ACT

Renée Hlozek
University of Oxford

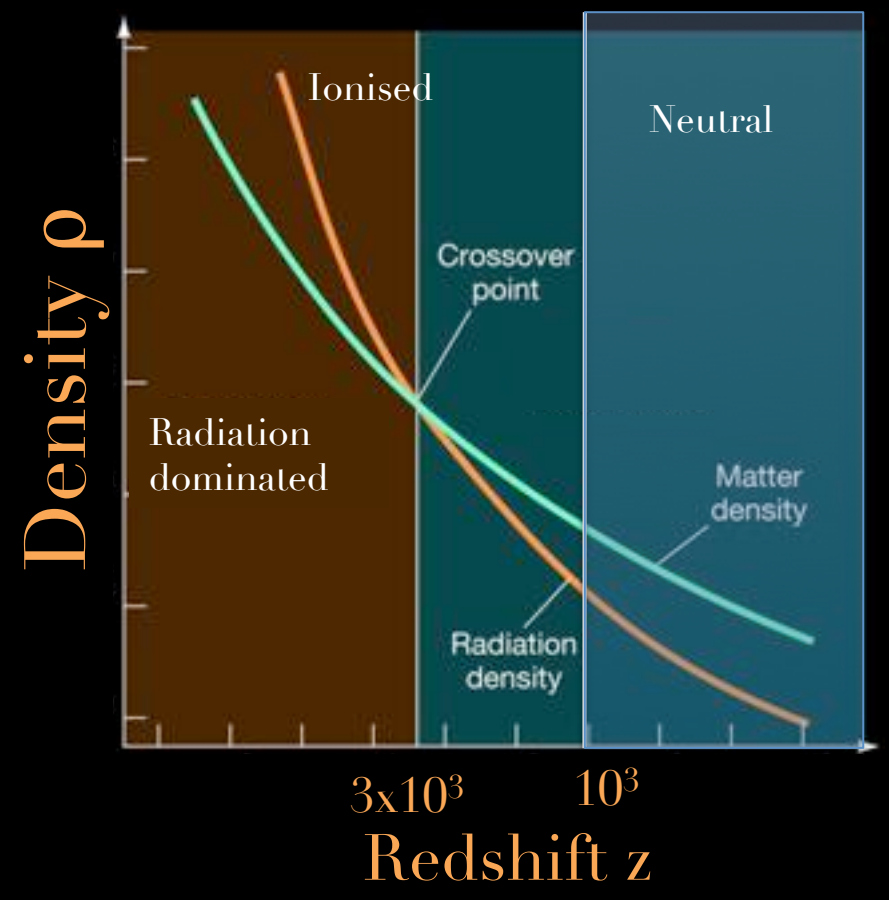
Cosmological parameters from the 2008 spectra

V. Acquaviva [1,2]
P. Ade [3]
P. Aguirre [4]
M. Amiri [5]
J. Appel [6]
E. Battistelli [7,5]
J. R. Bond [8]
B. Brown [9]
B. Burger [5]
J. Chervenak [10]
S. Das [29,6,1]
M. Devlin [2]
S. Dicker [2]
W. B. Doriese [11]
J. Dunkley [12,6,1]
R. Dunner [4]
T. Essinger-Hileman [6]
R.P. Fisher [6]
J.W. Fowler [6]
A. Hajian [6]
M. Halpern [5]
M. Hasselfield [5]
C. Hernandez-Monteagudo [13,2]
G. Hilton [11]
M. Hilton [14,15]
A. D. Hincks [6]
R. Hlozek [12]
K. Huffenberger [16,6]
D. Hughes [17]
J. P. Hughes [18]
L. Infante [4]
K.D. Irwin [11]
N. Jarosik [6]
R. Jimenez [19]
J.B. Juin [4]
M. Kaul [2]
J. Klein [2]
A. Kosowsky [9]
J.M. Lau [20,6]
M. Limon [21]
Y.T. Lin [22,1,4]
R. Lupton [1]
T.A. Marriage [1,6]
D. Marsden [2]
K. Martocci [23,6]
P. Mauskopf [3]
F. Menanteau [18]
K. Moodley [14]
H. Moseley [10]
B. Netterfield [24]
M.D. Niemack [11,6]
M.R. Nolta [8]
L.A. Page (PI) [6]
L. Parker [6]
B. Partridge [25]
H. Quintana [4]
B. Reid [19,1]
N. Sehgal [20,18]
J. Sievers [8]
D. Spergel [1]
S.T. Staggs [6]
O. Stryzak [6]
D. Swetz [2]
E. Switzer [23,6]
R. Thornton [26,2]
H. Trac [27,1]
C. Tucker [3]
L. Verde [19]
R. Warne [14]
G. Wilson [28]
E. Wollack [10]
Y. Zhao [6]

[1] Princeton University Astrophysics (USA)
[2] University of Pennsylvania (USA)
[3] Cardiff University (UK)
[4] Pontifica Universidad Catolica de Chile (Chile)
[5] University of British Columbia (Canada)
[6] Princeton University Physics (USA)
[7] University of Rome "La Sapienza" (Italy)
[8] CITA, University of Toronto (Canada)
[9] University of Pittsburgh (USA)
[10] NASA Goddard Space Flight Center (USA)
[11] NIST Boulder (USA)
[12] Oxford University (UK)
[13] Max Planck Institut fur Astrophysik (Germany)
[14] University of KwaZulu-Natal (South Africa)
[15] South African Astronomical Observatory
[16] University of Miami (USA)
[17] INAOE (Mexico)
[18] Rutgers (USA)
[19] Institute de Ciencies de L'Espai (Spain)
[20] KIPAC, Stanford (USA)
[21] Columbia University (USA)
[22] IPMU (Japan)
[23] KICP, Chicago (USA)
[24] University of Toronto (Canada)
[25] Haverford College (USA)
[26] West Chester University of Pennsylvania (USA)
[27] Harvard-Smithsonian CfA (USA)
[28] University of Massachusetts, Amherst (USA)
[29] BCCP UC Berkeley and LBL (USA)

Oxford Physics

The Cosmic Microwave Background



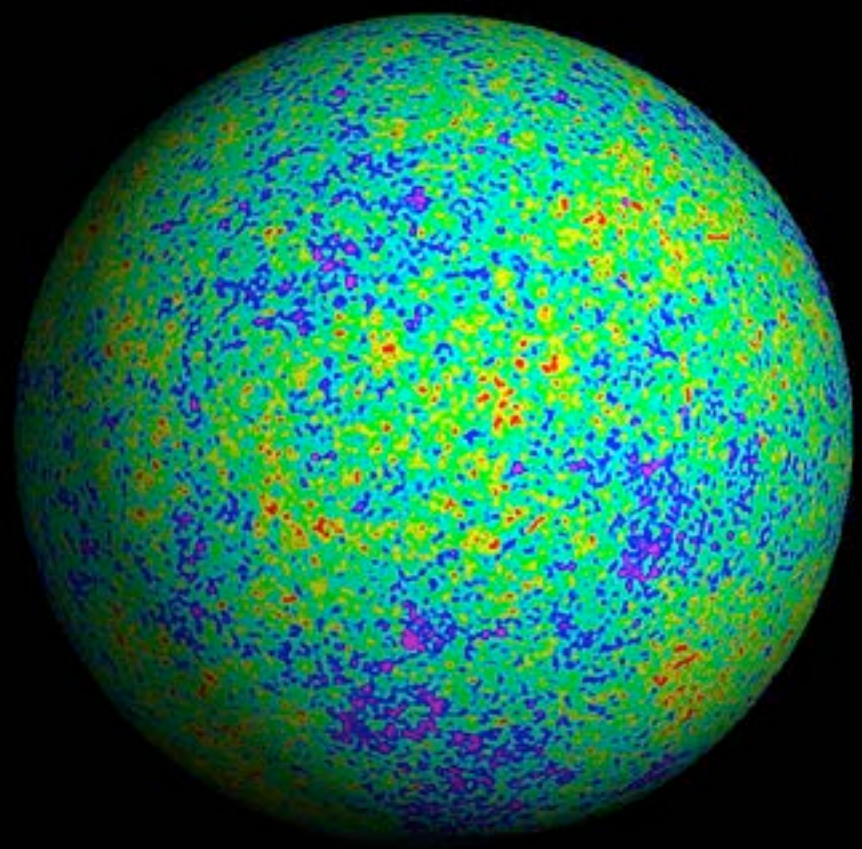
Linear theory → 'clean physics'

Basic elements well understood
→ numerical codes

The Cosmic Microwave Background

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

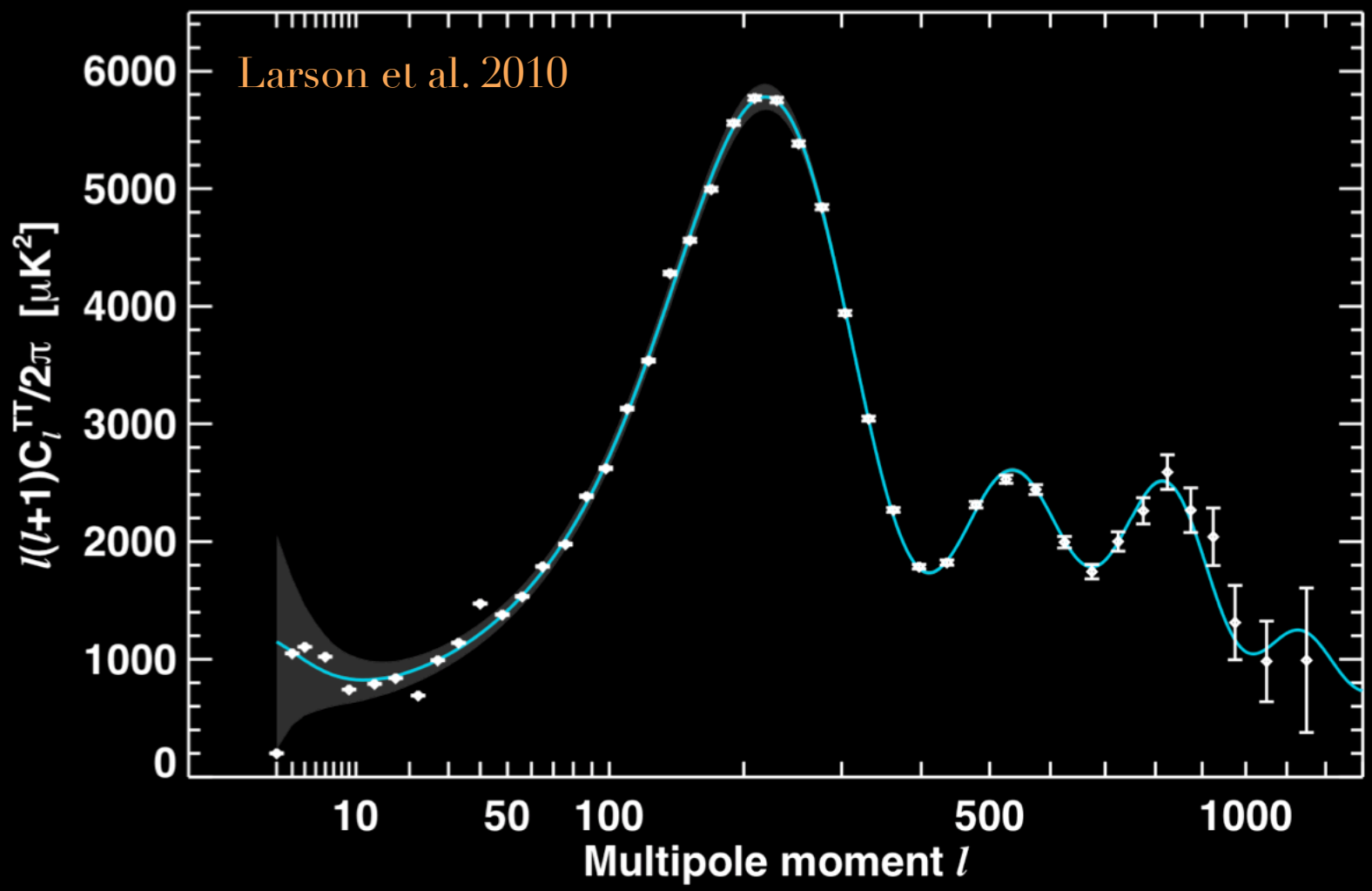
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$



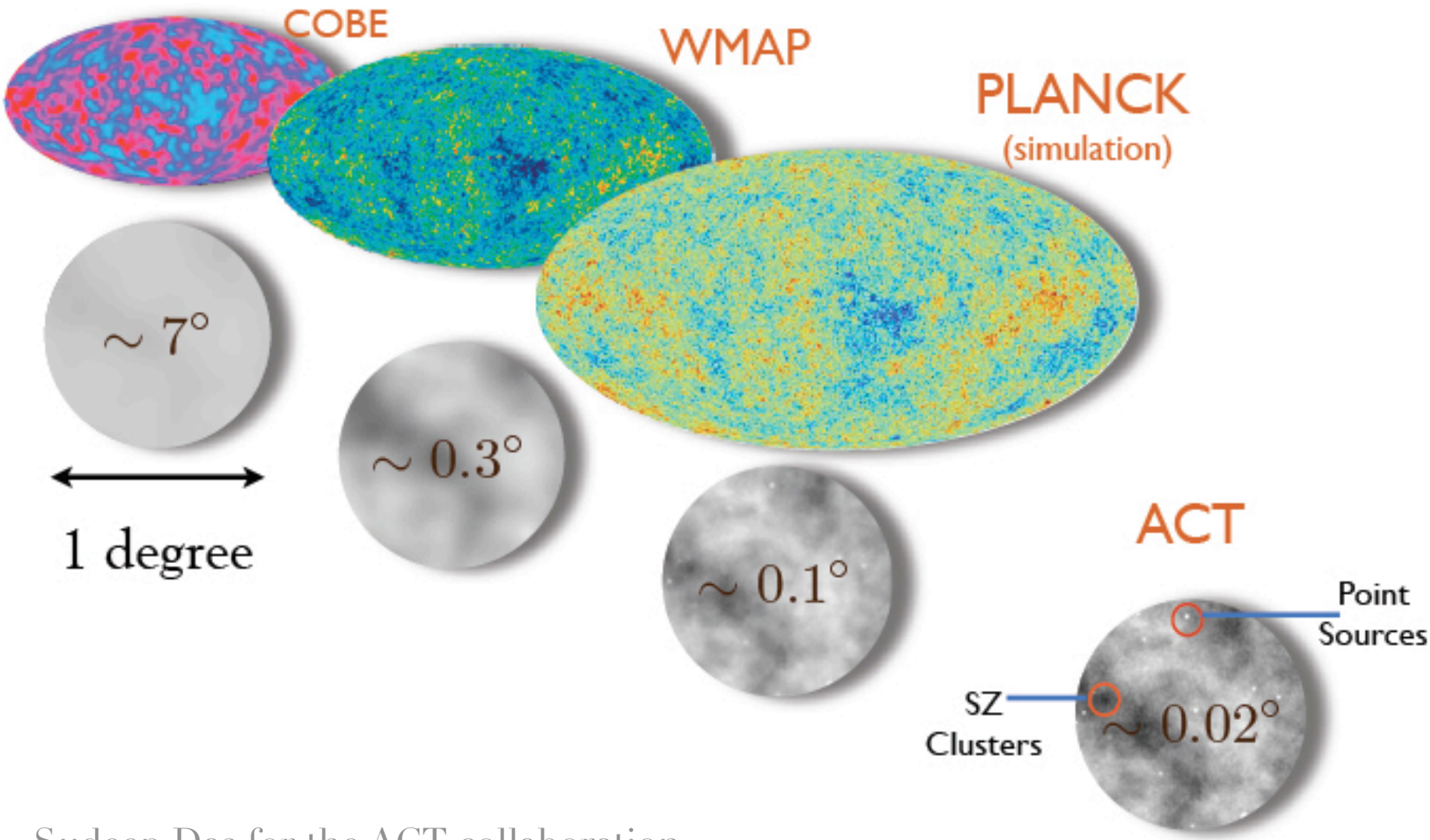
Linear theory → 'clean physics'

Basic elements well understood
→ numerical codes

WMAP 7


Larson et al. 2010
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
10
50
100
500
1000
Multipole moment l

ACT probes new scales



Sudeep Das for the ACT collaboration

The Atacama Cosmology Telescope

Located in Cerro Toco, Northern Chile

High and dry: 5200 m above sea level, 0.49mm PWV

6m off-axis Gregorian primary

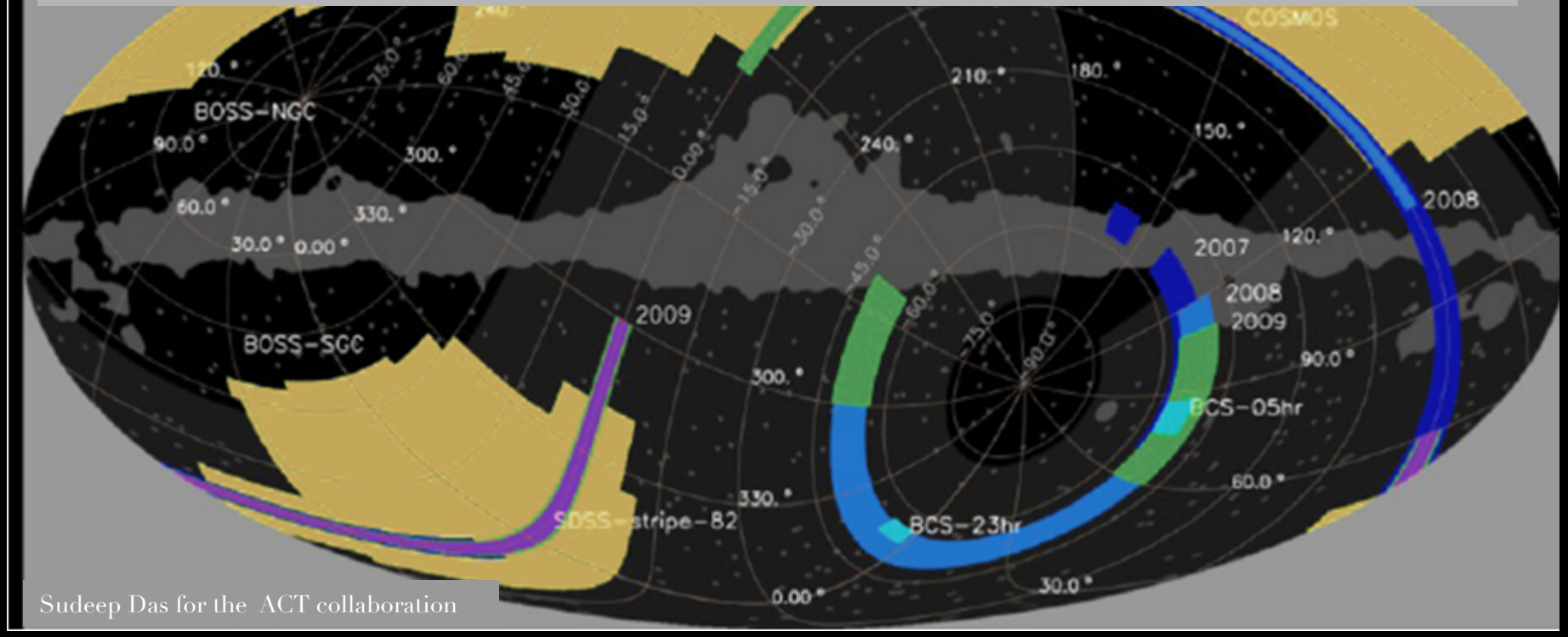
1' resolution

3 frequency channels:

148, 218, 277 GHz

The Survey

For the results in this talk, we focus on the Southern Survey over 300 deg^2 at 148 and 218 GHz



Sudeep Das for the ACT collaboration

2007	2009	Stripe 82	BCS
2008	ACT Range	BOSS	Masked

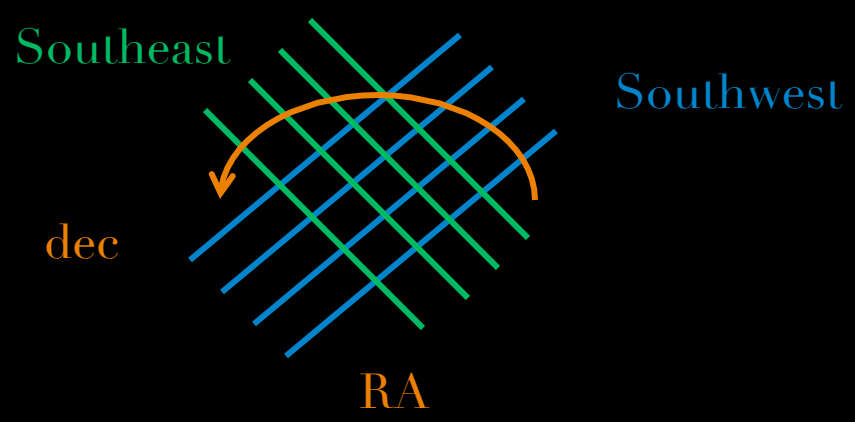
Observing Stra(c)tegy

Observe mainly at night: 20:30 – 09:30 local time

Fixed elevation of 53° South

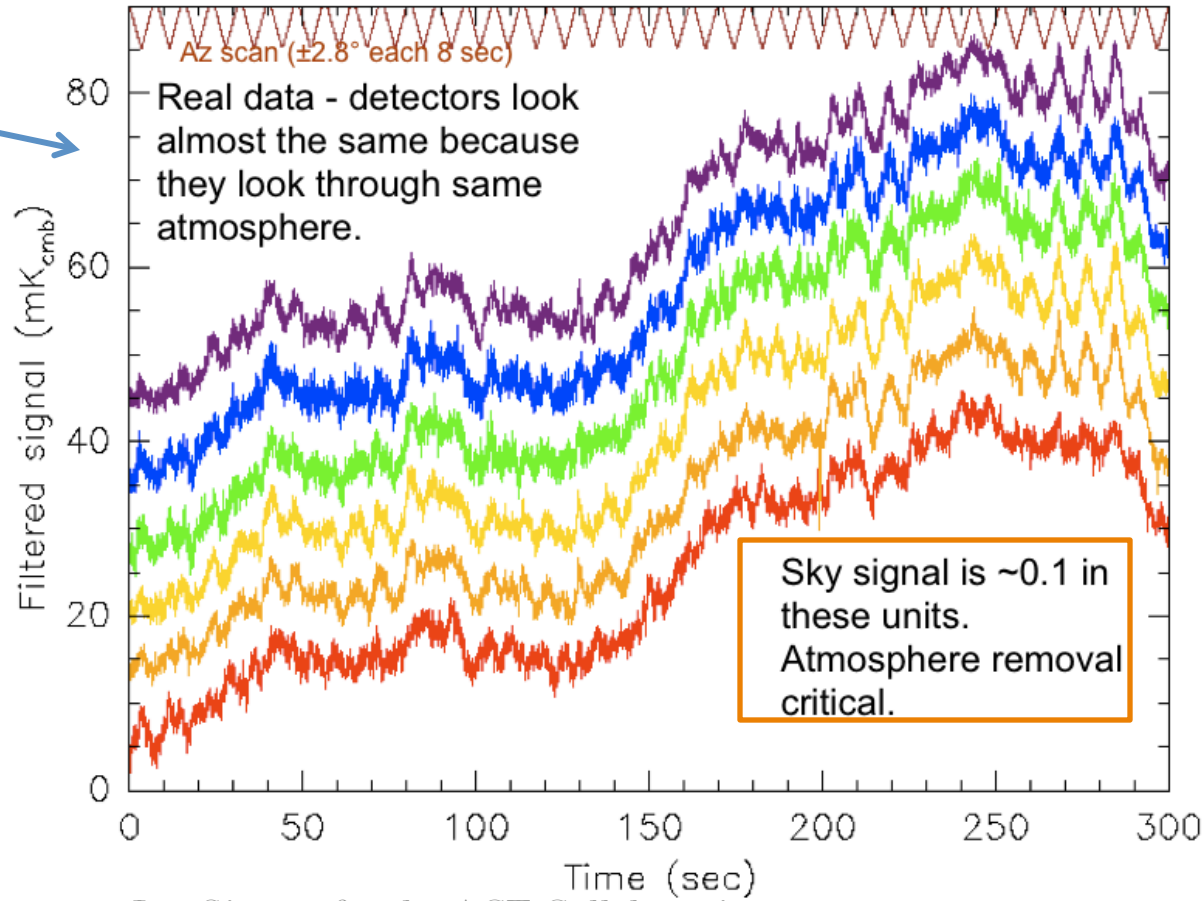
Rapid scanning: 6 degrees every 8 seconds

Cross-linking: observe each patch twice per night



The ACT of Mapping

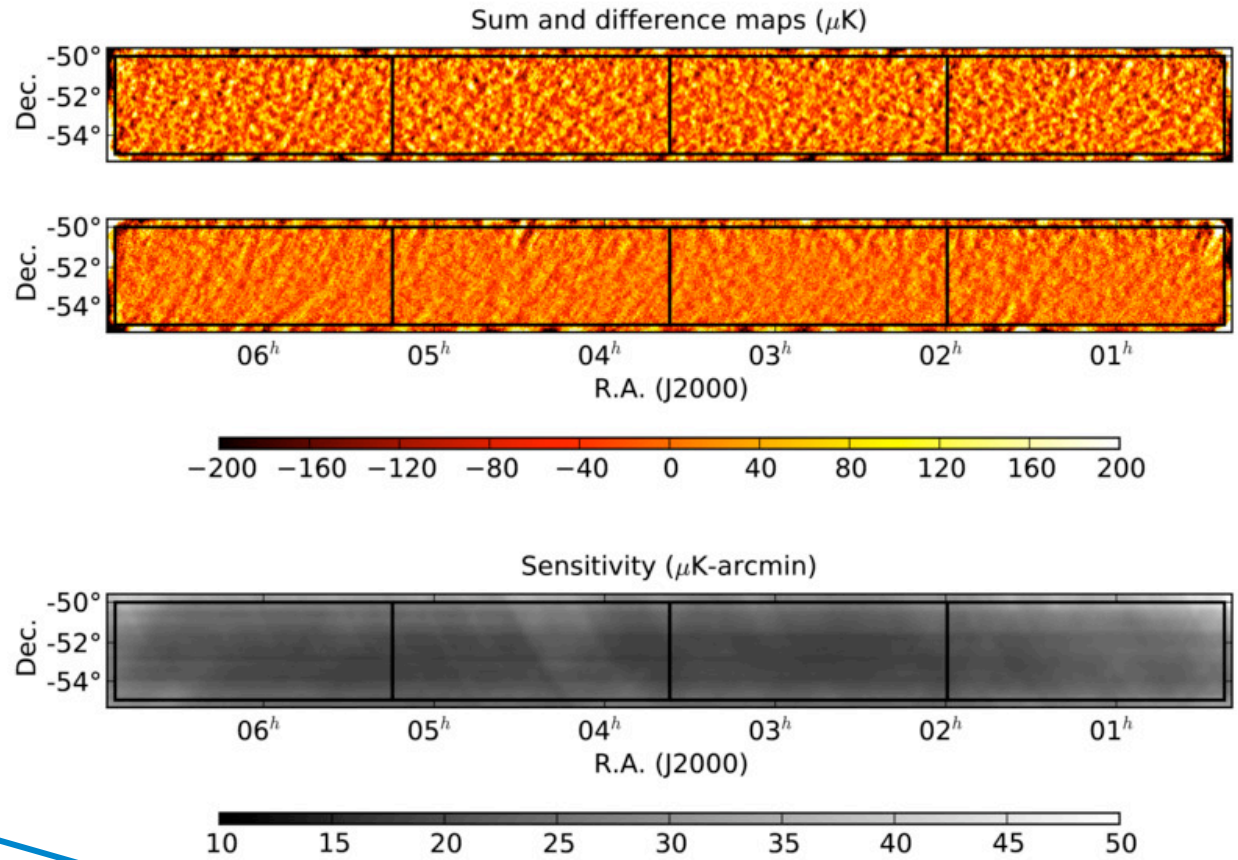
The challenge is to go from raw ACT data to reliable maps of the sky (ie. with a transfer function on average = 1)



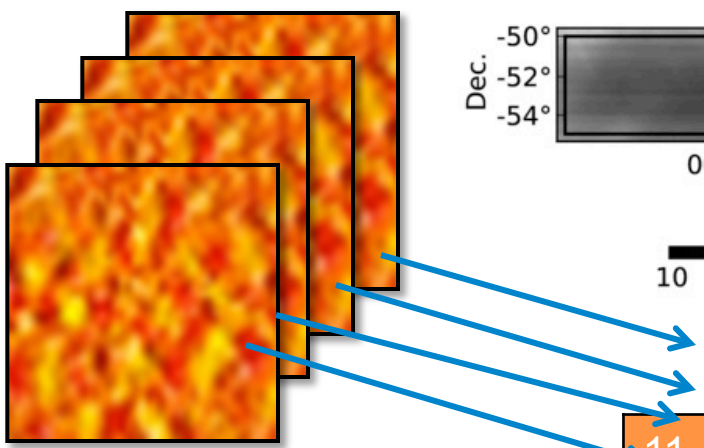
Jon Sievers for the ACT Collaboration

Noise is complicated, includes correlations between detectors from atmosphere, etc.

ACT Data



Split data into
4 subsets



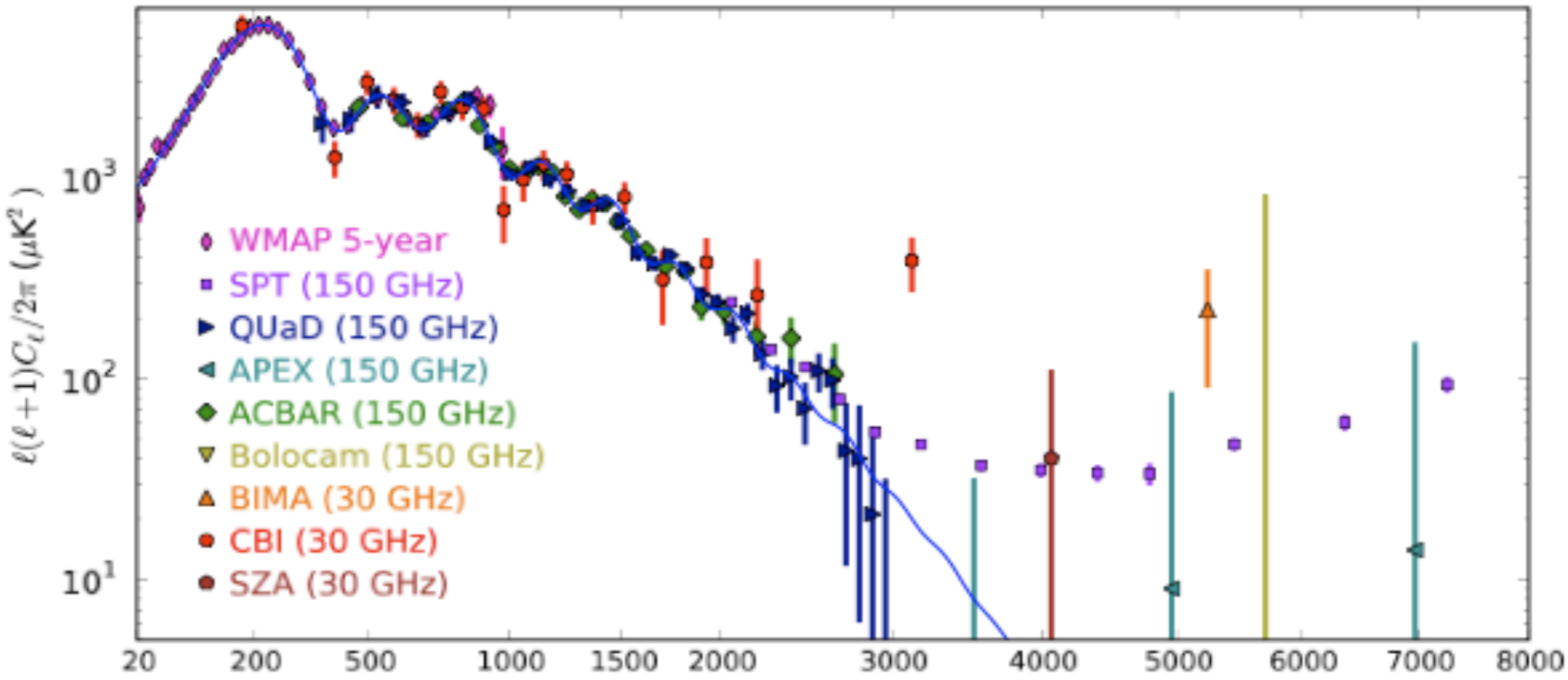
4 patches of 5x14.8° size

11	12	13	14
21	22	23	24
31	32	33	34
41	42	43	44

Auto spectra
estimate the
noise per patch

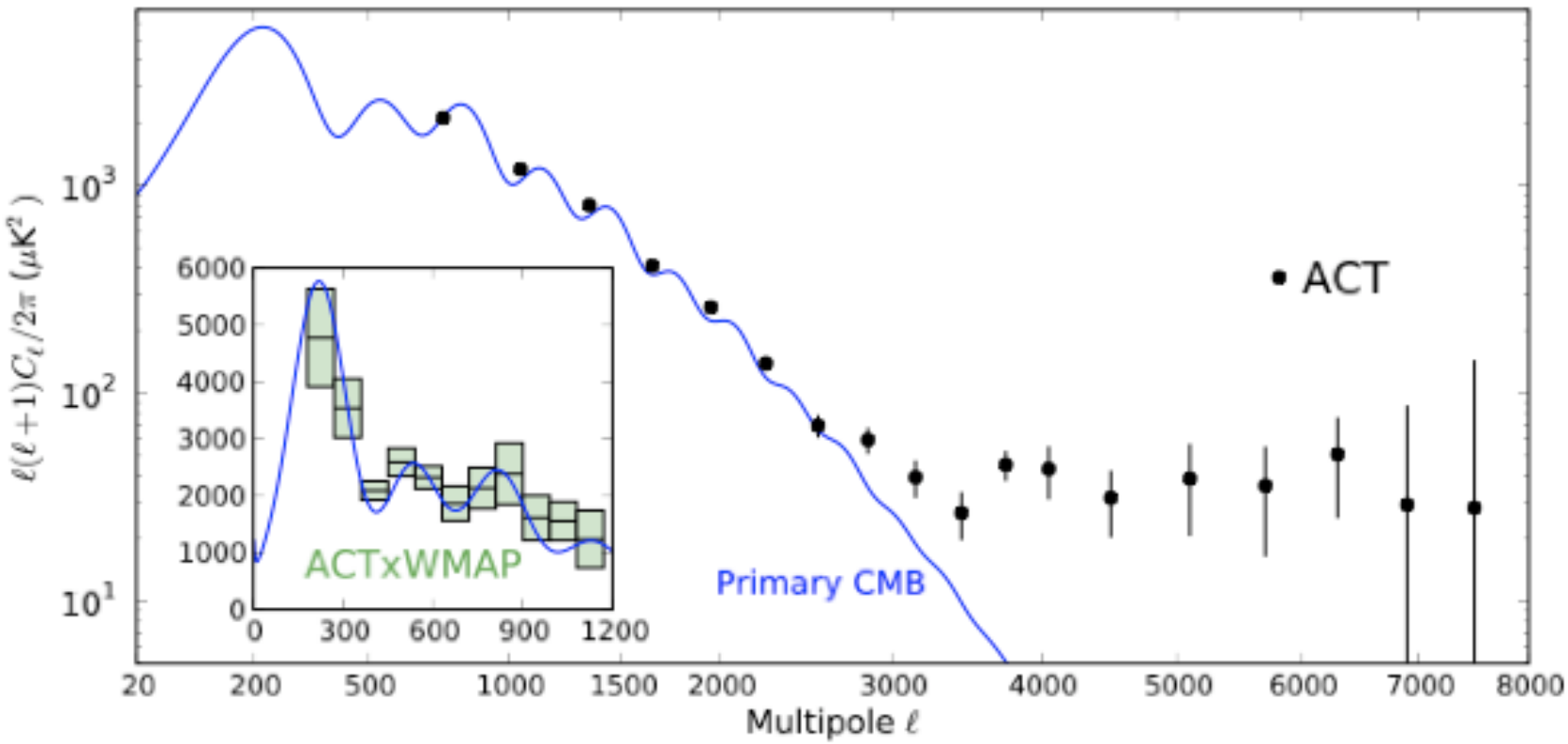
Use the mean of the
6 cross-spectra within a
patch

The story so far...



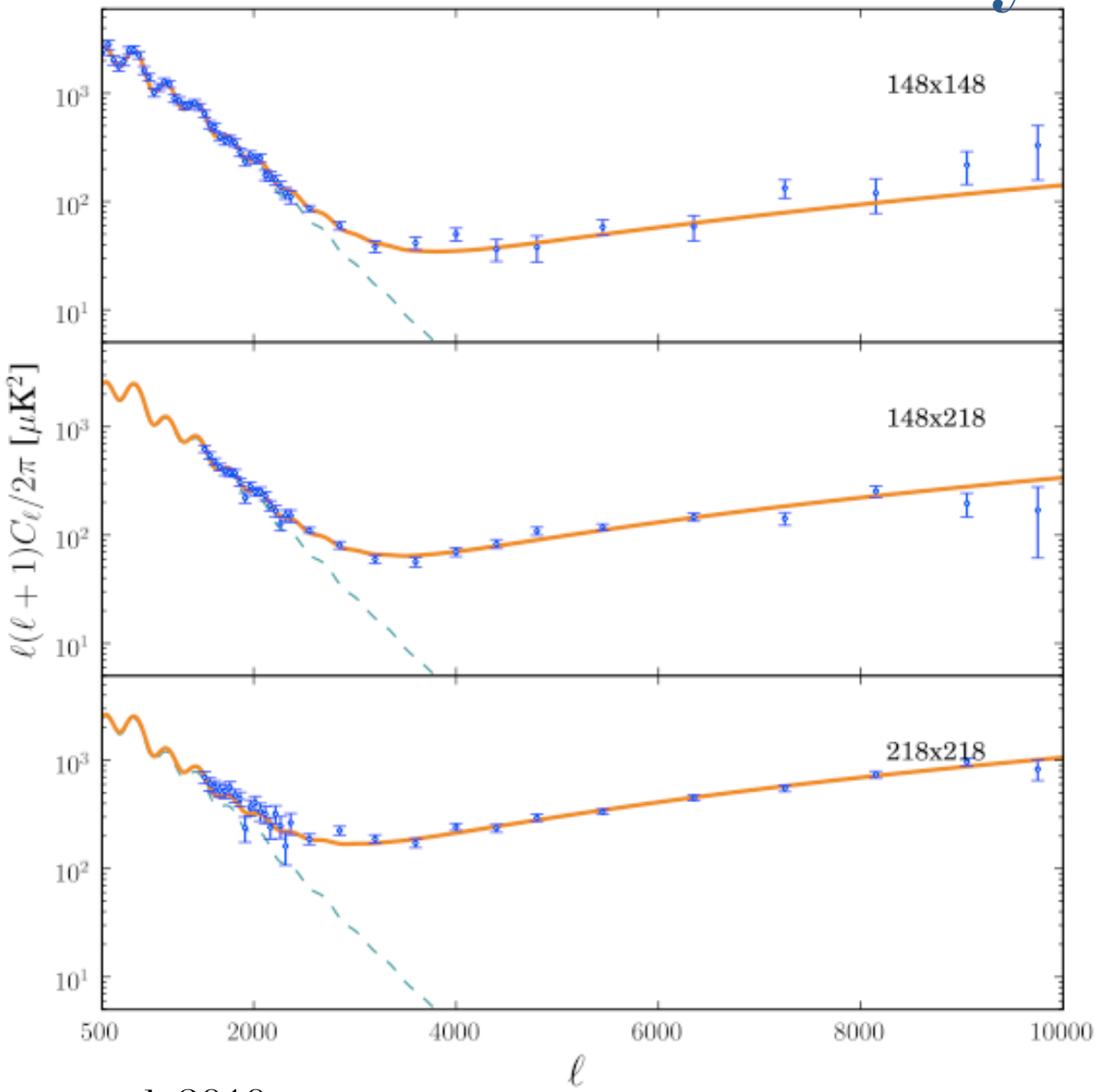
Fowler et al. 2010

The story so far...



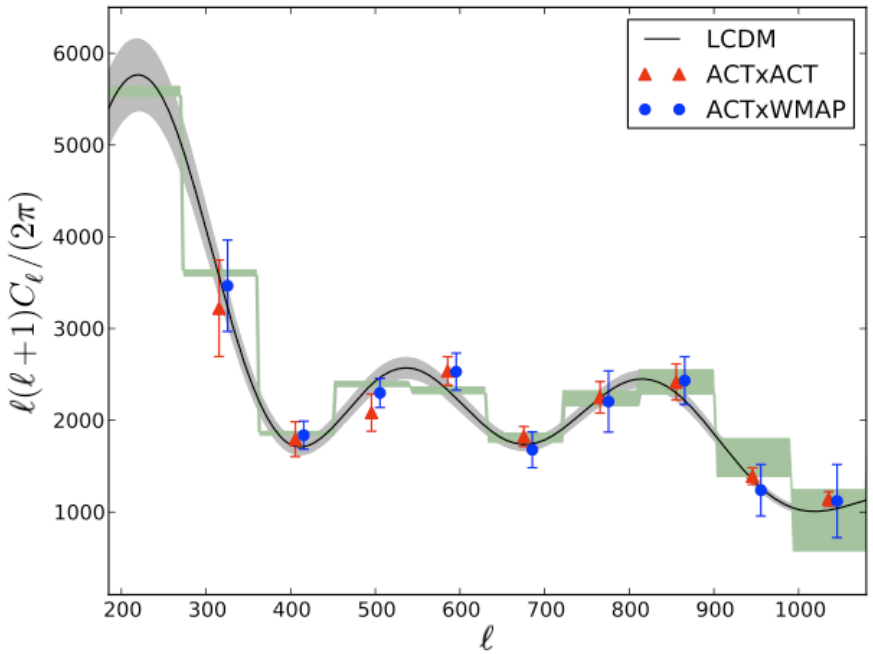
Fowler et al. 2010

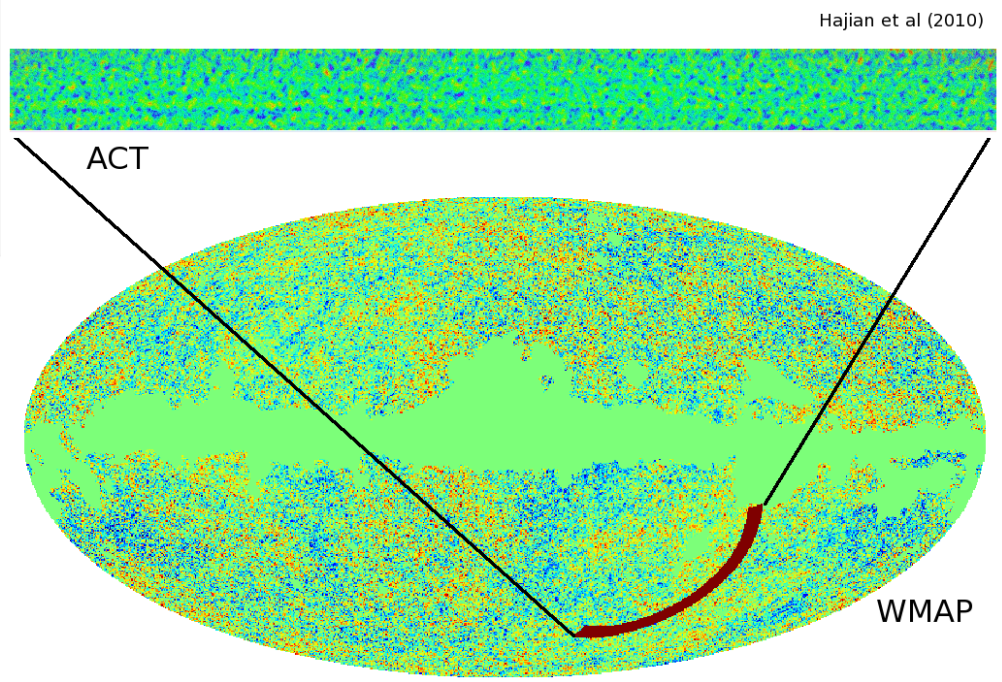
2008 Southern Survey



Das, Marriage et al. 2010

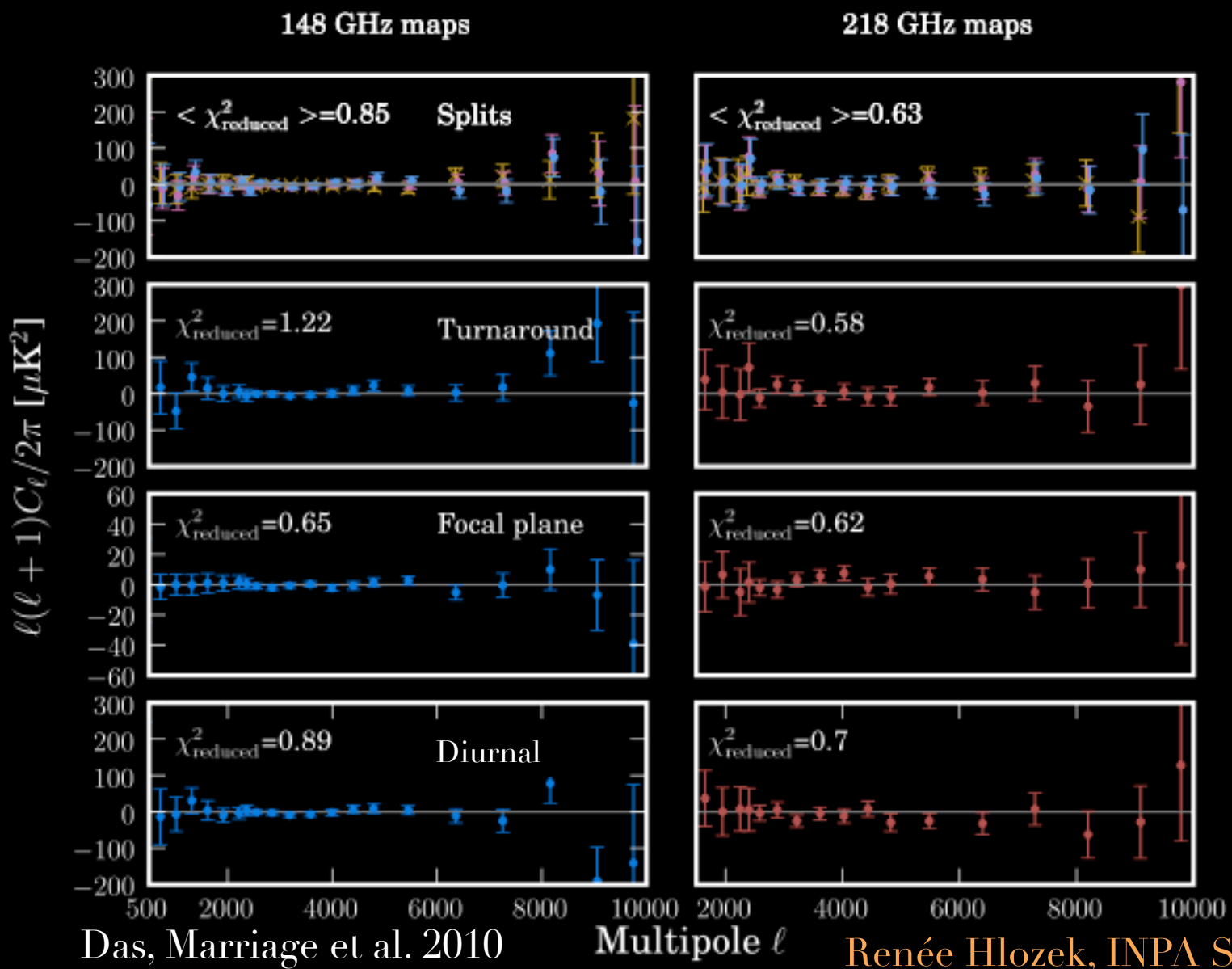
WMAP calibration





Haijan et al. 2010

Null tests



Das, Marriage et al. 2010

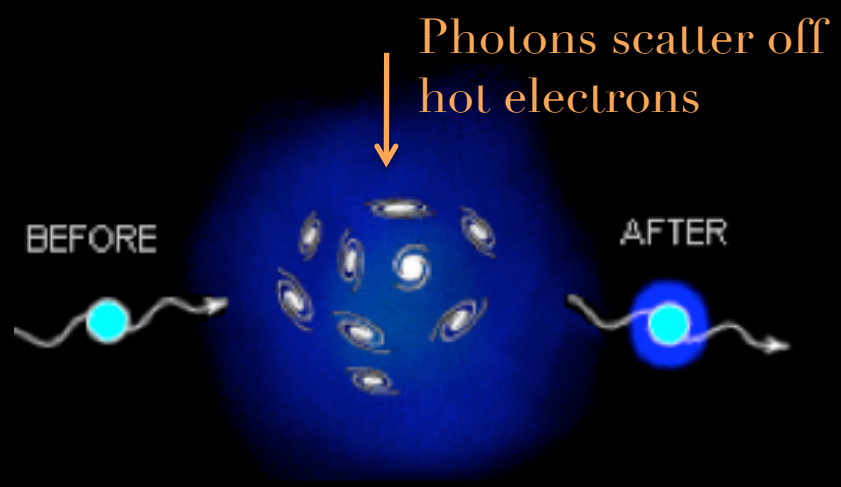
Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

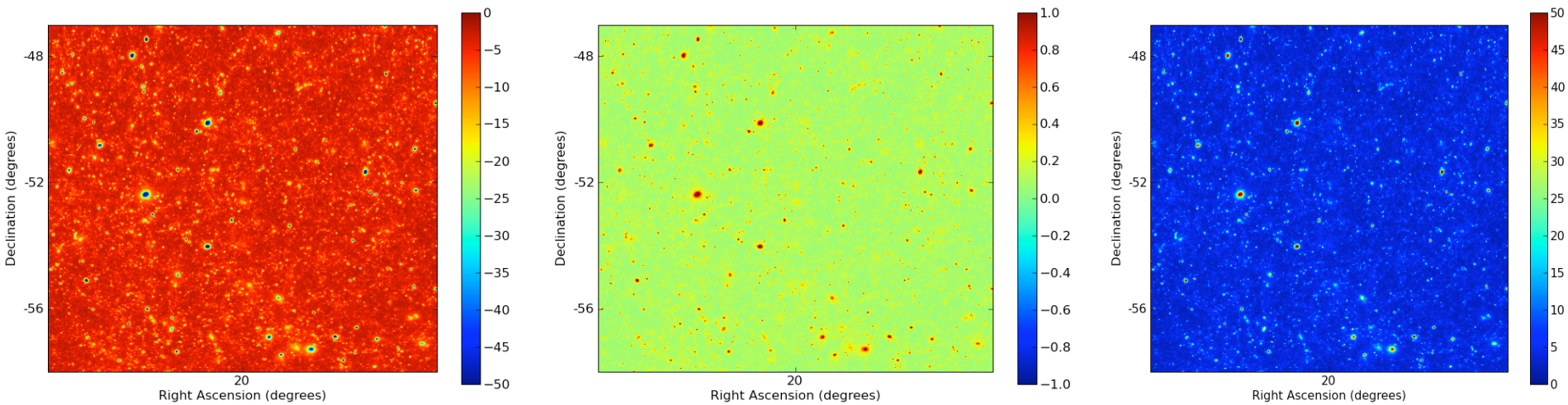
$$\mathcal{B}_\ell \equiv \ell(\ell+1)C_\ell/2\pi$$

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$



SZ effect is frequency dependent



Sehgal et al. 2009

Multi-frequency model

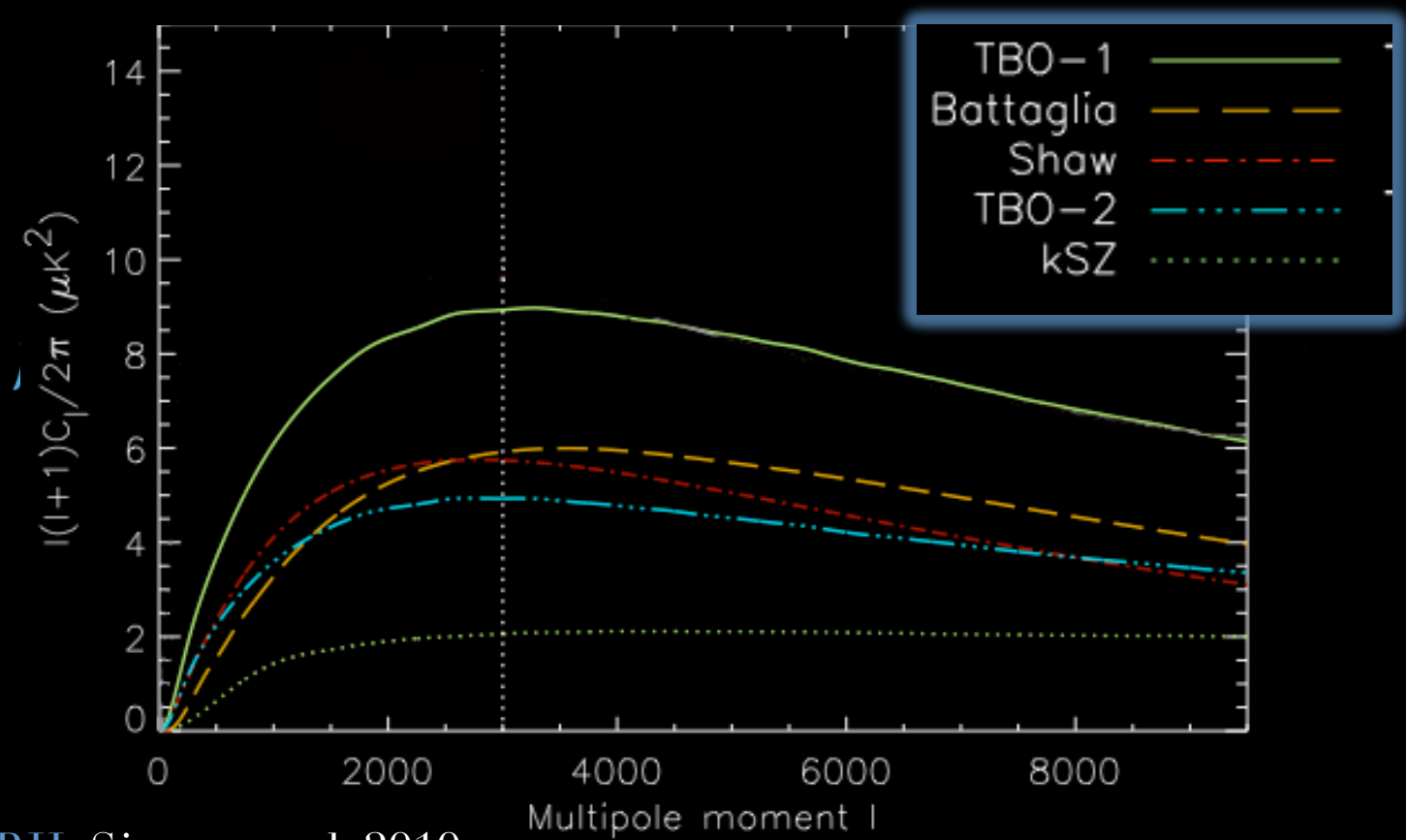
$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

$$\mathcal{B}_\ell^{\mathrm{SZ,ij}} = A_{\mathrm{tSZ}} \boxed{\frac{f(\nu_i)}{f(\nu_0)} \frac{f(\nu_j)}{f(\nu_0)}} \mathcal{B}_{0,\ell}^{\mathrm{tSZ}} + A_{\mathrm{kSZ}} \mathcal{B}_{0,\ell}^{\mathrm{kSZ}}$$

frequency dependence
of the SZ

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$



Dunkley, RH, Sievers et al. 2010

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

Power law frequency dependence

$$\mathcal{B}_\ell^{\mathrm{IR,ij}} = \left[A_d \left(\frac{\ell}{3000} \right)^2 + A_c \mathcal{B}_{0,\ell}^{\mathrm{clust}} \right] \frac{g(\nu_i)}{g(\nu_0)} \frac{g(\nu_j)}{g(\nu_0)} \left(\frac{\nu_i}{\nu_0} \frac{\nu_j}{\nu_0} \right)^{\alpha_d - 2}$$

Poisson clustering

Conversion between thermodynamic and antenna temp units

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

Dusty galaxies sit in halos → ACT detects clustering at 5σ

Power law frequency dependence

$$\mathcal{B}_\ell^{\mathrm{IR,ij}} = \left[A_d \left(\frac{\ell}{3000} \right)^2 + A_c \mathcal{B}_{0,\ell}^{\mathrm{clust}} \right] \frac{g(\nu_i)}{g(\nu_0)} \frac{g(\nu_j)}{g(\nu_0)} \left(\frac{\nu_i}{\nu_0} \frac{\nu_j}{\nu_0} \right)^{\alpha_d - 2}$$

Poisson clustering

Conversion between thermodynamic and antenna temp units

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

$$\mathcal{B}_\ell^{\mathrm{rad,ij}} = A_s \left(\frac{\ell}{3000}\right)^2 \frac{g(\nu_i)}{g(\nu_0)} \frac{g(\nu_j)}{g(\nu_0)} \left(\frac{\nu_i}{\nu_0}\frac{\nu_j}{\nu_0}\right)^{\alpha_s - 2}$$

Radio sources modelled as Poisson sources

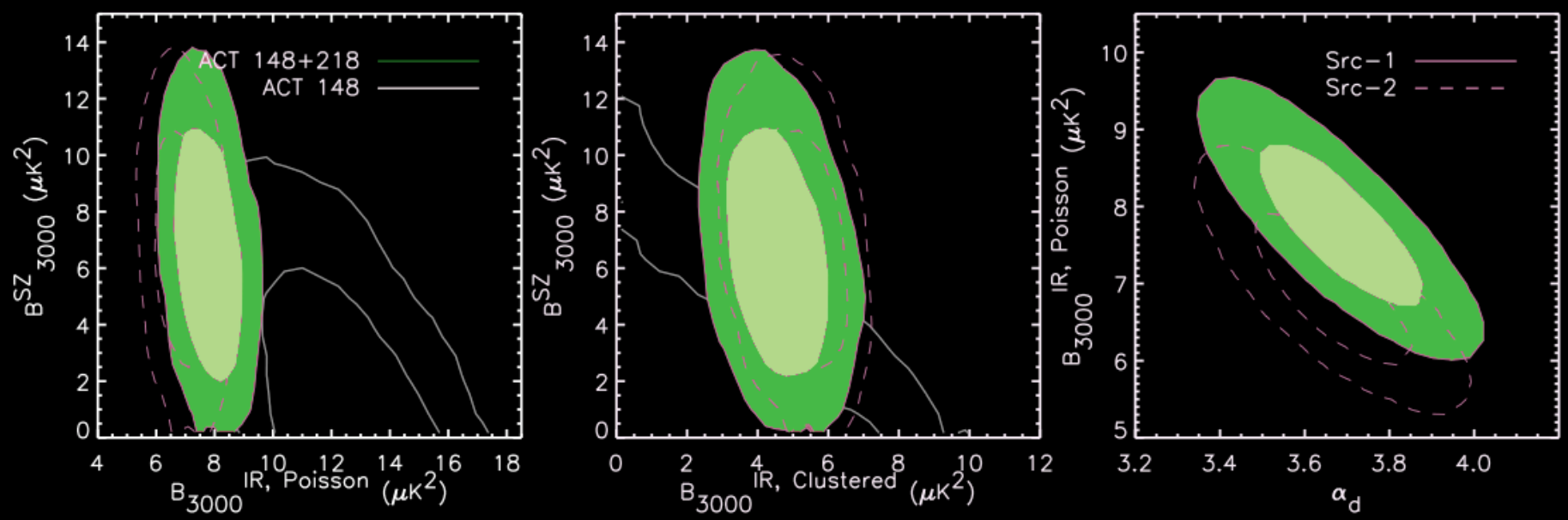
Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$

One frequency is not enough to separate components

Multi-frequency model

$$\mathcal{B}_\ell^{\mathrm{th,ij}} = \mathcal{B}_\ell^{\mathrm{CMB}} + \mathcal{B}_\ell^{\mathrm{tSZ,ij}} + \mathcal{B}_\ell^{\mathrm{kSZ,ij}} + \mathcal{B}_\ell^{\mathrm{IR,ij}} + \mathcal{B}_\ell^{\mathrm{rad,ij}} + \mathcal{B}_\ell^{\mathrm{Gal,ij}}$$



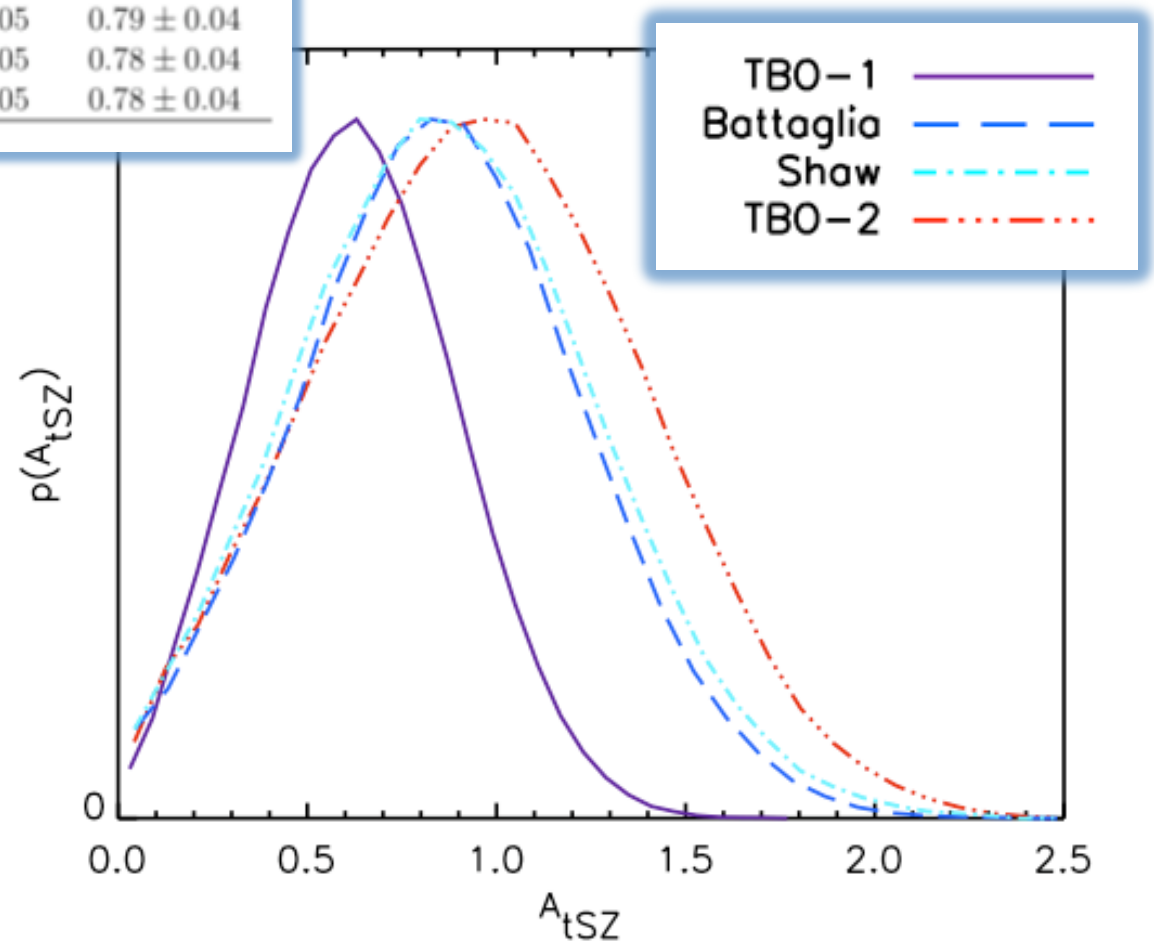
Dunkley, RH, Sievers et al. 2010

SZ amplitude

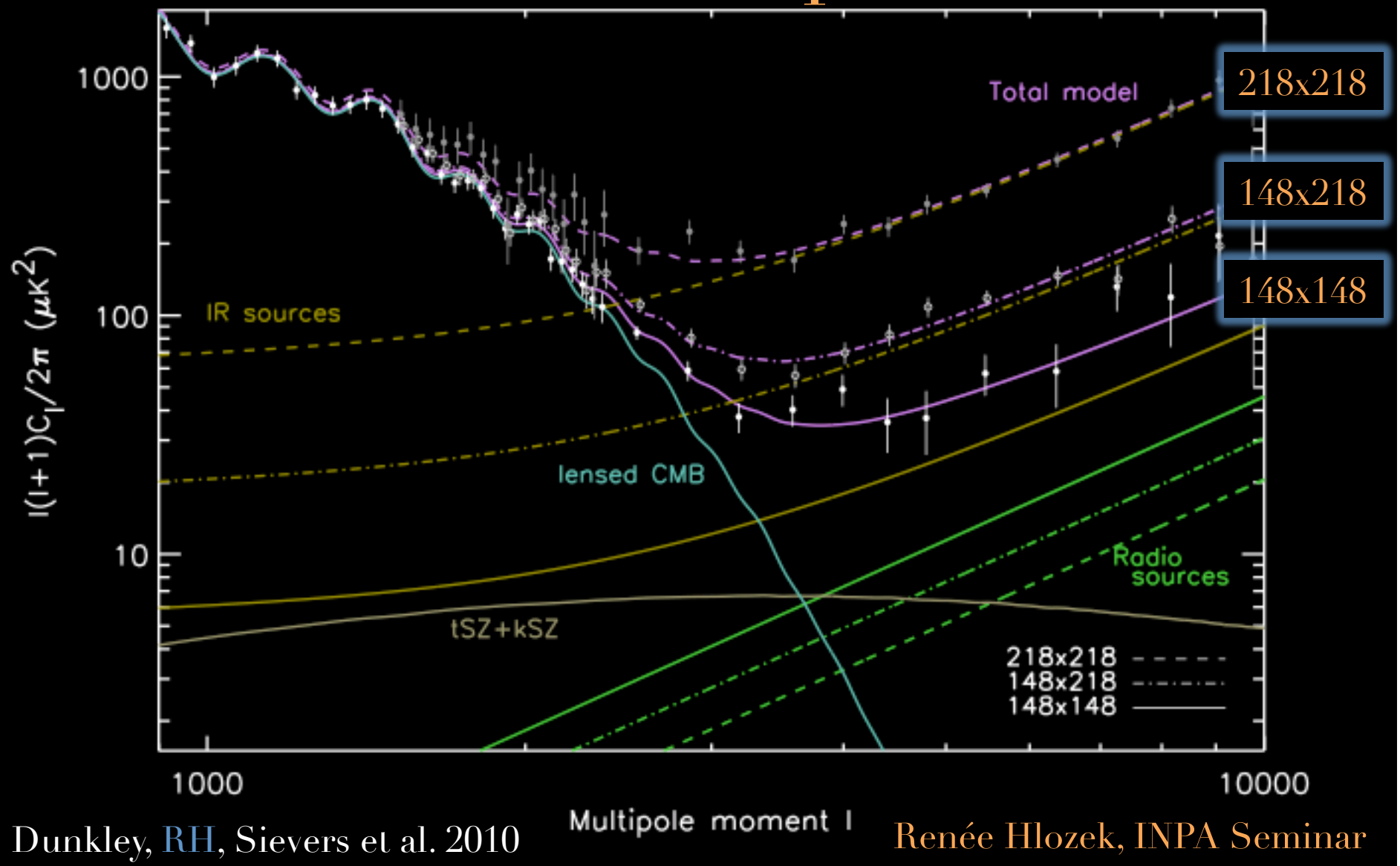
Template[a]	A_{tSZ}[b]	$\mathcal{B}^{SZ}_{3000}$[c] (μK^2)	$\sigma_8^{SZ,7}$ $0.8 \times (A_{tSZ}^{1/7})$	$\sigma_8^{SZ,9}$ $0.8 \times (A_{tSZ}^{1/9})$
TBO-1	0.62 ± 0.26	6.8 ± 2.9	0.74 ± 0.05	0.75 ± 0.04
TBO-2	0.96 ± 0.43	6.7 ± 3.0	0.78 ± 0.05	0.79 ± 0.04
Battaglia	0.85 ± 0.36	6.8 ± 2.9	0.77 ± 0.05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

Consistent with SPT value of A_{SZ}=0.55±0.21 (Lueker et al. 2009)

Value depends on templates → different gas physics



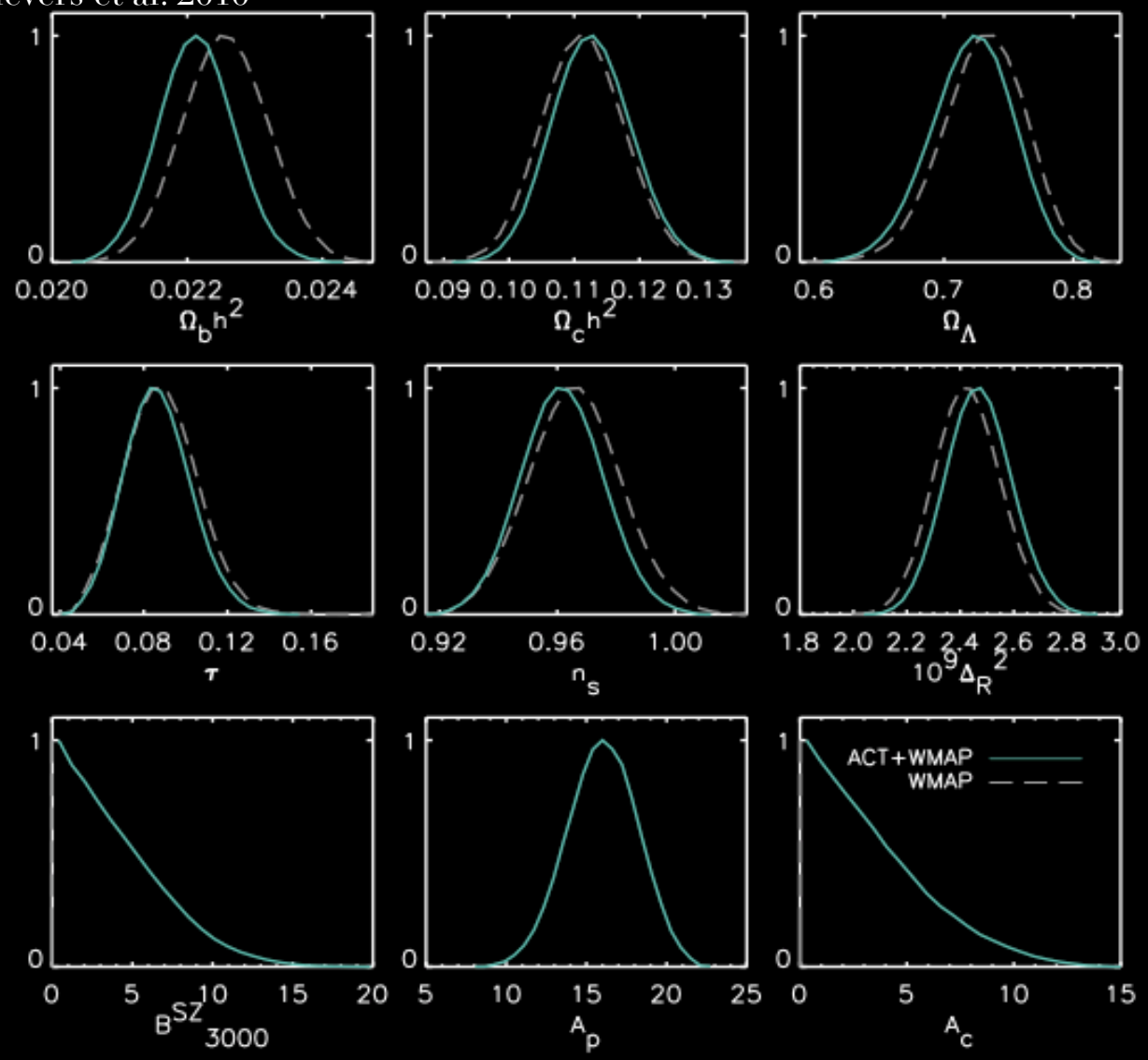
The ACT components



Dunkley, RH, Sievers et al. 2010

Consistency with ΛCDM

Dunkley, RH, Sievers et al. 2010

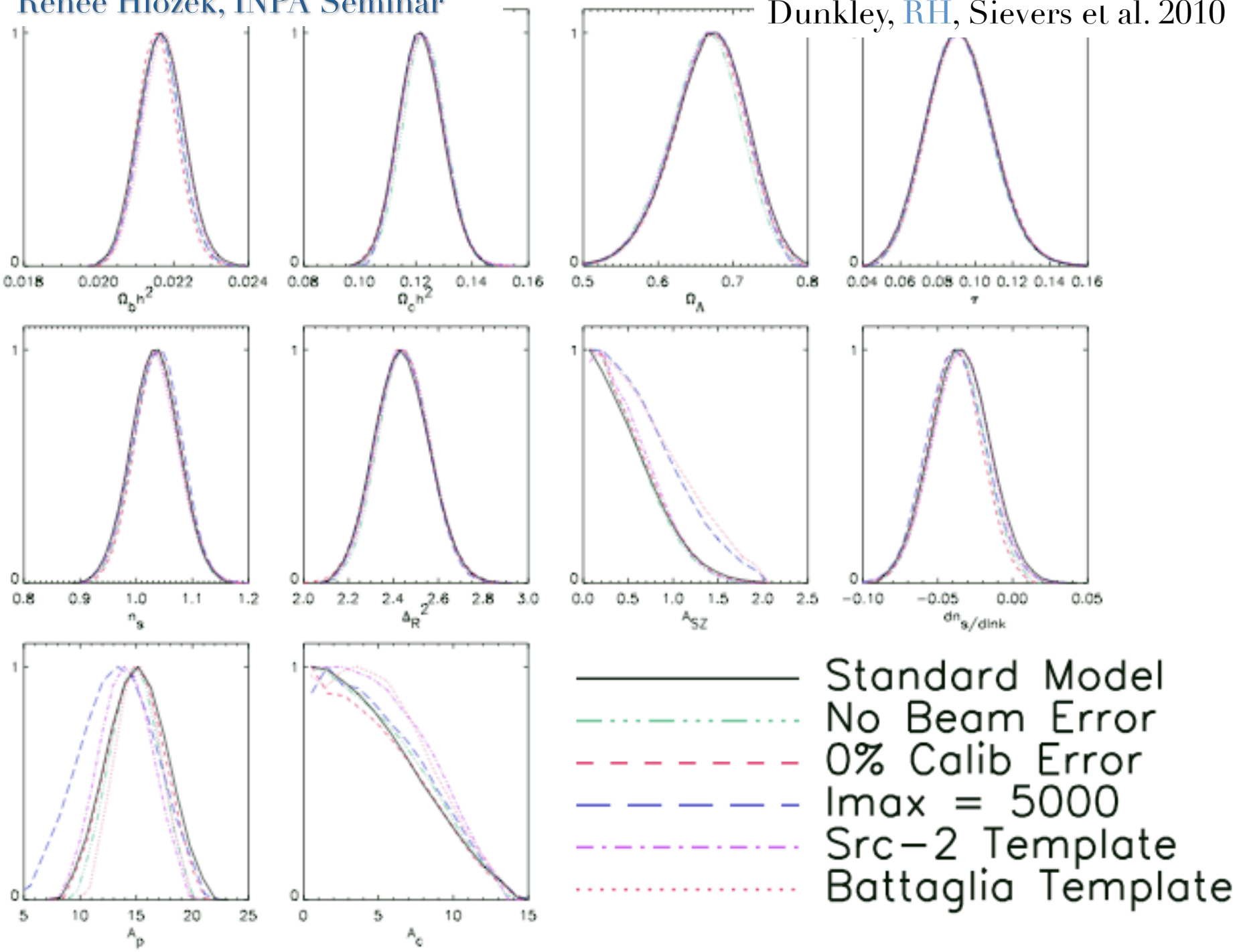


Testing the likelihood

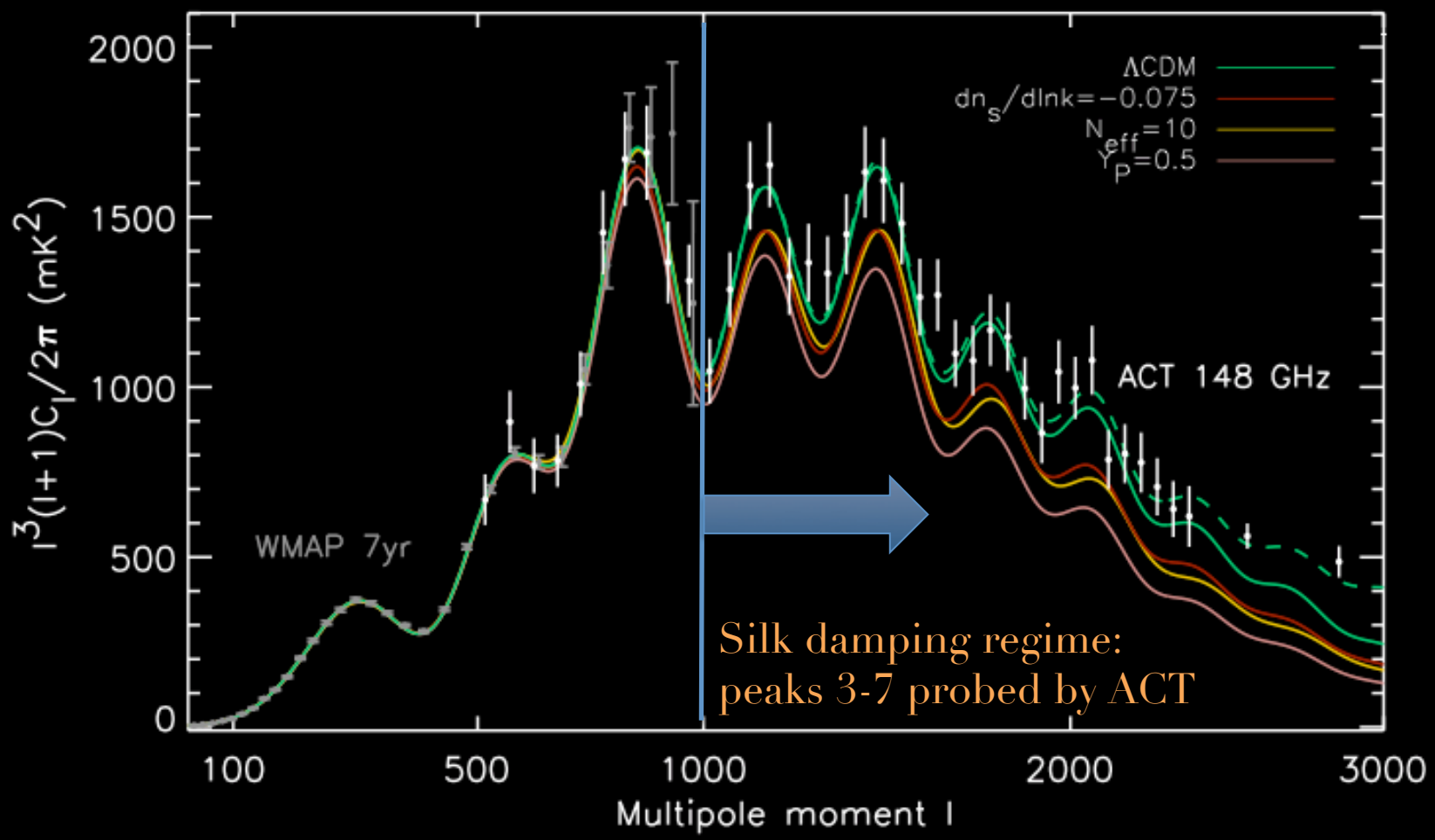
- Assumptions:
  - range of multipole: $500 < \ell < 10000$.
  - 2% calibration in temperature
  - including beam error
  - Src-1 clustered template
  - TBO-1 SZ template

Are our results sensitive to these assumptions?

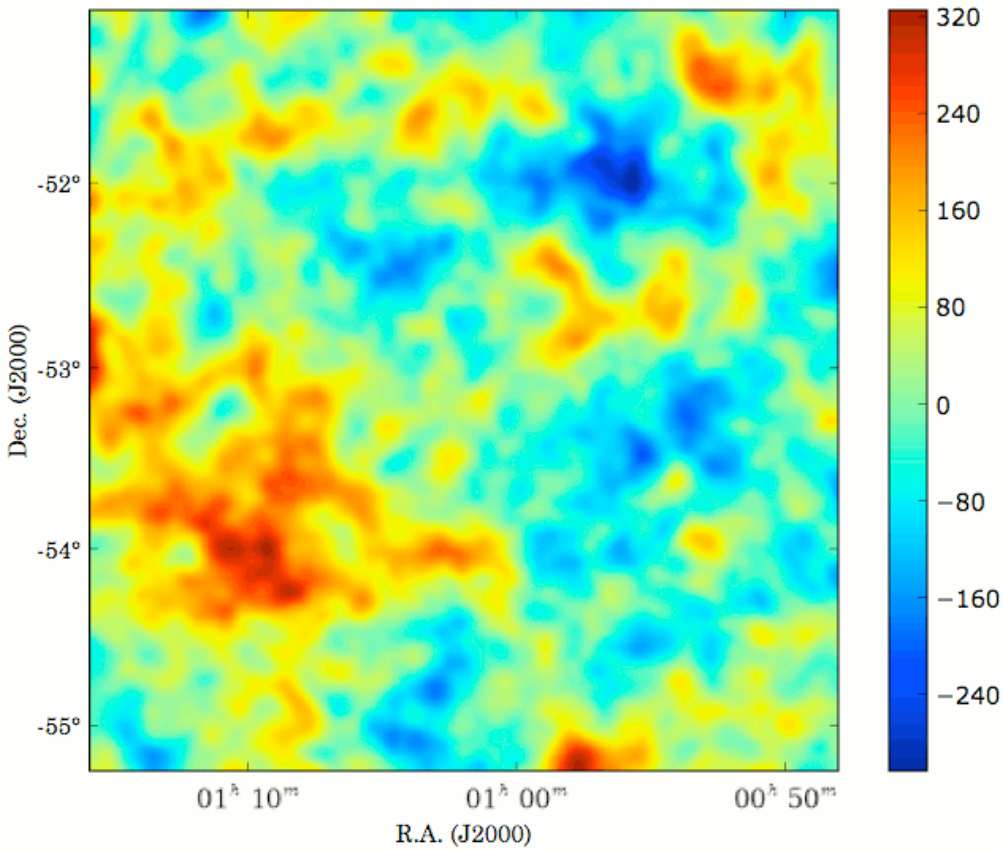
Dunkley, RH, Sievers et al. 2010



Where is ACT's power?

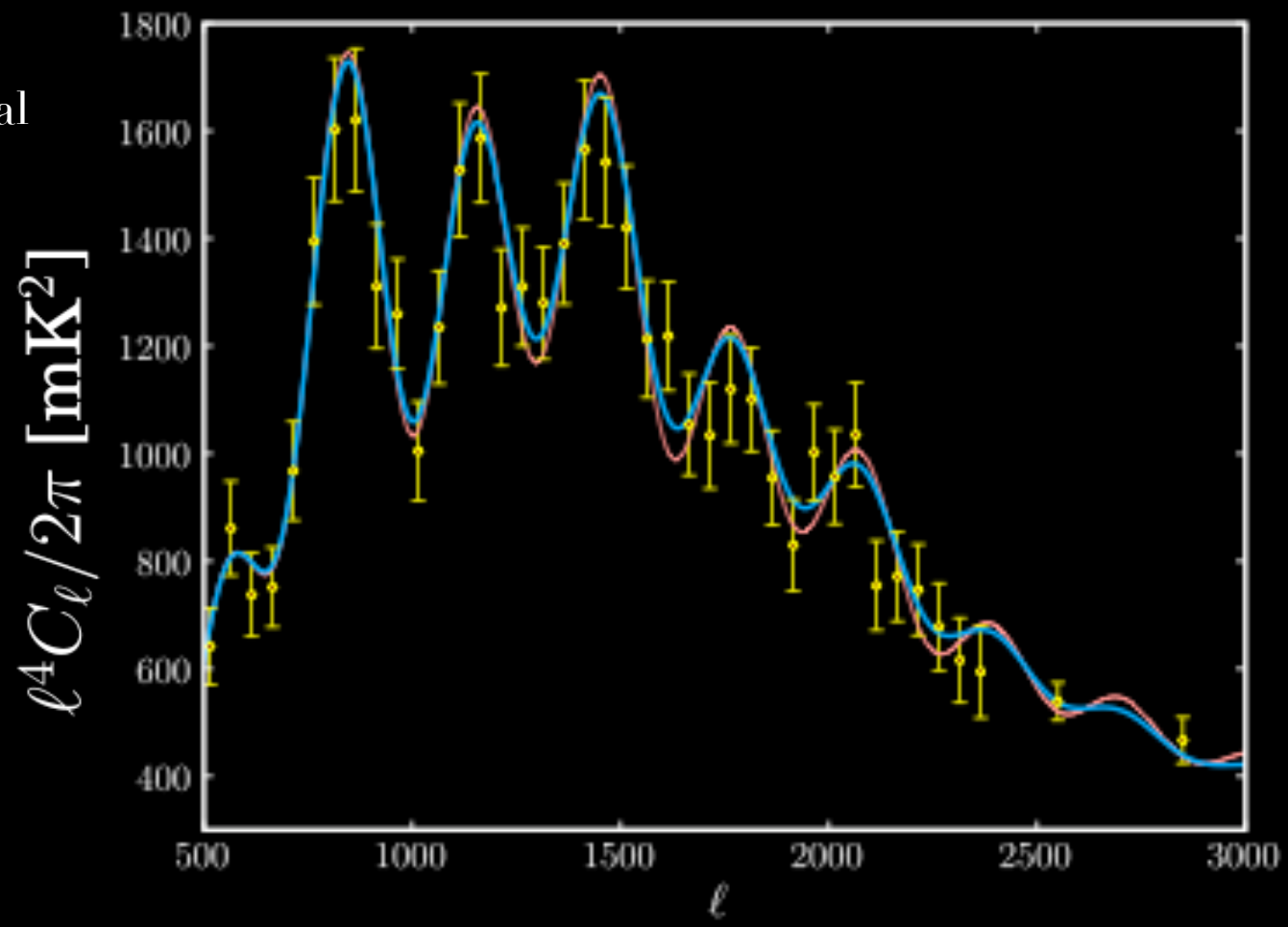


ACT detects lensing



ACT detects lensing

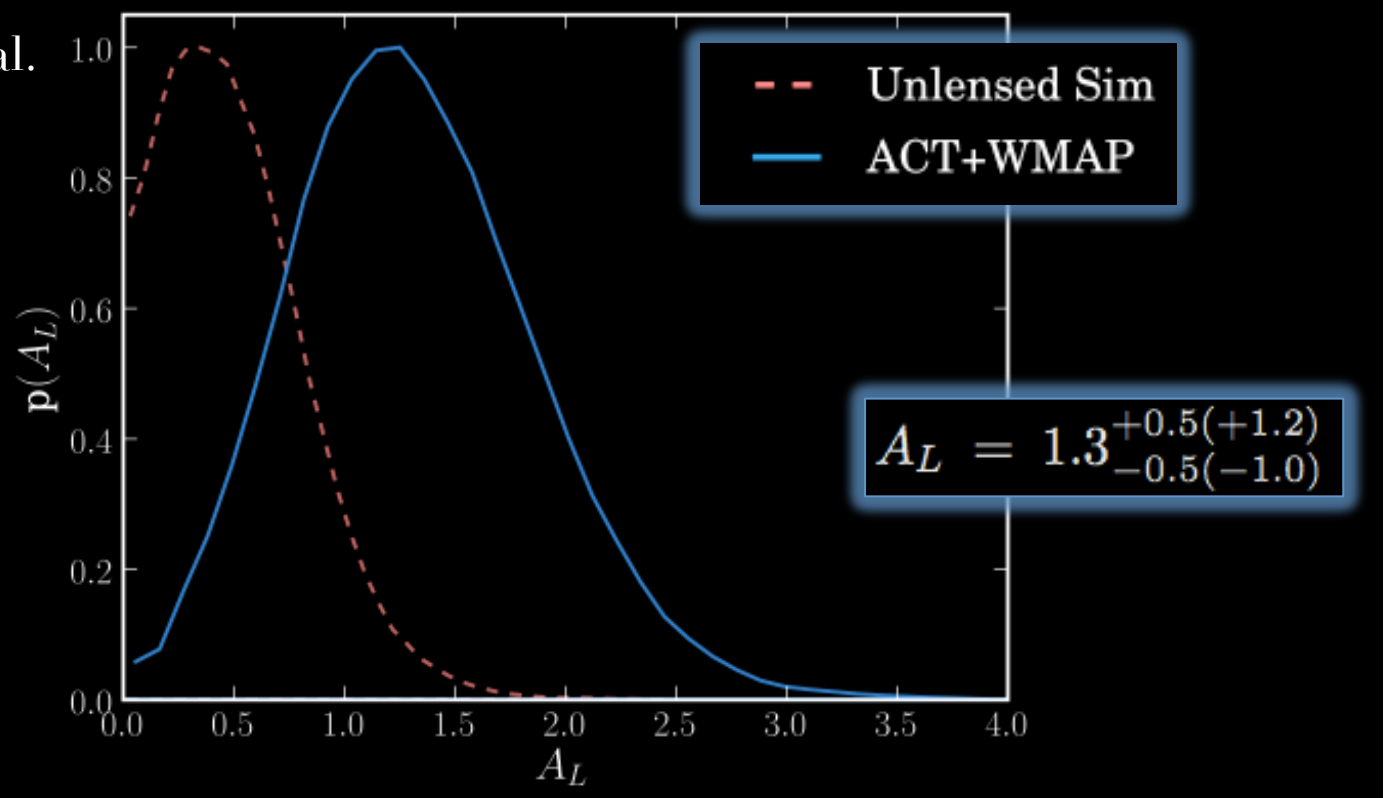
Das, Marriage et al
2010



Best-fit lensed spectrum has $\Delta\bar{\chi}^2 = 8$ less than unlensed spectrum

ACT detects lensing

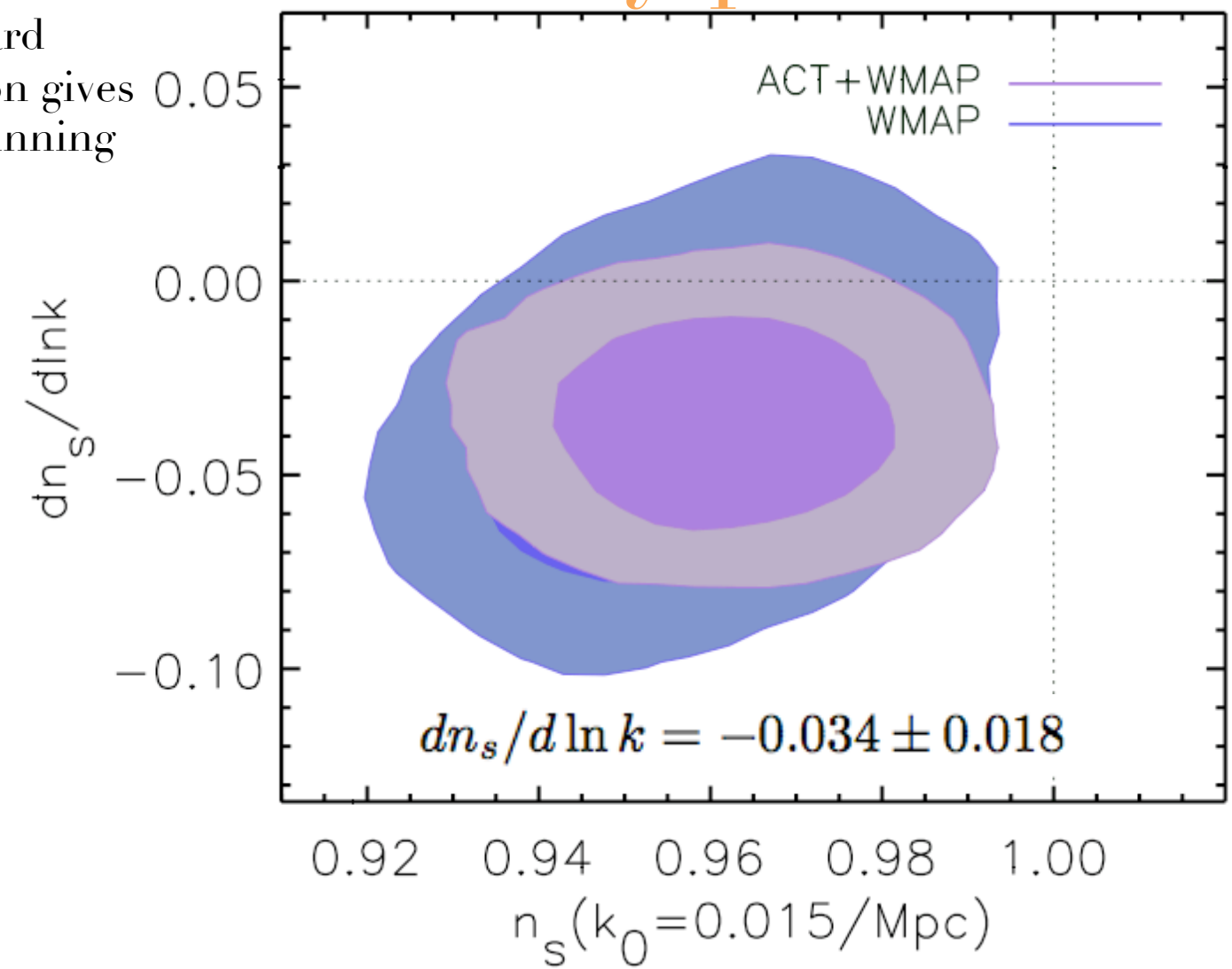
Das, Marriage et al. 2010



Best-fit lensed spectrum has $\Delta\bar{\chi}^2 = 8$ less than unlensed spectrum

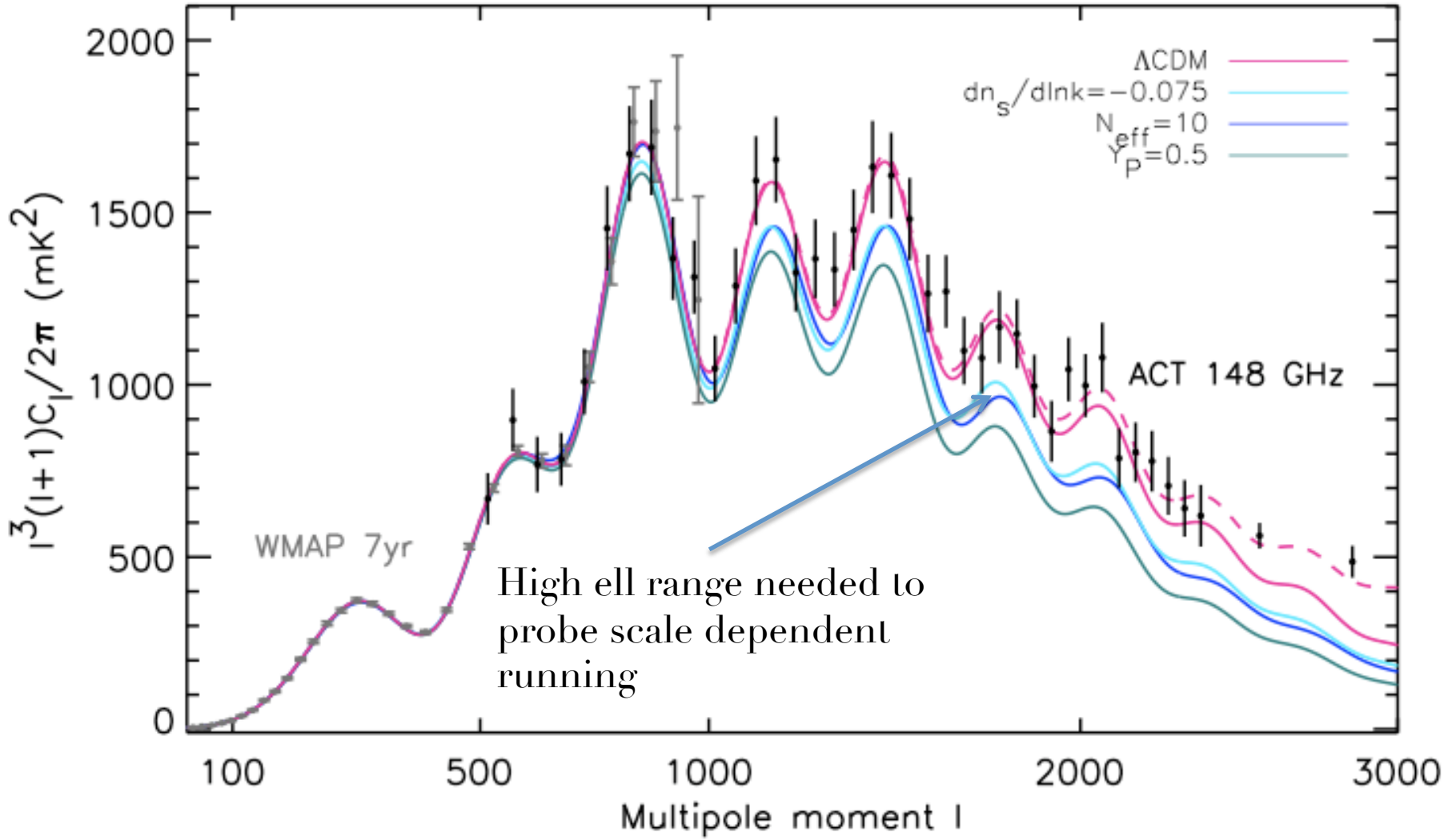
Inflationary parameters

Standard inflation gives zero running



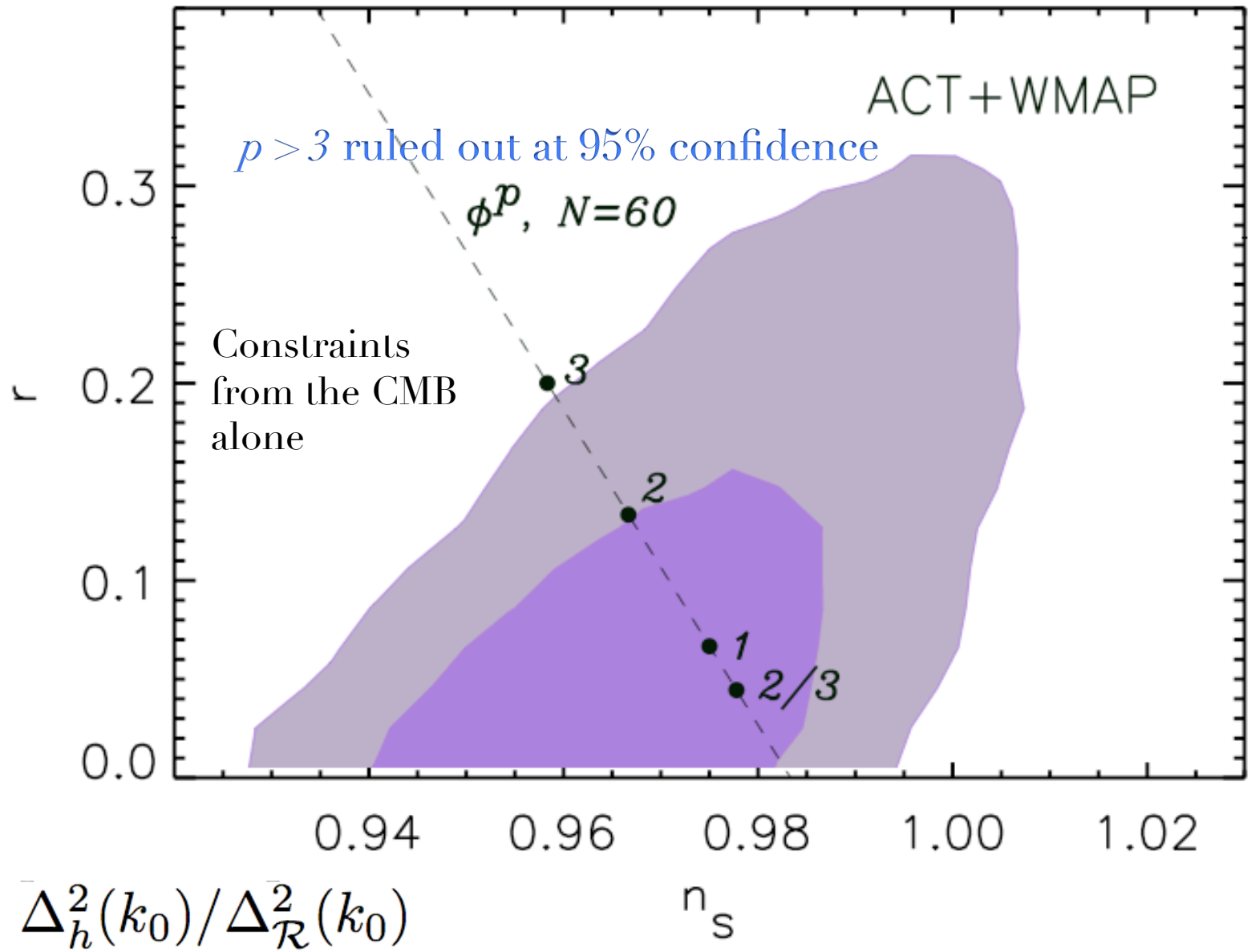
Dunkley, RH, Sievers et al. 2010

Inflationary parameters



Dunkley, RH, Sievers et al. 2010

Dunkley, RH, Sievers et al. 2010

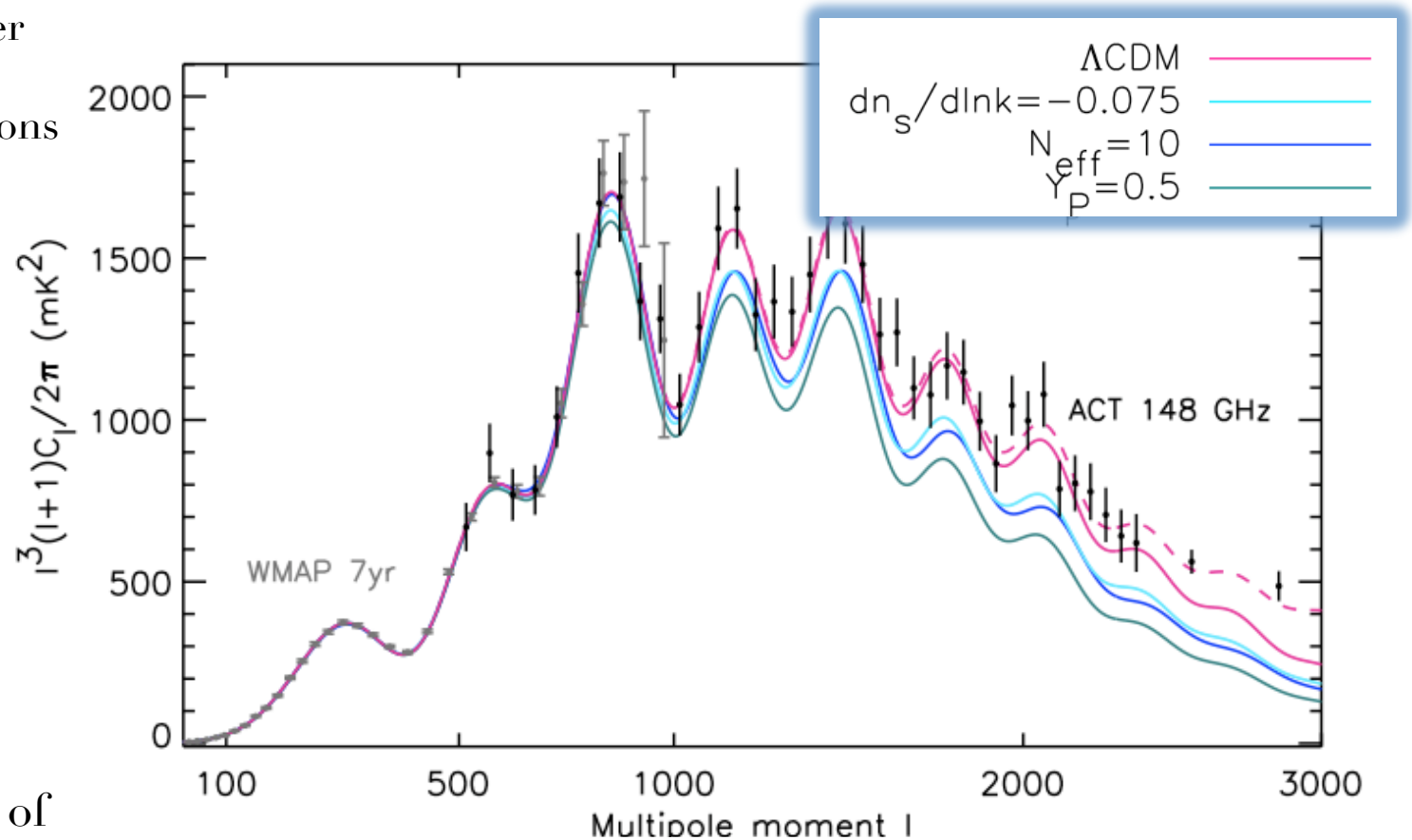


$r = \Delta_h^2(k_0)/\Delta_{\mathcal{R}}^2(k_0)$

Relativistic Species

Relativistic species:

damping of power
+
shift in peak positions

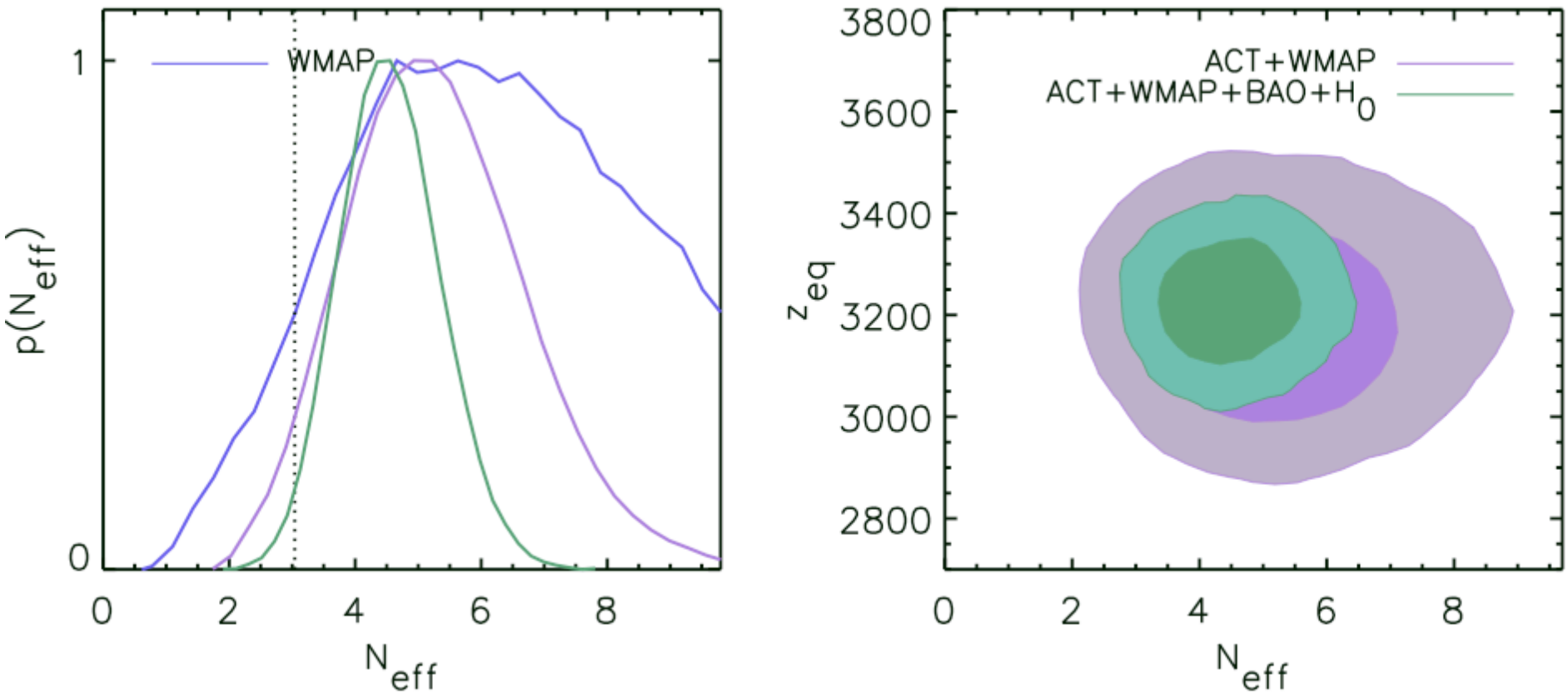


WMAP only constrains redshift of equality → small scale needed for Silk damping tail

$$N_{\rm eff} = 5.3 \pm 1.3 \ (68\% \ {\rm CL})$$

Relativistic Species

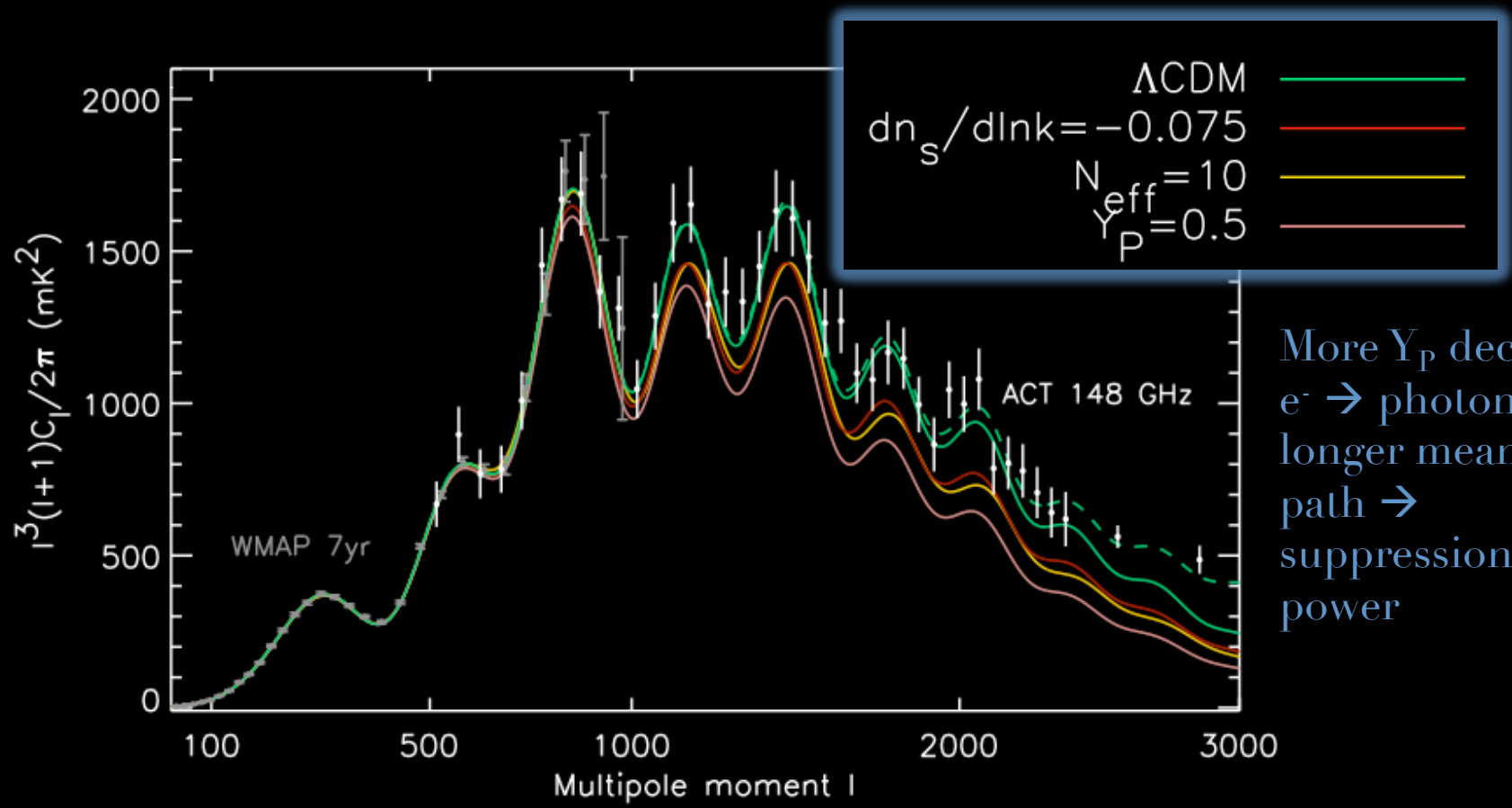
Dunkley, RH, Sievers et al. 2010



$$N_{\rm eff} = 5.3 \pm 1.3 \ (68\% \ {\rm CL})$$

Primordial Helium

What if Big Bang Nucleosynthesis was non-standard?

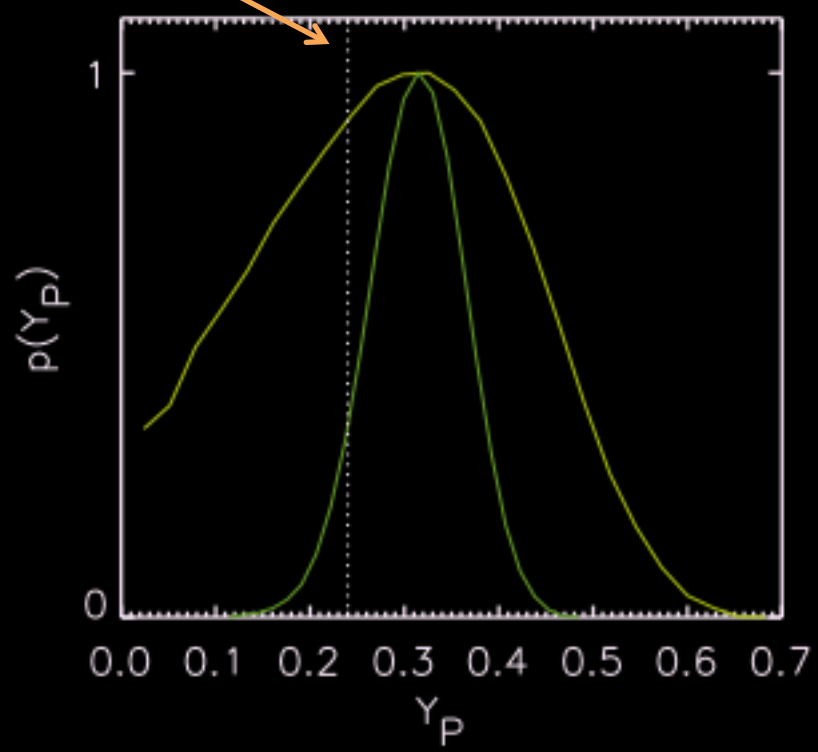


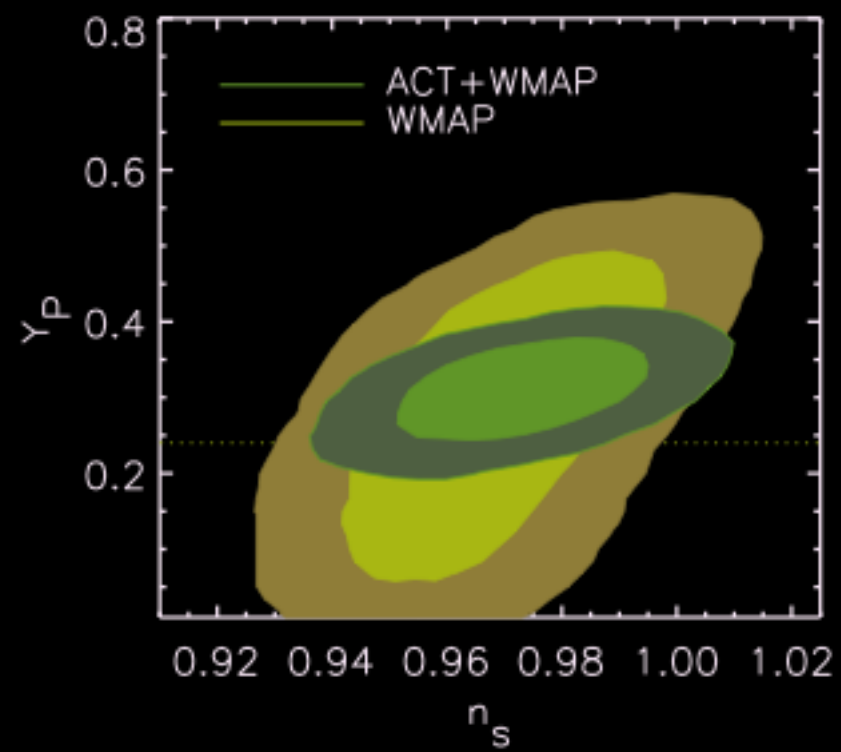
More Y_P decreases e^- → photons have longer mean free path → suppression of power

Primordial Helium

Standard assumptions are Yp = 0.24

$$Y_P = 0.313 \pm 0.044 \text{ (68\% CL)}$$





Zero primordial Helium ruled out at > 6σ

Primordial Helium

Standard assumptions are Yp = 0.24

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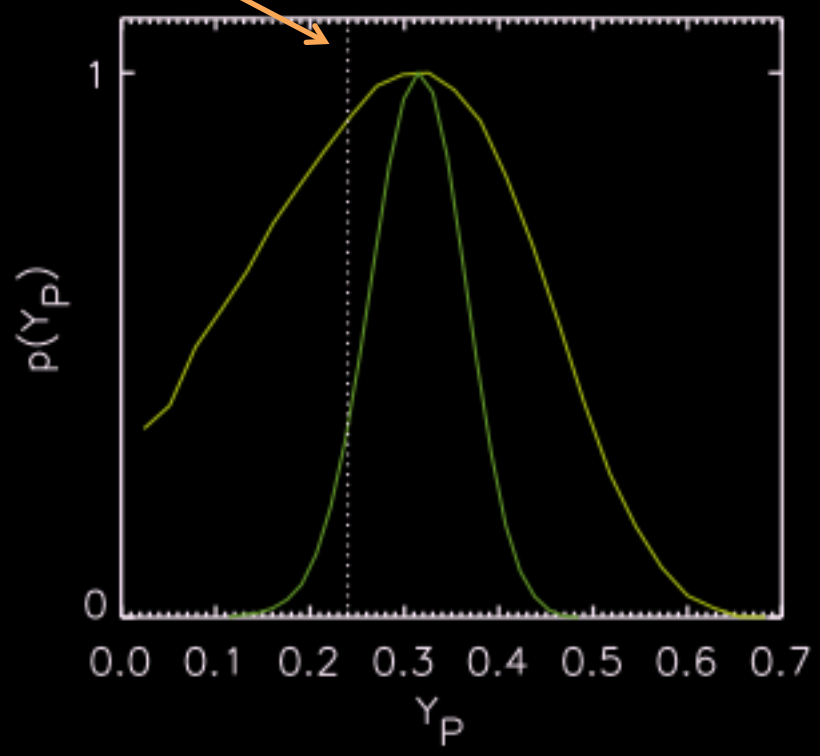
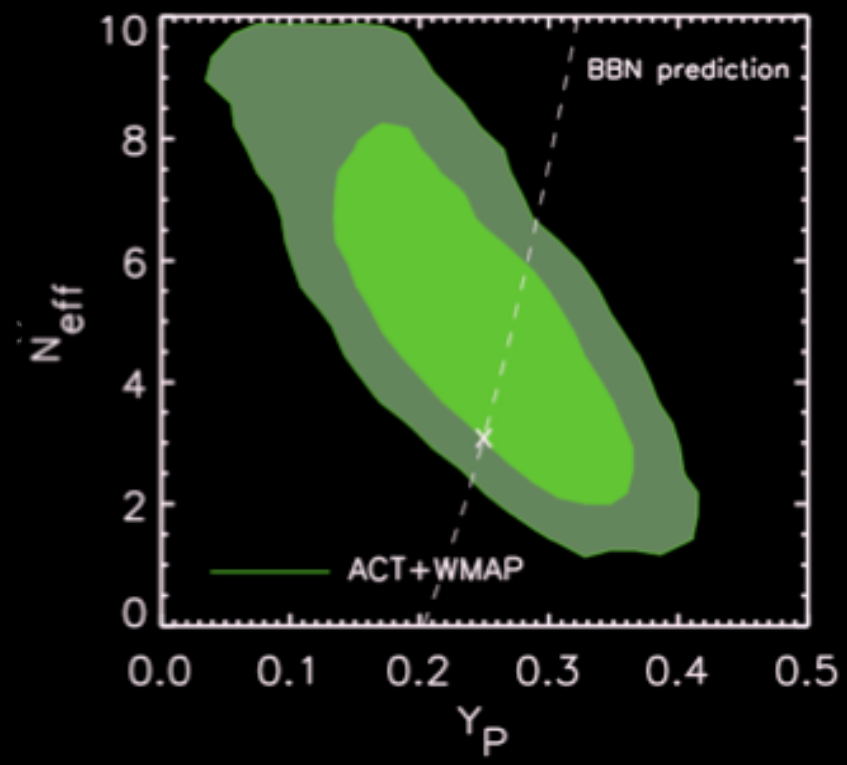
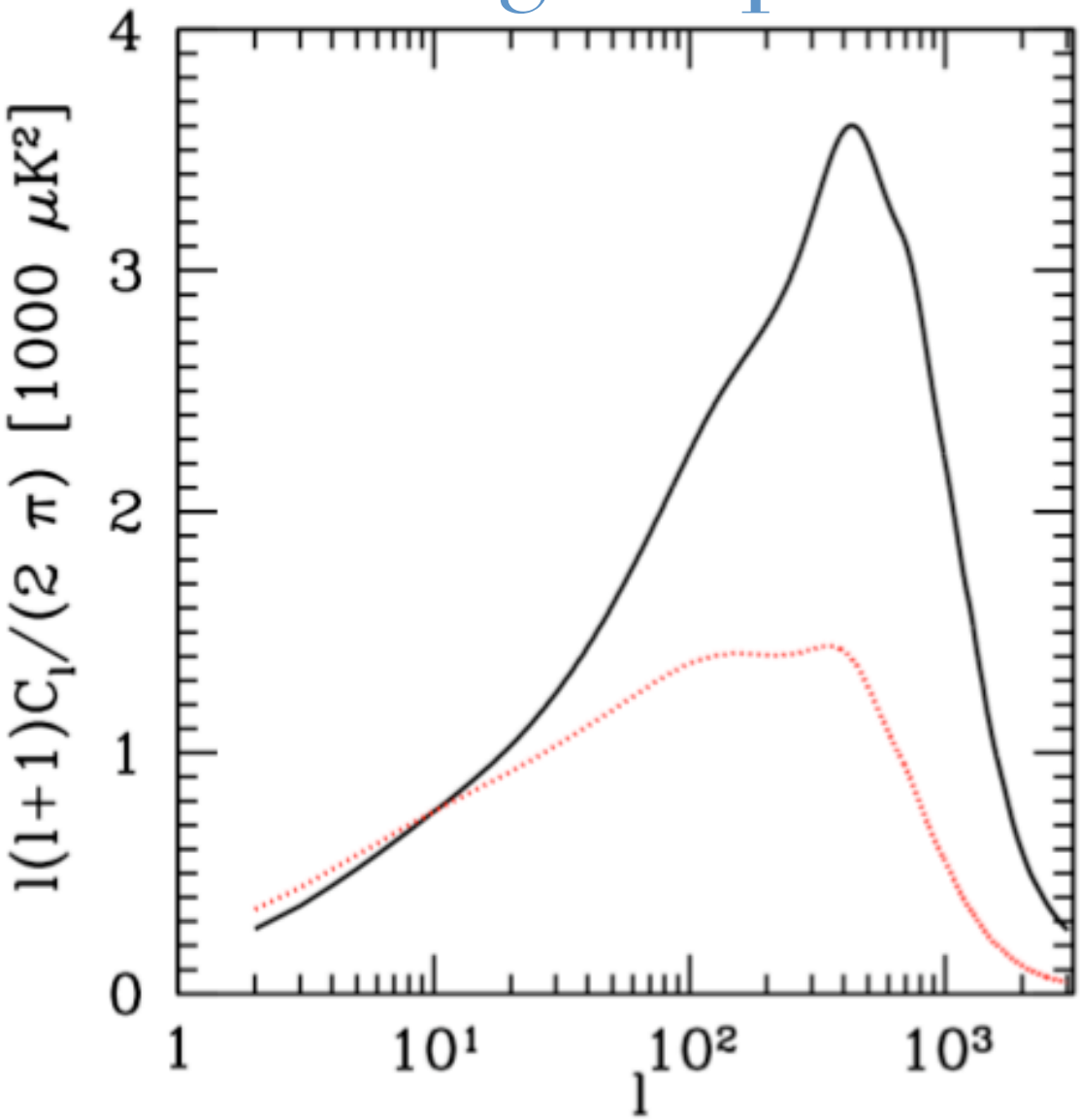




Zero primordial Helium ruled out at > 6σ

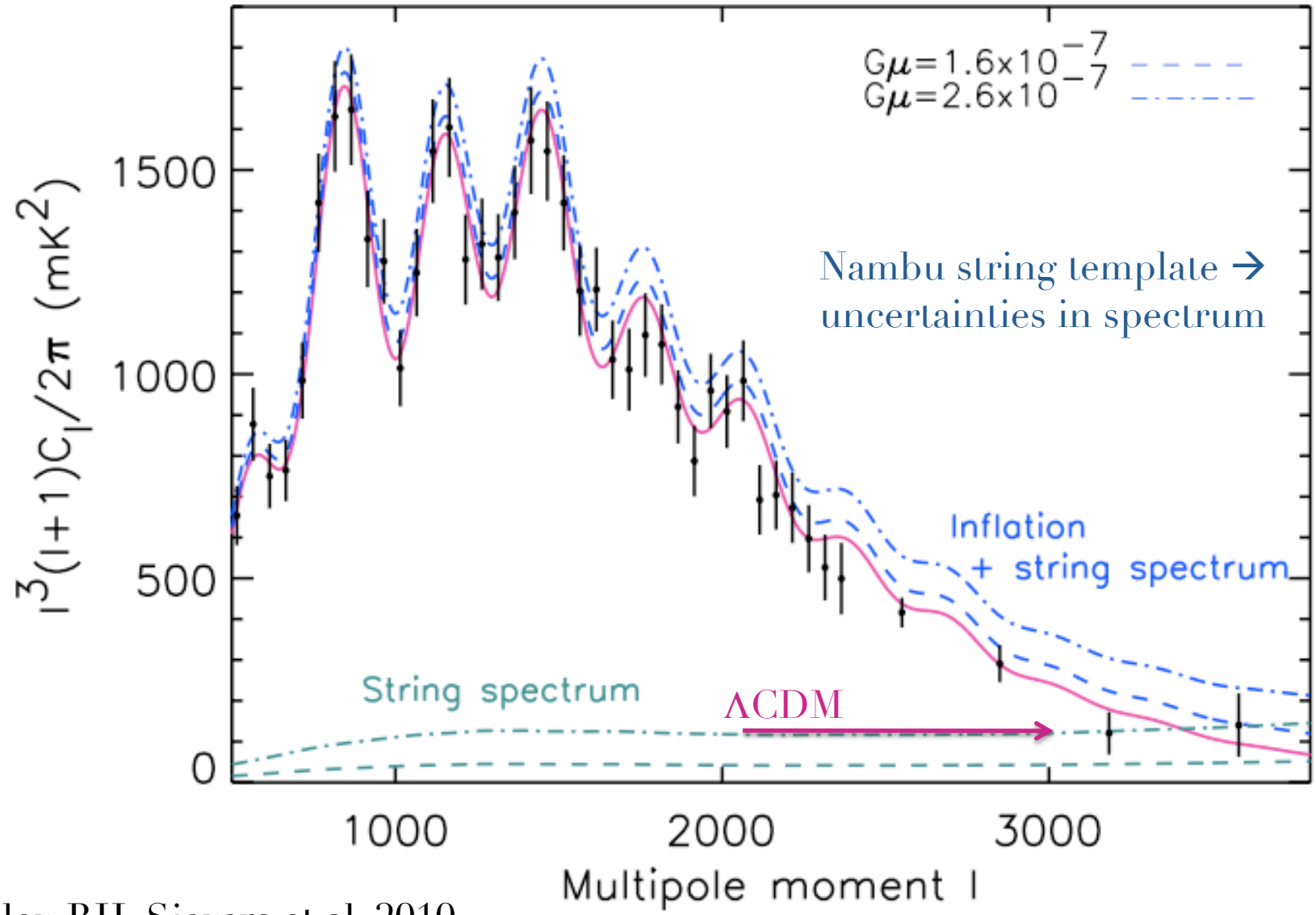
String amplitude



Battye & Moss, 2010

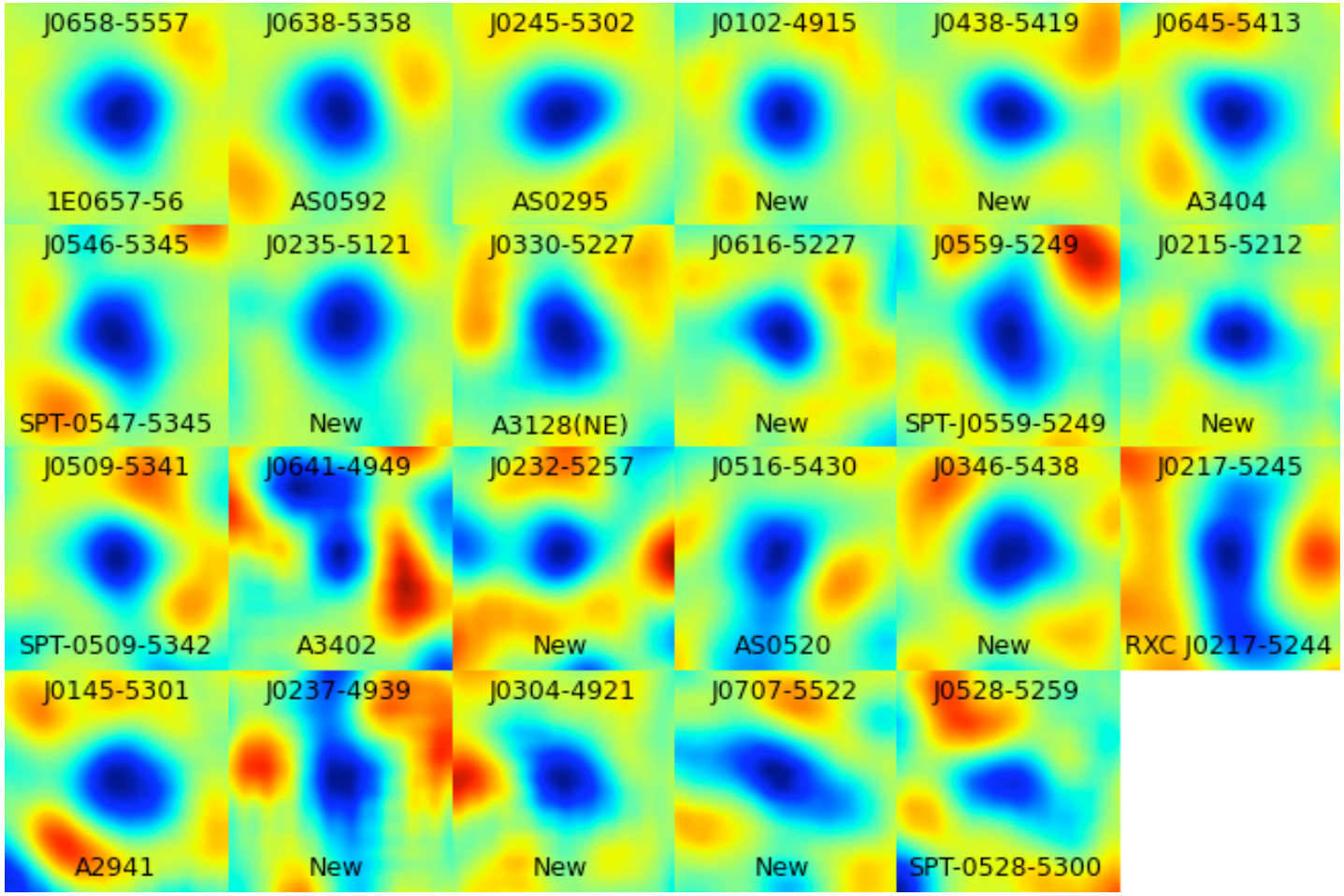
Dunkley, RH, Sievers et al. 2010

String amplitude



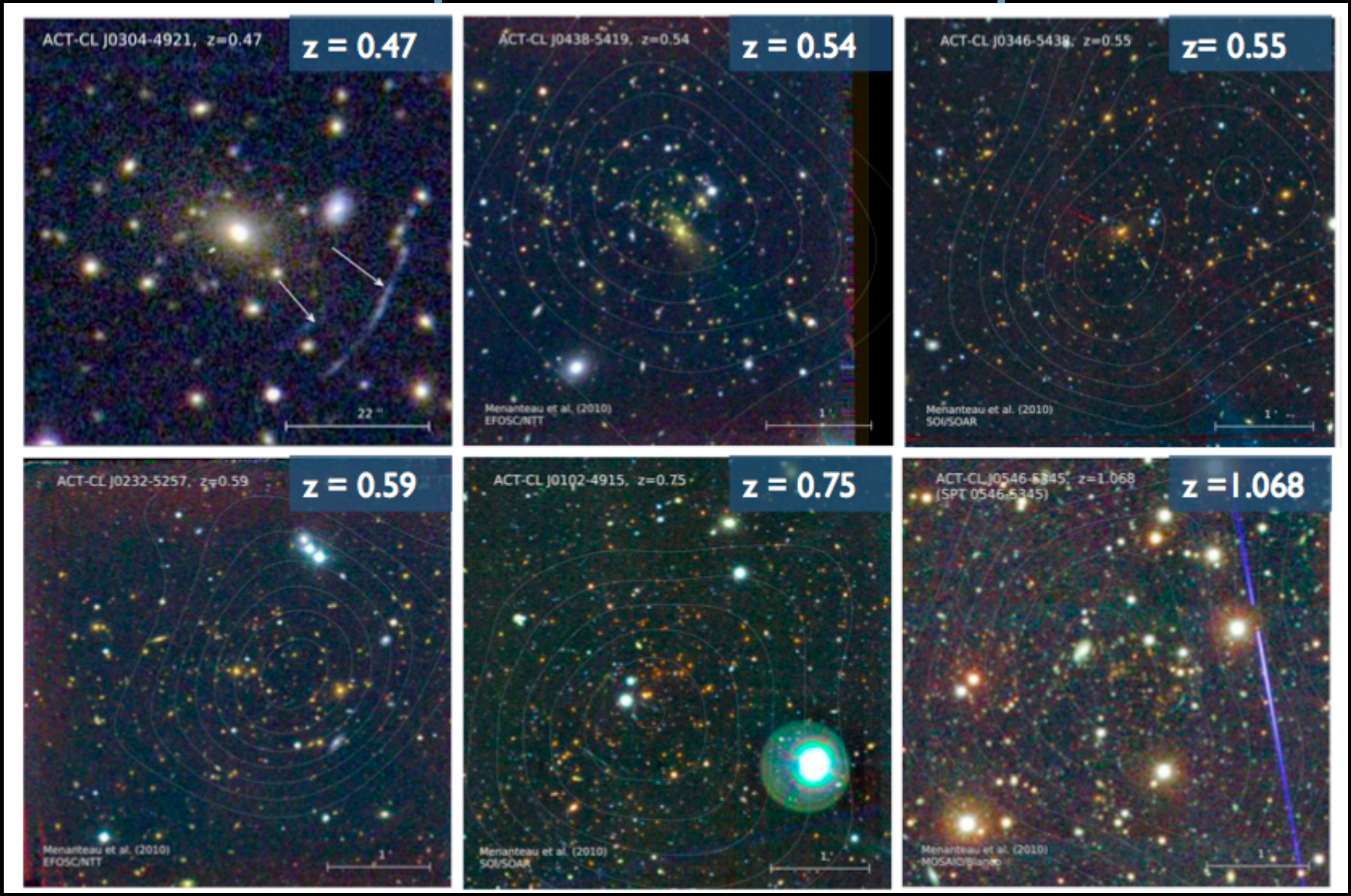
Dunkley, RH, Sievers et al. 2010

ACT Cluster detection



Marriage et al. 2010

Optical Followup

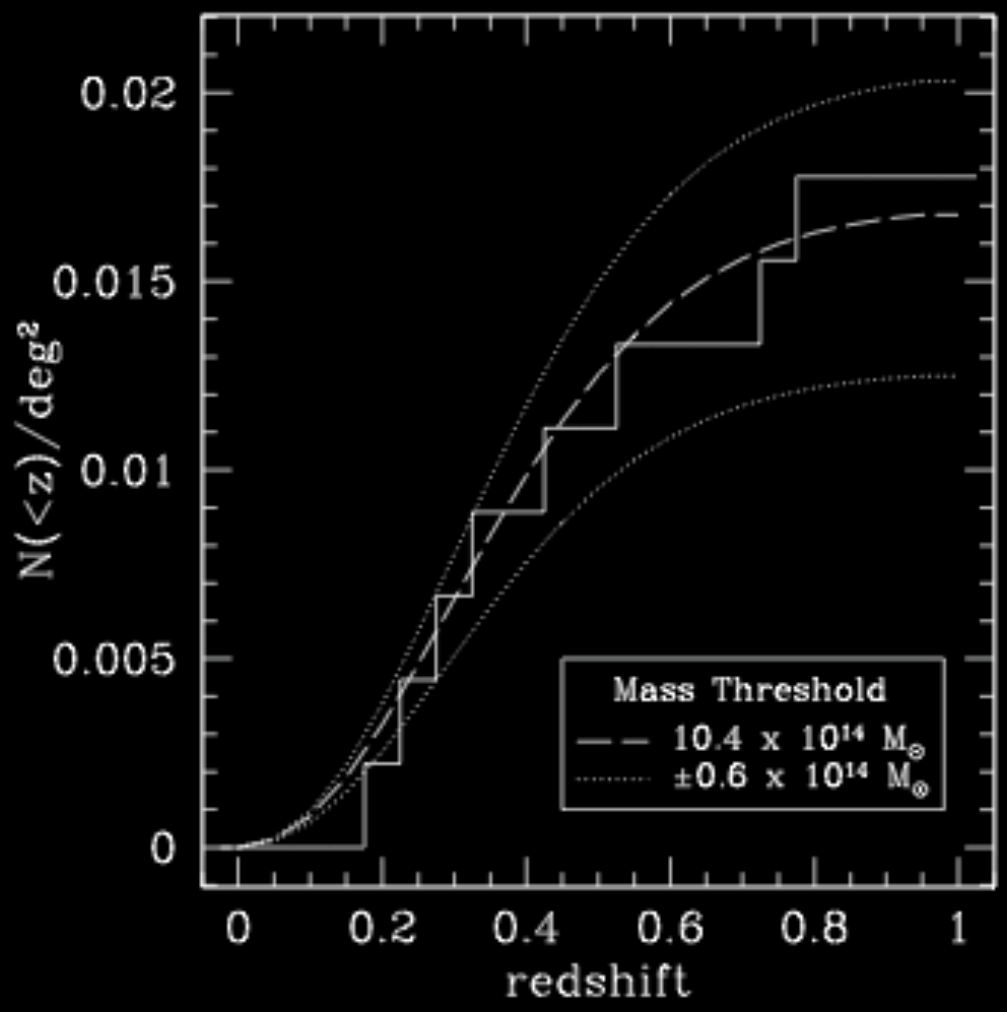


Menanteau et al. 2010

Cluster number counts

Basic cosmological model fits the data well

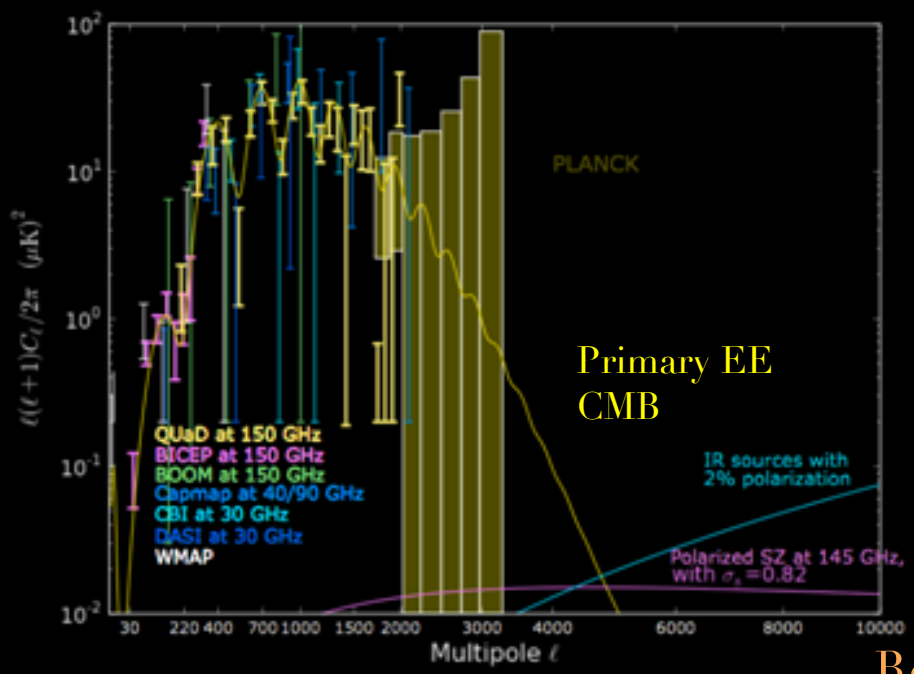
See cluster cosmology analysis in
Sehgal et al. 2010



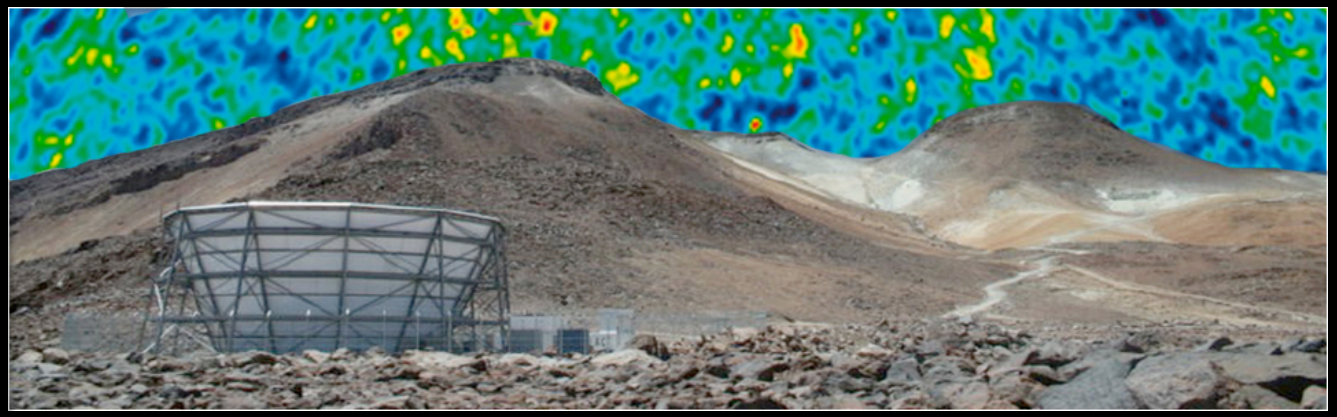
What is the next ACT?

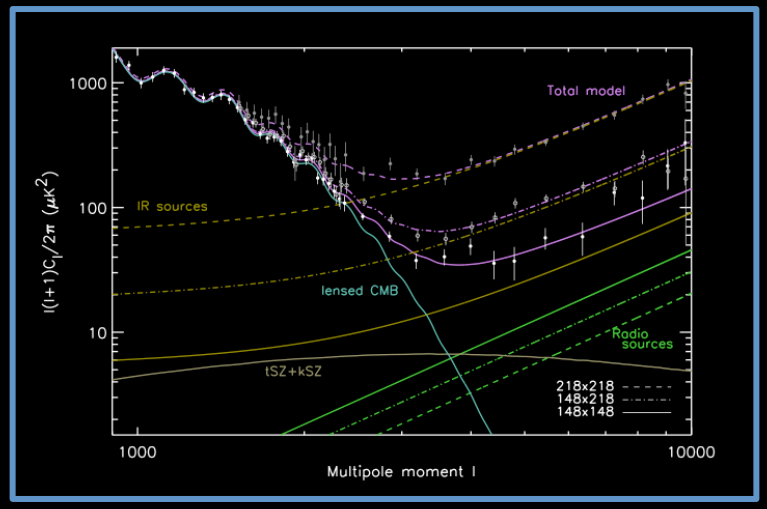
These results are Southern Survey – analysis to come of equatorial data.

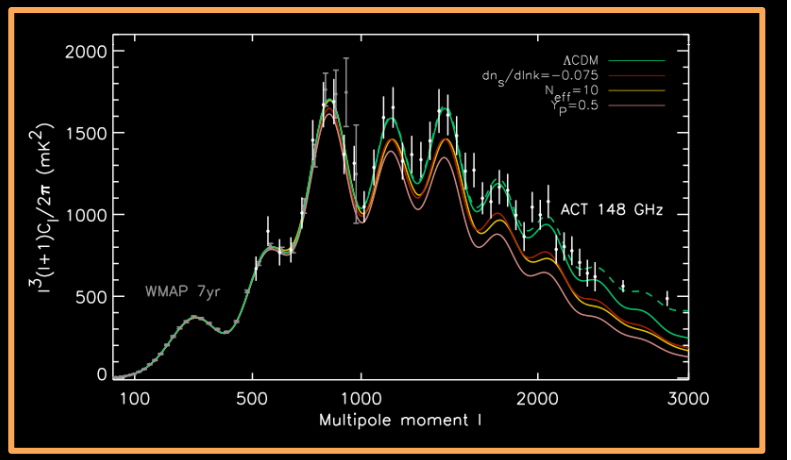
ACTPol:



Summary




Total model
IR sources
lensed CMB
Radio sources
tSZ+kSZ
218x218
148x218
148x148
1000
100
10
1000
10000
Multipole moment l
l(l+1)C_l/2π (μK^2)


ΛCDM
dn_s/dlnk=−0.075
N_eff=10
Y_p=0.5
ACT 148 GHz
WMAP 7yr
2000
1500
1000
500
0
100
500
1000
2000
3000
Multipole moment l
l^3(l+1)C_l/2π (mK^2)