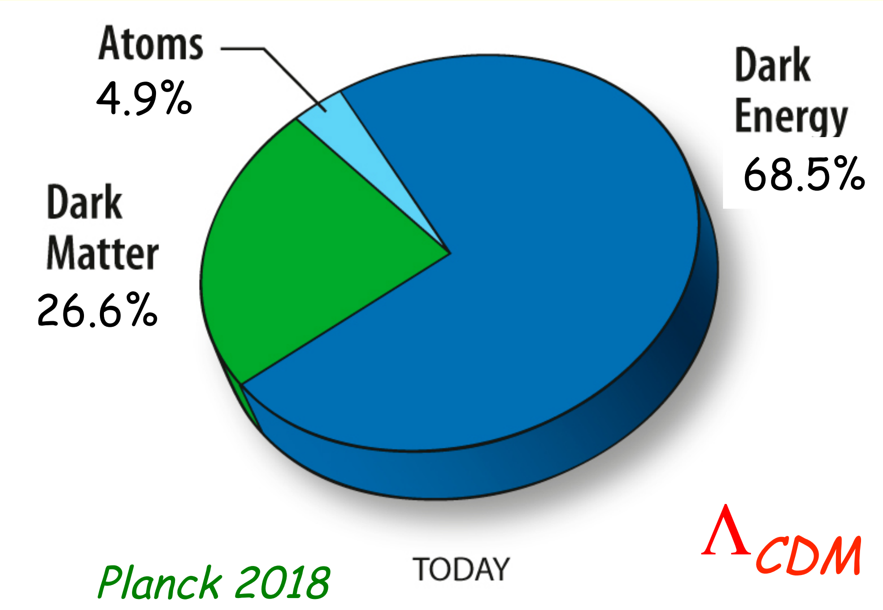
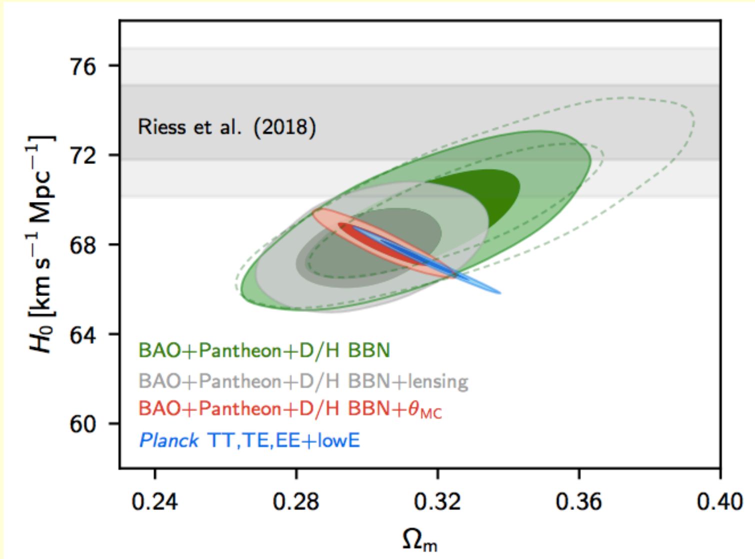
Constraining dark energy

V.Ruhlmann-Kleider
CEA/Irfu/DPhP - Saclay

1) State of the art, Type Ia supernovae (SNe Ia)
2) Baryonic acoustic oscillations (BAO) and beyond (RSD)
3) Weak lensing (WL)
4) **The H_0 tension**

The H_0 tension



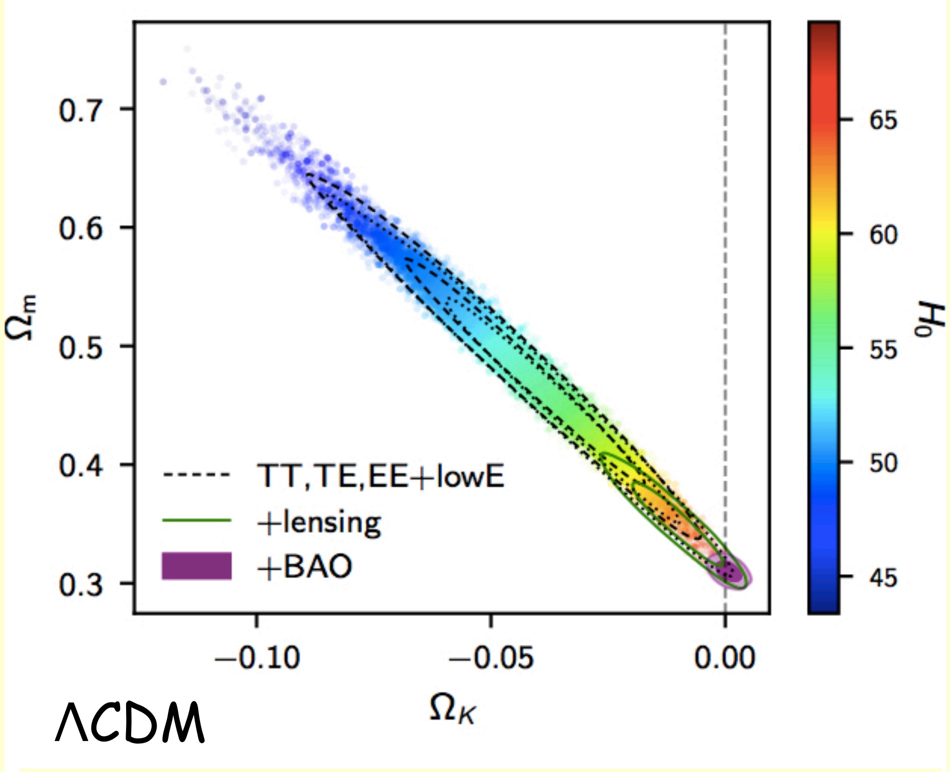


Planck Collaboration, arXiv:1807.06209

1. Current status
2. The distance ladder method
3. Other direct measurement methods

Status

Planck 2018 ΛCDM fits



Planck Collaboration, arXiv:1807.06209

- Flat ΛCDM fit:

H_0=67.37±0.54$km/s/Mpc$

(all Planck data)

H_0=67.66±0.42$km/s/Mpc$

(all Planck data+BAO)

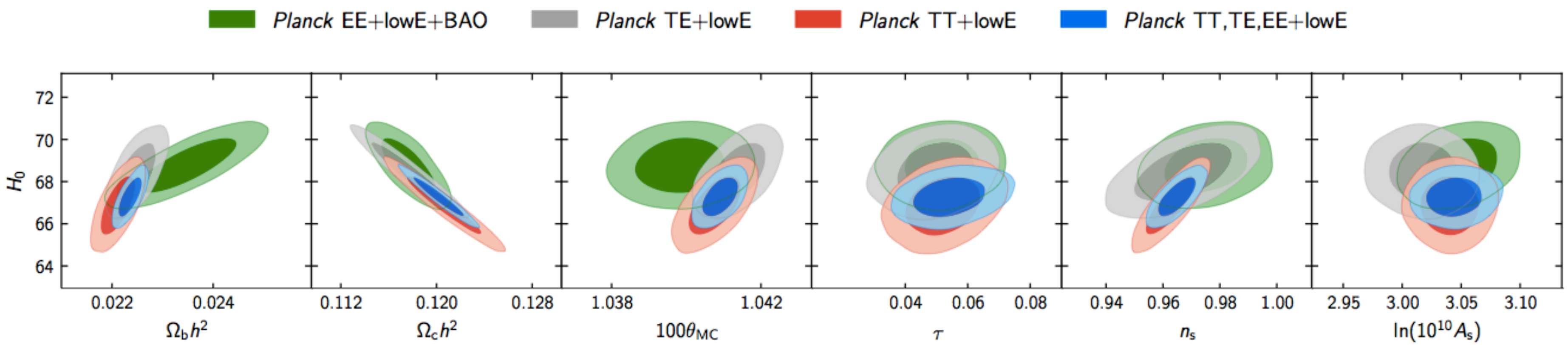
- But flat ΛCDM fit of H_0 in tension with direct cosmic ladder measurement of H_0 :

e.g. H_0=73.5±1.6$km/s/Mpc$ ⇒ 3.6σ tension

A.Riess et al, 2018, ApJ, 861, 126R

Cross-check from Planck

- 2018: 3.6σ tension. Failure of Λ_{CDM} or unidentified systematic uncertainty in one or the other analysis ?



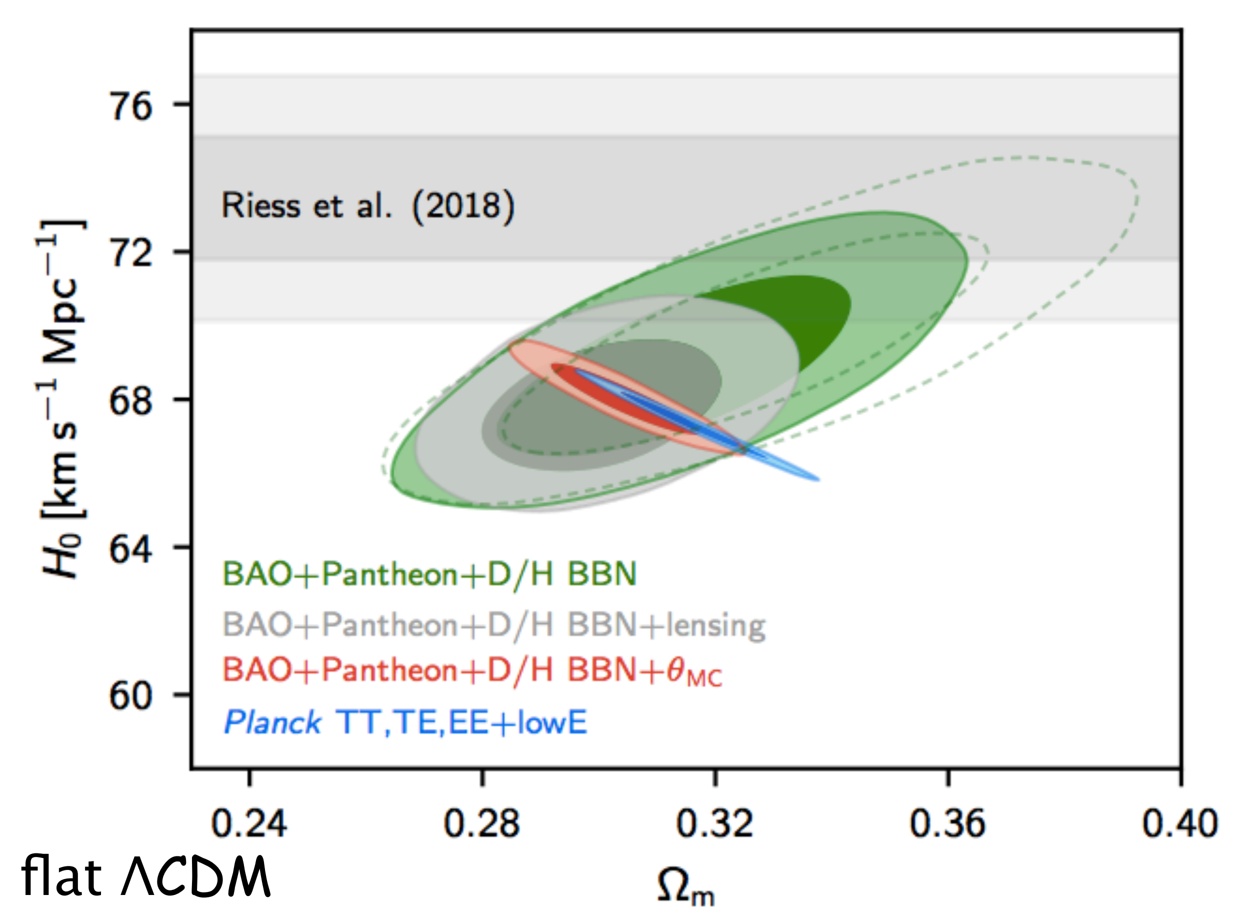
flat ΛCDM

Planck collaboration. 2018, arXiv:1807.06209

- Part of the CMB data (polarisation) prefer a higher value of H_0 …. but not as high as the direct measurement of H_0

Cross-check from Planck

Planck collaboration, arXiv:1807.06209



⇒ Cross-check : use different data, with minimal input from the CMB e.g. BAO/SNIa/BBN/θ_{CMB}

The inverse ladder method (simplified)

- CMB: measure angular acoustic scale θ_* at 0.03% in flat ΛCDM, almost independently of cosmology model (0.06%)
- BAO: measure $D_M(z)/r_d$ at various $z<2.5$

⇒measurements: $D_M(z^*)/r_s$ and $D_M(z_{BAO})/r_d$

- Standard BBN: constrains $\Omega_b h^2$ at 20% (we also have T_{CMB} to fix $\Omega_\gamma h^2$)

⇒r_s,r_d known functions of $\Omega_m h^2$ in standard linear perturbation theory

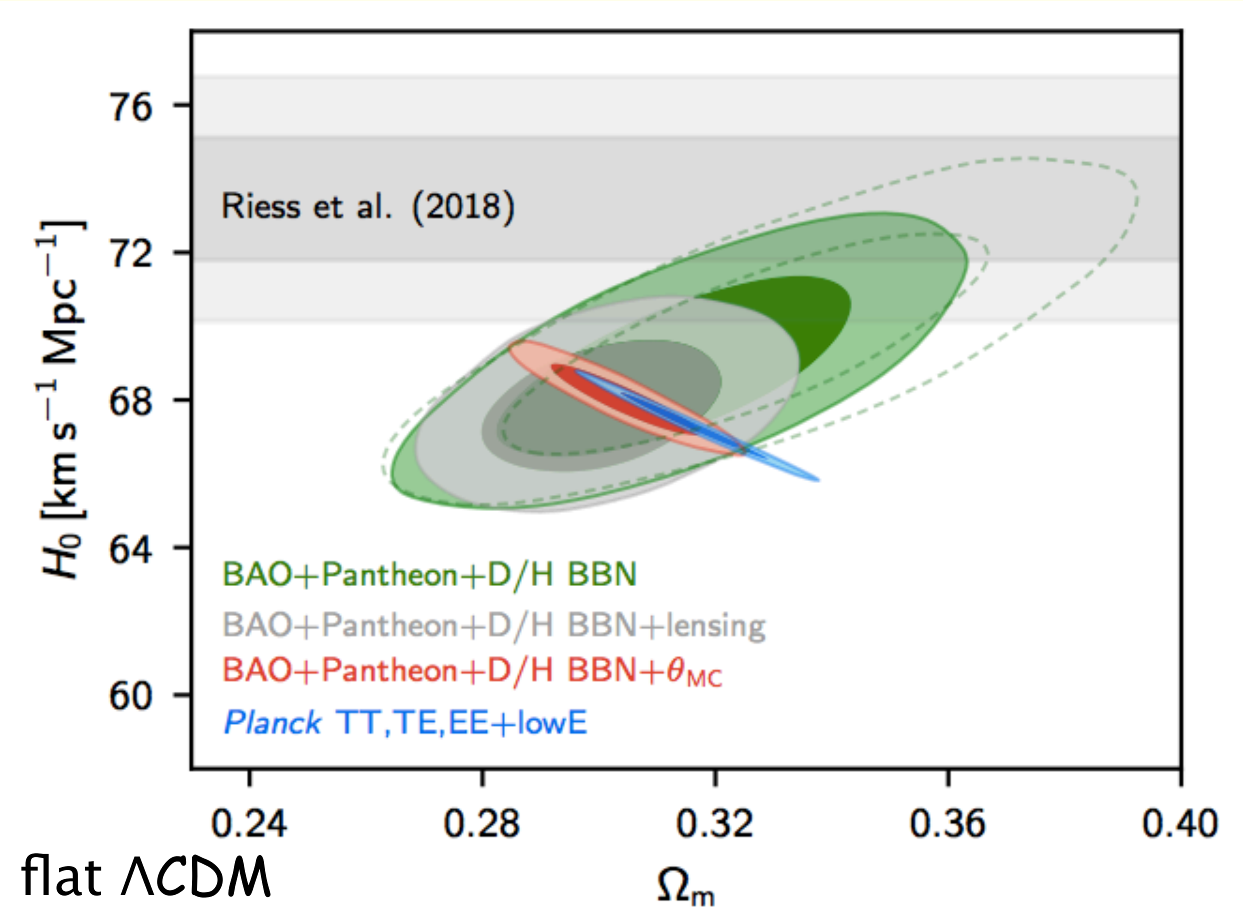
⇒$D_M(z^*)$ and $D_M(z_{BAO})$ calibrated as a function of $\Omega_m h^2$

- SNe Ia: measure $D_L(z)=(1+z)D_M(z)$ at multiple $z<2$, HD offset is ~ $M_B-5\log_{10}(c/H_0/1\text{Mpc})$ with M_B unknown

⇒H_0 from the slope of the distance-redshift relation, once M_B is calibrated by BAO/CMB distances

Cross-check from Planck: conclusion

Planck collaboration, arXiv:1807.06209



- Tension is not confined exclusively to Planck results
- Modifying the dark sector does not solve the discrepancy

Distance ladder

Measuring H_0 : a complex task

- Hubble law ($d \lesssim 50$Mpc) : $v = H_0 d \Rightarrow cz = H_0 d$ => relate distances and redshifts

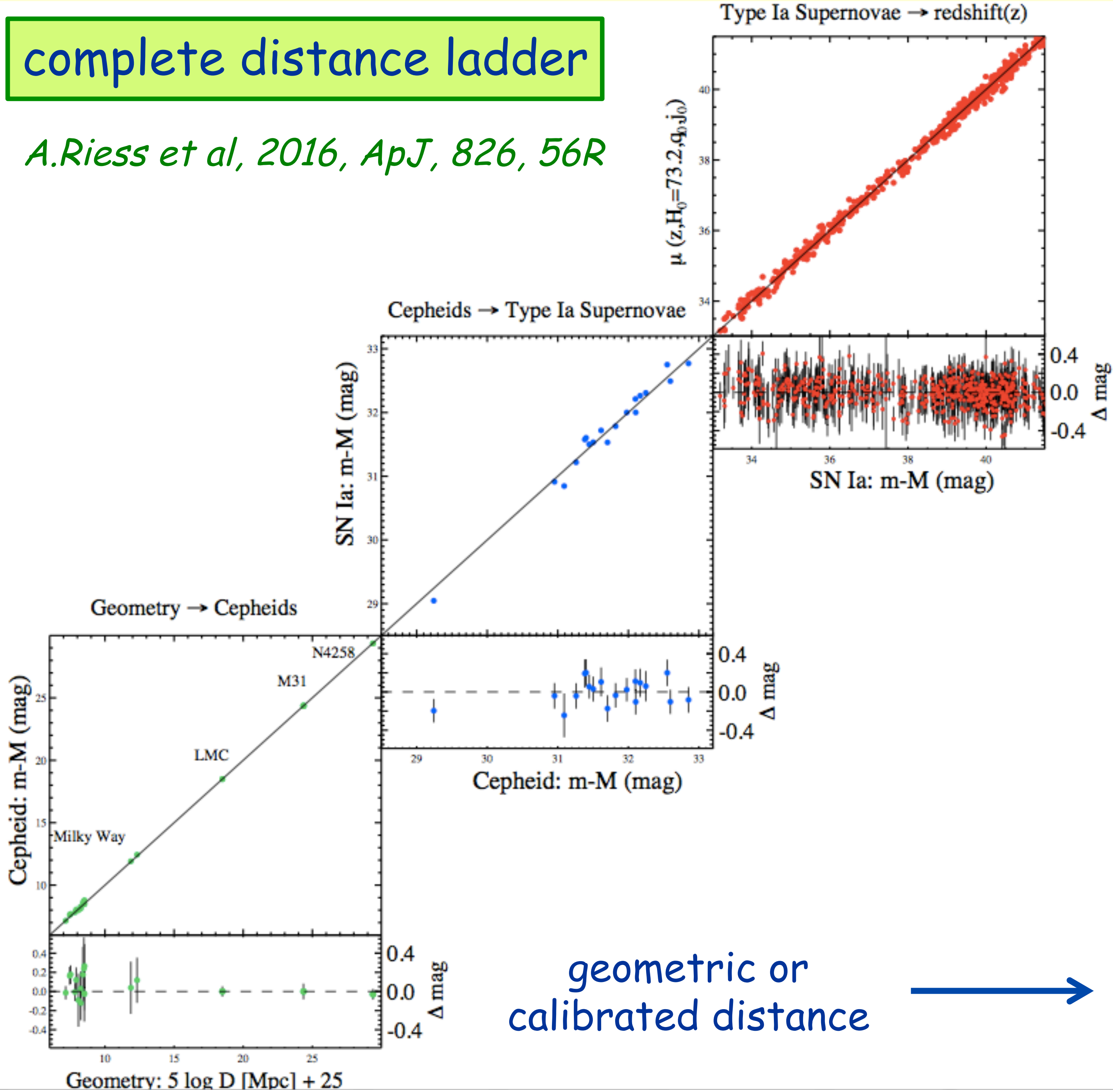
- Direct measurement of distances restricted to short distances (e.g. through parallax, limited to 5kpc with Gaia).

- At larger distances rely on apparent magnitudes of standard candles. Requires distance-to-magnitude calibration i.e. other objects to propagate calibration step by step from short to large distances (distance ladder).

- Example: H_0 measurement from nearby SNe Ia and Cepheid distance scale (most precise method).

complete distance ladder

A.Riess et al, 2016, ApJ, 826, 56R



relative distance indicator

geometric or calibrated distance

The ladder rungs (an ultrasimplified view)

1. An absolute distance anchor (e.g. Masers in NGC4258 : distance from maser motions in the central black hole disk).
   ⇒distances of Cepheids in anchor galaxy are calibrated

$$m_{4258}^{Cepheid} - M_{4258}^{Cepheid} = 5\log_{10} D_{4258} = m_{4258}^{Cepheid} - bP_{4258}^{Cepheid} - ZP$$

2. Cepheids in some SNIa hosts : P-L relation calibrated thanks to Cepheids in the first rung (b,ZP)
   ⇒distances of these SNIa hosts are calibrated

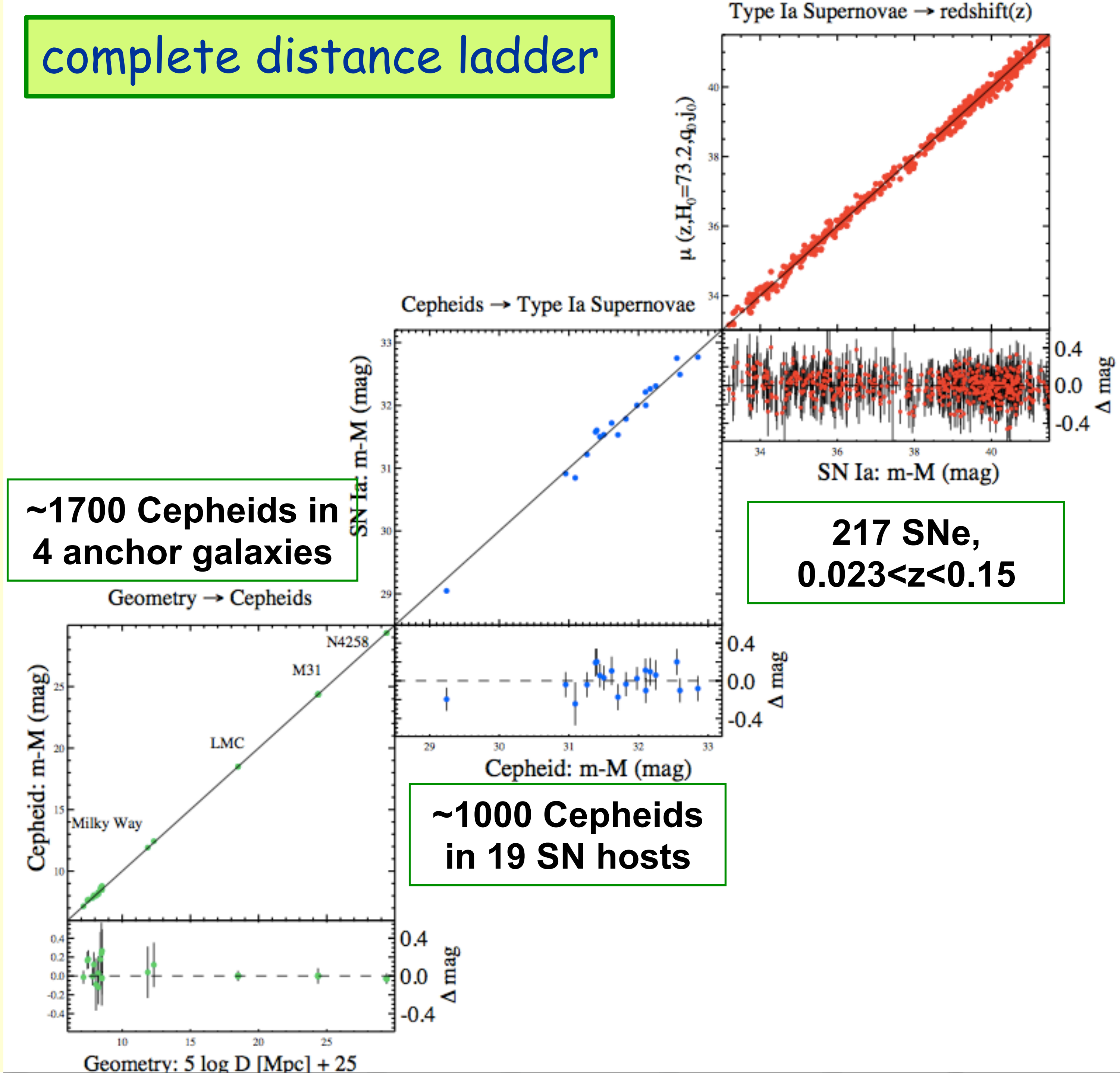
$$m_B^{SN} - M_B = 5\log_{10} D_{SN} = m_{host}^{Cepheid} - M_{host}^{Cepheid} = m_{host}^{Cepheid} - bP_{host}^{Cepheid} - ZP$$

3. SNe Ia in HD : offset in magnitude (M_B) calibrated thanks to SNIa hosts and Cepheids in the second rung (+q_0 known) ⇒H0

$$m_B^{SN} - M_B = 5\log_{10}\left[cz\left(1+0.5(1-q_0)z\ldots\right)\right] - 5\log H_0$$ ⇒$dH_0/H_0 \sim dm_B/2.2$

4. Actual method : global fit to all Cepheid and SN Ia data

complete distance ladder



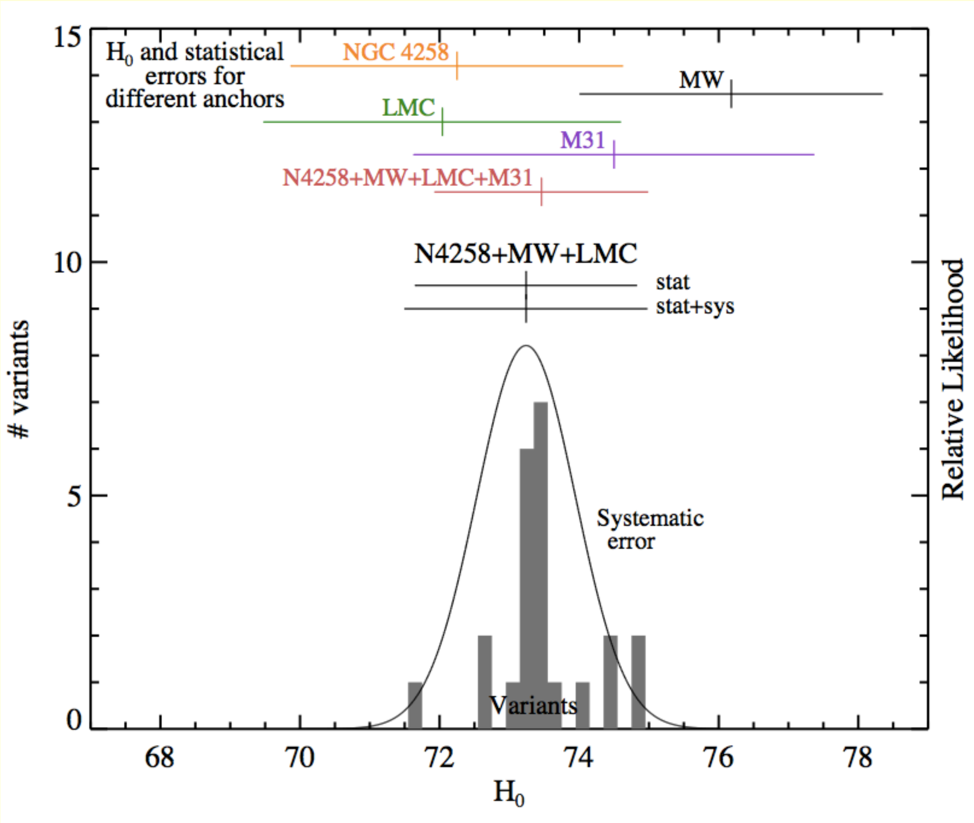
~1700 Cepheids in 4 anchor galaxies

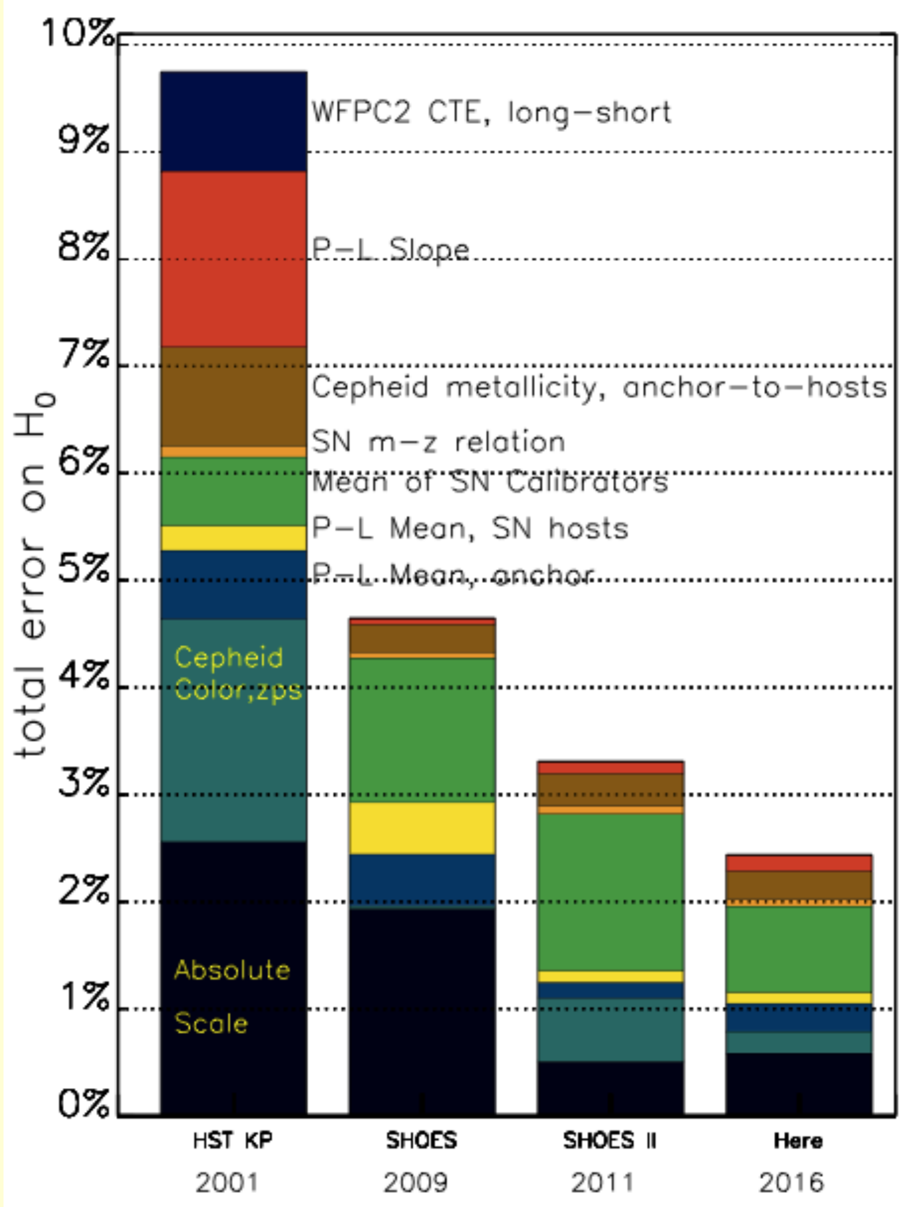
217 SNe, 0.023<z<0.15

~1000 Cepheids in 19 SN hosts

Uncertainties in H_0 measurement

A.Riess et al, 2016, ApJ, 826, 56R





$H_0 = 73.24 \pm 1.74 km/s/Mpc$

3.4σ tension

Recent updates

- 2018: MW anchorage: 15 Cepheids with ground based photometry replaced by 50 Cepheids measured on the same HST photometry as Cepheids in SN Ia hosts + use of Gaia DR2 parallaxes (Gaia ZP offset refitted).

  A.Riess et al, 2018, ApJ, 861, 126R $H_0 = 73.5 \pm 1.6 km/s/Mpc$ 3.6σ

- 2019: LMC anchorage: 70 Cepheids measured on the same HST photometry as Cepheids in SN Ia hosts added to R2016 sample of 785 Cepheids from the ground + absolute distance from new 20 DEB data

  A. Riess et al., 2019, ApJ, 876, 85R $H_0 = 74.03 \pm 1.42 km/s/Mpc$ 4.4σ

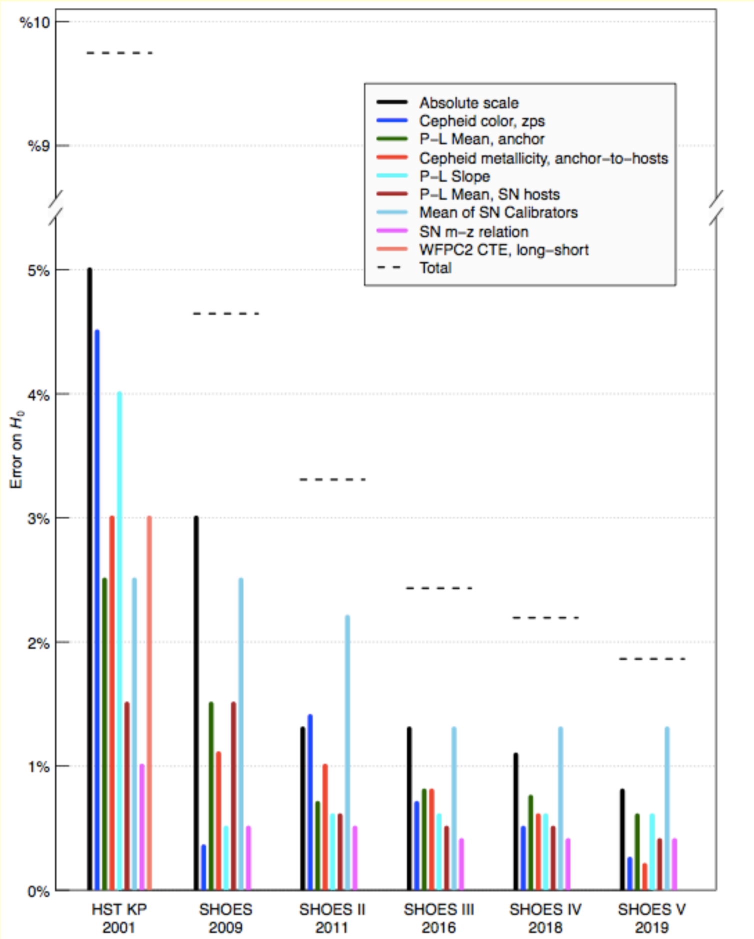
- 2019b: N4258 anchorage: improved maser modelling

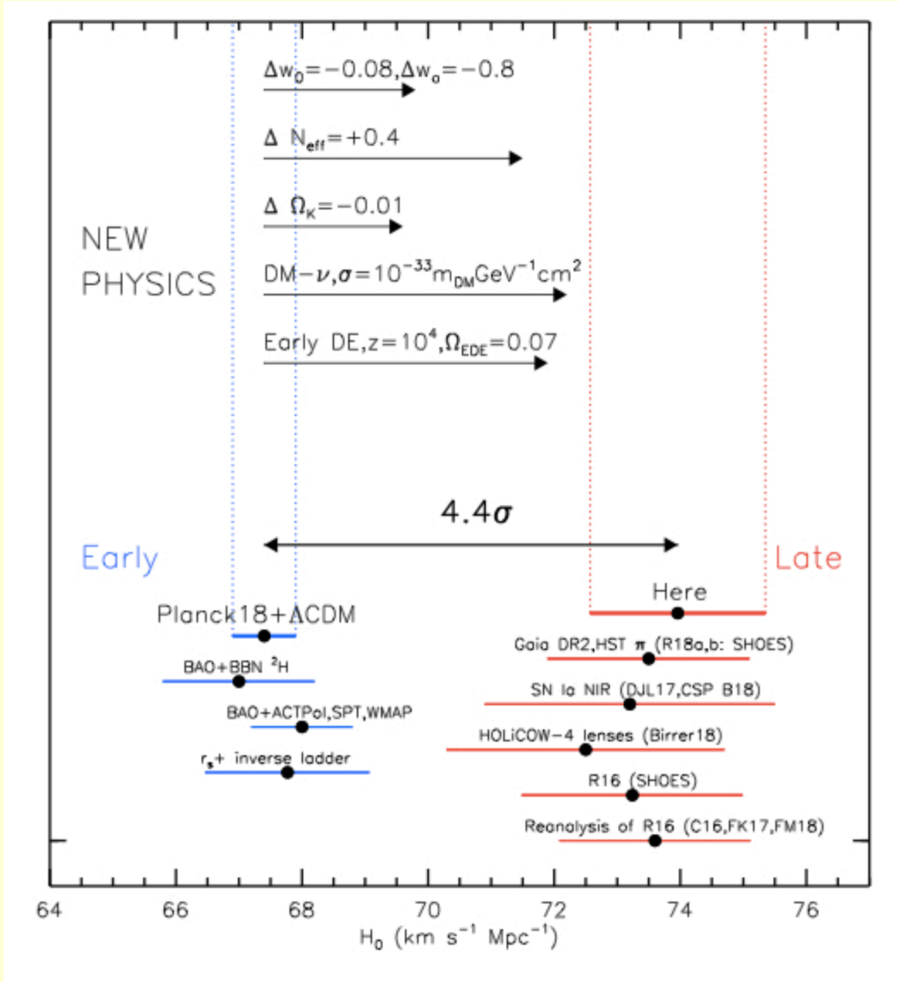
  M.J.Reid et al., arXiv:1908.05625 $H_0 = 73.5 \pm 1.4 km/s/Mpc$ 4.2σ

- Prospects: more SN Ia calibrators (Cepheids in SN hosts), less systematics due to environment in SNIa distances, improved parallaxes from future Gaia data (2022)

Cross-check from Riess et al

A. Riess et al., 2019, ApJ,876, 85R





Failure of Λ_{CDM} ? or unidentified systematic uncertainty in either analysis ? Need for independent measurement methods

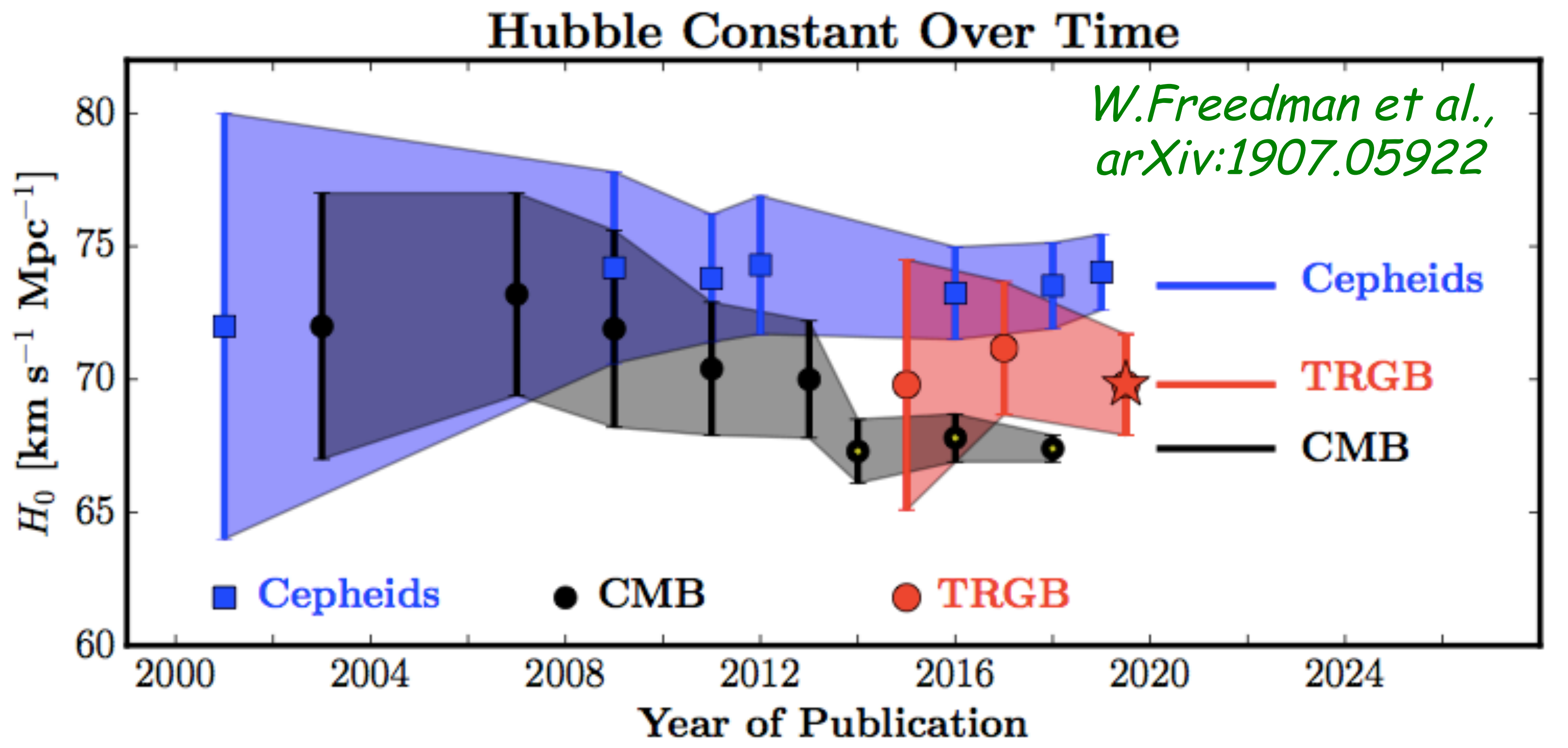
The TRGB alternative calibration route

- Cepheid calibration of SNIa distances → Tip of the Red Giant Branch calibration. Similar (better) accuracy, less systematics.
  - TRGB stars: He flash →discontinuity in the luminosity function →distance
  - Multiple advantages over Cepheids: no need for multiple observations, minimal effect from photometry blending (halo TRGBs), low reddening and extinction, shallow sensitivity to metallicity, no concern of different slopes with period, better match to SNIa host masses.
- Rung 1: LMC absolute distance from 20 DEBs + LMC TRGB distance from ground-based data (+ conversion to HST system)
- Rung 2: HST measurement of TRGB distances to 9 galaxies hosting 11 SNe Ia + TRGB distances to 6 galaxies hosting 7 SNe Ia from archival data
- Rung 3: 100 SNe Ia from CSP-I

$$\Rightarrow \quad H_0 = 69.8 \pm 0.8 \pm 1.7 \, km/s/Mpc$$

W.Freedman et al., arXiv:1907.05922

note: similar trend when using the SNIa sample from Riess et al

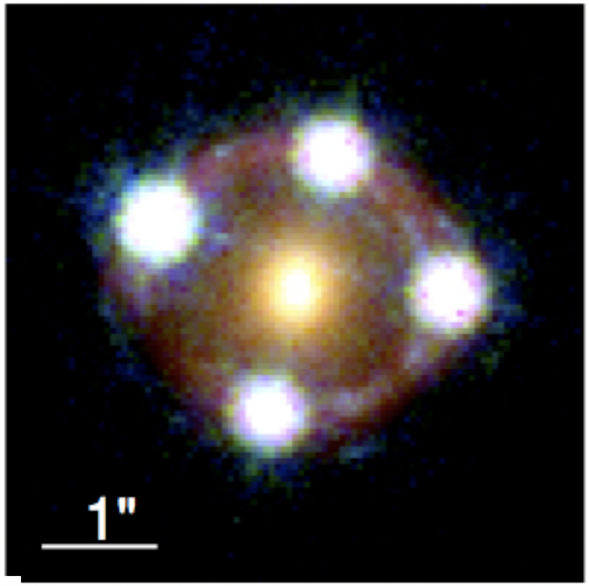


- Systematic effect in Cepheid distance scale ? More likely, incorrect TRGB LMC-based calibration (M.J.Reid et al., arXiv: 1908.05625, W.Yuan et al, arXiv:1908.0093 H_0=72.4±2.0km/s/Mpc)
- Prospects for TRGB:
  - accurate Gaia parallaxes ⇒ extend TRGB method to MW, RR Lyrae stars
  - enlarge number of HST observed SNIa hosts with TRBG stars
  - enlarge number of SNIa hosts with TRGB stars thanks to JWST (TRGB stars brighter in IR, not the case for Cepheids)

Time delay cosmography

- time delays between multiple images of a gravitationally lensed variable source
- source variability: makes time delays measurable

HST



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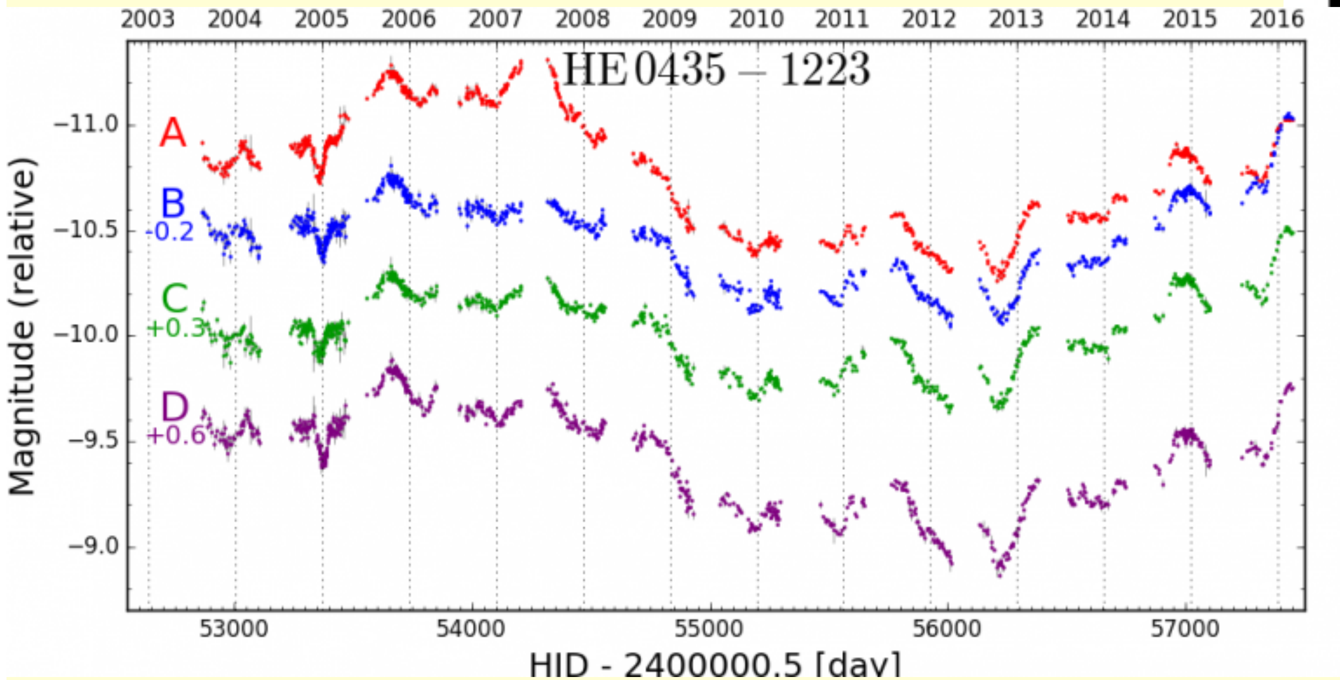


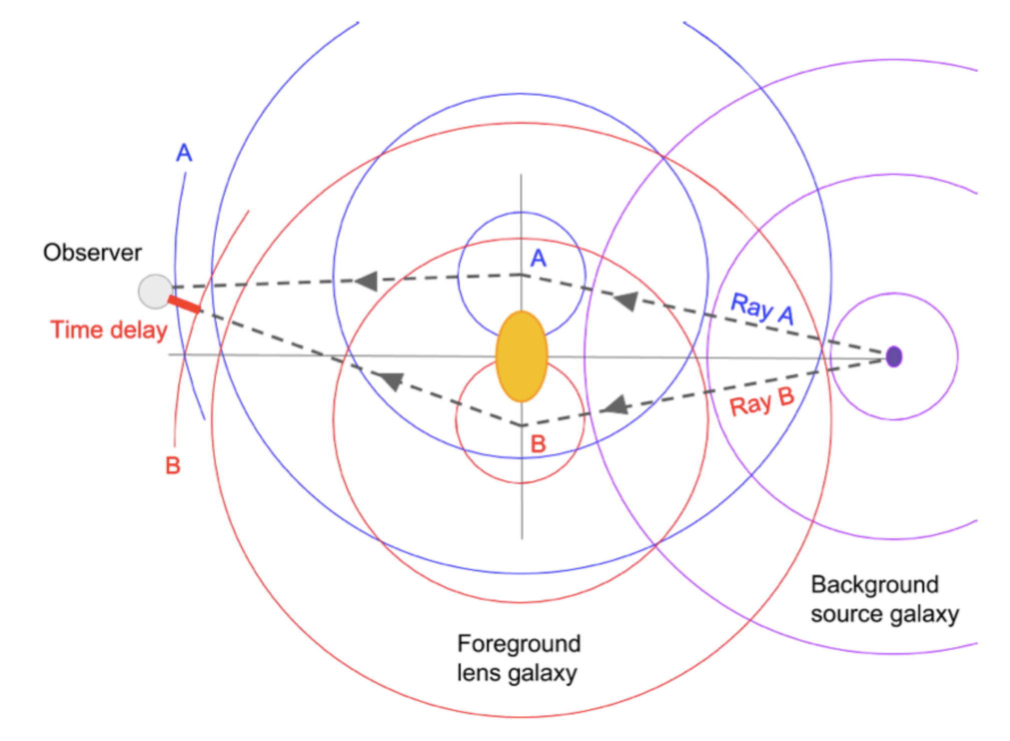
Lens monitoring over years, COSMOGRAIL program

V.Bonvin et al., 2017, MNRAS,465, 4914B

⇒time-delay distance, $D_{\Delta t}$: one-step, independent H_0 measurement

Time delay cosmography: principle

T.Treu, P.Marshall, 2016,A&ARv,24,11T



$$\Delta\tau_{AB} = \frac{D_{\Delta t}}{c}\Delta\Phi_{AB}$$

$$\Delta\Phi_{AB} = \tfrac{1}{2}(\theta_A - \beta_A) - \psi(\theta_A) - \tfrac{1}{2}(\theta_B - \beta_B) - \psi(\theta_B)$$

θ apparent
β unlensed
source position

ψ projected lens gravitational potential

$$D_{\Delta t} = (1+z_d)\frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$$

- angular diameter distances (D_d, D_s, D_{ds}): depend on z_d, z_s, & cosmology (H_0 and Ω_k, mostly)
- model of the lens mass distribution $\Rightarrow \theta - \beta, \psi(\theta)$ predictions
- Note: WL from the mass distribution along l.o.s must also be accounted for

Requirements for time delay cosmography

- Time delay accuracy:
  - typical values: $\theta-\beta \sim 1$ arcsecond ⇒ $\Delta\tau_{AB} \sim 10$days
  - ⇒ long-term dedicated photometric monitoring of the lens

  e.g. COSMOGRAIL program
- Lens galaxy mass distribution modelling:
  - Lens Einstein ring image & stellar velocity dispersion are important to break degeneracies between lens mass model/cosmology
  - ⇒ Deep high-resolution imaging (space or with (AO) adaptative optics) and spectroscopic data (possibly spatially resolved) of the lens

  e.g. HST/Keck imaging and VLT/Keck spectroscopy
- Weak lensing effects in the lens plane and along l.o.s.:
  - ⇒ Deep wide-field spectroscopy and imaging

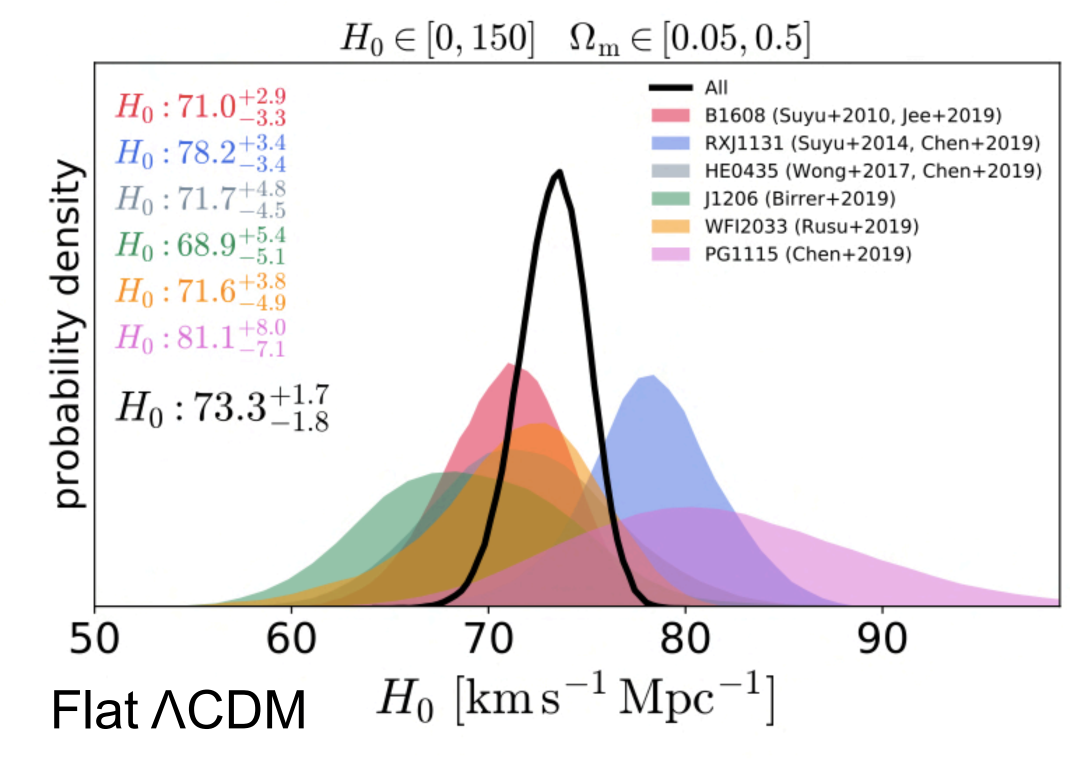
  e.g. Keck/VLT/Gemini spectroscopy and CFHT/Subaru/Gemini/Spitzer/Blanco/VLT imaging

- Current precision on $D_{\Delta t}$ (per lens): 6-7% (stat) > syst

Most precise result : H0LiCOW collaboration

Joint analysis of 6 gravitationally lensed quasars $(0.3<z_d<0.7, 0.6<z_s<1.8)$

K.C.Wong et al, arXiv:1907.04869



$H_0 = 73.3^{+1.7}_{-1.8}$ *km/s/Mpc*

3.1σ tension / Planck

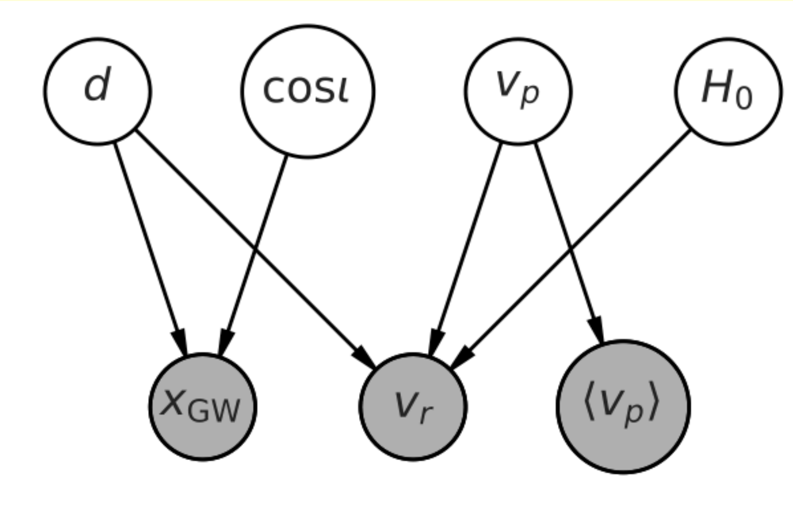
Tension also in other models (oΛCDM, flat wCDM, w(z)CDM...) or when combining Time Delays with cosmological SNIa samples in various models.

- Prospects: 1% constraint on H_0 with 40 lensed quasars (near future); LSST (detection, monitoring) + JWST or ground-based AO (follow-up)
- Recent concern: too few parameters in lens model ⇒ underestimated H_0 errors, present accuracy likely ~10% *C.S.Kochanek, arXiv:1911.05083*

GW standard sirens

- GW170817: signal from the merger of a binary neutron-star system, GW signal and electromagnetic counterpart from the host galaxy NGC4993 measured
- GW signal x_{GW} ⇒ luminosity distance, binary orbital inclination angle (3 detectors: accurate measurements of d and cosι)
- em counterpart ⇒position, z_h⇒ Hubble flow velocity from host recession velocity (v_r) corrected for peculiar velocities ($<v_p>$)

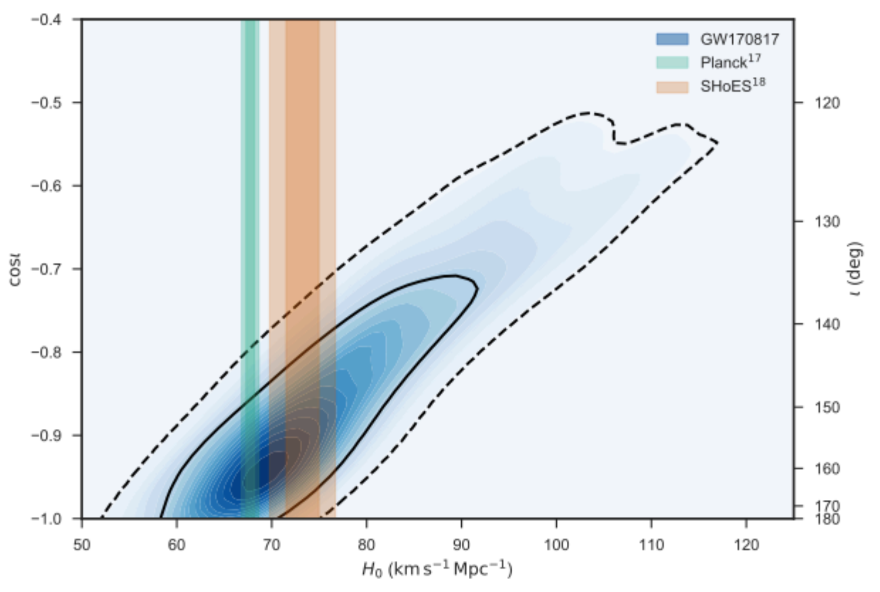
LIGO & VIRGO Collaborations et al, Nature, 2017, 551, 85-88

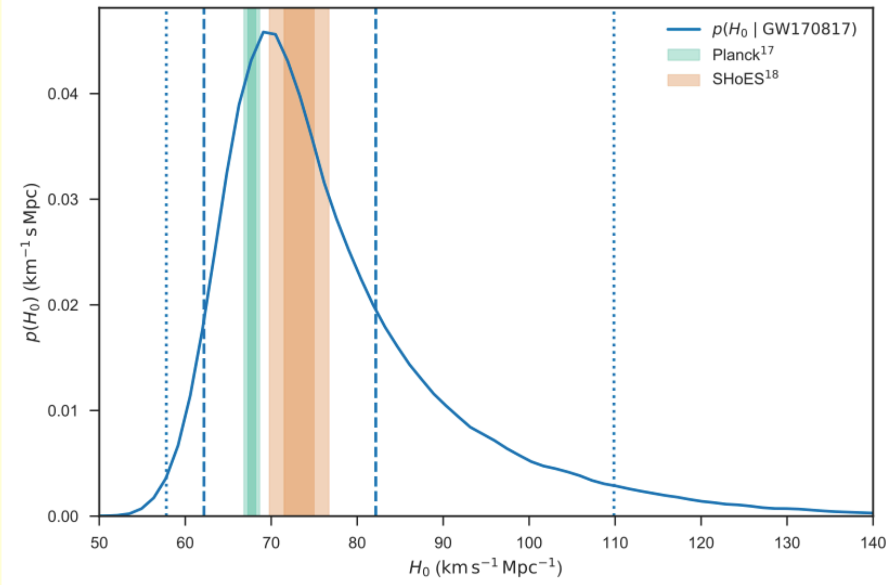


- one-step, independent H_0 measurement, with absolute distance scale based on RG

GW170817 standard siren

LIGO & VIRGO Collaborations et al, Nature, 2017, 551, 85





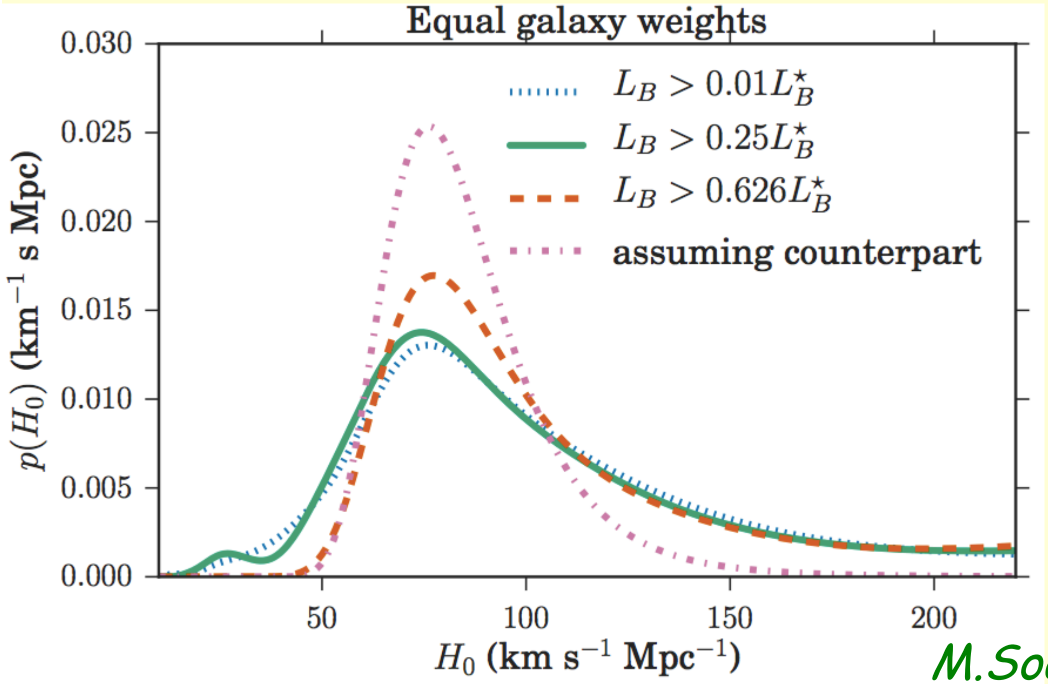
$$H_0 = 70^{+12}_{-8}\, km/s/Mpc$$

- Main source of uncertainty: degeneracy distance/inclination
- Note: after recalibration of O2 data:

$$H_0 = 68^{+18}_{-8}\, km/s/Mpc$$ *B.P. Abbott et al, arXiv:1908.06060*

More on GW sirens

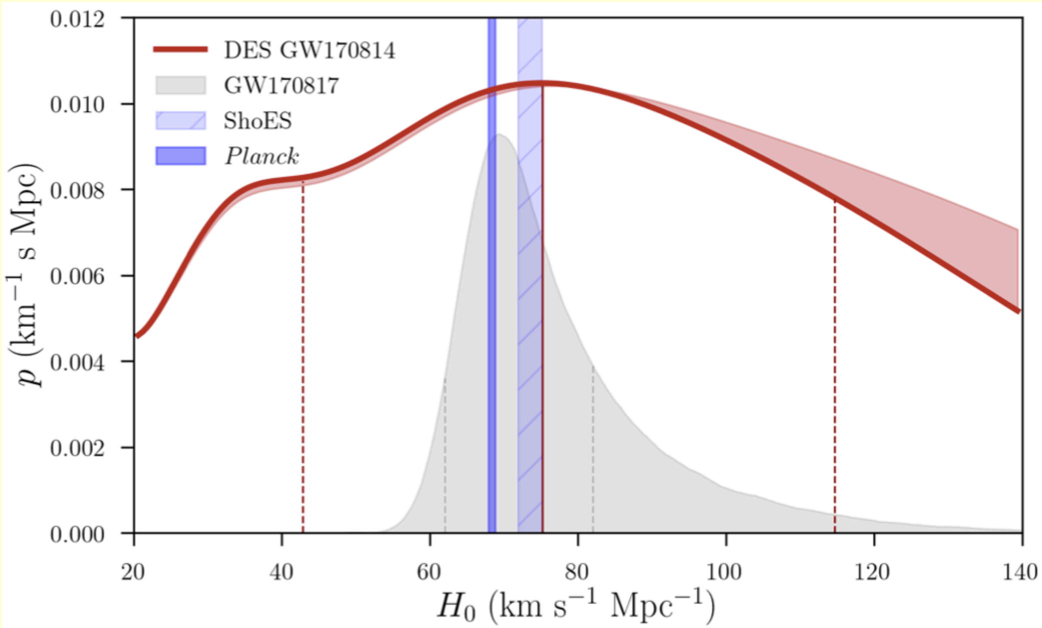
M.Fishbach aet l, 2019, ApJ, 871L,13F



- GW170817: statistical analysis over all possible host galaxies in the GW localization region (proof of principle)

$$H_0 = 76^{+37}_{-18}\, km/s/Mpc$$

M.Soares-Santos et al, 2019, ApJ, 876L,7S

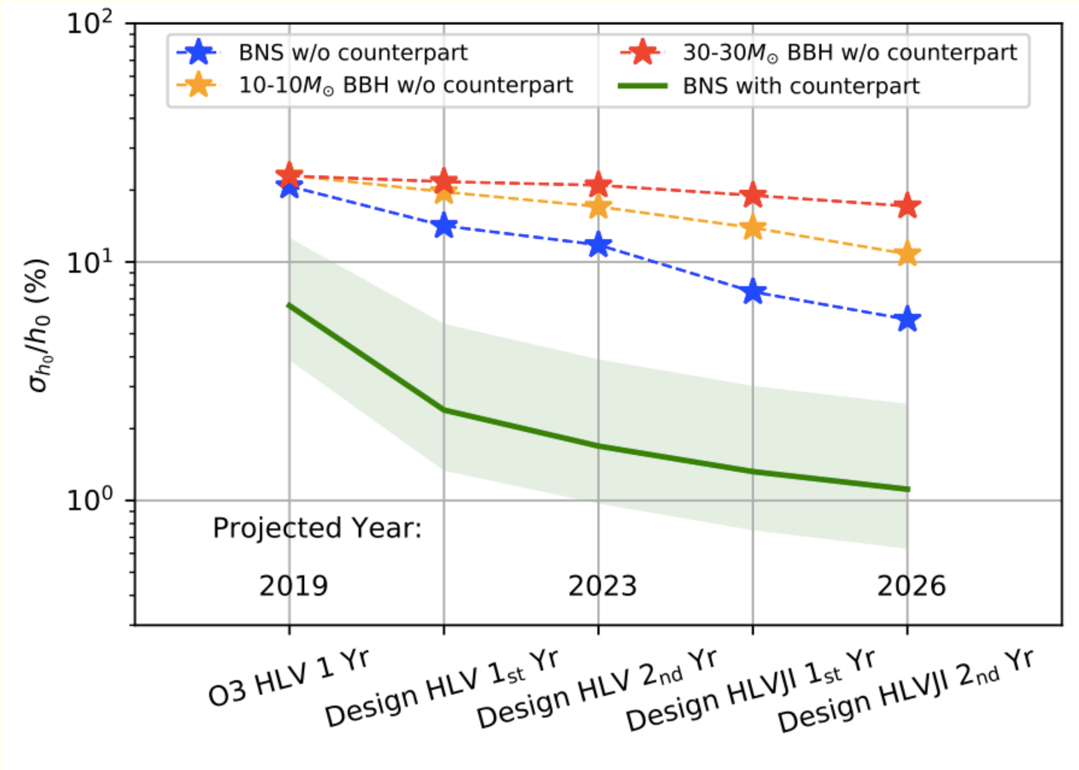


- GW170814: statistical analysis applied to black-hole merger, using DES galaxies as potential hosts (photo z's)

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

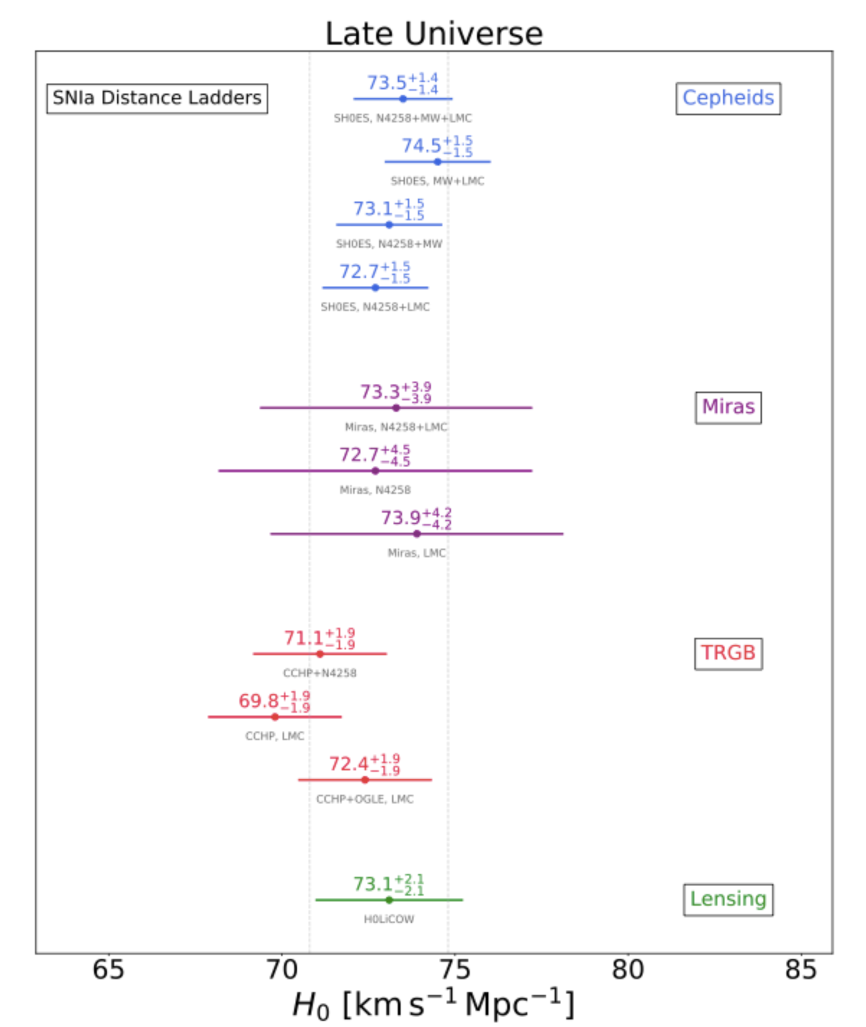
Prospects for standard siren method

Chen H., Fishbach M., Holz D., 2018, Nature,562,545C



- H_0 analysis on large simulated data with realistic measurement uncertainties, galaxy peculiar velocities and selection effects. Main uncertainty on predicted accuracy = BNS merger rate.
- O(50) events with identified unique em counterpart ⇒ 2% on H_0

CONCLUSIONS



C.D.Huang et al, arXiv:1908.10883

- Direct measurements of H_0 disagree with Λ_{CDM} constraints (>3σ).

- Tension between data from the late vs early Universe in Λ_{CDM} ?
- Non standard primordial physics ?
- Systematic not accounted for ?

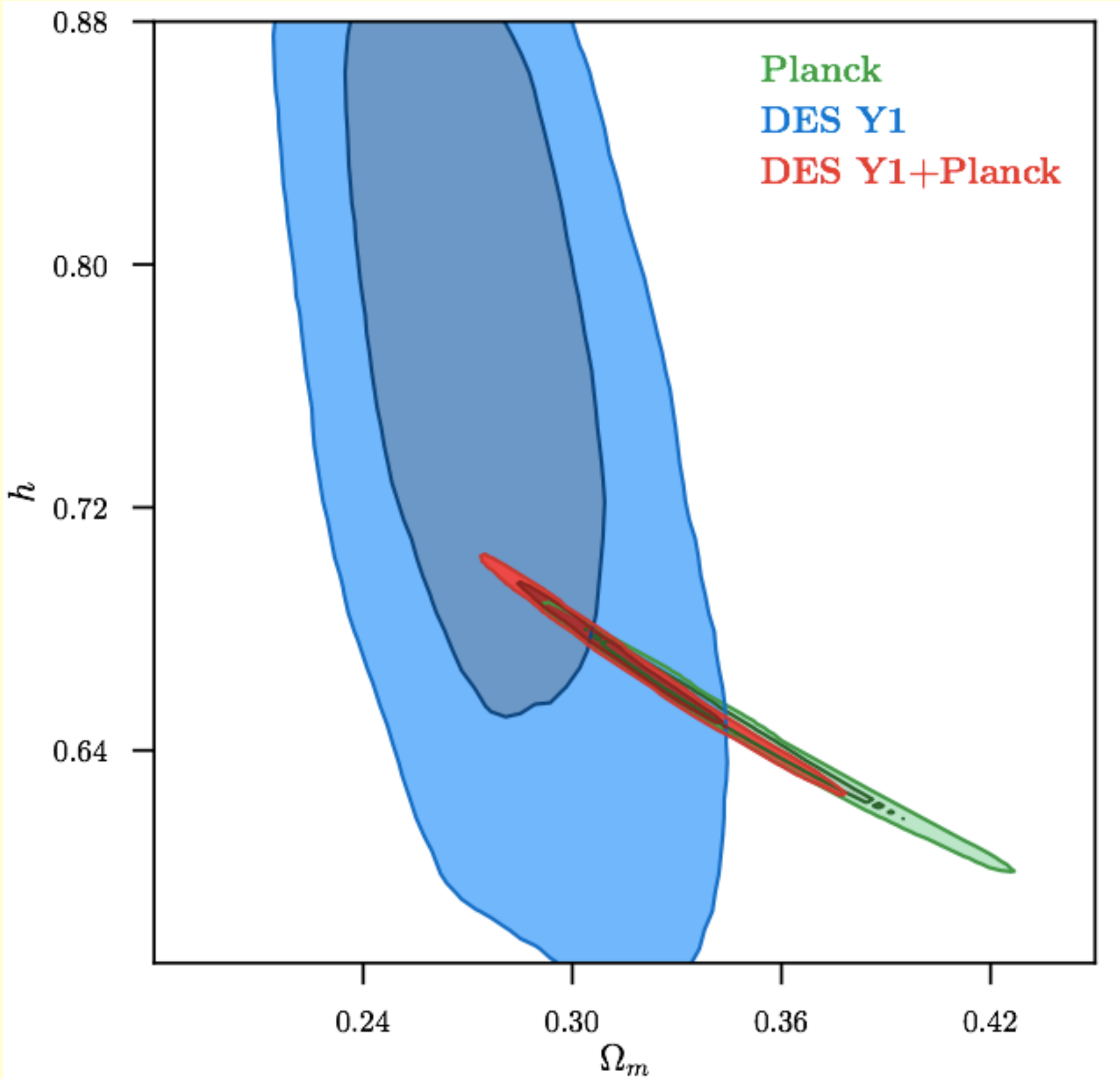
- Need for new independent measurement methods (new relative distance calibrators in SNIa distance ladder, time delay cosmography, GW standard sirens…

…Stay tuned !

Back up slides

DES-Y1 joint analysis, constraint on H_0

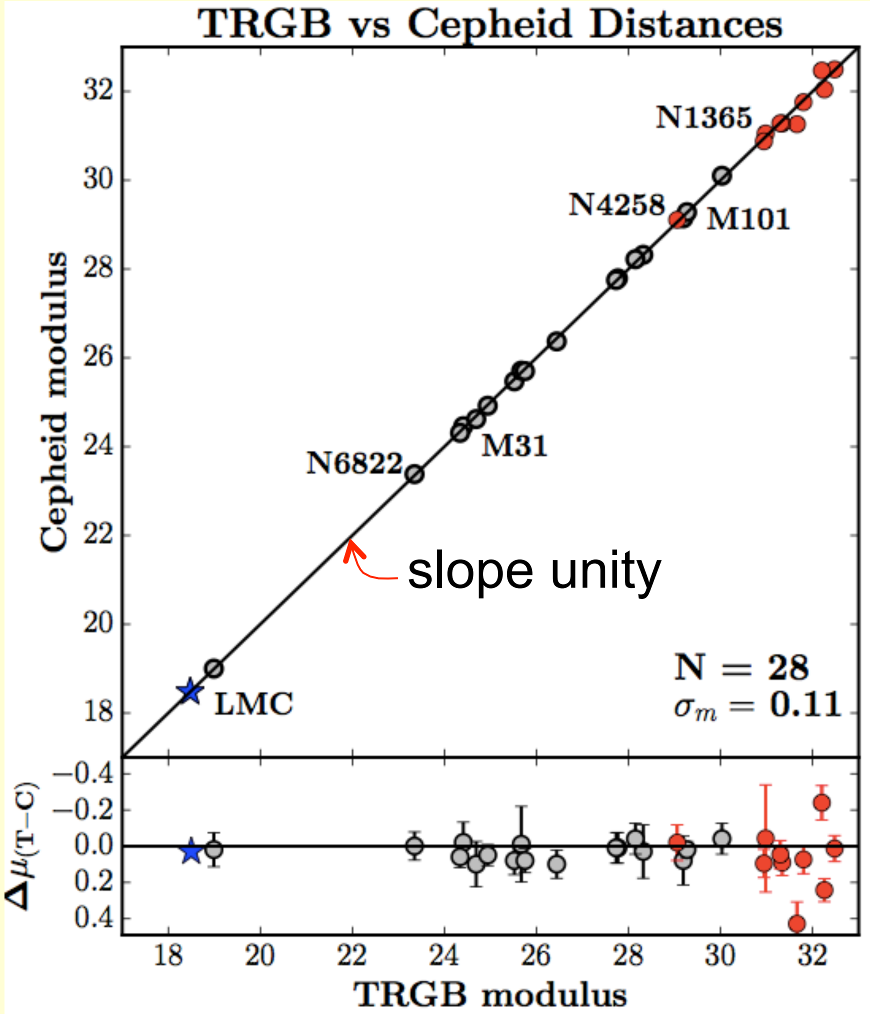
- DES-Y1 analyses: do not contrain H_0 directly
- Combined with Planck: shift the H_0 inference towards local measurements
- Not very conclusive yet, WL must gain in precision first

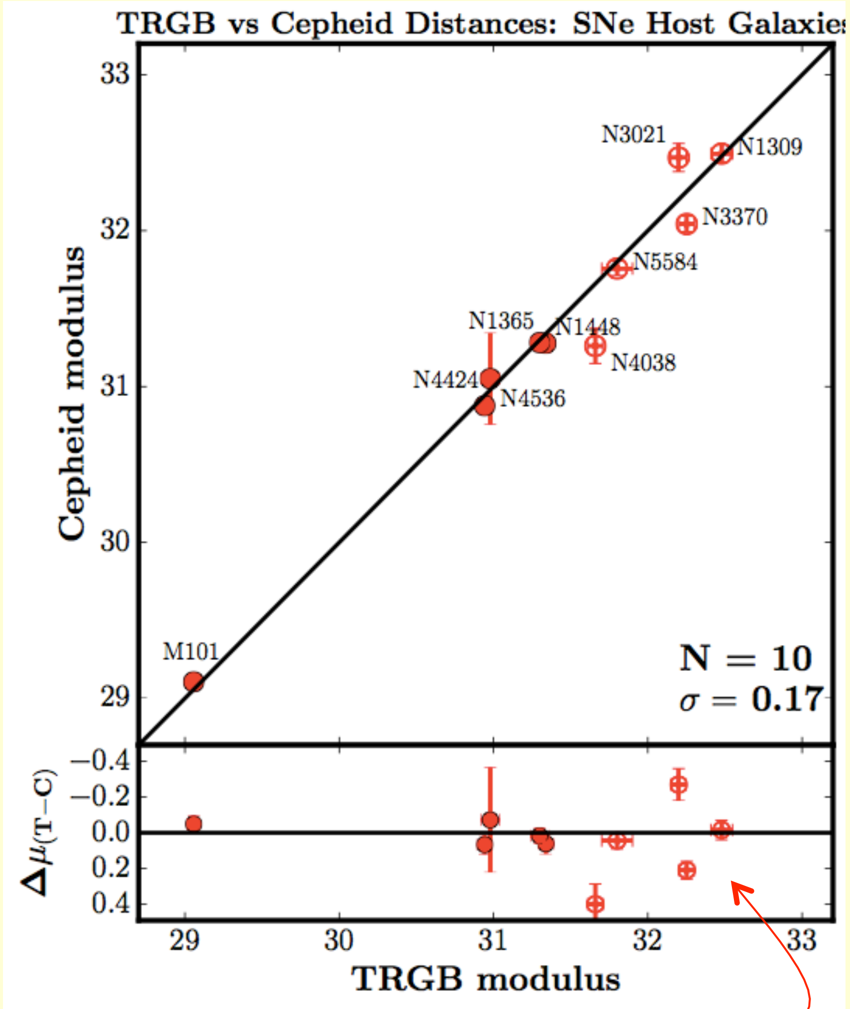


T.M.C.Abbott et al, 2018,Phys. Rev. D98, 043526

TRGB

W.Freedman et al., arXiv:1907.05922

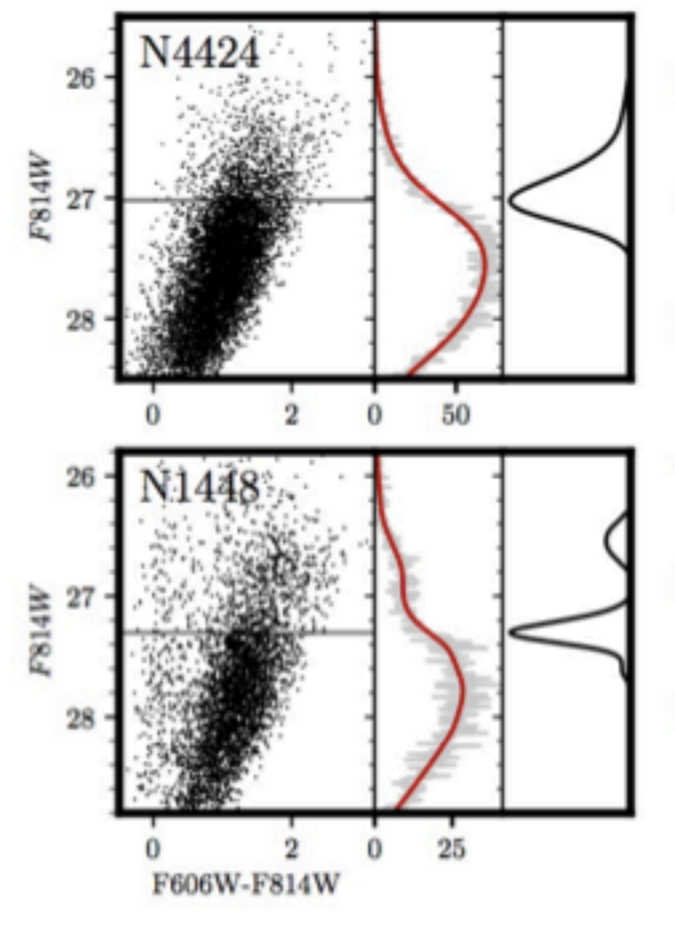




mean offset: 0.06 mag

Nearest galaxies: σ=0.05 mag ⇒ both distances agree within 5%

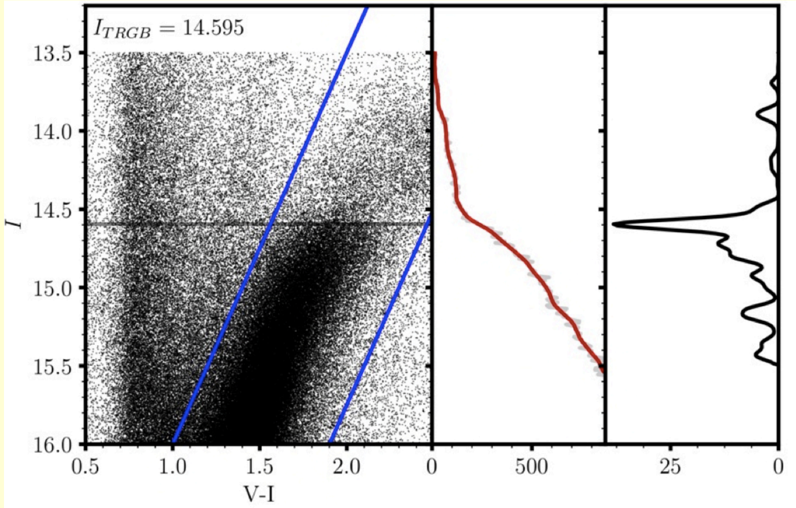
SNIa host galaxies: σ=0.17 mag >> individual errors, underestimated ?



2 CCHP SNIa host galaxies

TRGB

W.Freedman et al., arXiv:1907.05922

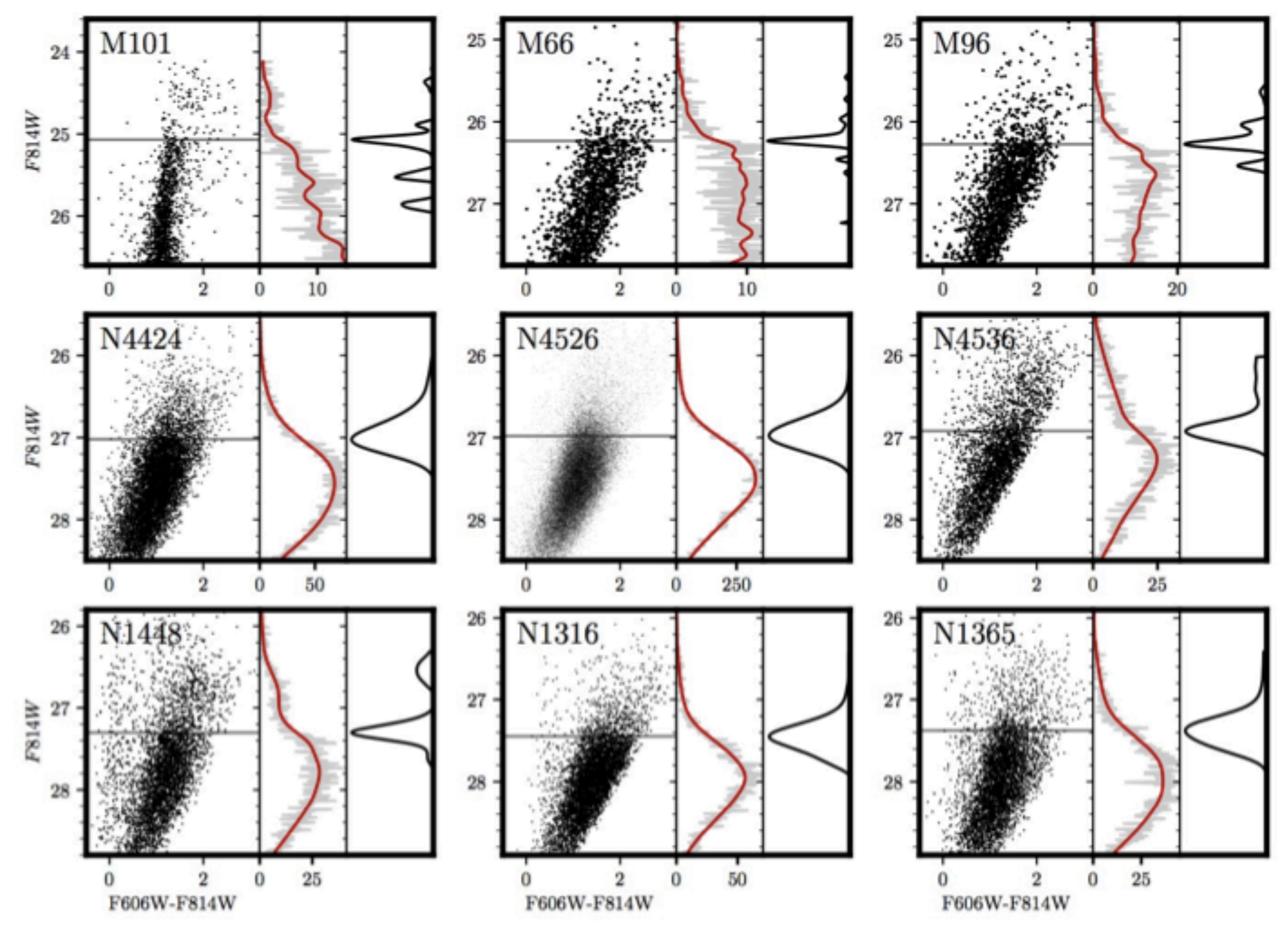


Outer part of the LMC

- TRGB magnitude measured from the abrupt discontinuity in the color-selected, marginalized I-band luminosity function
- Measurement of TRGB tip in the LMC, extinction correction, conversion of the ground-based I-band system to the HST photometric system

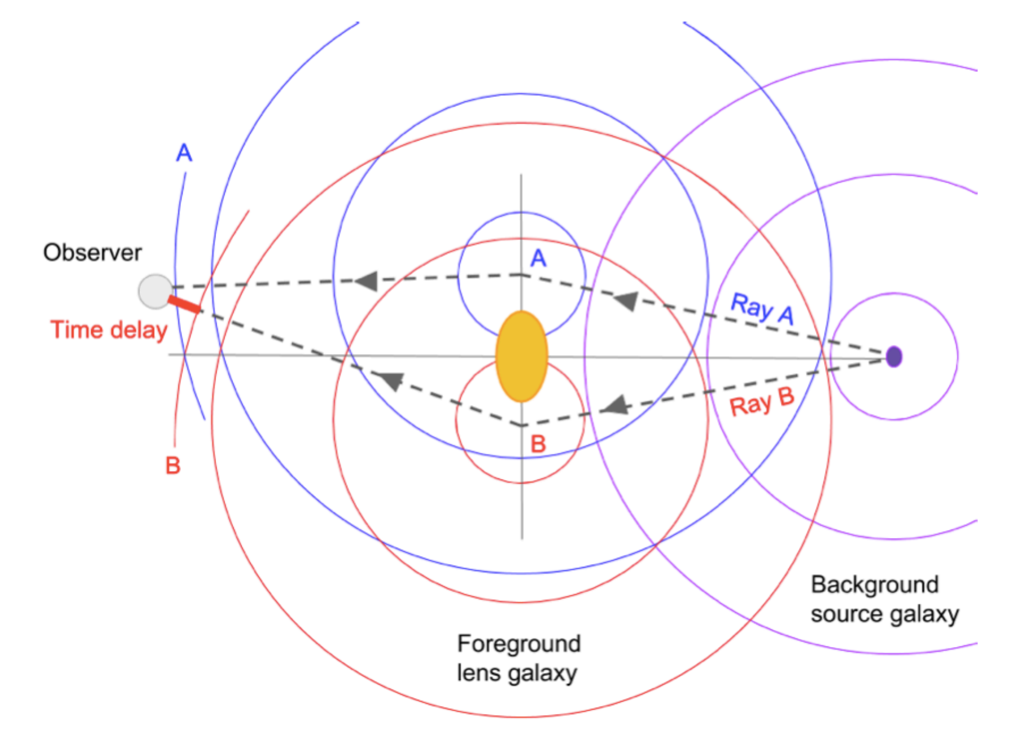
TRGB

W.Freedman et al., arXiv:1907.05922



Time delay cosmography: principle

T. Treu, P. Marshall, 2016, A&ARv, 24, 11T



$$\Delta\tau_{AB} = \frac{D_{\Delta t}}{c} \Delta\Phi_{AB}$$

$$\Delta\Phi_{AB} = \tfrac{1}{2}(\theta_A - \beta_A) - \psi(\theta_A) - \tfrac{1}{2}(\theta_B - \beta_B) - \psi(\theta_B)$$

$$D_{\Delta t} = (1 + z_d) \frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$$

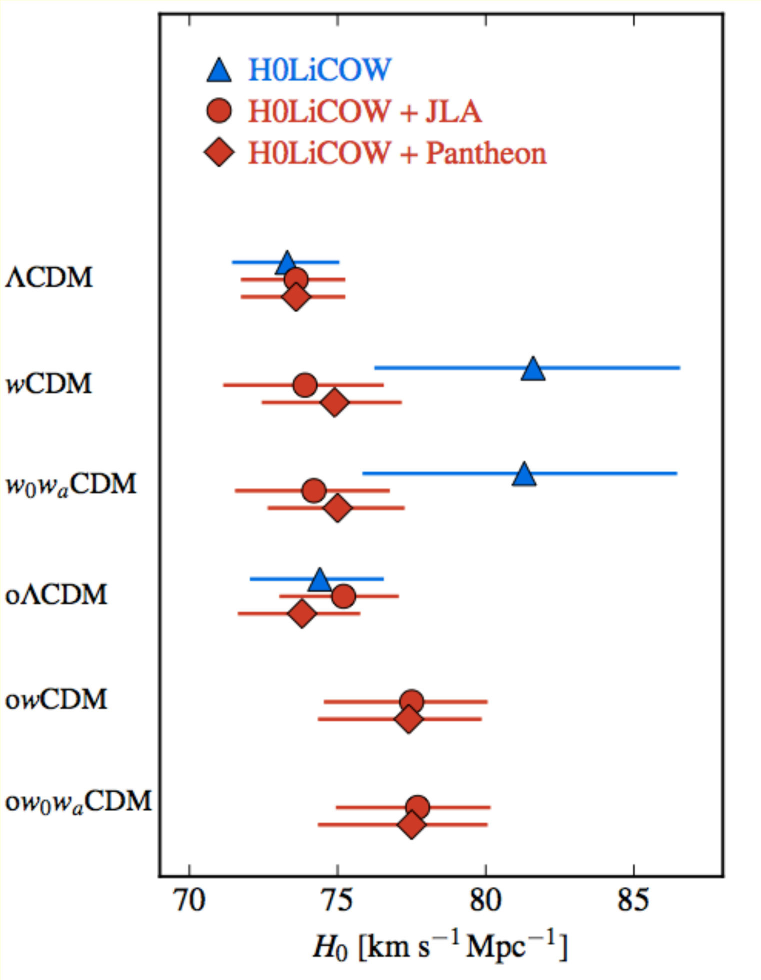
θ apparent / β unlensed — source position

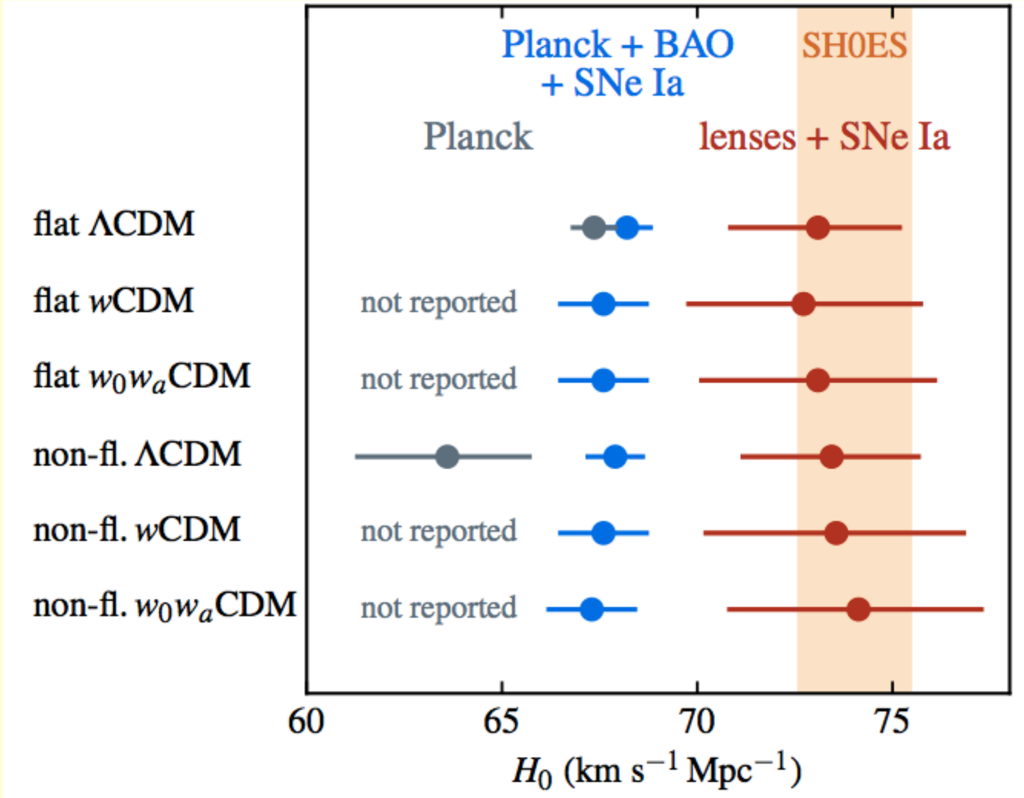
ψ projected lens gravitational potential

- model of the lens mass distribution ⇒ $\theta - \beta, \psi(\theta)$ predictions
- angular diameter distances (D_d, D_s, D_{ds}): depend on z_d, z_s, cosmology

Time delay cosmography + SNIa samples

- Calibration of absolute SNIa distances with time delay cosmography. Tension with Planck remains (> 2 to 3σ)





S.Taubenberger et al., arXiv:1905.12496

4 H0LiCOW lenses

K.C.Wong et al., arXiv:1907.04869

6 H0LiCOW lenses