The world as it will be seen after WMAP

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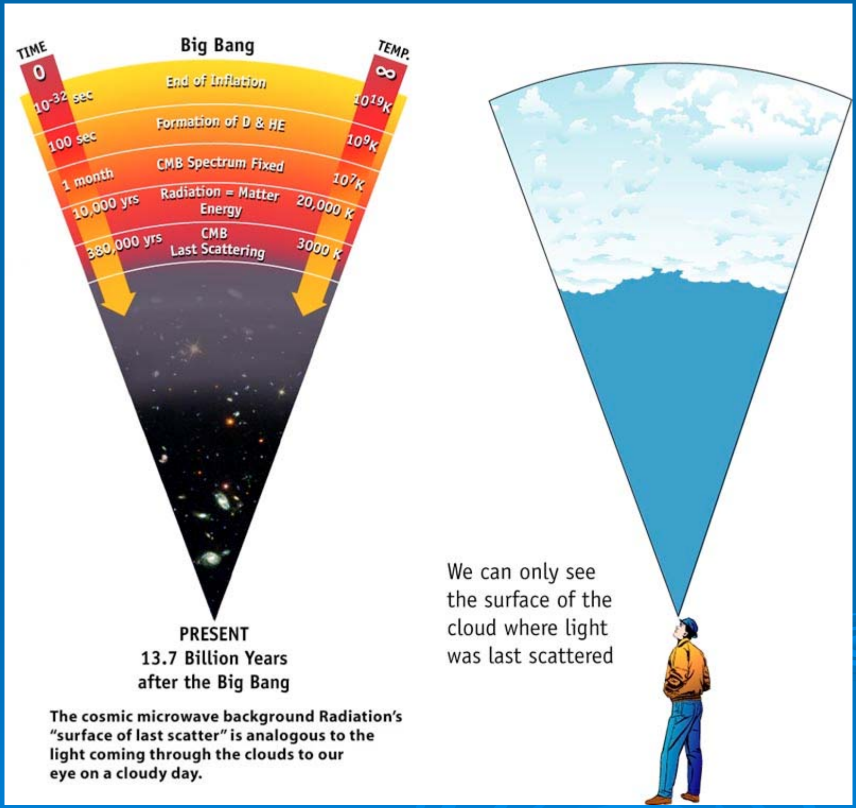
Outline

- CMB physics
- Status of the CMB observations and future experimental probes
- Challenges for future CMB
- The science goals of the Planck satellite

CMB physics

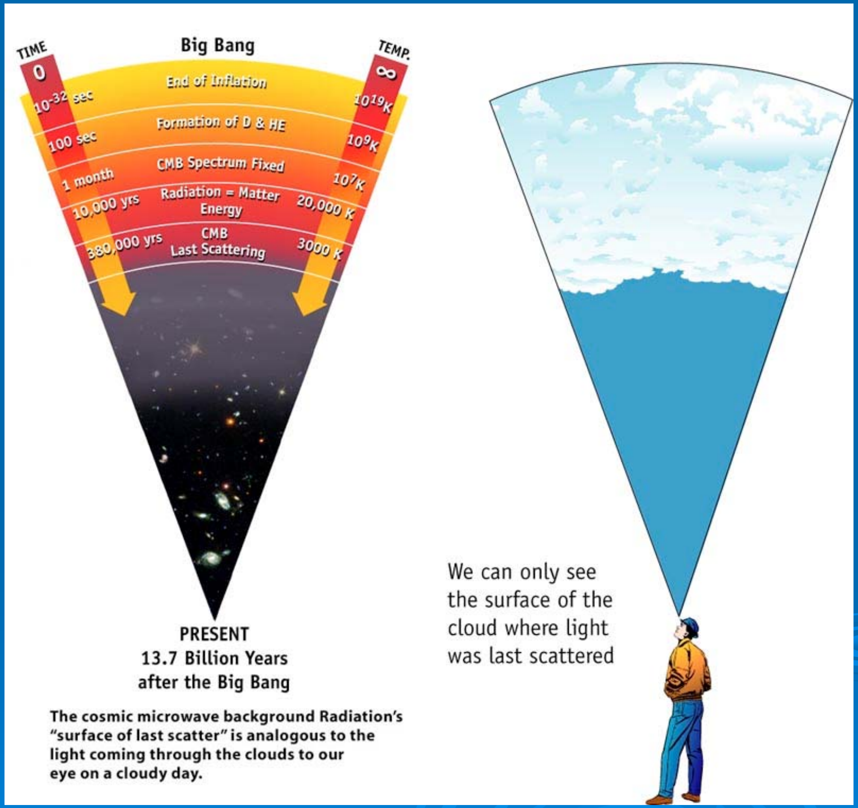
CMB: where and when?

- 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



CMB anisotropy: phenomenology

- Primordial perturbations in the curvature affect all cosmological species
- Perturbation evolution for all components proceeds accordingly to the cosmic geometry and expansion
- The anisotropy in the CMB represents the snapshot of cosmological perturbations in the photon component only, at decoupling time



Animation from the NASA WMAP team

CMB physics: Boltzmann equation

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

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

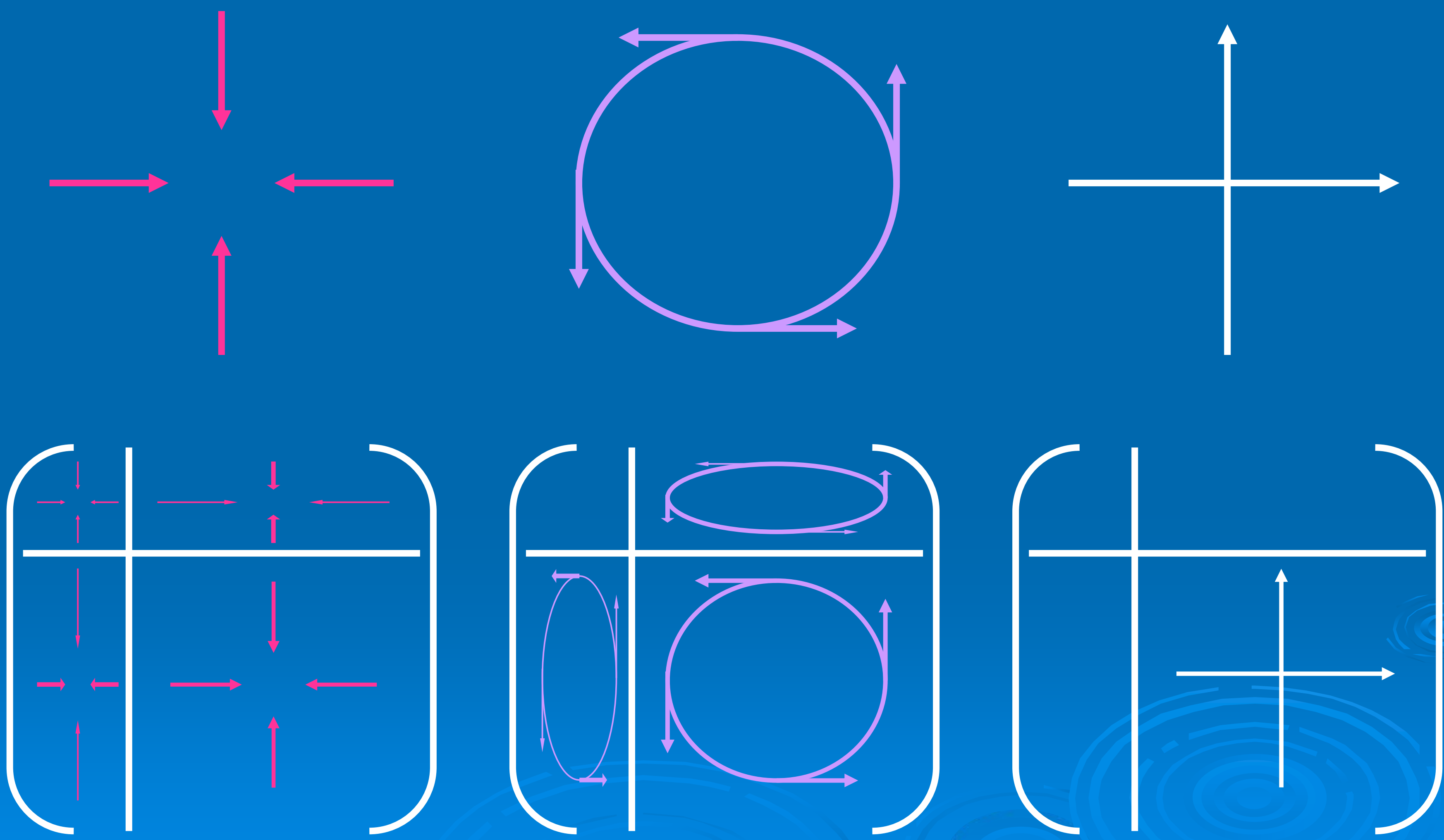
CMB physics: Boltzmann equation

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

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

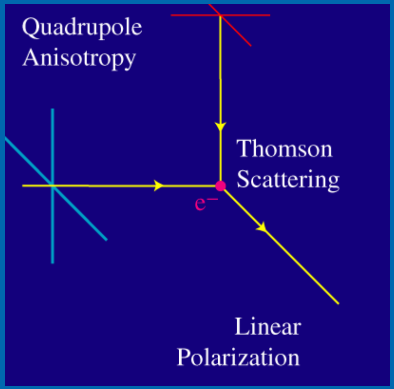
metric = photons + neutrinos + baryons + leptons + dark matter

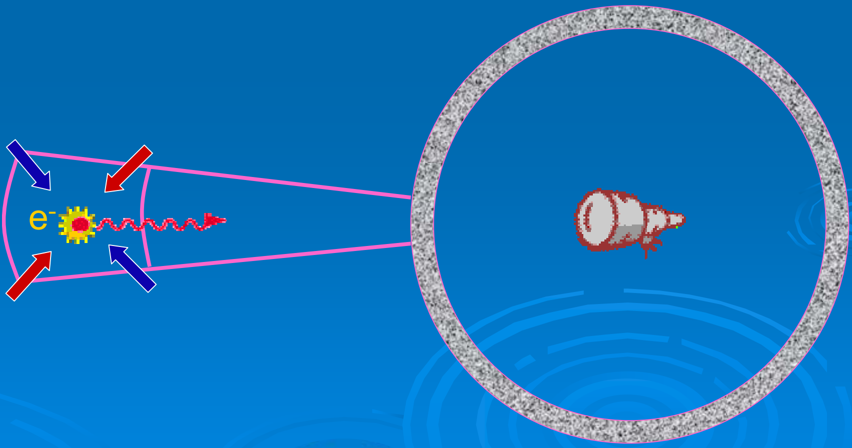
CMB physics: metric



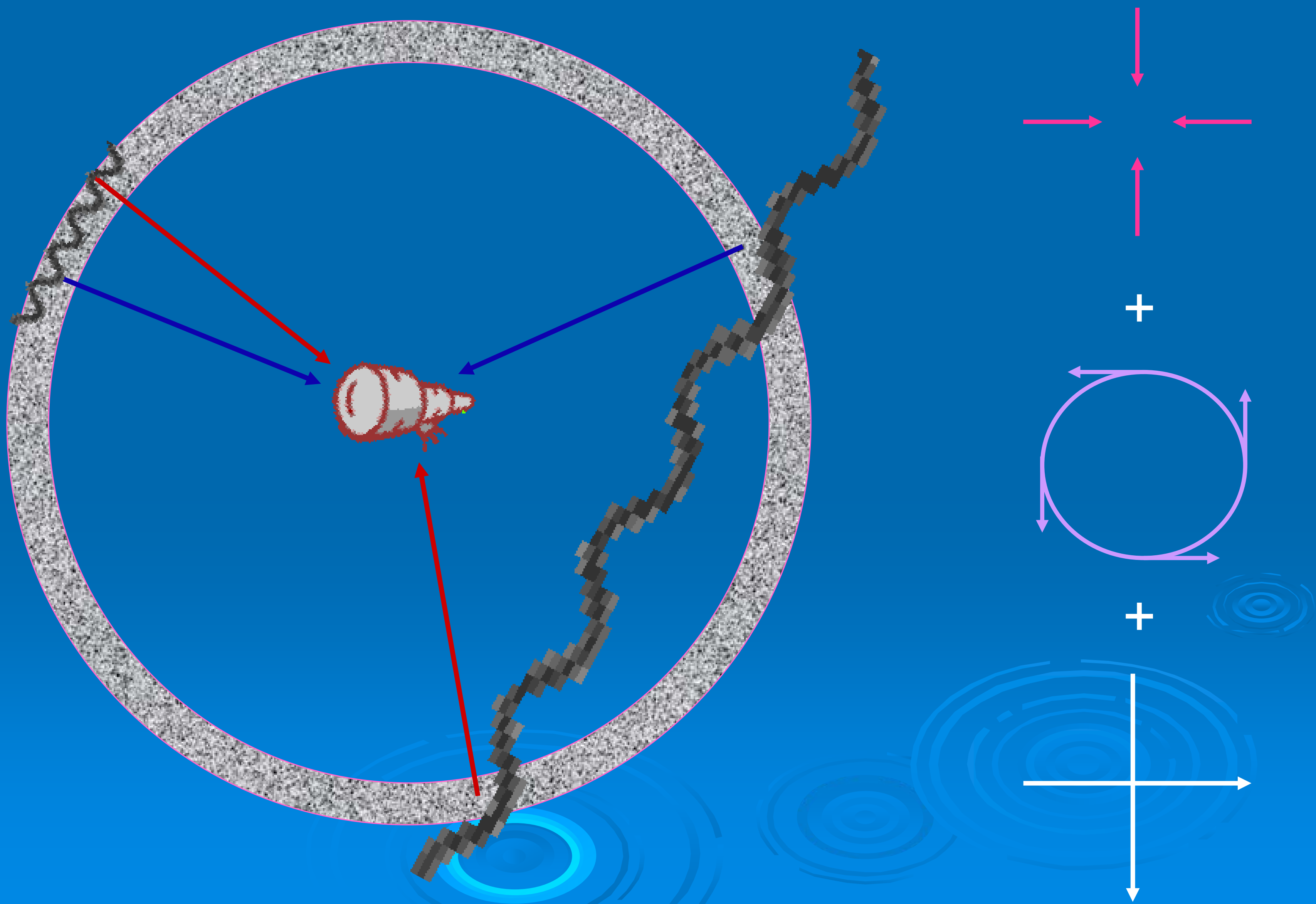
CMB Physics: Compton scattering

- 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

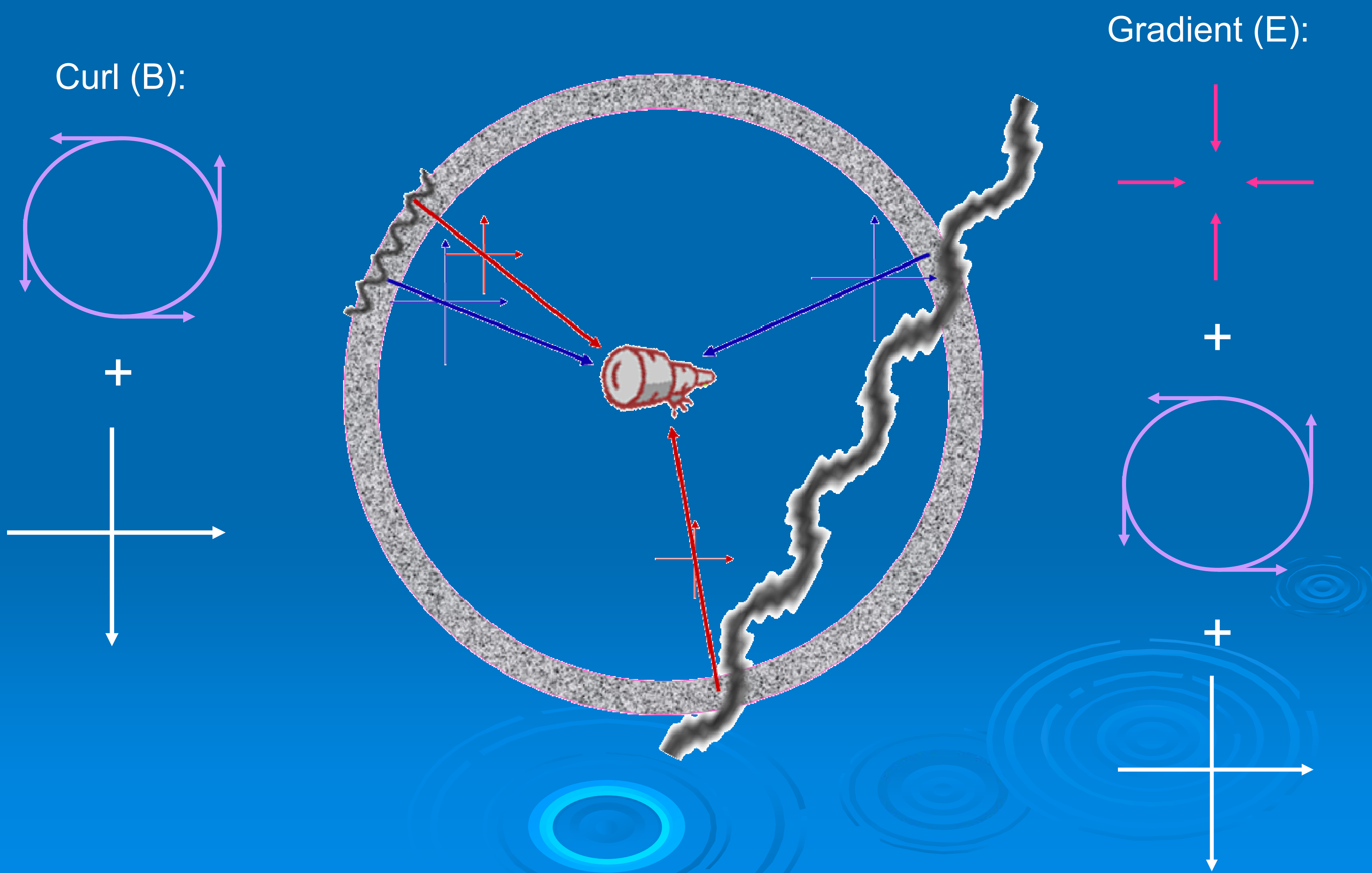




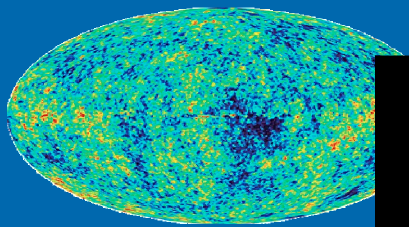
CMB anisotropy: total intensity

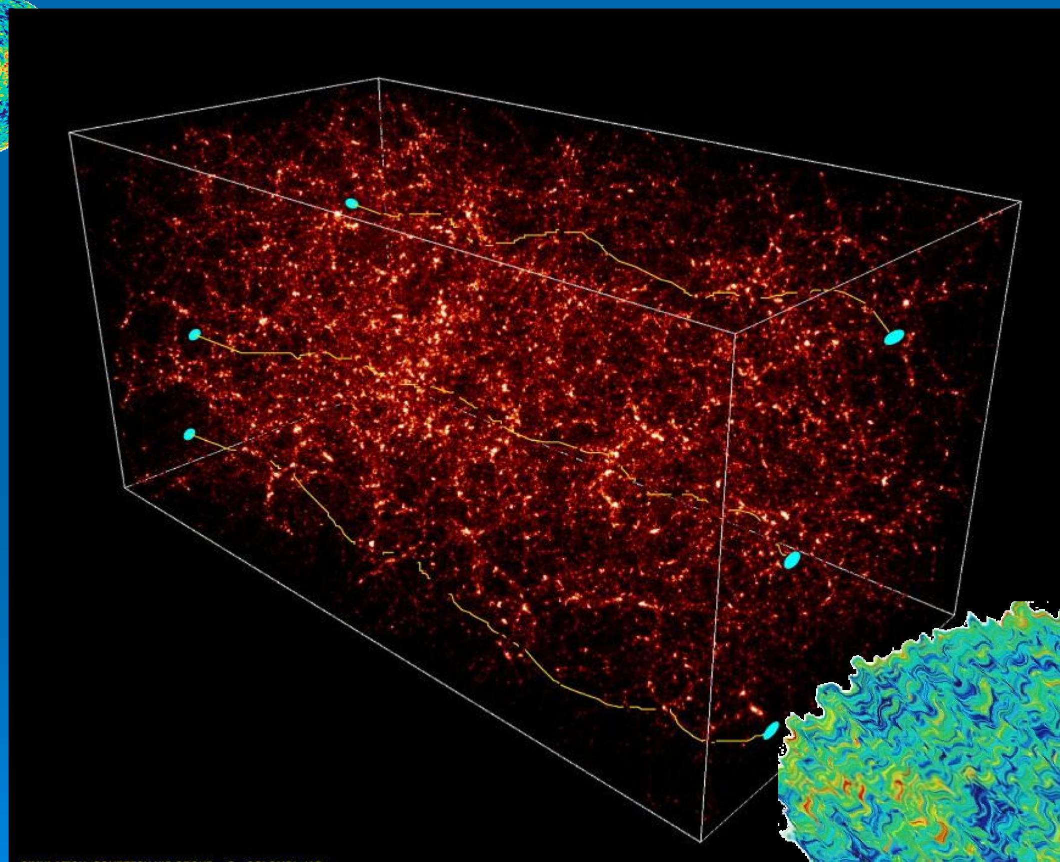


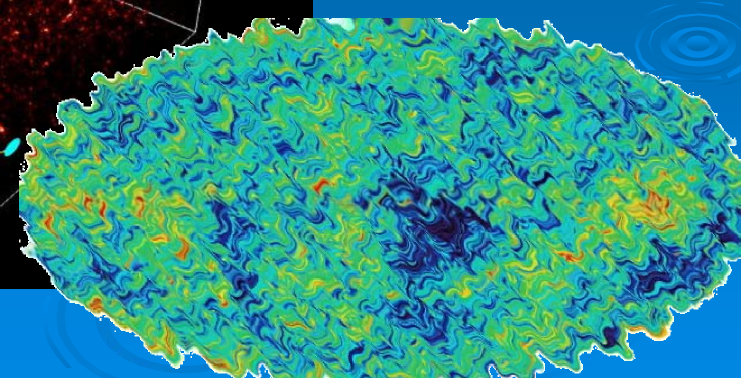
CMB anisotropy: polarization



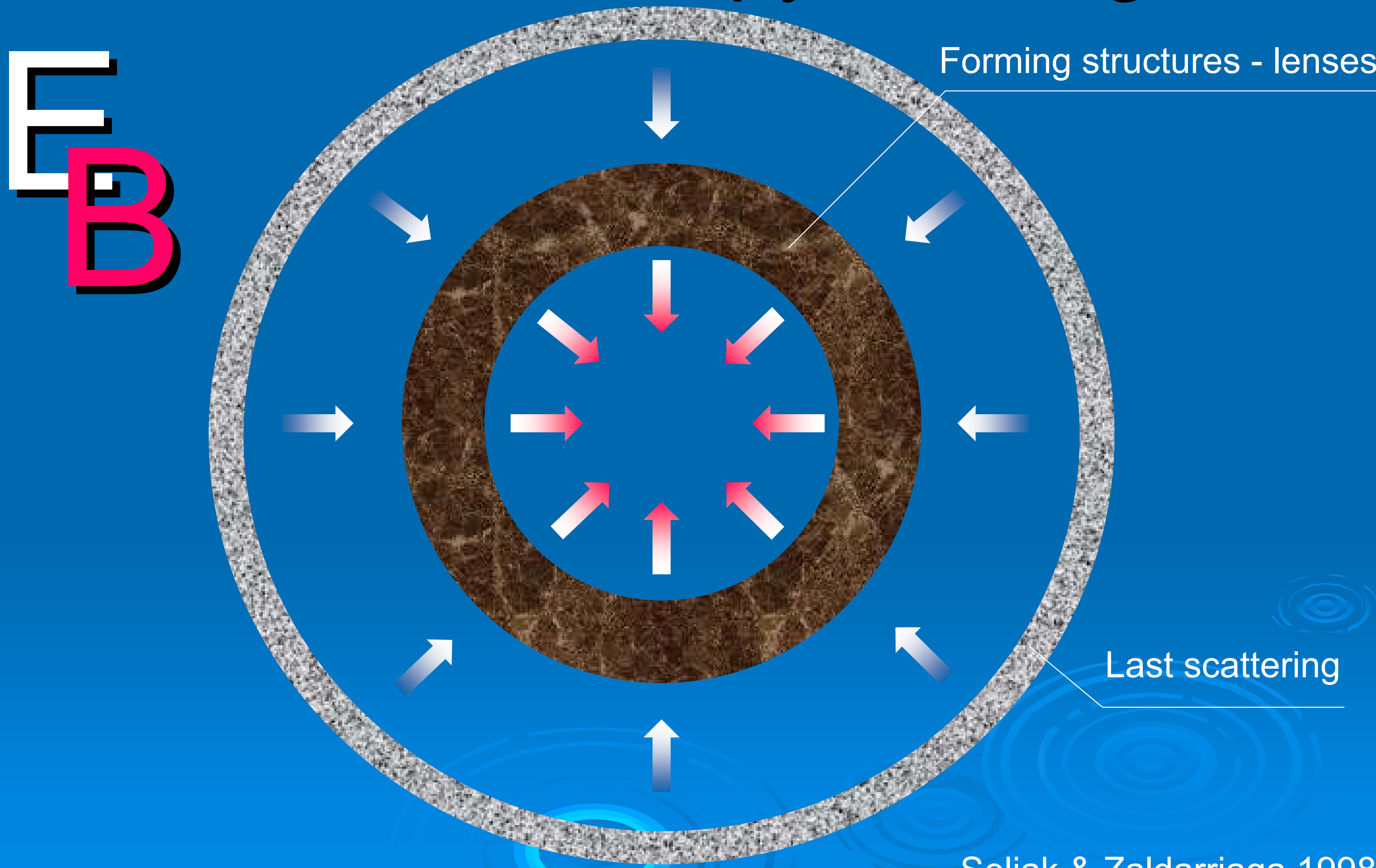
CMB anisotropy: lensing





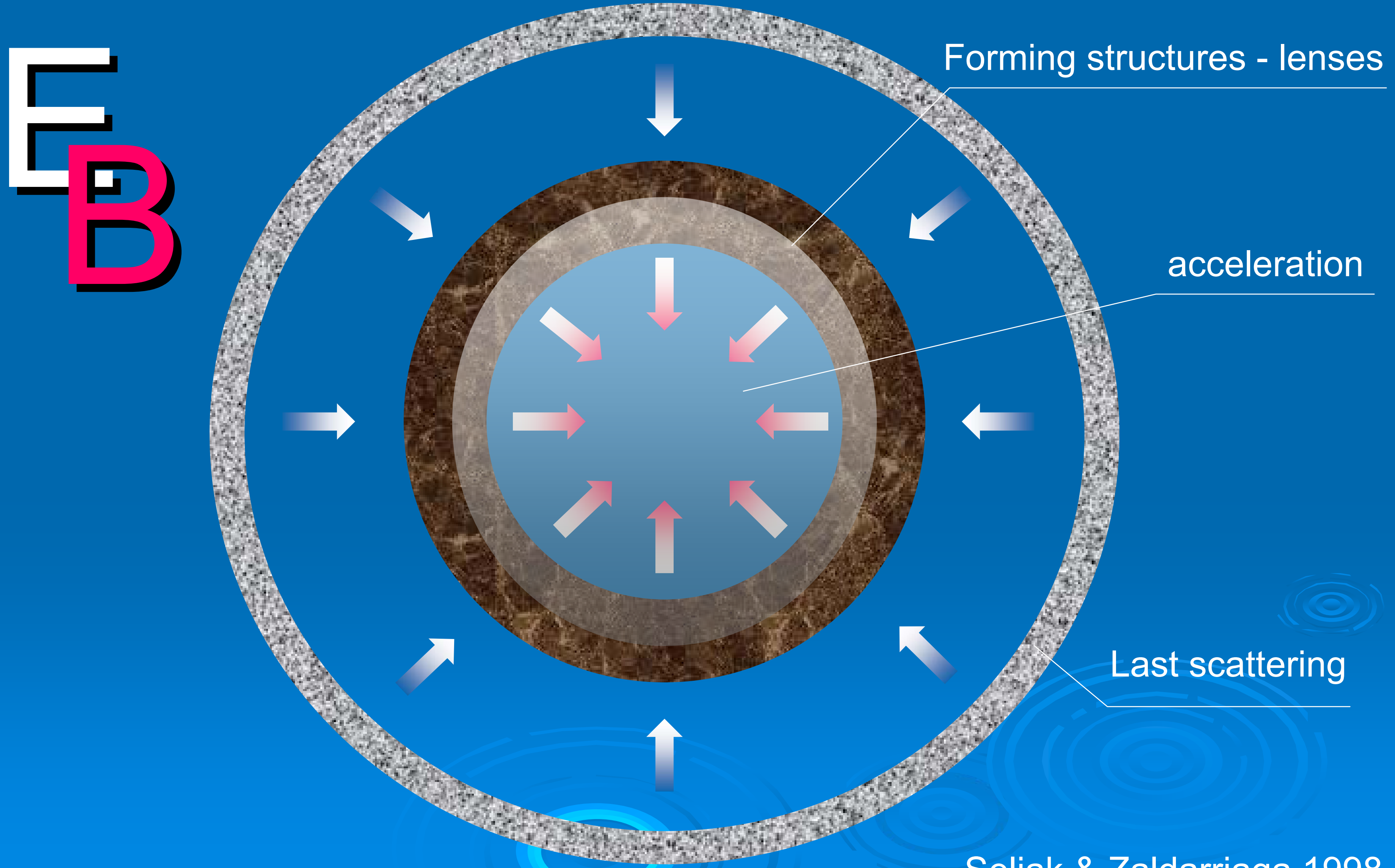


CMB anisotropy: lensing



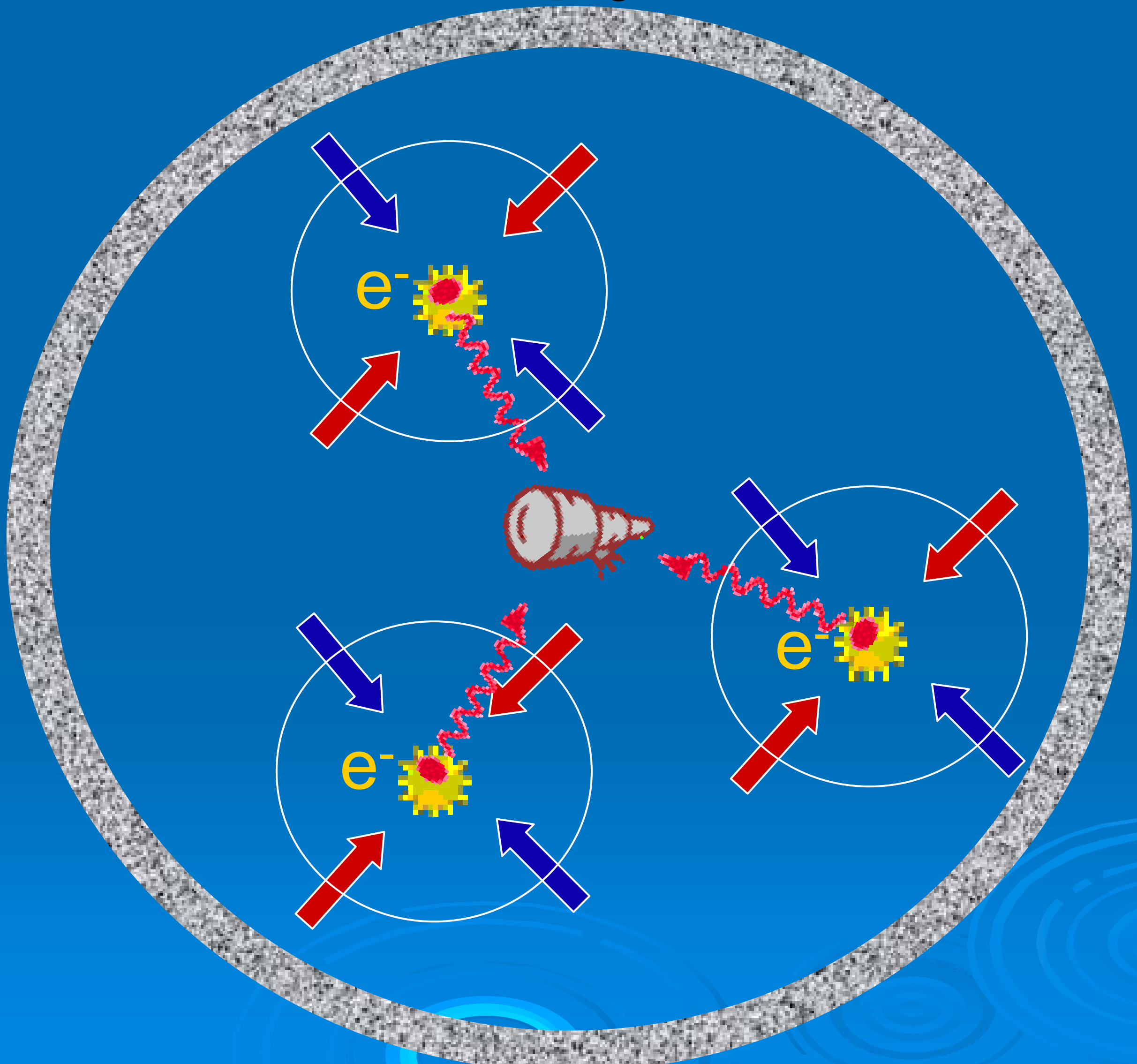
Seljak & Zaldarriaga 1998

CMB anisotropy: lensing



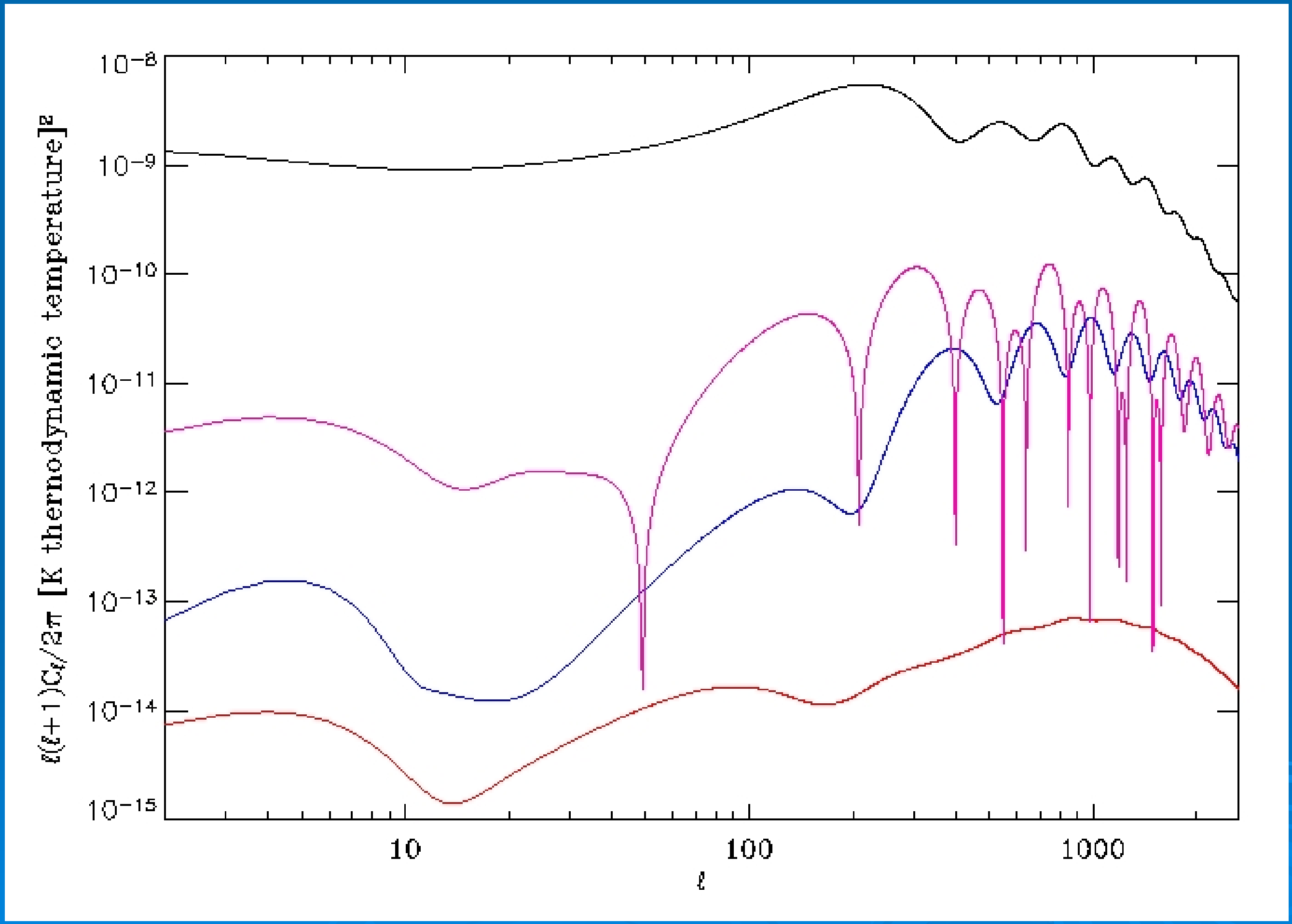
Seljak & Zaldarriaga 1998

CMB anisotropy: reionization



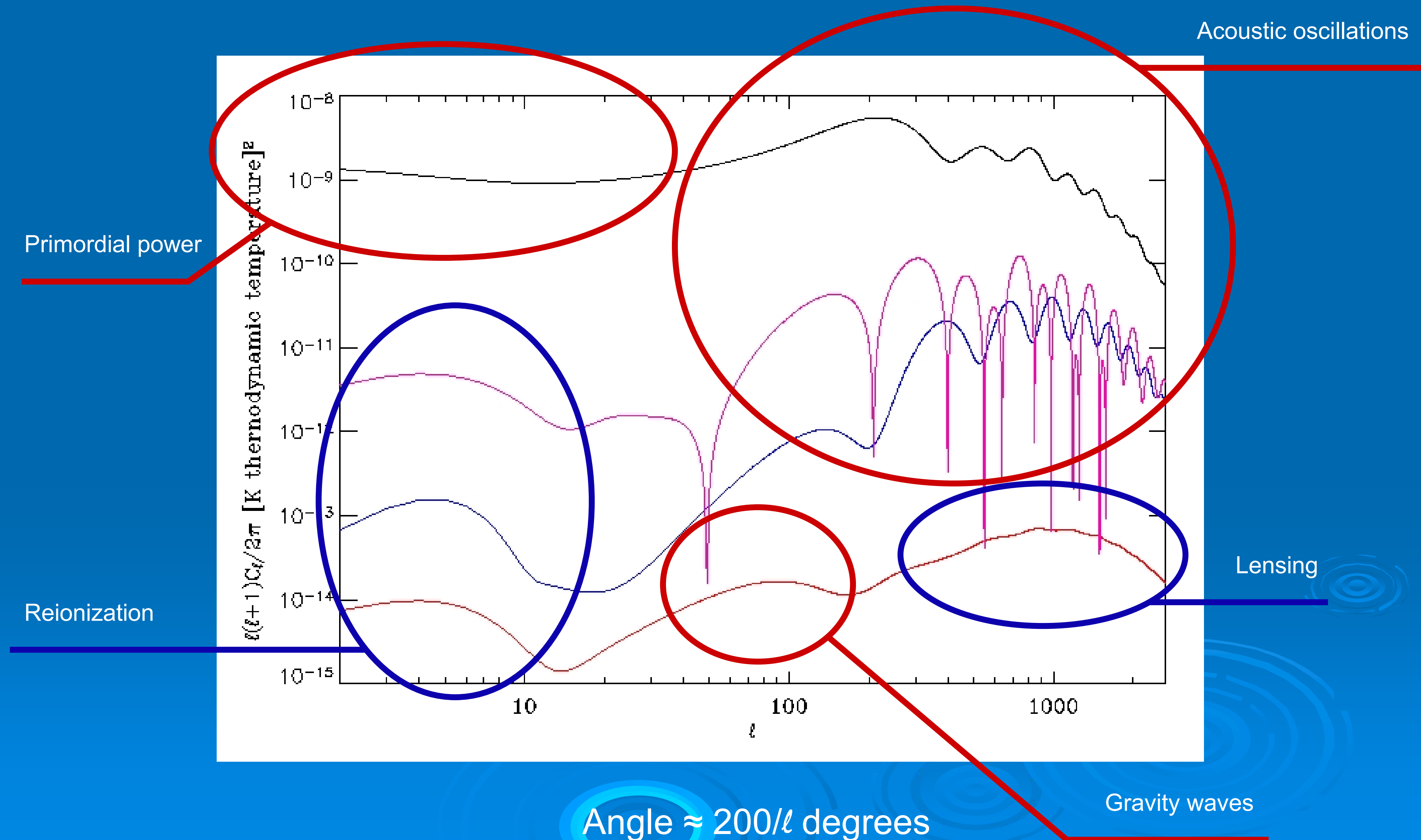
Status of the CMB observations and future experimental probes

CMB angular power spectrum



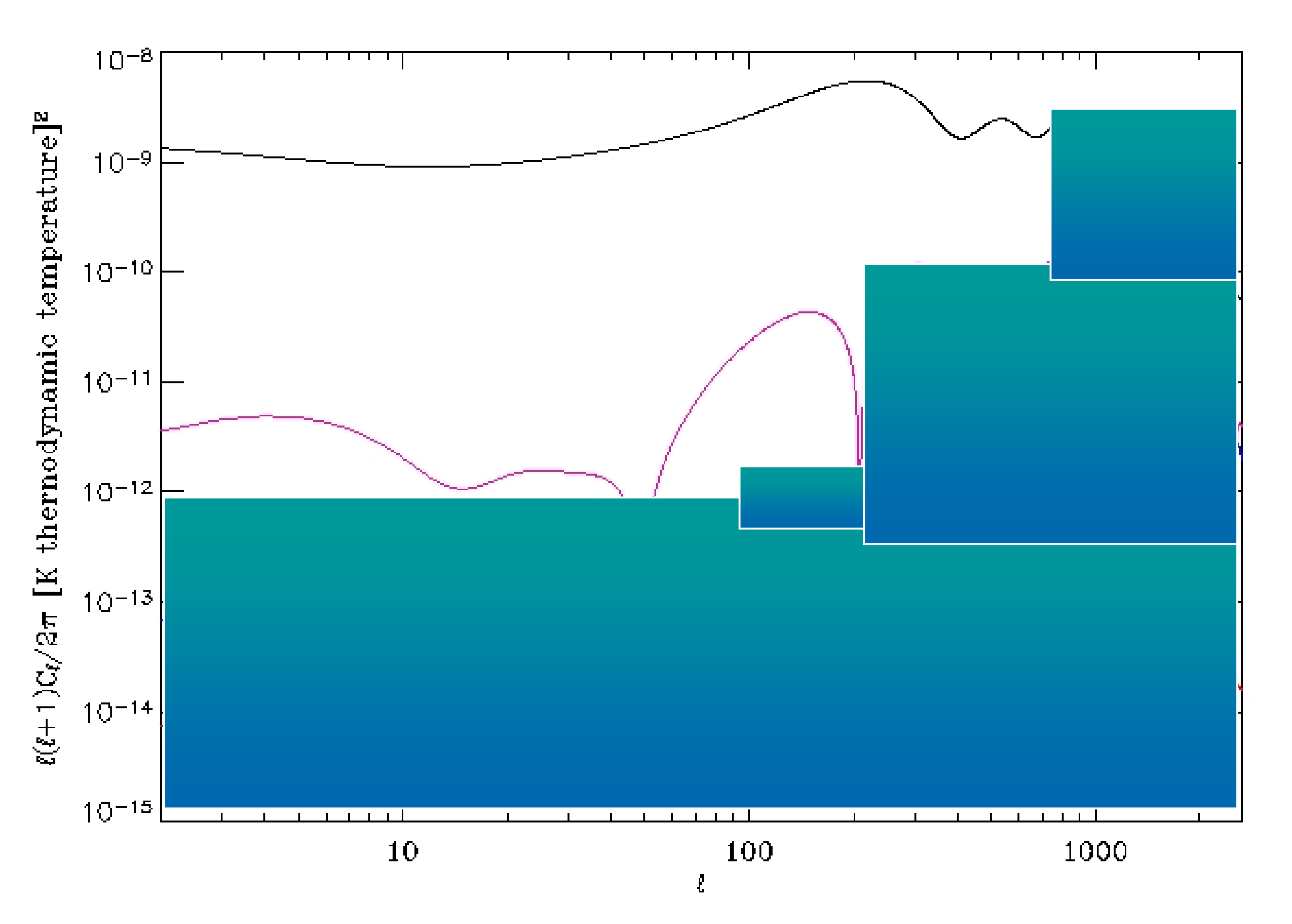
Angle ≈ 200/ℓ degrees

CMB angular power spectrum



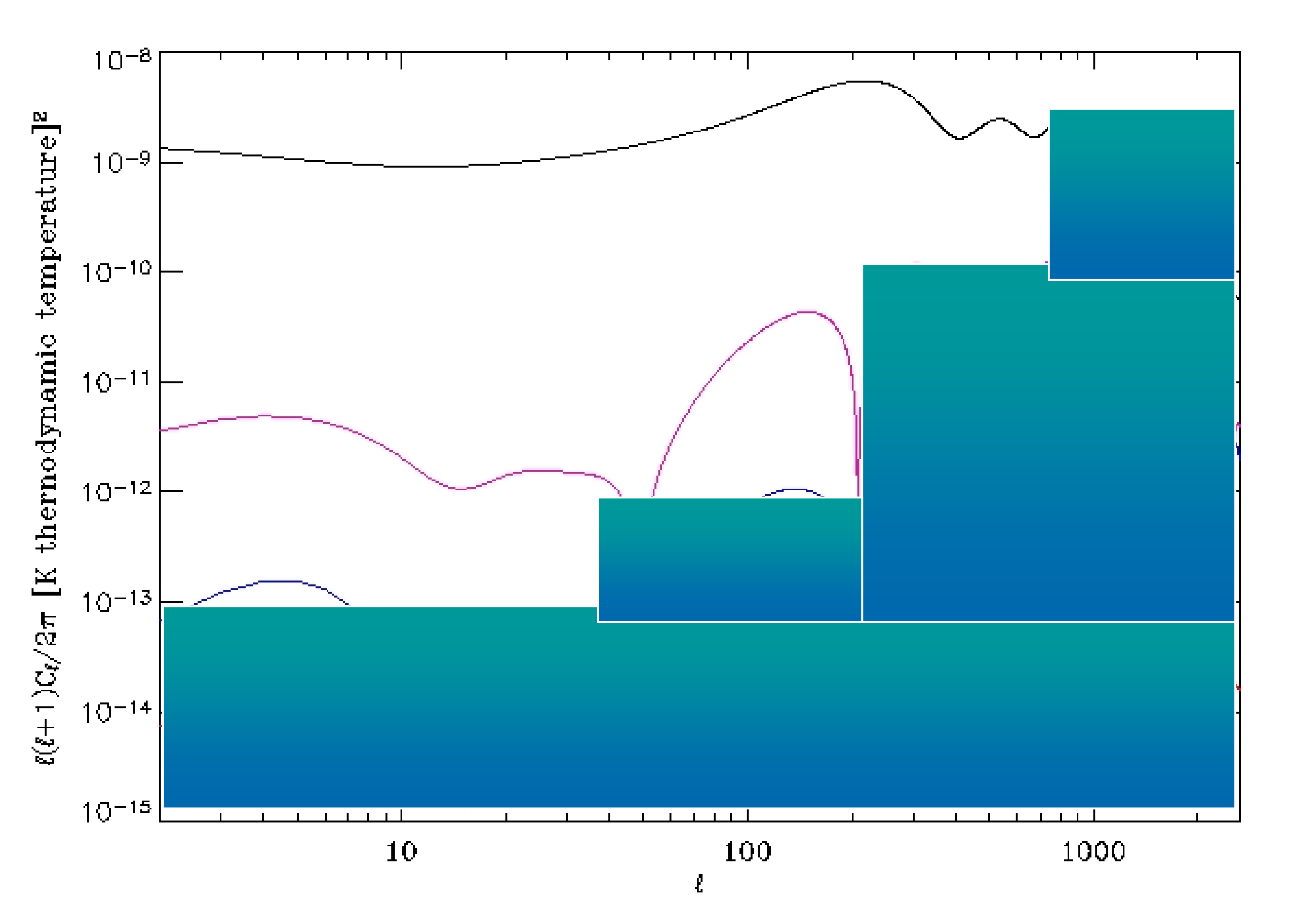
Angle ≈ 200/ℓ degrees

WMAP first year



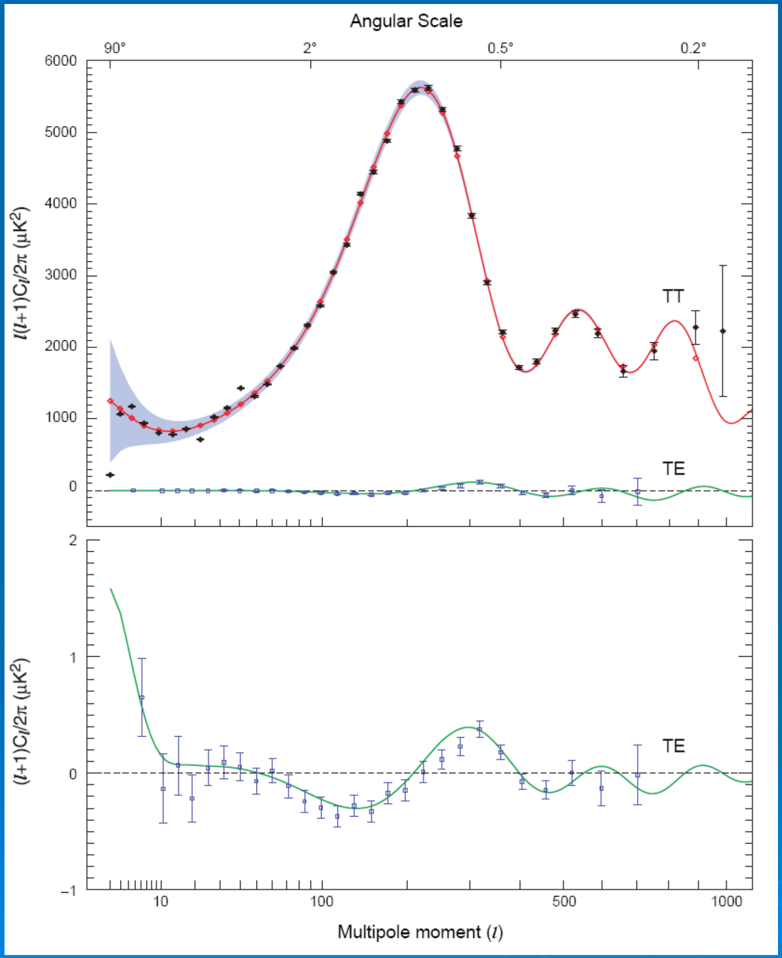
Angle ≈ 200/ℓ degrees

WMAP third year

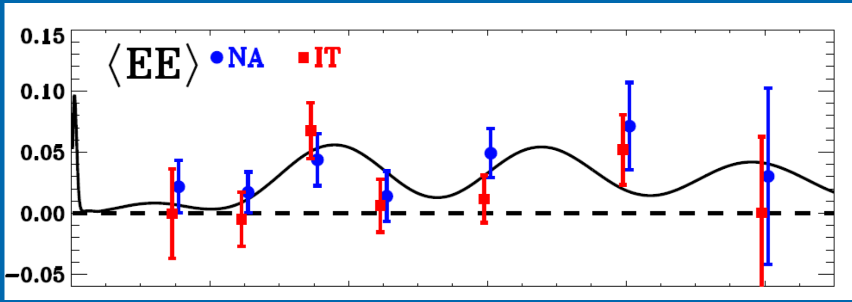


Angle ≈ 200/ℓ degrees

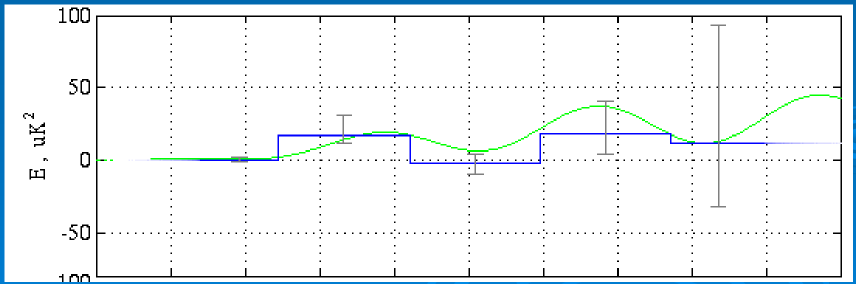
CMB angular power spectrum



WMAP



boomerang



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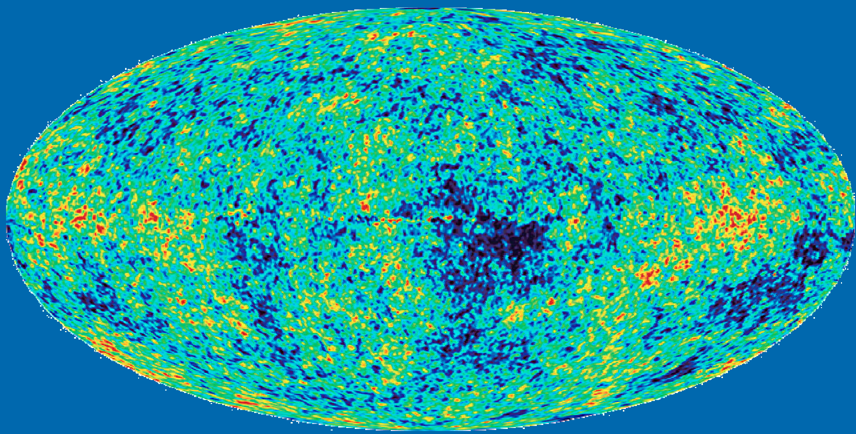
CMB anisotropy statistics: unknown, probably still hidden by systematics

- Evidence for North south asymmetry (Hansen et al. 2005)
- Evidence for Bianchi models (Jaffe et al. 2006)
- Poor constraints on inflation, the error is about 100 times the predicted deviations from Gaussianity (Komatsu et al. 2003)
- Lensing detection out of reach

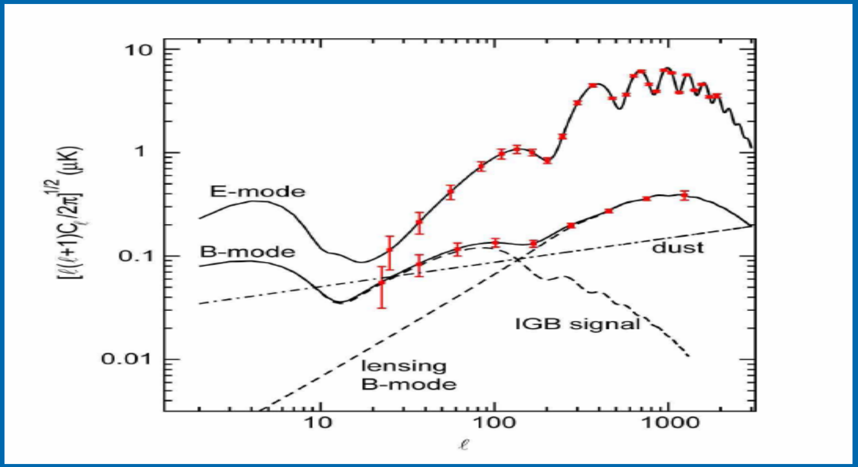


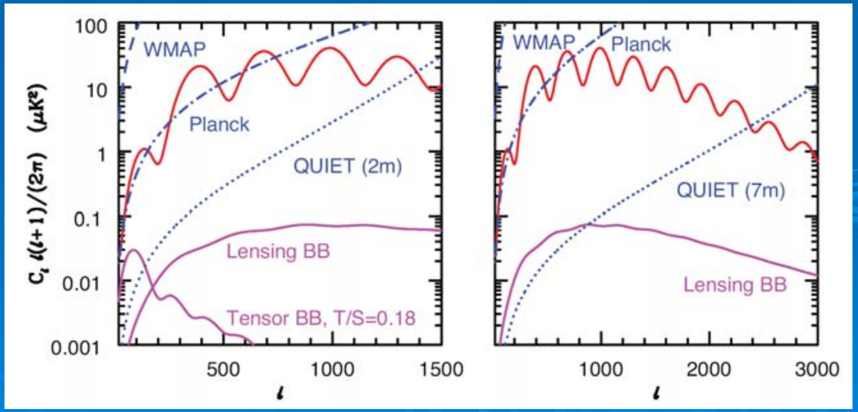
Other cosmological backgrounds?

- 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…

Forthcoming CMB polarization probes

- Planck
- EBEx (US, France, Italy), baloon, same launch time scale as Planck for the north american flight
- QUIET (US, UK), ground based
- Clover (UK, …)
- Brain
- …
- Complete list available at the Lambda archive lambda.gsfc.nasa.gov

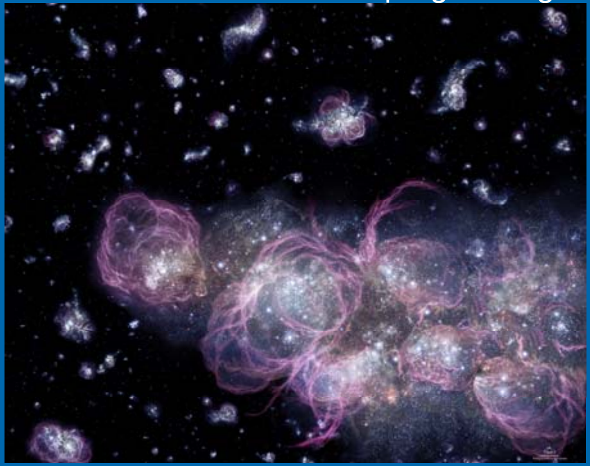


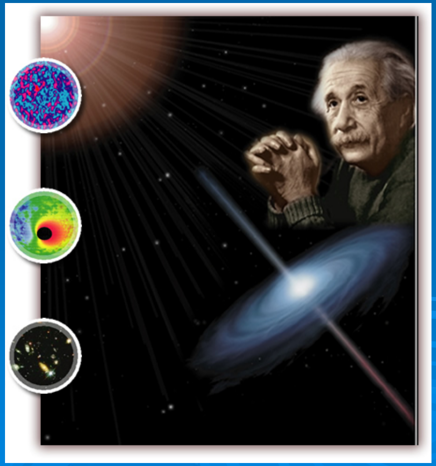


Cosmic vision beyond Einstein

- NASA and ESA put out separate calls of opportunity for a polarization oriented future (2020 at least) CMB satellite
- Technologies, design, options for joint or separate missions are being discussed in these months

Cosmic vision program logo





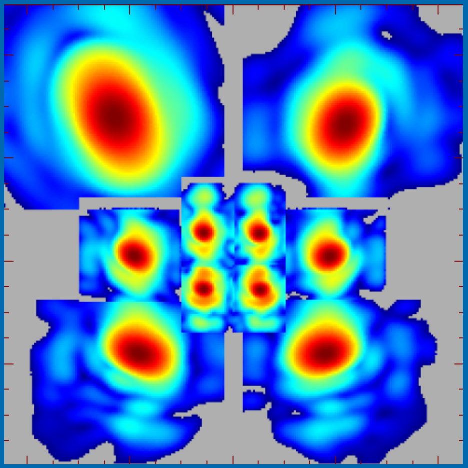
Beyond einstein logo

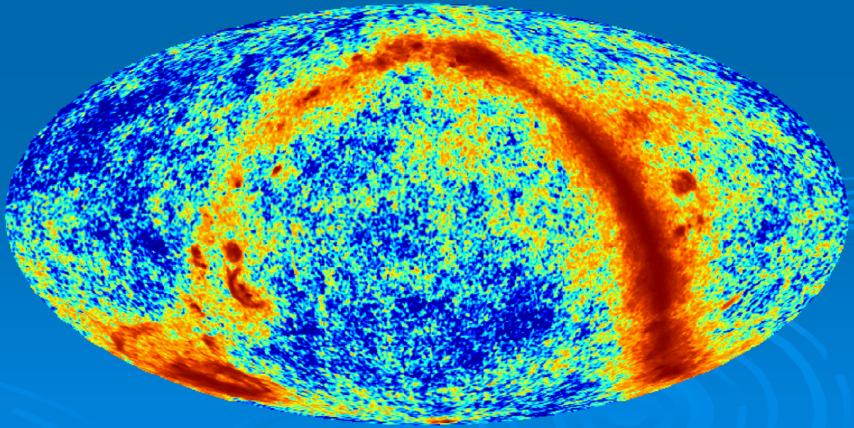
Challenges for future CMB

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 ☹

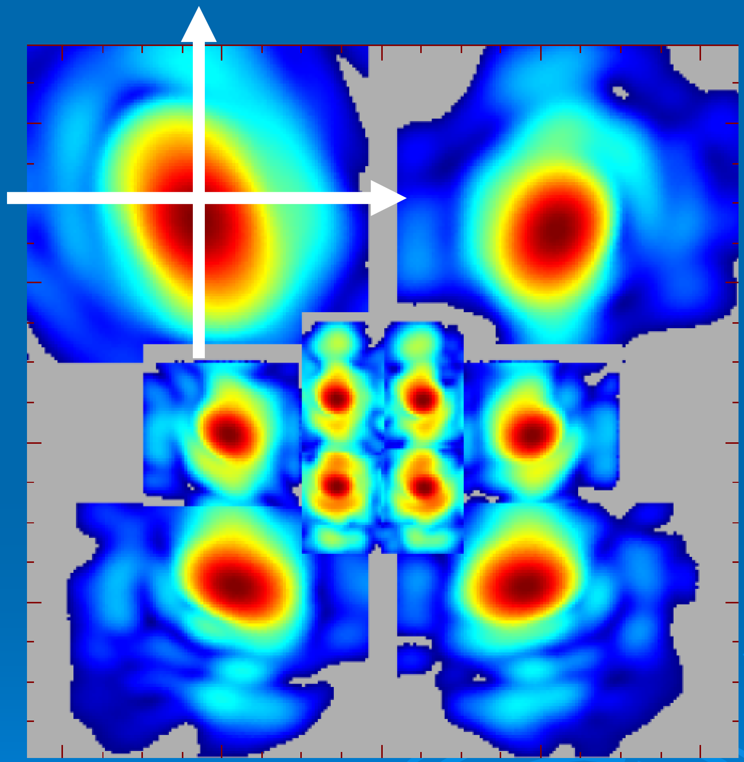
Jarosik et al. 2006





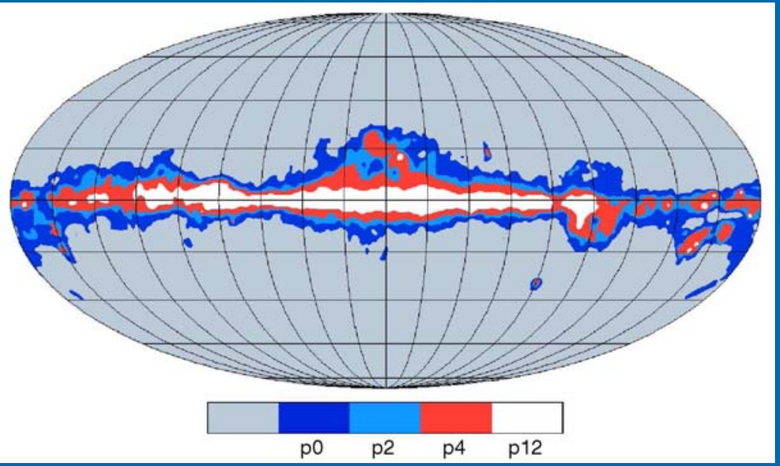
Challenges for future CMB: systematics from beam shape

- 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

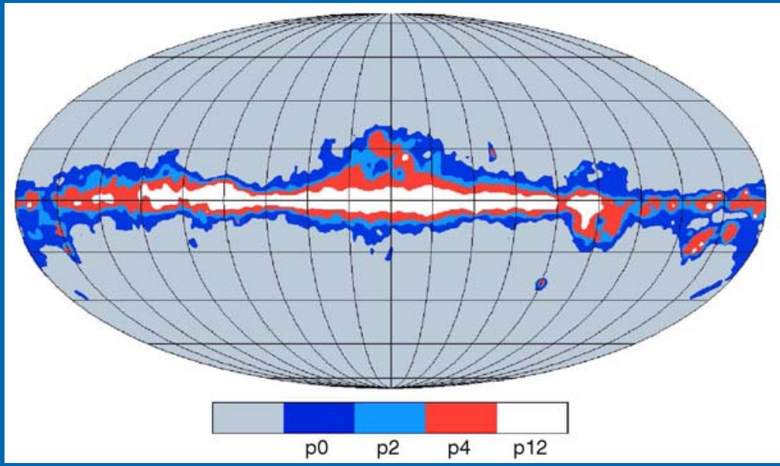
Bennett et al. 2006



- 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
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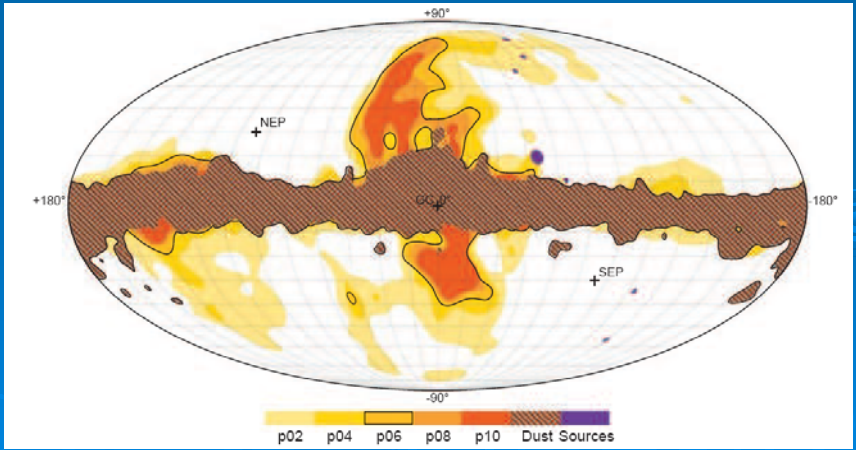
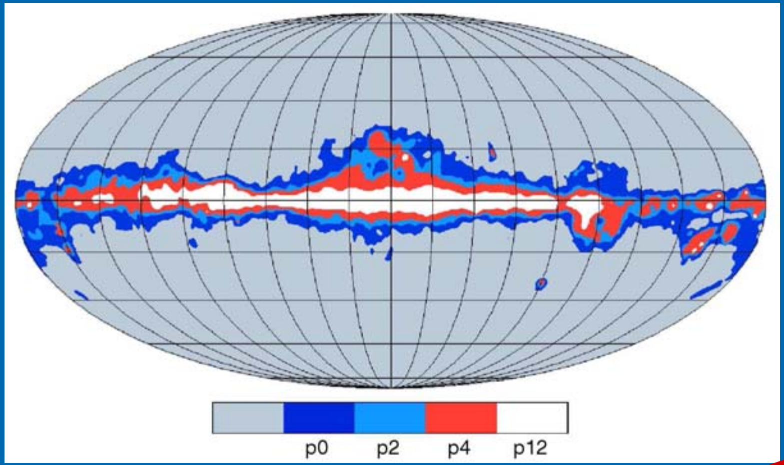


Page et al. 2006

Challenges for future CMB: foreground emission

Bennett et al. 2006



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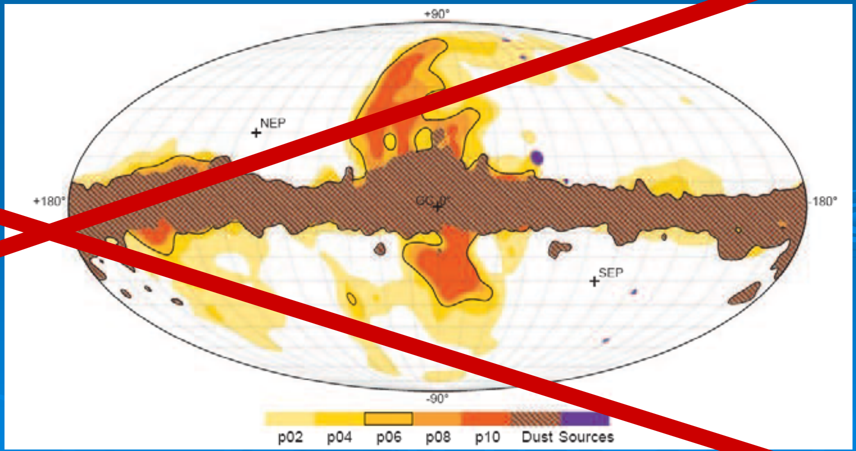
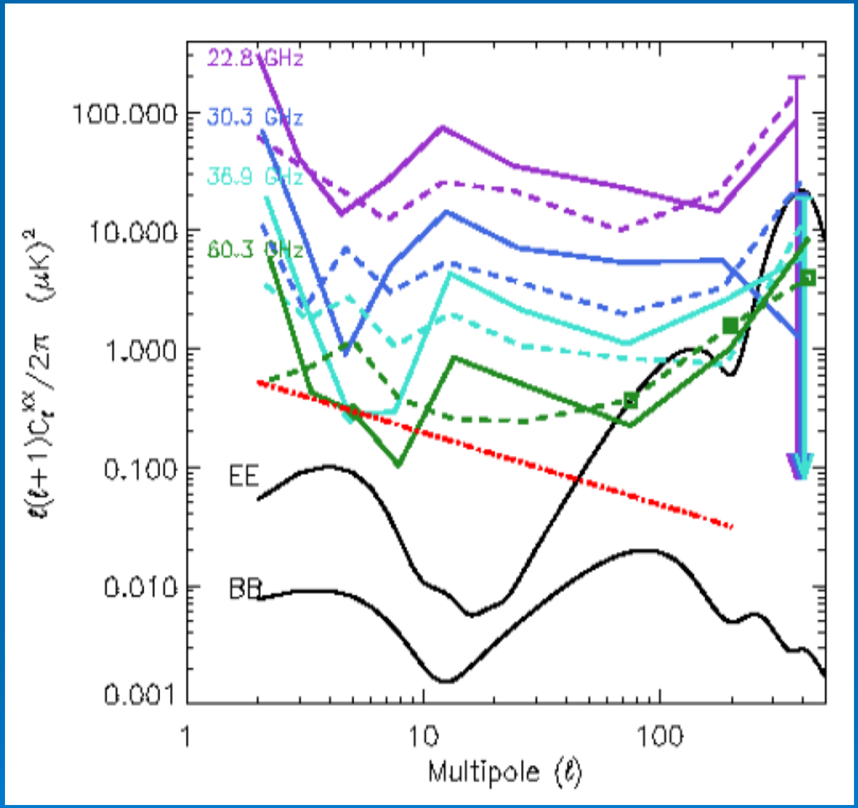
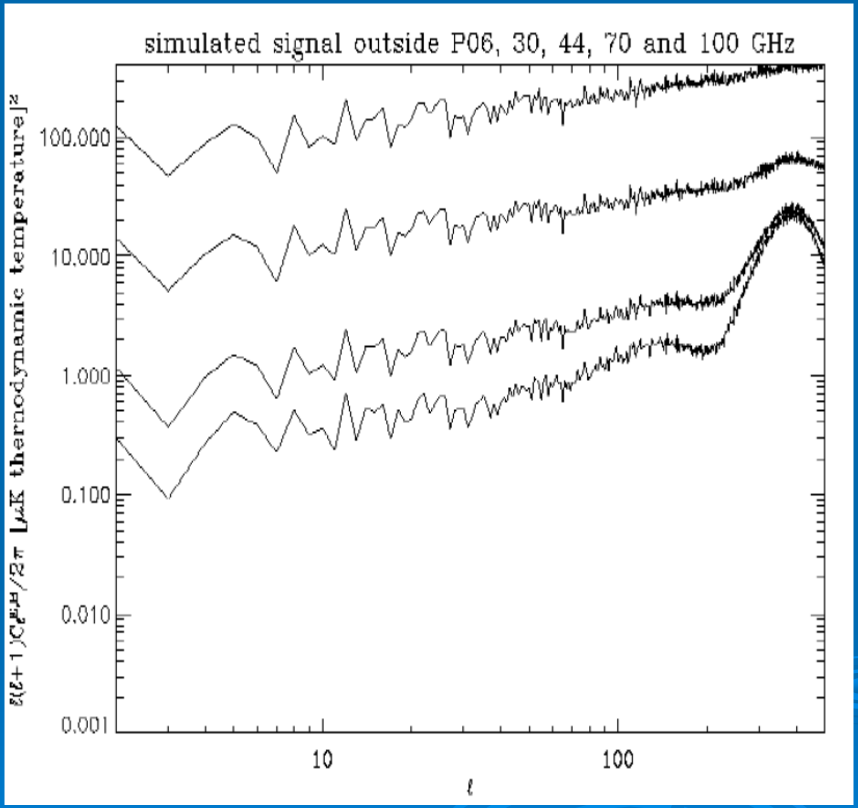


Page et al. 2006

Challenges for future CMB: foreground emission



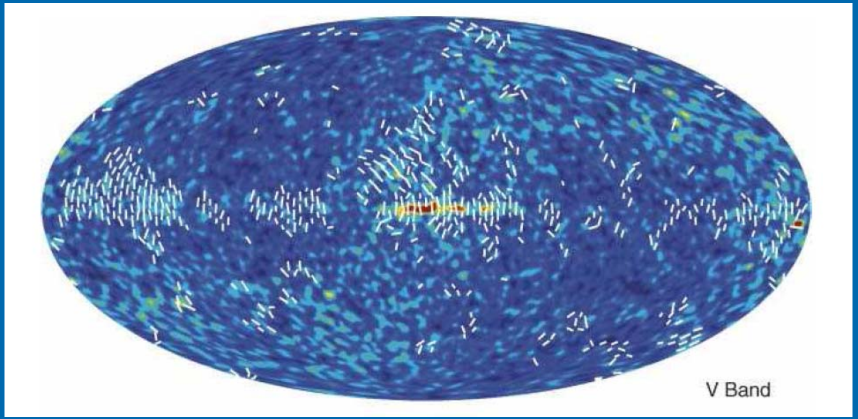
Page et al. 2006



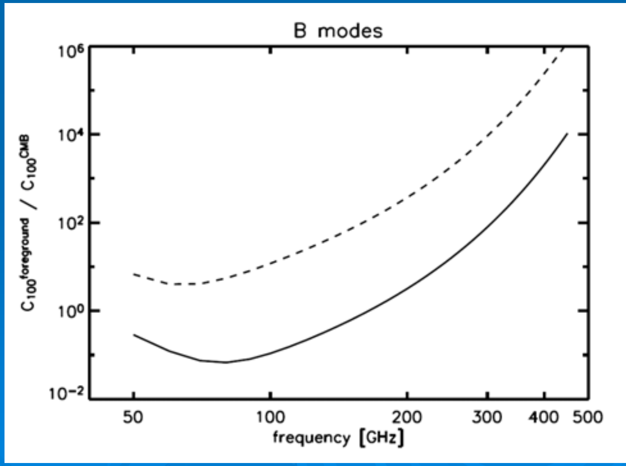
Planck reference sky

Are there foreground clean regions at all in polarization?

Page et al. 2006

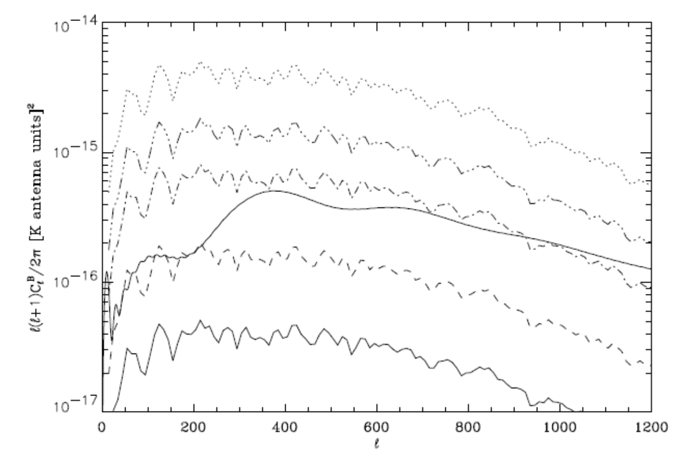


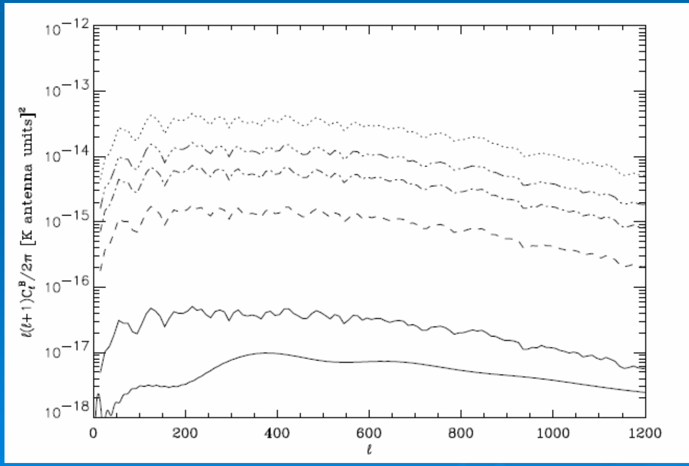
- WMAP has no detection in large sky areas in polarization
- Very naive estimates may be attempted in those areas, indicating that the foreground level might be comparable to the cosmological B mode at all frequencies, in all sky regions

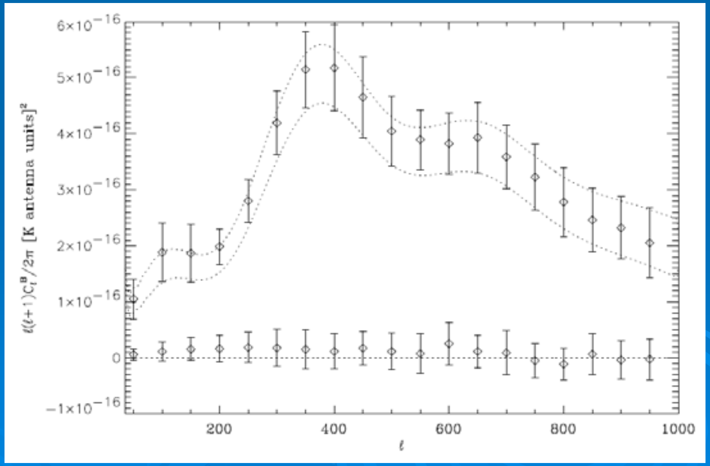


Shall we ever get rid of foregrounds?

- 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







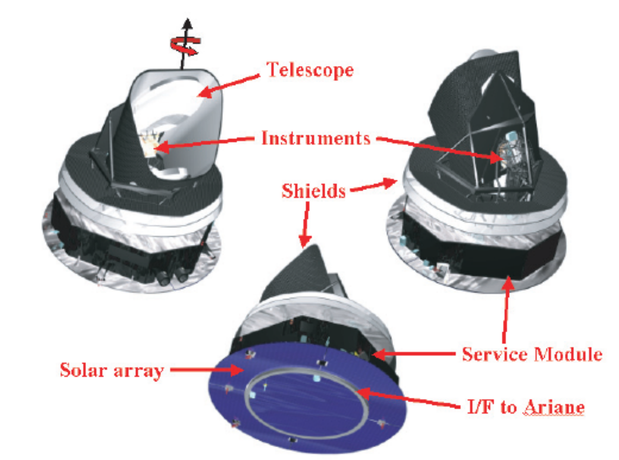
Stivoli et al. 2006

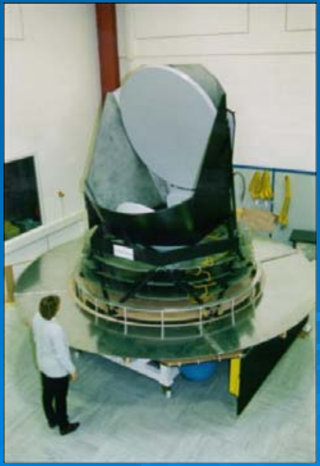
The science goals of the Planck satellite

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

Planck

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





Planck contributors

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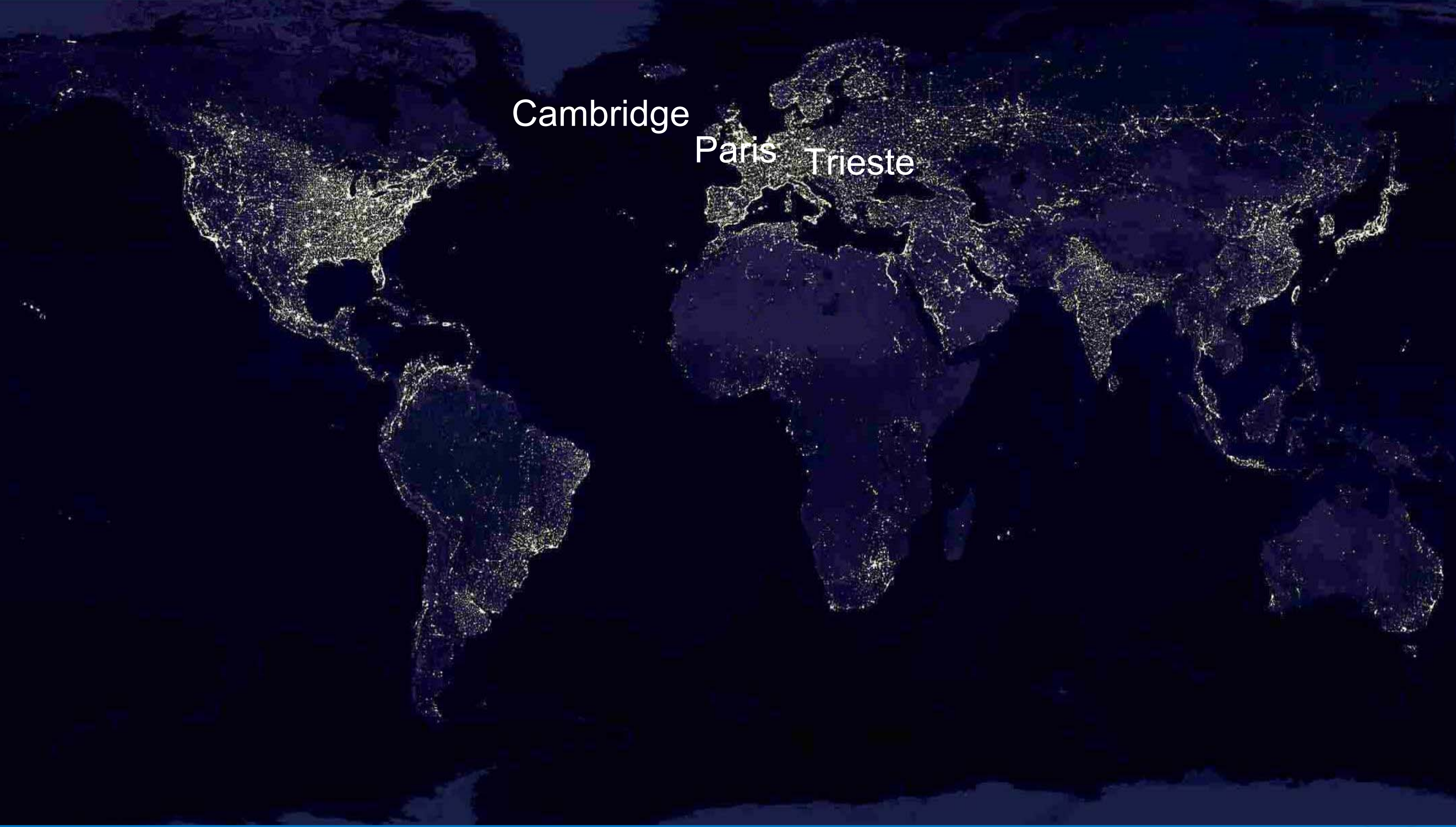
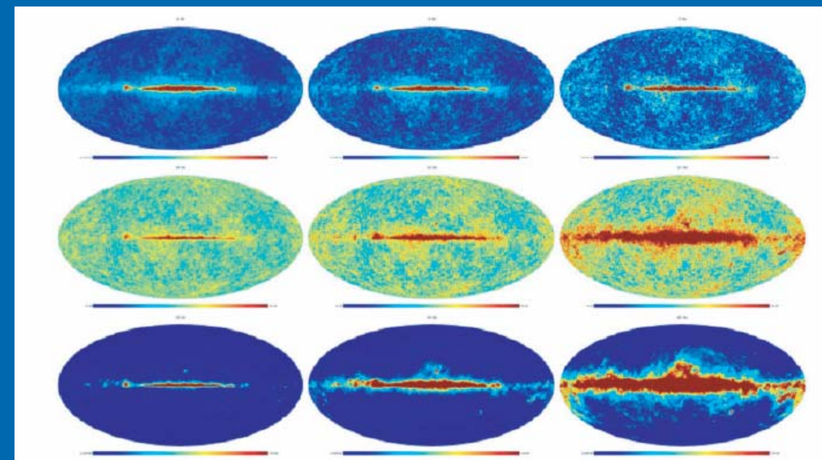


Planck data processing sites

Planck data deliverables

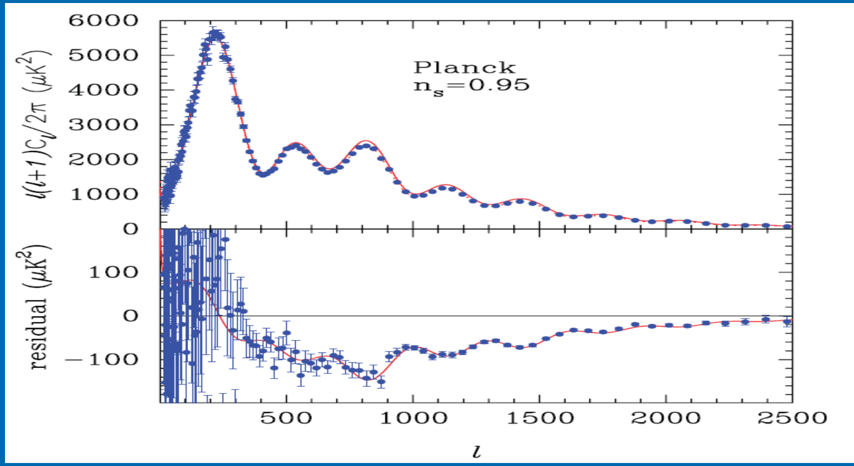
- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33' to 7' between 30 and 143 GHz, 5' at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

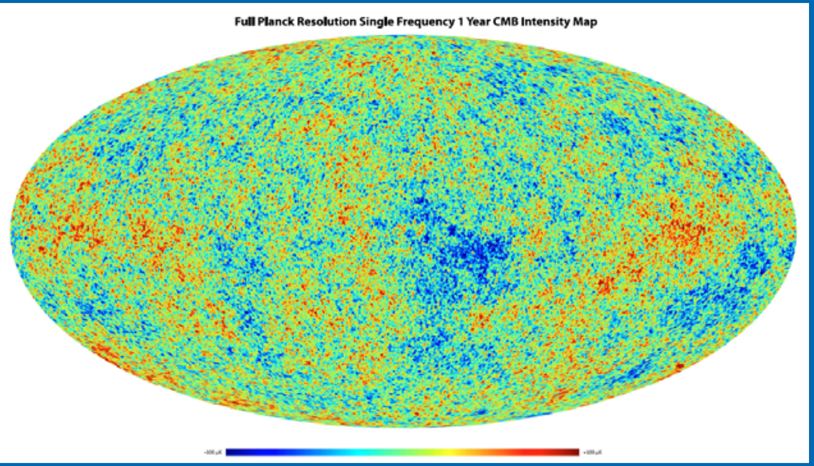


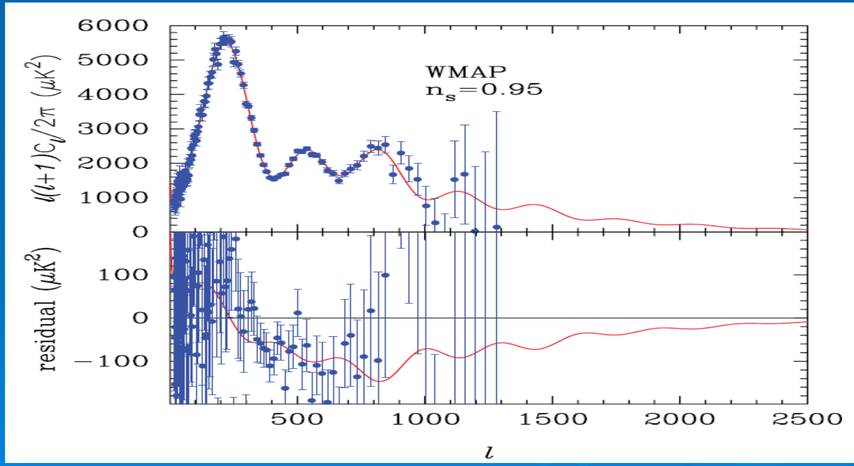
PLANCK GALAXY SURVEYS

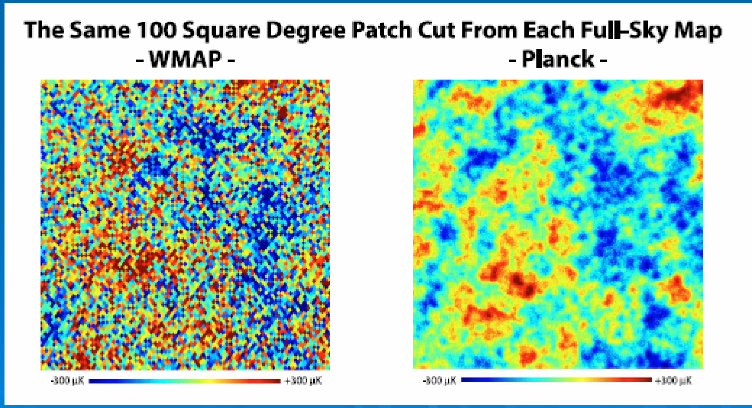
	FREQUENCY [GHz]				
	143	217	353	550	850
Confusion limit [mJy, 3σ]	6.3	14.1	44.7	112	251
Planck All Sky Survey sensitivity [mJy, 3σ]	26	37	75	180	300
Planck Deep Survey sensitivity [mJy, 3σ]	10	18.4	49	170	280
Number of galaxies [all sky]	570	860	1700	4400	35000

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

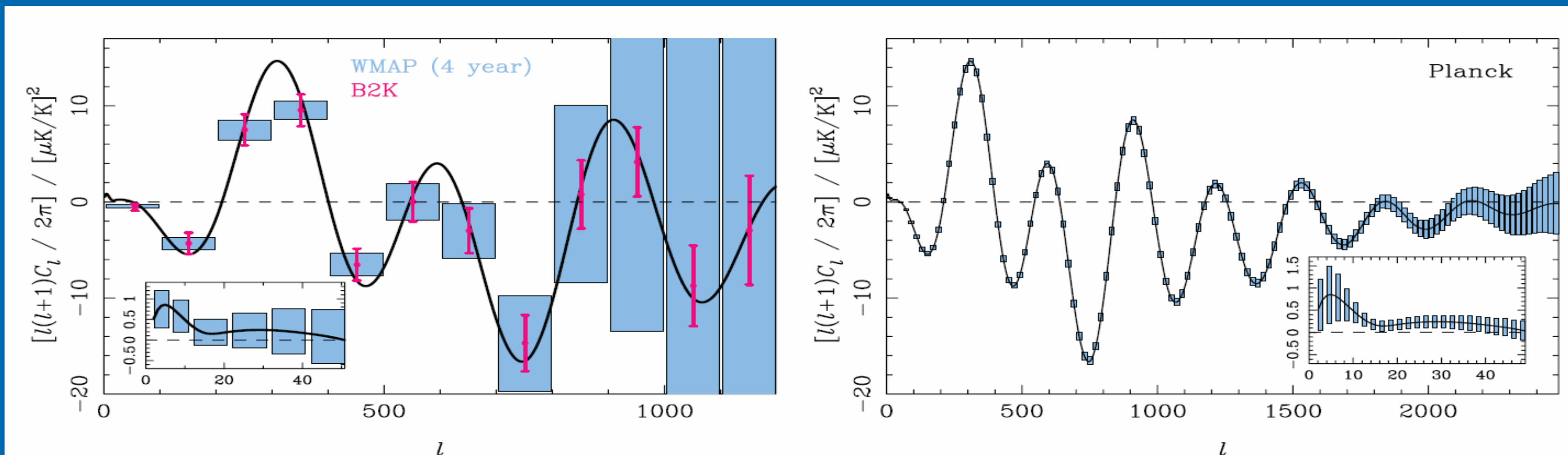


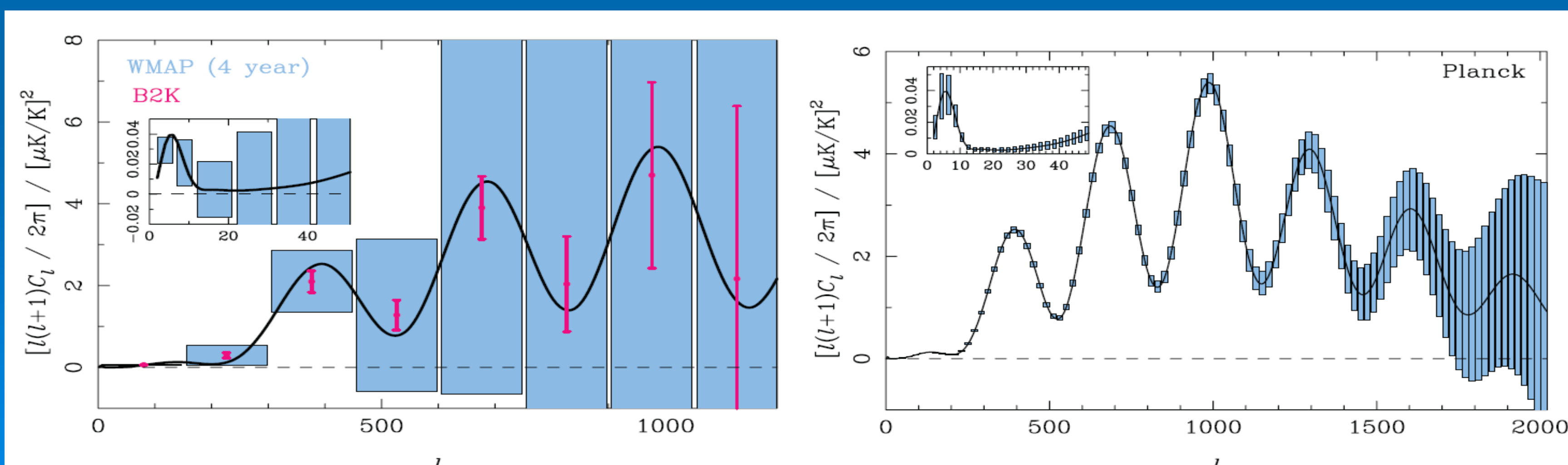




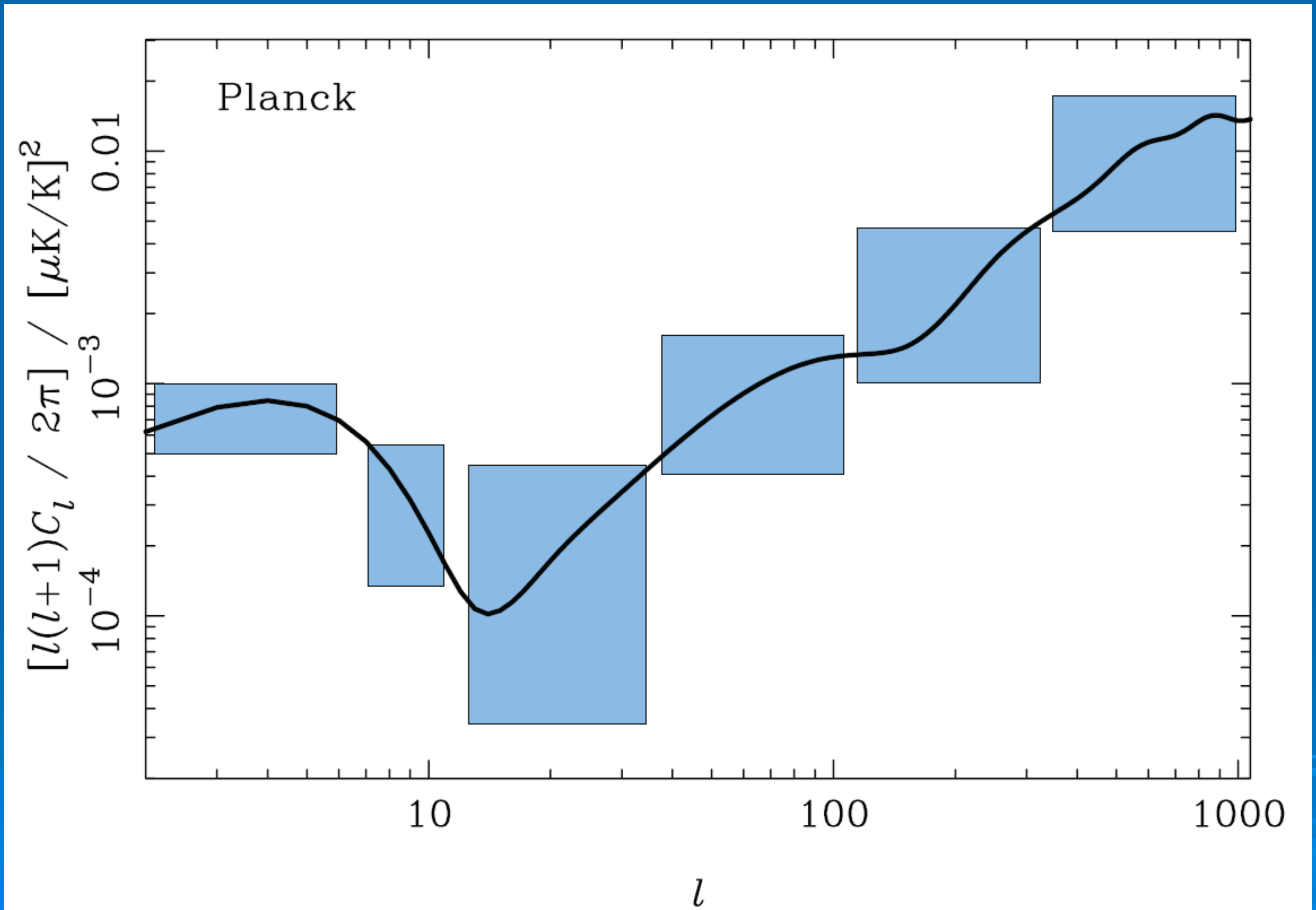


Planck scientific deliverables: CMB polarization

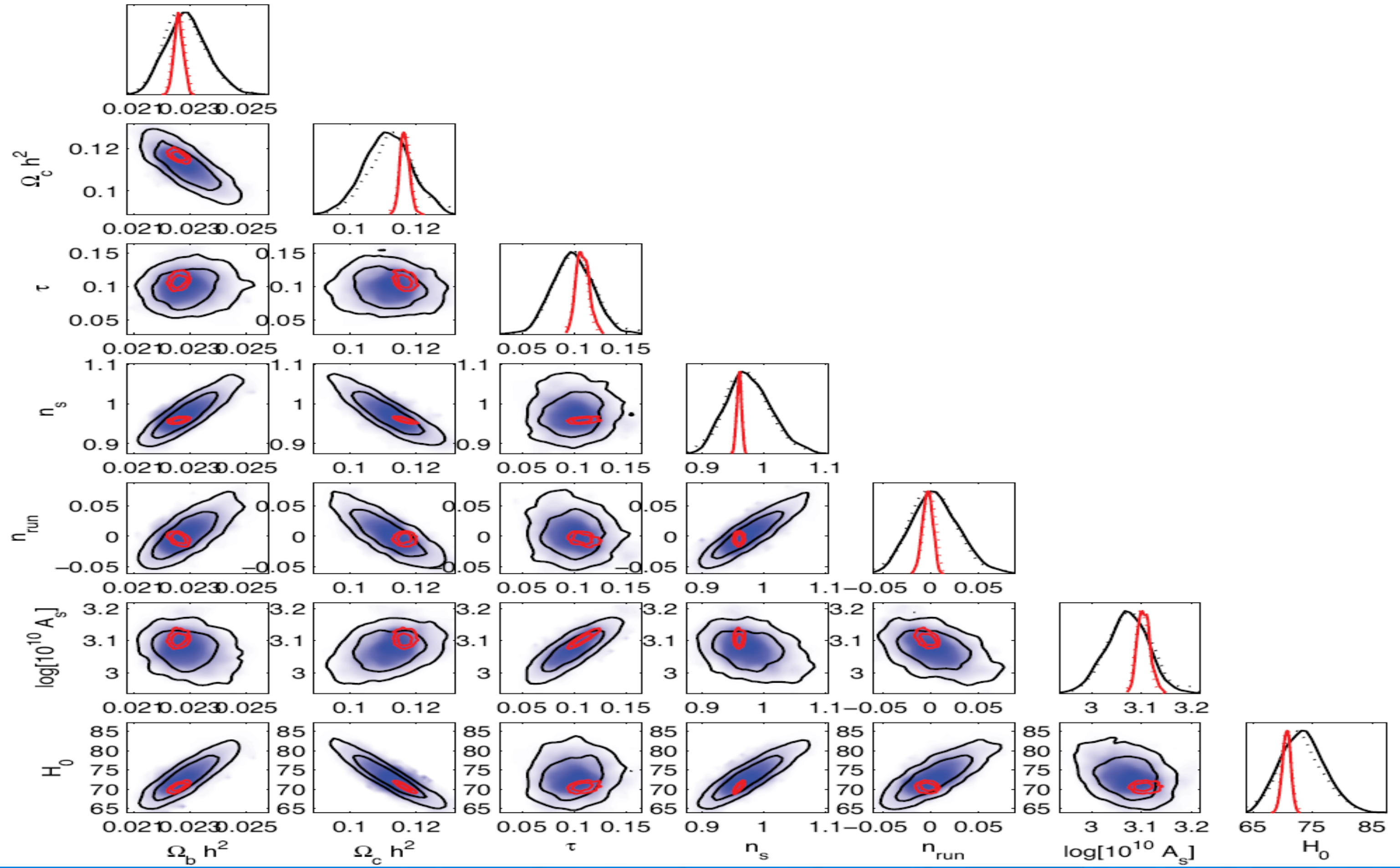




Planck and polarization CMB B modes



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
- …

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