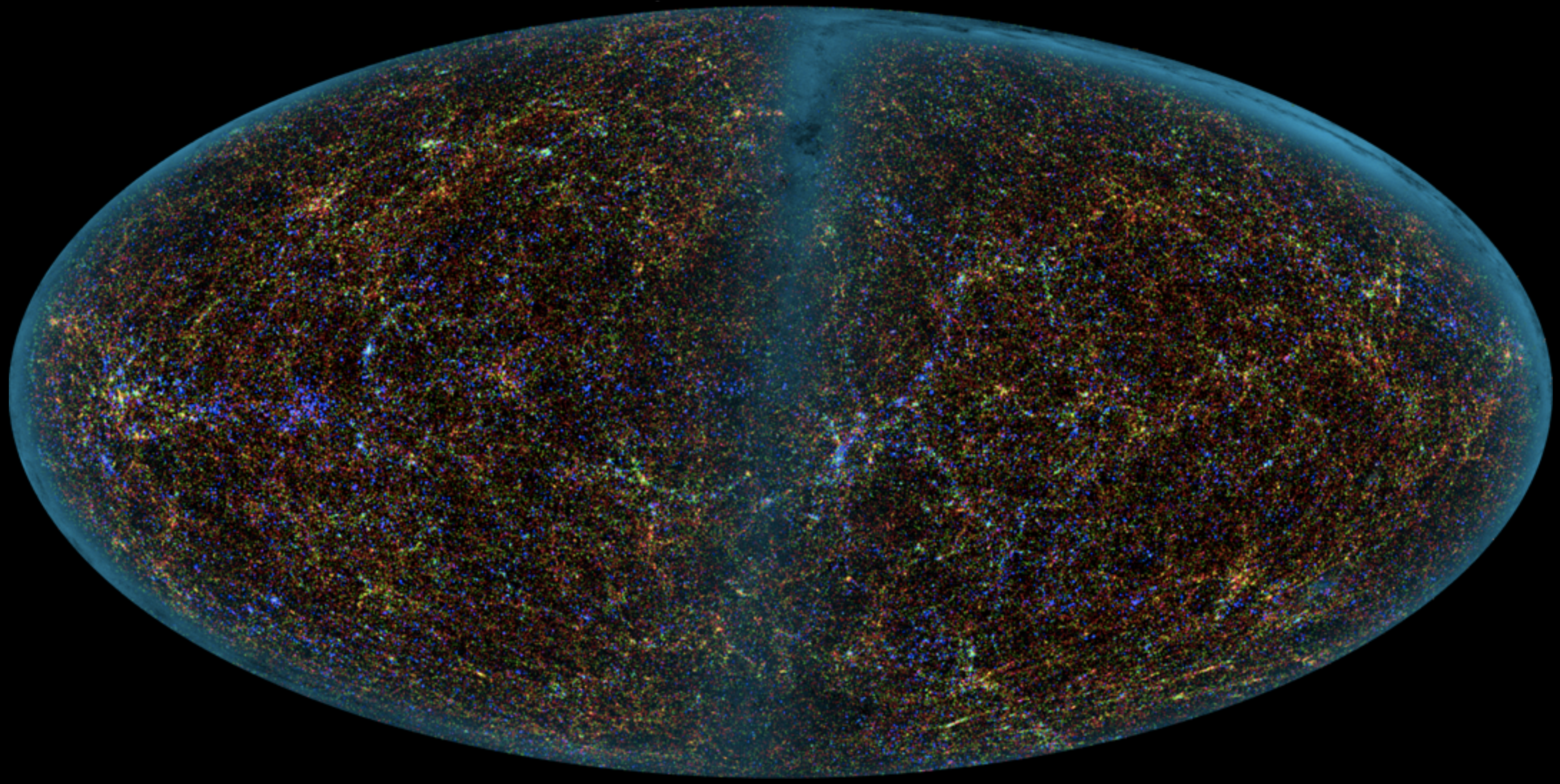
Cosmology

and Large Scale Structure



Today
More CMB
Reionization

Next time: Review, Homework 5 due
One week hence: Exam

1 December 2022

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

CMB power spectrum

Etc. pole

$\ell = 1,2,3$

$\ell = 4,5,6$

$\ell = 7,8,9$

$\ell = 10,11,12$

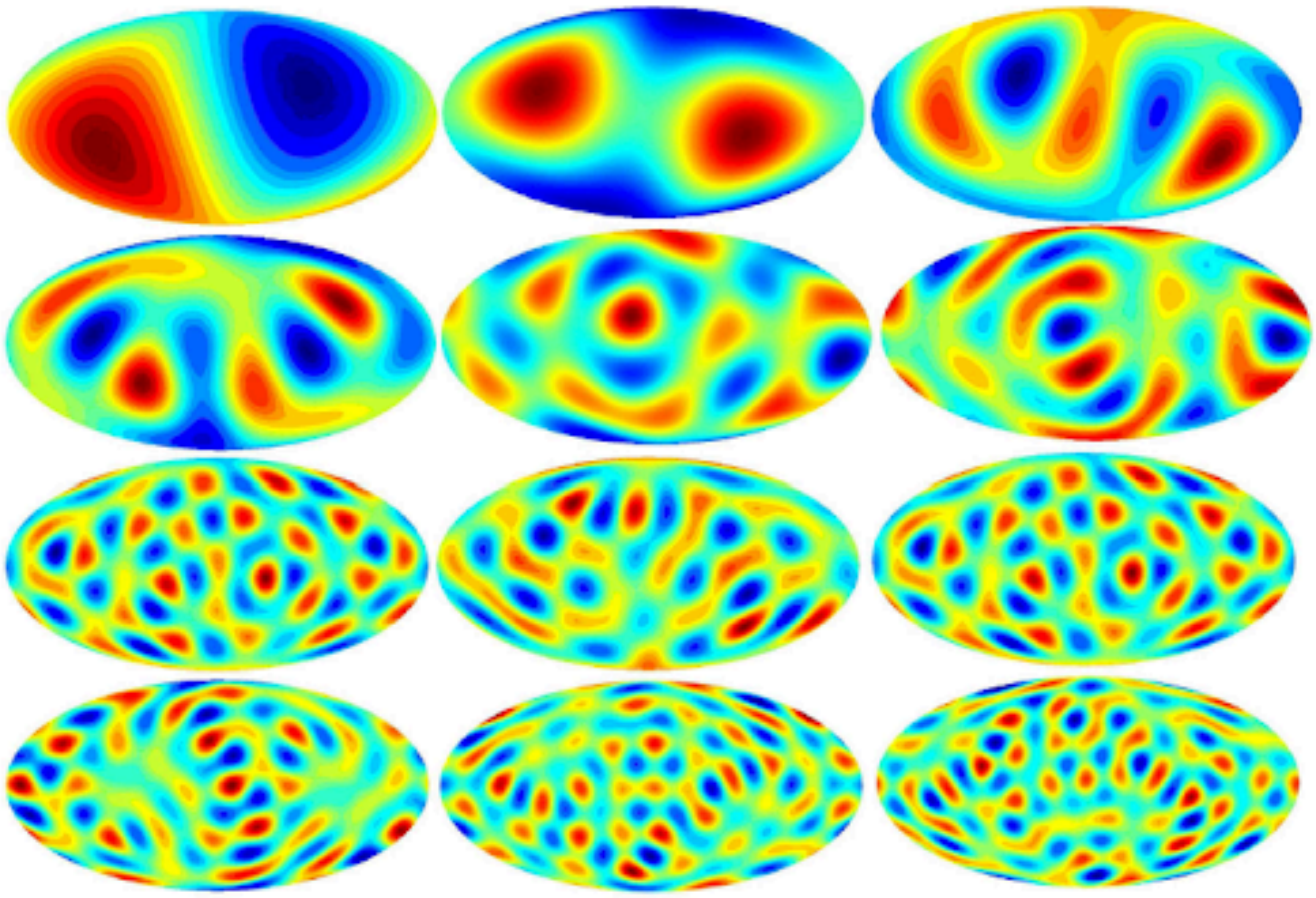
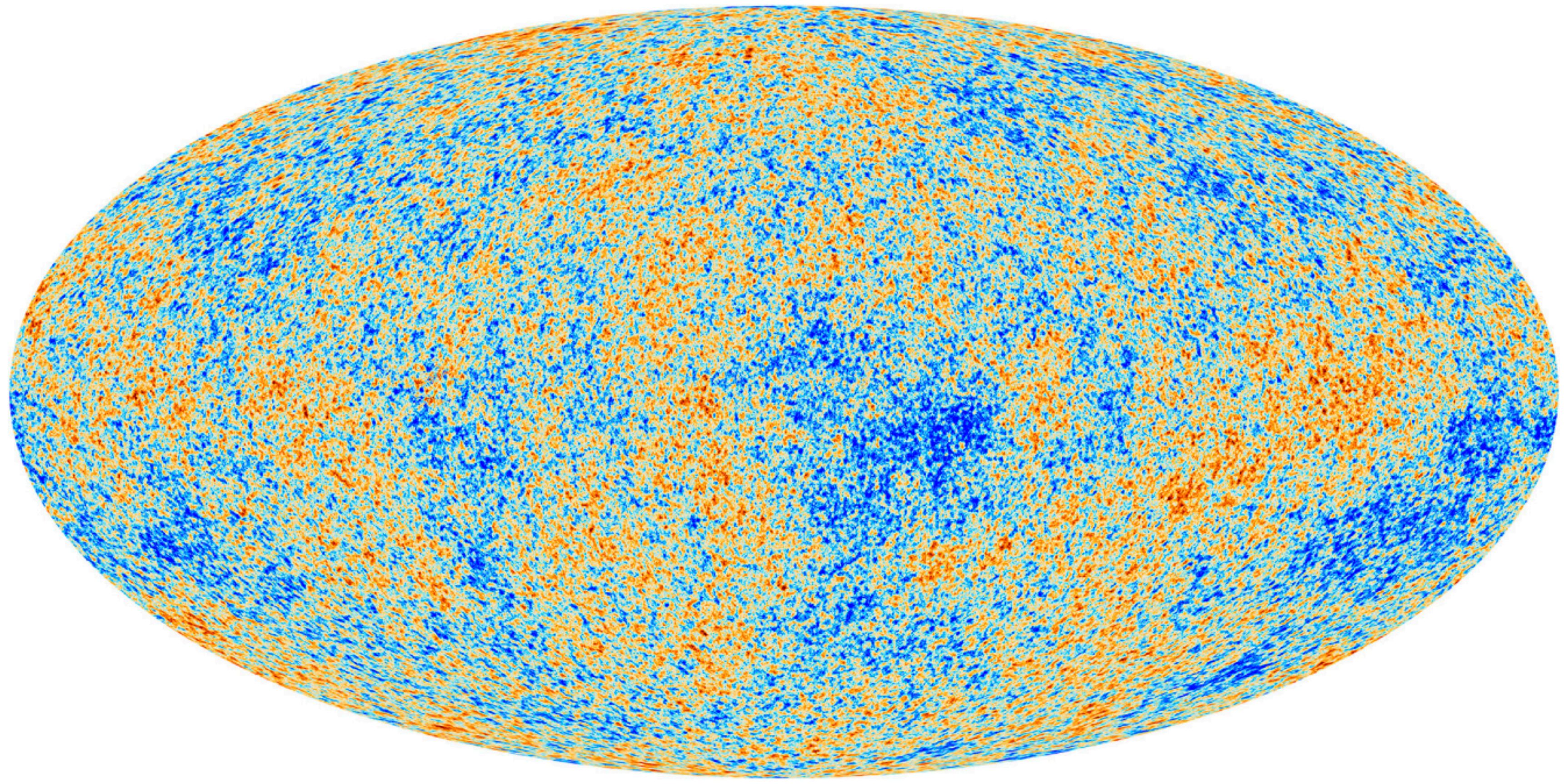


Figure 6: Randomly generated skies containing only a single multipole ℓ. Staring from top left: $\ell = 1$ (dipole only), 2 (quadrupole only), 3 (octupole only), 4, 5, 6, 7, 8, 9, 10, 11, 12. Figure by Ville Heikkilä.



Spherical harmonics provide a convenient way to decompose the fluctuations observed on the sky

$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} A_{\ell m} Y_{\ell m}$$

with Fourier transform

$$A_{\ell m} = \int_{\text{sky}} \frac{\Delta T}{T}(\theta, \phi) Y^*_{\ell m} d\Omega$$

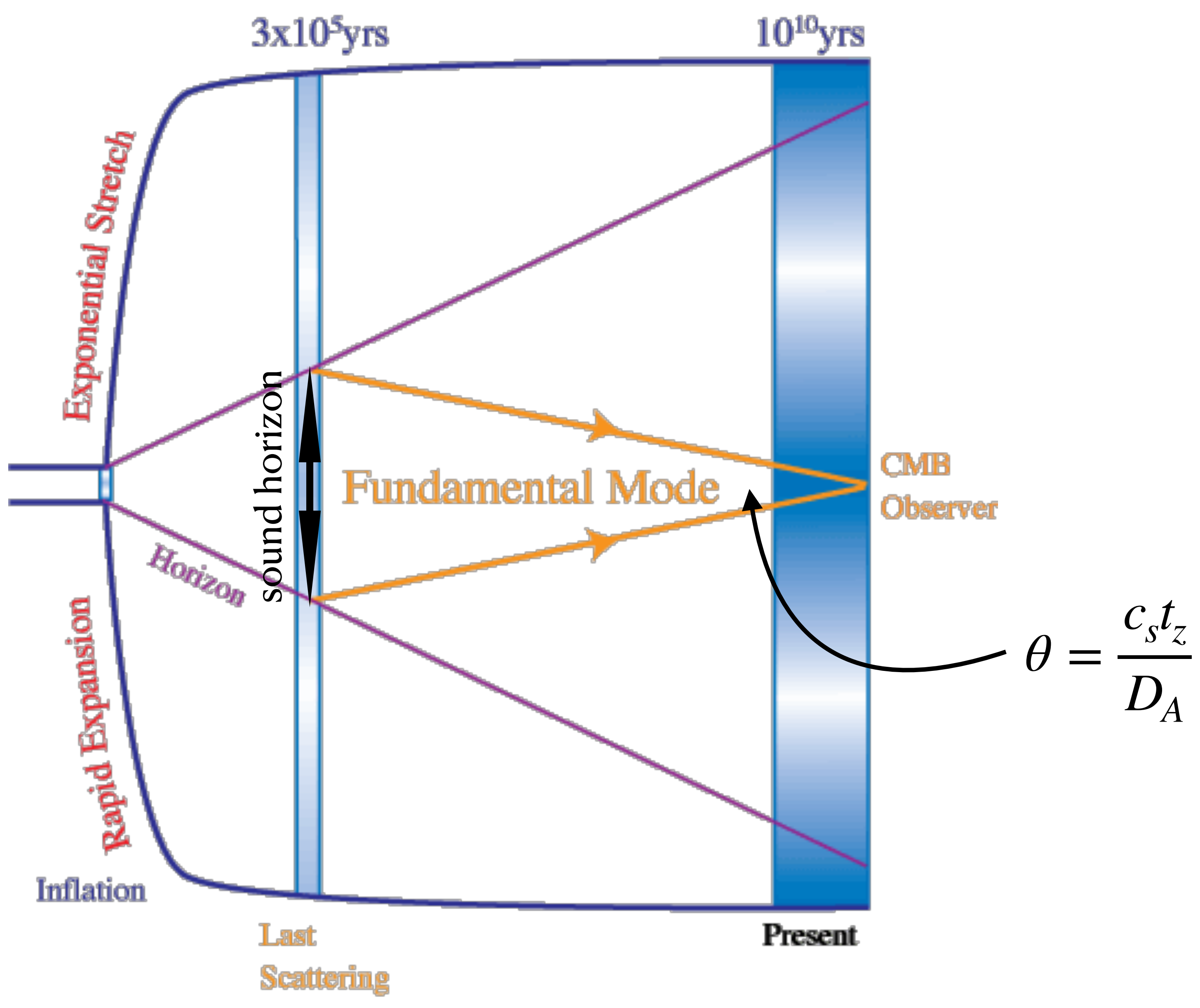
giving the power in fluctuations on an angular scale $\frac{\pi}{\ell}$

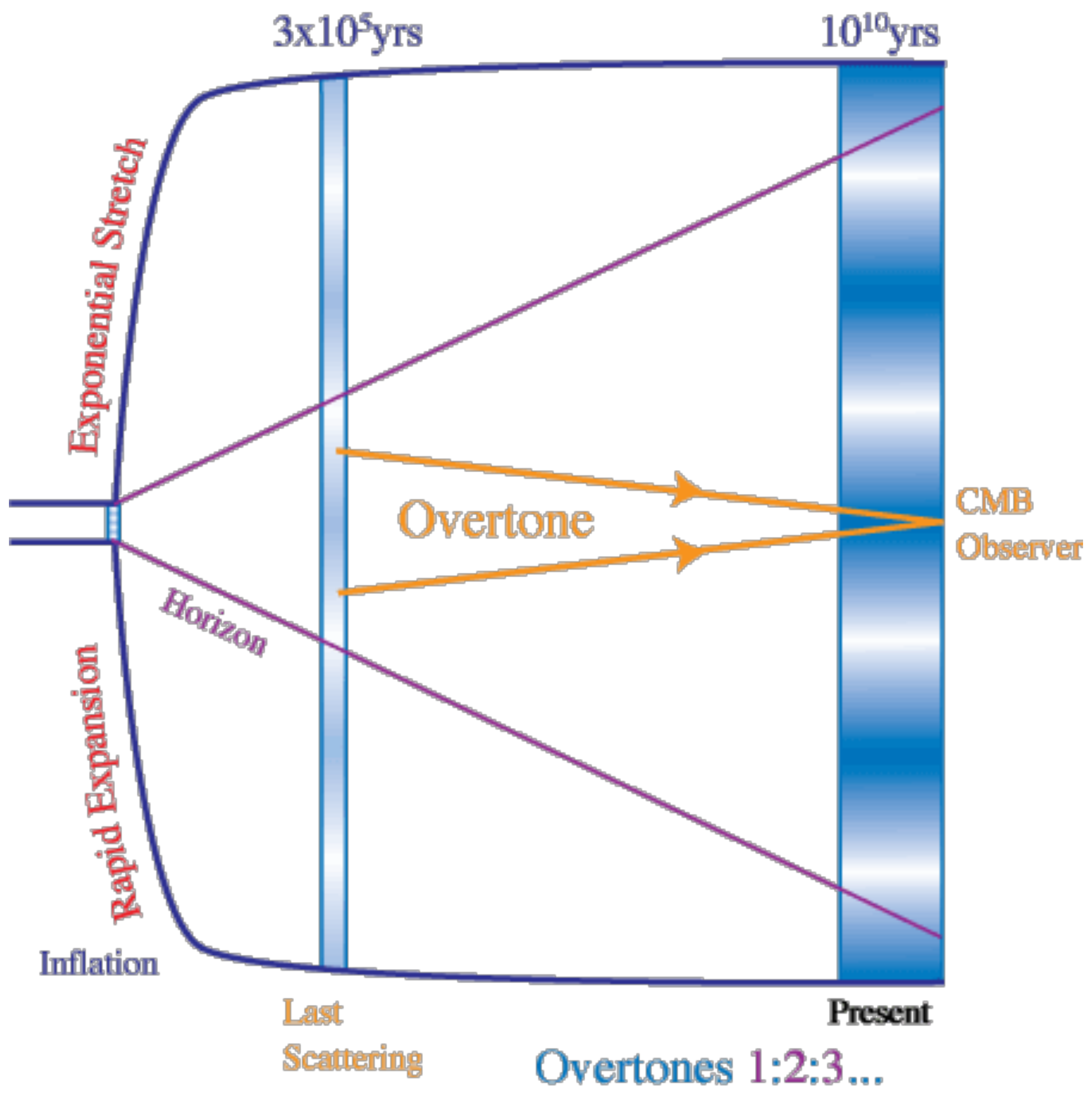
$$C_\ell = \frac{1}{2\ell + 1} \sum_m A_{\ell m} A^*_{\ell m} = \langle |A_{\ell m}|^2 \rangle$$

note: $1^\circ = 0.0175$ radians so one degree corresponds to $\frac{\pi}{\ell} = 0.0175$, hence $\ell = 180$.
Multipole ℓ varies inversely with angular scale.

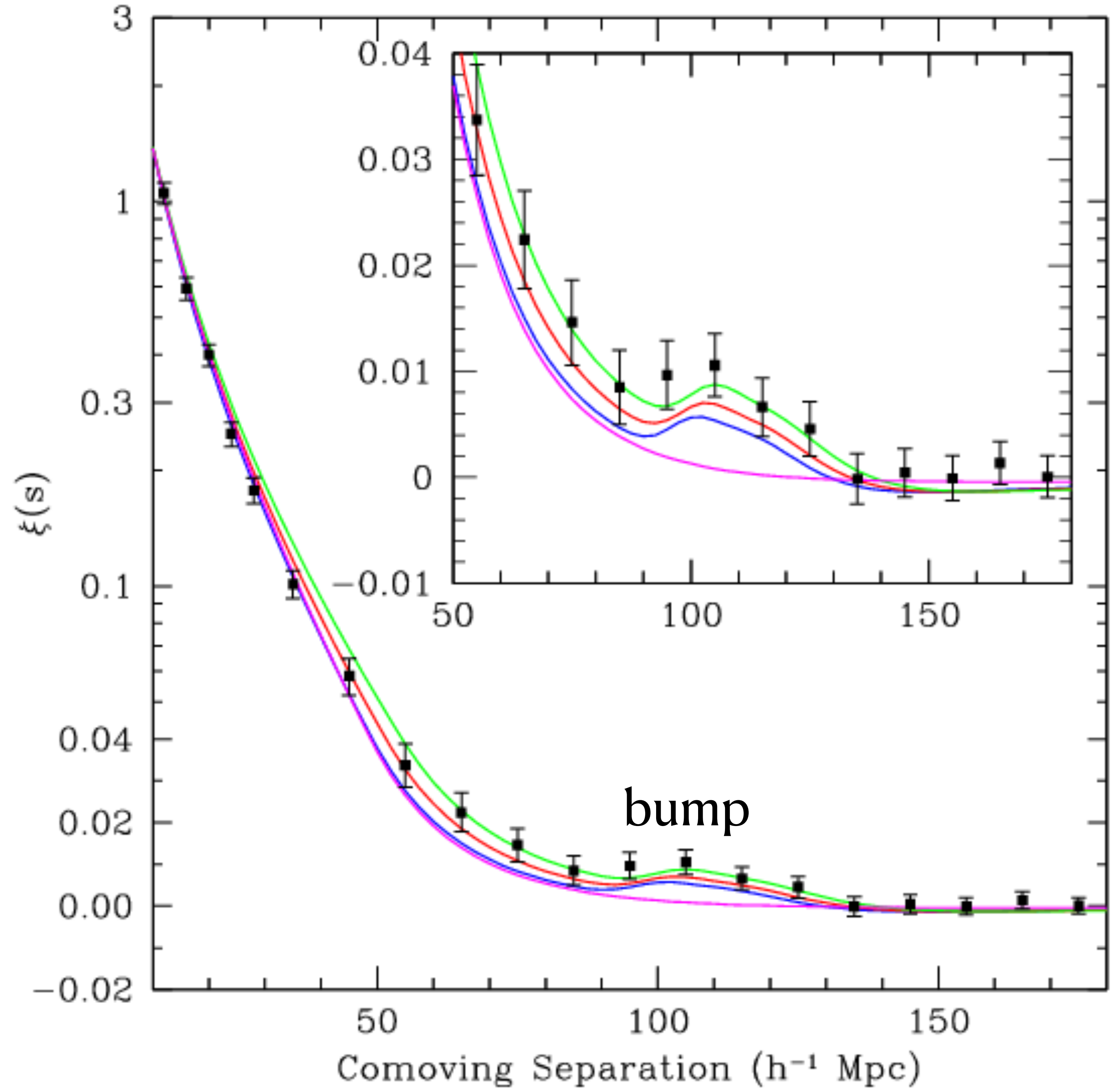
CMB power spectrum

Detailed shape of the acoustic power spectrum depends sensitively on cosmic parameters.
First and foremost, the location of the first peak measures the angular diameter distance to the surface of last scattering. This is the best evidence that the universe is very nearly flat: $\Omega_k = -0.011 \pm 0.006$ (Planck X 2018)





Baryon acoustic oscillation in galaxy correlation function



Eisenstein et al. (2005)

From Wayne Hu's CMB tutorial - http://background.uchicago.edu/index.html

CMB power spectrum

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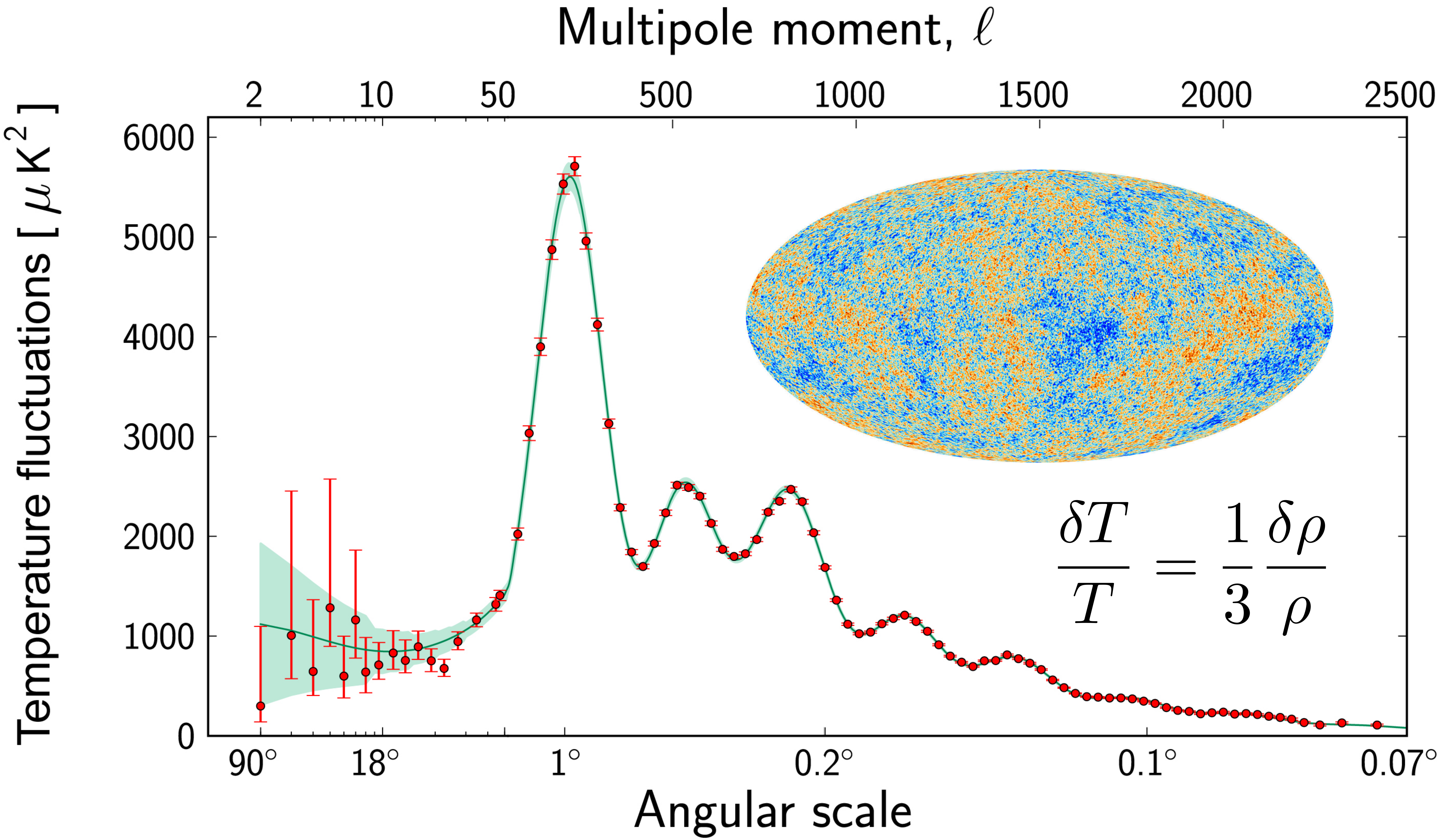
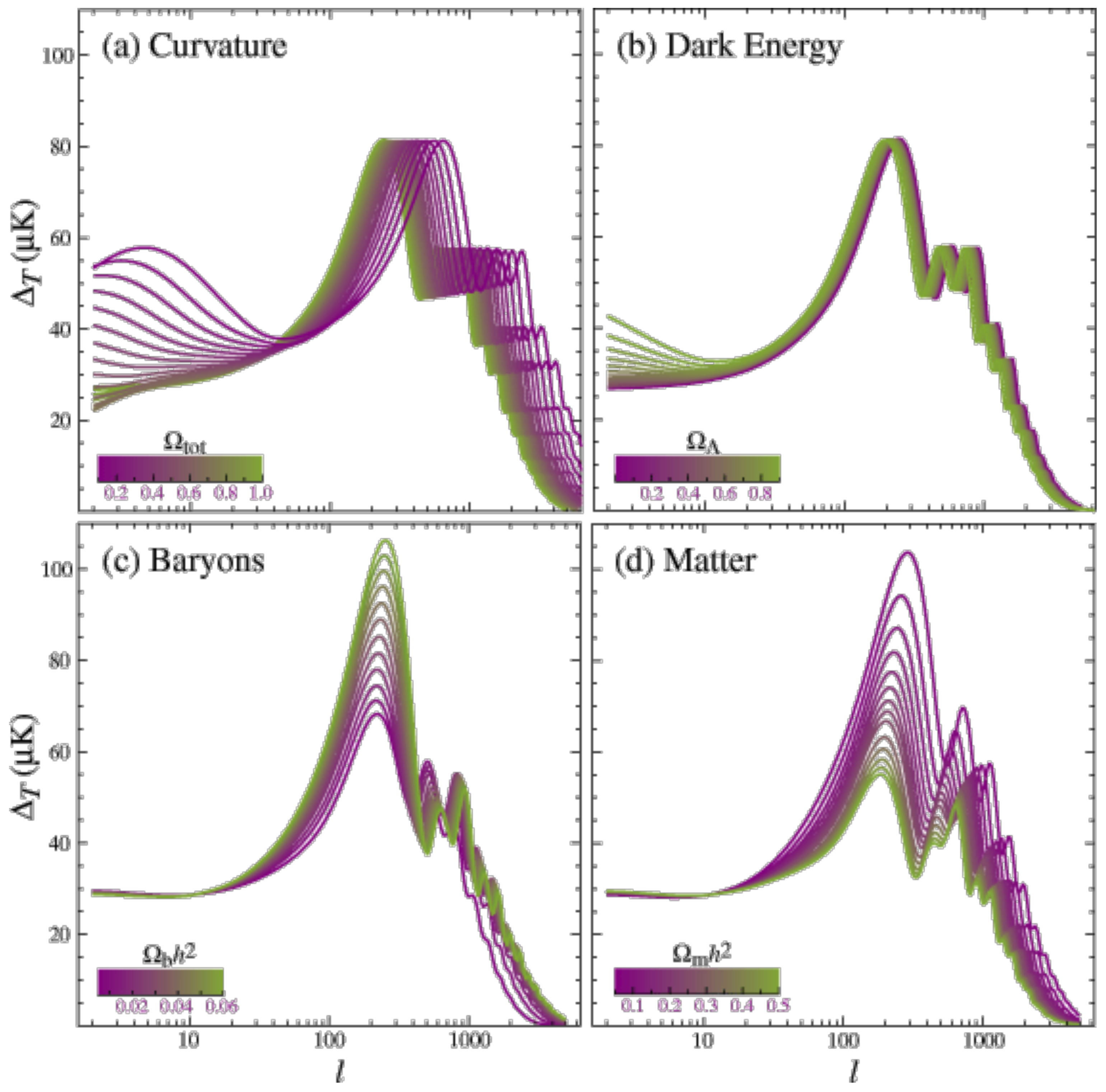


CMB power spectrum

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.

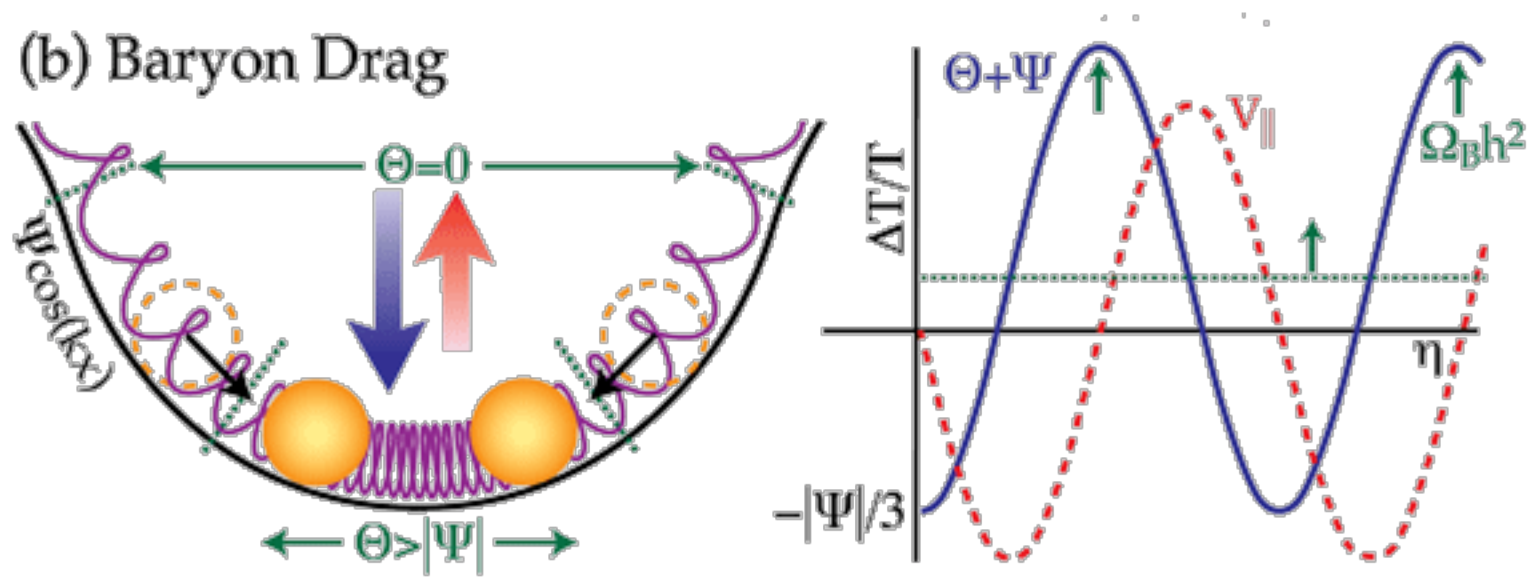
Compression and rarefaction nearly cancel out, but don't quite. Left with

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

Damped and driven oscillator

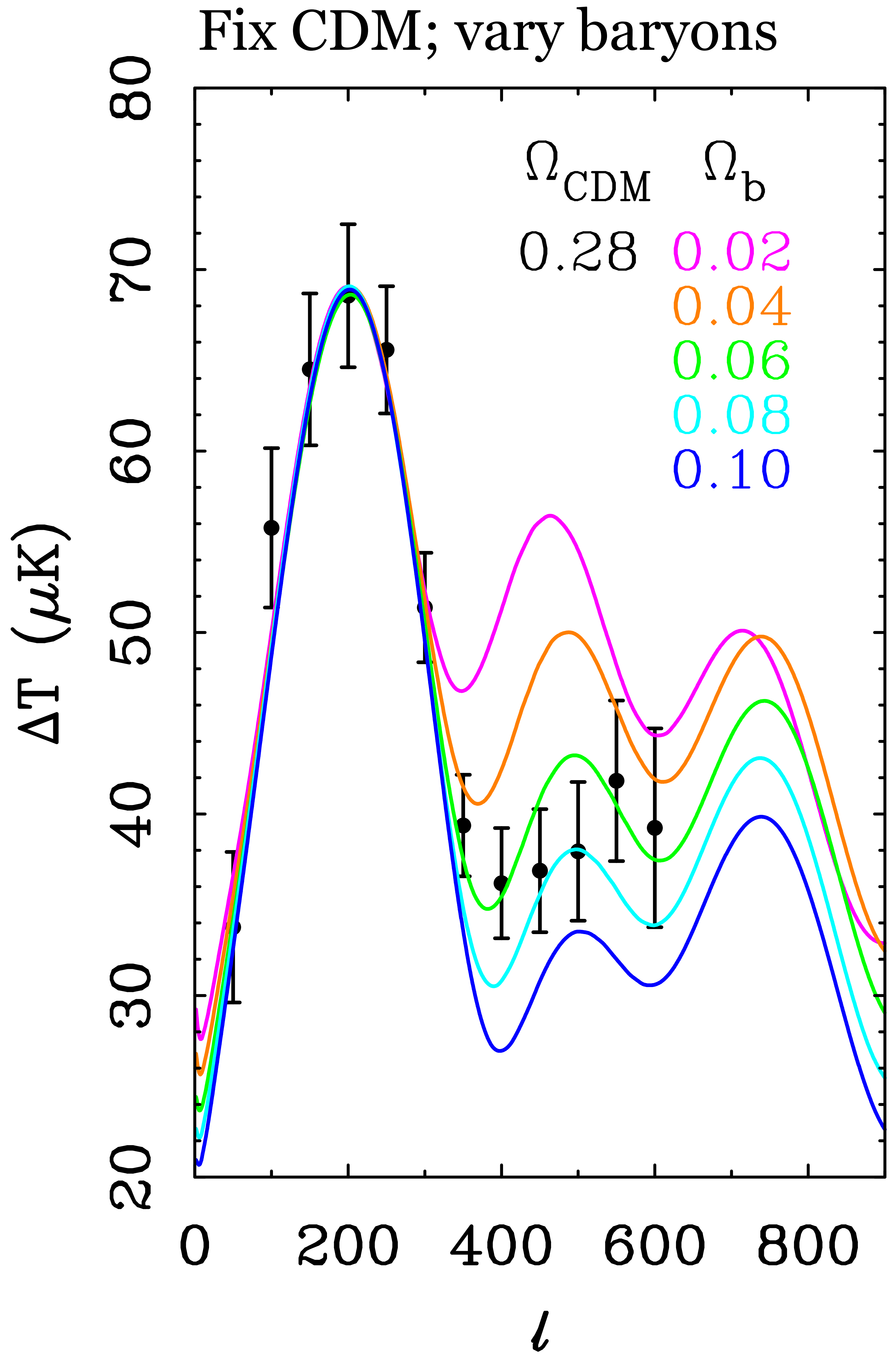
Baryons damp oscillations, like a kid dragging his feet on a swing.
pure damping spectrum in limit of all baryons

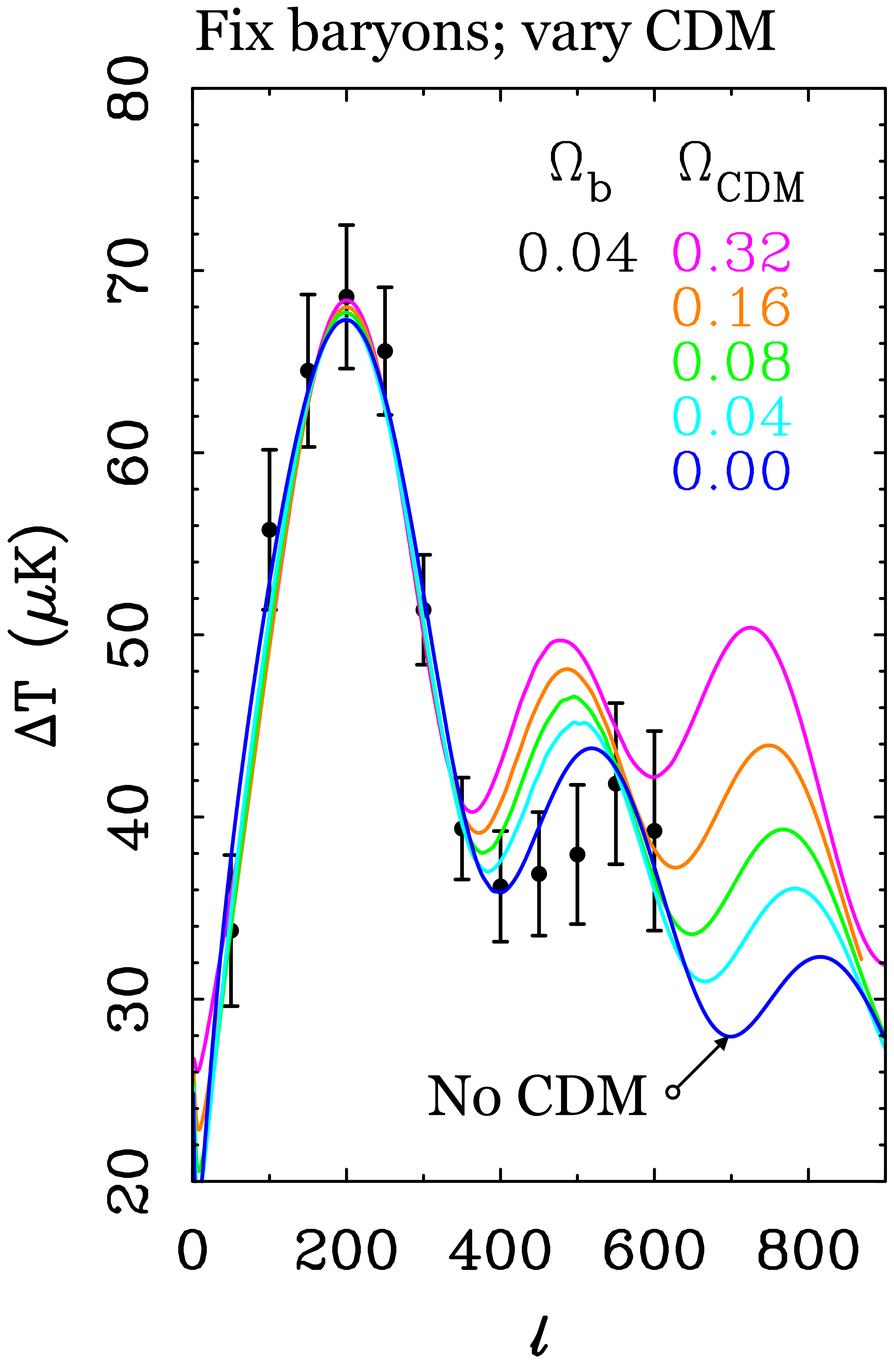
Dark matter helps drive oscillations, like a parent pushing the kid.



Wayne Hu provides a nice CMB tutorial at http://background.uchicago.edu/index.html

CMB dependence on the density of baryonic and non-baryonic matter





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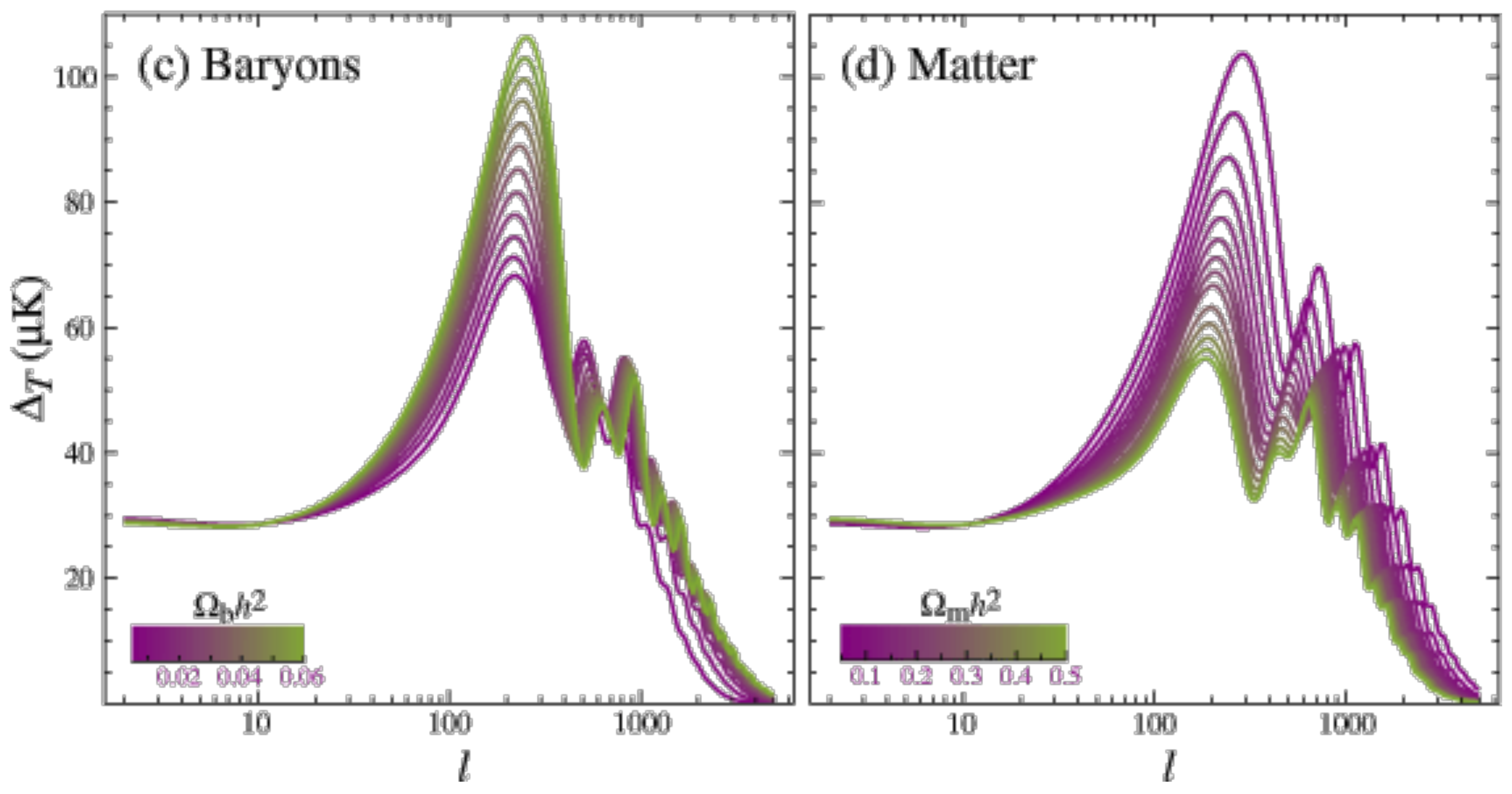
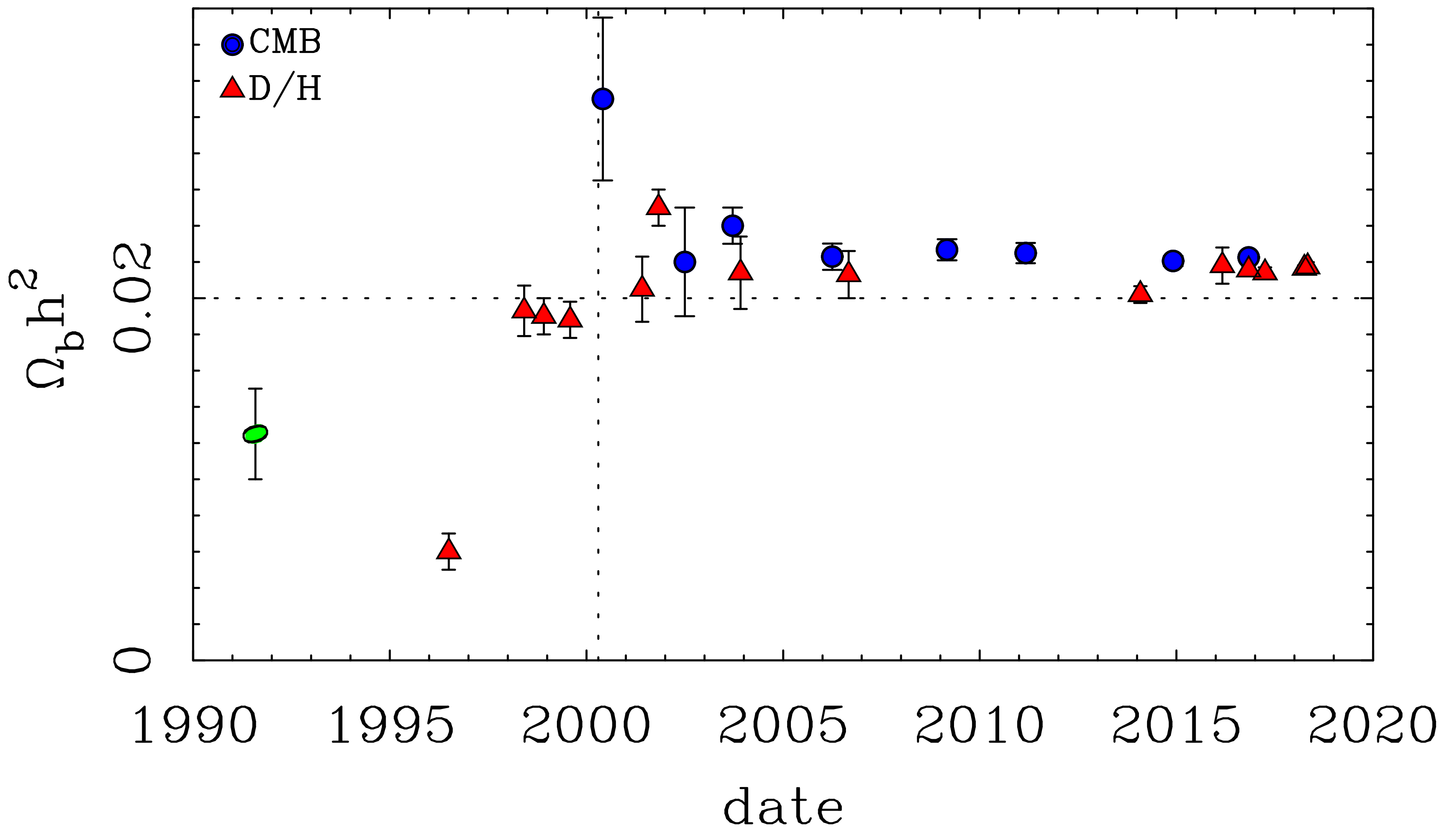
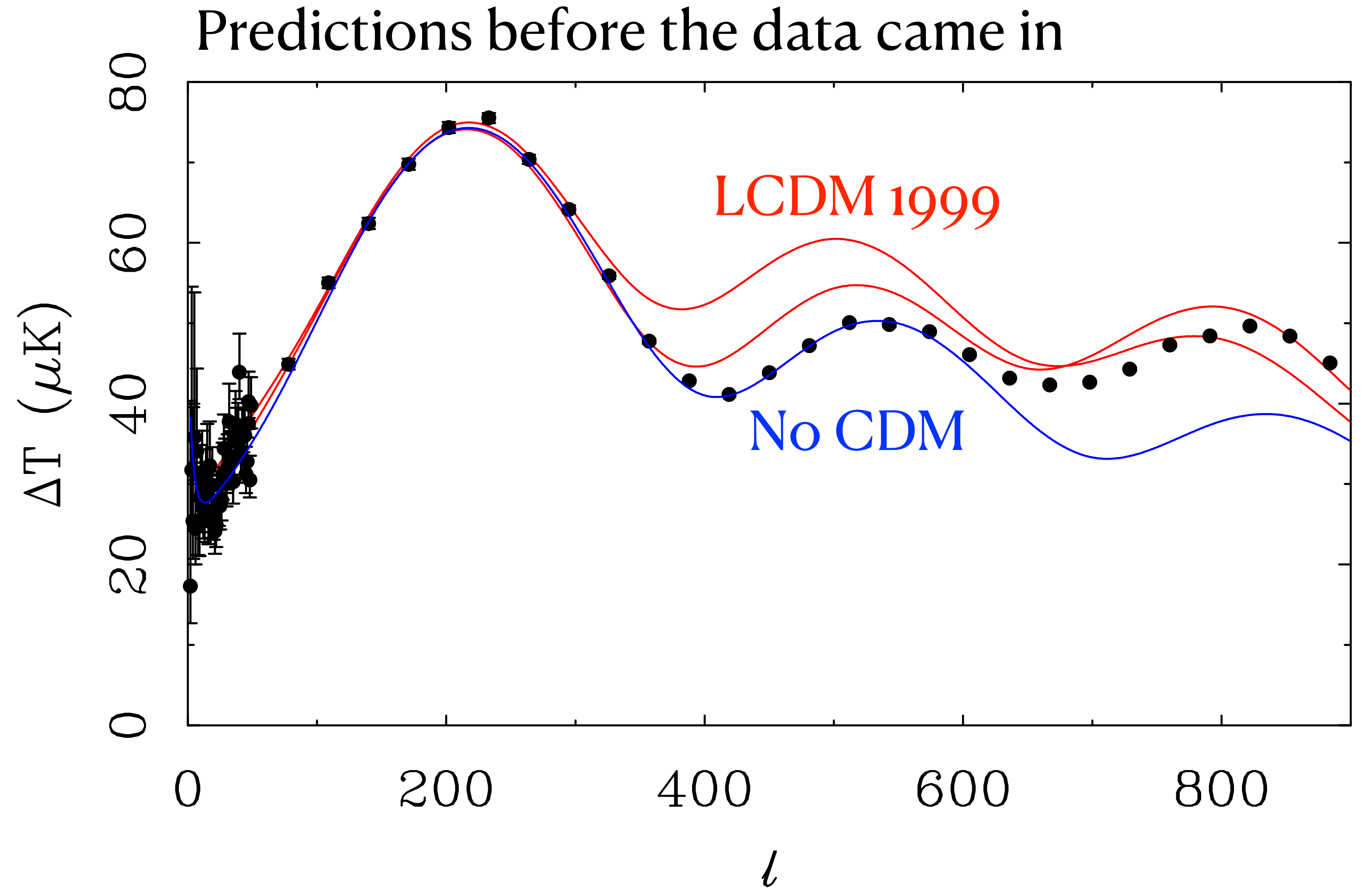
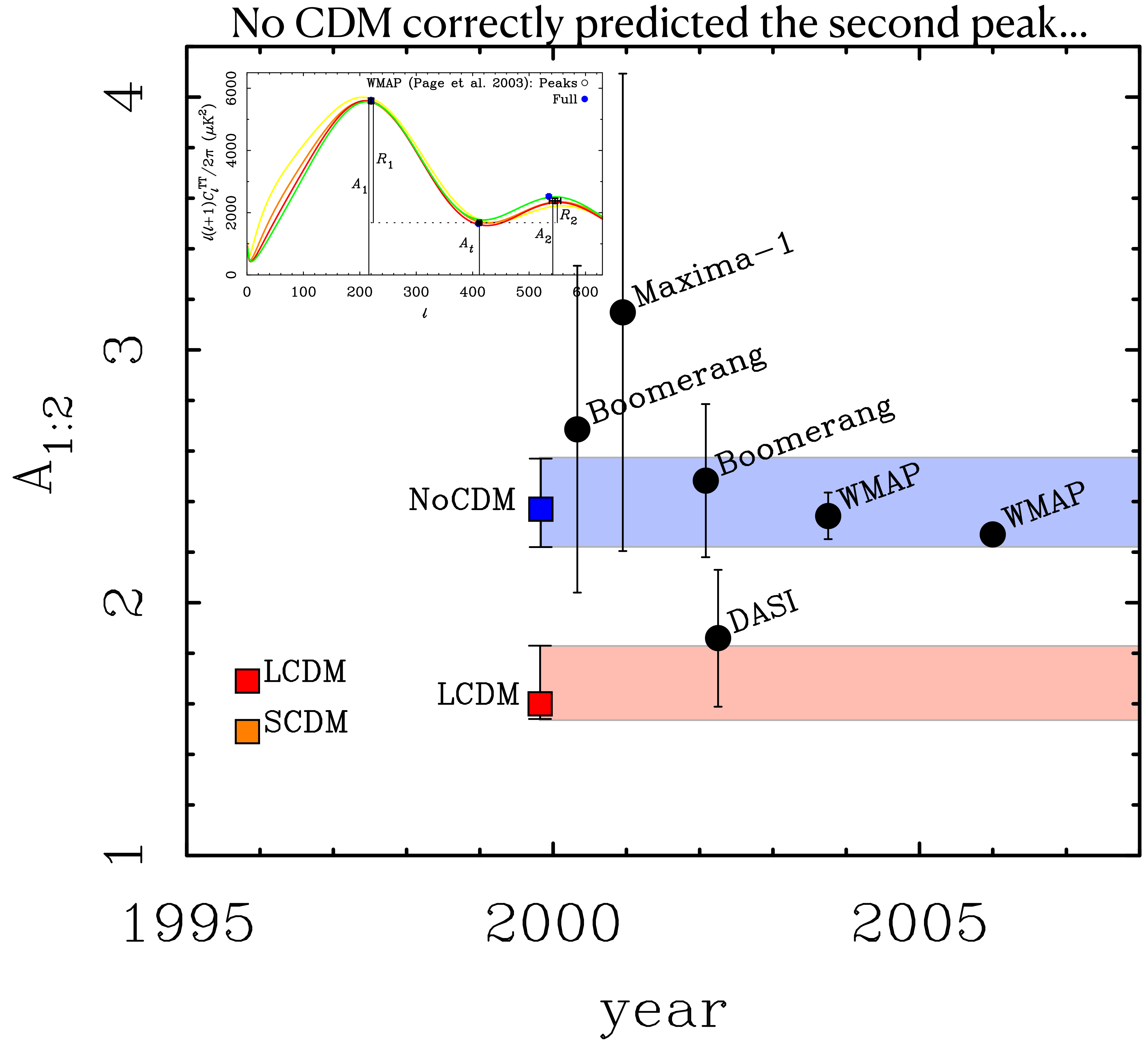
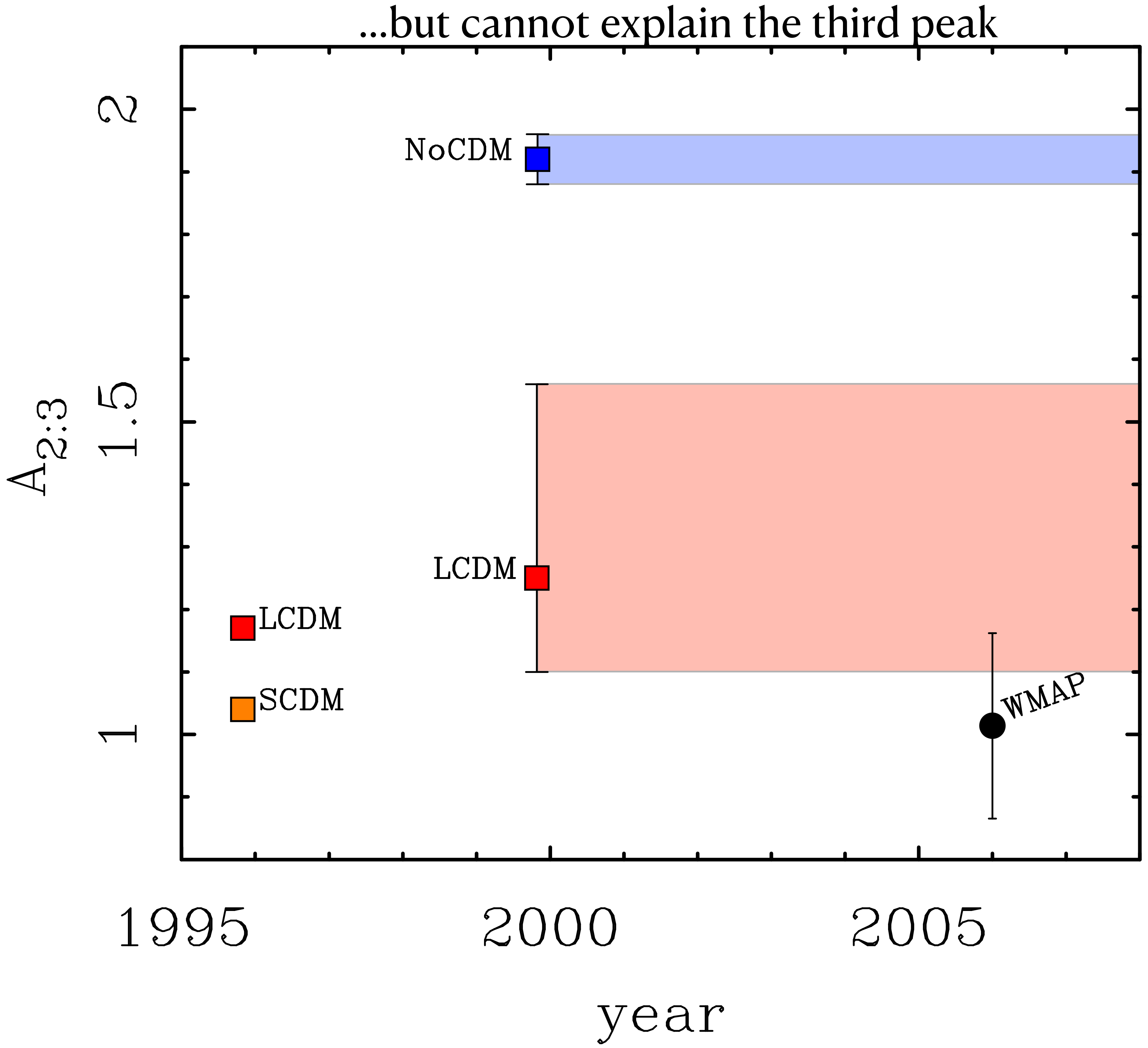


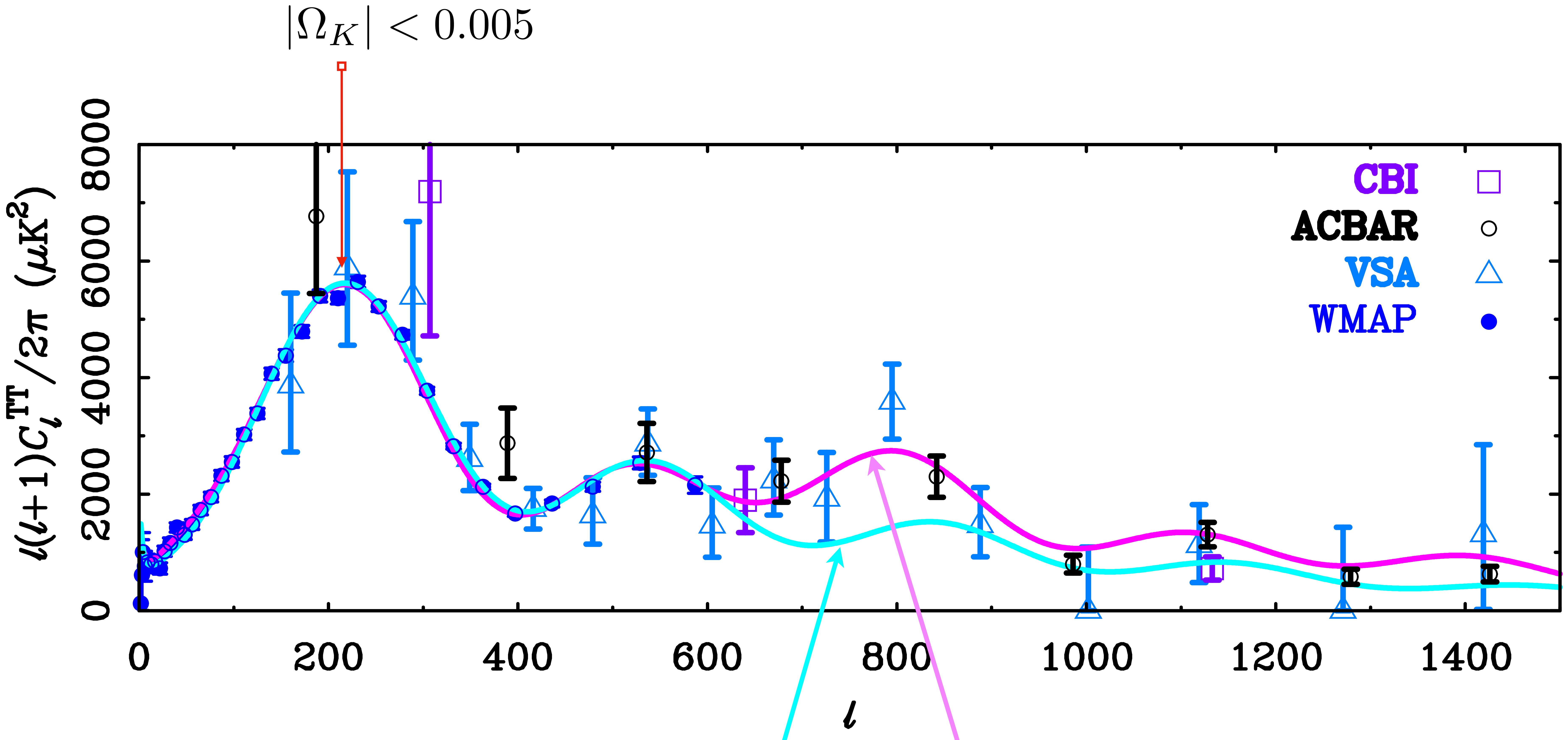

CMB
D/H
$\Omega_b h^2$
0
0.02
1990
1995
2000
2005
2010
2015
2020
date


Predictions before the data came in
LCDM 1999
No CDM
ΔT (μK)
0
20
40
60
80
0
200
400
600
800
ℓ


No CDM correctly predicted the second peak...
$A_{1:2}$
1
2
3
4
1995
2000
2005
year
WMAP (Page et al. 2003): Peaks
Full
Maxima-1
Boomerang
Boomerang
WMAP
WMAP
DASI
NoCDM
LCDM
LCDM
SCDM


...but cannot explain the third peak
$A_{2:3}$
1
1.5
2
1995
2000
2005
year
NoCDM
LCDM
LCDM
SCDM
WMAP

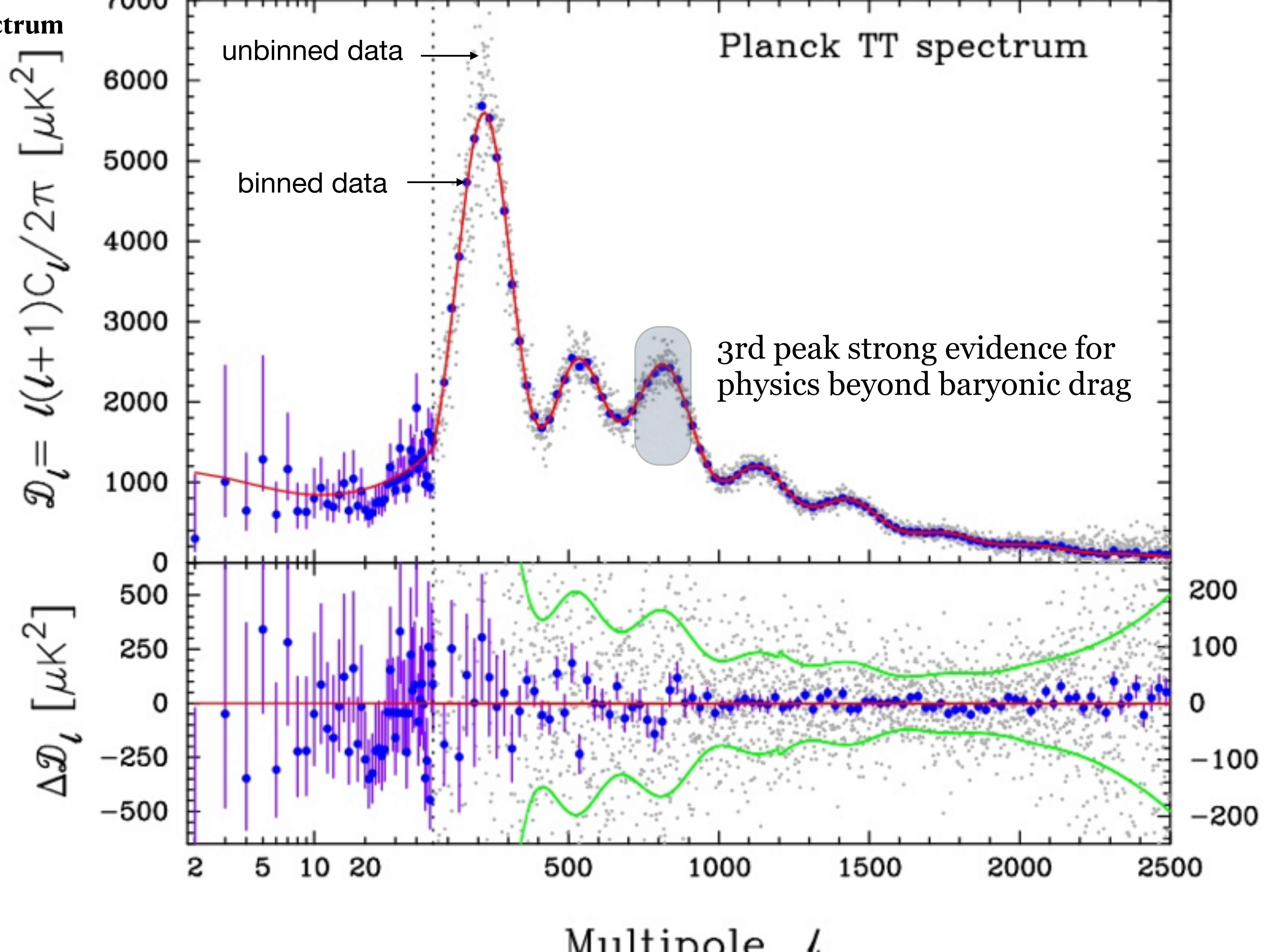
CMB power spectrum



$$k^2\Phi = 4\pi G(\rho_b\delta_b + \rho_\gamma\delta_\gamma + \rho_{CDM}\delta_{CDM})$$

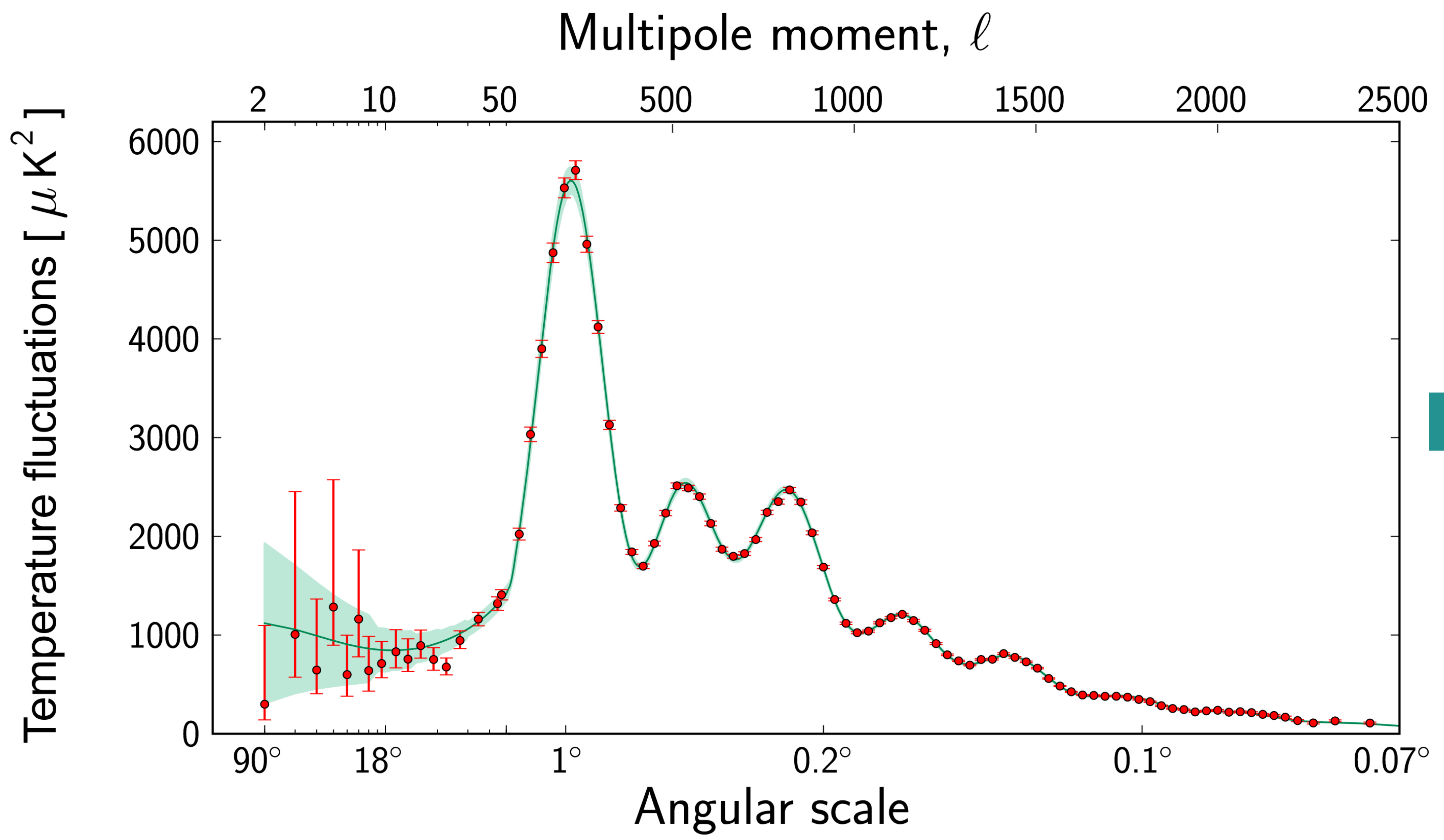
baryons a net drag **CDM a net forcing term**

CMB power spectrum



CMB power spectrum

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



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2 Baseline model

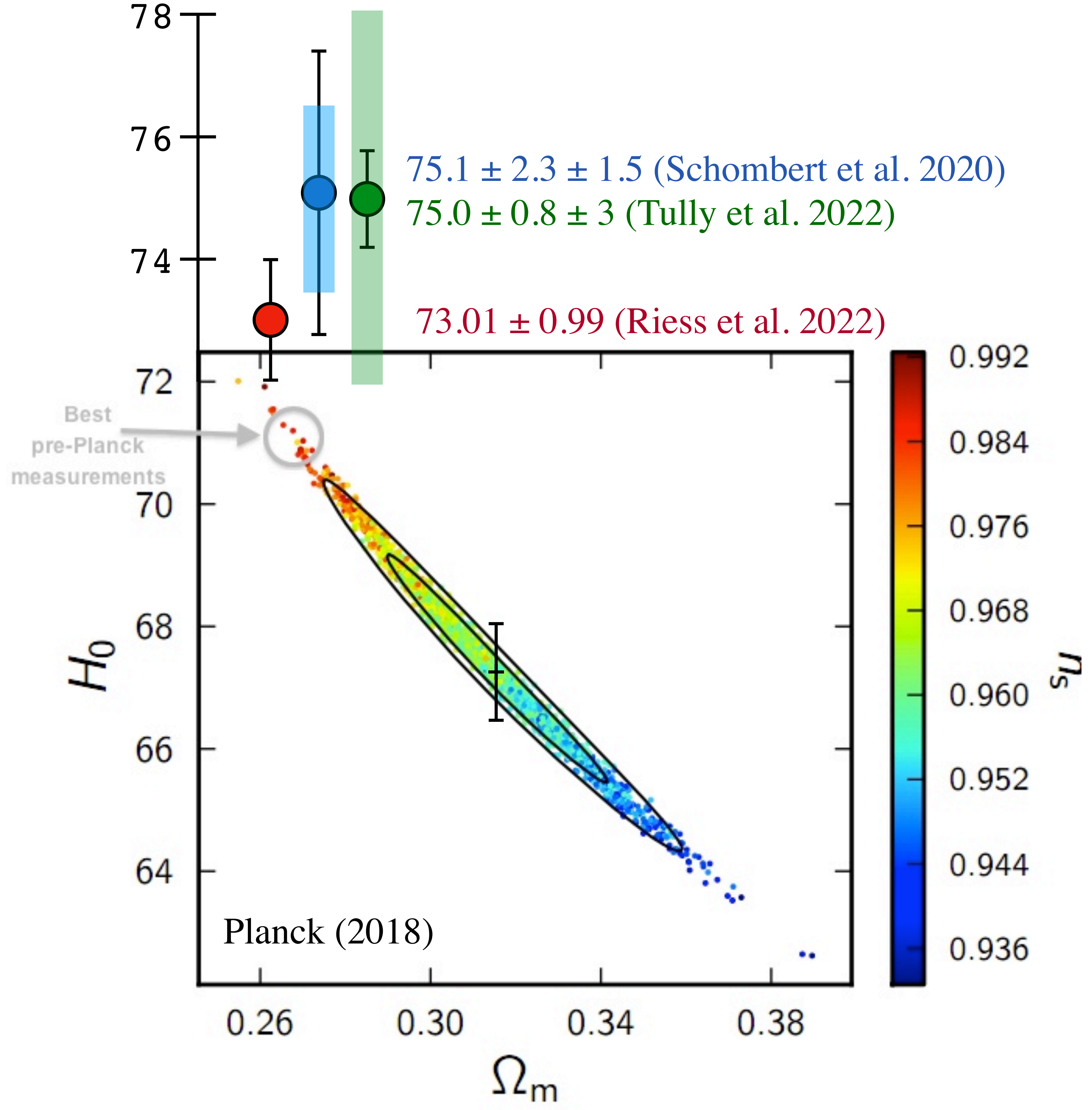
2.1 base_plikHM_TT_lowl_lowE

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
$\boldsymbol{A^{CIB}_{217}}$	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
$\boldsymbol{A^{tSZ}_{143}}$	7.03	5.1 ± 2.0	D_{810}	2538.2	2536 ± 14	$D_M(2.33)$	5777.8	5778 ± 16
$\boldsymbol{A^{PS}_{100}}$	254.9	263 ± 28	D_{1420}	815.5	814.4 ± 5.1	$f\sigma_8(0.15)$	0.4642	0.464 ± 0.012
$\boldsymbol{A^{PS}_{143}}$	49.8	49 ± 8	D_{2000}	229.94	229.5 ± 1.8	$\sigma_8(0.15)$	0.7500	0.7492 ± 0.0075
$\boldsymbol{A^{PS}_{143\times 217}}$	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
$\boldsymbol{A^{PS}_{217}}$	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
$\boldsymbol{A^{dustTT}_{100}}$	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
$\boldsymbol{A^{dustTT}_{143}}$	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
$\boldsymbol{A^{dustTT}_{143\times 217}}$	19.43	18.3 ± 3.3	z_*	1090.292	1090.30 ± 0.41	$\sigma_8(0.61)$	0.5904	0.5899 ± 0.0051
$\boldsymbol{A^{dustTT}_{217}}$	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^{143}_{2000}	30.49	31.2 ± 3.0
H_0	66.86	66.88 ± 0.92	z_{drag}	1059.437	1059.39 ± 0.46	$f^{143\times 217}_{2000}$	33.34	33.6 ± 2.0
Ω_Λ	0.6791	0.679 ± 0.013	r_{drag}	147.182	147.21 ± 0.48	f^{217}_{2000}	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			

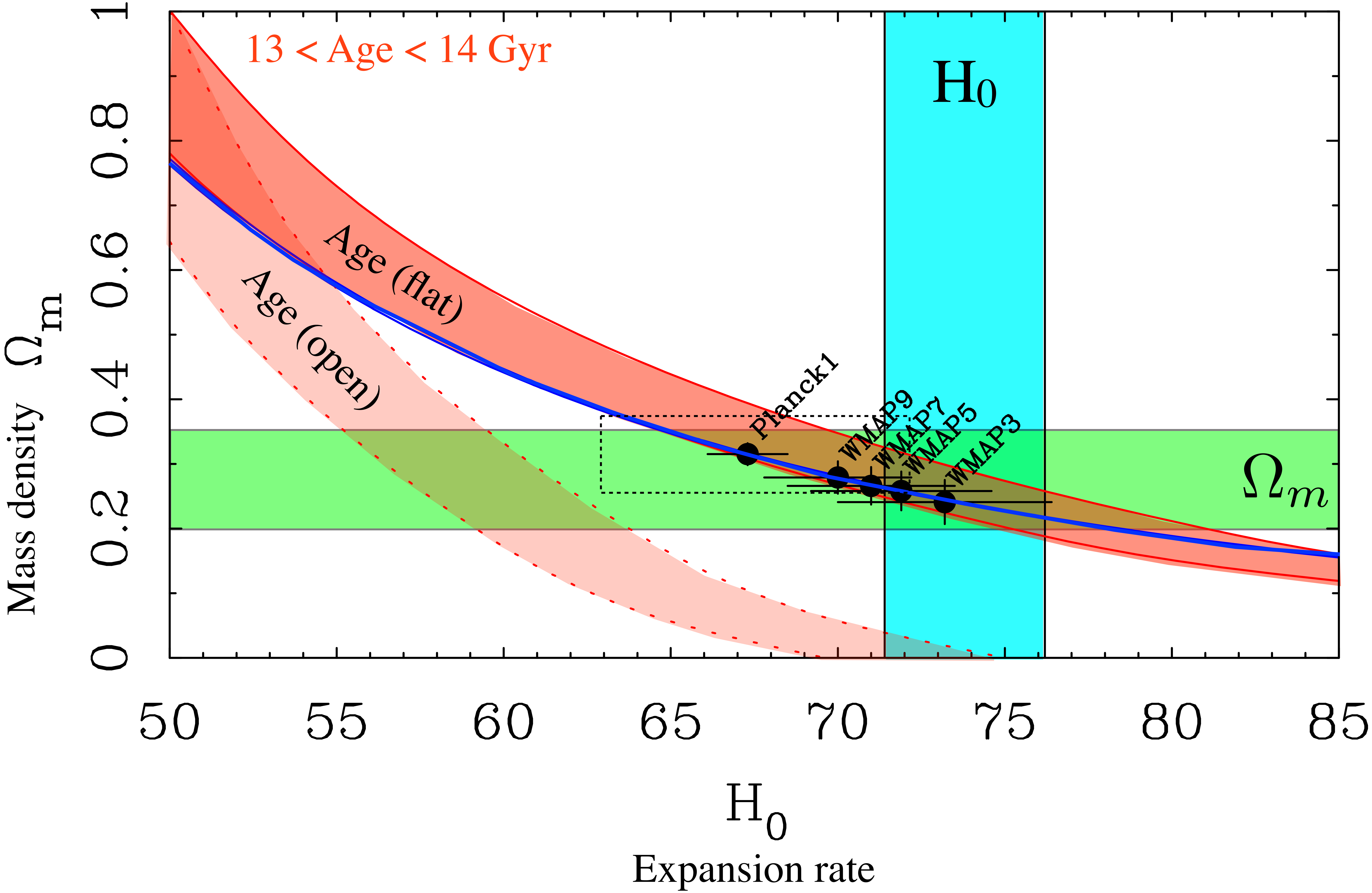
Best-fit $\chi^2_{eff} = 1179.58$; $\bar{\chi}^2_{eff} = 1199.58$; $R - 1 = 0.00927$
χ^2_{eff}: CMB - simall_100x143_offlike5_EE_Aplanck_B: 395.88 commander_dx12_v3_2_29: 23.60 plik_rd12_HM_v22_TT: 758.75

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

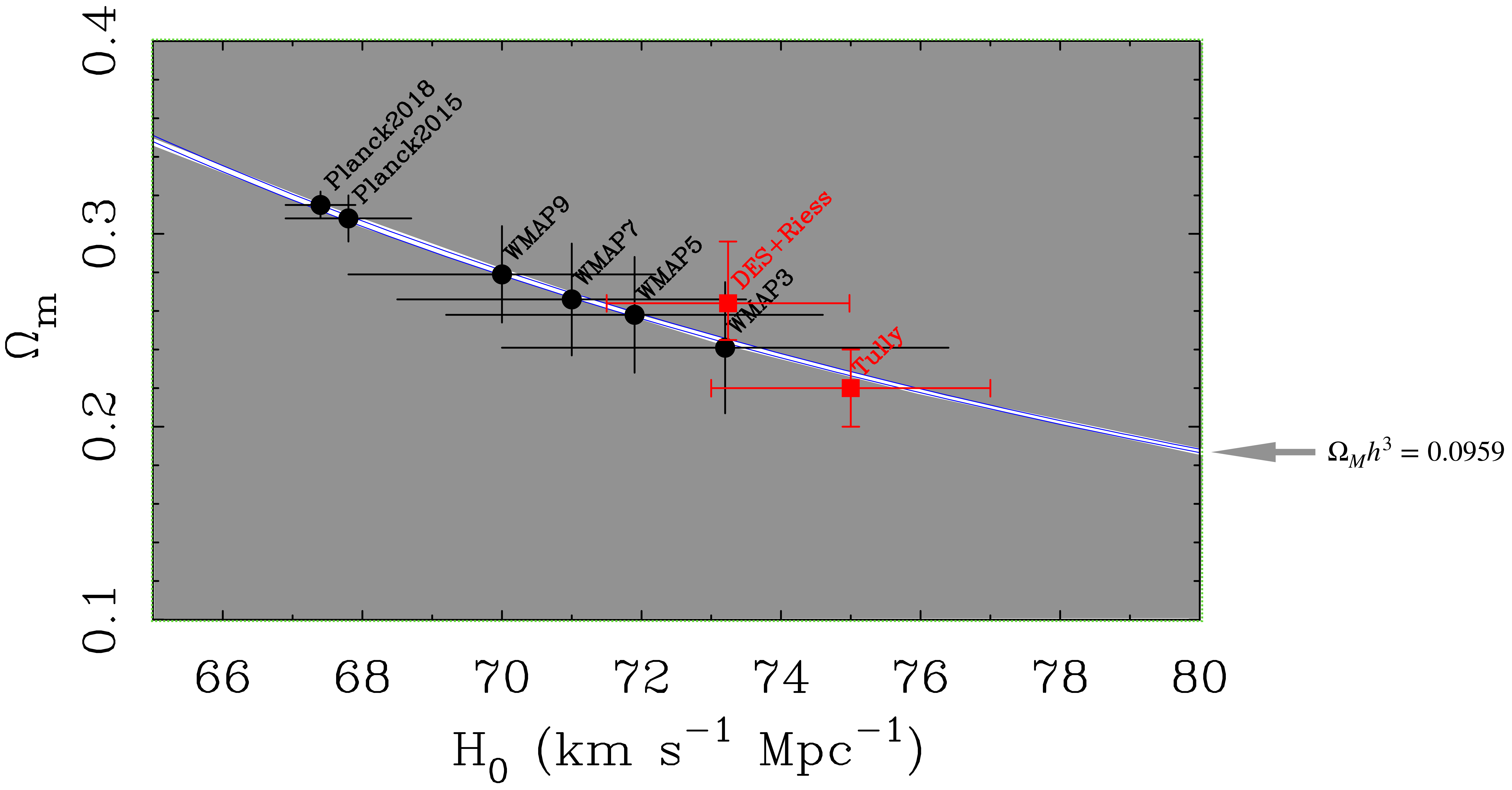
Hubble constant tension



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

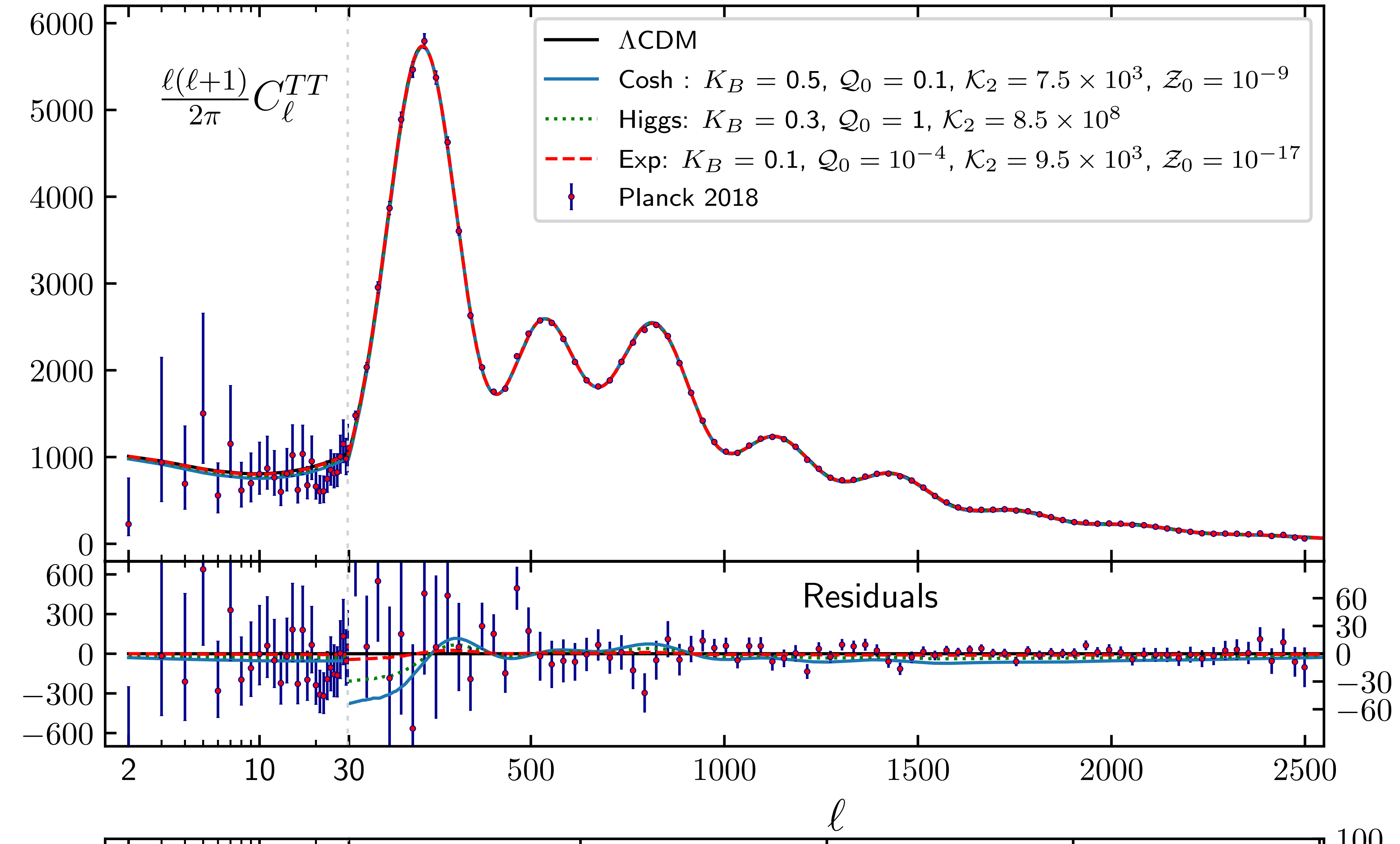


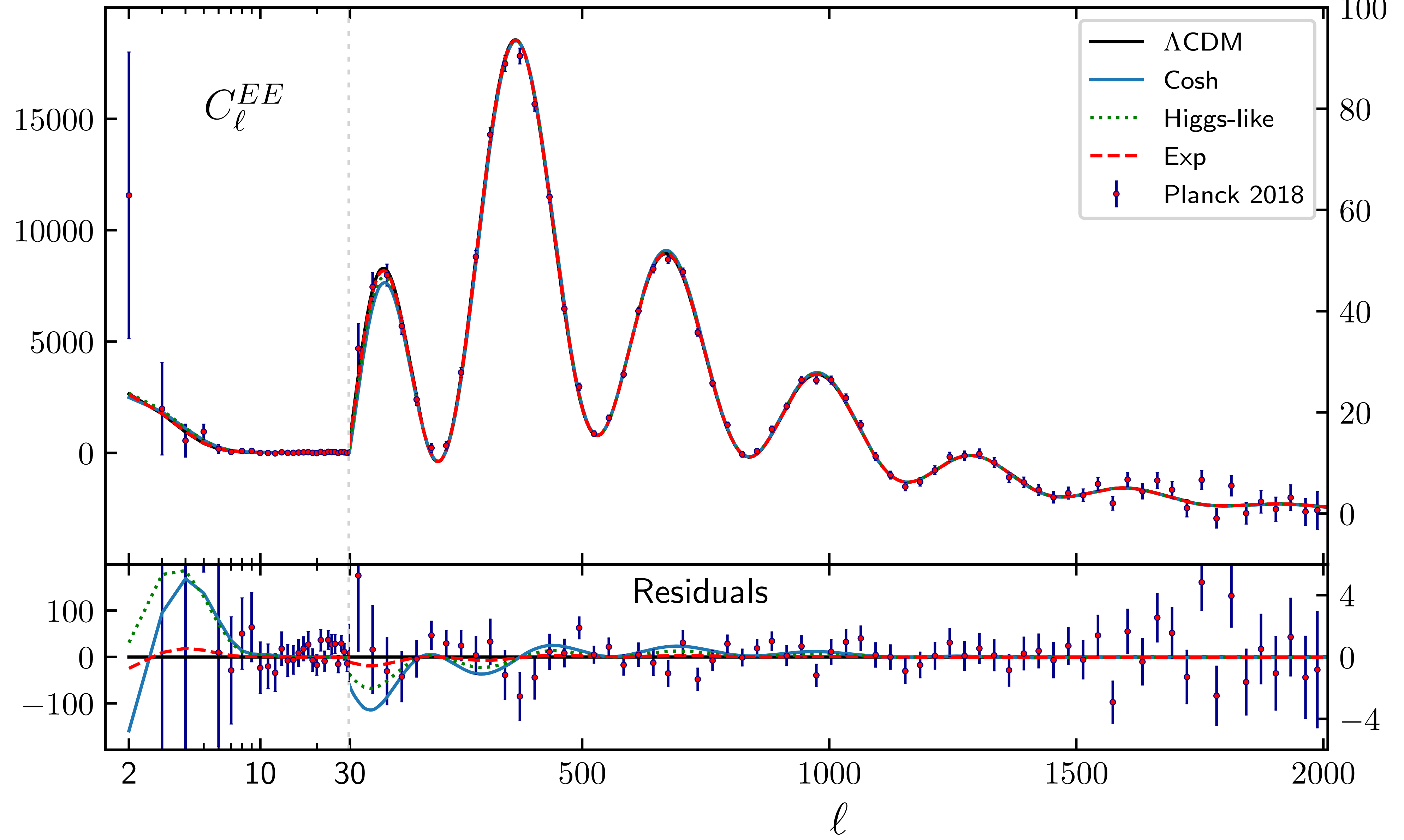
Cosmology today: tension in H_0 …and Ω_m



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

CMB acoustic power spectrum



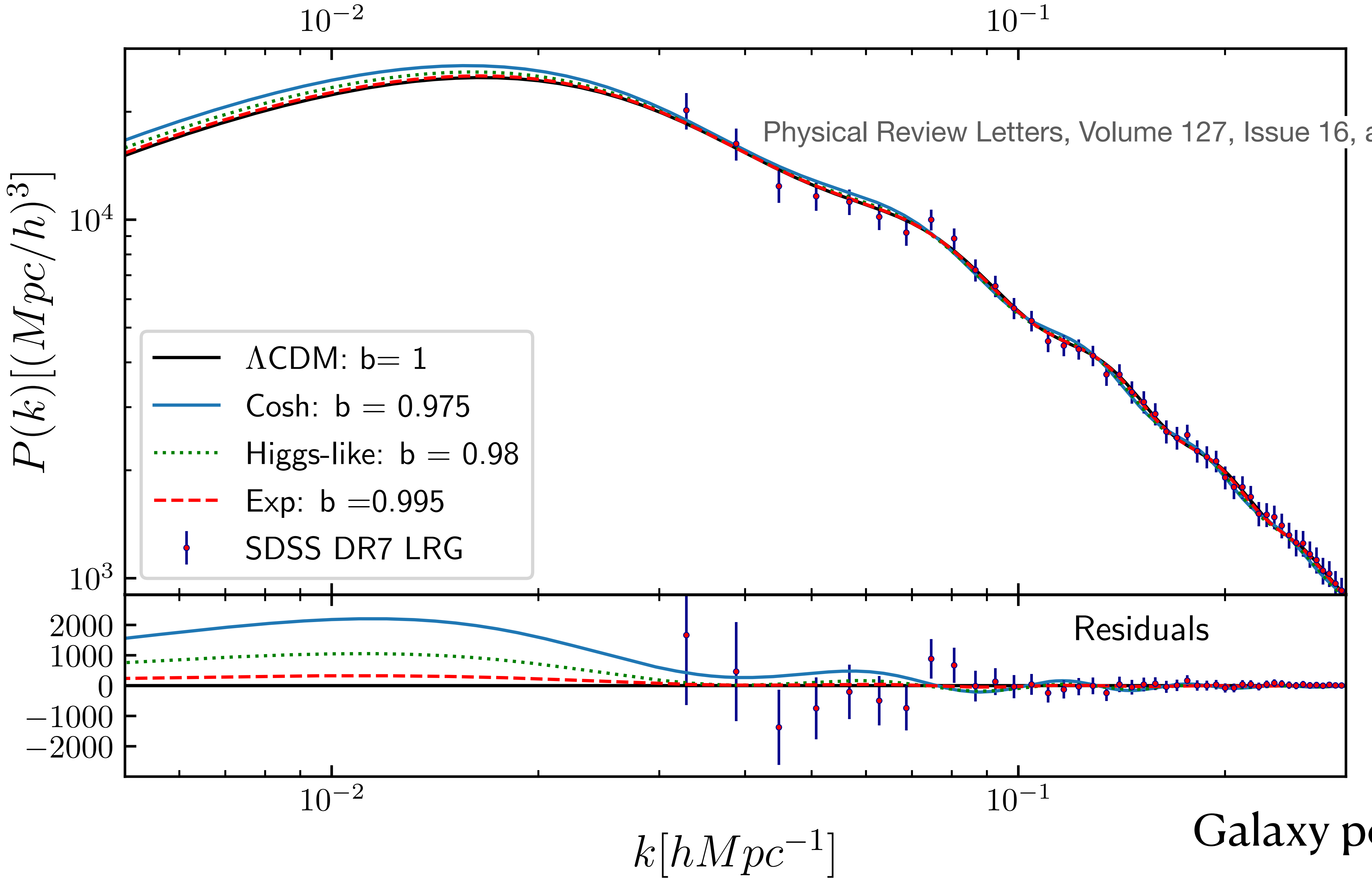


CMB polarization power spectrum

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: $\Omega_{CDM}h^2 = 0.1206 \pm 0.0021$

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



Physical Review Letters, Volume 127, Issue 16, article id.161302

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