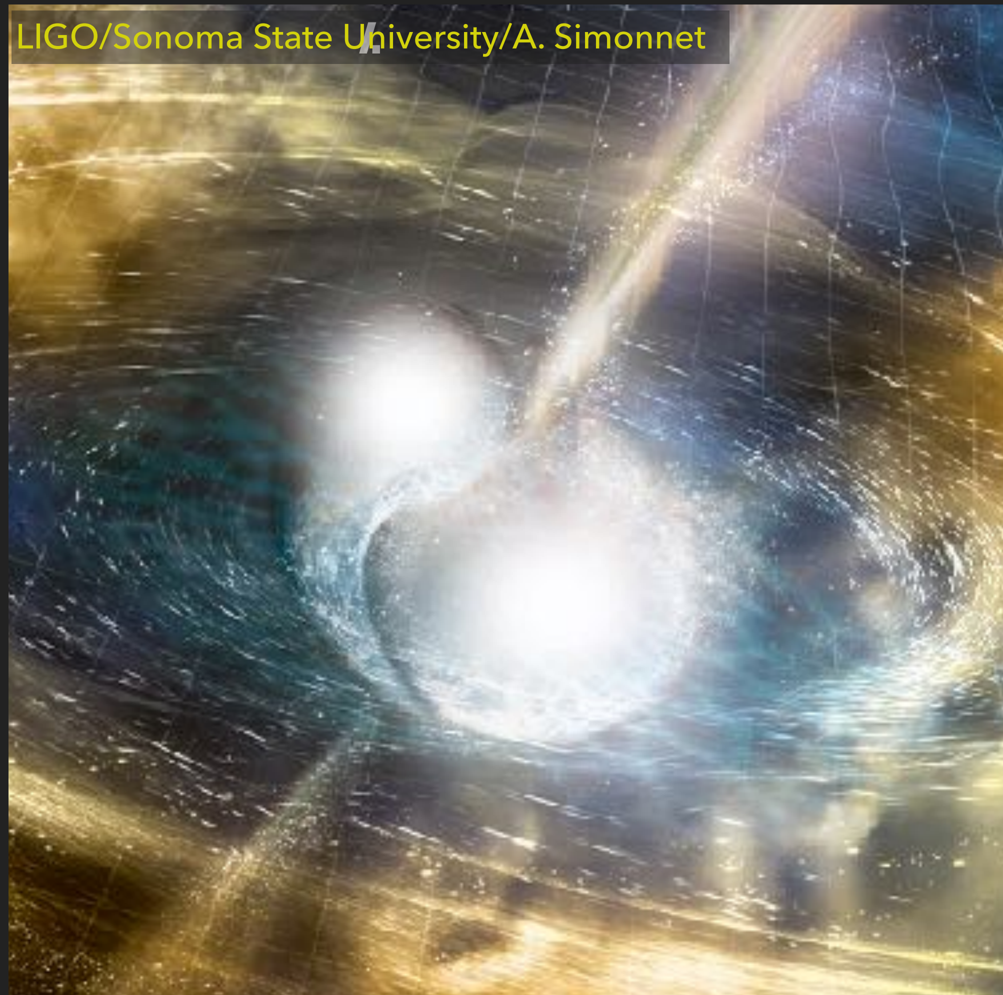
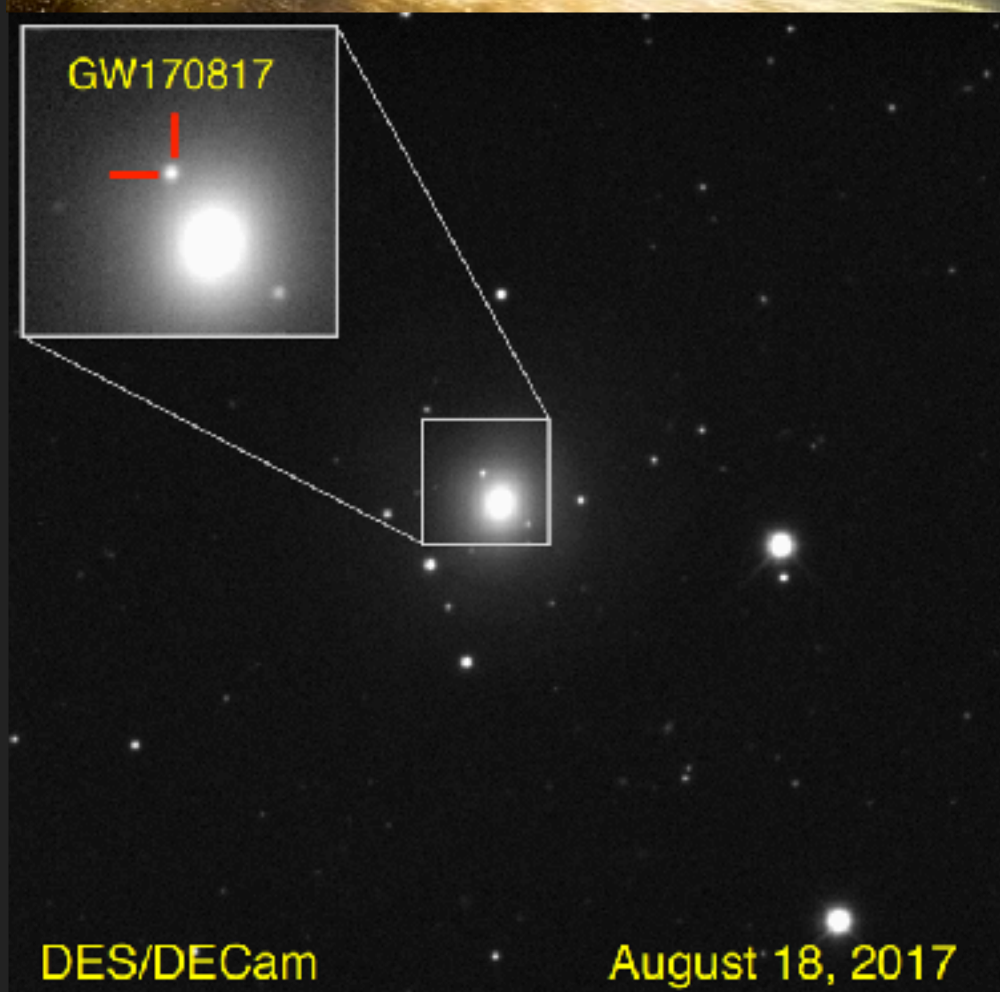


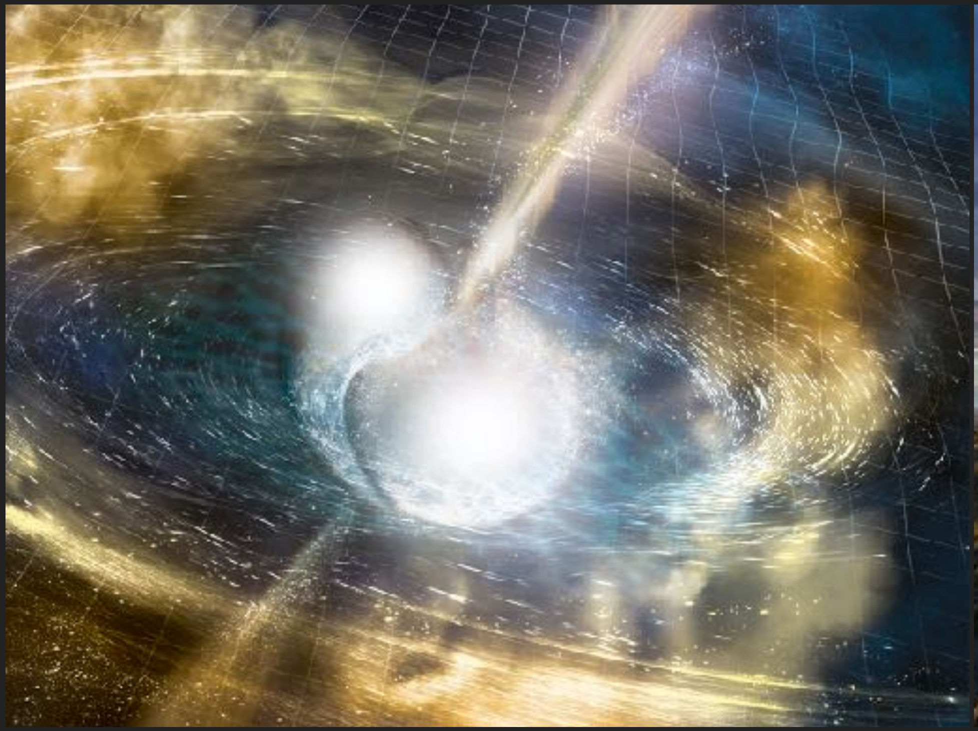


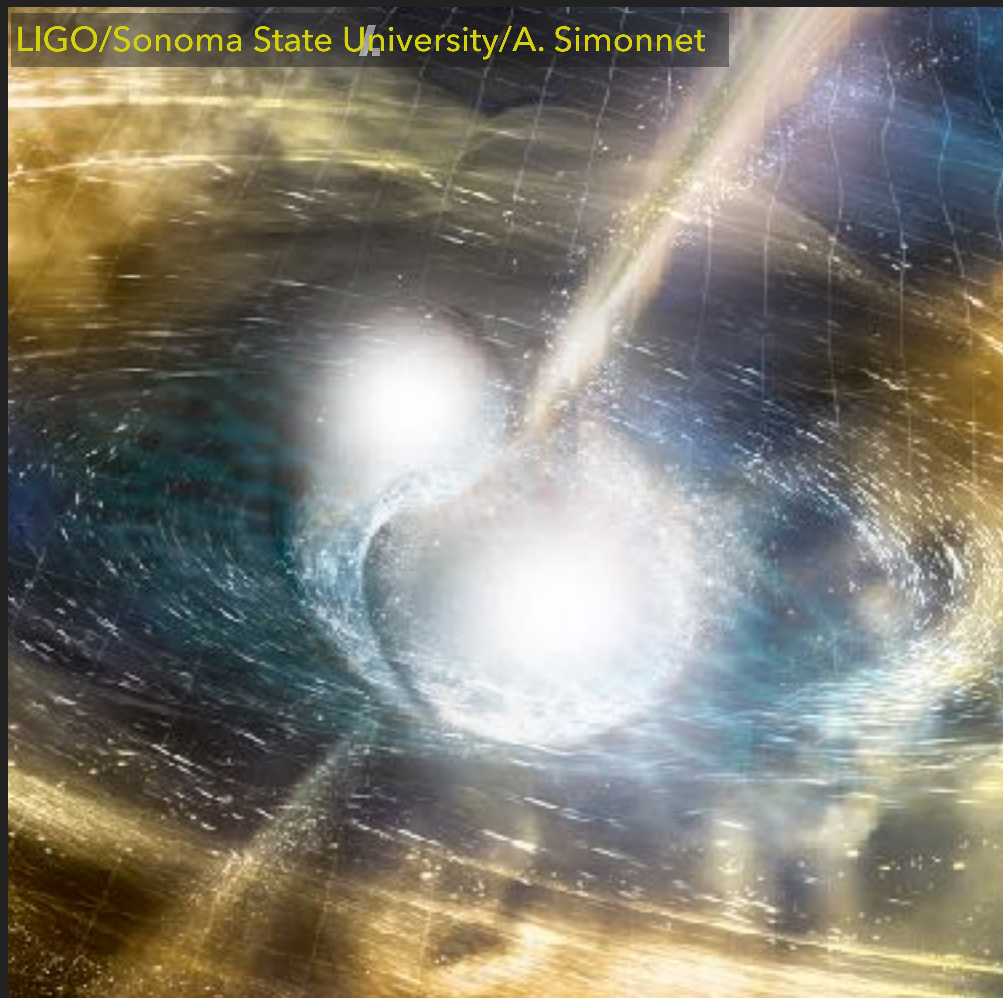
Multi-messenger probes for fundamental physics

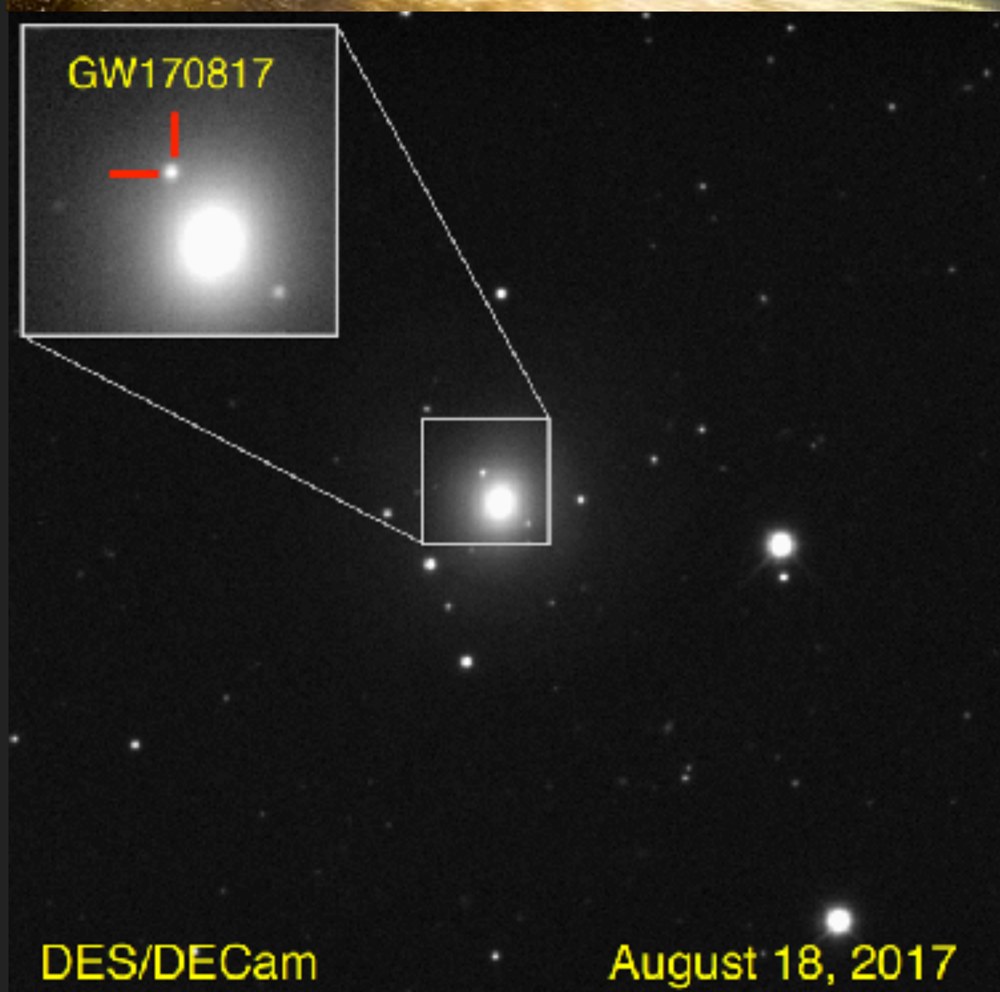
Daniel Holz
University of Chicago

Caveats

- “Multi-Messenger”=gravitational waves and electromagnetic waves
    - Ignoring neutrinos, cosmic rays,…
- Not just “fundamental physics”, but also astrophysics & cosmology
- Not a broad review. Focus on some recent work





What do we learn from combining gravitational-waves and photons?

Daniel Holz
University of Chicago

Some results from the last year

- Nonparametric inference of neutron star composition, equation of state, and maximum mass with GW170817 Essick, Landry, & DH 2020 *PRD*
- Direct Astrophysical Tests of Chiral Effective Field Theory at Supranuclear Densities Essick, Tews, Landry, Reddy, & DH, arXiv:2004.07744
- Black hole shadows, photon rings, and lensing rings Gralla, DH, & Wald 2019 *PRD*
- A Future Percent-level Measurement of the Hubble Expansion at Redshift 0.8 with Advanced LIGO Farr, Fishbach, Ye, & DH 2019 *ApJL*
- Standard sirens with a running Planck mass Lagos, Fishbach, Landry, & DH 2019 *PRD*
- Calibrating gravitational-wave detectors with GW170817 Essick & DH 2019 *CQG*
- Counting on Short Gamma-Ray Bursts: Gravitational-Wave Constraints of Jet Geometry Farah, Essick, Doctor, Fishbach, & DH, *ApJ* in press

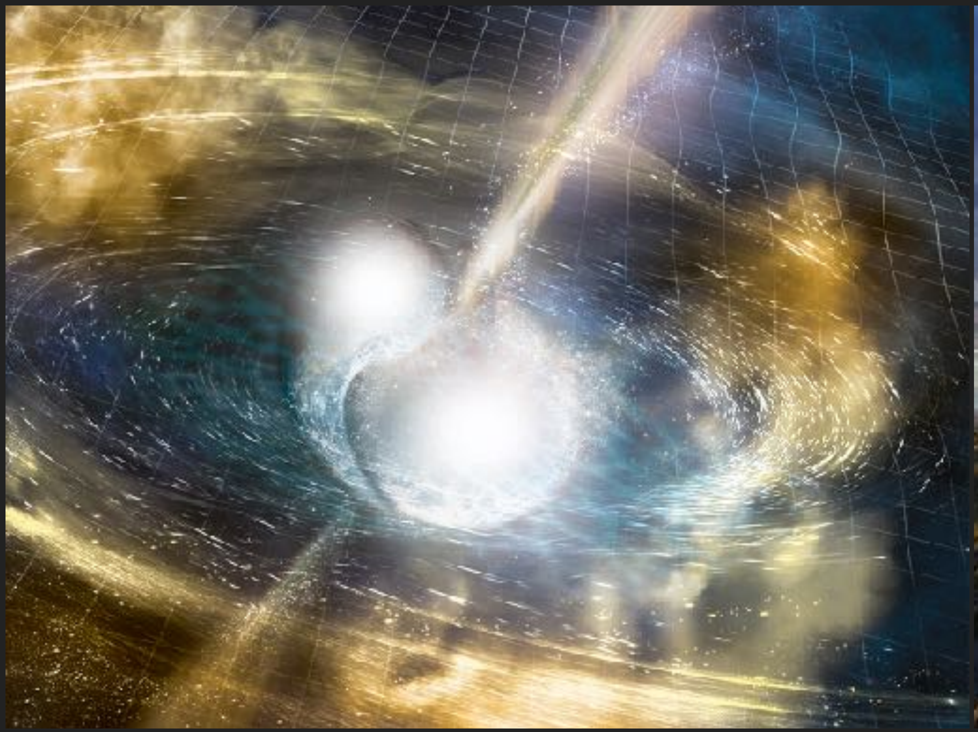
Some results from the last year

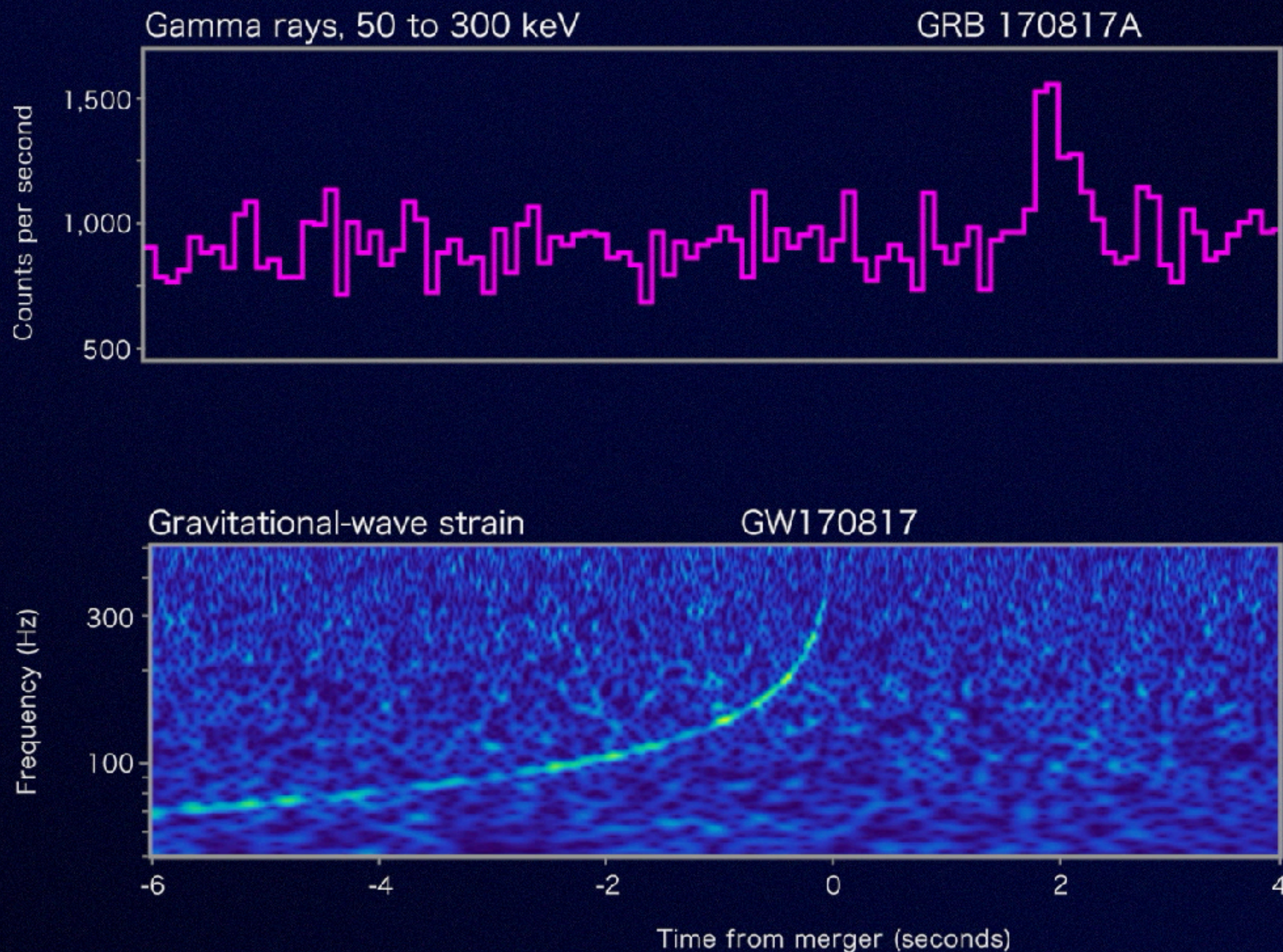
- Shouts and Murmurs: Combining Individual Gravitational-Wave Sources with the Stochastic Background to Measure the History of Binary Black Hole Mergers Callister, Fishbach, DH, & Farr, arXiv:2003.12152
- Black Hole Coagulation: Modeling Hierarchical Mergers in Black Hole Populations Doctor, Wysocki, O'Shaughnessy, DH, & Farr, *ApJ* in press
- Picky Partners: The Pairing of Component Masses in Binary Black Hole Mergers Fishbach & DH 2020 *ApJL*
- The Most Massive Binary Black Hole Detections and the Identification of Population Outliers Fishbach, Farr, & DH 2020 *ApJL*
- The binary-host connection: astrophysics of gravitational wave binaries from their host galaxy properties Adhikari, Fishbach, DH, Wechsler, & Fang, arXiv:2001.01025
- Making GW190412: isolated formation of a 30+10 $M_\odot$ binary black-hole merger Olejak, Belczynski, DH, Lasota, Bulik, & Miller, arXiv:2004.11866

GW170817

GW170817 is revolutionary

- For the very first time, we are hearing the thunder and seeing the lightning from an astronomical cataclysm. (The thunder comes first, though)
- The combination of gravity and light provide unique probes
- Constrain general relativity, equation-of-state at supranuclear density, astrophysics, cosmology,…



Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

Do gravitons and photons travel at the same speed?

GRB170817A “Speed of Gravity”

- The gravitational waves and gamma-rays traveled for ~100 million years, and yet arrived within 1.7 seconds of each other
- Their speeds must be very similar:

$$-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

  - Upper bound: generated at same time
  - Lower bound: GRB emission 10 seconds later

Do gravitons and photons travel at the same speed?

Yes!

Do gravitons and photons see the same Universe?

Do gravitons and photons see the same Universe?

- Can modify general relativity by adding extra dimensions, and/or scalar fields
  - can potentially account for dark matter and/or dark energy
  - if the gravitons “leak” into the bulk/higher dimensions, then gravity is modified
  - gravitational leakage would cause GW sources to appear farther away than they really are
- GW170817 offers our first opportunity to test this
  - Are the distances inferred from gravitational waves and photons consistent?

How many spacetime dimensions?

- In GR, we have:

$$h \propto \frac{1}{d}$$

- In modified gravity theories, flux conservation gives

$$h \propto \frac{1}{d^\gamma}$$

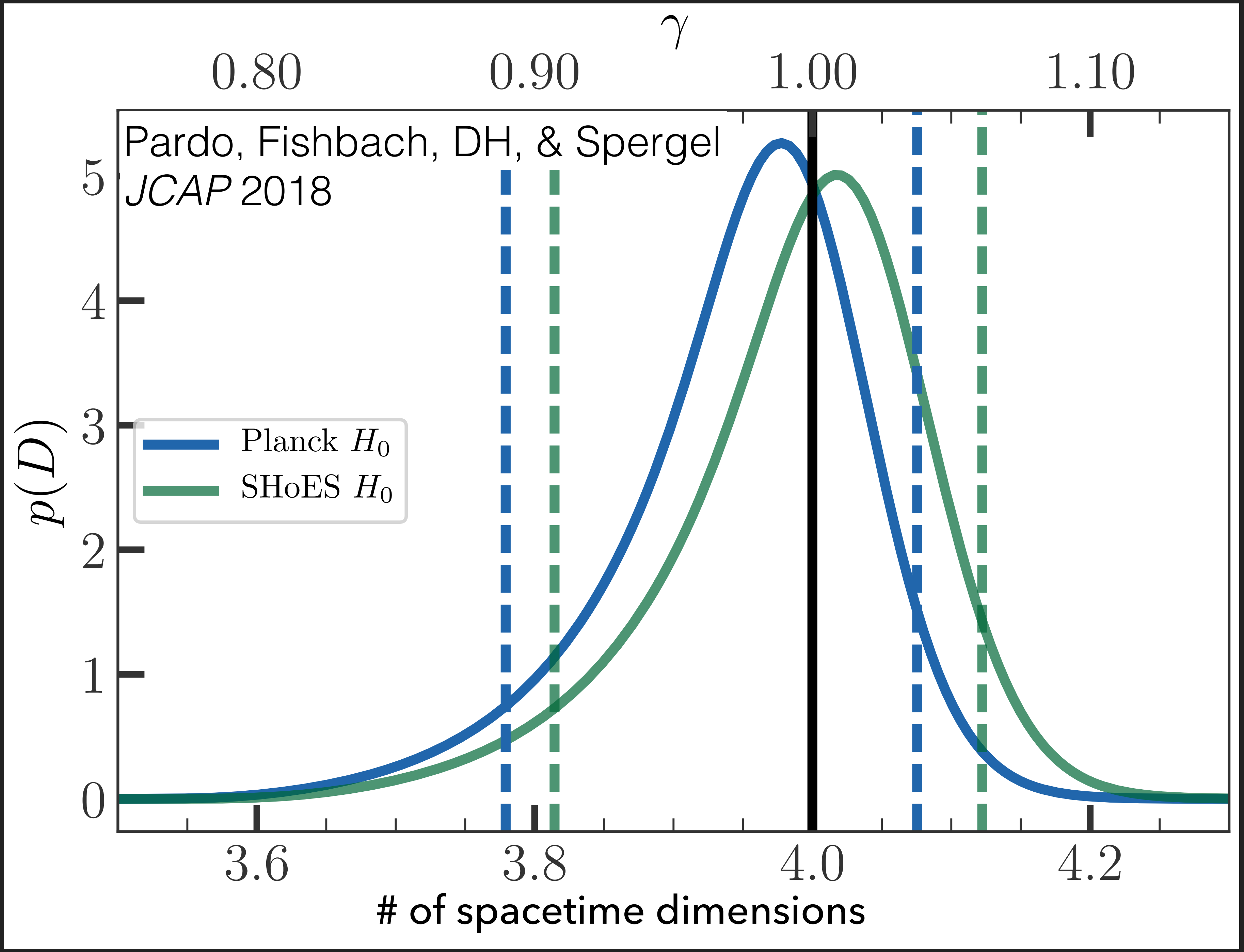
with

$$\gamma = \frac{D-2}{2}$$

- Some theories have a screening scale, R, and transition steepness, n

$$h \propto \left[1 + \left(\frac{d}{R}\right)^{n(D-r)/2}\right]^{-1/n} \frac{1}{d}$$

How many spacetime dimensions?



- Do gravitational waves "leak" into an extra dimension?
- No! Gravity and light travel through the same Universe

Time varying Planck mass?

- Time-varying Planck mass affects amplitude of GWs
- Define running of the Planck mass:

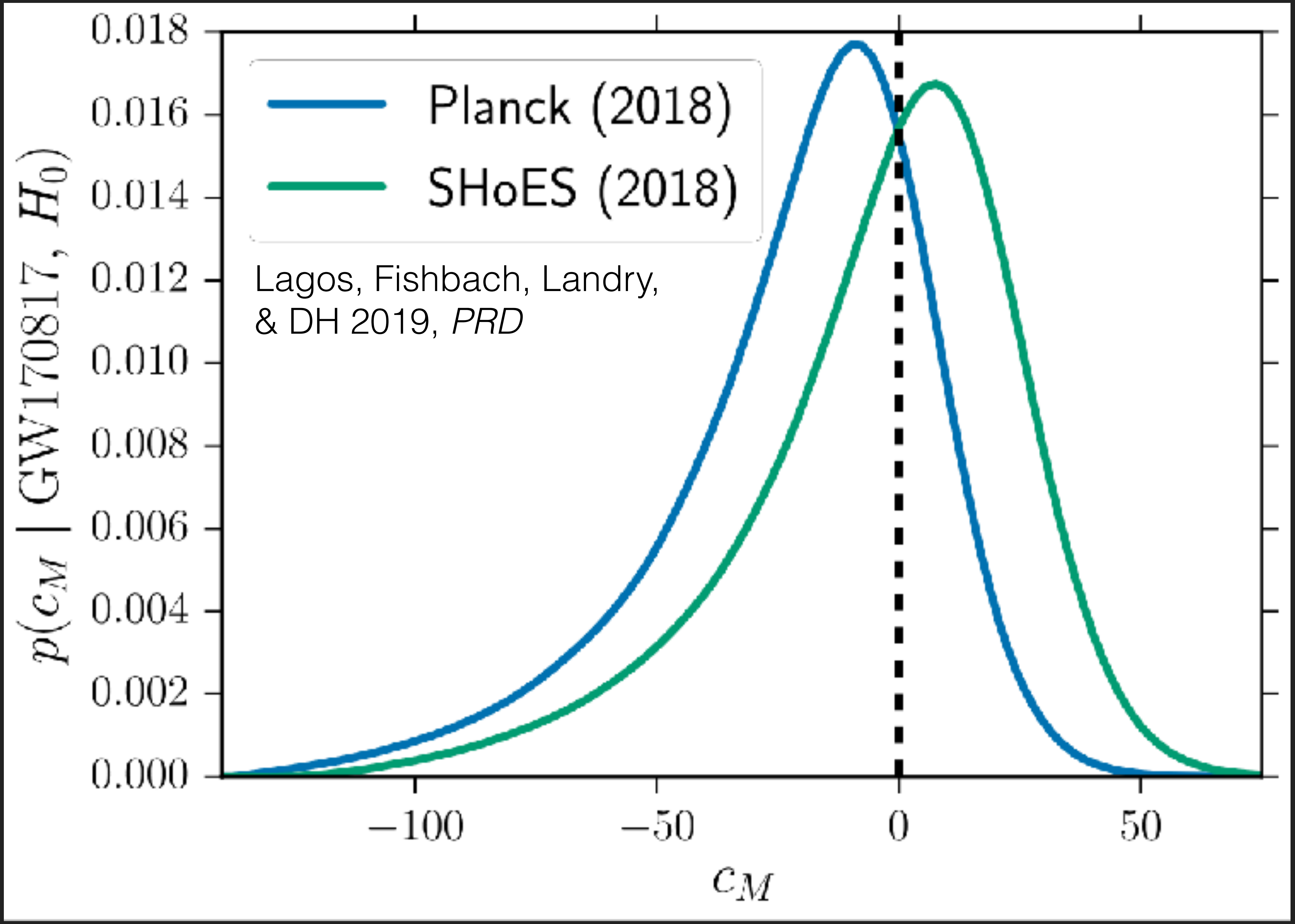
$$\alpha_M \equiv \frac{d \ln(M_*/M_P)^2}{d \ln a}$$

- Time parameterization:

$$\alpha_M(z) = c_M \frac{\Omega_{\rm DE}(z)}{\Omega_{\rm DE}(0)}$$

- Characterized by c_M where $c_M = 0$ is GR with constant Planck mass

Time varying Planck mass?



- GW170817 is consistent with $c_M = 0$
- No evidence for running of the Planck mass

Do gravitons and photons see the same Universe?

Yes!

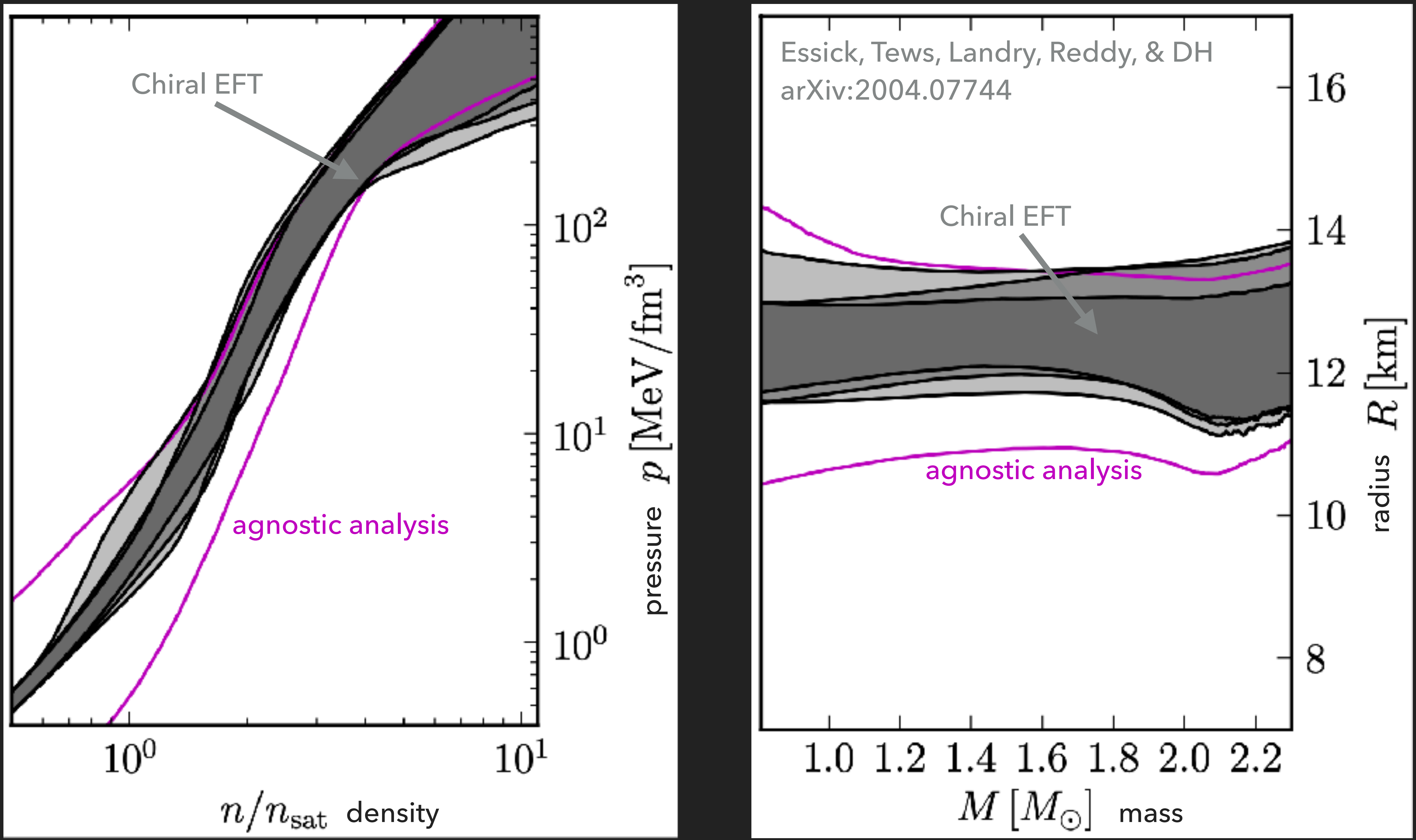
In what follows, assume GR is correct

What is the equation of state of neutron-star matter?

Constrain the neutron star equation of state

- The properties of the neutron star are embedded in the waveform of emitted gravitational waves
- Combining GW data with electromagnetic data provides unprecedented constraints on the equation-of-state of neutron stars
    - Use a non-parametric analysis (Landry & Essick 2019 *PRD*; Essick, Landry, & DH 2020 *PRD*)
    - Combined analysis of gravitational-wave data, electromagnetic measurements of massive pulsars, and NICER X-ray observations of PSR J0030+0451 (Essick, Tews, Landry, Reddy, & DH, arXiv:2004.07744)
    - Direct astrophysical tests of Chiral EFT at supranuclear densities

Constrain the neutron star equation of state



- Constraints from gravitational-waves (GW170817) and electromagnetic observations of pulsars (radio and X-ray)

How does the Universe make binary neutron stars?

How does the Universe make binary neutron stars?

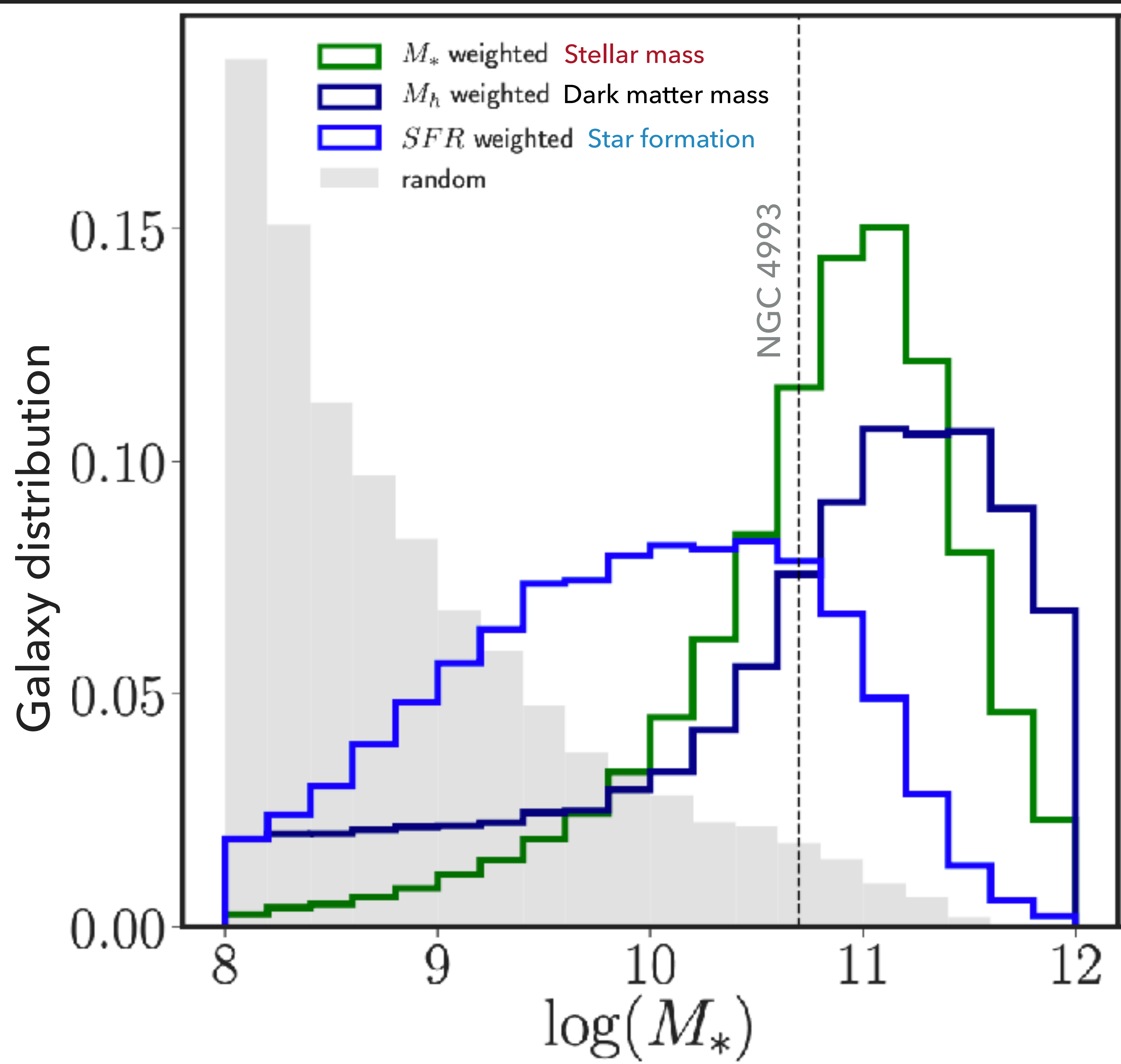
- Simplest description:
    - Binary neutron stars are formed at some evolving rate
        - Probably related to star formation rate
    - There is a delay between the time of formation of the binary and its eventual merger
        - Assume this is described by a delay time distribution (e.g. $dN/dt \propto t^{\alpha}$ with $\alpha = -1.5$; Dominik,..DH 2012 ApJ)

Host galaxy properties

- Binary neutron stars are formed in galaxies
- Observable properties of a galaxy (e.g. stellar mass, star formation rate, metallicity) carry information about its history
- Examine properties of binary host galaxies to learn about how binary neutron stars are formed!
- Binary-host connection (Adhikari, Fishbach, DH, Wechsler, & Fang; arXiv:2001.01025)


Hubble Heritage Team

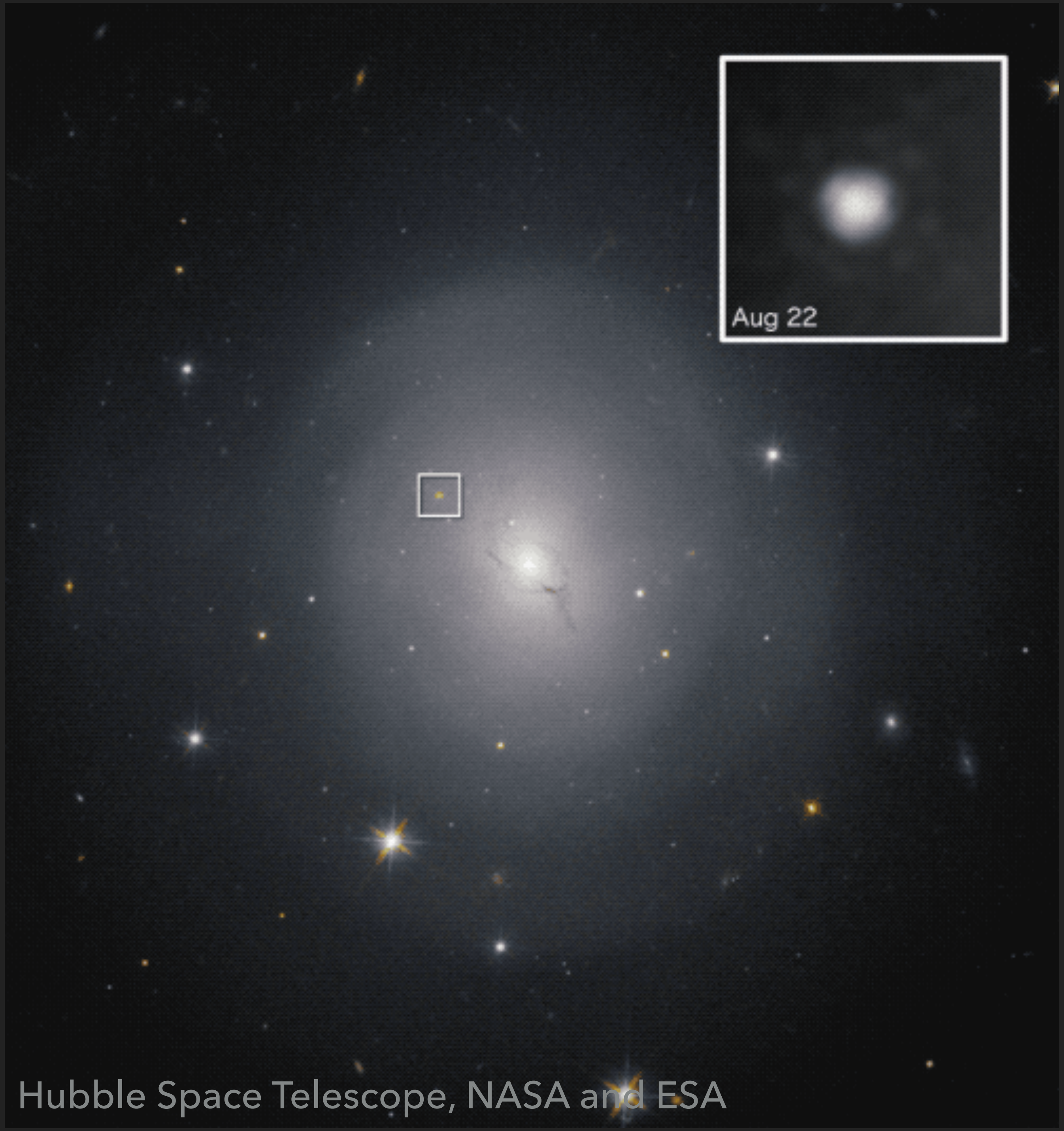
Star formation, stellar mass, or dark matter?!



- Different weightings produce different distributions of host galaxy properties

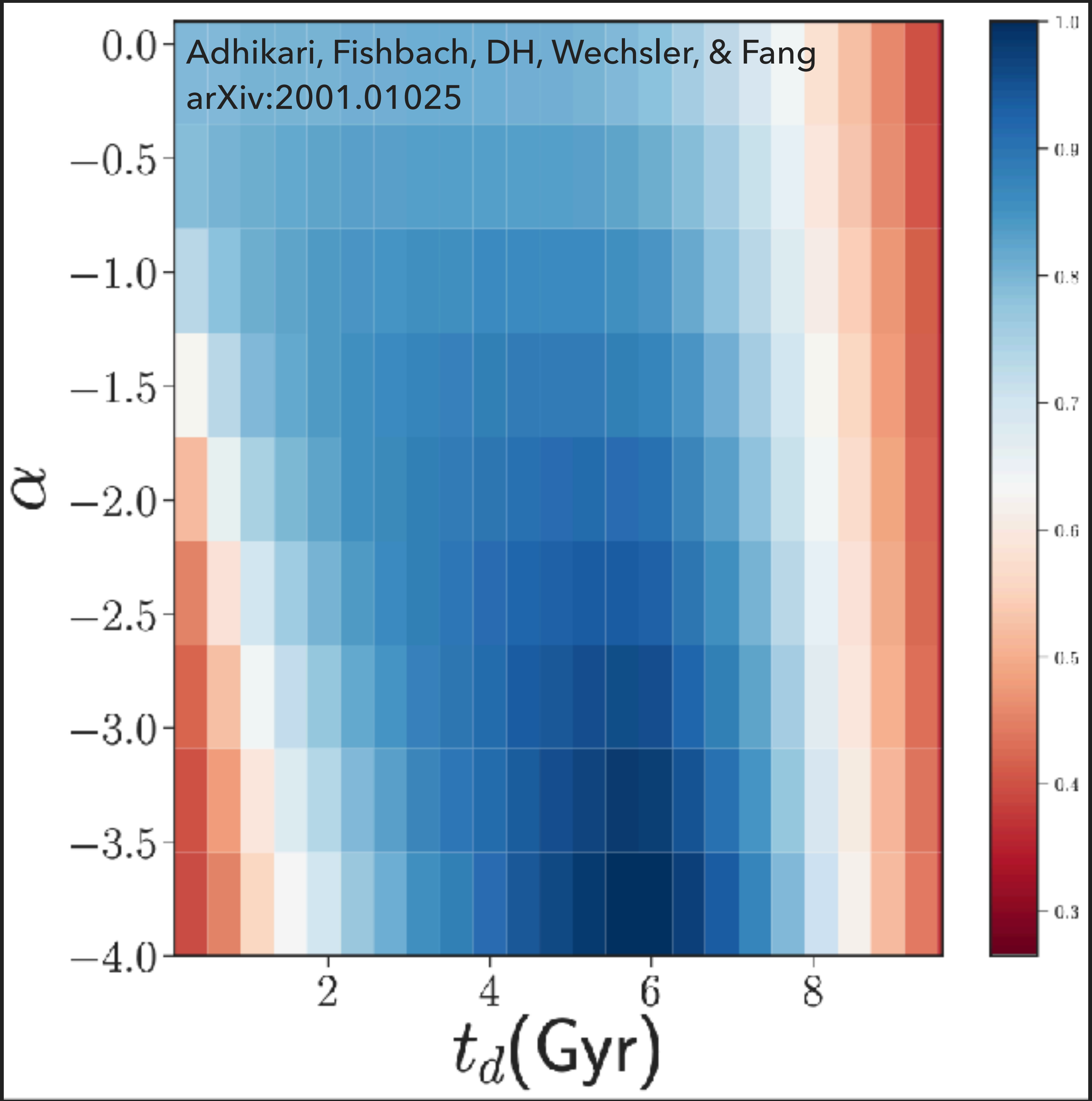
Binary-host connection event #1: GW170817!

- Binary neutron-star merger in gravitational-waves
- Identification of host galaxy: NGC 4993



Hubble Space Telescope, NASA and ESA

What do we learn from NGC 4993?



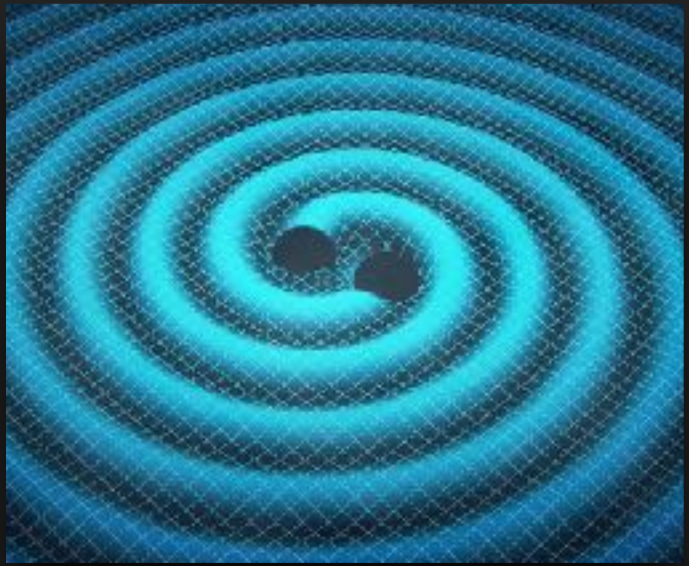
- NGC 4993 prefers a minimum time delay of ~6 Gyr and a relatively steep slope
- This is because it has a lower than expected star-formation rate for its measured stellar mass

What is the Hubble constant?

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*

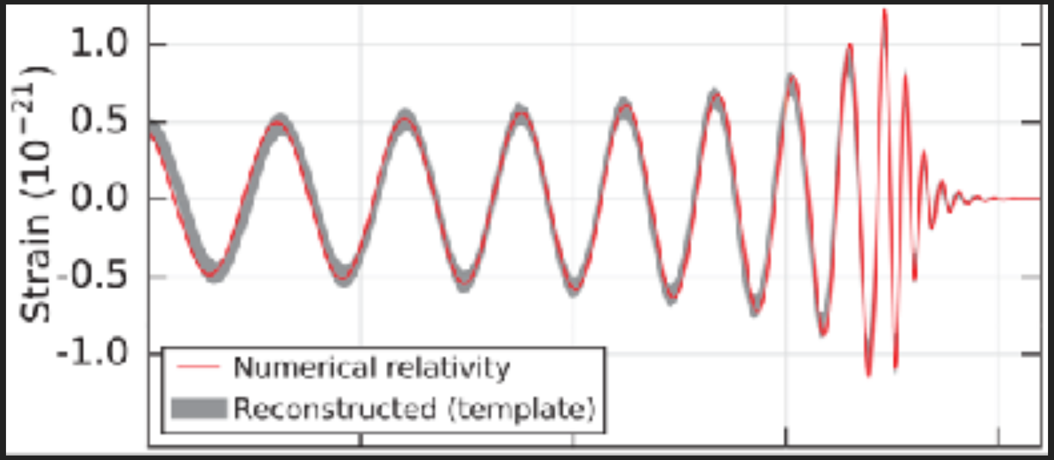
* Proposals to use mass distribution, EOS, etc.
Finn 1996; Taylor, Gair, & Mandel 2012; Messenger & Read 2012; Del Pozzo, Li, & Messenger 2017



What is a standard siren?

- 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 good is a standard siren?

- From the measured amplitude of the waves can directly calculate the absolute distance to the source
    - No distance ladder. Calibrated by general relativity
- The gravitational waves do not provide a redshift
    - Need an electromagnetic counterpart!
- Combining GW distance and EM redshift/recession velocity:
    - Can directly fit for Hubble relation (nearby)

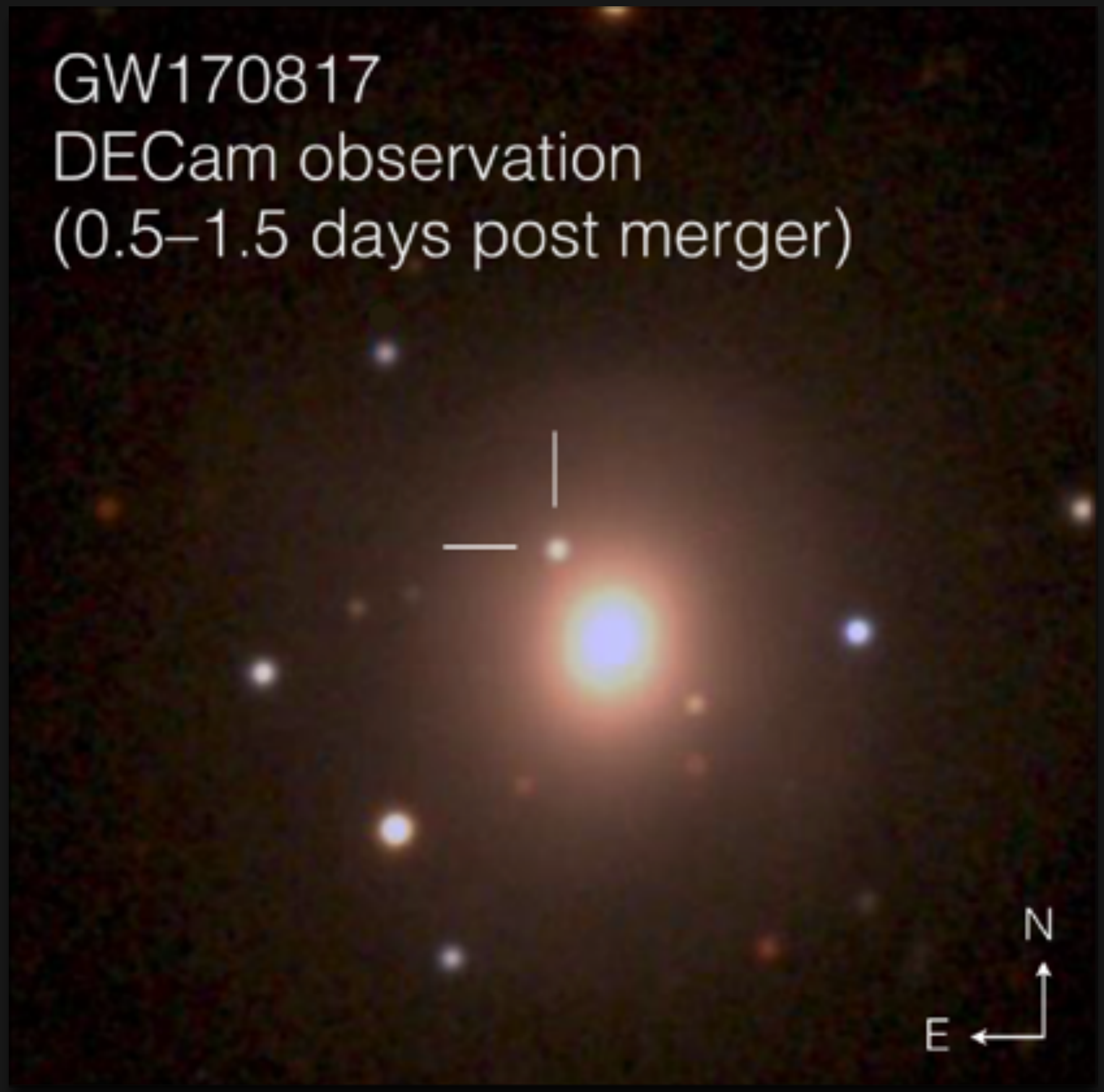
$$v = H_0\, d$$

from EM

from GW

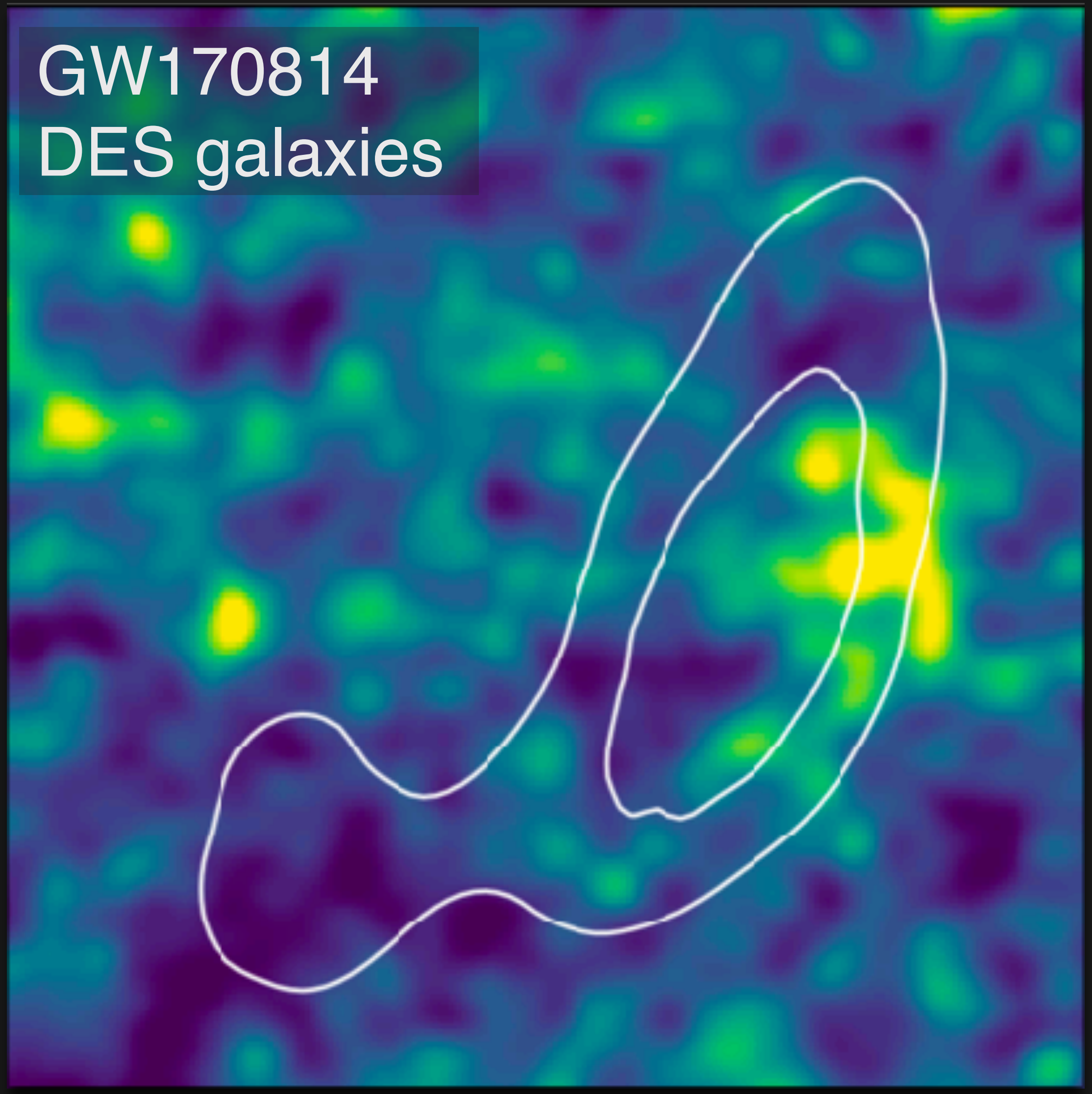
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

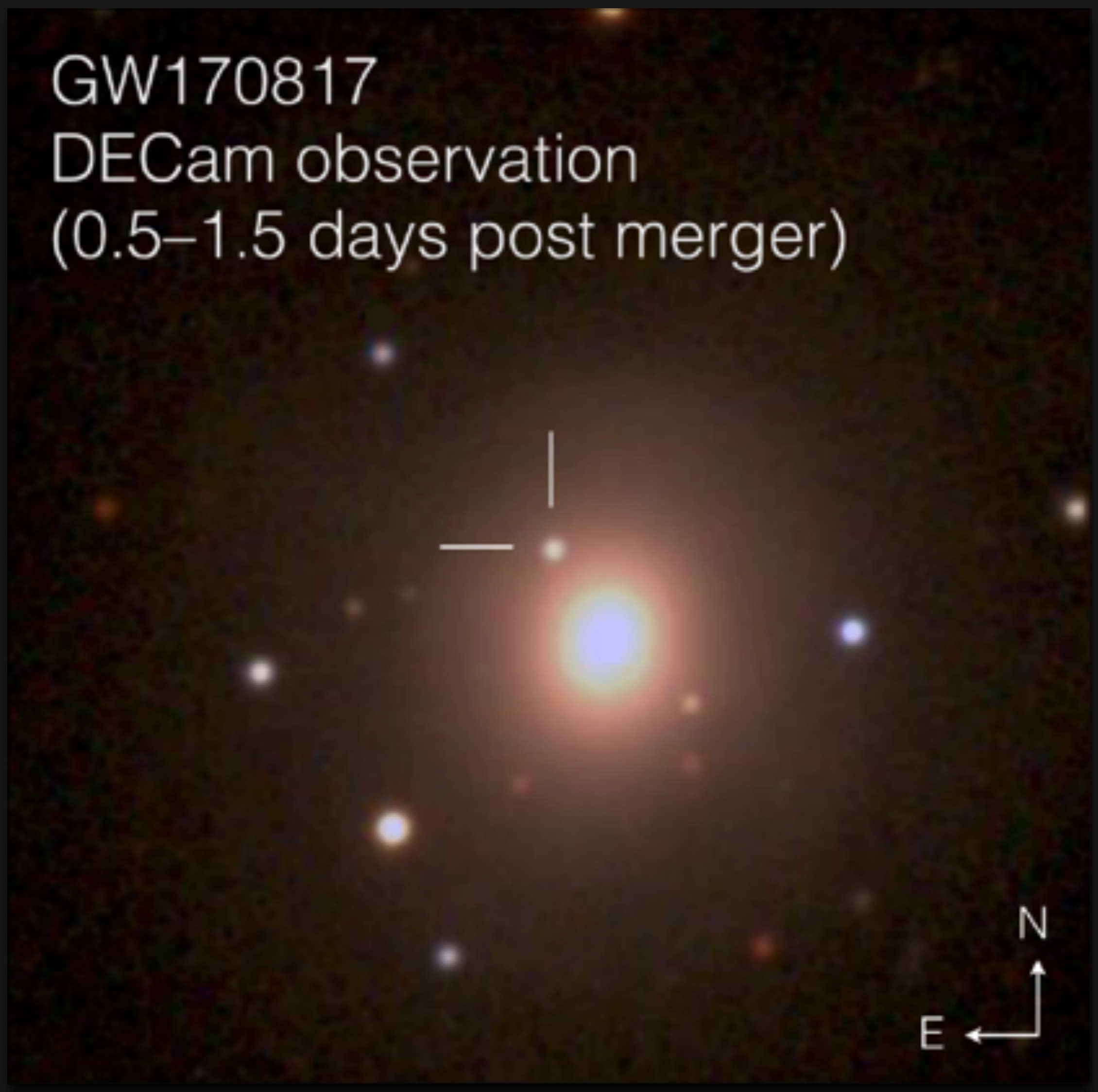
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

Counterpart/Bright



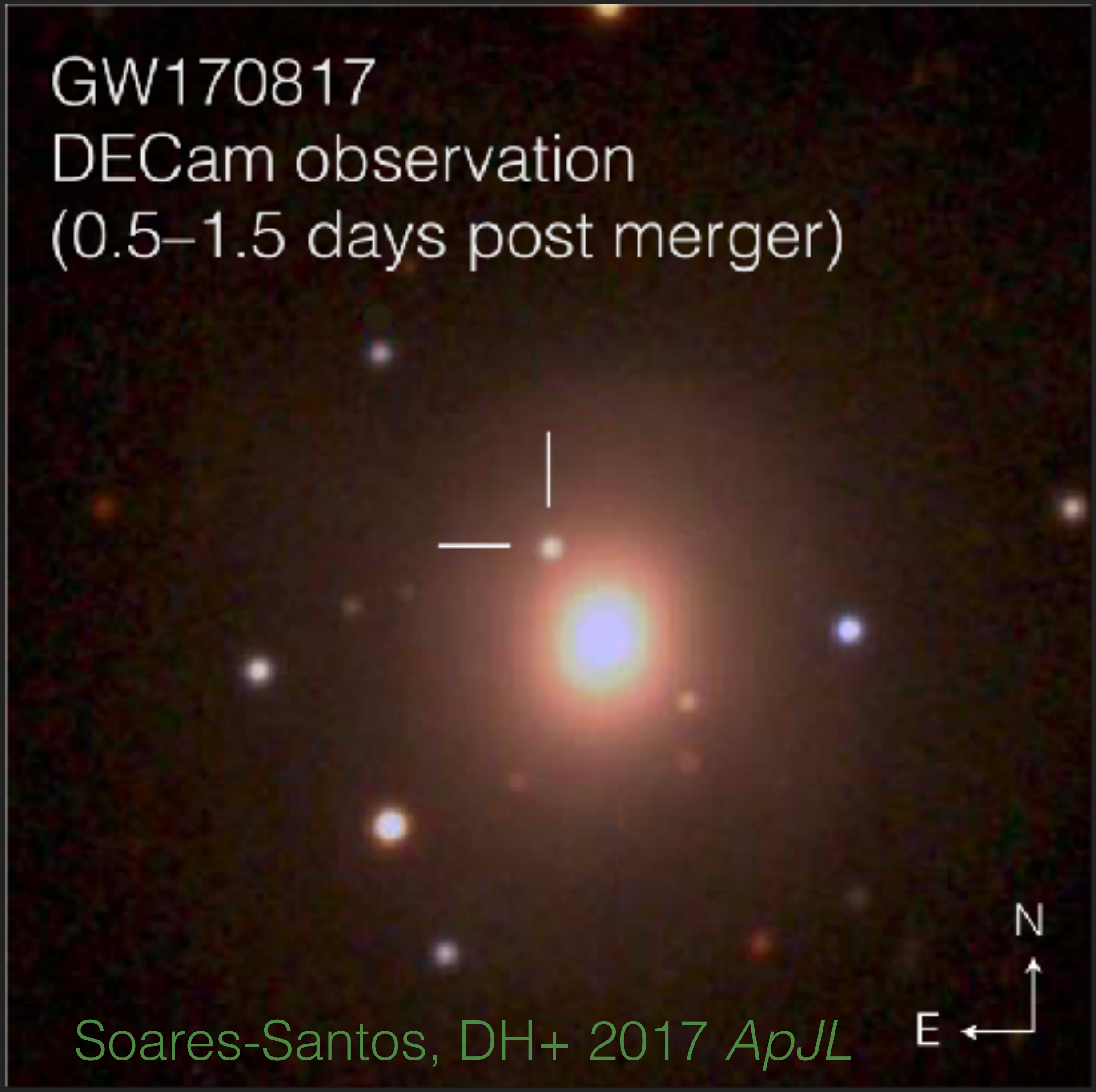
Unique host galaxy

- 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….



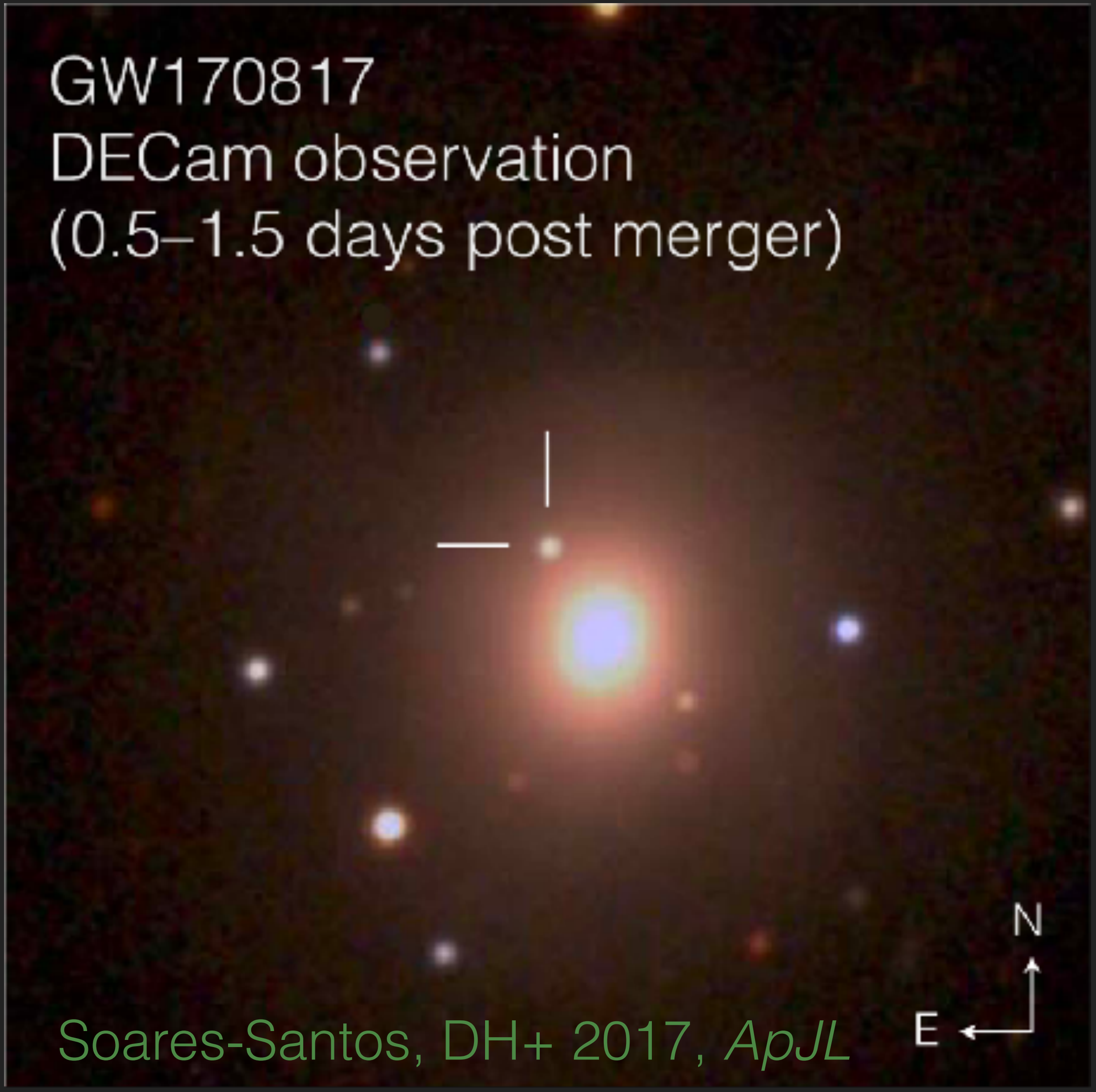
Soares-Santos, DH+ 2017 *ApJL*

Caveat: GW17081 is too good!

- Host galaxy is so close (40 Mpc) that peculiar motions are important. We use 6dF and 2MASS estimates to estimate bulk flow of the group (error: ~150 km/sec).

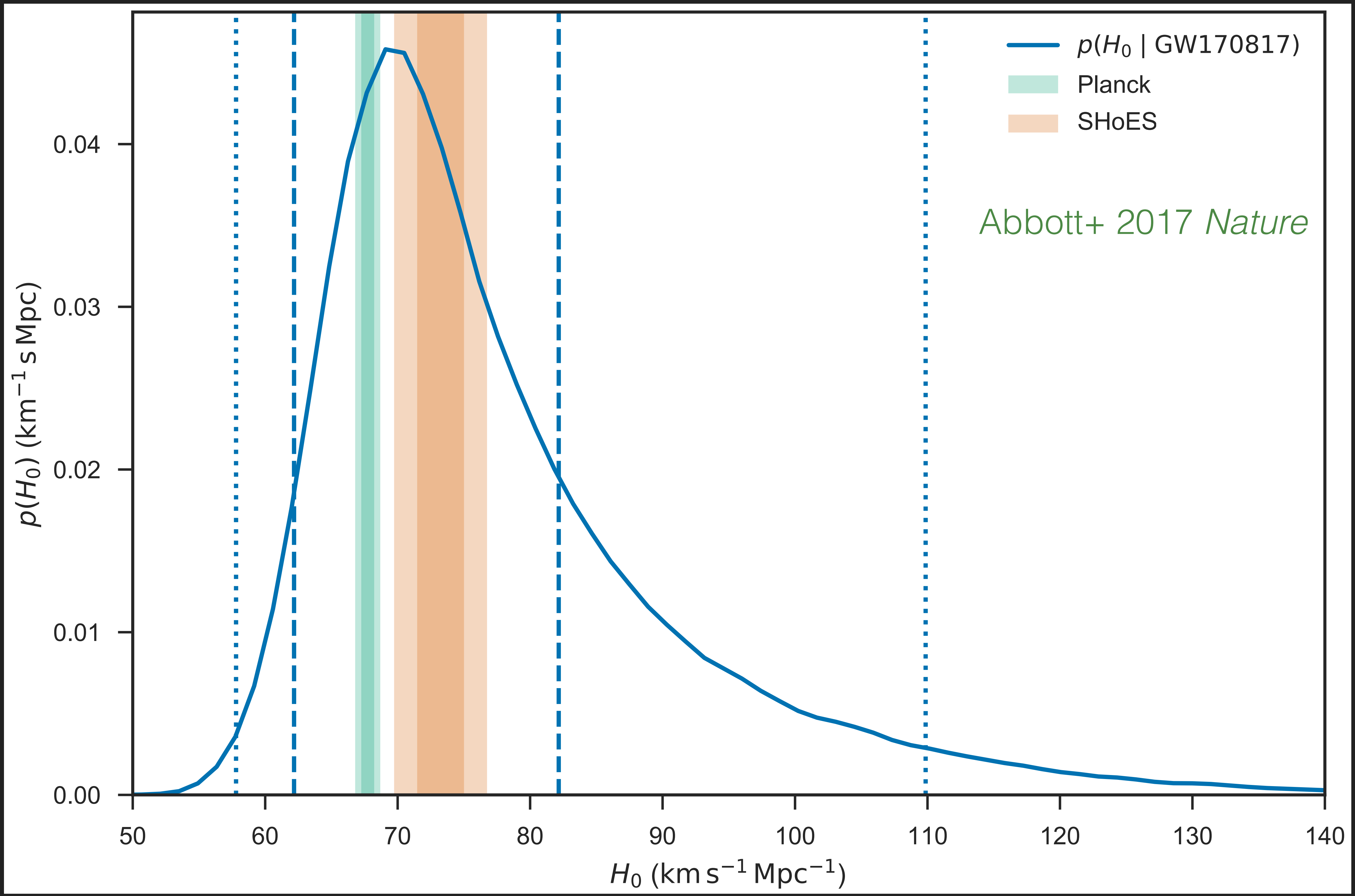
- Virial velocity: NGC 4993 belongs to a group of galaxies with center-of-mass velocity 3327 ± 72 km/s in the CMB frame (Crook+ 2007)

- Bulk flow: correct for coherent bulk flow of 310 ± 150 km/s (Springob+ 2014)



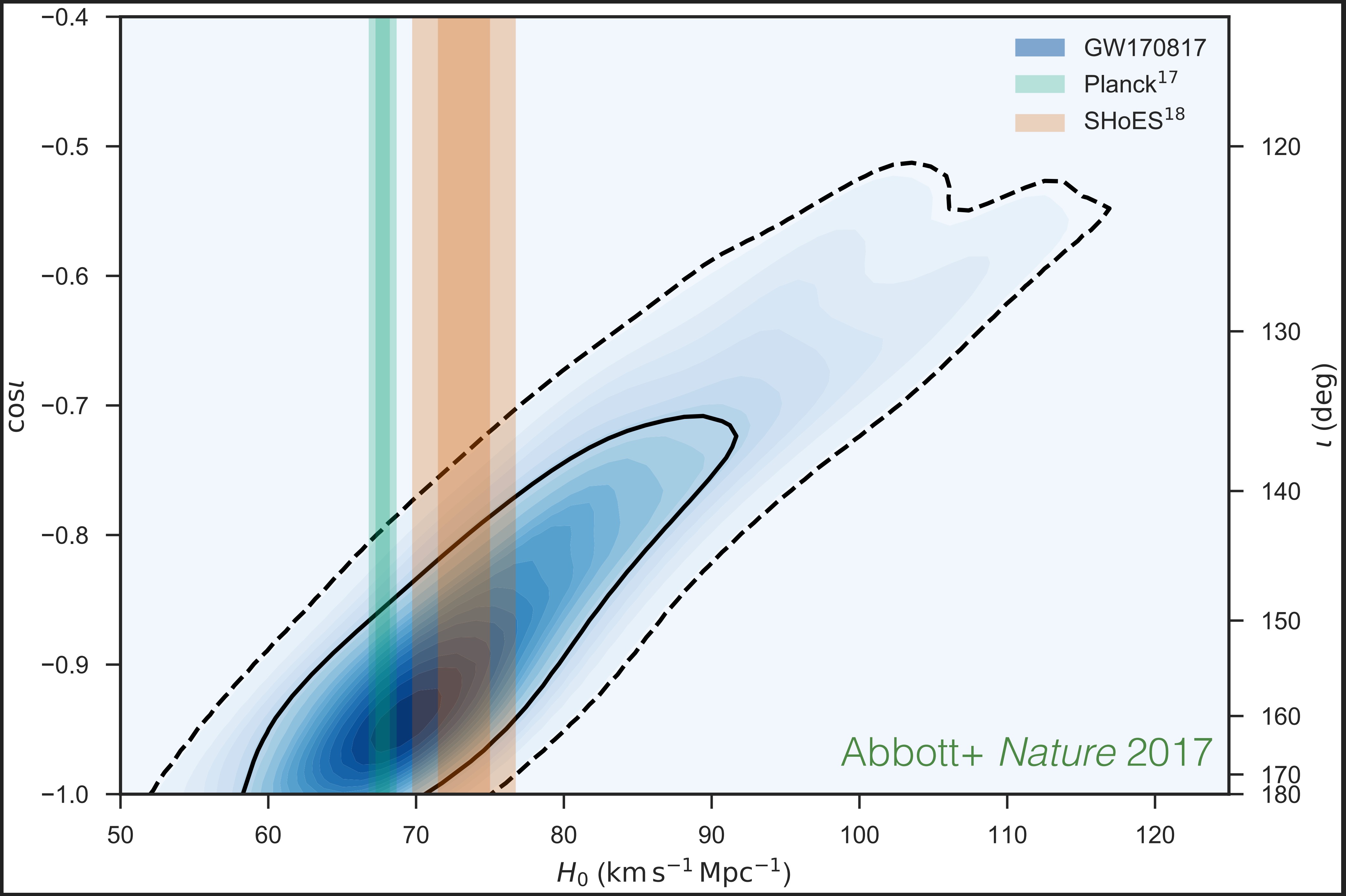
Soares-Santos, DH+ 2017, *ApJL*

Standard siren measurement of the Hubble constant



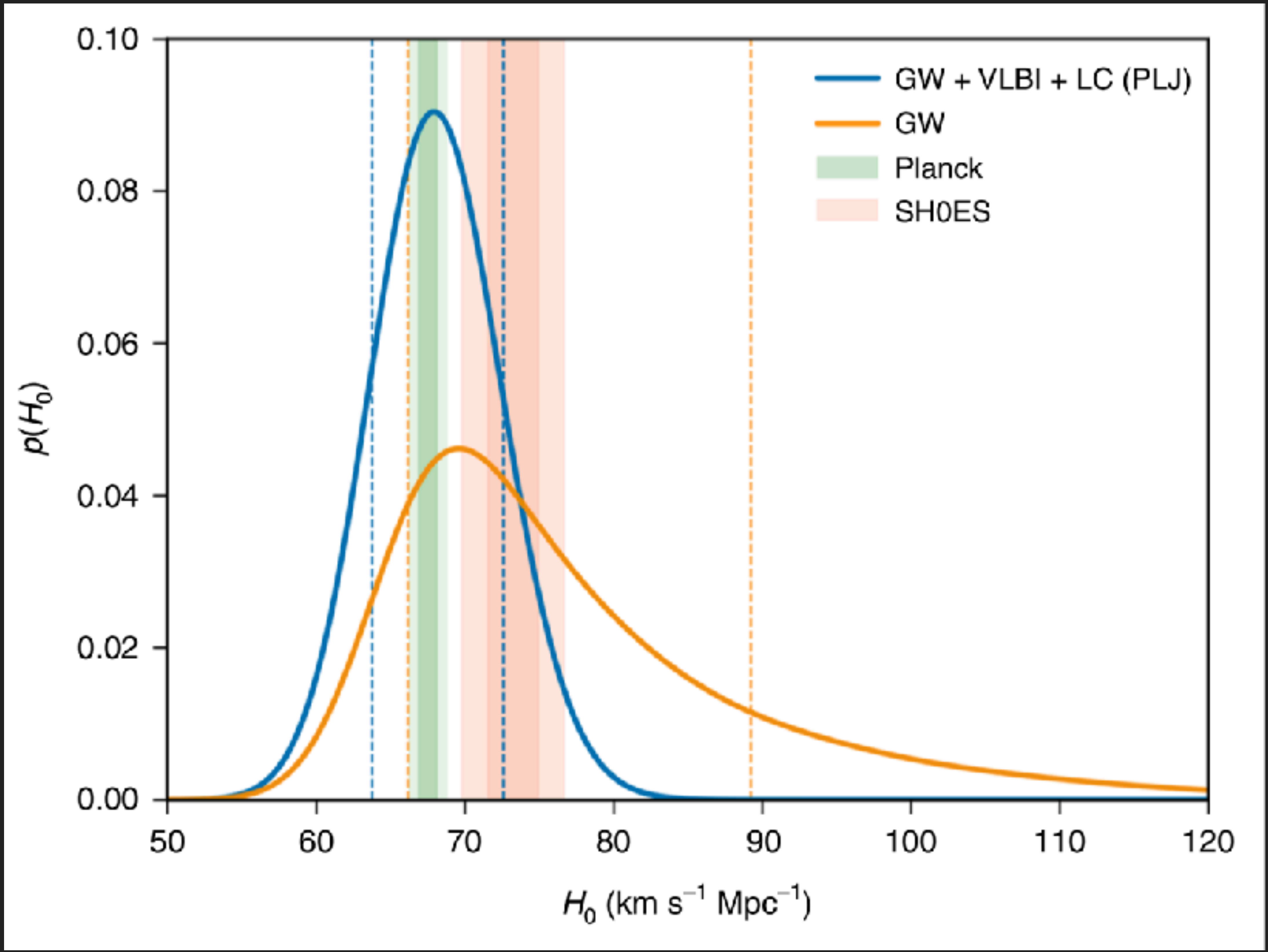
$$H_0 = 70.0^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

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 inclination, can improve cosmology

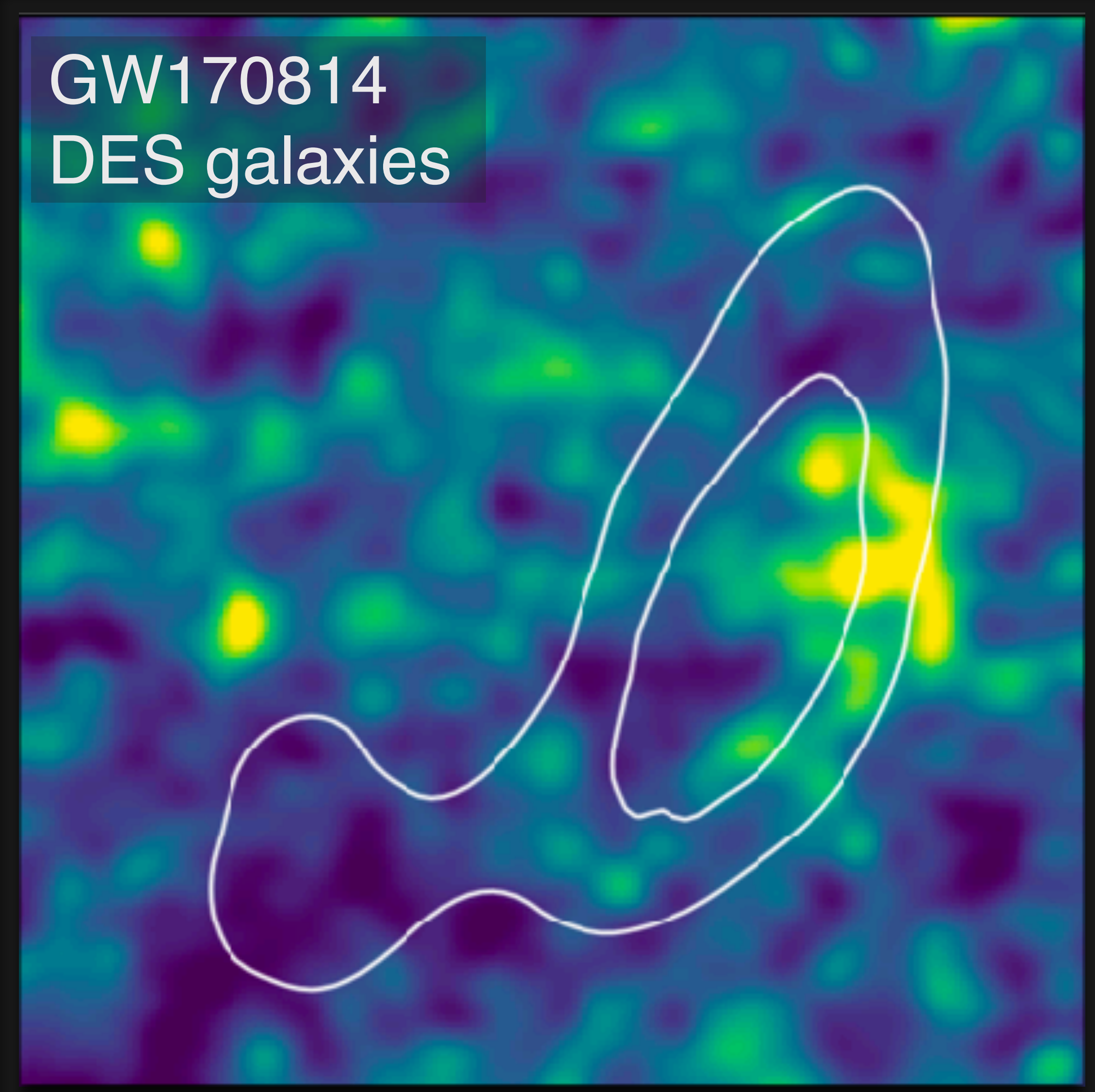


Hotokezaka+ 2018 based on radio observations from Mooley+ 2018
Also Abbott+ 2017; Guidorzi+ 2017

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

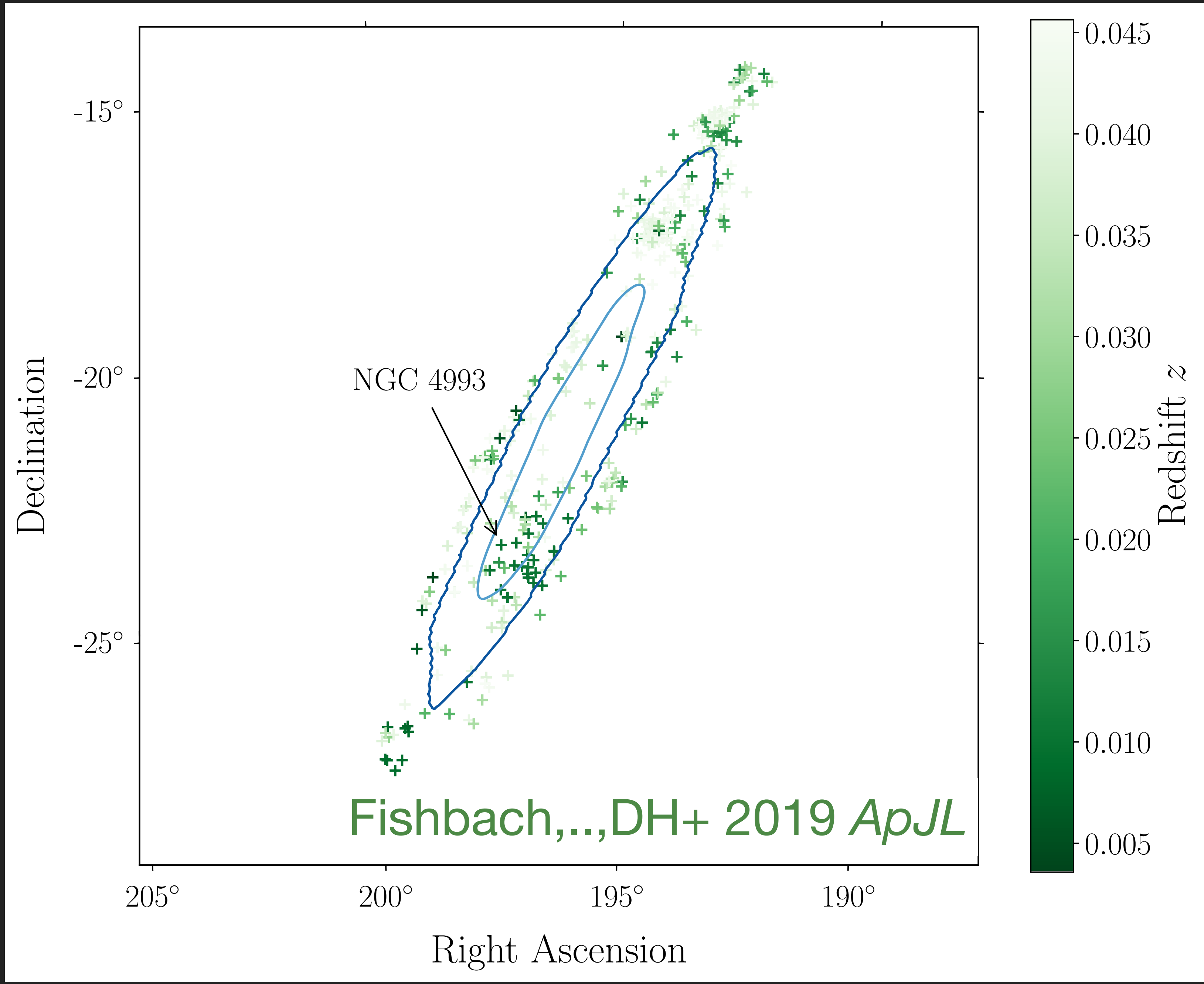


Use all galaxies in localization volume

Schutz 1986; Macleod & Hogan 2008; Del Pozzo 2012

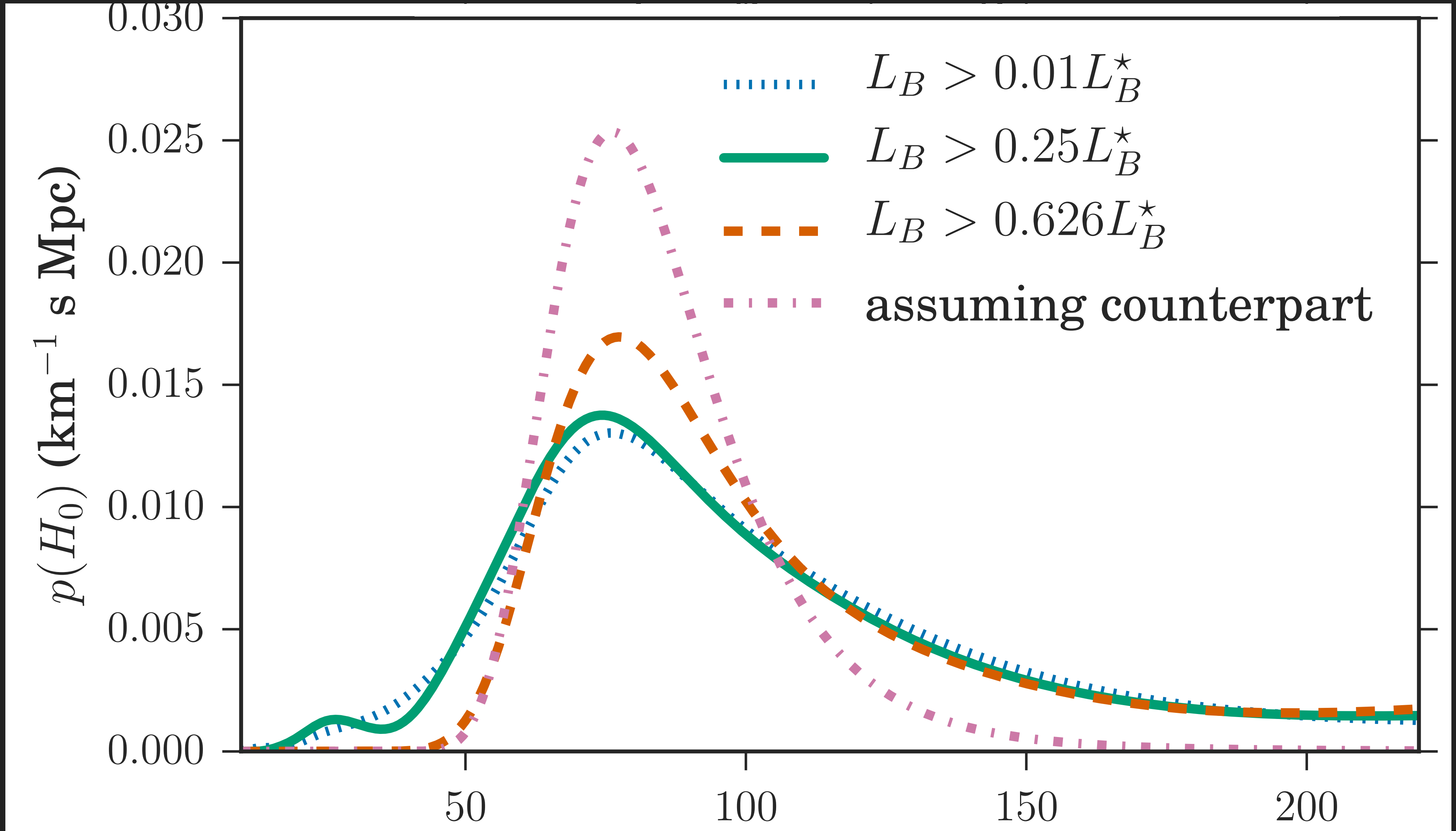
GW170817 as a dark standard siren

- 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*

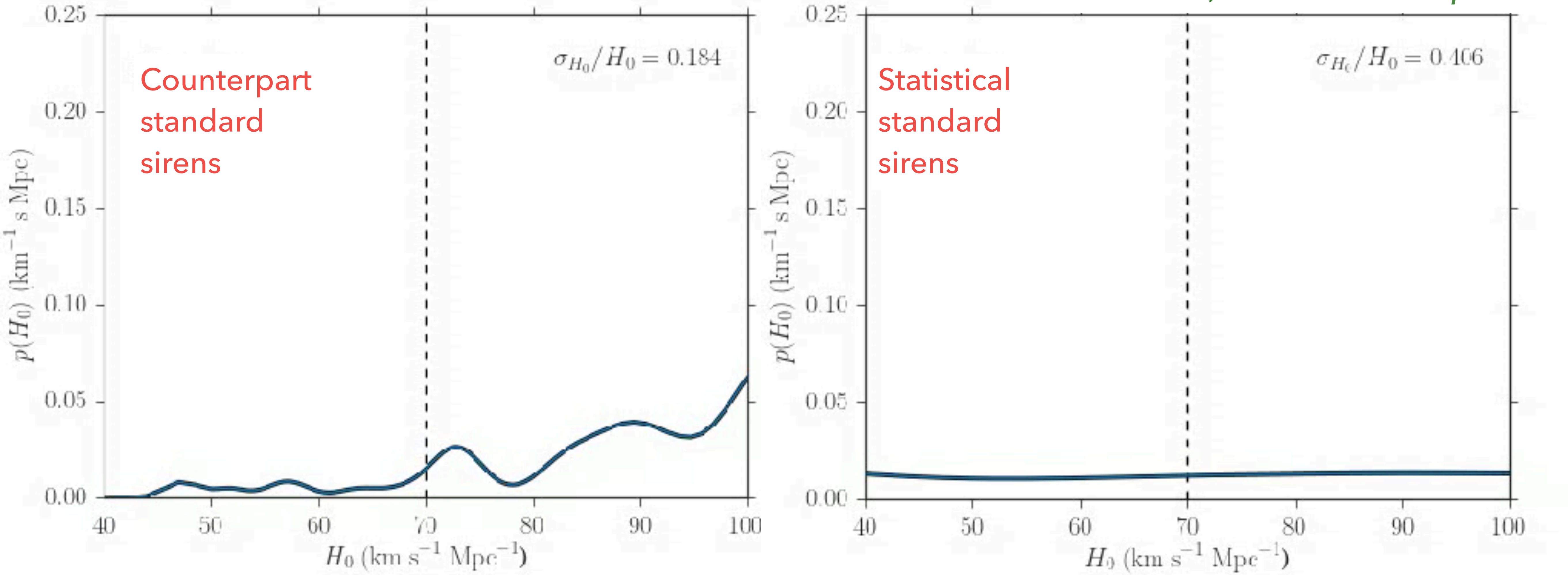
$$H_0 = 77^{+37}_{-18}\ \mathrm{km/sec/Mpc}$$

What will the future bring?

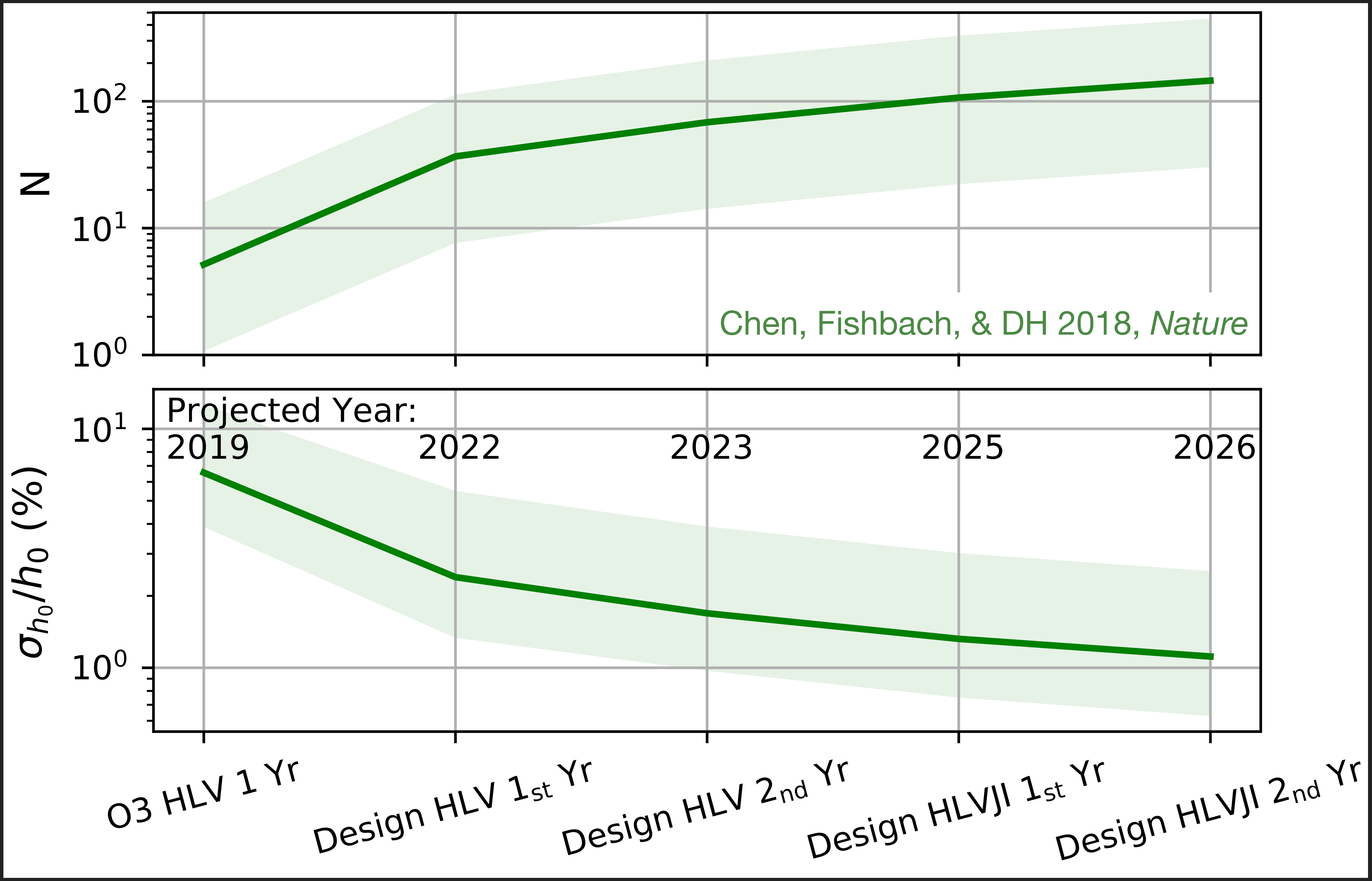
Simulations of standard siren convergence

- 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+ 2019 *ApJL*

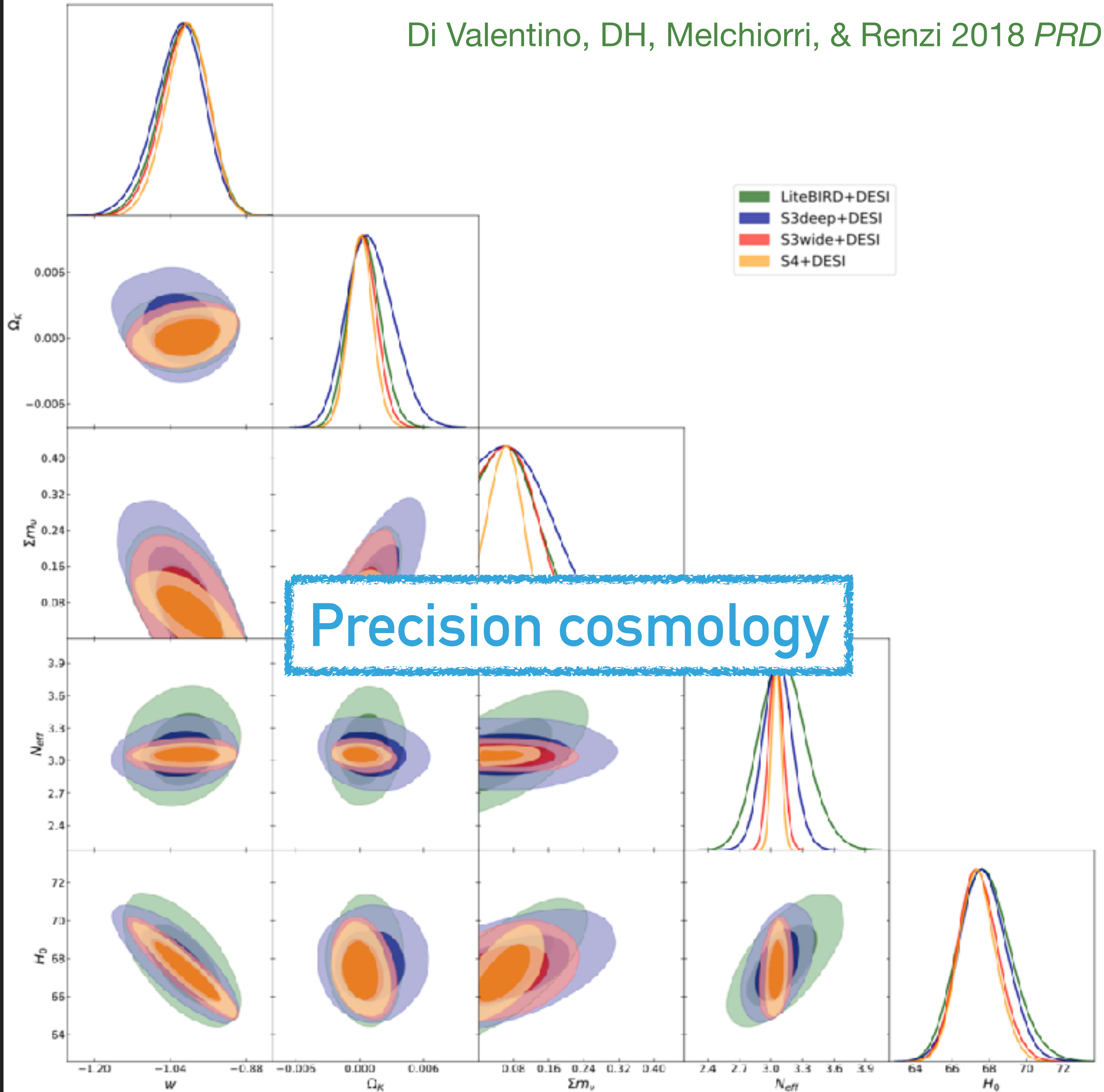


H_0 to 2% by 2023, 1% by 2026*



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

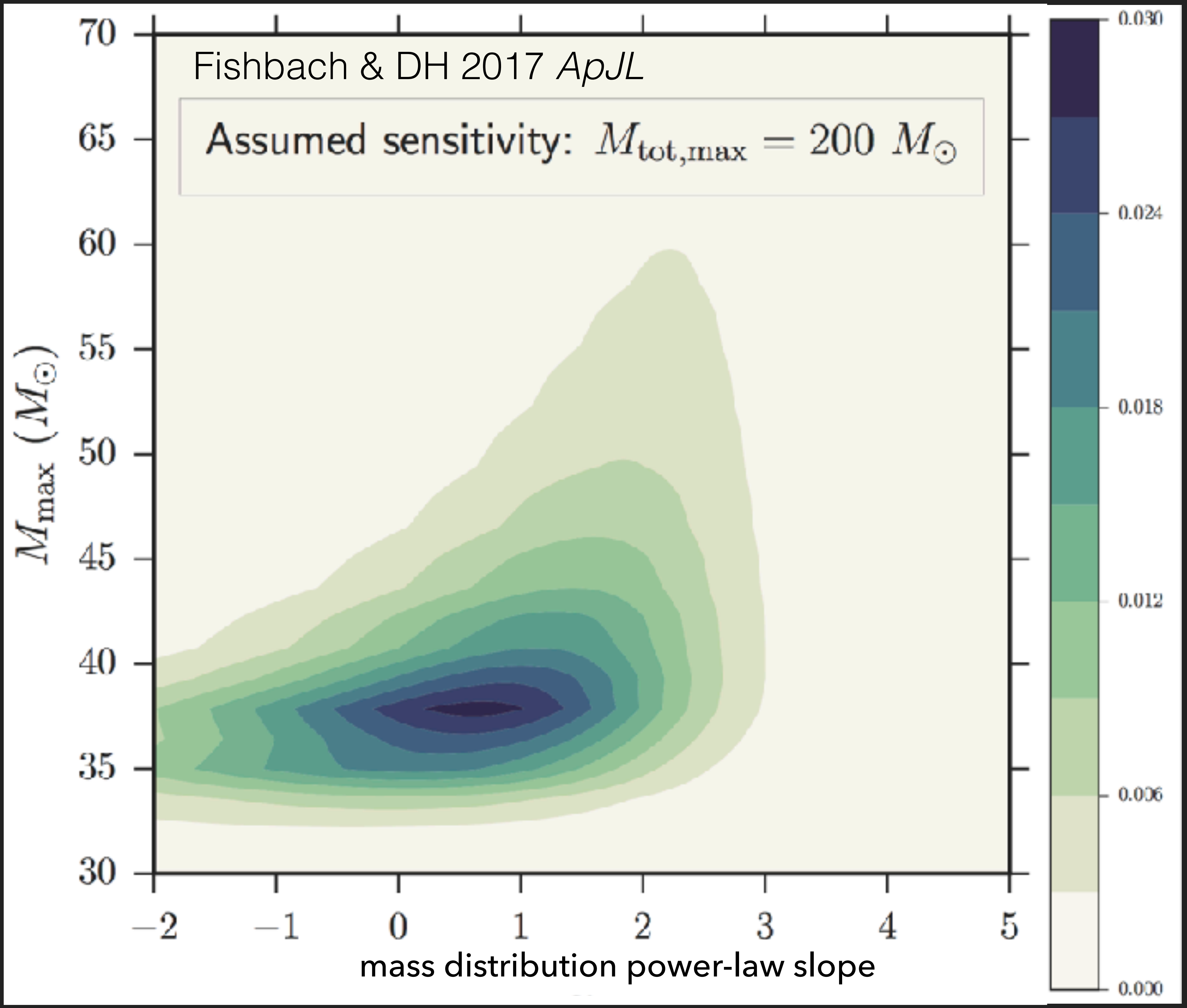
Di Valentino, DH, Melchiorri, & Renzi 2018 *PRD*



A new method for standard siren cosmology

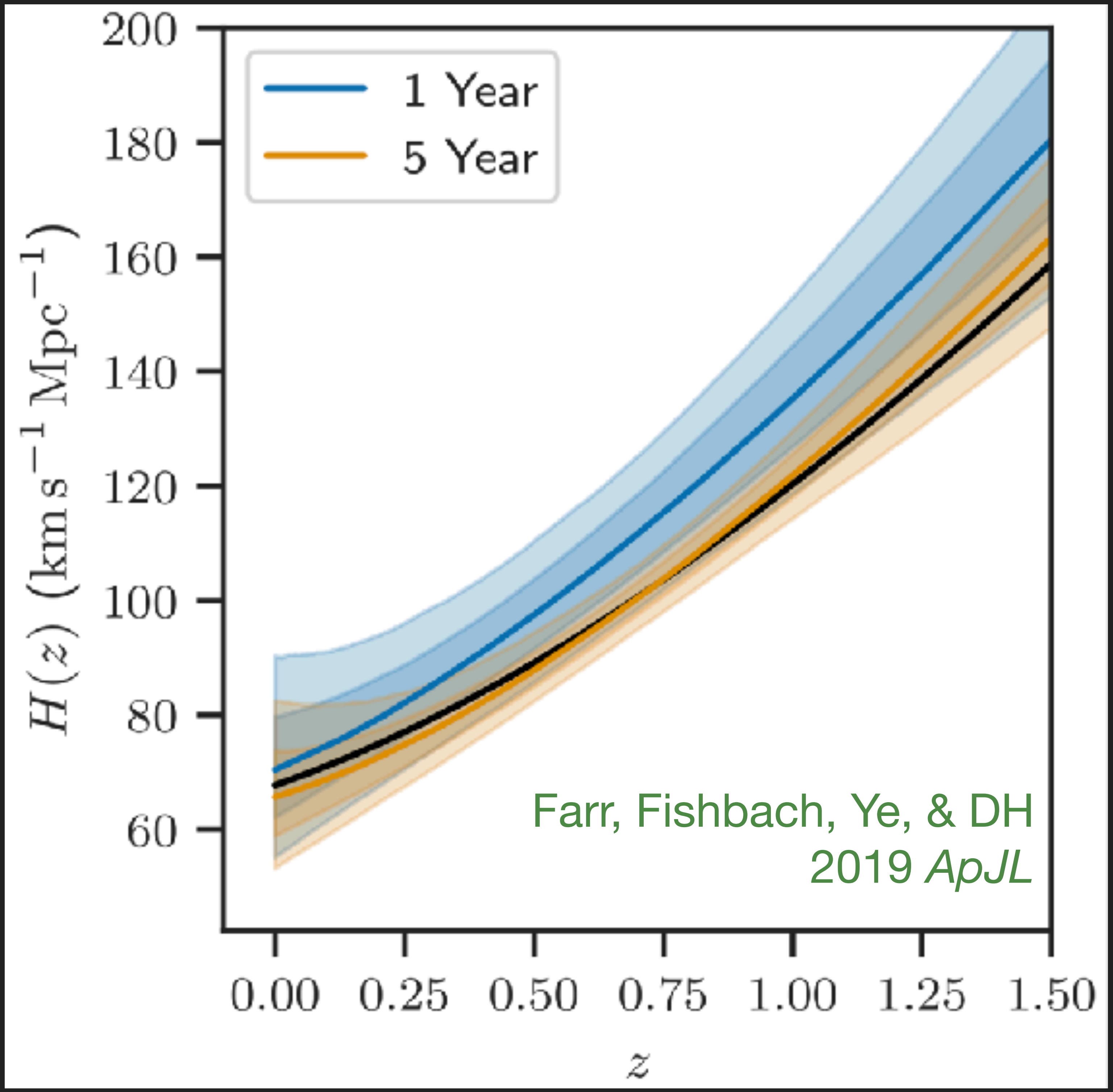
Where are LIGO's big black holes?

- 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&A*)



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%



Standard siren systematics

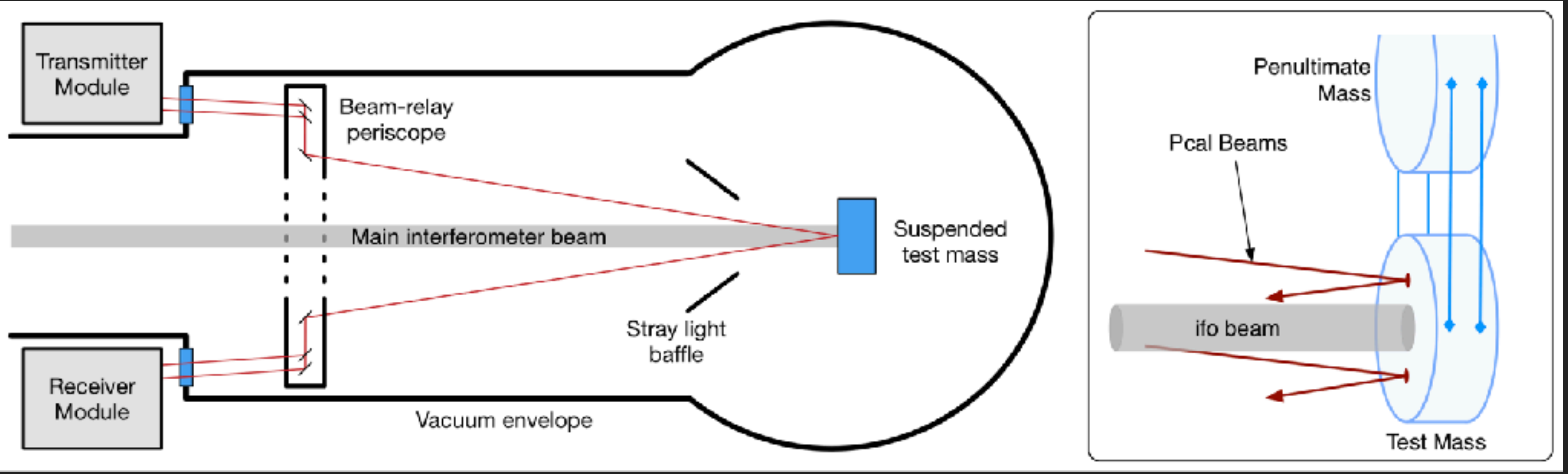
- Peculiar velocities (Howlett & Davis 2019; should become negligible soon)
- Model selection (priors over GW population impact final results [e.g. rate evolution, mass distribution]; Abbot+ 2017; Chen, Fishbach, & DH 2018; Fishbach, DH+ 2018; Feeney+ 2018; Mortlock+ 2019)
- Inclination distribution (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%

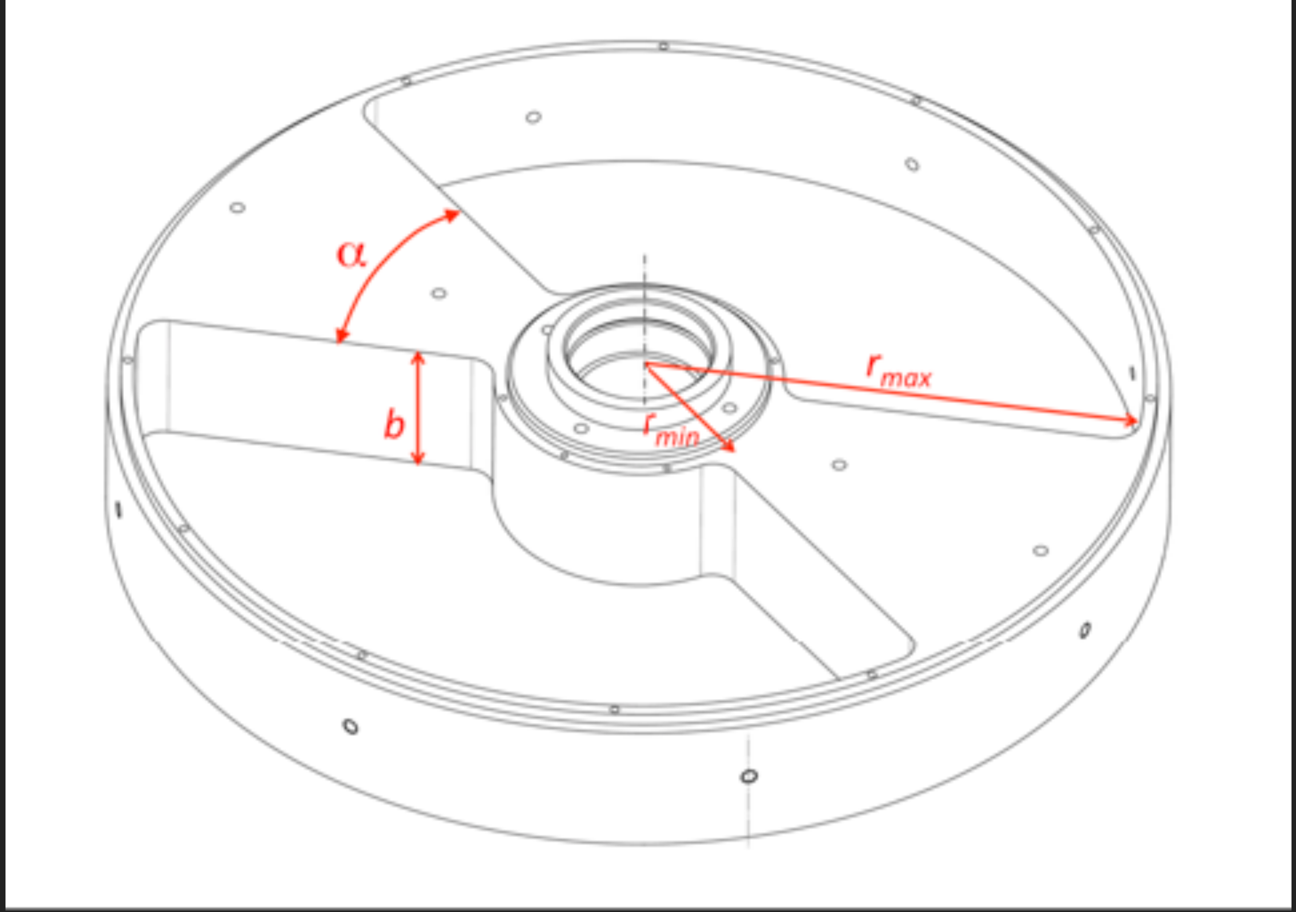
Parameter	Relative Uncertainty
Laser Power [$\mathcal{P}$]	0.57 %
Angle [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.40 %
Overall	**0.75 %**

Karki+ 2016; Cahillane+ 2017

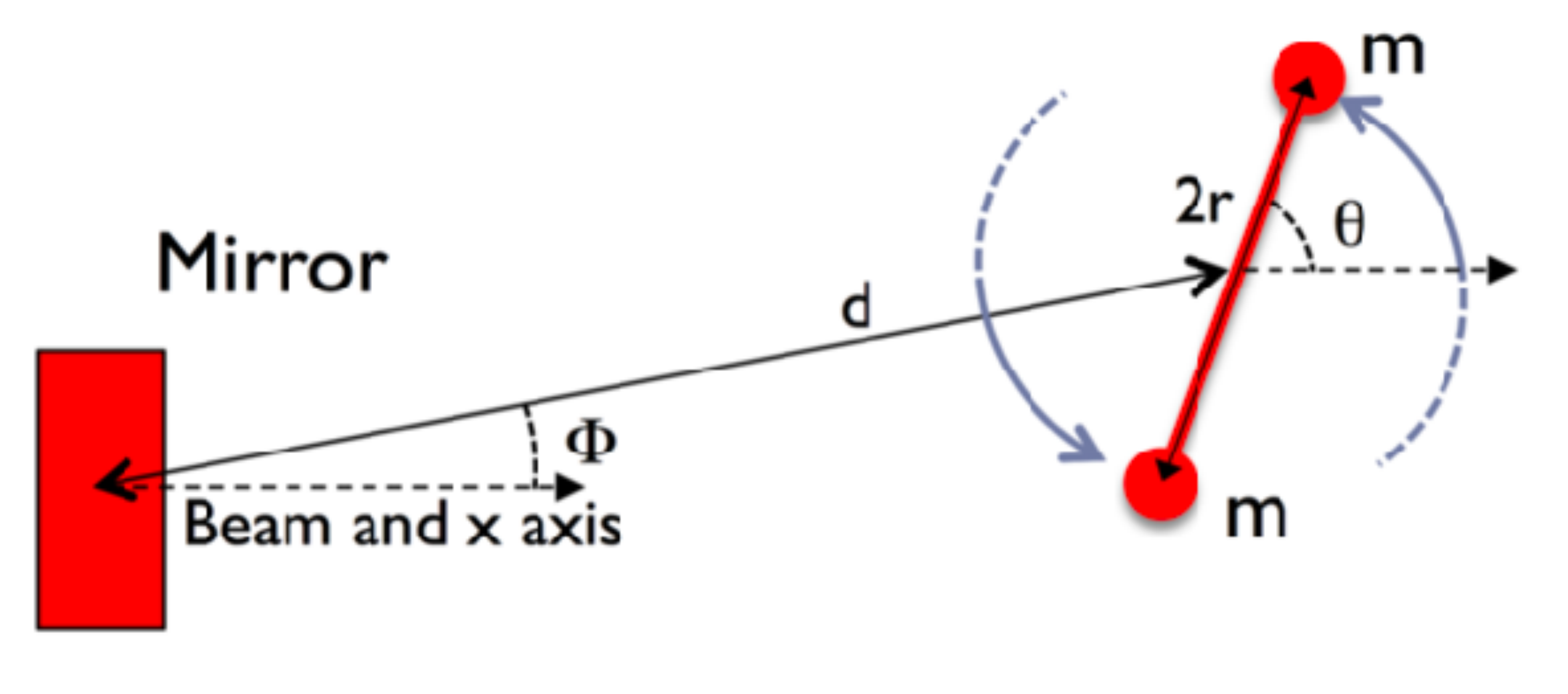


Newtonian calibrator

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

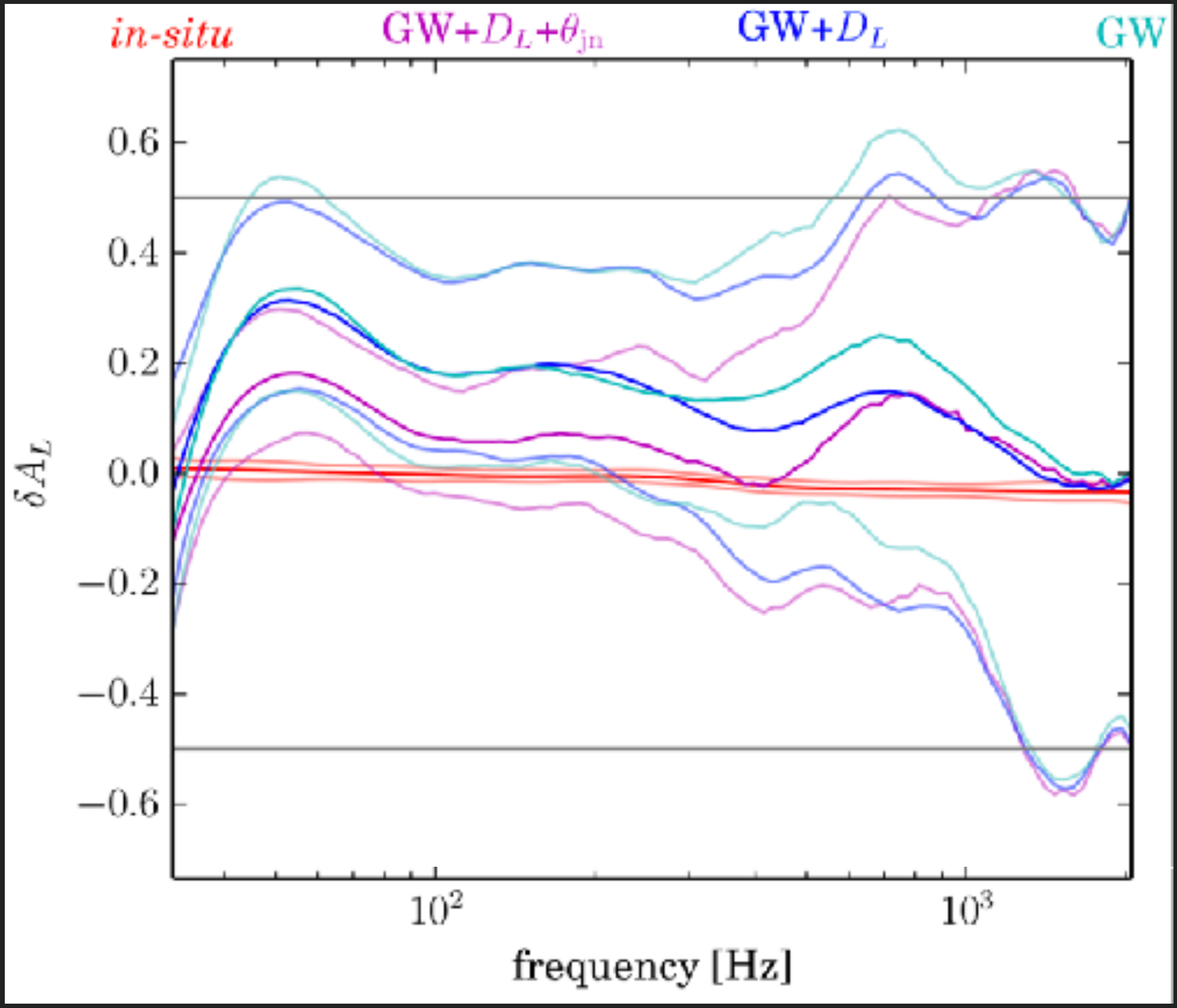


Estevez+ 2018



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%

The future is loud and bright

- GW170817 heralds the era of gravitational-wave multi-messenger astronomy
- LIGO, Virgo, and KAGRA have suspended O3
    - GW190425 (heavy BNS), GW190412 (asymmetric BBH),…
- Are expected to turn back on at design sensitivity in ~18 months
- The future should bring additional spectacular events, and hopefully some interesting surprises as well!