Title: Late Universe CMB Science

Date: Nov 29, 2007 11:30 AM

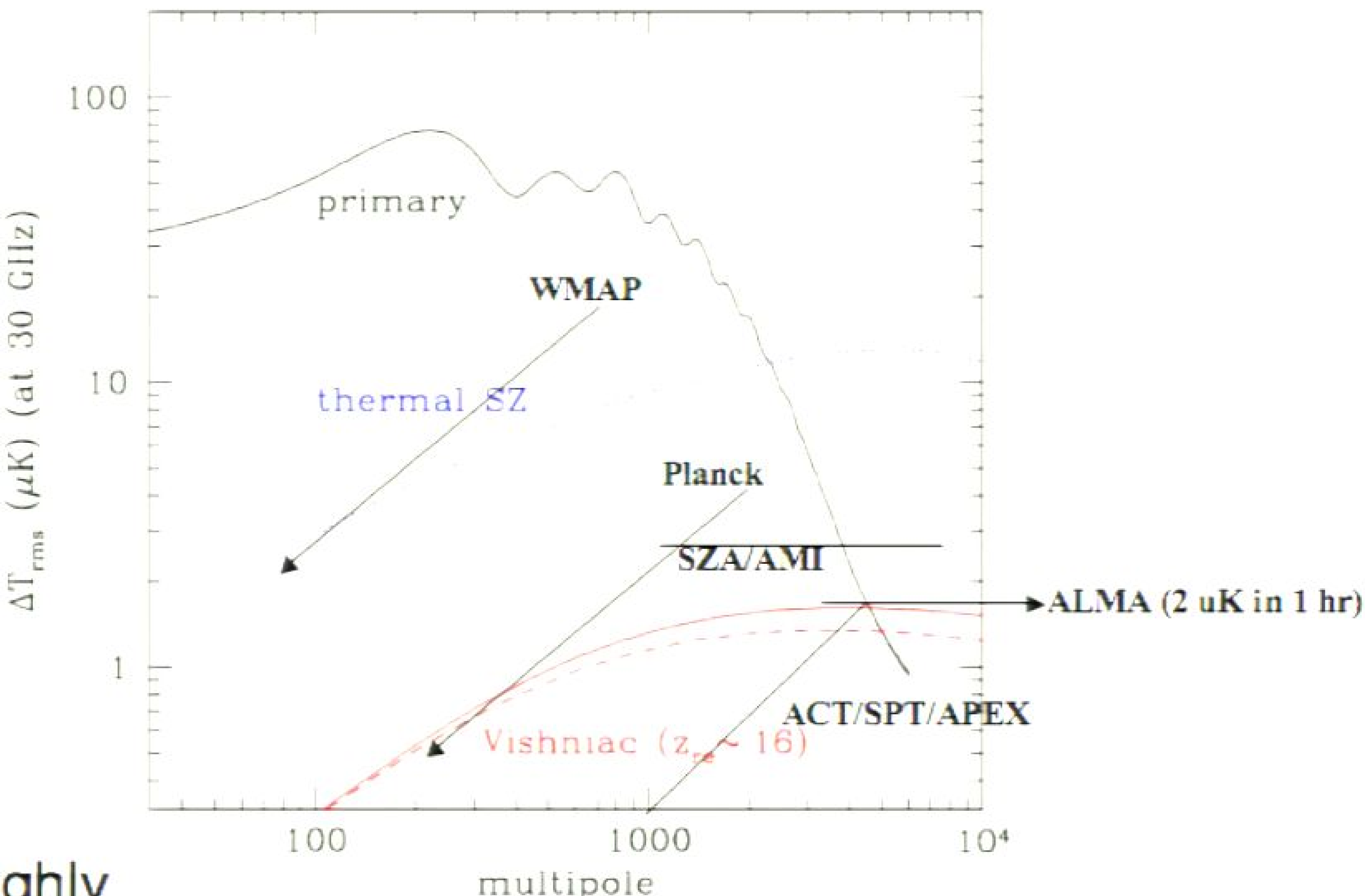
URL: http://pirsa.org/07110075

Abstract:

CMB "secondary anisotropy" science opportunities

- Galaxy cluster surveys
  - Dark energy, cosmological parameters
- Fine scale CMB temperature anisotropy
  - Primordial P(k), secondary anisotropies, lensing
- Future fine scale polarization studies
  - Foregrounds, de-lensing, remote quadrupole measurements

Measuring the CMB



Old and highly incomplete list….

SPT Collaboration

Berkeley
University of California

William Holzapfel
Adrian Lee
Helmuth Spieler
Martin White
Sherry Cho
Bradford Benson
Huan Tran
Martin Lueker
Jared Mehl
Tom Plagge
Dan Schwan
Erik Shirokoff

Case

John Ruhl
Tom Montroy
Zak Staniszewski

Harvard-Smithsonian Center for Astrophysics

Antony Stark

ASTRONOMY

Joe Mohr

THE UNIVERSITY OF CHICAGO

John Carlstrom (P.I)
Steve Padin (Proj. Manager)

Stephan Meyer
Clem Pryke
Tom Crawford
Jeff McMahon
Clarence Chang
Kathryn Miknaitis
Joaquin Vieira
Ryan Keisler
Lindsey Bleem
Jonathan Stricker

Colorado
University of Colorado at Boulder

Nils Halverson

JPL

Erik Leitch

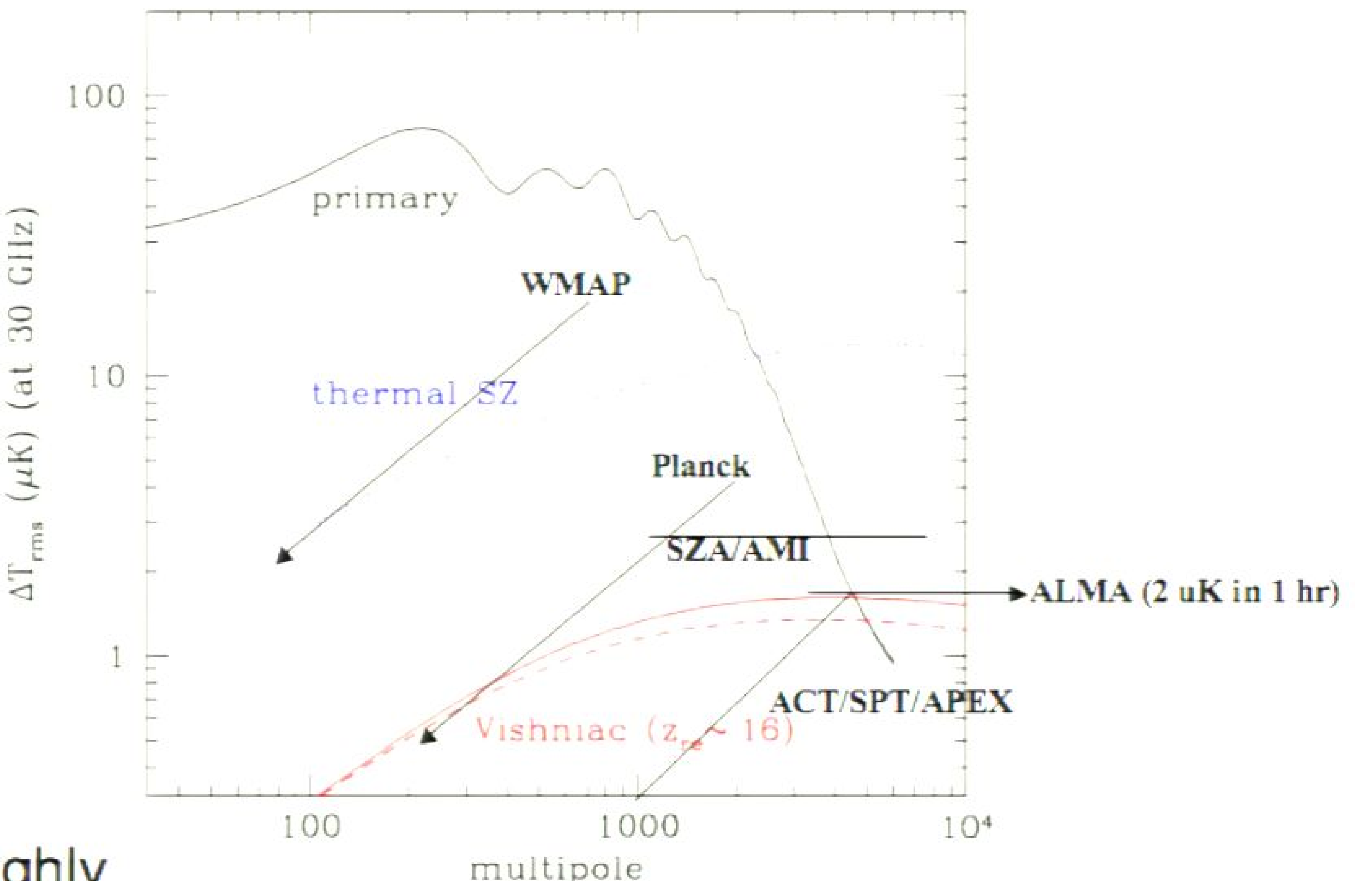
McGill

Matt Dobbs
Gil Holder
Trevor Lanting

UC DAVIS
UNIVERSITY OF CALIFORNIA

Lloyd Knox
Jason Dick

Measuring the CMB



Old and highly incomplete list….

SPT Collaboration

Berkeley
University of California

William Holzapfel
Adrian Lee
Helmuth Spieler
Martin White
Sherry Cho
Bradford Benson
Huan Tran
Martin Lueker
Jared Mehl
Tom Plagge
Dan Schwan
Erik Shirokoff

Case

John Ruhl
Tom Montroy
Zak Staniszewski

Harvard-Smithsonian Center for Astrophysics

Antony Stark

ASTRONOMY

Joe Mohr

THE UNIVERSITY OF CHICAGO

John Carlstrom (P.I)
Steve Padin (Proj. Manager)

Stephan Meyer
Clem Pryke
Tom Crawford
Jeff McMahon
Clarence Chang
Kathryn Miknaitis
Joaquin Vieira
Ryan Keisler
Lindsey Bleem
Jonathan Stricker

Colorado
University of Colorado at Boulder

Nils Halverson

JPL

Erik Leitch

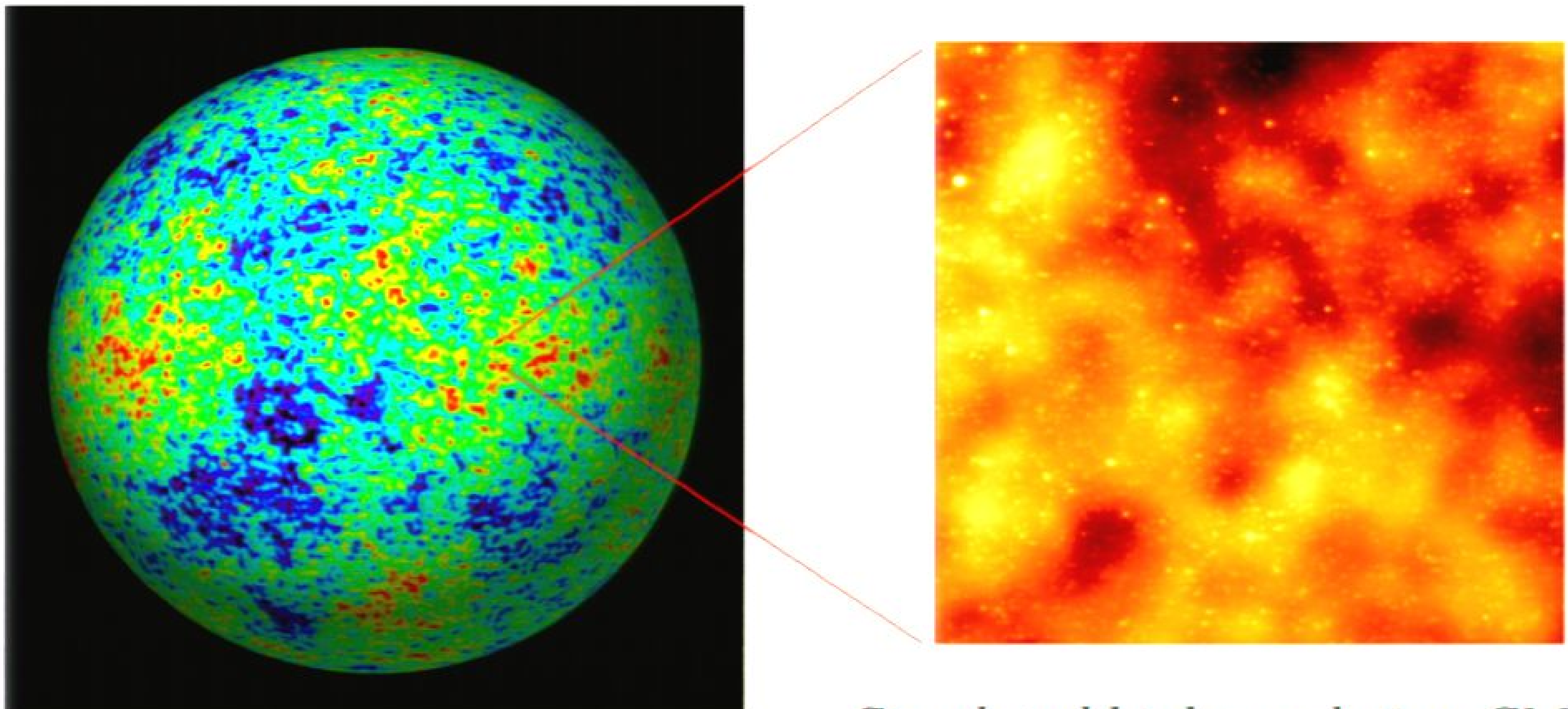
McGill

Matt Dobbs
Gil Holder
Trevor Lanting

UC DAVIS
UNIVERSITY OF CALIFORNIA

Lloyd Knox
Jason Dick

The CMB at High Resolution?



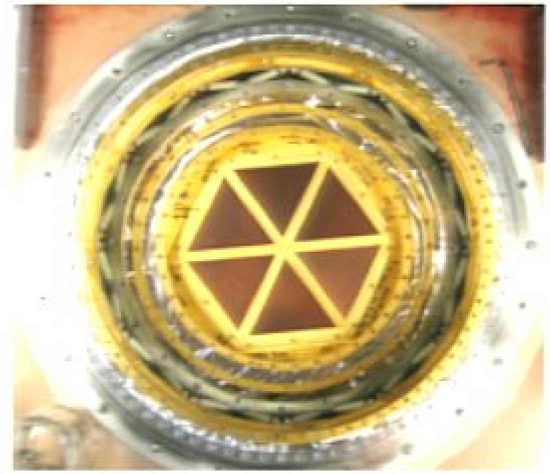
WMAP image (1 degree resolution) Bennett et al 2003

Simulated high resolution CMB map (2 degrees by 2 degrees)

Overview

Primary Science Goals

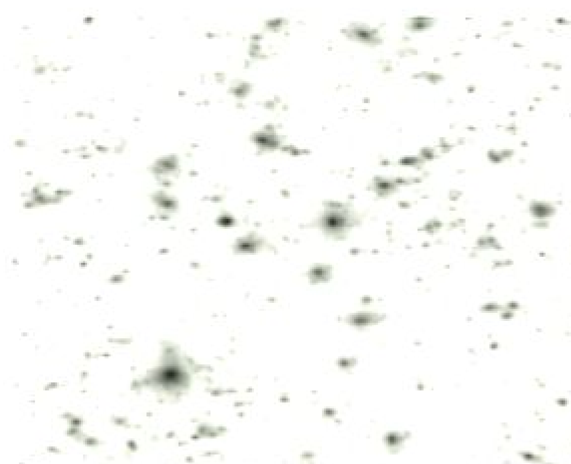
1) SZ cluster survey
2) Fine scale CMB anisotropy
3) CMB Polarization



Telescope and Receiver

10m off-axis Gregorian telescope with low-noise optical design located at the South Pole

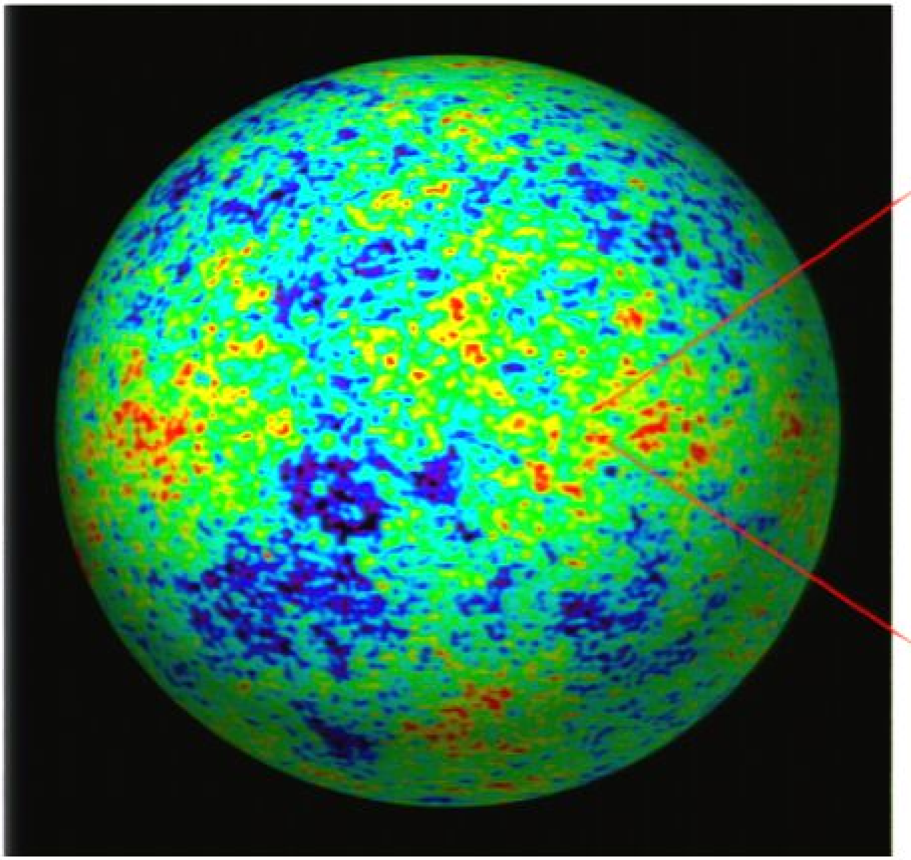
960 element TES coupled multi-wavelength bolometer array



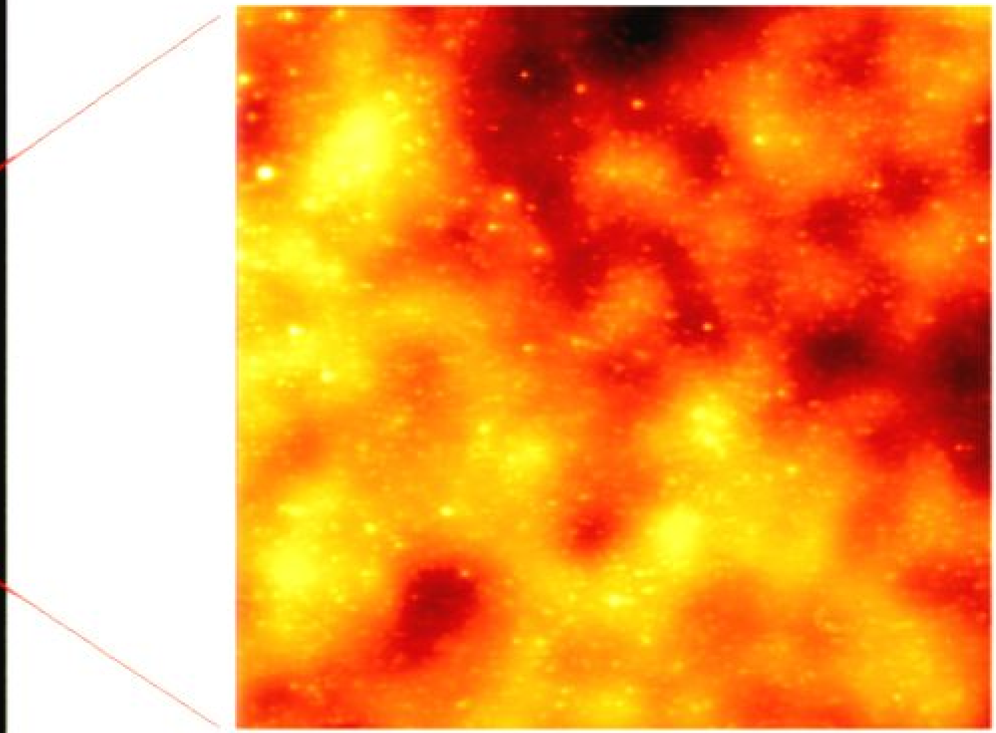
Simulated SZ sky

Slide by J. Vieira (Chicago)

The CMB at High Resolution?

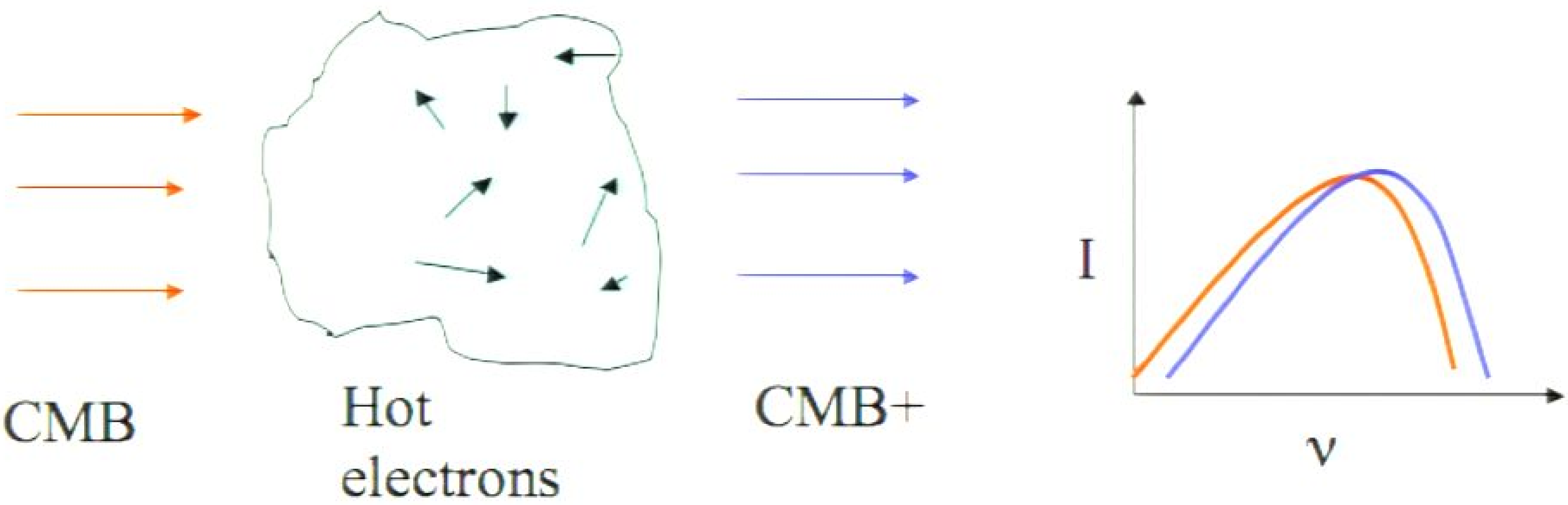


WMAP image (1 degree resolution) Bennett et al 2003



Simulated high resolution CMB map (2 degrees by 2 degrees)

Thermal Sunyaev-Zel'dovich Effect

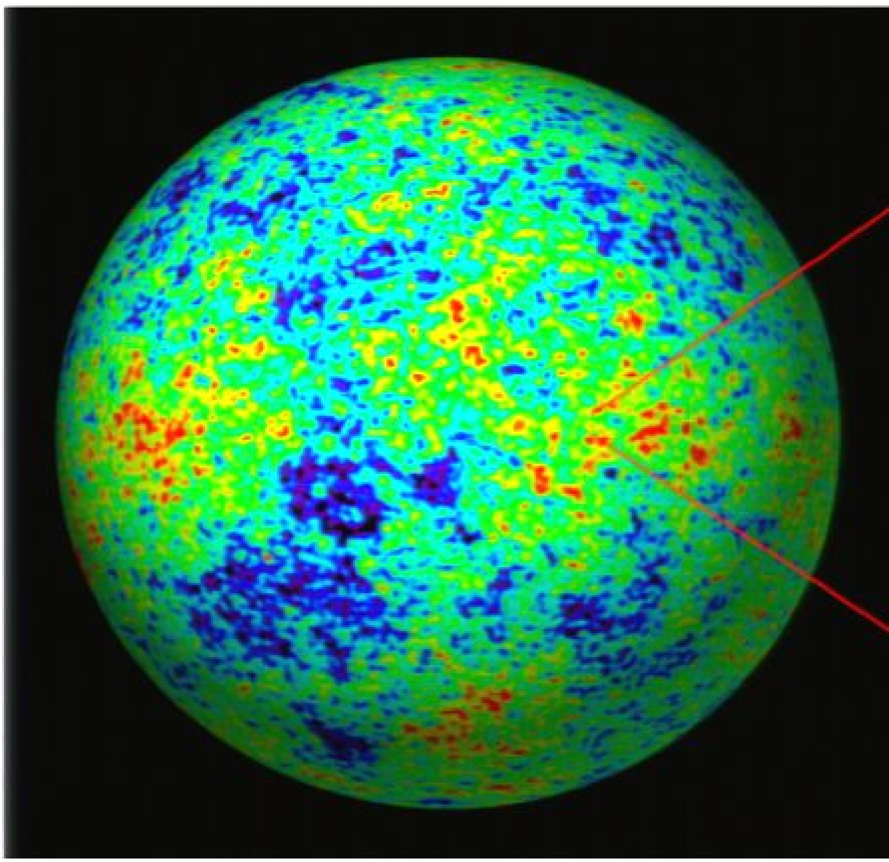


Optical depth: $\tau \sim 0.01$

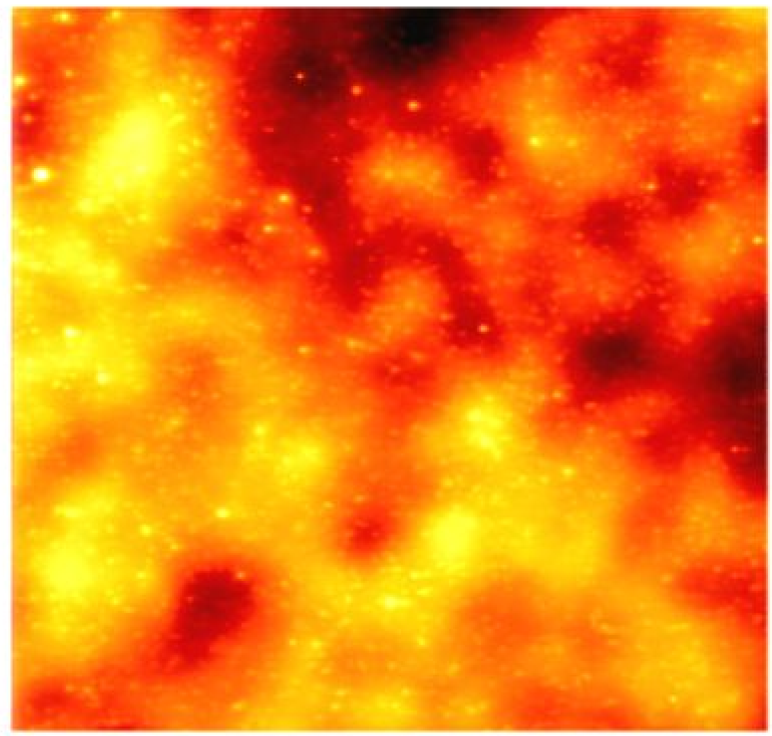
Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

Typical cluster signal: ~500 uK

The CMB at High Resolution?



WMAP image (1 degree resolution) Bennett et al 2003



Simulated high resolution CMB map (2 degrees by 2 degrees)

SZ Observables I

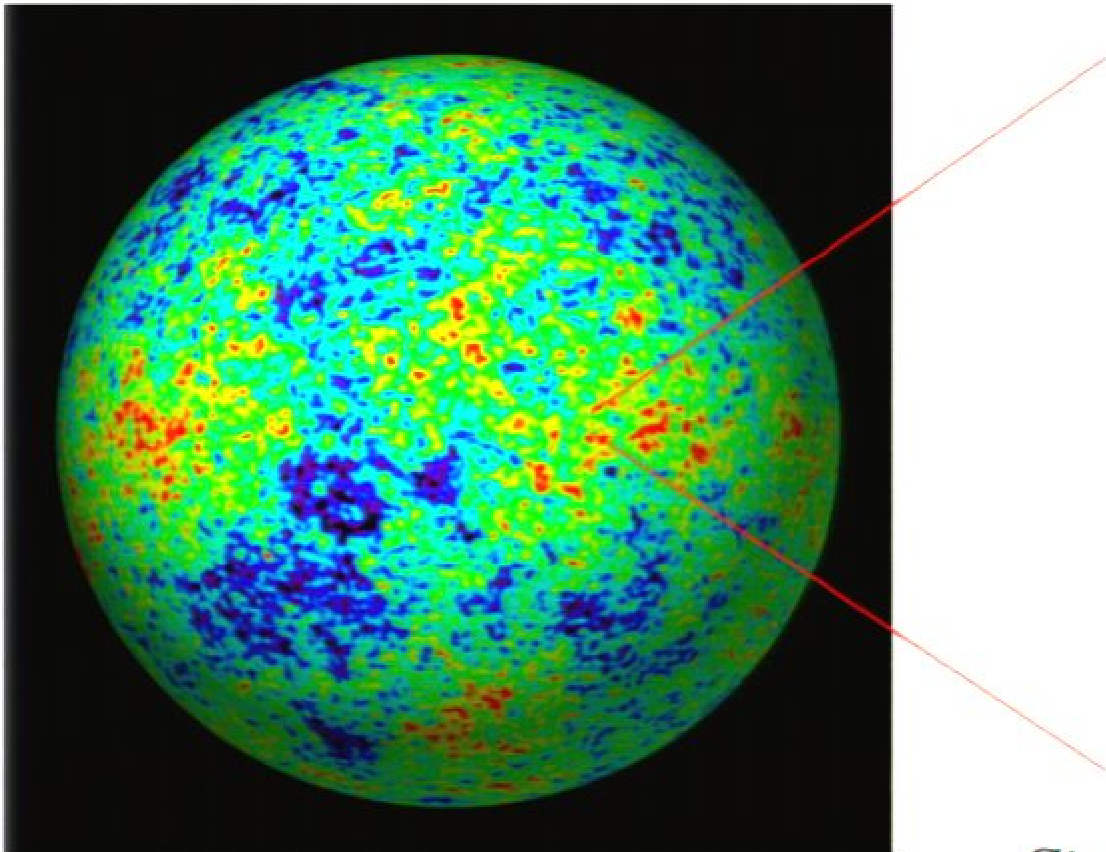
Along a line of sight:

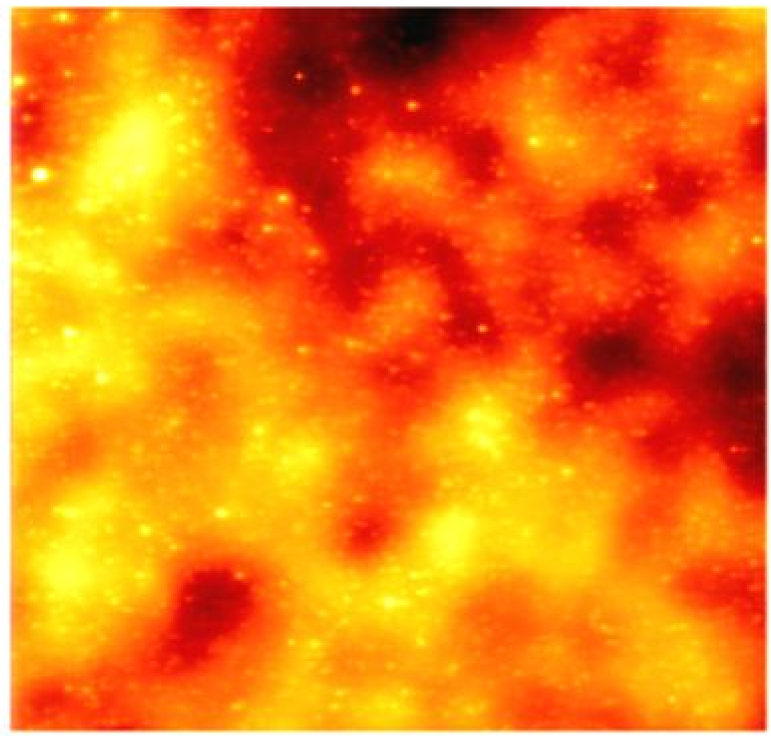
$$\frac{\Delta T}{T} = g(\nu)\int dl \left(\frac{kT}{m_e c^2}\right) n_e(l)\sigma_T$$

DEPENDS ONLY ON CLUSTER PROPERTIES !!!!

- Surface brightness is independent of redshift
- Temperature weighted electron column density
- Integrated pressure (quasi-static effects unimportant)

The CMB at High Resolution?

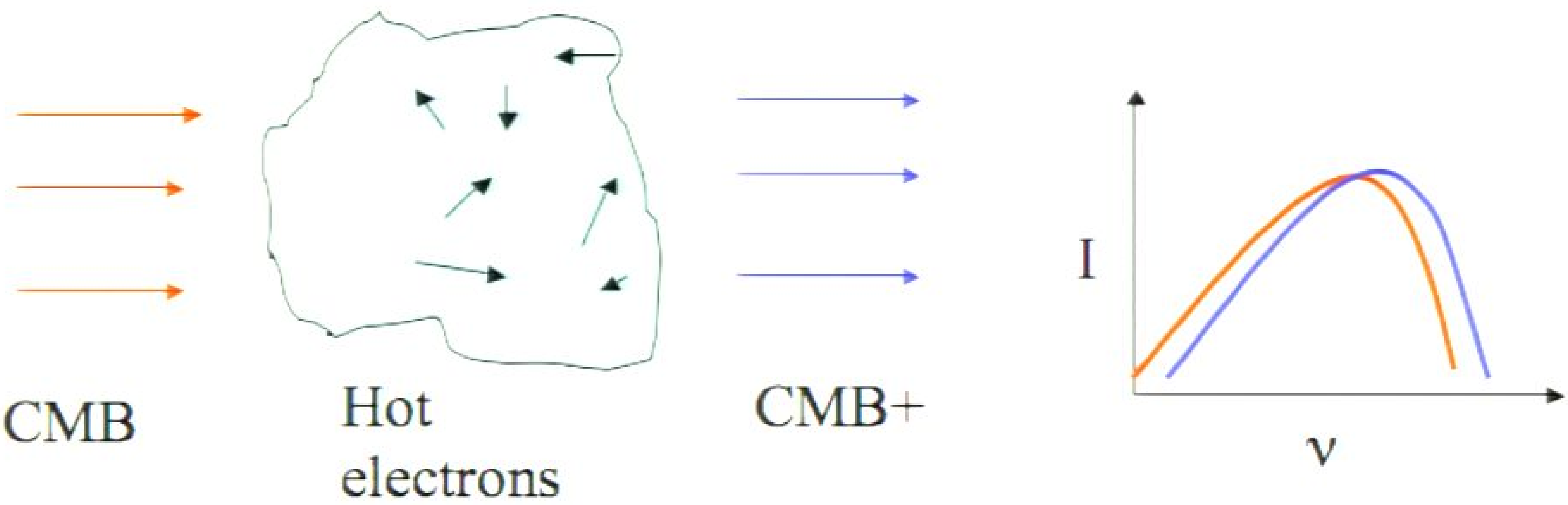




WMAP image (1 degree resolution) Bennett et al 2003

Simulated high resolution CMB map (2 degrees by 2 degrees)

Thermal Sunyaev-Zel'dovich Effect



Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

Typical cluster signal: ~500 uK

SZ Observables I

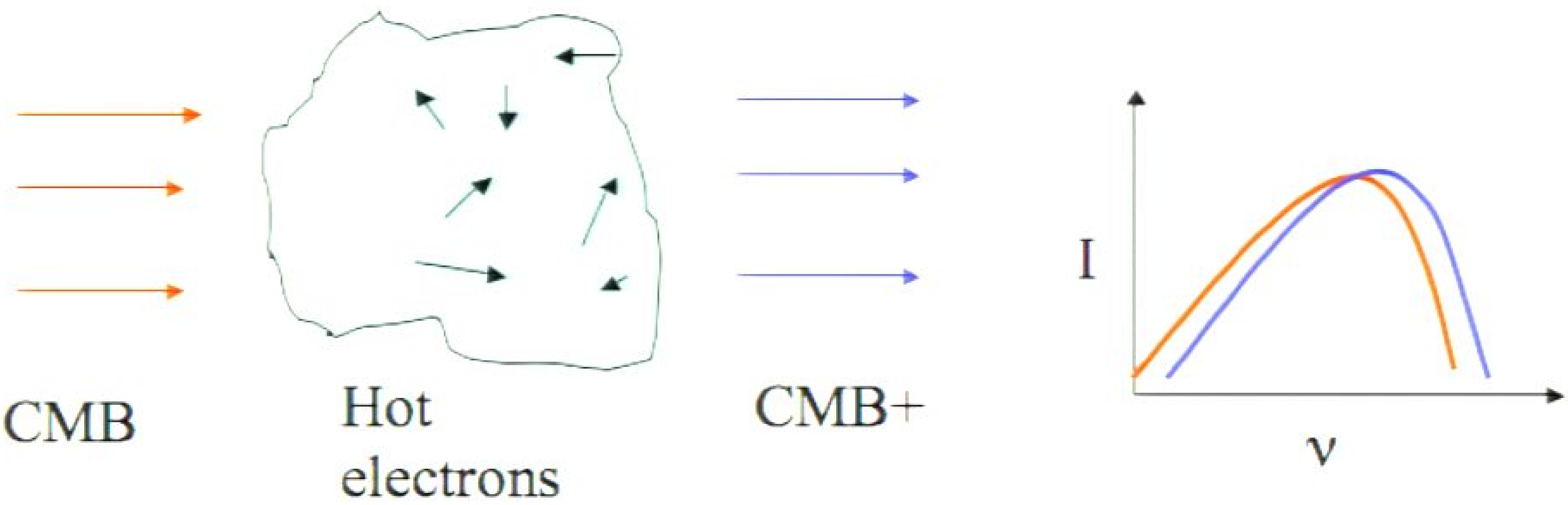
Along a line of sight:

$$\frac{\Delta T}{T} = g(\nu)\int dl \left(\frac{kT}{m_e c^2}\right) n_e(l)\sigma_T$$

DEPENDS ONLY ON CLUSTER PROPERTIES !!!!

- Surface brightness is independent of redshift
- Temperature weighted electron column density
- Integrated pressure (quasi-static effects unimportant)

Thermal Sunyaev-Zel'dovich Effect

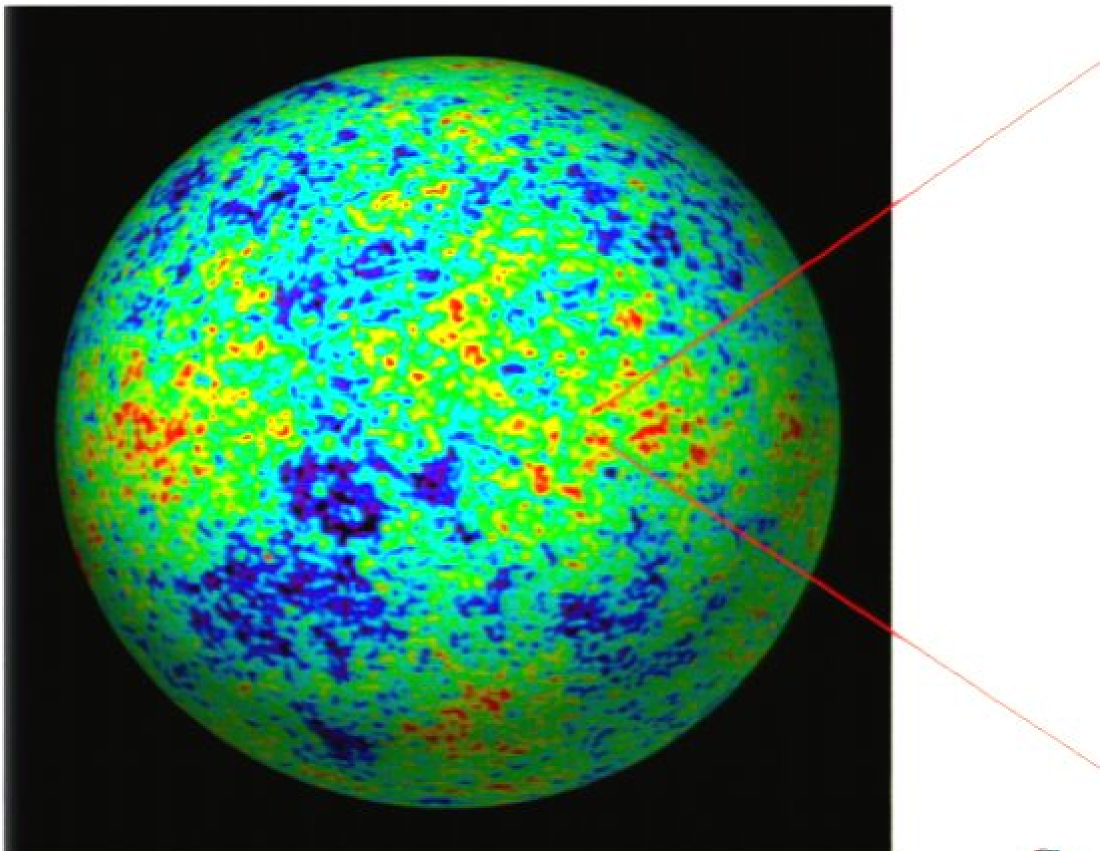


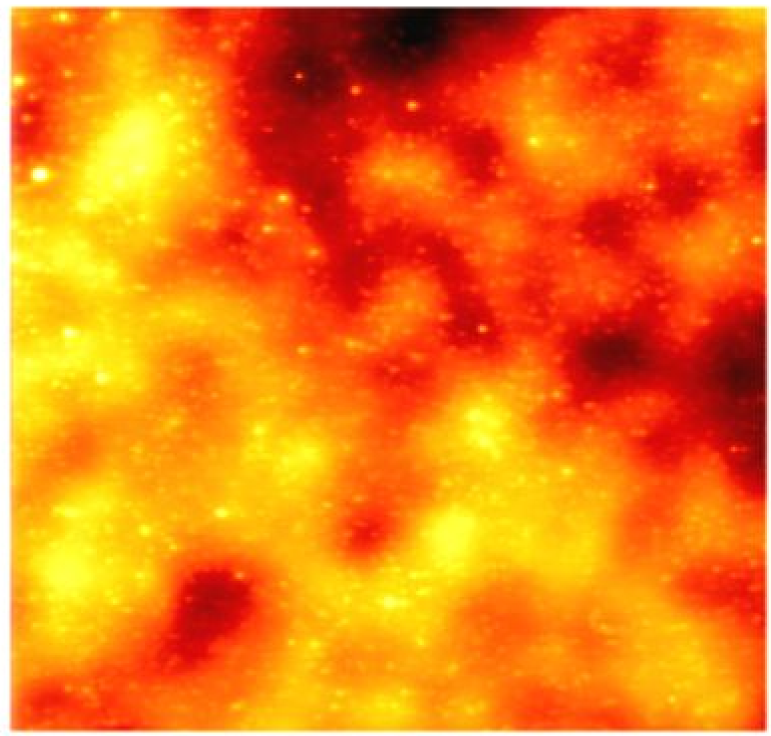
Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\dfrac{kT}{m_e c^2} \sim 0.01$

Typical cluster signal: ~500 uK

The CMB at High Resolution?





WMAP image (1 degree resolution) Bennett et al 2003

Simulated high resolution CMB map (2 degrees by 2 degrees)

SZ Observables I

Along a line of sight:

$$\frac{\Delta T}{T} = g(\nu)\int dl \left(\frac{kT}{m_e c^2}\right) n_e(l)\sigma_T$$

DEPENDS ONLY ON CLUSTER PROPERTIES !!!!

- Surface brightness is independent of redshift
- Temperature weighted electron column density
- Integrated pressure (quasi-static effects unimportant)

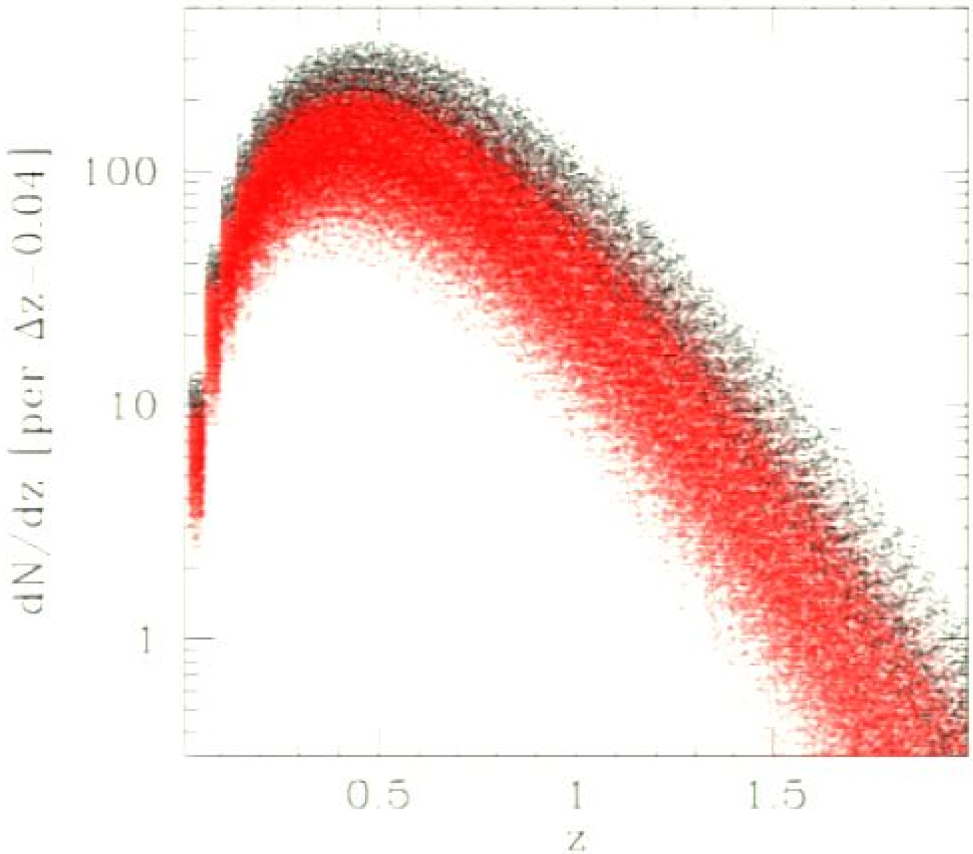
Galaxy Cluster Surveys

- Number counts of galaxy clusters a sensitive probe of cosmology

Sigma8 from 0.6-0.9 (clockwise from top left)

Don’t We Know Everything Already?

- Physical parameters of early universe very well understood, but late-time parameters less so
- Expected cluster counts uncertain by factor of several due to cosmology



Range in expected SPT cluster counts using WMAP+all MCMC chain (red: masses 25% higher than expected; black: clusters are as I would expect them to be)

Cartoon Cosmology: Counting Galaxy Clusters

$$\frac{d^2N}{dz\,d\ln S} = \int \frac{dP(\ln S\,|\,\ln M, z)}{d\ln S}\,\frac{dn}{d\ln M}\,d\ln M\,\frac{dV}{dz}$$

PHYSICS!!!!

Observed distribution as function of flux and redshift

Mapping between cluster observable and theory mass (e.g., Gaussian+)

Mass function

Volume element

(Jenkins, Press-Schechter)

SZ Observables II

Integrated effect from cluster:

$$S \propto \int \Delta T \, d\Omega \propto \frac{1}{d_A(z)^2} \int n_e kT \, dV$$

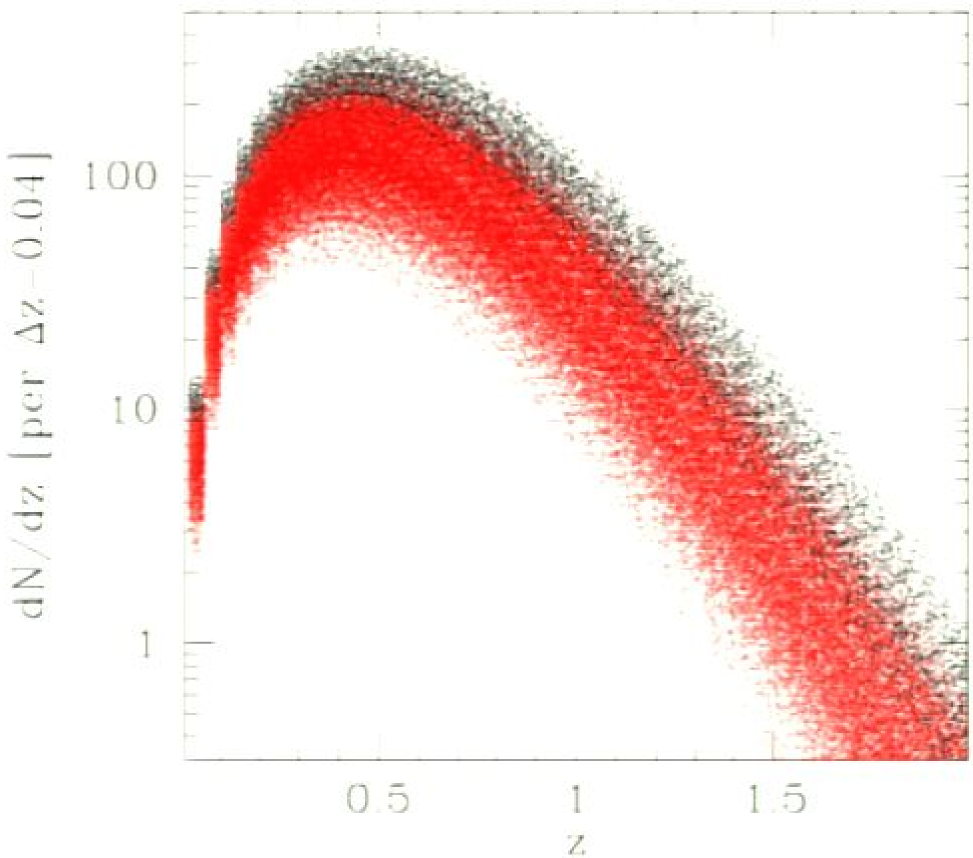
- proportional to total thermal energy of electrons
- angular diameter distance, not luminosity distance

Simple expectation:

$$S_{sz} = AM^{5/3}[\Delta(z)E^2(z)]^{1/3} d_A^{-2}(z)$$

Don't We Know Everything Already?

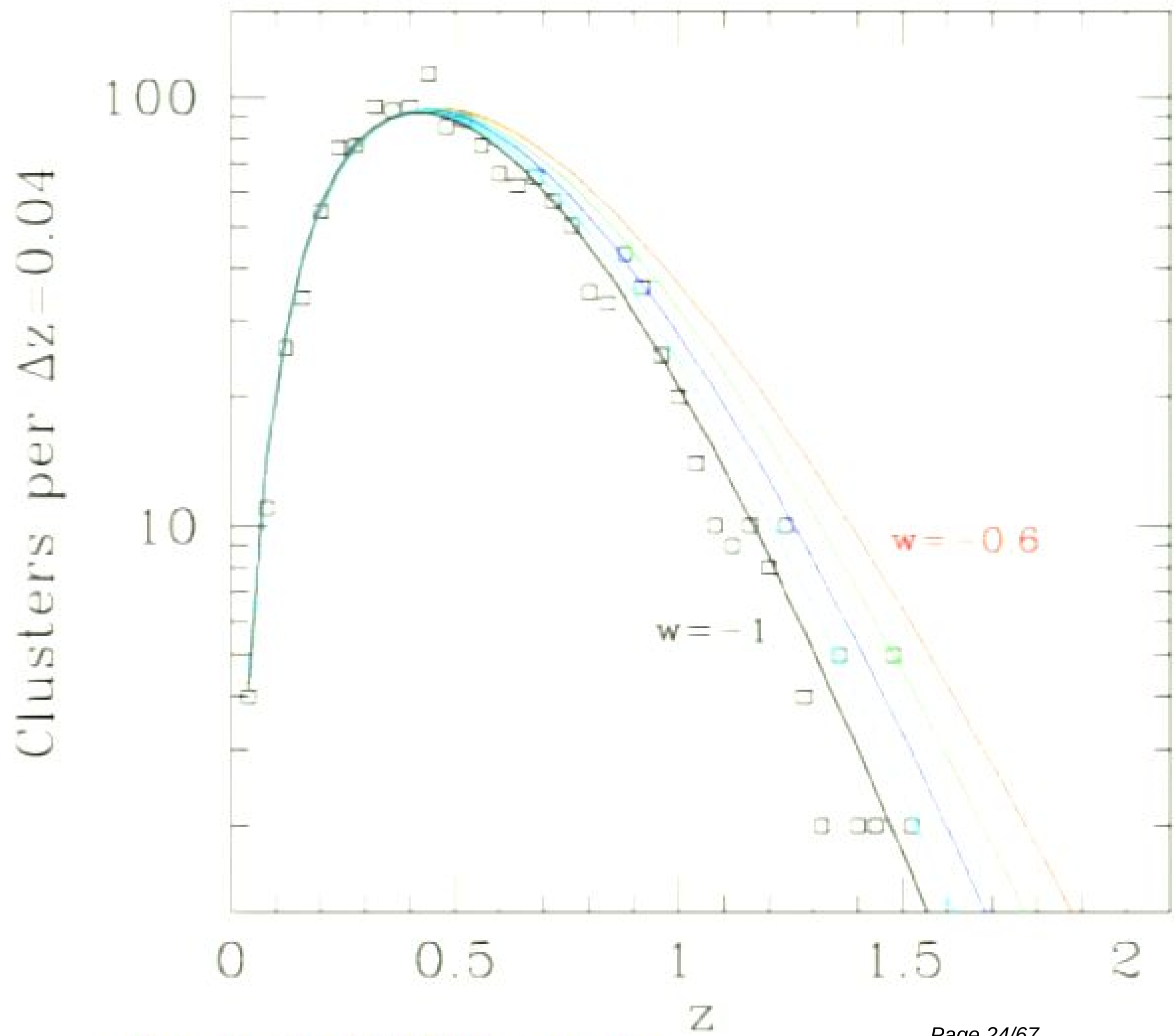
- Physical parameters of early universe very well understood, but late-time parameters less so
- Expected cluster counts uncertain by factor of several due to cosmology



Range in expected SPT cluster counts using WMAP+all MCMC chain (red: masses 25% higher than expected; black: clusters are as I would expect them to be)

Dark Energy with SZ Surveys

- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity



Predicted SPT counts

Cartoon Cosmology: Counting Galaxy Clusters

$$\frac{d^2N}{dz\,d\ln S} = \int \frac{dP(\ln S \mid \ln M, z)}{d\ln S} \frac{dn}{d\ln M} d\ln M \frac{dV}{dz}$$

PHYSICS!!!!

Observed distribution as function of flux and redshift

Mapping between cluster observable and theory mass (e.g., Gaussian+)

Mass function

(Jenkins, Press-Schechter)

Volume element

SZ Observables II

Integrated effect from cluster:

$$S \propto \int \Delta T \, d\Omega \propto \frac{1}{d_A(z)^2} \int n_e kT \, dV$$

- proportional to total thermal energy of electrons

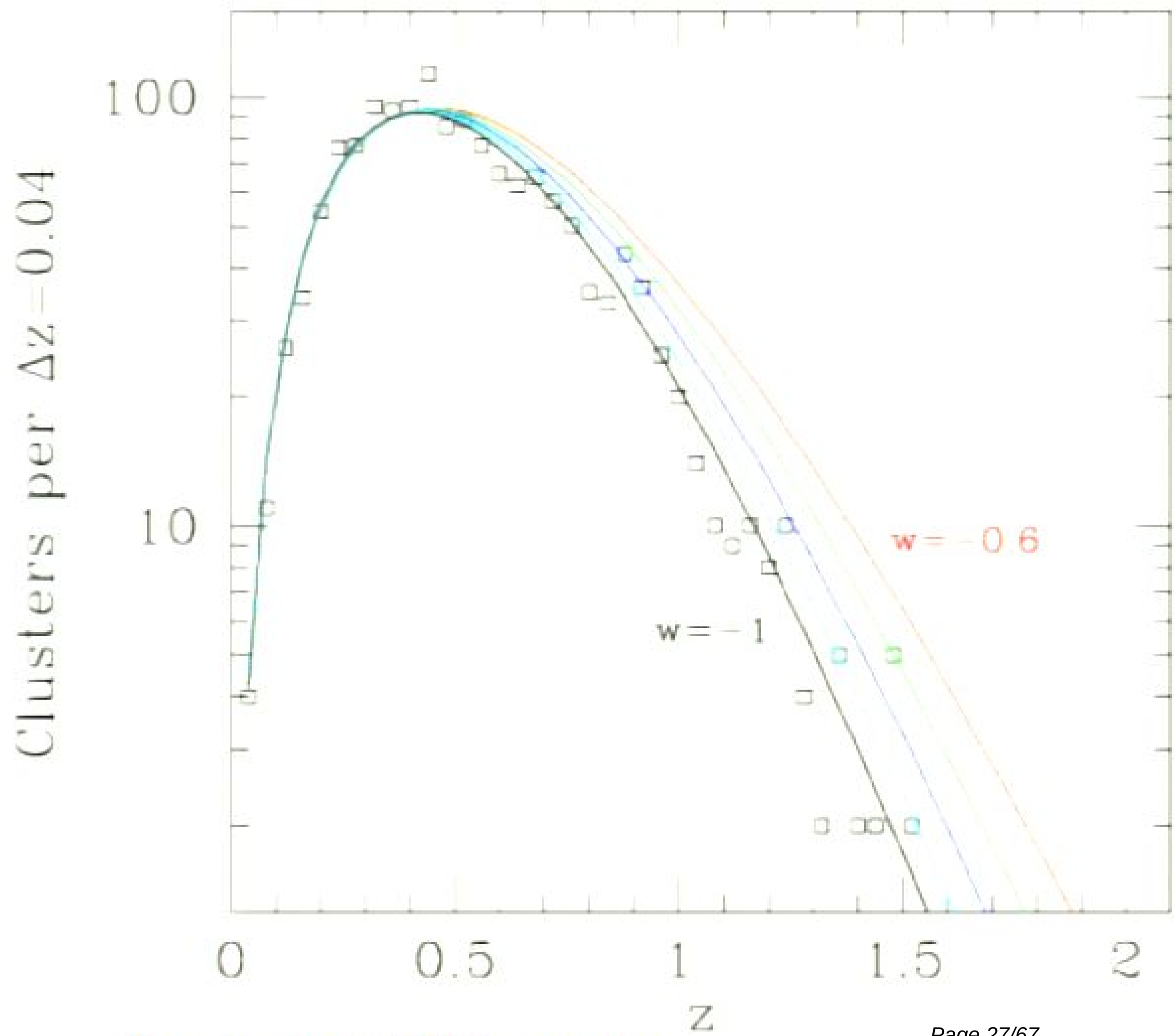
- angular diameter distance, not luminosity distance

Simple expectation:

$$S_{sz} = AM^{5/3}[\Delta(z)E^2(z)]^{1/3} d_A^{-2}(z)$$

Dark Energy with SZ Surveys

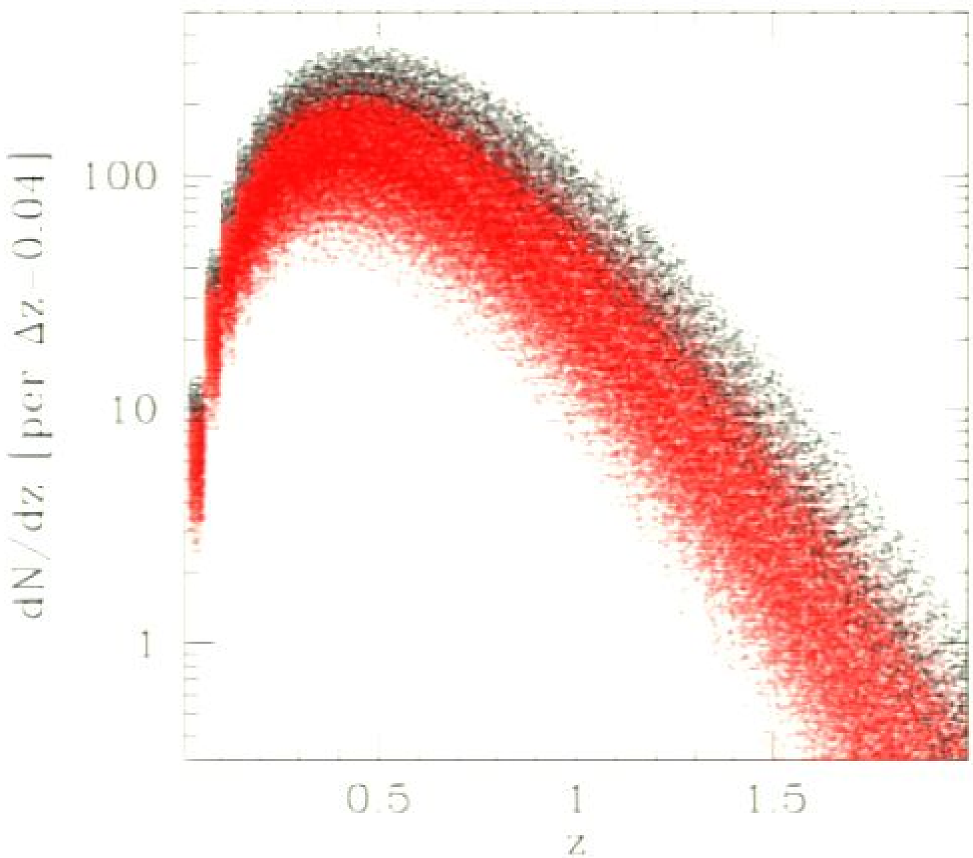
- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity



Predicted SPT counts

Don't We Know Everything Already?

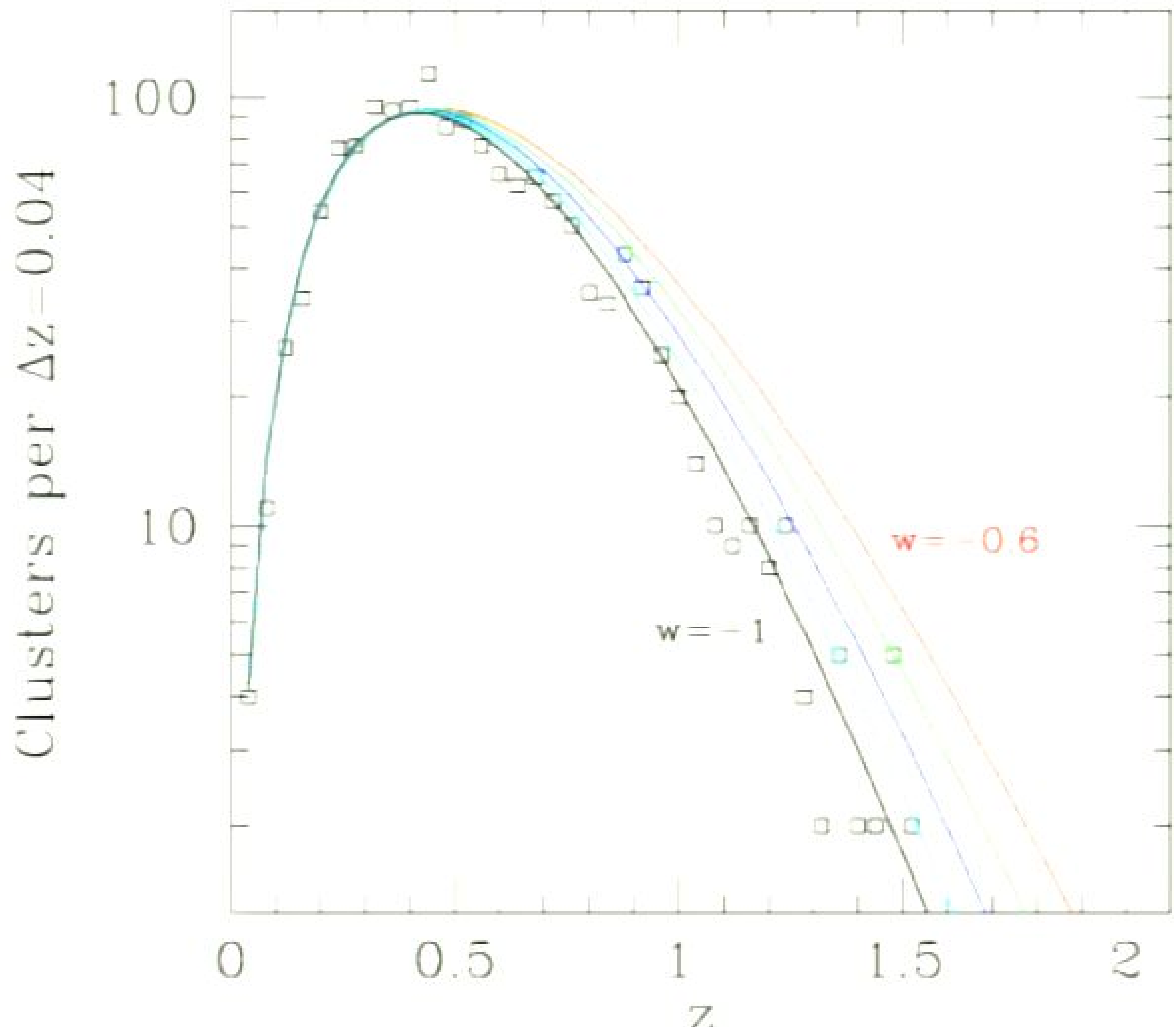
- Physical parameters of early universe very well understood, but late-time parameters less so
- Expected cluster counts uncertain by factor of several due to cosmology



Range in expected SPT cluster counts using WMAP+all MCMC chain (red: masses 25% higher than expected; black: clusters are as I would expect them to be)

Dark Energy with SZ Surveys

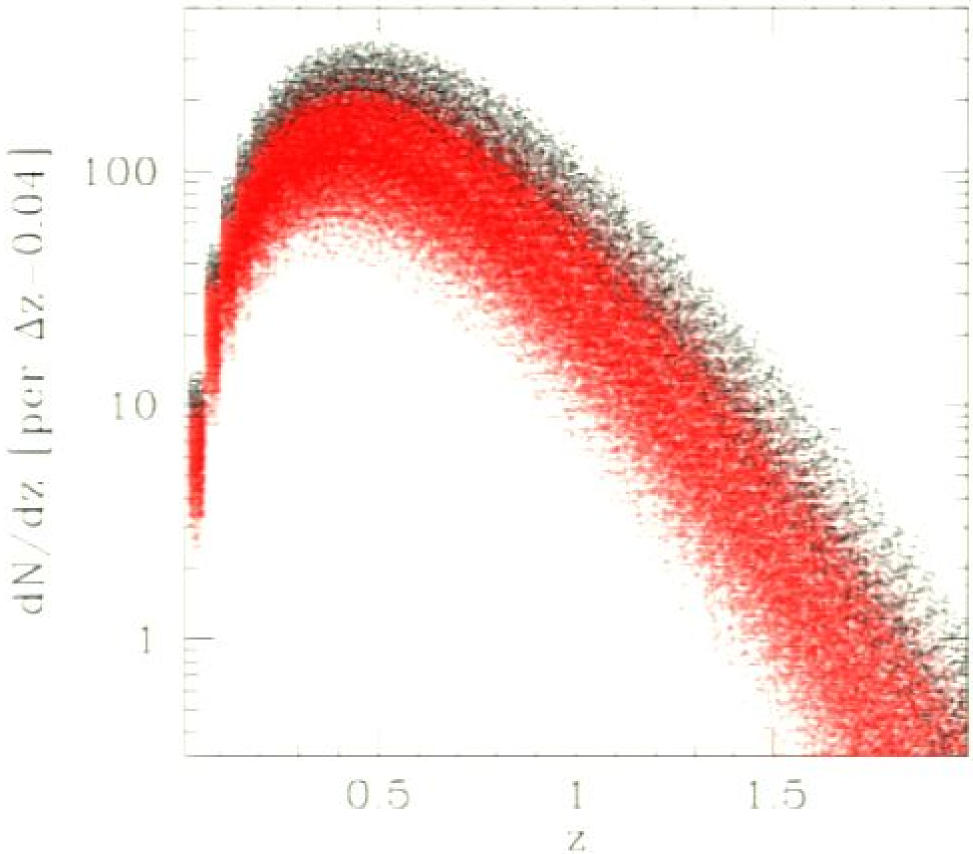
- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity



Predicted SPT counts

Don't We Know Everything Already?

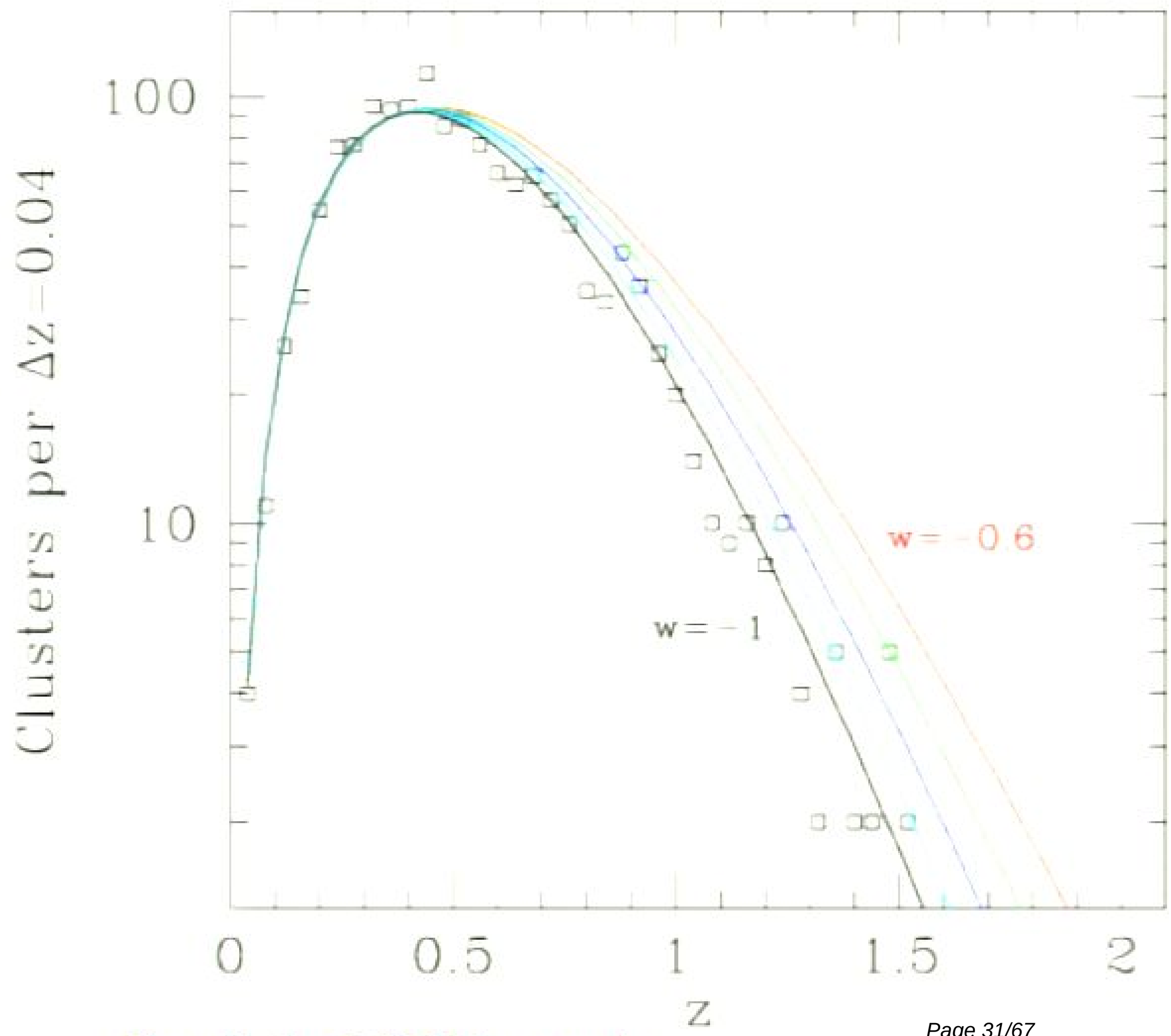
- Physical parameters of early universe very well understood, but late-time parameters less so
- Expected cluster counts uncertain by factor of several due to cosmology



Range in expected SPT cluster counts using WMAP+all MCMC chain (red: masses 25% higher than expected; black: clusters are as I would expect them to be)

Dark Energy with SZ Surveys

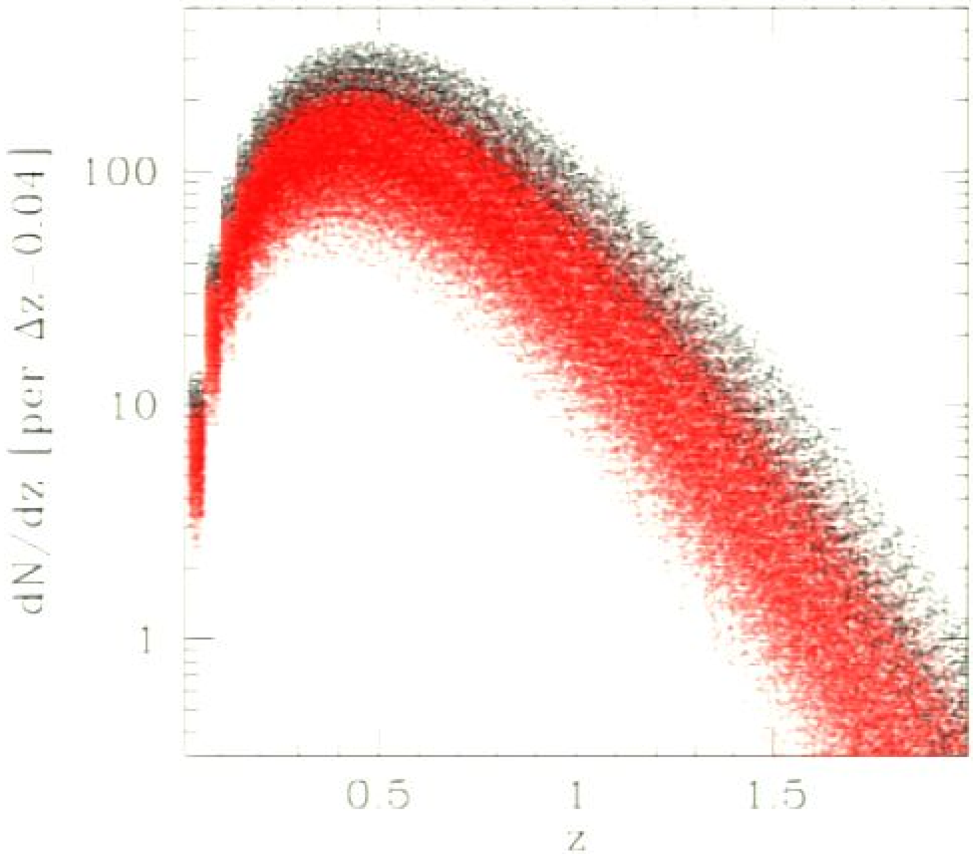
- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity



Predicted SPT counts

Don't We Know Everything Already?

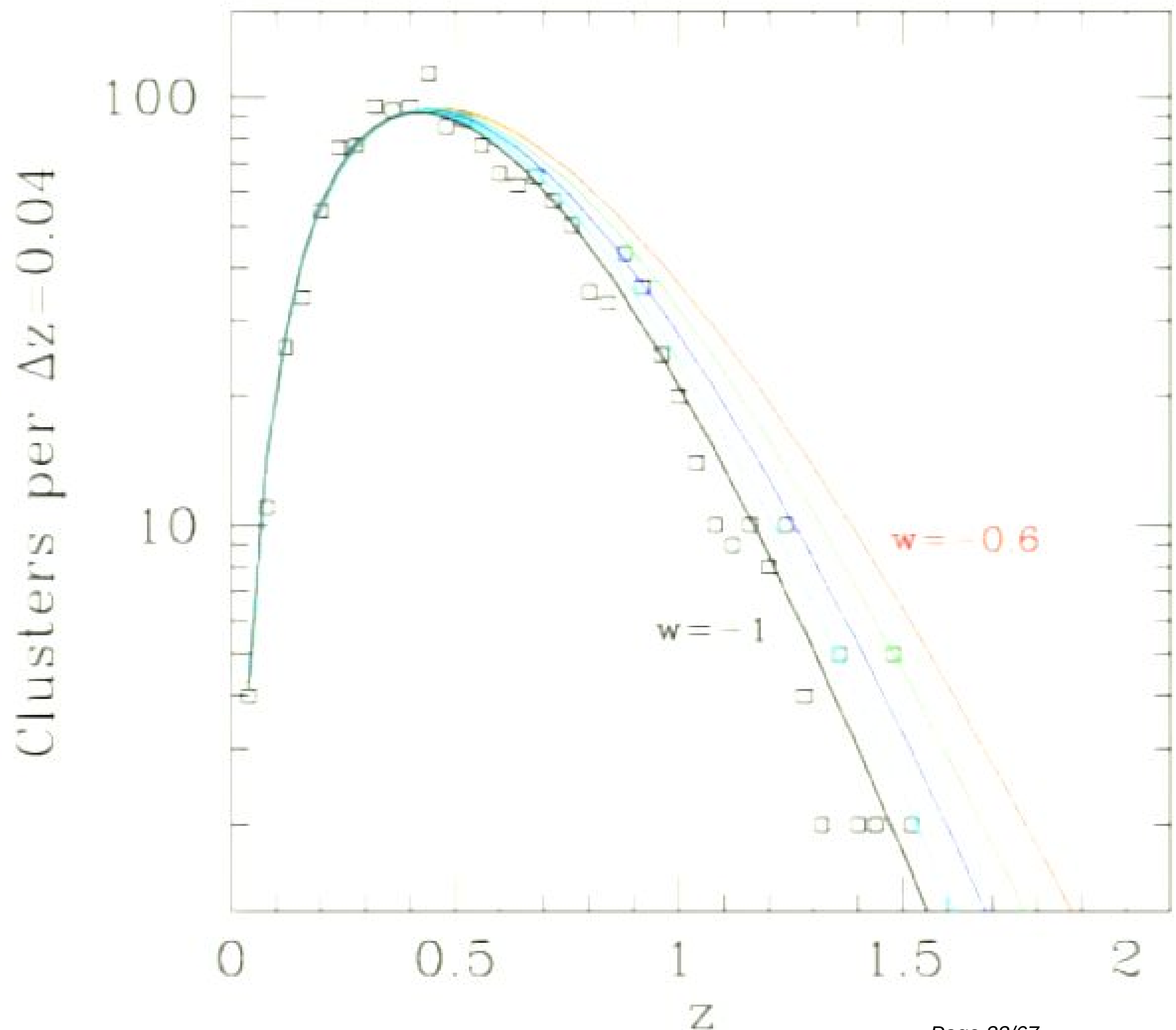
- Physical parameters of early universe very well understood, but late-time parameters less so
- Expected cluster counts uncertain by factor of several due to cosmology



Range in expected SPT cluster counts using WMAP+all MCMC chain (red: masses 25% higher than expected; black: clusters are as I would expect them to be)

Dark Energy with SZ Surveys

- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity



Predicted SPT counts

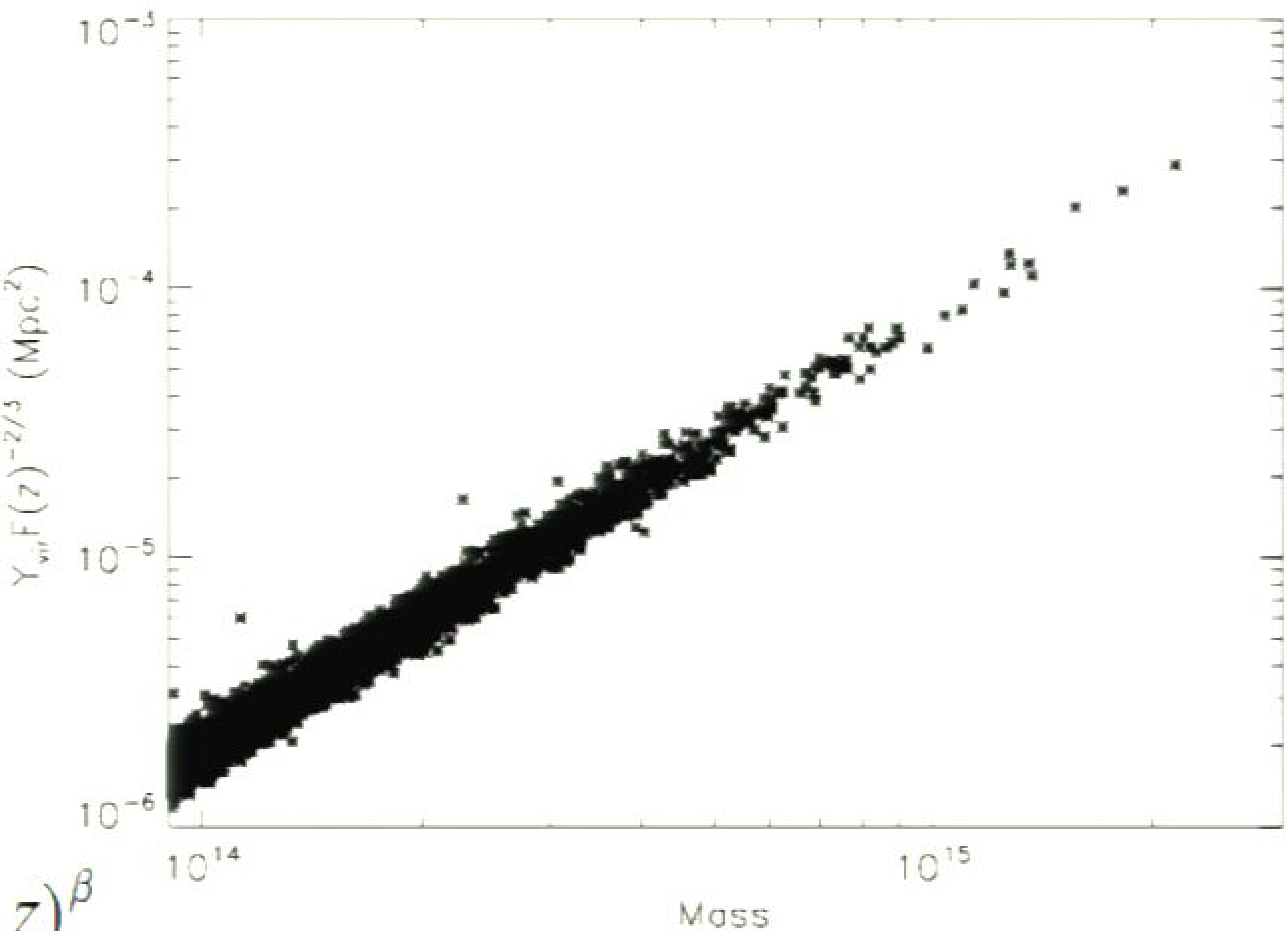
"Self-Calibration"

Assume virial scaling of SZ flux as f(M,z); parameterize deviations as unknown power laws with unknown normalization + unknown scatter

Fit for cluster parameters and marginalize

Majumadar & Mohr ; Lima & Hu

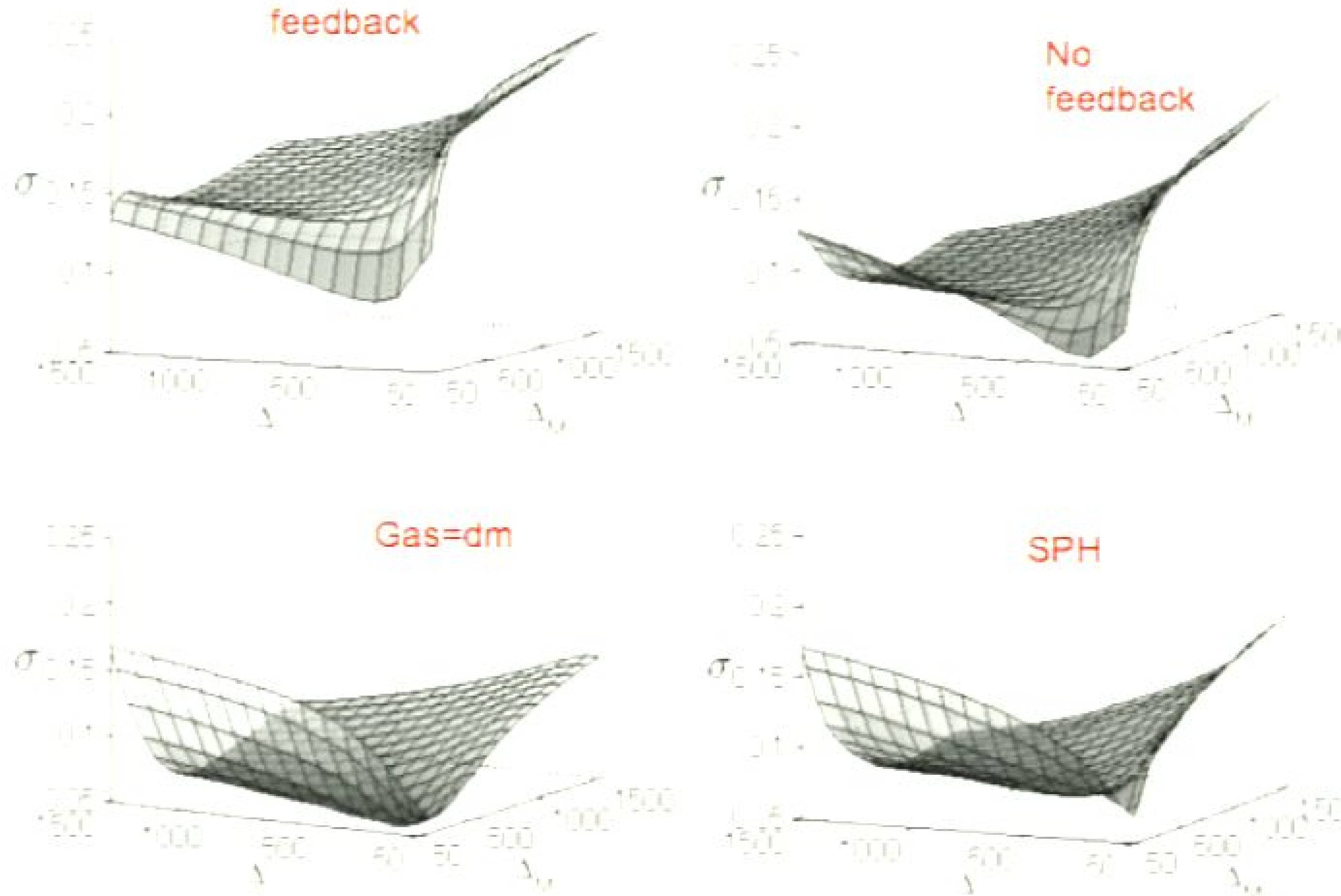
$$Y_{obs} = Y_{theory} A M^{\alpha} (1+z)^{\beta}$$



Hallman et al

Understanding SZ flux

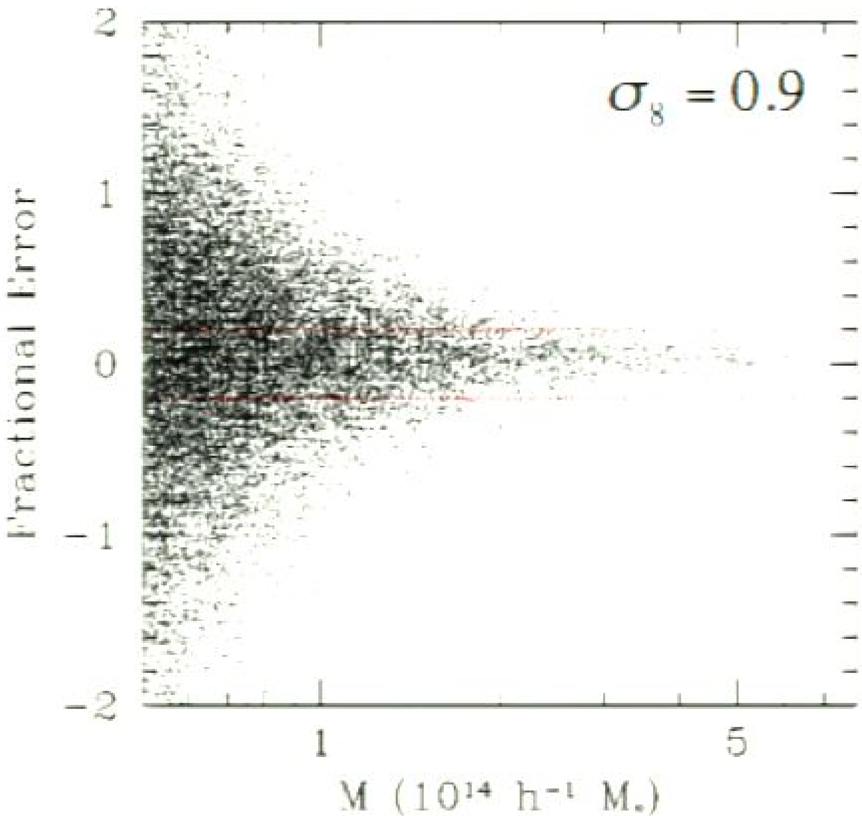
Mapping between SZ integrated flux depends on cluster physics and definitions of "total flux" and "mass"



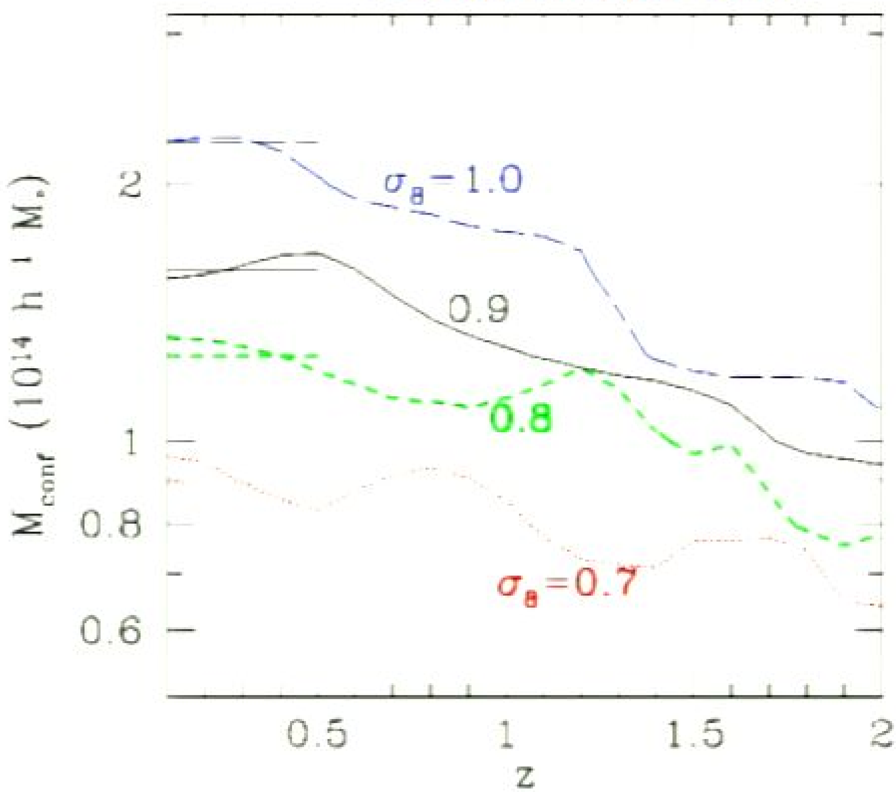
Each plot assumes different physics; within each plot we see scatter vs various "flux" and "mass" definitions

Shaw et al.; see also Afshordi

SZ Confusion



GH, McCarthy, Babul

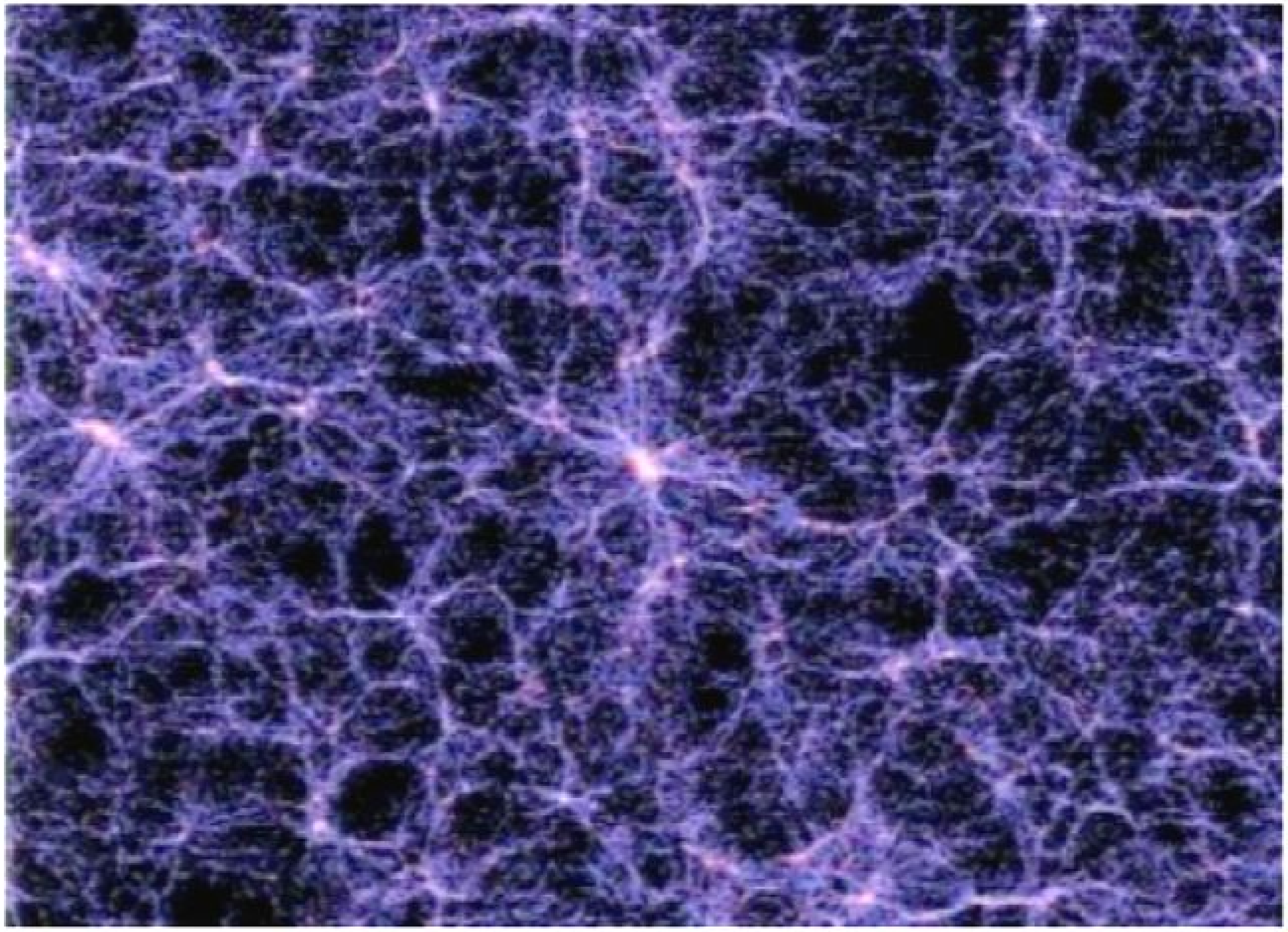


(input-measured)/input for simulated filtered SZ maps

Mass at which rms error is 20%

Assuming single frequency

Clusters are clustered



But wait, there's more…

- Not only were those N objects observed, there were no others
- Recipe to include this: replace all w terms in expressions with a term that includes correlations:

$$W_i(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_i) = \sum_{j=0}^{\infty} \frac{(-n)^j}{j!} \int \ldots \int w_{i+j}(\vec{x}_1, \ldots \vec{x}_{i+j}) dV_{i+1} \ldots dV_{i+j}$$

$$W_0 = nV[-1 + 0.91(nV\bar{\xi}(r)) - 2.2(nV\bar{\xi}(r))^2 + 13(nV\bar{\xi}(r))^3 + \ldots$$

See: White (1979); Dodelson et al (1998)

Astrophysics in the CMB

- Heating/cooling of the intracluster medium messes with SZ effect
- Cluster-correlated radio point sources (totally unknown high frequency behaviour & redshift evolution)
- IR galaxies (a lot of them!)

Gas Physics and the SZ Effect

0.85
degrees
on a side

(McCarthy
et al)

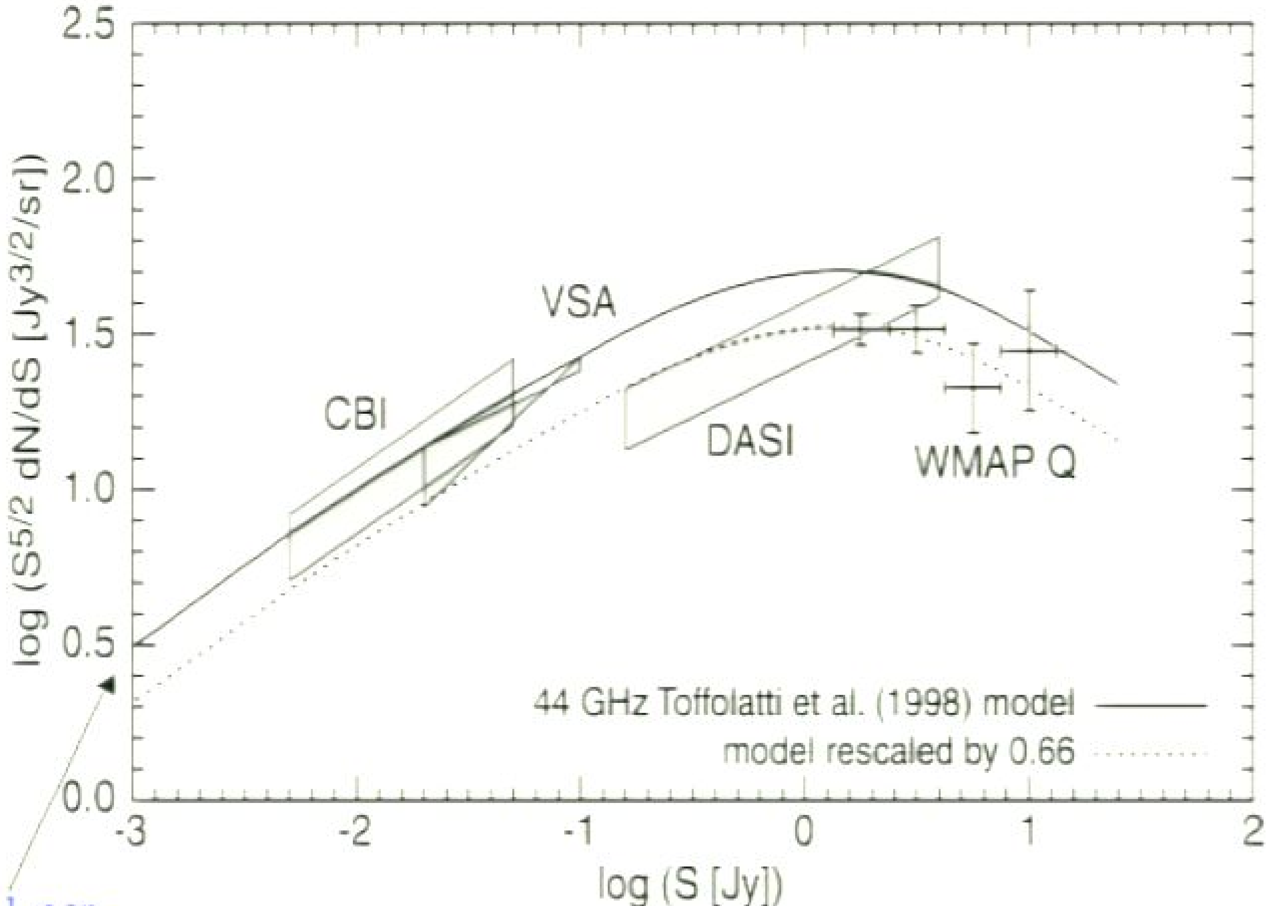
no AGN feedback strong AGN feedback

- Adding entropy to the intracluster medium has strong impact on maps

What About Radio Galaxies?

• random Poisson radio source almost certainly not a problem at 150 GHz and above

• *correlated* (central cD, etc.) radio sources could be a problem, depending on spectral index [SZA will be handy]



~ 0.01 per square arcminute

Bennett et al (2003) [WMAP foregrounds paper]

Galaxy Cluster Radio Sources

- highly uncertain at high frequencies
- highly uncertain at z>0.2
- best guess estimates: few % of clusters may be affected

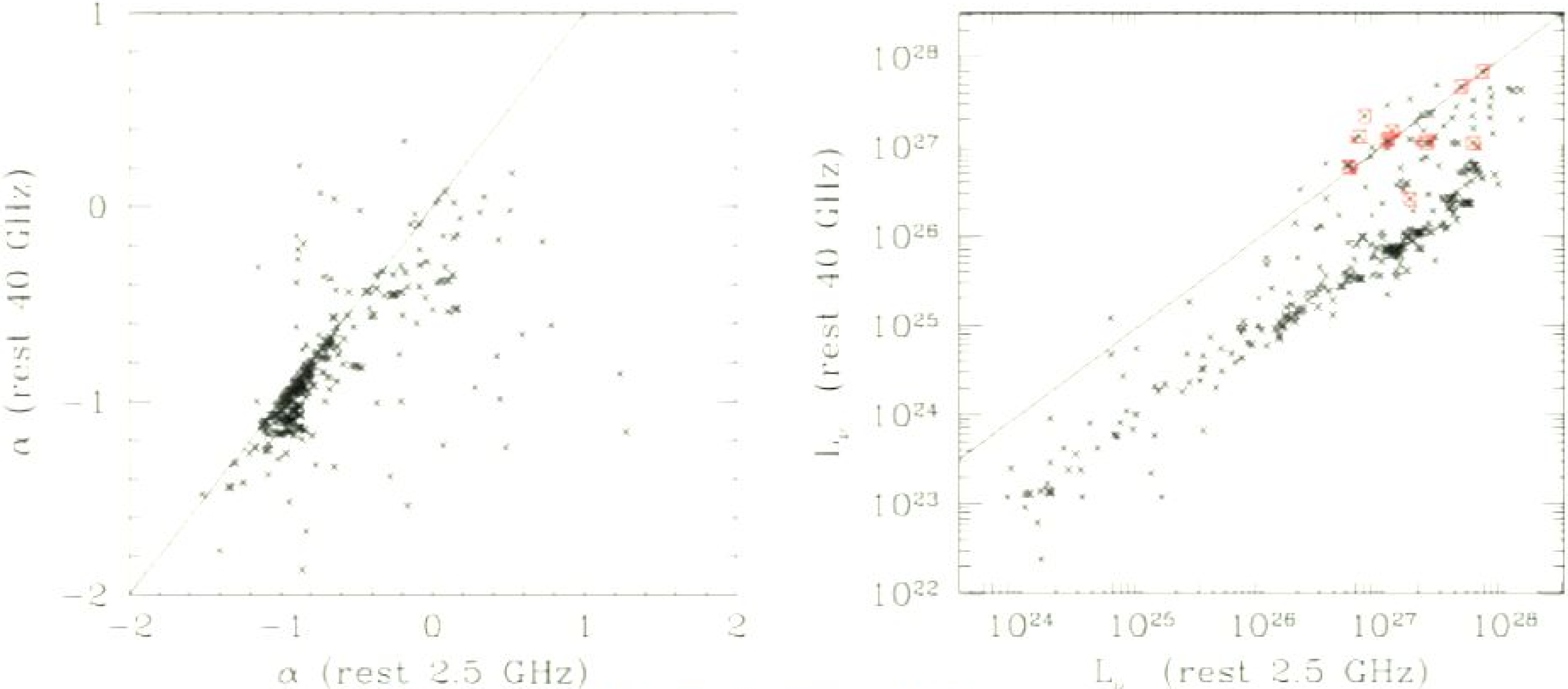
Roughly one bright radio source per cluster at 1.4 GHz

Fraction of bright gals w/ radio source

FIG. 8.—Rich [illegible] and low redshifts. The open di[illegible] two component power law model are the low-z RLF from Ledlow & Owen (1996). The open squares are the high-z points from this paper. As discussed in the text, the lowest power, high-z point is severely affected by incompleteness, and the second lowest power point may be somewhat affected (see text for details). Otherwise, the agreement between the high- and low-z RLFs is very good.

Stocke et al 1999

Extrapolating Radio Sources



Red squares: flat or rising spectra a 40 GHz

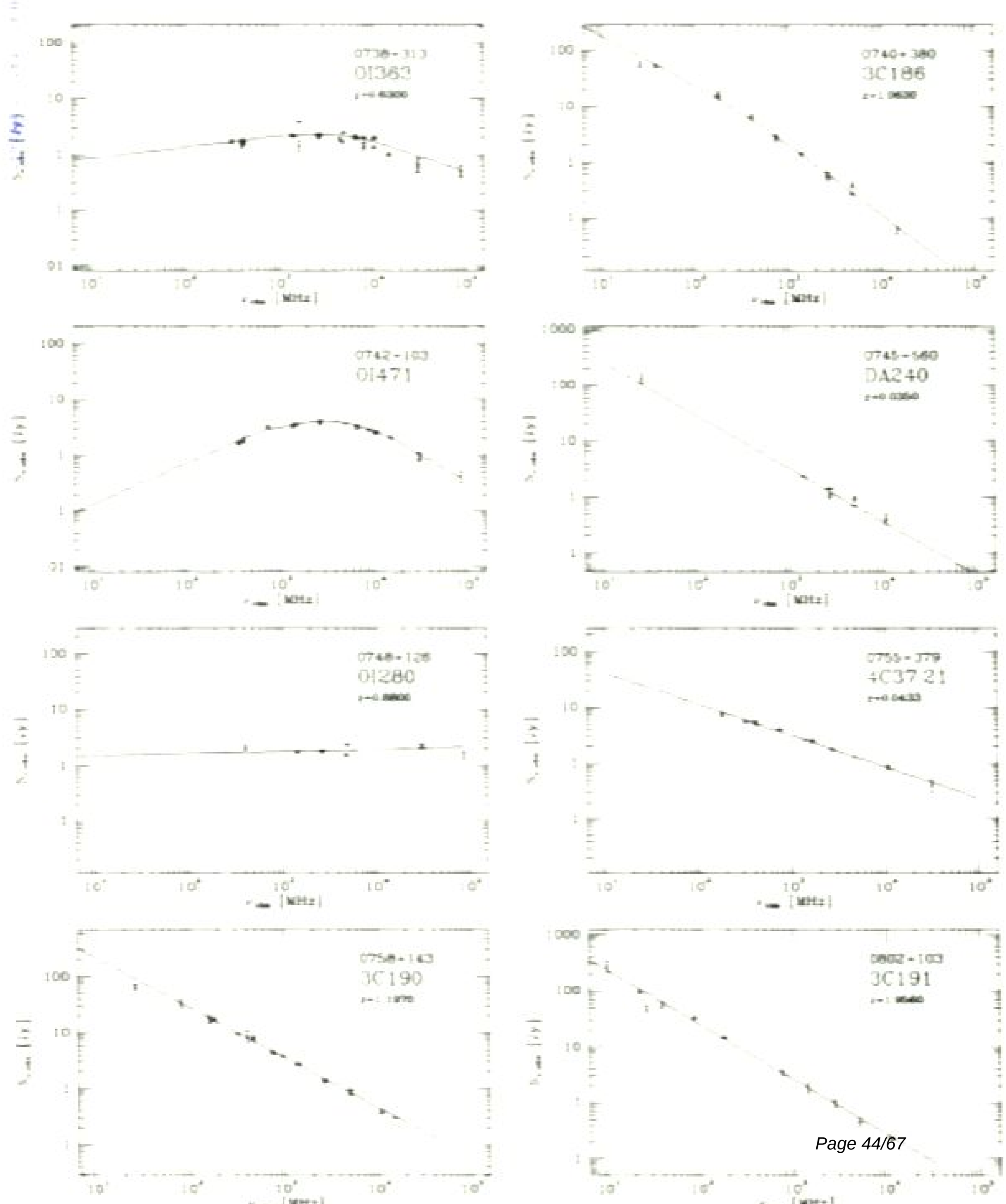
Data from Herbig & Readhead 1992

Bottom line: a few % of radio sources should be as bright at high frequencies as at 1.4 GHz => few % of clusters will have radio sources bright at high frequencies

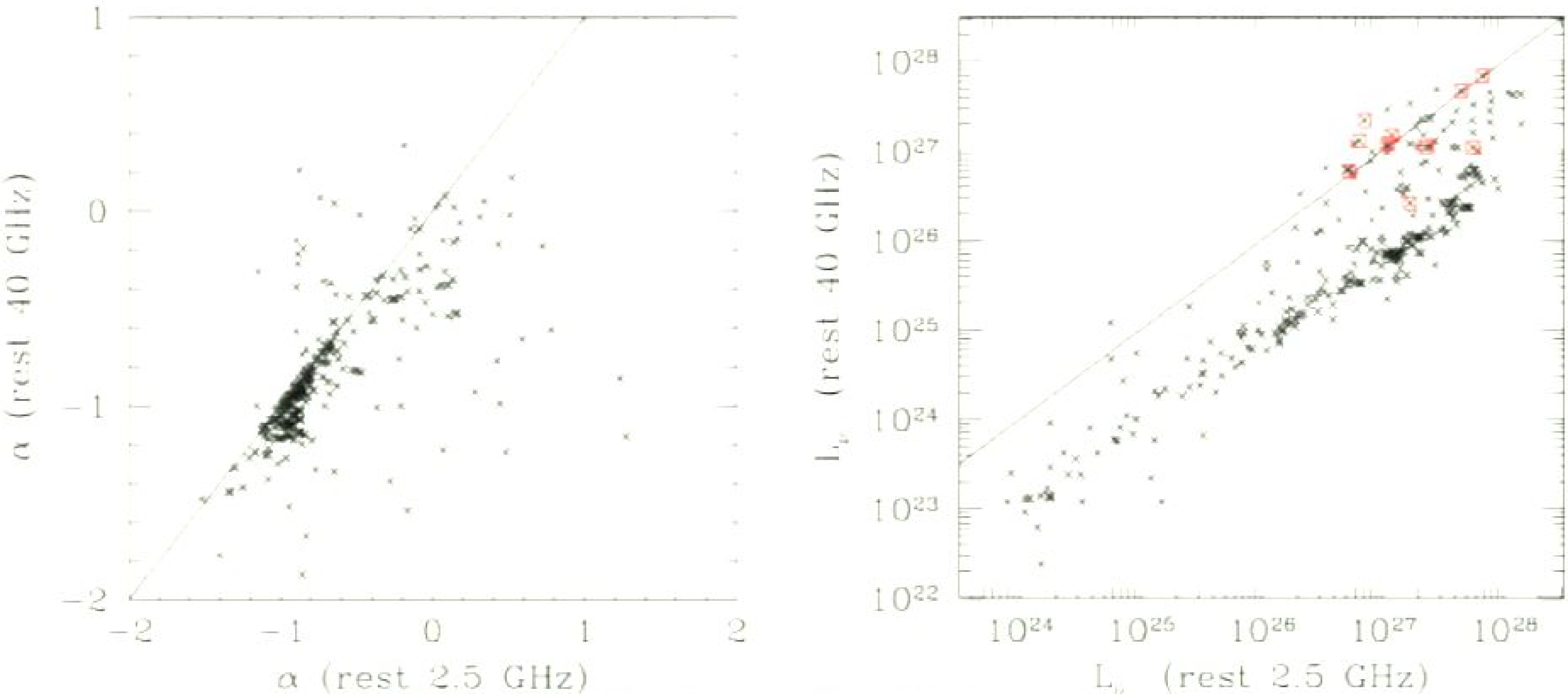
Radio Source Spectra

[a public service announcement]

- non-trivial spectra (e.g., Herbig & Readhead 1992)
- Need more data at low fluxes and high frequencies (lots of data at 1.4 GHz)
- simple observational question that is now being answered…



Extrapolating Radio Sources



Red squares: flat or rising spectra a 40 GHz

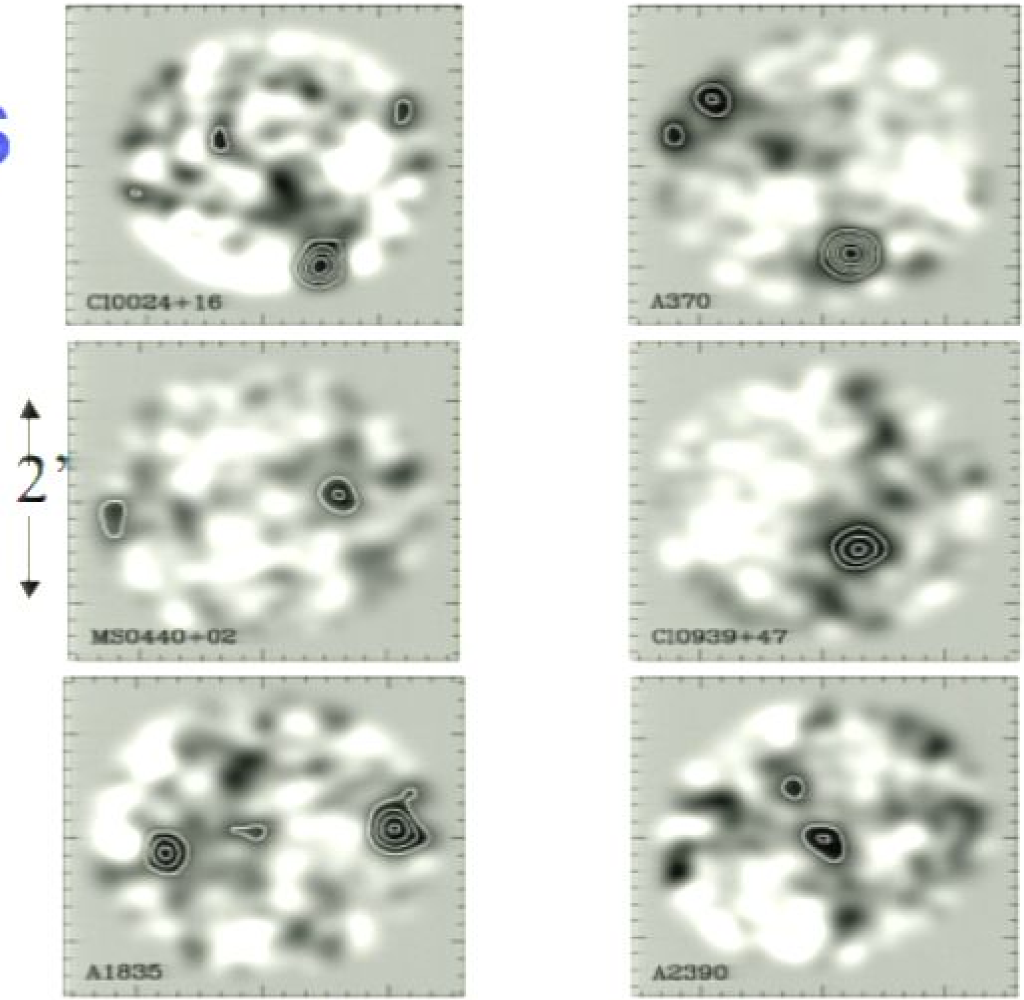
Data from Herbig & Readhead 1992

Bottom line: a few % of radio sources should be as bright at high frequencies as at 1.4 GHz => few % of clusters will have radio sources bright at high frequencies

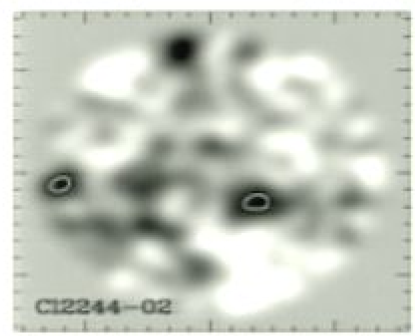
Dusty Galaxies in Clusters

- *Many massive clusters have significant point sources at 850 um (350 GHz)*
- <u>1 mJy at 150 GHz in a 1' beam => ~ 30 uK</u>
- *How well can these be subtracted?*
- ***Not a problem for ALMA***

(30 σ in 60 seconds)



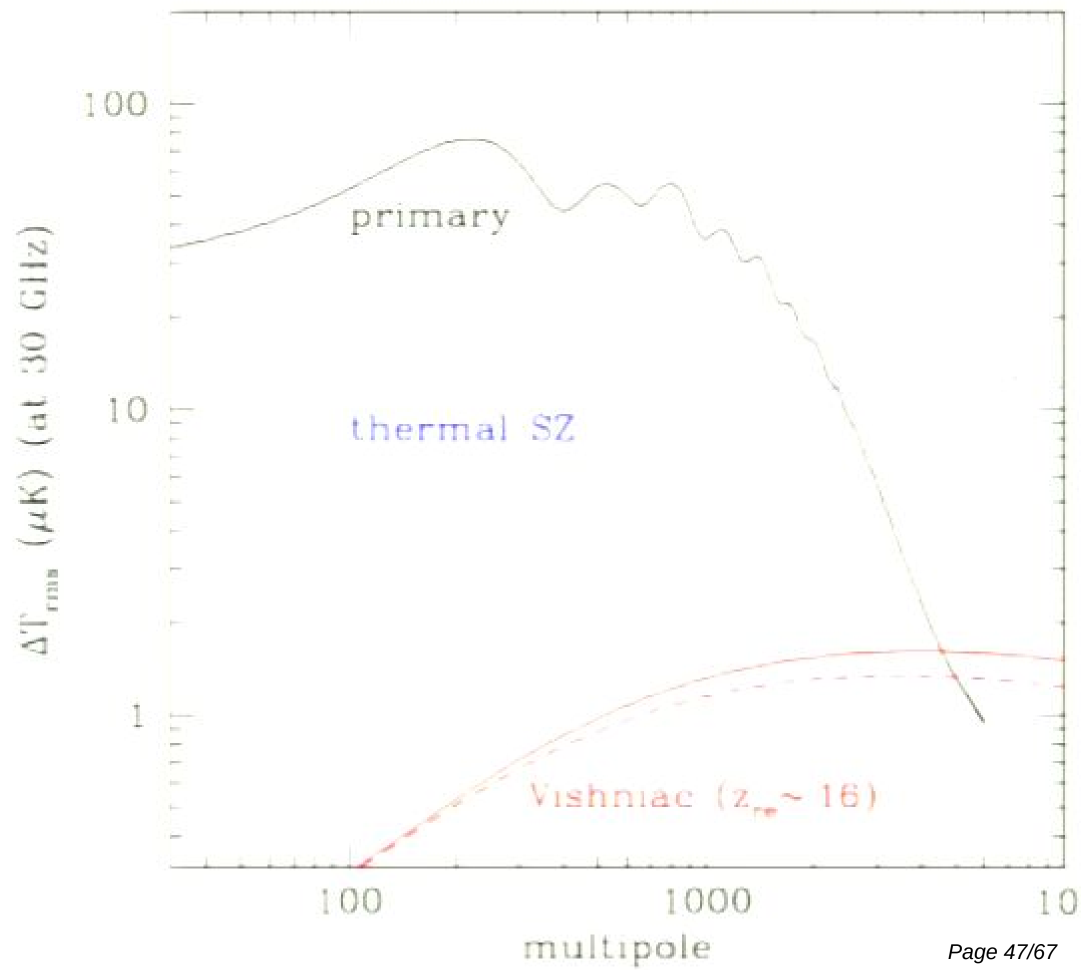
Several mJy fluxes at 350 GHz



Smail et al (2002)

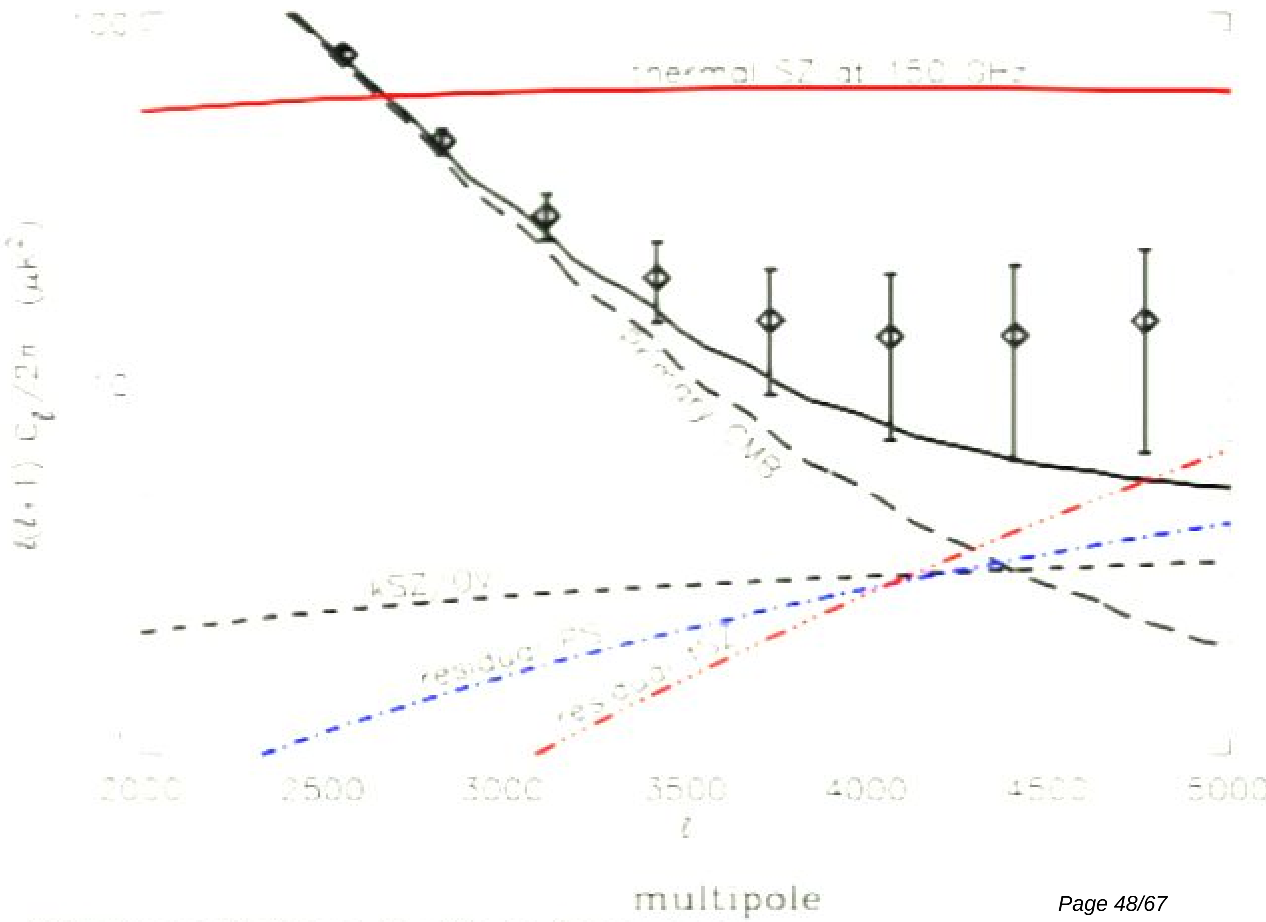
Fine Scale CMB anisotropy

- SPT is sample variance limited over 4000 square degrees every month to ℓ~2000



Fine Scale CMB anisotropy

- SPT is sample variance limited over 4000 square degrees every month to ℓ~2000

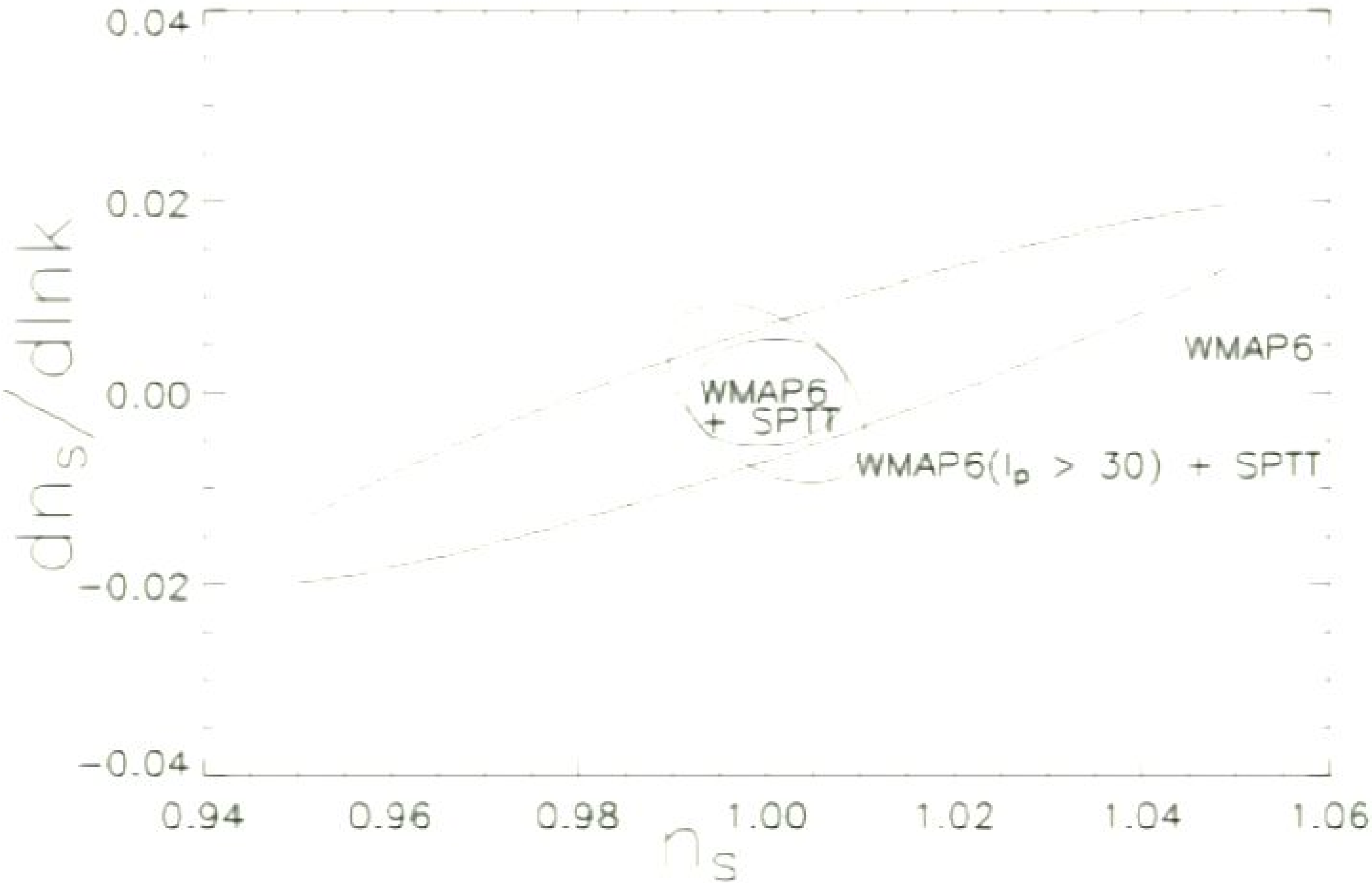


SPT predictions by Tom Crawford

Matter power spectrum

Small scales provide long lever on P(k) measurements

Provides strong constraints on inflation models

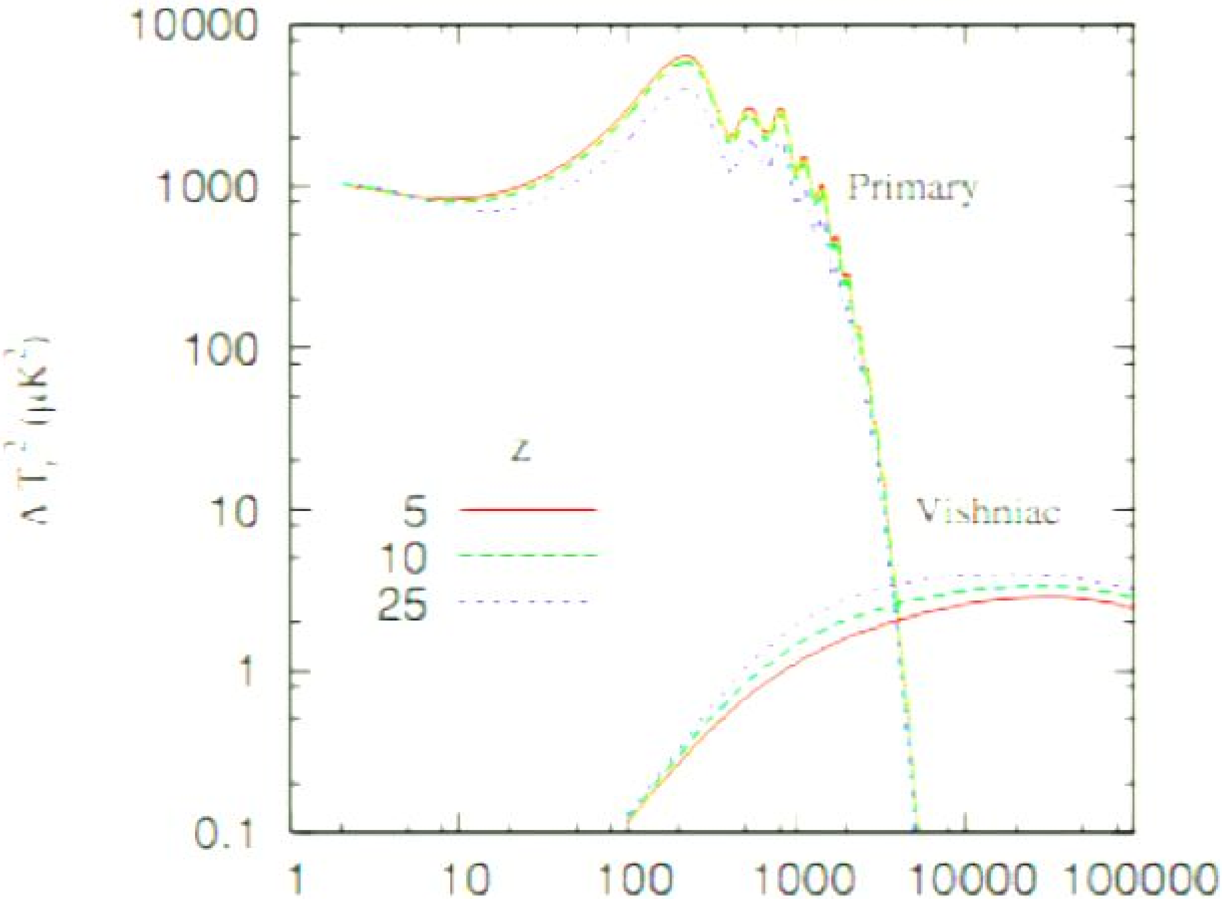


Lloyd Knox

Reionization signatures in the CMB

- Simplest is Vishniac effect: free electrons with non-zero velocities and density fluctuations

Varying z of reionization

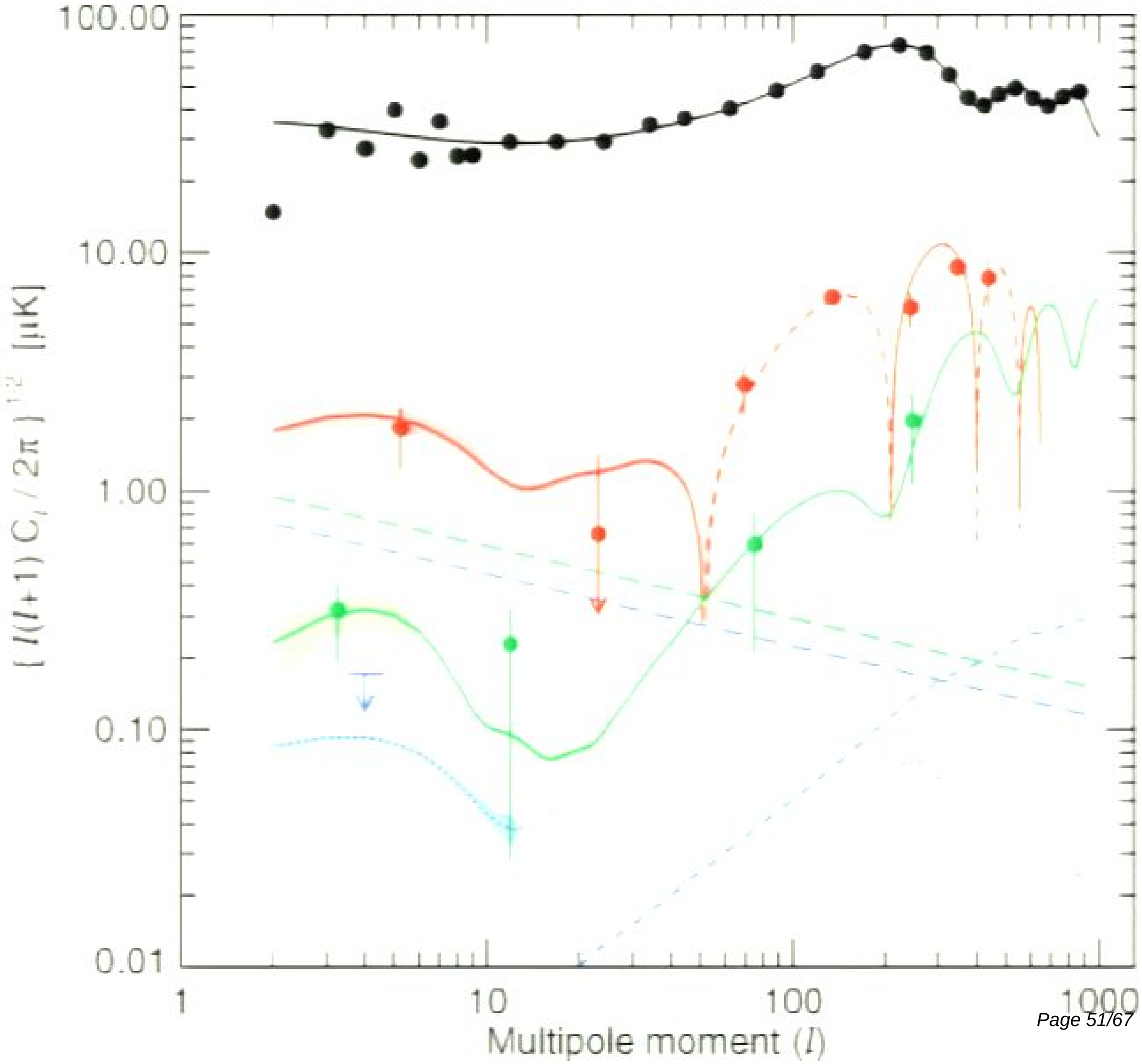


Dudley-MSc thesis

CMB Polarization

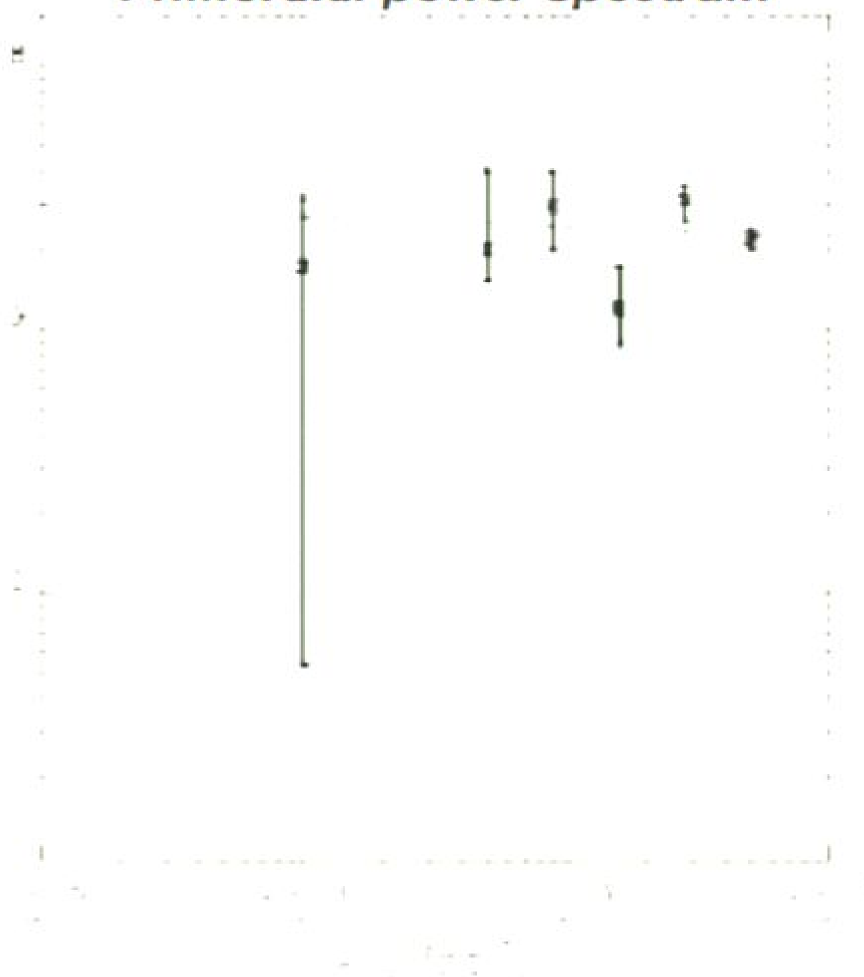
quadrupole
anisotropy
+
Thomson
scattering

=polarization



Interplay between Power spectrum reconstruction and reionization studies

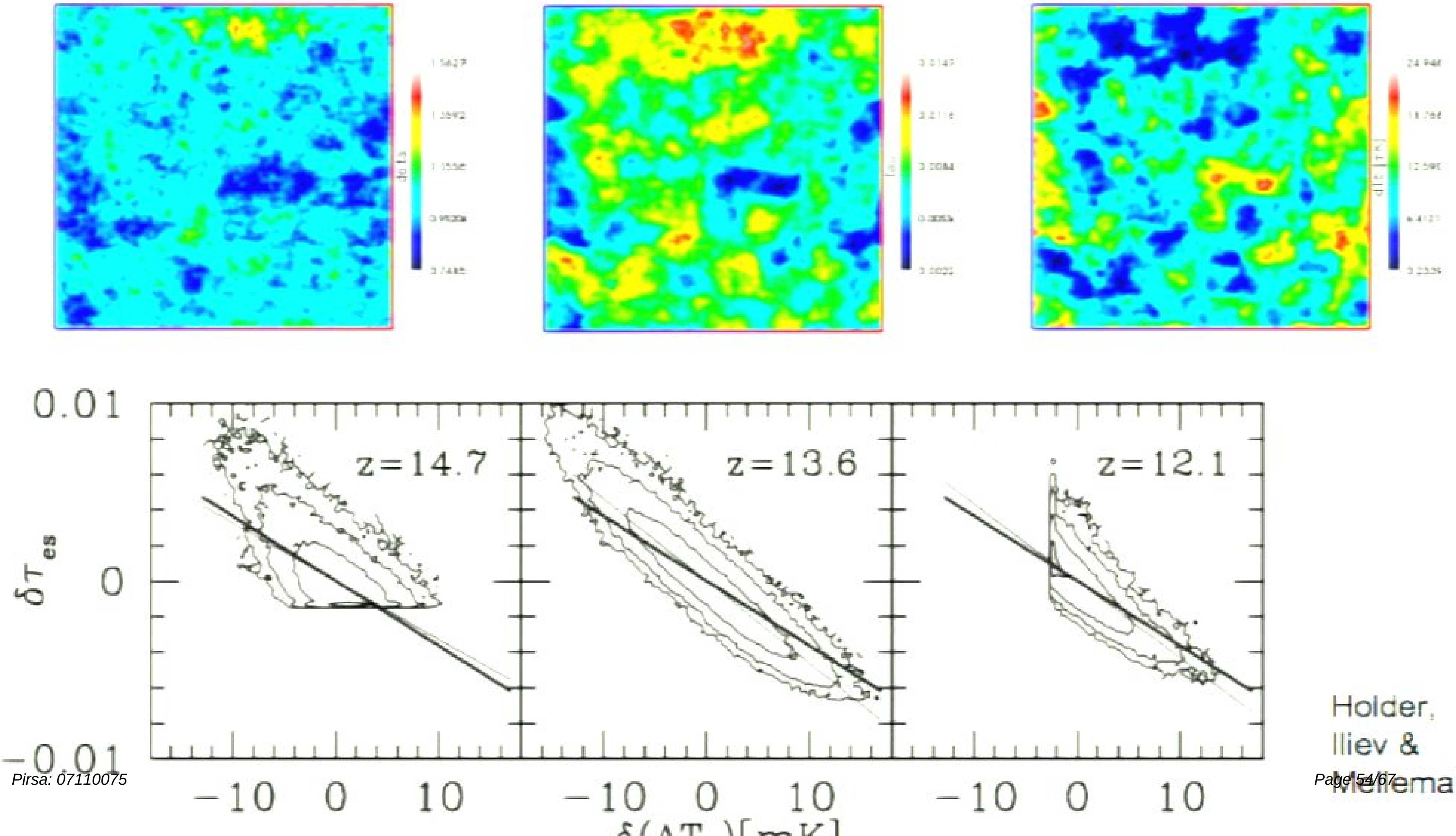
- Low CMB quadrupole precipitated rash of P(k) reconstruction
- Rescattered CMB sourced by P(k) => How well can we measure reionization?



Remote quadrupole measurements

- Ionized bubbles during reionization lead to small scale CMB polarization signal
- Bubbles show up as holes in redshifted 21cm emission
- Cross-correlation gives direct measure of amplitude and direction of quadrupole at the position of the bubble

Thomson optical depth/21cm anti-correlation



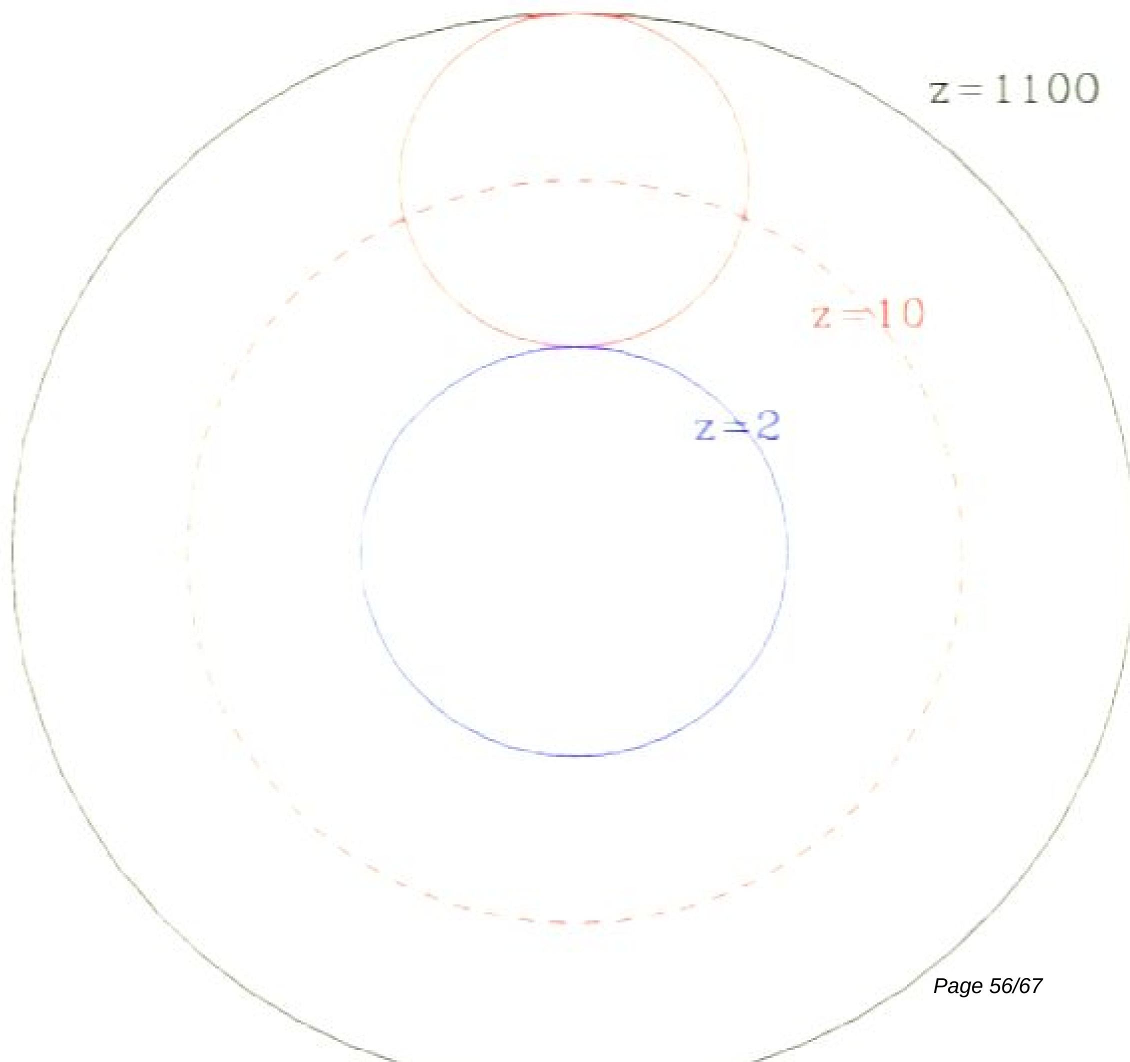
Holder, Iliev & Mellema

Remote quadrupole measurements

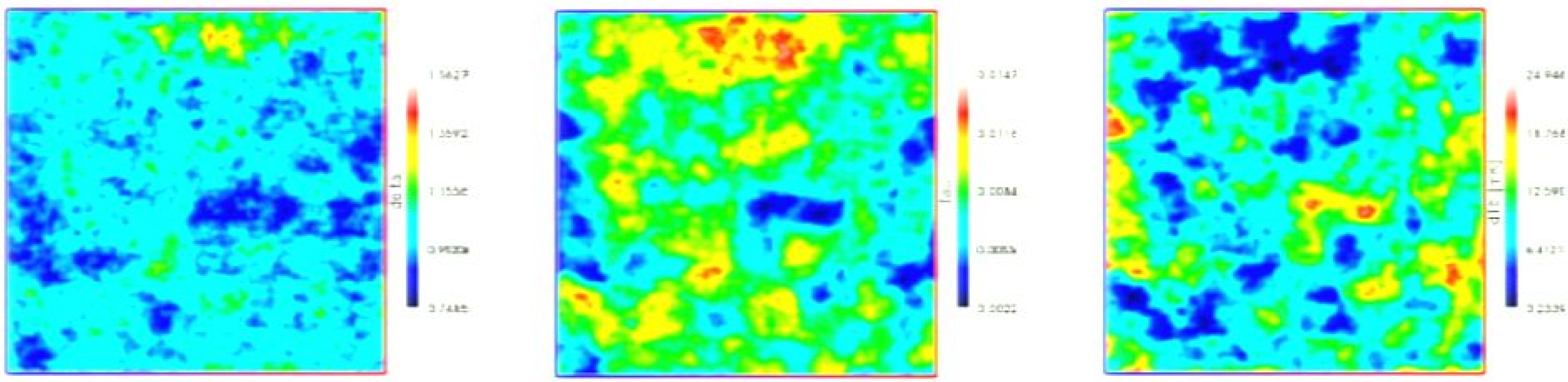
- Ionized bubbles during reionization lead to small scale CMB polarization signal
- Bubbles show up as holes in redshifted 21cm emission
- Cross-correlation gives direct measure of amplitude and direction of quadrupole at the position of the bubble

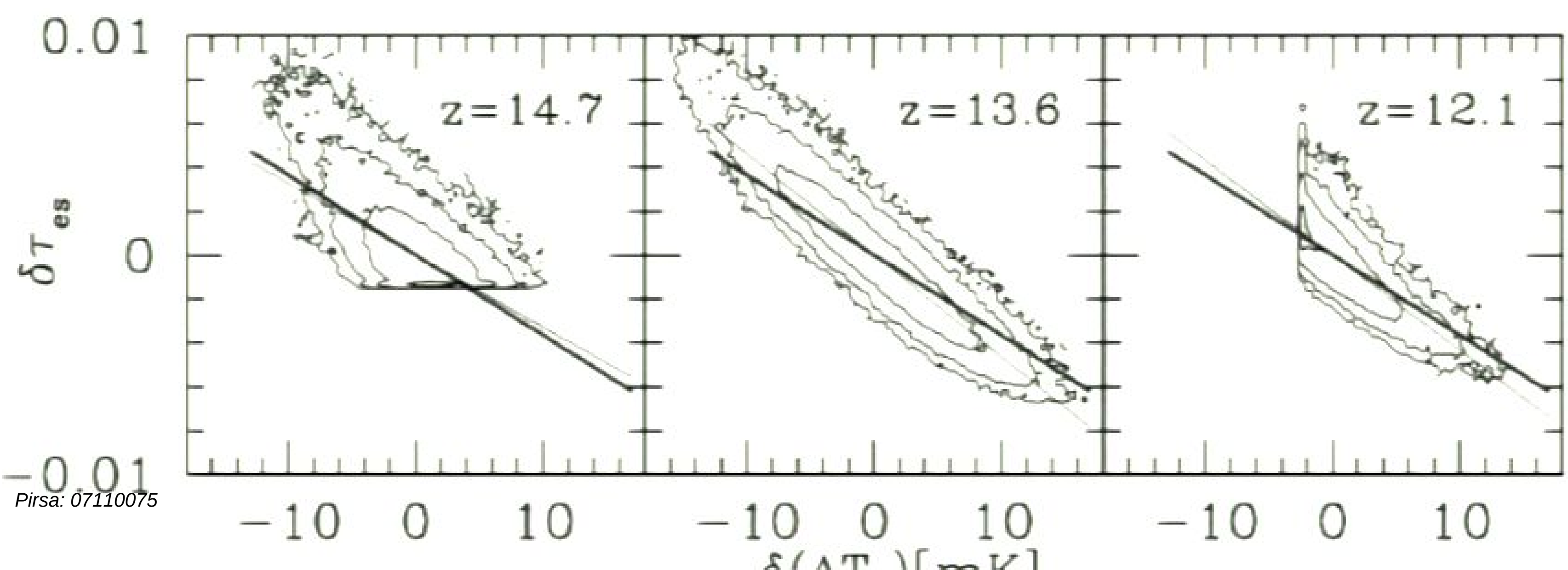
The benefits of alien collaborators at z~10

- Surface of last scattering at z=10 has little overlap with ours
- More than 1/2 of signal from "dark ages"
- Good enough data over large patch of sky allows reconstruction of "initial conditions" for most of Hubble volume
- **Needs polarized 0.1 uK on arcminute scales and mK redshifted 21 cm**



Thomson optical depth/21cm anti-correlation





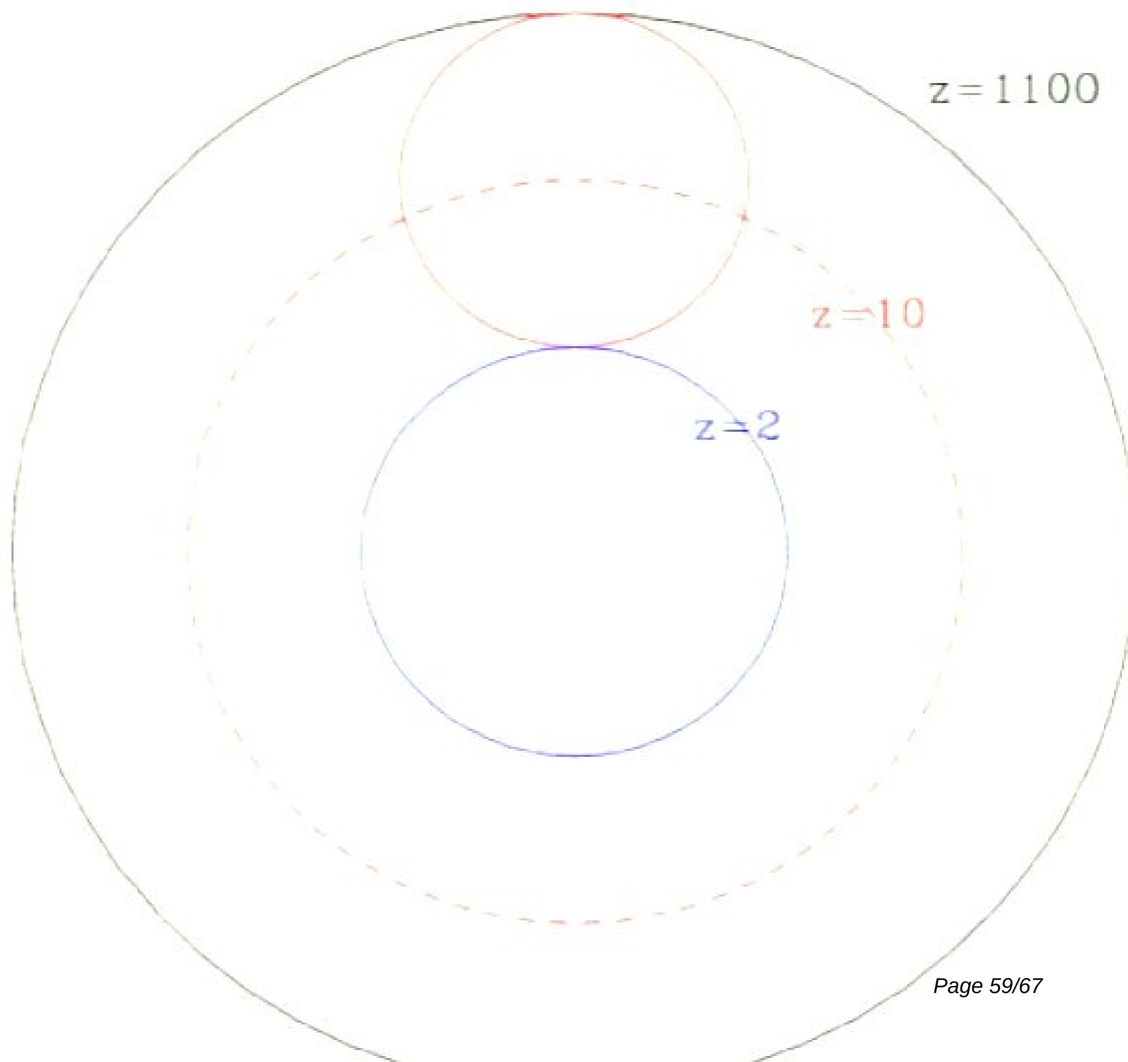
Holder, Iliev & Mellema

Remote quadrupole measurements

- Ionized bubbles during reionization lead to small scale CMB polarization signal
- Bubbles show up as holes in redshifted 21cm emission
- Cross-correlation gives direct measure of amplitude and direction of quadrupole at the position of the bubble

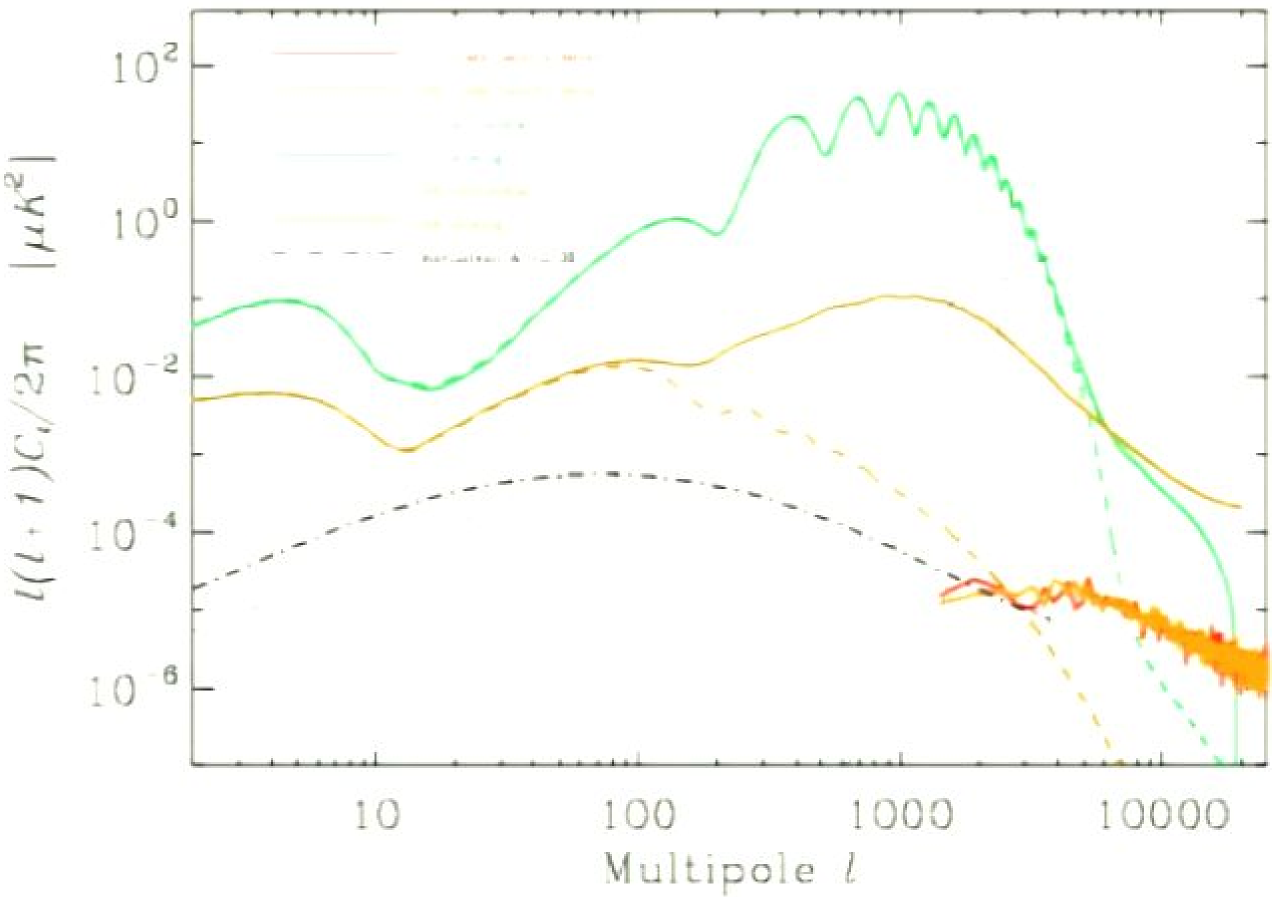
The benefits of alien collaborators at z~10

- Surface of last scattering at z=10 has little overlap with ours
- More than 1/2 of signal from "dark ages"
- Good enough data over large patch of sky allows reconstruction of "initial conditions" for most of Hubble volume
- **Needs polarized 0.1 uK on arcminute scales and mK redshifted 21 cm**



CMB Pol. & Patchy Reionization

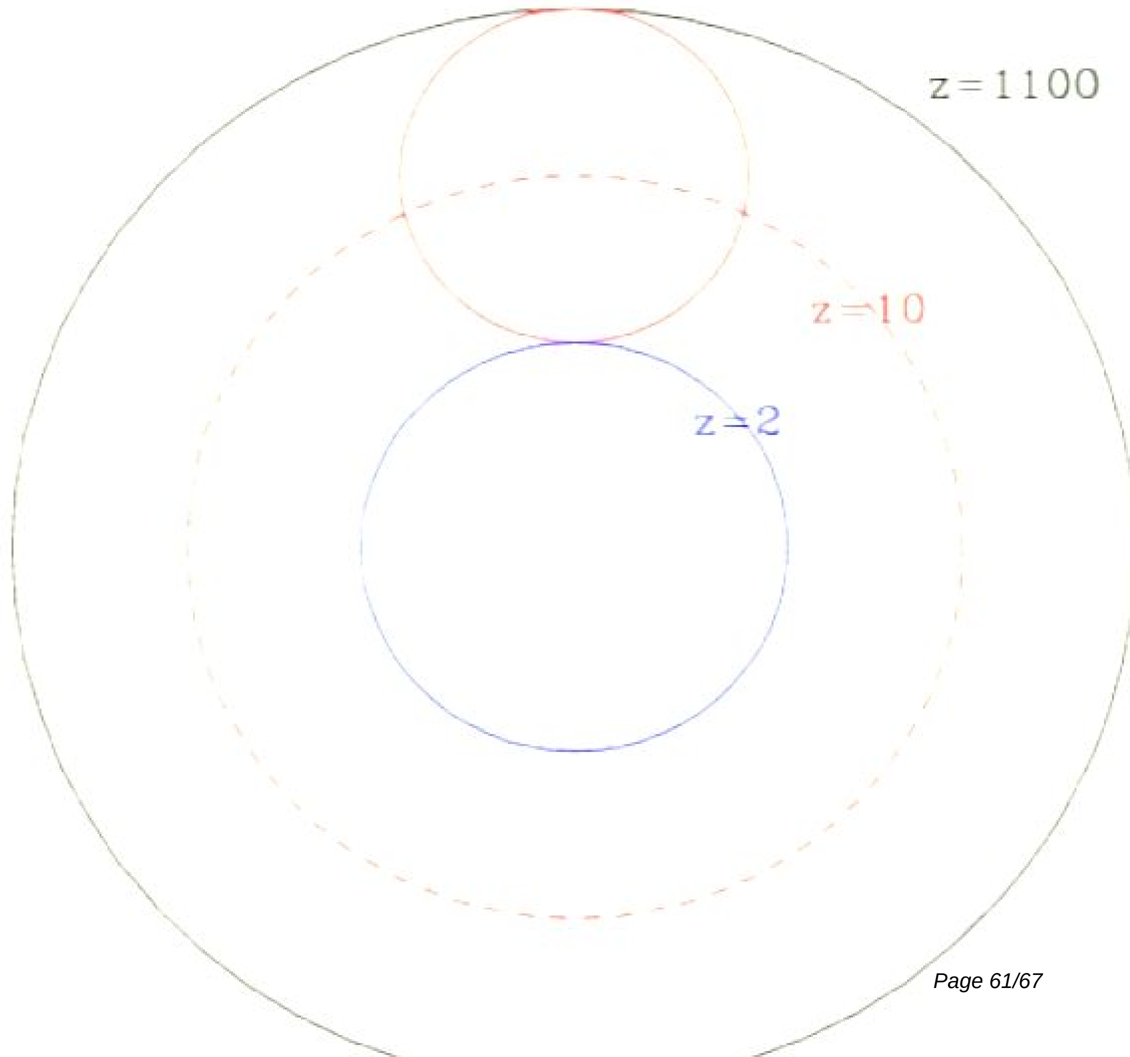
- Unlikely to be a problem for inflation B modes



Dore et al

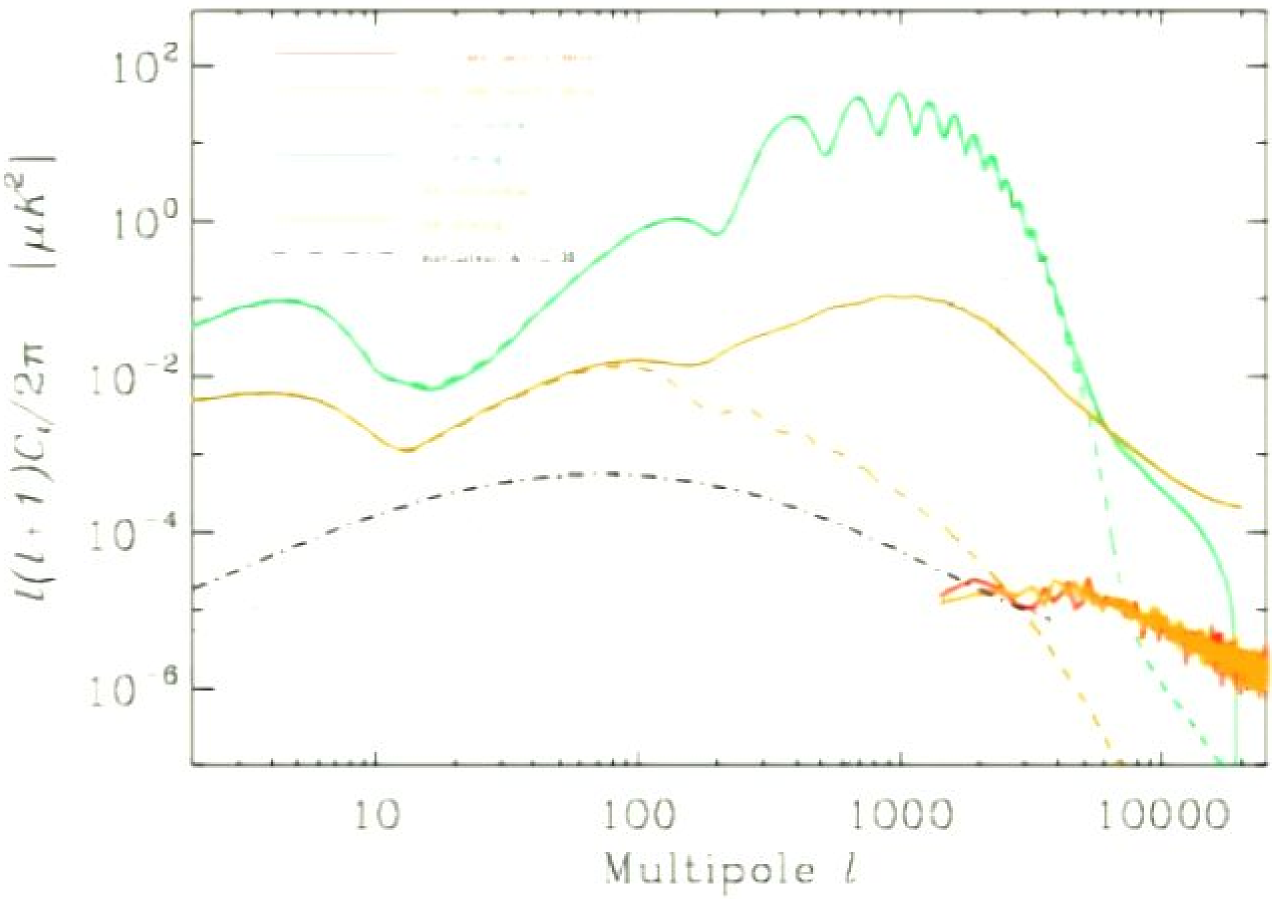
The benefits of alien collaborators at z~10

- Surface of last scattering at z=10 has little overlap with ours
- More than 1/2 of signal from "dark ages"
- Good enough data over large patch of sky allows reconstruction of "initial conditions" for most of Hubble volume
- **Needs polarized 0.1 uK on arcminute scales and mK redshifted 21 cm**



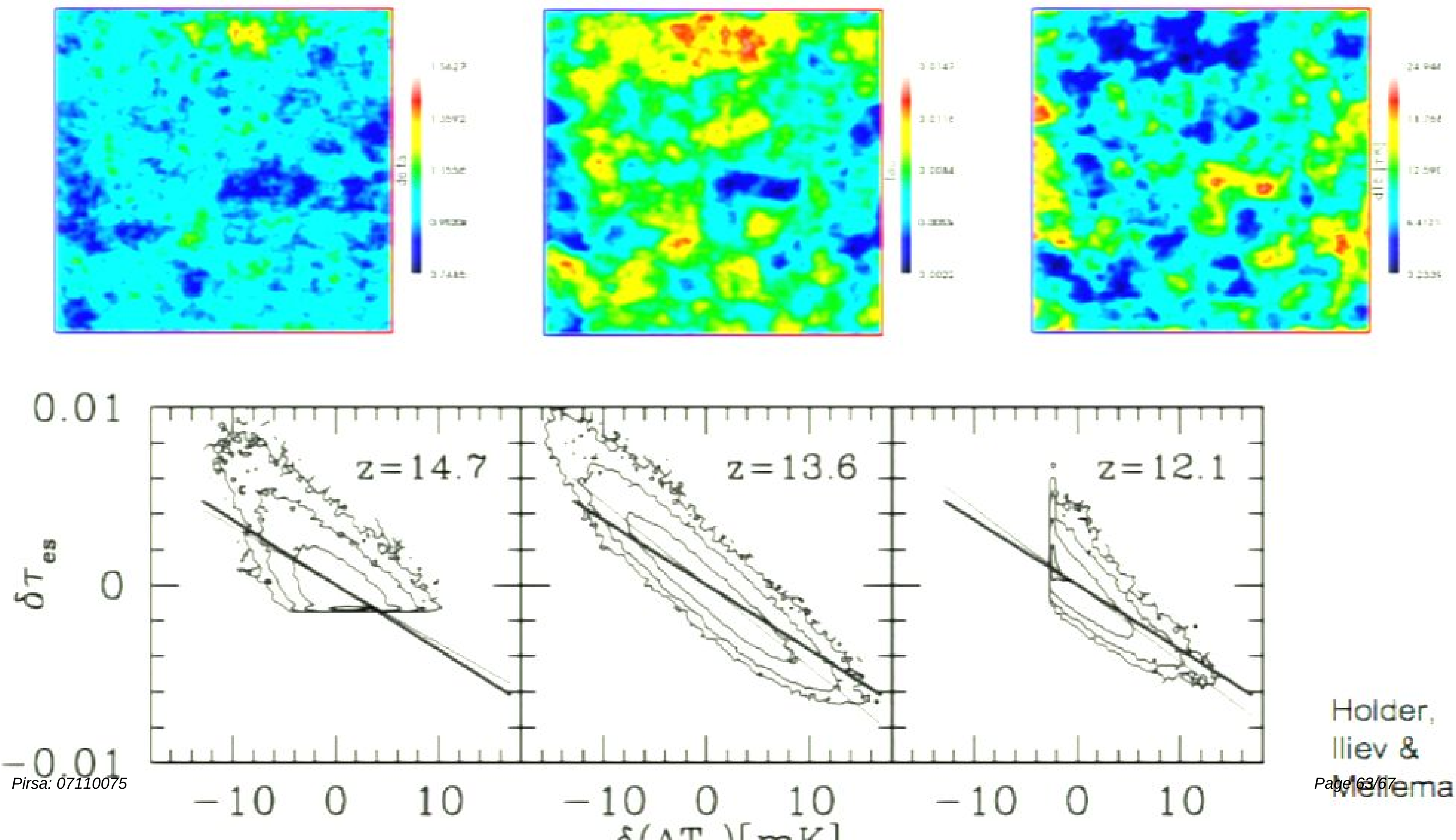
CMB Pol. & Patchy Reionization

- Unlikely to be a problem for inflation B modes



Dore et al

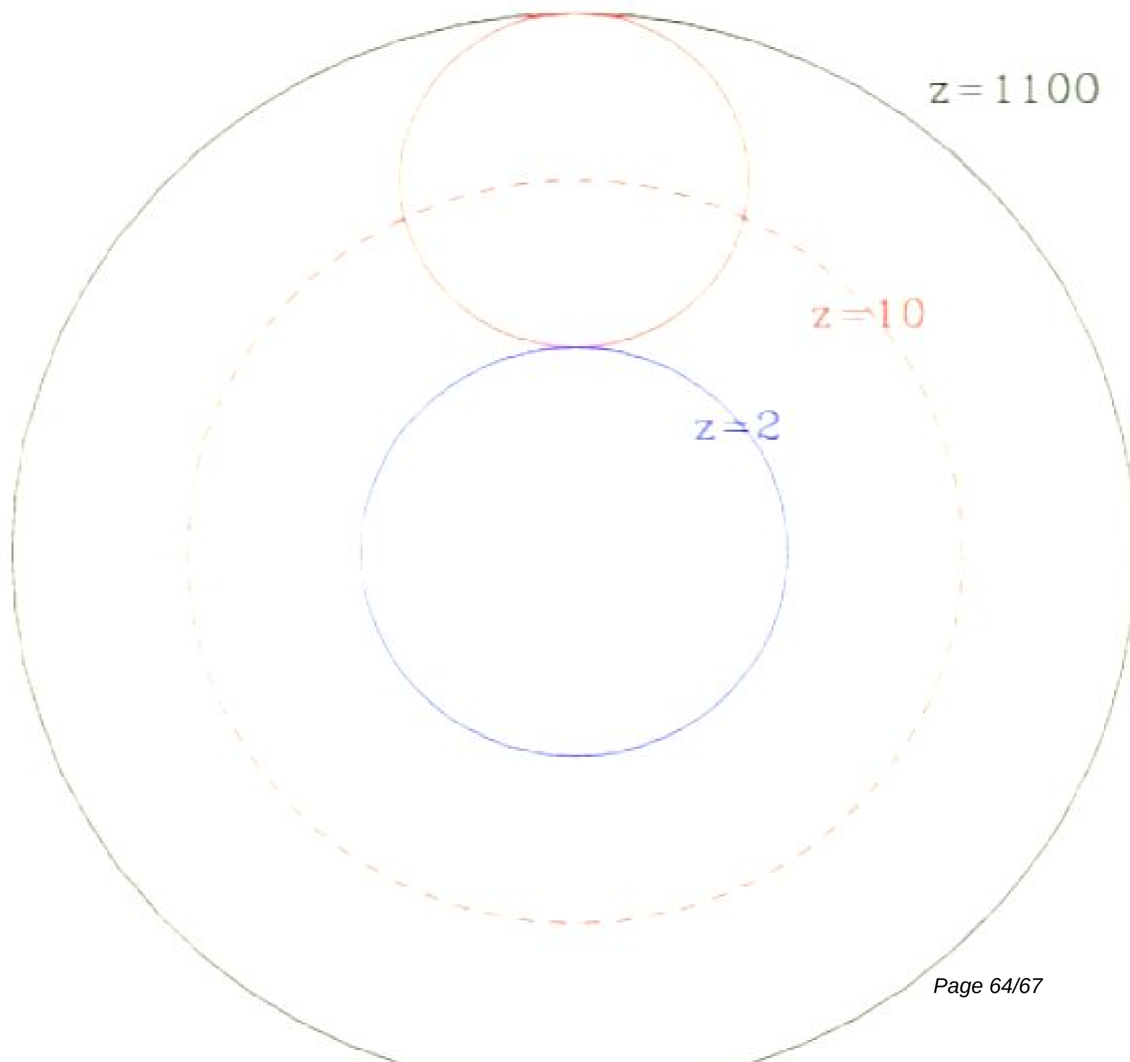
Thomson optical depth/21cm anti-correlation



Holder, Iliev & Mellema

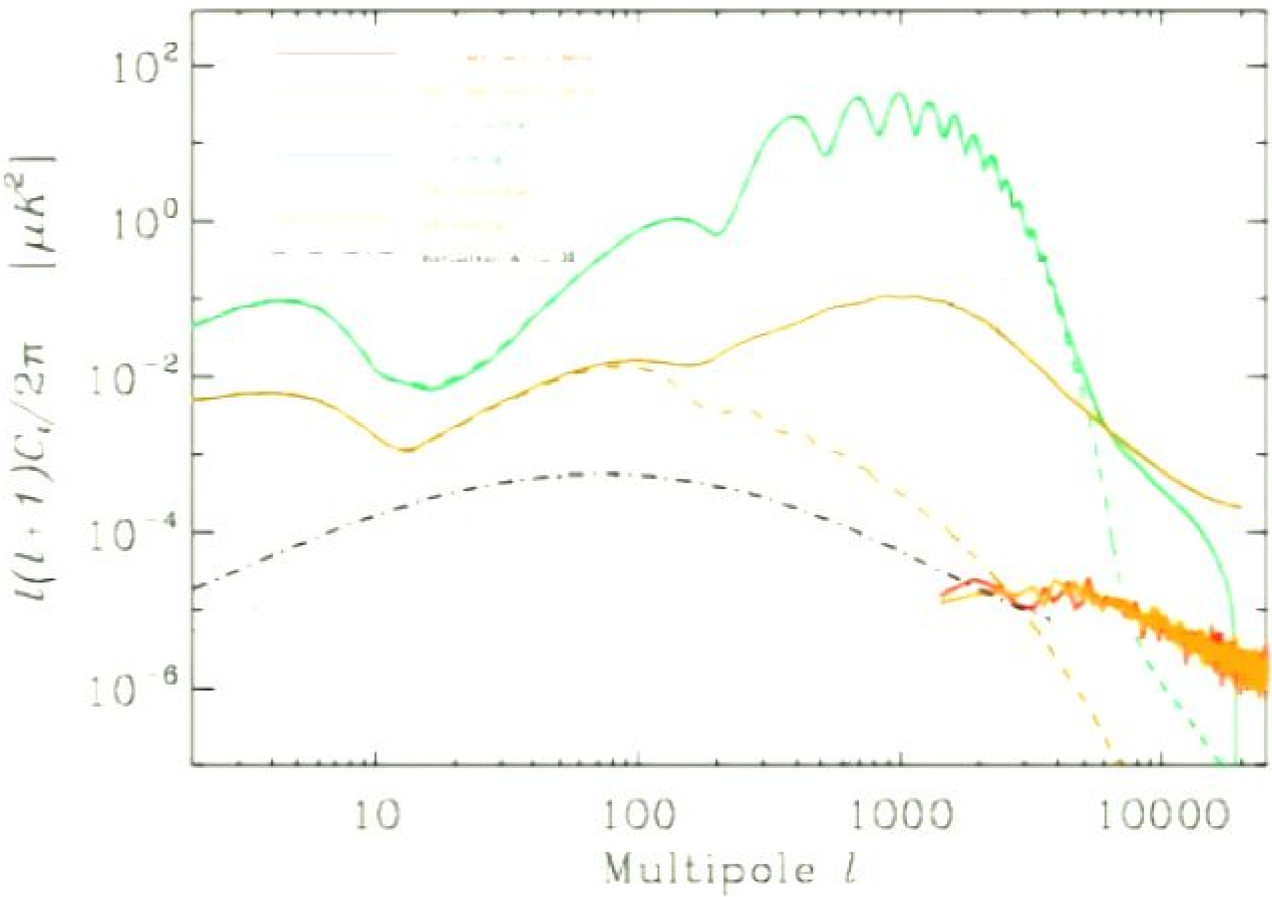
The benefits of alien collaborators at z~10

- Surface of last scattering at z=10 has little overlap with ours
- More than 1/2 of signal from "dark ages"
- Good enough data over large patch of sky allows reconstruction of "initial conditions" for most of Hubble volume
- **Needs polarized 0.1 uK on arcminute scales and mK redshifted 21 cm**



CMB Pol. & Patchy Reionization

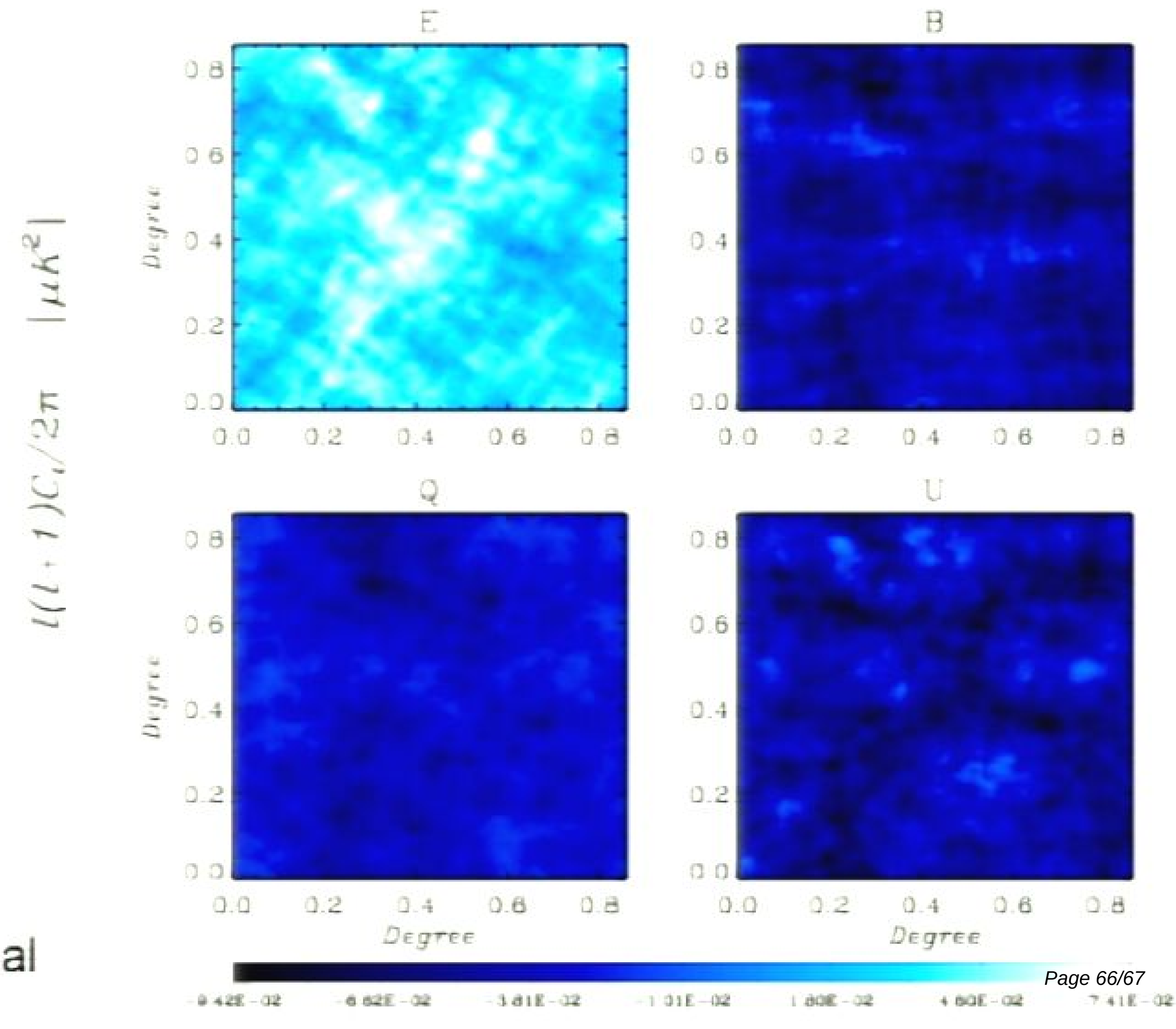
- Unlikely to be a problem for inflation B modes



Dore et al

CMB Pol. & Patchy Reionization

- Unlikely to be a problem for inflation B modes



Dore et al