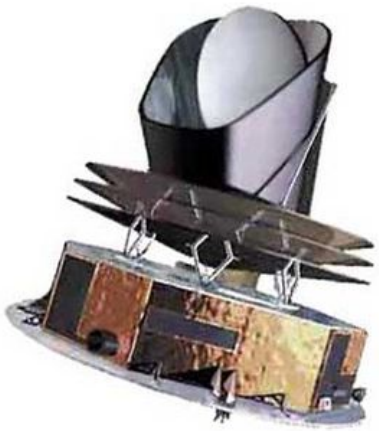
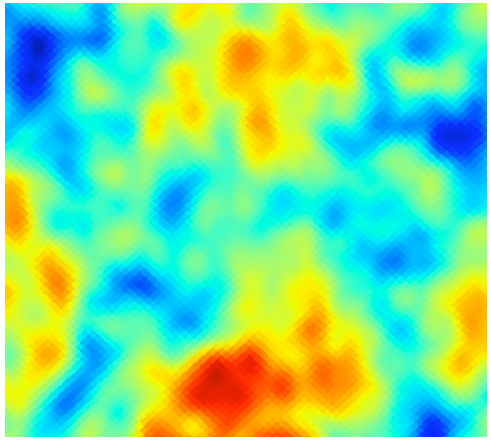
Cosmology from the small-scale CMB



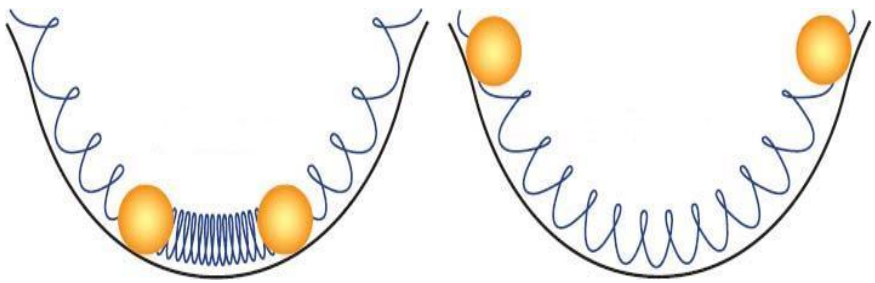


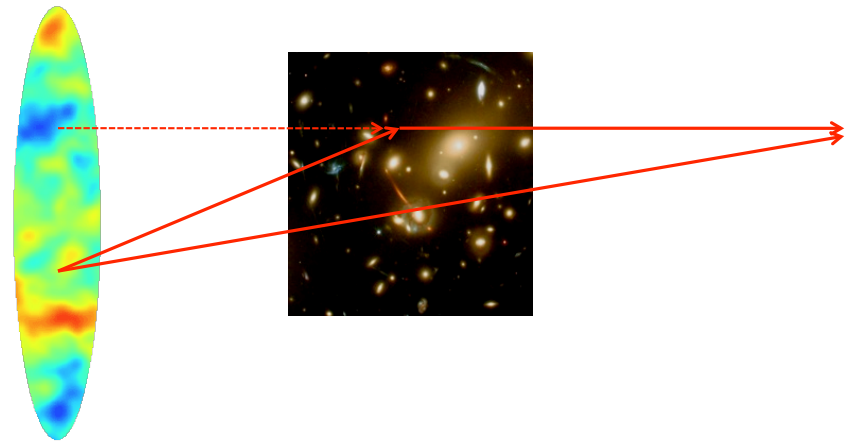
Jo Dunkley

Oxford Astrophysics

COSMO 2013, Sept 3

The small-scale CMB: early and late





Damped acoustic oscillations: probes primordial spectrum and recombination process

Lensing of the CMB: coherent distortion of signal by LSS

z=1000

z~1-3 (1000-0)

t

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 (Dunkley, Calabrese, Naess, Allison)
- 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

***See also R. Hlozek talk this pm*

esa

planck

cnes

asi agenzia spaziale italiana

NASA

cnrs

DTU Space National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC Consejo Superior de Investigaciones Científicas

HFI PLANCK

PLANCK LFI

National Research Council of Italy

Gobierno de España Ministerio de Ciencia e Innovación

IAS orsay

IAP

INAF - IASF BO ISTITUTO NAZIONALE DI ASTROFISICA ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

Aalto University

APC

ioa

KICC Kavli Institute for Cosmology Cambridge

Cavendish Astrophysics

University of Cambridge

Cardiff University Prifysgol Caerdydd

irfu cea saclay

cea energie atomique • energies alternatives

CESR

CITA–ICAT

cnrs IN2P3 Les deux infinis

ipac Infrared Processing and Analysis Center

Helsinki Institute of Physics

Instituto de Astrofísica de Canarias

IFCA Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

ISDC Data Centre for Astrophysics

JPL

LAL Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris LERMA

LPSC Grenoble Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI Maynooth

INAF Osservatorio Astronomico di Padova

University of Oxford

Dipartimento di Fisica Sapienza Università di Roma

Science & Technology Facilities Council Rutherford Appleton Laboratory

Università degli Studi di Roma Tor Vergata

Osservatorio Astronomico di Trieste

UBC

UC Universidad de Cantabria

UCSB

SISSA

ALMA

ESO

US University of Sussex

esa

University of Helsinki

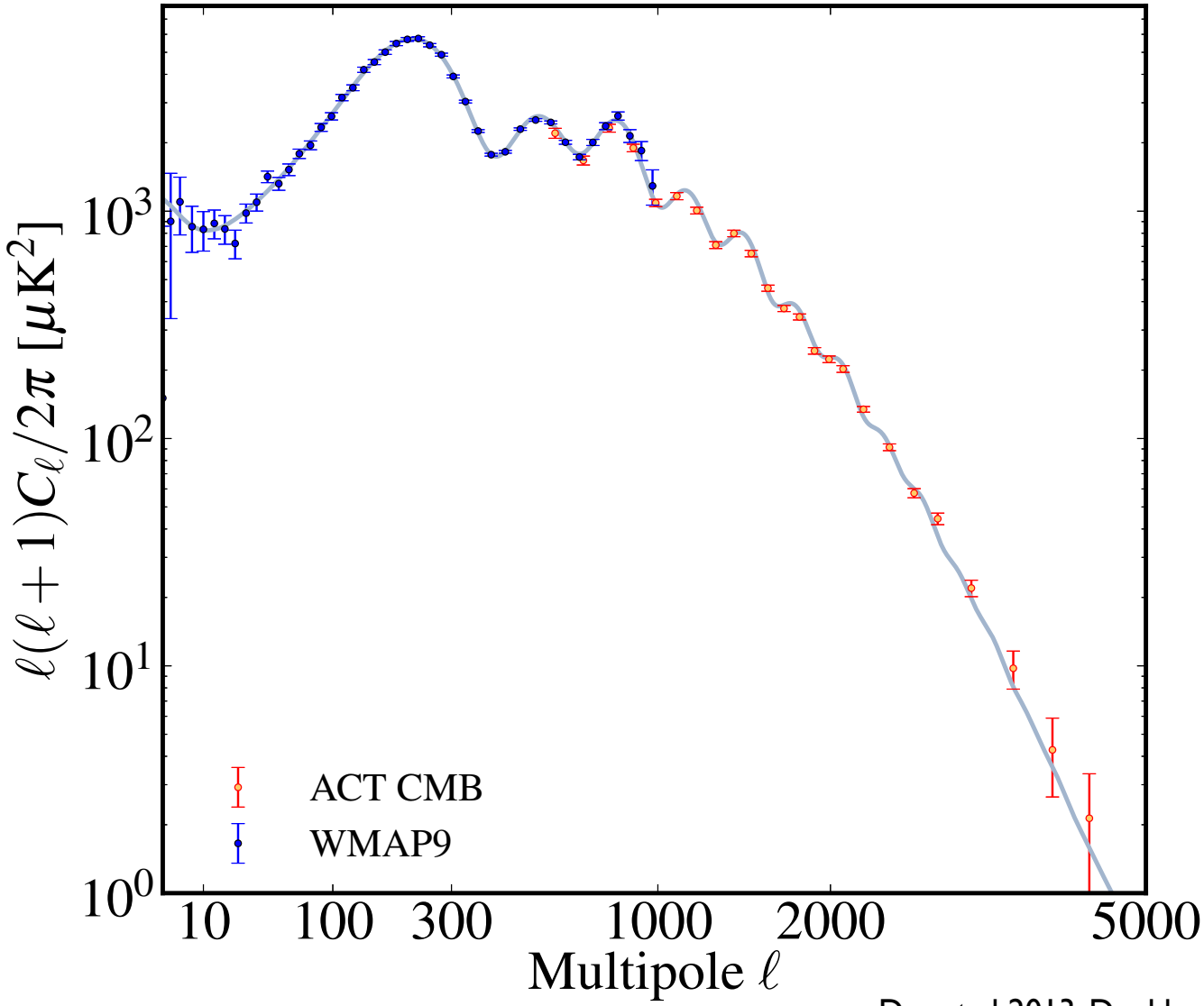
Université de Genève

University of Toronto

Université de Paris-Sud XI

ASI Science Data Center

Small scales measured by ACT



Das et al 2013, Dunkley et al 2013

Foregrounds marginalized using l<10000

+Planck: full-sky to l=2500

Is inflation the right paradigm?

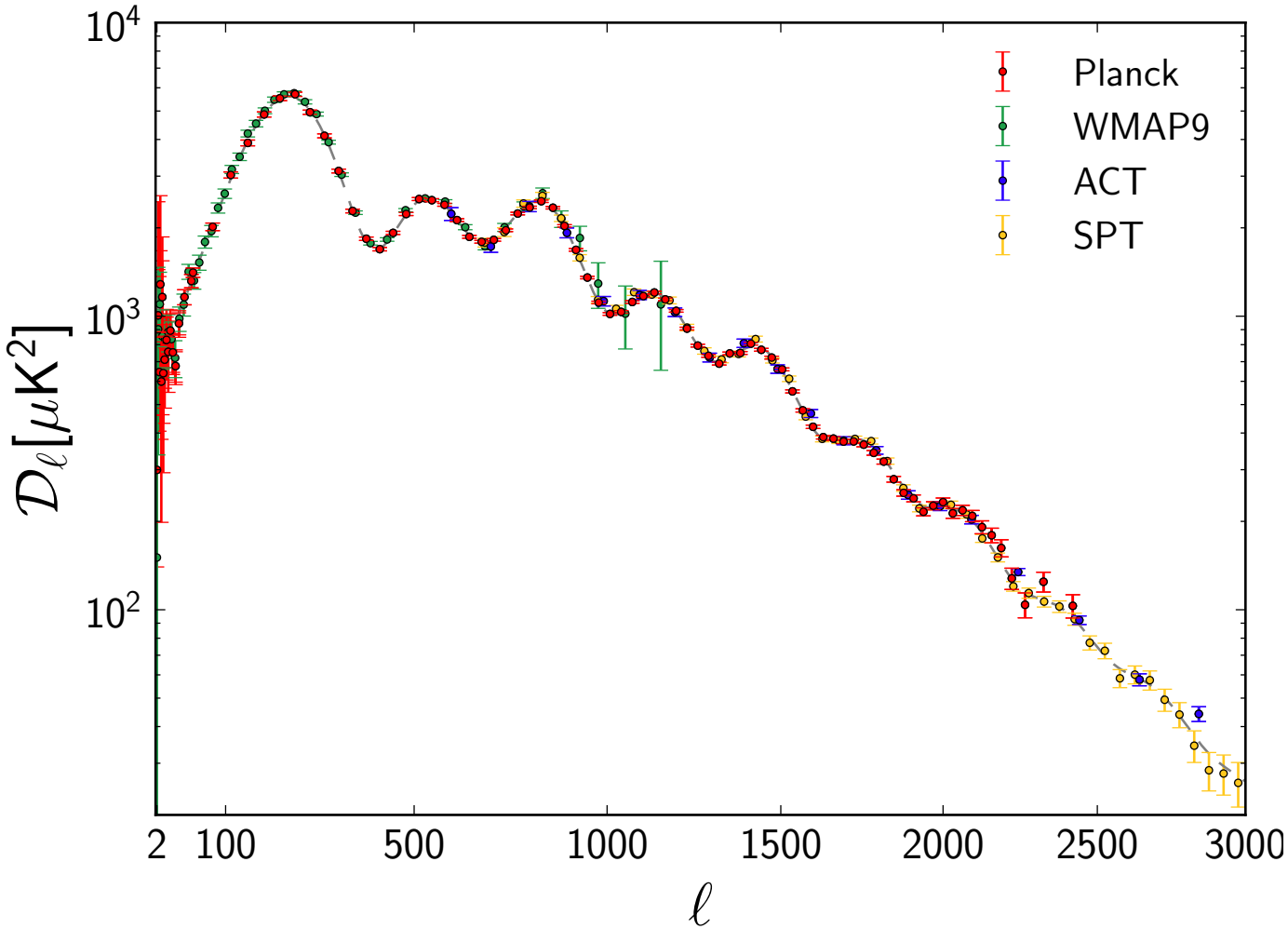
Which inflation model?

Is Dark Energy a constant, or a dynamical component?

What are the masses of the neutrinos?

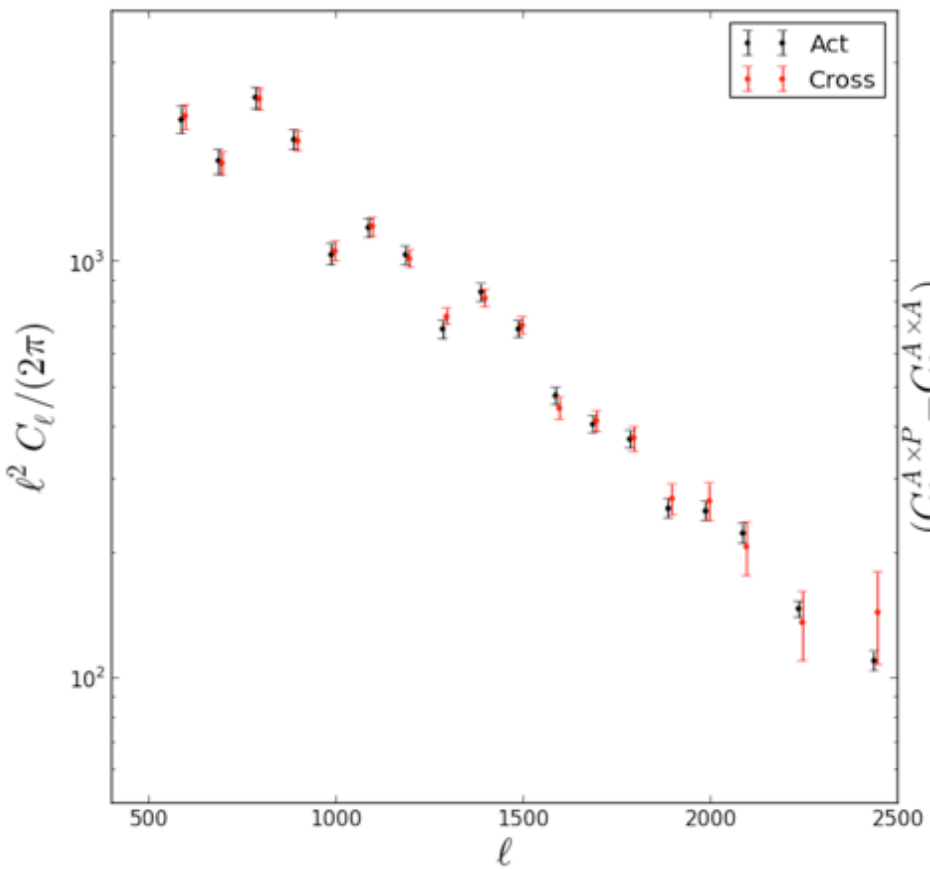
Are there extra relativistic species?

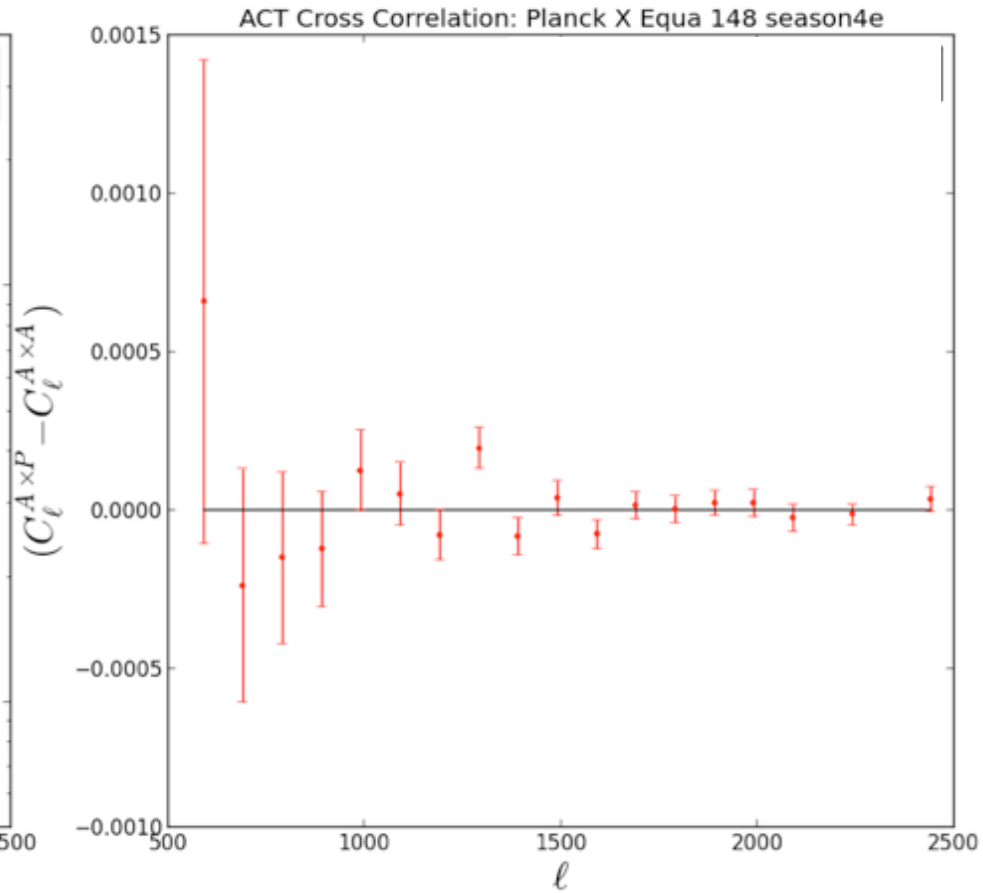
Are there other high energy signatures?



Planck Collab 1 2013, Story et al 2012, Das et al 2013, Calabrese et al 2013

Example Planck x ACT: 143 GHz

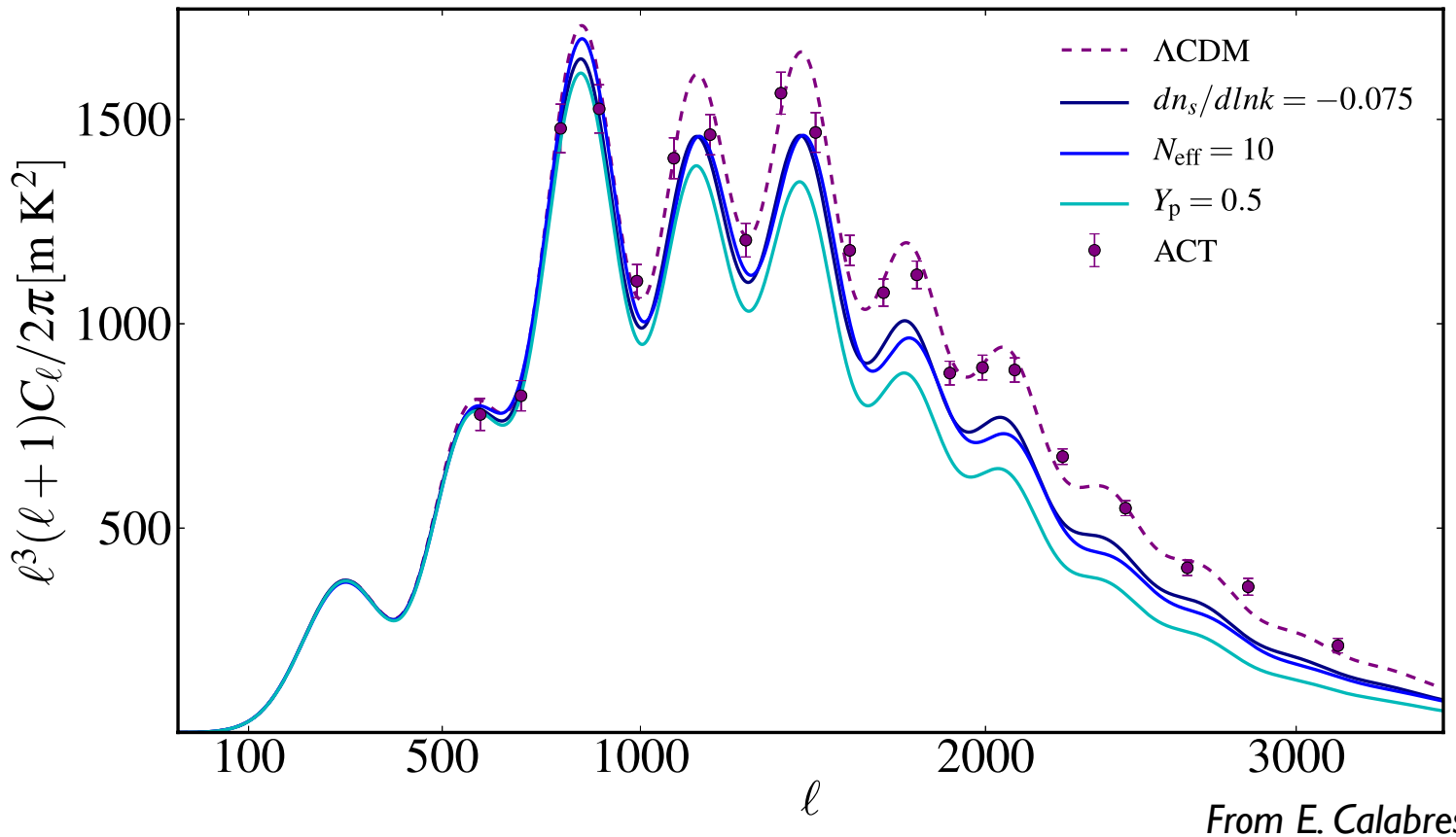




Preliminary, from Thibaut Louis for ACT

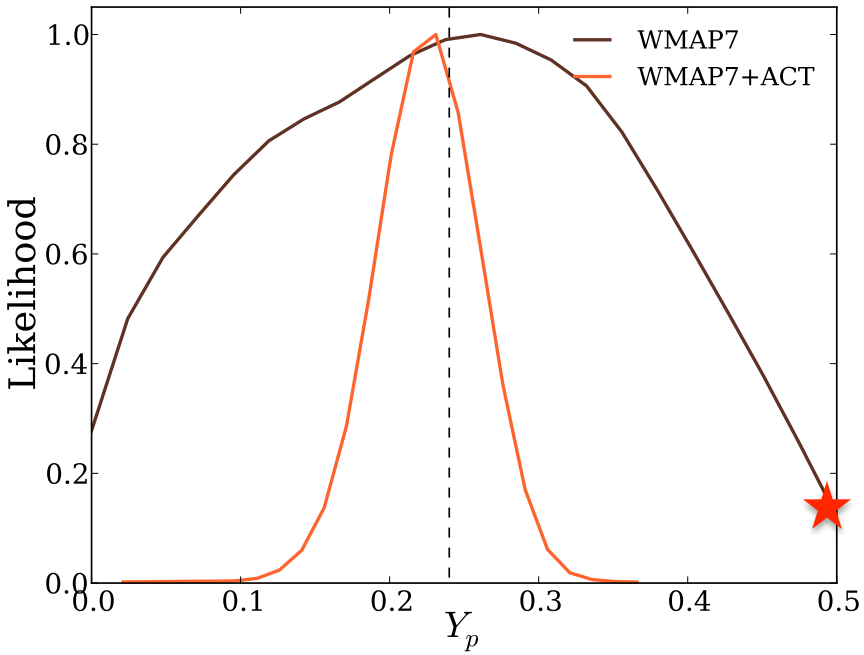
Cosmology from the higher acoustic peaks

1. Measure Silk damping, test recombination *[neutrinos, helium, early dark energy, dark matter annihilation, time-varying constants]*
2. More decades for primordial spectrum *[index and its running]*
3. Probe scales where non-'standard' fluctuations could be seen *[cosmic strings, isocurvature]*

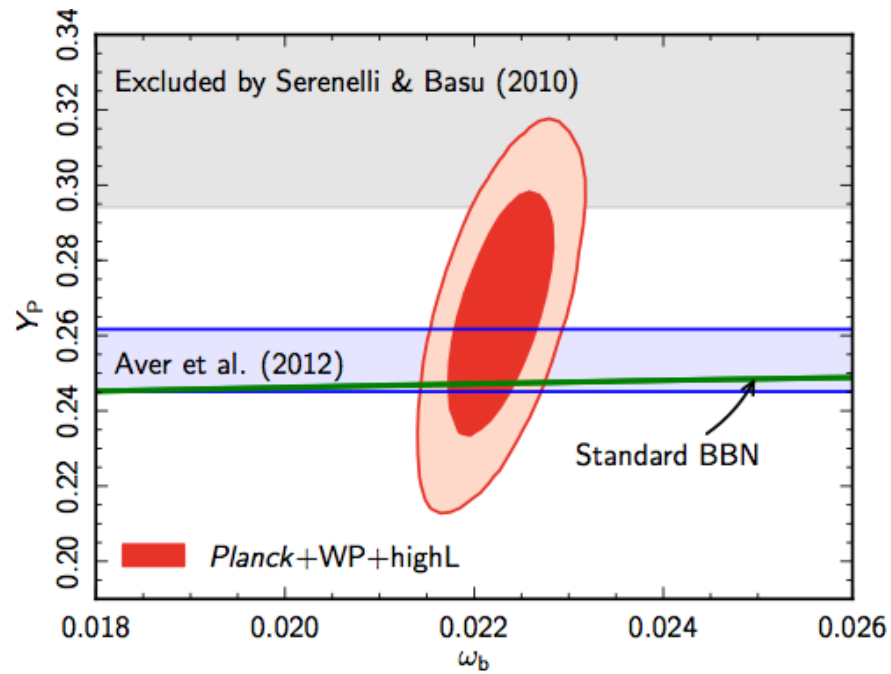


From E. Calabrese, for ACT

(1) Primordial helium



Sievers, Hlozek et al. 2013



Planck collab XVI 2013

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

Instead can test BBN: more helium decreases electron density, increasing mean free path and Silk damping: $n_e = n_b(1-Y_P)$

$Y_P = 0.23 \pm 0.03$ (ACT+WMAP7)

$Y_P = 0.27 \pm 0.02$ (Planck+)

(1) Relativistic species

Usually assume 3 neutrino species.

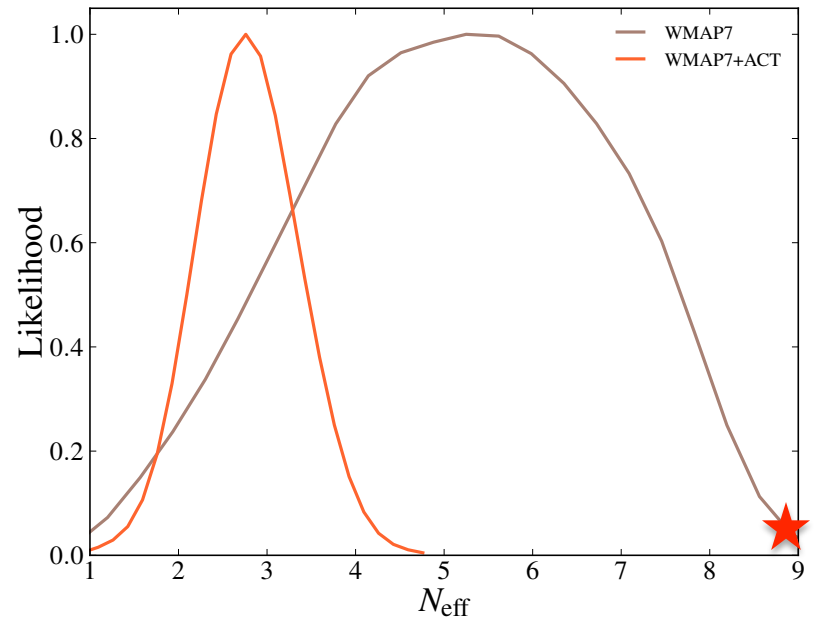
$$\rho_{rel} = \left[\frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right] \rho_\gamma$$

More species: longer radiation domination, suppress early acoustic oscillations, and add phase shift

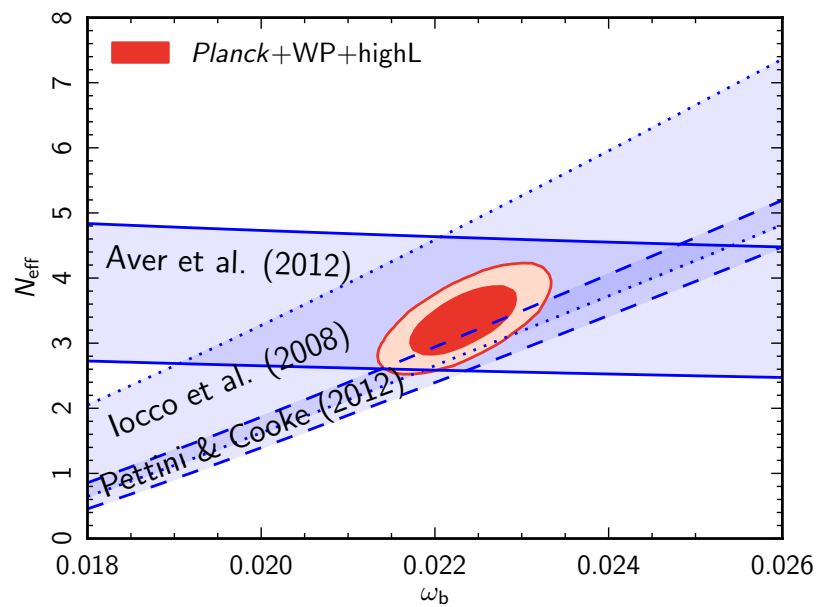
ACT+WMAP9: $N_{eff} = 2.9 \pm 0.5$ (Calabrese et al 2013)

ACT+SPT+WMAP9: $N_{eff} = 3.4 \pm 0.4$ (Calabrese et al 2013)

Planck+: $N_{eff} = 3.4 \pm 0.3$ (Planck Collab 2013)



ACT: Sievers, Hlozek et al. 2013



Planck Collab XVI 2013

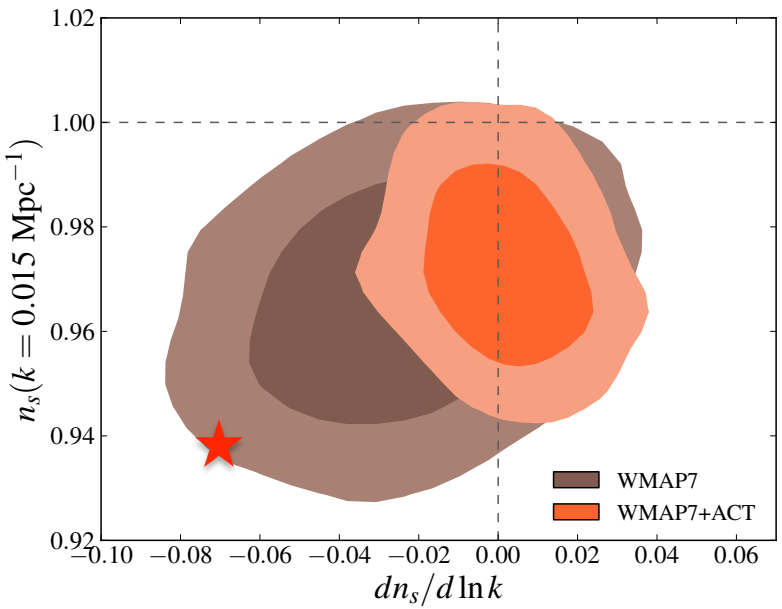
(2) Primordial spectrum

- Test inflation: period of exponential expansion for > 60 e-folds.
- Fluctuations expected almost power law. Running index, expected ~0.001.

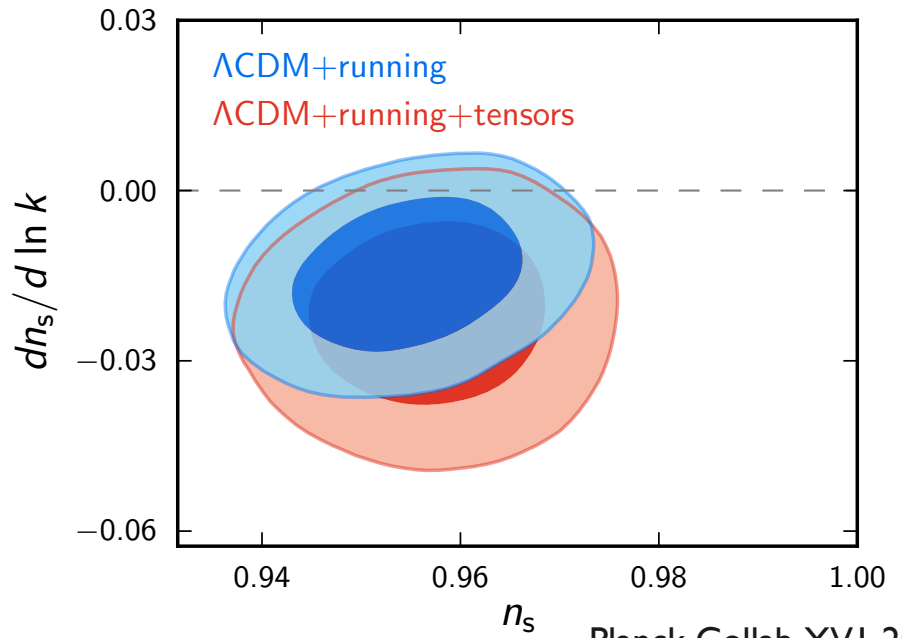
  $dn_s/d\ln k = -0.004 \pm 0.012$ (ACT+WMAP7)

  $dn_s/d\ln k = -0.015 \pm 0.009$ (Planck+)

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

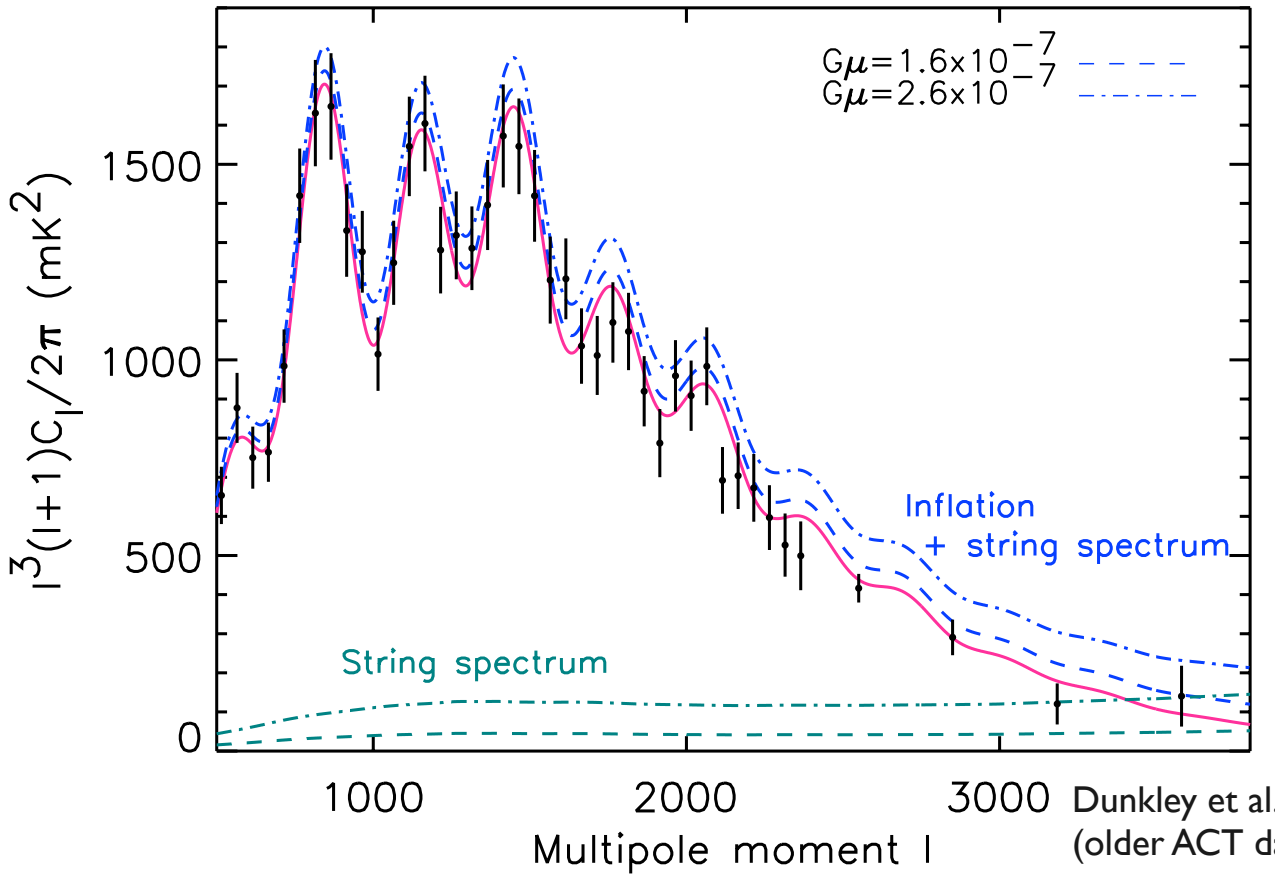


Sievers, Hlozek et al. 2013



Planck Collab XVI 2013

(3) Cosmic strings



Dunkley et al. 2010
(older ACT data)

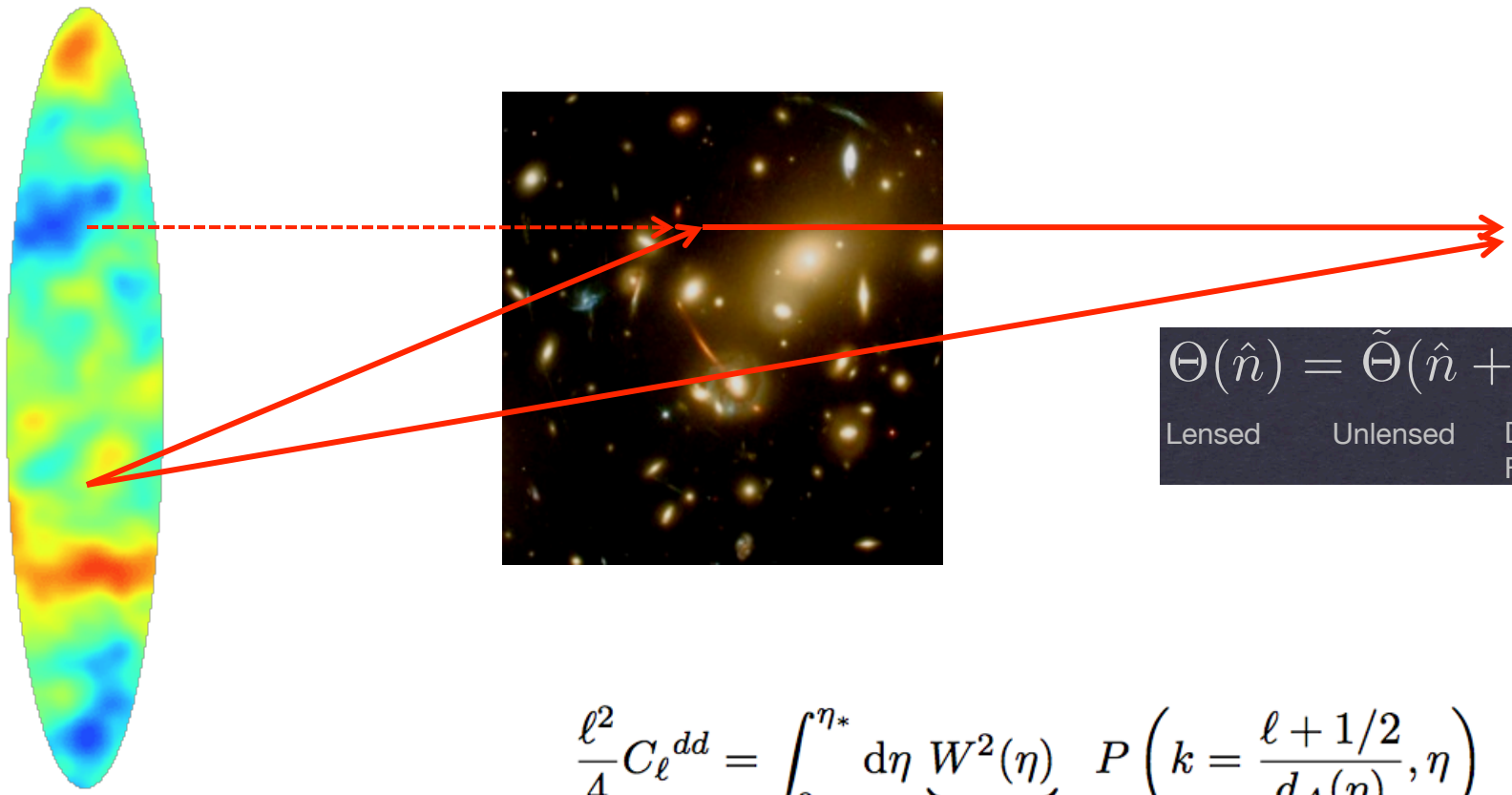
Cosmic strings may be sub-dominant source of anisotropy.

Example: Nambu string sims (Battye & Moss 2010).

$G\mu < 1.1 \times 10^{-7}$ (95%, ACT+WMAP, Sievers et al 2013)

Spectral index less than unity: hybrid inflation disfavored.
Similar limits from Planck.

Lensing of the CMB

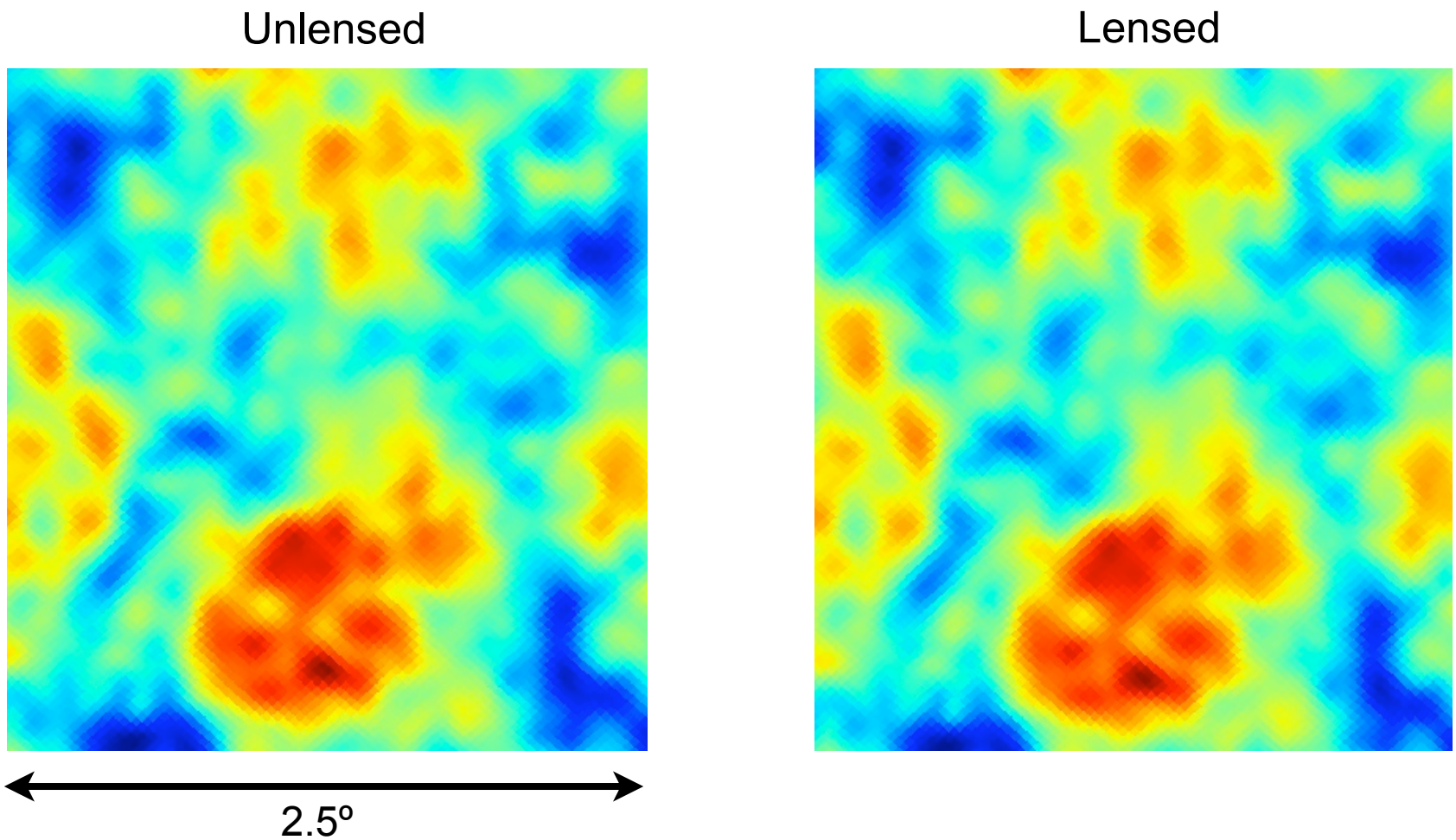


$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

Lensed Unlensed Deflection Field

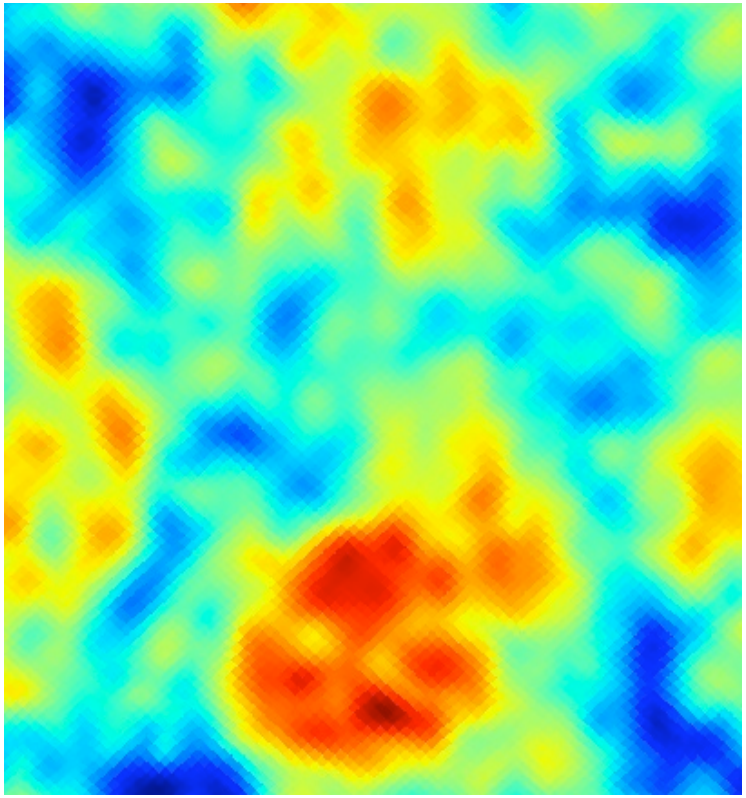
$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \, \underbrace{P\left(k = \frac{\ell + 1/2}{d_A(\eta)}, \eta\right)}_{\text{matter}}$$

Integrated mass fluctuations along the line of sight
Deflection is a couple of arcminutes, but coherent on degree scales.



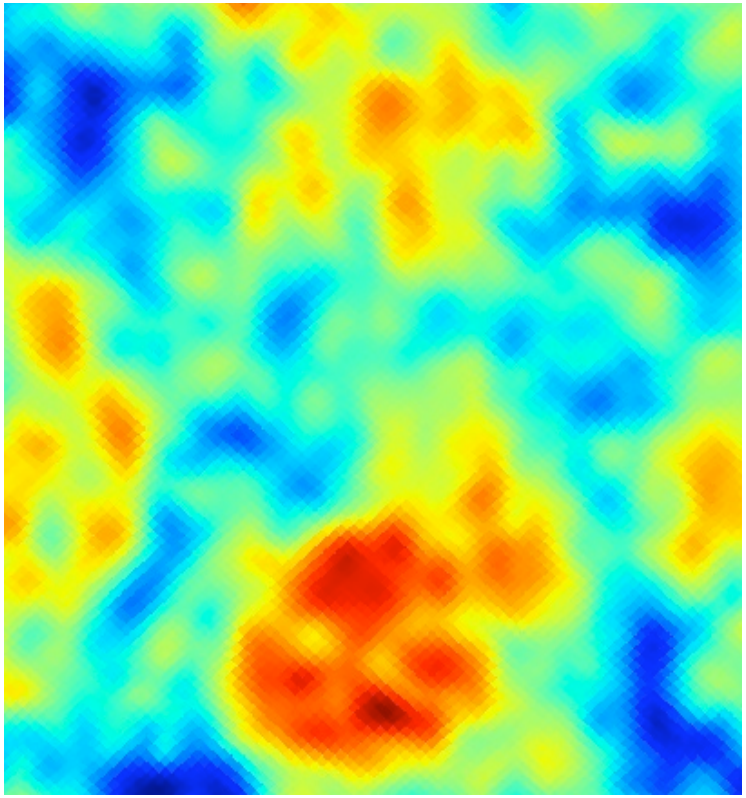
From A. Benoit-Levy

Lensed



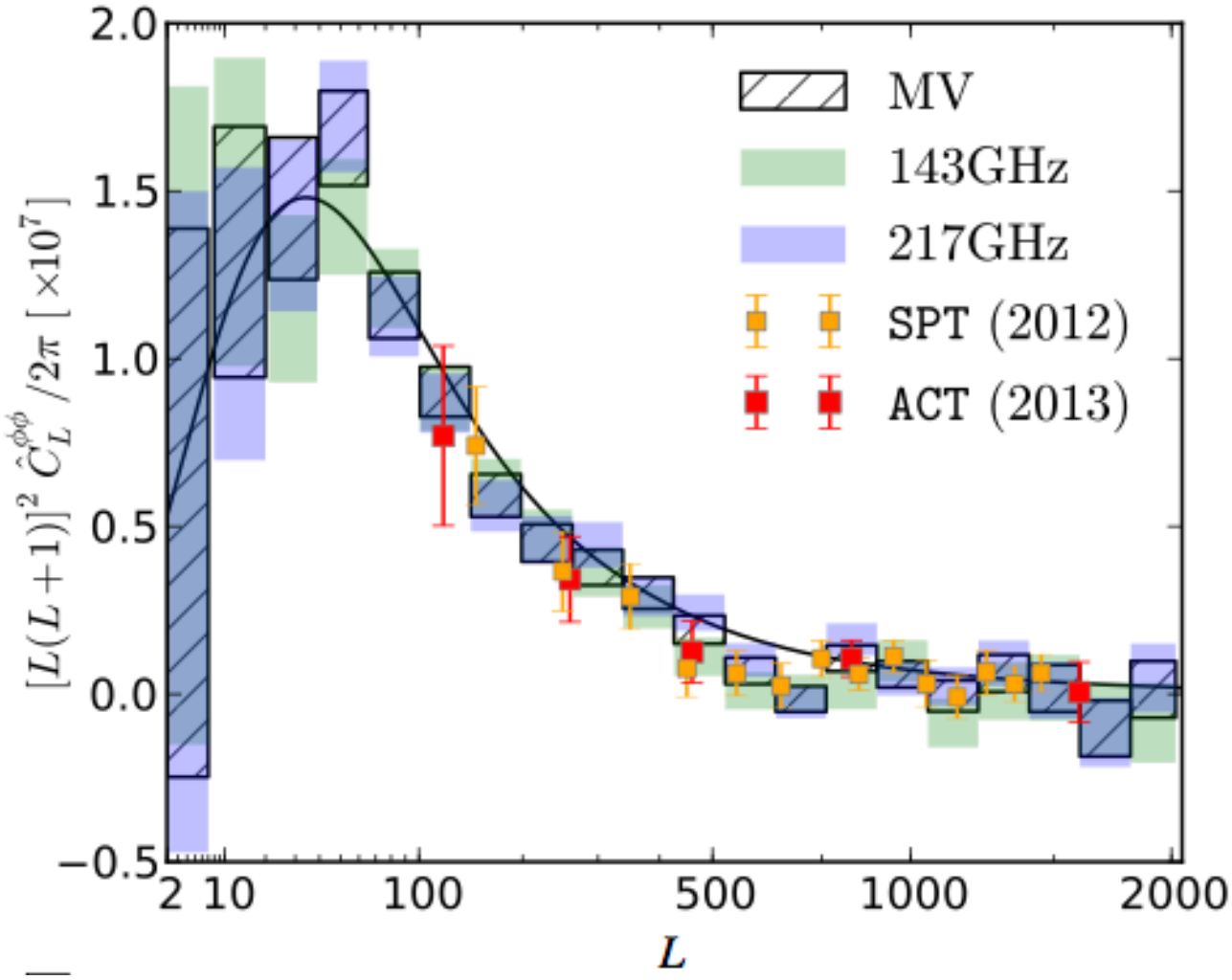
2.5º

Lensed



From A. Benoit-Levy

Lensing now measured in the CMB



First direct measurement: ACT 2011, 4σ (Das et al, update in 2013)

Then SPT in 2012 (Van Engelen et al, 6σ)

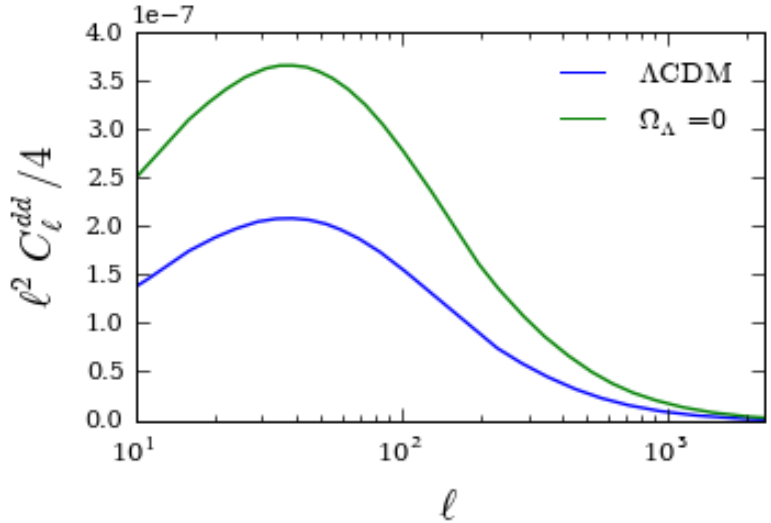
Now Planck in 2013 (Planck Collab XVII, 25σ)

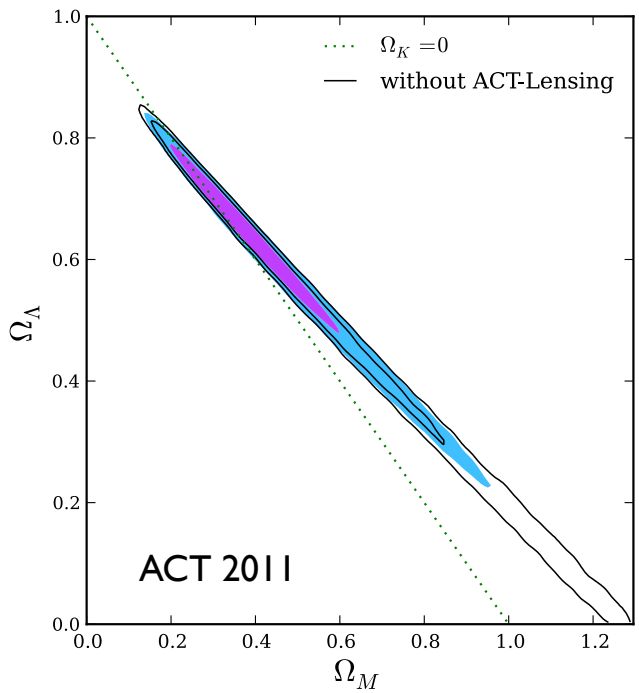
Lensing estimator $\hat{\phi}_{\ell m} \propto \left[(C^{-1}T)\nabla(SC^{-1}T)\right]_{\ell m}$

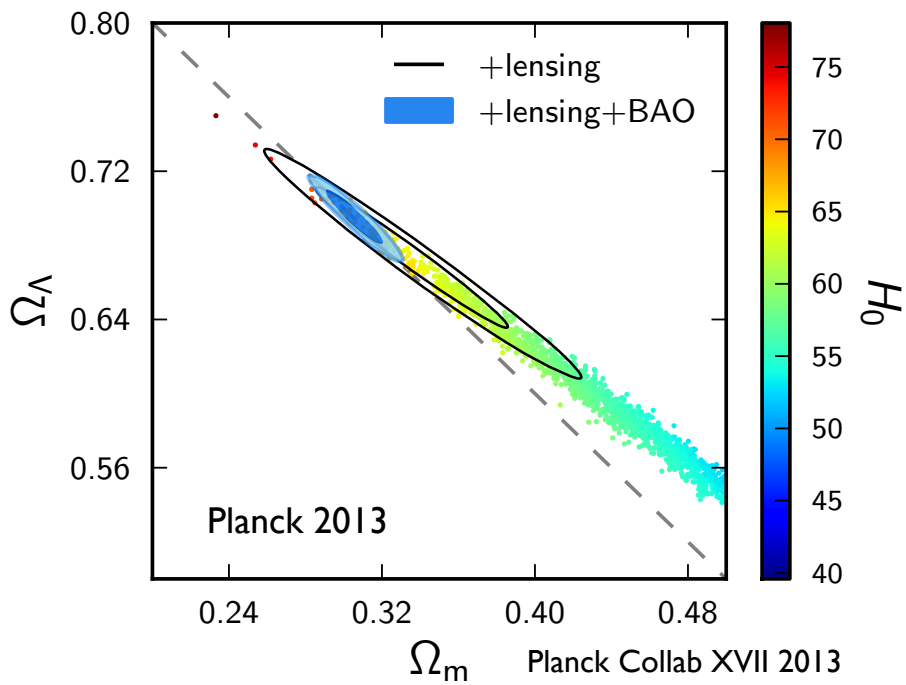
Late-time physics

With primary CMB, cannot measure curvature.

Planck measures curvature through lensing
(more closed, less dark energy → more lensing)
Similarly, probes neutrino mass and dark energy





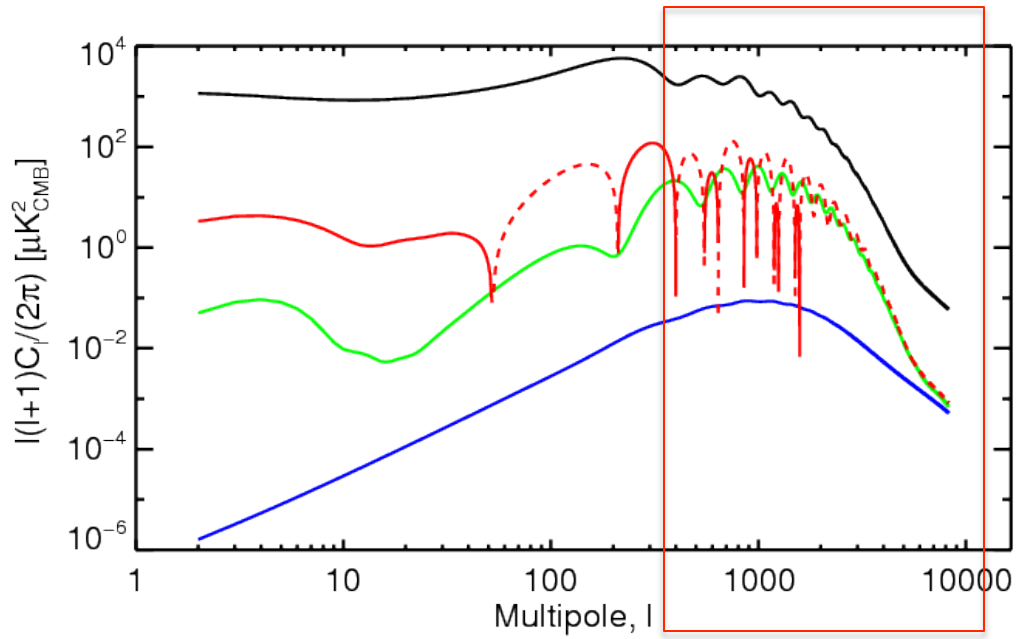


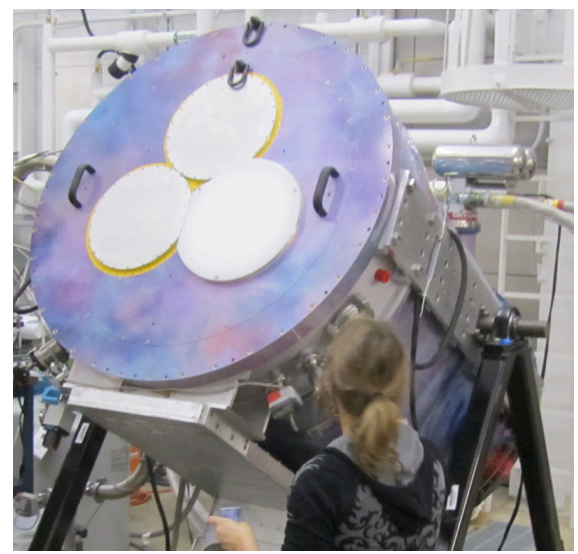
Planck Collab XVII 2013

ACT: Sherwin, Dunkley, Das et al 2011

ACTPol

- Small-scale polarization
- First light last month. 25 times faster survey speed, and polarization sensitivity
  - Wide and deep surveys Niemack et al. (2010)
- Improve temperature sensitivity by ~4x plus polarization.
- Equatorial observations: overlap with many other wavelength data.





ACTPol science

(1) Get E-mode damping tail

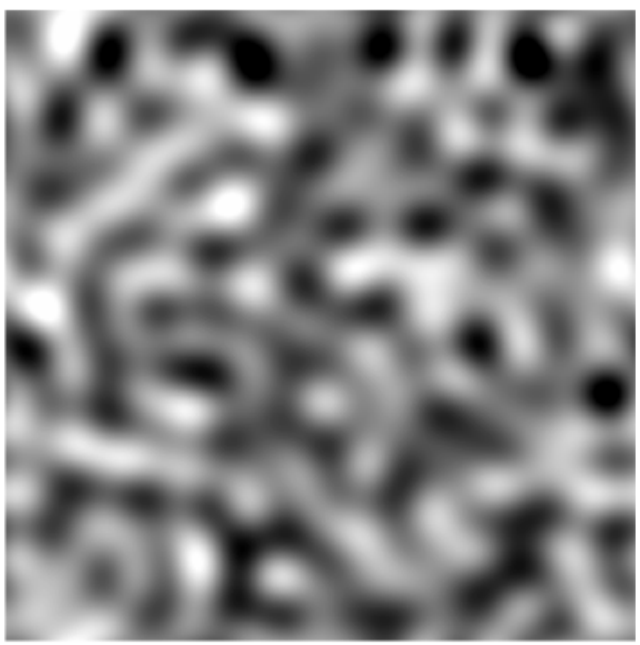
(2) Lensing turns E-modes into B-modes; have enhanced measurement of lensing

Constrain sum of neutrino masses: into Σm_ν<0.2 eV regime at 95% CL.

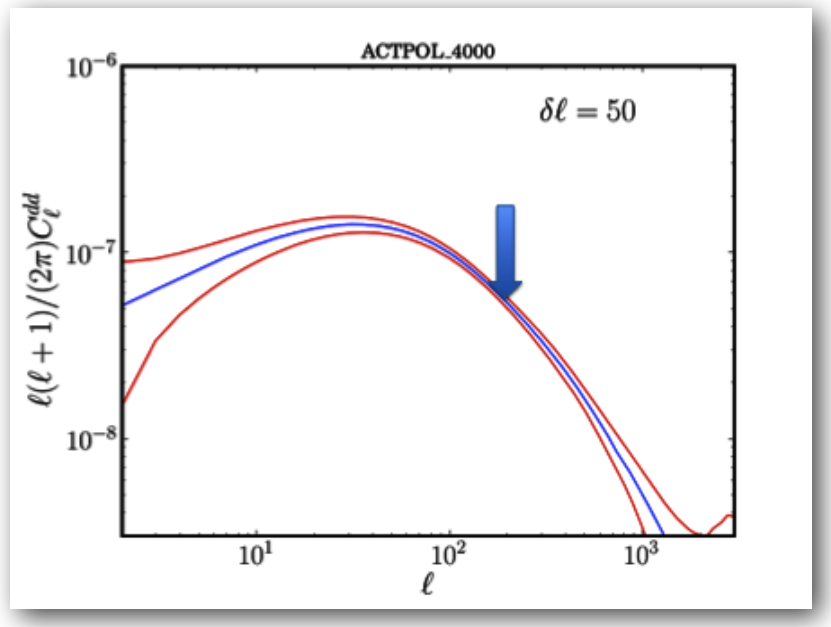
Probe curvature, dark energy, modified gravity.

Strong cross-correlation capabilities

$\sigma(\Sigma\, m_\nu) \approx 0.07$ eV (ACTPol + Planck)

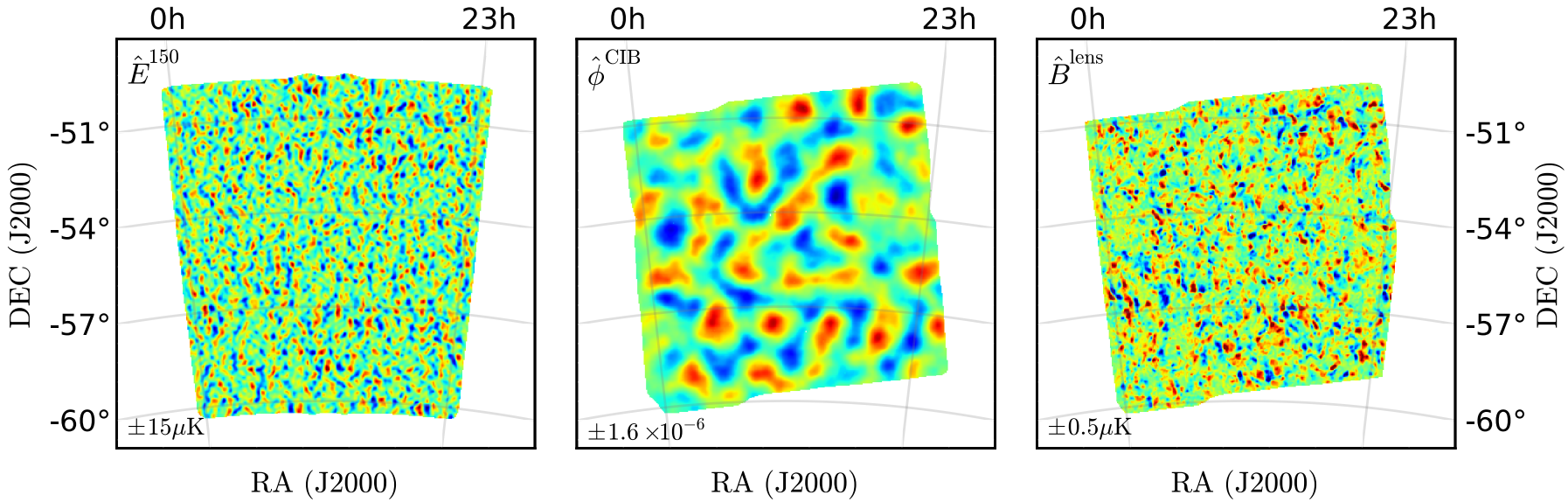


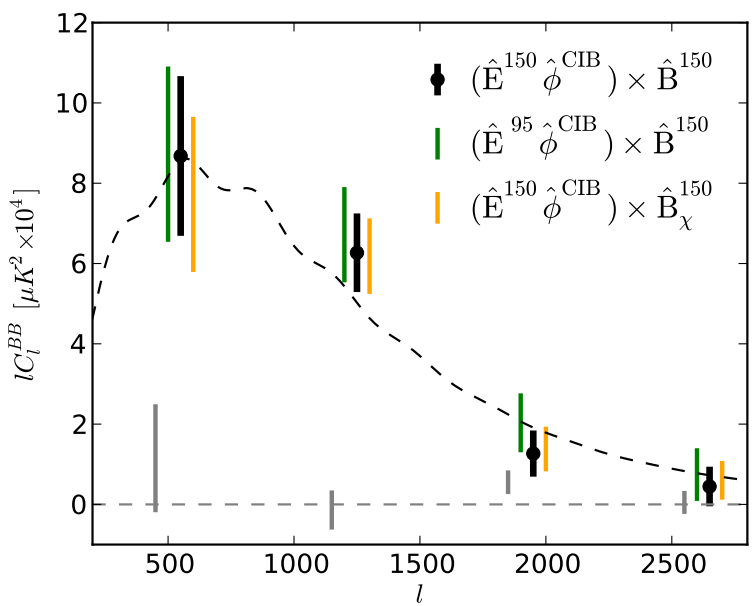
ACTPOL-DEEP:
150 sq-deg @ 3 μK-arcmin (temp)
and 5 μK-arcmin (pol)



ACTPOL-WIDE:
4000 sq-deg @ 20 μK-arcmin (temp)
and 28 μK-arcmin (pol)

New: SPTpol B-modes





Hanson et al 2013

PolarBear also taking data

Summary

- At small scales the CMB probes both recombination and lensing
- Temperature spectrum measured by ACT, SPT, Planck to l~3000. Excellent consistency ACT+WMAP v Planck. Deviations from simple model are much more strongly limited.
- CMB lensing is fast-growing! Probes clustering of matter and expansion rate. Detected in ACT, SPT, and Planck. Geometric degeneracy now broken.
- Small-scale CMB polarization measurements from ACTPol coming; first lensing B-modes from SPTpol. Excellent prospects for neutrino physics, cross-correlations with other probes.