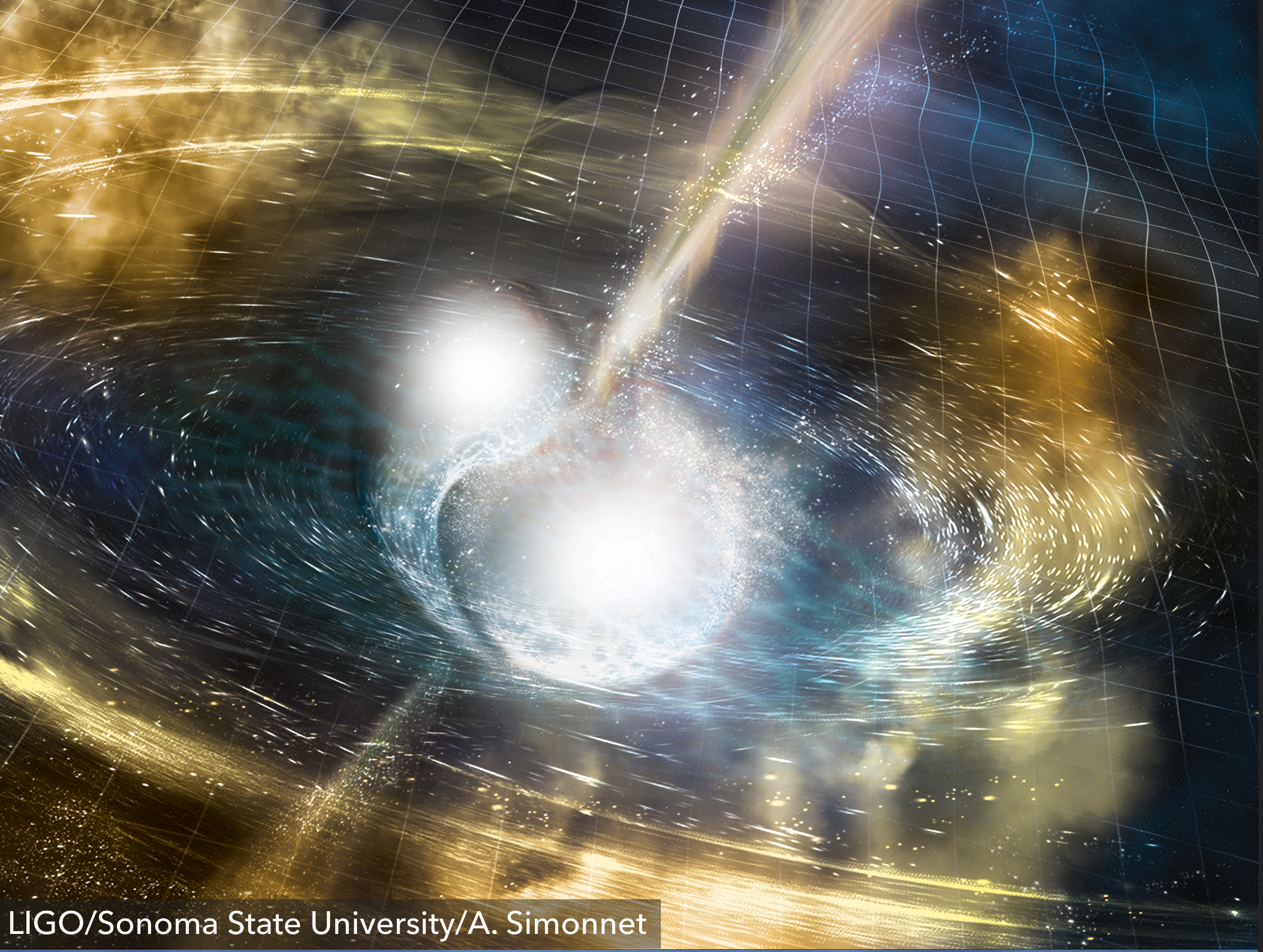


Update on standard siren science

Daniel Holz
University of Chicago

Gravitational-wave astronomy has arrived!

Recent papers on GW astrophysics

- Facilitating follow-up of LIGO-Virgo events using rapid sky localization
  Chen & DH 2017, *ApJ*
- Observational Selection Effects with Ground-based Gravitational Wave Detectors; Chen, Essick, Vitale, & DH 2017, *ApJ*
- Are LIGO's Black Holes Made From Smaller Black Holes?
  Fishbach, DH, & Farr 2017, *ApJL*
- Statistical Gravitational Waveform Models: What to Simulate Next?
  Doctor, Farr, DH, & Pürrer 2017, *PRD*
- Where are LIGO's Big Black Holes?
  Fishbach & DH 2017, *ApJL*
- Does the Black Hole Merger Rate Evolve with Redshift?
  Fishbach, DH, & Farr 2018, *ApJL*

- Explaining LIGO's observations via isolated binary evolution with natal kicks
  Wysocki et al. 2018, *PRD*
- Using spin to understand the formation of LIGO's black holes
  Farr, DH, & Farr 2018, *ApJL*

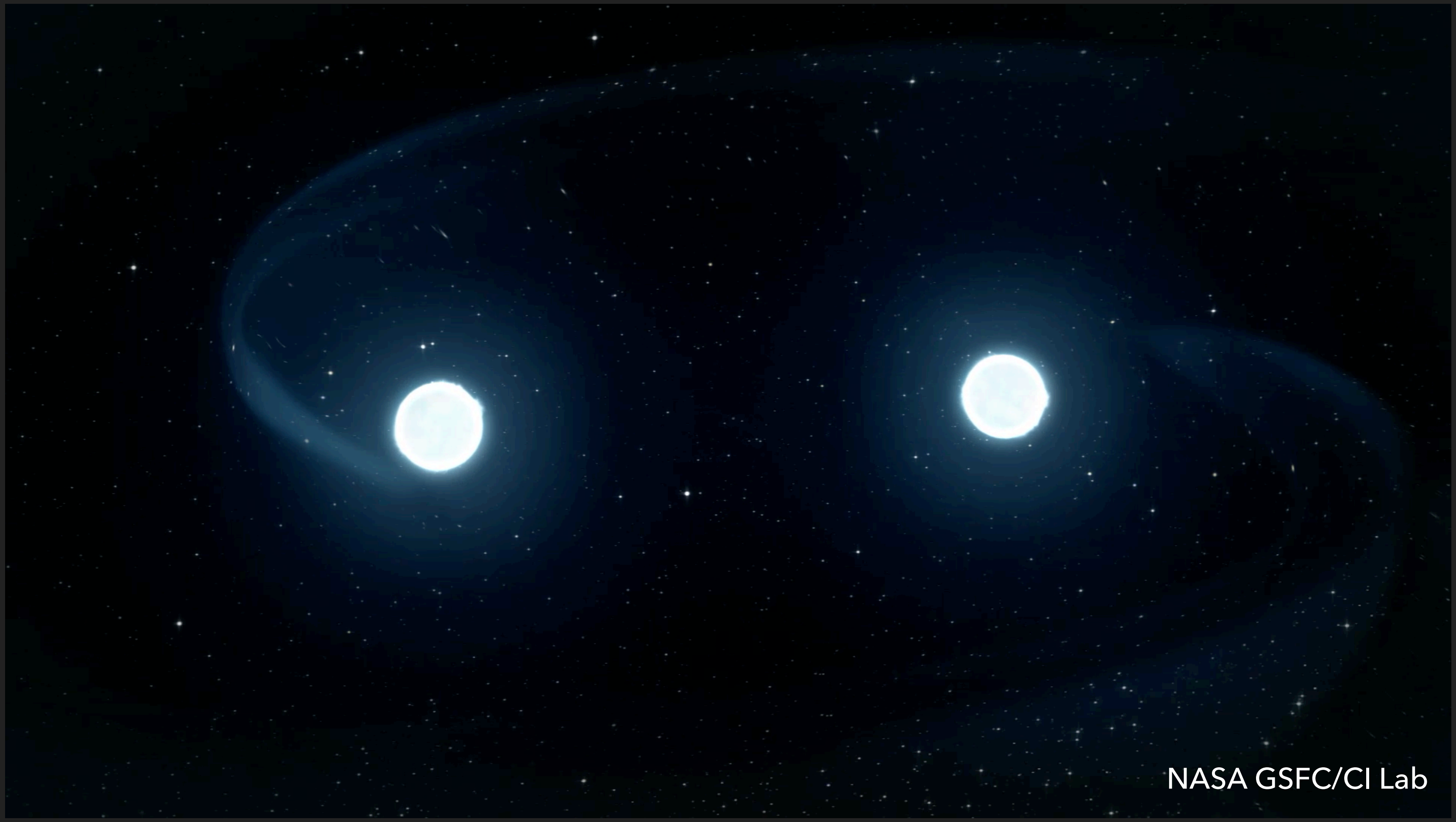
Recent papers on GW astrophysics

- A Precise Distance to the Host Galaxy of the Binary Neutron Star Merger GW170817 Using Surface Brightness Fluctuations; Cantiello et al. 2018, *ApJL*
- Limits on the number of spacetime dimensions from GW170817
Pardo, Fishbach, DH, & Spergel 2018, *JCAP*
- Impact of inter-correlated initial binary parameters on double black hole and neutron star mergers; Klencki et al. 2018, *A&A*
- Standard sirens with a running Planck mass
Lagos, Fishbach, Landry, & DH 2019, *PRD*
- Calibrating gravitational-wave detectors with GW170817
Essick & DH 2019, CQG

- The evolutionary roads leading to low effective spins, high black hole masses, and O1/O2 rates of LIGO/Virgo binary black holes; Belczynski+ 2019
- Picky Partners: The Pairing of Component Masses in Binary Black Hole Mergers
Fishbach & DH 2019
- Black hole shadows, photon rings, and lensing rings
Gralla, DH, & Wald 2019, PRD

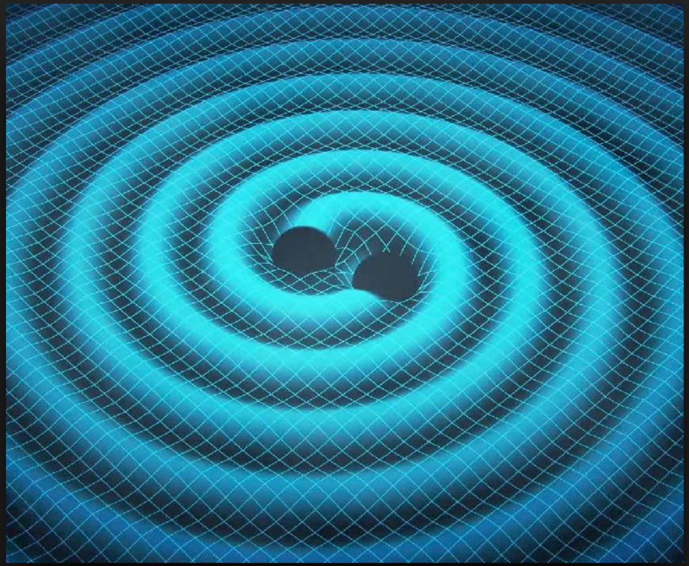
Gravitational-wave astronomy has arrived!

Gravitational-wave cosmology has arrived!



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

- Strongest harmonic (widely separated):

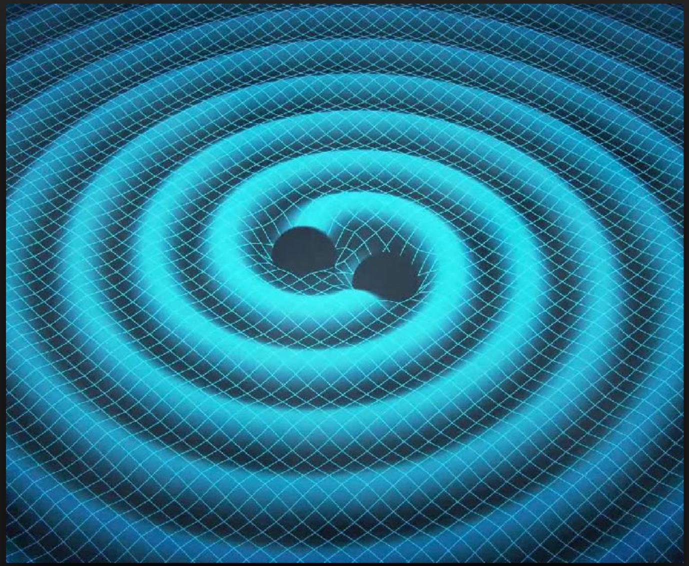
$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$

- 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?

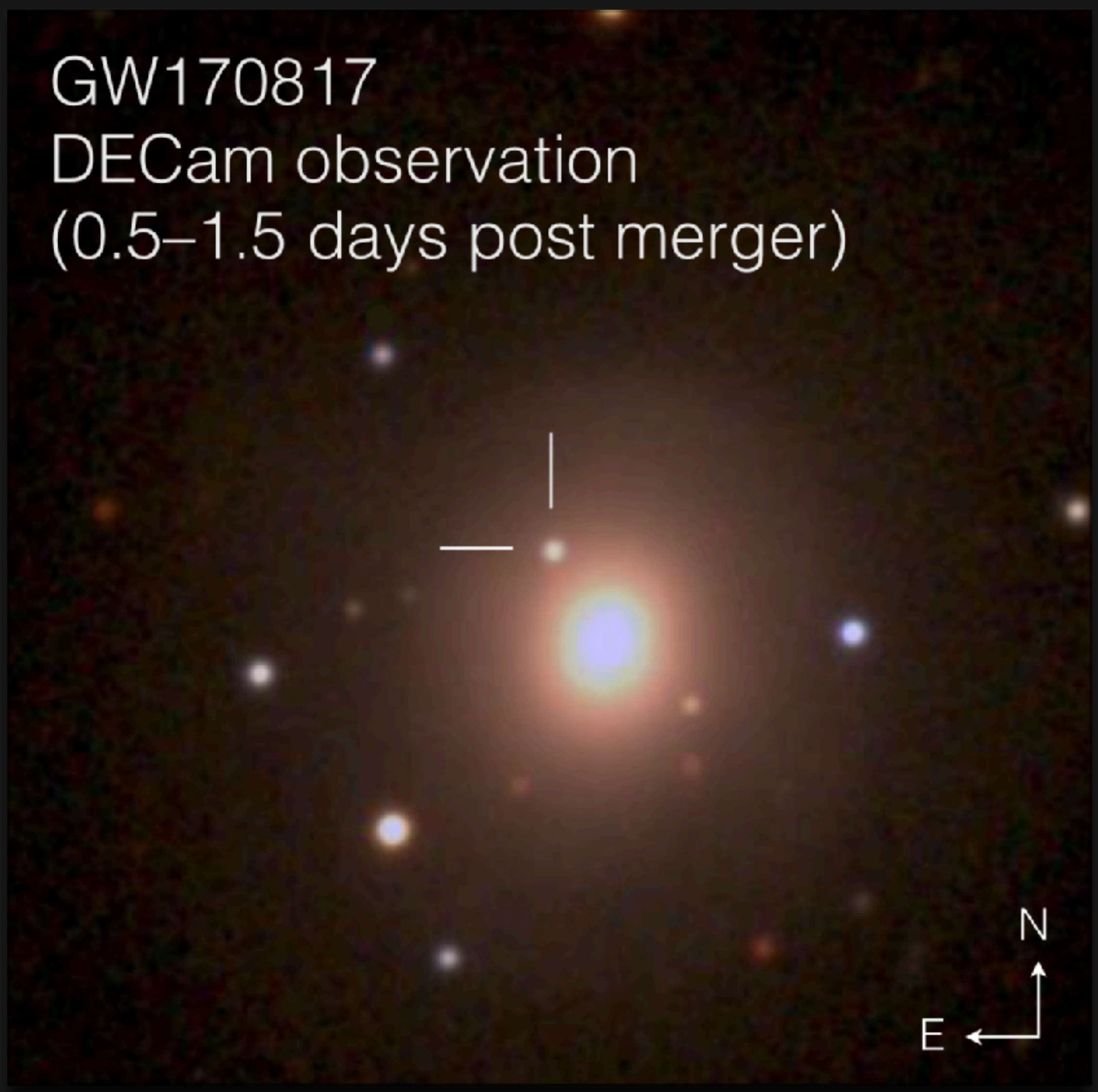
- Black holes are the simplest macroscopic objects in the Universe
- Binary coalescence is understood from first principles; provides direct absolute measurement of luminosity distance (Schutz 1986)
- Distance calibration provided by General Relativity
- Need independent measurement of redshift to constrain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



* Proposals to use mass distribution, EOS, etc.
Finn 1996; Taylor, Gair, & Mandel 2012; Messenger & Read 2012; Del Pozzo, Li, & Messenger 2017

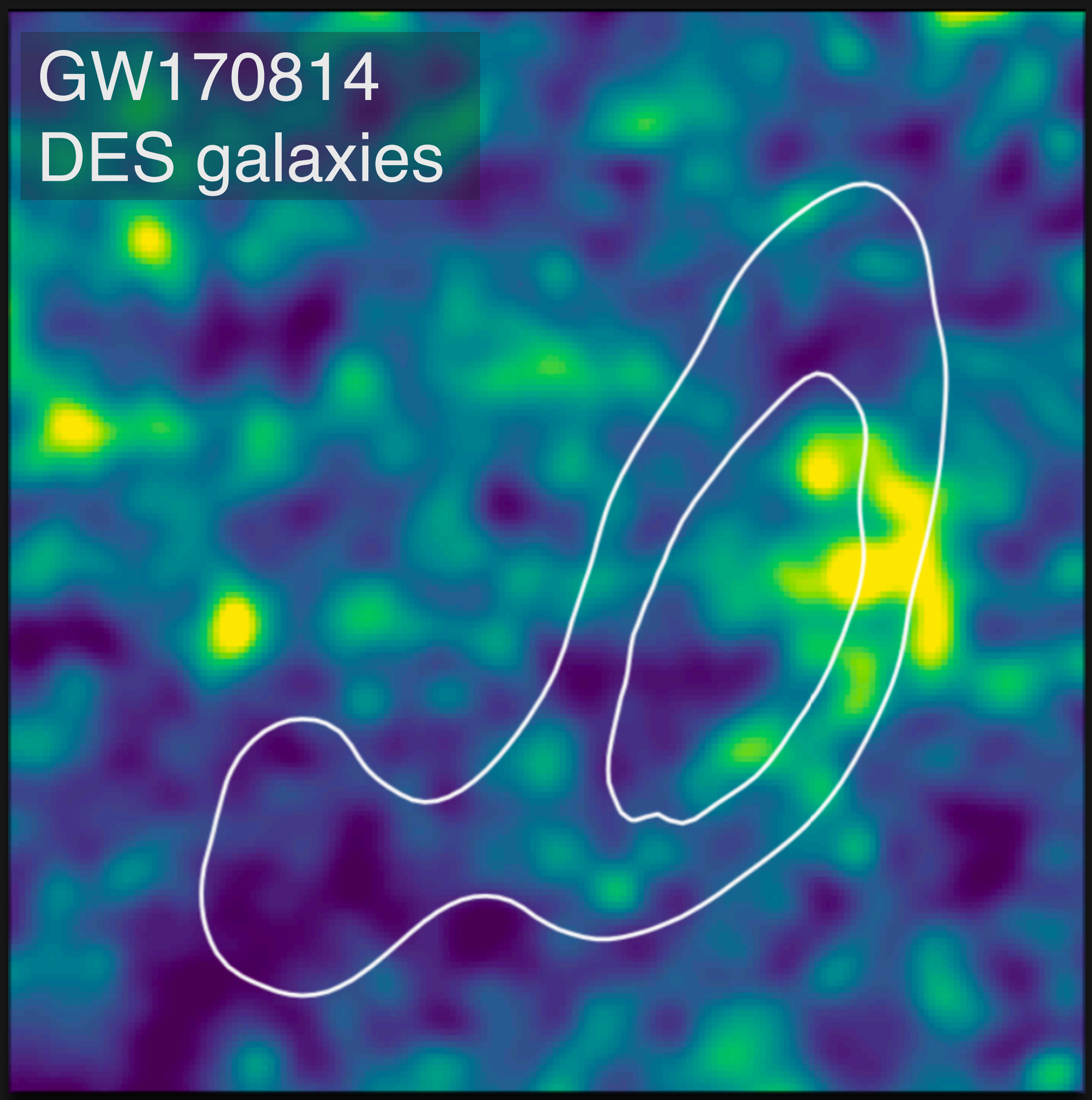
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

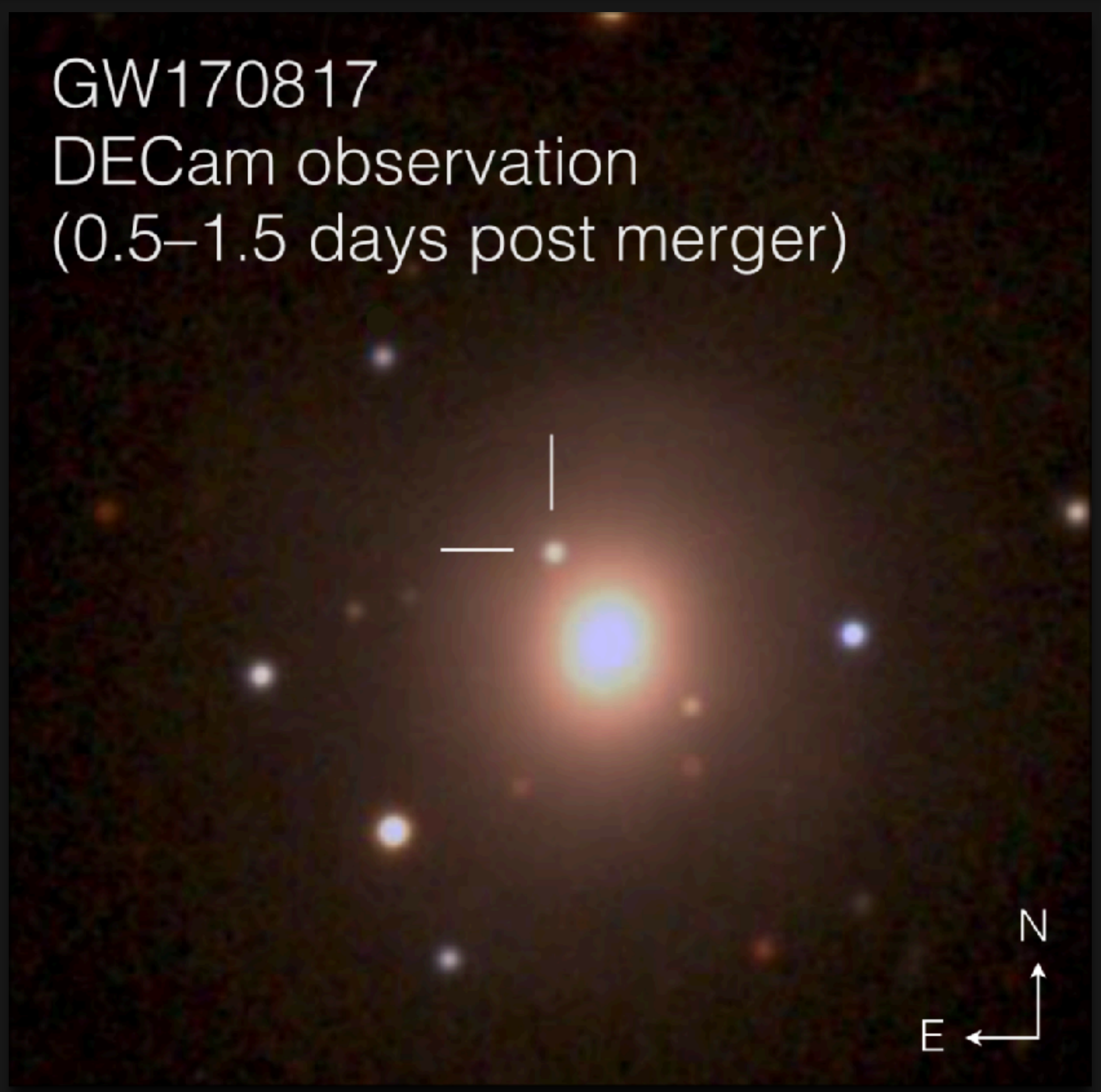
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

Counterpart/Bright



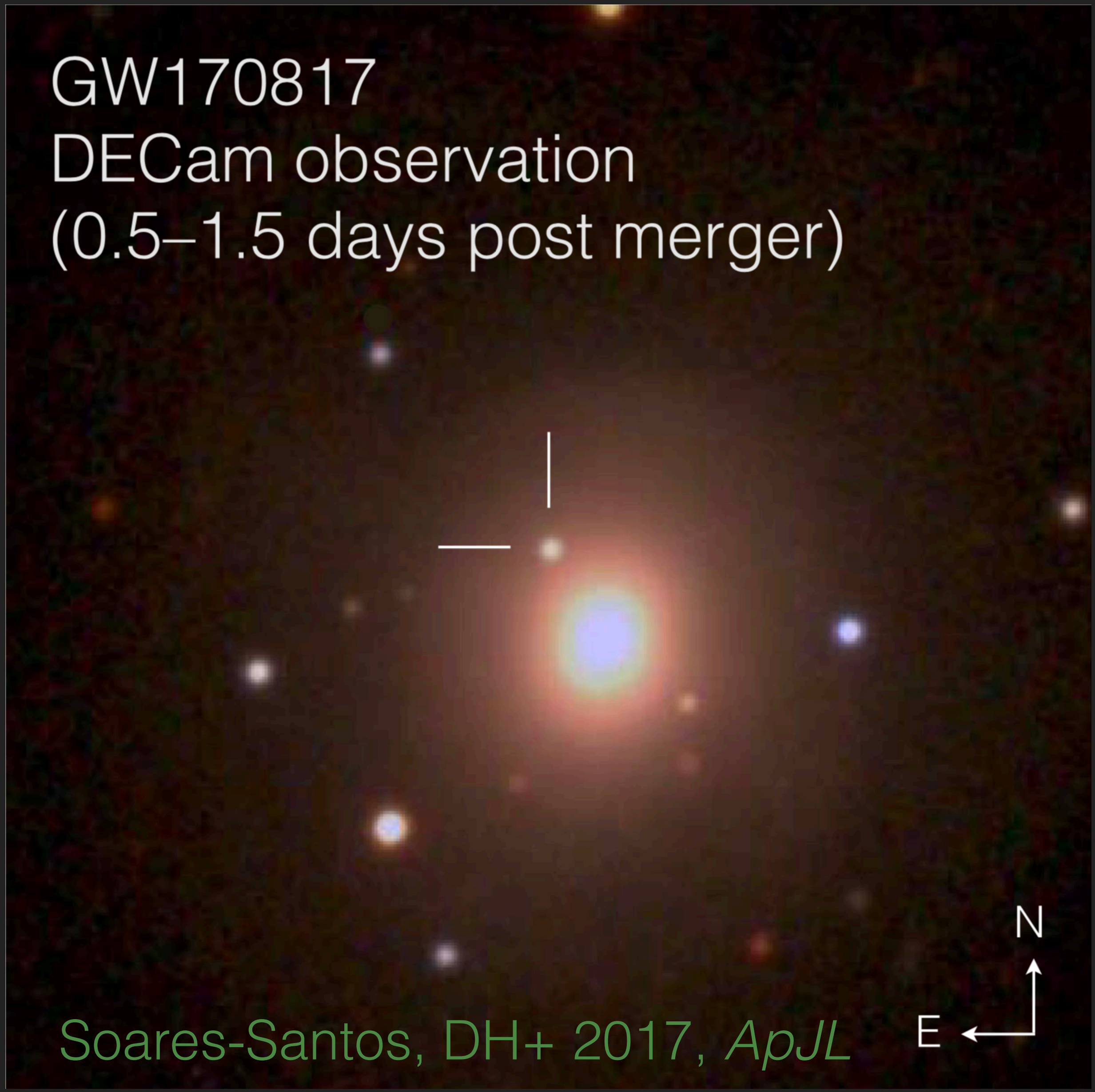
Unique host galaxy

- 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 was an ideal standard siren

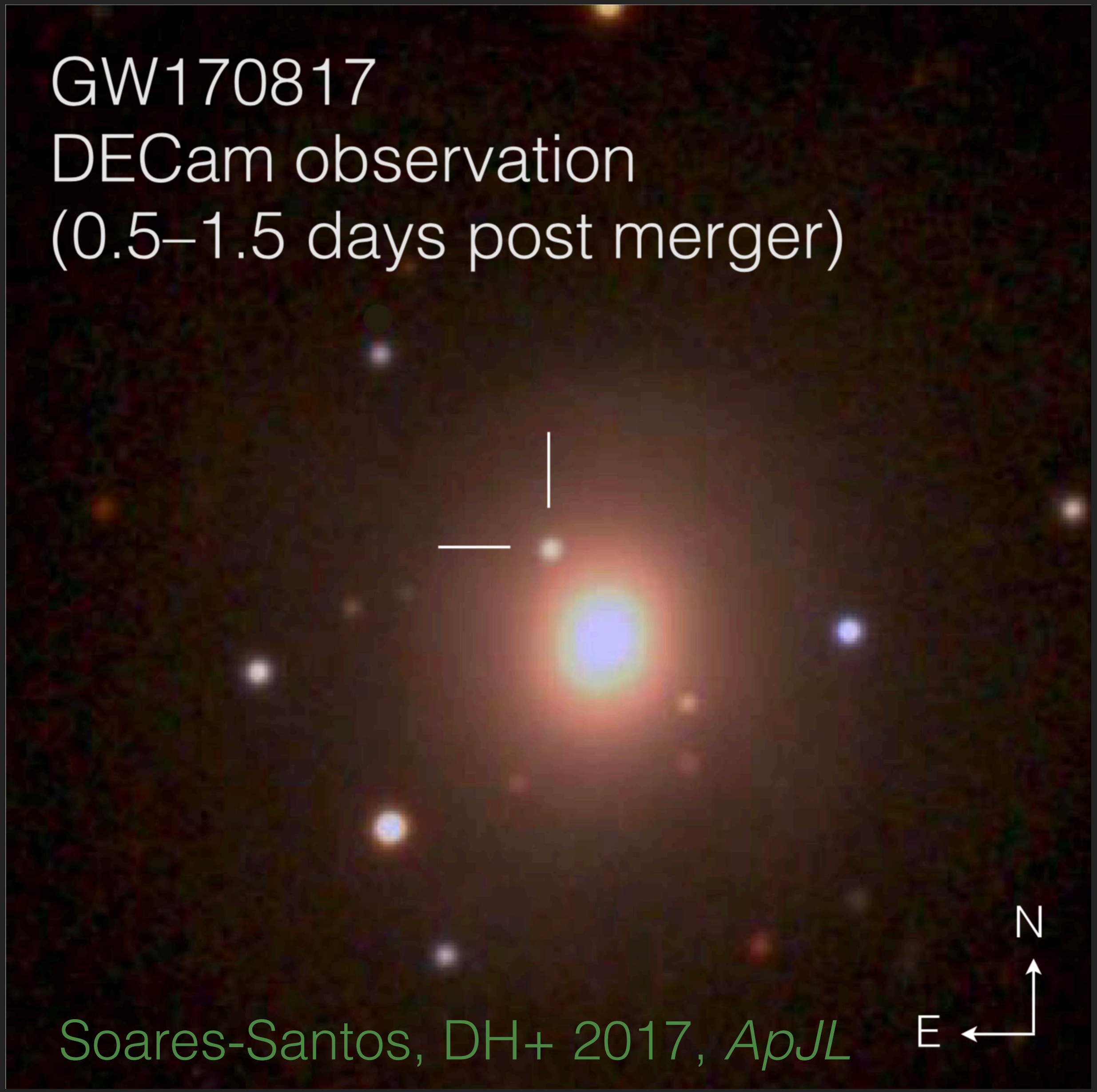
- GW170817 was detected in gravitational waves
    - Very high SNR
    - Excellent measurement of distance
- GW170817 had an optical counterpart
    - Host galaxy is NGC 4993
    - Measurement of redshift
- Poster child for the standard siren method….



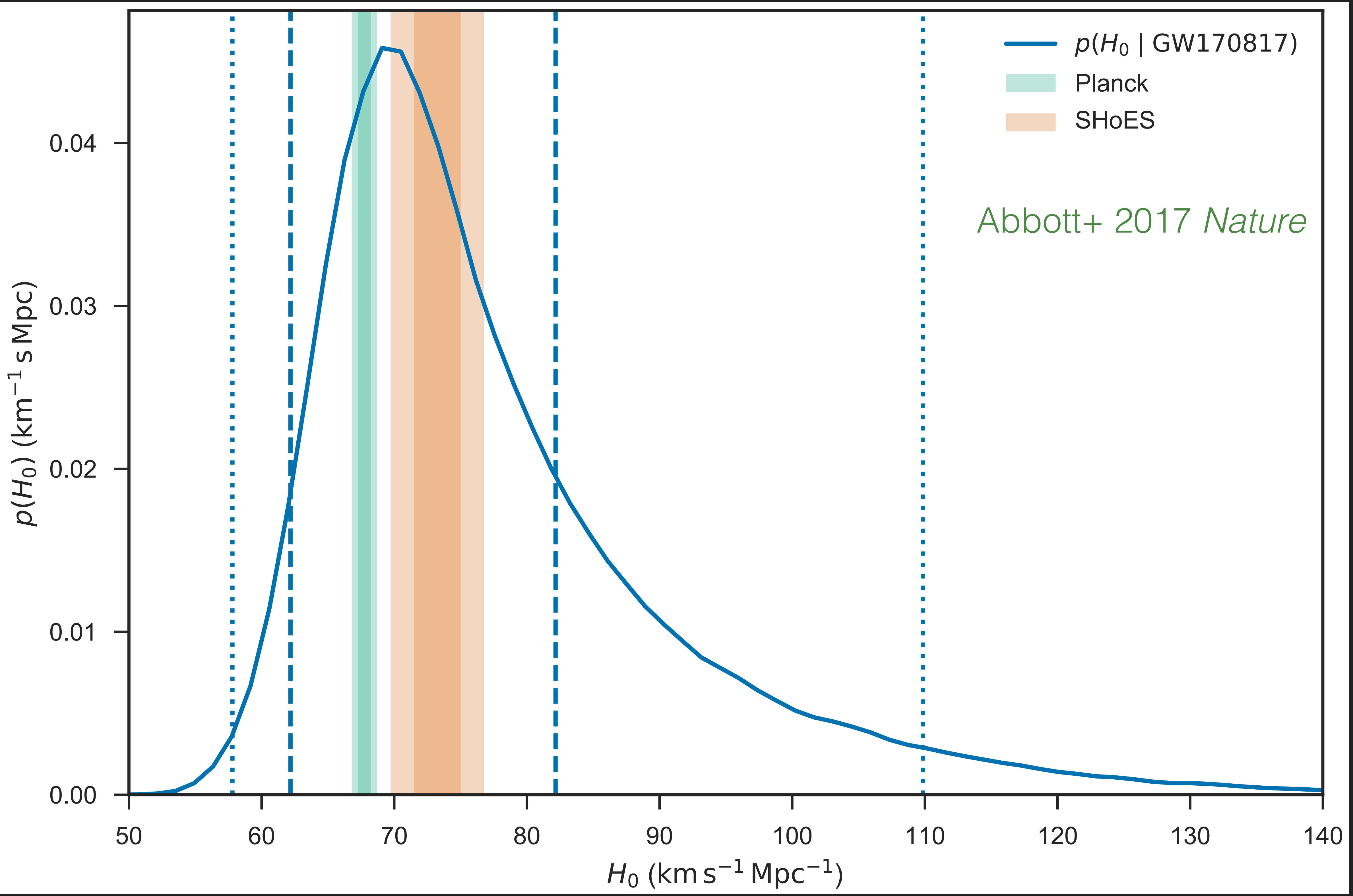
Soares-Santos, DH+ 2017, *ApJL*

Caveat: GW17081 was 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)

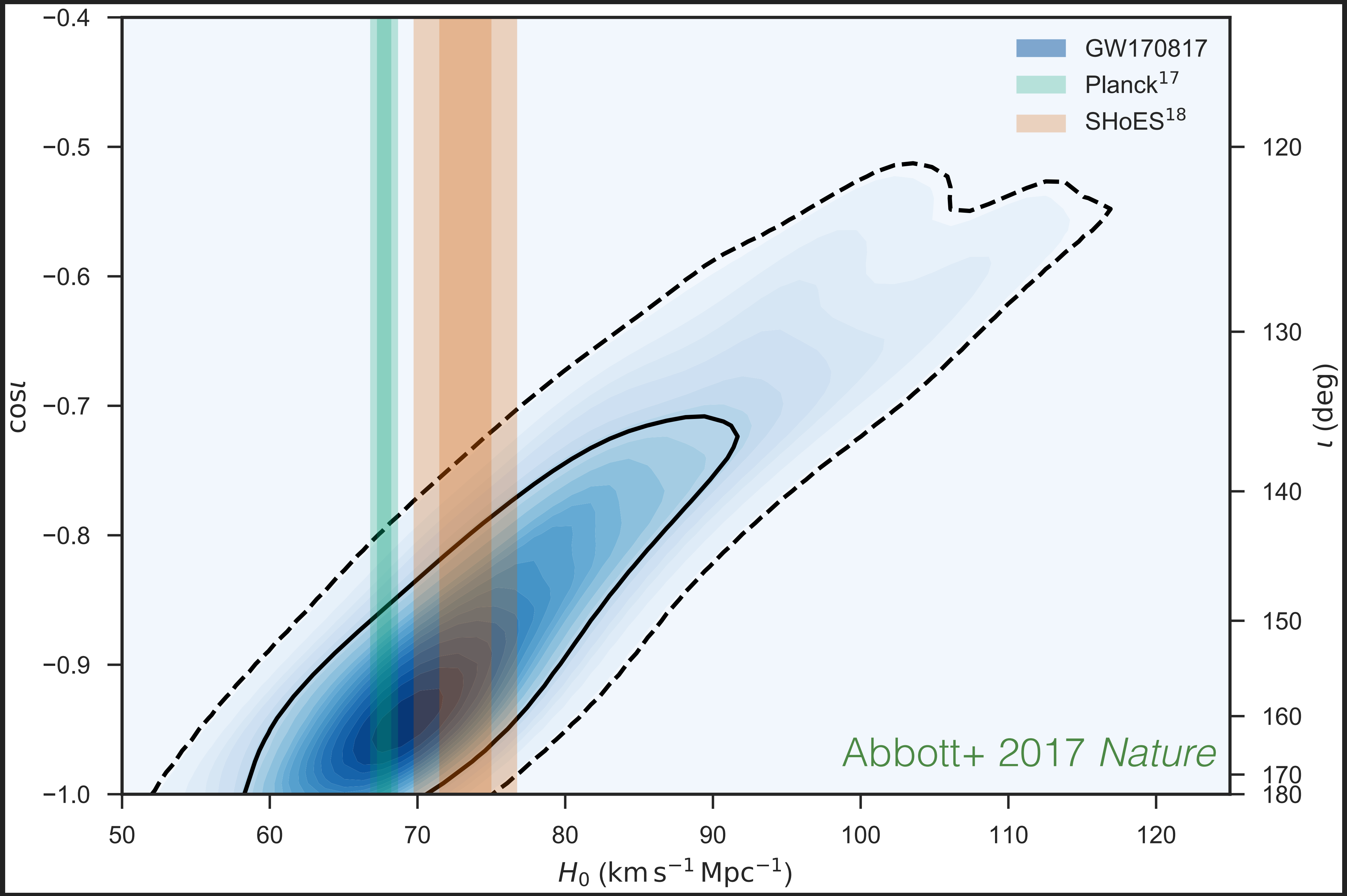


Standard siren measurement of the Hubble constant



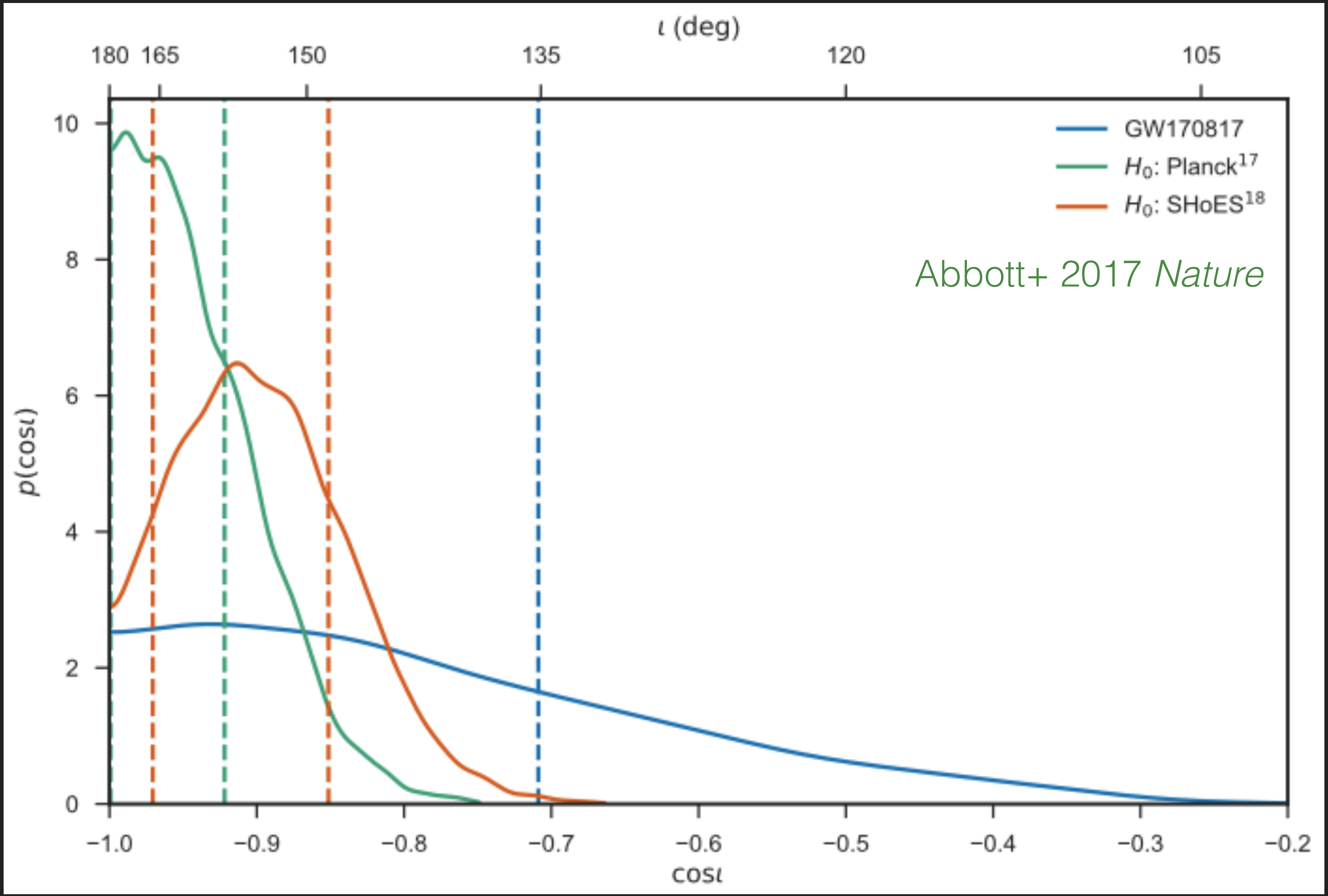
$$H_0 = 70.0^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Distance is correlated with inclination



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

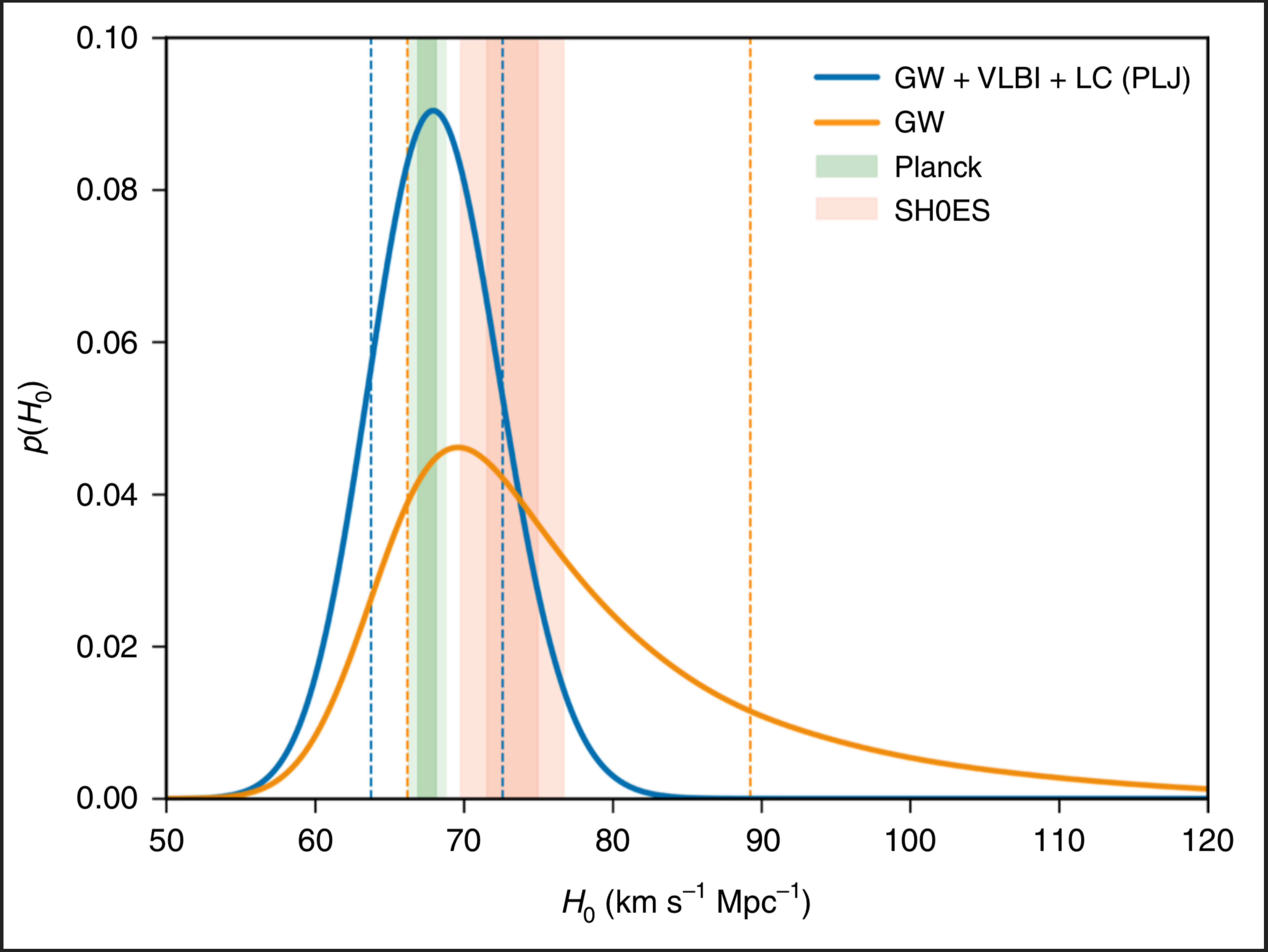
If you know cosmology, can improve inclination



Abbott+ 2017; Mandel 2018; Finstad+ 2018

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

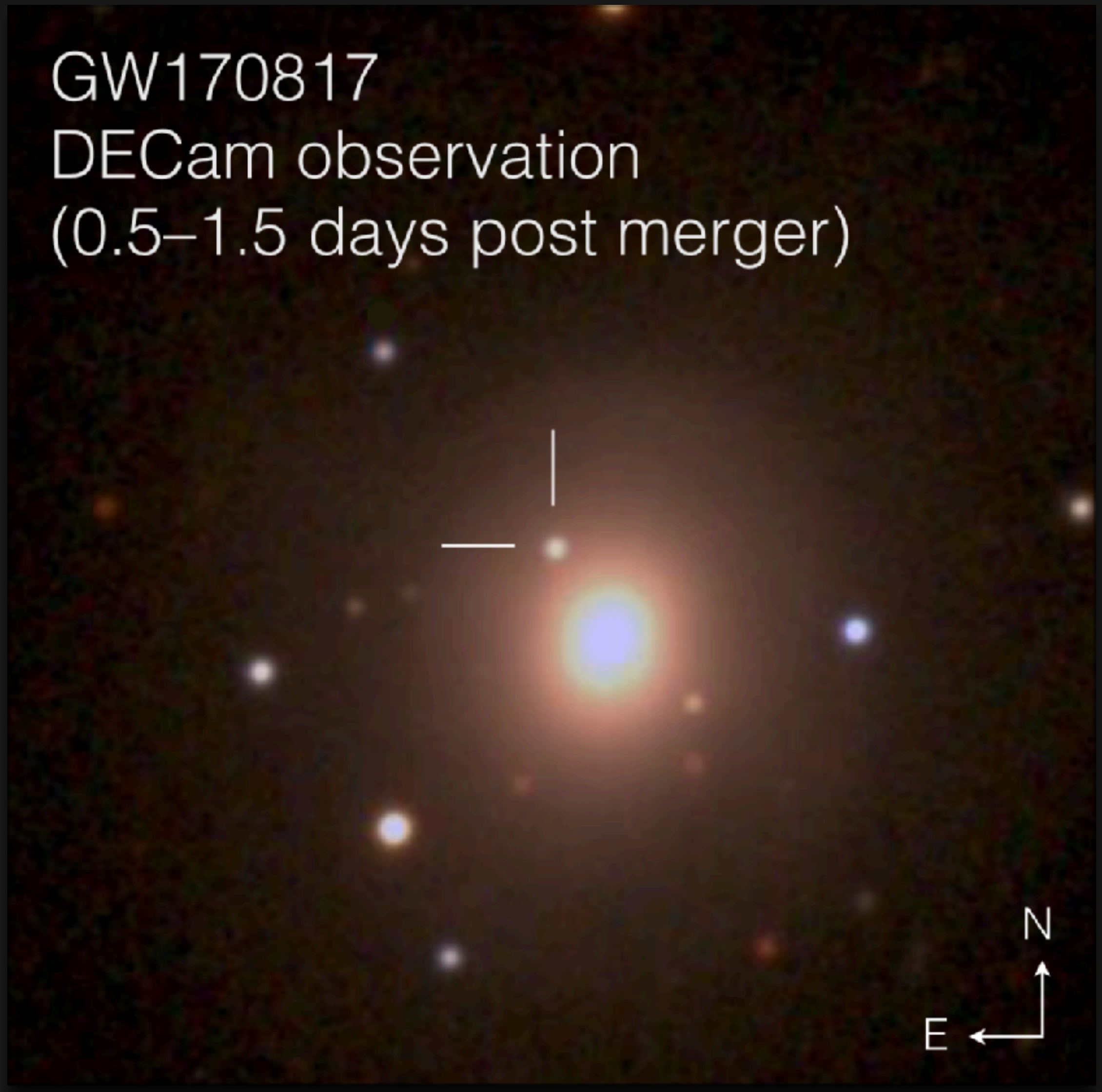
If you know inclination, can improve cosmology



Hotokezaka+ 2018 based on radio observations from Mooley+ 2018

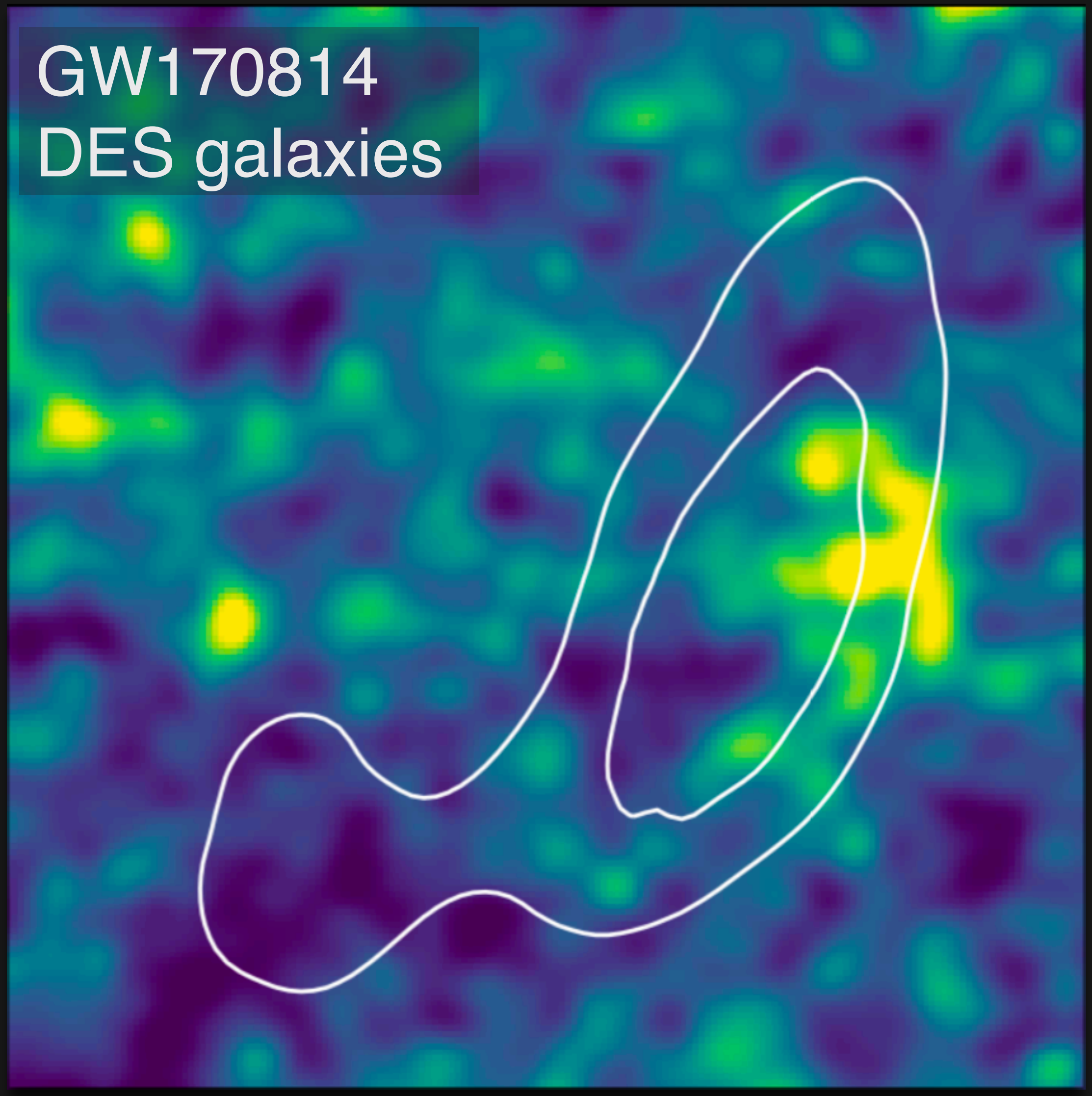
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

Statistical/Dark

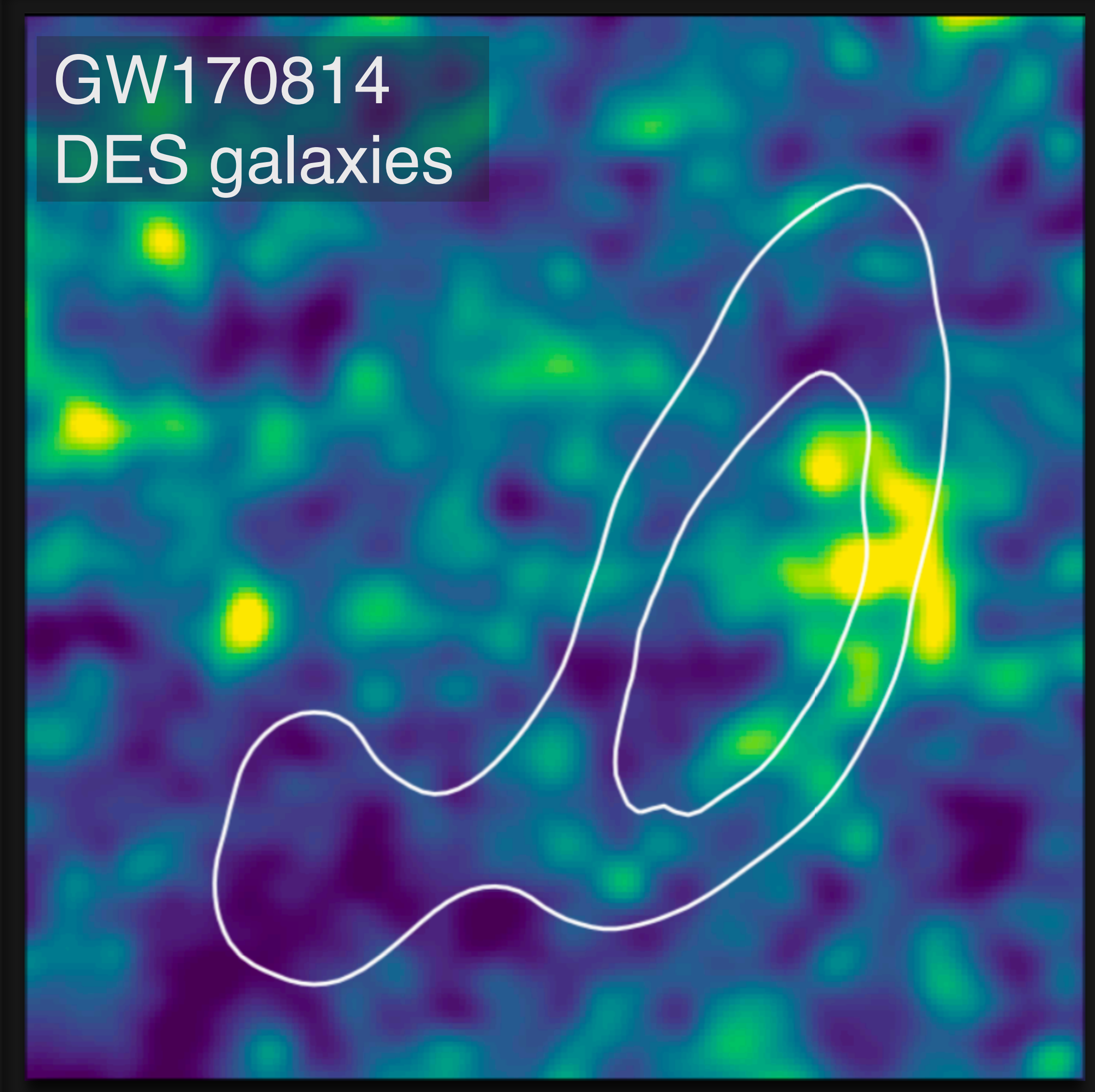


Use all galaxies in localization volume

Two standard siren approaches

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

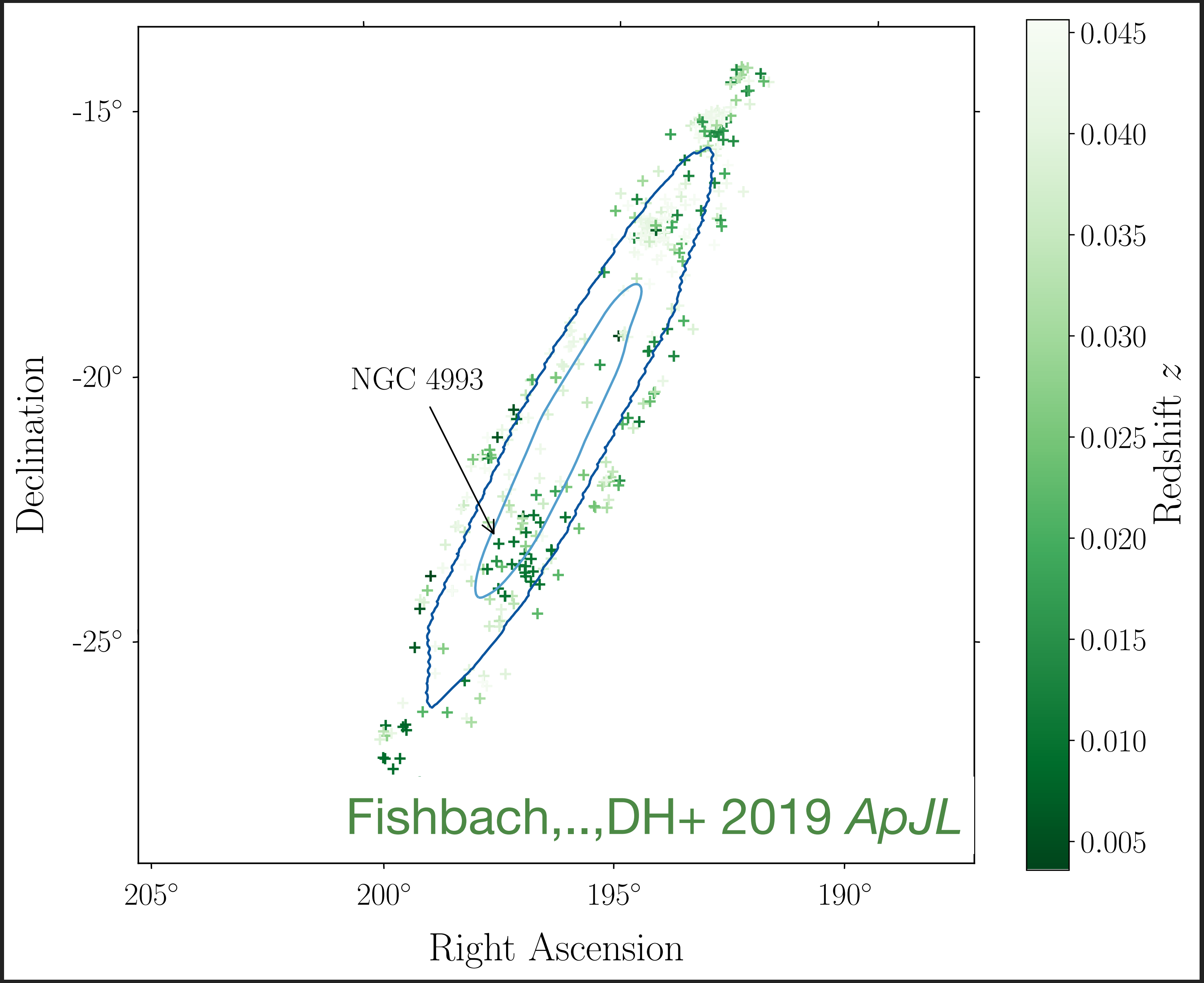


Use all galaxies in localization volume

Schutz 1986; Macleod & Hogan 2008; Del Pozzo 2012

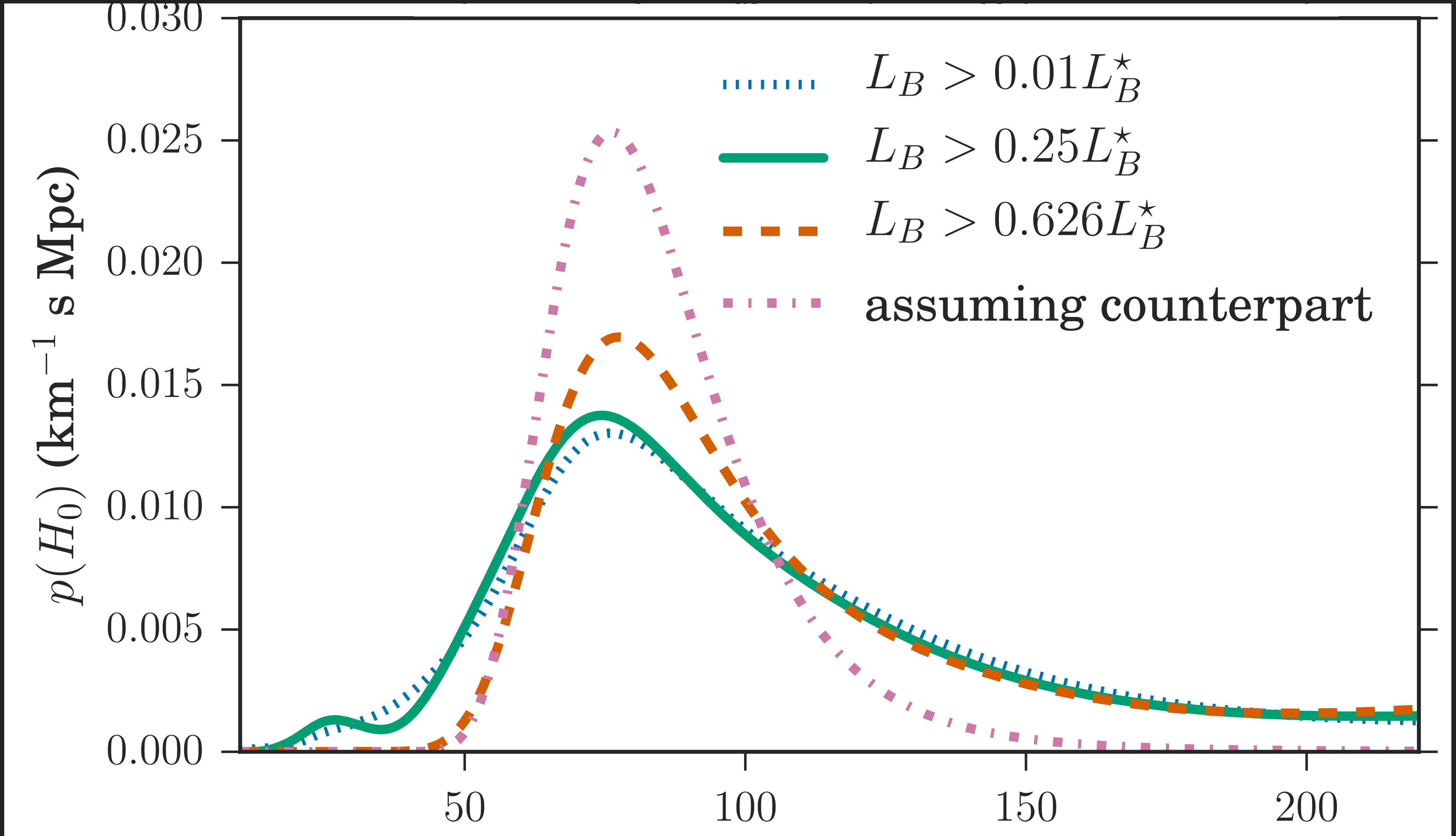
GW170817 as a dark standard siren

- GW170817 was only ~40 Mpc away!
- GW170817 was localized to 16 deg^2 on the sky
- GW170817 localization volume was relatively small: 215 Mpc^3 (90% confidence region)
- Have catalog of ~400 galaxies in the localization volume (GLADE catalog; Dálya+ 2018)



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*

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

GW170817 as a dark standard siren

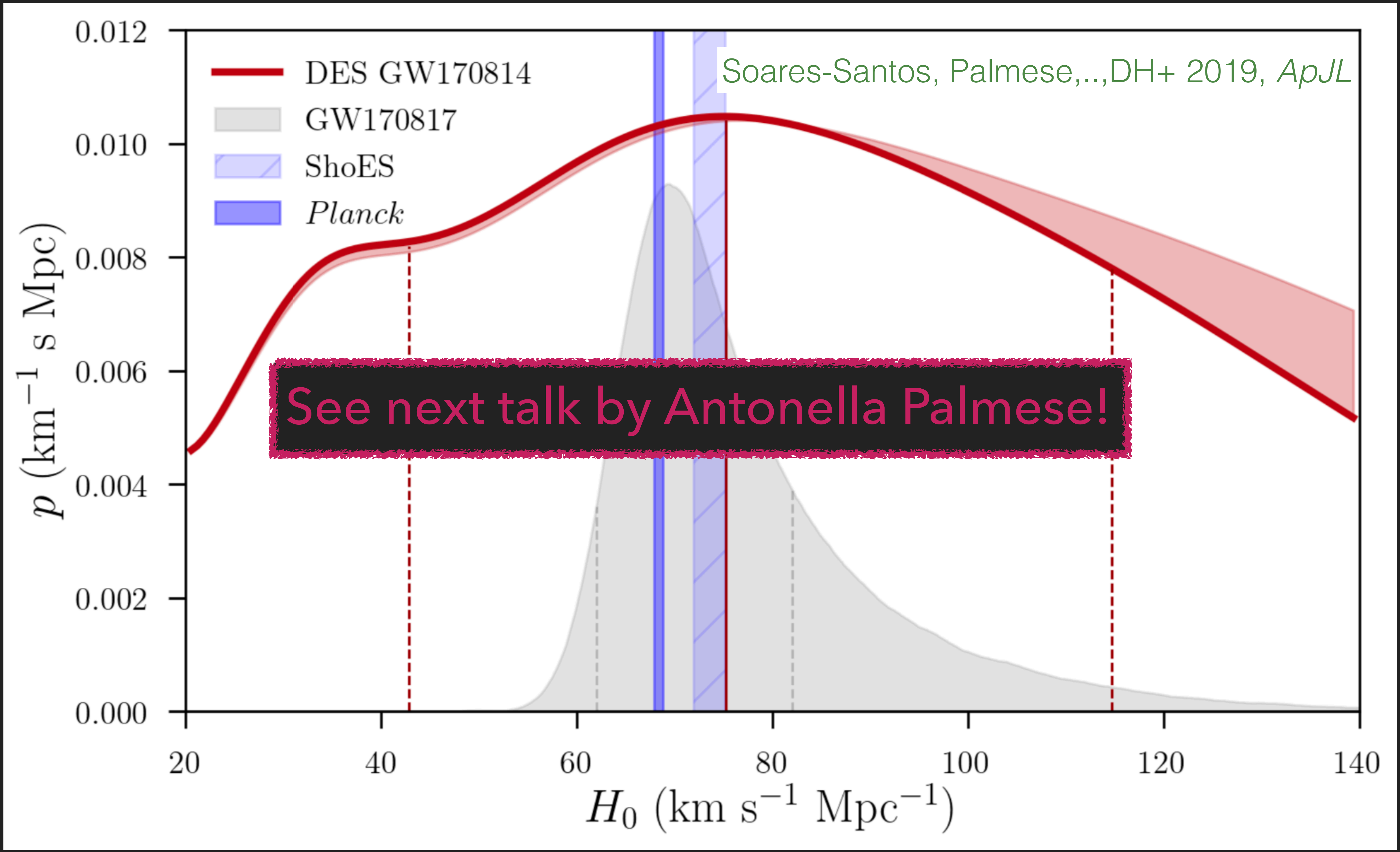
GW170814 as a dark standard siren

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
- ~80,000 galaxies in the localization volume

Soares-Santos, Palmese,..,DH+ 2019
Gray,..,DH+ 2019; Abbott+ 2019

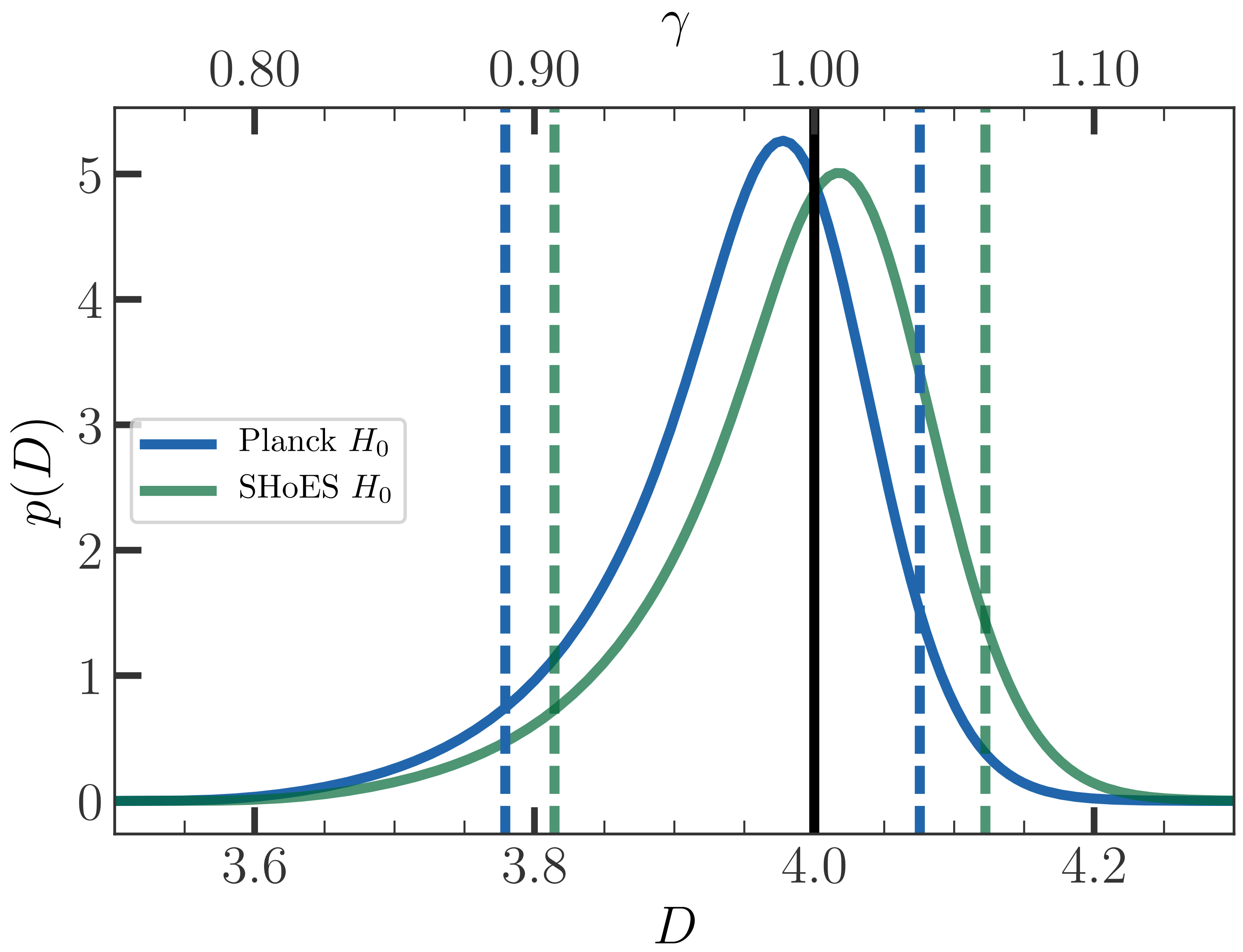
GW170814 as a dark standard siren



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

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)

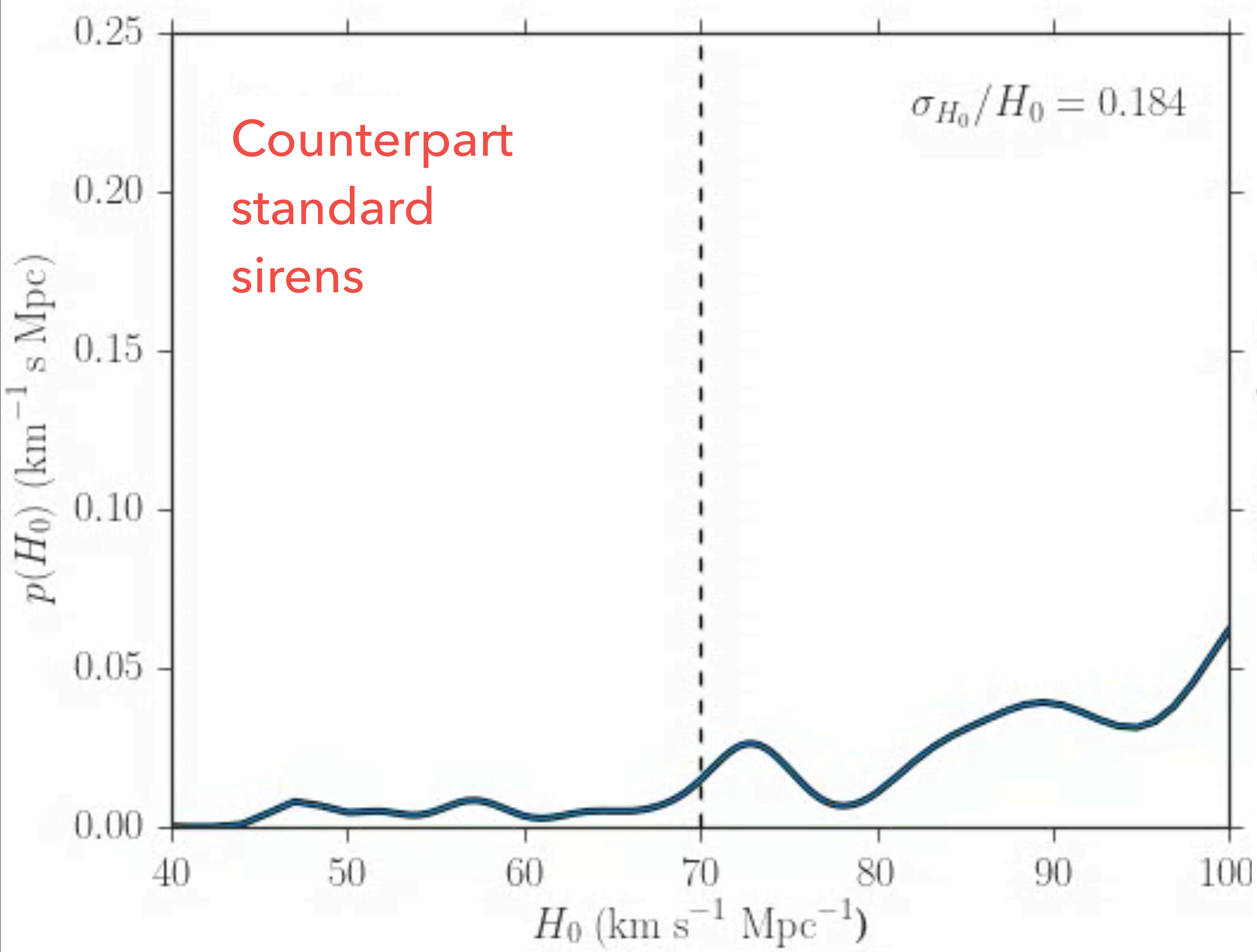


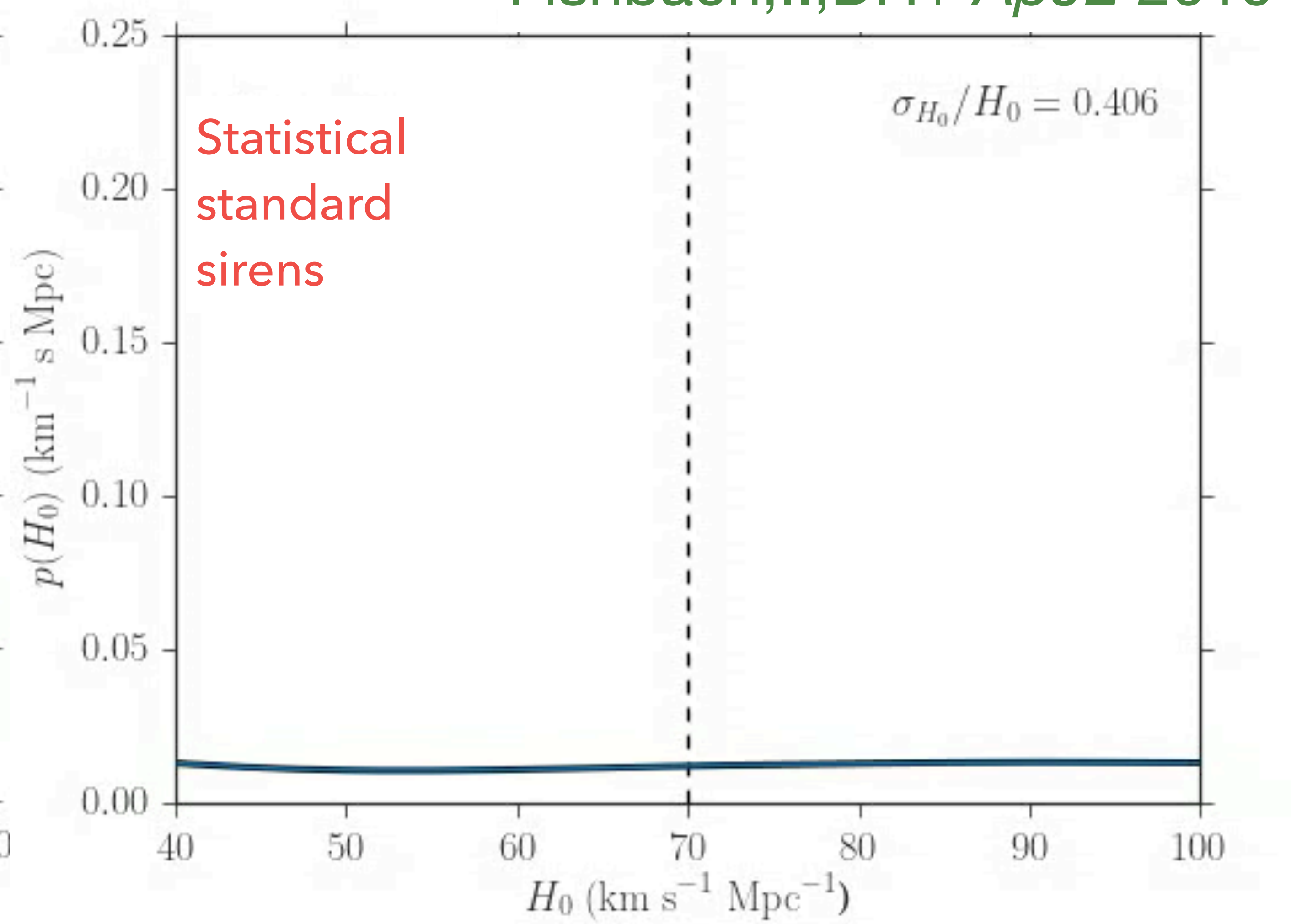
What will the future bring?

Simulations of standard siren convergence

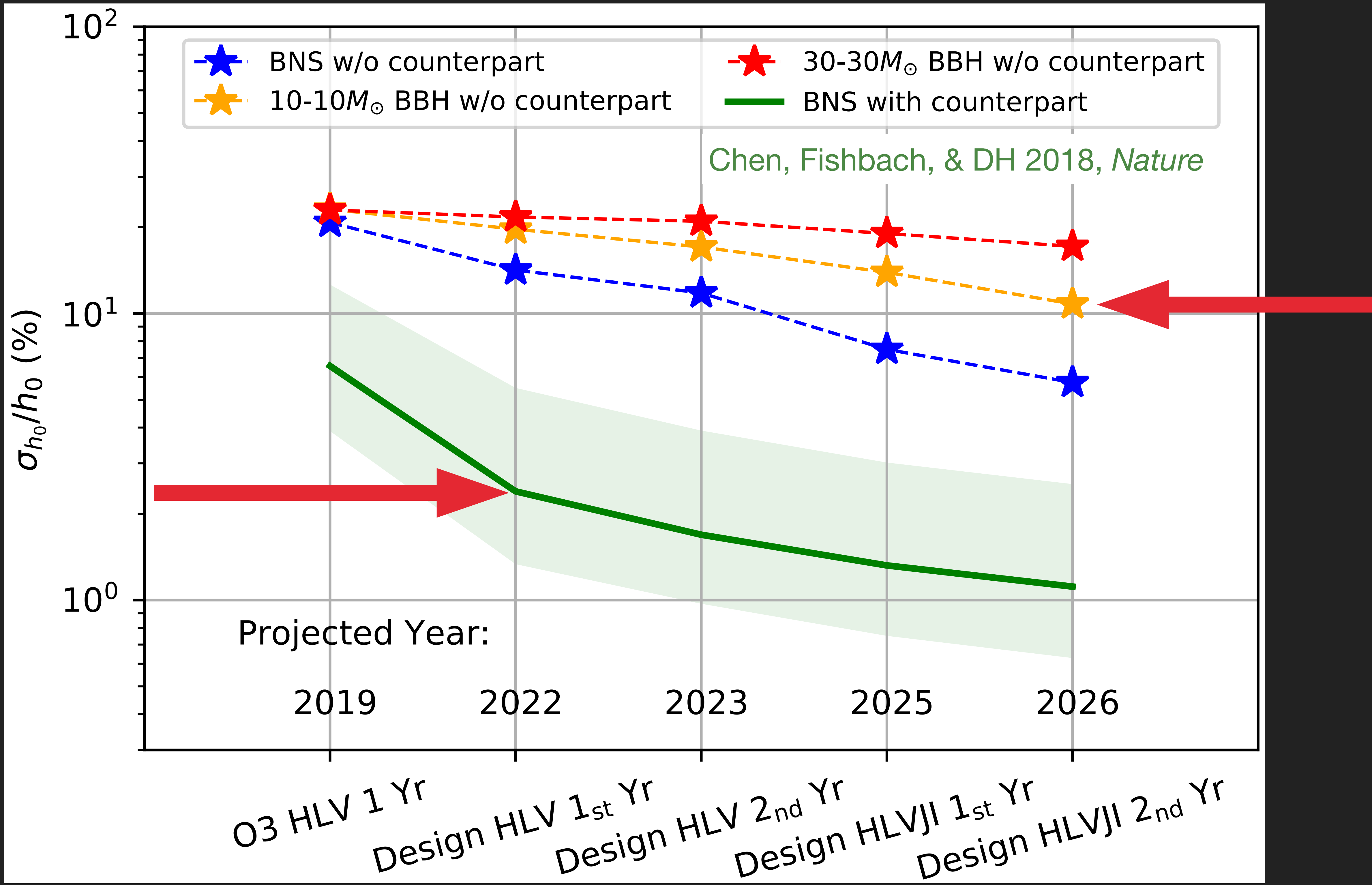
- Mock binary neutron star events from "First Two Years" dataset (Singer, Chen, DH+ 2014)
- Inject events into MICE mock galaxy catalog (Crocce+ 2015)

Fishbach,..,DH+ *ApJL* 2019



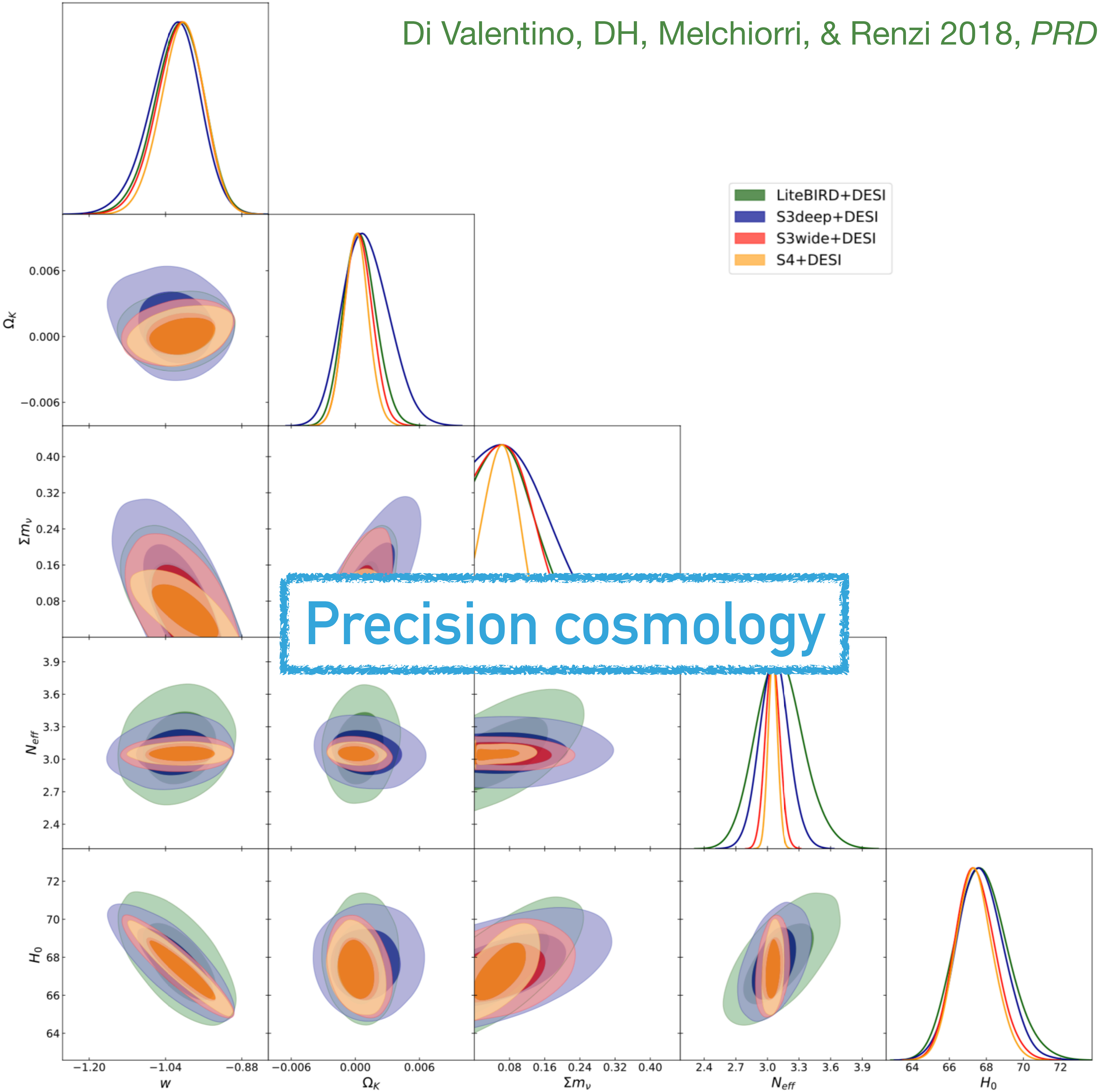


Precision standard siren cosmology



- With one year at design sensitivity (starting ~2021?) we get to ~2.5% measurement of the Hubble constant, help adjudicate current tension!?
- Statistical/Dark sirens have roughly order of magnitude larger errors. Although there are many more, so could be worse

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



Precision cosmology

What will the future bring?

- Additional measurements lead to improved H_0 constraints (Dalal, DH, Hughes, & Jain 2006; Nissanke+ 2010, 2013; Chen, Fishbach, & DH 2018; Feeney+ 2018, Mortlock+ 2019)
    - *N* counterpart standard siren events converge as $\sim 15\%/\sqrt{N}$
    - *N* s… verge as $\sim 40\%/\sqrt{N}$

See review talk by Samaya Nissanke on Friday morning

- Surprises? BBH counterparts? Lots of NSBHs?
- *LISA*!
- Cosmic Explorer? Einstein Telescope?

Standard siren systematics

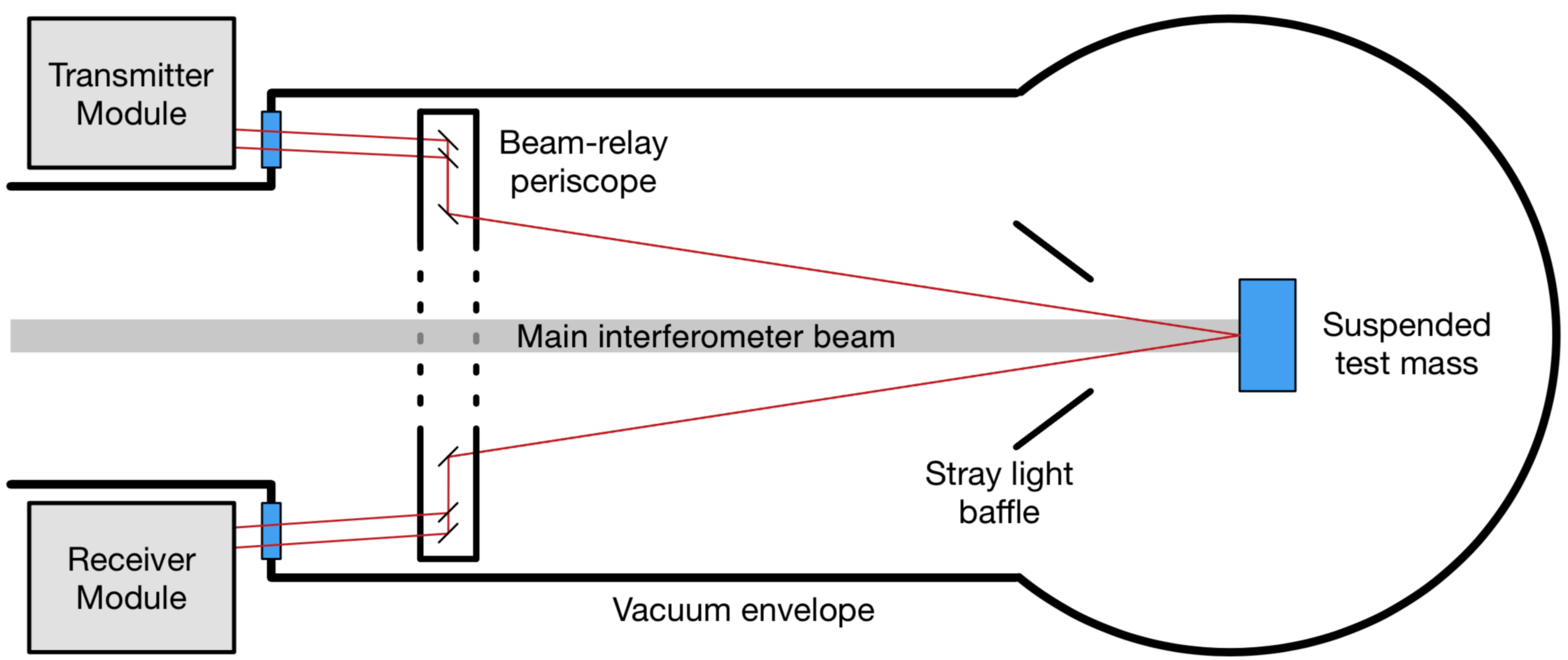
- Peculiar velocities (Howlett & Davis 2019; should become negligible soon)
- Model selection (priors over GW population impact final results [e.g. rate evolution, mass distribution]; Abbot+ 2017; Chen, Fishbach, & DH 2018; Fishbach, DH+ 2018; Feeney+ 2018; Mortlock+ 2019)
- Inclination distribution (can be fit out)
- EM constraints on inclination (only if EM constraints are used)
- 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
    - 1% measurement of H_0 requires 1% calibration of amplitude response

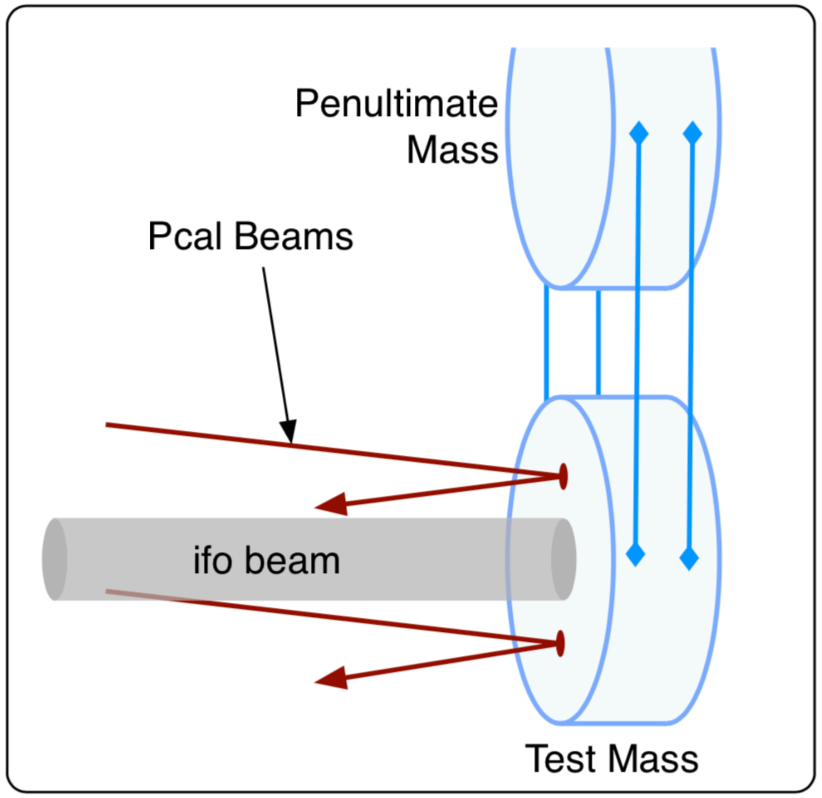
Photon calibrator

- 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 [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.40 %
Overall	**0.75 %**

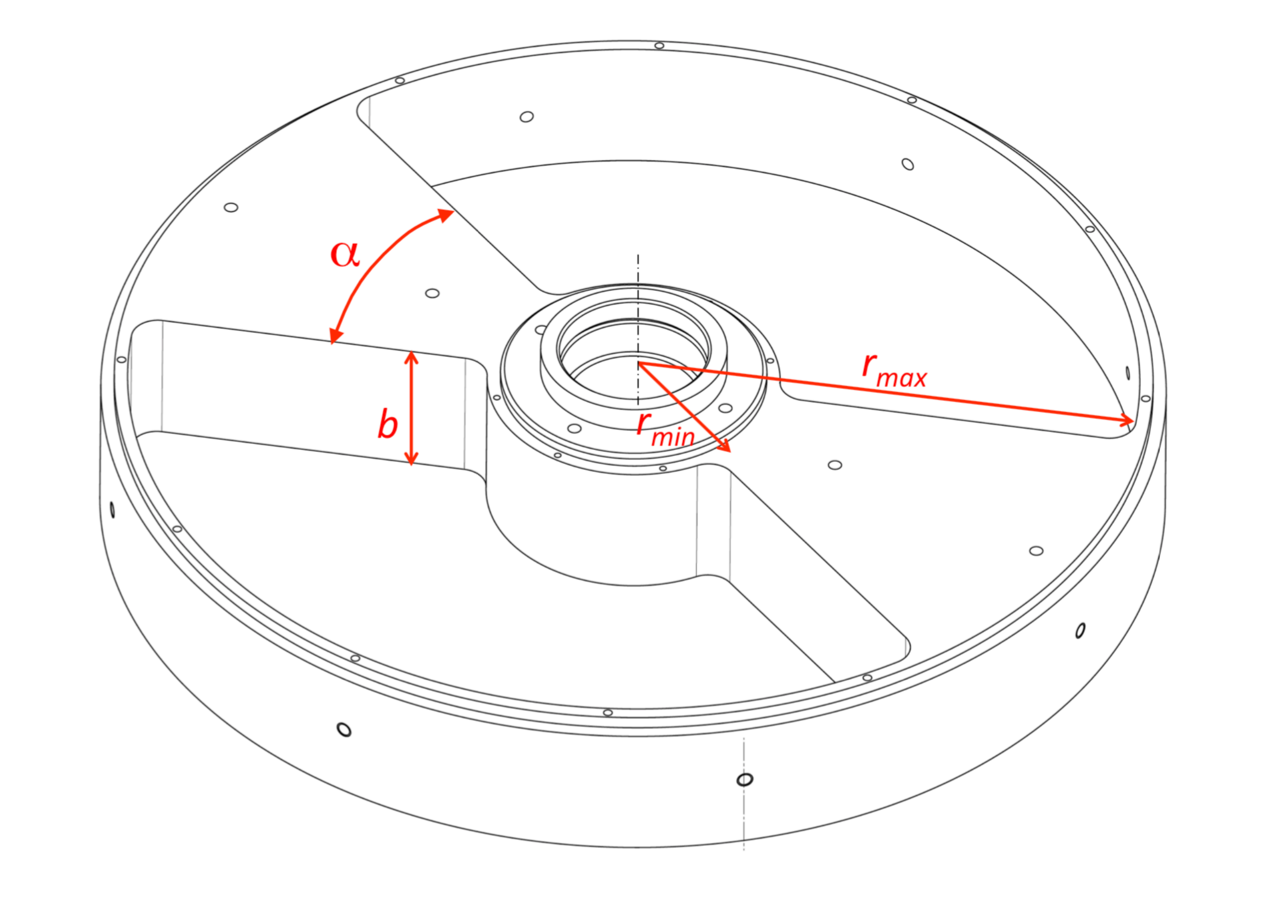
Karki+ 2016; Cahillane+ 2017



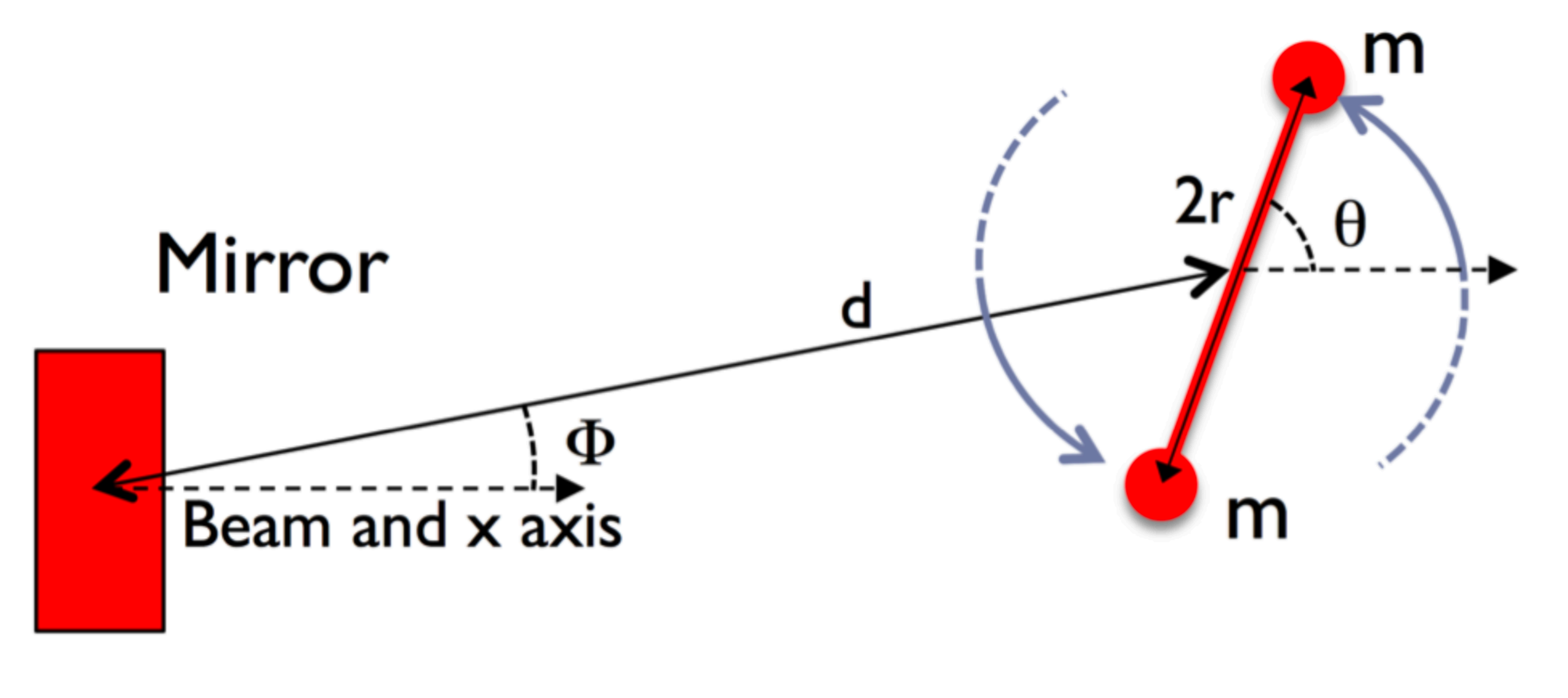


Newtonian calibrator

- 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%?

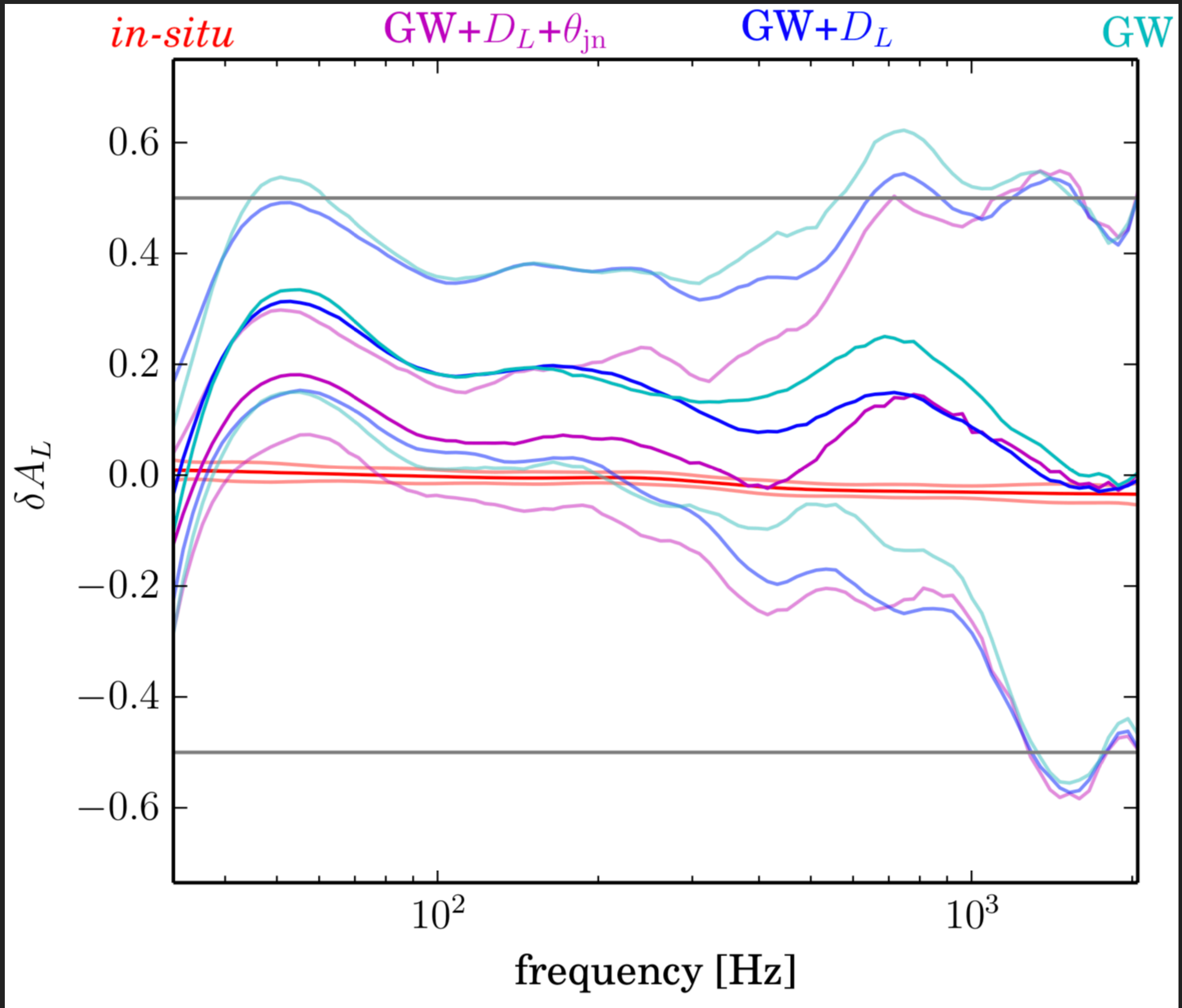


Estevez+ 2018



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

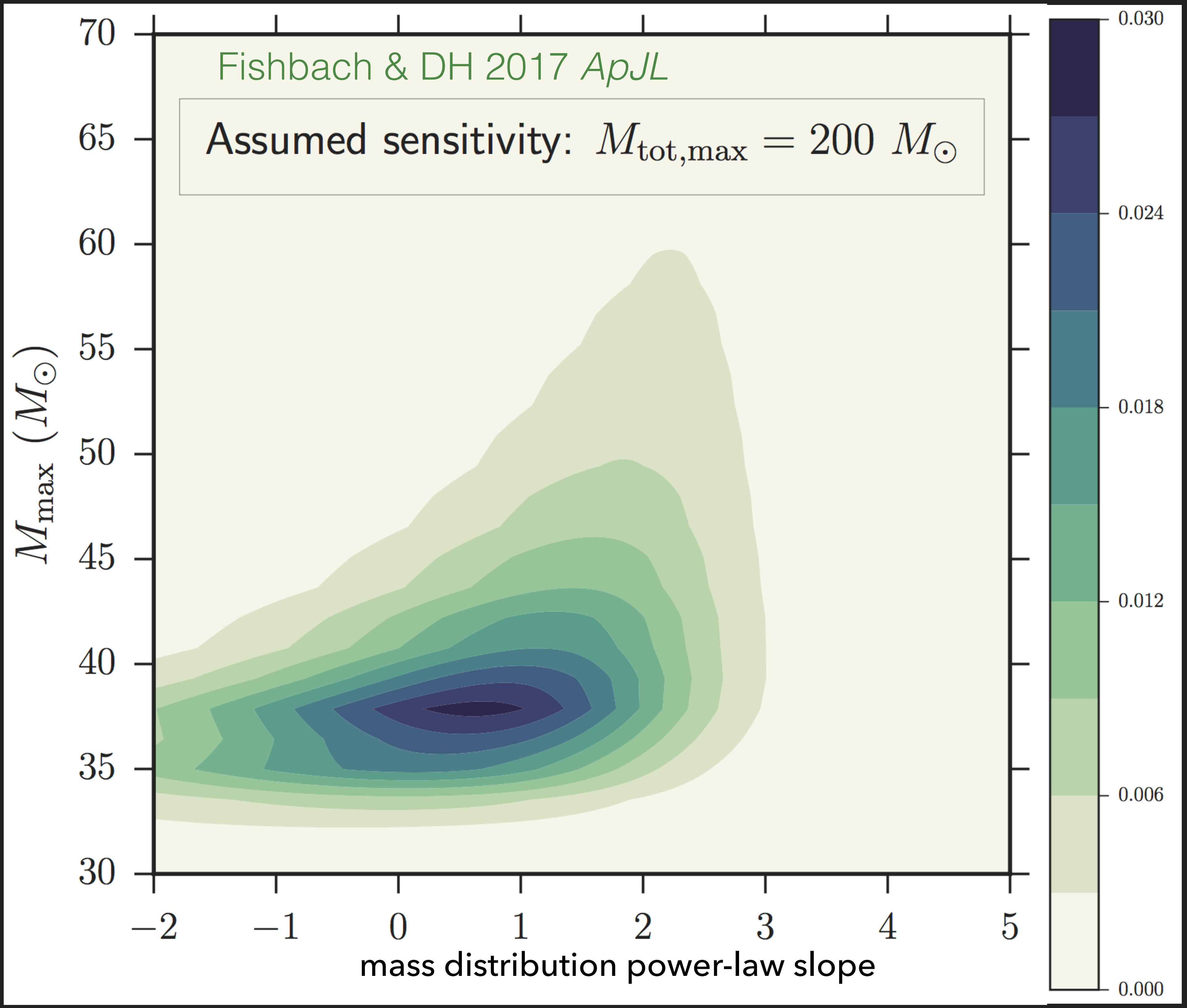


Essick & DH 2019 *PRD*

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

Where are LIGO's big black holes?

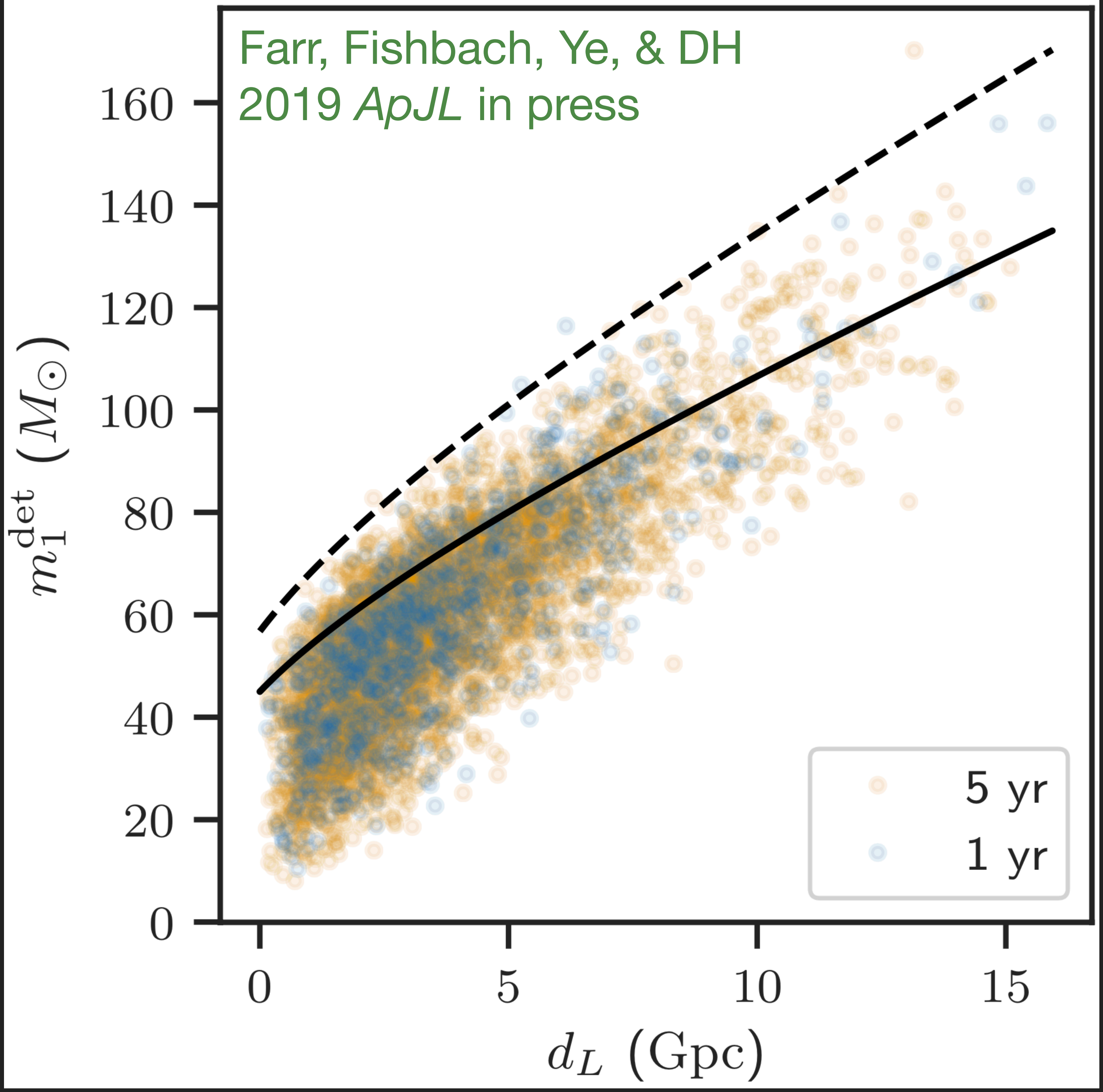
- The biggest BH LIGO has detected is ~30 $M_\odot$
- LIGO is sensitive to BHs up to >100 $M_\odot$
- Absence of evidence is evidence of absence
- We argue that there is a mass gap, as expected from pulsational/pair instability supernovae



Belczynski,..,DH+ 2016

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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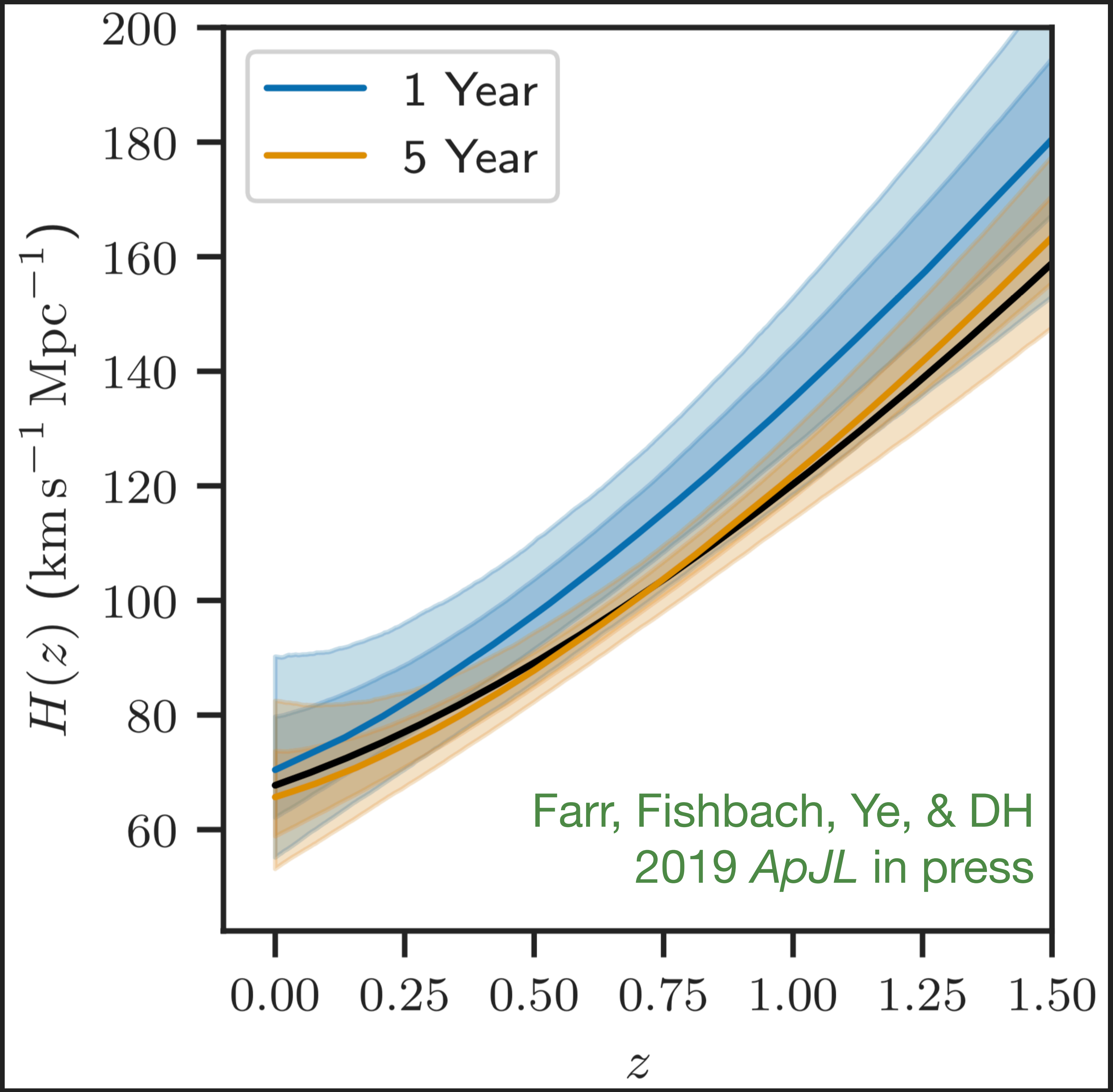
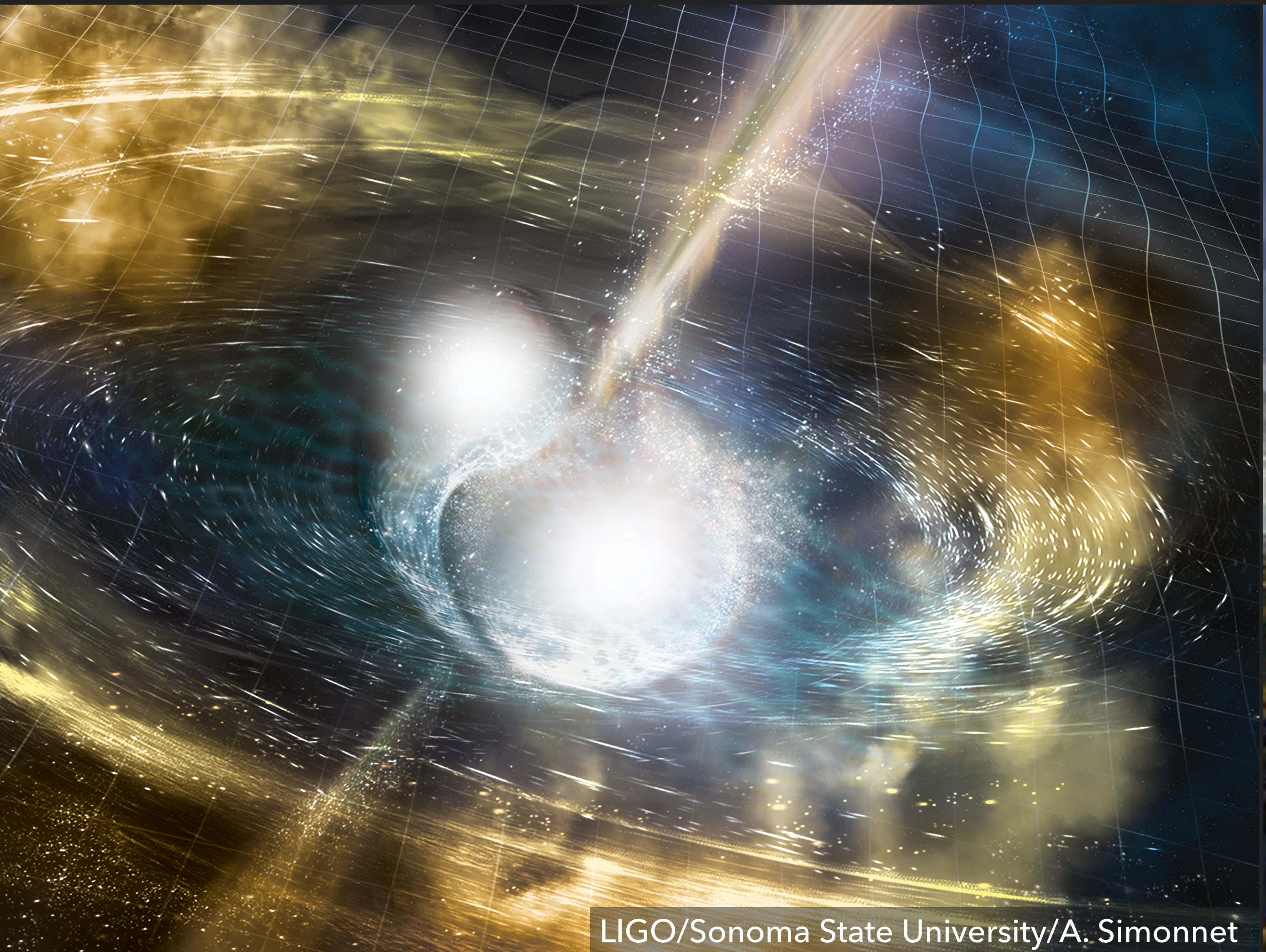


The future is loud and bright

- 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
- We are at the beginning of the beginning of gravitational-wave astronomy and cosmology!!


LIGO/Sonoma State University/A. Simonnet


LIGO