

Expectations and challenges from future CMB science

Carlo Baccigalupi, SISSA



Outline

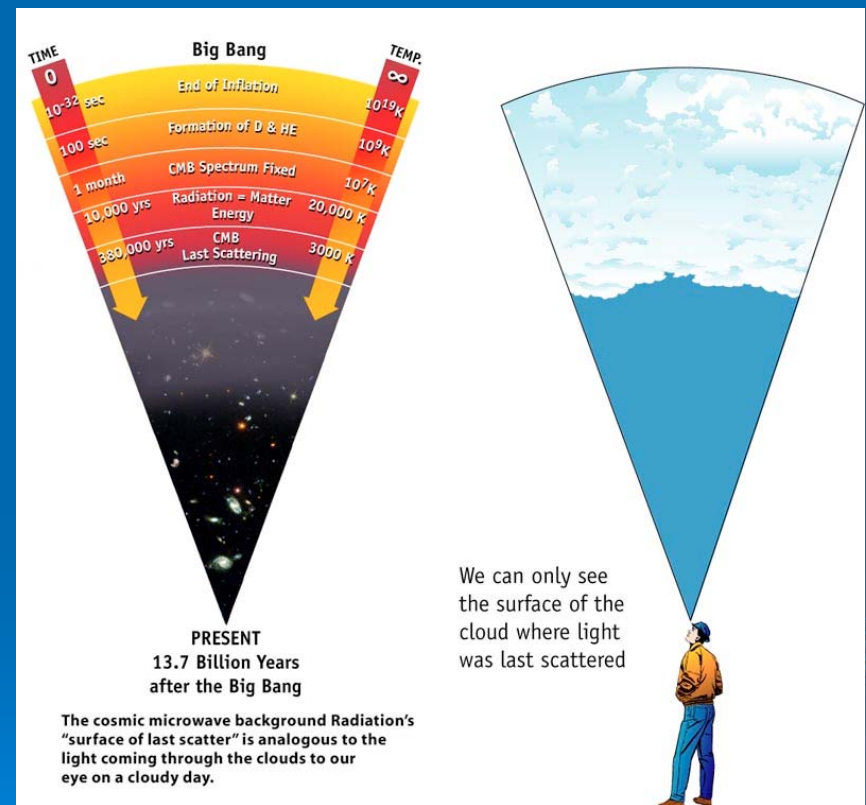
- CMB physics
- Status of CMB observations
- Challenges for future CMB
- The science goals of the Planck satellite
- Conclusions, ☹/☺

CMB physics



CMB: where and when and how

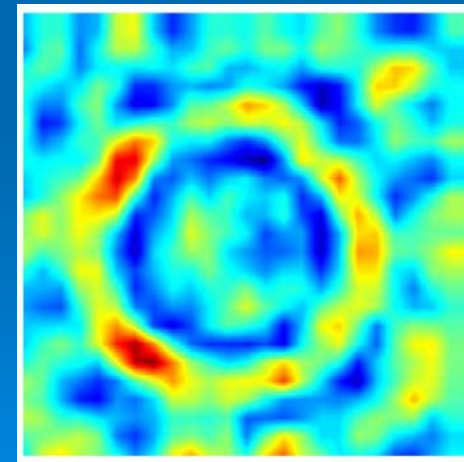
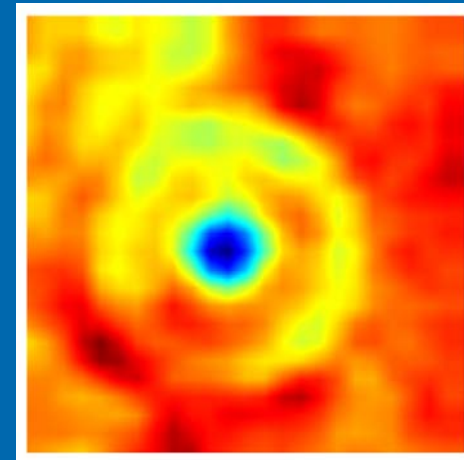
- Opacity: $\lambda = (n_e \sigma_T)^{-1} \ll H^{-1}$
- Decoupling: $\lambda \approx H^{-1}$
- Free streaming: $\lambda \gg H^{-1}$
- Cosmological expansion, constants and baryon abundance conspire to activate decoupling about 300000 years after the Big Bang, at about 3000 K photon temperature
- Expansion 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

B99

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CMB physics: Boltzmann equation

d photons

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

d baryons+leptons

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CMB physics: Boltzmann equation

d neutrinos

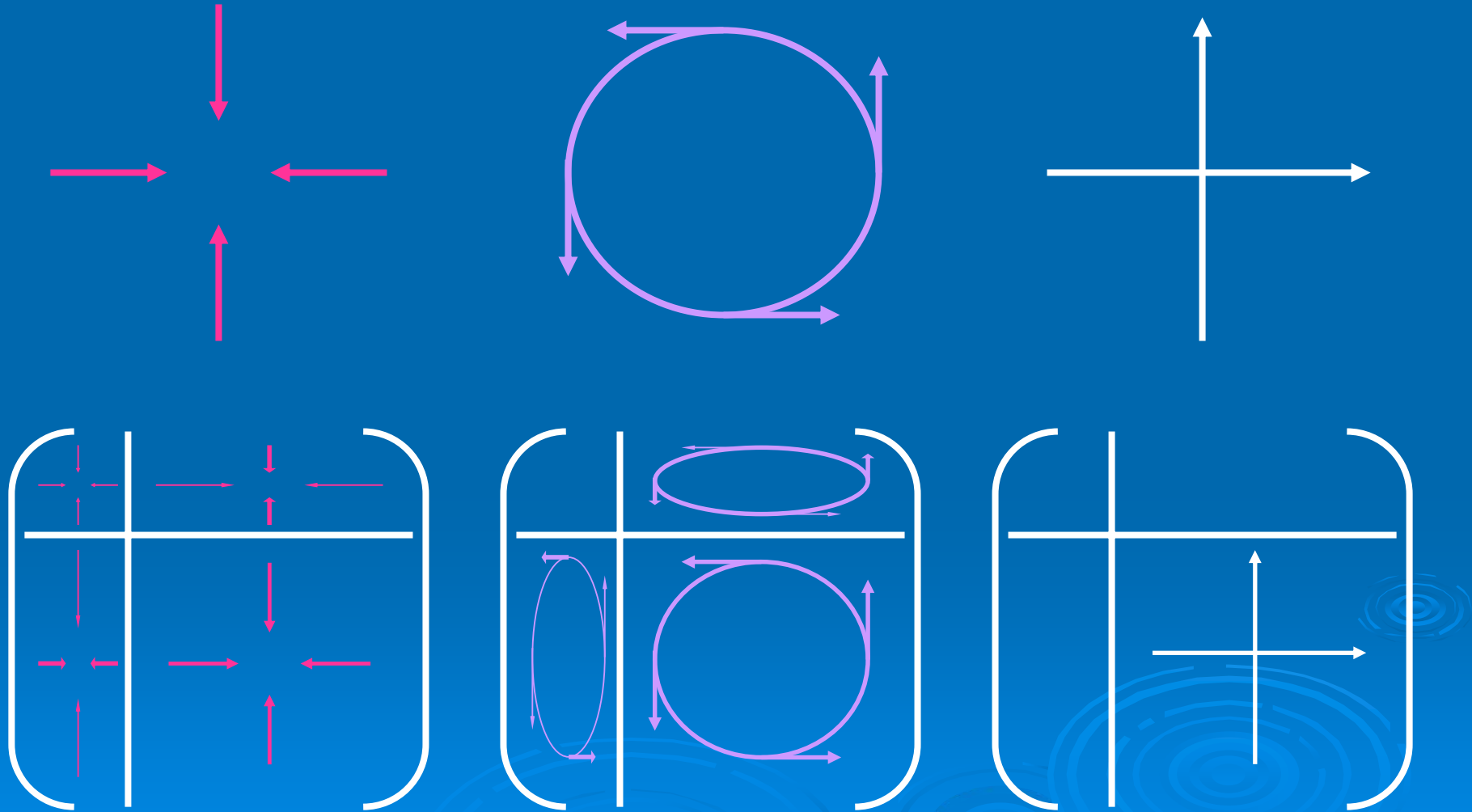
$$\frac{d \text{ neutrinos}}{dt} = \text{metric} + \text{weak interaction}$$

d dark matter

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

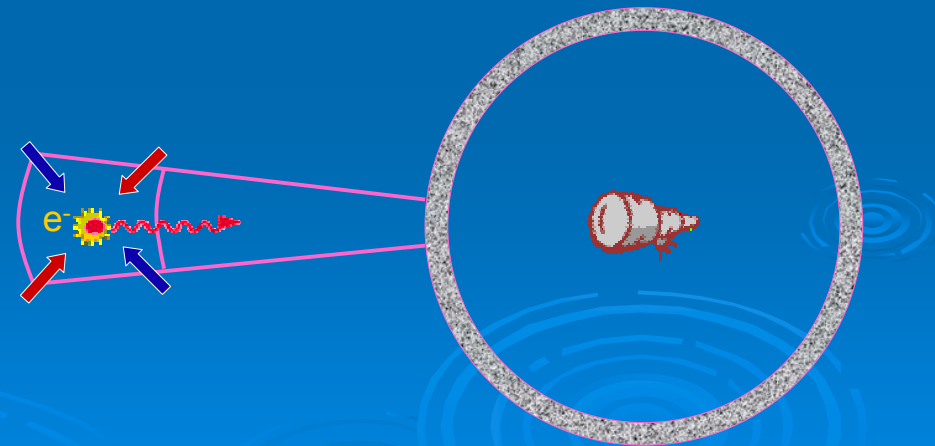
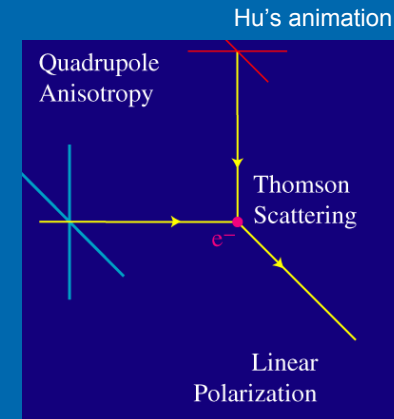
metric = photons + neutrinos + baryons + leptons + dark matter

CMB physics: metric

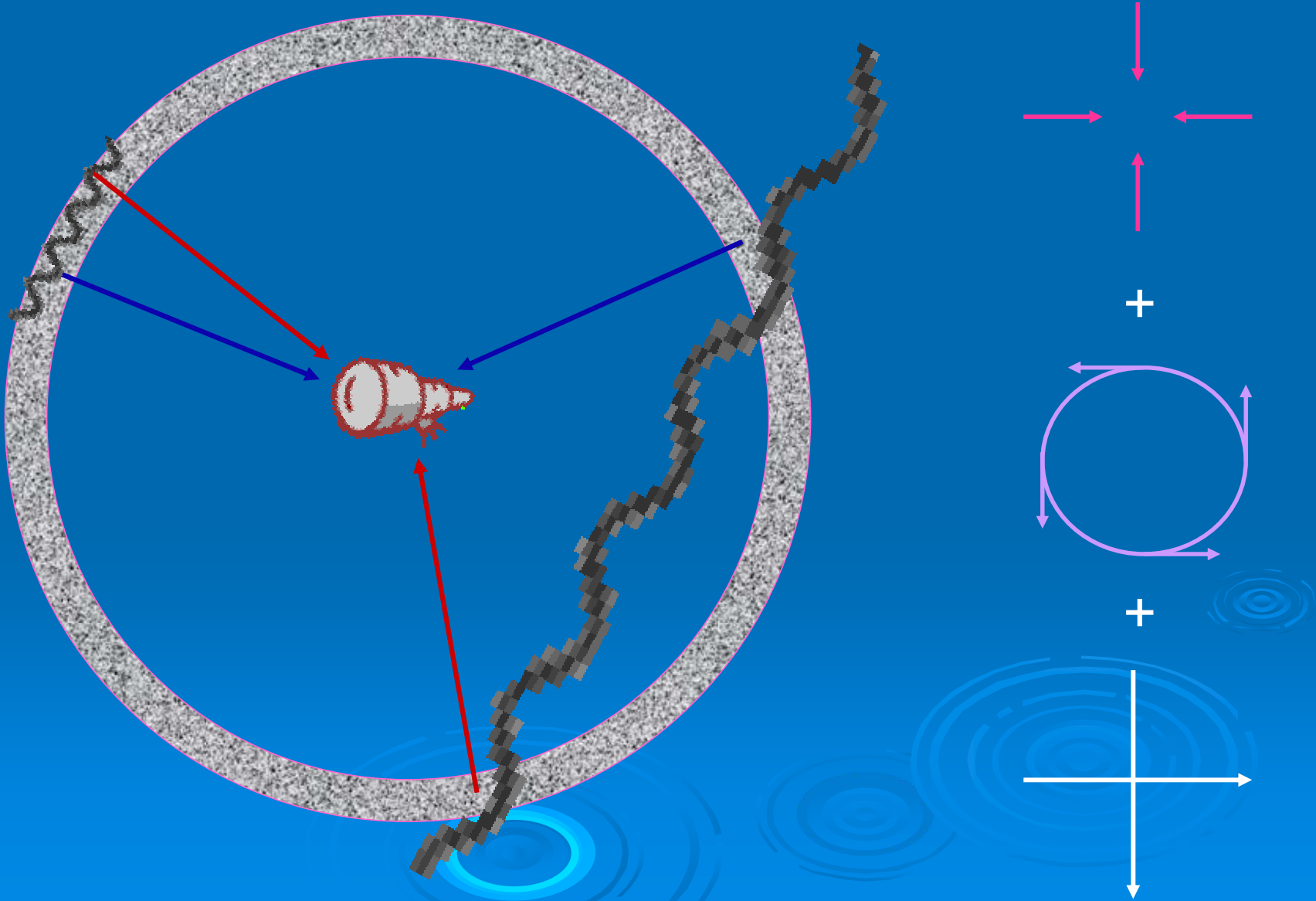


CMB Physics: Compton scattering

- 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

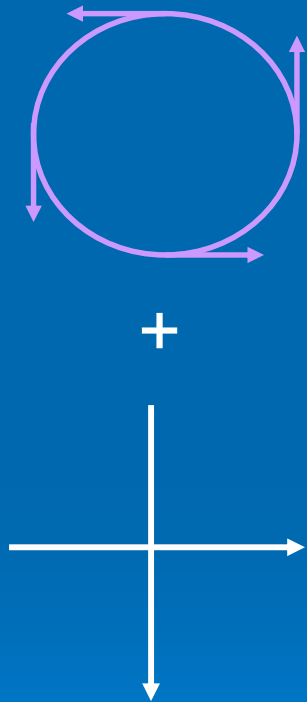


CMB anisotropy: total intensity

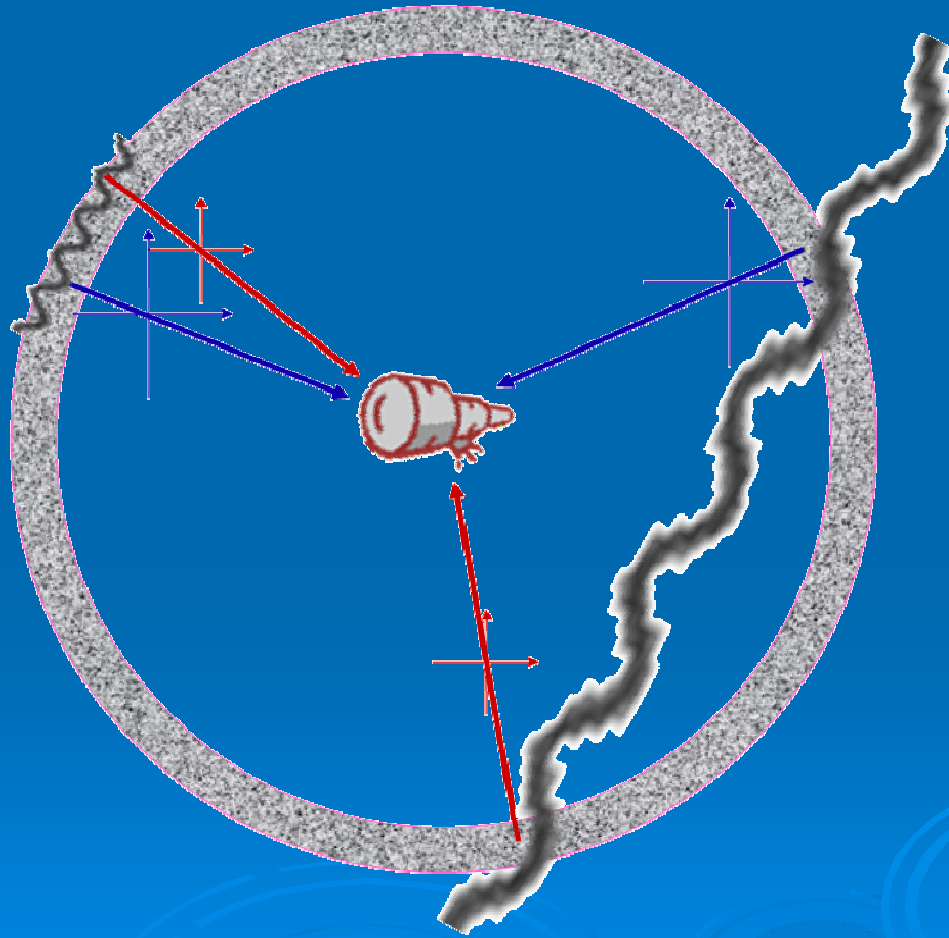
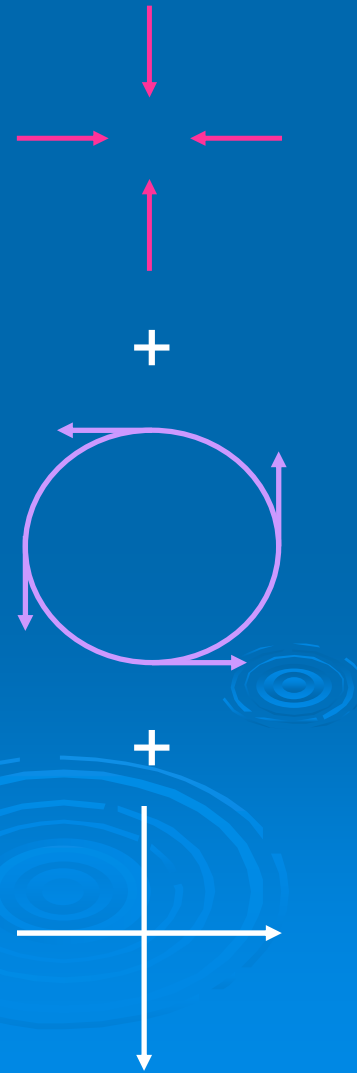


CMB anisotropy: polarization

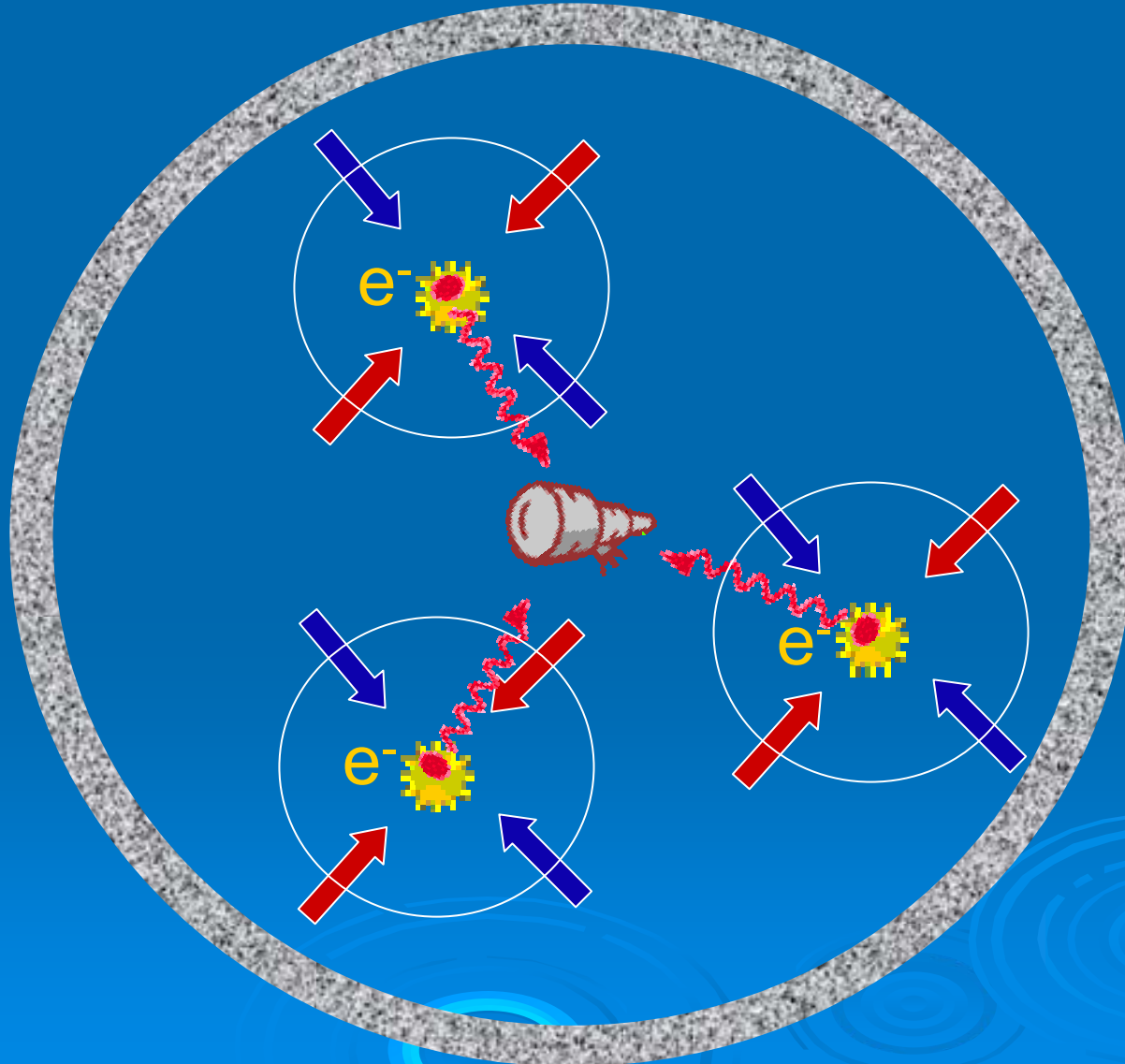
Curl (B):



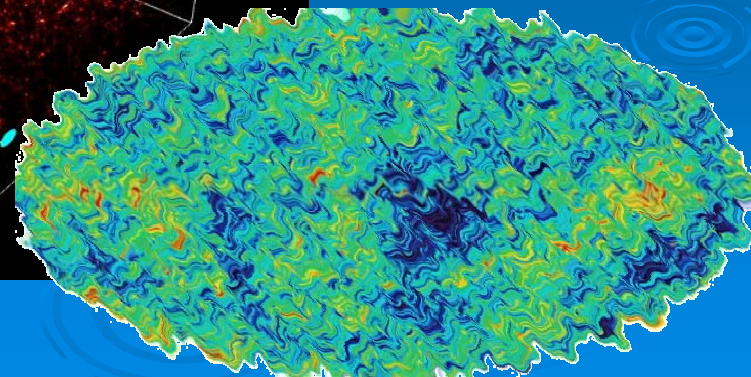
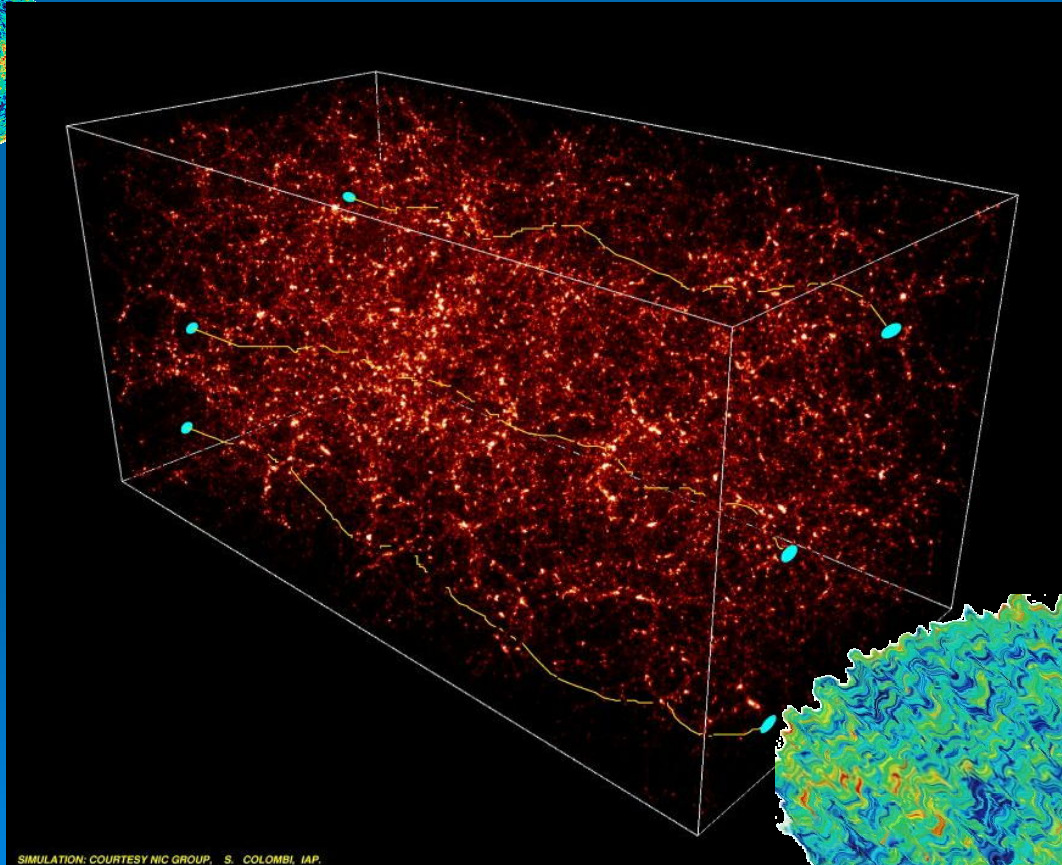
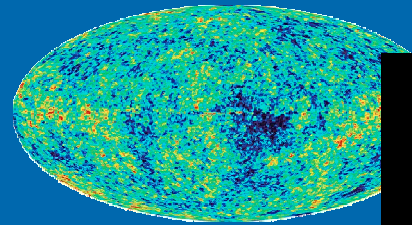
Gradient (E):



CMB anisotropy: reionization



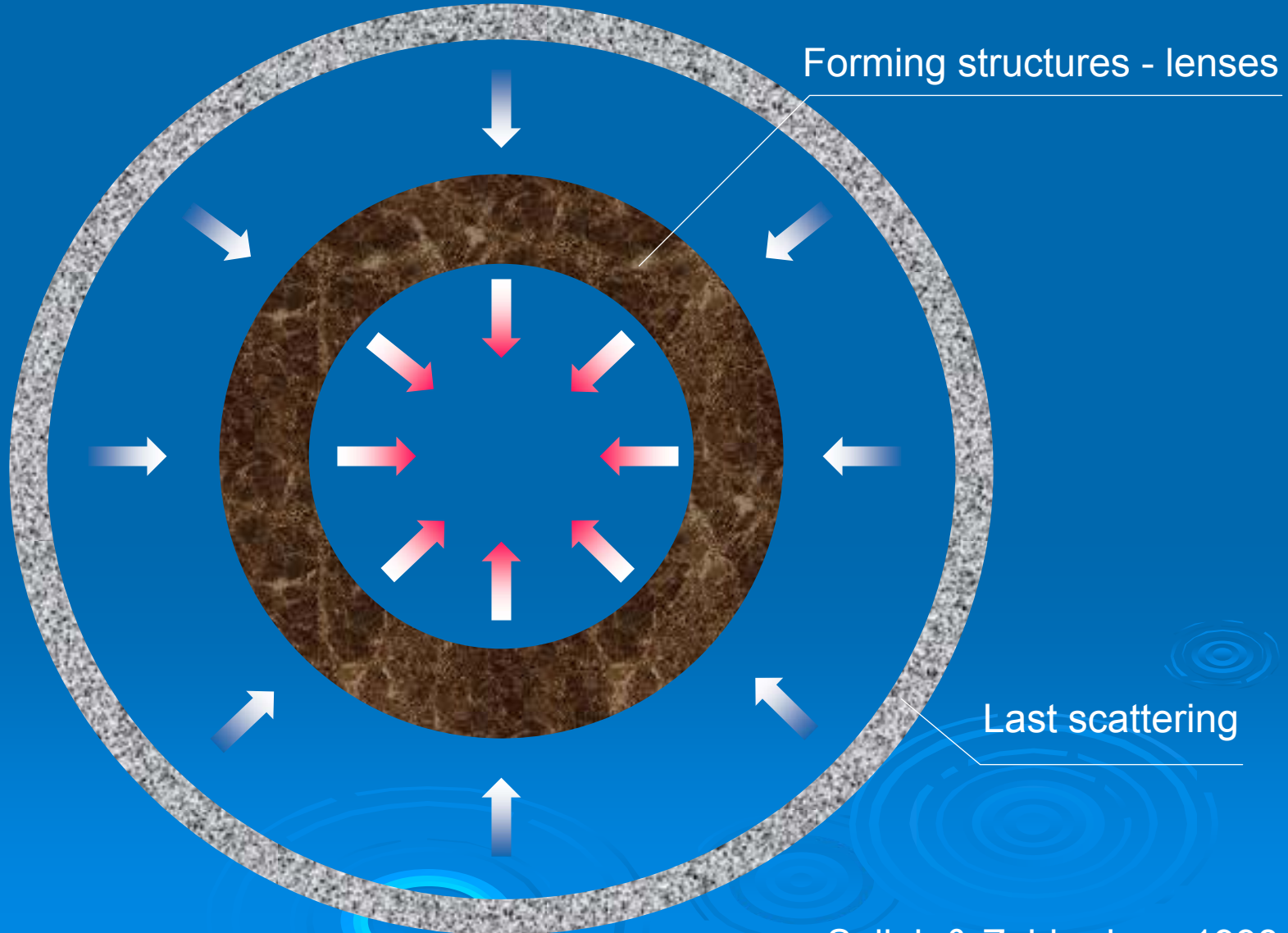
CMB anisotropy: lensing



SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

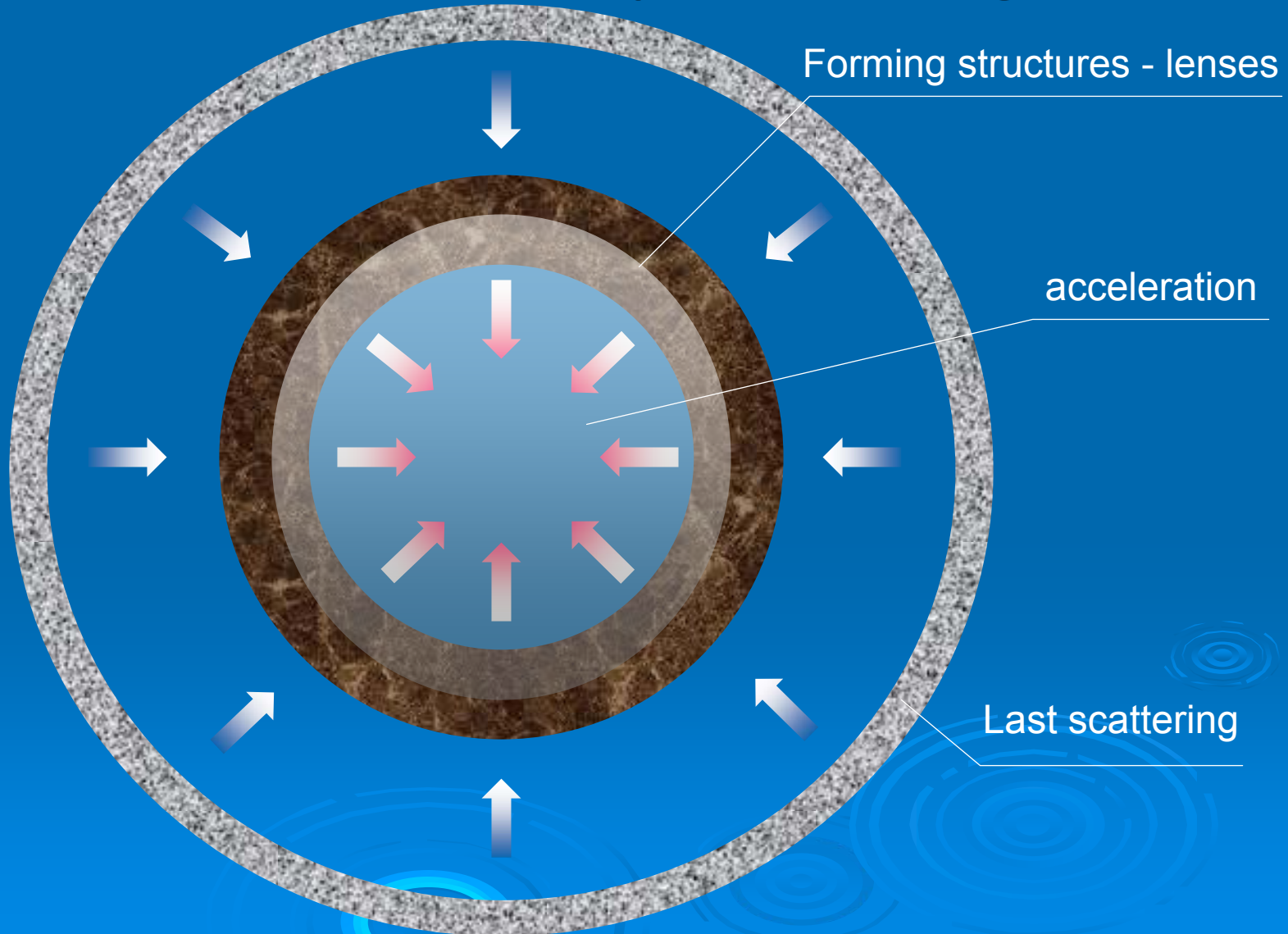
CMB anisotropy: lensing

E
B



CMB anisotropy: lensing

E
B



Status of CMB observations



CMB anisotropies

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

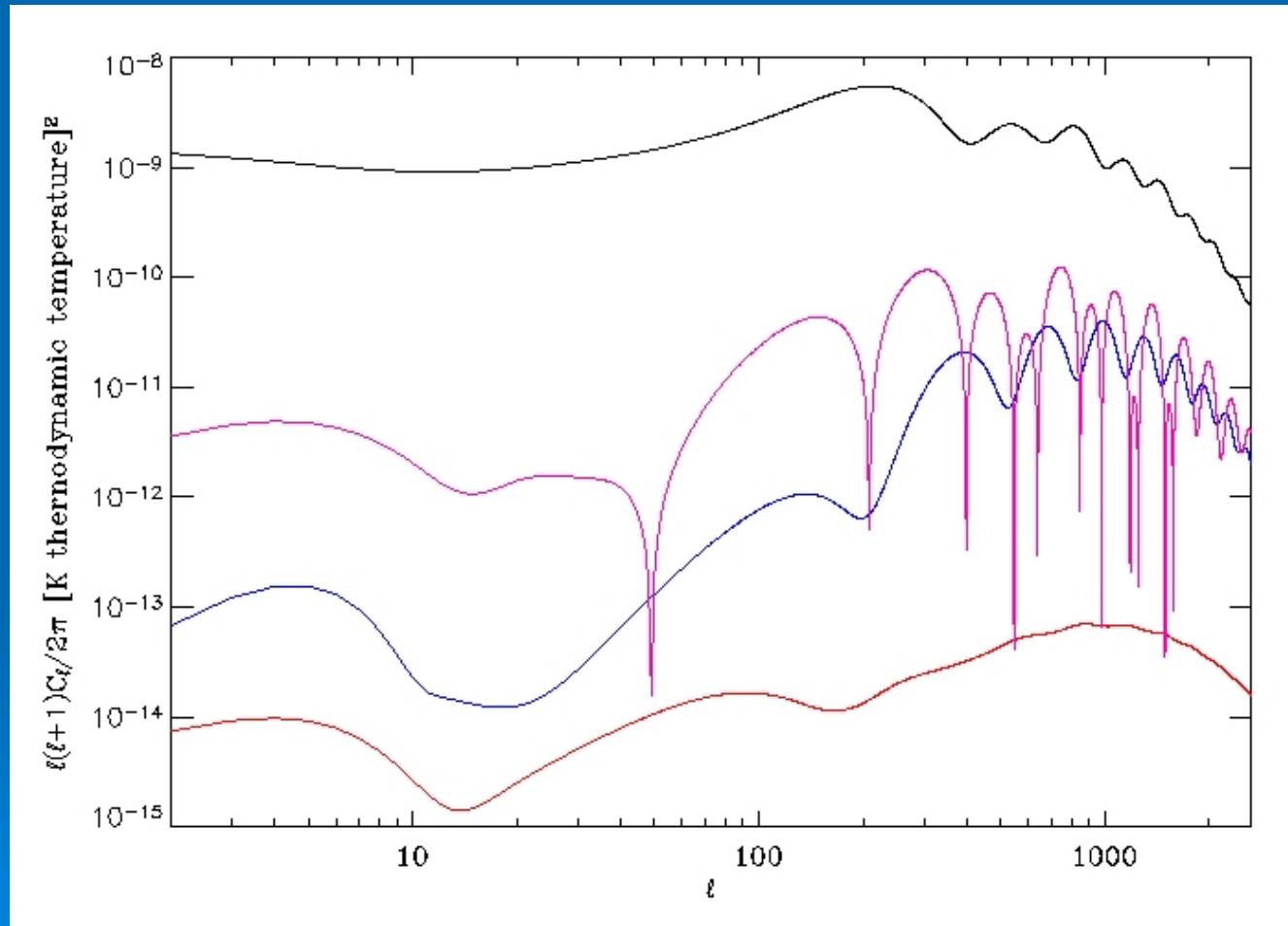
$a_{lm}^T, a_{lm}^E, a_{lm}^B$

spherical harmonics

information compression

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

CMB angular power spectrum



Angle $\approx 200/l$ degrees

CMB angular power spectrum

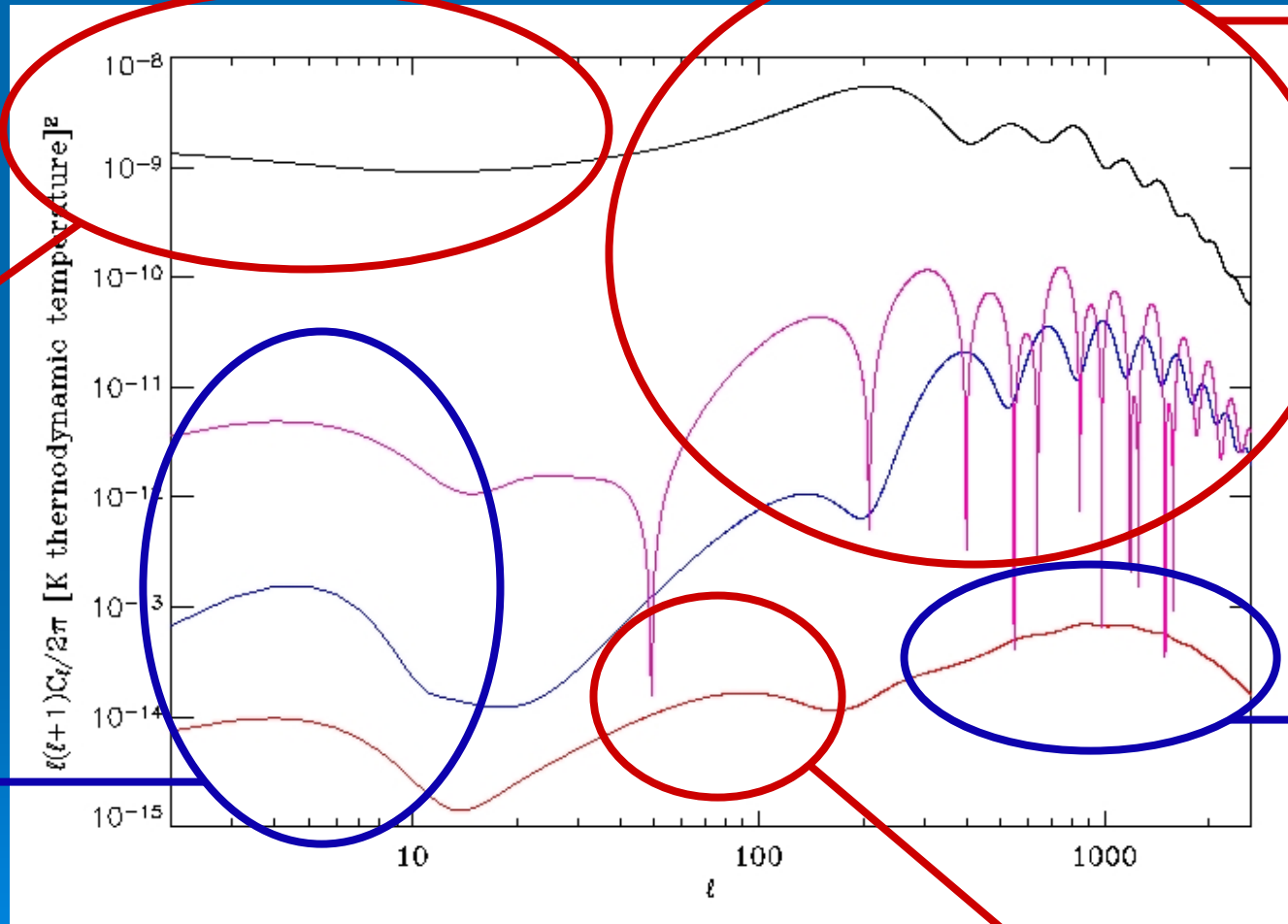
Acoustic oscillations

Primordial power

Reionization

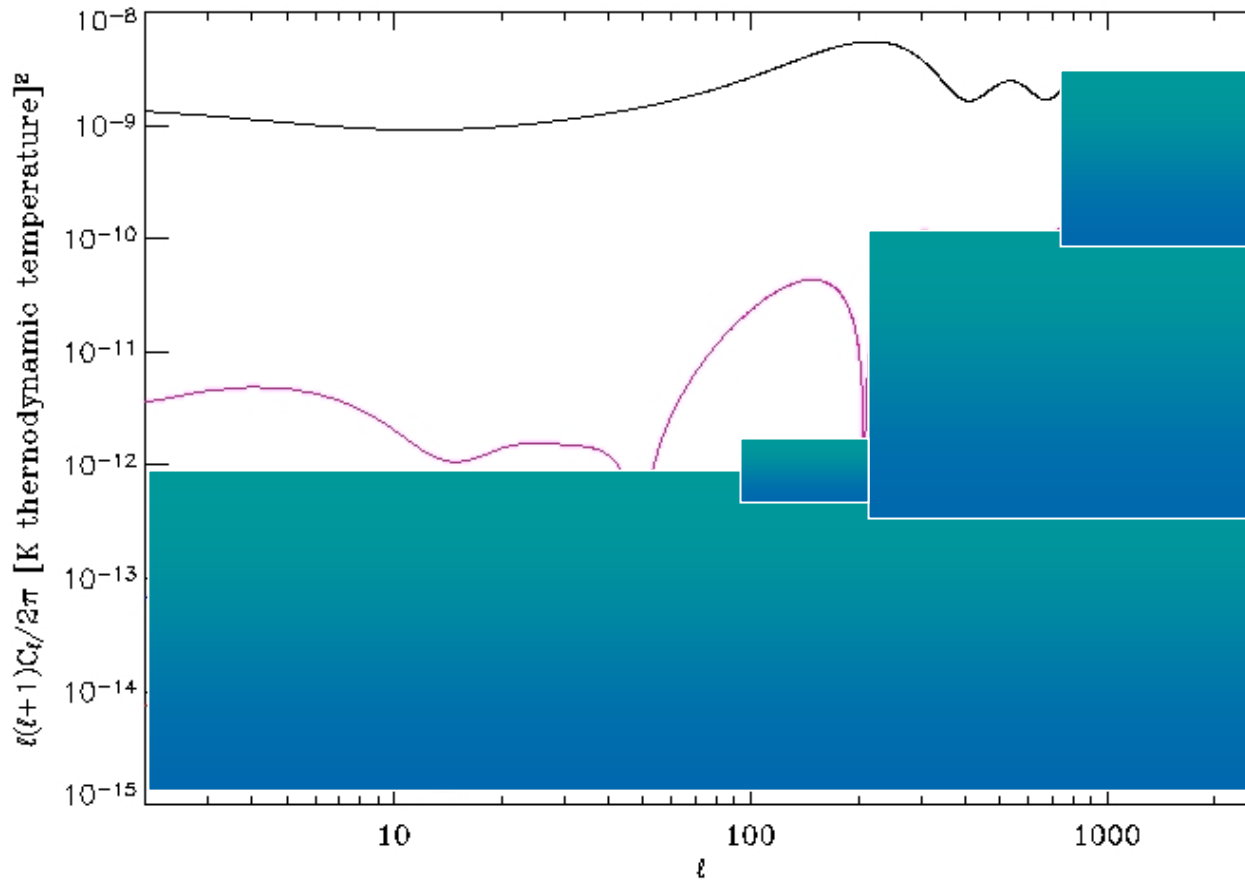
Lensing

Gravity waves



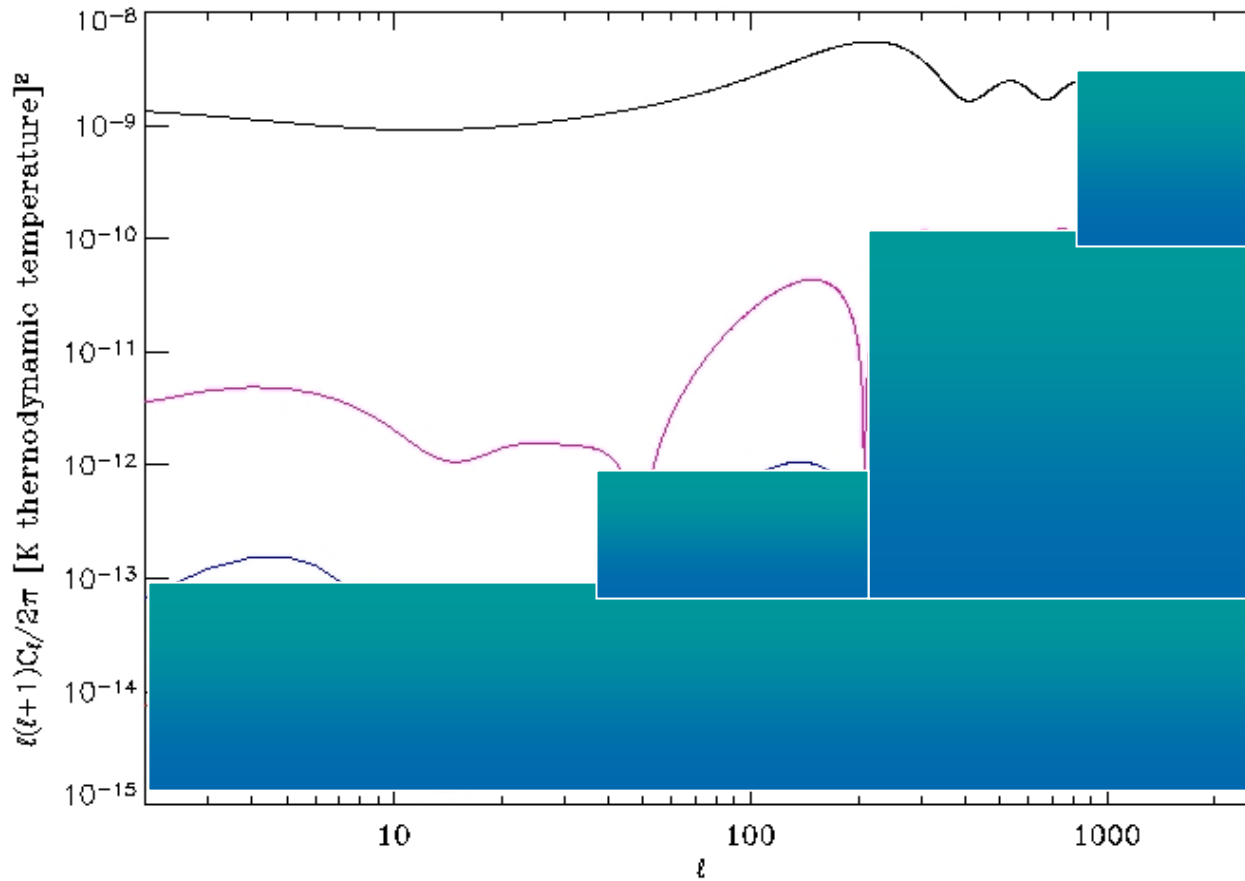
Angle $\approx 200/l$ degrees

WMAP first year



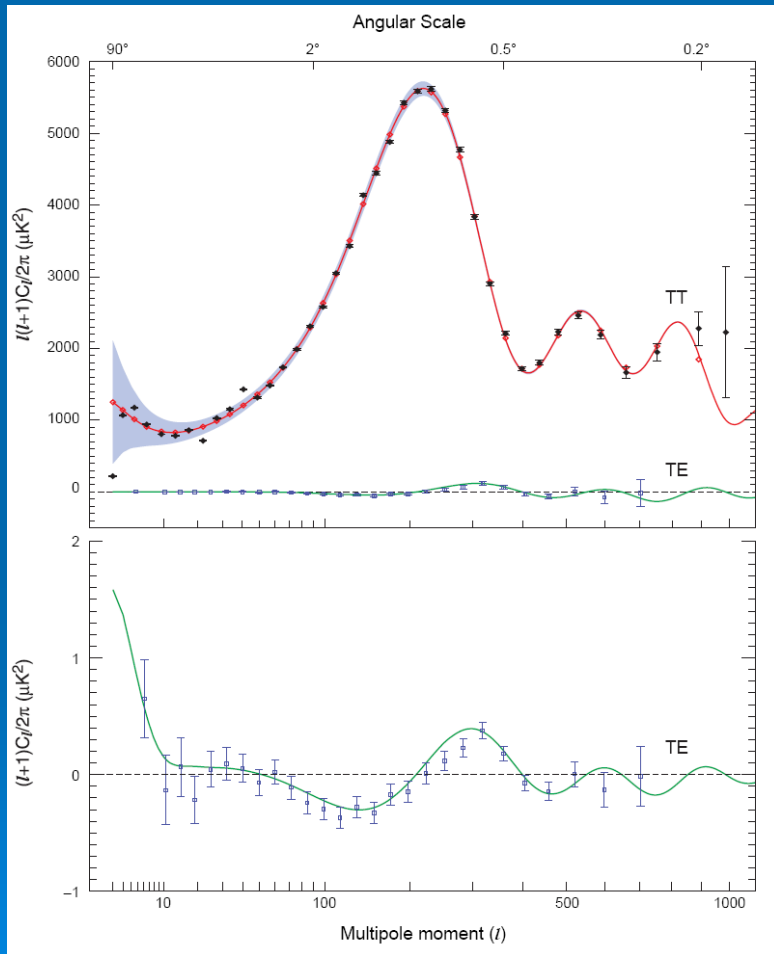
Angle $\approx 200/l$ degrees

WMAP third year

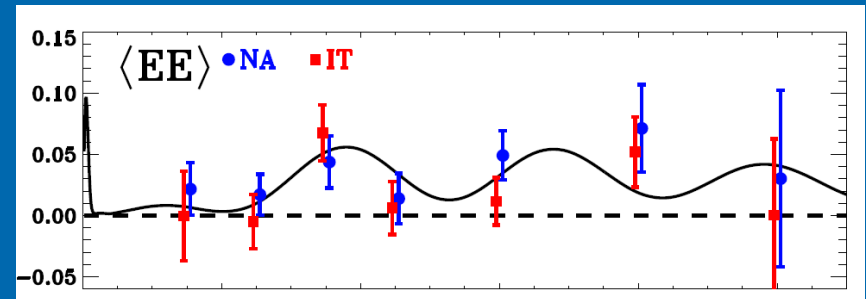


Angle $\approx 200/\ell$ degrees

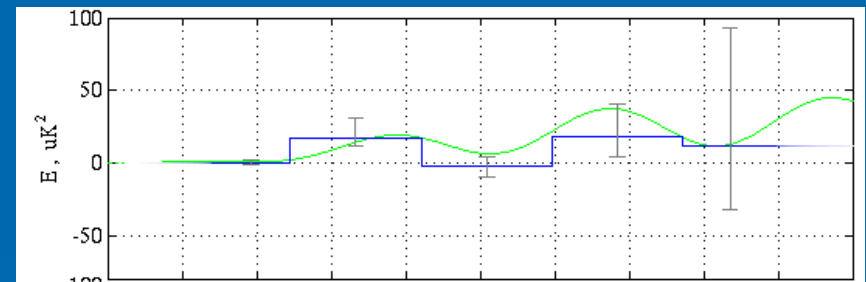
CMB angular power spectrum



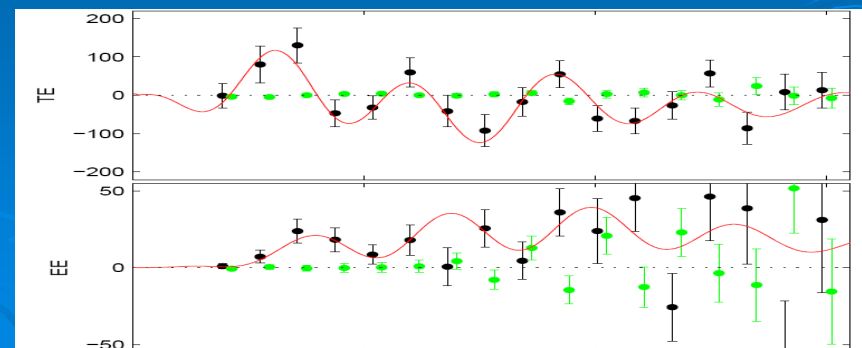
WMAP



boomerang

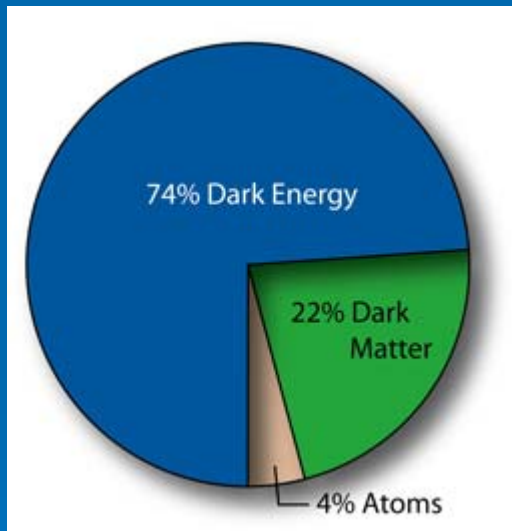


dasi

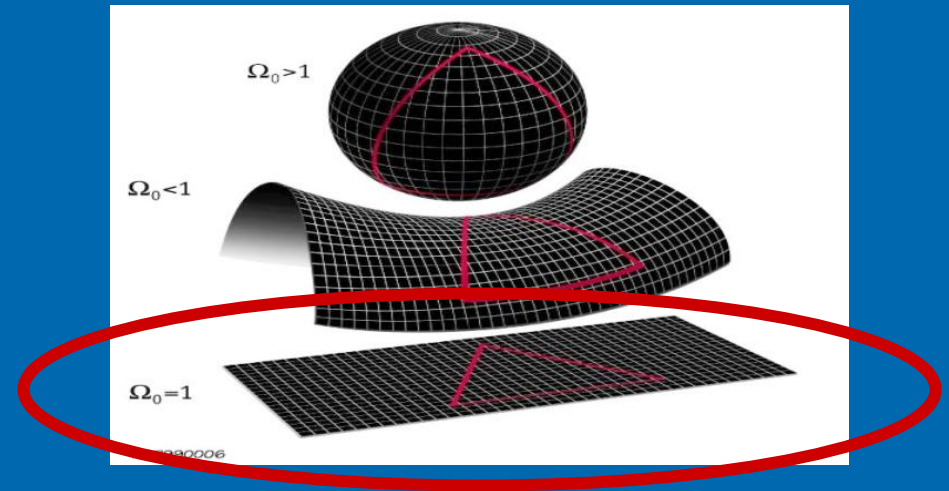
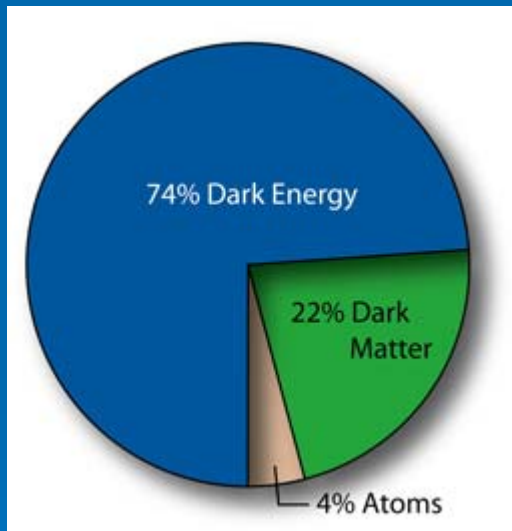


quad

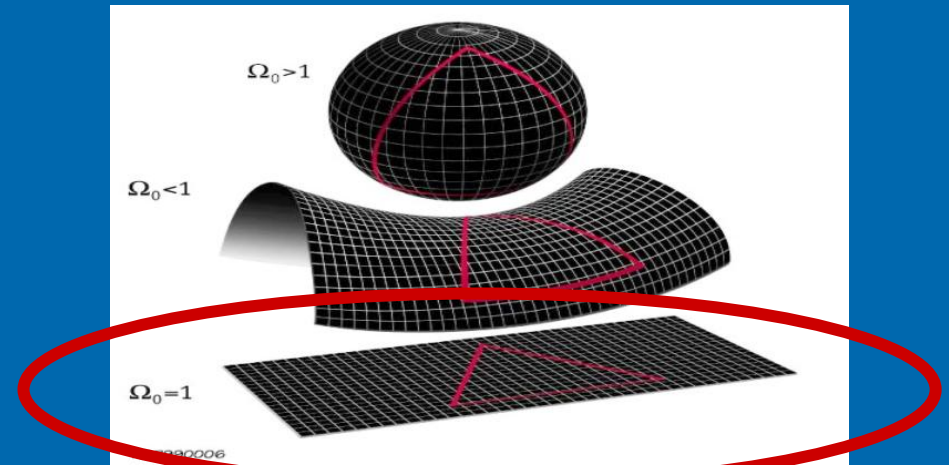
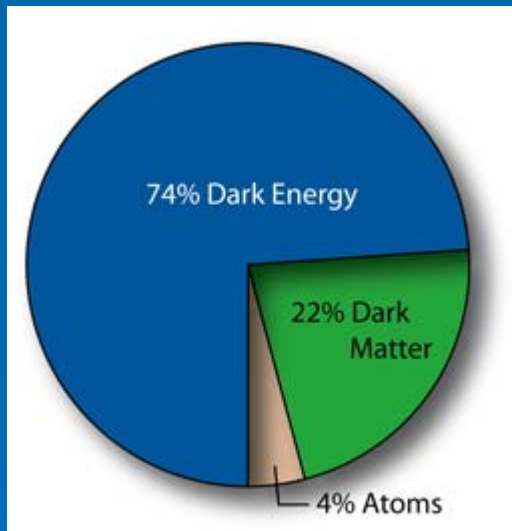
Cosmological concordance model



Cosmological concordance model

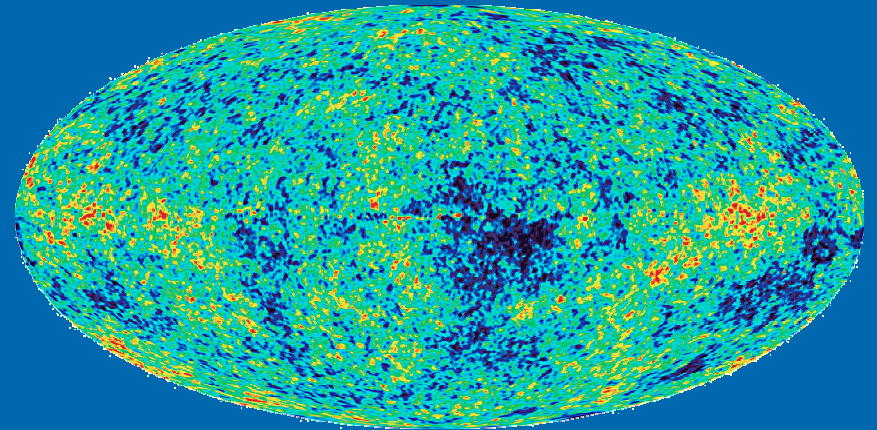


Cosmological concordance model



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 or marginal, see smith et al. for a 3.4σ detection correlating WMAP and NVSS galaxies

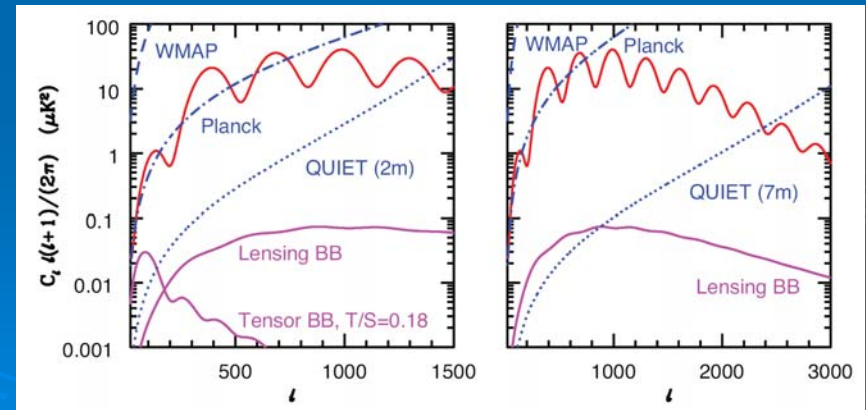
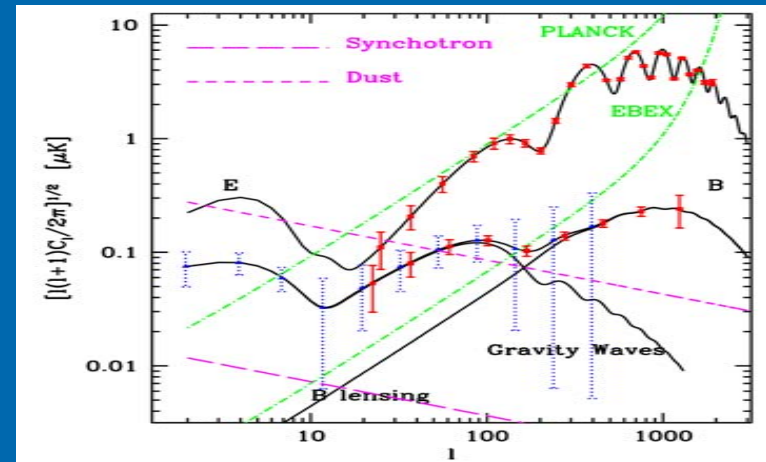


Other cosmological backgrounds?

- 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...

Forthcoming CMB polarization probes

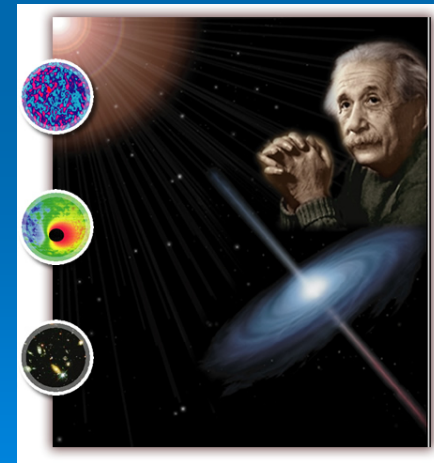
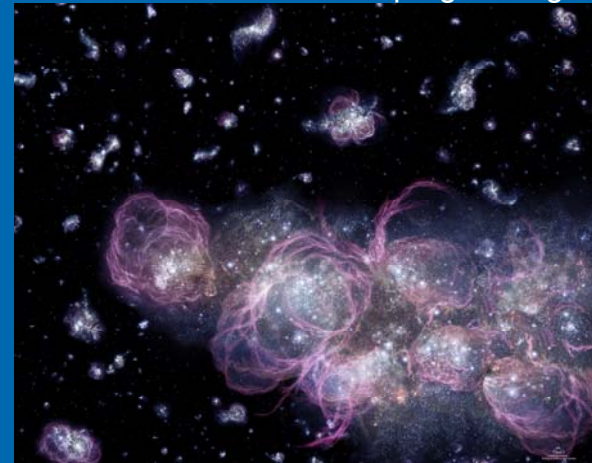
- Planck
- EBEx (US, collaborators in France, Italy, UK), balloon, same launch time scale as Planck for the north american flight
- SPIDER (US, ...)
- QUIET (US, UK), ground based
- Clover (UK, ...)
- Brain
- ...
- Complete list available at lambda.gsfc.nasa.gov
- Time scale: approximately one year for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

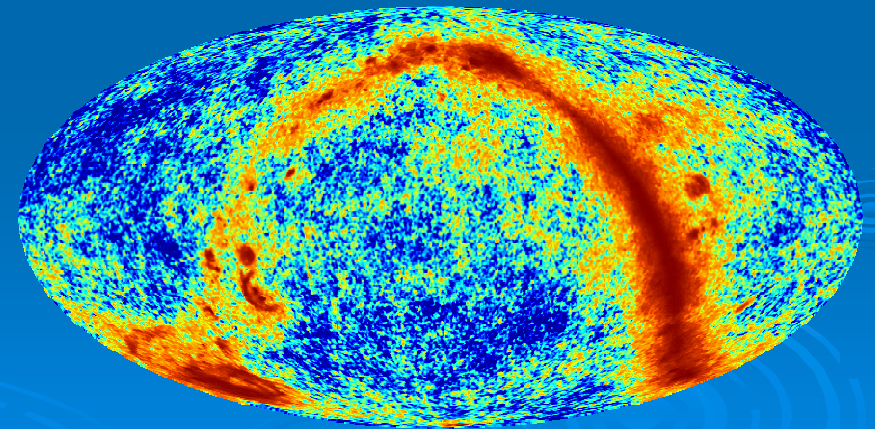
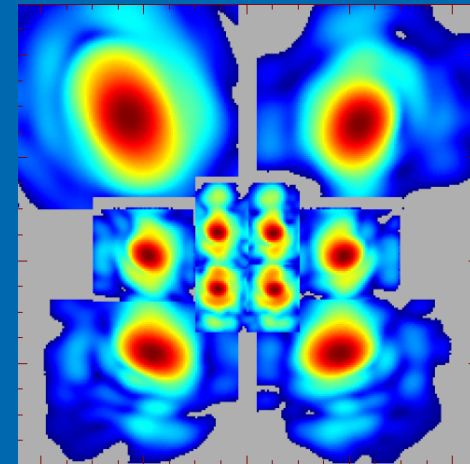
Challenges for future CMB



Challenges for future CMB

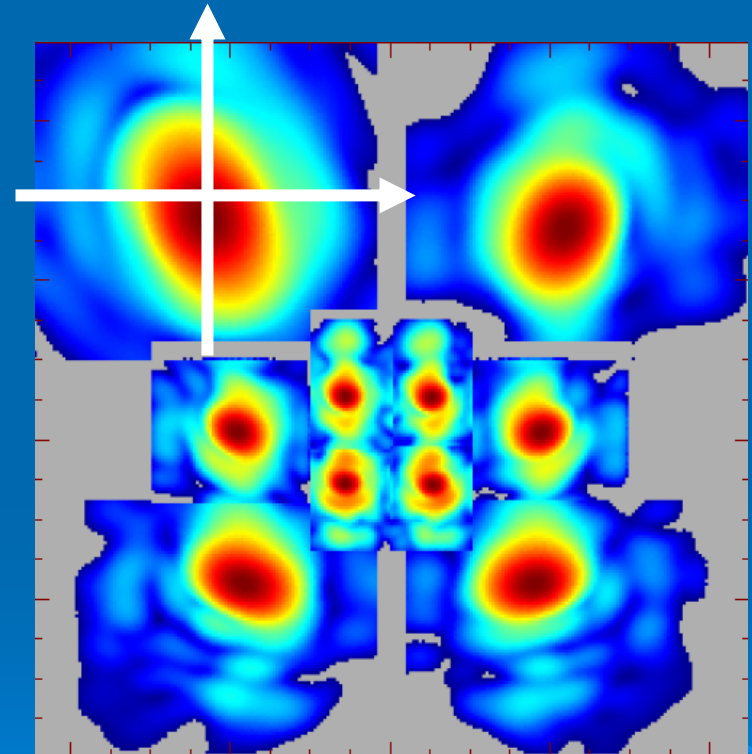
- The sensitivity can be increases with the detector number 😊
- The systematics from the instrument must be controlled at the level of the signal 😞
- The emission from foregrounds may cover the B signal over the all sky, at all frequency 😞

Jarosik et al. 2006



Challenges for future CMB: systematics from beam shape

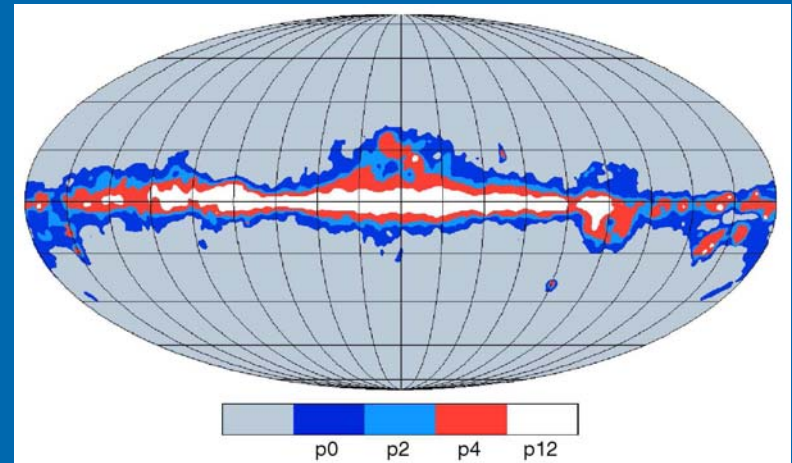
- Asymmetric beams cause unwanted polarization from total intensity, leakage of E modes into B, ...
- No way to circularize the beams, rather the beam shape has to be reconstructed in flight to subtract the bias from the signal



Challenges for future CMB: foreground emission

Bennett et al. 2006

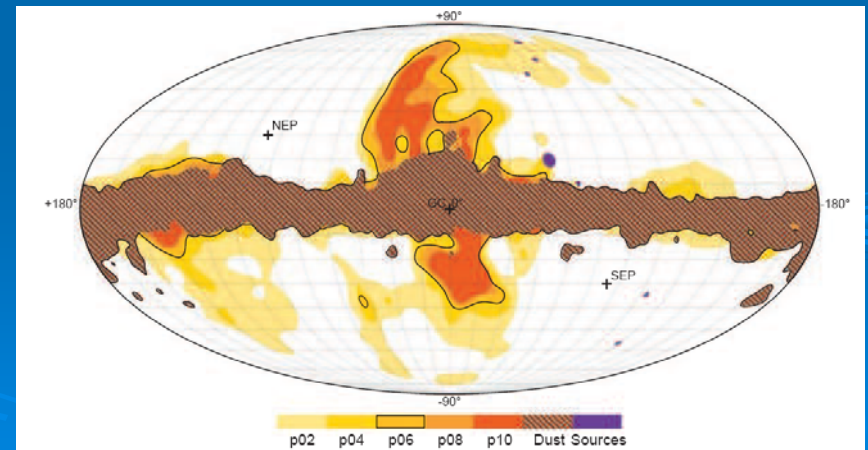
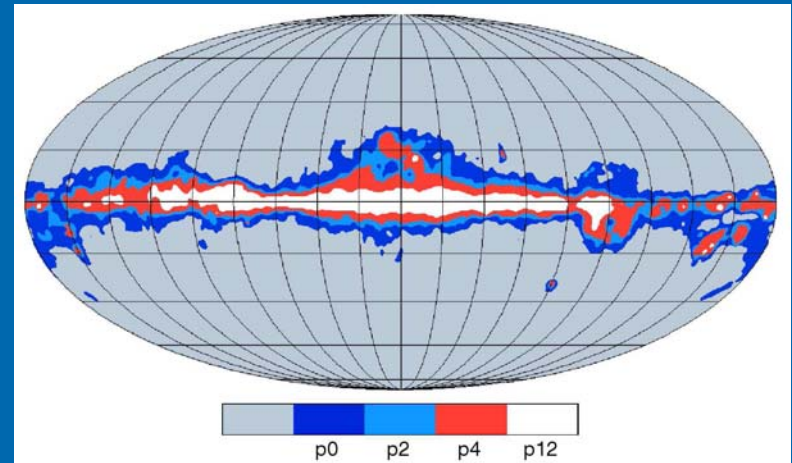
- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brightest part of the Galactic emission, the sky is dominated by CMB



Challenges for future CMB: foreground emission

Bennett et al. 2006

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

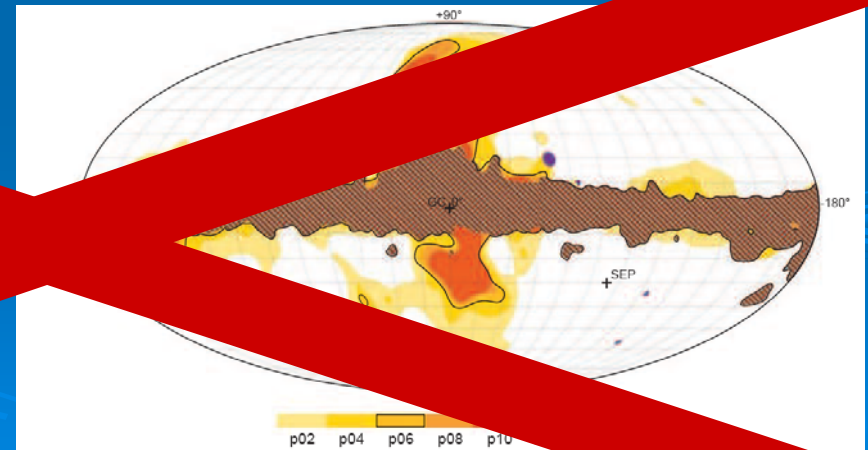
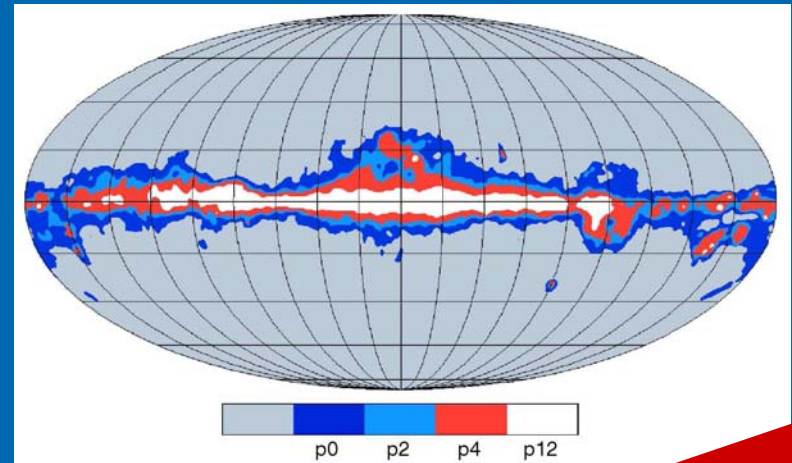


Page et al. 2006

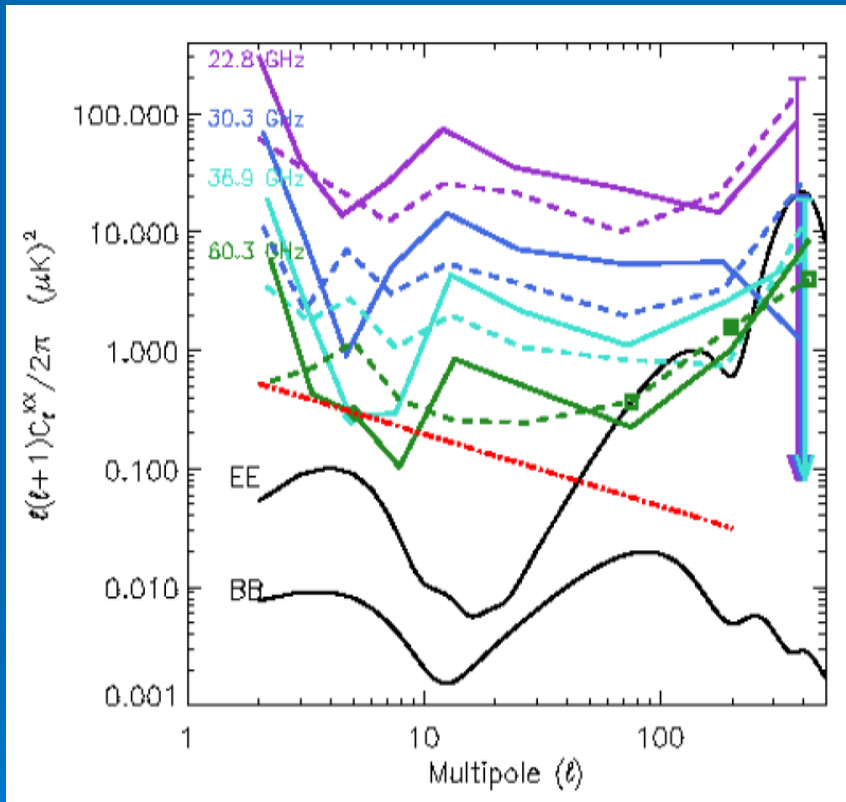
Challenges for future CMB: foreground emission

Bennett et al. 2006

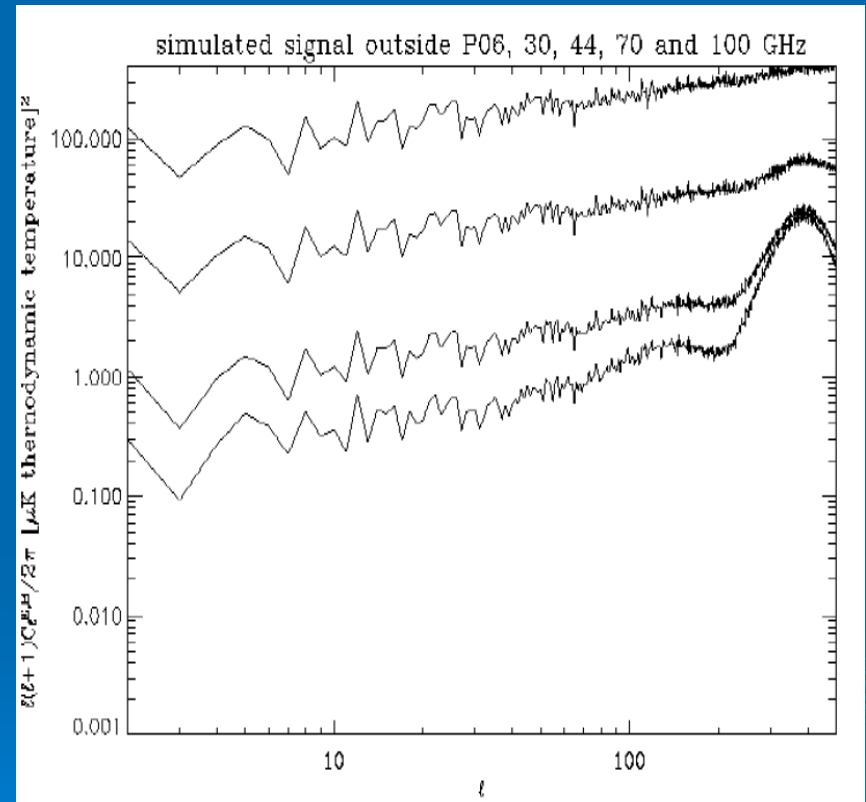
- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brightest part of the Galactic emission, the sky is dominated by CMB polarization, at frequencies between 60 and 90 GHz, after cutting out the brightest part of the Galactic emission, the sky is dominated by CMB



Challenges for future CMB: foreground emission



Page et al. 2006

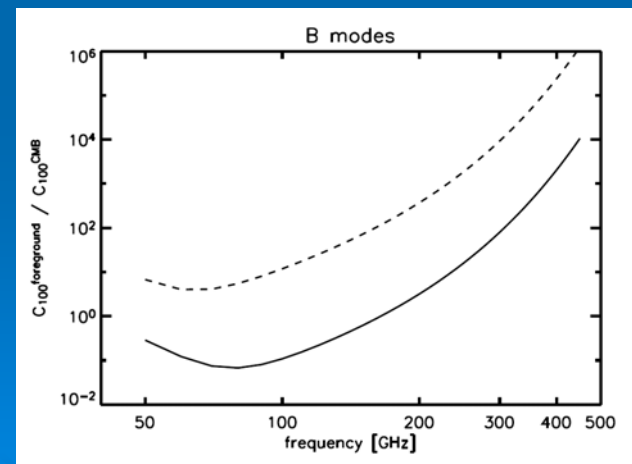
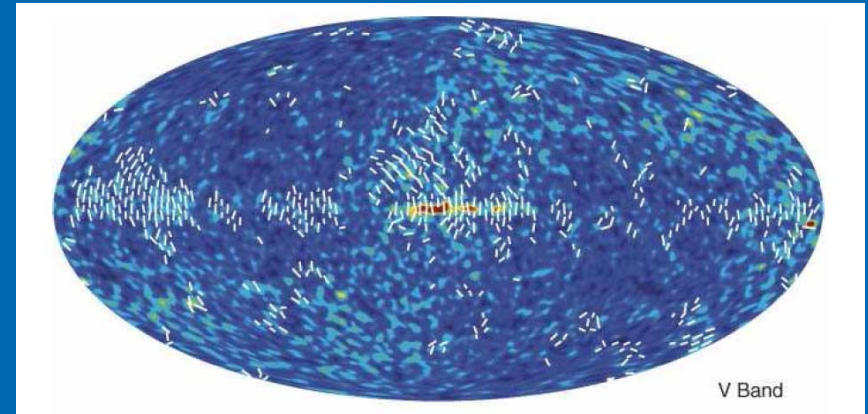


Planck reference sky

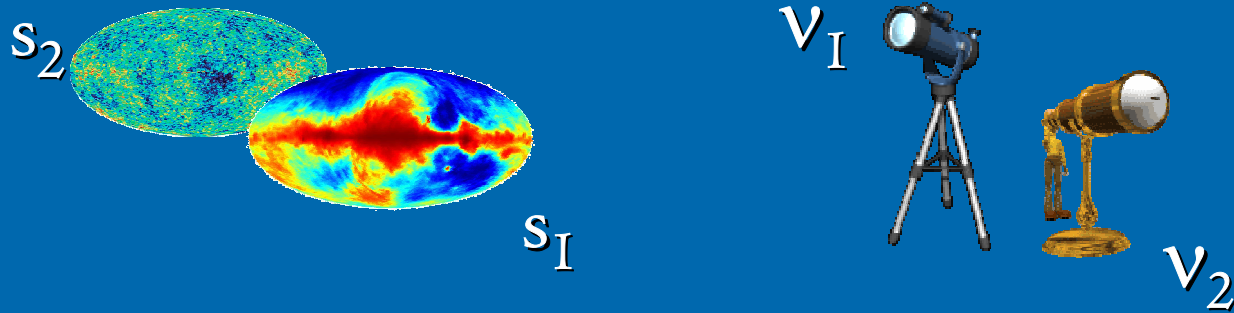
Are there foreground clean regions at all in polarization?

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



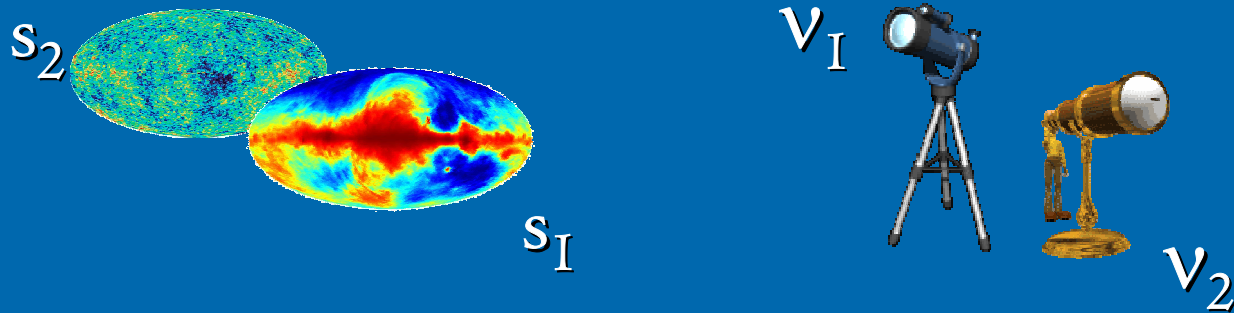
Living with foregrounds: component separation



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

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

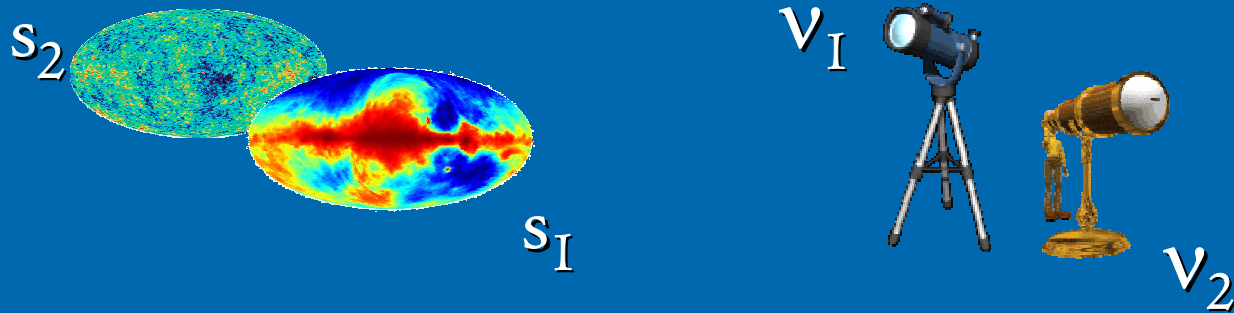
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Living with foregrounds: component separation



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

Invert for \mathbf{s} !

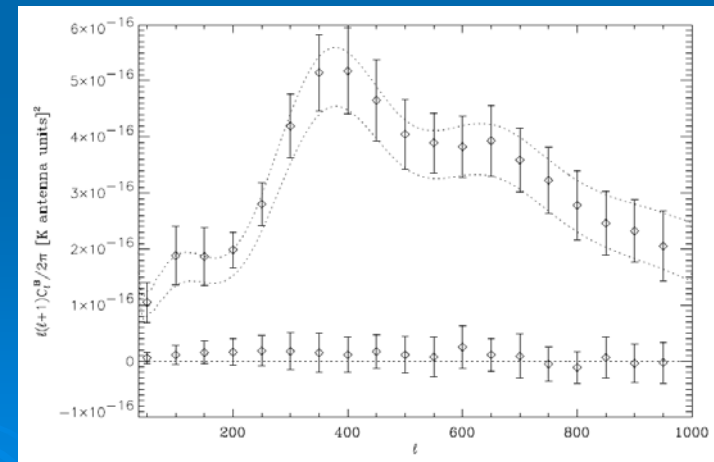
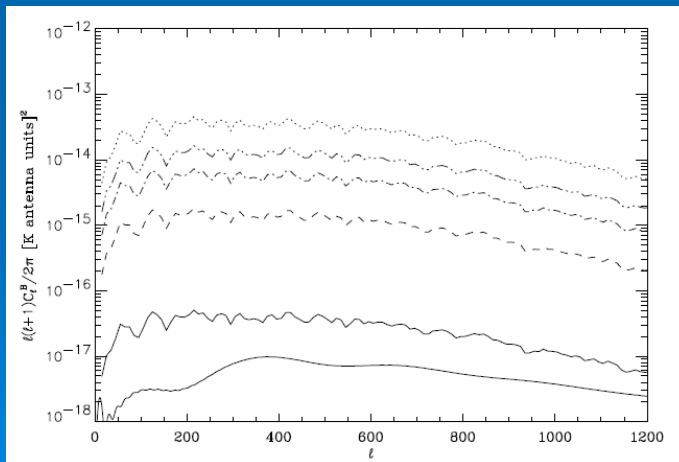
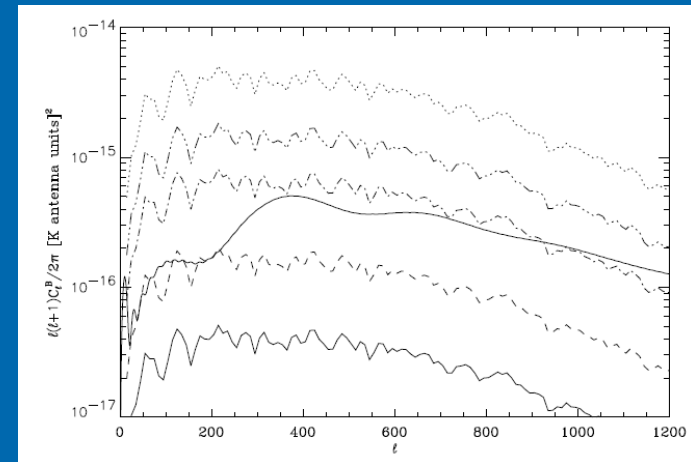
Living with foregrounds: component separation

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

- Non-blind approach: use prior knowledge on \mathbf{A} and \mathbf{s} in order to stabilize the inversion, likely to be suitable for total intensity
- Blind approach: do not assume any prior either on \mathbf{A} or \mathbf{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, promising 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

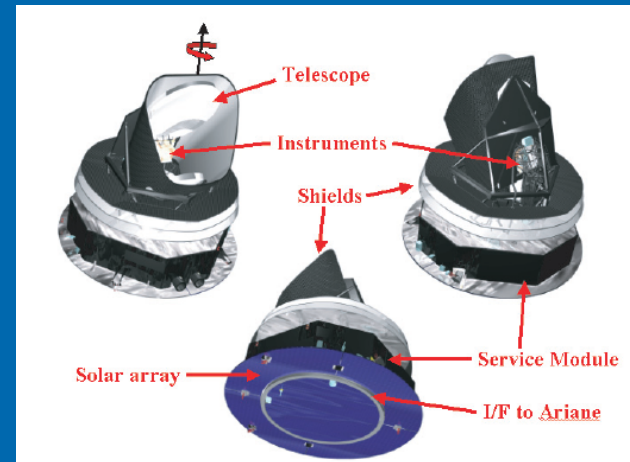
The science goals of the Planck satellite

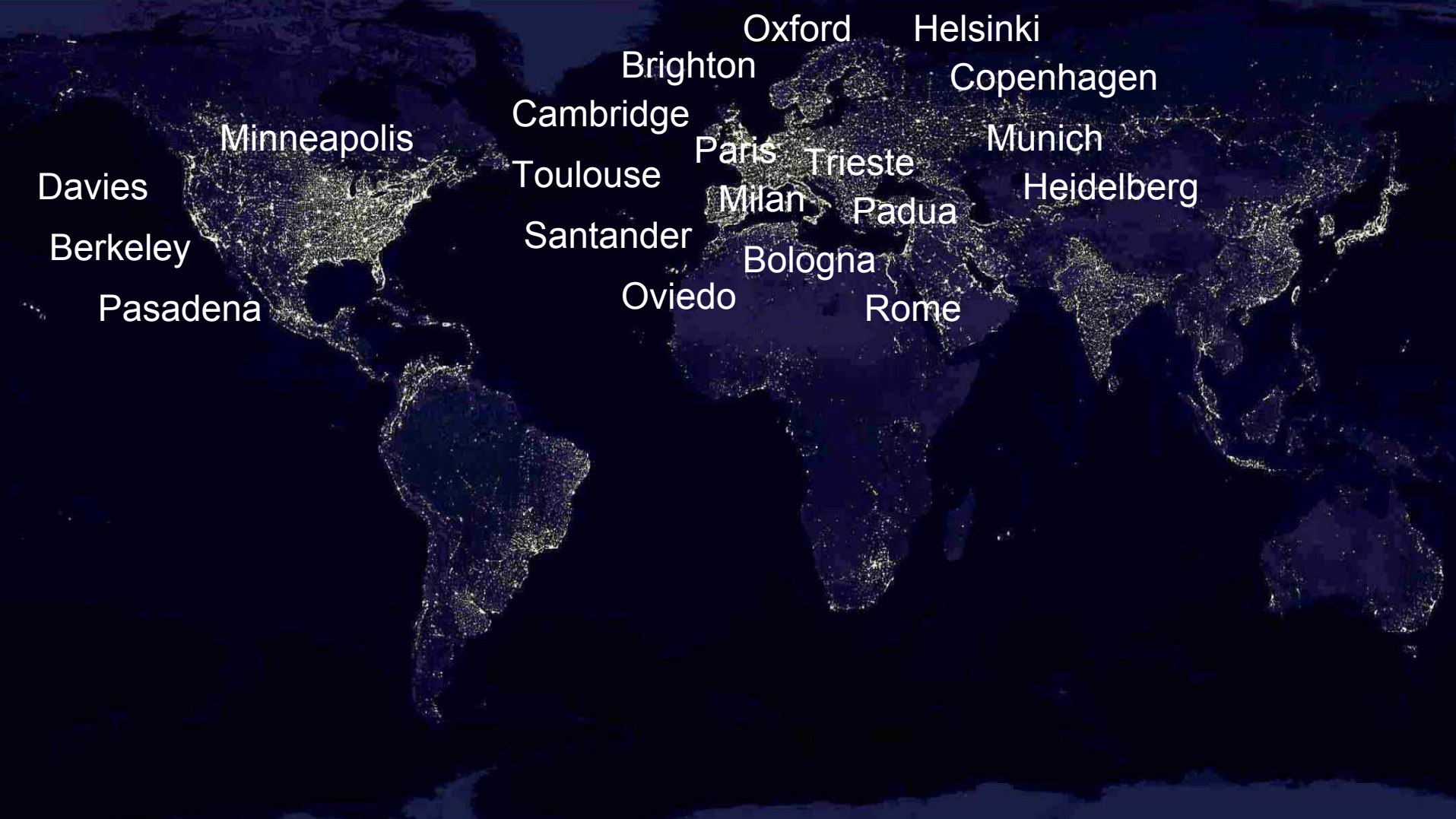
Source: Planck scientific program bluebook,
available at www.rssd.esa.int/Planck



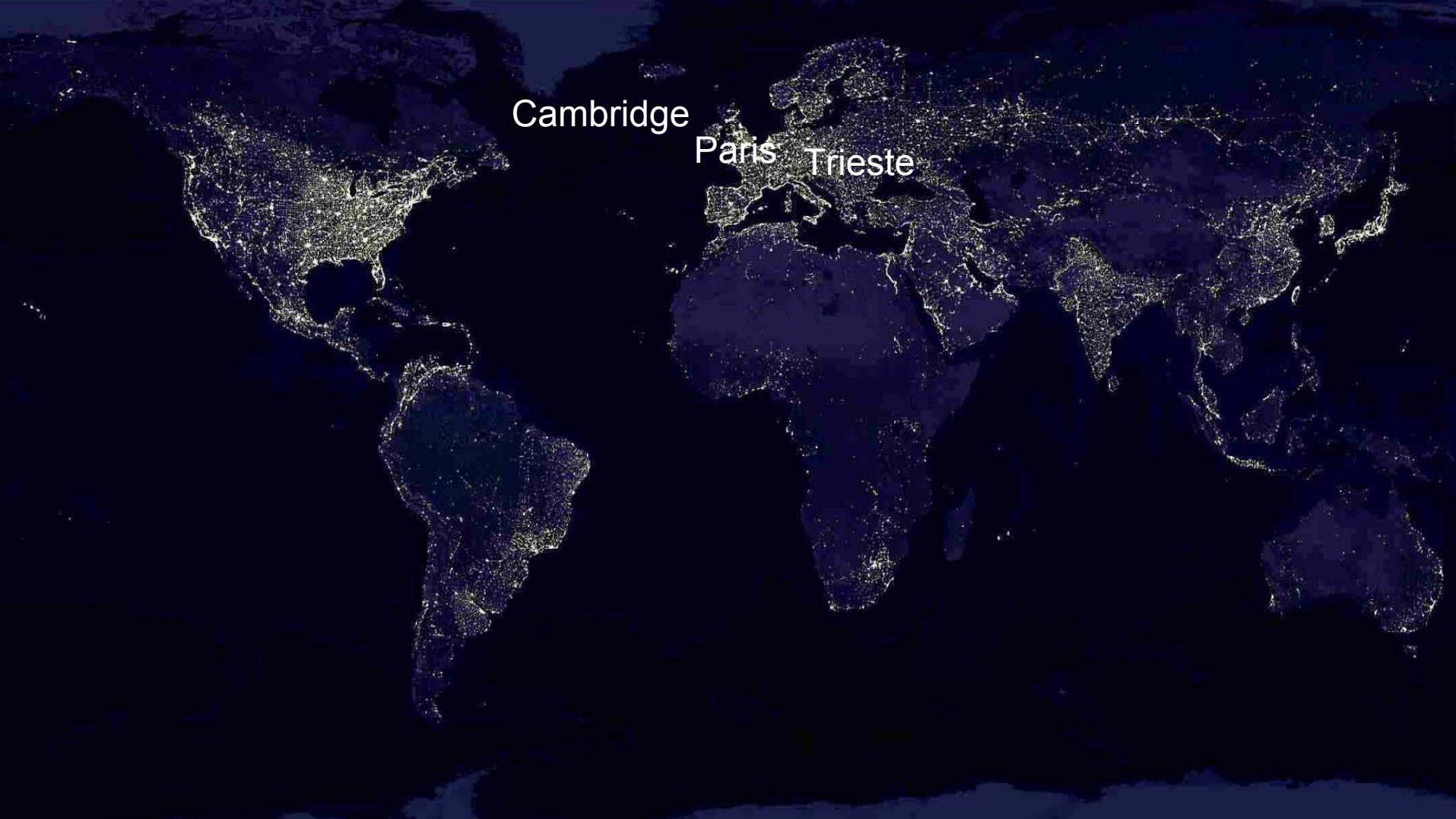
Planck

- 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



Cambridge

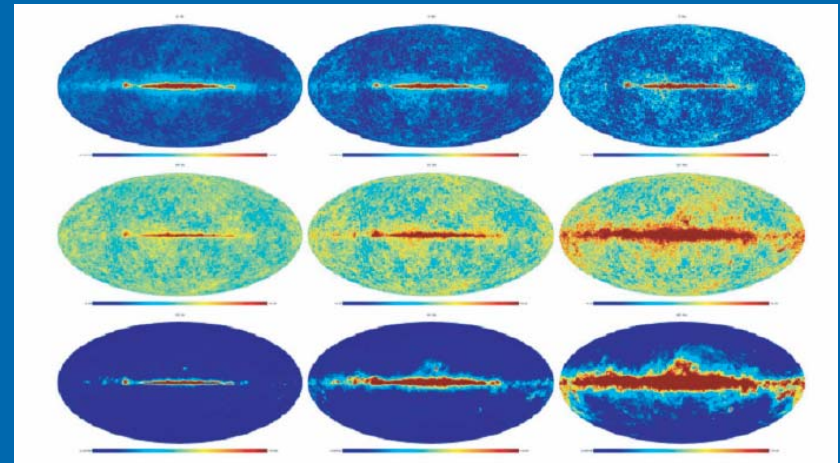
Paris

Trieste

Planck data processing sites

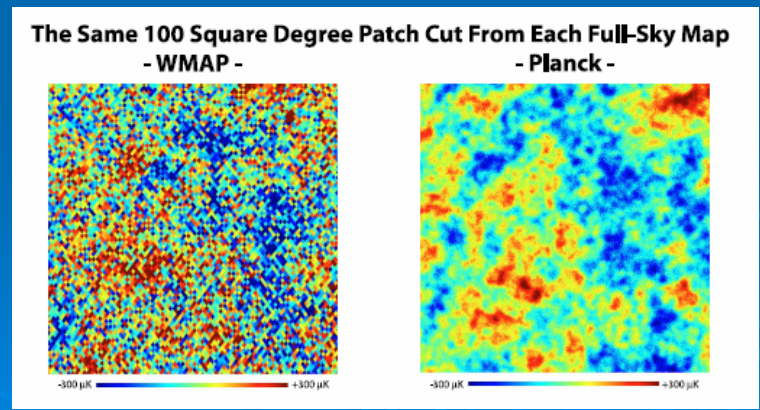
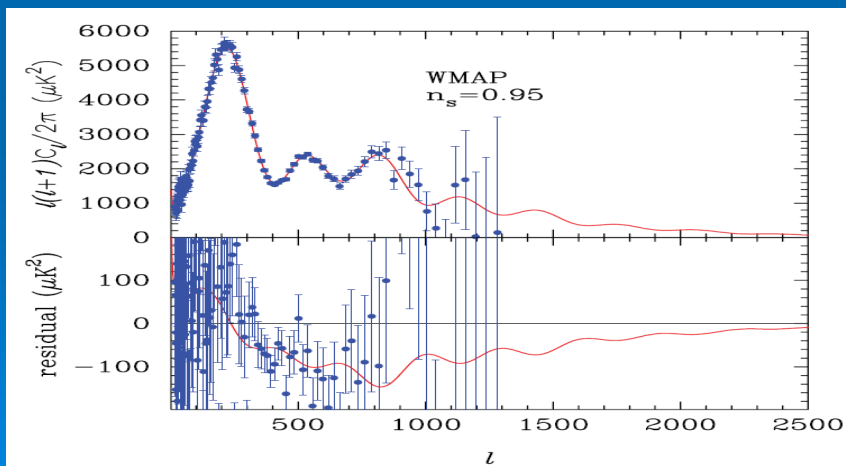
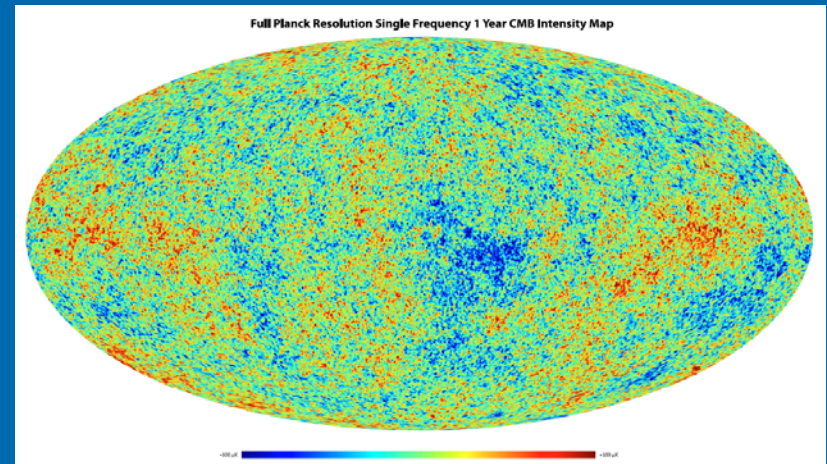
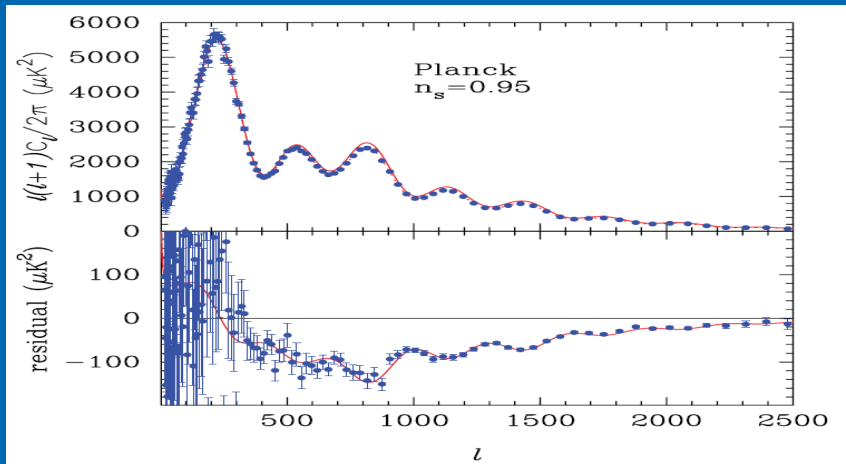
Planck data deliverables

- 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

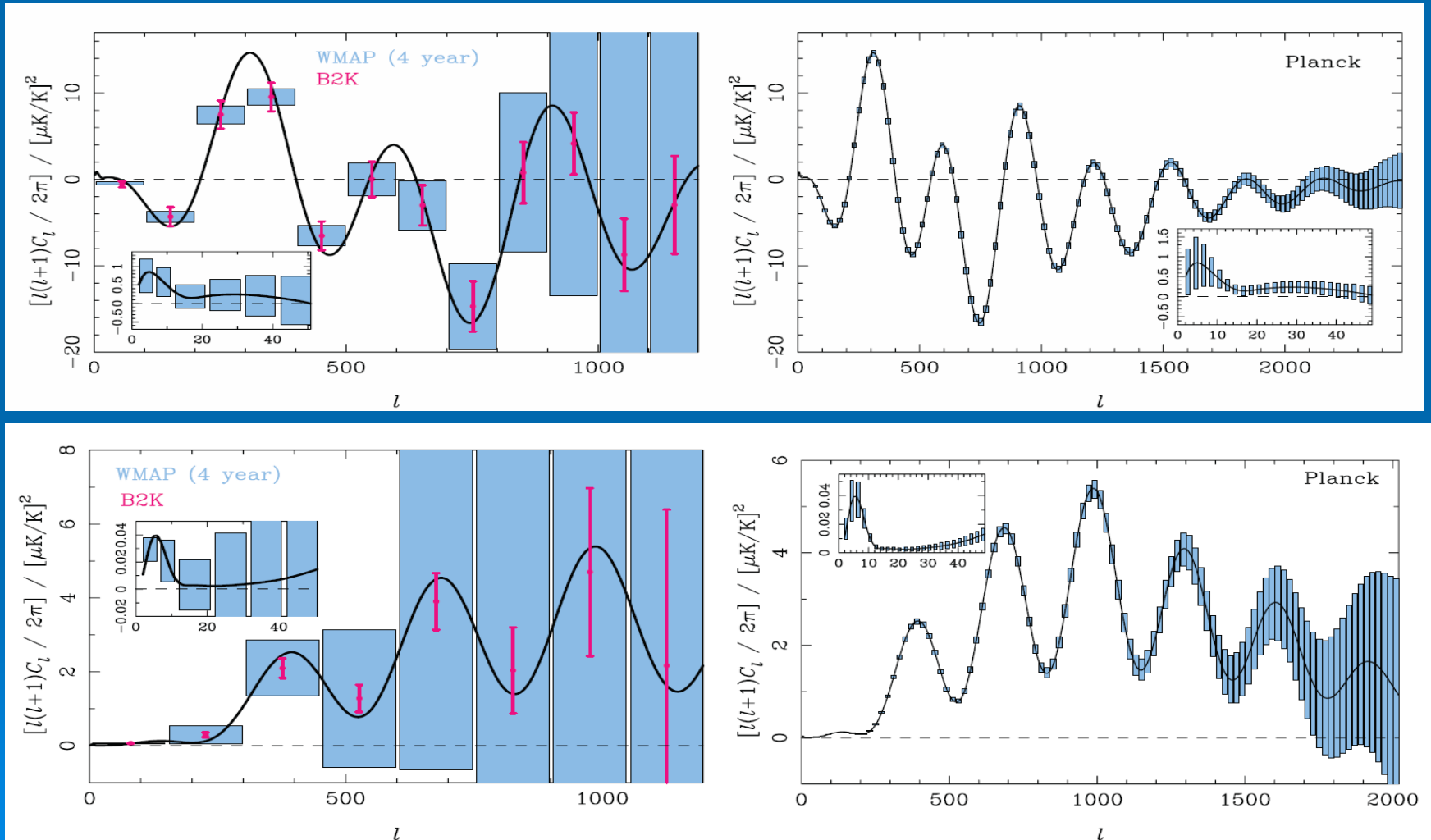


PLANCK GALAXY SURVEYS					
	FREQUENCY [GHz]				
	143	217	353	550	850
Confusion limit [mJy, 3σ]	6.3	14.1	44.7	112	251
Planck All Sky Survey sensitivity [mJy, 3σ]	26	37	75	180	300
Planck Deep Survey sensitivity [mJy, 3σ]	10	18.4	49	170	280
Number of galaxies [all sky]	570	860	1700	4400	35000

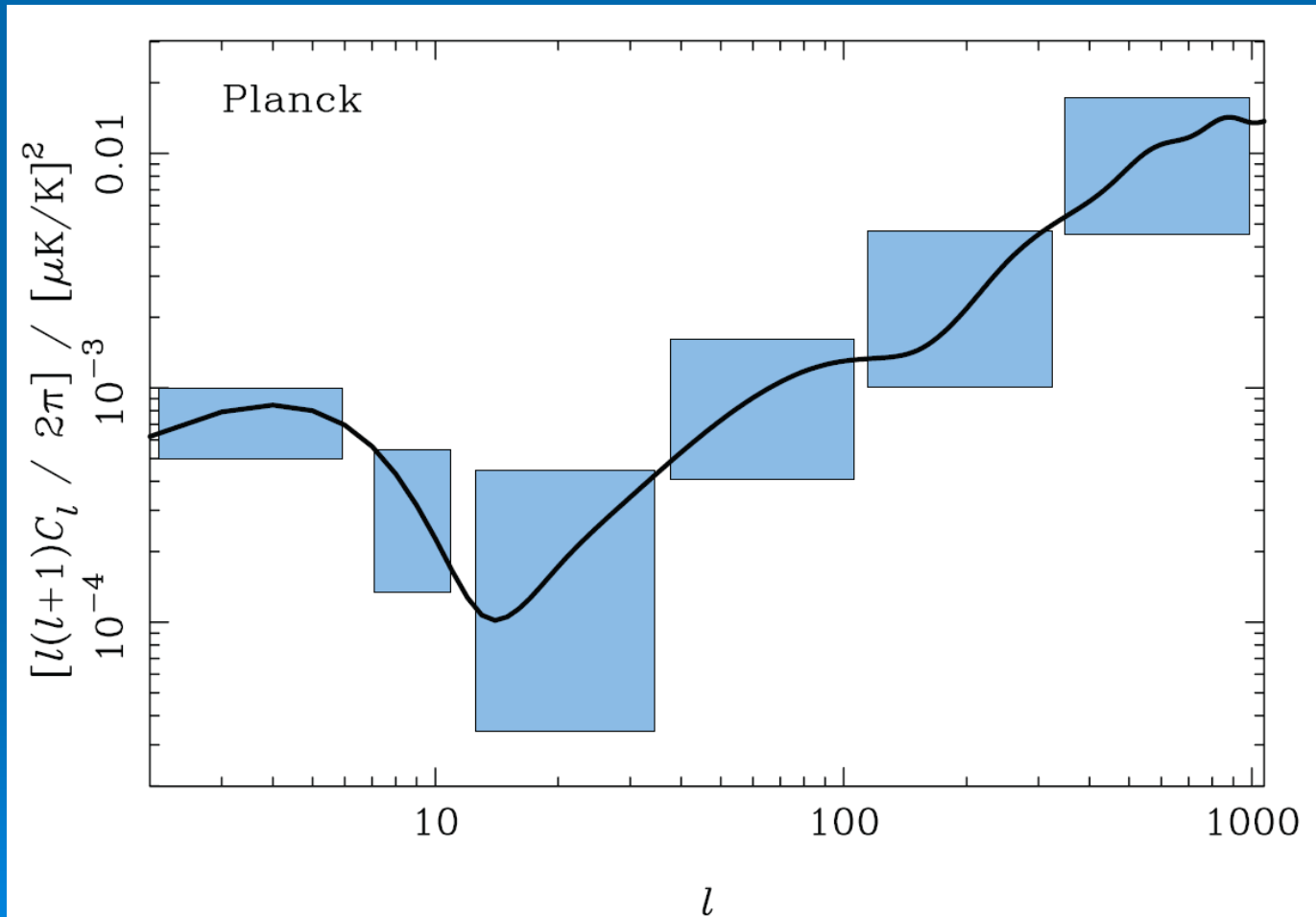
Planck scientific deliverables: CMB total intensity and the era of imaging



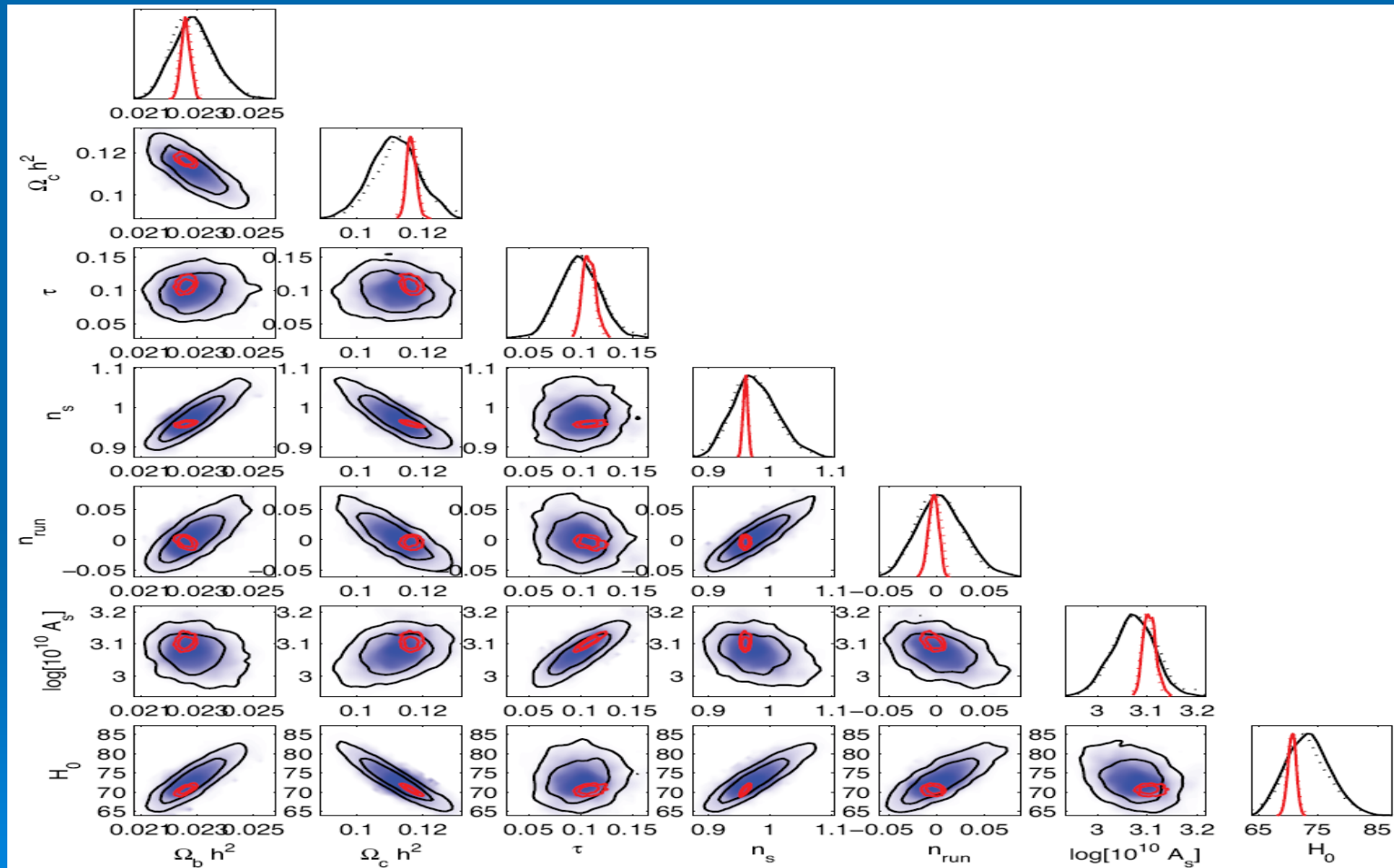
Planck scientific deliverables: CMB polarization



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 mechanism 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



Theorist



- Modest or controllable foreground emission, systematics under control
- 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
- Time scale: from a few to 20 years



Theorist

Cosmological tensors

Spacetime foam