Title: Simulations of the Microwave Sky

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Abstract: New high-resolution, cosmological-scale simulations of the microwave sky have been created based on the most recent observational data. Currently these imulations are in use by the ACT team to test their data analysis pipeline. These simulations are also flexible enough to be of use to SPT and Planck. We discuss the various components of the simulations, their construction, and comparison to observational data.

Simulations of the Microwave Sky

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Motivation for Simulations

- Current and upcoming microwave experiments with complex data analysis pipelines (ACT, SPT, Planck)
- Microwave science from power spectrum, SZ clusters, and cross-correlations of microwave components
- Useful to run simulations through the same data analysis pipeline to verify accurate recovery of known inputs and cosmology
- This necessitates high-resolution, cosmological-scale, microwave simulations that include the most accurate astrophysical components current observations will allow

Simulation Components

- Primordial microwave background lensed by intervening structure between last scattering surface and observers today
- Thermal SZ signal from hot gas in galaxy clusters
- Kinetic SZ signal from bulk motion of galaxy clusters and intergalactic medium
- Higher-order relativistic corrections to the thermal and kinetic SZ signal from galaxy clusters
- Dusty star forming galaxies that emit largely in infrared but have significant microwave emission
- Radio galaxies, such as active galactic nuclei, that have significant microwave emission
- Dust, synchrotron, and free-free emission from the Galaxy

Simulation Components

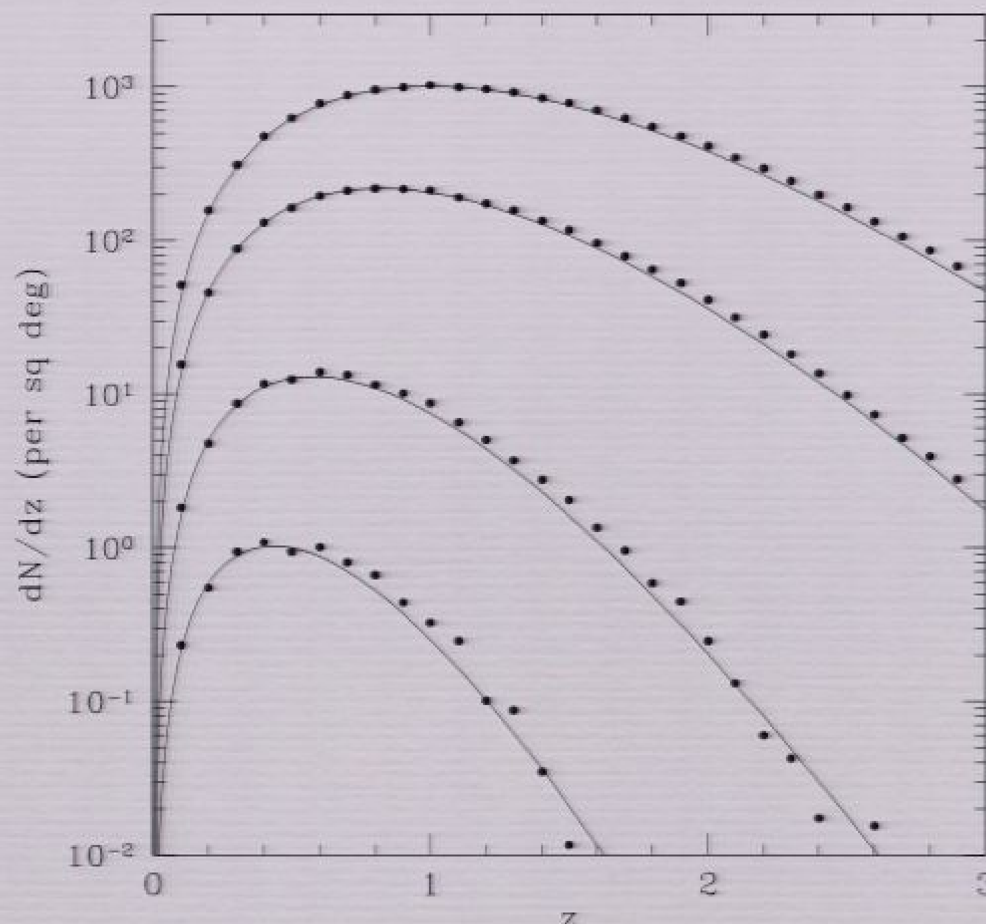
- Format: HEALPix full-sky with Nside=8192 (resolution= 0.4')
- Frequencies: 30, 90, 148, 219, 277, and 350 GHz
- Catalogs of all the halos and their properties (ra, dec, redshift, mass, radius, integrated SZ signal etc.)
- Catalogs of all the radio and infrared galaxies and their properties (ra, dec, redshift, flux in each band)
- Large-scale structure is made for one octant of full sky and mirrored eight times

Recent Improvements

- input cosmology based closely on WMAP5 parameters
- radio and infrared galaxy populations are clustered and correlated with the galaxy cluster populations
- the primordial microwave background has been lensed by the dark matter structure in the N-body simulation via a ray-tracing code
- the contribution to the kinetic SZ signal from the intergalactic medium has been included, in addition to that from galaxy clusters
- the gas prescription to model the SZ signals has been refined
- easy to use HEALPix format
- more frequencies to widen applicability to SPT and Planck

Large-Scale Structure Simulation

- TPM code (Bode et al. 2000; Bode & Ostriker 2003)
- Cosmology consistent with WMAP5 results
- Volume is 1000 Mpc/h on a side and particle mass is $6.8 \times 10^{10} h^{-1} M_\odot$
- Particles covering one octant are saved so for comoving distances larger than 1000 Mpc/h have some duplication of structure
- Halos down to FOF mass of $1 \times 10^{13} M_\odot$ and below z < 3 included



Comparison with Jenkins et al. 2001
Mass limits from top to bottom:
$M_{min} = (0.07, 0.2, 1, 3) \times 10^{14} M_\odot / h$

Figure credit: Hy Trac

Lensing of the Primary CMB

- CMB has same WMAP5 cosmology as LSS
- For l < 20, alm's from WMAP5 ILC map
- Lensing done with ray-tracing code (Das and Bode 2008)

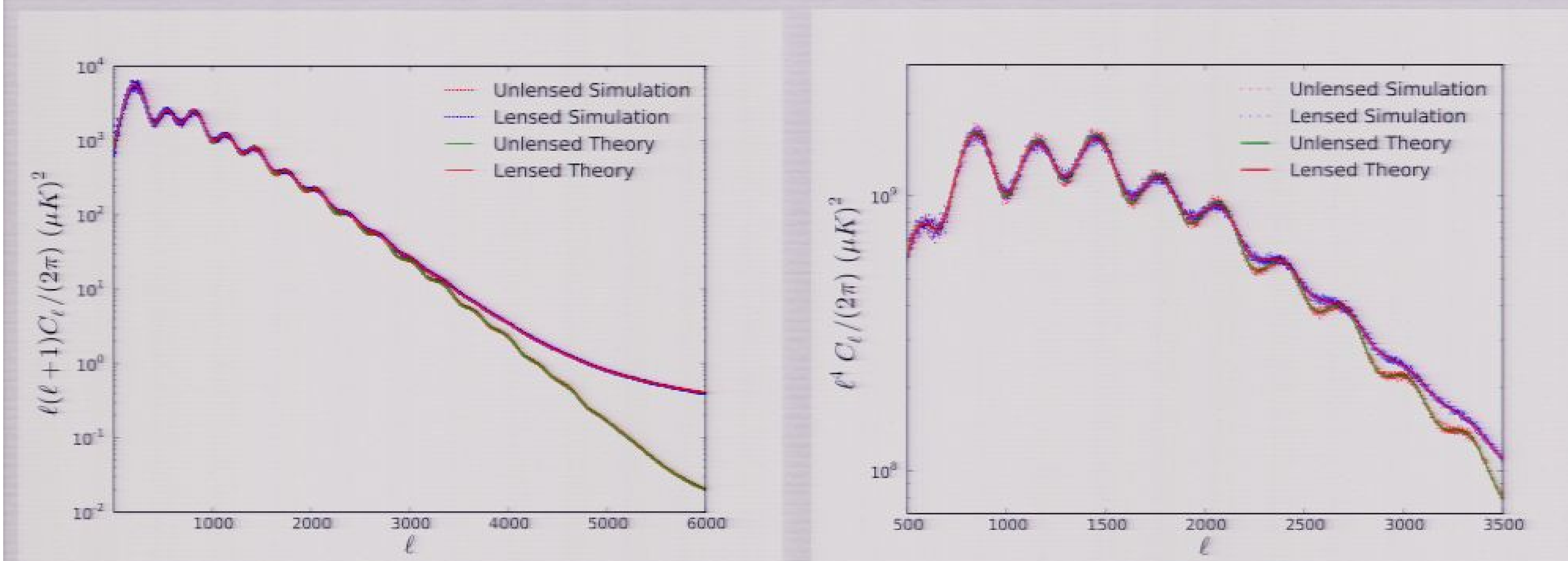


Figure credits: Sudeep Das

Lensing of the Primary CMB

Motivation for ray-tracing:

1.) Measurement of lensing distortions in the CMB leads to reconstruction of projected matter distribution (sensitive to dark energy density and neutrino mass)

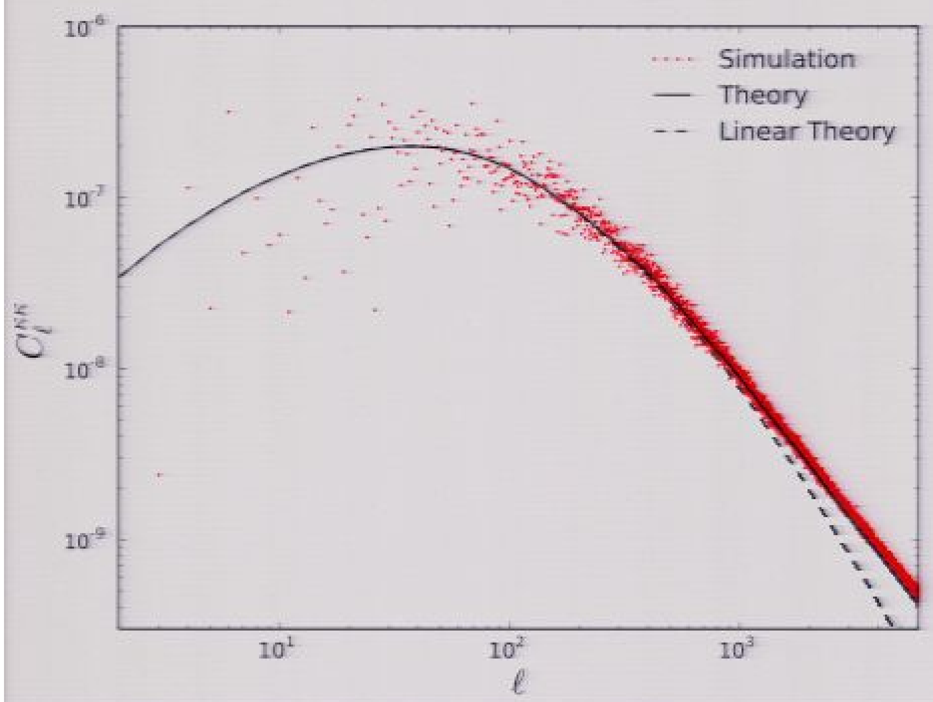
2.) Cross-correlation of CMB lensing with tracers of large-scale structure informs understanding of structure formation and gravity on large scales

Requires CMB lensing which is internally consistent with LSS and secondary components (SZ signals, infrared and radio galaxies)

Lensing steps

- Generate a surface overdensity for each shell - over 400 shells (time slices)
- Use above to generate effective convergence map for octant; for contributions beyond farthest shell use Gaussian random realization based on theoretical power spectrum
- Replicate octant to make full sky convergence map
- From convergence map, generate deflection field
- Use deflection field to lens CMB

Lensing of the Primary CMB



Power spectrum of simulated effective convergence map compared to theory curves from CAMB

Difference map between lensed and unlensed CMB maps

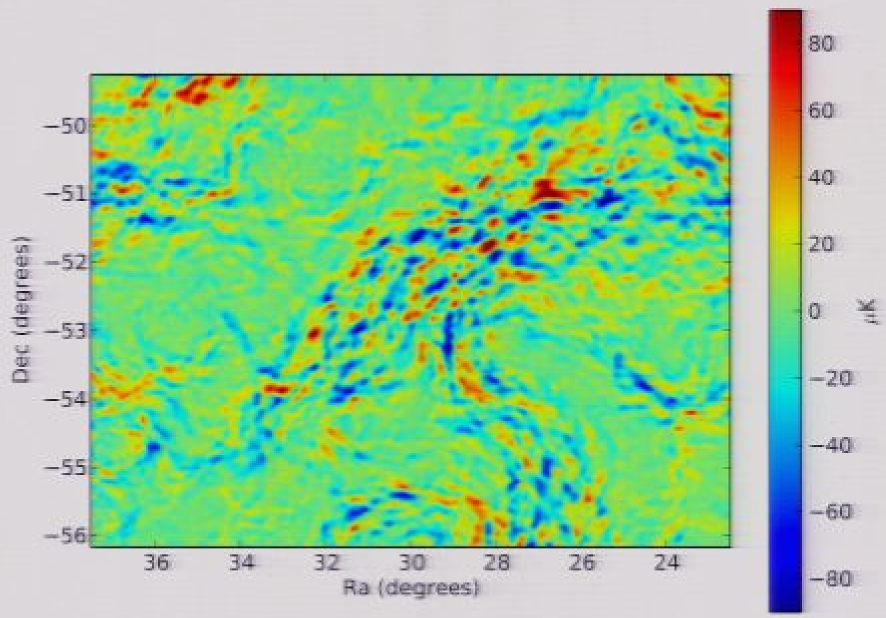


Figure credits: Sudeep Das

SZ Signal

- SZ model described in Bode, Ostriker, Vikhlinin in prep (see Paul's talk) and Trac et al. in prep
- Assumes polytropic equation of state and hydrostatic equilibrium
- Four free parameters: star formation rate (depends on halo mass and redshift), non-thermal pressure, dynamical energy transfer from dark matter to gas, feedback from AGN (depends on star formation rate)
- Model calibrated with X-ray gas fractions as function of temperature (Sun et al. 2009, Vikhlinin et al. 2006)

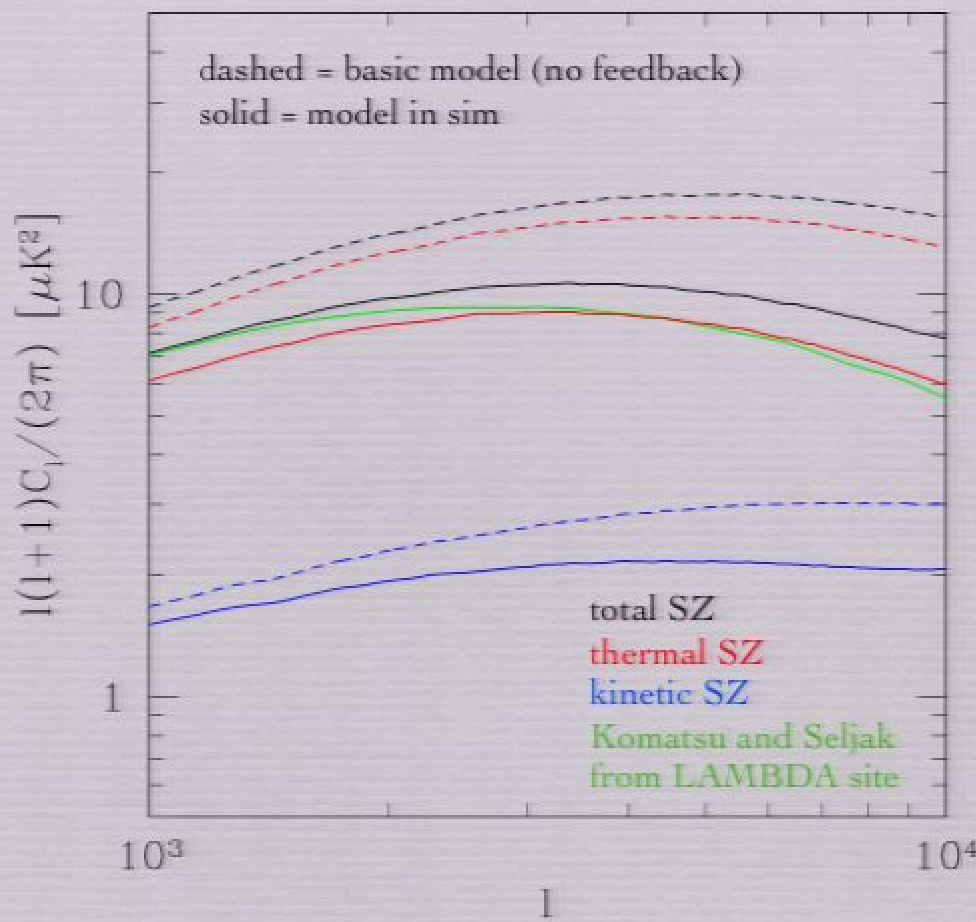


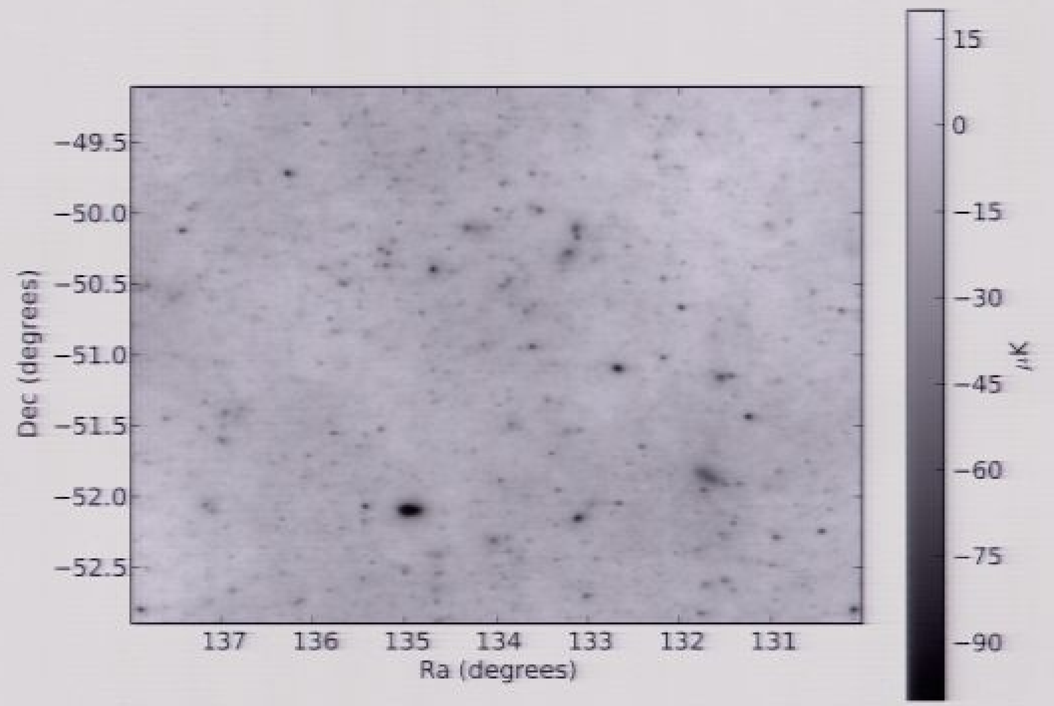
Figure credit: Hy Trac

SZ Signal

- Halos with FOF mass $> 3 \times 10^{13} M_{\odot}$ and with z < 3 made with method described above

- For smaller halos to $1 \times 10^{13} M_{\odot}$ and IGM, calculated the effective pressure (from velocity dispersion) and line-of-sight momentum

- For the 3 < z < 10 universe the temperature is assumed to be 10^4K (because did not have effective pressure of particles). KSZ has significant contribution from this redshift range.



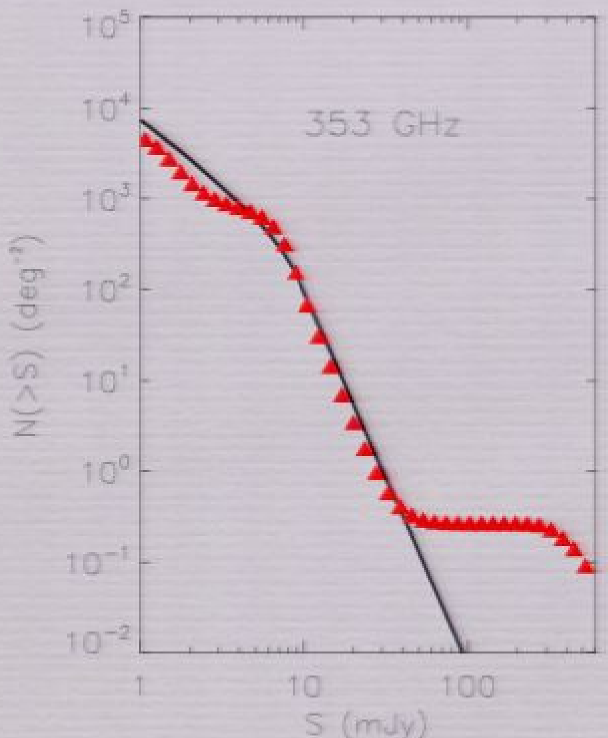
Sim map of SZ signal at 148 GHz

Infrared Point Sources

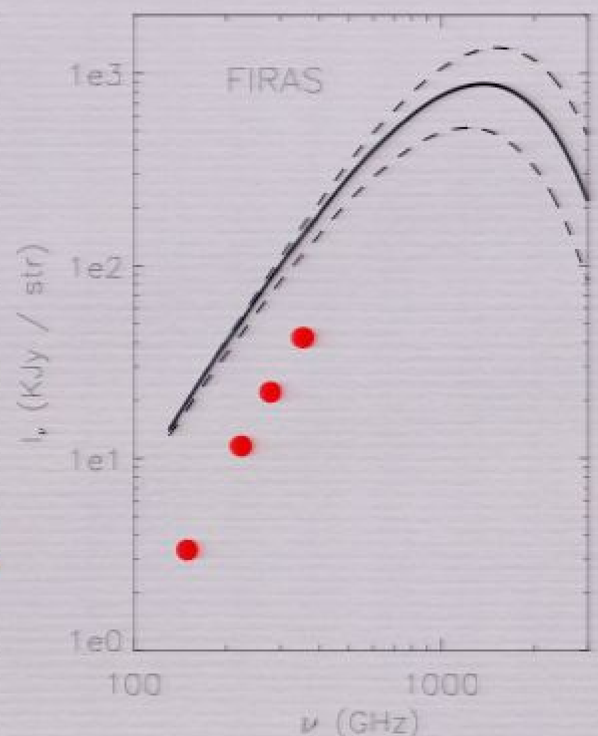
- Model for infrared sources partially based on Righi et al. 2008
- 6 parameter model to populate halos which must satisfy the following observational constraints:
  - COBE/FIRAS infrared background as in Fixsen et al. 1998 must be upper limit of total infrared intensity
  - Effective spectral index for the spectral intensity $(I_\nu \propto \nu^\alpha)$ should be close to $\alpha \sim 2.6$ between 145 and 350 GHz (Knox et al. 2004, Dunne et al. 2000)
  - Source counts must be compatible with SCUBA counts at 353 GHz in flux range from 1 to 50 mJy (Choppin et al. 2006)
  - Source counts must be compatible with BLAST high flux population
  - Power of infrared sources cannot exceed upper limit from ACBAR (Reichardt et al. 2008)

Infrared Point Sources

Black line is best-fit to SCUBA counts, red is model; Counts at high flux match recent BLAST data



Model underpredicts FIRAS background due to lack of halos below $1 \times 10^{13} M_\odot$ in simulation



Thick black line is clustering term; thin black is poisson term; red is total; blue is ACBAR limit

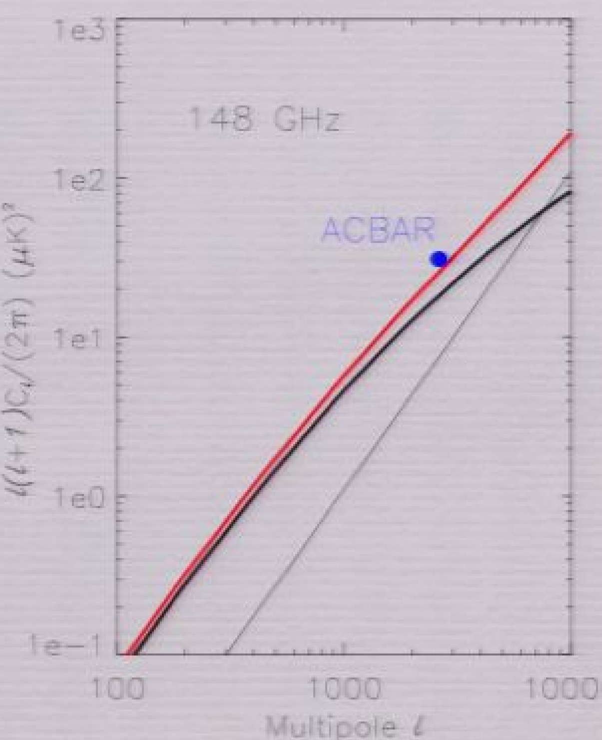


Figure credits: Carlos Hernandez-Monteagudo

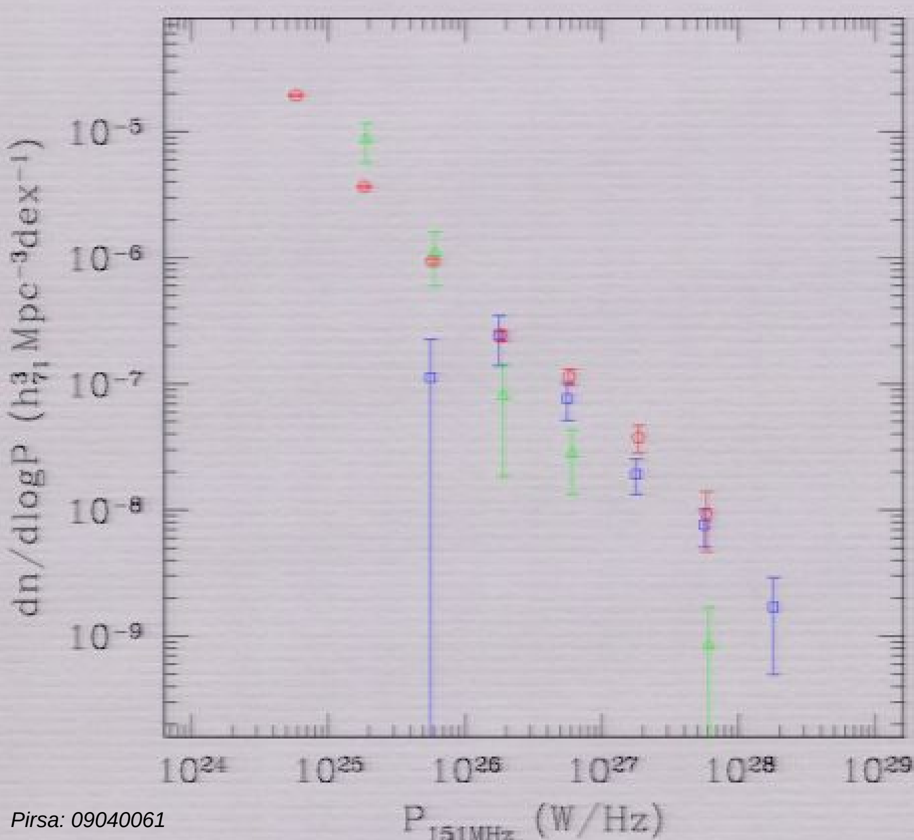
Radio Point Sources

- We create a radio source model which reproduces the local 151 MHz radio luminosity function (RLF) at z~0.1
- The RLF is a convolution of the halo mass function, halo occupation number, and radio luminosity distribution of sources
- We parameterize the halo occupation number and luminosity distribution, and adjust the parameters to match the RLF
- Then we divide the sources into two populations with differing density evolutions with redshift and match the source counts at various frequencies
- For a more complete description of the model see Lin et al. in prep and next talk

Radio Point Sources

The 151 MHz radio luminosity function at z < 0.3. Green and blue points are two populations of radio sources from the 3CRR survey (Laing et al. 1983).
Red is our model.

1.4 GHz data from Katgert et al. 1988, Windhorst et al. 1993, Bondi et al. 2003, and Huynh et al. 2005.
33 GHz data from Wright et al. 2009, Cleary et al. 2005
95 GHz model from de Zotti et al. 2005.
145 GHz data from ACBAR (Reichardt et al. 2009)
Red is our model.



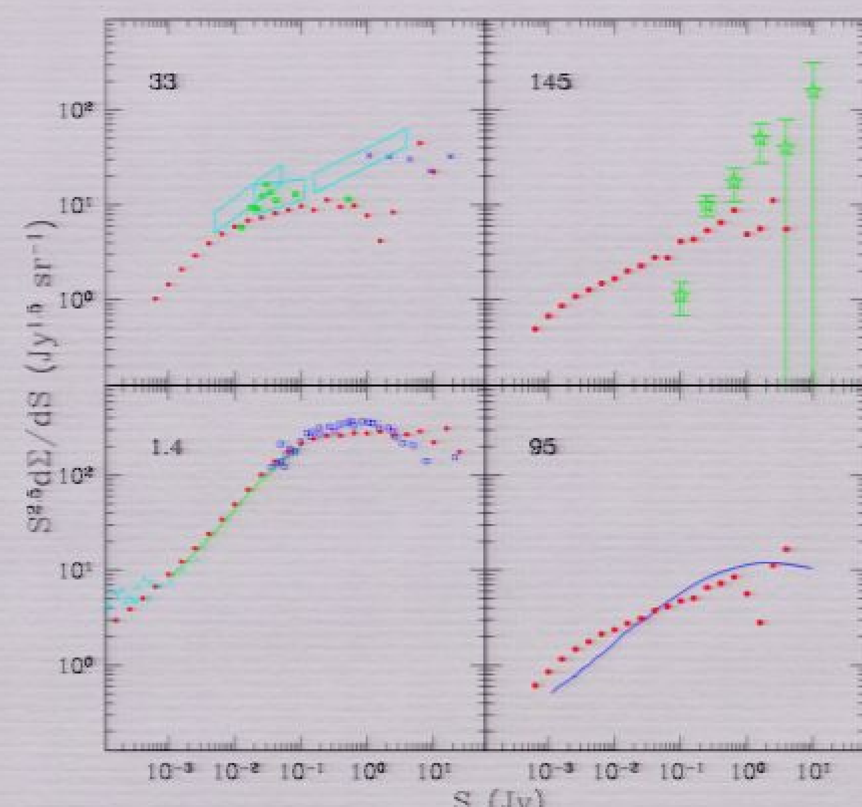
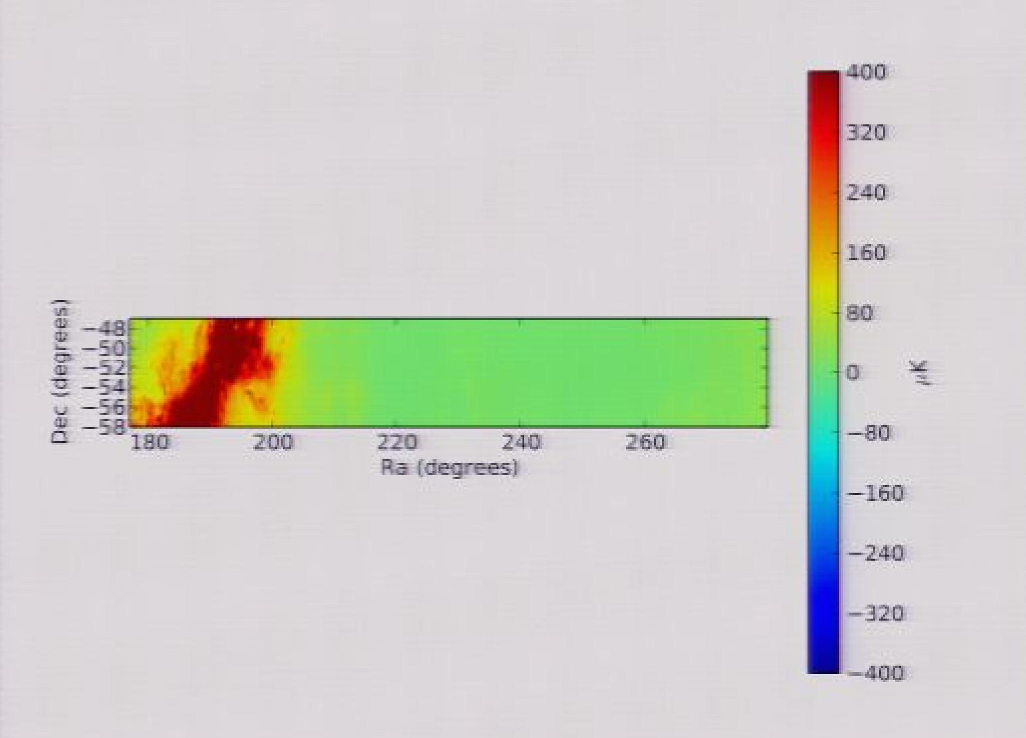


Figure credits: Yen-Ting Lin

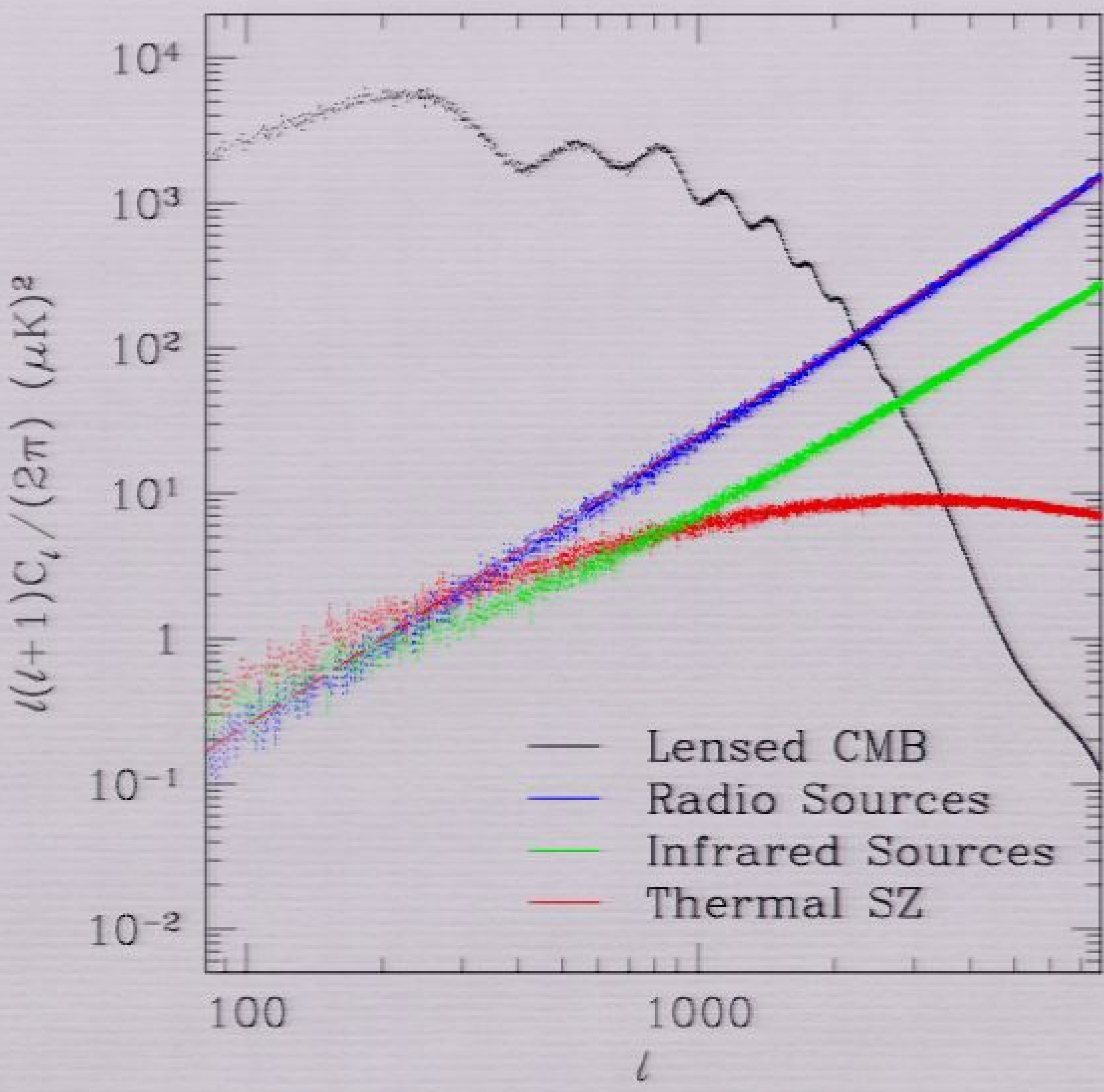
Galactic Emission

- Use "model 8" prediction from Finkbeiner et al. 1999, which is an extrapolation to microwave frequencies of dust maps from Schlegel et al. 1998
- The model is a two-component fit to IRAS, DIRBE, and FIRAS data
- Bennett et al. 2003 show this model to be a reasonable template for dust emisson in WMAP maps
- Plans to add synchrotron and free-free emission under consideration



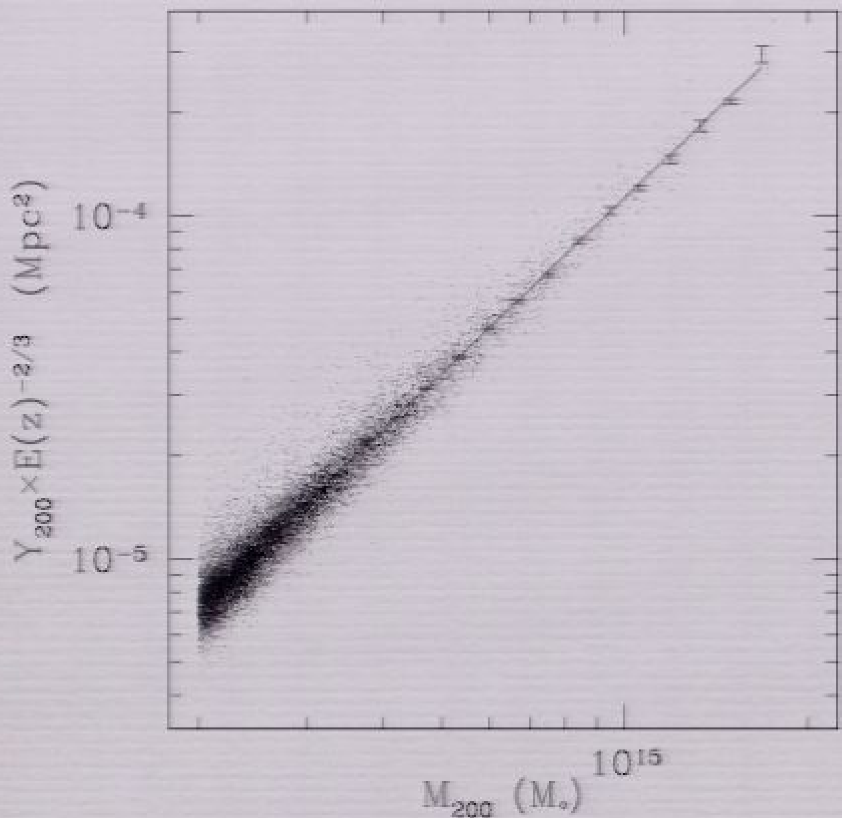
Power Spectra

- Can see clustering of infrared sources at low ell. BLAST has detected this clustering of dusty galaxies at higher frequencies (Viero et al. 2009)
- Power spectrum of radio sources matches Toffolatti et al. 1998 rescaled by 0.64, which was shown to be a good fit to WMAP5 source counts by Wright et al. 2008 (dashed red line)



Power spectra at 148 GHz

Y-M Relation



$$\frac{Y_\Delta}{E(z)^{2/3}} = 10^\beta \left(\frac{M_\Delta}{10^{14} M_\odot}\right)^\alpha$$

Expect α to be 5/3 for self-similar relation

Scatter is roughly 15-20% for $M_\Delta > 2 \times 10^{14} M_\odot$

Best-fit parameters and scatter for Y-M relation for $M_\Delta > 2 \times 10^{14} M_\odot$

Relation	α	σ_α	β	σ_β	Reduced χ^2	Clusters	Bins	σ_{YM}
$Y_{200} - M_{200}$	1.696	0.004	-5.647	0.002	1.8	12970	19	0.15
$Y_{500} - M_{500}$	1.679	0.009	-5.504	0.004	2.8	4900	8	0.18
$Y_{500} - M_{200}$	1.708	0.004	-5.765	0.002	1.9	12970	19	0.14

Summary

- New full sky HEALPix simulations of the microwave sky at six frequencies have been created
- They include all the significant microwave components matched to most recent observations
- Each component has a separate map, and there is also a combined sky map - allows flexibility to use only some components or insert differing model for any component
- These sims are used by the ACT team to test their analysis pipeline, and hopefully can be of use to other CMB experiments
- Plan is to make sims public soon

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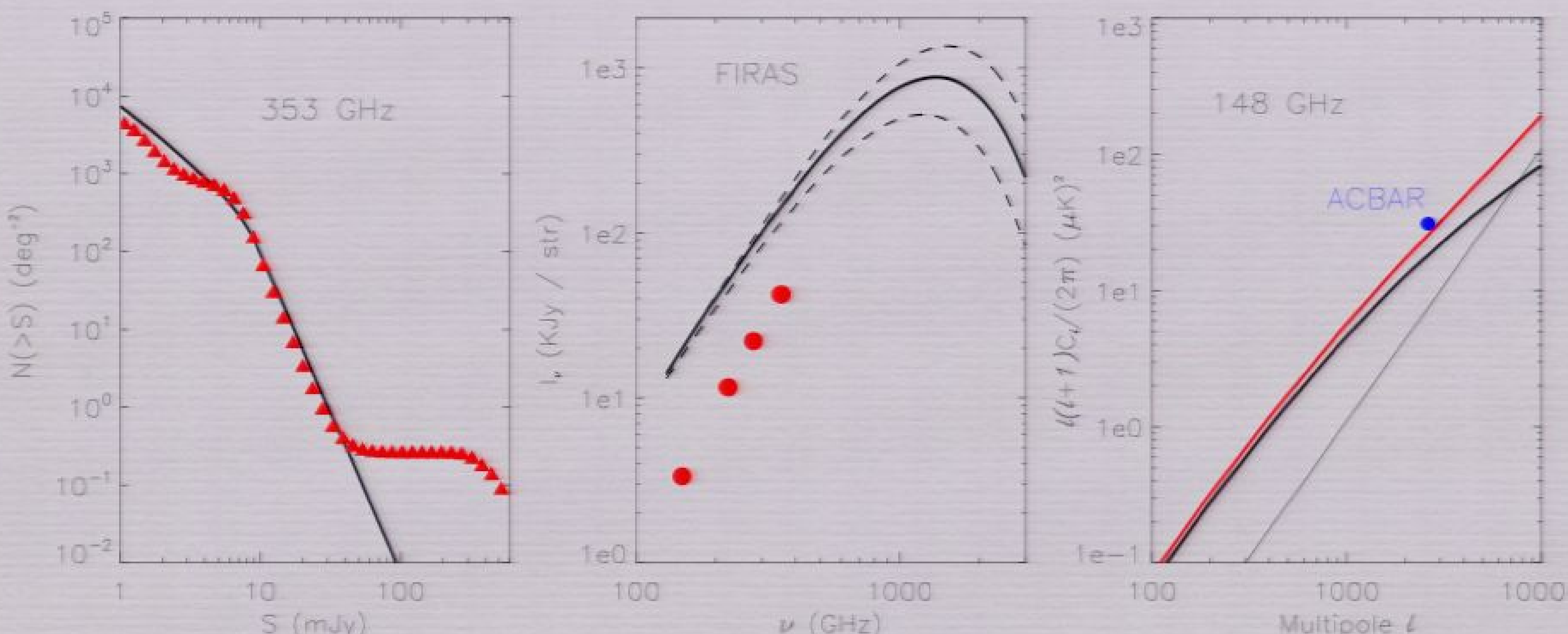

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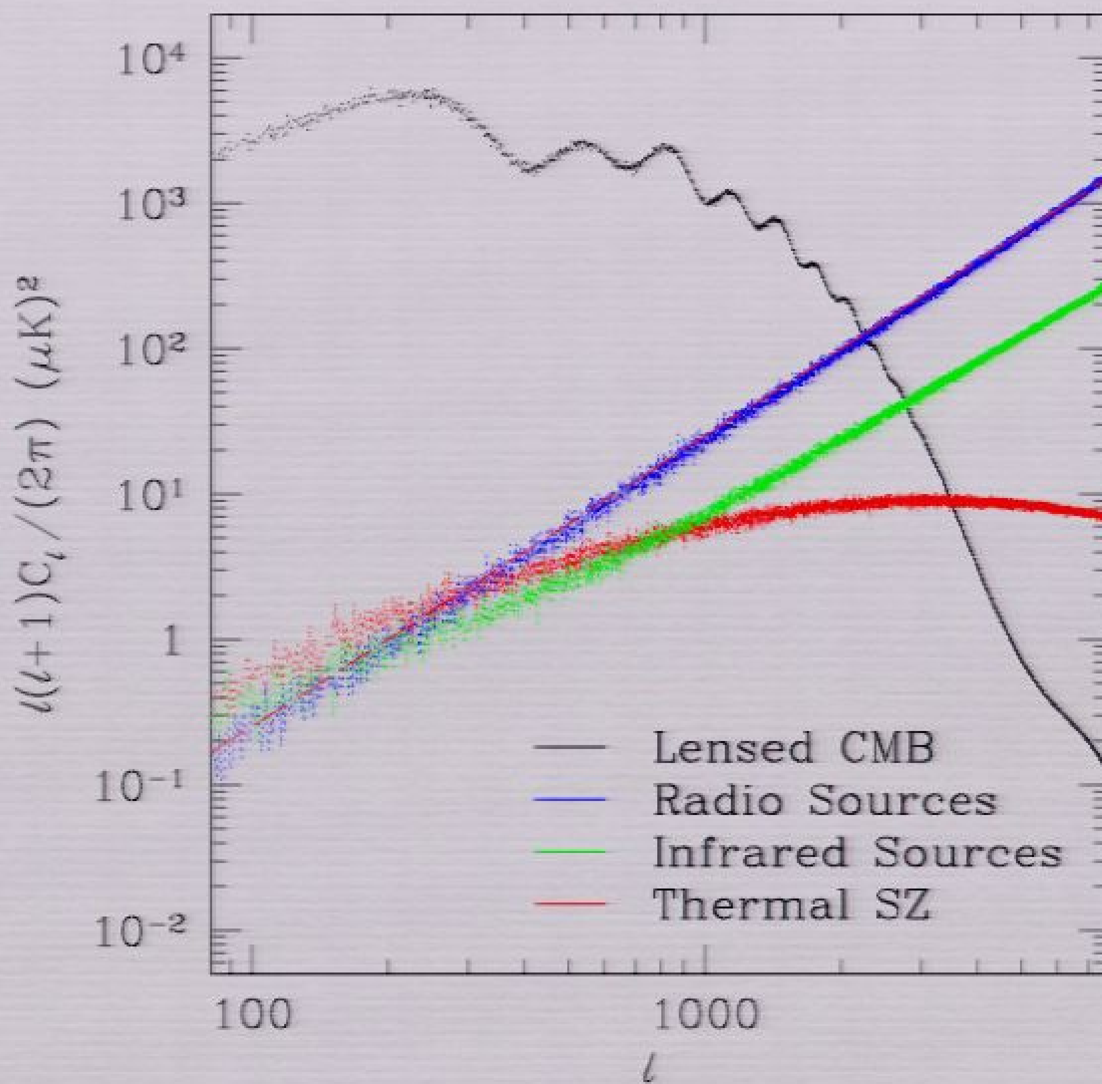

Power spectra at 148 GHz

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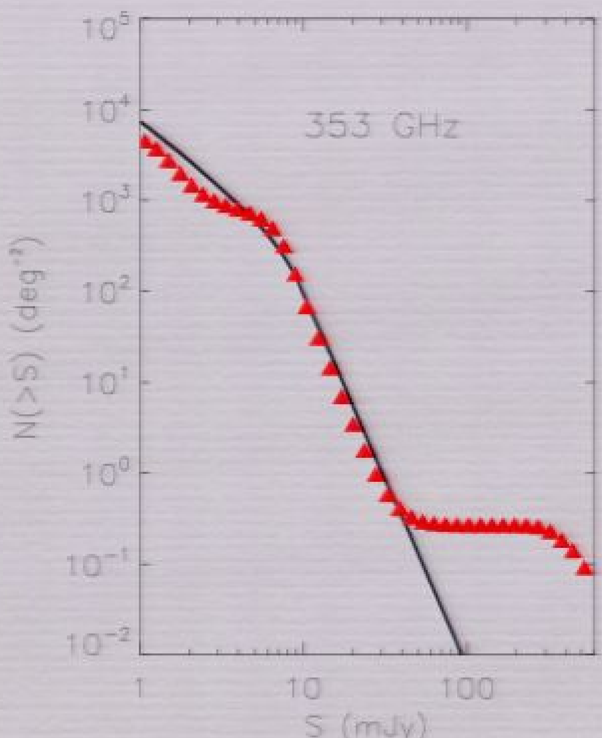

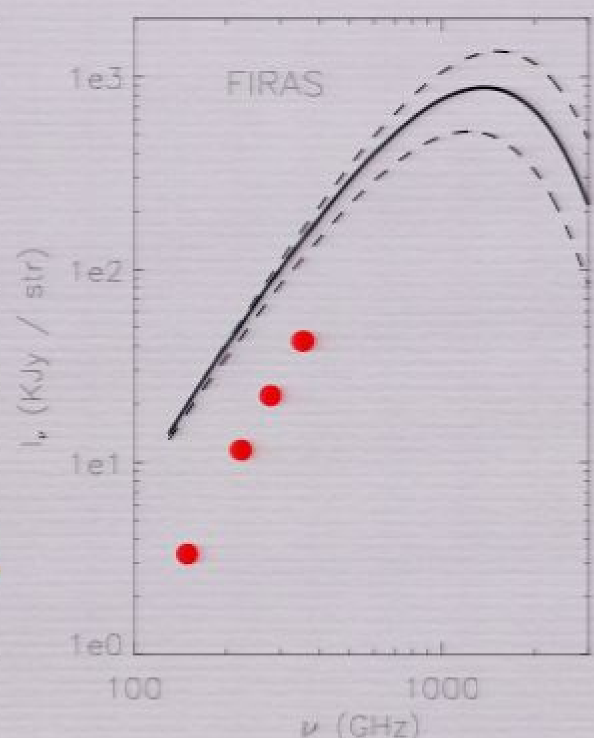

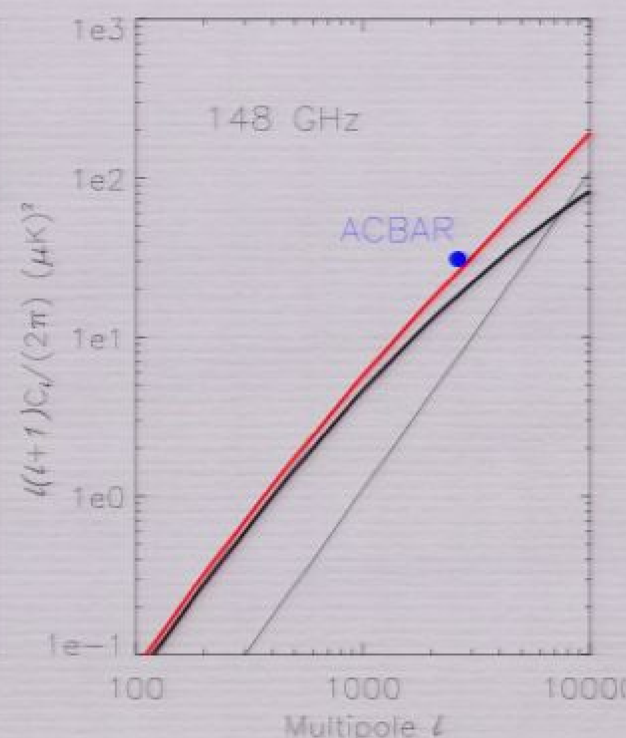

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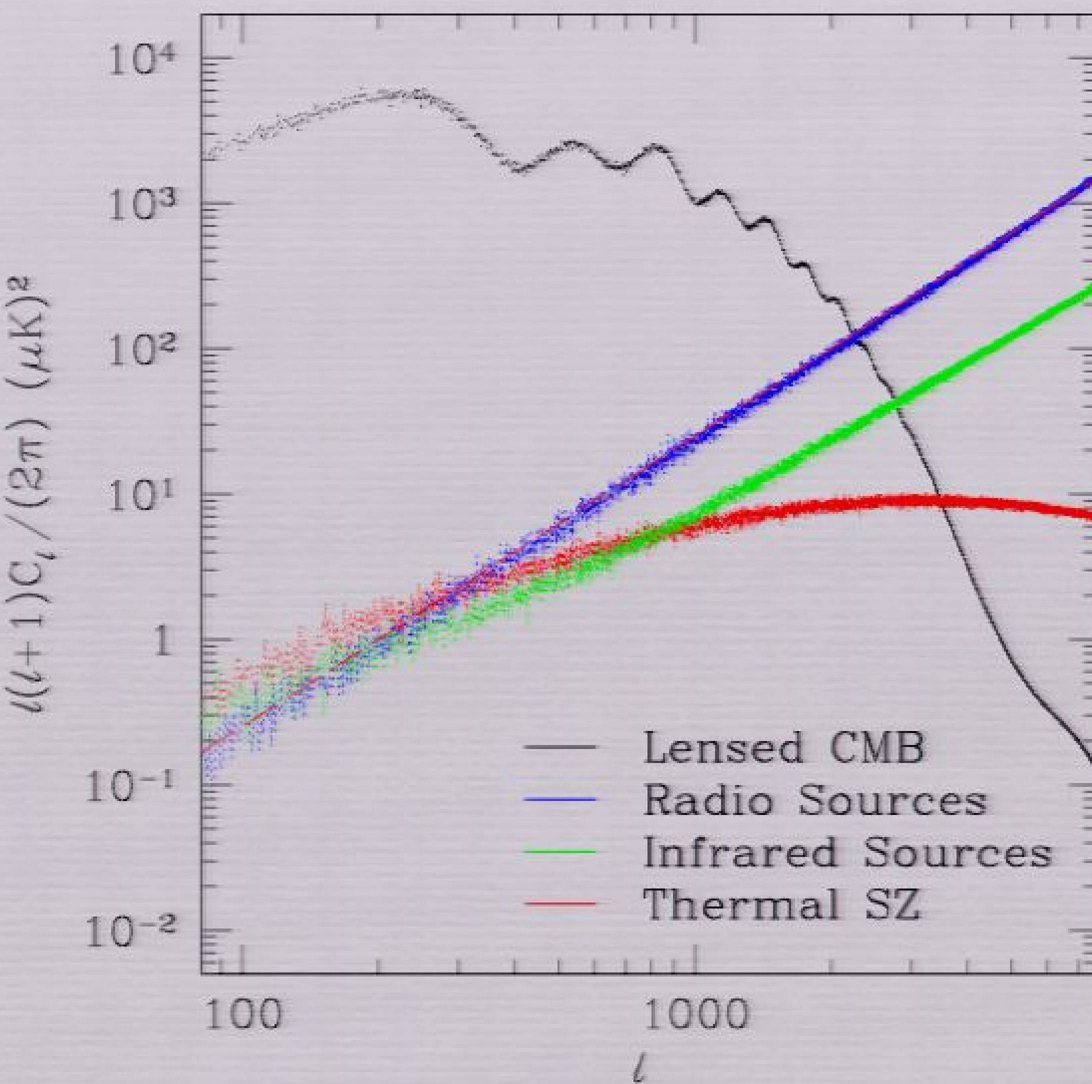

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