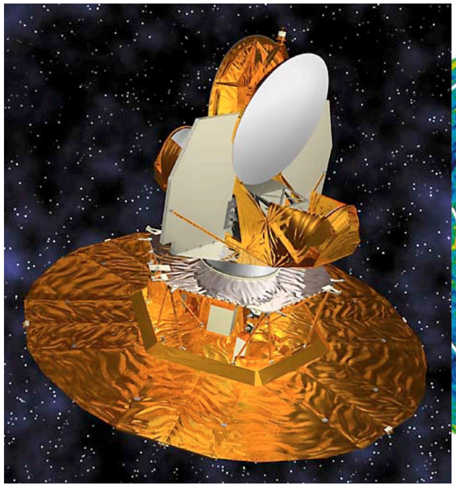
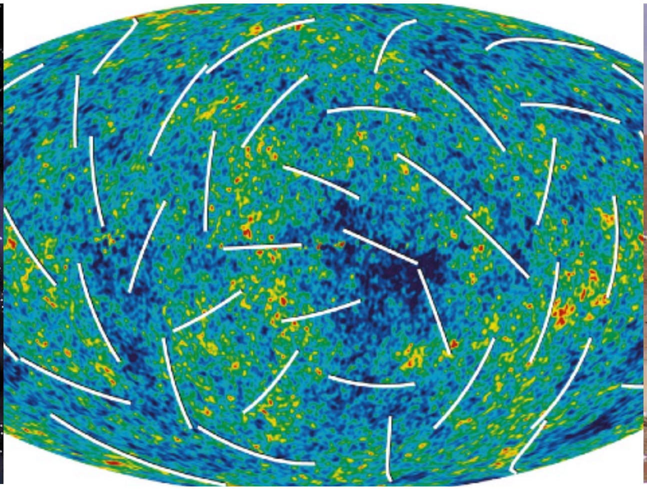
Cosmology from ACT and WMAP: the microwave sky from $2<\ell<10000$


Joanna Dunkley

Oxford Astrophysics

COSMO/CosPA 2010, Tokyo, Sep 28 2010

WMAP 7-Year Science Team

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- N. Jarosik
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- H.V. Peiris
- L. Verde

Launched 2001. WMAP has now collected 9 years of data as of August 2010, and has ended operations.

7-year papers from Jan 2010:

- Jarosik et al., "Sky Maps, Systematic Errors, and Basic Results" 1001.4744
- Gold et al., "Galactic Foreground Emission" 1001.4555
- Larson et al., "Power Spectra and WMAP-derived parameters" 1001.4635
- Bennett et al., "Are there Cosmic Microwave Background anomalies?" 1001.4758
- Komatsu et al., "Cosmological Interpretation" 1001.4538
- Weiland et al., "Planets and celestial calibration sources" 1001.4731

Atacama Cosmology Telescope

- Barcelona ICE
- Univ of British Columbia (Canada)
- Univ of Cape Town (S Africa)
- Cardiff University (UK)
- Columbia University (USA)
- Haverford College (USA)
- INAOE (Mexico)
- Univ of Kwa-Zulu Natal (S Africa)
- Univ of Massachusetts (USA)
- NASA/GSFC (USA)
- NIST (USA)
- Univ of Oxford (UK: Dunkley, Hlozek, Addison)
- Univ of Pennsylvania (USA)
- **Princeton University (USA) (PI L. Page)*
- Univ of Pittsburgh (USA)
- Pontifica Universidad Catolica (Chile)
- Rutgers University (USA)
- Univ of Toronto (Canada)
- Collaborators at La Sapienza, MPI, Miami, Stanford, Berkeley, Chicago, CfA, LLNL, IPMU Tokyo

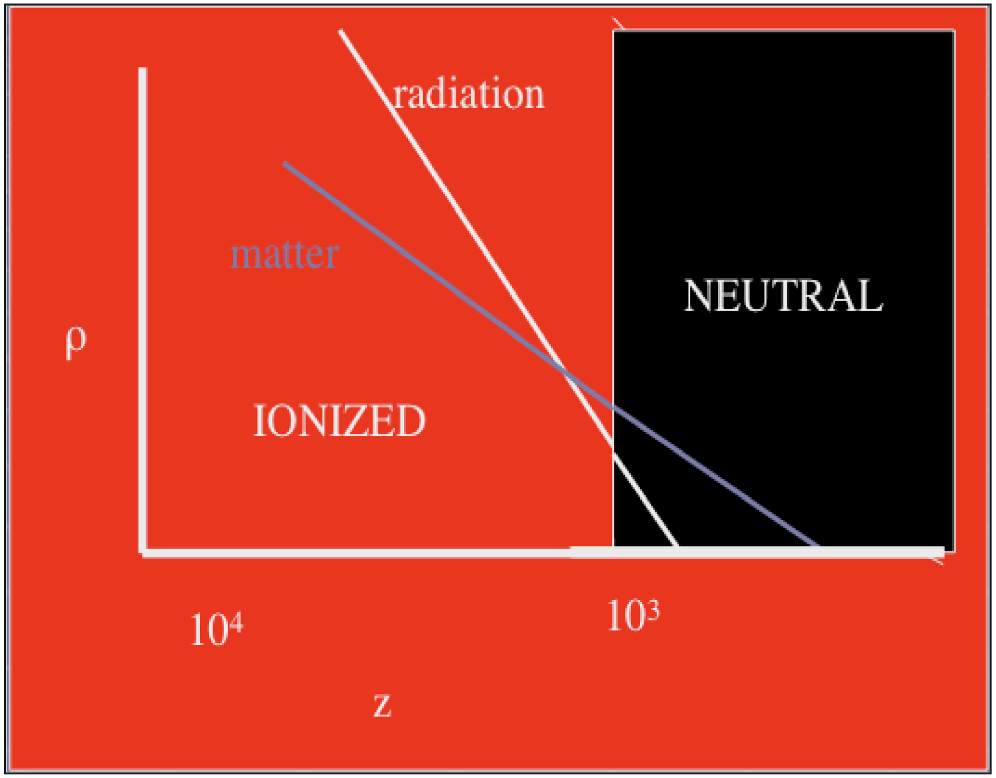
→ ~ 90 collaborators

ACT 2008-data papers

Hincks et al 2009	‘Beam Profiles and First SZ Cluster Maps’, 0907.0461
Fowler et al 2010	‘A Measurement of the 600< ell <8000 Cosmic Microwave Background Power Spectrum at 148 GHz’, 1001.2934

Swetz et al 2010	‘The Receiver and Instrumentation’, 1007.0290
Marriage et al 2010	‘Extragalactic Sources at 148 GHz in the 2008 Survey’, 1007.5256
Menanteau et al 2010	‘Physical Properties and Purity of a Galaxy Cluster Sample Selected via the Sunyaev-Zel'dovich Effect’, 1006.5126
Hajian et al 2010	‘Calibration with WMAP Using Cross-Correlations’, 1009.0777
Das et al 2010	‘A Measurement of the CMB Power Spectrum at 148 and 218 GHz from the 2008 Southern Survey’, 1009.0847
Dunkley et al 2010	‘Cosmological Parameters from the 2008 Power Spectra’, 1009.0866

The Cosmic Microwave Background

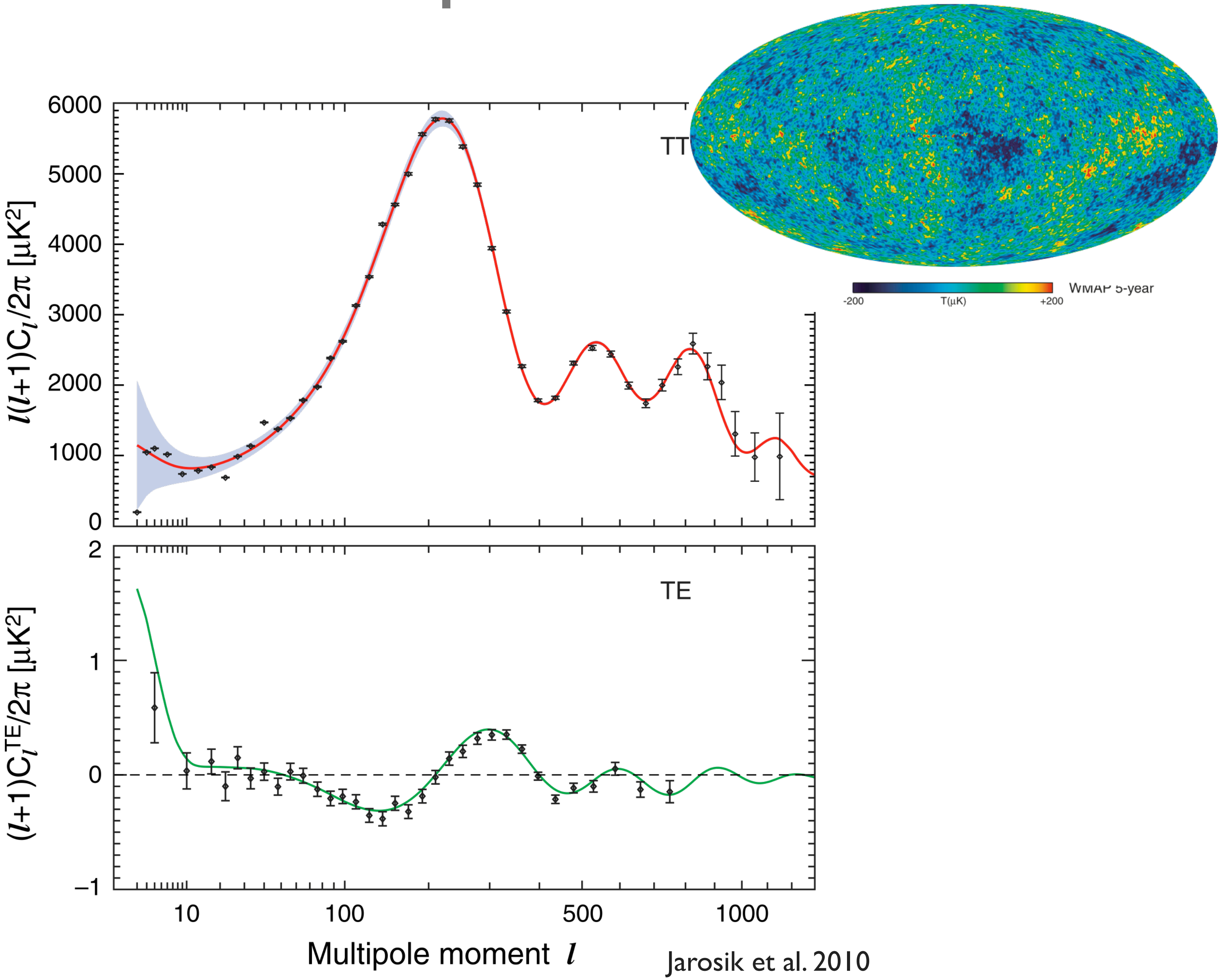


- Linear theory (at early times)
- Basic elements are well understood. Initial fluctuations evolve.
- Numerical codes predict power spectrum in a given universe.

$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

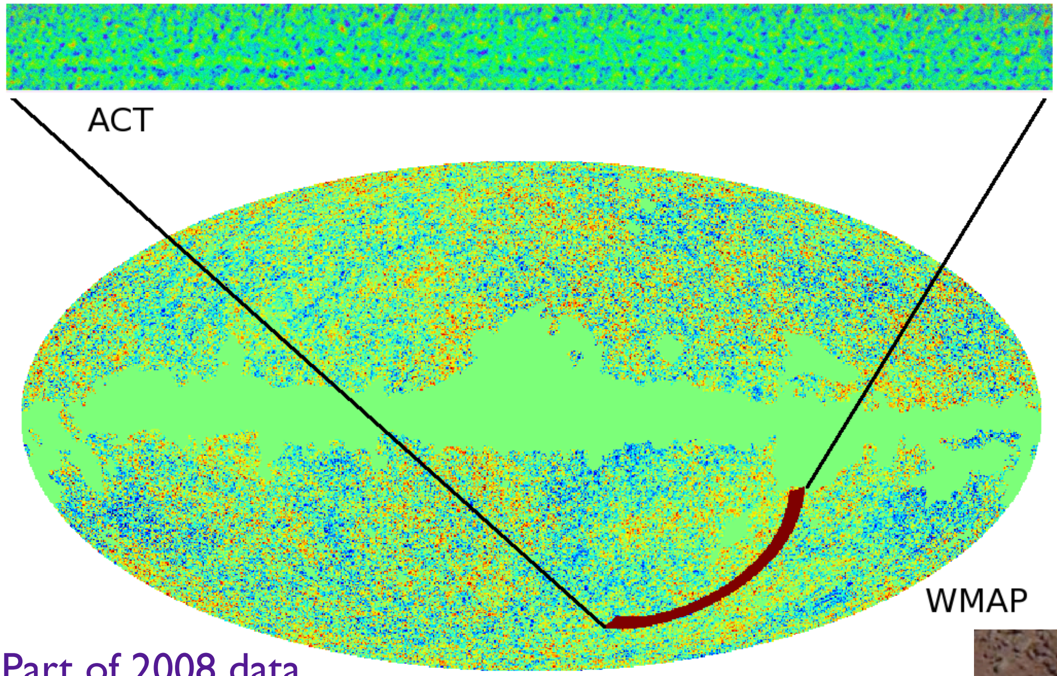
7-year WMAP spectrum



Jarosik et al. 2010

ACT probes new scales

Hajian et al (2010)



Part of 2008 data

5200 meter elevation, one of driest places on planet

1° field of view, 6-meter primary, 2-meter secondary, 1.4’ resol

3 frequencies: 148, 220, 270 GHz, 3000 TES detectors

ACT 148-218 GHz power spectra

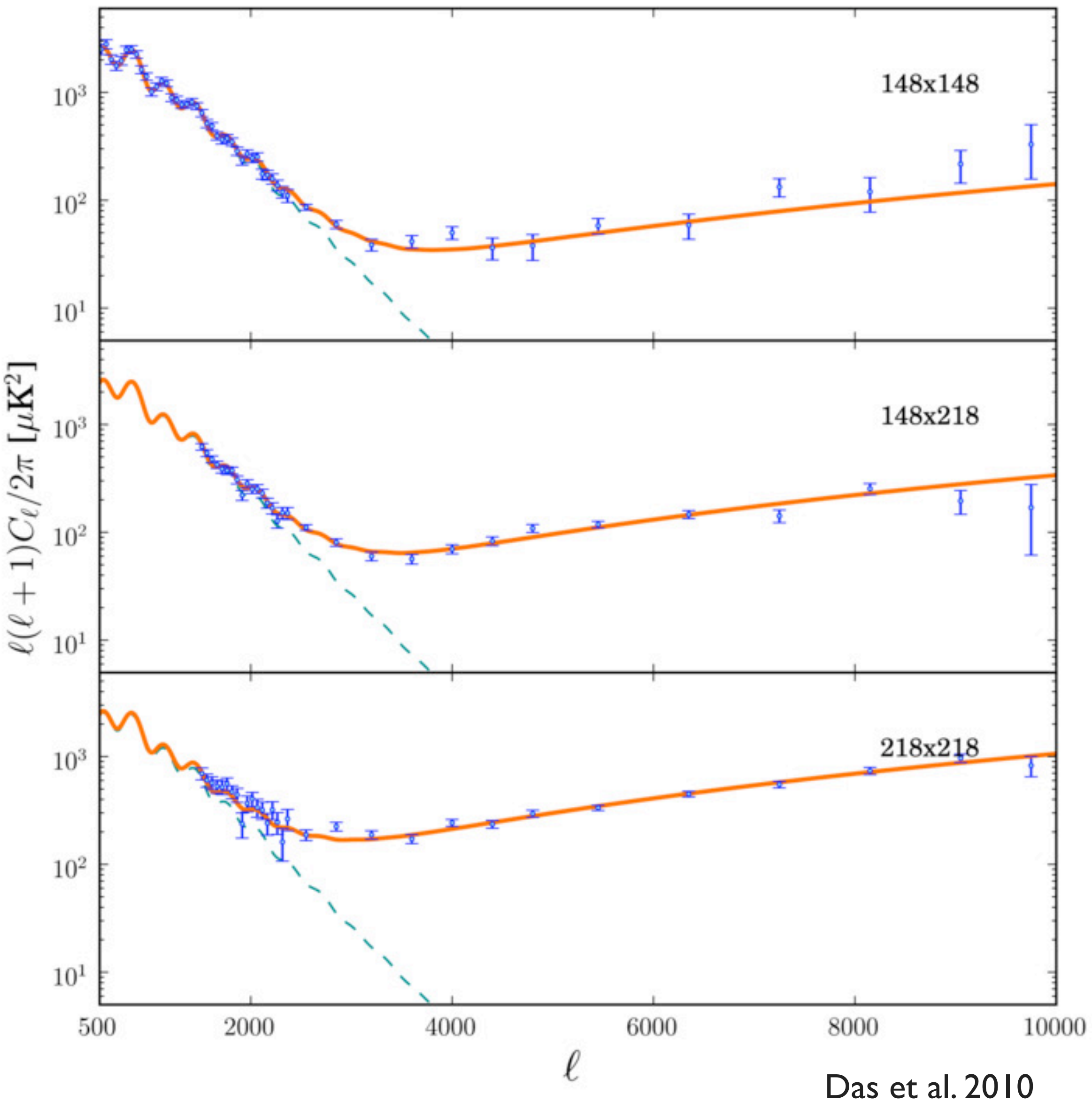
- WMAP extends to l=1000
- ACT:
 500<l<10000 for 148 GHz,
1500<l<10000 for 218 GHz

- Higher acoustic peaks and Silk damping tail probed

- CMB dominates out to l~3000 for 148 GHz, and l~2000 for 218 GHz

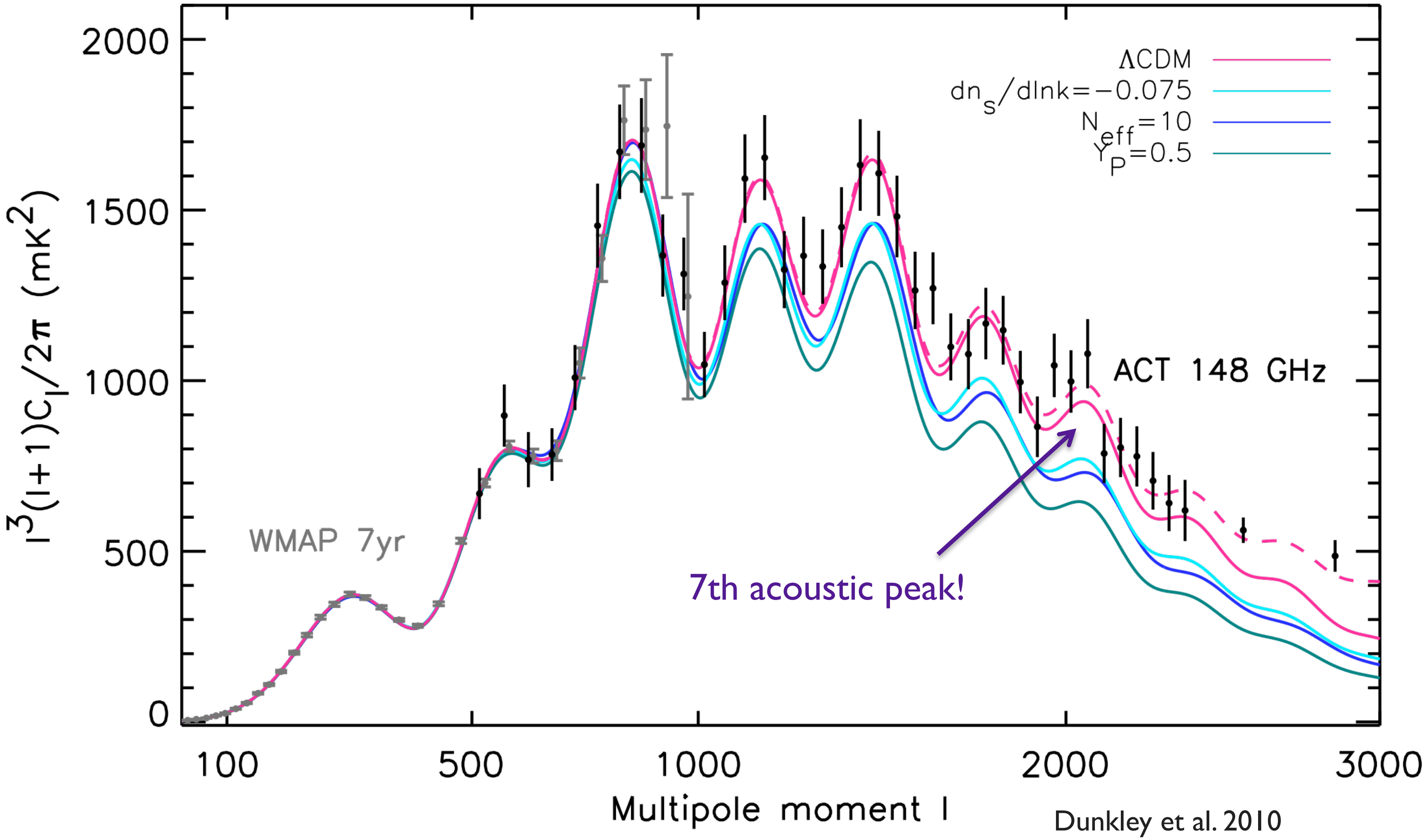
- High ell dominated by point source and SZ.

- The 500<l<2500 range has previously been probed by e.g. ACBAR/QUAD.



Das et al. 2010

ell<3000 CMB TT power spectrum



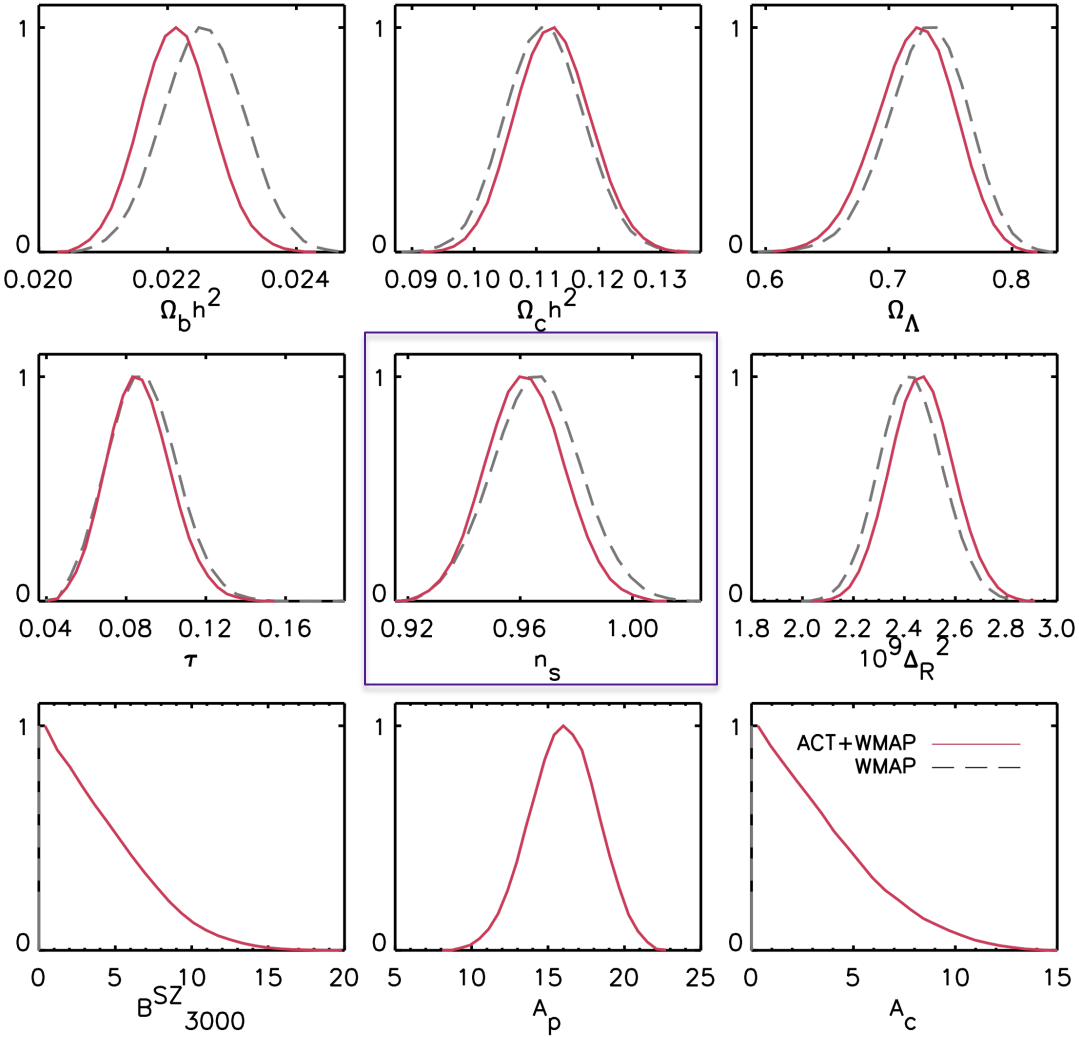
7th acoustic peak!

Dunkley et al. 2010

ΛCDM Parameters

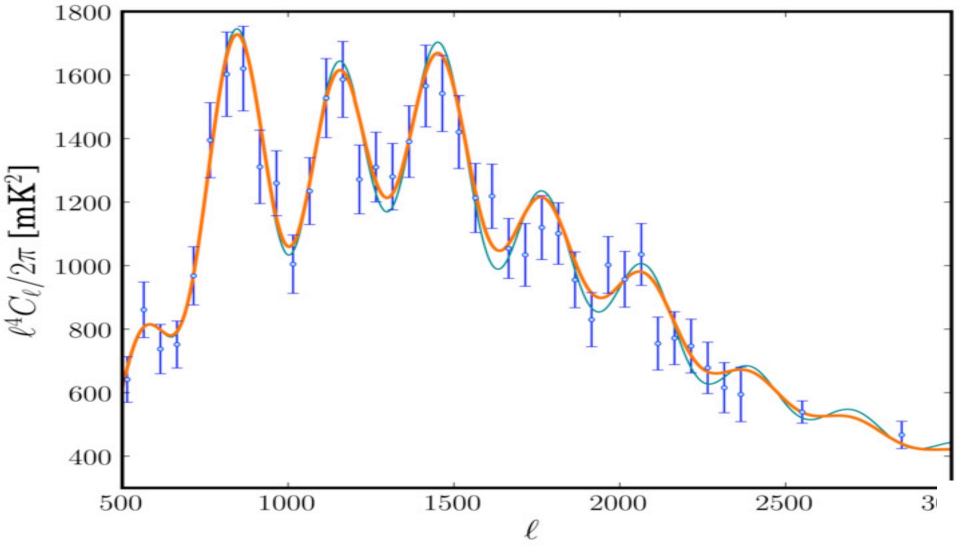
- 6-parameter LCDM continues to fit the data well
- Scale invariant n_s=1 now disfavored at 3σ from CMB data alone, in support of inflation.

- Simple secondary parameter model captures high ell behavior.



Dunkley et al. 2010

The CMB appears to be lensed



$$\underbrace{\Theta(\hat{n})}_{\text{Lensed}} = \underbrace{\tilde{\Theta}(\hat{n}}_{\text{Unlensed}} + \underbrace{\nabla\phi)}_{\text{Deflection Field}}$$

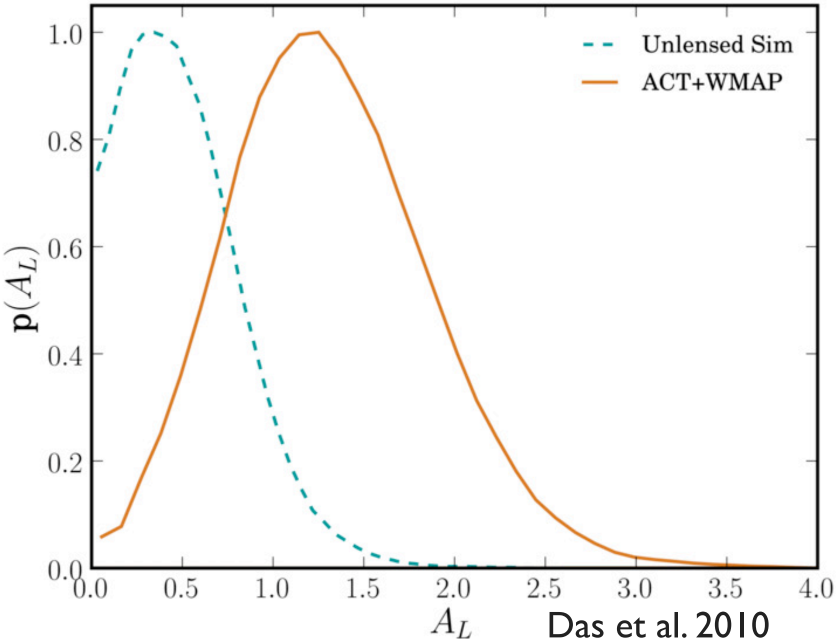
$$\phi = -2\int \underbrace{\boxed{\frac{d_A(\eta_0-\eta)}{d_A(\eta)\,d_A(\eta_0)}}}_{\text{Geometry}}\underbrace{\boxed{\Phi(\eta\hat{n},\eta)}}_{\text{Matter potential}}$$

- An unlensed spectrum would have sharper features

- Test for lensing in spectrum by marginalizing over (unphysical) parameter A_L, scaling lensing potential. [Calabrese et al 2008]

- Expect A_L=1, and unlensed has A_L=0. See lensing at almost 3σ level:

$$A_L = 1.3 \pm 0.5^{+1.2}_{-1.0} \text{ (68, 95\% CL)}$$

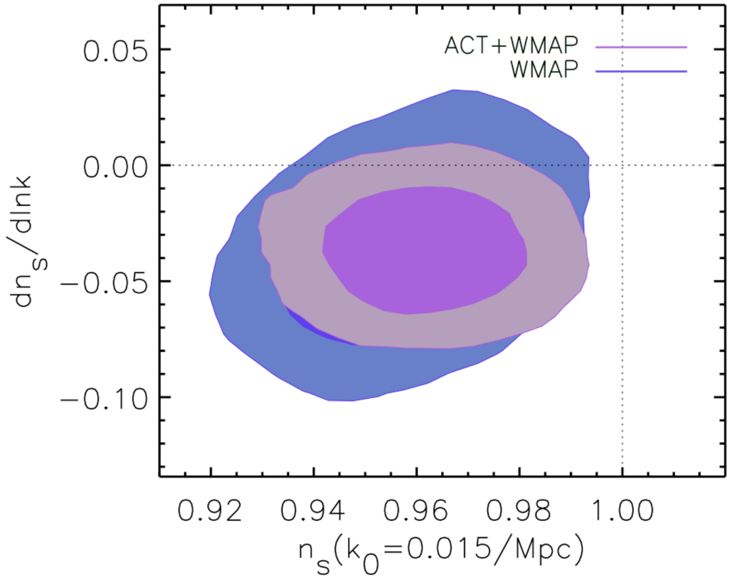


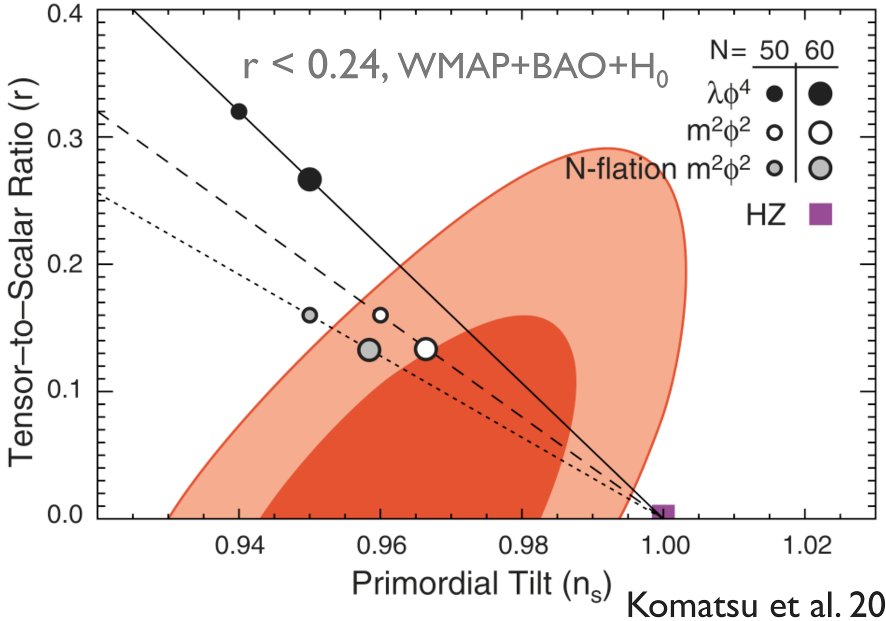
Das et al. 2010

Inflation: limits from spectrum

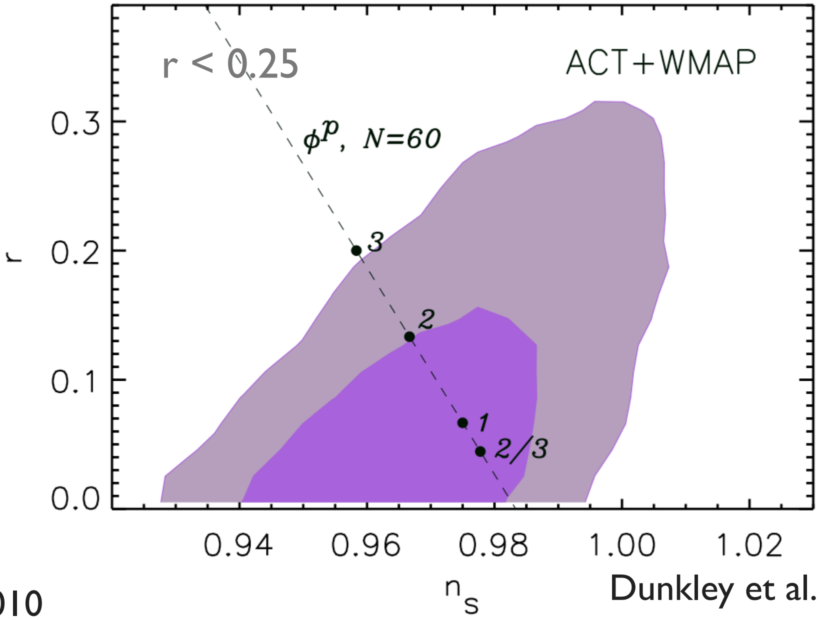
- Effective field theory, period of exponential expansion for > 60 e-folds.

- Running index, find
  - $dn_s/d\ln k = -0.024 \pm 0.015$ (ACT+WMAP+BAO+H0)
- New upper limit on tensors, find
  - $r < 0.19$ (95% CL, ACT+WMAP +BAO+H0)





Komatsu et al. 2010



Dunkley et al. 2010

$$\Delta^2(k_0)\left(k\right)^{n_s(k_0)-1+\frac{1}{2}\ln(k/k_0)dn_s/d\ln k}$$

Inflation: Non-Gaussianity limits

Can look for non-Gaussianity by looking for non-zero bispectrum, 3-point function

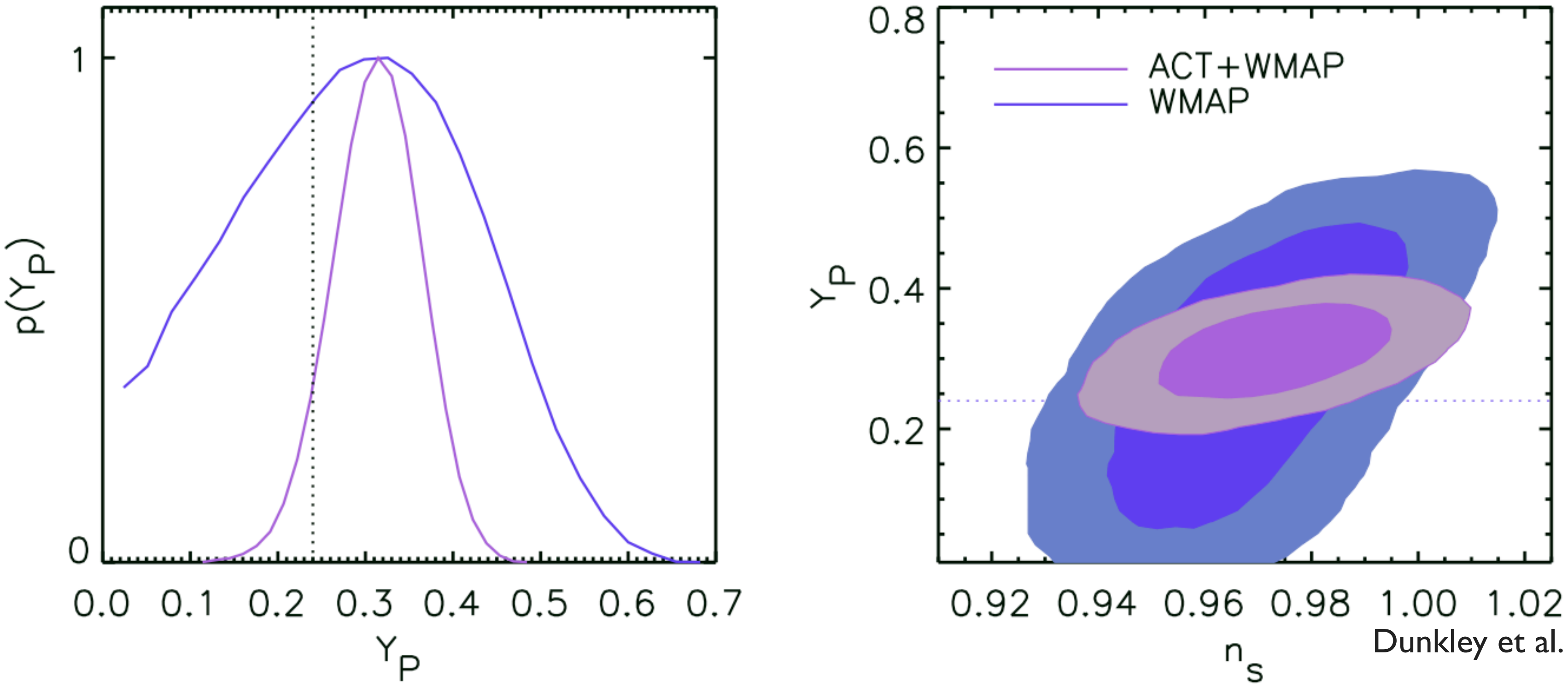
Define 'f_{NL}' using curvature fluctuations:
$\Phi(x)=\Phi\mathrm{gauss}(x)+f_{NL}[\Phi\mathrm{gauss}(x)]^2$

From WMAP 7-year maps, see no detection of 3-point functions of primordial curvature perturbations (Komatsu et al 2010).

The 95% CL limits are:
$-10 < f_{NL}$ local < 74
$-214 < f_{NL}$ equilateral < 266
$-410 < f_{NL}$ orthogonal < 6

So, the WMAP data are consistent with the prediction of simple single-inflation models. Looking forward to Planck errors of ~5.

Primordial helium: detected at 6σ



Dunkley et al. 2010

Usually assume Y_P*=0.24, predicted by BBN:* $Y_P = 0.2485+0.0016[(273.9\Omega_b h^2-6) +100\ (S-1)]$*, Steigman*

More helium decreases electron density, increasing Silk damping.

We find $Y_p = 0.313 \pm 0.044$ (68% CL, ACT+WMAP)

(Already 3σ detection from WMAP+ACBAR+QUAD, Komatsu et al 2010)

A universe with no helium is now ruled out at 6 sigma from CMB – it would produce too much small scale power. Provides test of BBN epoch.

Relativistic species

'Assume' N=3 neutrino species.

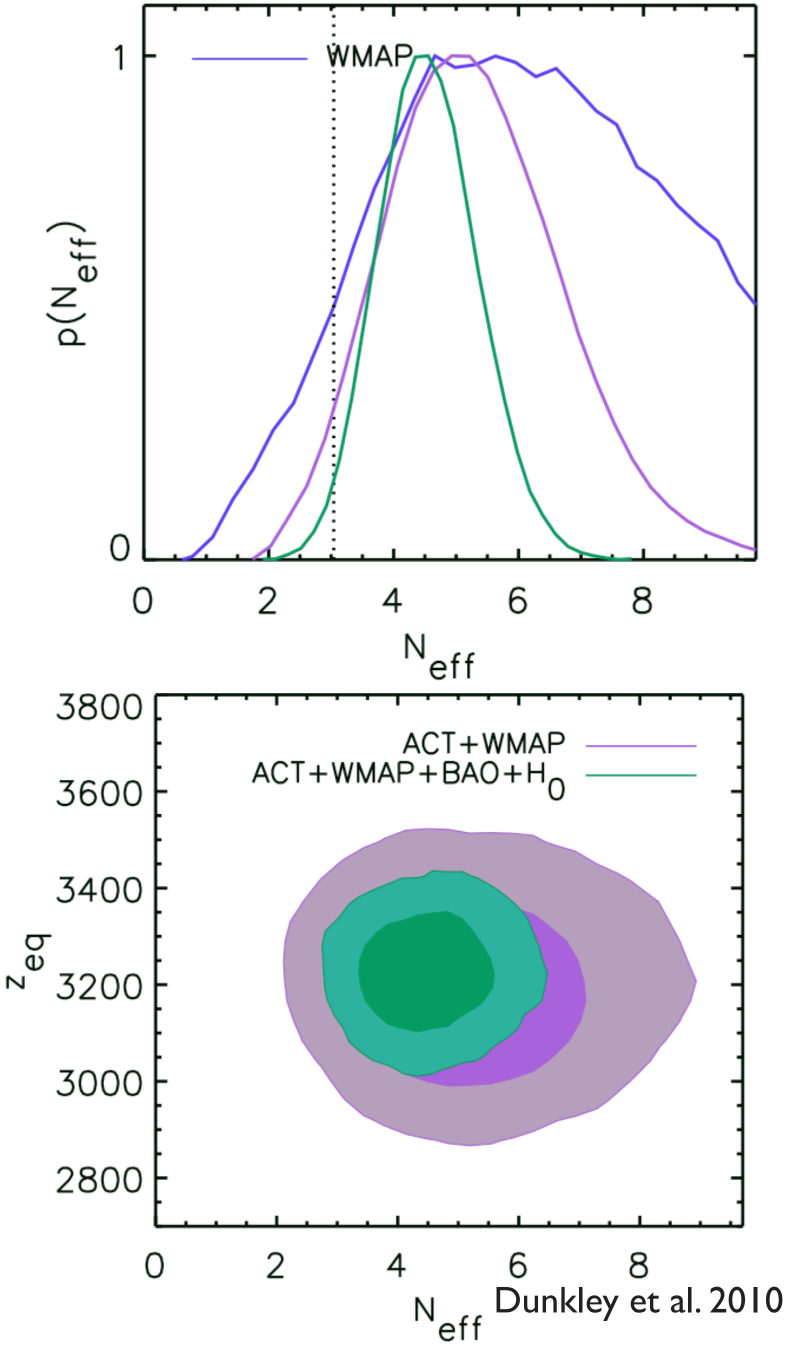
$$\rho_{rel} = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_{\gamma}$$

More species, longer radiation domination.
Changing Neff changes equality redshift.

Also - species suppress early acoustic oscillations in primary CMB, and phase shift in primary CMB. Distinct to zeq.

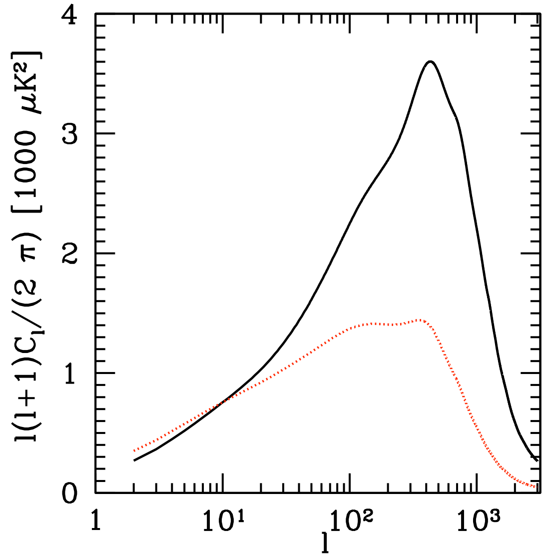
For ACT+WMAP7 we find $N_{eff} = 5.3 \pm 1.3$
(CMB now constrains it from above)

Error reduced to ± 0.75 with BAO and H_0 measures. Mean value higher than 3.04 but N=3 still fits data well!



Dunkley et al. 2010

Bounds on cosmic strings



From shape of spectrum, cosmic strings cannot be dominant source of anisotropy.

May be sub-dominant. Expected spectrum is uncertain.

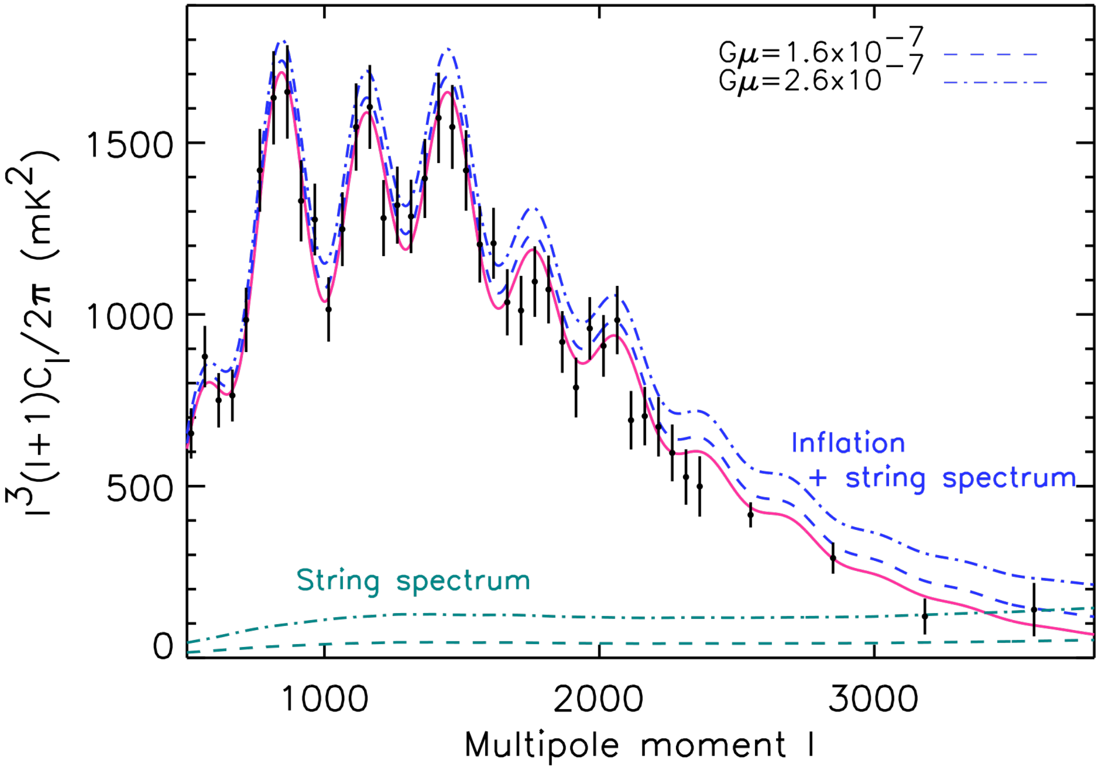
We take Nambu string sims as in Battye & Moss 2010. At small scales expect ell^{-1} scaling.

Find upper limits for ACT+WMAP:

$G\mu < 1.6 \times 10^{-7}$ (95%)

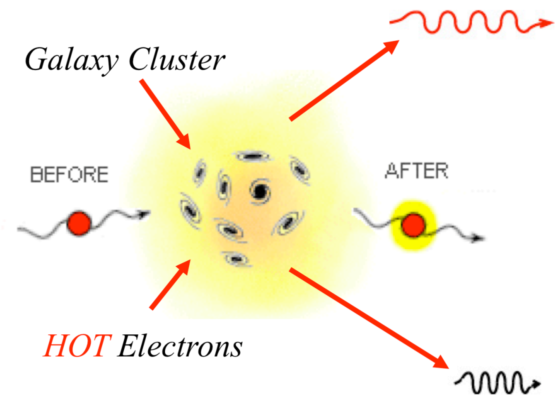
(pre-ACT was $2.6\text{x}10^{-7}$)

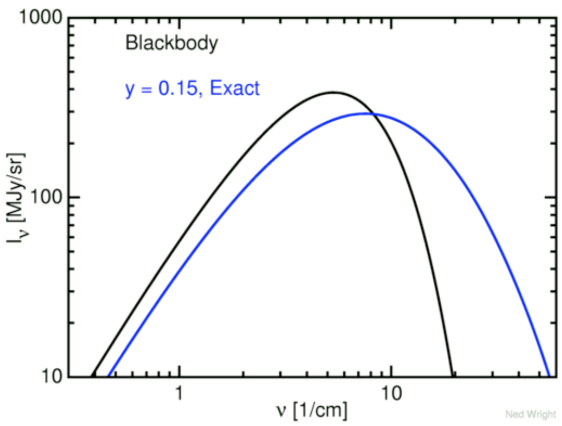
Spectral index prefers to be less than unity (0.963±0.013), disfavoring hybrid inflation models predicting n~1

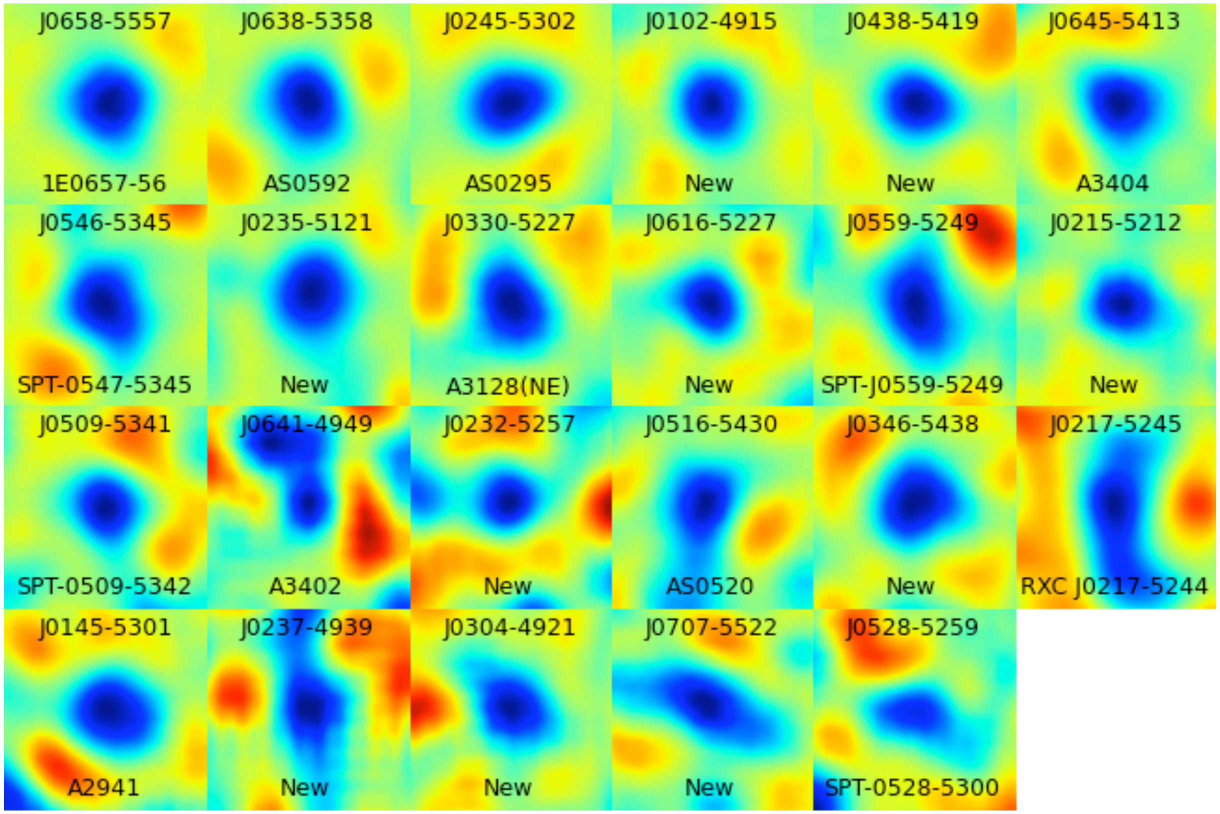


Dunkley et al. 2010

Sunyaev-Zel'dovich clusters in ACT



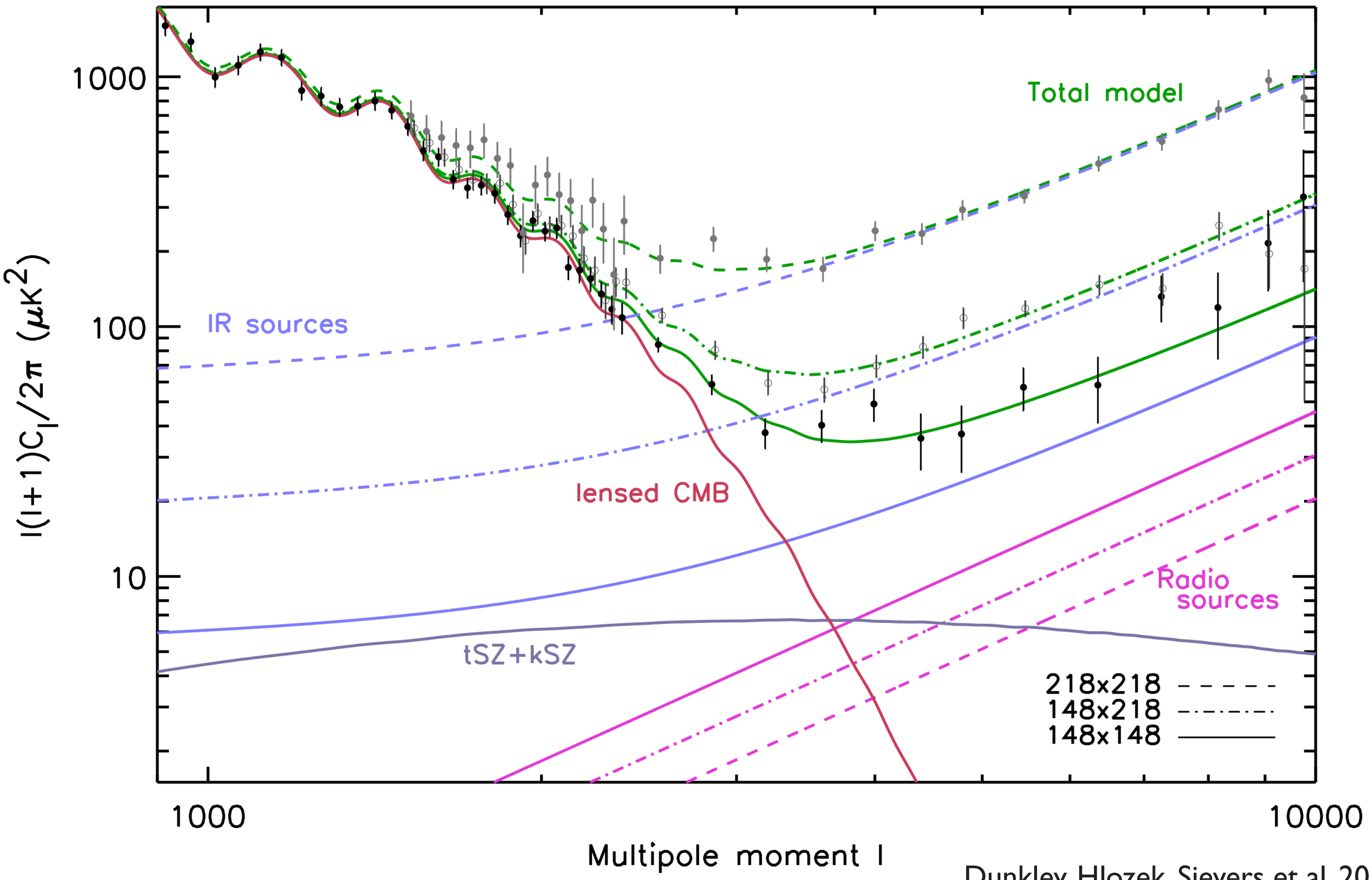




Marriage et al. 2010 in prep

- All been optically followed up (Menanteau et al 2010) and have redshift (out to z~1).
- For high significance clusters, concordance cosmological model fits the number of clusters well for a given mass limit (Sehgal et al 2010 in prep).

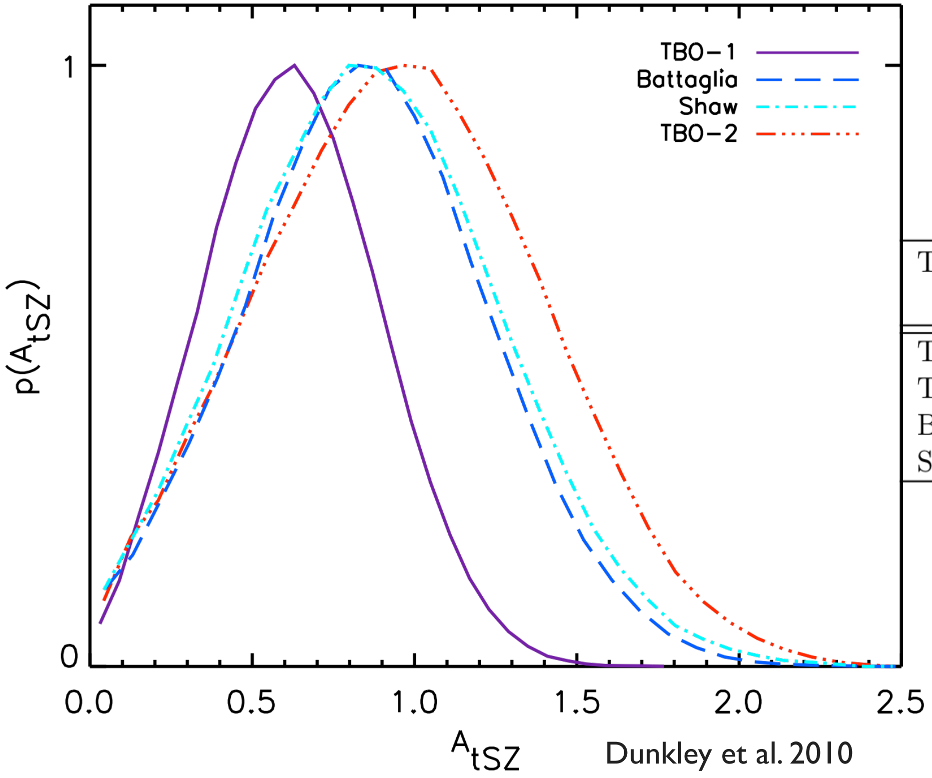
Small-scale power



Dunkley, Hlozek, Sievers et al. 2010

SZ power: $l(l+1)C_l/2\pi = 7 \pm 3\ \mu K^2$, preferred at 95% level.

Sunyaev Zel’dovich power



Dunkley et al. 2010

Template[a]	$A_{\rm tSZ}$[b]	$\mathcal{B}_{3000}^{\rm SZ}$[c] ($\mu$K^2)	$\sigma_8^{\rm SZ,7}$ $0.8 \times (A_{\rm tSZ}^{1/7})$	$\sigma_8^{\rm SZ,9}$ $0.8 \times (A_{\rm tSZ}^{1/9})$
TBO-1	0.62 ± 0.26	6.8 ± 2.9	0.74 ± 0.05	0.75 ± 0.04
TBO-2	0.96 ± 0.43	6.7 ± 3.0	0.78 ± 0.05	0.79 ± 0.04
Battaglia	0.85 ± 0.36	6.8 ± 2.9	0.77 ± 0.05	0.78 ± 0.04
Shaw	0.87 ± 0.39	6.8 ± 3.0	0.77 ± 0.05	0.78 ± 0.04

- Make predicted spectrum for SZ power for $\sigma_8 = 0.8$. Then scale it with some amplitude, A_{tSZ}.
- $A_{tSZ} = 1$ is prediction for $\sigma_8 = 0.8$. Then, $A_{tSZ} \sim \sigma_8^7$.
- ACT sees consistent power with SPT, but also with simple gas model templates.

- Kinetic SZ upper limit: <8 μK^2 (95% CL) at l =3000.

Summary of results

- With WMAP and ACT we measure the microwave power spectrum from $2 < \ell < 10000$; CMB is subdominant beyond ell~3000.

- *Standard ΛCDM:* the model continues to fit, and lensing of the CMB is required at almost 3σ significance.
- *Inflation:* ACT's longer lever arm gives new constraints on inflationary parameters: $r < 0.25$ from CMB alone and a running index disfavored. WMAP further constrains non-Gaussianity to $-10<f_{NL}<74$.
- *Non-standard physics*: relativistic species detected at 4σ, primordial helium at 6σ, and cosmic string contribution further limited.
- *Sunyaev-Zel'dovich*: New SZ clusters have been detected; numbers are consistent with ΛCDM. ACT (and SPT) see a preference for non-zero SZ power in spectrum.

- WMAP has 2 years more data; ACT has >75% data still to analyse.
- Planck results due 2012; ACTPol/SPTPol starting up 2012