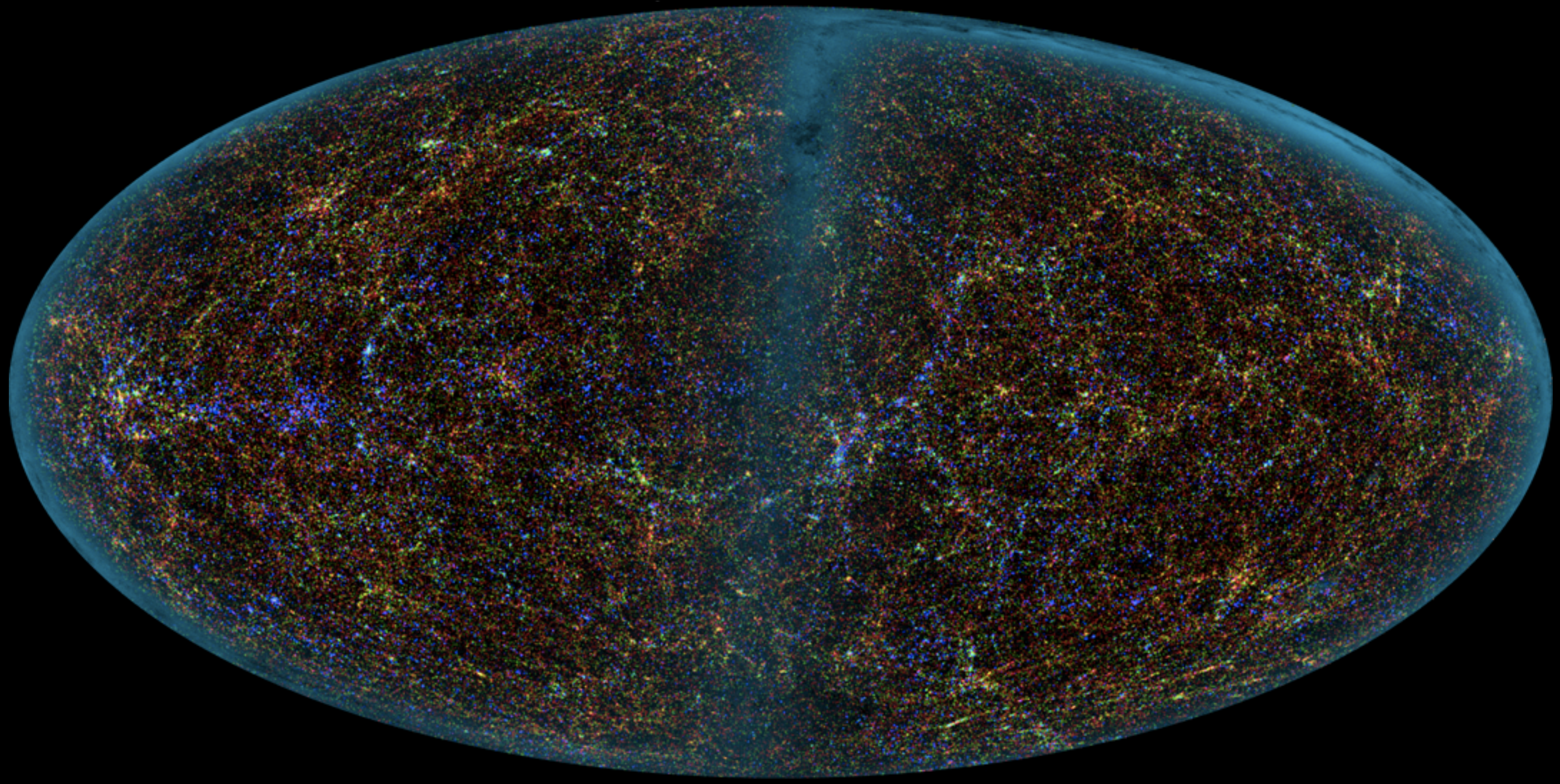
Cosmology

and Large Scale Structure



<u>Today</u>

More CMB

Cosmic Dawn

& Reionization

Homework 5 due next time

21 November 2024

http://astroweb.case.edu/ssm/ASTR328/

Cosmological Parameters

The search for two parameters has become six, maybe seven

two parameters

- Hubble expansion rate
  - H_0
- Mass density
  - Ω_m

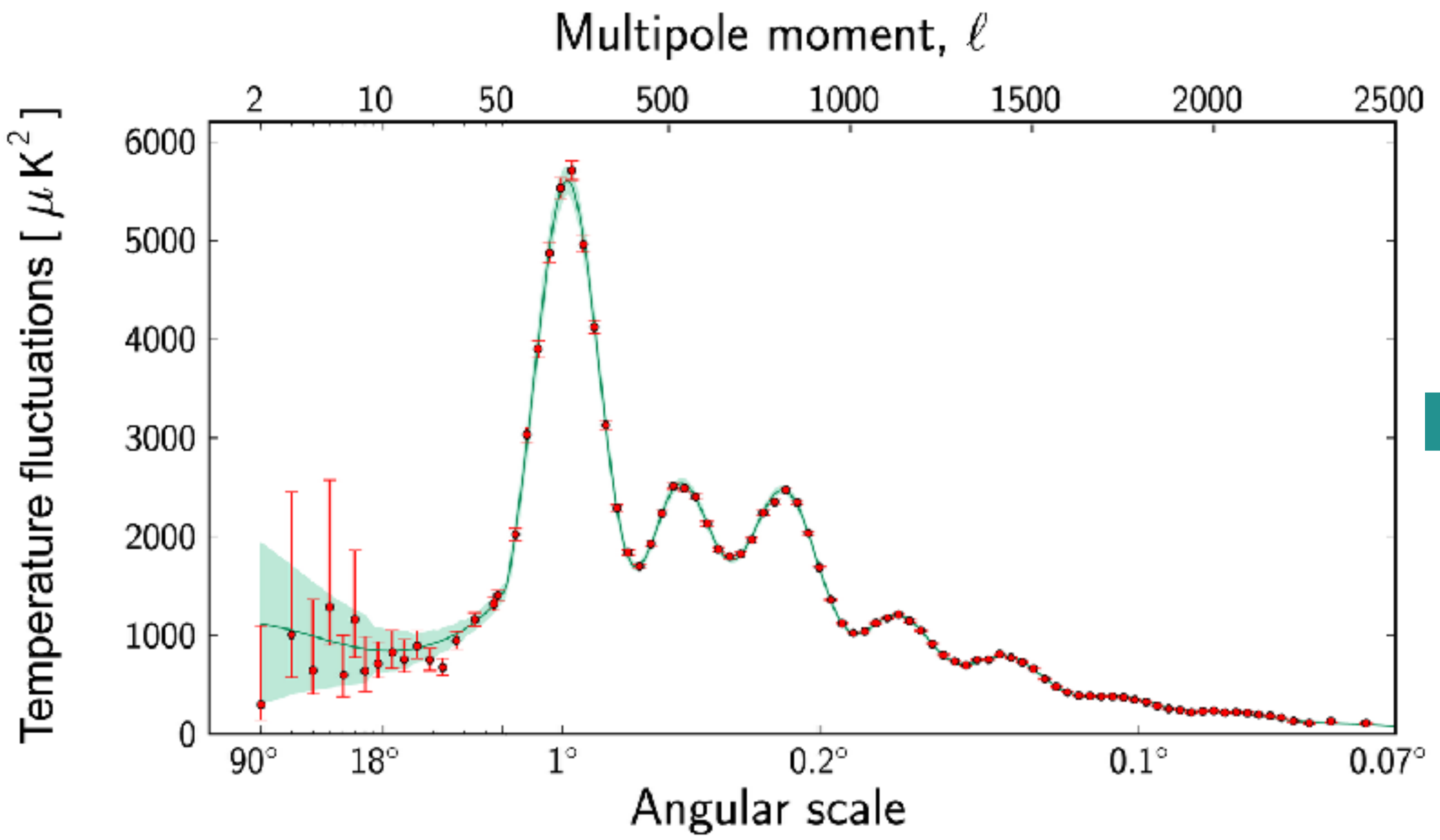
Or simply H_0, q_0
but in the absence of dark energy,
$q_0 = \frac{1}{2}\Omega_m$

six parameters

- Hubble expansion rate
  - H_0
- Power spectrum index and normalization
  - n $[P(k) \propto k^n]$
  - σ_8 (amplitude of mass fluctuations in 8 Mpc spheres)
- Mass-energy density
  - Normal matter (baryon) density Ω_b
  - Dark matter density $\Omega_{\rm CDM}$
  - Dark energy density (cosmological constant) Ω_Λ
  - Neutrino mass density Ω_ν (they're mass as well as energy)

CMB power spectrum

Detailed shape of the acoustic power spectrum depends sensitively on cosmic parameters.



Best-fit cosmology obtained from multi-parameter fit. Well constrained, but not unique - lots of parameter degeneracy.

2 Baseline model

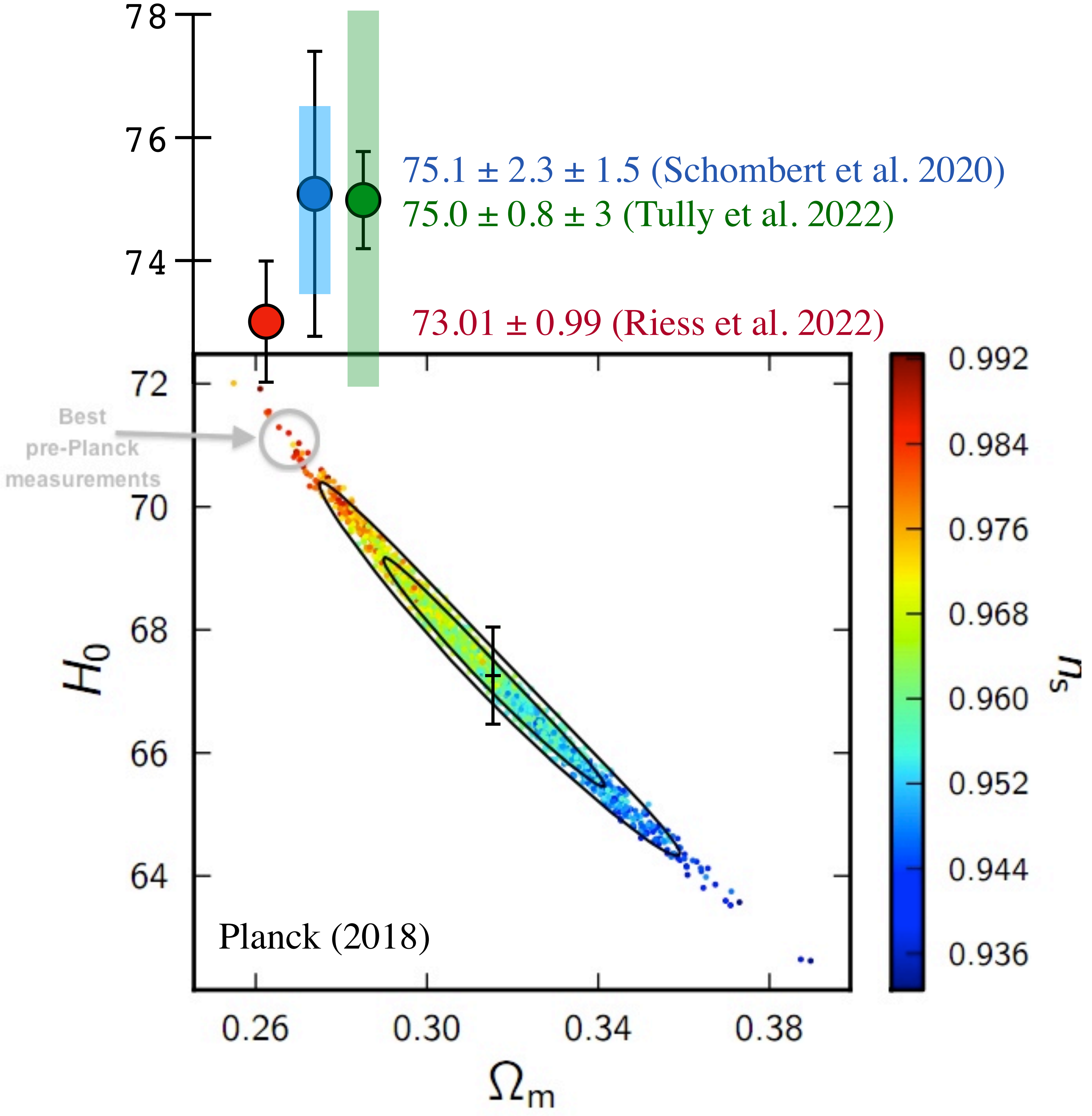
2.1 base_plikHM_TT_lowl_lowE

Parameter	Best fit	68% limits	Parameter	Best fit	68% limits	Parameter	Best fit	68% limits
$\boldsymbol{\Omega_b h^2}$	0.022126	0.02212 ± 0.00022	$\sigma_8\Omega_m^{0.25}$	0.6116	0.611 ± 0.012	$H(0.15)$	72.23	72.25 ± 0.78
$\boldsymbol{\Omega_c h^2}$	0.12068	0.1206 ± 0.0021	$\sigma_8/h^{0.5}$	0.9938	0.993 ± 0.016	$D_M(0.15)$	647.8	647.7 ± 7.9
$\boldsymbol{100\theta_{MC}}$	1.040748	1.04077 ± 0.00047	$r_{drag}h$	98.40	98.5 ± 1.6	$H(0.38)$	82.50	82.52 ± 0.56
$\boldsymbol{\tau}$	0.0523	0.0522 ± 0.0080	$\langle d^2\rangle^{1/2}$	2.4537	2.454 ± 0.038	$D_M(0.38)$	1542.6	1542 ± 16
$\boldsymbol{\ln(10^{10}A_s)}$	3.0413	3.040 ± 0.016	z_{re}	7.54	7.50 ± 0.82	$H(0.51)$	89.310	89.32 ± 0.44
$\boldsymbol{n_s}$	0.9635	0.9626 ± 0.0057	$10^9 A_s$	2.0933	2.092 ± 0.034	$D_M(0.51)$	1996.8	1997 ± 18
$\boldsymbol{y_{cal}}$	1.00046	1.0004 ± 0.0025	$10^9 A_s e^{-2\tau}$	1.8853	1.884 ± 0.014	$H(0.61)$	94.998	95.01 ± 0.35
$\boldsymbol{A_{217}^{CIB}}$	48.5	48 ± 7	D_{40}	1231.7	1234 ± 15	$D_M(0.61)$	2322.3	2322 ± 20
$\boldsymbol{\xi^{tSZ\times CIB}}$	0.32	—	D_{220}	5710.4	5713 ± 42	$H(2.33)$	236.75	236.7 ± 1.3
$\boldsymbol{A_{143}^{tSZ}}$	7.03	5.1 ± 2.0	D_{810}	2538.2	2536 ± 14	$D_M(2.33)$	5777.8	5778 ± 16
$\boldsymbol{A_{100}^{PS}}$	254.9	263 ± 28	D_{1420}	815.5	814.4 ± 5.1	$f\sigma_8(0.15)$	0.4642	0.464 ± 0.012
$\boldsymbol{A_{143}^{PS}}$	49.8	49 ± 8	D_{2000}	229.94	229.5 ± 1.8	$\sigma_8(0.15)$	0.7500	0.7492 ± 0.0075
$\boldsymbol{A_{143\times 217}^{PS}}$	47.3	44 ± 9	$n_{s,0.002}$	0.9635	0.9626 ± 0.0057	$f\sigma_8(0.38)$	0.4804	0.4798 ± 0.0095
$\boldsymbol{A_{217}^{PS}}$	119.9	115 ± 10	Y_P	0.245295	$0.24529^{+0.00011}_{-0.000088}$	$\sigma_8(0.38)$	0.6638	0.6631 ± 0.0060
$\boldsymbol{A^{kSZ}}$	0.00	< 4.84	Y_P^{BBN}	0.246621	$0.24661^{+0.00011}_{-0.000089}$	$f\sigma_8(0.51)$	0.4779	0.4773 ± 0.0082
$\boldsymbol{A_{100}^{dustTT}}$	8.86	8.9 ± 1.8	10^5D/H	2.6321	2.634 ± 0.042	$\sigma_8(0.51)$	0.6208	0.6202 ± 0.0055
$\boldsymbol{A_{143}^{dustTT}}$	10.80	10.7 ± 1.8	Age/Gyr	13.8300	13.830 ± 0.037	$f\sigma_8(0.61)$	0.4722	0.4716 ± 0.0072
$\boldsymbol{A_{143\times 217}^{dustTT}}$	19.43	18.3 ± 3.3	z_*	1090.292	1090.30 ± 0.41	$\sigma_8(0.61)$	0.5904	0.5899 ± 0.0051
$\boldsymbol{A_{217}^{dustTT}}$	94.8	93.3 ± 7.4	r_*	144.442	144.46 ± 0.48	$f\sigma_8(2.33)$	0.29733	0.2971 ± 0.0025
$\boldsymbol{c_{100}}$	0.99965	0.99961 ± 0.00061	$100\theta_*$	1.040956	1.04097 ± 0.00046	$\sigma_8(2.33)$	0.30613	0.3059 ± 0.0027
$\boldsymbol{c_{217}}$	0.99825	0.99826 ± 0.00063	$D_M(z_*)$/Gpc	13.8759	13.878 ± 0.044	f_{2000}^{143}	30.49	31.2 ± 3.0
H_0	66.86	66.88 ± 0.92	z_{drag}	1059.437	1059.39 ± 0.46	$f_{2000}^{143\times 217}$	33.34	33.6 ± 2.0
Ω_Λ	0.6791	0.679 ± 0.013	r_{drag}	147.182	147.21 ± 0.48	f_{2000}^{217}	107.77	108.2 ± 1.9
Ω_m	0.3209	0.321 ± 0.013	k_D	0.14058	0.14054 ± 0.00052	χ^2_{simall}	395.88	397.0 ± 1.7
$\Omega_m h^2$	0.14345	0.1434 ± 0.0020	$100\theta_D$	0.161051	0.16107 ± 0.00027	χ^2_{lowl}	23.60	23.9 ± 1.3
$\Omega_m h^3$	0.095909	0.09589 ± 0.00046	z_{eq}	3412.7	3411 ± 48	χ^2_{plik}	758.7	771.4 ± 5.5
σ_8	0.8126	0.8118 ± 0.0089	k_{eq}	0.010416	0.01041 ± 0.00014	χ^2_{prior}	1.35	7.3 ± 3.7
S_8	0.8405	0.840 ± 0.024	$100\theta_{eq}$	0.8106	0.8109 ± 0.0089	χ^2_{CMB}	1178.2	1192.3 ± 5.5
$\sigma_8\Omega_m^{0.5}$	0.4604	0.460 ± 0.013	$100\theta_{s,eq}$	0.44817	0.4483 ± 0.0046			

Best-fit $\chi^2_{eff} = 1179.58$; $\bar{\chi}^2_{eff} = 1199.58$; $R - 1 = 0.00927$
χ^2_{eff}: CMB - simall_100x143_offlike5_EE_Aplanck_B: 395.88 commander_dx12_v3_2_29: 23.60 plik_rd12_HM_v22_TT: 758.75

https://wiki.cosmos.esa.int/planck-legacy-archive/images/b/be/Baseline_params_table_2018_68pc.pdf

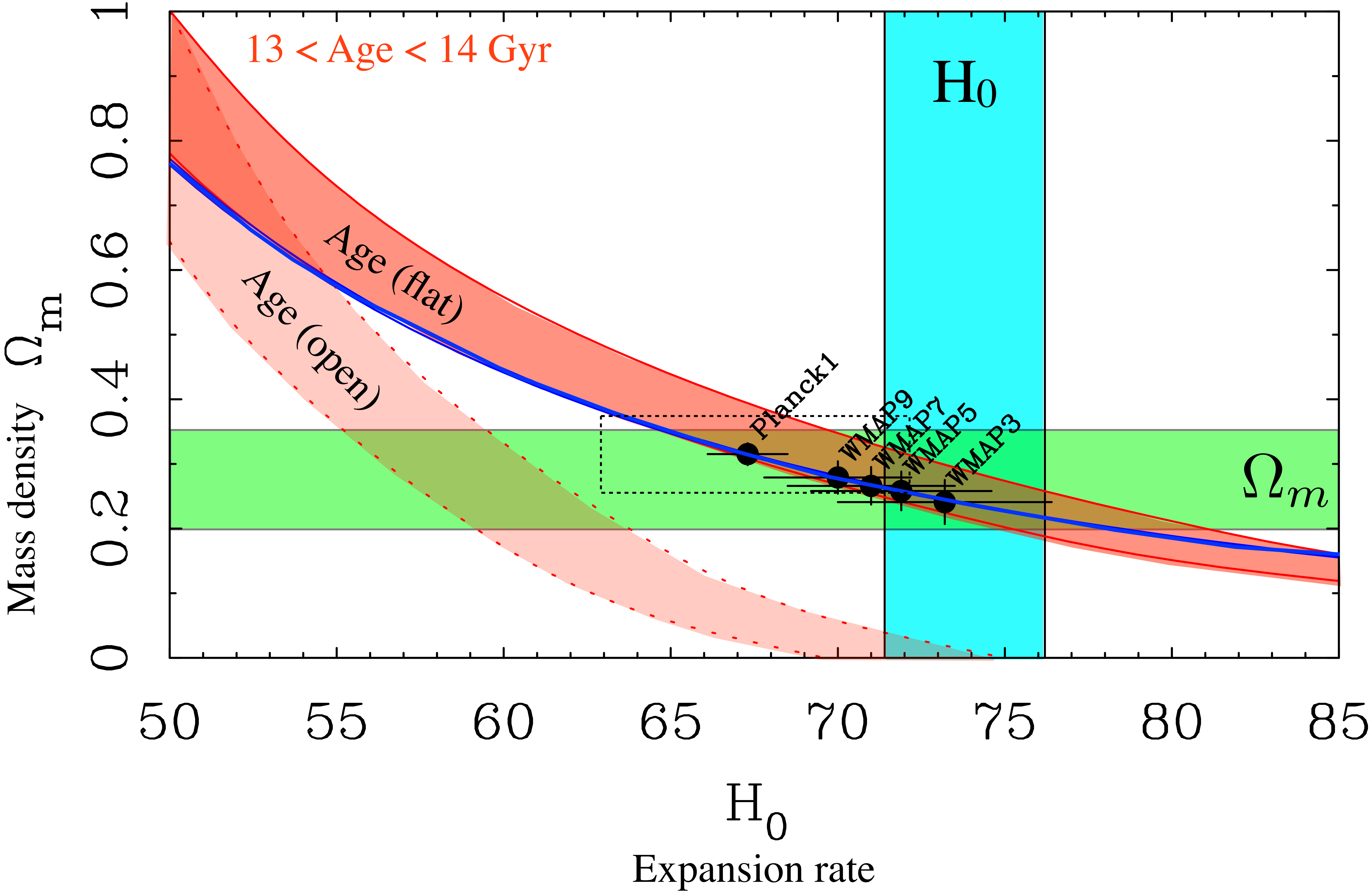
Hubble constant tension



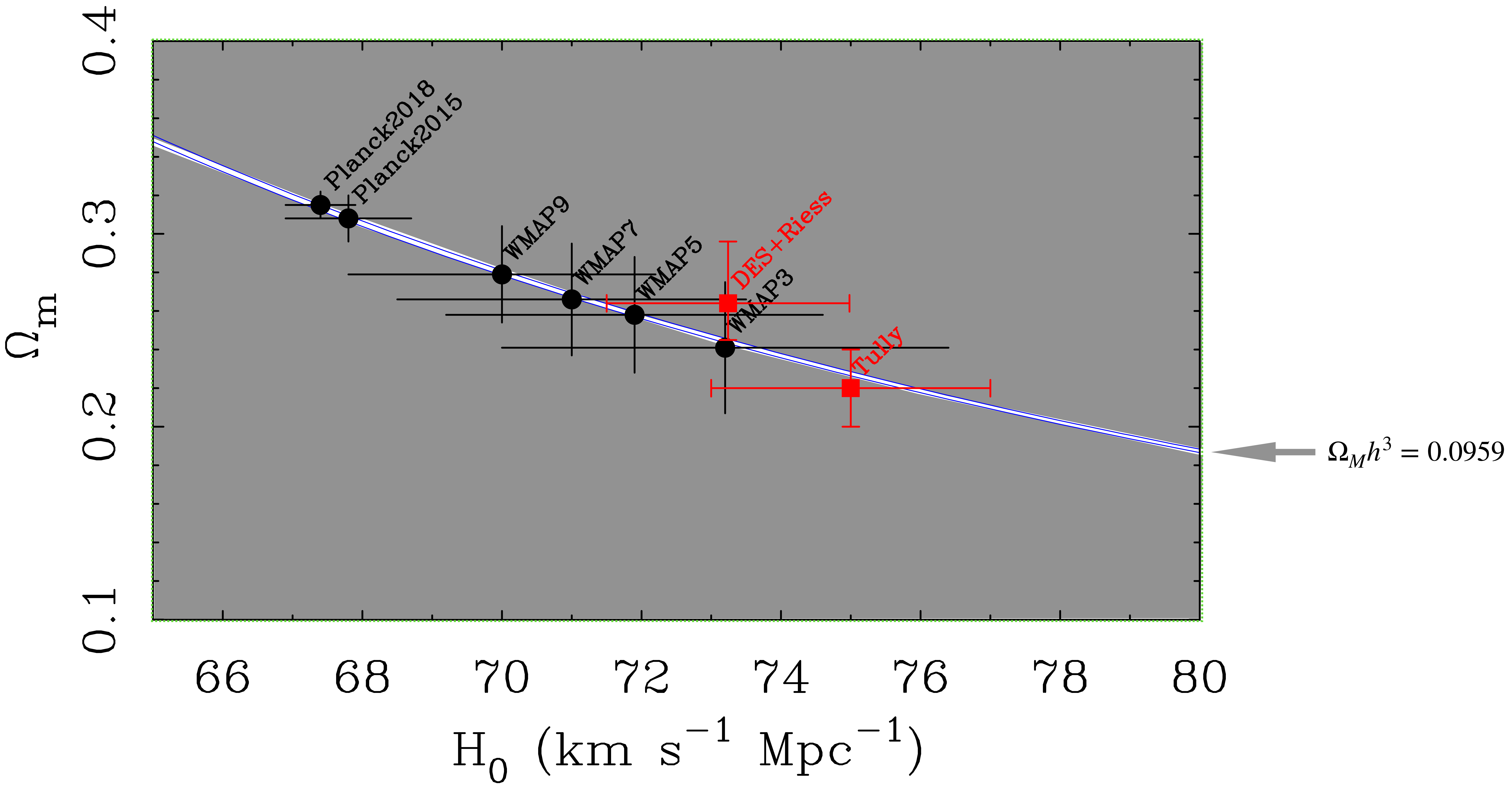
covariance between parameters

$$\Omega_M h^3 = 0.0959$$

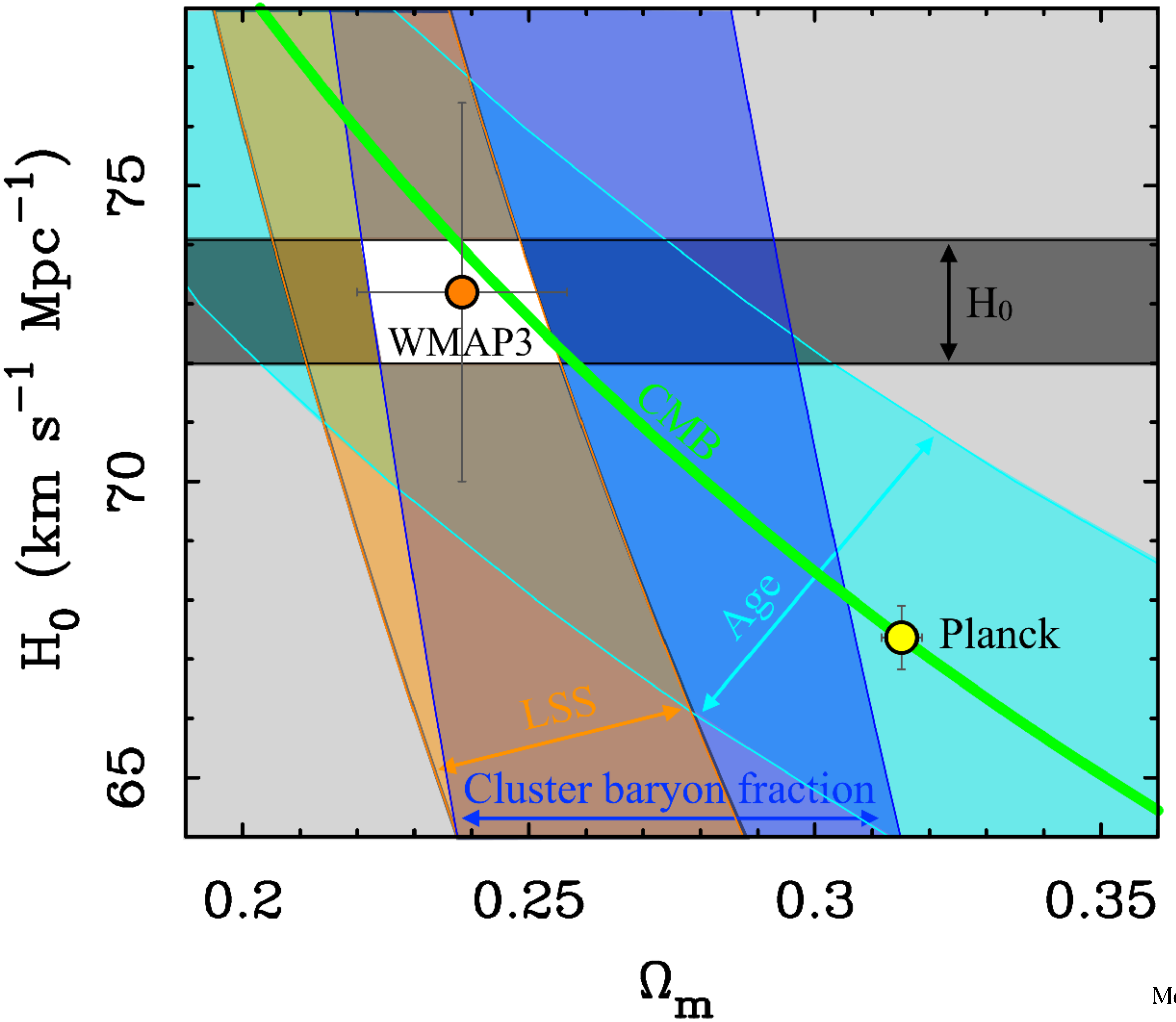
Planck constraint: $\Omega_m h^3 = 0.0959 \pm 0.0006$



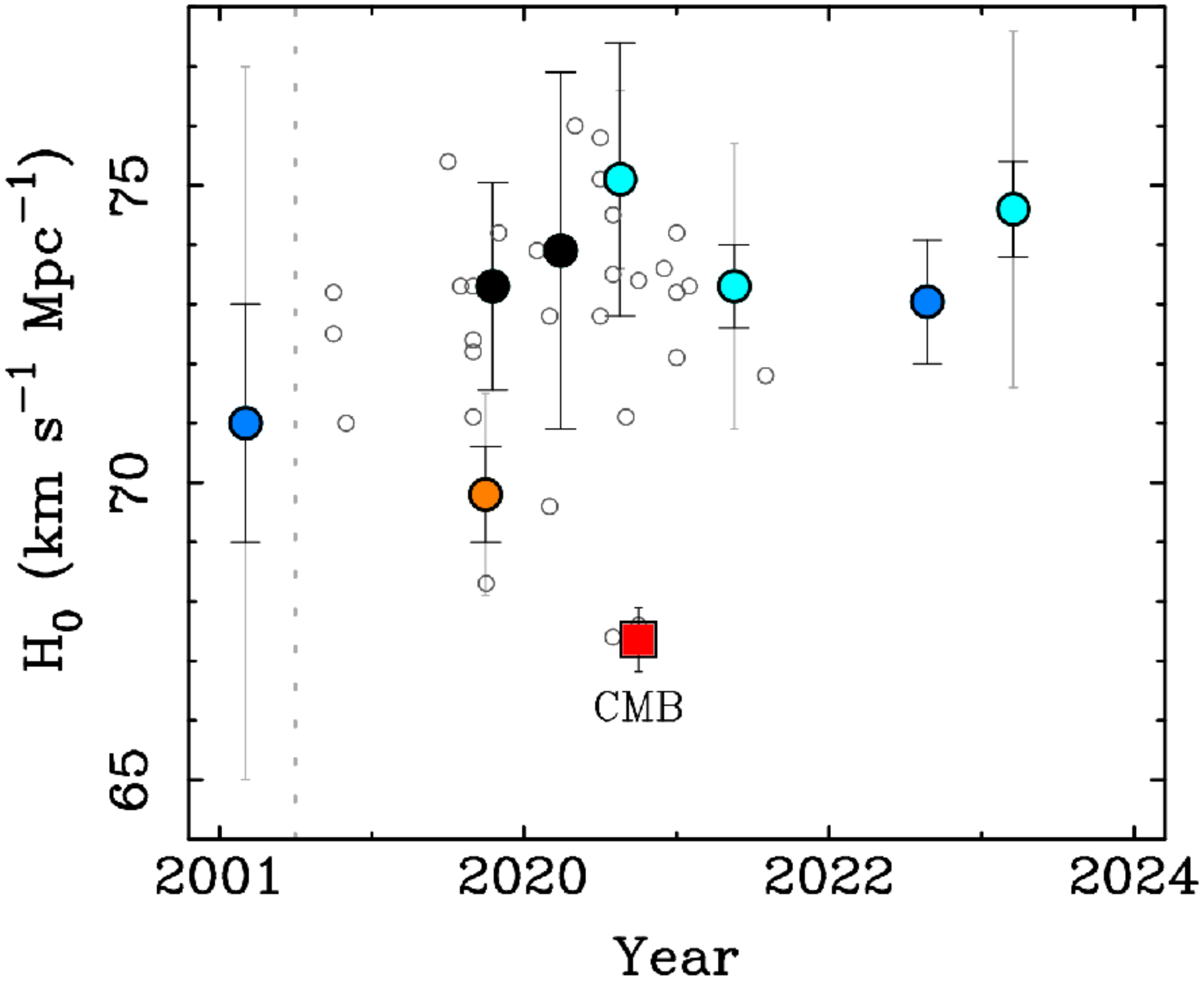
Cosmology today: tension in H_0 …and Ω_m

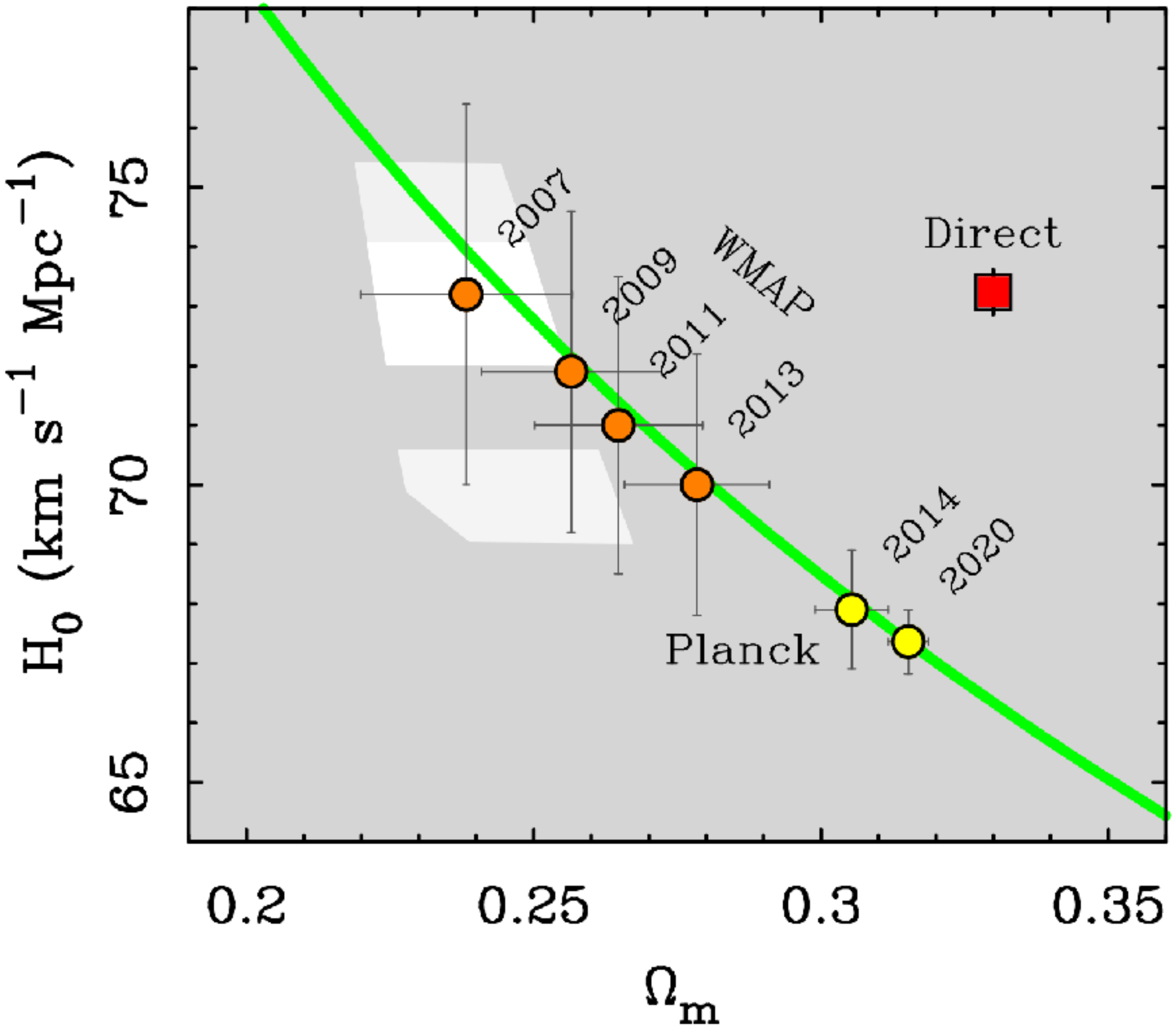


The CMB best fits have marched away from the original concordance region



McGaugh (2024) *Universe*, **10**, 48





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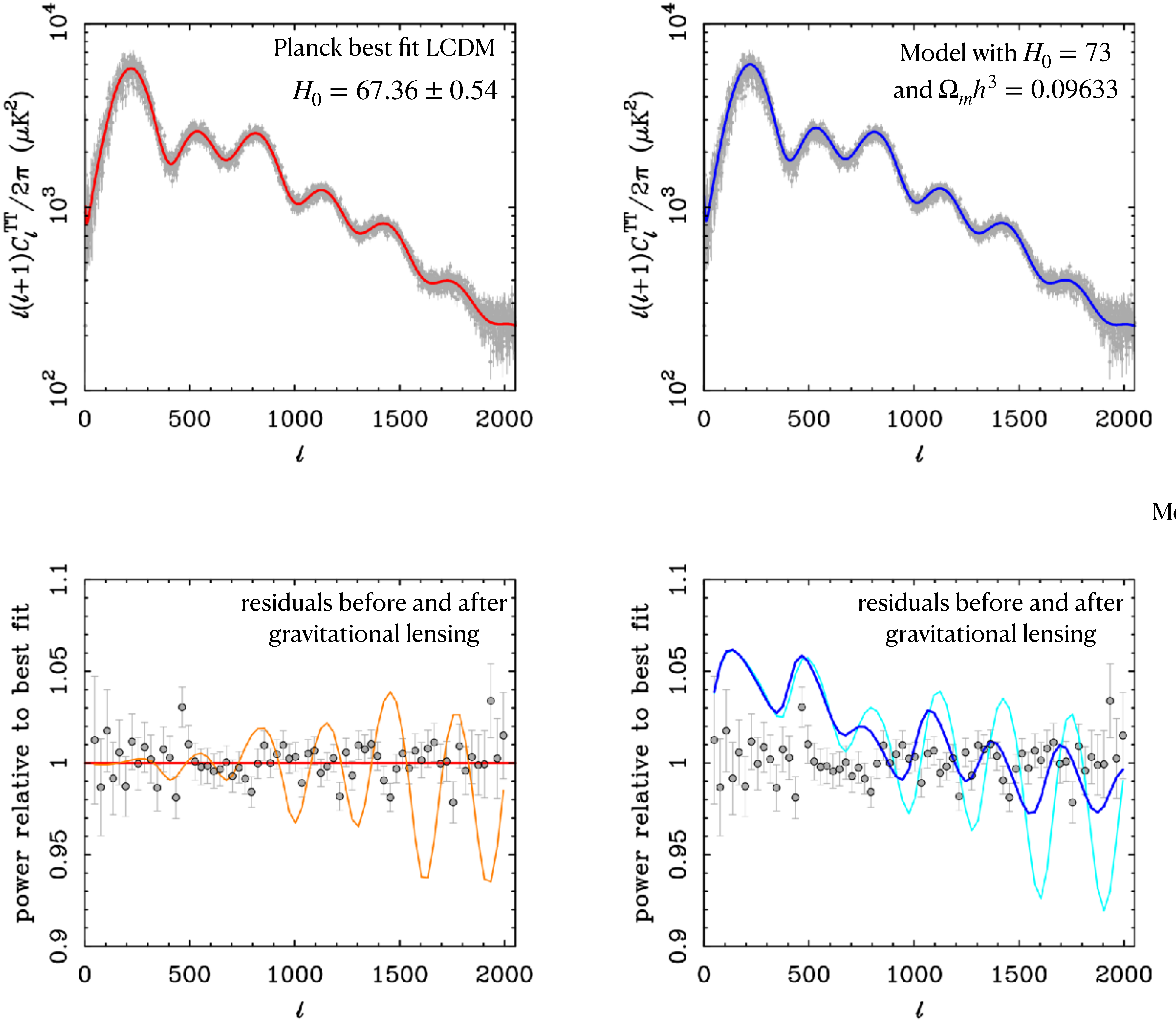
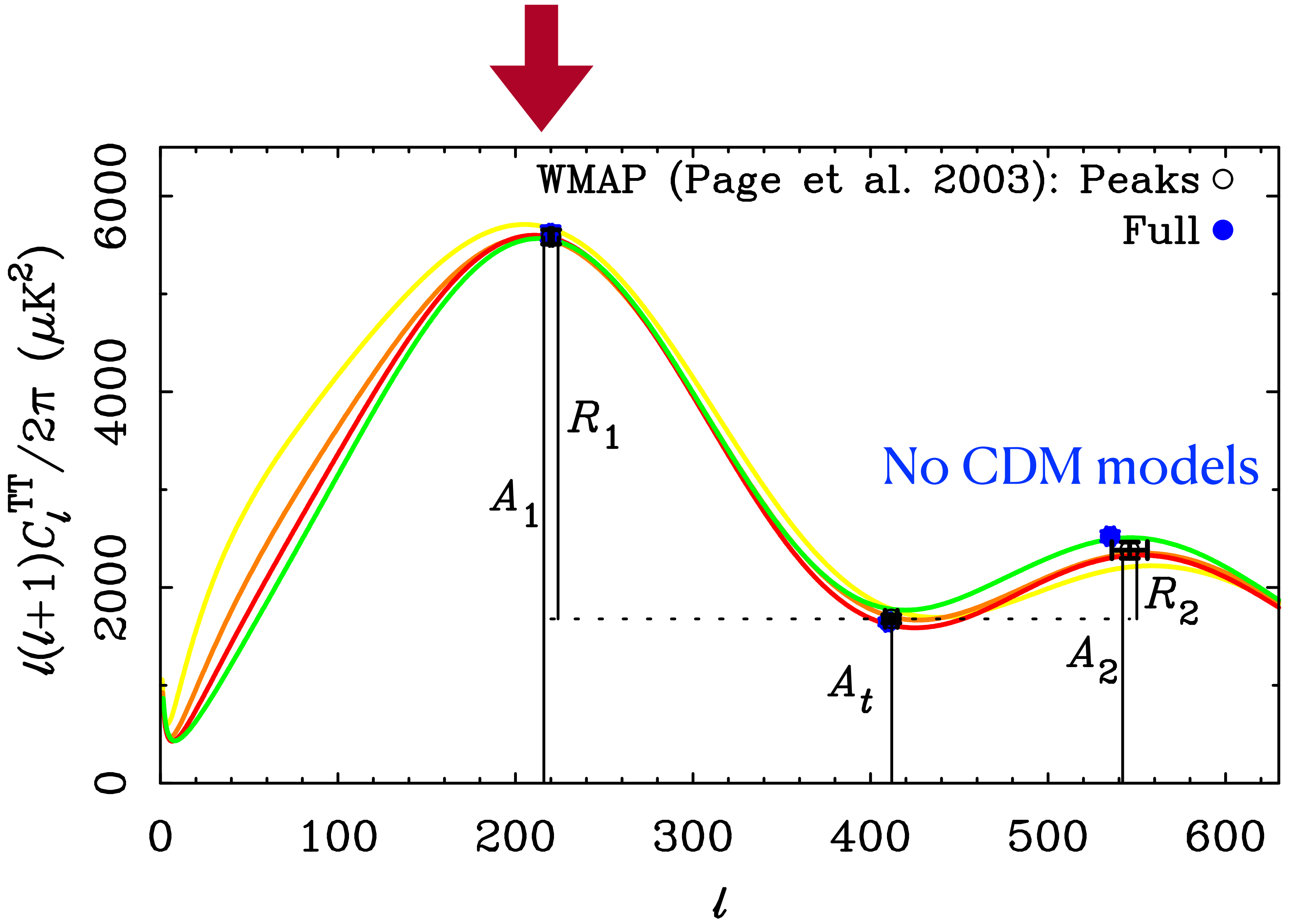
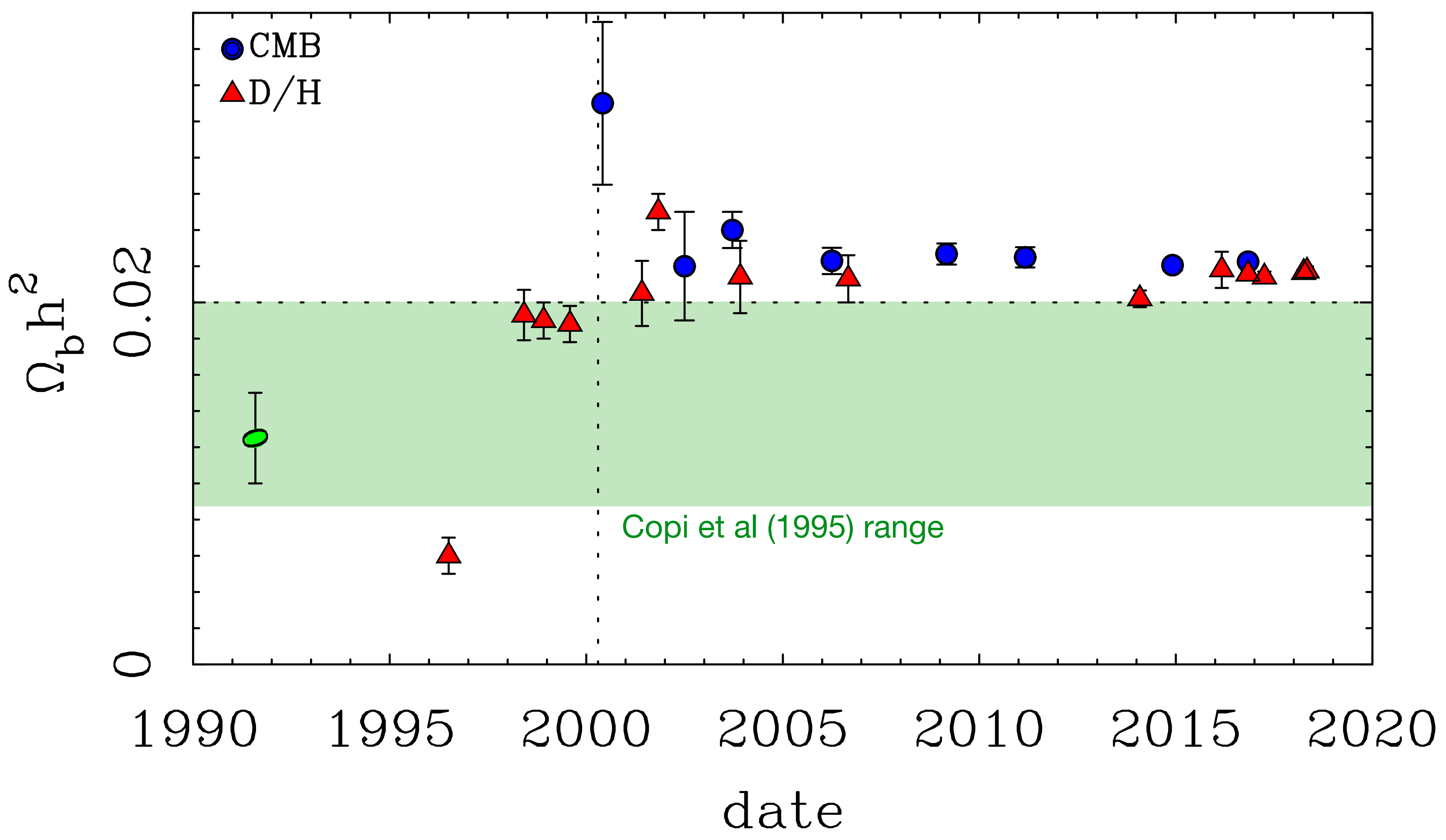


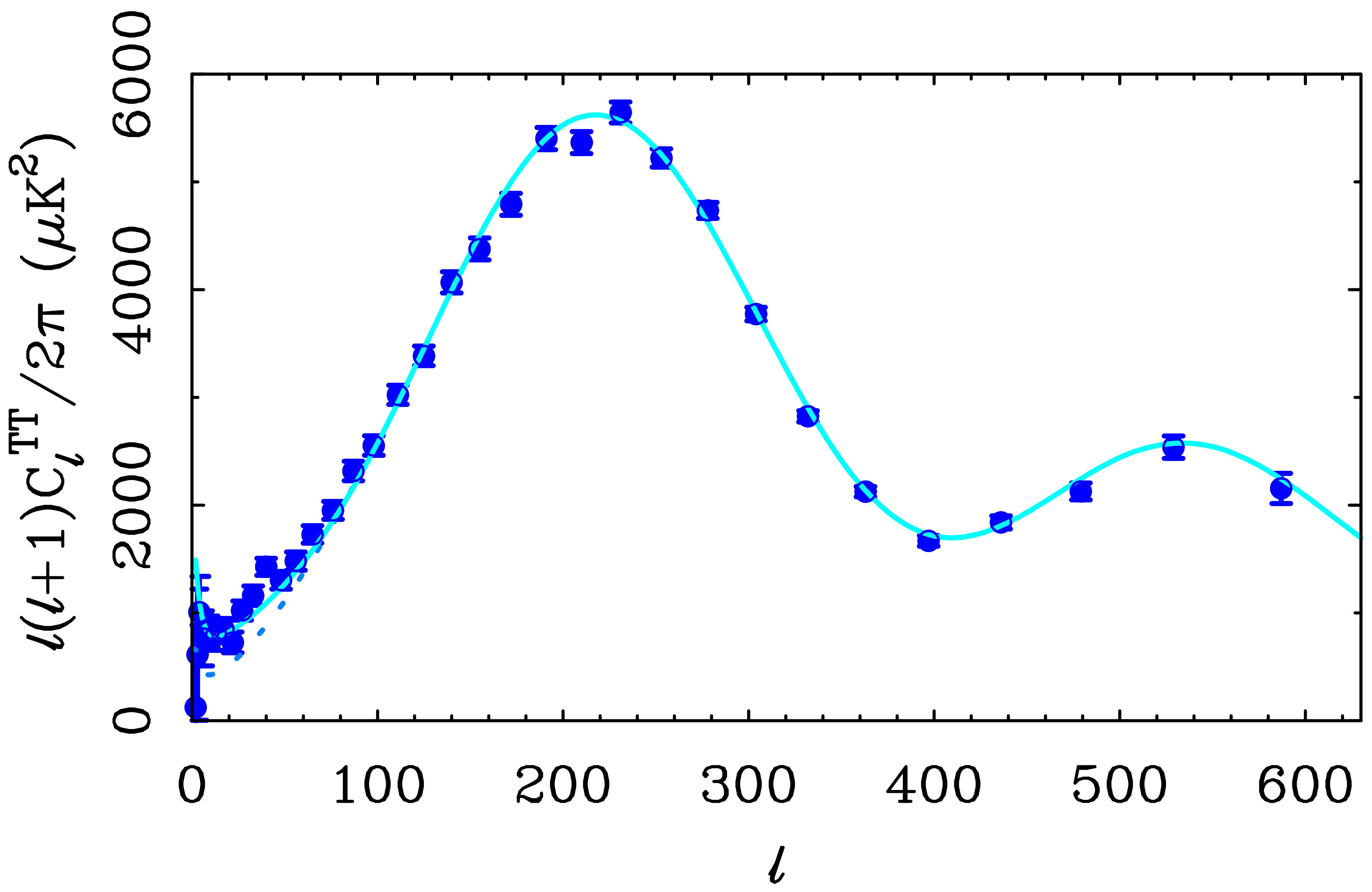
McGaugh (2024) *Universe*, **10**, 48

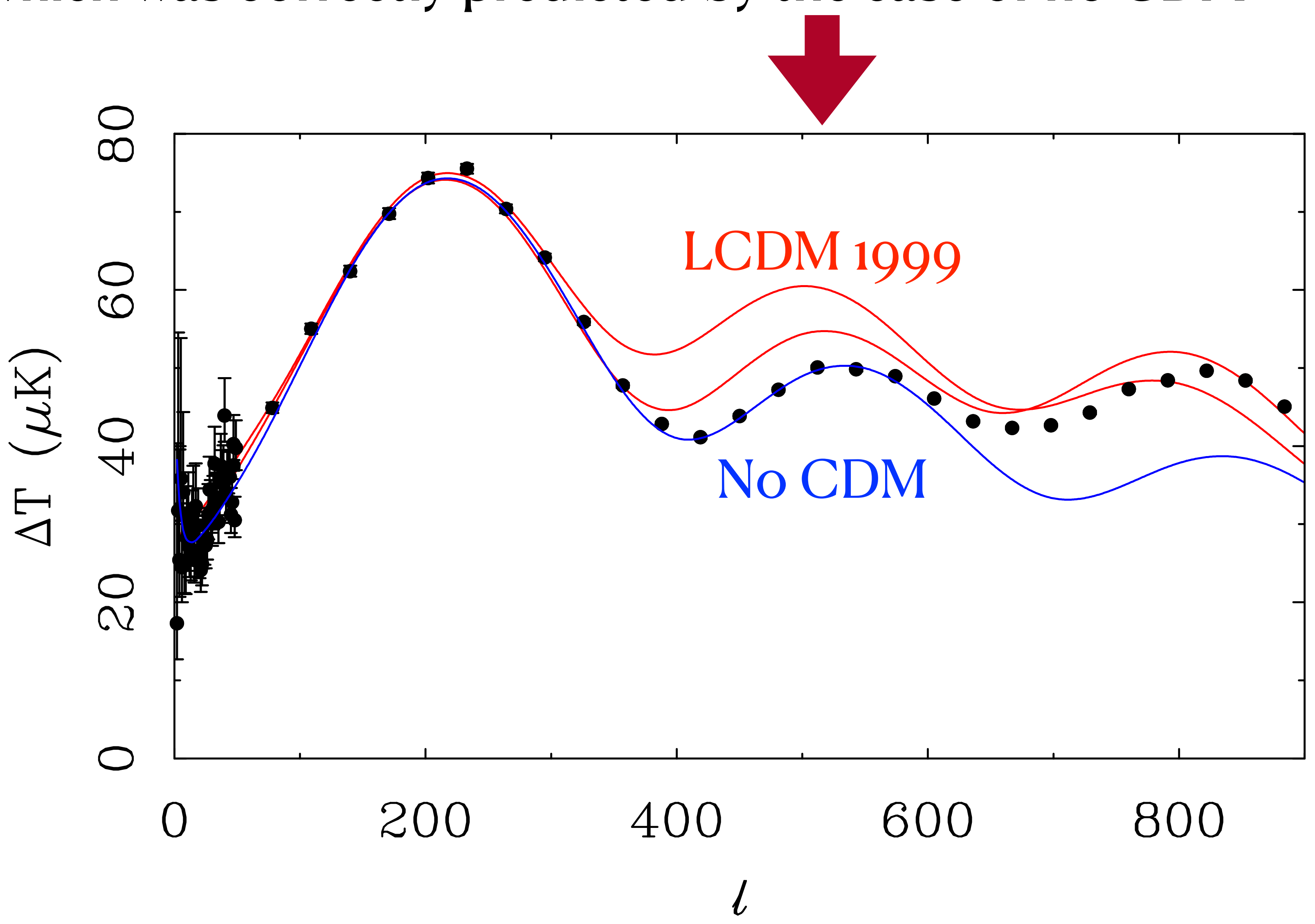
LCDM correctly predicted the location of the first peak, which is consistent with the expected flat geometry ($|\Omega_k| < 0.005$)



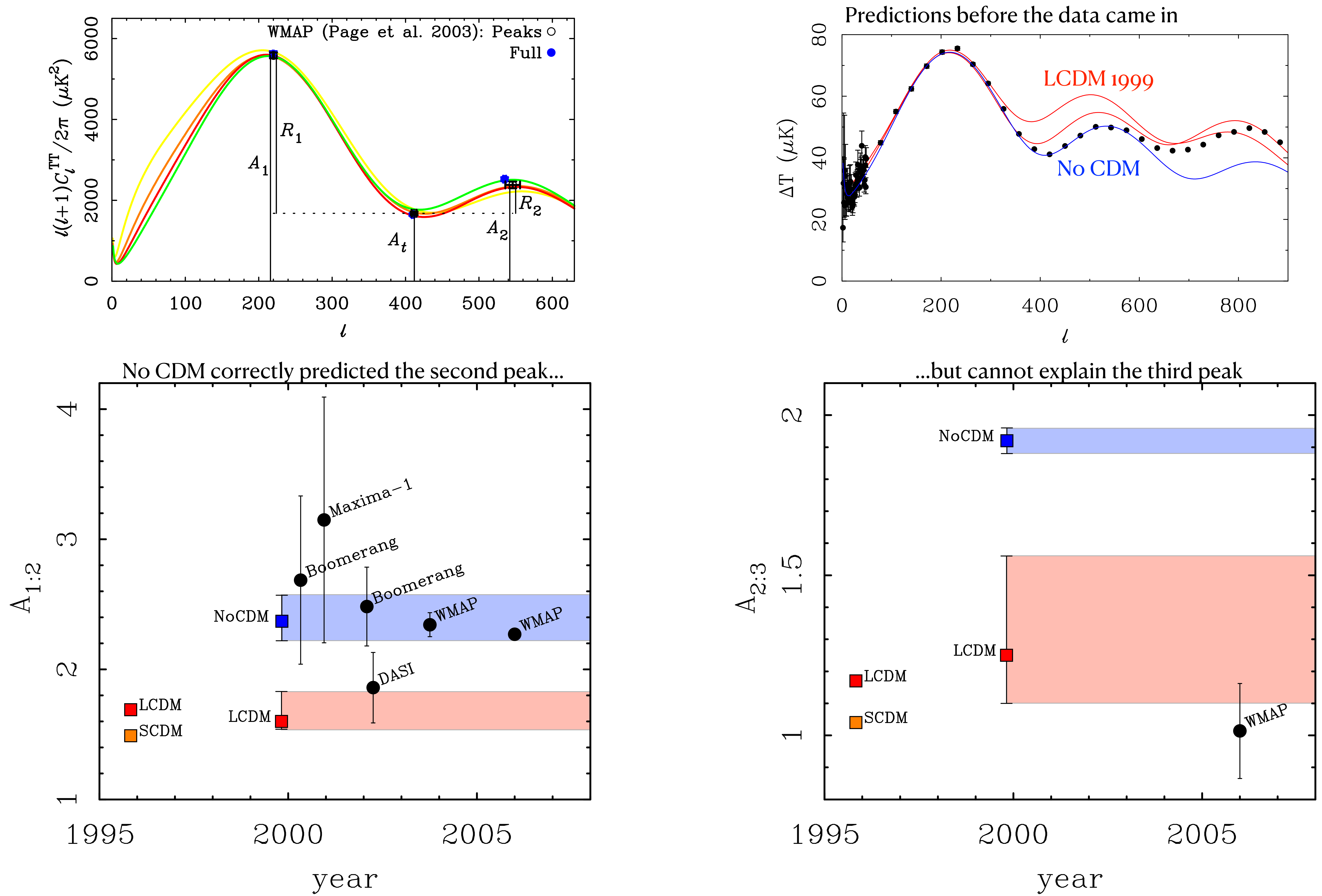


LCDM did not correctly predicted the amplitude of the second peak, which was correctly predicted by the case of no CDM

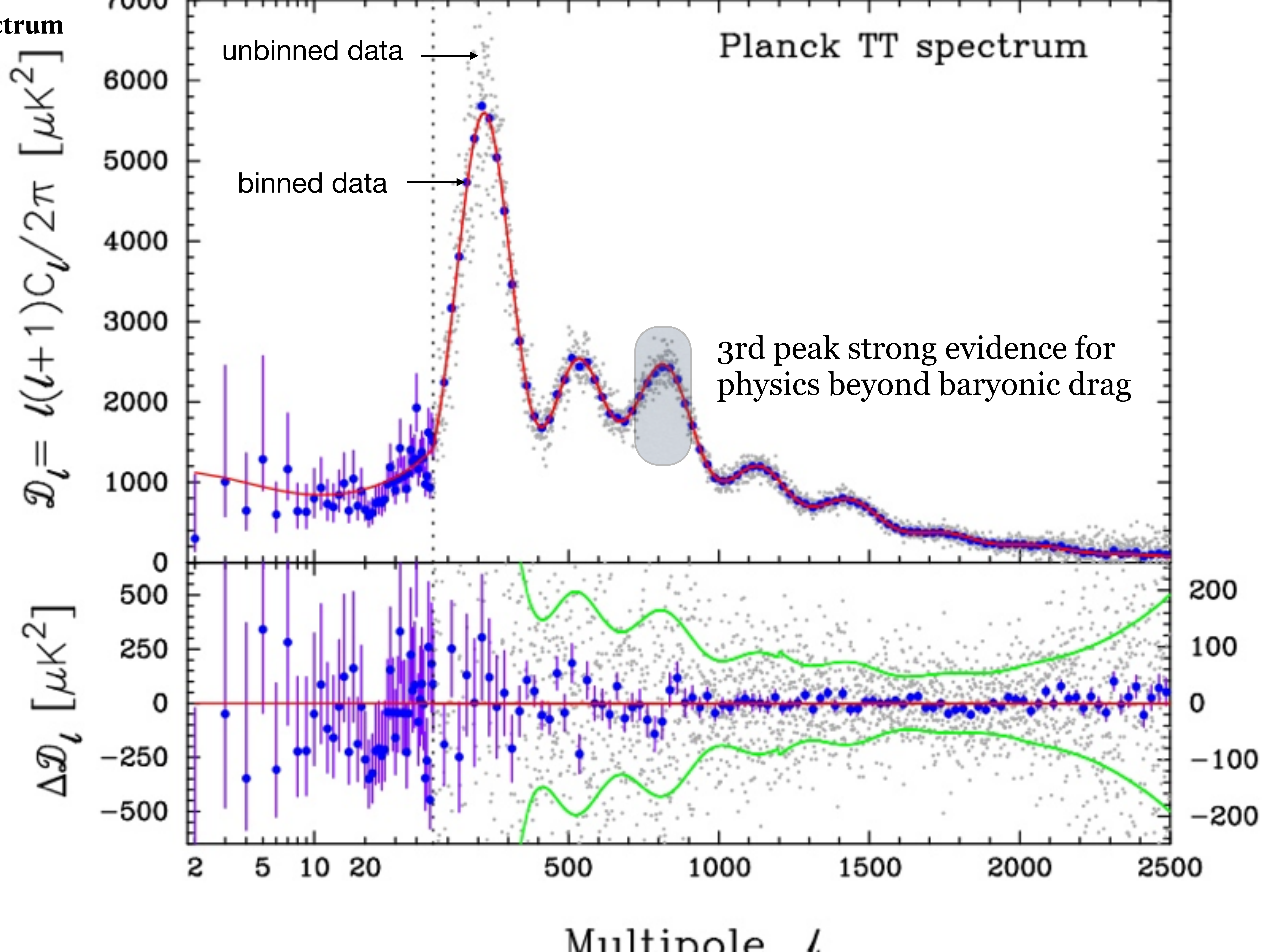




The amplitude of the second peak was the driver of the increase in the baryon density over the expectation of BBN


WMAP (Page et al. 2003): Peaks
Full
$\ell(\ell+1)C_\ell^{TT}/2\pi\ (\mu K^2)$
ℓ
A_1
R_1
A_t
A_2
R_2
Predictions before the data came in
LCDM 1999
No CDM
ΔT (μK)
ℓ
No CDM correctly predicted the second peak...
$A_{1:2}$
Maxima−1
Boomerang
Boomerang
WMAP
WMAP
DASI
NoCDM
LCDM
LCDM
SCDM
year
...but cannot explain the third peak
$A_{2:3}$
NoCDM
LCDM
LCDM
SCDM
WMAP
year

CMB power spectrum



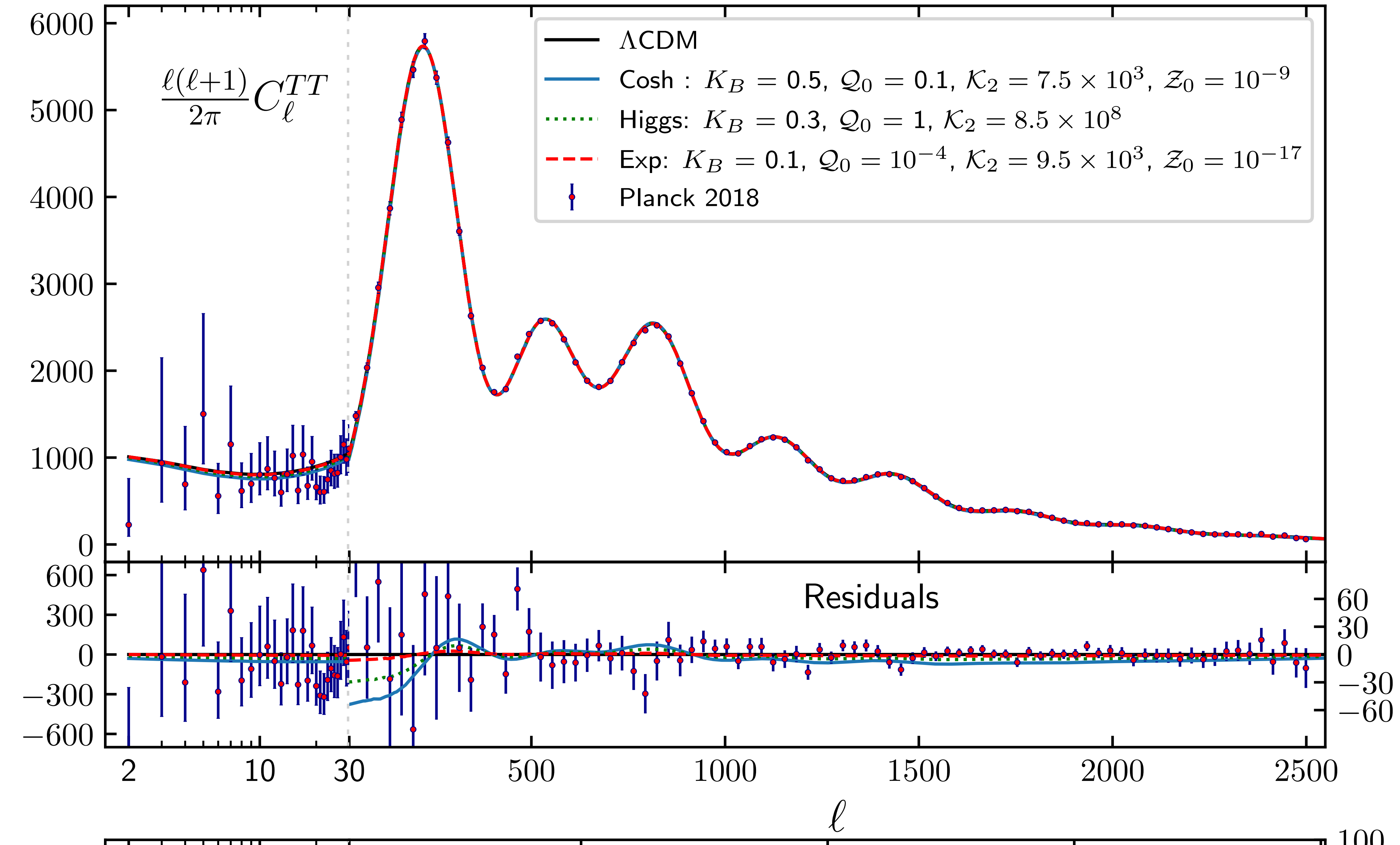
Does it *have* to be CDM?

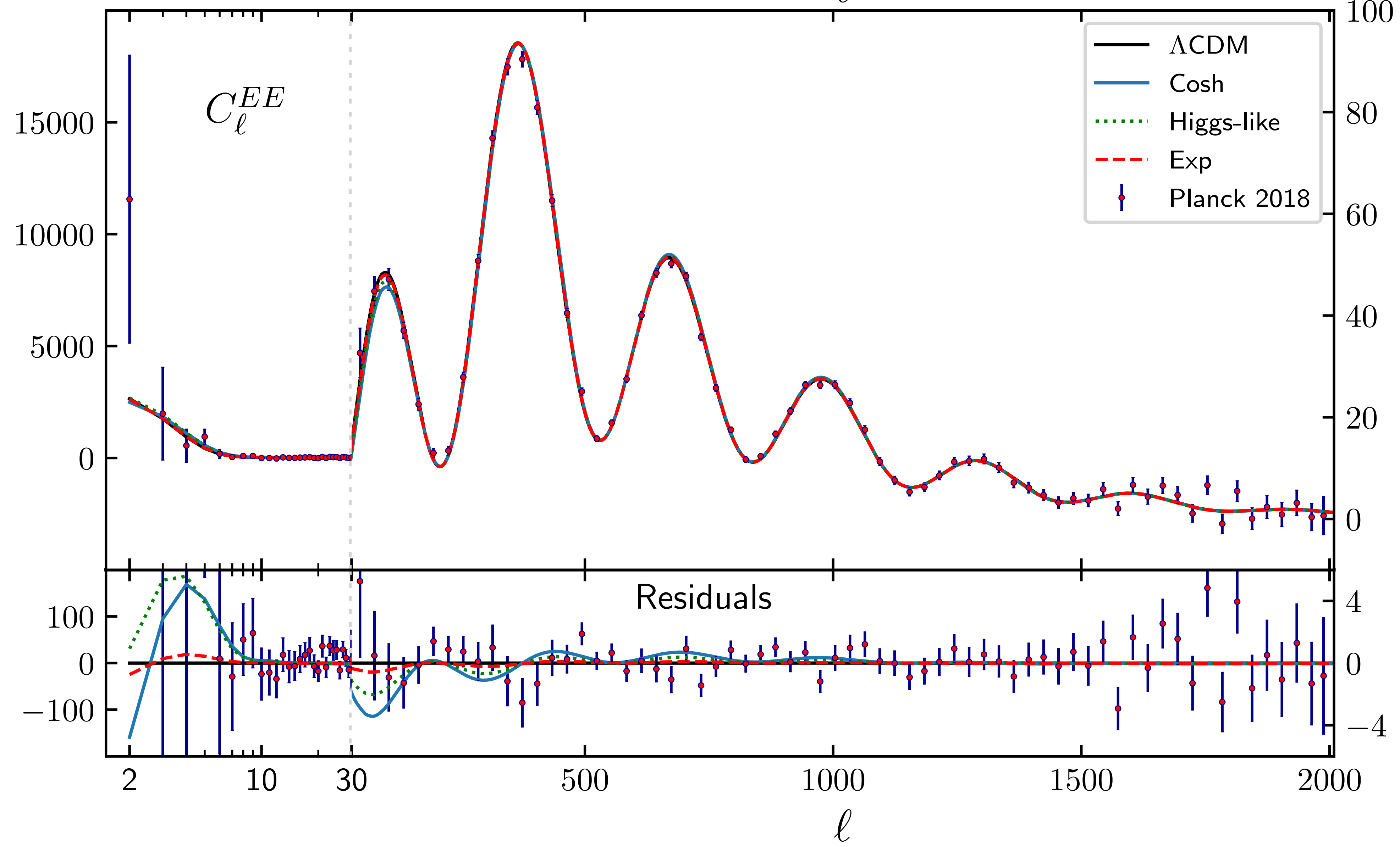
3rd peak strong evidence for physics beyond baryonic drag.

This is usually interpreted to require the existence of non-baryonic cold dark matter, which Planck requires at over 50 σ: $\Omega_{\text{CDM}}h^2 = 0.1206 \pm 0.0021$

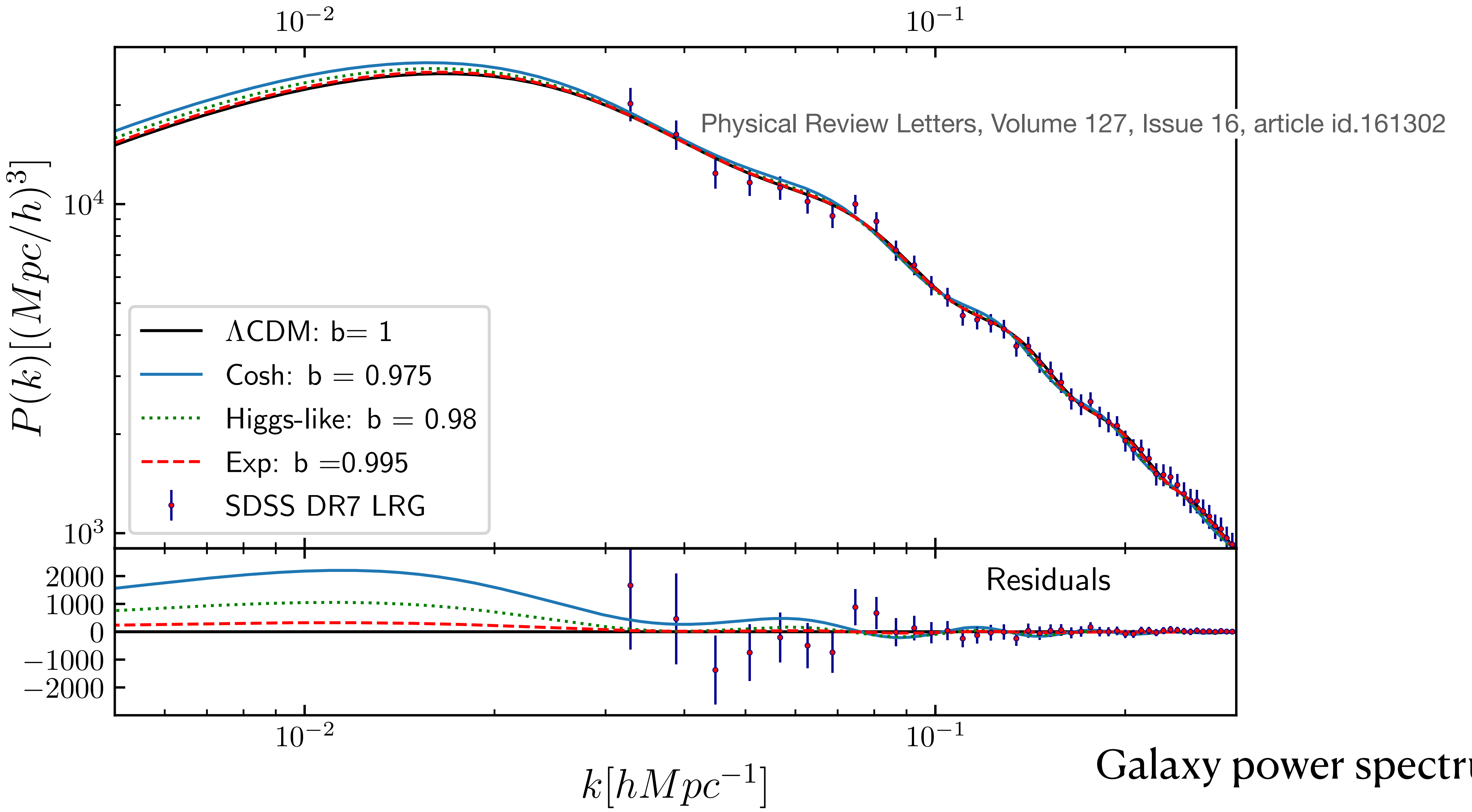
However, the interpretation remains ambiguous - could also be a modification of gravity (e.g., AeST gives an identical power spectrum.) (Skordis & Zlosnik 2021, PRL, 127, 161302)

CMB acoustic power spectrum





CMB polarization power spectrum



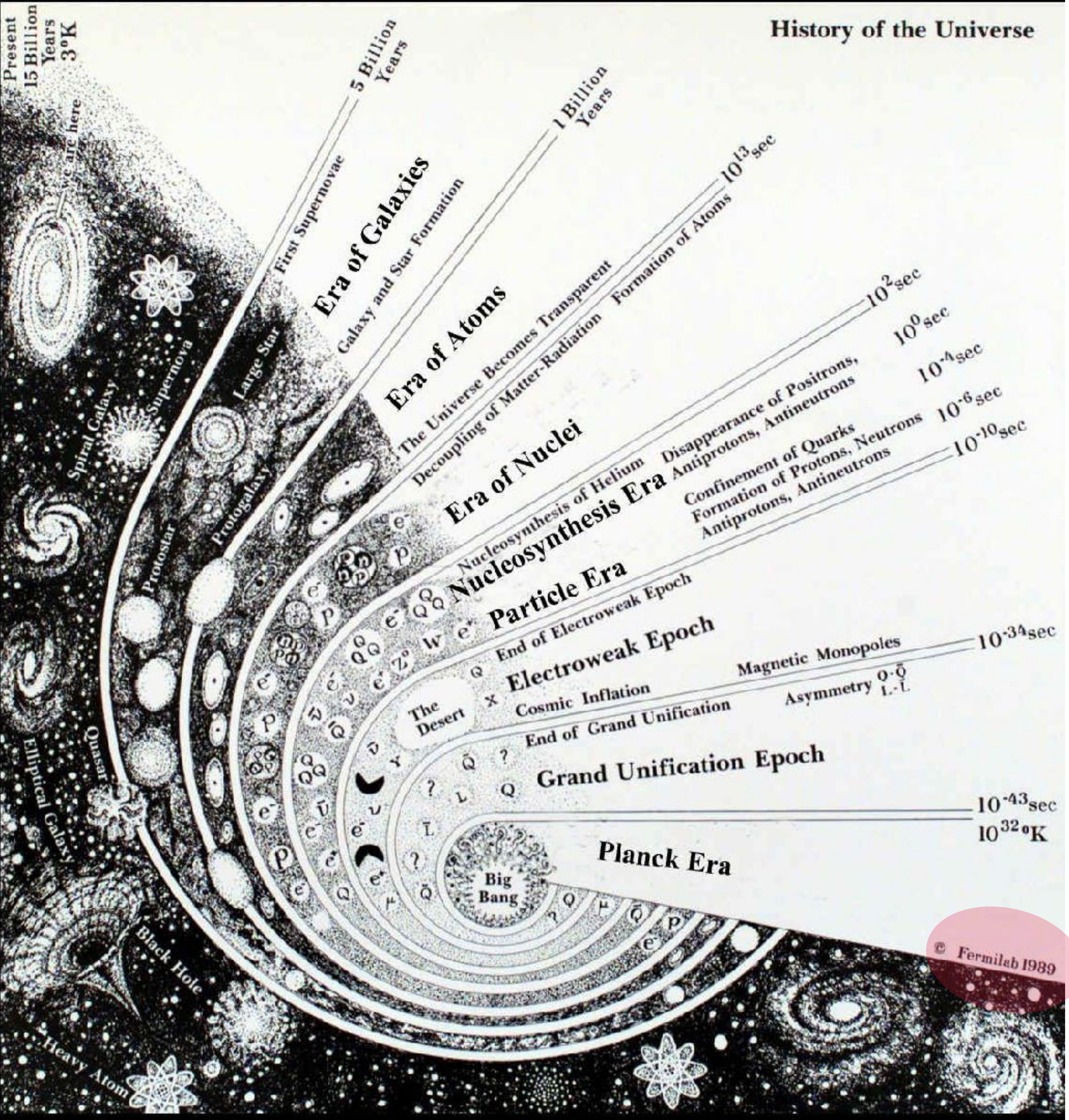
Galaxy power spectrum

"Cosmologists are often wrong, but never in doubt"

- Lev Landau

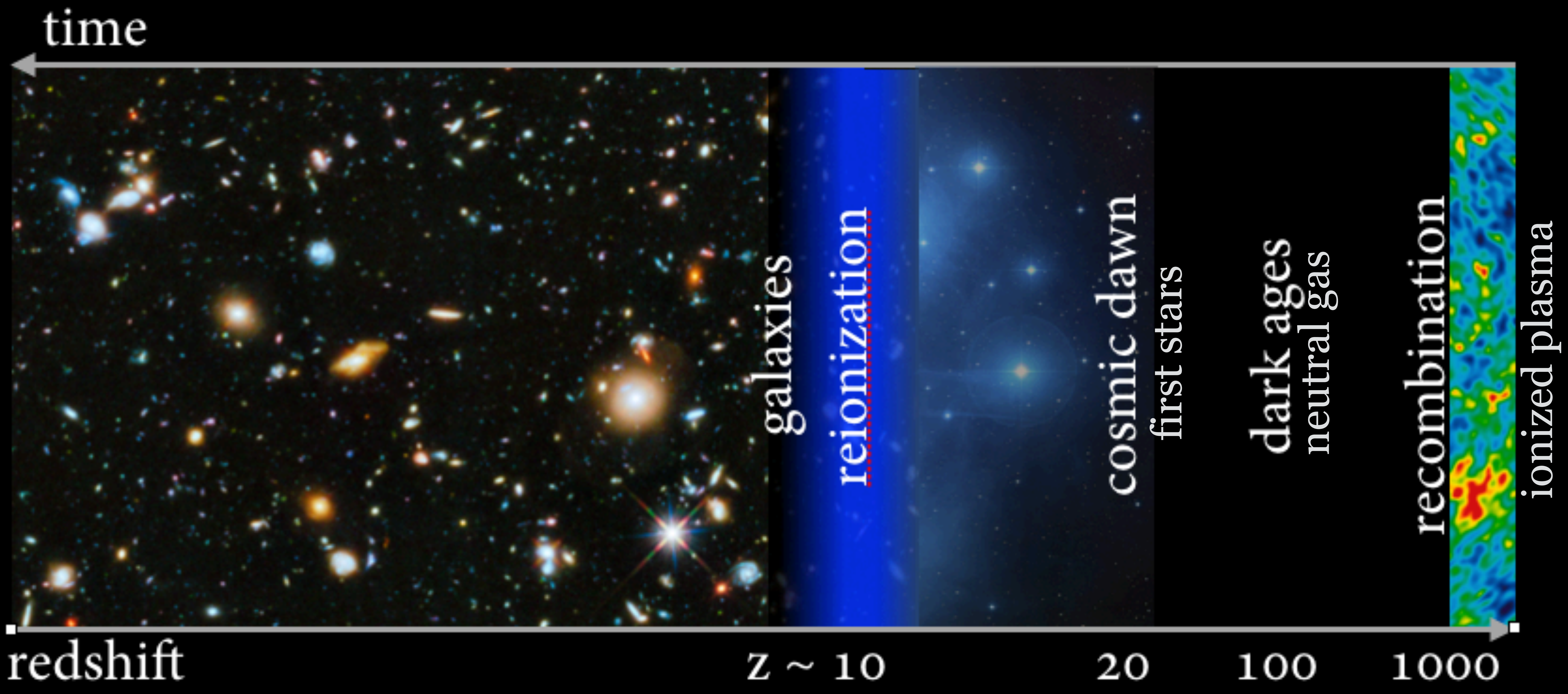
Cosmological parameters by decade

Quantity	"Standard CDM" SCDM 1988	"Concordance model" LCDM 1995	WMAP5 2008	Planck 2018
Ω_m	1	0.35	0.258±0.027	0.315 ± 0.007
Ω_Λ	0	0.65	0.742	0.696 ± 0.009
$\Omega_b h^2$	0.0125 ±0.0025	0.015 0.009 - 0.020 "reasonable range"	0.02273 ±0.00062	0.0224 ±0.0001
H_o	50	65	71.9±2.7	67.4 ± 0.5
dark matter	CDM	CDM	CDM	CDM



Time	Event
$t \sim 10^{-43}$ s	Planck scale (*speculative*)
$t \sim 10^{-38}$ s	GUT scale (*speculative*)
$t \sim 10^{-35}$ s	Inflation (*speculative*)
$t \sim 10^{-12}$ s	Standard Model forces emerge
$t \sim 10^{-8}$ s	WIMPs decouple (*speculative*)
$t \sim 10^{-5}$ s	quarks condense into baryons (*baryogenesis*)
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends
$t \sim 1$ s	neutrinos decouple
$t \sim 4$ s	electron-positron annihilation ends
$t \sim 10^{2}$ s	Big Bang Nucleosynthesis
$t \sim 10^{5}$ yr	Matter-radiation equality
$t \sim 4 \times 10^{5}$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^{6}$ yr	Gas temperature decouples from radiation
$t \sim 10^{7}$ yr	Dark Ages
$t \sim 5 \times 10^{8}$ yr	Cosmic dawn (first stars)
$t \sim 10^{9}$ yr	Galaxies form
$t \sim 4 \times 10^{9}$ yr	Peak star formation
$t \sim 9 \times 10^{9}$ yr	Sun forms
$t \sim 13 \times 10^{9}$ yr	Life on earth

Next frontier: 21 cm absorption at high redshift



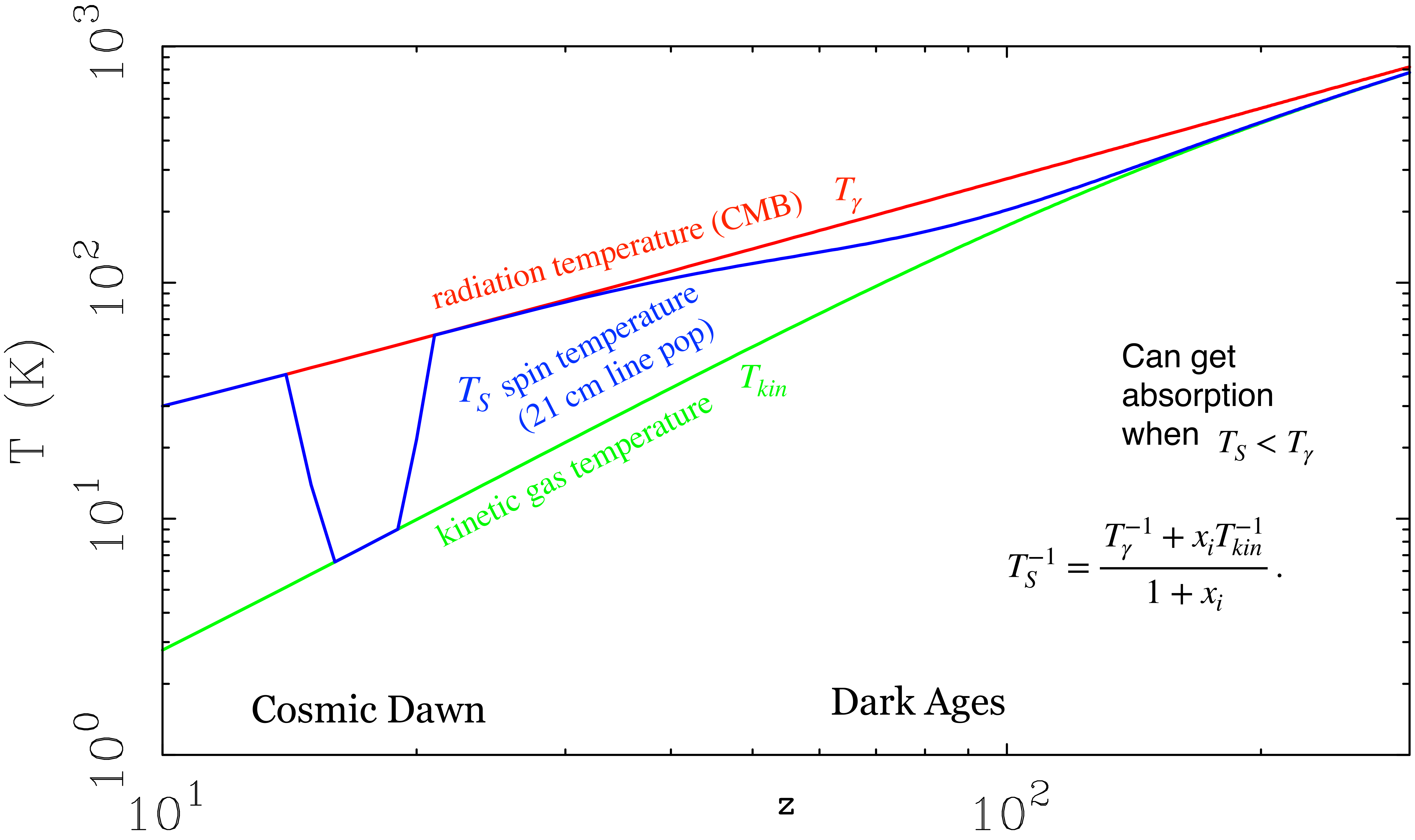
Radio wavelength photons traveling to us from the epoch of recombination can be absorbed by neutral gas during the dark ages and at cosmic dawn

Three Temperatures:

T_γ radiation temperature (the energy of the relic radiation field that is now the CMB)

T_{kin} kinetic temperature (gas kinetic motion - what we normally think of as temperature)

T_S spin temperature (21 cm line - statistical distribution of levels in atomic hydrogen)



$$T_S^{-1} = \frac{T_\gamma^{-1} + x_i T_{kin}^{-1}}{1 + x_i} .$$

Prediction for 21 cm absorption at high redshift

Spin temperature bracketed by the radiation temperature and the kinetic gas temperature:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_i T_{kin}^{-1}}{1 + x_i}.$$

x_i { Dark ages: atomic collisions; Cosmic dawn: Lyman α photons }

x_i couples the spin temperature to the kinetic gas temperature

$T_0 = 20$ mK

$\omega_b = \Omega_b h^2$

$$f_b = \frac{\Omega_b}{\Omega_m}$$

$\mathrm{x_{HI}}$ neutral hydrogen fraction ($\mathrm{x_{HI}} \approx 1$ during the dark ages)

21 cm brightness temperature:

$$T_{21}(z) = T_0 \frac{\mathrm{x_{HI}}}{\mathfrak{h}_z} \left[(1+z) f_b \left(\frac{\omega_b}{0.02} \right) \right]^{1/2} \left(1 - \frac{T_\gamma}{T_S} \right)$$

absorption when $T_S < T_\gamma$

$$\mathfrak{h}_z = \frac{H(z)}{\tilde{H}(z)}$$

$$H^2(z) = H_0^2[\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 - \Omega_k(1+z)^2]$$

$$\tilde{H}(z) = H_0 \Omega_m^{1/2}(1+z)^{3/2}$$ → (This is an approximation)

Expansion history specifies path-length photons must traverse.

This usual approximation $\tilde{H}(z)$ may not suffice.

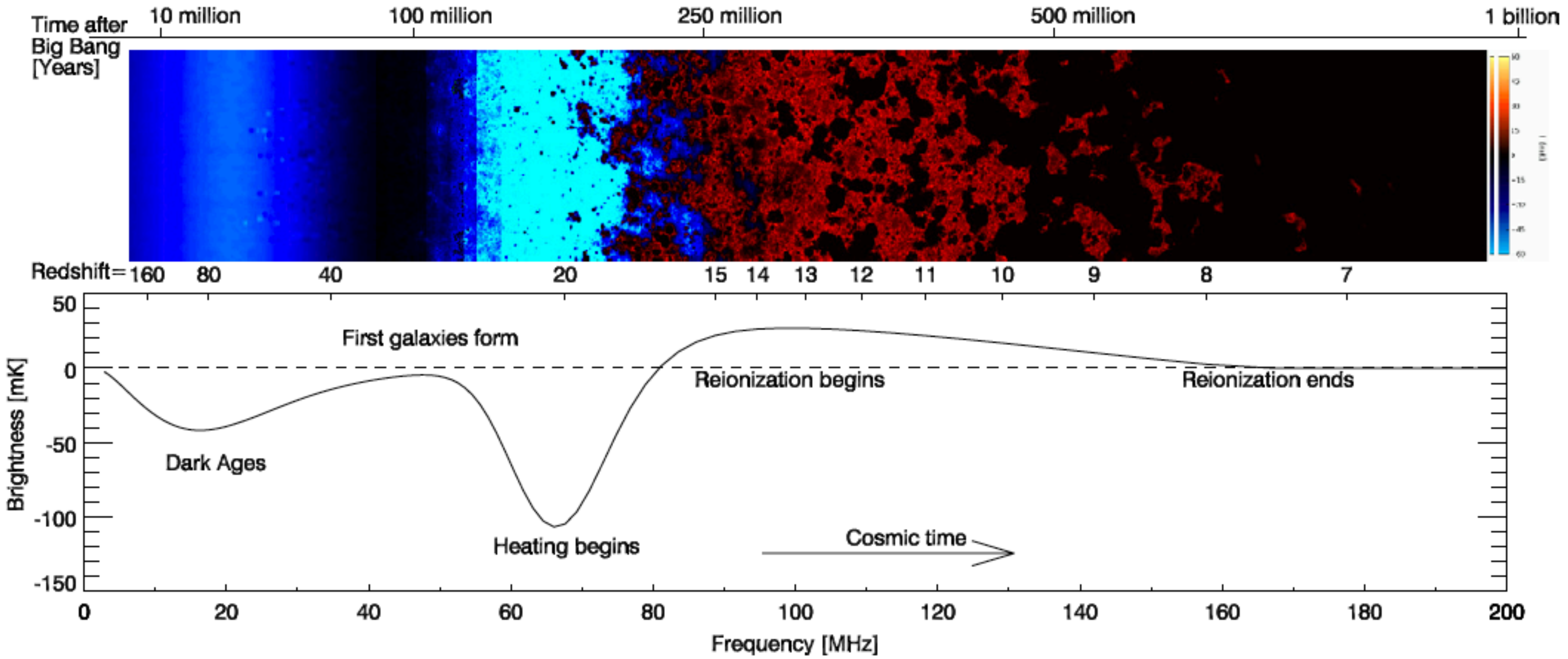


Figure 1. The 21 cm cosmic hydrogen signal. (*a*) Time evolution of fluctuations in the 21 cm brightness from just before the first stars formed through to the end of the reionization epoch. This evolution is pieced together from redshift slices through a simulated cosmic volume [1]. Coloration indicates the strength of the 21 cm brightness as it evolves through two absorption phases (purple and blue), separated by a period (black) where the excitation temperature of the 21 cm hydrogen transition decouples from the temperature of the hydrogen gas, before it transitions to emission (red) and finally disappears (black) owing to the ionization of the hydrogen gas. (*b*) Expected evolution of the sky-averaged 21 cm brightness from the 'Dark Ages' at redshift 200 to the end of reionization, sometime before redshift 6 (solid curve indicates the signal; dashed curve indicates $T_b = 0$). The frequency structure within this redshift range is driven by several physical processes, including the formation of the first galaxies and the heating and ionization of the hydrogen gas. There is considerable uncertainty in the exact form of this signal, arising from the unknown properties of the first galaxies. Reproduced with permission from [2]. Copyright 2010 Nature Publishing Group.