Planck LCDM and Extensions

Planck Collaboration
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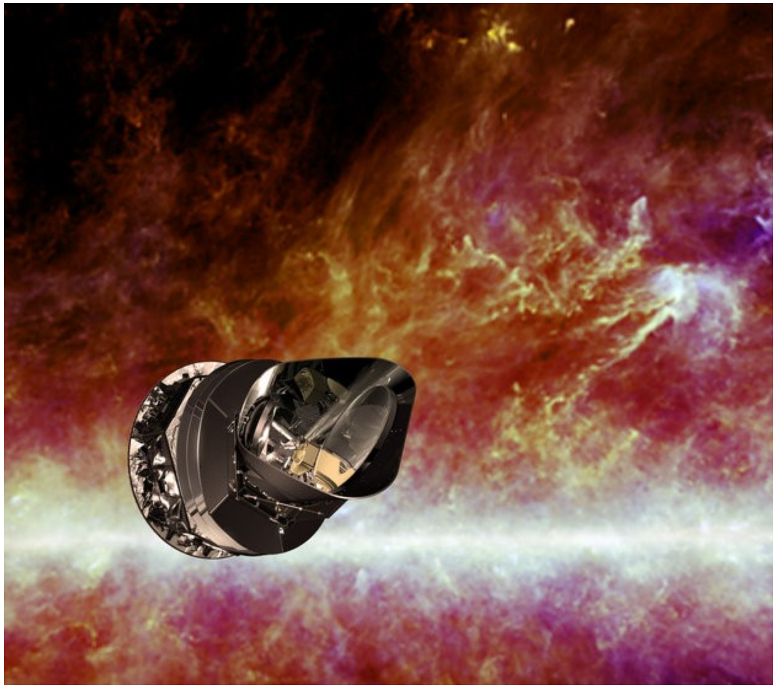
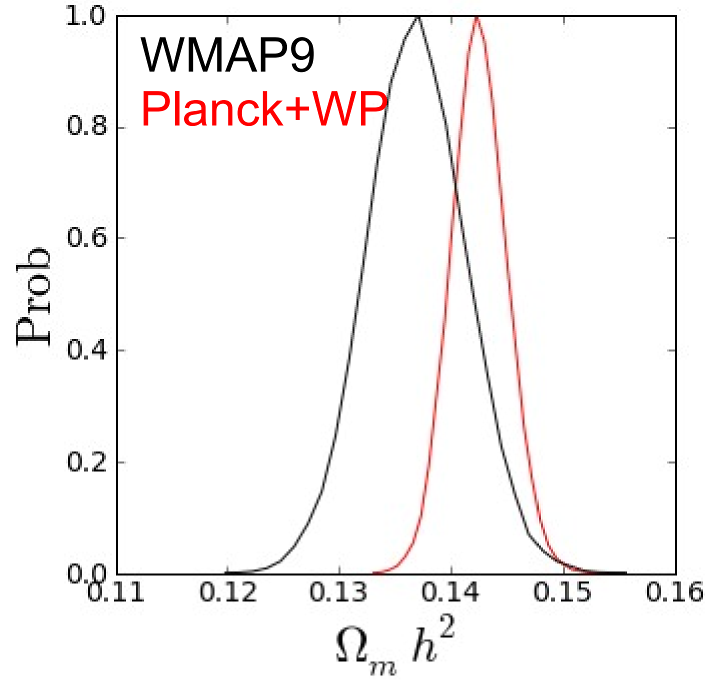
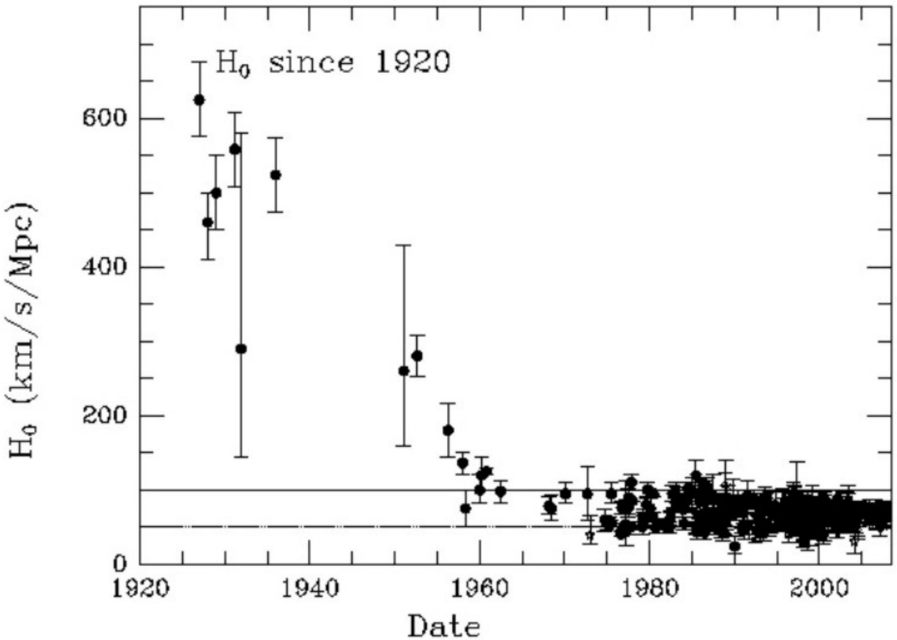
Planck, SPT member

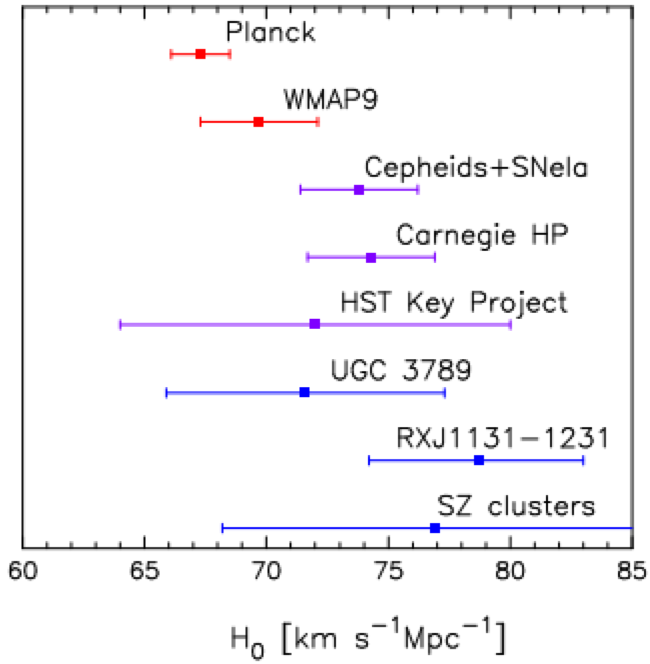


Santa Fe Cosmology Workshop – July 8th 2013

Intro


WMAP9
Planck+WP
Prob
1.0
0.8
0.6
0.4
0.2
0.0
0.11
0.12
0.13
0.14
0.15
0.16
$\Omega_m h^2$


H_0 since 1920
H_0 (km/s/Mpc)
600
400
200
0
1920
1940
1960
1980
2000
Date


Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
H_0 [km s^{-1}Mpc^{-1}]

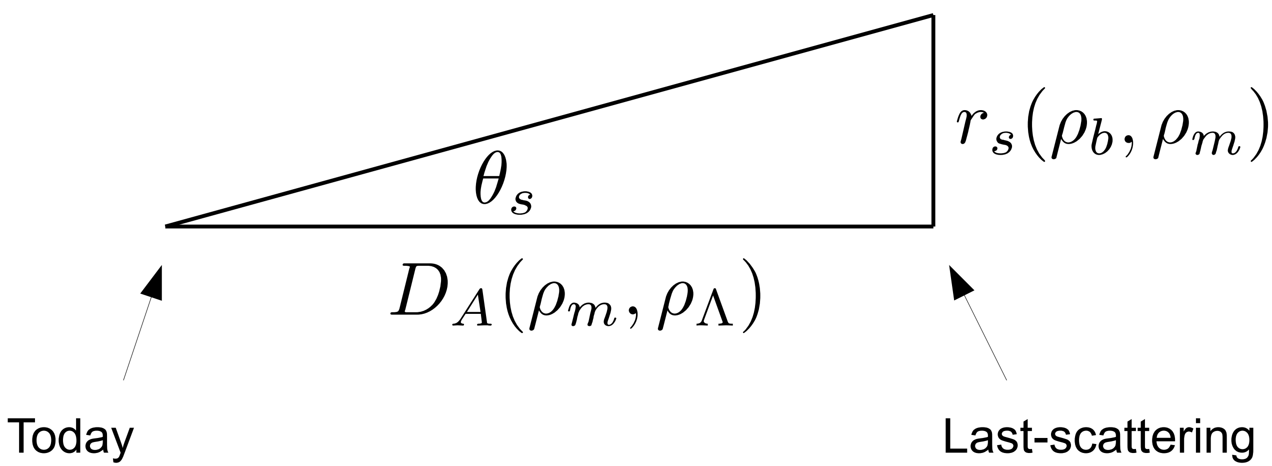
Outline

- LCDM
  - H_0 from the CMB?
  - Planck-WMAP
  - Lensing
  - Damping
  - Robustness tests
  - Planck-SPT
- LCDM+Extensions

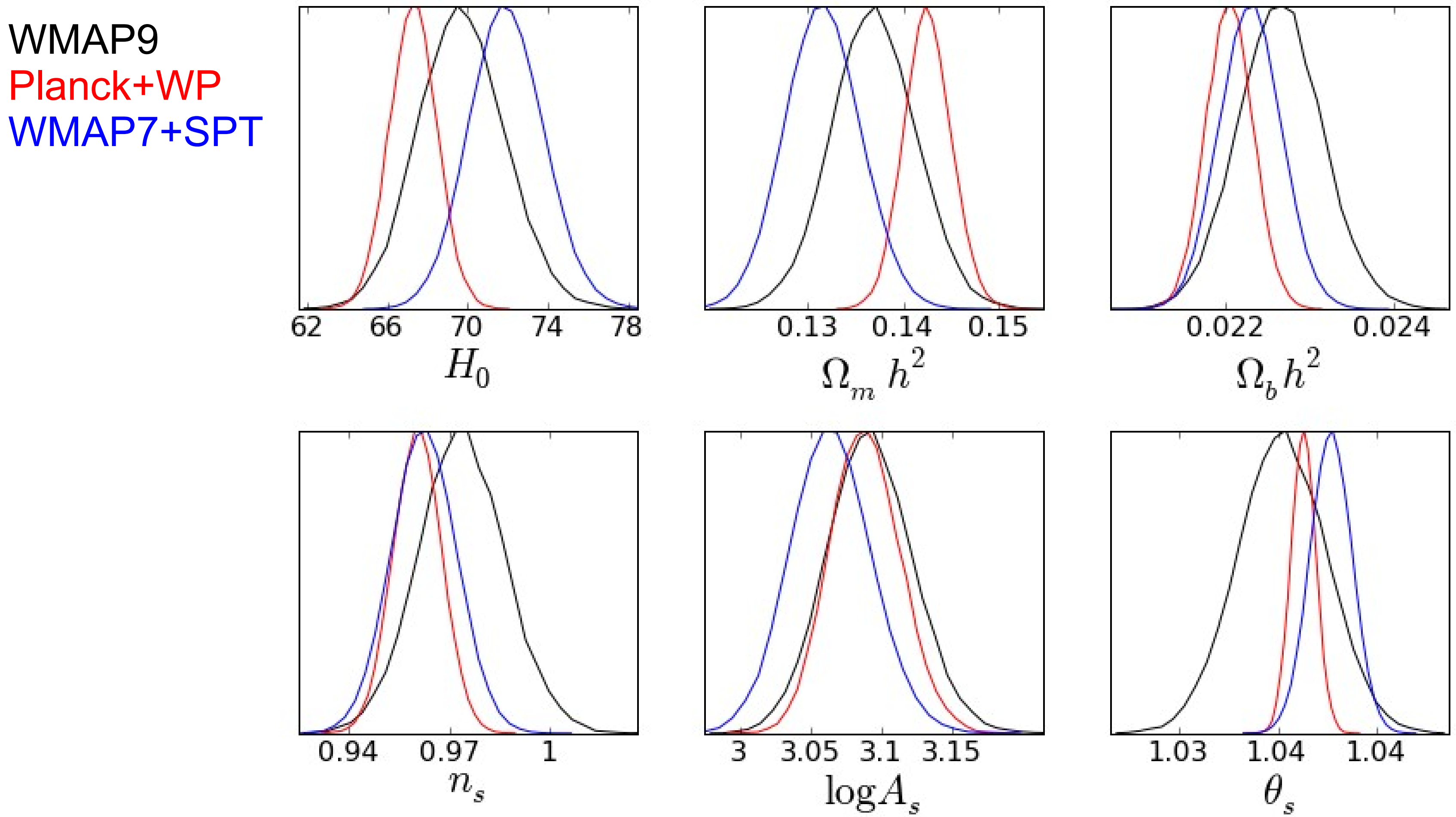
How CMB measurements of ρ_m provide an inference of H_0

$$H_0^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_\Lambda\right)$$

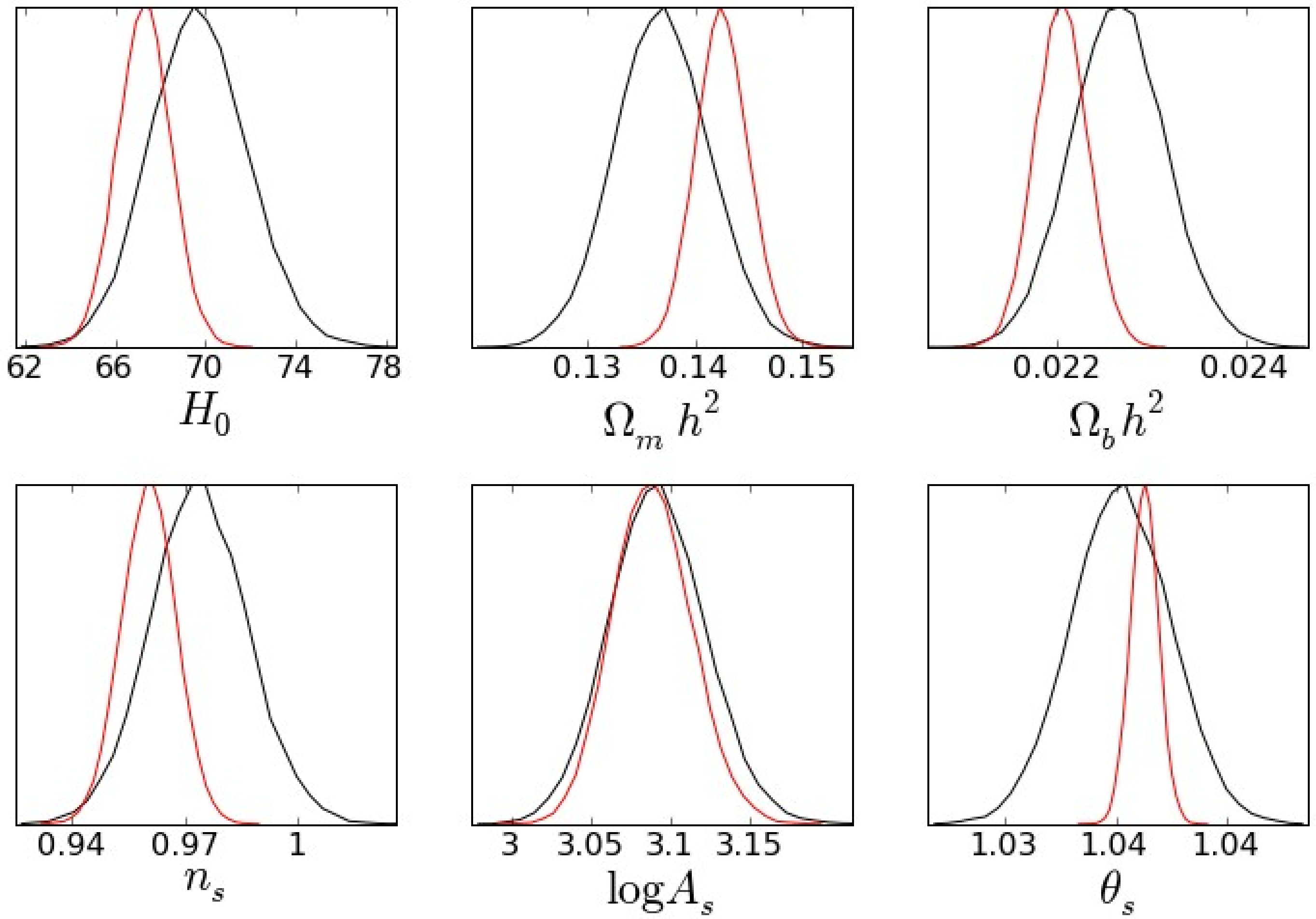
R=0.95 $\rho_m \uparrow \quad H_0 \downarrow$



In particular, assuming $\sum m_\nu = 0.06\mathrm{eV}$
lowers H_0 by 0.6 km/s/Mpc (50% sigma)

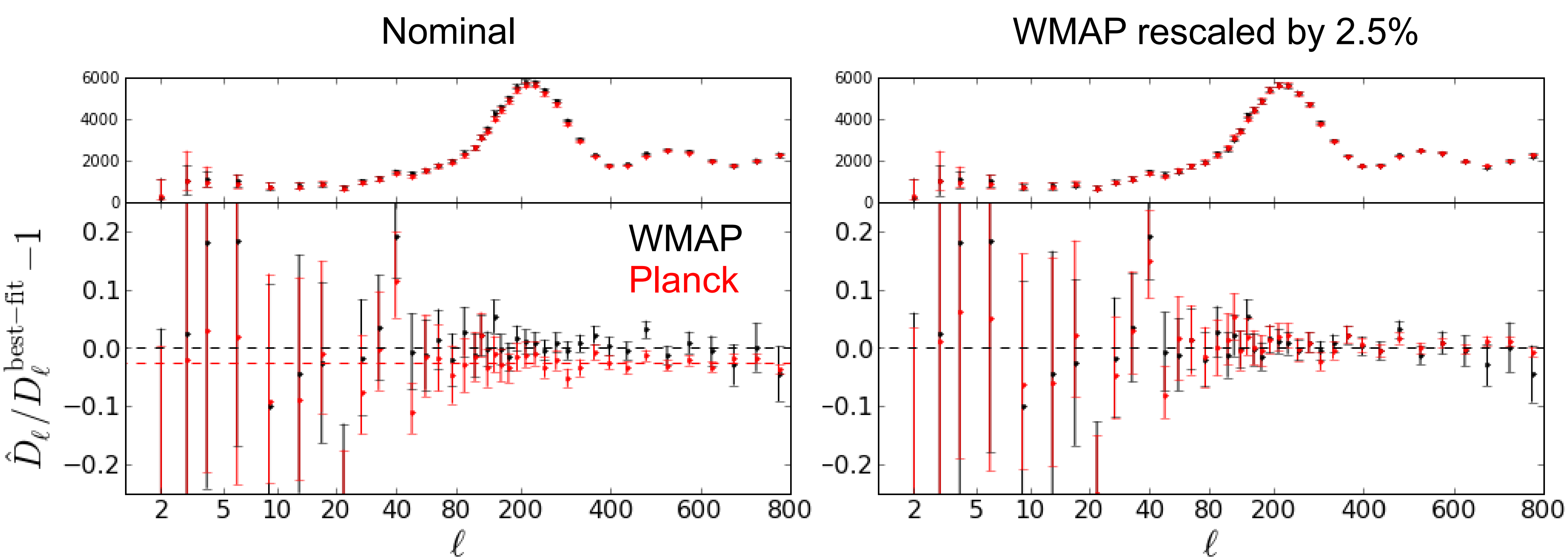

WMAP9
Planck+WP
WMAP7+SPT
62
66
70
74
78
H_0
0.13
0.14
0.15
$\Omega_m h^2$
0.022
0.024
$\Omega_b h^2$
0.94
0.97
1
n_s
3
3.05
3.1
3.15
$\log A_s$
1.03
1.04
1.04
θ_s

WMAP9
Planck+WP



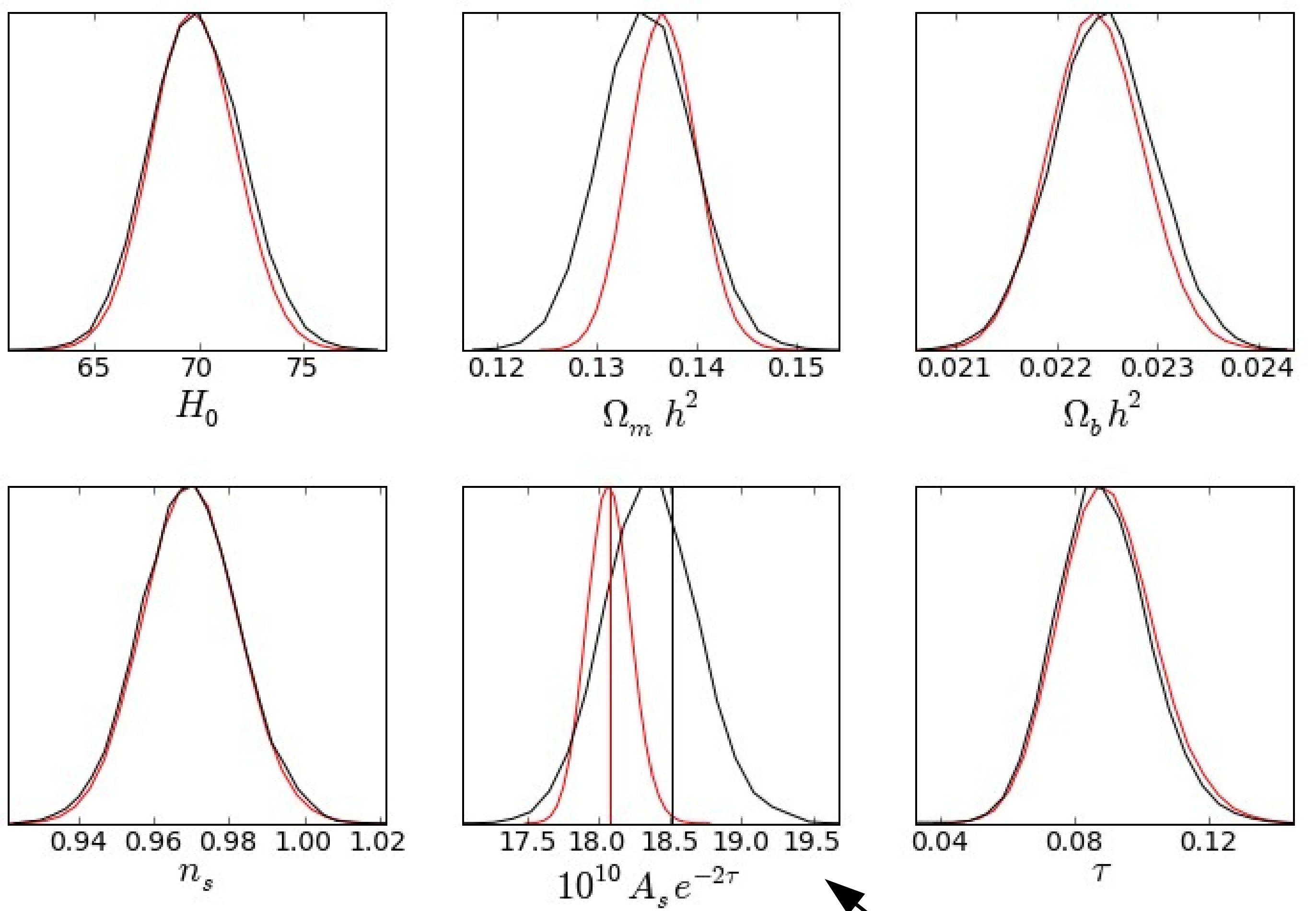
WMAP-Planck Agreement

- The majority of differences between Planck and WMAP look something like a 2.5% rescaling



Note: different masks, beam uncertainties not included in error bars
The can be important and the Planck Consistency Paper (in prep) will address some of them

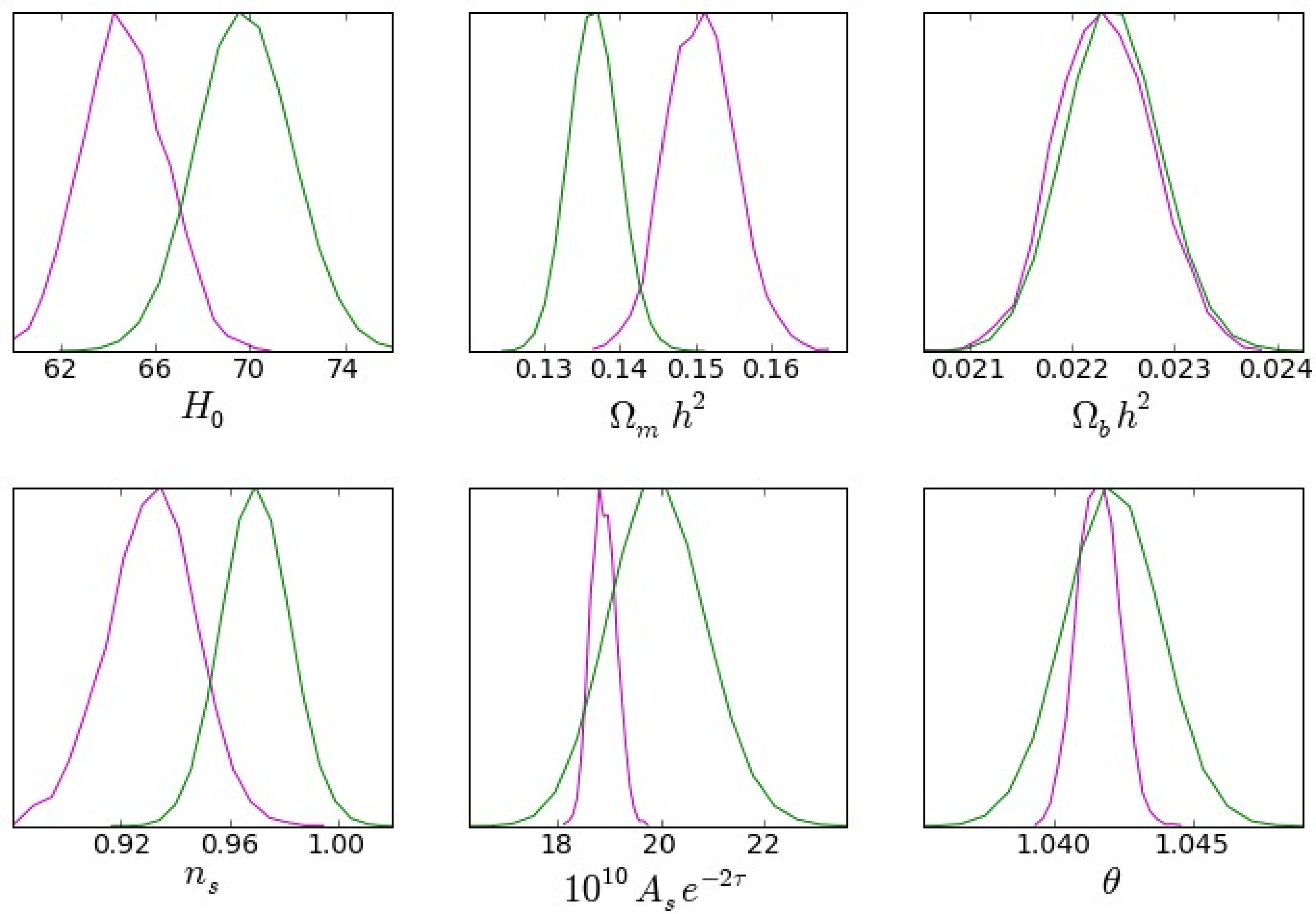
WMAP9 (L<800)
Planck+WP (L<800)



The 2.5% difference is absorbed almost entirely by the amplitude

To understand WMAP/Planck differences other than the amplitude, we need to understand Planck L<800 vs. L>800 differences

Planck+WP (L<800)
Planck+WP (L>800, tau fixed)

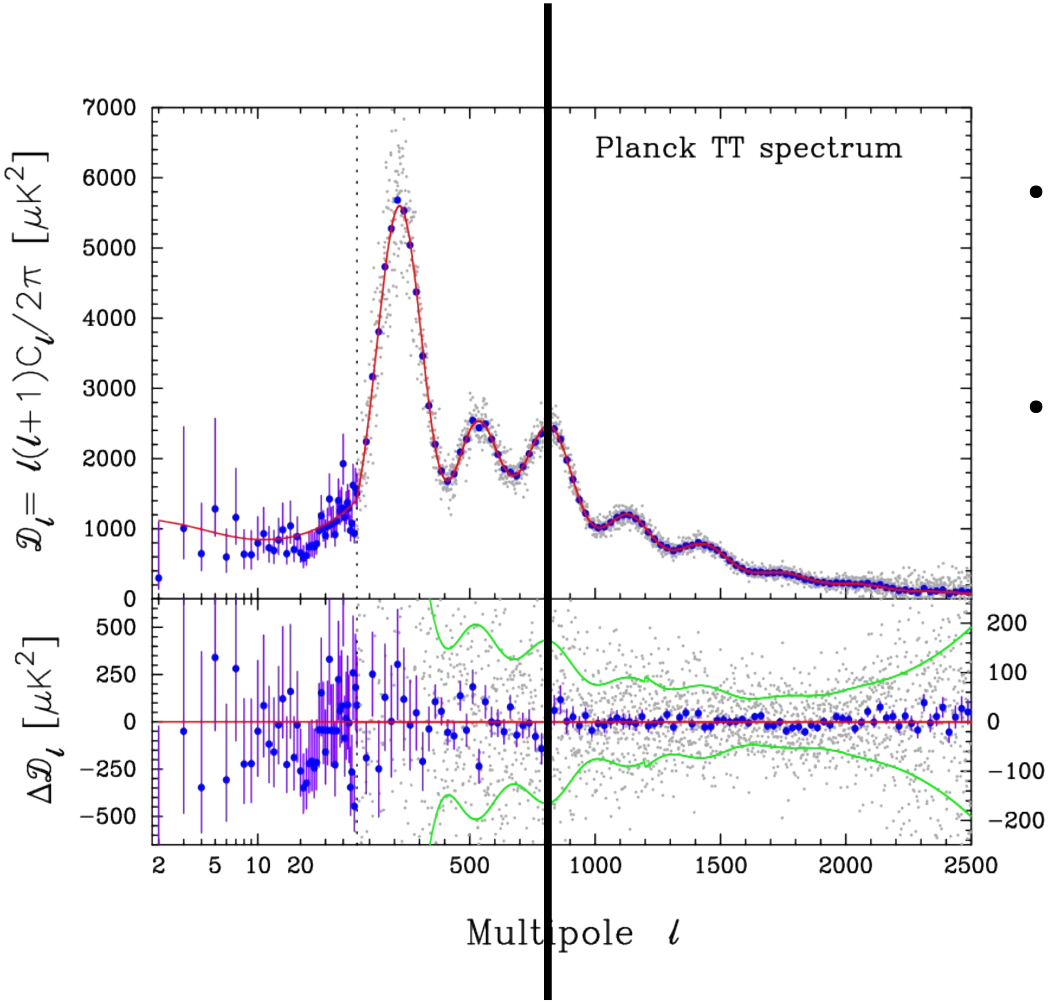


Note: LCDM is a good fit to the *overall* data

Also note: I didn't include beam uncertainties which might widen the L>800 constraints some

How do we measure LCDM parameters from L<800 and L>800?

- **Ommh2** via 1st to 3rd peak amplitude ratio
- **Ombh2** via even to odd peak amplitude ratio

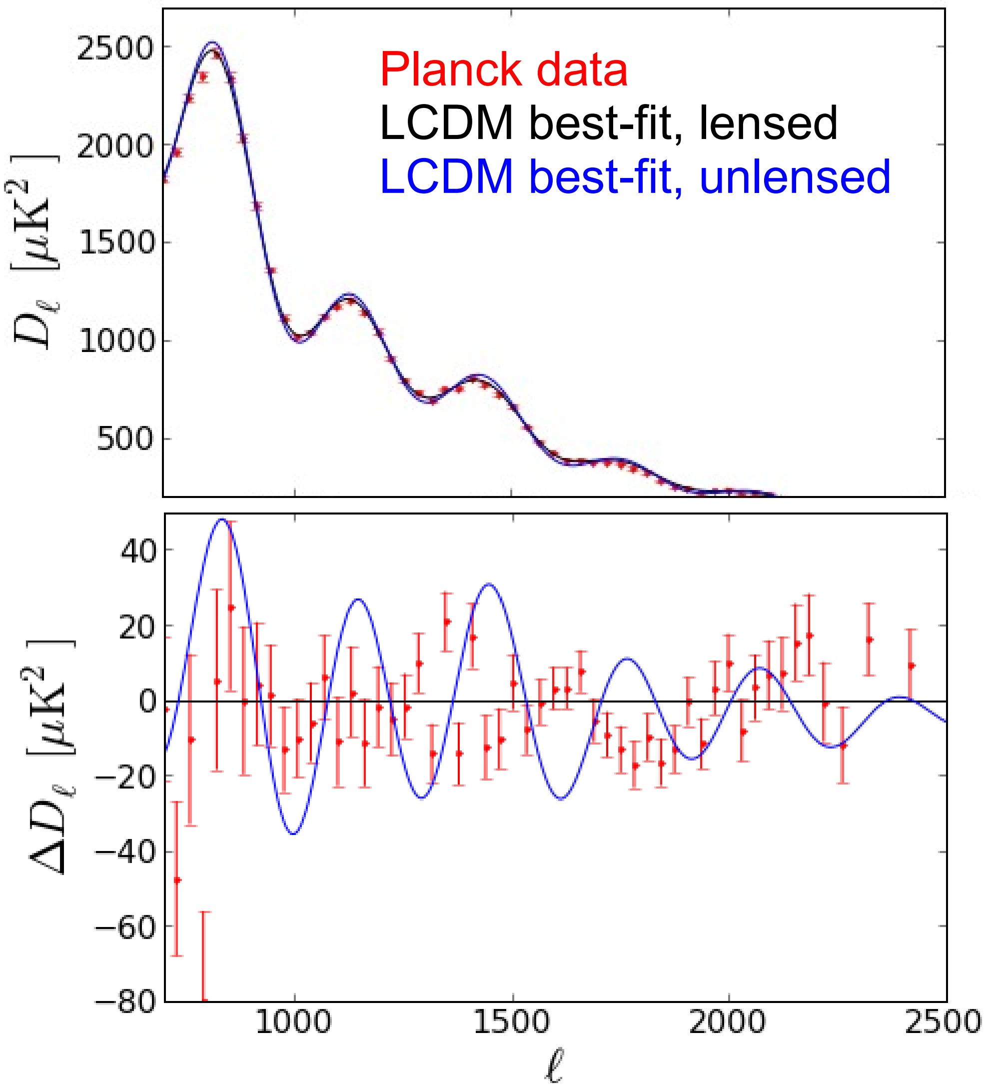


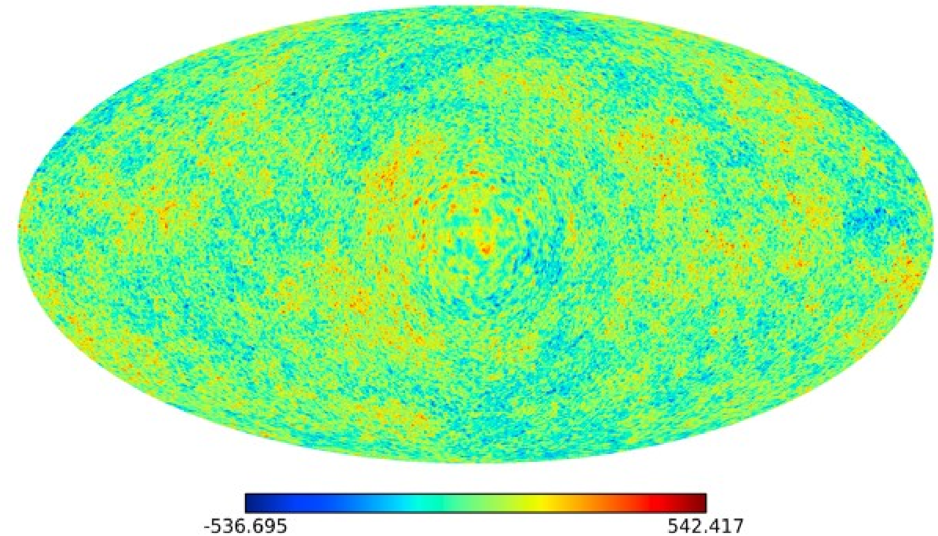
- **Ommh2** via smoothing of the peaks due to lensing
- **Ombh2** via amount of power suppression due to Silk damping

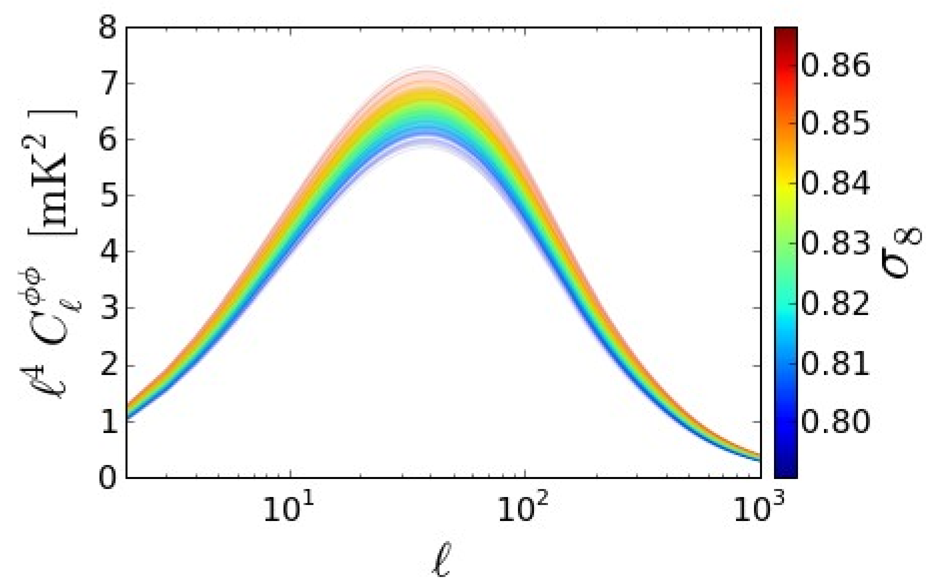
Duncan Hanson

Lensing

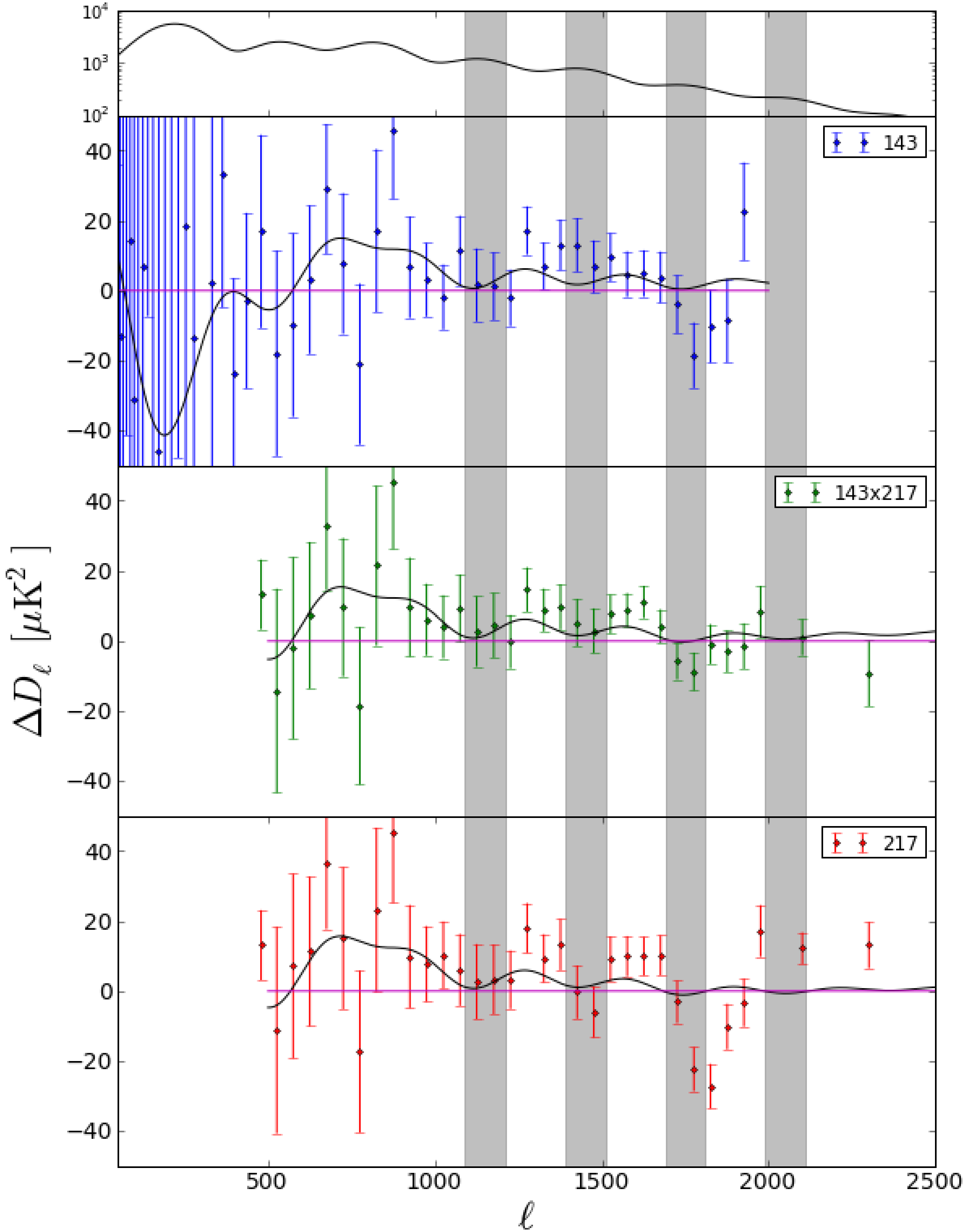
$$C_\ell^{TT,\text{lensed}} \approx C_\ell^{TT,\text{unlensed}} * C_\ell^{\phi\phi}$$





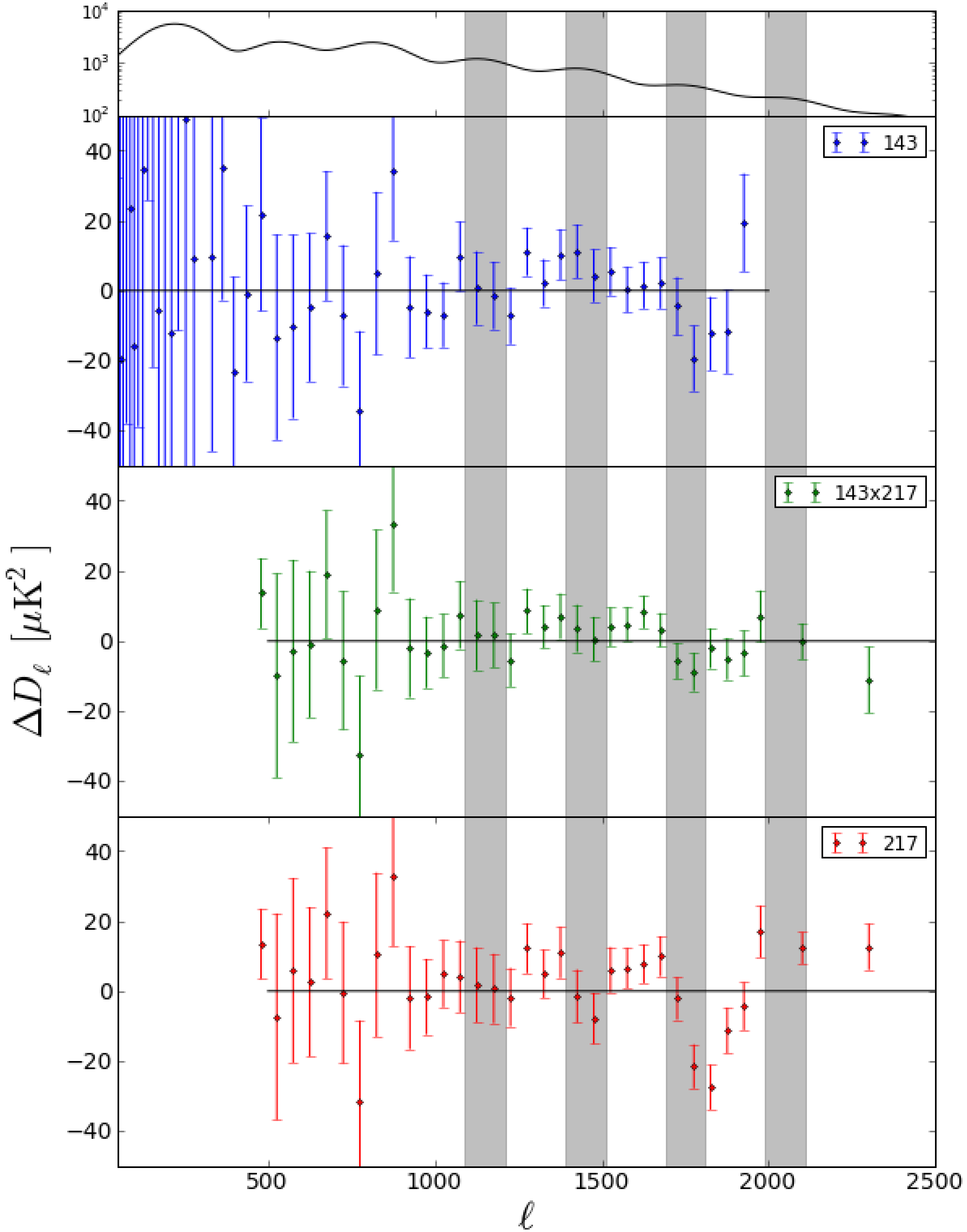


ρ_m ↑ σ_8 ↑

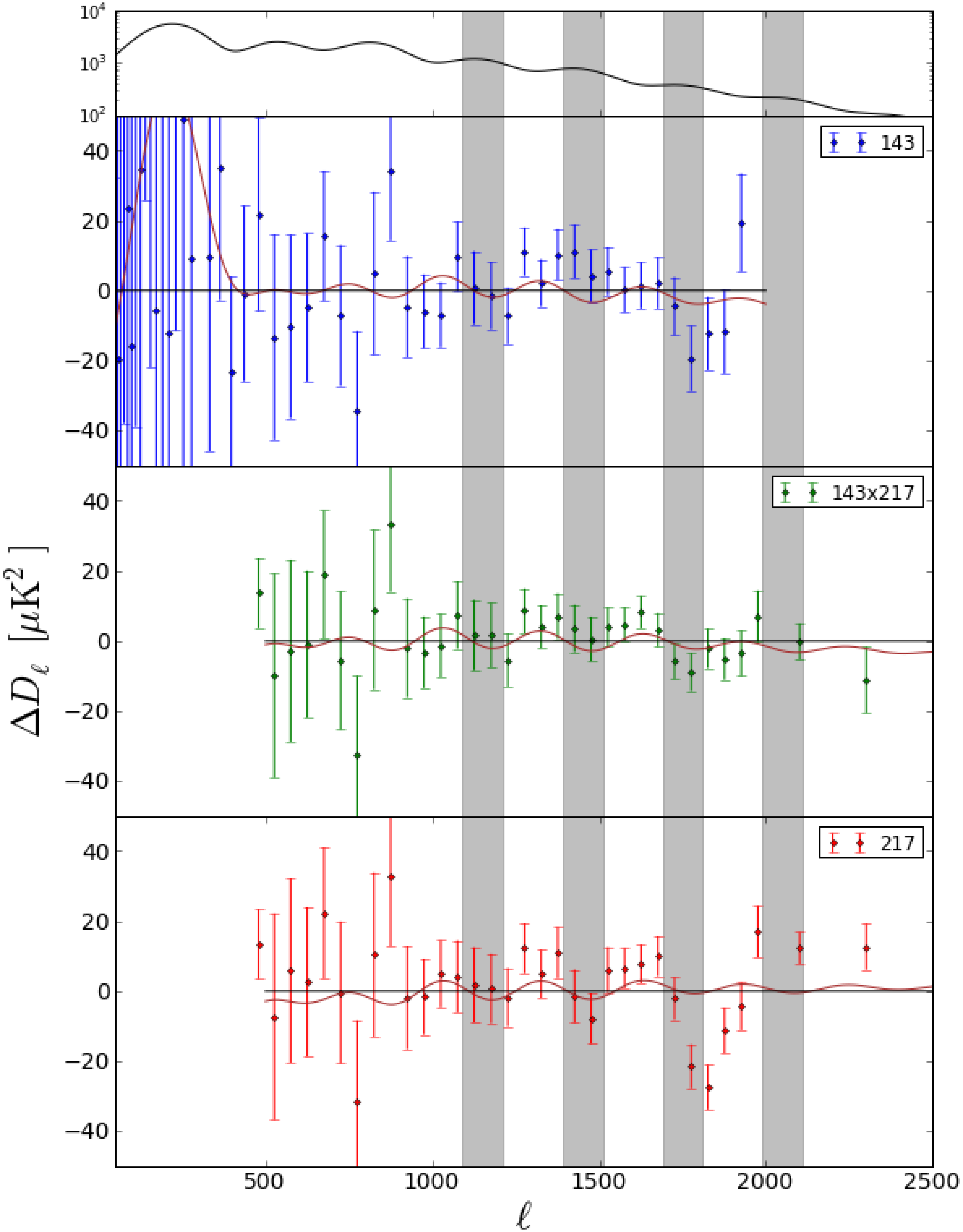


Planck+WP (L<800) LCDM best-fit

Planck+WP LCDM best-fit

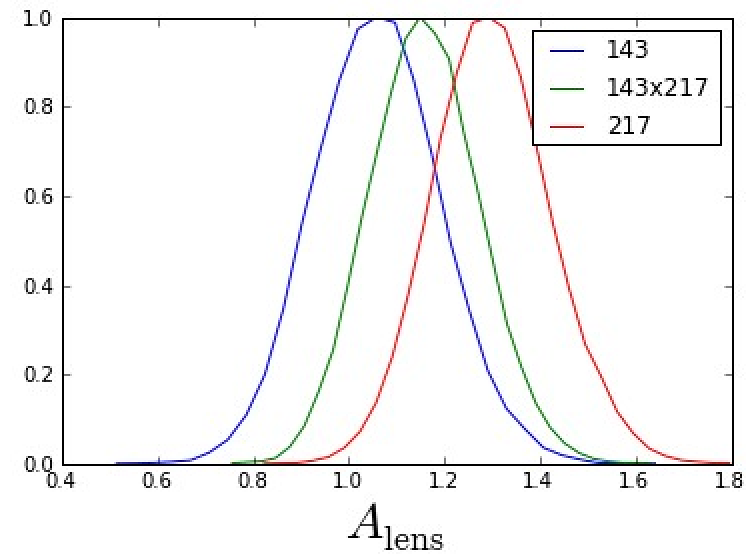


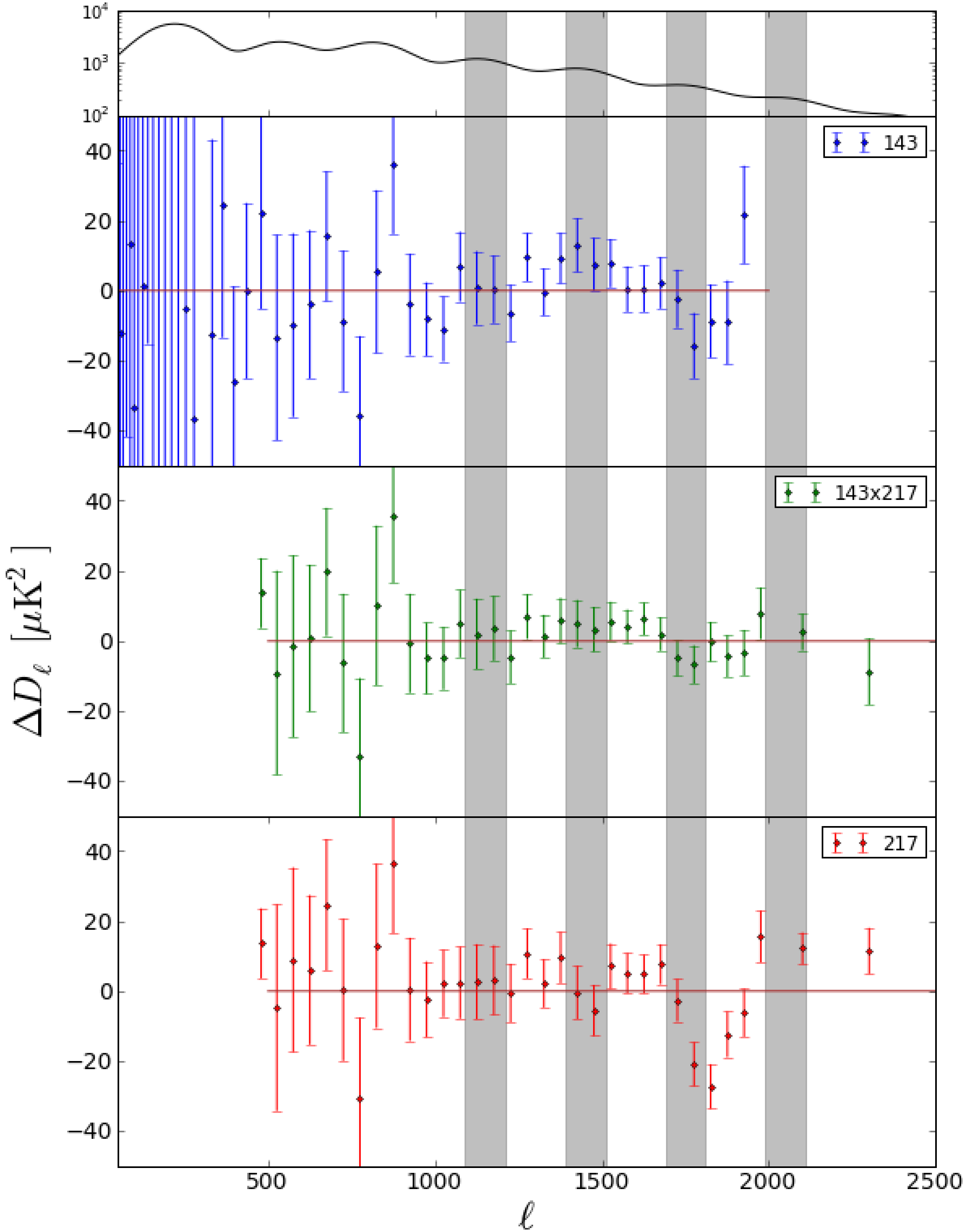
Planck+WP LCDM best-fit



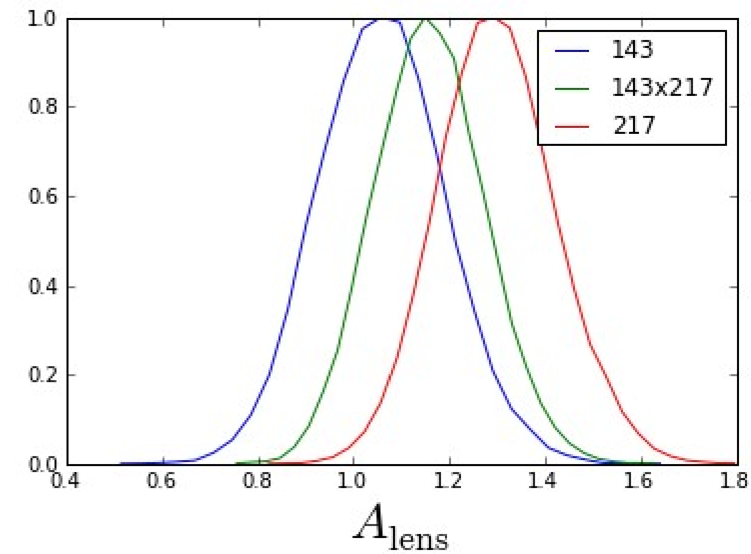
Planck+WP LCDM best-fit

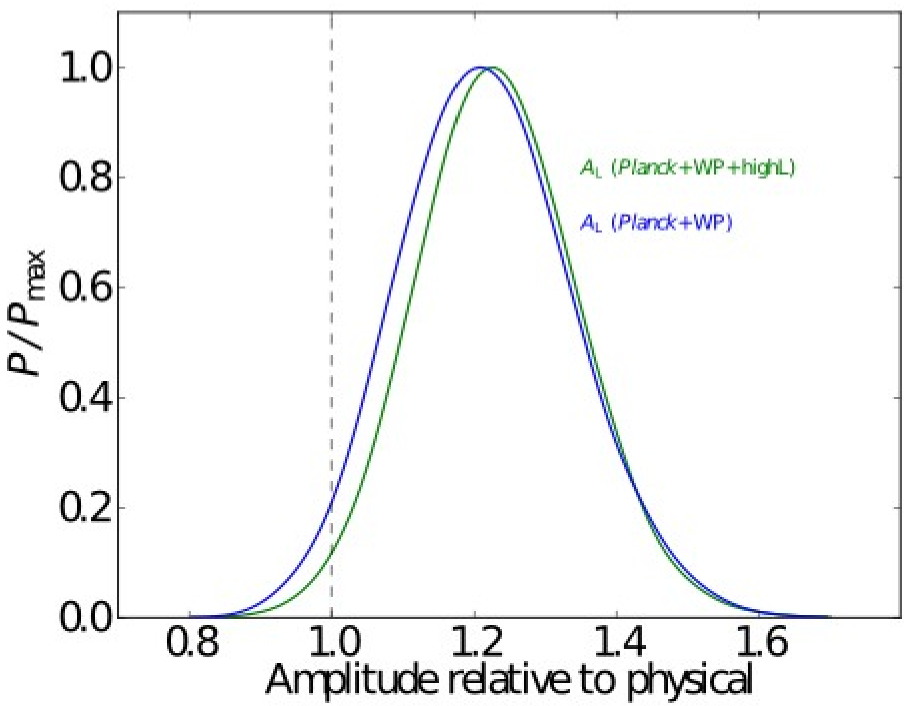
Planck+WP LCDM+Alens best-fit

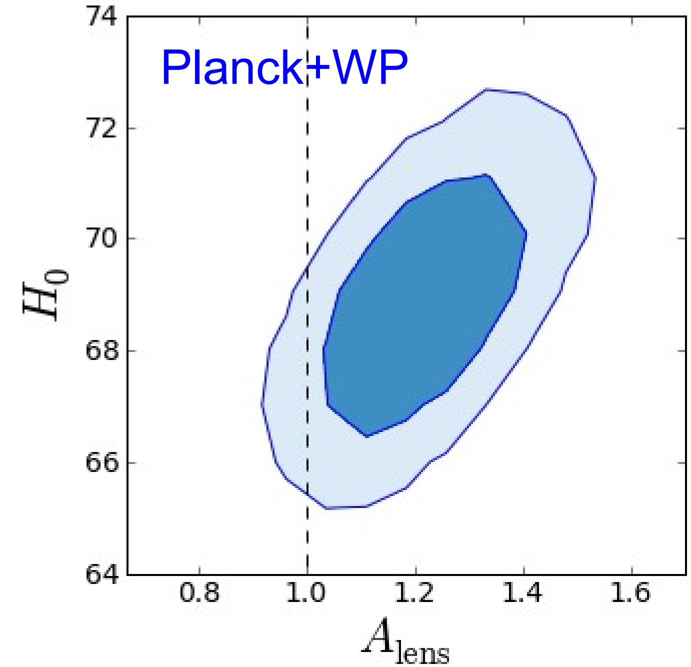




Planck+WP LCDM+Alens best-fit

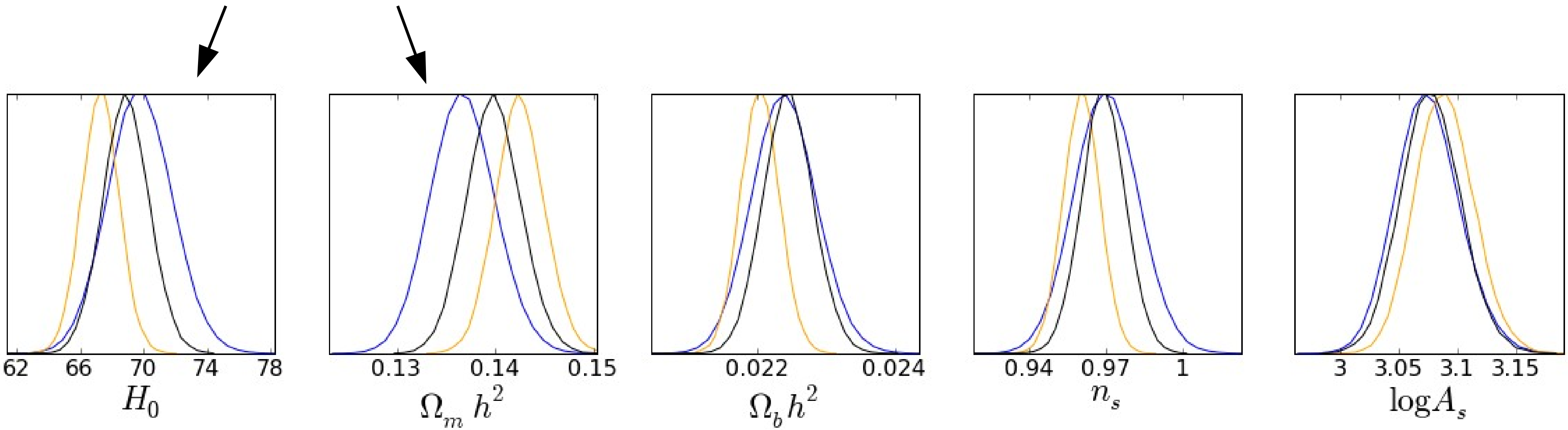



1.0
0.8
0.6
0.4
0.2
0.0
P / P max
0.8
1.0
1.2
1.4
1.6
Amplitude relative to physical
A L (Planck+WP+highL)
A L (Planck+WP)


Planck+WP
74
72
70
68
66
64
H 0
0.8
1.0
1.2
1.4
1.6
A lens

Removing lensing information by marginalizing over Alens returns you significantly towards the L<800 constraints

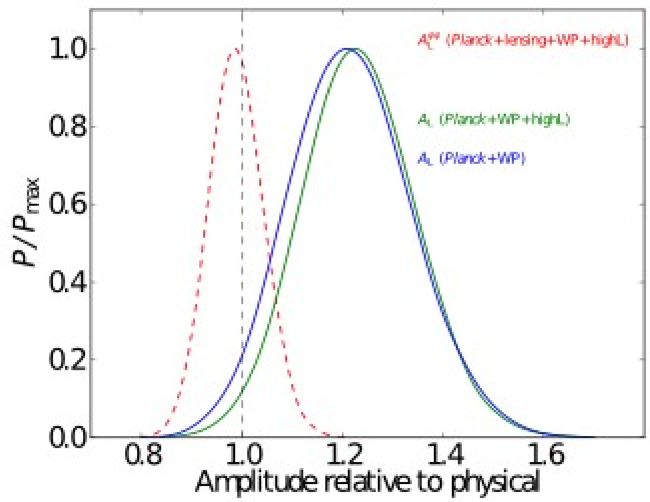
What else at L>800 is driving this remaining shift?



Planck L<800 LCDM
Planck L<2500 LCDM
Planck L<2500 LCDM+Alens

Why is it useful to know that lensing is important?

- What does the CMB 4-point function tell us about lensing?
  - No preference for higher lensing



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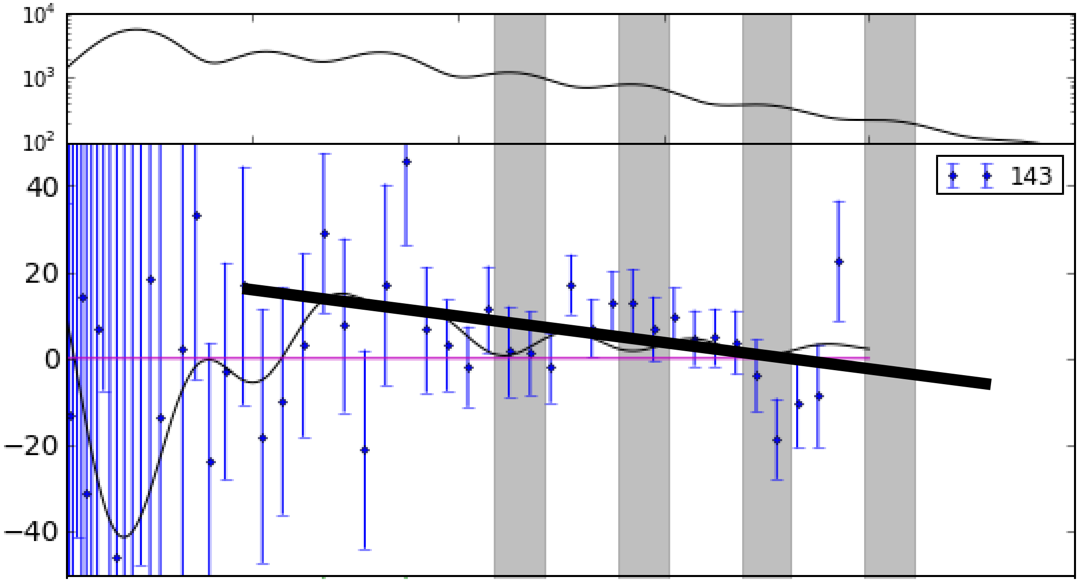
- What do other experiments tell us about lensing?
  - SPT slight preference for *less* lensing, 1 sigma
  - ACT slight preference for *more* lensing, 1.8 sigma

What's the other remaining feature?

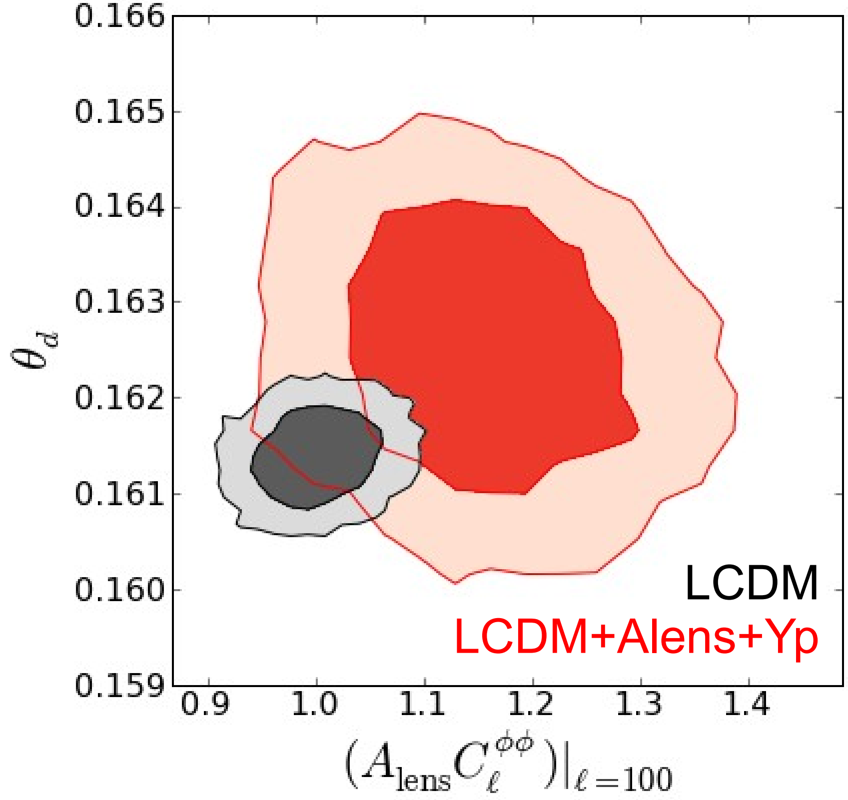


There's that overall tilt / excess

This leads us to consider nrun, Yp

Damping

Freeing Y_p (helium fraction) is to damping as freeing A_{lens} is to lensing



- Unlike freeing A_{lens}, freeing Y_p does not return you closer to L<800 values
- Data prefer *more* power, but also *more* damping, so its actually through degeneracies with other parameters that more damping is preferred
- Need to understand this more...

Extra-galactic Foregrounds

Emission from external galaxies and Sunyaev-Zeldovich effects contribute anisotropy power at high L

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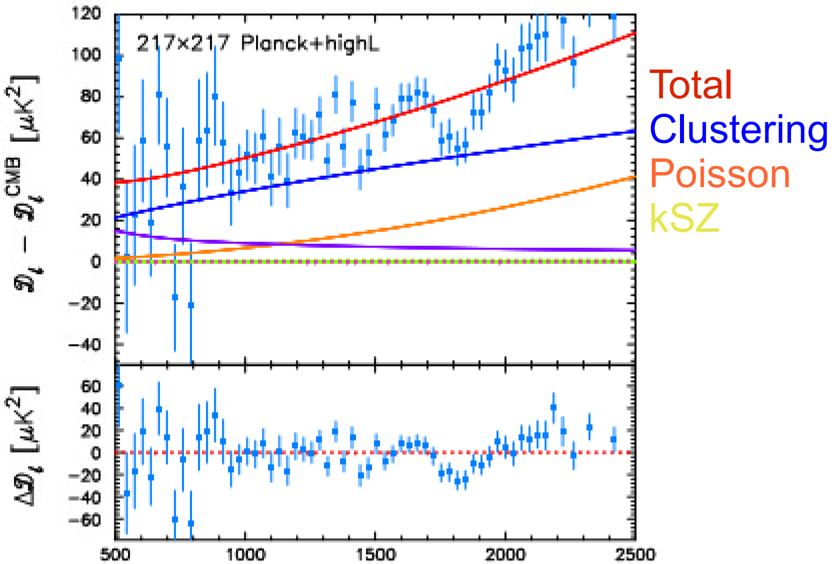
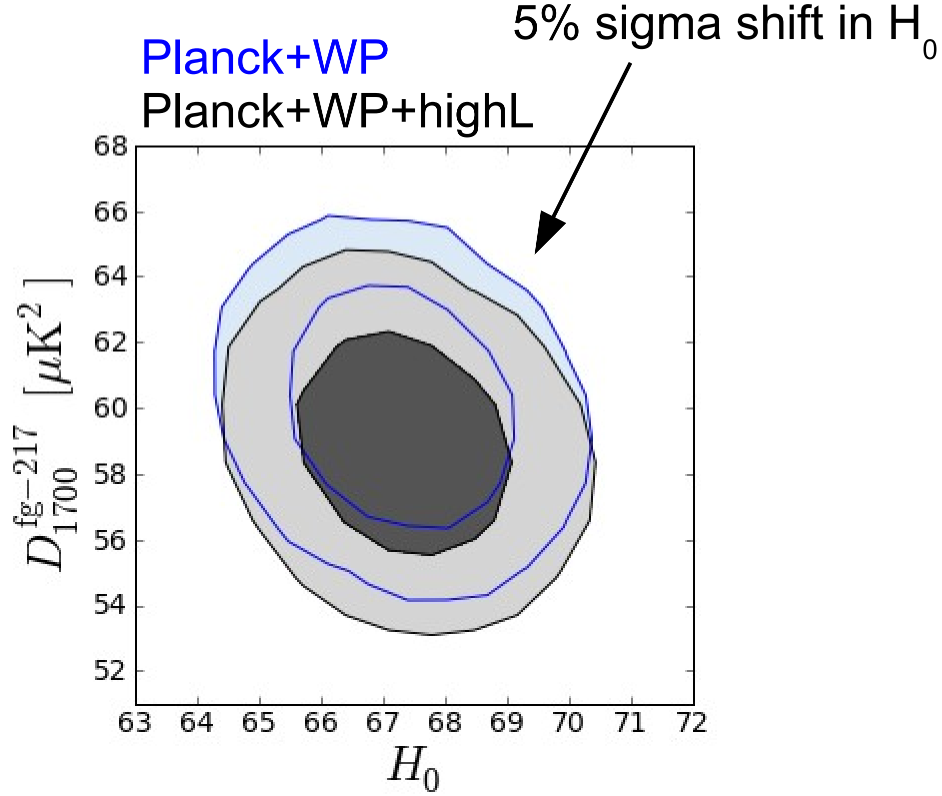


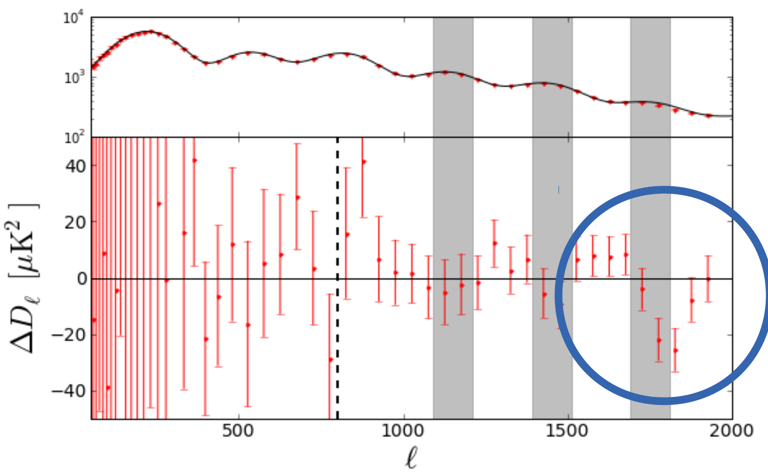


- Internal tests showed that the choice extra-galactic foreground model at most shifted H_0 by 20% sigma.

"low" H0 is robust to extra-galactic foreground modeling

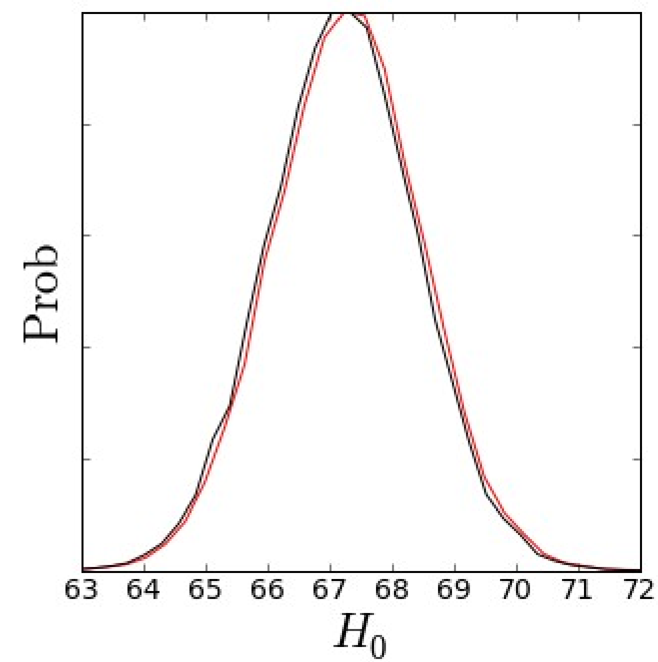
L=1800 feature

Planck 217-only data



- Pulling towards higher Alens
- Identified in the Inflation paper as the source of a local feature in the primordial power-spectrum reconstruction
- Not present in SPT or ACT

Planck+WP
Planck+WP 1700<L<1900 removed



Low-L "anomaly"

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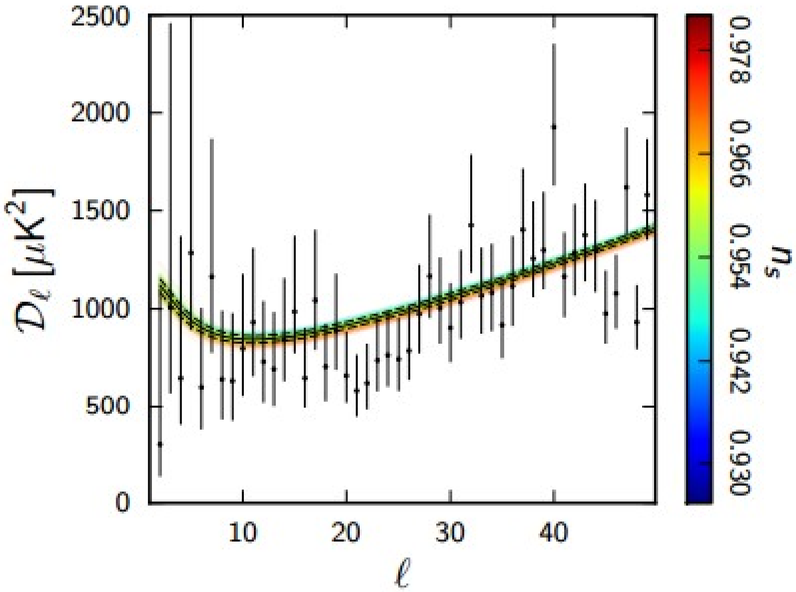
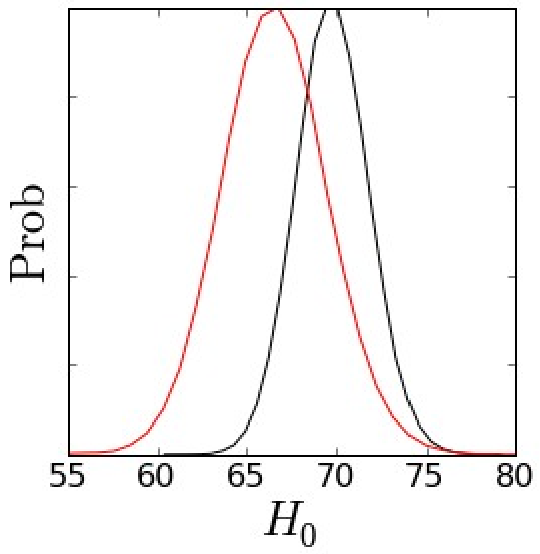


Low-L deficit was noted in WMAP, and grew worse in Planck because the best-fit model changed

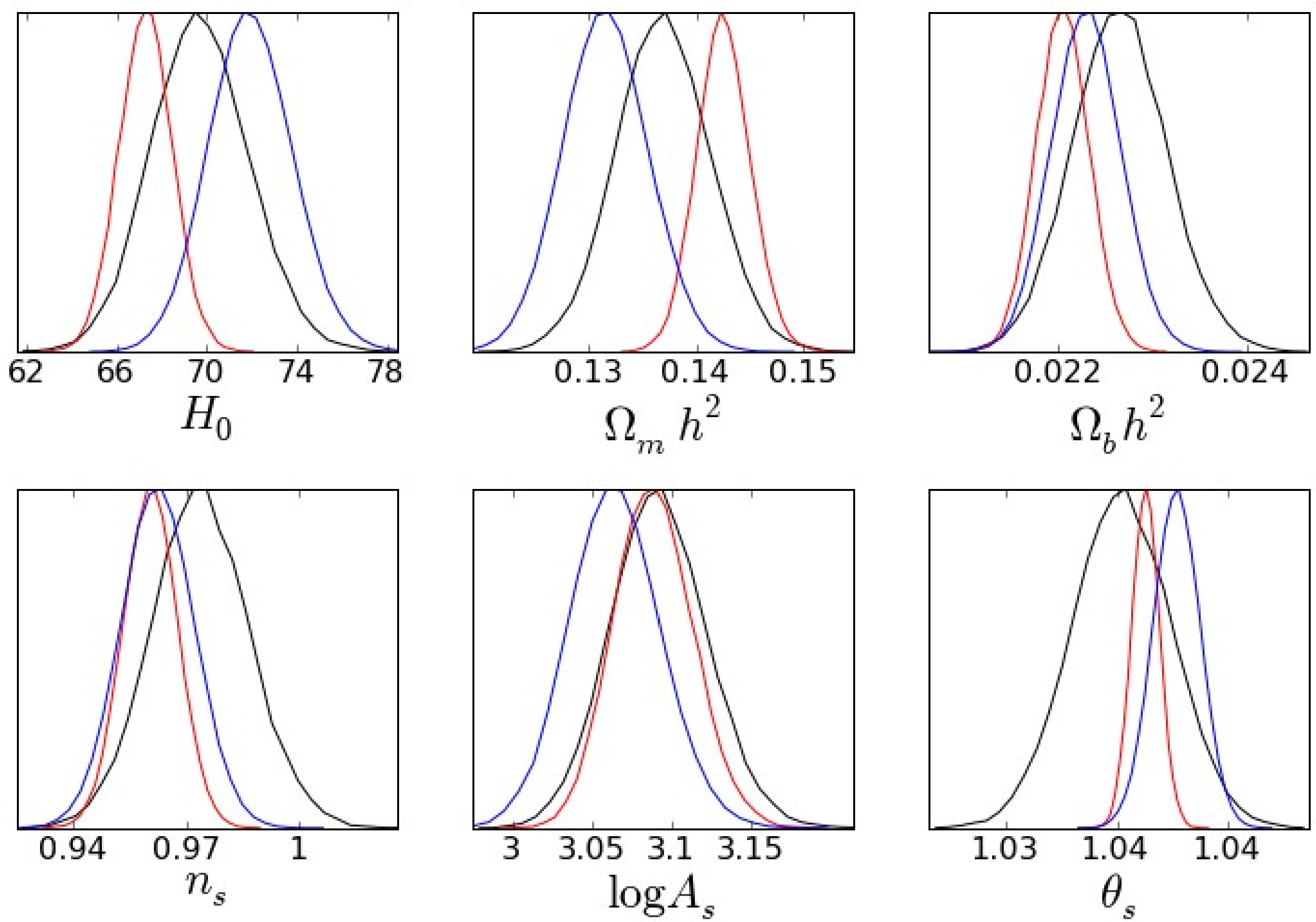
Planck+WP L<800
Planck+taup 50<L<800



Planck-SPT

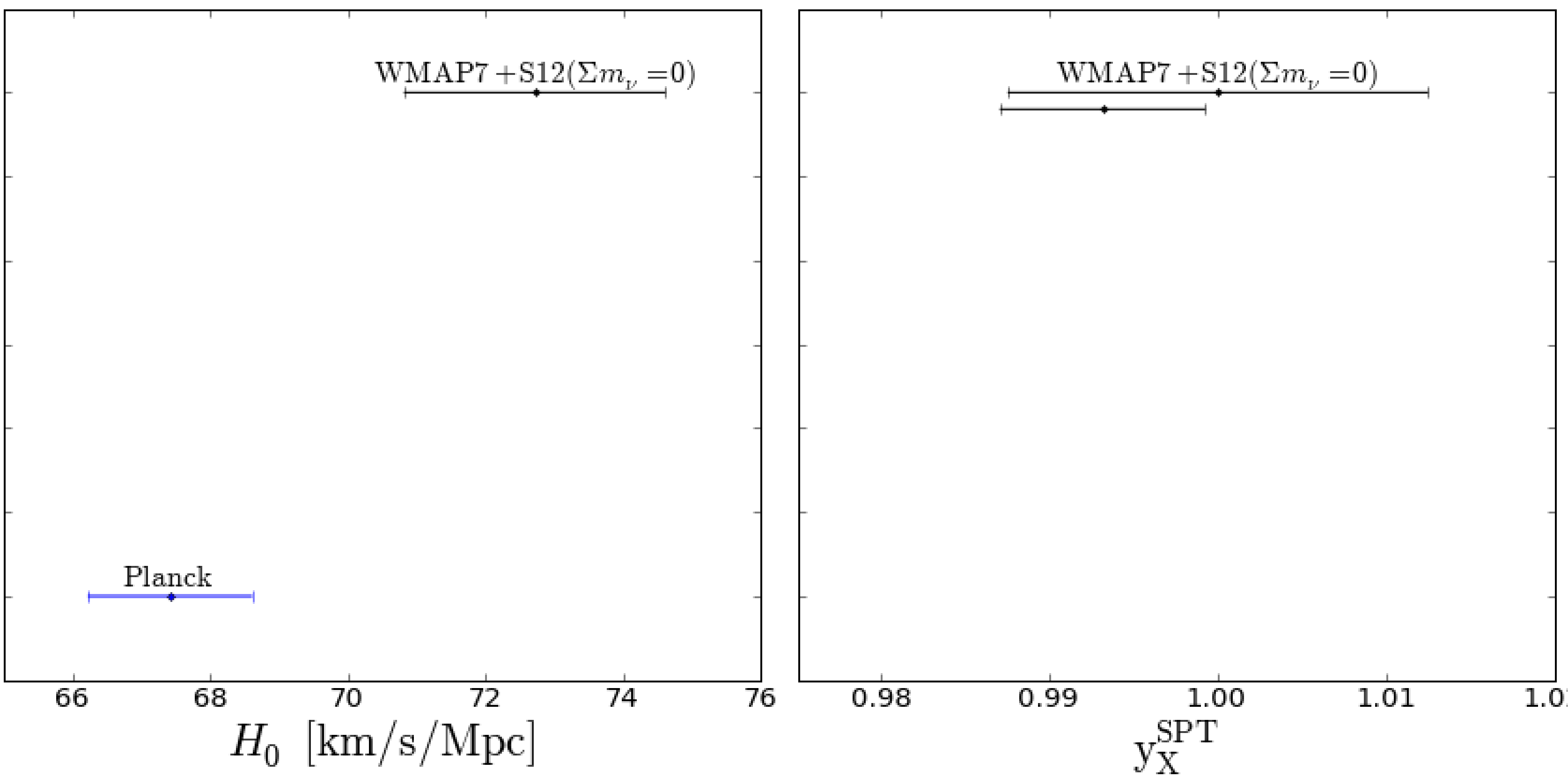
- SPT also measured the damping tail so why did H0 go *up* from WMAP?

WMAP9
Planck+WP
WMAP7+SPT



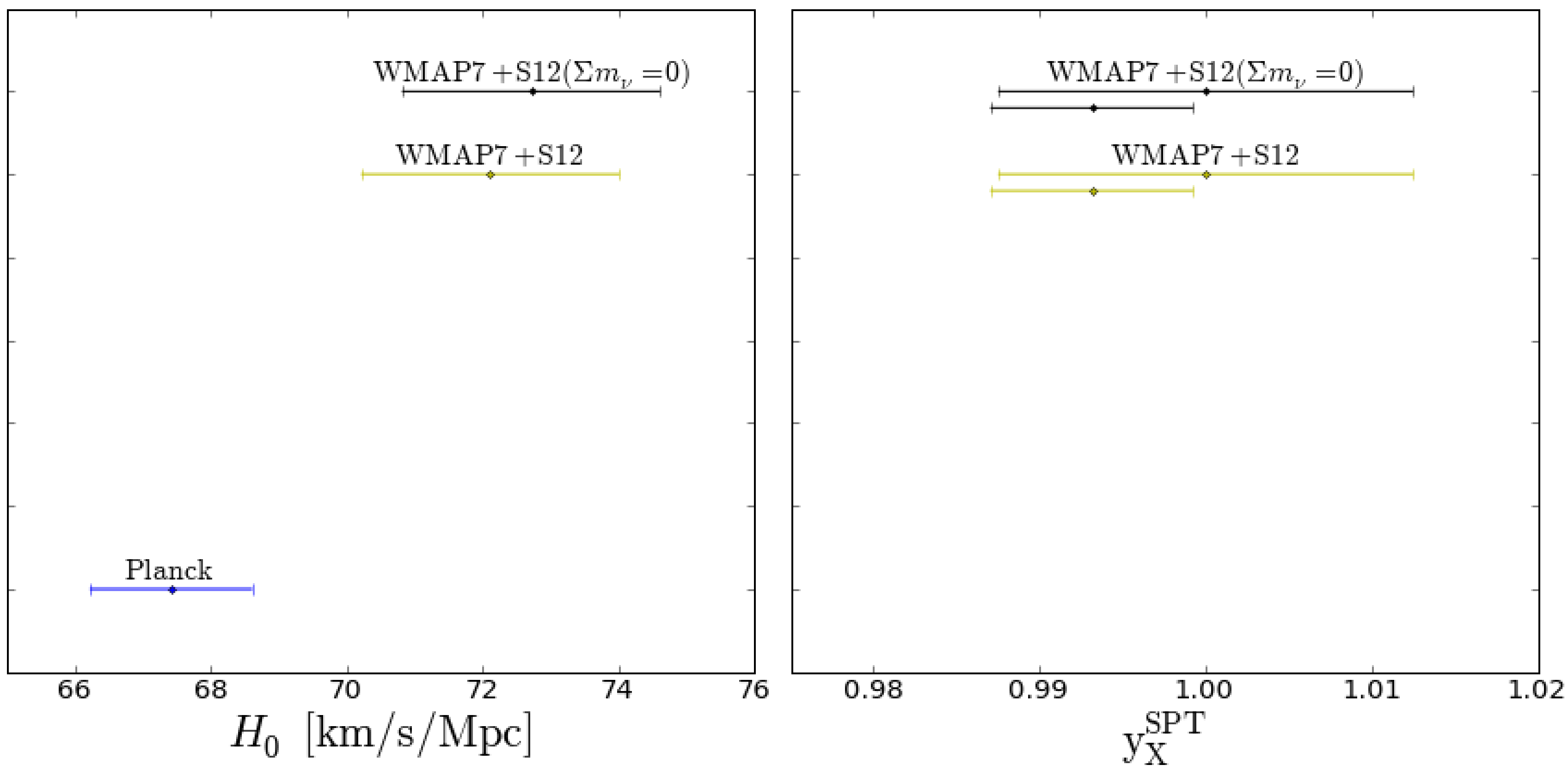
Planck-SPT

- Lets single out H0 since other shifts are correlated with it



Planck-SPT

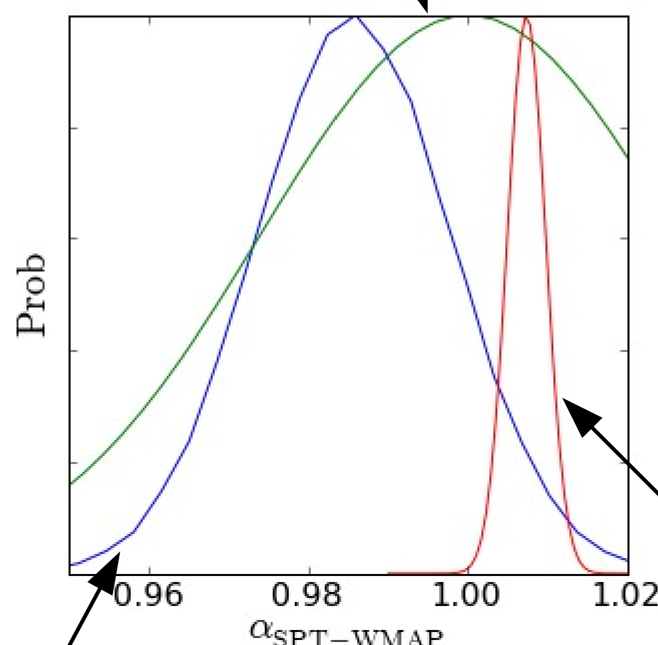
- Assumption neutrino mass = 0.06eV



Planck-SPT

- Using Planck to improve SPT calibration to WMAP

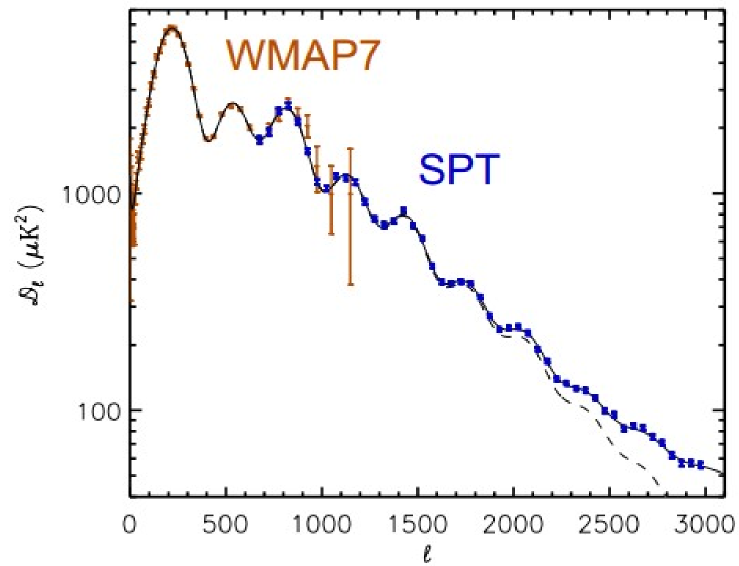
Calibration prior from matching to WMAP7 (1.00 +/- 0.025)



Posterior from chain (0.985 +/- 0.012)

Using Planck to calibrate WMAP7 and SPT to each other

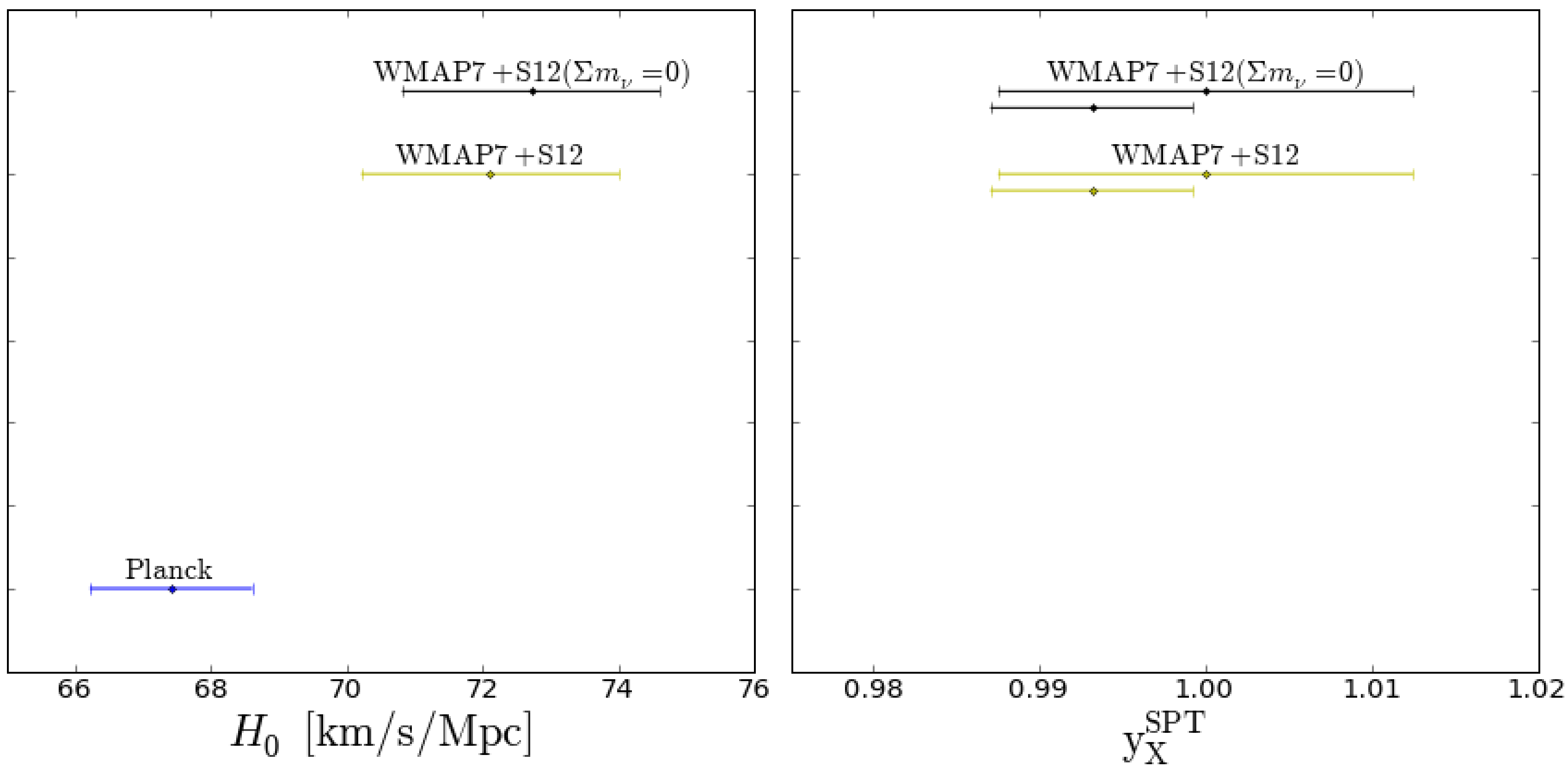
Story et al. 2012



Planck-SPT

- Why does the posterior sit lower?
  - SPT "excess" on [650,1100] in S12 band-powers of (19 +/- 12) uK^2
    - Identified in Hou et al 2012 as the source for mild preference for running
    - Goes to (1.3 +/- 4.2) uK^2 in Planck
  - SPT preference for *low* lensing
    - Low lensing → low Omm → lower third peak relative to first → lower SPT calibration to match that

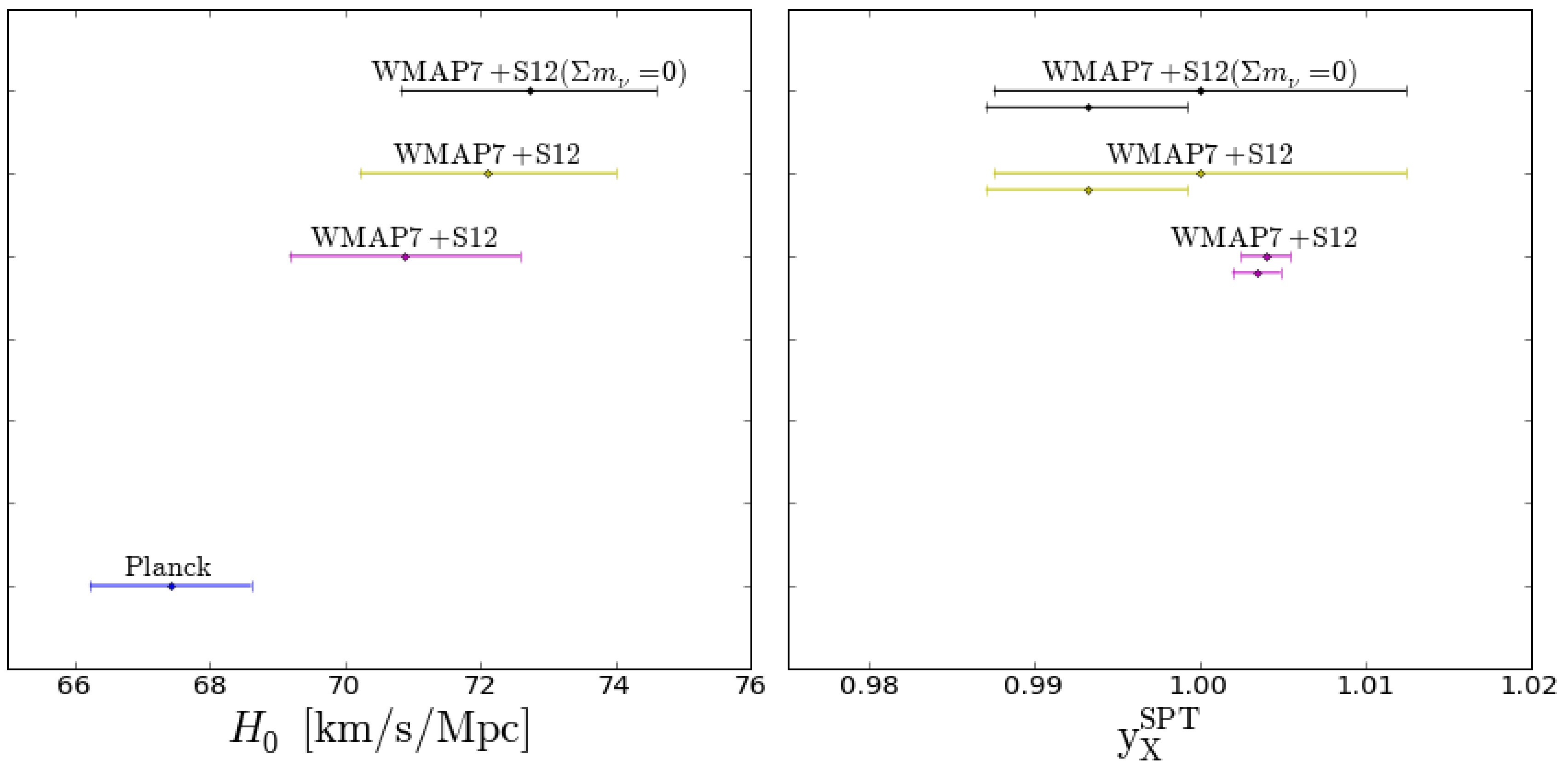
Planck-SPT



WMAP7 +S12(Σm_ν =0)
WMAP7 +S12
Planck
66
68
70
72
74
76
H_0 [km/s/Mpc]
WMAP7 +S12(Σm_ν =0)
WMAP7 +S12
0.98
0.99
1.00
1.01
1.02
y_X^{SPT}

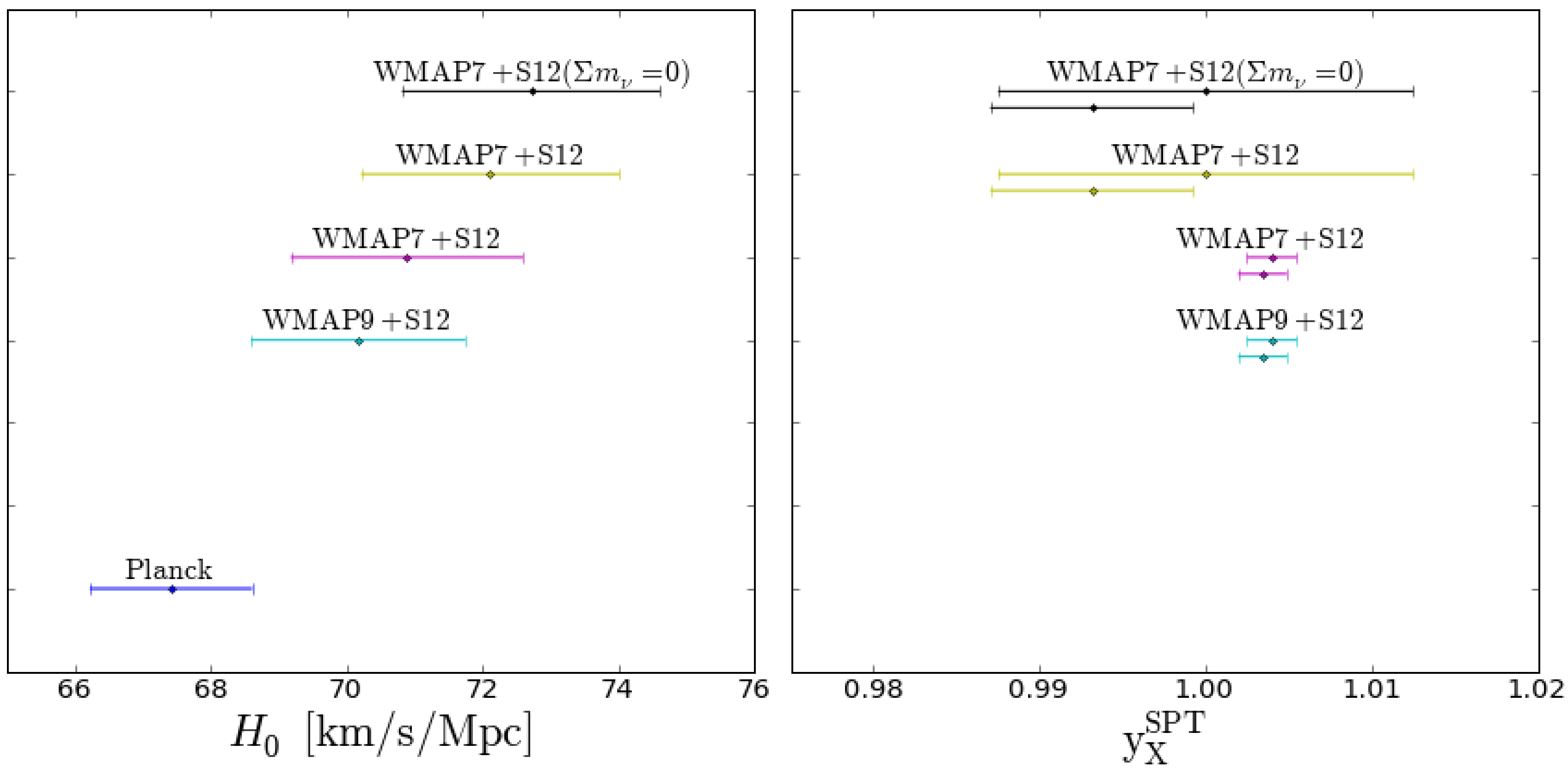
Planck-SPT

- Add in calibration information



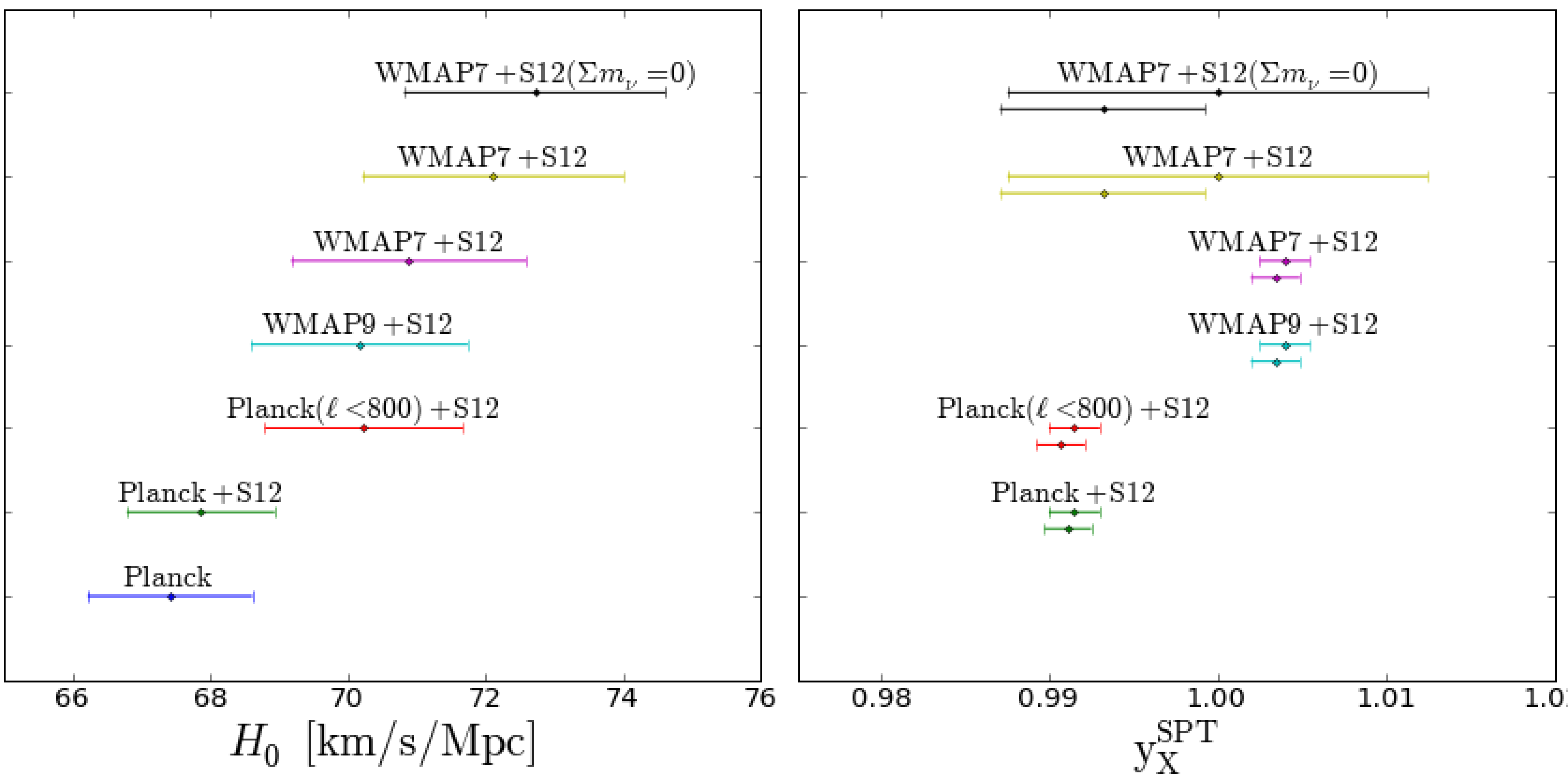
Planck-SPT

- WMAP7 → WMAP9



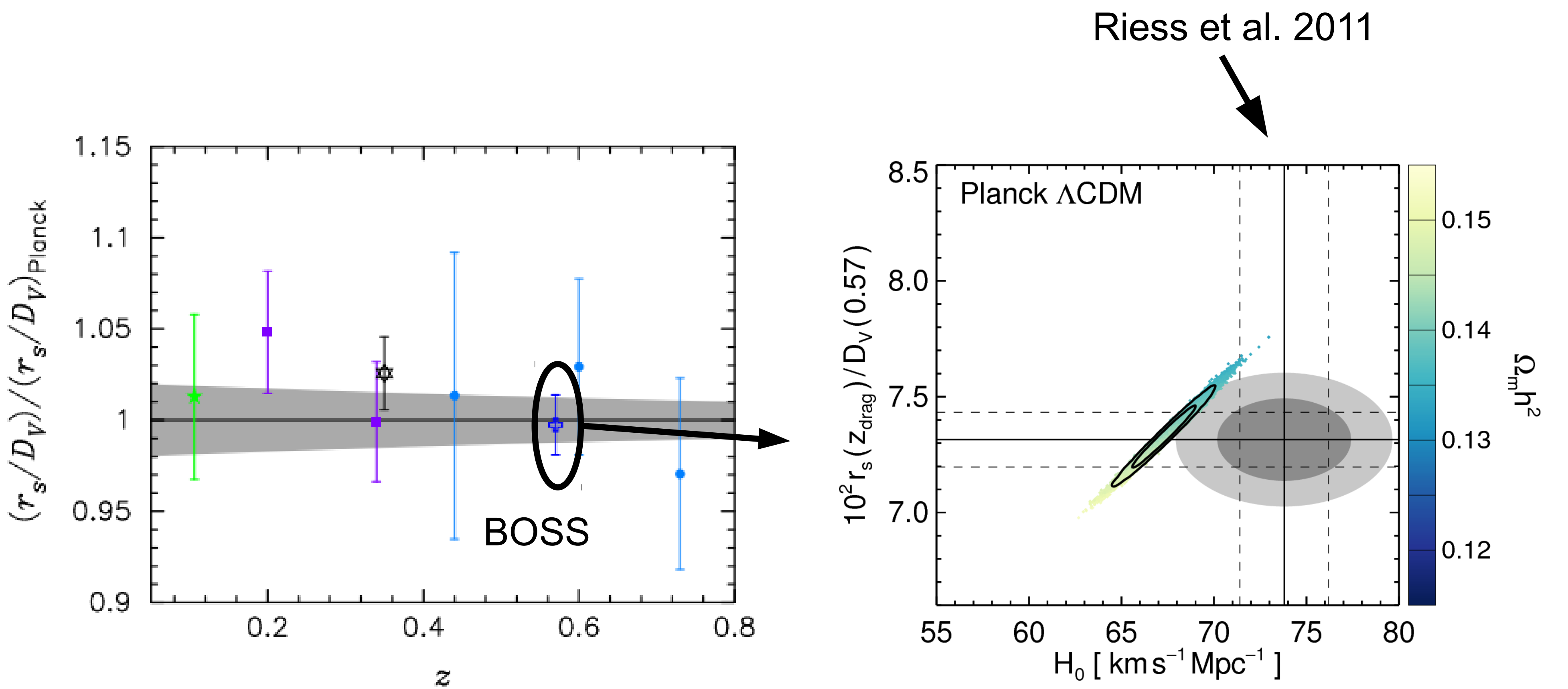
Planck-SPT

- Remaining difference is due different preference for lensing at L>800 between Planck and SPT

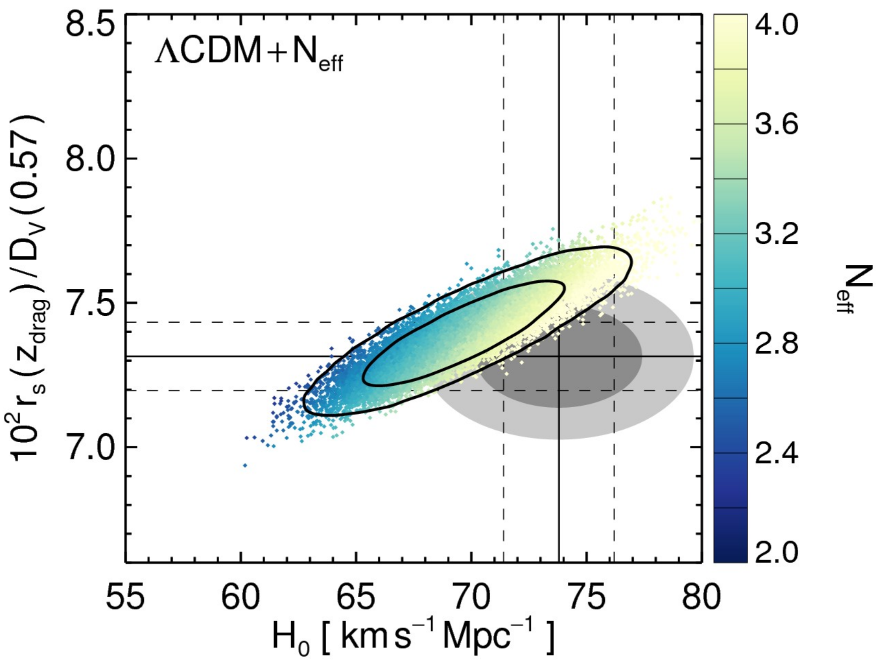


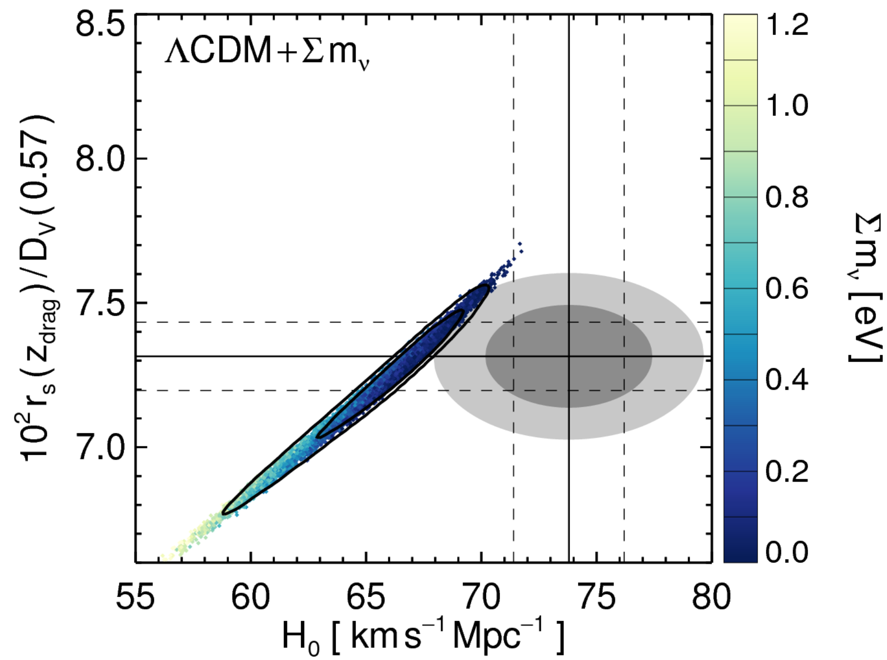
LCDM+Extensions

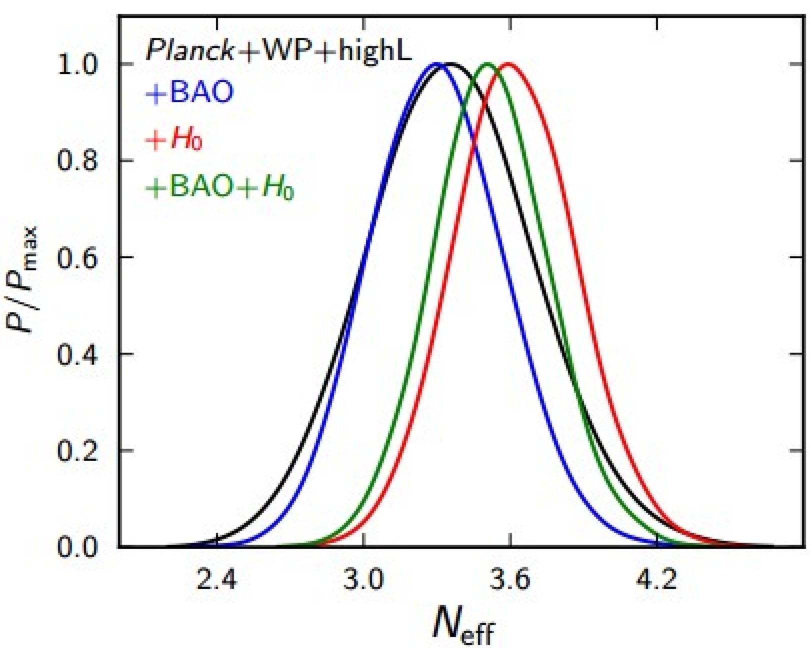
- Since LCDM is already a good fit to the data, let's talk about extension in the context of Planck + external data sets

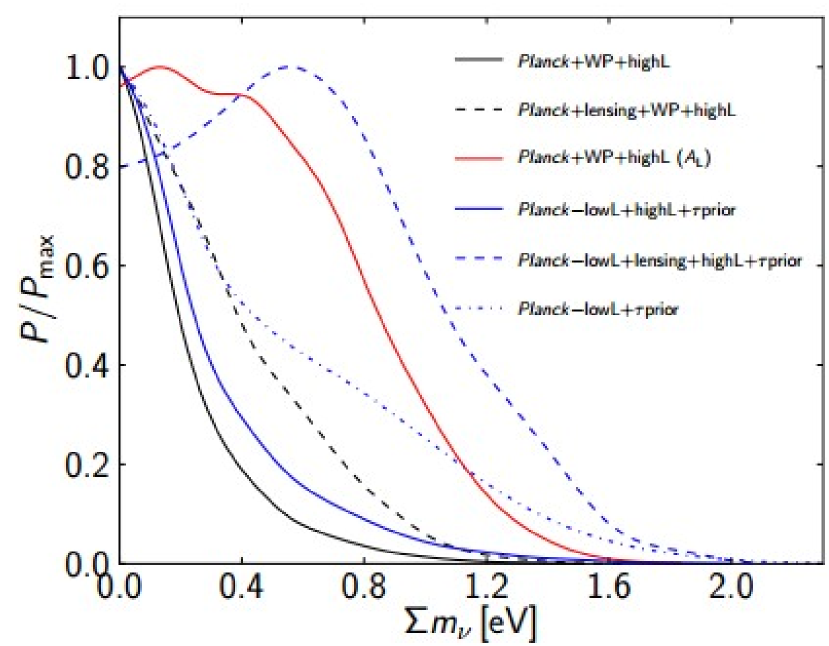


LCDM+Extensions





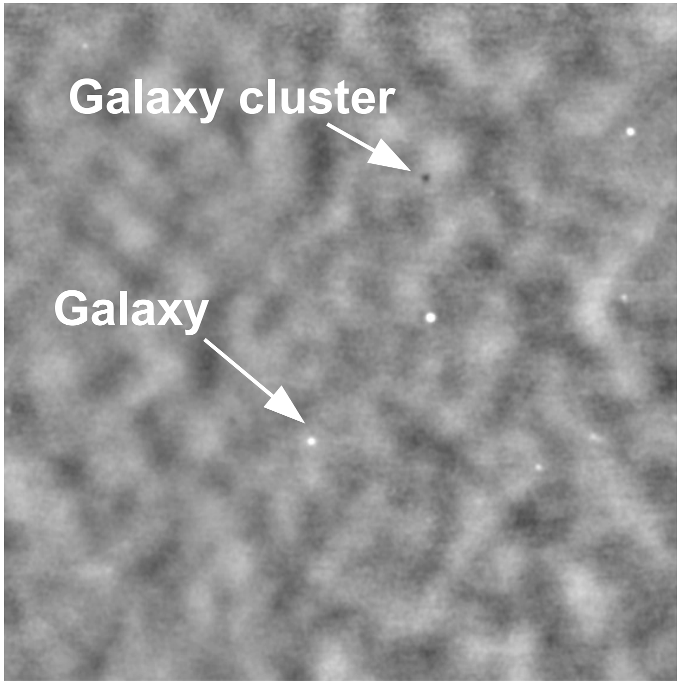




Conclusion

- Lensing is playing an important role in driving the shift in constraints from L<800 to full L range
  - We will soon learn a lot more about lensing from Planck polarization and other ground based polarization experiments
- 217 GHz plays an important role
- The shifts are robust to foreground modeling
- The L < 800 preference for slightly higher H_0 is related to the "low-L anomaly"
- With more data / different assumptions we now find that even WMAP+SPT does not favor significantly higher H_0

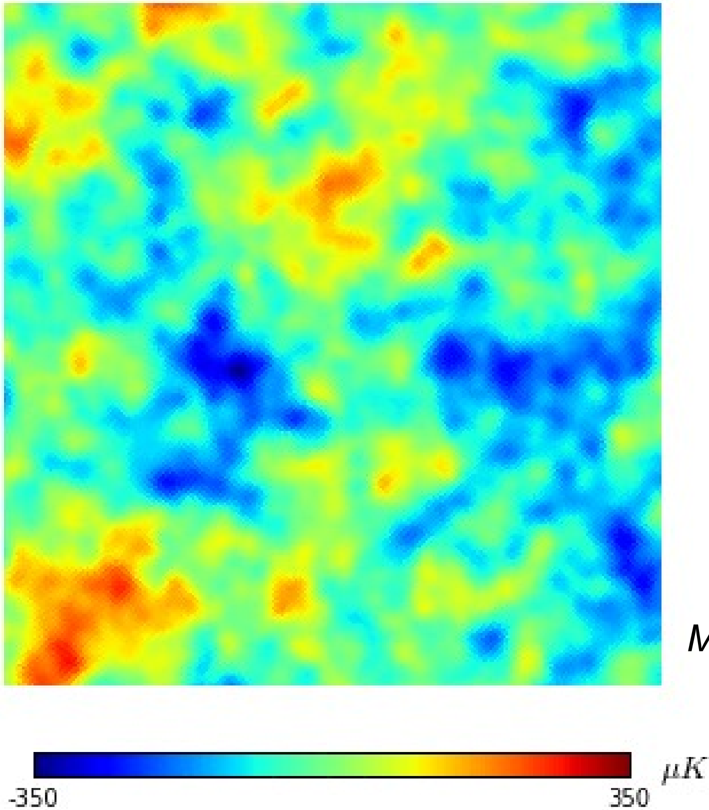
Resolved foregrounds:



SPT Collaboration

To scale

Unresolved foregrounds:
(Noise-free simulation)



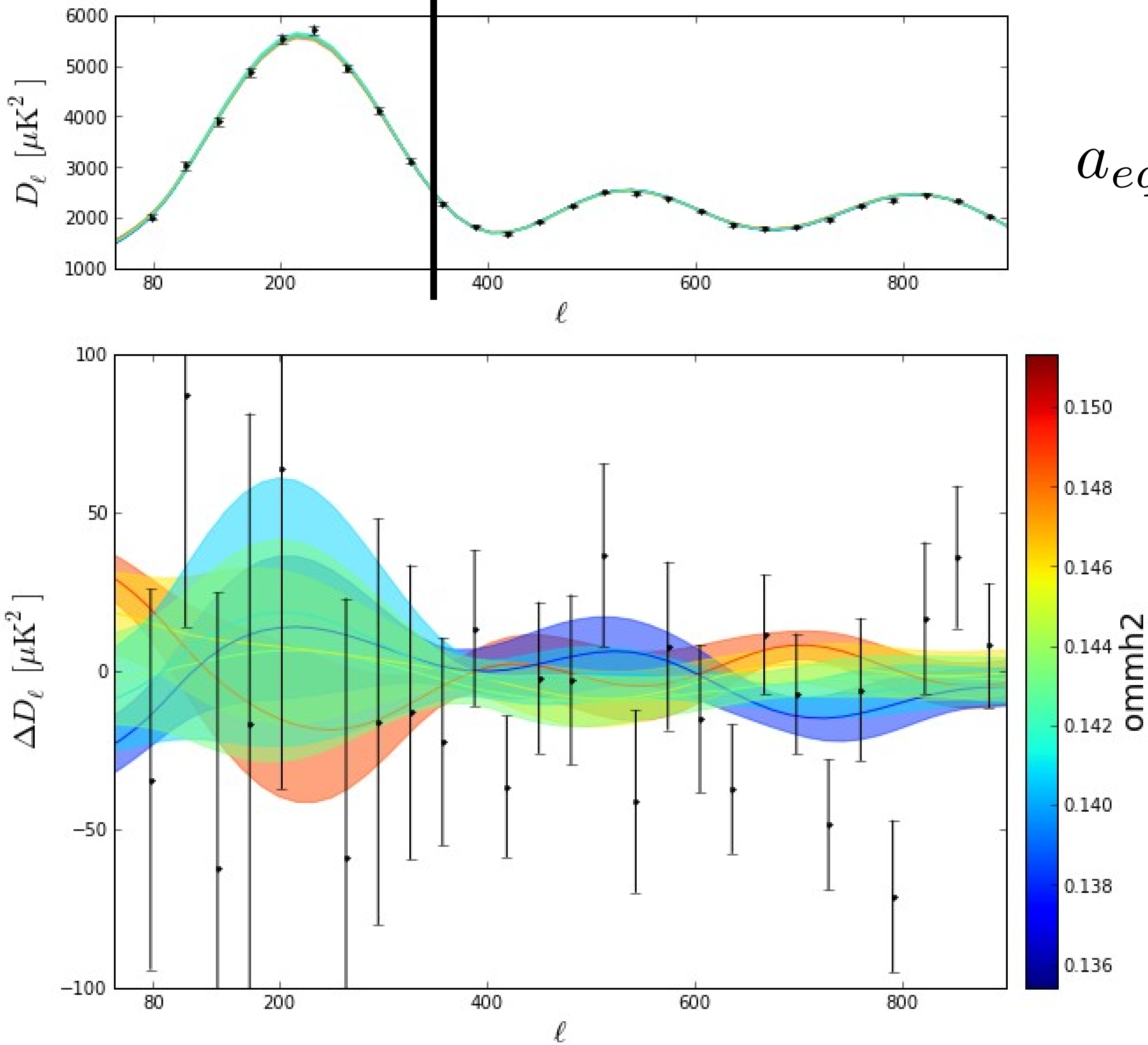
Millea

aeq later, smaller ommh2 ⟵ ⟶ aeq earlier, larger ommh2

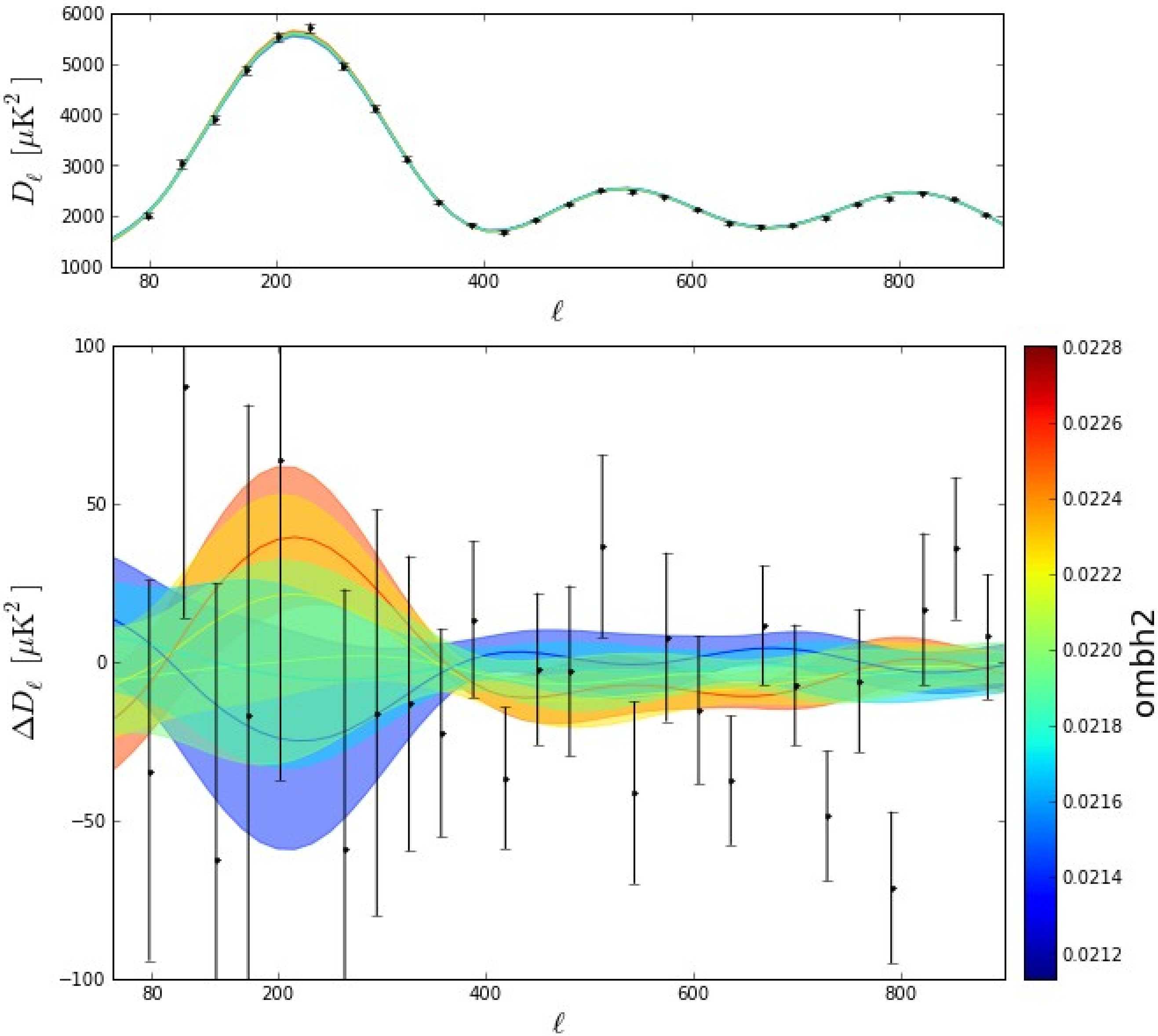
Entered horizon during matter
(potentials don't decay)

Entered horizon during radiation
(potentials decay, fluctuations bounce-back higher)

$$a_{eq} = \frac{\rho_r}{\rho_m} = \frac{\Omega_r h^2}{\Omega_m h^2}$$



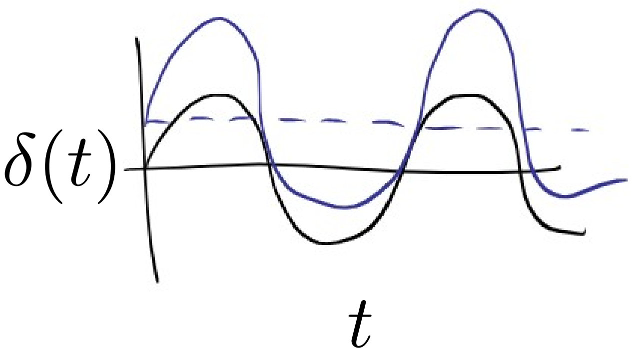
Millea



Plasma is acting like a driven oscillator

- Baryons – inertia
- Photons – pressure
- Gravity – driving

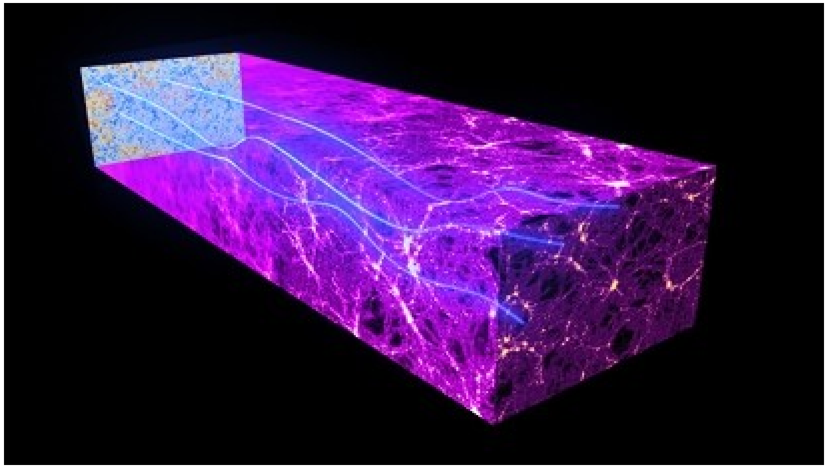
Creates an offset:

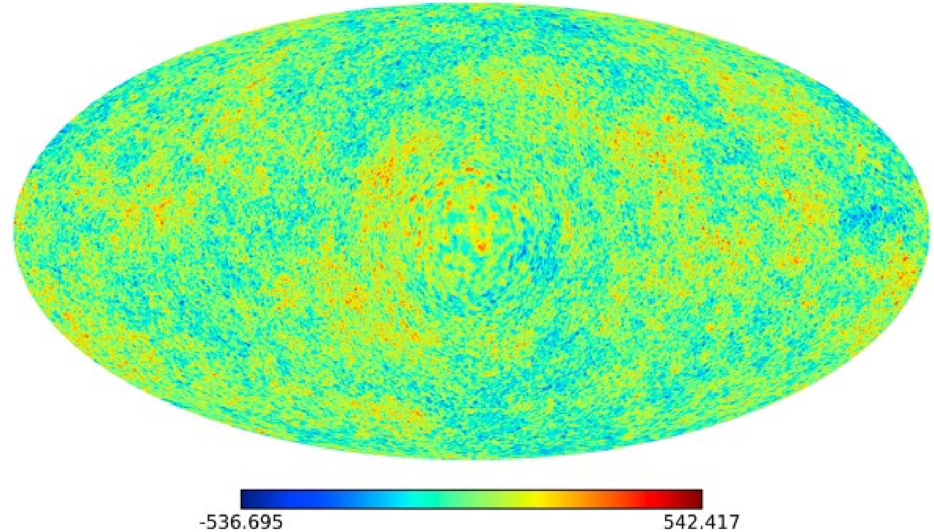


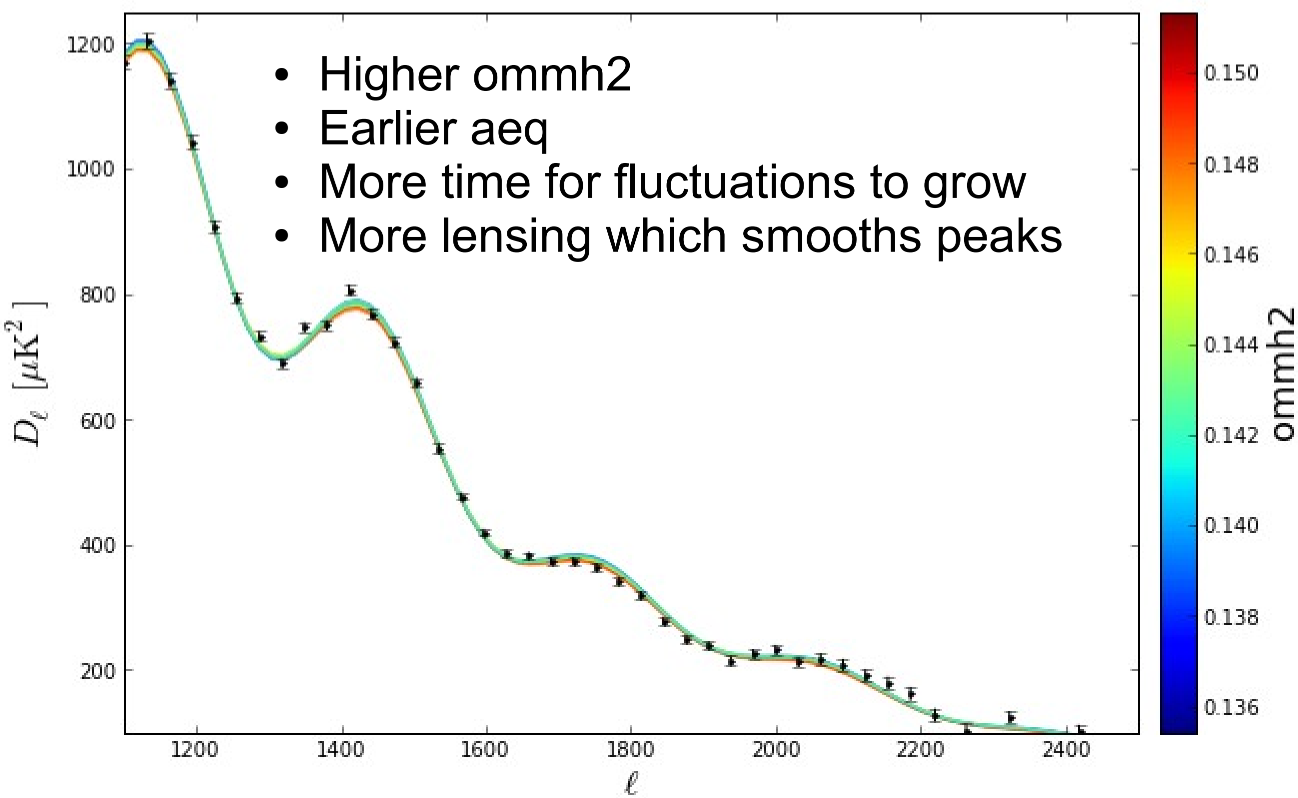
Millea

Lensing

Duncan Hanson







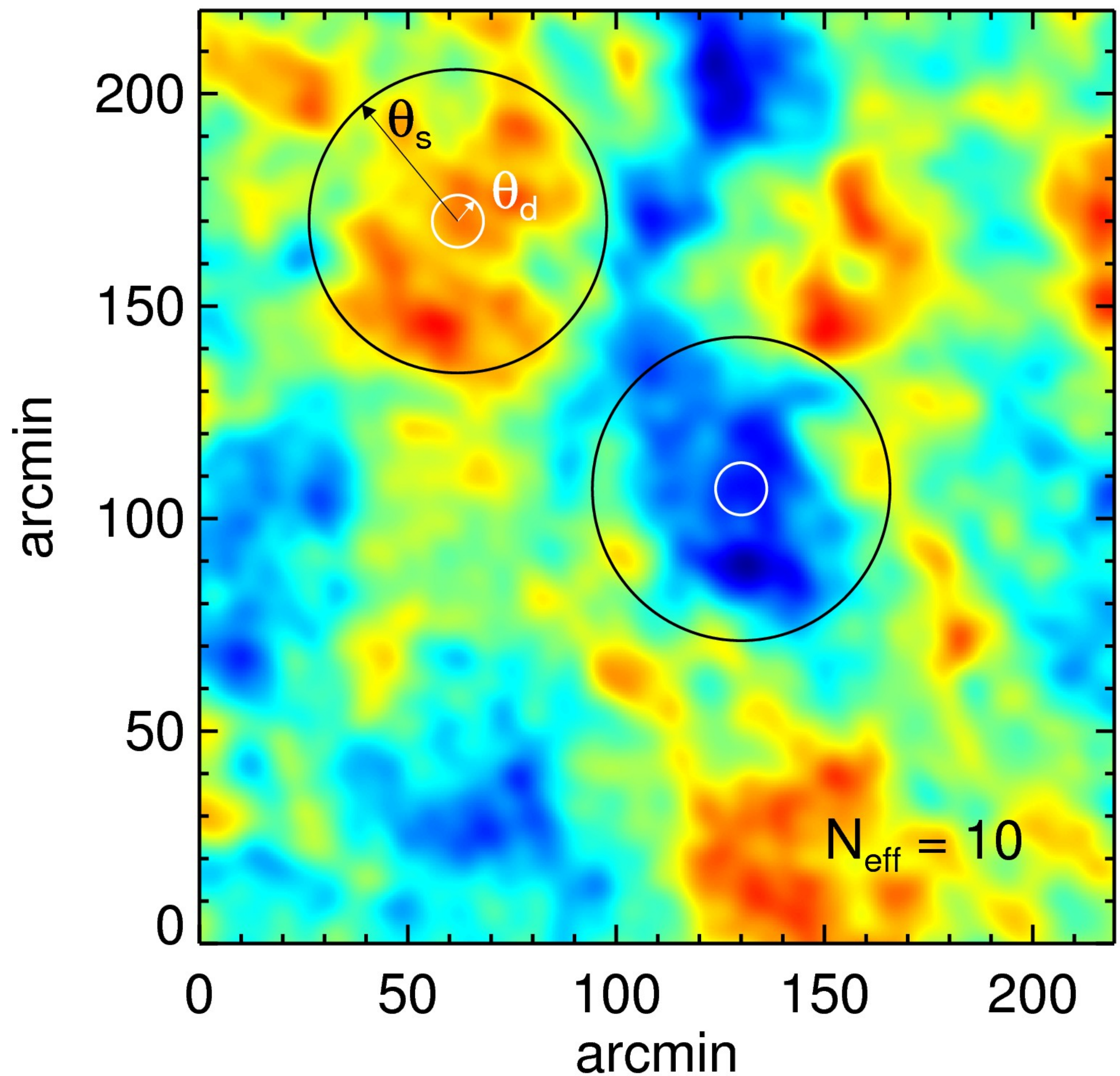
- Higher ommh2
- Earlier aeq
- More time for fluctuations to grow
- More lensing which smooths peaks

Millea

Can arbitrarily scale this effect up and down using a parameter called Alens.

Only Alens=1 is physical

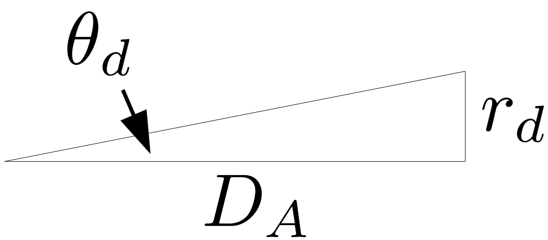
Damping

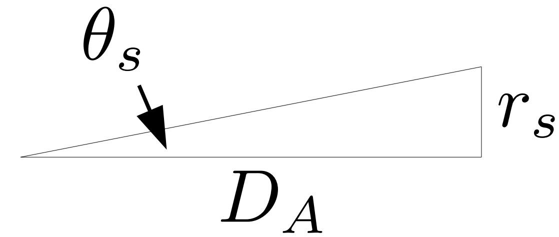


To scale

Zhen Hou

Damping





$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H(a)}$$

n_e ← $\Omega_b h^2, Y_p$

$H(a)$ ← $\Omega_m h^2$

$$r_s = \int_0^{t_*} c_s \frac{dt}{a} = \int_0^{a_*} \frac{c_s da}{a^2 H(a)}$$

c_s ← $\Omega_b h^2$

$H(a)$ ← $\Omega_m h^2$

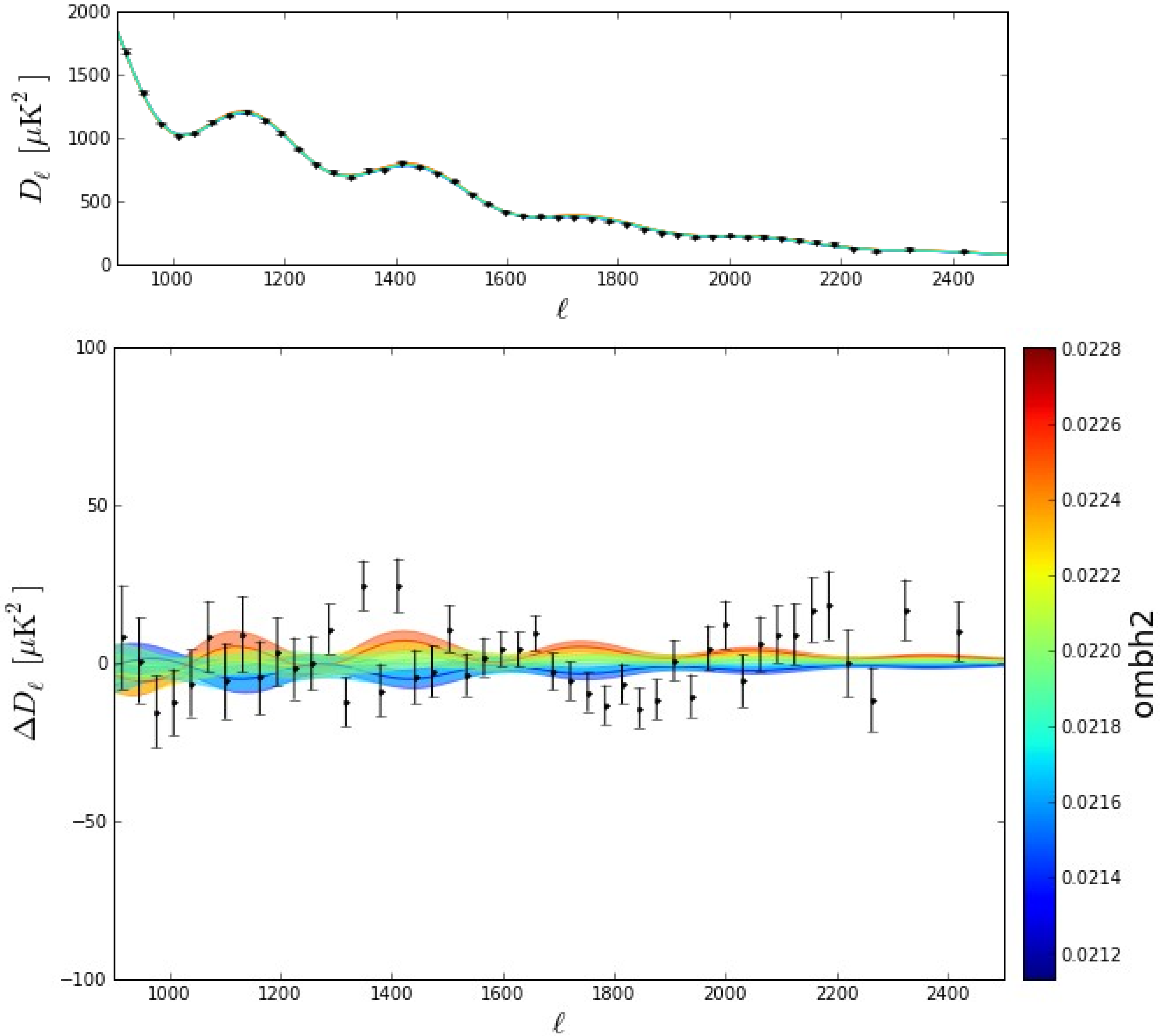
$$\frac{\theta_d}{\theta_s} = \frac{r_d / D_A}{r_s / D_A} = \frac{r_d}{r_s}(\Omega_b h^2, \Omega_m h^2, Y_p)$$

Tightly constrained → θ_d / θ_s

Already constrained by lensing → $\Omega_m h^2$

Not (usually) a free parameter, analogous to Alens → Y_p

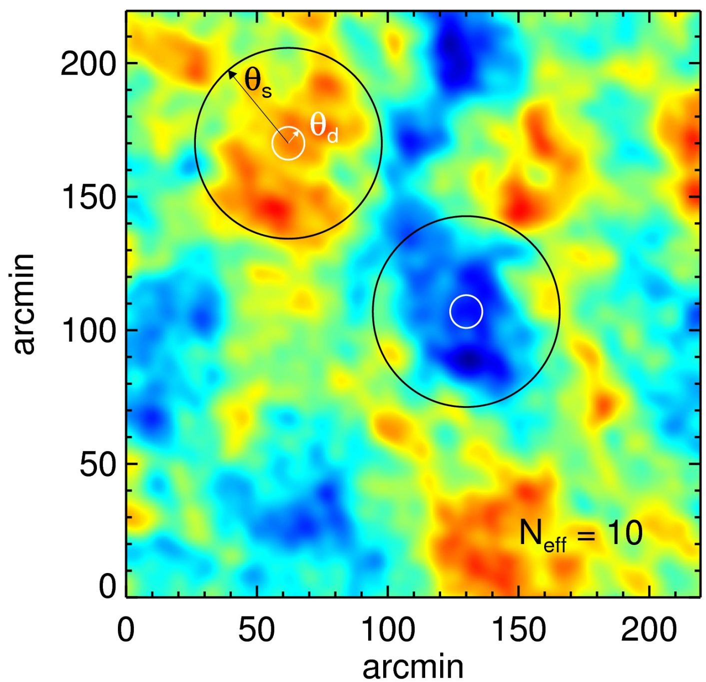
Damping



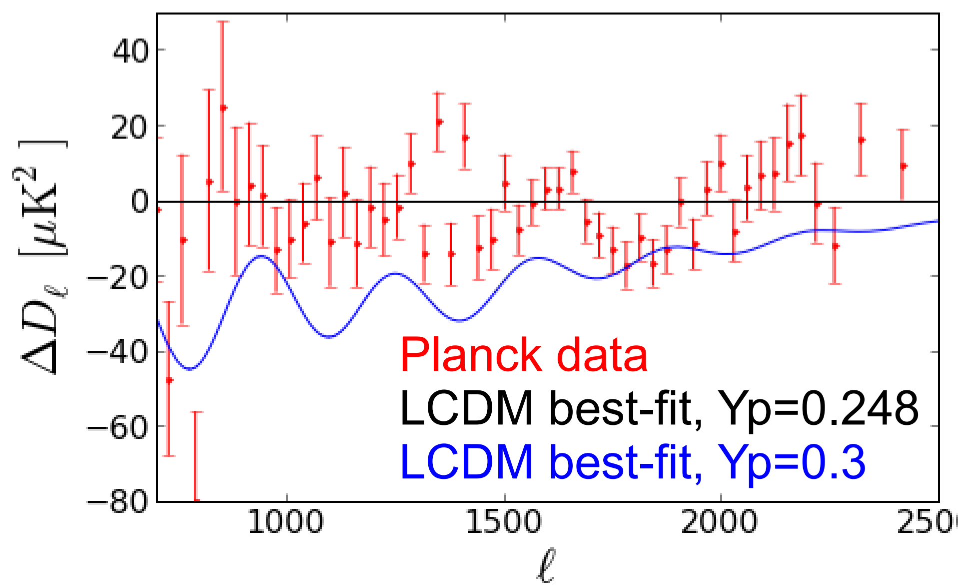
Millea

Damping

See Zhen Hou's talk on **Wednesday** for an excellent description of the effects of damping



Zhen Hou



Already constrained by lensing and L<800

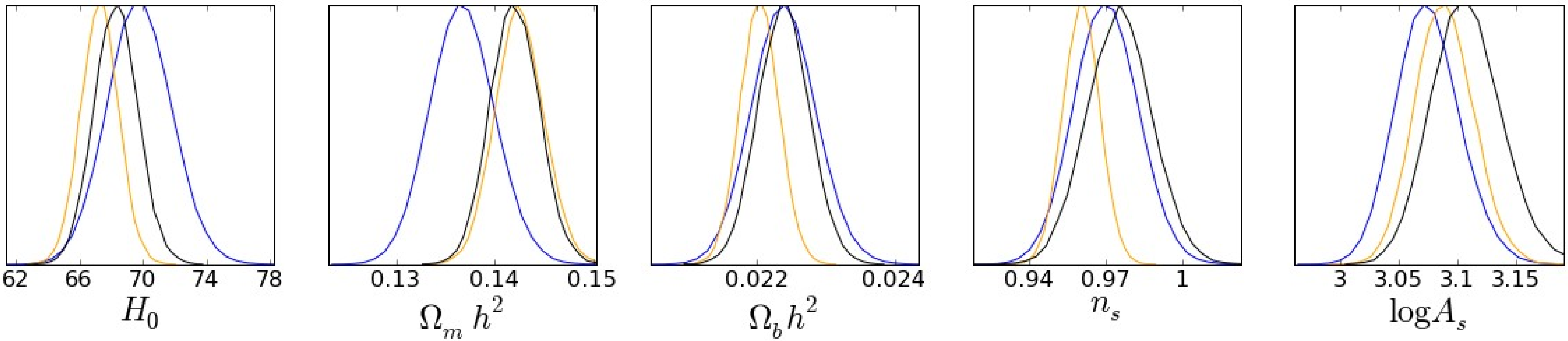
Tightly constrained

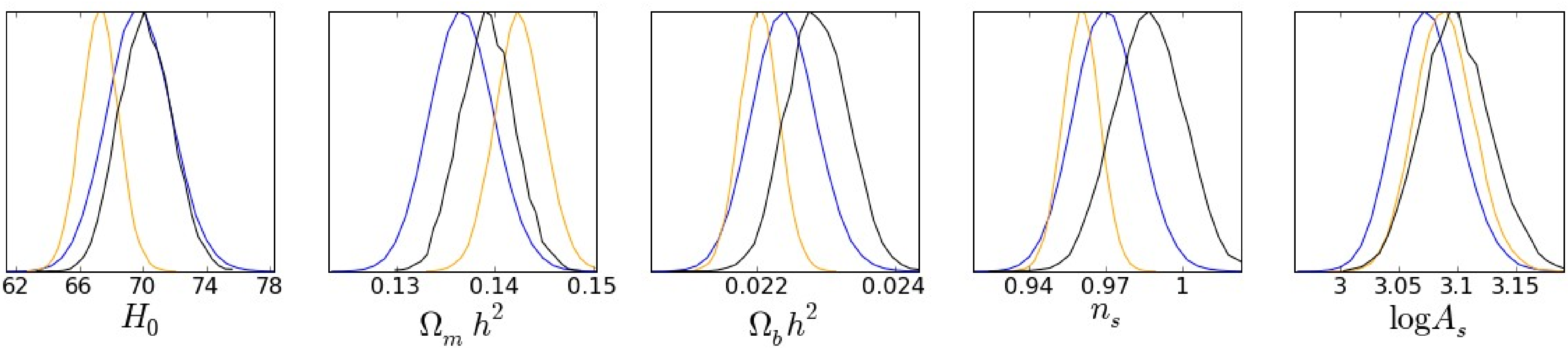
$$\frac{\theta_d}{\theta_s} = \frac{r_d/D_A}{r_s/D_A} = \frac{r_d}{r_s}(\rho_b, \rho_m, Y_p)$$

Not a free parameter in LCDM, analogous to Alens

Damping

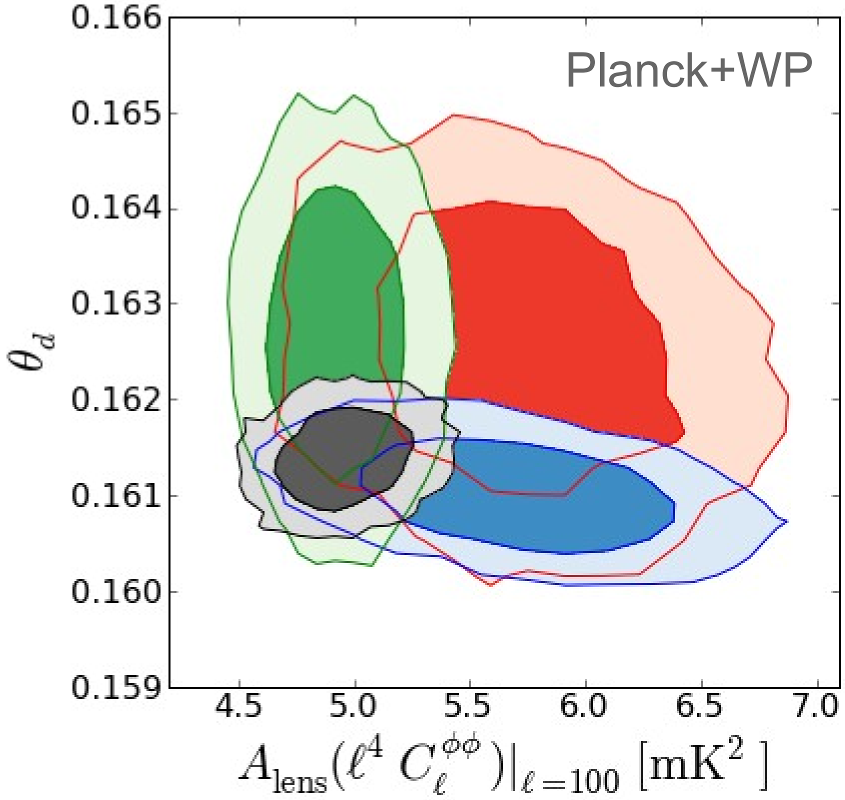
Planck L<800 LCDM
Planck L<2500 LCDM
Planck L<2500 LCDM+Yp





Planck L<800 LCDM
Planck L<2500 LCDM
Planck L<2500 LCDM+Alens+Yp

Lensing and Damping



LCDM
LCDM+Alens
LCDM+Yp
LCDM+Alens+Yp

Just black and red

Degeneracies between thetad and tilt