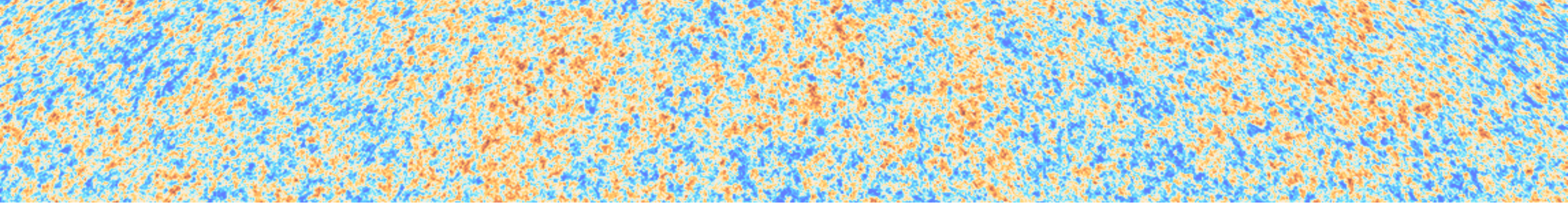


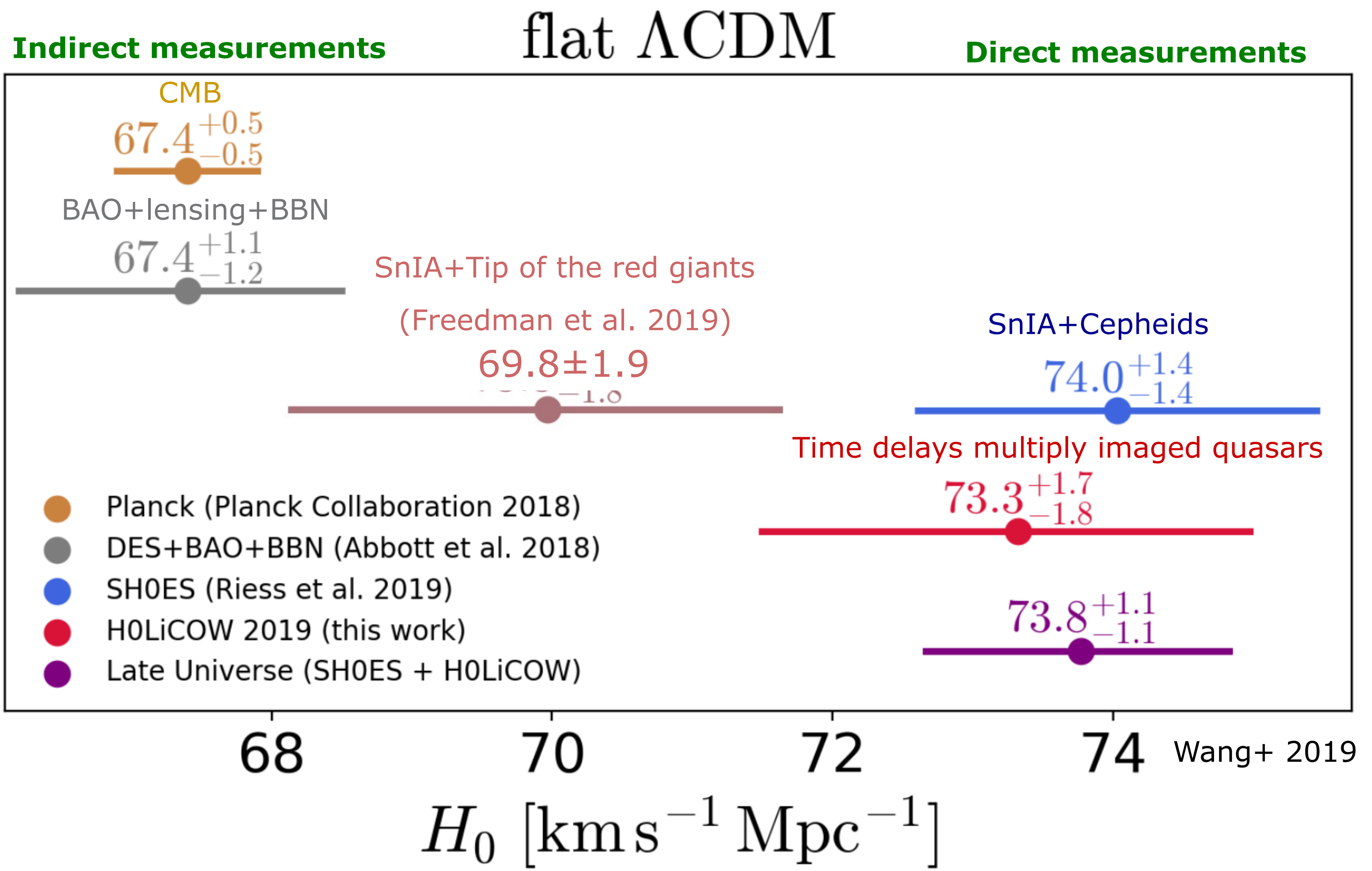
The H_0 debate (from a CMB prospective)

Silvia Galli

IAP

Paris 18/11/2019

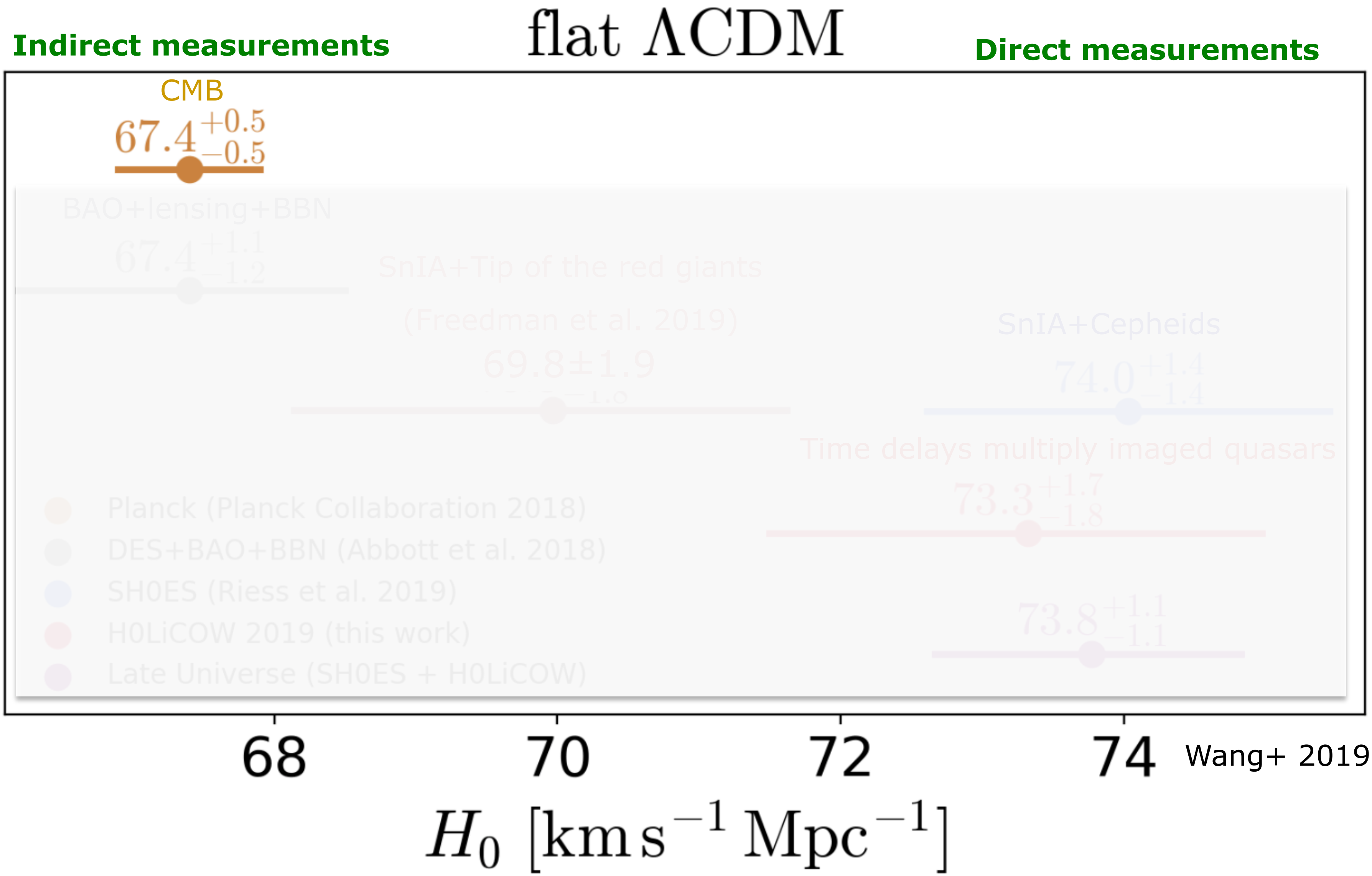
Strong tension between early and late universe probes of H_0.



Overview

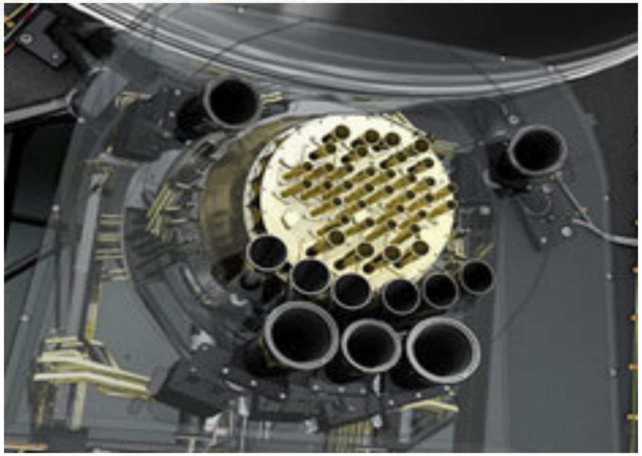
1. Measurements
    a. CMB measurements and indirect
    b. BAO results
    c. SnIa
    d. Tip of the Red giants
    e. Quasar results
    f. Tip of the Red giants
2. Systematics?
3. Physical interpretations:
    a. Late versus Early solutions.
    b. Neutrino, Early dark energy.

CMB



flat ΛCDM
Indirect measurements
Direct measurements
CMB
$67.4^{+0.5}_{-0.5}$
BAO+lensing+BBN
$67.4^{+1.1}_{-1.2}$
SnIA+Tip of the red giants
(Freedman et al. 2019)
69.8±1.9
SnIA+Cepheids
$74.0^{+1.4}_{-1.4}$
Time delays multiply imaged quasars
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]
Wang+ 2019

The Planck satellite



3rd generation full sky satellites (COBE, WMAP)
Launched in 2009, operated till 2013.
2 Instruments, 9 frequencies.

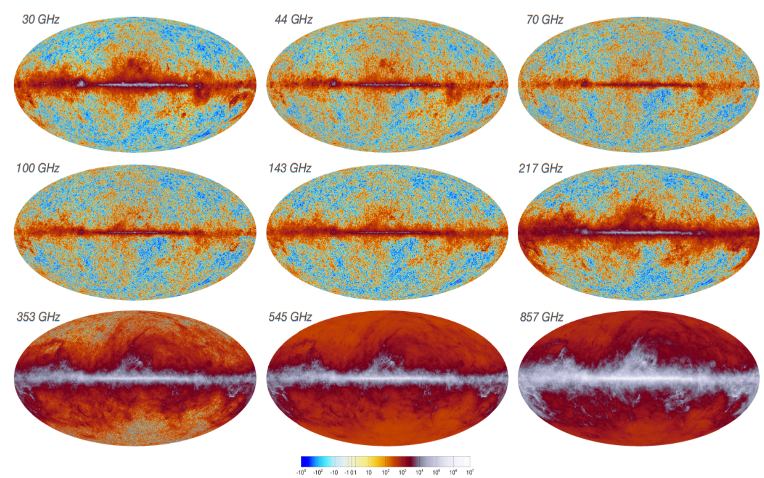
LFI:
- 22 radiometers at **30, 44, 70 Ghz.**

HFI:
- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**
- **30-353 Ghz polarized.**

- **1st release 2013: Nominal mission**, 15.5 months, Temperature only (large scale polarization from WMAP).

- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization, large scale pol. from LFI.
  Intermediate results 2016: low-l polarization from HFI

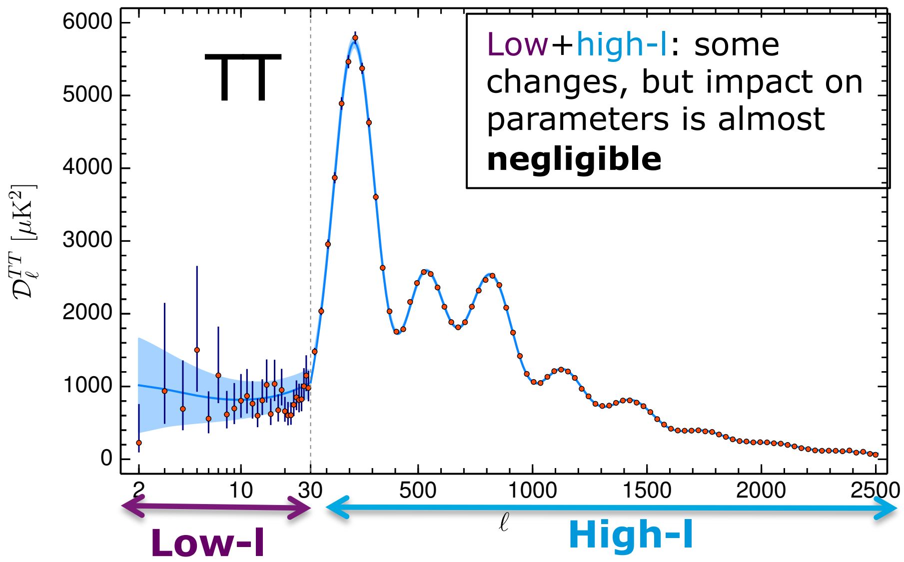
- **3nd release 2018: Full mission, improved polarization, low/high-l from HFI.** Better control of systematics specially in pol., still systematics limited.

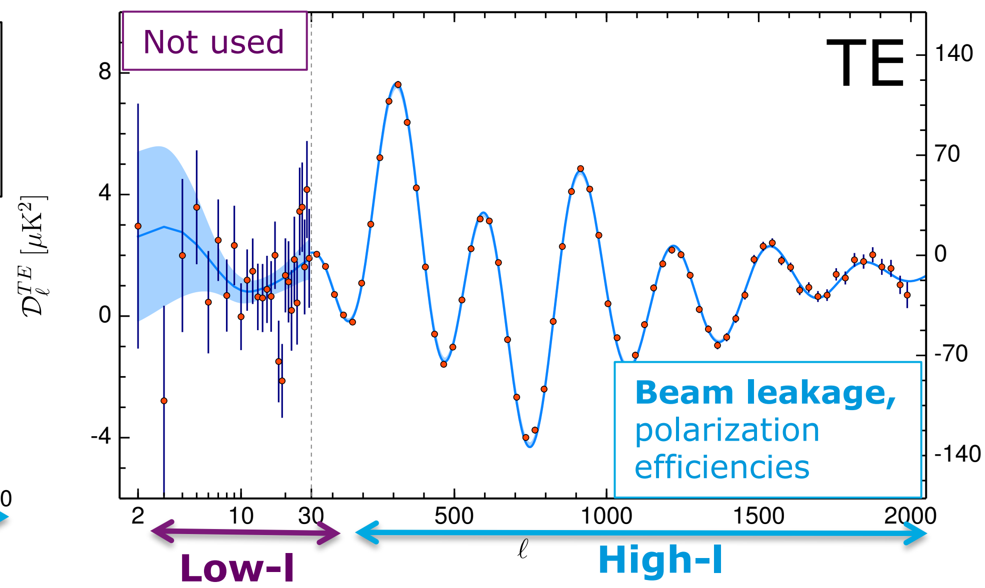


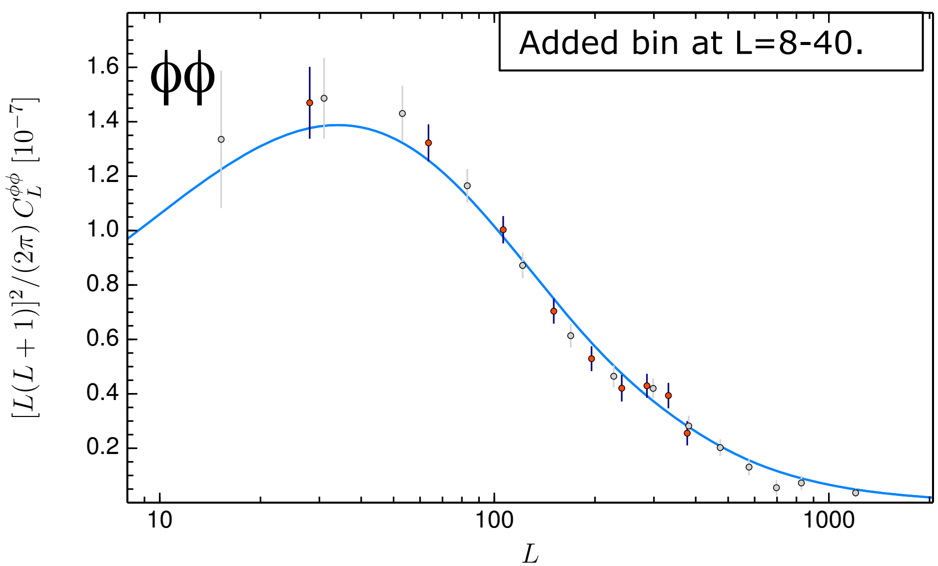
2018 Power spectra

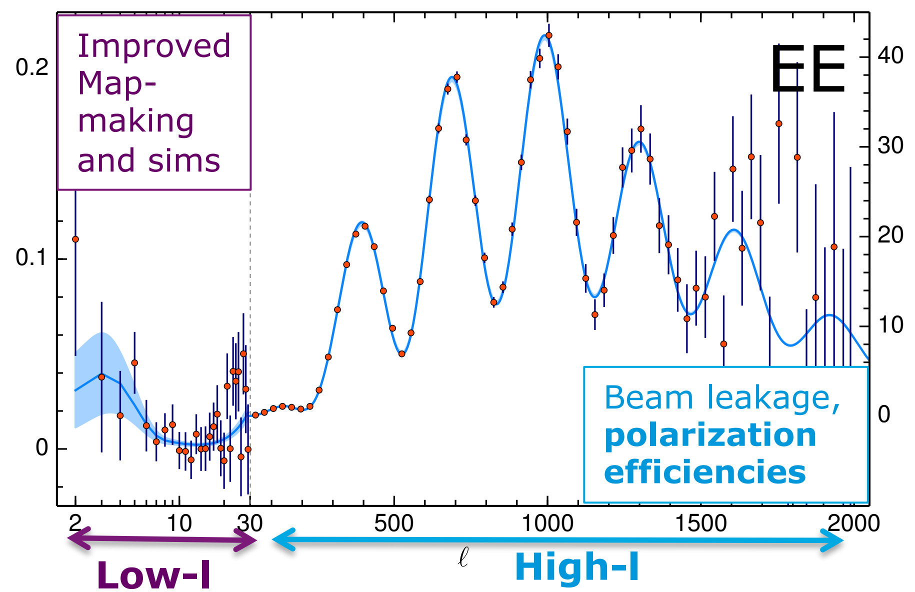
TT, TE, EE: different likelihoods at low-l (<30) and high-l (>30).

Better systematics modeling in polarization

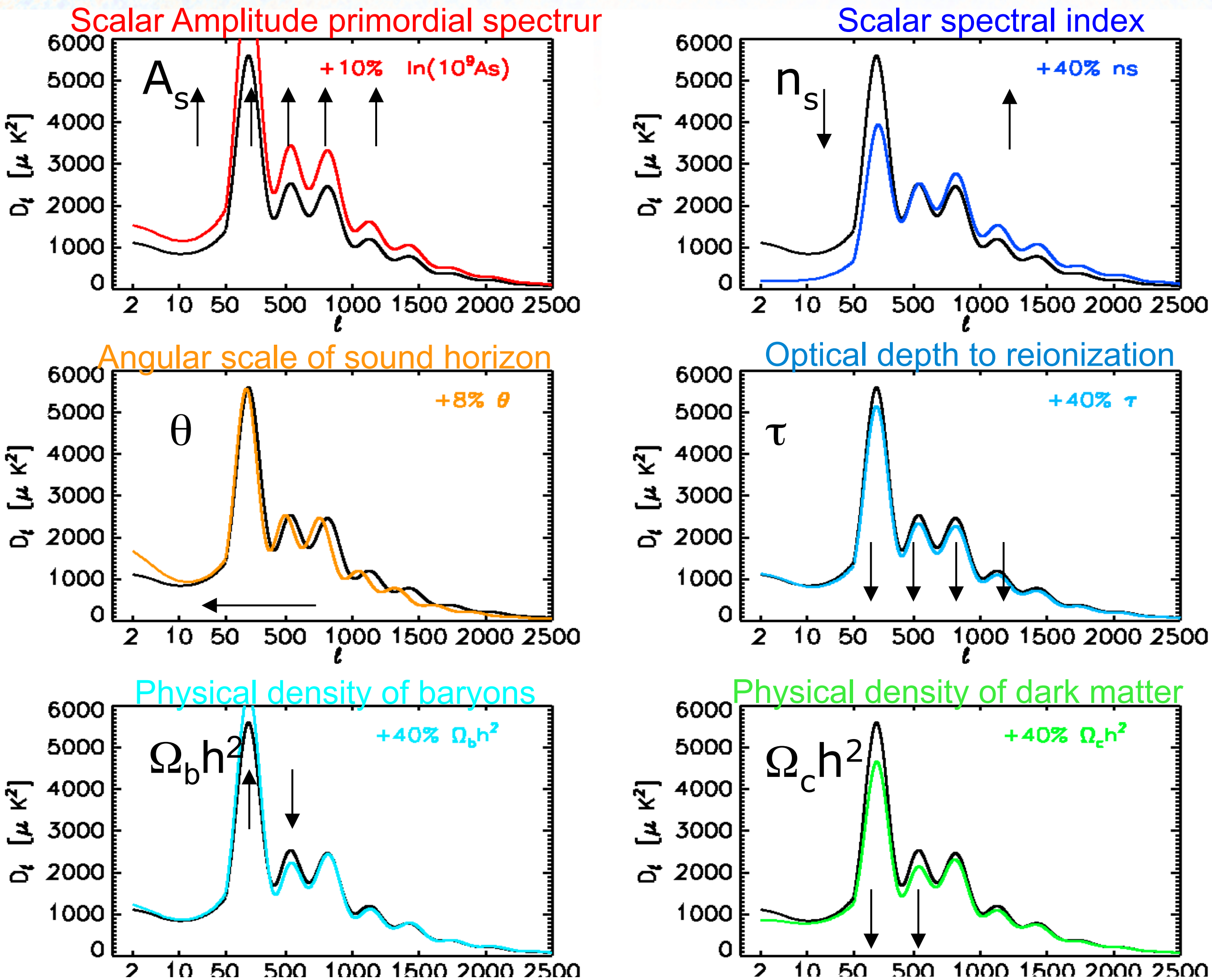








6 ΛCDM parameters



- Initial conditions A_s, n_s:

$$\boxed{\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}}$$

- Acoustic scale of sound horizon θ
- Reionization τ

- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:

- Adiabatic initial conditions
- Neff=3.046
- 1 massive neutrino 0.06eV.
- Tanh reionization (Δz=0.5)

planck

Baseline ΛCDM results 2018

(Temperature+polarization+CMB lensing)

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s\, 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

Robust against changes of likelihood, <0.5σ.

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales.
- n_s is 8σ away from scale invariance (even in extended models, always >3σ)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

Indirect measurement of the Hubble constant from the CMB

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks

$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$$\boxed{H^2(z) = \mathbf{H_0}^2(\Omega_m (z+1)^3 + \Omega_{DE} + ..)}$$

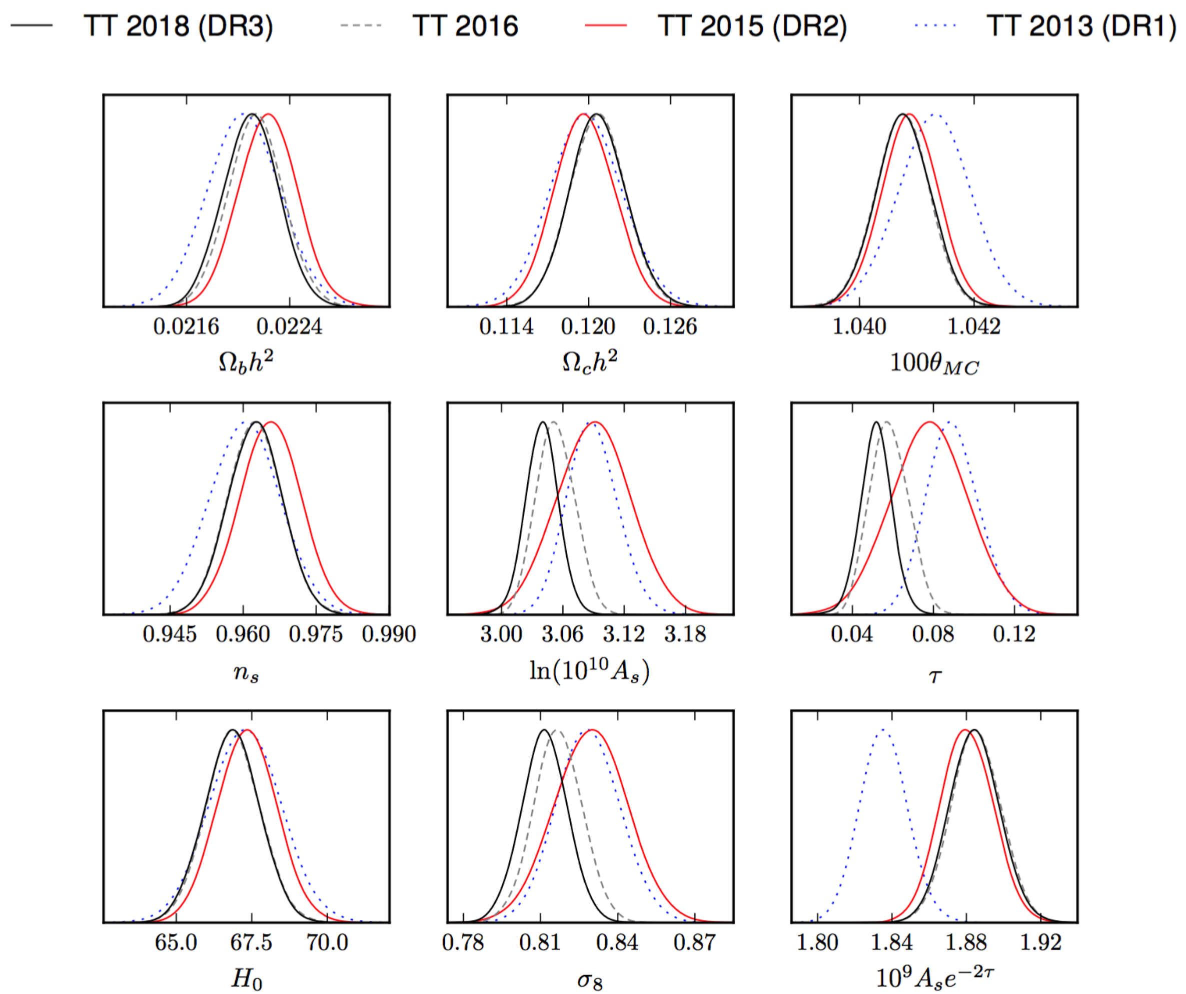
Model dependent!

Take away message stable across releases

Changes across releases compatible with statistical fluctuations.

ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

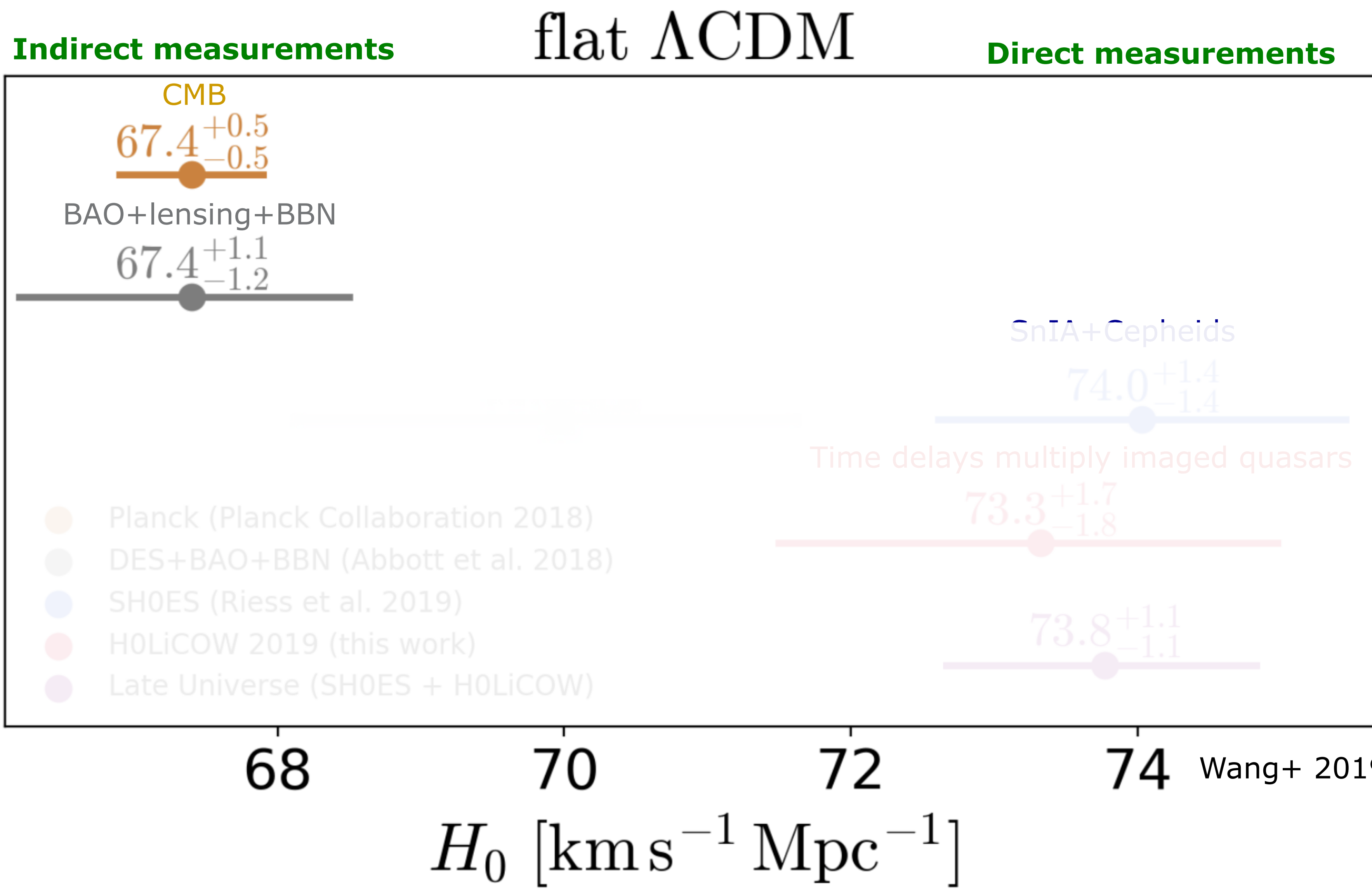
Just a few (2-3σ) curiosities.



No extension of LCDM where H_0 is high from Planck data alone

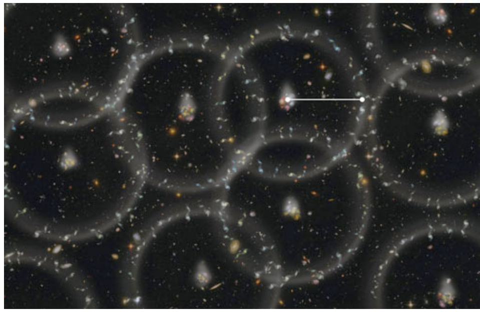
Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

BAO



Wang+ 2019

Indirect measurement of the Hubble constant from the BAO



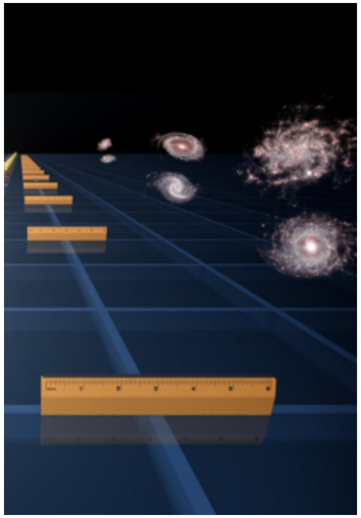
Baryon acoustic oscillation scale imprint in galaxy distribution.

BAO only measures angular dimension of sound horizon at baryon drag at different redshifts.

Need CALIBRATION: calculate r_s assuming a model.

In LCDM, this means that BAO depends on ω_m, $H_{0,}$ and ω_b

Need measurements at different z to break degeneracy ω_m-$H_{0,}$ and need ω_b to calculate r_s



Standard ruler

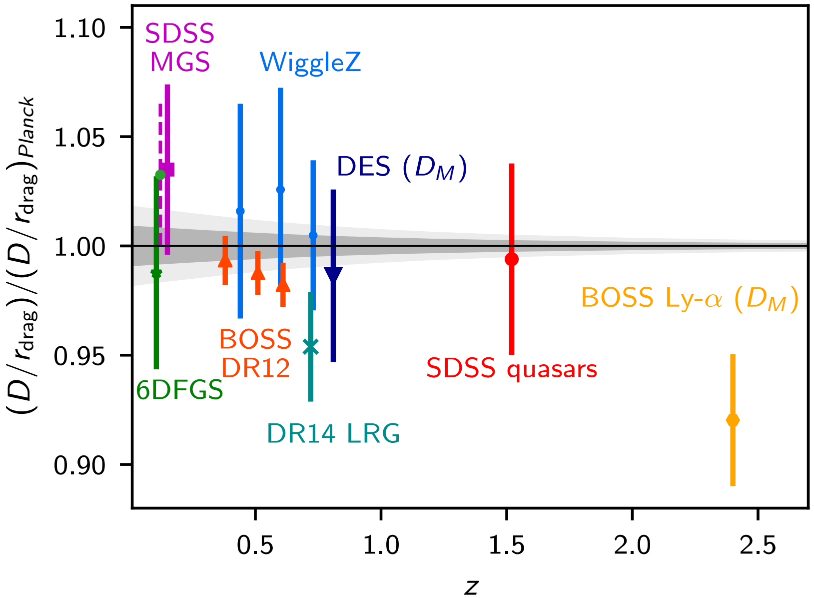
known size

+

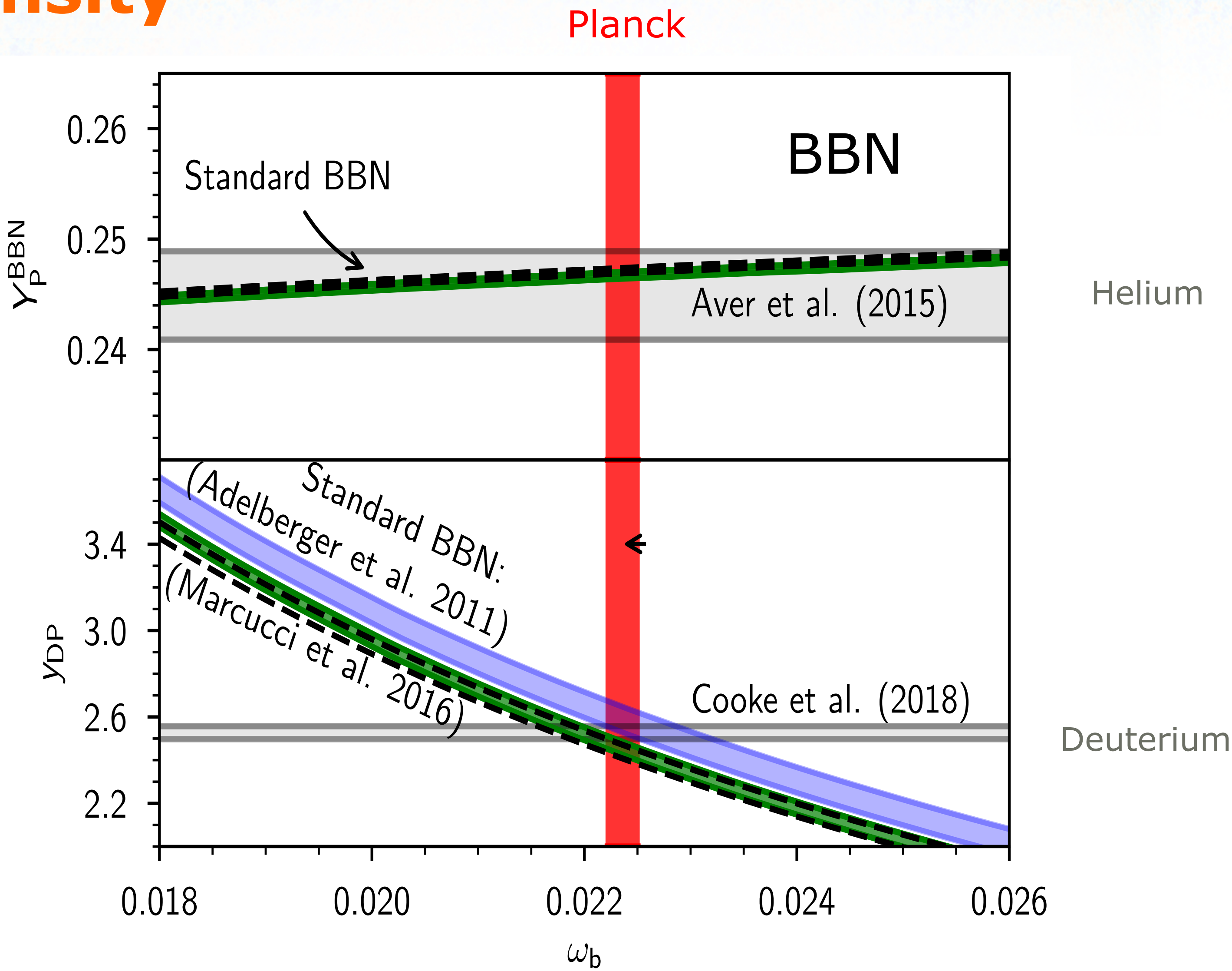
measure apparent size

↓

distance

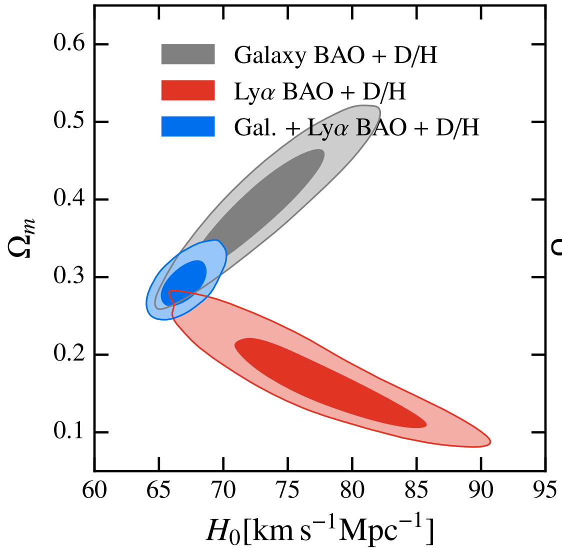


BBN calculations of the baryon density



Planck collaboration 2018

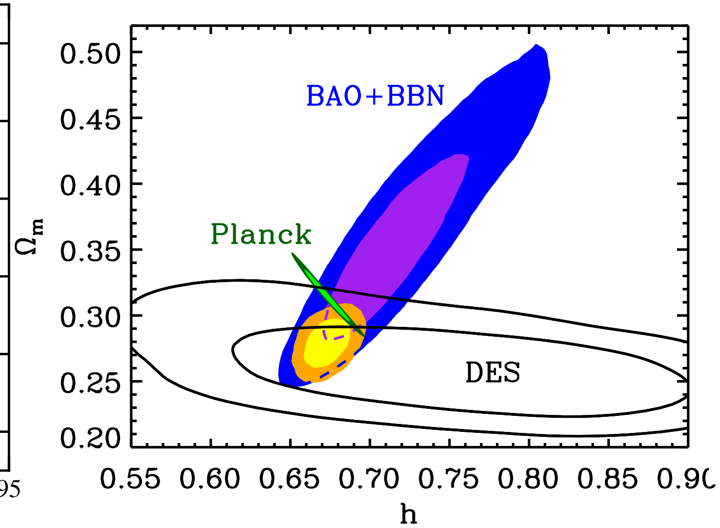
BAO and H_0



Gal BAO+Ly BAO+D/H

H0=66.98 ± 1.1

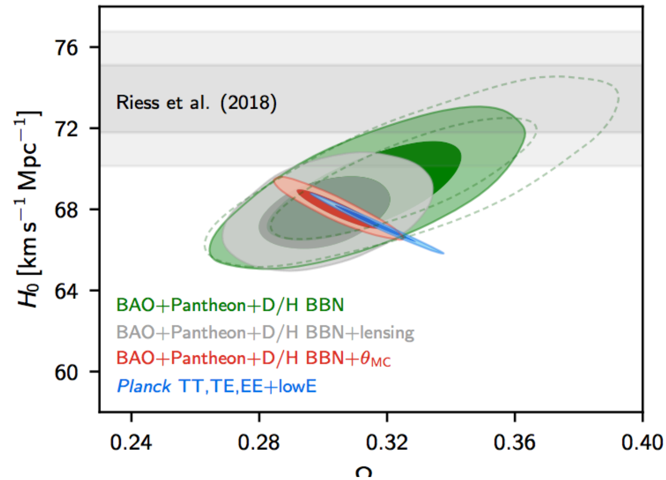
Addison+ 2018



Clustering+weak lensing+ Gal BAO+D/H

H0=67.4+-1.1

DES collaboration 2017



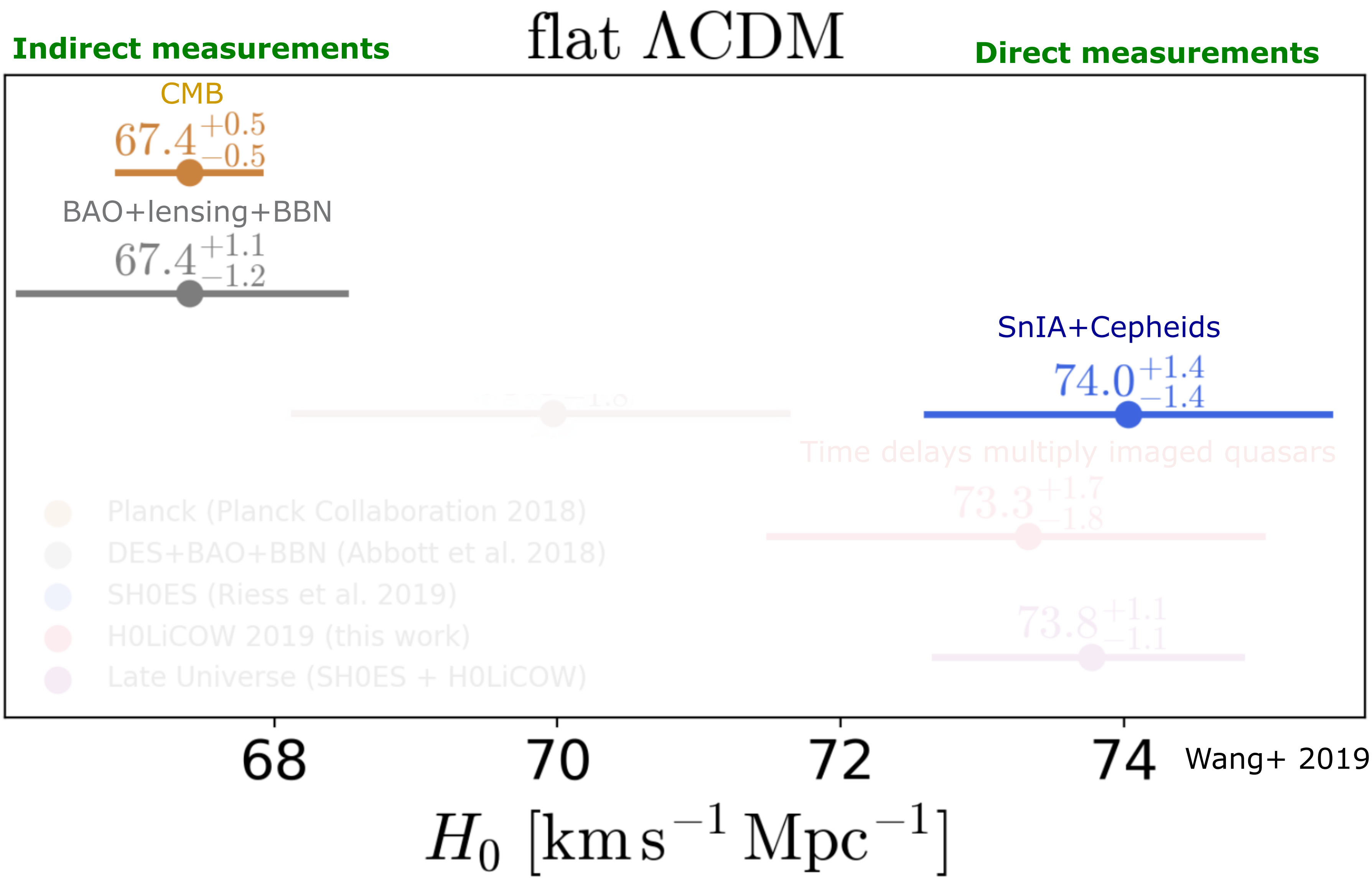
Gal BAO+D/H+Supernovae +theta$_{CMB}$

H0=67.9 ± 0.8

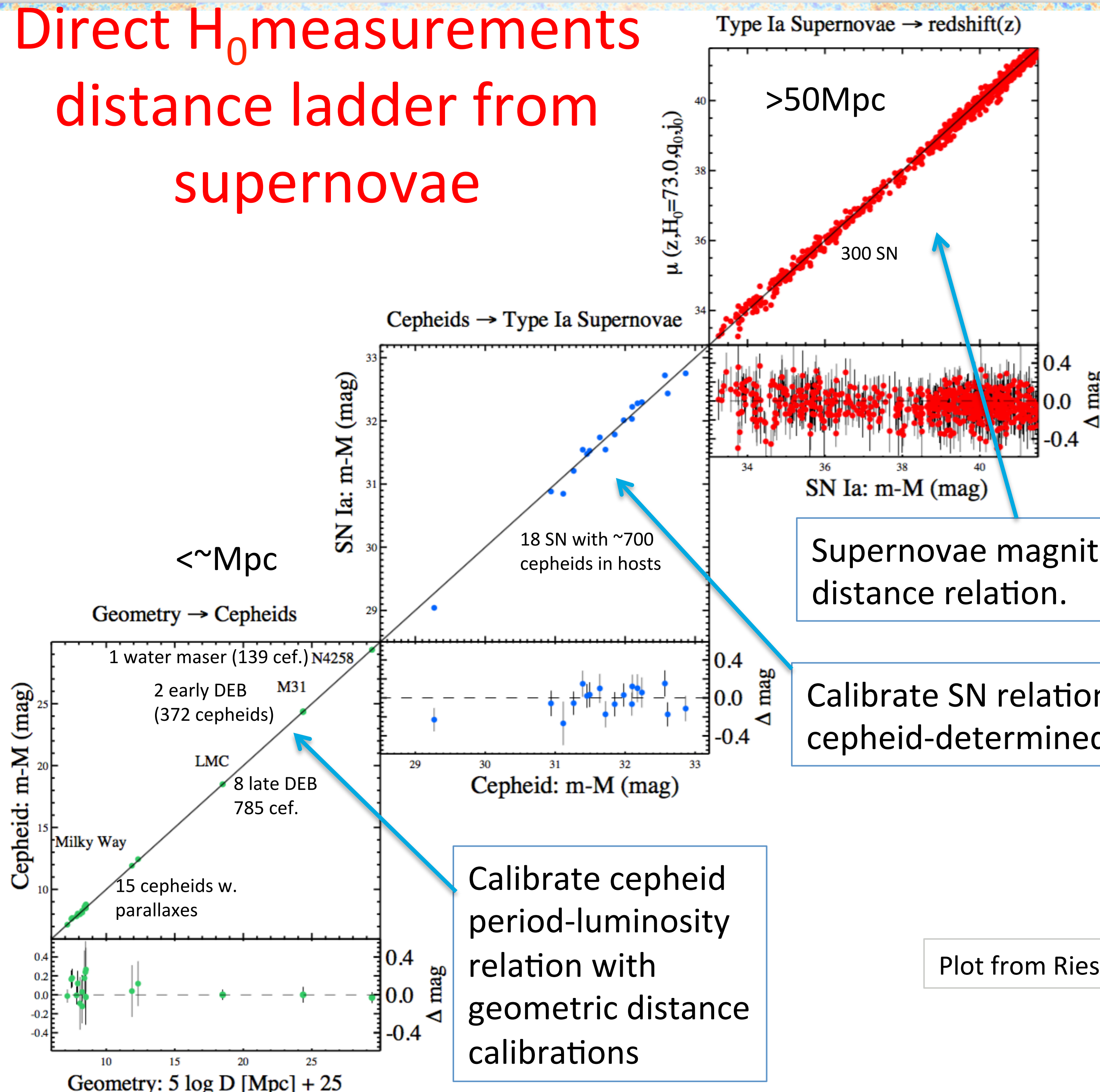
Planck collaboration 2018

- BAO measure a combination of Ω_m and H_0 r_d, with the degeneracy evolving with z (Galaxy BAO z~0.1-0.6, Lyα BAO z~2.3)
- To break H_0 r_d(to "calibrate" the BAO), r_d from CMB or deuterium+BBN.

Supernovae+Cepheids



Direct H_0 measurements distance ladder from supernovae



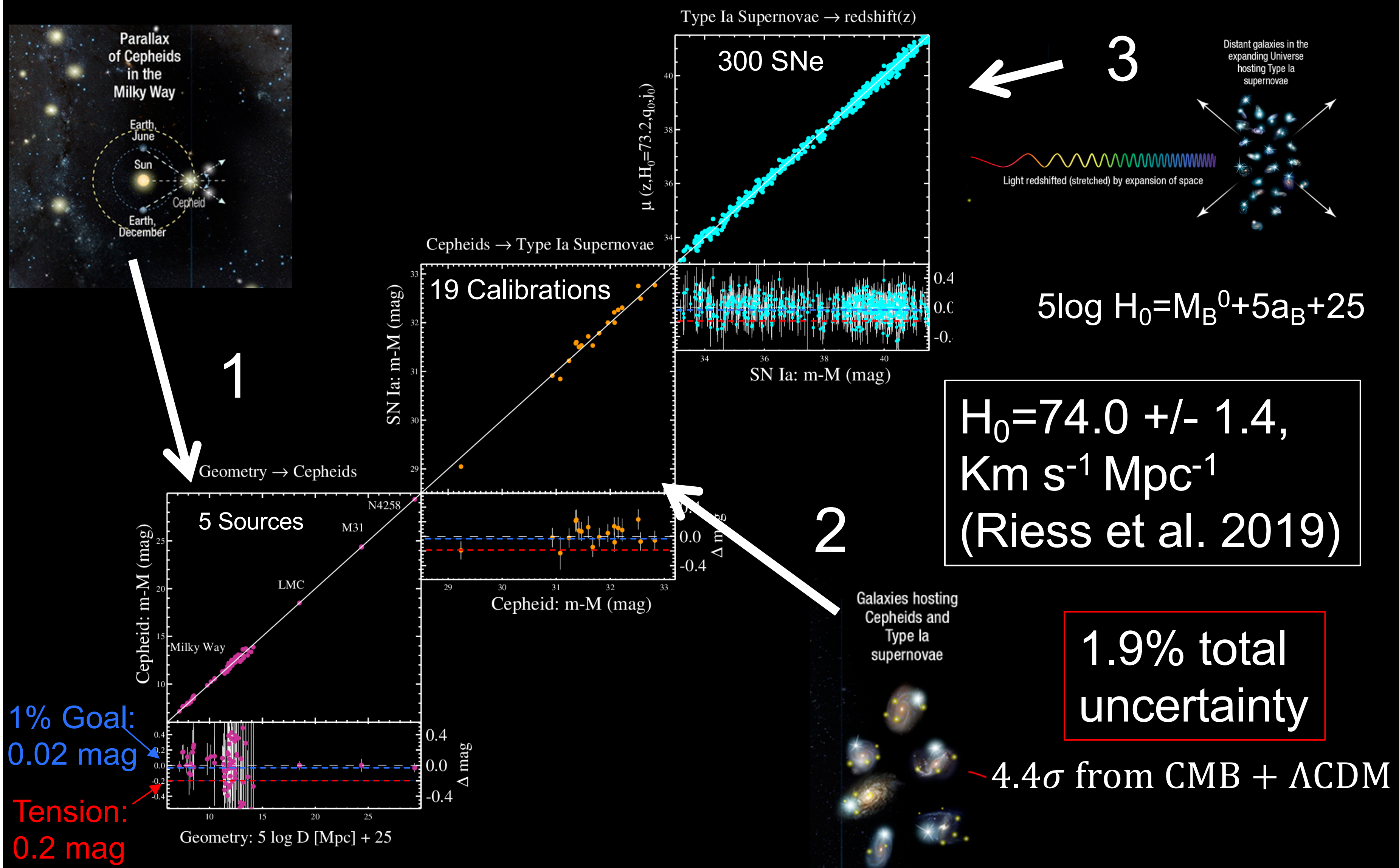
Supernovae magnitude-distance relation.

Calibrate SN relation with cepheid-determined distances

Calibrate cepheid period-luminosity relation with geometric distance calibrations

Plot from Riess 2016

The Hubble Constant in 3 Steps: Present Data



$5\log H_0 = M_B^0 + 5a_B + 25$

$H_0 = 74.0 \pm 1.4$, Km s^{-1} Mpc^{-1} (Riess et al. 2019)

1.9% total uncertainty

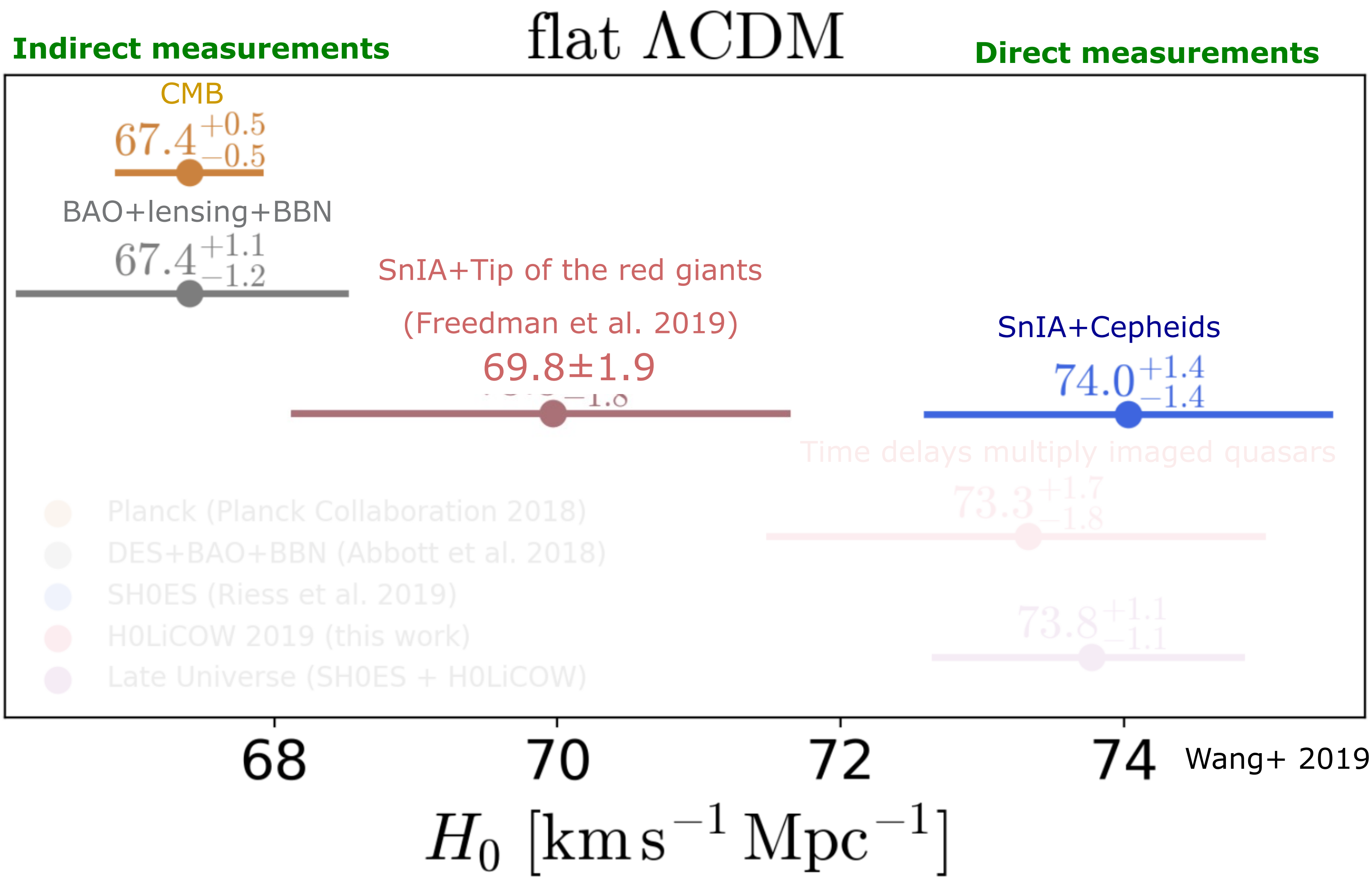
4.4σ from CMB + ΛCDM !

Credit:A. Riess 2019

Local anchors

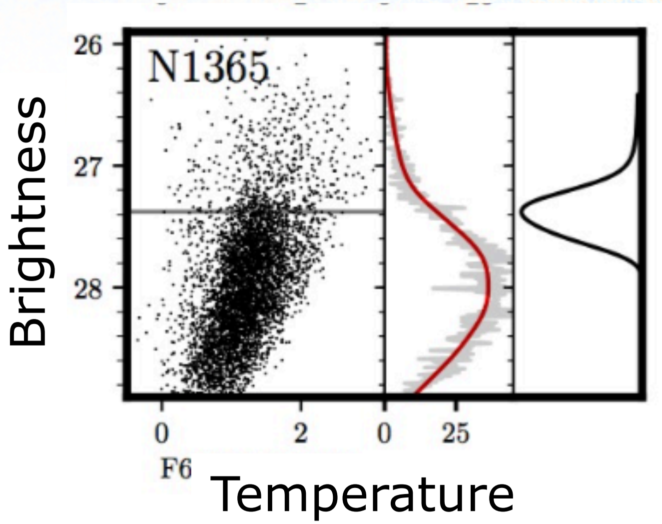
Independent Geometric Source	σ	H_0
NGC 4258 $H_2$0 Masers: Humphreys et al 2013, Riess et al 2016 Reid et al. (2019)	~~2.6%~~ 1.5%	~~72.3~~ ~72.0
LMC 20 Late Detached Eclipsing Binaries: Pietzrynski et al. 2019 +70 HST LMC Cepheids Riess et al (2019)	1.3%	74.2
Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018	3.3%	75.7
Milky Way 50 Gaia+HST, Long P Parallaxes: Riess et al. 2018	3.3%	73.7

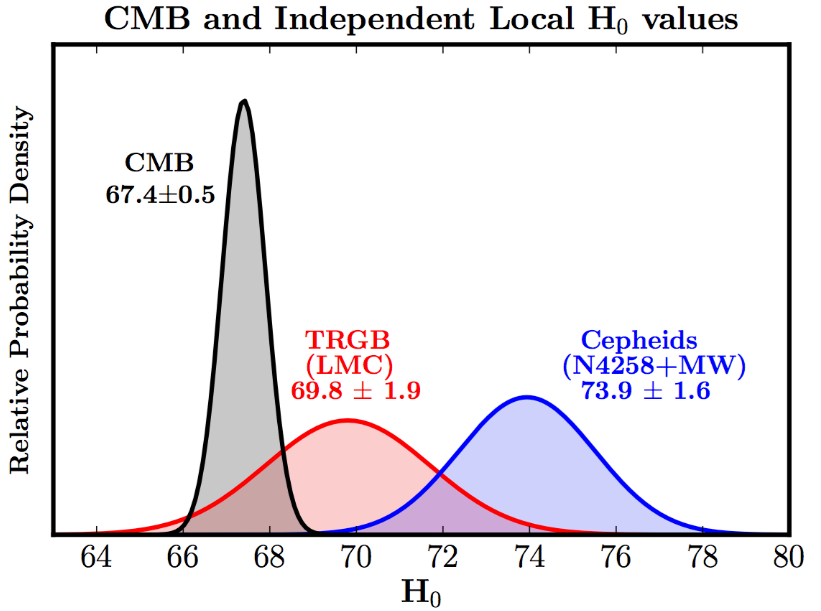
Supernovae+Tip of the red Giants



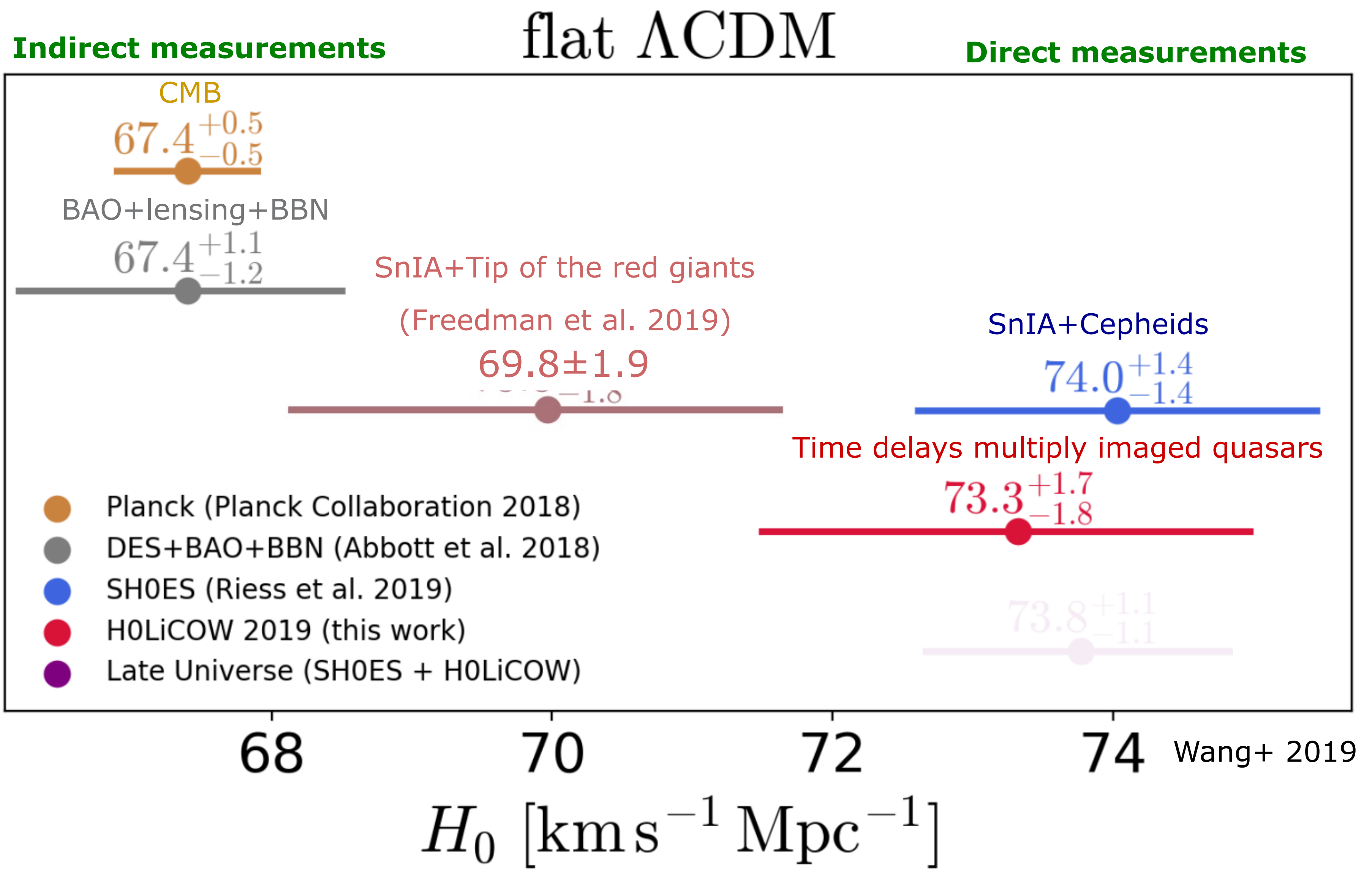
Tip of the red giants branch

- Measure of the position of the brightest **luminosity** of Red Giants before helium flash (when helium core starts fusion), which is used as a standard candle.
- Used instead of cepheids to calibrate SnIA in second rung of the ladder.
- Brightness calibrated by measuring TRGB in the LMC, whose distance is determined from detached eclipsing binaries.
- CCHP program uses Carnegie Supernova Project I (CSP-I) sample containing about 100 well- observed SNe Ia, independent of Sh0ES program.
- In agreement both with Planck (1.2σ) and SnIA+cepheids (1.7σ).

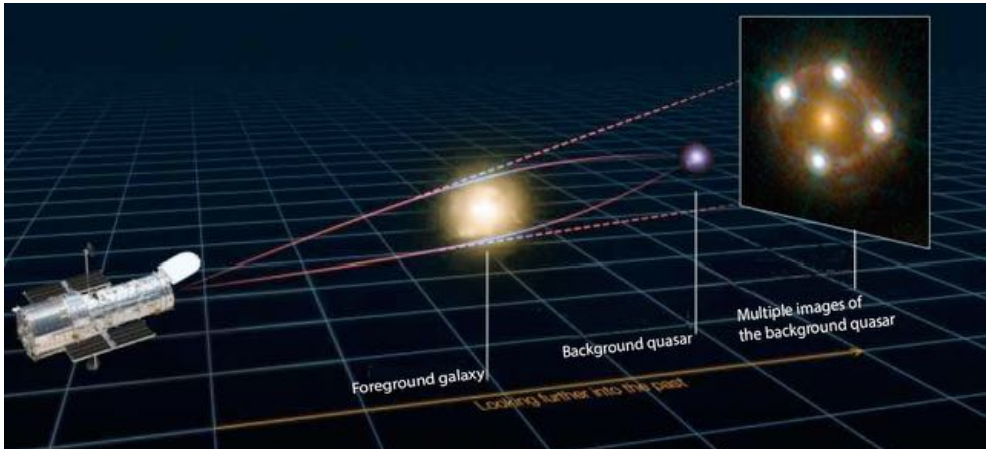




Time dealys of multiply imaged quasars



Time delays of multiply imaged quasars



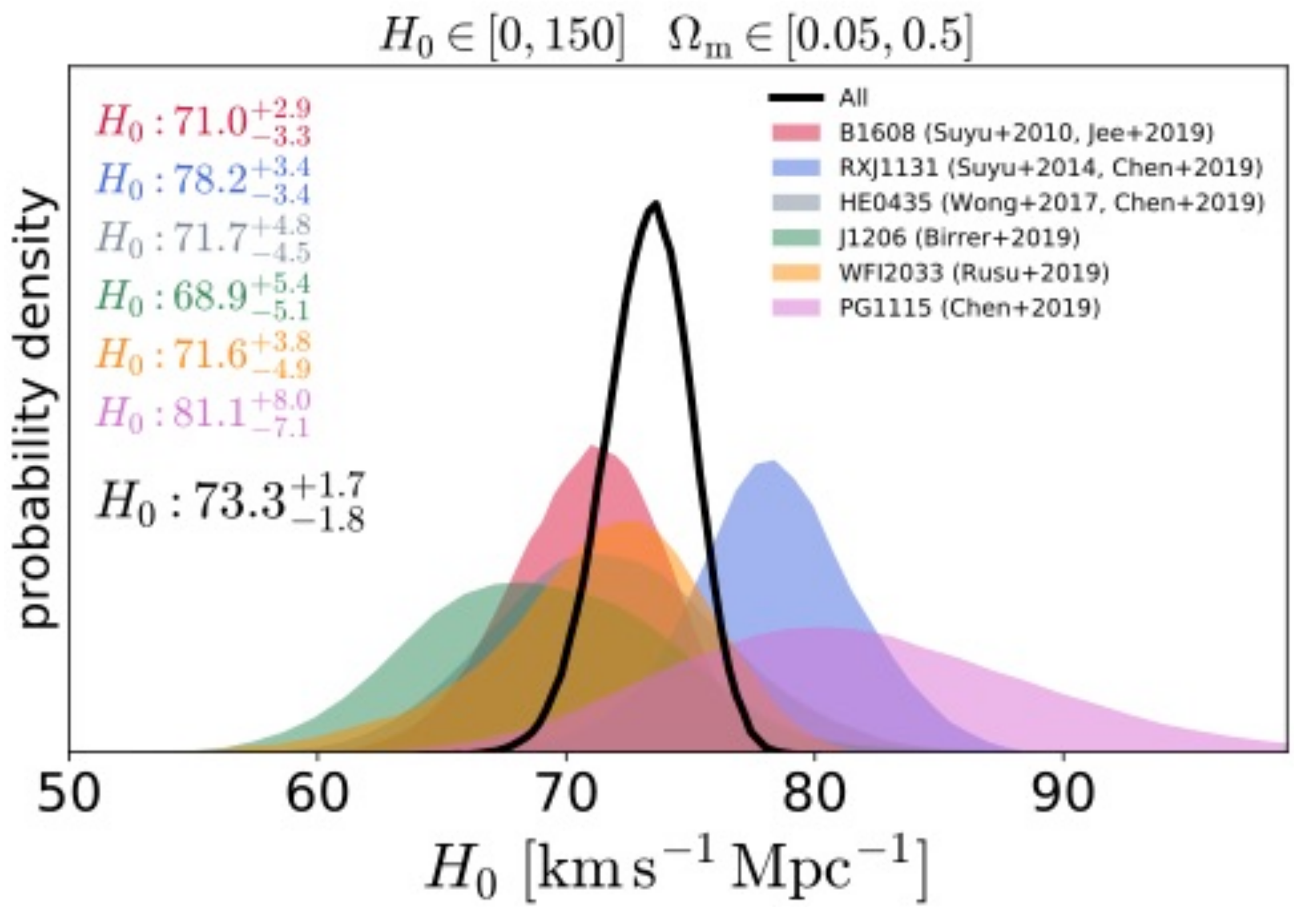
Courtesy: Martin Millon

- Multiple images of quasars arrive at different times due to different paths and different travelled potential.
- Time differences depend on distances and thus on H0

$$\Delta t_{ij} = \frac{D_{\Delta t}}{c}\left[\frac{(\boldsymbol{\theta}_i - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}_i) - \frac{(\boldsymbol{\theta}_j - \boldsymbol{\beta})^2}{2} + \psi(\boldsymbol{\theta}_j)\right] \qquad D_{\Delta t} \equiv (1 + z_{\mathrm{d}})\frac{D_{\mathrm{d}} D_{\mathrm{s}}}{D_{\mathrm{ds}}}$$

- Need to measure the time-delay between two images, measure and model the potential and the line of sight effects.

Results in ΛCDM



Wong+ 2019

Model dependent measurement

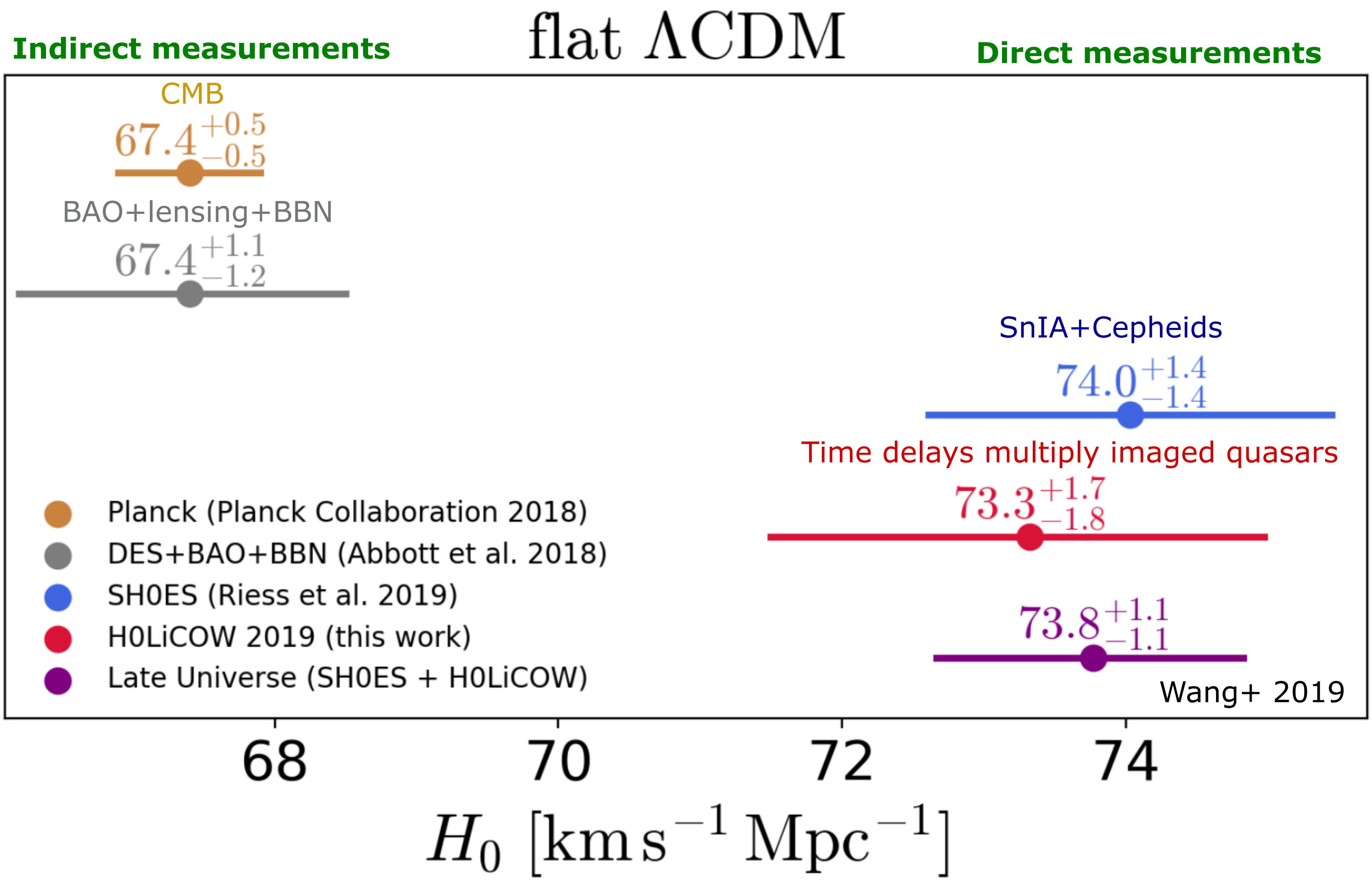
Model	H_0 (km s^{-1} Mpc^{-1})	Ω_m	Ω_Λ or Ω_{DE}	Ω_k	w or w_0	w_a
UΛCDM	$73.3^{+1.7}_{-1.8}$	$0.30^{+0.13}_{-0.13}$	$0.70^{+0.13}_{-0.13}$	$\equiv 0$	$\equiv -1$	$\equiv 0$
UoΛCDM	$74.4^{+2.1}_{-2.3}$	$0.24^{+0.16}_{-0.13}$	$0.51^{+0.21}_{-0.18}$	$0.26^{+0.17}_{-0.25}$	$\equiv -1$	$\equiv 0$
UwCDM	$81.6^{+4.9}_{-5.3}$	$0.31^{+0.11}_{-0.10}$	$0.69^{+0.10}_{-0.11}$	$\equiv 0$	$-1.90^{+0.56}_{-0.41}$	$\equiv 0$
Uw_0w_aCDM	$81.3^{+5.1}_{-5.4}$	$0.31^{+0.11}_{-0.11}$	$0.69^{+0.11}_{-0.11}$	$\equiv 0$	$-1.86^{+0.63}_{-0.45}$	$-0.05^{+1.45}_{-1.37}$

Reported values are medians, with errors corresponding to the 16th and 84th percentiles.

Lens name	α (J2000)	δ (J2000)	z_d	z_s
B1608+656[a]	16:09:13.96	+65:32:29.0	0.6304[a]	1.394[b]
RXJ1131−1231[c]	11:31:51.6	−12:31:57.0	0.295[c]	0.654[d]
HE 0435−1223[e]	04:38:14.9	−12:17:14.4	0.4546[f,g]	1.693[h]
SDSS 1206+4332[i]	12:06:29.65	+43:32:17.6	0.745[j]	1.789[i]
WFI2033−4723[k]	20:33:41.9	−47:23:43.4	0.6575[l]	1.662[h]
PG 1115+080[m]	11:18:16.899	+7:45:58.502	0.311[n]	1.722[m]

Z_{source} ~0.6-1.7
Z_{lens} ~0.2-0.7

Strong tension between early and late universe probes of H_0.



So what’s wrong?

- Statistical fluctuation starts to be unlikely
- Systematics in distance ladder and time delays? And/or in CMB and BAO?
- Extension of LCDM?

Systematics in direct measurements?

- H_0 reanalysis of the Riess (2011/2016) data:
  - Zhang et al. 2017 (arXiv:1706.07573v1): Riess 2011 data,global fit, impact of systematics from cepheids (outliers, anchors, period) and SNIA. Applied on R11, finds H_0 = 72.5 ± 3.1(stat) ± 0.77(sys) km/s/Mpc
  - Follin & Knox 2017 (arXiv:1707.01175) (modelling of cepheid photometry. H_0=73.3 ± 1.7 (stat) km/s/Mpc)
  - Cardona et al. 2017 (arxiv:1611.06088): Bayesian hyper-parameters for outlier rejection. H_0 = 73.75 ± 2.11 km/s/Mpc
  - Feeney et al. 2017 (arXiv:1707.00007): Bayesian hierarchical model, impact of non-gaussian likelihoods. H_0 = 72.72 ± 1.67 km/s/Mpc
  - Dhawan et al 1707.00715.pdf. Use of NIR observations of a subsample of the Riess 2016 supernovae (9/19 for the intermediate calibration rung, 27/300 SN in the Hubble flow). H_0=72.8 ± 1.6 (stat.) ± 2.7 (syst.) km/s/Mpc.

H_0 consistently high!

Consistency between CMB experiments: the role of cosmic variance and multipole range

Planck vs WMAP

Baselines

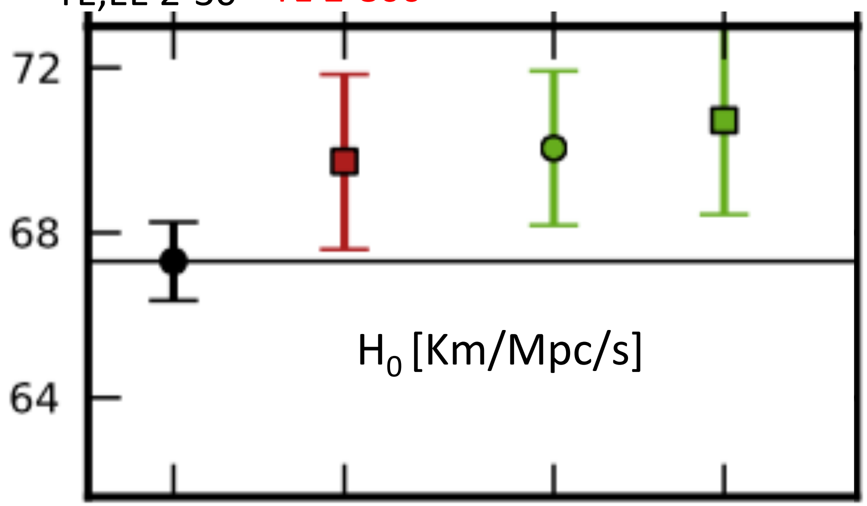
Planck
TT 2-2500
TE,EE 2-30

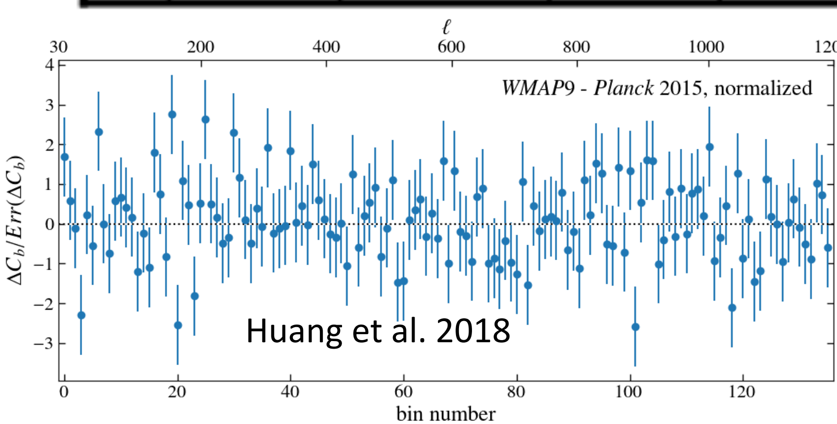
WMAP
TT 2-1200
TE 2-800

Only TT, same τ

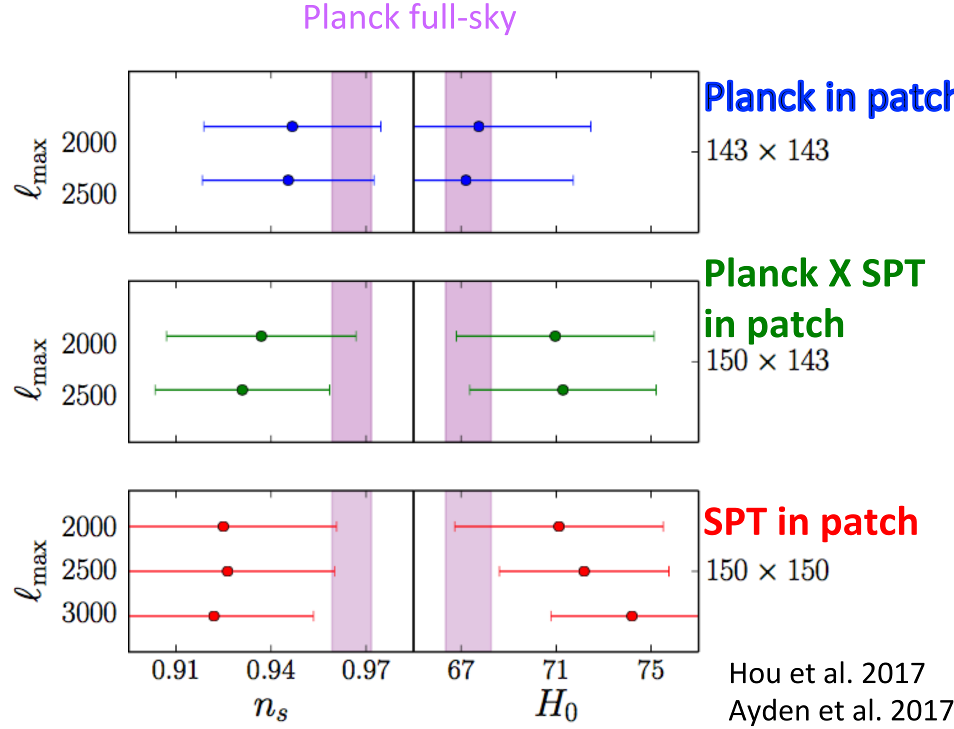
Planck WMAP

TT 2-800





Planck vs SPT-SZ



Hou et al. 2017
Ayden et al. 2017

Aylor et al. 2017 arXiv:1706.10286
Hou et al. 2017 arXiv: 1704.00884

Systematics in the CMB ?
Consistency between different experiments

Planck 2018	H_0=67.4±0.5
Riess+ 2019	H_0=74.0±1.4

- WMAP and SPT give somewhat larger values of H_0
  - WMAP9* H_0=70±2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ* H_0=75.0 ± 3.5 (Story et al. 2012)

See also
SPTPol (TE,EE)
H_0 =71.2 ± 2.12 (Henning+17)

ACTPol (TT,TE,EE)
H_0 =67.3 ± 3.6 (Louis+17)

- Are these consistent with the low H_0 Planck measurement? When adding BAO, yes!
  - Combining WMAP ACT and SPT with BAO to decrease errors low H_0
    - WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne

      H_0= 68.1 ± 0.7 (2.5σ tension) (Aubourg+ 2015)

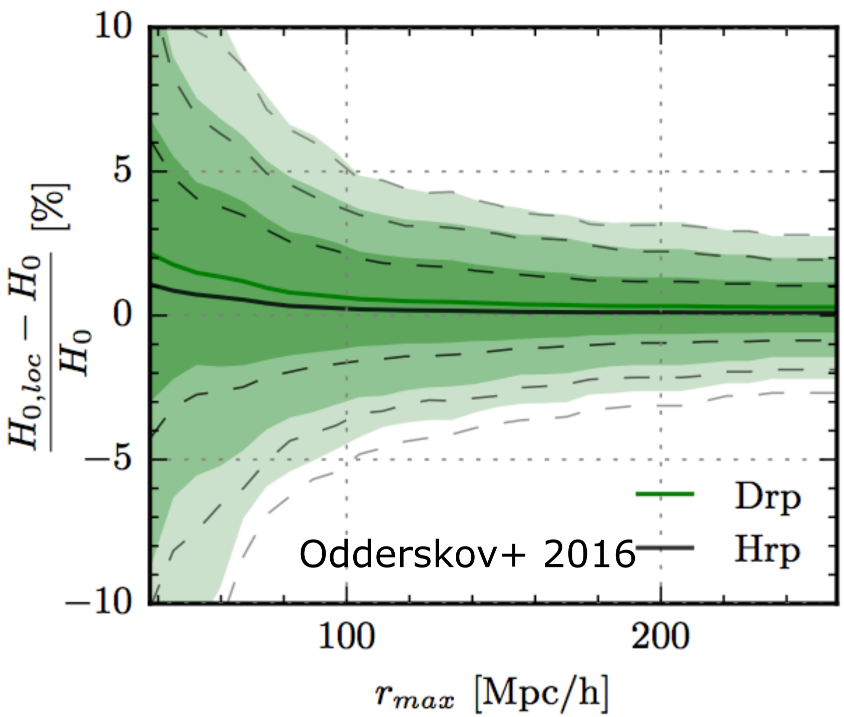
    - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)

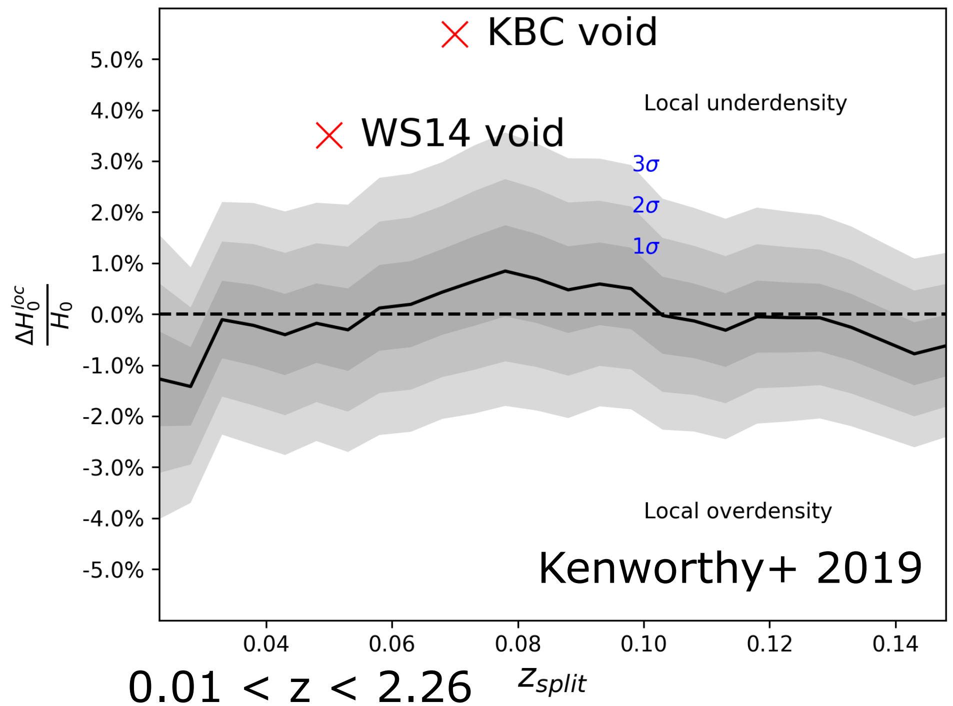
      H_0 = 69.3 ± 0.7 (1.9s tension) (Bennet+ 2014)
  - Planck, WMAP and SPT are consistent with each other.

*NB: these were obtained using slightly different assumptions for neutrino mass and optical depth w.r.t. Planck, see also Calabrese+16

Whatever it is, it's not a giant void!

Peculiar velocities. If we live in a large void and peculiar velocities are not properly taken into account when measuring redshifts, the local measurements of H_0 might be biased (e.g. Keenan 2013, Romano+ 2016). However, simulations show it would need to be a very atypical void (e.g. Marra+ 2013, Wojtak+ 2013, Odderskov+ 2016, Wu+ 2017), sample variance at the level of ~0.3km/s/Mpc. Supernovae at different redshifts do not show any deviation.





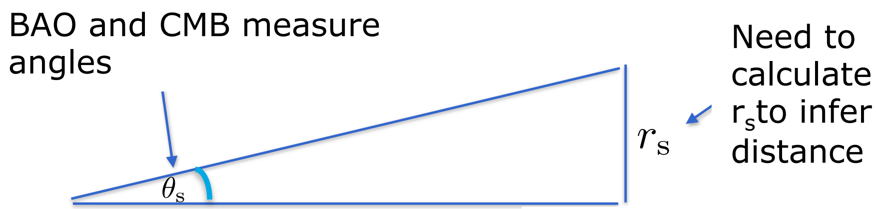
Early and late time solutions

1. Change in late time universe

- (late-time dynamics of dark matter and/or dark energy, e.g. dynamical dark energy, decaying DM (Poulin+ 2018, Vattis+ 2019) interacting dark matter-dark energy etc..) => highly constrained by BAO, Supernovae and other probes.
- Modified gravity changes to Cepheid period-luminosity relation (Desmond et al. 1907.03778)=> but might be constrained by time delays.

See also e.g. Bernal +2016, Lemos+ 2018, Aylor 2018

2. Change in the early time physics. BAO and CMB measure angles, assuming calculation of sound horizon r_s.one can infer the distances and thus H_0=> changing r_s can change inferred H_0, but hard because usually these models impact other observables as well.



$$D_A(z=1100) = \int_0^z dz'/H(z')$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$