Challenging the ΛCDM model

A pedagogical overview

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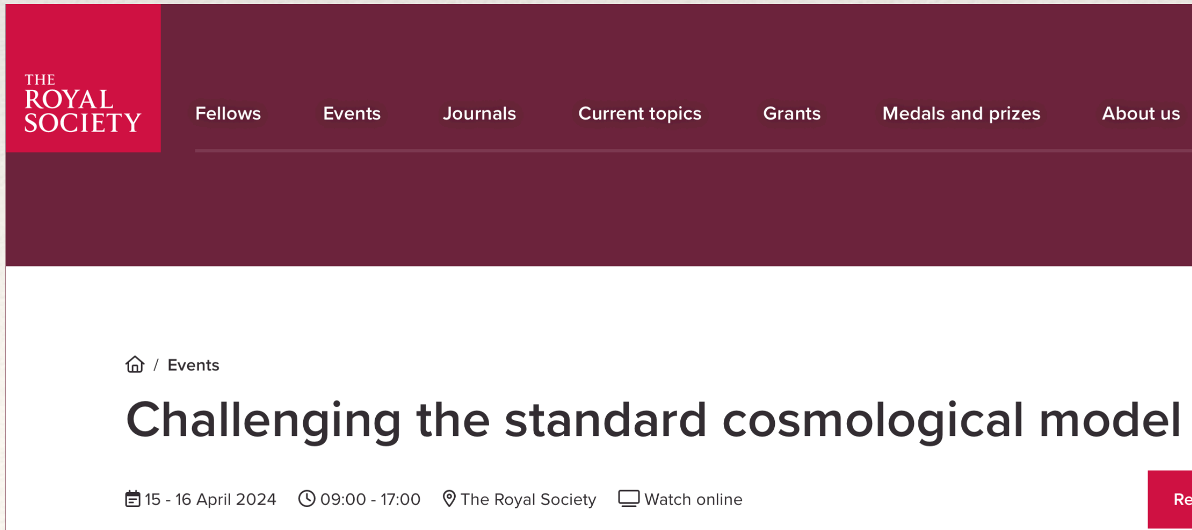
21cm Cosmology workshop , Hangzhou, China, July 2024

- Cosmological parameters from CMB measurements
  - Planck results
  - Focus on Planck H_0 measurement
- Local H_0 determination using SNIa
- Beyond FRW and homogeneous universe
  - σ_8 , S_8 : a measure of matter inhomogeneity level
  - σ_8 from weak-lensing / shear
  - σ_8 from CMB lensing
  - σ_8 from clusters
- DESI results , a biased selection
  - *H_0 by DESI*

Partially based on a conference organised at the RAS in London, April 2024

See Also
E. Abdalla et all (2022)

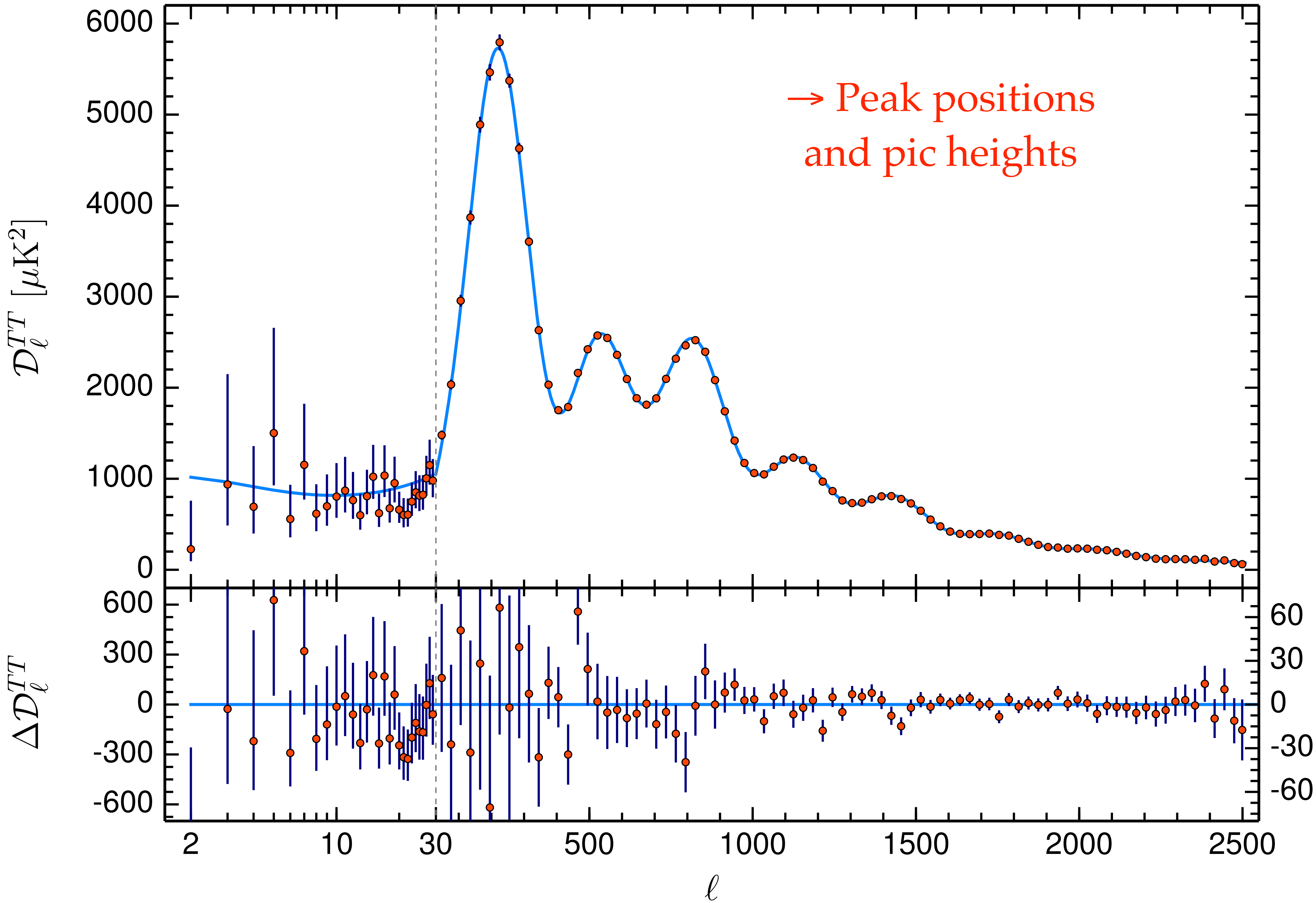


Cosmological parameters from CMB

- Planck results
- Focus on H_0

Local H_0 measurements

Planck TT spectrum



→ Peak positions
and pic heights

Planck 2018 results (Cosmological Parameters)
A&A 2020

Base-ΛCDM cosmological parameters from *Planck* TT,TE,EE+lowE+lensing.

Physical densities

Peak positions

Fitted parameters

Derived parameters

Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2]−[1])/σ_1	Combined
$\Omega_b h^2$ ...	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$ ...	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$ ...	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ ...	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$ ...	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s ...	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$ ...	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1} Mpc^{-1}] ...	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m ...	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr] ...	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8 ...	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ ...	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re} ...	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$ ...	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc] ...	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

Planck-ΛCDM : $H_0 \simeq 67.4 \pm 0.6$ km/s/Mpc (< 1% accuracy)

How do we get H_0 from CMB ?

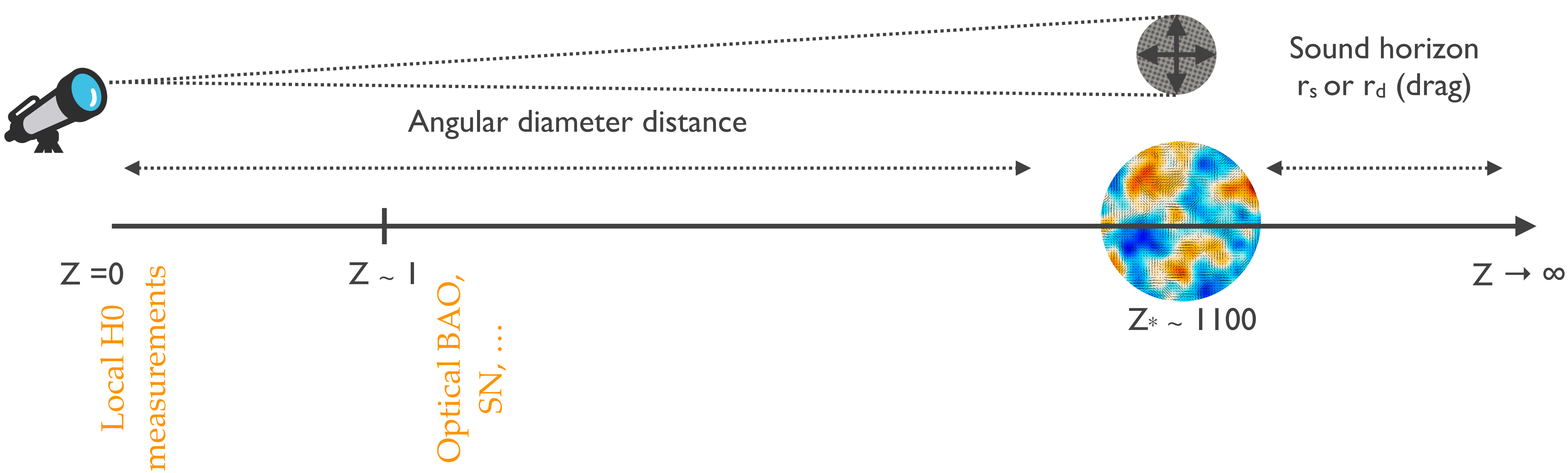
$$H(z) = \frac{\dot{a}}{a} \qquad d\eta = \frac{dt}{a} = -\frac{dz}{H} \qquad H(z) = H_0\, E(z)$$

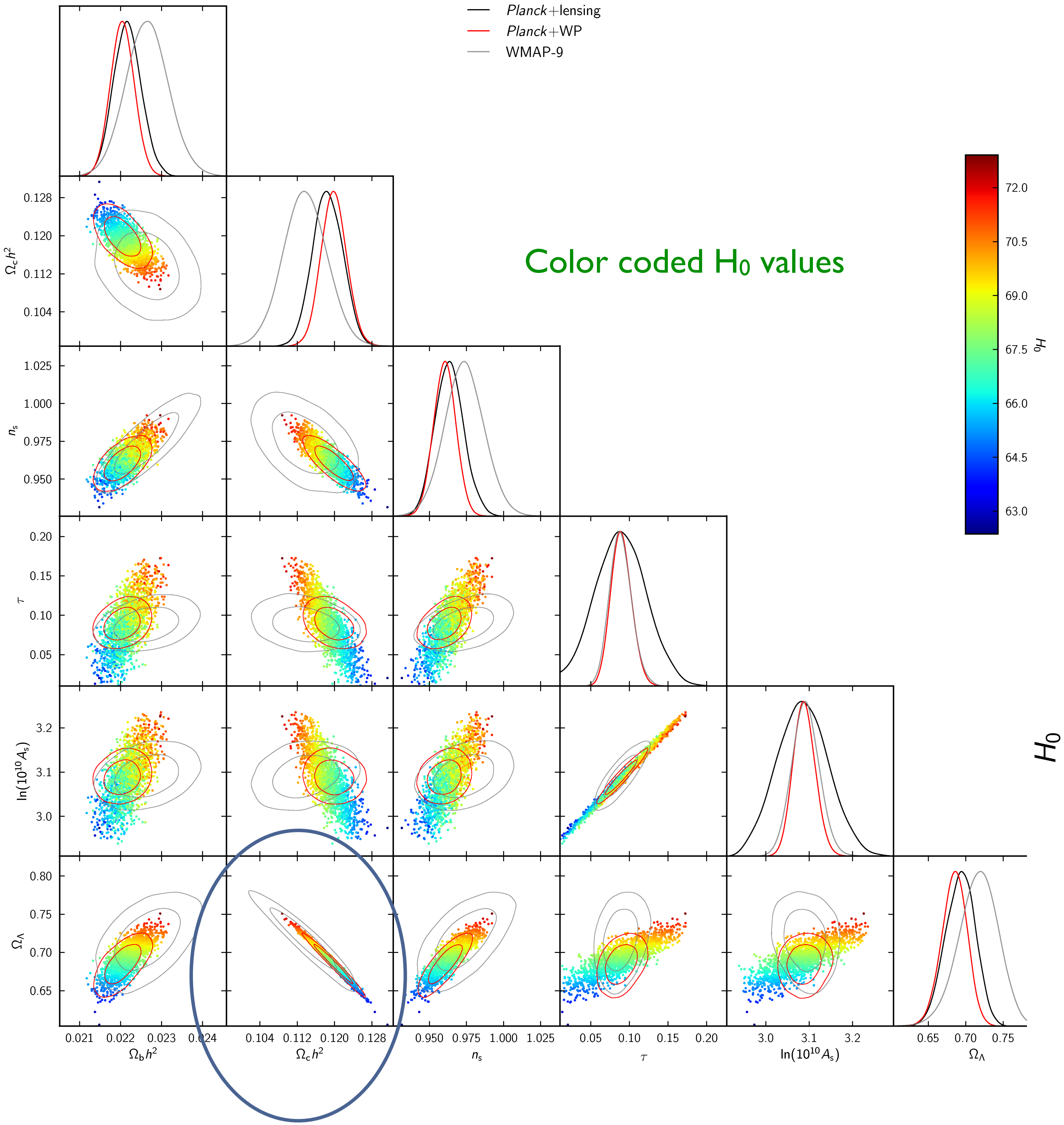
$$E(z) = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \qquad \Lambda\text{CDM}$$

$$\theta_* = \frac{r_s}{D_A}$$

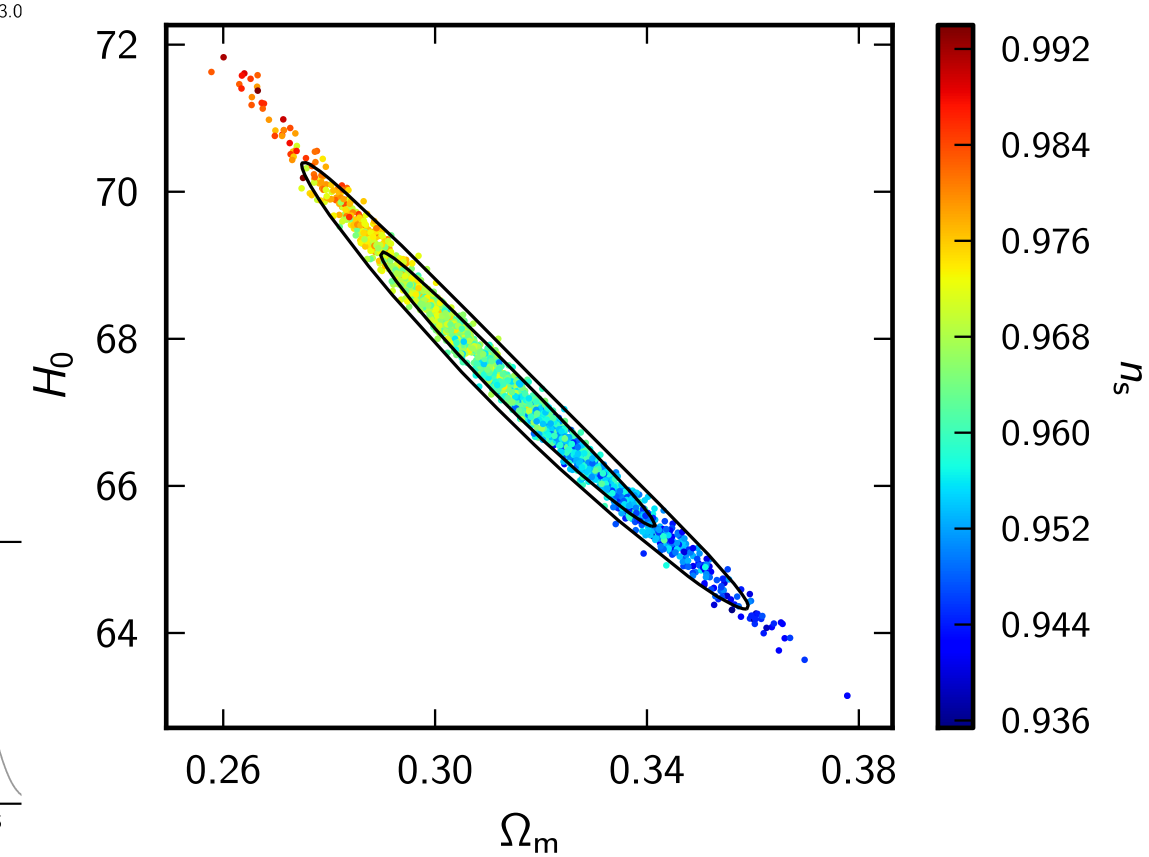
- Peak positions constrain universe geometry → Flat : $\Omega_m + \Omega_\Lambda \sim 1$
- Nearly un-sensitive to H_0 (cancels out in the ratio)
- photons-baryon plasma physics and oscillations sensitive to physical densities , hence to h = H0/100 km/s/Mpc
- Physical densities ($\Omega_c h^2$, $\Omega_b h^2$) constrained by the peak amplitudes

$$D_A \sim \frac{c}{1+z_*}\int_0^{z_*}\frac{1}{H(z)}dz \qquad r_s \sim \int_{z_*}^{\infty}\frac{c_s(z)}{H(z)}dz$$





Color coded H_0 values



Planck 2013 cosmological parameters
A&A 2014

H0 tensions

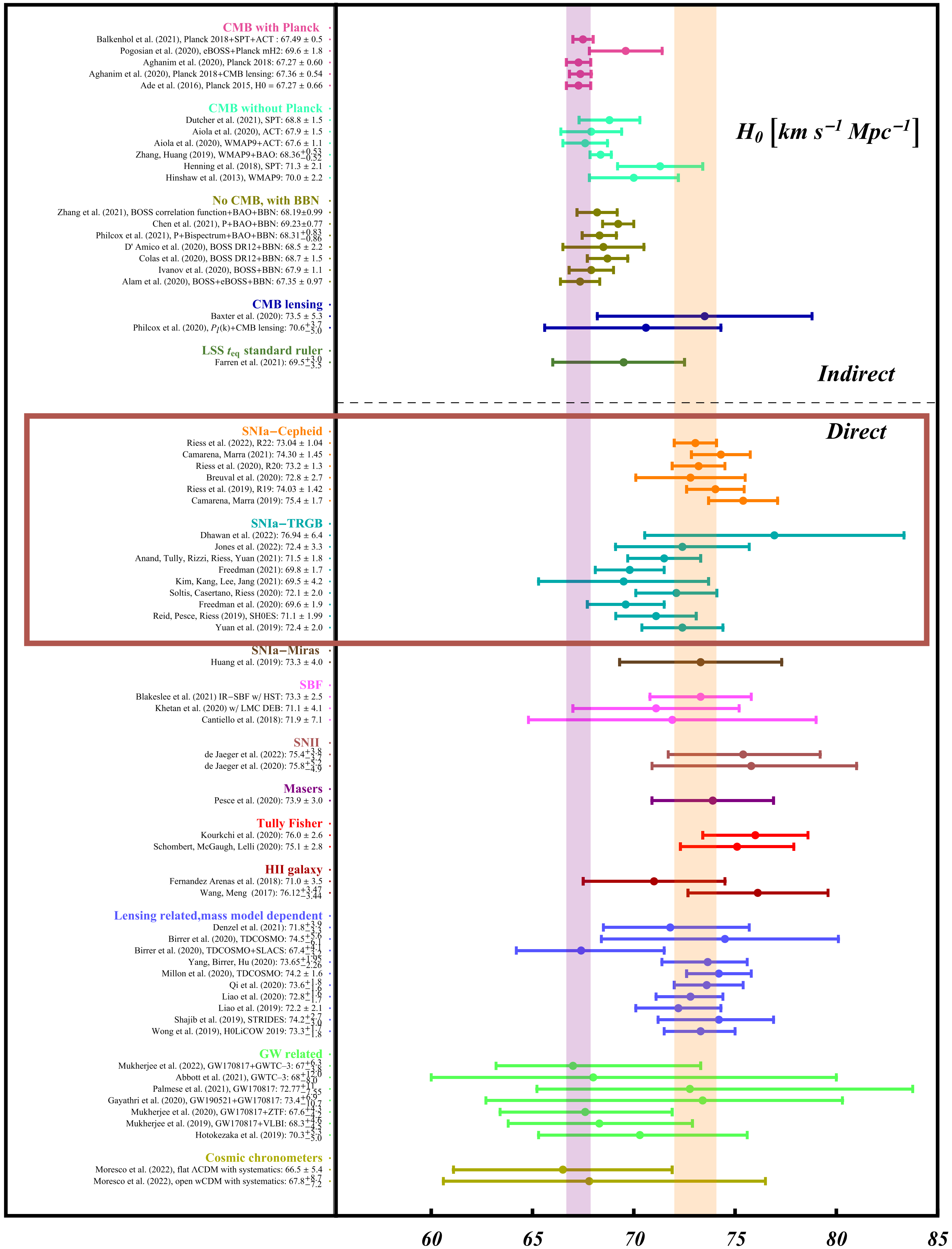
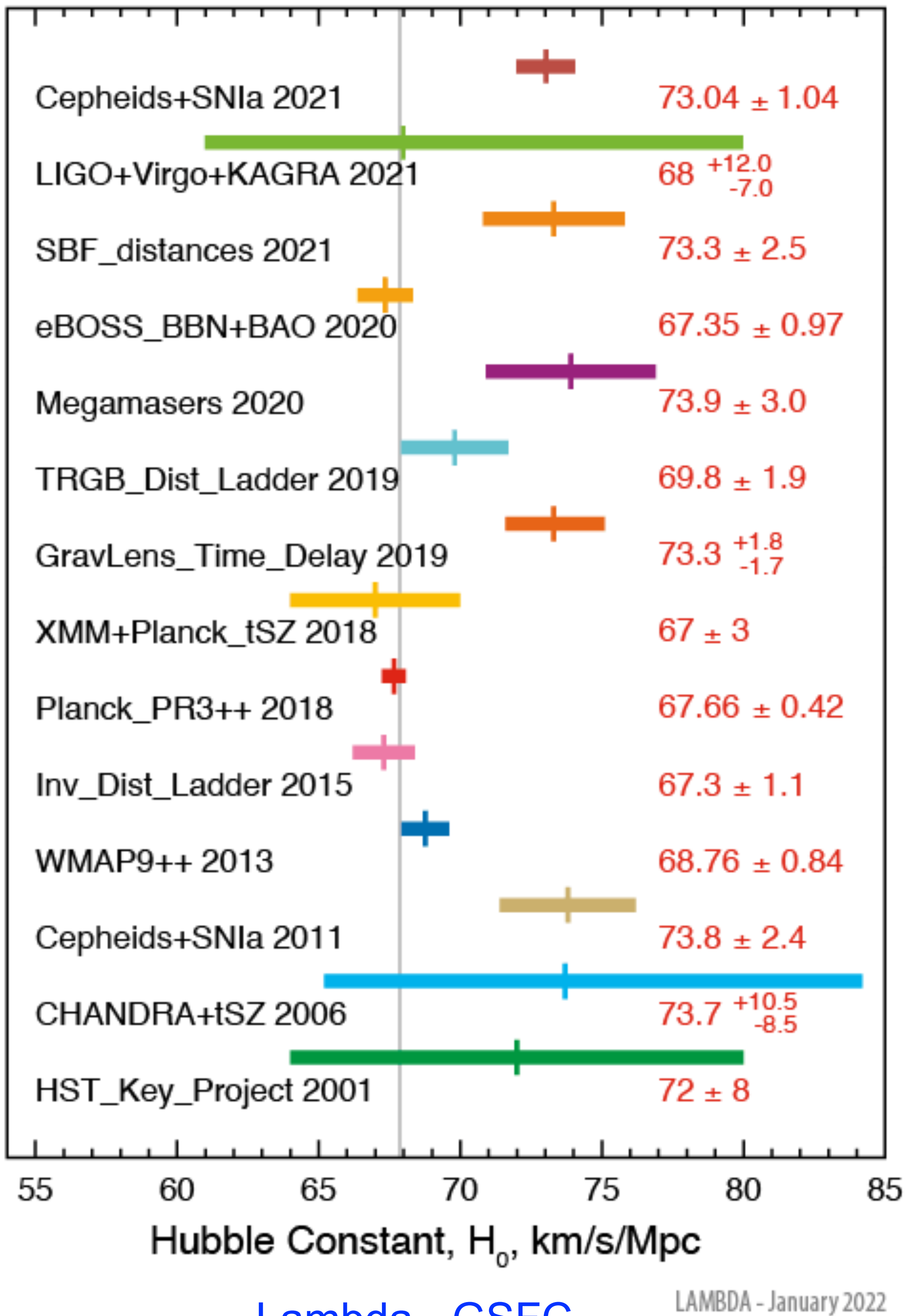


Fig. 2. 68% CL constraint on H_0 from different cosmological probes (based on Refs. Di Valentino et al. (2021g); Perivolaropoulos and Skara (2021b)).

⬅ E. Abdalla et all (2022)



Lambda - GSFC

Direct H_0 measurement

Hubble constant: a historical review , R. Brent Tully (2023) arXiv:2305.11950

The Hubble constant , N. Jackson (2015) Living Reviews in Relativity

Progress in direct measurement of the Hubble Constant, W. Freedman & F. Madore (2023) JCAP

The local value of H0, A. Riess & L. Breuval (2023) arXiv:2308.10954

$$z \ll 0 \quad \rightarrow \quad H_0\, c\, \delta t = H_0 d \simeq c\, z$$

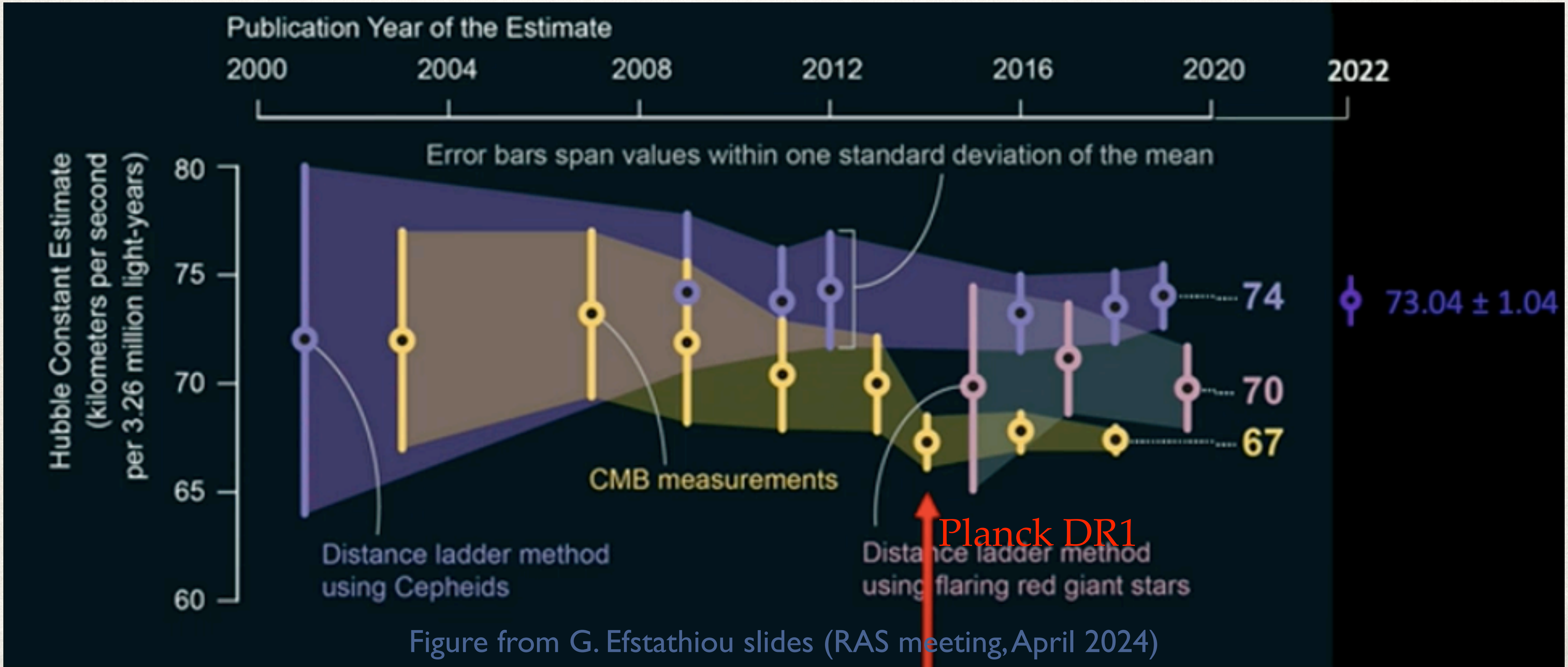
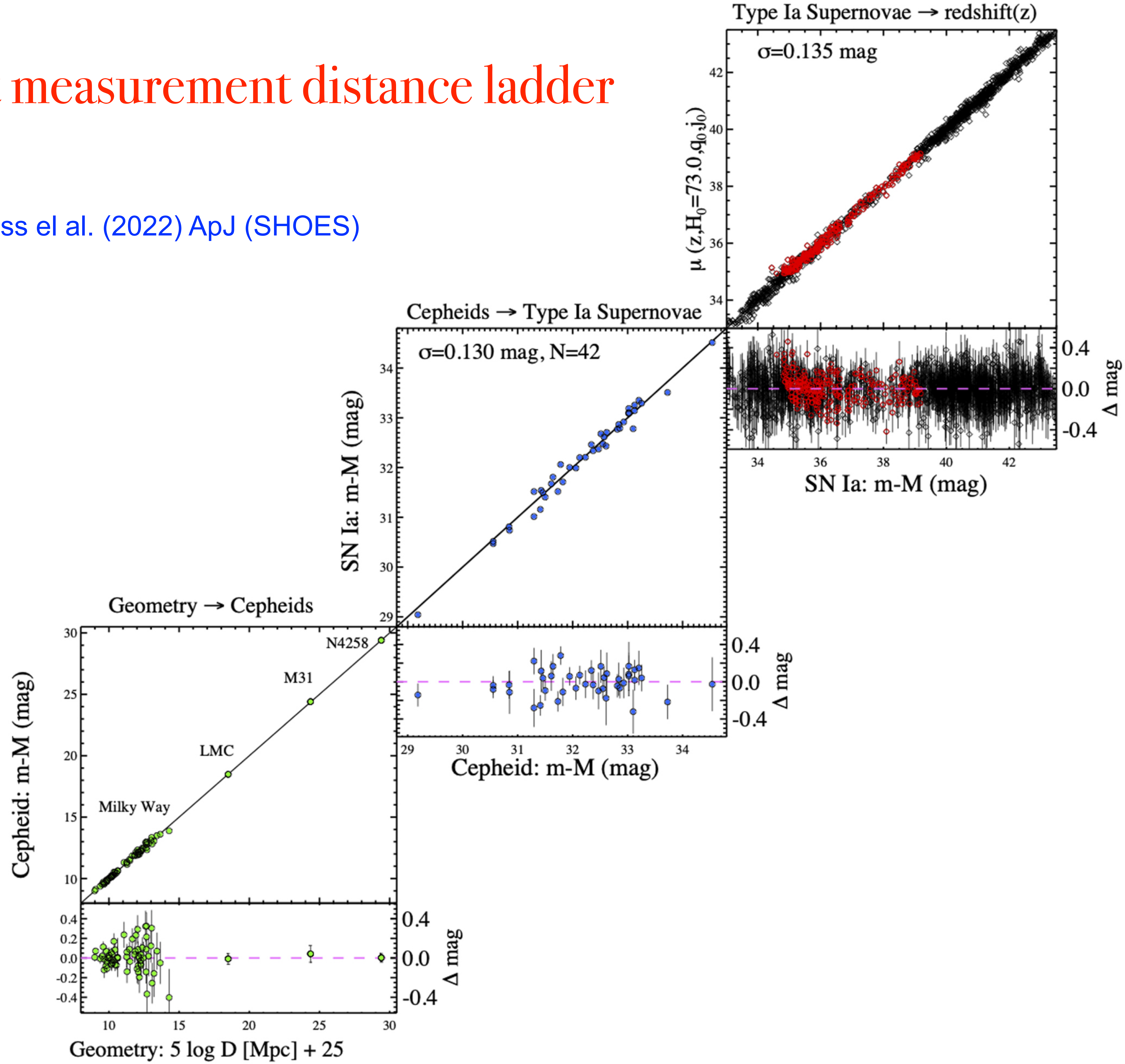


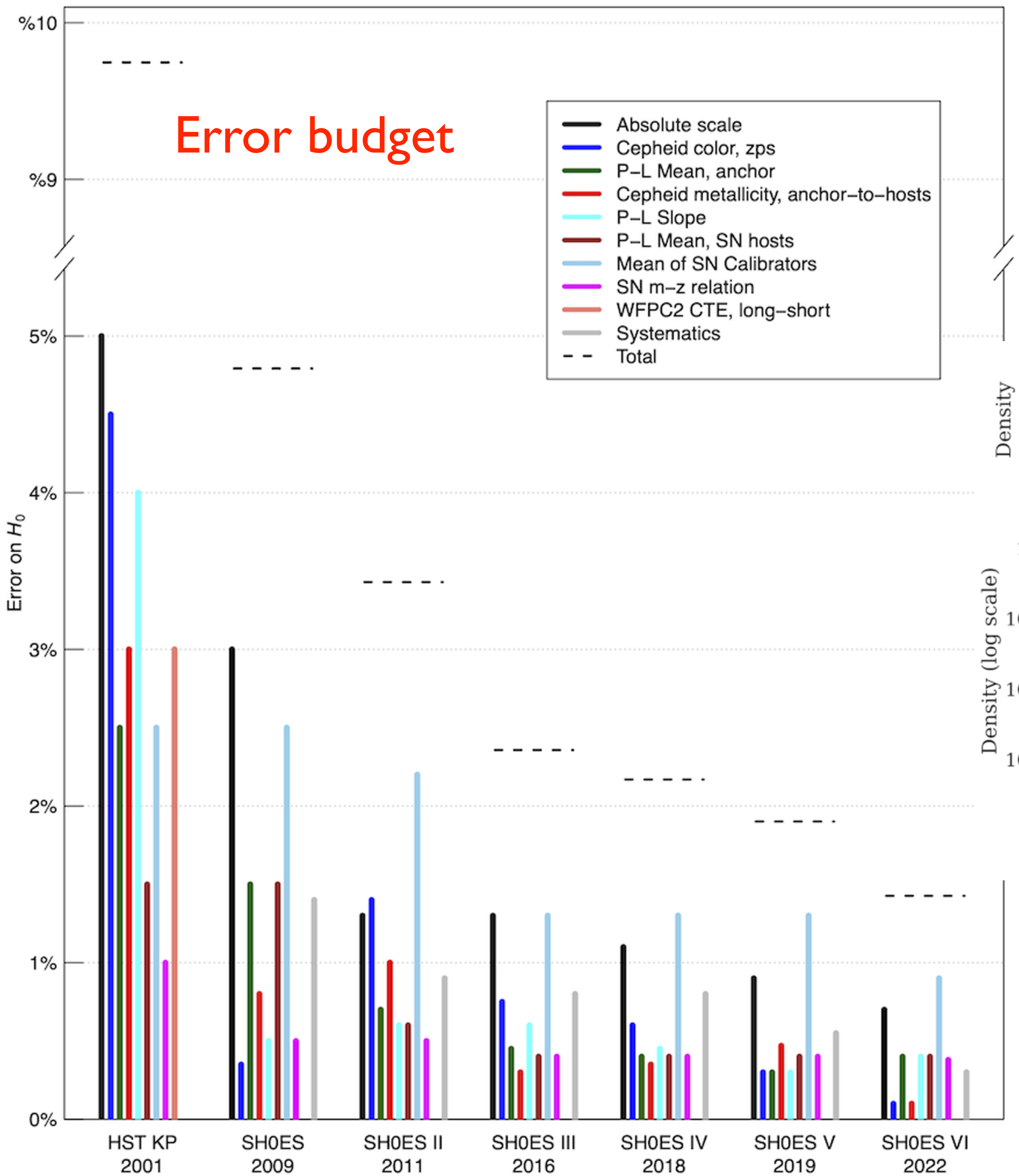
Figure from G. Efstathiou slides (RAS meeting, April 2024)

H0 direct measurement distance ladder

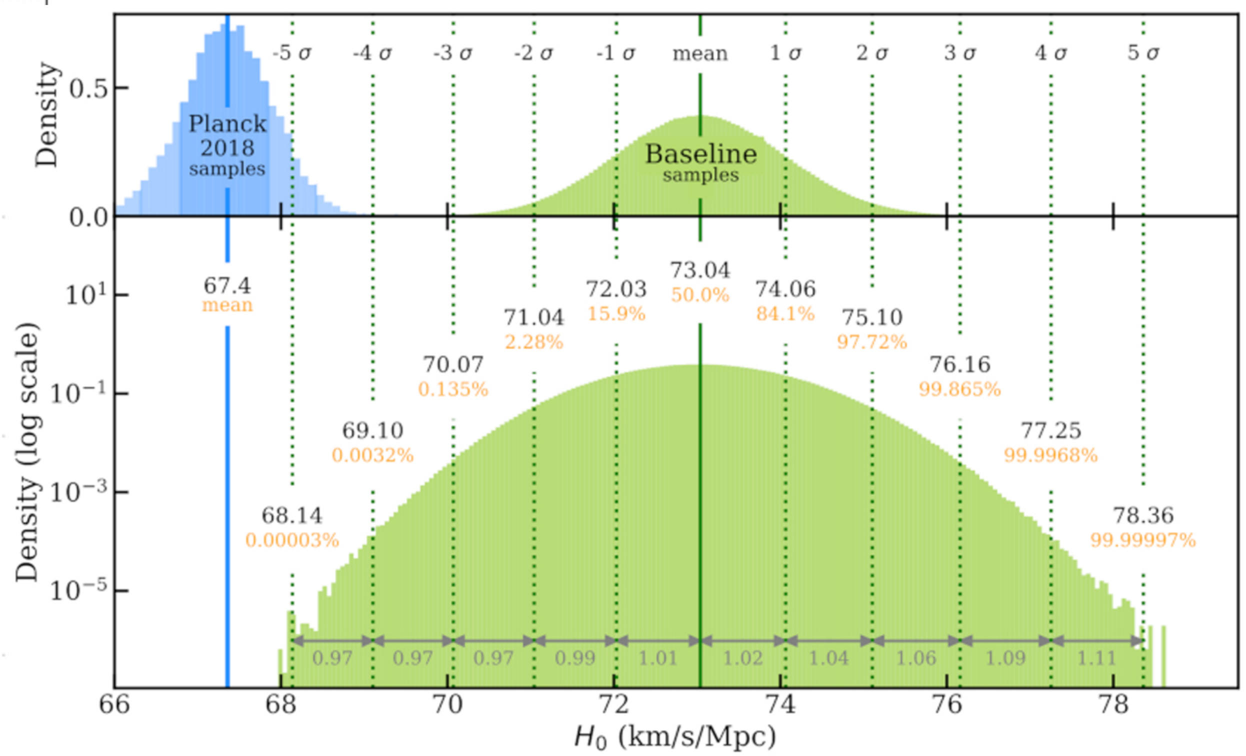
A. Riess el al. (2022) ApJ (SHOES)



H0 direct measurement (SHOES)

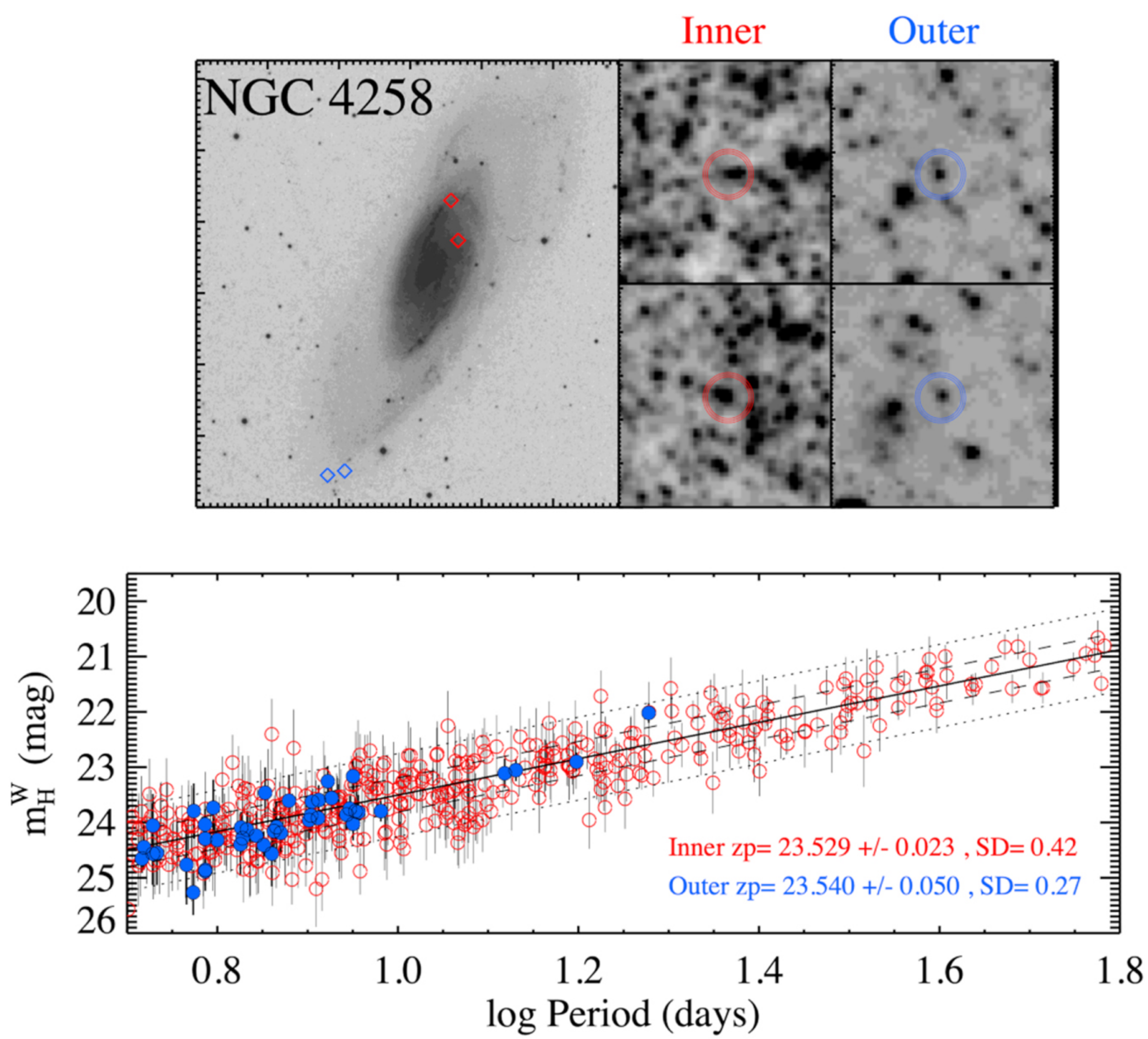


$$H_0 = 73.04 \pm 1.04 \text{km s}^{-1}\ \text{Mpc}^{-1}$$



A. Riess el al. (2022) ApJ (SHOES)

Photometry in crowded fields : blending



A. Riess el al. (2022) ApJ (SHOES)

JWST HST

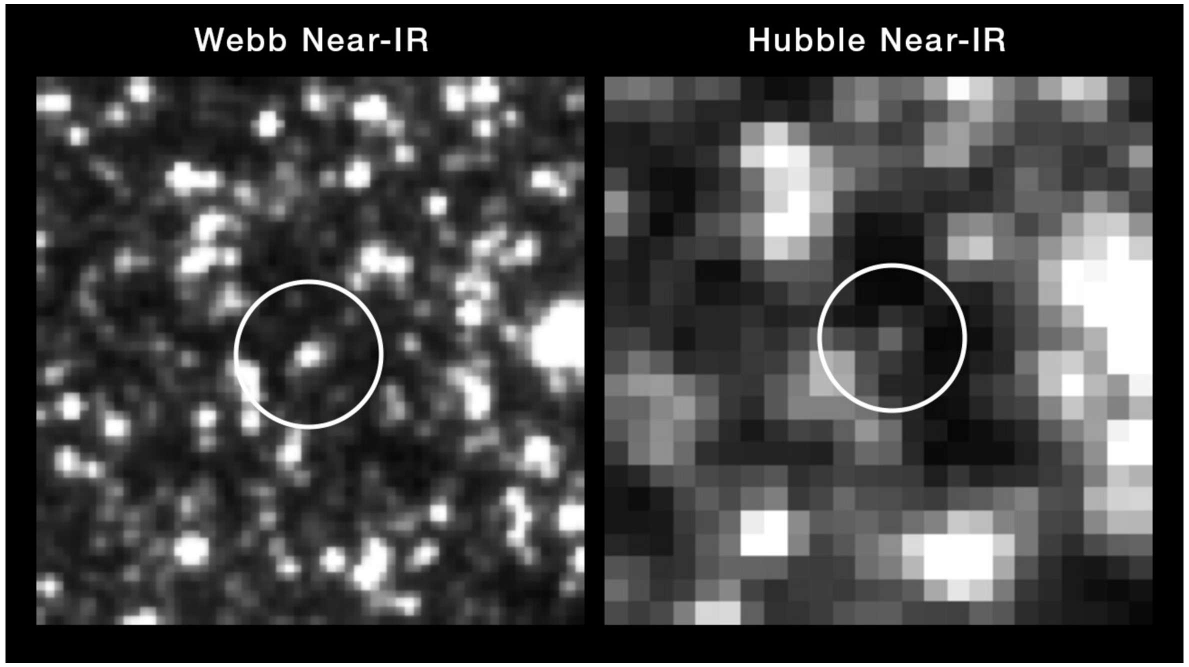
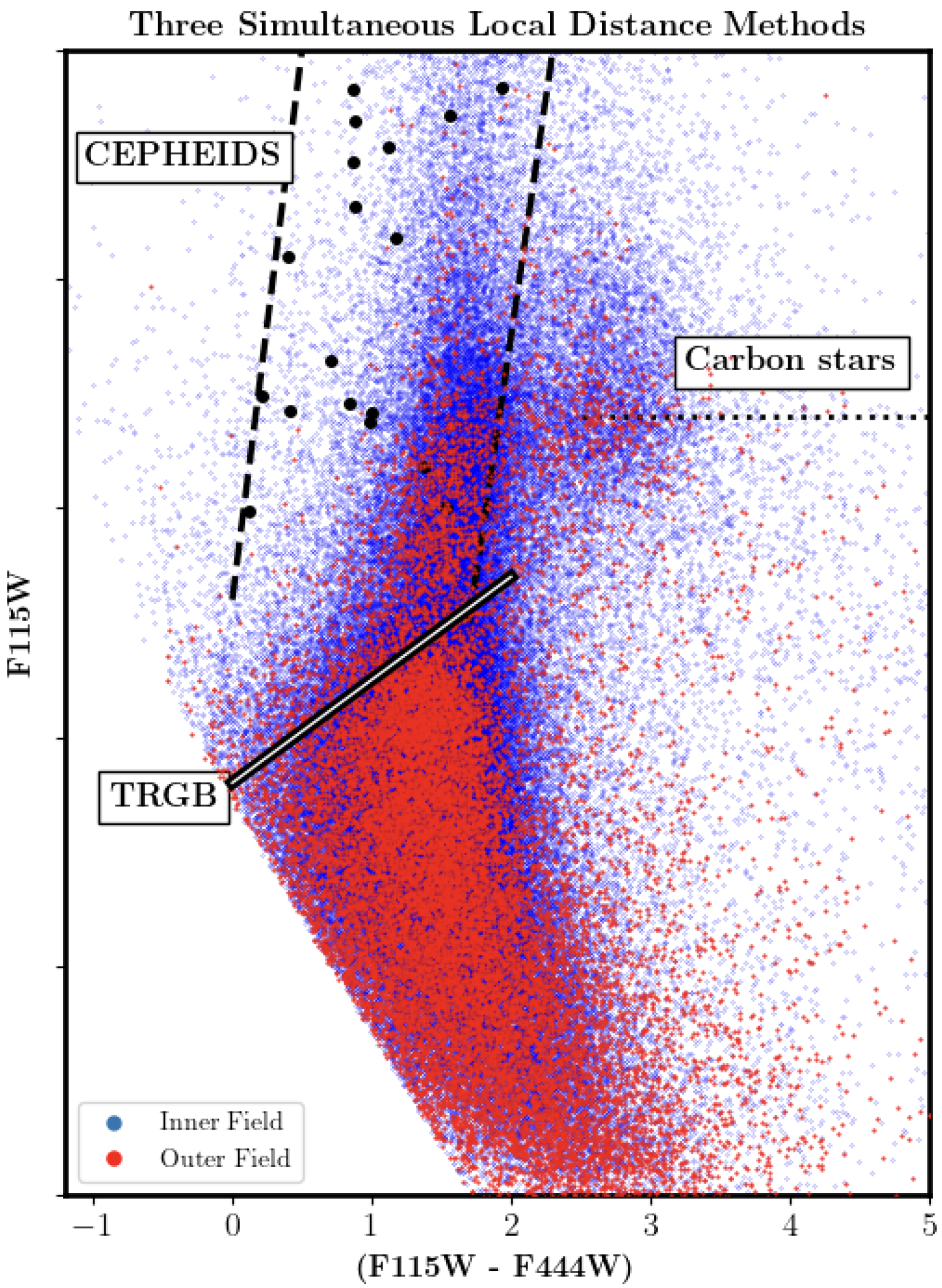


Image comparison from ESA web site

Crowding not an issue :
A. Riess el al. (2024). arXiv:2401.04773

H_0 direct measurement with TRGB



Freedman & Madore (2023) JCAP

Hoyt et al 2024

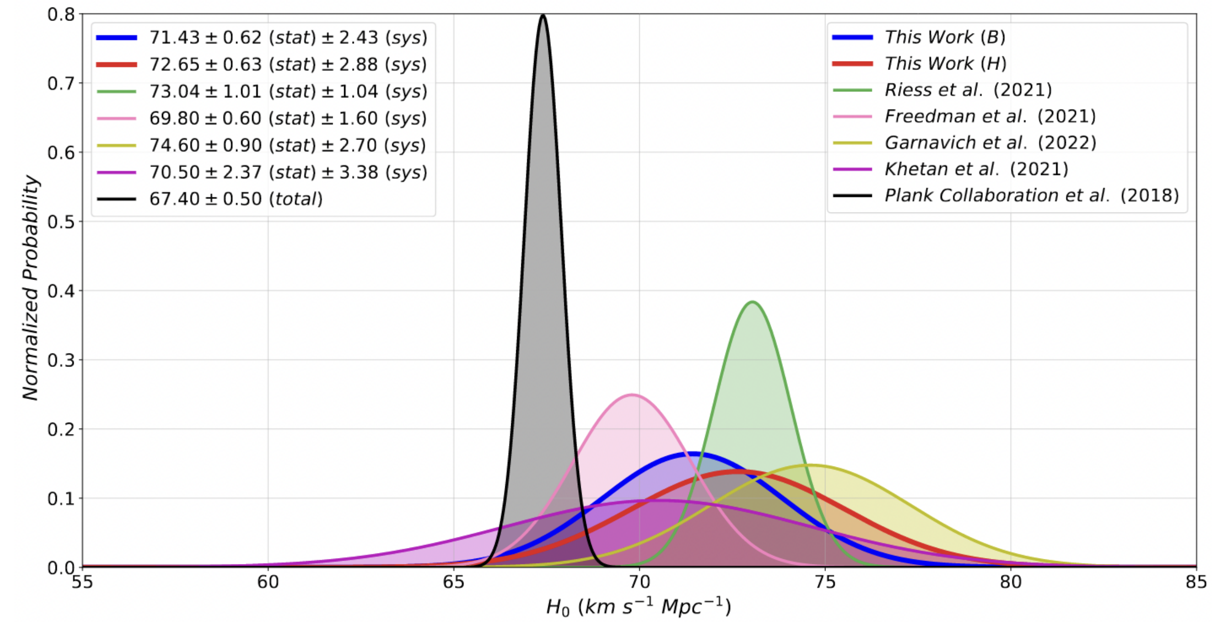
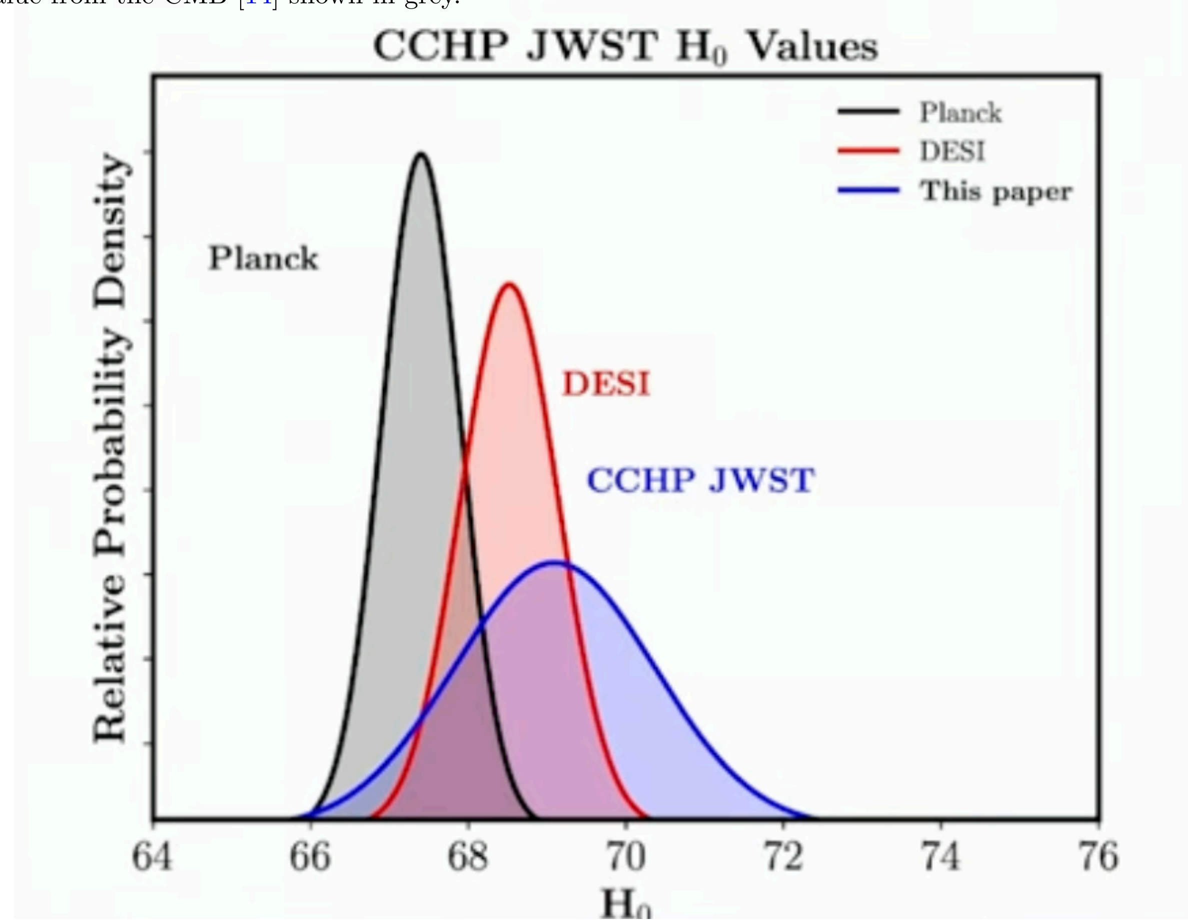


Figure 14. Probability distributions for H_0 for calibrations based on Cepheids [145], the TRGB [28] SBF from [88], compared to recent published values from the literature. The Planck Collaboration value from the CMB [14] shown in grey.



$$H_0 \quad = \quad 69.1 \quad \pm 1.5\,\mathrm{km/s/Mpc}$$

σ_8 : a measure of matter density inhomogeneity

- Planck constraints on σ_8 / S_8
- σ_8 / S_8 from weak lensing
- CMB lensing
- σ_8 / S_8 from clusters

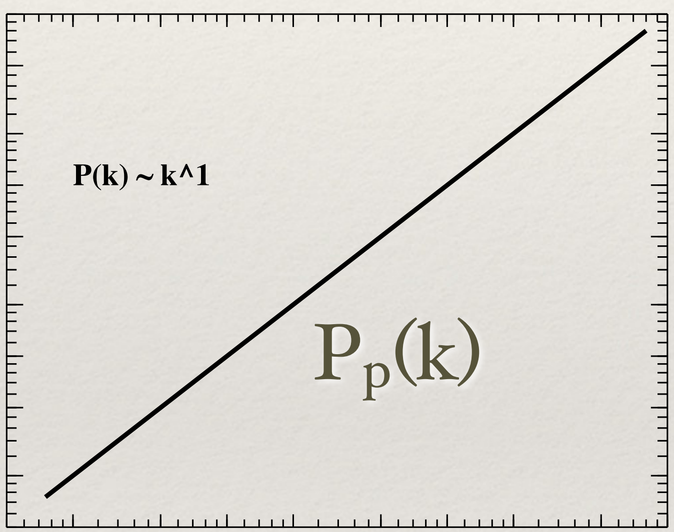
σ_8 measurements

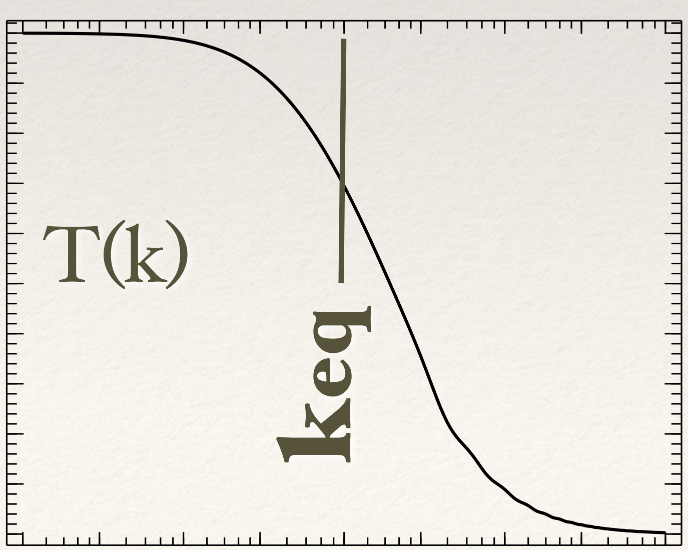
- σ_8 from WL
- σ_8 from CMB lensing
- σ_8 from CMB clusters

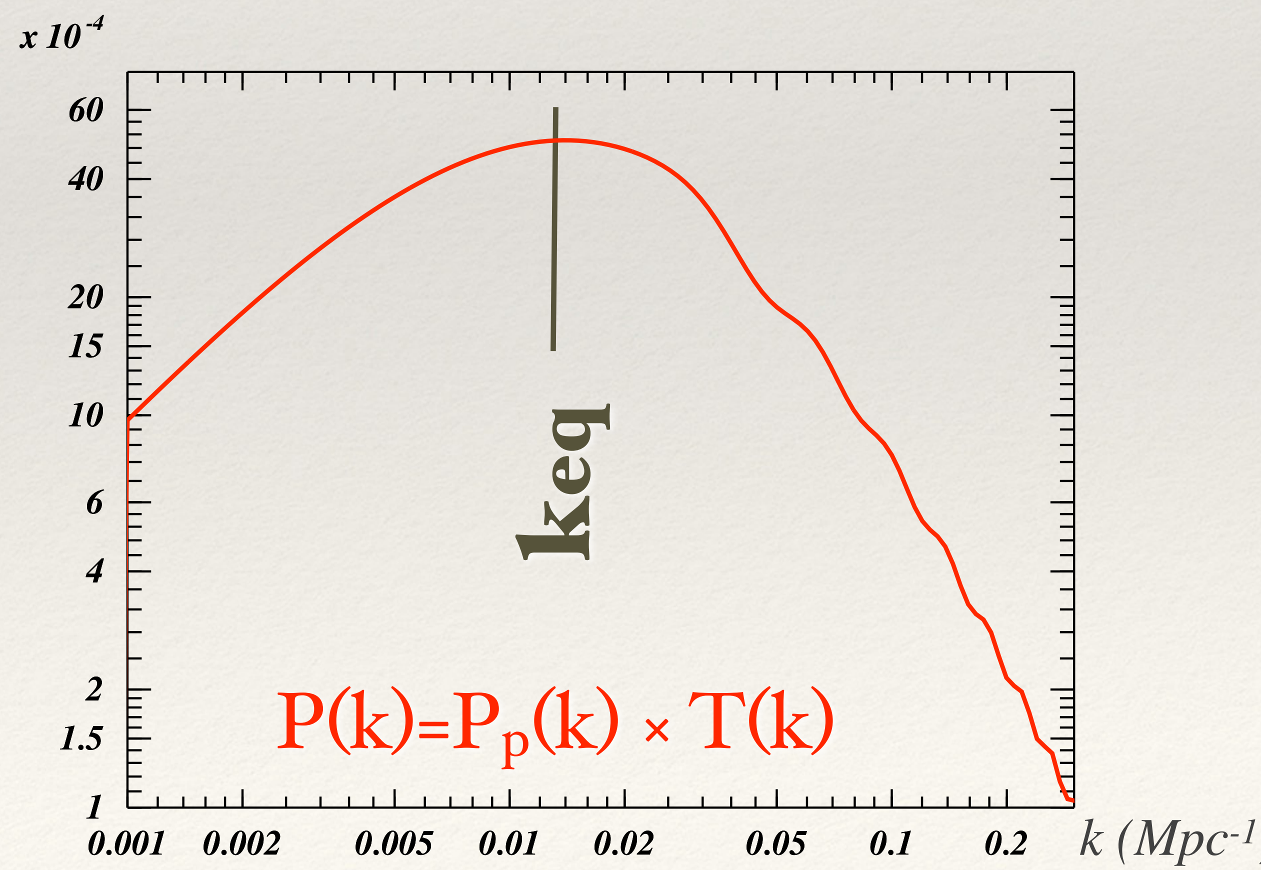
σ_8 : RMS of mass density fluctuations smoothed with an $8h^{-1}$Mpc top hot filter (box with $R = 8h^{-1}$Mpc side) at z=0

$$\sigma_8^2 \sim \int k^2 P(k) W^2(kR)\, dk$$

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$







σ_8 : back to CMB/Planck

Base-ΛCDM cosmological parameters from *Planck* TT,TE,EE+lowE+lensing.

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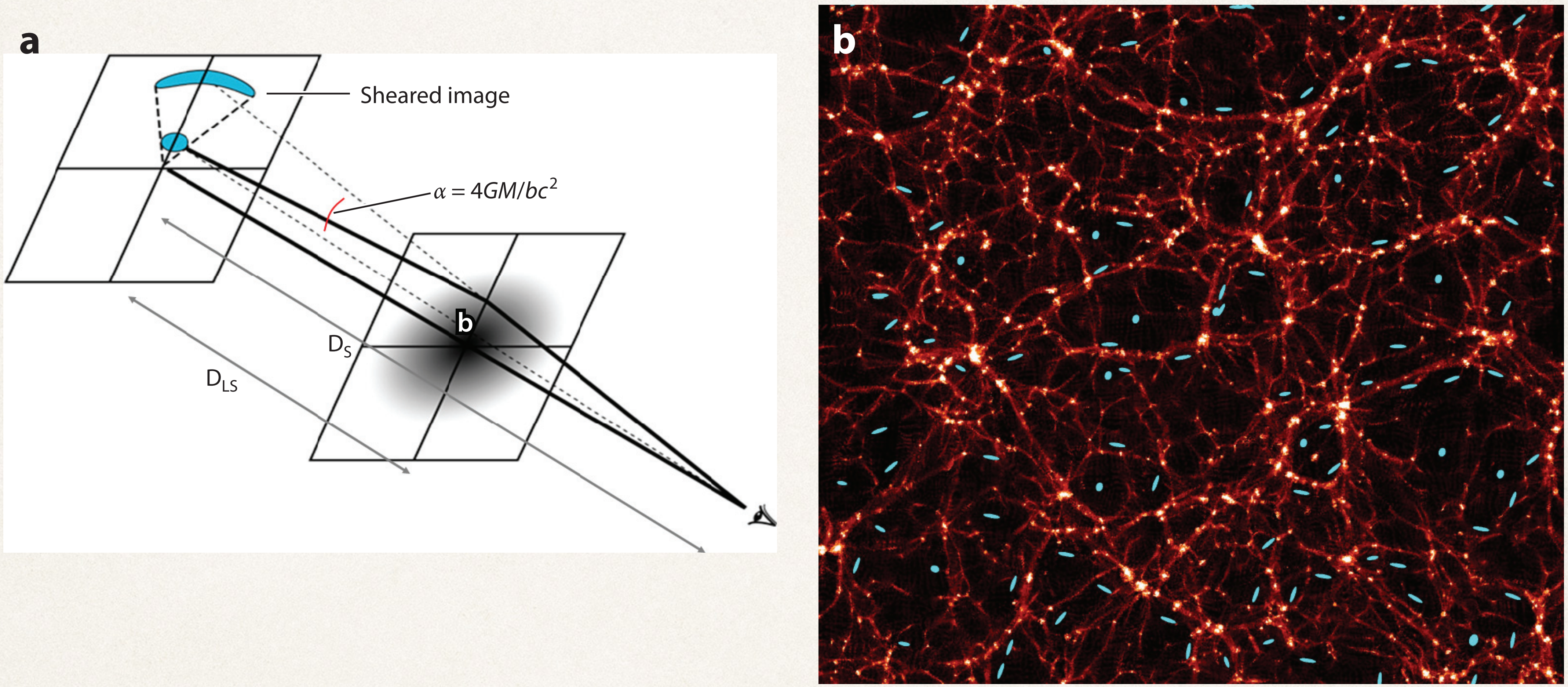
Planck measures the amplitude and power law index of the primordial spectrum

Weak Lensing

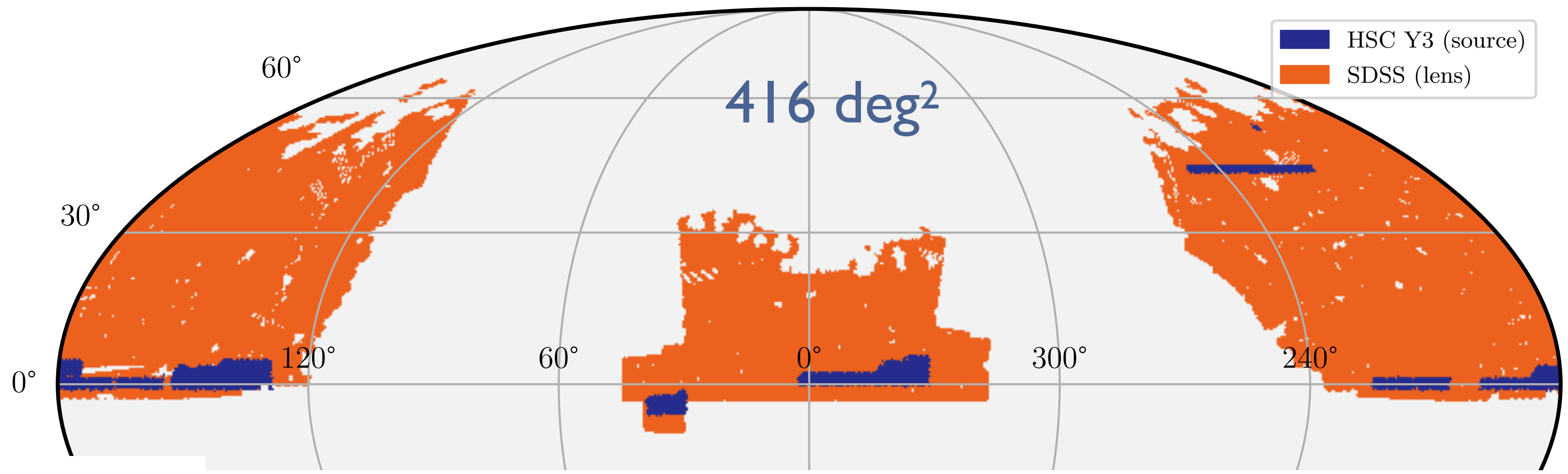
Weak Lensing for precision cosmology, R. Mandelbaum, Ann. Rev. A&A (2018)

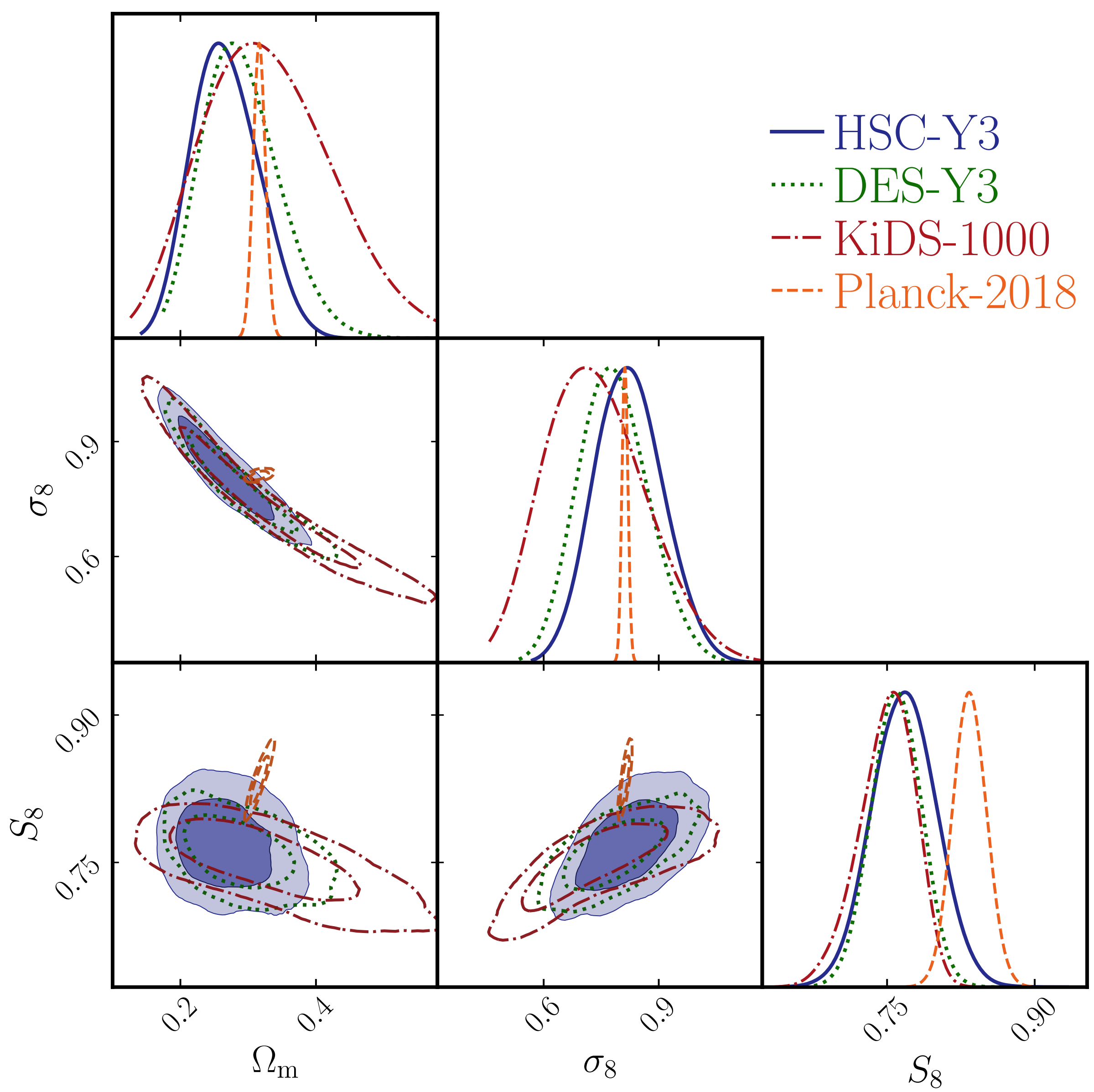


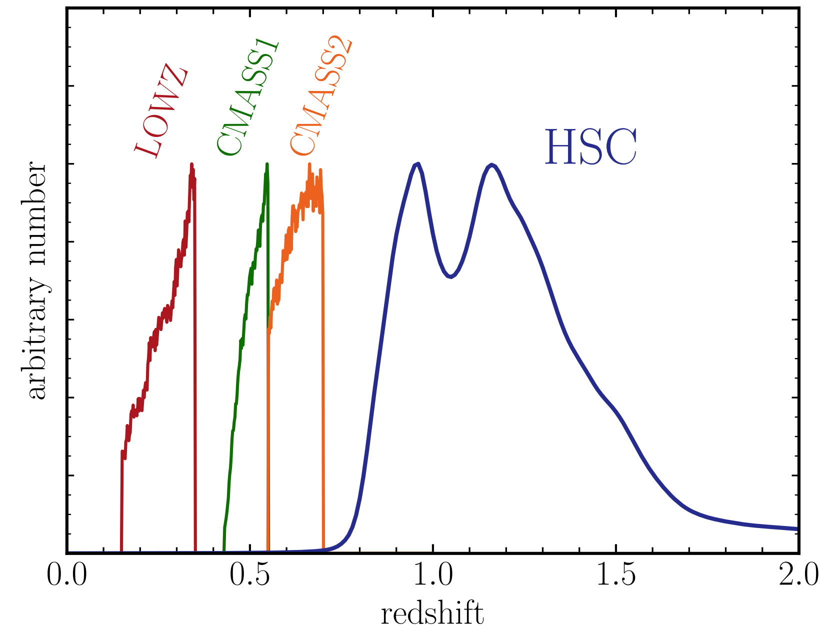
- Measure galaxy ellipticities → estimate shear field
- Obtain foreground mass maps
- Shear (lensing signal) strength depends on the gravitational potential, hence the inhomogeneity level and the total matter density
- The S8 parameter captures this dependency

WL surveys :
KiDS, DES, HSC , Euclid,
Rubin/LSST, Roman …

HSC weak lensing
(example)





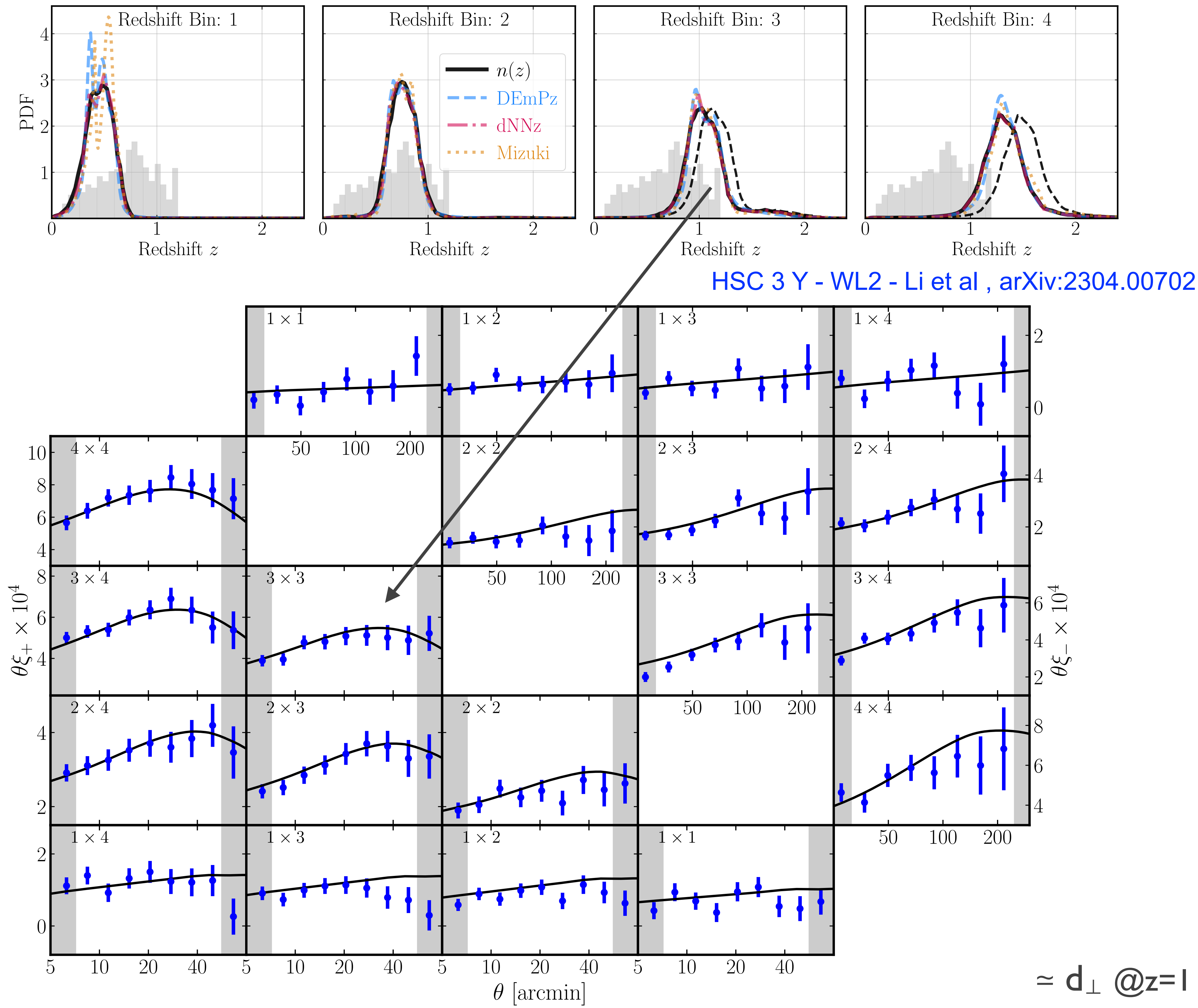


HSC 3 Y - More et al , arXiv:2304.00703

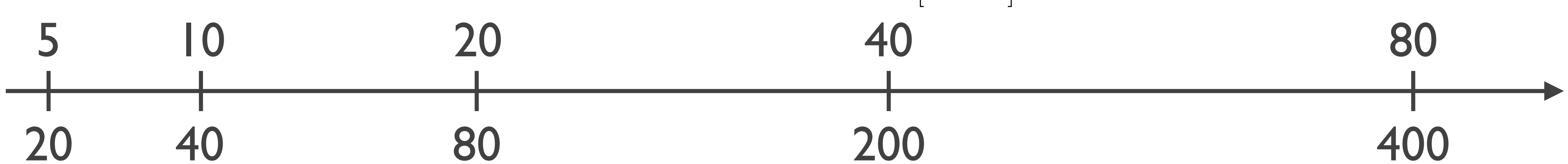
HSC 3 Y - WL2 - Li et al , arXiv:2304.00702

HSC 3 Y - WL1 - Dalal et al , arXiv:2304.00701

HSC weak lensing

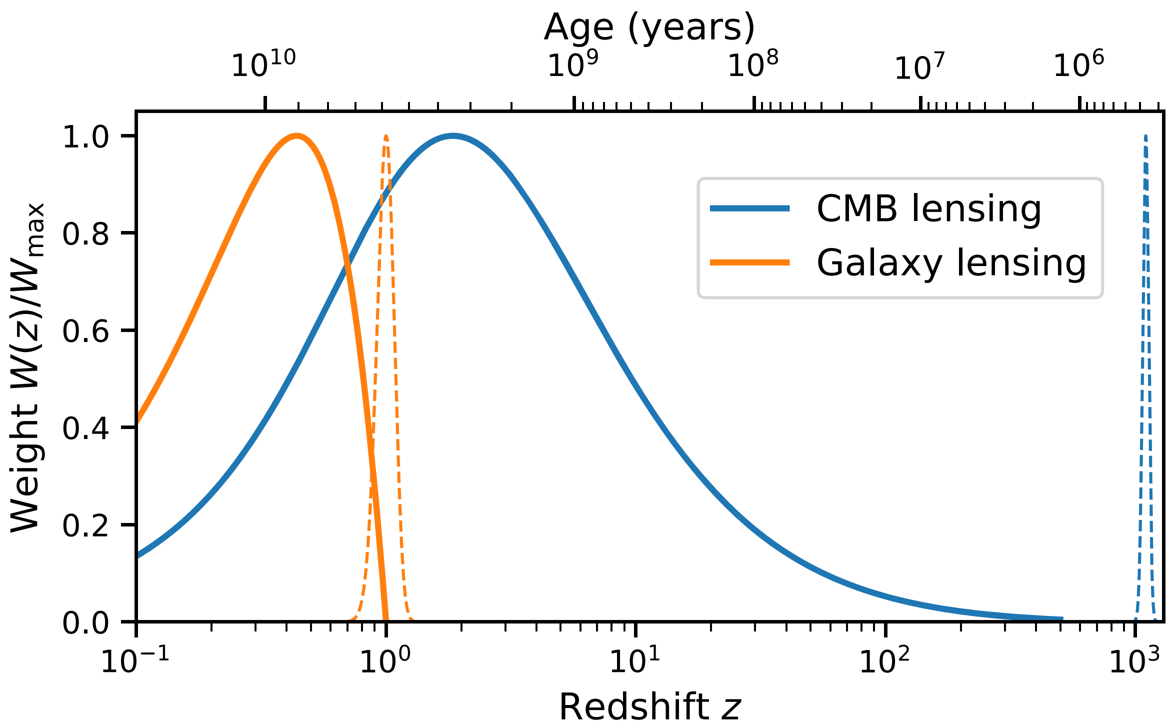


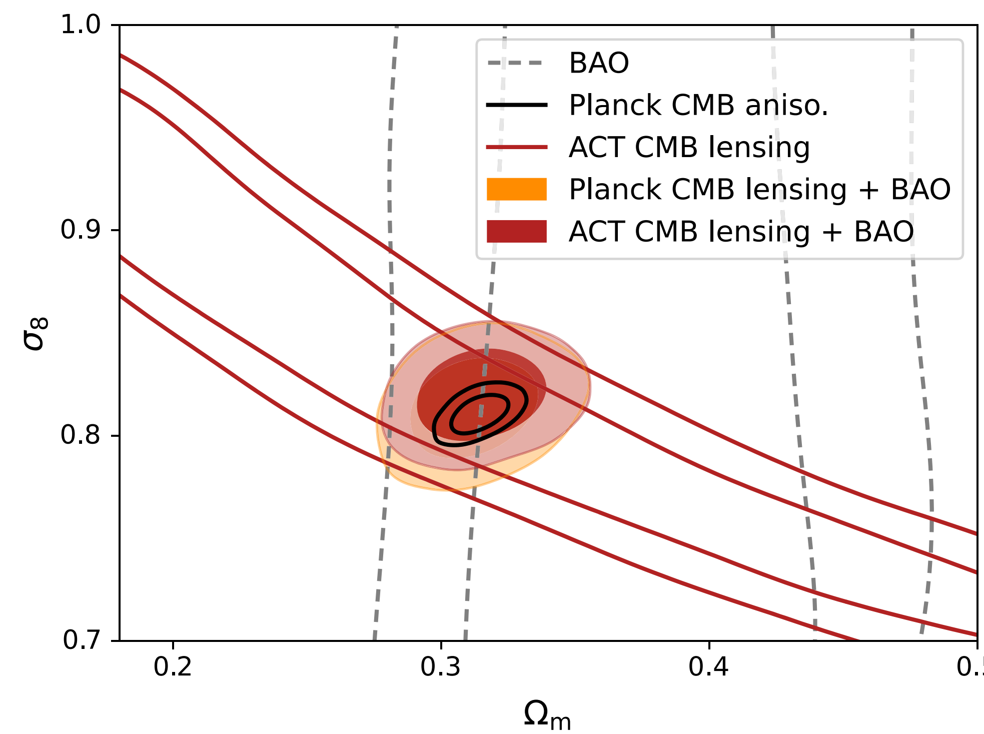
HSC 3 Y - WL2 - Li et al , arXiv:2304.00702

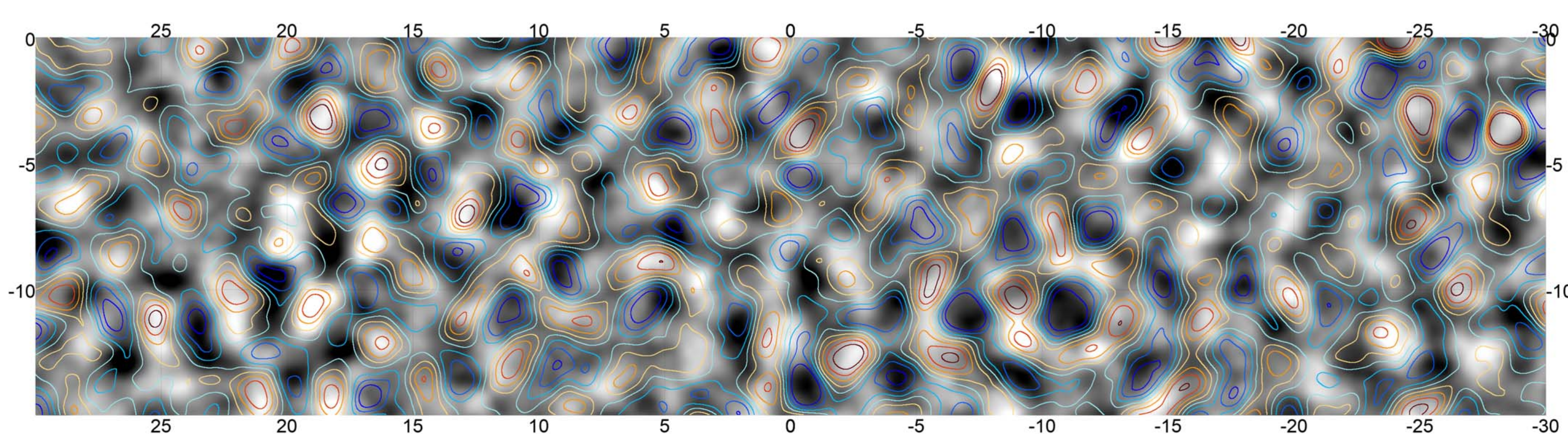


CMB lensing

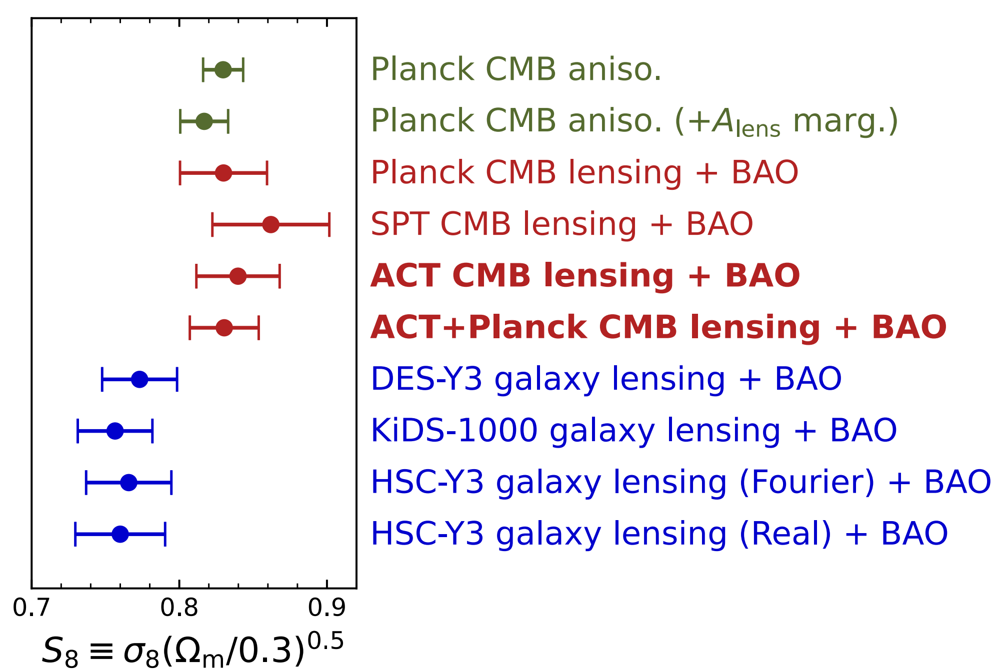
ACT - CMB Lensing   arXiv:2304.05203





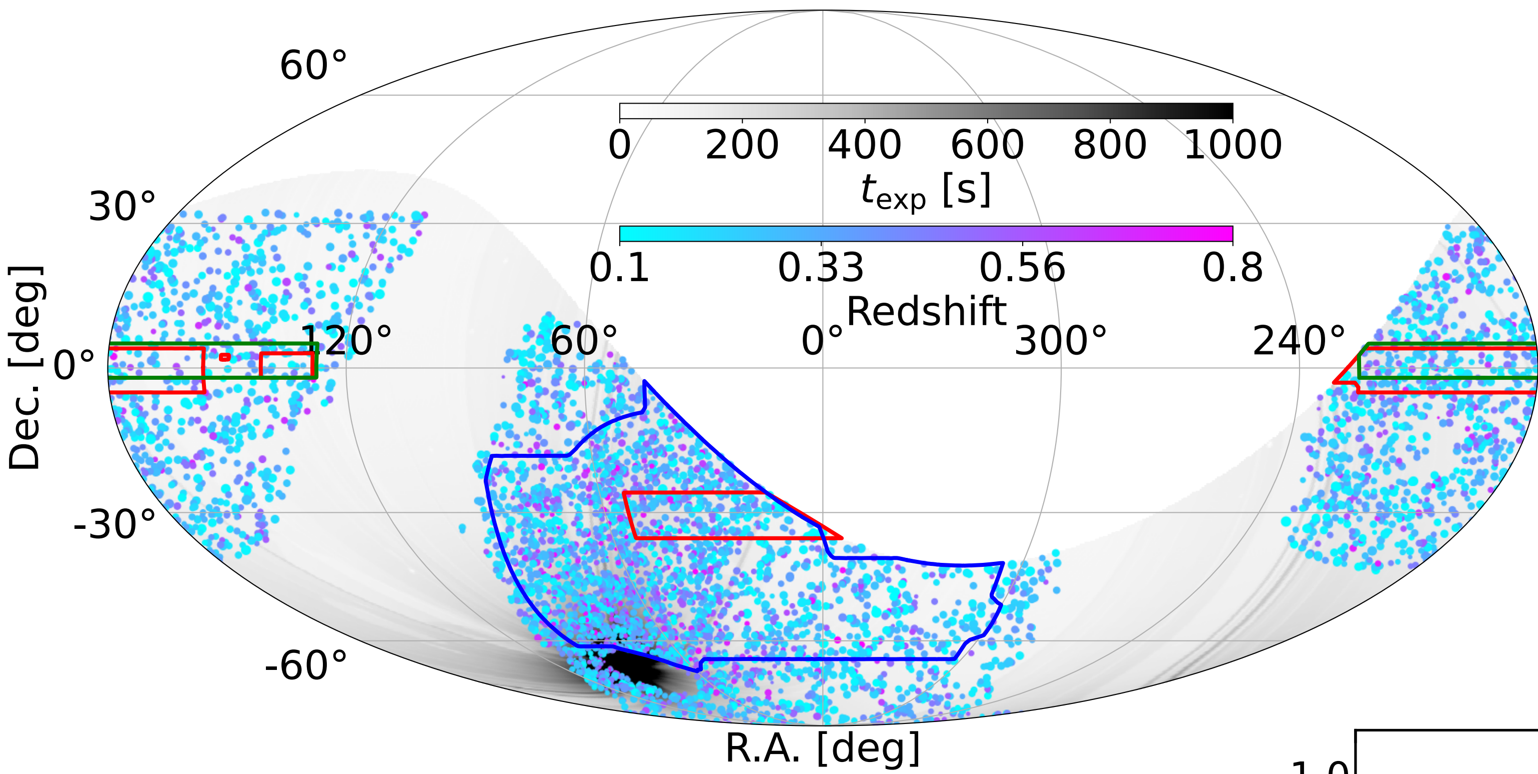


Zoom in (900 deg2) ACT lensing mass map
contours : dusty galaxies from Planck CIB

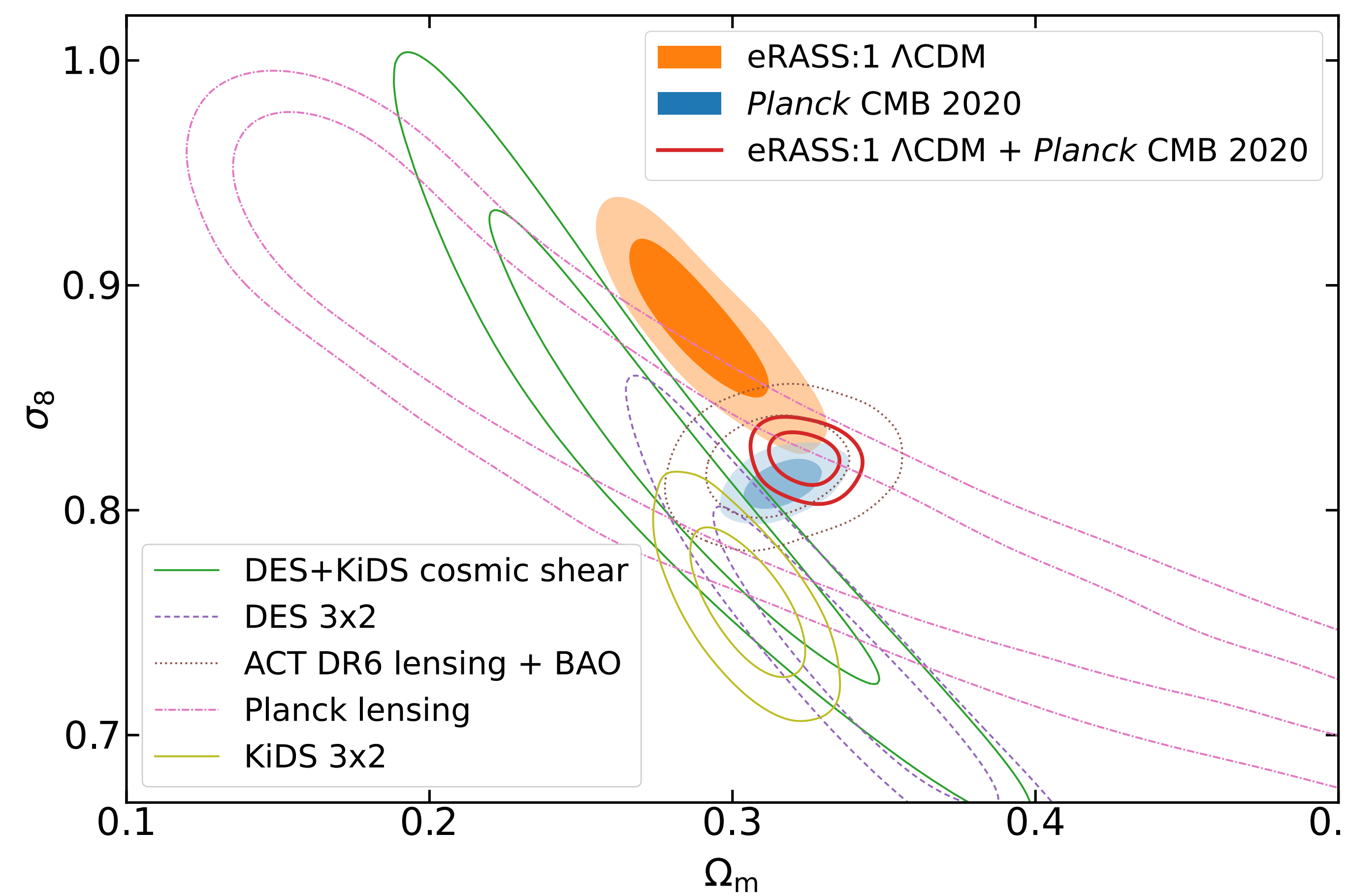


σ8 from X-ray clusters

SGR/eROSITA all sky survey - arXiv:2402.08458

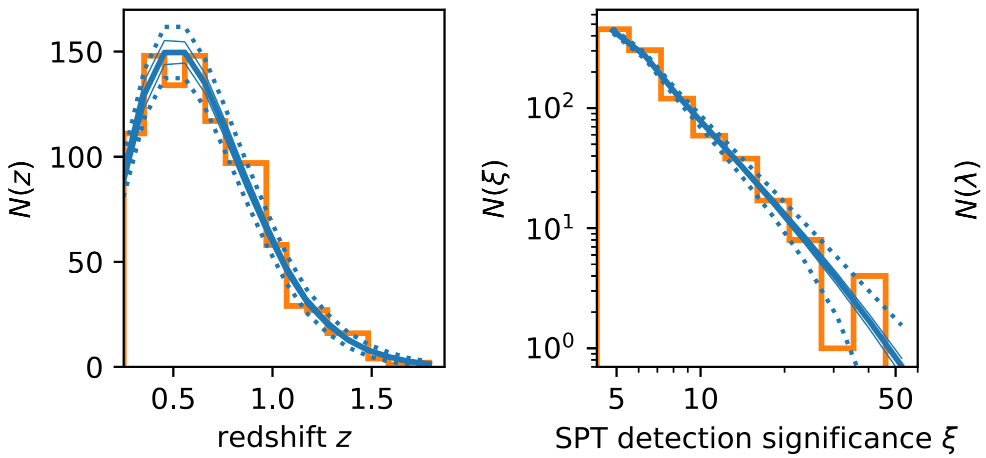


5259 confirmed clusters in the Western Galactic Hemsiphere (eRASS1)



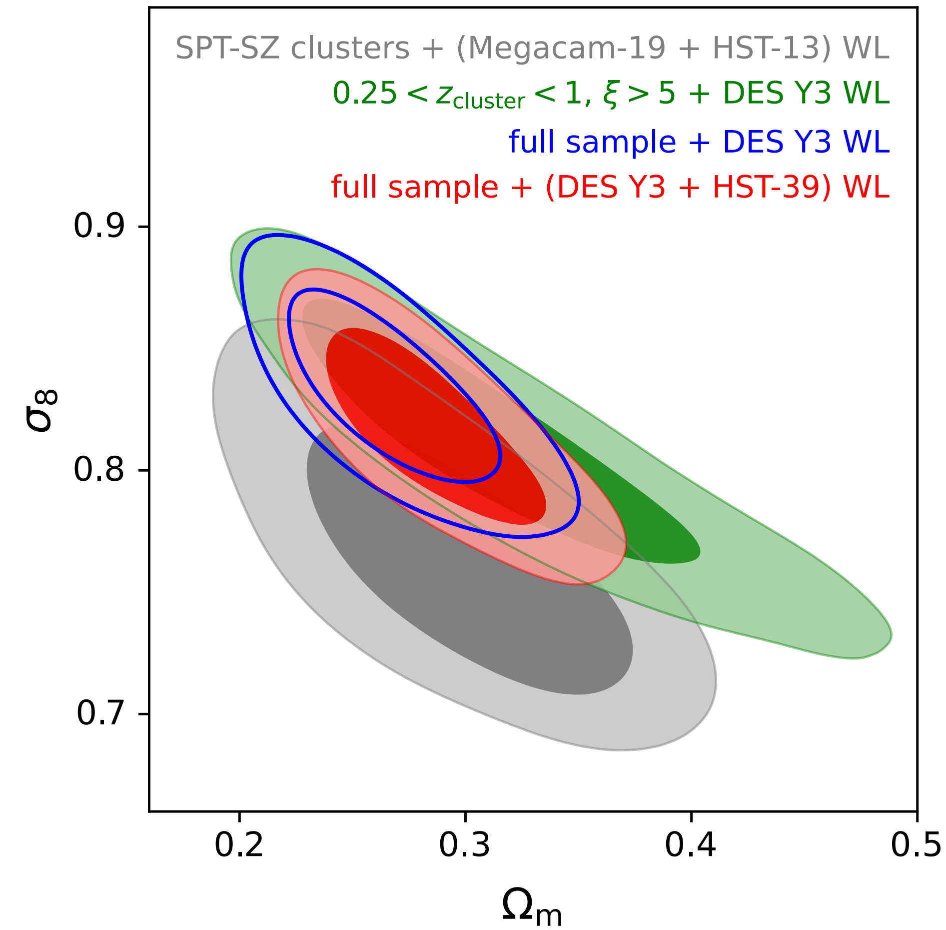
σ8 from SZ clusters

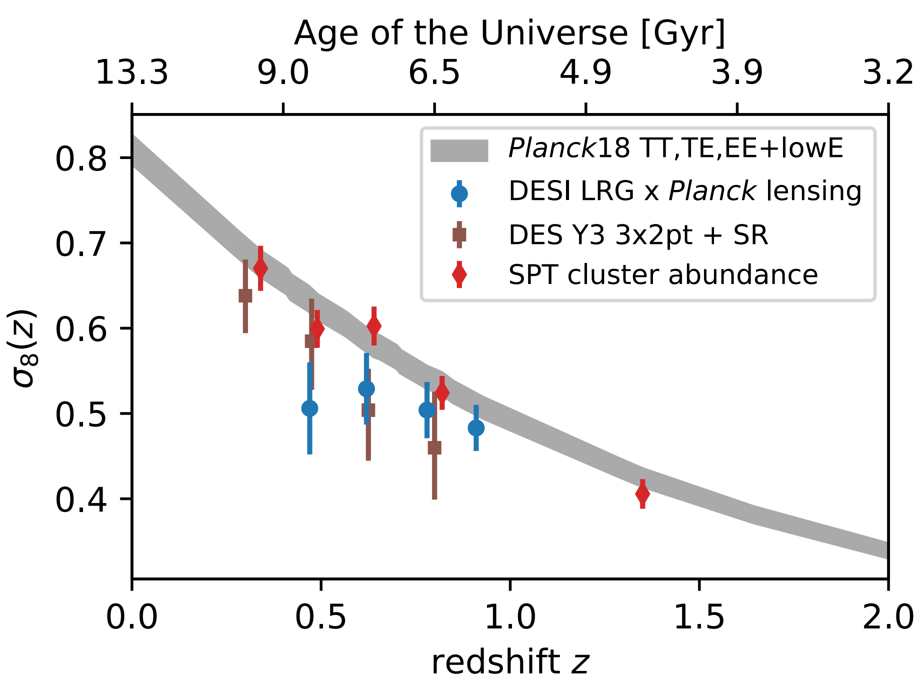
SPT clusters + DES/HSC WL - arXiv:2402.08458



1005 clusters of the SPT sample

Grey : previous SPT analysis (smaller sample)

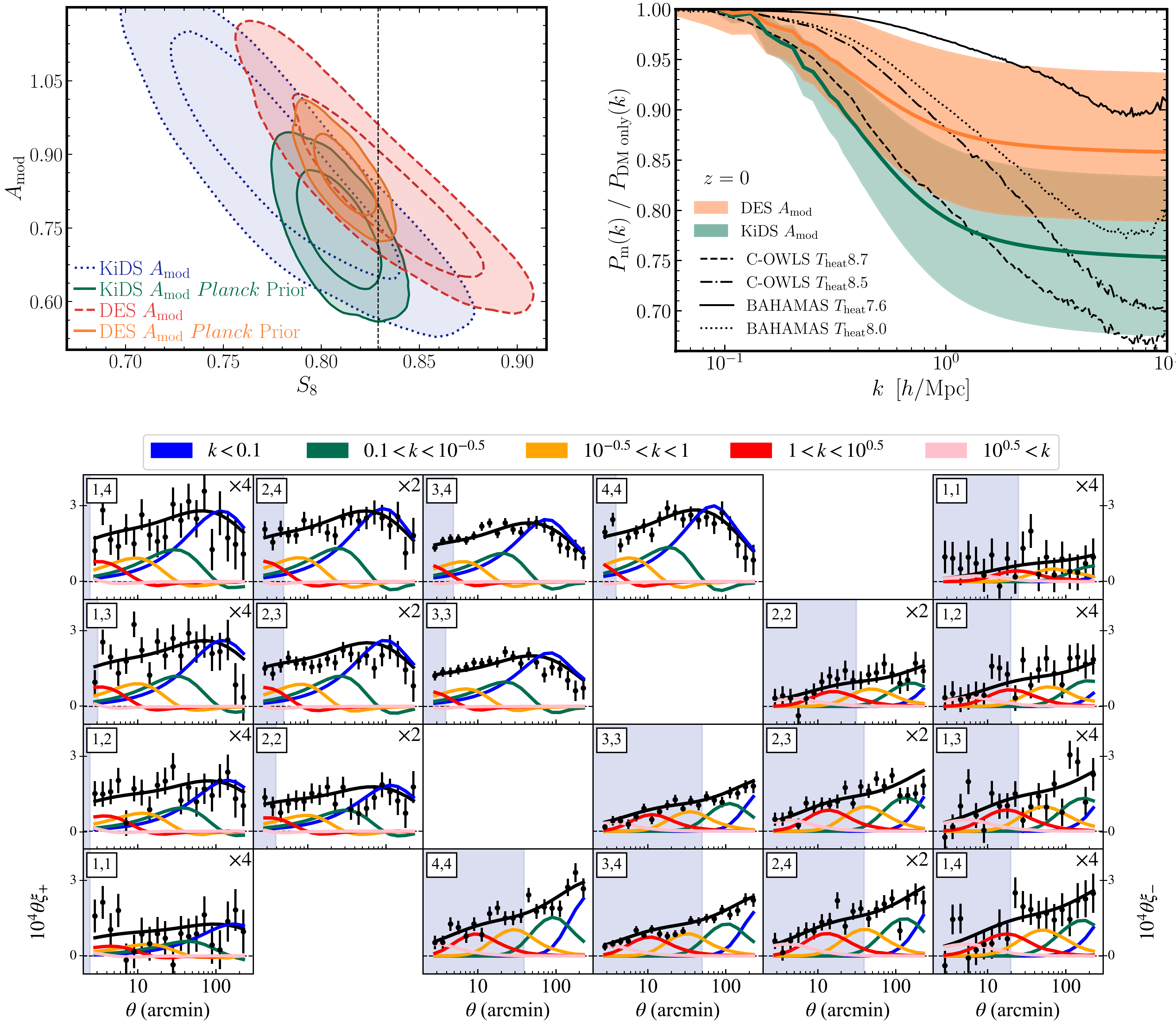




Redshift evolution

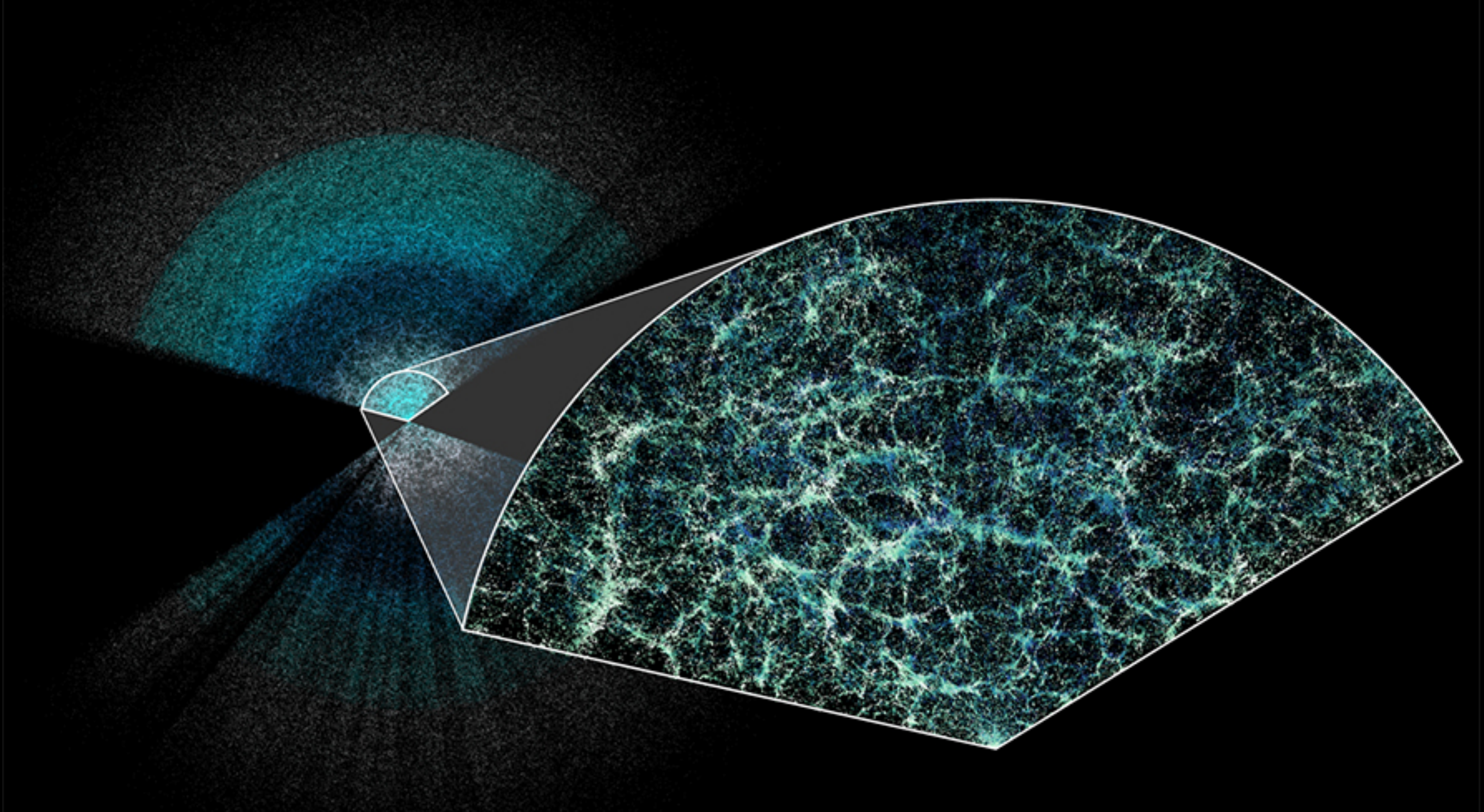
Small scale suppression of matter power spectrum as a solution to S8 puzzle

Preston, Amon, Efstathiou , MNRAS, 2023



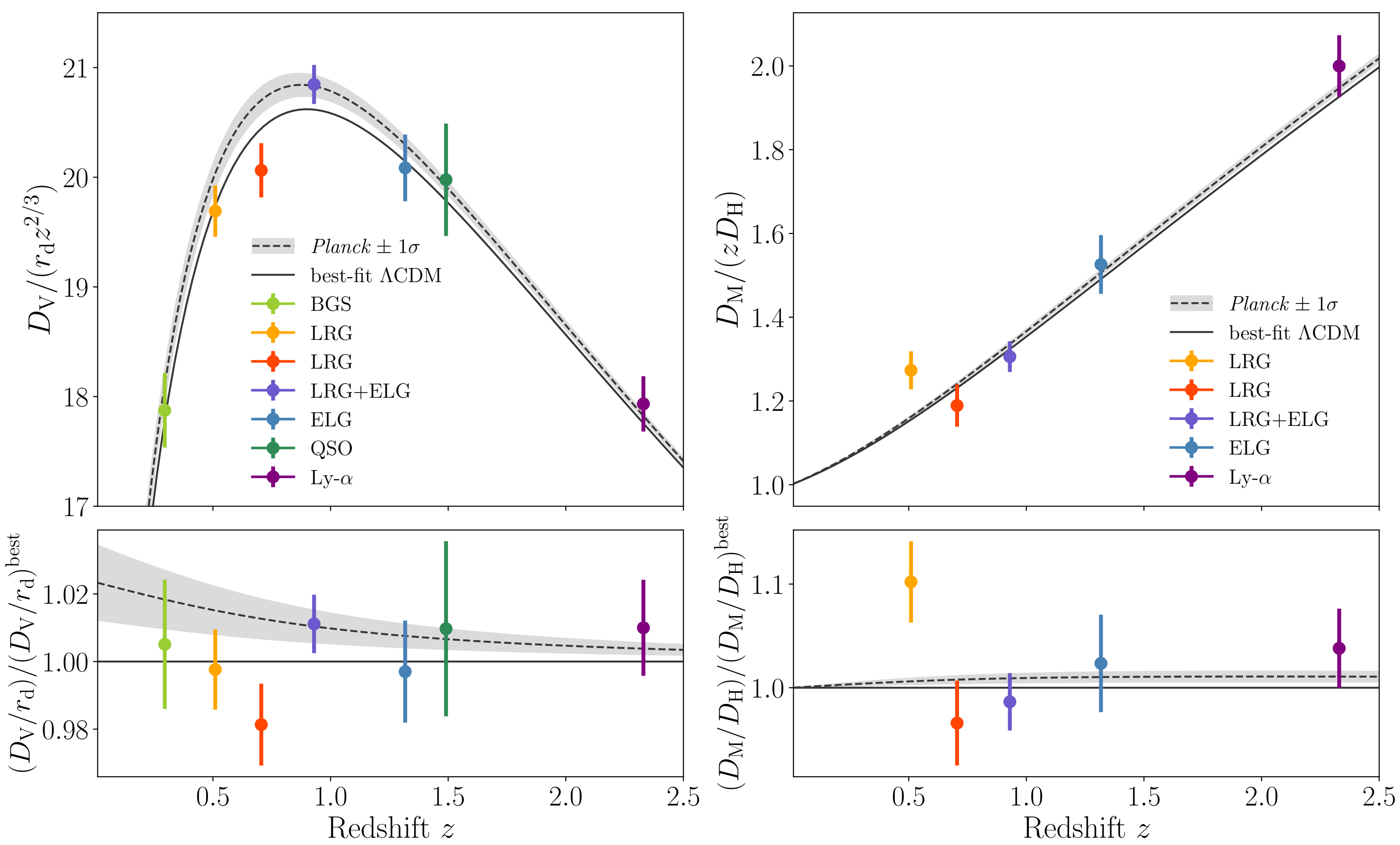
DESI results

(biased selection)

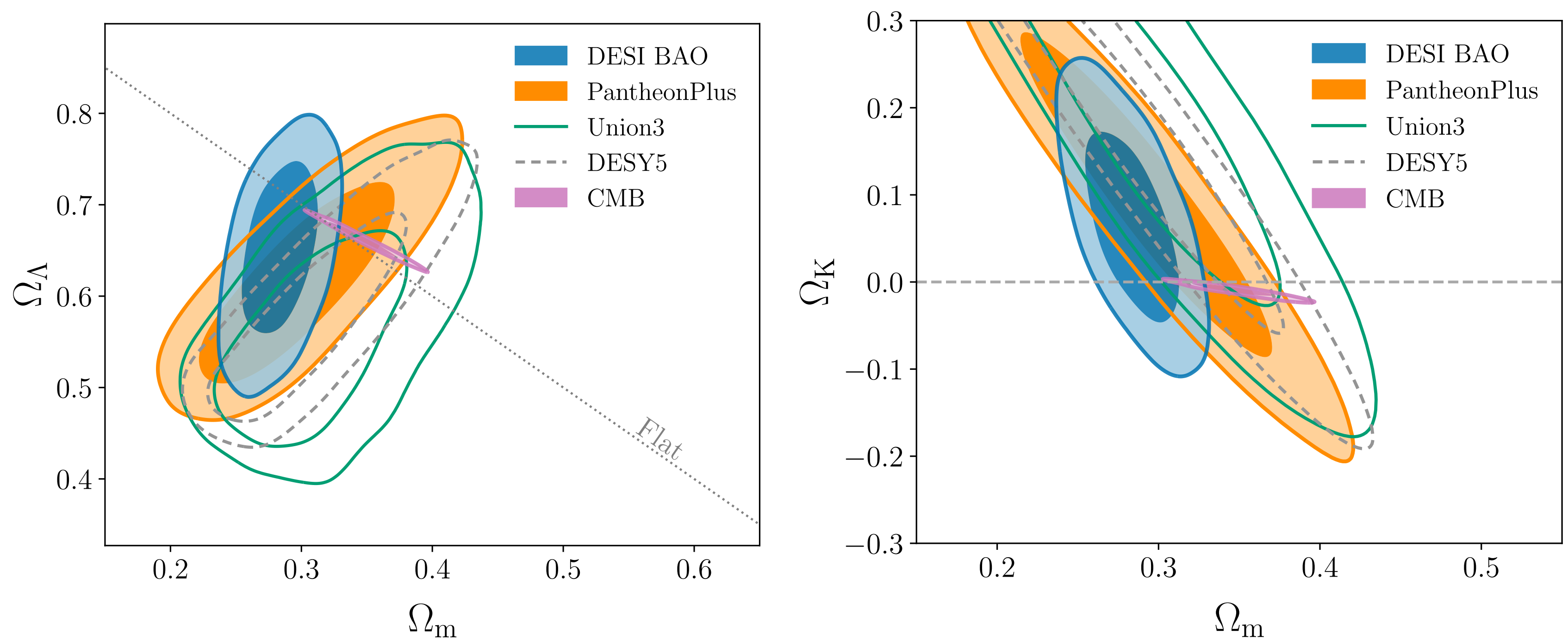


DESI - https://www.desi.lbl.gov/

DESI cosmology results (I)



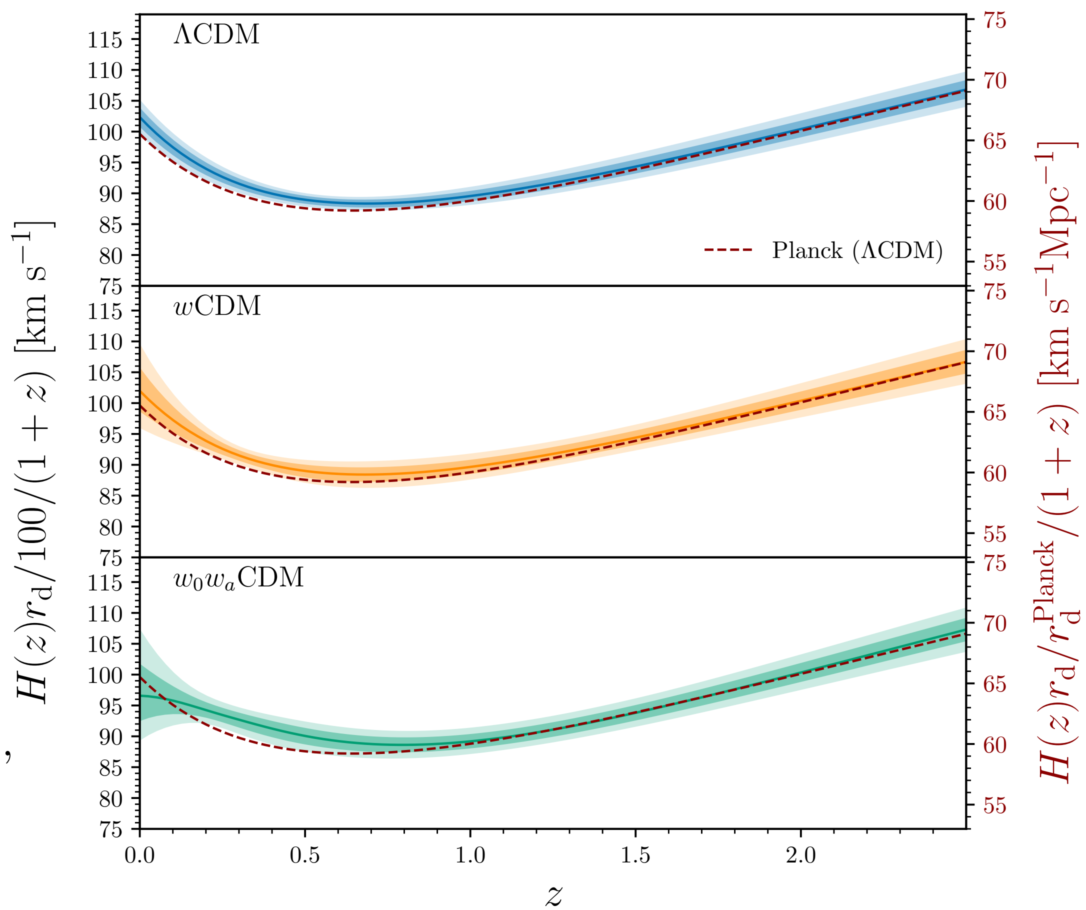
DESI 2024 VI :
cosmological constraints from BAO
arXiv:2404.03002



DESI cosmology results (II)

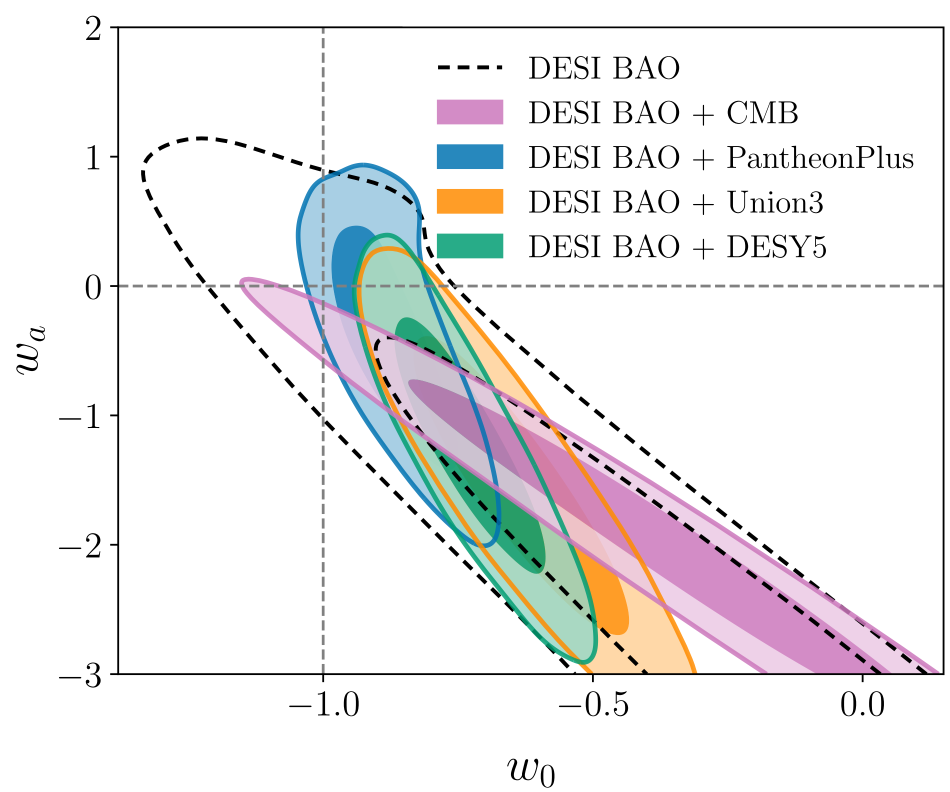
Evidence for DE (w0, wa) at ~ 3 σ level

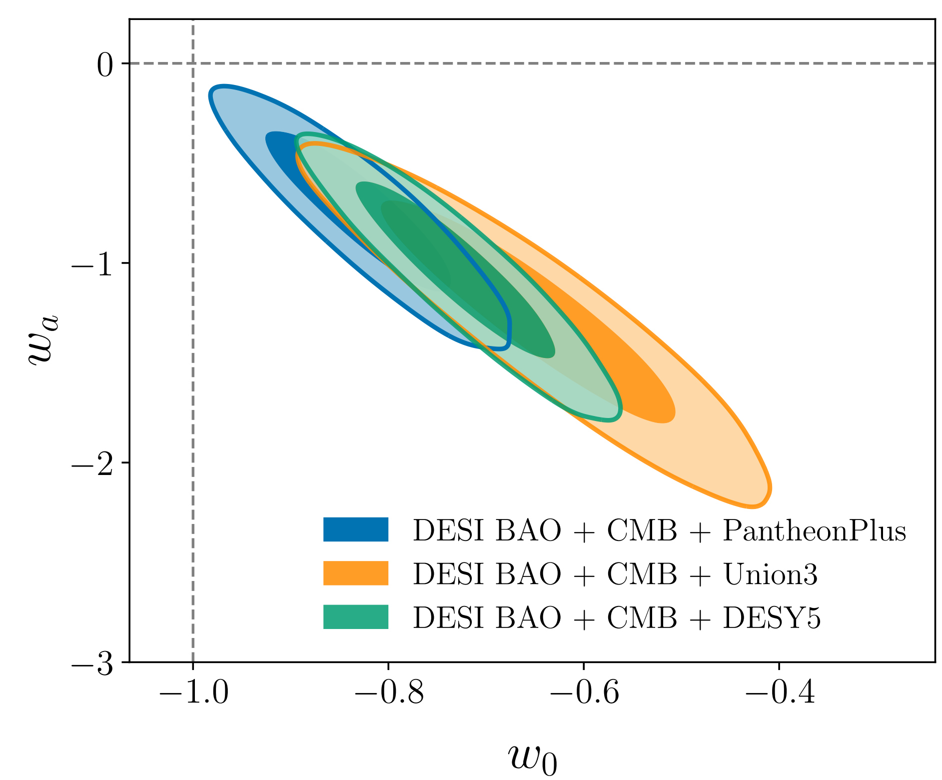
$$\left.\begin{aligned}\Omega_\mathrm{m} &= 0.293 \pm 0.015,\\ w &= -0.99^{+0.15}_{-0.13},\end{aligned}\right\}\ \text{DESI BAO},$$



DESI 2024 VI :
cosmological constraints from BAO
arXiv:2404.03002

$$\left.\begin{aligned}w_0 &= -0.45^{+0.34}_{-0.21},\\ w_a &= -1.79^{+0.48}_{-1.0},\end{aligned}\right\}\ \text{DESI BAO+CMB},$$





Summary

The ΛCDM model provides an impressively accurate description of the universe evolution, at least at large scales, over more than 13 billion years, from $z \sim 10^9$ to today ($z=0$), although some tensions are present, at the level of ~ 10% or 3-4 σ

Discrepancy between early (CMB) and late (direct) measurements of H0

Not all direct determination of H0 agree on its value

Might be due to some observational systematics (e.g. distance scales with Cepheids)

If real, will point toward mechanisms changing the evolution of the cosmic expansion (e.g Early/Late DE …)

Possible tensions also on the level of matter density inhomogeneity (σ_8/S_8) , as derived from CMB and the one measured at lower redshifts ($z \sim 1$)

However, the lower value of (σ_8/S_8) obtained from WL measurements at low redshifts seems incompatible with the ones obtained at low redshifts by other probes (CMB lensing, clusters …)

Again, systematics in observations can not yet be completely excluded

WL signal is sensitive to the non linear clustering scales - which might be affected also by baryonic effects - might also hint to physical and cosmological effects (e.g. SIDM …)

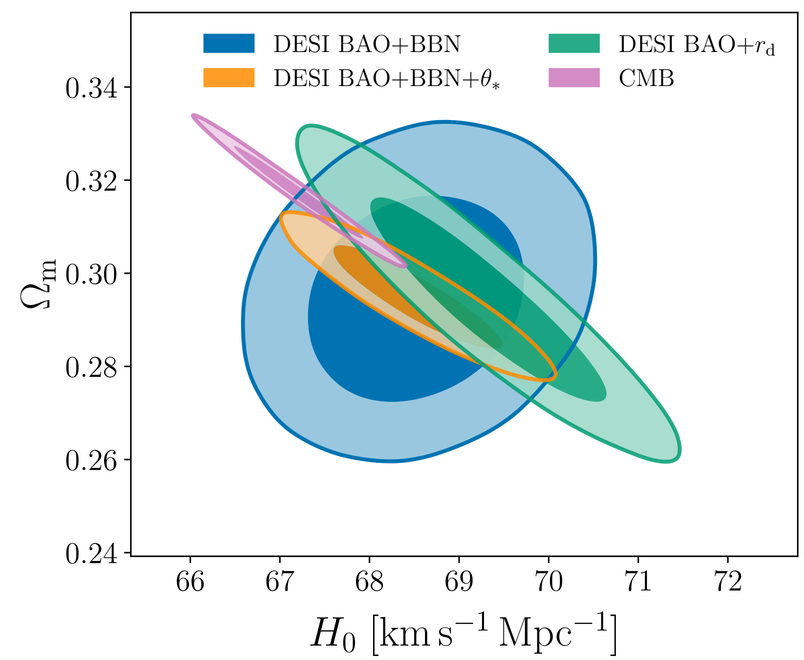
See Anomalies in Physical Cosmology, J. Peebles arXiv:2208.05018

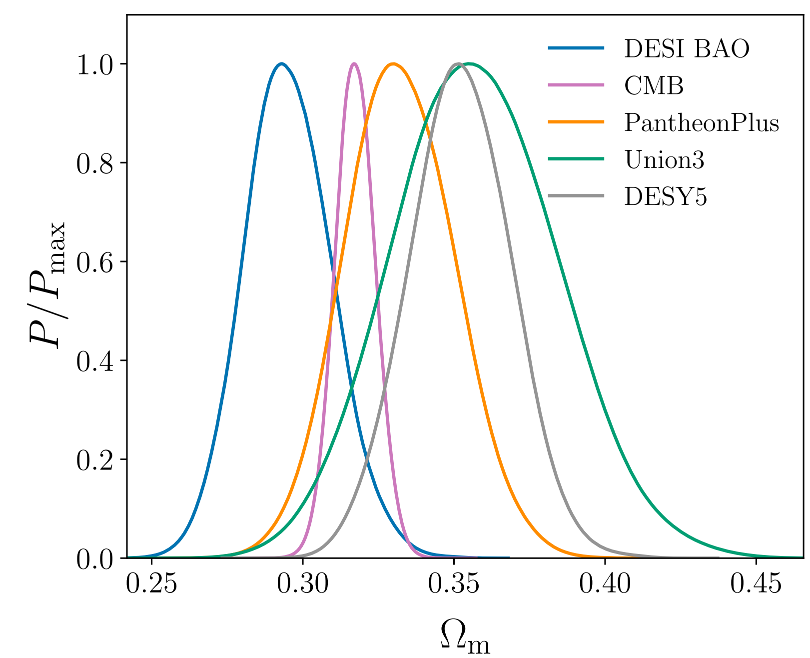
END

H_0 determination by DESI

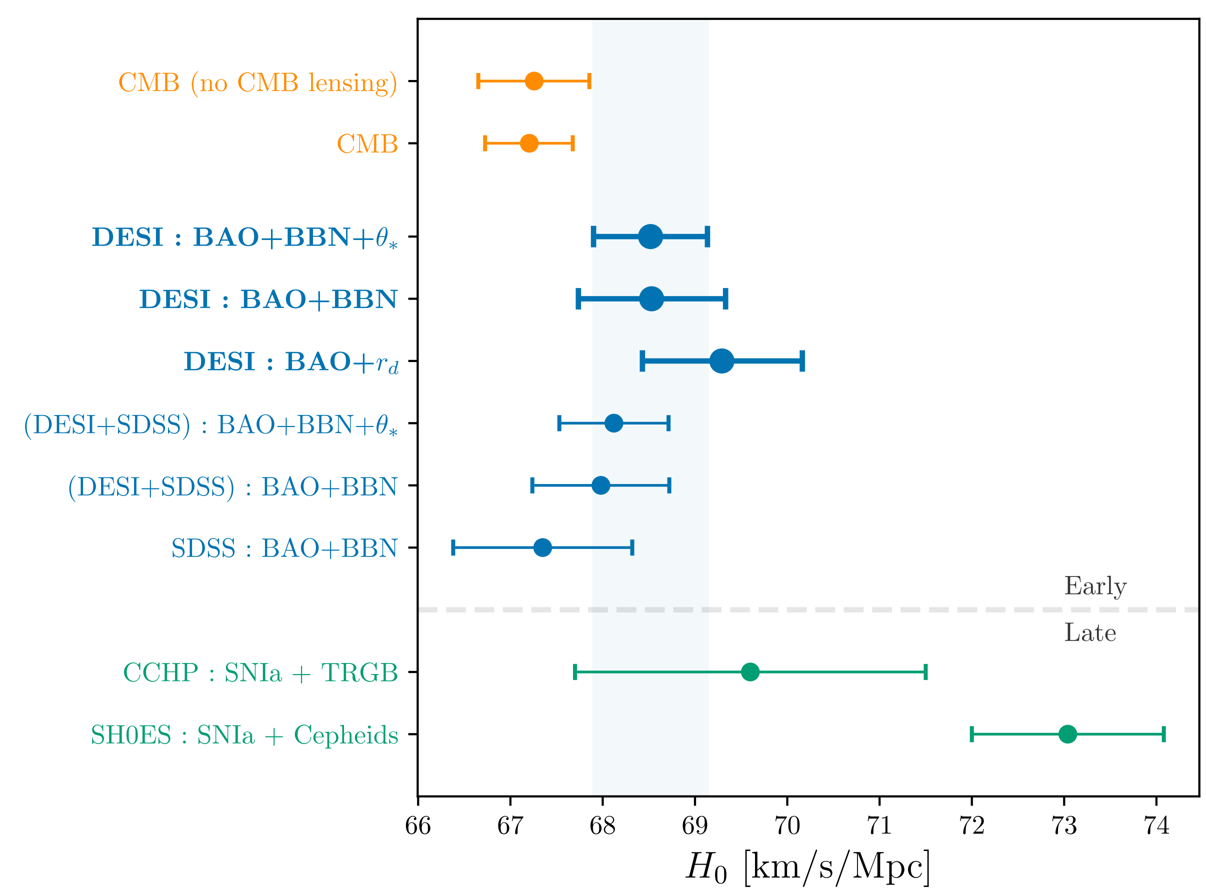
DESI 2024 VI :
cosmological constraints from BAO
arXiv:2404.03002

See Schöneberg et al. JCAP 2022
for the method used





model/dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_K$	w or w_0	w_a
Flat ΛCDM					
DESI	0.295 ± 0.015	—	—	—	—
DESI+BBN	0.295 ± 0.015	68.53 ± 0.80	—	—	—
DESI+BBN+θ_*	0.2948 ± 0.0074	68.52 ± 0.62	—	—	—
DESI+CMB	0.3069 ± 0.0050	67.97 ± 0.38	—	—	–
ΛCDM+Ω_K					
DESI	0.284 ± 0.020	—	65^{+68}_{-78}	—	—
DESI+BBN+θ_*	0.296 ± 0.014	68.52 ± 0.69	$0.3^{+4.8}_{-5.4}$	—	—
DESI+CMB	0.3049 ± 0.0051	68.51 ± 0.52	2.4 ± 1.6	—	—



$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz \; . \qquad E(z) \approx \sqrt{\Omega_m(1+z)^3 + \omega_r/h^2(1+z)^4},$$

$$\omega_r \approx 2.47 \cdot 10^{-5} \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\left(\frac{T_{\rm cmb}}{2.7255\,{\rm K}}\right)^4$$

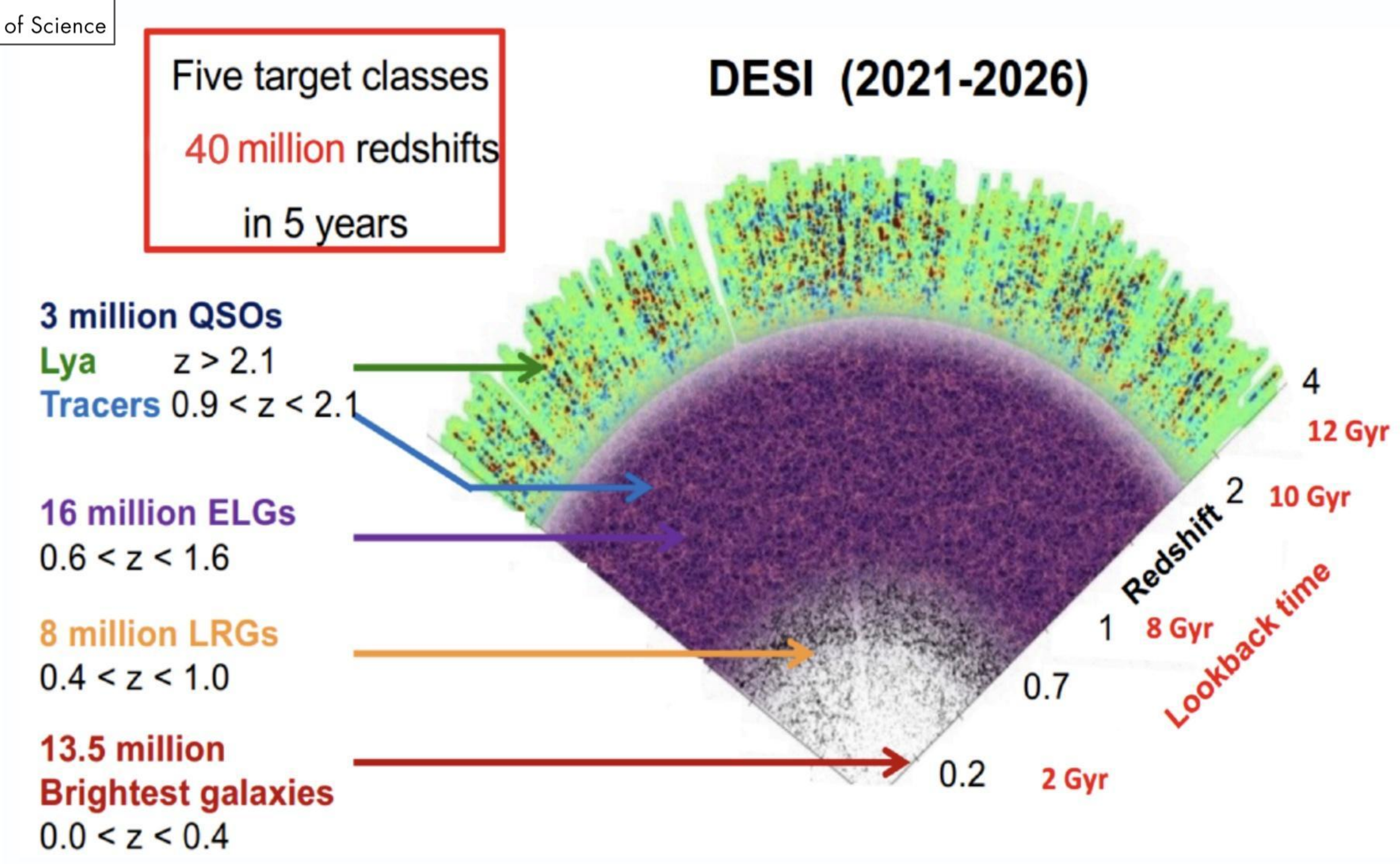
Schöneberg et al. JCAP 2022

Major questions in cosmology

- Why the dark energy and the dark matter densities are of the same order (coincidence problem)? Is this coincidence suggesting an interaction between the DE and the DM?
- Are dark energy and inflation connected (as for example in Quintessential Inflation models)? Can we have dark energy with AdS vacua (presence of a negative)?
- How well have we tested the Cosmological Principle? Is the Universe at cosmic scales homogeneous and isotropic?
- Can local inhomogeneity or anisotropy replace the need for dark energy?
- What is the level of non-Gaussianity?
- Do we need quantum gravity, or a unified theory for quantum field theory and GR to complete the standard cosmological model?
  How does pre-inflation physics impact our observations today? How can we resolve the big bang singularity?
- Can theoretical frameworks, like effective (quantum) field theory have further implications for the dark sector, especially DE?
- How much can we learn from cosmological dark ages and how does its physics impact our models of cosmology?
- How crucial is physics beyond the SM of particle physics for precision cosmology?
- How can we explain the matter-antimatter asymmetry in the observed Universe? There has been observational evidence for a matter–
  antimatter asymmetry in the early Universe, which leads to the remnant matter density we observe today. The bounds on the presence
  of antimatter in the present-day Universe include the possibility of a large lepton asymmetry in the cosmic neutrino background.
- What are the mutual implications for cosmology and Quantum Gravity of hypotheses like the swampland conjectures?

Extracted from E. Abdalla et al., Journal of High Energy Astrophysics (2022)

Tracers of the matter distribution



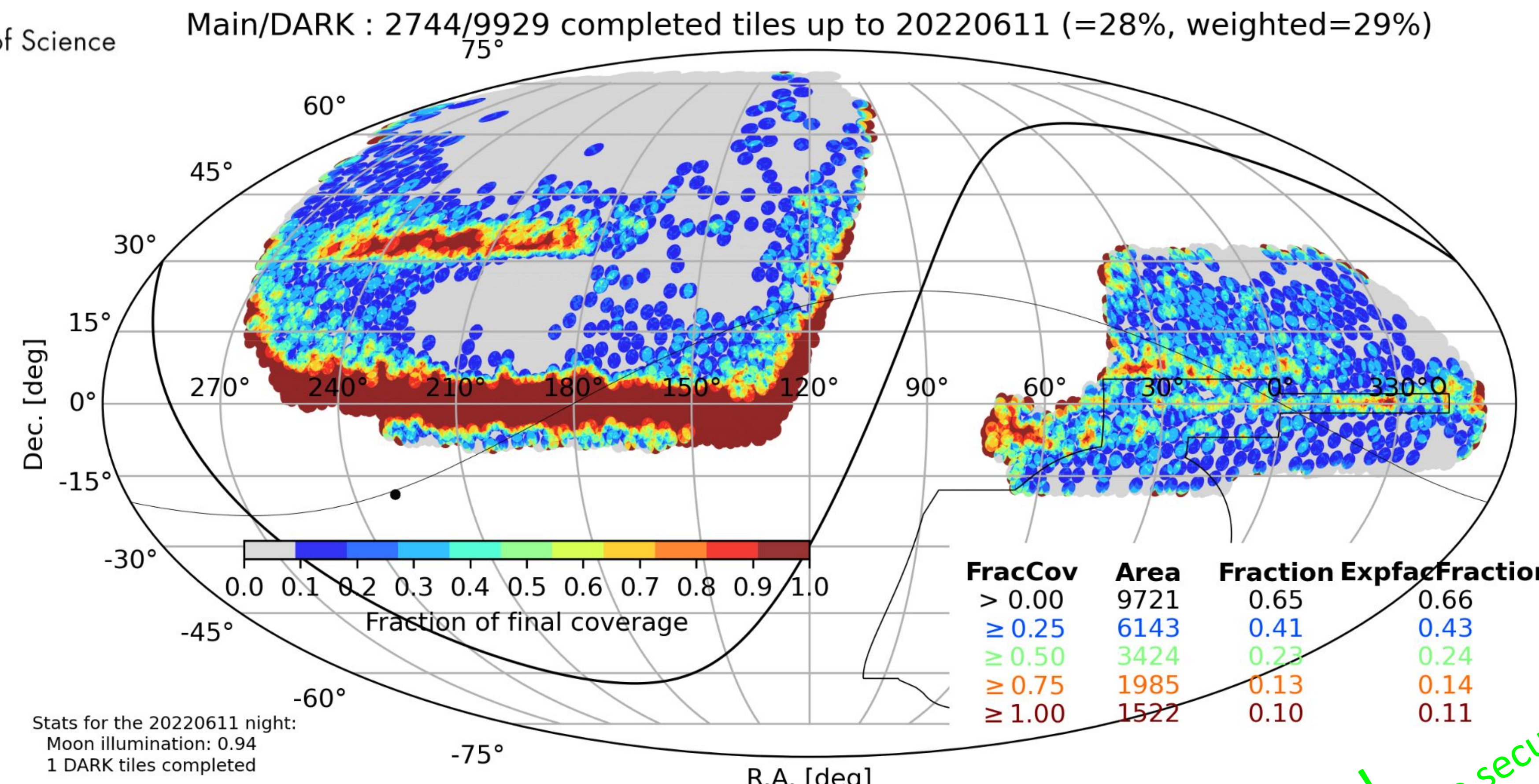
DESI - from Moriond 2024 presentation , E. Burtin

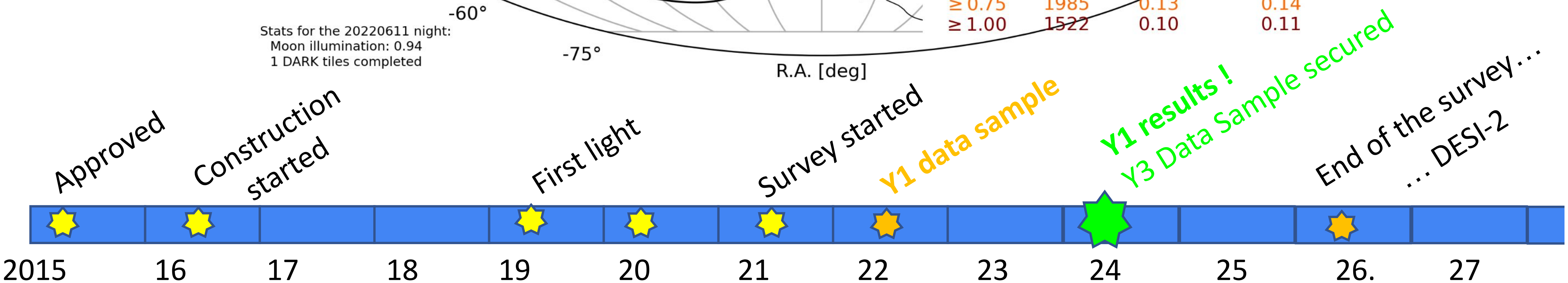
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 Data footprint

Full coverage
14,200 deg^2





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