Introduction to Cosmology

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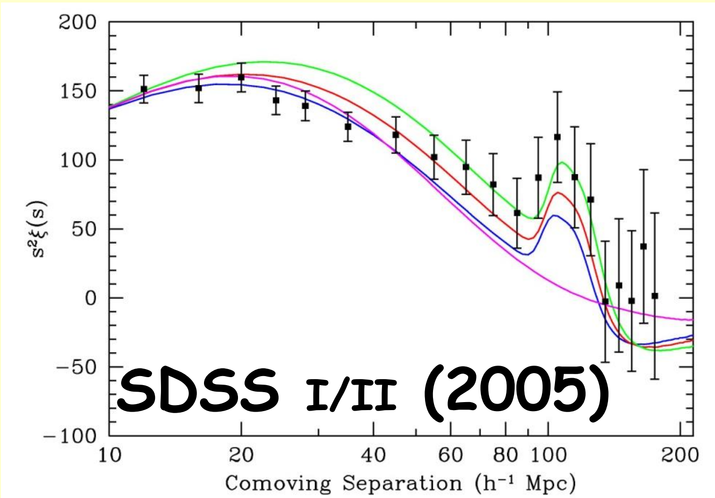
1) The Big Bang model
2) Content of the Universe
3) Cosmological probes
4) **Large Scale Structure: from SDSS to DESI**
5) **The Hubble constant tension**

Large Scale Structure, from SDSS to DESI

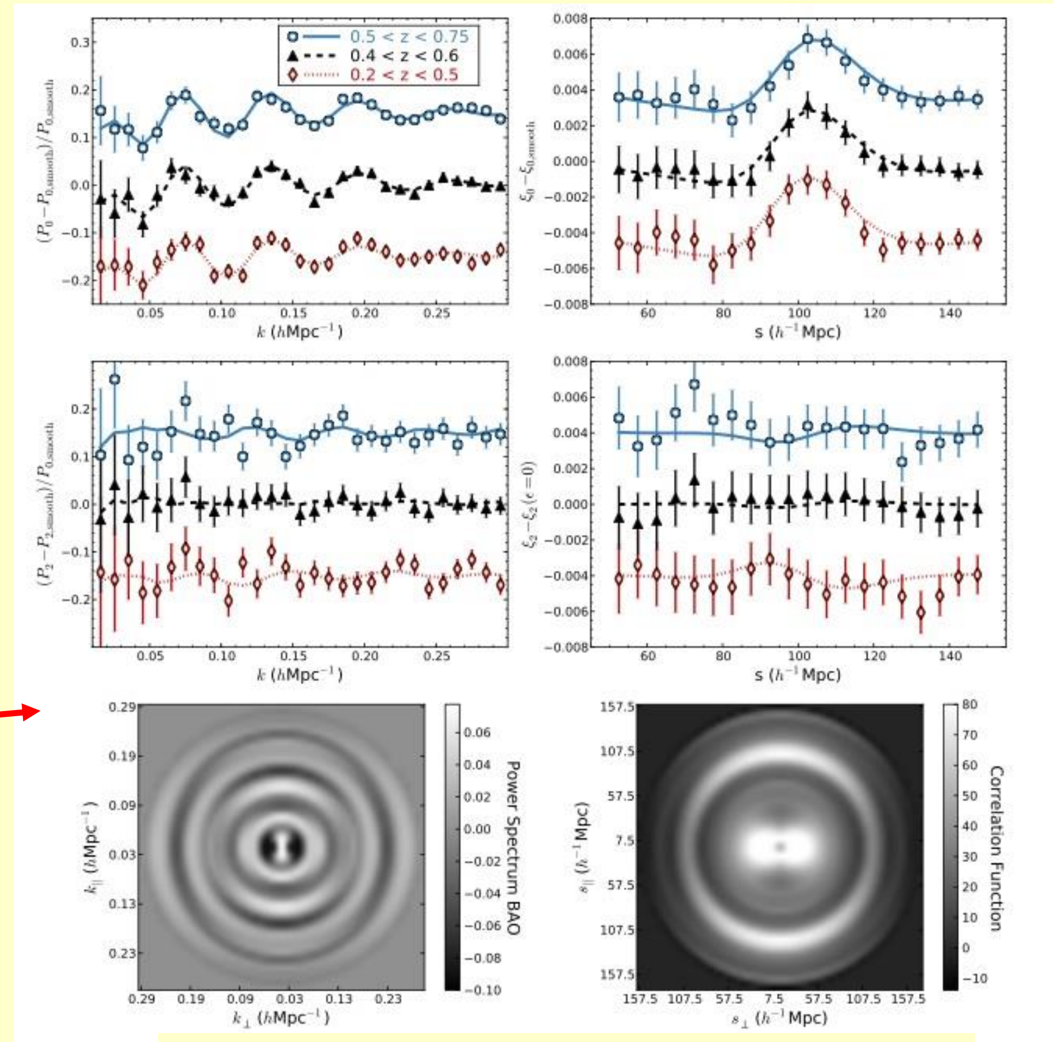
BAO: from detection to precise measurement

(see lecture 2)



D.Eisenstein et al., 2005, ApJ, 633, 560

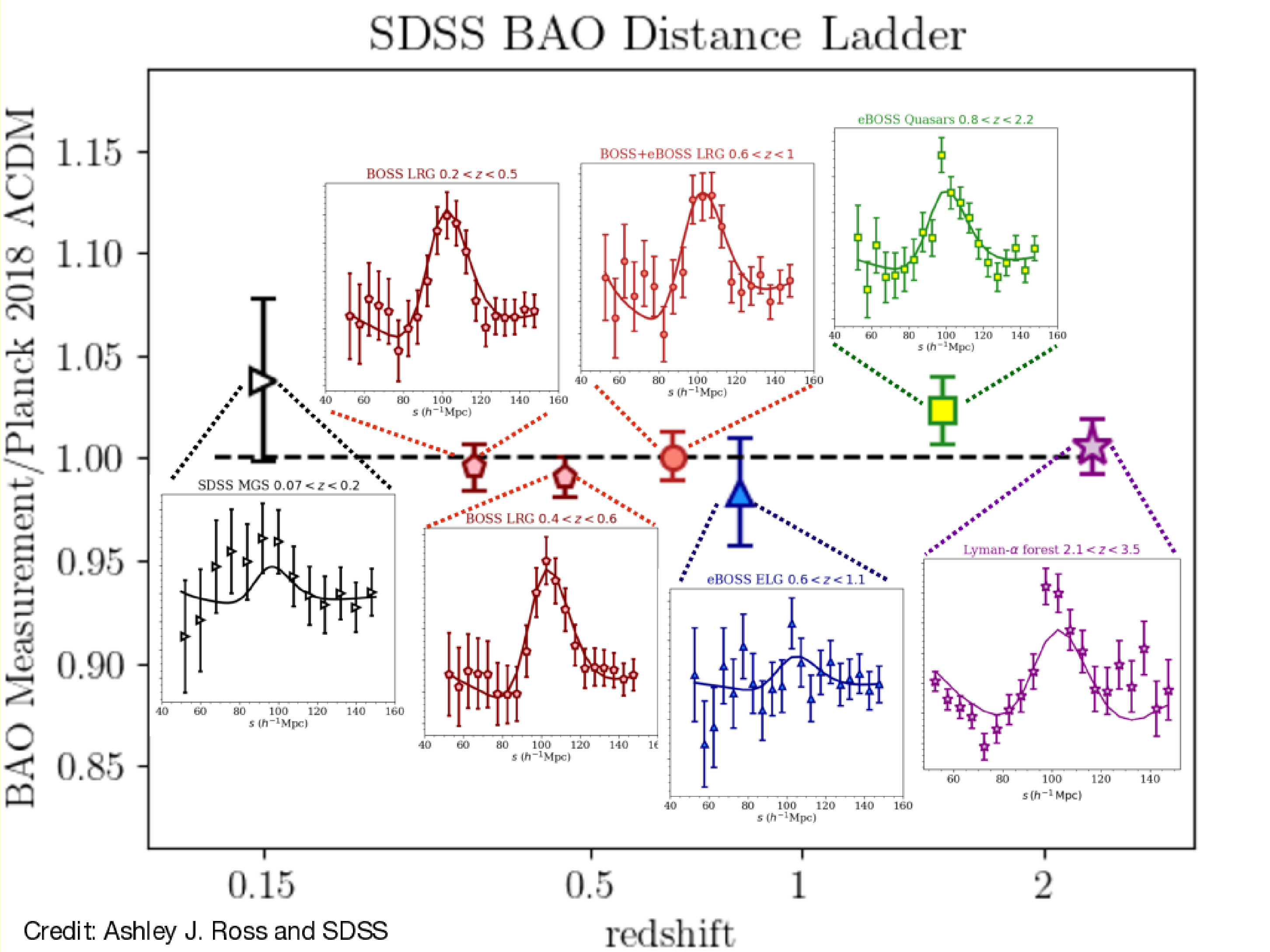
SDSS III (2017)



S. Alam et al., 2017, MNRAS,470, 2617A

- 8σ detection of BAO peak in LRG galaxy clustering
- 5σ detection of BAO peak in Lyα forest signal

BAO: final results from SDSS I to IV (2021)



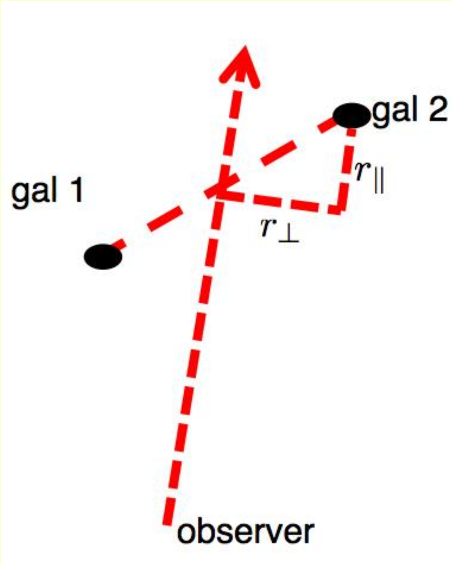
https://www.sdss.org/science/cosmology-results-from-eboss/

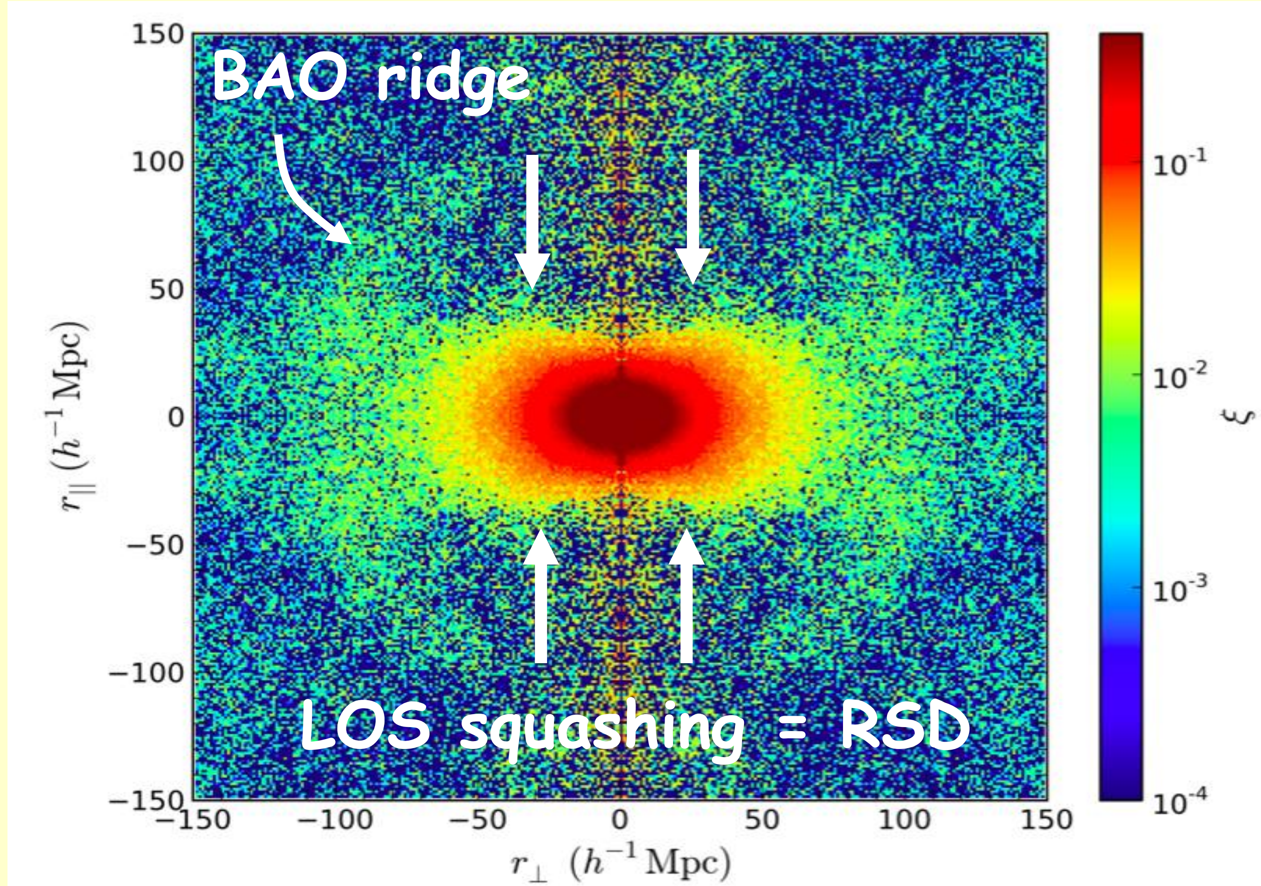
BAO scales measured for different matter tracers over 0.15<z<2.5, with different technics (2PCF, P(k)), ⊥ and ∥ to the line of sight. Precision : ≲5%, stat > syst

Very good overall agreement with Planck 2018 best-fit.

Large scale structure: beyond BAO

L.Samushia et al, 2014, MNRAS, 439, 3504



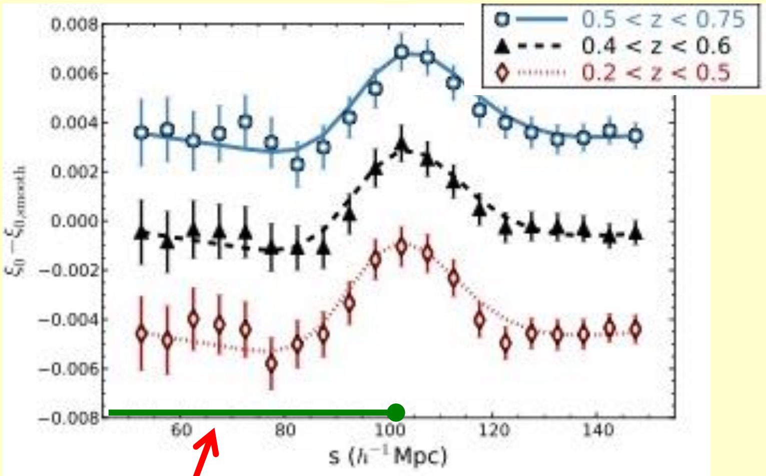


observed redshift: Hubble expansion + peculiar velocity due to gravity

Redshift Space Distortion: a way to measure structure growth & test gravity, full shape analysis of matter power spectrum required

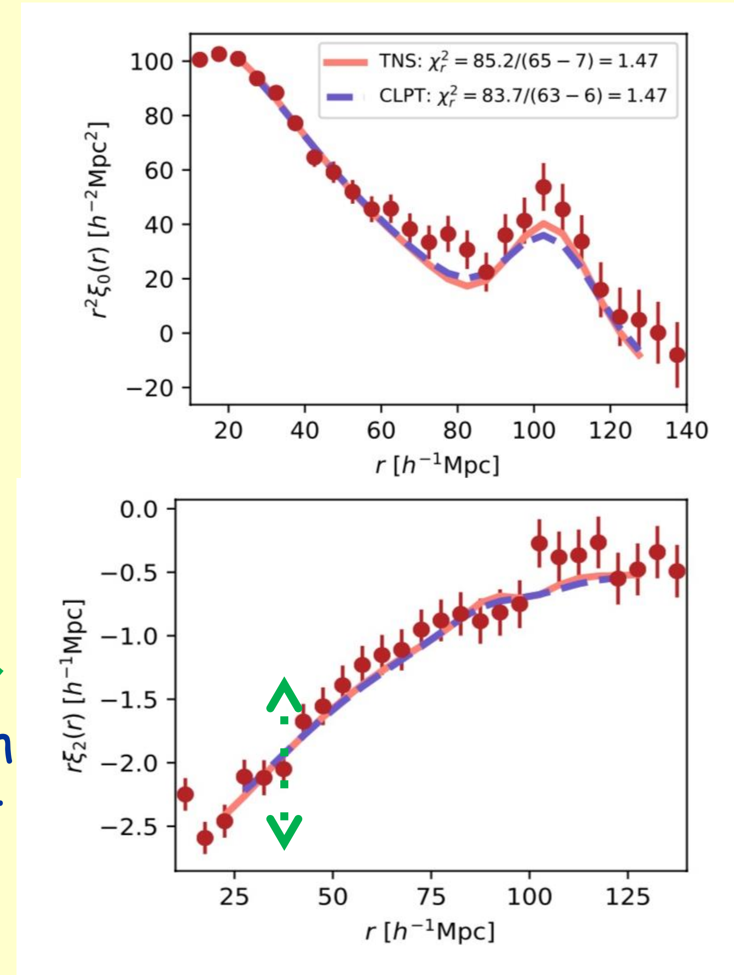
From BAO …

S. Alam et al., 2017, MNRAS,470, 2617A



BAO scale

… to full shape analysis



J. Bautista et al., 2021, MNRAS, 500, 736

quadrupole amplitude $\propto$ gravity strength
=> linear growth rate ($f\sigma_8$) measurement

requires modelling of matter clustering on small scales (i.e. below BAO scale) down to the quasi-linear regime

RSD modelling

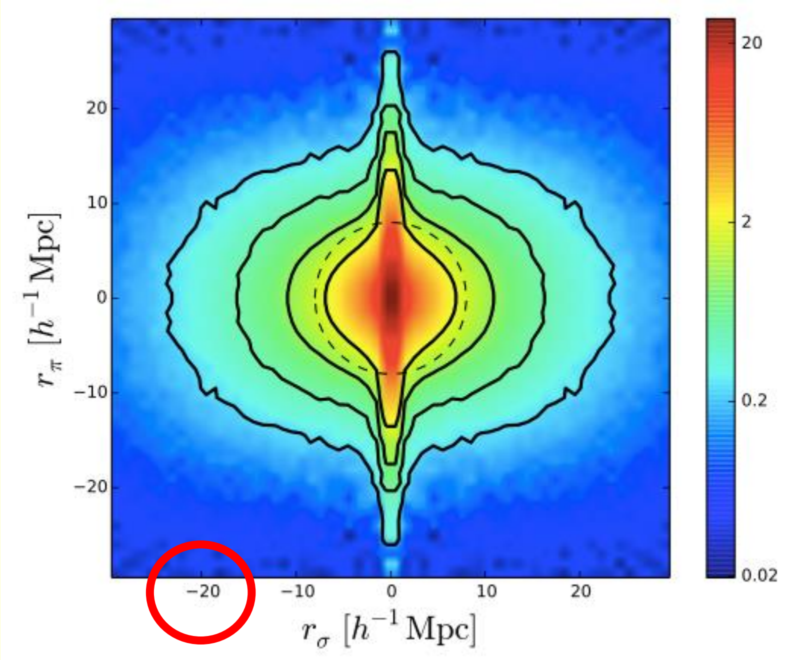
- Taruya, Nishimichi, Saito model (2010) used in BOSS/eBOSS:

$$P_g(k,\mu)=e^{-(fk\mu\sigma_v)^2}\left[P_{g,\delta\delta}(k)+2f\mu^2P_{g,\delta\theta}(k)+f^2\mu^4P_{\theta\theta}(k)+b^3A(k,\mu,f)+b^4B(k,\mu,f)\right]$$

Kaiser effect
(large scale infall velocities)
$r > 8h^{-1}$Mpc

TNS corrections

Finger of God effect
(incoherent velocities)
$r_\sigma \ll 8h^{-1}$Mpc



B. Reid et al., 2014, MNRAS,444..476R

- with:

$\mu \equiv \cos(\vec{k},\vec{u}_{los})$

$\sigma_v^2 \equiv \langle v_{los}^2 \rangle$

δ,θ ***density, velocity***

- and:

$P_{g,\delta\delta}, P_{g,\delta\theta} \xleftrightarrow{\text{bias model}} P_{\delta\delta}, P_{\delta\theta}$

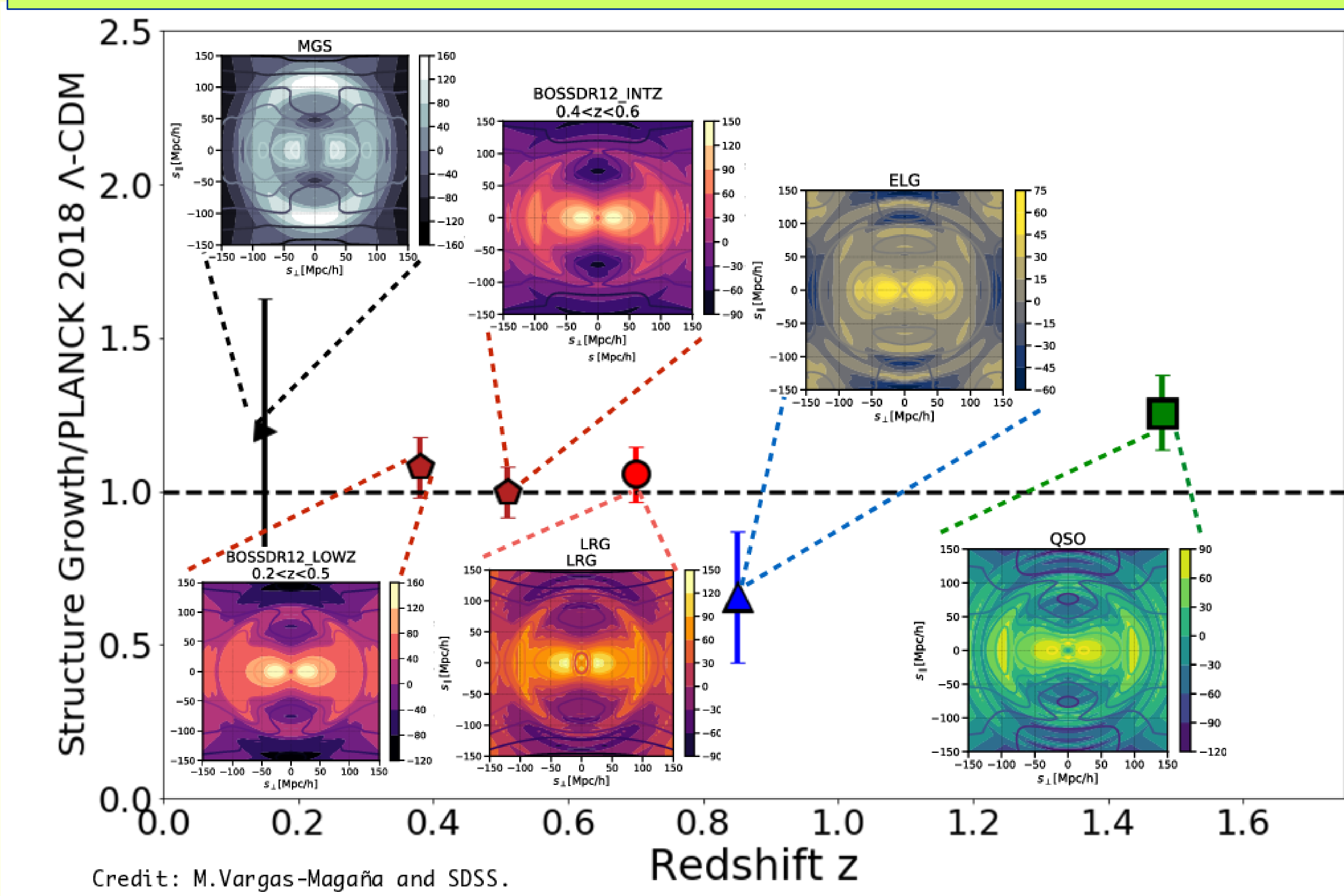
$P_{\delta\delta}, P_{\delta\theta}, P_{\theta\theta}, A, B$: 2-loop PT

f: linear growth rate

b: linear bias

RSD: final results from SDSS I to IV (2021)

https://www.sdss.org/science/cosmology-results-from-eboss/

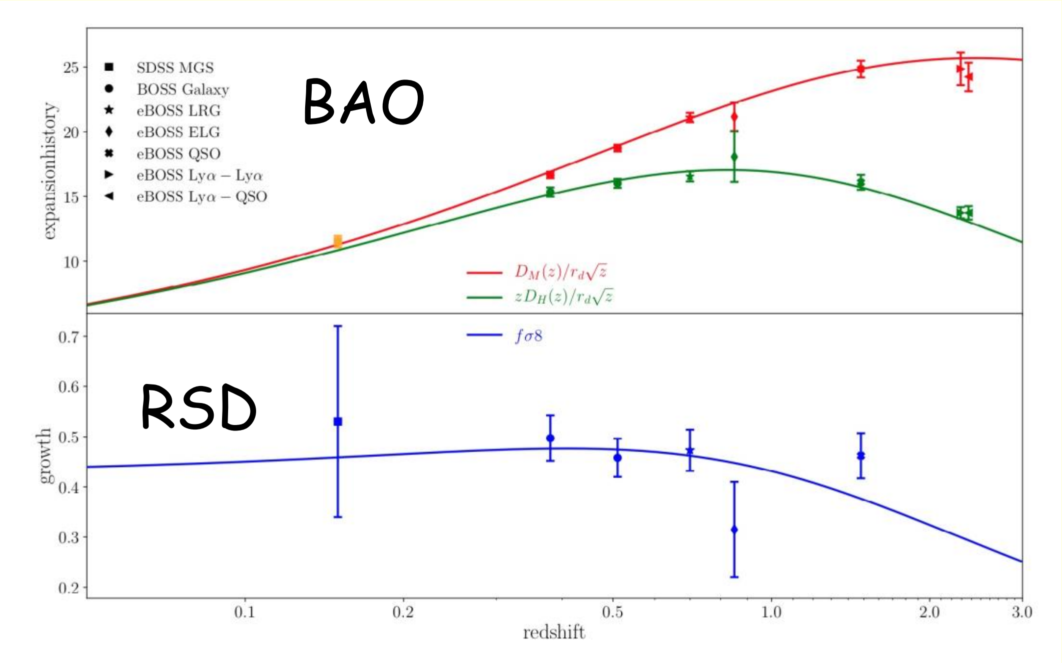


Structure growth rate measured for different matter tracers over 0.07<z<1.5, with different technics (2PCF, P(k)). Best precision: 6-10%

Good overall agreement with Planck 2018 best-fit but test is not stringent.

SDSS LSS summary

Alam et al, PRD 103 (2021) 083533



wCDM constraints

w=-1.026±0.033 (CMB+BAO+SN)

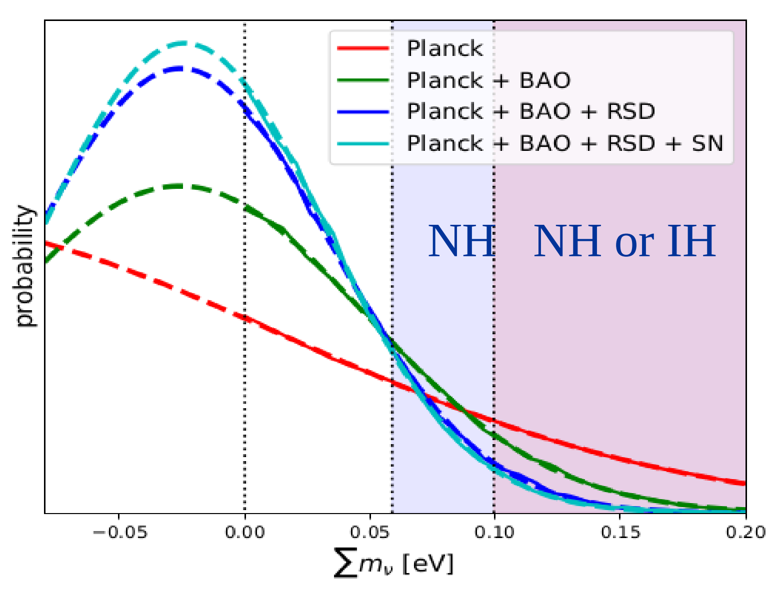
w=-1.09±0.11 (CMB+RSD)

Λ_{CDM} + Σm_ν constraints

$\Sigma m_\nu \leq 0.129$ (CMB+BAO)

$\Sigma m_\nu \leq 0.102$ (CMB+BAO+RSD)

(95%CL)



The Dark Energy Spectroscopic Instrument

Abareshi et al, arXiv:2205.10939

- Mayall telescope @ Kitt Peak NO, Arizona
- 4 m, 8 deg^2 FoV
- FP: 5,000 robotically positioned fibers
- 10 triple-arm spectrographs (360-980nm, $\lambda/\delta\lambda$=2000/5500)

- Started: 14/05/2021 for 5yrs
- 14,000 deg^2, 40 million redshifts

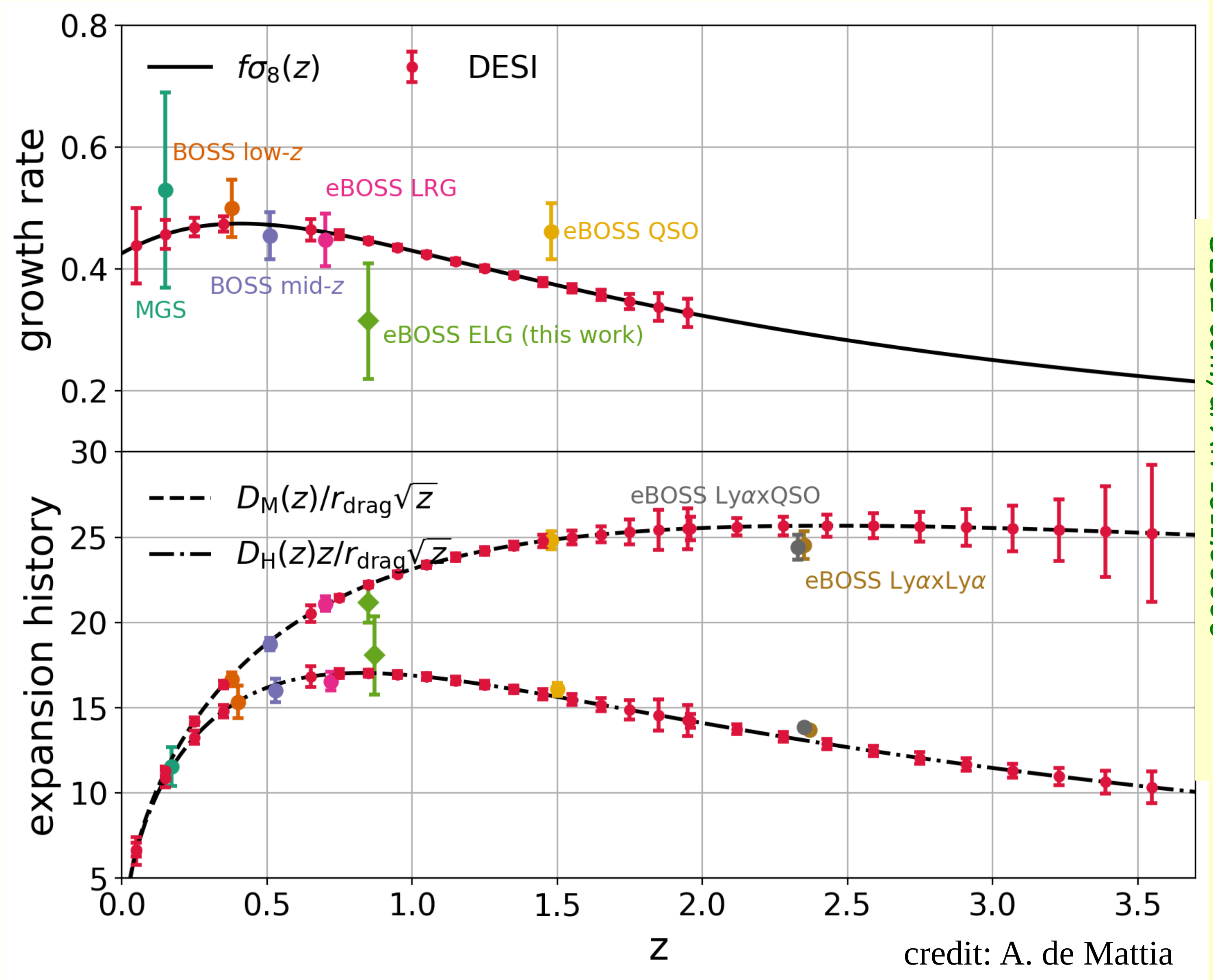
~ 10 x SDSS BAO surveys

DESI: a wide spectroscopic survey dedicated to clustering measurements, BAO scales and growth rate (through RSD)

Prospects

RSD:
18 z bins,
δz=0.1

BAO:
29 z bins,
δz=0.1

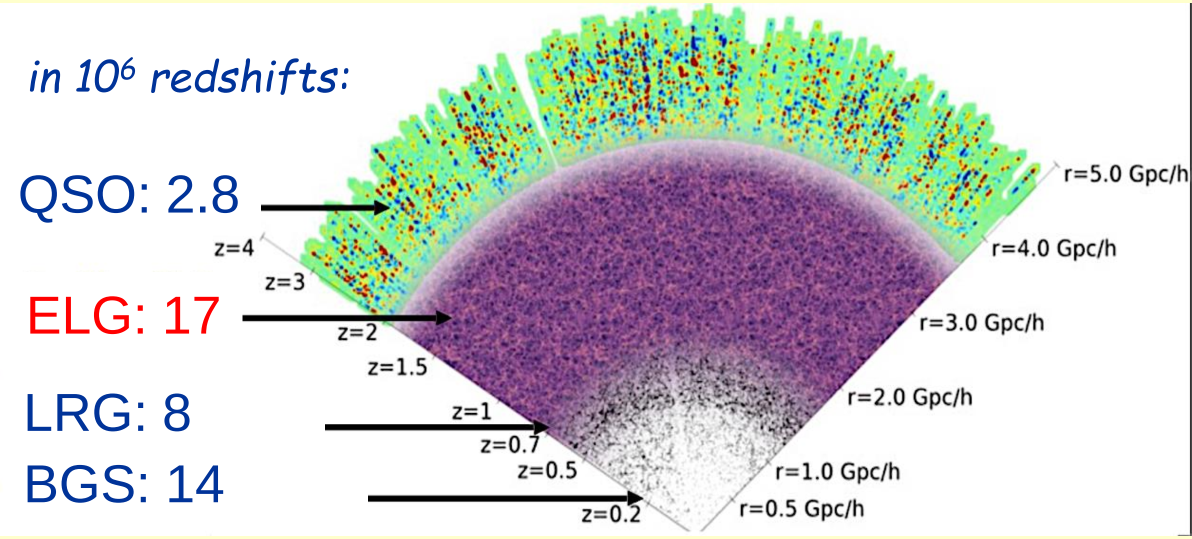


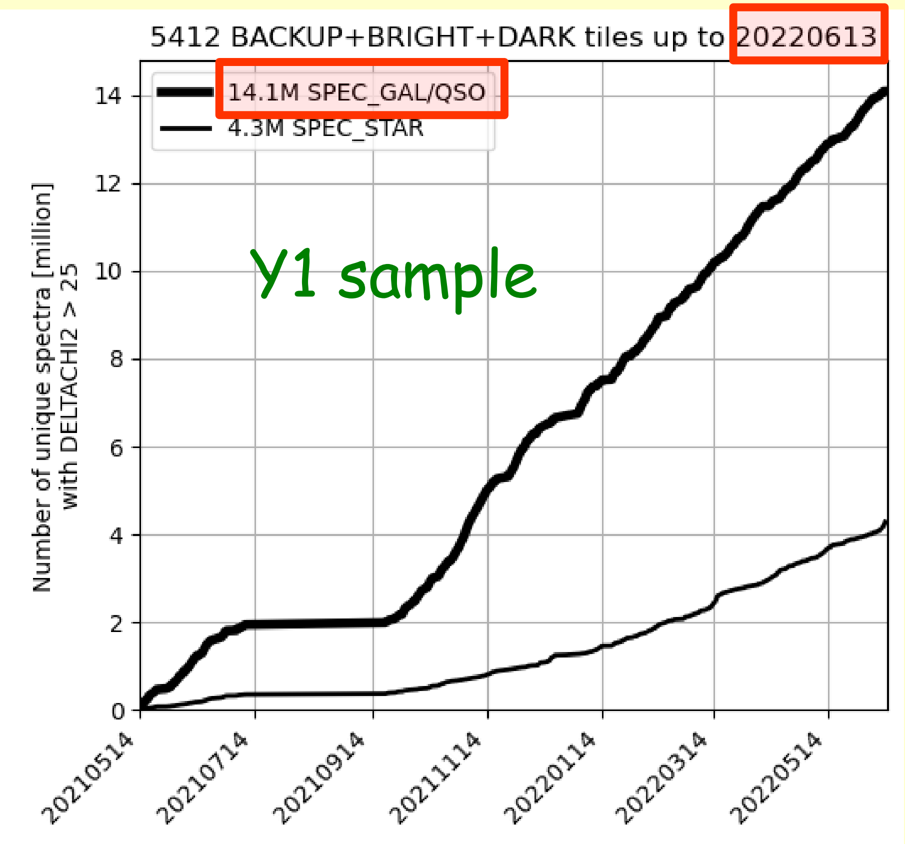
DESI coll., arXiv:1611.00036

⇒ Forecast (BAO+RSD+Planck): $\delta w_p = 0.01$ $\delta w_a \approx 0.1$ ($w_0\, w_a$CDM model)

DESI tracers

expected: 40. 10^6 redshifts in 5yrs





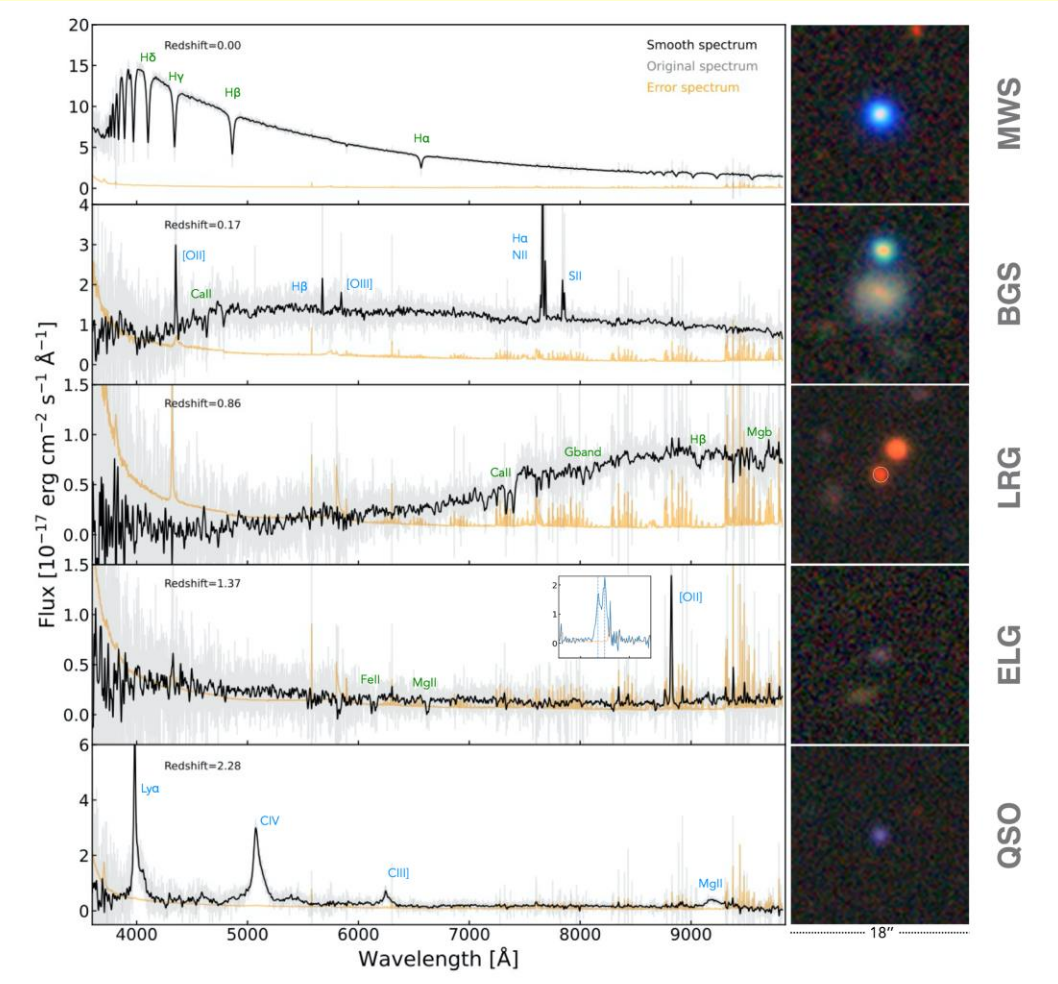
Survey status

Program completeness:

- dark time: 28.8%
- bright time: 41.2%

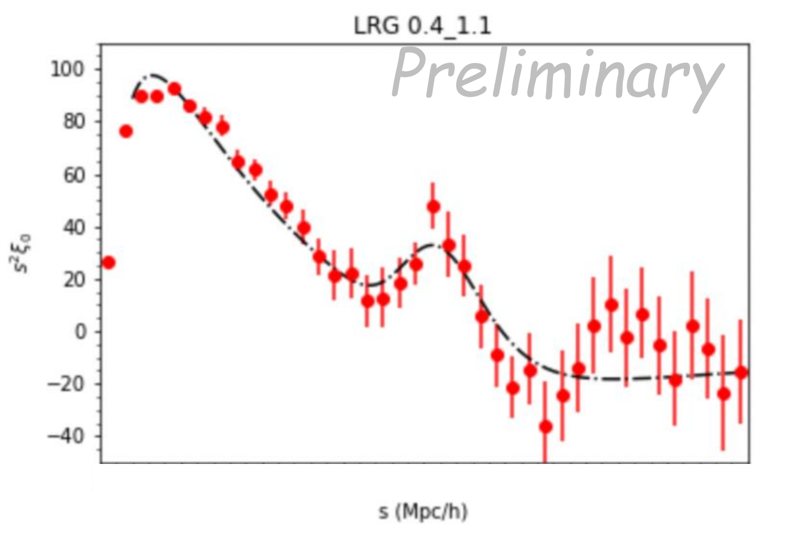
Present status: observations resumed on September, 10 after a ~3-month shutdown due to wildfires in June

Science output



https://www.desi.lbl.gov/category/blog

- Published: instrument, target selection validation
- To come in early 2023: galaxy-DM halo connection, BAO on early data (~1.8 10^6 redshifts)



To come by end 2023: Y1 clustering analyses and cosmological results

Stay tuned !

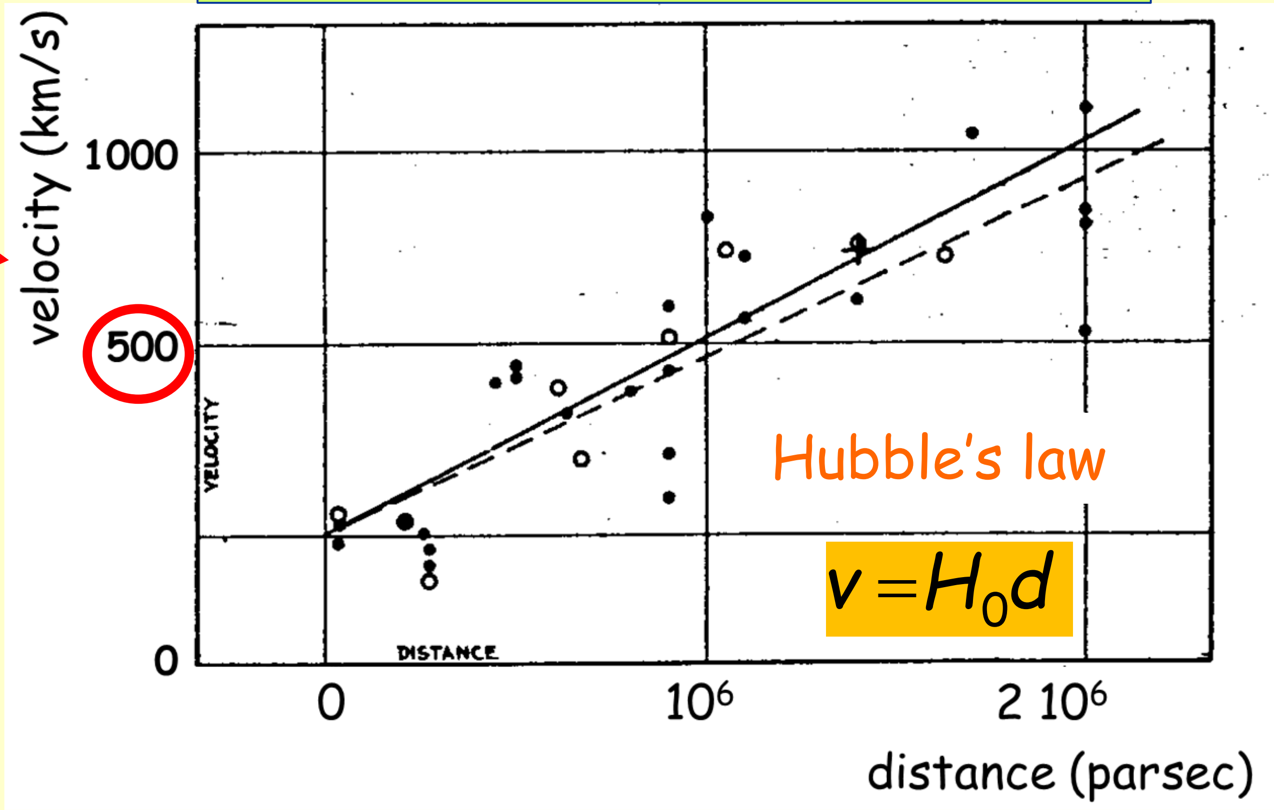
The Hubble constant tension

Direct measurement

(see lecture 1)

redshift converted into velocity

$z \sim v/c$



- H_0: Hubble constant
- Initial value, 1929:

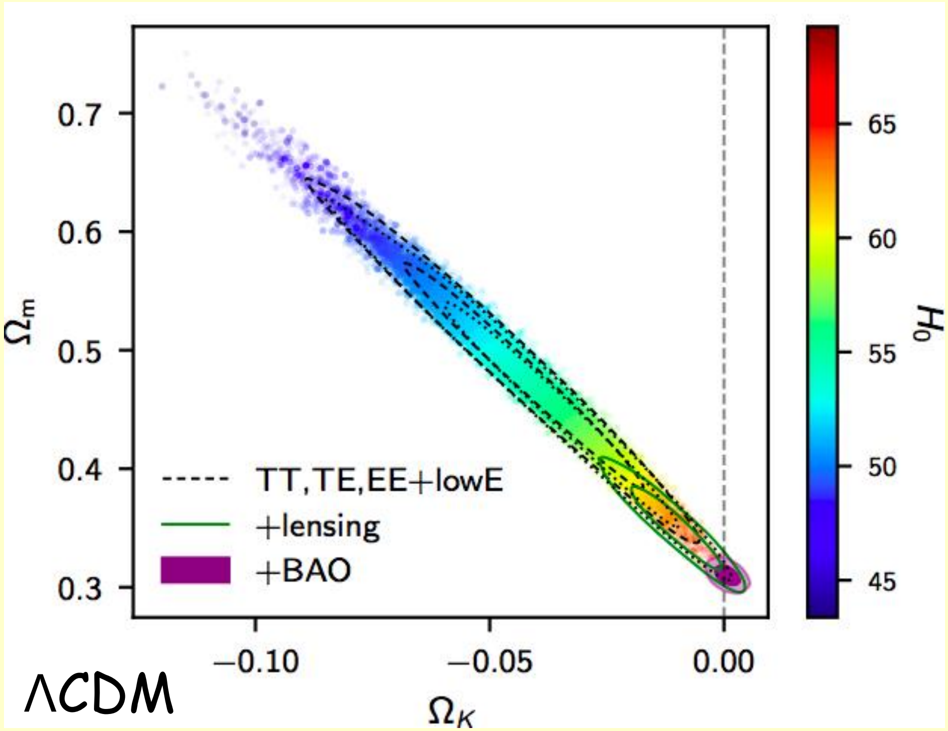
$$H_0 \sim 500\ km/s/Mpc$$

- most precise direct measurement to date (2022):

$$H_0 = 73.04 \pm 1.04 km/s/Mpc$$

A. Riess et al, ApJ 944L (2022) 7R

A closer look at final Planck ΛCDM fits



Planck Collaboration, A&A 641 (2020) A6

- Flat ΛCDM fit:

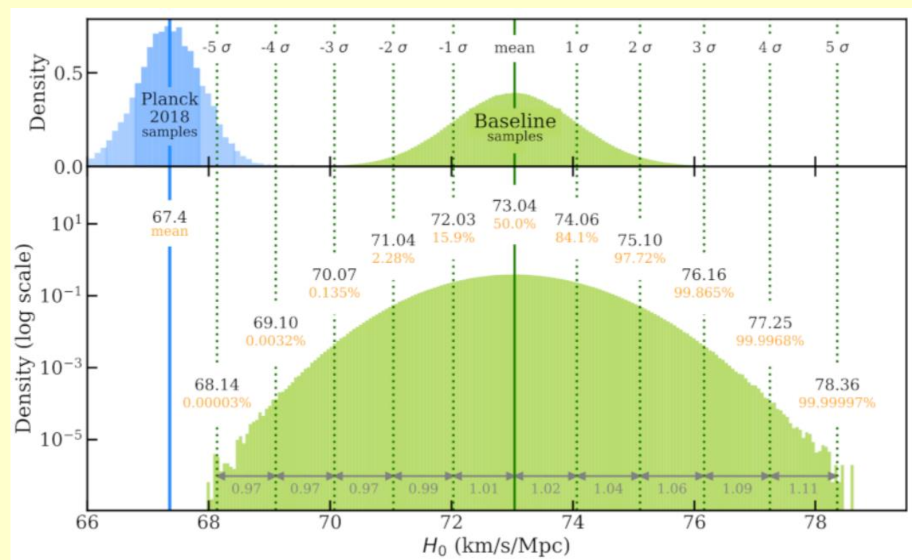
H_0=67.66±0.42km/s/Mpc

(all Planck data+BAO)

- flat ΛCDM fit of H_0 in tension with direct H_0 measurement !

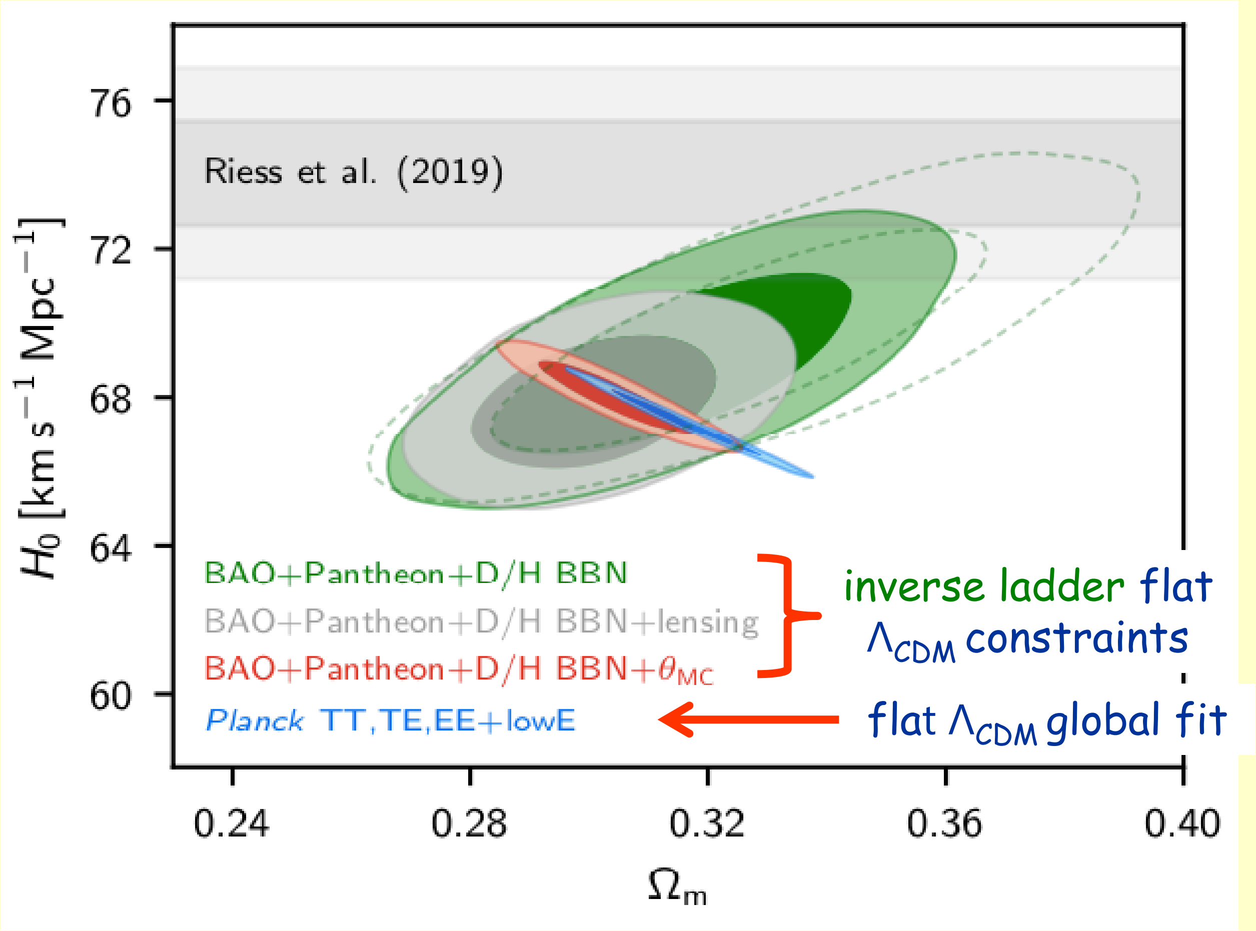
⇒ 5σ tension

A. Riess et al, ApJ 944L (2022) 7R



Cross-check from Planck

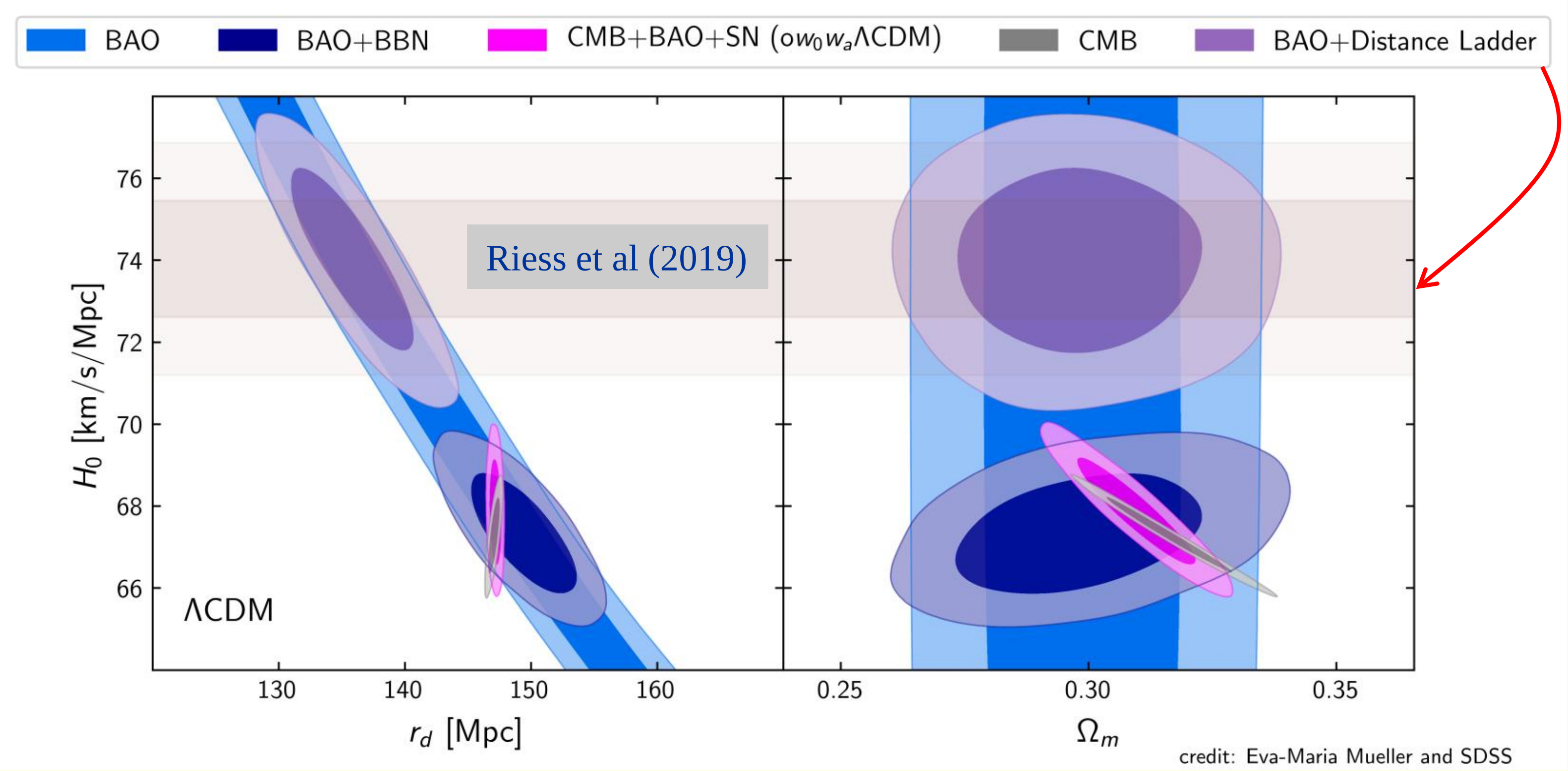
Planck Collaboration, A&A 641 (2020) A6



⇒ H_0 tension still there with minimal/no input from the CMB in inverse ladder constraints (~fits with priors from high redshift data)

Inverse ladder constraints from SDSS

Alam et al, PRD 103 (2021) 083533



H_0=67.87±0.86 km/s/Mpc (CMB + BAO + SN data, oww_aCDM model)

H_0=67.35±0.97 km/s/Mpc (BAO + BBN data, ΛCDM model)

⇒ tension cannot be restricted to systematic errors in Planck data or to the strict assumption of the ΛCDM model

Hint for non standard physics before decoupling ?

Measuring H_0 directly: a complex task

- Direct measurement of H_0: intercept of the distance-redshift relation (at logD~0)

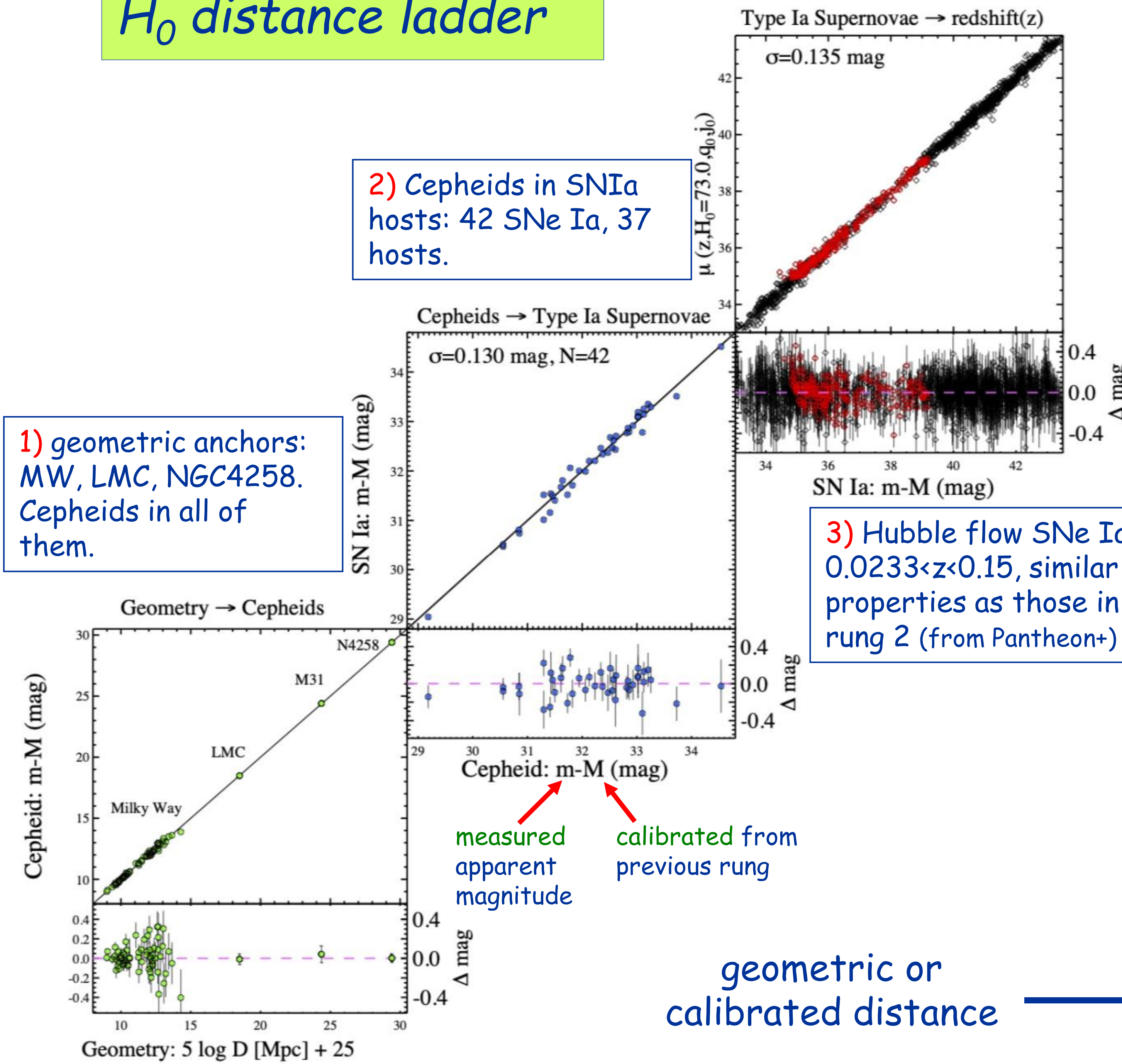
- Direct measurement of distances: short distances only (e.g. through parallaxes, D < 5kpc with Gaia).
- At large distances: use apparent magnitudes $m = M + 5\log D$ of standard candles.

- 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 from a nearby Cepheid-SN Ia sample (most precise method).

H_0 distance ladder



2) Cepheids in SNIa hosts: 42 SNe Ia, 37 hosts.

1) geometric anchors: MW, LMC, NGC4258. Cepheids in all of them.

3) Hubble flow SNe Ia: 0.0233<z<0.15, similar properties as those in rung 2 (from Pantheon+)

measured apparent magnitude

calibrated from previous rung

relative distance indicator ↑

geometric or calibrated distance →

A. Riess et al, ApJ 944L (2022) 7R

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

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

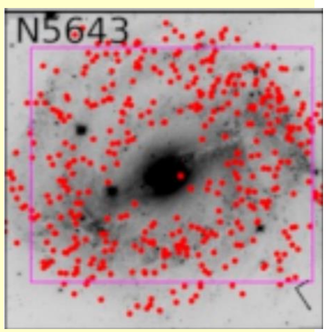
3. **SNe Ia in Hubble flow:** offset in magnitude (M_B) calibrated thanks to SNIa hosts and Cepheids in the second rung (+q_0 known) ⇒H_0

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

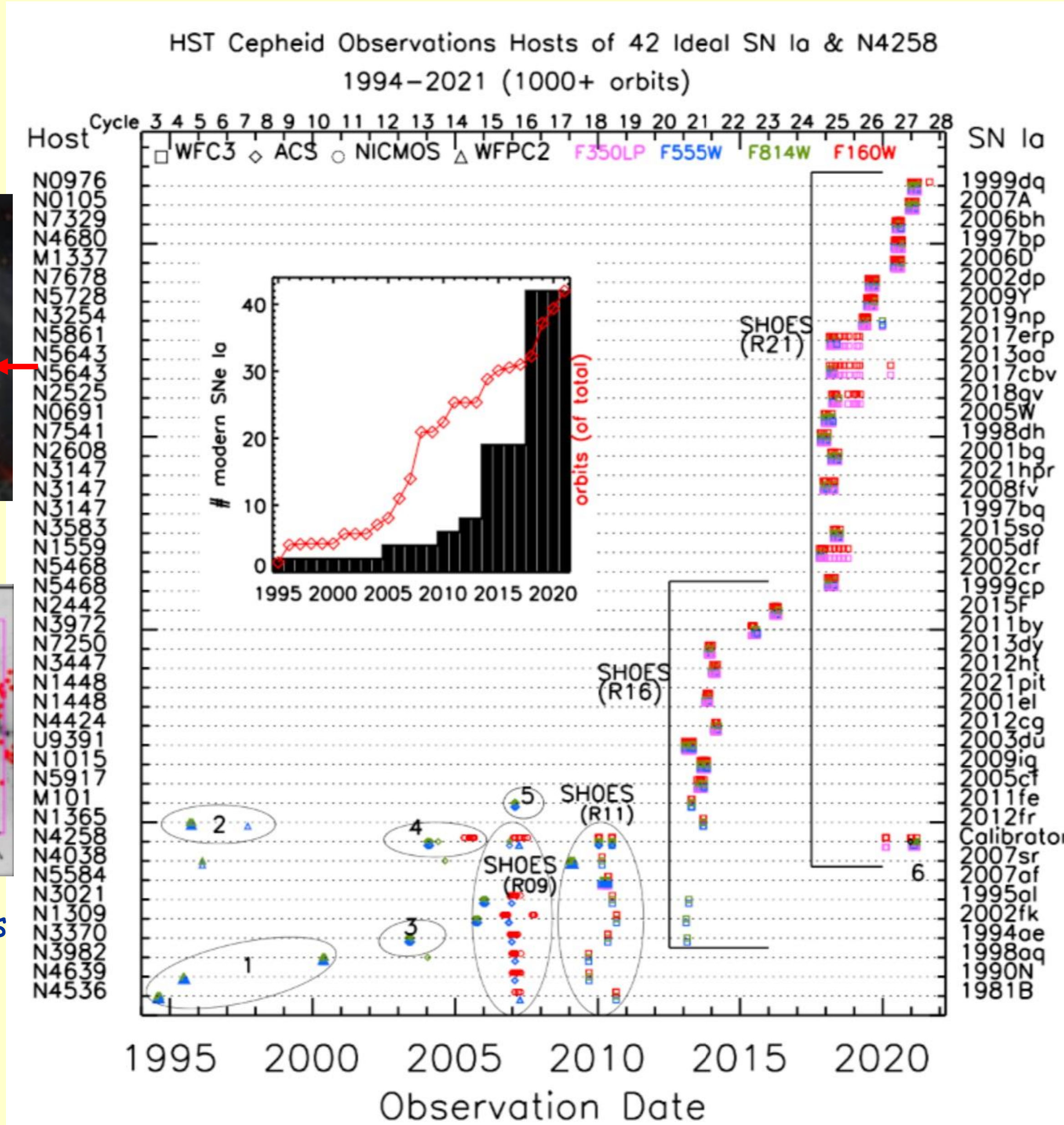
4. **Actual method:** global fit to all Cepheid and SN Ia data (with cov)

Two decades of Cepheid observations

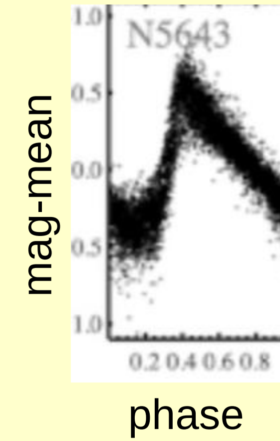
N5643



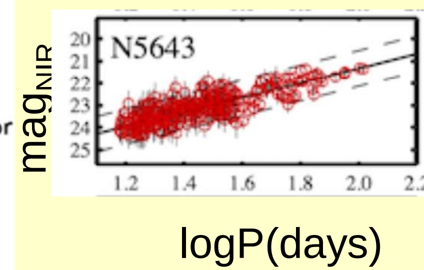
Cepheid positions
(251 Cepheids)



Cepheid optical mag
vs time

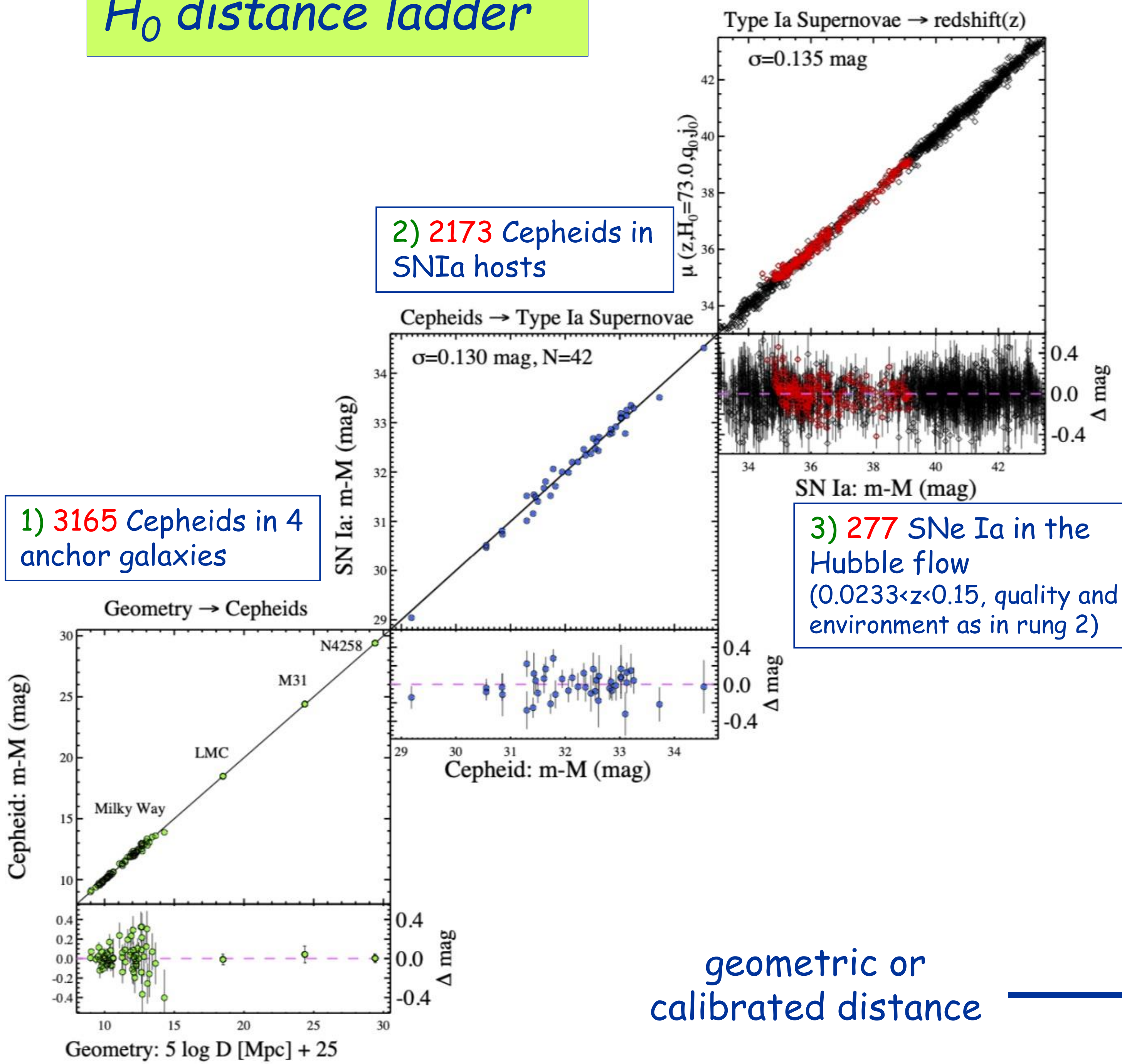


Cepheid NIR mag
vs period



A. Riess et al, ApJ 944L (2022) 7R

H_0 distance ladder



2) 2173 Cepheids in SNIa hosts

1) 3165 Cepheids in 4 anchor galaxies

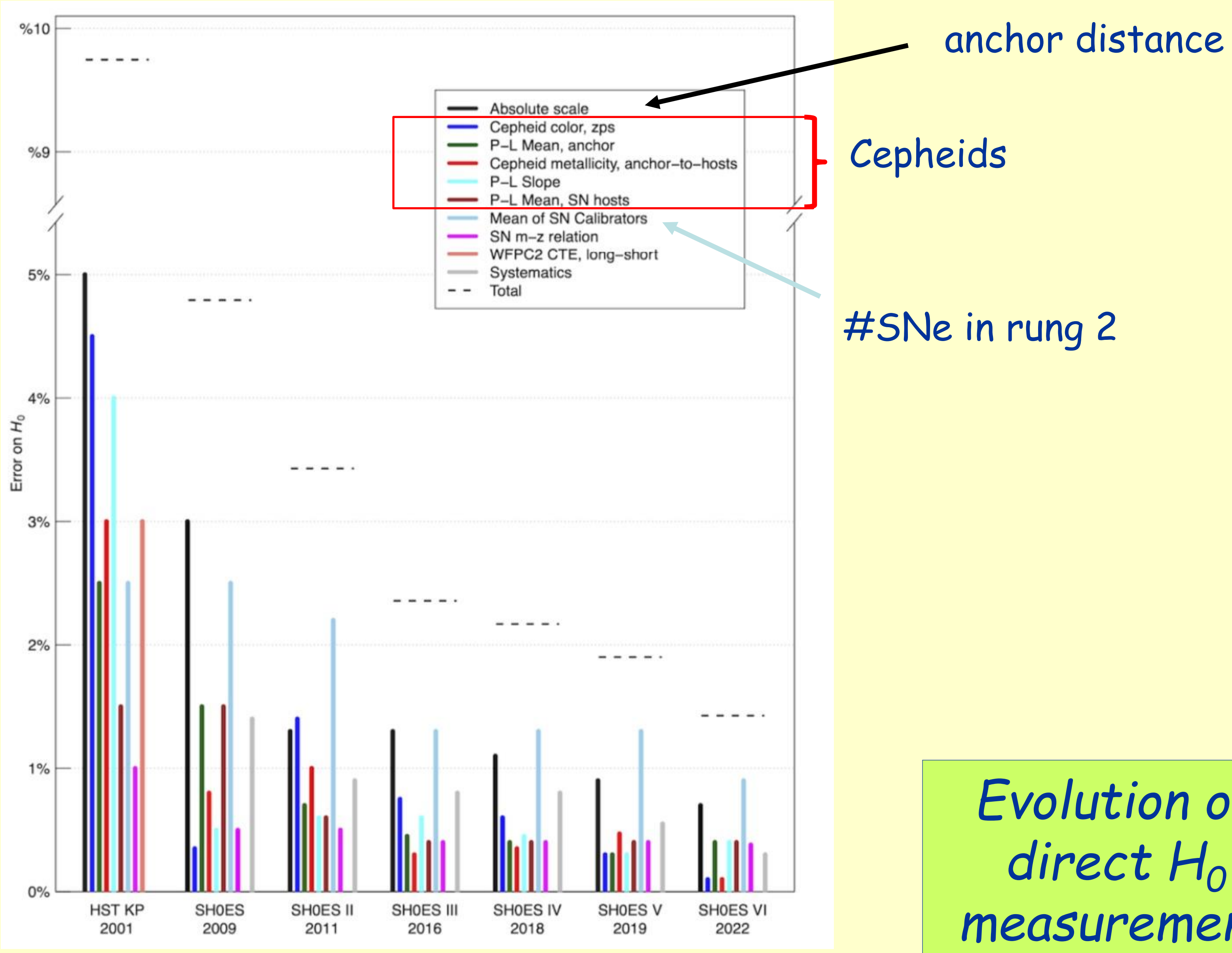
3) 277 SNe Ia in the Hubble flow (0.0233<z<0.15, quality and environment as in rung 2)

relative distance indicator

geometric or calibrated distance

A. Riess et al, ApJ 944L (2022) 7R

A. Riess et al, ApJ 944L (2022) 7R



Evolution of direct H_0 measurement precision

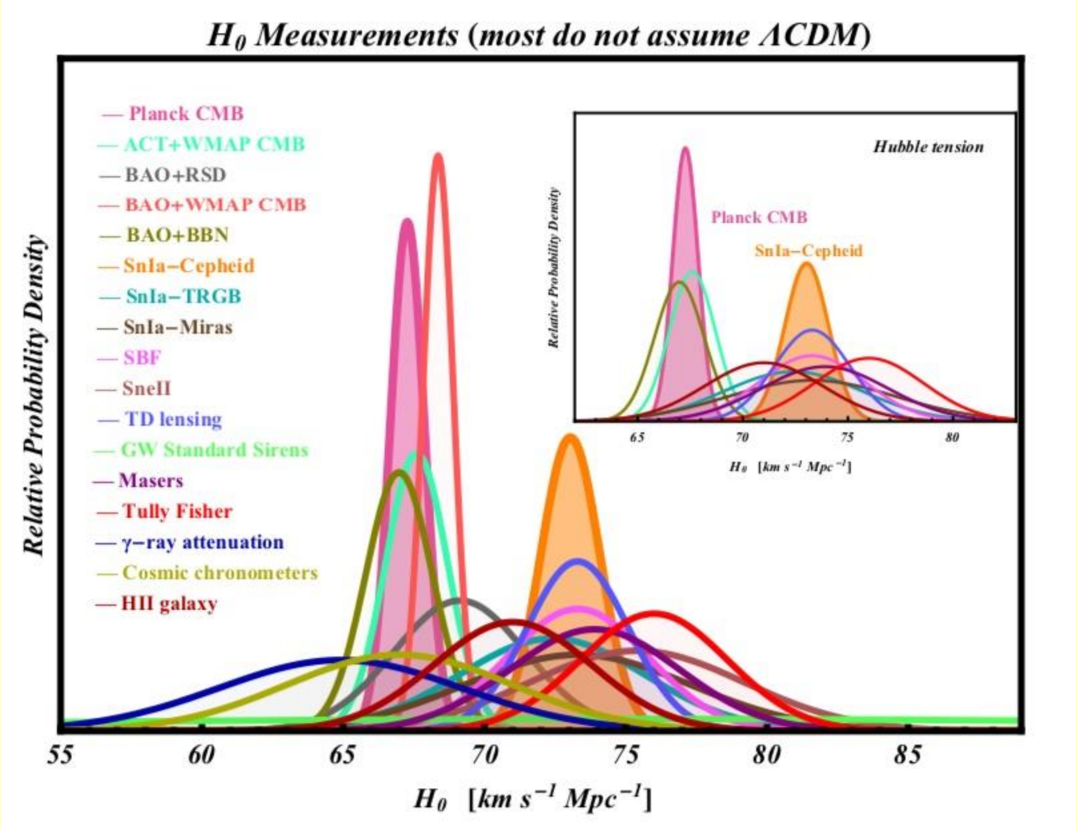
Recap

- local H_0 measurement ≠ H_0 constraints using early Universe data (BBN, CMB)
- No systematic uncertainty obviously missed in either method

- Hint for non standard pre-decoupling physics ? (e.g. early dark energy)

- Need for independent measurements (TRGB calibration of SNeIa, time delay cosmography, masers in the Hubble flow, GW standard sirens)

  and well controlled ones

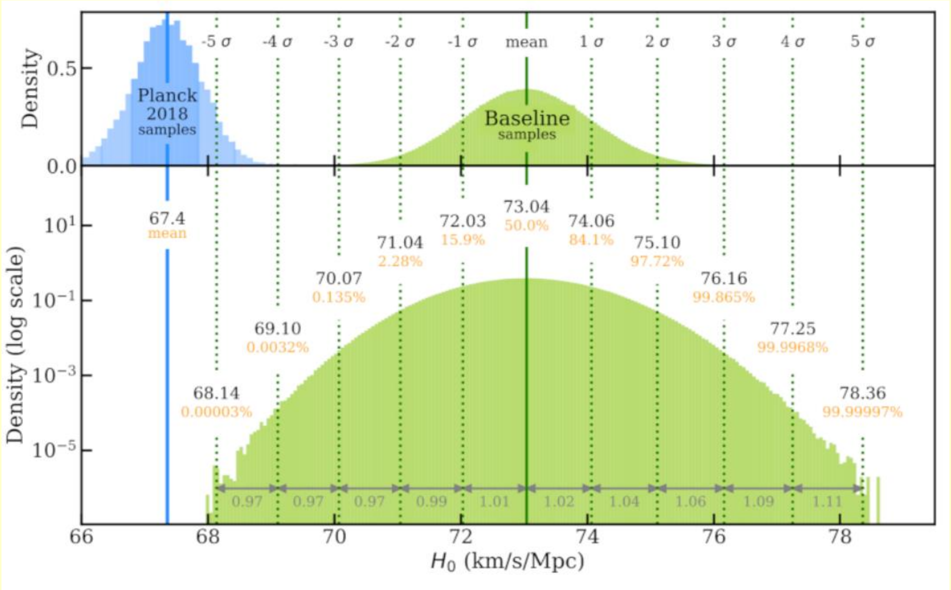


L.Perivolaropoulos & F.Skara, arXiv:2105.05208

CONCLUSIONS (4)

- Much progress in Large Scale Structure measurements: beyond BAO data available (RSD, WL) but impact is modest for now

- Future of LSS: DESI (2021-2026) then: Rubin-LSST, Euclid, Roman-WFIRST, all with similar constraining power on the DE equation of state, DESI-II ….



- H_0 value:
  - direct vs Λ_{CDM} fit disagree
  - need for well controlled results from independent measurement methods (time delays, distant megamasers, GW standard sirens … + future CMB projects)

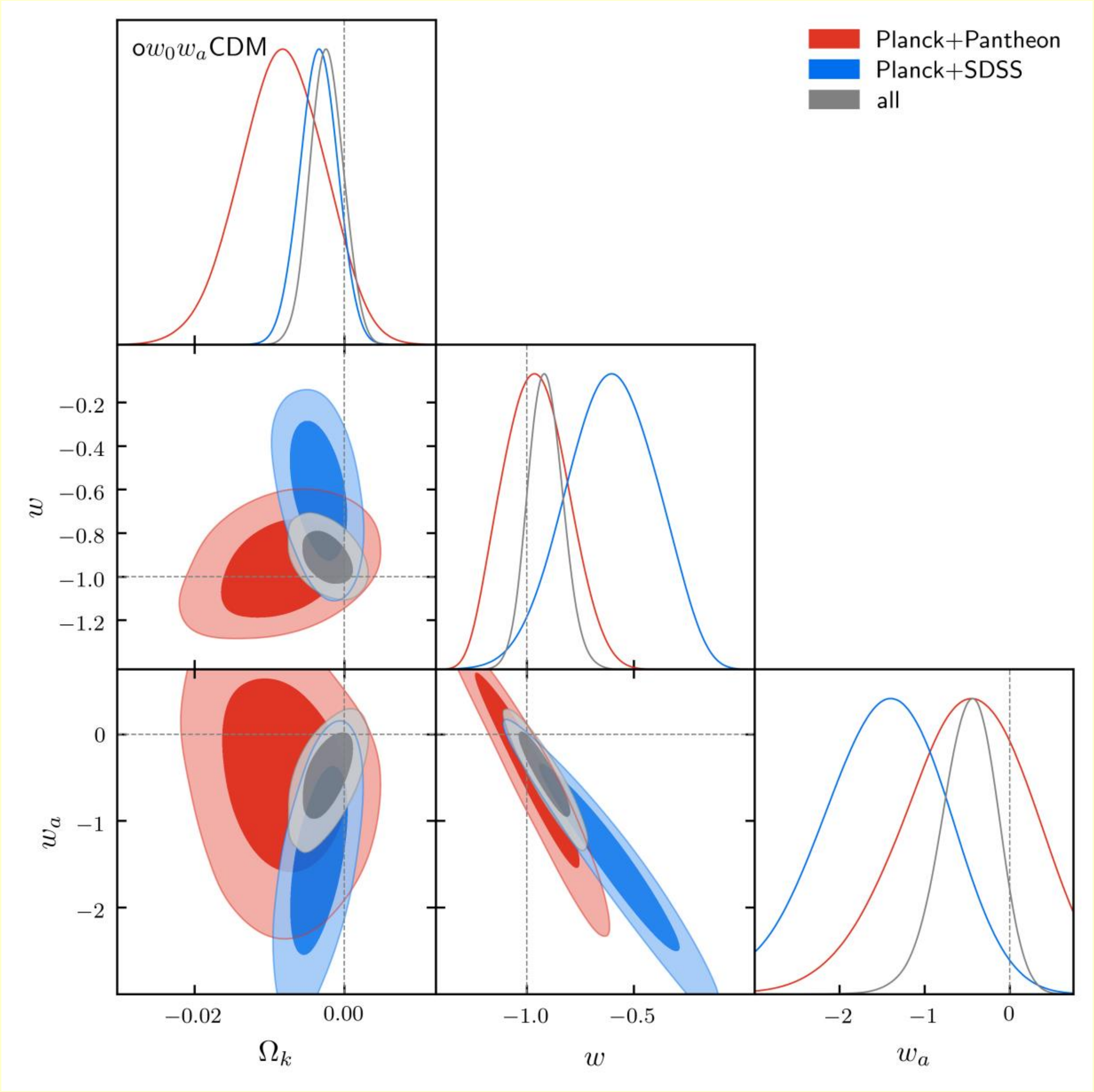
BACK UP SLIDES

Cosmological constraints from SDSS final paper

open ww_aCDM

- Ω_k~0 (<1σ)
- w~-1 (1.1σ)
- w_a~0 (1.3σ)

ΛCDM preferred by data



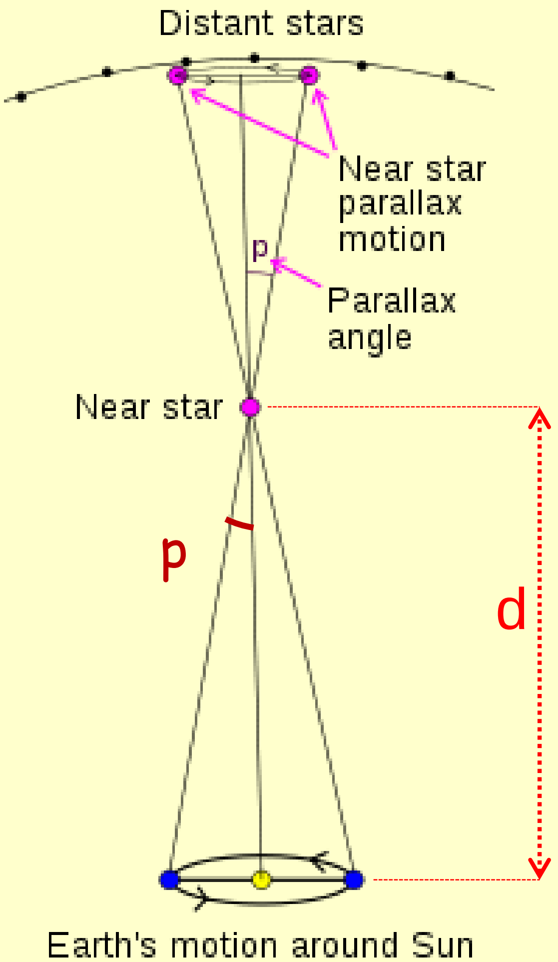
- flat wCDM:

w=-1.020±0.027

(Planck, SDSS BAO+RSD, SN, DES 3x2pt data)

Alam et al, PRD 103 (2021) 083533

Measuring stellar distances: the parallax method



- Parallax angle : due to differences in the apparent position of a star (wrt distant stars) viewed from different orbital positions of the Earth
- Definition:

  1 pc = distance d when p is 1″

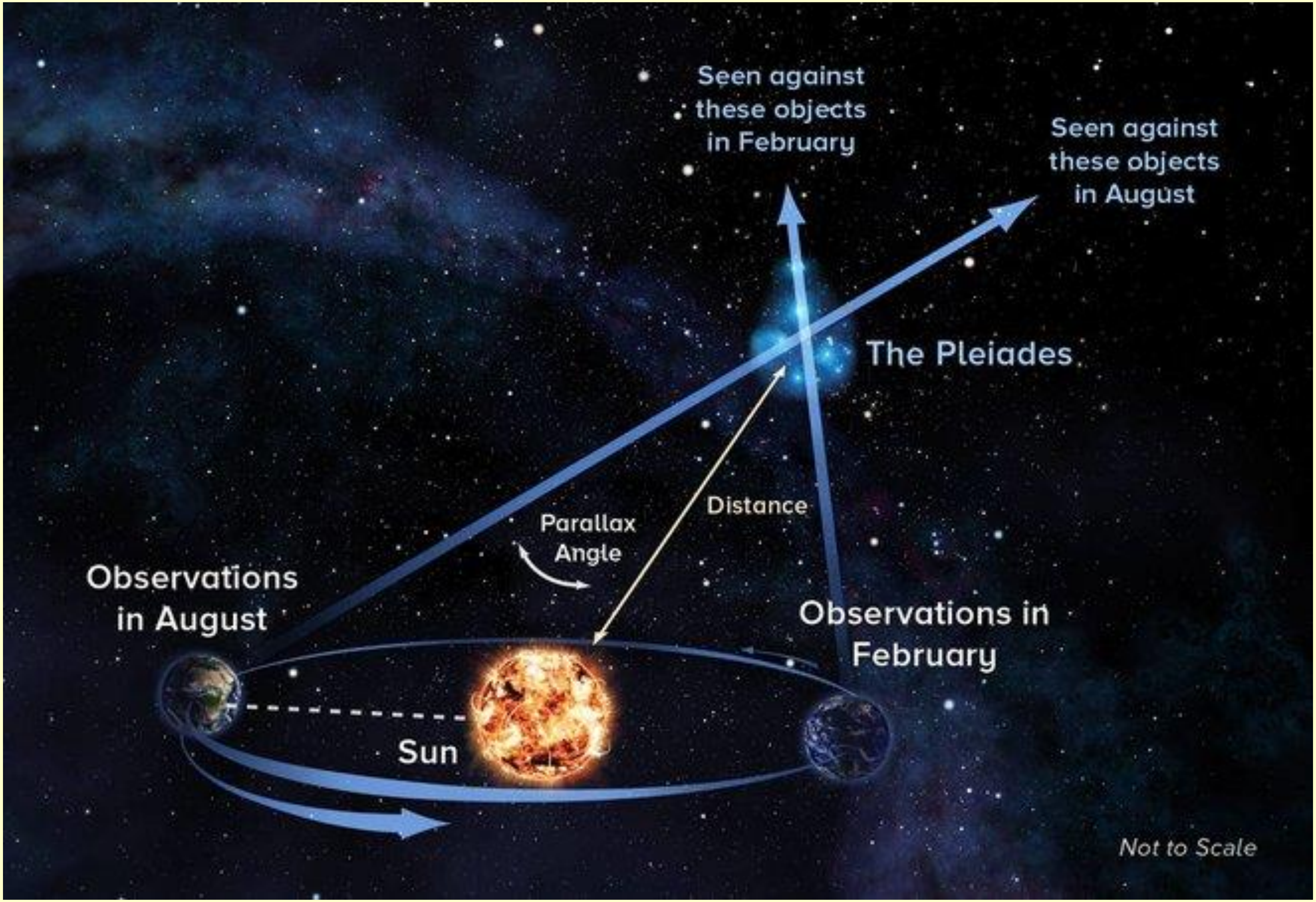
- Application:

  $\delta p \sim 0.001'' \Rightarrow d < 500$ pc

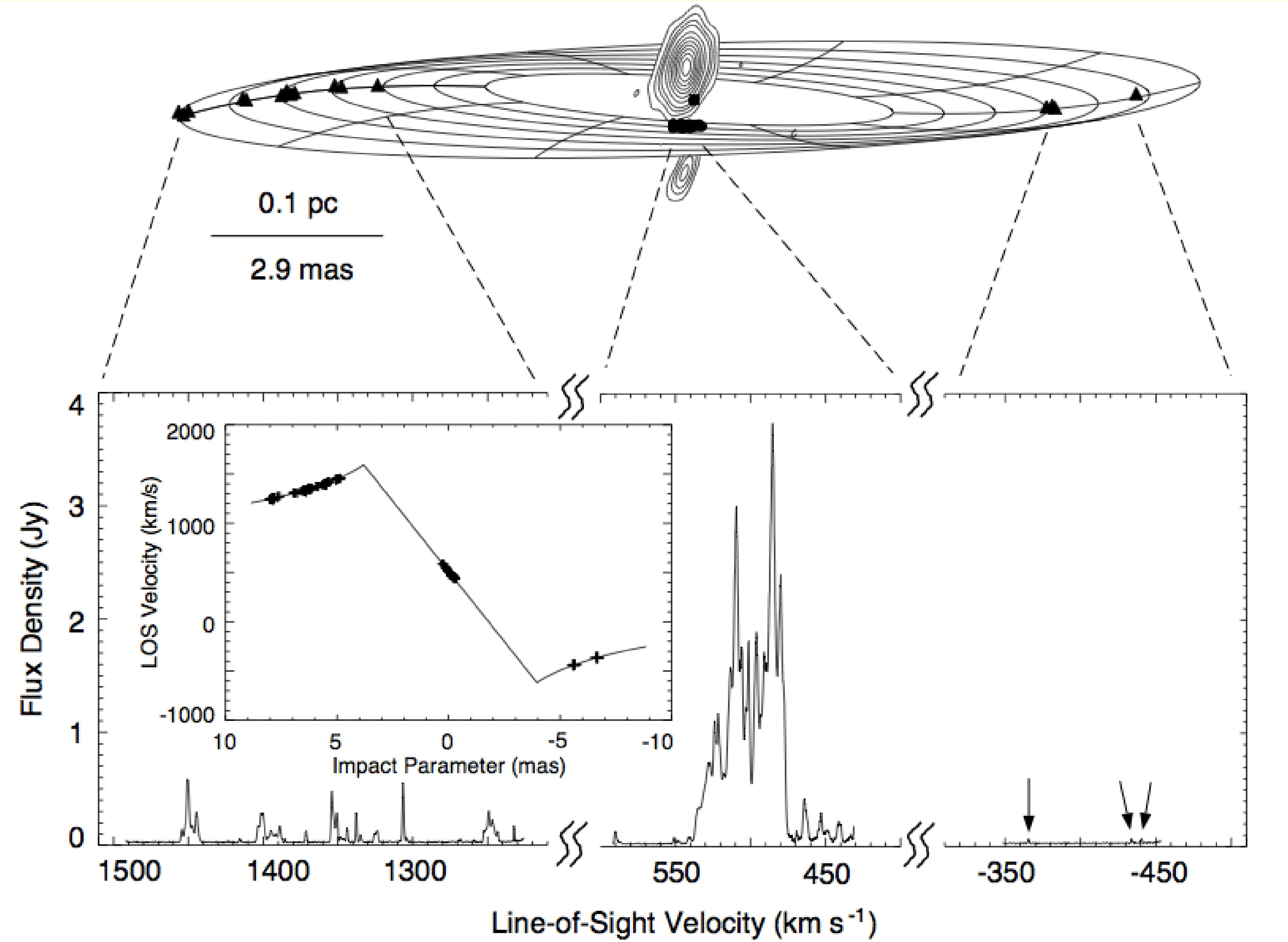
  Hipparcos satellite (1989), 10^5 stars, $\delta p \sim 0.001''$

  Gaia satellite (launched 2013), 10^9 stars, $\delta p \sim 24$ μas (achieved in EDR3(2020) for *G*<15)

- provides a basis for measuring other astronomical distances (cosmic distance ladder)

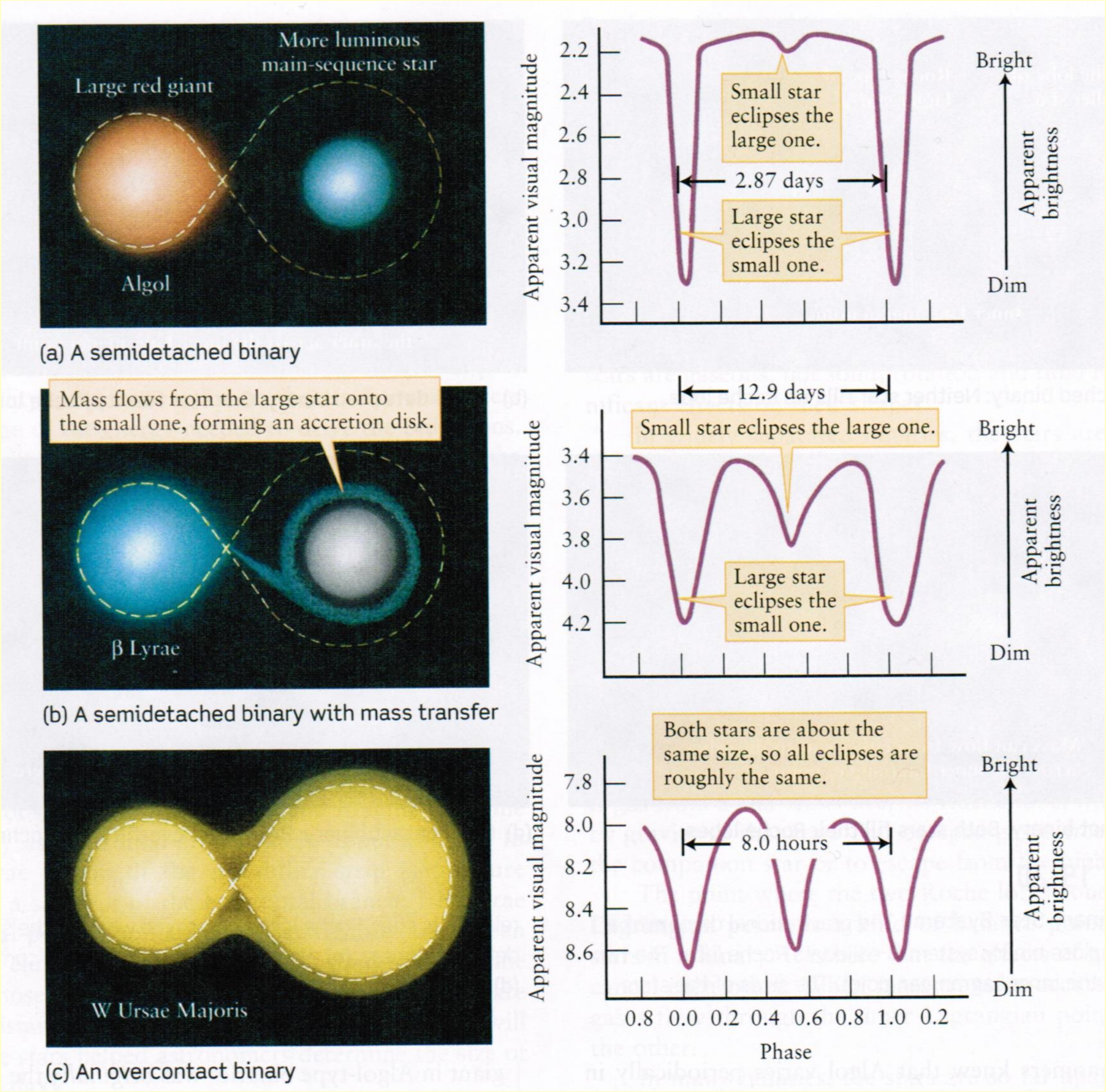

Seen against
these objects
in February
Seen against
these objects
in August
The Pleiades
Distance
Parallax
Angle
Observations
in August
Observations in
February
Sun
Not to Scale

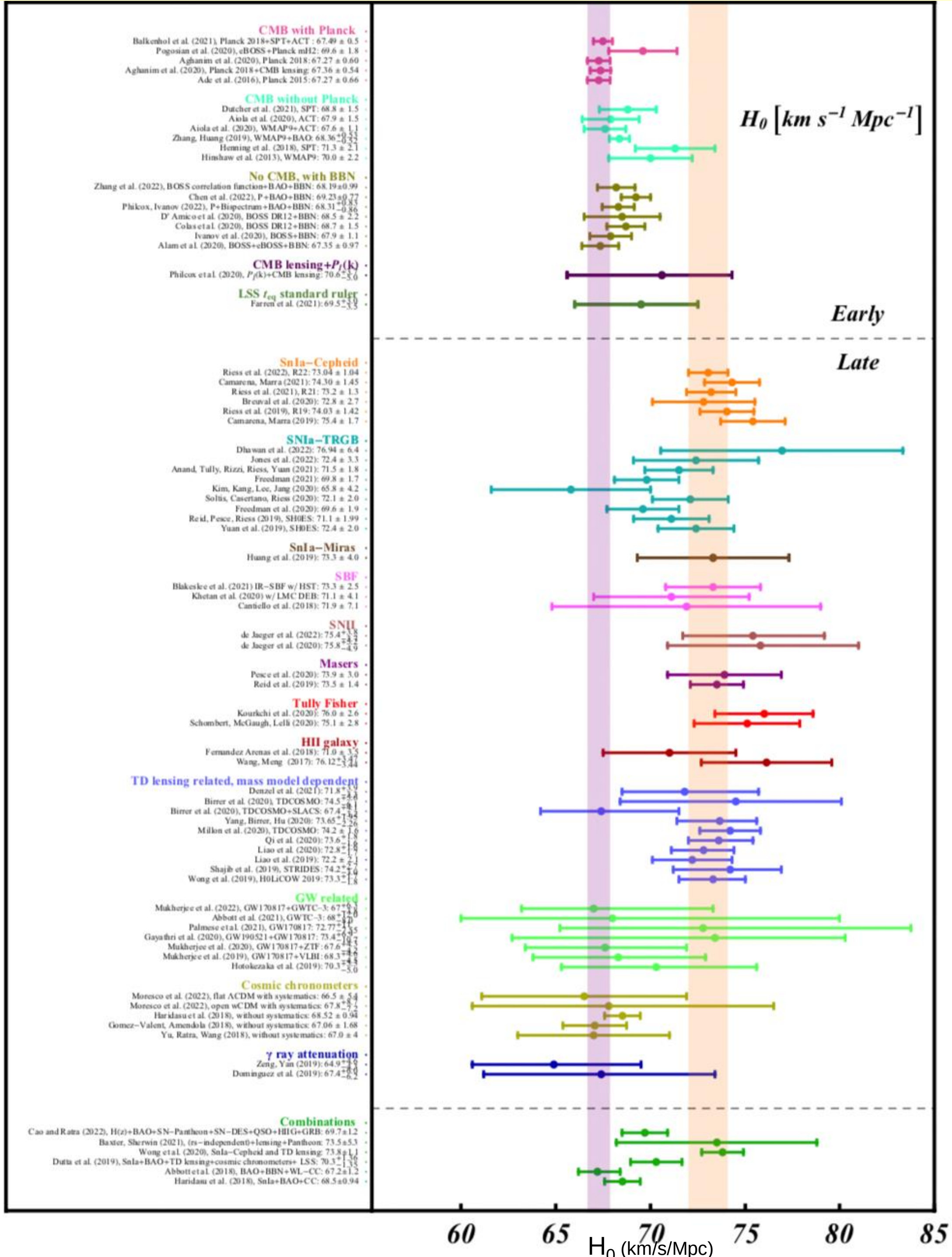
Water masers in NGC 4258



J.Herrnstein et al, 1999, Natur, 400, 539H

Detached eclipsed binaries





H_0 measurements

- Compilation of
  L.Perivolaropoulos & F.Skara, arXiv:2105.05208

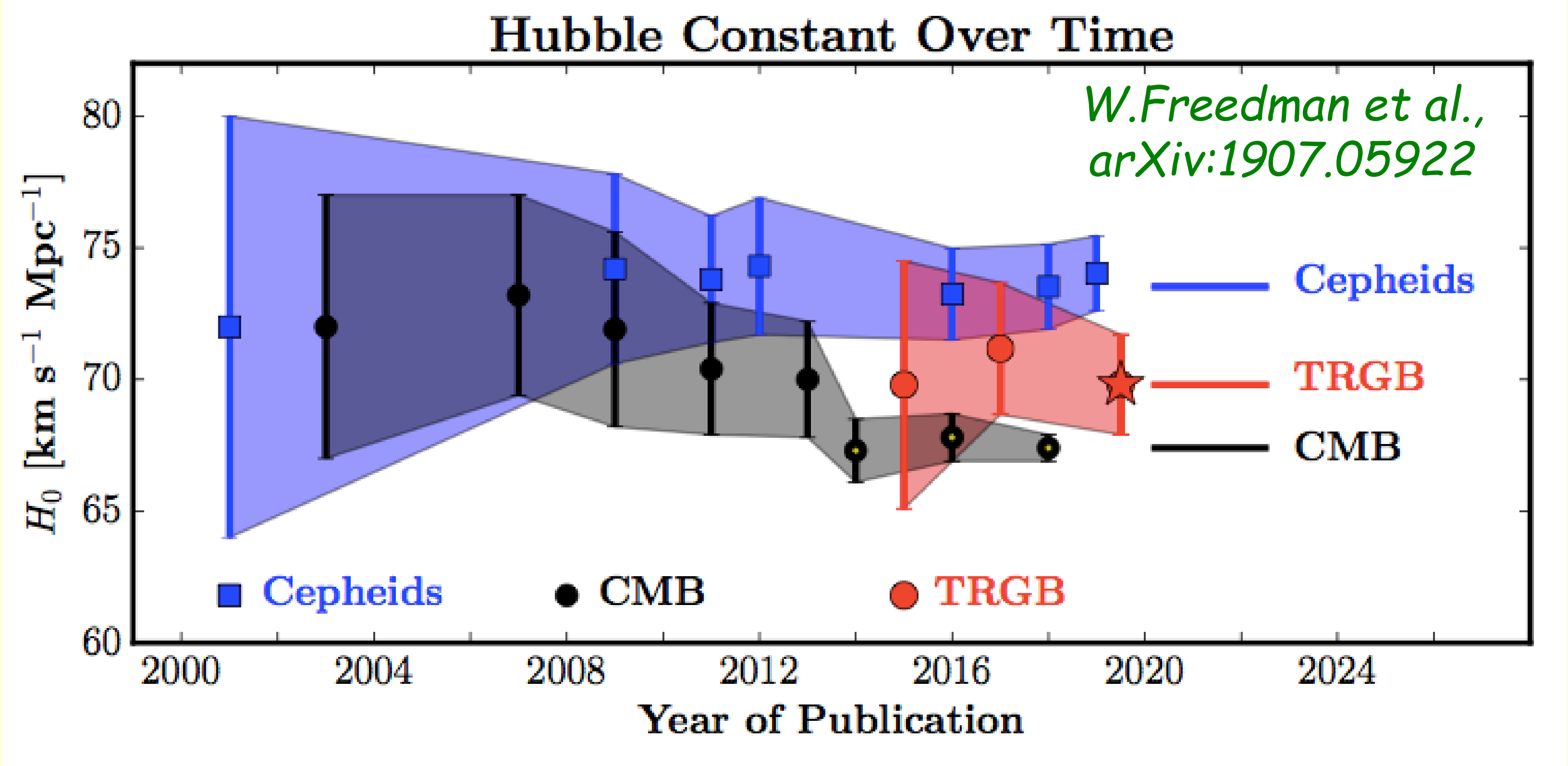
The TRGB alternative calibration route

- 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 (2019)

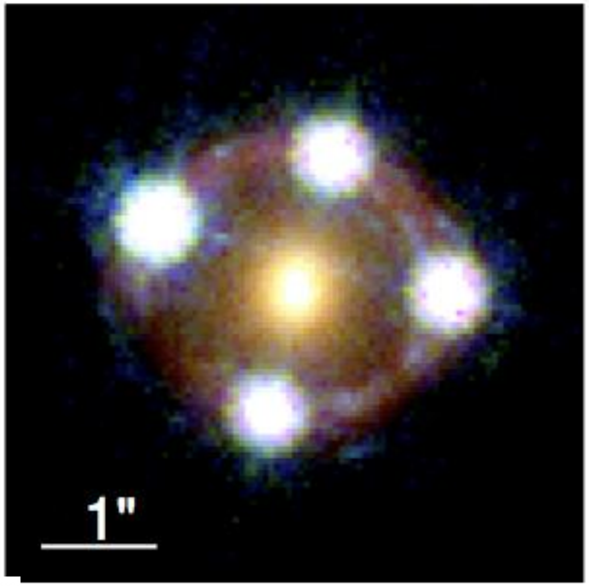


- Systematic effect in Cepheid distance scale ? More likely, incorrect TRGB LMC-based calibration (M.J.Reid et al., arXiv:1908.05625, W.Yuan et al, arXiv:1908.0093 H_0=72.4±2.0km/s/Mpc)
- Prospects for TRGB:
  - accurate Gaia parallaxes ⇒ extend TRGB method to MW, RR Lyrae stars
  - enlarge number of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

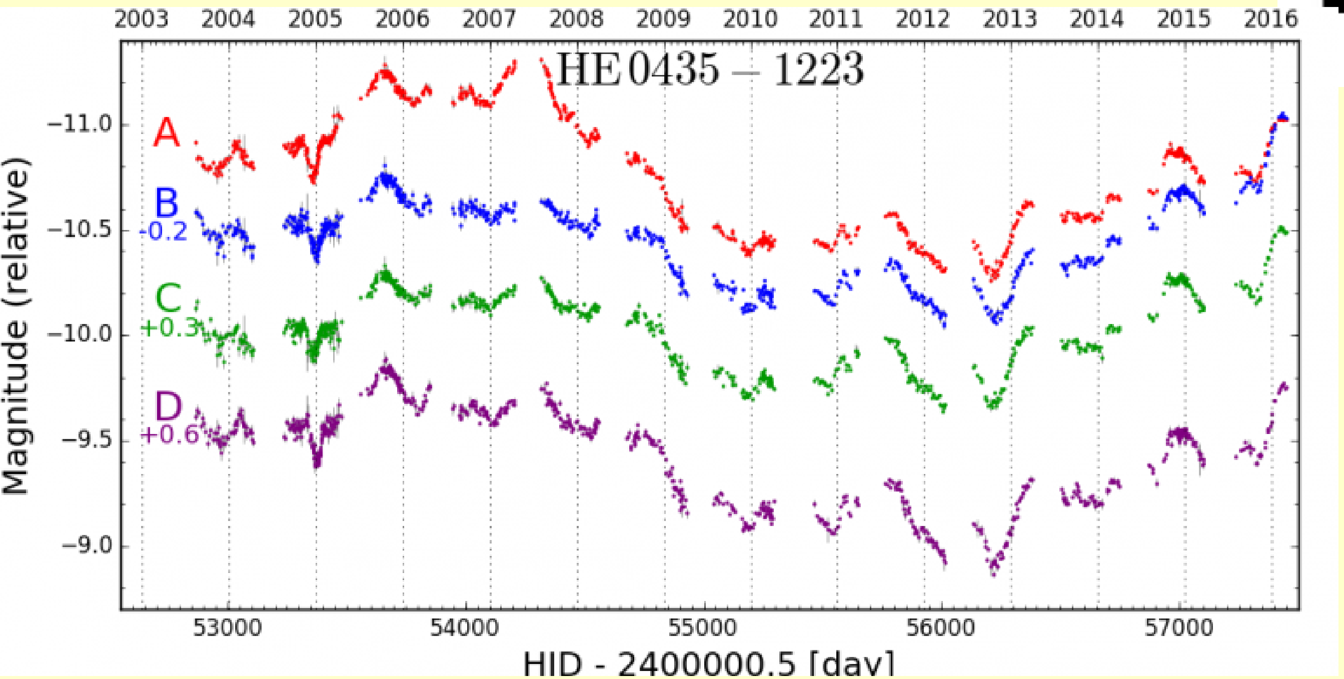
Time delay cosmography

HST

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



(c) HE 0435−1223



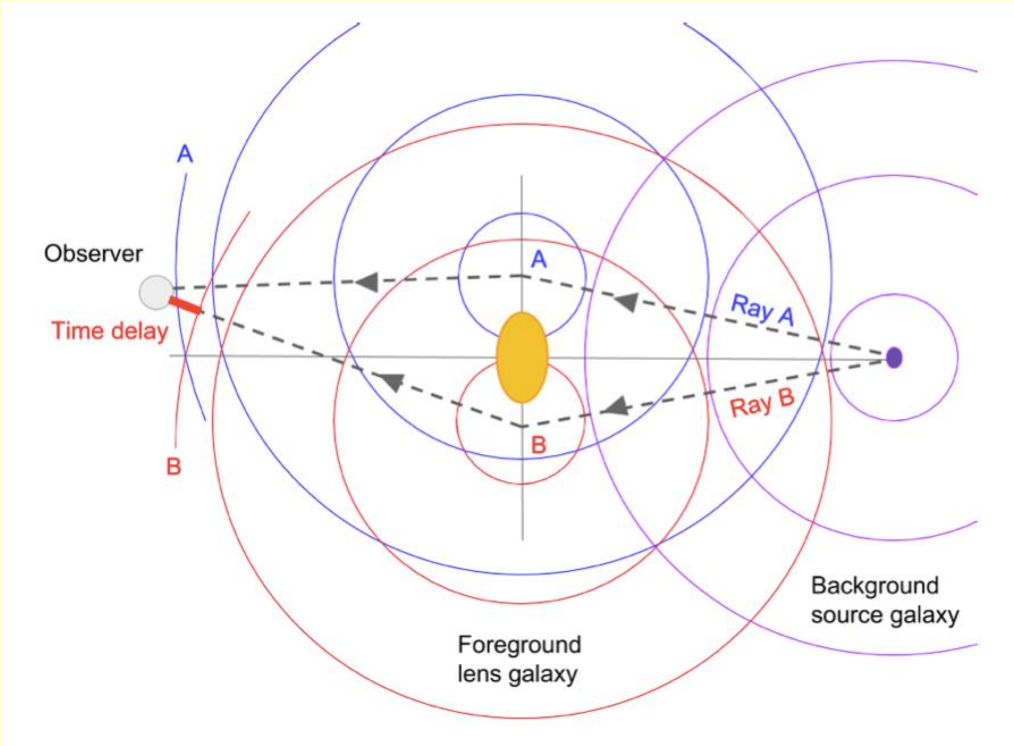
Lens monitoring over years, COSMOGRAIL program

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 source position

β unlensed source position

ψ projected lens gravitational potential

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

- 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 ⇒ $\theta - \beta, \psi(\theta)$ 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: θ-β ~ 1 arcsecond ⇒ $\Delta\tau_{AB}$ ~ 10days
  - ⇒ 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

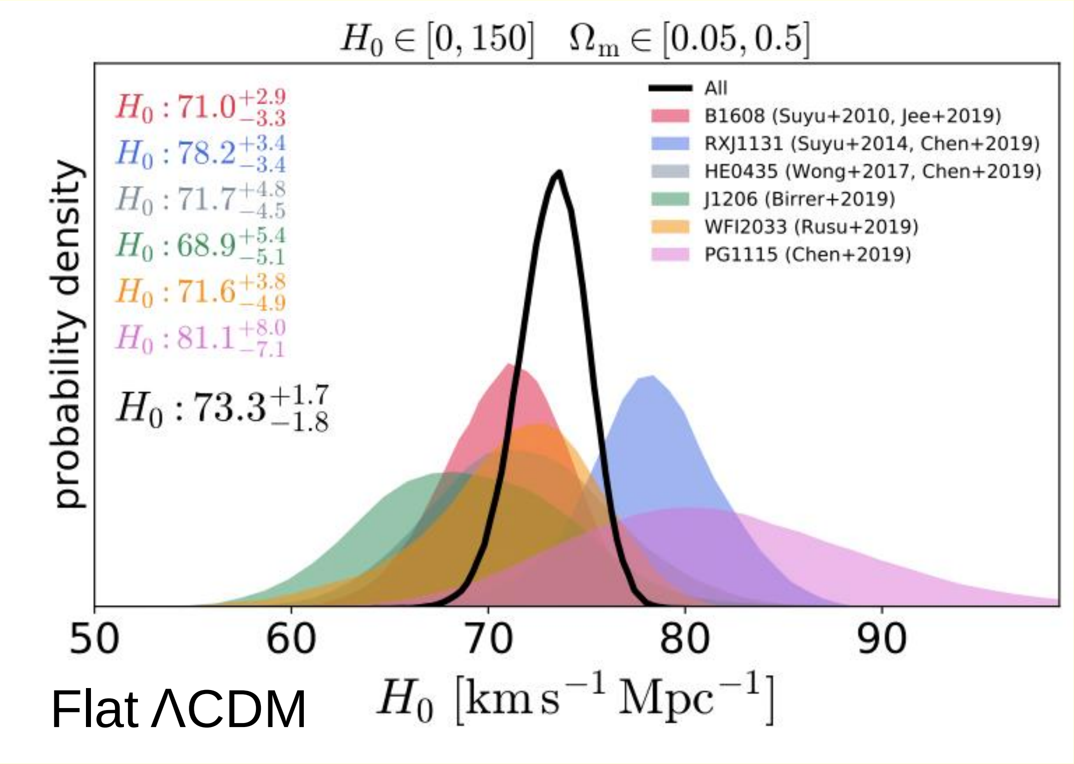
e.g. Keck/VLT/Gemini spectroscopy and CFHT/Subaru/Gemini/Spitzer/Blanco/VLT imaging

- 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

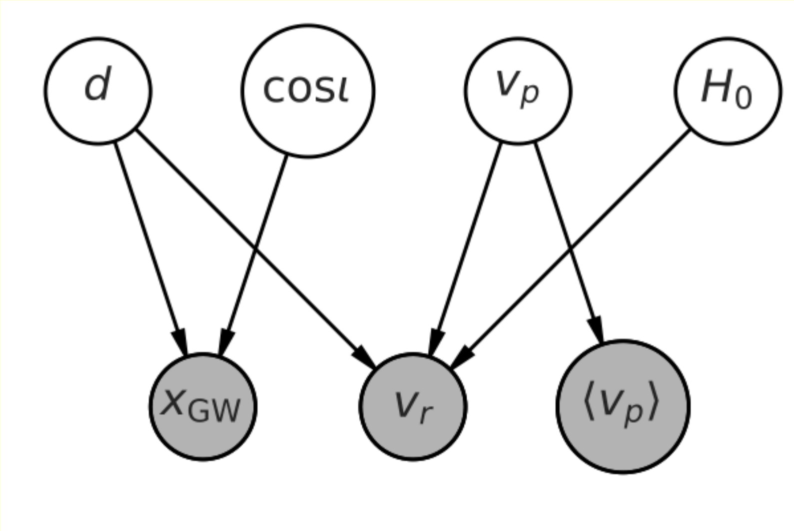
Tension also in other models (oΛCDM, flat wCDM, w(z)CDM...) or when combining Time Delays with cosmological SNIa samples in various models.

- 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 $\cos i$)
- em counterpart ⇒position, z_h⇒ Hubble flow velocity from host recession velocity (v_r) corrected for peculiar velocities ($\langle v_p \rangle$)

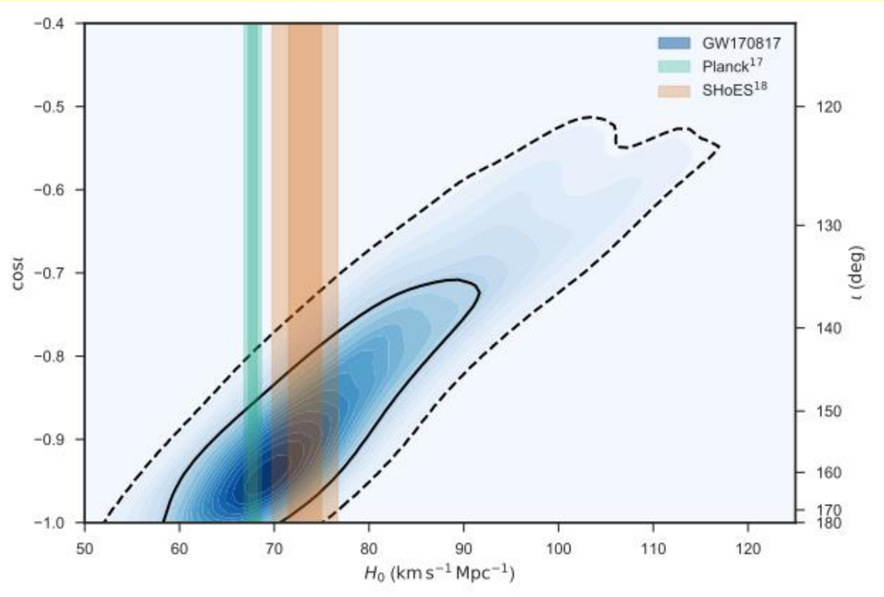
LIGO & VIRGO Collaborations et al, Nature, 2017, 551, 85-88

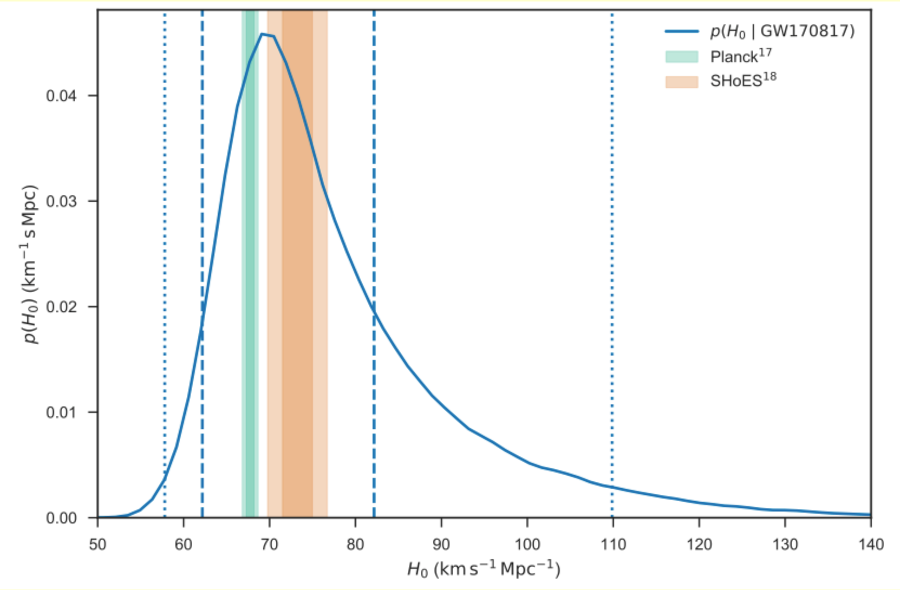


- one-step, independent H_0 measurement, with absolute distance scale based on RG

GW170817 standard siren

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





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

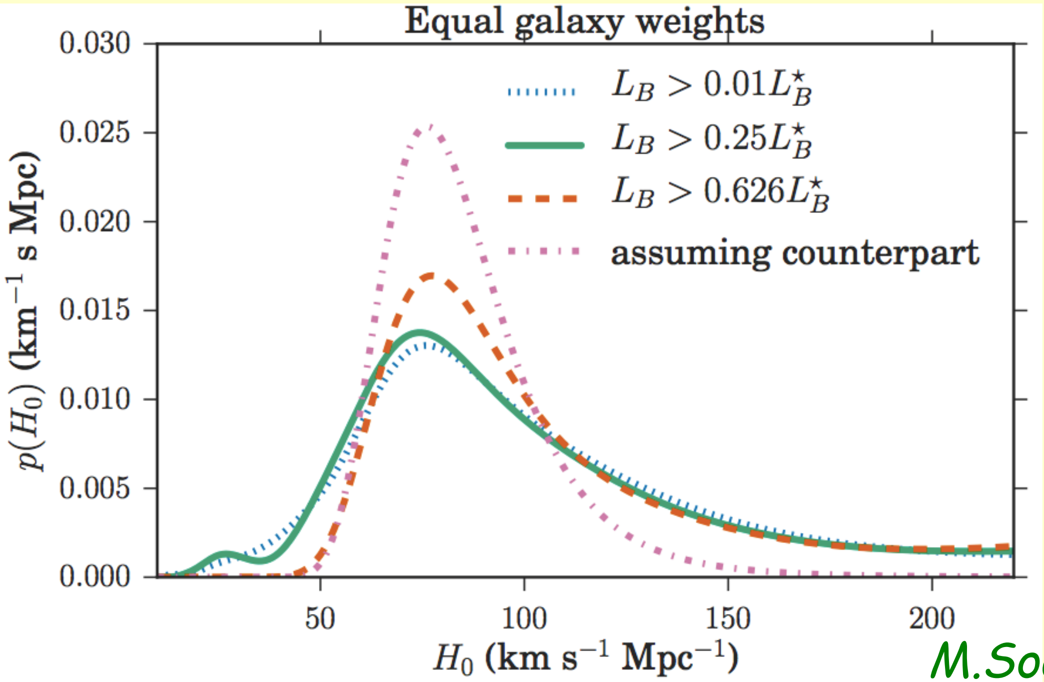
- Main source of uncertainty: degeneracy distance/inclination
- Note: after recalibration of O2 data:

$$H_0 = 68^{+18}_{-8}\, km/s/Mpc$$

B.P. Abbott et al, arXiv:1908.06060

More on GW sirens

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



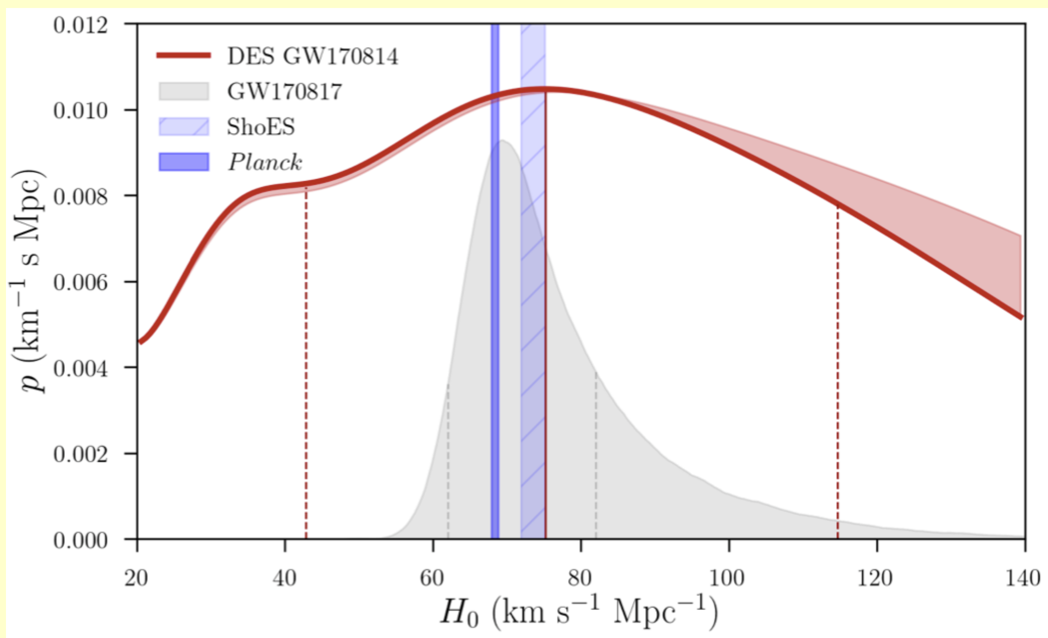
- GW170817: statistical analysis over all possible host galaxies in the GW localization region (proof of principle)

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

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

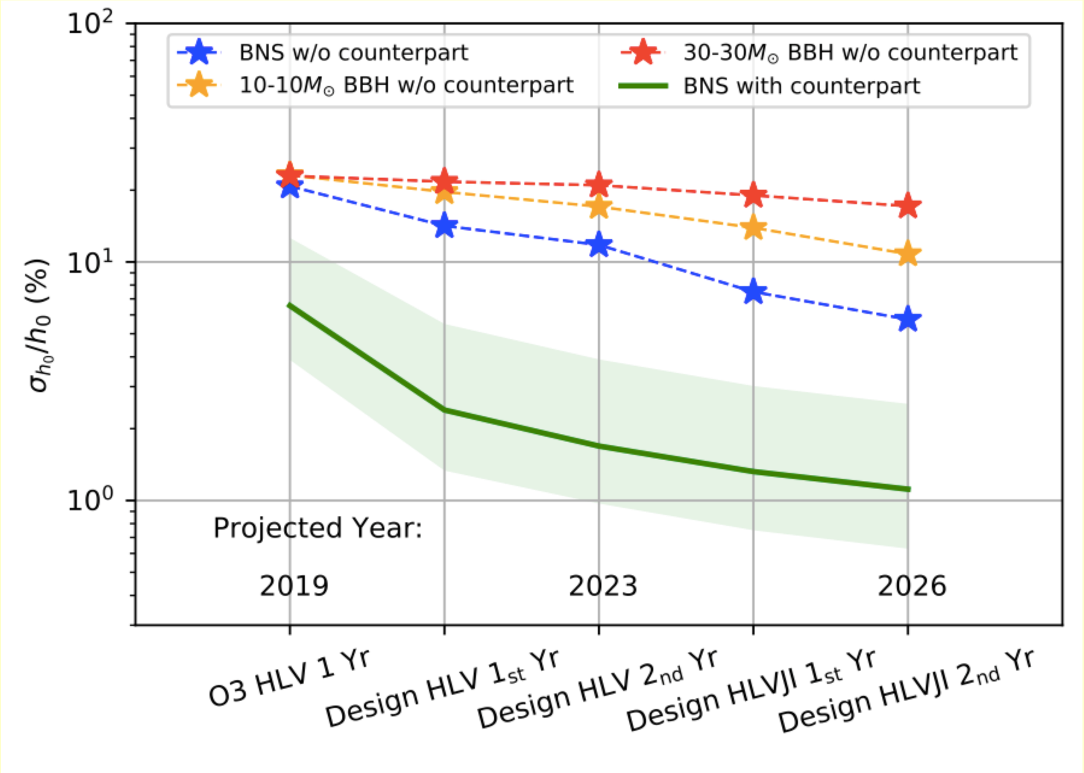
- GW170814: statistical analysis applied to black-hole merger, using DES galaxies as potential hosts (photo z's)

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



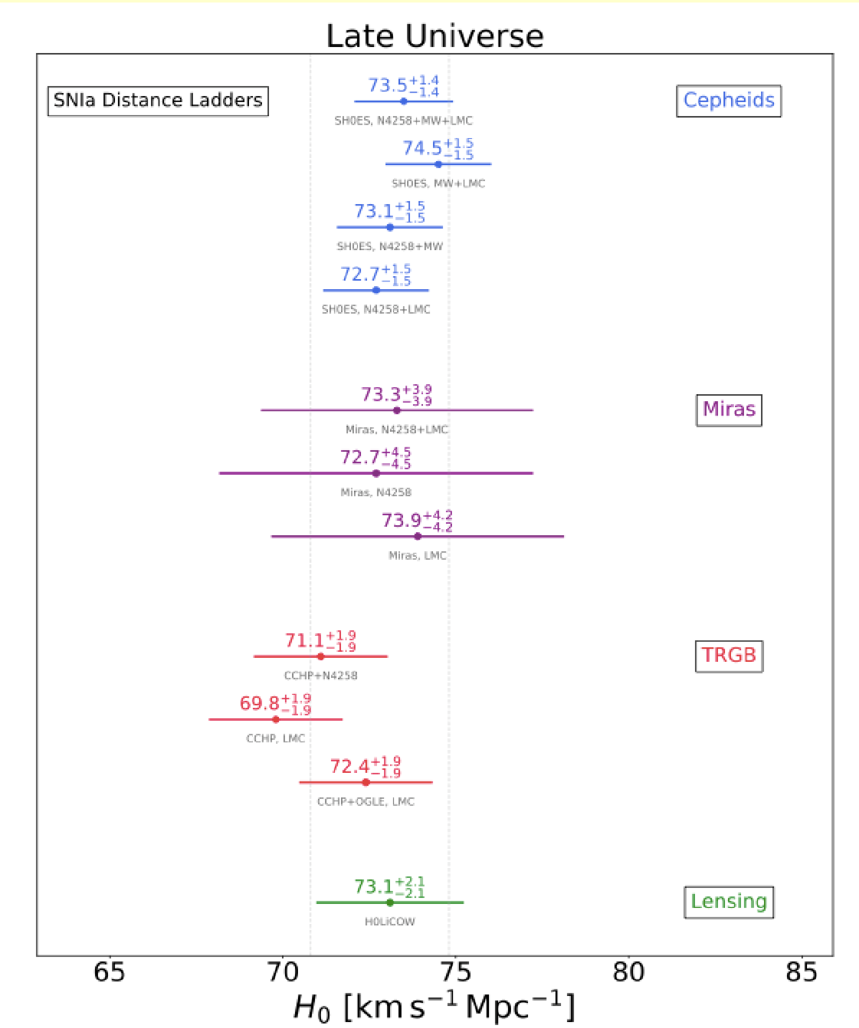
Prospects for standard siren method

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 on H_0 tension (2019)



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 !

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 $z<2.5$

$\Rightarrow$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 $\Omega_\gamma h^2$)

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

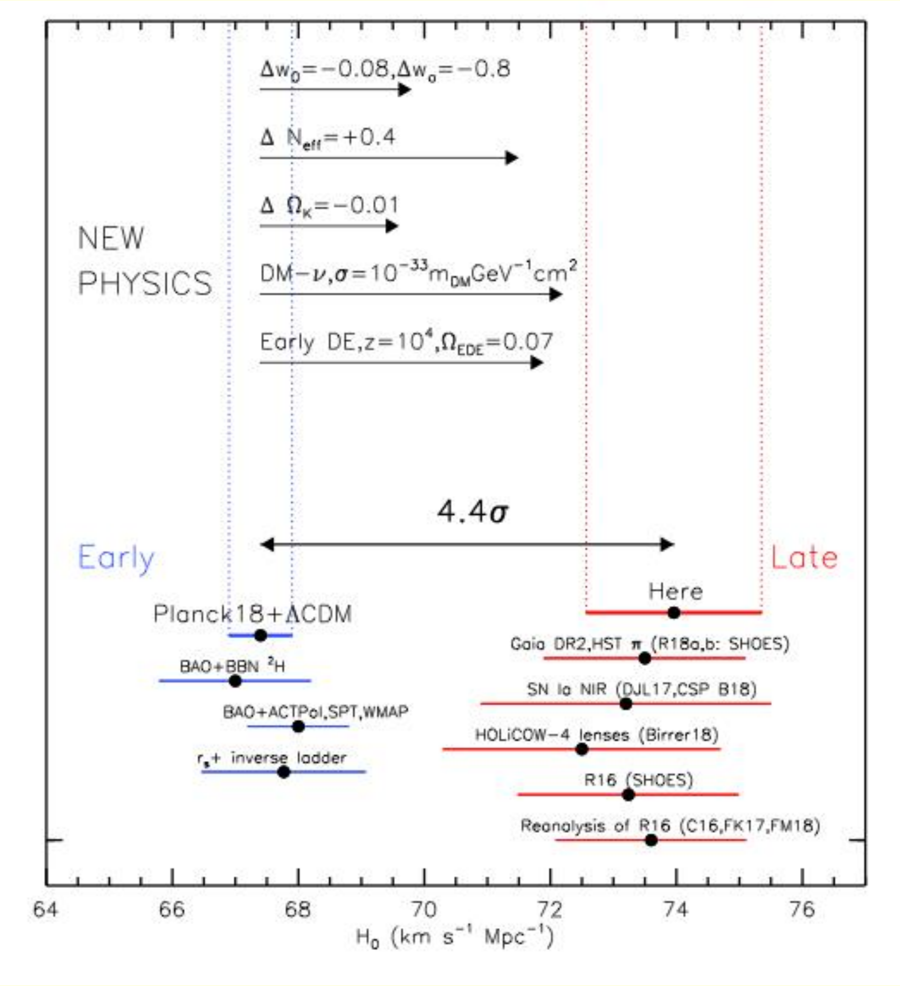
$\Rightarrow D_M(z^*)$ and $D_M(z_{BAO})$ calibrated as a function of $\Omega_m h^2$

- **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

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

Cross-check from Riess et al

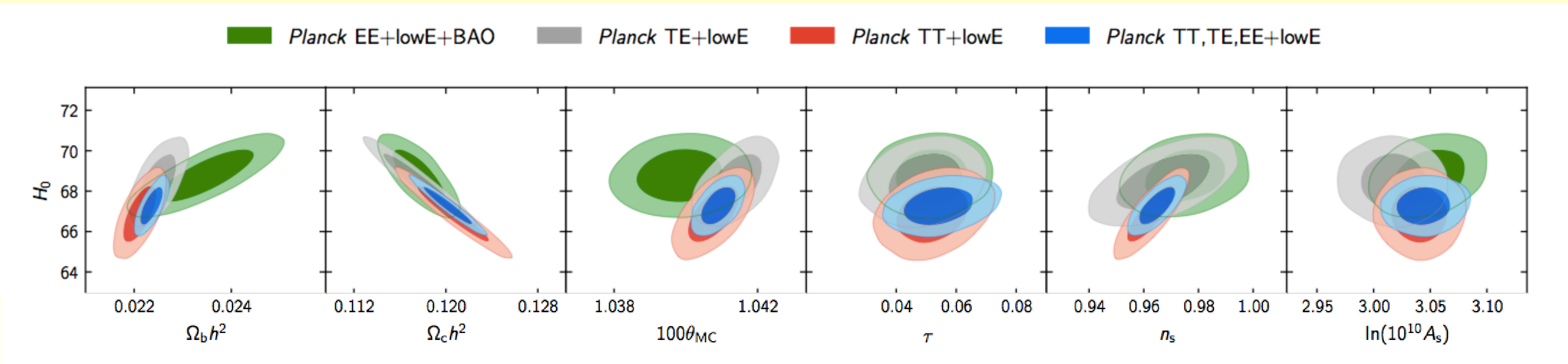
A. Riess et al., 2019, ApJ,876, 85R



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

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