

Cosmology W13

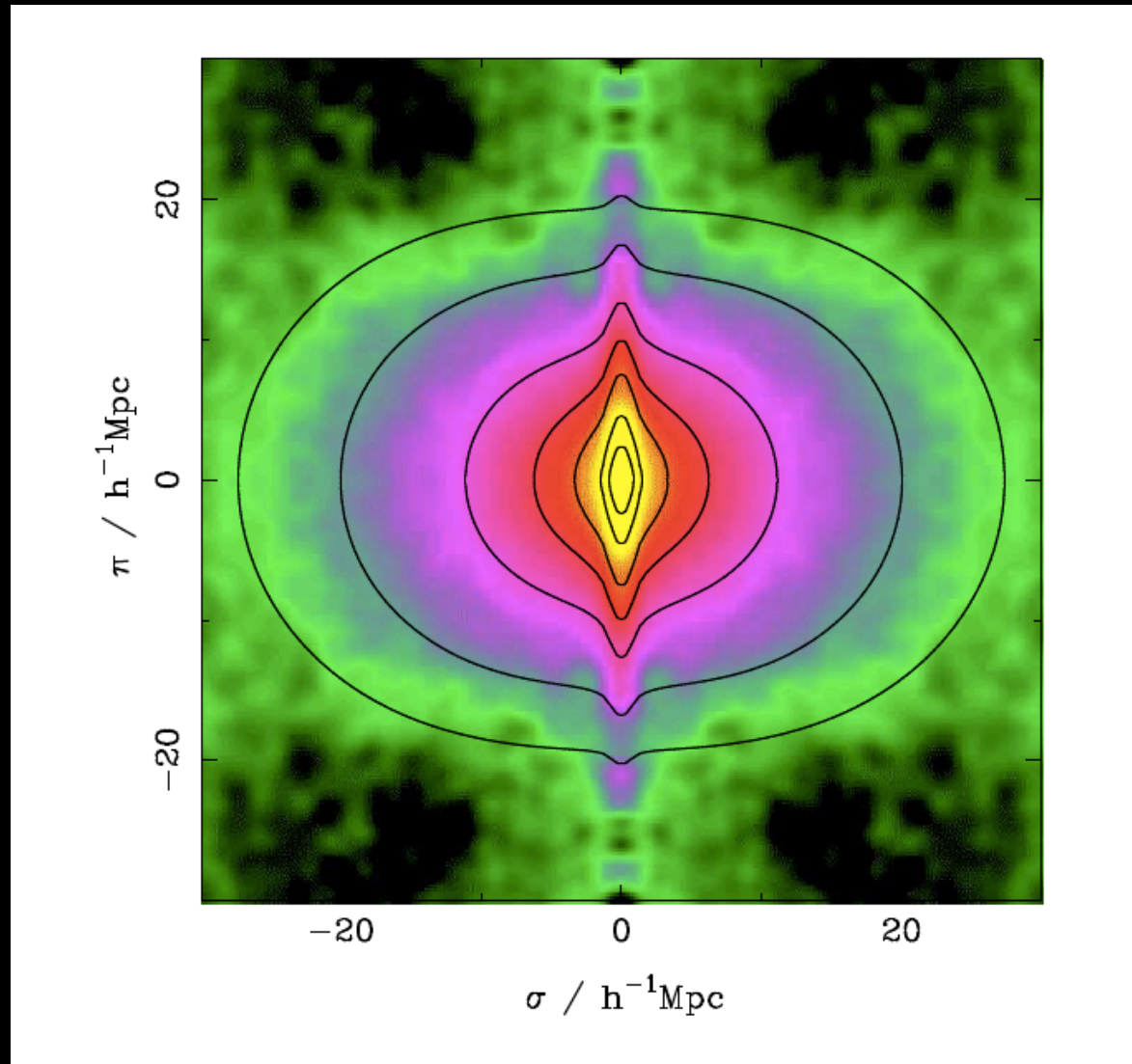


Lecture 13: March 6 2013

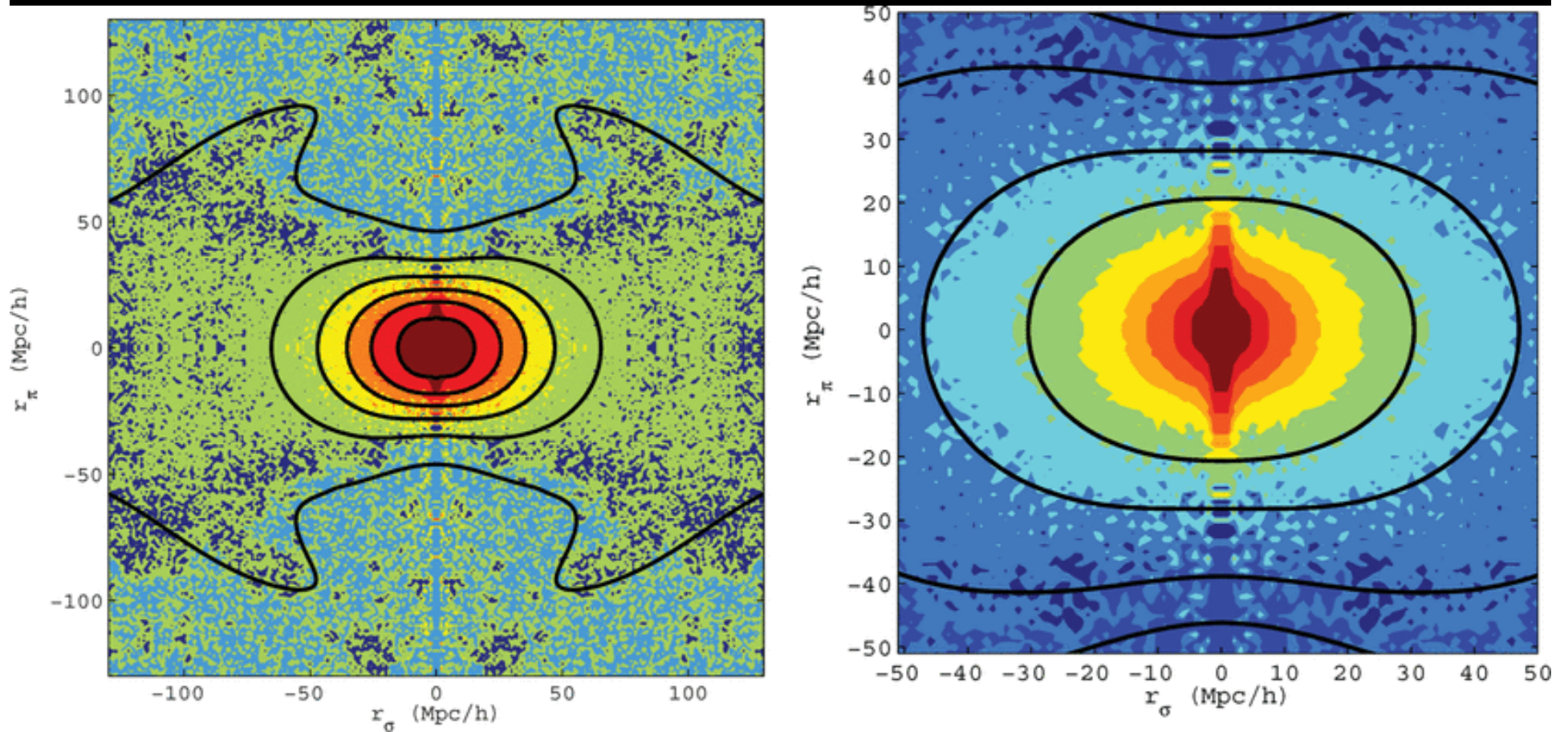
The cosmic microwave background

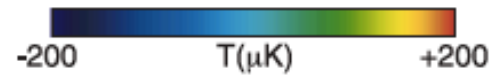
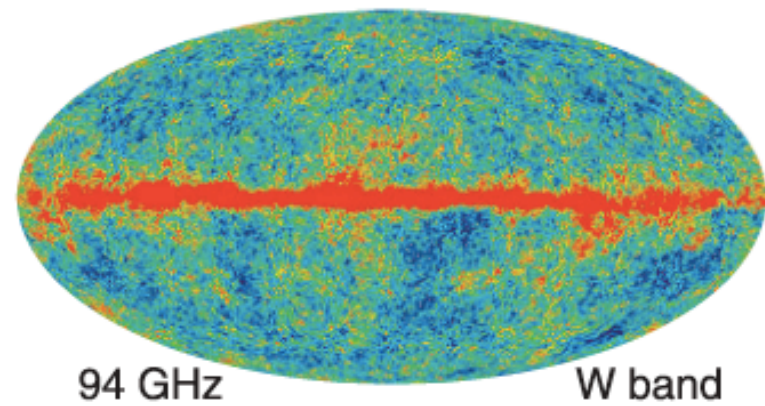
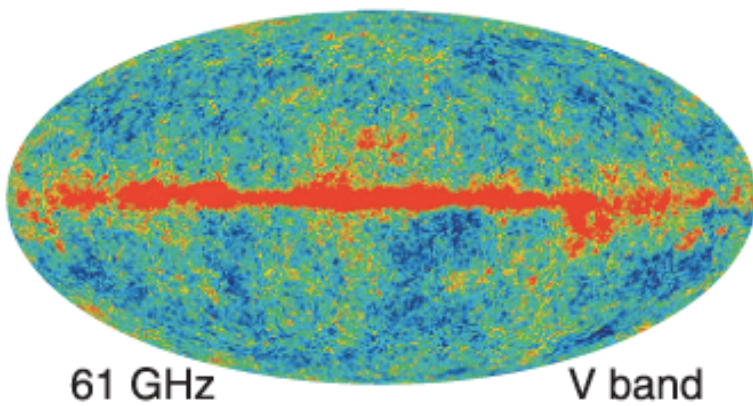
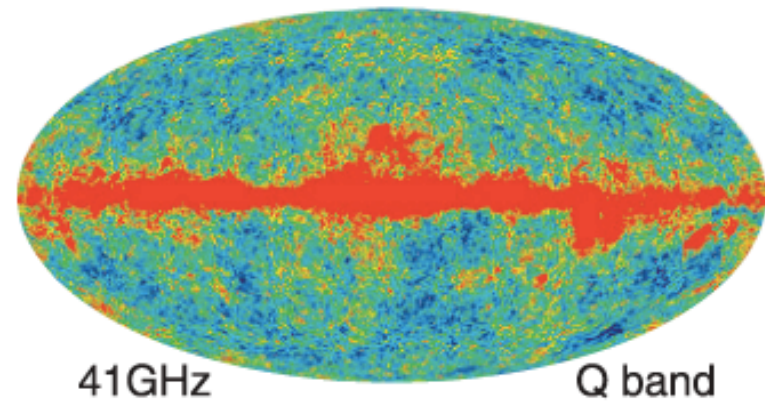
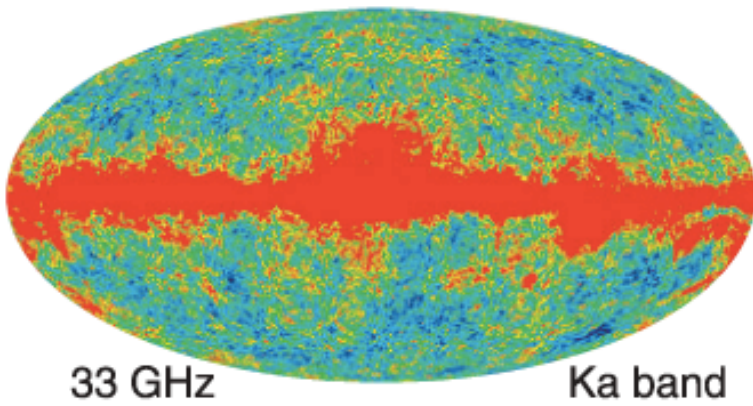
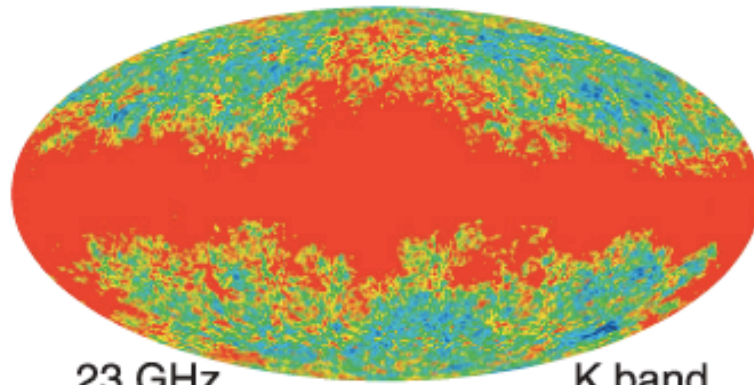
- Last scattering “surface”
- Relevant scales
- Acoustic peaks
- Observations

Before CMB: Redshift space distortions

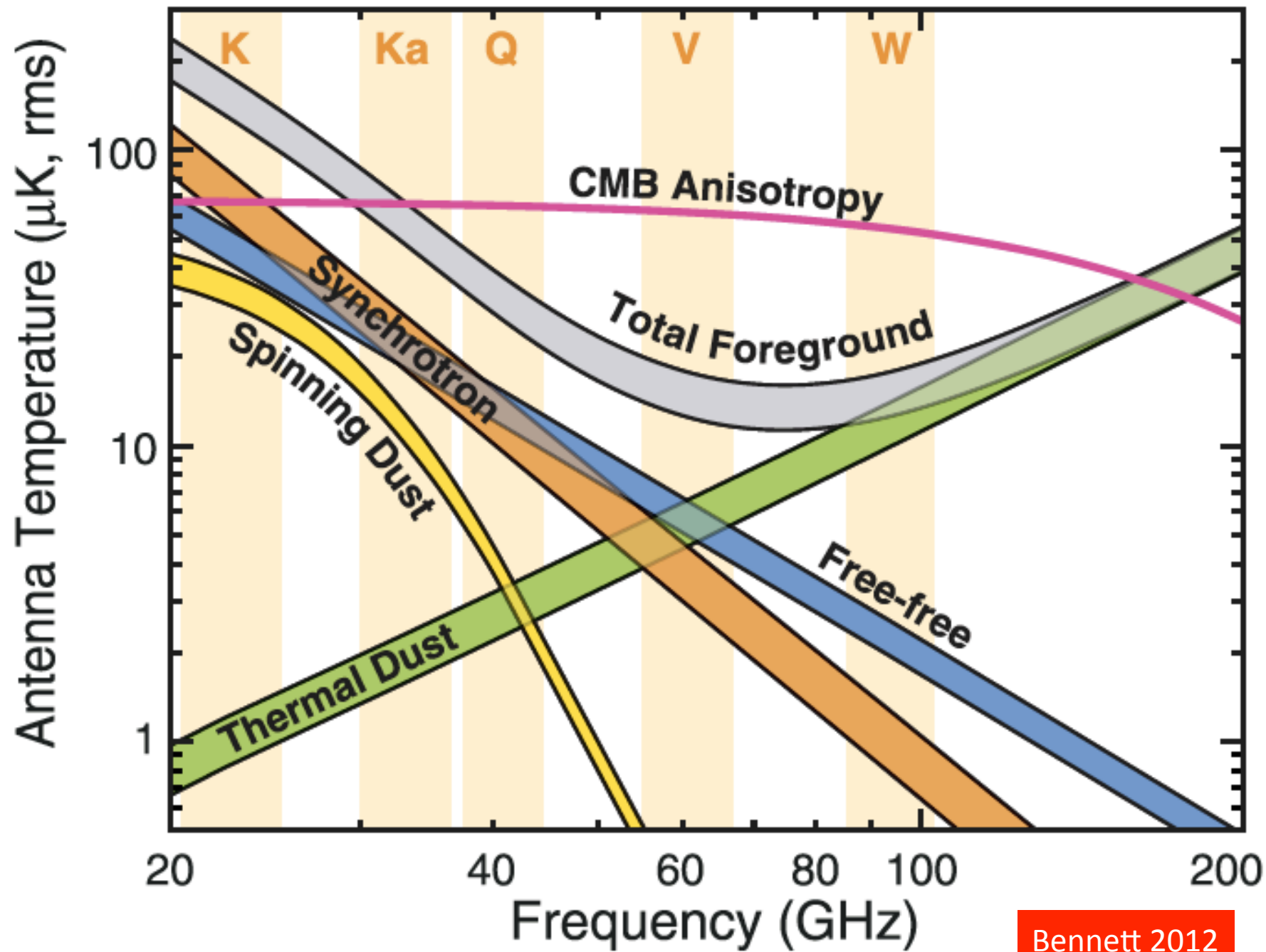


Redshift space distortions





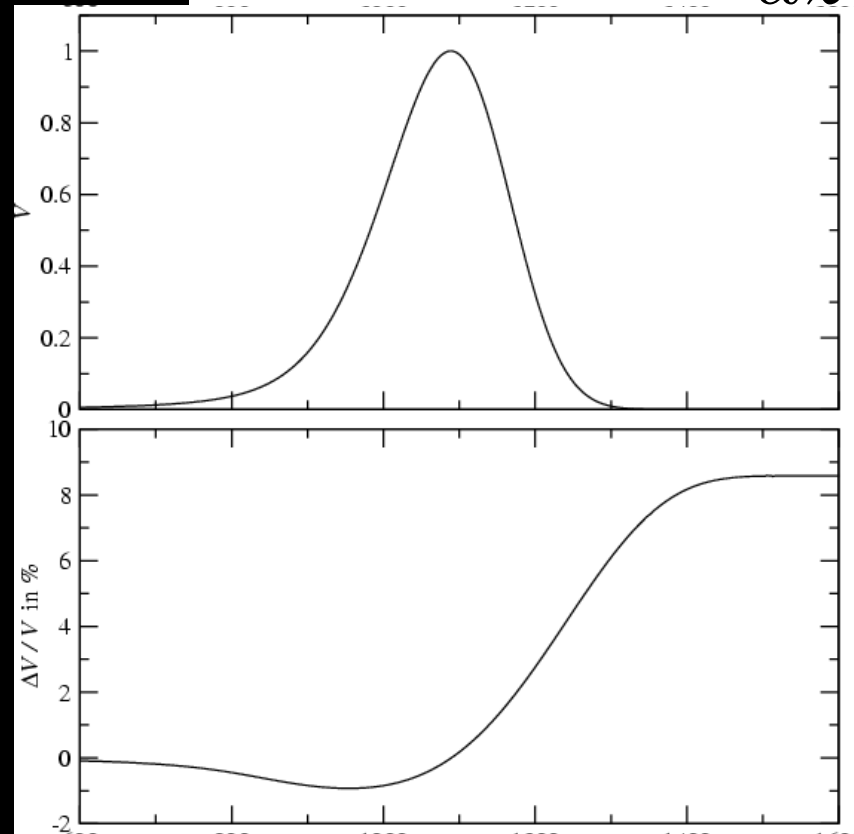
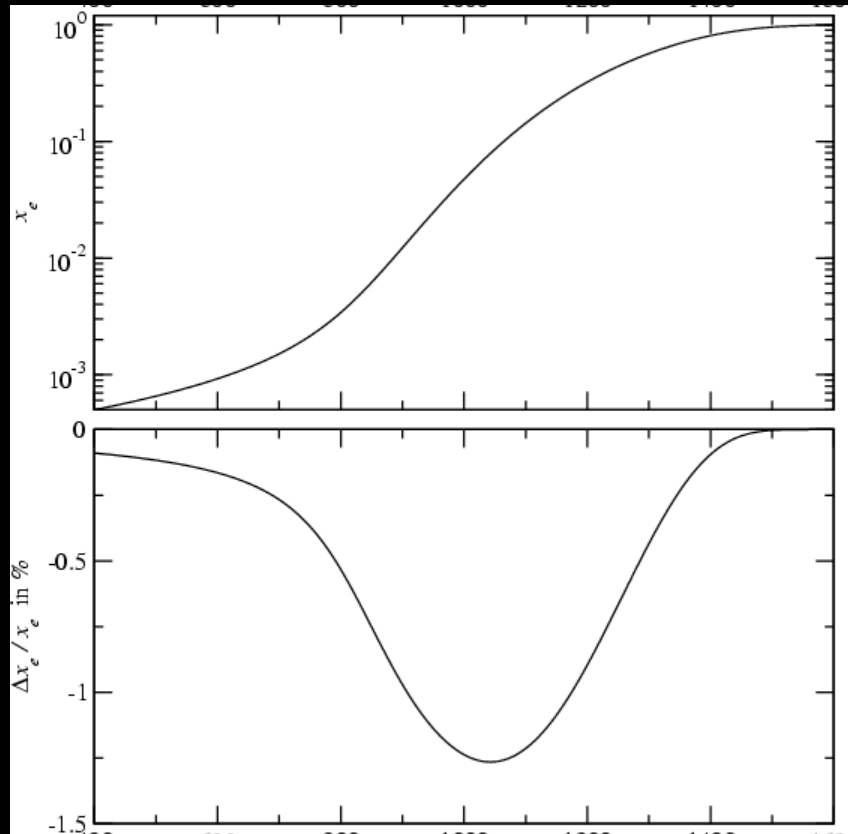
Bennett 2012



The thickness of the last scattering surface

$$v(z)dz = e^{-\tau} \frac{d\tau}{dz} dz$$

Reionization



Relevant scales

- Thickness of last scattering $Dz \sim 200$ at $z \sim 1000-1200$: ~ 40 Mpc comoving ~ 3 arcmin
- Silk damping scale at recombination: $\sqrt{1/3 l_{ct}} \sim 9$ Mpc
- Sound horizon $\sim c_s t \sim 56$ Mpc
- Jeans length before recombination is much larger than sound horizon ~ 900 Mpc
- Particle horizon $3ct \sim 500$ Mpc (at recombination) ~ 40 Mpc (at equivalence)

Statistical description of CMB power spectrum

- Expand $\Delta T/T$ in spherical harmonics
- For symmetry, coefficients of spherical harmonics are related to power on each angular scale $\theta \approx \pi/l$

$$a_{lm} = \int_{4\pi} \frac{\Delta T}{T}(\theta, \phi) Y_{lm}^* d\Omega$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{+l} a_{lm} a_{lm}^* = \langle |a_{lm}|^2 \rangle_m$$

A simple guide to interpret CMB power spectra: large scales

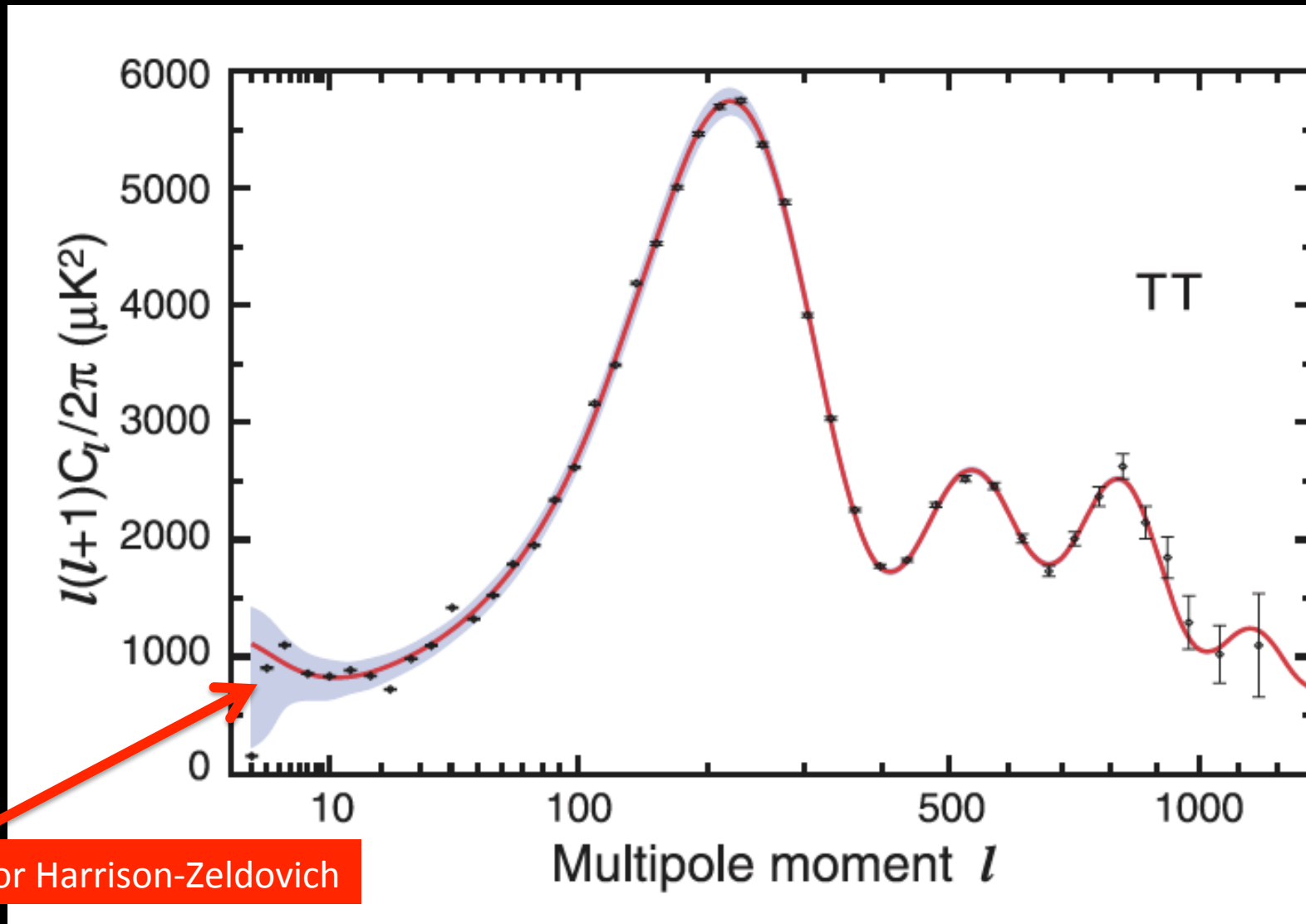
- On scales larger than the particle horizon ($\sim 2^\circ$) will be close to initial perturbations.
- For Harrison-Zeldovich initial perturbations we

expect

$$P(k) = Ak \rightarrow C_l = \frac{8\pi A}{l(l+1)}$$

- In addition photons will have to climb out or down from initial large scale perturbations (Sachs-Wolf effect) + and then through perturbations along the line of sight (ISW and Rees-Sciama)

WMAP9

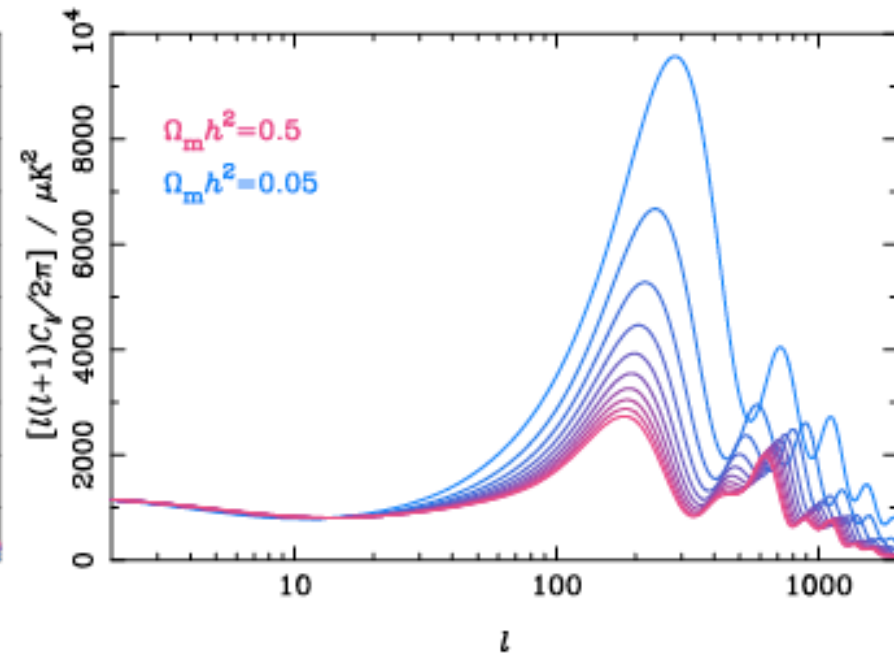
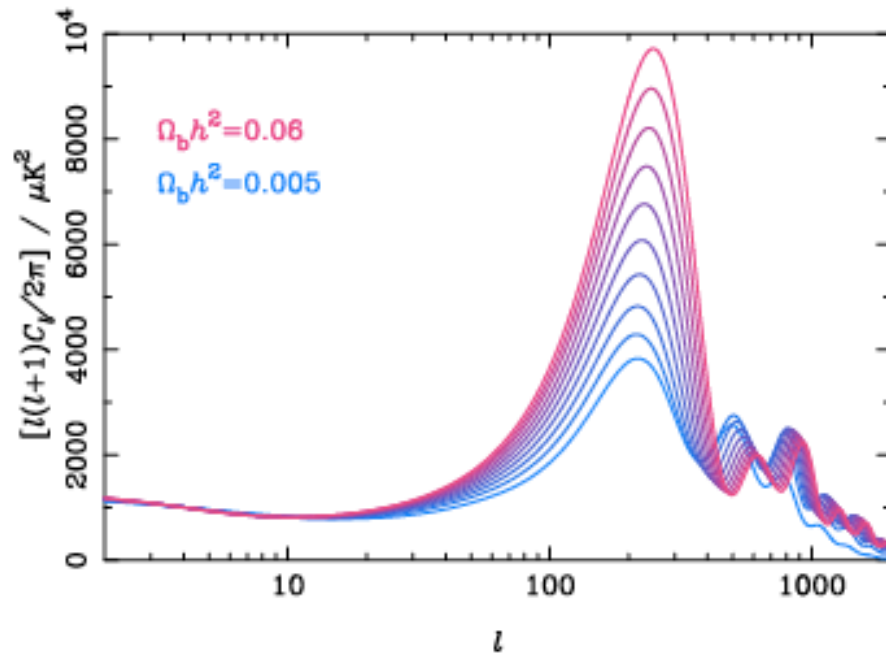


Flat for Harrison-Zeldovich

A simple guide to interpret CMB power spectra: intermediate scales

- Between sound horizon and Silk damping scale
- Sound horizon is much smaller than jeans length so you have standing waves. Modes that are integer fractions of the inverse horizon sound wavelength
- location of the peaks depends most strongly on t recombination (so matter density) and also weakly on baryon to photon ratio (through sound speed)

A simple guide to interpret CMB power spectra: intermediate scales

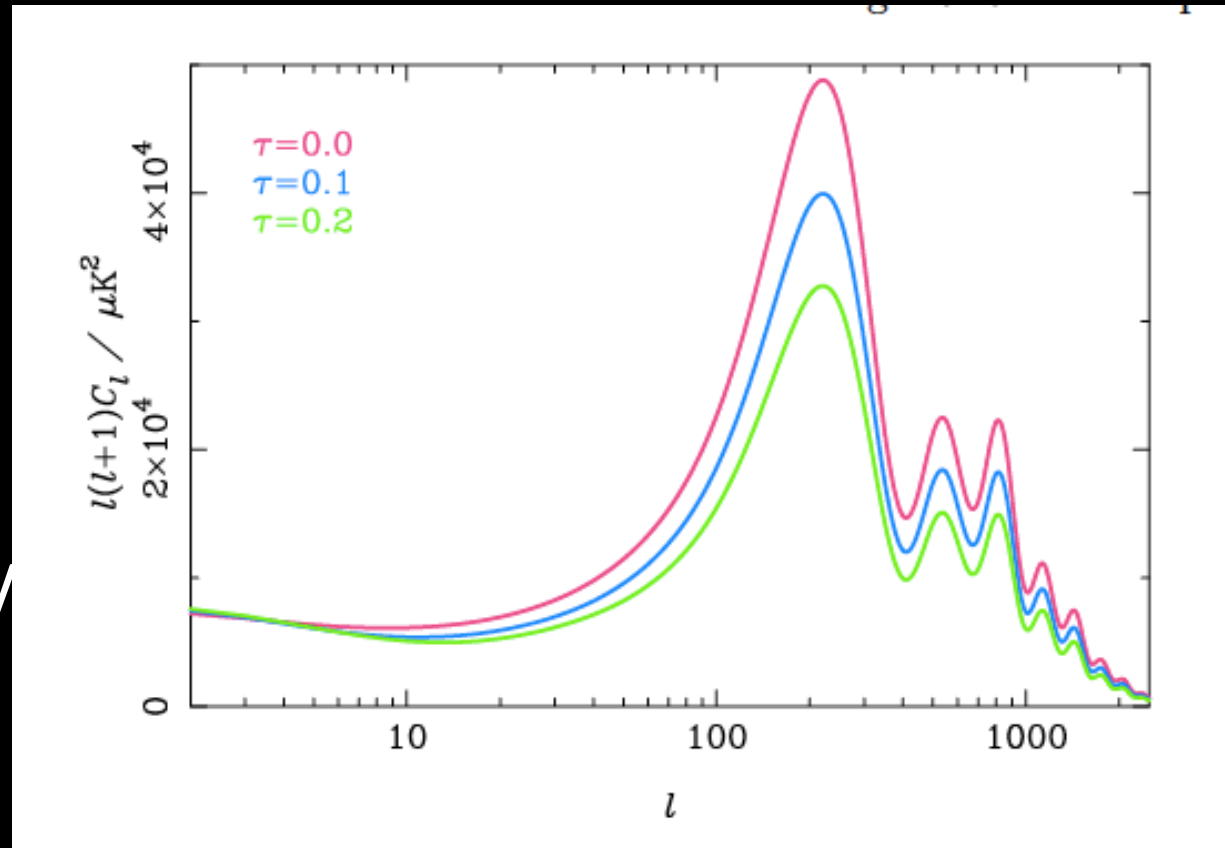


A simple guide to interpret CMB power spectra: small scales

- Silk damping (exponential)
- Statistical damping on scales smaller than the thickness of the scattering layer
- SZ thermal and kinetic effect adds extra power on cluster scales (subarcmin)

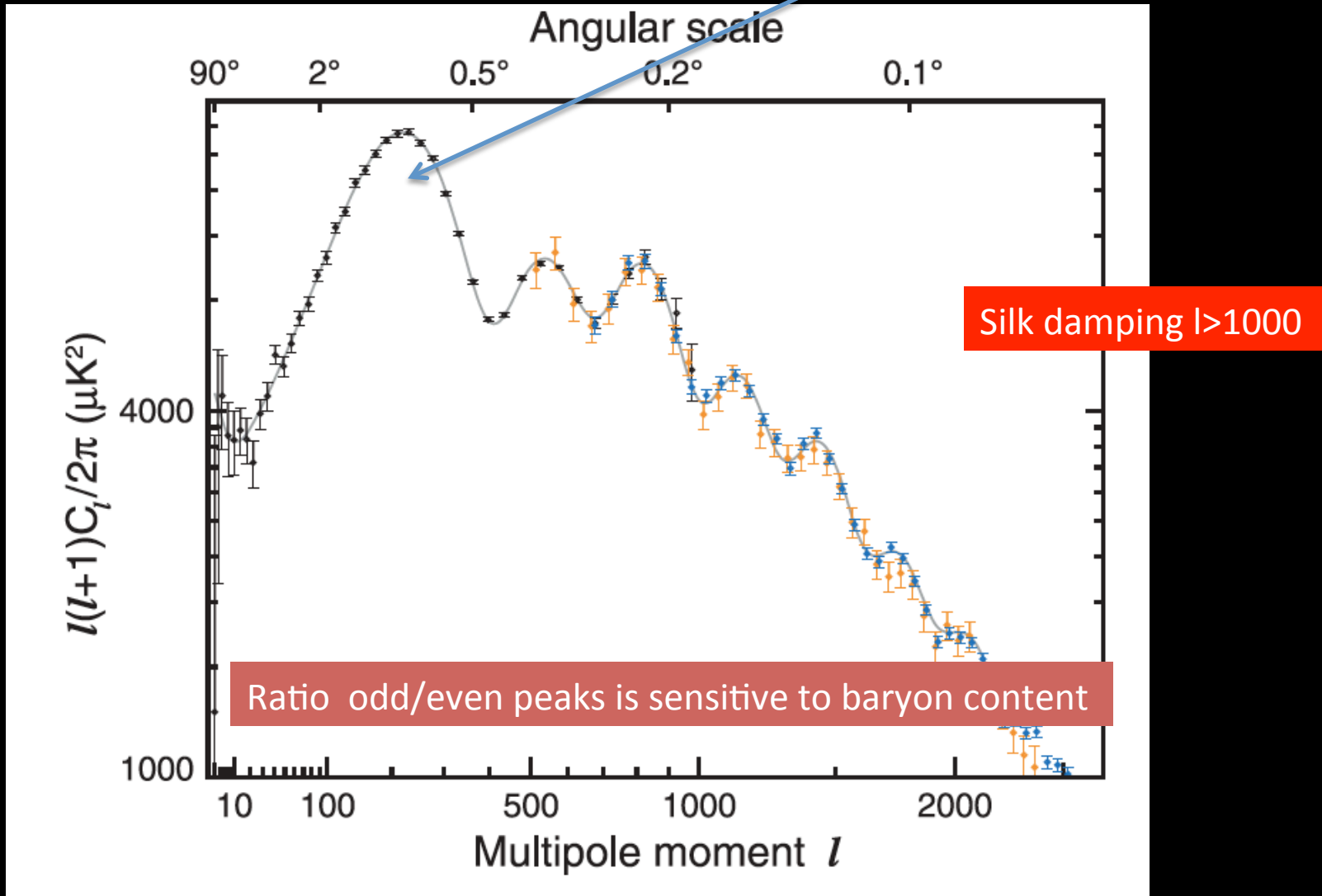
Additional effects: CMB and reionization

- Additional optical depth due to reionization attenuates fluctuations but not exactly so that one can measure z of reionization



WMAP9

Sound horizon



WMAP9 – six parameter model

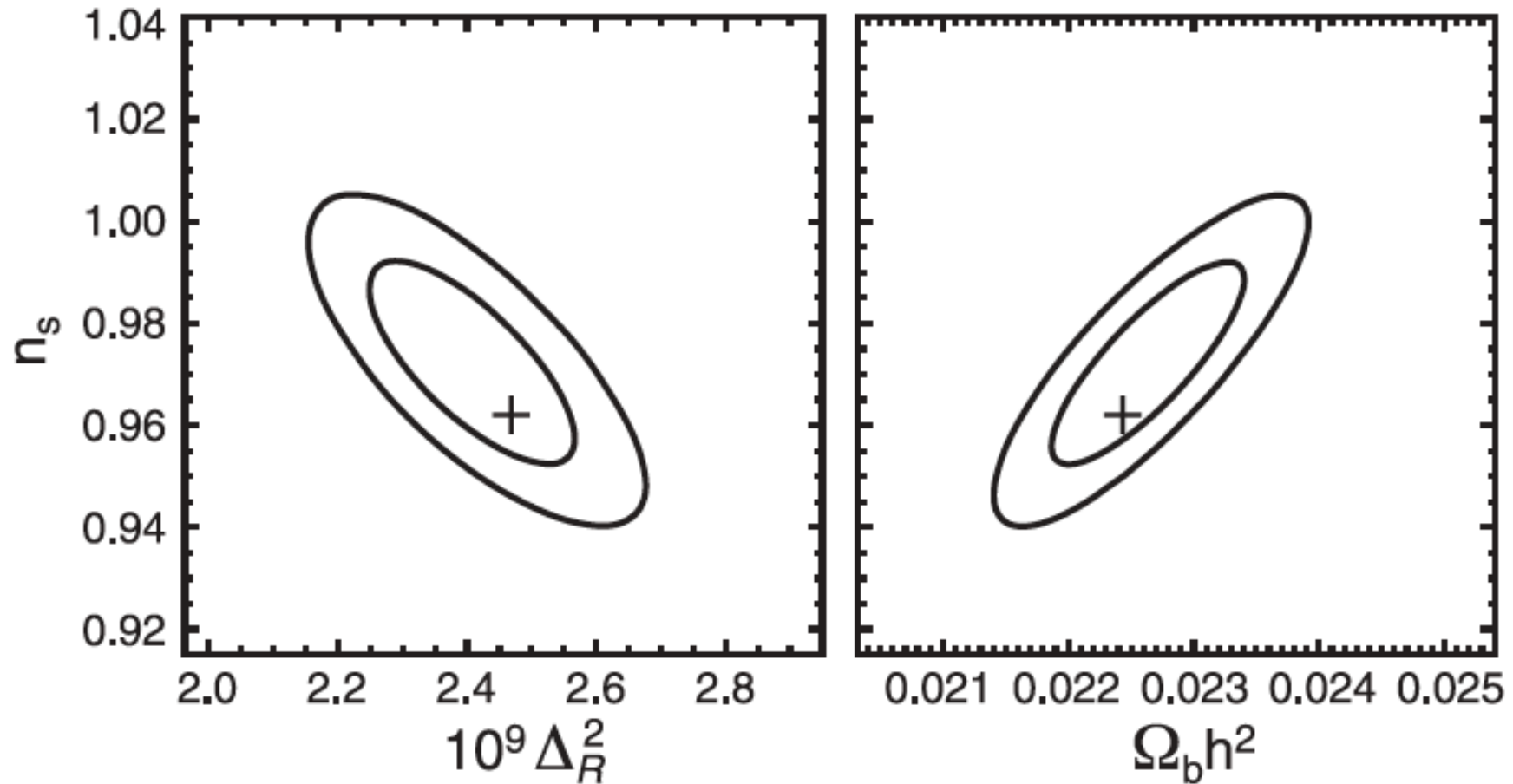
TABLE 2
MAXIMUM LIKELIHOOD Λ CDM PARAMETERS^a

Parameter	Symbol	WMAP data	Combined data ^b
Fit ΛCDM parameters			
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002 \text{ Mpc}^{-1}$	$10^9 \Delta_{\mathcal{R}}^2$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
Derived parameters			
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100h \text{ km/s/Mpc}$	H_0	69.7	69.7
Density fluctuations @ $8h^{-1} \text{ Mpc}$	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	z_{eq}	3273	3280
Redshift of reionization	z_{reion}	10.36	9.97

^a The maximum-likelihood Λ CDM parameters for use in simulations. Mean parameter values, with marginalized uncertainties, are reported in Table 4.

^b “Combined data” refers to WMAP+eCMB+BAO+ H_0 .

WMAP9 – six parameter model



WMAP9 – BBN and neutrinos

TABLE 7
RELATIVISTIC DEGREES OF FREEDOM AND BIG BANG NUCLEOSYNTHESIS^a

Parameter	WMAP	+eCMB	+eCMB+BAO	+eCMB+BAO+ H_0
Number of relativistic species ^b				
N_{eff}	> 1.7 (95% CL)	3.89 ± 0.67	2.96 ± 0.36	3.26 ± 0.35
n_s	0.988 ± 0.027	$0.985^{+0.018}_{-0.019}$	$0.9563^{+0.0100}_{-0.0102}$	0.9636 ± 0.0094
Primordial helium abundance ^b				
Y_{He}	< 0.42 (95% CL)	0.299 ± 0.027	0.295 ± 0.027	0.299 ± 0.027
n_s	0.973 ± 0.016	0.982 ± 0.013	0.973 ± 0.011	0.977 ± 0.011
Big bang nucleosynthesis ^c				
N_{eff}	...	2.92 ± 0.79	2.47 ± 0.37	2.83 ± 0.38
Y_{He}	...	$0.302^{+0.038}_{-0.039}$	$0.317^{+0.030}_{-0.031}$	$0.308^{+0.032}_{-0.031}$
n_s	...	0.978 ± 0.019	0.969 ± 0.012	0.976 ± 0.011

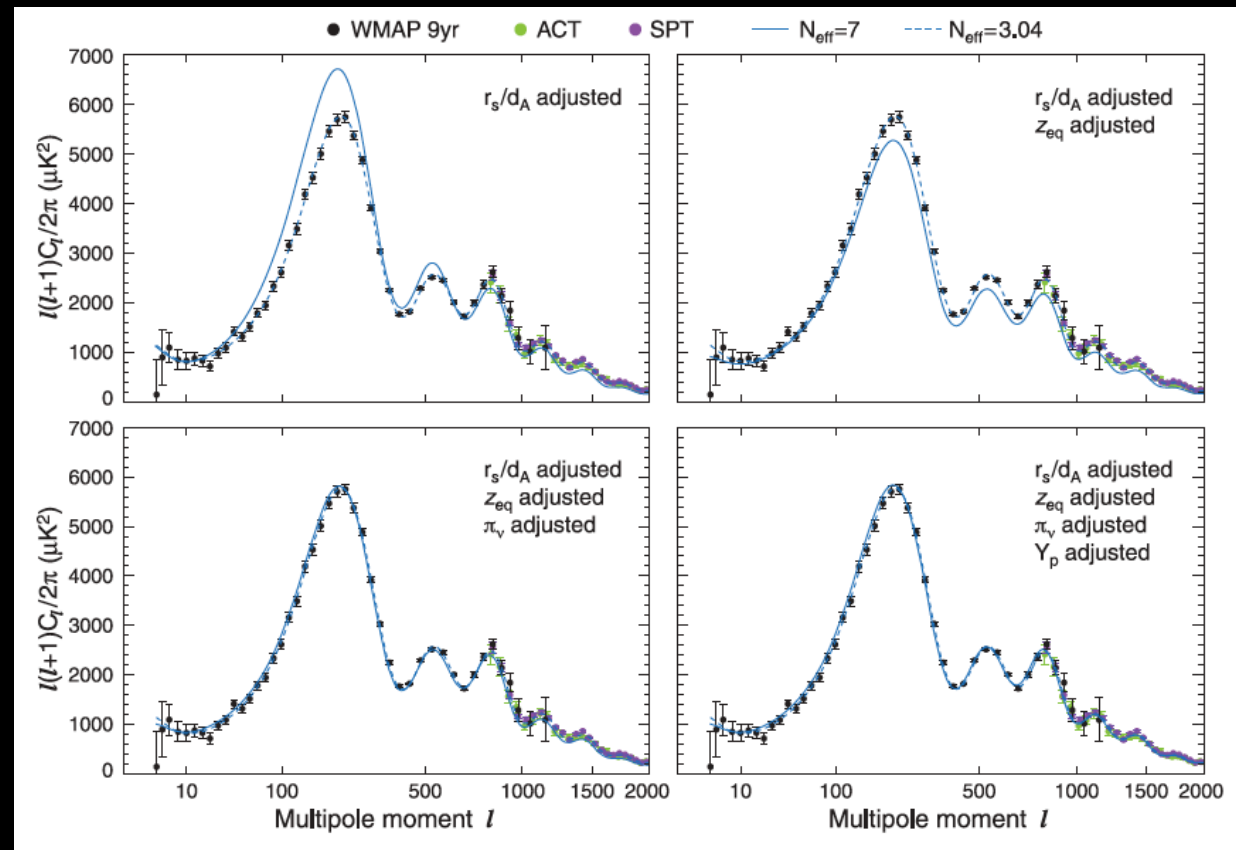
^a A complete list of parameter values for these models may be found at <http://lambda.gsfc.nasa.gov/>.

^b The parameters N_{eff} and Y_{He} comprise one additional parameter each in these table sections.

^c The parameters N_{eff} and Y_{He} are fit jointly in this section.

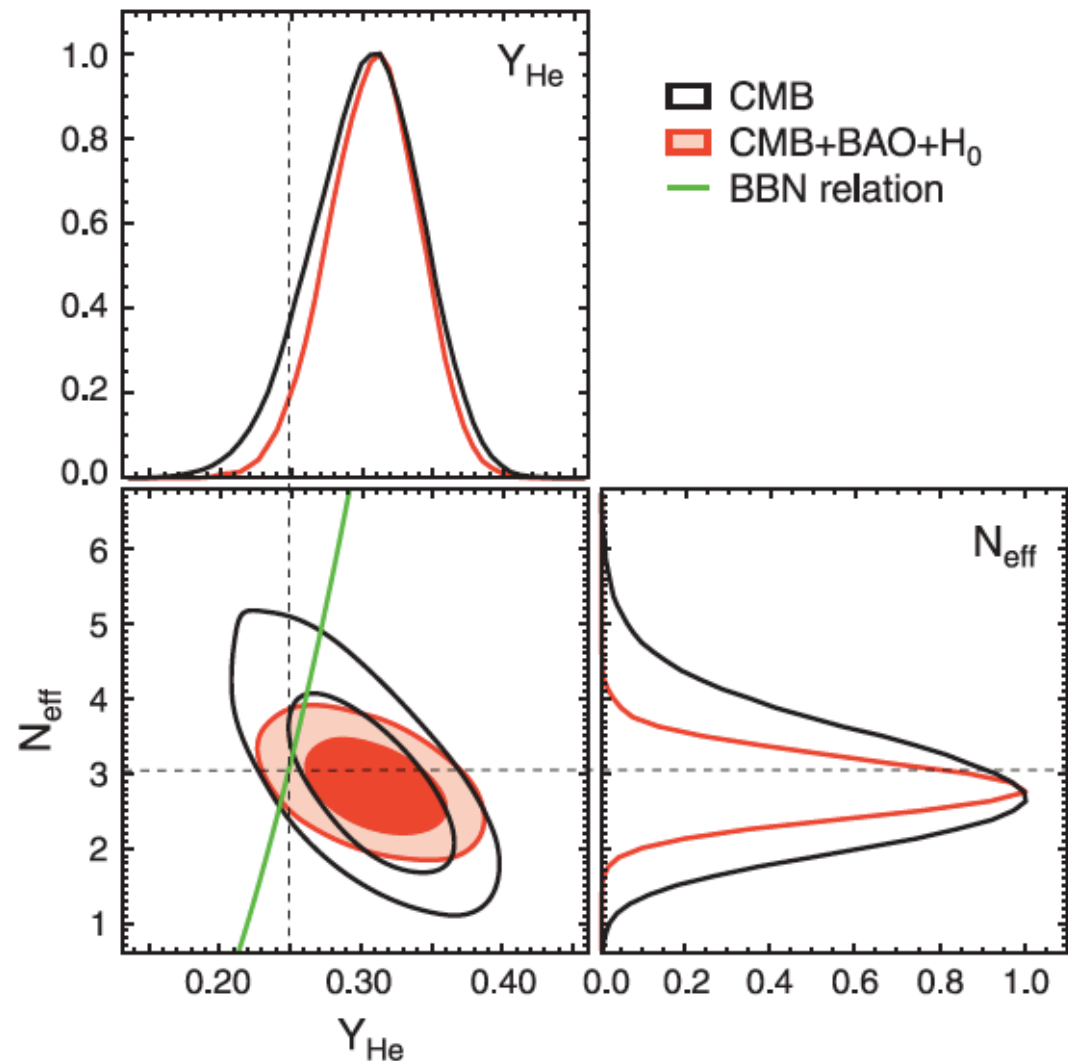
WMAP9 – BBN and Neff

- Extra rel species change expansion speed hence sound horizon
- Change epoch of equality changing ISW
- Increases silk damping so more suppression of high l peaks
- Anisotropic stress



WMAP9 – BBN and N_{eff}

- Extra rel species change expansion speed hence sound horizon
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WMAP9 – neutrino masses

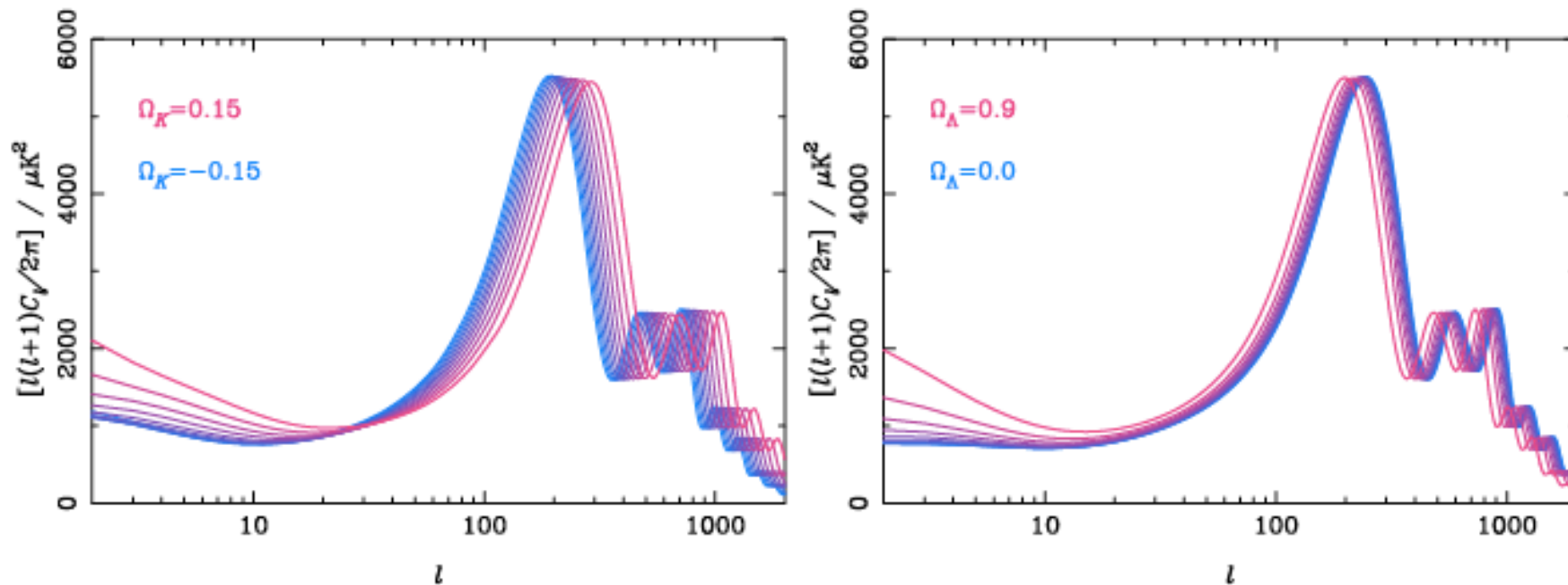
TABLE 8
NEUTRINO MASS^a

Parameter	WMAP	+eCMB	+eCMB+BAO	+eCMB+BAO+H ₀
New parameter				
$\sum m_\nu$ (eV)	< 1.3 (95% CL)	< 1.5 (95% CL)	< 0.56 (95% CL)	< 0.44 (95% CL)
Related parameters				
σ_8	$0.706^{+0.077}_{-0.076}$	$0.660^{+0.066}_{-0.061}$	$0.750^{+0.044}_{-0.042}$	0.770 ± 0.038
$\Omega_c h^2$	$0.1157^{+0.0048}_{-0.0047}$	0.1183 ± 0.0044	0.1133 ± 0.0026	0.1132 ± 0.0025
Ω_Λ	$0.641^{+0.065}_{-0.068}$	$0.586^{+0.080}_{-0.076}$	0.695 ± 0.013	0.707 ± 0.011
$10^9 \Delta_{\mathcal{R}}^2$	2.48 ± 0.12	2.59 ± 0.12	$2.452^{+0.075}_{-0.074}$	2.438 ± 0.074
n_s	0.962 ± 0.016	0.947 ± 0.014	0.9628 ± 0.0086	$0.9649^{+0.0085}_{-0.0083}$

^a A complete list of parameter values for this model may be found at <http://lambda.gsfc.nasa.gov/>.

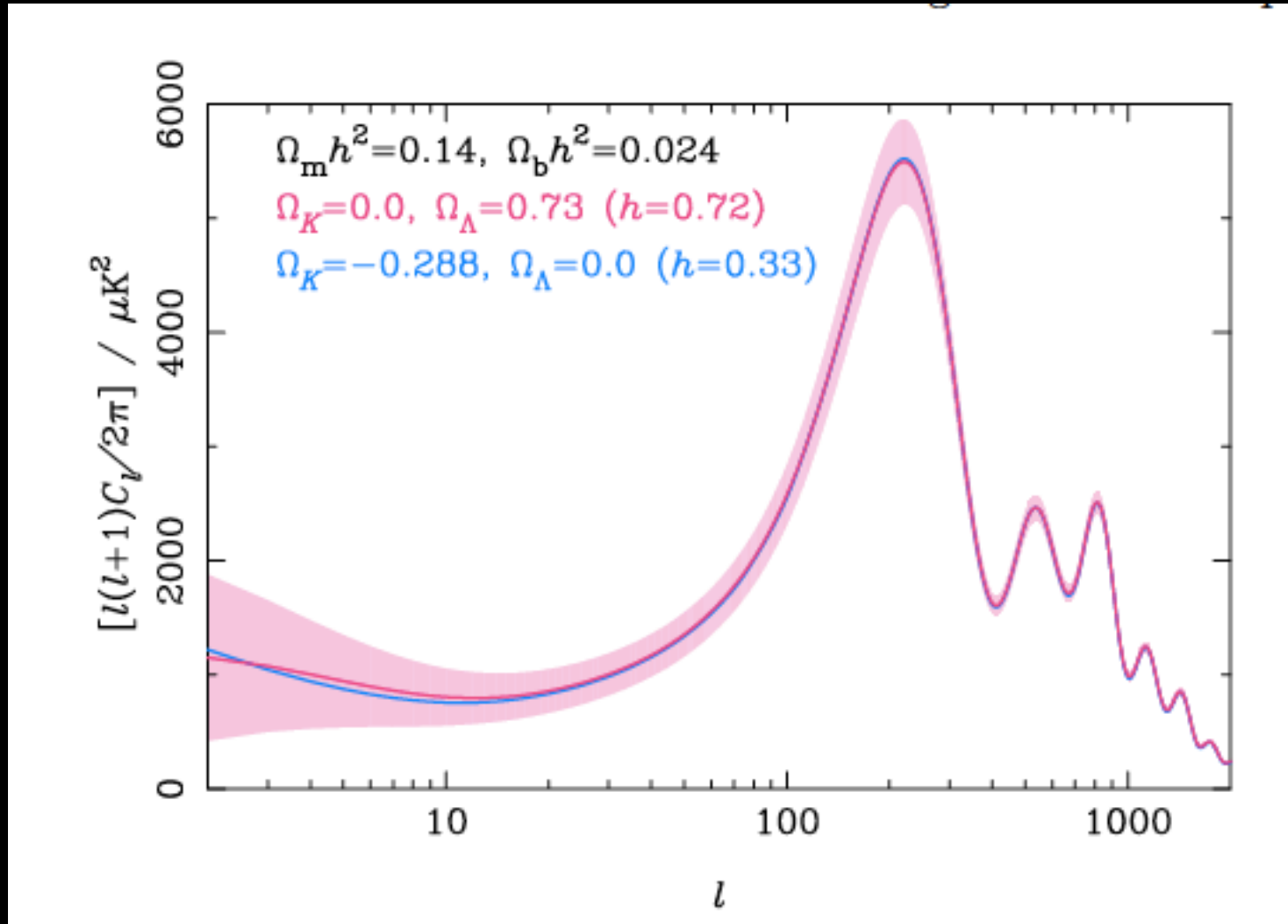
- Neutrino mass if high makes them not relativistic (hard upper bound)
- At lower mass, changes slightly sound horizon and angular diameter distance. Both are degenerate with H₀ so one needs additional measurements to break it.
- Also on small scales neutrinos have high speeds compared to CDM so reduce clustering (degeneracy with sigma₈),

CMB, flatness and dark energy

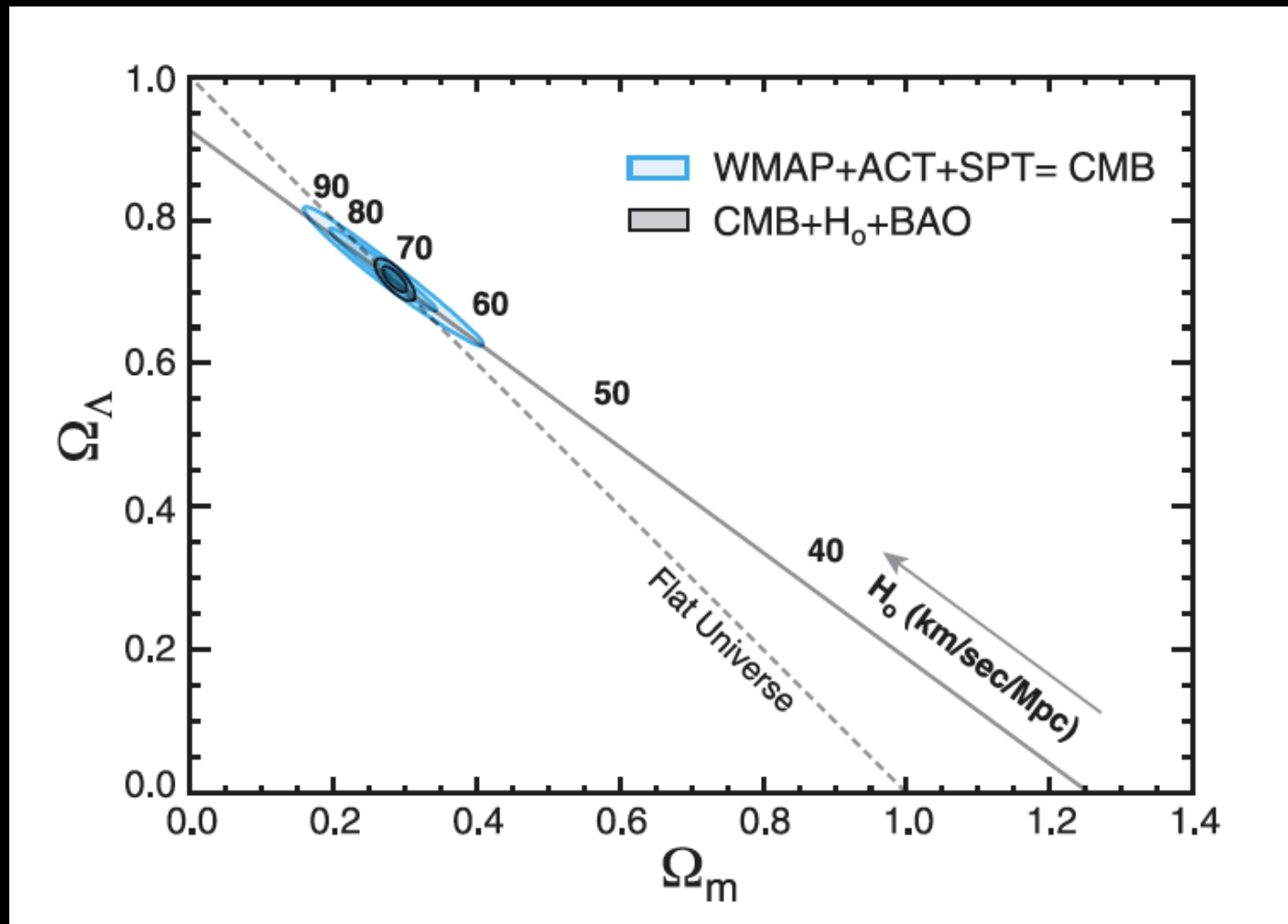


Through angular diameter distance and ISW (limited by cosmic variance)

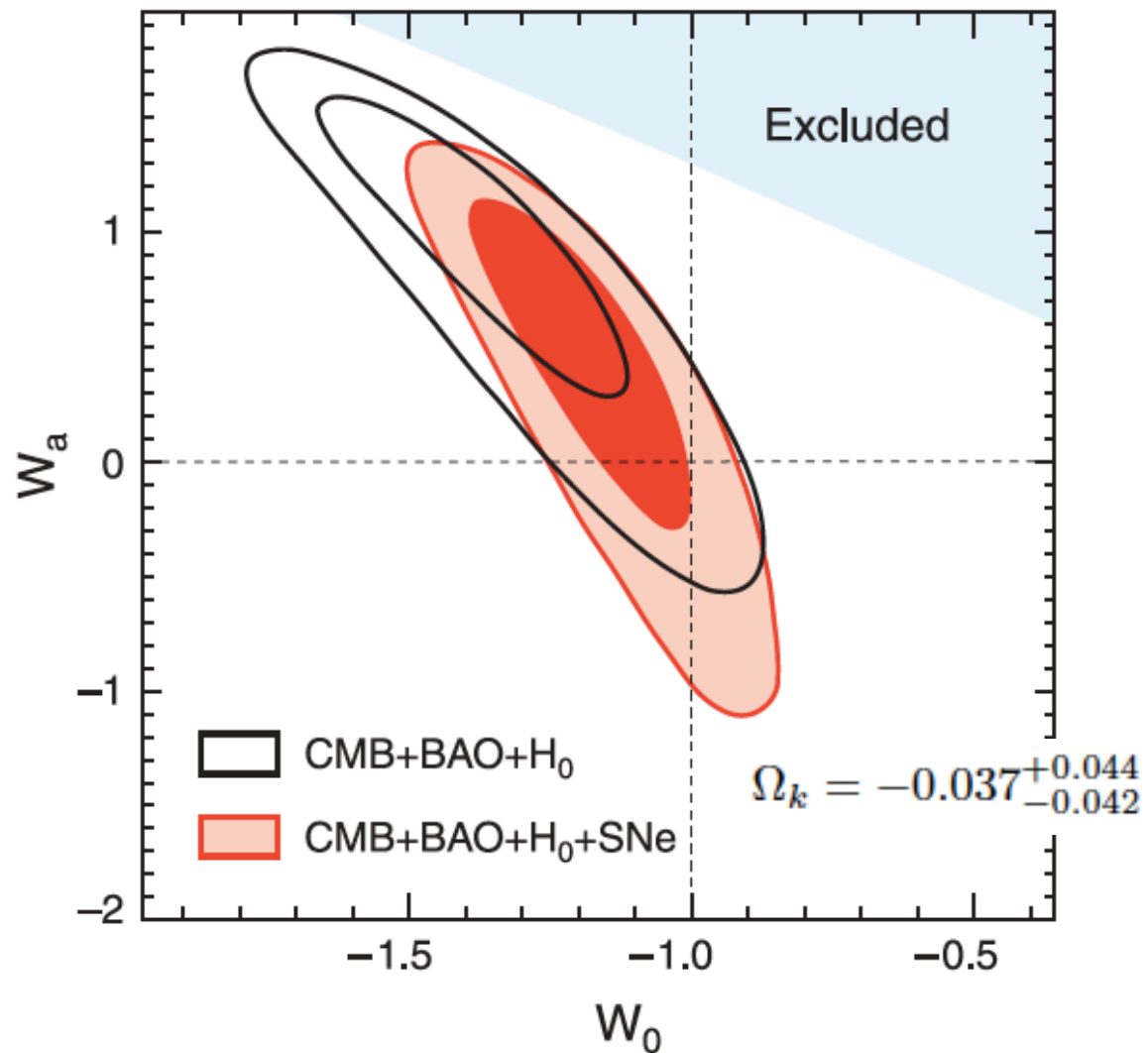
CMB, flatness and dark energy



WMAP9 – flatness degeneracy



WMAP9 – adding w



flat

WMAP-only

The end