CMB Foregrounds & Secondary Anisotropies

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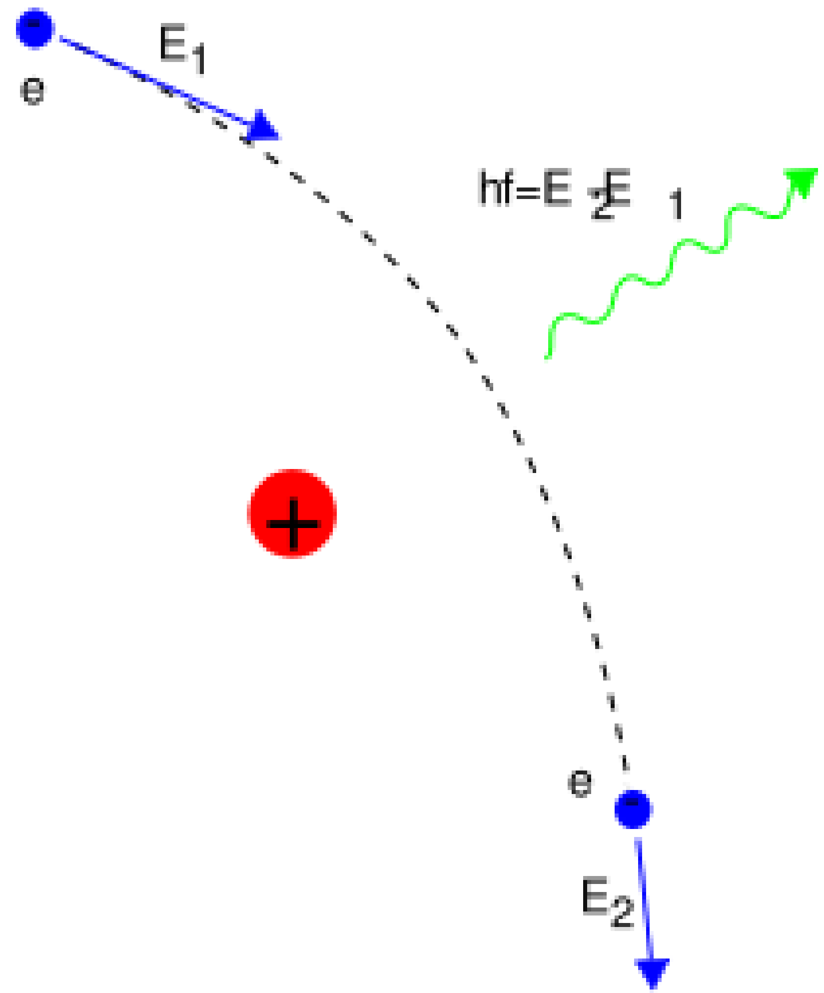
Outline

- Foregrounds (new photons)
    - Free-free (bremsstrahlung)
    - Synchrotron
    - Dust emission
    - Point sources (amalgam of other 3)
    - The southern hole
- Secondaries (redshifting, scattering)
    - Compton scattering on electrons
        - Bulk electron motions (Ostriker-Vishniac, kinetic SZ)
        - Thermal electron motions (thermal SZ)
        - Induced polarization (large scales, small scales)
    - Gravitational redshifting
        - Evolving potentials (ISW, Rees-Sciama)
    - Gravitational lensing

Free-Free (Bremsstrahlung)

- Electron accelerated by Coulomb interaction with ions
- accelerating dipole => dipole radiation
- Intrinsically unpolarized (superposition of many orientations)



Wikipedia

Foregrounds

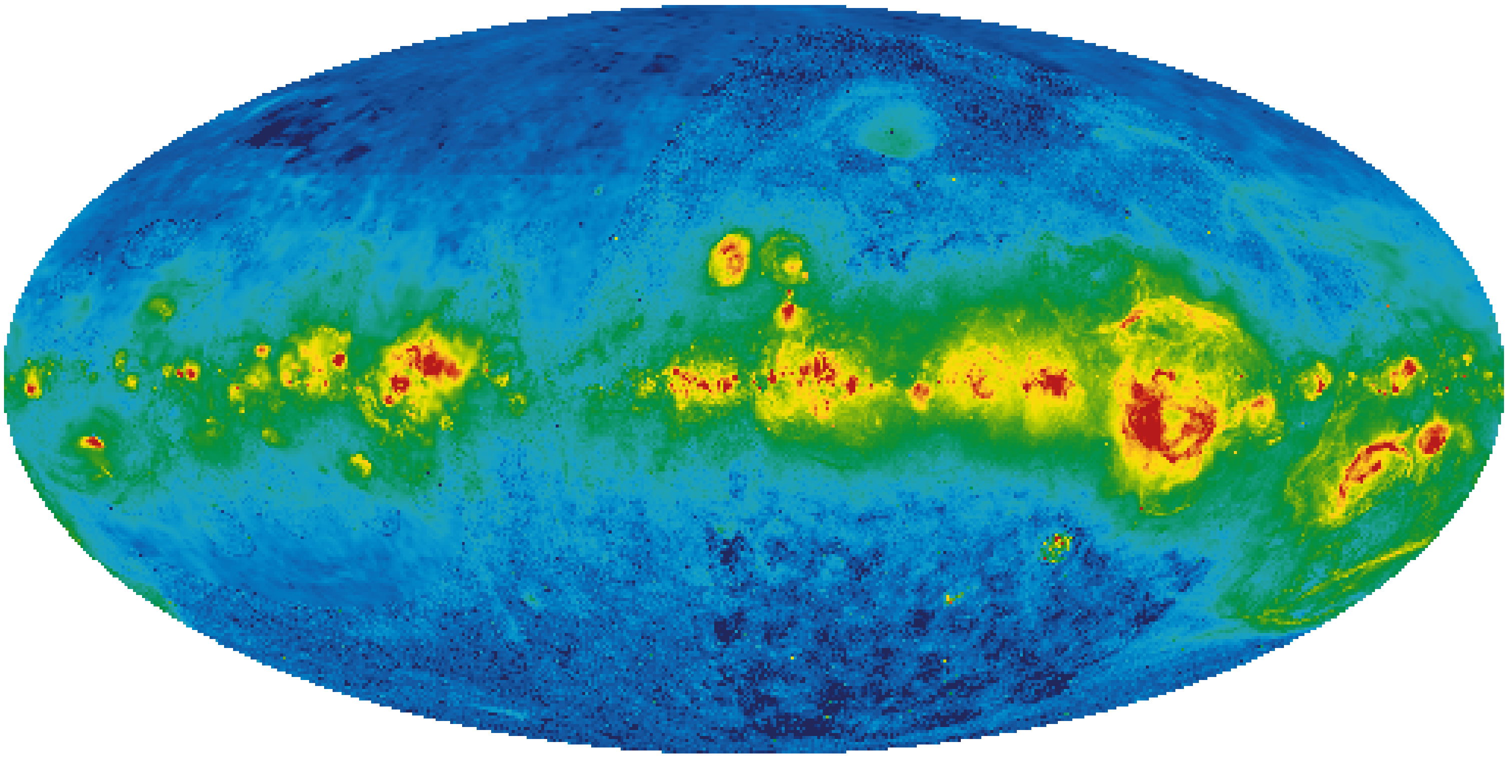
Free-Free Spectrum

QuickTime™ and a
decompressor
are needed to see this picture.

Rybicki & Lightman

- Two-body scattering (n^2)
- Nearly flat in energy up to cutoff frequency
- Sourced by thermal electrons, just like collisionally excited radiative transitions => Hα as a possible tracer

Free-Free Distribution?



- Hα map from combination of several surveys (compiled by Finkbeiner)

From LAMBDA

Synchrotron

- Electrons spiraling in magnetic field
- Can be highly polarized
- Non-relativistic: “cyclotron”
- Relativistic: “synchrotron”
- Can be highly (75%) polarized!

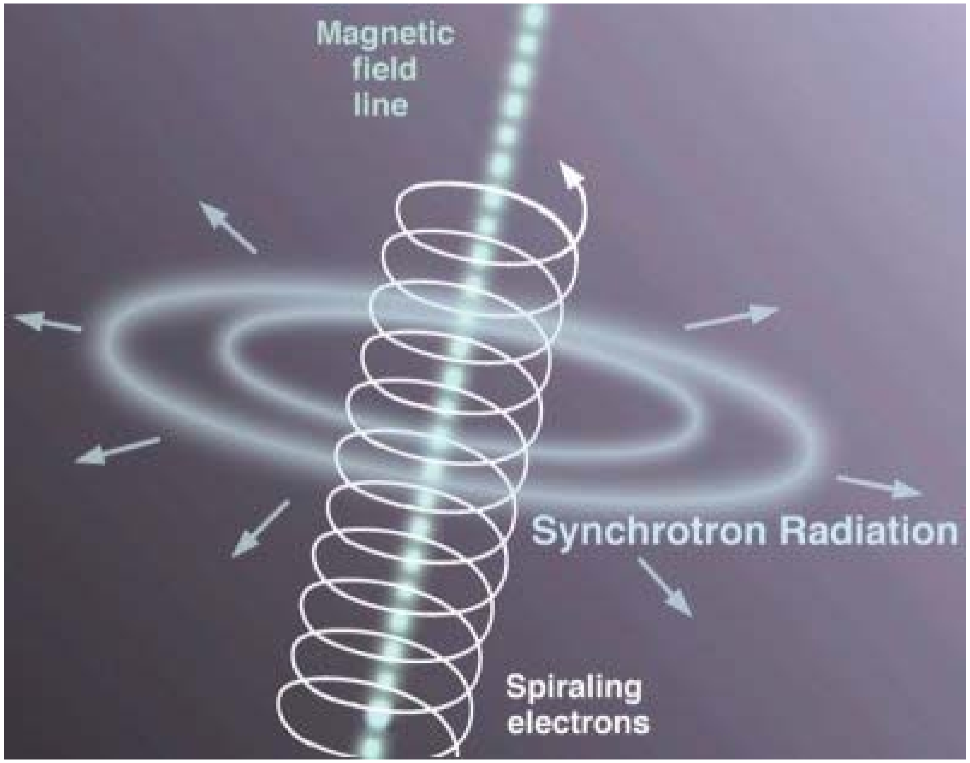


Image Credit: "Gemini Observatory"

Synchrotron Spectrum

- Depends on electron energy distribution
- Non-thermal electrons thought to be accelerated at shocks
- Varying electron energy spectrum leads to varying synchroton spectral index

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Rybicki & Lightman

Fermi acceleration: $p=1+t_{acc}/t_{esc}$

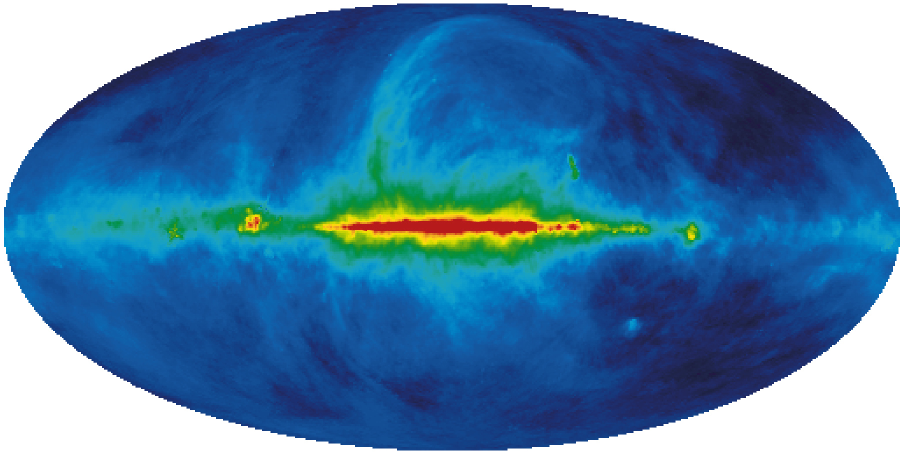
"Observed": p~2-3

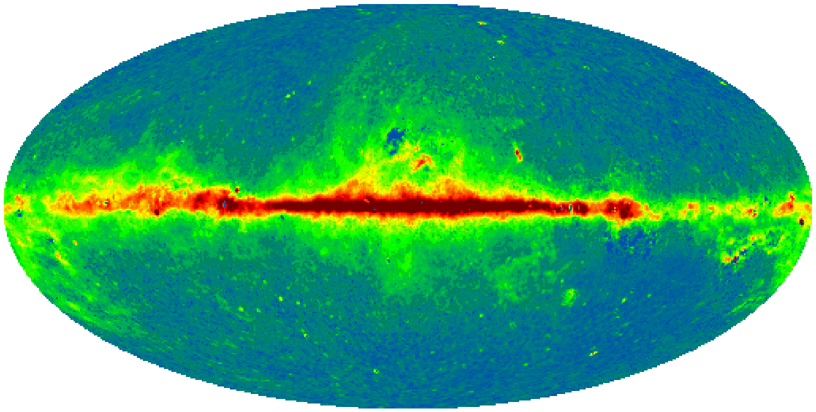
$\Rightarrow$ Intensity power law index ~0.5-1

$\Rightarrow$ temperature index ~2.5-3

Synchrotron Distribution?

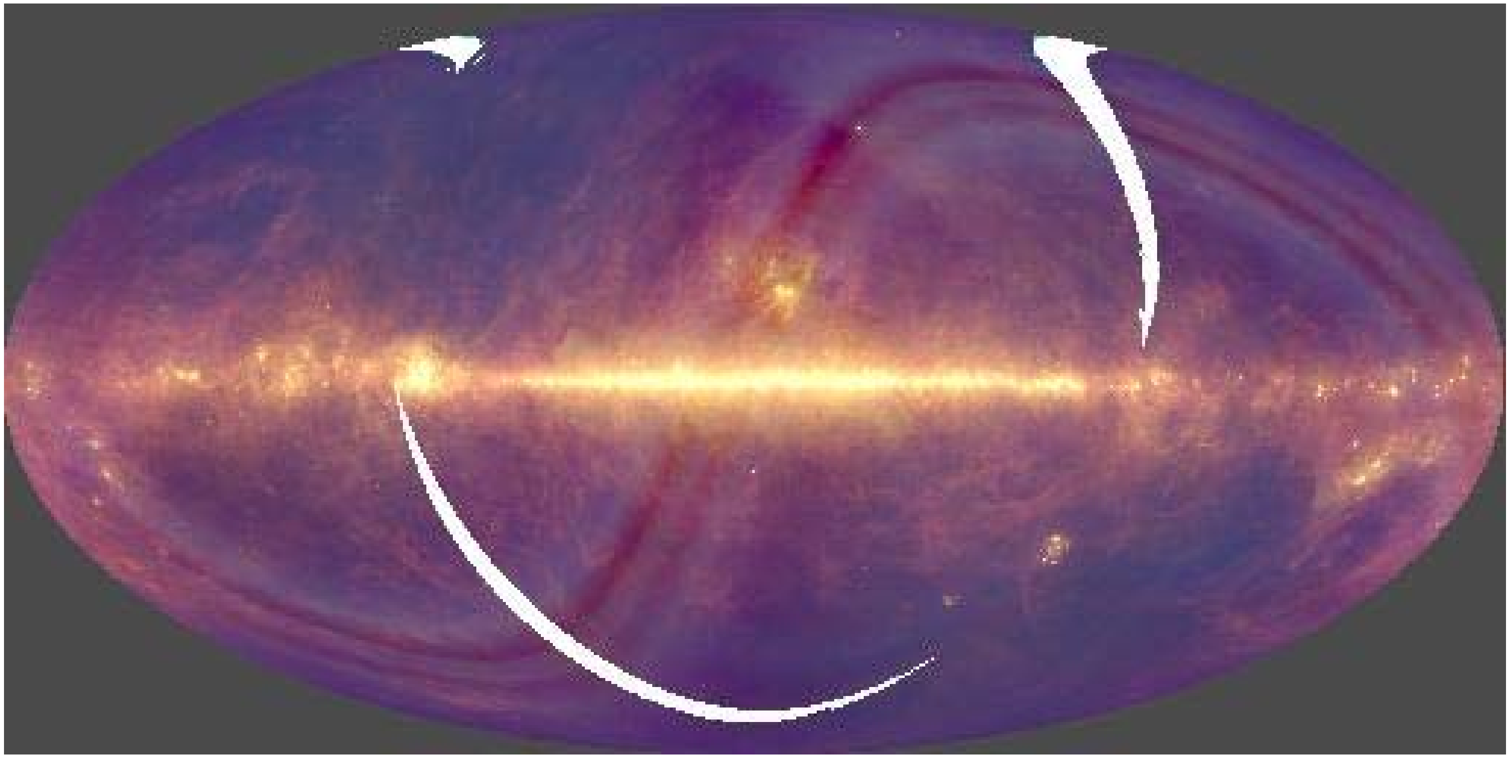
- Possible template: “Haslam map”
- 408 MHz
- Index expected to (and appears to) vary by +-0.3 spatially, and probably steepens with frequency





From LAMBDA

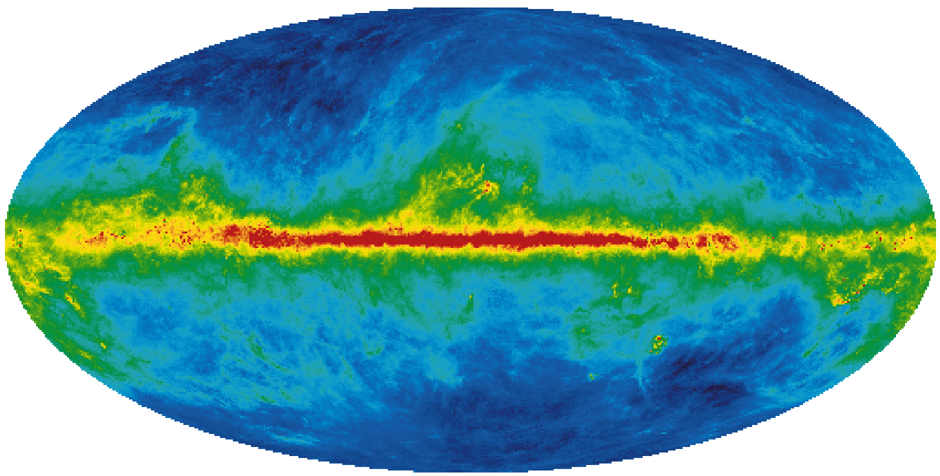
Thermal Dust

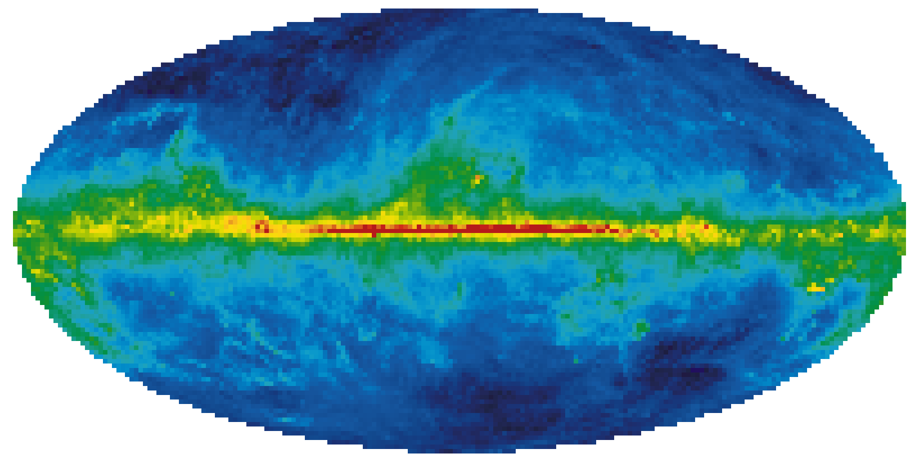


- Thermal emission from few nm-few um (or mm, or km) sized dust grains
- T~20-150K => peaks in the submm-IR

From LAMBDA

IRAS/DIRBE Template





94 GHz Model Dust map

0.4 to 400 uK

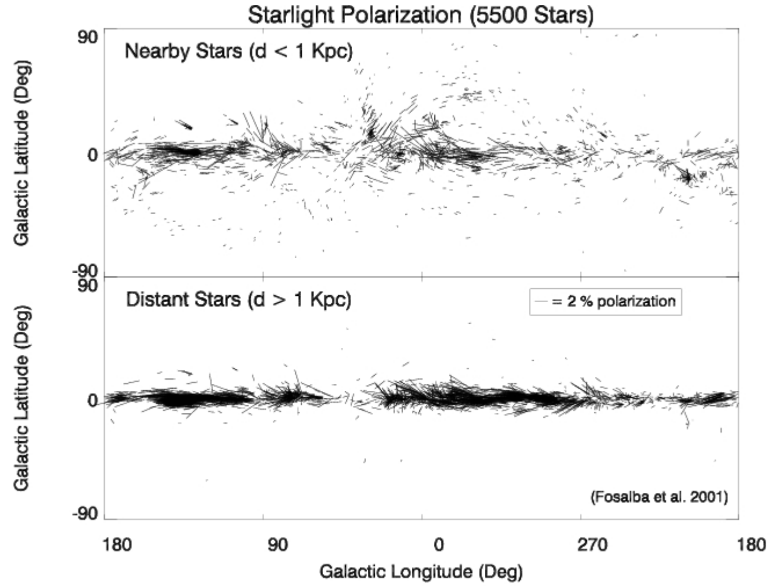
Derived reddening map

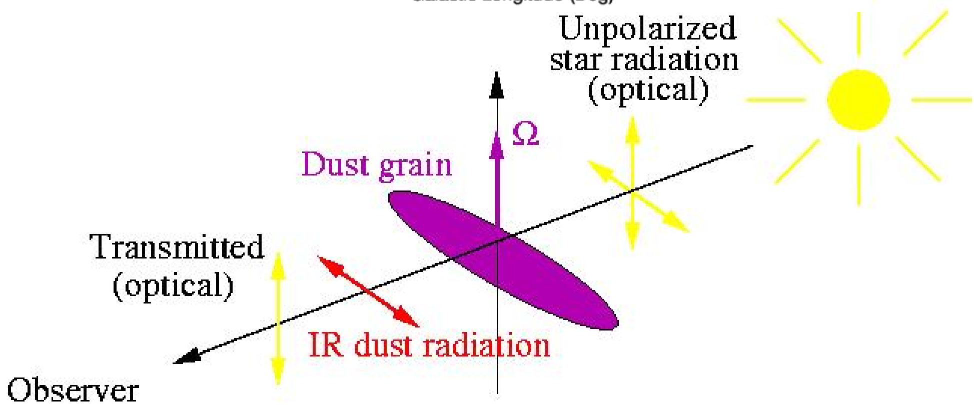
(0 to 6.3 mag)

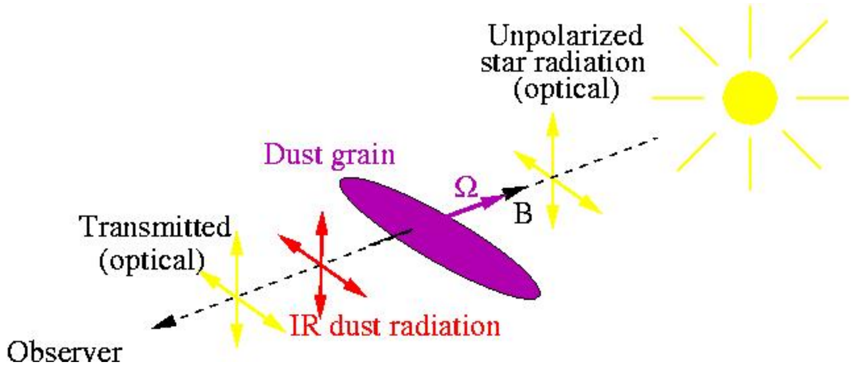
Finkbeiner, Schlegel, Davis 1999; available at LAMBDA

Dust Polarization

- Dust grains could be aligned by magnetic field
- Evidence for this through polarization of optical starlight
- Preferential alignment of grains leads to partially polarized thermal dust emission







From Planck website

Spinning Dust?

- Excess signal at low frequencies (10-50 GHz) that is IR-correlated
- Could be due to very small, spinning dust
- $kT \sim I\omega^2$ => few GHz for nm-sized grains ("nanoclusters"?)
- WMAP calls it dust-correlated synchrotron and absence of evidence

CMB/DIRBE correlation

QuickTime™ and a
decompressor
are needed to see this picture.

CMB/Haslam

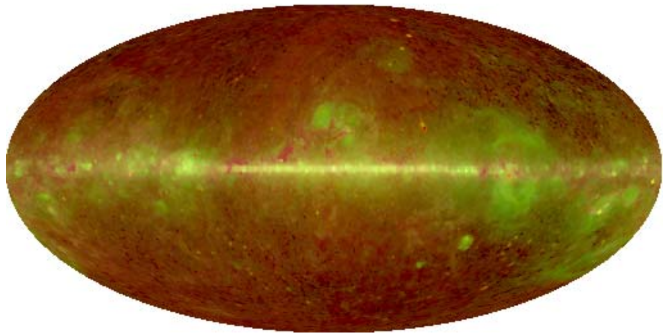
De Oliveira-Costa et al 2000

WMAP results

Green:free-free; red: synch; blue:dust

K-band

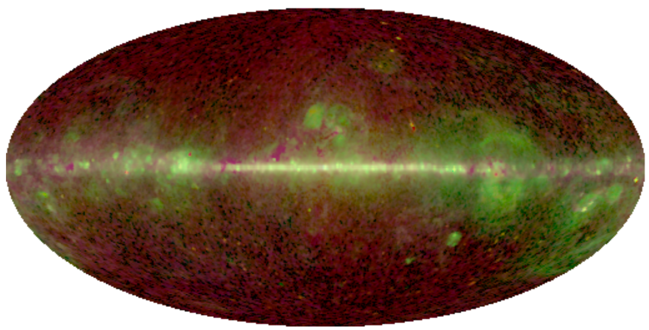
(23 GHz)



QuickTime™ and a
decompressor
are needed to see this picture.

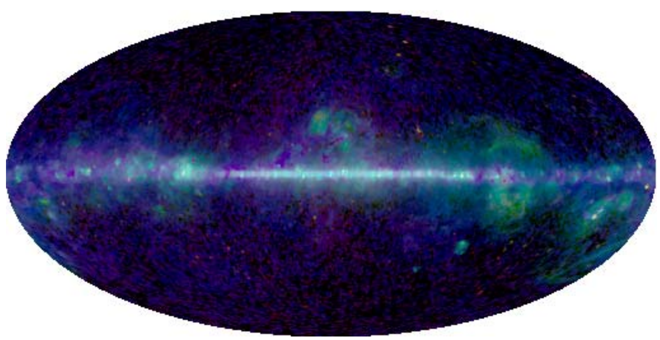
Q-band

(41 GHz)

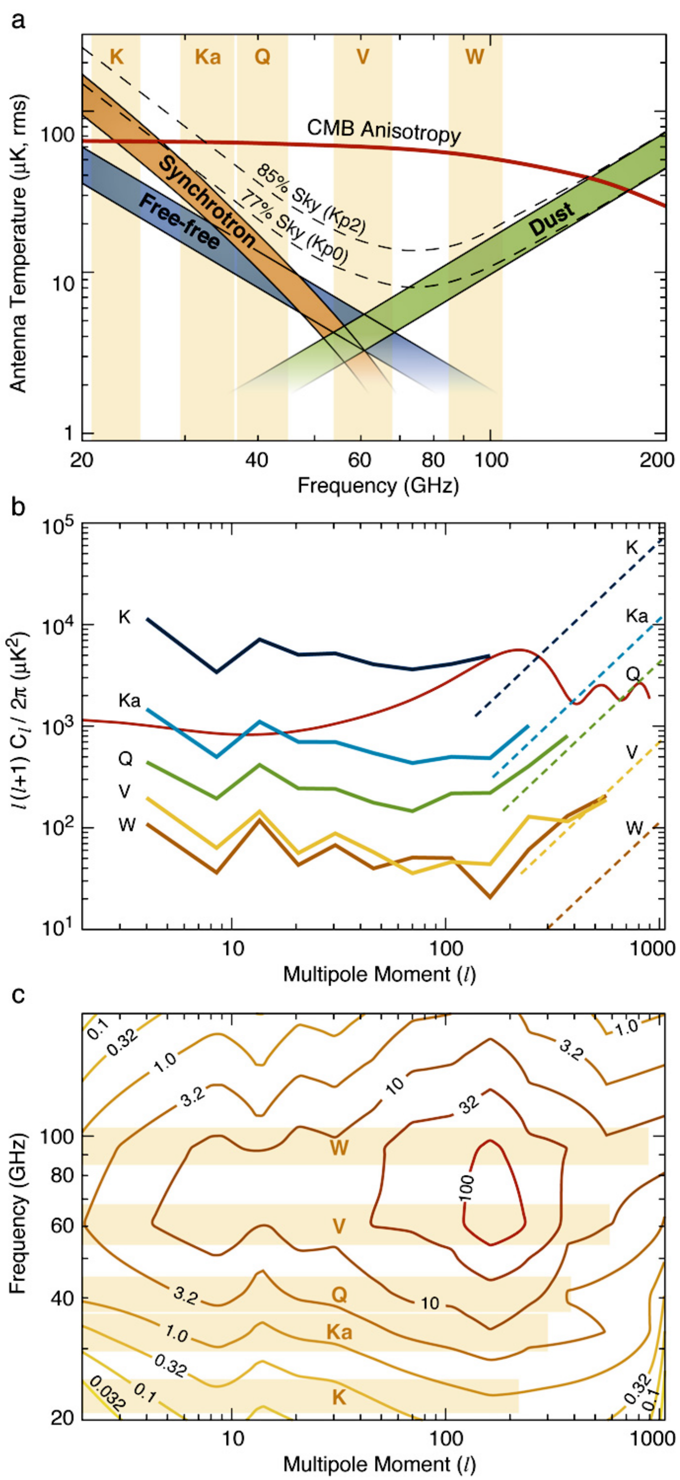


W-band

(90 GHz)



From LAMBDA



Frequency scaling of individual physical components

Spatial scaling (in multipole space) of each frequency channel after CMB removal

Flat band power…

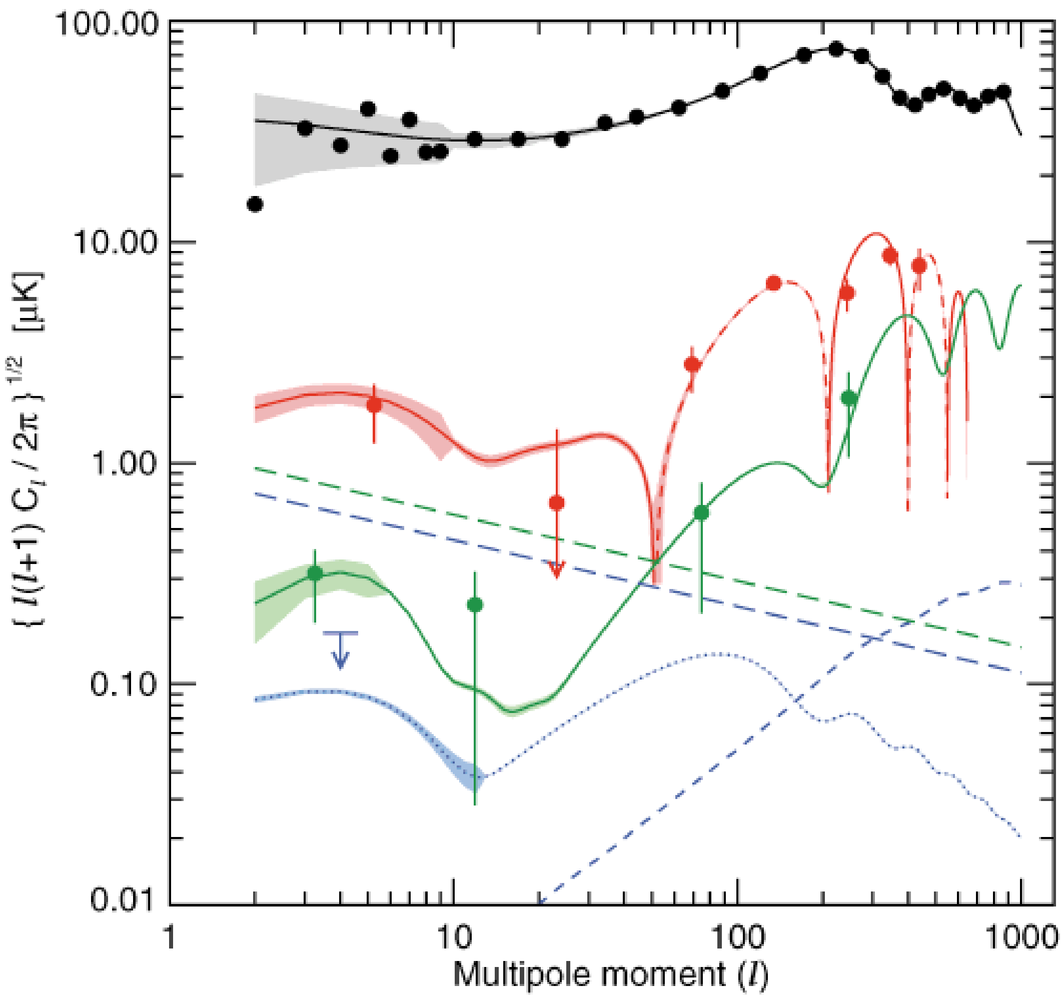
Ratio of CMB power to foreground power

From LAMBDA; Bennett et al 2003

Spatial and frequency scaling

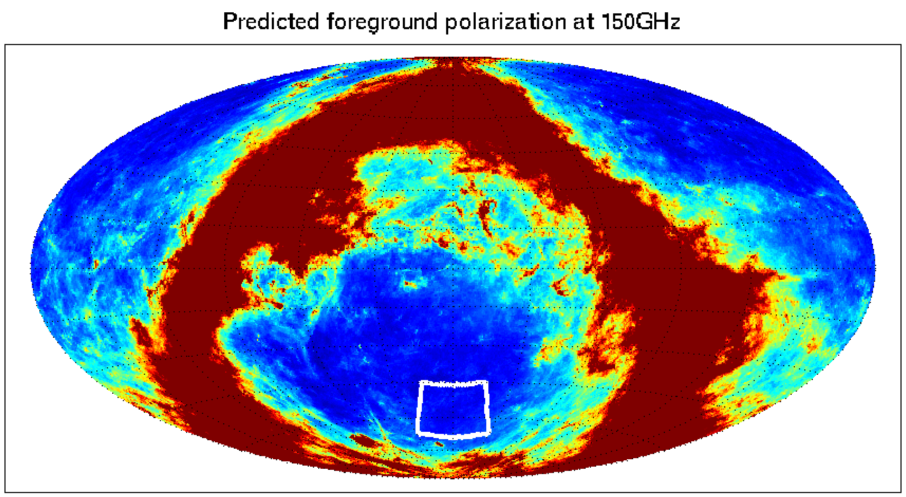
WMAP Results II

- Dashed lines indicate foreground levels in WMAP polarization data (at 65 GHz), averaged over relatively clean sky area (I.e., outside galaxy mask)

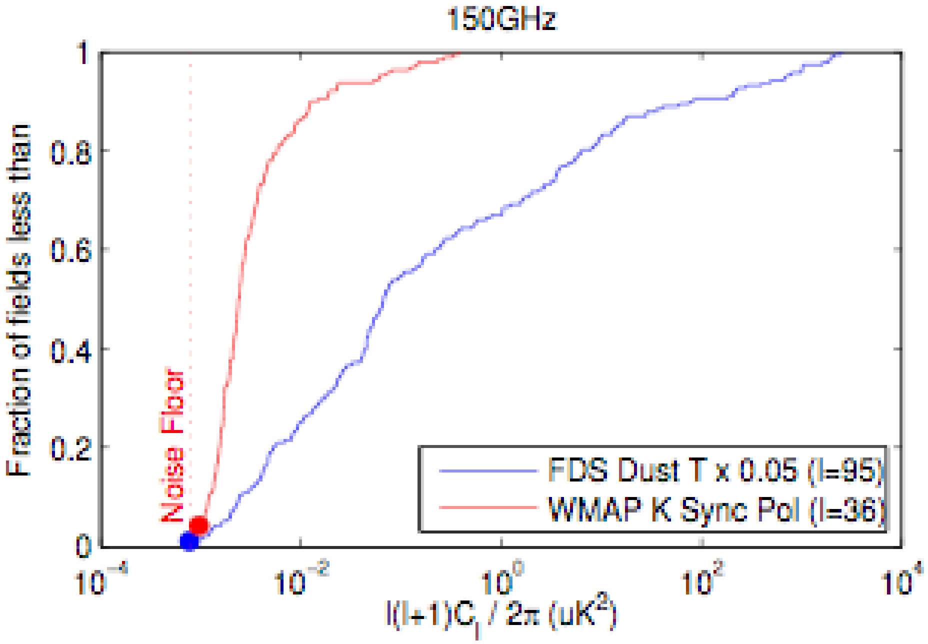


From LAMBDA; WMAP3

“The Southern Hole”



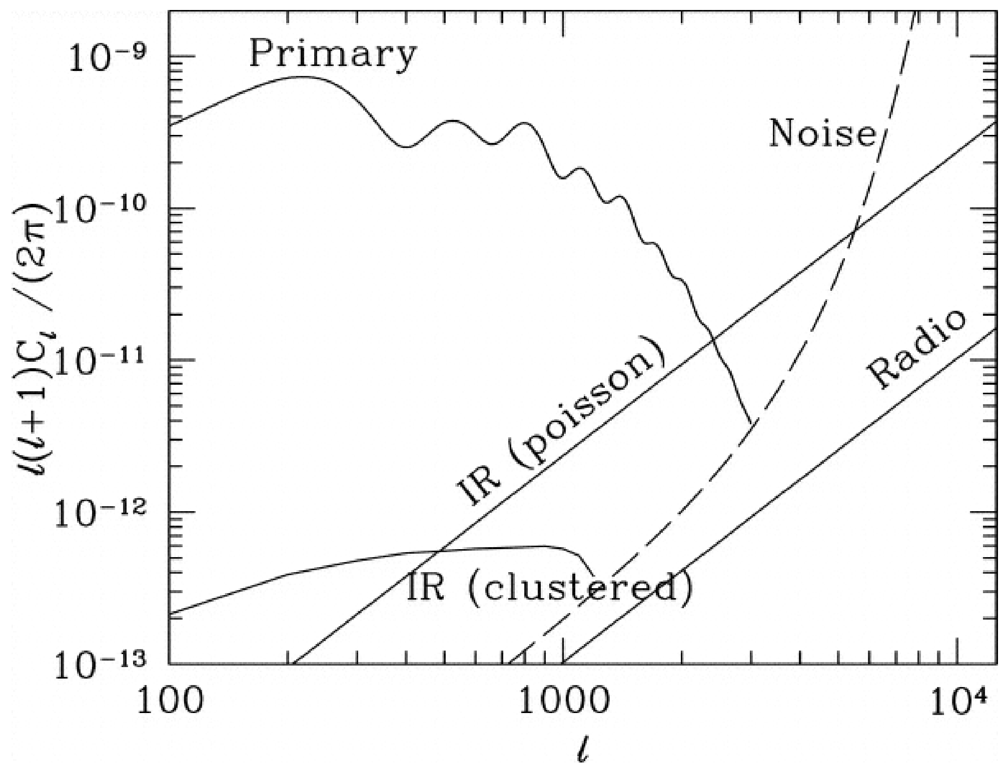
Kovac & Barkats 2007



- There exist very clean patches
- “southern hole” has ~2% of the sky at very low foreground level
- Cleanest parts of the sky can be orders of magnitude cleaner than typical regions

Point Sources

- Spatial power spectrum looks like white noise (I.e., important on small scales)
- Bright sources can be masked



Majumdar & White 2004;

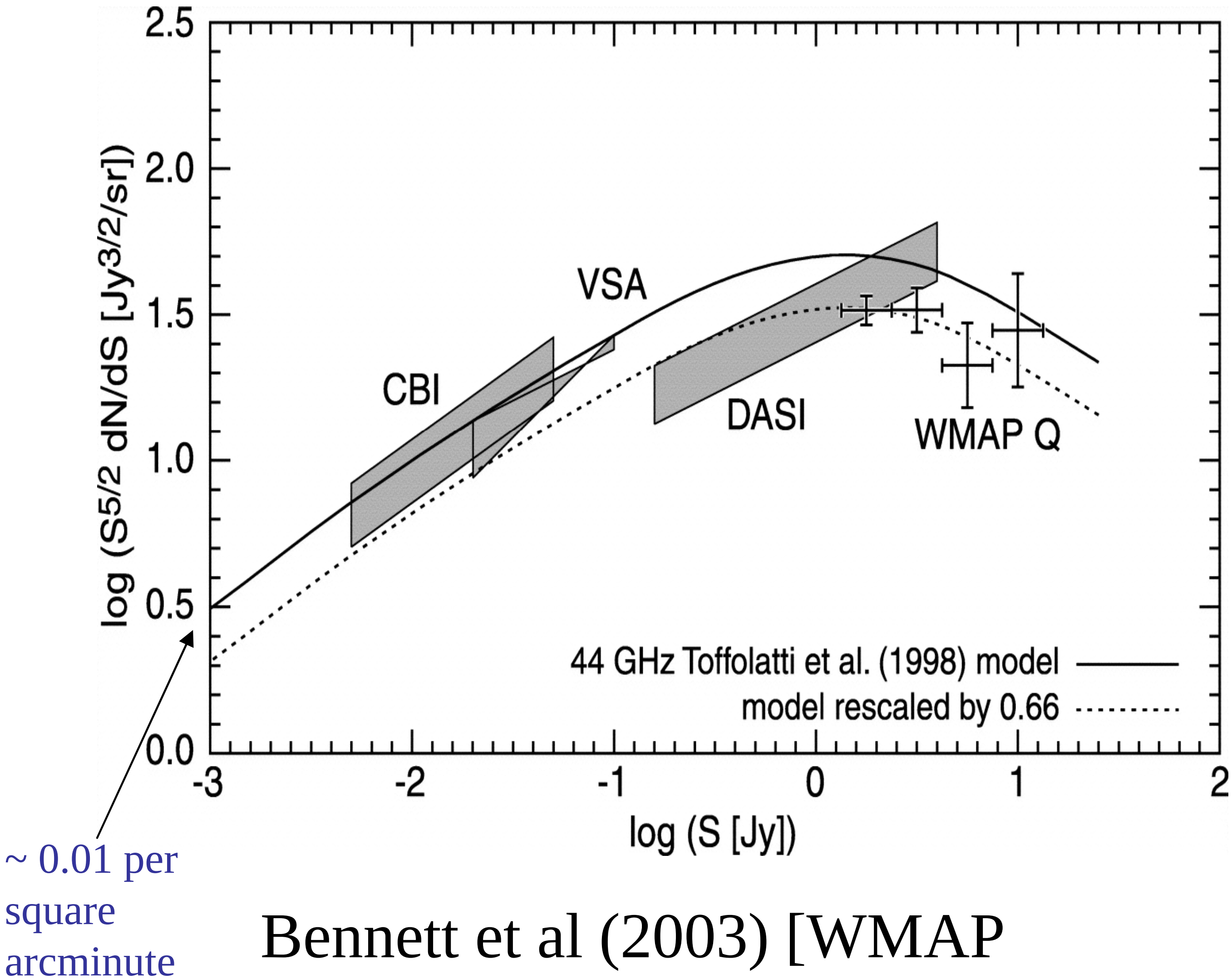
220 GHz pt src estimates assuming all sources above 5 mJy removed

Radio Galaxies

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

• radio sources correlated with clusters, galaxies, etc. could be problematic for studies of secondaries

•Generally falling spectra in flux (flat => $1/\nu^2$ in CMB units)



Bennett et al (2003) [WMAP foregrounds paper]

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)

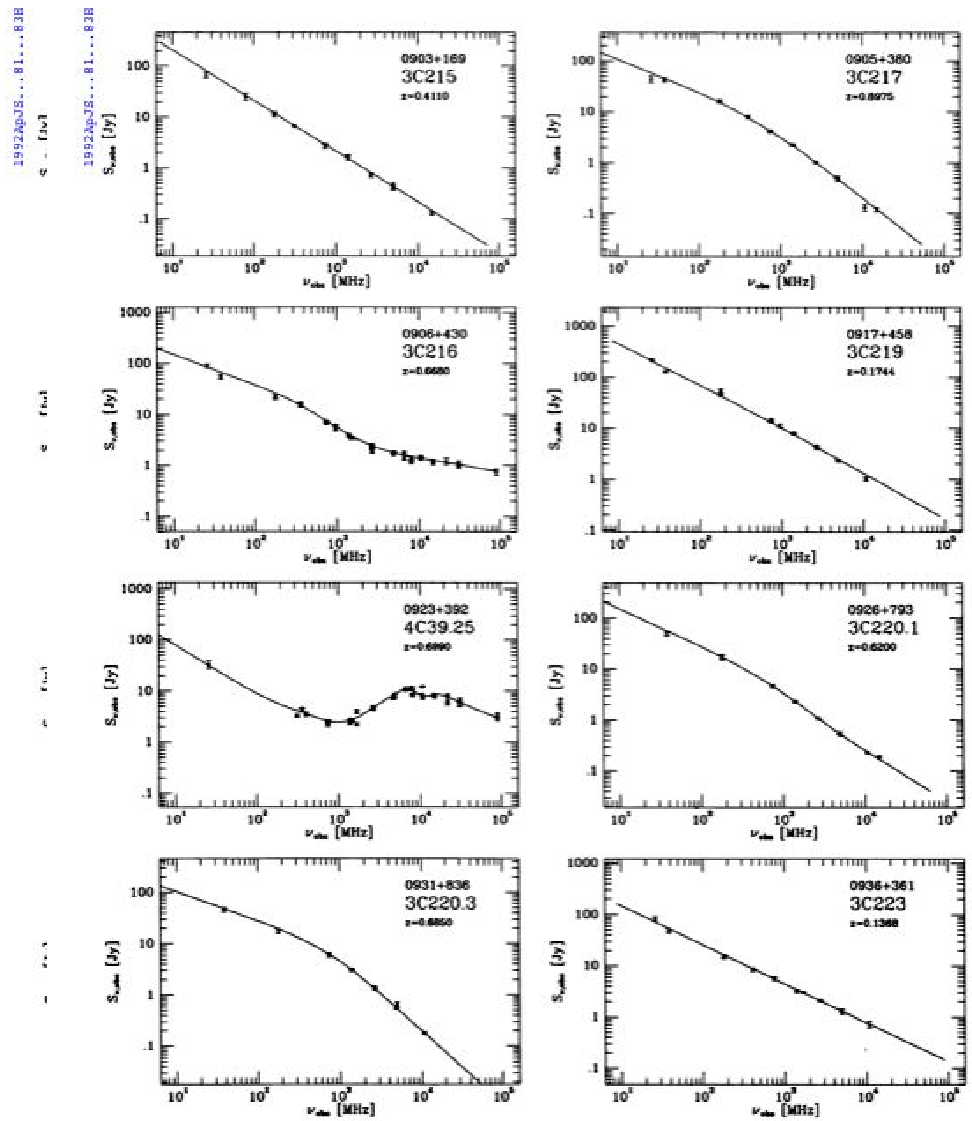


Fig. 1—*Continued*

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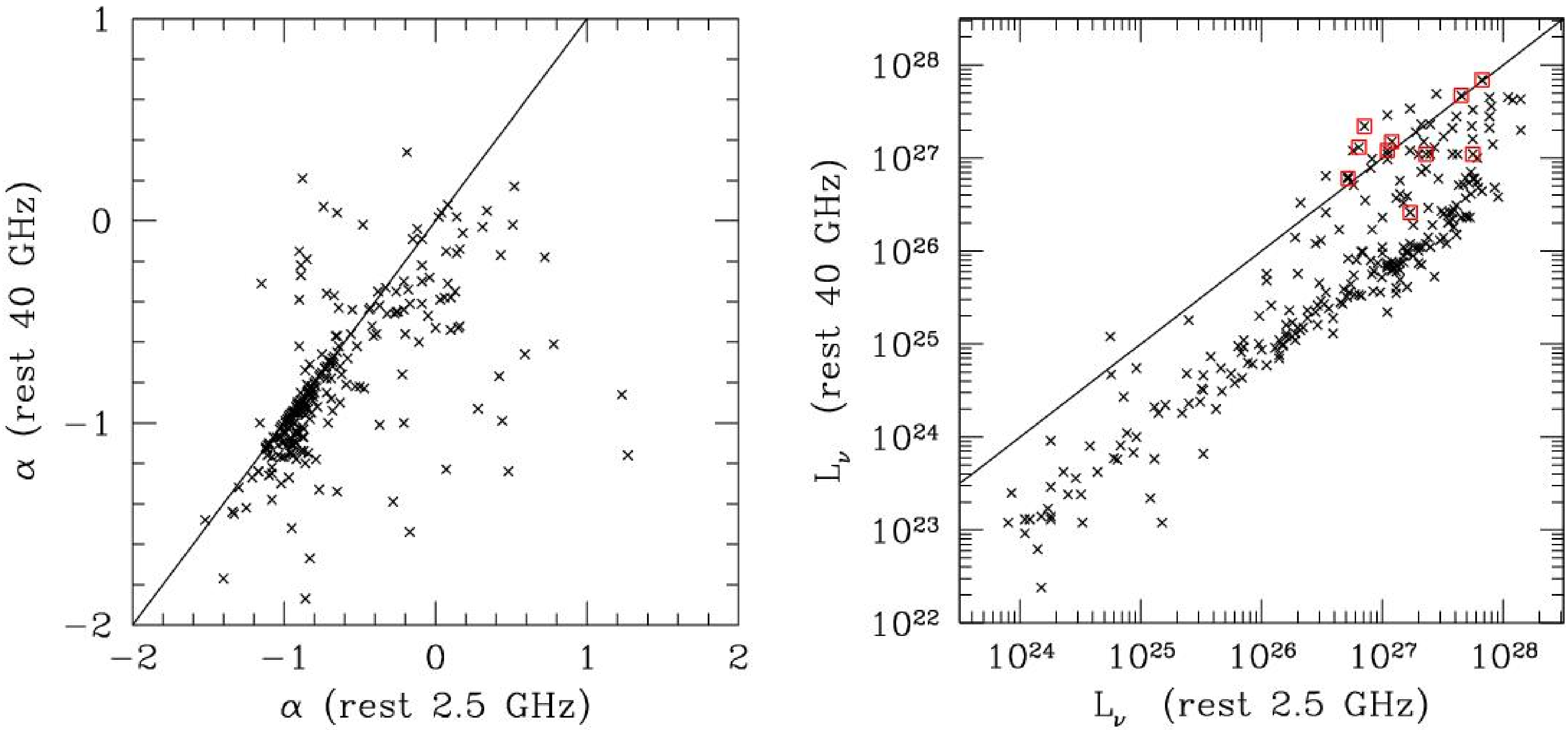
Extrapolating Radio Sources



Red squares: flat or rising spectra at 40 GHz

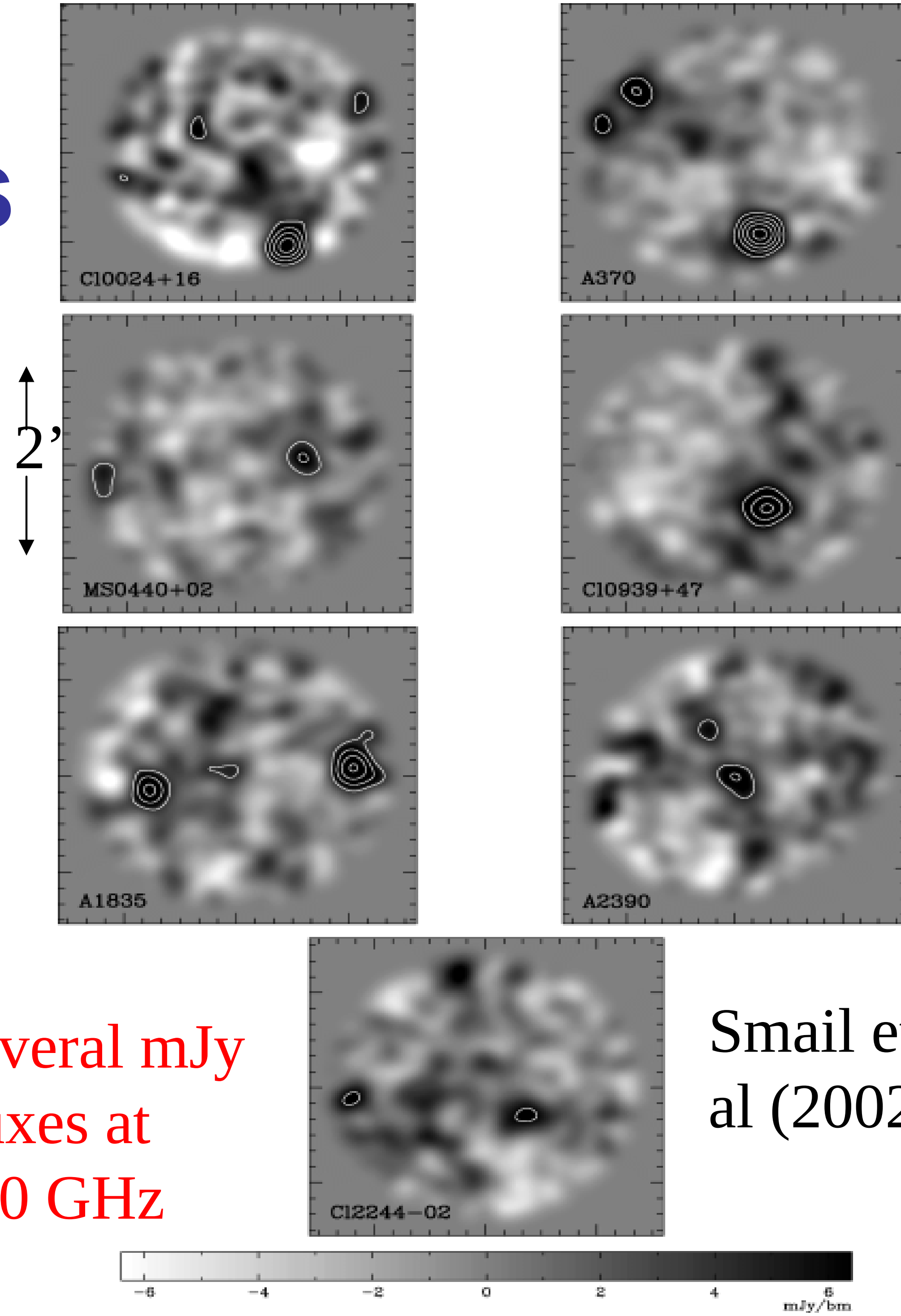
Data from Herbig & Readhead 1992

Bottom line: a few % of radio sources should be as bright at high frequencies as at 1.4 GHz (in flux, not temperature)

Dusty Galaxies

- 1 mJy at 150 GHz in a 1' beam => ~ 30 uK
- *How well can these be subtracted?*
- ***Not a problem for ALMA***

(30 σ in 60 seconds)



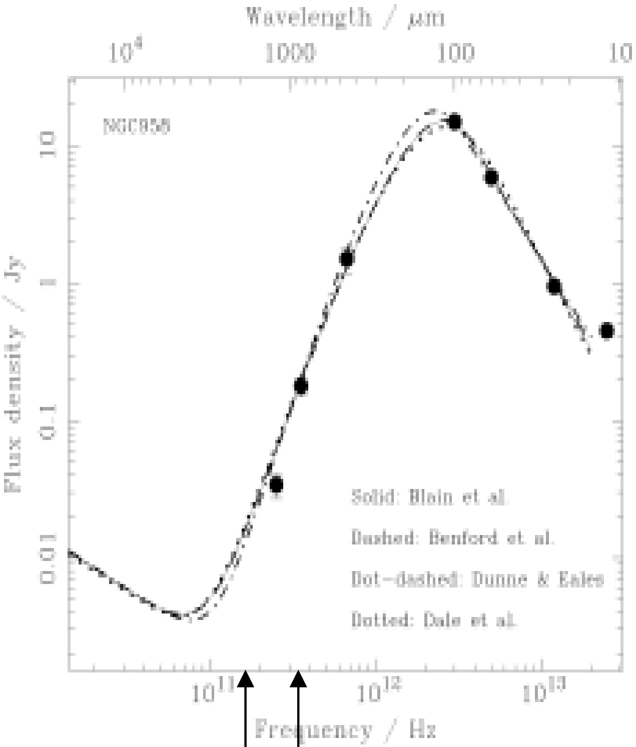
Several mJy fluxes at 350 GHz

Smail et al (2002)

Spectral Homogeneity?

Blain et al 2002

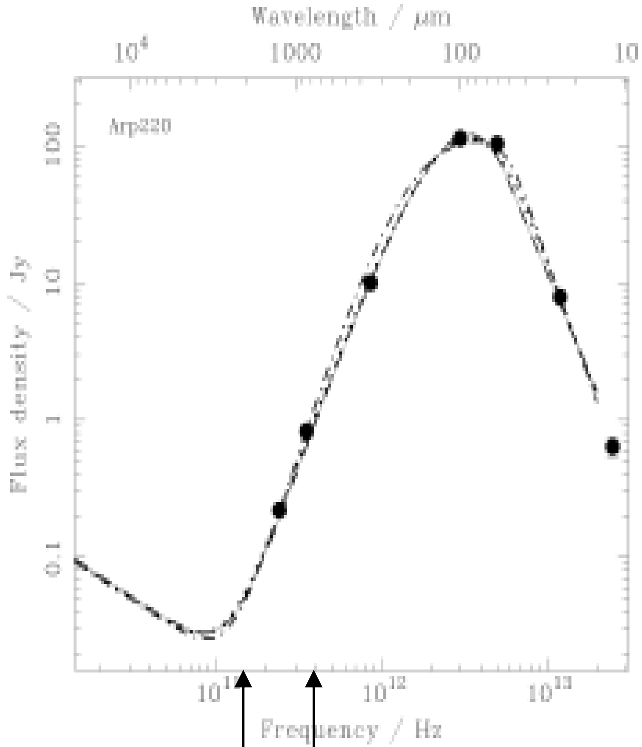
z = 0.02



T~30 K

150 350
GHz

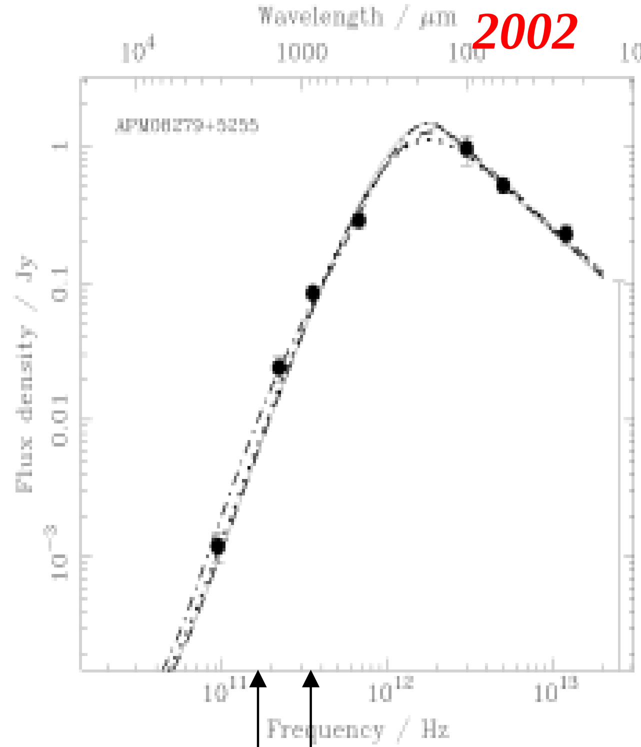
z = 0.02



T~40 K

150 350
GHz

z = 3.8



T~90 K

150 350
GHz

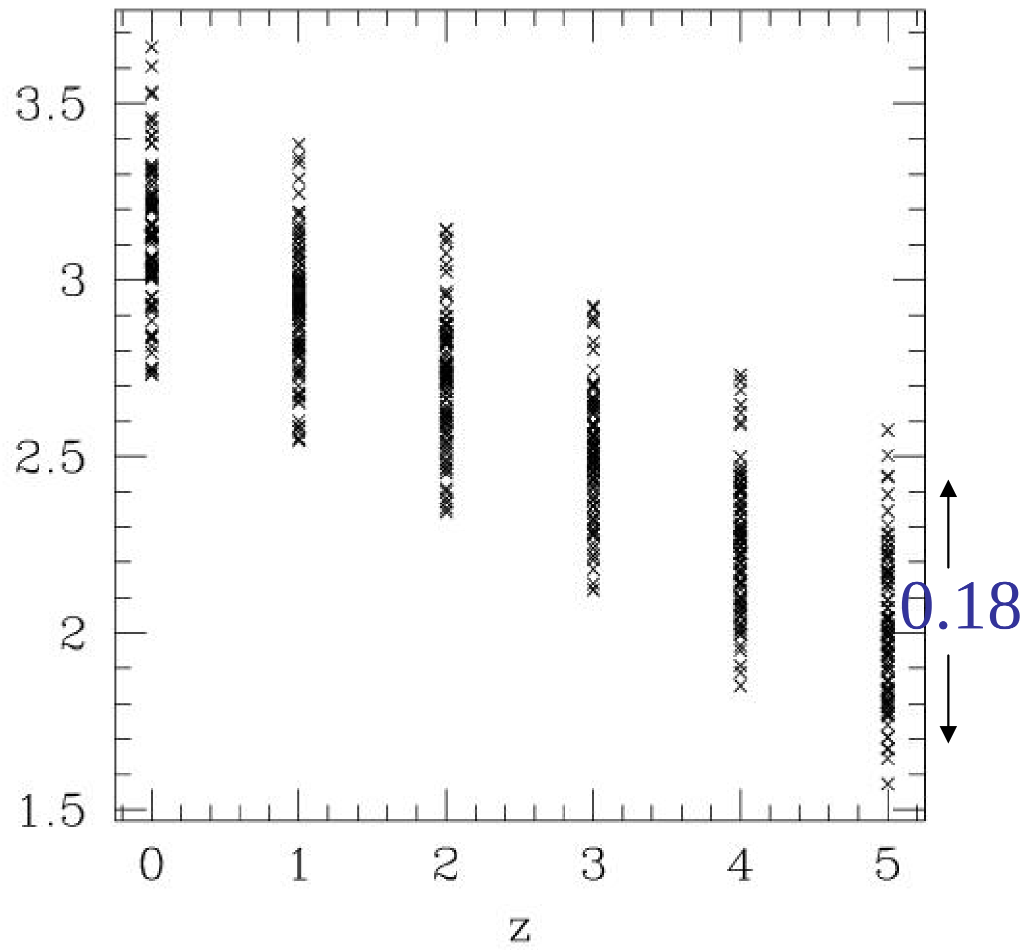
What are Local Galaxies Like?

• use local sample of luminous dusty galaxies (Dunne et al 2000)

• calculate 350/150 GHz spectral index for same sources at a variety of redshifts

$$S(Jy) = S_o \nu^{\alpha}$$

r.m.s. ~ 0.4 (over all z)



Warnings: a) this is based on old data

b) these data actually suck for this purpose

Secondaries

Compton (Thomson) Scattering

- Note angle dependence of scattering
- Looks like a quadrupole
  - Unpolarized input quadrupole leads to outgoing polarized emission (from orthogonality of spherical harmonics)
  - Input dipole is not preserved (front-back symmetry!)

QuickTime™ and a
decompressor
are needed to see this picture.

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decompressor
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decompressor
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Rybicki & Lightman

Peculiar Velocities (Kinetic SZ)

- Pure redshift, blueshift => thermal spectrum

$$\frac{\Delta T}{T} = \tau \left(\frac{\mathrm{v}}{c} \right)$$

Typical cluster signal: ~20 uK

Kinetic SZ from large scale structure:
"Vishniac Effect'' (*expected signal ~1 uK*)

Astrophysical confusion:
•dusty submm-luminous galaxies
• Internal bulk flows (>100 km/s)

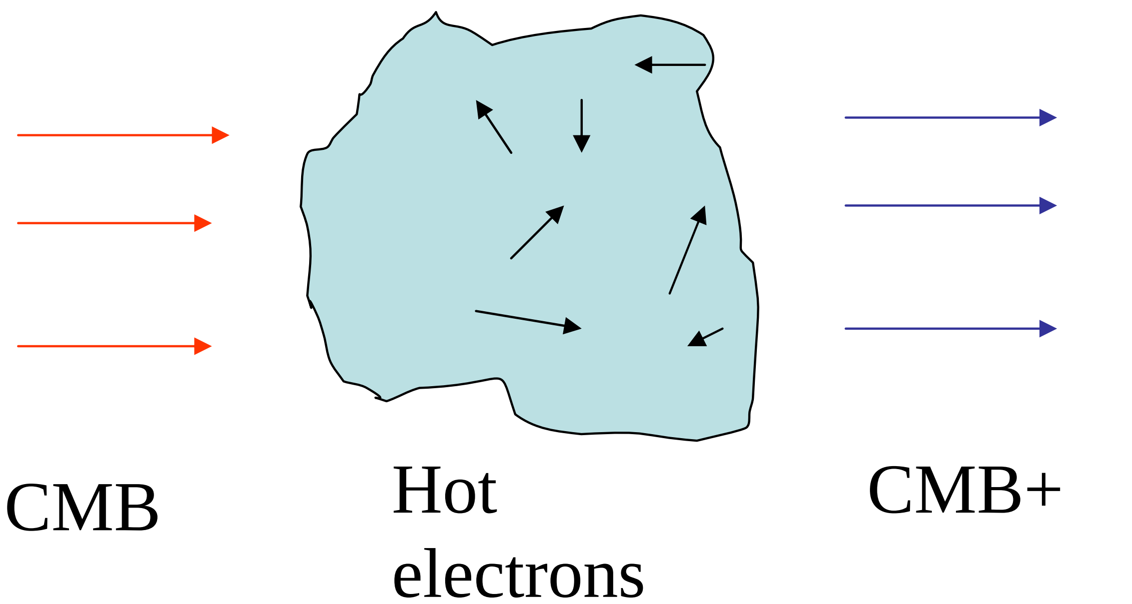
Range in allowed Vishniac effect

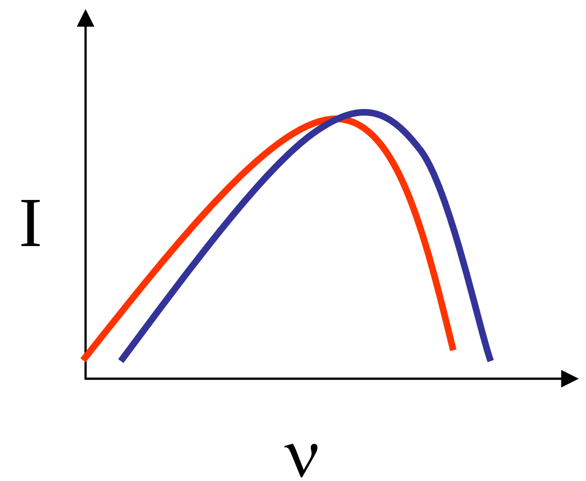
- Even using the extremely well-constrained cosmological parameters, factor of 3 uncertainty !!
- Astrophysical uncertainties comparable….

QuickTime™ and a decompressor
are needed to see this picture.

Dudley-MSc thesis

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 massive 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 !!!!

- Independent of redshift
- Temperature weighted electron column density
- Unique spectral signature

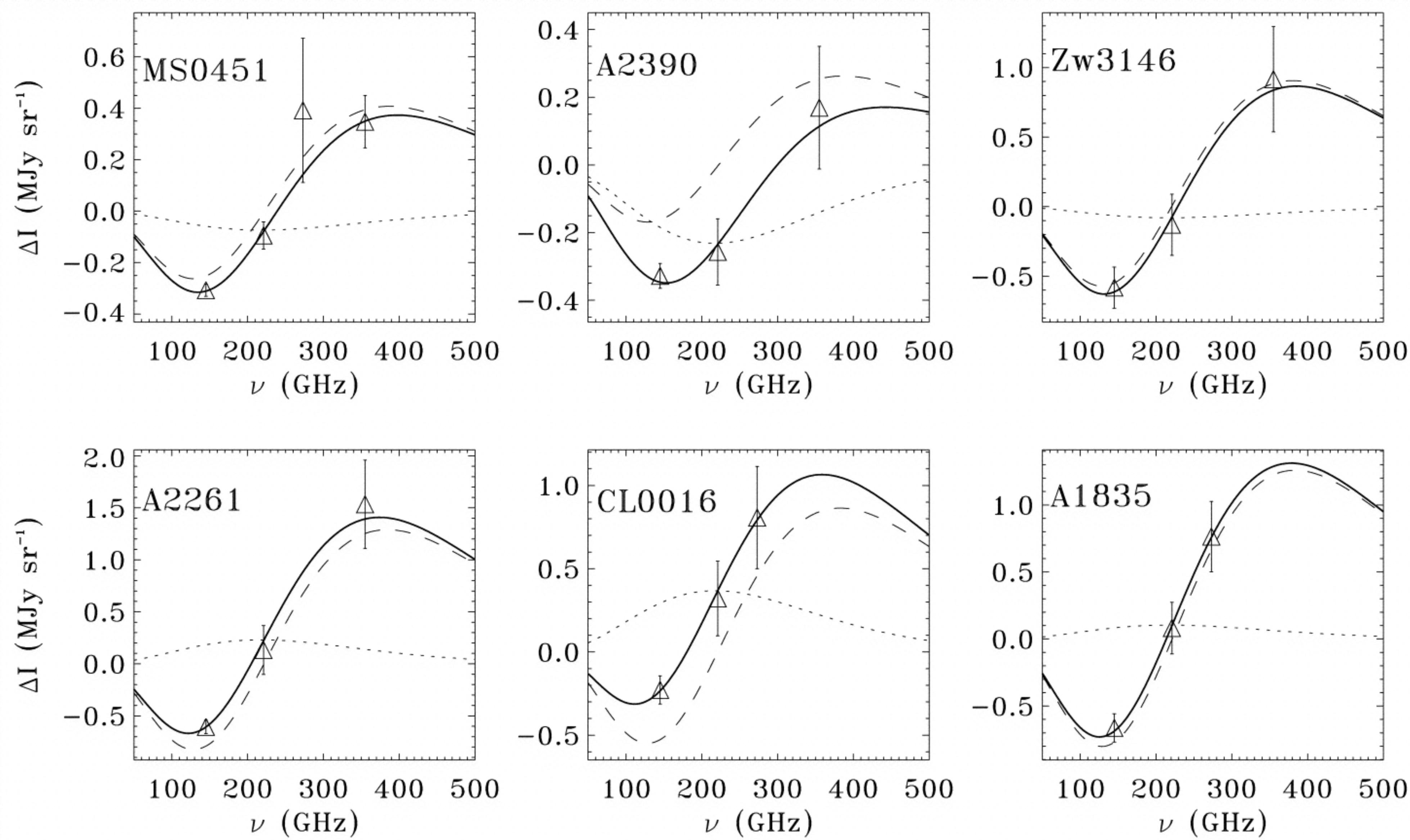
SZ Observables II

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
- Temperature weighted electron inventory
- angular diameter distance, not luminosity distance

Non-Thermal Spectrum

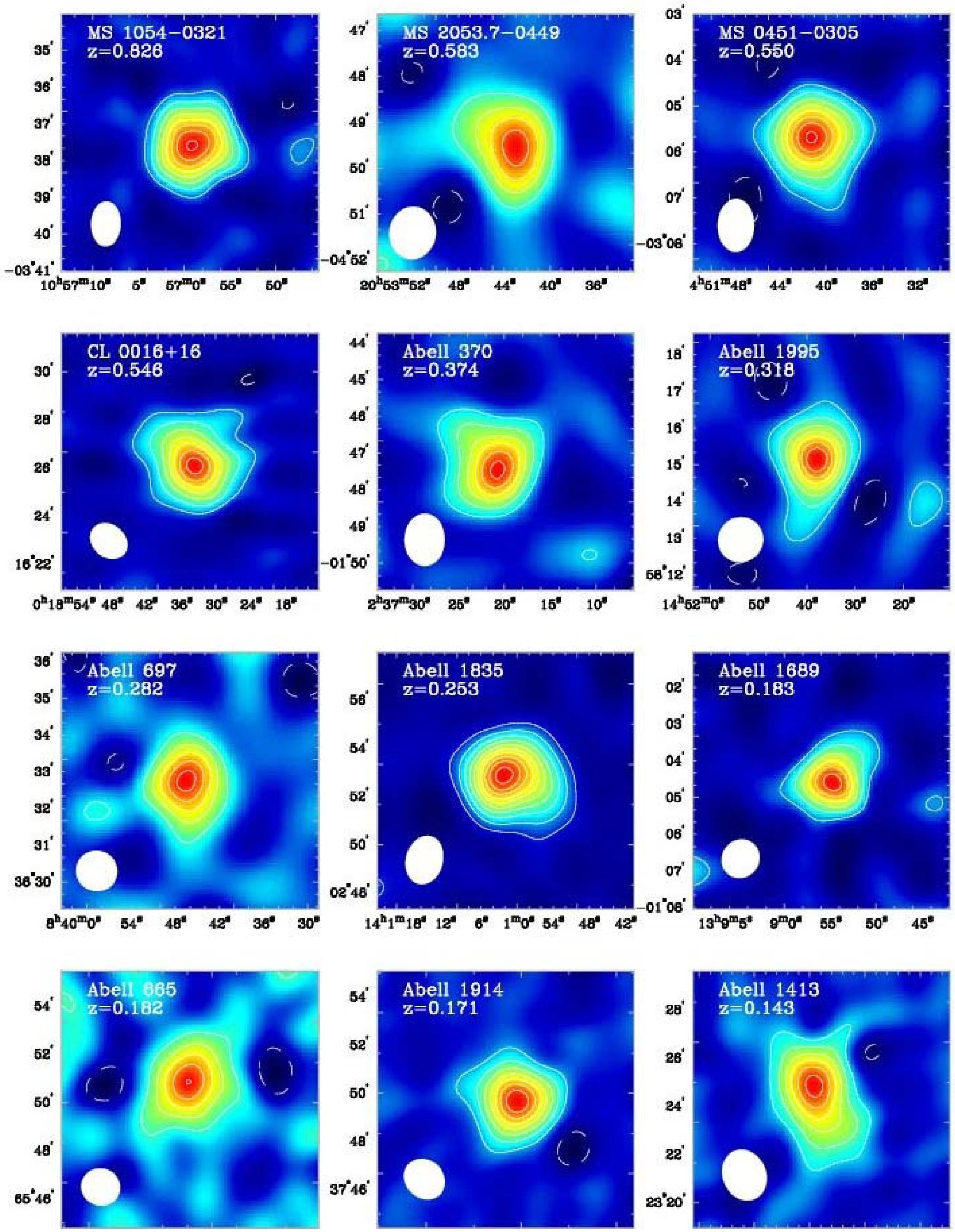


Benson et al 2003 (SuZIE II)

Z=0.83

Massive, X-ray selected clusters

Typical exposure ~40 hr



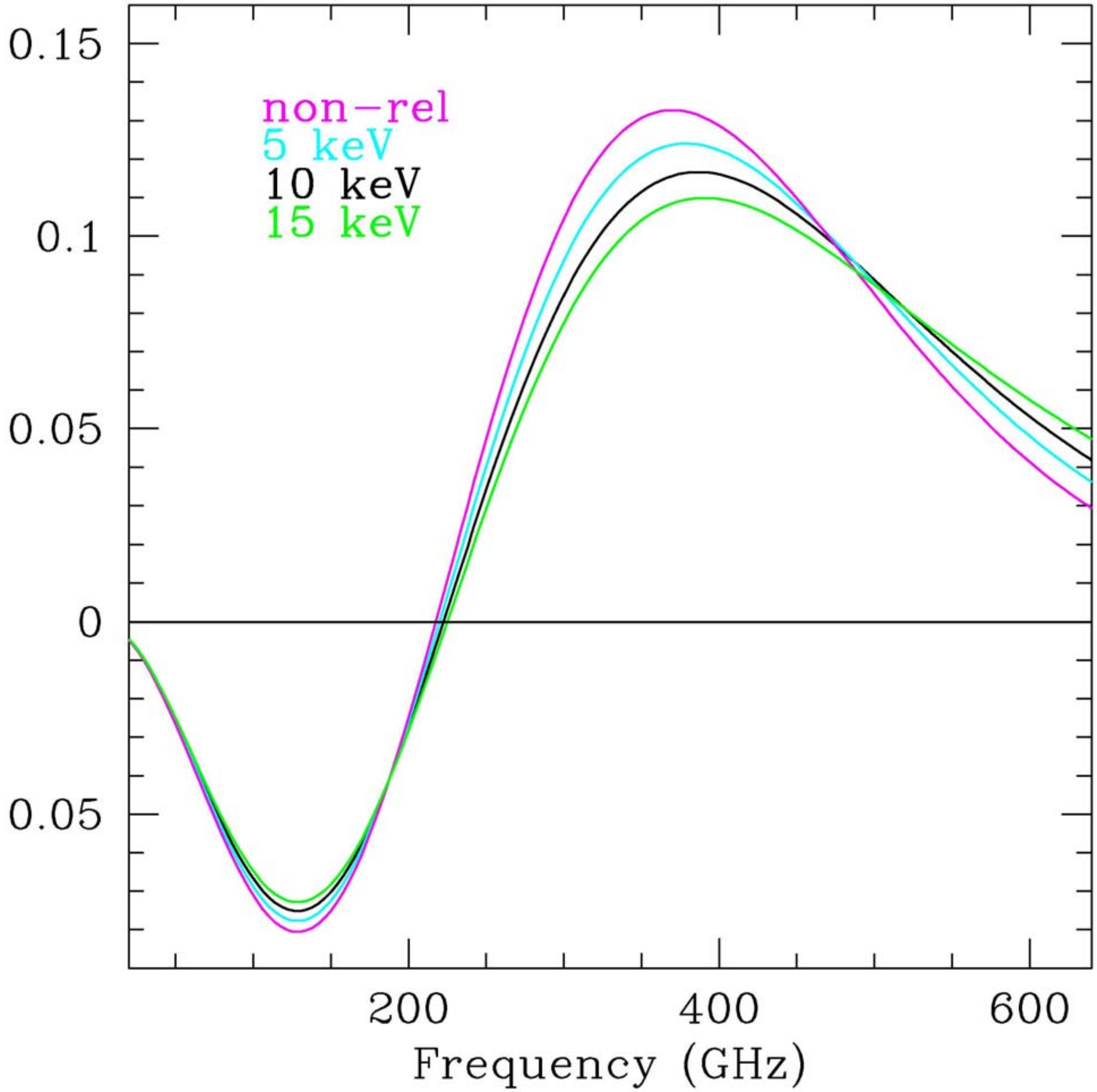
Z=0.14

Carlstrom & Joy SZ Imaging Project (30 GHz)

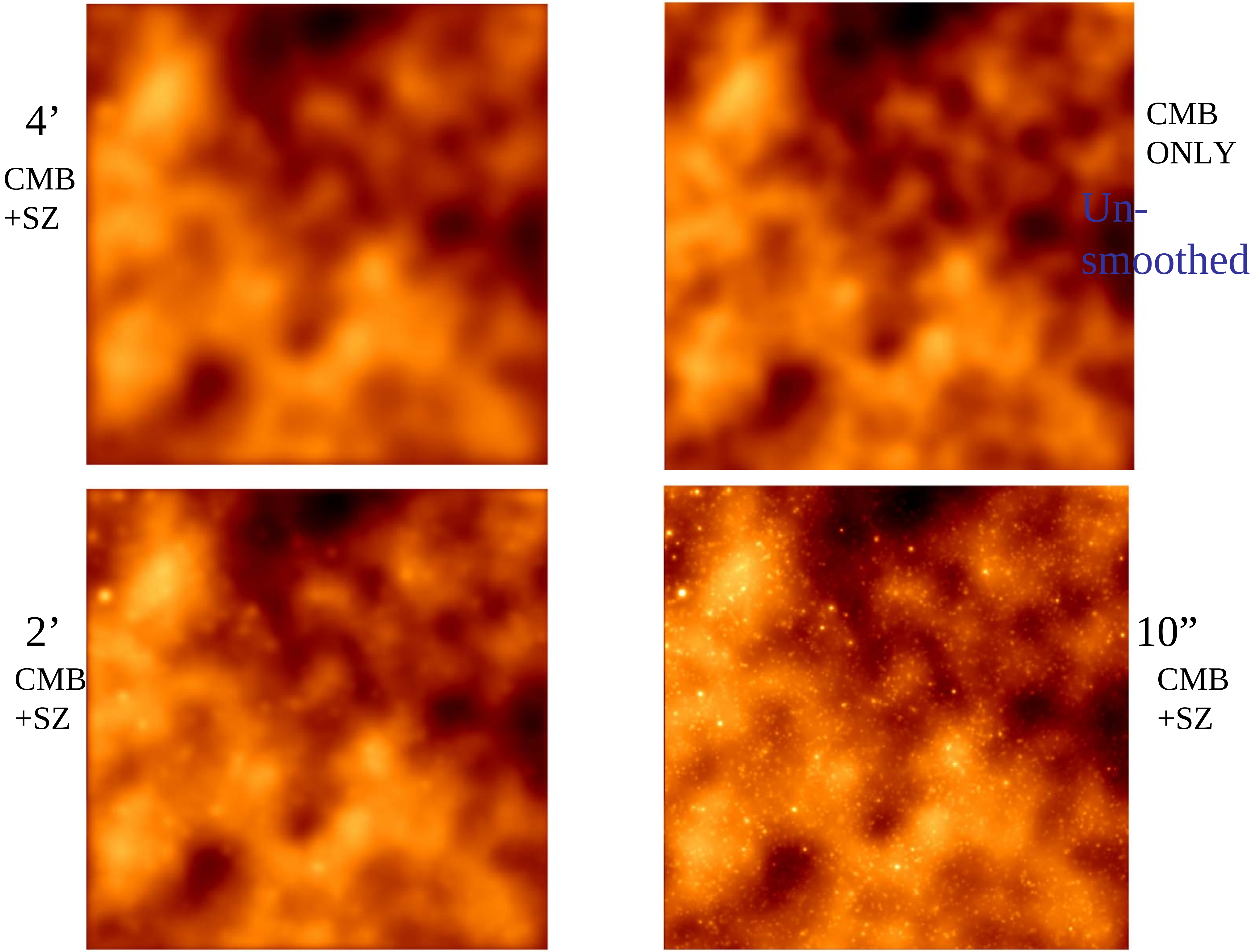
Relativistic Corrections to Thermal SZ Effect

uK imaging should allow 1 kev accuracy in

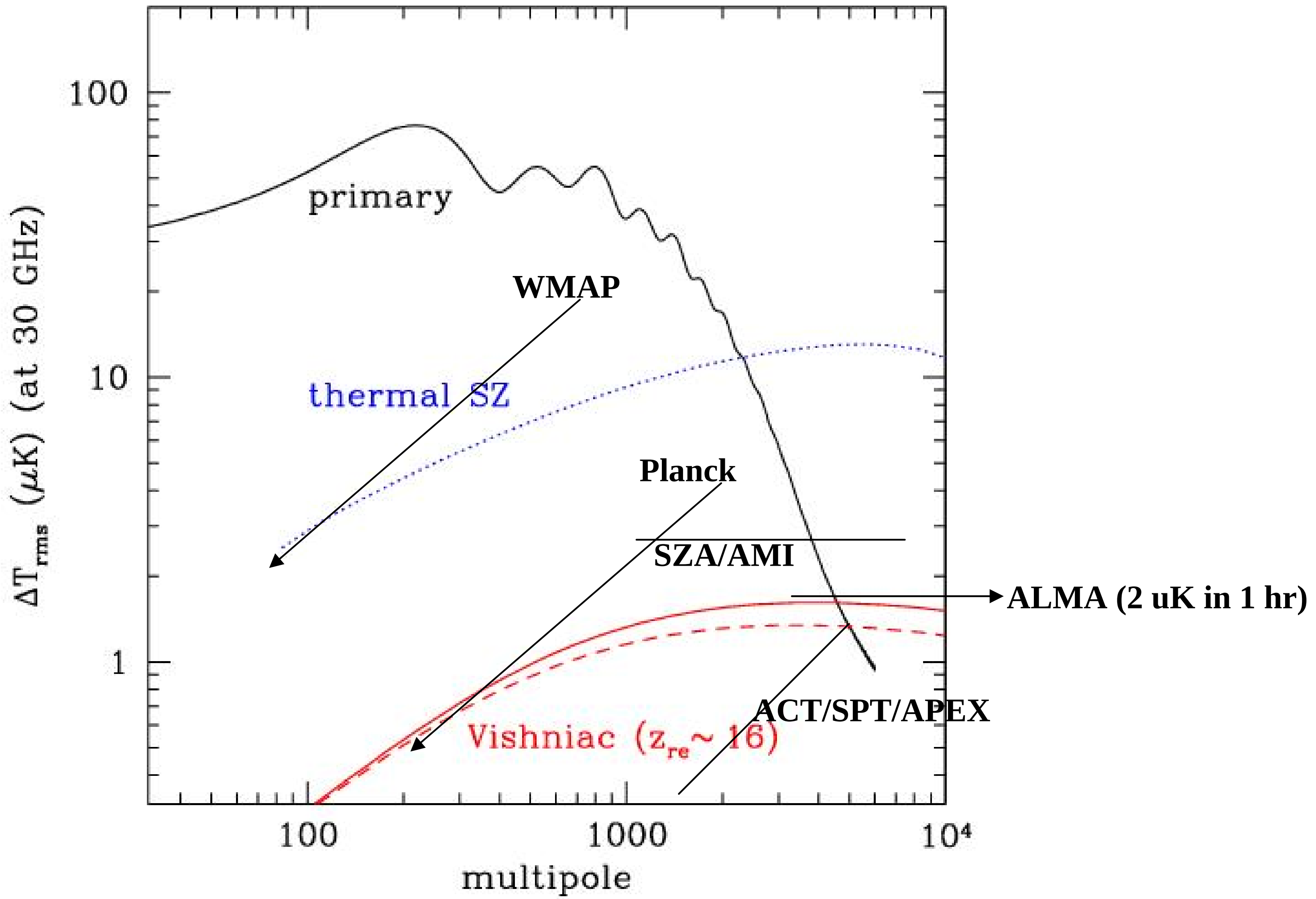
SZ temperature



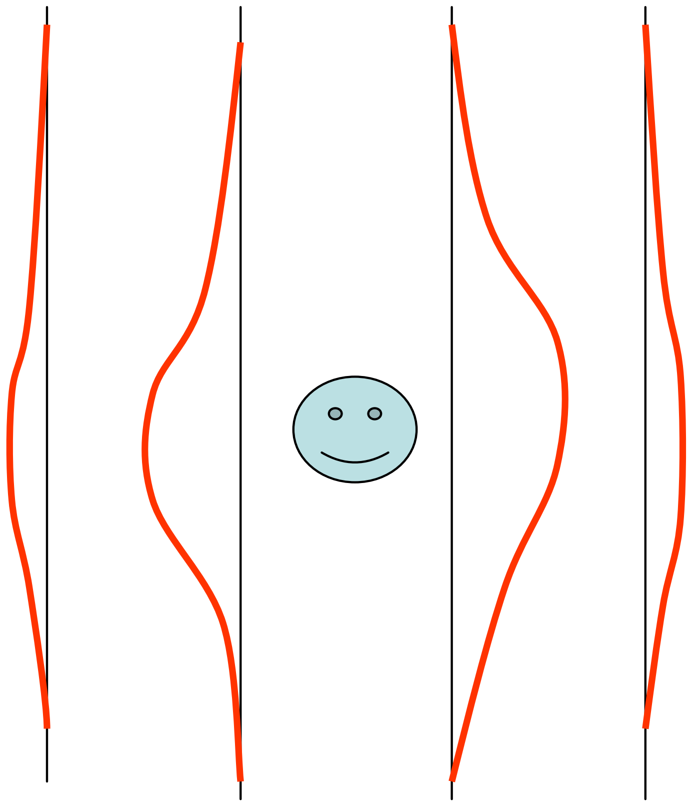
Same order of magnitude as kinetic SZ effect


4’
CMB
+SZ
CMB
ONLY
Un-
smoothed
2’
CMB
+SZ
10”
CMB
+SZ

Measuring the CMB With Upcoming Instruments



Lensing of the CMB



Typical CMB gradient

-- 10 uK/arcmin (Temp)

-- 1 uK/[1/5 arcmin] (Pol)

Typical deflection angle

-- ~ 0.1-1 arcmin

(Seljak and Zaldarriaga)

Small Small-Angle Signals…

•<u>CMB lensing</u>:

$$\Delta T \approx \phi \nabla T \approx few\, 10^{-5} \bullet few\, 10^{-2} K / rad \approx \mu K$$

$$\Delta P \approx \phi \nabla P \approx few\, 10^{-5} \bullet \frac{few}{few} 10^{-2} K / rad \approx 0.5\, \mu K$$

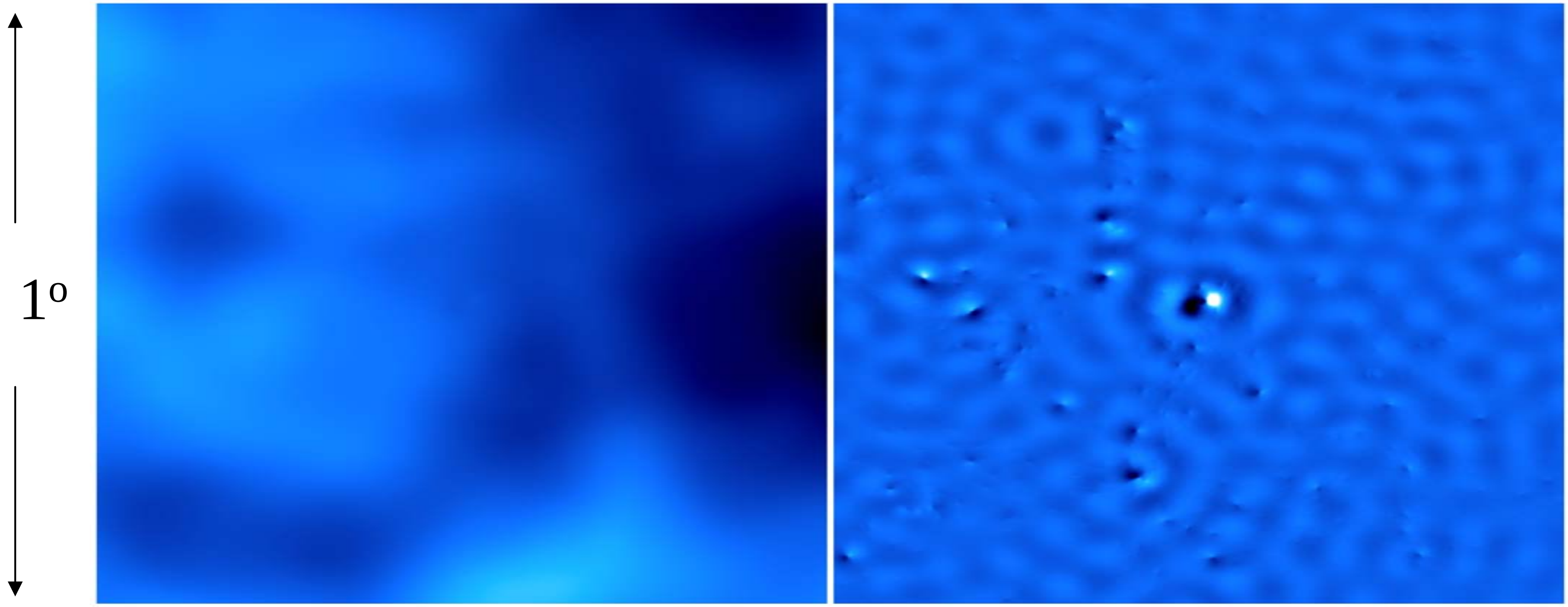
•<u>Moving cluster</u>:

$$\Delta T / T \approx \phi v / c \approx few\, 10^{-5} \bullet 10^{-3} \approx 0.1\, \mu K$$

•<u>Rees-Sciama (changing potential)</u>:

$$\Delta T / T \approx \phi\, t_{cross} / t_{cluster} \approx few\, 10^{-5} \bullet 10^{-3} \approx 0.1\, \mu K$$

What Does Lensing Look Like?



Holder & Kosowsky 2004

Lensed CMB map

(NO SZ effects etc.)

Same map high-pass filtered

(5 uK peak)

Polarization E-Modes & B-Modes

E Mode

QuickTime™ and a
decompressor
are needed to see this picture.

Pol direction at 0º or 90º to direction of change

B Mode

QuickTime™ and a
decompressor
are needed to see this picture.

Pol direction at 45º to direction of change

Kovac 2000

B Modes from E Modes

Before: pure E mode (left) and pure B mode (right)

QuickTime™ and a
decompressor
are needed to see this picture.

From B-pol.org

After: large point mass lenses image

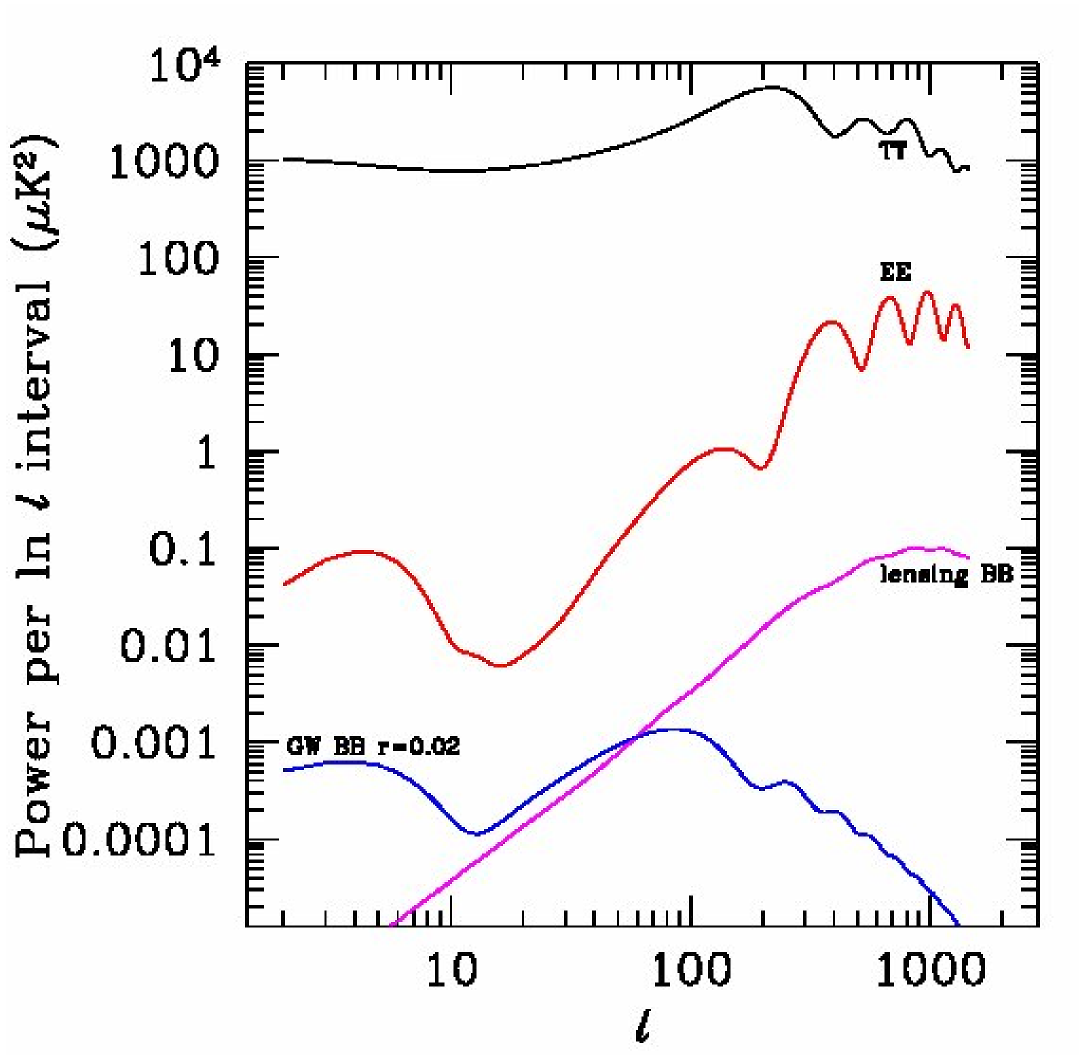
QuickTime™ and a
decompressor
are needed to see this picture.

Lensing done with "Lens an astrophysicist"

http://theory2.phys.cwru.edu/~pete/GravitationalLens/

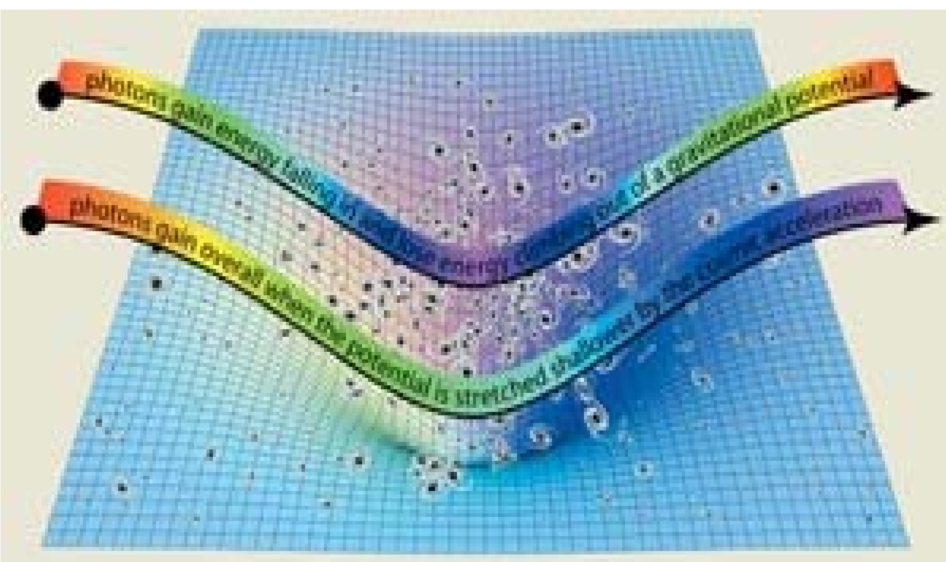
Lensing B Modes

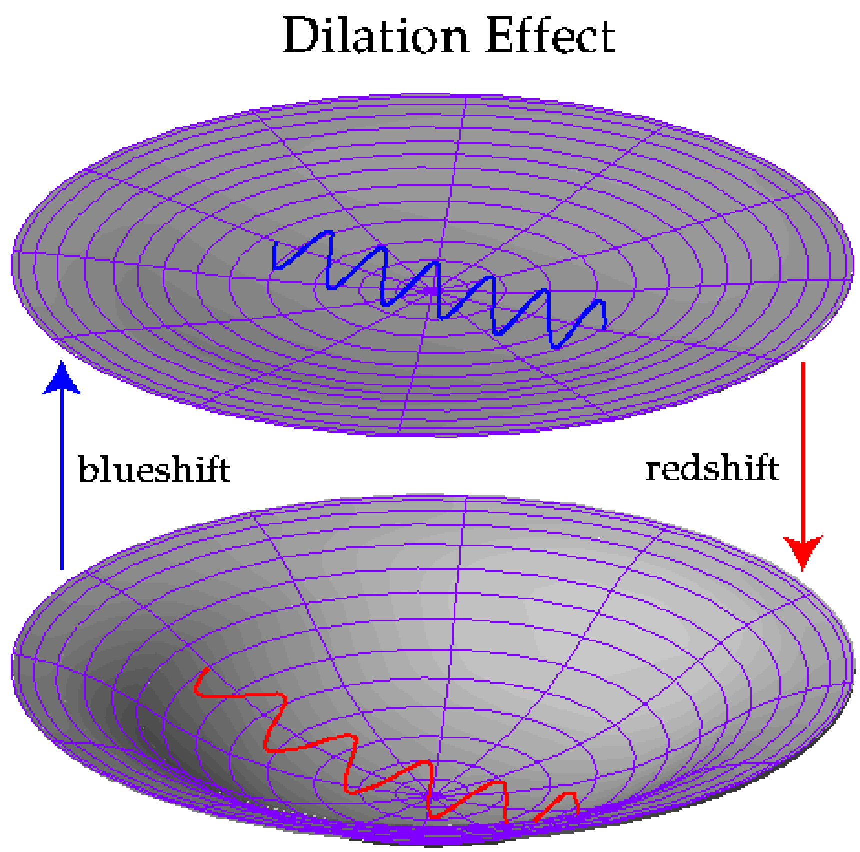
- bad foreground for primordial B modes for r<0.1
- non-Gaussian => power spectrum is not the whole story
- in principle, can clean out lensing signal with good enough measurements (need signal/noise >1 per mode to be cleaned)



Integrated Sachs-Wolfe Effect

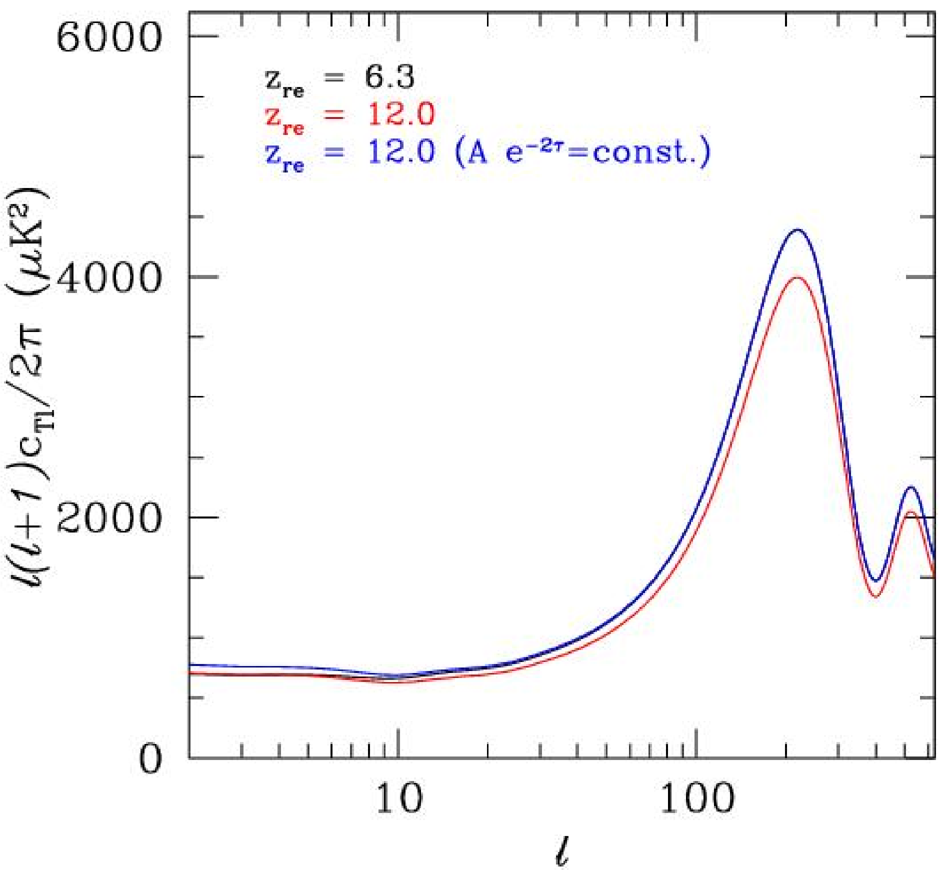
- *decay of potentials leads to differential gravitational redshifts*
- *potentials only decay when universe is not matter-dominated; I.e., today (dark energy dominated)*
- *possible probe of dark energy properties*



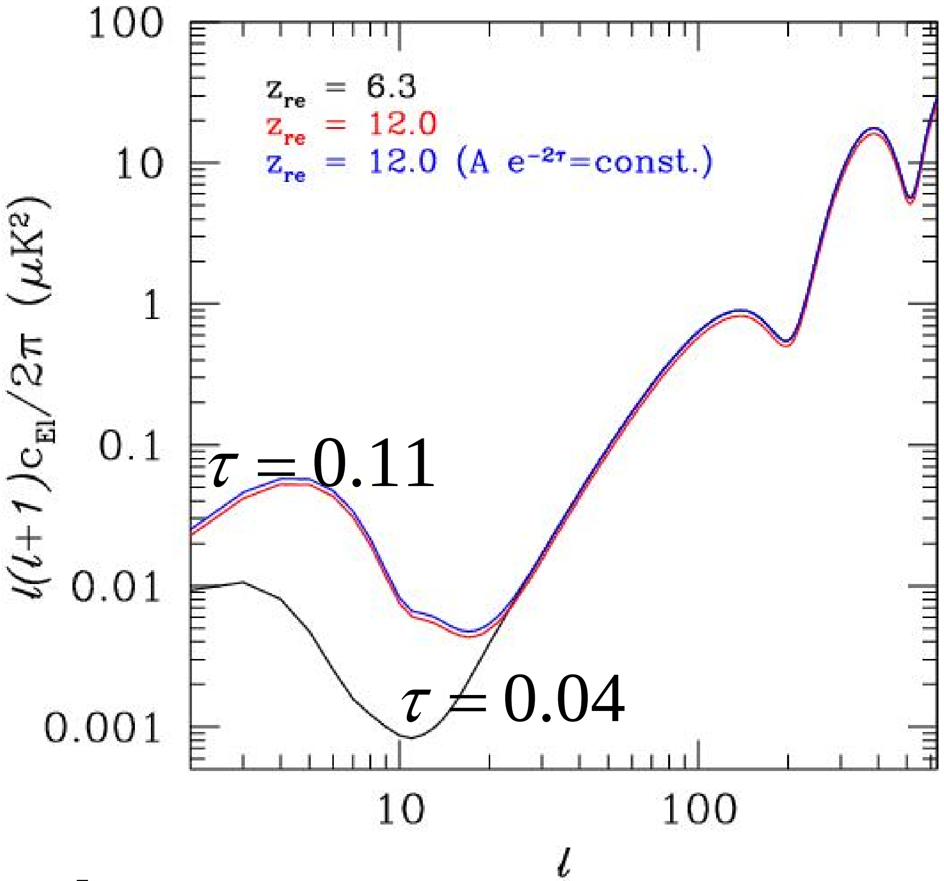


Hu & Scranton 2004

Reionization and the CMB



temperature



polarization

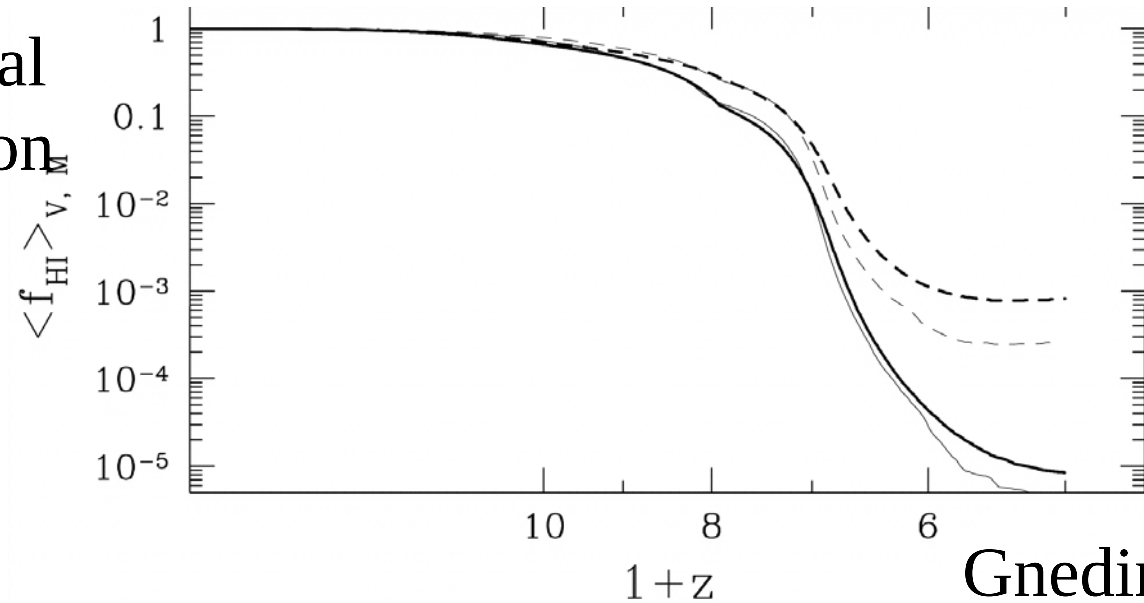
WMAP: +- 0.03 ; Planck: +-0.005 ; ???: +-0.002

Ionization and CMB Polarization

- Thomson scattering: Unpolarized quadrupole radiation field leads to linearly polarized scattered signal
- Reionization leads to scattering of CMB photons (optical depth 10-20%)
- On all scales perturbations reduced
- Scattering of quadrupole leads to linear polarization on scale comparable to horizon at time of scattering
- Zaldarriaga 1997

Ionization History I

Neutral fraction



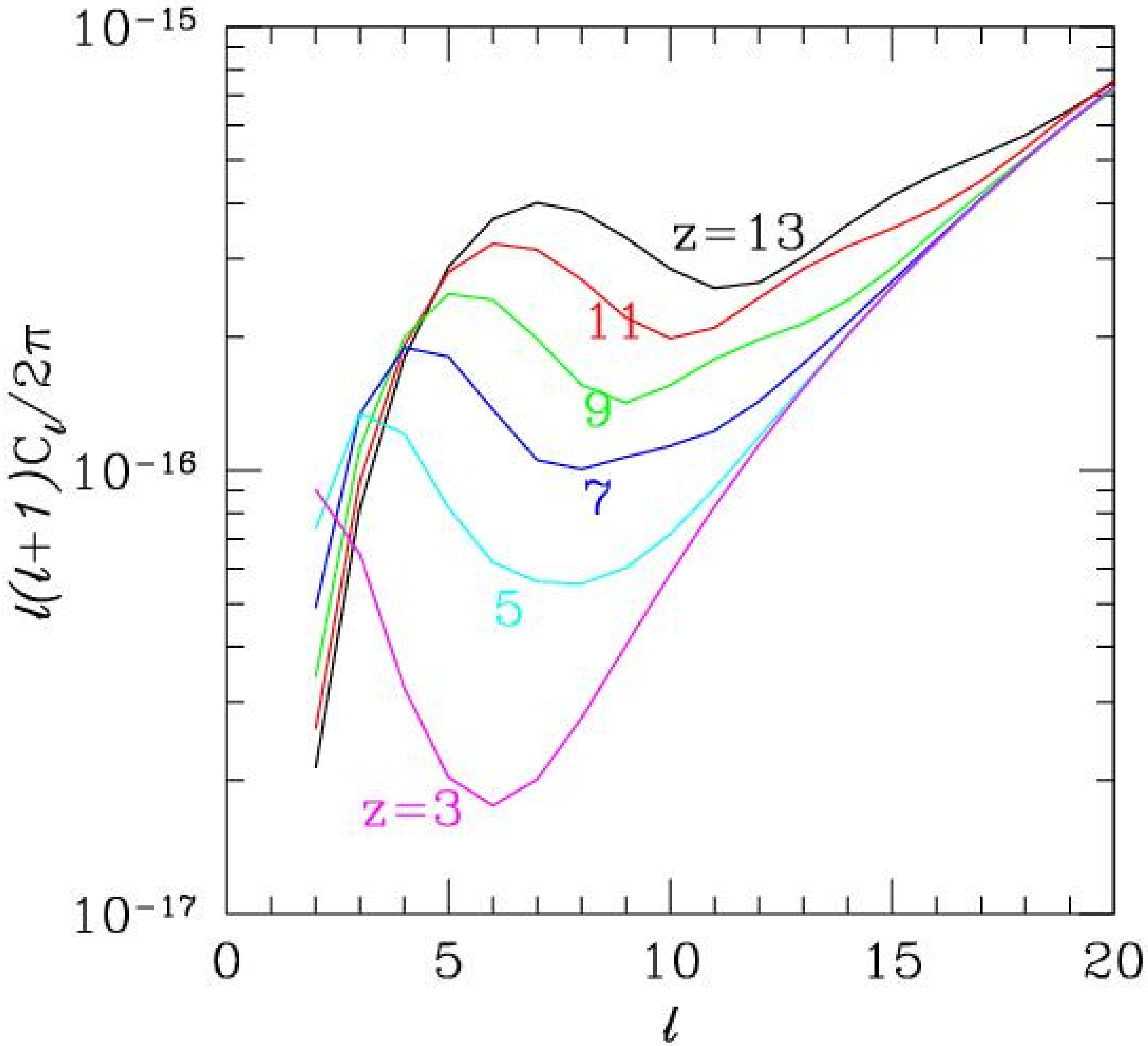
Gnedin 2000

• reionization happens fast!

• to match SDSS quasars, needed late reionization (Cen & McDonald, Fan et al, Gnedin; all 2002)

Ionization and CMB Polarization

“Pulse” of ionization dz=1

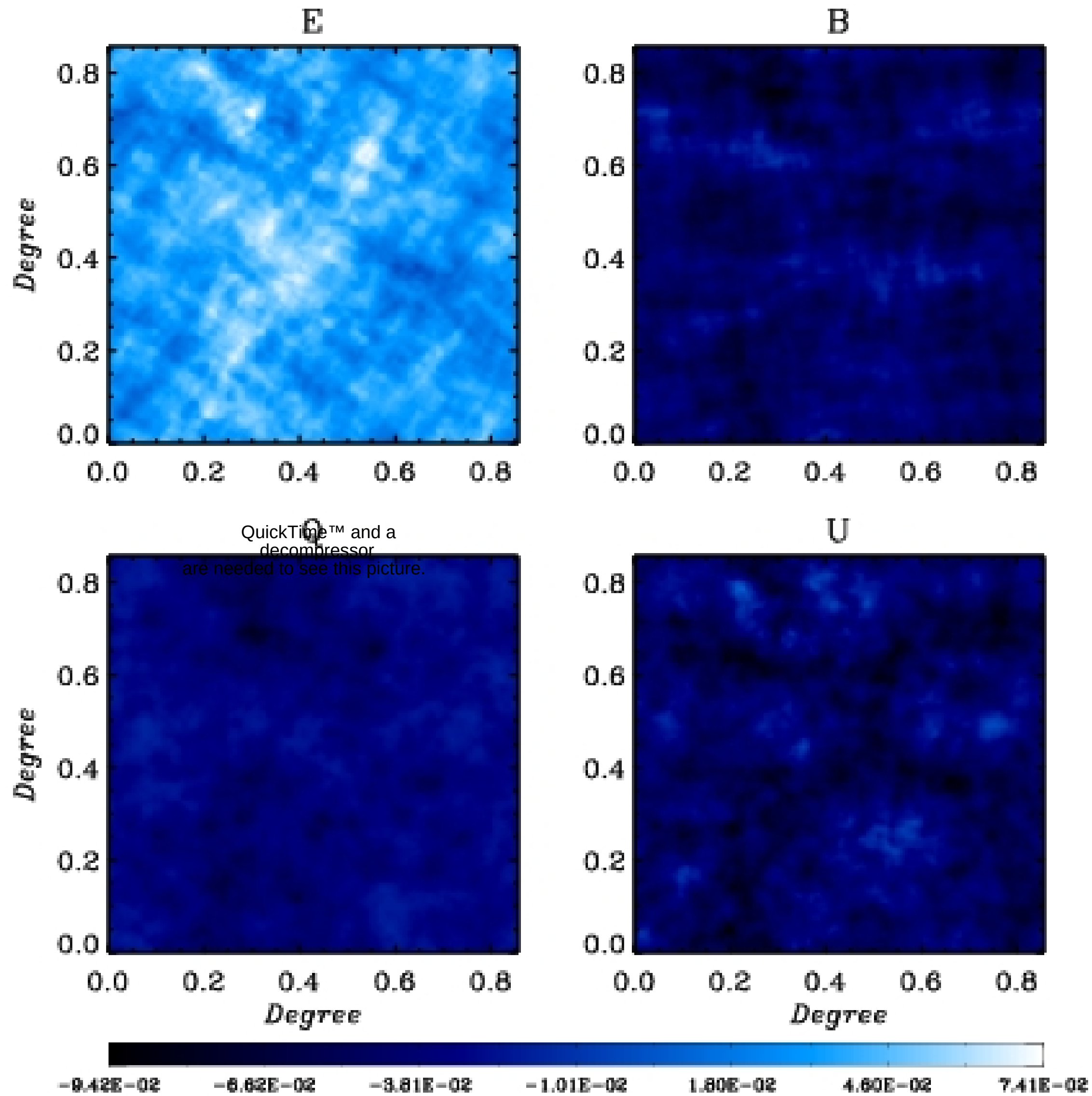


Reionization bump tells you about reionization!

(very coarsely, and in a foreground-laden part of the CMB spectrum)

CMB Pol. & Patchy Reionization

- Unlikely to be a problem for inflation B modes
- Patchy reionization signal below lensing!
- Nearly equal E&B: most of the patchy signal from a narrow range in z



Summary

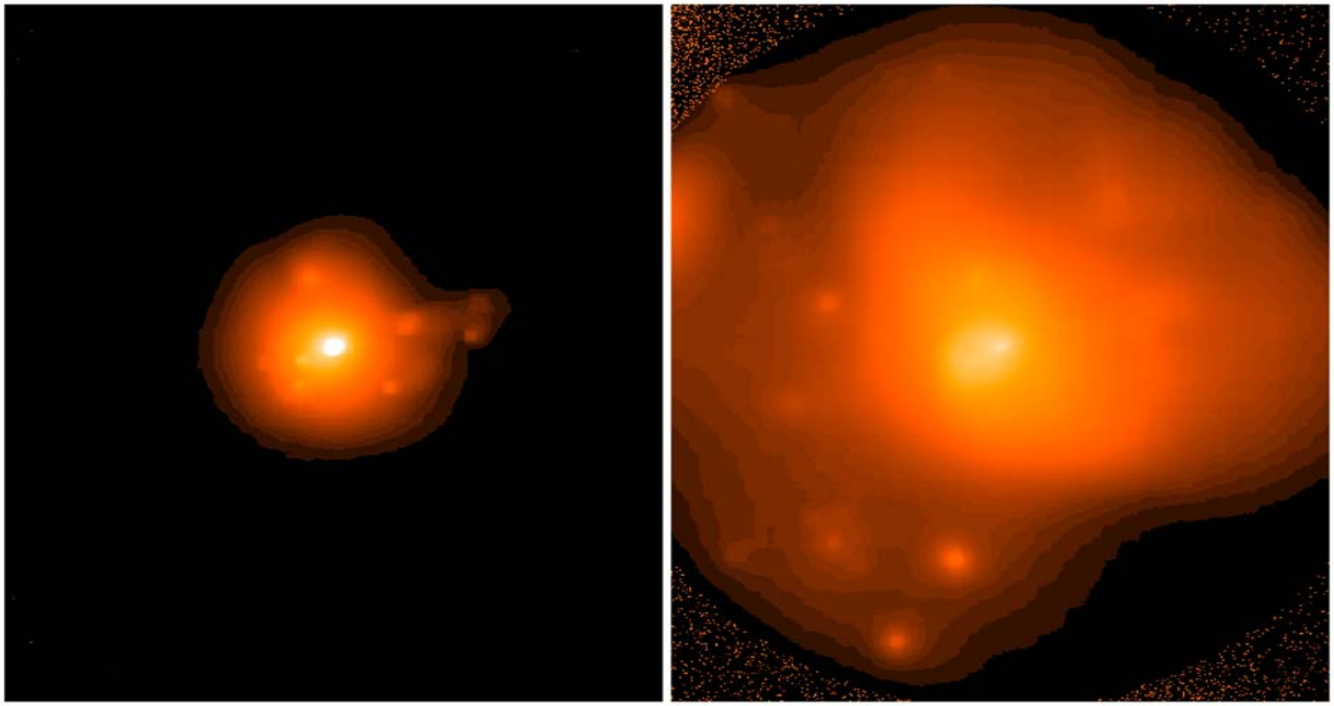
- Foregrounds (new photons)
  - Free-free (bremsstrahlung) - low freq, low pol
  - Synchotron - low freq, high pol
  - Dust emission - high freq, high pol
  - Point sources (amalgam of other 3) - low AND high freq, ?pol
  - The southern hole - 2% of the sky is very clean
- Secondaries (redshifting, scattering)
  - Compton scattering on electrons
    - Bulk electron motions (Ostriker-Vishniac, kinetic SZ)
    - Thermal electron motions (thermal SZ)
    - Induced polarization (large scales, small scales)
  - Gravitational redshifting
    - Evolving potentials (ISW, Rees-Sciama)
  - Gravitational lensing

Cool things, let's measure them

Light Scattering in the ICM

- Roughly 1% of all photons traversing a cluster get scattered
- Quadrupole anisotropy in radiation leads to polarized scattered light
- What is the local radiation field in a cluster? (e.g., *bright central AGN*)

13’



Polarized scattered light thermal SZ

-Assume 1 Jy central source (at 1 cm)

- Assume unbeamed, steady

-Log stretch (0.1 uK - mK)

- Unique radial polarization pattern
- Huge amplitude: polarized mK in central arcminute (i.e., few mJy of polarized flux)