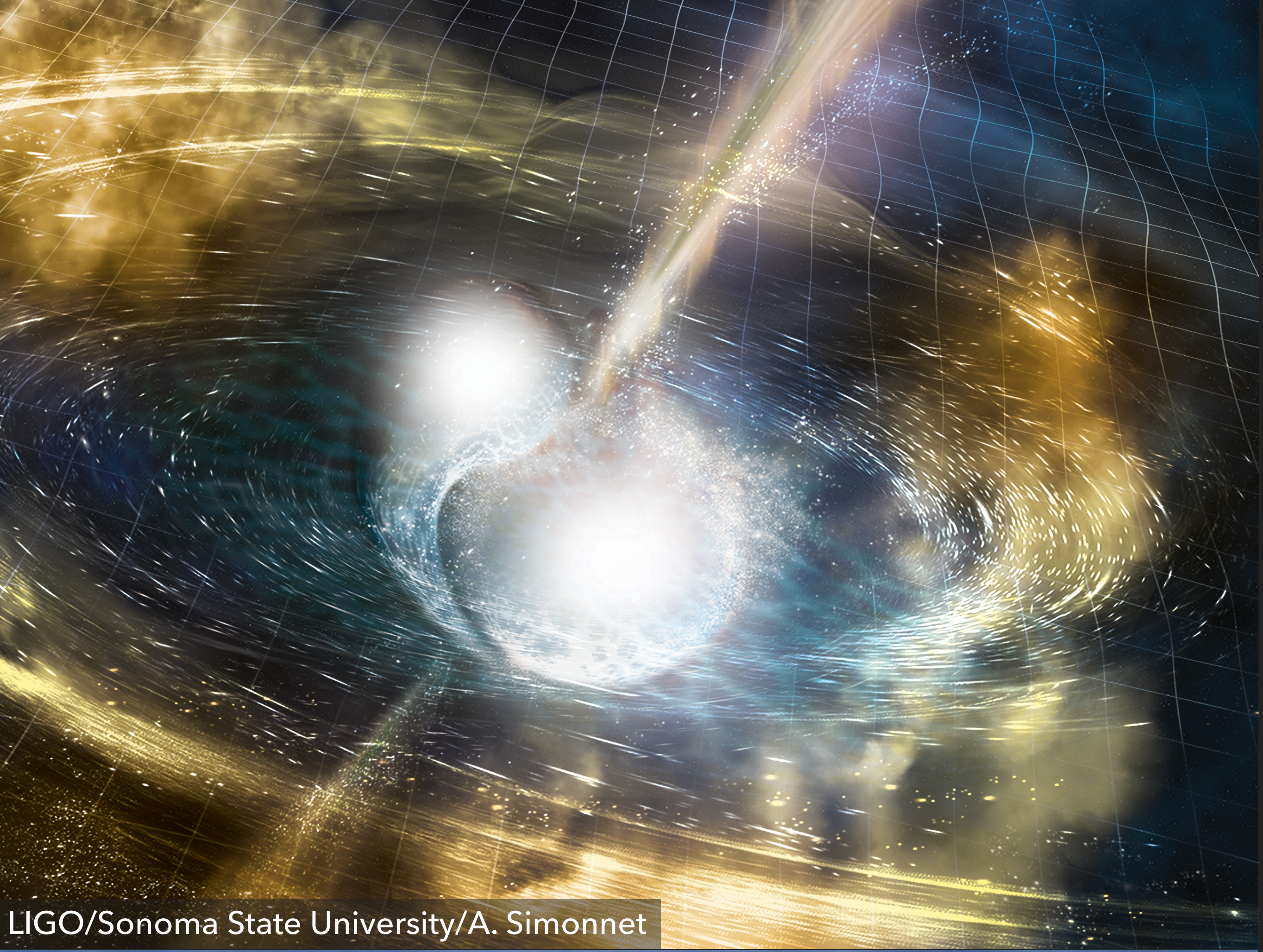


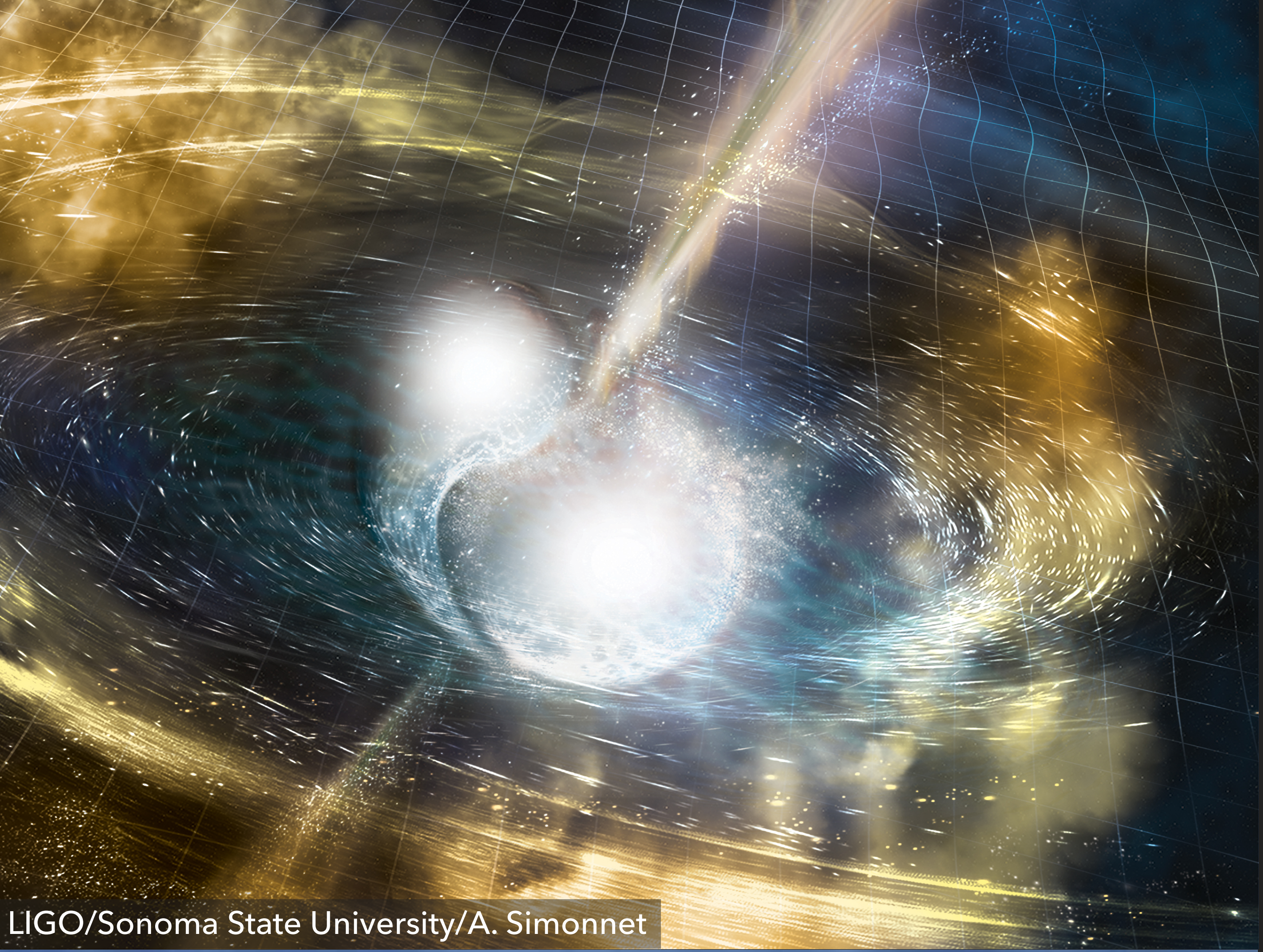
LIGO/Sonoma State University/A. Simonnet

LIGO

Cosmology with standard sirens and the Hubble constant tension: an outlook

Daniel Holz

University of Chicago



LIGO/Sonoma State University/A. Simonnet

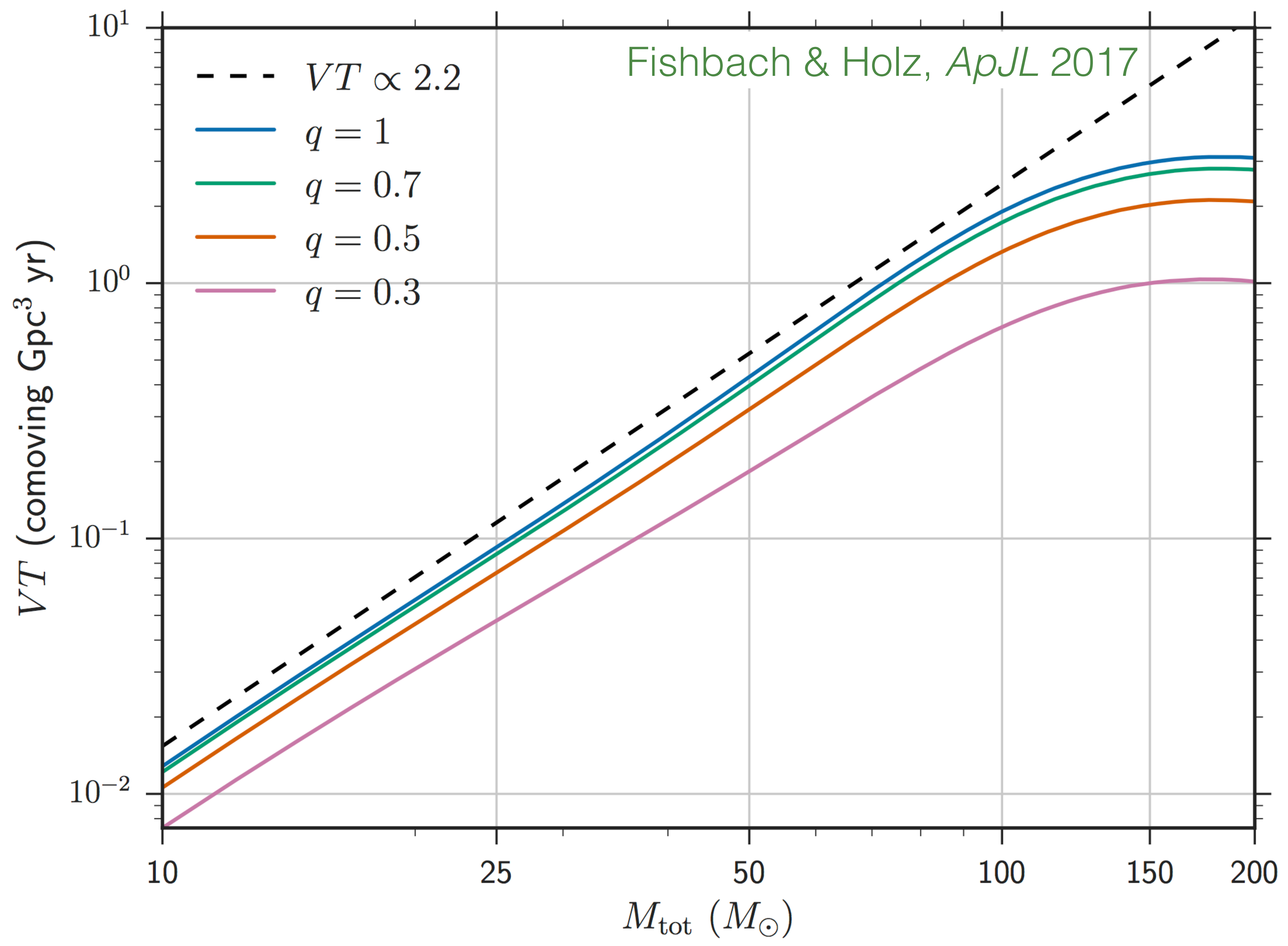
LIGO

Some gravitational wave astro/cosmo results

Daniel Holz

University of Chicago

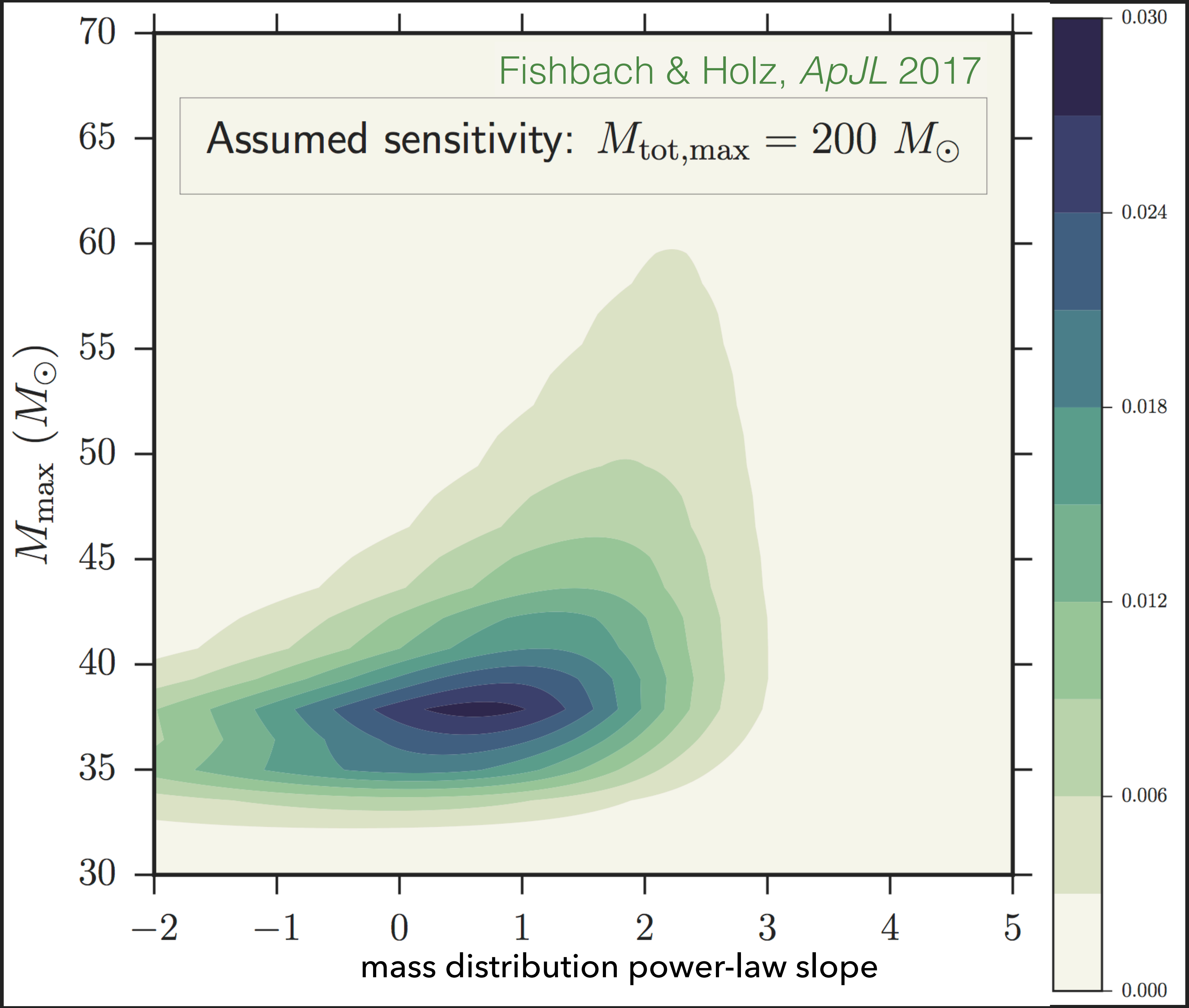
Where are LIGO's big black holes?



- LIGO/Virgo is sensitive to big (>40/40 $M_\odot$) binary black holes to very large distances (z>0.5)
- Over 90% of the sensitive volume is above 40/40 $M_\odot$

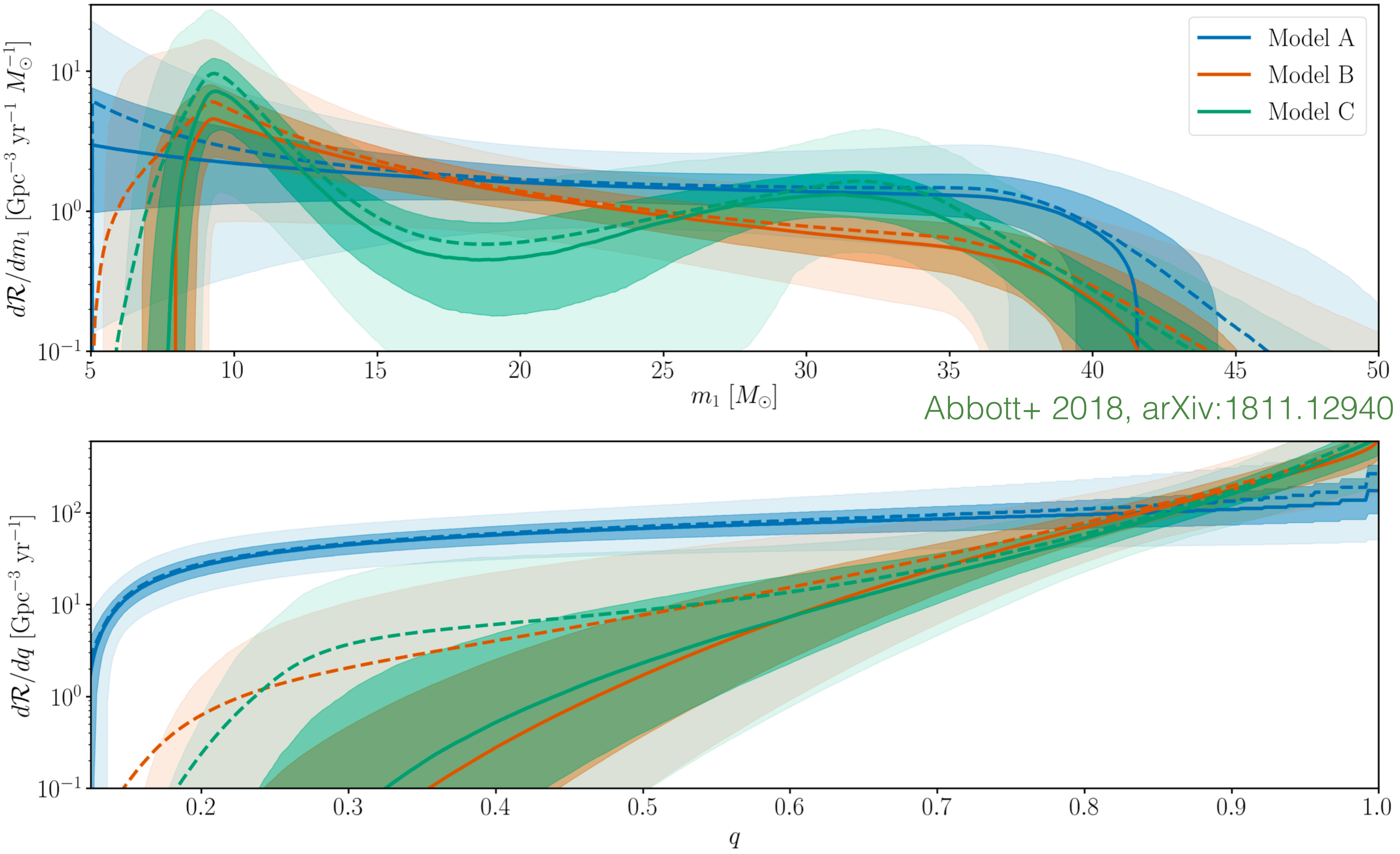
Where are LIGO’s big black holes?

- 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



Papers and discussion by Chris Belczynski, Emanuele Berti, etc .

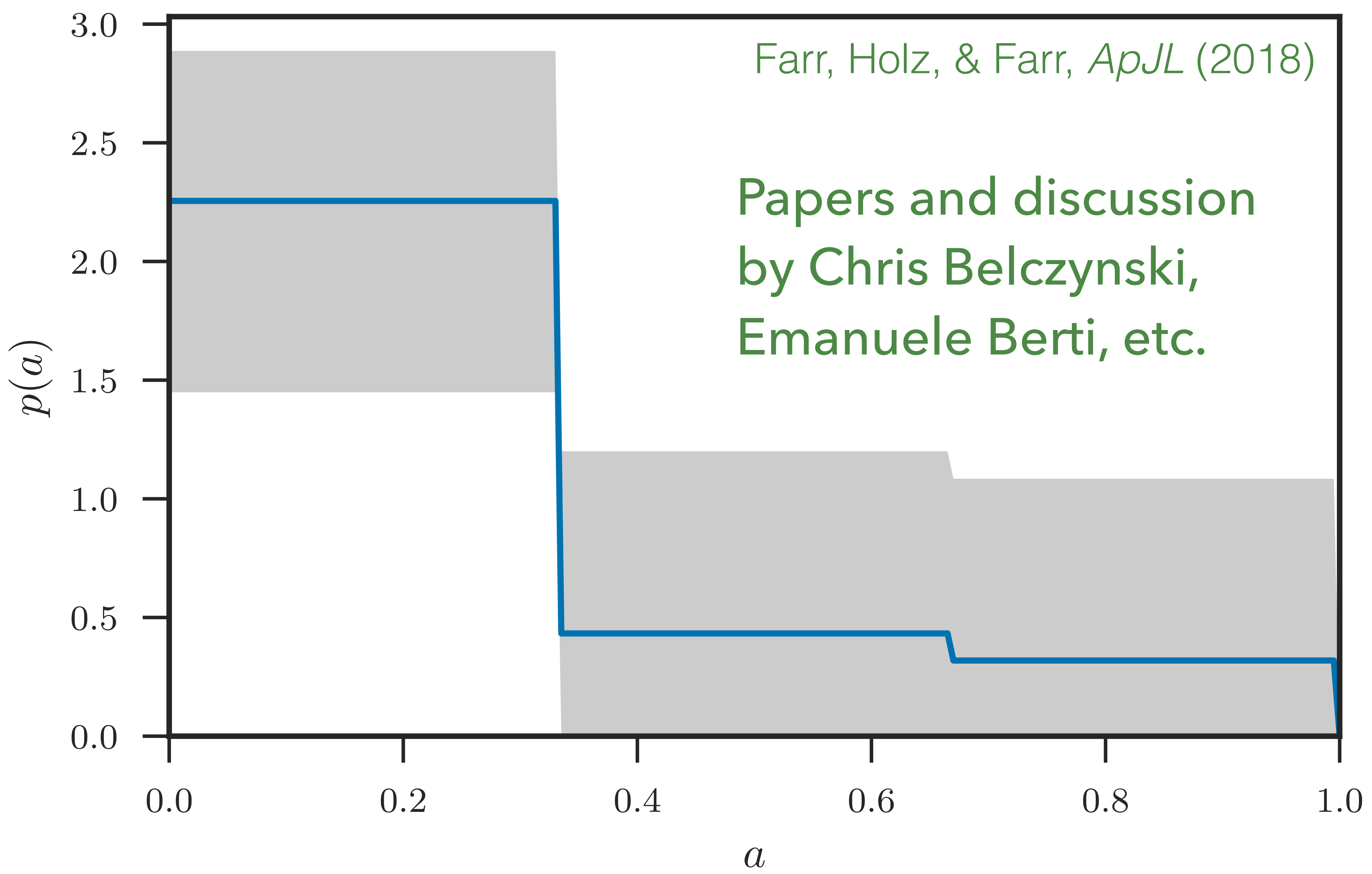
Where are LIGO's big black holes?



Abbott+ 2018, arXiv:1811.12940

Ongoing work with Chris Belczynski, Emanuele Berti, Duncan Brown, Tomek Bulik, Richard O'Shaughnessy, Zoheyr Doctor, etc.

How did LIGO's black holes form?

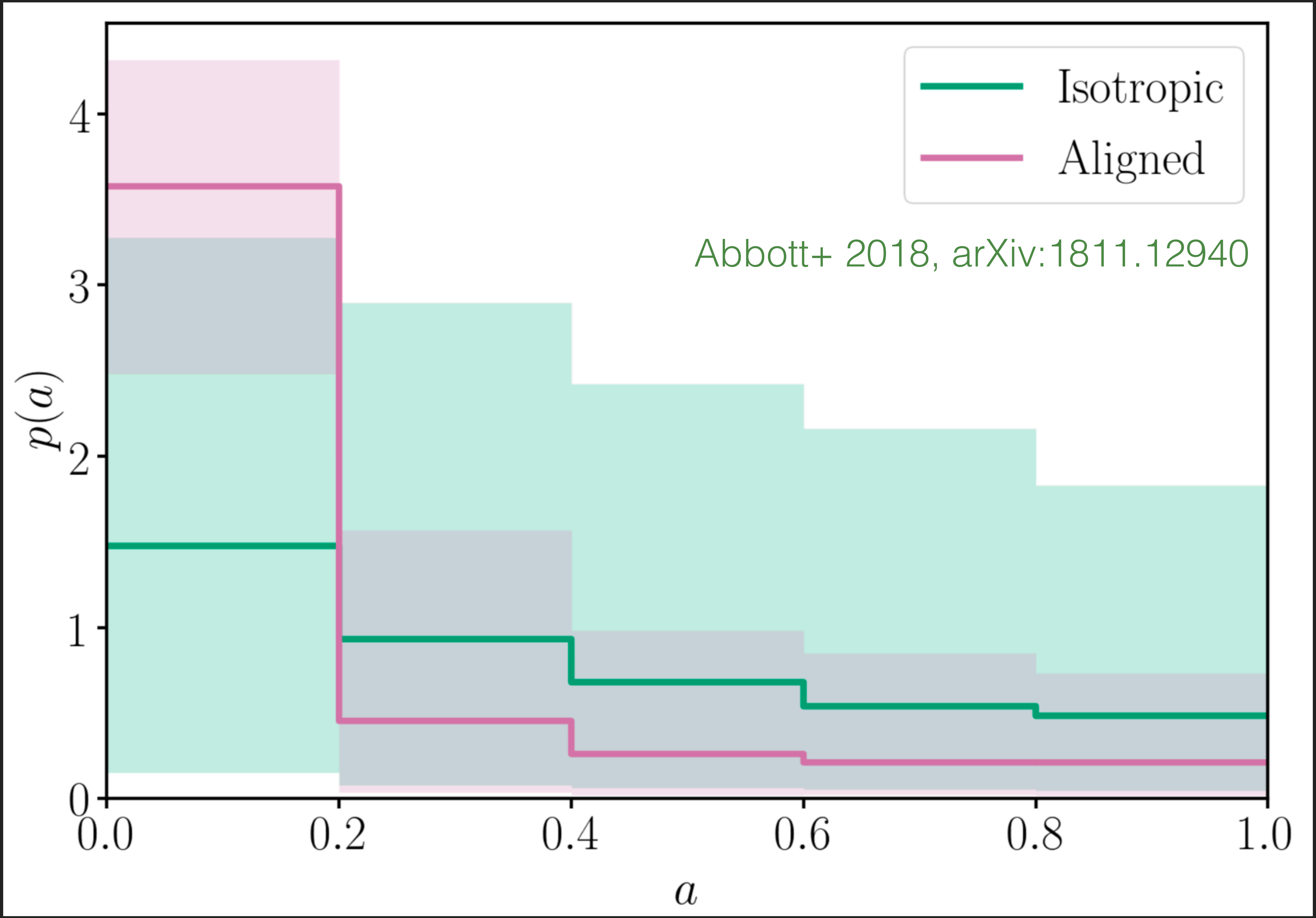


Farr, Holz, & Farr, *ApJL* (2018)

Papers and discussion by Chris Belczynski, Emanuele Berti, etc.

- Are the spins of the LIGO black holes aligned or isotropic? (corresponding to isolated or dynamical formation) We find weak evidence for aligned.
- We produce spin magnitude distributions (assuming aligned)

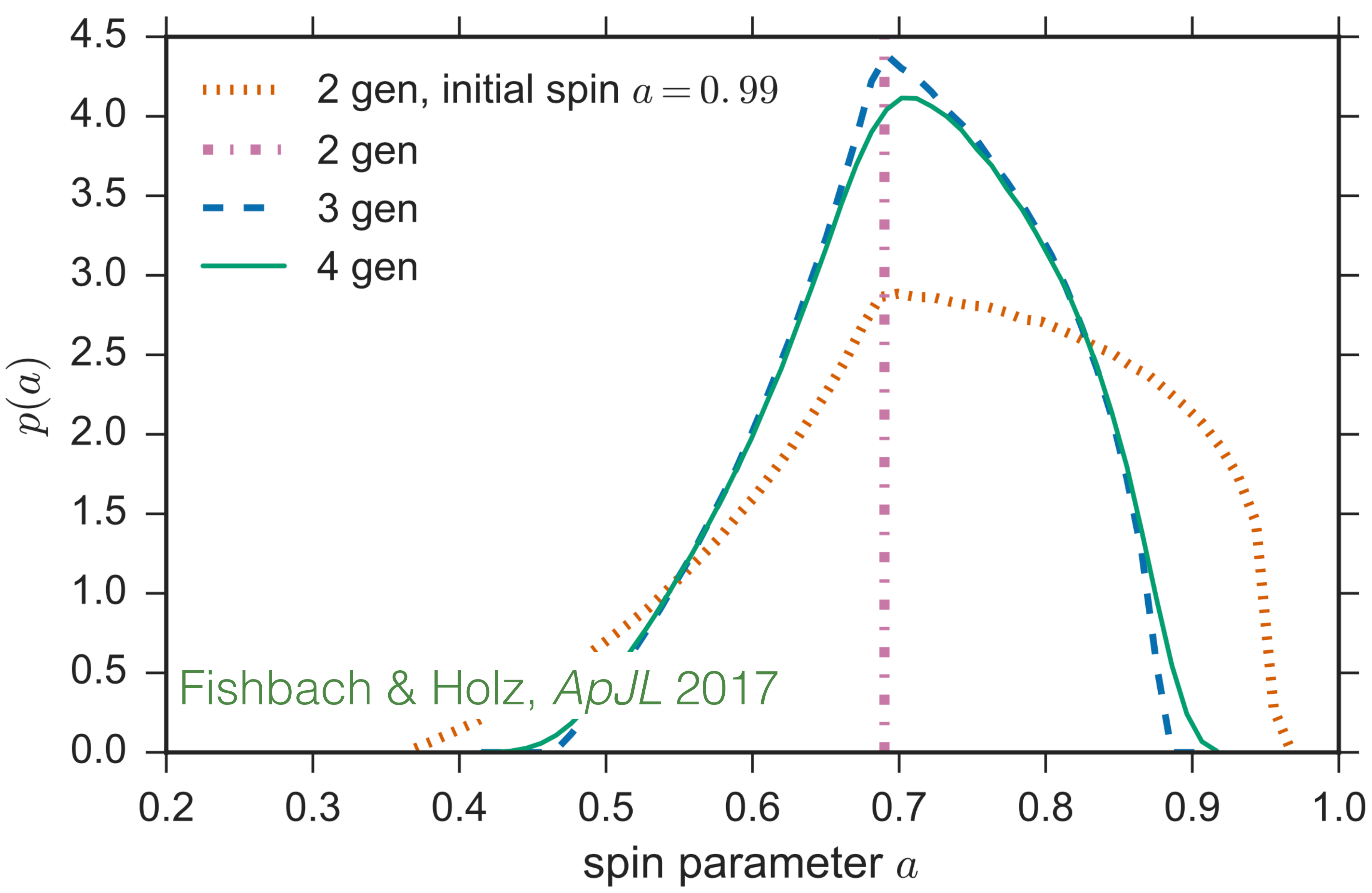
How did LIGO's black holes form?



Abbott+ 2018, arXiv:1811.12940

Are LIGO's Black Holes Made From Smaller Black Holes?

- There is a universal spin for merged black holes
- It is very hard to shed the orbital angular momentum
- Puts pressure on dark matter models, which (might) have hierarchical formation
- Mass gap BHs?

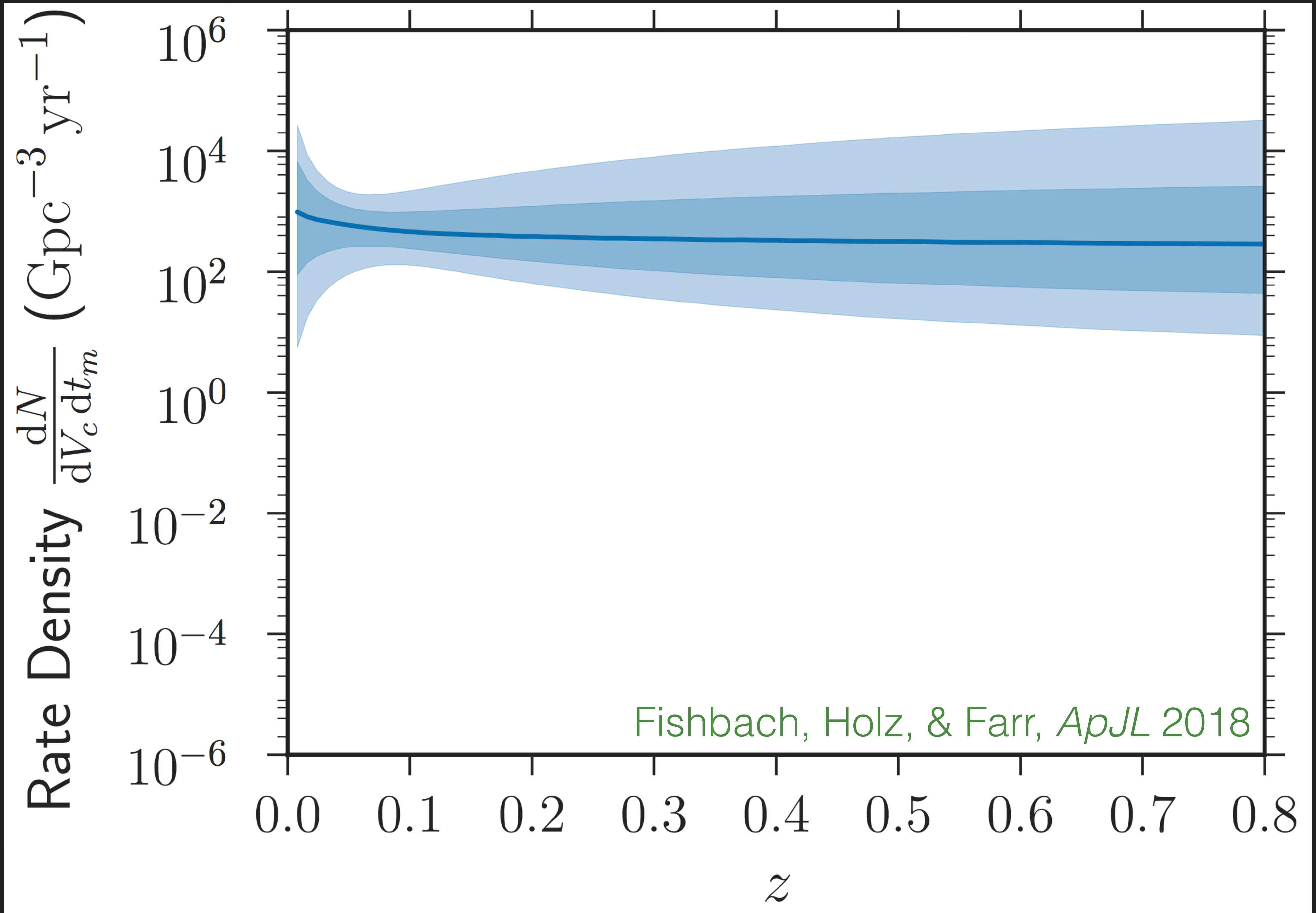


Fishbach & Holz, *ApJL* 2017

- Are the LIGO/Virgo events consistent with being from BHs spinning at *a*~0.7? Probably not.

Papers and discussion by Emanuele Berti

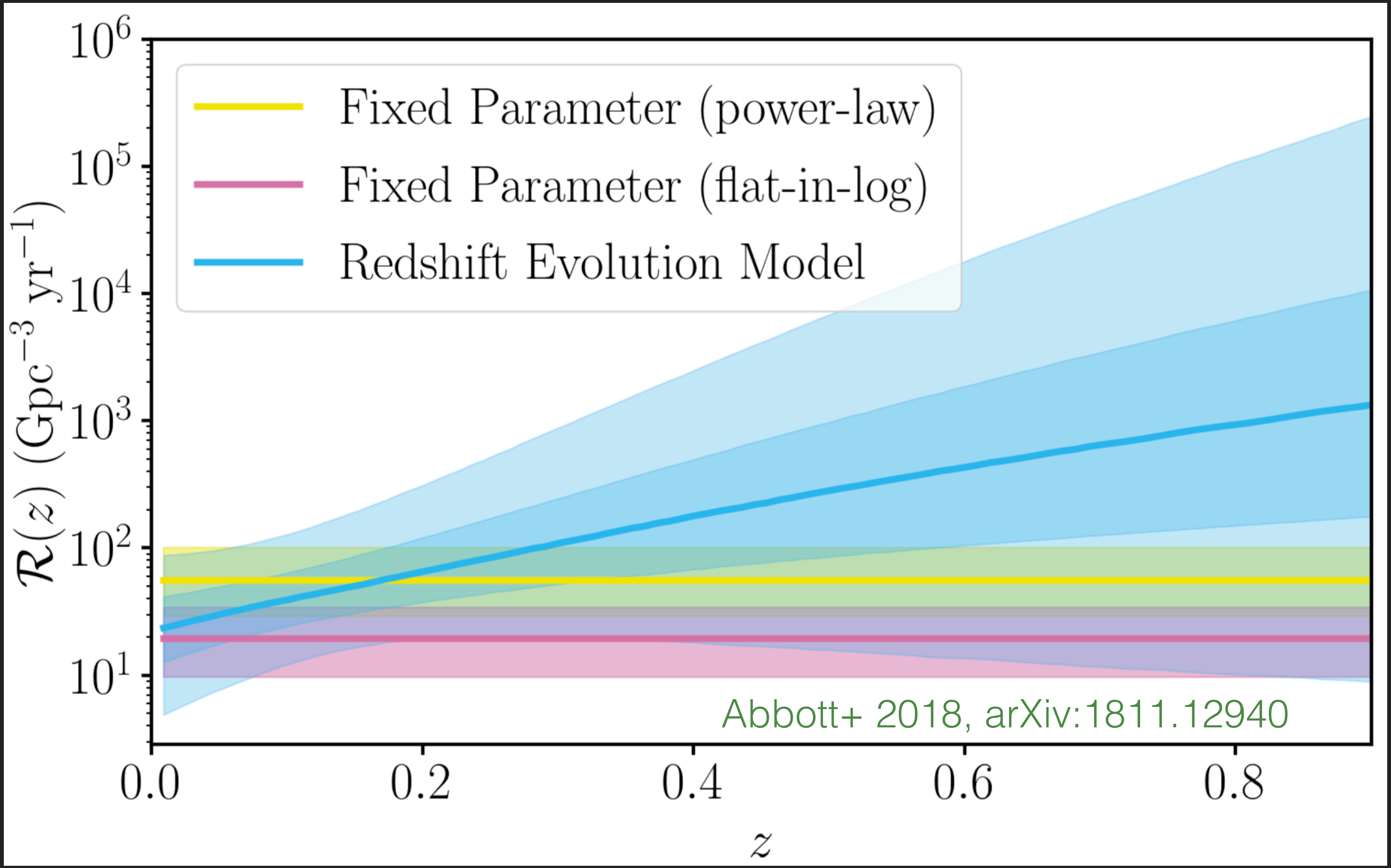
Does the rate of mergers evolve over time?



Fishbach, Holz, & Farr, *ApJL* 2018

- No evidence for evolution (yet)
- Powerful probe of how compact objects are made

Does the rate of mergers evolve over time?

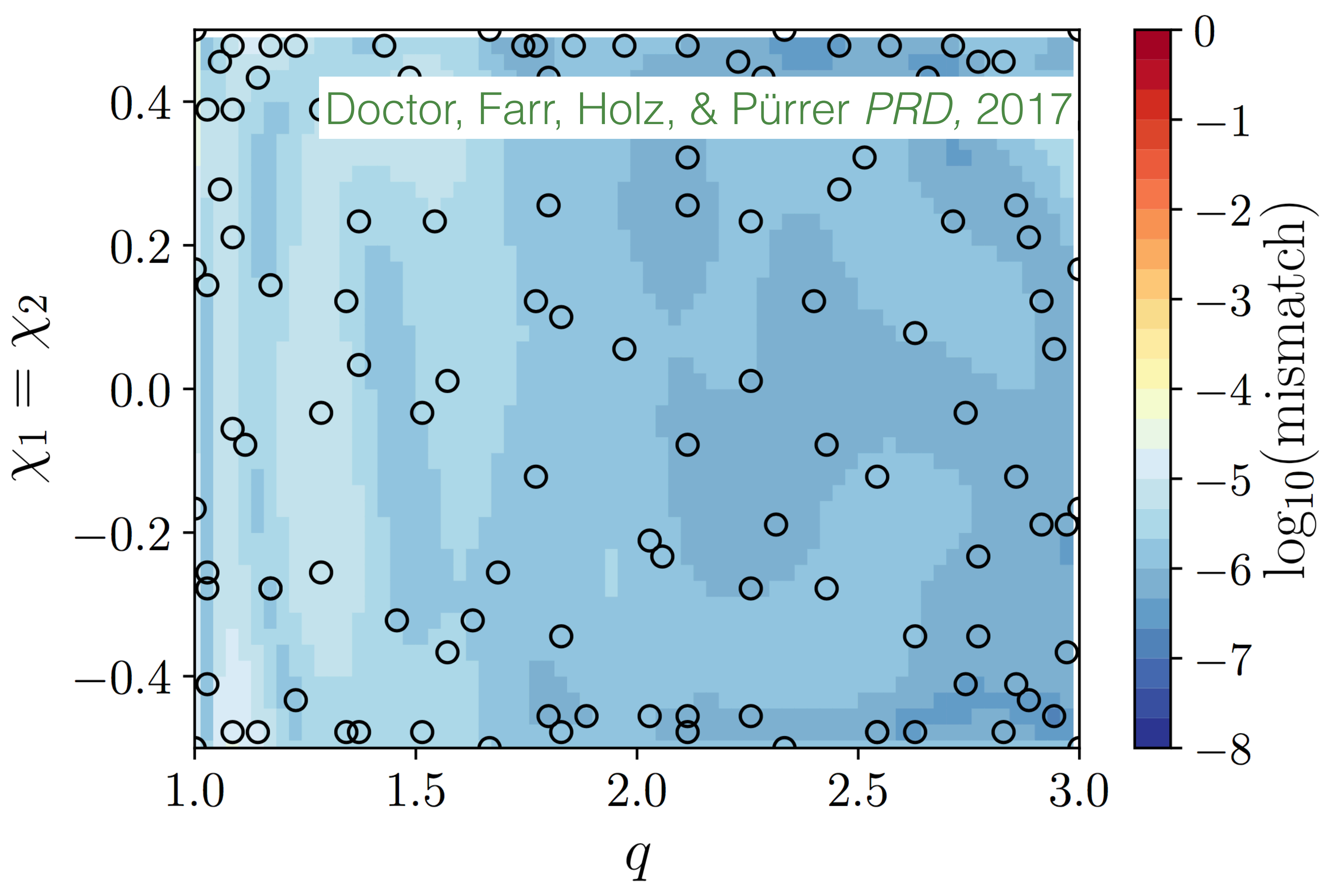


Abbott+ 2018, arXiv:1811.12940

- Preliminary evidence for evolution!!

Building better waveforms through machine learning

- We use machine learning to build a better waveform approximate
- Fast and accurate, and also comes with error bars
- 2d: mass ratio, *q*, and equal-and-aligned spins, χ
- Extension to higher dimensions in progress



- Because of error bars, can guide future placement of numerical relativity simulations
- Ongoing work with Zoheyr Doctor, Ben Farr, Reed Essick, and Phil Landry. Applications to EOS, KN lightcurves, etc.

Do gravitons and photons see the same Universe?

- It is popular to 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
    - Because the standard siren measurement works, we already know that photons and gravitons see a similar universe. We can quantify this

Do gravitons and photons see the same Universe?

Pardo, Fishbach, Holz, & Spergel, *JCAP* 2018

- In GR, we have:

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

- In modified gravity theories, flux conservation gives

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

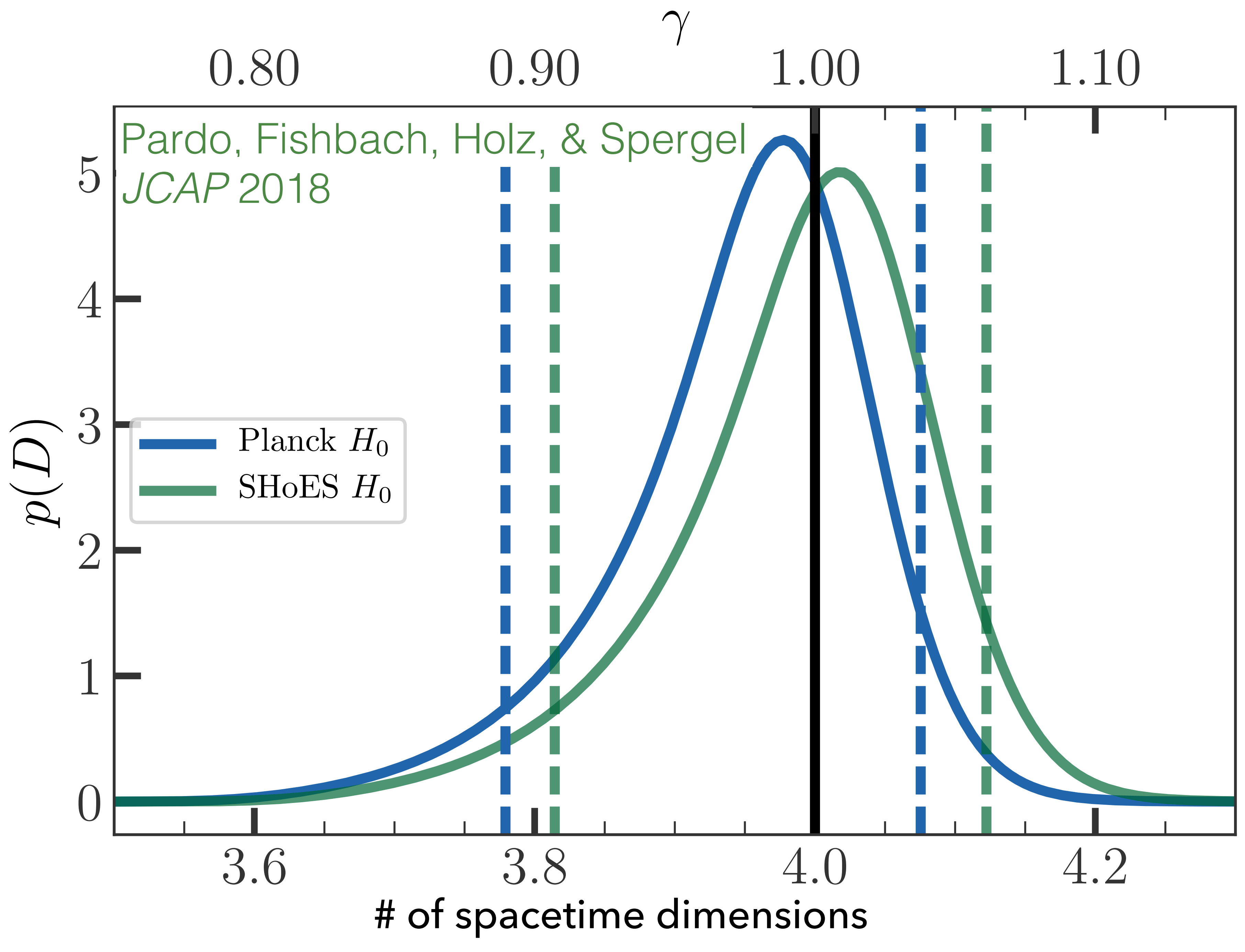
with

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

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

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

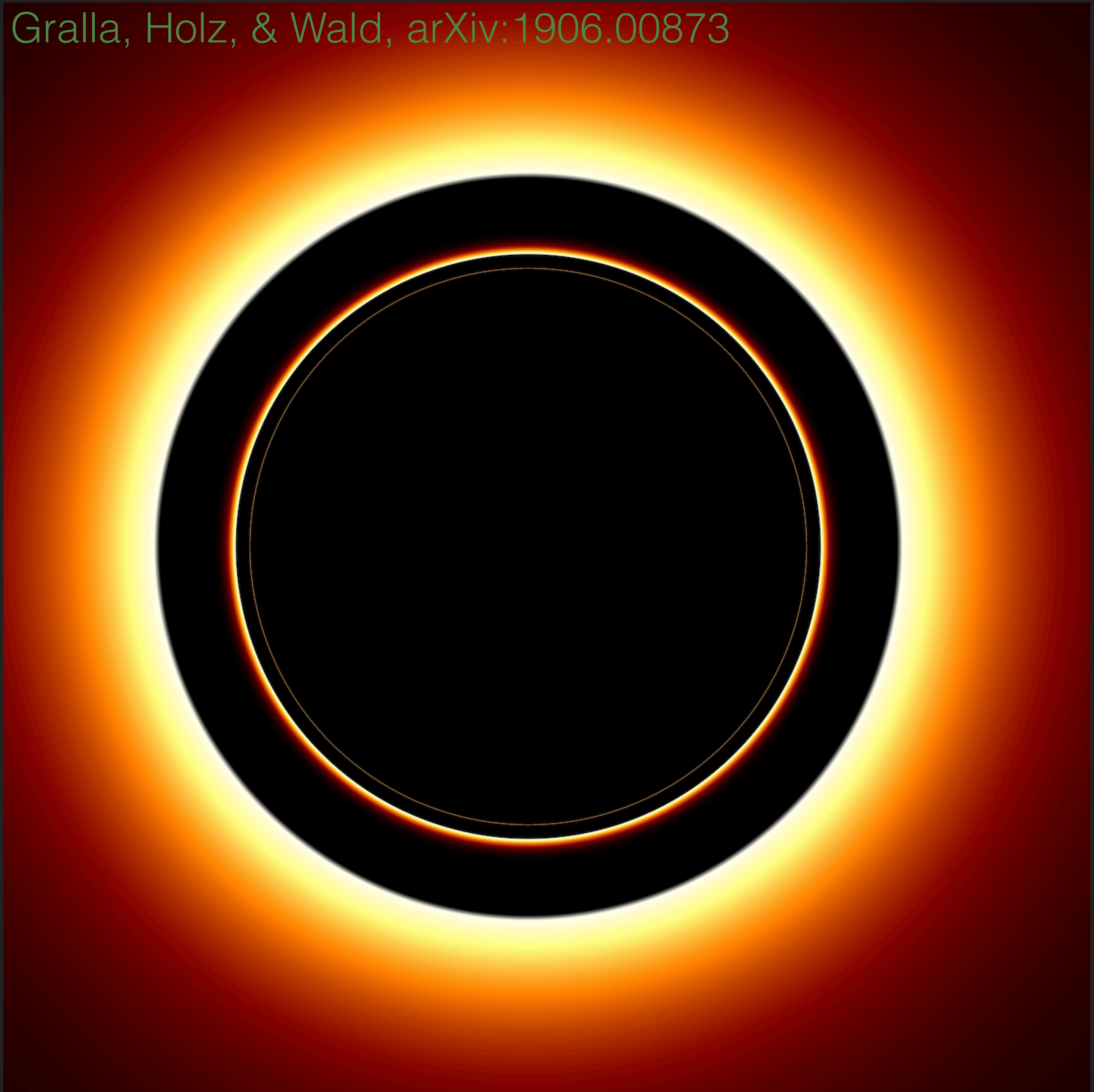
How many spacetime dimensions?



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

Black hole shadows and photon rings

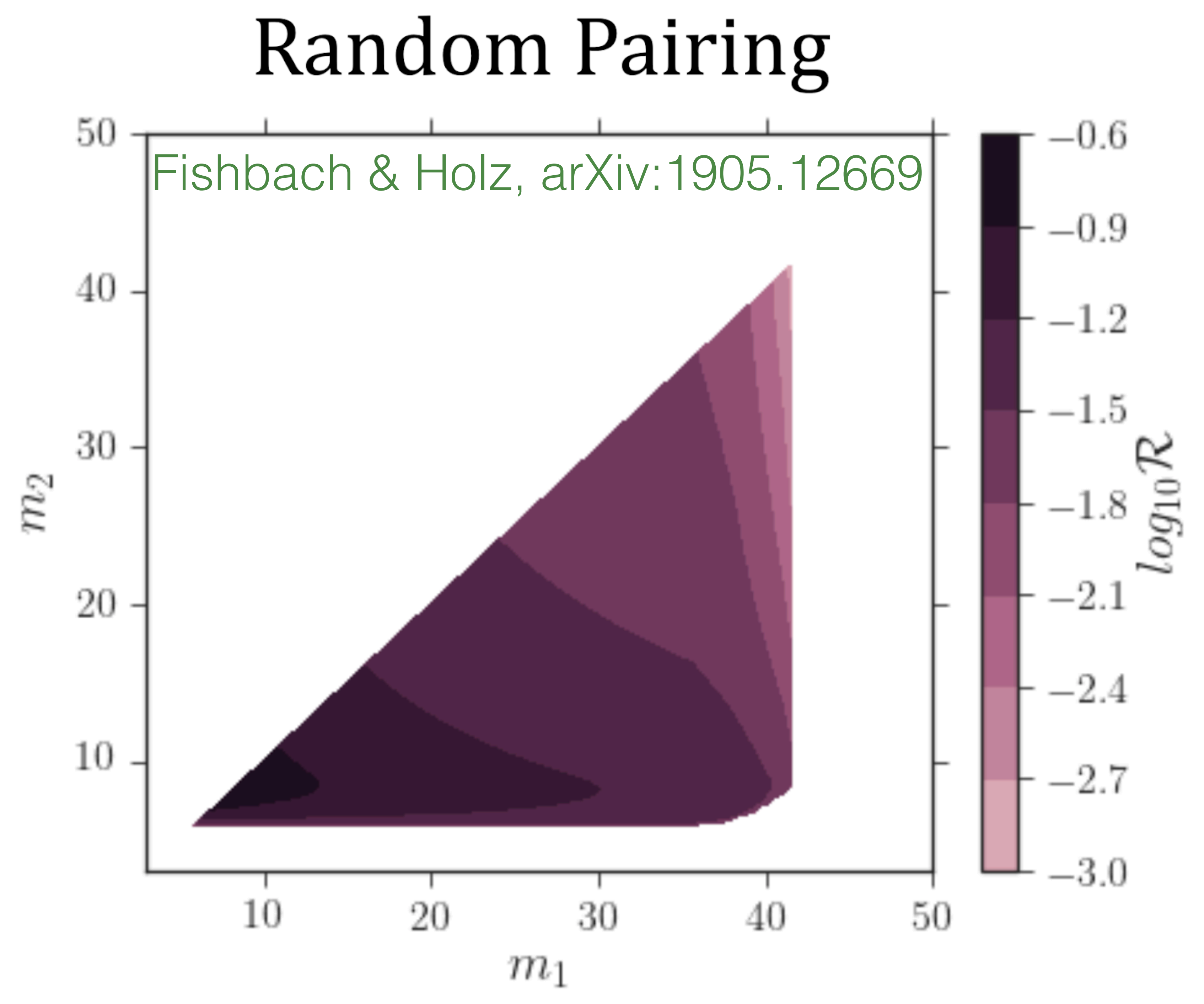
- EHT has produced an amazing image
- They are not seeing the shadow of a black hole, nor are they seeing photon rings (photons circling around the BH many times)
- They are seeing interesting properties of the accretion disk around the ISCO



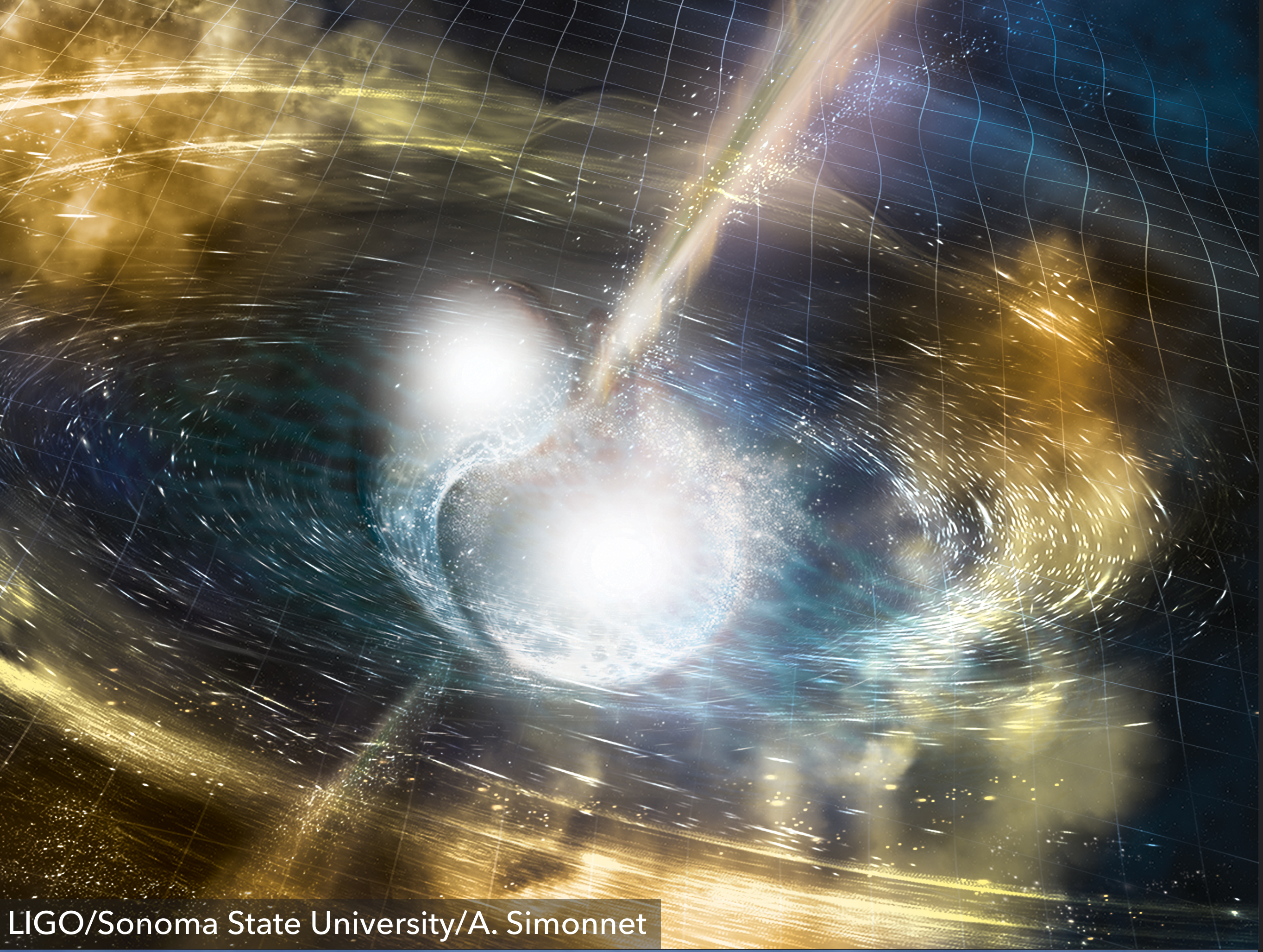
Gralla, Holz, & Wald, arXiv:1906.00873

Picky Partners

- Universe does not assemble black holes randomly
- We show that it is ~7 times more likely that the component BHs in a given binary are always equal than that they are randomly paired
- Properties of the black hole pairings provide insight into formation channels



Papers and discussion by Emanuele Berti



LIGO/Sonoma State University/A. Simonnet

LIGO

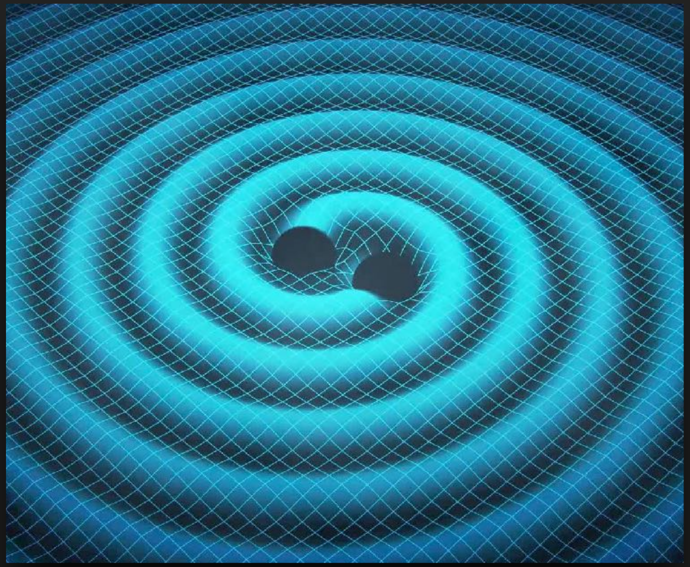
Cosmology with standard sirens and the Hubble constant tension: an outlook

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, and provides a direct absolute measurement of luminosity distance (Schutz ’86)
- Calibration is provided by General Relativity
- Need independent measurement of redshift to do cosmology*

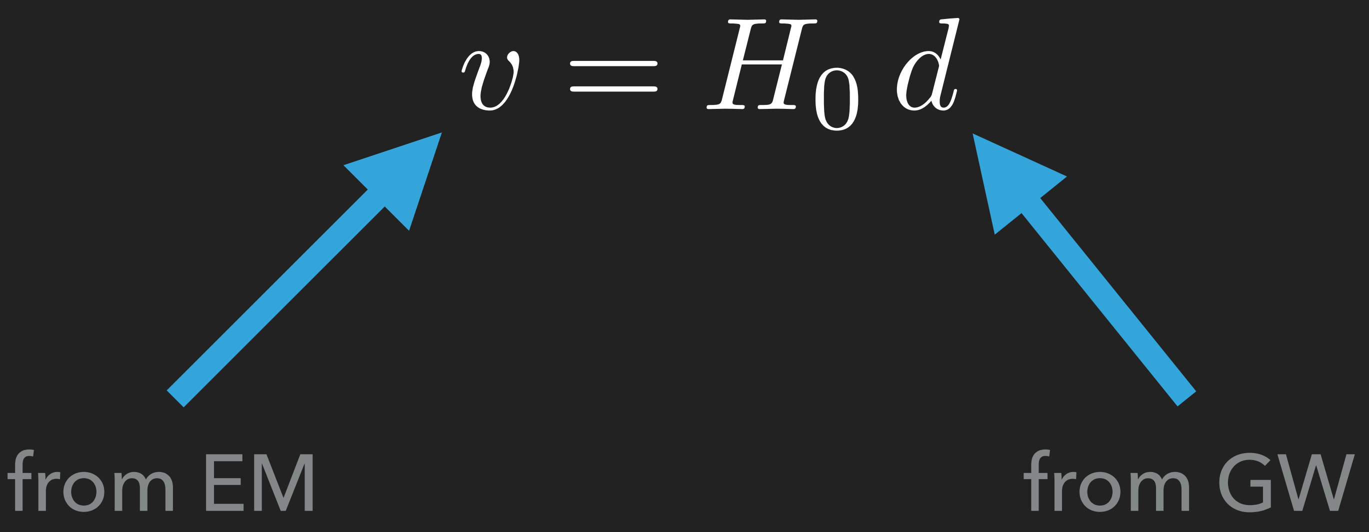


* Proposals to use mass distribution, EOS, etc.

Paper by Jocelyn Read

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)

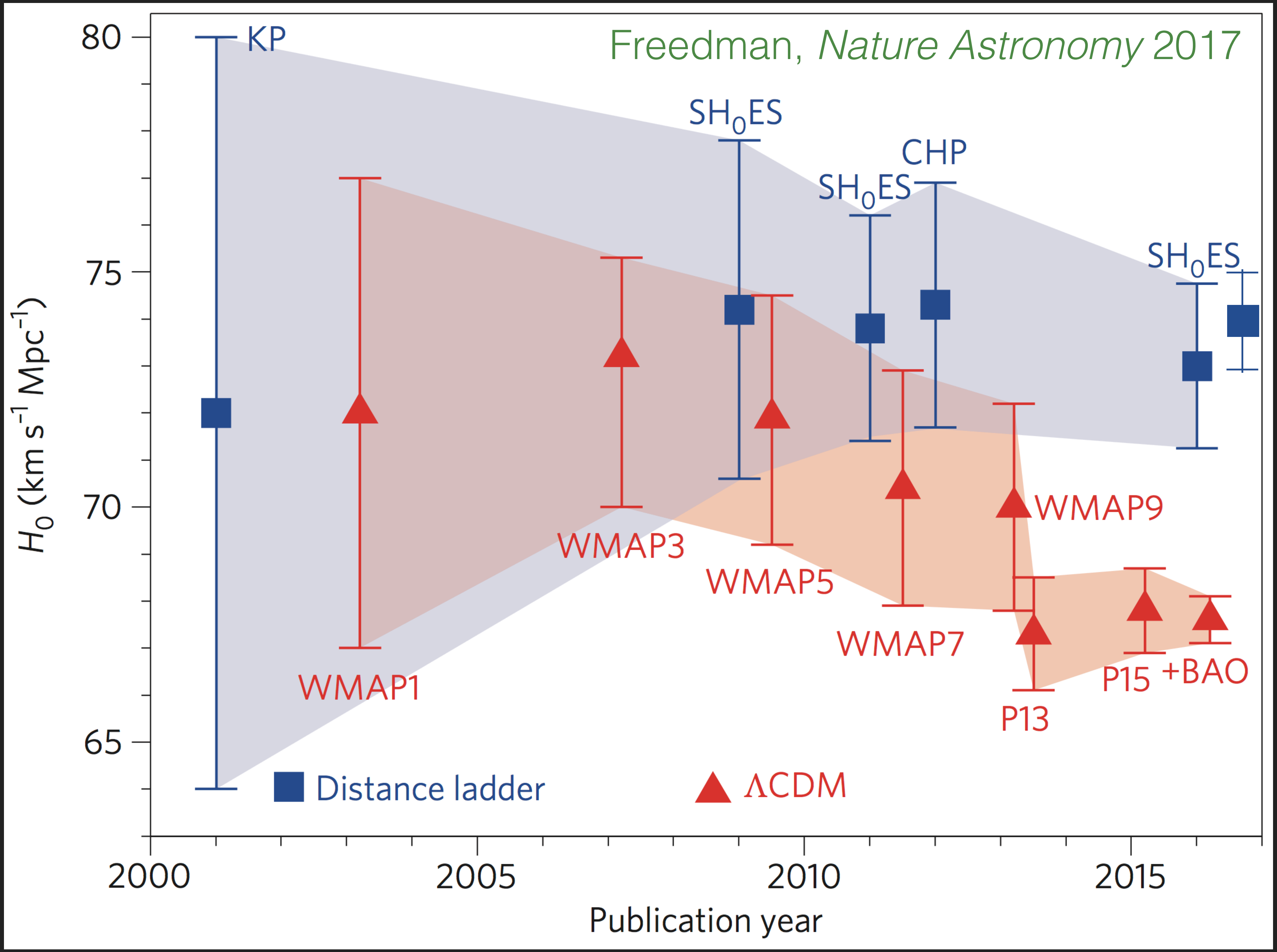


$$v = H_0 \, d$$

from EM

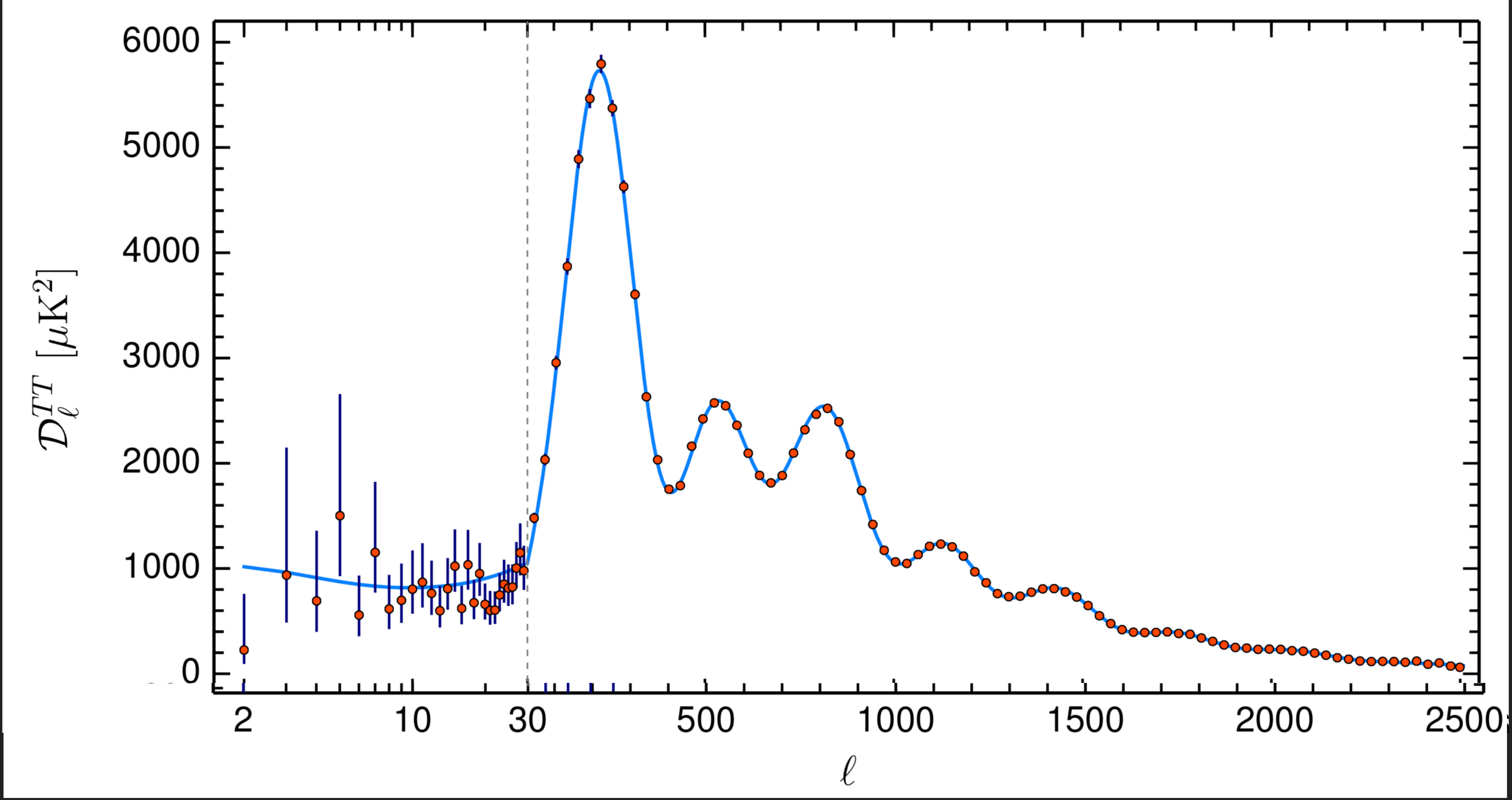
from GW

Who cares about the Hubble constant?



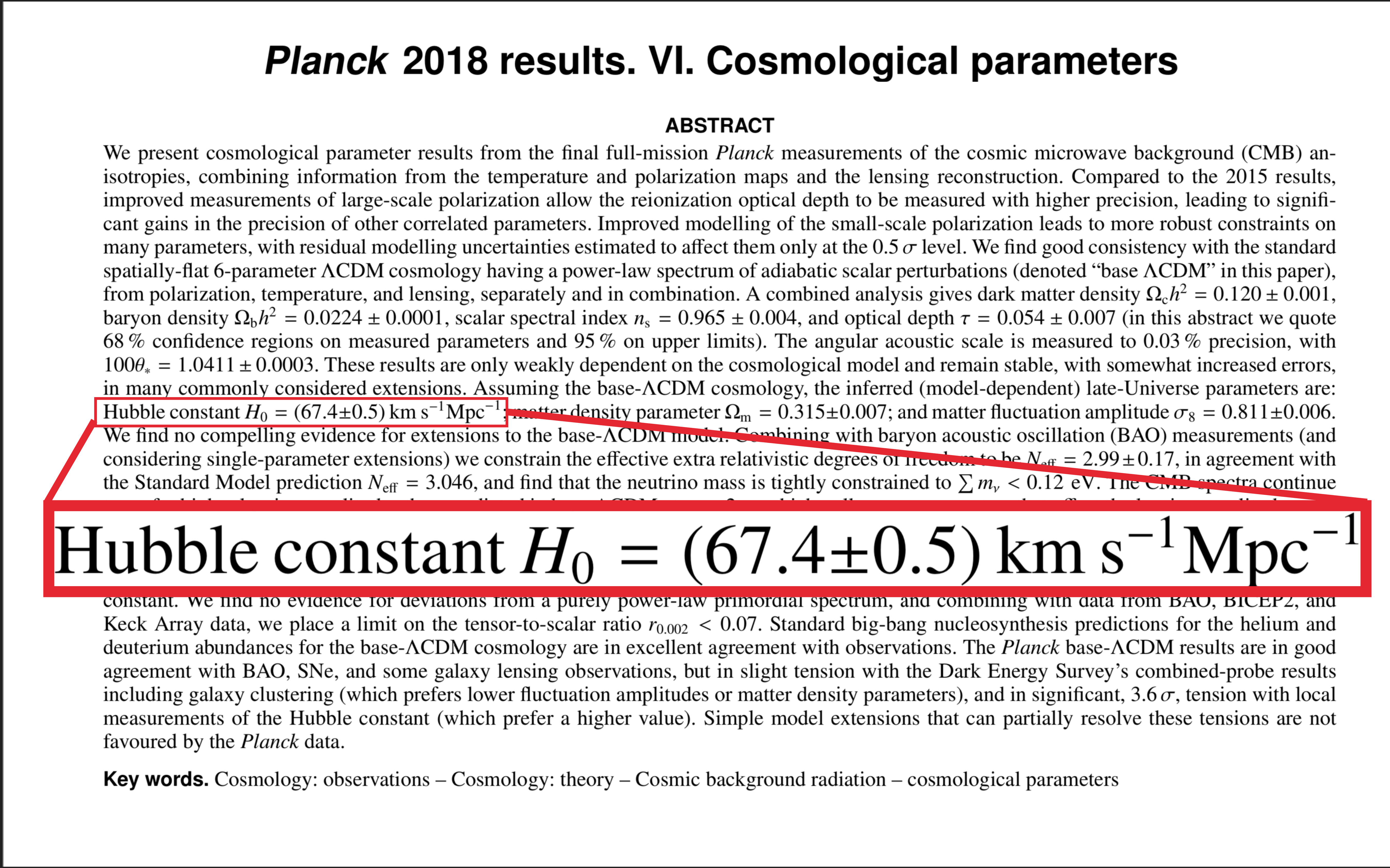
- >4σ discrepancy between early Universe (CMB) and late Universe (Type Ia supernova) measurements of the Hubble constant
- Systematics? New physics?!

CMB/Early universe measurements of H_0



- Planck precision cosmology

CMB measurements of H_0



Planck 2018 results. VI. Cosmological parameters

ABSTRACT

We present cosmological parameter results from the final full-mission *Planck* measurements of the cosmic microwave background (CMB) anisotropies, combining information from the temperature and polarization maps and the lensing reconstruction. Compared to the 2015 results, improved measurements of large-scale polarization allow the reionization optical depth to be measured with higher precision, leading to significant gains in the precision of other correlated parameters. Improved modelling of the small-scale polarization leads to more robust constraints on many parameters, with residual modelling uncertainties estimated to affect them only at the $0.5\,\sigma$ level. We find good consistency with the standard spatially-flat 6-parameter ΛCDM cosmology having a power-law spectrum of adiabatic scalar perturbations (denoted "base ΛCDM" in this paper), from polarization, temperature, and lensing, separately and in combination. A combined analysis gives dark matter density $\Omega_c h^2 = 0.120 \pm 0.001$, baryon density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral index $n_s = 0.965 \pm 0.004$, and optical depth $\tau = 0.054 \pm 0.007$ (in this abstract we quote 68 % confidence regions on measured parameters and 95 % on upper limits). The angular acoustic scale is measured to 0.03 % precision, with $100\theta_* = 1.0411 \pm 0.0003$. These results are only weakly dependent on the cosmological model and remain stable, with somewhat increased errors, in many commonly considered extensions. Assuming the base-ΛCDM cosmology, the inferred (model-dependent) late-Universe parameters are: Hubble constant $H_0 = (67.4 \pm 0.5)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$; matter density parameter $\Omega_m = 0.315 \pm 0.007$; and matter fluctuation amplitude $\sigma_8 = 0.811 \pm 0.006$. We find no compelling evidence for extensions to the base-ΛCDM model. Combining with baryon acoustic oscillation (BAO) measurements (and considering single-parameter extensions) we constrain the effective extra relativistic degrees of freedom to be $N_{\mathrm{eff}} = 2.99 \pm 0.17$, in agreement with the Standard Model prediction $N_{\mathrm{eff}} = 3.046$, and find that the neutrino mass is tightly constrained to $\sum m_\nu < 0.12$ eV. The CMB spectra continue

Hubble constant $H_0 = (67.4 \pm 0.5)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

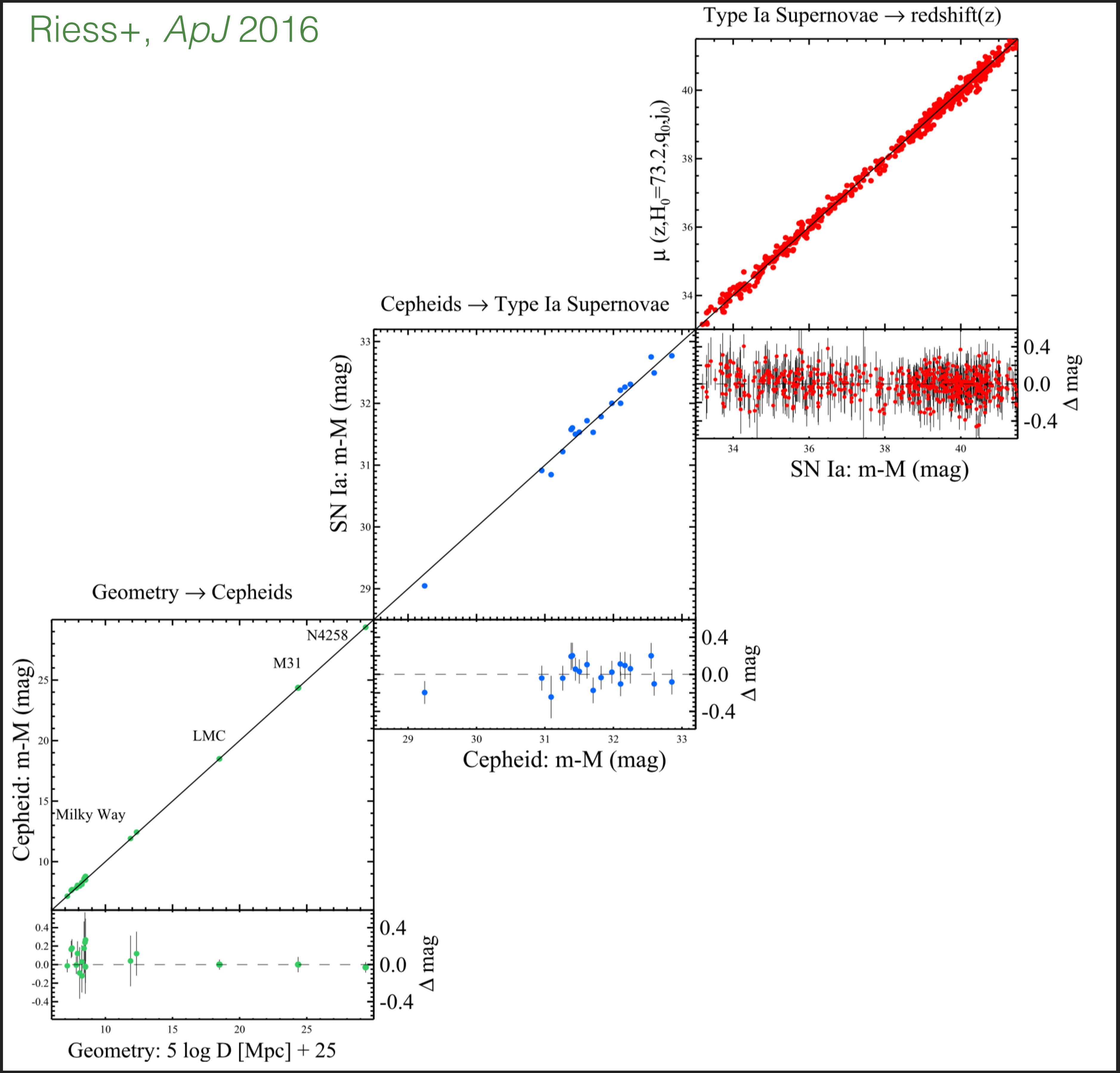
constant. We find no evidence for deviations from a purely power-law primordial spectrum, and combining with data from BAO, BICEP2, and Keck Array data, we place a limit on the tensor-to-scalar ratio $r_{0.002} < 0.07$. Standard big-bang nucleosynthesis predictions for the helium and deuterium abundances for the base-ΛCDM cosmology are in excellent agreement with observations. The *Planck* base-ΛCDM results are in good agreement with BAO, SNe, and some galaxy lensing observations, but in slight tension with the Dark Energy Survey's combined-probe results including galaxy clustering (which prefers lower fluctuation amplitudes or matter density parameters), and in significant, $3.6\,\sigma$, tension with local measurements of the Hubble constant (which prefer a higher value). Simple model extensions that can partially resolve these tensions are not favoured by the *Planck* data.

Key words. Cosmology: observations – Cosmology: theory – Cosmic background radiation – cosmological parameters

- Hubble constant to <1%!

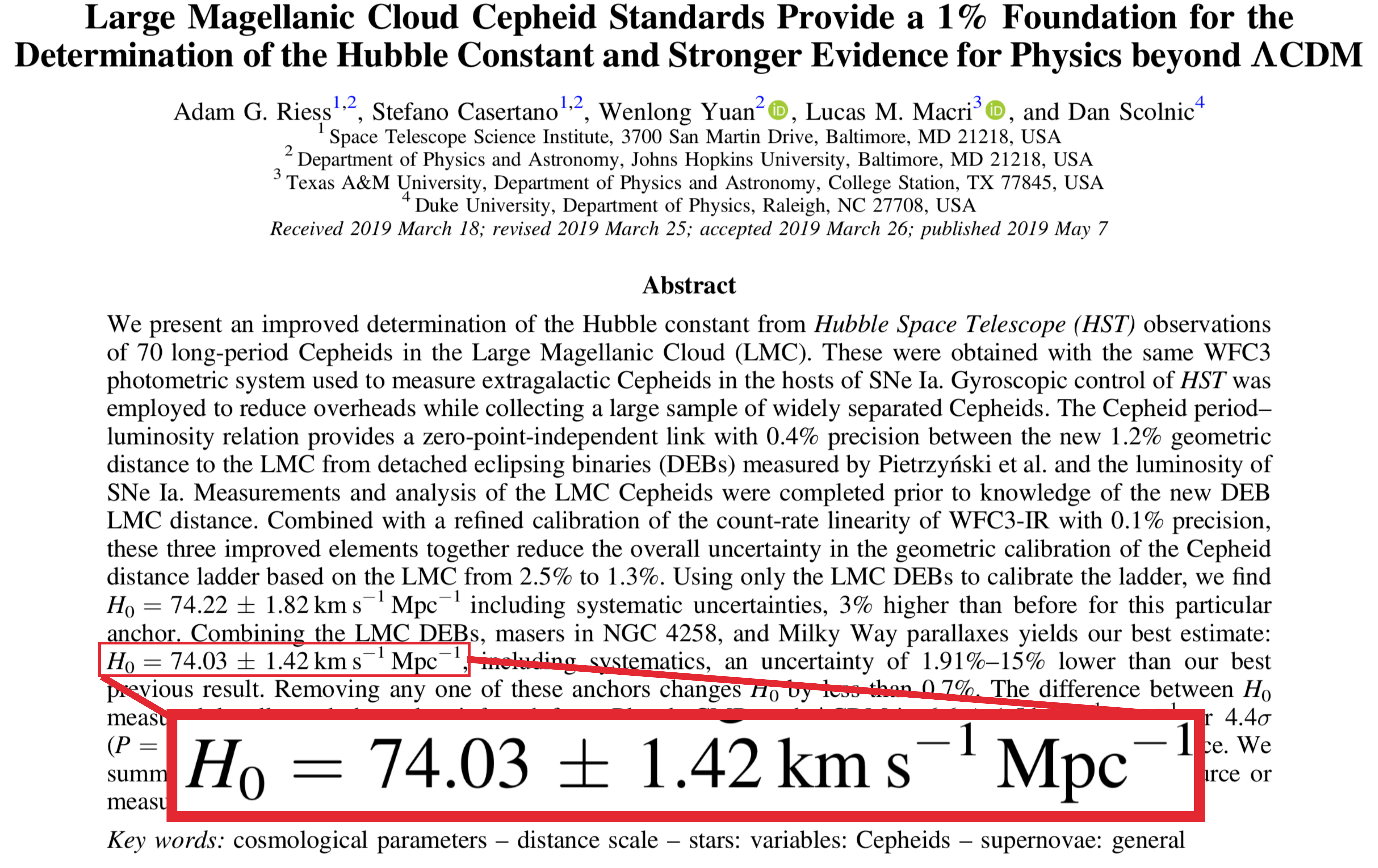
Supernova measurements of H_0

- Type Ia standard candles
- Distance ladder
- Extensive data
- Multiple independent consistency checks



Riess+, *ApJ* 2016

Supernova measurements of H_0



Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM

Adam G. Riess[1,2], Stefano Casertano[1,2], Wenlong Yuan[2], Lucas M. Macri[3], and Dan Scolnic[4]
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[2] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
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Received 2019 March 18; revised 2019 March 25; accepted 2019 March 26; published 2019 May 7

Abstract

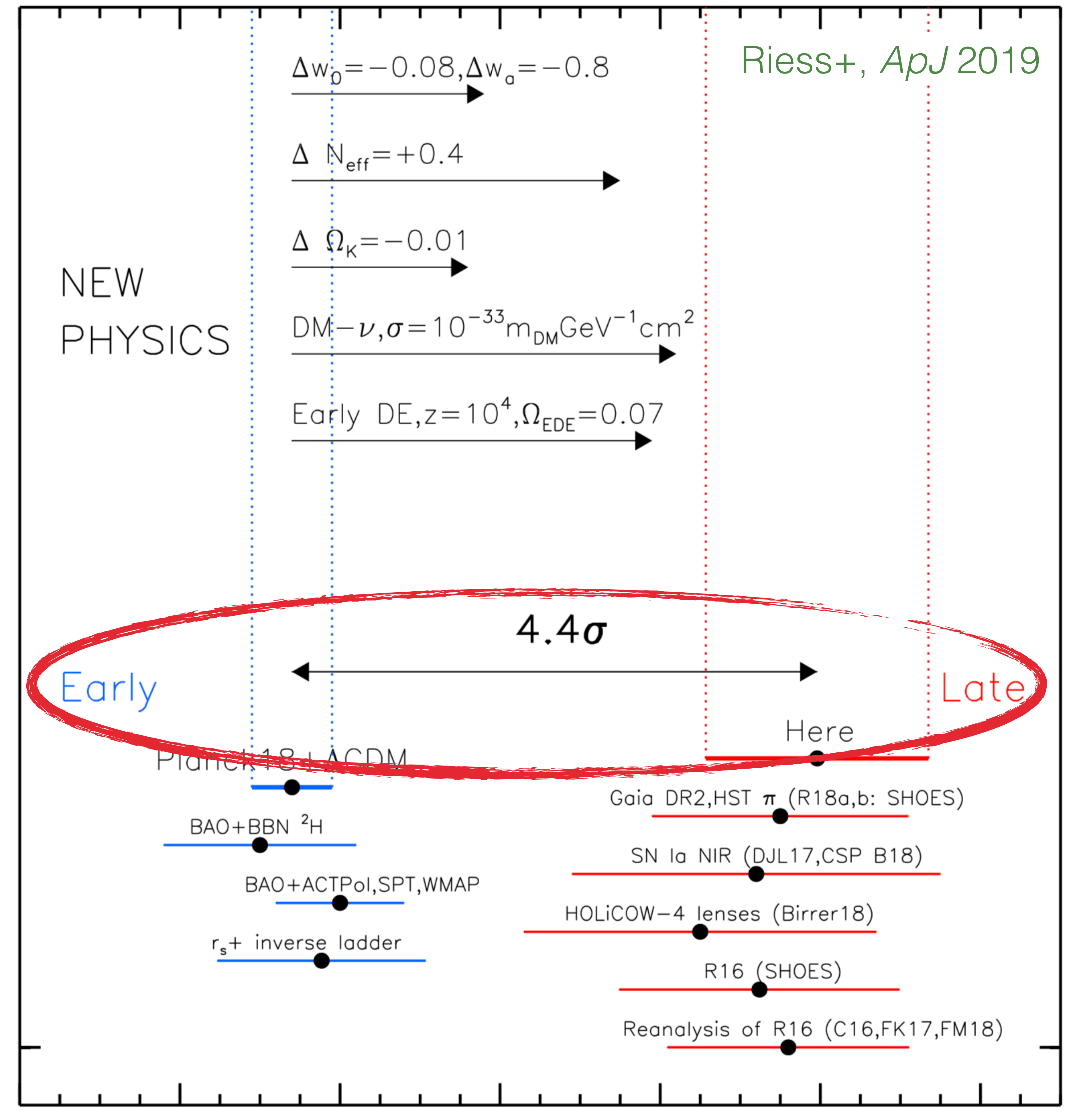
We present an improved determination of the Hubble constant from *Hubble Space Telescope (HST)* observations of 70 long-period Cepheids in the Large Magellanic Cloud (LMC). These were obtained with the same WFC3 photometric system used to measure extragalactic Cepheids in the hosts of SNe Ia. Gyroscopic control of *HST* was employed to reduce overheads while collecting a large sample of widely separated Cepheids. The Cepheid period–luminosity relation provides a zero-point-independent link with 0.4% precision between the new 1.2% geometric distance to the LMC from detached eclipsing binaries (DEBs) measured by Pietrzyński et al. and the luminosity of SNe Ia. Measurements and analysis of the LMC Cepheids were completed prior to knowledge of the new DEB LMC distance. Combined with a refined calibration of the count-rate linearity of WFC3-IR with 0.1% precision, these three improved elements together reduce the overall uncertainty in the geometric calibration of the Cepheid distance ladder based on the LMC from 2.5% to 1.3%. Using only the LMC DEBs to calibrate the ladder, we find $H_0 = 74.22 \pm 1.82\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ including systematic uncertainties, 3% higher than before for this particular anchor. Combining the LMC DEBs, masers in NGC 4258, and Milky Way parallaxes yields our best estimate: $H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, including systematics, an uncertainty of 1.91%–15% lower than our best previous result. Removing any one of these anchors changes H_0 by less than 0.7%. The difference between H_0
meas … r 4.4σ
(P = … ce. We
summ … rce or
measu

$$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

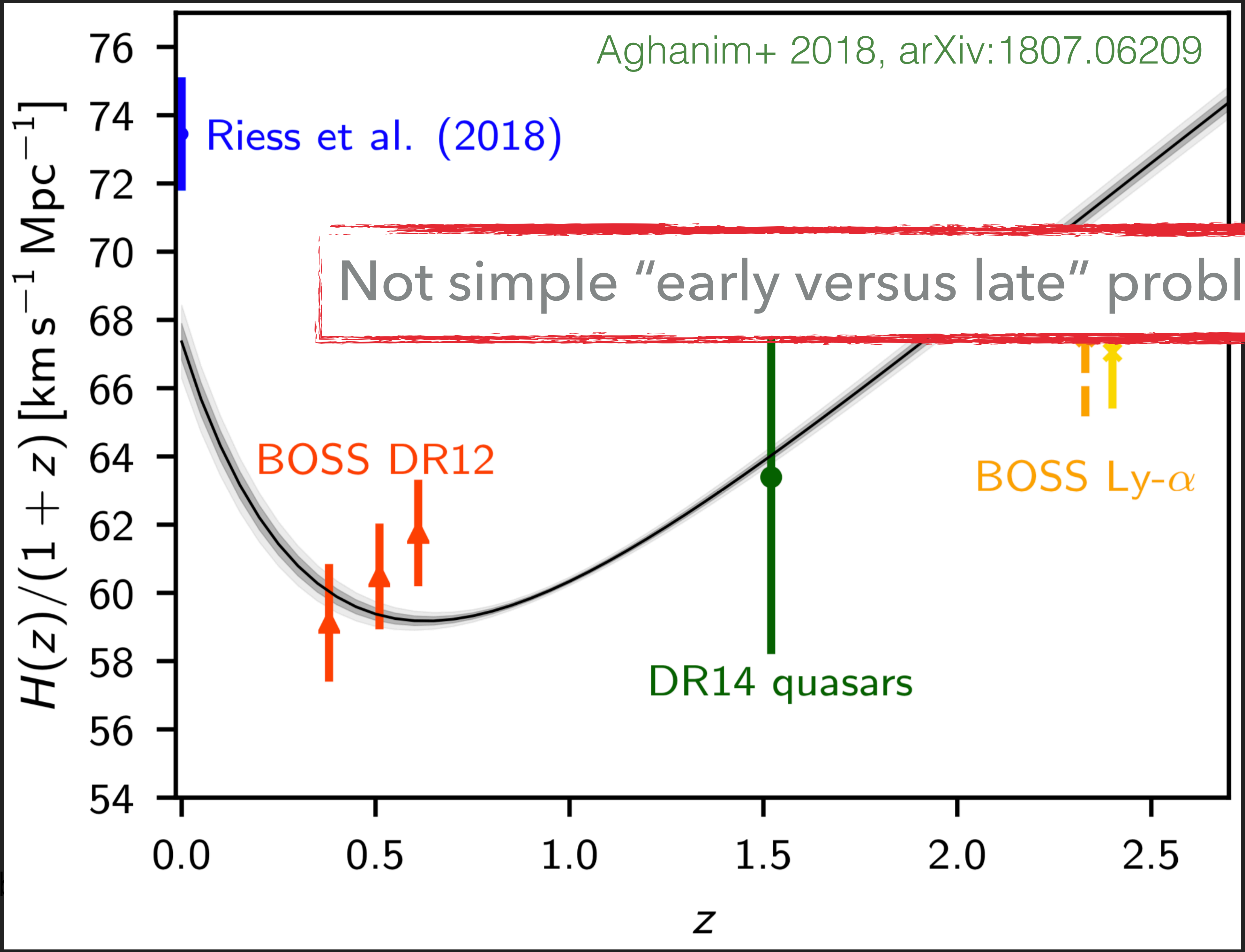
Key words: cosmological parameters – distance scale – stars: variables: Cepheids – supernovae: general

Early vs. late universe tension

- 4.4 σ discrepancy!



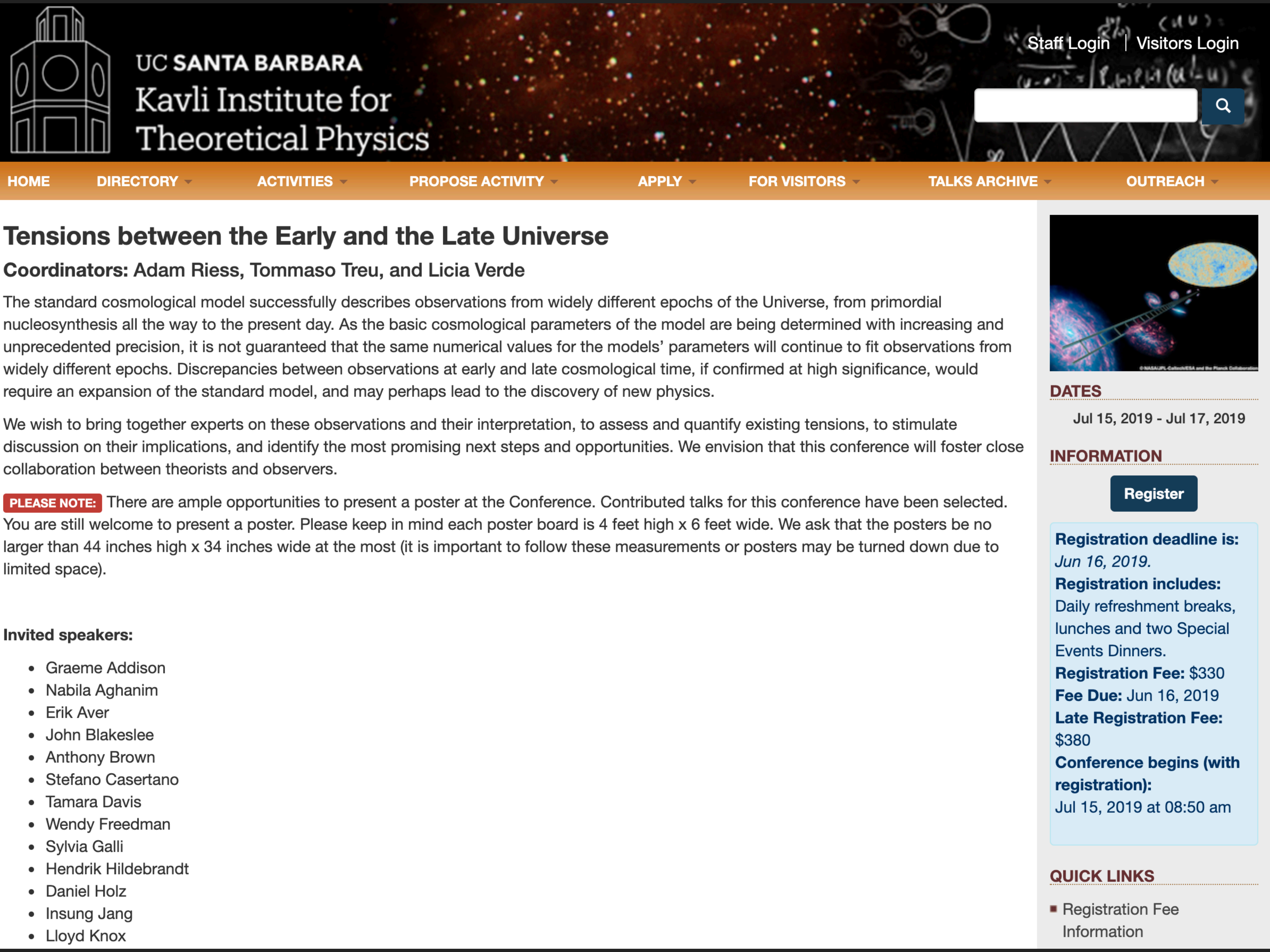
Early vs. late universe tension



Not simple “early versus late” problem!

Abl

- Inverse distance ladder to infer H0
- Grey band is Planck, superposed points are BAO



Tensions between the Early and the Late Universe

Coordinators: Adam Riess, Tommaso Treu, and Licia Verde

The standard cosmological model successfully describes observations from widely different epochs of the Universe, from primordial nucleosynthesis all the way to the present day. As the basic cosmological parameters of the model are being determined with increasing and unprecedented precision, it is not guaranteed that the same numerical values for the models' parameters will continue to fit observations from widely different epochs. Discrepancies between observations at early and late cosmological time, if confirmed at high significance, would require an expansion of the standard model, and may perhaps lead to the discovery of new physics.

We wish to bring together experts on these observations and their interpretation, to assess and quantify existing tensions, to stimulate discussion on their implications, and identify the most promising next steps and opportunities. We envision that this conference will foster close collaboration between theorists and observers.

PLEASE NOTE: There are ample opportunities to present a poster at the Conference. Contributed talks for this conference have been selected. You are still welcome to present a poster. Please keep in mind each poster board is 4 feet high x 6 feet wide. We ask that the posters be no larger than 44 inches high x 34 inches wide at the most (it is important to follow these measurements or posters may be turned down due to limited space).

Invited speakers:

- Graeme Addison
- Nabila Aghanim
- Erik Aver
- John Blakeslee
- Anthony Brown
- Stefano Casertano
- Tamara Davis
- Wendy Freedman
- Sylvia Galli
- Hendrik Hildebrandt
- Daniel Holz
- Insung Jang
- Lloyd Knox

DATES

Jul 15, 2019 - Jul 17, 2019

INFORMATION

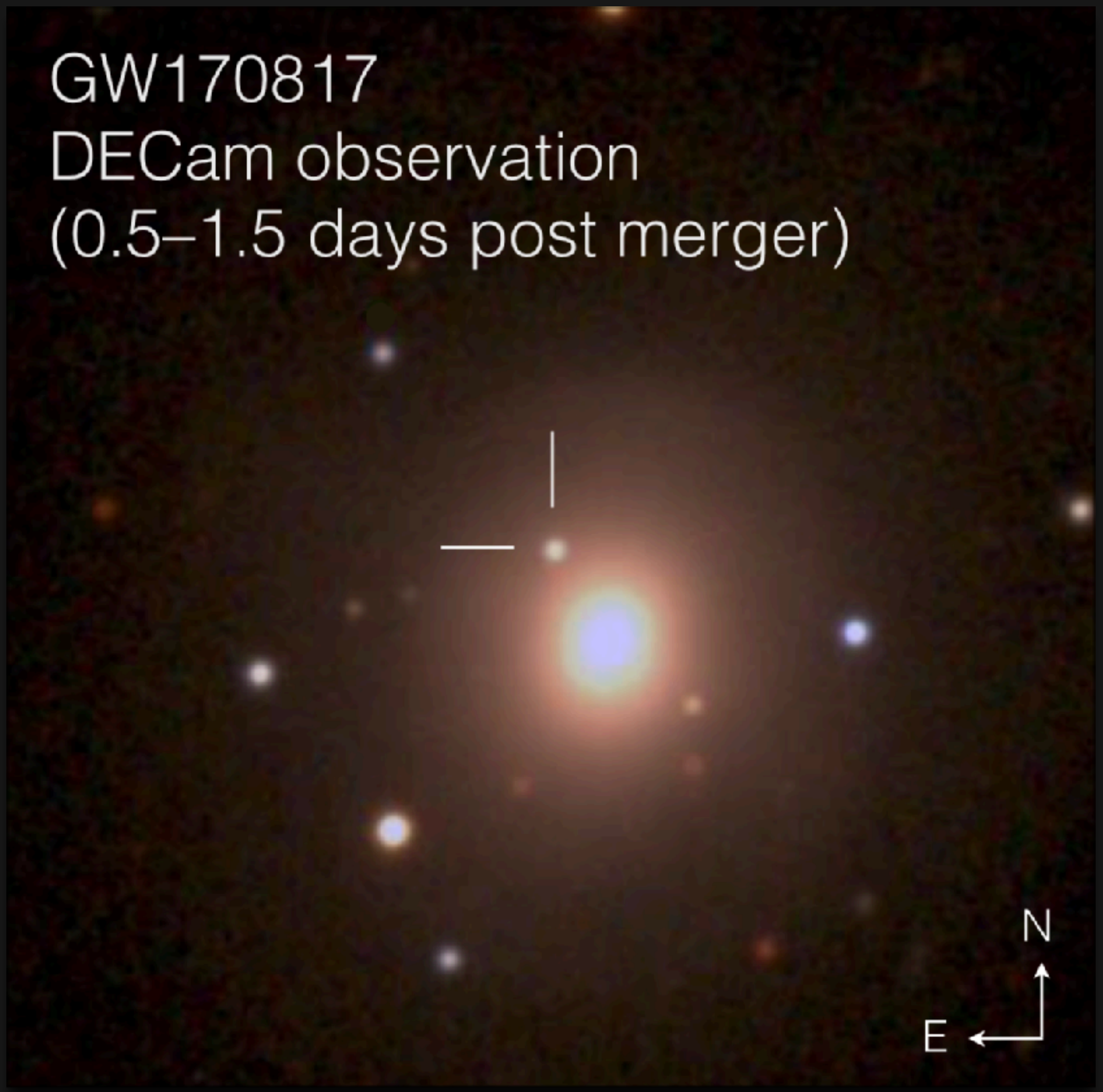
Registration deadline is: *Jun 16, 2019.*
Registration includes: Daily refreshment breaks, lunches and two Special Events Dinners.
Registration Fee: $330
Fee Due: Jun 16, 2019
Late Registration Fee: $380
Conference begins (with registration): Jul 15, 2019 at 08:50 am

QUICK LINKS

- Registration Fee Information

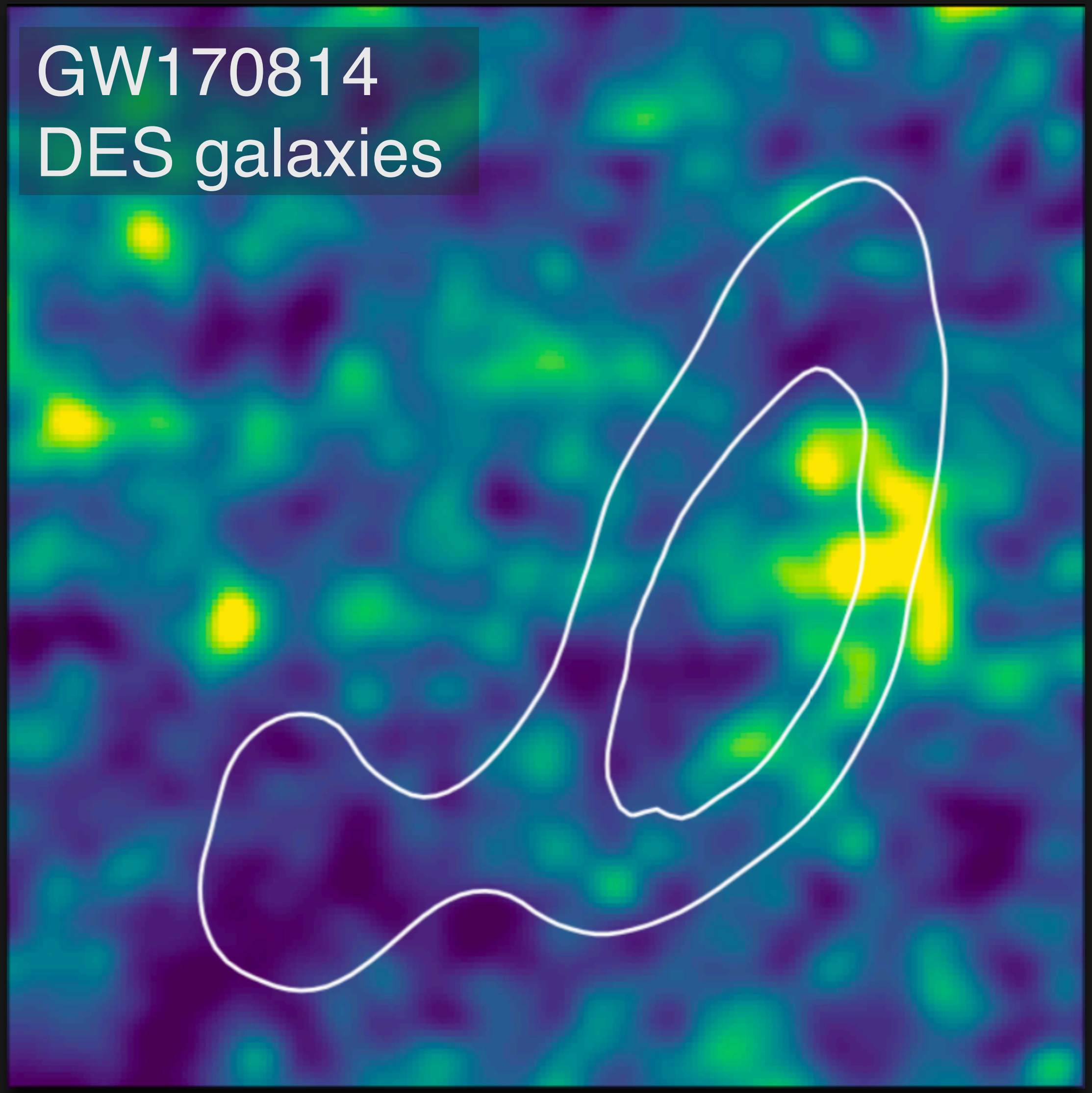
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

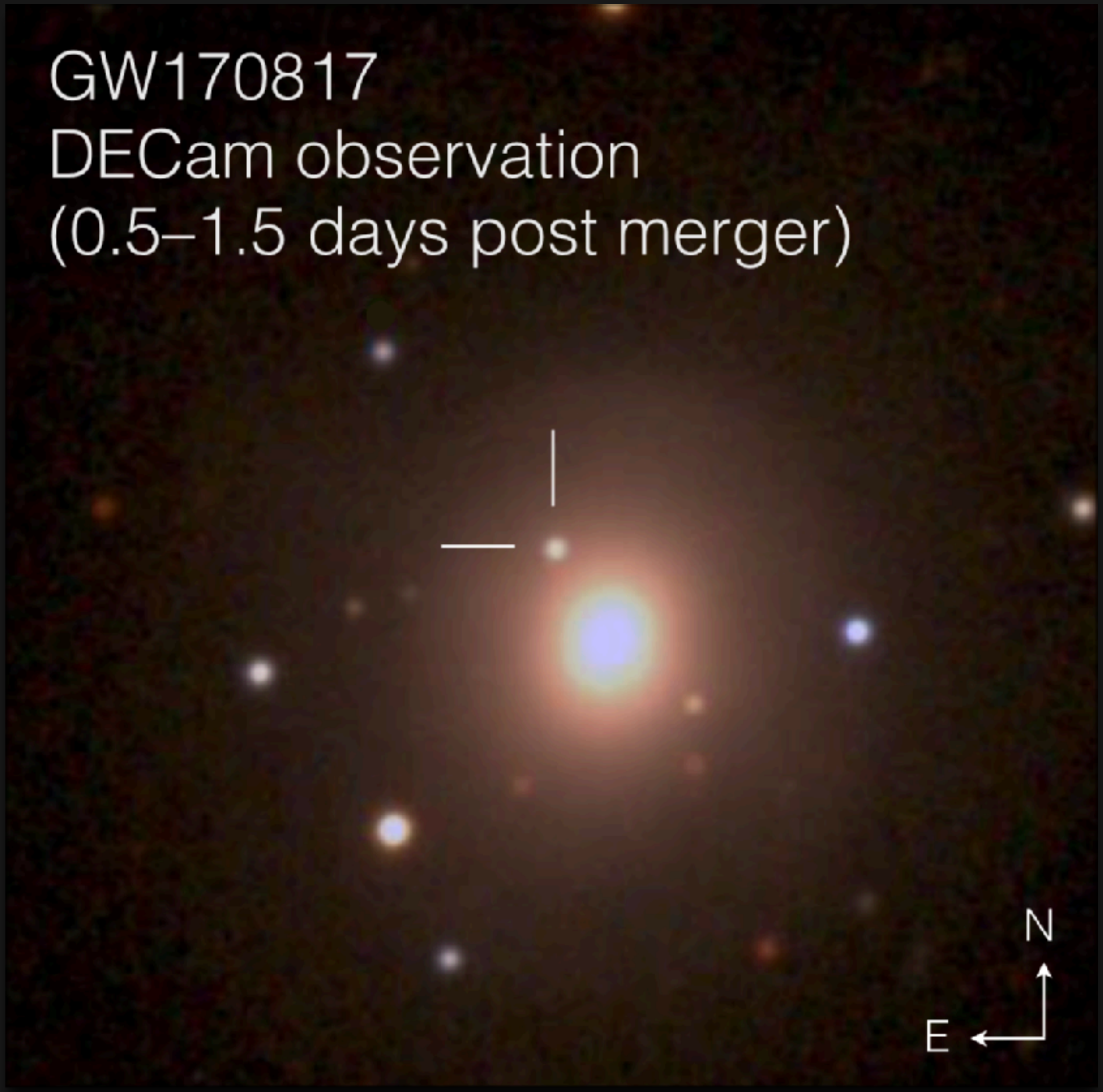
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

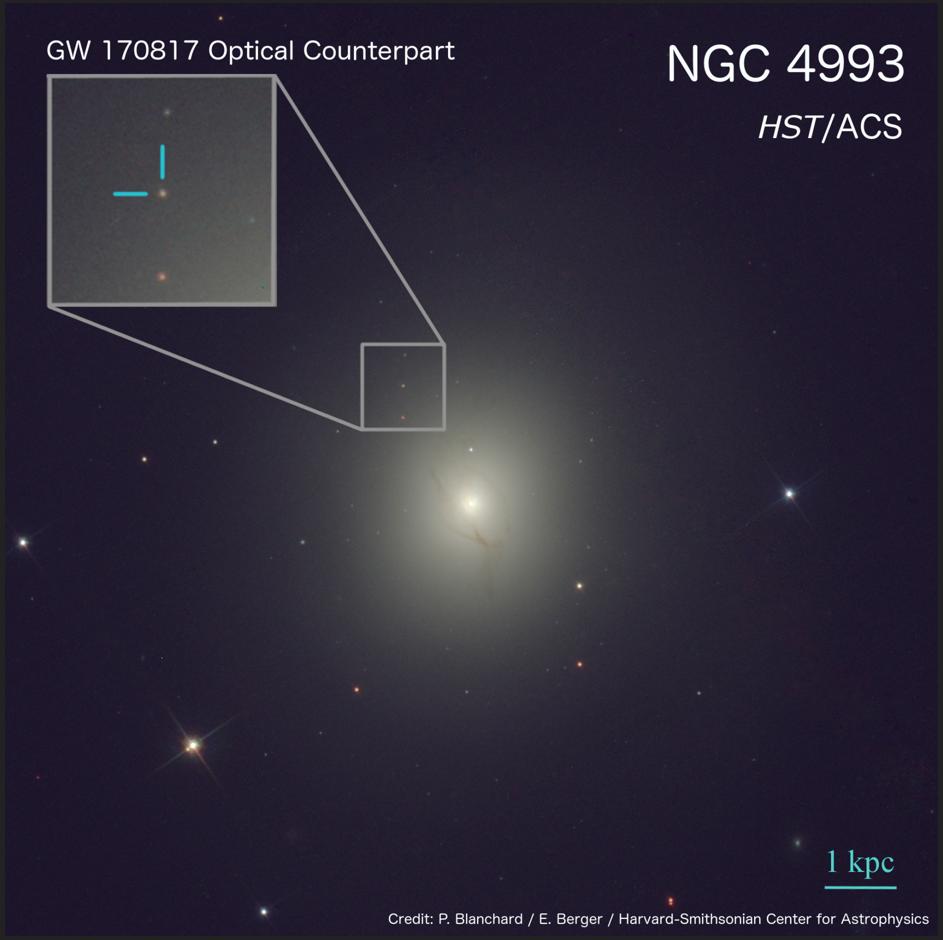
Counterpart/Bright



Unique host galaxy

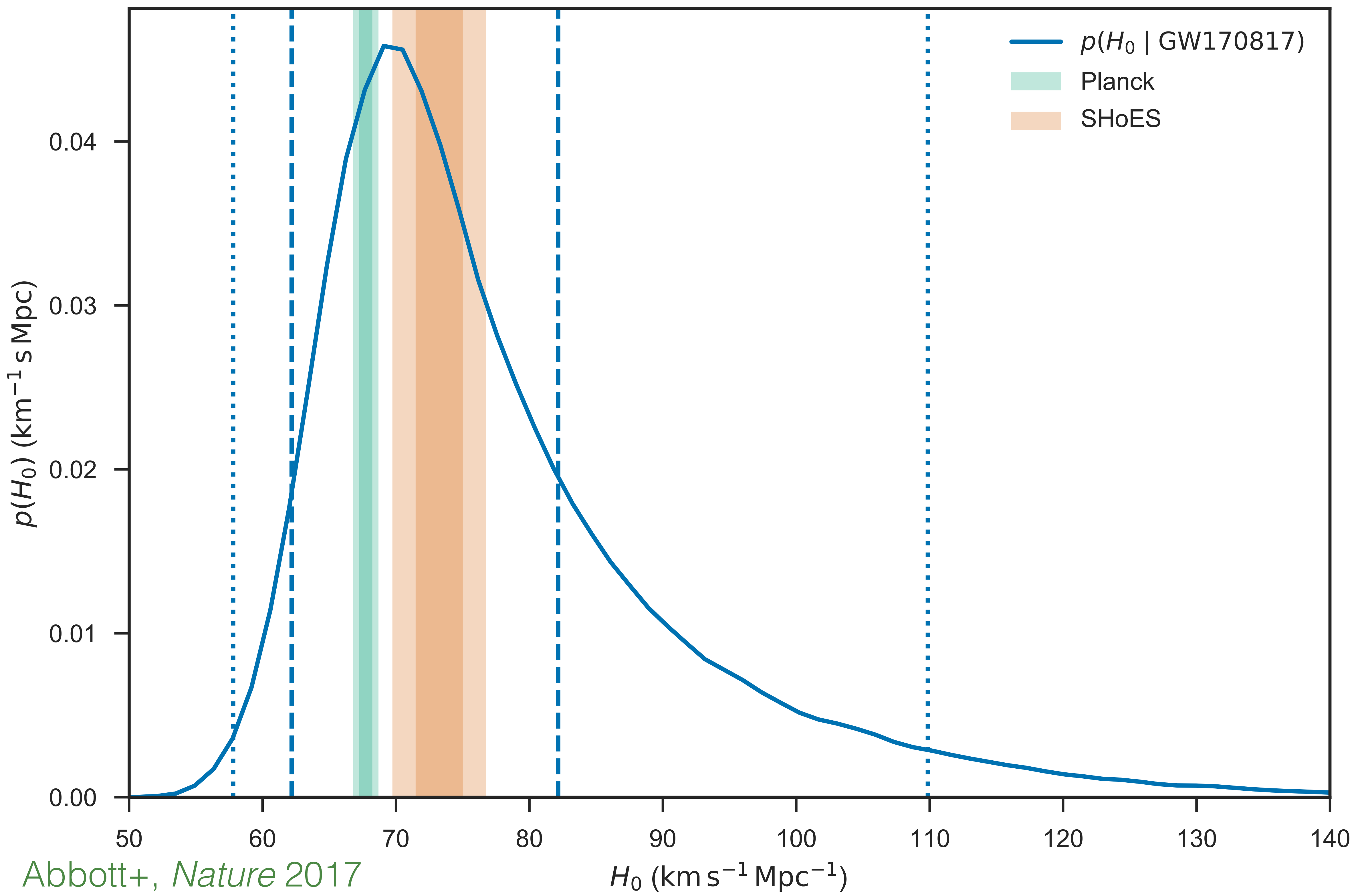
GW170817 is an ideal standard siren

- GW170817 was detected in gravitational waves
    - Very high SNR
    - Excellent measurement of distance
- GW170817 has an optical counterpart
    - Host galaxy is NGC 4993
    - Measurement of redshift
        - Caveat: Galaxy is so close that peculiar motions are important. We need to estimate bulk flow of the group. We use 6dF and 2MASS estimates (error: ~150 km/sec)
- Poster child for the standard siren method….



Credit: P. Blanchard / E. Berger / Harvard-Smithsonian Center for Astrophysics

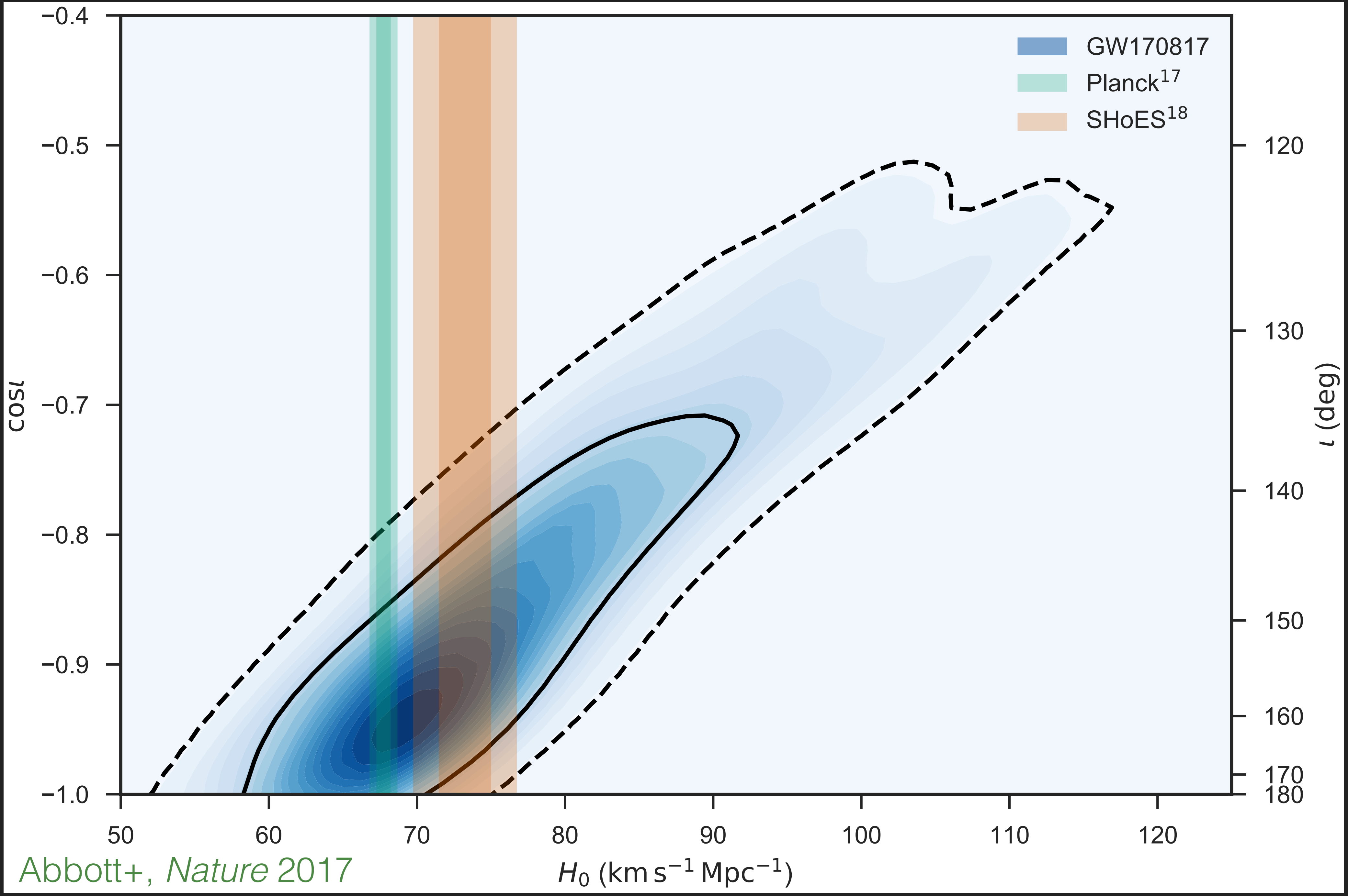
Standard siren measurement of the Hubble constant



Abbott+, *Nature* 2017

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

Distance is correlated with inclination

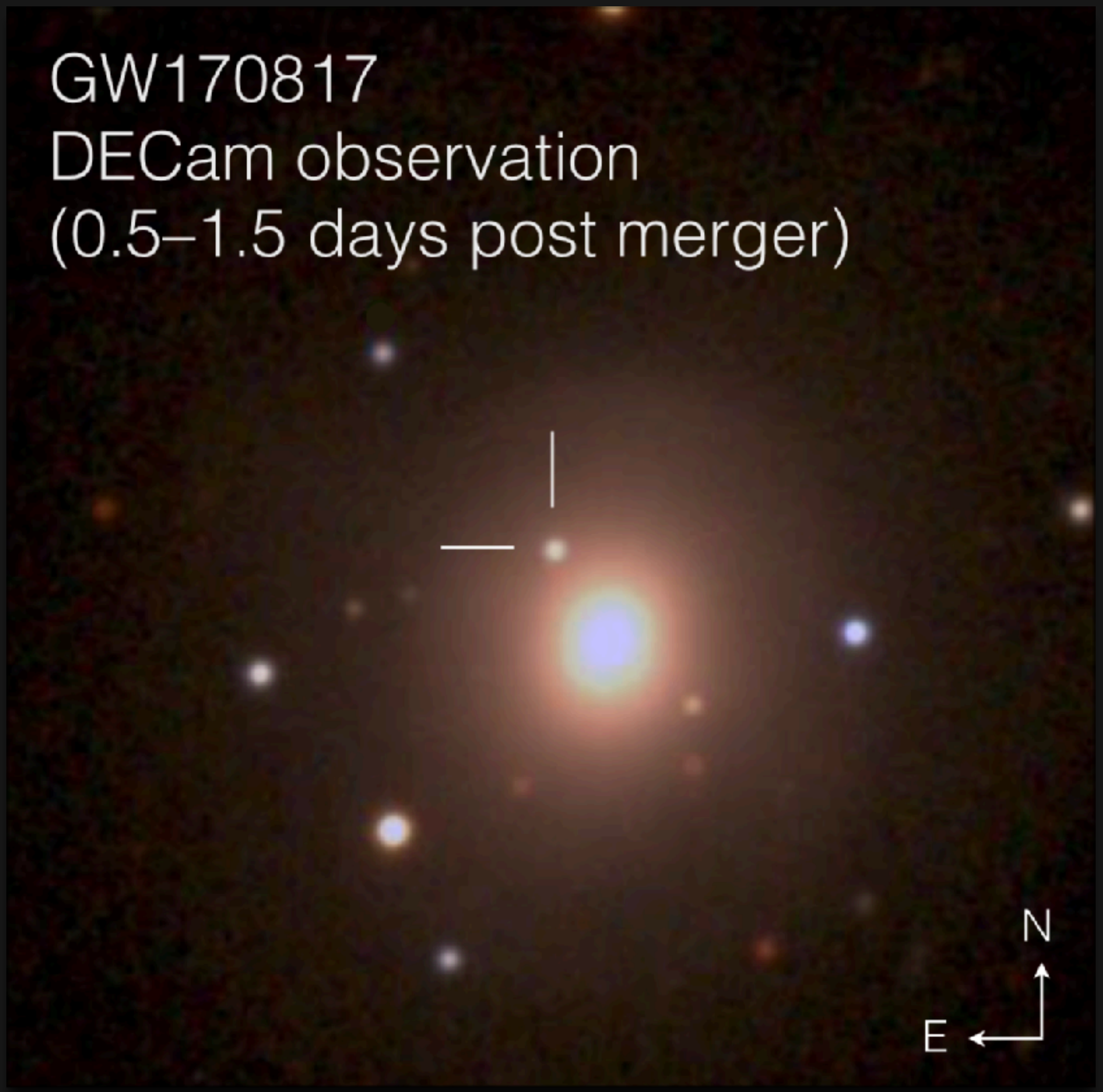


Abbott+, *Nature* 2017

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

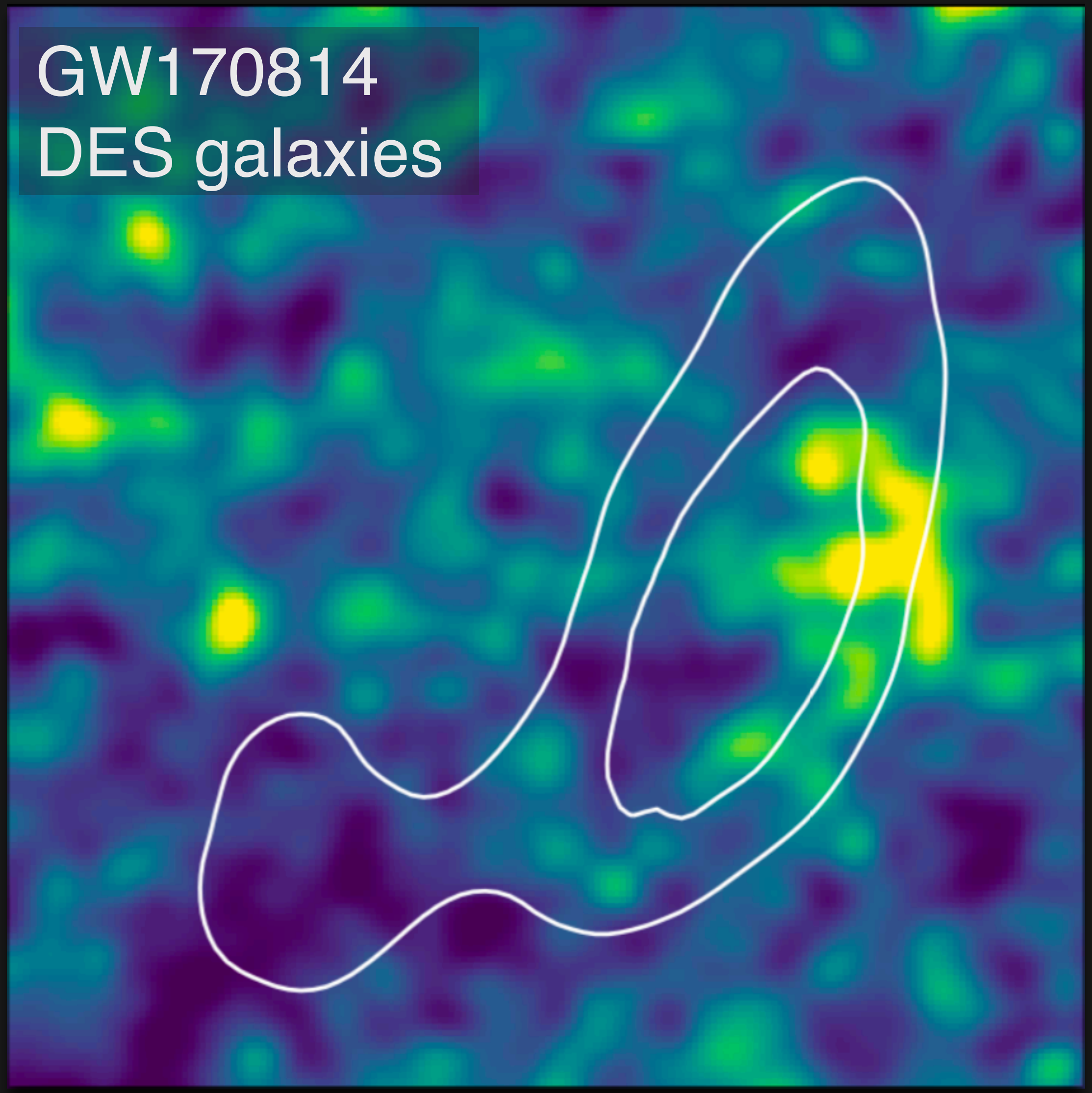
Two standard siren approaches

Counterpart/Bright



Unique host galaxy

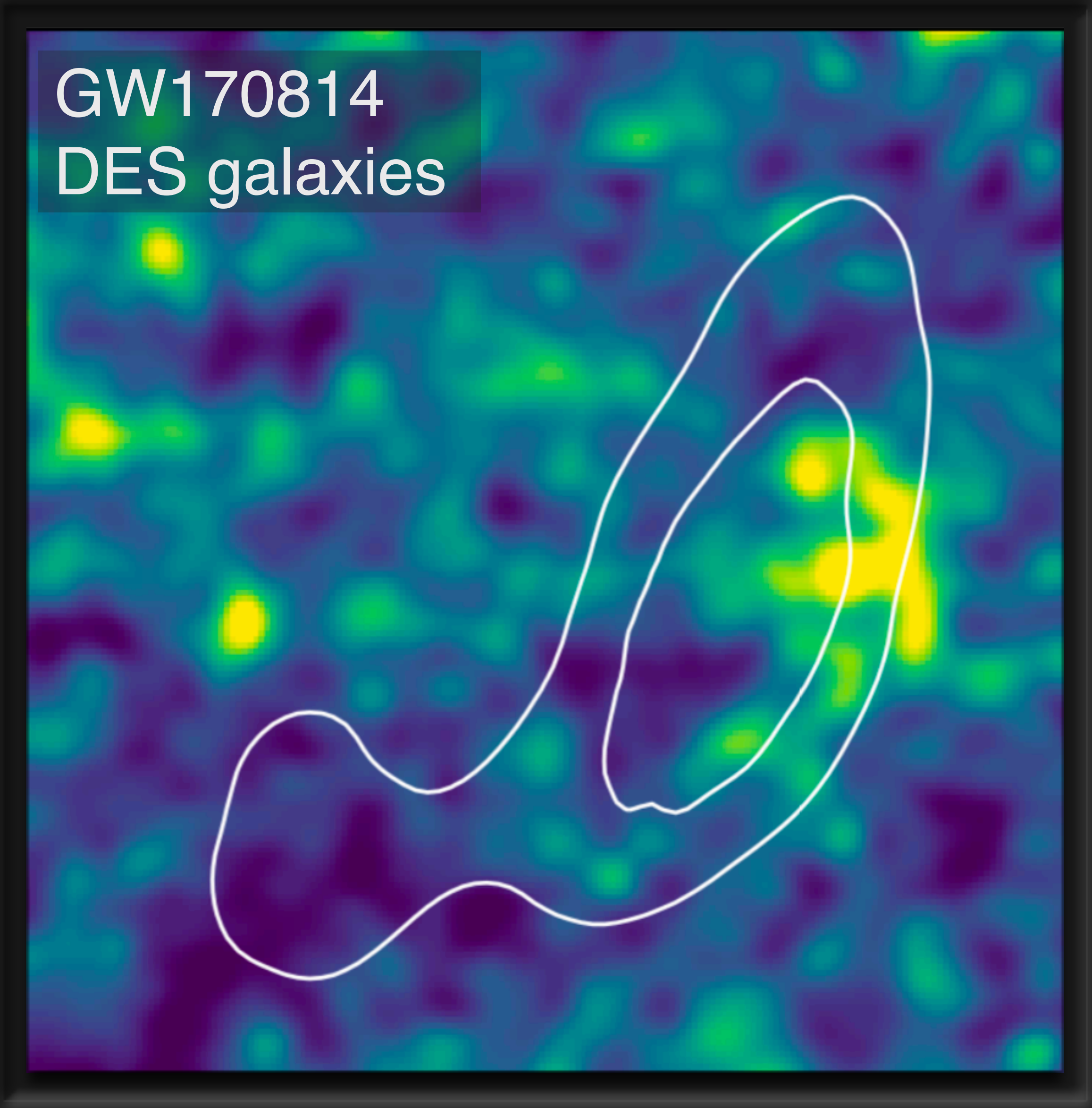
Statistical/Dark



Use all galaxies in localization volume

Two standard siren approaches

Statistical/Dark

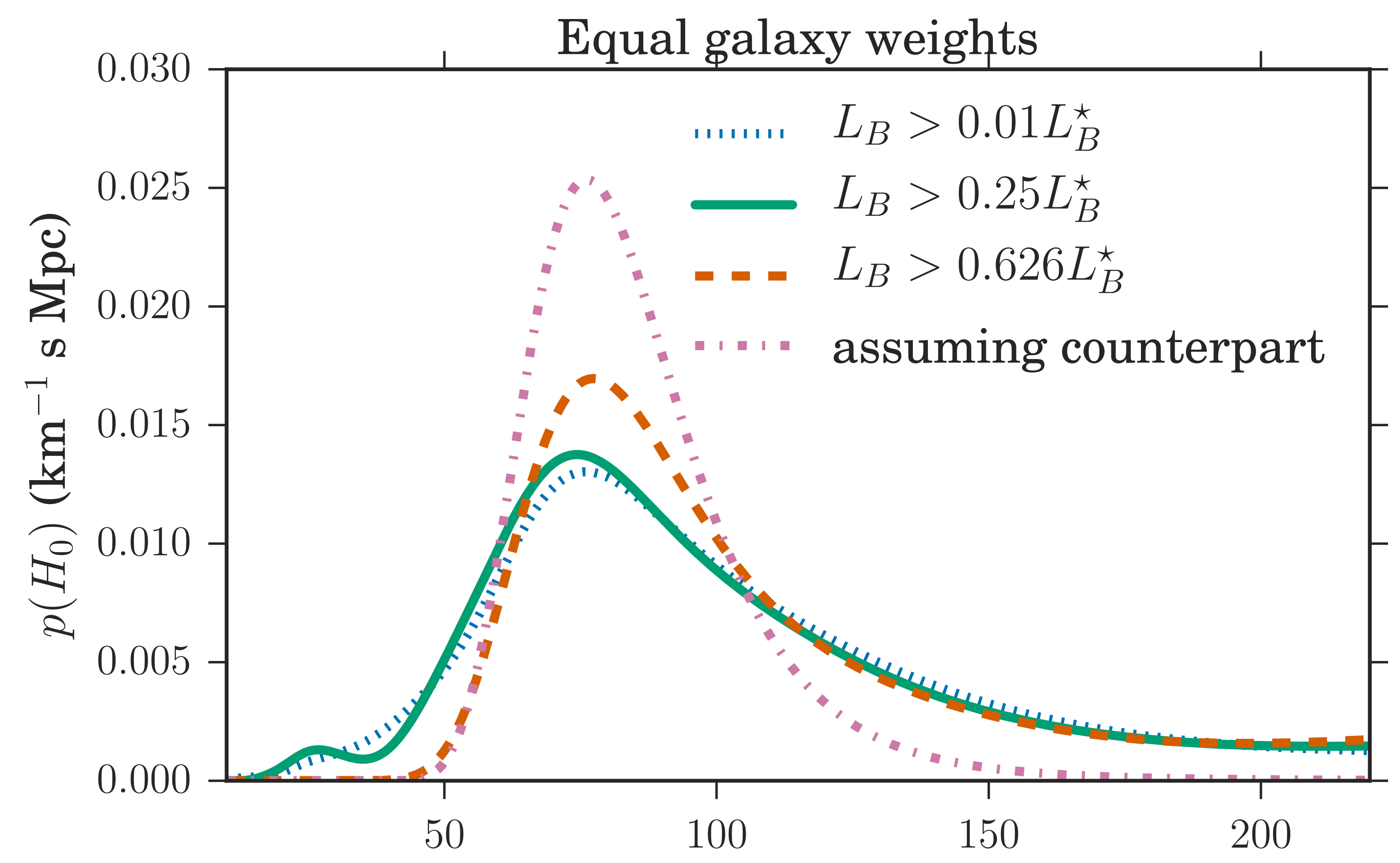


Use all galaxies in
localization volume

GW170817 as a dark standard siren

- GW170817 was nearby: only ~40 Mpc away!
- The GW170817 localization volume was relatively small: 215 Mpc^3
- Ignore the electromagnetic counterpart

- Have catalog of galaxies within the localization volume
- How well do we determine the Hubble constant using the statistical approach?



Fishbach+, *ApJL* 2018

GW170817 as a dark standard siren

GW170814 as a dark standard siren

GW170814 as a dark standard siren

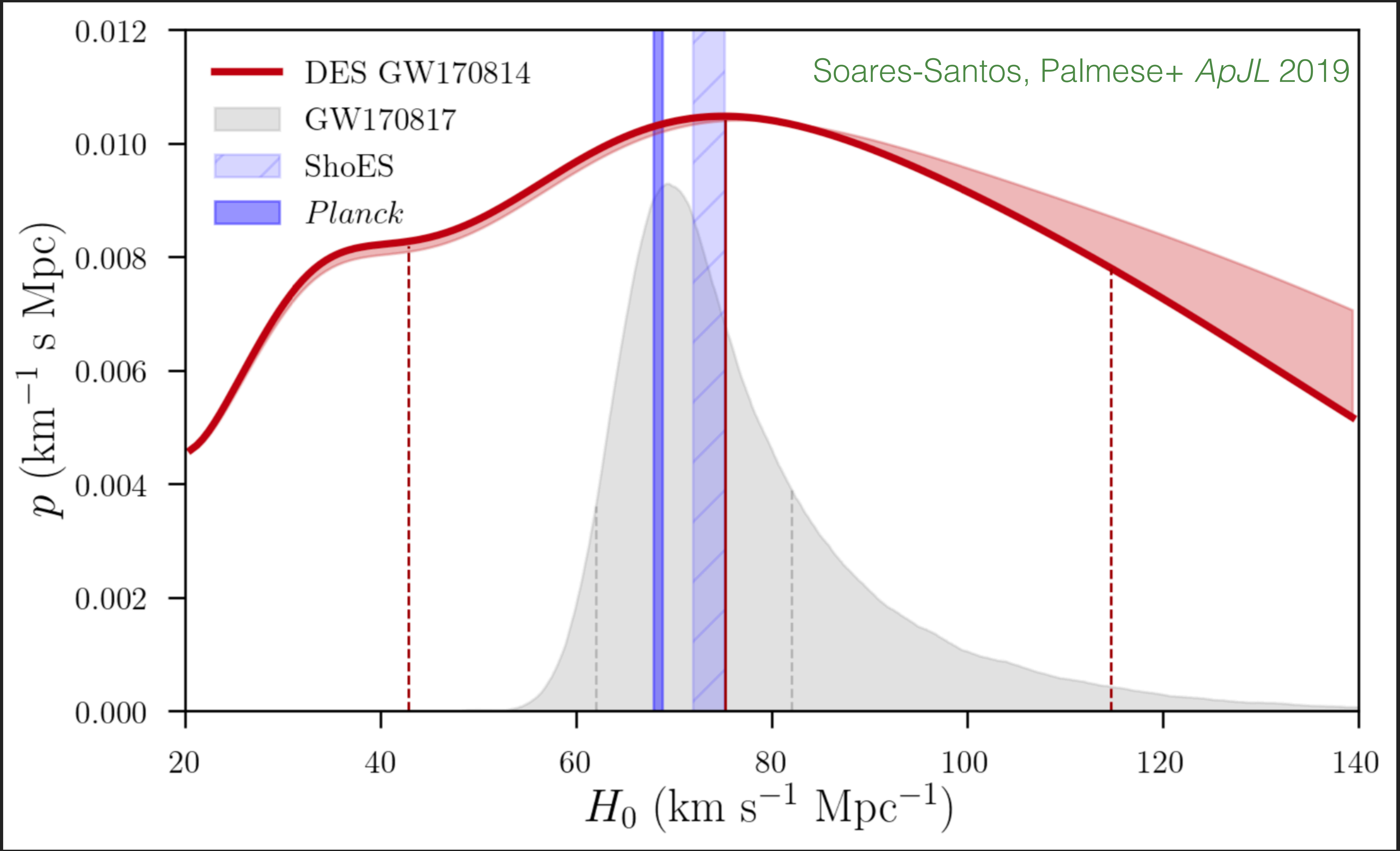
- GW170814 was first "triple" binary black hole: Hanford, Livingston, and Virgo detectors help constrain localization volume
- GW170814 localization volume was relatively small: $2\text{x}10^6$ Mpc^3
- No electromagnetic counterpart
- GW170814 happens to fall in the middle of the DES footprint!
- Get 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 weight? Metallicity? Something else?
- Spectroscopic or photometric redshifts? For photometric redshifts, significant systematic errors
- Role of large-scale structure
- Role of priors

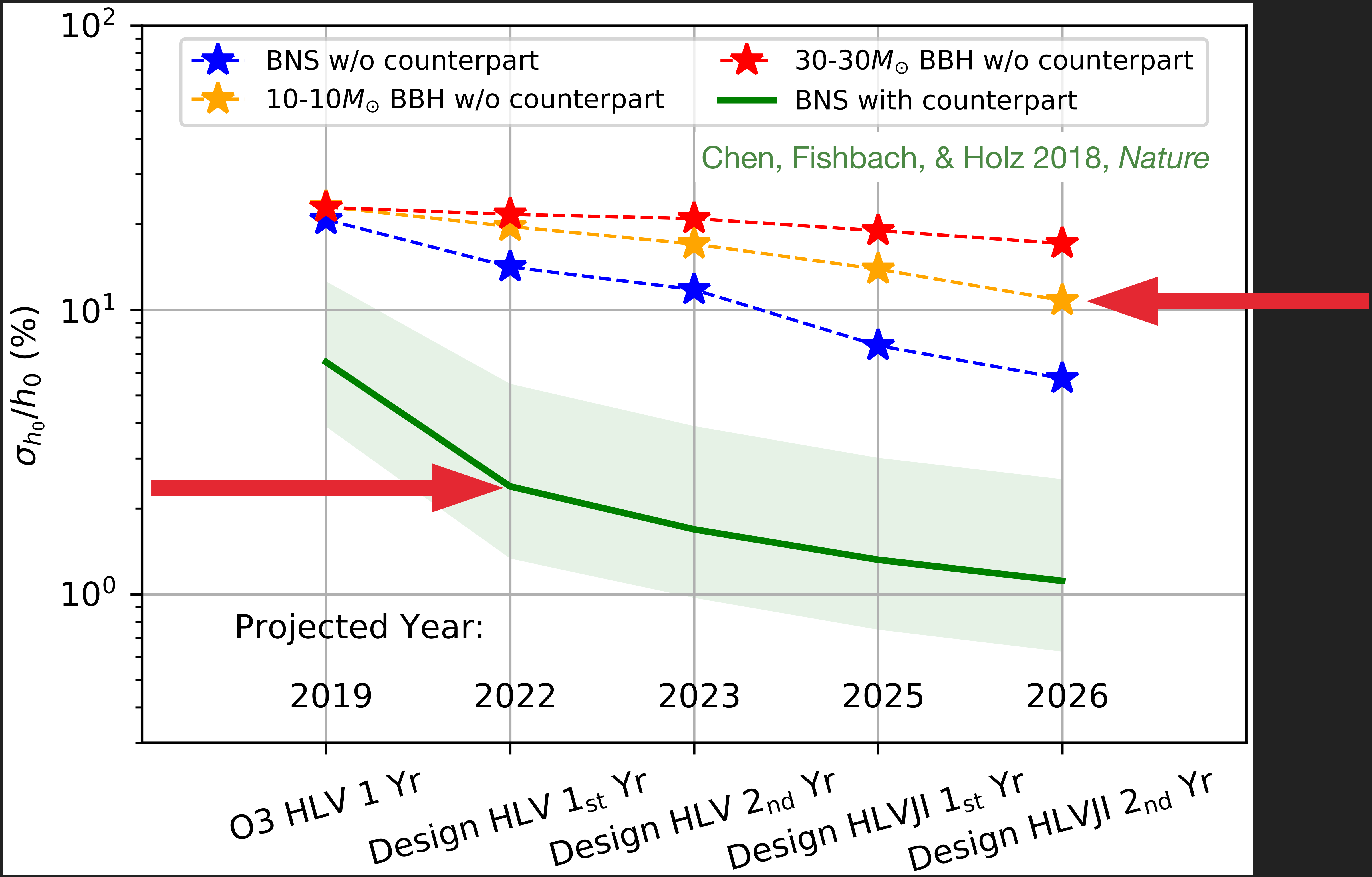
GW170814 as a dark standard siren



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

What will the future bring?

Precision standard siren cosmology

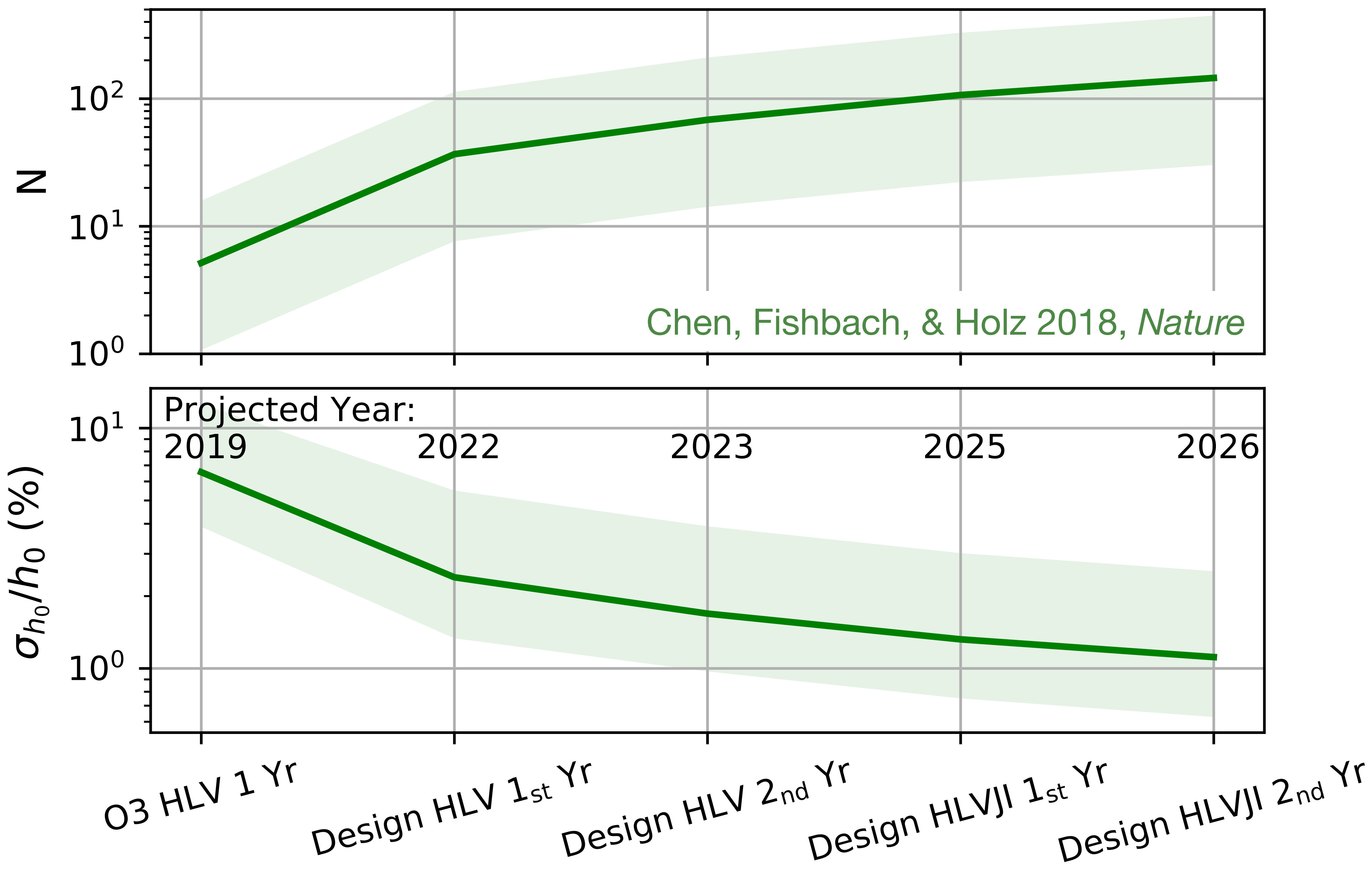


Chen, Fishbach, & Holz 2018, *Nature*

- With one year at design sensitivity (starting ~2022?) we get to ~2.5% measurement of the Hubble constant: helps adjudicate current tension!?

- Statistical/Dark sirens are roughly order of magnitude behind. Although there are many more, each one is worse

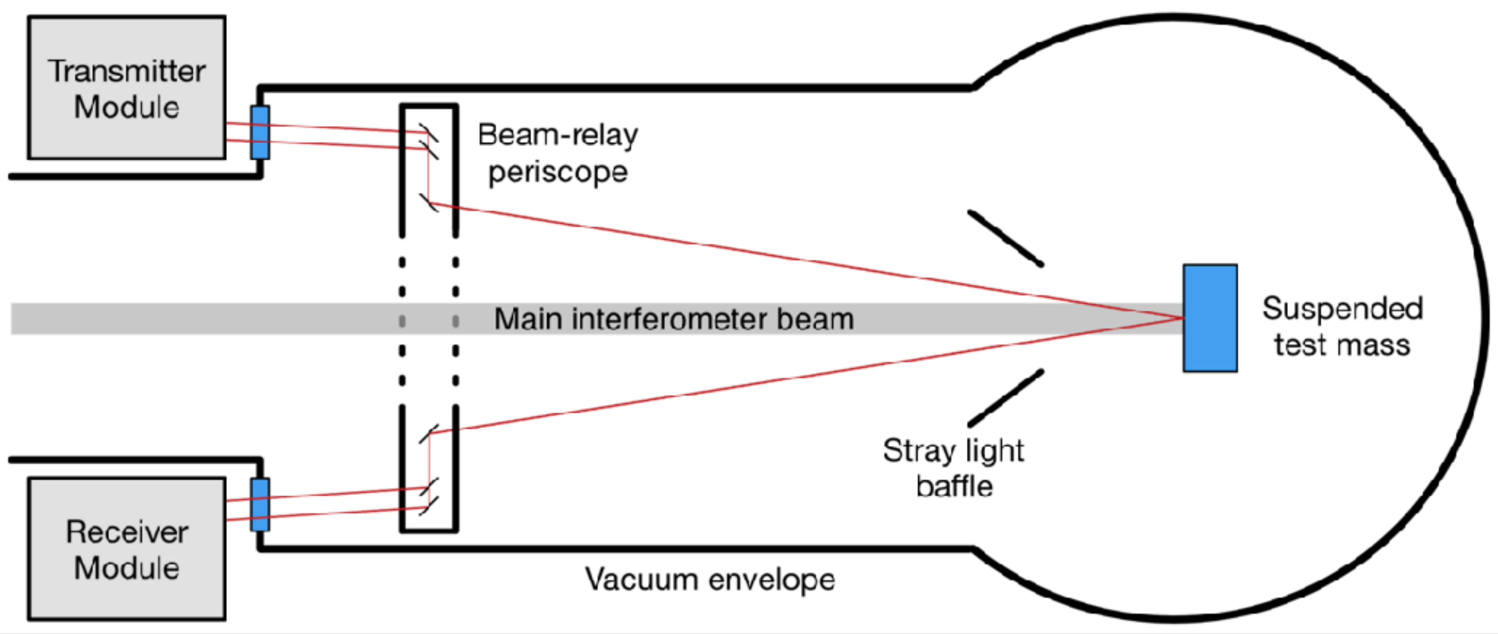
H_0 to 2% by 2023, 1% by 2026*



*convergence may be slower if the detection rate is low

Standard siren systematics

- Absolute calibration of GW detectors: amplitude response as a function of frequency
- Inclination degeneracy (if not all GW sources have associated EM counterparts; can be fit)
- Peculiar velocities (should become negligible soon)
- Model selection (priors over GW population impact final results [e.g. rate evolution, mass distribution])
- Galaxy mis-identification? Redshift systematics?

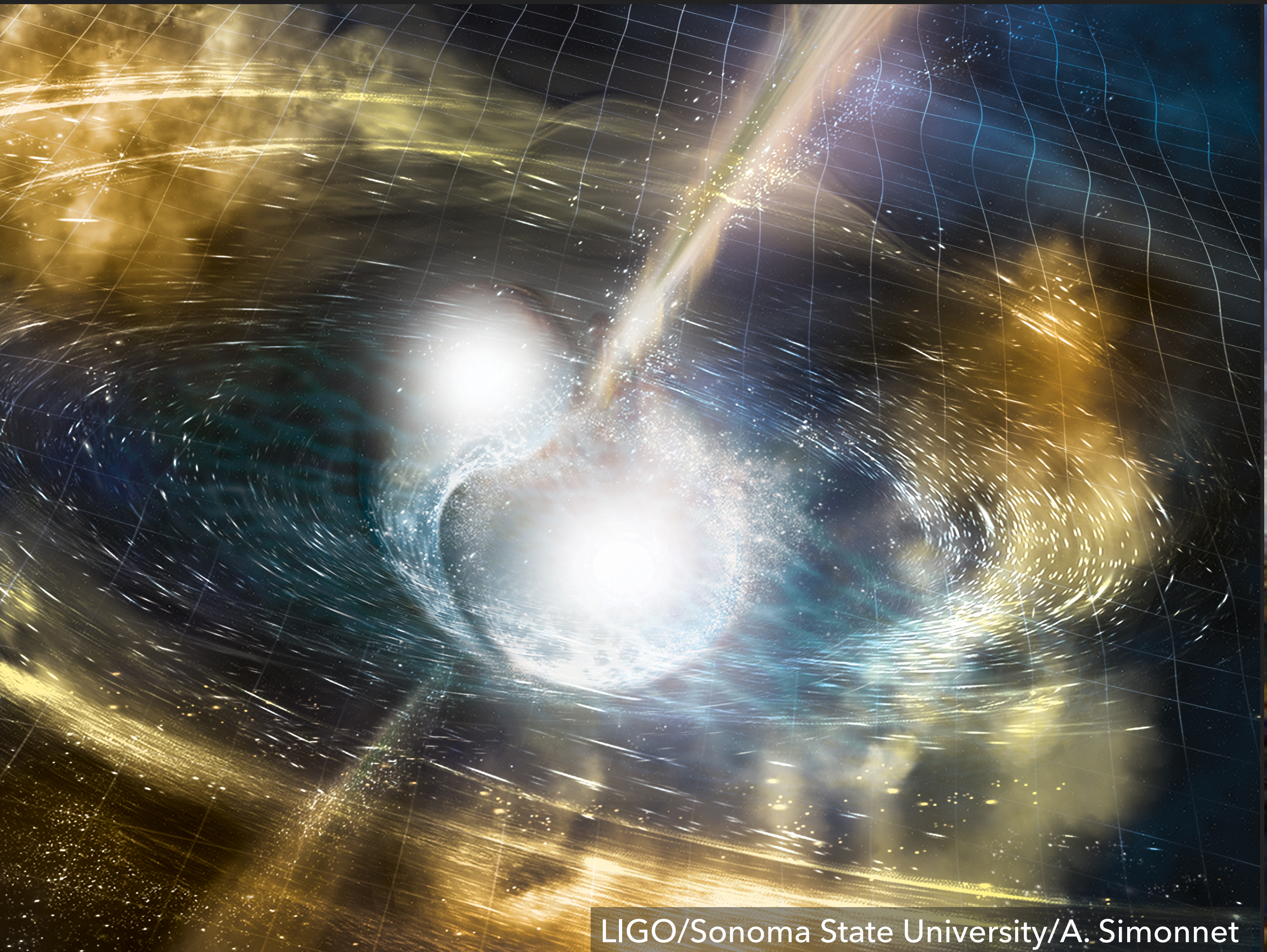


Astronomical calibration!

Essick & Holz arXiv:1902.08076

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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