Physics of CMB Polarization and Its Measurement

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Outline

- Physics of CMB and its Polarization
  - What does WMAP shed light on?
  - Unsolved Problems: Beyond SM
  - CMB Polarization as a Probe for Inflation
- Measurement of CMB Polarization
  - Detection Techniques
  - Experimental Status and Prospects
    - Current Measurements (1st generation)
    - 2nd Generation Experiments, and beyond

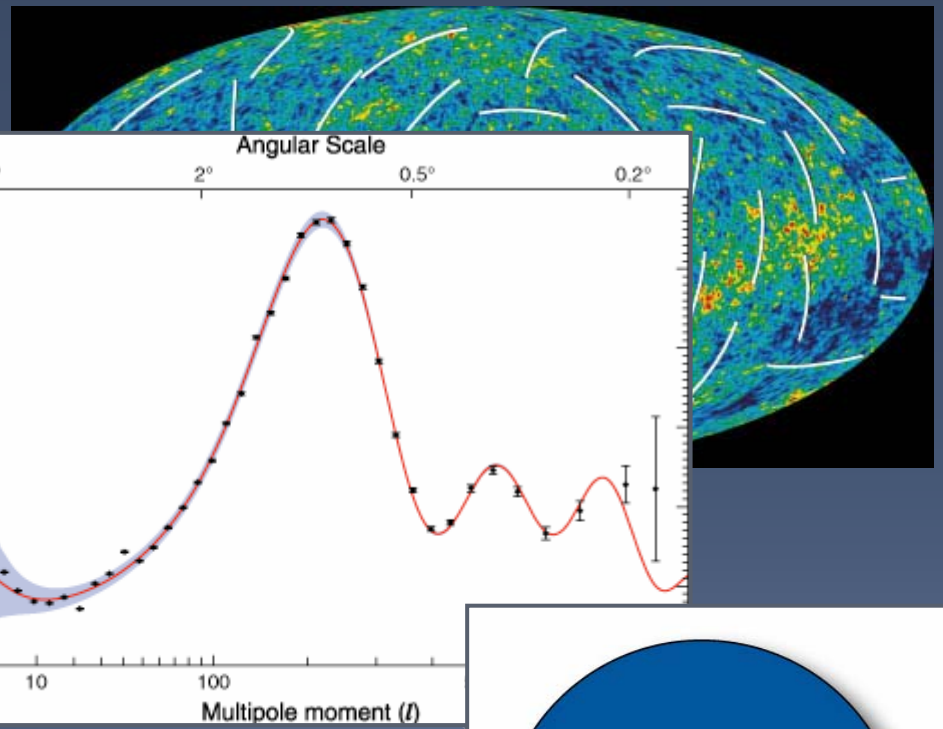
Physics of CMB and Its Polarization

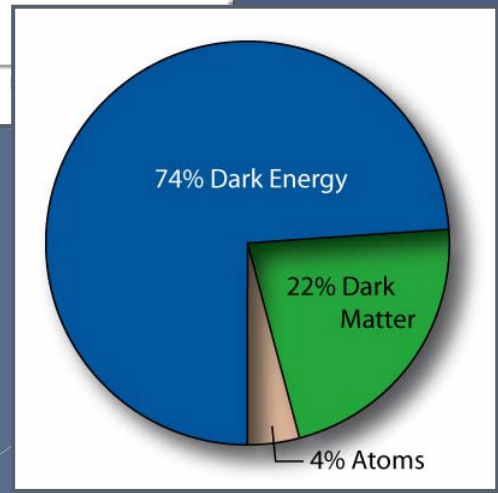
Cosmology After WMAP

NASA/WMAP Science Team

WMAP (+ Others)

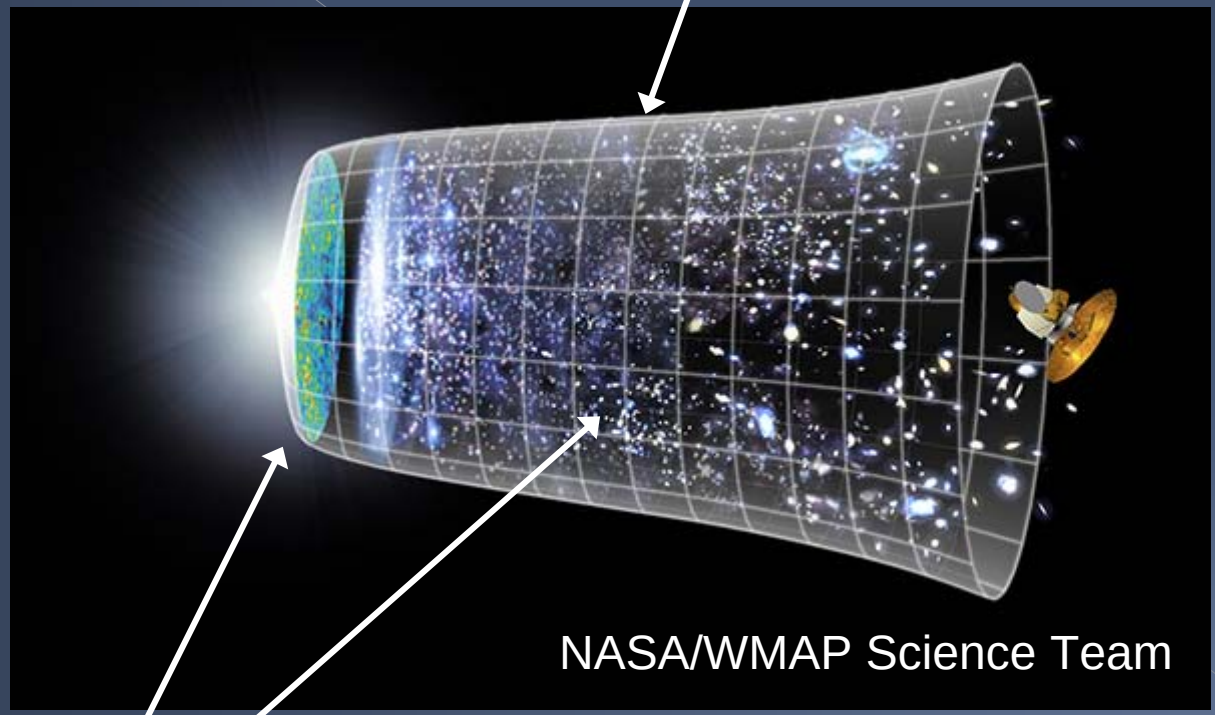
- Flat ΛCDM
  - $\Omega_{all} \sim 1$
  - $\Omega_{\Lambda} = 0.74 \pm 0.06$
  - $\Omega_m h^2 = 0.13 \pm 0.01$ ($\Omega_m \sim 0.26$)
  - $\Omega_b h^2 = 0.022 \pm 0.001$
- +Implications
  - Dark Energy ~ Λ
  - Consistent w/ Inflation





Solved and Unsolved Problems

Solved: Time Evolution of the Universe



Unsolved: Physics of the Beginning (Inflation)
Source of the Evolution (Dark Energy, Dark Matter)

Unsolved Problems

- Inflation
  - Is it true?
  - What's the correct model?
  - Shape of potential: Physics at GUT Scale?
  - Signature: Primordial Gravitational-Wave (CGB?)
  - Detectable via CMB Polarization

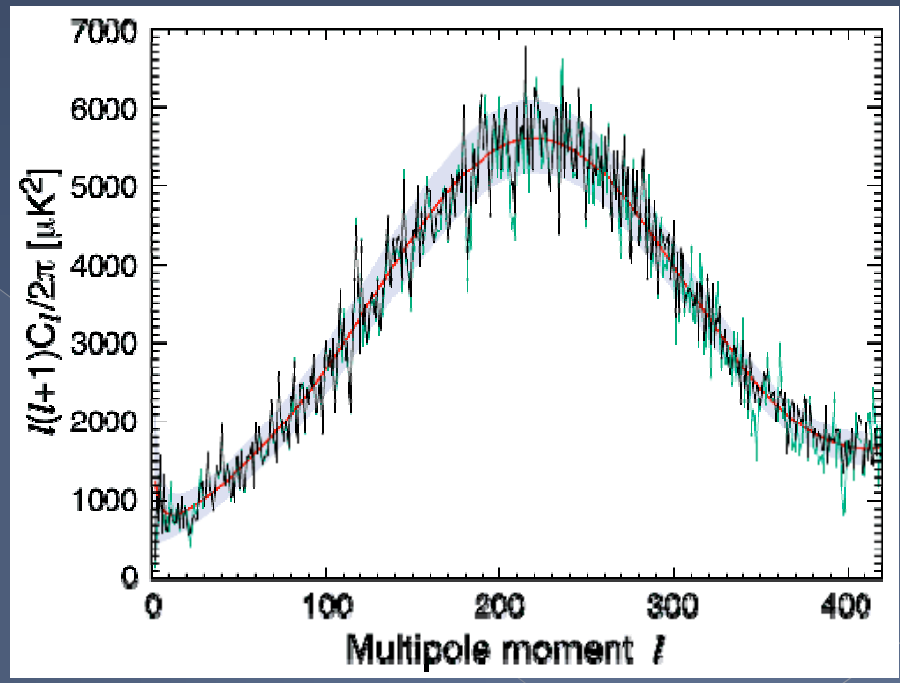
- Dark Energy
  - Equation of State: $w = p/\rho$
  - Dark Energy = Cosmological Constant? (i.e., $w = -1$?)

Cluster Survey, Weak Lensing, CMB SZE, ABO, SNe Ia, etc...

Digression: Can we go further with CMB?

- Cosmic Variance
  - We want to measure the "PDF" of CMB.
  - We only have one realization (our sky), i.e., one event.
  - *TT* at small *l* (incl. first peak) is now cosmic variance limited.
- To go further:
  - *TT* at large *l*
  - Polarization

Three-Year WMAP, Hinshaw *et al*.



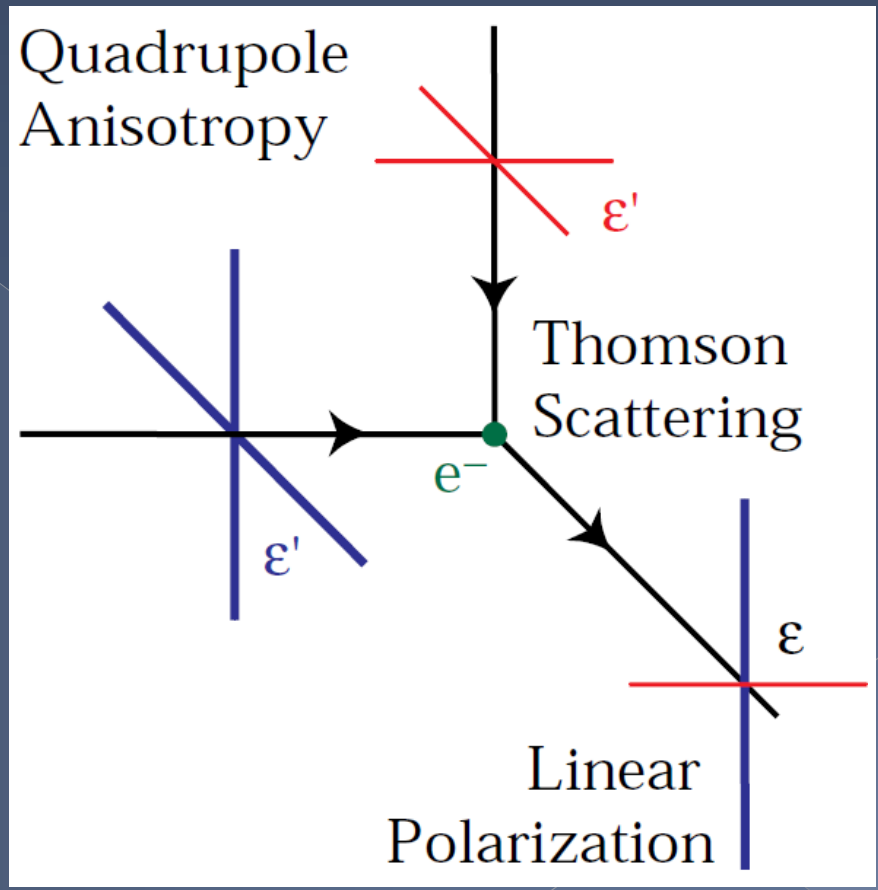
TT (Temperature) Correlation

Black: WMAP Three-Year
Green: WMAP First-Year
Gray Band: Cosmic Variance Expectation

CMB Polarization

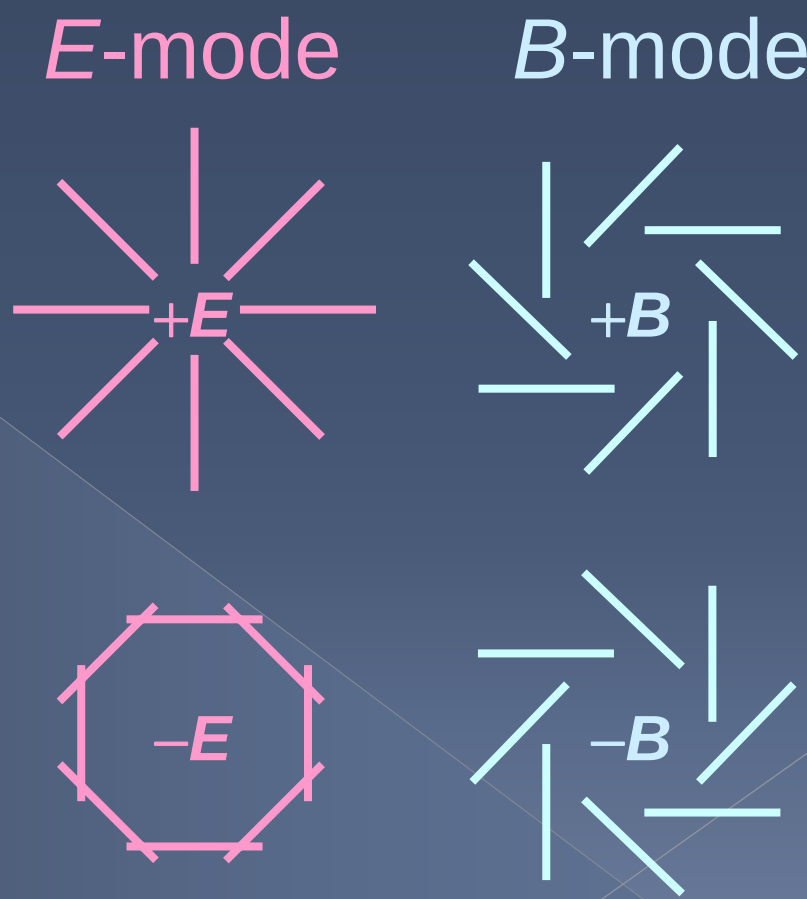
- CMB is from last (Thomson) scattering
  - →Linearly polarized
- Anisotropy
  - →Non-zero overall polarization

A CMB Polarization Primer (Hu & White)



E-mode and *B*-mode

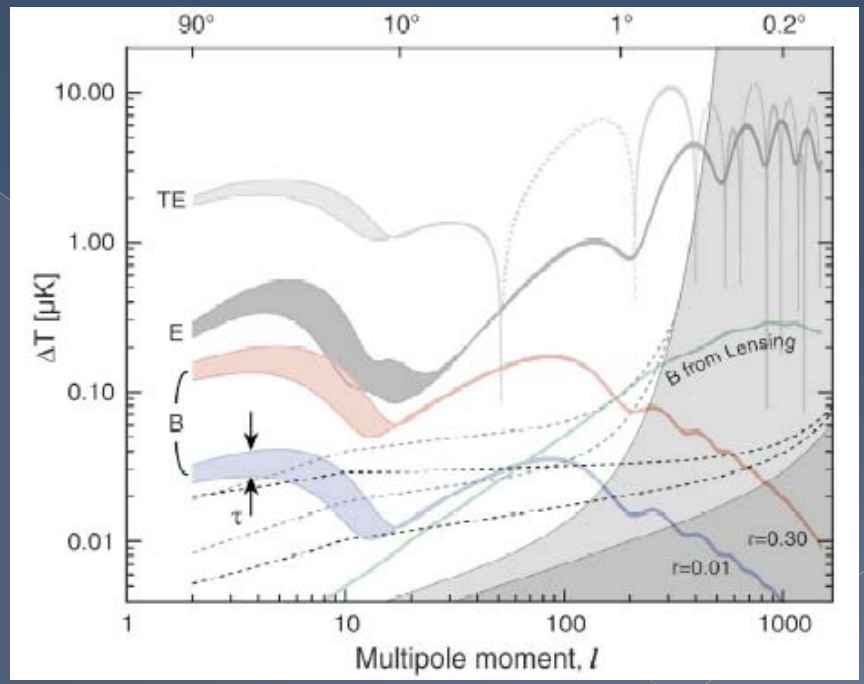
- Polarization: Tensor-field
  - Tensor = “Bar” without direction
  - c.f. Vector = “Bar” with direction
- Decomposable into *E*-mode and *B*-mode
  - Analogous to the vector field decomposition to (rot. free mode) + (div. free mode)



B-mode Polarization

- Only sourced by gravitational wave from Inflation
  - Unique signal of Inflation
  - Intensity of *B*-mode → Tensor/Scalar $\propto$ V
  - V: Inflation potential, GUT scale ?
- Gravitational lensing converts *E*-mode → *B*-mode at large *l*.

TT is around here (~$10^3\mu$K)



$r = (T/S)^2$

T/S~0.1 if V~GUT scale

More on CMB Polarization

- Lensing *B*-mode
  - Not only contamination for primordial *B*-mode
  - Can be a probe for mass distribution → information for Dark Energy w
- *E*-mode and *TE*-correlation
  - Improvement in cosmological parameters
  - Consistency check (robustness w.r.t. assumptions such as adiabaticity)
- *TB*- and *EB*-correlation
  - Zero (otherwise, there is parity violation)

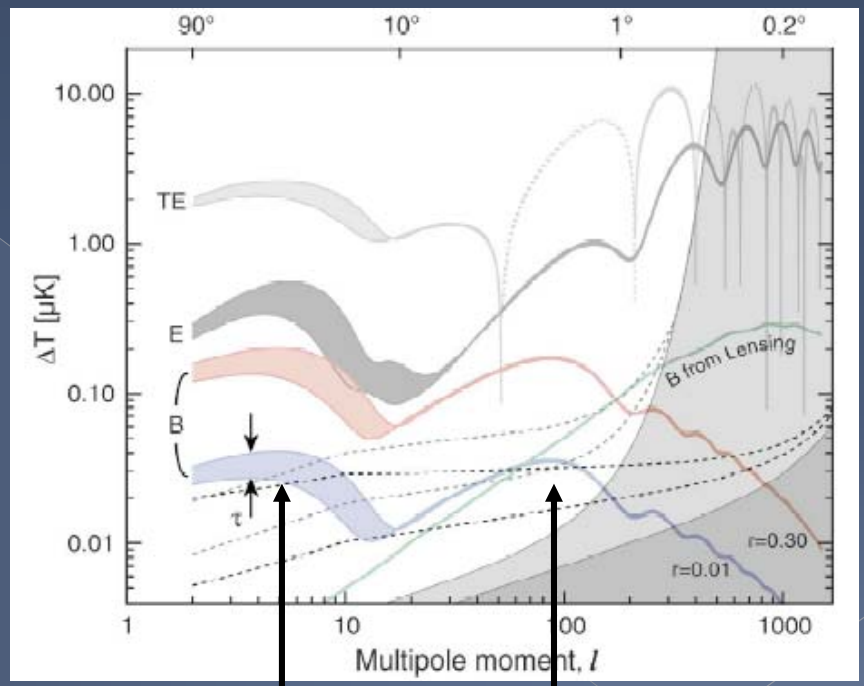
Measurement of CMB Polarization

Primary Target: *B*-mode

Two possible targets

- Small l (l~5: ~50°)
  - Free from lensing *B*
  - Originates from reionization
  - Advantageous to Satellite
- Large l (l~100: ~2°)
  - Could be lensing *B* dominant (subtract?)
  - Ground based is competitive

CMB Task Force



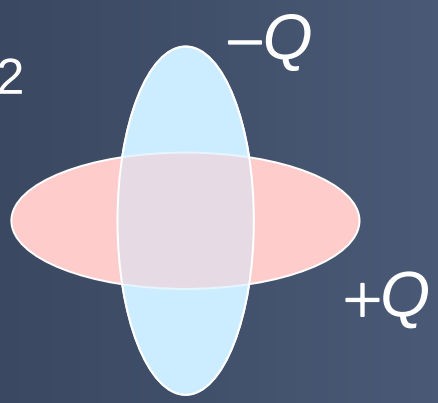
l~5 l~100

NOTE: atmosphere is not polarized

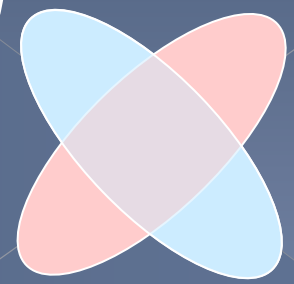
Basics of Polarization

- Stokes parameters (*I*, *Q*, *U*, *V*)
  - A set of parameters fully characterizing intensity and polarization of radio wave.
  - *I*: Intensity (→ *T* in CMB)
  - *Q*, *U*: Two linear polarization (→ *E*, *B* in CMB)
  - *V*: Circular polarization (zero in CMB)

$Q = E_x^2 - E_y^2$



$U = 2E_xE_y$

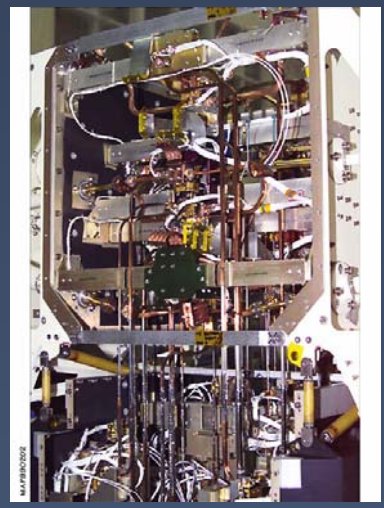


Order

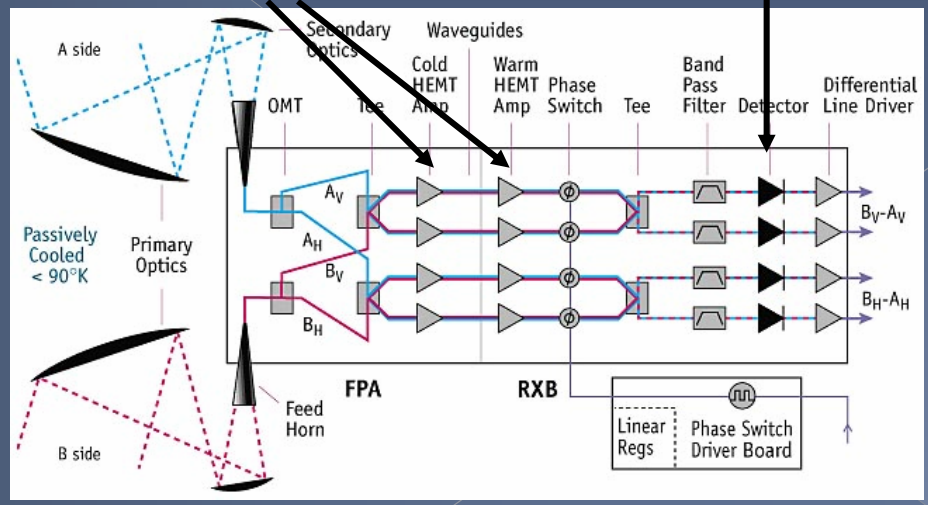
- Two technologies: Bolometer vs. HEMT
- Feasibility
- Array
- Choice of band
  - Which region of 20GHz~500GHz
  - “Foreground” contribution

HEMT (+ diode detector)

- "Usual" way of radio wave detection: amp. → rectification
- Established technology
  - WMAP, DASI, CAPMAP, ...
- Limited by quantum noise: $T_{\mathrm{det}} \propto h\nu/k$
  - Good in low ν (ν<100GHz)



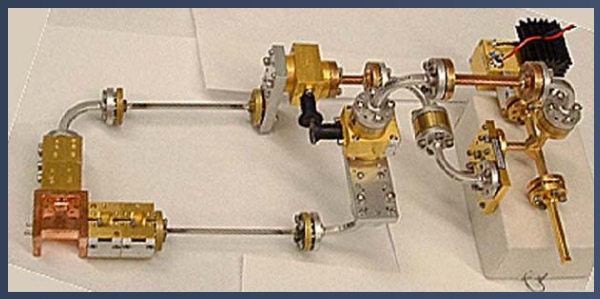
WMAP receiver



HEMT (+ diode detector)

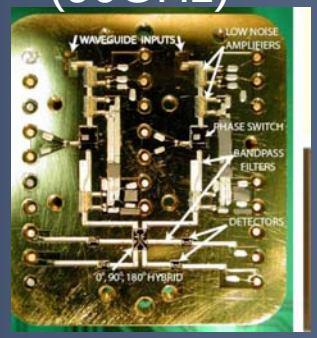
- (Pseudo-)Correlation polarimeter Gain diff. cancellation
- Recent technology breakthrough (MMIC+packaging) for arraying

CAPMAP polarimeter



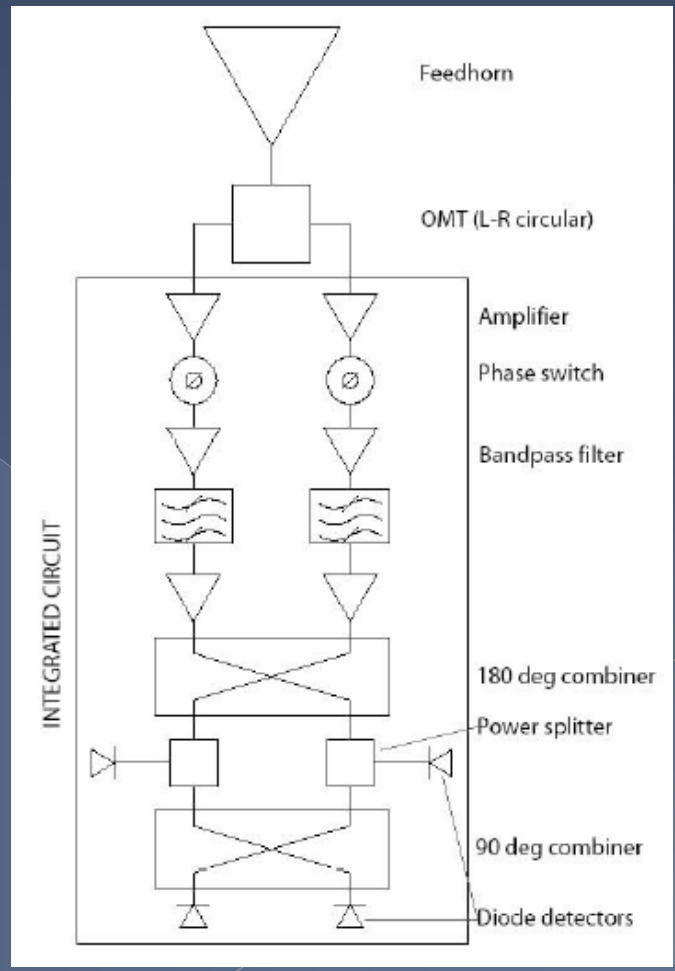
~30cm

QUIET polarimeter (90GHz)



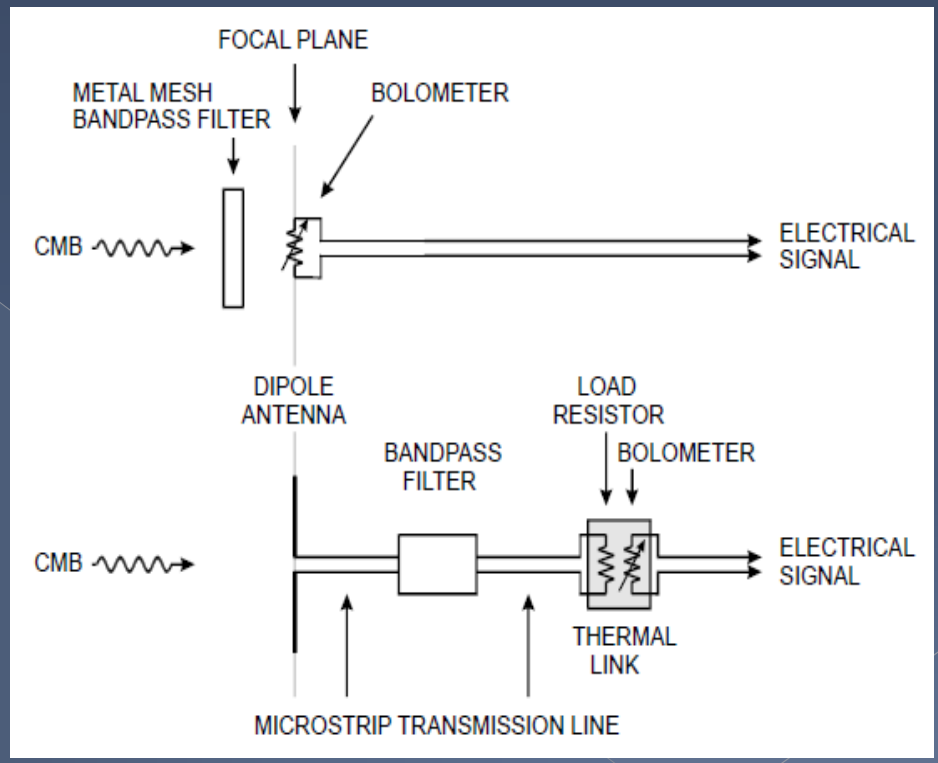
~3cm

Pseudo-correlation polarimeter
(from CMB task force)



Bolometer

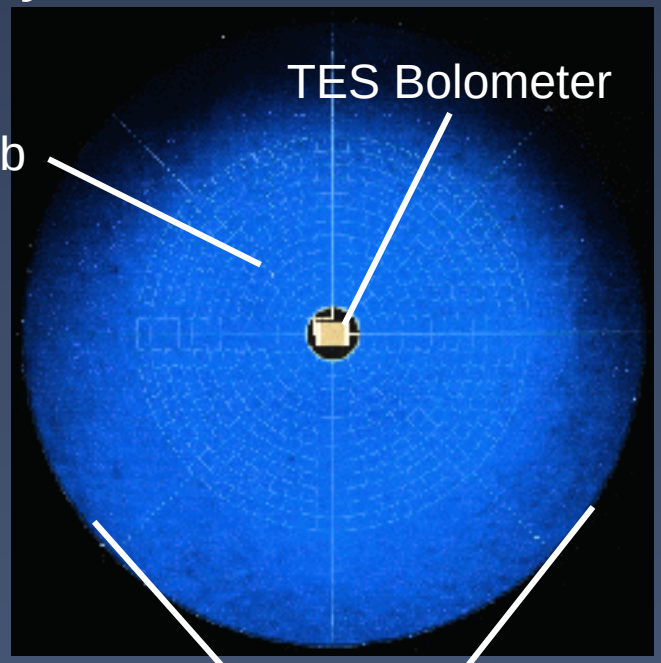
- Direct detection of total "power" of radio wave
- No quantum noise limit
- Technically challenging
- Low ν → large heat load → Difficulty in low ν
  - Overcome by antenna coupled bolometer
- Promising detector type in future

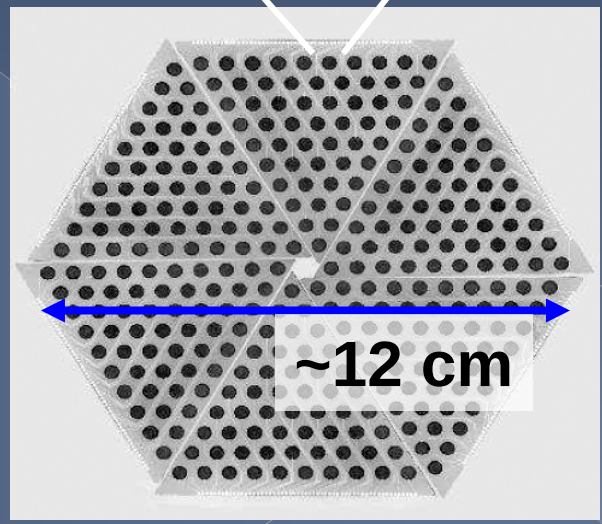


Bolometer

- Good at making large array
- Antenna coupled bolometer has polarization sensitivity (PSB) $|Ex|^2$, $|Ey|^2$ measurement

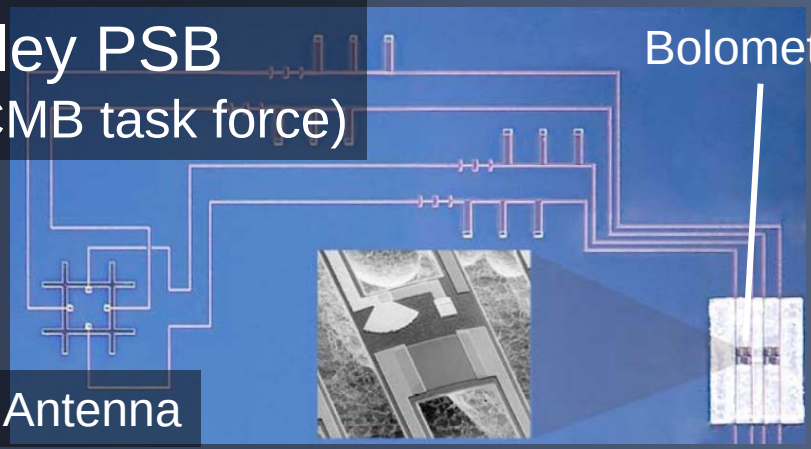
Berkeley Bolometer





SPT Bolometer Array

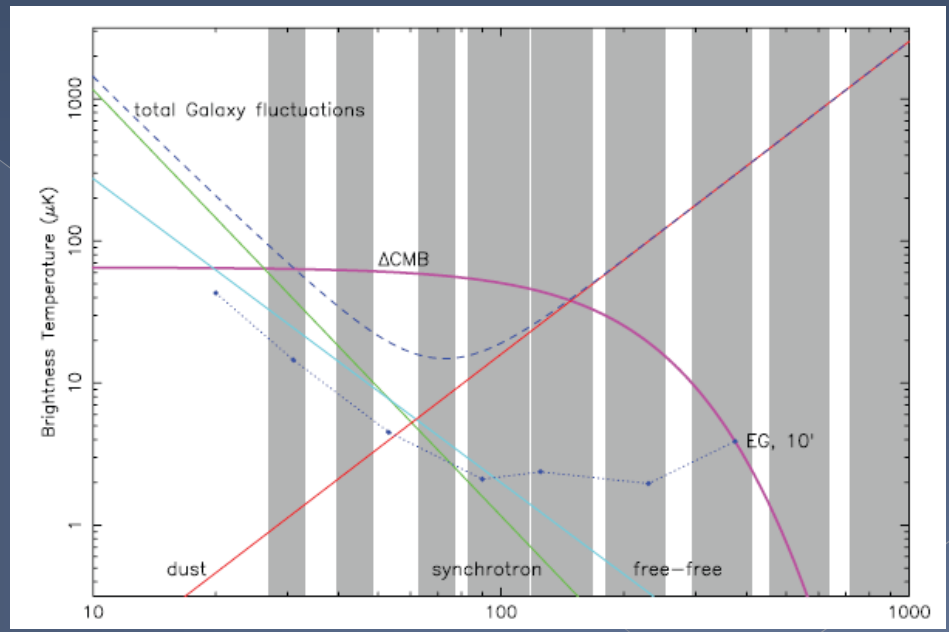
Berkeley PSB
(from CMB task force)



“Foreground”

- Contamination for “Background” measurement: “Foreground”
- Primary, inevitable systematic error
- Two large sources
  - Synchrotron radiation from cosmic ray
  - Dust emission (dust aligned in *B* field)

PLANCK “Blue Book”



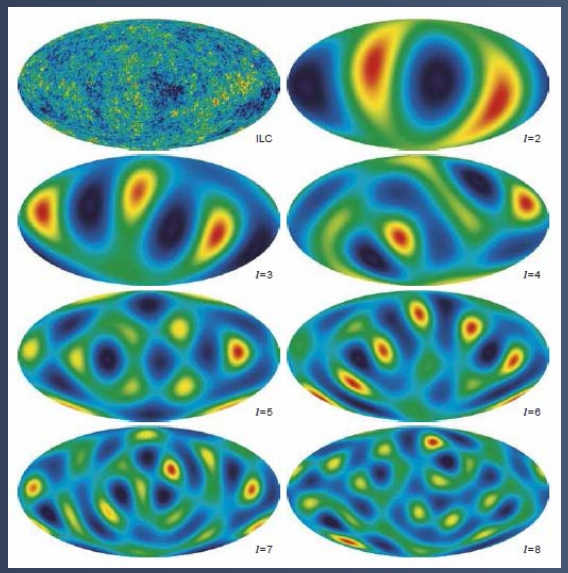
Spectra of CMB and foreground sources

Choice of Technology

- HEMT
  - Quantum noise limit: $T_{\mathrm{det}} \sim h\nu/k_{\mathrm{B}}$
  - Good at ν<100GHz
  - Relatively established
  - MMIC + packaging technology for array
  - (Pseudo-)correlation polarimeter
- Bolometer
  - No quantum noise limit
  - Good at ν>100GHz
  - Also good at ν<100GHz with antenna coupling
  - Challenging
  - Suitable for array
  - “Brute force” polarimeter
  - (Correlator type is also possible)

Multi-pole analysis

- TT correlation (scalar field)
  - Spherical harmonics expansion



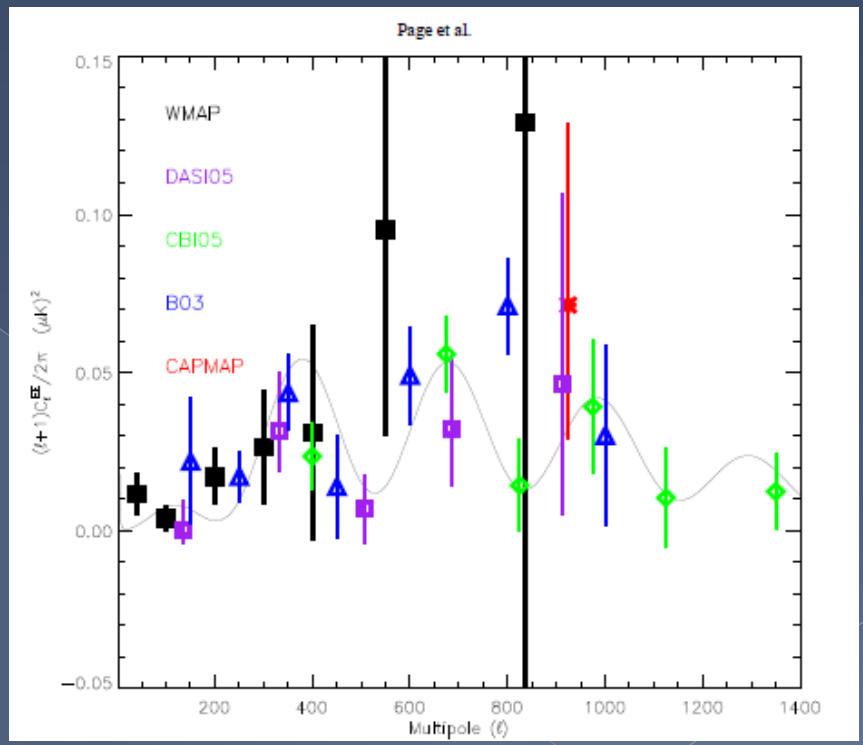
Three-Year WMAP, Hinshaw *et al*.

- Polarization (tensor field)
  - Tensor spherical harmonics expansion
  - Simple FT of div. and rot. field (for small patch of the sky)
- Practical difficulty
  - Irregular sampling
  - Border of patch

Current Status

- Significantly non-zero *EE* correlation is found
  - WMAP, DASI, CBI, BOOMERanG, CAPMAP
- WMAP *TE* correlation
  - Improvement of limits on cosmological parameters
- No significant *BB* measurement, yet

EE Correlation



Three-Year WMAP, Page *et al*.

Coming Experiments

- Targets
  - Primordial *B* from inflation
  - Lensing *B* for mass profile measurement (experiments w/ high resolution)
  - *E* to improve limits on cosmological parameters
- Detector improvement
  - Large array → Better statistics
  - Better detector sensitivity

Coming Experiments

Balloon
Taking data
(Main target=SZE)

- Bolometer
  - (AMiBA), BICEP, BRAIN/CIOVER, *EBEX*, MBI-B, *MAXIPOL*, *PAPPA*, PolarBeaR, Polatron(?), QUaD, (SPT), *Spider*
- HEMT
  - *BaR-SPOrt*(?)/SPOrt(?), QUIET
- Bolometer + HEMT (depending on freq.)
  - PLANCK

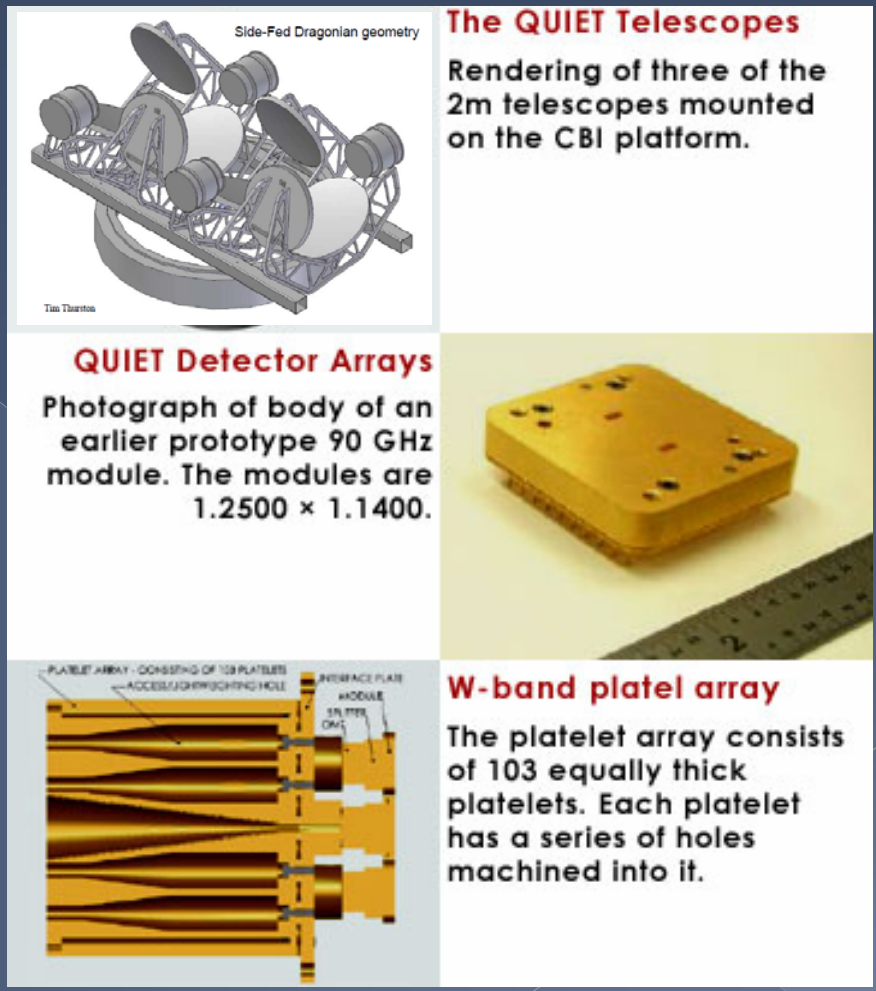
See the following site for compilation
http://lambda.gsfc.nasa.gov/links/experimental_sites.cfm

QUIET

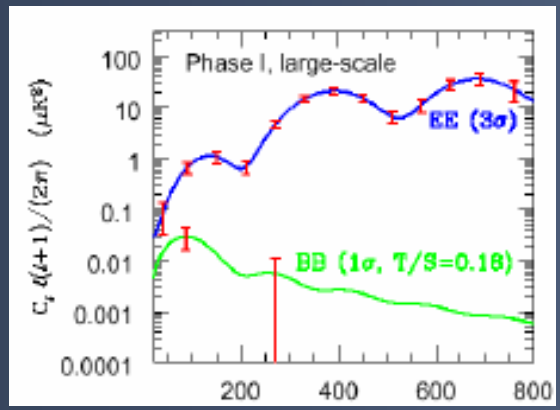
- *Q*/*U* Imaging ExperimenT
- Detector: HEMT
  - Two bands: W-band (90GHz) and Q-band (40GHz)
  - HEMT array (91 elements for W, 19 elements for Q)
  - The only next generation HEMT experiment
  - The only next generation (*B* competitive) program straddling across 60GHz
    - NOTE: 60GHz = WMAP implies lowest foreground
- Site: Chile, Atacama
- Collaboration
  - ~10 US institutes (incl. CAPMAP&CBI) + Oxford, MPI Bonn
  - ~20 staff + students
- Cost: ~a few M USD

QUIET

All the figures from QUIET web site
http://quiet.uchicago.edu/



Sensitivity



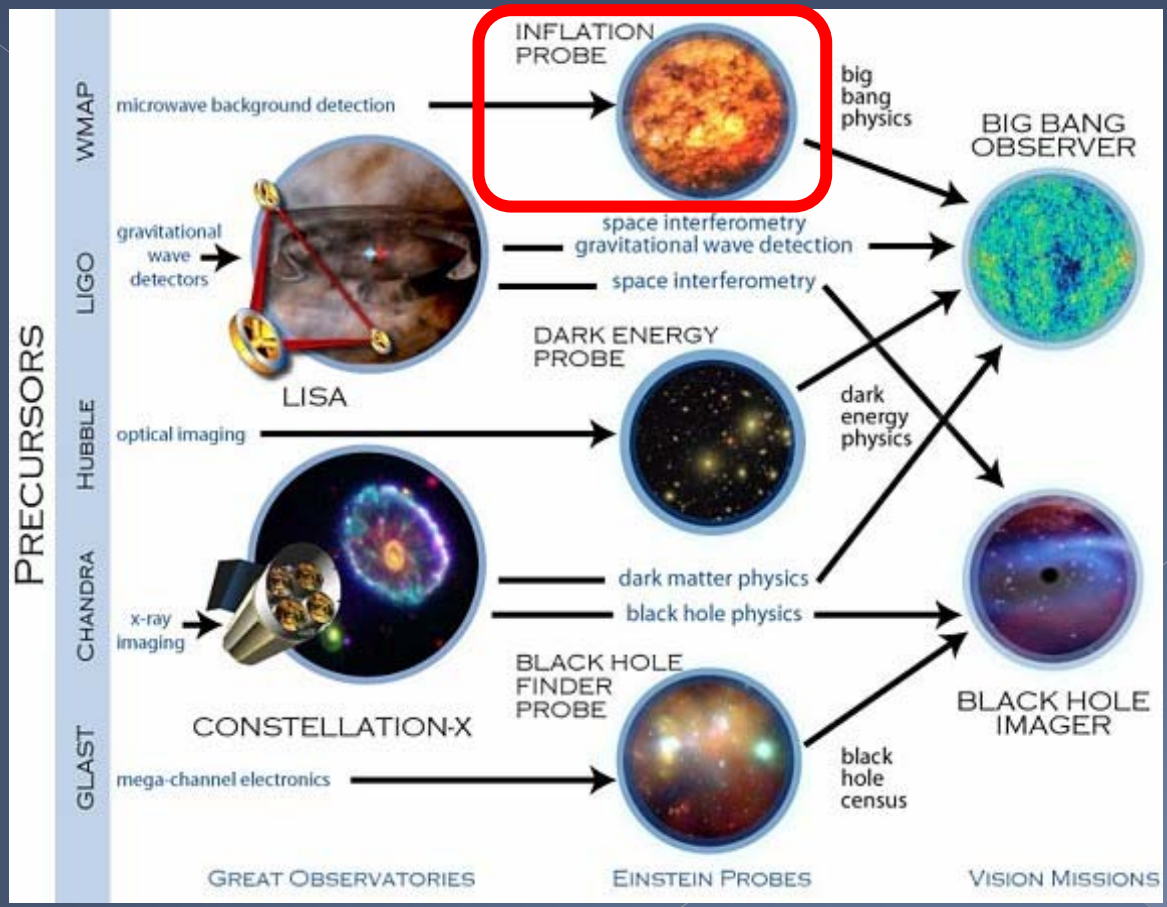
Deployment: 2007 Fall, First Science Result: 2008 Summer

Next Next Generation

- Ultimate CMB experiment
  - Satellite
  - Target: *B*-mode at low *l*
  - Bolometer
- (Ground Based)
- Japanese community may take part
  - Tohoku
  - KEK
  - …

Beyond Einstein Program

http://universe.nasa.gov/program.html



Summary

- Unsolved Problems of Cosmology
  - Inflation and Dark Energy
- *B*-mode Polarization of CMB
  - Sensitive to Inflation
- Detector Technology
  - Bolometer vs. HEMT
- Current Measurement: *E*-mode found
- Experiments Dedicated to *B*-mode: coming soon…