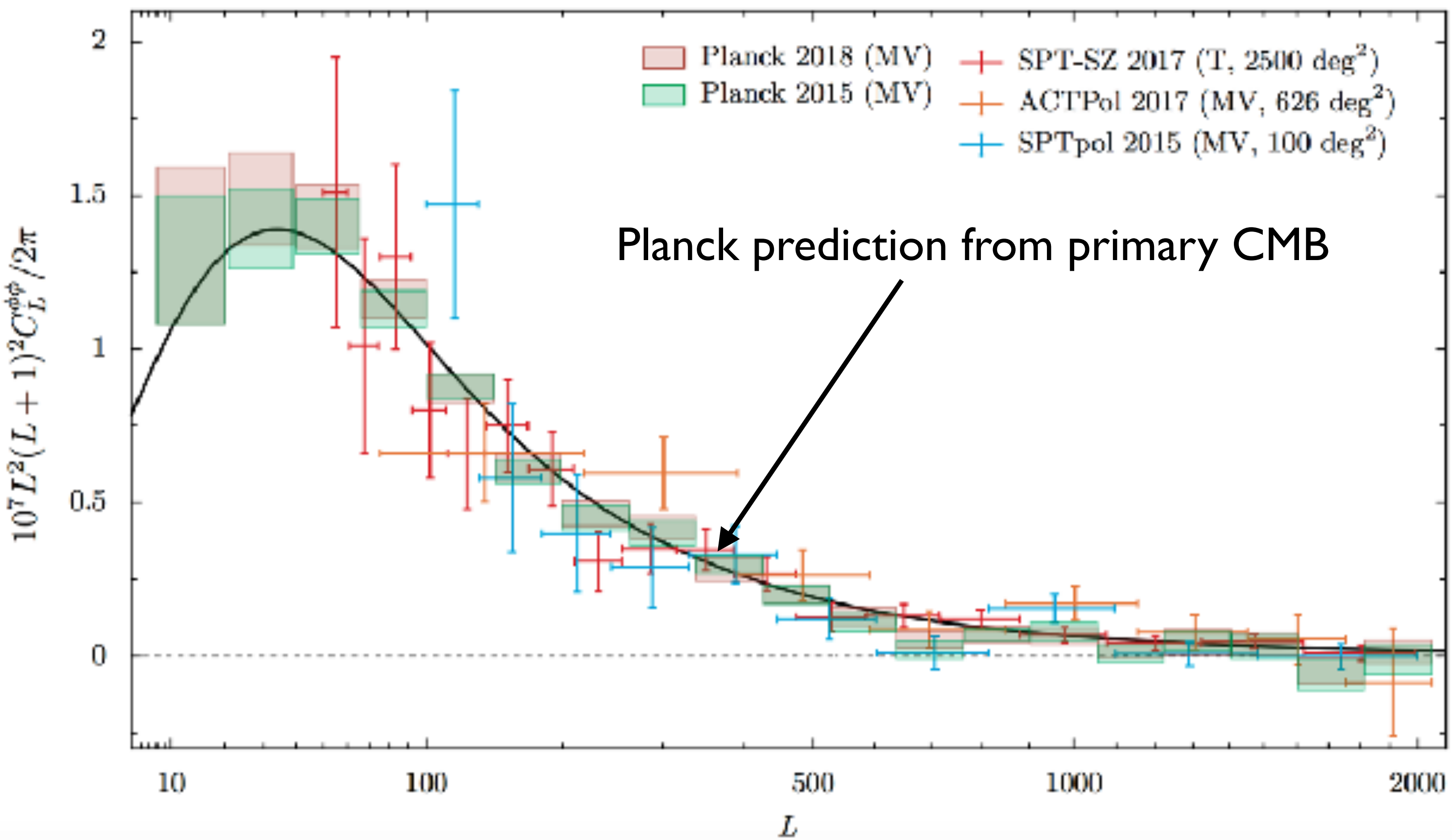
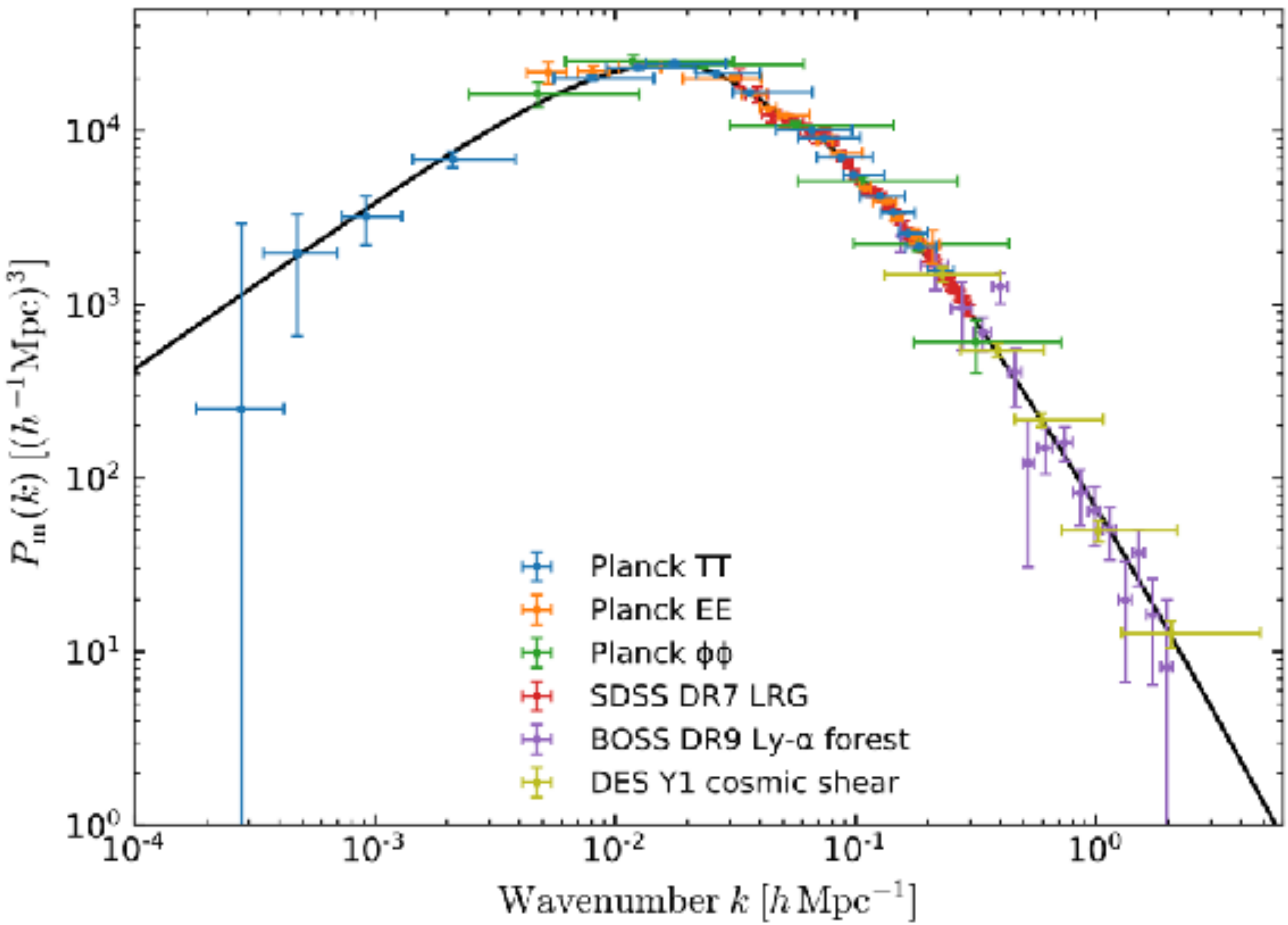
Cosmic Consistency



CMB lensing amplitude and scale dependence

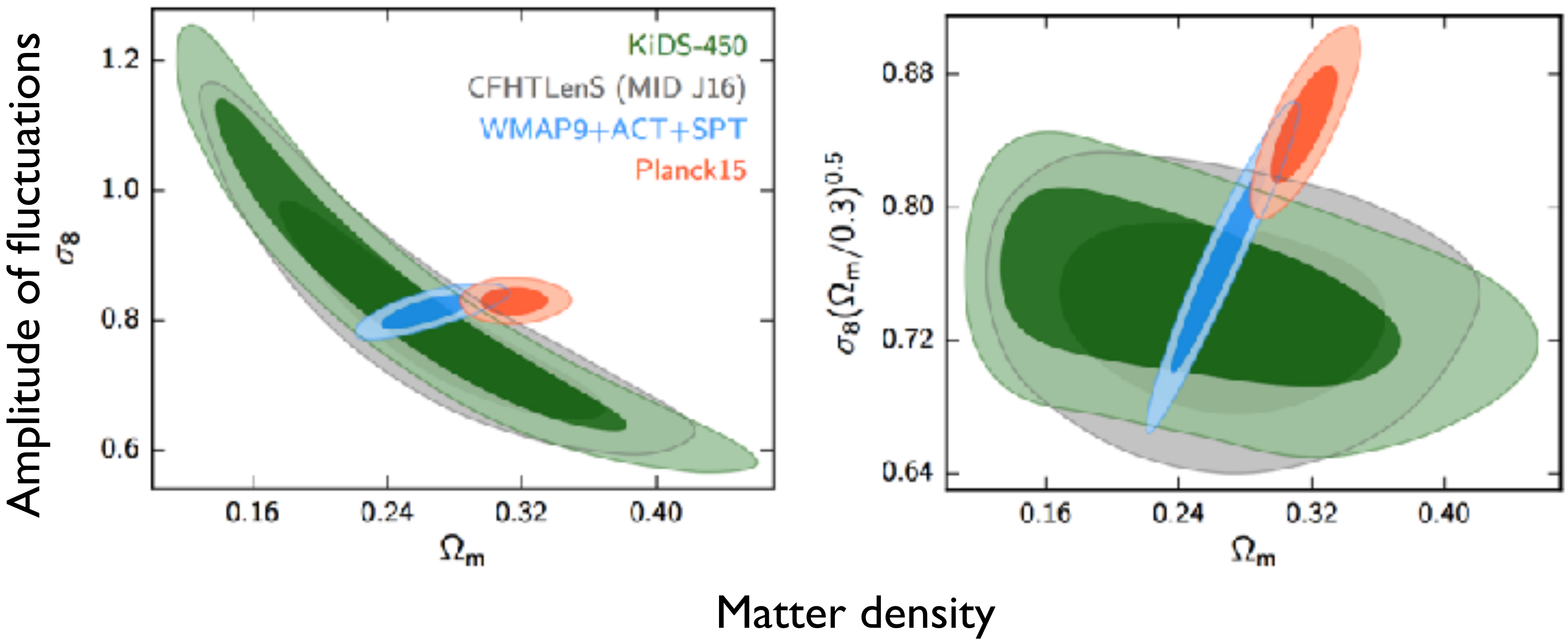
Planck Collaboration (2018), ACTPol (Sherwin et al 2017),
SPTPol (Story et al 2015), SPT-SZ (Simard et al 2017)

Cosmic consistency



Planck Collaboration (2018) summarising constraints on the matter power spectrum from a world collection of surveys spanning ~14 Gyr in time and 3 decades in scale

Cosmic (in)consistency? growth of structure

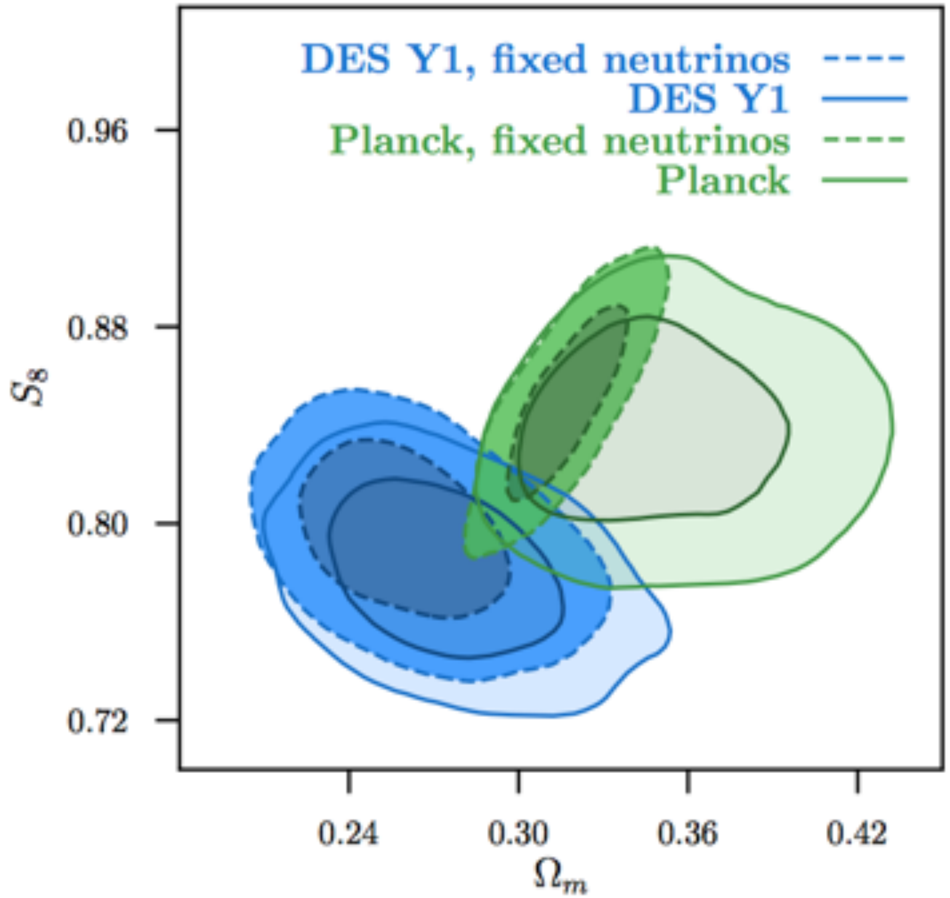


weak gravitational lensing measurements
(450 sq. deg.)

KiDS Collaboration (Hildebrandt et al 2017)

Cosmic (in)consistency? watch this space!

Amplitude of fluctuations



Matter density

DARK ENERGY SURVEY

weak gravitational lensing + galaxy clustering measurements
(1321 sq. deg.)

DES Collaboration (2017)

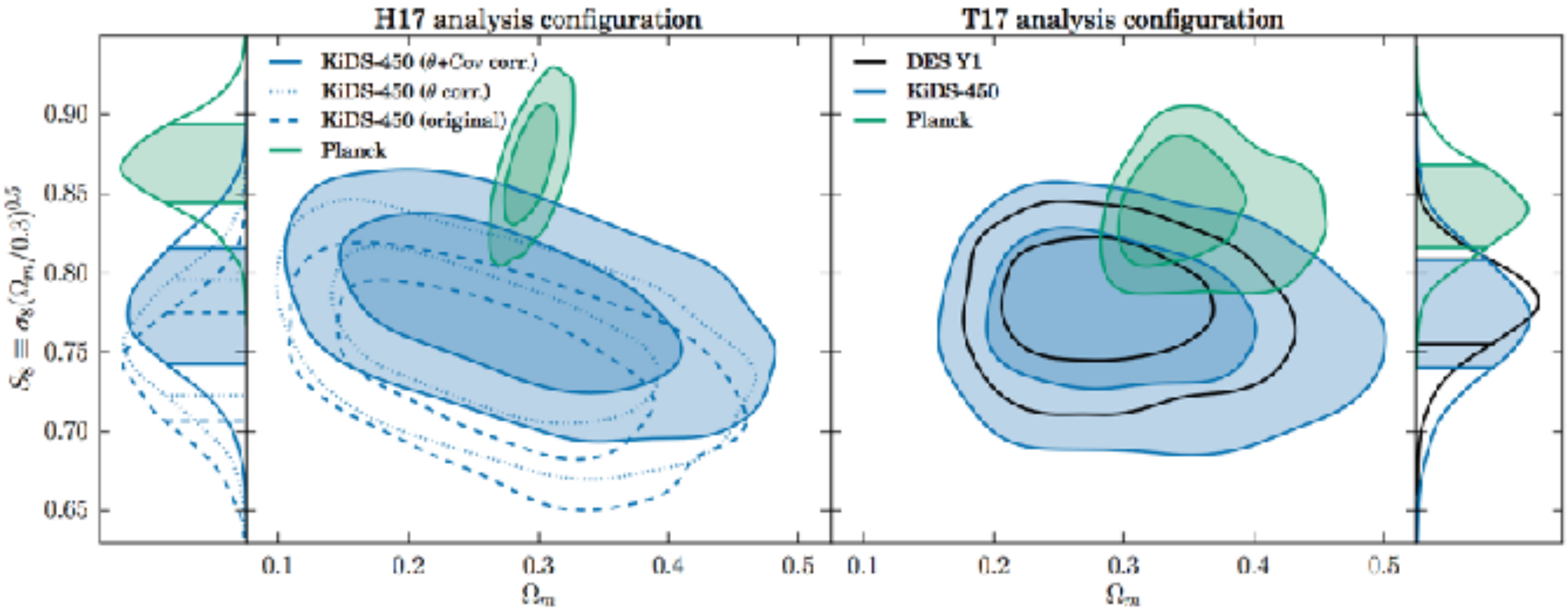
Revisiting internal consistency of cosmic shear measurements

DARK ENERGY SURVEY

Neutrino mass fixed

Neutrino mass marginalised

Amplitude of fluctuations



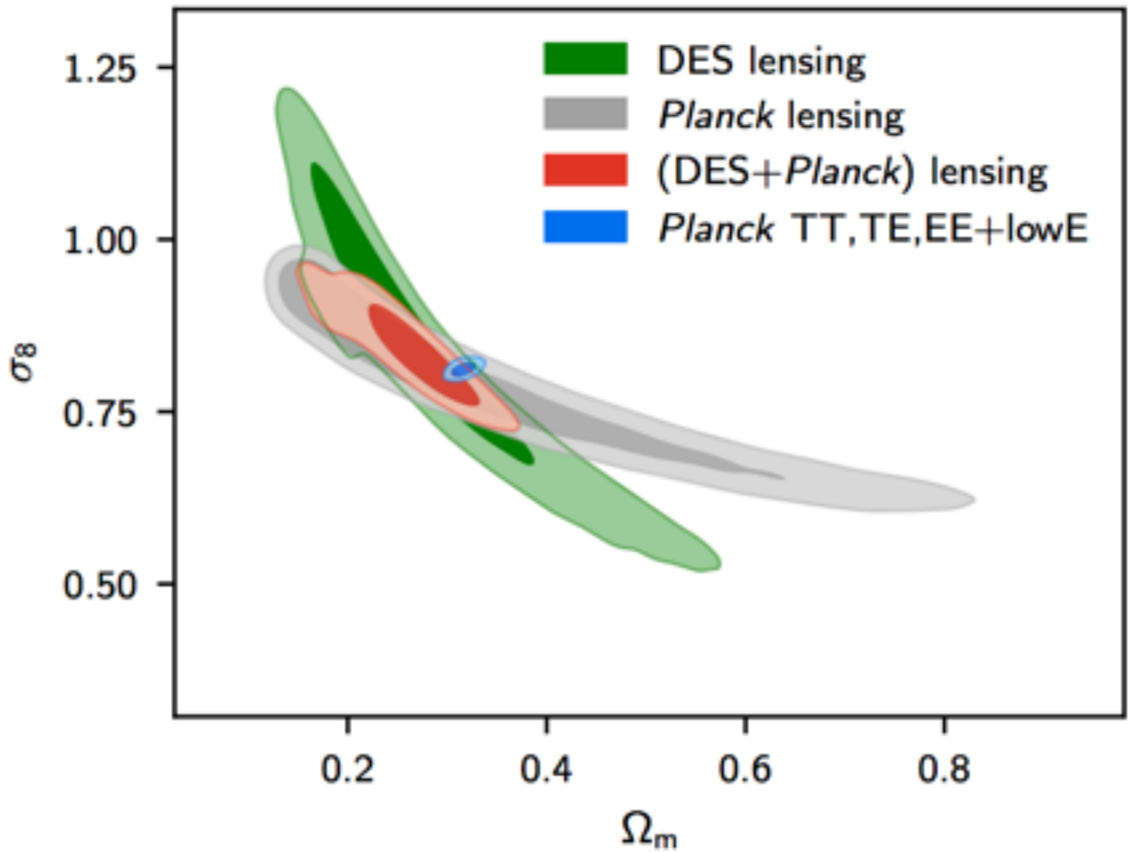
Matter density

Updated treatment of shape noise and multiplicative shear calibration uncertainty

DES Collaboration (Troxel et al 2018)

Cosmic Consistency? watch this space!

Amplitude of fluctuations



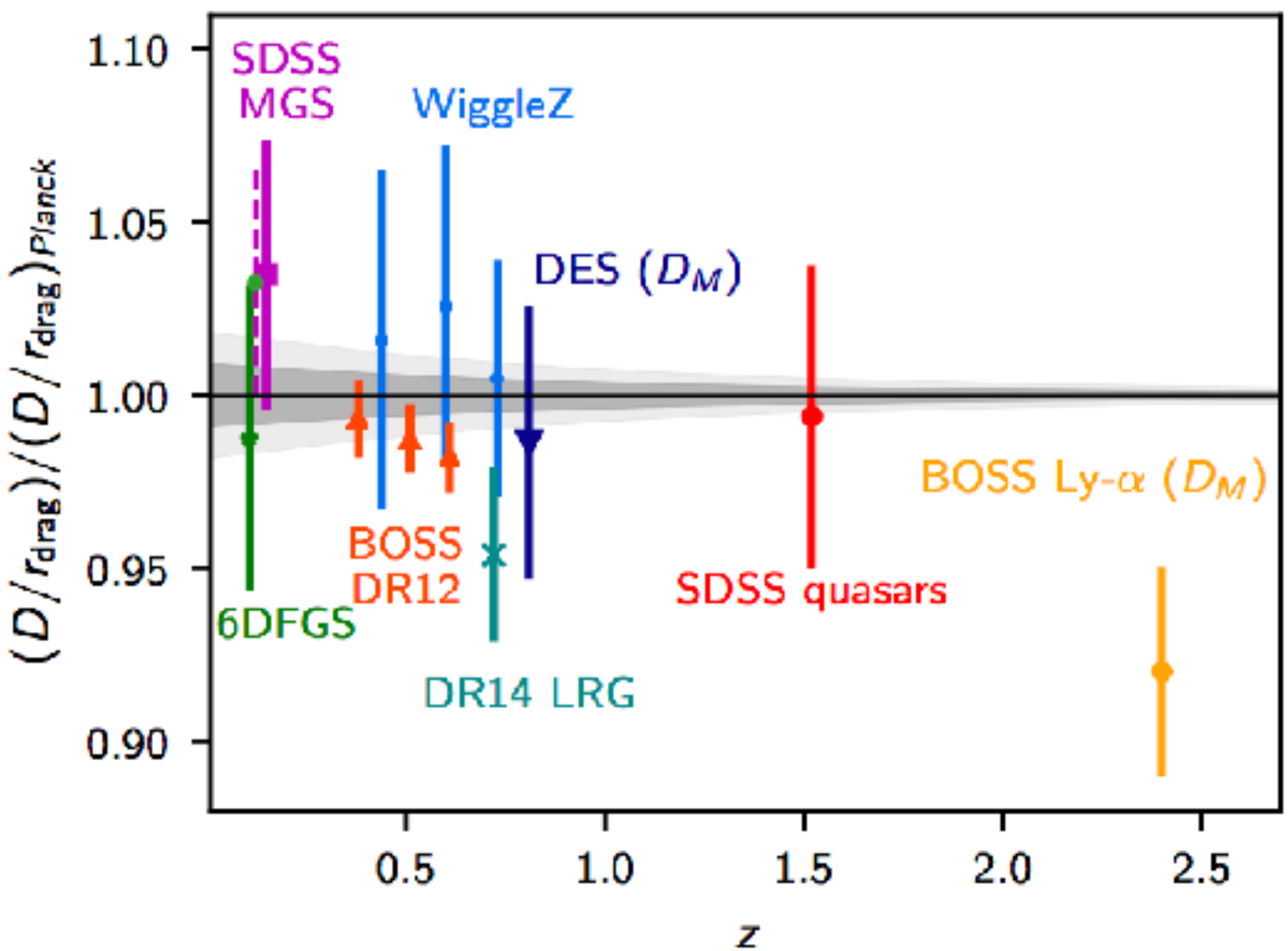
Matter density

DARK ENERGY SURVEY

weak gravitational lensing vs CMB lensing

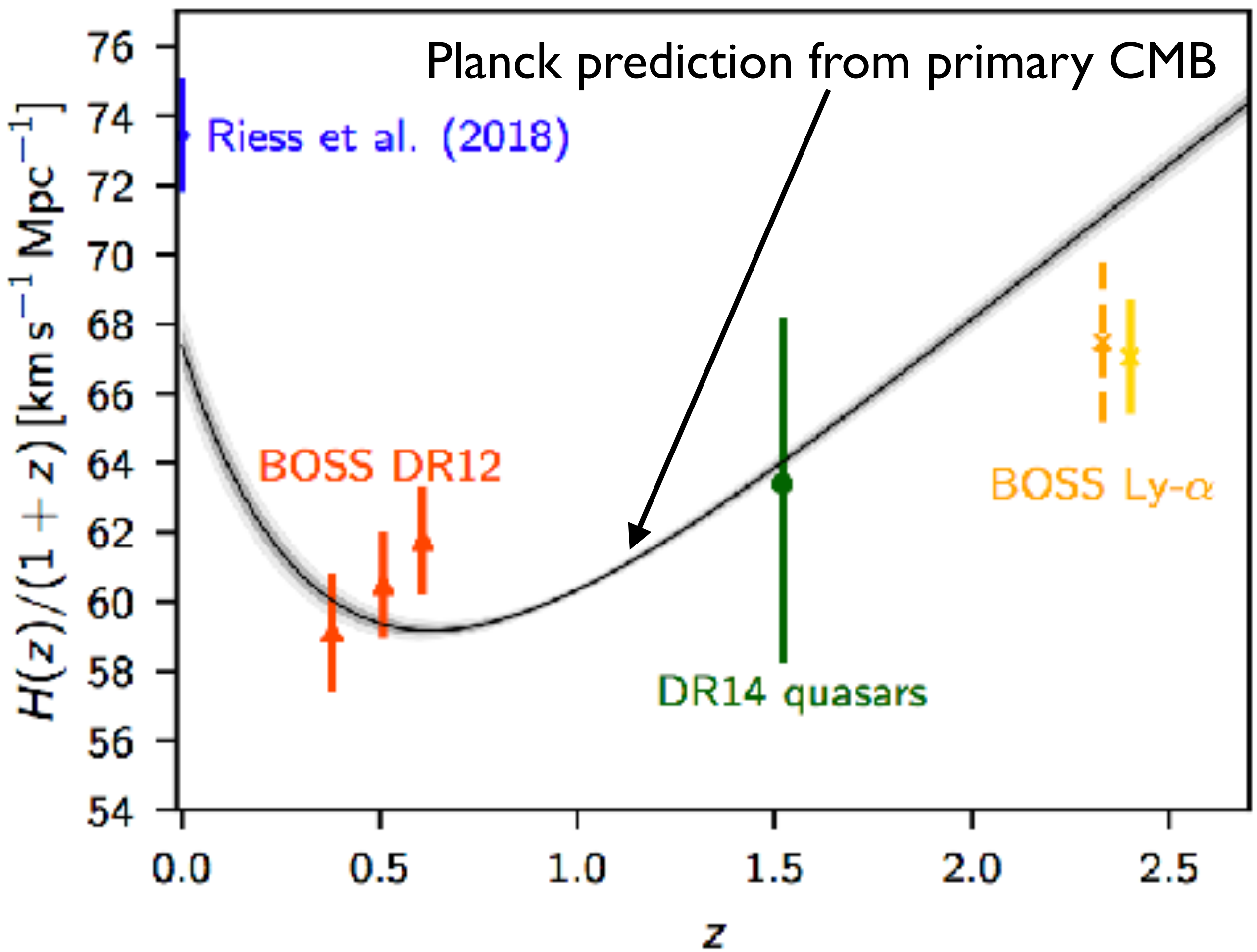
Planck Collaboration (2018); DES Collaboration (Troxel et al 2017)

Cosmic consistency? Acoustic scale distance ratio



Planck Collaboration (2018) summarising BAO standard ruler
"Hubble diagram" from a world collection of surveys

Cosmic (in)consistency? expansion history



H0 measurement (Riess et al. 2016)

DR12 BOSS Galaxy BAO (Alam et al. 2016)

DR14 BOSS Quasar BAO (Zarrouk et al 2018)

DR12 BOSS Lyman alpha forest BAO (Bautista et al 2017; du-Mas-des-Bourboux et al. 2017)

Measurements compiled by: Planck Collaboration (2018)

H_0: Cosmological vs distance ladder measurements

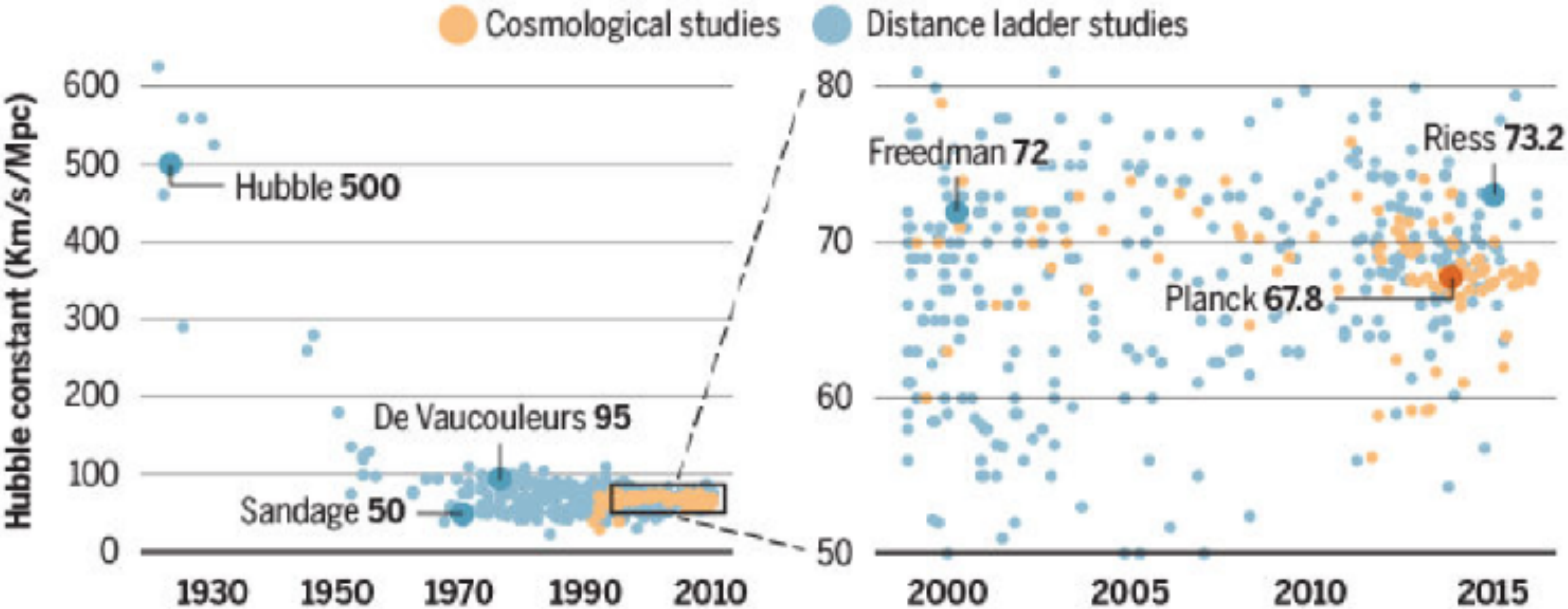
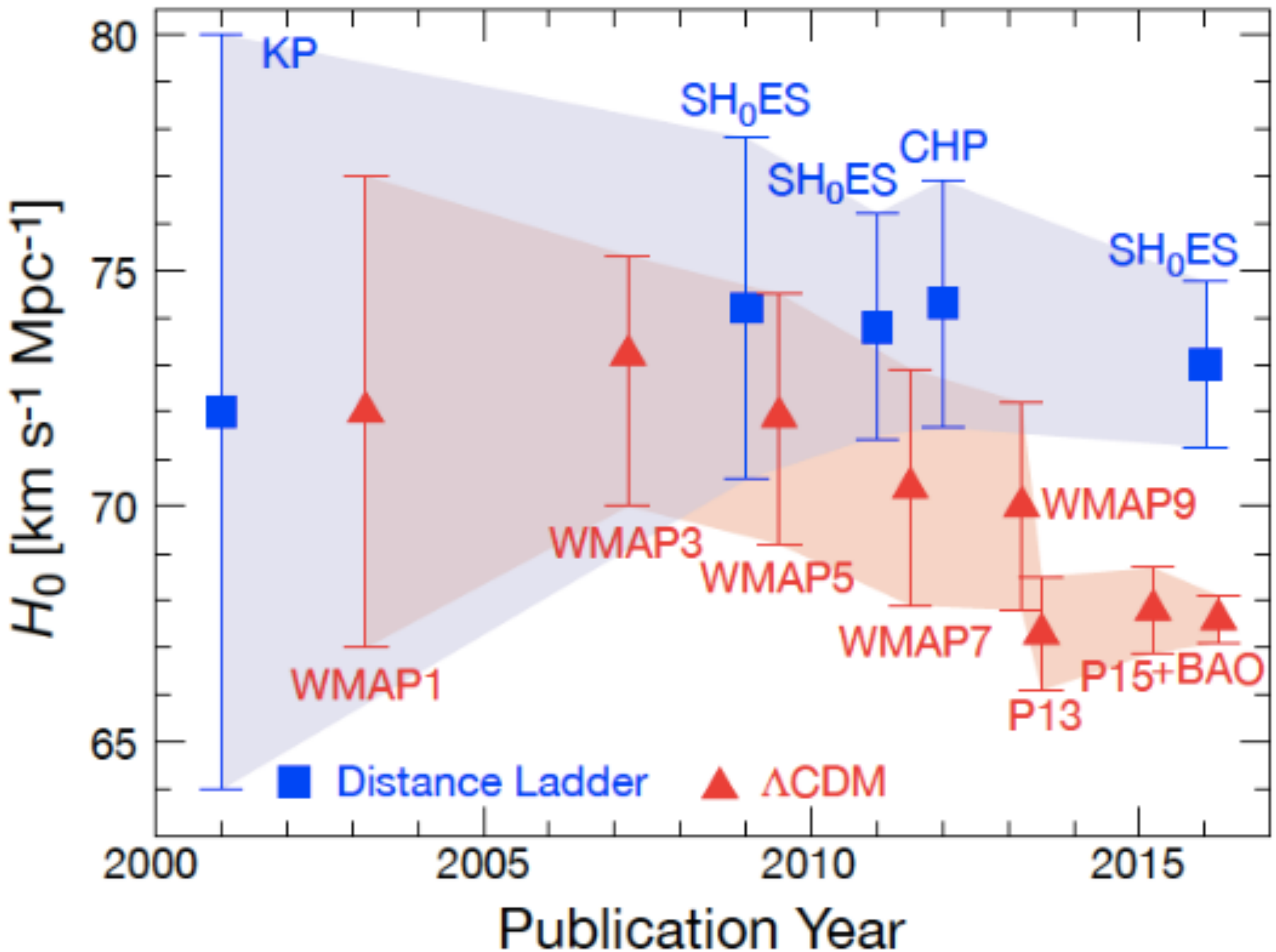


Figure: Science Magazine

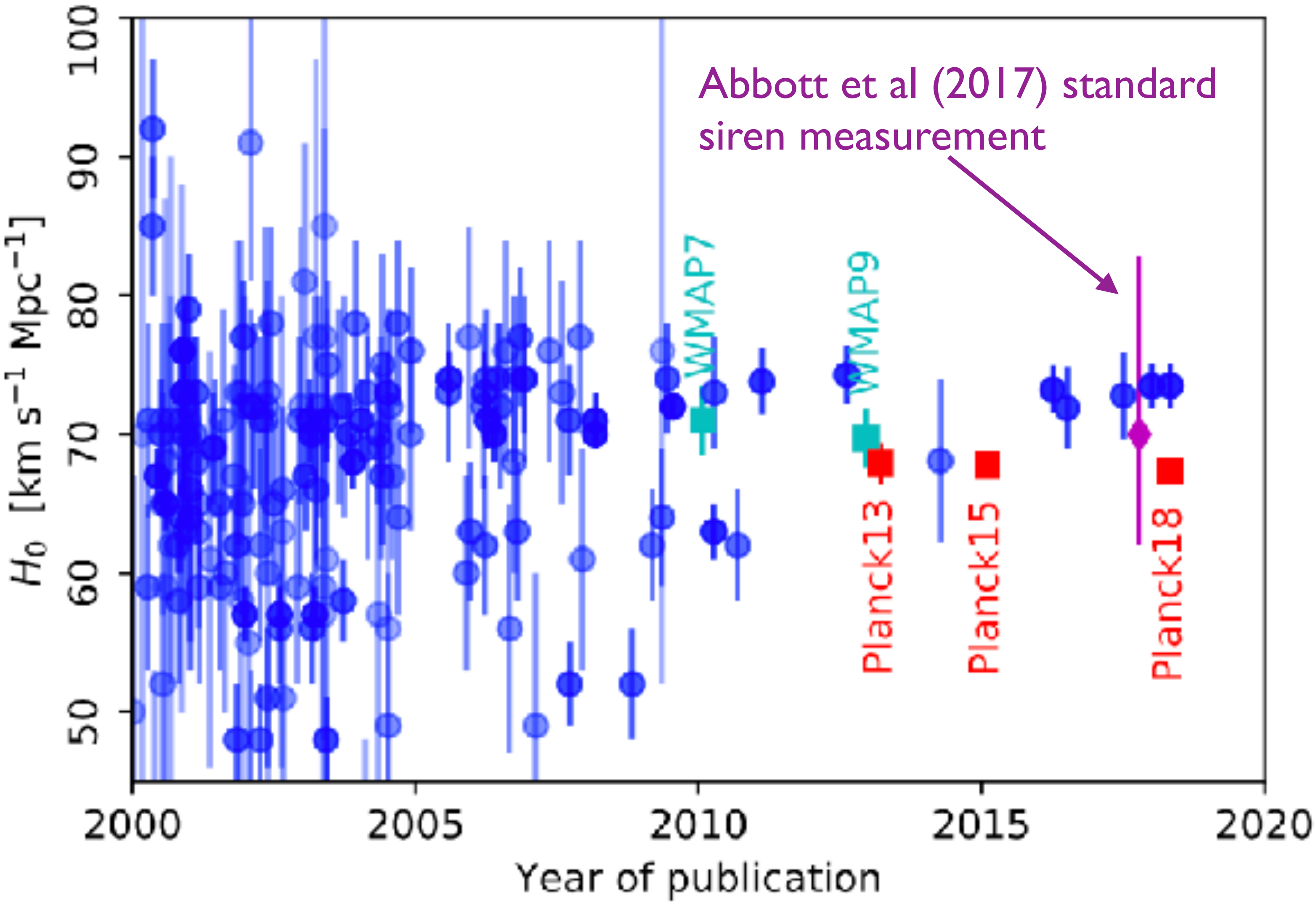
Cosmic (in)consistency: real or "tension in a teapot"?



Systematics? astrophysics? (new) physics?

Freedman (2017) adapted from Beaton et al (2016)

Cosmic (in)consistency: latest



Currently a ~3.5σ tension

Compiled by Planck Collaboration (2018)

Prospects for Resolving the H_0 Tension with Standard Sirens

arXiv:1802:03404

Stephen M. Feeney, Hiranya V. Peiris, Andrew R. Williamson,
Samaya M. Nissanke, Daniel Mortlock,
Justin Alsing, Dan Scolnic

H_0: why care, and how?

- Cosmological parameter that can be measured locally, assuming minimal physical model.
- "Simplest" method: measure ***robust*** distance and redshift
- Use distance ladders assuming minimal cosmology
    - "local": use nearby Cepheids w/ known distances to calibrate supernovae @ $z \simeq 0.2$
    - "inverse": use supernovae and BAOs to extrapolate CMB sound horizon @ radiation drag scale from $z=1100$ to ~ 0
- Use CMB anisotropies assuming complete cosmology

Model Assessment: posterior predictive distribution

- Sampling distribution of new data **d'** given old data **d** and model *I* with parameters $\boldsymbol{\theta}$

$$\Pr(\mathbf{d}'|\mathbf{d}, I) = \int \underbrace{\Pr(\mathbf{d}'|\boldsymbol{\theta}, I)}_{\text{likelihood of new data}} \underbrace{\Pr(\boldsymbol{\theta}|\mathbf{d}, I)}_{\text{posterior of old}} \, d\boldsymbol{\theta}$$

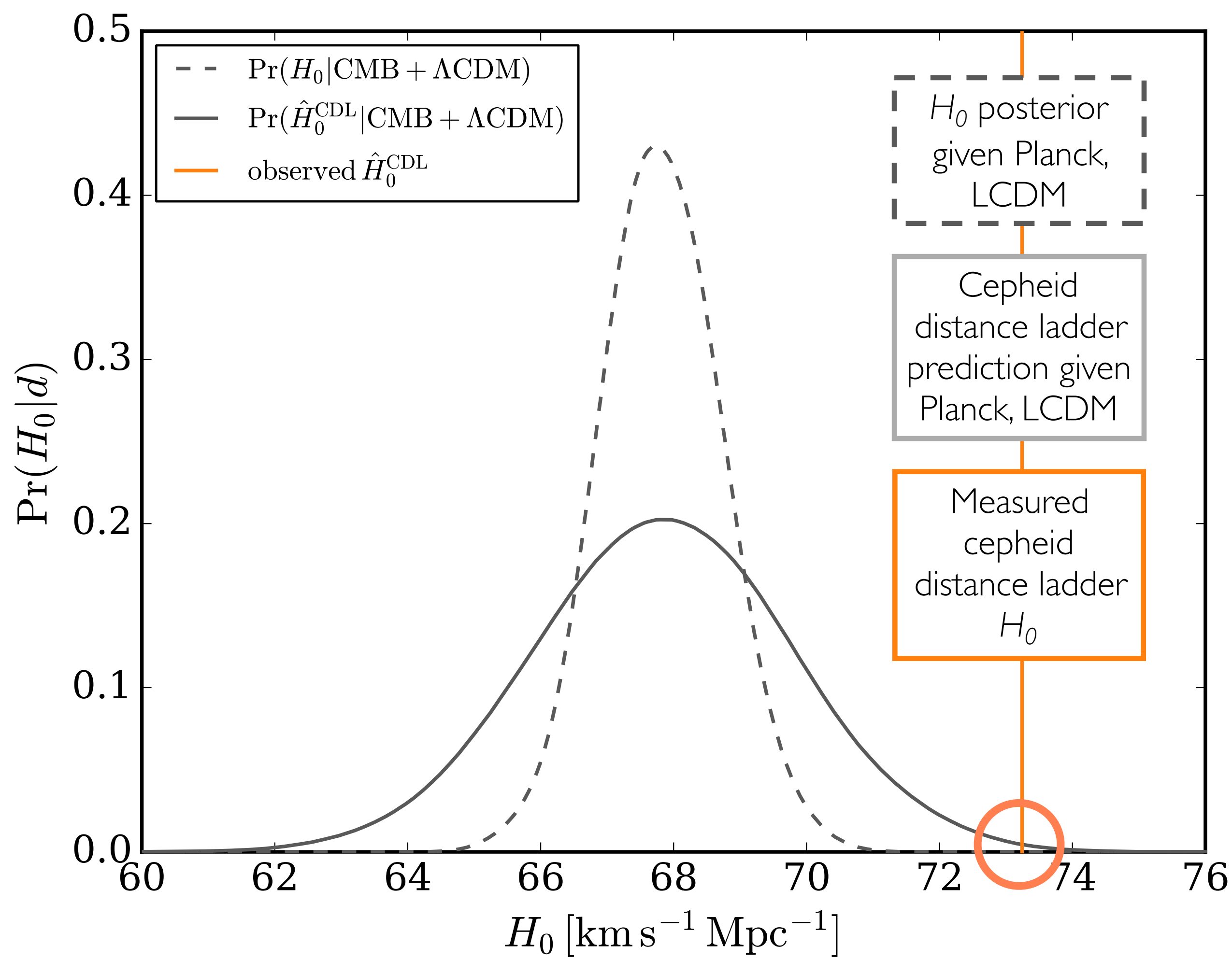
- "Convolution" of likelihood of new data w/ posterior of old

- Compare measured values to PPD: are new data consistent with being a draw from the model?

- Model ***assessment*** (no need for alternative model), weak dependence on prior

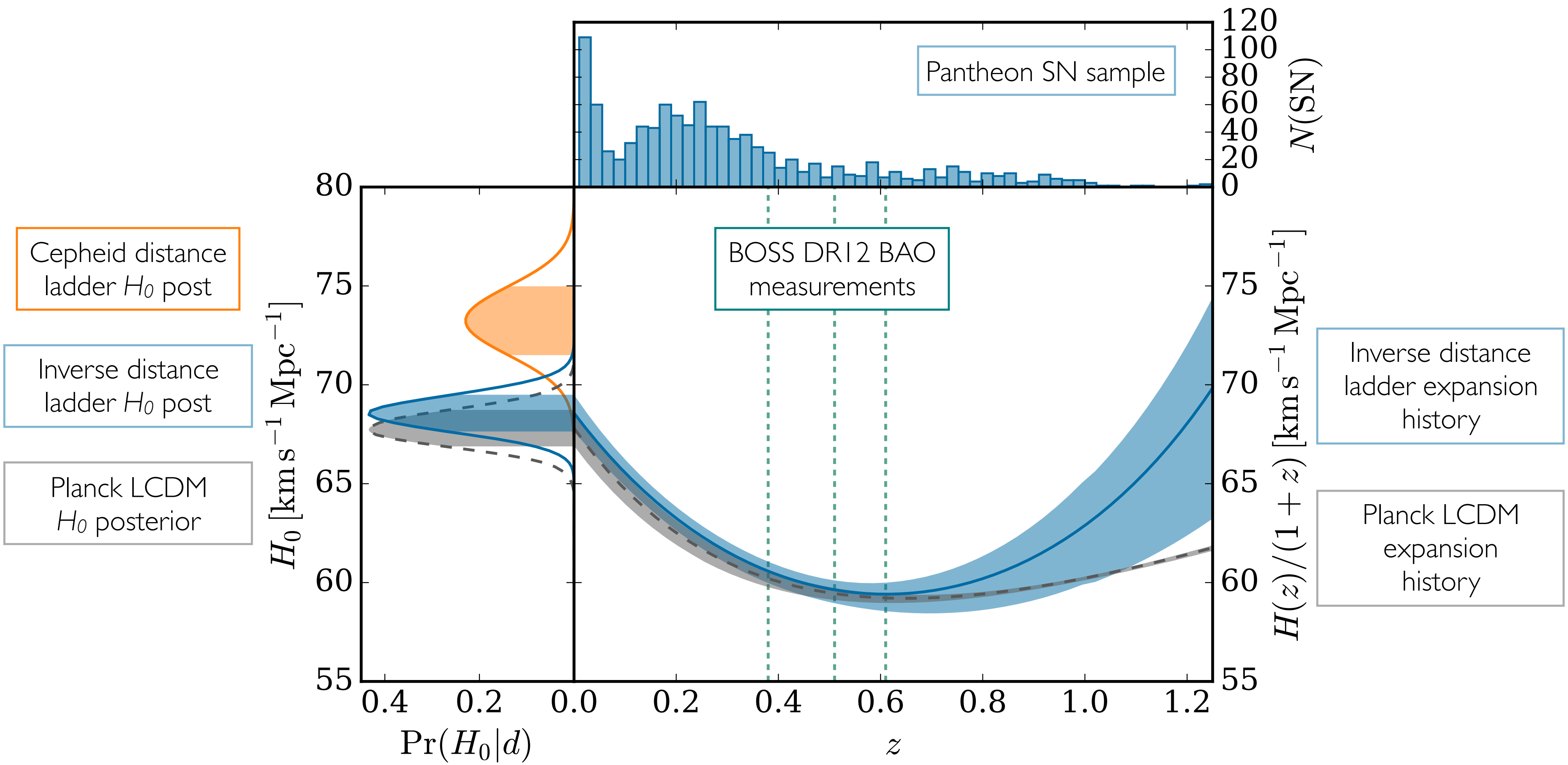
Quantifying tension with PPD

- Treat Cepheid distance ladder H_0 as data: $\hat{H}_0^{\mathrm{CDL}}$
- PPD: predicted sampling distribution of $\hat{H}_0^{\mathrm{CDL}}$ given Planck CMB data, LCDM
- Is SH_0ES measurement consistent with draw from PPD?
- Summarize tension using PPD(observed H_0) / max(PPD) = **<u>1/45</u>**



- NB: standard Gaussian 3-sigma threshold corresponds to **1/90**.

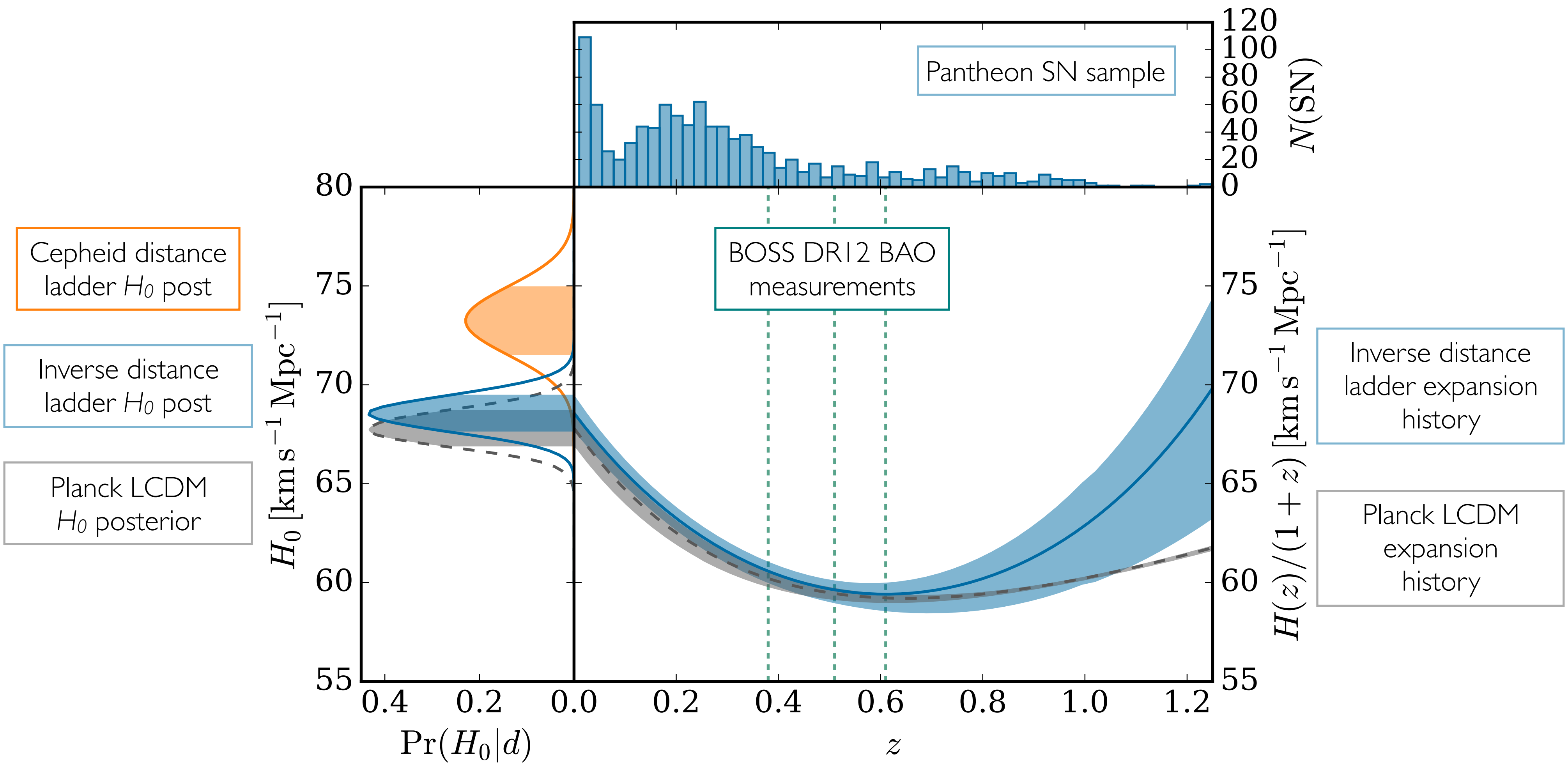
Can other data arbitrate?



- Inverse distance ladder: BOSS BAOs + Pantheon SNe (Scolnic+:1710.00845) + CMB drag scale from Planck
- Assume smooth expansion & pre-recombination physics only

Feeney et al (2018)

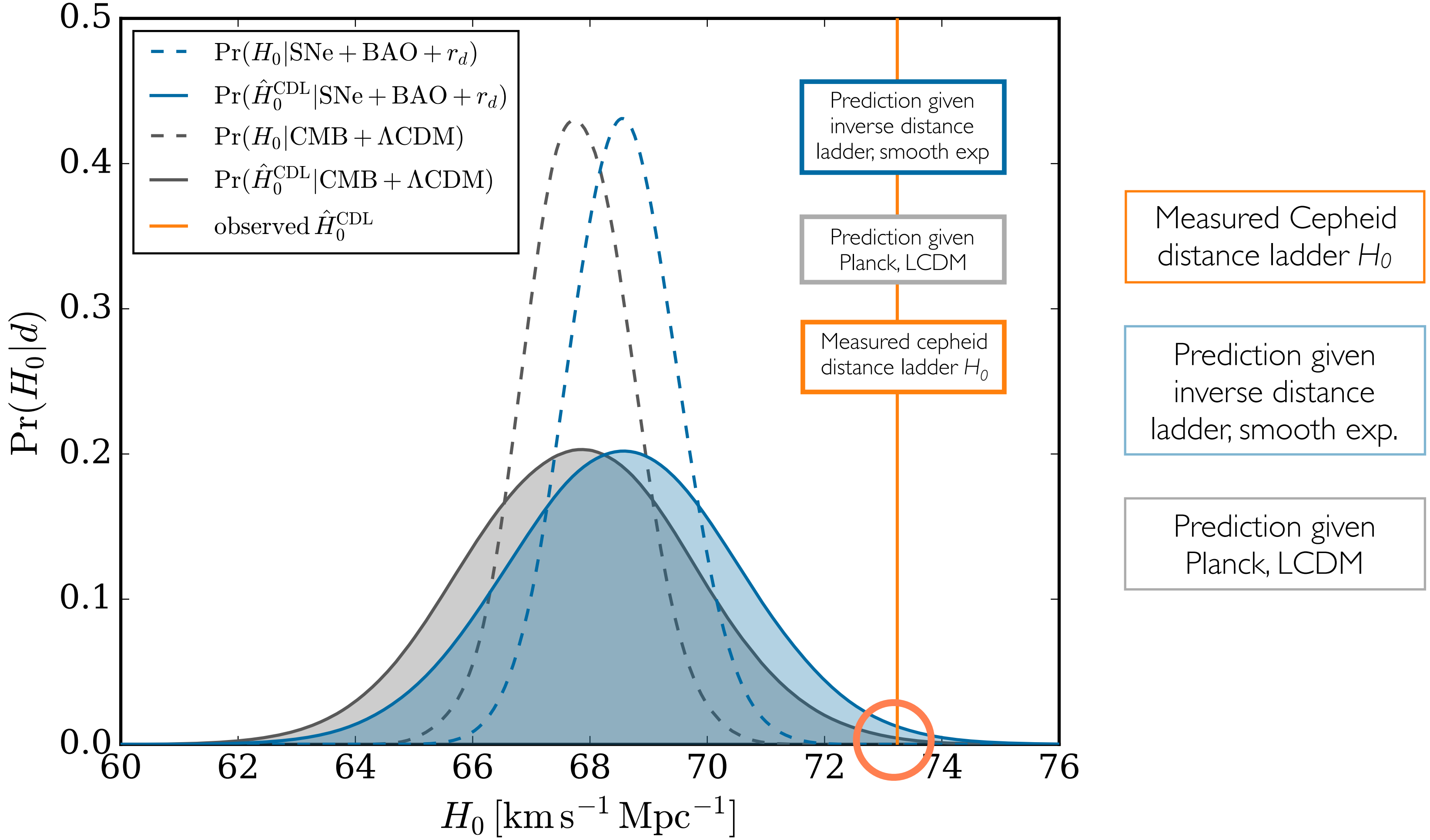
H_0 tension and inverse distance ladder



- Inverse distance ladder H_0 posterior agrees with Planck LCDM
- Distance ladders are in significant tension

Feeney et al (2018)

Quantifying tension: inverse distance ladder

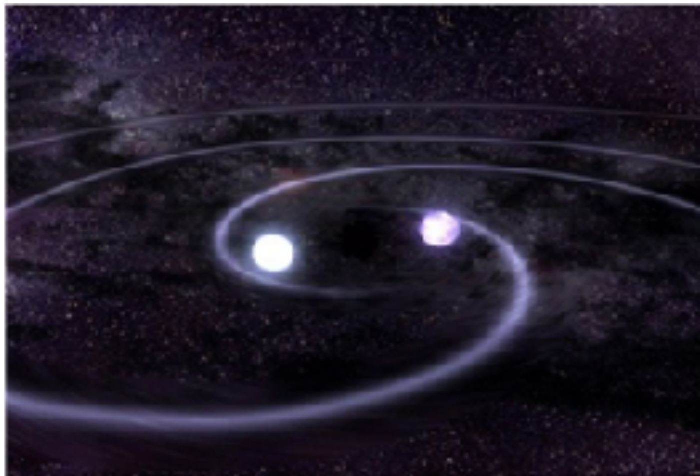


- Compute sampling distribution of $\hat{H}_0^{\mathrm{CDL}}$ given inverse distance ladder observations, assuming smooth expansion

- Summarize tension using PPD(observed H_0) / max(PPD) = **1/17**

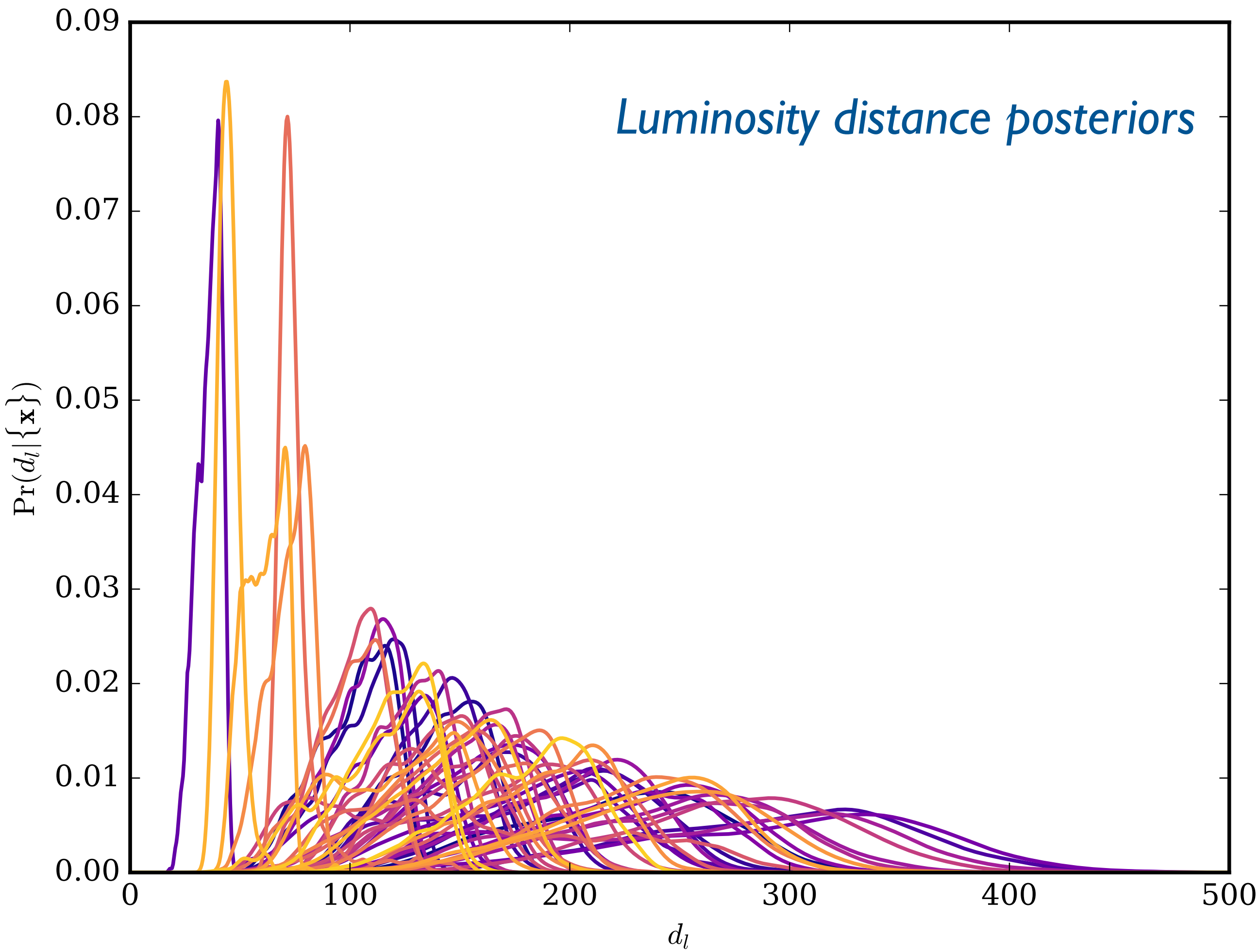
The story so far

- Two distance ladder measurements inconsistent with draw from same model
- But supernovae in common…
- New independent data to arbitrate tension? GW standard sirens!



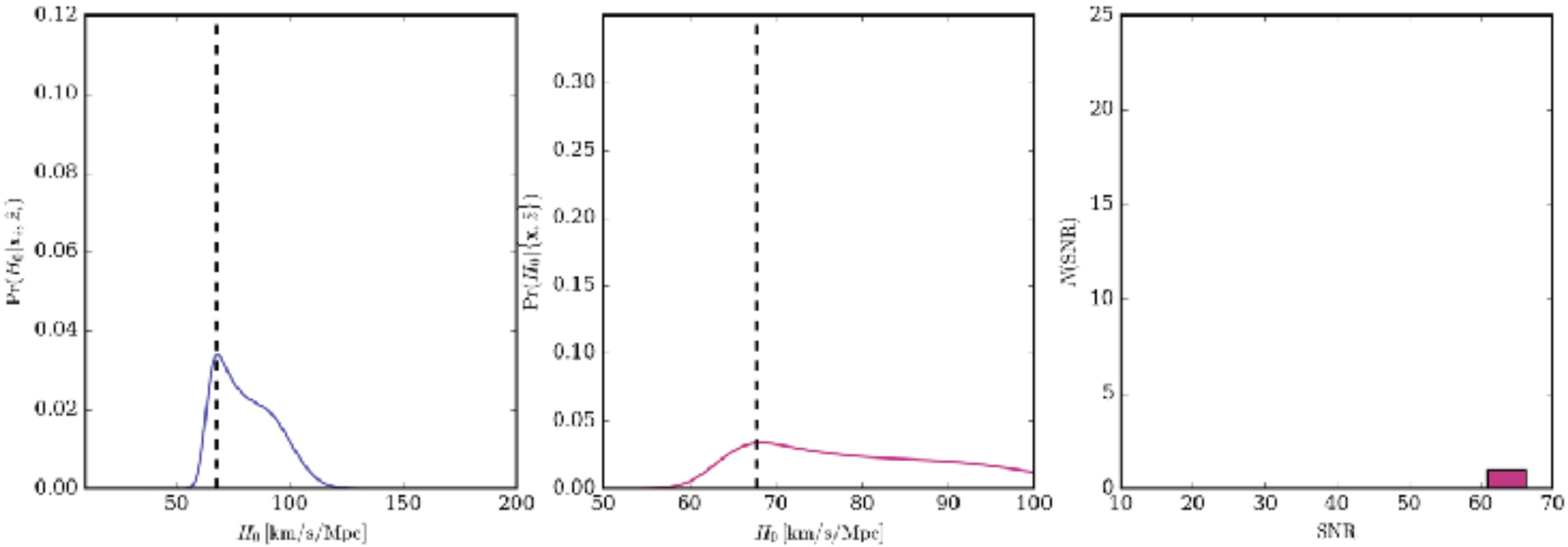
Arbitrating H_0 tension with GW standard sirens

- Simulate binary neutron star mergers w/ EM counterparts (angular position and redshift known)
- Four years of LIGO/Virgo, assuming R_{BNS}=1500/Gpc^3/yr
- Waveforms injected in coloured noise, analysed with lalinference_mcmc (Veitch+:1409.7215)
- 51 **detectable** events



Feeney et al (2018)

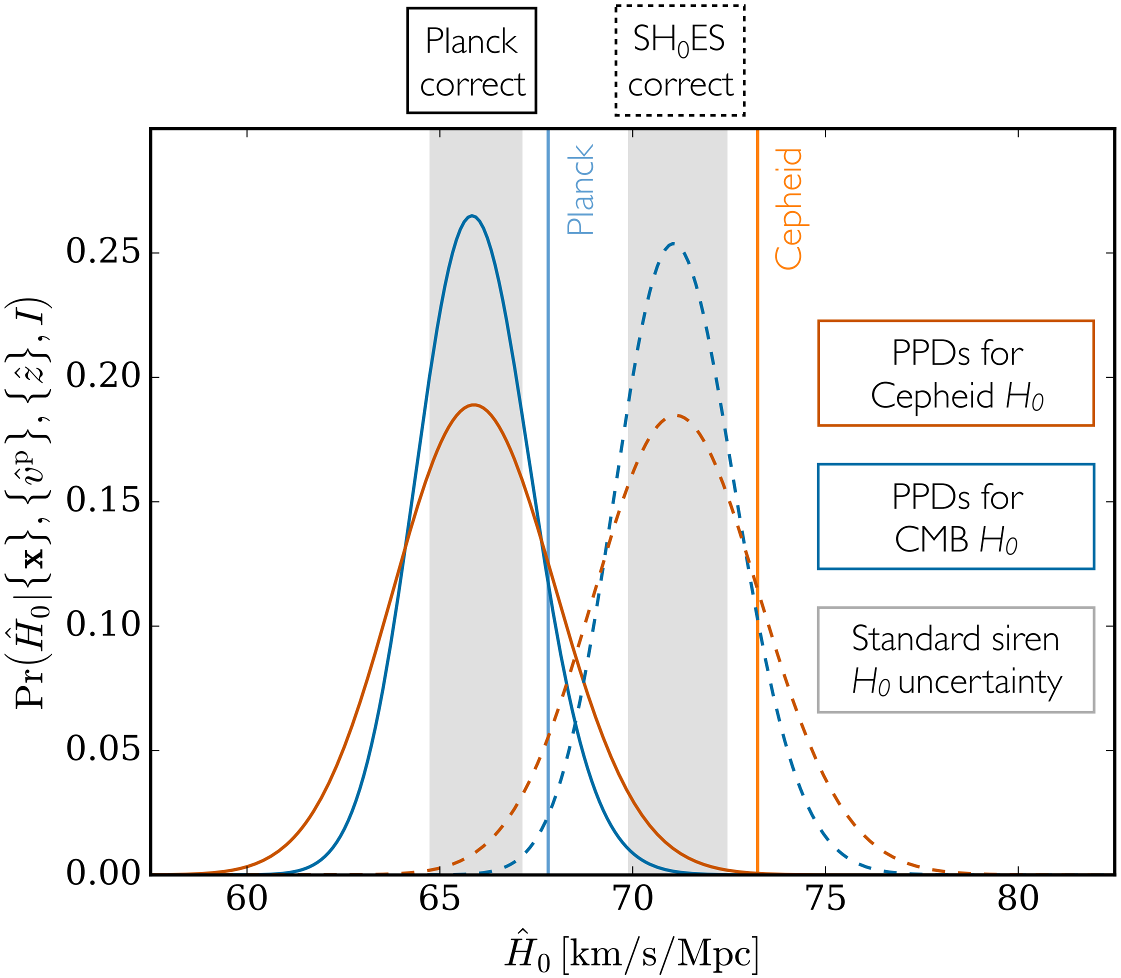
Arbitrating H_0 tension with GW standard sirens



- Compute H_0 posterior assuming perfect redshift measurements + Gaussian peculiar velocity likelihoods
- Sample of 51 mergers sufficient to arbitrate tension (though sample variance important)

Feeney et al (2018)

Arbitrating tension using standard sirens



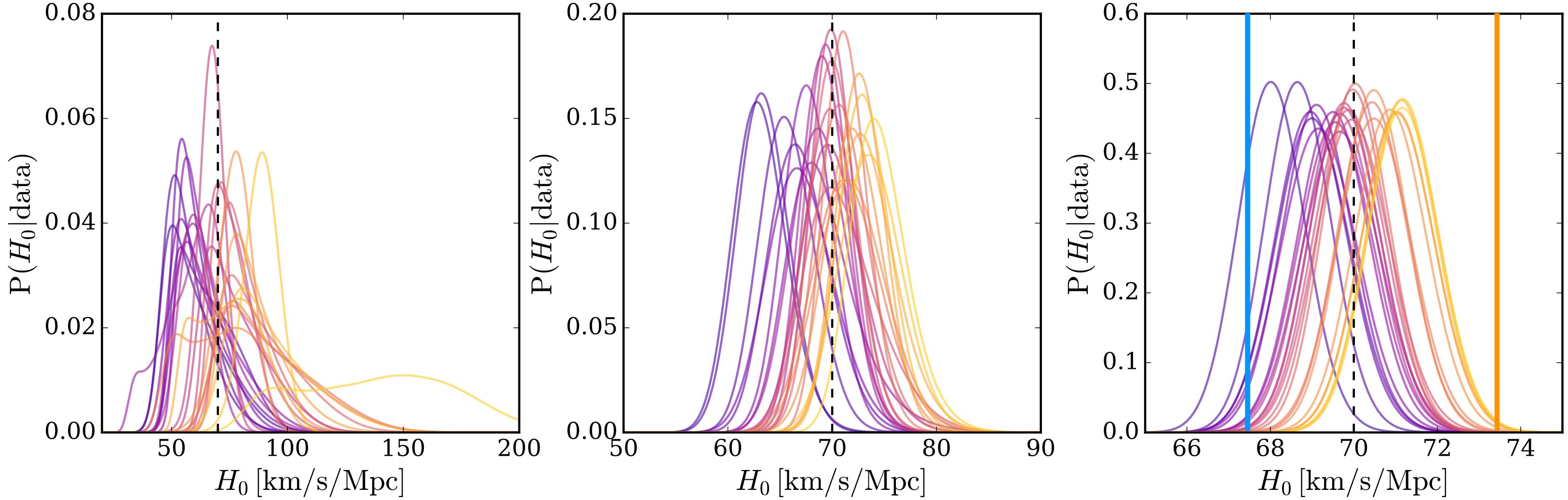
PPD Ratios

Obs. H_0 \ True H_0	Planck	CDL
Planck	1/2	1/10
CDL	1/300	1/2

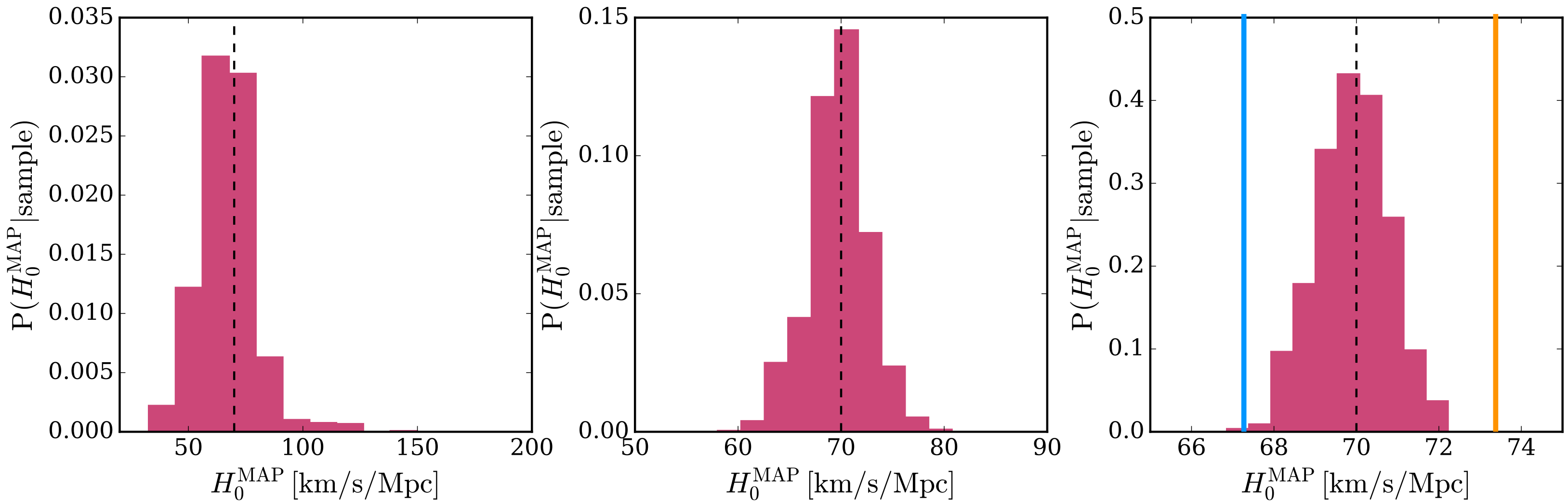
- Plotting PPD for CMB and Cepheid distance ladder given simulated standard siren sample and assumed H_0
- Sample of 51 mergers sufficient to arbitrate tension (though sample variance important)

Are H0 estimates from std siren samples unbiased?

sample size: 1 *sample size: 10* *sample size: 100*

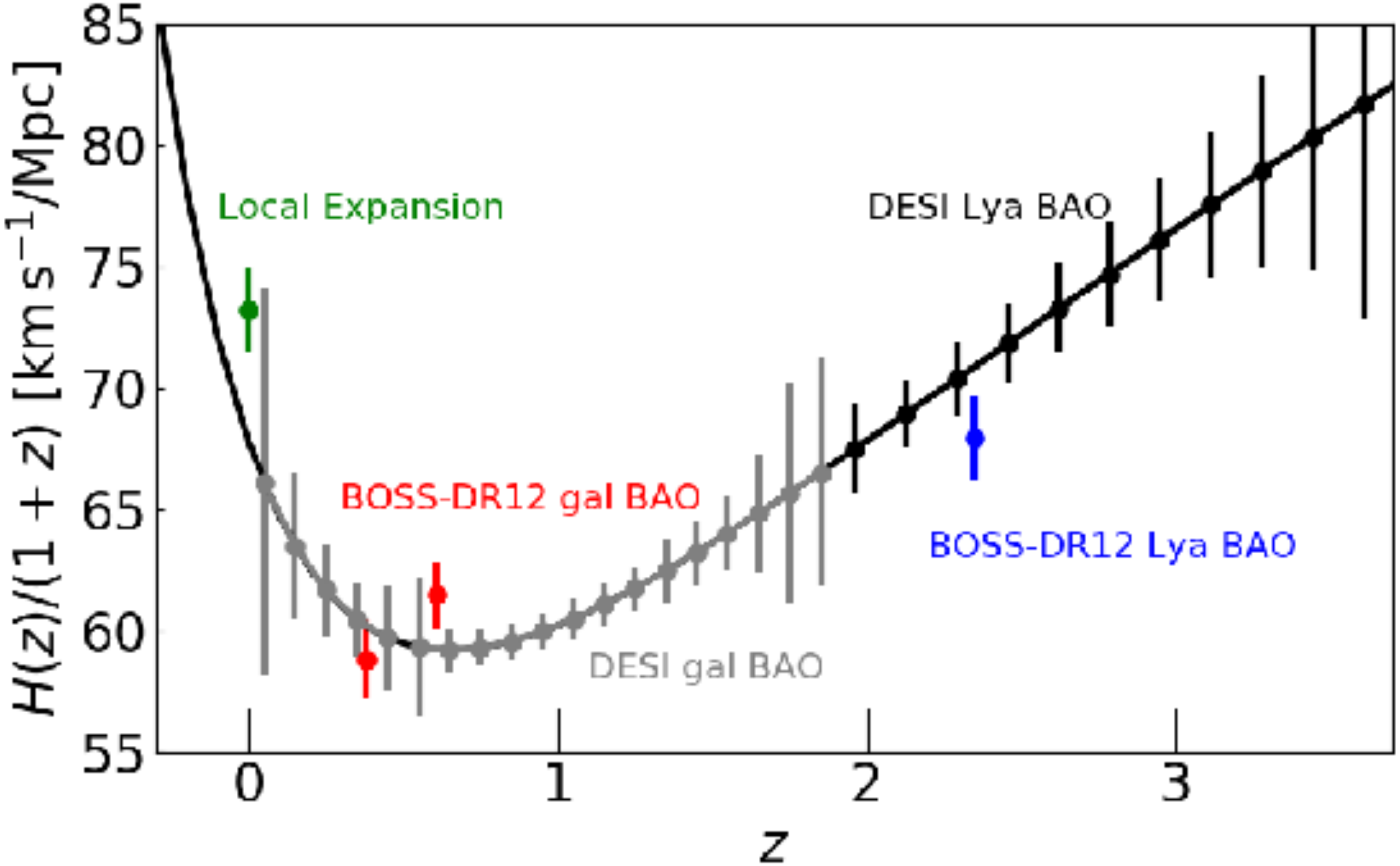


posteriors for 25 independent realisations



histograms of MAP estimates for 1000 simulated samples

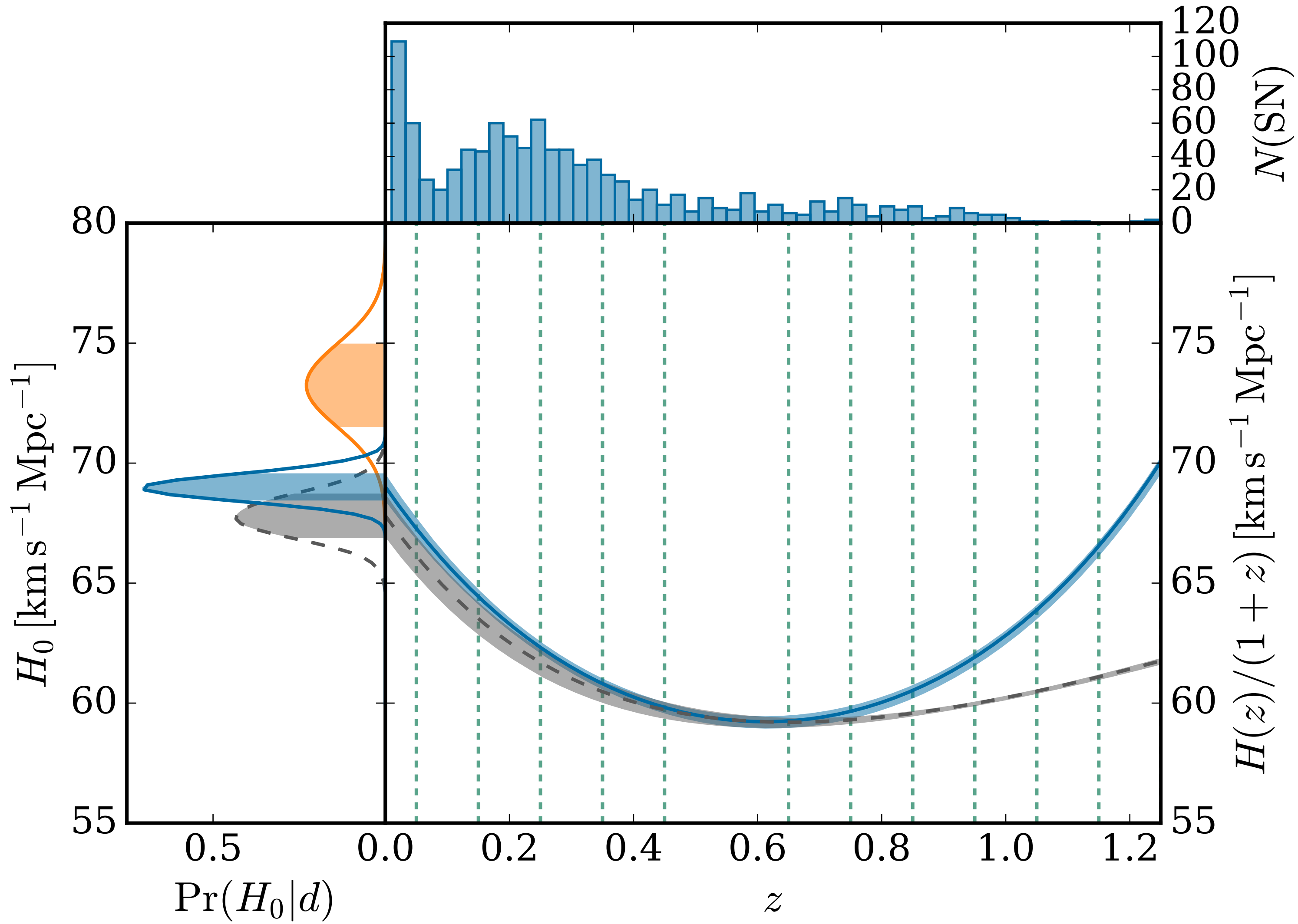
Mortlock et al (in prep)



DESI (first light 2019)

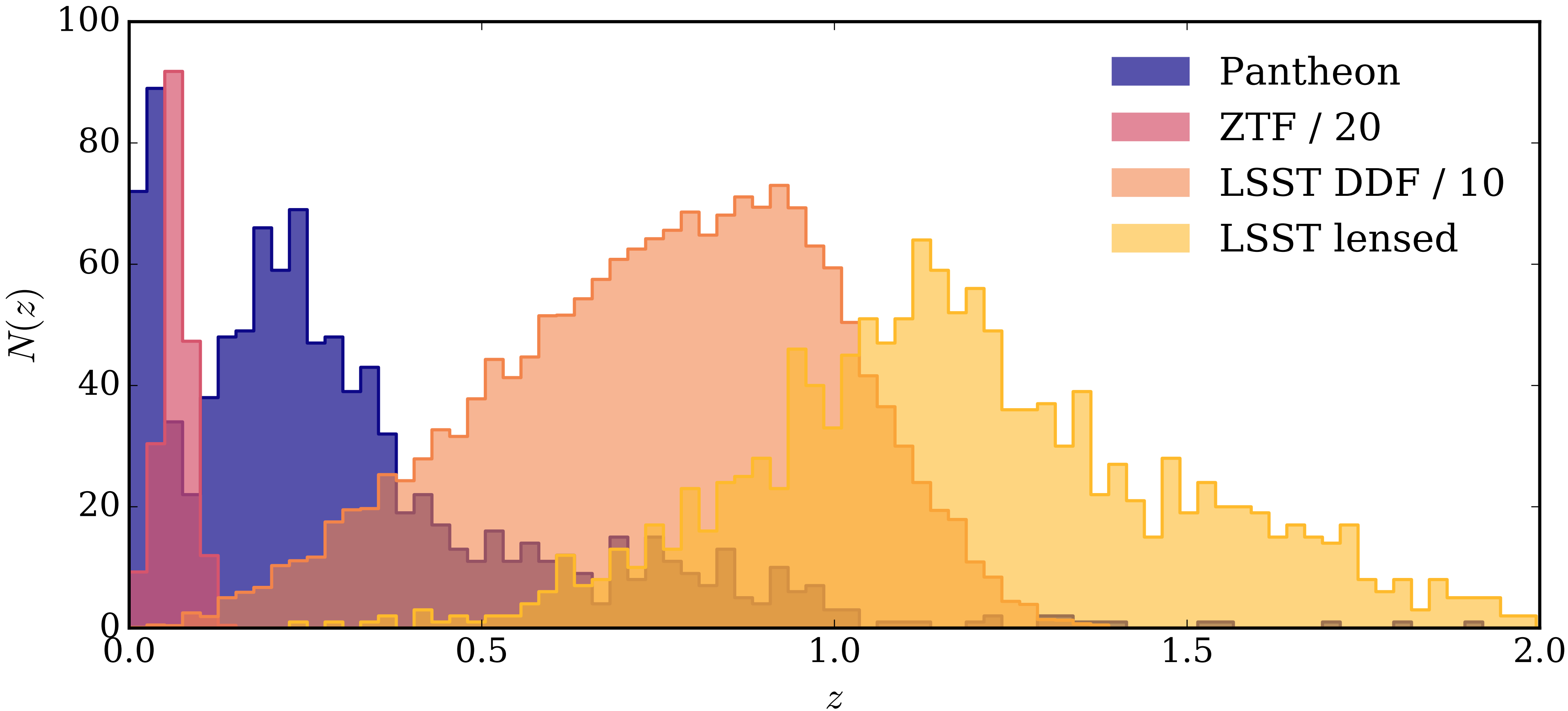
Forecasts: Font-Ribera et al (2014)

Inverse distance ladder and expansion history: prospects with DESI



Preliminary! w/ Feeney and Font-Ribera

Standard candles: prospects with ZTF and LSST



Preliminary! w/ Feeney, Biswas, Goldstein, Goobar, Scolnic

LSST survey of 18,000 sq deg

(half the sky)

- 4 billion galaxies (with photo-z)
- Time domain:
  - 5 million asteroids
  - 1 million supernovae
  - 1 million gravitational lenses
  - 100 million variable stars

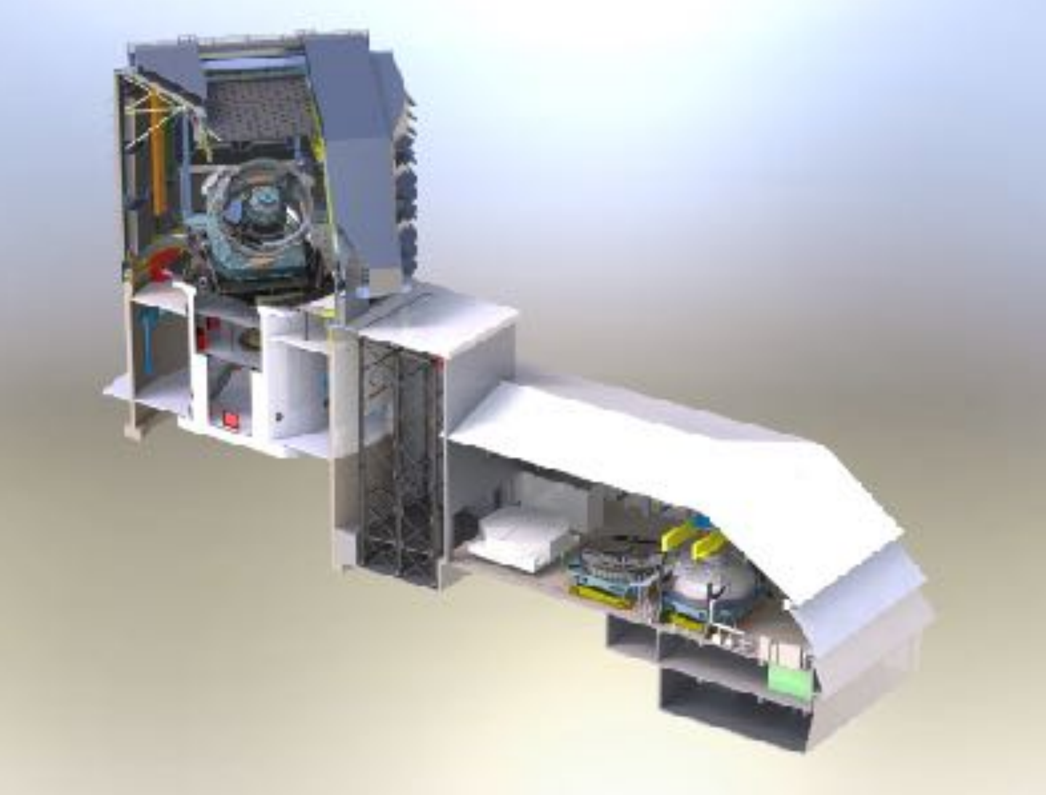
+ new phenomena

survey of 37 billion objects in space and time

Expand space-time volume a thousand times over current surveys!

BACKGROUND IMAGE CREDIT: UCL / PONTZEN

First light: 2019



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