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Introduction to CMB Science Day 2

- Polarization Theory
- Secondary Anisotropies
- Technical Issues
- Foregrounds
- Experiments, results, the future

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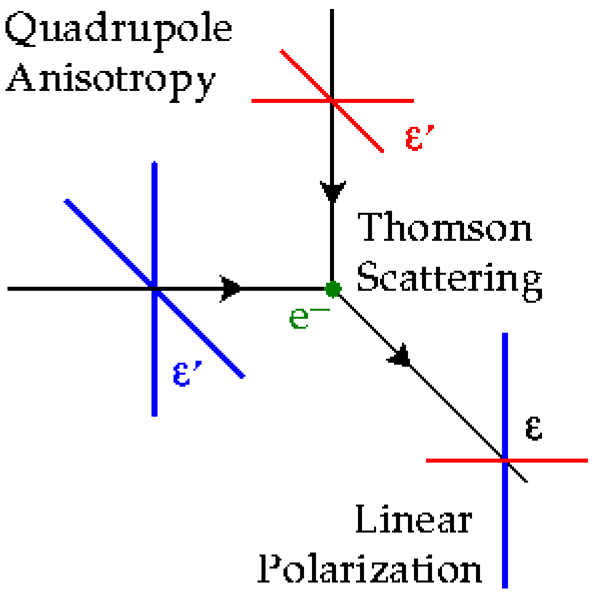
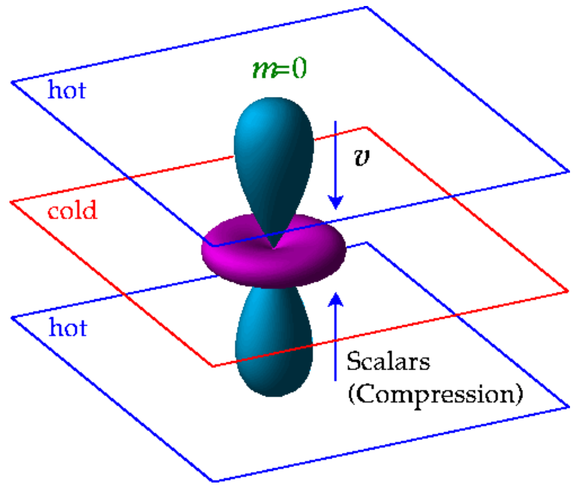
Polarization

- Linear polarization predicted by gravitational instability paradigm.
  - If observed temperature anisotropies are result of primordial fluctuations, their presence at last scattering will polarize CMB anisotropies.
- Probes epoch of last scattering directly.
- Different sources of temperature anisotropies (scalar, vector and tensor) give different polarization patterns
- ~10 times lower, ~1 μK

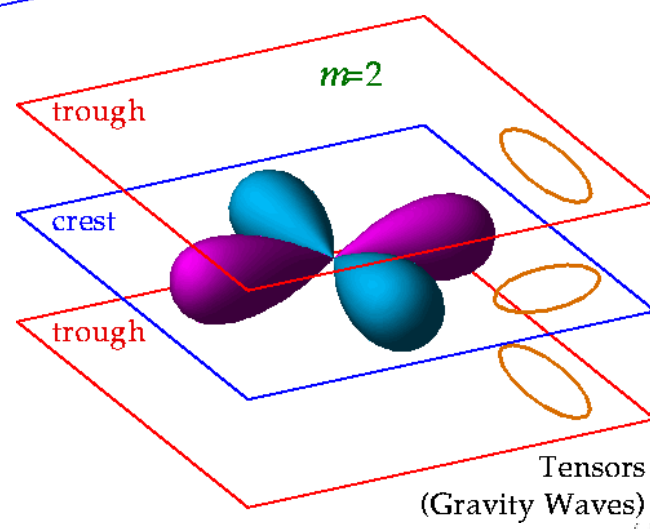
Generation of polarized CMB radiation by Thomson scattering (Hu)





Scalar quadupole moment

Tensor quadrupole moment



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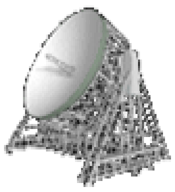
Scalar Polarization

- Relatively large because at last scattering photons likely to travel significant distance between scatterings
  - By definition!
- Only occurs on causally-connected angular scales
  - acoustic peaks when generated at last scattering
  - Large scales when generated by re-ionization
- Somewhat smaller-scale than structure in total intensity as driven by gradients in brightness
- Polarized brightness up to 10% of total intensity fluctuations on small scales.



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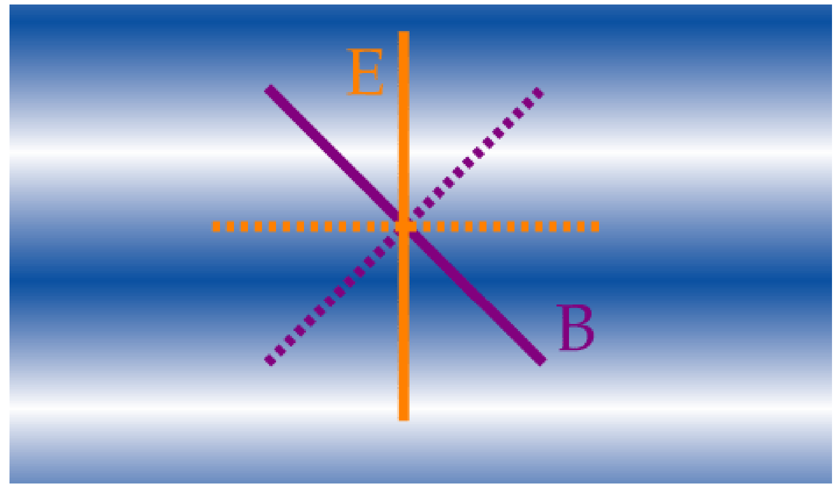
Tensor Polarization

- Driven by very-large scale gravitational waves generated in inflation
- Essentially negligible on ‘causal’ scales, strongest below $\ell = 100$ (~2°)

E-mode vs B-mode

- Polarization pattern on sky can be separated into two orthogonal modes:
  - E-mode or gradient mode
  - B-mode or curl mode
- For plane waves, E-modes polarized alternately parallel & perpendicular to wave vector
- B-modes at 45°
- B-modes have opposite parity to E-modes
- B-modes only generated by tensor fluctuations



Hu

- Names based on obscure & confusing analogy with EM fields; ignore!
- (Polarization always refers to electric field orientation)

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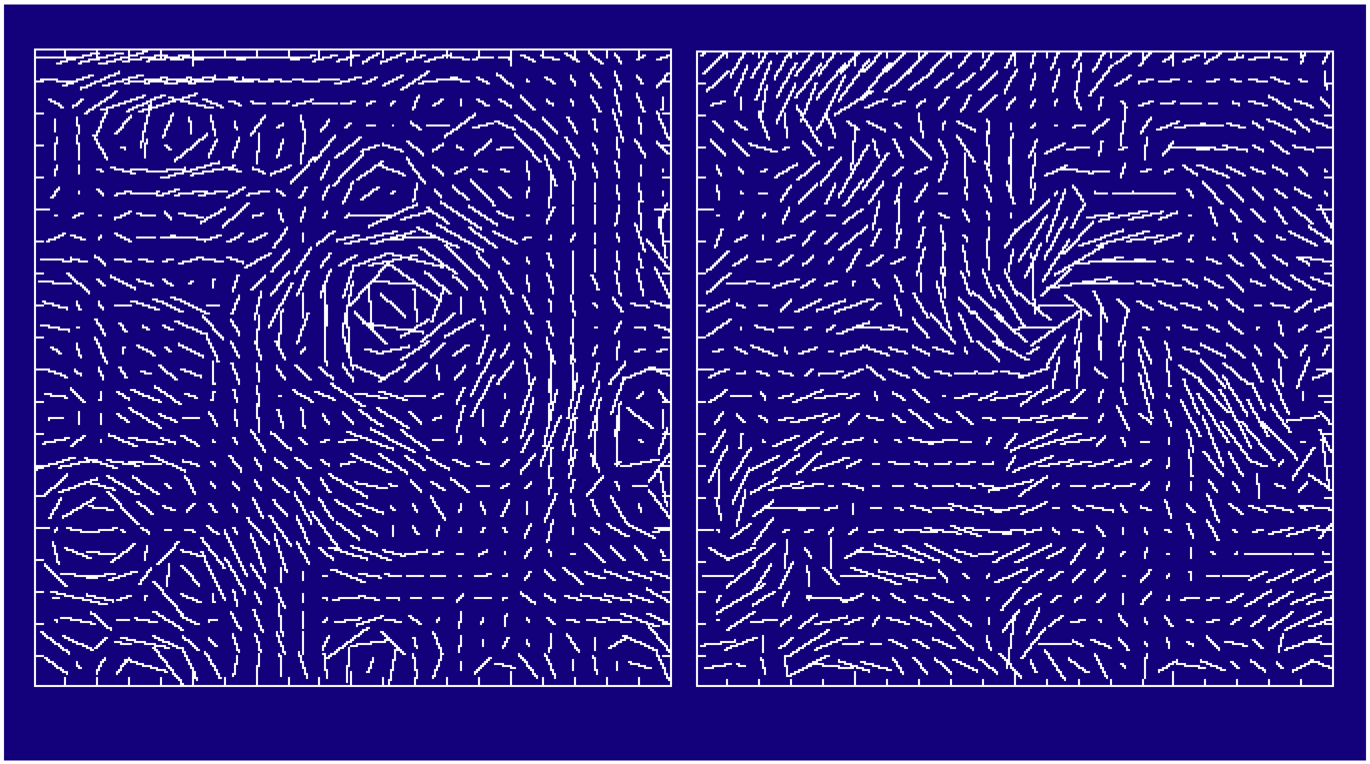
E-mode vs B-mode



Wayne Hu

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${}_{\pm 2}Y_{lm}$: Spin-2 Spherical Harmonics

- Polarization normally represented by Stokes parameters

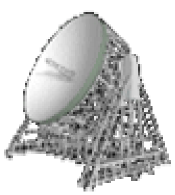
  $I \propto |E_x|^2 + |E_y|^2$
  - Total intensity

  $Q \propto |E_x|^2 - |E_y|^2$

  $U \propto Re(E_x E_y^*)$
  - Linear pol^n

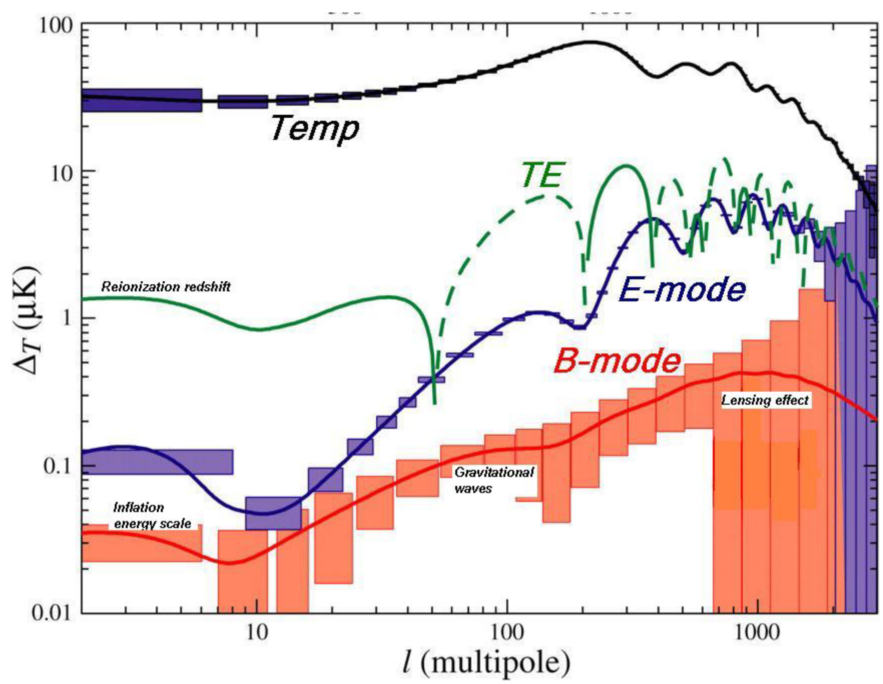
  $V \propto |E_R|^2 - |E_L|^2$
  - Circular pol^n
- But depend on coordinate system defining x and y

- Polarization is "Spin-2" quantity
  - orientation but no direction
- Analyse in terms of "spin-2 spherical harmonics" ${}_{\pm 2}Y_{lm}$
- Harmonic coefficients can be summed & differenced to yield pure E- and B-modes
- E mode parity $(-1)^\ell$
- B mode parity $(-1)^{\ell+1}$
- $a_{lm}^{E,B}$ Coefficients coord-dependent, but not C_ℓ



Polarization C_ℓ Spectra

- E-mode peaks interleave with total power
- E-mode correlated with Temp (Stokes I), alternately positive & negative
- B-mode uncorrelated due to opposite parity
- Note bump at ℓ < 10 due to scattering after re-ionization
- Tensor mode only separable from scalar in B-mode pol (no scalar contribution)
- B-mode amplitude assumes maximum possible scalar-to-tensor ratio r



Hu & Dodelson, (2002)

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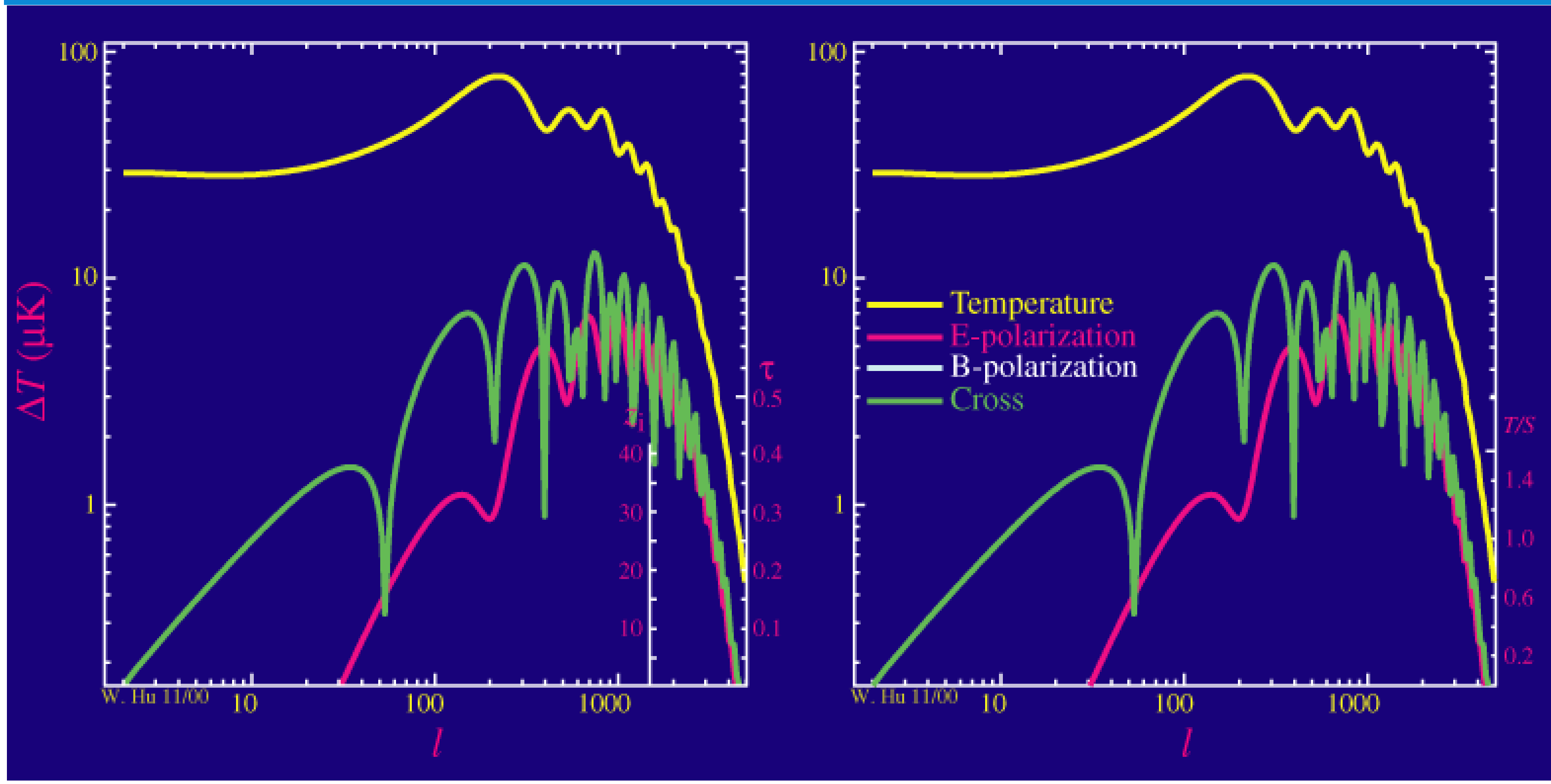
Parameters affecting Polarization



Hu

Reionization   Tensor/scalar

Secondary fluctuations

Gravity	Early/Late ISW Rees-Sciama Lensing
Local reionisation	Thermal SZ Kinematic SZ
Global reionisation	Suppression Vishniac New Doppler

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Gravitational Lensing

- We see CMB through the distorting gravitational lens of the intervening large-scale structure.
- Main effect is on scales ~ a few arcmin:
  - lensing by massive clusters.
- Non-gaussian signal dominated by relatively isolated features
- Biggest impact is on B-mode polarization:
  - lensing does not alter polarization angle
  - does moves apparent source of radiation
  - Hence converts pure E-mode to give residual B-mode
  - At low ℓ, quasi-point-source signal $\rightarrow$ "white noise", constant C_ℓ.
  - Rolls off at $\ell > 1000$ as clusters resolved
- Combination of total intensity and polarization allows lensing to be modelled in principle to reduce effect by ~ 1 order of magnitude, provided lenses well resolved.

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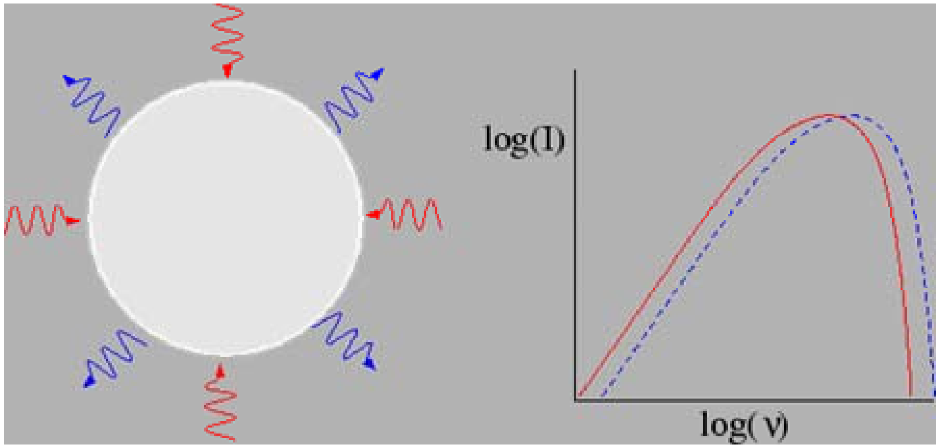
Integrated Sachs-Wolfe Effect

- CMB photons are affected by the fluctuating gravitational potential along line-of-sight.
  - Gain energy (in local frame) as they enter a potential well (e.g. cluster)
  - Lose energy as they leave
  - If potential static no net effect
- ISW: effect of potentials evolving in time
  - Largest if there is dark energy as this increases path length for given redshift.
- Will be correlated with forground structures (galaxy clusters etc)
  - Isolate via cross-correlation

Sunyaev-Zel'dovich Effect

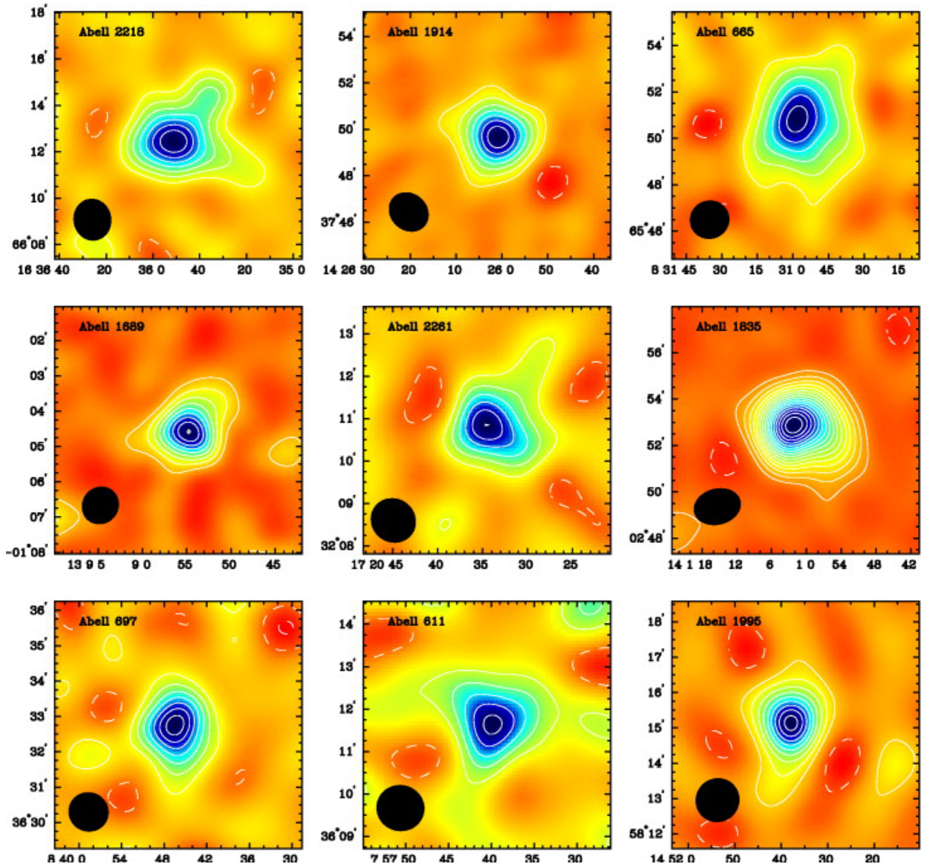
- Local re-ionisation of baryons in hot intracluster medium.
- CMB photons scattered off free electrons.
- Electrons @ 10^8 K, vs 3-6 K for photons, so Inverse Compton (photons gain energy).
- Optical depth $\tau \sim 10^{-4}$ -10^{-3}
  - Produces 'hole' in CMB below 200 GHz



- If cluster moving towards us, photons blue-shifted - Kinematic S-Z effect.
  - Hard to measure as distortion has Planck spectrum

Observed S-Z effect

- Results from Carlstrom group (Grego et al 2001)
- More evidence that CMB is at high redshift!



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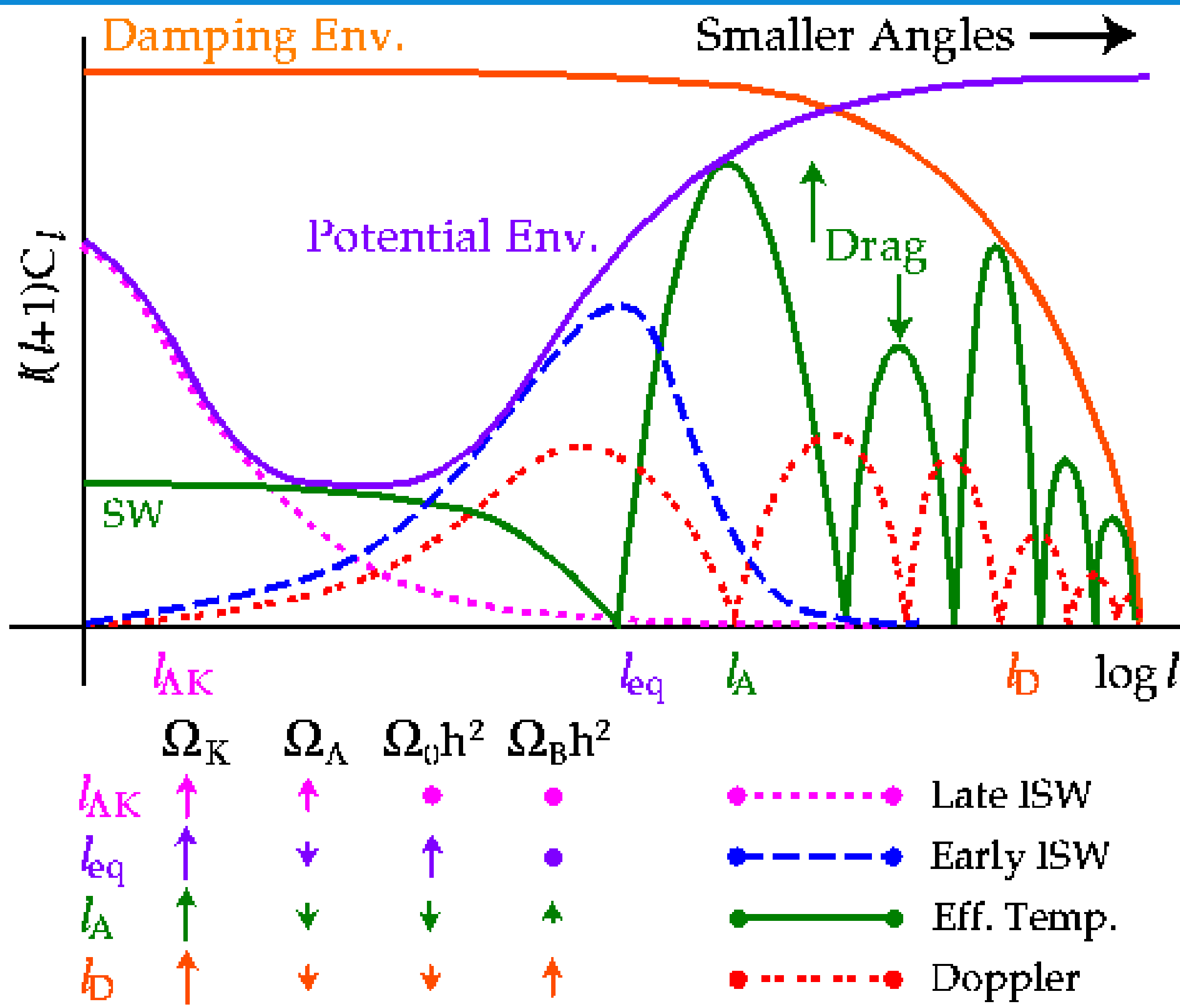
Global reionization

- Does occur:
  - *Absence of Gunn-Peterson trough at $z < 6$*
- Suppresses power on small scales ($\ell \gg 10$).
- Large scales unaffected.
- New anisotropies arise on new scattering surfaces.
- Polarization signature
- Ostriker-Vishniac effect ($\ell \sim 10000$)

Contributions to C_ℓ spectrum



Credit:
Wayne Hu

Technical Issues

- Sample & cosmic variance
- Sensitivity
- Detector Technologies
- Differential measurement
- How to avoid deconvolution
- C_ℓ window functions

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Cosmic Variance

- Estimate of C_l from full sky data is:

$$\widetilde{C}_l = \frac{1}{2l+1}\sum_{m=-l}^{l} a_{lm}a_{lm}^{*} = \frac{1}{2l+1}\left\{a_{l0}^{2} + \sum_{m=1}^{l} 2\left[\Re(a_{lm})^2 + \Im(a_{lm})^2\right]\right\}$$

  - Negative-*m* terms duplicate positive-*m* terms due to reality condition.
  - Since $\langle a_{lm}a_{lm}^{*}\rangle = C_l$ for all *m*, the variance of its real and imaginary parts for $m \neq 0$ is $C_l/2$.
- $(2l+1)\widetilde{C}_l / C_l$ is a sum of unit-variance Gaussians: χ^2 distributed, with $(2\ell+1)$ degrees of freedom:
  - mean $(2\ell+1)$, variance $2(2\ell+1)$
- So even ideal measurement of the sky only gives a fractional accuracy of $\sqrt{[2/(2\ell+1)]}$ for each C_l: cosmic variance

Sample Variance

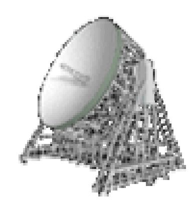
- By the same token, in small fields, few independent fluctuations: cannot get higher SNR than $1/\sqrt{N}$ where N is the number of uncorrelated regions/modes: sample variance.
  - Moral: no point in observing to SNR > 2 in small areas: better to do more sky at lower SNR.
- Polarization measurements also independent (nearly) $\rightarrow$ another $2\ell+1$ samples from all-sky E-mode spectrum
  - If you can measure it to SNR > 1!
- Since C_ℓ quite smooth, can improve SNR by binning.

Noise in C_ℓ Spectra

- ‘White noise’: any random function on the sky with negligible correlation length
  - Instrumental noise (not necessarily constant rms per pixel)
  - Randomly distributed point sources
- Its C_ℓ spectrum is constant, say N_ℓ
- Sky+noise is sum of uncorrelated variables so variances add:

$$\sigma(C_l) = \sqrt{\frac{2}{2l+1}}(C_l + N_l)$$

- NB: N_ℓ from instrumental noise is inversely prop. to observing time — hence errors in C_ℓ fall as direct inverse of time!
  - Until you hit cosmic variance limit…
- N_ℓ from point sources is dominated by the brightest sources (unlike confusion in maps). Find and subtract them!



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Sensitivity

System temperature

$$\Delta T = \frac{\eta T_{\mathrm{sys}}}{\sqrt{B\tau}}$$

Integration time

Bandwidth

At least 10 μK sensitivity needed

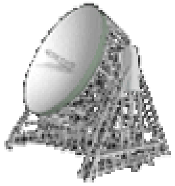
So need B large, τ long.

To amplify or not?

- Amplification: allows replication of signal, required to operate synthesis array, useful for polarimetry
- But inevitably adds noise even in ideal case, especially at $h\nu \gtrsim kT_b$
- To avoid amplification need very cold (0.1 K) detectors, held at very stable temperature.
- Upshot: bolometers best at > 90 GHz, amplifiers below.

State-of-the art Receivers

- MIC Amplifiers up to 120 GHz
  - cool to 15K
  - T_{sys}=10 K at 33 GHz, state of the art.
  - Rule of thumb is 1/3 K per GHz.
  - 7 times worse than quantum limits, limited by internal noise
  - 20% bandwidth, defined (not very well) by tuned circuits
- Bolometers 100 GHz to infrared.
  - cooled to 0.1K
  - 30-50% bandwidth
  - Custom filters (Cardiff University)
  - 7 times worse that quantum limits, limited by losses in filters etc (nearly perfect detectors)



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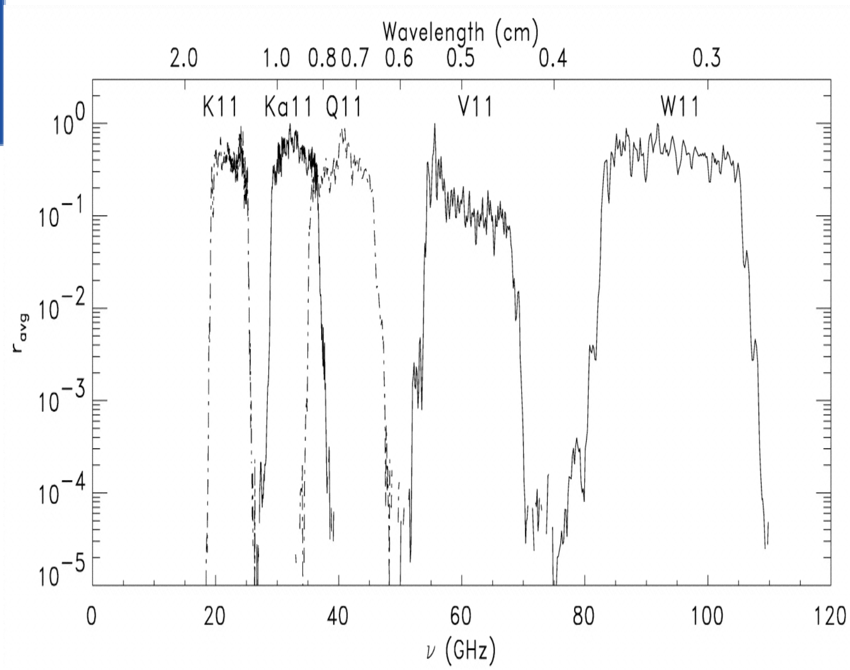
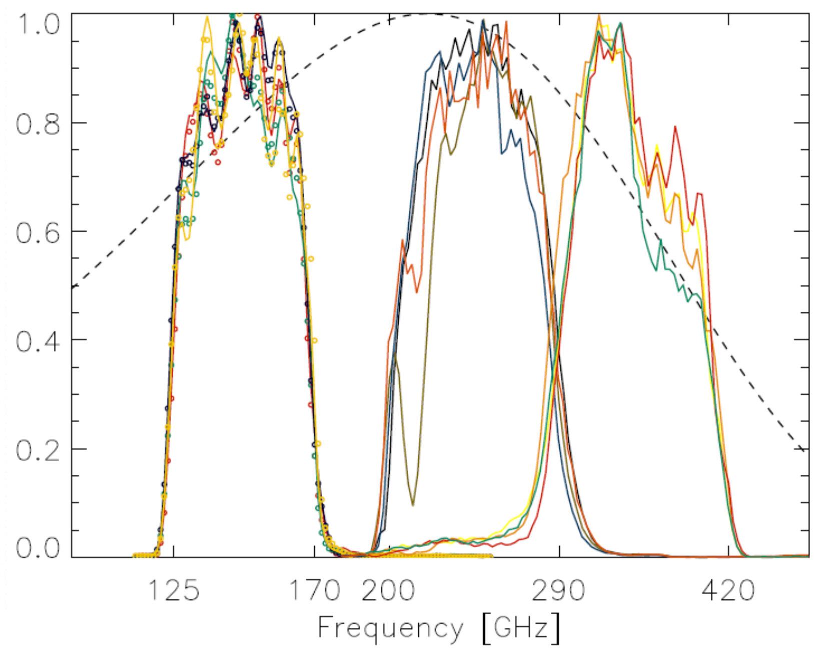
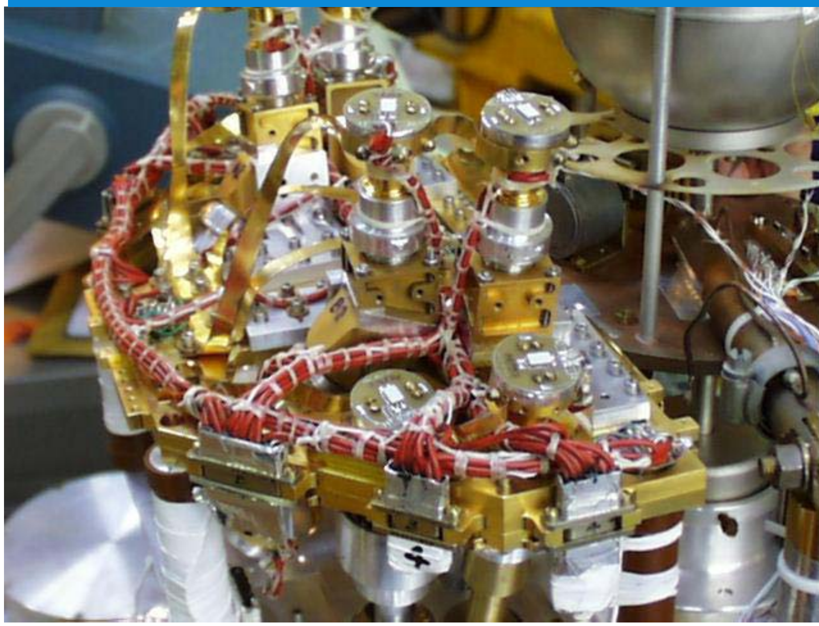
Bandpasses





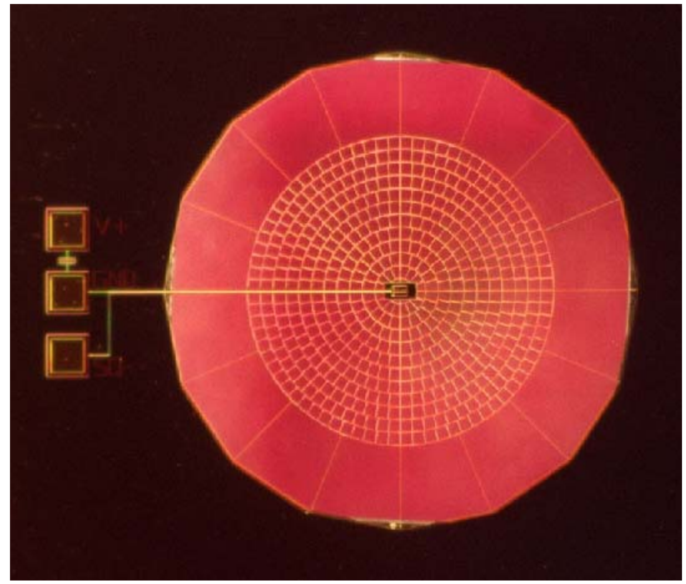
- WMAP
- Boomerang

BOOMERANG Instrumentation



Focal Plane:

Cooled to 0.28 K in helium dewar



- Spider-web Bolometer:
  micromachined mesh of silicon nitride
  Germanium thermistor at centre

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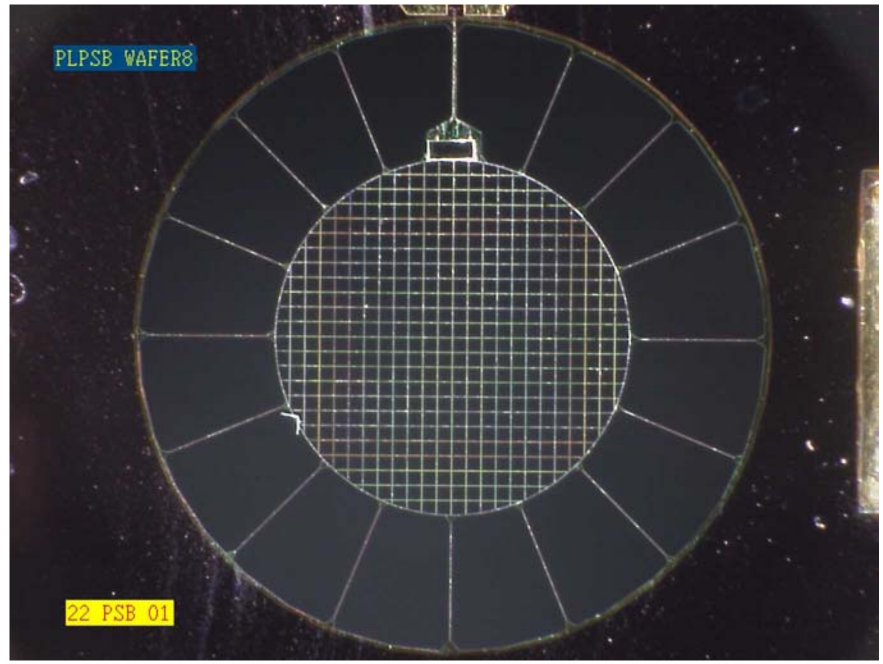
Polarization-Sensitive Bolometers

- Two planes of absorbing mesh, with orthogonal wires.
- Each rejects ‘wrong’ polarization with 90-95% efficiency
- Used on Boomerang 2003 flight, QUaD experiment, *Planck* HFI, etc.



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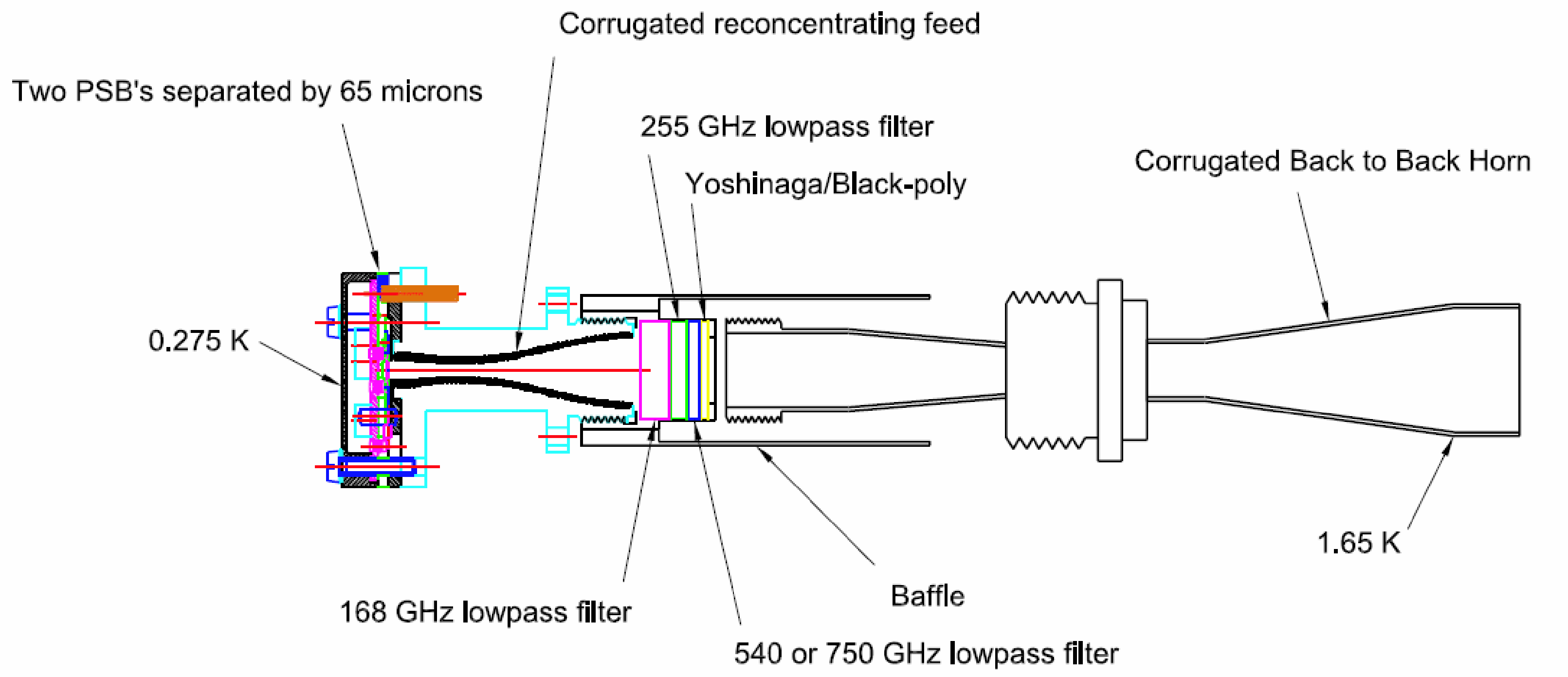
PSB Optics



- Typical layout: Boomerang 2003 design

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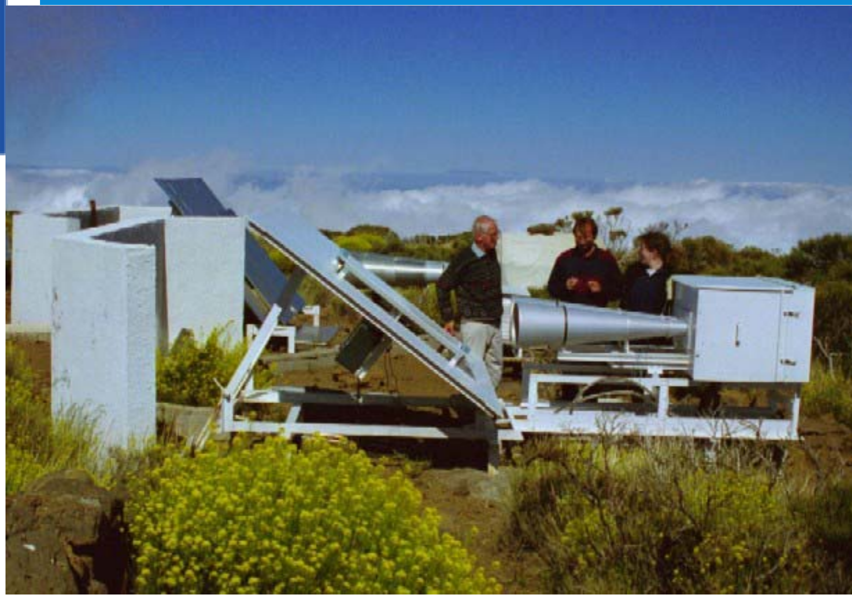
Corrugated Horns for clean beams



- Large:
  - 15 GHz feeds on Tenerife experiment
- Small:
  - 145 GHz Boomerang feeds

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Sources of error (1)

- Statistical noise
  - instrumental, at limits of current receiver technology.
  - cool receivers
  - atmospheric, emission from water vapour not uniform
  - observe at high altitude, poles or space.
  - Intrinsic signal fluctuations

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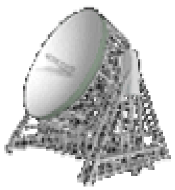
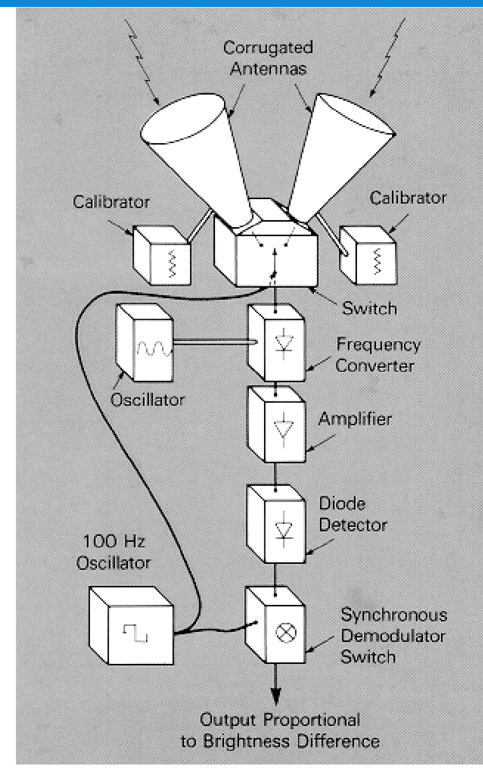
Sources of error (2)

- Systematic
  - Gain stability: slow drifts in gain produce 1/f noise, especially in amplifiers
  - Enhanced by any instability in physical temp, esp. in bolometers
  - Microphonics
  - CR hits
- Foregrounds
  - Earth, sun or moon in sidelobes - screen.
  - Galactic emission, synchrotron, free-free and dust - spectral differentiation.
  - Radio sources - spatial differentiation.



Differential Measurement (1)

- μK signals vs Several K offset (CMB + instrumental + atmospheric):
  - Measure Differential T!
  - PSD to cancel offsets
- COBE, WMAP measured ΔT between beams pointing at large angles (1 or 2 radians)
  - Reconstruct sky from many differences with different orientations
  - Typically residual offset 0.5 K from instrumental matching



COBE DMR:
Differential Microwave Radiometer

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Differential Measurement (2)

- Planck Low Frequency Instrument (LFI) measures (sky-load) using on-board 4 K noise source
- Most instruments repeatedly ‘chop’ between target and reference
  - Spin scanning in satellite & some ground experiments.
- Multiplying interferometers effectively ‘chop’ between sine and cosine channels, cancelling uniform signals.

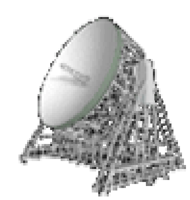
- Polarimeters:
  - Differencing:

    $Q = |E_x|^2 - |E_y|^2$

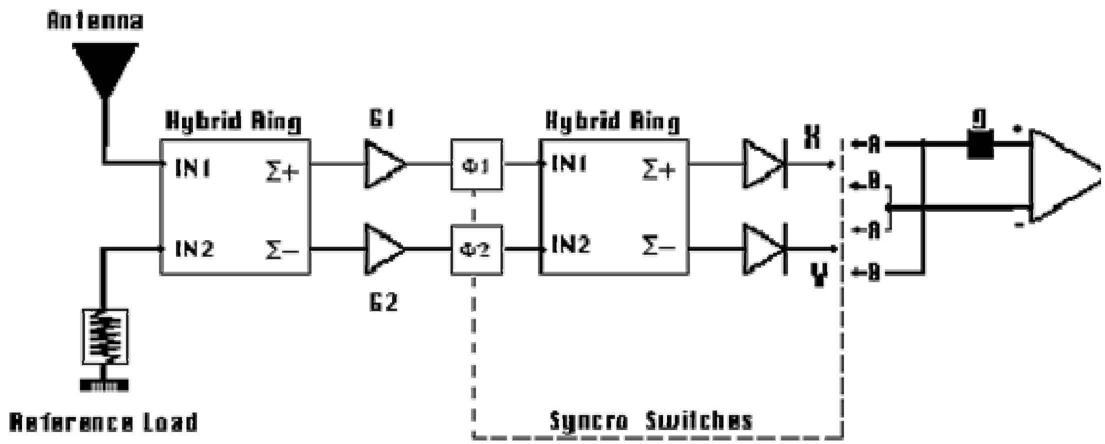
    - Limited by gain errors
  - Multiplying:

    $Q + iU = \langle E_R E_L^* \rangle$

    - Limited by R vs. L leakage
  - Nearly ideal, as differencing through identical optics, identical patch of sky



Planck LFI receiver



- Hybrids mix signal from sky & load to give sum & difference. Hence both signals pass through same amplifiers and have same gain.
- Second hybrid unmixes signals
- Phase switch flips signals alternately between backend amplifiers, allowing PSD to remove backend offsets and drifts.

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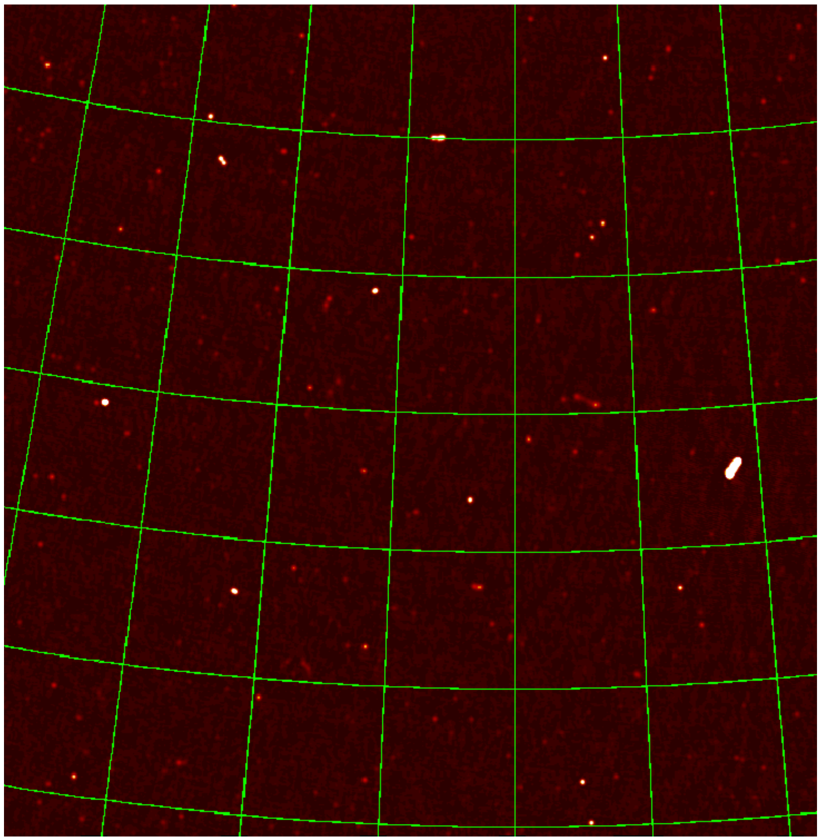
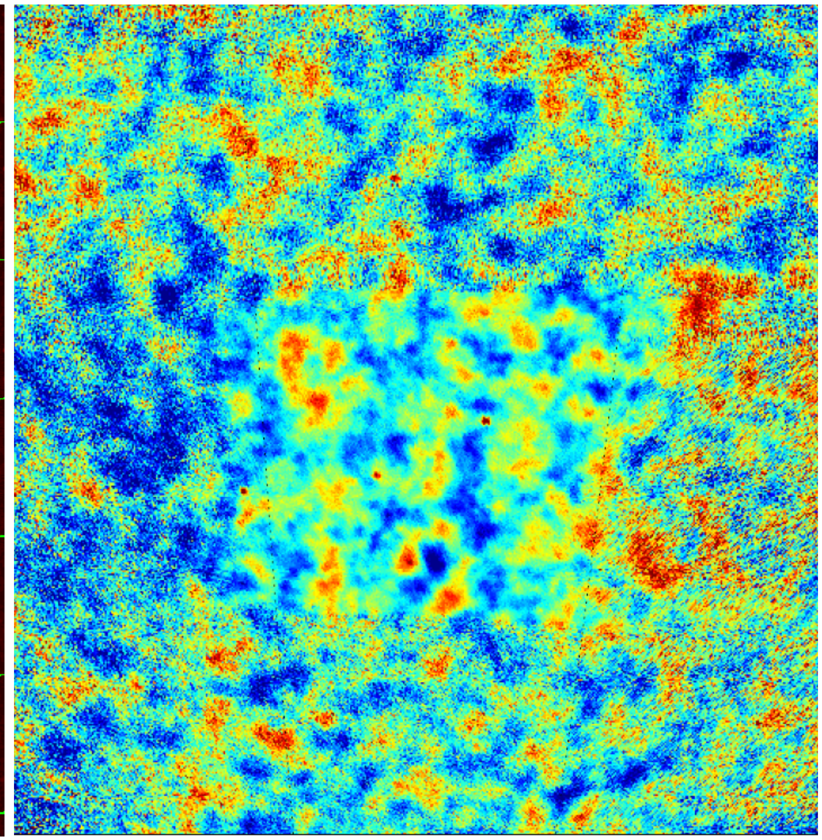
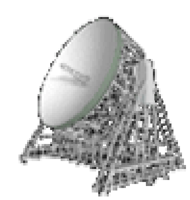
A Full Sky



The sky at 21 cm (NVSS)



The sky at 2 mm (Boomerang)



Avoiding Deconvolution

- Deconvolution algorithms work best with substantial prior information, esp. nearly empty and all-positive sky
  - CMB fails on both counts
- Error propagation in non-linear deconvolution a nightmare: only possible approach is huge Monte Carlo analysis: not practical for large images.

1. Minimize need for deconvolution by making beam very pure
   - e.g. Planck `Airy rings' < −30 dB below peak
   - Make beam circular so orientation does not affect flux at given sky position
2. Measure harmonic directly: for interferometers 'Visibilities' are direct measure of a_{lm}
3. Compare "dirty" data directly to theoretical models folded through instrumental response.

Window functions

- Theoretical a_{lm} analysis assumes all sky coverage and infinite resolution.
- Window function - how sensitive experiment is to each ℓ value
- Measured anisotropy is multiplied by window function.

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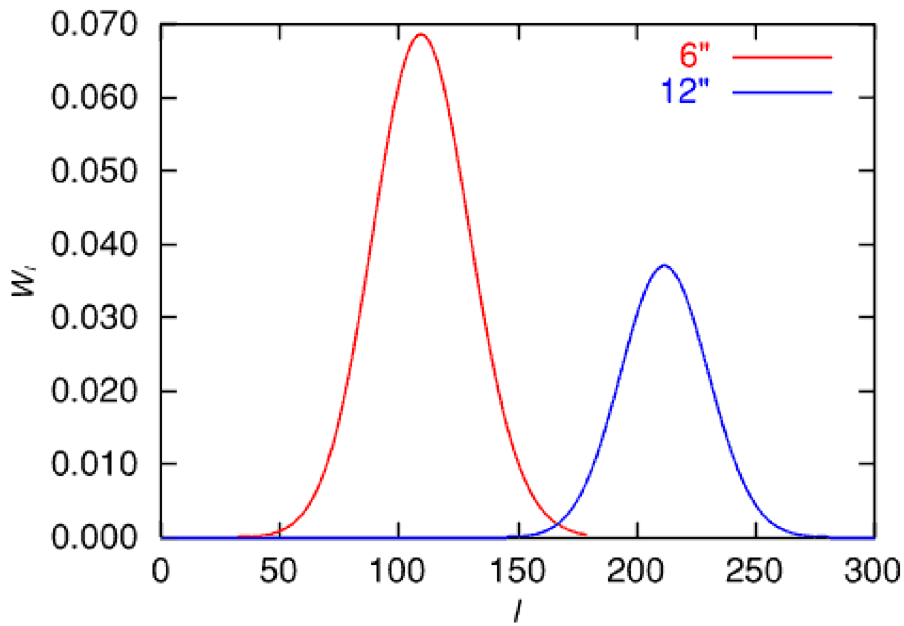
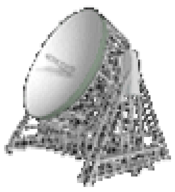
Example window function

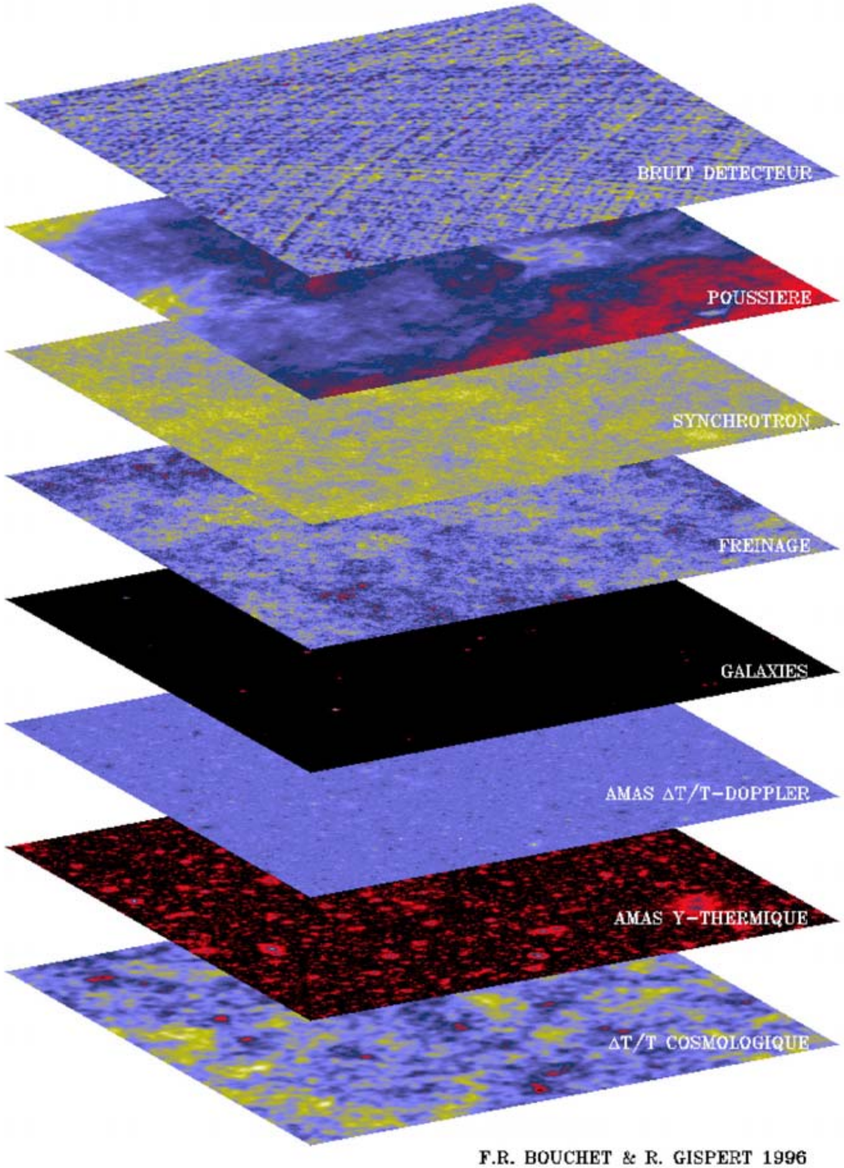
- Window functions for the two spacings of the 33 GHz interferometer on Tenerife
- Window functions depend on the telescope beam and the observing mode





Foregrounds

- Thermal Dust:
  - COBE FIRAS, Planck HFI
- Anomalous Dust:
  - COSMOSOMAS, WMAP, Planck LFI
- Free-free / Synchrotron:
  - Arecibo, C-BASS, Planck LFI
- AGN & SZ clusters
  - OCRA, Planck



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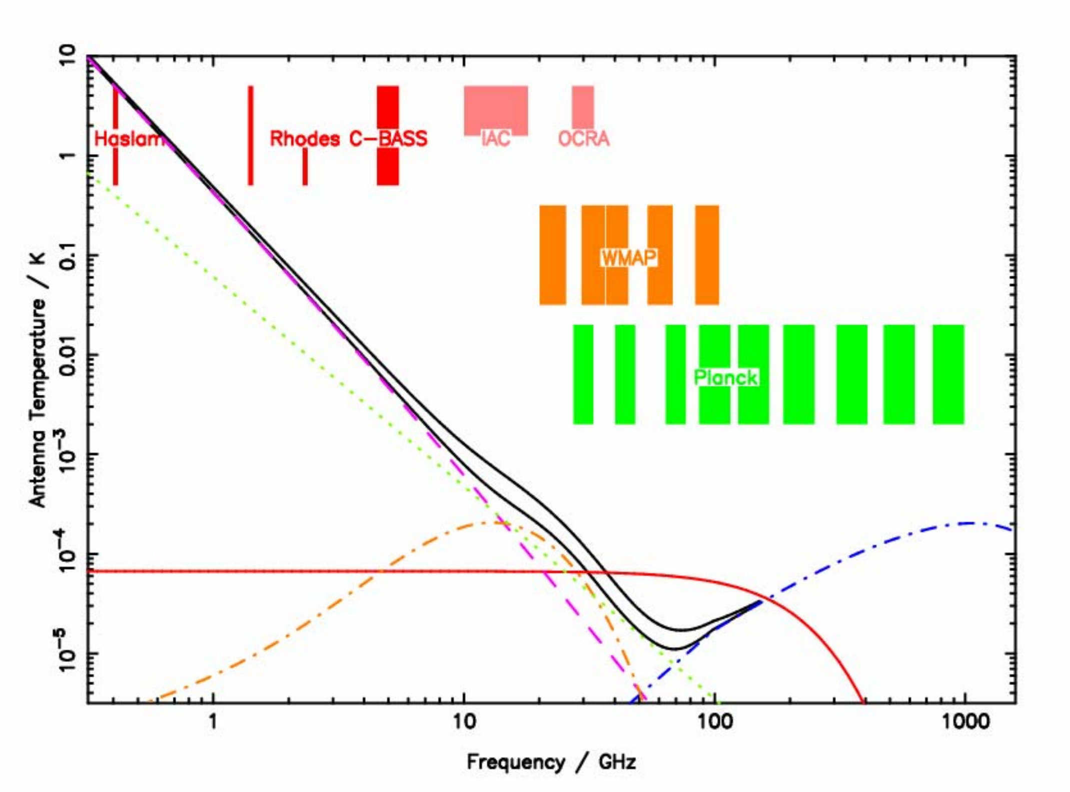
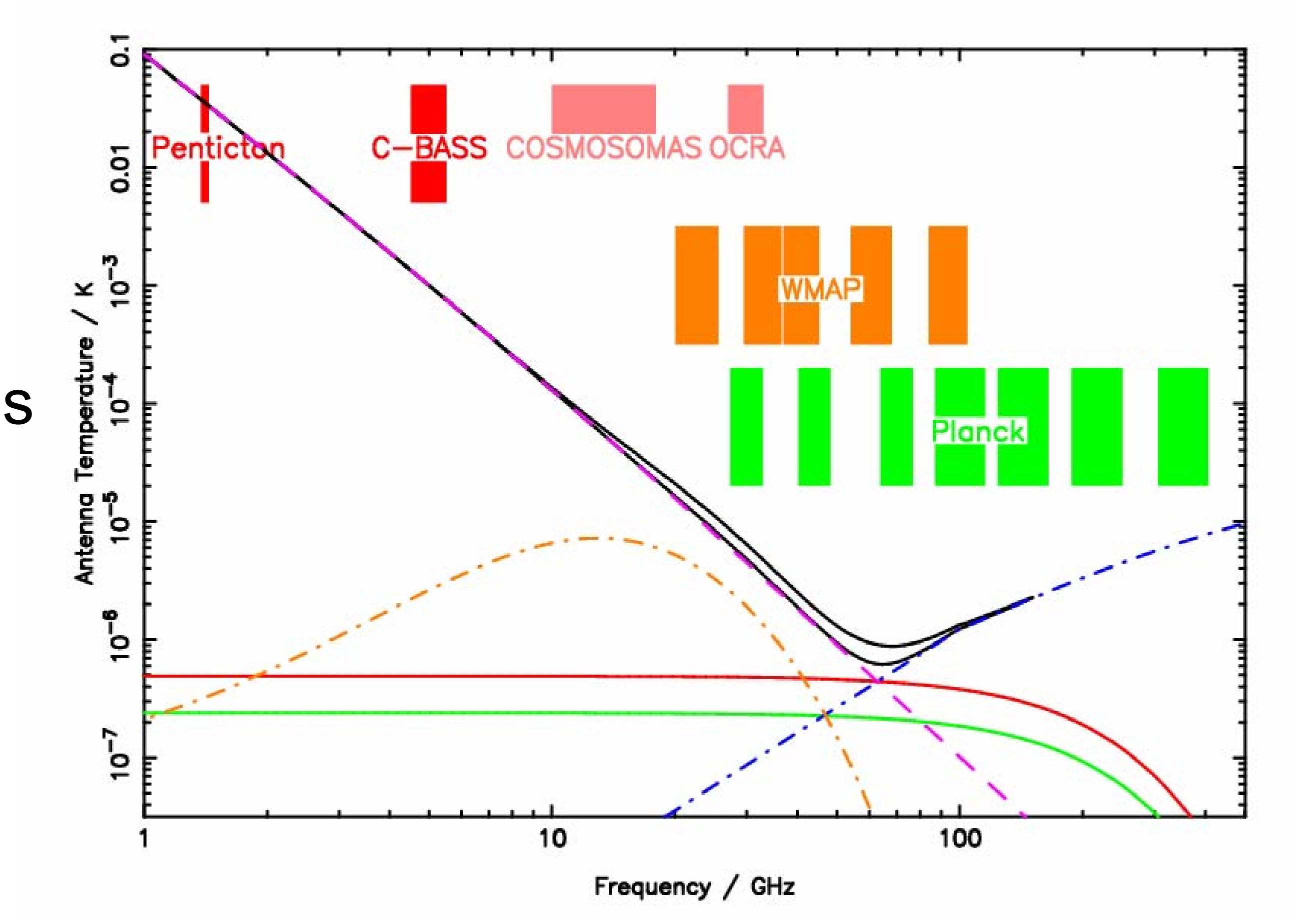
Foreground SED (?)

- RMS amplitudes on 1° scales
  - CMB
  - Thermal & Anomalous dust
  - Synchrotron
  - Free-Free



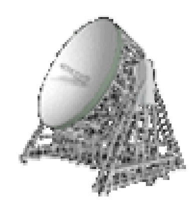
Polarized Foreground SED (???)

RMS Q,U
on 1° scales
(maybe!)



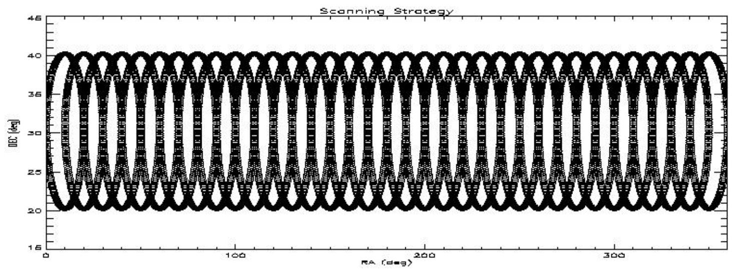
Foreground Removal

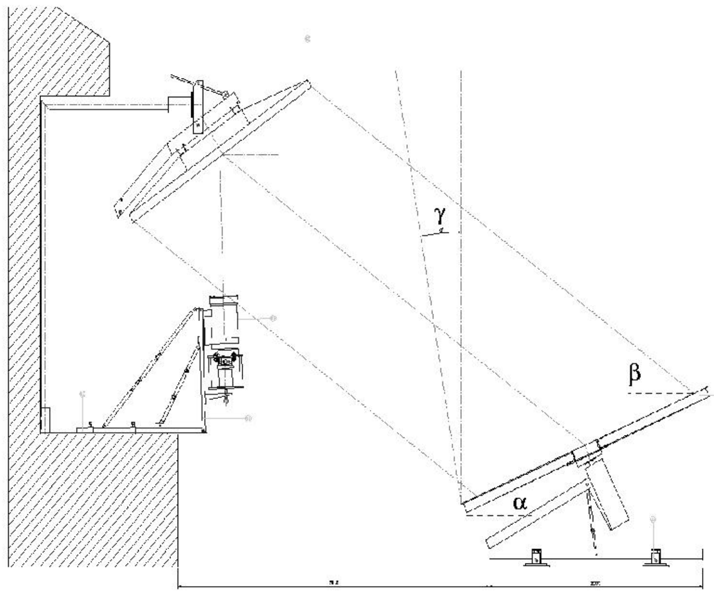
- CMB T, E dominates at high latitudes (e.g. WMAP)
- BUT Planck is not a detection experiment: precise measurement requires accurate subtraction.
- Planck polarization sensitivity relies on (nearly) full-sky coverage
  - *Not just 'clean' regions!*
- Crucial B-modes <3% of E-mode: under foregrounds nearly everywhere



COSMOSOMAS

- "Cosmological Structures on Medium Angular Scales"
- 11-16 GHz strip survey, 1° beam
- 3 fixed receivers fed by rotating flat mirrors.
- Operated on Tenerife by IAC, with major design & operation input from R. A. Watson.





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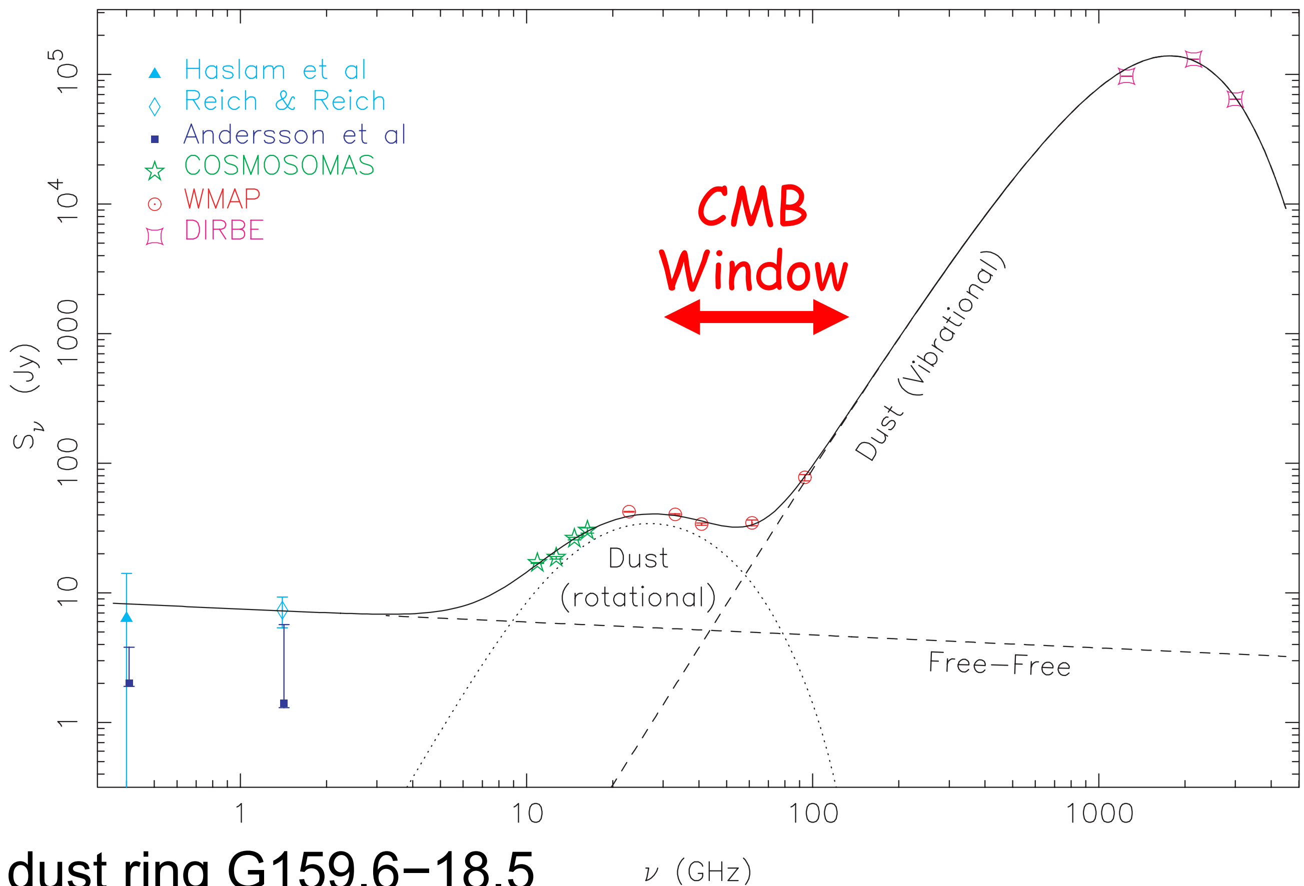
Anomalous Dust



SED of dust ring G159.6−18.5

Models of Anomalous Emission

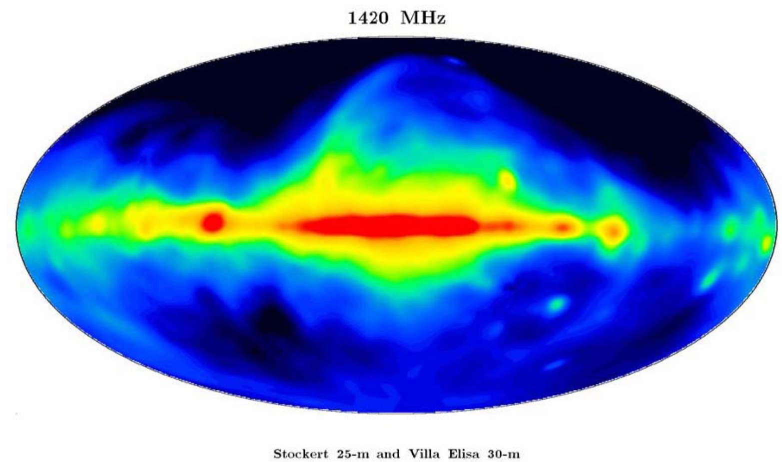
- Synchrotron (WMAP team)
  - ✘
  - Why correlated with Cirrus clouds at high latitude?
  - Rising spectrum at 10 GHz
- Free-Free (Leitch et al.)
  - ✘
  - Poor correlation with Hα
  - Rising spectrum
- Spinning VSGs (Draine & Lazarian 1997)
  - ~ maybe
  - → Weakly polarized
- Magnetic dipole transitions in large grains (Lazarian & Draine 1998)
  - ~ maybe
  - → Moderately polarized

Anomalous Dust

- Exact spectrum?
  - Subtract free-free, synchrotron etc
- Distribution and correlation with other components?
- Polarization?
  - Diagnostic of spinning VSGs vs. magnetic dipole transitions in large grains

Synchrotron: Cosmic Ray Physics

- Synchrotron emission traces the life-cycle of cosmic rays
  - Acceleration processes and sites
    - Shocks?
    - Re-connection?
  - Diffusion/convection
  - Scattering from Alfvén waves
  - Radiative losses



Reich, Testori & Reich 2004

- Short-λ polarization ➔ B-field angle

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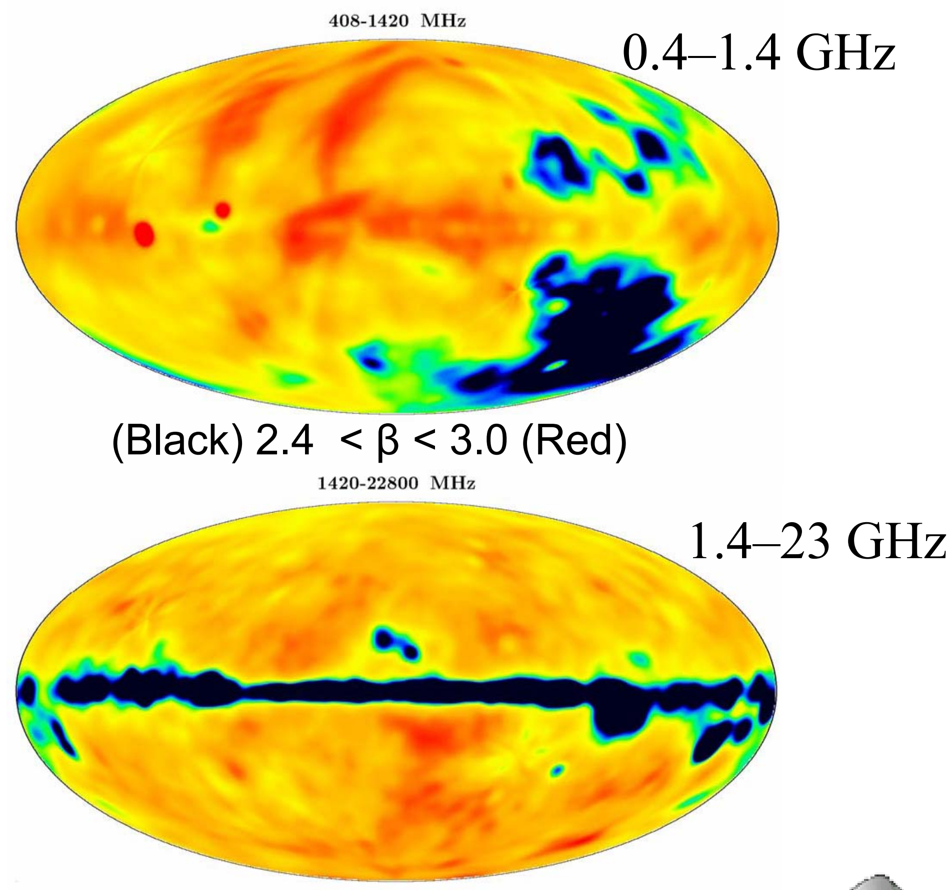
Existing Spectral Index Data

- From Reich, Reich & Testori (2004)
  - 5° resolution
- Substantial structure
  - O(1) subtraction errors if not accounted for



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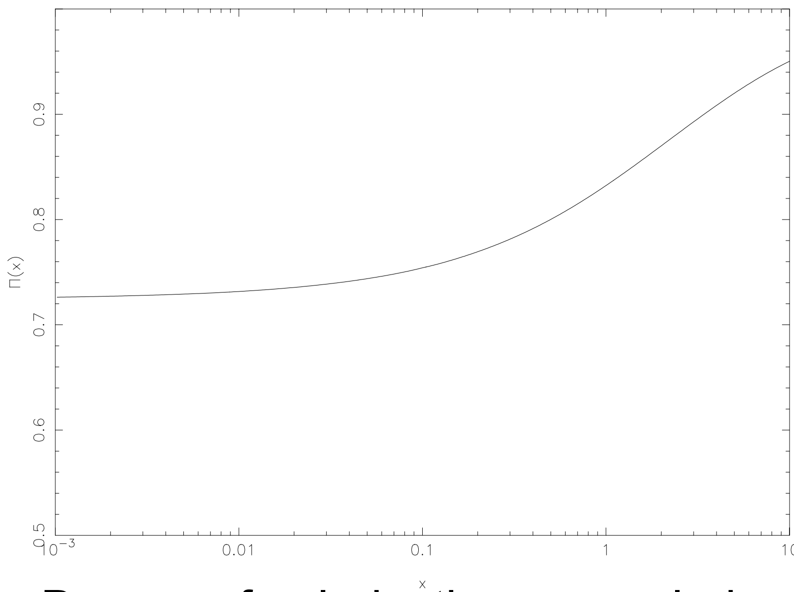
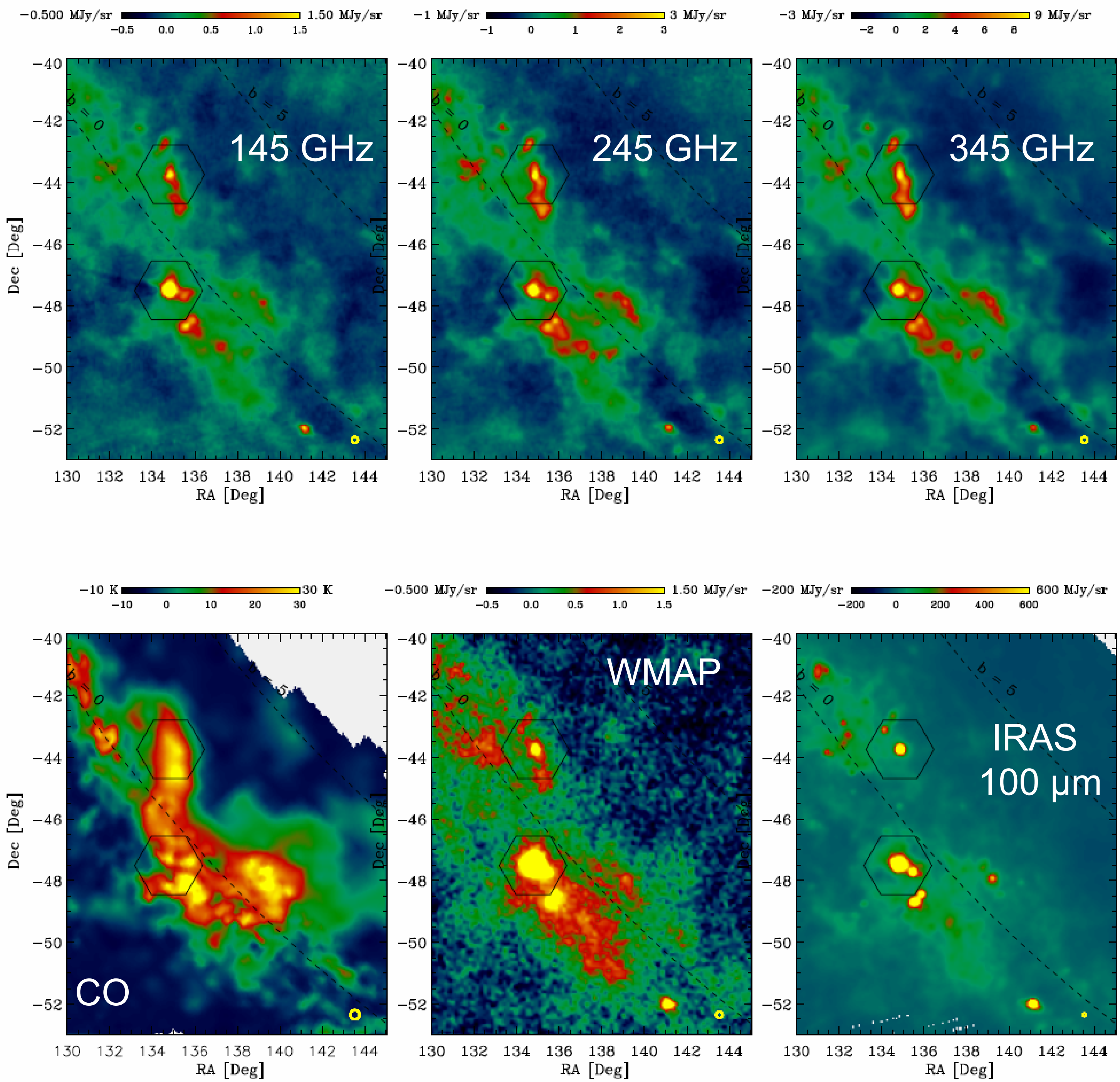
Synchrotron Polarization

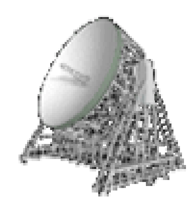
- Synchrotron polarization varies with frequency for curved spectra (as expected in the Galaxy).
- Detail of variation depends on B-field geometry, dependence of electron energy on pitch angle.
  - Diagnostic of scattering efficiency.



Degree of polarization vs. scaled frequency for “single burst” spectral ageing model

(Leahy, Black & Chan in prep.)

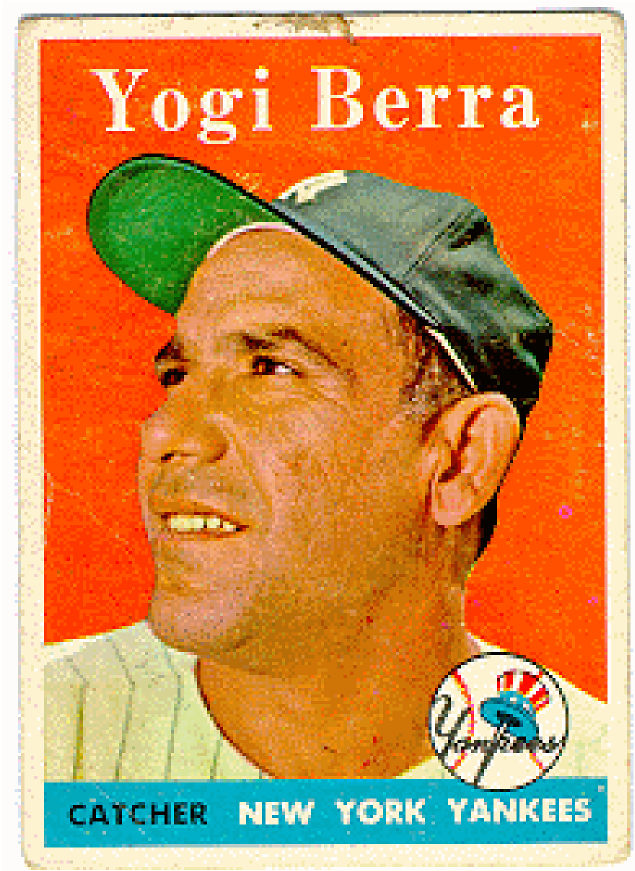

−0.500 MJy/sr 1.50 MJy/sr
145 GHz
−1 MJy/sr 3 MJy/sr
245 GHz
−3 MJy/sr 9 MJy/sr
345 GHz
−10 K 30 K
CO
−0.500 MJy/sr 1.50 MJy/sr
WMAP
−200 MJy/sr 600 MJy/sr
IRAS
100 µm
b = 0
b = 5
Dec [Deg]
RA [Deg]



CMB Experiments

You can observe a lot just by watchin'

– Yogi Berra



Observations of CMB fluctuations

- 1992: DMR instrument on COBE satellite detects Sachs-Wolfe fluctuations with $\delta_{\mathbf{k}} \approx 2\times10^{-5}$.
- 1992-2000: many instruments detect fluctuations on both large and small scales.
- 2000: BOOMERanG balloon experiment confirms 1st acoustic peak at $l \approx 220 \rightarrow$ nearly flat universe, $\Omega_0 \approx 1$.
- 2000: Cosmic Backgound Imager confirms damping.
- 2001: BOOMERanG and DASI confirm 2nd peak.

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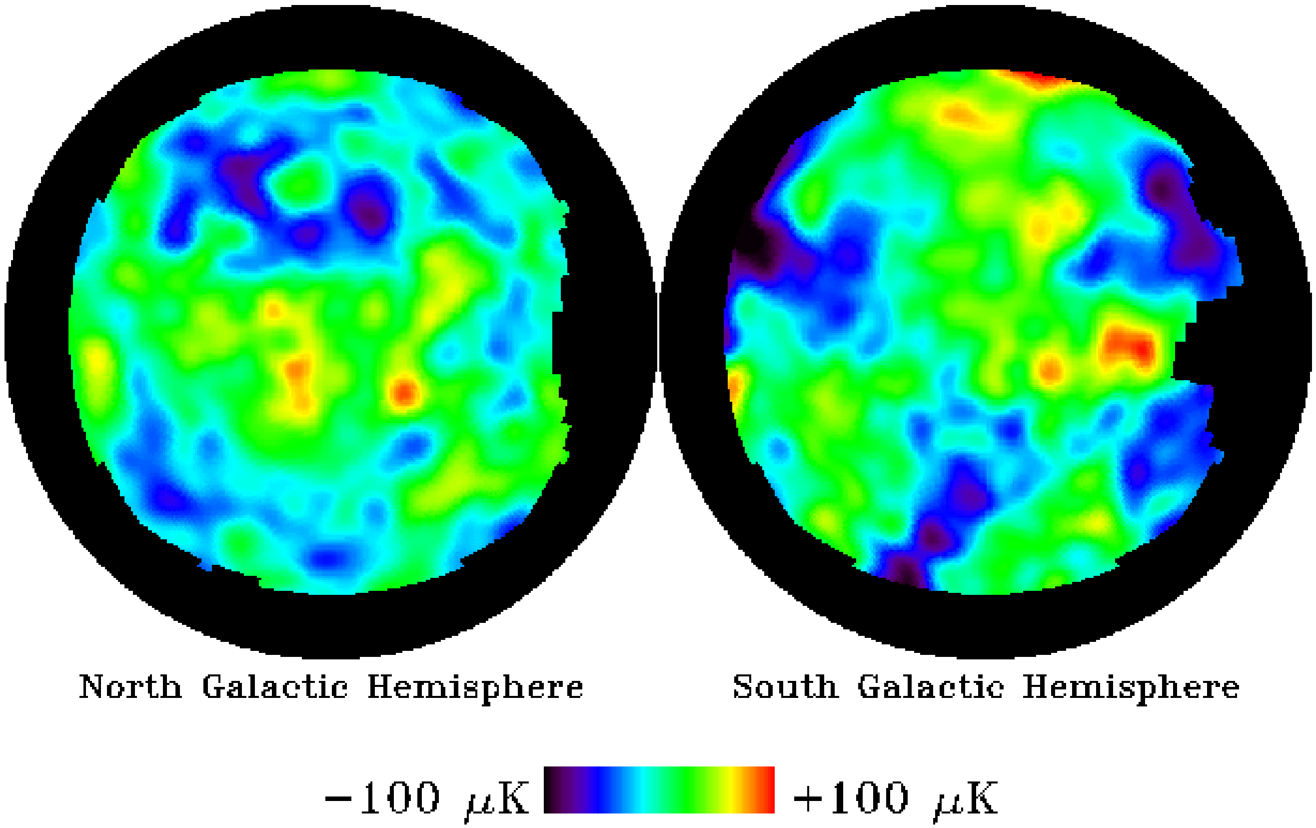
4 years of data from COBE



signal:noise ≈ 2

BOOMERanG Launch

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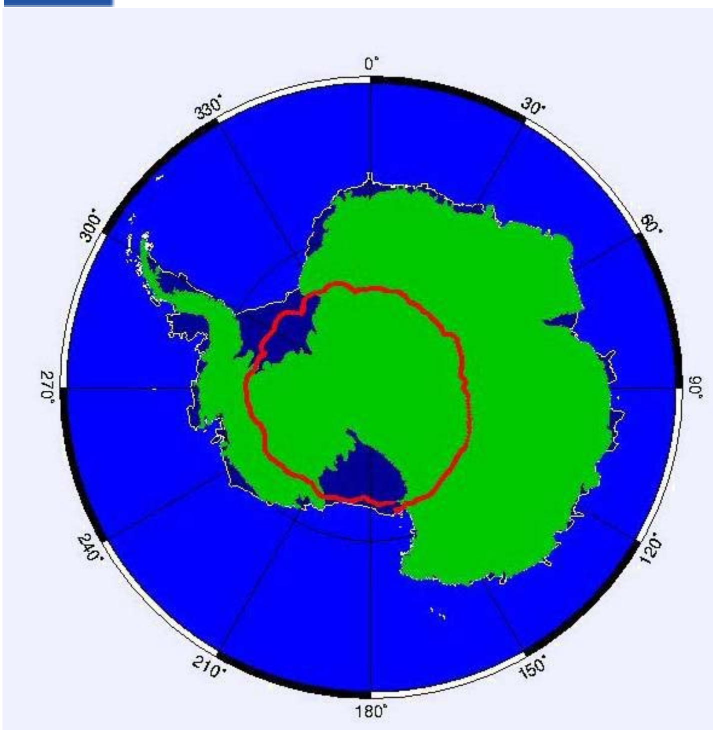
BOOMERanG (contd)



Gondola

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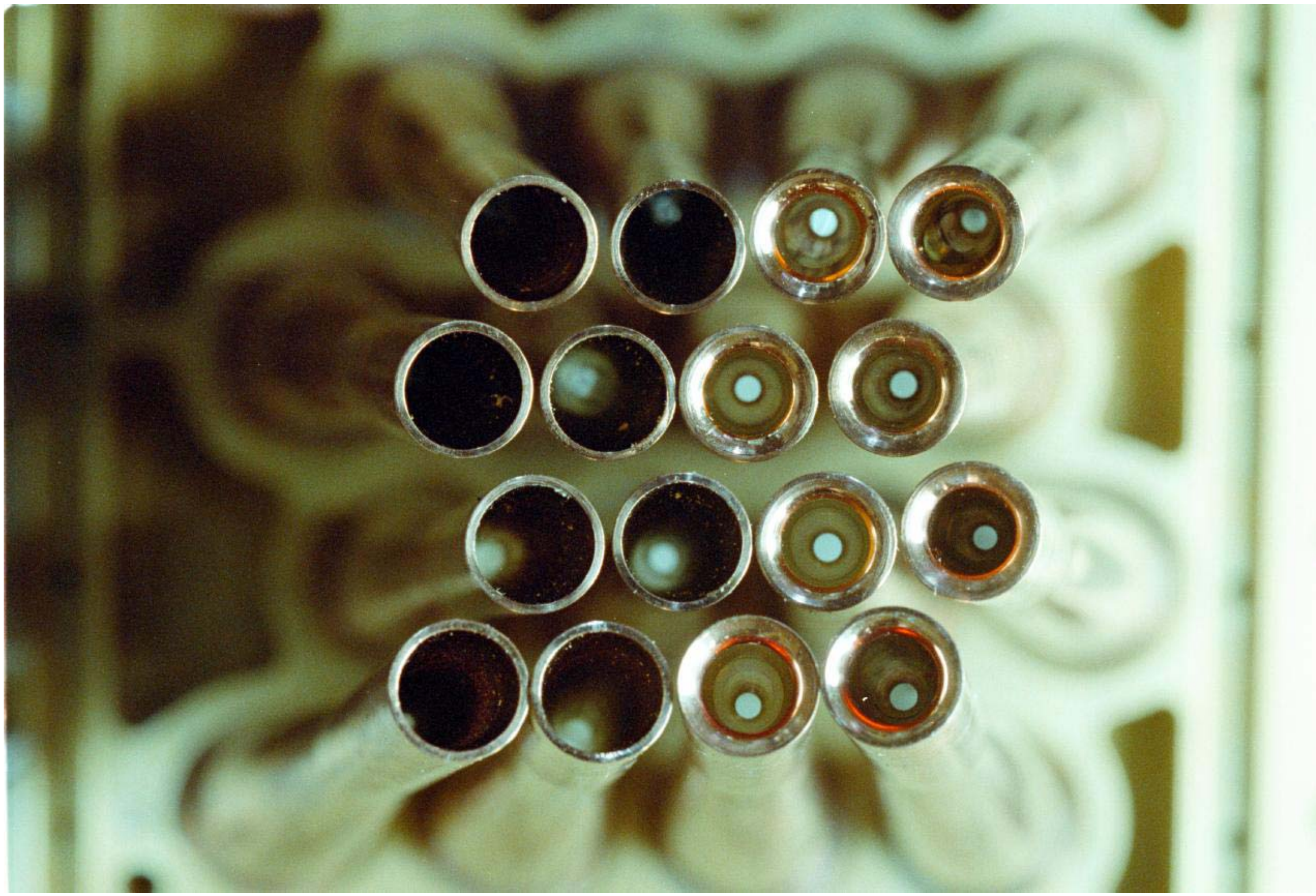
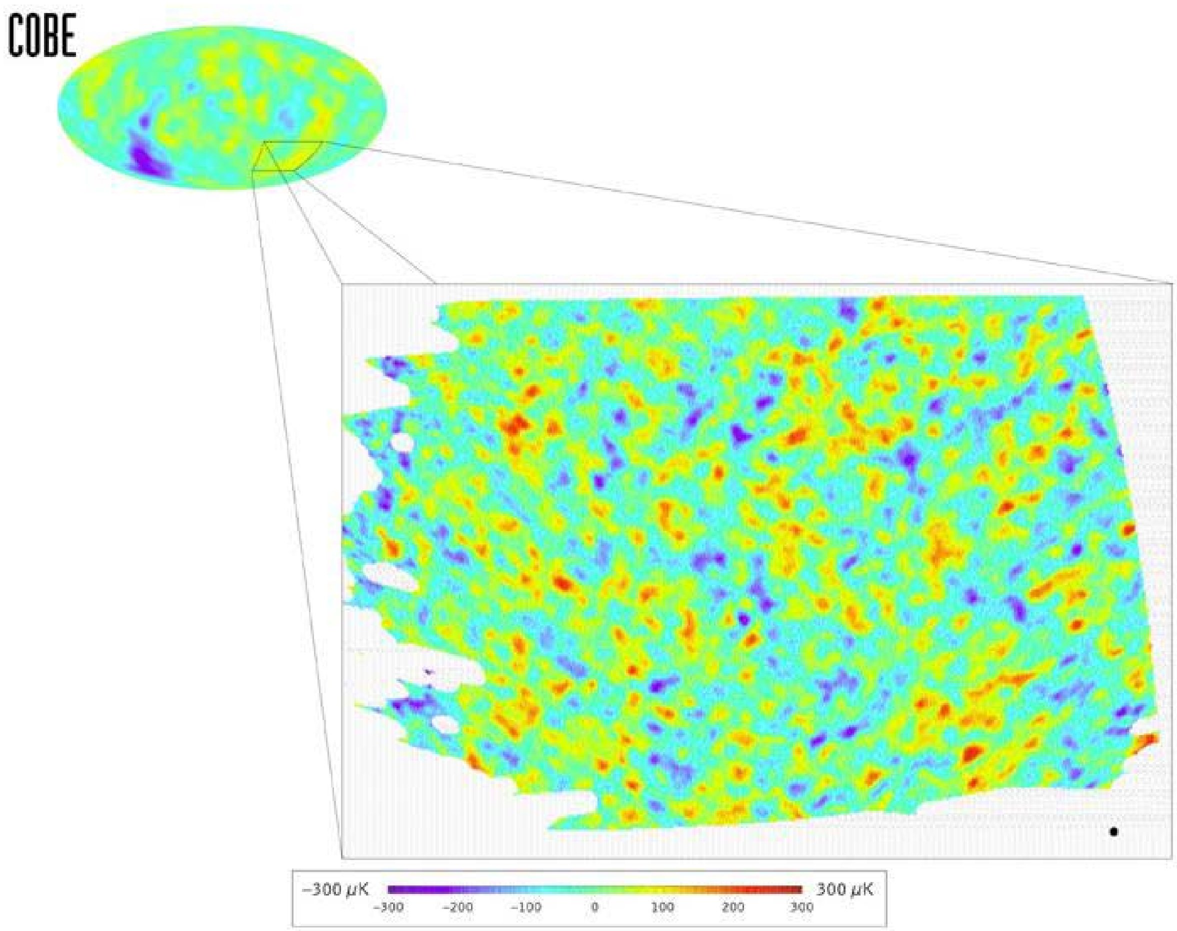
M A X I M A

Millimeter Anisotropy eXperiment IMaging Array

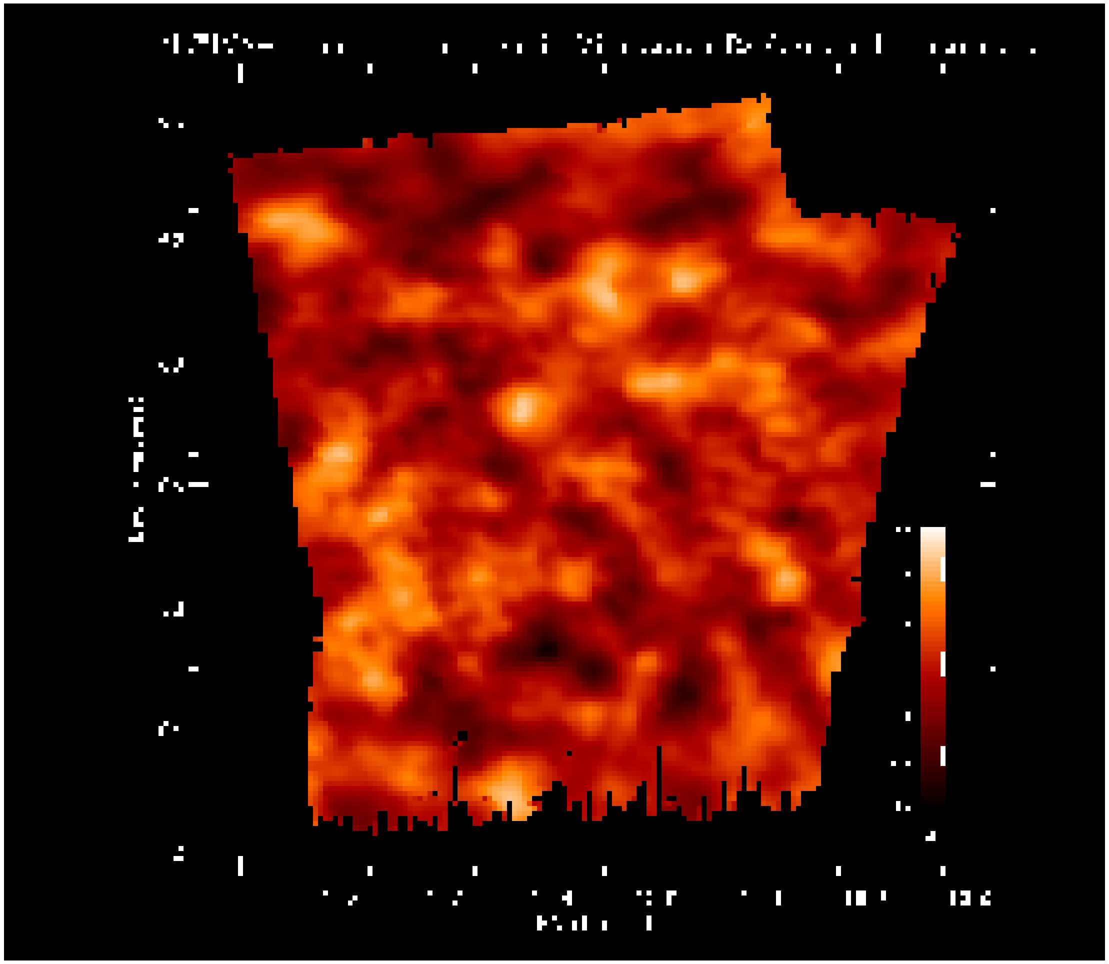
MAXIMA Focal Plane



BOOMERanG vs. COBE



MAXIMA map



19th – 20th November 2005 ENIGMA Winter School

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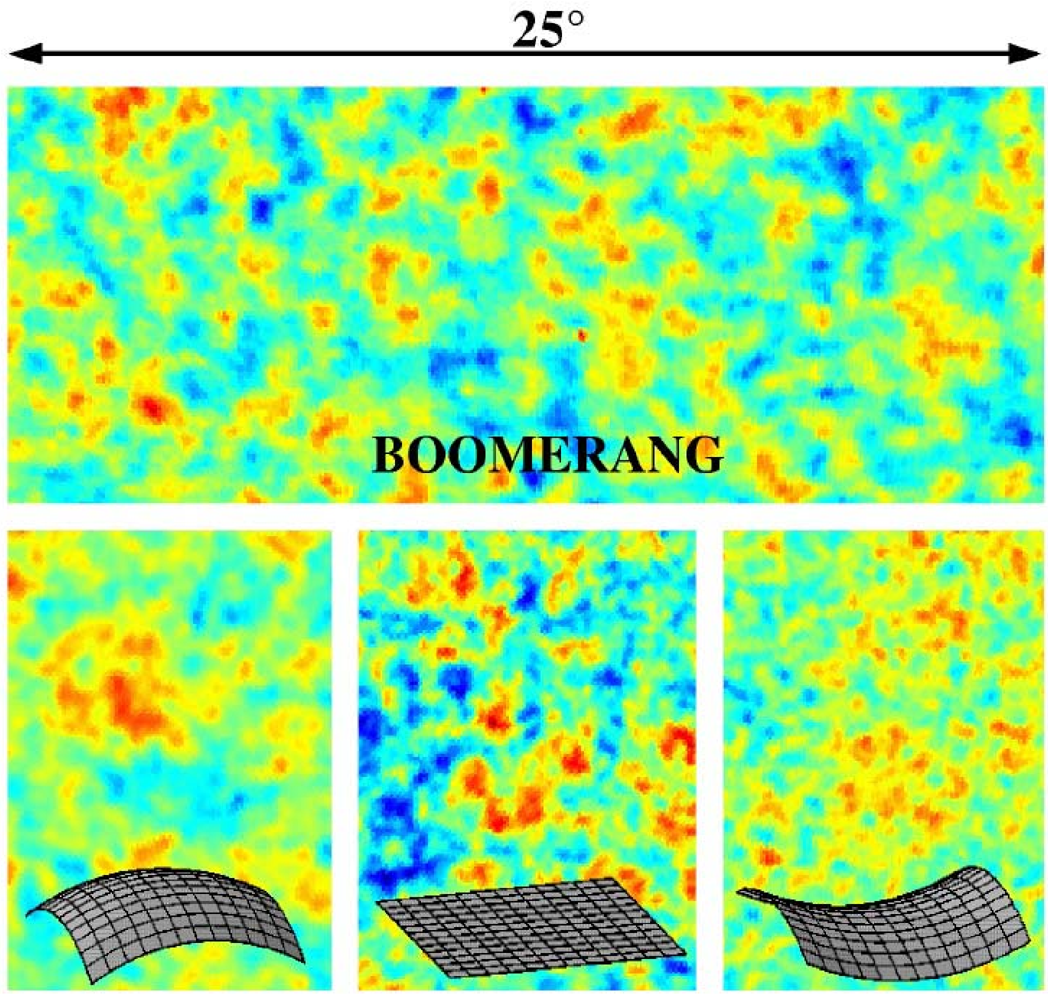
BOOMERanG vs. Simulations



2002 Angular Power Spectrum

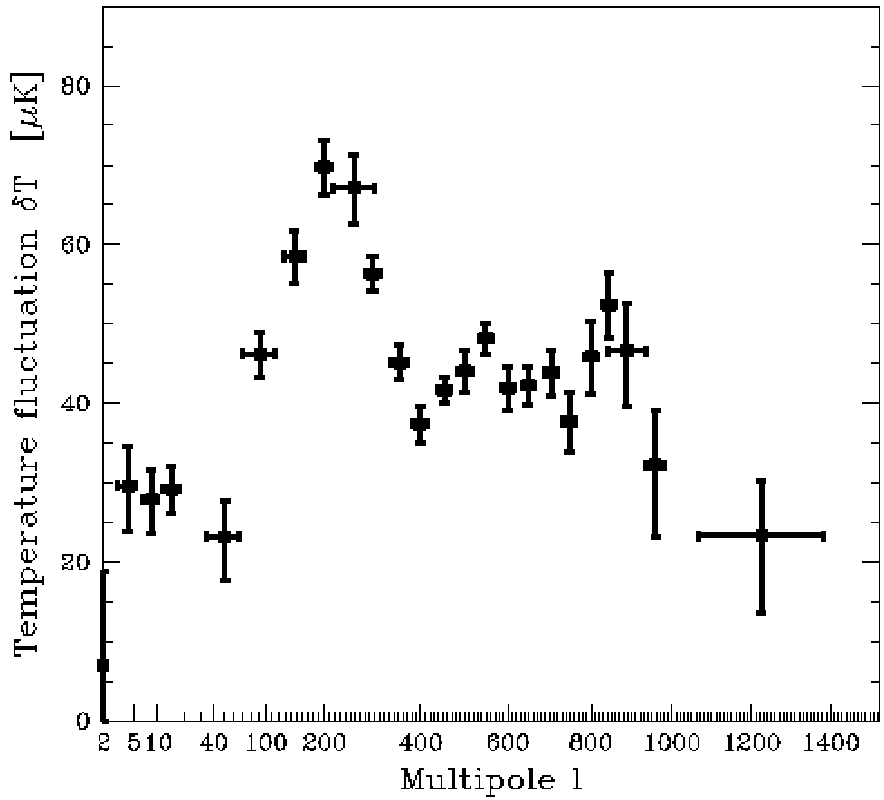


FIG. 2. Combination of all data from Figure 1. These error bars include the effects of beam and calibration uncertainties, which causes long-range correlations of order 10% over the peaks. In addition, points tend to be anti-correlated with their nearest neighbors, typically at the level of a few percent. The horizontal bars give the rms widths of the window functions.

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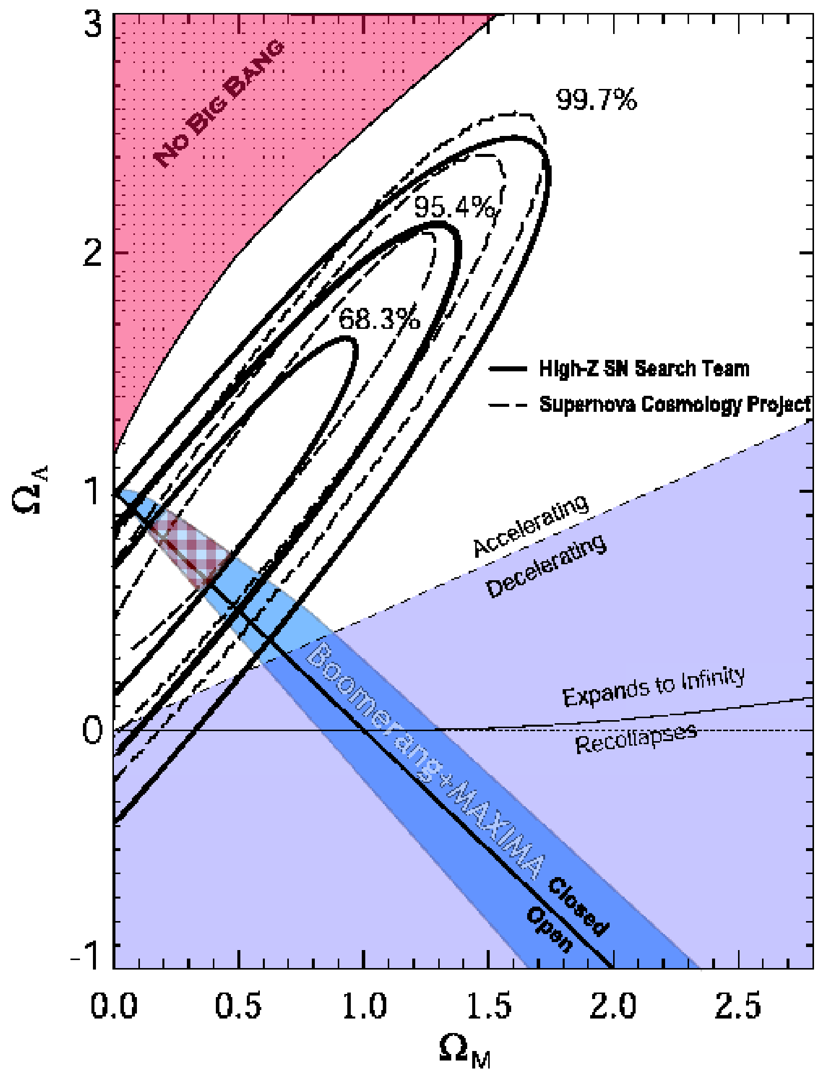
Constraints

- Two independent teams find same results for SNIa
- With $\Omega_m \approx 0.3$,
- $\Rightarrow \Omega_\Lambda \approx 0.7$.
- Implies flat universe: $\Omega_0 \approx 1$.
- Concordance Model.
- Worry: cosmological evolution of SNIa?



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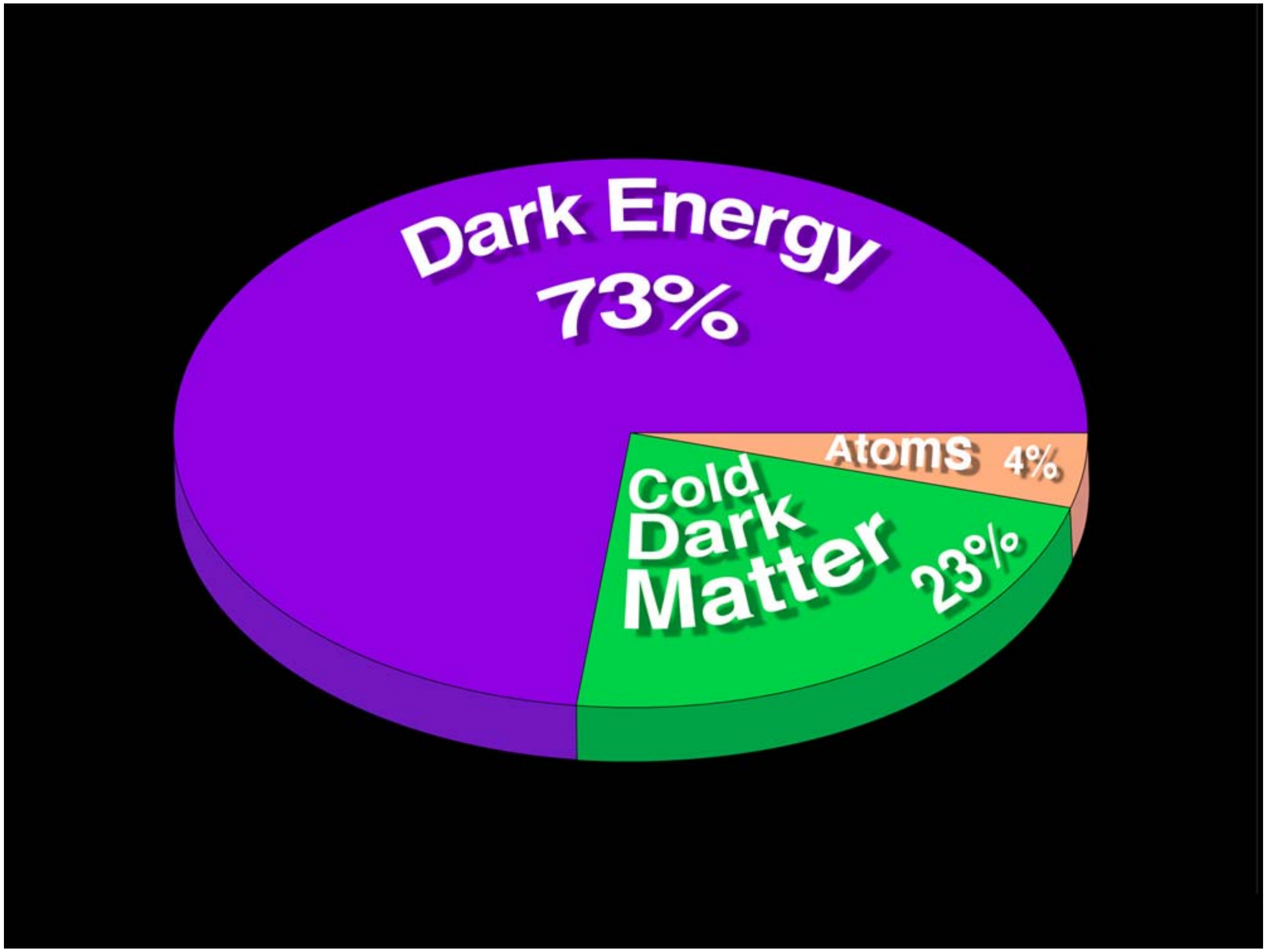
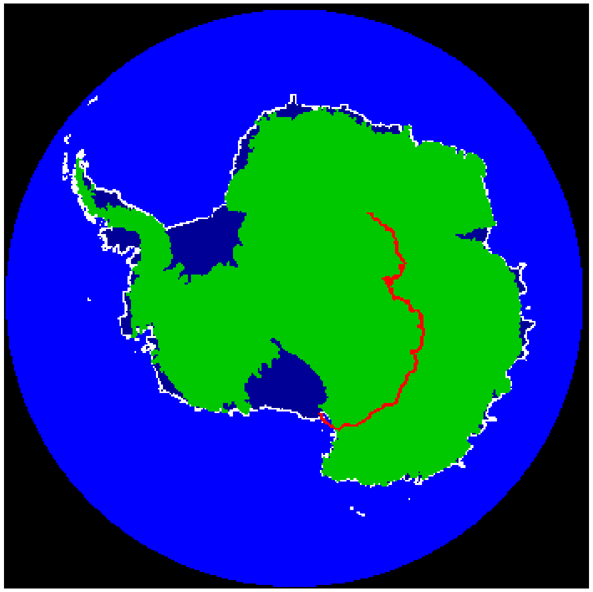
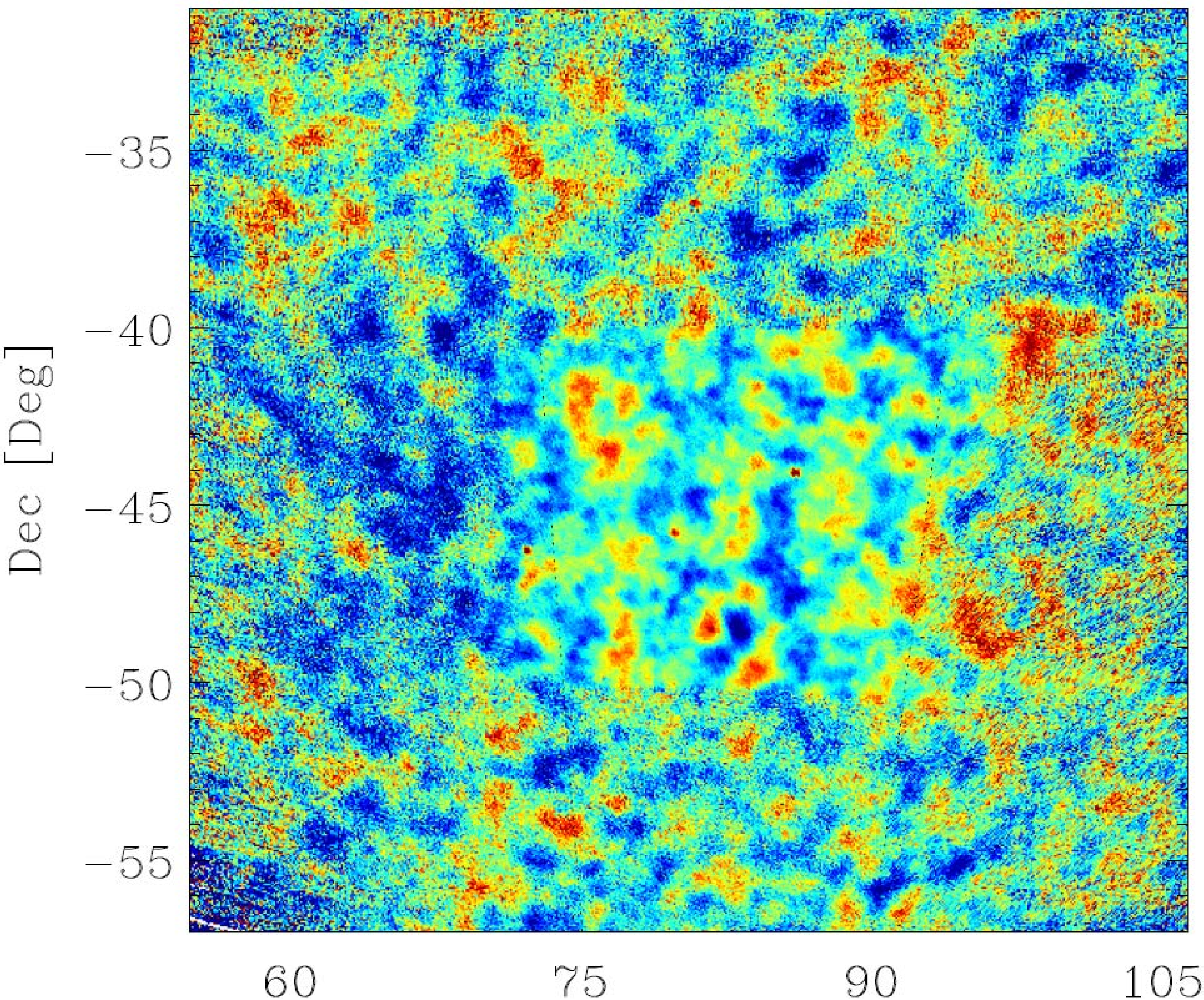
Cosmic Contents

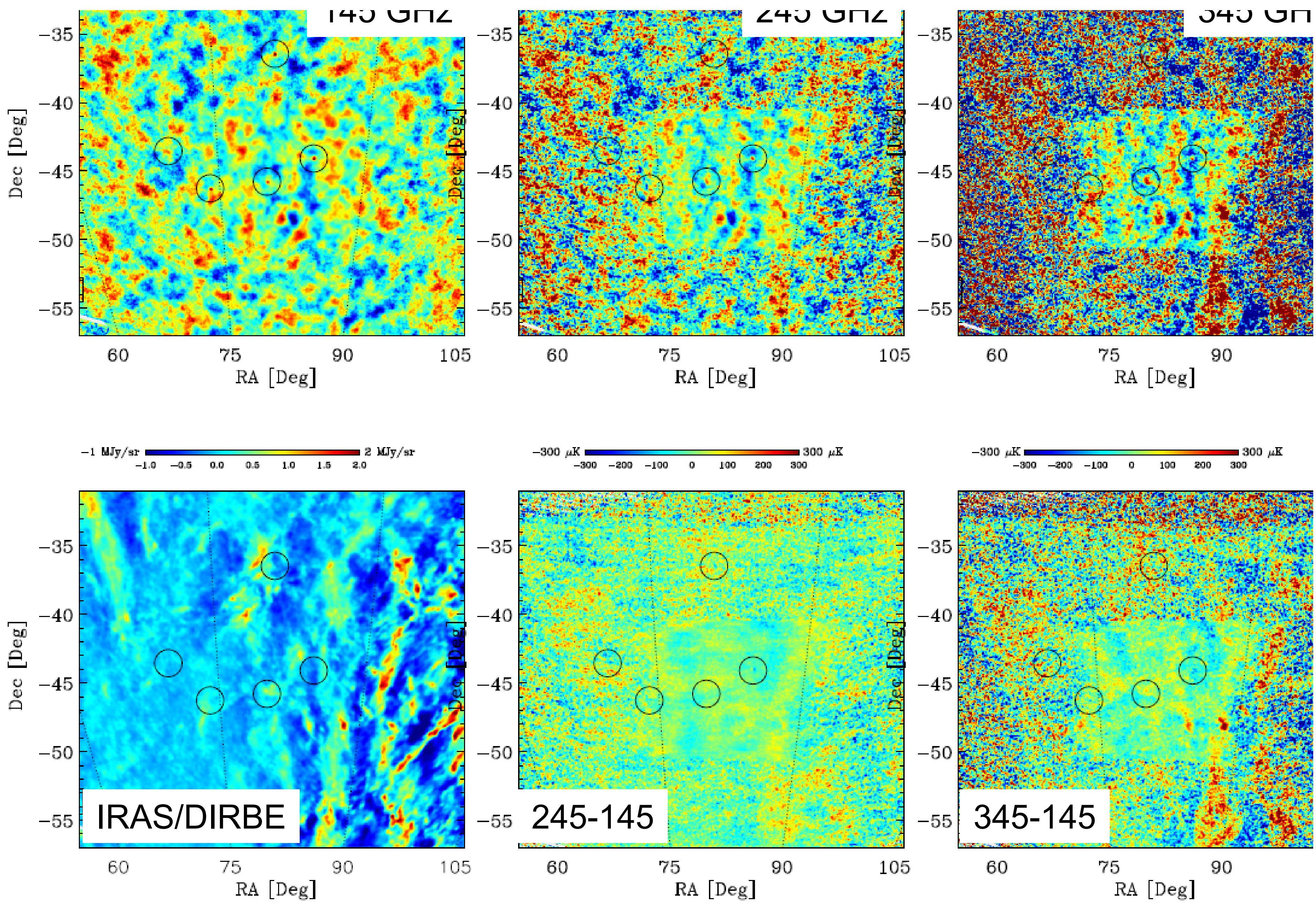


B2K3 Flight





Dec [Deg]
−35
−40
−45
−50
−55
60
75
90
105


Dec [Deg]
RA [Deg]
−1 MJy/sr
2 MJy/sr
−300 μK
300 μK
IRAS/DIRBE
245-145
345-145

Very Small Array

Cryostats on table

Source subtraction dishes

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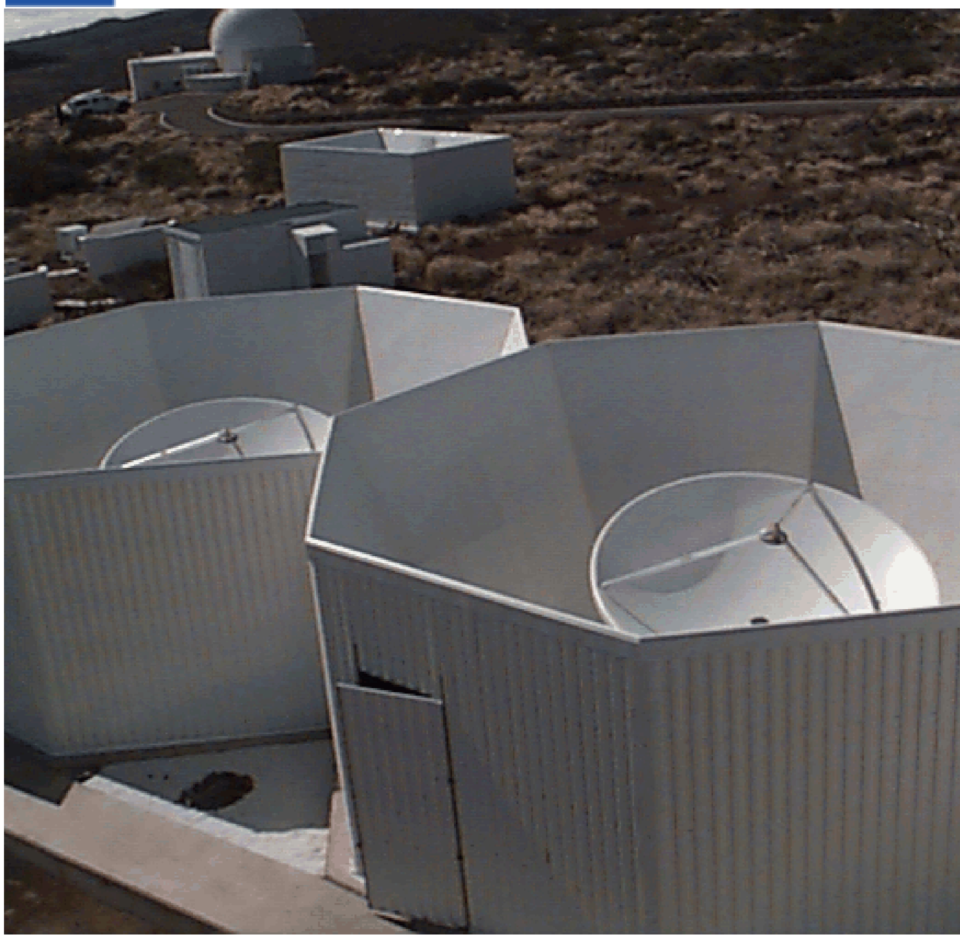
VSA



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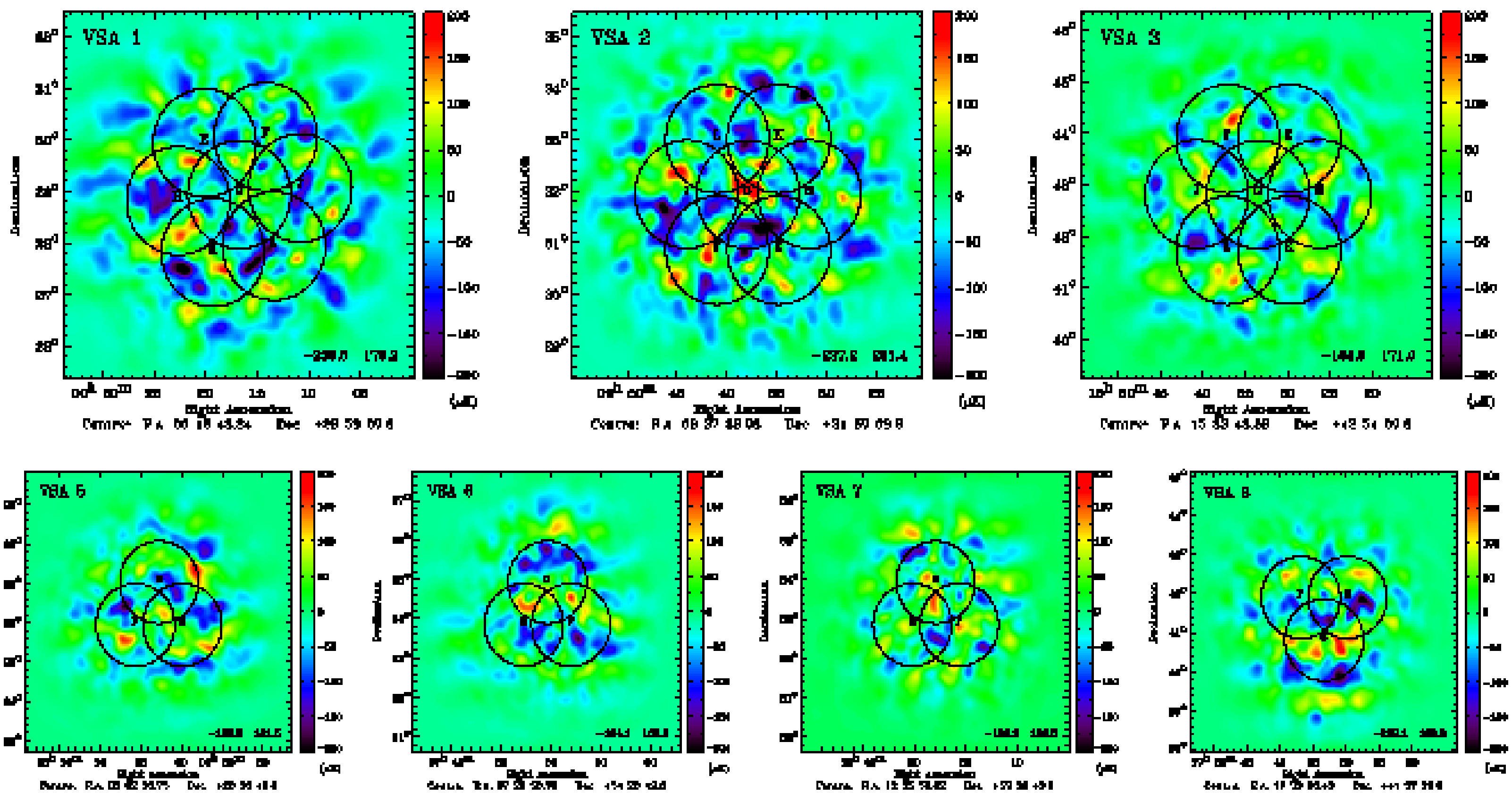
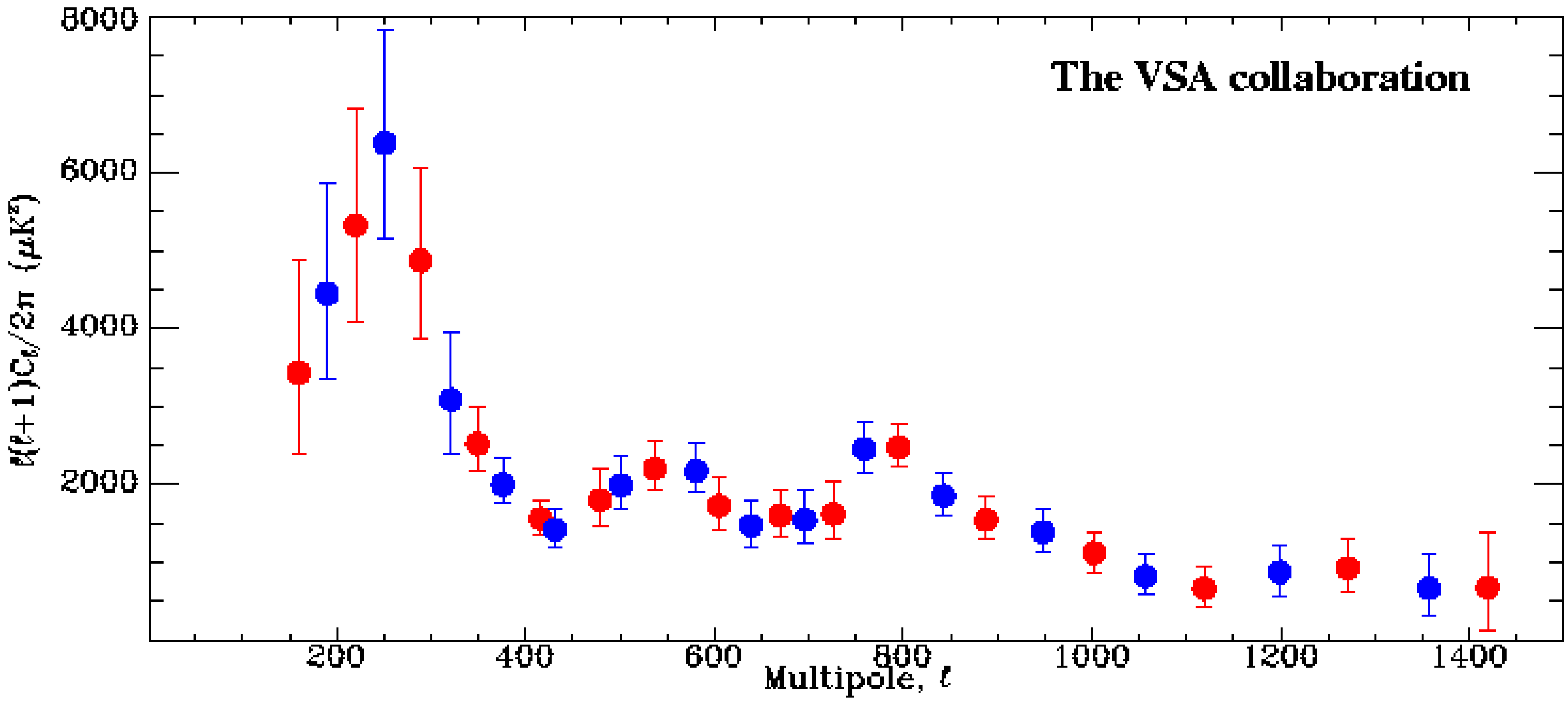
VSA maps



VSA Spectrum



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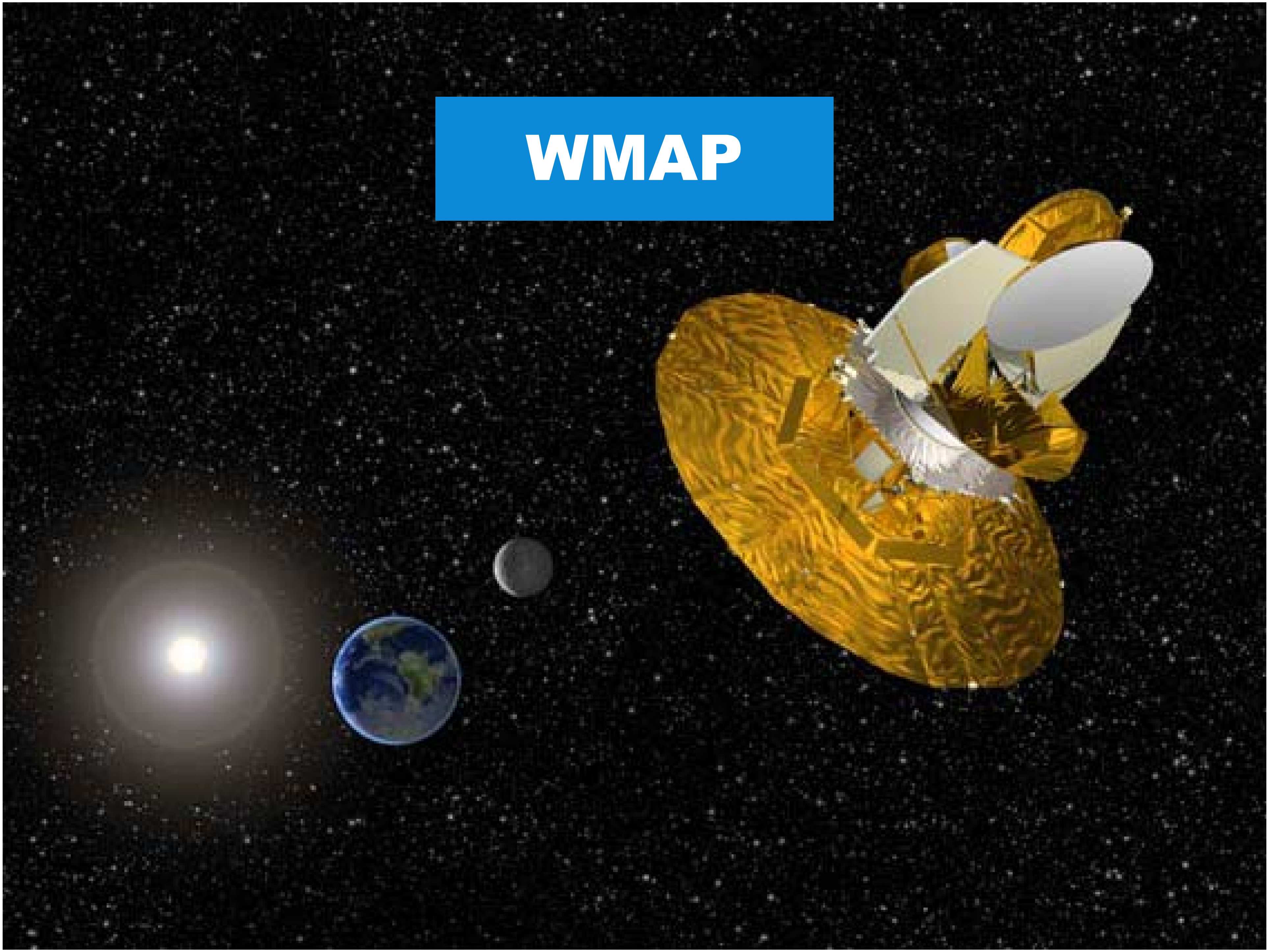
Cosmic Background Interferometer


WMAP

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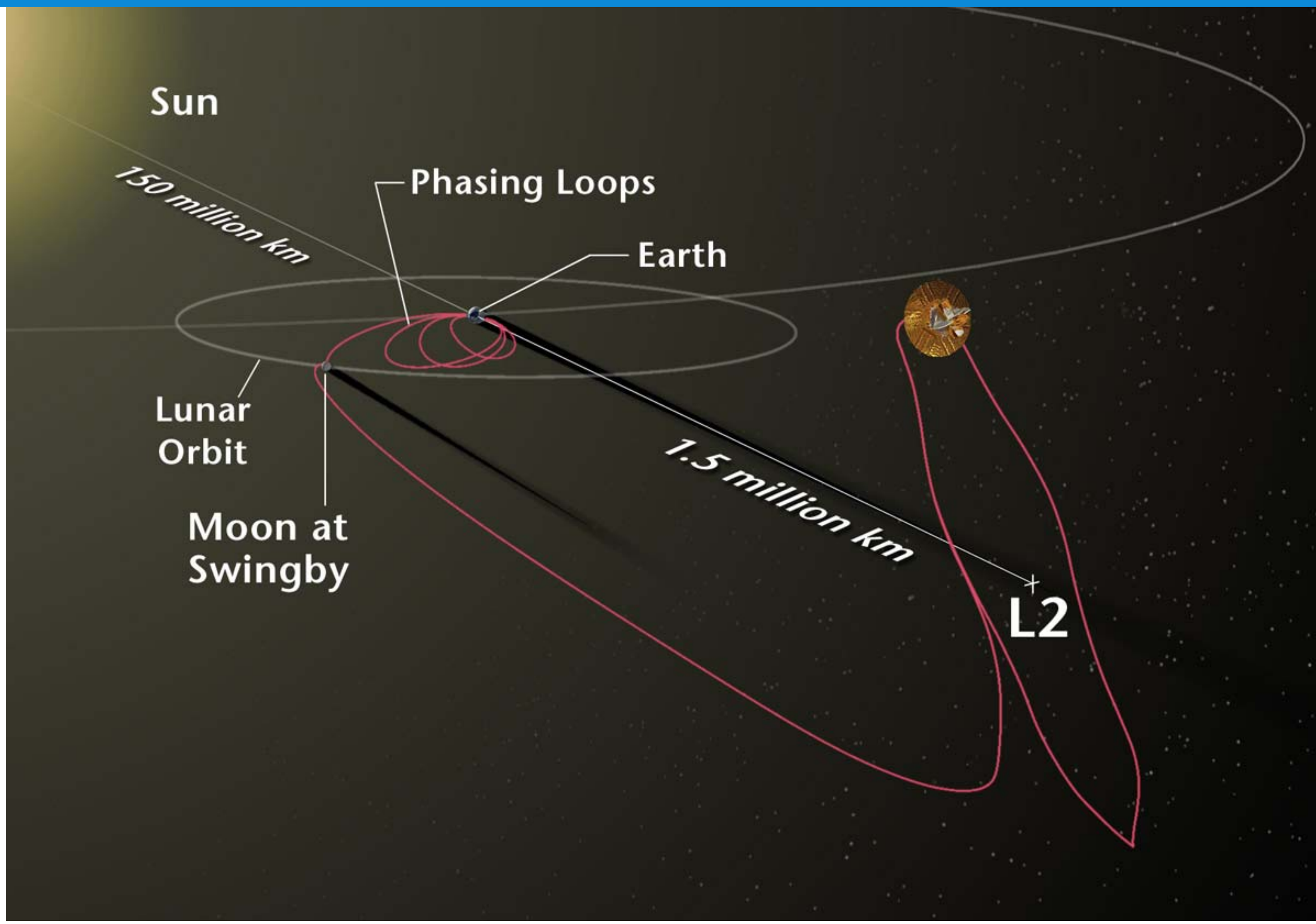
WMAP: L2 Orbit



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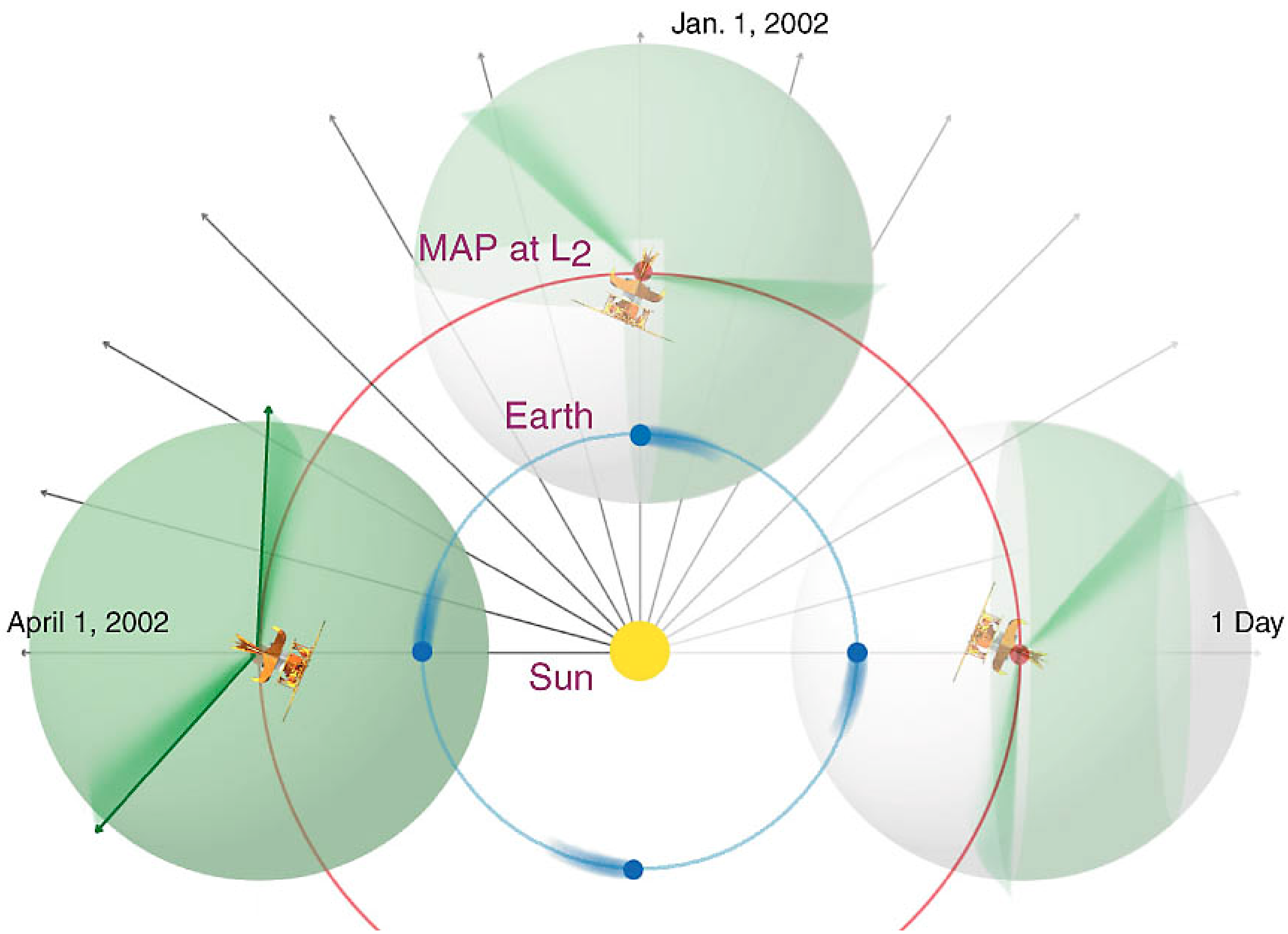
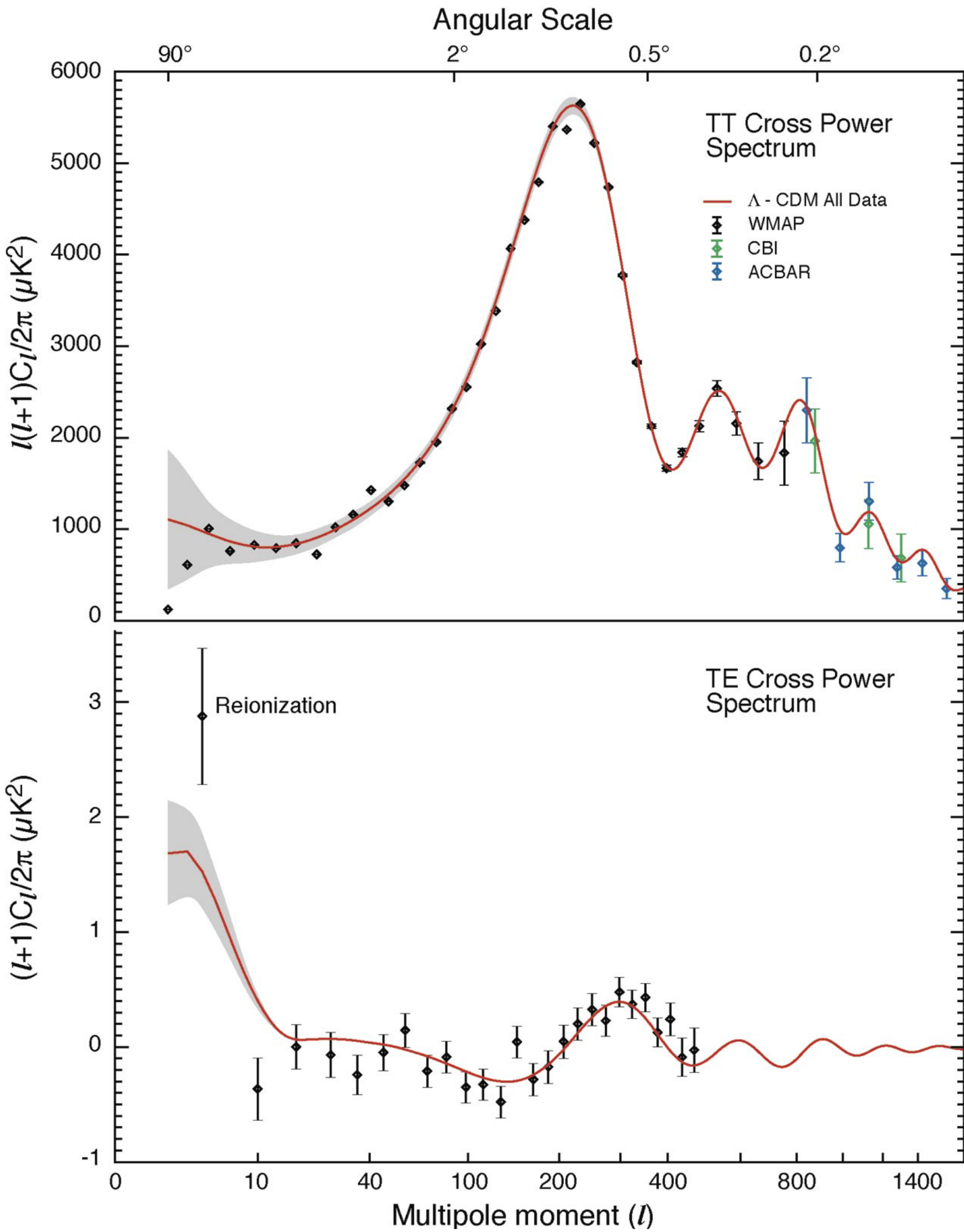
WMAP: Scanning




Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)Cl/2π (μK²)
Reionization
TE Cross Power Spectrum
(l+1)Cl/2π (μK²)
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)

19th – 20th Nc

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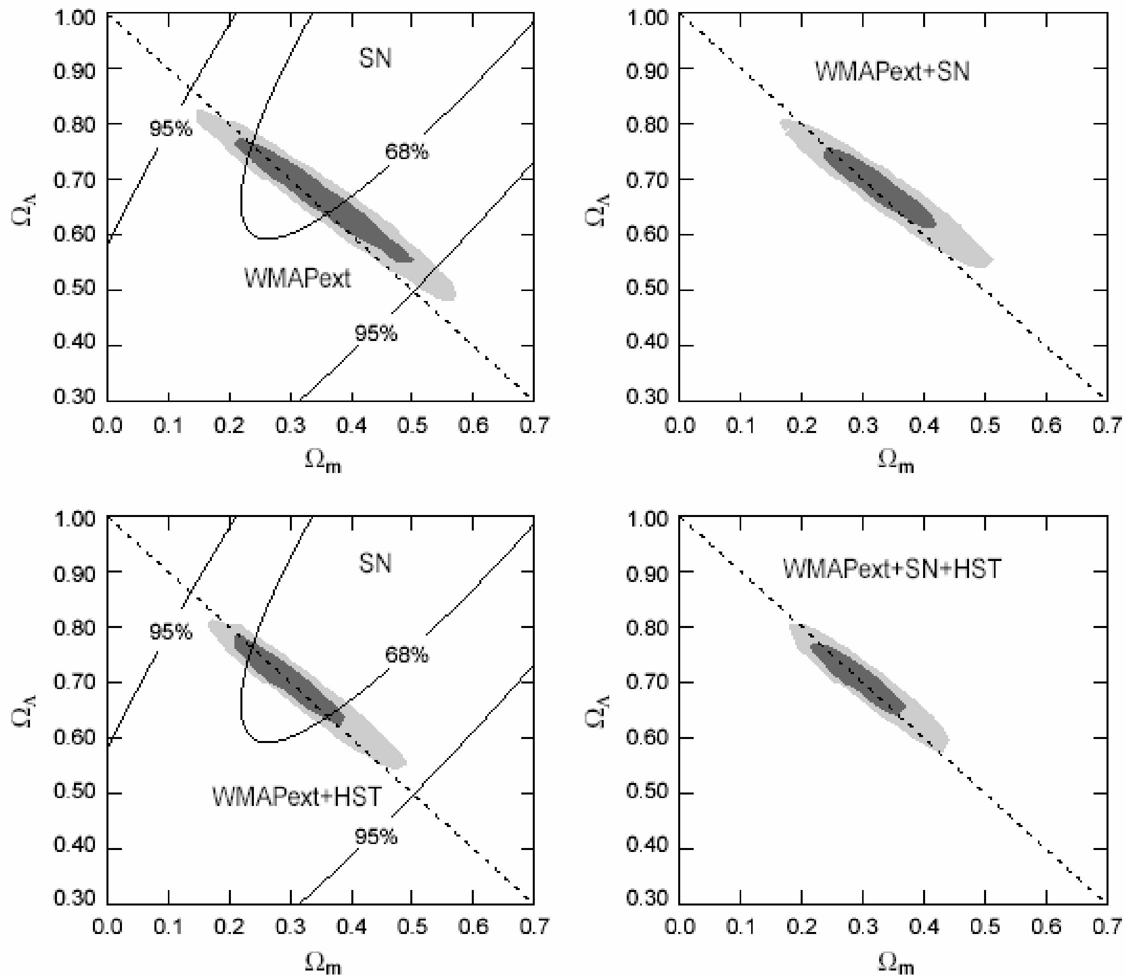
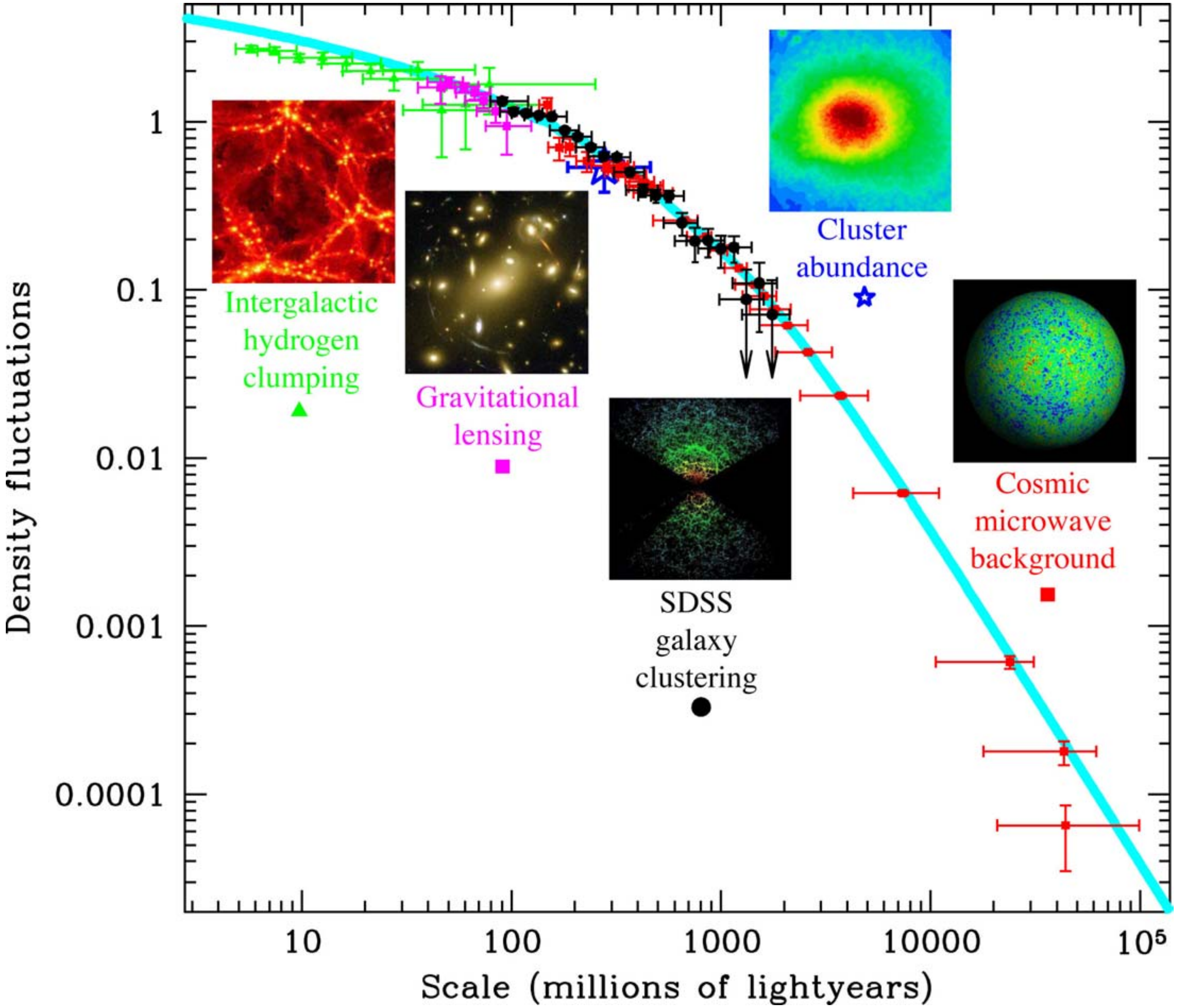
A Flat Universe?





Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10^5
Scale (millions of lightyears)
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background

Old Universe - *New* Numbers

$\Omega_{tot} = 1.02 \pm 0.02$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73 \pm 0.04$

$\Omega_b h^2 = 0.0224 \pm 0.0009$

$\Omega_b = 0.044 \pm 0.004$

$n_b = (2.5 \pm 0.1) \times 10^{-7}\,\mathrm{cm}^{-3}$

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27 \pm 0.04$

$\Omega_\nu h^2 < 0.0076$ (95% CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{\mathrm{cmb}} = 2.725 \pm 0.002$ K

$z_r = 20^{+10}_{-9}$ (95% CL)

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$r(k_0 = 0.002\,\mathrm{Mpc}^{-1}) < 0.71$ (95% CL)

$A(k_0 = 0.05\,\mathrm{Mpc}^{-1}) = 0.833^{+0.086}_{-0.083}$

$n_\gamma = 410.4 \pm 0.9\,\mathrm{cm}^{-3}$

$n_s = 0.99 \pm 0.04$ (WMAP only)

$\eta = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$

$\Omega_b \Omega_m^{-1} = 0.17 \pm 0.01$

$\sigma_8 = 0.84 \pm 0.04$

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$z_{\mathrm{dec}} = 1089 \pm 1$

$\Delta z_{\mathrm{dec}} = 195 \pm 2$

$h = 0.71^{+0.04}_{-0.03}$

$r_s = 147 \pm 2$ Mpc

$d_C = 14.0^{+0.2}_{-0.3}$ Gpc

$\theta_A = 0.^\circ598 \pm 0.^\circ002$

$l_A = 301 \pm 1$

$t_0 = 13.7 \pm 0.2$ Gyr

$t_{\mathrm{dec}} = 379^{+8}_{-7}$ kyr

$\Delta t_{\mathrm{dec}} = 118^{+3}_{-2}$ kyr

$z_{\mathrm{eq}} = 3233^{+194}_{-210}$

$\tau = 0.17 \pm 0.04$

$n_s(k_0 = 0.05\,\mathrm{Mpc}^{-1}) = 0.93 \pm 0.03$ with $dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

These "best" cosmological parameter values are from a combination of a wide variety of cosmological measurements, including the WMAP, COBE, CBI, and ACBAR CMB measurements and 2dFGRS, HST, SNIa, and Lyman-alpha forest measurements.

CMB Results since WMAP

- VSA high-ℓ results (2004)
- CBI Polarization (2004)
- ARCHEOPS Dust Polarization (2004)
- COSMOSOMAS Spinning Dust (2005)
- Boomerang Polarization (2005)
- WMAP NG analysis (2003-05)
- WMAP, VSA, CBI still observing.

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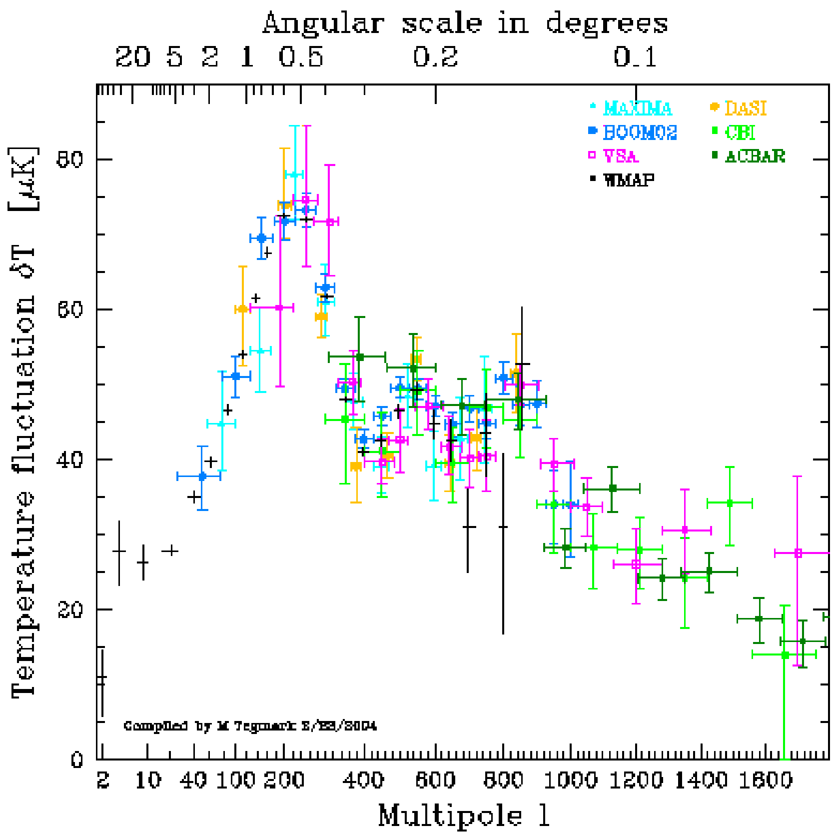
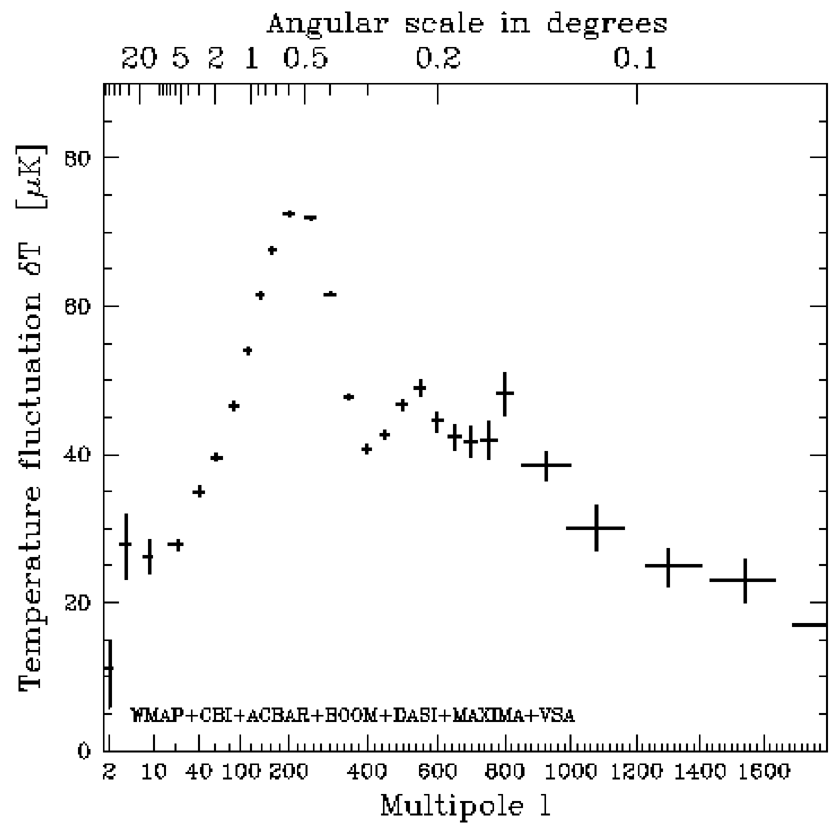
Summary of current data





Figures: Max Tegmark

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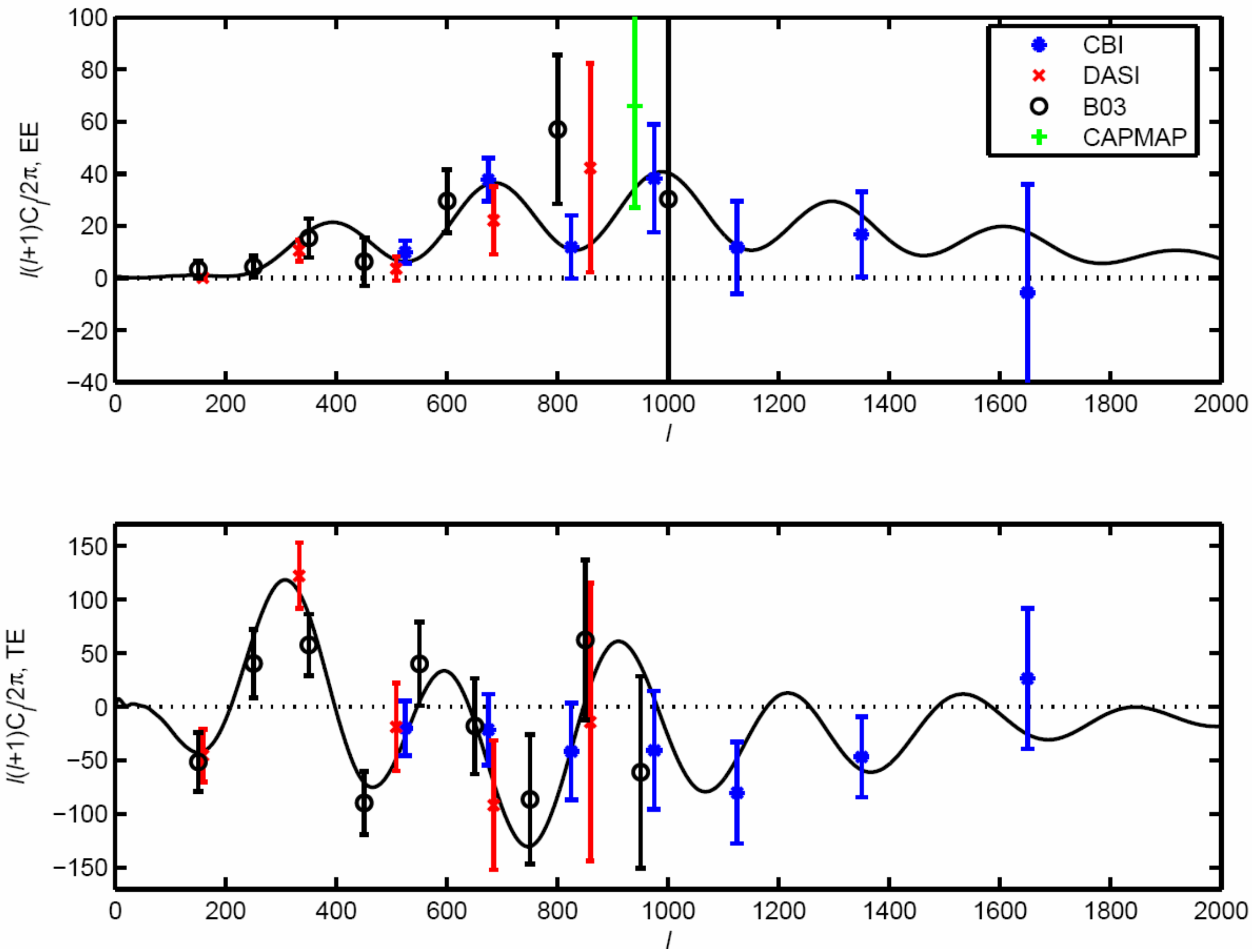
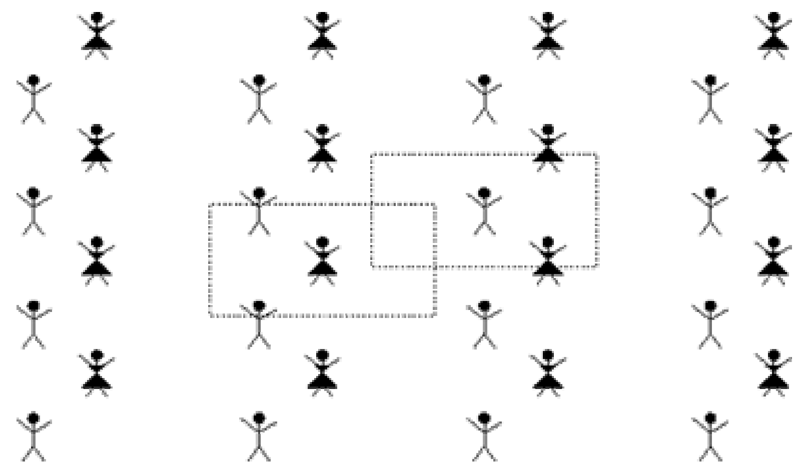
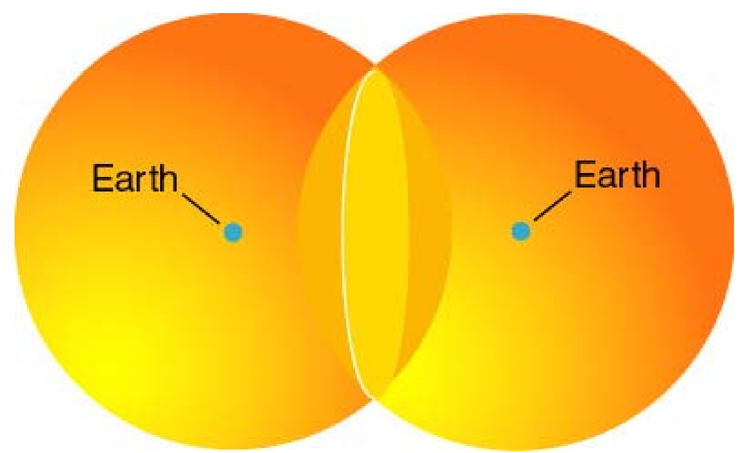
Current Polarization Results



Weird Cosmology

- A Compact Universe?
- Signatures:
  - Repeating structures (cosmic crystallography)
    - Not seen yet
  - Less power at very low ℓ
    - Yes!
  - Circles in the sky
    - No, still looking





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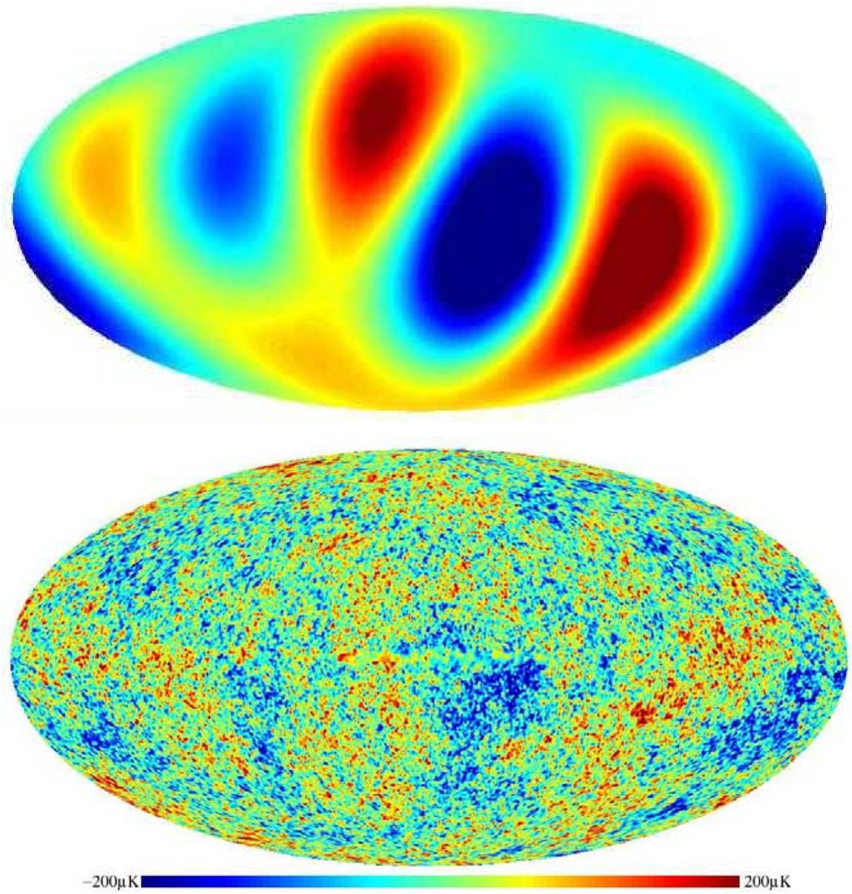
Weird Cosmology

- Non-Gaussianity
  - *Any sign of structure in the phase of CMB fluctuations signals physics beyond the inflationary paradigm*
- Axis of Evil:
  - *Quadrupole and octopole line up!*
- North vs. South
  - *Peculiar structures in southern Eliptic/Galactic hemisphere.*



Tegmark et al. 2003

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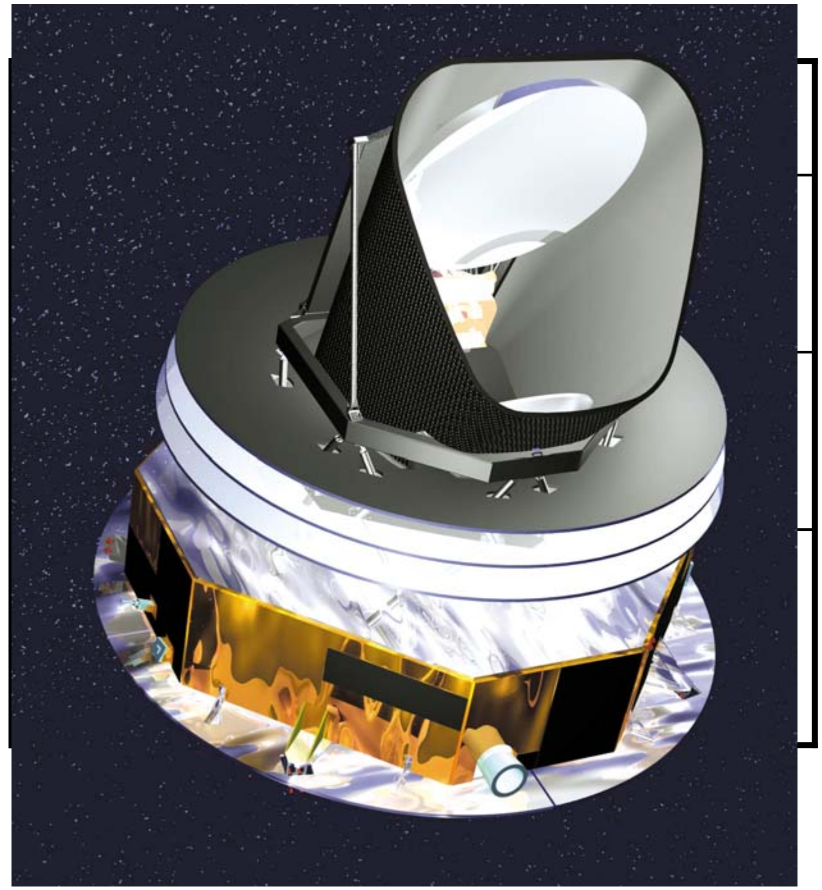
ESA's *Planck* mission

- "Last word" in CMB temperature observations: accuracy set by foreground residuals
  - Resolve "cosmic degeneracies"
  - Non-Gaussian cosmology
    - Clusters: SZ, lensing
    - Strings
    - ???
  - Galactic & extragalactic astronomy
- Polarization: best power spectrum yet
  - Low SNR but 12 million pixels
- First chance of detecting primordial B-mode polarization



Planck mission status

- November 2005:
  - Delivery of Flight Model components ongoing
- Launch: August 3rd 2007
- PV Phase: Oct-Dec 2007
- Survey starts: Jan 2008
- Survey ends: Feb 2009
- Proprietary period ends: Feb 2011.

Planck Cryo Qualification Model under test at CSL, Liège.

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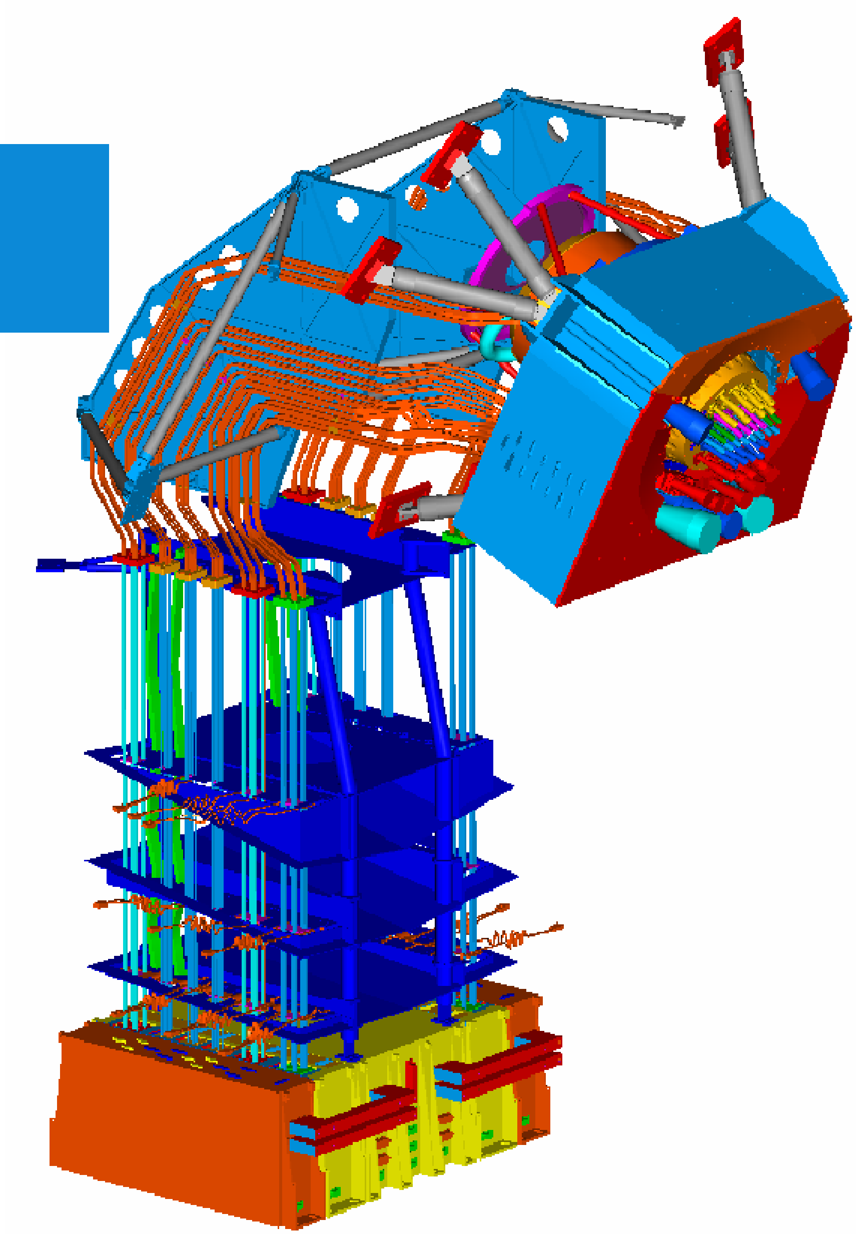
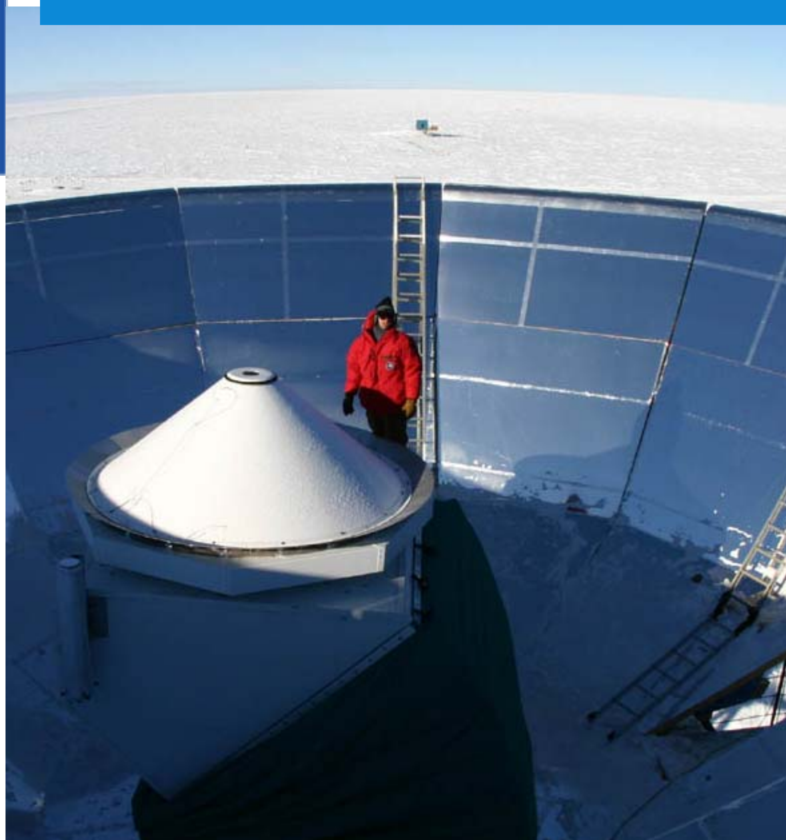
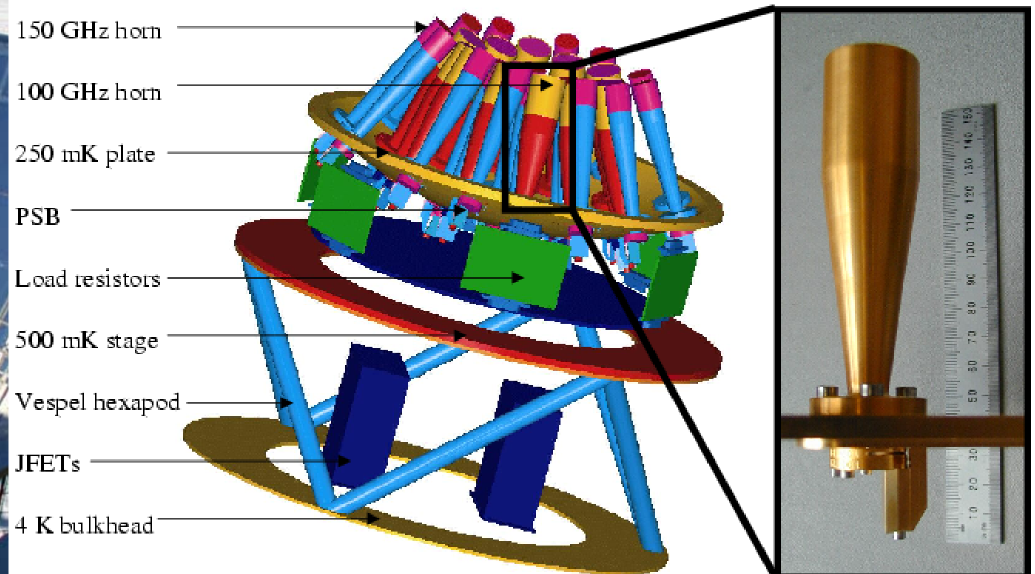
Planck Instrument

- LFI front end connected to warm backend in service module via waveguides.
- Elaborate thermal control to keep 250 K temperature differential
- Also lines to coolers in the SM.
- HFI self-contained in helium dewar, only data connections to SM.



South Pole: QUaD





Uses old DASI mount

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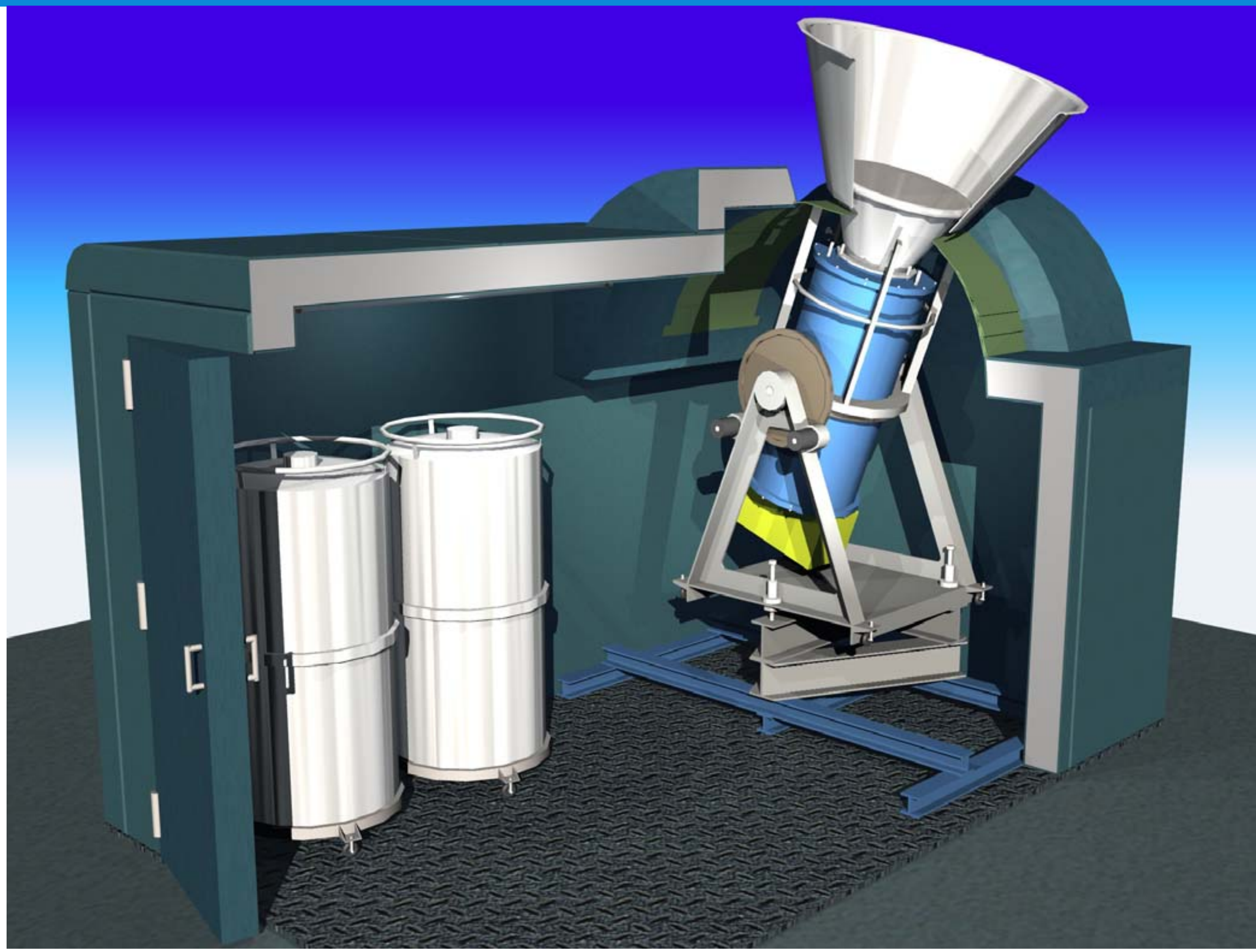
South Pole: BICEP



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New Projects

- *Planck*
  - All-sky, high precision
  - High-ℓ
  - CMB & foreground pol^n
- Balloon
  - Boomerang 2K3 (Dust pol^n)
  - EBEX (Pol^n)
  - SPIDR (Pol^n)
- Ground-based:
  - QUAD (Pol^n)
  - BICEP (Pol^n)
  - CLOVER (Pol^n)
  - GEM-P (Synchrotron pol^n)
  - QUIET (Pol^n)
  - VSA+ (Higher ℓ)
  - C-BASS (Synchrotron pol^n)