The CMB…

…and its polarization!!

Slight Review

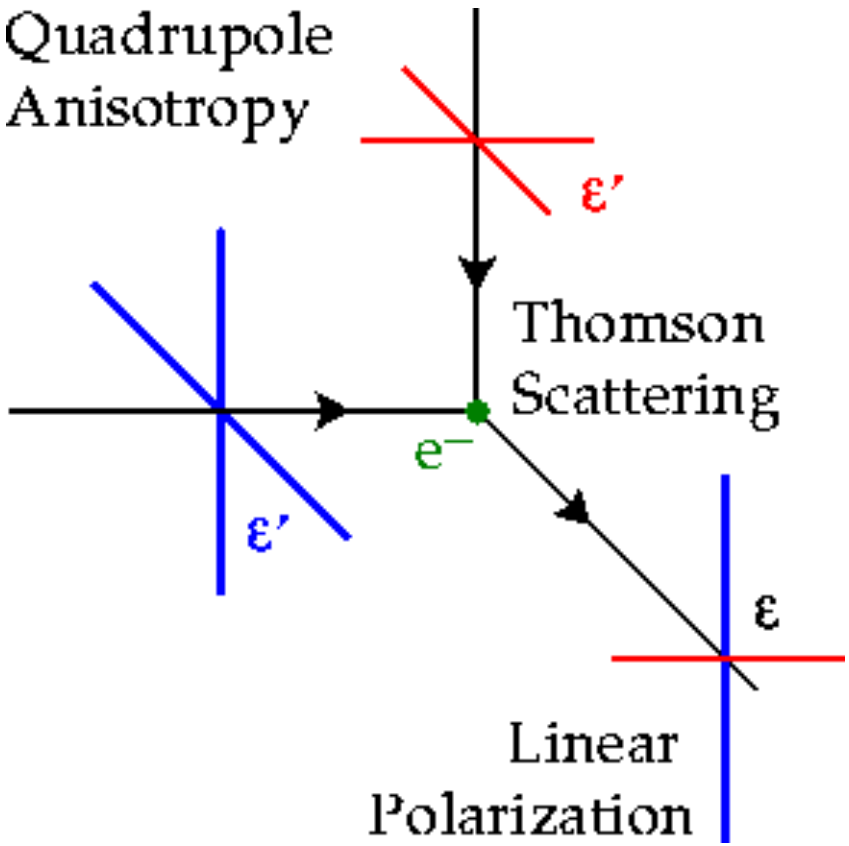
- What is polarization?
- Stokes Parameters (measured wrt):
  - I : total field
  - Q : along x (or y) axis
  - U : along 45° axis
  - V : circular
- So…how is light unpolarized?

What causes the CMB Polarization?

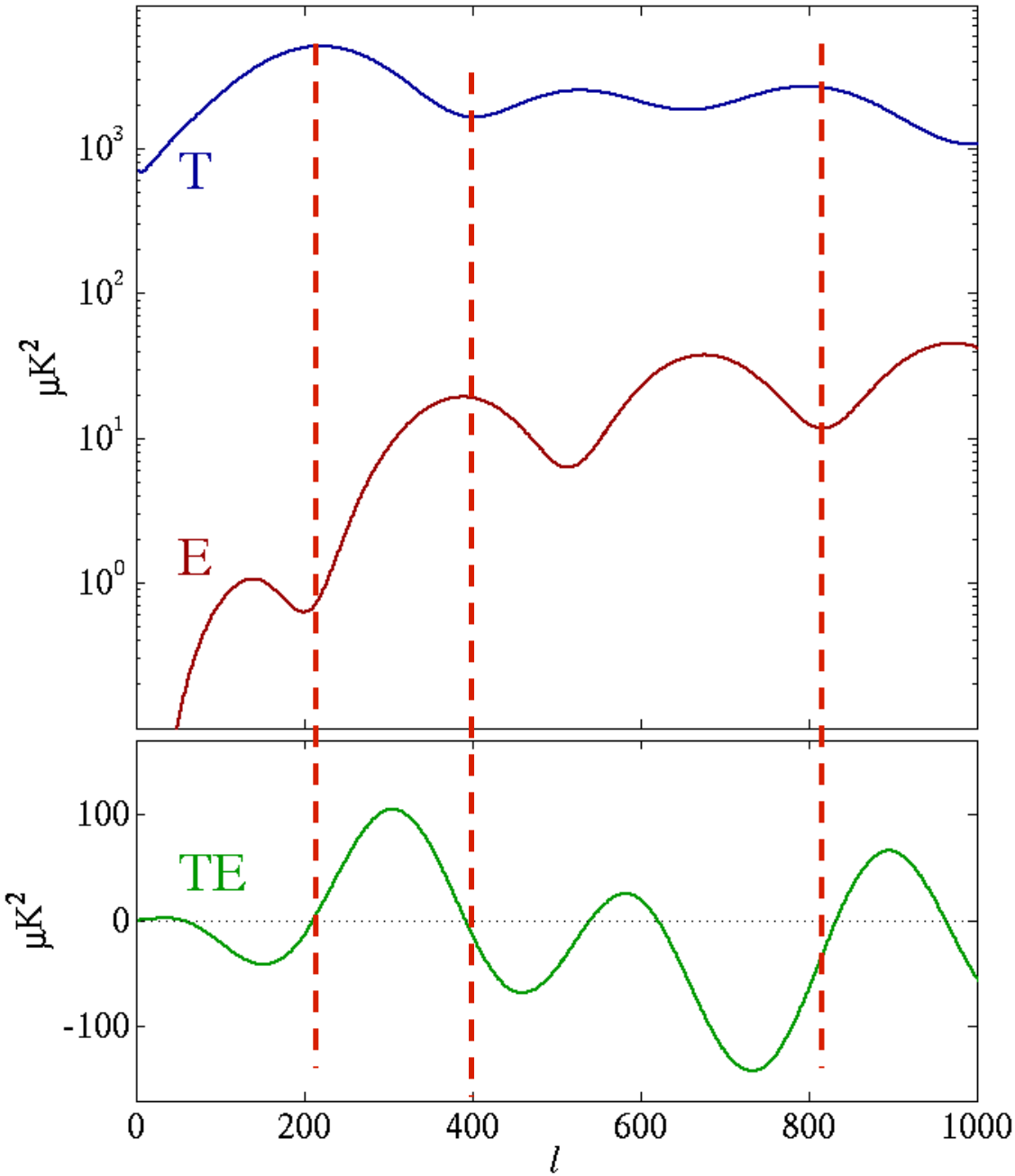
- Classical Thomson Scattering
- What's the difference between Compton and Thomson?
  - Recall: $\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$
- Primarily electric field
  - Recall B=E/c

What should it look like?

- Polarization is proportional to the quadrupole moment of the plasma.
- Primary generation of quadrupole is due to Doppler shifts, i.e. it is dependent on the velocity of the field.
- Expect correlation between temperature fluctuations and polarization.
- Do we expect temperature and polarization to be in phase or out of phase?



from Hu & White, 1997


T
E
TE
10^3
10^2
10^1
10^0
μK^2
100
0
-100
μK^2
0
200
400
600
800
1000
l

Modes

- So do we measure polarization in units of Stokes parameters?
- No!
- Instead, we use linear combinations of Q and U to form E and B *modes*.
- Why?
- Answer: Convenience.
- Polarization from Thomson scattering of primordial plasma should be all E-mode.

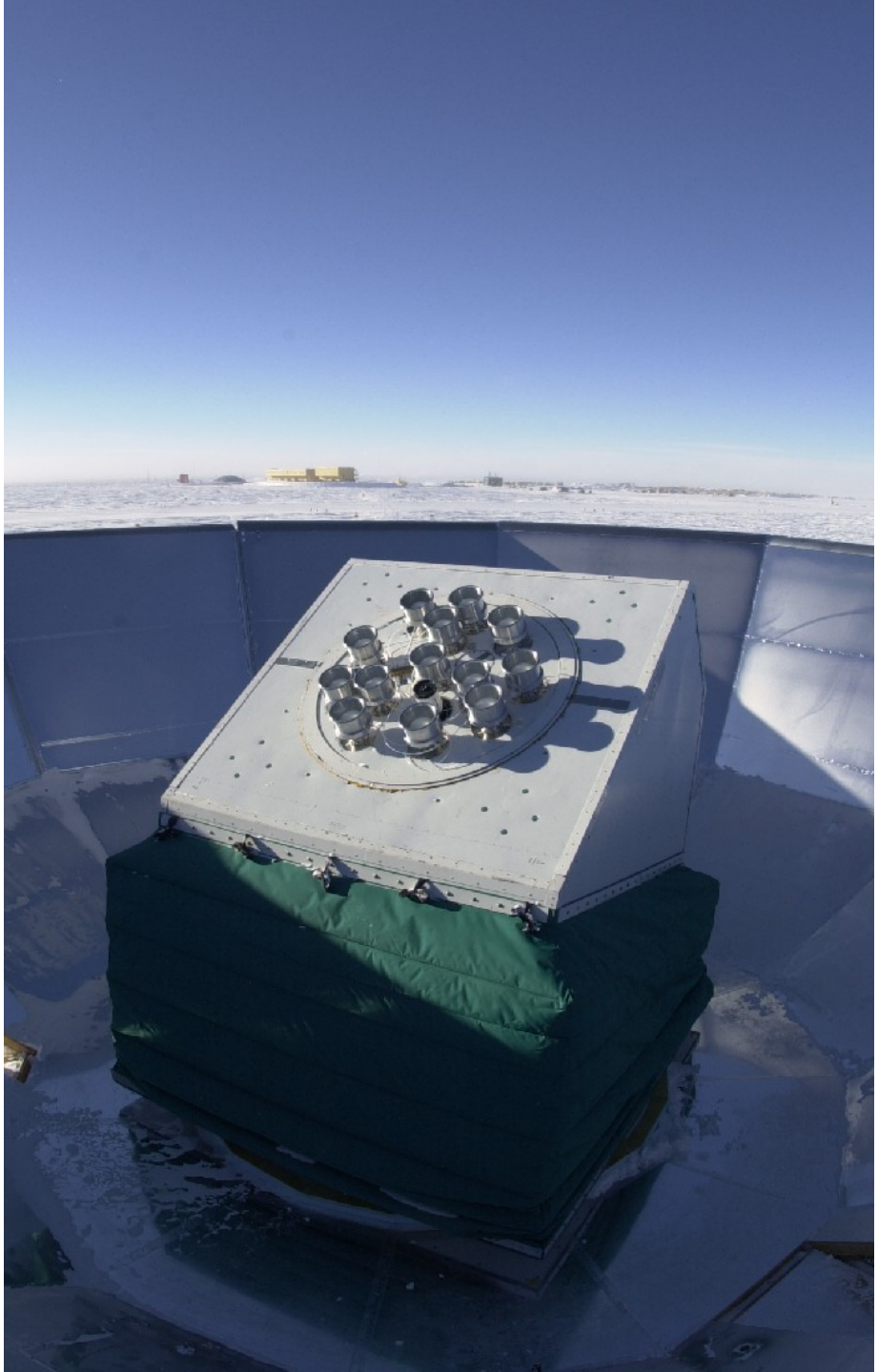
Also…

- Gravitational wave polarization
- Leads to E-mode polarization but…
- Also leads to B-mode polarization.
- What causes the B-mode?

In this paper

- Previously, only upper limits placed on polarization
- First done by Wilson and Penzias, improved by others
- But now, polarization has been detected!
- Degree Angular Scale Interferometer (DASI)

DASI!!!



Measurements

- Two, 3.4^{o} fields separated by 1h in RA (RA=23h 30min, RA=00h 30min, DEC=-55°)
- Why these fields?
- Results:
  - high confidence of detection ($\geq 4.9\sigma$)
  - E-mode level of .8 (predicted is from .9 to 1.1)
  - Upper limit of .59 for B-mode
  - TE correlation detected and consistent

Measurements

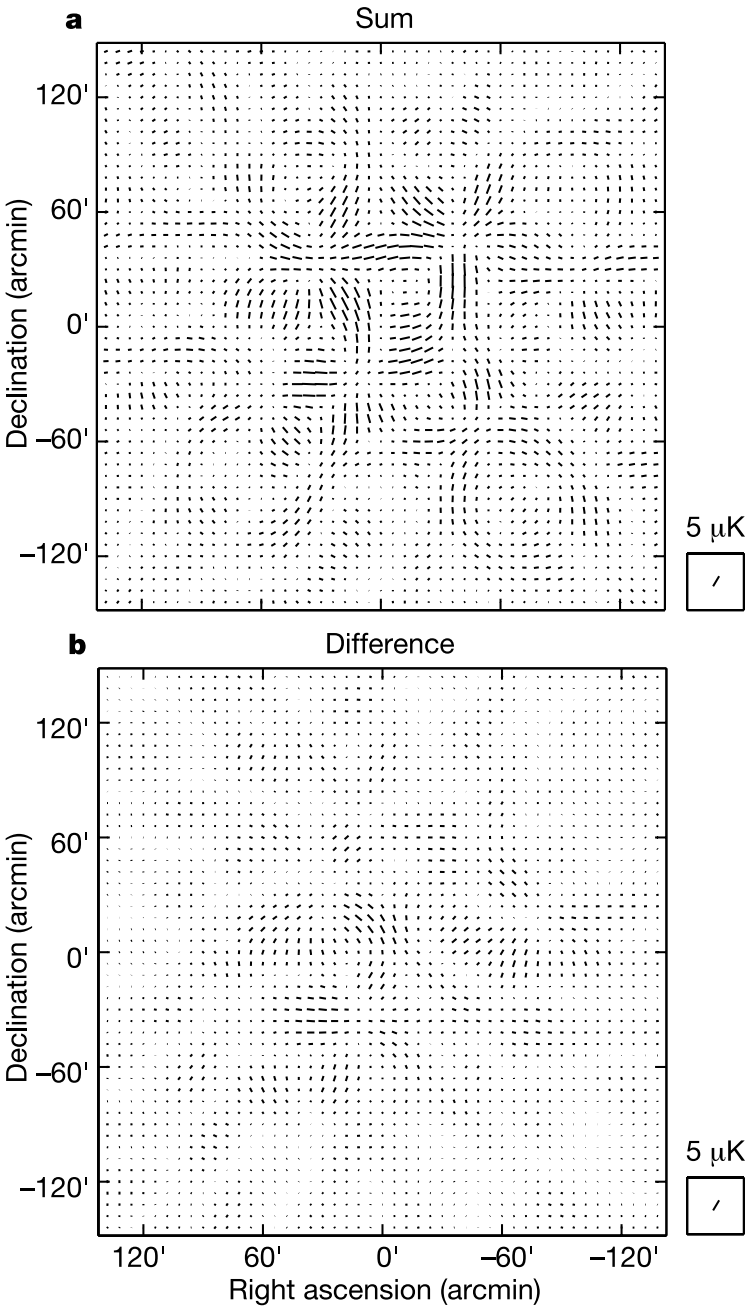
- One measures left polarized, one measures right polarized. From this and from knowing the intensity (found from measuring right or left circularly polarized in both), we can measure the degree of linear polarization.
- Calibration from RCW38

Measurements

- Every data point is considered to be signal plus noise: $\Delta = s + n$
- Noise, n, is assumed to be Gaussian with known zero mean.
- Why is this a good assumption?
- What happens if this is not a good assumption?

Measurements

- How do we know if what we find is the true signal of the CMB?
- χ^2 tests!
- $\chi^2 = \Delta^T C_N \Delta$

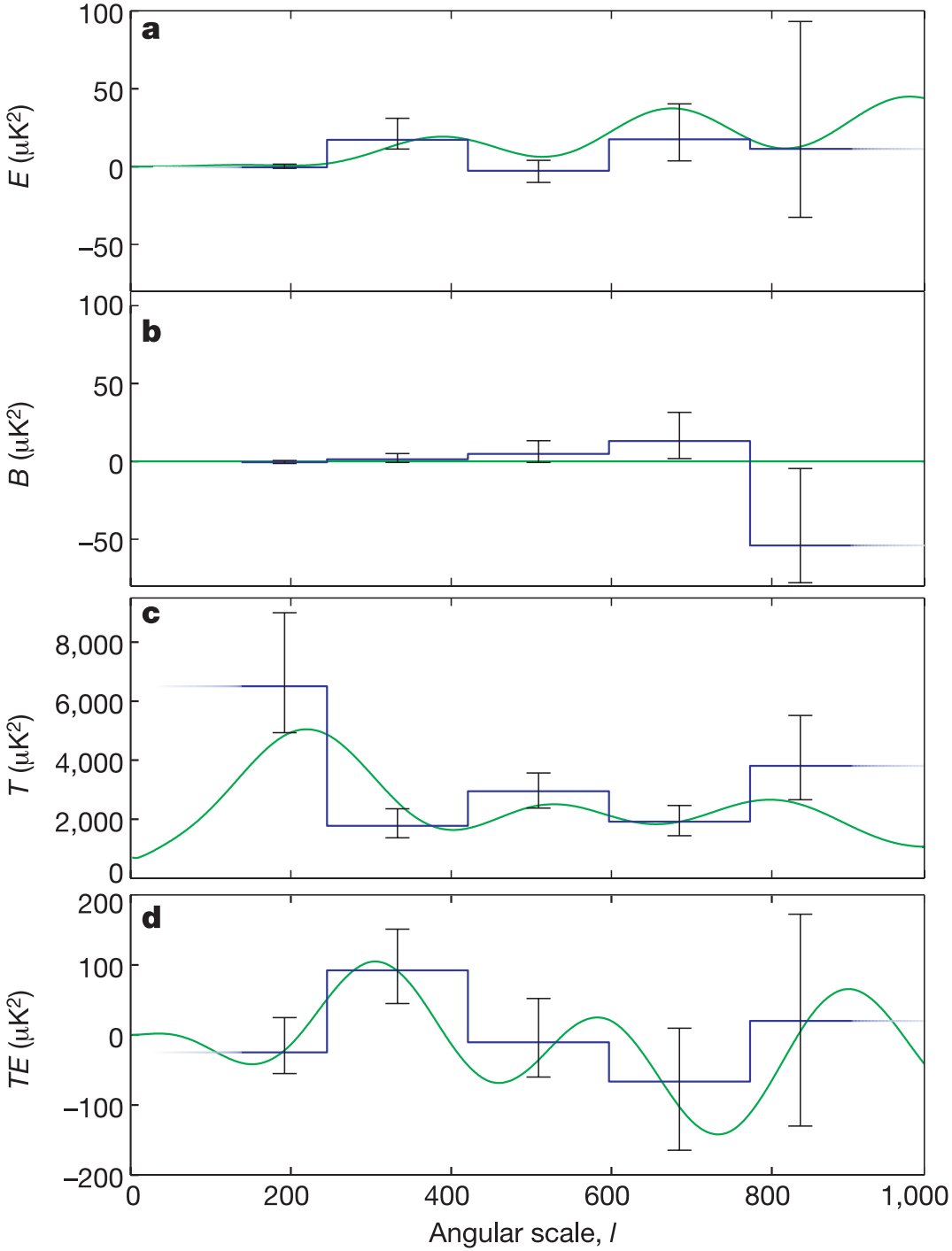


χ^2 Results

- These two plots show the result of summing (upper) and differencing (lower) the data with s/n > 1 in the "split by year" χ^2 data
- Sum (upper) is consistent with a polarized signal
- Difference (lower) is consistent with Gaussian noise

Likelihood Analysis

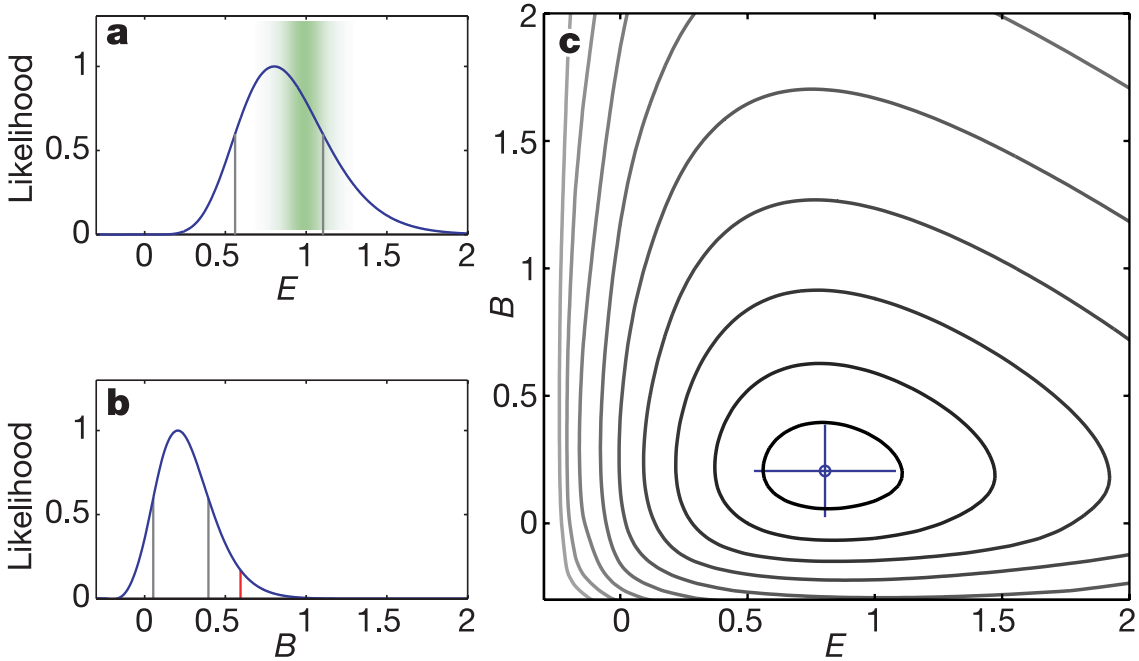
- CMB can be characterized statistically by: T, E, and B amplitudes, and the correlations TE, TB, and EB.
- Assumed model : ΛCDM, flat curvature, 5% baryonic matter, 35% dark matter, 60% dark energy, H_0 = 65 km/s/Mpc.



- What do you notice about the relationship between E and T?
- Is this what we expect?
- Why is the theoretical value for B set to zero?
- What are the current values for the parameters in the ΛCDM model, and would that change the result?

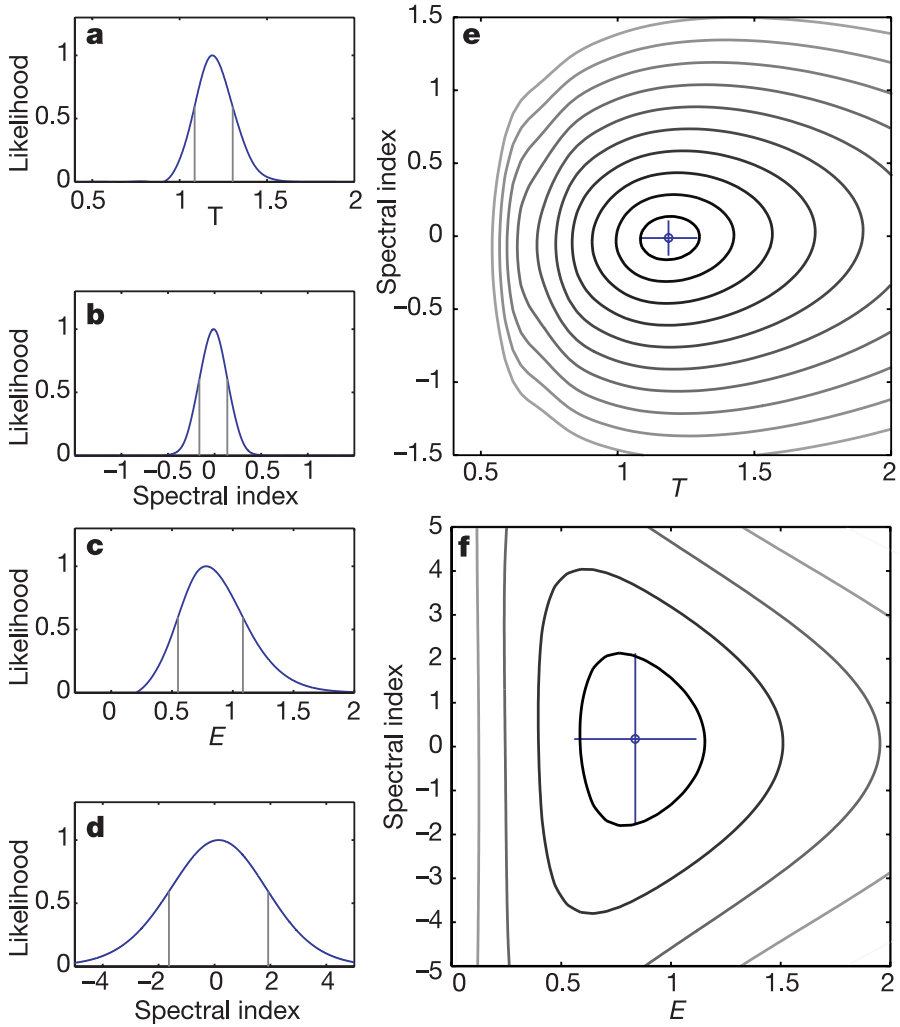
Likelihood Analysis Results

- E/B Results
- ML(E)=.80 (.56, 1.1)
- For B: 95% confidence is less than .56, so we can regard this as an upper limit.
- Significance of E detection is 4.92σ



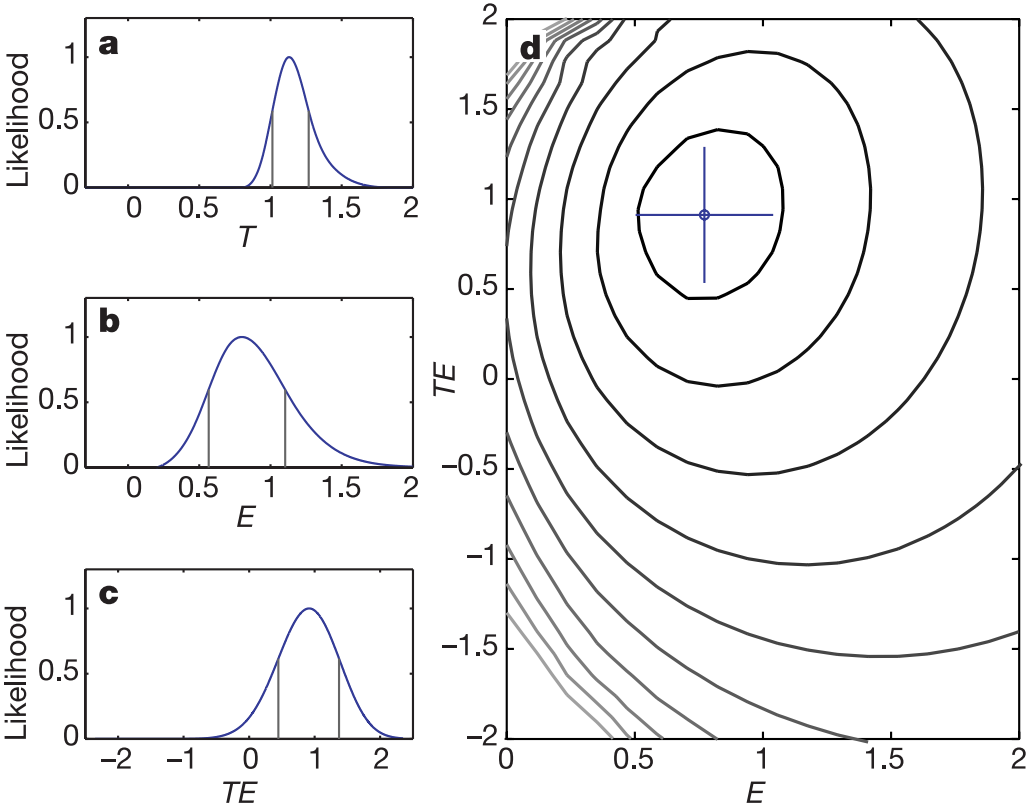
Likelihood Analysis Results

- T/β_T Results
- Normalized to 2.73 K Planck, so ideally we expect $\beta_T = 0$
- ML(T) = 1.19 (1.09, 1.30)
- ML(β_T) = -.01 (-.16, .14)



Likelihood Analysis Results

- T/E Results
- ML(TE) = .91 (.45, 1.37)



Conclusions

- It has been statistically confirmed that the CMB is in fact linearly polarized.
- It was also found that there exists a strong correlation between temperature fluctuations and polarization amplitude.
- No determination of the B-modes have been made.
- Theory is preserved!