Planck and sub-orbital CMB probes at work: challenge and expectations for cosmology and astrophysics

Carlo Baccigalupi, SISSA

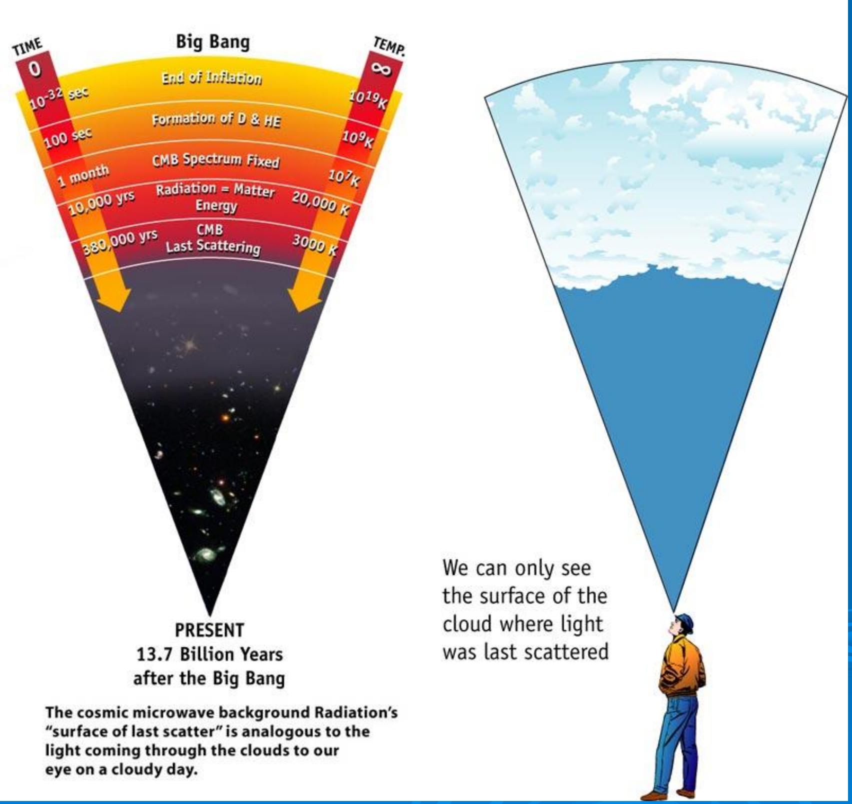
Outline

- CMB physics
- Status of CMB observations
- Data analysis and scientific goals of the Planck satellite
- B mode hunters, the case of EBEX
- Conclusions, ☹/☺

CMB physics

CMB: where and when and how

- Opacity: $\lambda = (n_e \sigma_T)^{-1} \ll H^{-1}$
- Decoupling: $\lambda \approx H^{-1}$
- Free streaming: $\lambda \gg H^{-1}$
- Cosmological expansion, constants and baryon abundance conspire to activate decoupling about 300000 years after the Big Bang, at about 3000 K photon temperature
- Expansion and the metric perturbations affect all cosmological species
- The CMB is a snapshot of cosmological perturbations in the photon component only



CMB: where, when and how

Baccigalupi, Amendola, Occhionero 1996-2000

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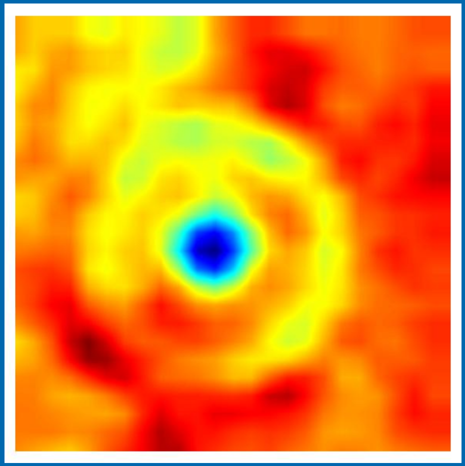
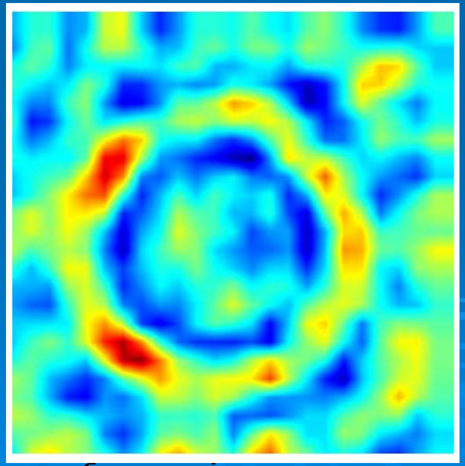




Animation from the NASA WMAP team

CMB physics: Boltzmann equation

$$\frac{d\ \text{photons}}{dt} = \text{metric} + \text{Compton scattering}$$

$$\frac{d\ \text{baryons+leptons}}{dt} = \text{metric} + \text{Compton scattering}$$

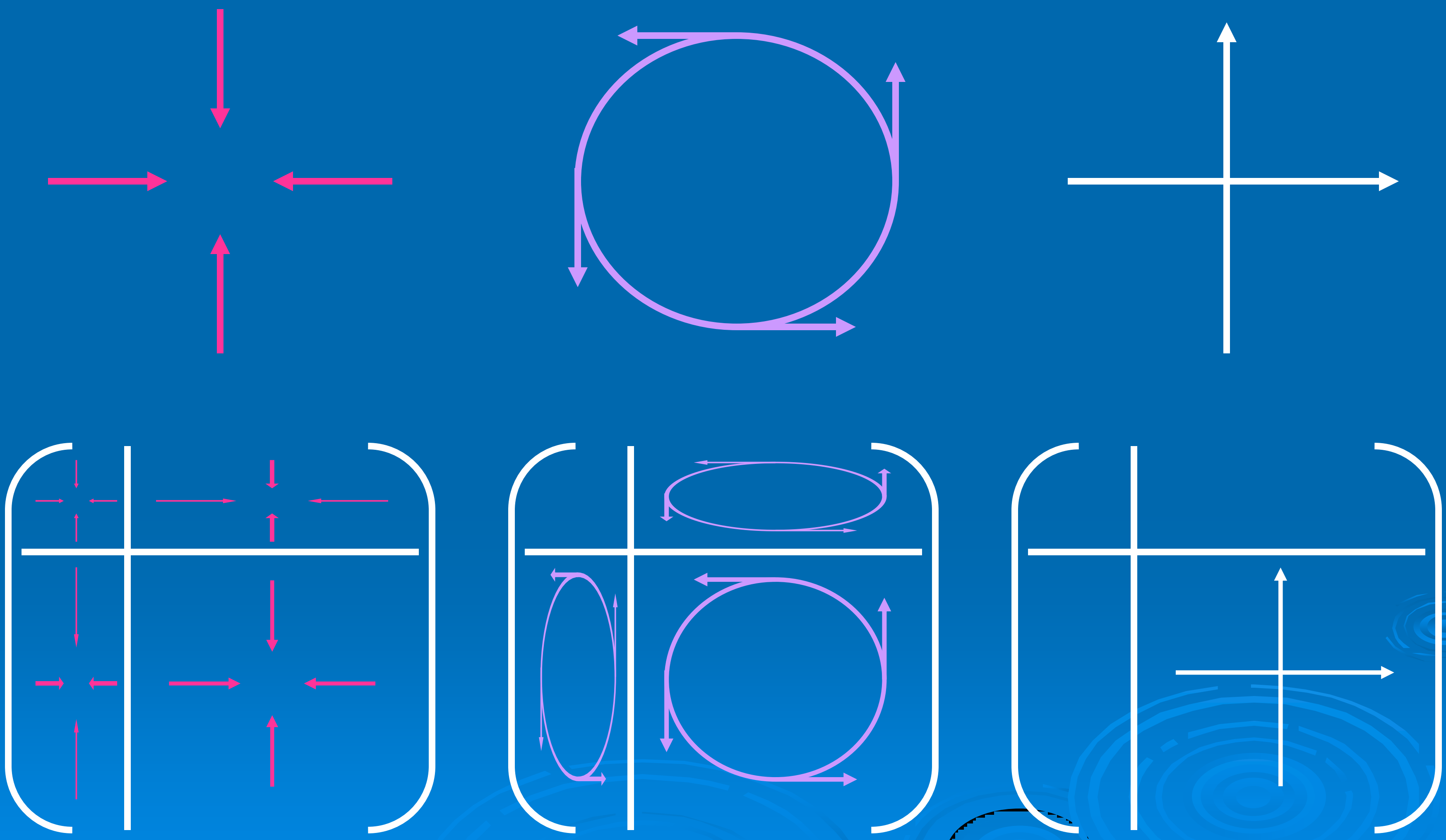
CMB physics: Boltzmann equation

$$\frac{d\ \text{neutrinos}}{dt} = \text{metric} + \text{weak interaction}$$

$$\frac{d\ \text{dark matter}}{dt} = \text{metric} + \text{weak interaction (?)}$$

metric = photons + neutrinos + baryons + leptons + dark matter

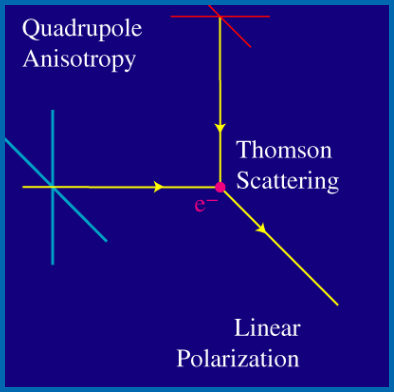
CMB physics: metric

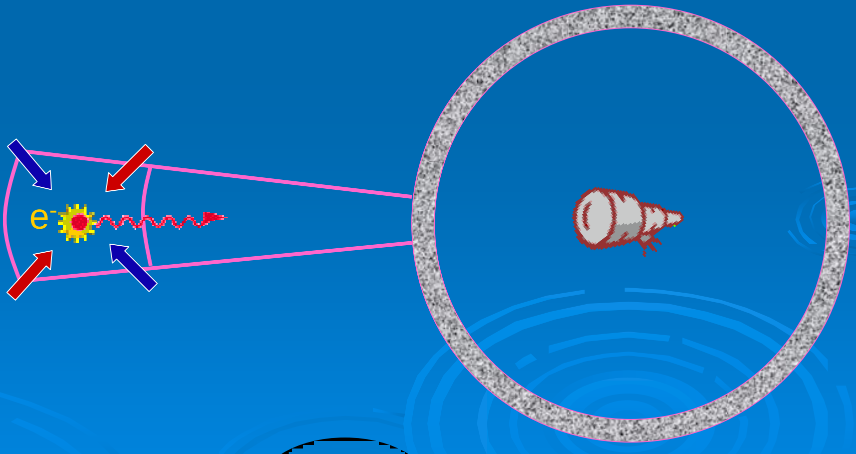


CMB Physics: Compton scattering

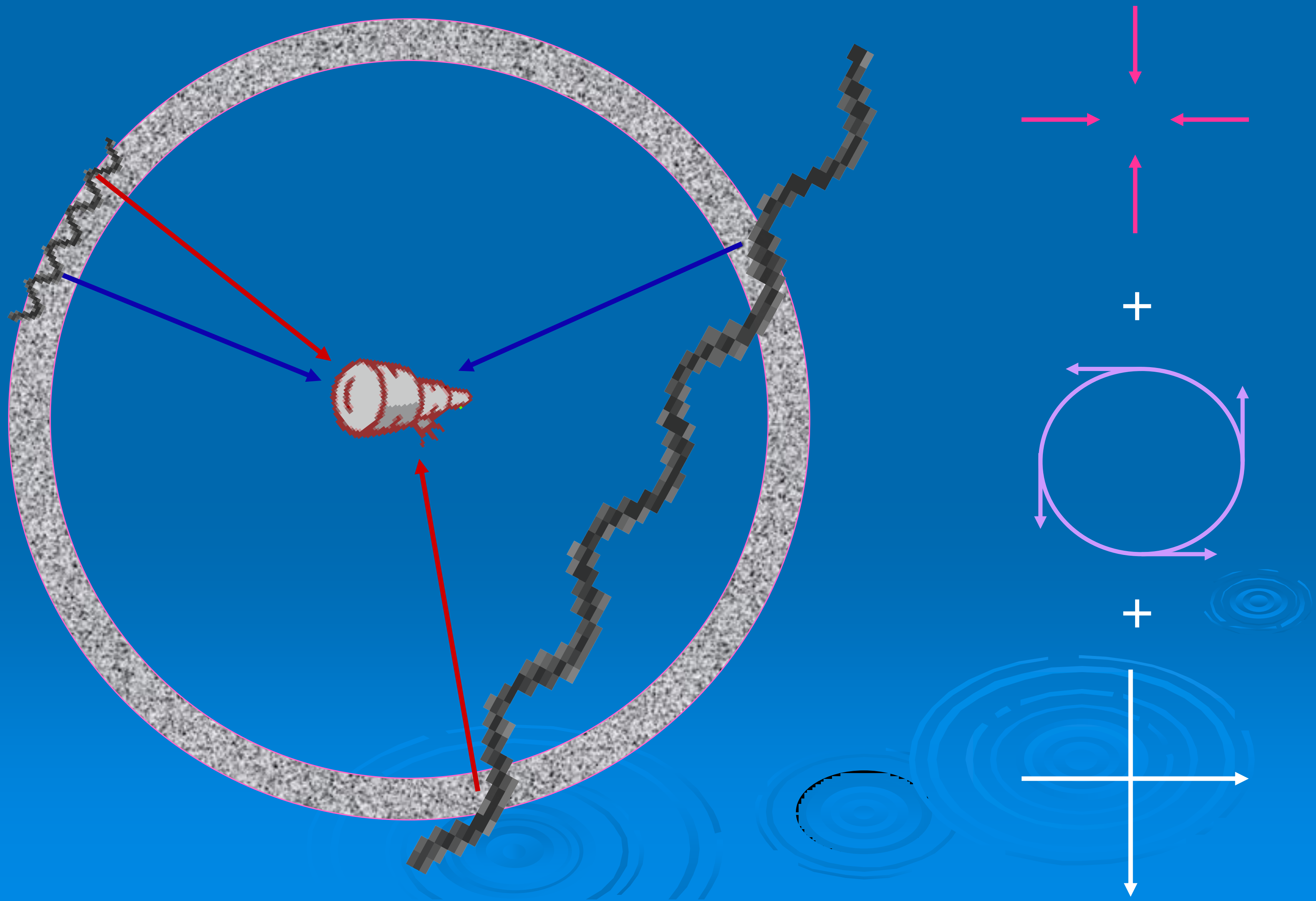
- Compton scattering is anisotropic
- An anisotropic incident intensity determines a linear polarization in the outgoing radiation
- At decoupling that happens due to the finite width of last scattering and the cosmological local quadrupole

Hu's animation

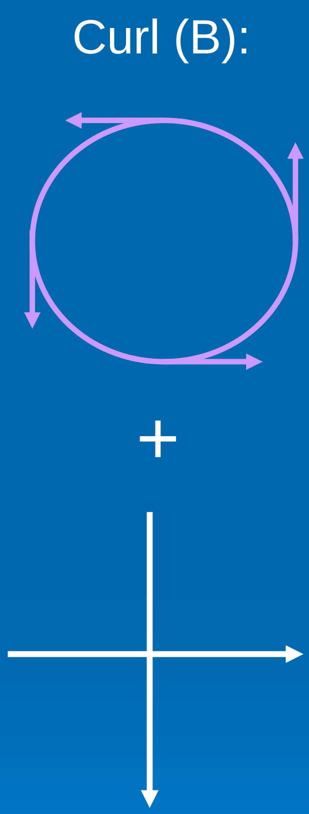


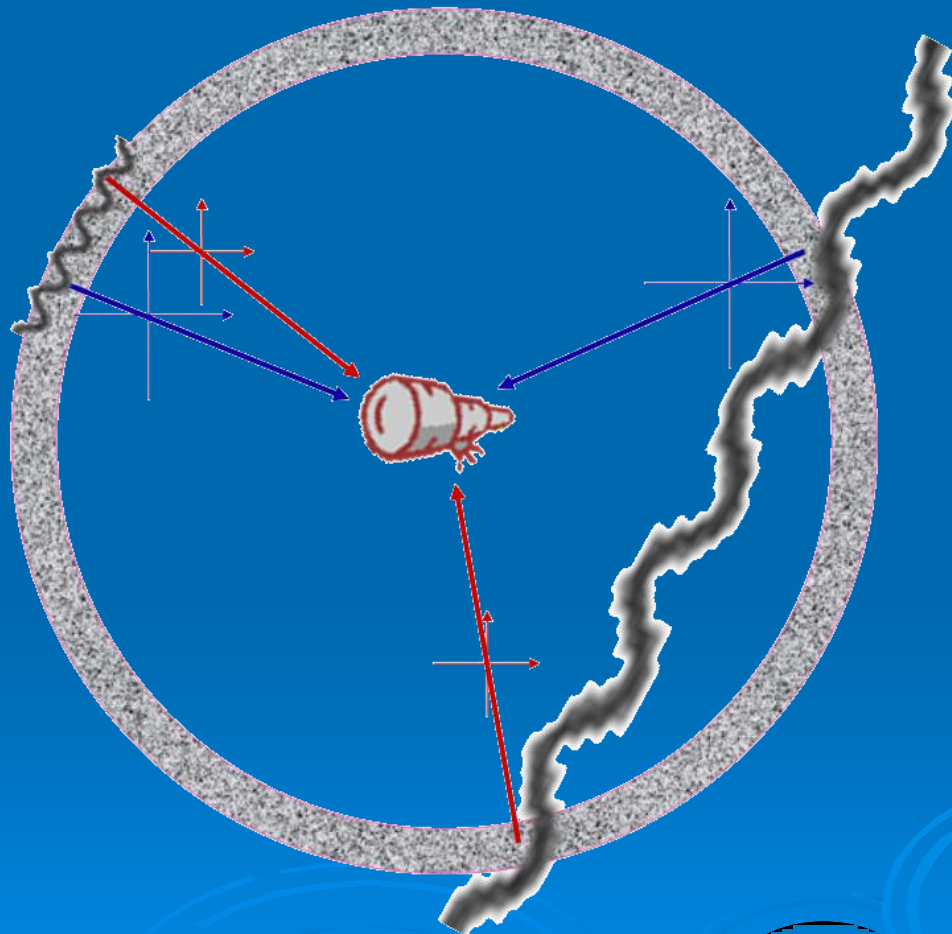


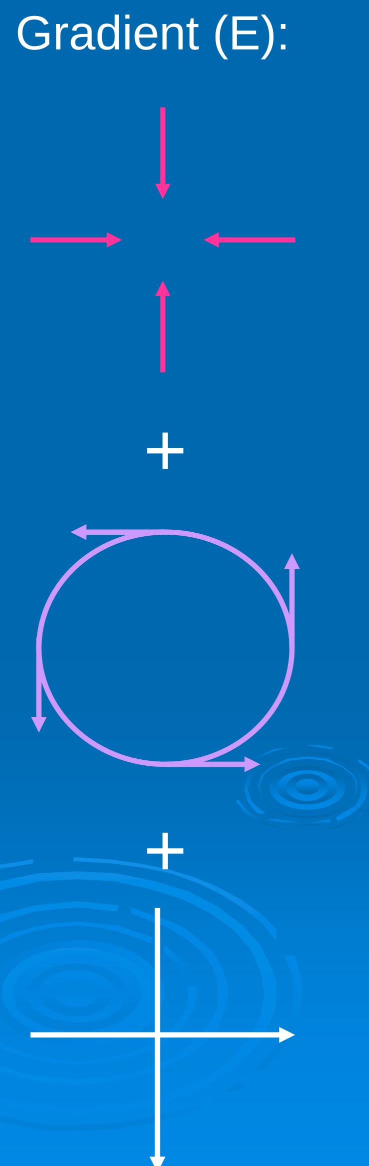
CMB anisotropy: total intensity



CMB anisotropy: polarization

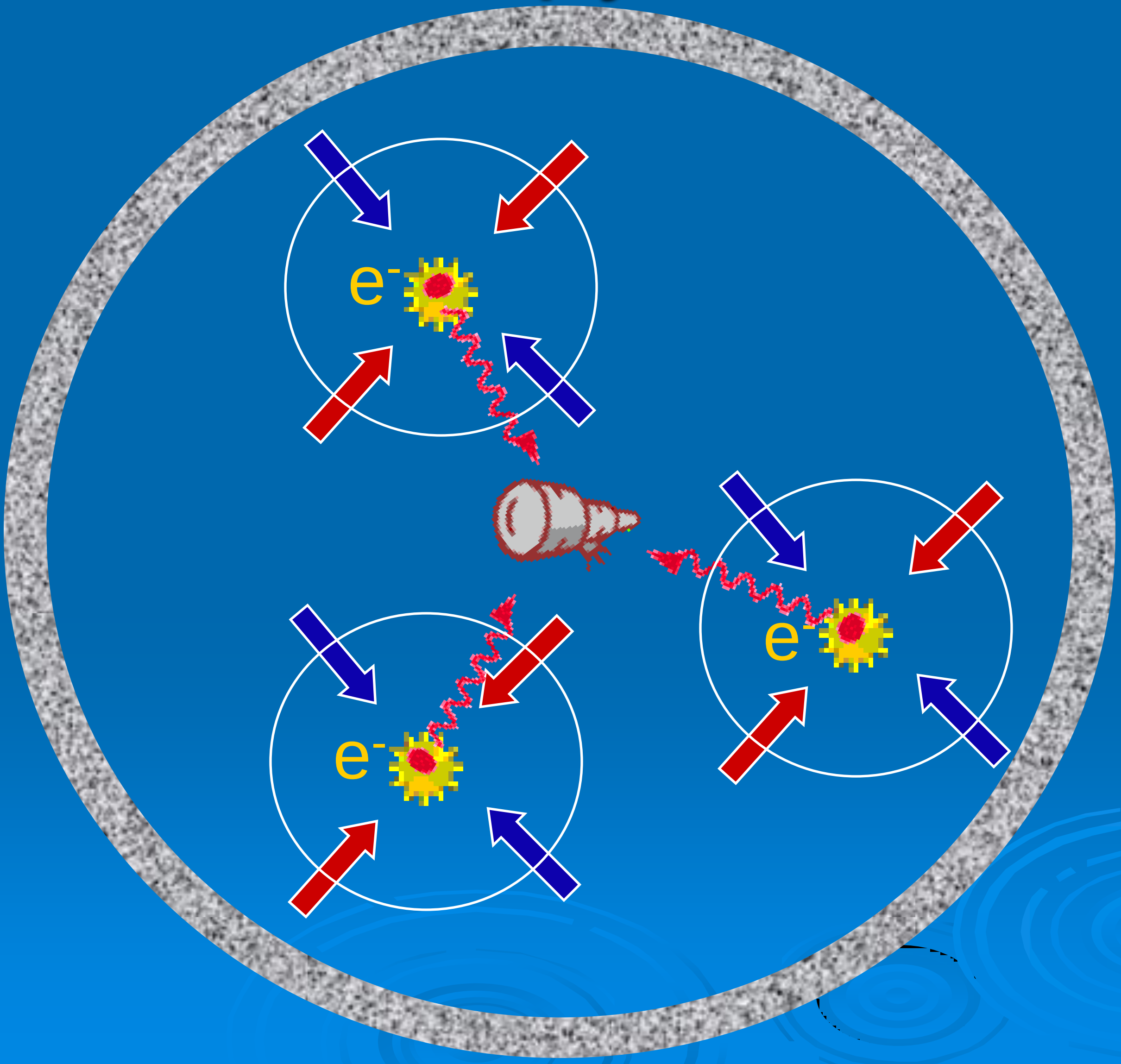




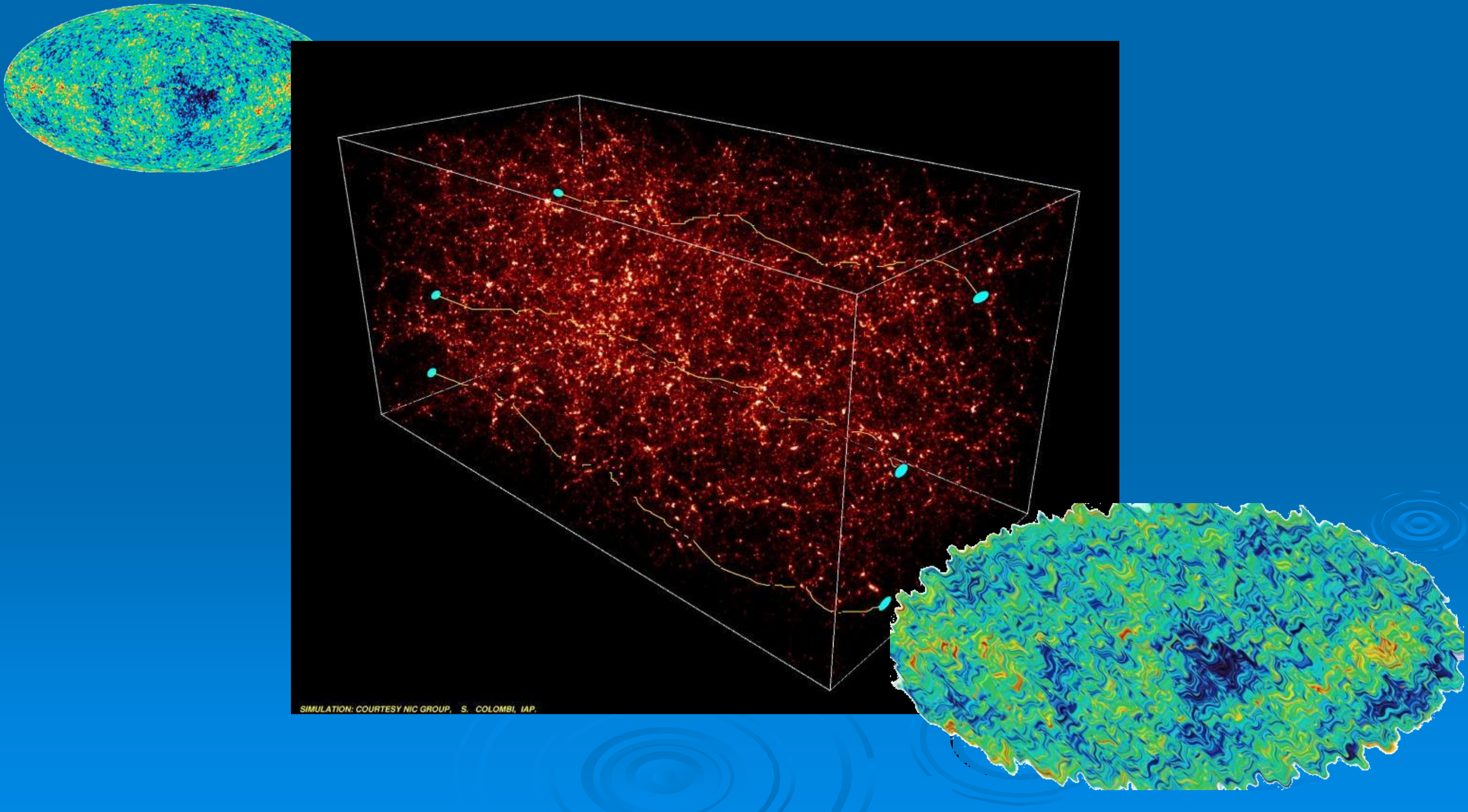


Kamionkowski et al. 1997, Seljak & Zaldarriaga 1997

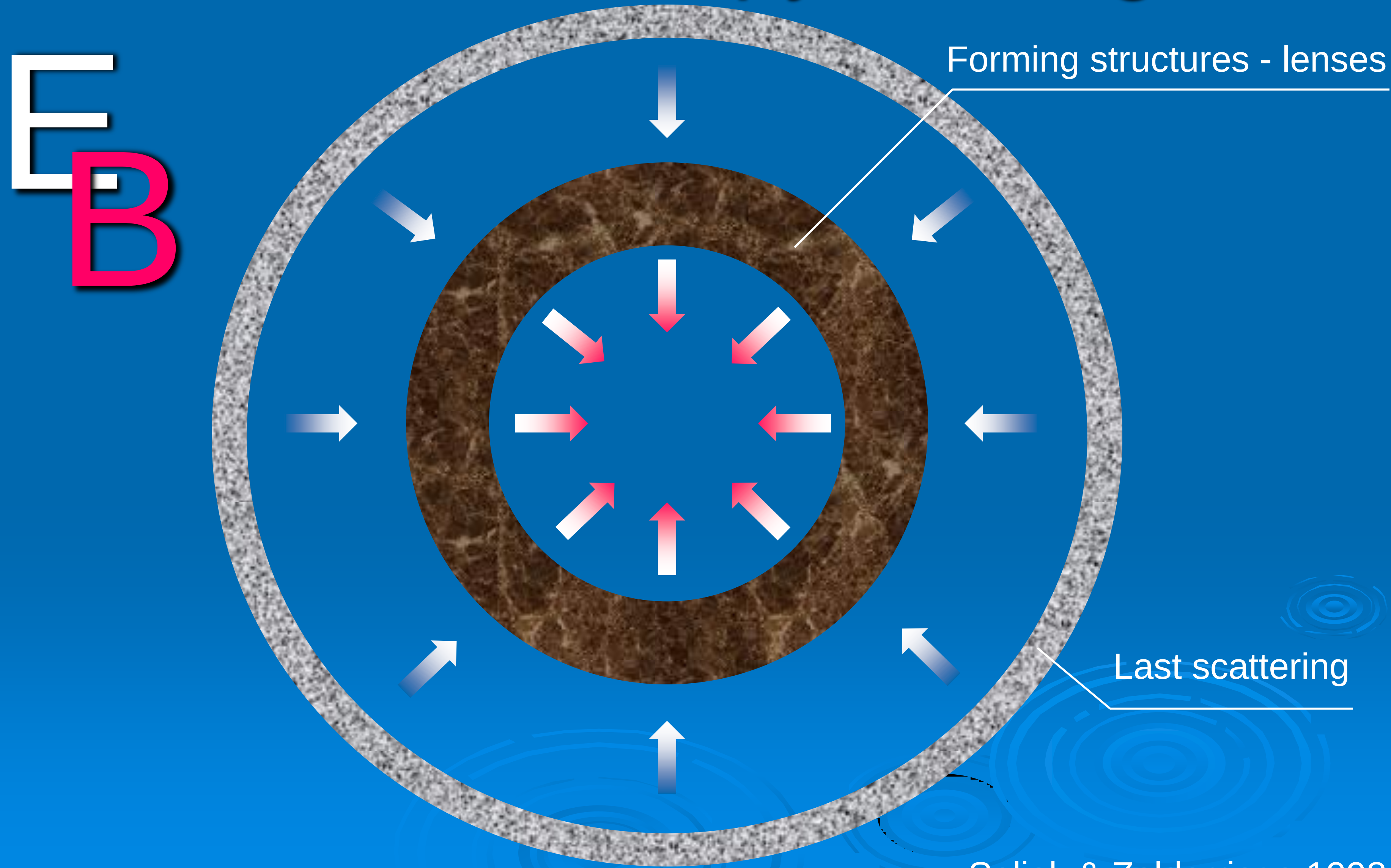
CMB anisotropy: reionization



CMB anisotropy: lensing

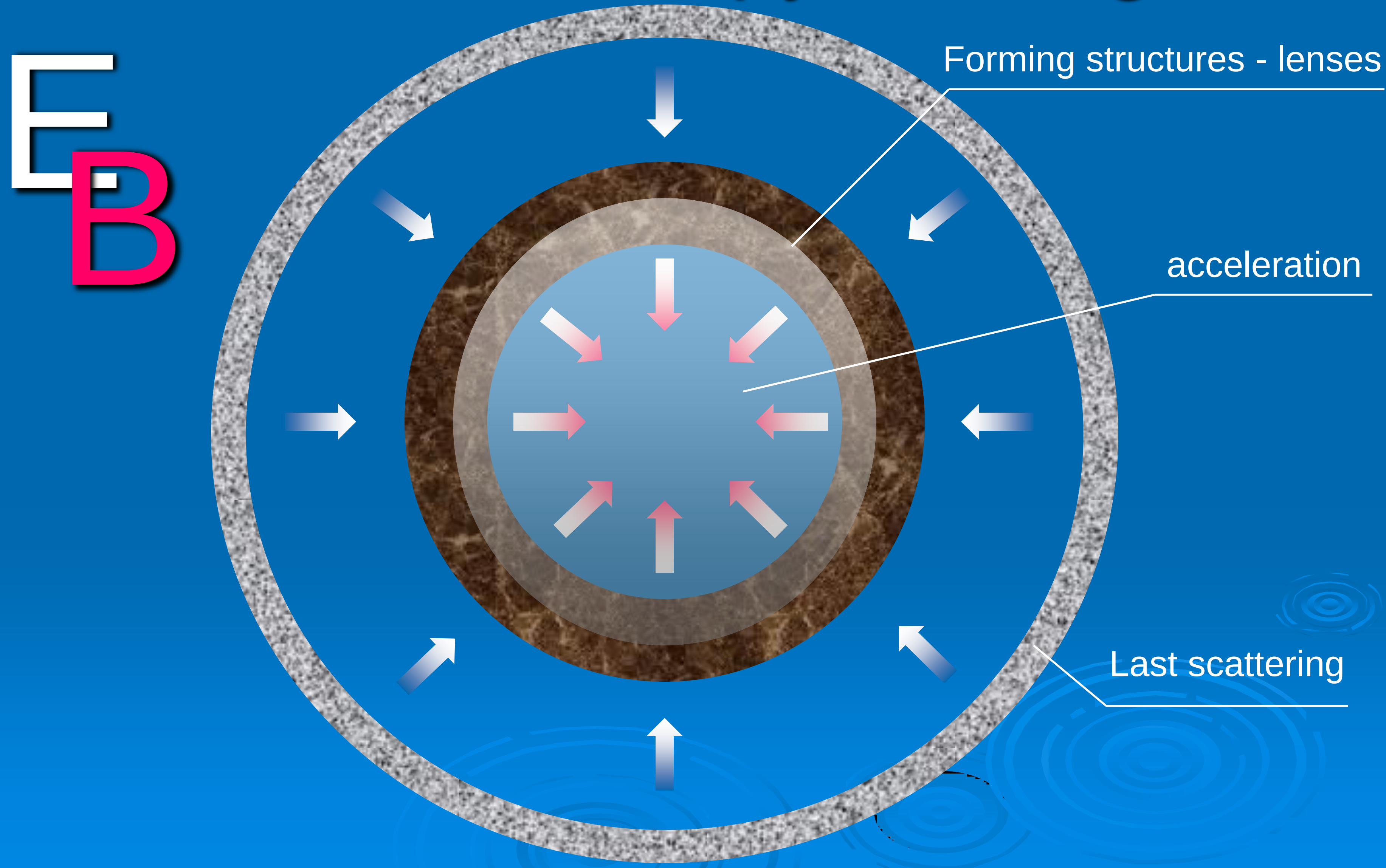


CMB anisotropy: lensing



Seljak & Zaldarriaga 1998

CMB anisotropy: lensing



Status of CMB observations

CMB anisotropies

$T(n), Q(n), U(n), V(n)$

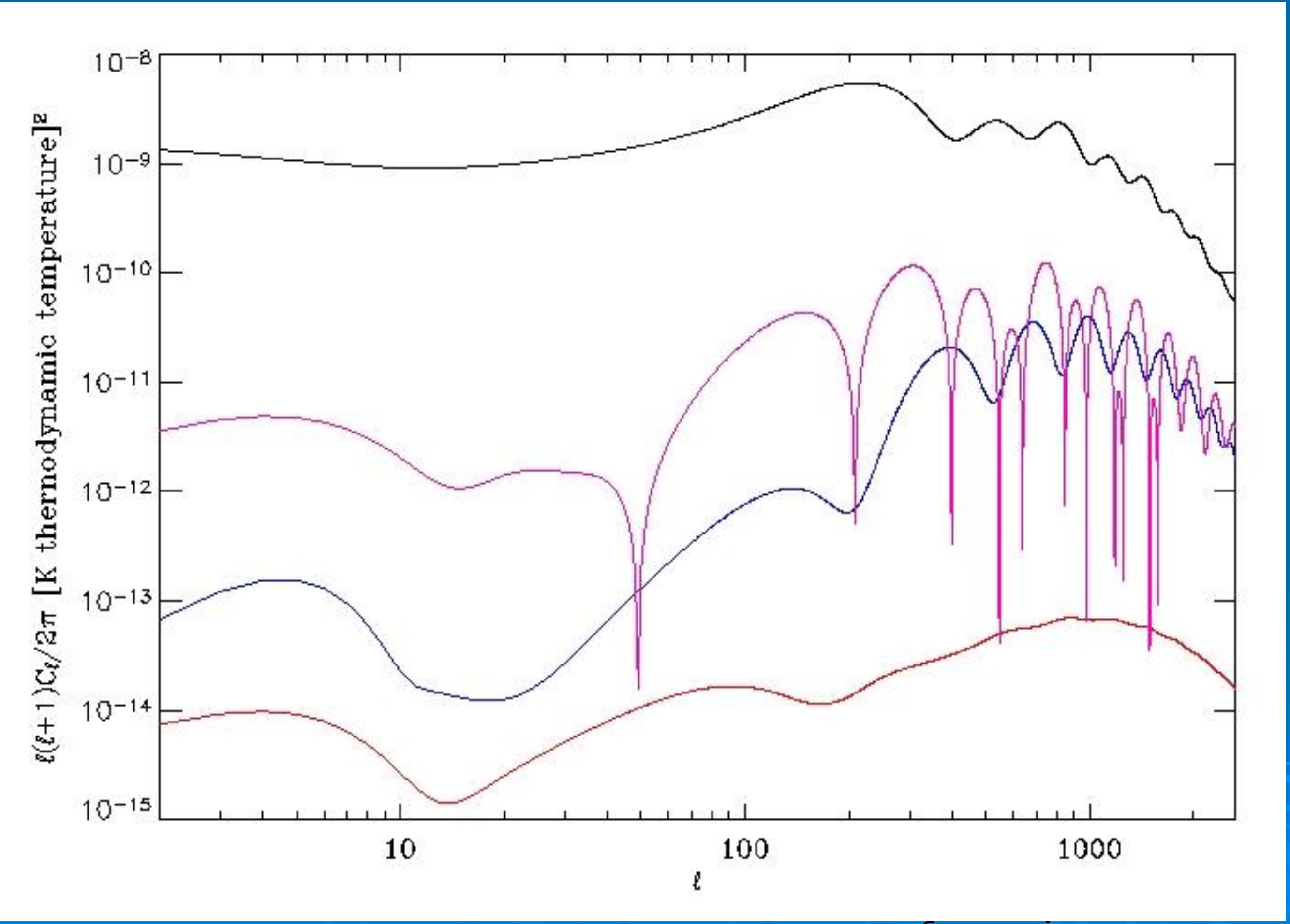
spherical harmonics

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

information compression

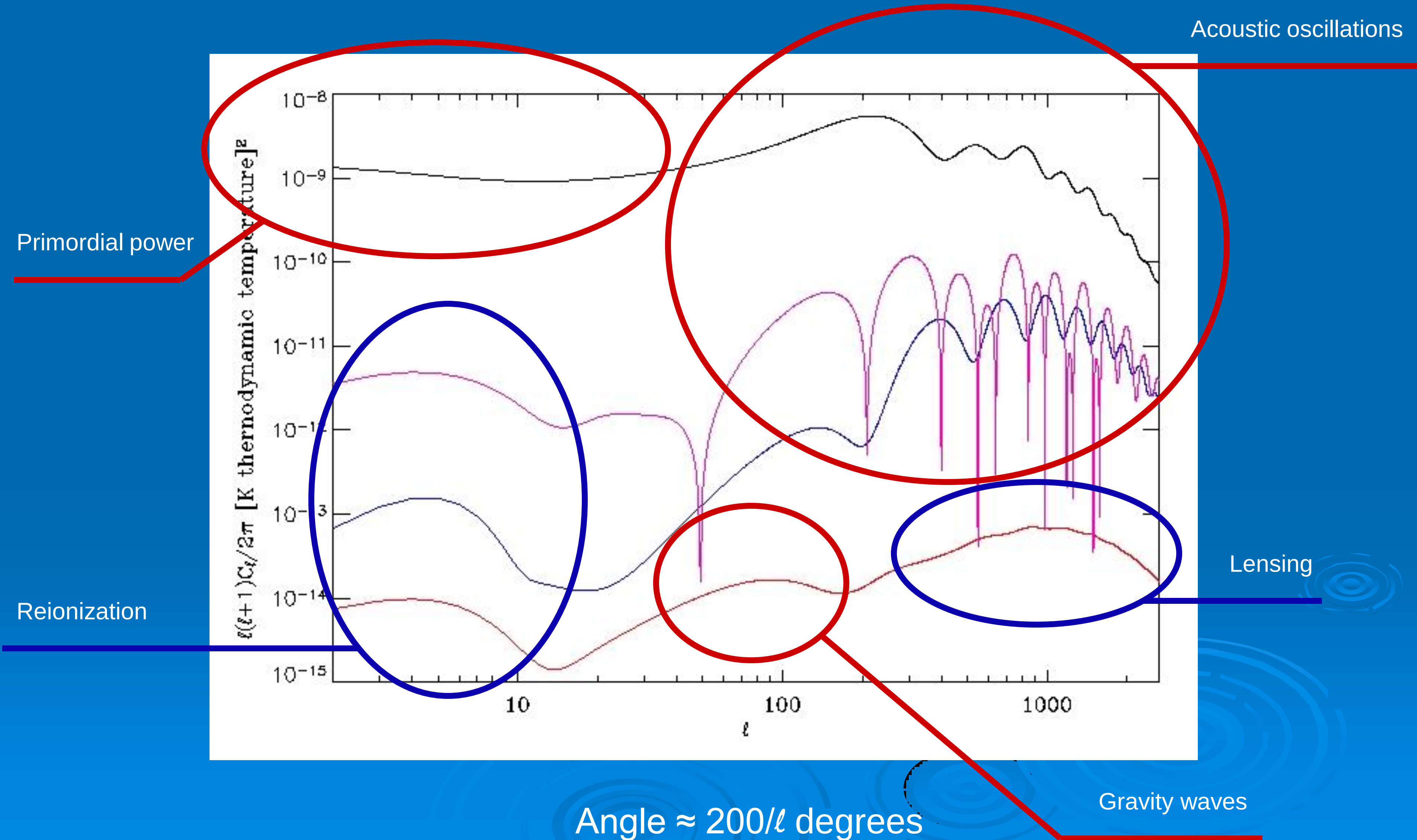
$$C_l=\Sigma_m (a_{lm}^{T,E,B})(a_{lm}^{T,E,B})^*/2(l+1)$$

CMB angular power spectrum



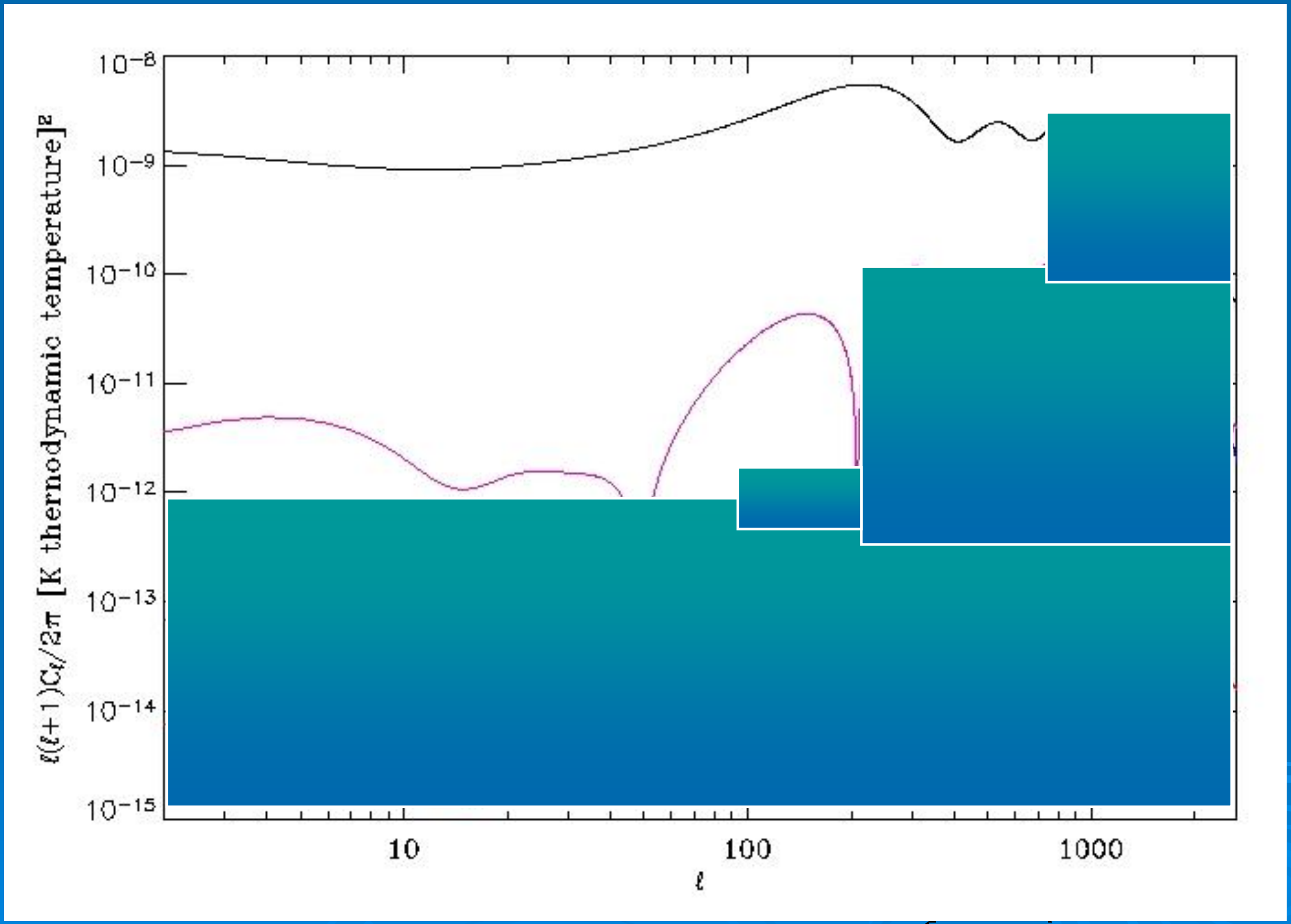
Angle ≈ 200/ℓ degrees

CMB angular power spectrum



Angle ≈ 200/ℓ degrees

WMAP first year



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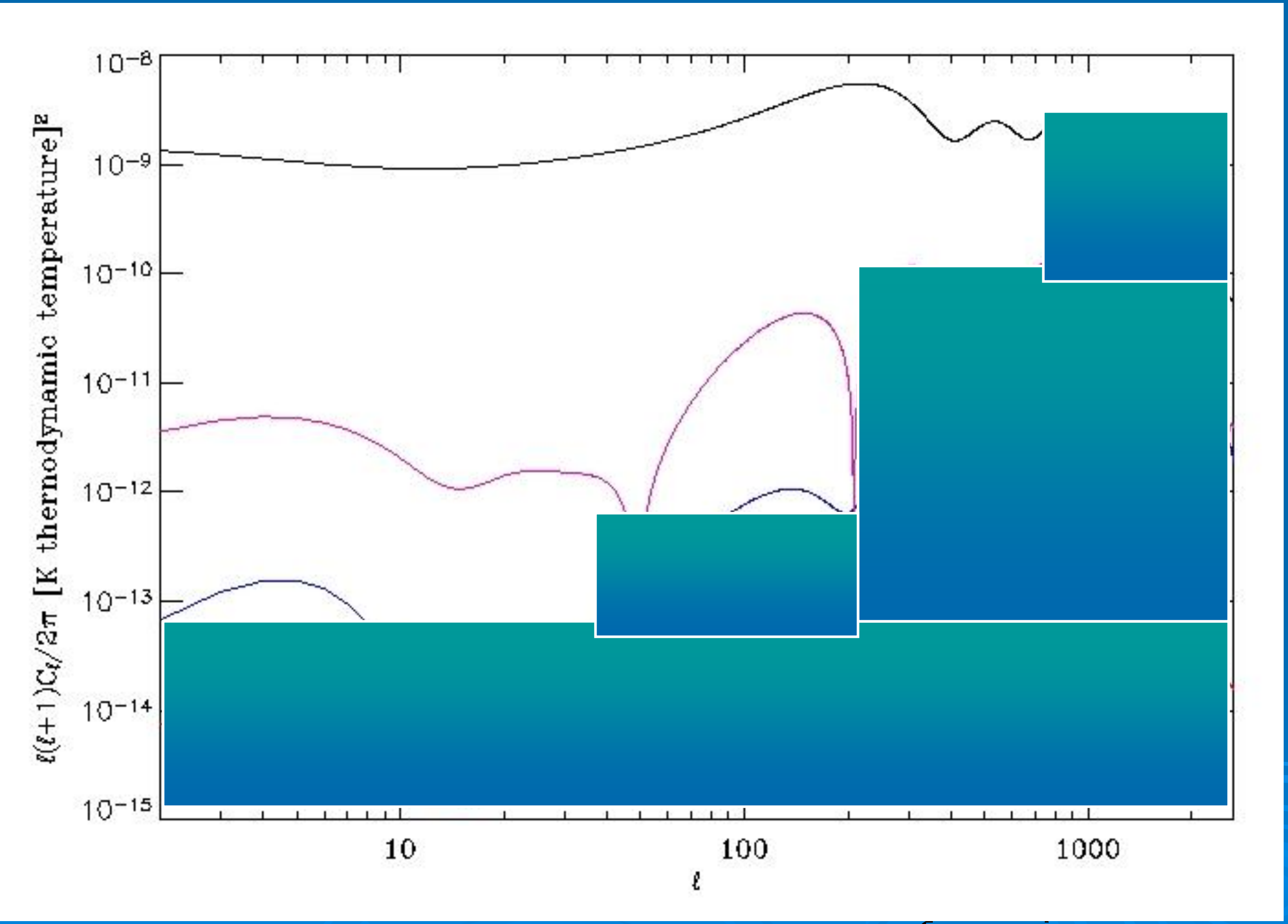
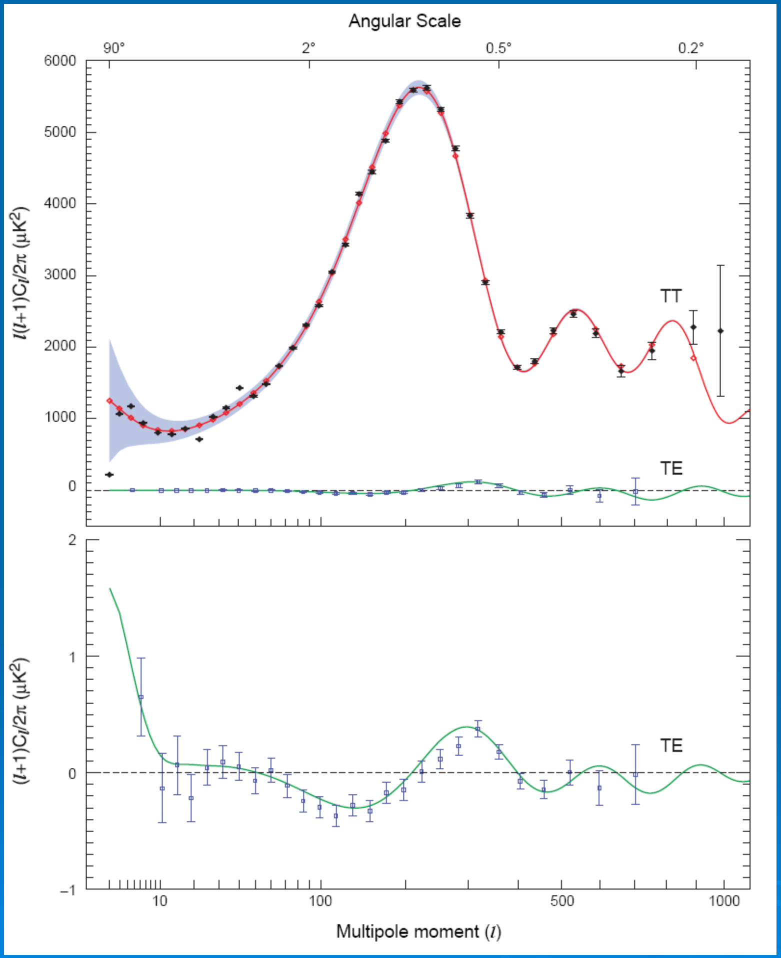
WMAP first year

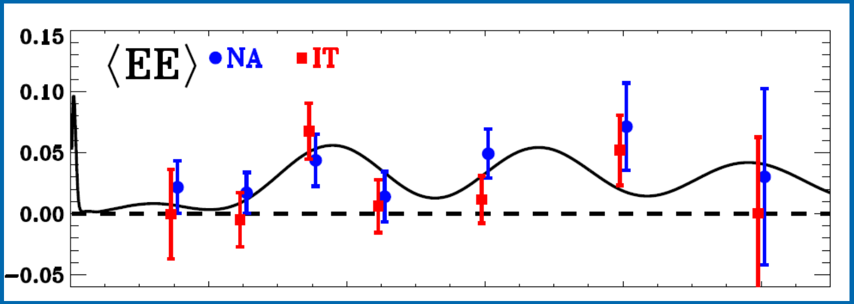


Angle ≈ 200/ℓ degrees

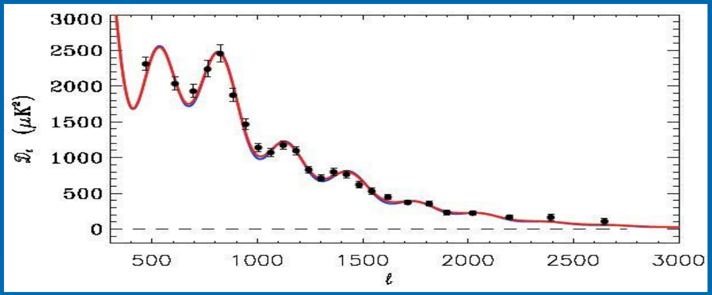
CMB angular power spectrum



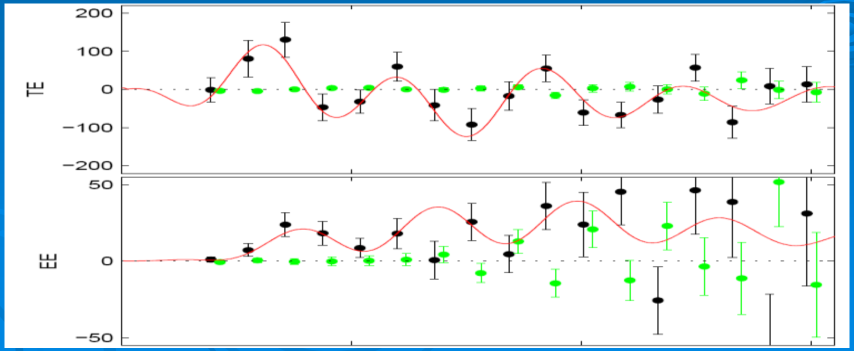
WMAP



boomerang

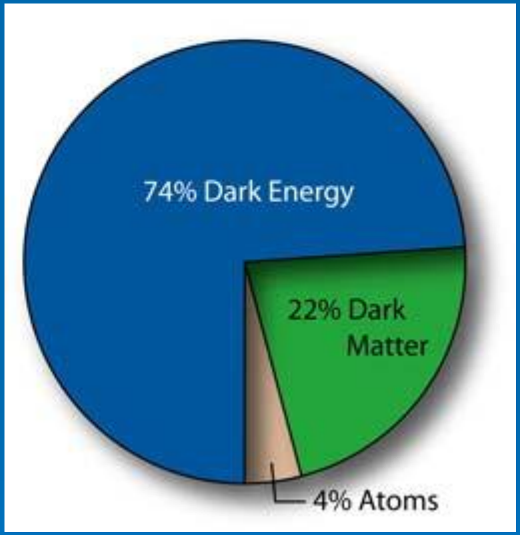


acbar



quad

Cosmological concordance model



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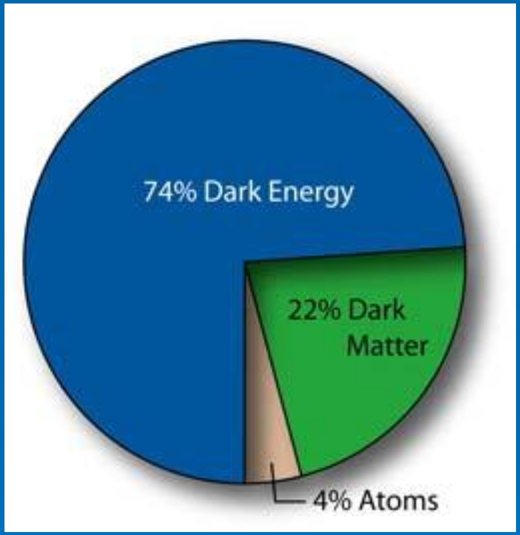

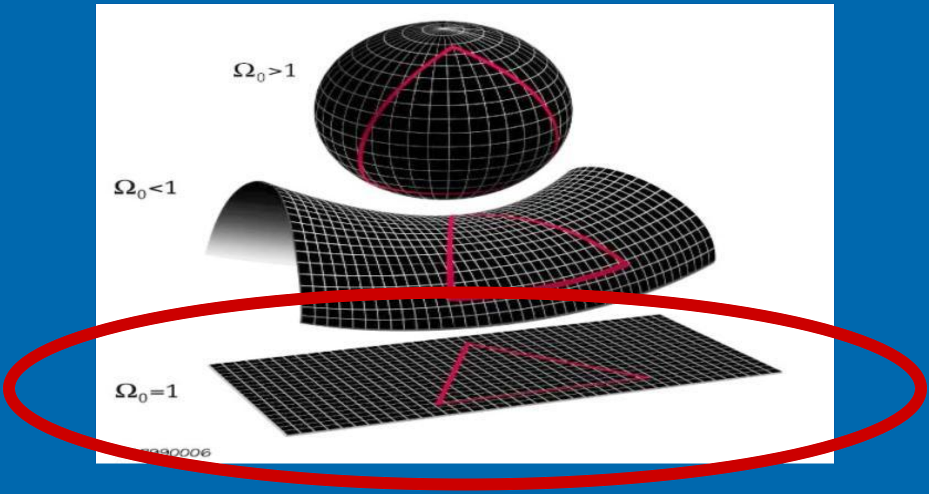

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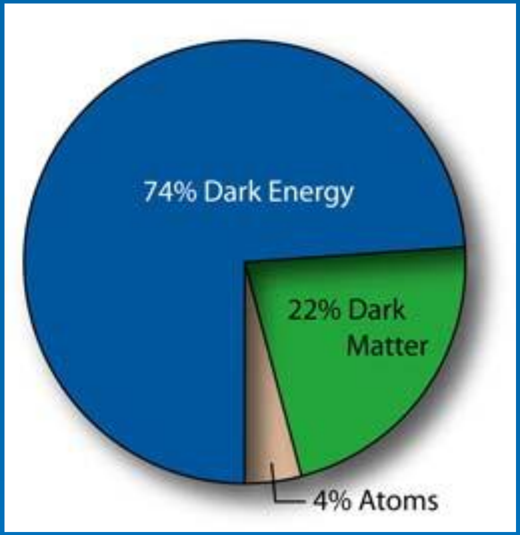
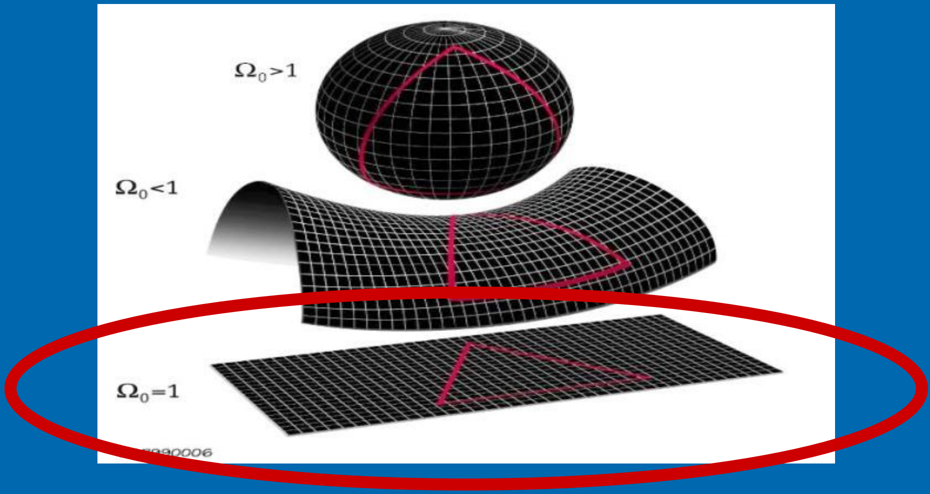
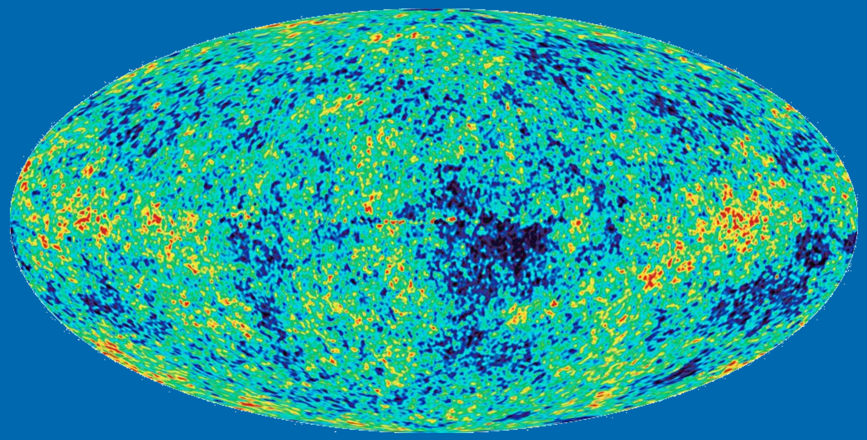




CMB anisotropy statistics: unknown, probably still hidden by systematics

- Evidence for North south asymmetry (Gorski et al. 2009)
- Evidence for Bianchi models (Jaffe et al. 2006)
- Poor constraints on inflation, the error is about 100 times the predicted deviations from Gaussianity (from WMAP)
- Lensing detection out of reach or marginal, see smith et al. for a 3.4σ detection correlating WMAP and NVSS galaxies

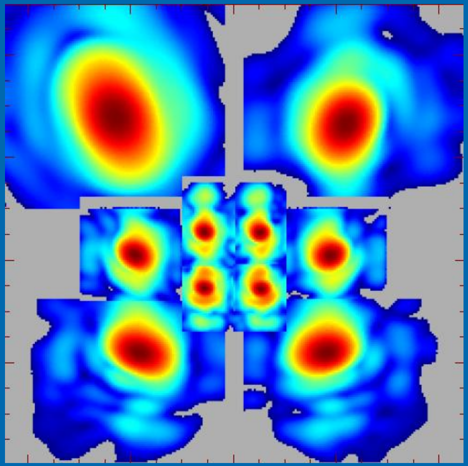


Other cosmological backgrounds?

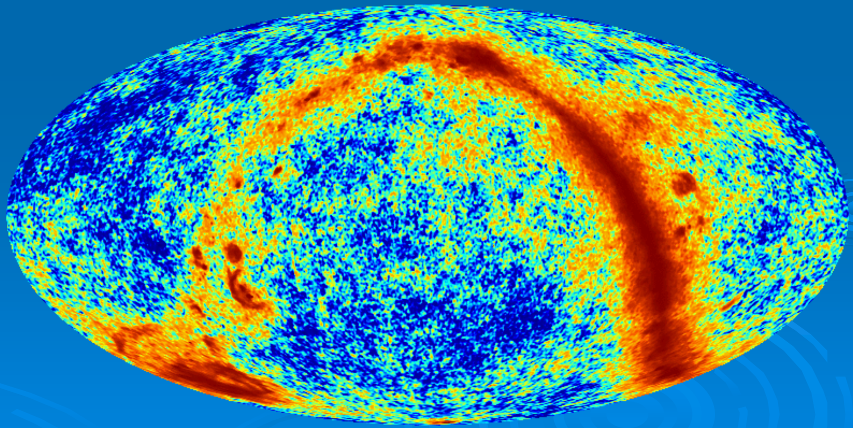
- Neutrinos: abundance comparable to photons ☺, decoupling at MeV ☺, cold as photons ☹, weak interaction ☹
- Gravity waves: decoupling at Planck energy ☺, abundance unknown ☹, gravitational interaction ☹
- Morale: insist with the CMB, still for many years…that's the best we have for long…

Challenges for future CMB

Jarosik et al. 2006

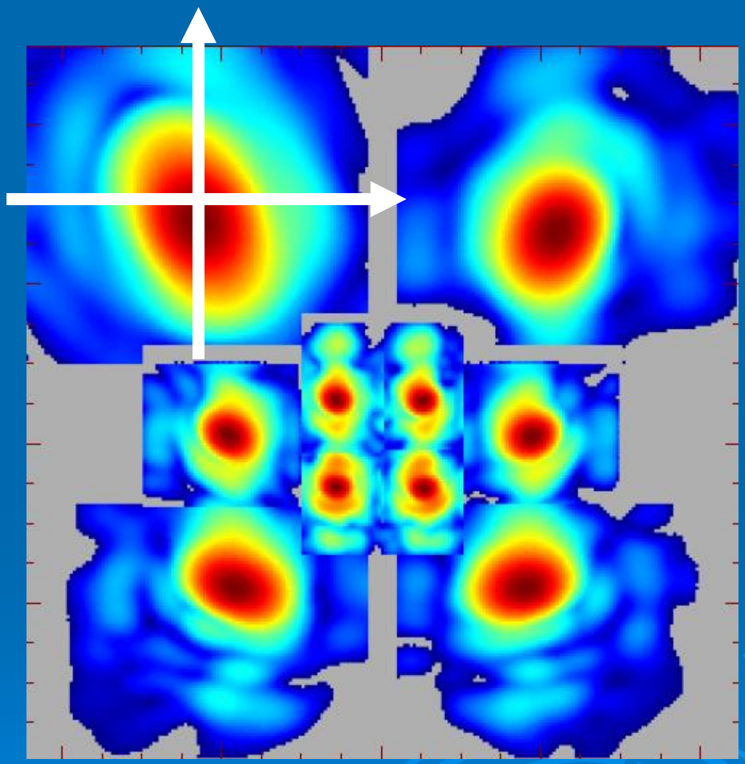


- The sensitivity can be increases with the detector number ☺
- The systematics from the instrument must be controlled at the level of the signal ☹
- The emission from foregrounds may cover the B signal over the all sky, at all frequency ☹



Challenges for future CMB: systematics from beam shape

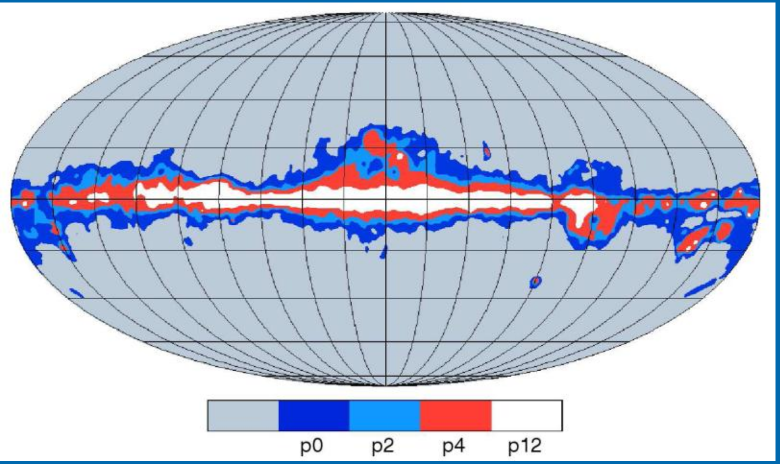
- Asymmetric beams cause unwanted polarization from total intensity, leakage of E modes into B, …
- No way to circularize the beams, rather the beam shape has to be reconstructed in flight to subtract the bias from the signal



Challenges for future CMB: foreground emission

Bennett et al. 2006

- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB



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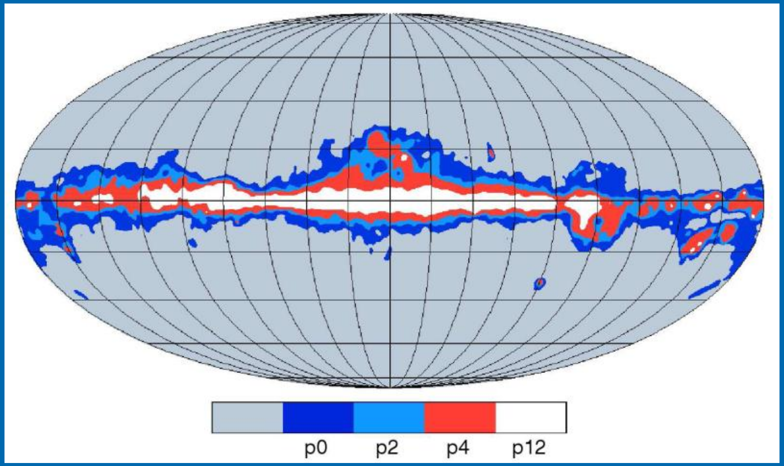

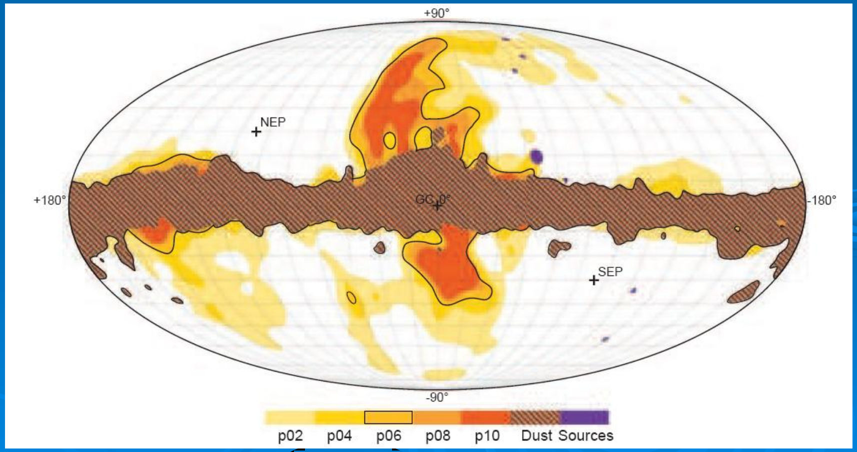

Page et al. 2007

- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB
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Bennett et al. 2006

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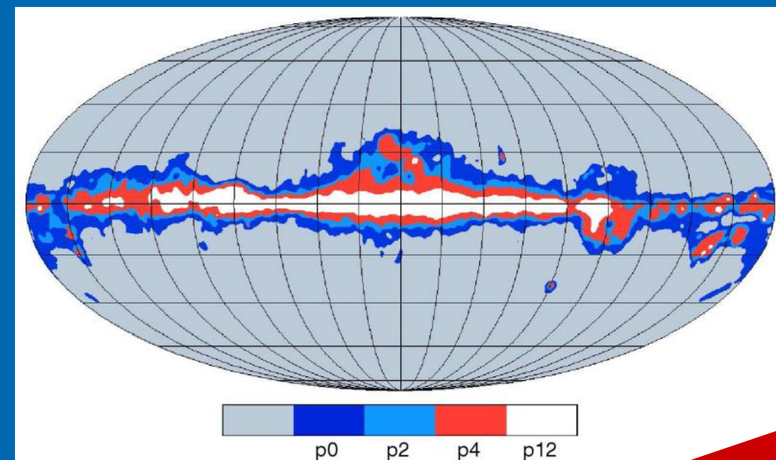
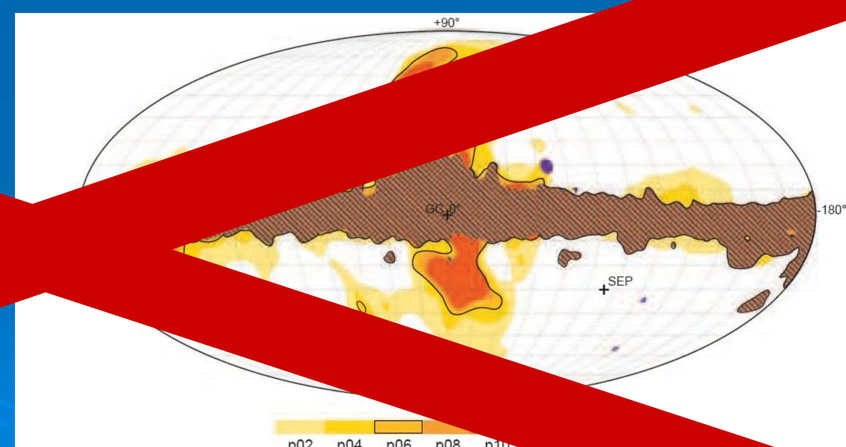


- polarization, at frequ… between 60 and 90 GHz, … cutting out the brighest p… f the Galactic emission t… sky is dominate… MB



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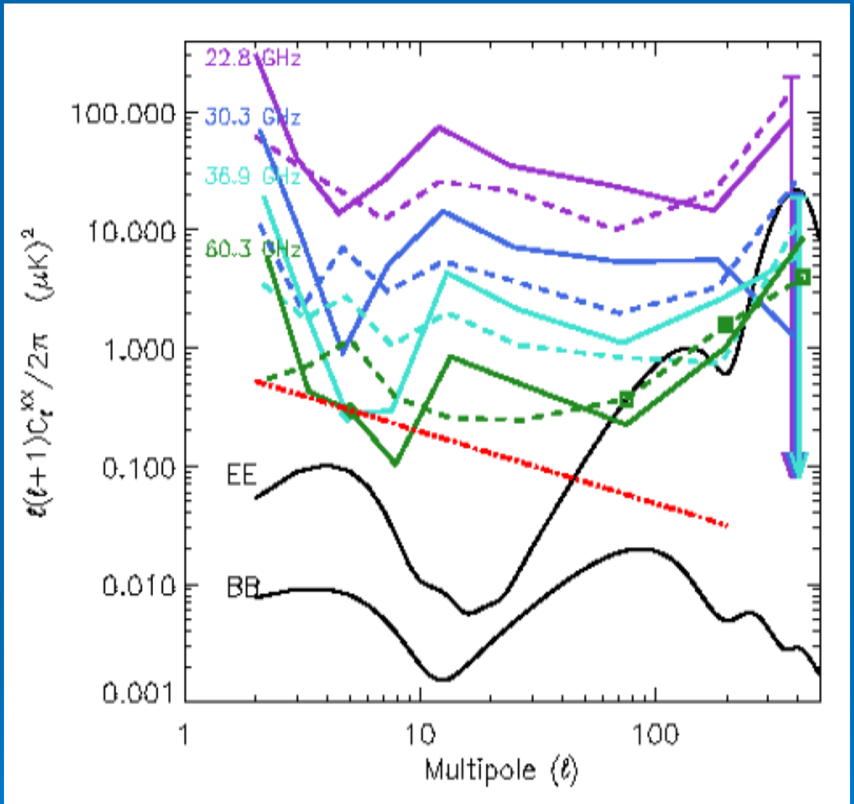
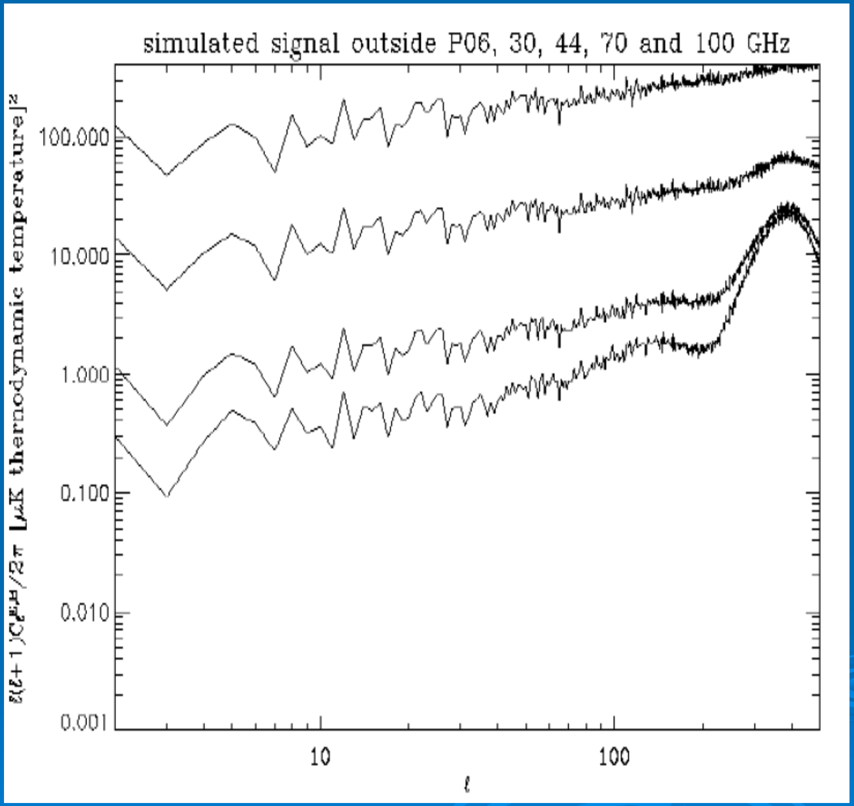


Page et al. 2006



Planck reference sky

Data analysis and scientific goals of the Planck satellite

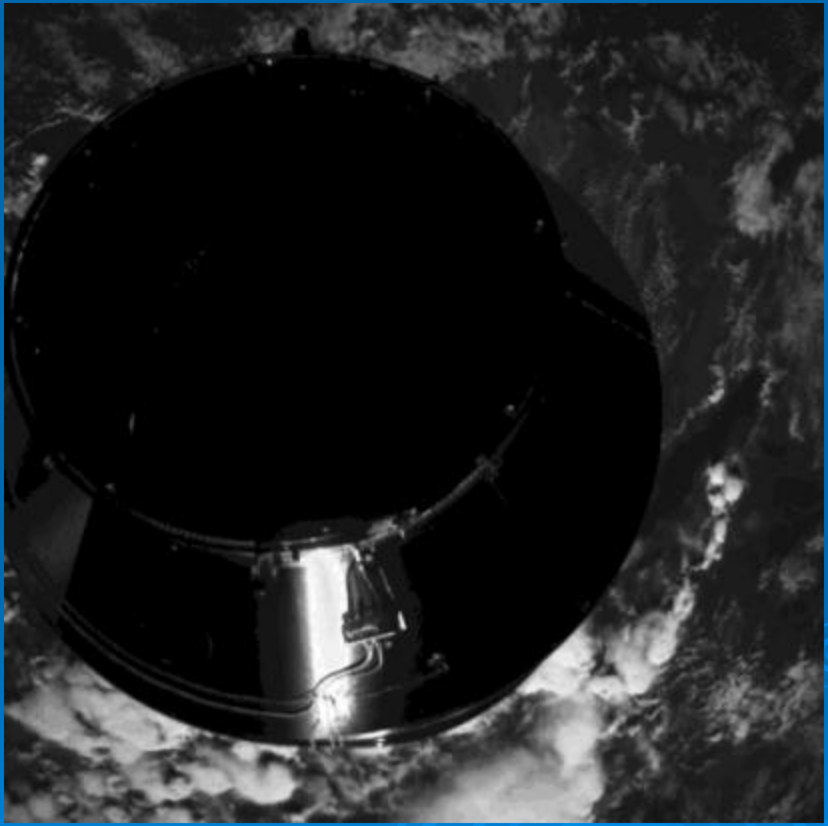
Source: Planck scientific program bluebook, available at www.rssd.esa.int/Planck

Planck

- Hardware: 600 ME, third generation CMB probe, ESA medium size mission, NASA (JPL, Pasadena) contribution, radiometer and bolomoter technology
- Software from 400 collaboration members in EU and US
- Two data processing centers (DPCs): Paris + Cambridge (IaP + IoA), Trieste (OAT + SISSA)

Planck DPC facilities

- DPC people physically in Trieste are about 20 at OATs and SISSA
- The data will be hosted on two computers, ENT (OATs, official products, 256 CPUs, hundreds of GB RAM, tens of TB disk space), HG1 (SISSA, simulations and scientific interpretation, 160 CPUs, hundreds of GB RAM, tens of TB disk space)



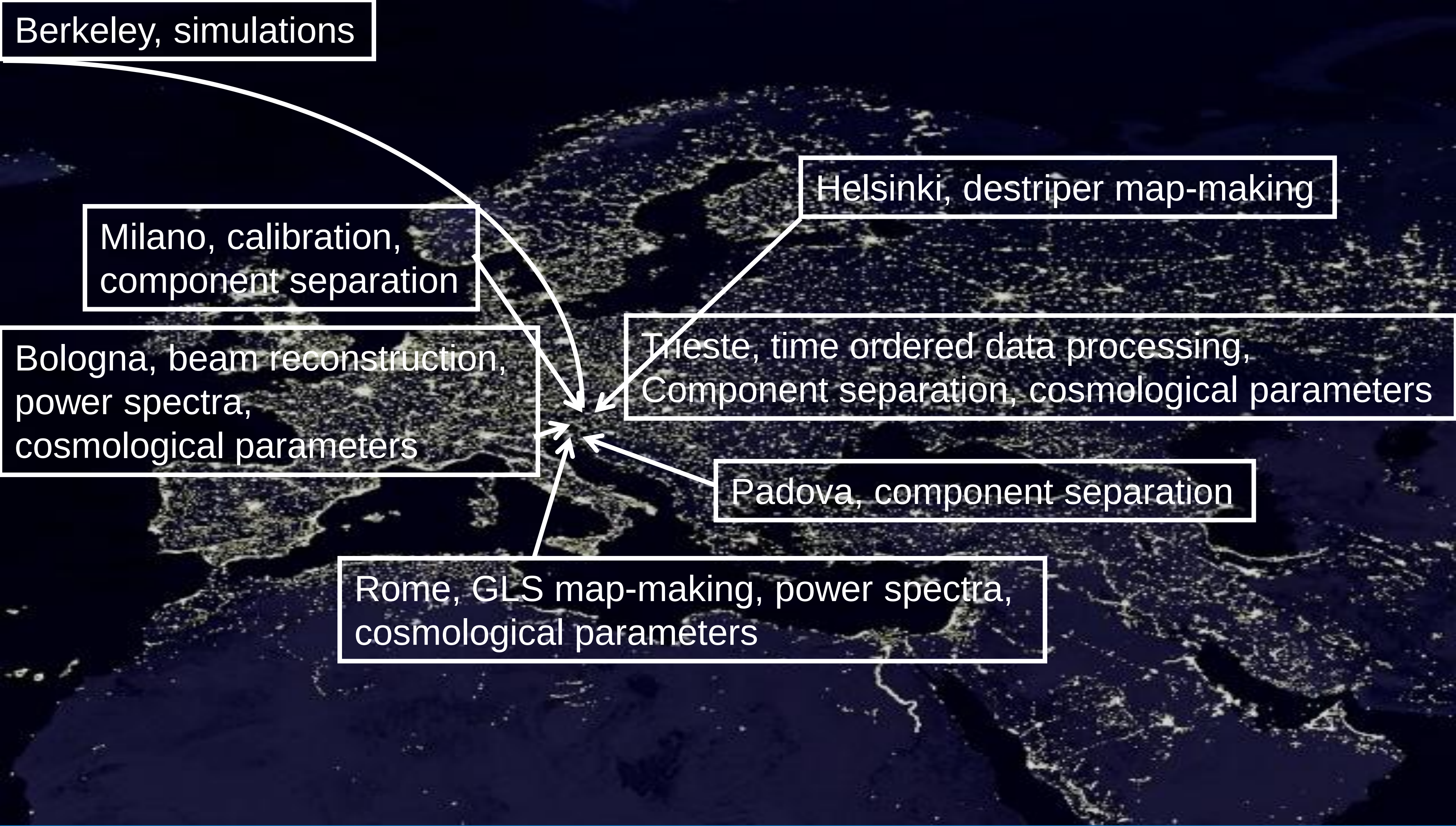
Planck milestones

- May 14th, 2009, launch, the High Frequency Instrument (HFI, bolometers) is on
- June 1st, 2009, active cryogenic systems are turned on
- June 8th, 2009, the Low Frequency Instrument (LFI, radiometers), is turned on
- Summer 2009, Planck gets to L2, survey begins, 14 months
- 2 years of proprietary period and data analysis
- Results end of 2011, 2012
- Possibility of mission extension for a second survey

Planck contributors

Planck data processing centers

Structure of our DPC

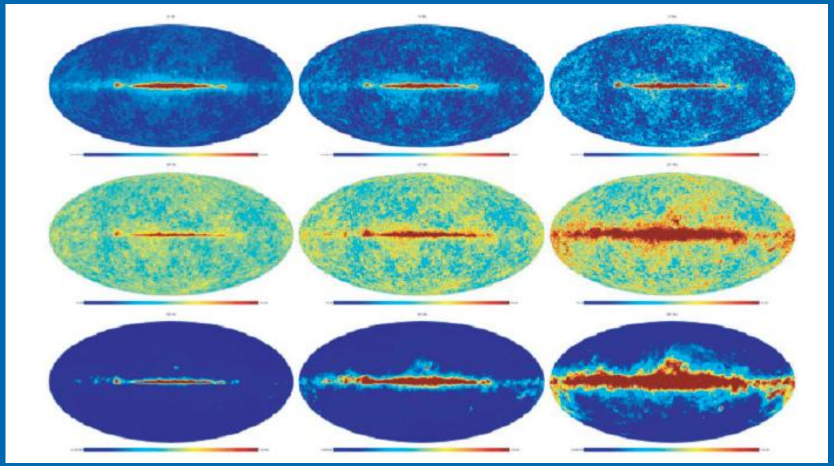


DPC duties, data analysis levels

- Level 1, telemetry, timelines processing, calibration
- Level 2, map-making
- Level 3, component separation, power spectra estimation, cosmological parameters
- The analysis is conducted separately in the two DPCs up to level 2, and jointly for level 3

Planck data deliverables

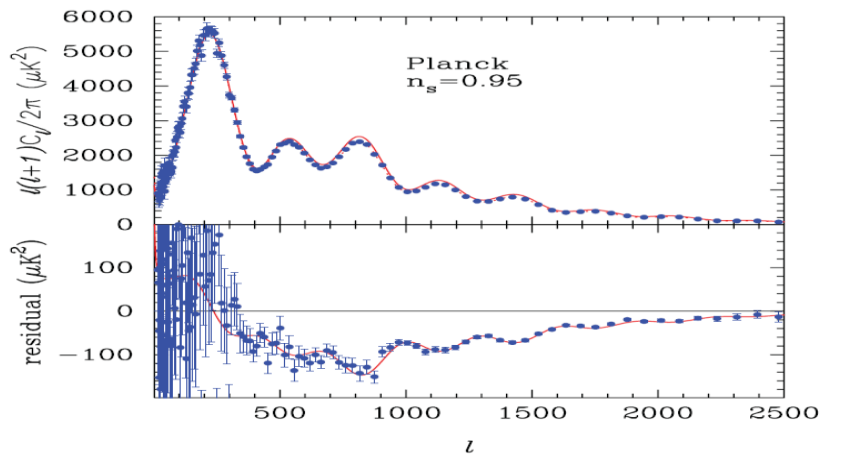
- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33' to 7' between 30 and 143 GHz, 5' at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

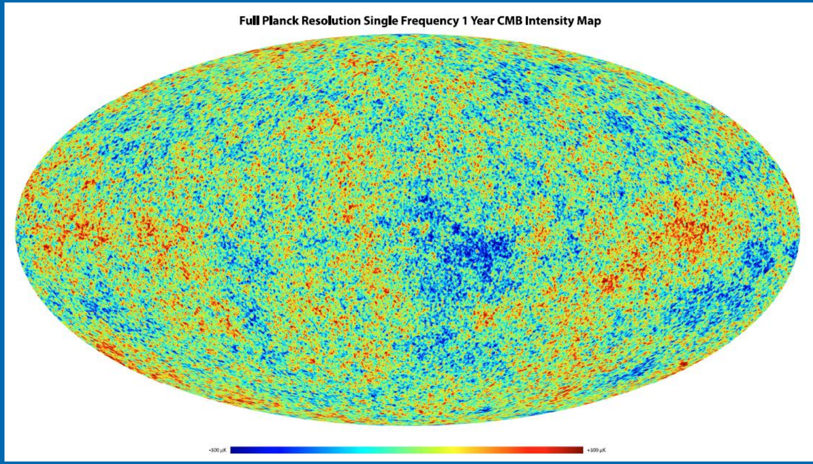


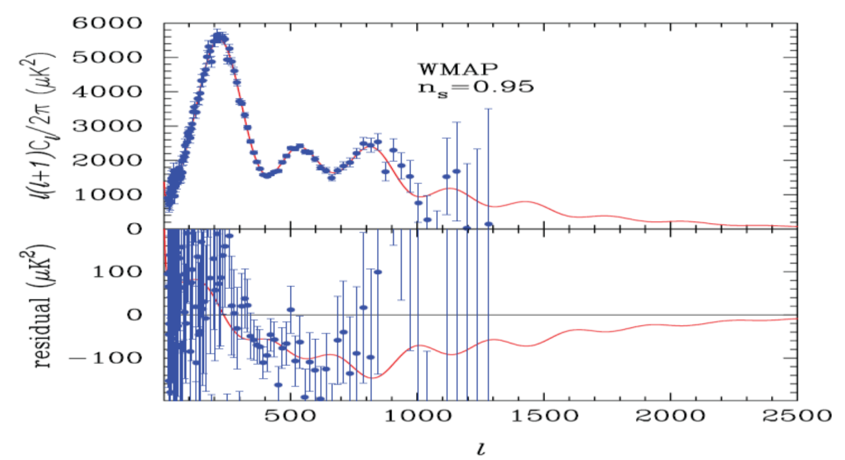
PLANCK GALAXY SURVEYS

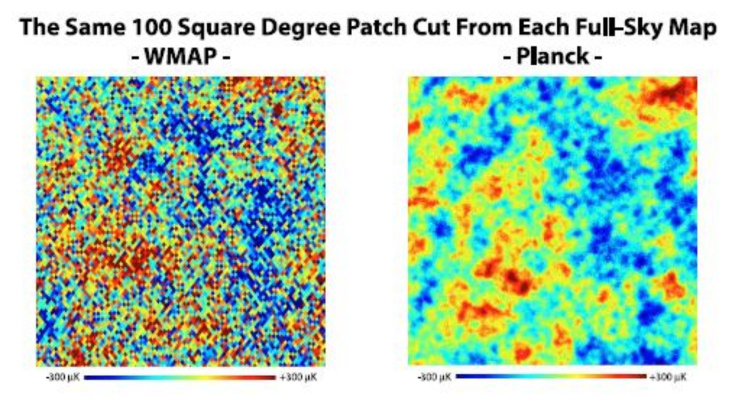
	FREQUENCY [GHz]				
	143	217	353	550	850
Confusion limit [mJy, 3σ]	6.3	14.1	44.7	112	251
Planck All Sky Survey sensitivity [mJy, 3σ]	26	37	75	180	300
Planck Deep Survey sensitivity [mJy, 3σ]	10	18.4	49	170	280
Number of galaxies [all sky]	570	860	1700	4400	35000

Planck scientific deliverables: CMB total intensity and the era of imaging

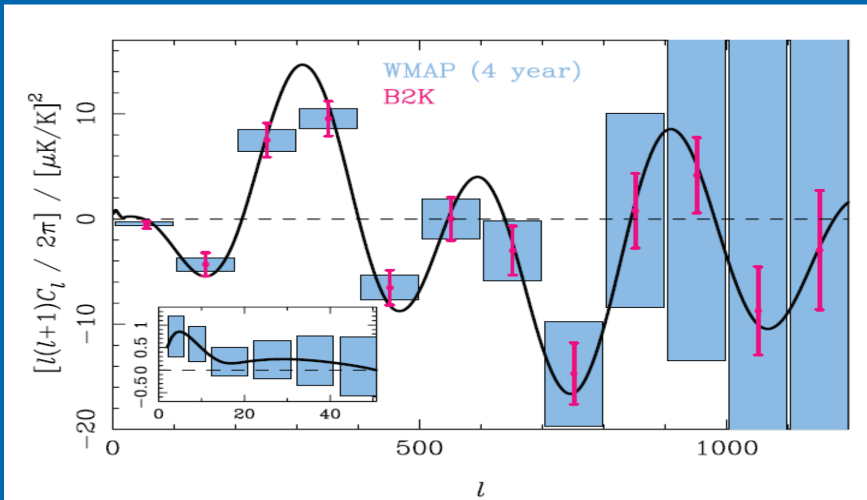


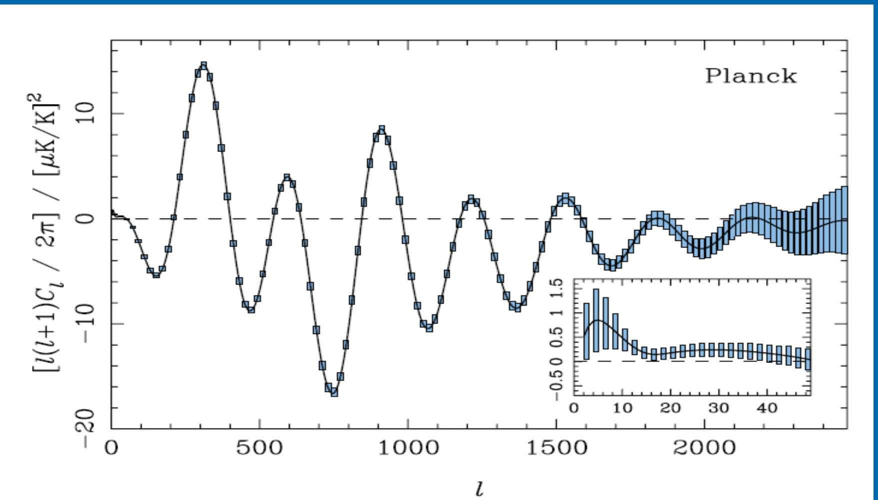


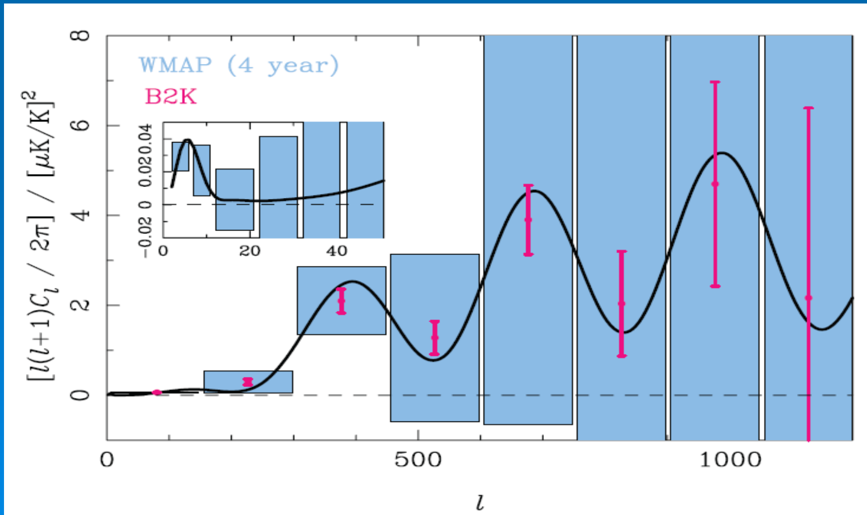


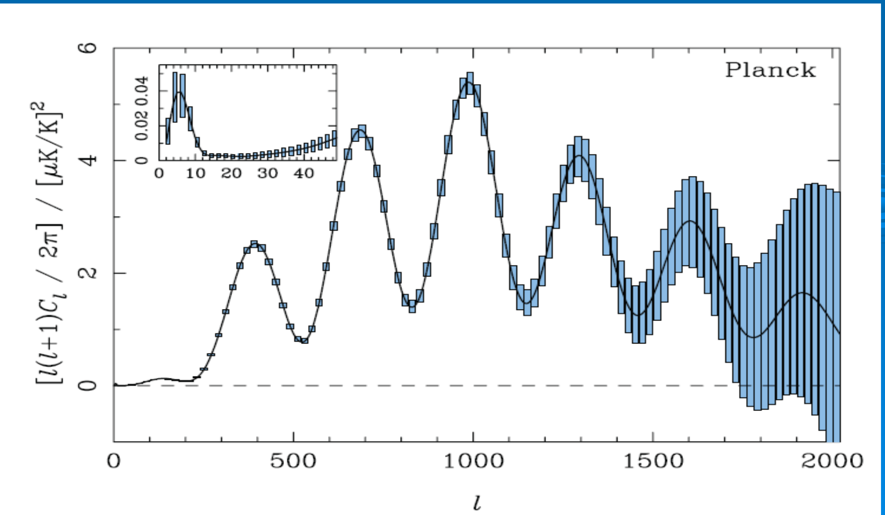


Planck scientific deliverables: CMB polarization

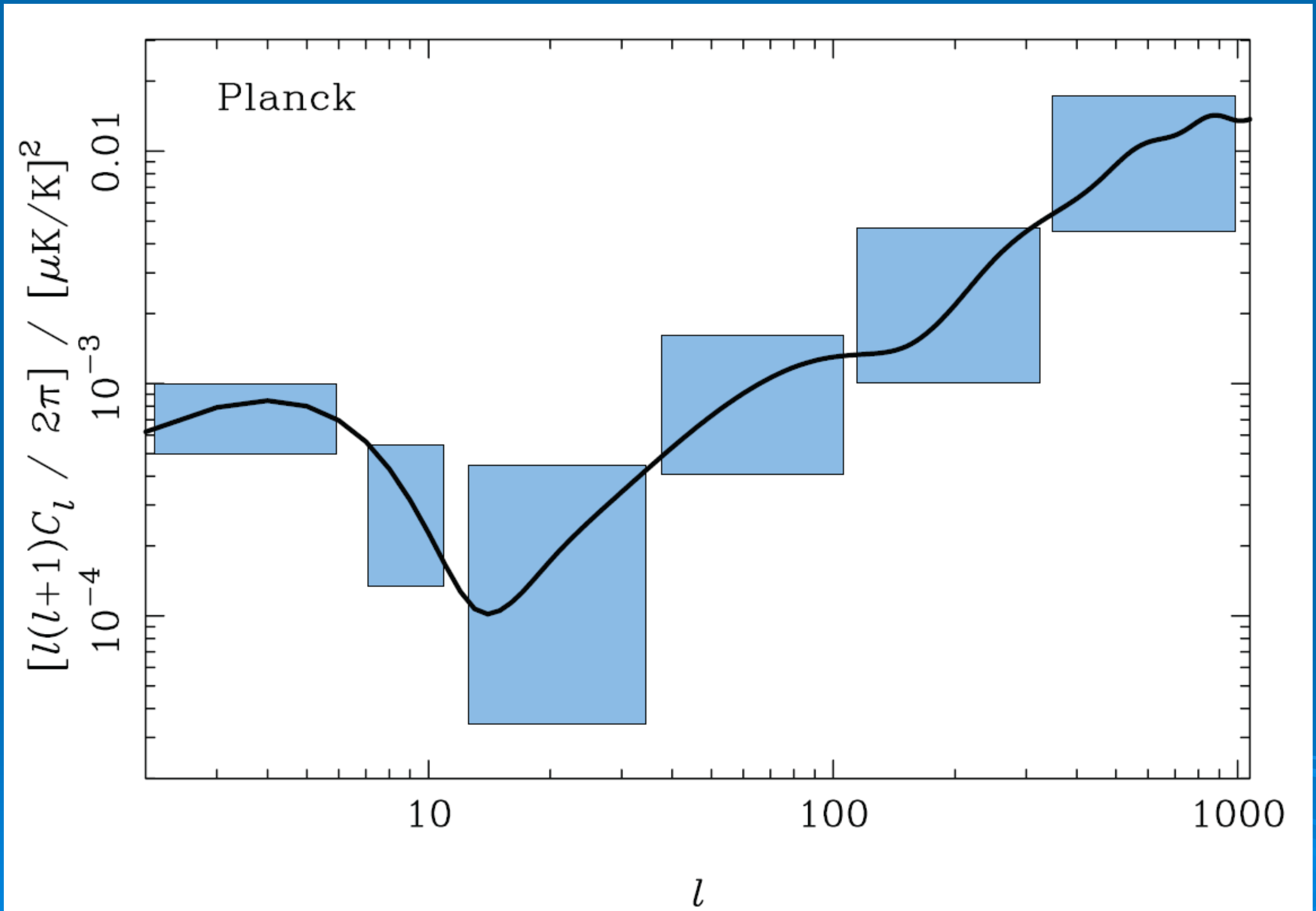




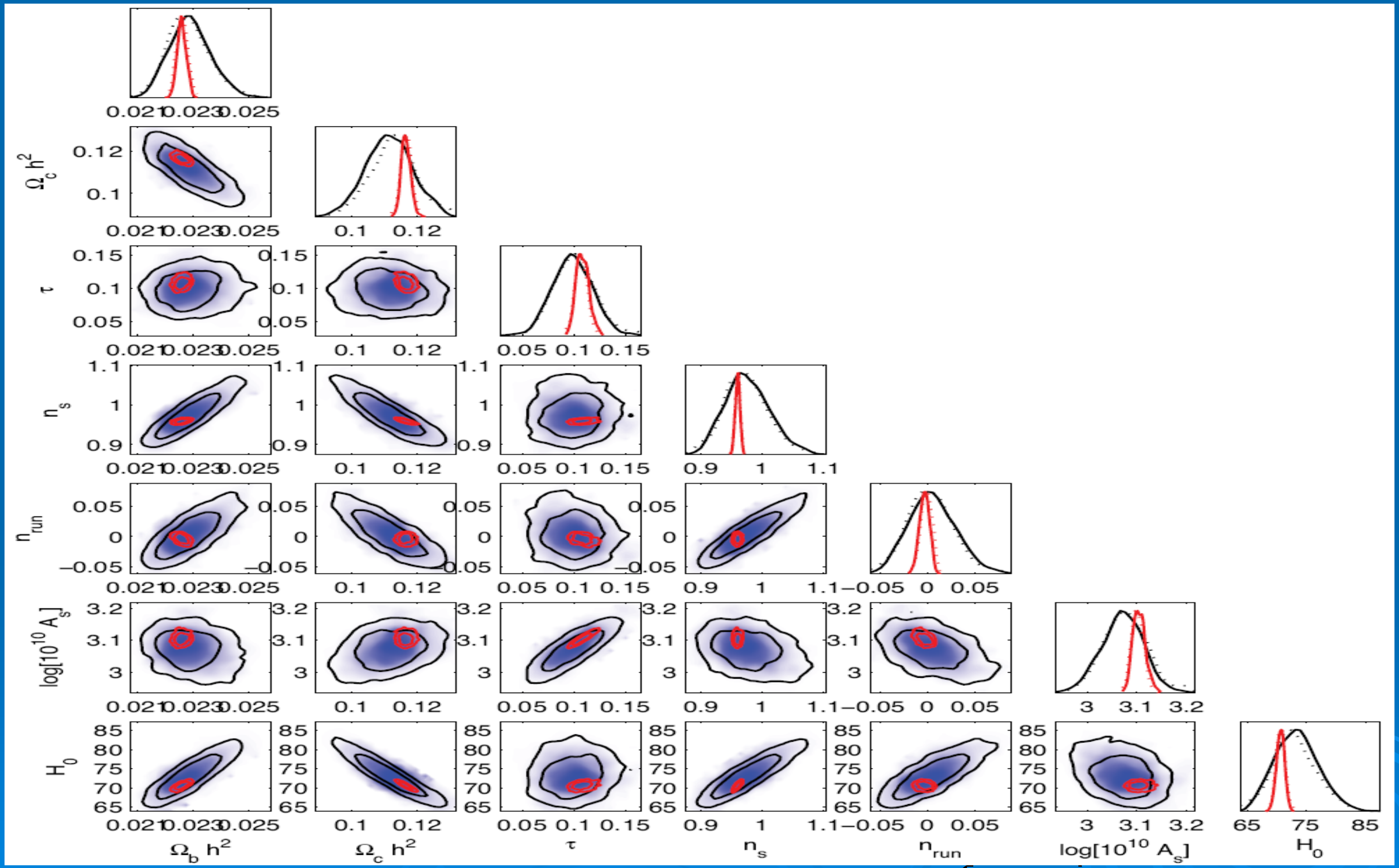




Planck and polarization CMB B modes



Planck scientific deliverables: cosmological parameters



Non-CMB Planck scientific deliverables

- Thousands of galaxy clusters
- Tens of thousands of radio and infrared extra-Galactic sources
- Templates for the diffuse gas in the Galaxy, from 30 to 857 GHz
- …

B mode hunters

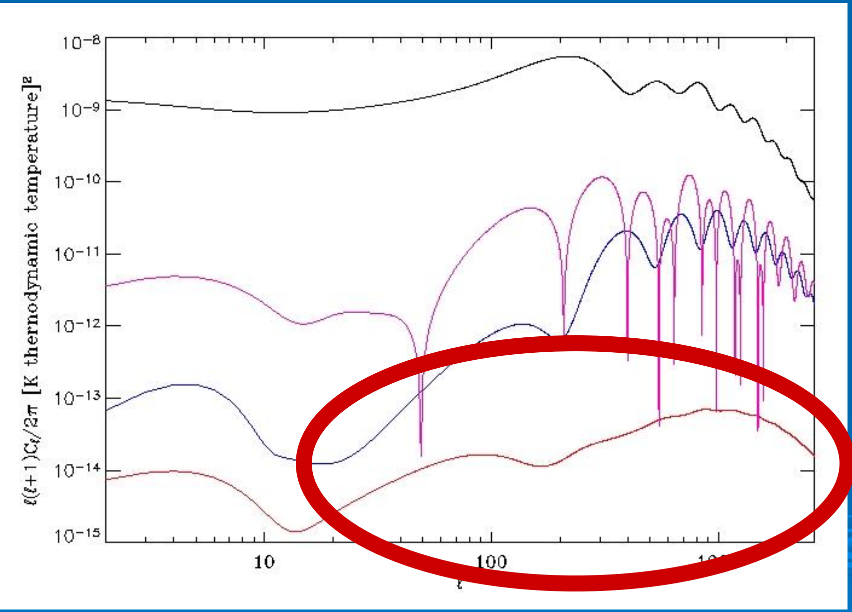
The case of the E and B Experiment,

on behalf of the EBEx collaboration,

groups.physics.umn.edu/cosmology/ebex

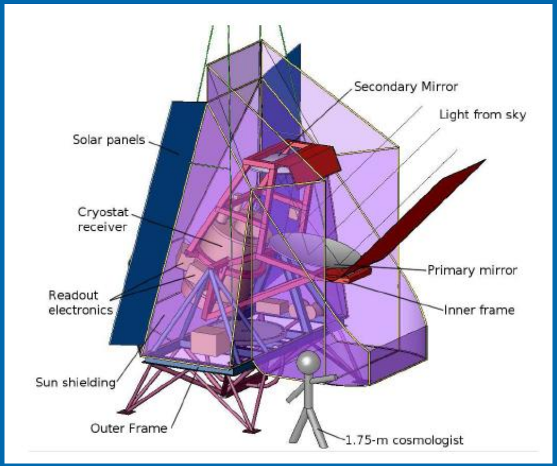
B modes hunters

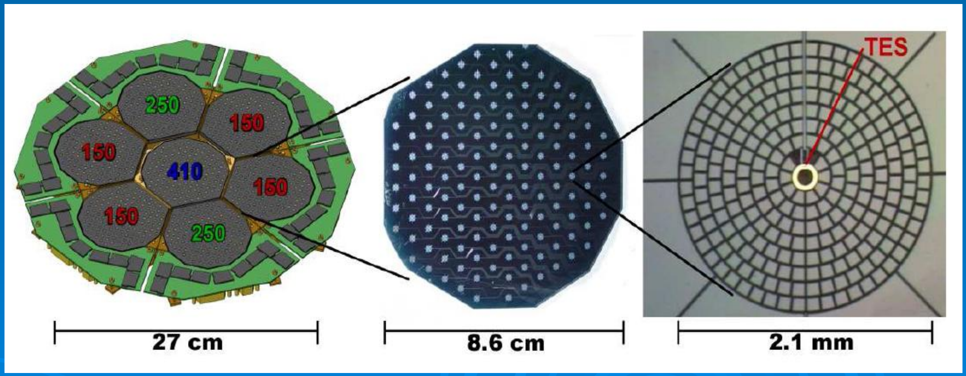
- Visit lambda.gfsc.nasa.gov for a complete list of all the ongoing and planned experiments
- Different technologies, ground based as well as balloon borne probes
- The instrumental sensitivity and angular resolution are high enough to get to a tensor to scalar ratio of about 10^{-2} via direct detection of cosmological B modes on the degree scale
- Some of the probes also are able to detect the lensing peak in the B modes
- All these experiments aim at the best measurement of CMB, although most important information is expected in particular for the B mode component of the diffuse Galactic emission
- The challenge of controlling instrumental systematics and foregrounds make these probes pathfinders for a future CMB polarization satellite



EBEX

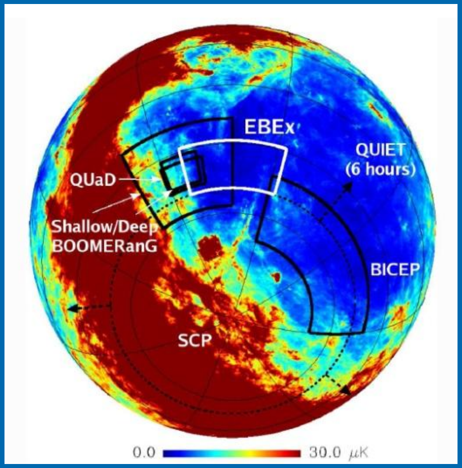
- Balloon borne
- Three frequency bands, 150, 250, 410 GHz
- About 1500 detectors
- 8 arcminutes angular resolution
- Sensitivity of 0.5 micro-K per resolution element
- Scheduled for flying from north america in May 2009, from Antarctica one year later

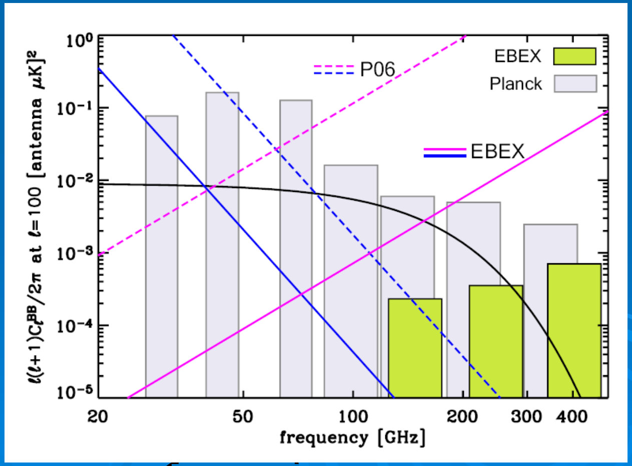


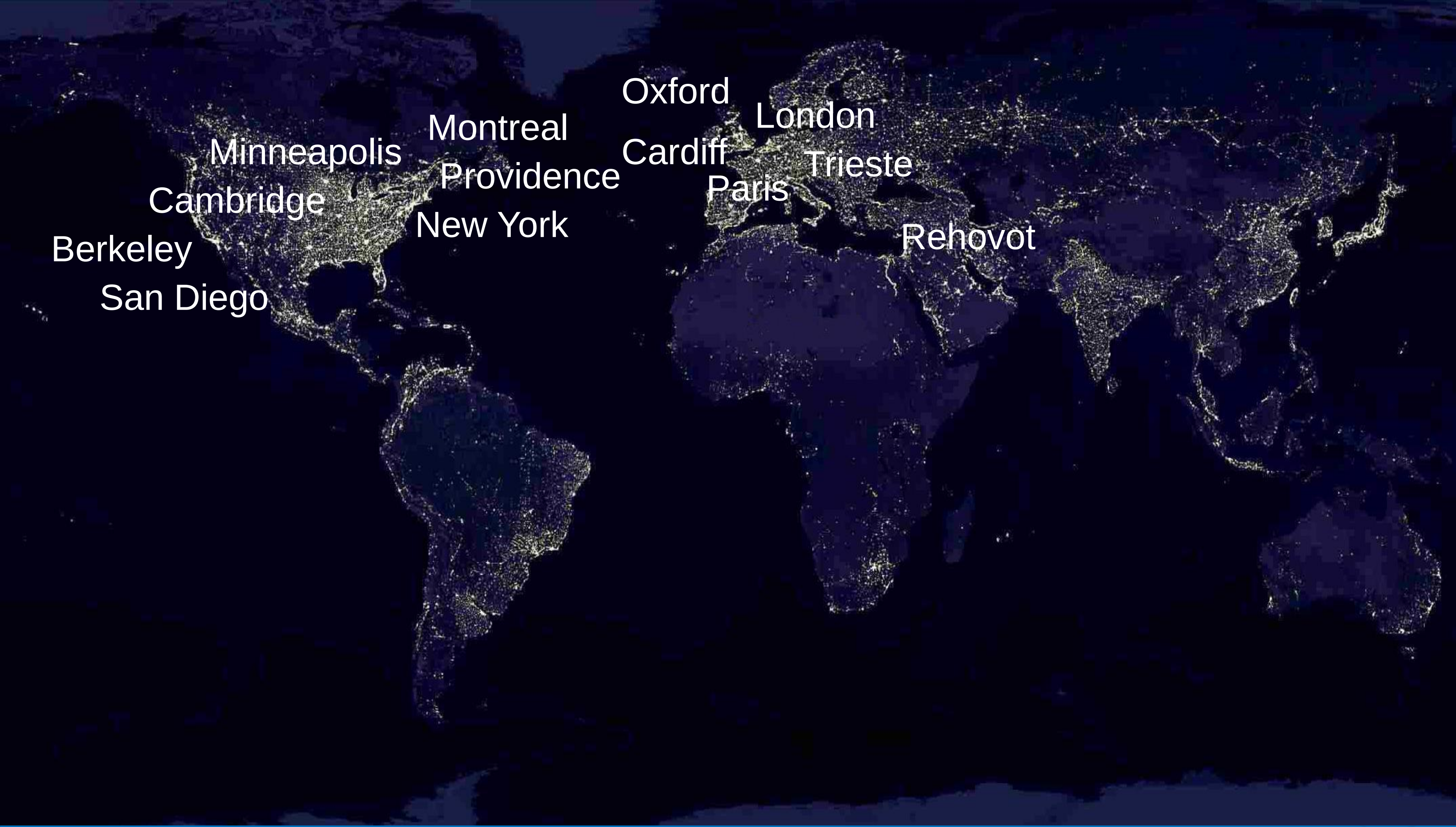


EBEX

- Targeting a low foreground area in the antarctica flight, already probed by previous observations for total intensity and E mode polarization
- Foregrounds, dominated by Galactic dust at the EBEx frequencies, are estimated to be still comparable to the cosmological signal for B
- Band location and number of detectors per band have been optimized for foreground subtraction



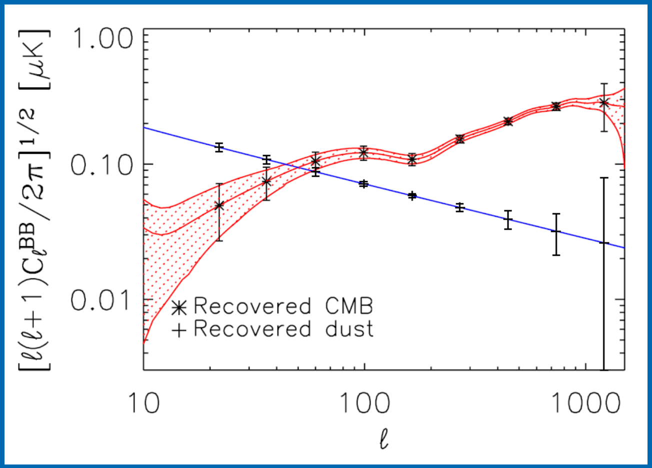


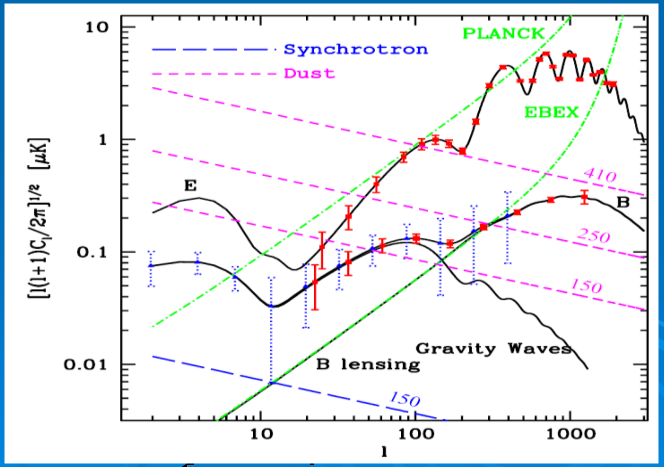


EBEX contributors

Expectations from EBEX

- Foreground parametrization and ICA foreground removal are going to be applied to the data to remove the contamination from the dust on the degree scale, also yielding most precious measures of the same Galactic signal for ongoing and future CMB probes
- The detector sensitivity should allow a detection of the tensor to scalar ratio equal to 0.1 with a signal to noise ratio of about 5, or setting a two sigma upper limit of 0.02, plus a mapping of the lensing peak in B modes





Conclusions

- The CMB will be the best signal from the early universe for long
- We have some knowledge of the two point correlation function, but most of the signal is presently unknown
- If detected, the hidden signatures might reveal mysteries for physics, like gravitational waves, or the machanism of cosmic acceleration
- We don't know if we will ever see those things, systematics and foregrounds might prevent that
- But we've no other way to get close to the Big Bang, so let's go for it and see how far we can go
- First go/no go criteria from Planck and other probes in just a few years, possible scenarios…

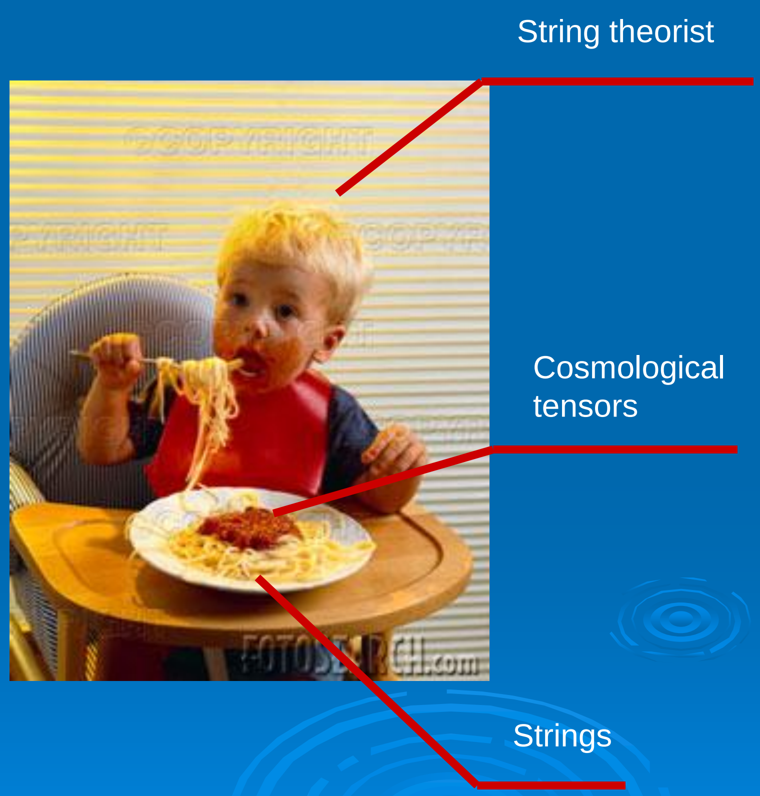
☹

- Polarized foreground too intense, no sufficient cleaning, systematics out of control
- Increase by one digit the cosmological parameters measurement, mostly from improvements in total intensity measurements
- Time scale: few years

String theorist

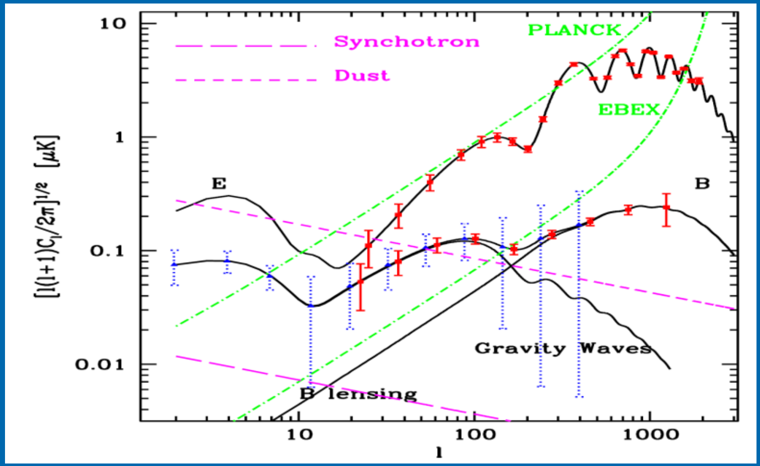
☺

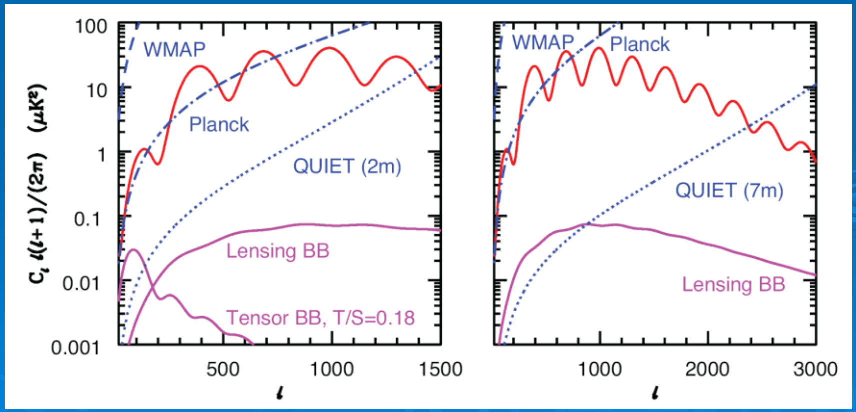
- Modest or controllable foreground emission, systematics under control
- Inflation severely constrained by primordial non-Gaussianities
- Cosmological gravity waves discovered from CMB B modes! Expected precision down to one thousandth of the scalar amplitude
- Percent measurement of the dark energy abundance at the onset of acceleration, from CMB lensing
- Other surprises…?
- Time scale: from a few to 20 years



Forthcoming CMB polarization probes

- Planck
- EBEx (US, collaborators in France, Italy, UK), baloon, same launch time scale as Planck for the north american flight
- SPIDER (US, …)
- QUIET (US, UK), ground based
- Clover (UK, …)
- Brain
- …
- Complete list available at lambda.gsfc.nasa.gov
- Time scale: approximately one year for test launches

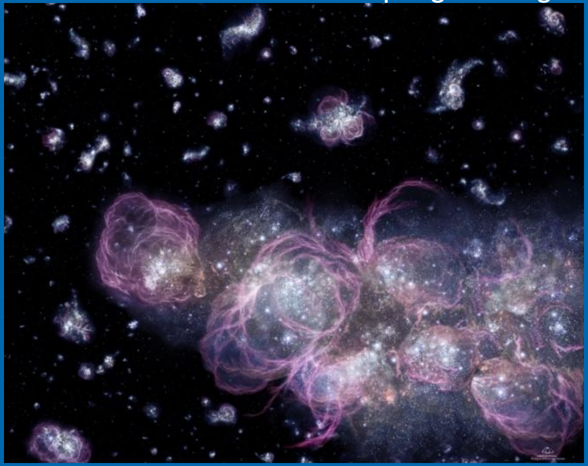


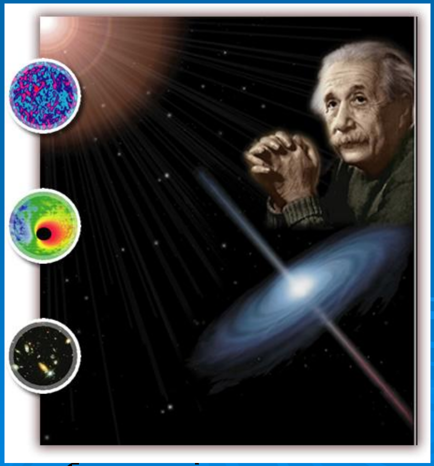


Cosmic vision beyond Einstein

- NASA and ESA put out separate calls of opportunity for a polarization oriented future (2020 or so) CMB satellite
- Technologies, design, options for joint or separate missions are in proposals which have been submitted in these weeks
- Promises: gravity waves, lensing and high redshift dark energy, inflationary non-Gaussianity

Cosmic vision program logo





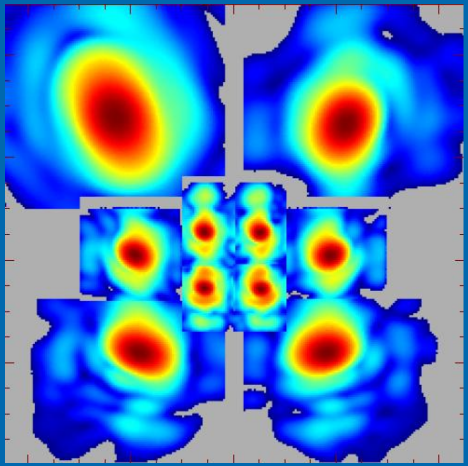
Beyond einstein logo

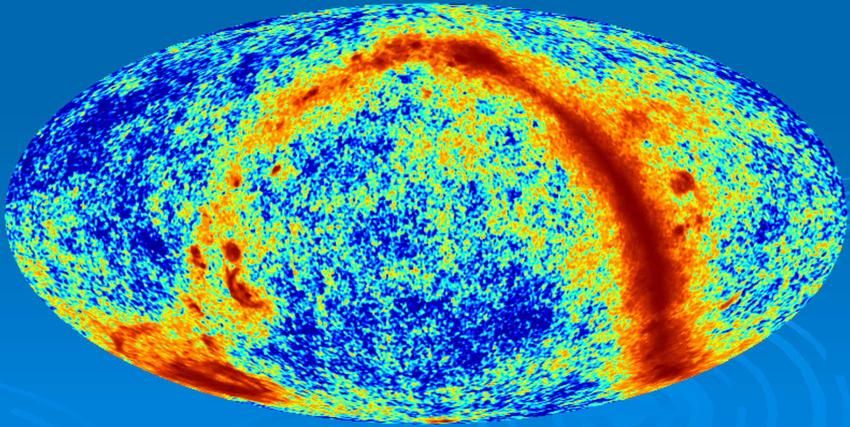
Challenges for future CMB

Challenges for future CMB

- The sensitivity can be increases with the detector number ☺
- The systematics from the instrument must be controlled at the level of the signal ☹
- The emission from foregrounds may cover the B signal over the all sky, at all frequency ☹

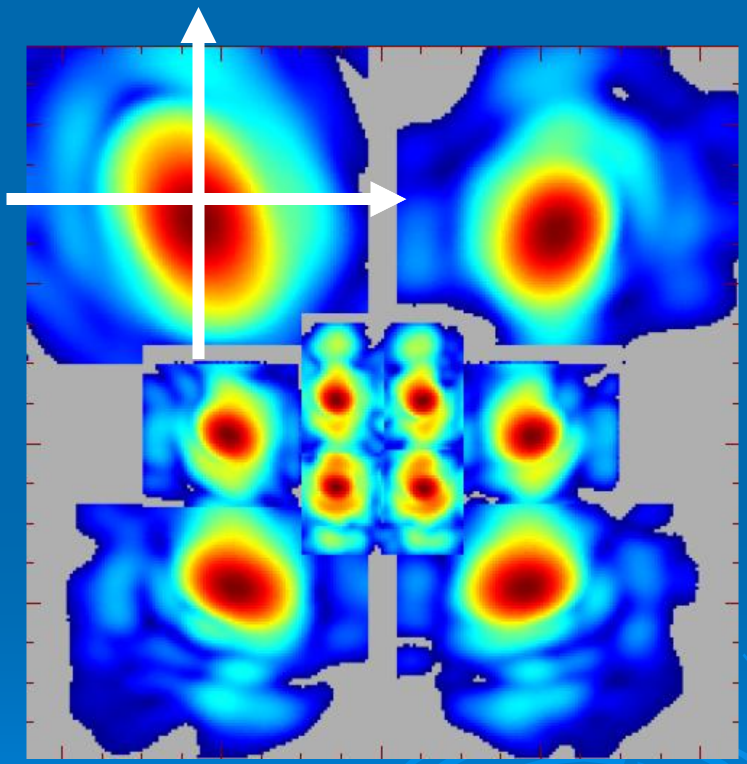
Jarosik et al. 2006





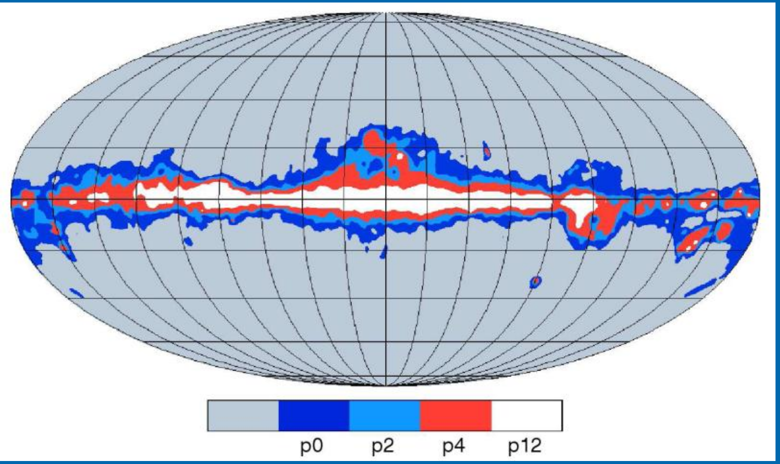
Challenges for future CMB: systematics from beam shape

- Asymmetric beams cause unwanted polarization from total intensity, leakage of E modes into B, …
- No way to circularize the beams, rather the beam shape has to be reconstructed in flight to subtract the bias from the signal



Challenges for future CMB: foreground emission

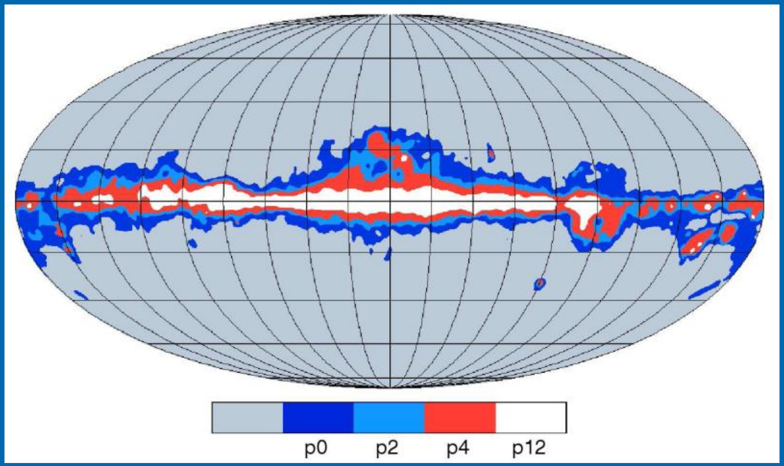
Bennett et al. 2006



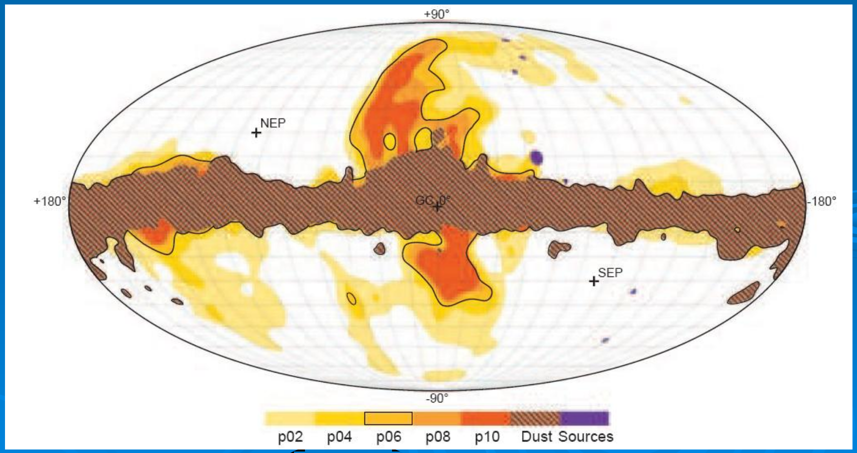
- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB

Challenges for future CMB: foreground emission

Bennett et al. 2006



- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB
- In polarization, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB

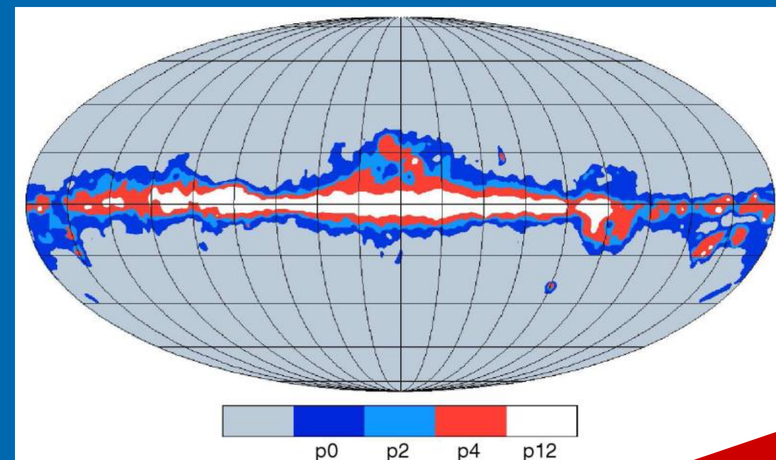


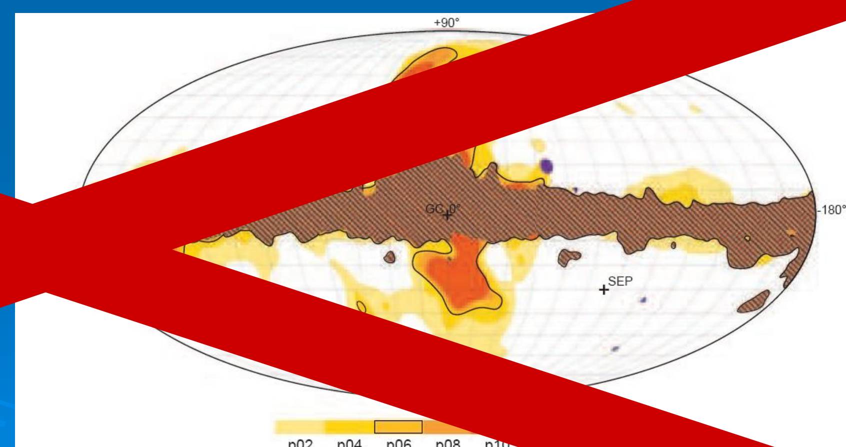
Page et al. 2006

Challenges for future CMB: foreground emission

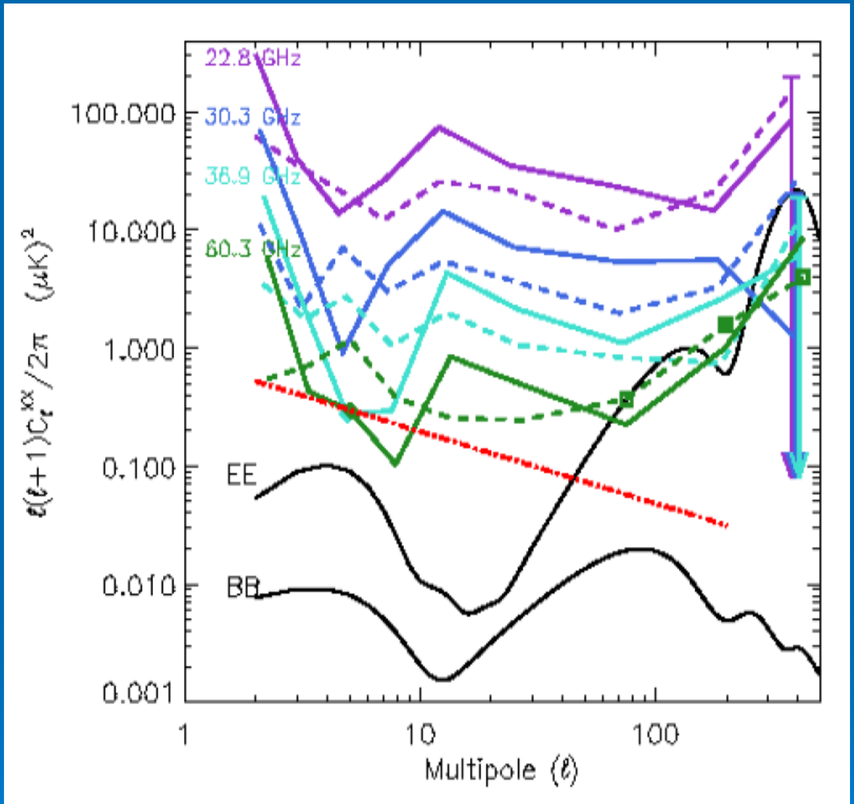
Bennett et al. 2006

- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB
- [illegible] polarization, at frequ[illegible] between 60 and 90 GHz, [illegible] cutting out the brighest p[illegible] the Galactic emission [illegible] sky is dominate[illegible]

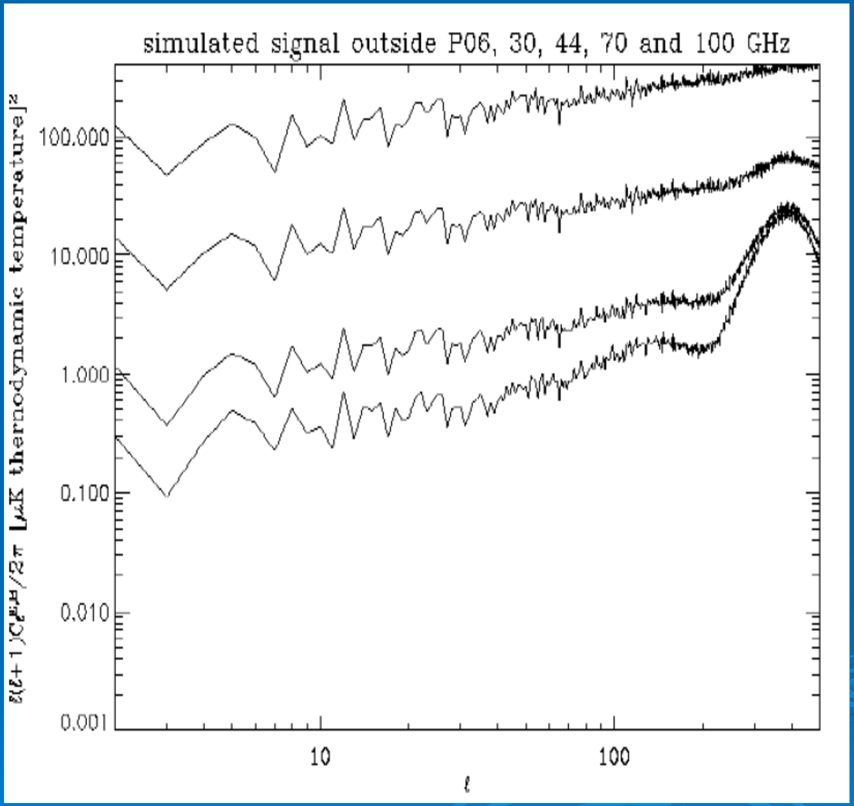




Challenges for future CMB: foreground emission



Page et al. 2006

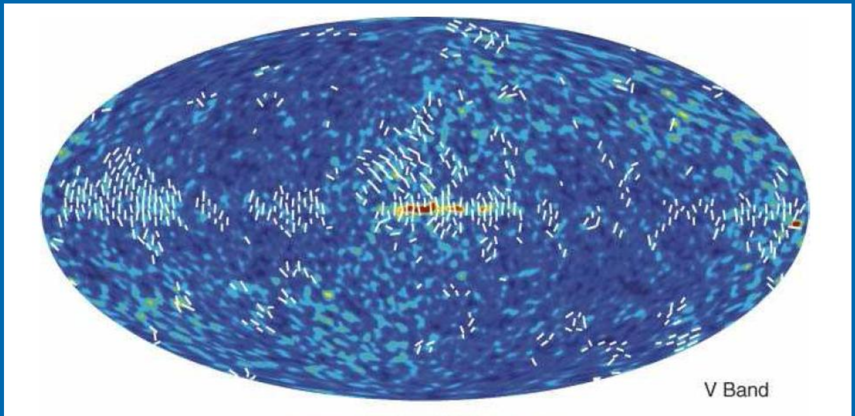


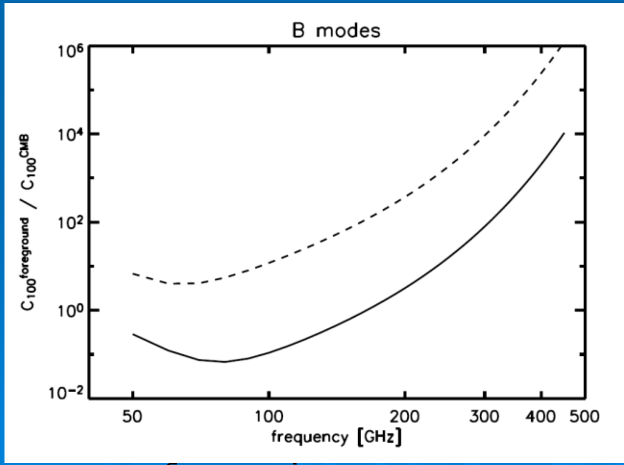
Planck reference sky

Are there foreground clean regions at all in polarization?

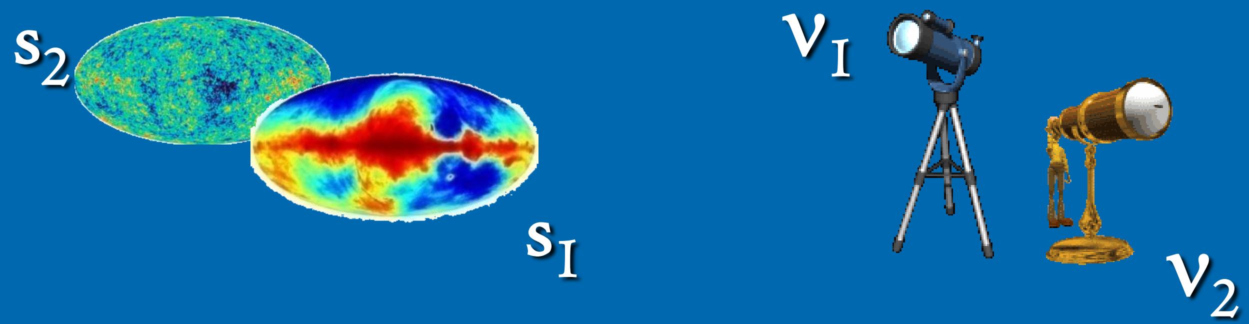
Page et al. 2006

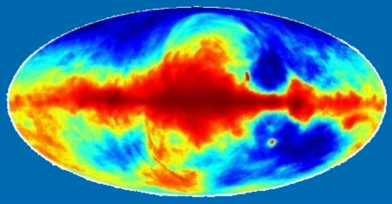
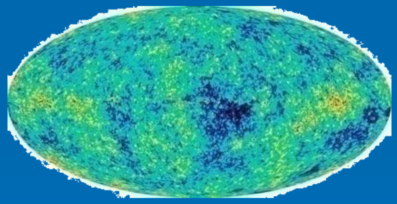
- WMAP has no detection in large sky areas in polarization
- Very naive estimates may be attempted in those areas, indicating that the foreground level might be comparable to the cosmological B mode at all frequencies, in all sky regions

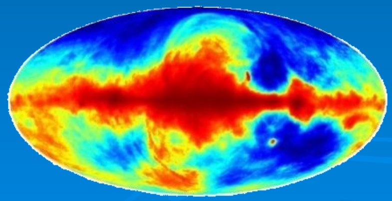
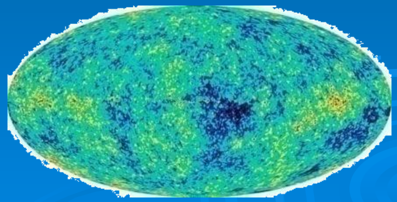




Living with foregrounds: component separation

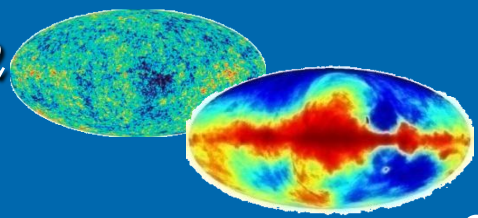


$x_1 = a_{11}$  $+ a_{12}$  $+ n_1$

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

Living with foregrounds: component separation

s_2



s_1

ν_1

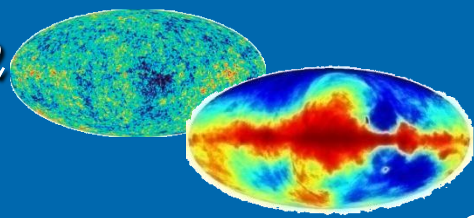
ν_2

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

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

Living with foregrounds: component separation

s_2



s_1

ν_1

ν_2

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

Invert for s!

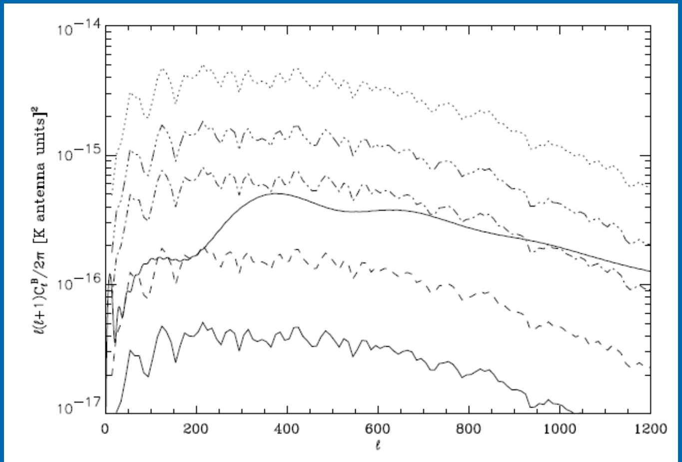
Living with foregrounds: component separation

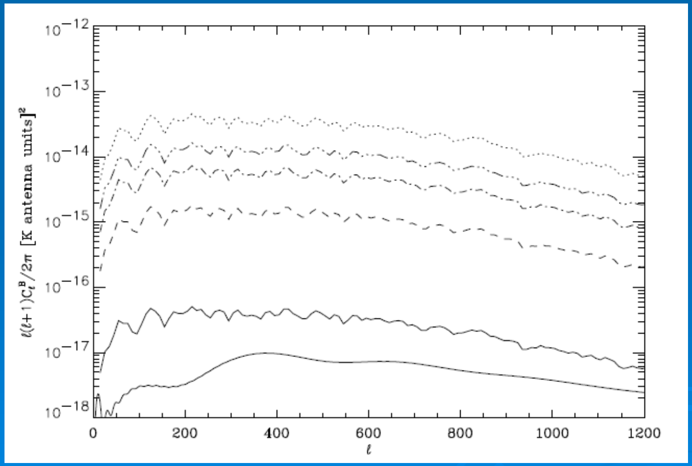
$$\mathbf{x} = \mathbf{A}s + \mathbf{n}$$

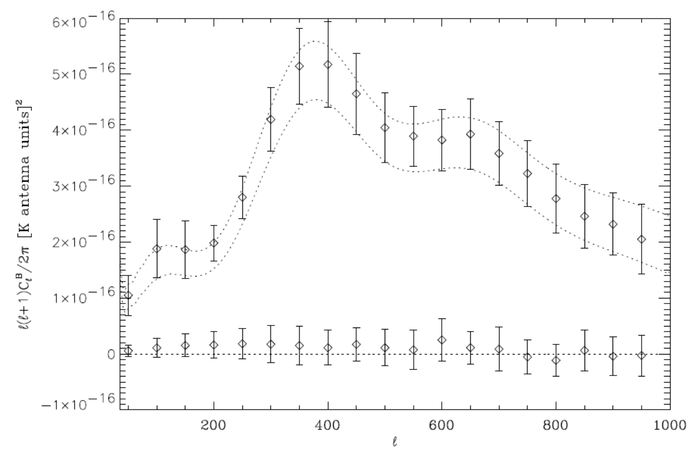
- Non-blind approach: use prior knowledge on A and s in order to stabilize the inversion, likely to be suitable for total intensity
- Blind approach: do not assume any prior either on A or s, likely to be used in polarization
- Parametrization: introduce extra ``cosmological parameters” parametrizing the foreground unknowns, and fit the data with those in, marginalizing afterwards, prosmising results in total intensity, to be tested in polarization
- Relevant literature from Brandt et al. 1994, to Maino et al. 2006, successful applications to COBE, BEAST, WMAP

Component separation in polarization

- Component separation studies how to separate CMB and foregrounds in astrophysical multi-frequency observations
- The independent component analysis exploits the statistical differences between the almost Gaussian CMB and the strongly non-Gaussian foregrounds
- Results are encouraging, although obtained so far without instrumental systematics







Stivoli et al. 2006