Cosmic Microwave Background, Foregrounds and Component Separation

What are foregrounds and
how to deal with them in CMB data analysis

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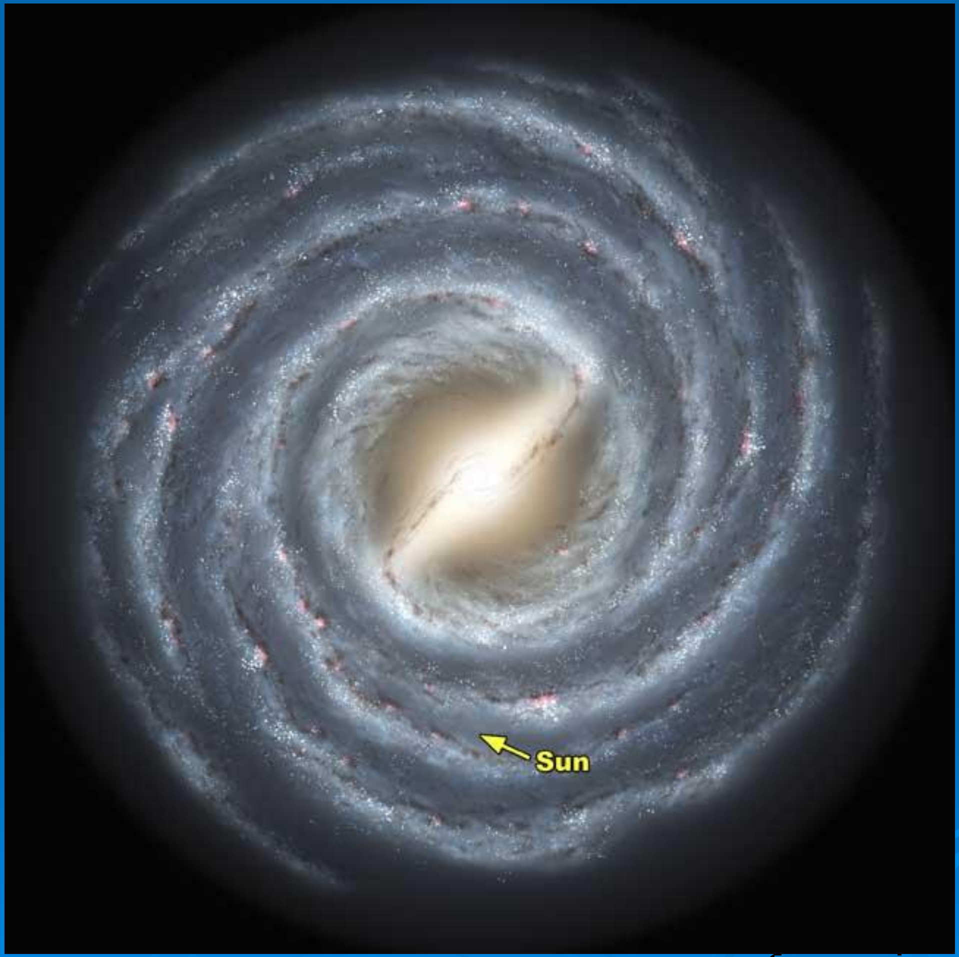
Astrophysics School ``Francesco Lucchin",
Bertinoro, May 24-29, 2009

Outline

- Foreground fundamentals
- The Galaxy
- Other galaxies
- Contamination to the CMB
- Why is it important to control foregrounds?
- Component separation

Foregrounds fundamentals

Foreground fundamentals: the Galaxy, the other galaxies, and their clusters



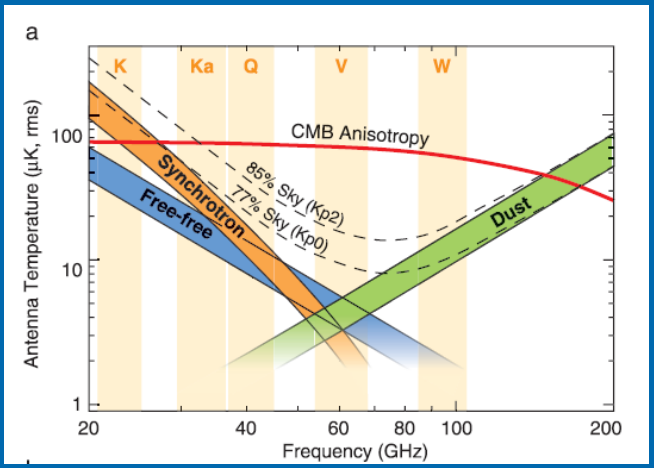
Foreground fundamentals: differences with respect to the CMB

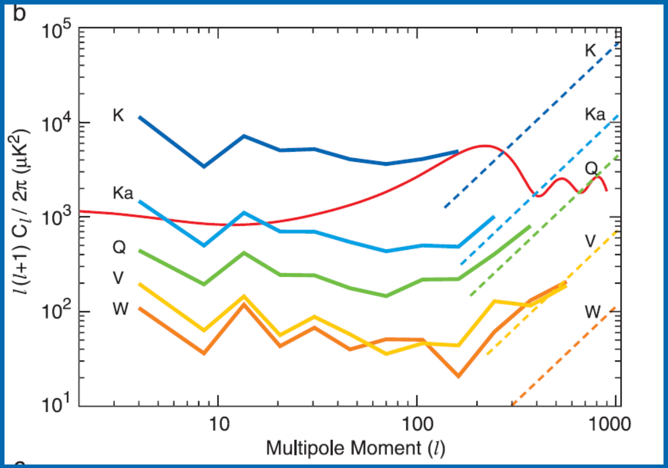
- Together with instrumental systematics, foregrounds are the ultimate limitation of CMB observations
- Unlike CMB, the foreground knowledge is mainly empirical, we know the main physical processes activating them, but their emission is calibrated mainly through observations
- Unlike CMB, the Galactic emission is strongly inhomogeneous, concentrated on the Galactic plane
- Unlike CMB, foregrounds are distributed non-linearly in the sky
- Unlike CMB the extra-Galactic emission is point-like, with the exception of a few, closeby galaxy clusters
- Unlike CMB, the foregrounds do not possess a black body frequency spectrum
- Unlike CMB, the foregrounds do possess a space varying frequency dependence
- Unlike CMB, the diffuse foreground emission is markedly non-Gaussian
- Unlike CMB, the foregrounds are expected to have equal power in the E and B modes of polarization

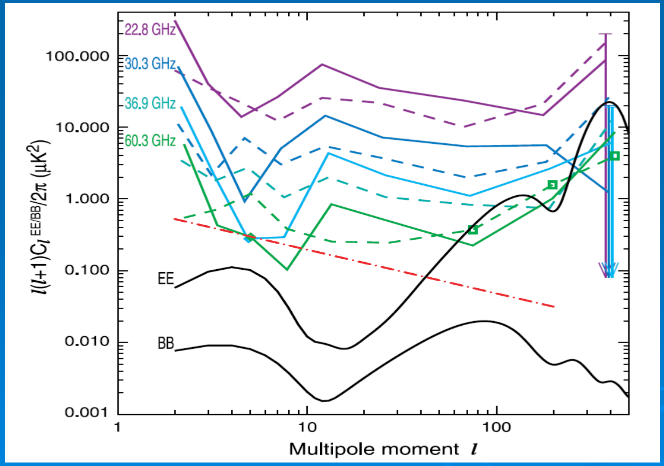
Foreground fundamentals: antenna temperature

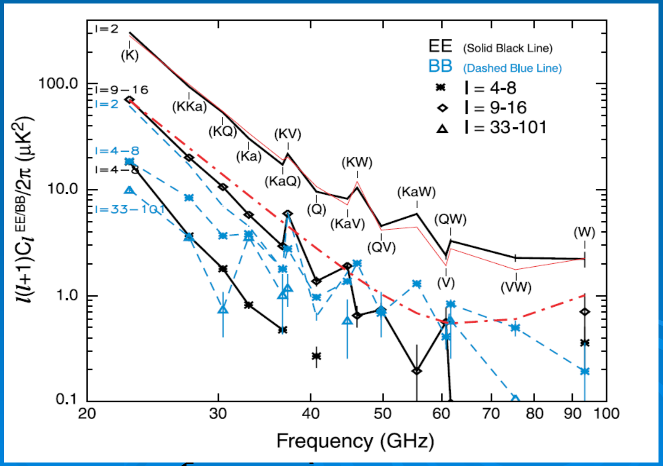
- You can use your favorite units for describing foreground emission, in total intensity as well as polarization
- In the community, a popular choice is represented by the antenna temperature TA, simply defined as the temperature that a black body would have in the Raileigh-Jeans region of the spectrum, corresponding to a given flux density
- In formulas, $T_A = c^2 \times$ flux density / (2 Boltzmann constant frequency)^2
- For a black body, the antenna temperature fluctuations are related to the thermodynamic ones by $\delta T_A = \delta T \times x^2 \times \exp(x) / (\exp(x)-1)^2$, where x=Planck constant × frequency / (Boltzmann constant × CMB temperature)

Foreground fundamentals







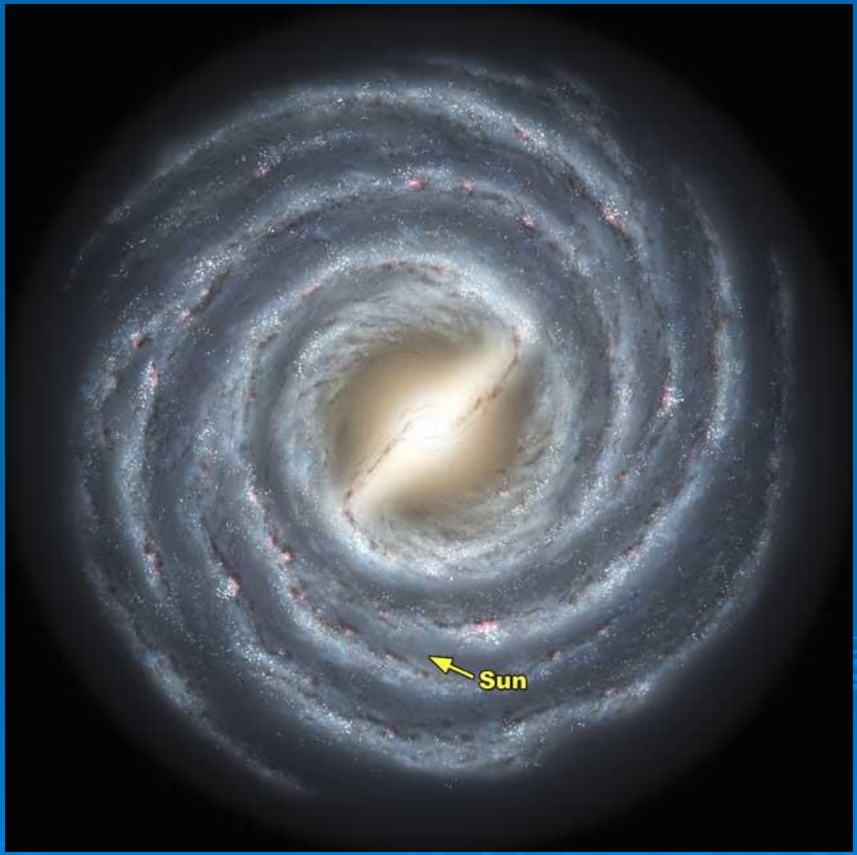


Bennett et al. 2003, Page et al. 2007

The Galaxy

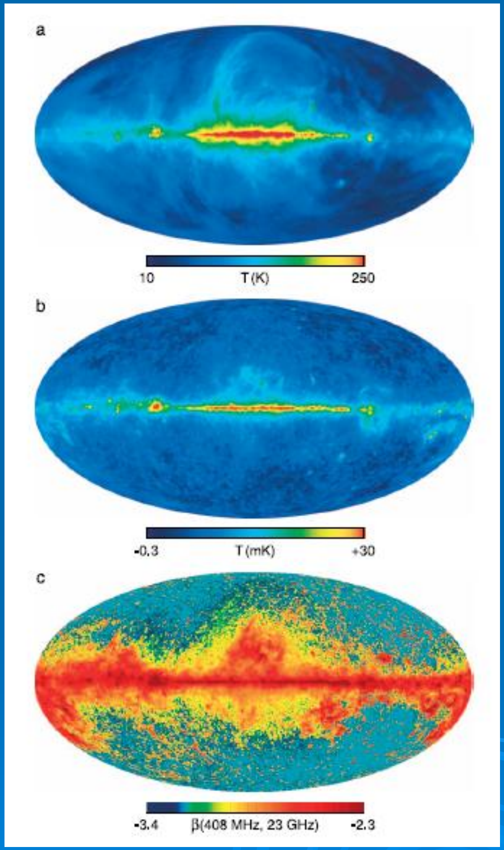
Milky way

- At microwaves, the main emission does not come from stars, but from the diffuse gas, either primordial and unprocessed, or ejected from stars through explosions
- The diffuse gas is composed by free electrons, ions, a variety of large molecules, also known as grains, such as silicates, …
- The galaxy is a hot system, 20 K or so, not isolated because heated back by starlight
- The galaxy possesses a magnetic field of order few μG, with a large scale component orthogonal to the plane and elongated along arms, and a largely unknown small scale component , largely generated by supernova remnants



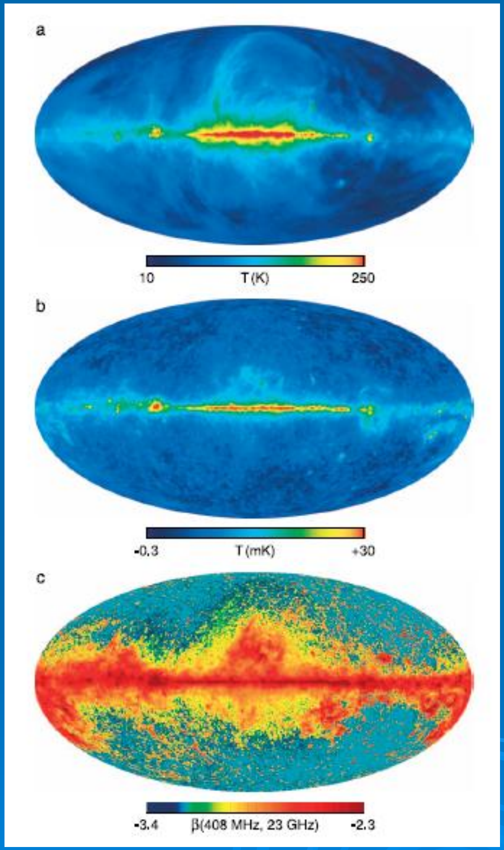
Foregrounds from the radio band: Galactic synchrotron

- What it is: cosmic ray electrons spiraling around the lines of the Galactic magnetic field, generated in particular by supernova remnants
- In frequency, it behaves as a decaying power law, because the electron number is a decreasing power law of their energy, $N(E) \propto E^{-|p|}$, with the flux density $F(f) \propto f^{-|b|}$, related by $b=-(|p|-1)/2$



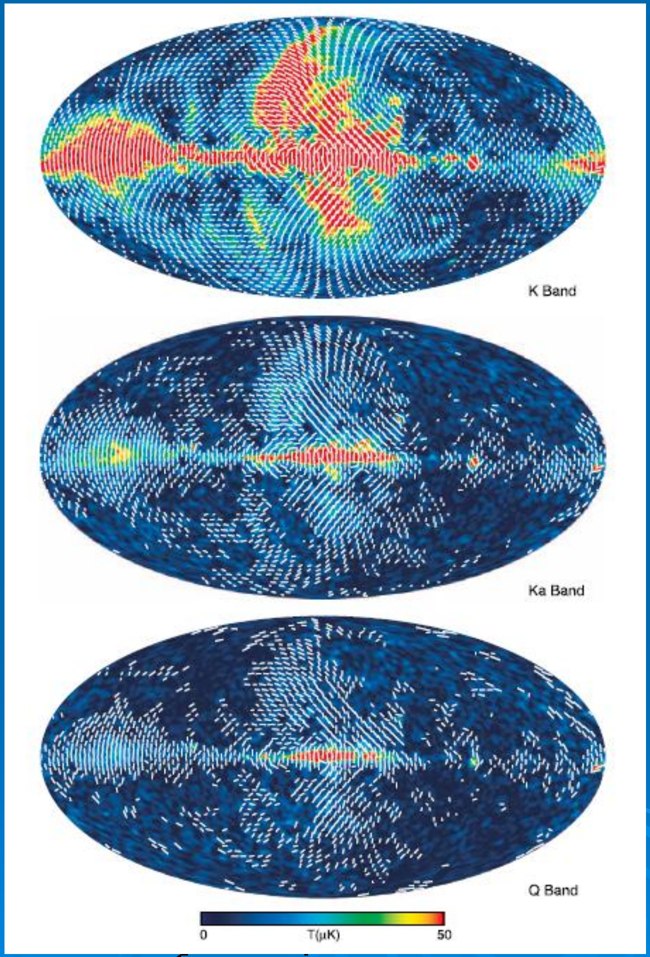
Foregrounds from the radio band: Galactic synchrotron

- The electron density varies substantially across the sky, making the frequency dependence depending on the direction of observation
- The spectrum tends to be steeper at high latitudes, spectral index -3 or less in antenna temperature, flatter at intermediate and low latitudes, -2.5 or so
- Existing information on all sky, in total intensity, taken in the radio band (Haslam et al. 1986, Reich et al. 1998) and at microwaves by WMAP (Bennett et al. 2003)



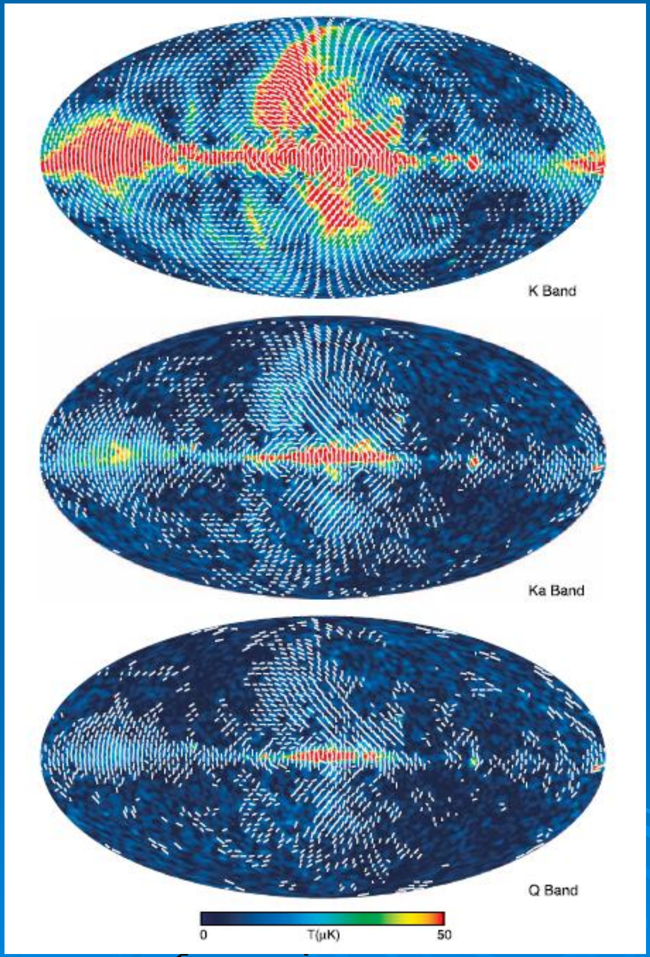
Foregrounds from the radio band: Galactic synchrotron

- The Galactic synchrotron is strongly polarized, up to 75% for the pure emission mechanism, which is actually never reached because of depolarization effects
- In the radio band, the main depolarization effect is given by Faraday rotation of the polarization angle, due to the two circular polarization modes composing linear polarization traveling with different velocities: rotation ~ 420 degrees / kpc / frequency^2, with frequency expressed in GHz, for a Galactic magnetic field of order 1 μG



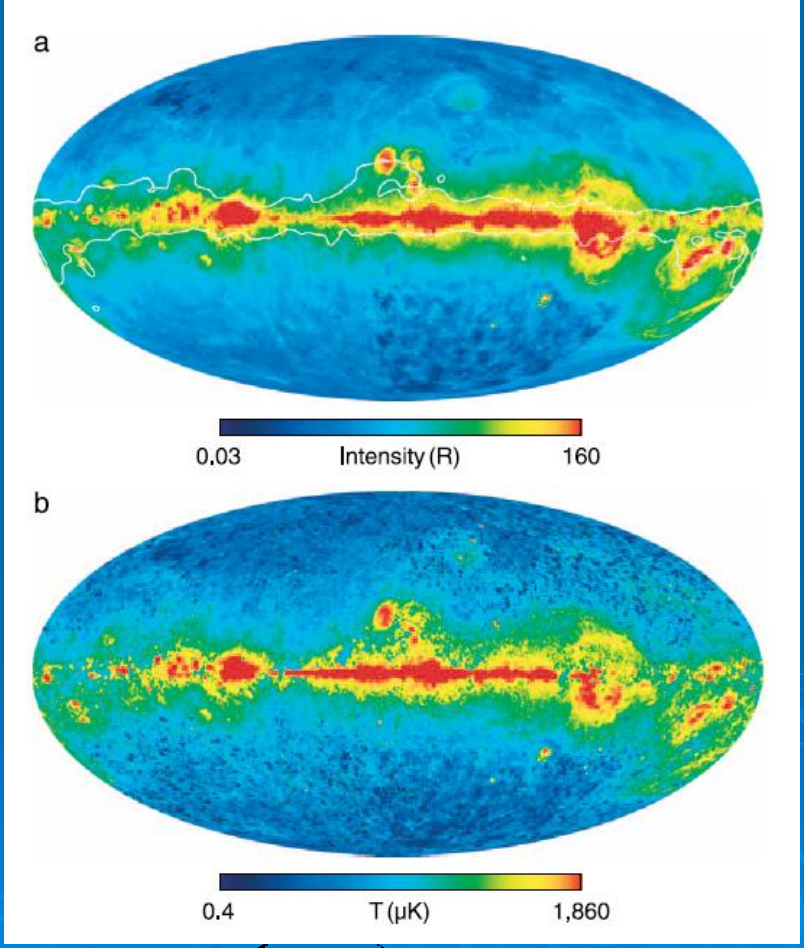
Foregrounds from the radio band: Galactic synchrotron

- At microwave frequencies, Faraday depolarization disappears, but still, line of sight effects lead to a measured polarized intensity of order 10% of the total one
- The frequency scaling is close to the one of total intensity, varying in the sky
- All sky polarization observations in the radio band exist (La Porta et al. 2006), affected by Faraday depolarization
- The main observations in the microwave bands are from WMAP (Kogut et al. 2007, Page et al. 2007), at 22 GHz where it is mostly dominating over CMB



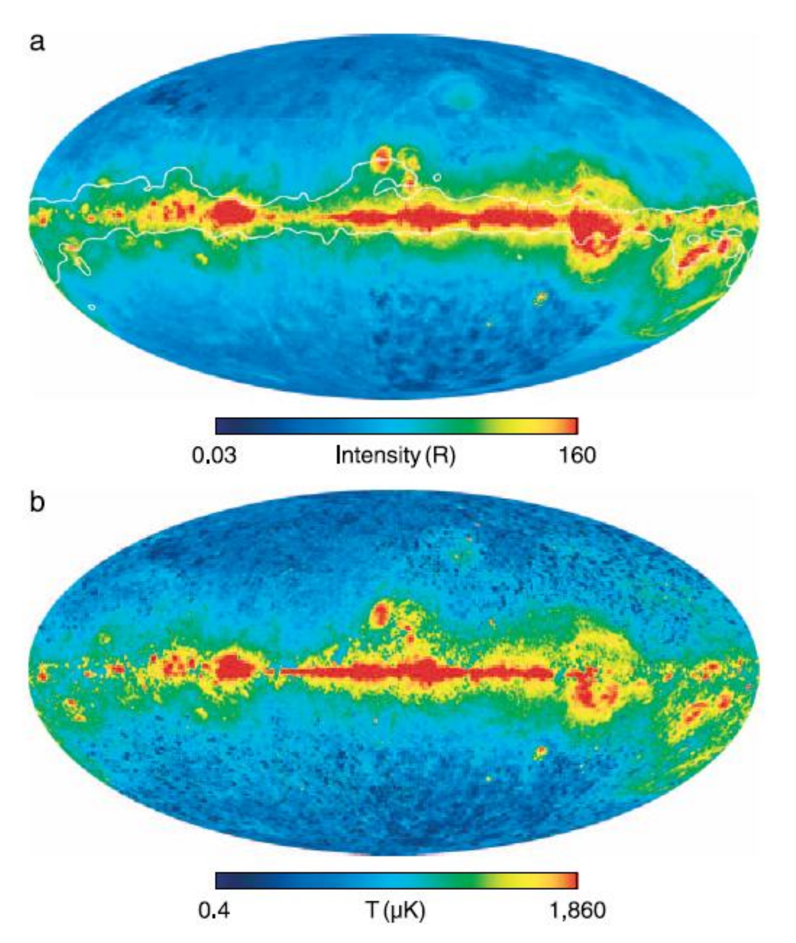
Foregrounds from the radio band: Galactic free-free

- What it is: Bremstraahlung radiation from free electrons hitting ions
- It never dominates the emission: at any frequency, synchrotron or CMB or other foregrounds are brighter
- It is measured through indirect Hα emission line (hydrogen 3 to 2 level transition), except in areas with high optical depth
- Analytic treatments exist for converting emission from Hα to free-free microwave intensity, depending on several parameters, like electron effective temperature, densities of electrons and ions, etc., making predictions particularly difficult and model dependent, requiring an empirical calibration of the emission



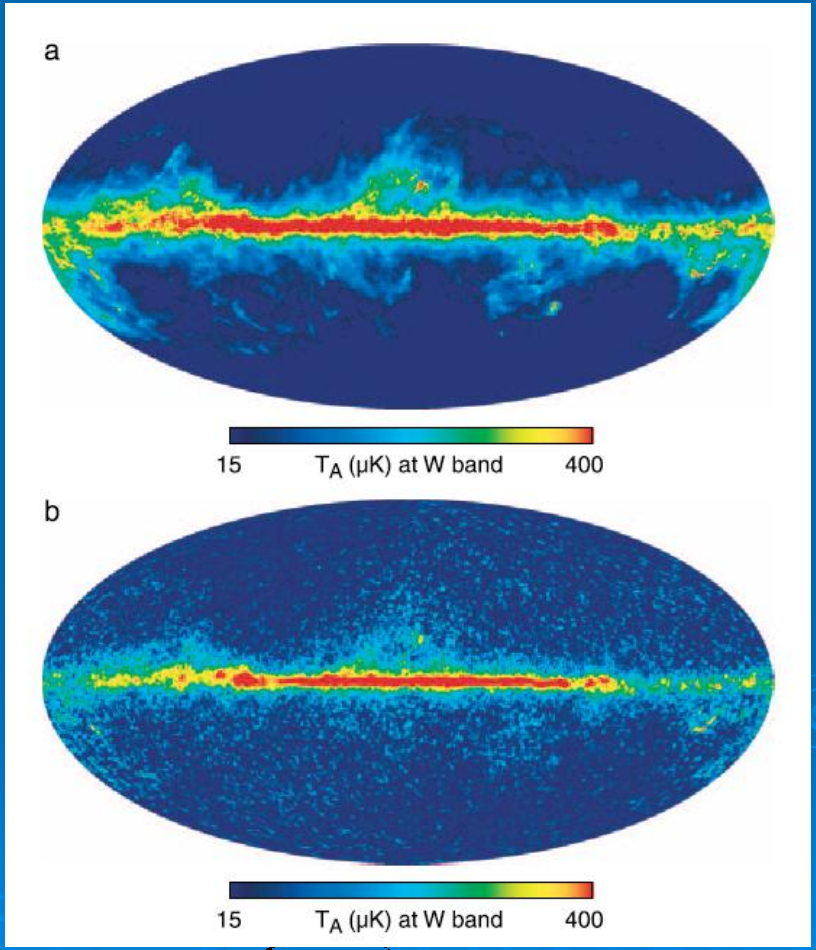
Foregrounds from the radio band: Galactic free-free

- Its emission decays in frequency, less fast than synchrotron, with spectral index about -2.15 in antenna temperature
- An Hα full sky map has been assembled (Finkbeiner 2003)
- WMAP free-free data are based on the assumed correlation with Hα (Bennett et al. 2003)



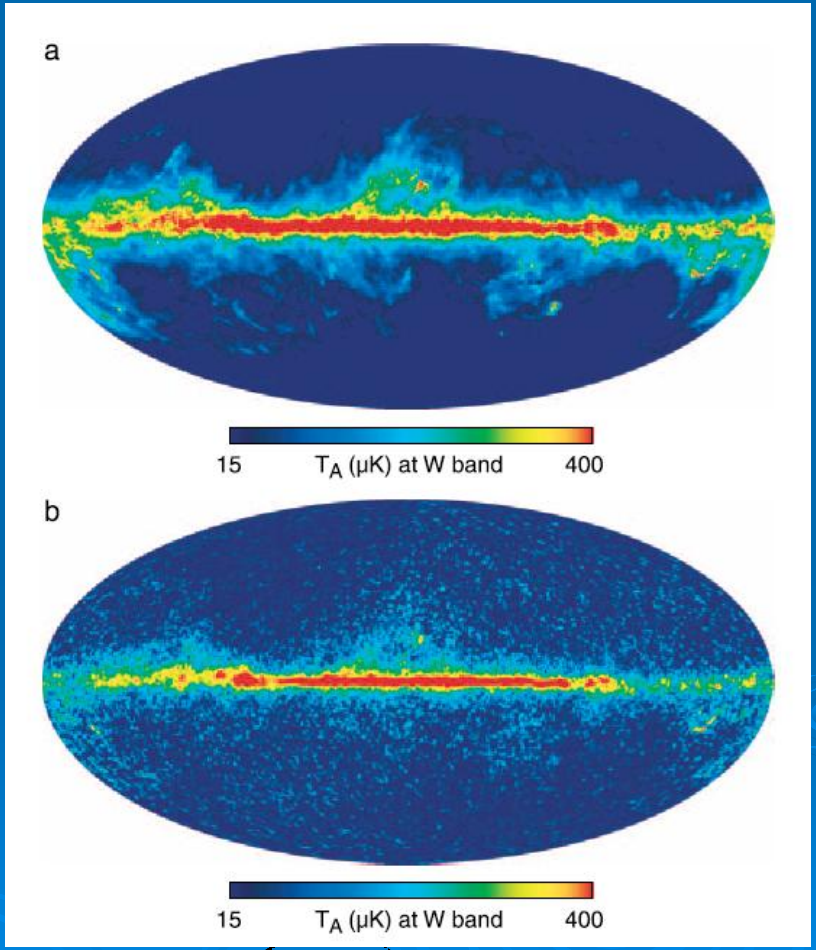
Foreground from the infrared band: Galactic dust

- What it is: molecules or dust grains form a thermal component, temperature of about 20 K, heated back by starlight
- The emission is described as a modified (grey) black body, raising with frequency in the microwave band
- Detailed physical content largely unknown; current best fit assumes two almost thermal species, with temperatures of about 9 and 16 K, dominating at frequency smaller or larger than a few hundreds GHz, respectively (Finkbeiner et al. 1999)



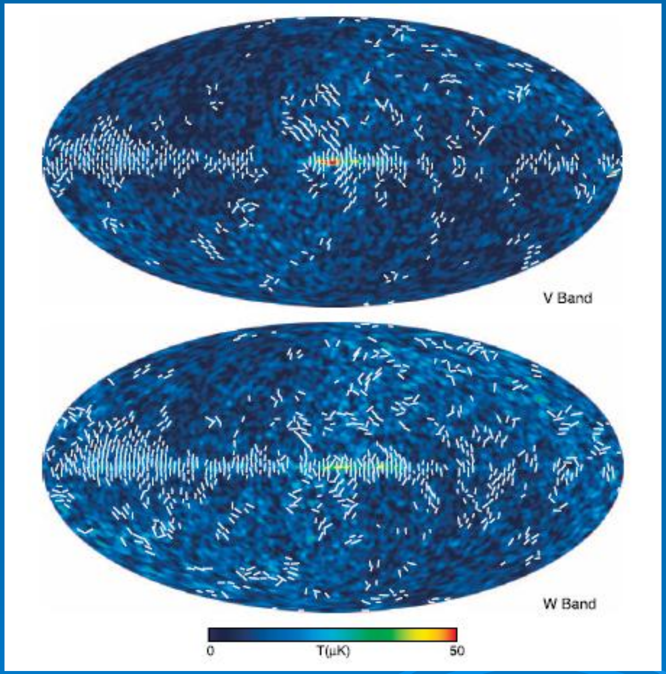
Foreground from the infrared band: Galactic dust

- The dust temperature(s) vary across the sky, at the level of 10%, at least on angular scales of a few degrees or more, as it is evident correlating data at 100 and 240 µm, making the dust spectral index varying in the sky comparably
- WMAP data (Bennett et al. 2003) are consistent with the extrapolation from IRAS data (data available, 6 arcminutes resolution, Finkbeiner et al. 1999), mostly at low Galactic latitudes, and in the W band
- A dust correlated component, suggested initially by Draine and Lazarian (1998) component may be present in the 20-40 GHz band (Gold et al. 2008, Miville-Deschenes et al. 2008, Bonaldi et al. 2007)



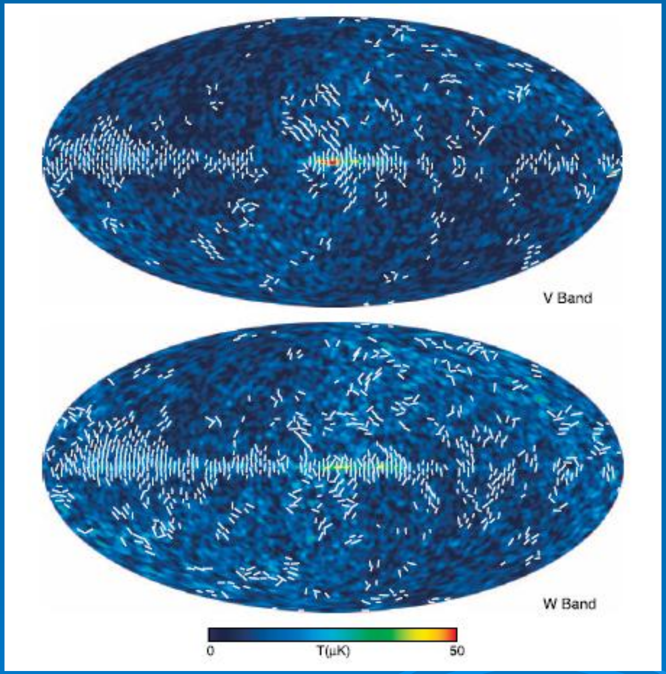
Foreground from the infrared band: Galactic dust

- The grains are magnetized, and get aligned locally with the direction of the Galactic magnetic field, making the overall emission polarized
- The intensity of the Galactic magnetic field is likely to align grains with high efficiency (Jones, 1995)
- Polarization properties may vary with frequency and sky direction; the dominance of different grain population at different frequencies may induce a loss of polarization efficiency for frequencies larger than a few hundreds of GHz (Vaillancourt et al. 2008)



Foreground from the infrared band: Galactic dust

- The polarized intensity was found to be about 5% of the total one along the Galactic plane by Archeops (Benoit et al. 2005) and WMAP (Page et al. 2007), confirming the dust to be one of the major CMB contaminant at high frequency
- At intermediate and high Galactic latitudes, the polarized intensity can be larger, reaching 10% or more, because of the absence of line of sight cancelation effects

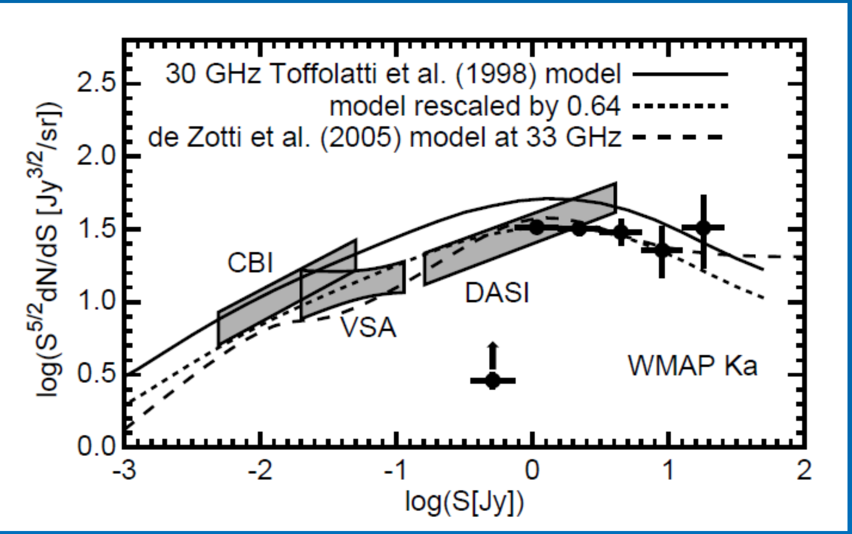


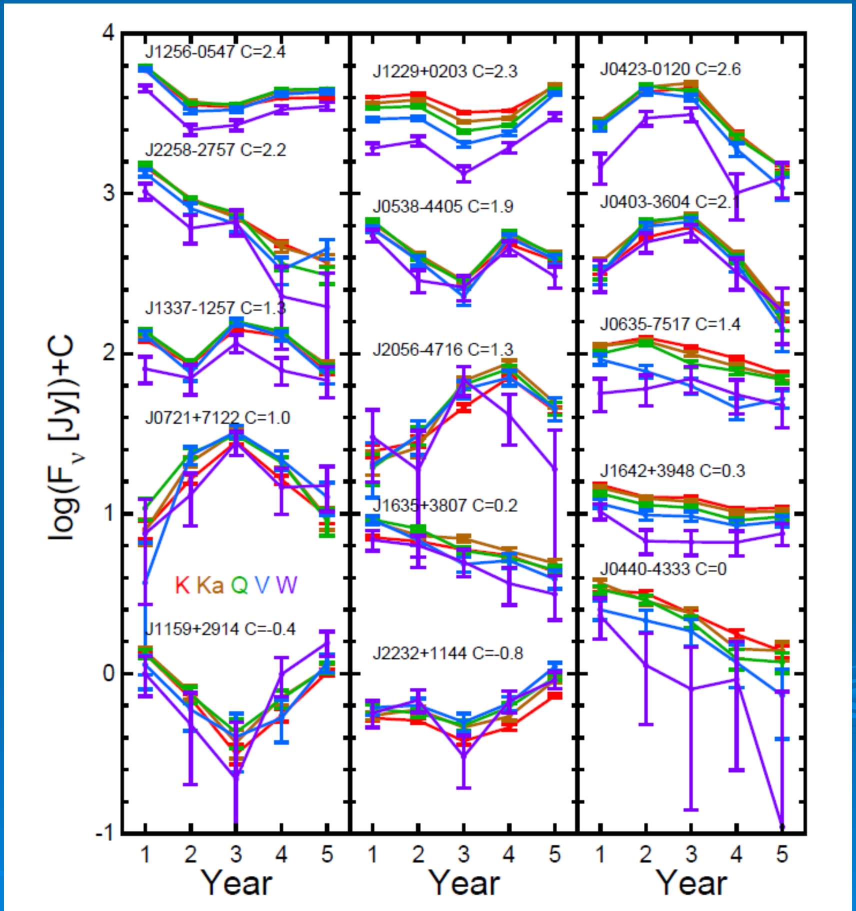
Other galaxies

Other galaxies

- To imagine the emission from other galaxies, you may simply think to the one from the Milky Way put at distance from us, emitting synchrotron emission in the radio, dust in the infrared band
- Being point-like, their signal behaves similarly to instrumental noise, having a flat power in the angular power spectrum, apart from clustering effects
- In clusters of galaxies, the central hot gas of electrons give kicks to the CMB photons, which migrate from low frequencies to high frequencies, distorting their spectrum through the Sunyaev Zel'dovich effect, yielding a signal which is interesting for single object detection, but fainter than point sources as a diffuse CMB contaminant
- Polarization angle is randomly distributed in the sky, therefore, a key quantity for the forecasted polarization emission is given by the average polarization fraction

Other galaxies

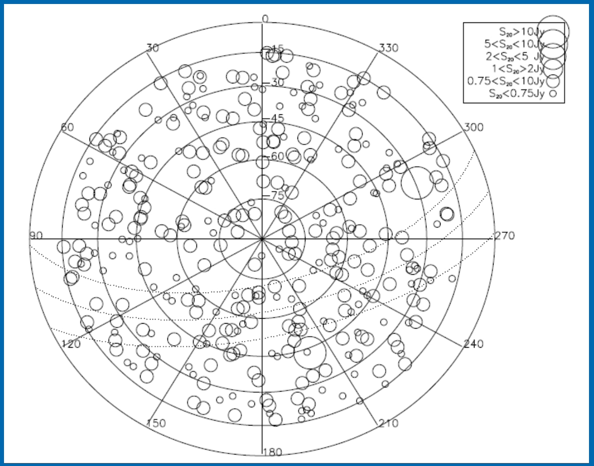


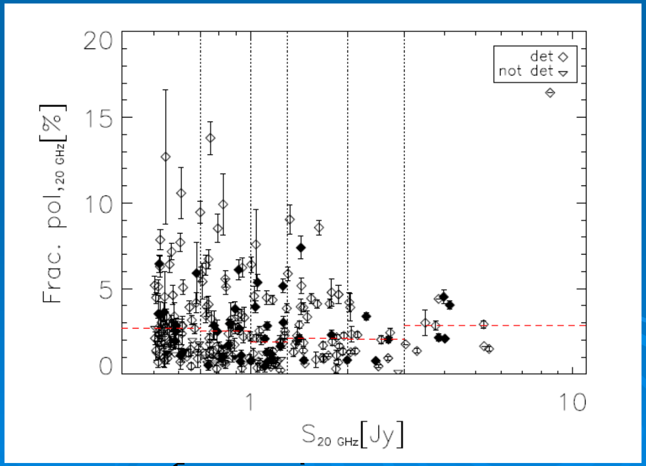


Wright et al. 2008, see also Massardi et al. 2009

Other galaxies

- The contamination to the CMB polarization from point sources is currently unknown
- Large surveys in the high frequency radio band exist (Massardi et al. 2008), indicating polarization fractions up to 10%
- Similar information in the infrared band is missing, current data on single objects indicate percentage polarization fraction or less
- If these levels are confirmed, polarized point sources may be thought to induce an effective noise component comparable to the CMB lensing signal in B modes

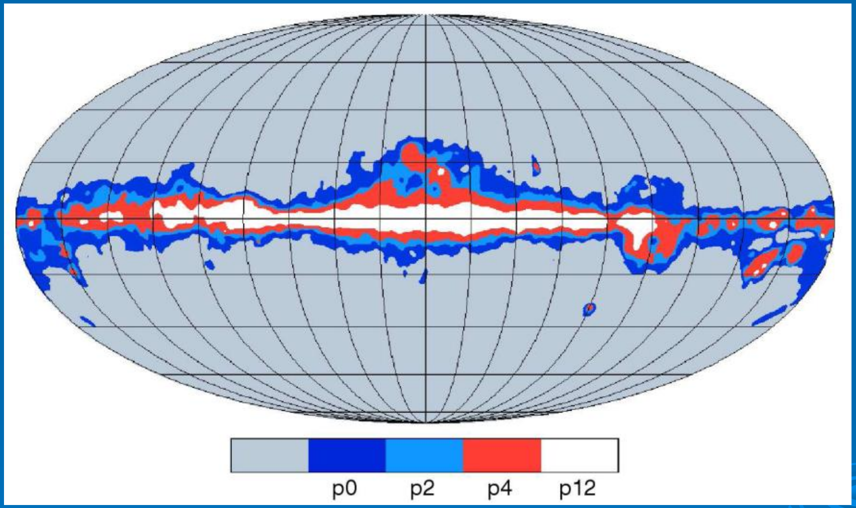




Contamination to the CMB

Masking the Galaxy: total intensity

- The sky emission is dominated by the Galaxy at all frequencies
- The contamination is always evaluated after removing its brightest part, together with the main known point sources
- In total intensity, the removal of the brightest part of the sky leaves the sky substantially dominated by the CMB at microwave frequencies
- The quantification of the contamination is usually done by means of the angular power spectrum of the masked sky



Bennett et al. 2006
see also Gold et al. 2008

Masking the Galaxy: polarization

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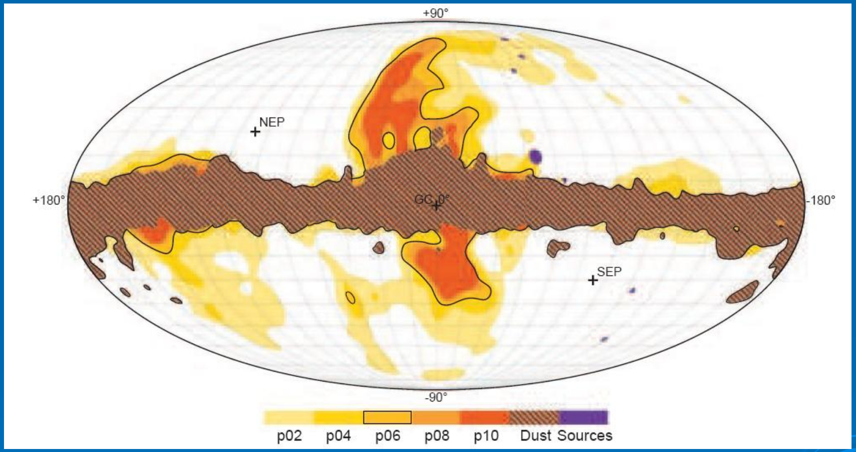

Page et al. 2006
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Masking the Galaxy: polarization

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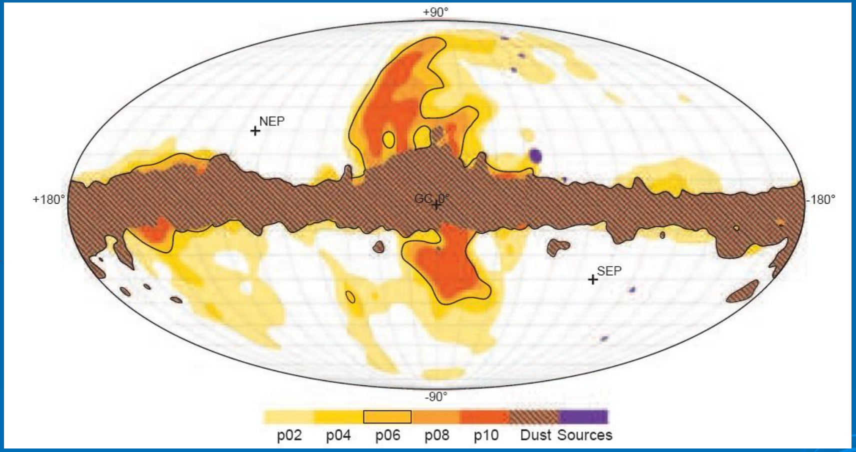

Page et al. 2006
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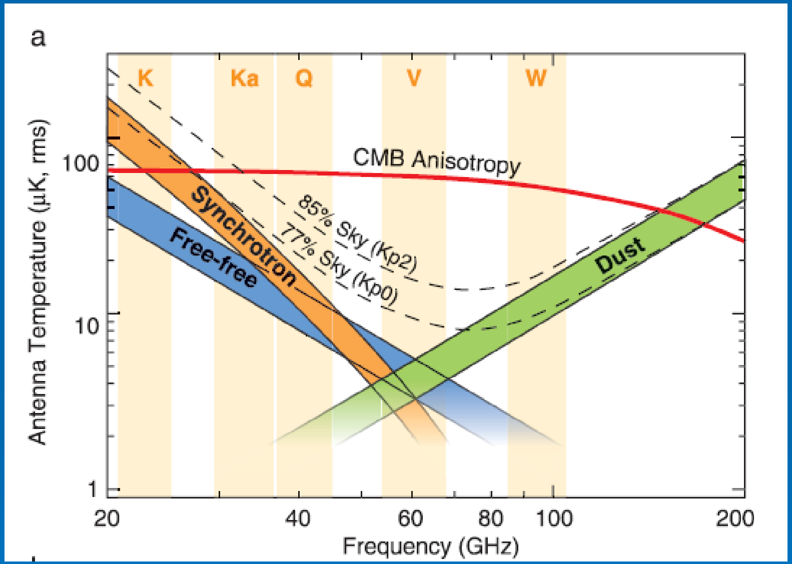
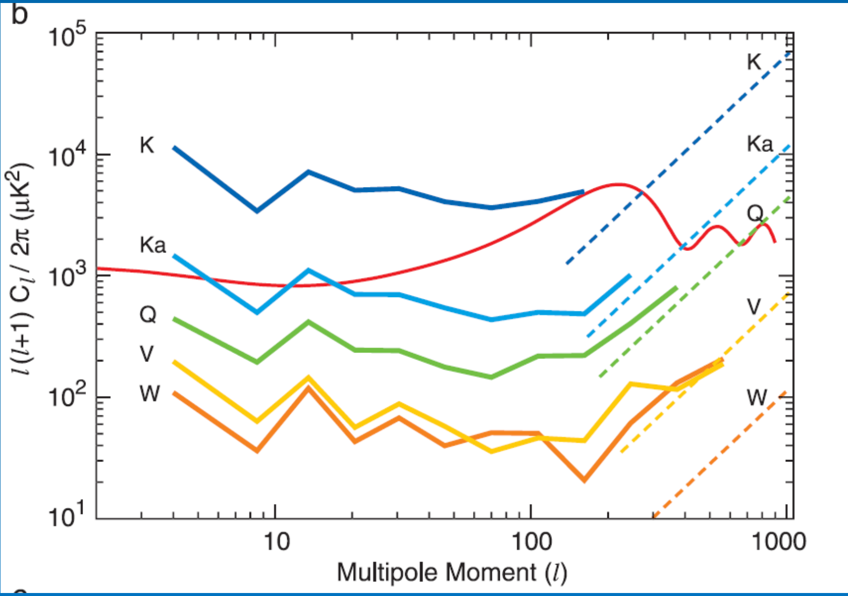
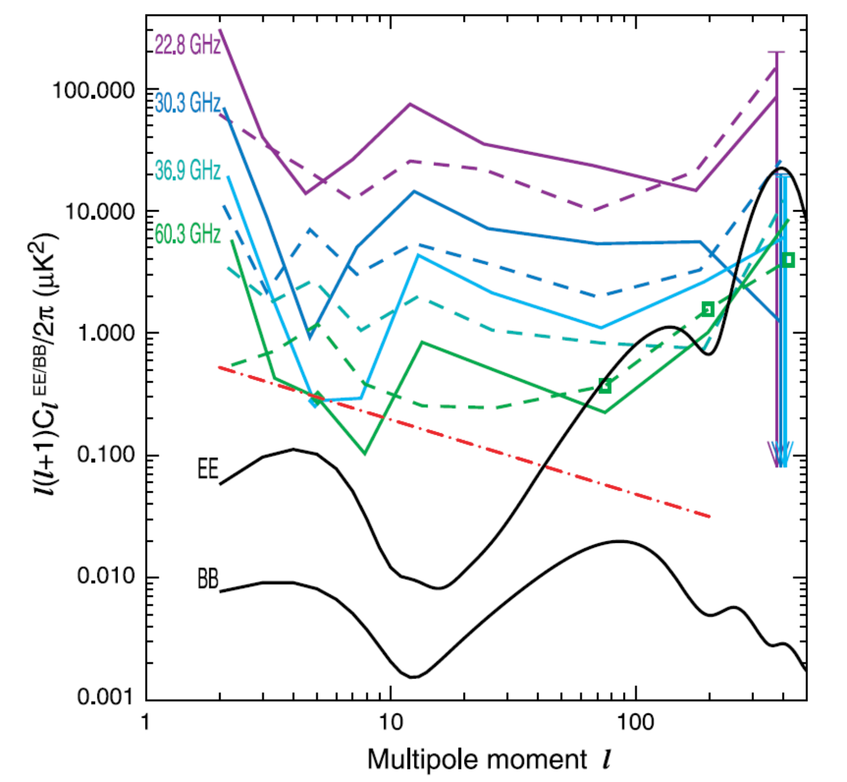
CMB contamination: total intensity

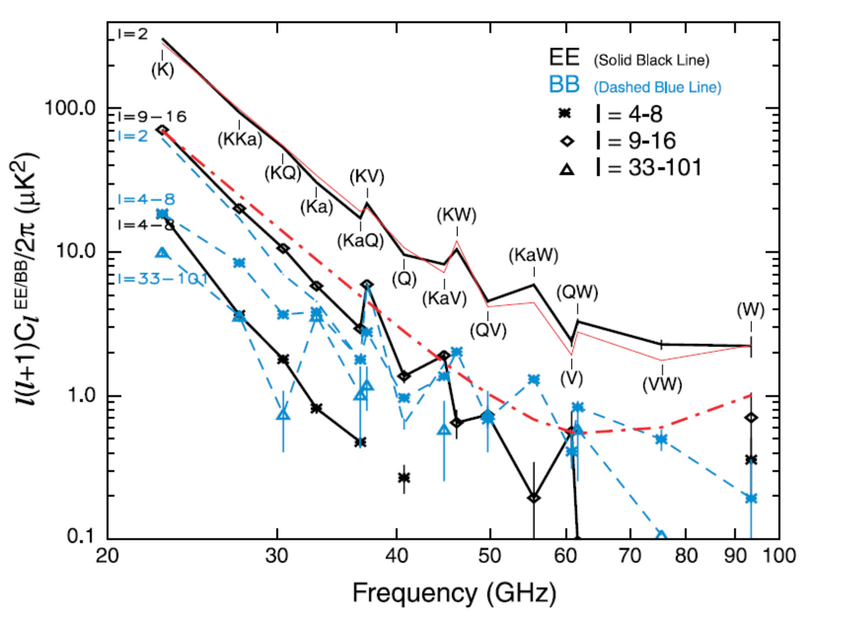




Bennett et al. 2003

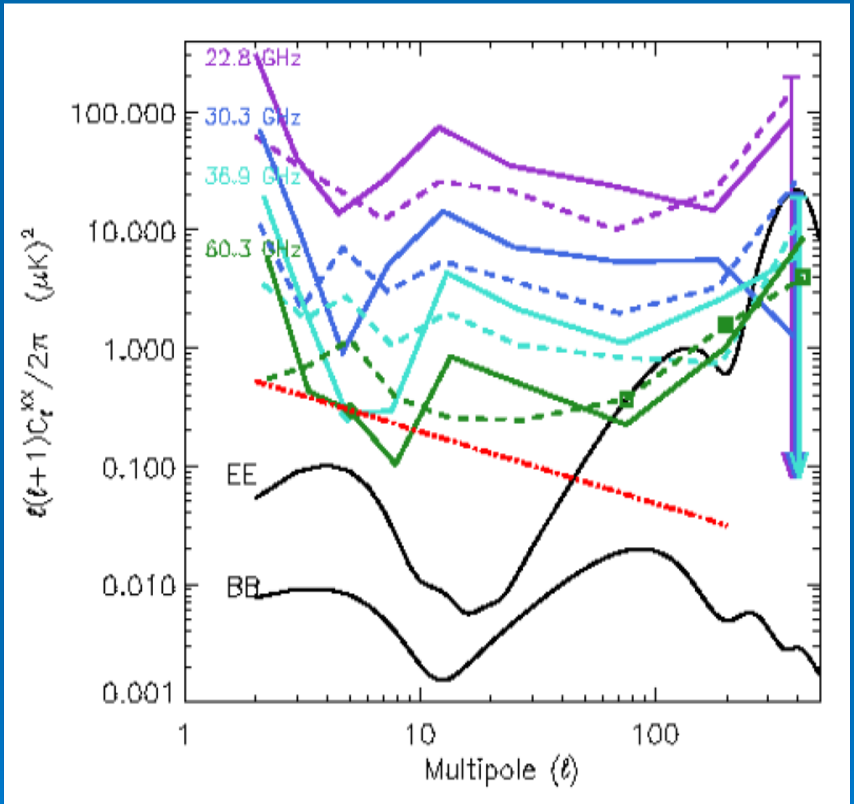
CMB contamination: polarization

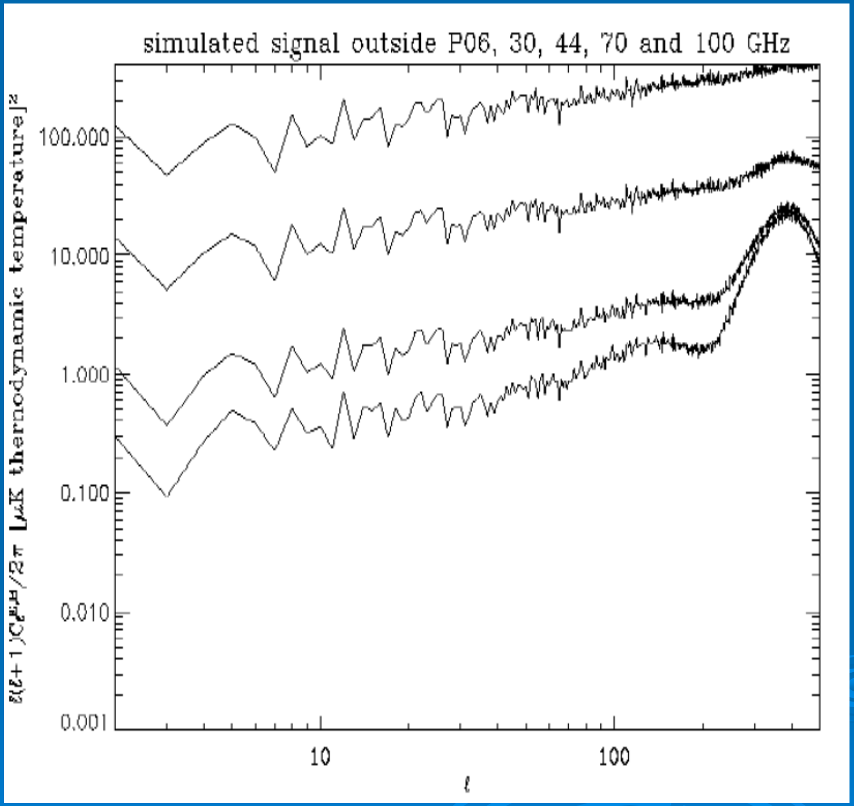




Page et al. 2006

A comparison between WMAP data and the Planck expectations



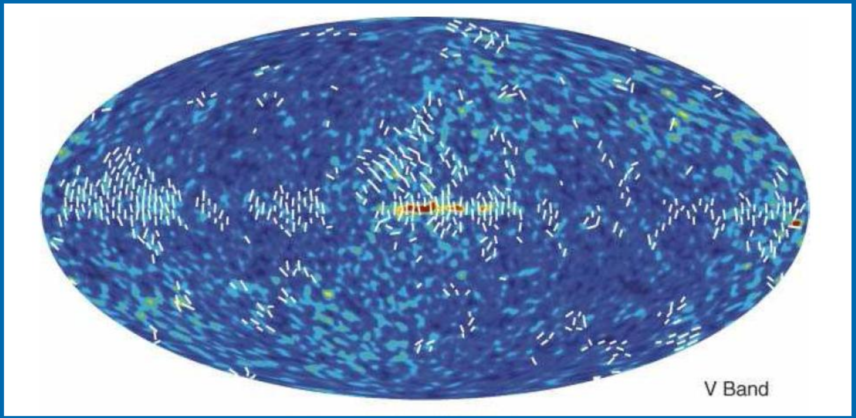


Page et al. 2006

Planck reference sky, 2004

Do we have any hope to see B modes?

Page et al. 2006



- WMAP has no detection in large sky areas in polarization
- Very naive estimates may be attempted in those areas, indicating that the foreground level might be comparable to the cosmological B mode at all frequencies, in all sky regions
- We need to rely on multi-frequency observations as well as robust data analysis techniques which are able to remove at most the foreground emission from polarization CMB data

Are there foreground clean regions at all in polarization?

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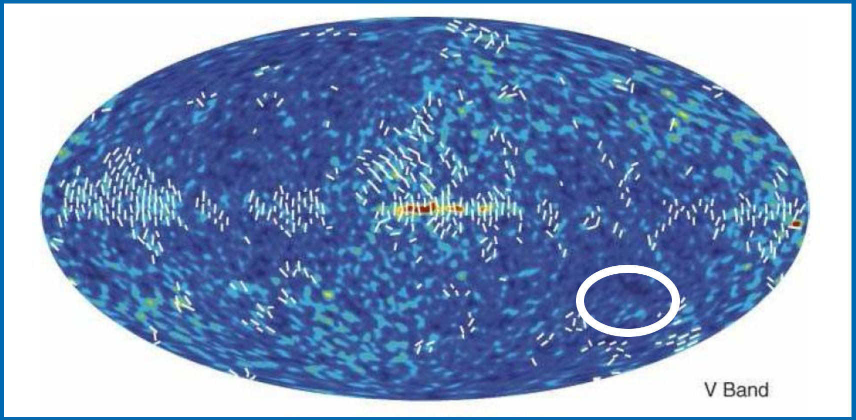
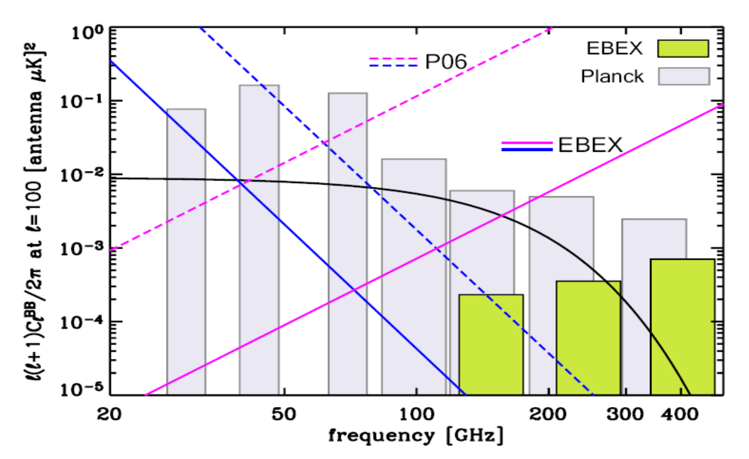
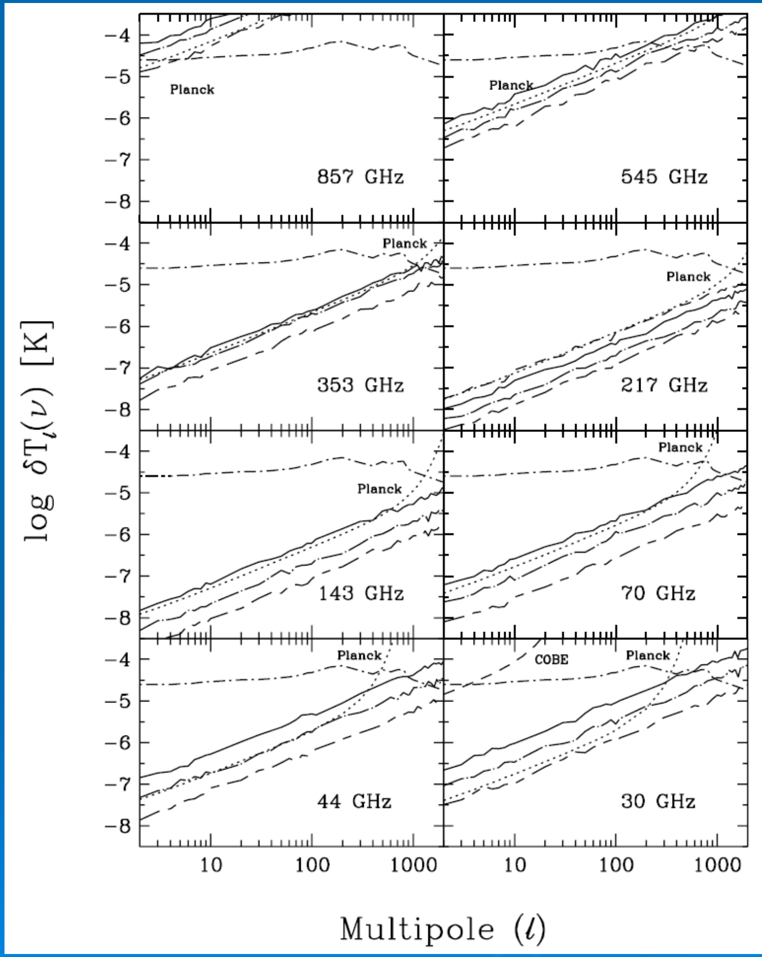
Page et al. 2006

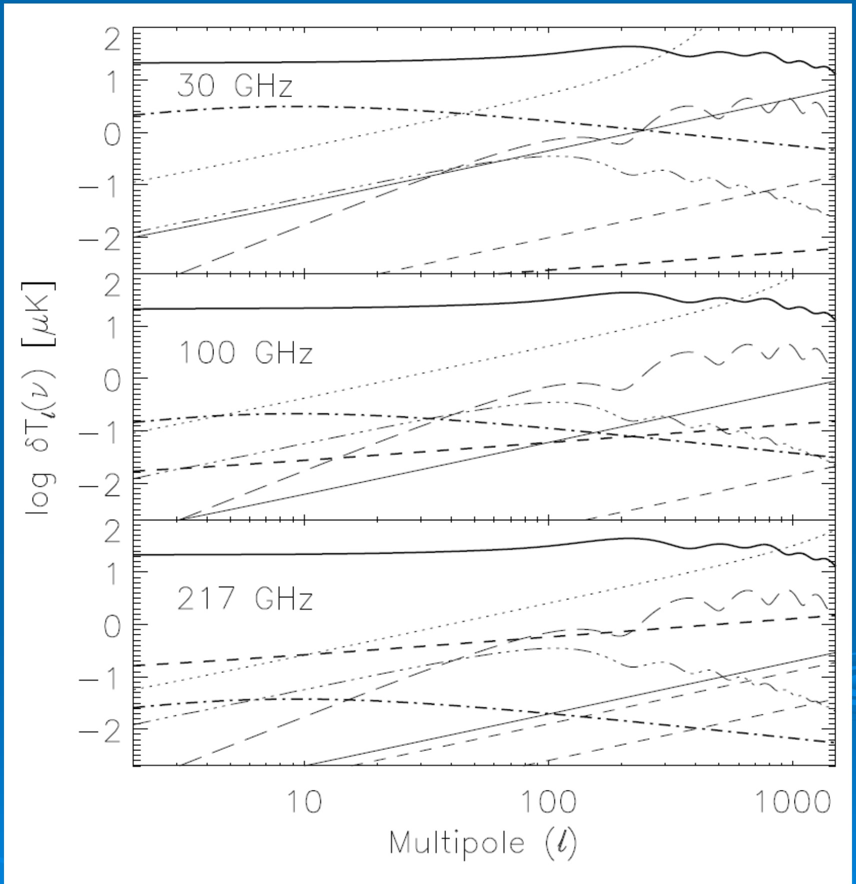




EBEX proposal to NASA, 2007

Contamination from point sources





Toffolatti et al. 1998, 1999

Why is it important to control foregrounds?

Why is it important to control foregrounds?

- Is the low quadrupole a problem? Unclear, it was demonstrated to depend on the foreground subtraction method (Bonaldi et al. 2007)
- Small scale CMB power, excess?
- North-south asymmetry?
- Primordial non-Gaussianity? WMAP data are non-Gaussian as some inflationary models predict (or a bit more, Yadav and Wandelt 2007), a debate is ongoing if this is an effect of unresolved foregrounds or not

CMB anisotropies

$T(\check{n}), Q(\check{n}), U(\check{n}), V(\check{n})$

spherical harmonics

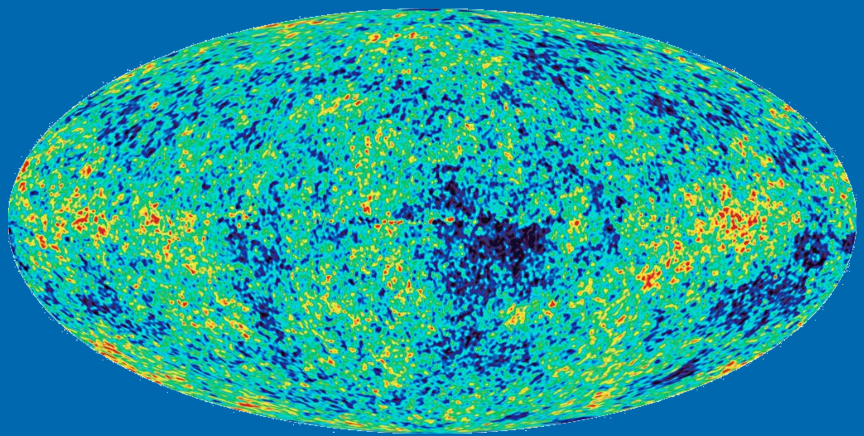
$a^T_{lm}, a^E_{lm}, a^B_{lm}$

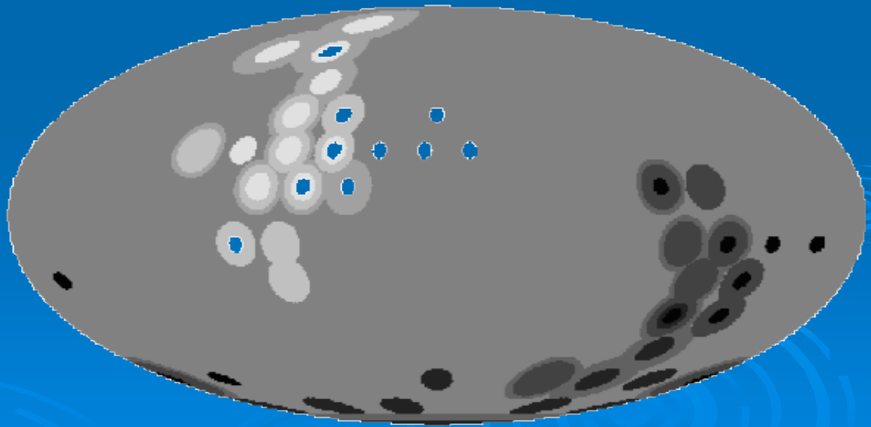
information compression

$C_l = \Sigma_m (a_{lm}^{T,E,B})(a_{lm}^{T,E,B})^*/2(l+1)$

Cosmic asymmetry?

- Evidence for north south asymmetry (Hansen et al. 2005, Hoftuft et al. 2009)
- Confirmed by several foreground subtraction methods (Maino et al. 2007)
- Consistency with Bianchi cosmological models (Jaffe et al. 2006)





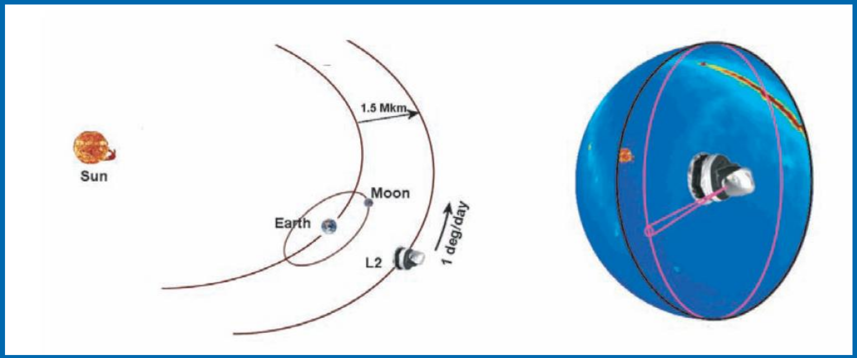
Suggested reading

- Baccigalupi 2003 for a pre-WMAP review on foregrounds, foreground B mode danger
- Bennett et al. 2003, for the WMAP results in total intensity
- Kogut et al. 2007, Page et al. 2007 for the WMAP results in polarization
- Gold et al. 2008, Dunkley et al. 2008, for the update on WMAP five years
- Wright et al. 2008, Massardi et al. 2007, 2008 for point source observations and assessment of the CMB contamination from them

Component separation

CMB data analysis: a fantastic information compression

- A typical CMB probe takes records of the sky radiation tens of times per second per detector, from weeks to years
- Sky maps contain tens of millions of resolution elements
- C_l are a few thousands
- Parameters representing physical quantities are a few



$$\Omega = 1$$

CMB data analysis levels

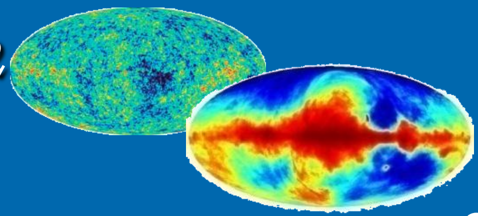
- Level 1, telemetry, timelines processing, calibration
- Level 2, map-making
- Level 3, point source extraction, component separation, CMB cleaning and power spectra estimation, cosmological parameters

Dealing with foregrounds

- First step: detecting and masking point sources
- Off-band known sources are masked
- Sky maps are convolved with beam-like filters (Wavelets, see Herranz et al. 2009), and signals above a certain threshold are identified as sources and removed
- The same operation, with the information of the SZ frequency scaling, is used to isolate and mask galaxy clusters
- Second step: diffuse component separation…

Component separation

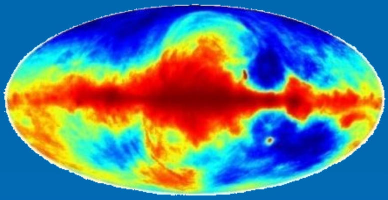
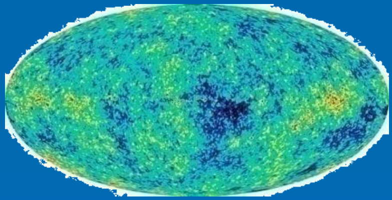
s_2

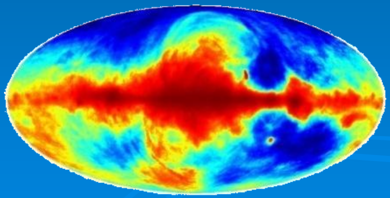
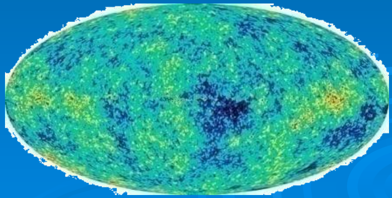


s_1

ν_1

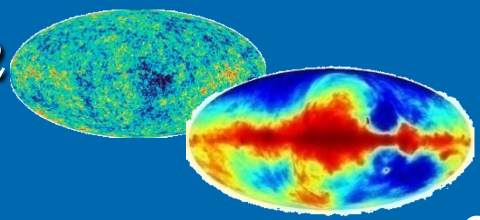
ν_2

$x_1 = a_{11}$  $+ a_{12}$  $+ n_1$

$x_2 = a_{21}$  $+ a_{22}$  $+ n_2$

Component separation

s_2



s_1

ν_1

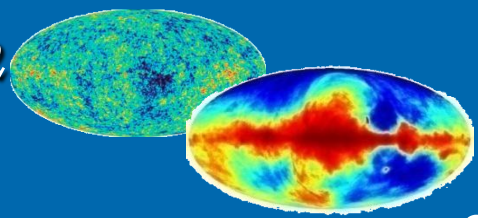
ν_2

$$x_1 = a_{11} \quad s_1 \quad + a_{12} \quad s_2 \quad + n_1$$

$$x_2 = a_{21} \quad s_1 \quad + a_{22} \quad s_2 \quad + n_2$$

Component separation

s_2



s_1

ν_1

ν_2

$$x = As + n$$

Invert for s!

Component separation: criteria to achieve separation

$$\mathbf{x} = \mathbf{A}s + \mathbf{n}$$

- In typical applications, s is unknown in polarization, while somewhat known in total intensity from non-microwave data; A is known to 10% accuracy, and is known to vary in the sky
- Physical aspects in the data are exploited in order to stabilize the inversion
- Statistics: CMB and foregrounds are statistically independent; by using the statistical distrubution provided by multi-frequency data, it is possible to recover each independent component (see e.g. the Independent Component Analysis, Maino et al., 2007, and references therein)
- Parametrization: foregrounds are modeled through parameters, entering either in A or s; single-resolution element multi-frequency fitting (see e.g. Stompor et al. 2009) or spatial correlations (see Bonaldi et al. 2006) may be used to estimate unknowns
- Relevant literature from Brandt et al. 1994, to Leach et al. 2008, successful applications to COBE, BEAST, WMAP

Independent Component Analysis (ICA)

- Assume statistical independence between different astrophysical emissions
- The statistics of their superposition tends to be close to Gaussianity
- Reverse the process with linear combinations of the signals at different frequencies, extremizing the non-Gaussianity
- The extrema correspond to the independent components
- Achievements: successfully recovered CMB results for COBE, BEAST, WMAP

See Maino et al. 2007, and references therein

Component separation: ICA

Correlated component analysis (CCA)

- Parametrize unknowns in A
- Construct the data correlation function, $C_x(\delta\theta,\delta\varphi)=\langle x(\theta,\varphi)x(\theta+\delta\theta,\varphi+\delta\varphi)\rangle$
- One has $C_x=AC_sA^T+C_n$
- Use enough data for estimating unknowns in A and C_s
- Perform a regularized inversion for s
- Achievements: successfully applied to WMAP data

See Bonaldi et al. 2007, and references therein

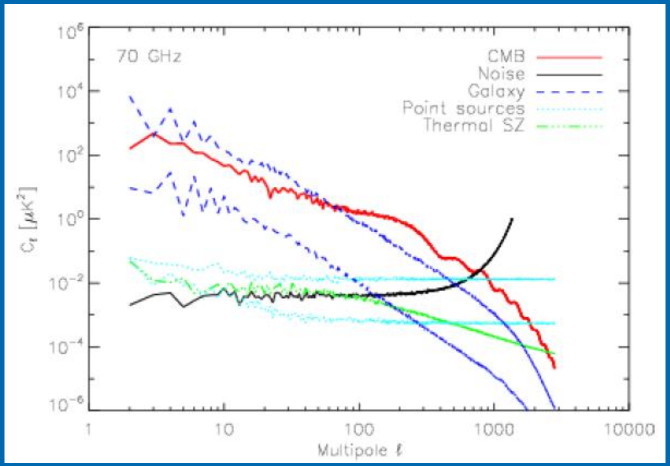
Pixel based parametric fitting

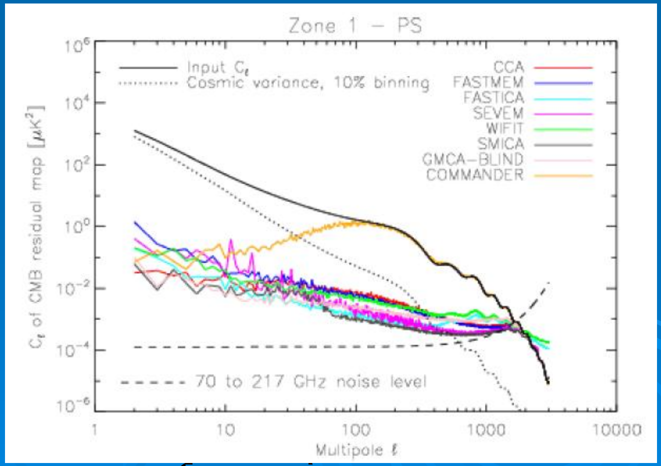
- Parametrize unknowns in A,s
- Write a likelihood ∝ $\exp[-(x-As)^T N^{-1}(x-As)]$
- Use multi-frequency data to fit for unknowns pixel by pixel
- Achievements: not many so far, successfully applied to WMAP large scales, but promising in terms of error propagation

See Stompor et al. 2009, and references therein

Where are we now with component separation?

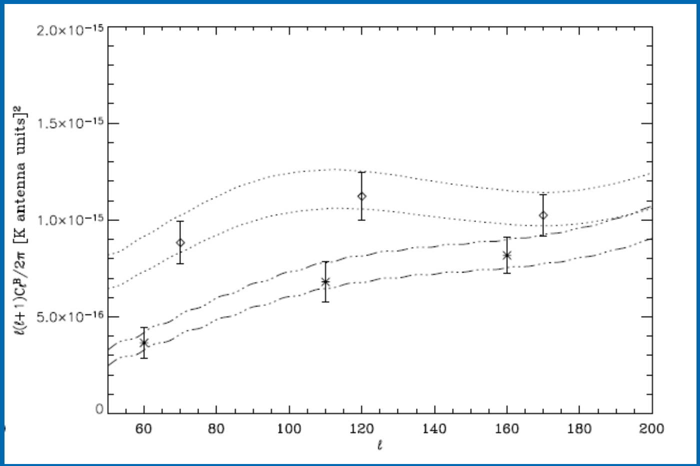
- In total intensity, a comparison of different methods applied to simulated Planck data exists (Leach et al. 2008)
- Preliminary results show a substantial cleaning from diffuse foregrounds, and a considerable residual contamination from unresolved point sources

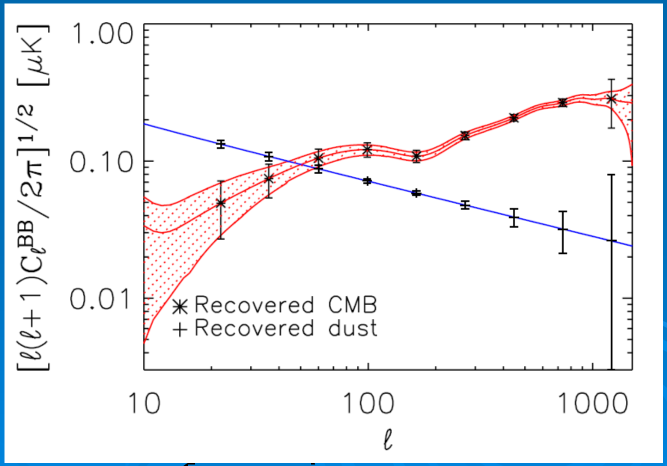




Where are we now with component separation?

- In polarization, a similar, unpublished analysis indicate a possible recovery of the EE CMB power spectrum up to l=1000
- A separate, most important case for component separation concerns sub-orbital probes, aiming at detecting B modes in likely conditions of substantial foreground contamination (see Stivoli et al., 2006, and the EBEX proposal to NASA, 2007)
- Estimation of the minimum detectable tensor power in presence of foreground cleaning is in progress





Suggested reading

- The Planck blue book is available at http://www.rssd.esa.int/Planck
- Oxley et al. 2005 for a description of EBEX
- Leach et al. 2008 for the present status of our capability of cleaning CMB from foregrounds with Planck, in total intensity
- Bonaldi et al. 2006, Stivoli et al. 2006, Stompor et al. 2009 for the component separation techniques we plan to exploit in the forthcoming years