Cosmic Microwave Background

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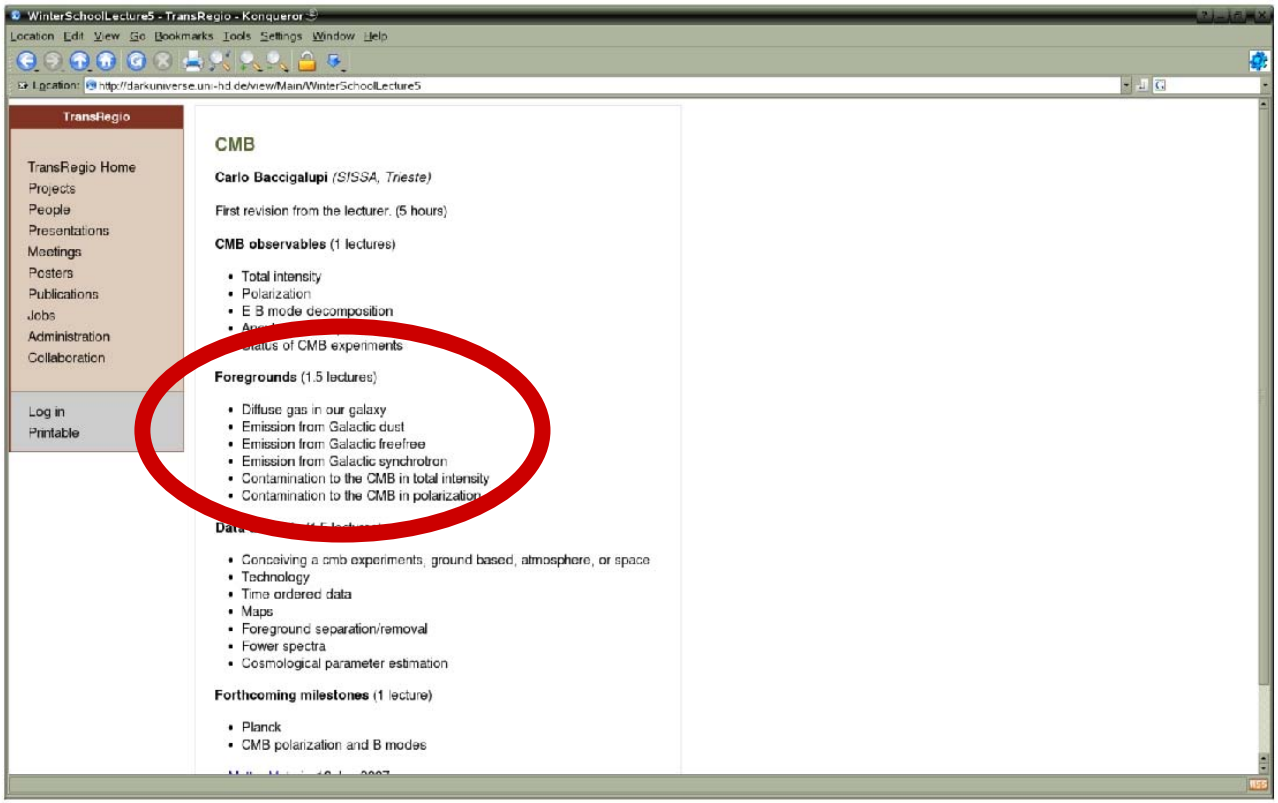
CMB lectures at TRR33, see the complete program at
darkuniverse.uni-hd.de/view/Main/WinterSchoolLecture5
These lectures are available in pdf format at
people.sissa.it/~bacci/work/lectures

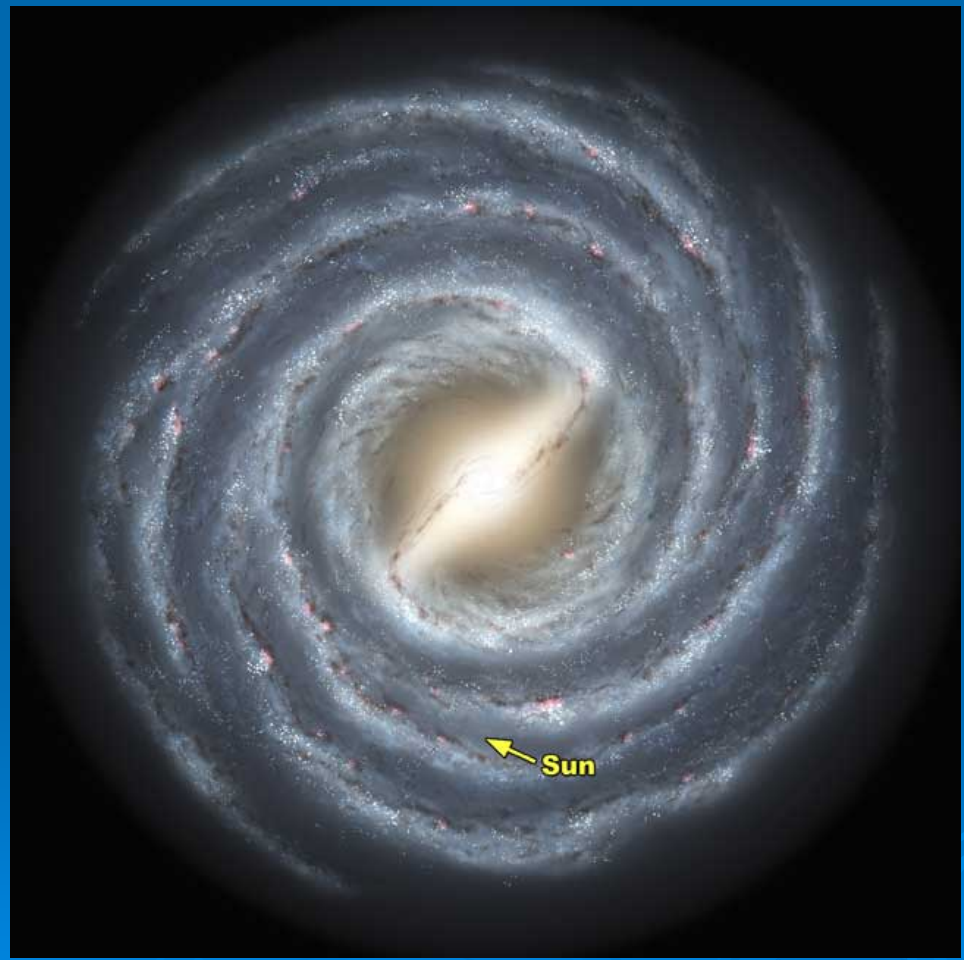
CMB and foregrounds



Outline

- Foreground fundamentals
- Galactic synchrotron
- Galactic free-free
- Galactic dust
- The other galaxies and clusters
- Contamination to the CMB

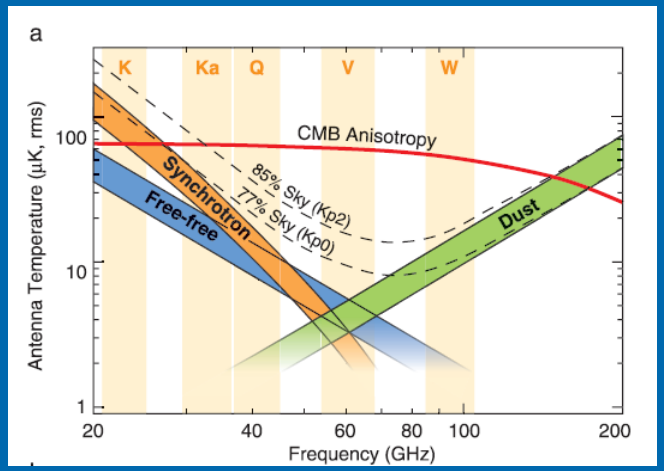
Foreground fundamentals: the Galaxy, the other galaxies, and their clusters

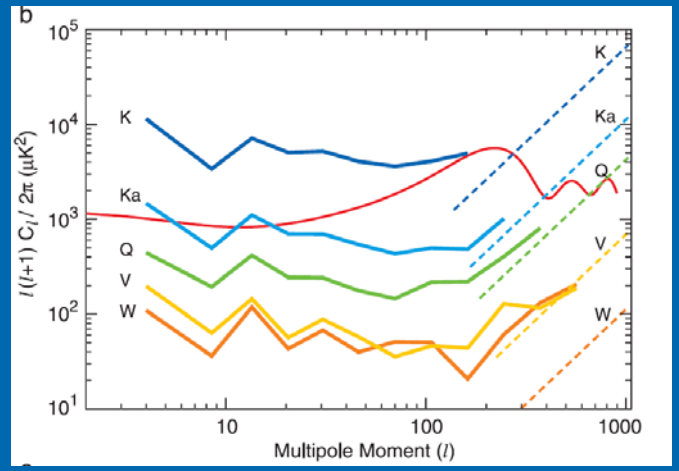


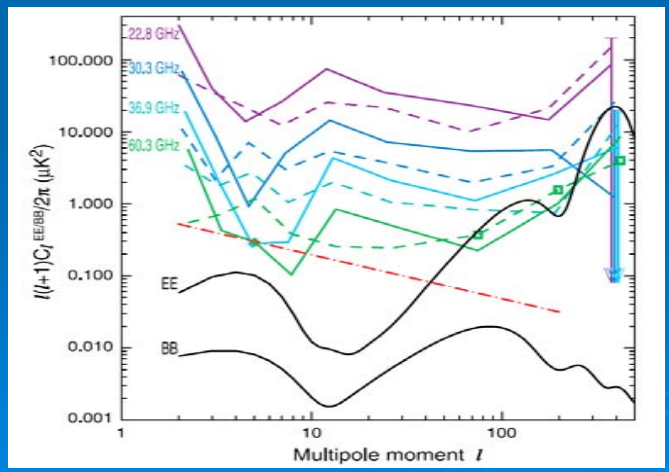
Foreground fundamentals: differences with respect to the CMB

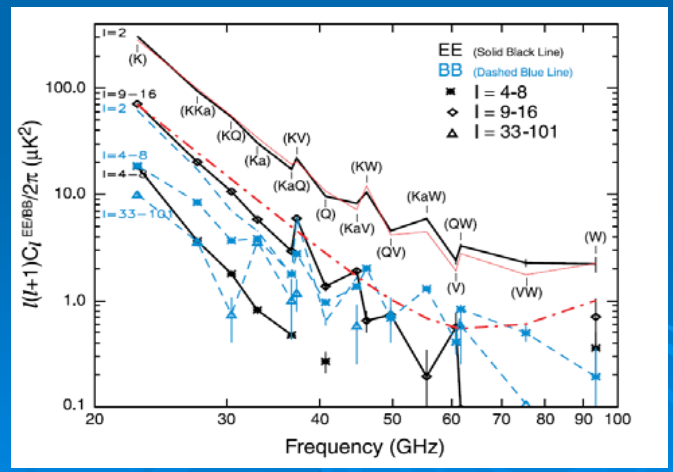
- Together with instrumental systematics, foregrounds are the ultimate limitation of CMB observations
- Unlike CMB, the foreground knowledge is mainly empirical, we know the main physical processes activating them, but their emission is calibrated mainly through observations
- Unlike CMB, the Galactic emission is strongly inhomogeneous, concentrated on the Galactic plane
- Unlike CMB, 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
- Unilike CMB, the emission from extra-Galactic object is point-like

Foreground fundamentals





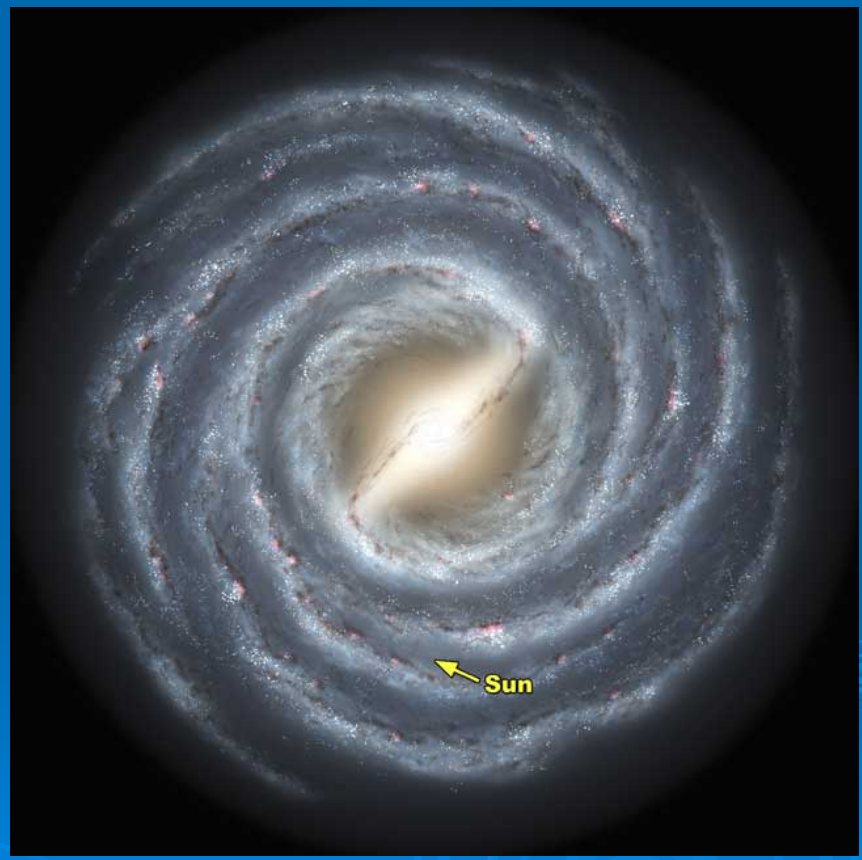




Bennett et al. 2003, Page et al. 2007

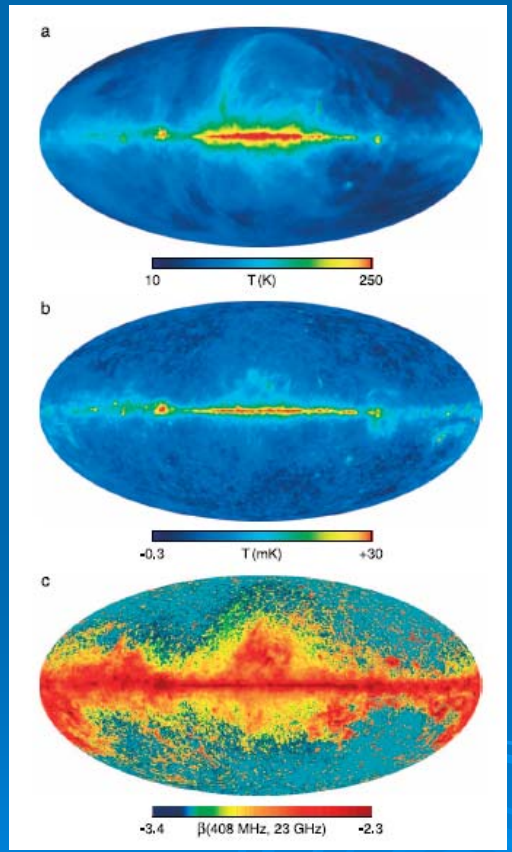
Milky way

- In 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 an hot system, 20 K or so, not isolated because heated back by starlight
- The galaxy possesses a magnetic field of order 10^{-10} Tesla, with a large scale component orthogonal to the plane and elongated along arms, and a largely unknown small scale component



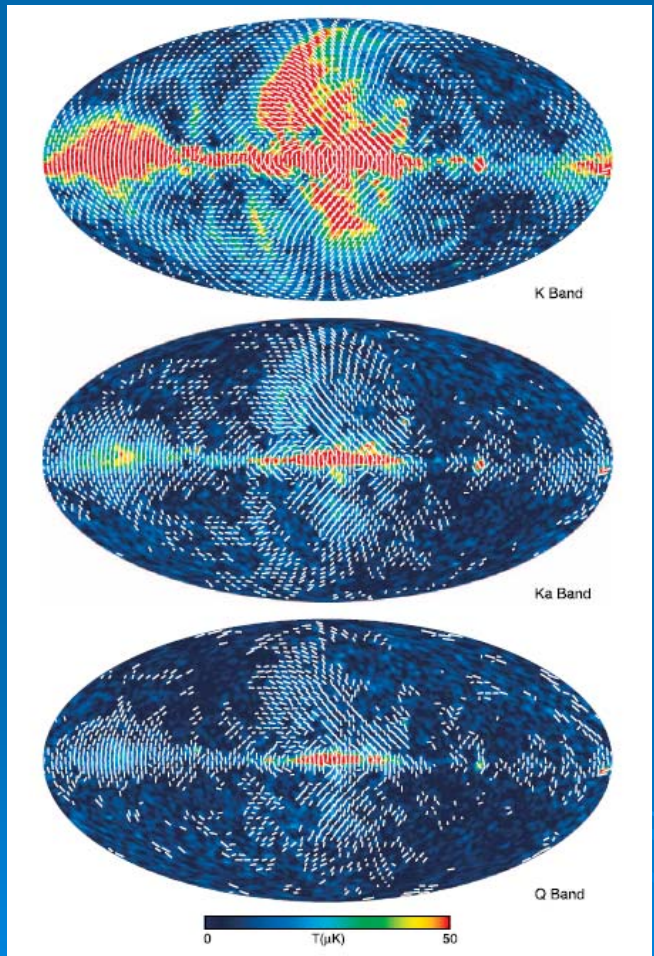
Foregrounds coming from the radio band: Galactic synchrotron

- What it is: free electrons spiraling around the lines of the Galactic magnetic field
- In frequency, it behaves as a decaying power law, because the electron number is a decreasing power law of their energy, $N(E) \propto E^{-|p|}$
- Existing information on all sky, in total intensity, taken in the radio band (Haslam et al. 1986, Reich et al. 1998) and in microwaves by WMAP (Bennett et al. 2003)



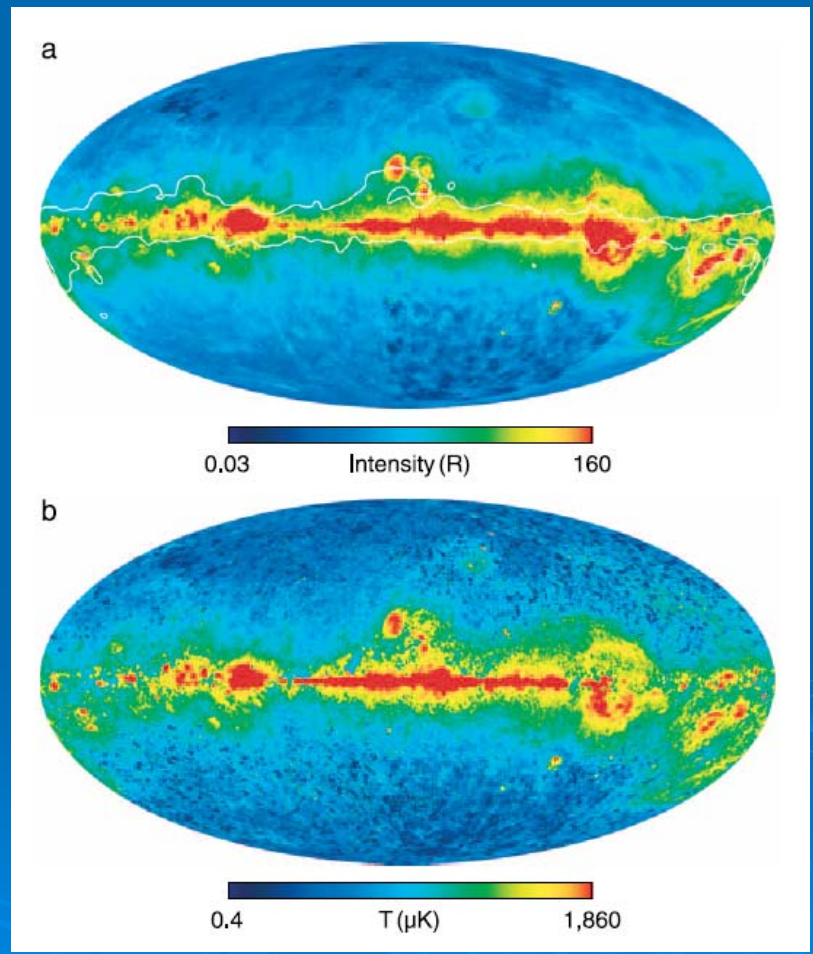
Foregrounds coming from the radio band: Galactic synchrotron

- The Galactic synchrotron is strongly polarized, the polarized intensity has been found to be a few ten percent of the total one
- The frequency scaling is close to the one of total intensity
- All sky observations in the radio band exist (La Porta et al. 2006), but are affected by masking effects like the Faraday rotation leading to 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



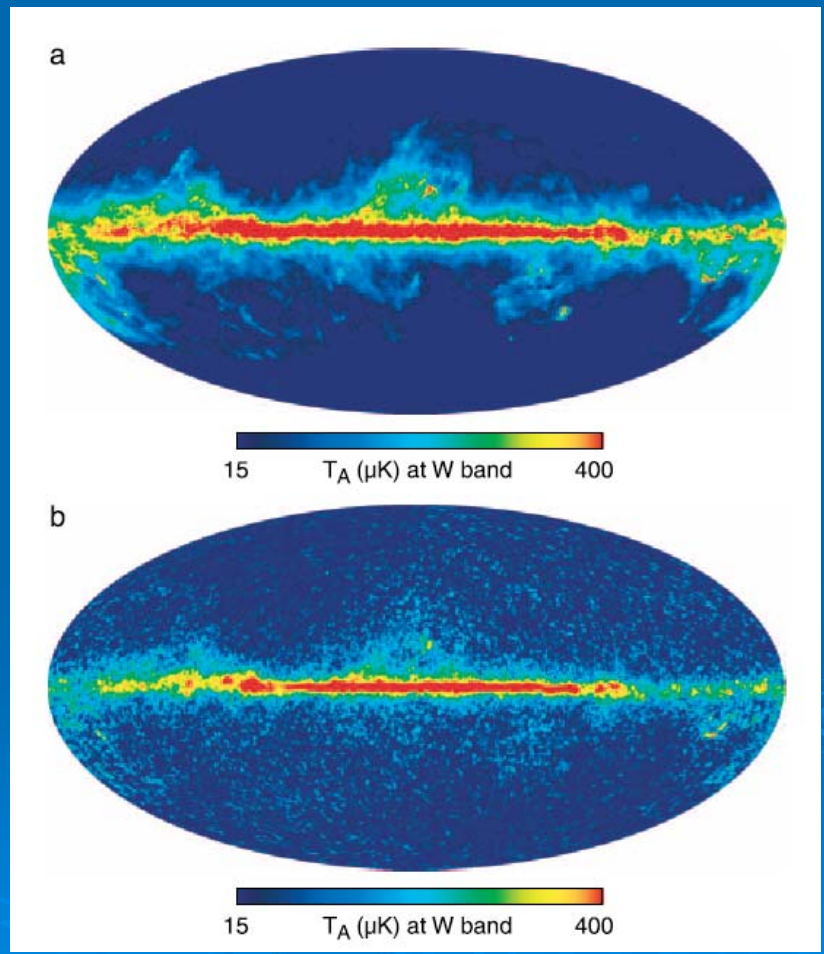
Foregrounds coming from the radio band: Galactic free-free

- 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
- Its emission decays in frequency, but less fast than synchrotron, because of the energy distribution of ions
- It is intrinsically unpolarized, the available observations from Hα surveys, WMAP data (Bennett et al. 2003)



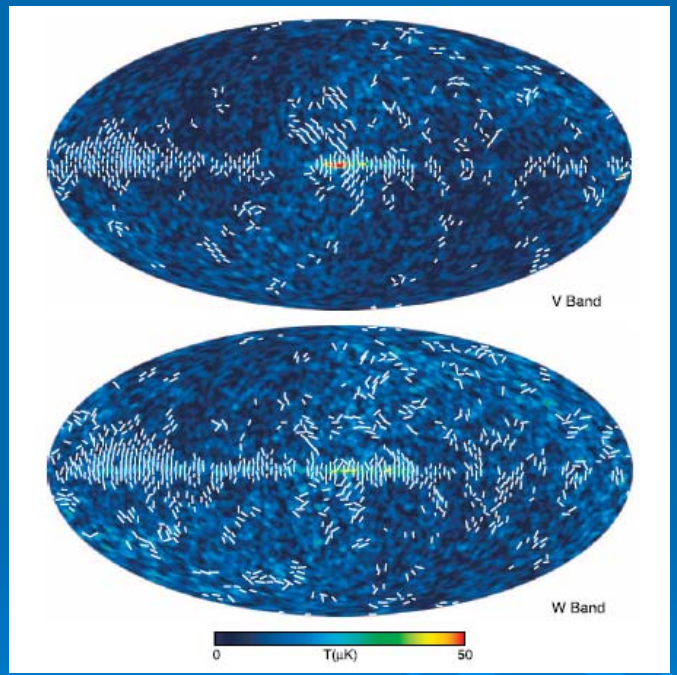
Foreground coming from the infrared band: Galactic dust

- 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
- An all sky template from IRAS at 3000 GHz exists for total intensity, and the extrapolation to the microwaves using a grey body spectrum was found consistent with the WMAP data (Bennett et al. 2003)



Foreground coming 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 polarized intensity was found to be about 10% of the toal one along the Galactic plane by Archeops (Benoit et al. 1995) and WMAP (Page et al. 2006), being probably higher at higher latitutdes



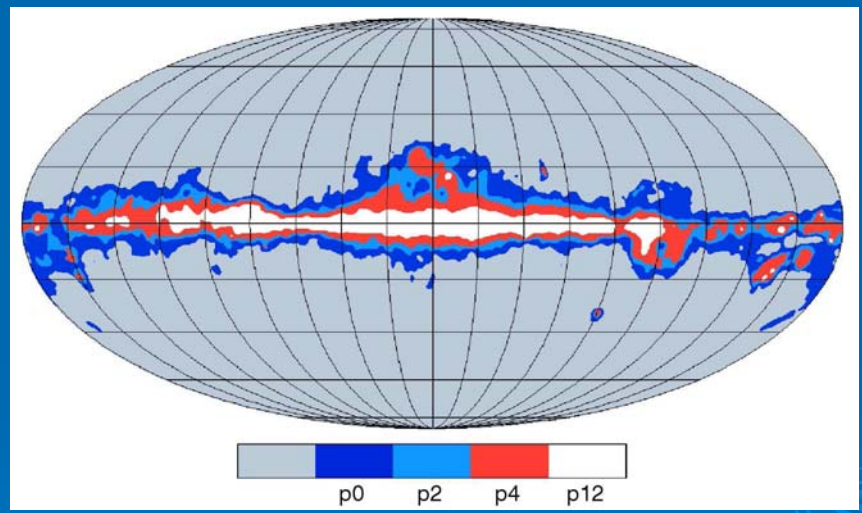
Other galaxies and their clusters

- 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
- Being point-like, their signal behaves similarly to instrumental noise
- The existing observations indicated a polarized intensity which is a few percent of the total one in the radio, comparable in the infrared band
- 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

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

Masking the Galaxy: polarization

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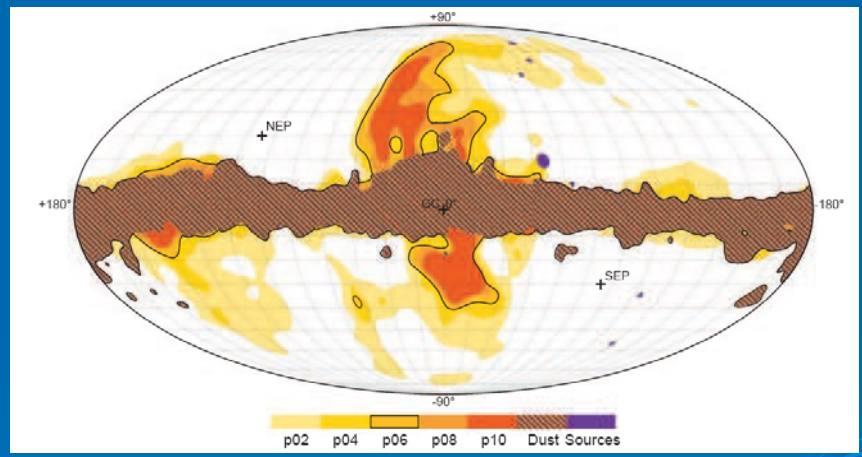

Page et al. 2006

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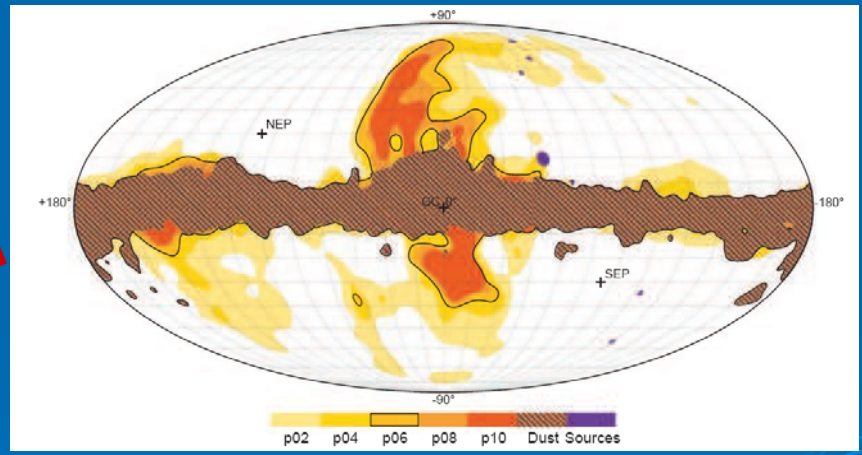
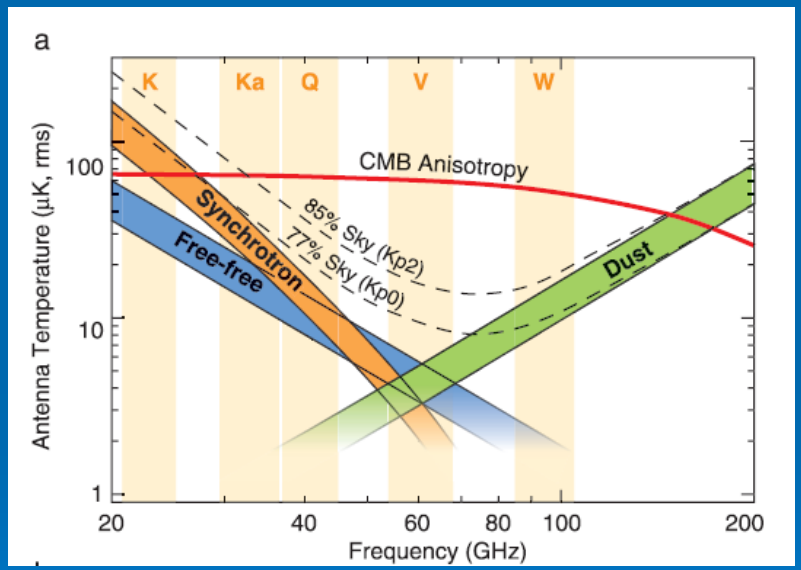
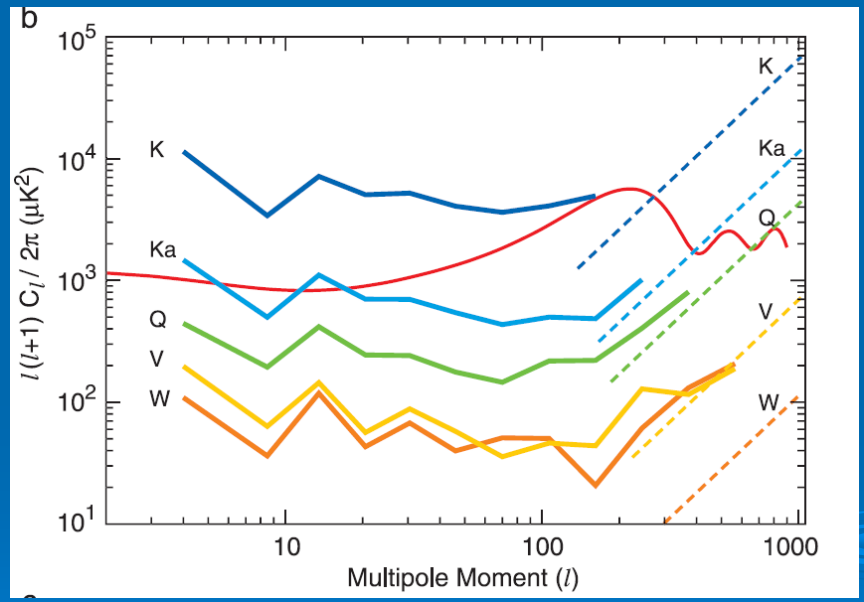


Page et al. 2006

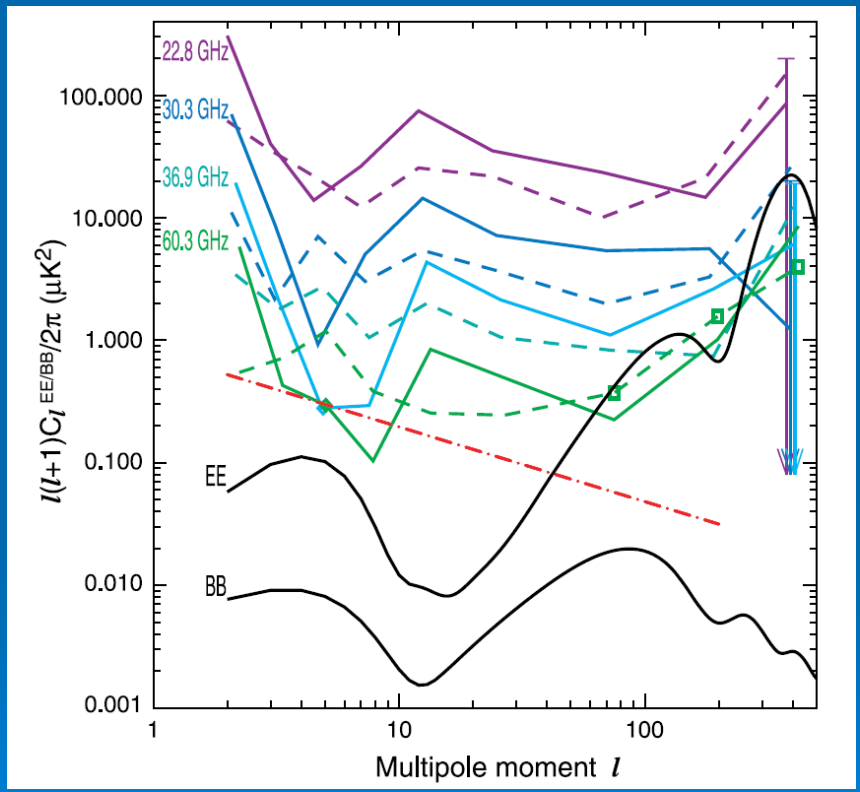
CMB contamination: total intensity

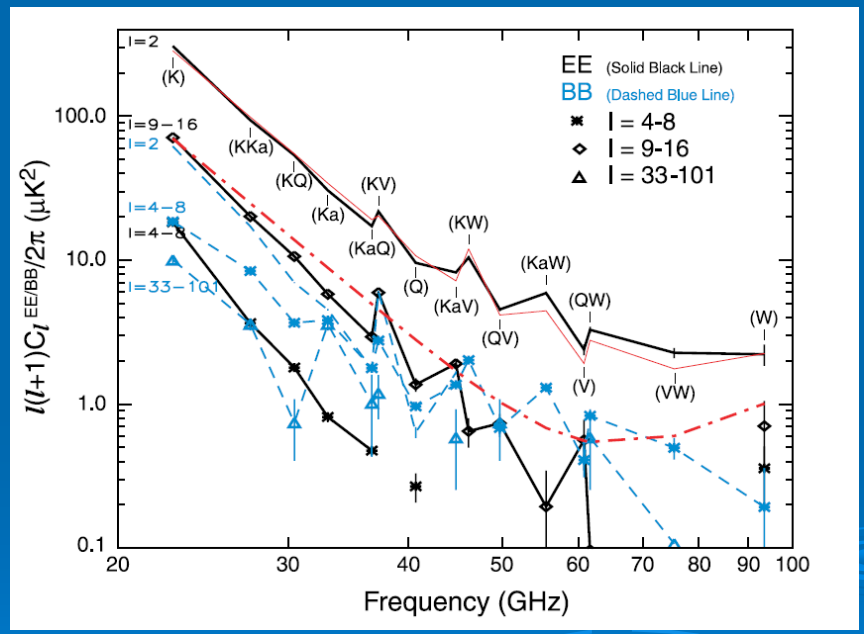




Bennett et al. 2003

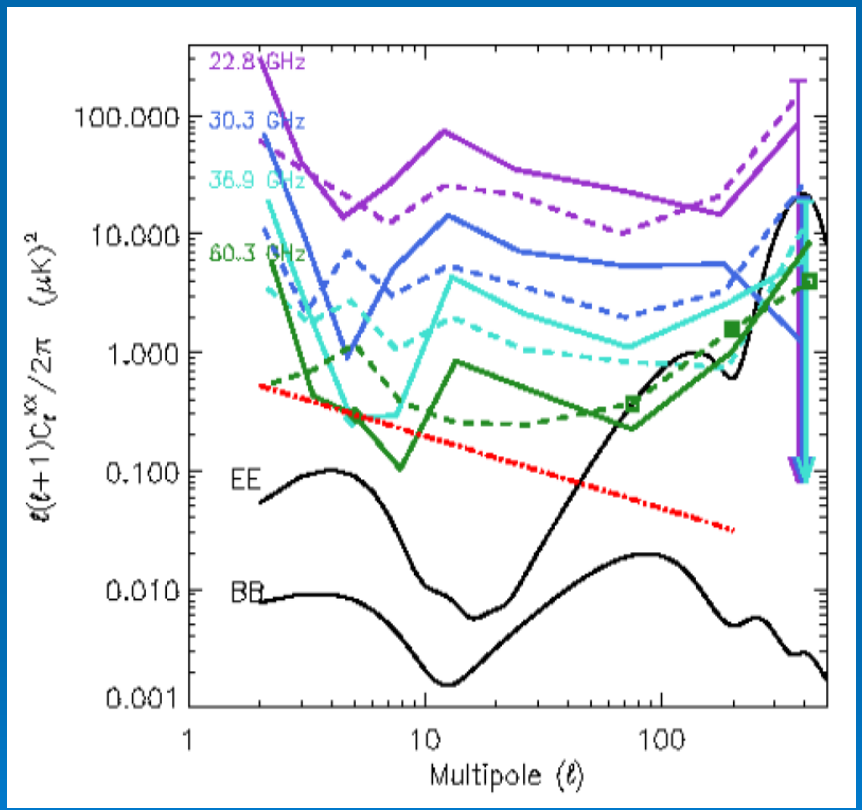
CMB contamination: polarization



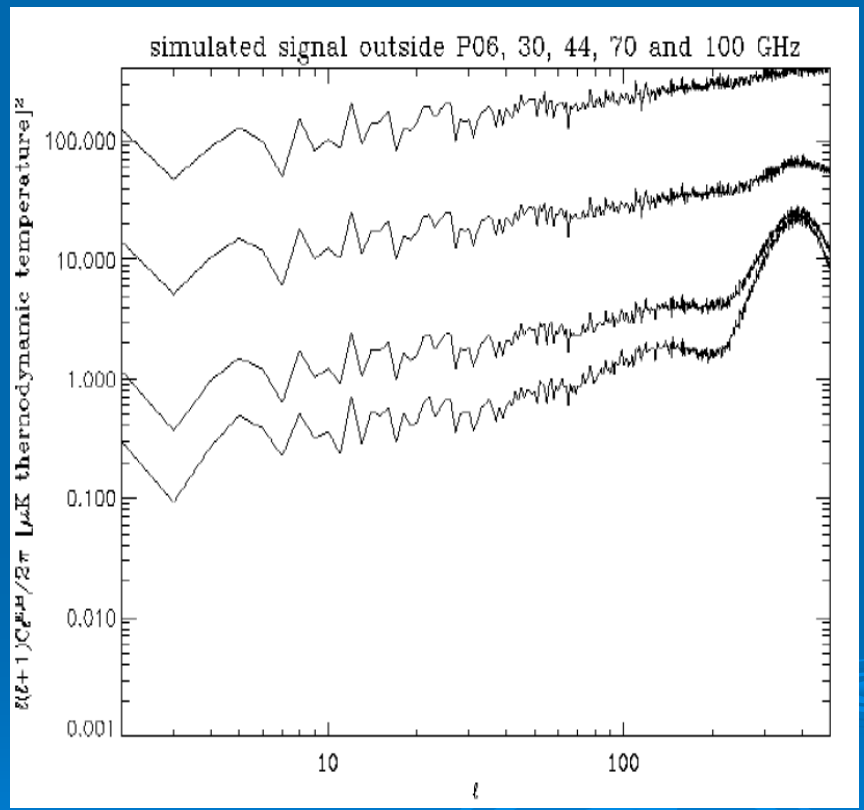


Page et al. 2006

A comparison between WMAP data and the Planck expectations



Page et al. 2006

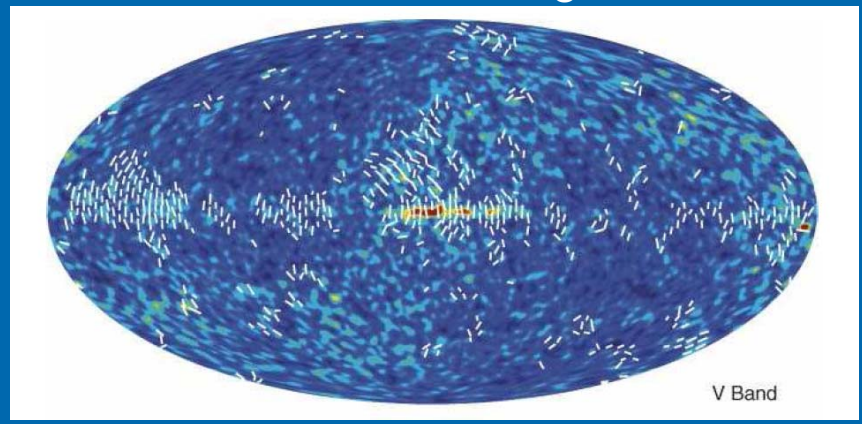


Planck reference sky, 2004

Do we have any hope to see B modes?

- 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

Page et al. 2006



Are there foreground clean regions at all in polarization?

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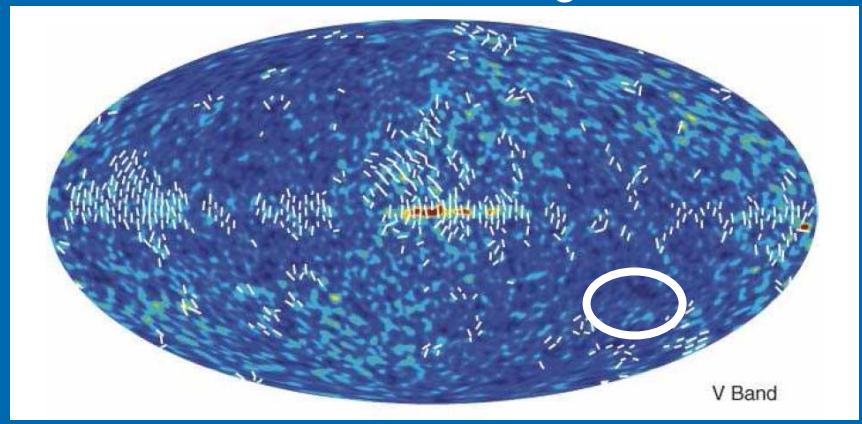

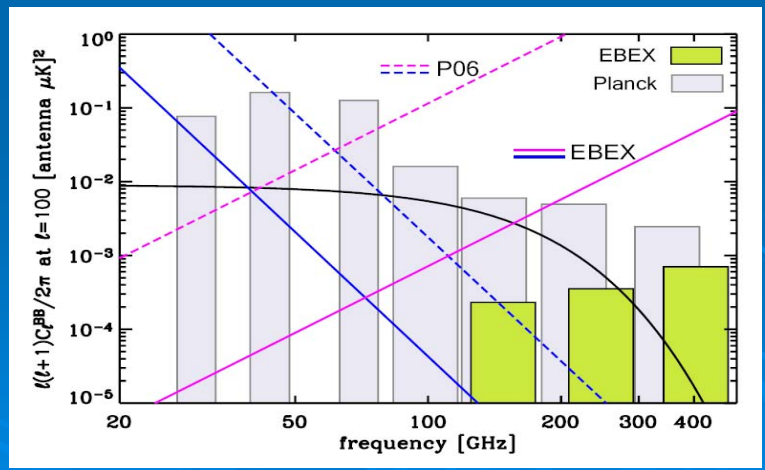

Baccigalupi, Hanany et al. 2007 for the EBEx collaboration

Suggested reading

- Baccigalupi 2003 for a pre-WMAP review on foregrounds
- 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