Microwave Foregrounds

One of the main challenges facing microwave experiments is to distinguish the cosmological signal from the foreground contamination.

Definition: what is a Foreground and what is a Signal? Where should we draw the line?

Historically, the CMB community agrees that effects occurring around or before recombination ($z \sim 10^3$) constitute a signal, whereas dust, free-free and synchrotron radiation (regardless if they are Galactic in origin or not) are foregrounds.

When taking a more goal-oriented approach, where the goal is to measure cosmological parameters, the issue is not when or how the signal was calculated, but how reliably it can be calculated. Therefore, a more operational definition of foreground was created:

A foreground is an effect whose dependence on cosmological parameters we cannot compute accurately from first principles at the present time.

Objectives: why people study foregrounds?

Accurate modeling and subtraction of the foreground contamination in order to correct the measured CMB power spectrum. To do a good job on removing foregrounds, we need to understand their frequency and scale dependence, frequency coherence, and better characterize their non-Gaussian behavior.

Unique opportunity to understand non-cosmological processes on the microwave frequencies.

Foregrounds discussed on this review:

At Judd's request, non-cosmological processes between 1-100 MHz, or Galactic foregrounds (dust, free-free and synchrotron radiation).

Chris' talk yesterday: Diffuse metal & molecular emission foreground.

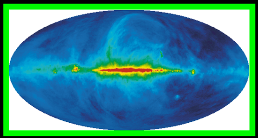
Ali's talk on Thursday: Radio sources ???

Microwave Foregrounds

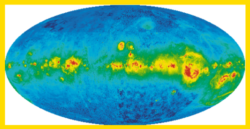
Our knowledge of Galactic foregrounds improved substantially since the COBE era. Whereas older models were mainly based on extrapolations from frequencies far outside the CMB range, a number of statistically significant detections of cross-correlation between CMB maps and various templates allow us to normalize many foreground signals directly at the frequencies of interest.

What are the Emission Mechanisms associated to the Galactic foregrounds?

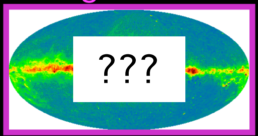
Synchrotron, 408 MHz

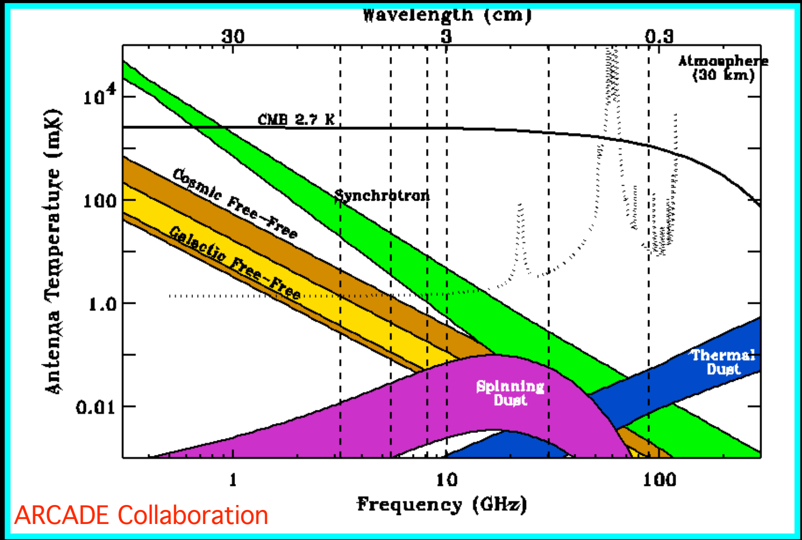


Free-free, 460 THz

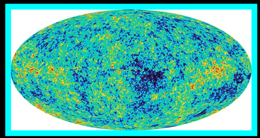


Foreground-X

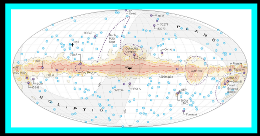




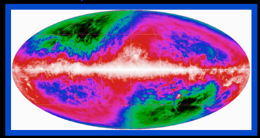
CMB



Point Sources



Dust, 3000 GHz

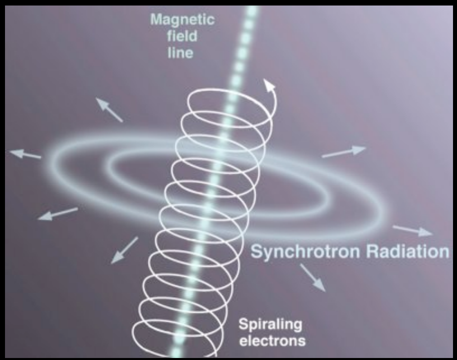


Notation: We defined C_l in the usual manner, as the variance of the amplitude of the fluctuations in the l-th multipole. We then model the power spectra of all components as power laws,

$$C_l = A\,\nu^{\alpha}\,l^{\beta}$$

Microwave Foregrounds

Our knowledge of Synchrotron Emission:



Electromagnetic radiation emitted by relativistic charged particles curving in magnetic field. Two of its characteristics include non-thermal power law spectra and polarization.

Foregrounds are model as power laws: $C_l = A\, \nu^{\alpha}\, l^{\beta}$

The spectral index ν depends on the energy distribution of the relativistic electrons, therefore it varies across the sky. It is also expected a spectral steepening towards higher frequencies, corresponding to a softer electron spectrum (Banday & Wolfendale, 1981).

Unpolarized Synchrotron Emission (slopes α and β):

Haslam 0.408 GHz ($\theta \sim 1^{\circ}$) : $\alpha = -2.8$ +/- 0.15 (Platania et al. 1998) and $-3.0 < \beta < -2.5$ (TE96, Bouchet et al. 1996).

Foreground X !!!

Reich & Reich 1.4 GHz ($\theta \sim 35'$) + Haslam : $-3.2 < \alpha < -2.9$ and $-3.0 < \beta < -2.6$ (La Porta et al. 2010).

Rhodes 2.3GHz ($\theta = 20'$) : $\alpha \sim -2.8$ with strong variation across the sky suggests and $\beta = -2.92$ +/-0.07 (Giardino et al. 2001).

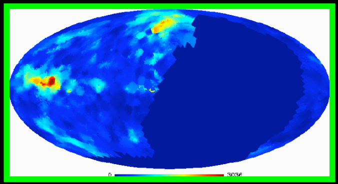
There is a good agreement between the WMAP K-band & the extrapolated Haslam 0.408 MHz map (Page et al. 2007).

Microwave Foregrounds

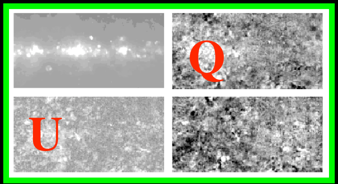
Polarized Synchrotron Emission (slopes α and β):

Foregrounds are model as power laws: $C_l = A\,\nu^{\alpha}\,l^{\,\beta}$

Brouw & Spoelstra 1976



Duncan et al. 1997



Analysis of the:

Leiden 0.408 – 1.4 GHz ($\theta \sim 2.3^{o} - 0.6^{o}$),

MLGS 1.4 GHz ($\theta \sim 9.35'$ & $|b| < 20^{o}$) and

Parkes 2.4 GHz ($\theta \sim 10.4'$ & $|b| < 10^{o}$)

surveys give $-1.8 < \beta < -1.4$ down to $l < 900$ (Tucci 2000/2002; Baccigalupi 2000, Burigana 2002, Bruscoli 2002, Giardino 2002, Caretti et al. 2005, La Porta et al. 2006).

When including the exactly treatment of leakage, we obtain $-1.9 < \beta_E < -0.5$ & $\alpha_E = -1.3$ down to $l < 100$ for the Leiden surveys (de Oliveira-Costa et al. 2003).

These results are taken with a grain of salt when it comes to their implications to the CMB contamination, for 3 reasons:

1. Extrapolations are done from low to high Galactic latitudes;
2. from low to high frequencies; and
3. much of the available data is undersampled.

Microwave Foregrounds

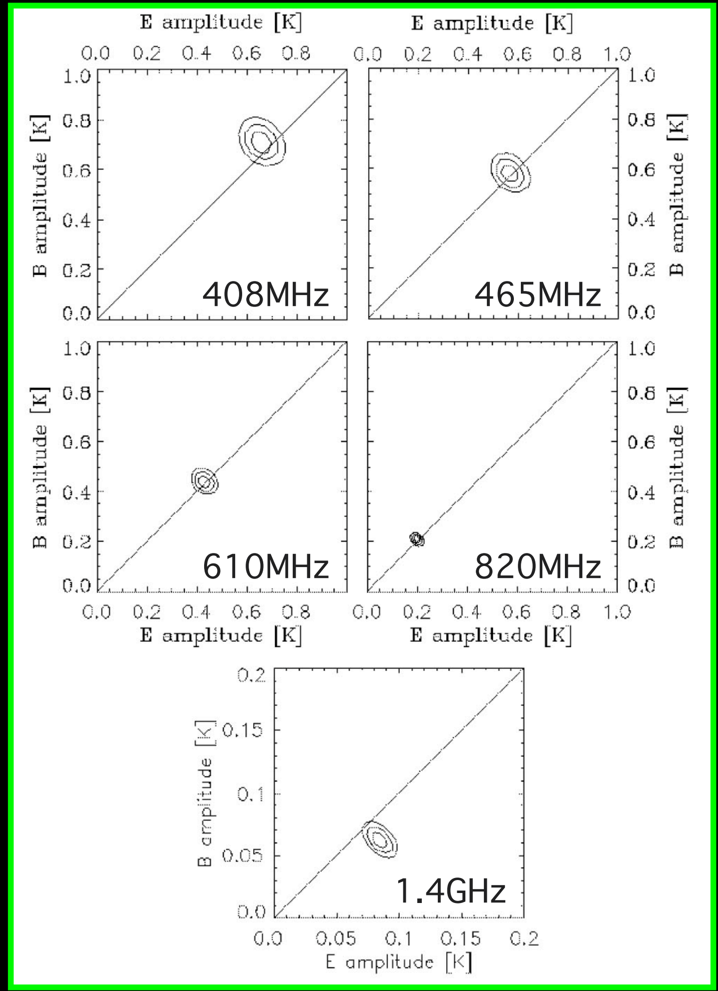
Polarized Synchrotron Emission (cont.):

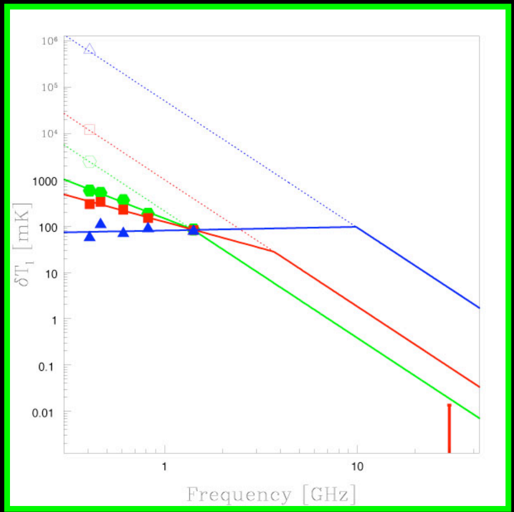
- There is a hint of E-domination at higher frequencies.
- Faraday Rotation & Depolarization effects depend not only on frequency but also on angular scale - they are important at low frequencies (ν < 10GHz) and on large angular scales.
- Combining the POLAR and radio frequency results, and the fact that the E-polarization of the abundant Haslam signal in the POLAR region is not detected at 30GHz, suggests that synchrotron polarization percentage at CMB frequencies is rather low.

α=-2.8 ➡ p<10%

α<-3.0 ➡ p<20%

α<-3.4 ➡ p<70%

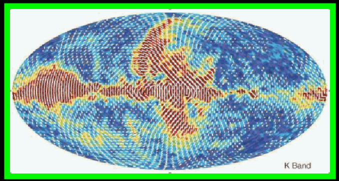




Microwave Foregrounds

Polarized Synchrotron Emission (WMAP results - 1° to 4° scales):

Page et al. 2007



Foregrounds are model as power laws: $C_l = A\,\nu^{\alpha}\,l^{\beta}$

Slope α: The foreground spectra is described by a 2 power-law component with $\alpha_s \sim -3$ and $\alpha_d \sim 2$, with the synchrotron spectral index steepening by $\Delta\alpha = 0.2$ as we go off the plane (Kogut et al. 2007) - a combined analysis using temperature and polarization data find a similar trend (Gould et al. 2008).

Outside the plane, $\alpha_s = -3.3$ has been used to clean the WMAP maps (Page et al. 2007).

Slope β: Analysis of the DRAO 1.4GHz ($\theta \sim 36'$ & $-29° < \mathrm{DEC} < 90°$) survey gives $-3.0 < \beta_{E,B} < -2.5$ for $l = 30 - 300$. Extrapolating these results to 70 GHz, they estimate a Galactic synchrotron contamination compatible with the WMAP3 data (La Porta et. al. 2006).

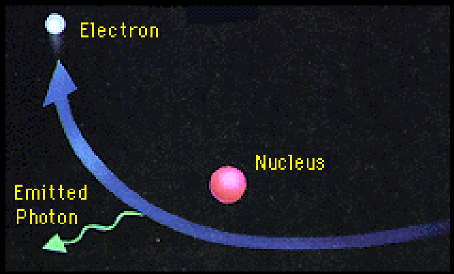
The WMAP5 provides our best estimate of the synchrotron morphology at degree scales: for the polarized emission, S/N >> 3 over 90% of the sky. The polarization angle has coherent structure over large patches of the sky, creating significant emission at low multipoles (or large angular scales).

Power spectra are dominated by foreground emission with roughly equal parts of E– and B–modes, which, when averaged over the high-latitude sky, are brighter than the CMB polarization even around the minimum of ~ 70 GHz. Also, $\beta_E = -0.6$ (Page et al. 2007).

From the Ka-band: The fractional polarization P/I is 0.05 at $|b| < 5°$ (which means that the Galactic plane region is highly depolarized); the NGS and the mid-latitudes has P/I = 0.3; while the high-latitudes (outside P06 mask) has P/I = 0.15 (Kogut et al. 2007).

Microwave Foregrounds

Our knowledge of Free-free Emission:



Free-free is an eletromagnetic radiation produced by the acceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.

Foregrounds are model as power laws: $C_l = A\, \nu^{\alpha}\, l^{\beta}$

Of all the diffuse Galactic foregrounds, free-free is the one with best known frequency dependence ($\nu \sim -2.15$). Hα in emission, which is produced by the same Warm Ionized Medium (WIM) responsible for the Bremsstrahlung, is a tracer of Galactic free-free.

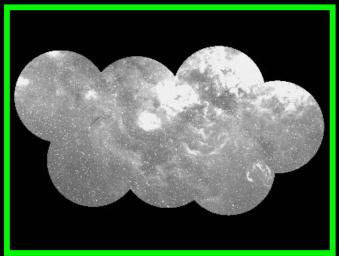
Unpolarized Free-free Emission:

Although the spectrum of free-free emission is well known, the amplitude and power spectrun are not.

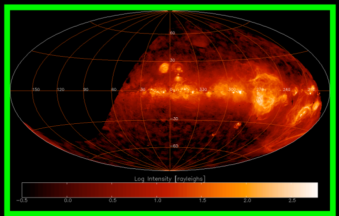
From the WHAM survey at the Tenerife observing region (at $20^{\circ} < b < 30^{\circ}$) :

$\beta \sim -3.0$ for $10 < l < 40$ (de Oliveira-Costa et al. 2000).

VTSS: Dennison et al. 1998



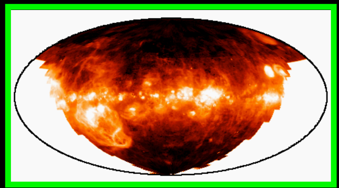
+



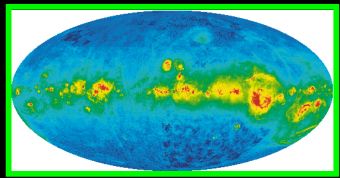
SHASSA: Gaustad et al. 2001

+

$\theta \sim 1^{\circ}$



WHAM: Reynolds et al. 2002

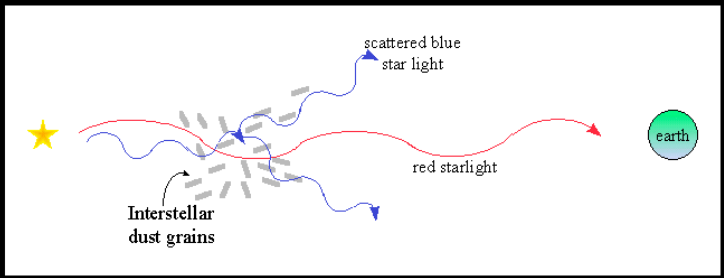


Finkbeiner 2003 ($\theta \sim 6'$)

Free map at http://lambda.gsfc.nasa.gov/

Microwave Foregrounds

Our knowledge of Dust Emission:



The dust grain absorbs and scatters starlight, and reradiates the absorbed energy at longer wavelengths.

Foregrounds are model as power laws:

$$C_l = A\,\nu^{\alpha}\left[\, e^{h\nu/kT} / \left(e^{h\nu/kT} - 1\right) \right] l^{\beta}$$

Unpolarized Dust Emission (slopes α and β):

Slope α: From a combined analysis of DIRBE & IRAS data, it was observed that the Galactic dust emission can be model by a two temperature component model, with $T_{(1,2)}$ = 9.5 K and 16 K and an emissivity of $\alpha_{(1,2)}$ = 1.7 and 2.7 (Schlegel et al. 1998). Previous estimates of α have ranged between 1.4 and 2.0 (Reach et al. 1995; Kogut et al. 1996).

From BOOMERanG 245 and 345 GHz channels, it was observed that the temperature of the dust component varies between 7 – 20 K, while the emissivity α varies between 1– 5 (Veneziani et al. 2010).

Slope β: Analysis of the DIRBE maps showed no evidence for a departure from $\beta = -3$ for $l < 300$ (Wright 1998).

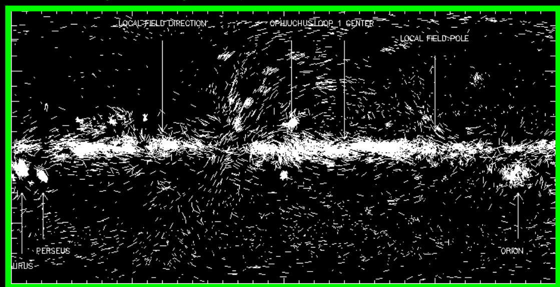
A combined DIRBE & IRAS analysis suggested $\beta = -2.5$ (Schlegel et al. 1998), while earlier works suggested $\beta \sim -3$ (Gautier et al. 1992, Low & Cutri 1994, Guarani et al. 1995, TE 1996).

The Archeops experiment also suggested $\beta \sim -3$, after a cosecant was subtracted (Ponthieu et al. 2005).

Microwave Foregrounds

Polarized Dust Emission (slopes α and β):

Heiles (2000) - 9,286 stars



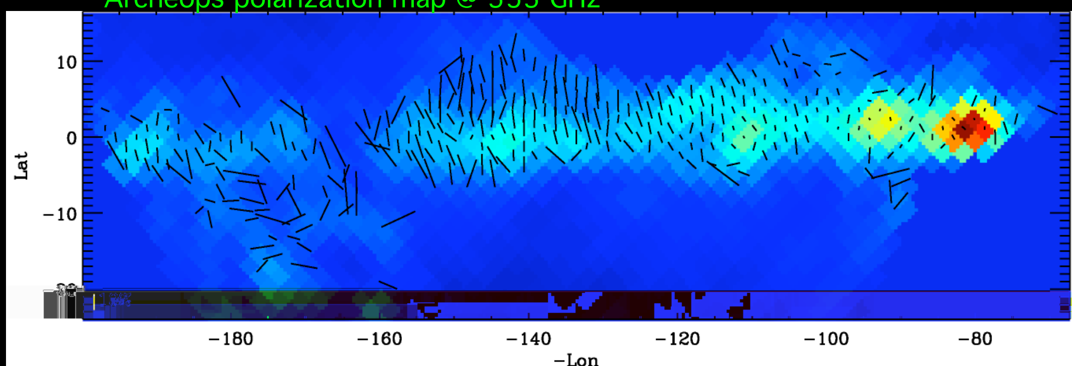
Starlight data (Heiles 2000) gives

$\beta \sim -1.5$ for $\theta > 10'$ ($l < 1000$) and $|b| < 10^{\circ}$ (Fosalba et al 2002);

while Dwingeloo survey gives

$\beta_E = -1.3$ for scales $>1^{\circ}$ (Sethi et al. 1998).

Archeops polarization map @ 353 GHz



Benoit et al. (2003)

More info at http://www.archeops.org/

The Archeops experiment detected polarized emission by dust at 353 GHz (Benoit et al. 2003).

They find that the diffuse emission of the plane is 4-5% polarized, and its orientation is mostly perpendicular to the Galactic plane.

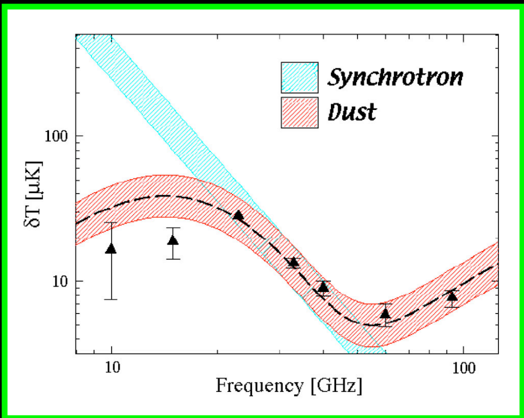
There is evidence for a powerful grain alignment mechanism throughout the interstellar medium.

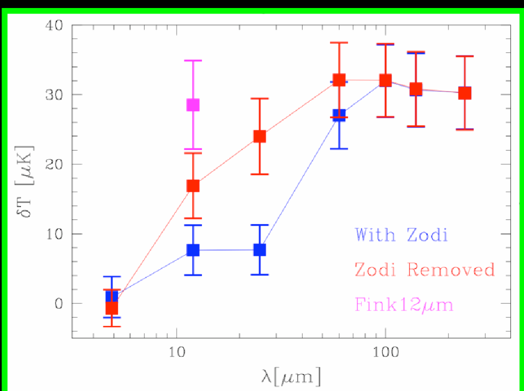
WMAP V- and W-bands: These maps show evidence of a dust polarization fraction of about 1% near the Galactic center and a few percent at intermediate latitudes, consistent with Archeops.

A low S/N estimate of the polarization angle was obtained for the V- and W-bands. However, due to high noise levels on these maps, these estimates were only measured at very large angular scales ($> 4^{\circ}$, $l > 50$).

Microwave Foregrounds

Our knowledge of Foreground-X:



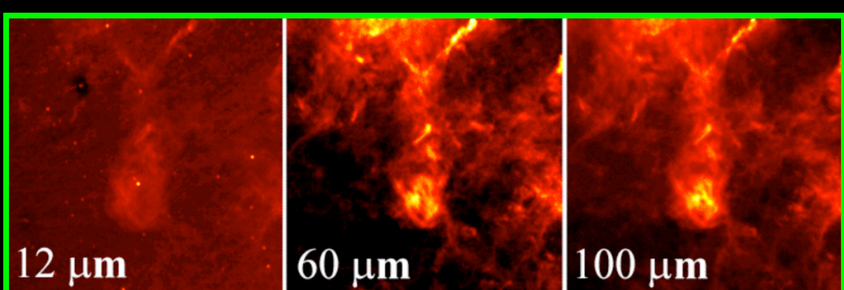


There is observacional evidence in favor of a 4^{th} component of emission in our Galaxy. This component, nicknamed Foreground-X, is spatially correlated with the 100 μm dust emission but with a spectrum that rising towards lower frequencies, subsequently flattening and turning down somewhere around 15 GHz.

There are statistical (eg, DMR, Saskatoon, OVRO, 19 GHz, Tenerife, SP94, WMAP, WMAP7+ARCADE2, etc.), as well as, direct (eg, Finkbeiner et al. 2004) detections of this anomalous component.

The are two possible mechanisms used to explain the Foreground-X:
the small ``spinning dust” grains (r ~ 0.001 μm, $\lambda \sim$ 10 – 30 μm)
and the ``large magnetic” grains (r > 0.1 μm, $\lambda \sim$ 50 – 200 μm)
– see review by Lazarian & Finkbeiner 2003.

It was observed a strong correlation between the excess emission and the short wavelength DIRBE/IRAS 12 μm map. This result seems to favor ``spinning dust” over ``magnectic dust” models (de Oliveira-Costa et al. 2002). In addition, a correlation between the excess emission and H_α was also detected at 40 GHz (Dobler & Finkbeiner 2008, Dobler et al. 2008).



Caveats:

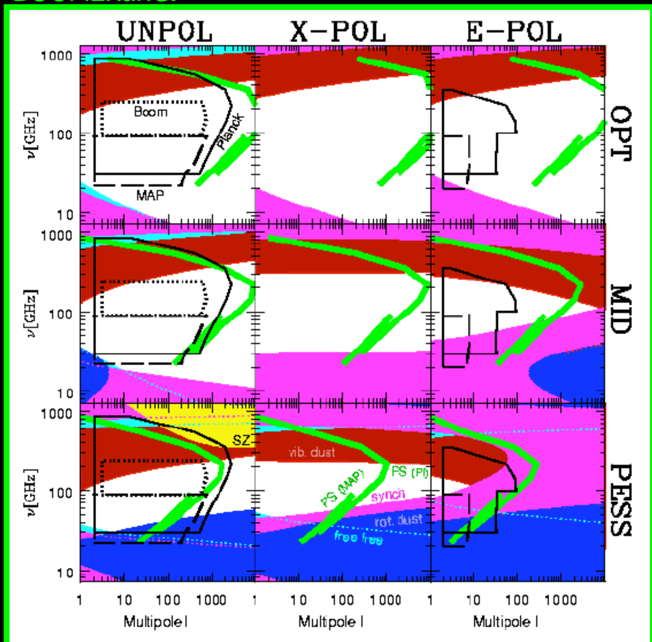
1. There is no template for this component, so how can we get the slope β?

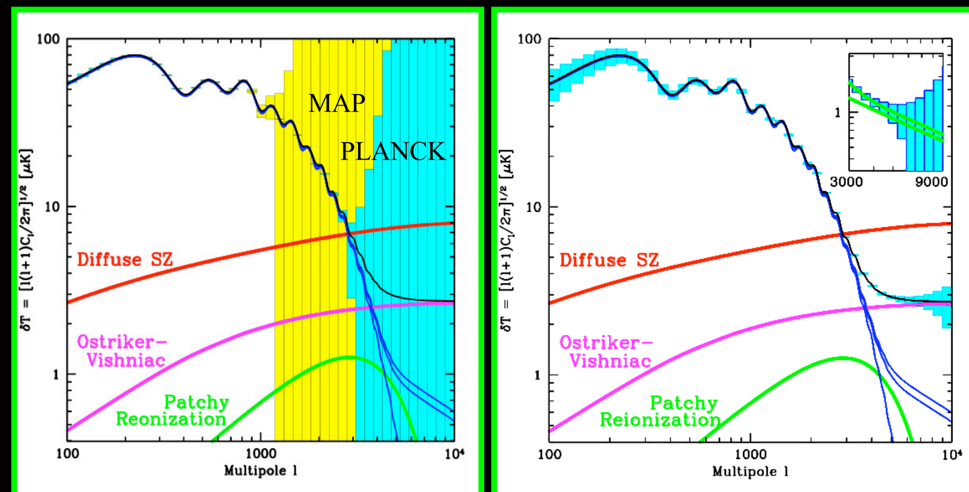
2. Is this component polarized? If yes, how to best separate it from the CMB?

Microwave Foregrounds

Which foreground should we care about ?

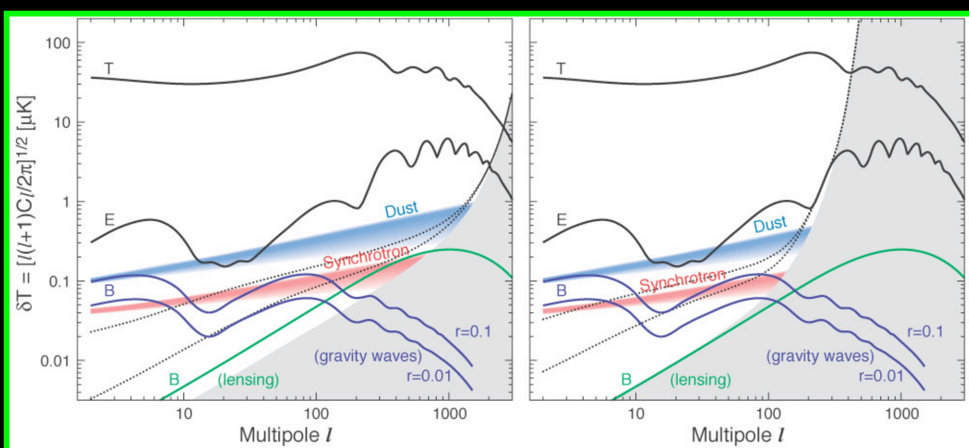
BOOMERanG:





ACT:

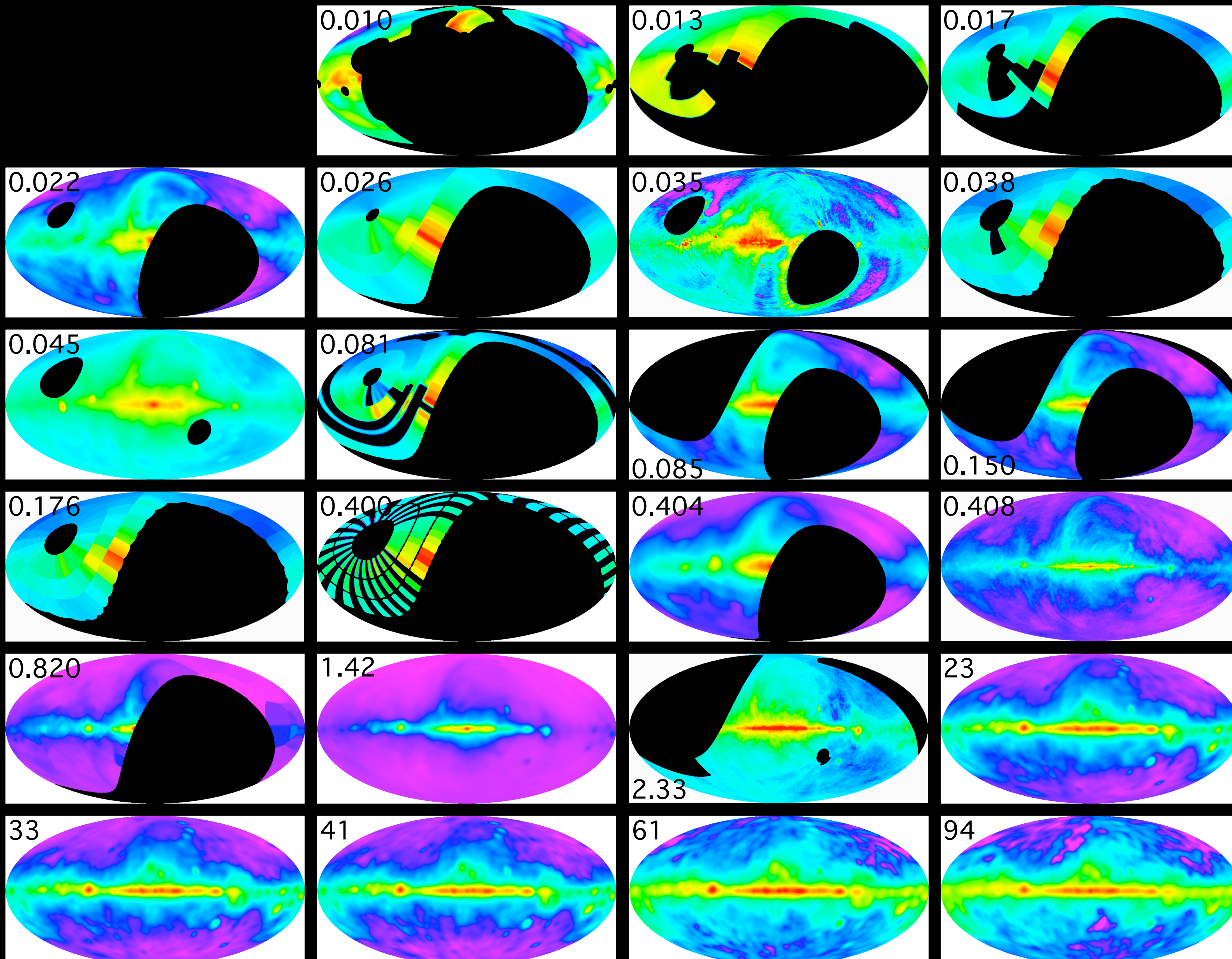
CMBpol:



Objectives of the study:

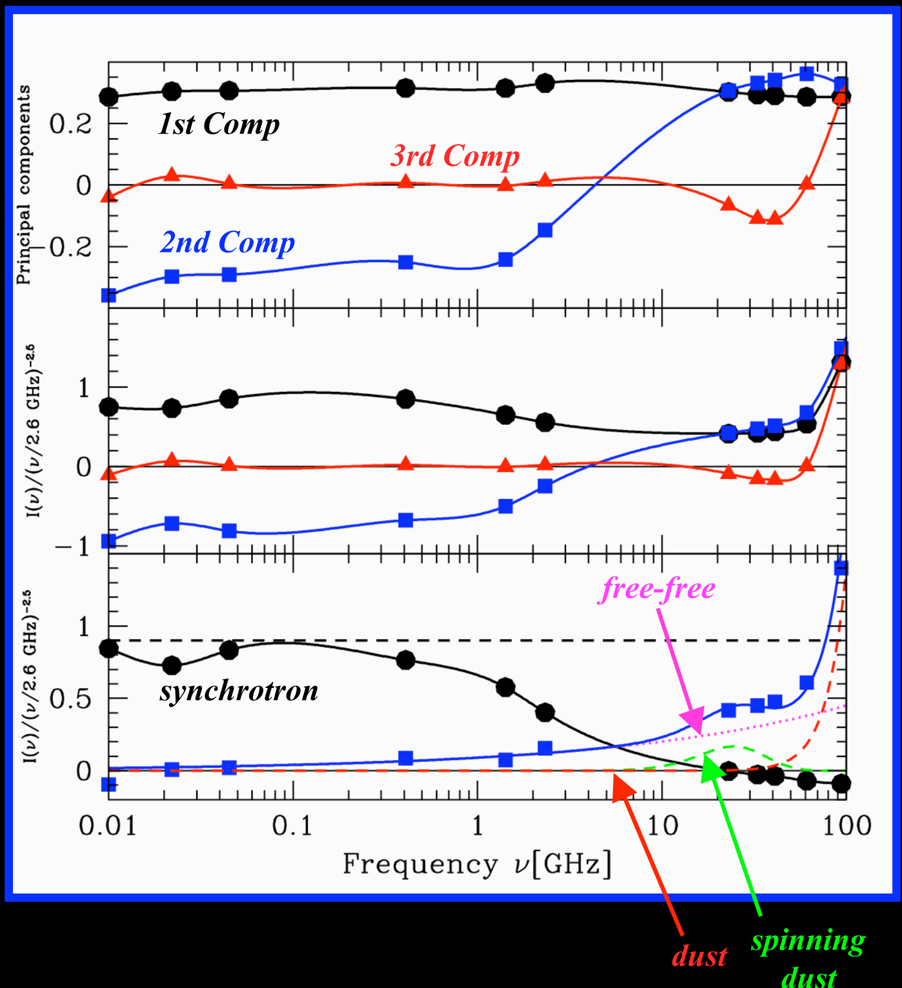
to assess the impact of foregrounds on CMB experiments. It helps to identify which foregrounds are most damaging and therefore most in need for futher study. It is useful for optmizing future missions and for assessing the science impact of design changes to ongoing experiments.

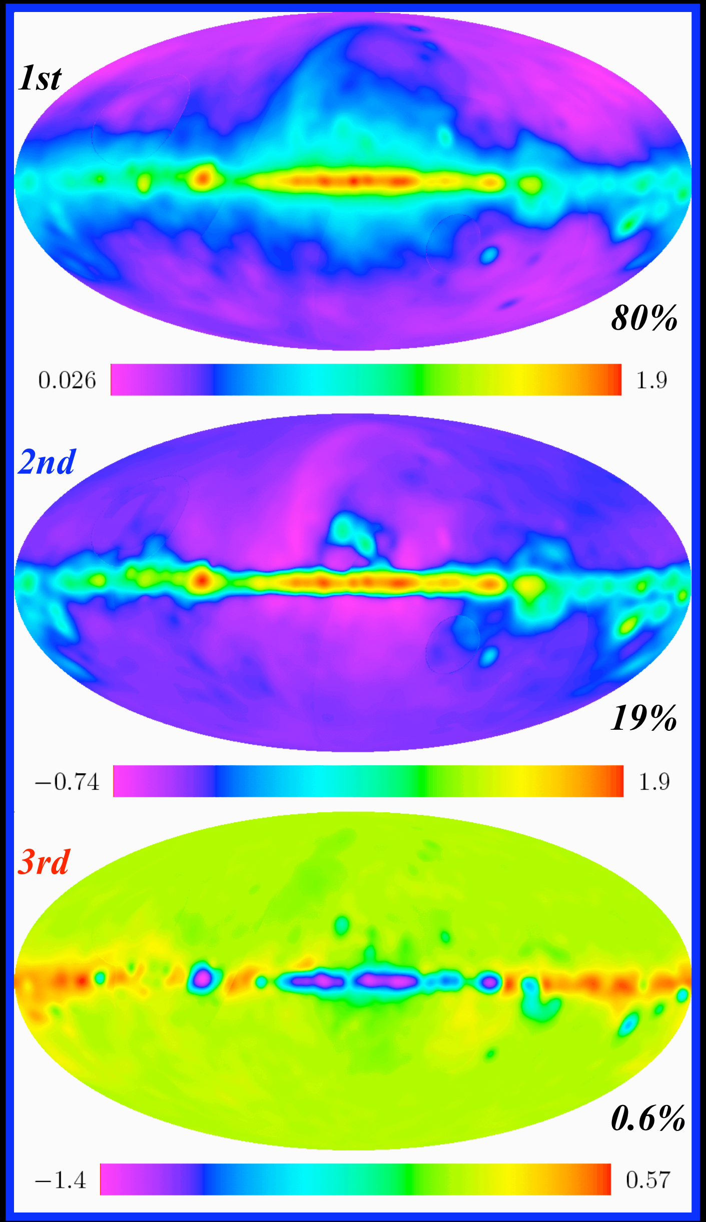
Modeling the diffuse emission from 10 MHz to 100 GHz:



Modeling the diffuse emission from 10 MHz to 100 GHz:

Principal Component Analysis:



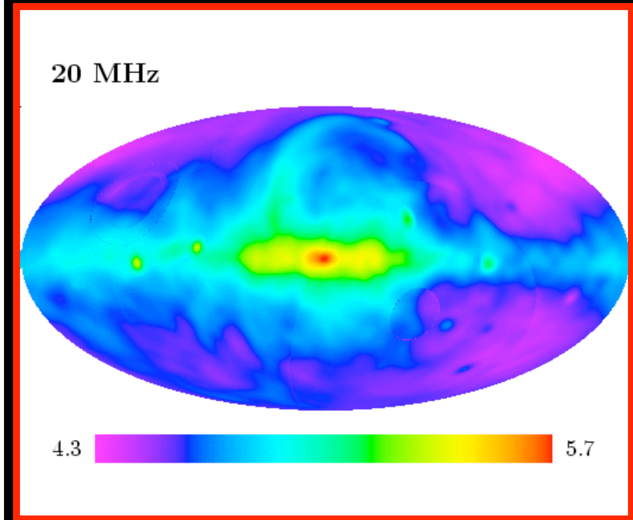


Modeling the diffuse emission from 10 MHz to 100 GHz:

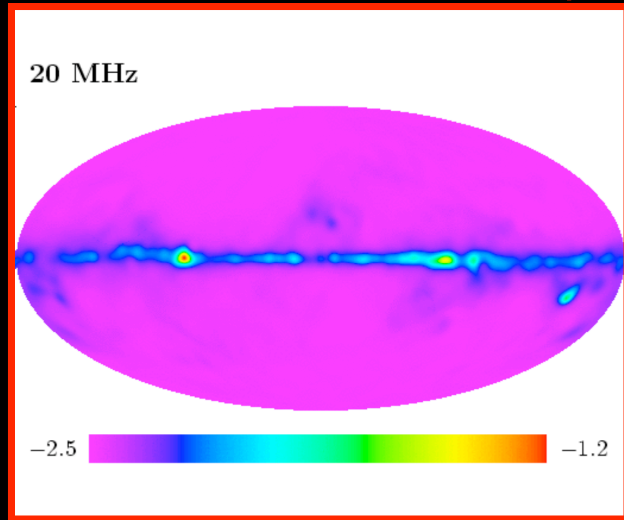
http://www.space.mit.edu/home/angelica/gsm

Movies:

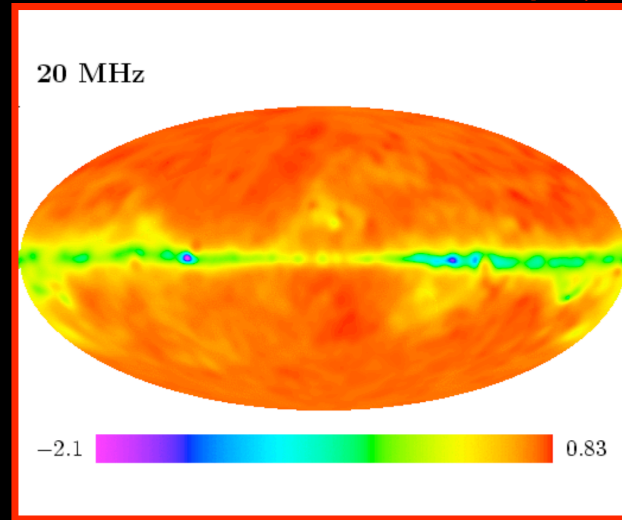
logT



spectral index, β

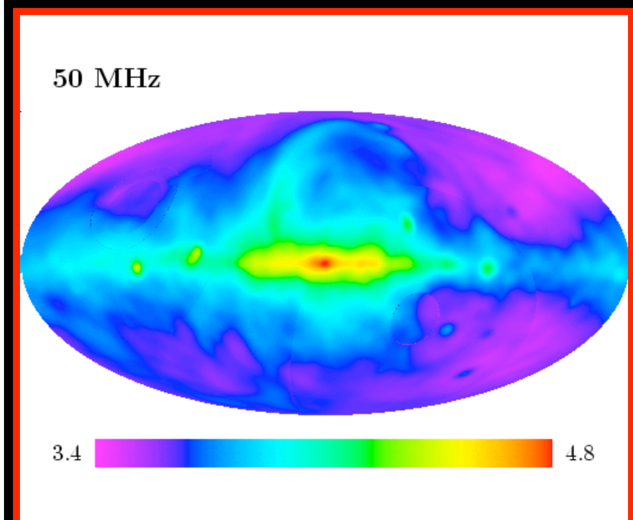


Running of β, γ

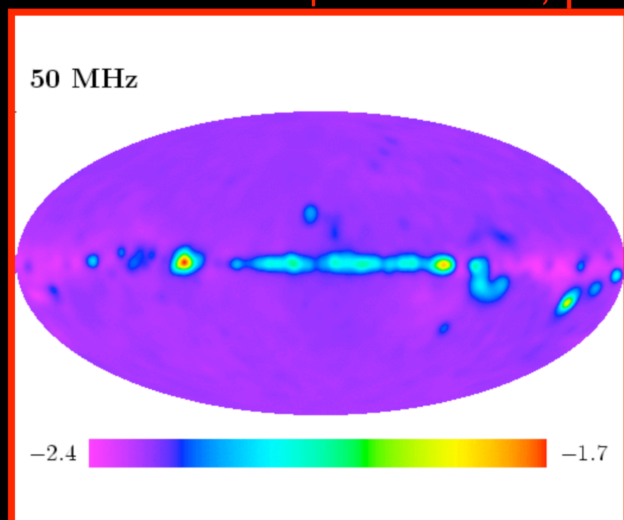


Movies, MWA range :

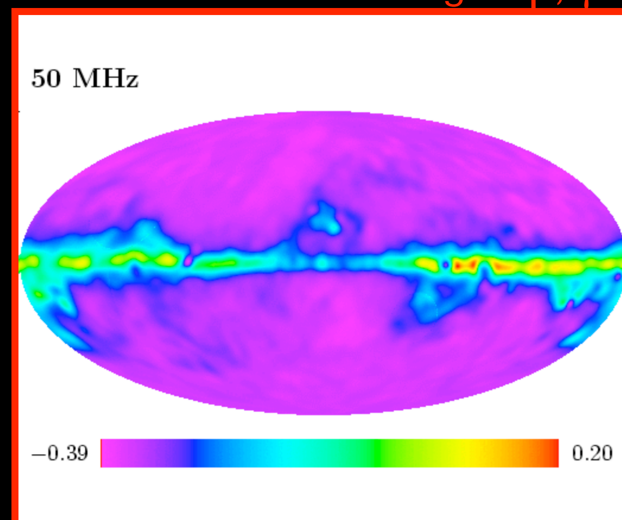
logT



spectral index, β



Running of β, γ



Microwave Foregrounds

To do a good job on removing foregrounds, we need to understand their frequency and scale dependence, frequency coherence, and better characterize their non-Gaussian behavior. Therefore, we will probably need a systematic program to characterize their properties.

Some questions we could argue about:

1. Should we fund polarized ground-based multi-frequency large-scale surveys of the sky at lower frequencies in order to better understand synchrotron emission?

   Value of β_E, polarization percentage p, if E-domination

2. If these surveys were done at frequencies around 3-15 GHz, how much could we learn about Foreground-X?

   We need a template for this component. Is this component polarized?

   QUIJOTE: 11-33 GHz, large area survey, polarized
   C-BASS: 5 GHz, all sky, polarized
   COSMOSOMAS: 11-18 GHz, large area survey, polarized
   GEM: 5 & 10 GHZ, large area survey, polarized

3. Should we fund dedicated dust polarization surveys?

   How much are we going to learn from POLAR array ???

   Should we fund starlight polarization surveys to better characterize dust polarization?