Post-reionization HI 21cm signal: A probe of negative cosmological constant

By

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with

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Based on ArXiv: 2309.01623

OUTLINE

- Cosmological paradigm and H_0 tension
- Negative cosmological constant
- Observational outlook
- 21cm signal from post-reionization epoch
- Constraints
- Summary

COSMOLOGICAL PARADIGM

Three unknown pillars:

- Inflation: an early stage of accelerated expansion which produces the initial, tiny, density perturbations, needed for structure formation.
- Dark Matter: a clustering matter component to facilitate structure formation.
- Dark Energy: an energy component to explain late time cosmic acceleration.

Cosmologist's wishlist !!

COSMOLOGICAL PARADIGM

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- Dark Energy: an energy component to explain late time cosmic acceleration.

Specific solutions for ΛCDM:

- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- Dark Matter is a pressureless fluid made of cold, i.e., with low momentum, and collisionless particles;
- Dark Energy is a cosmological constant term.

ΛCDM

- Space is homogenous and isotropic:

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

- Einstein's field equation:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \mathbf{\Lambda g_{\mu\nu}} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(a) = \frac{8\pi G}{c^4}\left(\sum_i \rho_i + \mathbf{\Lambda}\right) \qquad \text{(00 - Friedmann Eq)}$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\sum_i \rho_i + 3p_i\right) + \frac{\mathbf{\Lambda}}{\mathbf{3}} \qquad \text{(ij - Constraints of motion)}$$

- Energy conservation: $\nabla_\mu T^\mu_0 = 0$ gives

$$a^{-3}\frac{\partial(\rho a^3)}{\partial t} = -3\left(\frac{\dot{a}}{a}\right)p \quad ; \quad \rho_i(a) \propto a^{-3(1+w_i)}$$

- Hubble expansion rate:

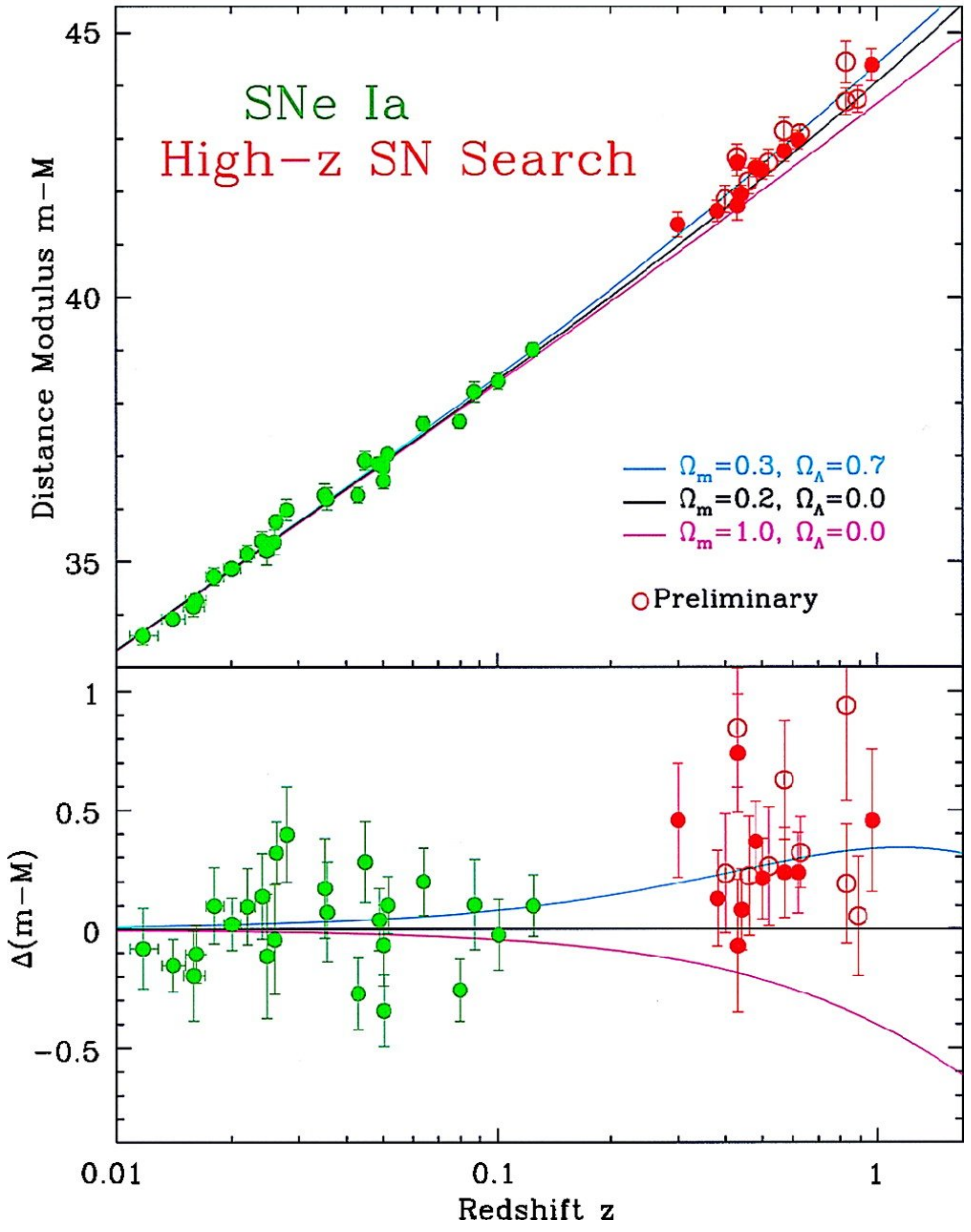
$$H^2(z) = H_0^2\left[\Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 + \Omega_{de0}(1+z)^{3(1+w_{de})}\right]$$

$$q_0 = \frac{1}{2}\left[\Omega_{m0} + (1+3w)\Omega_{\Lambda 0}\right], \quad w_i = p_i/\rho_i$$

- In 90's $H_0 = 60 - 80\text{km/s/MPc}$, $\Omega_{m0} = 1, \Omega_{\Lambda 0} = 0, q_0 > 0 \ (\Omega_{m0}/2)$

Distance modulus: $\mu = m - M = H_0 \left(\frac{d_L(z)}{10Mpc} \right) + 25$

Luminosity distance: $d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{E(z)}, \quad E(z) = \frac{H(z)}{H_0}$

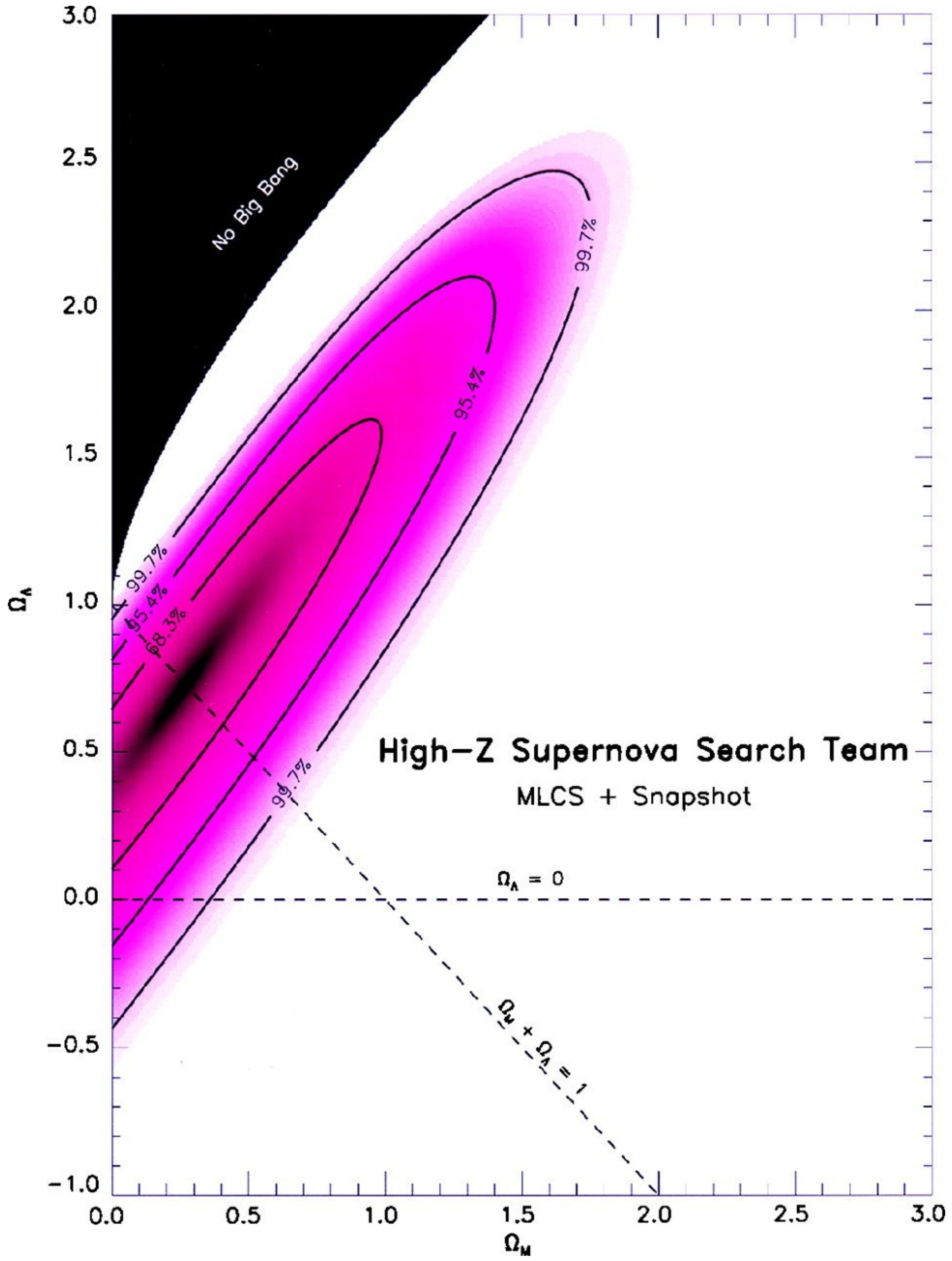


(Credit: Robert P Kirshner 1999)

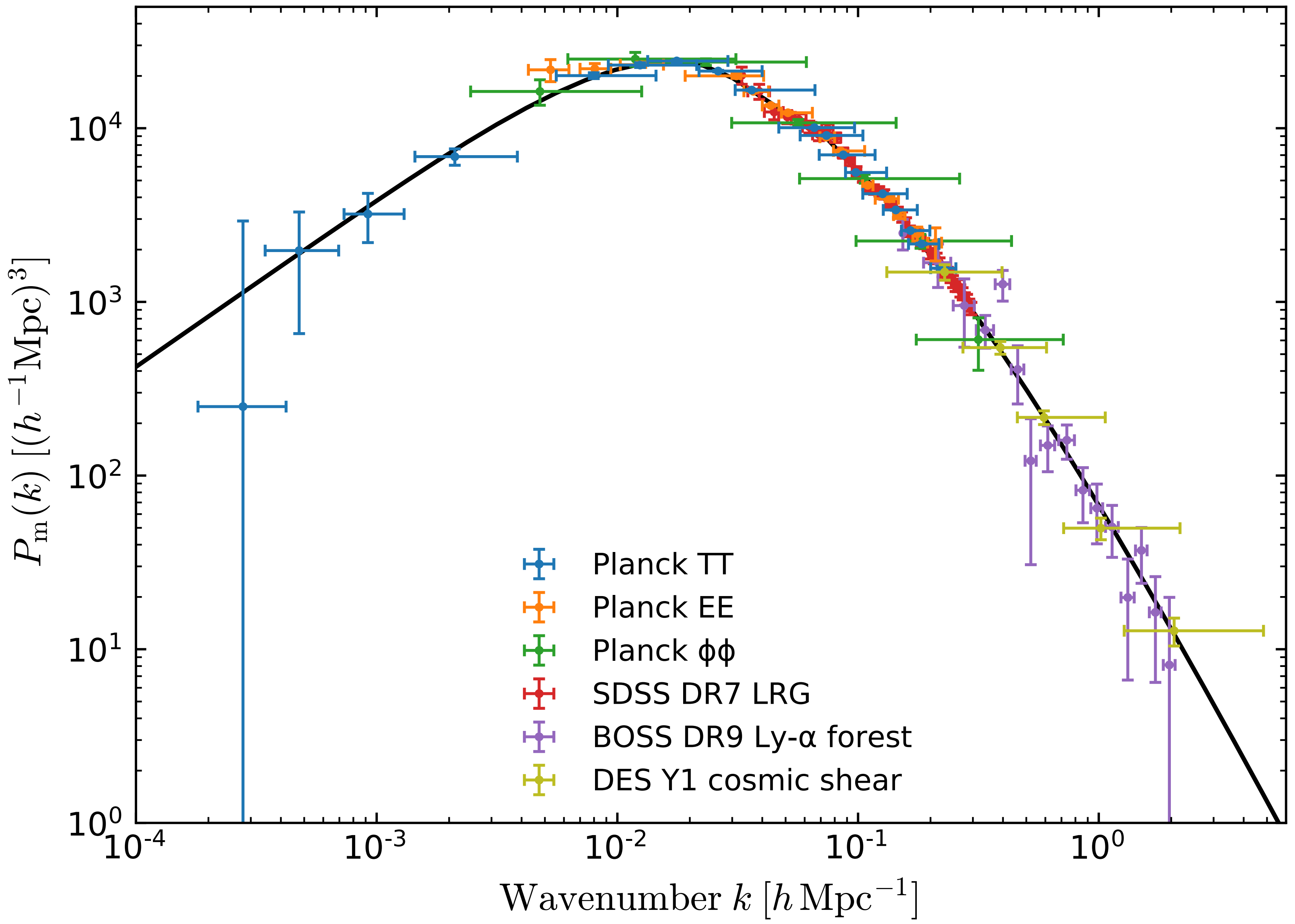
$\Omega_{m0} = 0.3, \ \Omega_{\Lambda 0} = 0.7$

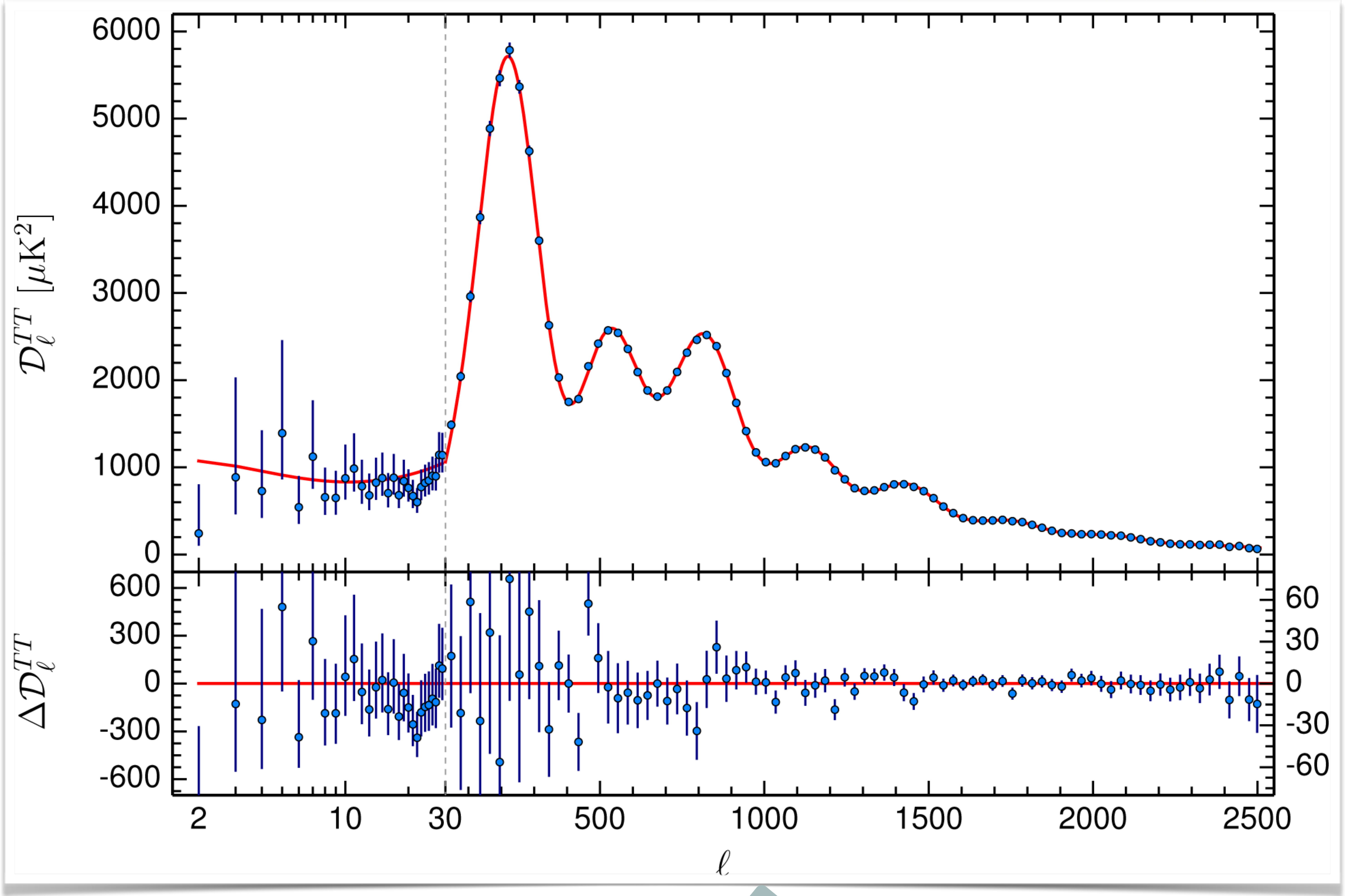
$q_0 < 0$ accelerating

Assuming $w = -1$

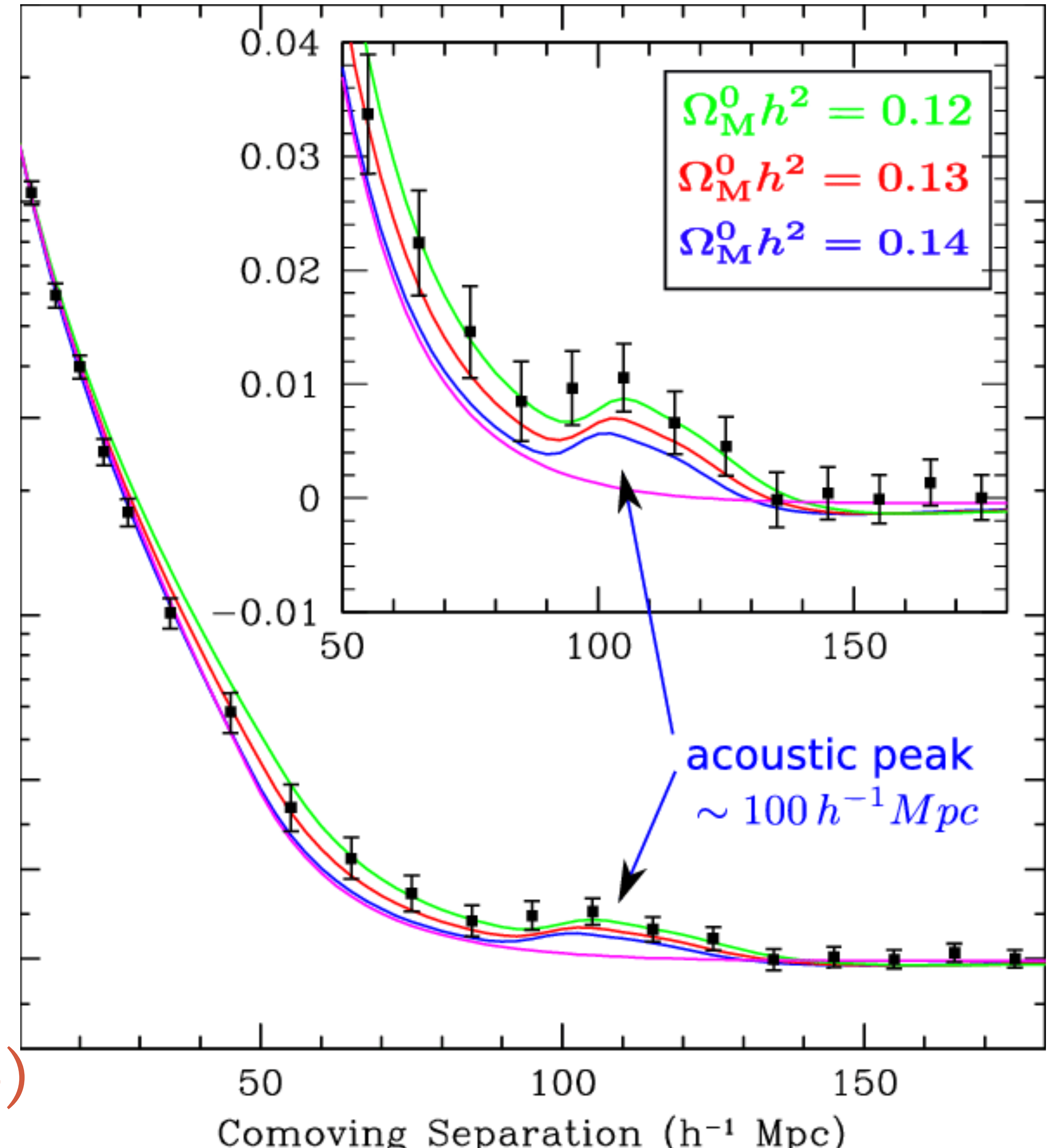


LSS (credit: Planck)





CMB TT (credit: Planck team)



SDSS LRG (credit: Eisenstein et.al 2005)

Everything seems so good so far !!!

WARNING !!!

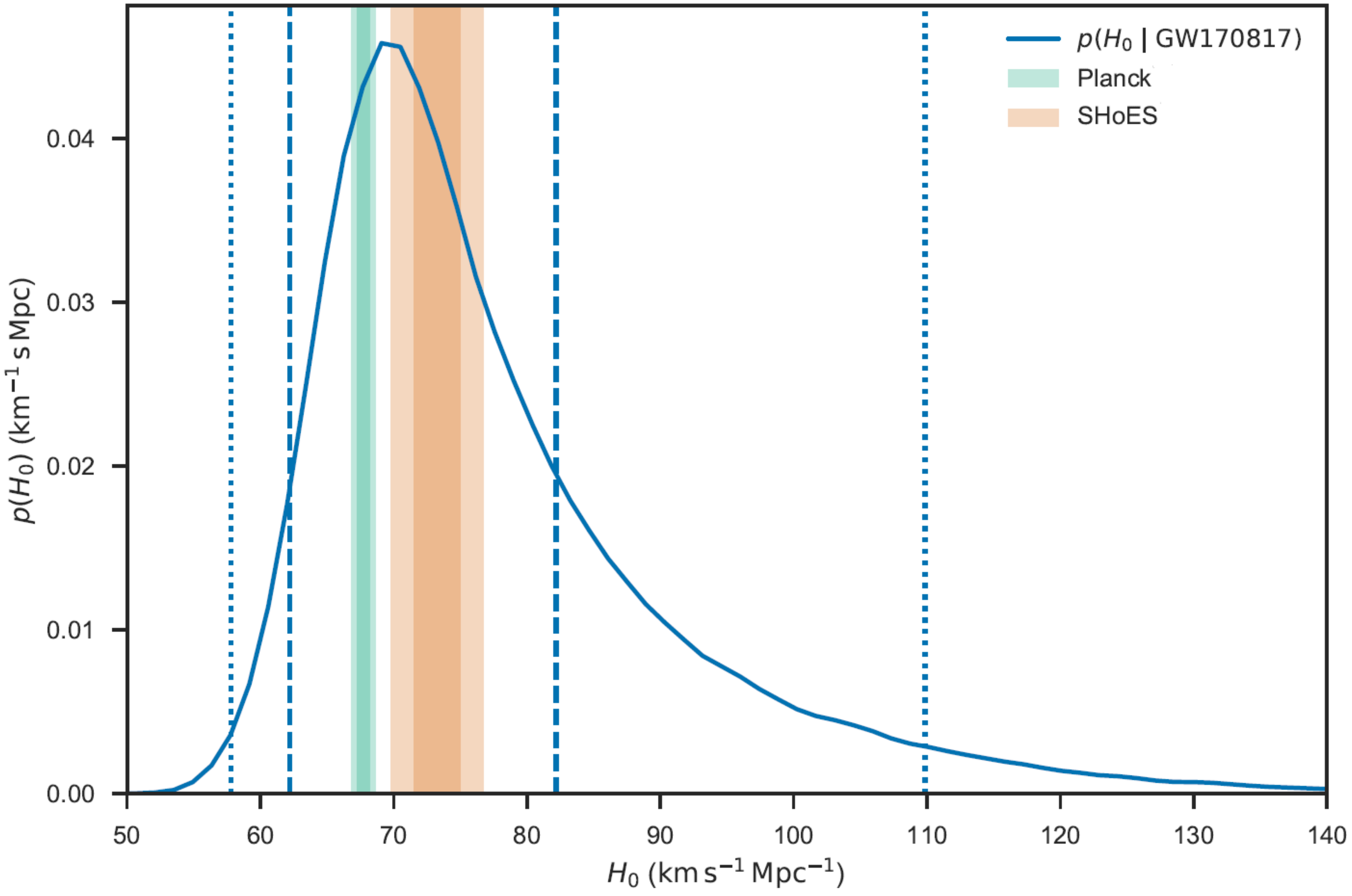
With the improvement of the number and the accuracy of the observations, deviations from ΛCDM may be expected.

And, actually, discrepancies among key cosmological parameters of the models have emerged with different statistical significance.

While some proportion of these discrepancies may have a systematic origin, their persistence across probes should require multiple and unrelated errors, strongly hinting at cracks in the standard cosmological scenario and the necessity of new physics.

These tensions can indicate a failure of the concordance ΛCDM model.

H0 TENSION ($\geq 5\sigma$)



(credit: LIGO)

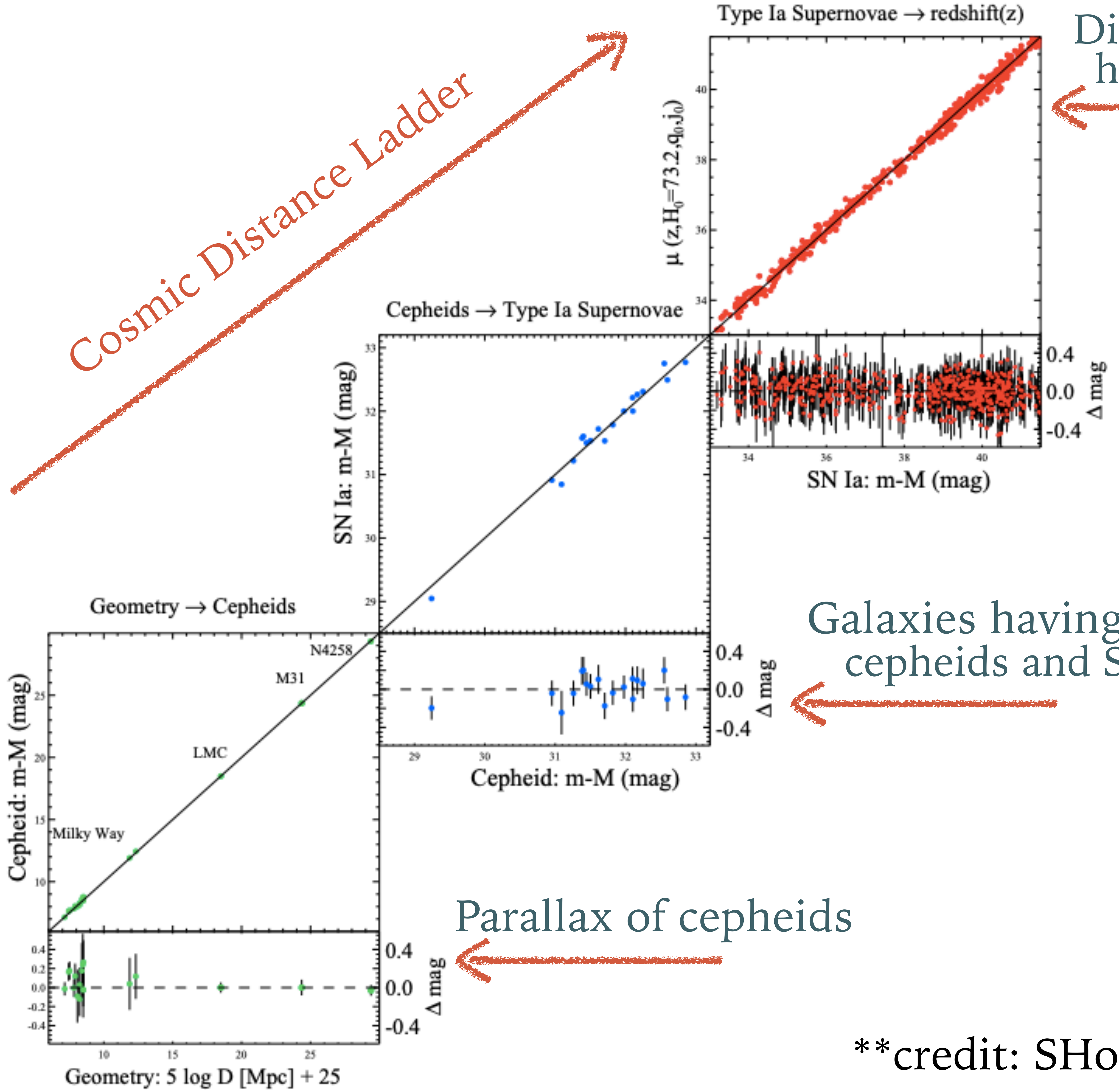
- Planck measurement of H_0 is based on early universe physics.

  $H_0 = 67.5 \pm 0.5$ km/s/Mpc

- SHoES measurement of H_0 is based on Astrophysics of stars.

  $H_0 = 73.7 \pm 1.04$ km/s/Mpc

SHOES MEASUREMENT OF H_0



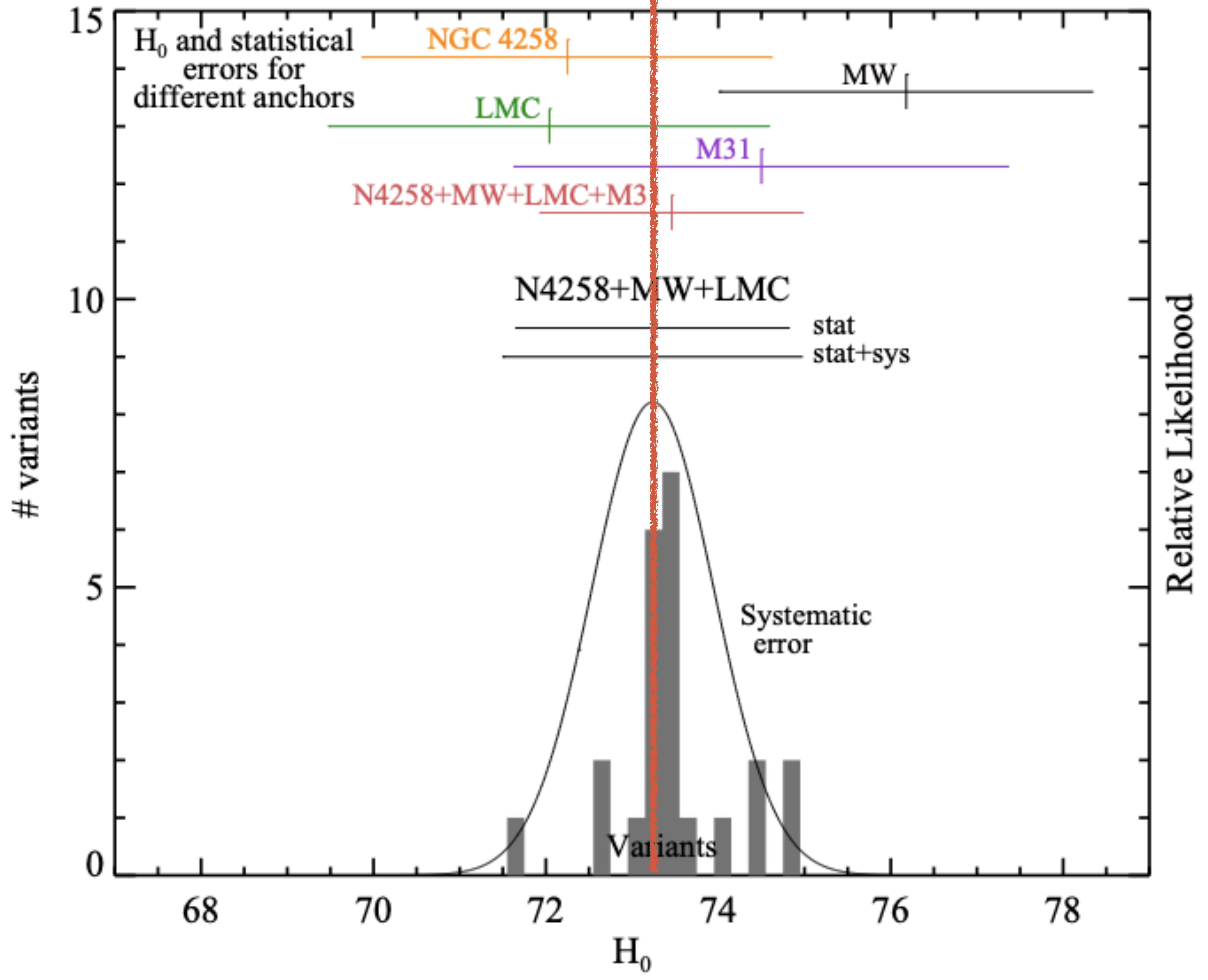
Cosmic Distance Ladder

Distant galaxies having SNIa

Galaxies having both cepheids and SNIa

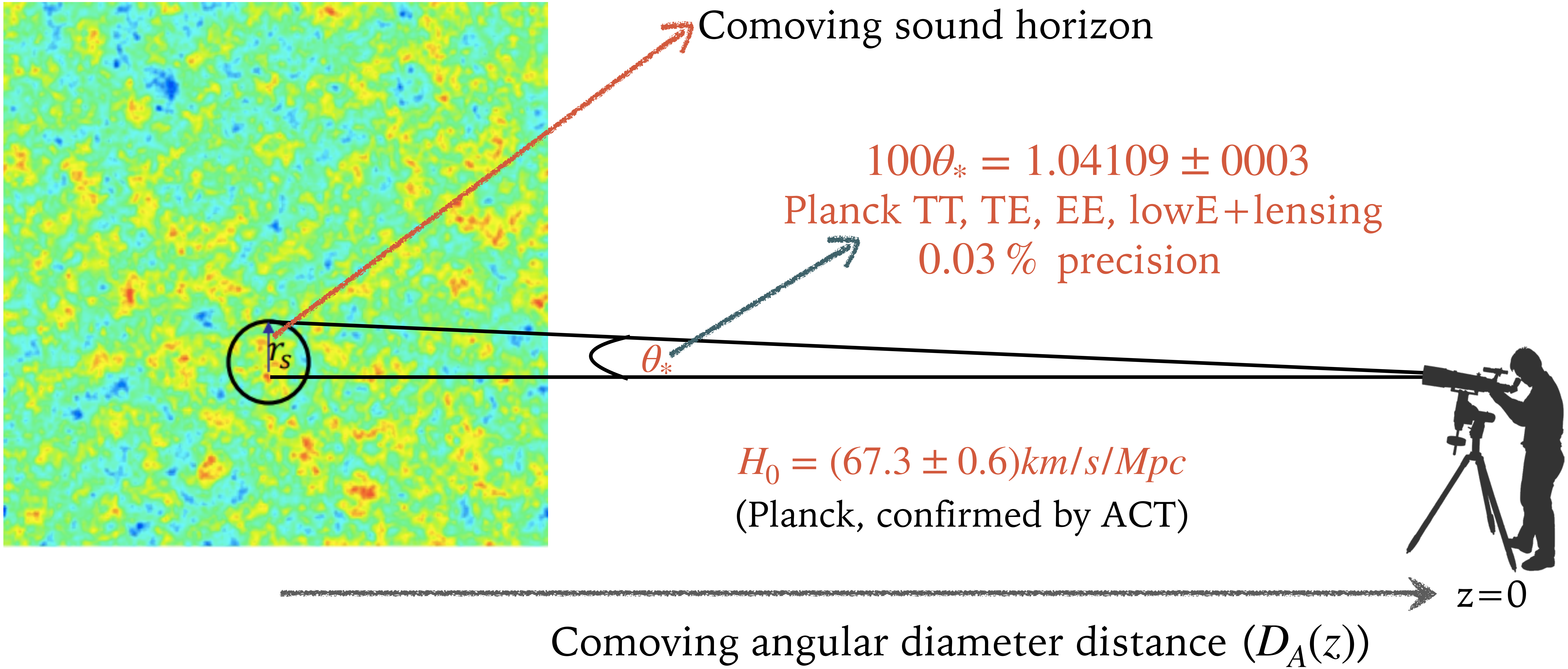
Parallax of cepheids

$H_0 = 73.30 \pm 1.04$ km/s/Mpc



**credit: SHoE ArXiv.1604.01424

HOW PLANCK MEASURES H_0 ??



HOW PLANCK MEASURES H_0 ?

- Step 1: Calculate Sound horizon

$$r_s(z_r) = \int_0^{a_r} \frac{c_s da}{a^2 H(a)} \; ; \; c_s(a) = c/\sqrt{3(1 + 3\rho_b/4\rho_\gamma)}$$

- Step 2: Angular size of the sound horizon from the peak spacing in CMB

$$\theta = \frac{\pi}{\Delta \ell}$$

- Step 3: Calculate the angular diameter distance for sound horizon

$$D_A = \frac{r_s}{\theta} = \frac{1}{1 + z_r} \int_0^{z_r} \frac{dz}{H(z)}$$

- Extrapolate $H(z)$ to $z = 0$ and get H_0 (Here Planck uses ΛCDM)

Crowded No More: The Accuracy of the Hubble Constant Tested with High Resolution Observations of Cepheids by *JWST*

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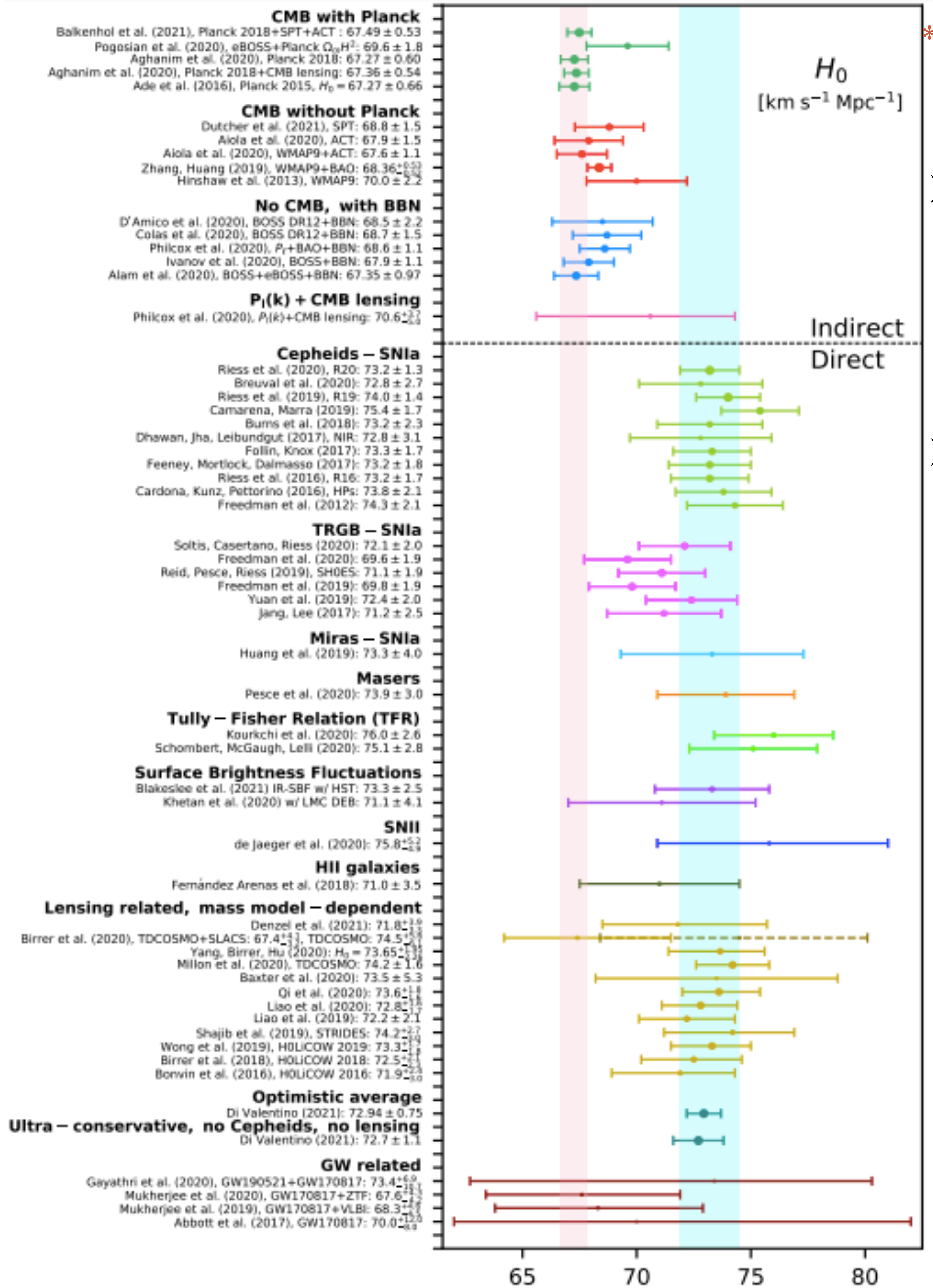
Agrees with low redshift SHoES measurements

ABSTRACT

High-resolution *JWST* observations can test confusion-limited *HST* observations for a photometric bias that could affect extragalactic Cepheids and the determination of the Hubble constant. We present *JWST* NIRCAM observations in two epochs and three filters of >320 Cepheids in NGC 4258 (which has a 1.5% maser-based geometric distance) and in NGC 5584 (host of SN Ia 2007af), near the median distance of the SH0ES *HST* SN Ia host sample and with the best leverage among them to detect such a bias. *JWST* provides far superior source separation from line-of-sight companions than *HST* in the NIR to largely negate confusion or crowding noise at these wavelengths, where extinction is minimal. The result is a remarkable >2.5× reduction in the dispersion of the Cepheid *P*–*L* relations, from 0.45 to 0.17 mag, improving individual Cepheid precision from 20% to 7%. Two-epoch photometry confirmed identifications, tested *JWST* photometric stability, and constrained Cepheid phases. The *P*–*L* relation intercepts are in very good agreement, with differences *(JWST*–*HST)* of 0.00±0.03 and 0.02±0.03 mag for NGC 4258 and NGC 5584, respectively. The difference in the determination of H_0 between *HST* and *JWST* from these intercepts is 0.02±0.04 mag, insensitive to *JWST* zeropoints or count-rate non-linearity thanks to error cancellation between rungs. We explore a broad range of

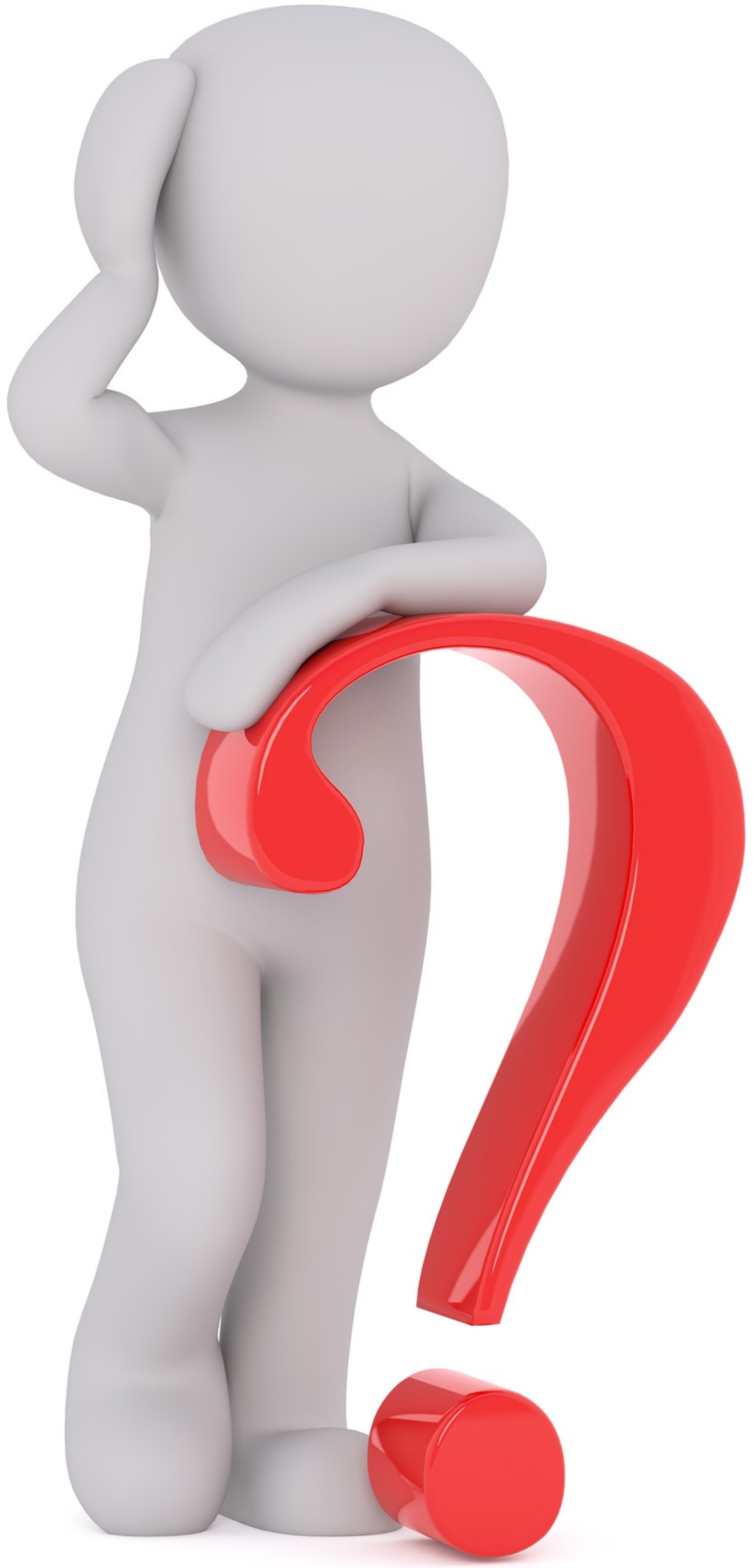


**credit: Di Valentino et al., (2021)

➤ Cyan vertical band corresponds to SHoES Team and the pink vertical band corresponds to Planck18 team within a ΛCDM scenario.

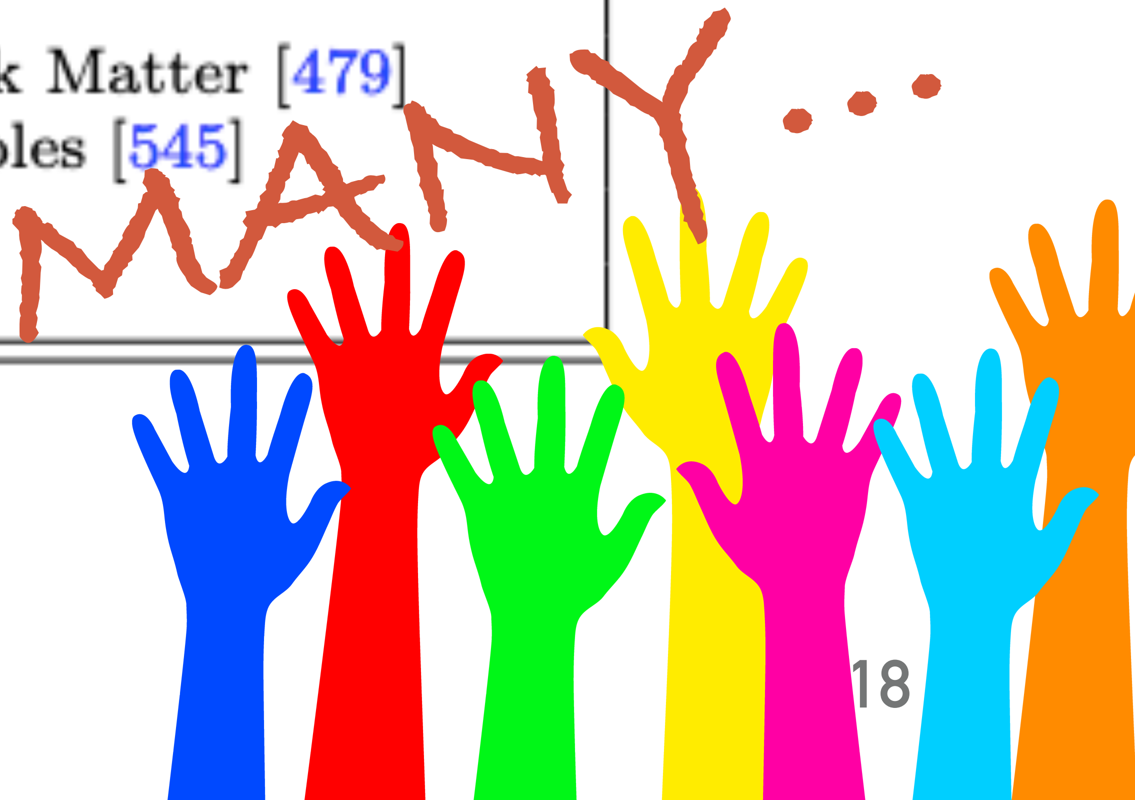
➤ The high precision and consistency of the data at both ends present strong challenges to the possible solution space and demands a hypothesis with enough rigor to explain multiple observations whether these invoke new physics, unexpected large-scale structures or multiple, unrelated errors.

POSSIBLE SOLUTION



POSSIBLE SOLUTION (FORMALLY)

tension $\lesssim 1\sigma$ *"Excellent models"*	tension $\lesssim 2\sigma$ *"Good models"*	tension $\lesssim 3\sigma$ *"Promising models"*
Early Dark Energy [228, 235, 240, 250]	Early Dark Energy [212, 229, 236, 263]	DE in extended parameter spaces [289]
Exponential Acoustic Dark Energy [259]	Rock 'n' Roll [242]	Dynamical Dark Energy [281, 309]
Phantom Crossing [315]	New Early Dark Energy [247]	Holographic Dark Energy [350]
Late Dark Energy Transition [317]	Acoustic Dark Energy [257]	Swampland Conjectures [370]
Metastable Dark Energy [314]	Dynamical Dark Energy [309]	MEDE [399]
PEDE [394]	Running vacuum model [332]	Coupled DM - Dark radiation [534]
Vacuum Metamorphosis [402]	Bulk viscous models [340, 341]	Decaying Ultralight Scalar [538]
Elaborated Vacuum Metamorphosis [401, 402]	Holographic Dark Energy [350]	BD-ΛCDM [852]
Sterile Neutrinos [433]	Phantom Braneworld DE [378]	Metastable Dark Energy [314]
Decaying Dark Matter [481]	PEDE [391, 392]	Self-Interacting Neutrinos [700]
Neutrino-Majoron Interactions [509]	Elaborated Vacuum Metamorphosis [401]	Dark Neutrino Interactions [716]
IDE [637, 639, 657, 661]	IDE [659, 670]	IDE [634–636, 653, 656, 663, 669]
DM - Photon Coupling [685]	Interacting Dark Radiation [517]	Scalar-tensor gravity [855, 856]
$f(\mathcal{T})$ gravity theory [812]	Decaying Dark Matter [471, 474]	Galileon gravity [877, 881]
BD-ΛCDM [851]	DM - Photon Coupling [686]	Nonlocal gravity [886]
Über-Gravity [59]	Self-interacting sterile neutrinos [711]	Modified recombination [986]
Galileon Gravity [875]	$f(\mathcal{T})$ gravity theory [817]	Effective Electron Rest Mass [989]
Unimodular Gravity [890]	Über-Gravity [871]	Super ΛCDM [1007]
Time Varying Electron Mass [990]	VCDM [893]	Axi-Higgs [991]
ΛCDM [995]	Primordial magnetic fields [992]	Self-Interacting Dark Matter [479]
Ginzburg-Landau theory [996]	Early modified gravity [859]	Primordial Black Holes [545]
Lorentzian Quintessential Inflation [979]	Bianchi type I spacetime [999]	
Holographic Dark Energy [351]	$f(\mathcal{T})$ [818]	



**credit: Di Valentino et al., (2021)

DARK ENERGY MODEL WITH NON ZERO VACUA

- Quintessence field*(ϕ) + Cosmological constant (Λ) → Total Dark Energy
- i.e $\rho_{DE} = \rho_\phi + \Lambda$ with the constraint $\rho_{DE} > 0$ (for late time cosmic acceleration)
- EoS: $w_\phi(a) = w_0 + w_a\,(1 - a)$ CPL model **Chavellier, Polarski & Linder
- This can be obtained by expanding $w(a)$ in the Taylor series around $a = 1$

$$w(a) = w\big|_{a=1} + (a-1)\frac{dw}{da}\bigg|_{a=1} + \frac{1}{2}(a-1)^2\frac{d^2w}{da^2}\bigg|_{a=1} + \mathcal{O}\left[(a-1)^3\right]$$

where w_0 is the present value i.e $w(a_0) = w_0 + w_a(1 - a_0) = w_0$ and the value of its slope $dw(a)/da = -w_a$.

- Density evolve: $\rho_\phi(a) \propto a^{-3(1+w_0+w_a)} \exp^{3w_a a}$

*According to ancient Greek science it denotes a fifth cosmic element after earth, fire, water & air. In Latin "fifth element"

QUINTESSENCE

- Quintessence is described by a canonical scalar field ϕ minimally coupled to gravity. A slowly varying field along a potential $V(\phi)$ can lead to the acceleration of the Universe.

$$S = \int d^4\vec{x}\sqrt{-g}\left[\frac{1}{2}M_{p_l}^2 R - \frac{1}{2}g^{\mu\upsilon}\partial_\mu\phi\partial_\upsilon\phi - V(\phi)\right] + S_m$$

- The dark energy EoS is $w_\phi \equiv \frac{P_\phi}{\rho_\phi} = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$

  Slow roll condition: $\dot{\phi}^2 < V(\phi)$ & $|\ddot{\phi}| < |V_\phi|$ where $V_\phi = dV(\phi)/d\phi$

- define the following dimensionless variables $x = \left(\frac{d\phi}{dN}\right)/\sqrt{6}M_{pl}, y = \frac{\sqrt{V}}{\sqrt{6}HM_{pl}}$ $, \lambda = -M_{pl}\frac{V_\phi}{V}, \Gamma = V\frac{V_{\phi\phi}}{V_\phi}$, we have: $\Omega_\phi = x^2 + y^2, w_\phi = \frac{2x^2}{x^2+y^2} - 1$.

- In spatially flat universe, evolution of $H(a)$

$$\frac{H(a)}{H_0} = \sqrt{\Omega_{m_0} a^{-3} + \Omega_{\phi 0} \exp\left[-3\int_1^a da' \frac{1 + w_\phi(a')}{a'}\right] + \Omega_{\Lambda 0}}$$

with $\Omega_{m0} + \Omega_{\phi 0} + \Omega_\Lambda = 1$ (CPL-ΛCDM)

This is same as adding a non-zero cosmological constant for the scalar field potential

$$V(\phi) = F(\phi) + V_0$$

V_0 can be positive (dS) or negative (AdS)

OBSERVATIONAL OUTLOOK

- $\theta_s(z) = \dfrac{s(z_d)}{(1+z)D_A(z)}$ $\qquad \delta z_s = \dfrac{s(z_d)H(z)}{c}$
- Related effective distance: $D_V(z) = \left[(1+z)^2 D_A^2(z)\dfrac{cz}{H(z)}\right]^{1/3}$ (**Eisenstein et. al. 2005)
- Define a dimensionless quantity: $r_{BAO}(z) = \dfrac{r_s}{D_V(z)}$
- 2df galaxy survey: $r_{BAO}(z=0.2) = 0.1980 \pm 0.0058$ and $r_{BAO}(z=0.35) = 0.1094 \pm 0.0033$ (Percival et. al. 2007)
- BOSS (SDSS III) CMASS_LRG: $r_{BAO}(z=0.57) = 0.07315 \pm 0.002$ (Anderson et. al. 2012)

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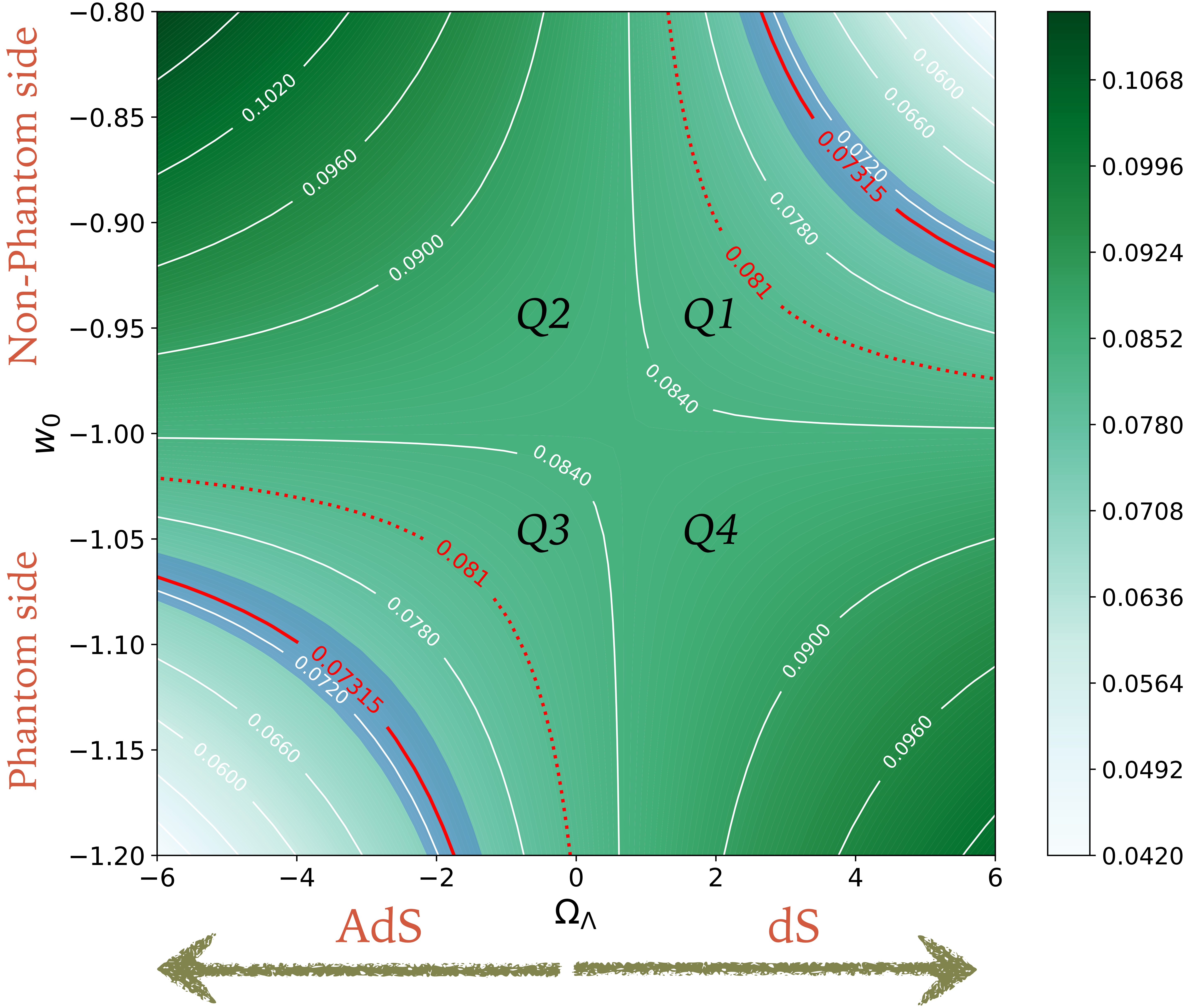
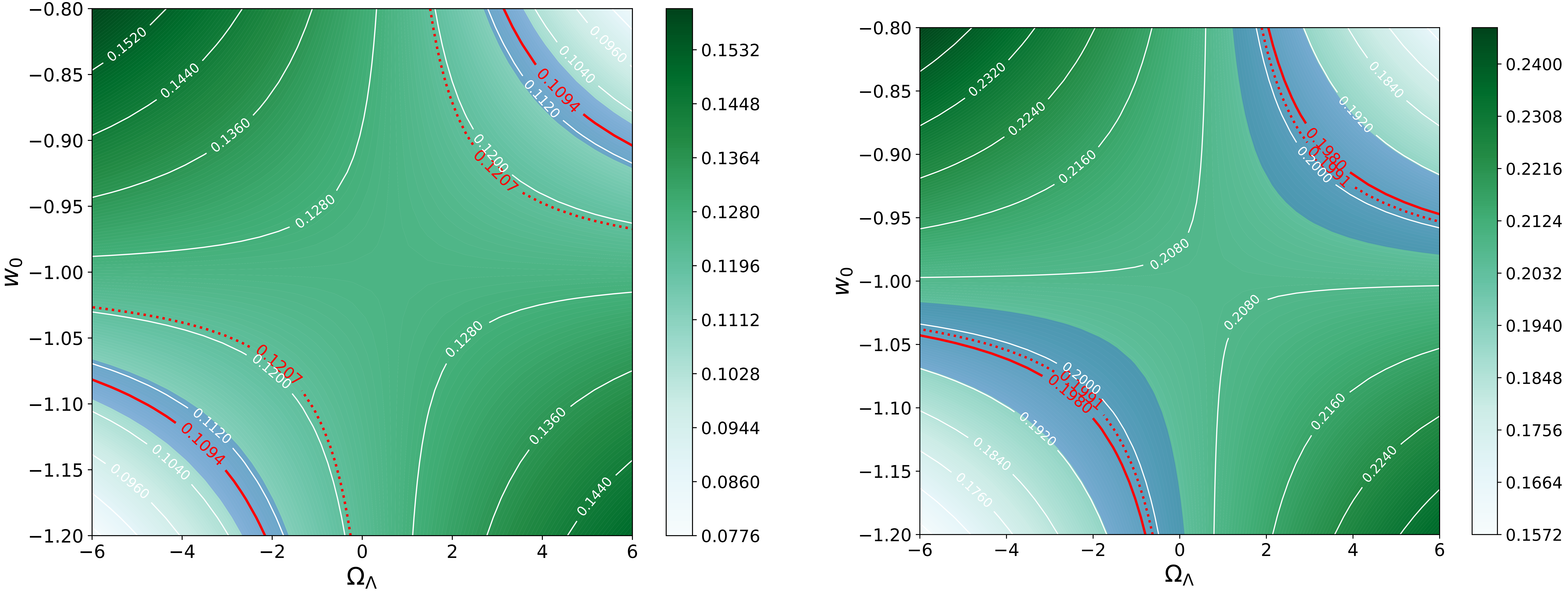


Task!!!

- Find out what is the possible combinations for (w_0, Ω_Λ) that give identical r_{BAO} in ΛCDM framework but with $H_0 = 72$ km/s/Mpc
- For simplicity we kept $w_a = 0$ and fix $\Omega_{m0} = 0.311$ measured by Planck.

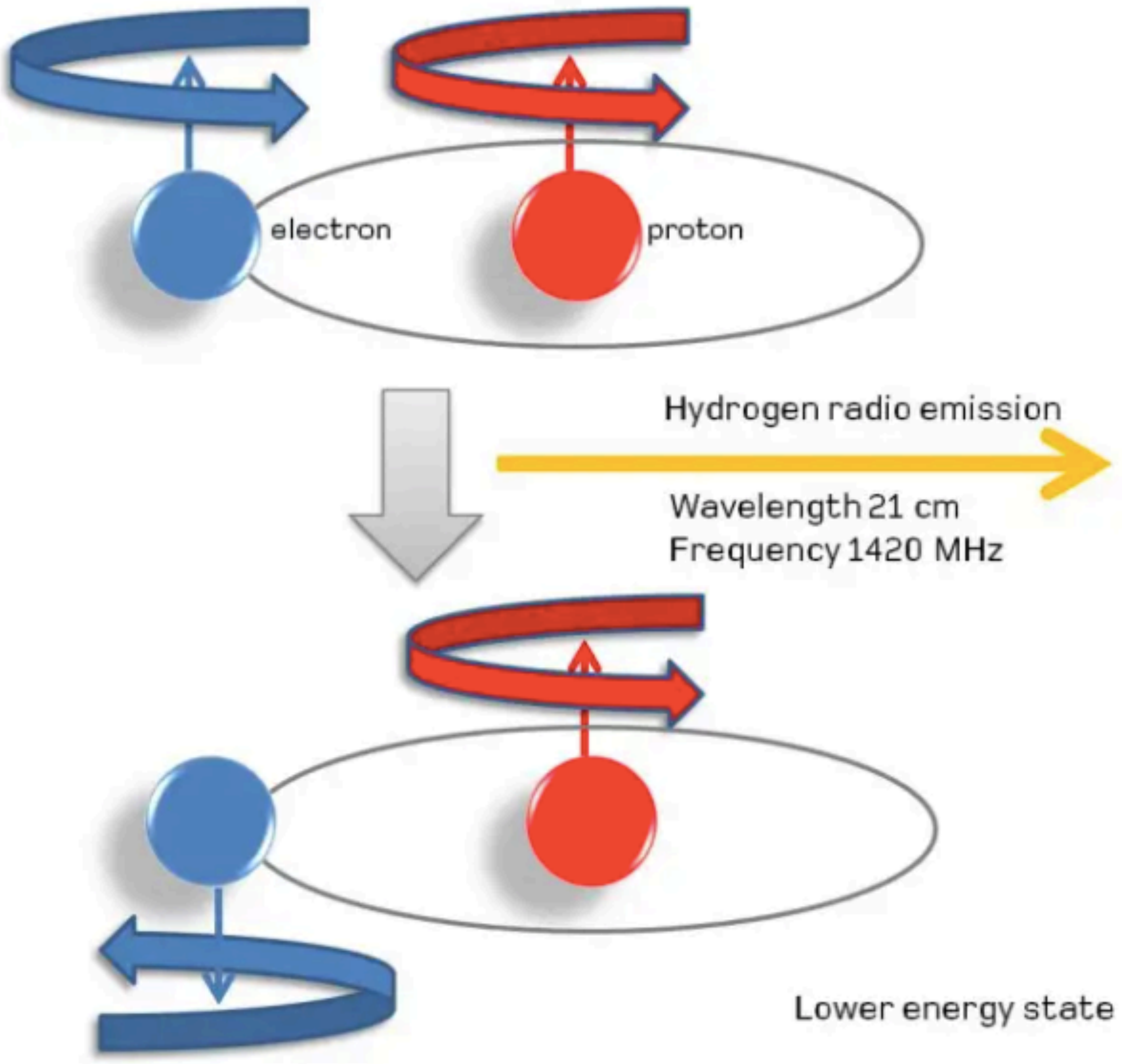
— observation data, ····· ΛCDM



$z = 0.35$ $z = 0.2$

Same but for different redshifts

21CM SIGNAL

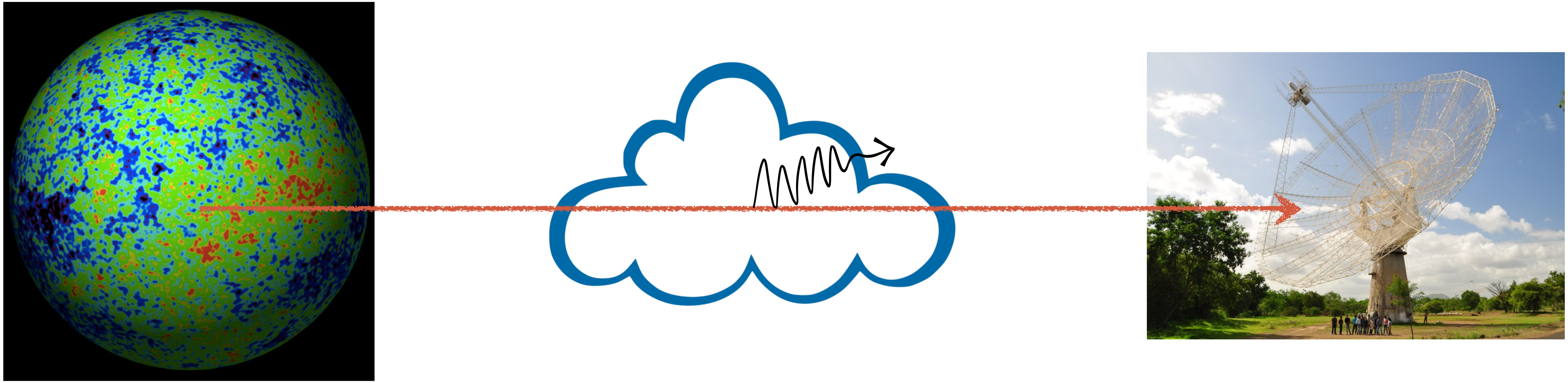


**credit: SKAO

- In H-atom electron and proton normally spin in the same direction.
- Occasionally, electron flips spin to other direction (happens only about once every 100million years for each atom)
- Emit radiation of 1420MHz ($\lambda = 21$cm)
- $\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp^{T_*/T_s}; T_* = h\nu_e/k_B = 0.68K$
- predicted: Henrik van de Hulst 1944 detected in 1951.

21CM SIGNAL

T_γ T_s $T_b = (T_s - T_\gamma)\tau / T_\gamma$

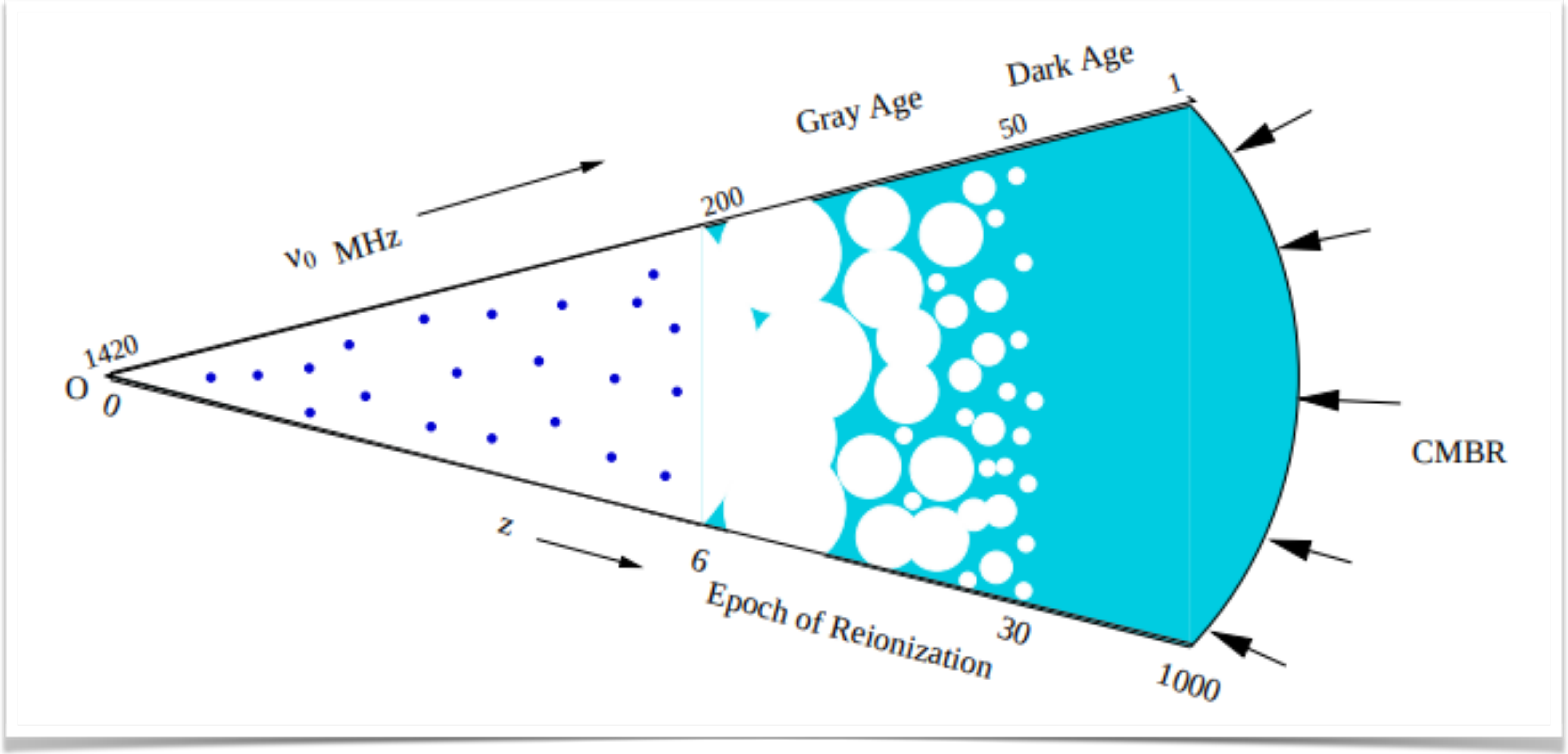


CMB acts as backlight

Neutral gas imprints signal
$z = 1,\ \nu_e = 1420$ MHz

Redshifted signal detected
$z = 0,\ \nu_e = 710$ MHz

21CM SIGNAL FROM POST-REIONIZATION EPOCH



- CMB photons free streaming from the LSS undergoes a dip in its brightness temperature on passing through a HI cloud depending on its optical depth and spin temperature.

- $$\delta T_b(\hat{n}, z) = \frac{(T_s - T_\gamma)\tau}{T_\gamma}$$
  $$= \left(1 - \frac{T_\gamma}{T_s}\right)\left(\frac{\rho_{HI}}{\bar{\rho}_H}\right)\left(1 - \frac{1}{aH}\frac{\partial V}{\partial r}\right)$$

**Fig. credit: S Bharadwaj & SK. Saiyad Ali, (2004)

21CM POWER SPECTRUM

- The 21cm power spectrum of this excess brightness temperature field is given by

$$P_{21}(k,z,\mu) = \mathscr{A}_T^2\,(1+f(z)\mu^2)^2\; P_m(k,z)$$

where $\mu = \frac{k_{\|}}{k} = \cos\theta$, $f = d\log D_+/d\log a$ is the growth rate and A_T is given by

$$\mathscr{A}_T(z) = 4.0mK\; b_T\bar{x}_{HI}(1+z)^2\left(\frac{\Omega_{b0}h^2}{0.02}\right)\left(\frac{0.7}{h}\right)\frac{H_0}{H(z)}$$

- The bias (with respect to the dark matter field) and the mean neutral fraction completely models the 21-cm signal in the post-reionization epoch.*

- $$P_{21}(k,z,\mu) = \frac{\mathscr{A}_T^2}{\alpha_{\|}\alpha_{\perp}^2}\left[b_T + \frac{f(z)\mu^2}{F^2+\mu^2(1-F^2)}\right]^2 P_m\left(\frac{k}{\alpha_{\perp}}\sqrt{1+\mu^2(F^{-2}-1)}, z\right)$$

(Alcock-Paczynski test: $\alpha_{\|} = H^f/H^r, \alpha_{\perp} = D_A^r/D_A^f, F = \alpha_{\|}/\alpha_{\perp}$)

ONGOING/UPCOMING EXPT.(S)

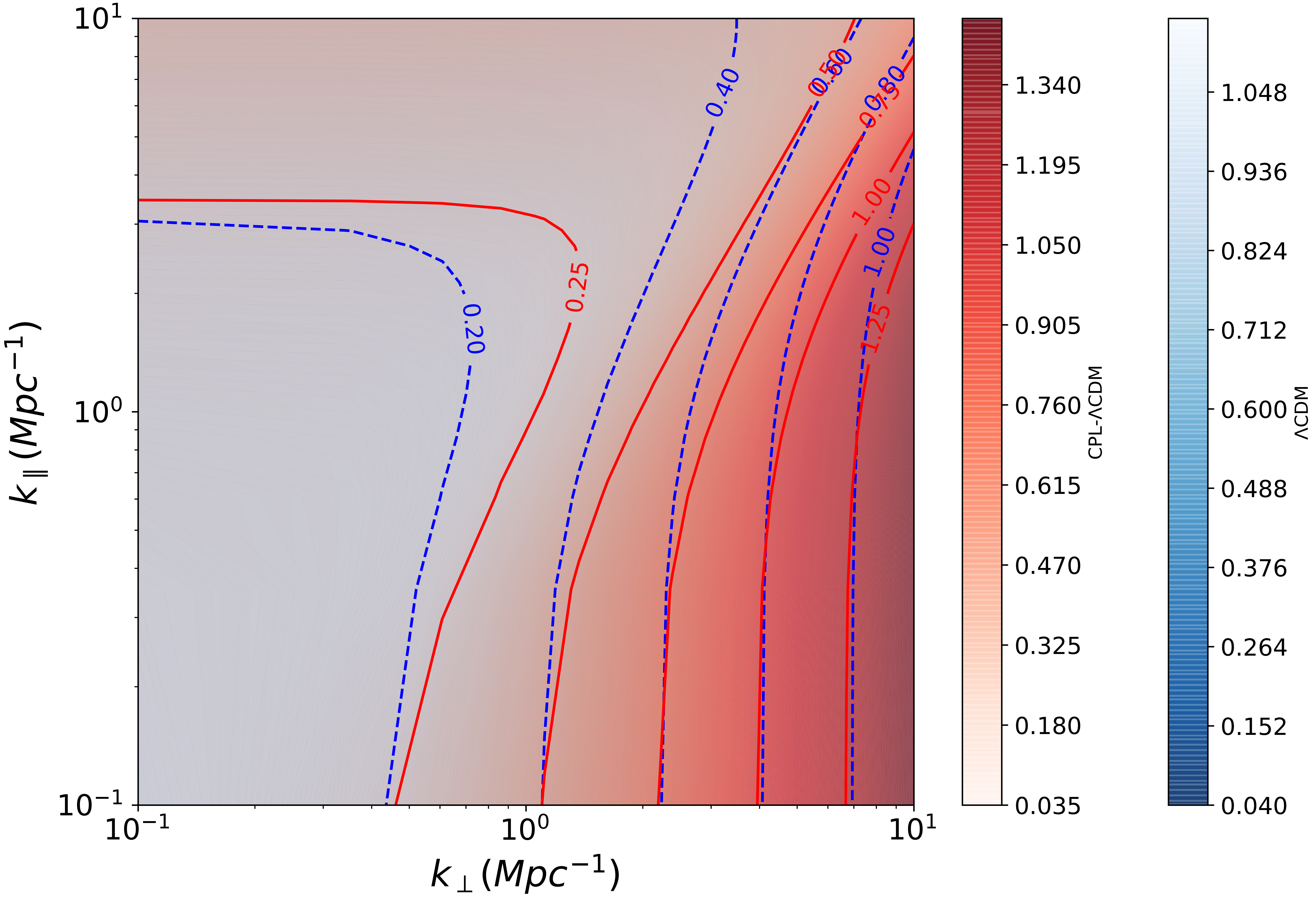
MWA (Australia)

CHIME (Canada)

uGMRT (India)

SKA (South Africa)

MeerKAT (Australia)



- 3D HI 21cm power spectrum at $z = 1$ in $(k_\perp, k_\parallel)$ space.
- The colorbar shows the value of the dimensionless quantity $\Delta^2_{21} = k^3 P_{21}(\mathbf{k})/(2\pi^2)$
- The asymmetry is indicative of redshift space distortions.
- Alcock-Paczynski effect enhanced the distortions

MULTIPOLES OF 21CM PS

- Redshift space 21cm power spectrum can be decomposed in the basis of Legendre polynomials$\mathscr{P}_\ell(\mu)$ as

$$P_{21}(k,\mu,z) = \sum_\ell P_\ell(z,k)\mathscr{P}_\ell(\mu)$$

- The first few Legendre polynomials are given by

$$\mathscr{P}_0(\mu) = 1, \;\; \mathscr{P}_2(\mu) = \frac{1}{2}\left(3\mu^2 - 1\right), \;\; \mathscr{P}_4(\mu) = \frac{1}{8}(35\mu^2 - 30\mu^2 + 3)$$

- Coefficients of the expansion of the 21cm power spectrum, can be found by inverting

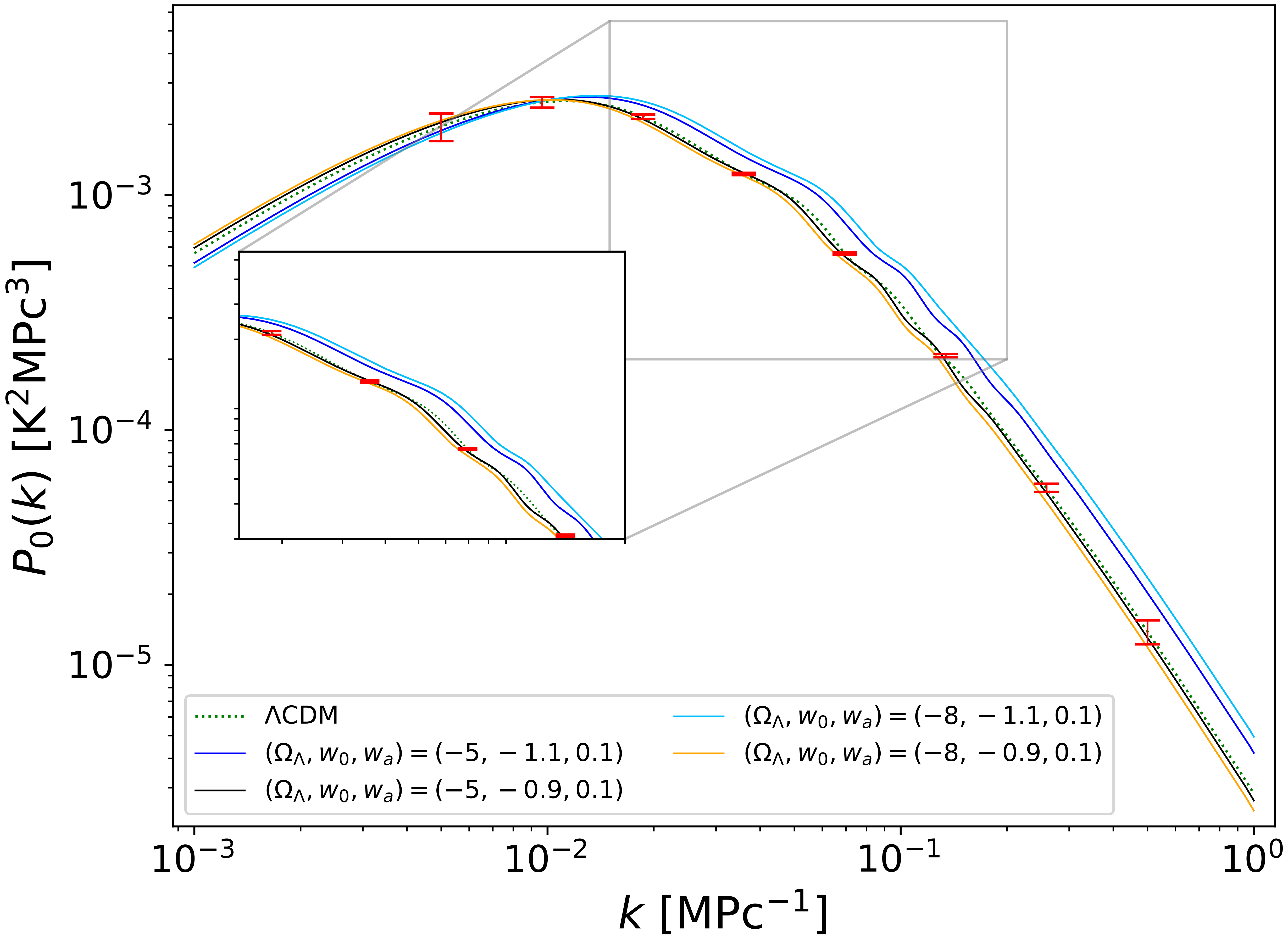
$$P_\ell(z,k) = \frac{(2\ell+1)}{2}\int_{-1}^{+1} d\mu \;\mathscr{P}_\ell(\mu)P_{21}(z,k,\mu)$$

SKA1-MID SPECIFICATIONS

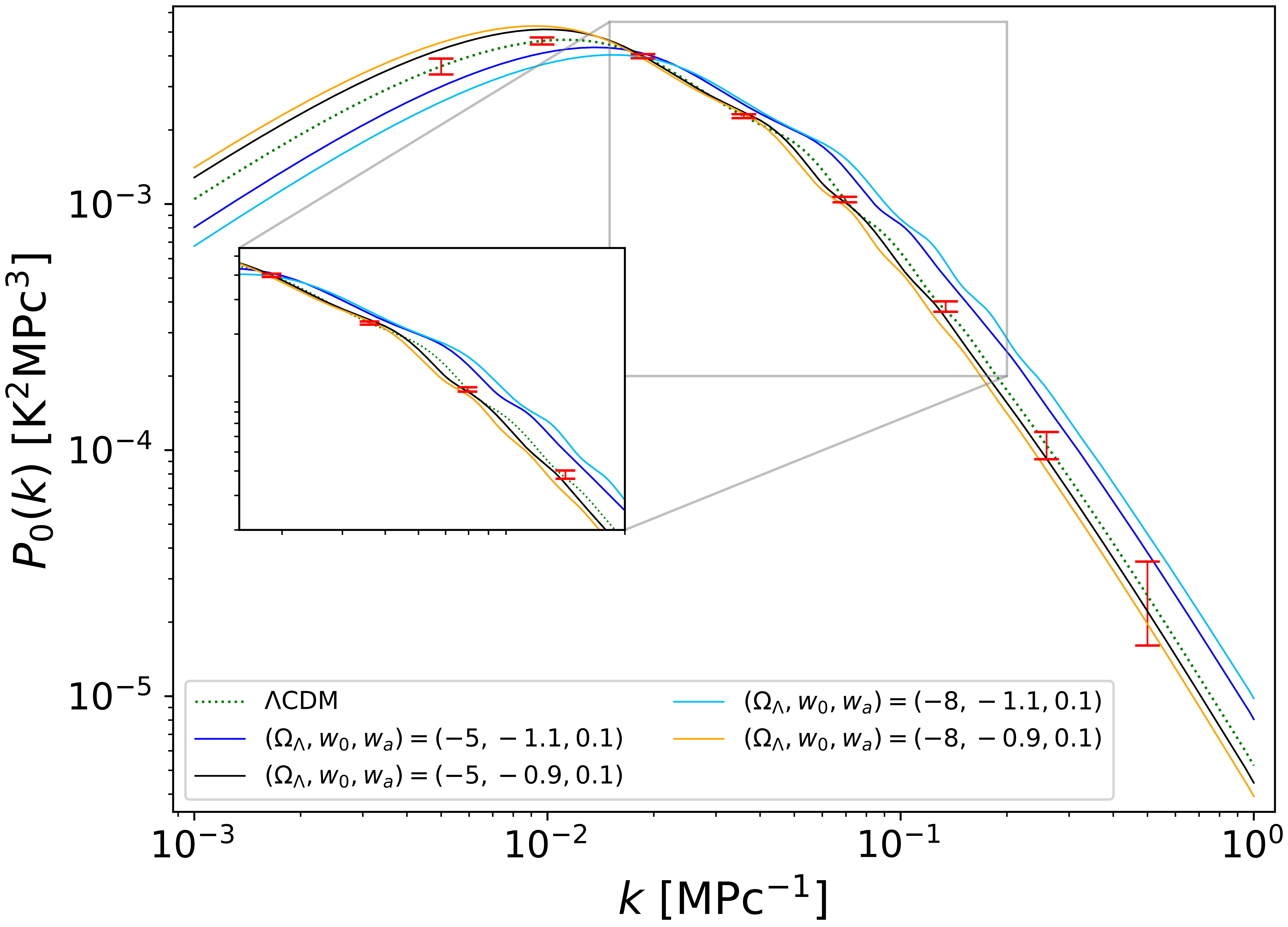
More info: www.skatelescope.org

- Medium deep band-2 survey sky area coverage 5,000 $\deg^2$ in frequency range $\nu = [0.95 - 1.75]GHz$, $z = [0 - 0.5]$
- Wide band-1 survey sky area coverage 20,000 $\deg^2$ in the frequency range $\nu = [0.35 - 1.05]GHz$, $z = [0.35 - 3]$
- No. of antennae $= 250$, $D_{dis} = 15m$, System temperature $T_{sys} = 60K$, Antennae efficiency $\epsilon = 0.7$, Total observation time $T_0 = 500 \times 150$ with 150 independent pointings, Bandwidth $B = 128MHz$

Monopole

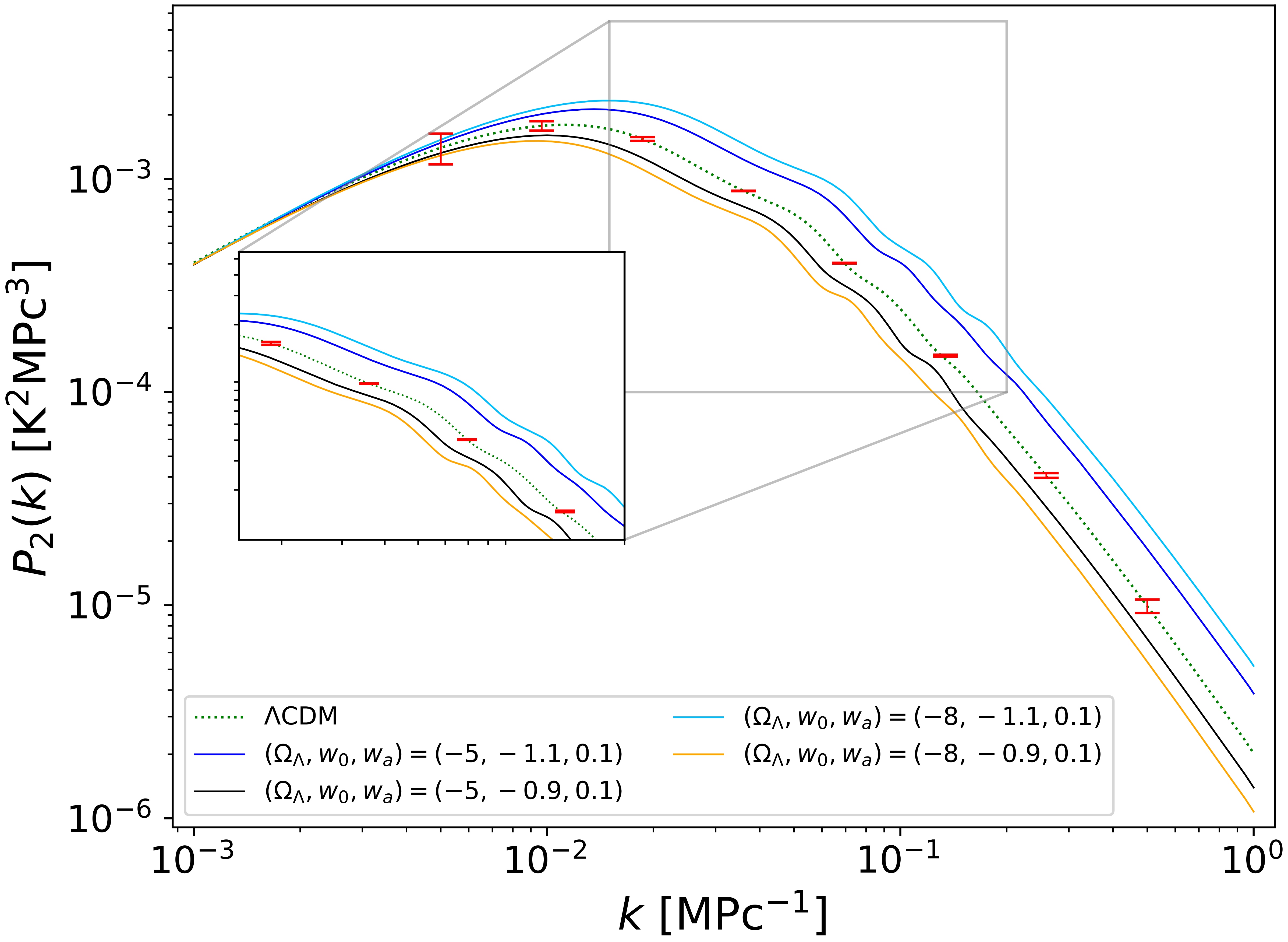


$z = 0.2$

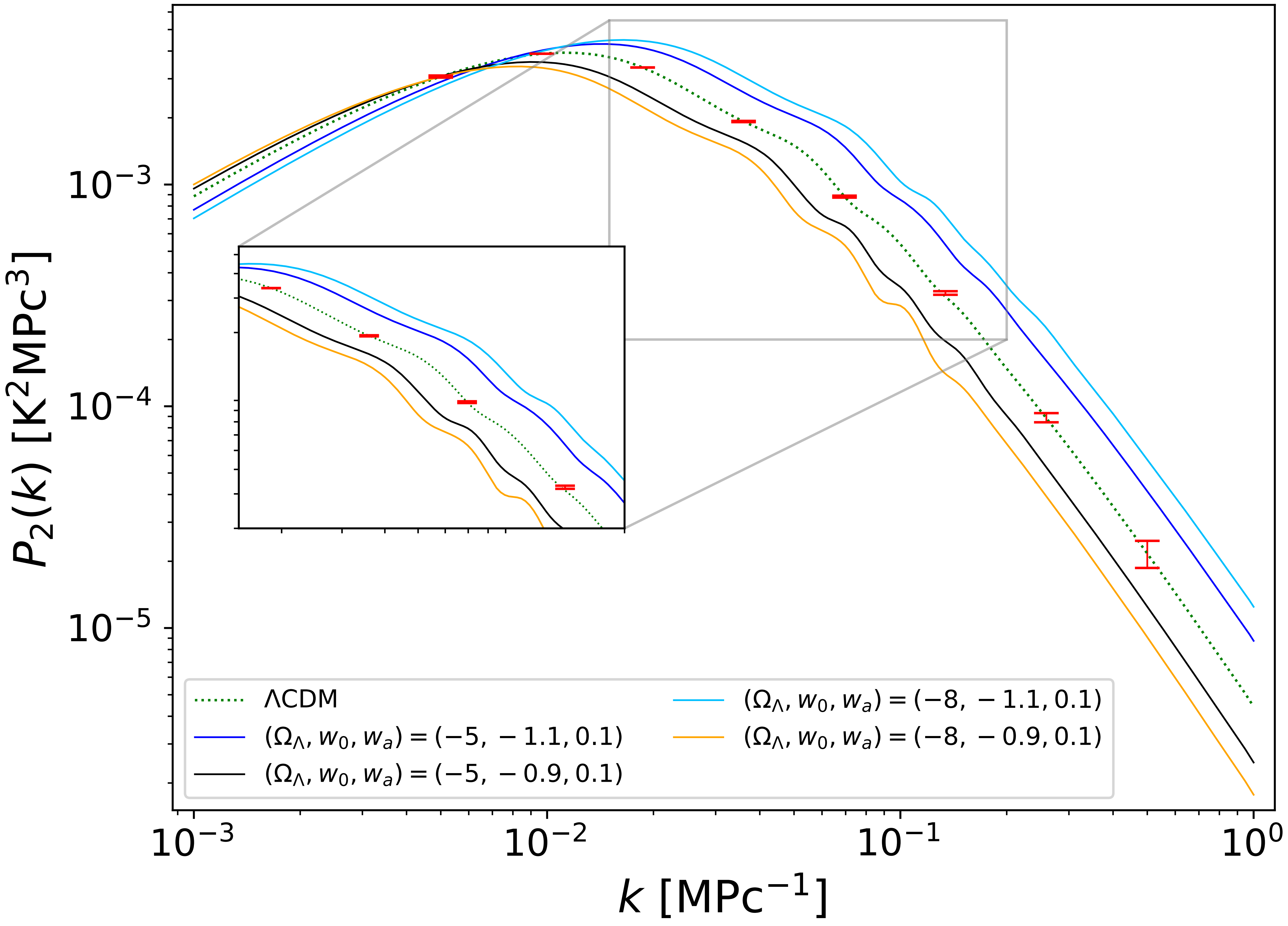


$z = 0.57$

Quadrupole

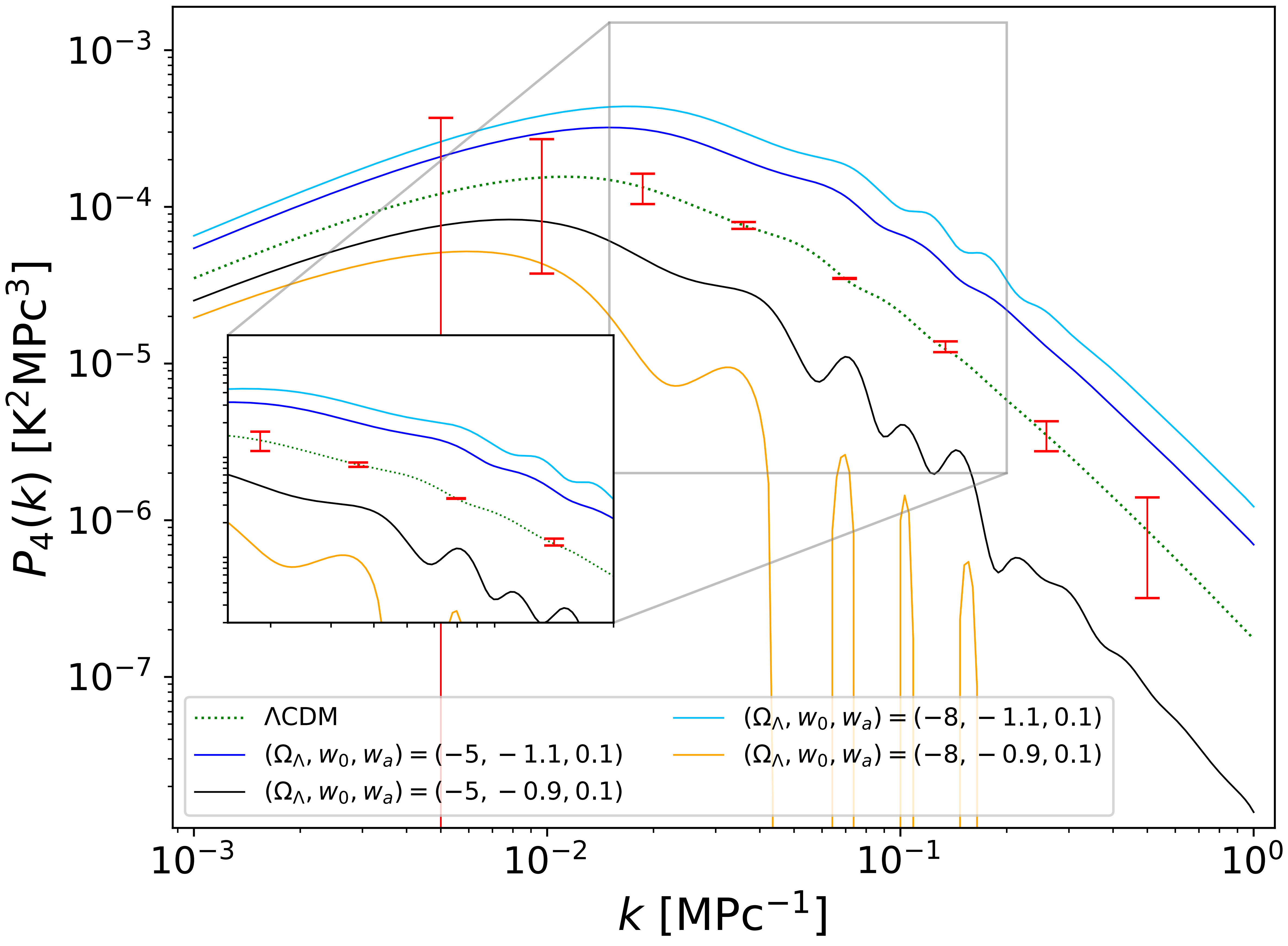


$z = 0.2$

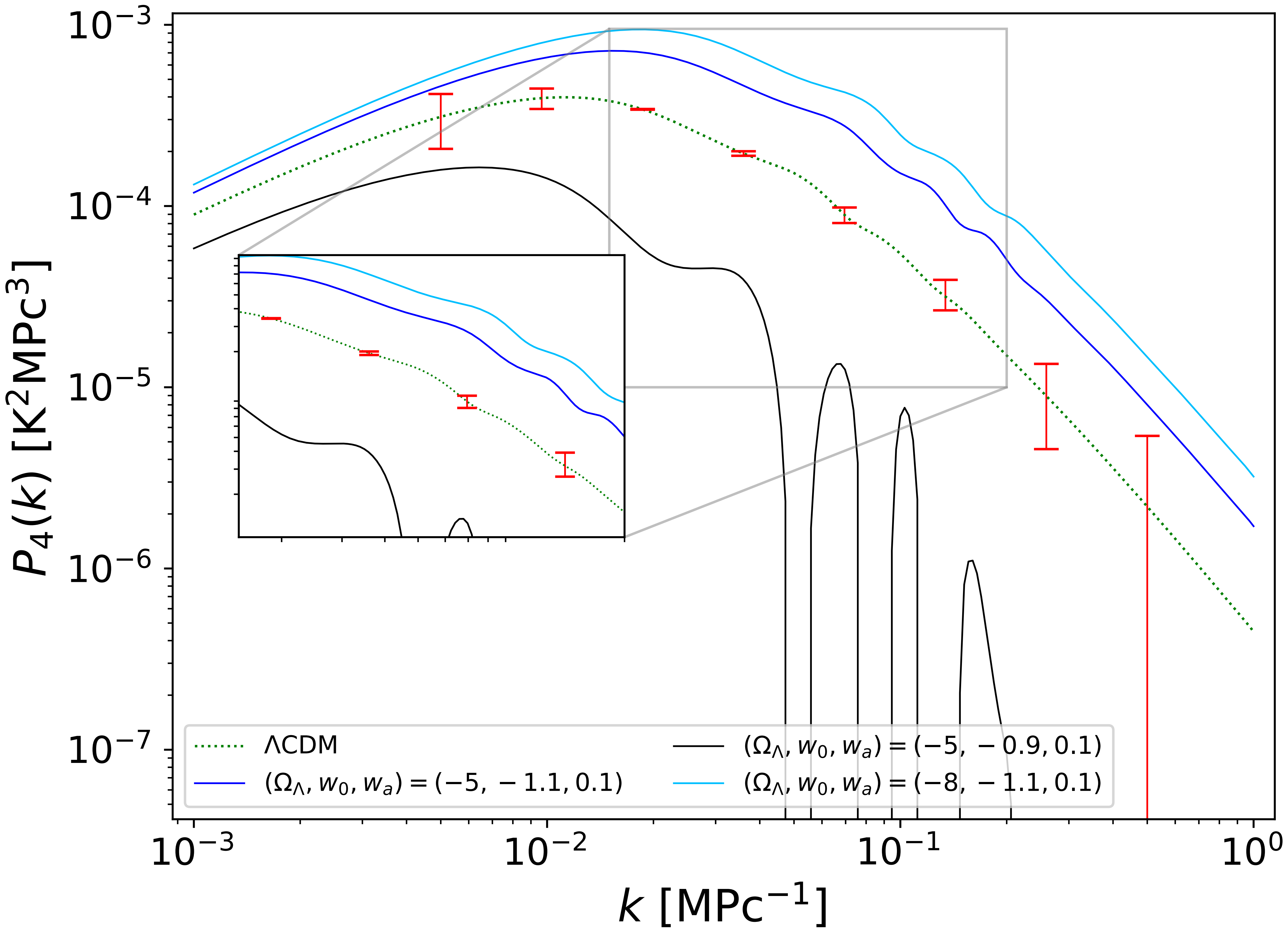


$z = 0.57$

Hexadecapole



$z = 0.2$



$z = 0.57$

BAO IMPRINTS

- The sound horizon at the epoch of recombination is given by

$$s(z_d) = \int_0^{a_r} \frac{c_s da}{a^2 H(a)} \; ; \; c_s(a) = c/\sqrt{3(1 + 3\rho_b/4\rho_\gamma)}$$

- rThe standard ruler 's' defines a transverse angular scale and a redshift interval in the radial direction as

$$\theta_s(z) = \frac{s(z_d)}{(1+z)D_A(z)} \qquad \delta z_s = \frac{s(z_d)H(z)}{c}$$

- Measurement of $\theta_s$and δz_s, allows the independent determination of $D_A(z)$ and $H(z)$.
- We calculate the expected error projections in five evenly space non-overlapping bins, in the redshift range $z = 0 - 3$ with $\Delta z = 0.5$.

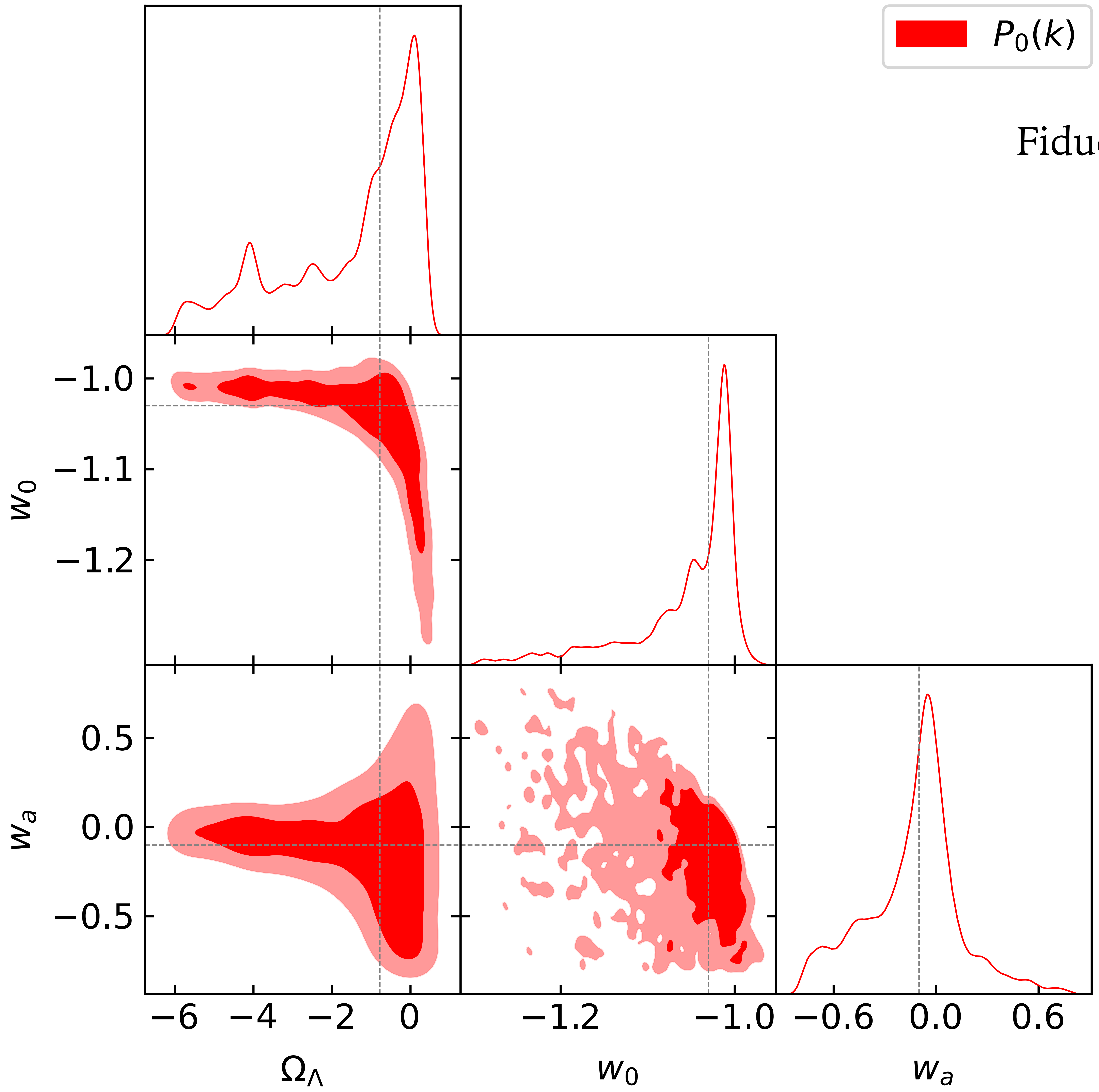
$$F_{ij} = \left(\frac{2\ell+1}{2}\right) \int dk' \int_{-1}^{+1} d\mu \, \frac{\mathscr{A}_T^2}{\alpha_\parallel \alpha_\perp^2} \left[b_T + \frac{f(z)\mu^2}{F^2 + \mu^2(1-F^2)} \right]^2 \frac{\mathscr{P}_\ell(\mu)}{\delta P_{21}^2(k,z,\mu)} \frac{\partial P_b(k')}{\partial p_i} \frac{\partial P_b(k')}{\partial p_j}$$

$$= \left(\frac{2\ell+1}{2}\right) \int dk' \int_{-1}^{+1} d\mu \, \frac{\mathscr{A}_T^2}{\alpha_\parallel \alpha_\perp^2} \left[b_T + \frac{f(z)\mu^2}{F^2 + \mu^2(1-F^2)} \right]^2 \frac{\mathscr{P}_\ell(\mu)}{\delta P_{21}^2(k,z,\mu)} \left(\cos x - \frac{\sin x}{x}\right)^2 f_i f_j A^2 e^{-2(k'\Sigma_s)^{1.4}} e^{-k'^2 \Sigma_{nl}^2}$$

$f_1 = \mu^2 - 1, f_2 = \mu^2, k_{nl} = (3.07h^{-1}Mpc)^{-1}, \; k_{silk} = (8.38h^{-1}Mpc)^{-1}$

$x = \sqrt{k^2(1-\mu^2)s_\perp^2 + k^2\mu^2 s_\parallel^2}$,

- BAO Power spectrum: $P_b(k') = A\frac{\sin x}{x} e^{-(k'\Sigma_s)^{1.4}} e^{-k'^2 \Sigma_{nl}^2/2}$
- Parameter(s): $p_i = \ln(s_\perp)^{-1}$ and $p_j = \ln s_\parallel$ Estimated error: $\sqrt{F_{ii}^{-1}}$



Fiducial values taken from Anjan A Sen et. al (2022)

$$\Omega_\Lambda = -0.883^{0.978}_{-2.987}$$

$$w_0 = -1.030^{0.023}_{-0.082}$$

$$w_a = -0.088^{0.162}_{-0.343}$$

(Constraints with $1-\sigma$ uncertainty)

SUMMARY

- ΛCDM paradigm: tensions from direct and indirect measurement of $\geq 5\sigma$
- Beyond ΛCDM: new physics at early universe or late universe.
- Allowing a dS/AdS minima gives a hope to alleviate tension.
- Observation of redshifted 21cm signal from post-deionization epoch can distinguishable from standard cosmological model with $> 3\sigma$ sensitivity.
- However 21cm signal alone can not put tight constraints, need to look more comprehensive approach.

TAKE HOME MESSAGE

- Dark energy is still an open problem. We have no idea (honestly !!)
- We're always hoping to find new things, but we're finding that our model is really, really good - - maybe disappointingly good. (Max Tegmark)
- Detection of 21cm signal will be a giant leap for precision cosmology.
- Upcoming SKA experiment promises to deliver qualitatively new insights on astrophysics and cosmology.

$$\Gamma\ \hbar\ \{\alpha_\eta\}^\kappa\ \varphi\ \ddot{o}\ \mu\ \ldots\ldots$$

Indian Institute of Technology Madras

Center for Strings, Gravitation & Cosmology

16-Sept-2023