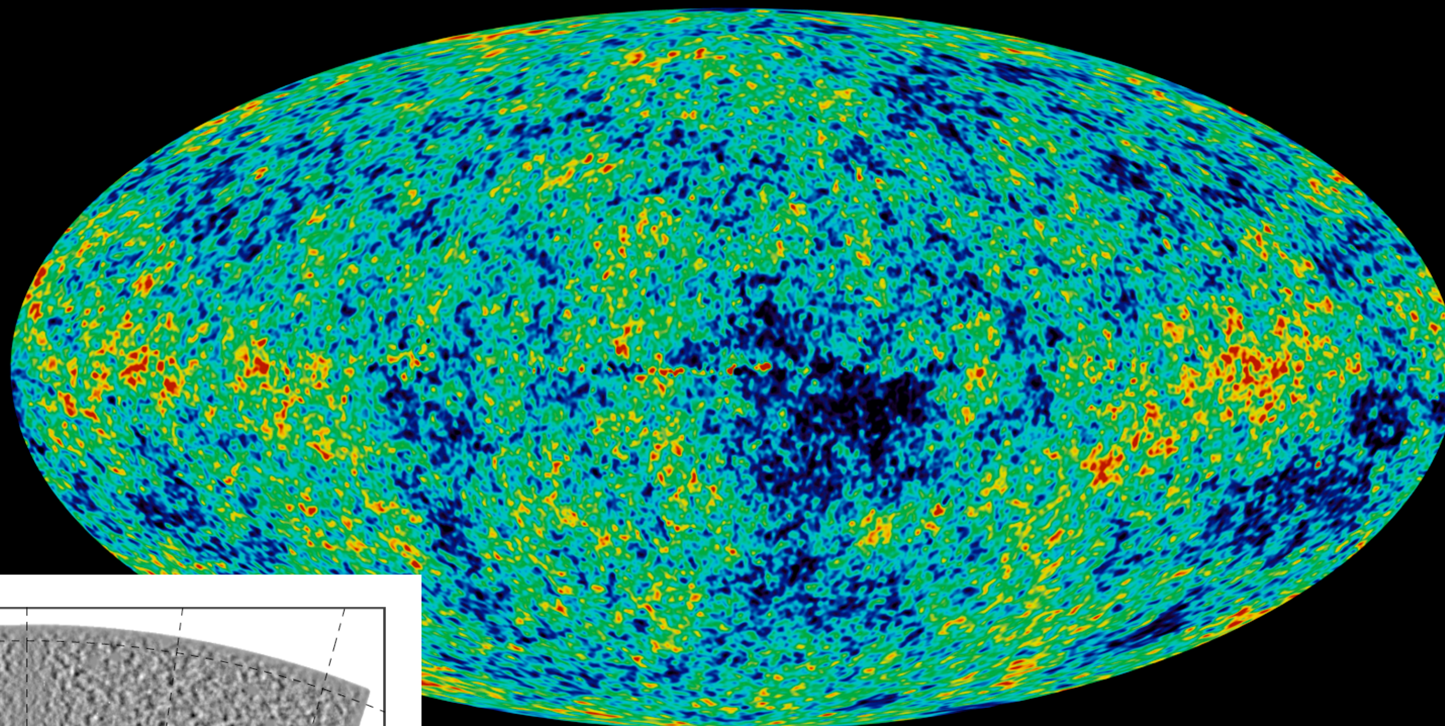
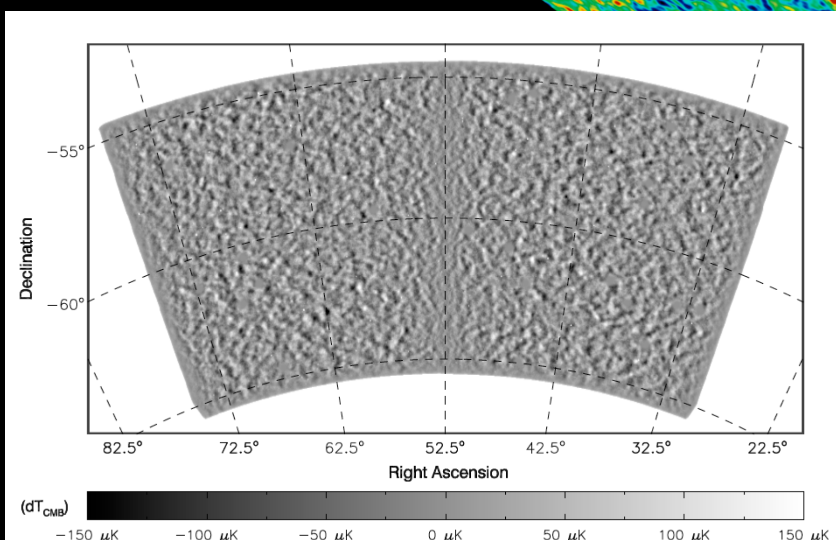
# Cosmic Microwave Background

Inflation, neutrinos, and Dark Energy







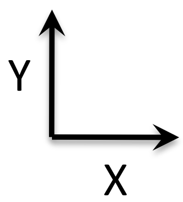
John Ruhl

Case Western Reserve University

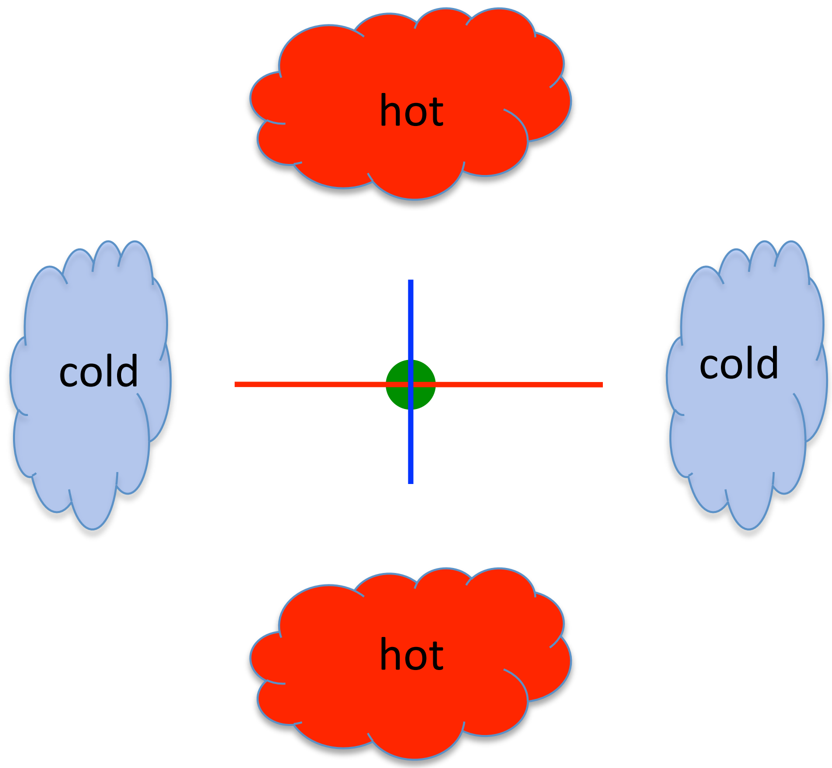

*13 September 2011*

# CMB Polarization

To get polarization from Thomson scattering, you need an anisotropic flux incident on the scattering electrons




(Observer is located in z direction, out of the page)



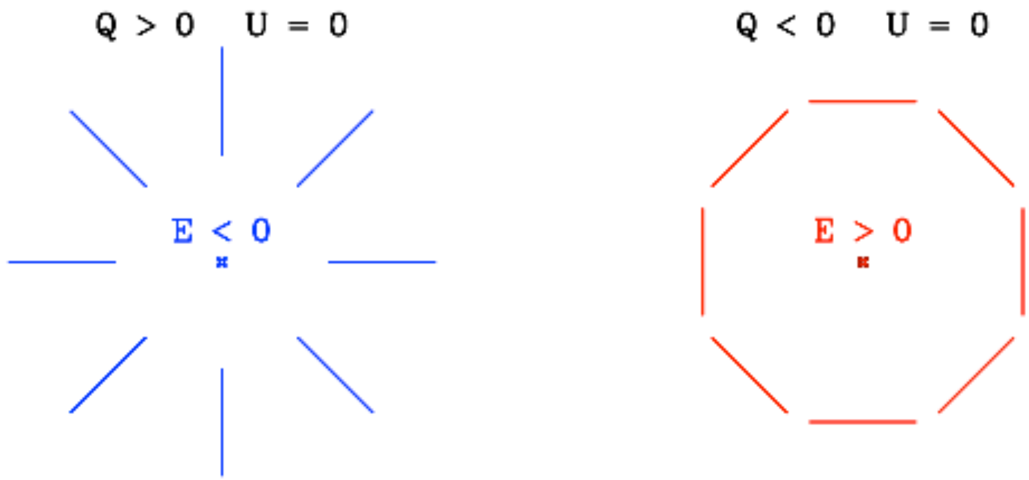

Polarization level depends on the **local quadrupole** seen by the scattering electrons.

Two ways to generate these **local quadrupoles**: density variations, and gravitational waves

# E and B mode patterns

(a basis set for polarization patterns)

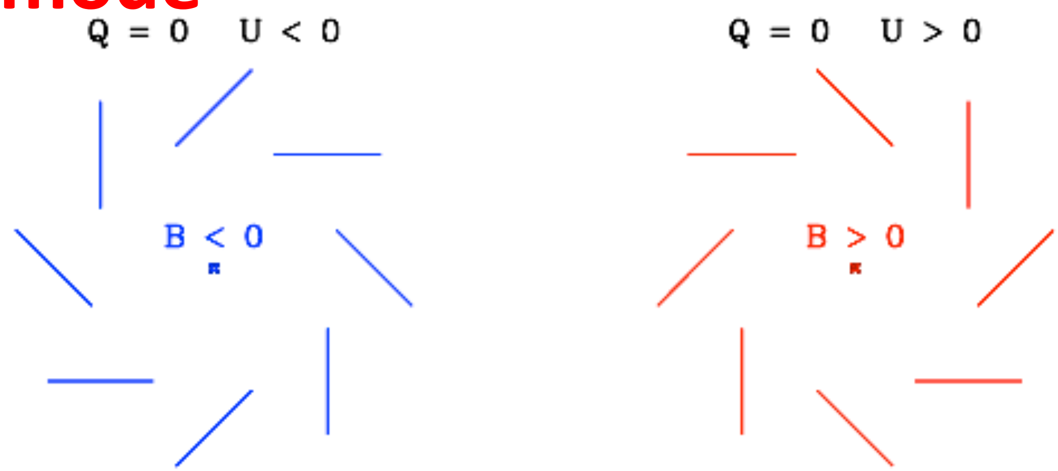
## E-mode




Unchanged under parity flip

(produced by density perturbations and gravity waves)

## B-mode

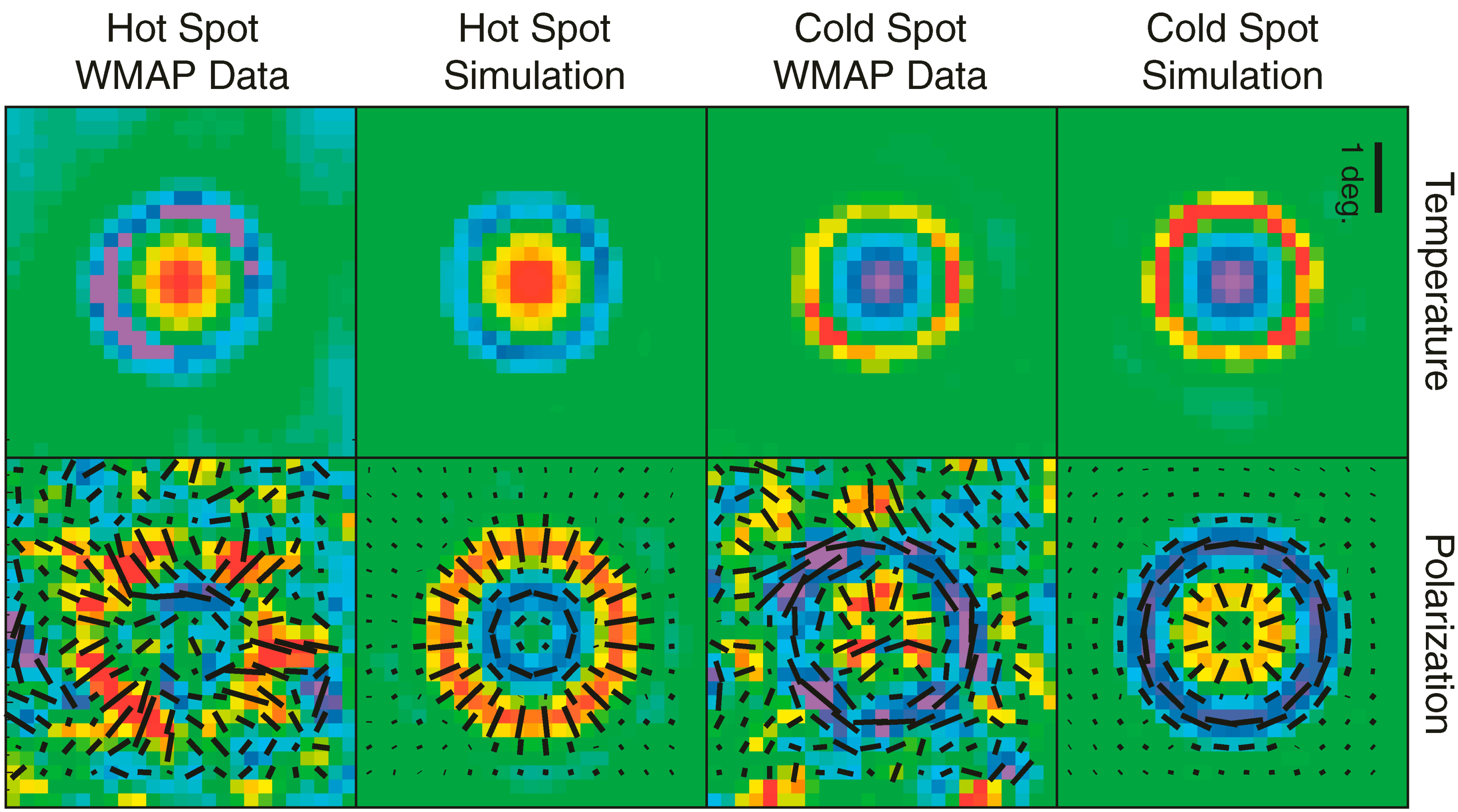



Sign reverses under parity flip

(produced only by gravity waves, not density perturbations)

*Figure from Seljak and Zaldarriaga, astro-ph/9805010*

# CMB <TE> and <EE>




WMAP07

# CMB Power Spectra

<TT>, <EE>, <TE>

Primarily sourced by density variations at z = 1000

Potentially a small contribution from gravitational waves

Some distortion by LSS

<BB>

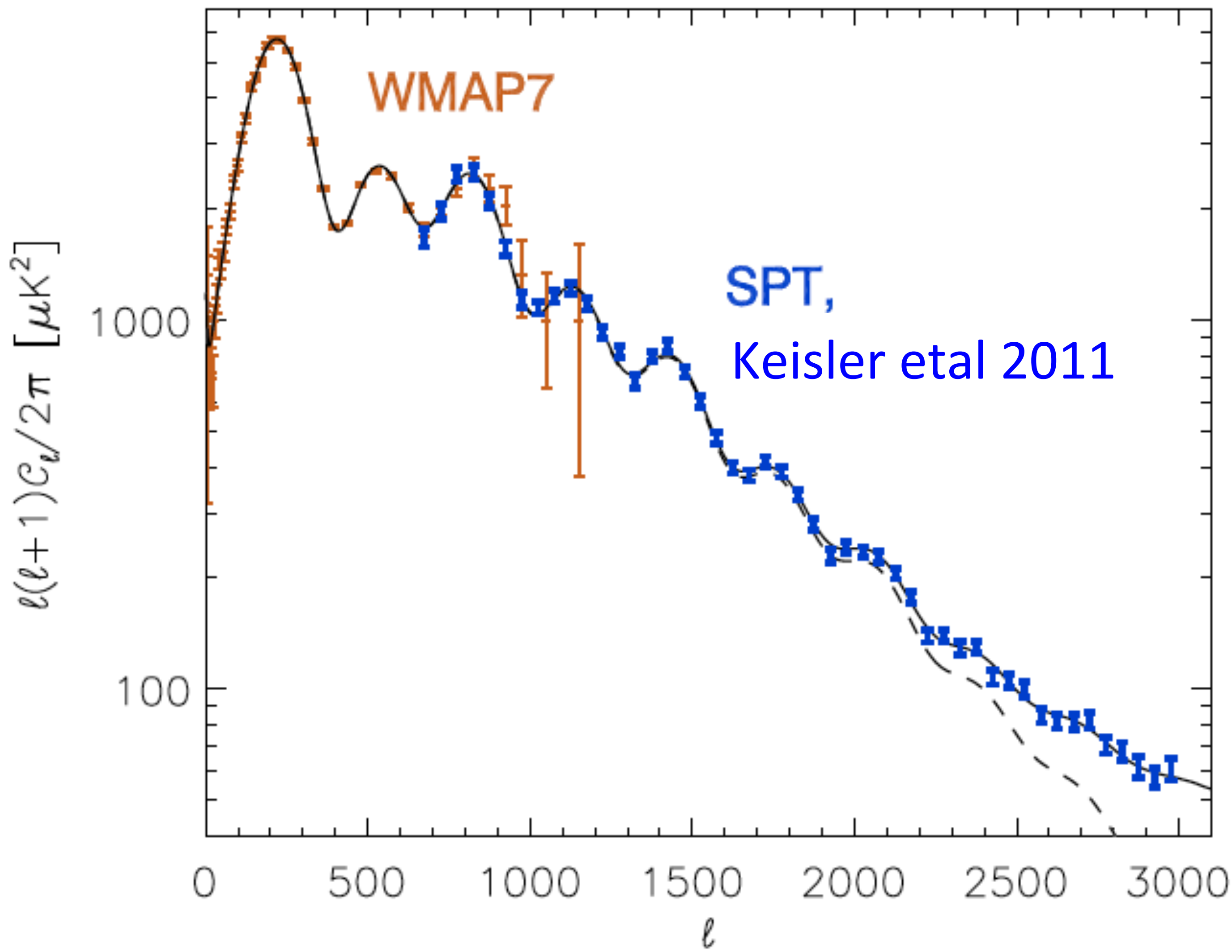
low ell: sourced by gravity waves at z=1000

high ell: <EE> converted to <BB> by LSS

Red = probe of inflation

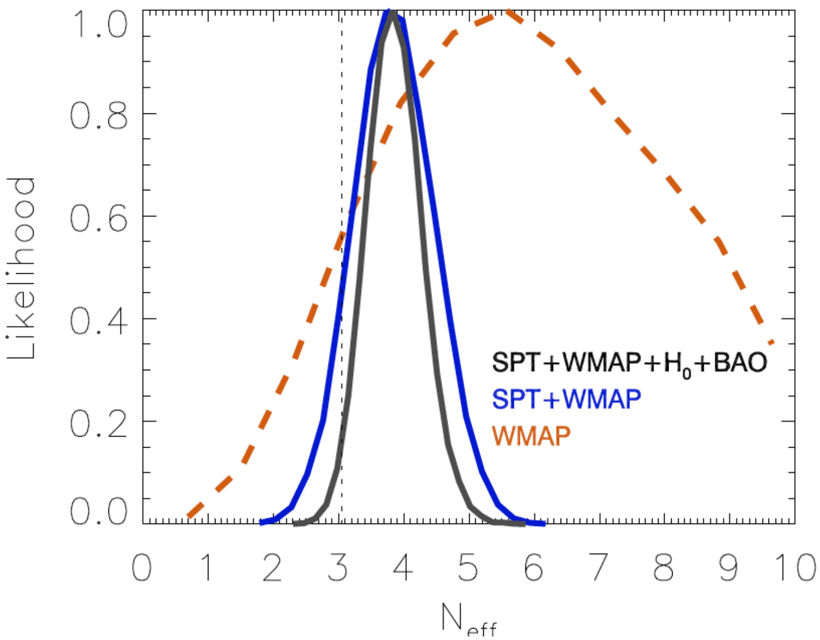
Blue = probe of DE and/or neutrinos

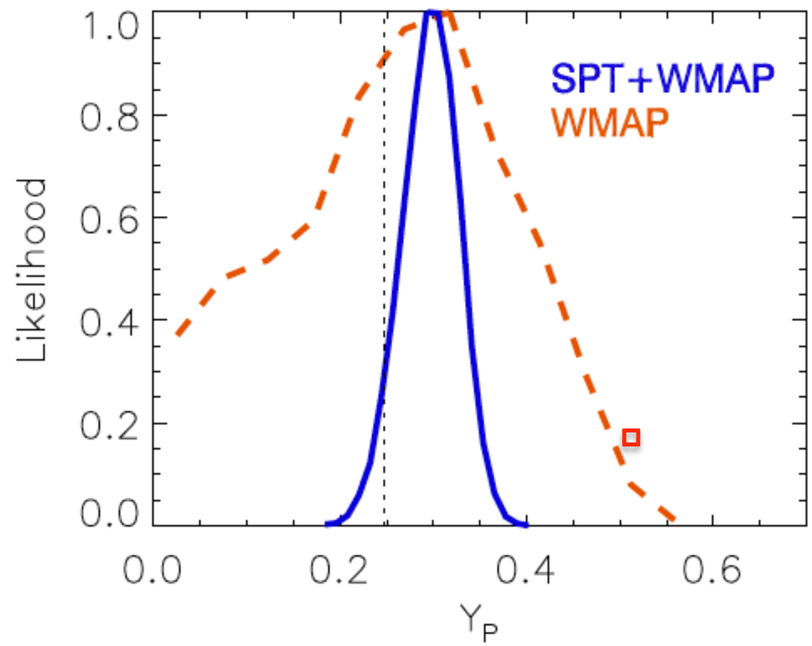
# CMB <TT>



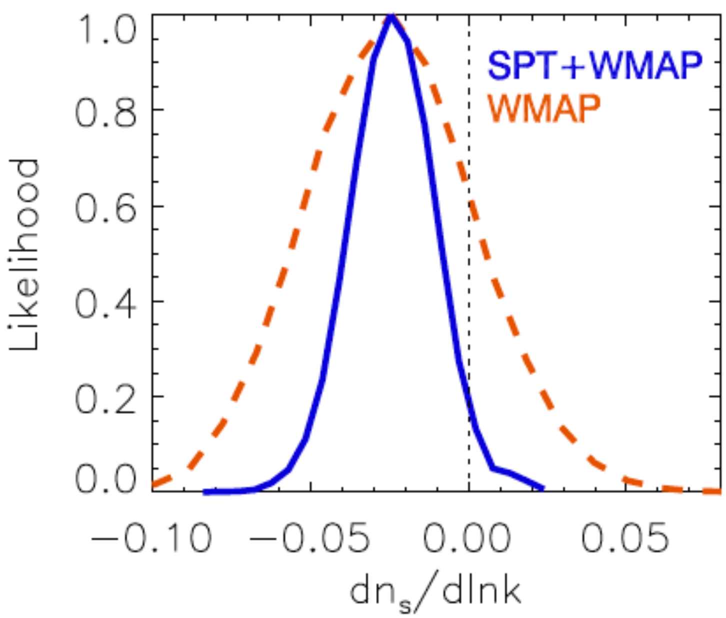

*Coming: Planck satellite first results due Jan 2013 or so.*

# SPT+WMAP <TT> results




Keisler etal 2011



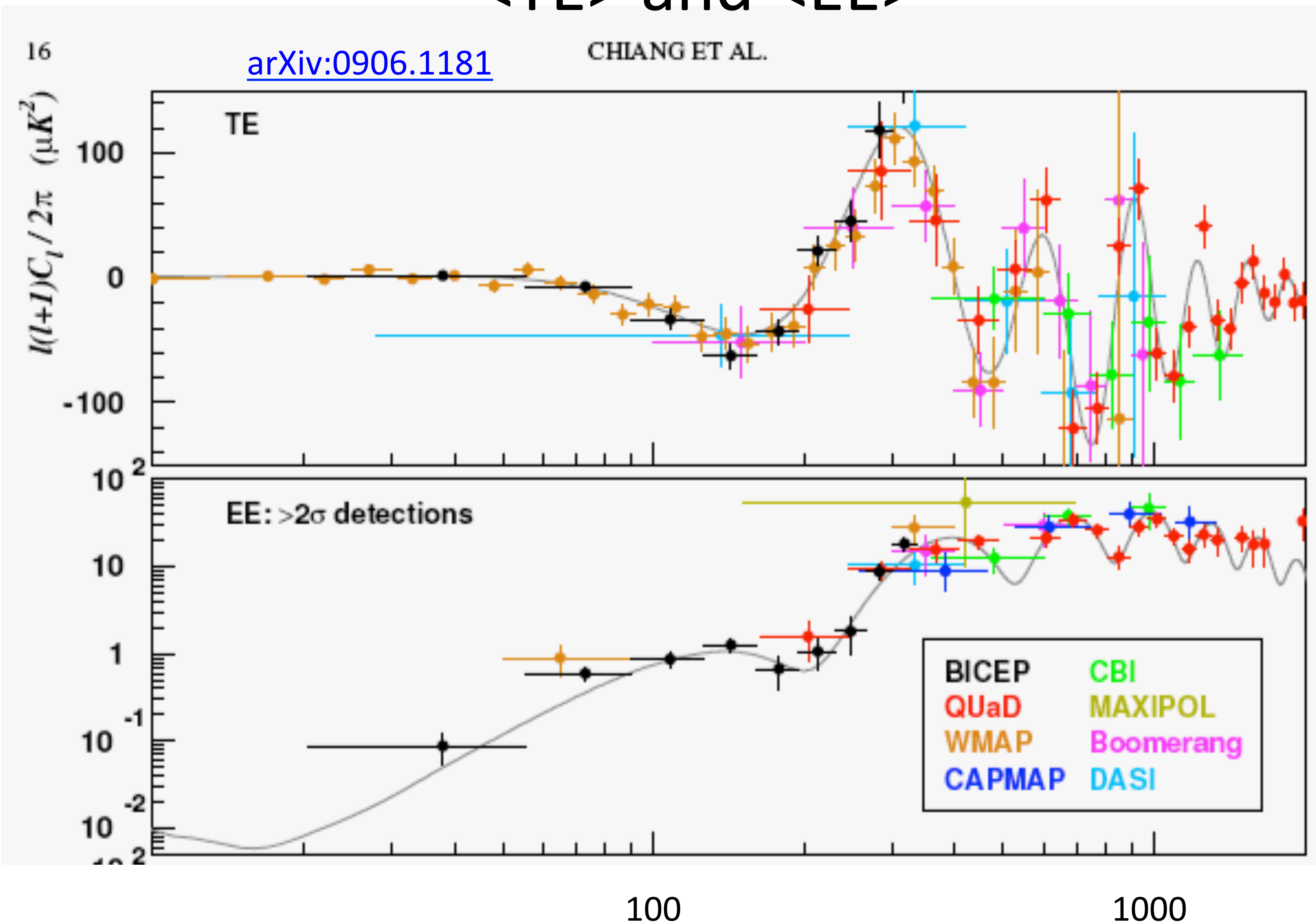

Hints at maybe interesting physics: N_eff, Yp, spectral tilt are all (individually) in about 1.7sigma tension with standard values… due to 2.5% lower than standard power at ell = 2000.

# SPT + WMAP <TT> results

r = T/S < 0.17
(at 95% confidence, CMB + H0 + BAO)

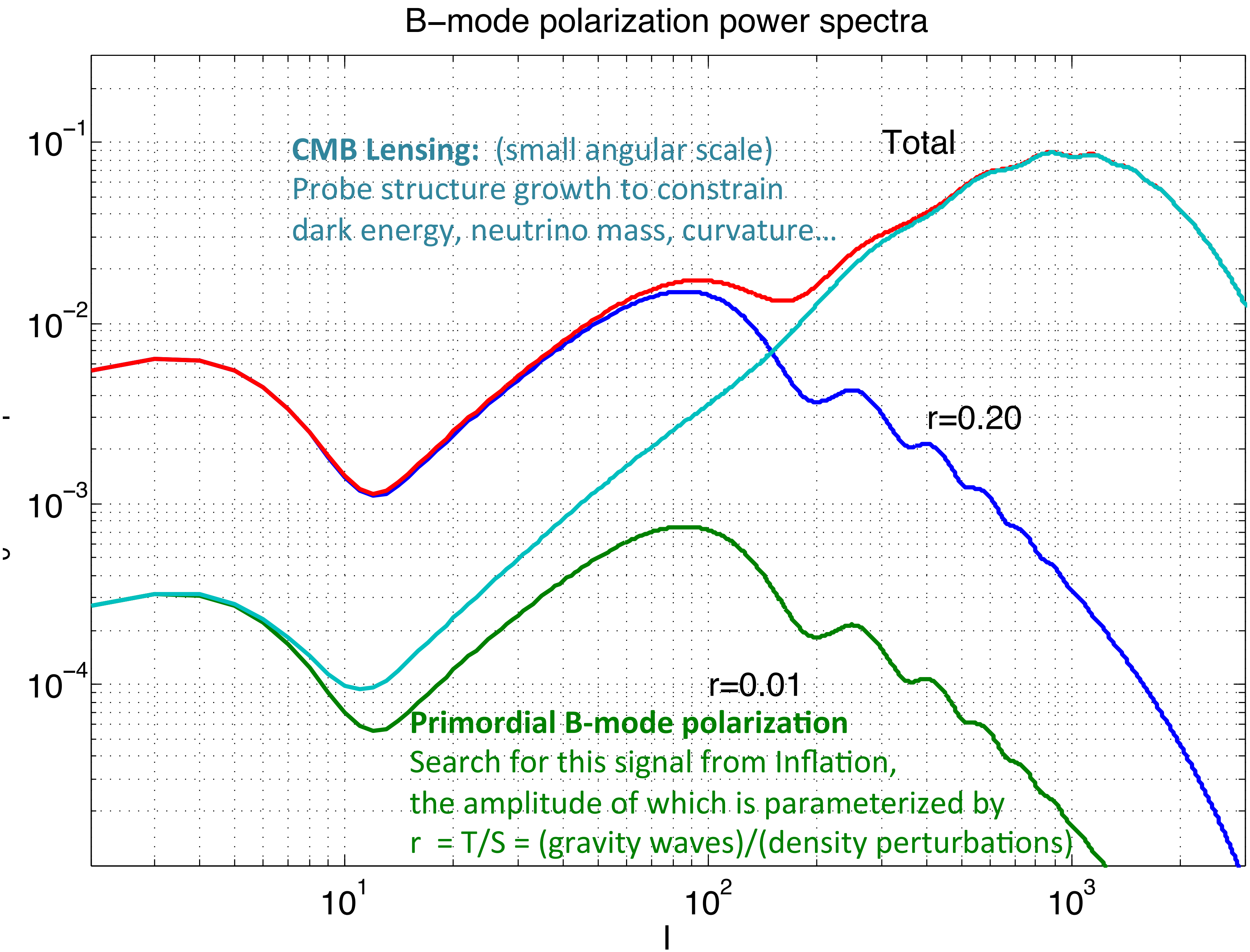
*(Best limit from <BB> is about 0.7 … the hope there is to push down to about r=0.01)*

# <TE> and <EE>

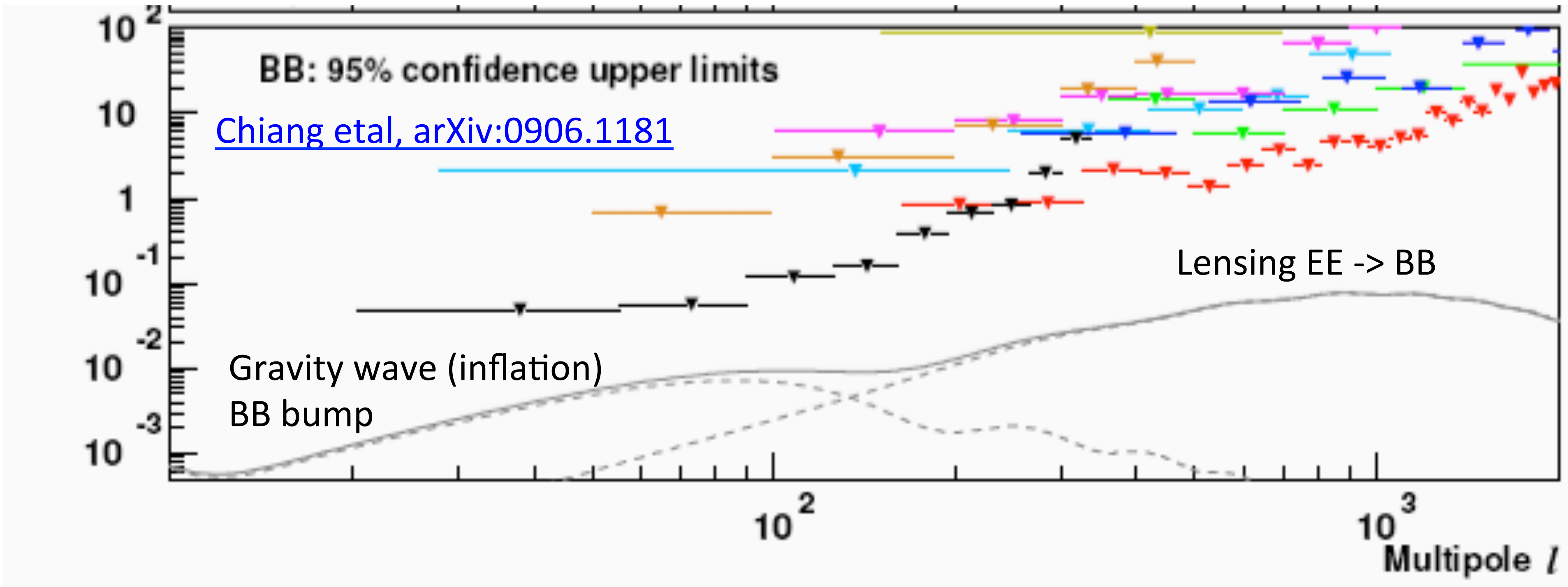



*Does not include subsequent QUIET and WMAP7…*

*Coming: Planck satellite first results due Jan 2013 or so.*


B−mode polarization power spectra
CMB Lensing: (small angular scale)
Probe structure growth to constrain
dark energy, neutrino mass, curvature…
Total
r=0.20
r=0.01
Primordial B-mode polarization
Search for this signal from Inflation,
the amplitude of which is parameterized by
r = T/S = (gravity waves)/(density perturbations)
l

# <BB>




BB limits on r are not yet as powerful as the TT+etc limits.

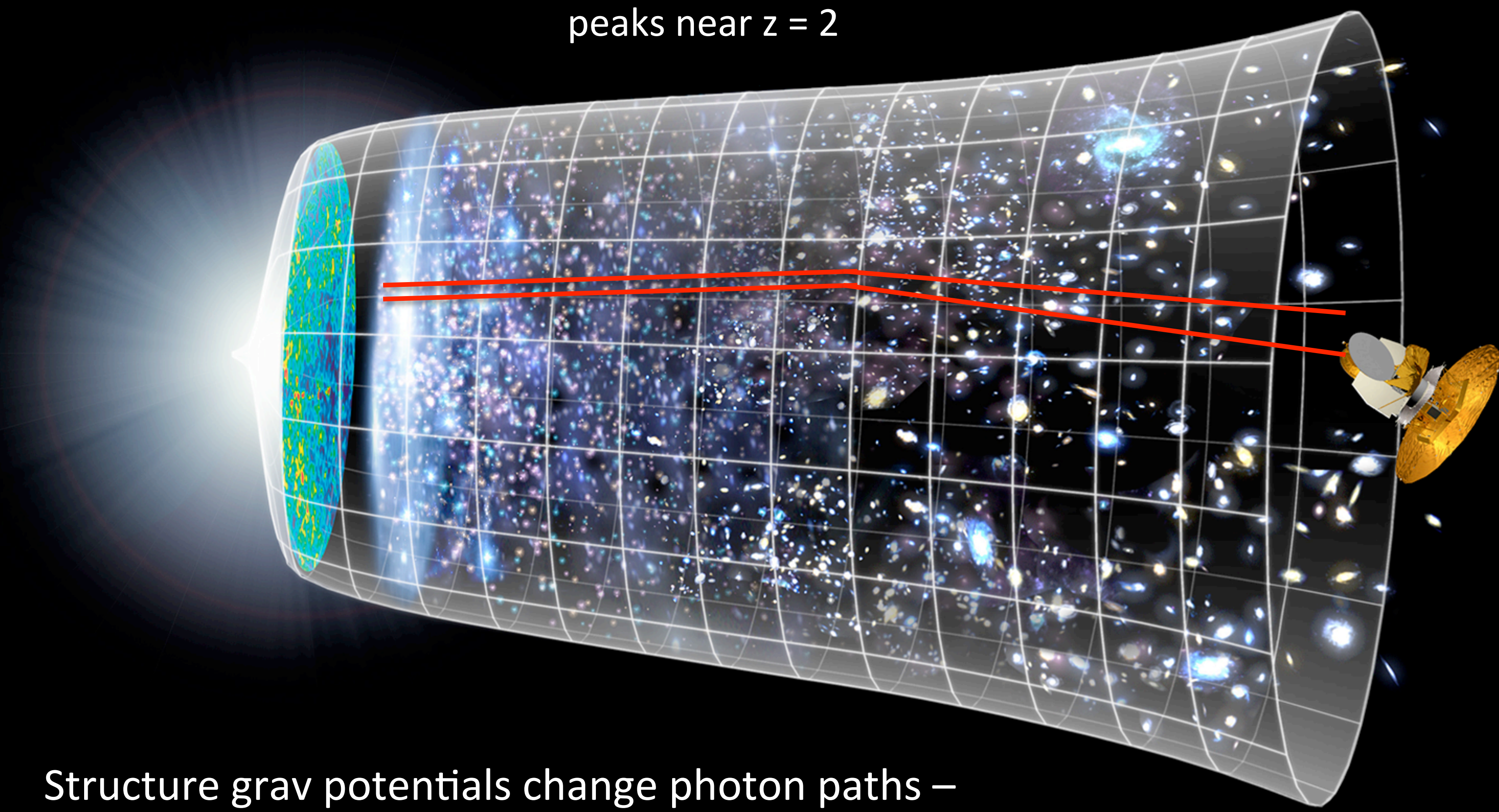
*Does not include subsequent QUIET and WMAP7… above statement is still true.*

*Planck will not make much headway here.*

# CMB Lensing

# CMB Lensing

Lensing kernel is broad but
peaks near z = 2



Structure grav potentials change photon paths –
Arcminute shifts that are coherent over ≈ degree scales,

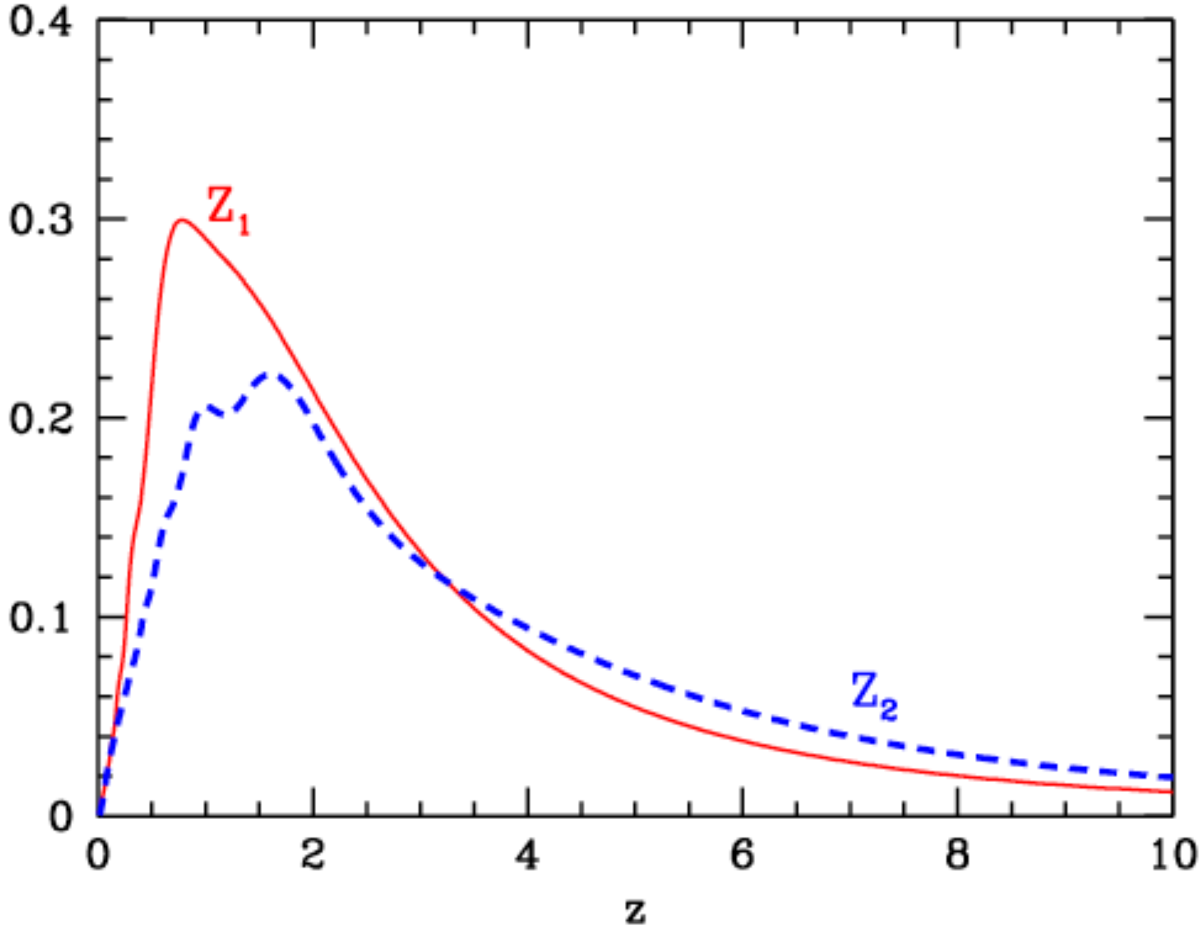
- Distorts T map,
- Remaps polarization field which converts E -> B

NASA/WMAP Science Team

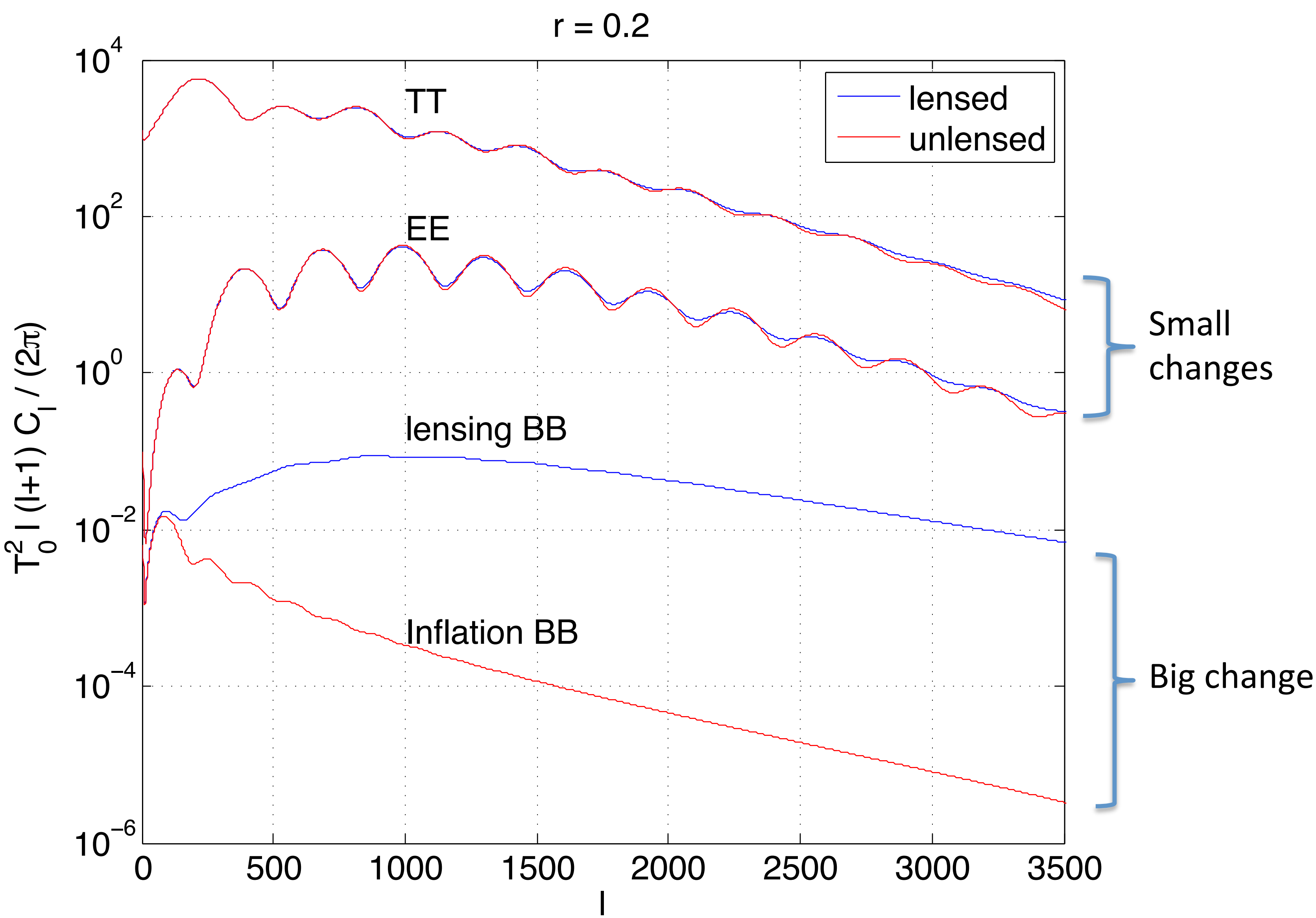
# CMB lensing kernel

Z = 0.5 to 3 or 4, long tail beyond;
much of it is z>1 which is not sensitive to normal DE, but is sensitive to early DE

*Smith, Hu and Kaplinghat - arXiv:astro-ph/0607315v1*

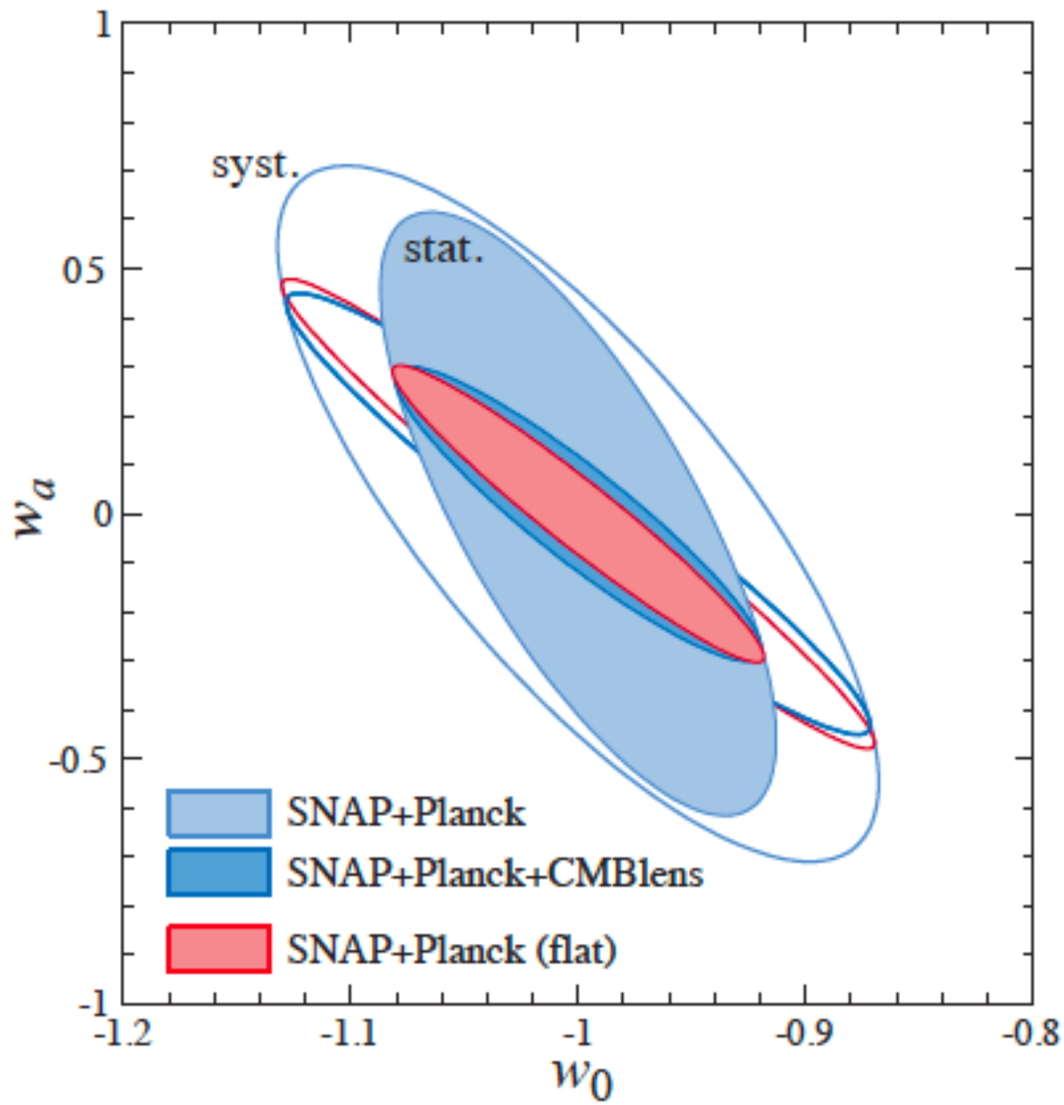


# CMB polarization angular power spectra



# Dark Energy

*CMB lensing  can help break degeneracies*

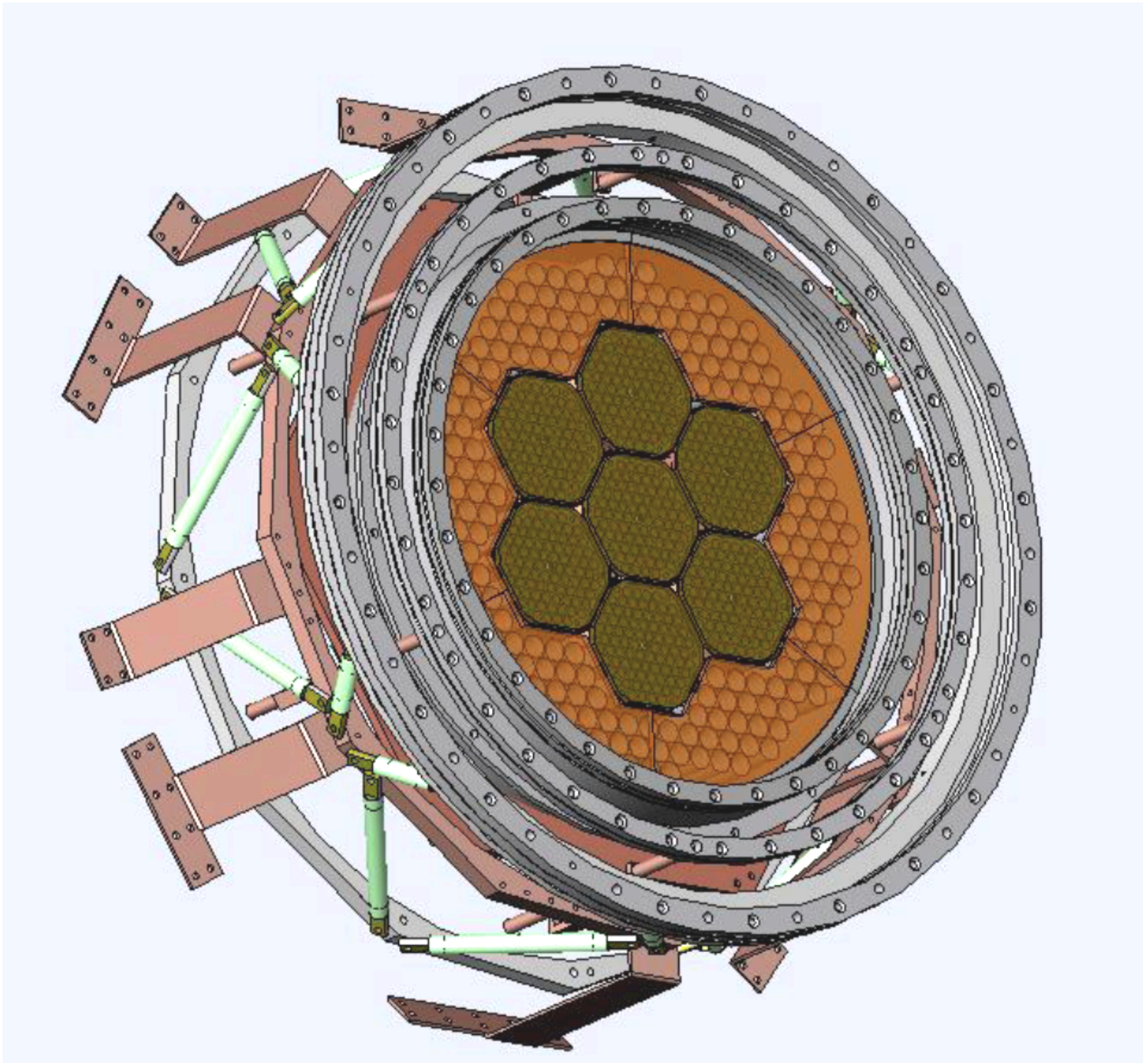



Hu, Hutterer and Smith, arXiv:astro-ph/0607315

# The South Pole Telescope Polarimeter (SPTpol)

**SPT Collaboration:**
U. Chicago
ANL
Cardiff
Case Western Reserve
LBNL
McGill
NIST
Smithsonian CfA
U. C. Berkeley
U. C. Davis
U. Colorado
U. Michigan

John Ruhl
Case Western Reserve Univ.

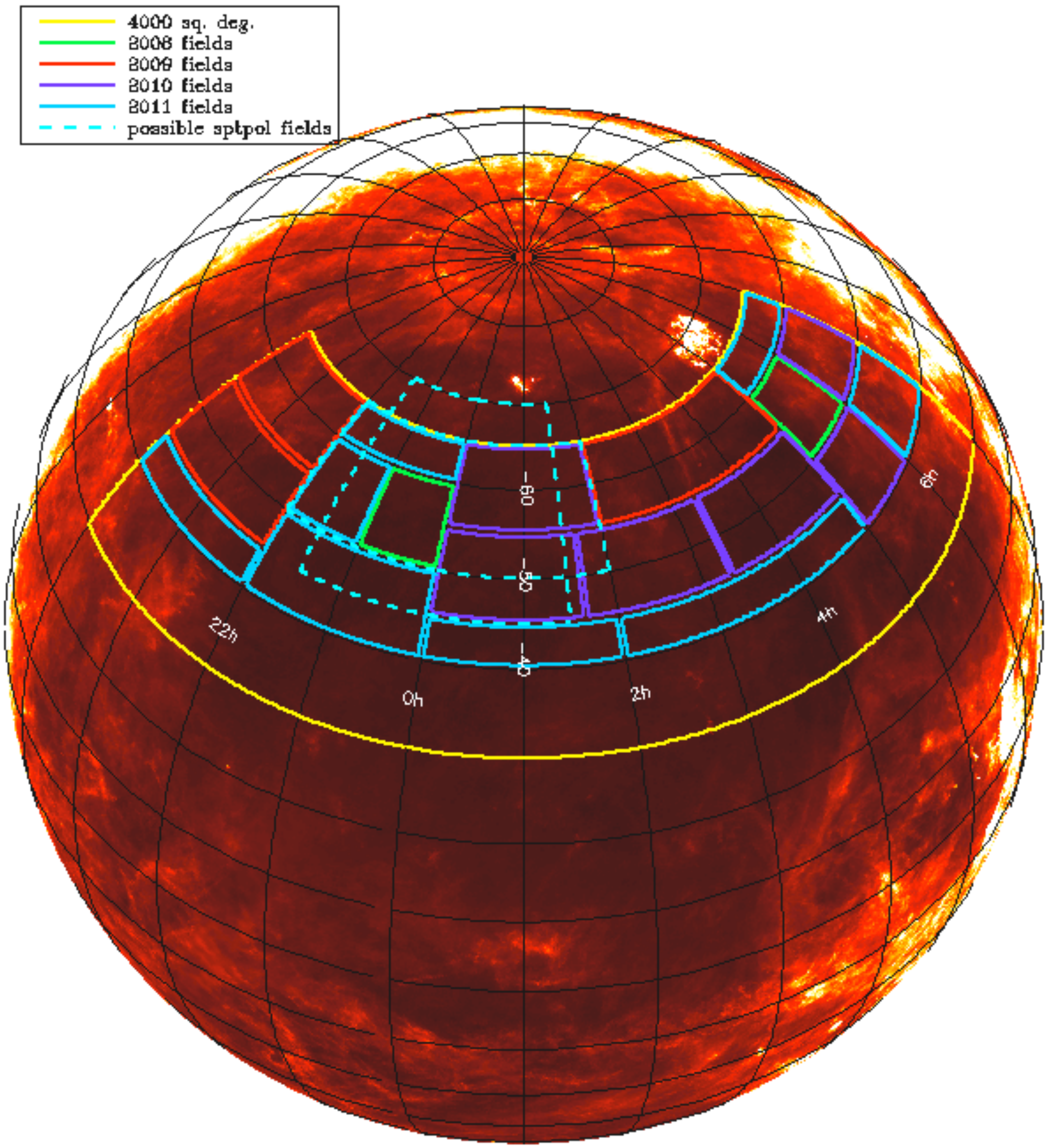


7*84 =588 pixels at 150GHz
192 pixels at 95GHz

(ANL building outer, 90GHz, detectors)

2007 specs: have since decreased 150GHz bolo # but improved per-detector sensitivity; Overall sensitivity still about the same; these depths are for a 625 sq. deg field.

| $\nu_0$ (GHz) | $\Delta\nu$ (GHz) | $P_o$ (pW) | $NEP_{bolo}$ (aW / $\sqrt{Hz}$) | $NEQ_{pixel}$ ($\mu K \sqrt{s}$) | # pixels | pixel spacing $f\,\lambda$ | Beam FWHM arcmin | Field depth $\mu K_{CMB}$ - arcmin |
|---|---|---|---|---|---|---|---|---|
| 95 | 35 | 9.8 | 61.5 | 300 | 144 | 1.73 | 1.6 | 7.7 |
| 153 | 36 | 6.6 | 53.5 | 390 | 720 | 1.60 | 1.0 | 4.5 |

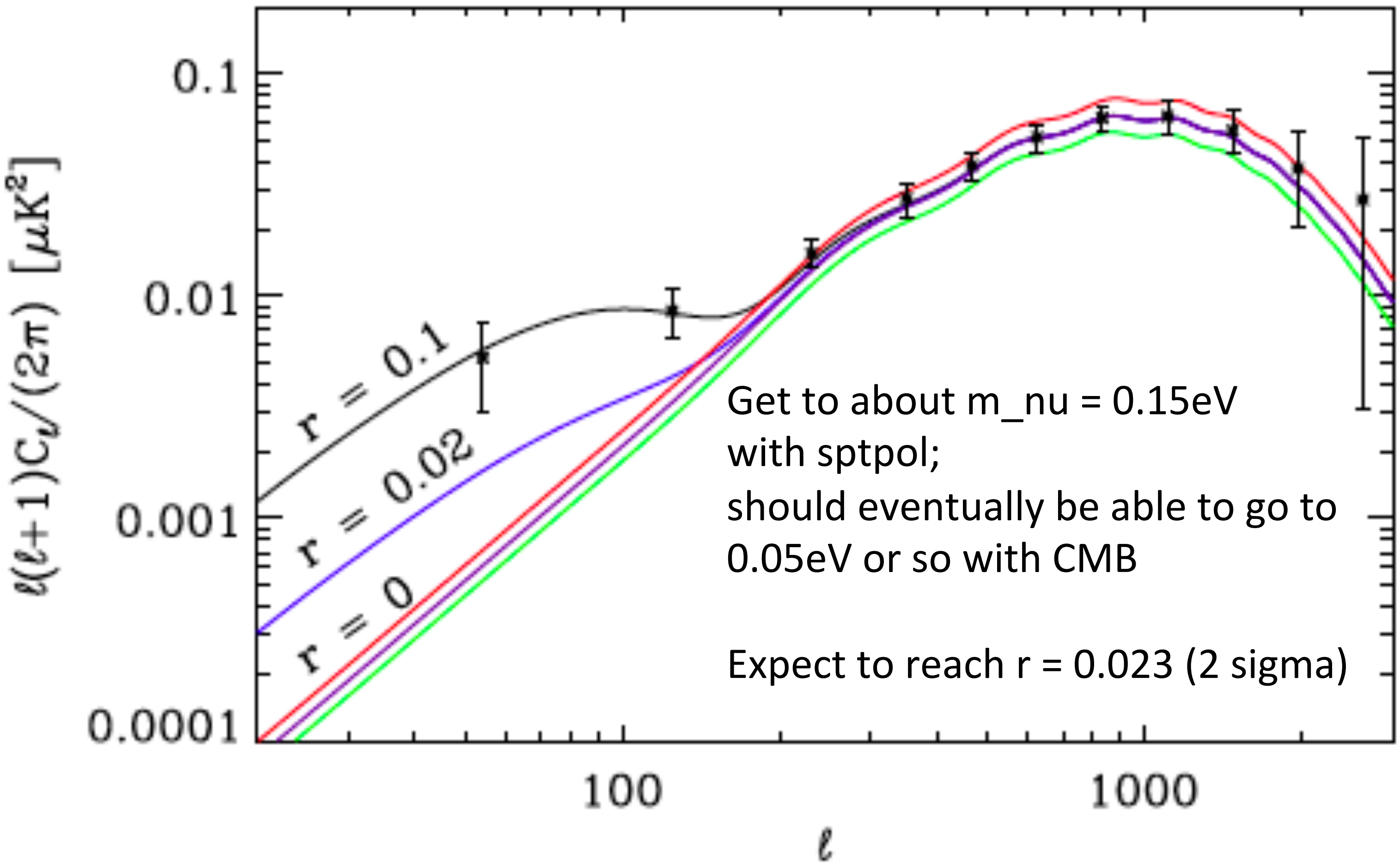



SPTpol field

**Green dashed lines**
Center: (0h, -57º)
Area: 625 sq.deg.

# SPTpol

## BB lensing power spectrum projected errors (after foreground removal)




(3 years of integration)

# Data Analysis Challenge

Large data timestreams – growing with each new instrument :

SPTpol:

$N_t = \mathcal{O}$(1000 detectors) * $\mathcal{O}$(100Hz sample rate) * $\mathcal{O}$(10^7 sec/year) * (3 years)

We've adapted our algorithms so that dealing with the data itself (one pass from timestream to science) is not so bad – the challenges are in doing the many 100's of simulations used to understand:

- transfer functions,
- noise,
- systematics

… all of which are crucial (and growing more so) for extracting (correct) science.

# The CMB Data Challenge

- Extracting fainter signals (polarization, high resolution) from the data requires:
  - larger data volumes to provide higher signal-to-noise.
  - more exacting analyses to control fainter systematic effects.

| Experiment | Start Date | Goals | $N_t$ | $N_p$ |
|---|---|---|---|---|
| COBE | 1989 | All-sky, low res, T | $10^9$ | $10^4$ |
| BOOMERanG | 1997 | Cut-sky, high-res, T | $10^9$ | $10^6$ |
| WMAP | 2001 | All-sky, mid-res, T+E | $10^{10}$ | $10^7$ |
| Planck | 2009 | All-sky, high-res, T+E(+B) | $10^{12}$ | $10^9$ |
| PolarBear | 2012 | Cut-sky, high-res, T+E+B | $10^{13}$ | $10^7$ |
| QUIET-II | 2015 | Cut-sky, high-res, T+E+B | $10^{14}$ | $10^7$ |
| CMBpol | 2020+ | All-sky, high-res, T+E+B | $10^{15}$ | $10^{10}$ |

- 1000x increase in data volume each over past & future 15 years
  - need linear analysis algorithms to scale through 10 + 10 M-foldings !

*Slide from Julian Borrill - LBL*

# CMB Data Analysis Evolution

Data volume & computational capability dictate analysis approach.

| Date | Data | System | Map | Power Spectrum | |
|---|---|---|---|---|---|
| 1997 - 2000 | B98 | Cray T3E x 700 | Explicit Maximum Likelihood (Matrix Invert - $N_p^3$) | Explicit Maximum Likelihood (Matrix Cholesky + Tri-solve - $N_p^3$) | Algorithms |
| 2000 - 2003 | B2K2 | IBM SP3 x 3,000 | Explicit Maximum Likelihood (Matrix Invert - $N_p^3$) | Explicit Maximum Likelihood (Matrix Invert + Multiply - $N_p^3$) | |
| 2003 - 2007 | Planck SF | IBM SP3 x 6,000 | PCG Maximum Likelihood (band-limited FFT – few $N_t$) | Monte Carlo (Sim + Map - many $N_t$) | |
| 2007 - 2010 | Planck AF EBEX | Cray XT4 x 40,000 | PCG Maximum Likelihood (band-limited FFT – few $N_t$) | Monte Carlo (SimMap - many $N_t$) | Implementations |
| 2010 - 2014 | Planck MC PolarBear | Cray XE6 x 150,000 | PCG Maximum Likelihood (band-limited FFT – few $N_t$) | Monte Carlo (Hybrid SimMap - many $N_t$) | |

*Slide from Julian Borrill - LBL*

# Lensing & computing

The "lensing" window is just now opening – very little has been done with real data yet…

One obvious area serious computing will be required is in understanding the cross-correlations of different data sets, eg

(SPTpol lensing map) x (DES galaxies)

which combines the CMB advantage of "only sensitive to mass" (eg measure bias) with the optical advantage of depth information.

Using these will require a very good understanding of structure formation/etc as f(cosmology) to go after dark energy properties, m_nu, etc.

END