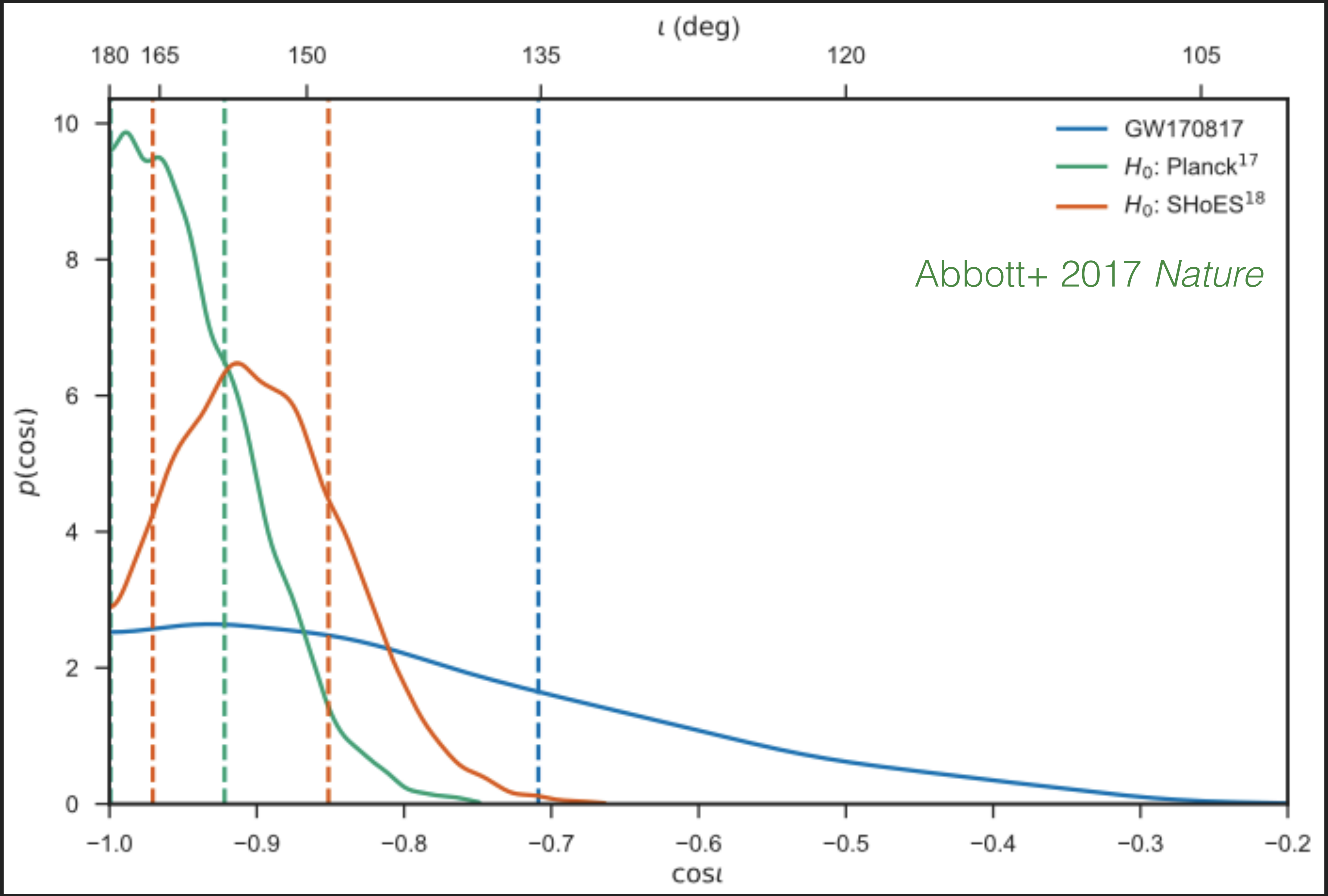
$$H_0 = 70.0^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Distance is correlated with inclination



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

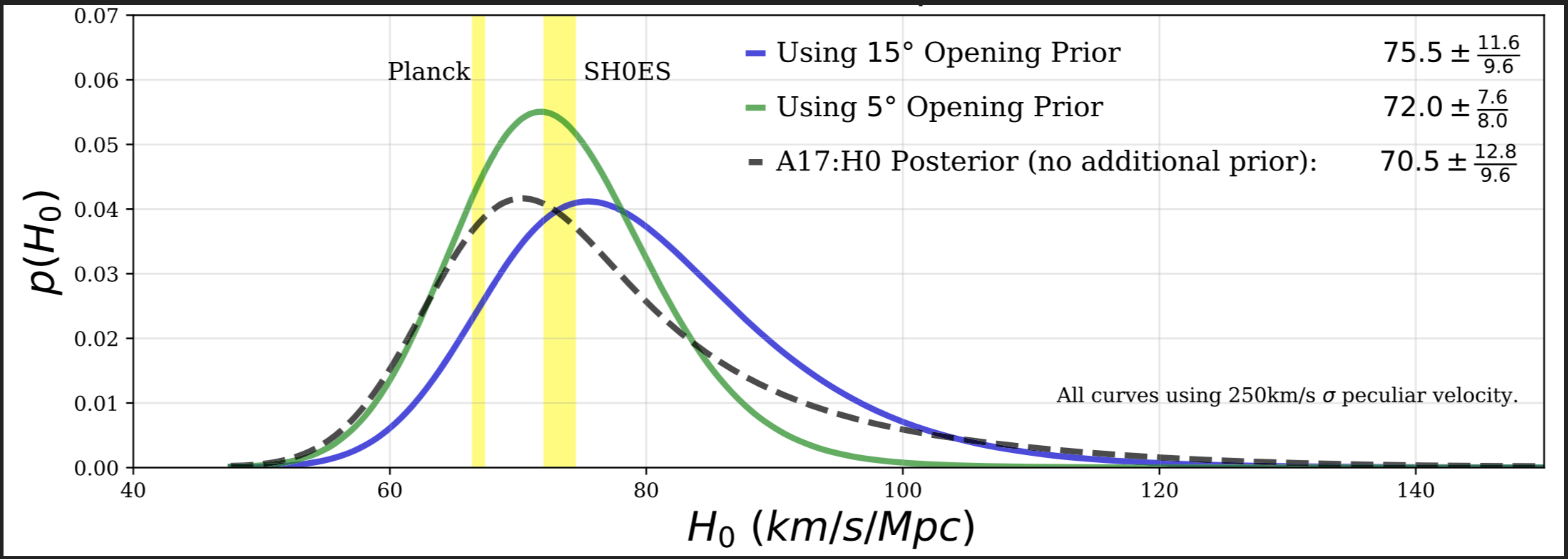
If you know cosmology, can improve inclination



Abbott+ 2017; Mandel 2018; Finstad+ 2018

- Alternatively, if you know distance, can improve inclination (e.g., using surface brightness fluctuations: Cantiello, Jensen, Blakeslee,..,DH+ 2018 *ApJL*)

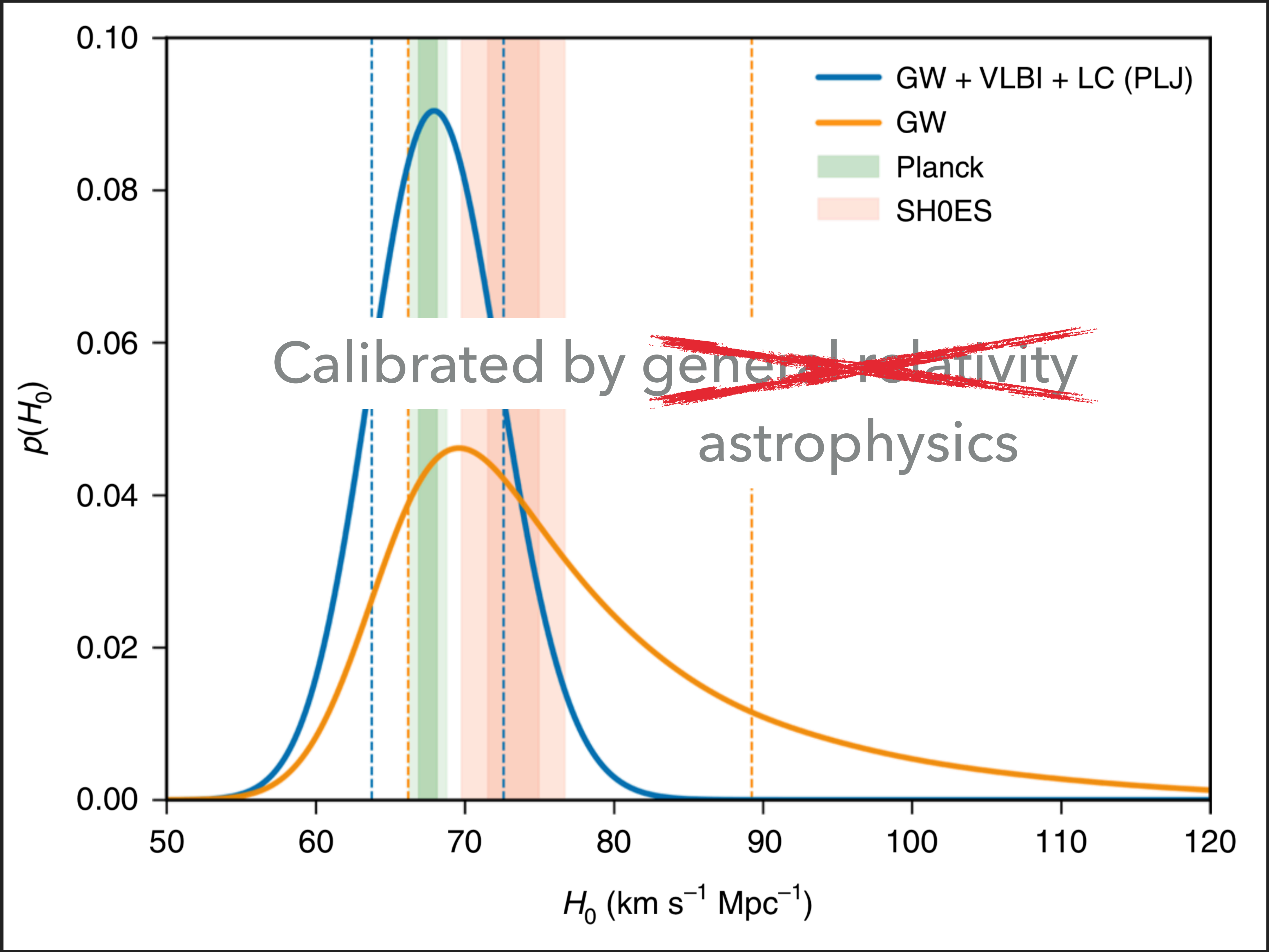
If you know inclination, can improve cosmology



Guidorzi, Margutti, Brout, Scolnic, Fong+ 2017 *ApJL*

- Using radio and X-ray data to model the jet

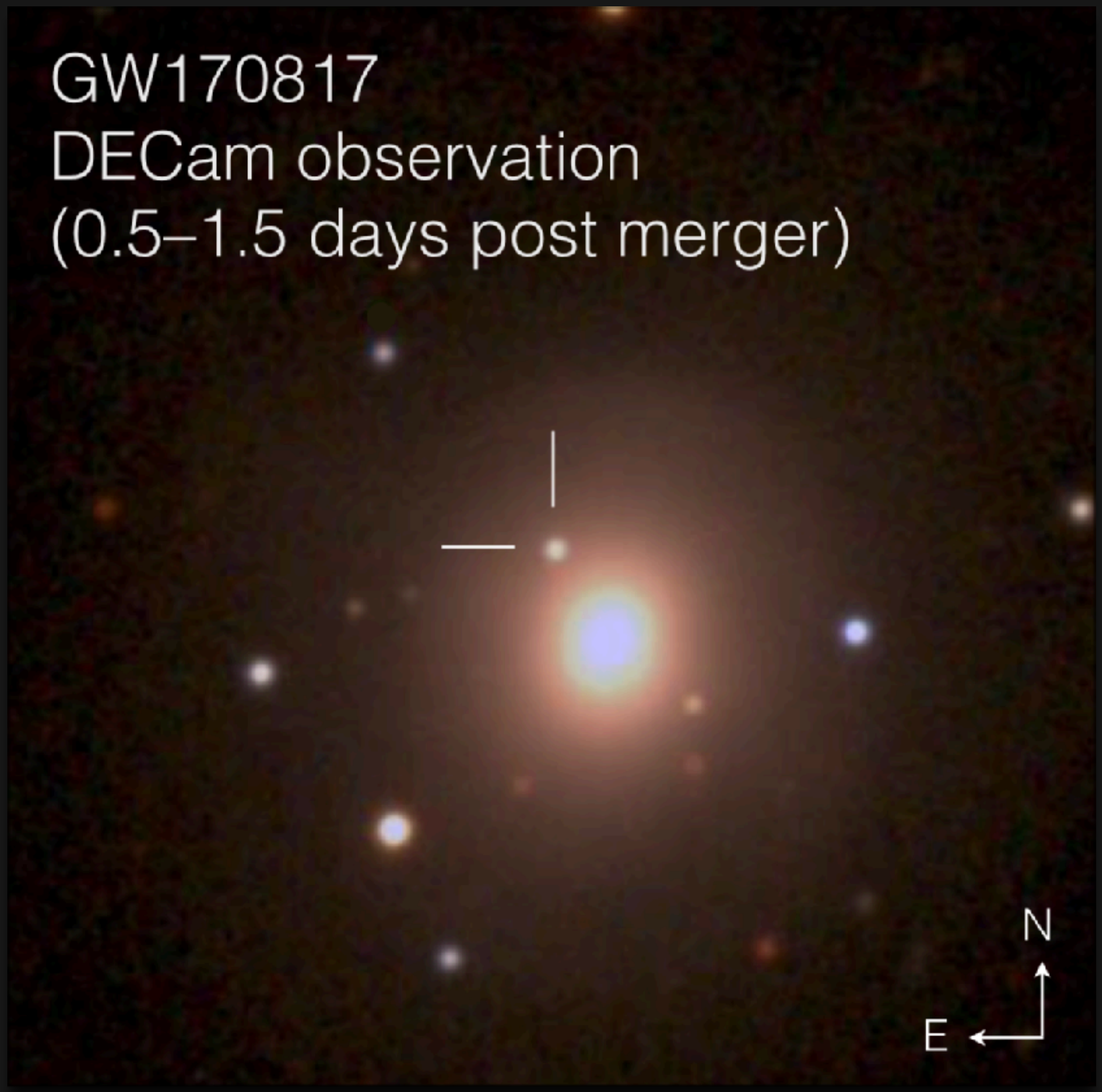
If you know inclination, can improve cosmology



Hotokezaka+ 2018 based on radio observations from Mooley+ 2018

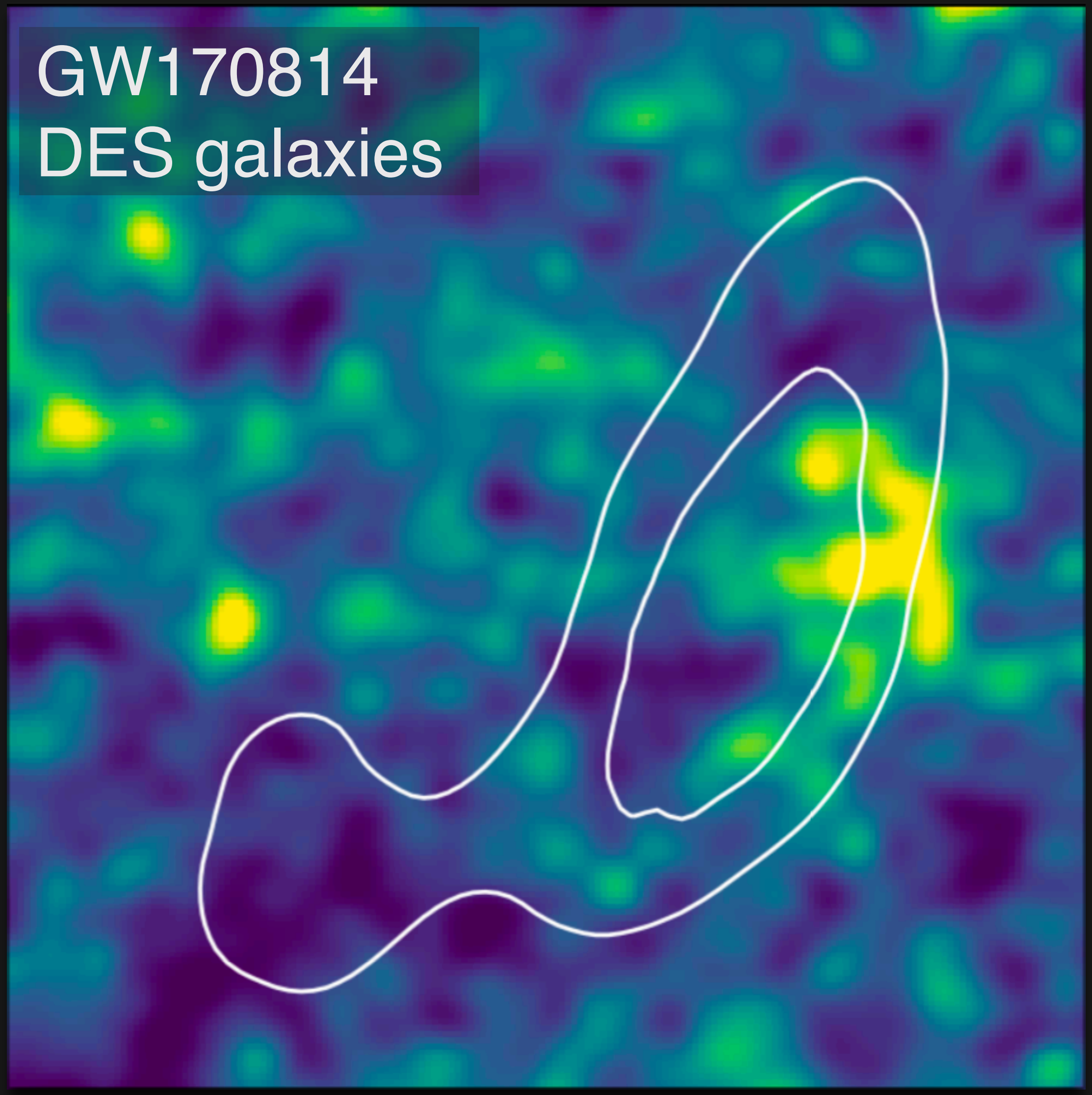
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

Statistical/Dark



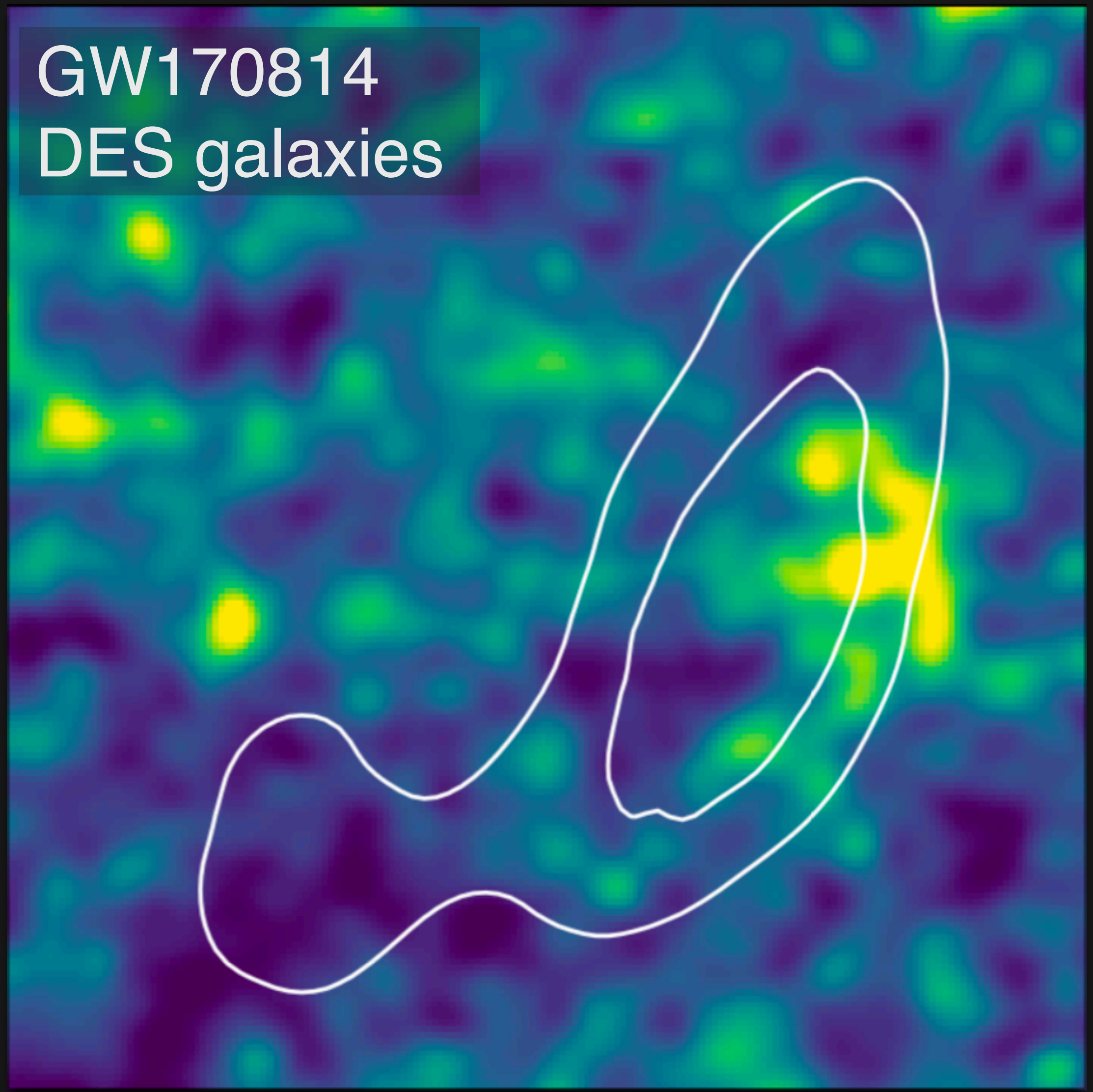
Use all galaxies in localization volume

Two standard siren approaches

- "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

Schutz 1986; Macleod & Hogan 2008; Del Pozzo 2012

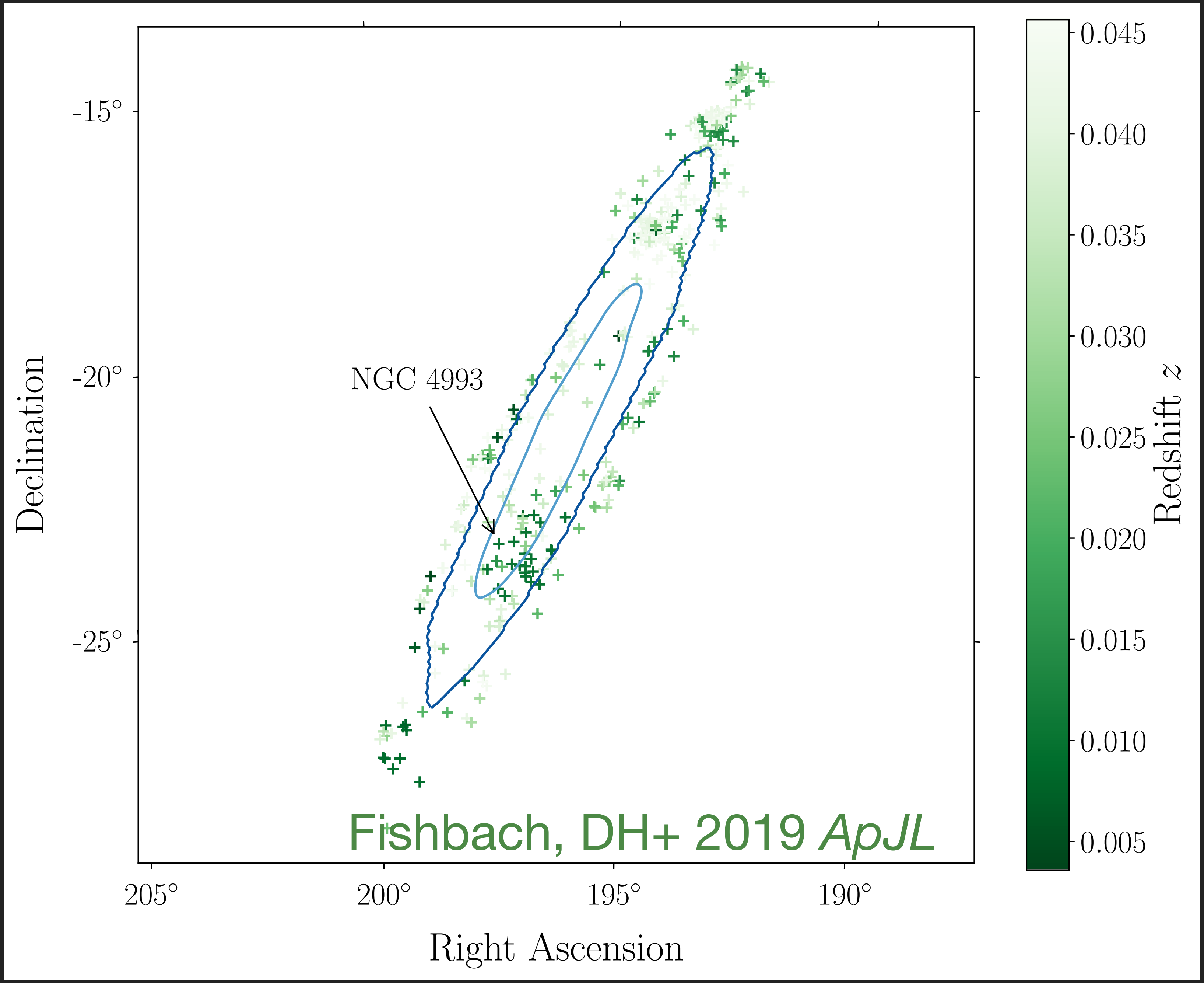
Statistical/Dark



Use all galaxies in localization volume

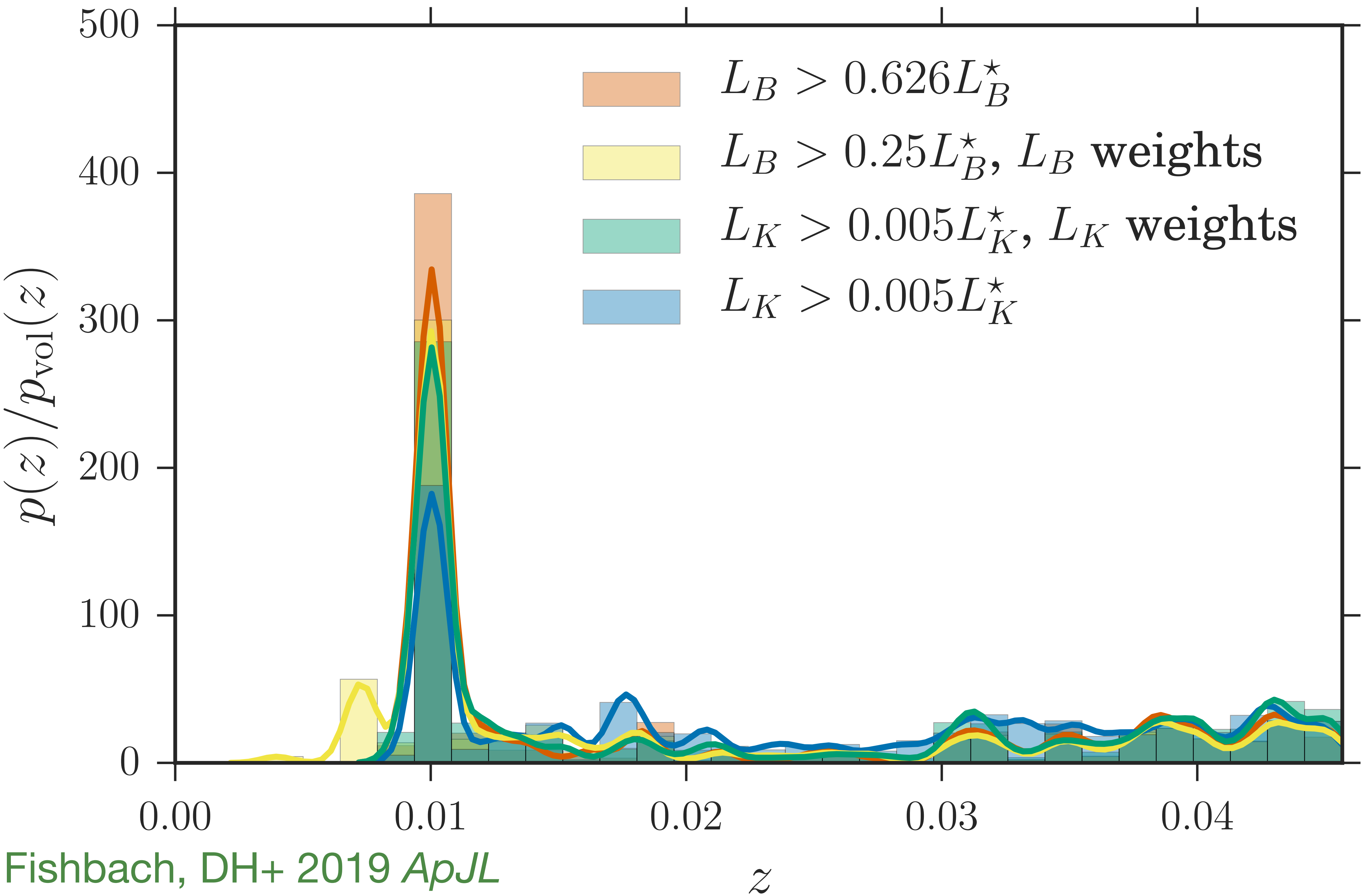
GW170817 as a dark standard siren

- GW170817 was only ~40 Mpc away!
- GW170817 was localized to 16 deg² on the sky
- GW170817 localization volume was relatively small:
  215 Mpc³
  (90% confidence region)
- Have catalog of ~400 galaxies in the localization volume (GLADE catalog; Dálya+ 2018)



GW170817 as a dark standard siren

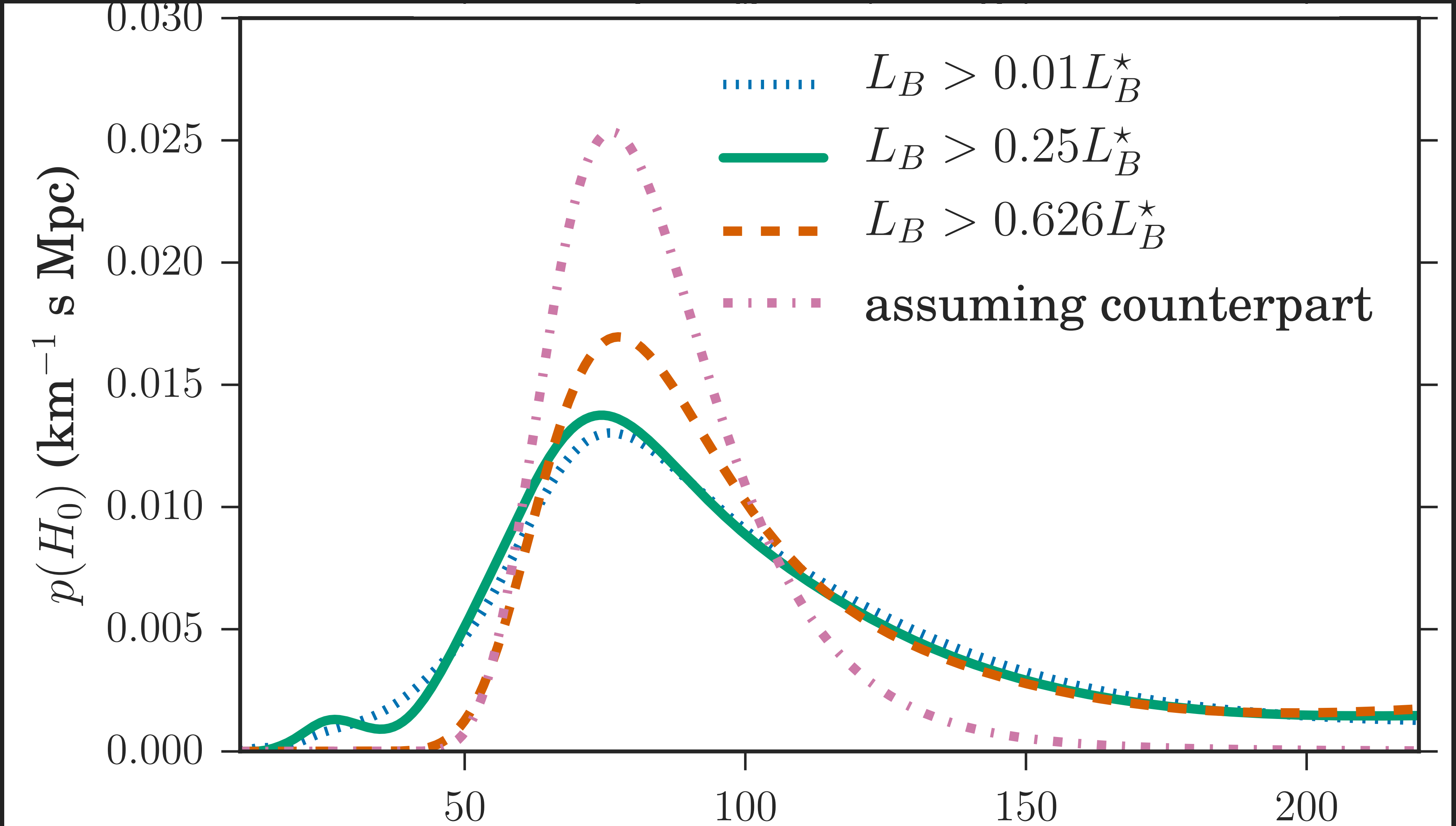
- Most of the galaxies in the GW170817 localization volume are found in a single galaxy group (including NGC 4993)



Fishbach, DH+ 2019 *ApJL*

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, DH+ 2019 *ApJL*

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

GW170814 as a dark standard siren

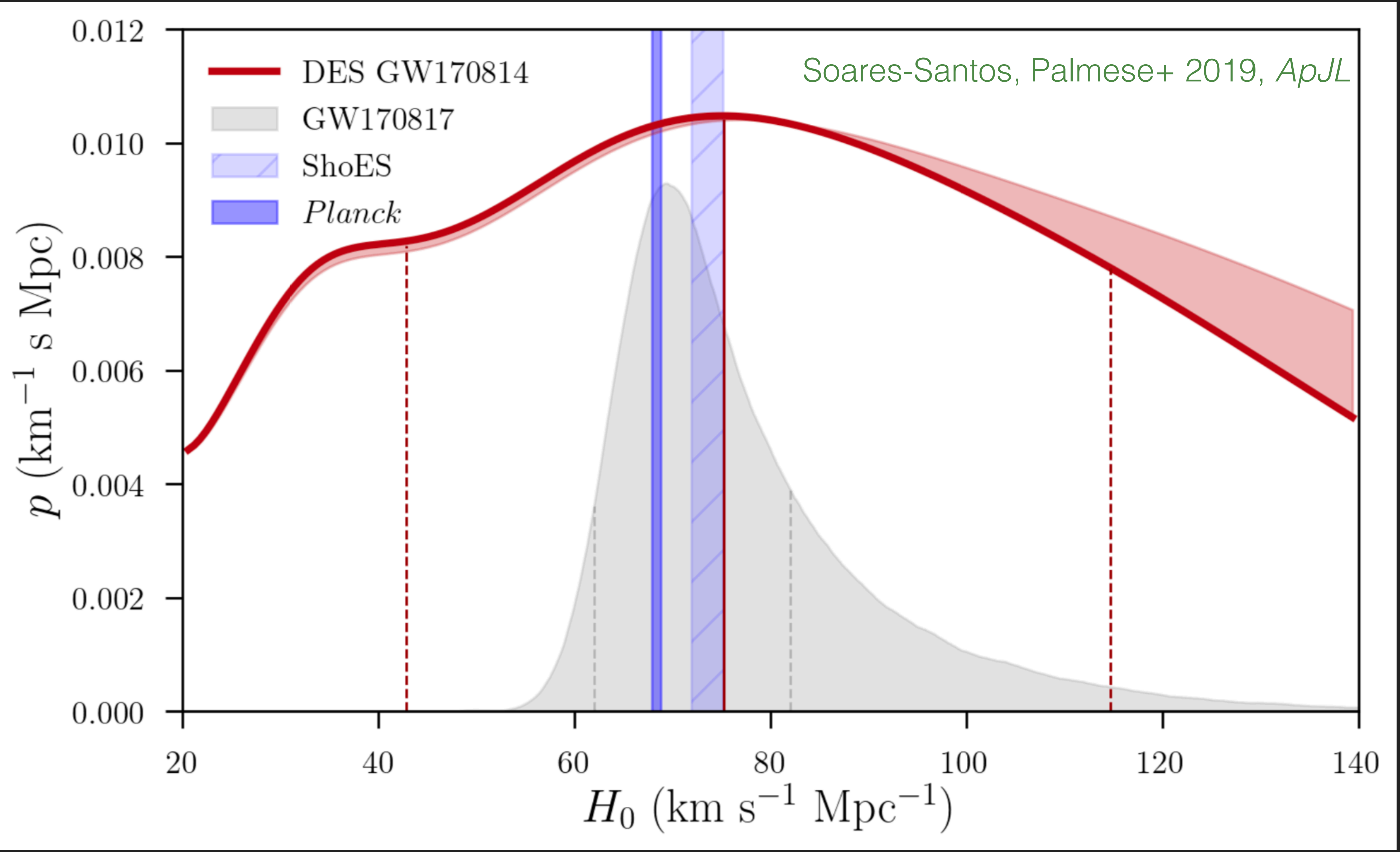
- GW170814 was first “triple” binary black hole: Hanford, Livingston, and Virgo detectors help constrain localization volume
- GW170814 localization volume was relatively small: 2×10^6 Mpc^3
- No electromagnetic counterpart
- GW170814 happens to fall in the middle of the DES footprint!
- Get a uniformly sampled, relatively deep catalog “for free”
- Use galaxy catalog plus gravitational-wave distances to infer posteriors for the Hubble constant
- 77,000 galaxies in the localization region

GW170814 as a dark standard siren

Lots of subtleties:

- What constitutes a galaxy? Do dwarf galaxies count?
- How deep is the catalog? Completeness corrections
- Weight galaxies? By stellar mass? Star formation? Metallicity? Something else?
- Spectroscopic or photometric redshifts? For photometric redshifts, significant systematic errors
- Role of large-scale structure
- Role of priors

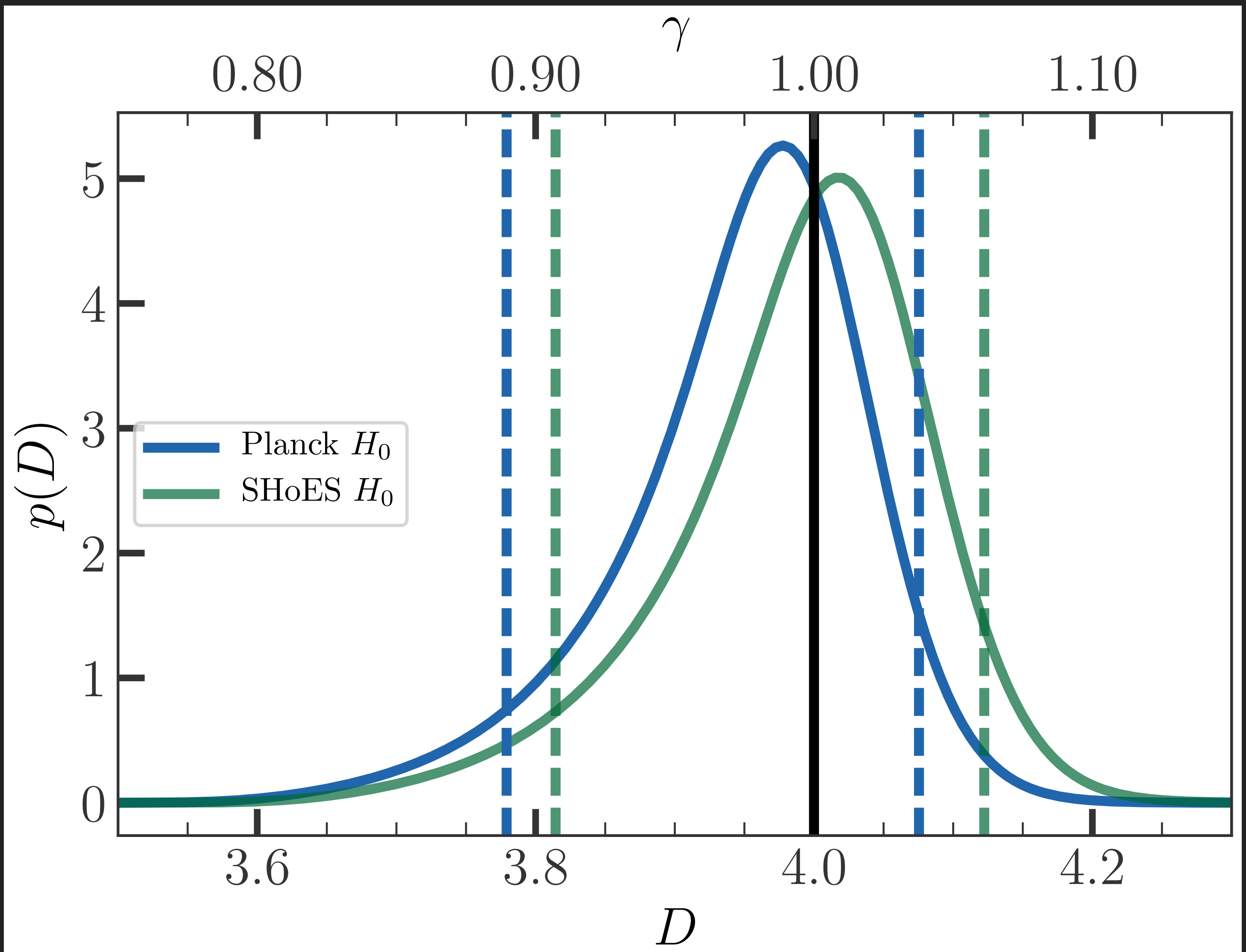
GW170814 as a dark standard siren



$$H_0 = 75^{+40}_{-32}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

What if general relativity is wrong?

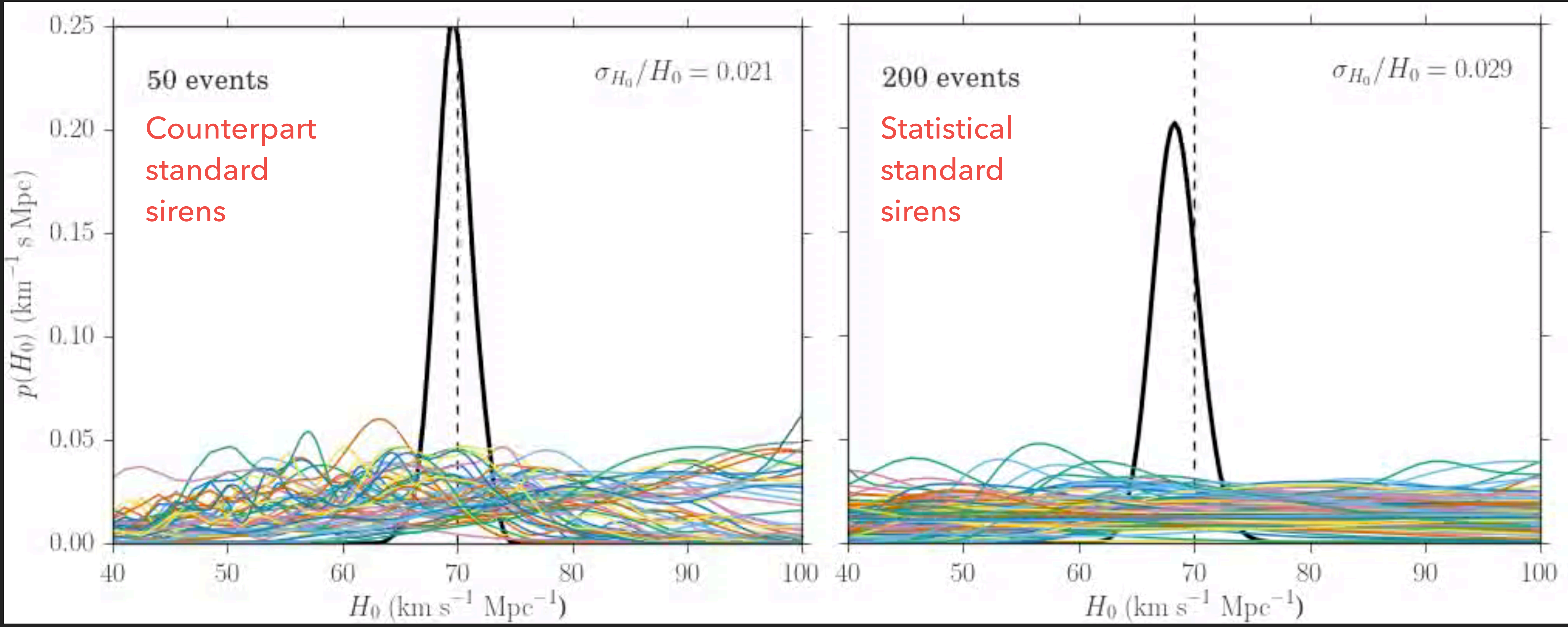
- Can use standard sirens to measure breakdown of GR (Nishizawa 2017; Belgacem+ 2017; Amendola+ 2017; Linder 2018)
- If gravitational wave and electromagnetic distances disagree could be signs of:



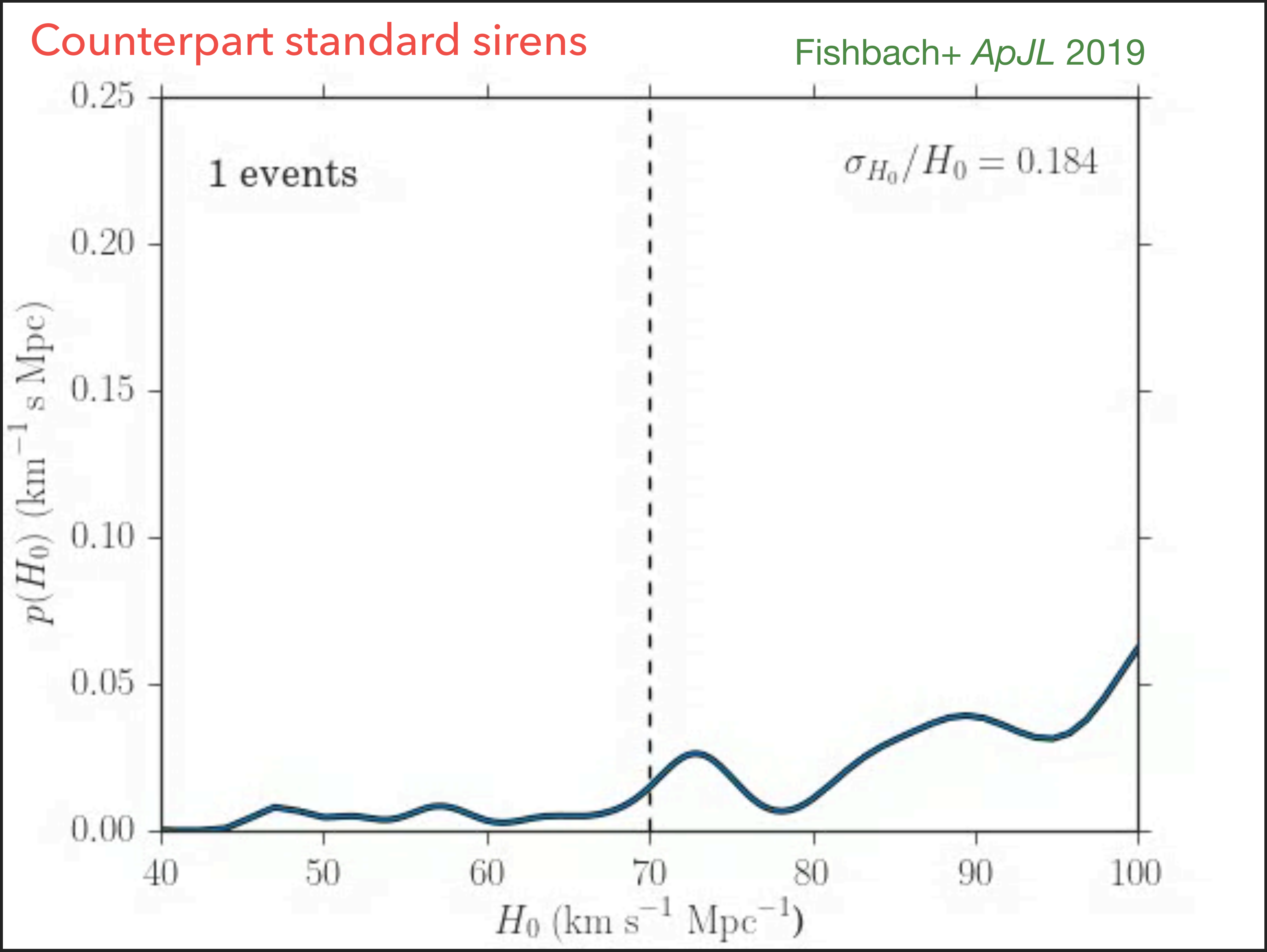
- Extra spacetime dimensions (Pardo, Fishbach, DH, & Spergel 2018)
- Running of the Planck constant (Lagos, Fishbach, Landry, & DH 2019)

Simulations of standard siren convergence

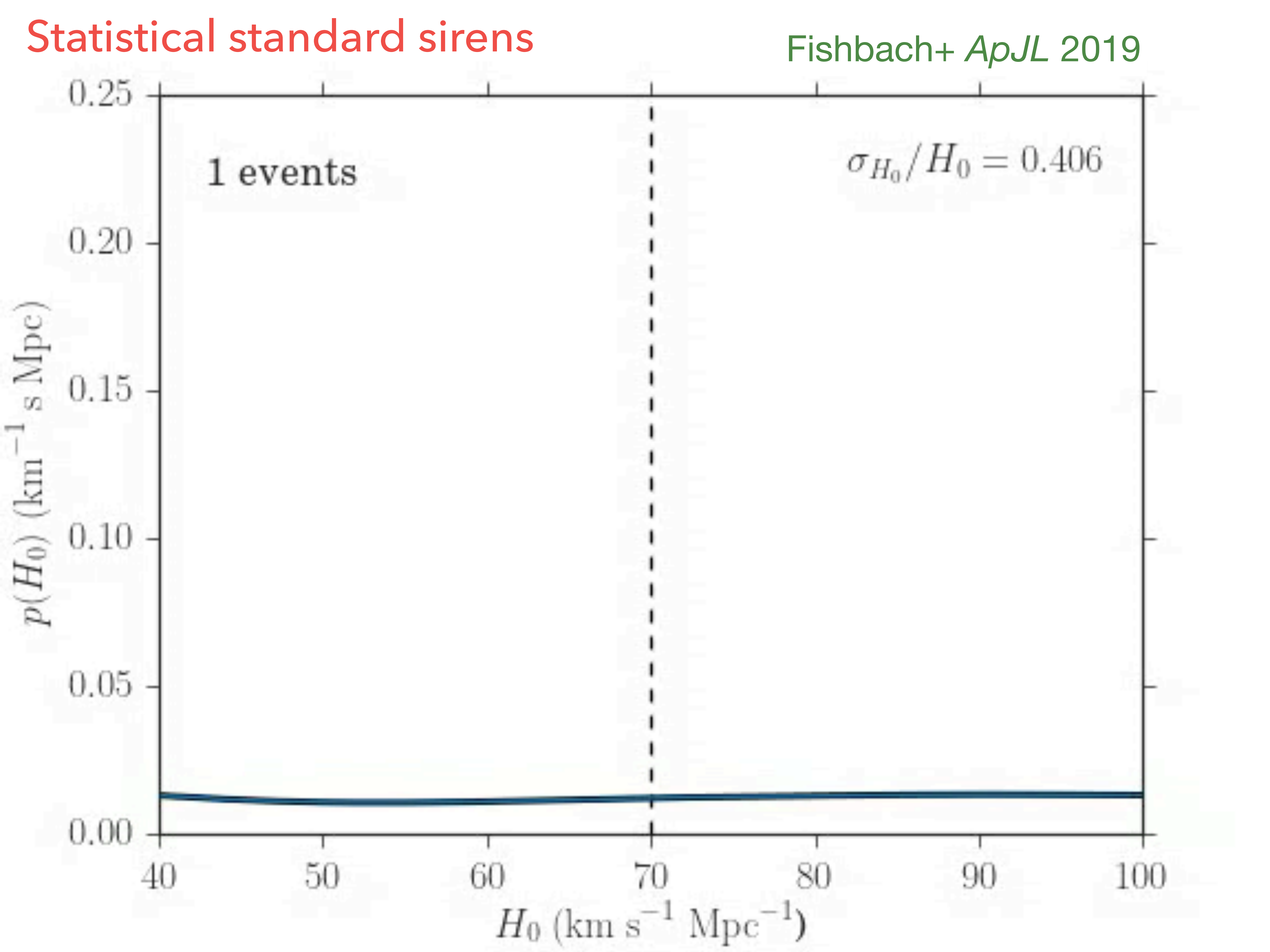
- Mock binary neutron star events from "First Two Years" dataset (Singer, Chen, DH+ 2014)
- Inject events into MICE mock galaxy catalog (Crocce+ 2015)



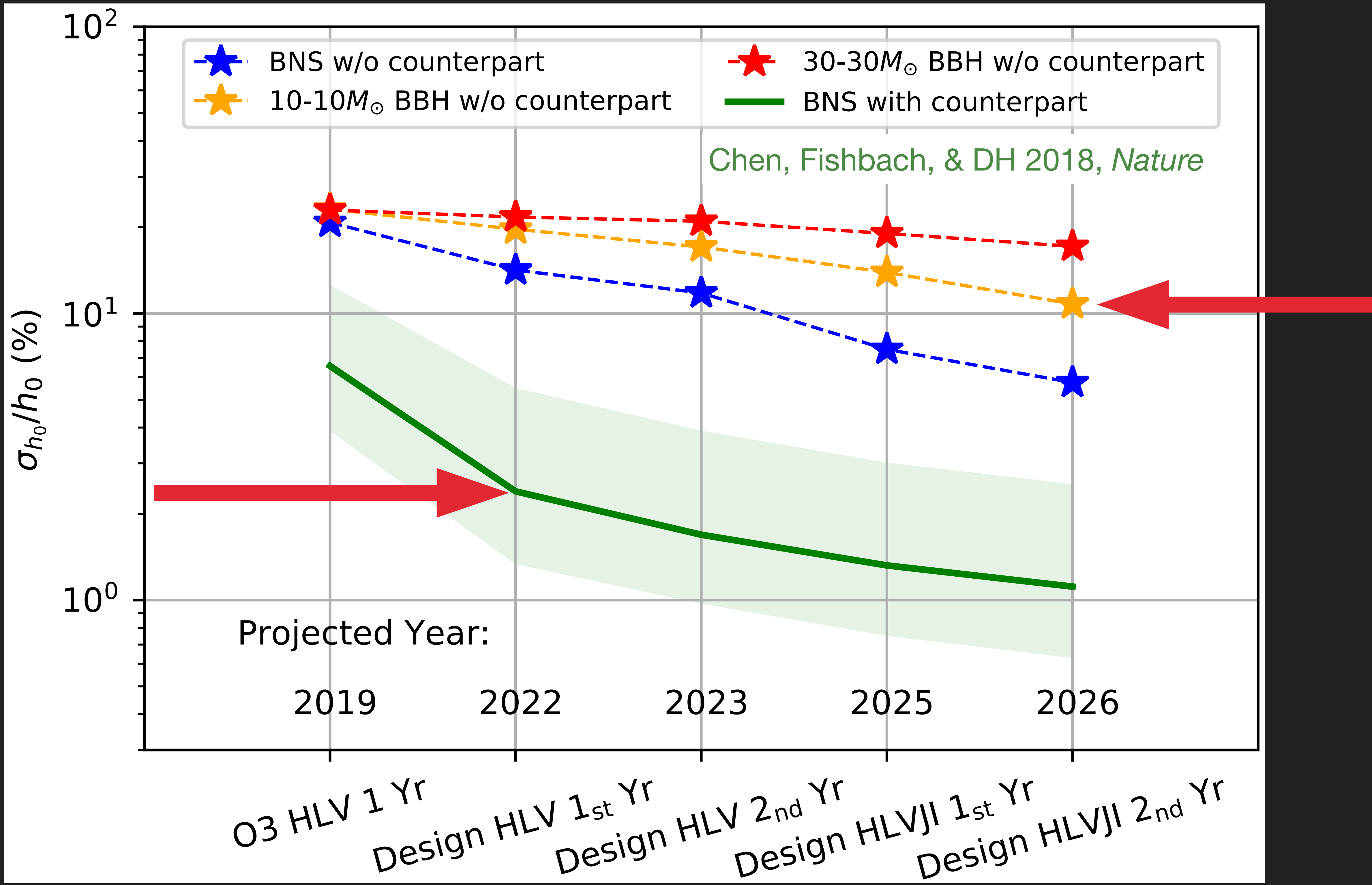
What will the future bring?



What will the future bring?

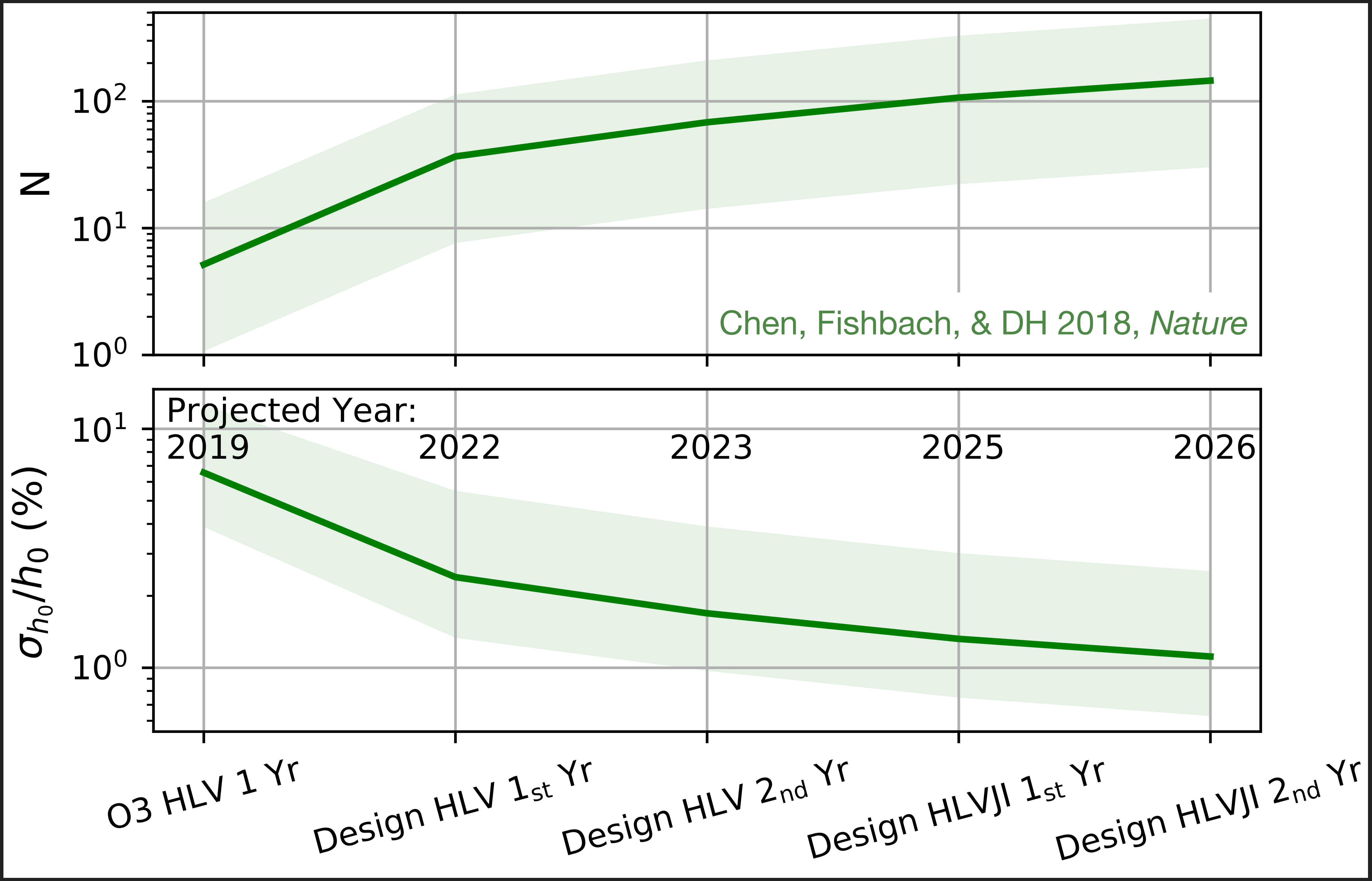


Precision standard siren cosmology



- Within a year at design sensitivity (starting ~2022) we get to ~2.5% measurement of the Hubble constant
- Statistical/Dark sirens are roughly one order of magnitude behind. Although there are many more, each one is much worse

H_0 to 2% by 2023, 1% by 2026*



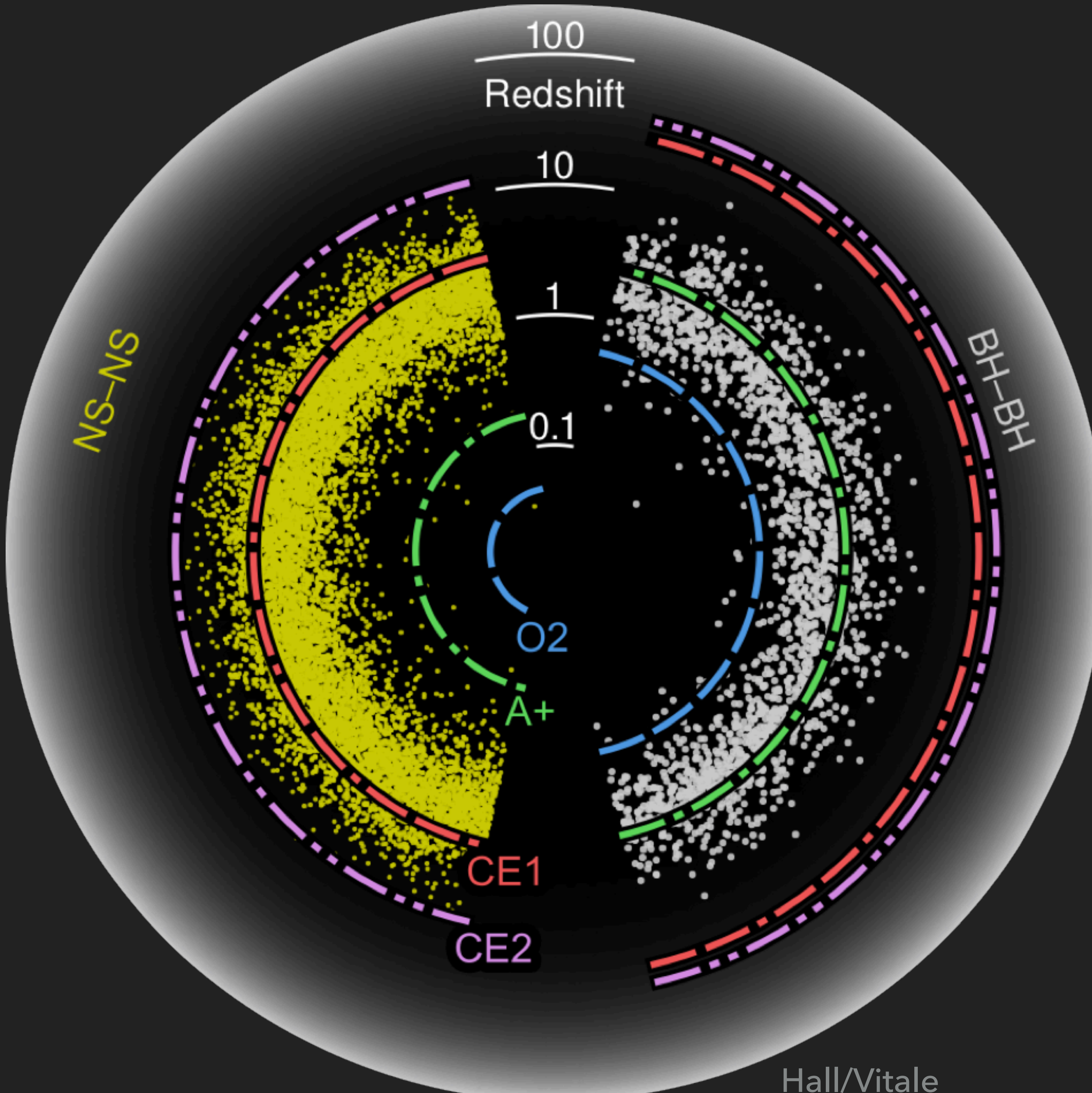
*convergence may be slower if low detection rate or missing BNS counterparts

What will the future bring?

- Additional measurements lead to improved H_0 constraints (Dalal, DH, Hughes, & Jain 2006; Nissanke, DH+ 2010, 2013; Chen, Fishbach, & DH 2018; Feeney+ 2018)
  - *N* counterpart standard siren events converge as $\sim 15\,\%/\sqrt{N}$
  - *N* statistical standard siren events converge as $\sim 40\,\%/\sqrt{N}$
- Surprises? BBH counterparts? Lots of NSBHs?
- *LISA*!
- Cosmic Explorer? Einstein Telescope?

Cosmic Explorer

- Detect all binary mergers in the Universe?
- Counterparts for a small fraction provide full expansion history
- 20 years away?



Hall/Vitale

Standard siren systematics

- Distance ladder
- Calibration of “standard”
- Extinction
- Metallicity
- Crowding
- Low-l versus high-l
- Line-of-sight large-scale structure
- …

Standard siren systematics

- Peculiar velocities (should become negligible soon)
- Model selection (priors over GW population impact final results [e.g. rate evolution, mass distribution])
- Inclination distribution (can be fit out)
- EM constraints on inclination (only if EM constraints are used)
- Statistical standard sirens: Galaxy mis-identification? Galaxy catalog incompleteness? Redshift systematics?
- Failure of general relativity?

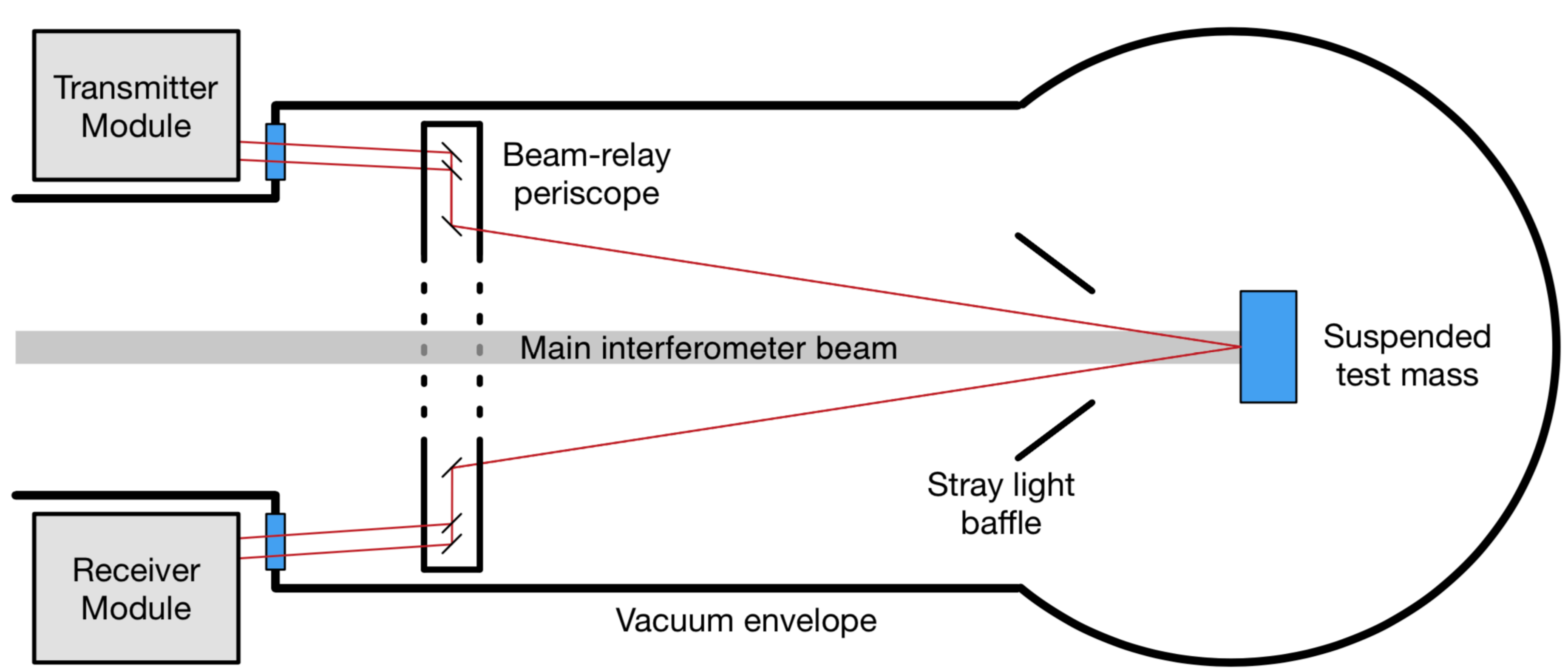
- Absolute calibration of GW detectors: amplitude response as a function of frequency
    - 1% measurement of H_0 requires 1% calibration of amplitude response

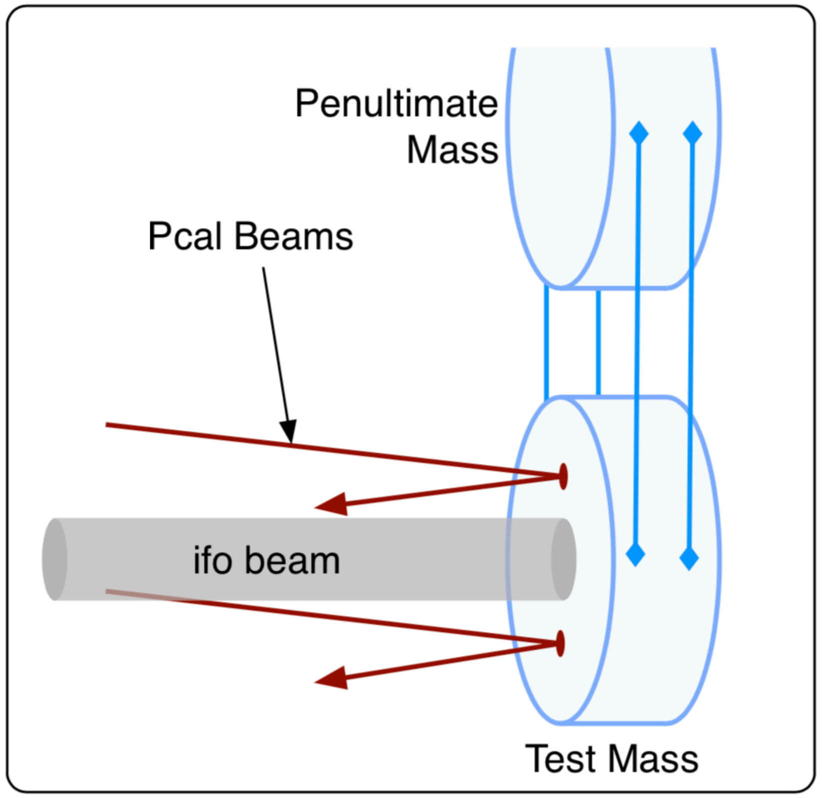
Photon calibrator

- Shine calibrated laser onto test masses. Use known radiation pressure to measure response of instrument at different frequencies
- Errors dominated by uncertainty in power of reference laser
- Current: ~5%
- Future: <1%

Parameter	Relative Uncertainty
Laser Power [$\mathcal{P}$]	0.57 %
Angle [cosθ]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a} \cdot \vec{b})M/I$]	0.40 %
Overall	**0.75 %**

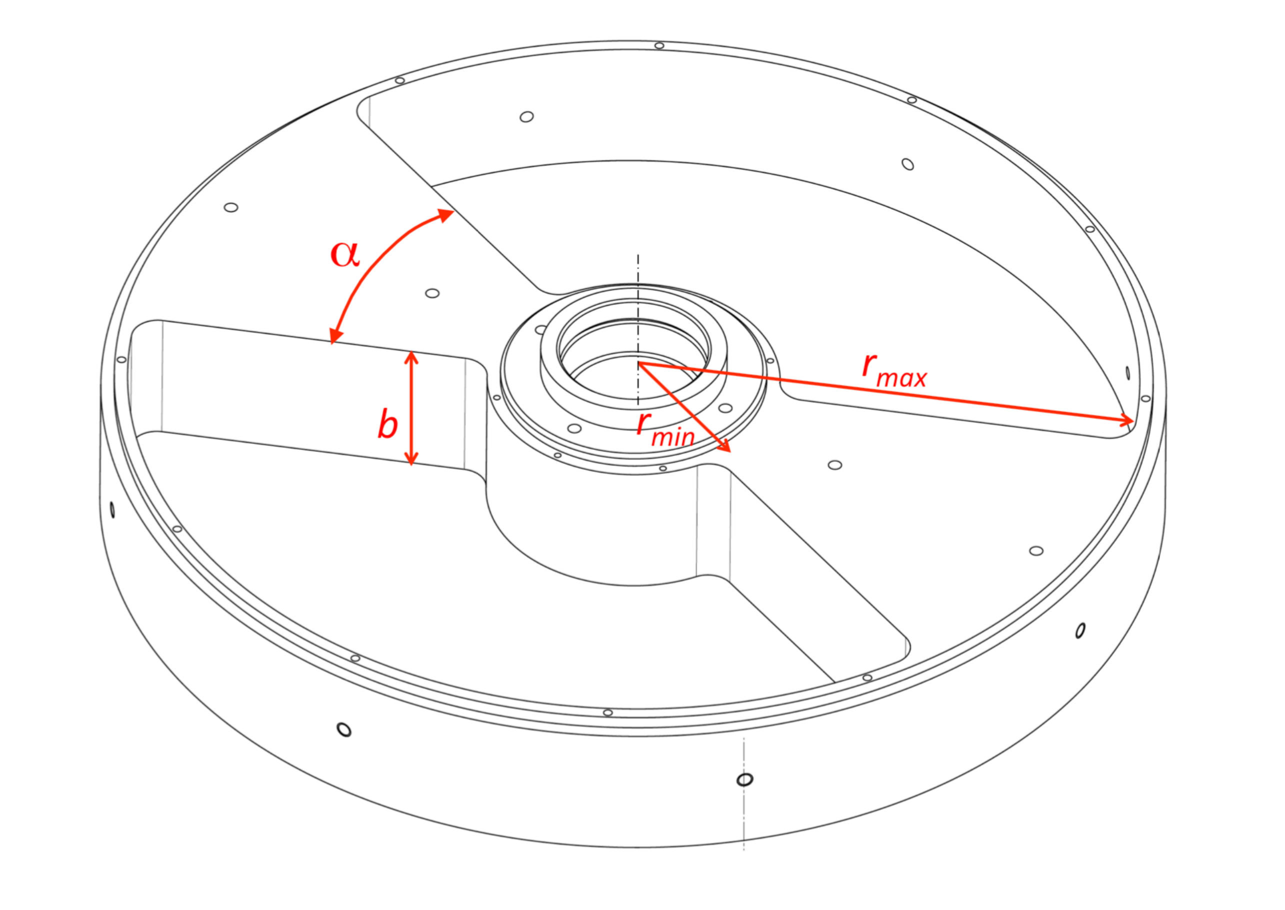
Karki+ 2016; Cahillane+ 2017



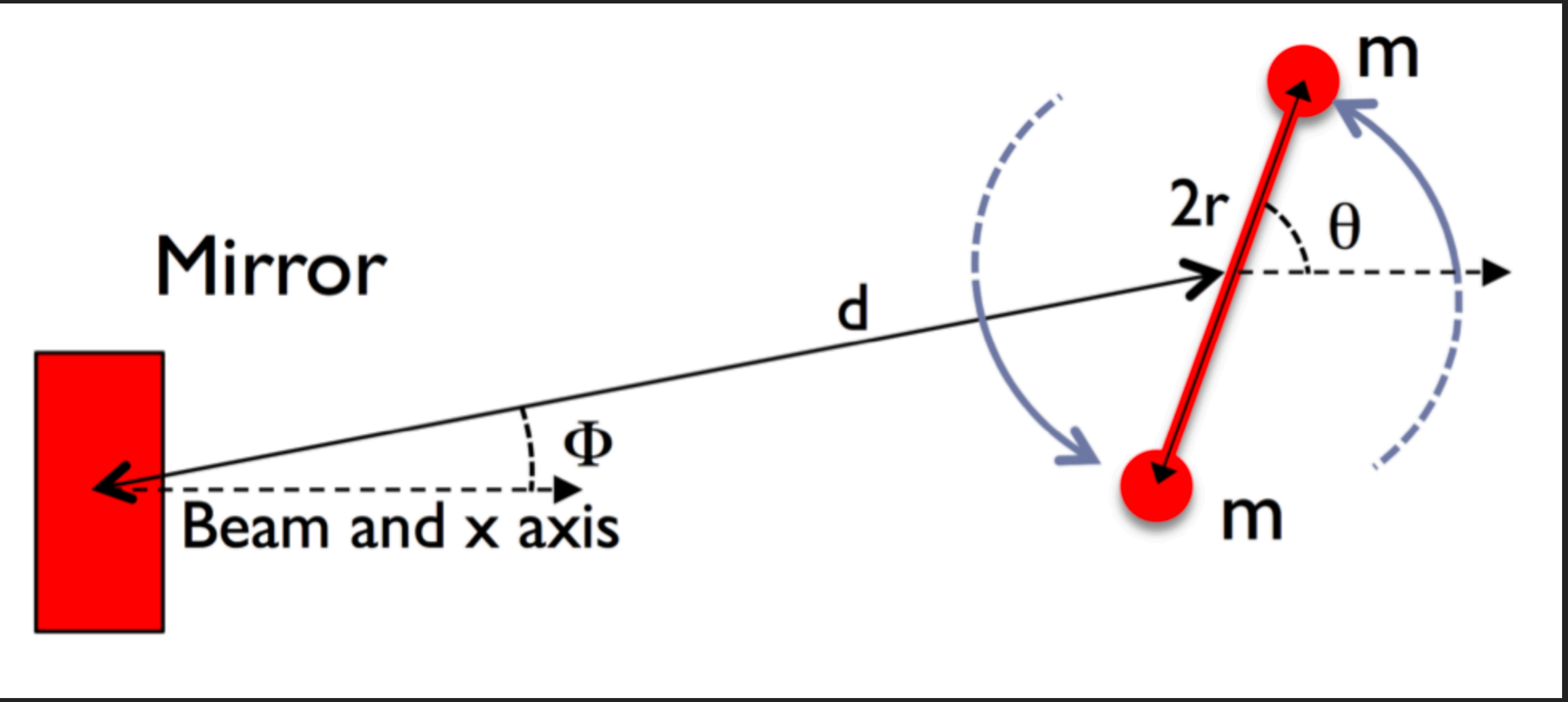


Newtonian calibrator

- Spin a dumbbell near the test masses. Alternating gravitational "force" on test masses calibrates response of instrument
- In initial development at Virgo
- non-gravitational coupling?
- Current: <10%
- Future: <1%?

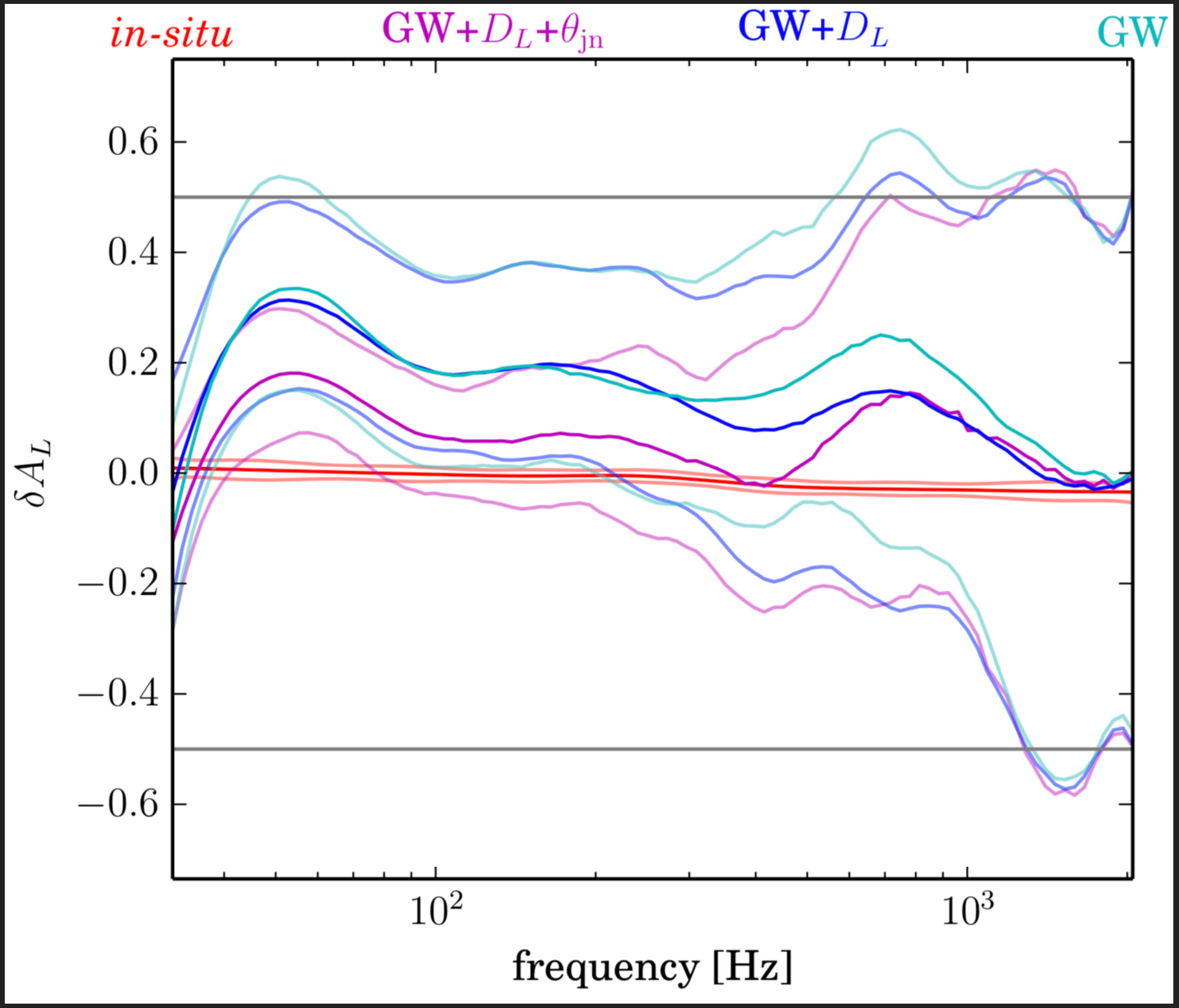


Estevez+ 2018



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

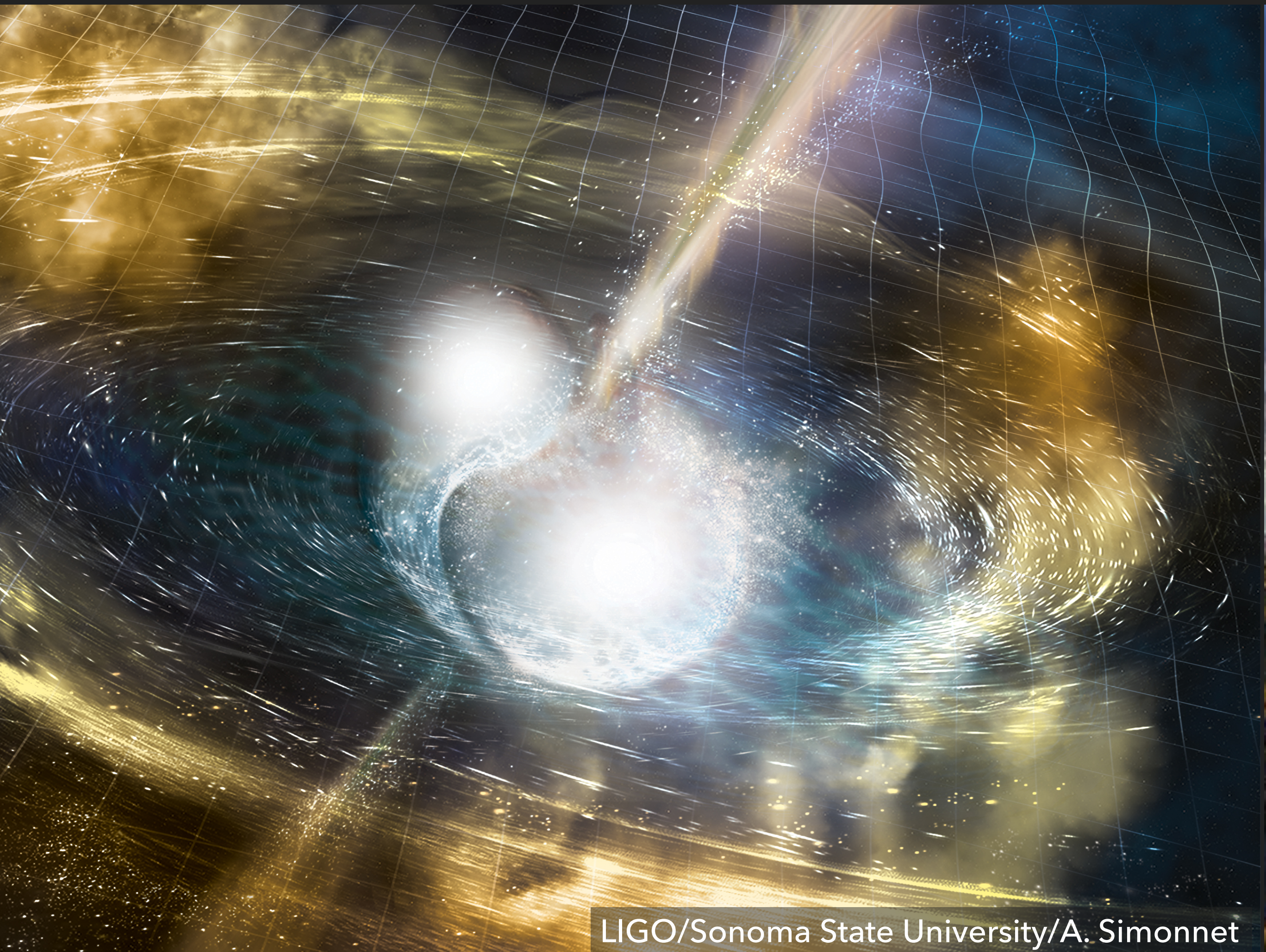


Essick & DH 2019

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

The future is loud and bright

- Standard sirens provide a self-calibrated, absolute, and direct measurement of the Hubble constant
- With GW170817 and GW170814 we have established that the method works
- It is now just a matter of time before standard sirens provide precision cosmological constraints



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