Future CMB Observations

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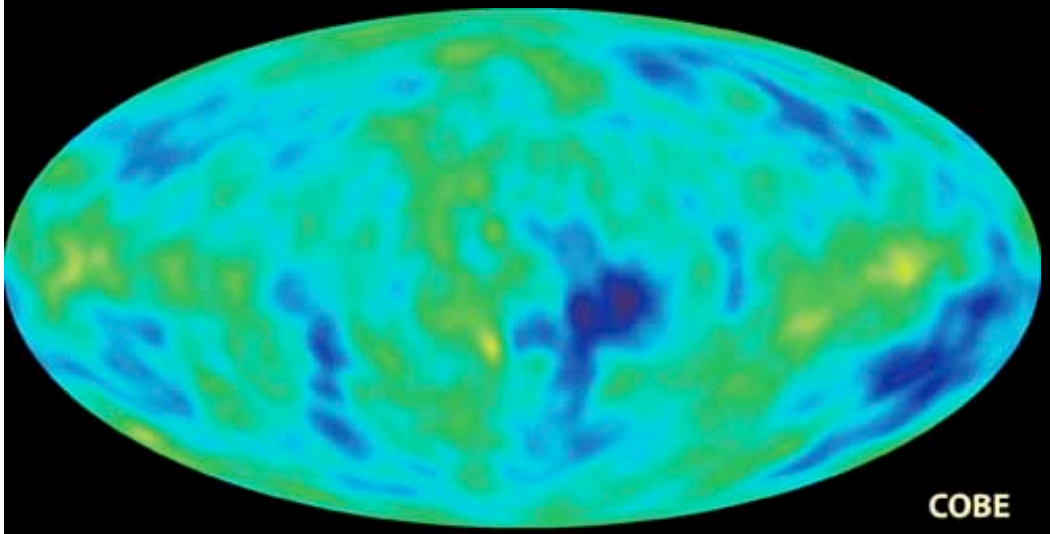
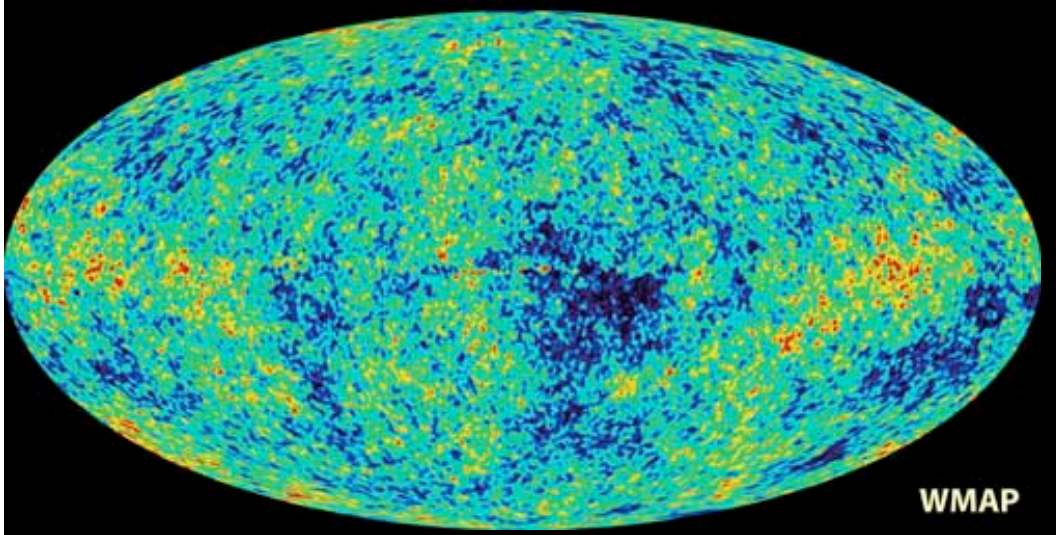
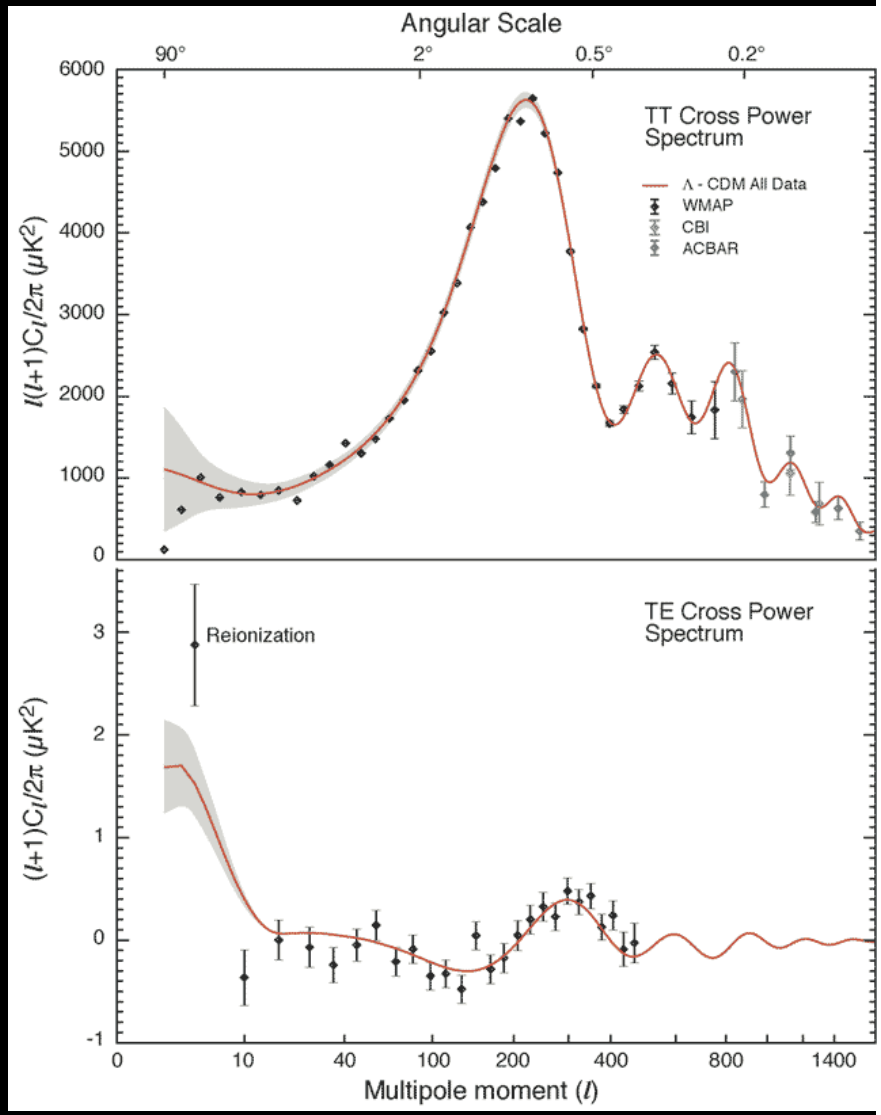
Outline

- Current State of the Art CMB
- SZE and Small-Scale CMB Anisotropy
  - What to expect from the data (optimistic/pessimistic)
  - Brief discussions of foregrounds and systematic errors
  - Types of Experiments
  - A case study instrument, the SZA
- CMB Polarization
  - What to expect from the data (optimistic/pessimistic)
  - Brief discussion of foregrounds and systematic errors
  - Types of Experiments
  - A case study ground-based instrument with coherent polarimeters (QUIET)
  - A case study balloon-based instrument with bolometers (EBEX)

WMAP Results with CBI, ACBAR







The Expected (WMAP, CBI, ACBAR, 2df, Lyman α forest)...

$h = 0.71^{+.04}_{-.03}$

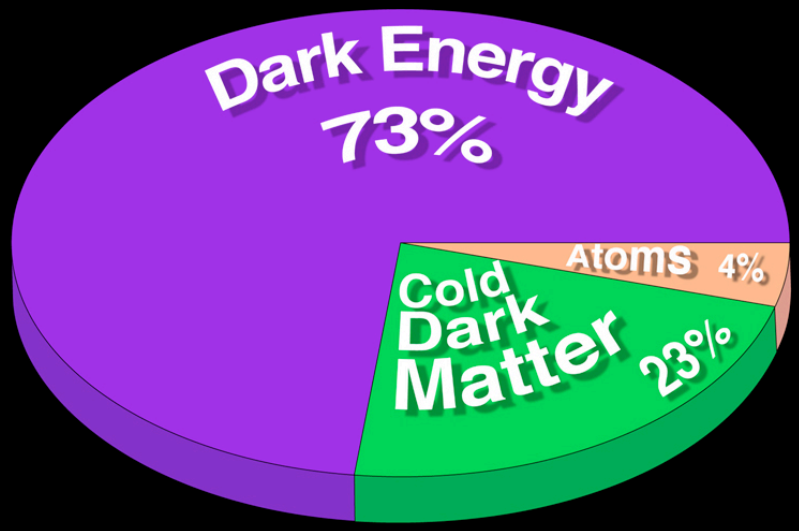
$\Omega_b h^2 = 0.0224 +/- 0.0009$

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

$\sigma_8 = 0.84 +/- 0.04$

Age = 13.7+/-0.2

n_s (0.05 Mpc^{-1}) = 0.93+/-0.03



The Surprising

Early Reionization (t = 0.17+/–0.04) implies an early generation of stars able to reionize the Universe at $z=20^{+10}_{-9}$

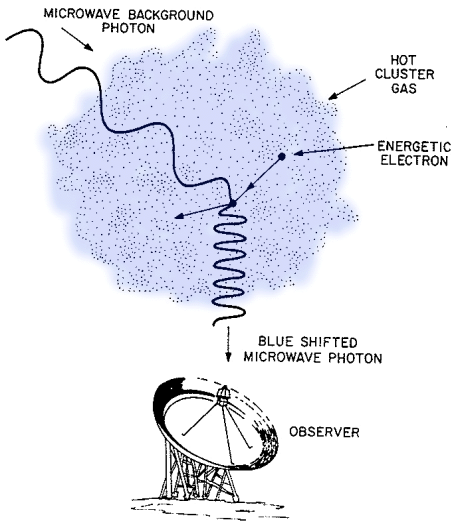
Low Quadrupole (in agreement with COBE) → cosmic variance?, finite universe?

Numbers from WMAP data combined with ACBAR, CBI, 2dfGRS, and Lyman α forest

SZE/Small Scale CMB Anisotropy

Science Goals and Systematics

The Sunyaev-Zel'dovich Effect (SZE)

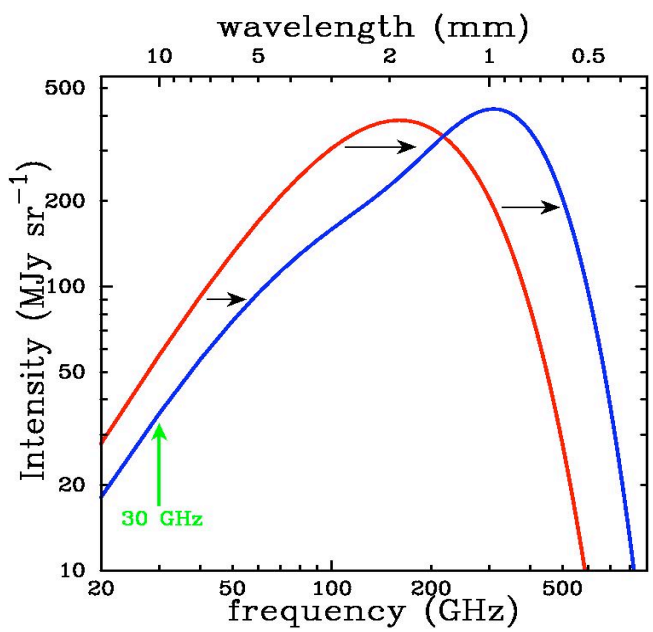


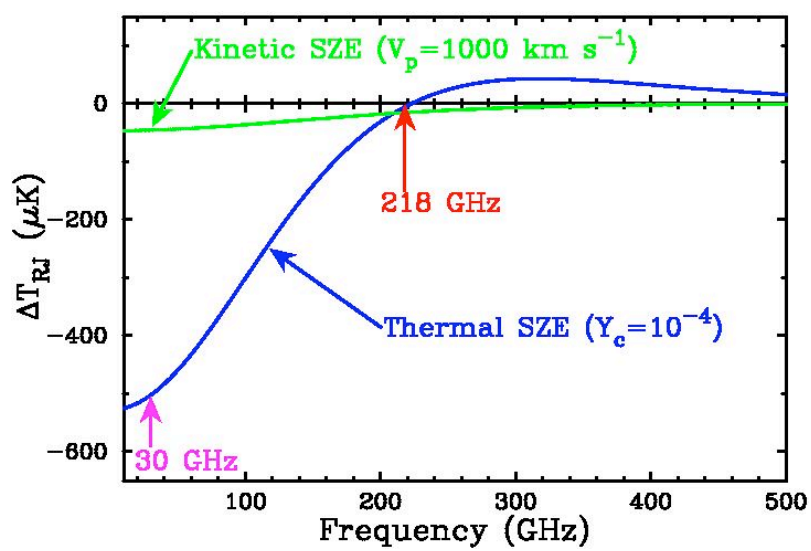
Adapted from L. Van Speybroeck

Produces a distortion in the CMB blackbody spectrum – depends on cluster physics

(redshift-independent)

$$\left.\frac{\ddot{A}T_{CMB}}{T_{CMB}}\right|_{RJ} = -2\int \frac{k_B T_e}{m_e c^2} n_e \acute{o}_T dl = -2y$$

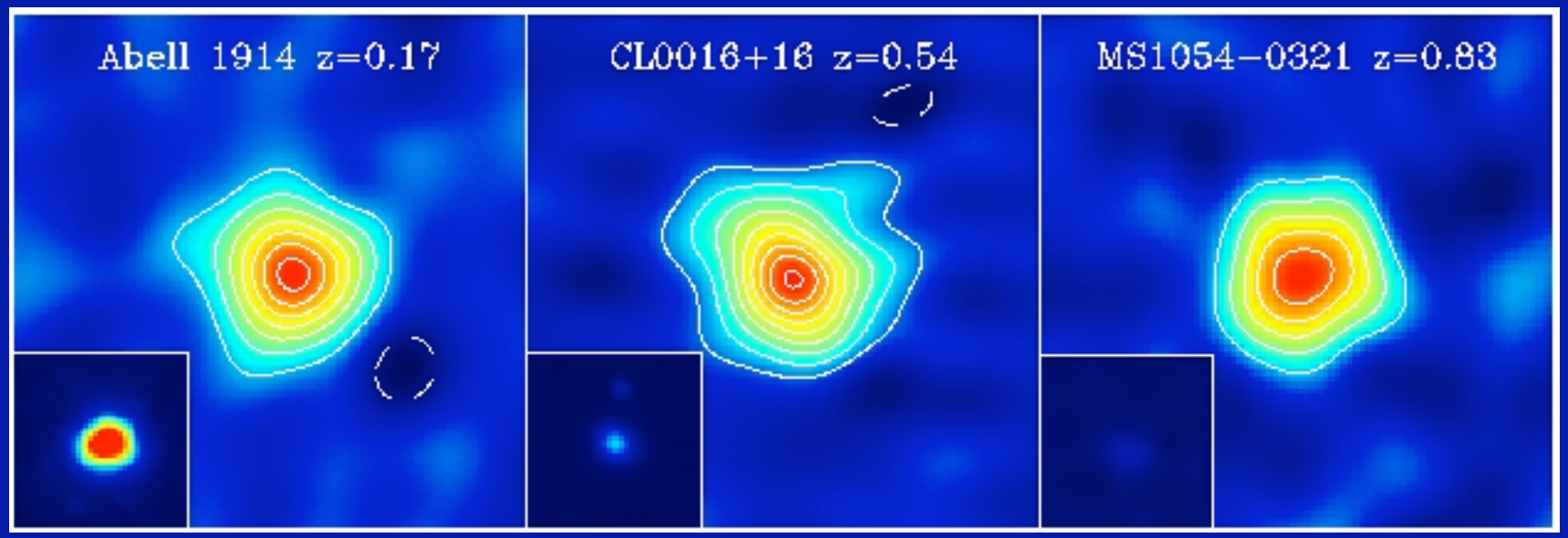




Plots courtesy of Reese

SZE Surveys – Exploit SZE redshift independence

Can Probe of Structure Formation and provide mass-limited cluster sample

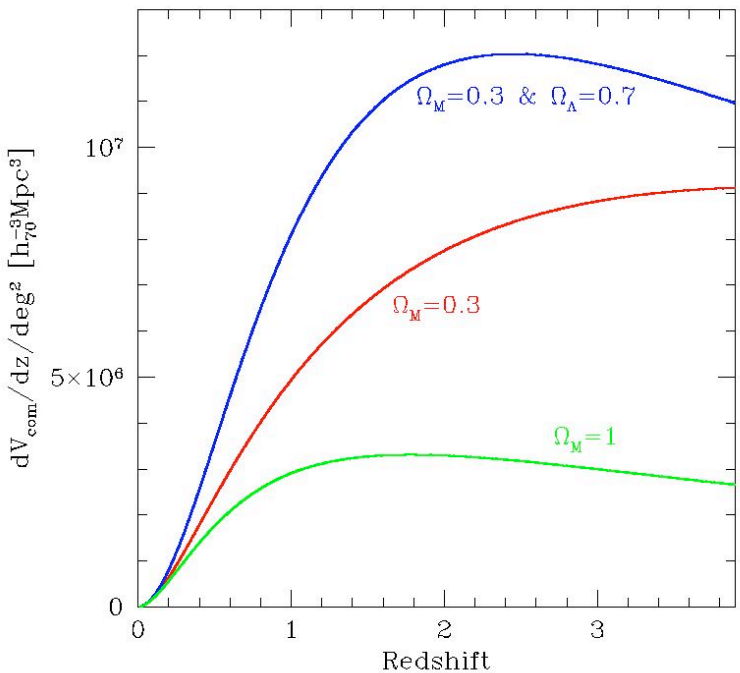


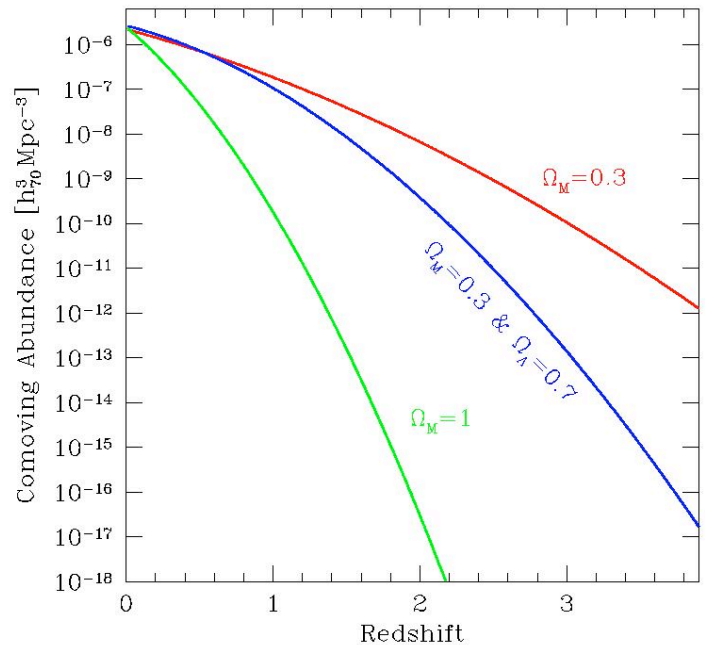
Carlstrom and Mohr

SZE contours every 75μK. Same range of X-ray surface brightness in all three insets.

$$\text{SZE Flux}: \; S \propto \frac{1}{d_A(z)^2} \int n_e T_e \, dV$$

Volume element & Cluster Abundance





Abundances are normalized to produce the observed local abundance of massive clusters (Mohr 2001)

Volume element: The volume per comoving redshift depends on cosmological parameters. Higher Ω_Λ or lower Ω_m quickly drives volume element up. Dominates at low redshift (z < 1)

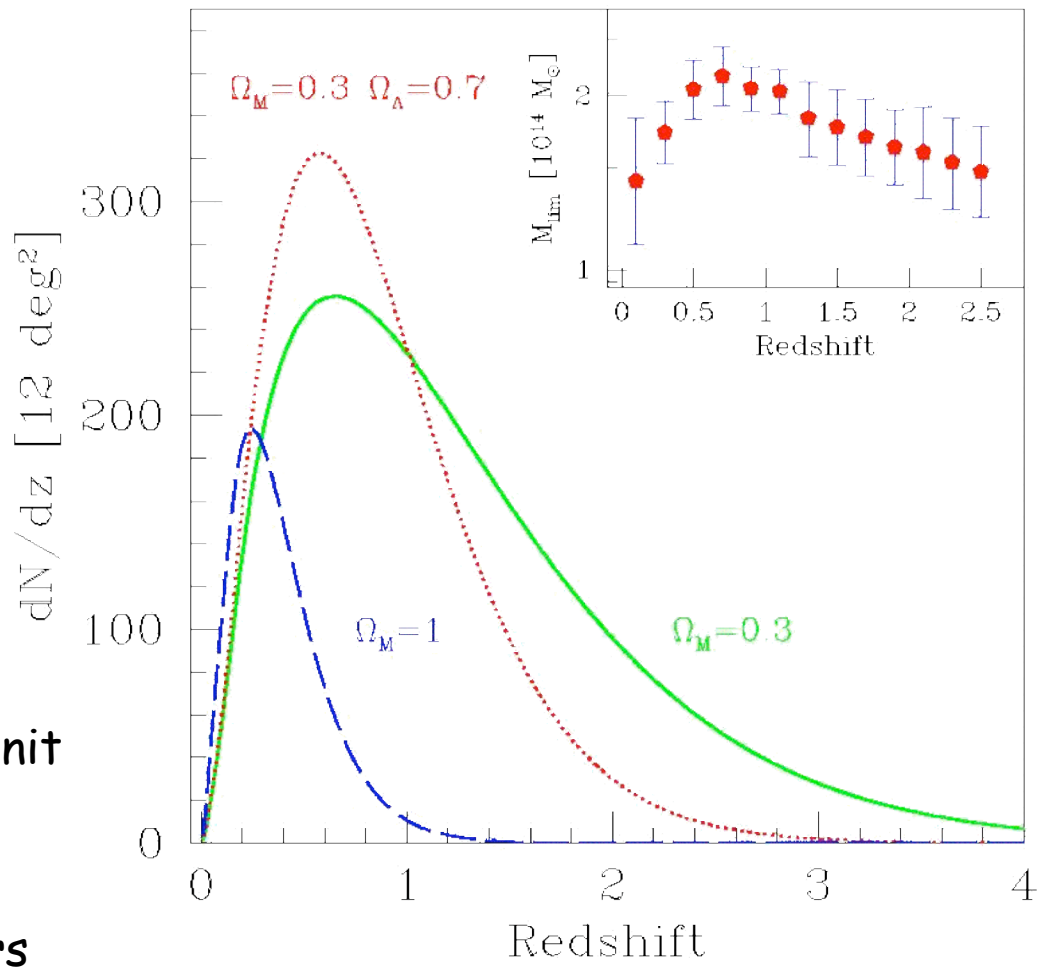
Cluster Abundance: Cluster number density evolves with z due to exponential dependence on amplitude of density fluctuations, σ_8. Dominates at high redshift (z > 1)

Cluster Redshift Distribution

Structure growth depends on Cosmological model

$$\frac{dN}{dzd\Omega} = \frac{dV_{com}}{dzd\Omega} n_{com}$$

$$= \frac{c}{H(z)} d_A^2 (1+z)^2 \int_{M_{\lim}(z)}^{\infty} dM \frac{dn}{dM}$$



Mohr 2001

- dV/dzdΩ = Comoving volume per unit redshift per unit solid angle
- n_{com} = Comoving density of clusters
- M_{lim} = minimum cluster mass above survey detection limit

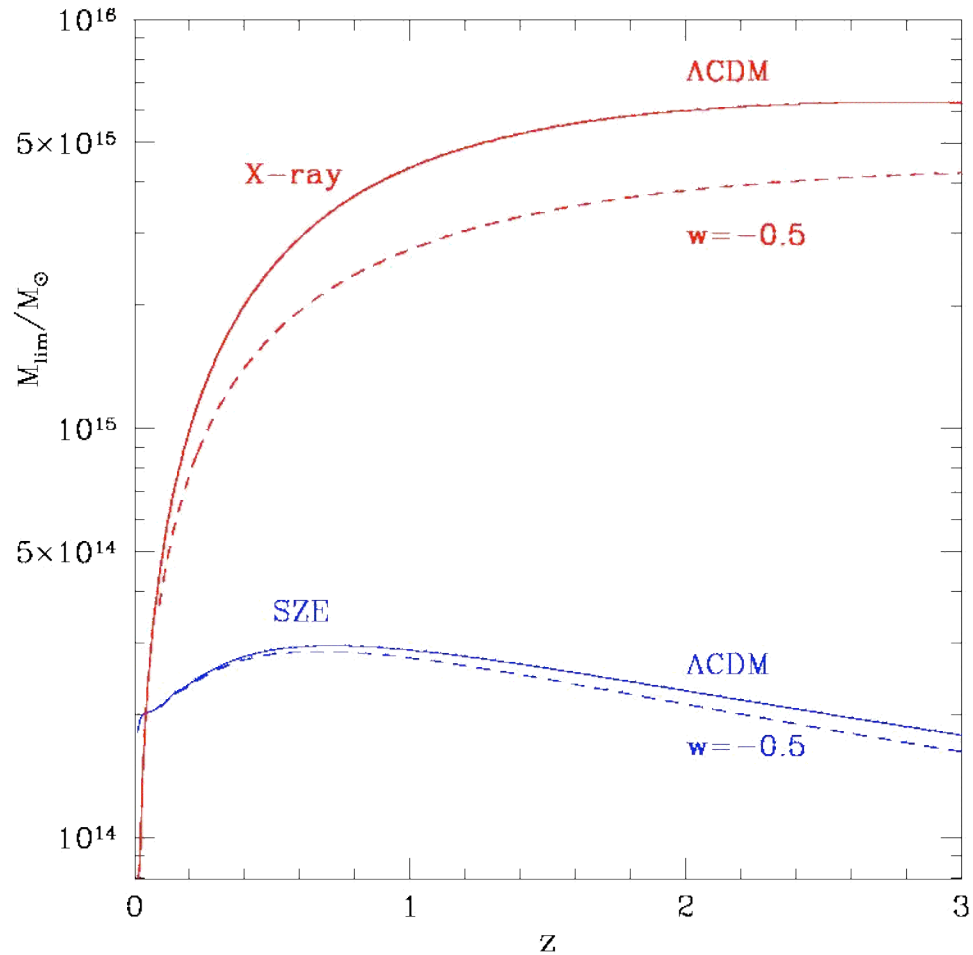
Limiting Cluster Virial Mass

- 10^4 deg^2 X-ray survey 3.6×10^6cm^{2}s at 1.5 keV (Ricker, Lamb, et al.)
- 12 deg^2 interferometric SZ survey similar to SZA

SZE Mass limit insensitive to z:

1) Increasing d_A with z → total SZ flux decreases as d_A^{-2} (increases limiting mass)

2) Cluster evolution offsets this effect: Clusters are denser at higher z so have higher virial temperatures at constant virial mass (M_{200})



Haiman, Mohr, and Holder 2001

Thermal SZE

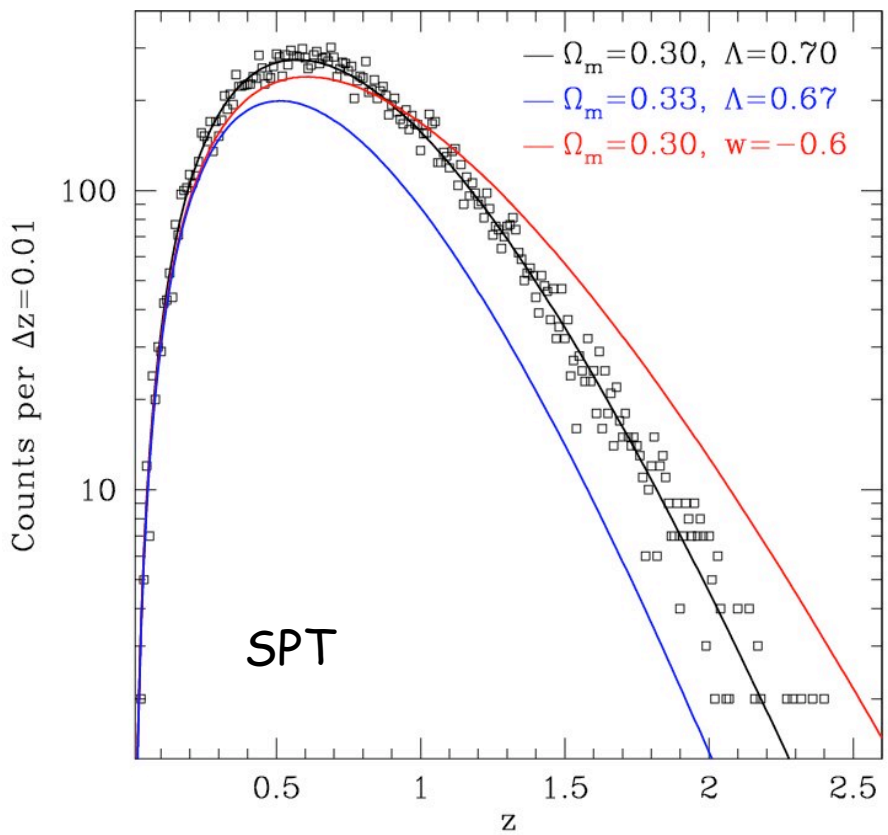
- Thermal SZE
  - Cluster Abundance dN/dz → Ω_M , Ω_Λ, w, w(t)?
  - Determine σ_8
  - ¬ Tests of Non-Gaussianity
  - Small-Scale CMB Angular Power Spectrum
  - Spatial power spectrum, P(*k*)
  - Cluster gas mass fraction → Ω_b
  - ¬ with X-ray observations
    - Angular Diameter distance/Hubble Constant
    - Scaling Relations, ΔS_ν-T_x, θ-T_x, T_x- ΔS_ν

Cluster Astrophysics

- cluster evolution
- cooling cores, cold fronts, shock fronts, evacuated cavities
- merger history, current dynamical state, relationship of intra-cluster gas to stellar population

Thermal SZE

What we plan to know…



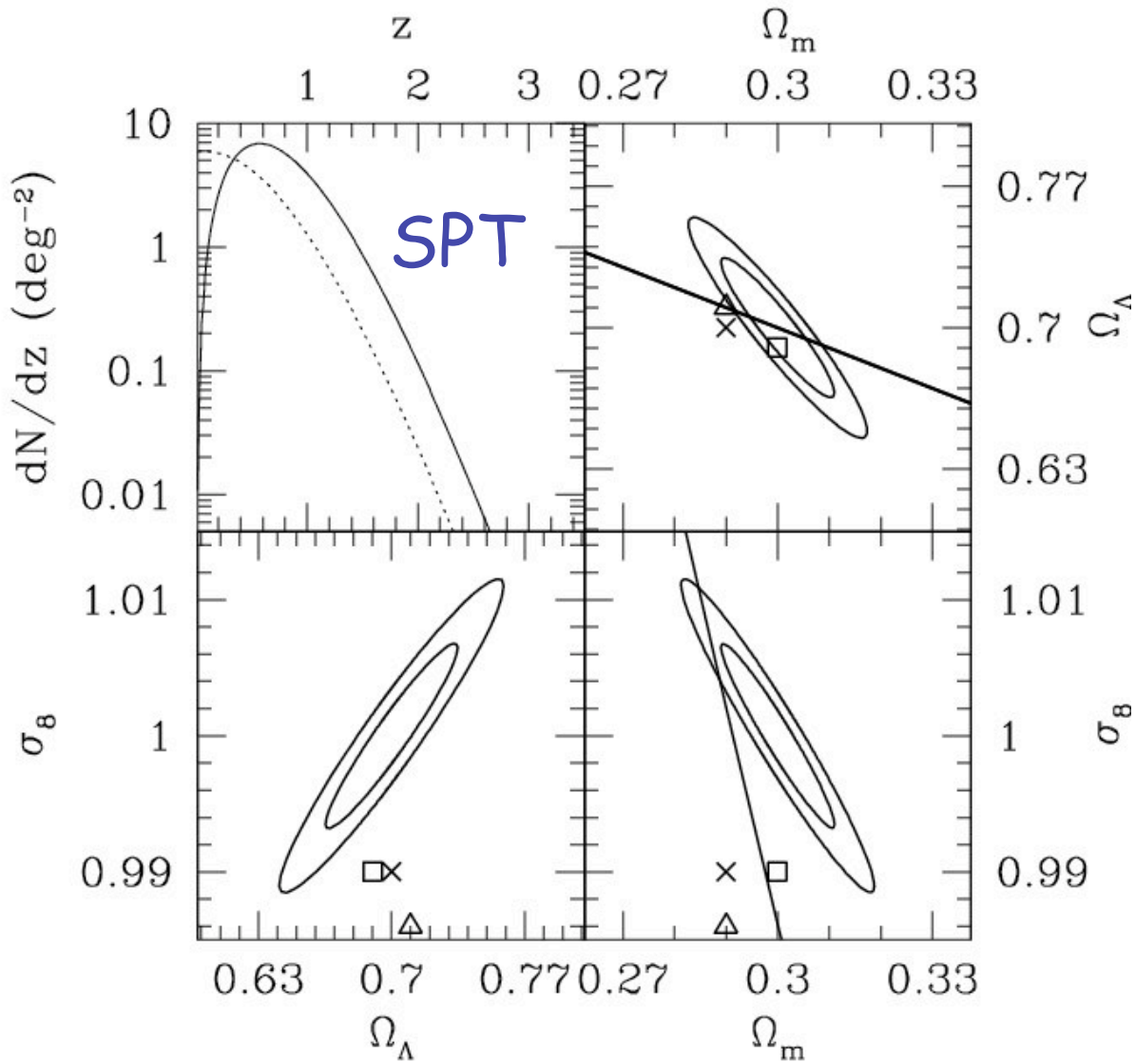
Cosmological Parameter Constraints

4000 sq deg
~17,000 clusters

□ : systematic tilt in the mass function $\sigma(M)^{0.1}$

△ : 10% reduction in mass function amplitude

x : +5% offset in limiting mass



Holder, Haiman & Mohr 2001, astro-ph/0105396

Mapping cluster observable to mass

Cluster mass limit insensitive to z (in principle) *but* potentially sensitive to astrophysical effects (cluster evolution with z, pre-heating, cooling, etc)

Mitigation Strategies

Detailed Study of individual clusters

Scaling relations

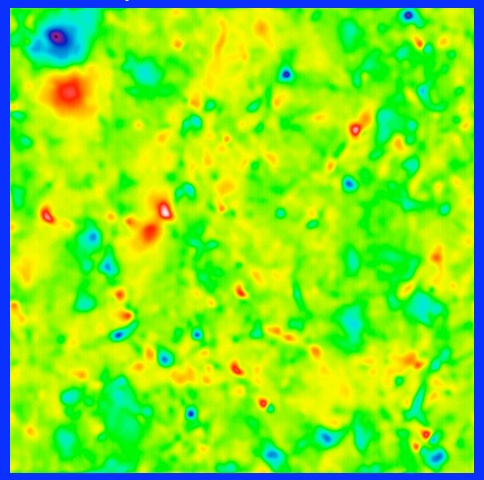
Self-Calibration (eg Majumdar and Mohr, Hu)

Kinetic SZ/Ostriker-Vishniac (OV)

CMB Anisotropy produced by scattering from ionized regions with bulk peculiar velocities – ionization by first stars (OV) or in clusters and filaments (KSZ)

$$\delta T \propto \left\langle n_e^2 \right\rangle^{1/2} \left\langle v_e^2 \right\rangle^{1/2}$$

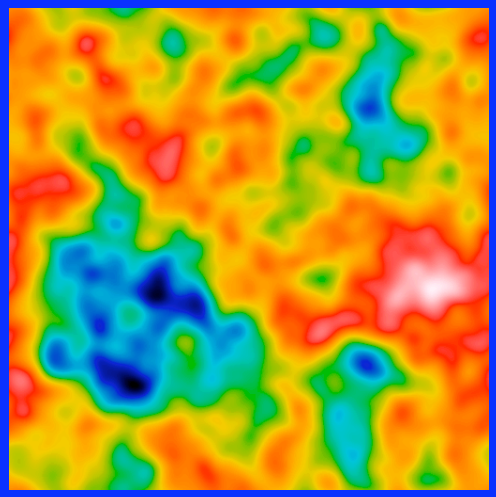
n_e=density of *hot electrons along the line of site,*
v_e=*velocity of hot electrons*



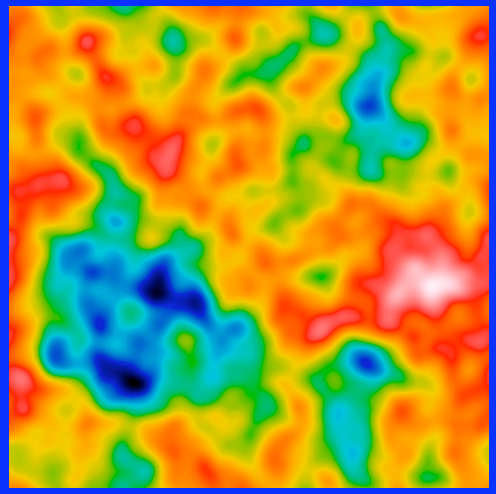
KSZ/OV

- **KSZ** measures cluster bulk velocity field at high z
- **OV power spectrum** measures the density and velocity fluctuations at reionization
- **Amplitude** of OV signal determines epoch of reionization.
- **Non-Gaussian** but with CMB frequency spectrum. Spatially distinguishable. Requires a high fidelity map

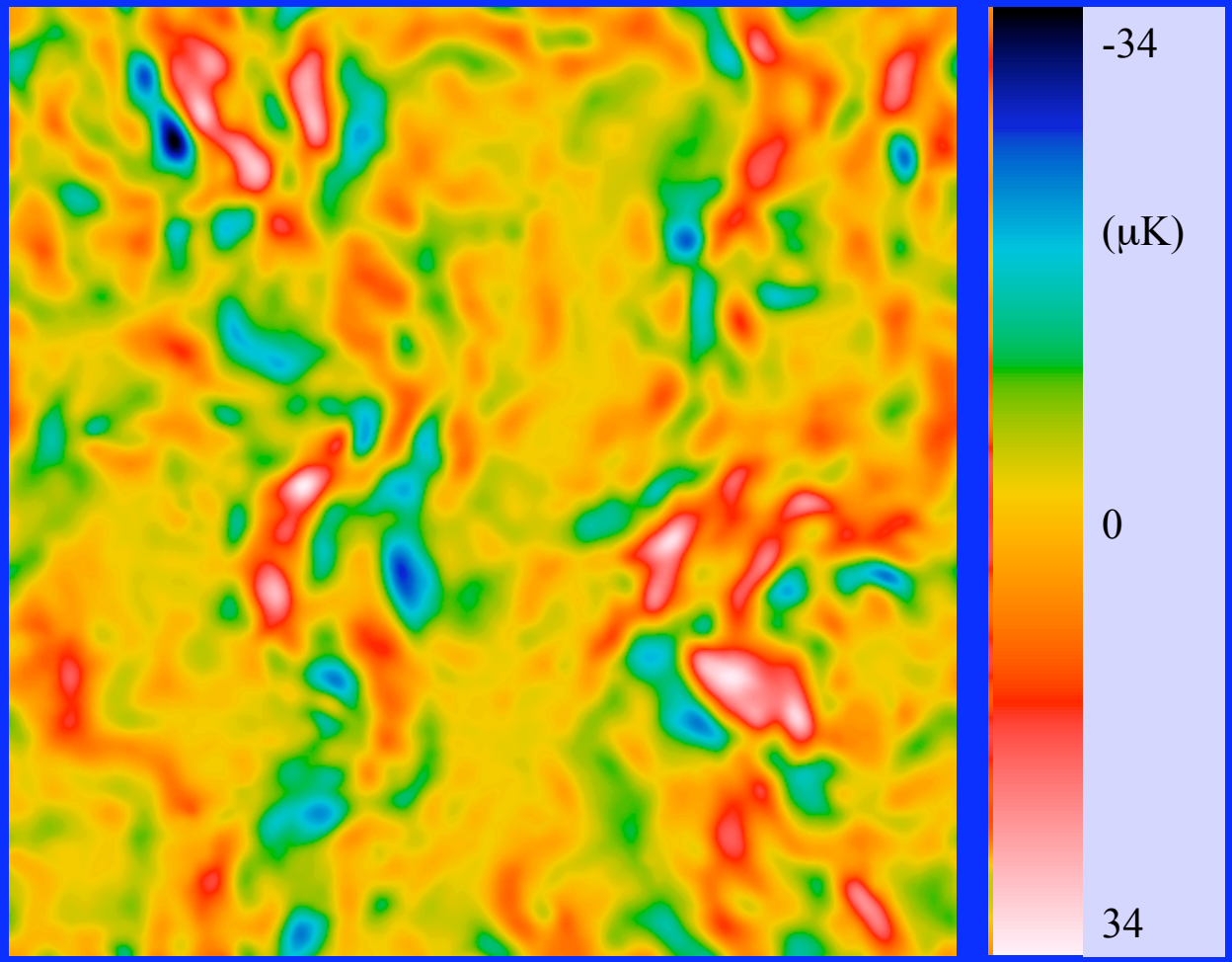
Lensing of the CMB



CMB



CMB + Lensing



Lensing Signal

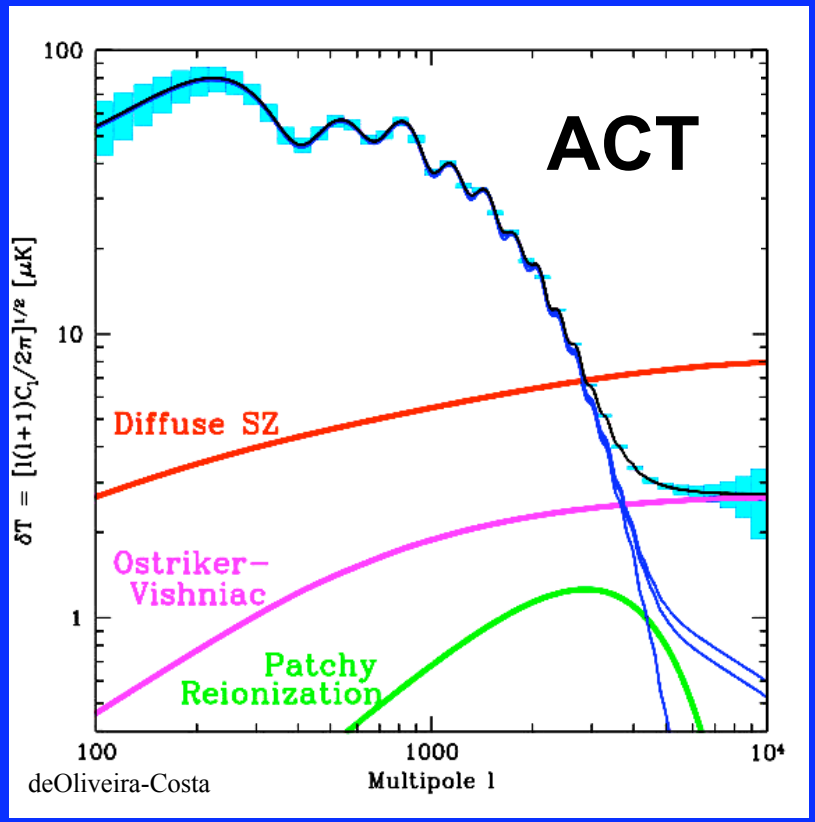
2% of CMB RMS

1.4°x 1.4°

simulations: Seljak and Huffenberger

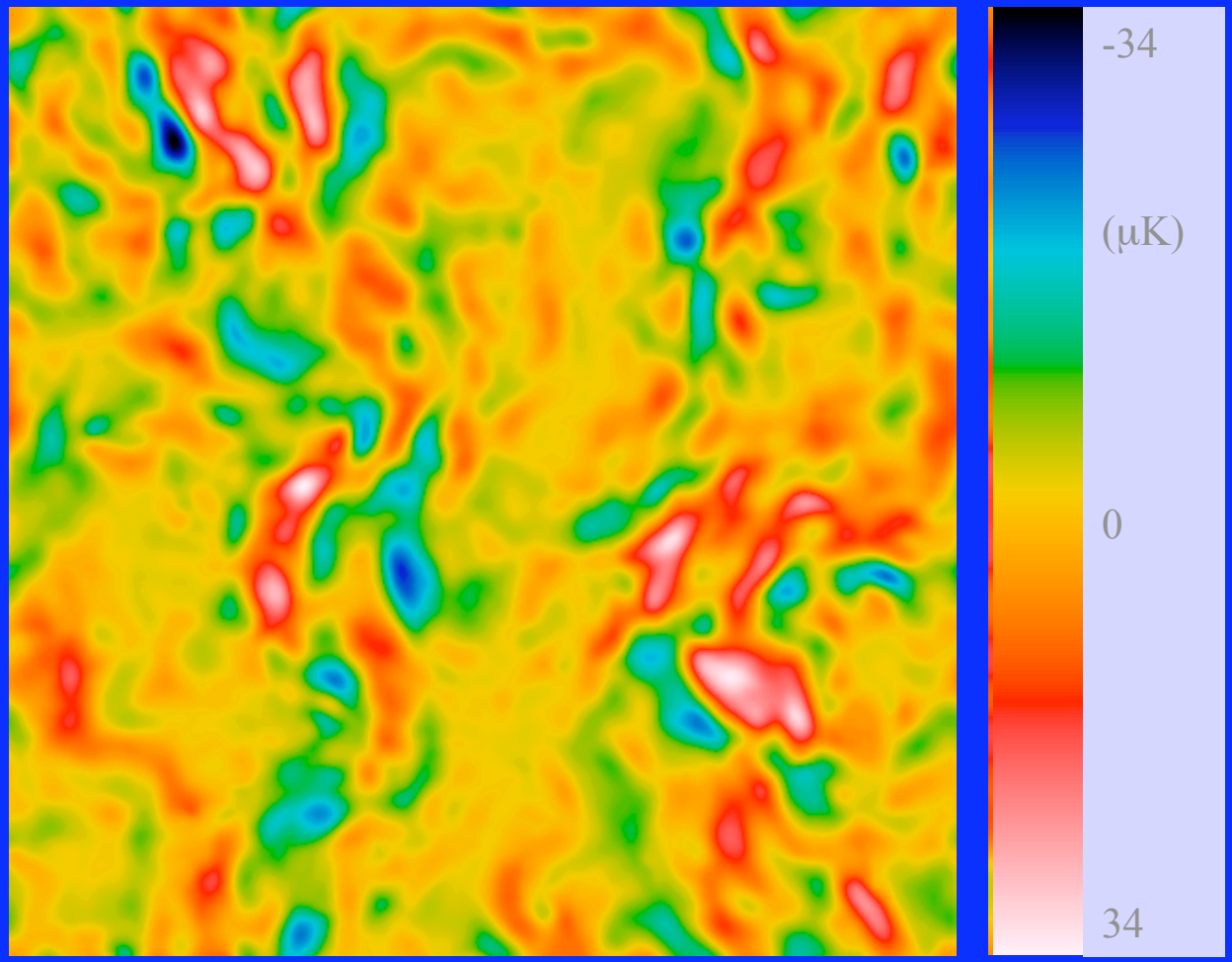
Lensing of the CMB

- Lensing arises from integrated mass fluctuations along the line of sight.
- The CMB acts as a fixed distance source, removing the degeneracy inherent to other lensing measurements.
- Signal at $l > 2000$
- Image distortion – only a minor effect in the power spectrum.



Lensing of the CMB

- Isolate from SZ and point sources spectrally.
- Identify with distinctive 4-point function.
- With a high fidelity map, can construct a projected mass map on arcminute scales



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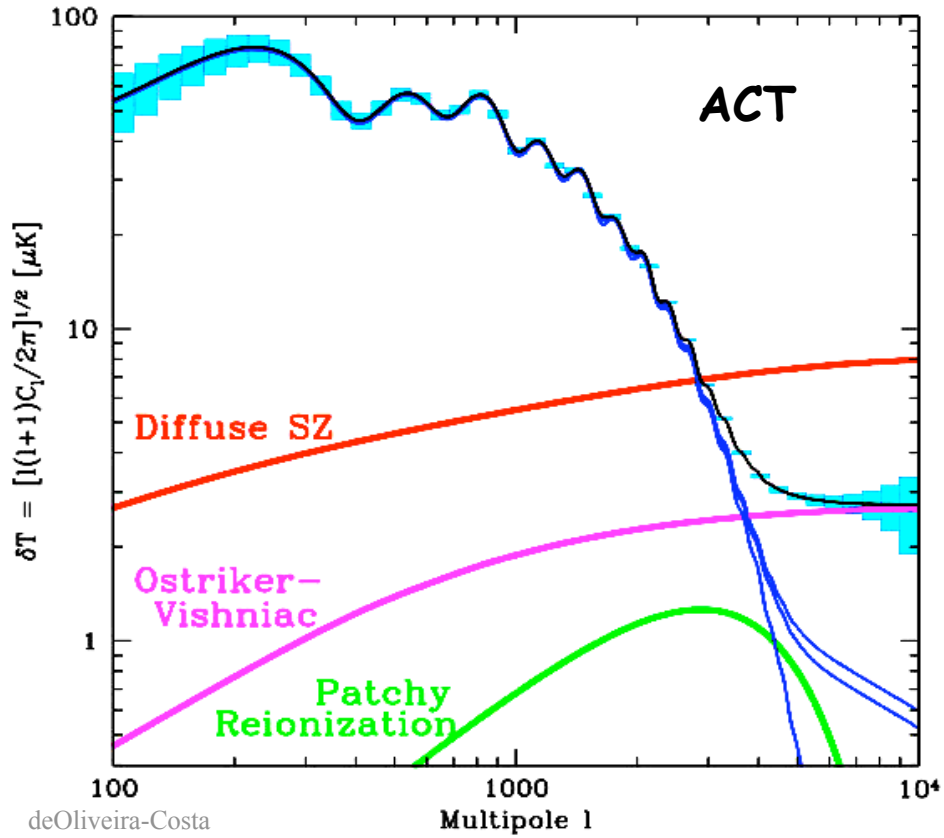
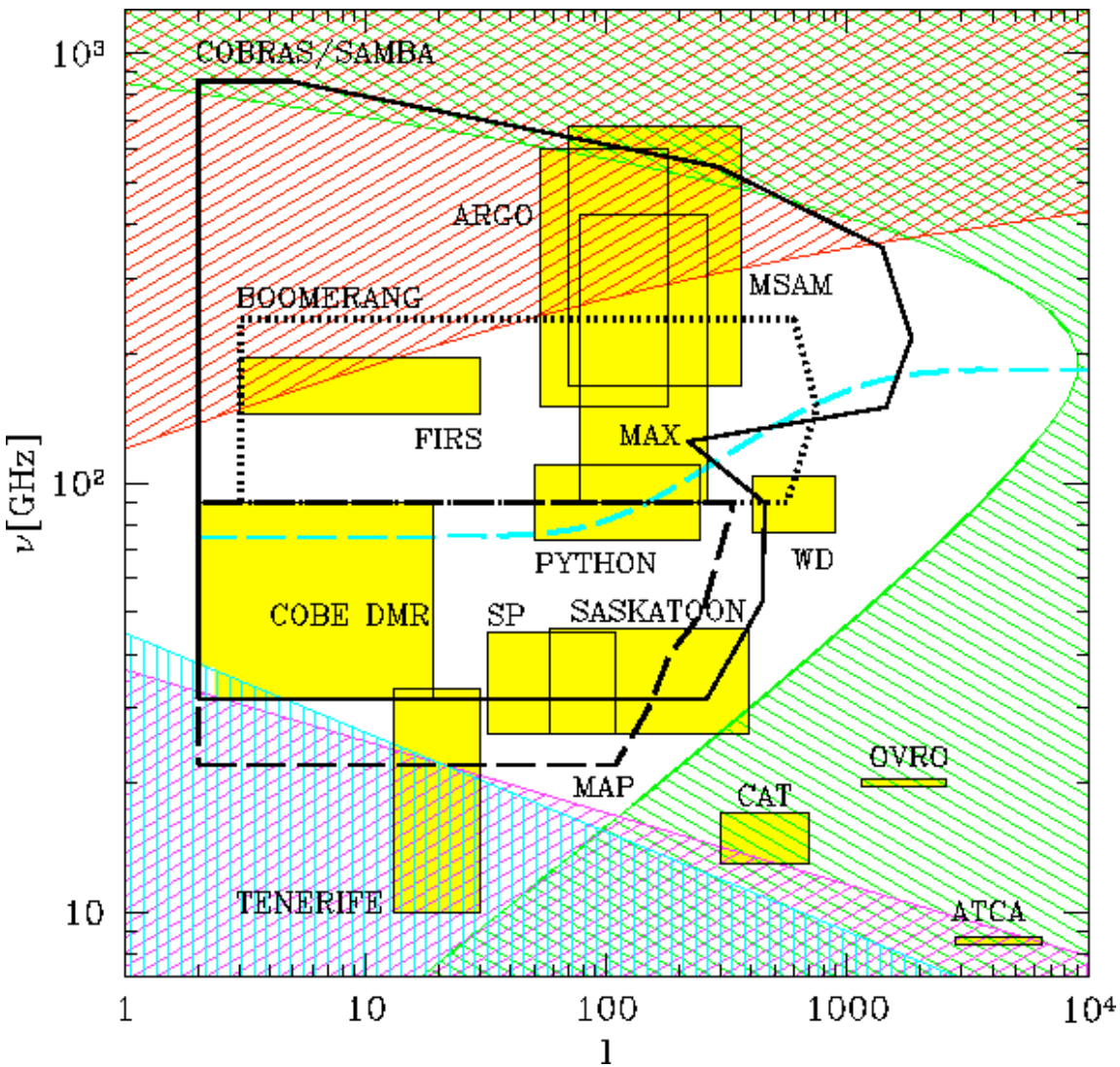
Small-Scale CMB Anisotropy

What we plan to know…



deOliveira-Costa

Foregrounds – Temperature Anisotropy



M. Tegmark

shaded regions indicate where foregrounds dominate primary CMB anisotropy

dust
free-free emission
synchrotron radiation
point sources

The white region in the center shows us that we got lucky…

Small-scale CMB and SZ pushed to observing ~150 GHz or using interferometers (simultaneous point source monitoring)

Most foregrounds still do not

Systematic Effects

Simlar to those for former and current CMB experiments

- sidelobes
- offsets
- pickup
- loading

going after smaller signals

- improved control of all systematics

need high fidelity mapping

- need cross-linked scan strategy

SZE/Small-Scale CMB Anisotropy

What we will certainly learn (5-10 years)

Better control of Instrumental Systematics (sidelobes, offsets, pickup, loading, etc etc etc.)

Small-scale foregrounds at many frequencies at sub μK levels (dust, free-free, synchrotron, point sources, ?)

Lots of things about galaxy clusters (can they be used as standard candles at all – self calibration, fitting functions, etc? Do we learn only astrophysics and no cosmology?)

σ_8, small-scale primary CMB anisotropy, small-scale secondary CMB anisotropy

SZE/Small Scale CMB Anisotropy

Current and Future Instruments

Interferometers

o Very stable so long integrations possible

o Each field observed with many detectors, high angular resolution → deep, detailed images

o Simultaneous point source observations separable – long baselines used for point source removal, short baselines give cluster sensitivity

o Brightness sensitivity is limited

Photo Credit: Leitch

Will yield early survey results (100s of clusters),

Future SZE Survey/Small Scale CMB Anisotropy Interferometers

SZA (Sunyaev-Zel'dovich Array) – currently observing

(N. Hemisphere, Owens Valley, CA)

- Chicago, Columbia, OVRO, MSFC
- 8 element interferometric array of 3.5 m dishes (30, 90 GHz)
- 100s of clusters survey, detailed imaging, small scale anisotropy (l~1000-2000)

AMI (Arcminute Microkelvin Imager) – first light achieved

(N. Hemisphere, Cambridge, England)

- MRAO/Cavendish/Cambridge group
- 10 element interferometric array of 3.7 m dishes (15 GHz)
- 100s of clusters survey, detailed imaging, small scale anisotropy (l~1000-2000)

AMIBA (Array for MIcrowave Background Anisotropy)

(N. Hemisphere, Mauna Loa, Hawaii)

- **ASIAA, Physics Dept of National Taiwan University, ATNF**
- **19 element interferometric array of 1.2m and 0.31m dishes (95 GHz)**
- **SZE, missing baryons, polarization anisotropy**

Bolometer Array Instruments

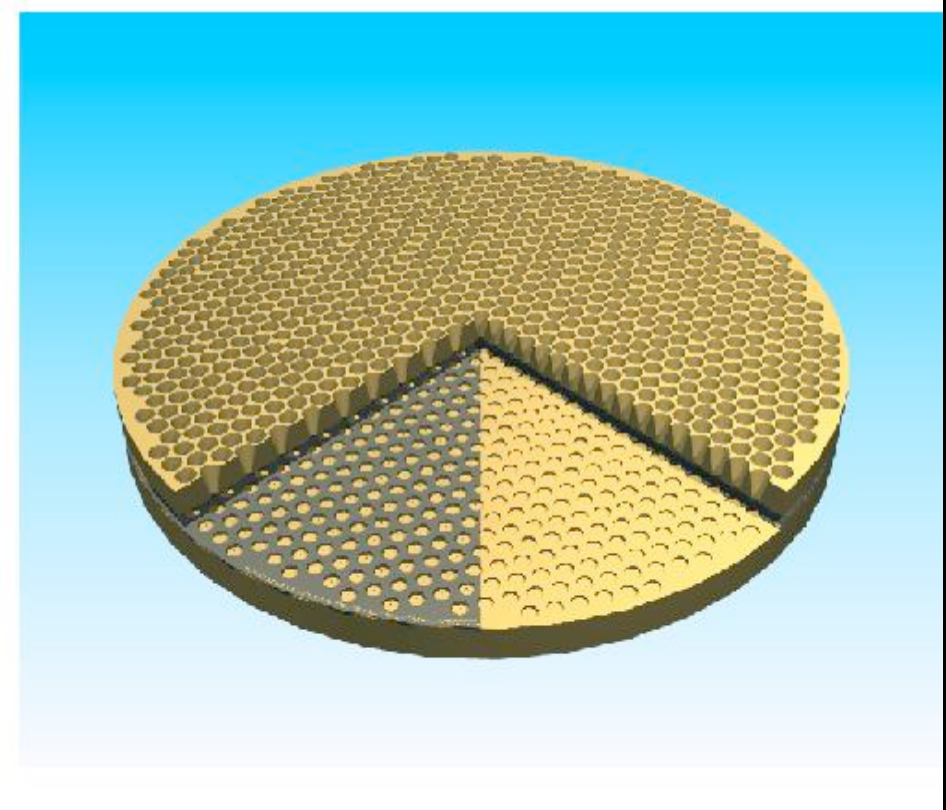
Very sensitive → short integrations required

Many detectors across the sky → Fast, large scale mapping

Single filled aperture → high sensitivity to low surface brightness objects

Angular resolution is limited

Will yield surveys containing 1000s to tens of 1000s of clusters



A. Lee

Future SZE Survey/Small Scale CMB Anisotropy Bolometer Array Instruments

Bolocam (currently operating) (N. Hemisphere (Hilo, Hawaii)

- Caltech 150 element array for the CSO ← EXISTS
- UMASS Bolocam-2 array on the 50-m LMT in Mexico
- Blank-field cluster survey, other astrophysics

APEX (Atacama Pathfinder Experiment) 2006

(S. Hemisphere, Atacama Desert, Chile)

- U.C. Berkeley 300 element array on the Max Planck prototype ALMA 12 m telescope at Atacama
- 1000s of SZ clusters, small scale anisotropy

SPT (South Pole Telescope) 2007 (S. Hemisphere, South Pole)

- Large team – PI J. Carlstrom at U. Chicago
- with 1000 element array being developed at U.C. Berkeley
- Optimized for detecting tens of thousands of clusters, also measure small-scale anisotropy

ACT (Atacama Cosmology Telescope) 2007

(S. Hemisphere, Atacama Desert, Chile)

- Large team – PI L. Page, Princeton
- with 1000 element array being developed at NASA/Goddard
- Optimized to measure small-scale CMB anisotropy, also measure 1000s of clusters

Planck 2007 (L2, all-sky)

- Large team – ESA/NASA

The Sunyaev-Zel'dovich Array (SZA)

Case Study and shameless promoting..

Columbia: Amber Miller, Stephen Muchovej, Tony Mroczkowski, David Tam, Ben Hooberman, Dan Harlow, Jhumki Basu (with Renaissance Charter School Students)

Chicago: John Carlstrom, Clem Pryke, John Cartwright, Ryan Hennessy, Chris Greer, Michael Loh, Matthew Sharp

Caltech: David Woody, David Hawkins, James Lamb, …

NASA/MSFC: Marshal Joy

JPL: Erik Leitch

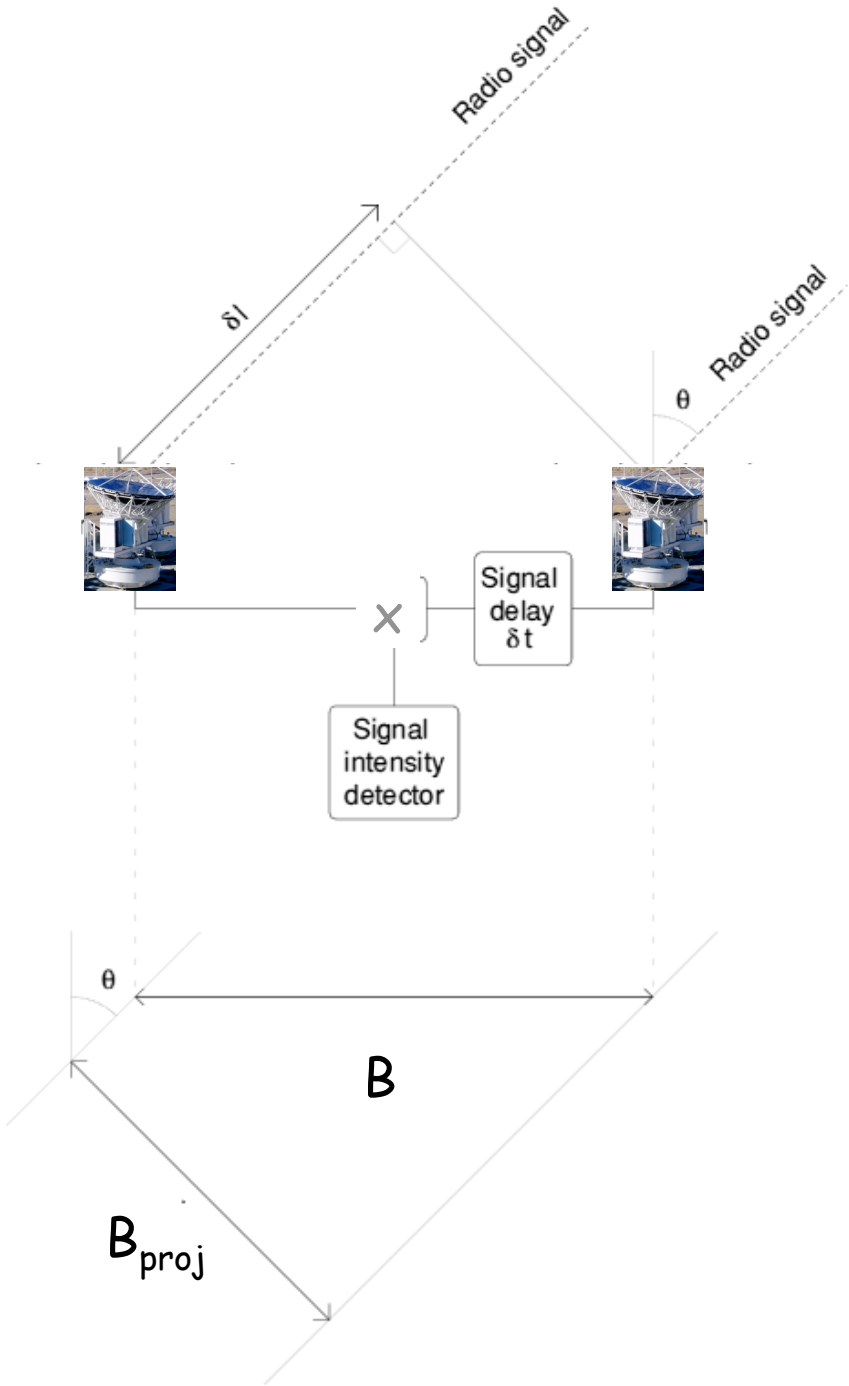
Photo: Leitch

Interferometry

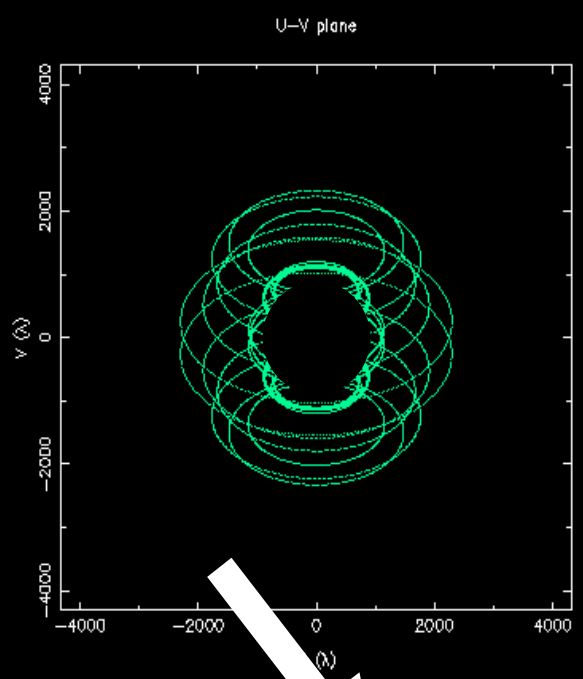
Interferometers measure the Fourier transform of the sky brightness distribution (multiplied by the primary beam) at a set of points described by the sampling function, S

S is the Fourier transform of the synthesized beam (the instrument response to a point source) set by the telescope location, the number of telescope pairs (baselines), array configuration, and the location of the source on the sky

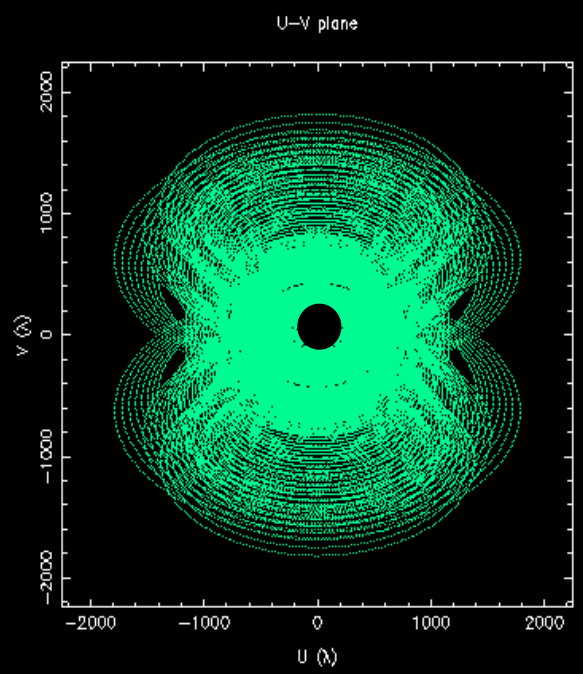
The sampling function, S describes the coverage in (u,v) space – coordinates describing orthogonal projections of the baselines normalized to the observing frequency



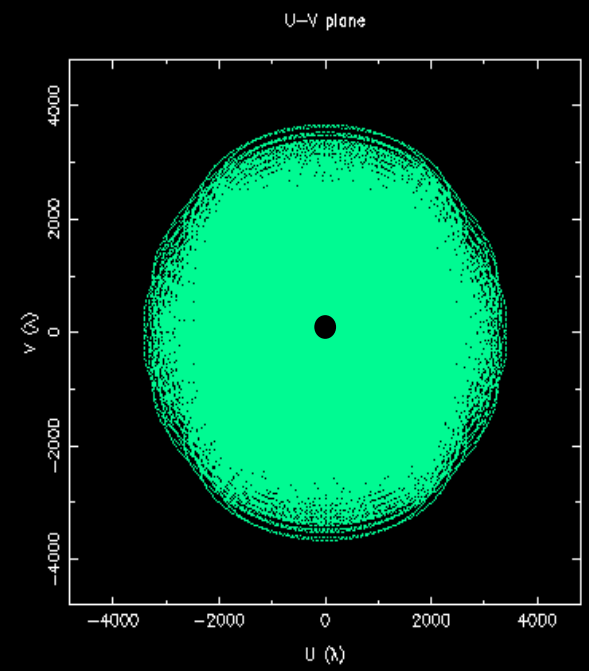
Interferometry



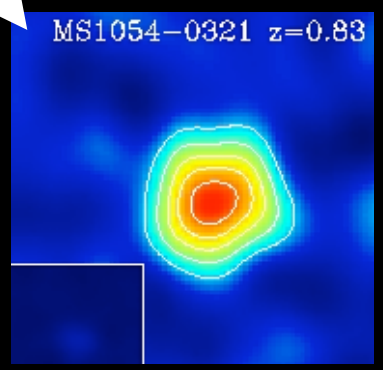
OVRO



SZA



CARMA + SZA



More complete u-v coverage results in a higher fidelity image

SZA Essentials

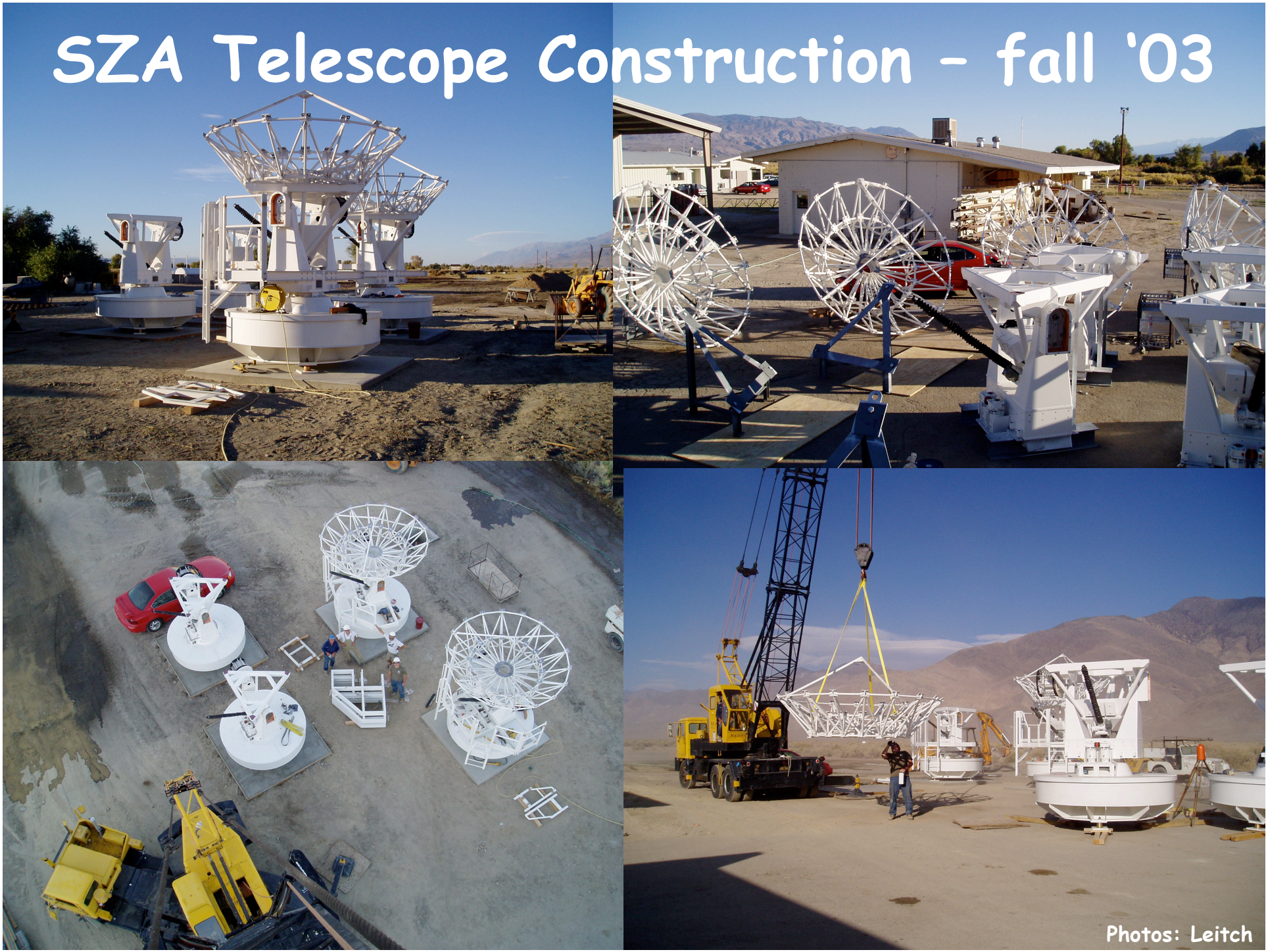
- Eight 3.5 m diameter telescopes
- Close-packed configuration maximizes sensitivity to cluster angular scales
- 30 GHz Receivers (cluster survey)
- 90 GHz Receivers (detailed cluster observations)
- Broadband 8 GHz digital correlator (dense sampling in the Fourier plane)
- Currently calibrating, taking engineering data, science data has started

- SZA to be integrated with OVRO and BIMA telescopes (CARMA) will allow detailed imaging to 5"

Photos: Leitch

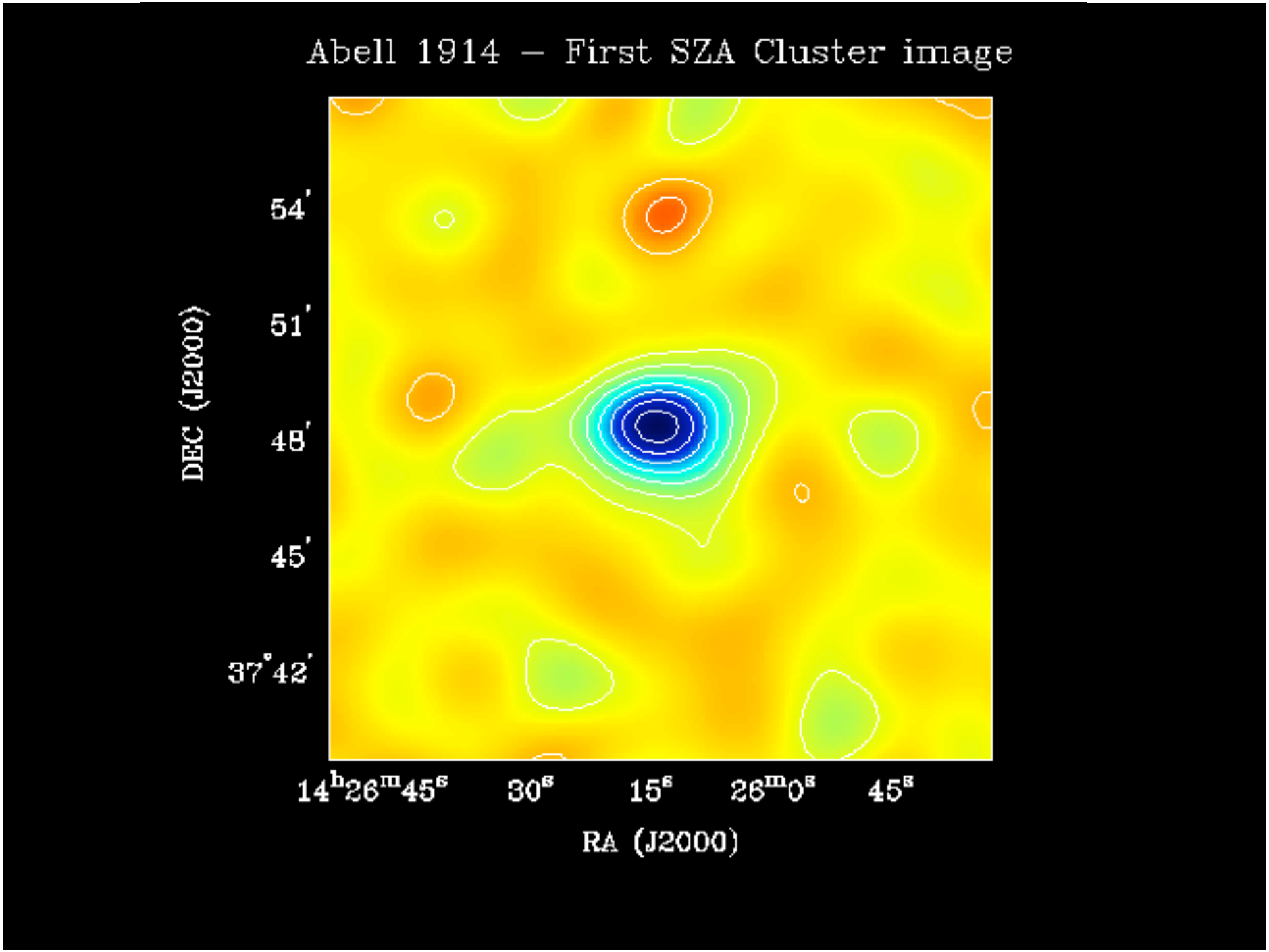
Receiver Construction and Testing - Columbia

SZA Telescope Construction – fall '03

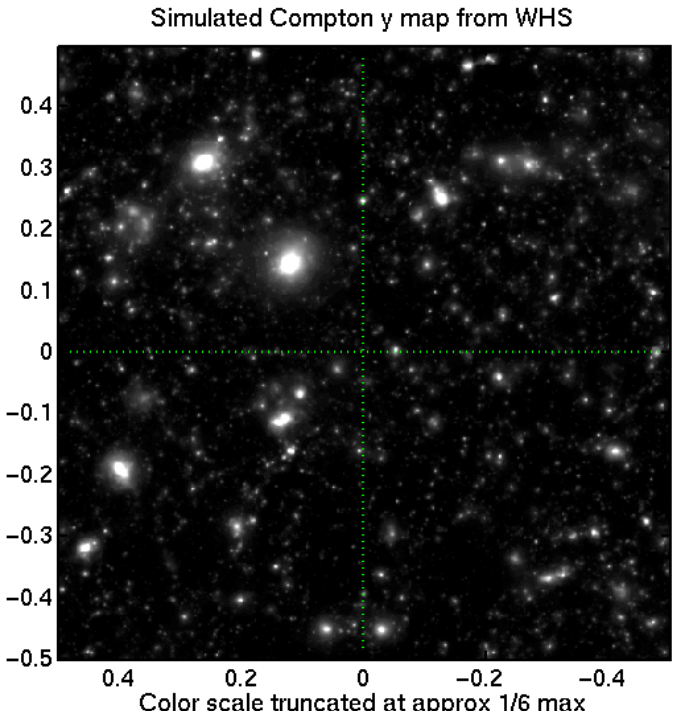


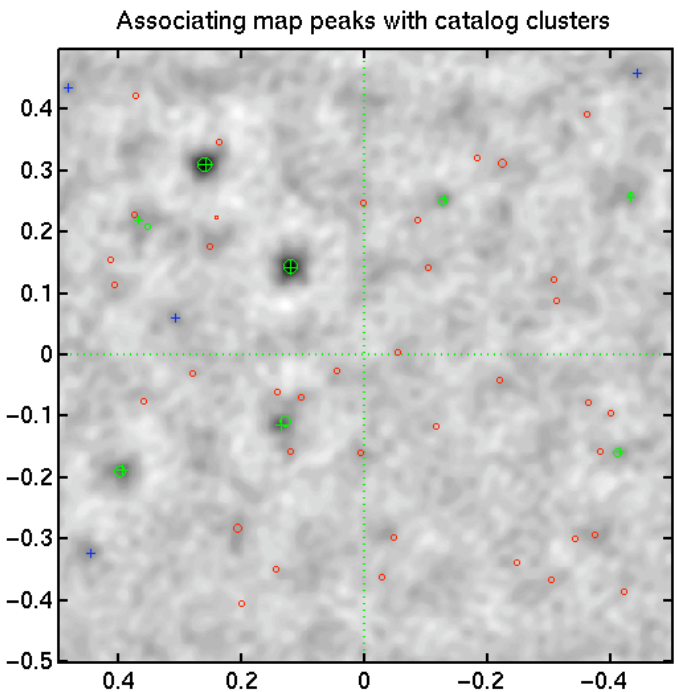
SZA Construction/Integration – winter '04

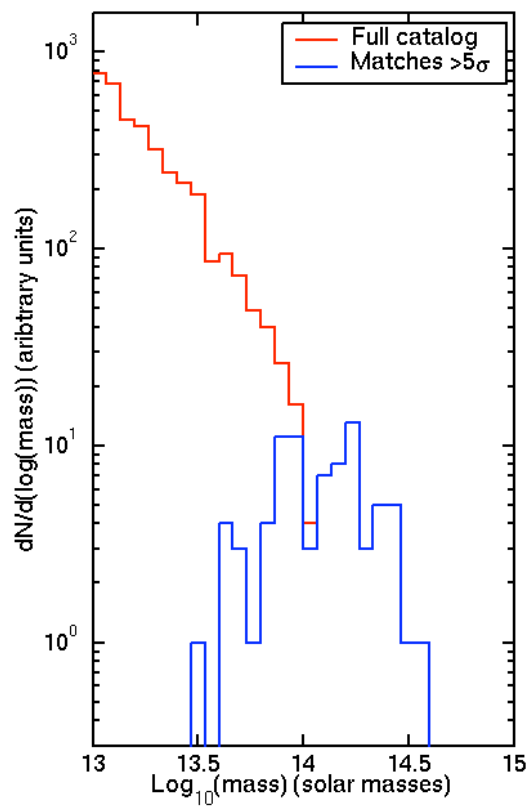
SZA Telescope Final Integration fall '04

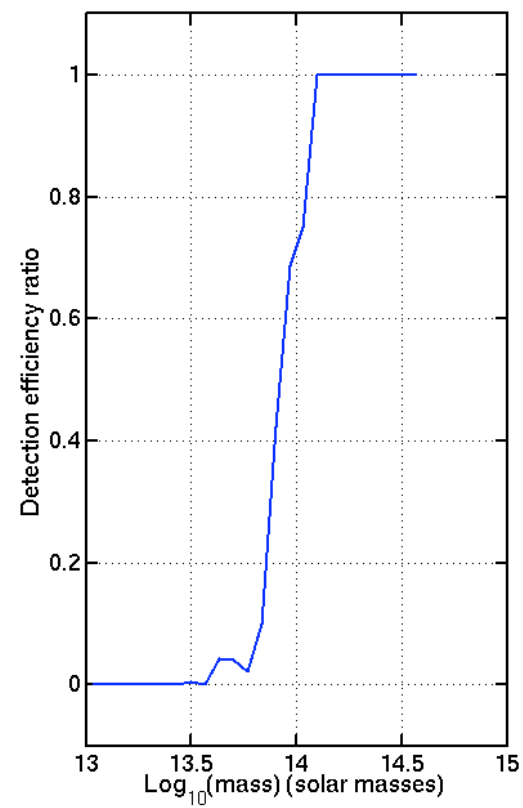

Abell 1914 – First SZA Cluster image
54′
51′
48′
45′
37°42′
DEC (J2000)
14h26m45s
30s
15s
26m0s
45s
RA (J2000)

Testing mass limit with mock SZA survey (Pryke)









White, Hernquist, Springel, (WHS) 15 of 1 deg x 1 deg images from hydro sims.

SZA Cluster Survey & Optical Follow-up

- 12 square degrees in four fields (each roughly three square degrees equally spaced in RA)
- expect ~100 clusters
- require photometric redshifts (requires imaging in several bands including near IR)
- fields need to be selected in order to
  - be properly spaced in RA to allow survey observations 24 hours/day
  - be properly positioned in declination (near zenith at transit) so as to minimize atmospheric contamination and to optimize imaging
  - minimize foregrounds (WMAP Ka band map)
  - to take advantage of as much publicly available optical data as possible for for redshift information

Tentative SZA Fields

1) NOAO Deep Wide Field Survey: Bootes Field (SZA I) – α=14.5h, δ=+34.0^o, publicly available imaging exists in all required bands

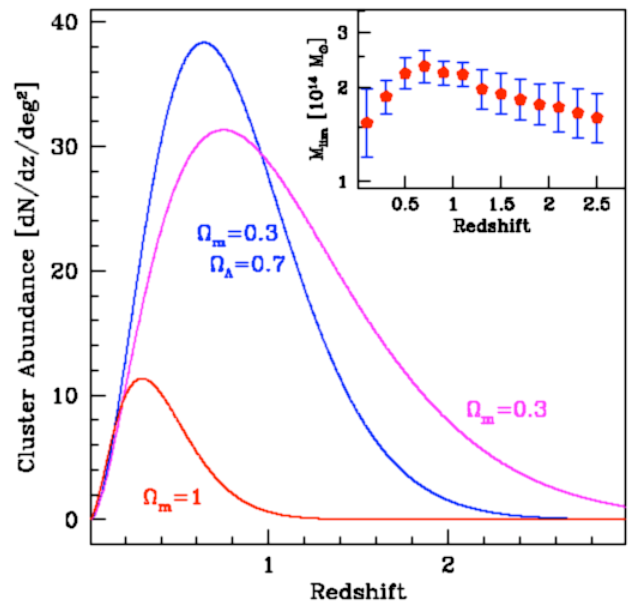
2) NOAO Deep Lens Survey: F2 (SZA II): α=9.33h, δ=+30.0^o, publicly available imaging exists in four bands, will require only near IR

3) SZA III: α=2.5h, δ=+30.0^o, need follow-up optical observations (proposed B_w, R, I, z', NIR)

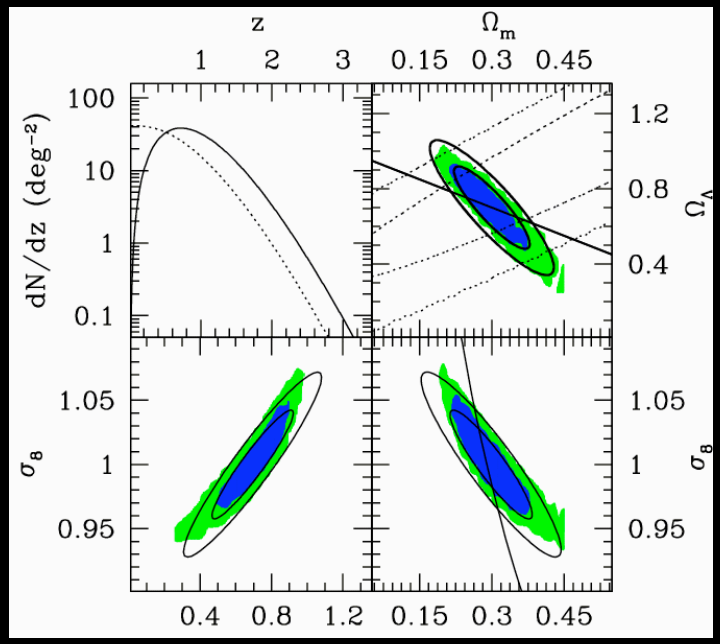
4) SZA IV: α=21.5h, δ=+34.0^o, need follow-up optical observations

Survey Science

- Cluster Abundance dN/dz
- Determine σ_8 to 5%
- Tests of Non-Gaussianity
- Small-Scale CMB Angular PowerSpectrum
- Spatial power spectrum, P(*k*)
- Combining with X-ray observations
  - Angular Diameter distance/Hubble Constant
  - Scaling Relations



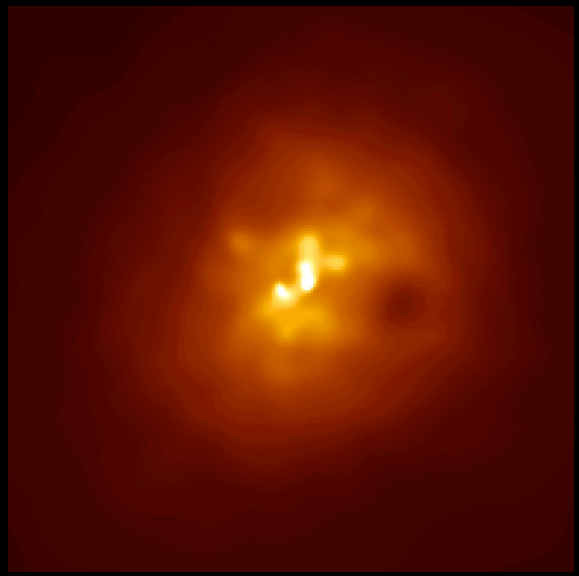
Mohr 2001



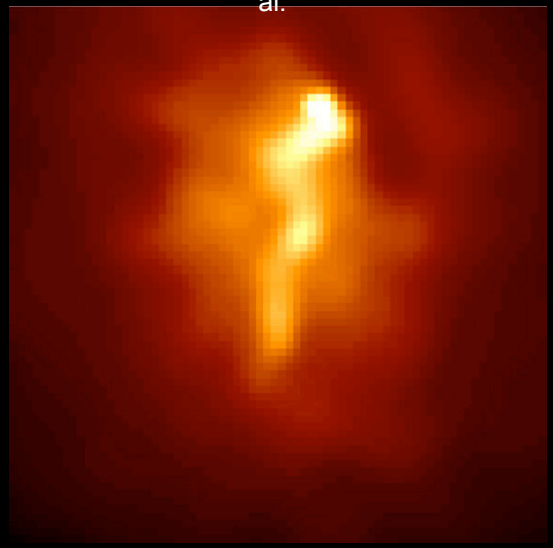
Carlstrom, Holder, Reese, 2002, ARAA V40

Pointed Cluster Observations

- SZE + X-ray + optical + cluster simulations comparison of individual objects ➔ study how various effects impact cosmological parameter determination
  - scatter in observables due to projection effects, ellipticity
  - uncertainty in gas density profile, cluster structure
  - cluster evolution
  - cooling cores, cold fronts, shock fronts, evacuated cavities
  - merger history, current dynamical state, relationship of intra-cluster gas to stellar population
- Study proto-cluster candidates



Abell 2597: NASA/CXC/Ohio U/B.McNamara et al.



Abell 1785: NASA/IoA/AC Fabian et al.

A SZA Test of SZE Scaling Relations

Learning about Structure Formation and Cosmology

From an Astrophysical perspective:

Would like to understand the processes responsible for structure formation on galactic and cluster scales. (AGN vs supernova heating, vs cooling)

From a Cosmological Perspective:

Would like to use X-ray and SZE cluster surveys to probe cosmology (break degeneracies in CMB and SN constraints). To do this, we need to understand the relationship between observables (X-ray luminosity, temperature, SZE decrement) and cluster mass.

A SZA Test of SZE Scaling Relations

What we know from X-ray observations

- The observed X-ray luminosity of galaxy clusters decreases more quickly with decreasing gas temperature than expected from self-similar scaling models
- Models that include heating (entropy injection) and preferential cooling of low entropy gas have been proposed to account for these observations

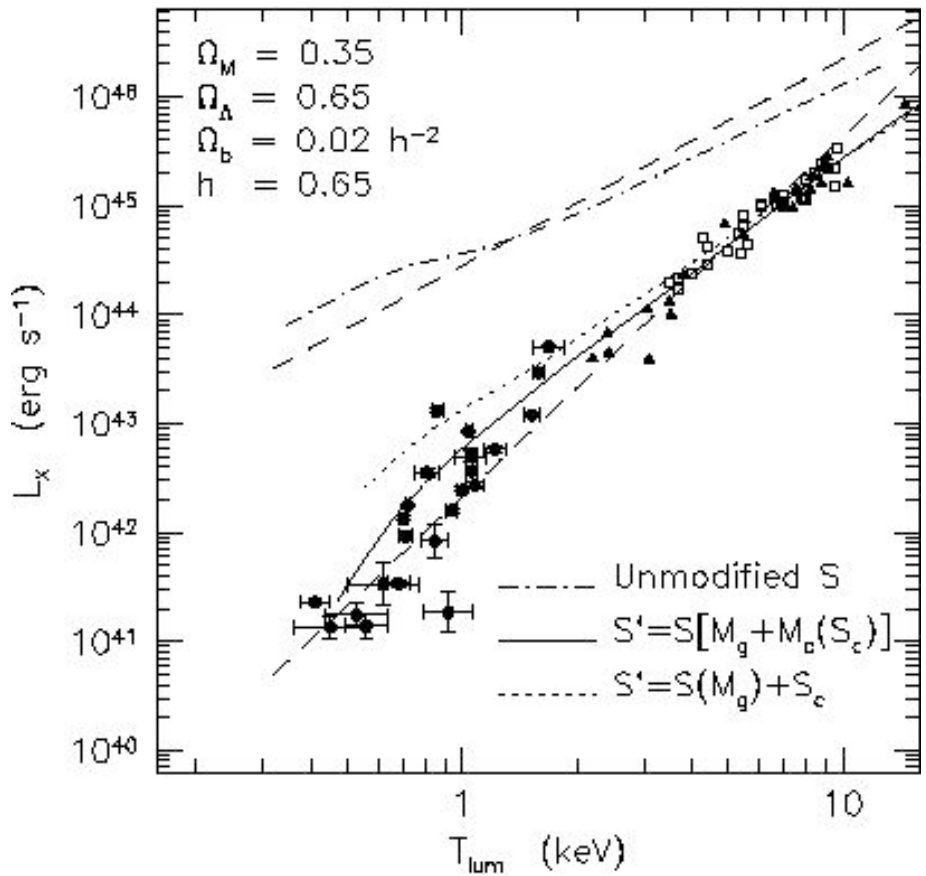


Fig 2 from Bryan and Voit (2005): The relation between bolometric X-ray luminosity and luminosity-weighted temperature for samples of observed clusters from Arnaud and Evrard (1999) , Markevitch (1998), and Helsdon and Ponman (2000). The dot-dashed line is the predicted relation from a hydrostatic equilibrium model with an unmodified entropy distribution, while the solid and dotted lines are the same model with low entropy material removed or heated, respectively. The assumed cosmological parameters for these models are shown in the upper left. The lower (upper) dashed line is a fit to numerical simulation with (without) radiative cooling from Pierce et al (2001).

A SZA Test of SZE Scaling Relations

SZE observations probe the integrated pressure along the line of sight (α n), while X-ray luminosity α n^2

Provides complementary information (SZE less sensitive to gas clumpiness and the central part of the cluster, more sensitive to outer regions of the cluster)

A SZA Test of SZE Scaling Relations

Our Preliminary SZE Cluster Sample – Targeted observations

- Two distinct samples chosen: (1) Abell-class rich clusters ($T_x \cong$ 5-10 keV), (2) poor clusters/groups ($T_x \cong$ 1-3keV)

- Objects are chosen to match our SZA beam, and to be located within 30 degrees of zenith at the Owens Valley site ($7^o < \delta < 67^o$)

- All objects in our sample have redshifts and X-ray temperature and luminosity measurements

- Selected from: Einstein (EMSS), ROSAT (WARPS, deep cluster survey, 160 square degree survey), Abell's cluster catalog, Mulchaey's atlas of groups, and clusters observed in targeted observations by the SZE imaging team at OVRO and BIMA, and the Chandra and XMM-Newton observatories

Our Secondary SZE Cluster Sample – Drawn from SZA Survey

A SZA Test of SZE Scaling Relations

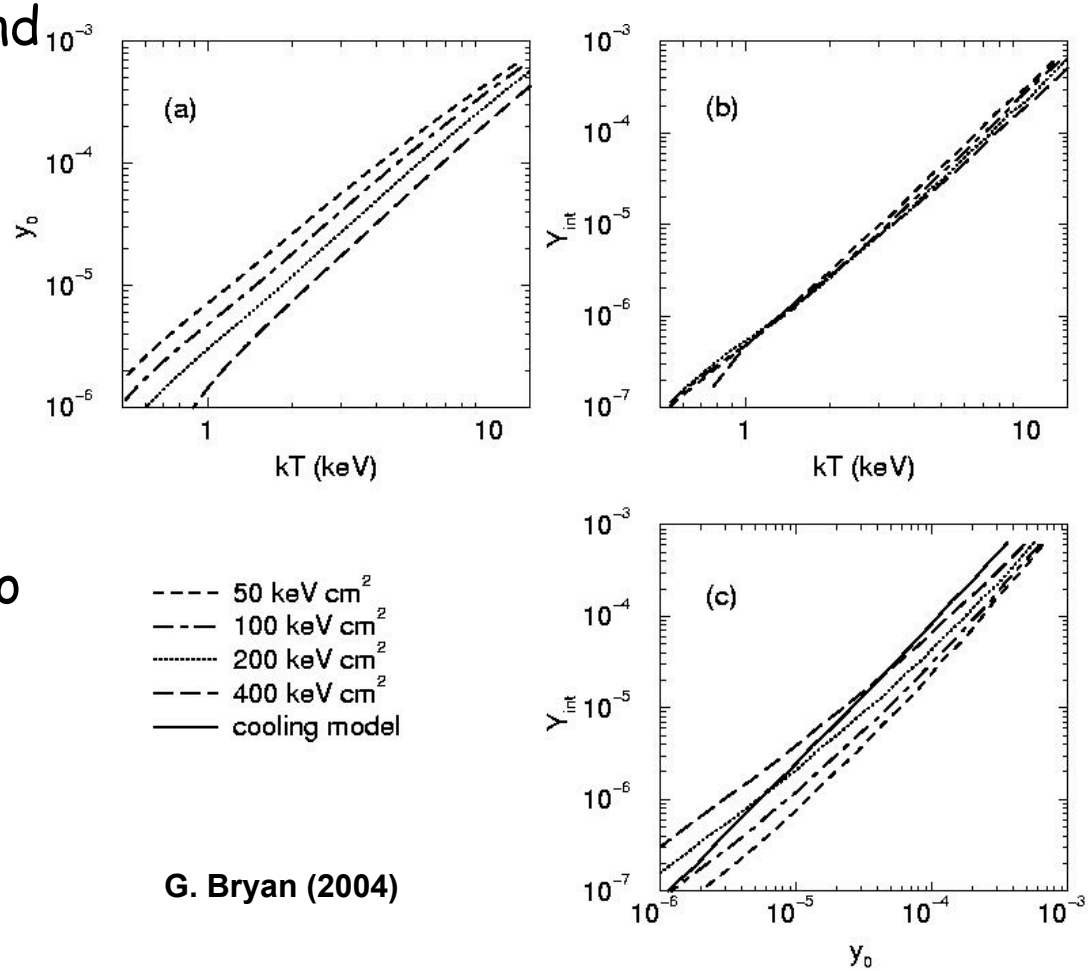
Use measurements of Y_o and Y_{int} to constrain models

Y_o is the central SZE decrement

Y_{int} is the total integrated SZE decrement

Note – distinct slope due to cooling (or gas depletion) relative to the gas heating by supernova.

Simulations show that we have the sensitivity to discriminate between these models



G. Bryan (2004)

Working toward understanding mass and redshift at which gas is heated/cooled/depleted

CMB Polarization Anisotropy

Science Goals and Systematics

CMB Polarization Anisotropy

E-mode polarization

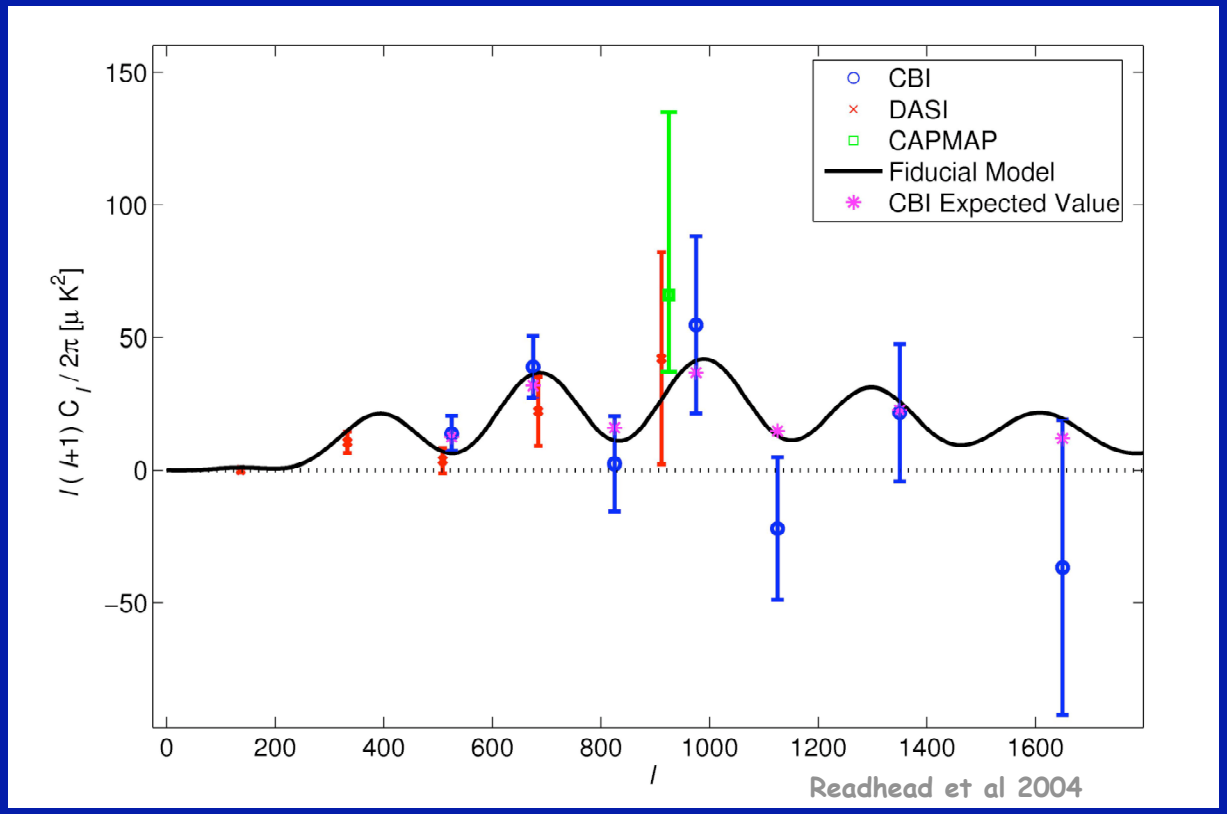
- Generated only by scattering (most direct probe of physics at recombination)
- Probe epoch of reionization by first stars (WMAP result)
- Serves as a consistency check on interpretation of temperature anisotropy as signature of gravitational instability model
- Remove degeneracies in cosmological parameters inferred from primary anisotropies and enhance precision with which cosmological

B-mode polarization

- Generated by perturbations in the spacetime metric – gravitational waves
- The amplitude of polarization from Inflation is proportional the square of the inflaton potential
- Detection of this signal may yield a measurement of the energy scale of inflation
- Yields clues to quantum gravity
- Separable from E modes by "curl" sig

E-Mode Polarization Power Spectrum

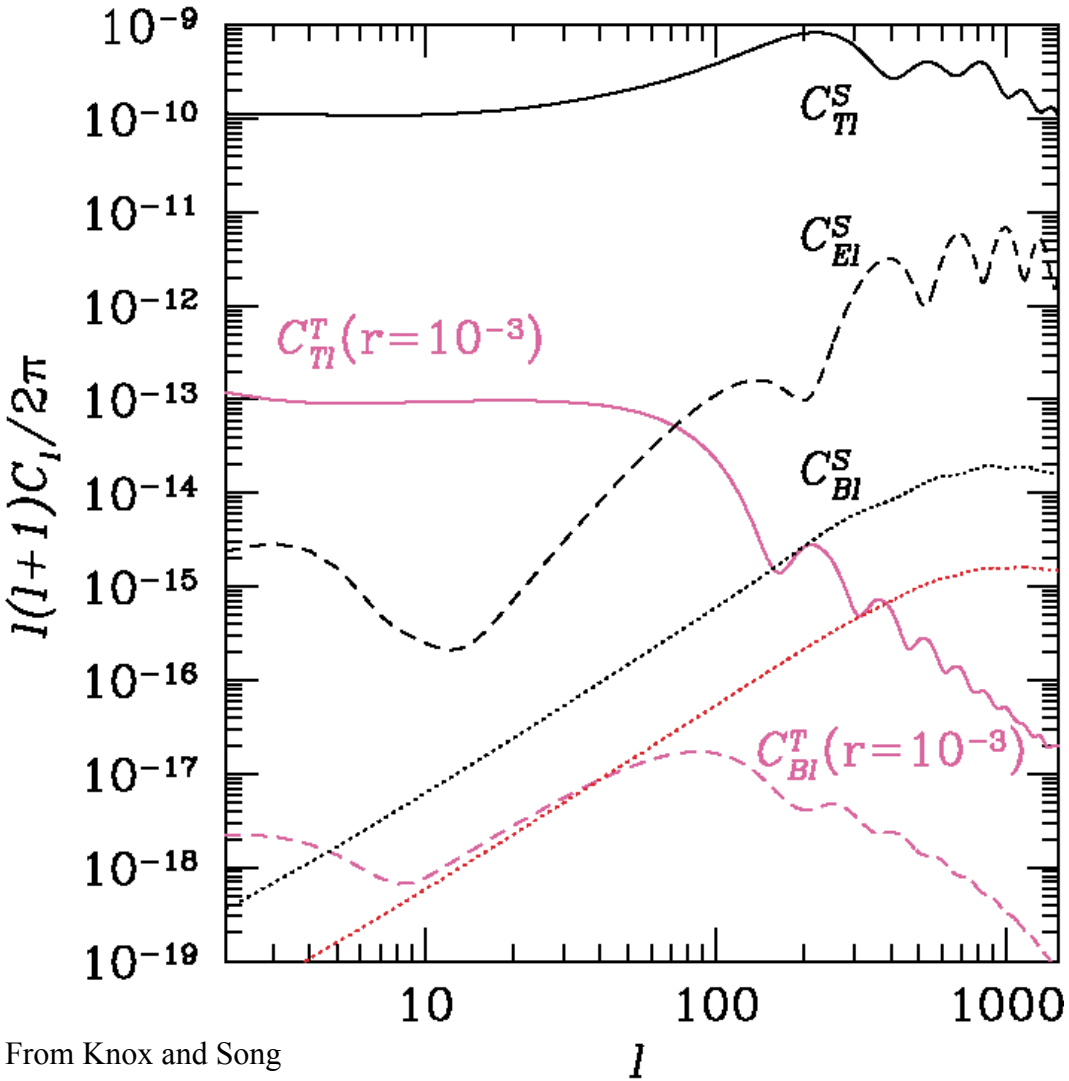
Current State of the Art



B-Mode Polarization Power Spectrum

Current State of the Art

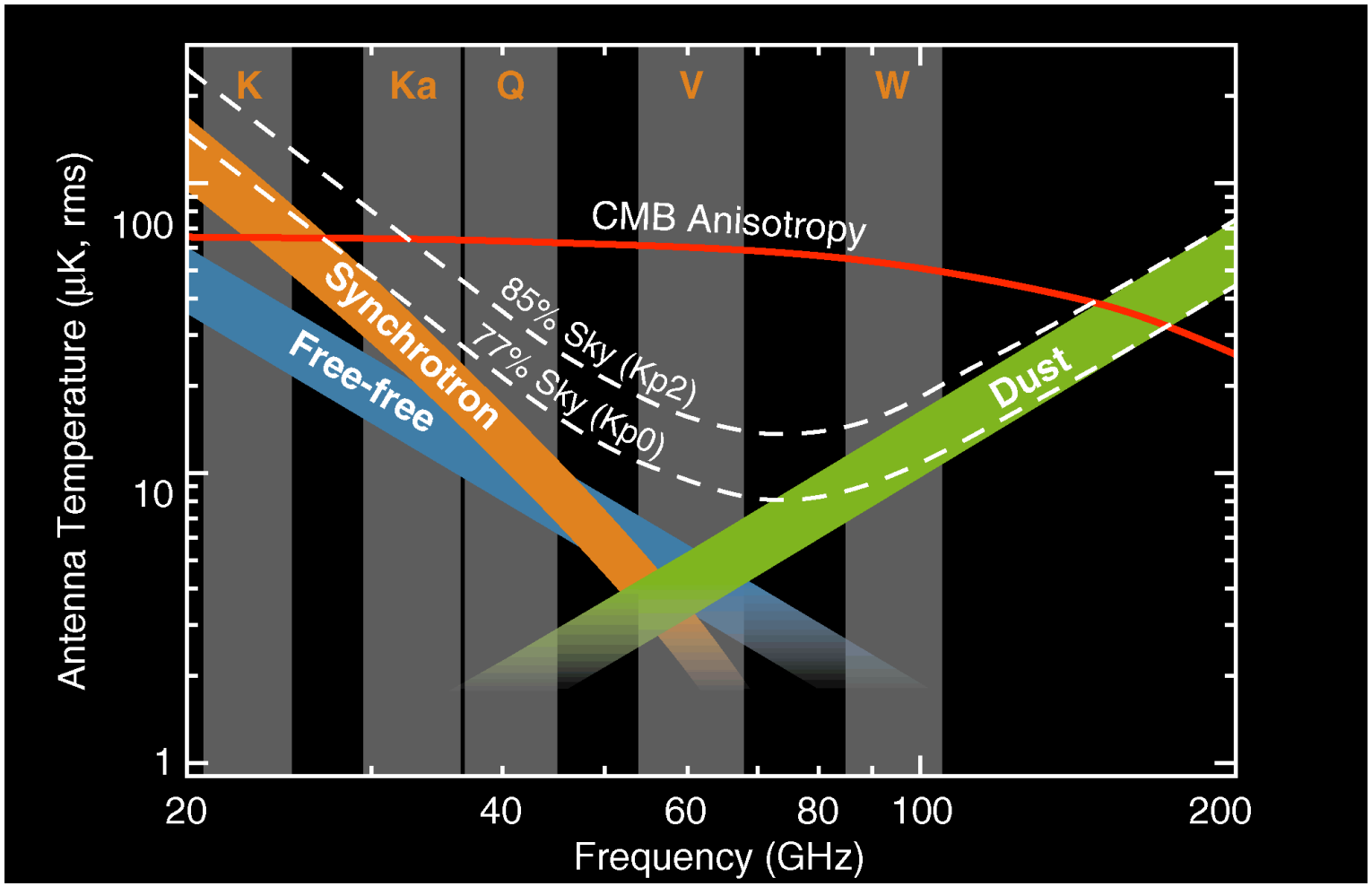
What we plan to know…



From Knox and Song

Foregrounds – Polarization Anisotropy

WMAP Temperature Foregrounds…



Foregrounds – Polarization Anisotropy

Polarized Foregrounds

- Frustratingly little is know about polarized foregrounds

- Models generally assume that foregrounds are polarized at the level ~10% (constant in l)

- Waiting for information from WMAP to inform future work

- In the mean time though, with educated guesses, we can predict that we will not be as lucky with polarized foregrounds – will probably dominate on most angular scales and most frequencies

- We will need to be more clever than we were with temperature anisotropies in order to characterize and remove them from the data

Polarized Foregrounds – Mitigation Strategies

- characterize foreground emission on many angular scales at many frequencies

- Choose sky regions in order to minimize foreground contamination

- Design instruments to observe at multiple frequencies (need n+1 frequencies to remove n foreground components)

- Collaborations should work together to observe the same patch of sky with multiple instruments operating in different frequency ranges (maximize frequency coverage)

Systematic Effects I

Systematics Produced by Instrument (independent of sky signal)

- Receiver gain drifts
- Cold Stage Temperature Drifts (can affect different detectors in a different way – eg diferent coupling to cold bath for different TES bolos)
- Emission/Reflection from Optical Elements (metal mirrors, high index of refraction lenses)
- Temperature Drifts in optical elements (diurnal, scan synchronous, spatial)
- Vibration-induced polarization
- Electrical variations

Systematic Effects I

Systematics Produced by Instrument (independent of sky signal) Mitigation Strategies

- Minimize scan synchronous effects by scanning/switching/rotating a half wave plate, etc on multiple timescales (should include timescales shorter than those on which electrical, thermal, etc variations take place)
- Maximize system stability
- Cool Optics (reduce emission)
- vary telescope rotation to scan the same piece of sky from different polarization angles

Systematic Effects II

Unpolarized Power aliased to False Polarization Signal

- miscalibration, drifts in calibration of two polarization arms (if separate detectors are used to measure orthogonal polarization states)
- main beam ellipticity
- sidelobe asymmetry
- bandpass mismatch
- pickup from sun, moon, ground, balloon, galaxy

Systematic Effects II

Unpolarized Power aliased to False Polarization Signal

Mitigation Strategies

- design as much of the receiver chain as possible to be common to both polarization states
- baffle optics to prevent stray emission from entering detectors
- cool mirrors, lenses (reduce reflected emission)
- cross-linked scan strategy

Systematic Effects III
Other Effects

- E-B mixing due to incomplete sky coverage (generation of ambiguous modes)

  Attempt to decompose a vector field on a finite plane into a gradient and a curl component

  Possible to calculate out (Lewis et al. 2002, Bunn et al. 2003)

- E→ B conversion due to foreground objects (lensing of polarization anisotropies by intervening galaxy clusters)

  Observe over wide range of l's in order to characterize and subtract lensing contribution from that due to primordial gravity waves

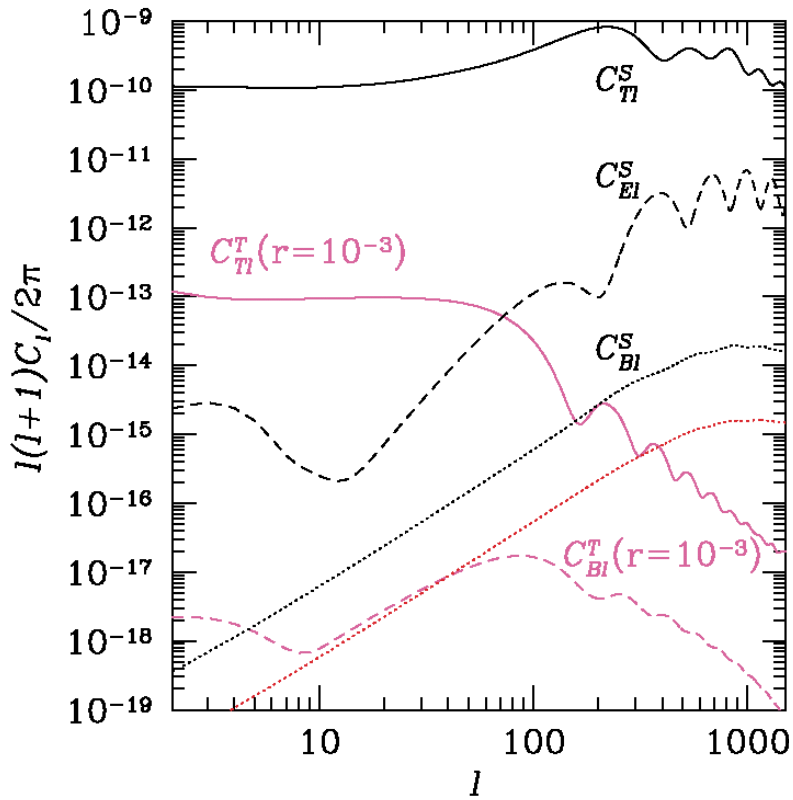
What we will certainly learn (5-10 years)…

Better control of Instrumental Systematics
(sidelobes, offsets, pickup, loading, instrumental polarization, E/B mixing, etc etc etc.)

polarized foregrounds at many frequencies at nK levels
(dust, free-free, synchrotron, point sources, atmosphere, etc.)

Significantly improved measurement of E-mode polarization

Significantly improved upper limit on B-mode polarization



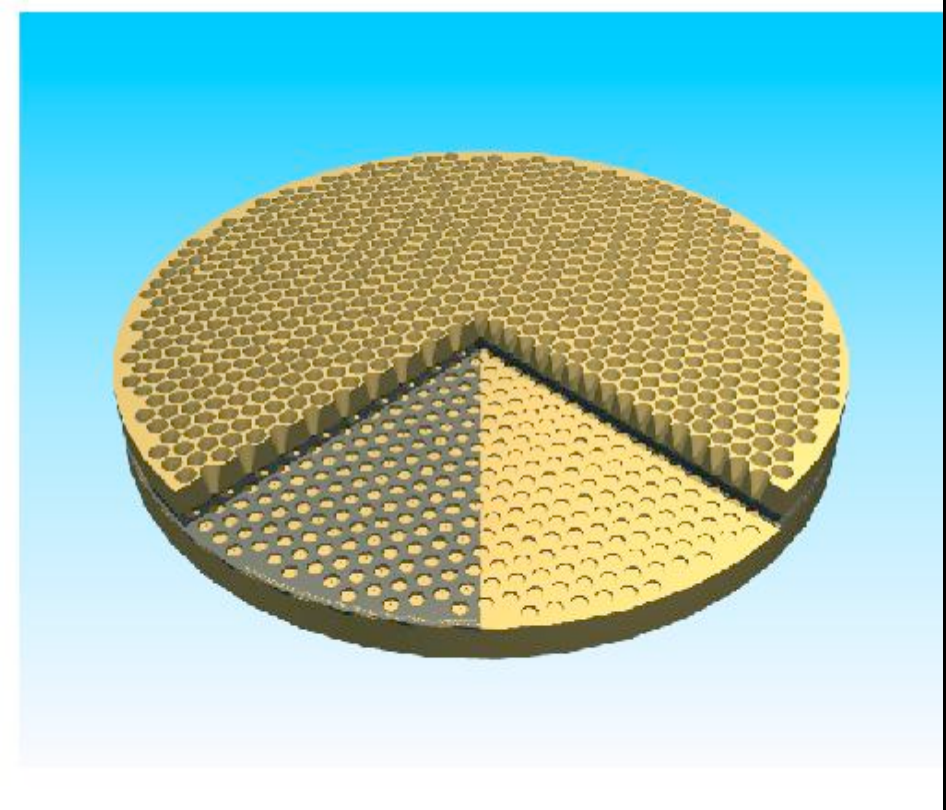
CMB Polarization Anisotropy

Current and Future Instruments

Bolometric Receivers

Highest sensitivity CMB detectors above ~150 GHz

Required to understand dust foregrounds

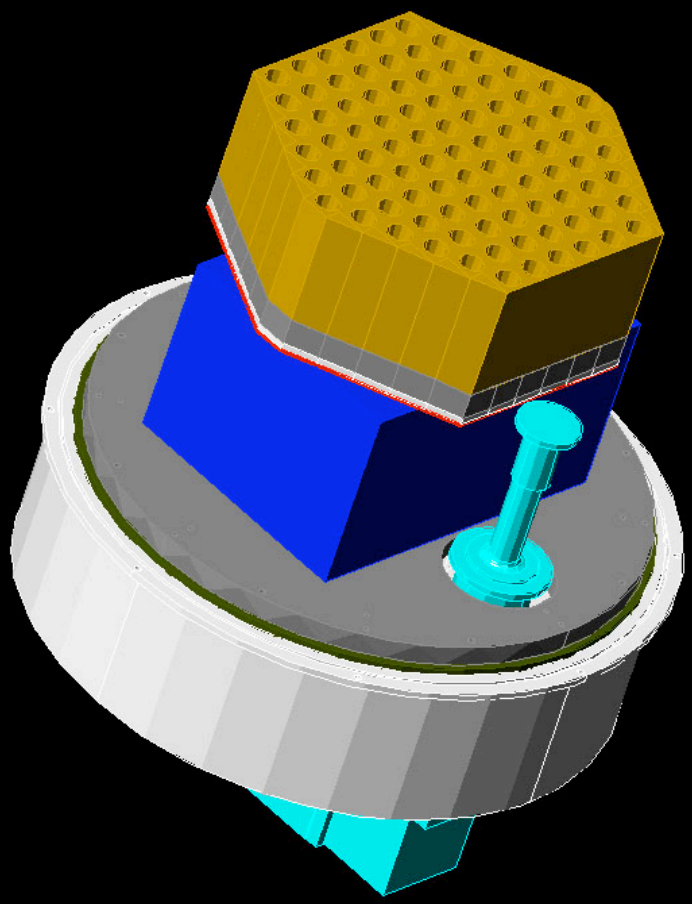


A. Lee

Coherent Radiometers

Best detectors at frequencies lower than ~100 GHz

Required to understand Synchrotron, free-free, possible spinning dust



Muchovej (Columbia)

Future CMB Polarization Anisotropy Instruments (Ground-Based)

Currently operating and/or already have data in hand

- **CAPMAP (HEMT) – N. Hemisphere (New Jersey, USA)**
  - **Princeton, Chicago, Miami, JPL**
- **DASI (HEMT – Interferometer) – S. Hemisphere (South Pole)**
  - **Chicago, Caltech, JPL**
- **CBI (HEMT – Interferometer) – S. Hemisphere (Atacama Desert, Chile)**
  - **Caltech, Chicago, JPL**

Upcoming – tens of detectors

- **QUaD (bolometer) – S. Hemisphere (South Pole) - funded**
  - **Stanford, Cardiff, Chicago, Caltech, JPL, IPAC**
- **BICEP (bolometers) – S. Hemisphere (South Pole) - funded**
  - **Caltech, JPL, Cardiff, San Diego**
- **AMIBA (HEMTs) - funded**
  - **ASIAA, Physics Department of National Taiwan University, ATNF**

Upcoming – hundreds to thousands of detectors

- **QUIET (HEMTs) – S. Hemisphere (Atacama Desert, Chile) – partially funded**
  - **Caltech, Chicago, Columbia, JPL, Miami, Princeton, Berkeley, Harvard, GSFC, Stanford, Oxford**
- PolarBear (bolometers) – N. Hemisphere (White Mountain, CA) - proposed
  - Berkeley, ?
- **CLOVER (bolometers) S. Hemisphere (Dome C, Antarctica) - funded**

Future CMB Polarization Anisotropy Instruments (Balloon and Satellite-Based)

Currently operating and already have data in hand

- B2K (polarization sensitive bolometers) – S. Hemisphere (from Antarctica)
  Caltech, JPL, Case Western Reserve, IFAC-CNR Firenze, INGV – Roma, IPAC, University of Toronto – CITA, Universita' di Roma "La Sapienza", Universita' di Roma, Tor Vergata, University of Cardiff, University of Pennsylvania

- Maxipol (bolometers) – N. Hemisphere (from Texas, New Mexico)
  Berkeley - LBNL, Minnesota, Queen Mary and Westfield College, Oxford, Instito Superior Tecnico, Copernicus Astronomical Center Poland, JPL, IROE-CNR Firenze, Universita' di Roma "La Sapienza", Universita' di Roma, Tor Vergata
- Archeops (bolometers) – N. Hemisphere (from Sweden)
  Orsay, Grenoble, Cardiff, Berkeley, Saclay, Paris, Toulouse, Caltech, JPL, IAP, Rome, Hawaii, Minneapolis, UBC
- WMAP (HEMTS) – L2
  Princeton, GSFC, UBC, University of Chicago, Brown, UCLA

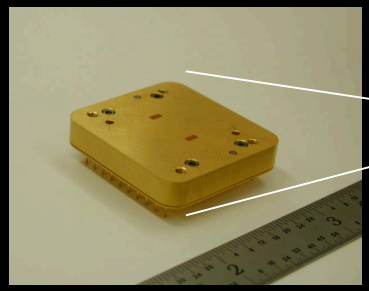
Upcoming

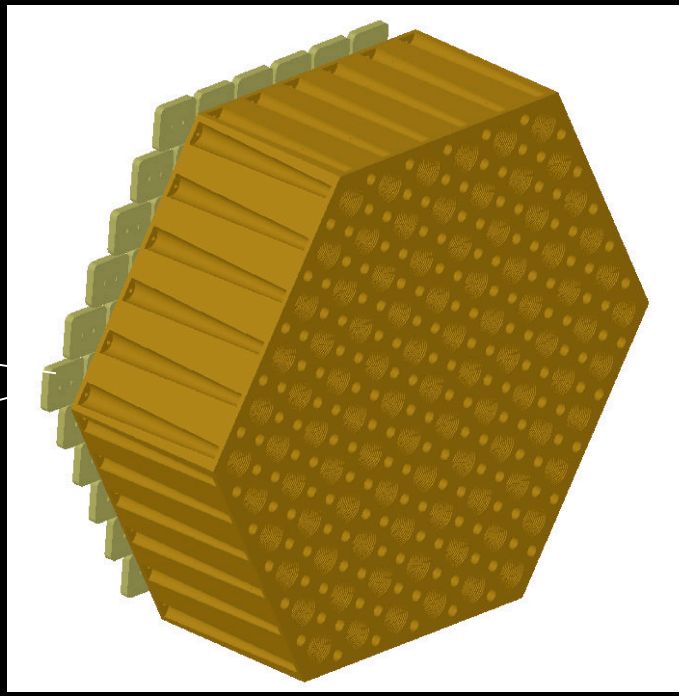
- EBEX (bolometers) – S. Hemisphere (from Antarctica) - funded
  Caltech, Chicago, Columbia, JPL, Miami, Princeton, Berkeley, Harvard, GSFC, Stanford, Oxford
- SPIDER – S. Hemisphere (from Antarctica) - proposed
  team not listed (led by Caltech, includes much of B2K team and some others)

QU Imaging ExperimenT (QUIET)

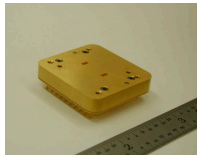
<u>The Collaboration</u>

- Columbia
- Chicago
- Caltech
- JPL
- Miami
- Princeton
- NASA Goddard
- Harvard
- Berkeley
- Stanford
- Oxford



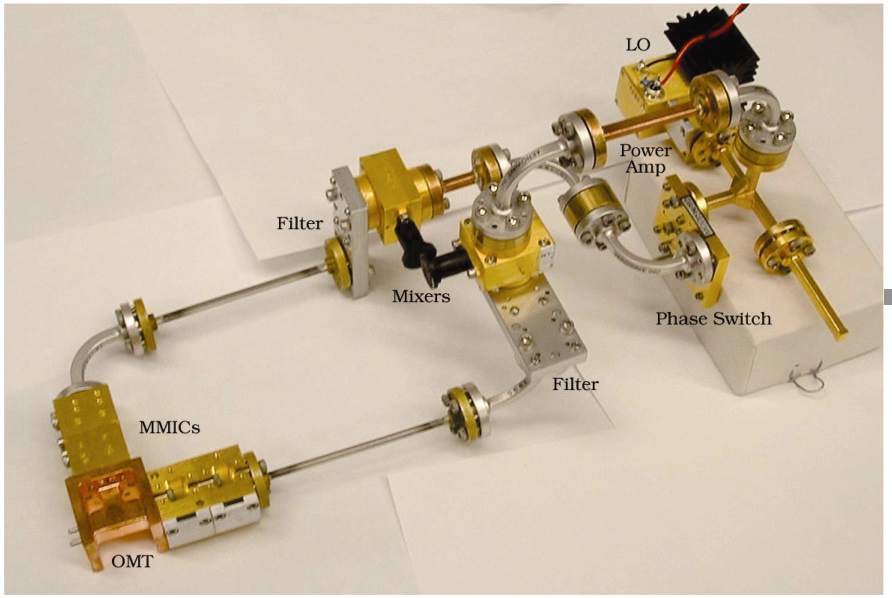


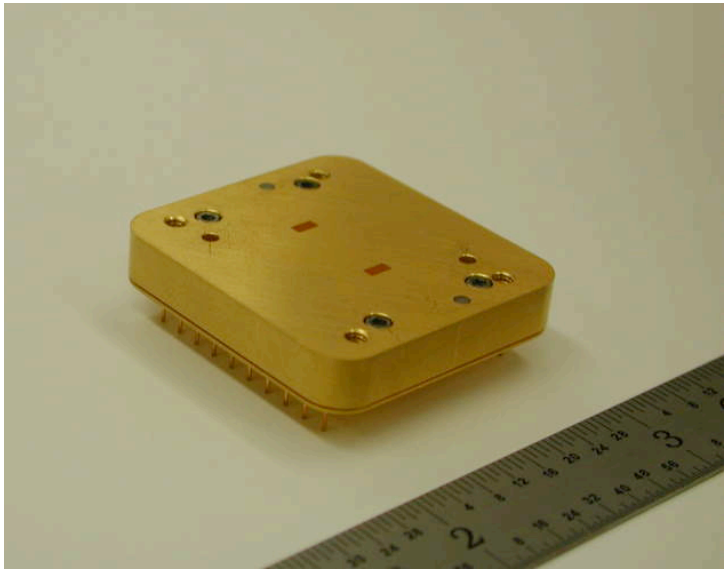
Breakthrough in MMIC Packaging makes QUIET possible



QUIET Polarimeter IC

CAPMAP 90 GHz Polarimeter





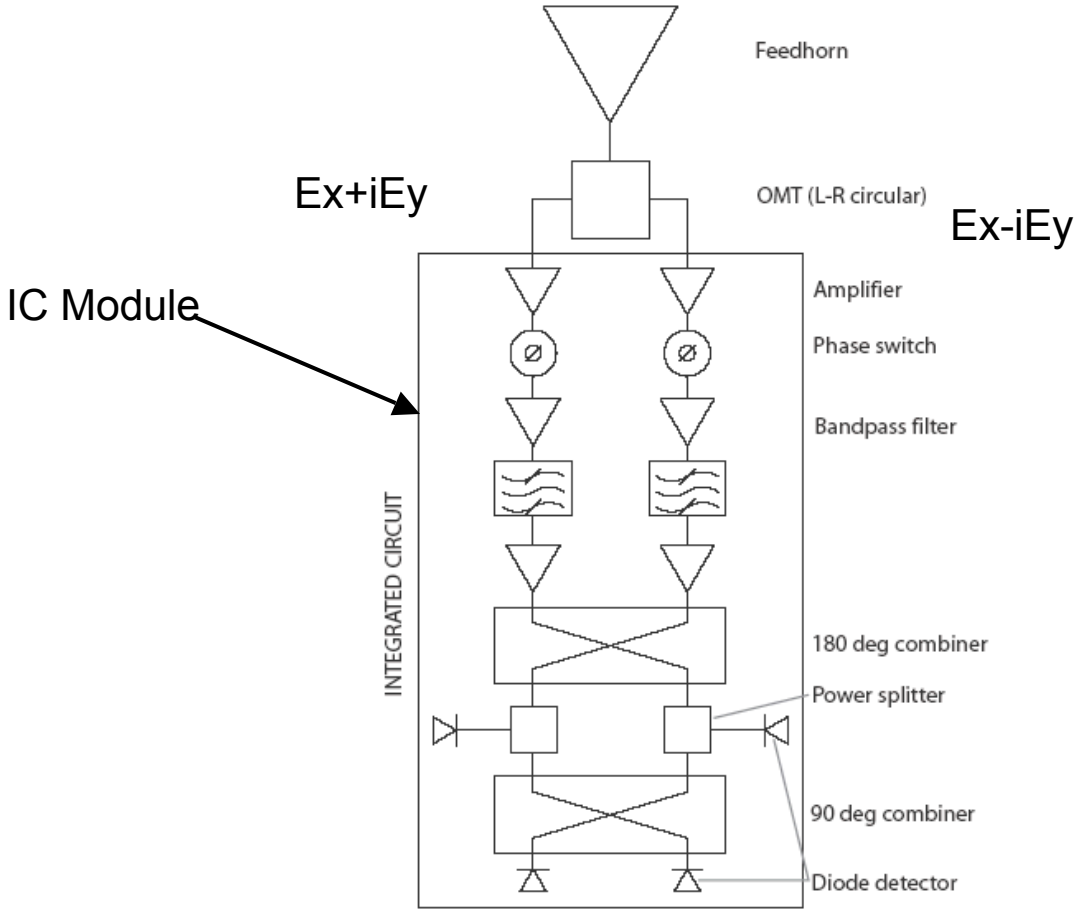
X-Y Polarizer

~ $40K and 50 physicist-hours for checking, characterizing, etc

~ $500 and automated assembly and test, completely scalable

Slide: Samtleben

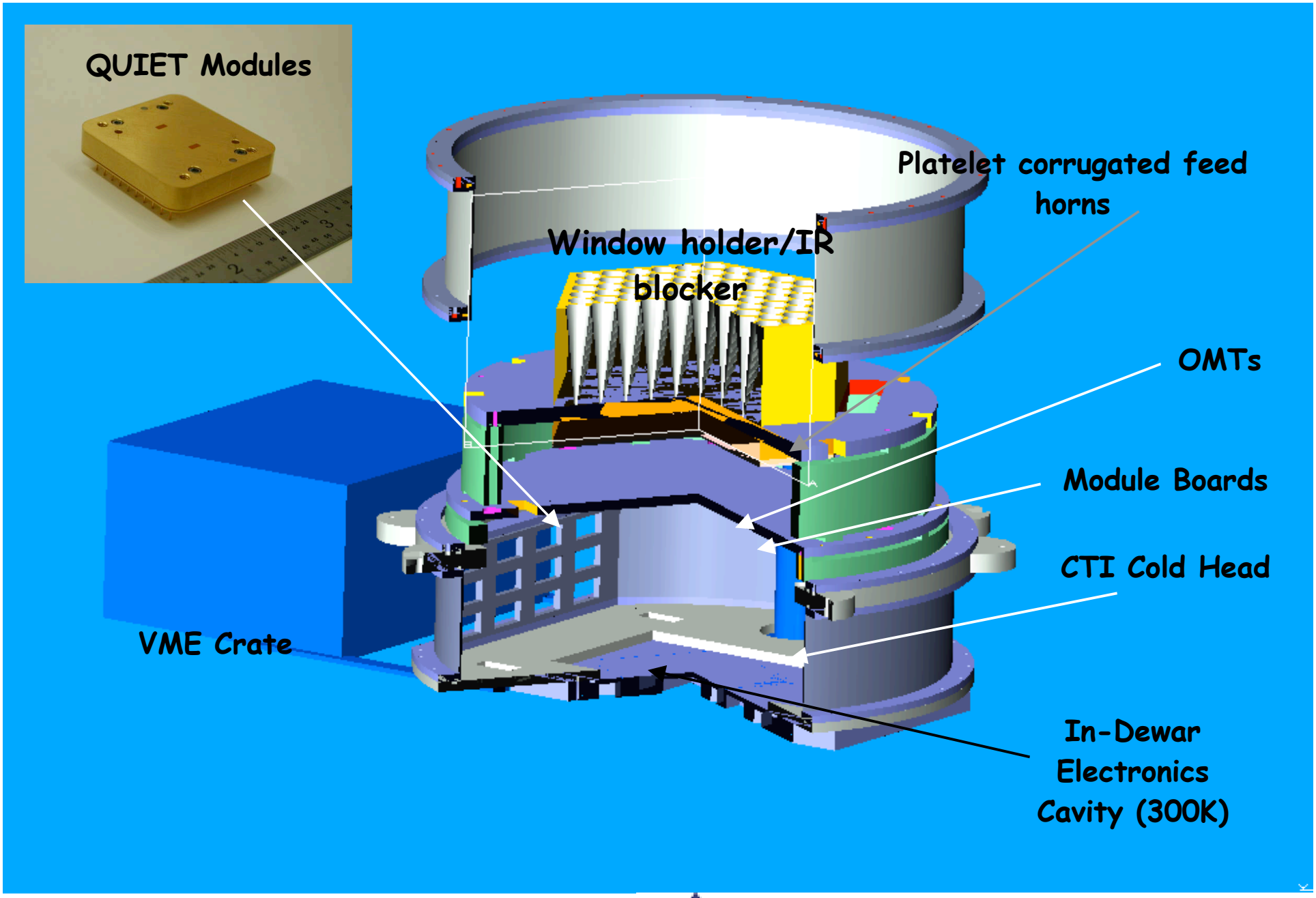
Q/U Polarimeter-Functional Schematic



Diode outputs following 180 degree pahse combiner are demodulated, low-pass filtered, and differenced ➔ **Stokes Q paramter**

Diode outputs are demodulated, low-pass filtered, and differenced ➔ **Stokes U paramter**

Drawing: Lawrence



Drawings: Laura Newburgh

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

CHILE: the Atacama Plateau

Large Scale QUIET

Small Scale QUIET

- 5000 meter (~16,000 ft.) elevation
- atmospheric transmission 0.988
- 1.38 mm PWV
- At the current CBI site, Near the former Toco site (future ACT site), Near the future site for ALMA – site has sufficient space for Lucent 7m telescope
- Logistical support available from San Pedro de Atacama

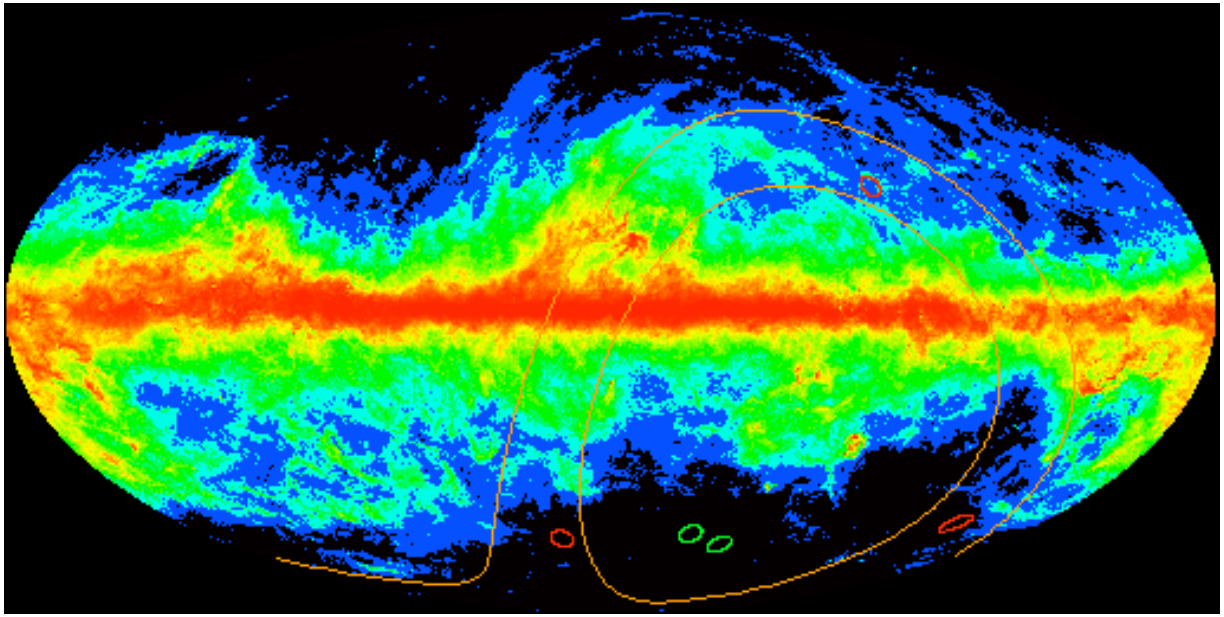
QUIET Foregrounds/Systematics Risk Mitigation

- observe in low foreground region of sky
- cross-linked scan strategy, observe each sky pixel at a range of parallactic angles
- observe at multiple frequencies (characterize synchrotron and free-free emission)
- coherent polarimeter design detects Q and U with the *same* detectors (polarized signal comes from product not difference in gains of two detectors)
- use corrugated feed horns (excellent polarization properties)
- observe the same patch of sky with hundreds of individual detectors (individual maps), use null tests in analysis

Where to Observe?

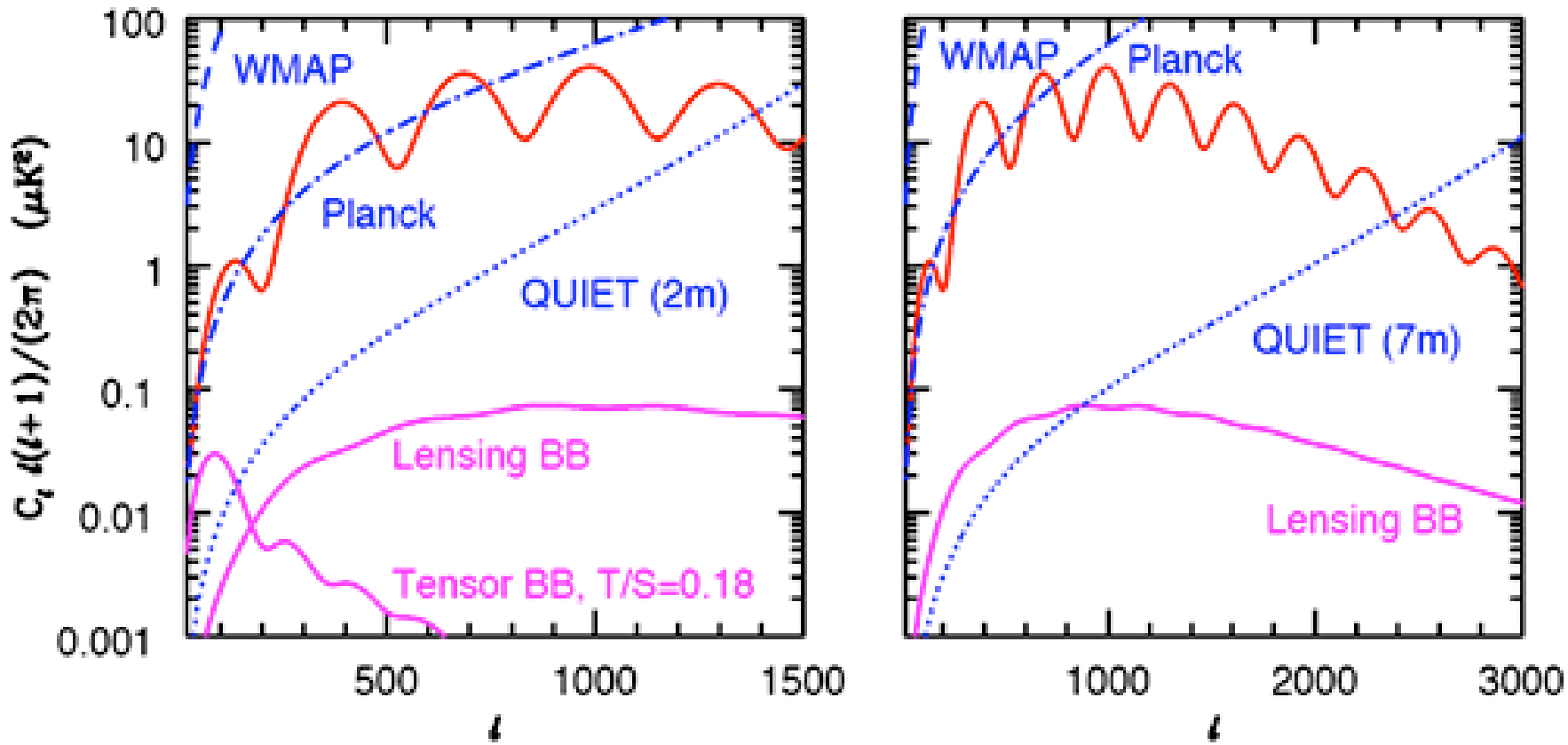
Identified three 5 deg. by 5 deg. regions

- Each passes directly overhead from CBI
- Can observe each for 6 hours a day
- Each is 50% less anisotropic than DASI fields



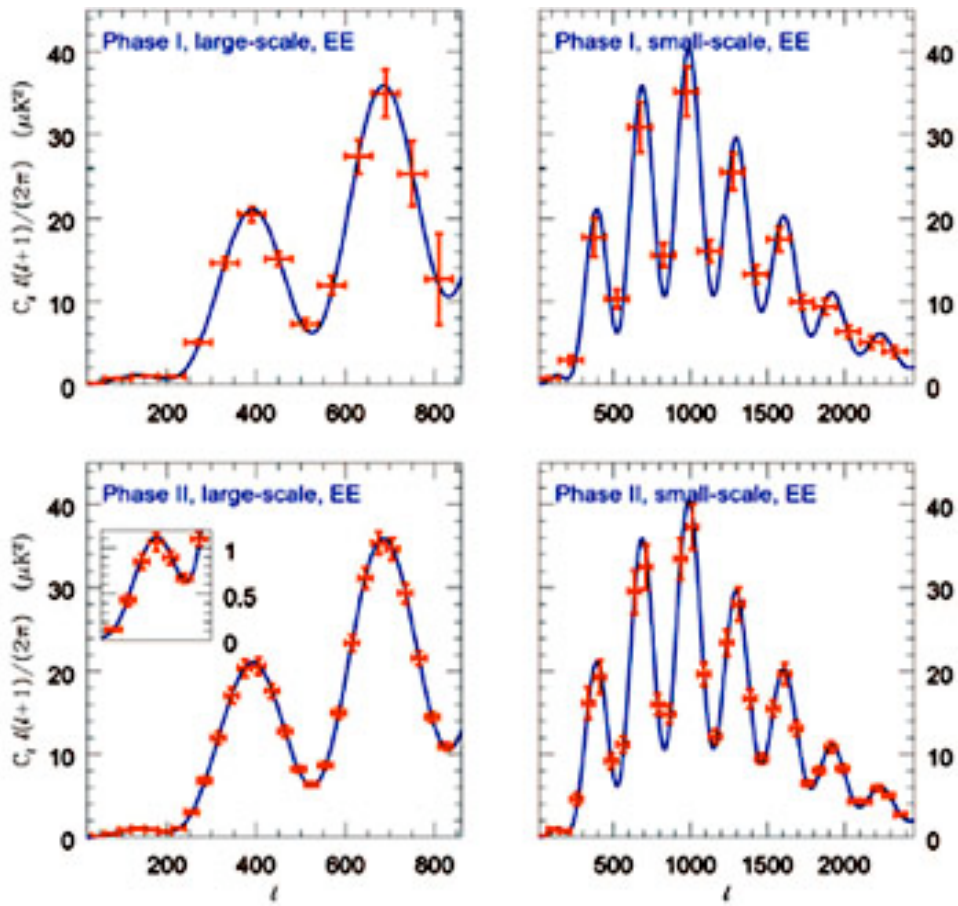
Keith Vanderlinde

Projected QUIET Sensitivity



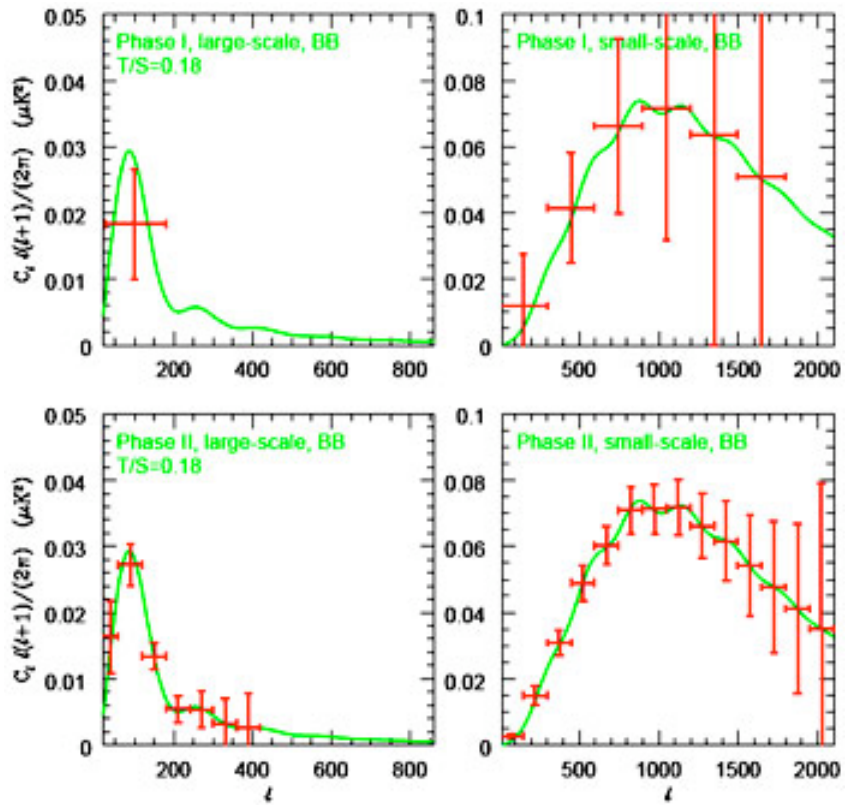
QUIET predicted power spectra and noise variances. T/S=0.18

Projected QUIET EE Sensitivity



QUIET EE power spectrum simulations, phase I and phase II, large and small scale experiments. Includes offset removal for each detector and marginalization over power in adjacent bands

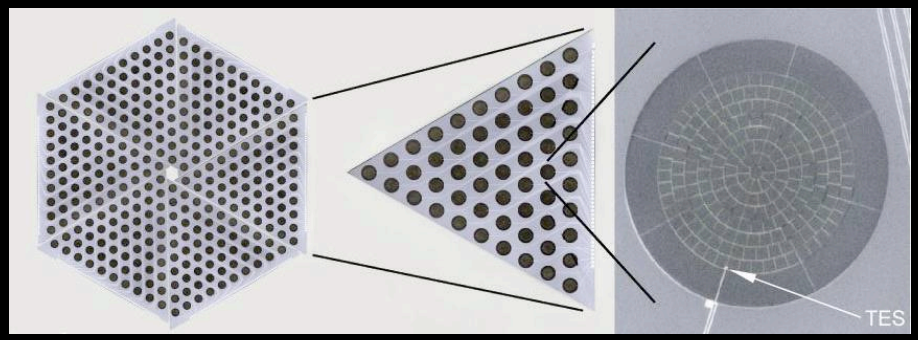
Projected QUIET BB Sensitivity



QUIET BB power spectrum simulations. On right is lensing power spectrum, on left is spectrum from primordial gravity waves corresponding T/S=0.18. Simulations include offset removal for each detector (increases error in lowest l-bin in lower left plot), the effects of E-B leakage, and marginalization over power in adjacent (E and B) bands.

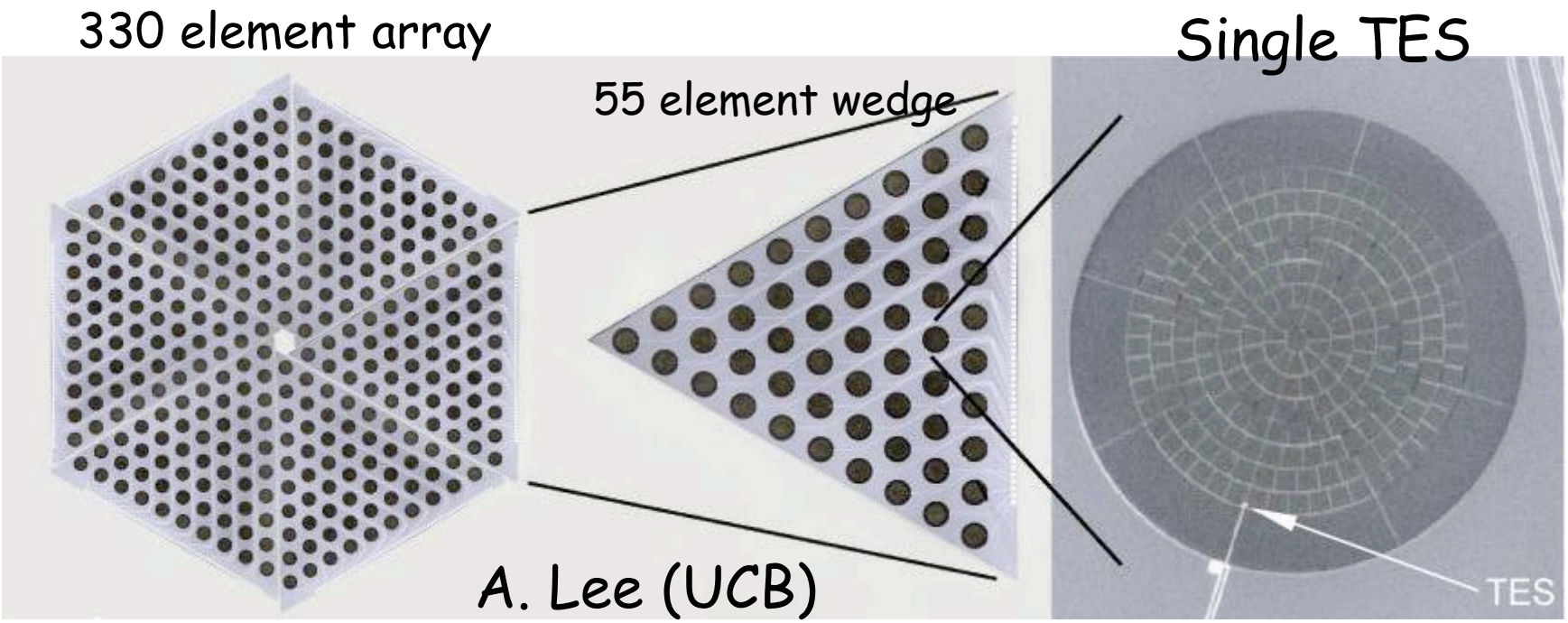
E B Experiment (EBEX)

The Collaboration



- University of Minnesota
- Columbia University
- Brown University
- Harvard University
- SISSA/ISAS – Trieste
- University of California, Berkeley
- University of California, San Diego
- University of Rome, La Sapienza
- University of Wales, Cardiff
- Weizmann Institute of Science, Israel

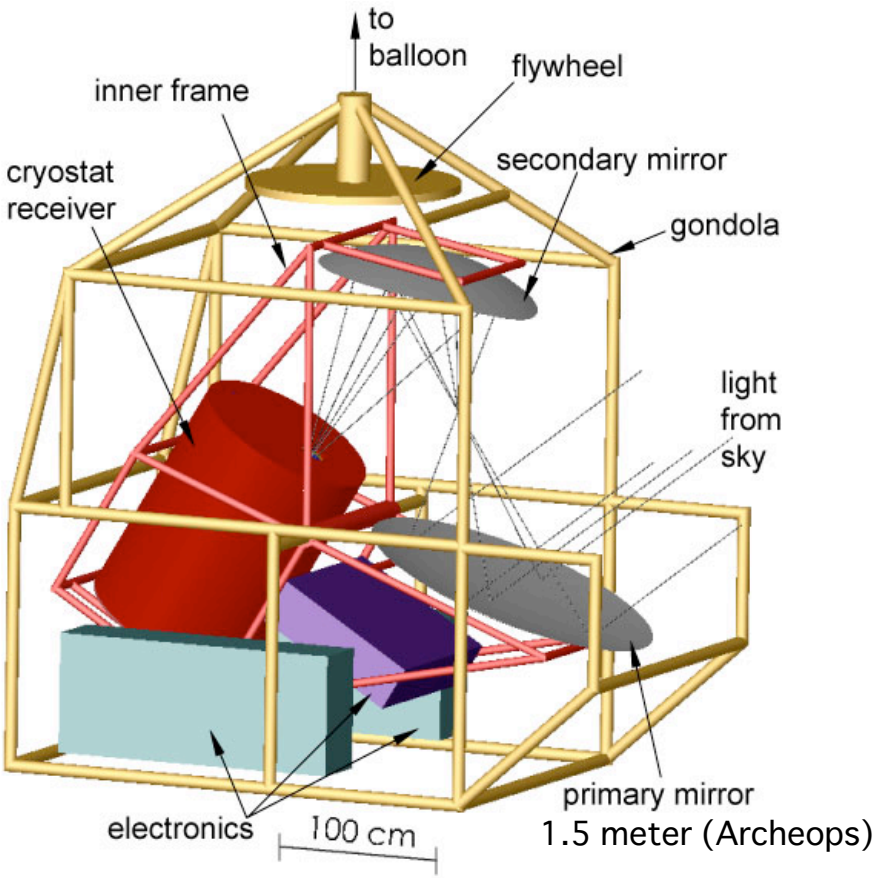
EBEX Focal Plane

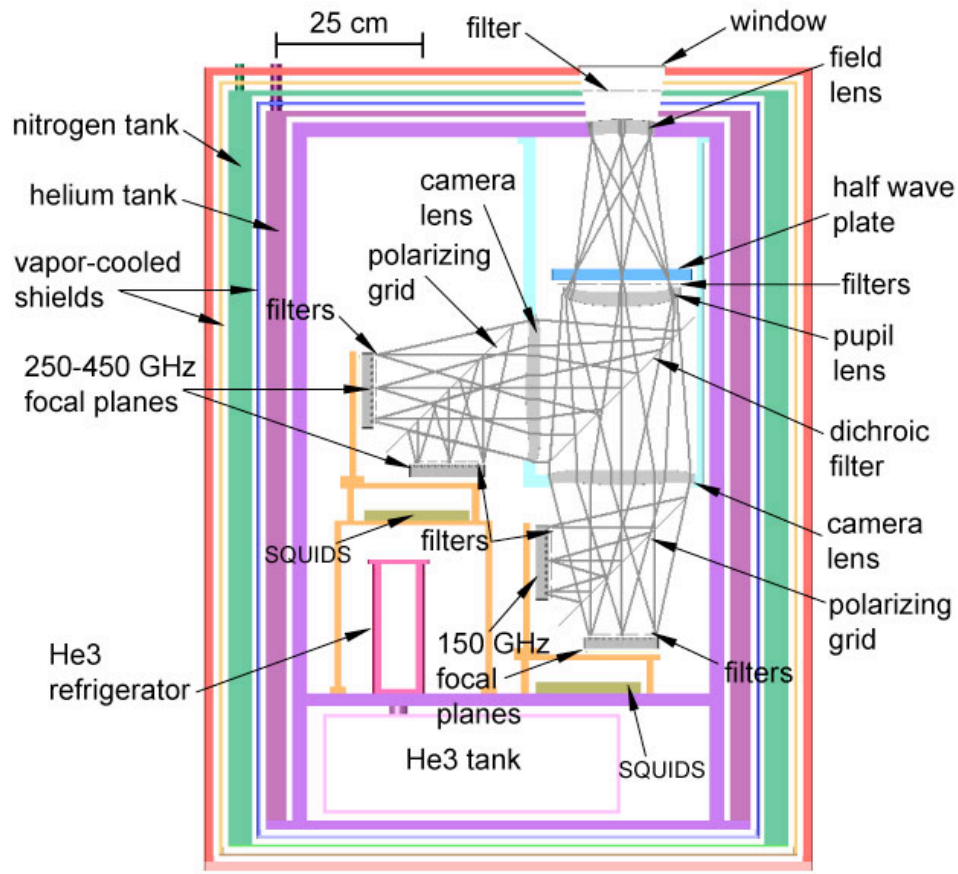


- Four focal planes each with 330 TES bolometers
- Each focal plane made of 6 wedges with 55 TES
- Two focal planes: 150 GHz;
- Two for 250-450 GHz

Slide: adapted from Hanany

EBEX Experiment





8′ FWHM Resolution @ 150 GHz (3′ FWHM @ 450 GHz)

To Fly on a Long Duration Balloon

Slide: adapted from Hanany

EBEX Foregrounds/Systematics Risk Mitigation

- observe in low foreground region of sky
- cross-linked scan strategy
- observe at multiple frequencies (characterize dust emission)
- use rotating half wave plate to modulate polarization more quickly than typical instrumental variations (temperature drifts, etc.)
- cool optics to 4K (except first two elements, passively cooled to 240K)
- observe the same patch of sky with hundreds of individual detectors (individual maps), use null tests in analysis

EBEX Science Goals

MUCH better measurements of E-mode that any other instrument to date

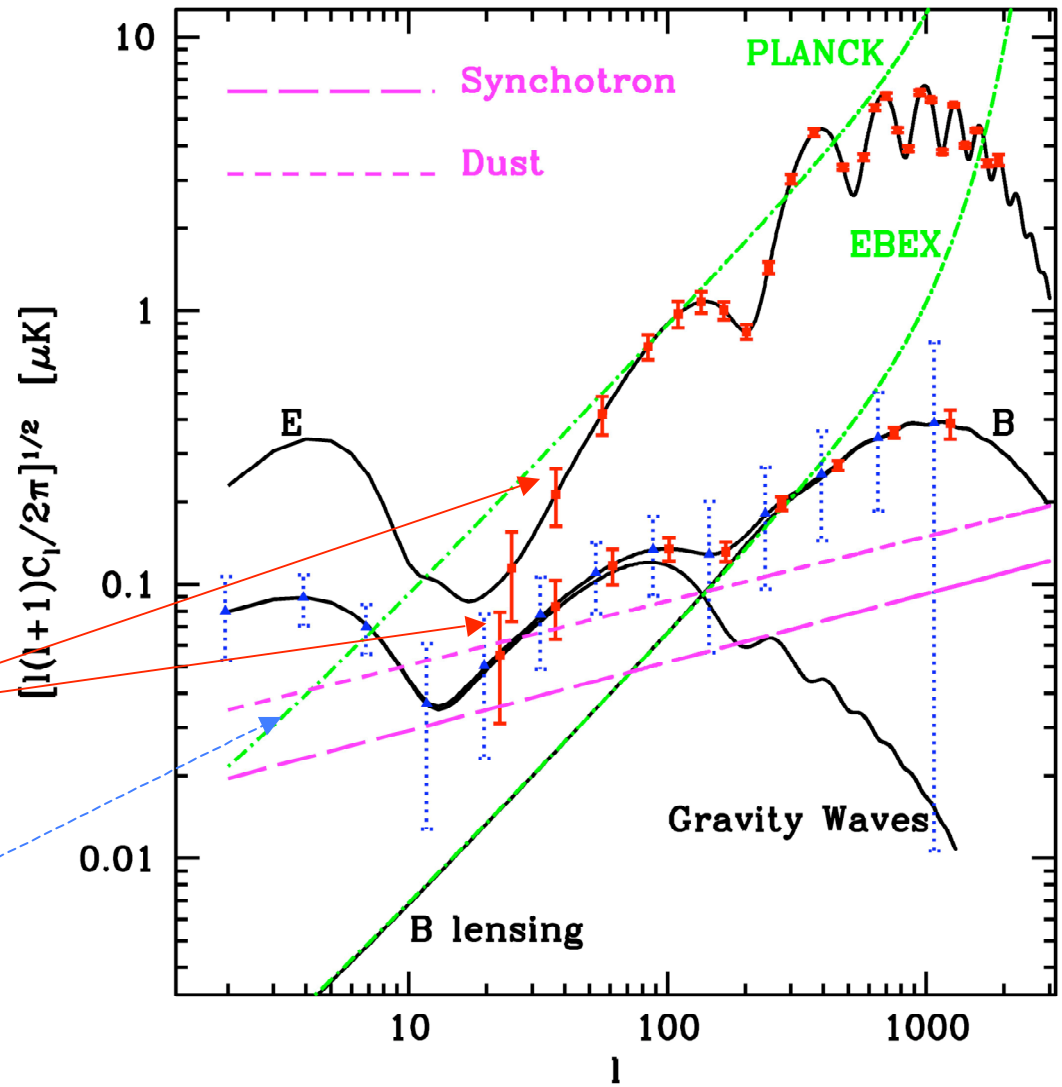
Detect or set upper bound on B-mode

Restrict T/S to X~10 better than now:

T/S<0.03 at 2_

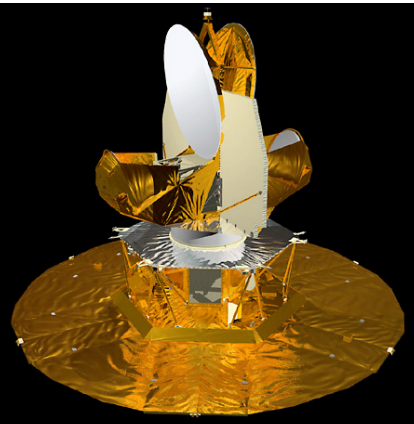
EBEX 14 days

Planck 1 year



Slide: adapted from Hanany

Conclusion



- CMB has come a long way
- CMB has a long way to come
- Lots of exciting things to look forward to in the future
  - Small-scale CMB temperature anisotropy
  - Sunyaev-Zel'dovich Effect
  - Polarization anisotropy
  - B-mo