Reading cosmological perturbations in the CMB: expectations from Planck and future probes

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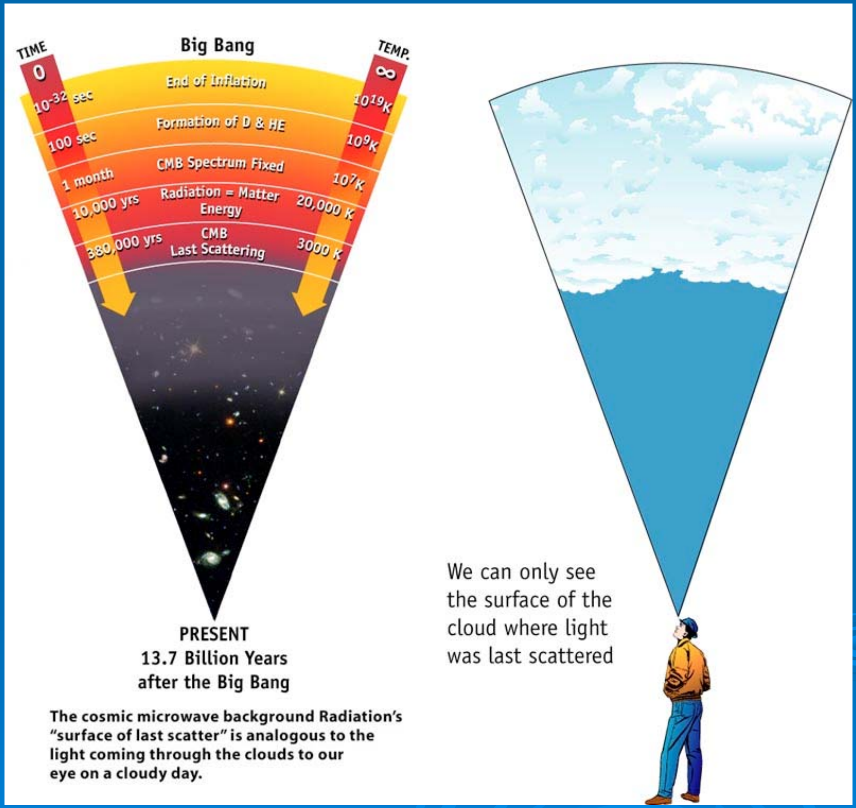
Outline

- CMB physics
- Status of the CMB observations
- Expectations and challenges for future CMB
- The science goals of the Planck satellite
- Conclusions, ☹/☺
- Adds-on: CMB lensing and dark energy, basics of CMB data analysis, foreground removal from CMB meaurements, …

CMB physics

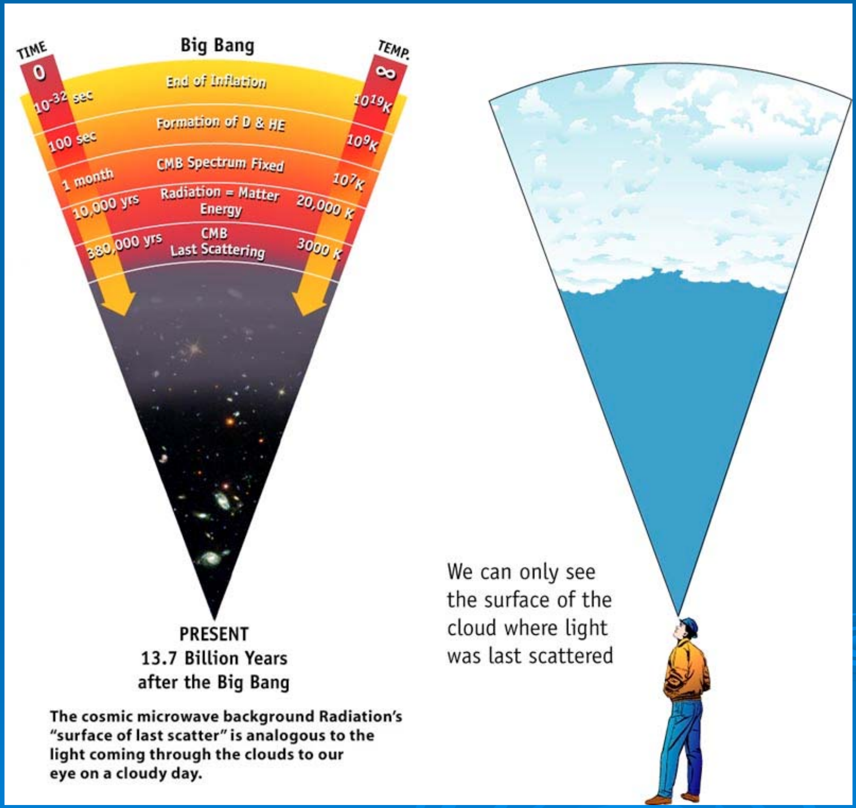
CMB: where and when?

- 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 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

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

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

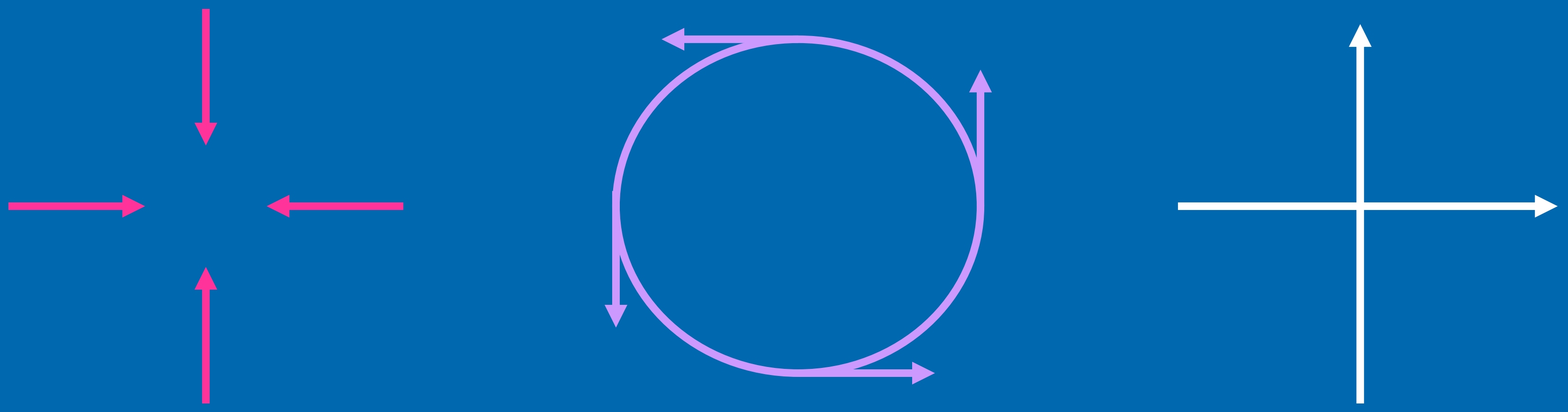
CMB physics: Boltzmann equation

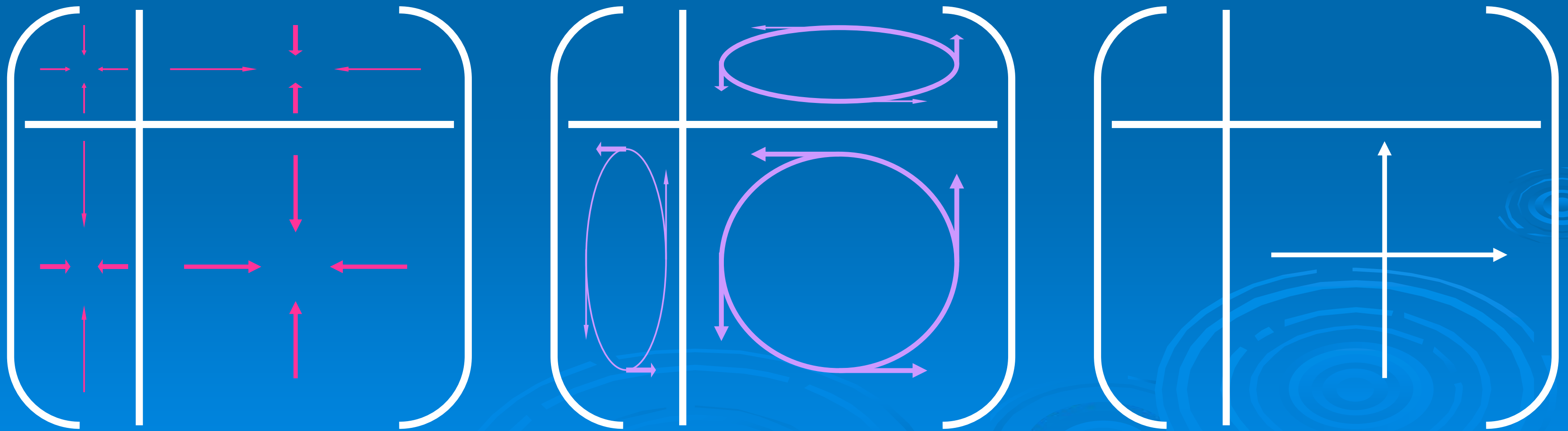
$$\frac{d\ \text{neutrinos}}{dt} = \text{metric} + \text{weak interaction}$$

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

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

CMB physics: metric

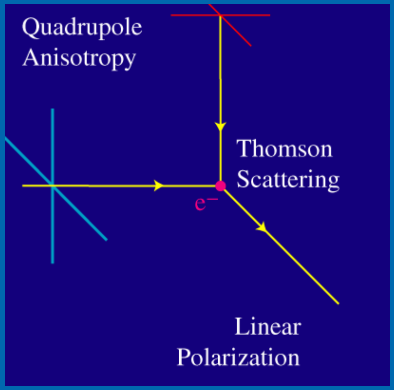


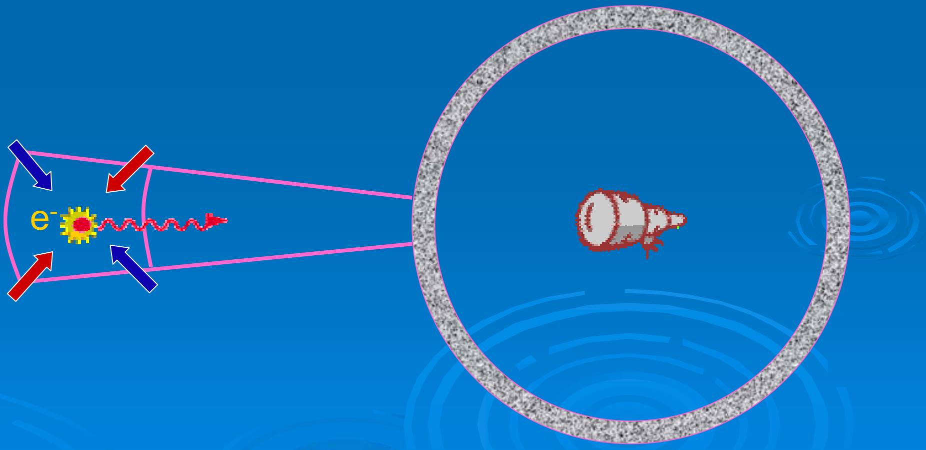


CMB Physics: Compton scattering

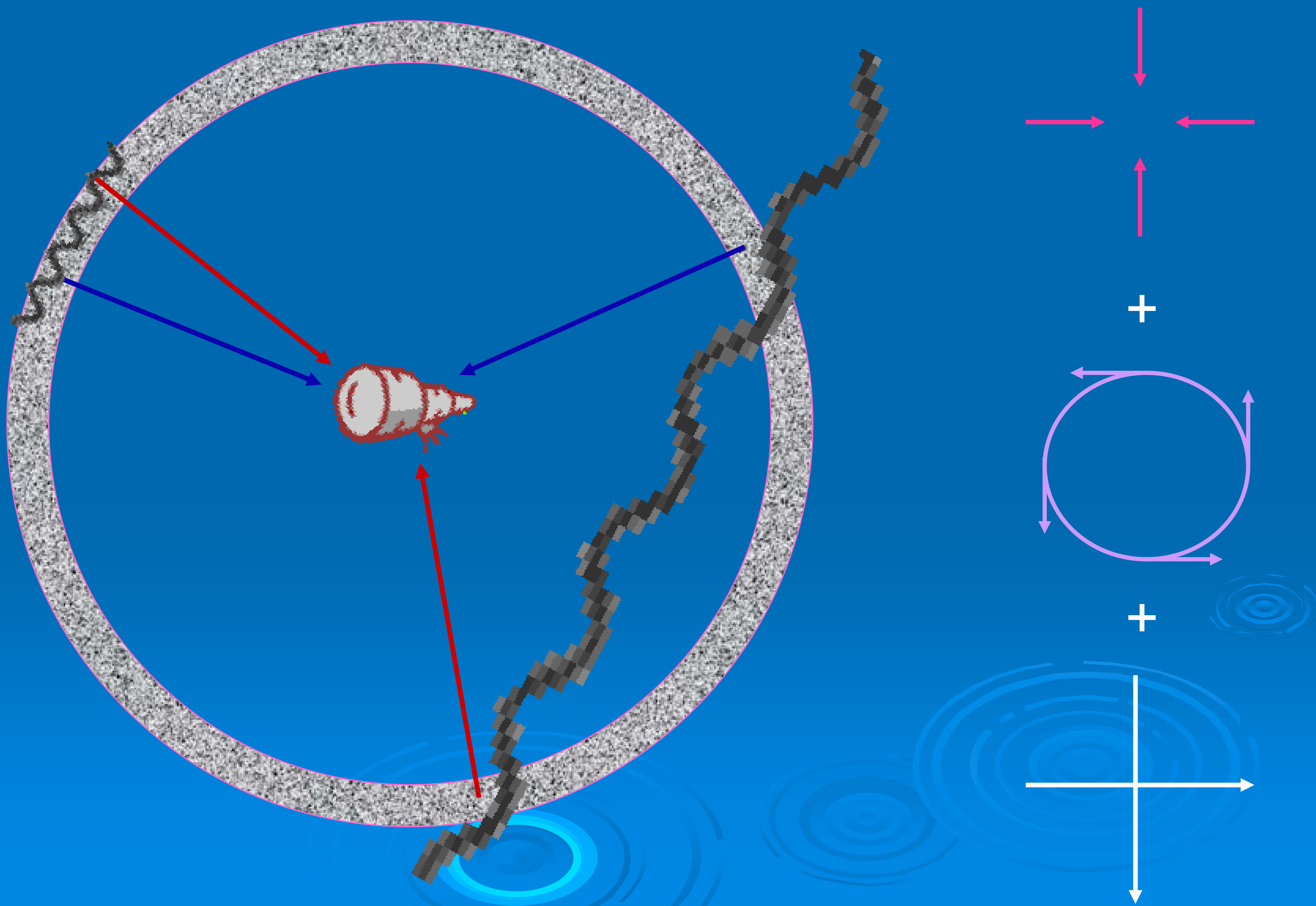
- Compton scattering is anisotropic
- An anisotropic incident intensity determines a linear polarization in the outgoing radiation
- At decoupling that happens due to the finite width of last scattering and the cosmological local quadrupole

Hu's animation

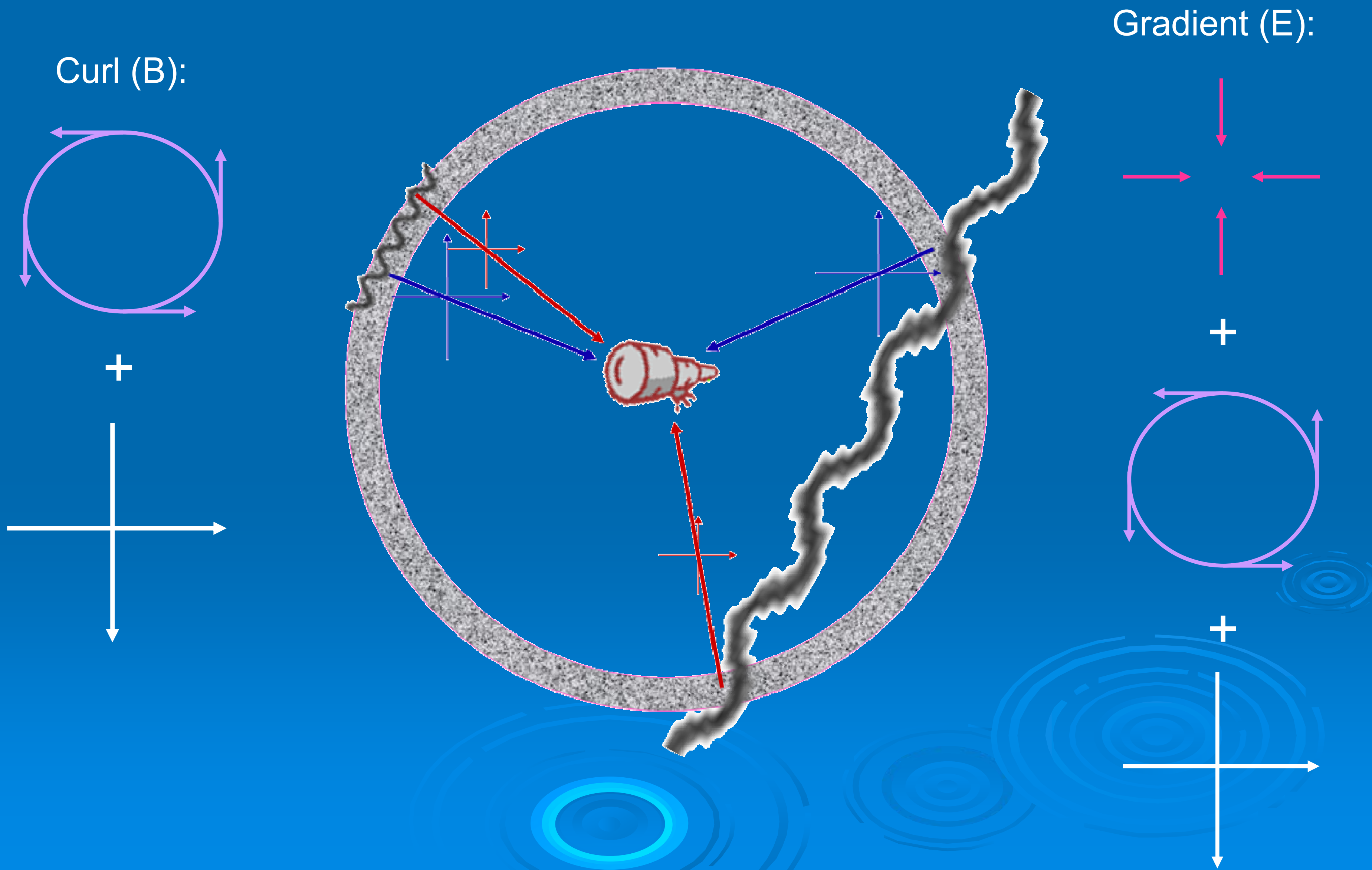




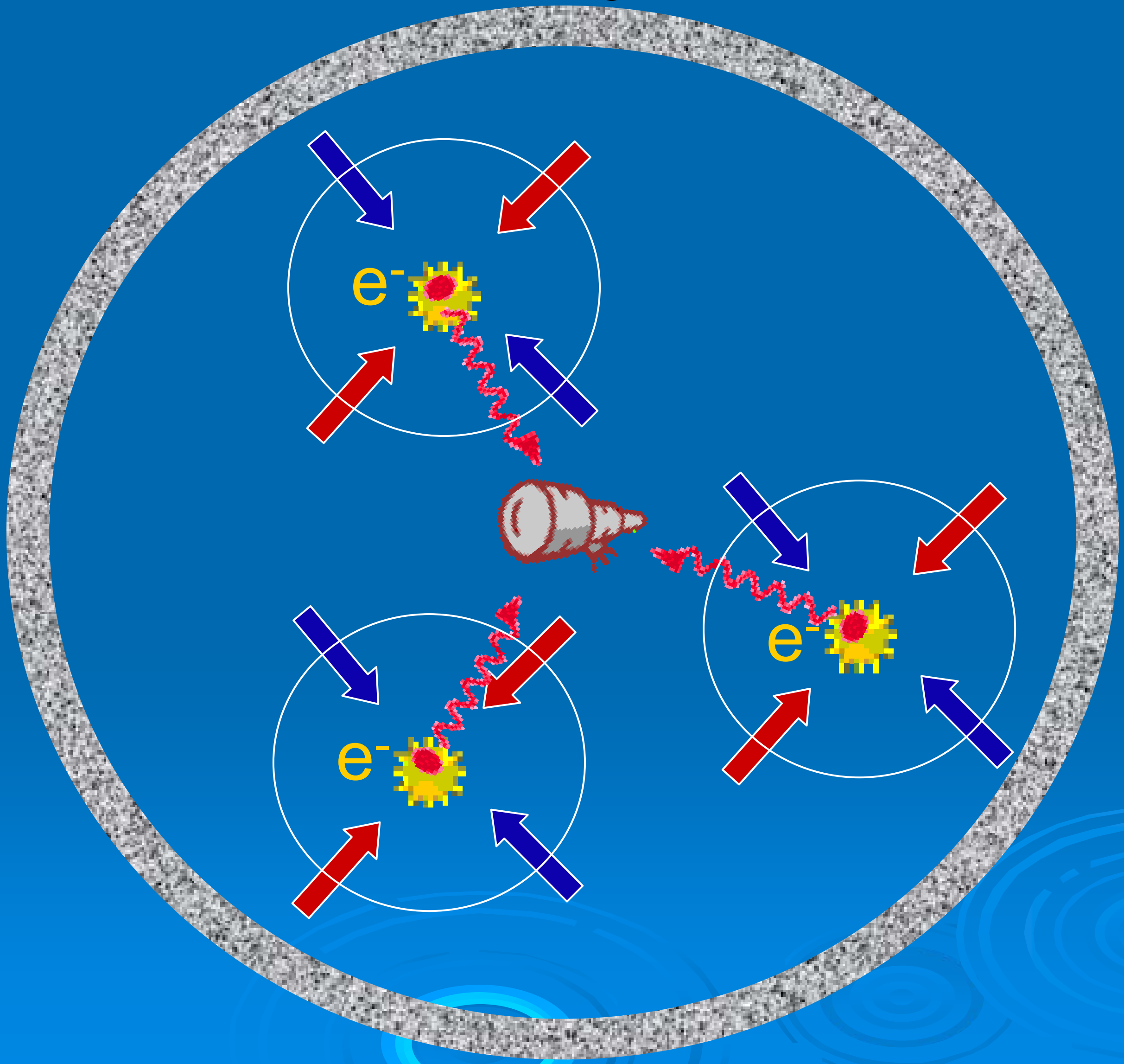
CMB anisotropy: total intensity



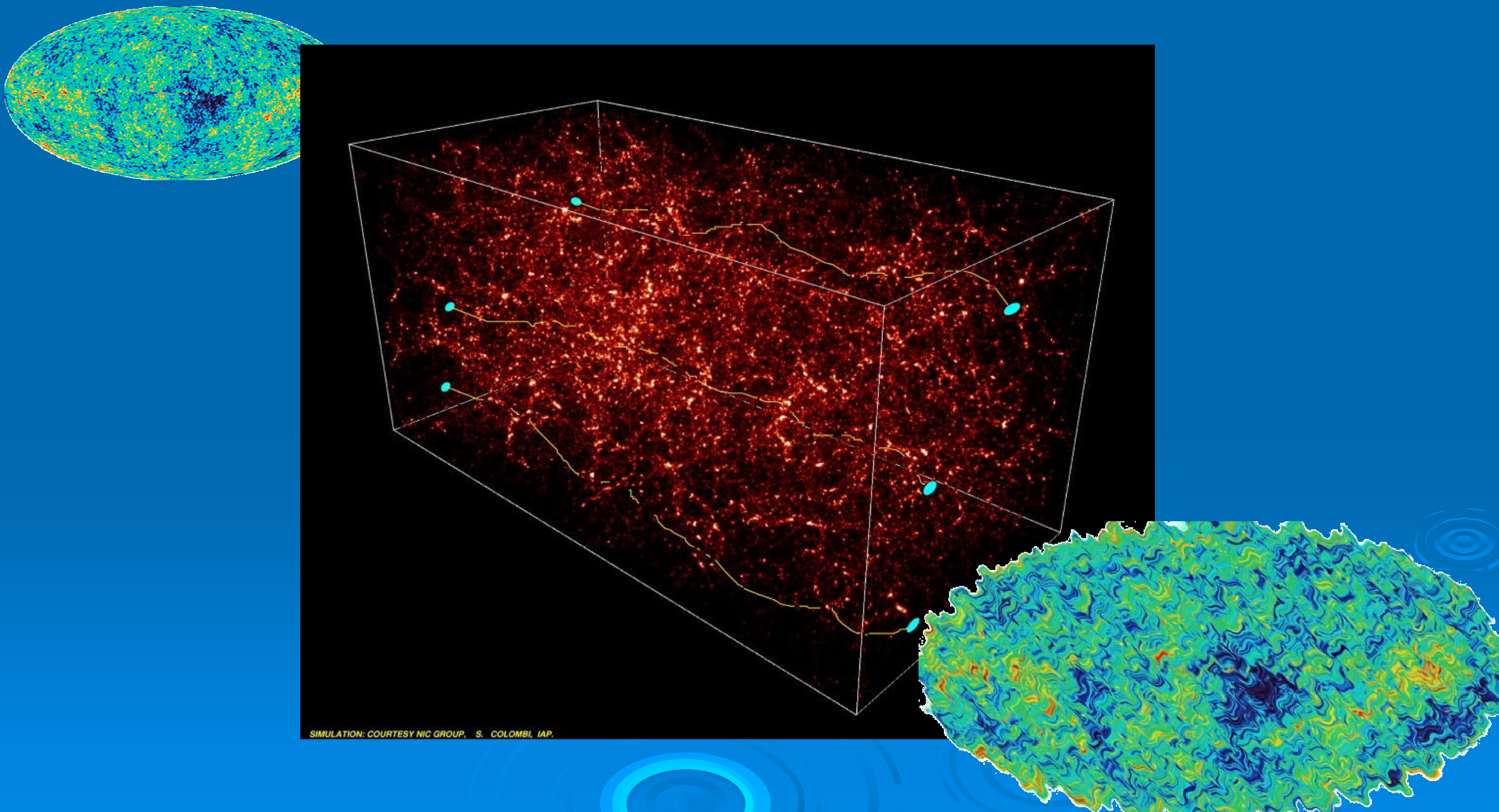
CMB anisotropy: polarization



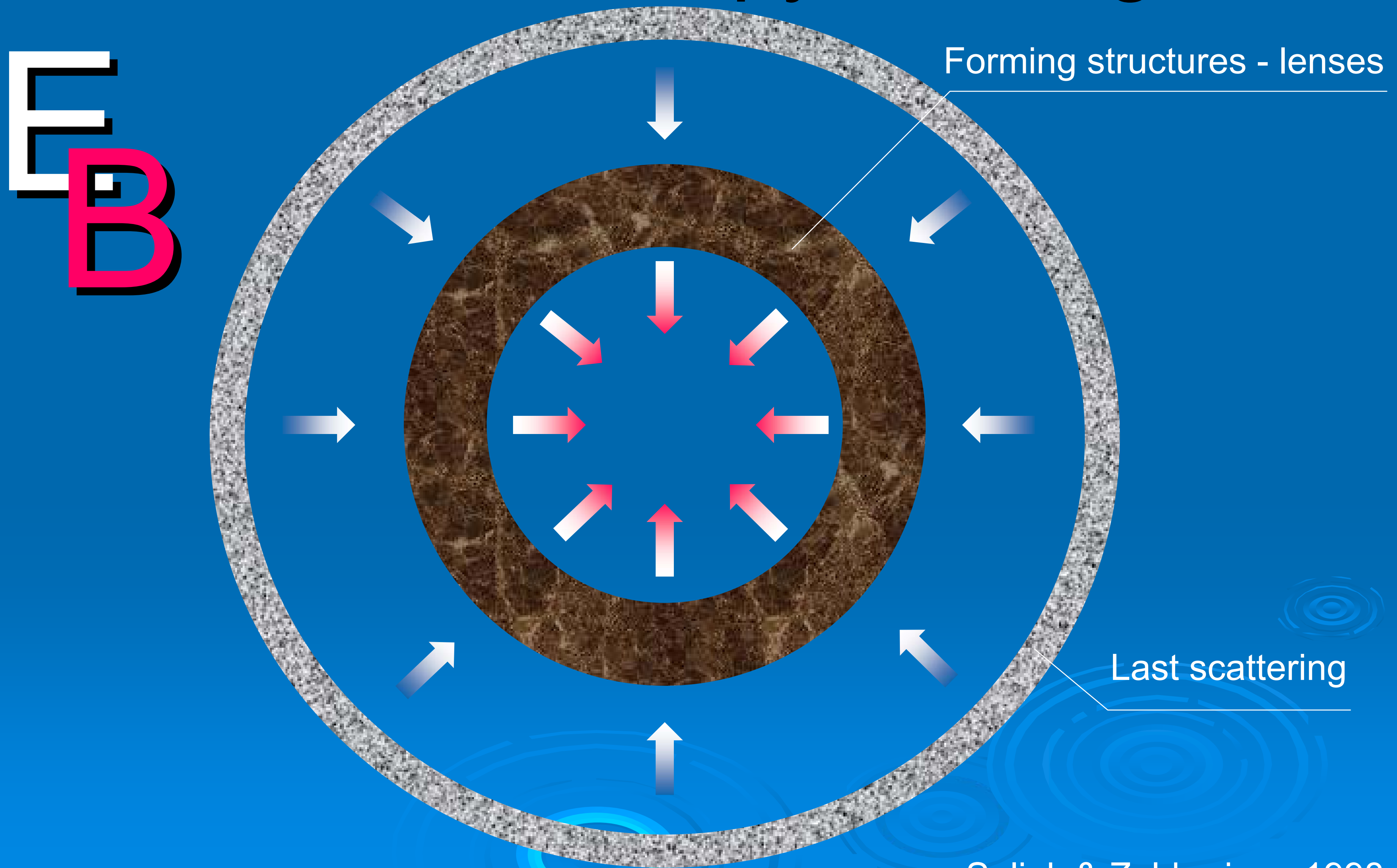
CMB anisotropy: reionization



CMB anisotropy: lensing

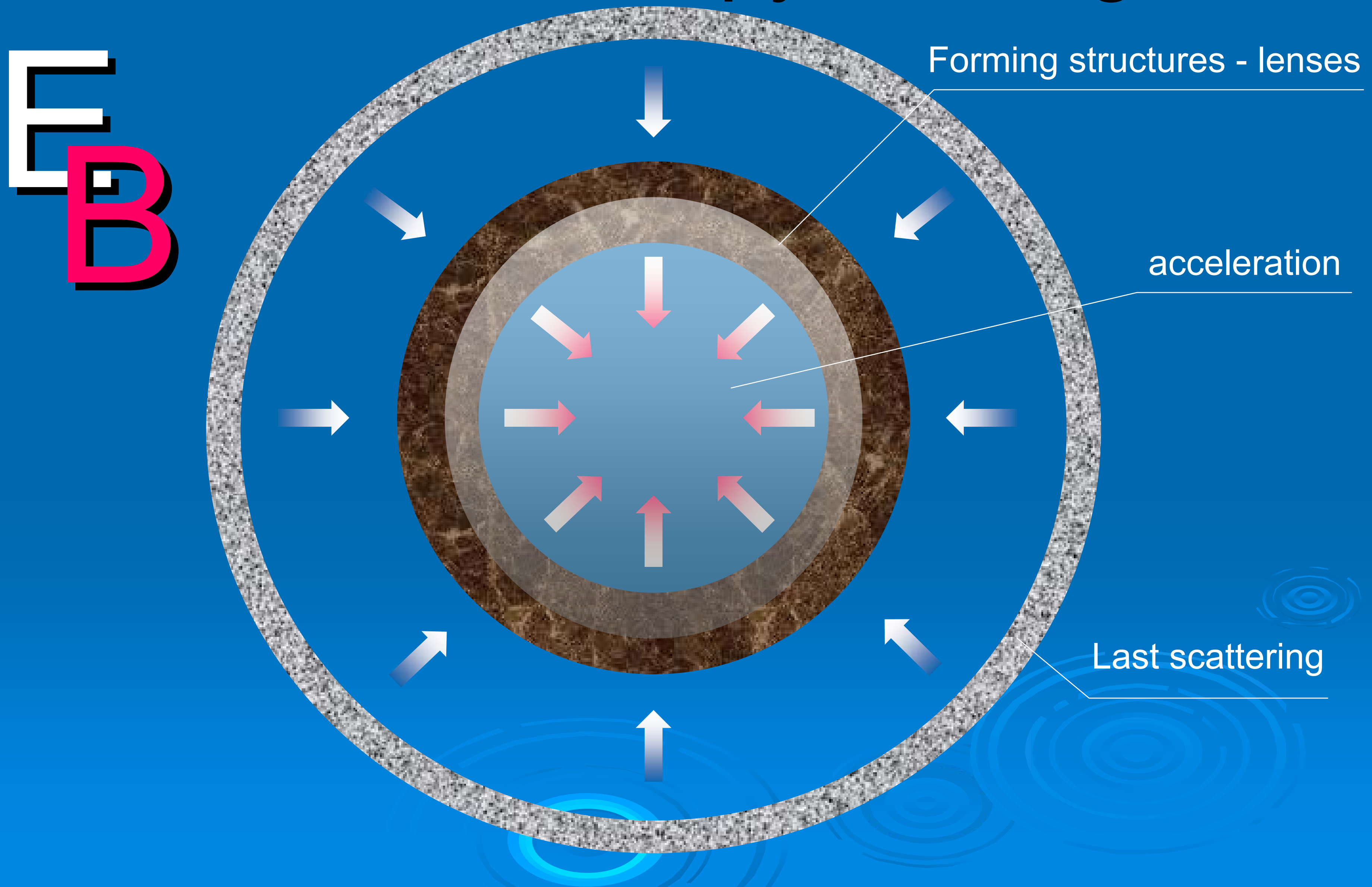


CMB anisotropy: lensing



Seljak & Zaldarriaga 1998

CMB anisotropy: lensing



Status of CMB observations

CMB anisotropies

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

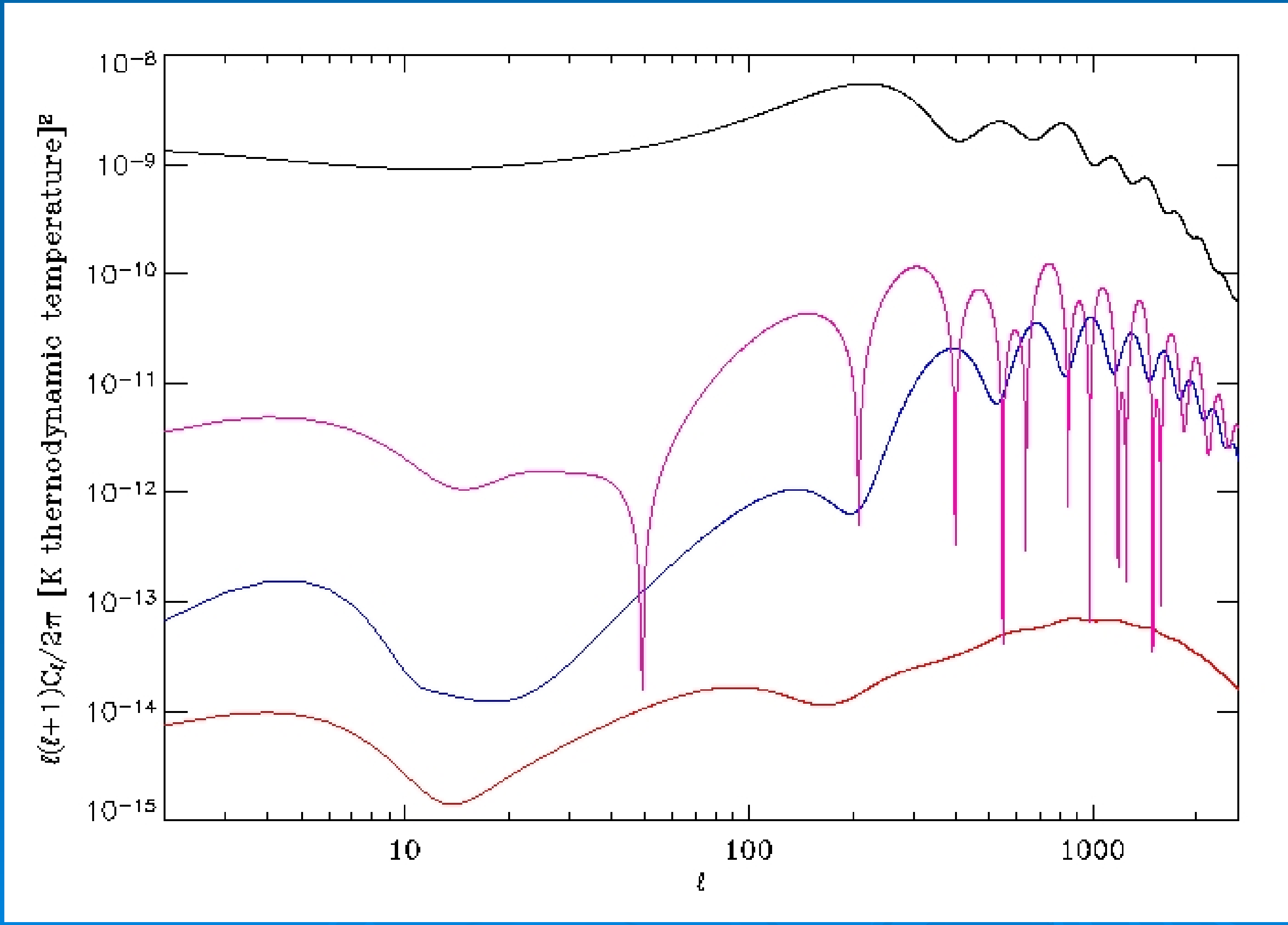
spherical harmonics

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

information compression

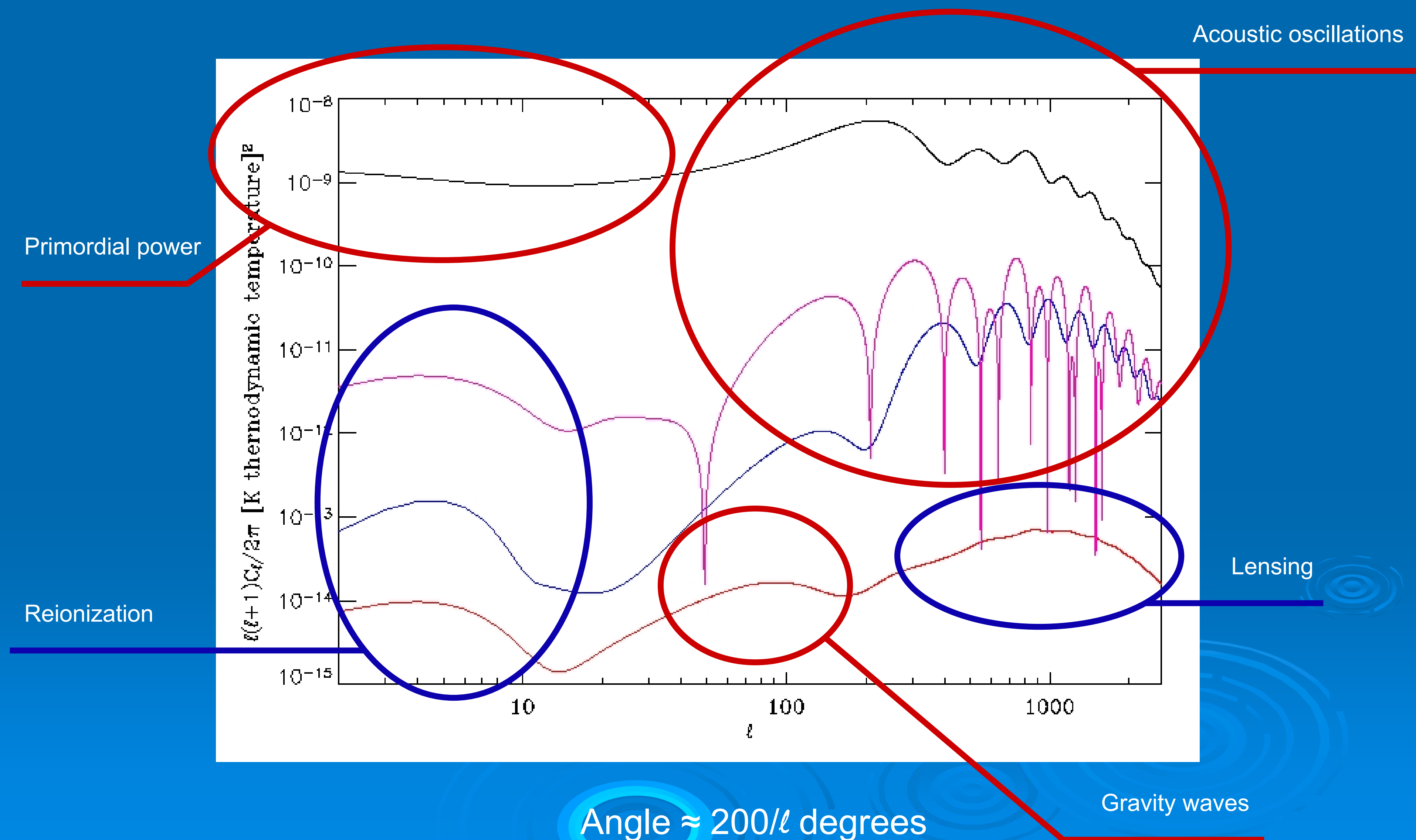
$C_l = \Sigma_m |a_{lm}{}^{T,E,B}|^2 / 2(l+1)$

CMB angular power spectrum



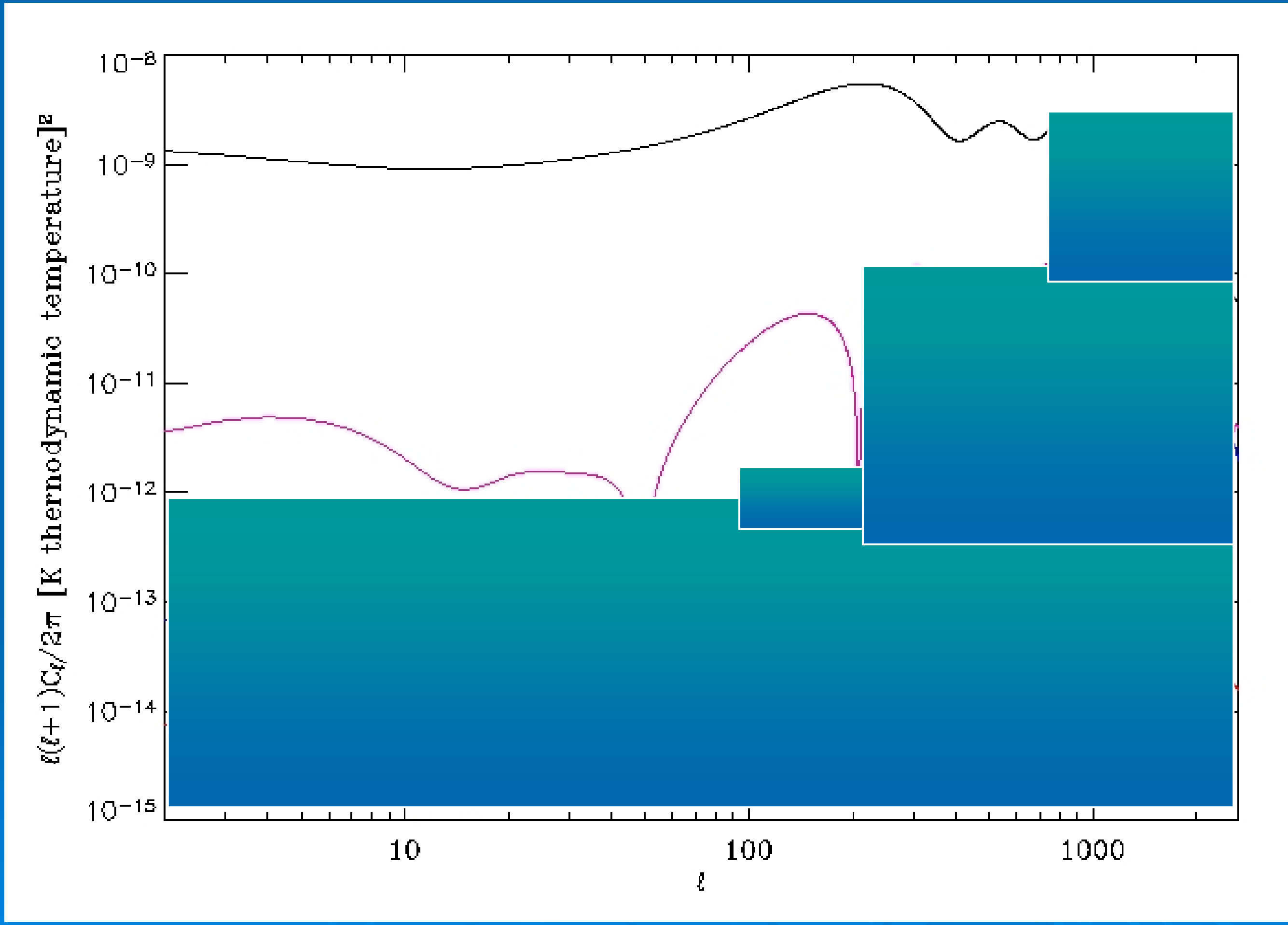
Angle ≈ 200/ℓ degrees

CMB angular power spectrum



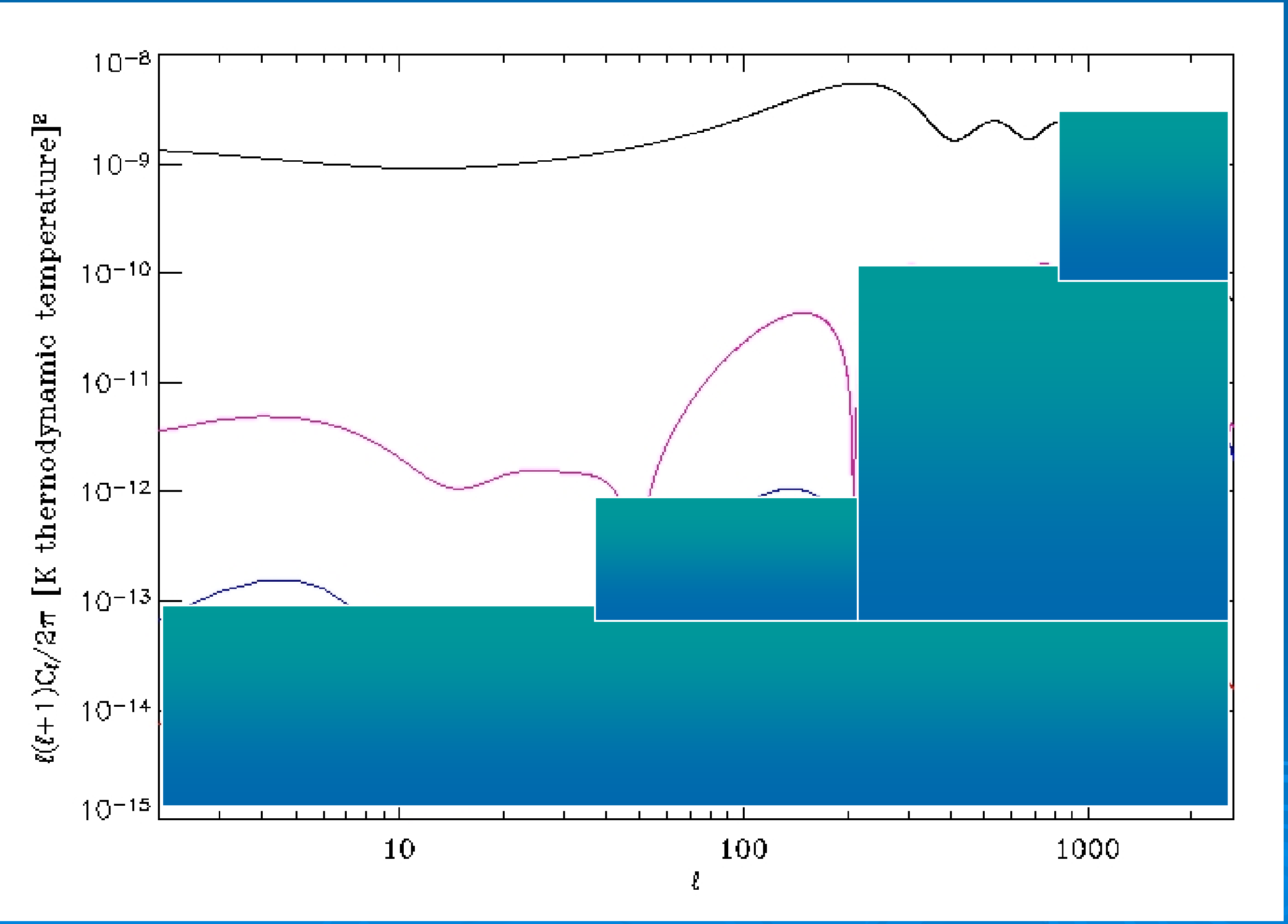
Angle ≈ 200/ℓ degrees

WMAP first year



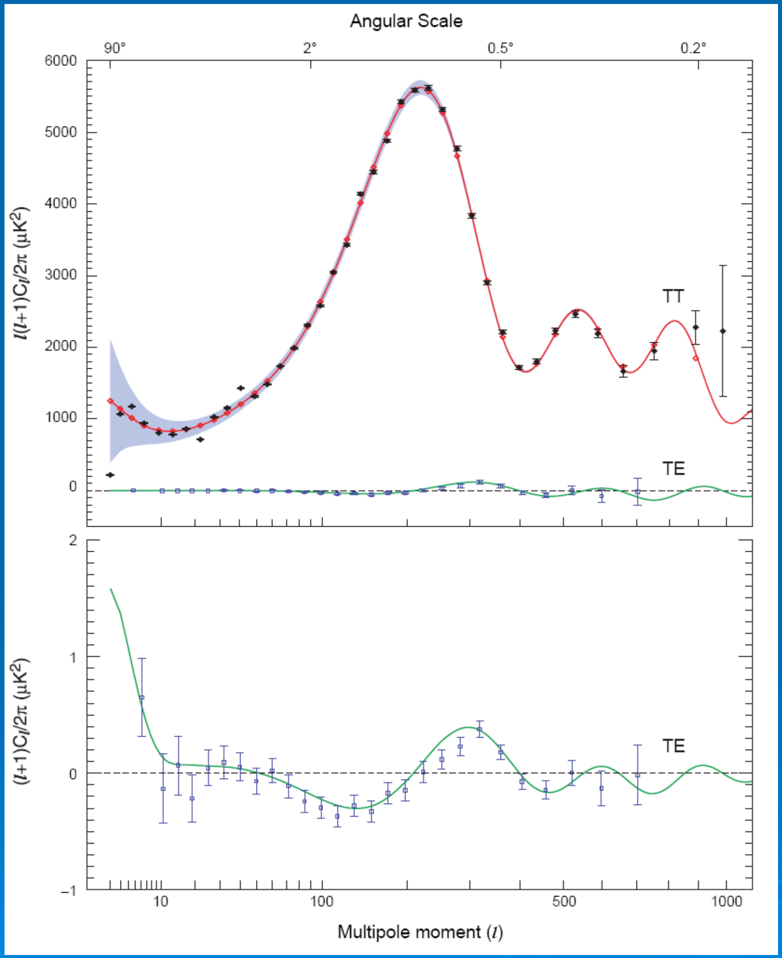
Angle ≈ 200/ℓ degrees

WMAP third year

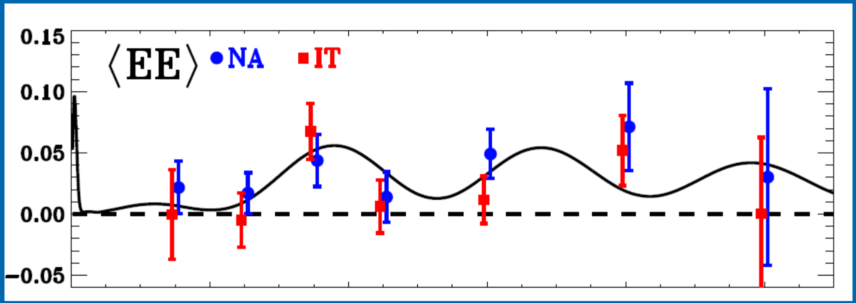


Angle ≈ 200/ℓ degrees

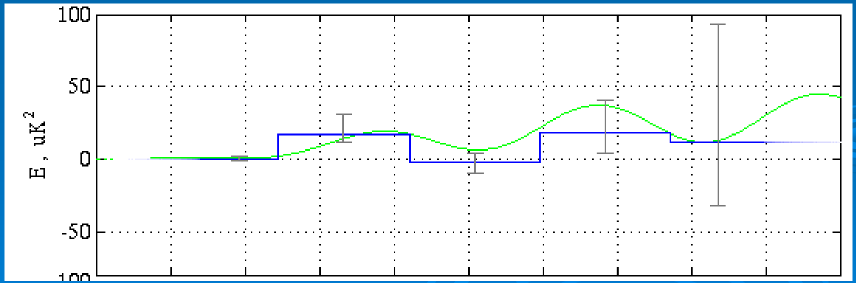
CMB angular power spectrum



WMAP



boomerang



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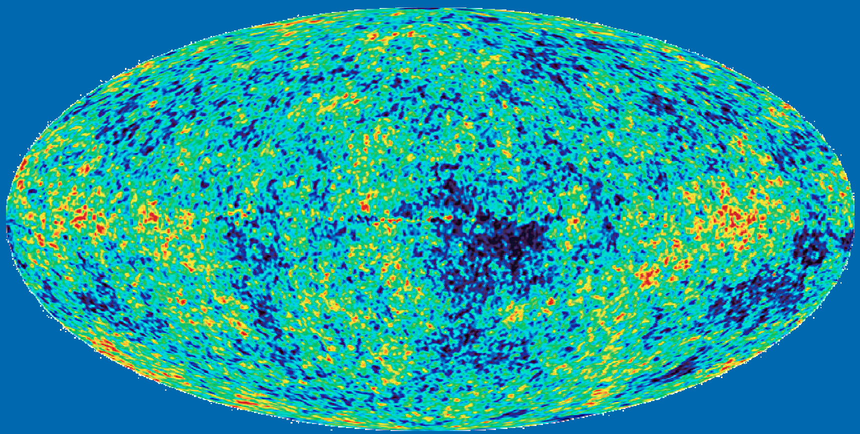
CMB anisotropy statistics: unknown, probably still hidden by systematics

- 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

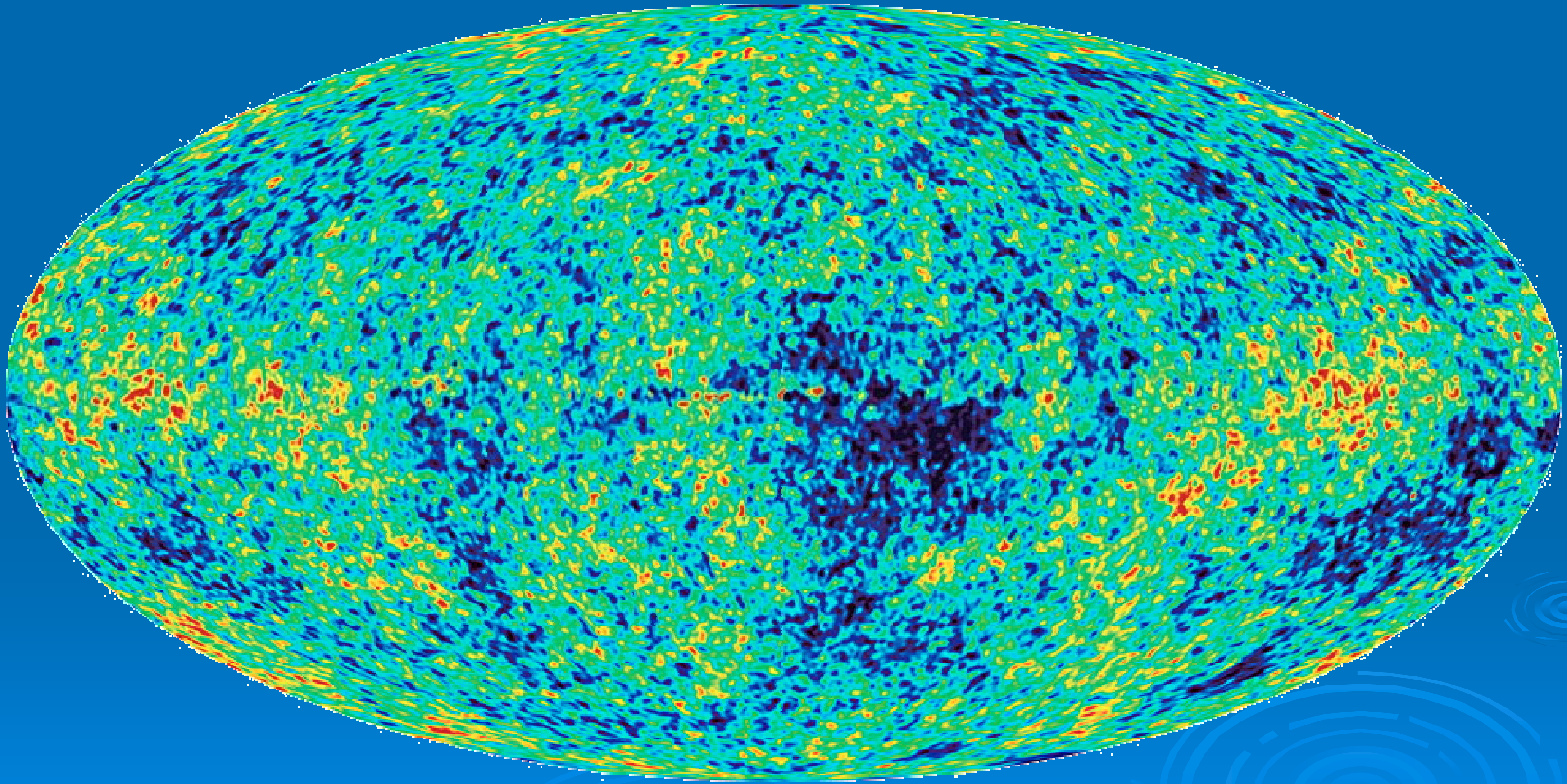


Other cosmological backgrounds?

- 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…

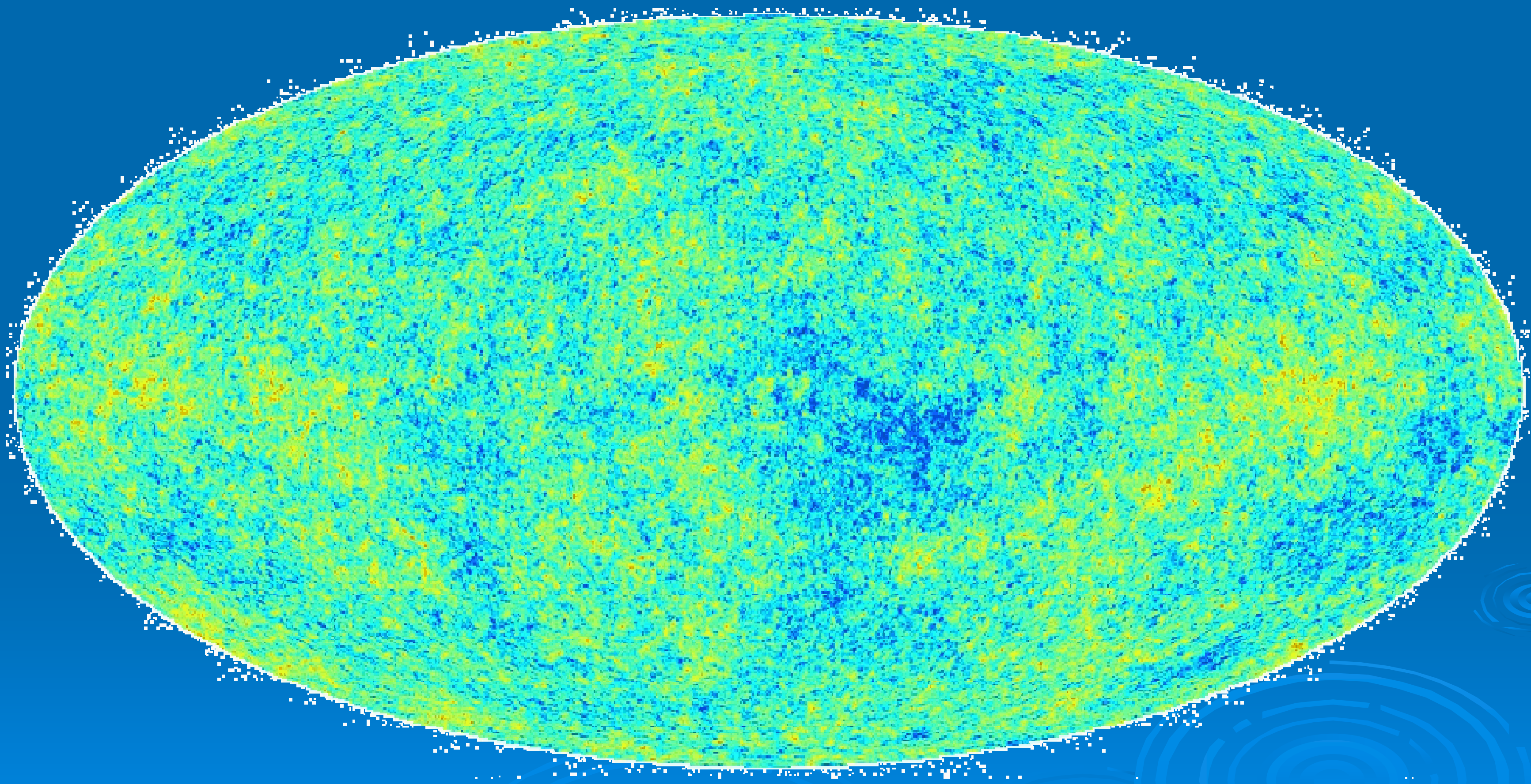
Expectations and challenges for future CMB

CMB 2006, imaging



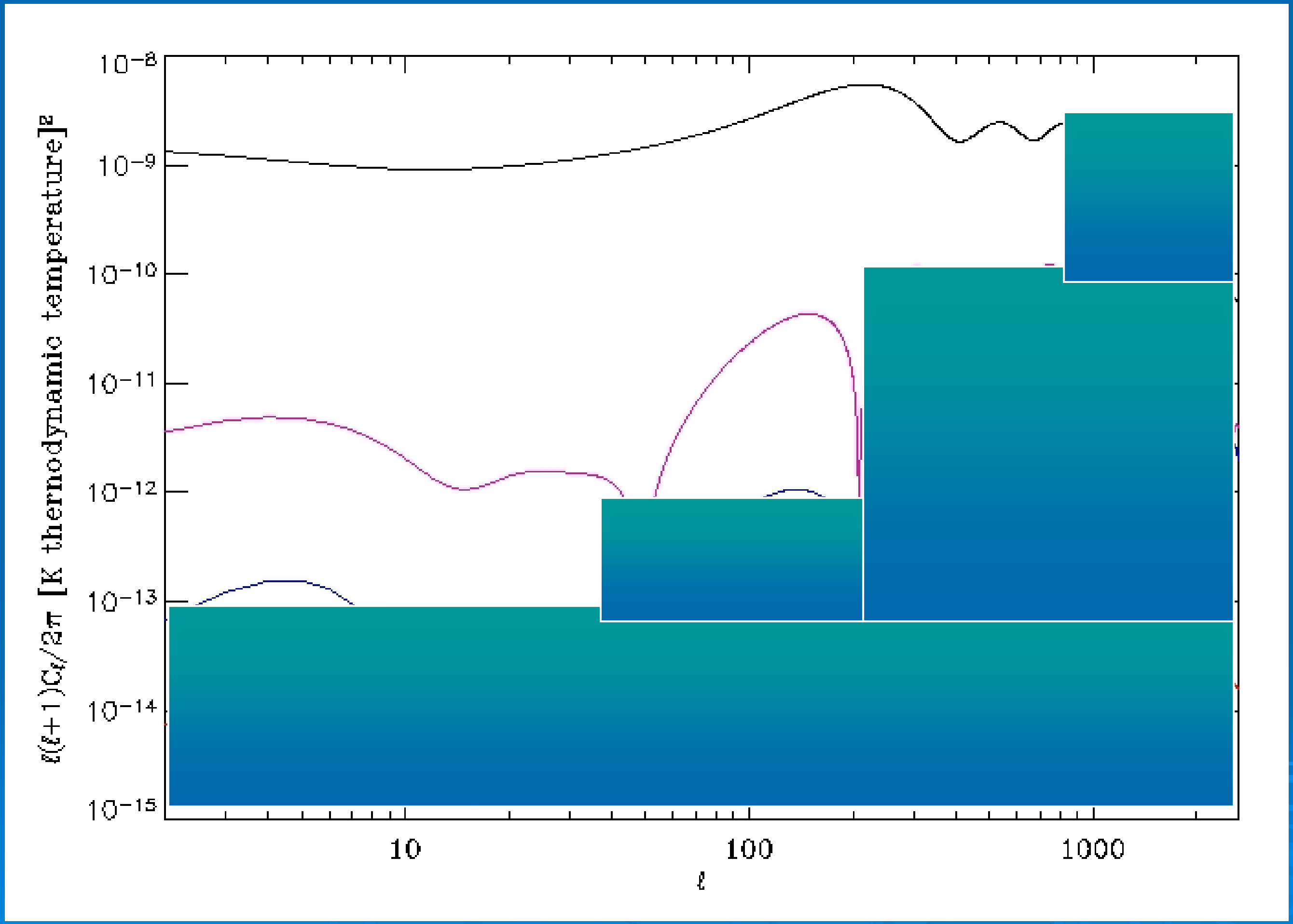
WMAP three years

CMB 2030, imaging



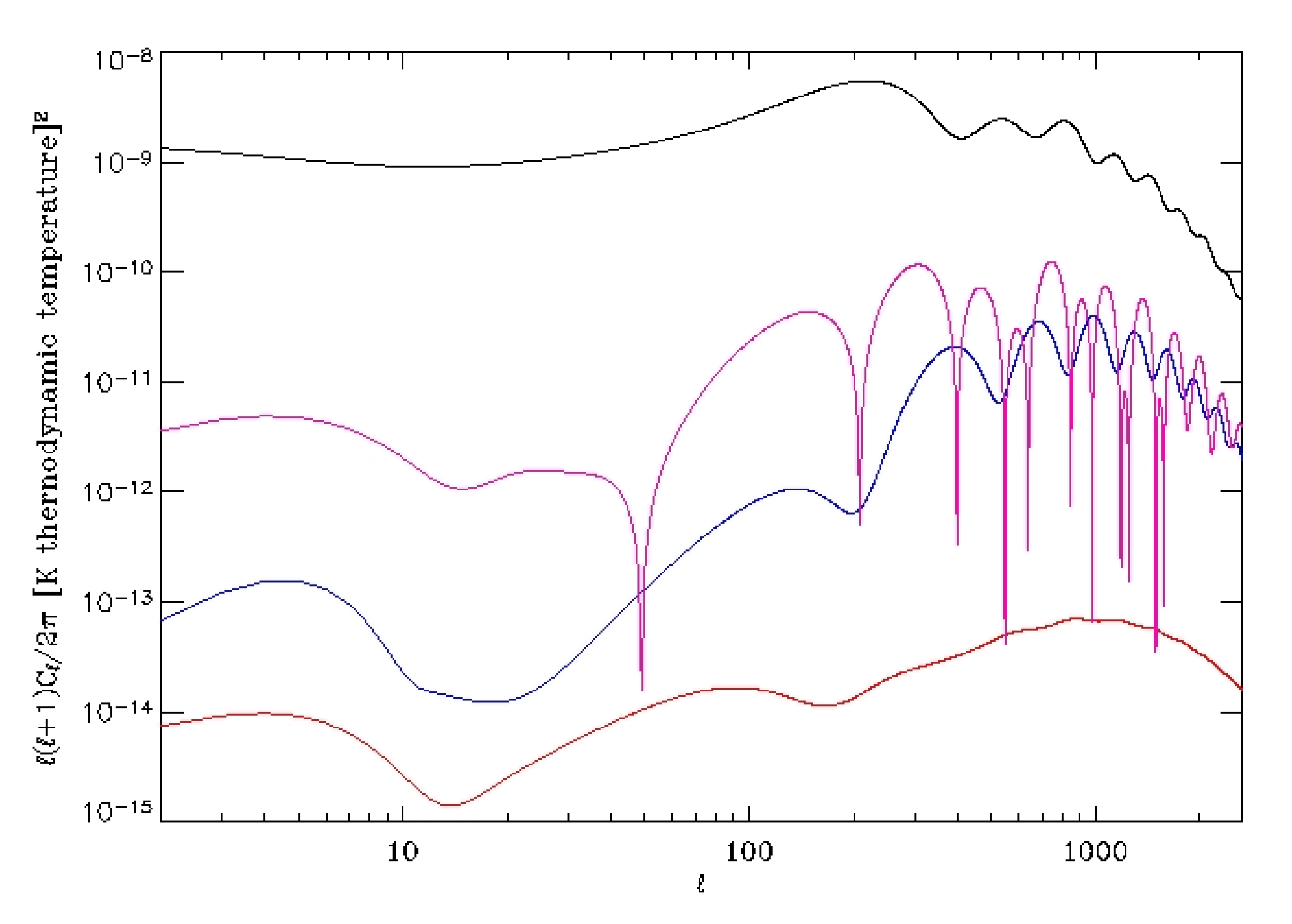
Planck reference sky

CMB 2003, power spectrum



WMAP three years

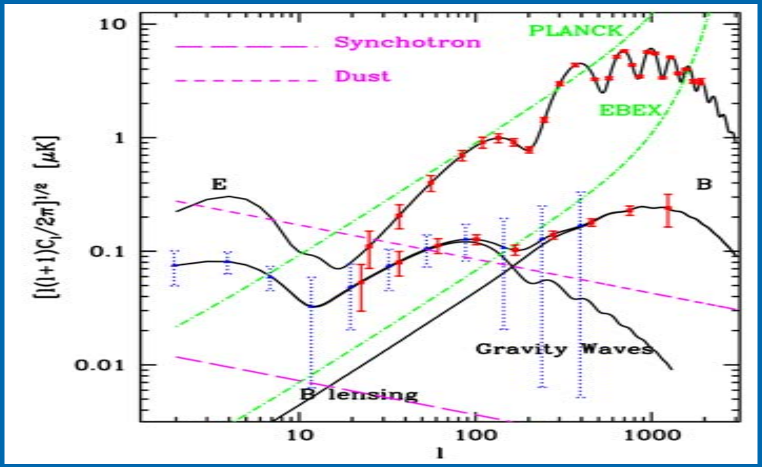
CMB 2030, power spectrum

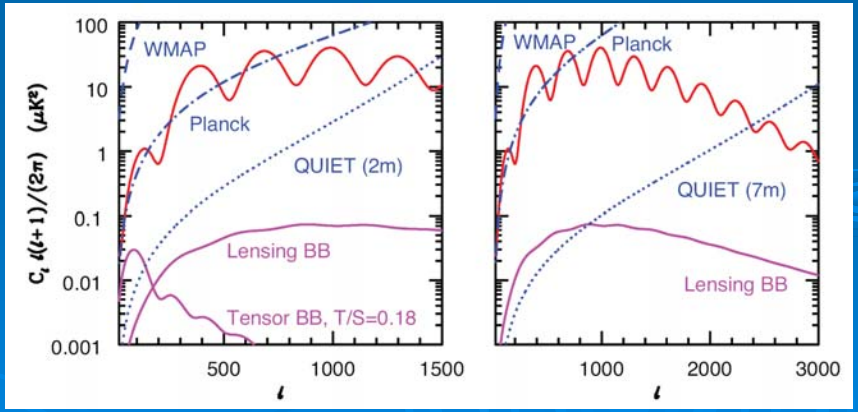


Post-Planck satellite

Forthcoming CMB polarization probes

- Planck
- EBEx (NASA, France, Italy, UK), 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

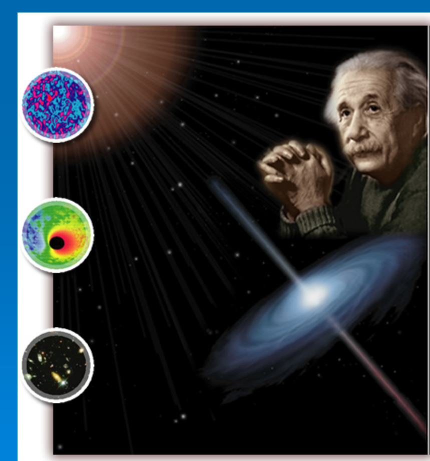




Cosmic vision beyond Einstein

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

Cosmic vision program logo

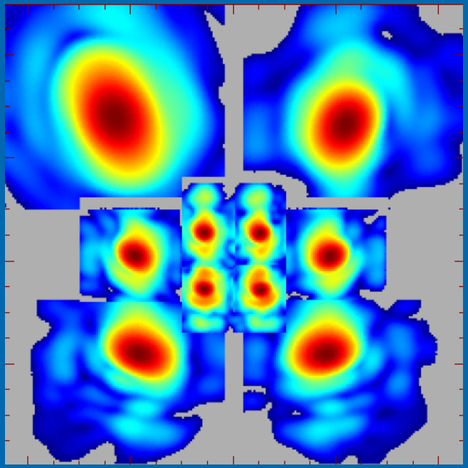


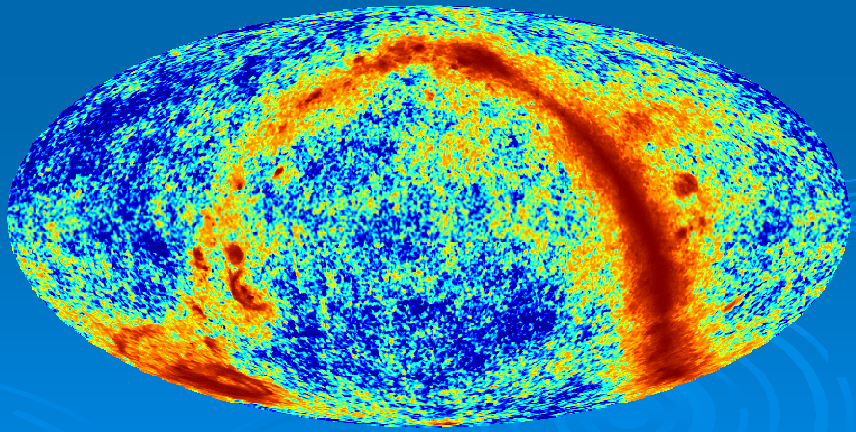
Beyond einstein logo

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 ☹

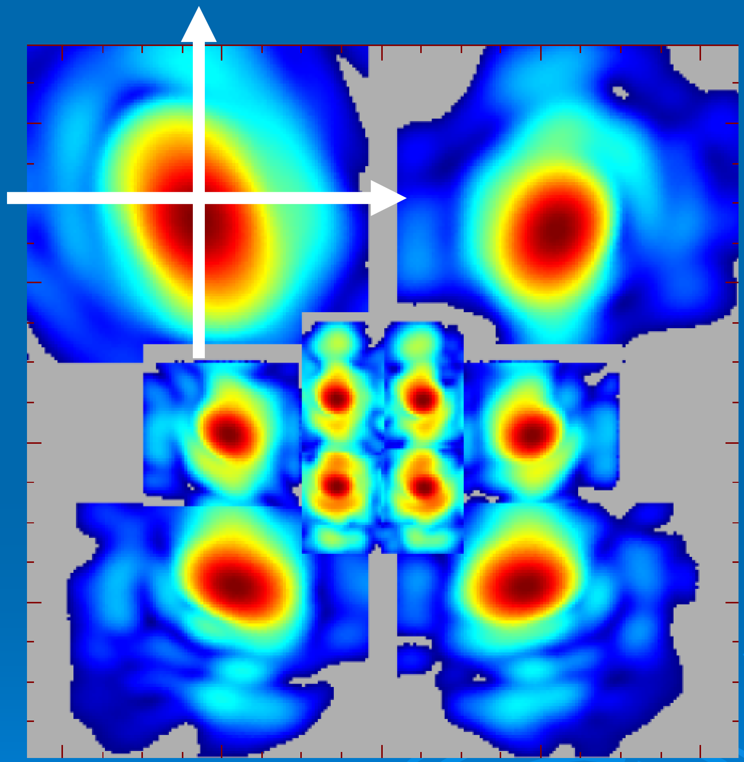
Jarosik et al. 2006





Challenges for future CMB: systematics from beam shape

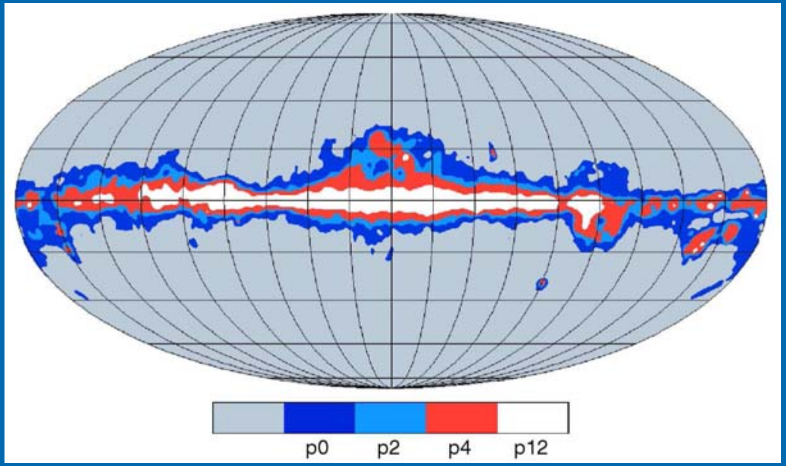
- Asymmetric beams cause unwanted polarization from total intensity, leakage of E modes into B, …
- No way to circularize the beams, rather the beam shape has to be reconstructed in flight to subtract the bias from the signal



Challenges for future CMB: foreground emission

- 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

Bennett et al. 2006



Challenges for future CMB: foreground emission

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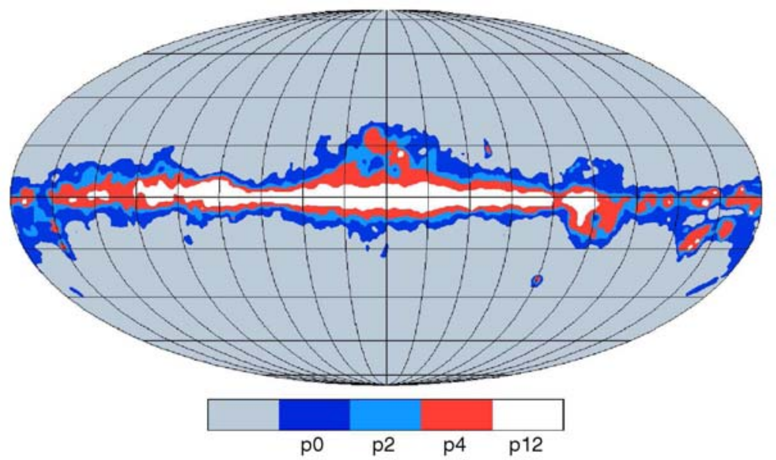
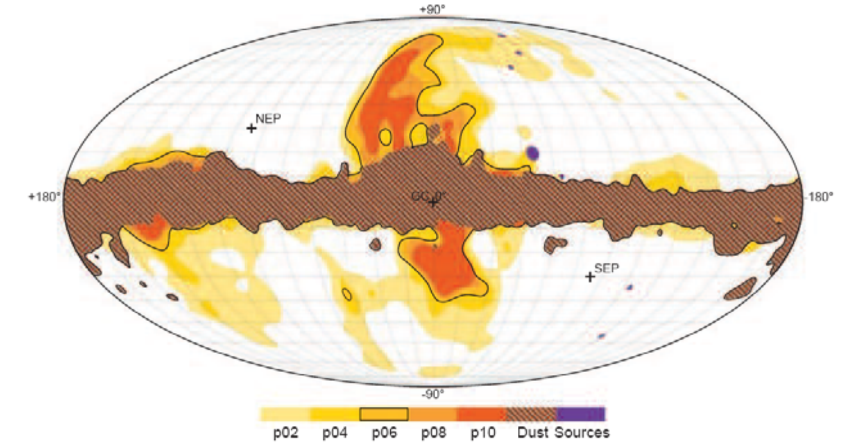
Bennett et al. 2006

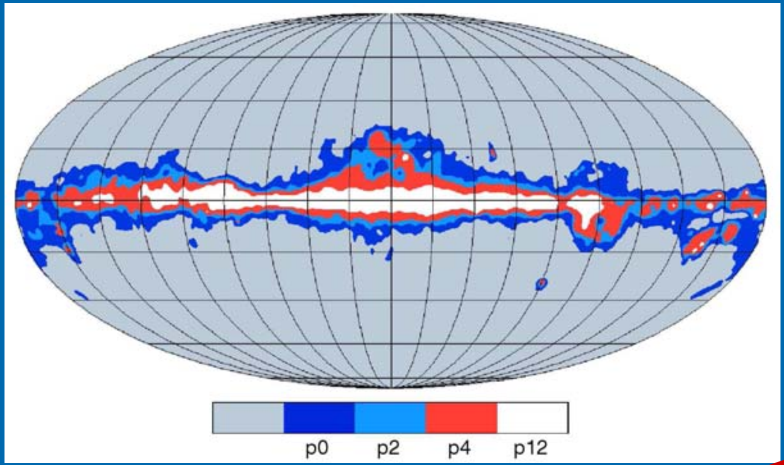




Page et al. 2006

Challenges for future CMB: foreground emission

Bennett et al. 2006



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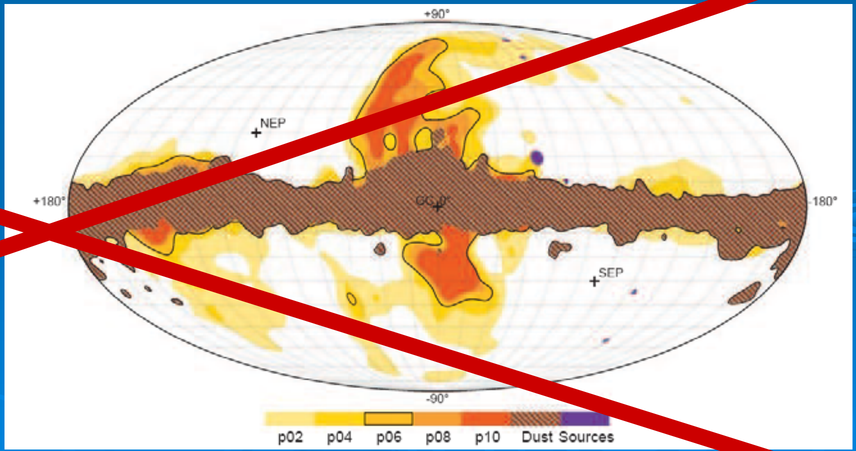
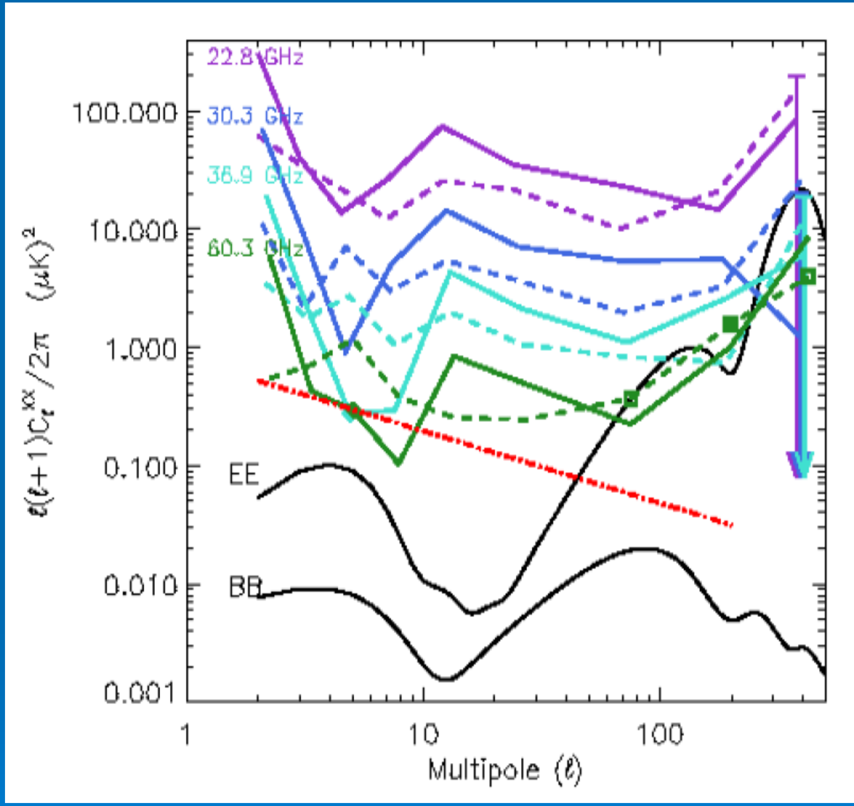
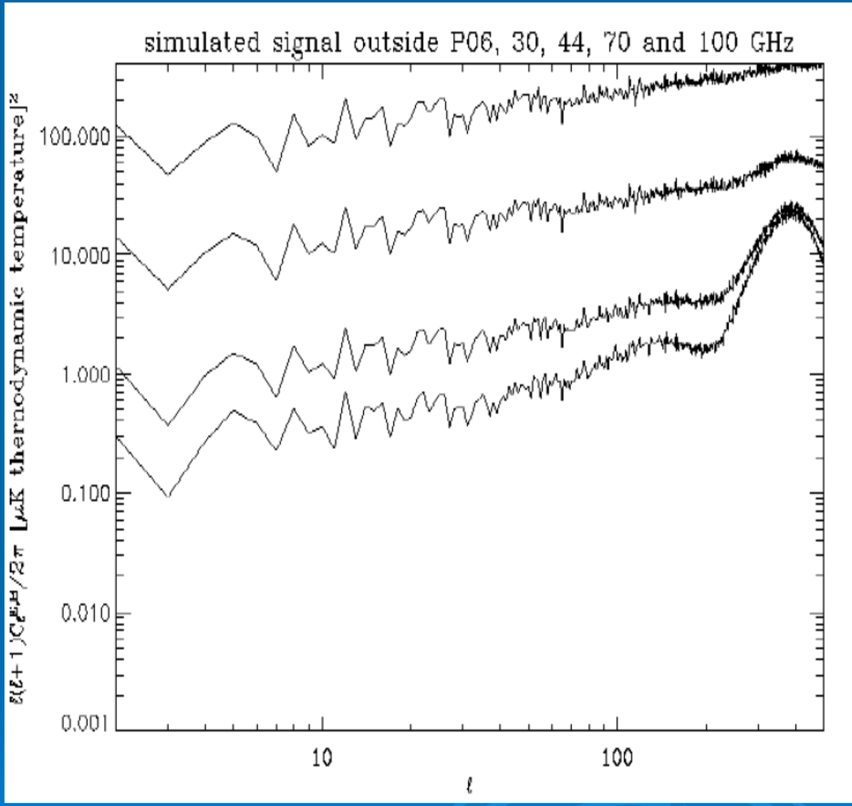


Page et al. 2006

Challenges for future CMB: foreground emission





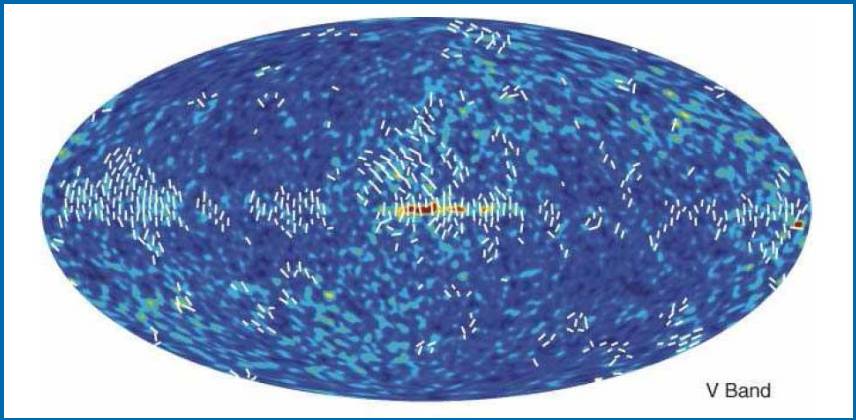
Page et al. 2006

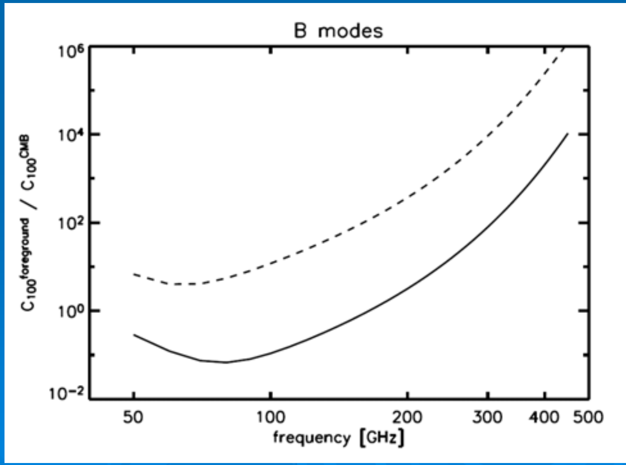
Planck reference sky

Are there foreground clean regions at all in polarization?

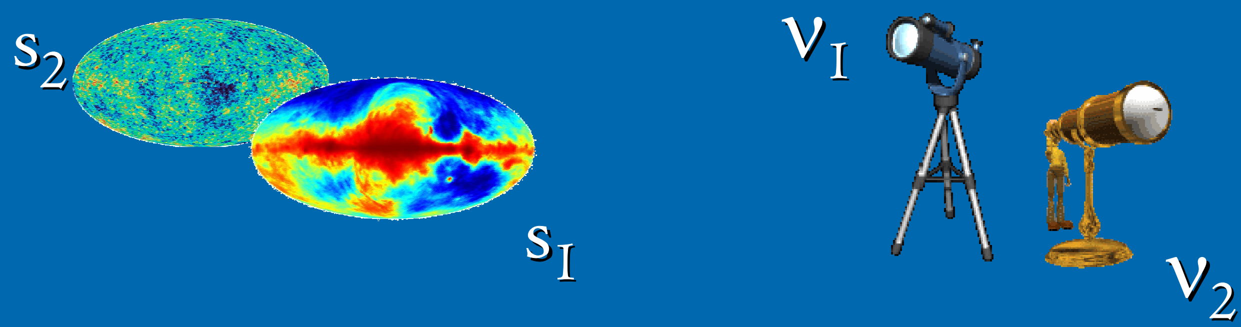
Page et al. 2006

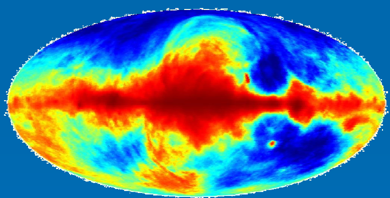
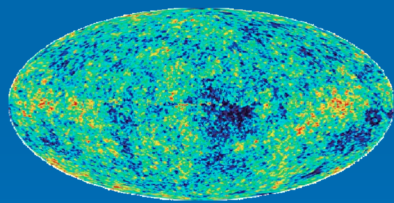
- WMAP has no detection in large sky areas in polarization
- Very naive estimates may be attempted in those areas, indicating that the foreground level might be comparable to the cosmological B mode at all frequencies, in all sky regions

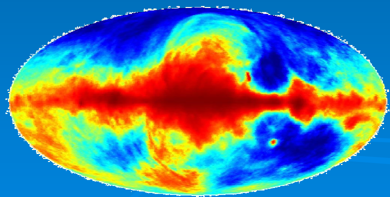
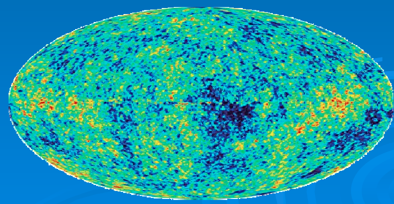




Living with foregrounds: component separation

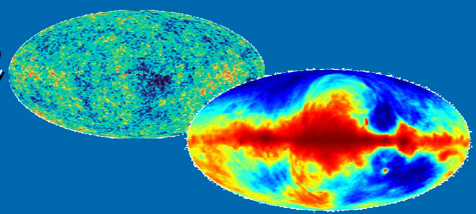


$x_1 = a_{11}$  $+ \, a_{12}$  $+ \, n_1$

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

Living with foregrounds: component separation

s_2



s_1

ν_1

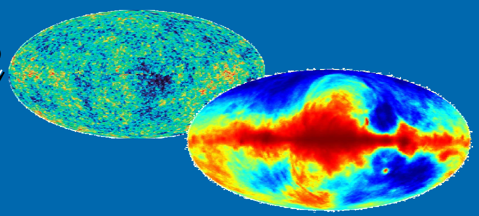
ν_2

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

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

Living with foregrounds: component separation

s_2



s_1

ν_1

ν_2

$$x = As + n$$

Invert for s!

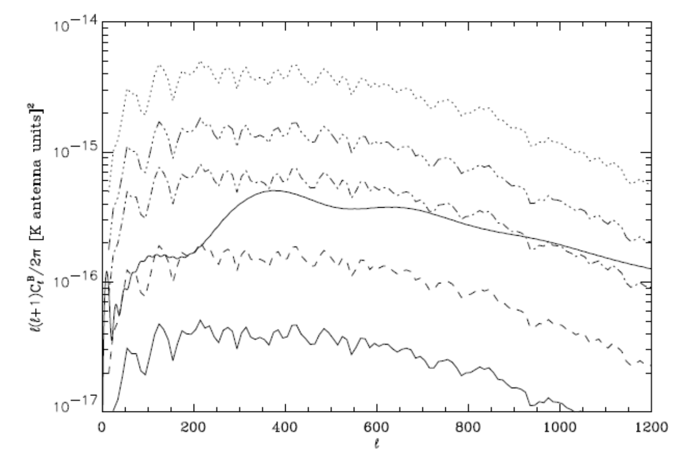
Living with foregrounds: component separation

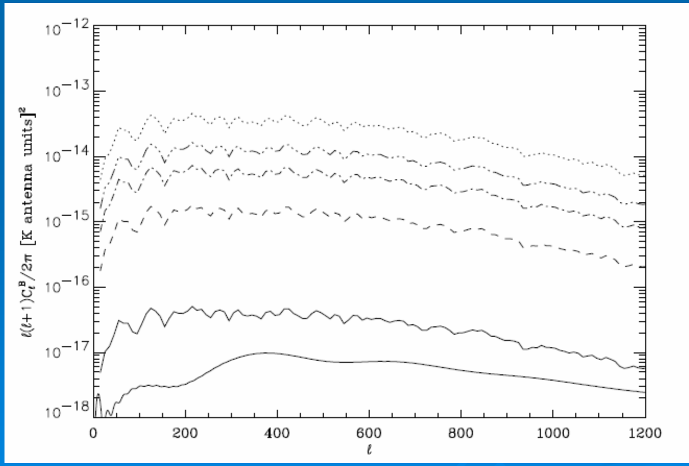
$$x = As + n$$

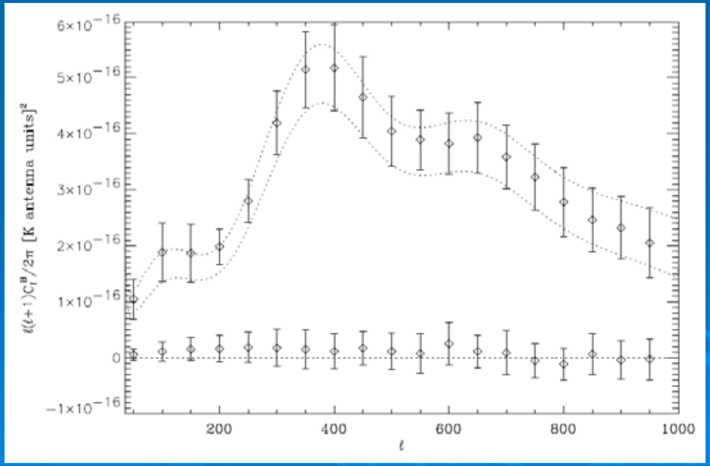
- Non-blind approach: use prior knowledge on A and s in order to stabilize the inversion, likely to be suitable for total intensity
- Blind approach: do not assume any prior either on A or s, likely to be used in polarization
- Relevant literature from Brandt et al. 1994, to Maino et al. 2006, successful 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







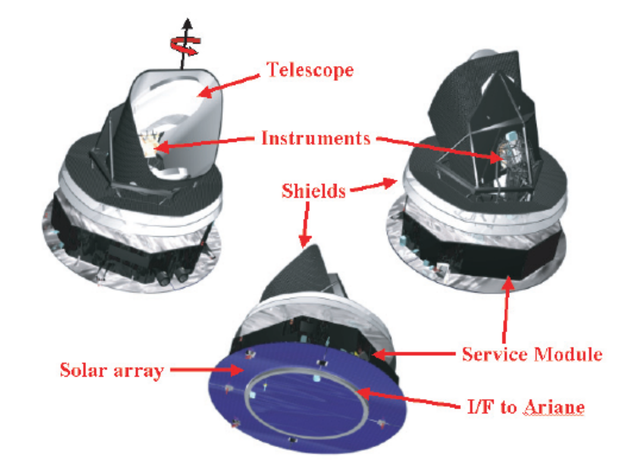
Stivoli et al. 2006

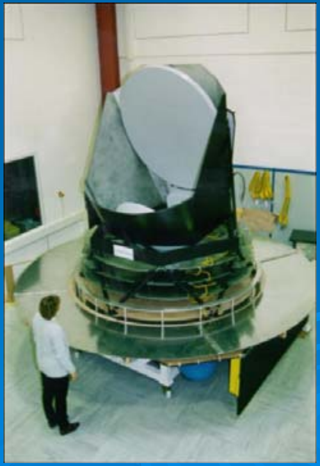
The science goals of the Planck satellite

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

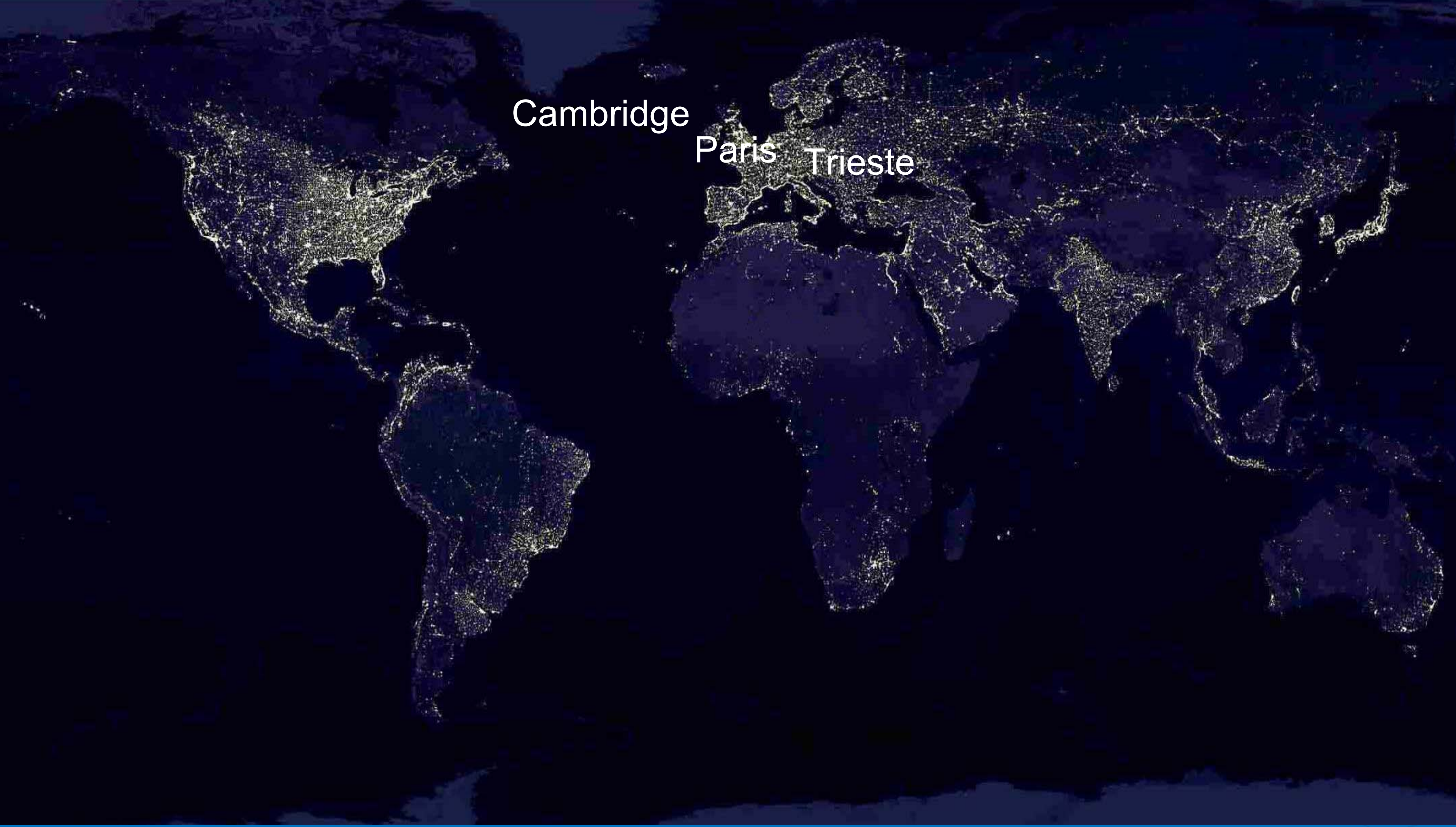
Planck

- 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)





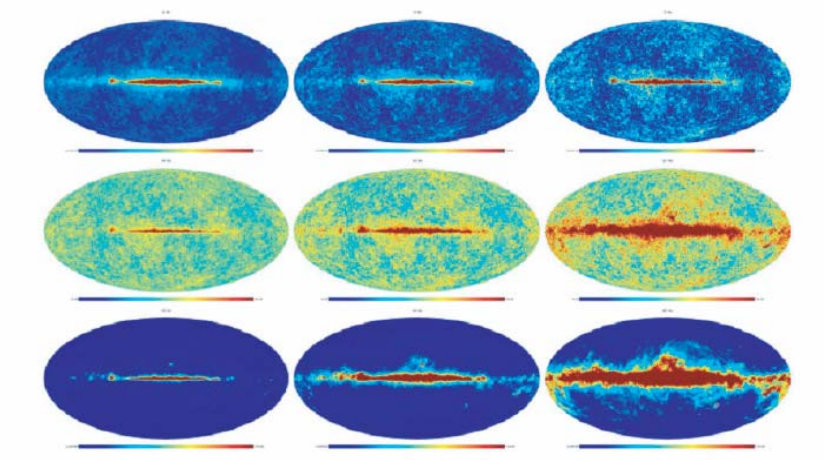
Planck contributors



Planck data processing sites

Planck data deliverables

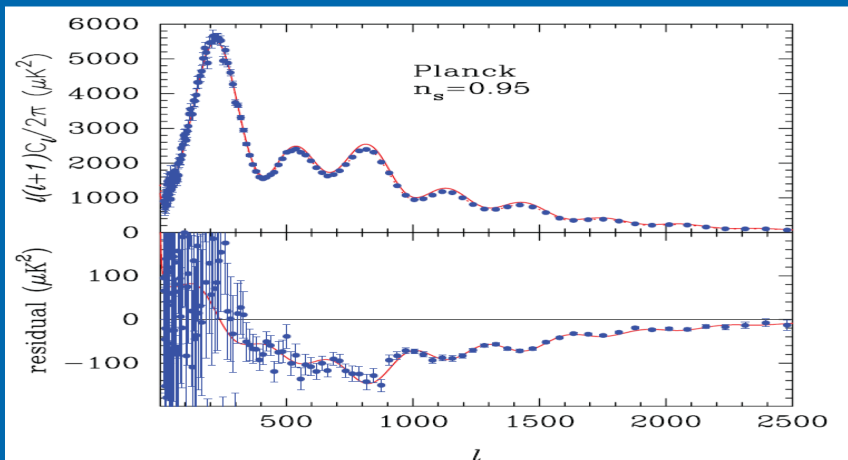
- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33' to 7' between 30 and 143 GHz, 5' at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

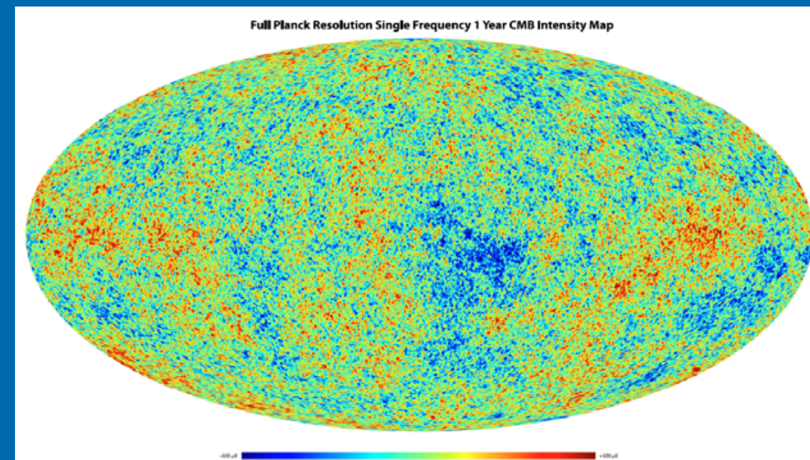


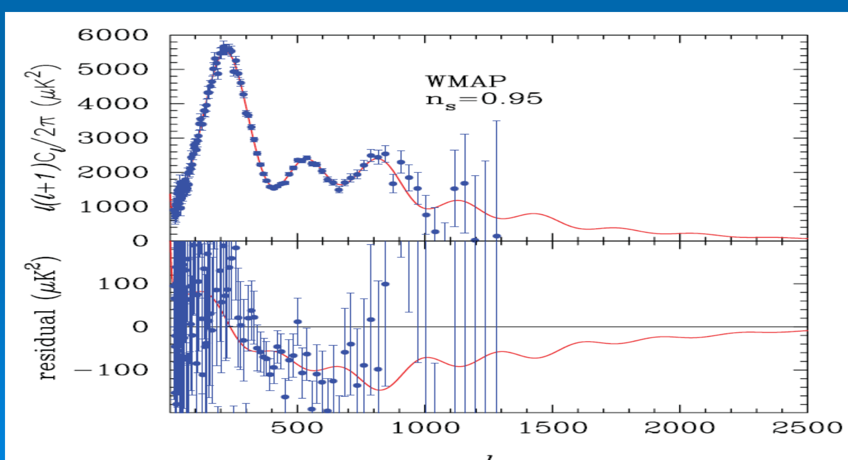
PLANCK GALAXY SURVEYS

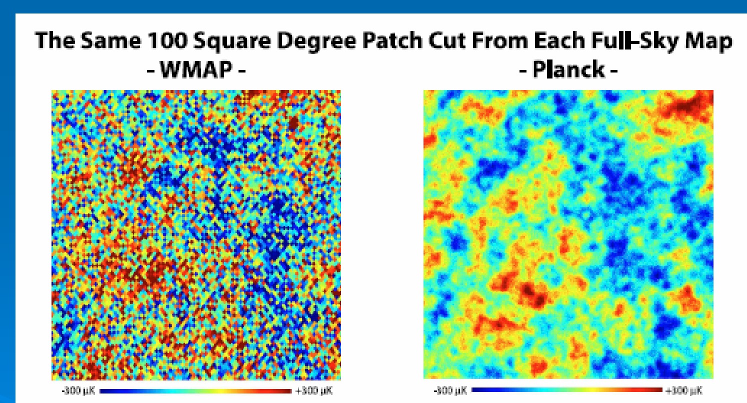
	FREQUENCY [GHz]				
	143	217	353	550	850
Confusion limit [mJy, 3σ]	6.3	14.1	44.7	112	251
Planck All Sky Survey sensitivity [mJy, 3σ]	26	37	75	180	300
Planck Deep Survey sensitivity [mJy, 3σ]	10	18.4	49	170	280
Number of galaxies [all sky]	570	860	1700	4400	35000

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

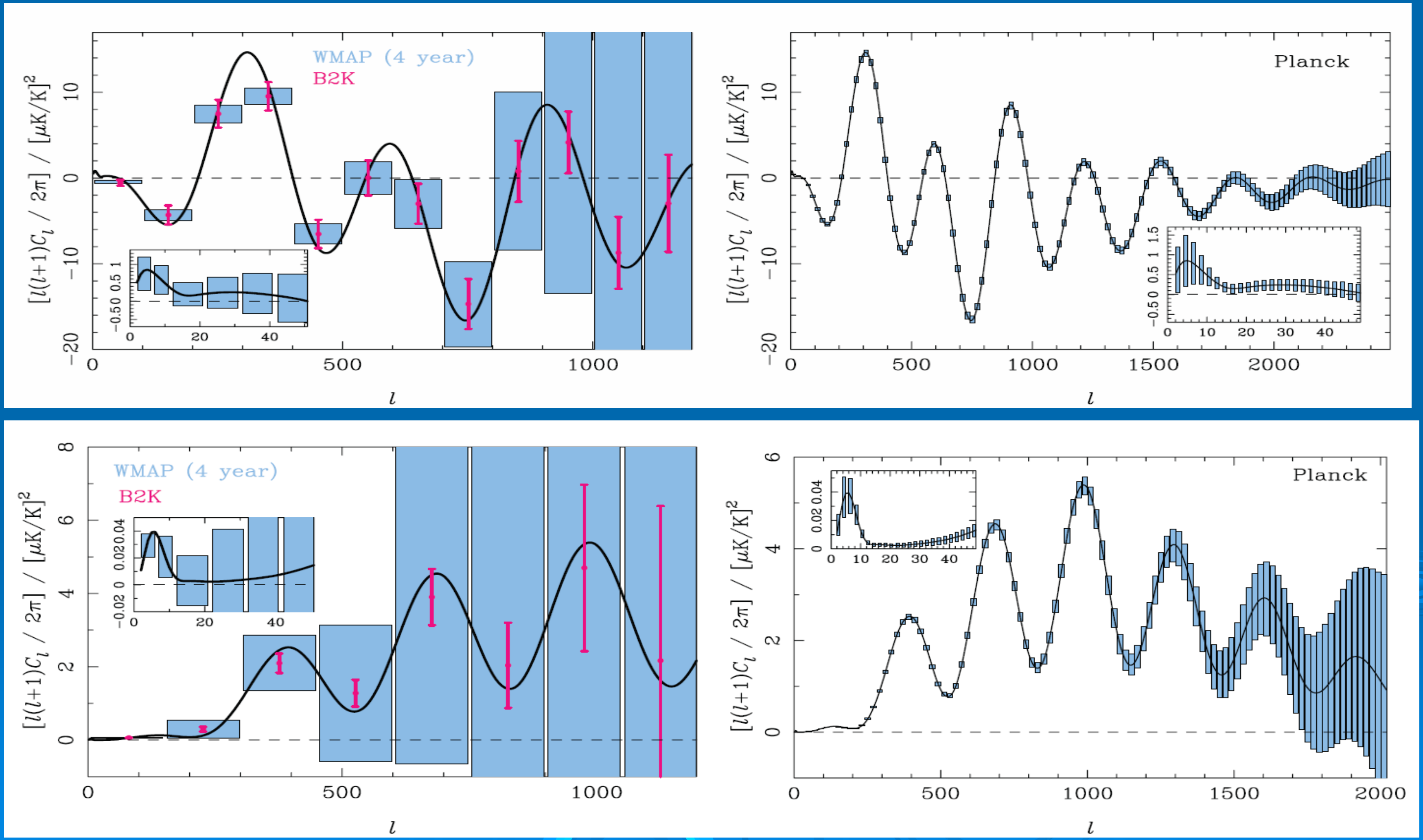




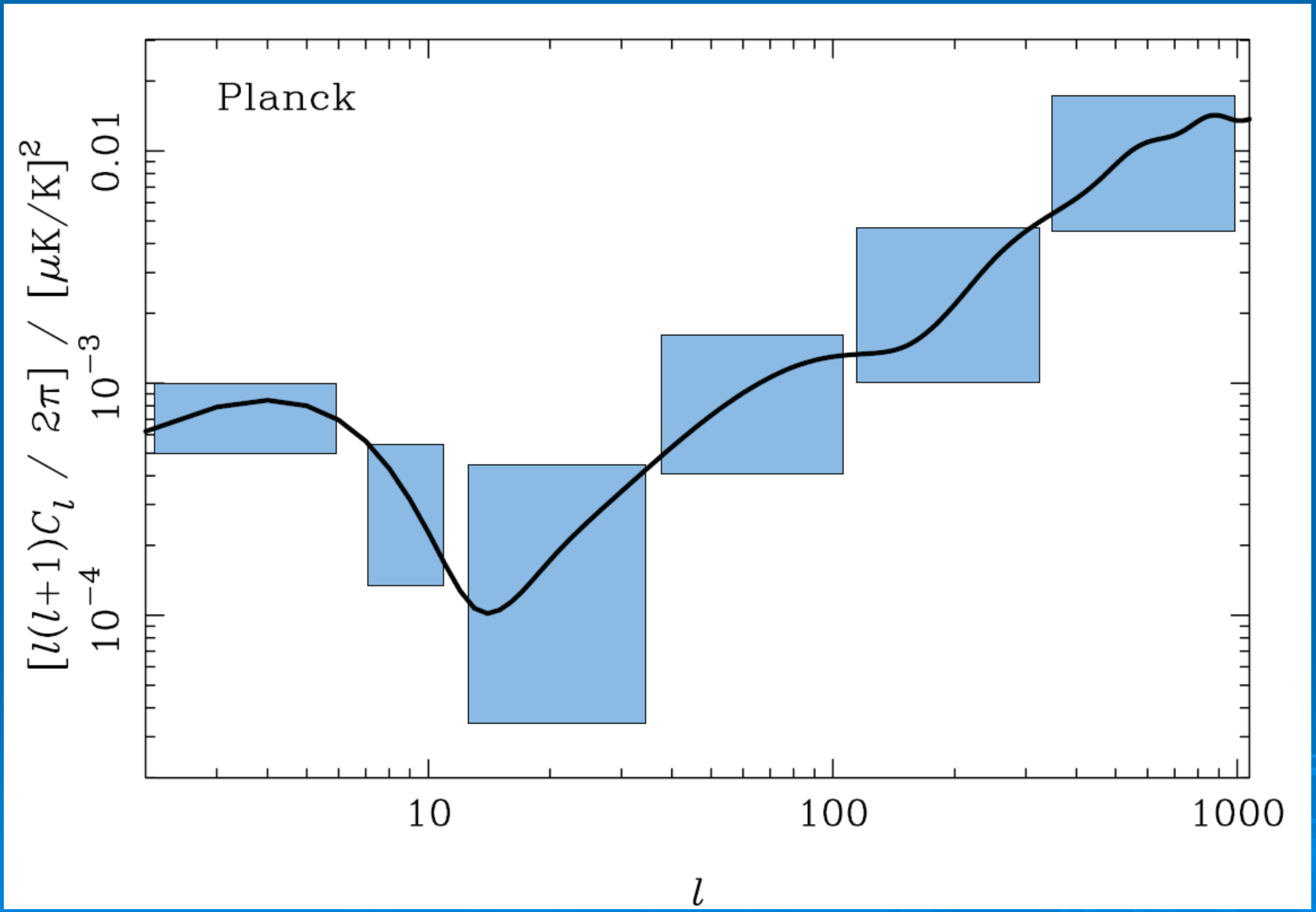




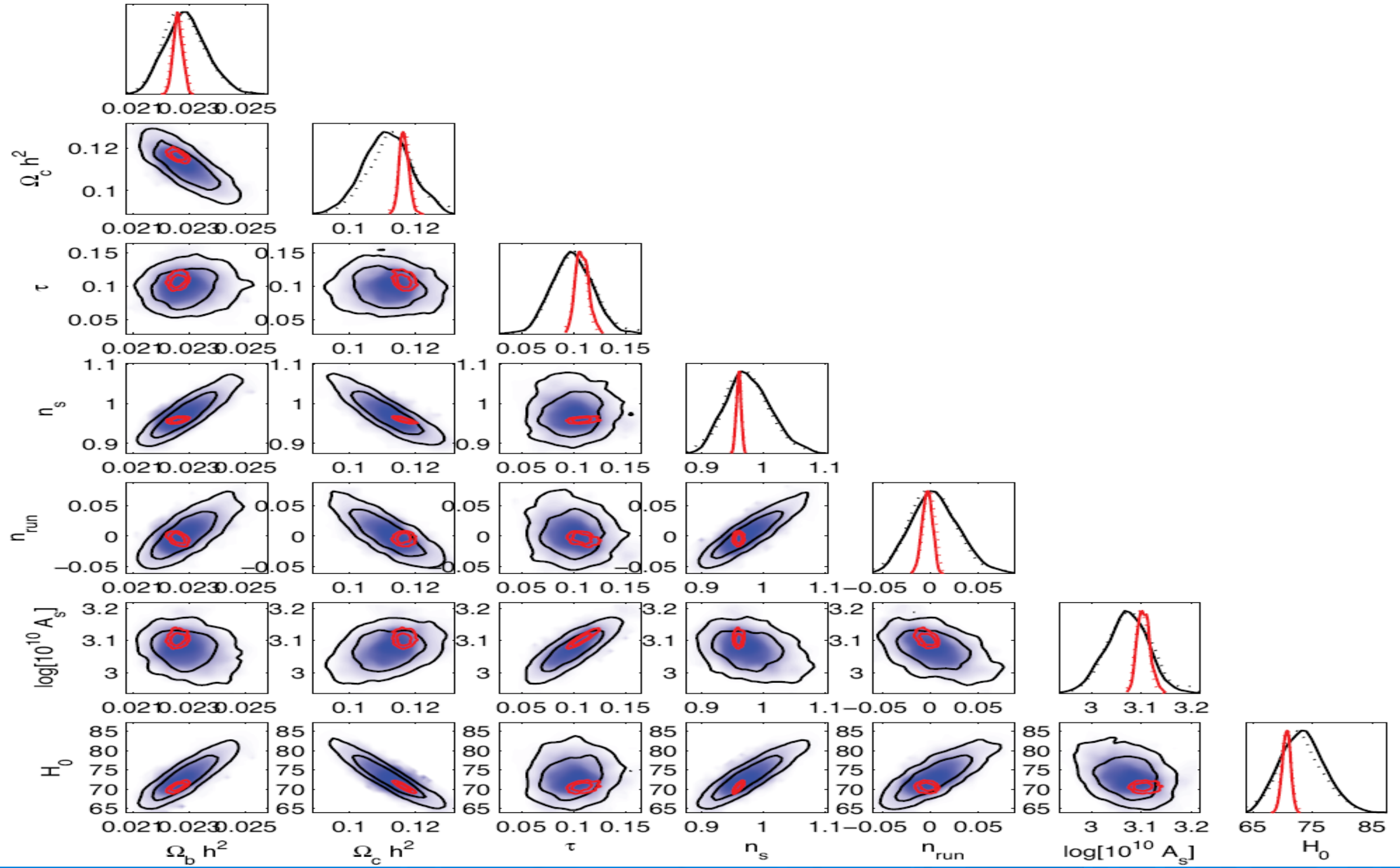
Planck scientific deliverables: CMB polarization



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, 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

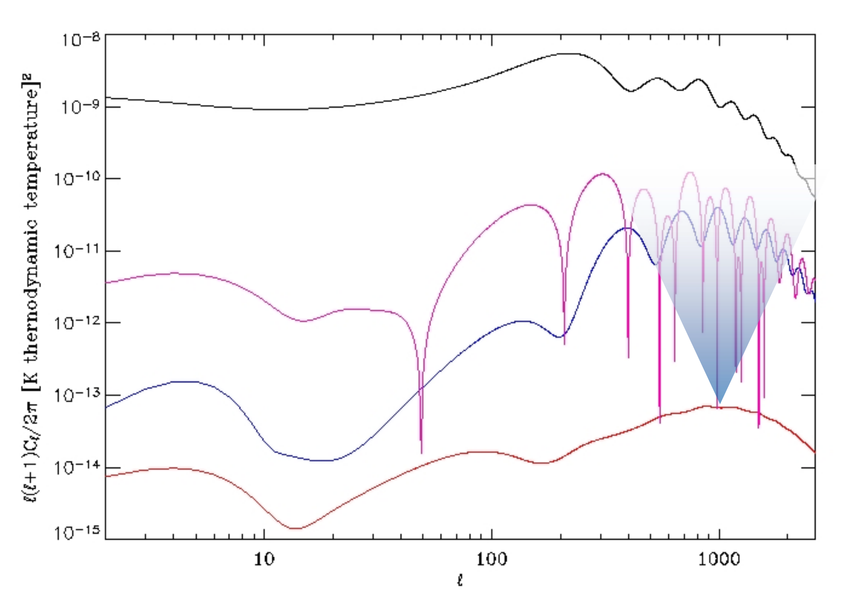
☺

- 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: 20 years

Add-on I: CMB lensing and dark energy

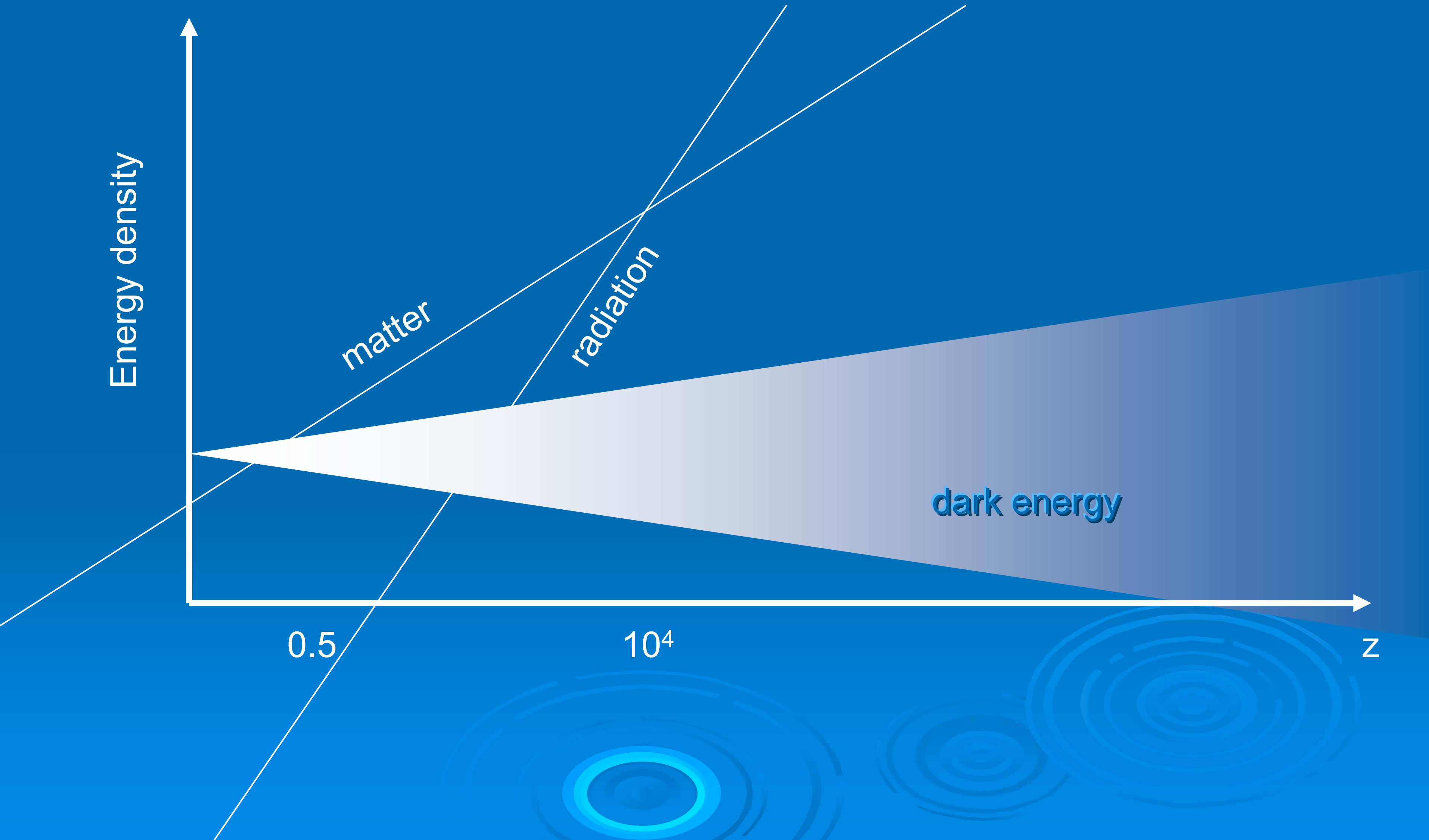
CMB lensing: a science per se

- Lensing is a second order cosmological effect
- Lensing correlates scales
- The lensing pattern is non-Gaussian
- Statistics characterization in progress, preliminary investigations indicate an increase by a factor 3 of the uncertainty from cosmic variance

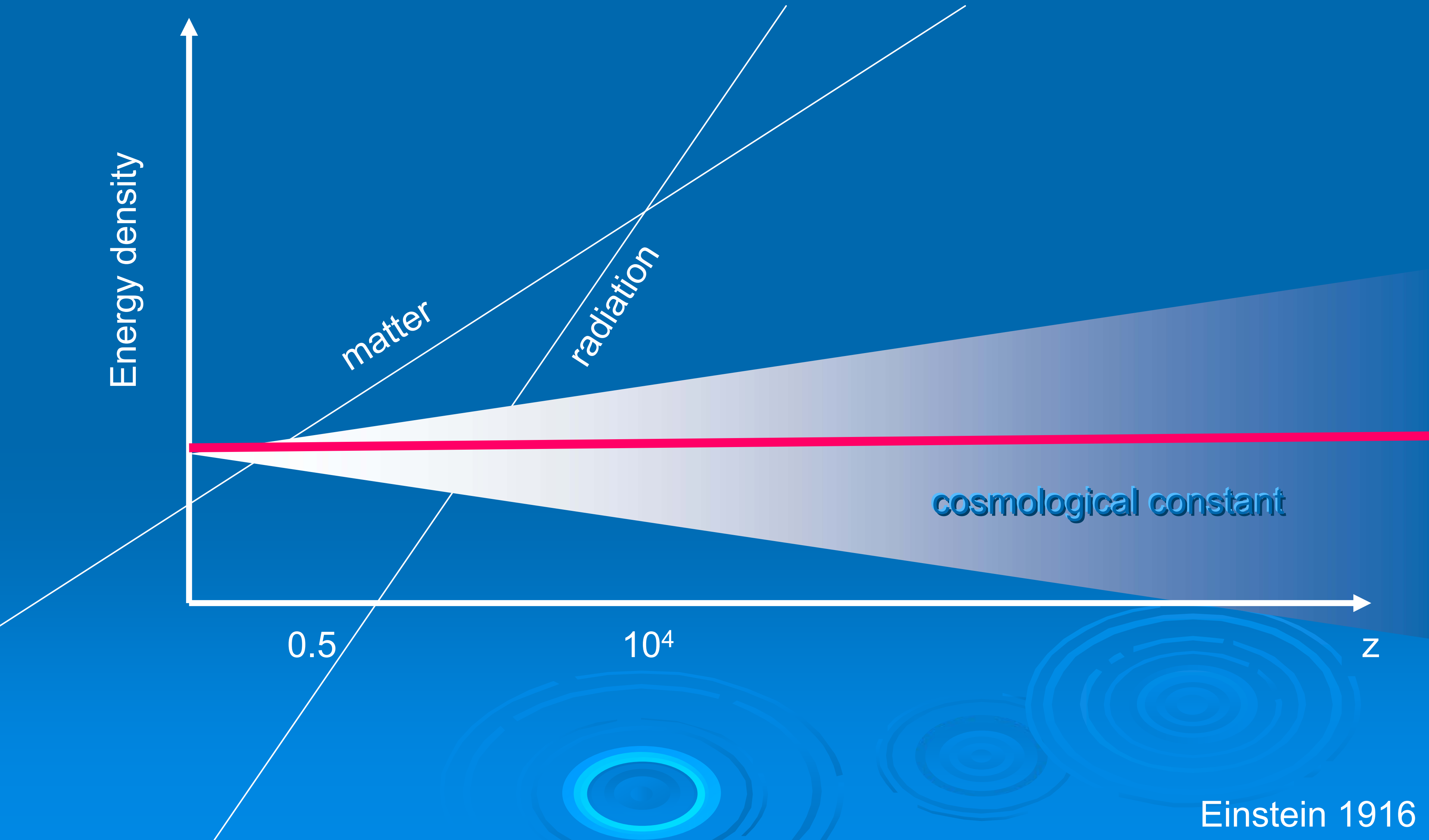


Smith et al. 2006, Lewis & Challinor 2006, Lewis 2005, …

CMB lensing and dark energy

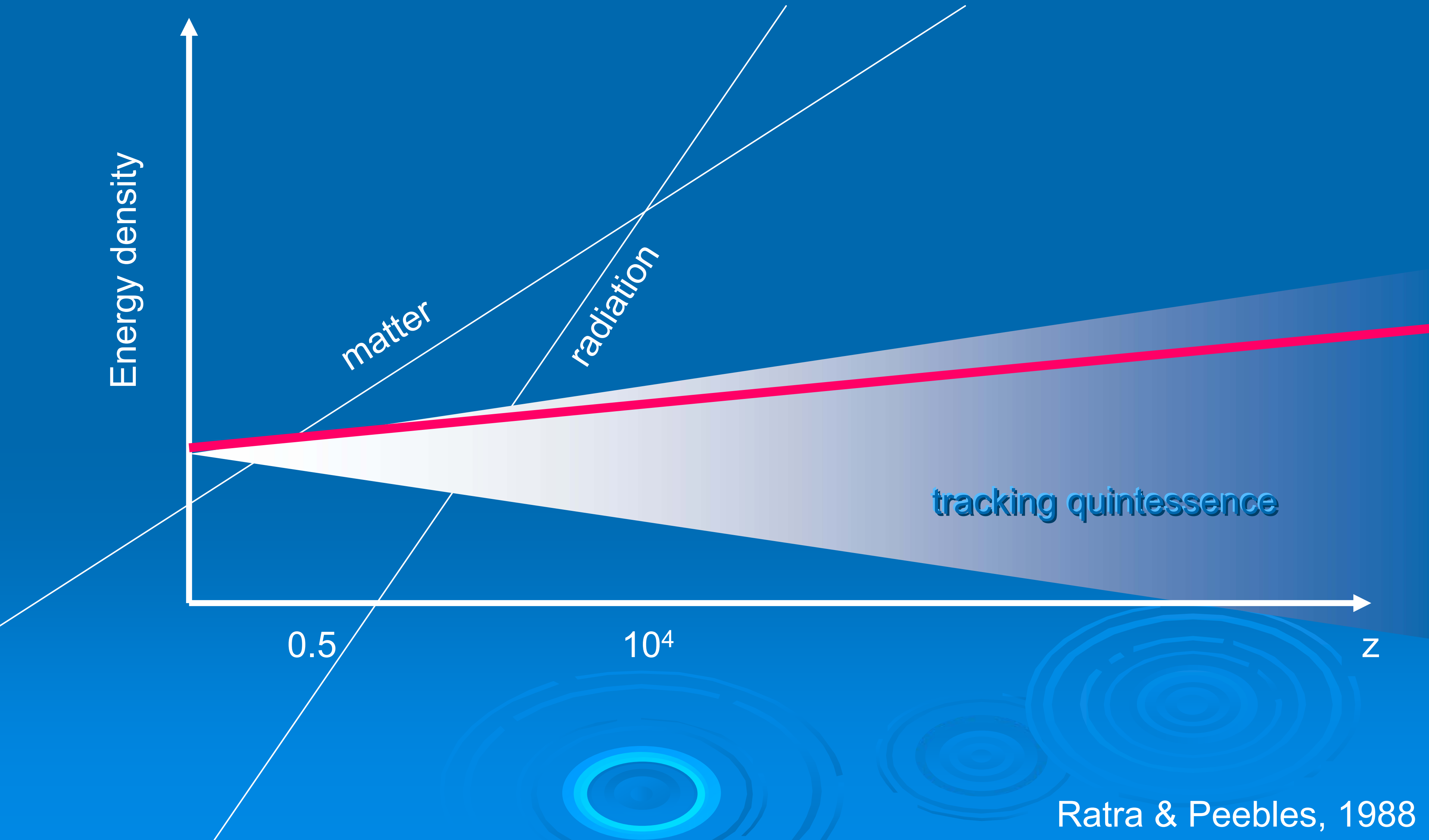


CMB lensing and dark energy



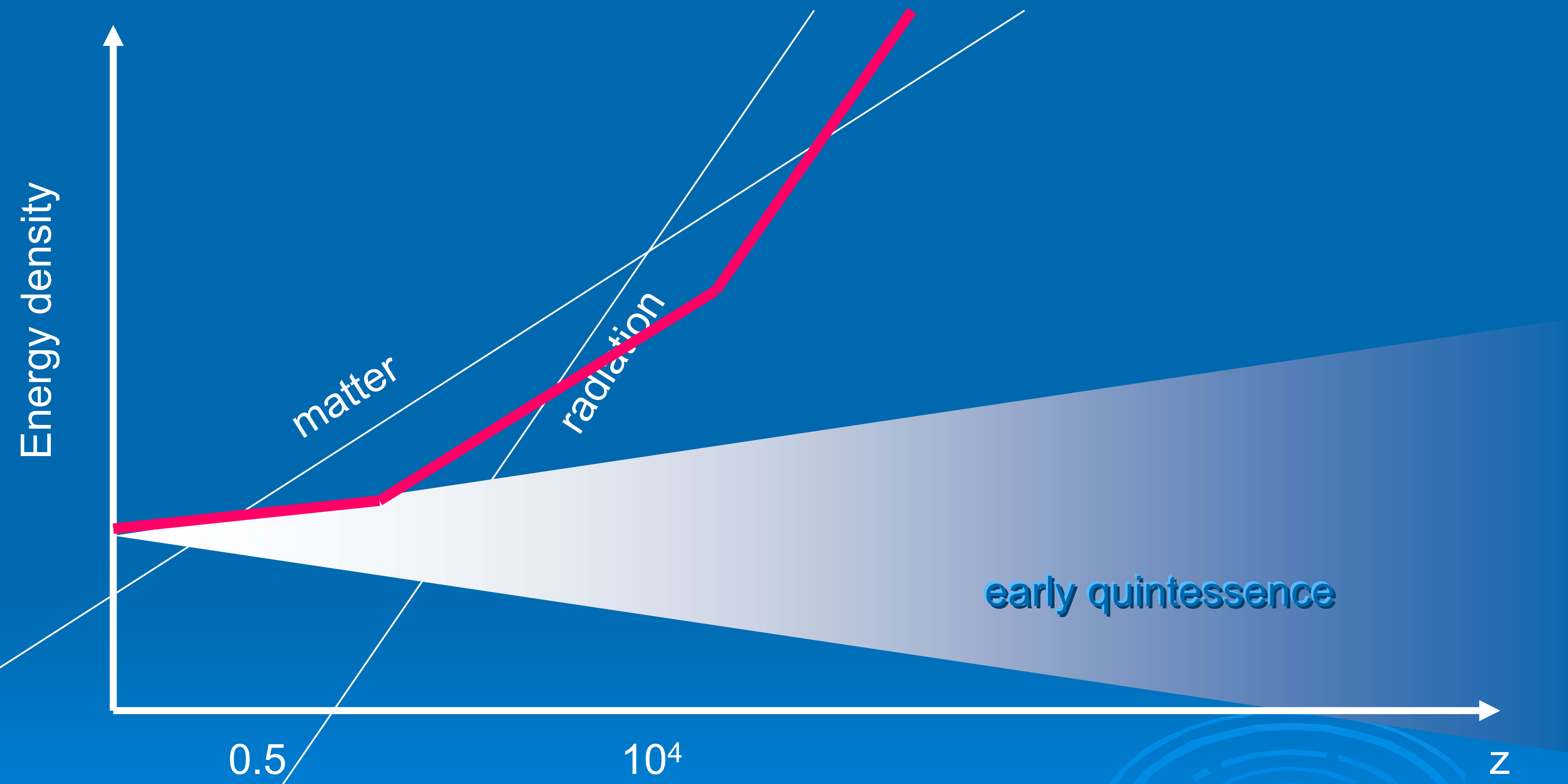
Einstein 1916

CMB lensing and dark energy



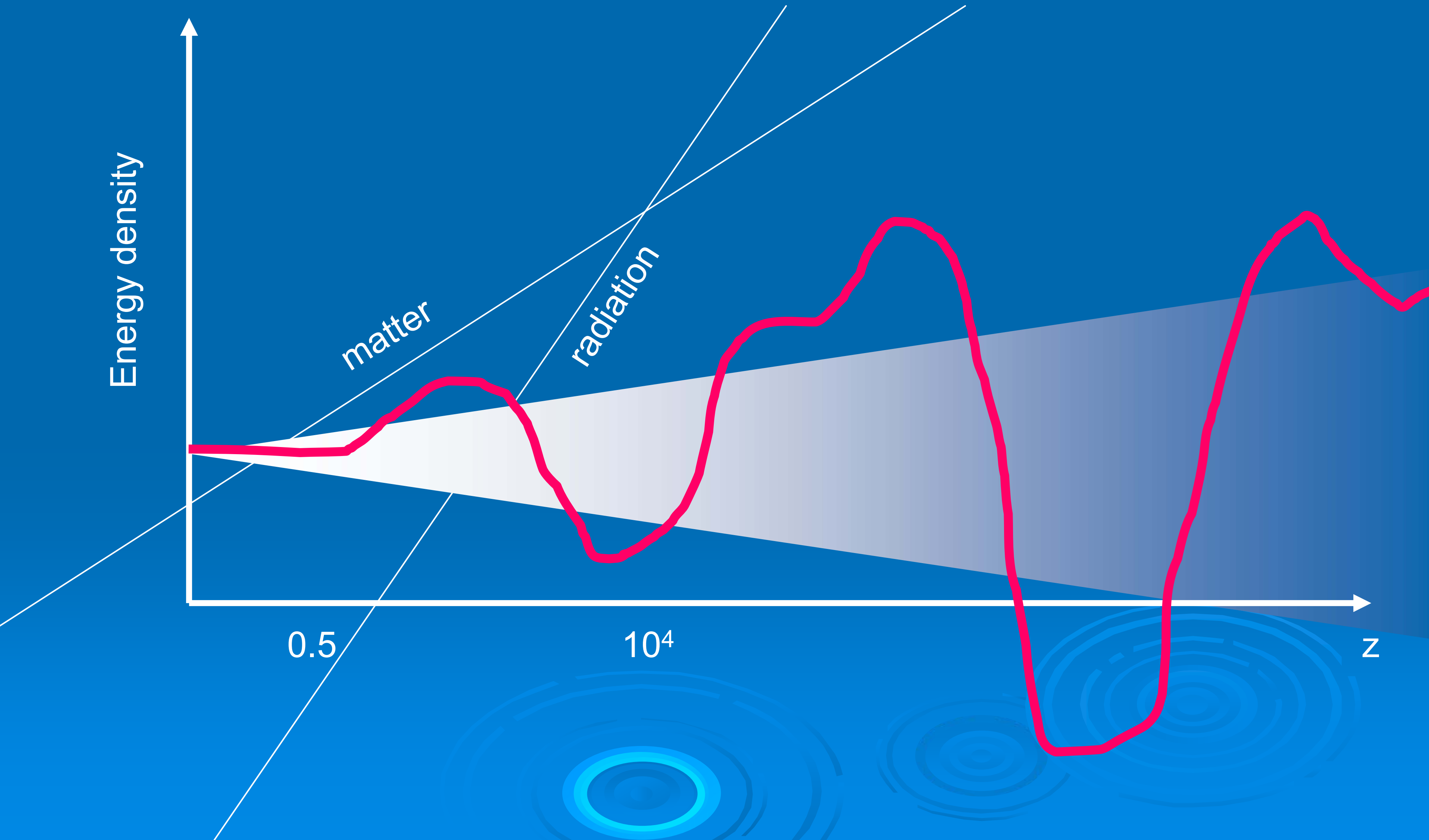
Ratra & Peebles, 1988

CMB lensing and dark energy

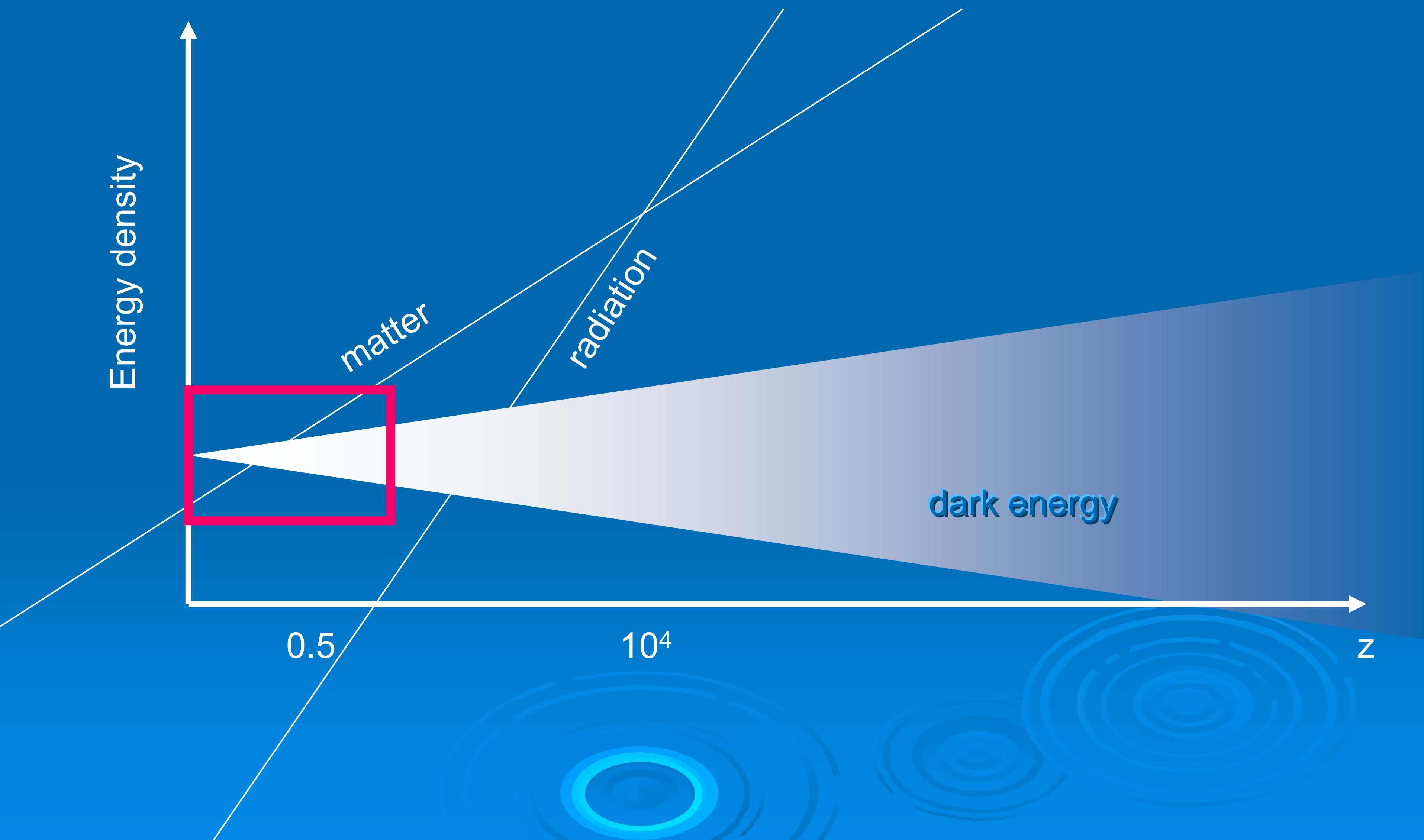


Wetterich 1988

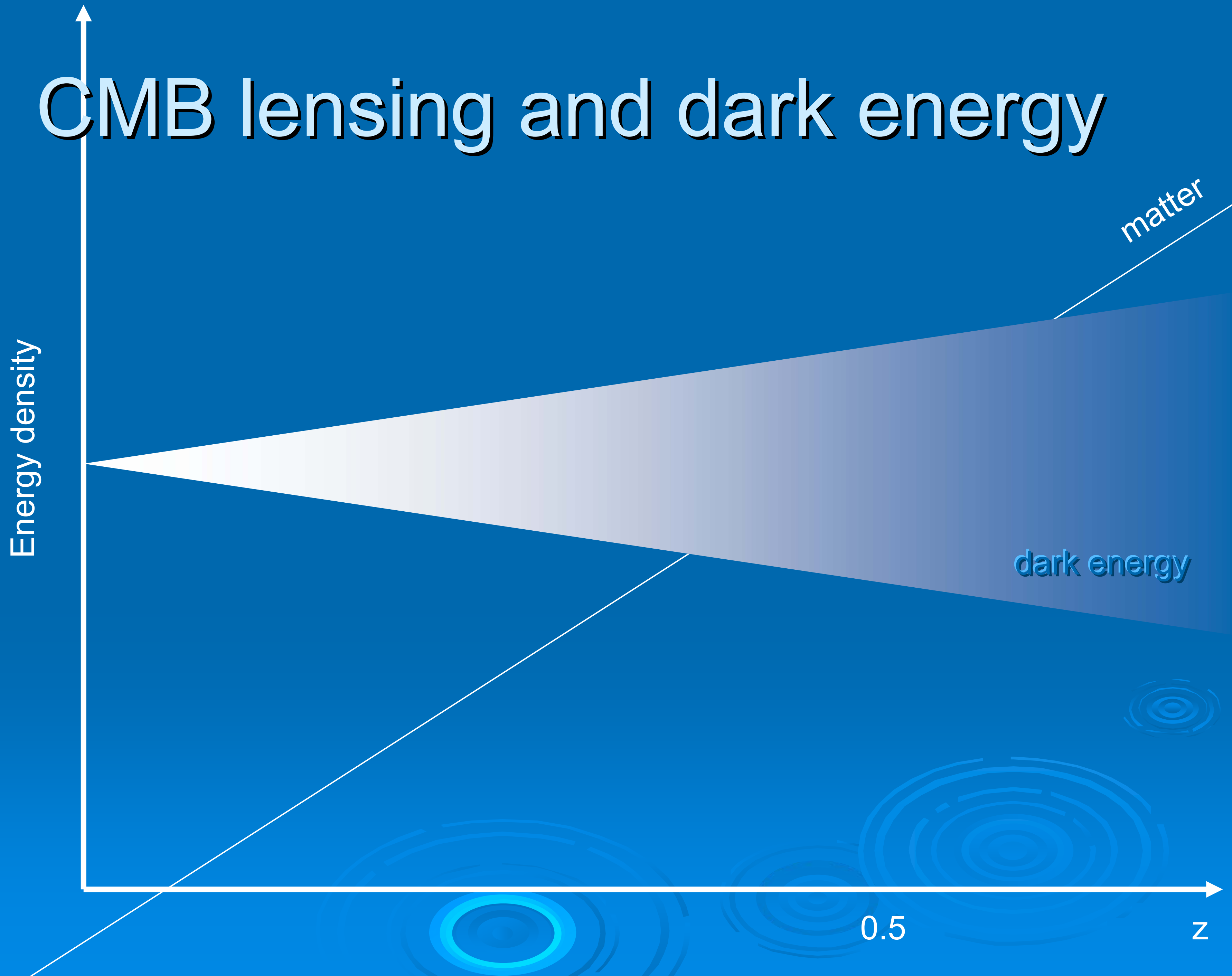
CMB lensing and dark energy



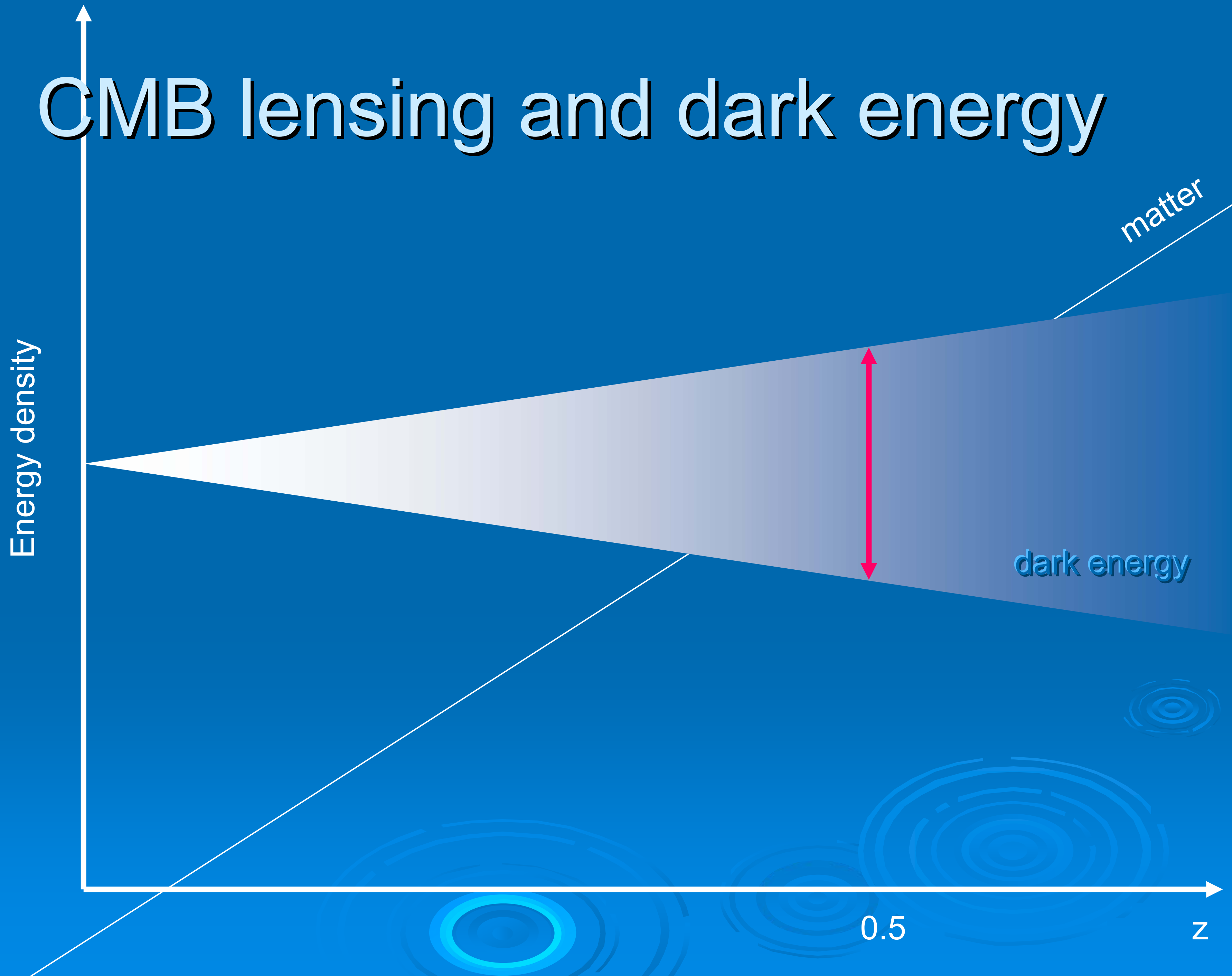
CMB lensing and dark energy



CMB lensing and dark energy



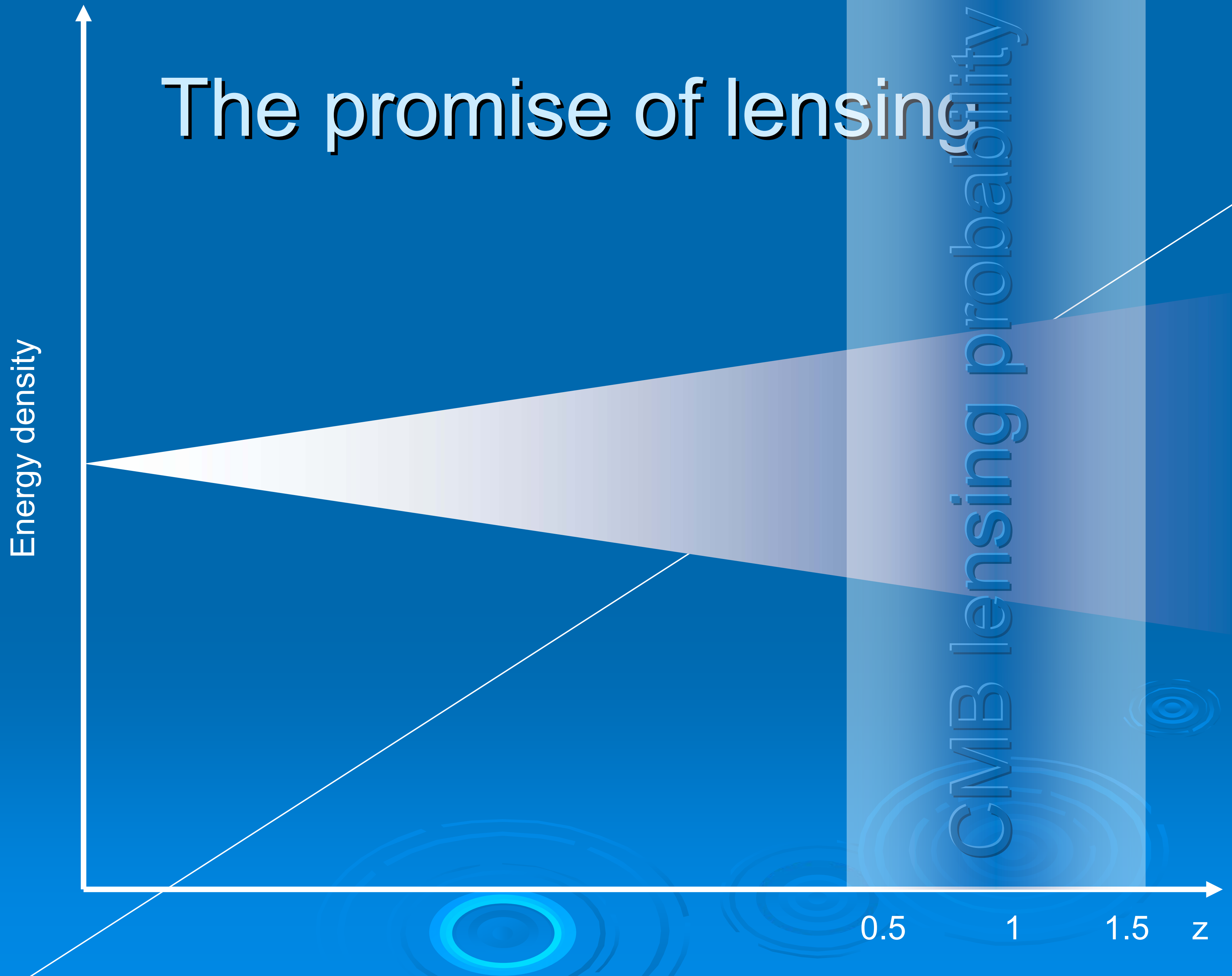
CMB lensing and dark energy



The promise of lensing

- By geometry, the lensing cross section is non-zero at intermediate distances between source and observer
- In the case of CMB as a source, the lensing power peaks at about z=1
- Any lensing power in CMB anisotropy must be quite sensitive to the expansion rate at the onset of acceleration

The promise of lensing

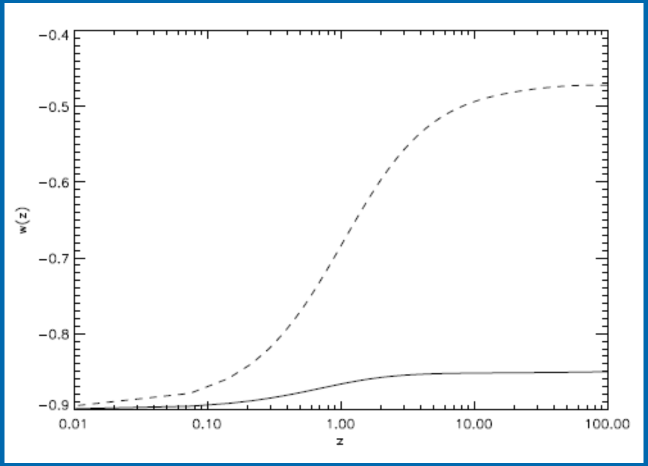


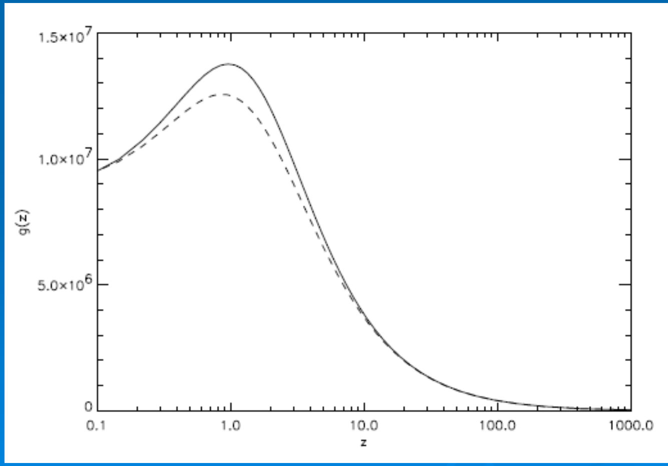
So let's play…

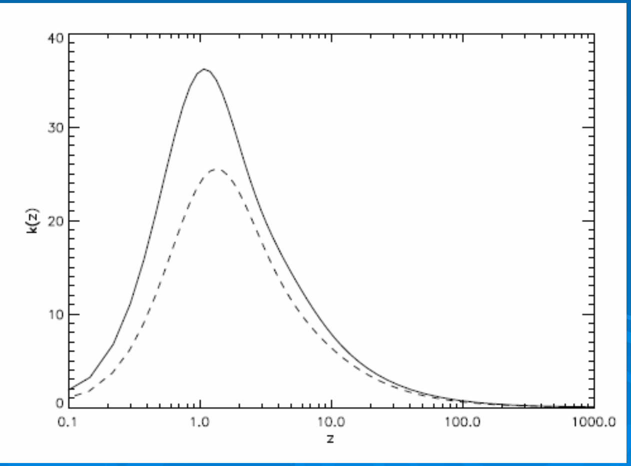
- Upgrade a Boltzmann code for lensing computation in dark energy cosmologies (Acquaviva et al. 2004 experienced doing that with cmbfast, lensing.f has to be substantially changed…)
- Get lensed CMB angular power spectra for different dark energy dynamics
- Look at the amplitude of lensing B modes

Play…

- SUGRA vs. Ratra-Peebles quintessence
- Check structure formation, linear perturbation growth rate, …
- Perturbations and distances affected by geometry coherently…
- Effects sum up in the lensing kernel



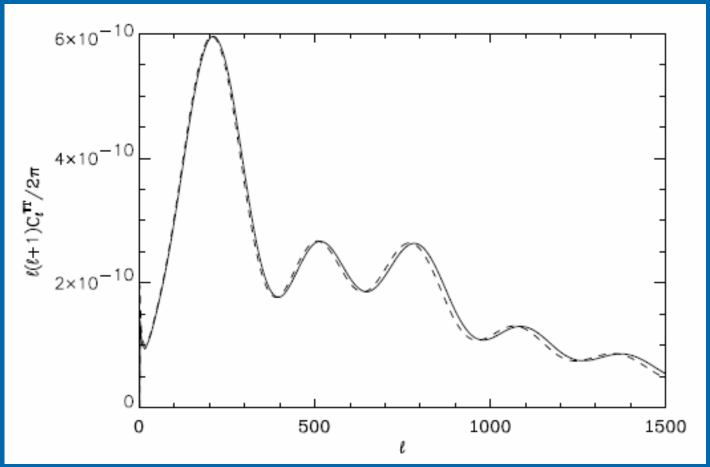


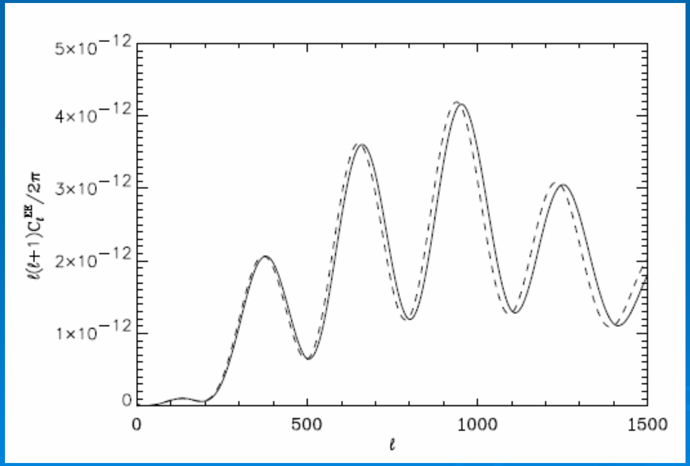


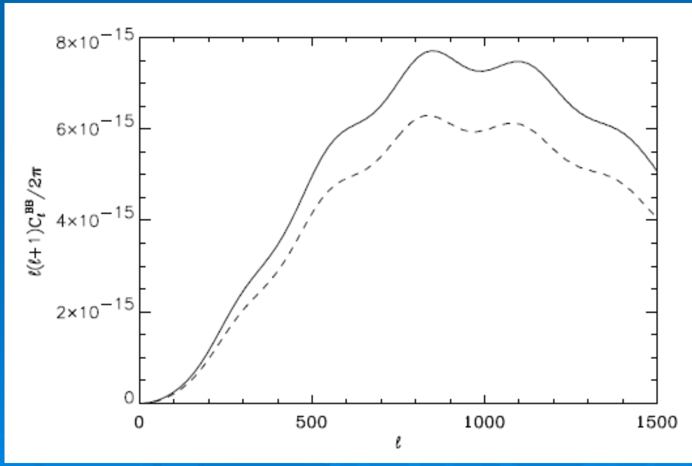
Acquaviva & Baccigalupi 2005

Play…

- TT and EE spectra: slight projection shift
- BB amplitude: reflecting cosmic density at structure formation/onset of acceleration

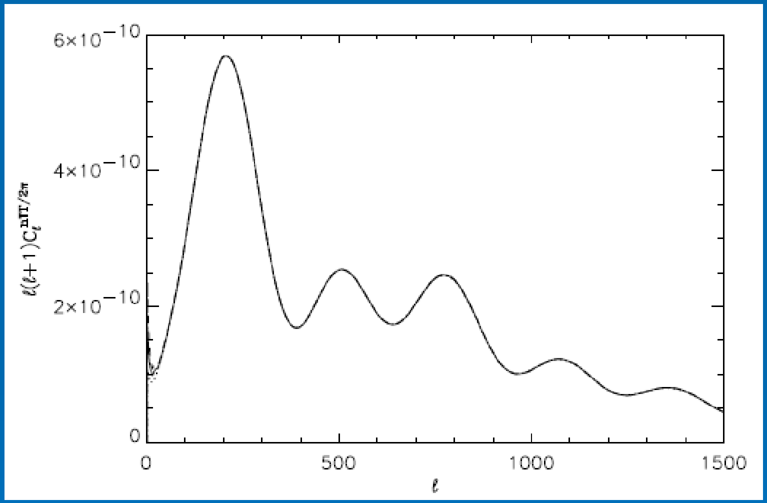


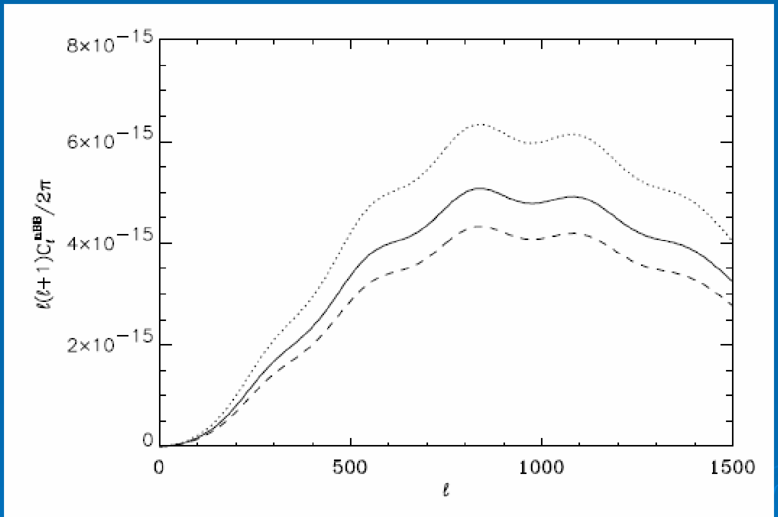




Acquaviva & Baccigalupi 2005

Breaking projection degeneracy





Acquaviva & Baccigalupi 2005

Get serious…

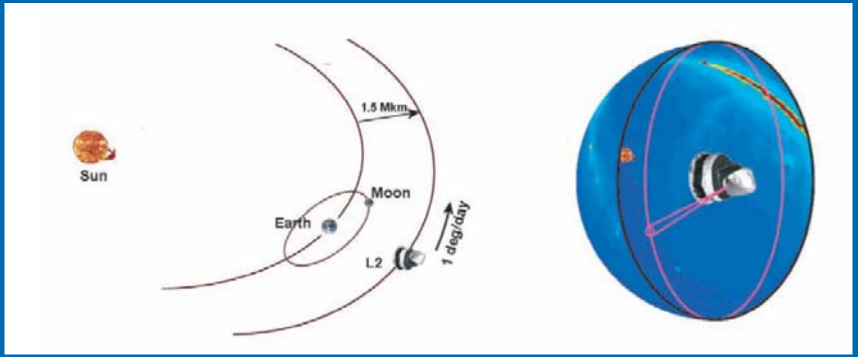
- A Fisher matrix analysis indicates that a 1%-10% measuremtent on both w_0 and w_a is achievable by having lensing B modes measured on a large sky area, few arcminute resolution, micro-K noise
- New relevance for searching B modes in CMB polarization?
- Independent check of the efficiency of the effect ongoing…
- Confirmed!

Acquaviva & Baccigalupi 2005

Basics of CMB data analysis

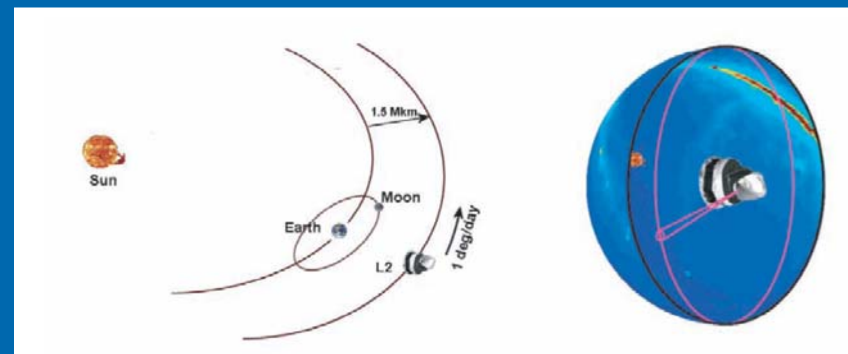
CMB data analysis: super-zip

- Before super-zip: a probe takes records of the sky radiation at about few tens KHz rate per detector, for weeks or years



CMB data analysis: super-zip

- Before super-zip: a probe takes records of the sky radiation at about few tens KHz rate per detector, for weeks or years
- After super-zip: few numbers measuring relevant cosmological quantities



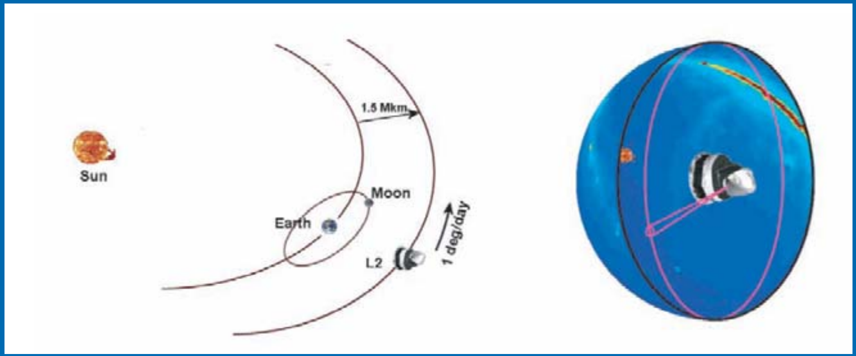
$\Omega = 1$

Super-zip main phases

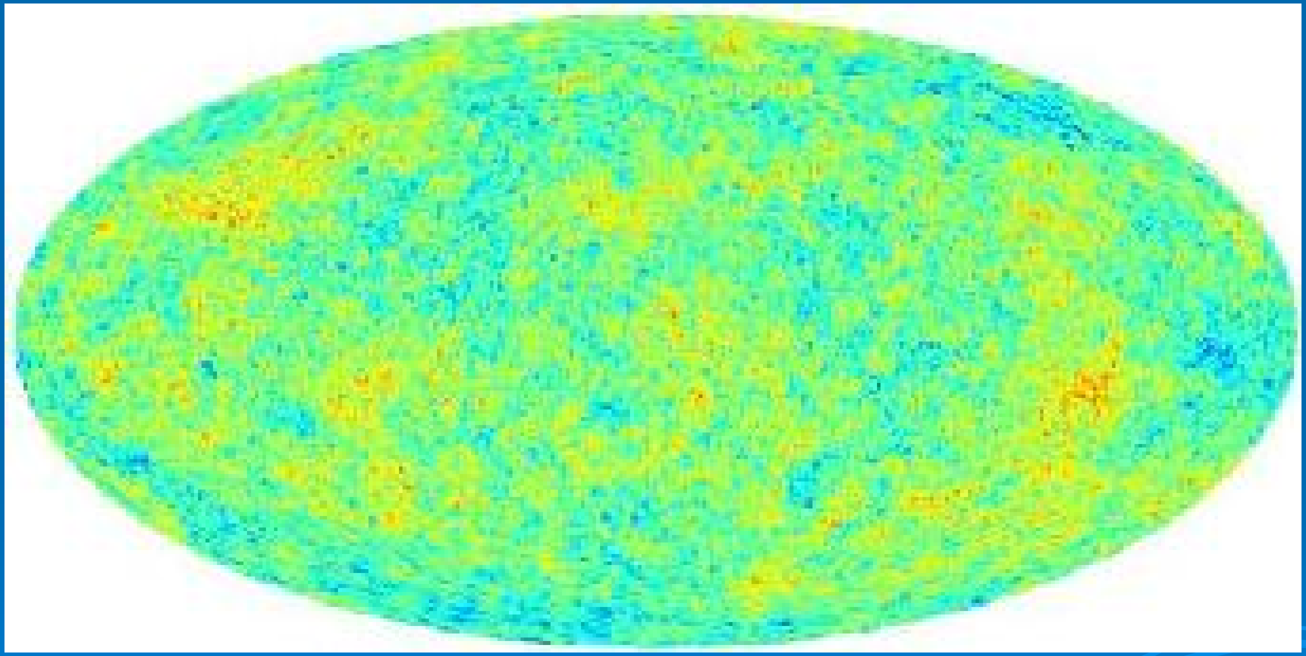
- Time ordered data
- Map-making
- Component separation

CMB data analysis: time ordered data

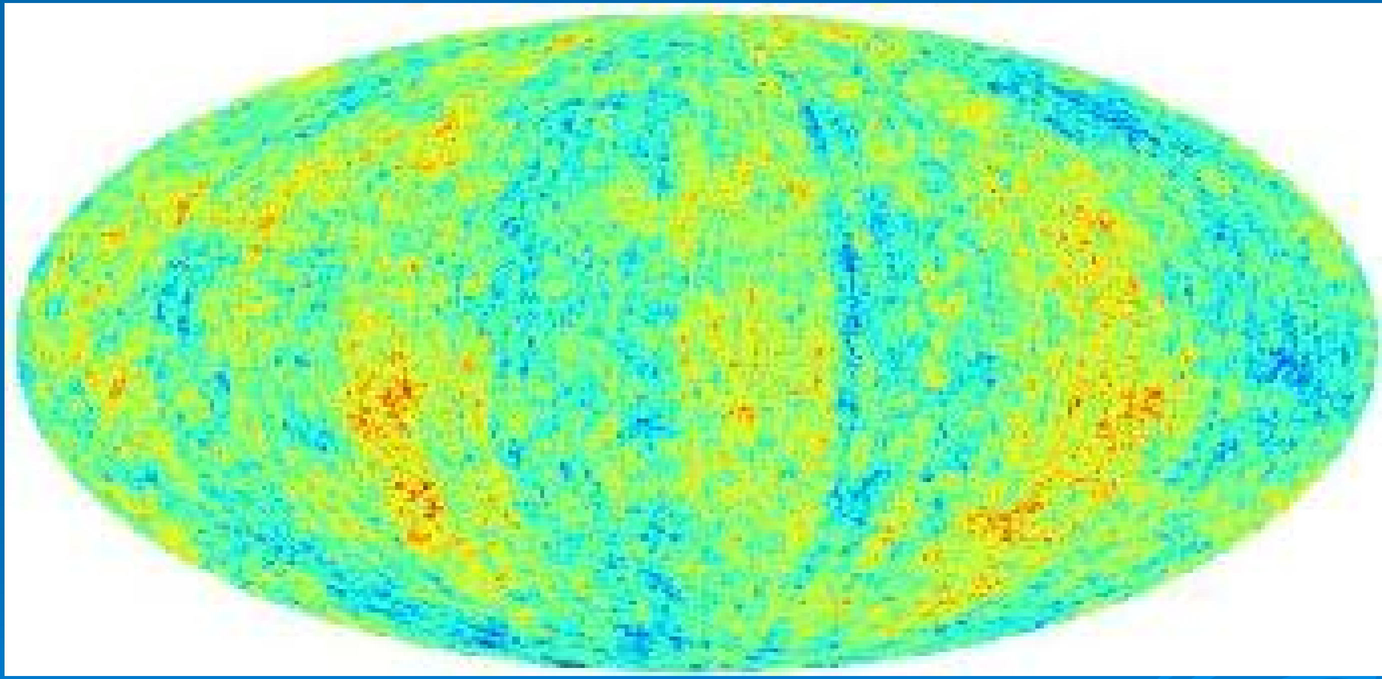
- Beam: at each point, the radiation is collected from a finite solid angle
- Noise: this is the stage where the noise is born
- Calibration: Volts must be converted in CMB units
- …



CMB data analysis: co-adding map-making



CMB data analysis: co-adding map-making

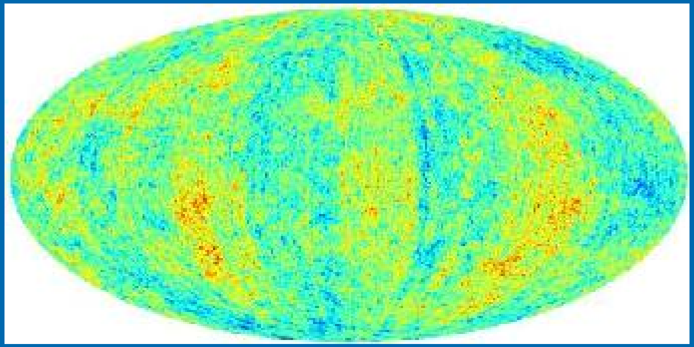


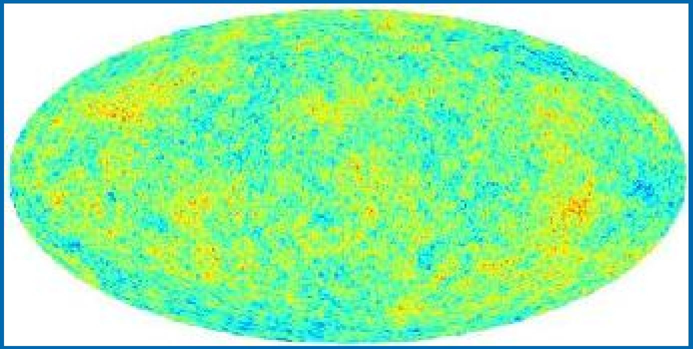
CMB data analysis: maximum likelihood map-making

$$D = Pm + n \qquad \boxed{m = (P^T N^{-1} P)^{-1} P^T N^{-1} d}$$

- P: pointing matrix, mixed time and map domain
- N: noise correlation matrix in the time domain
- N^{-1}: O(sample number^2)
- $P^T N^{-1} P$: O(sample number^2)
- $P^T N^{-1} d$: O(sample number^2)

CMB data analysis: destriping map-making

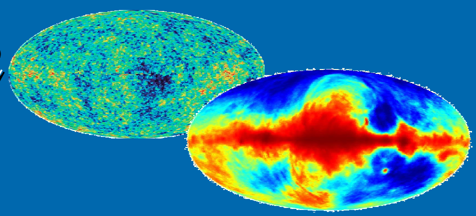




- Exploit redundancy, i.e. points in which different circles intersect, in order to estimate the noise offsets in the intersection points
- Subtract the offsets in order

CMB data analysis: component separation

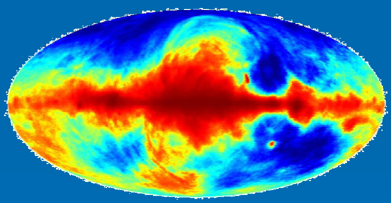
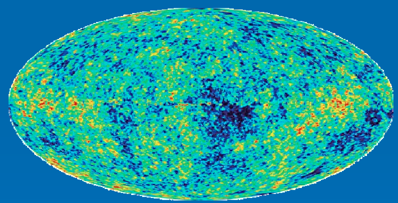
s_2

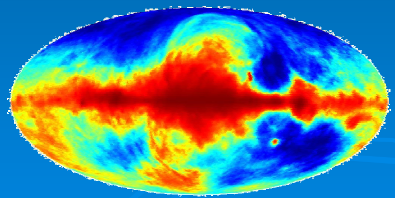
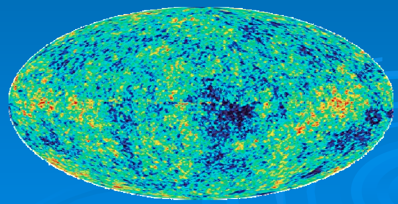


s_1

ν_1

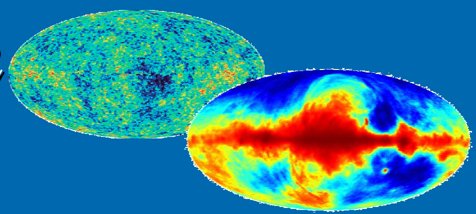
ν_2

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

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

CMB data analysis: component separation

s_2



s_1

ν_1

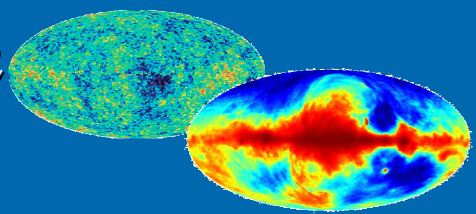
ν_2

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

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

CMB data analysis: component separation

s_2



s_1

ν_1

ν_2

$$x = As + n$$

Invert for s!

CMB data analysis: component separation

$$x = As + n$$

- 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

CMB data analysis: blind component separation

Pixels or Modes

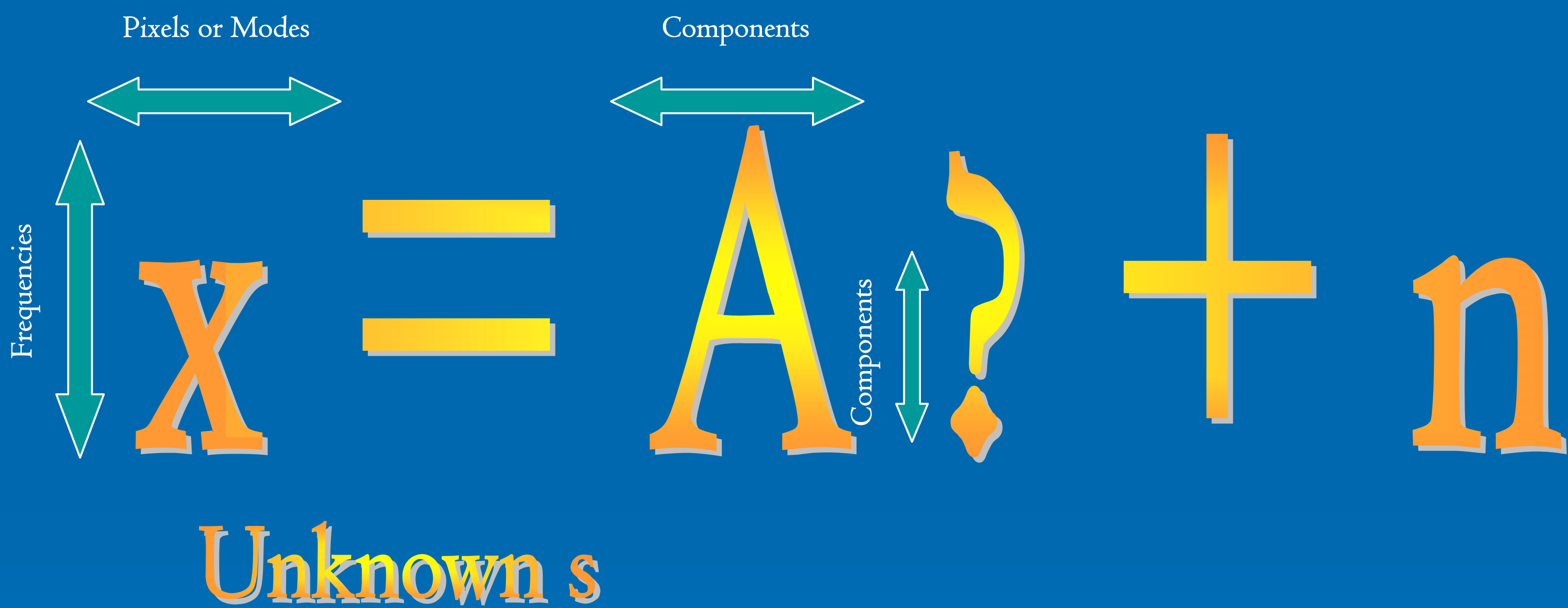
Components

Frequencies

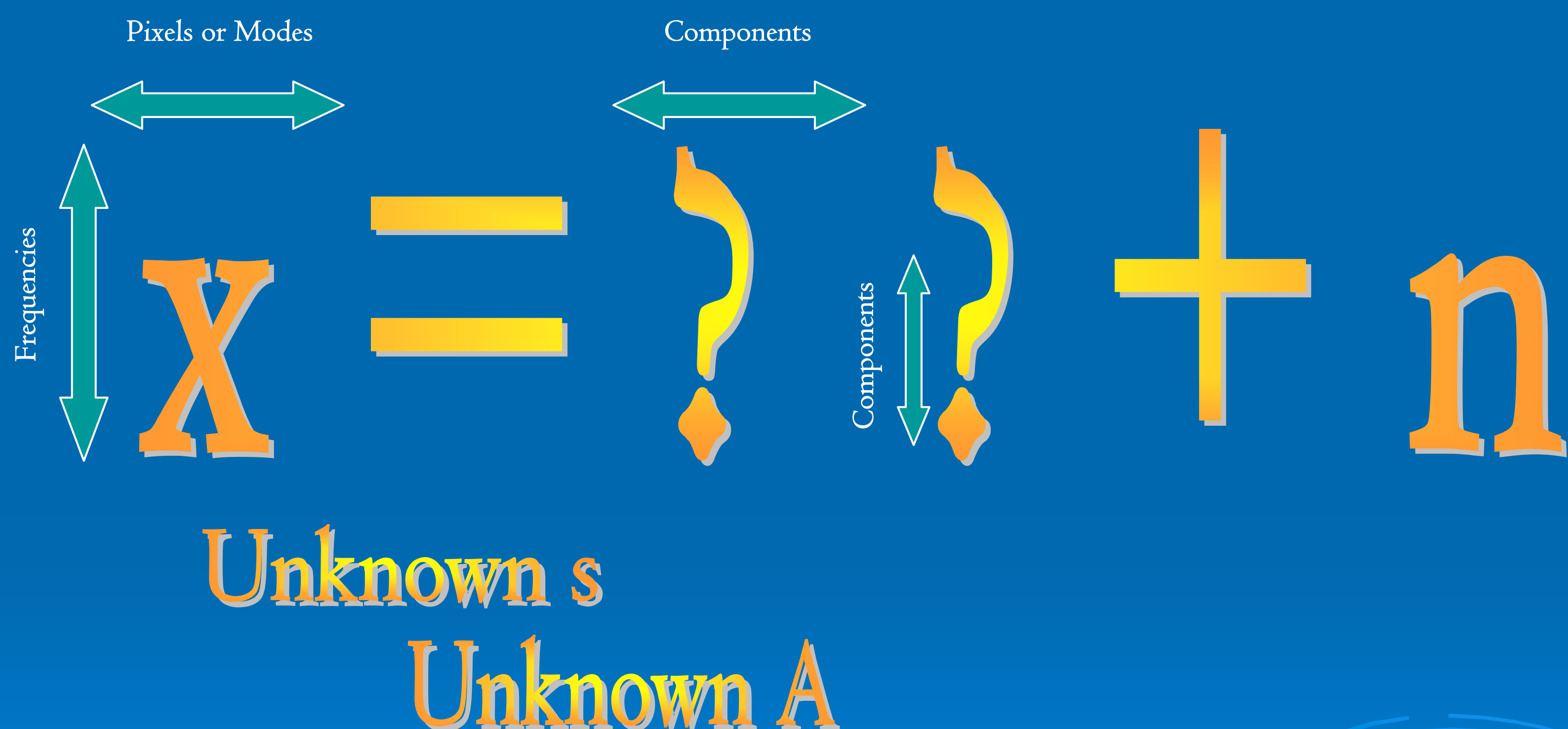
Components

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

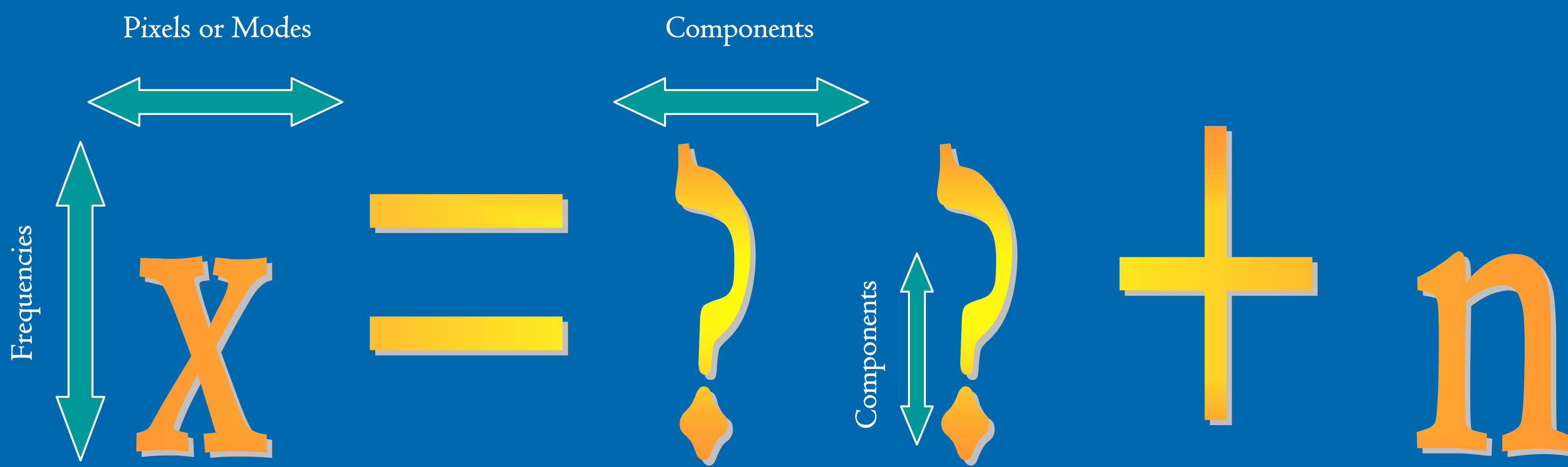
CMB data analysis: blind component separation



CMB data analysis: blind component separation



CMB data analysis: blind component separation



Unknown s

Unknown A

Find s!

CMB data analysis: blind component separation

Experience the Magic

Add-on II:
ICA performance

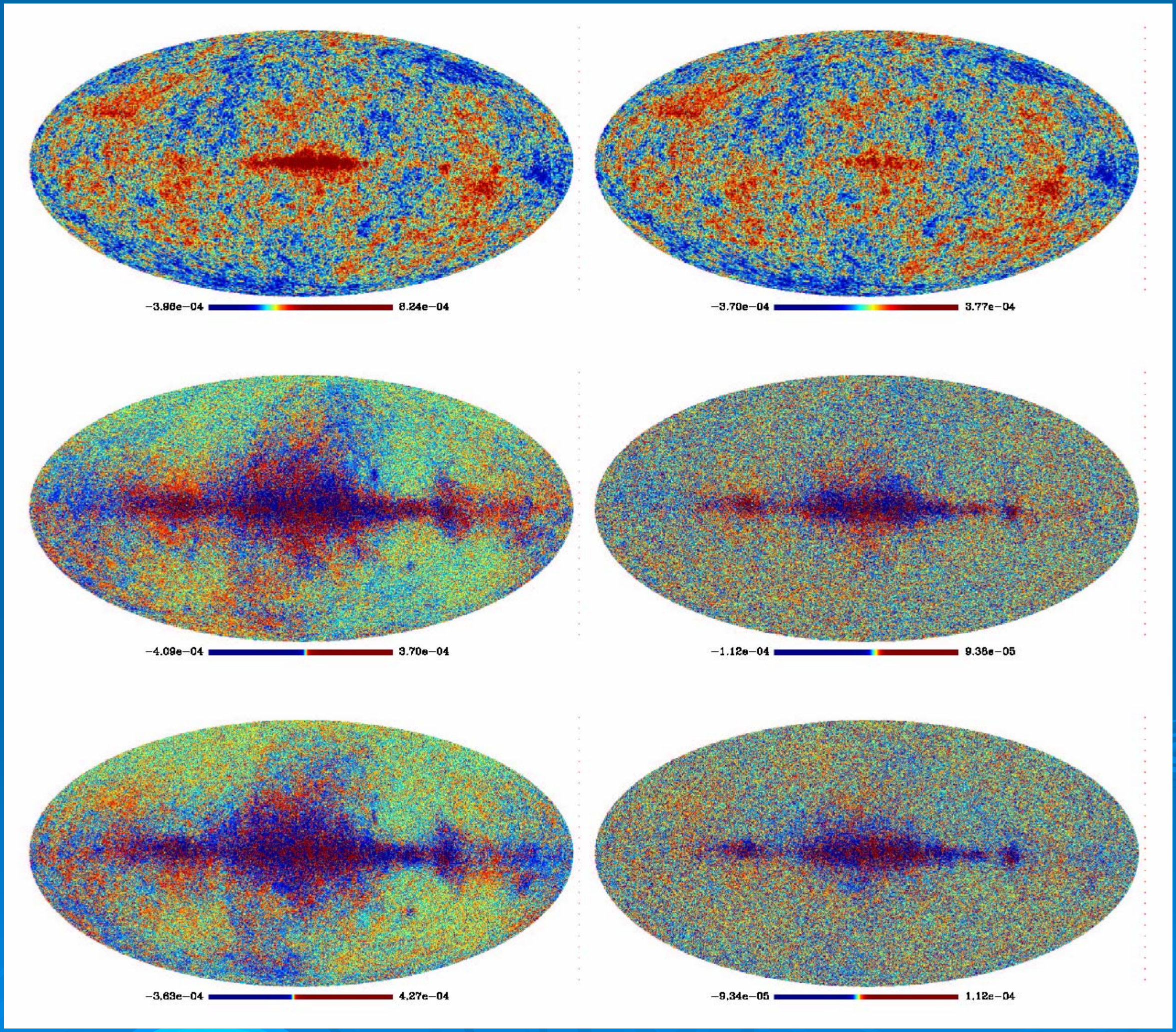
Independent Component Analysis (ICA)

- Assume statistical independence between different astrophysical emissions
- Their superposition tends to be close to Gaussianity
- Reverse the process with linear combinations of the signals at different frequencies, extremizing the non-Gaussianity
- Each extremum corresponds to one independent component

See Baccigalupi et al., 2004, and references therein

ICA performance

Mix CMB & Synchrotron at 50 & 80 GHz, 3 arcmin resolution, all sky, noiseless



T

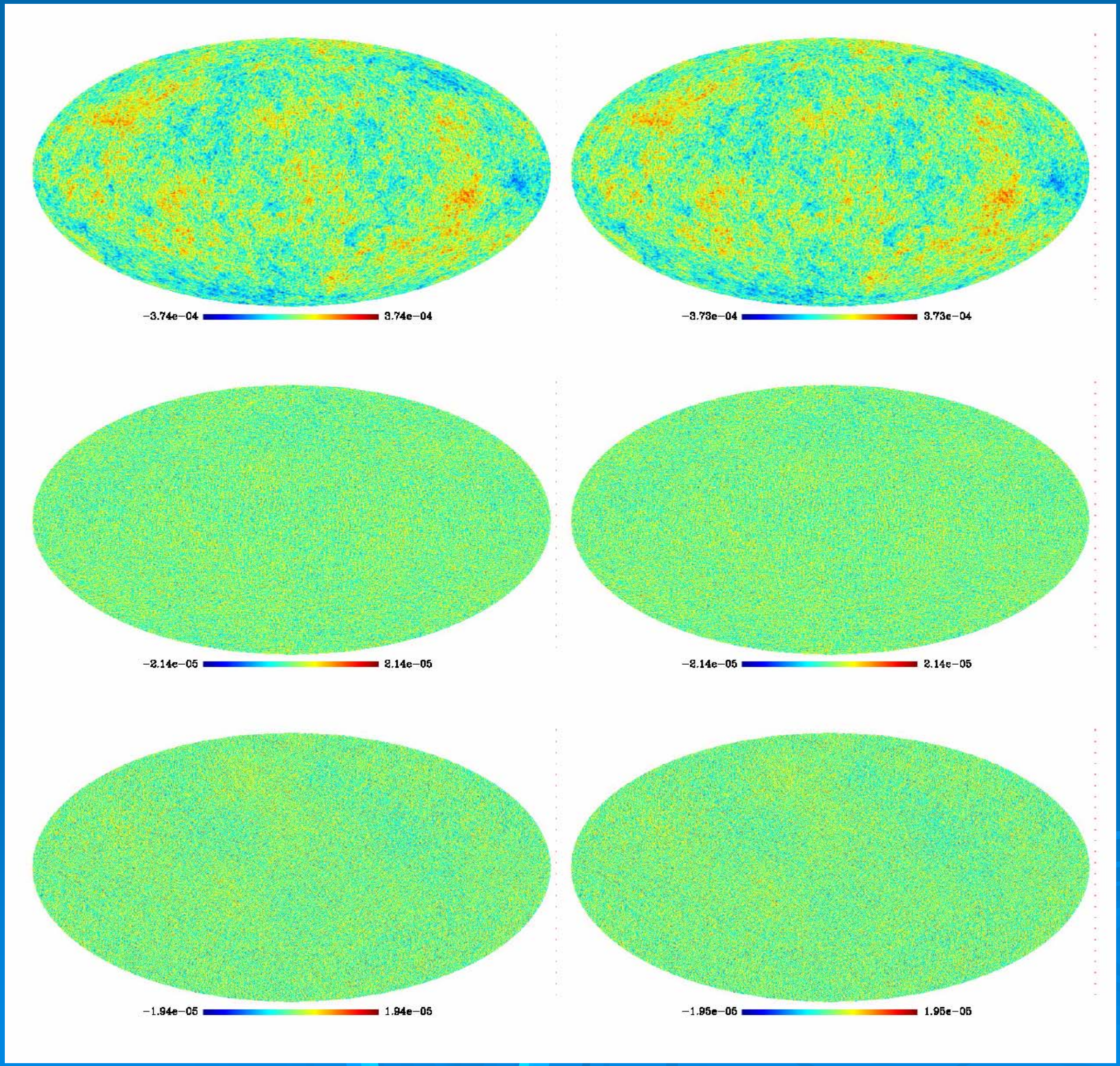
Q

U

50 GHz

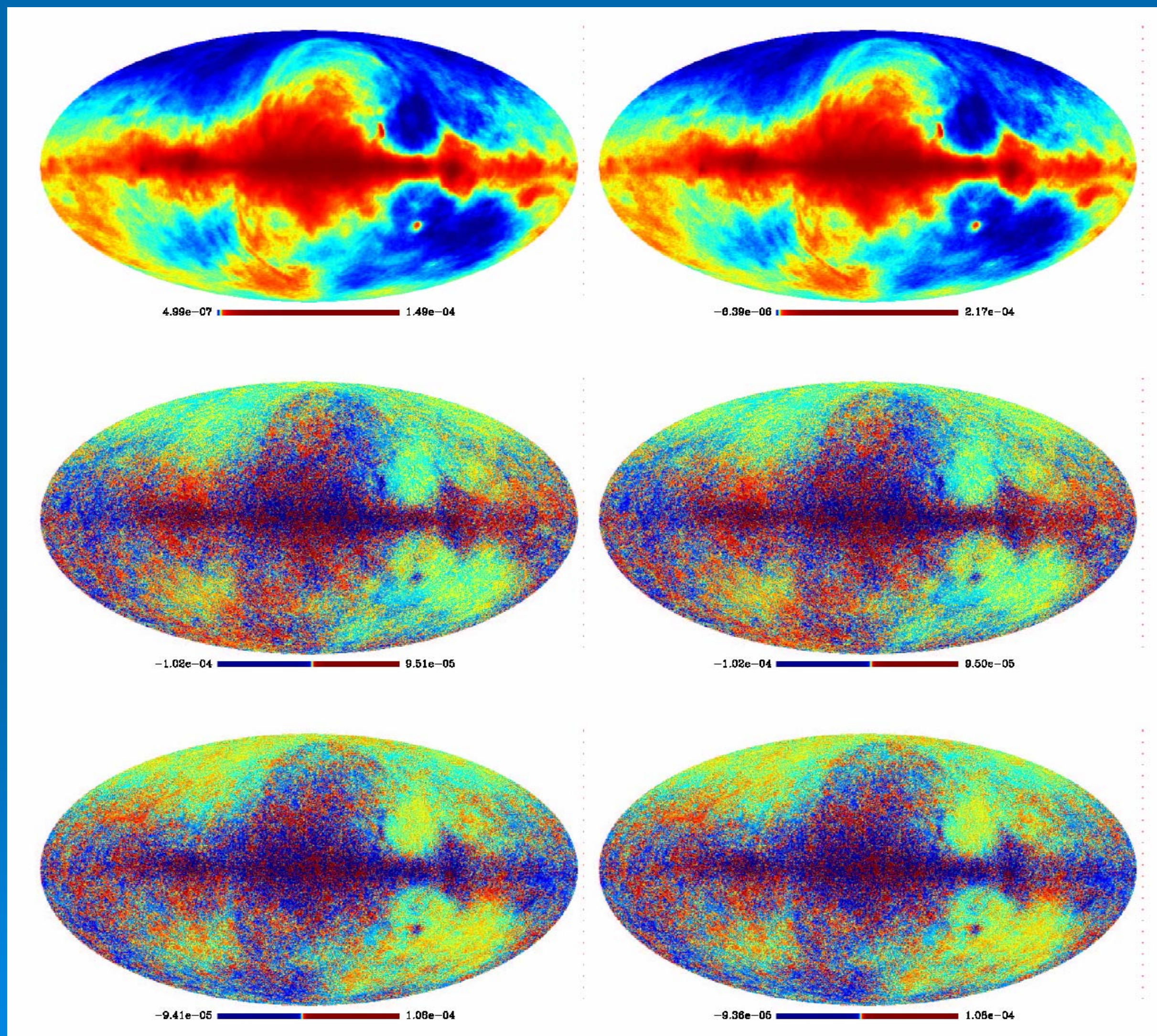
80 GHz

ICA performance



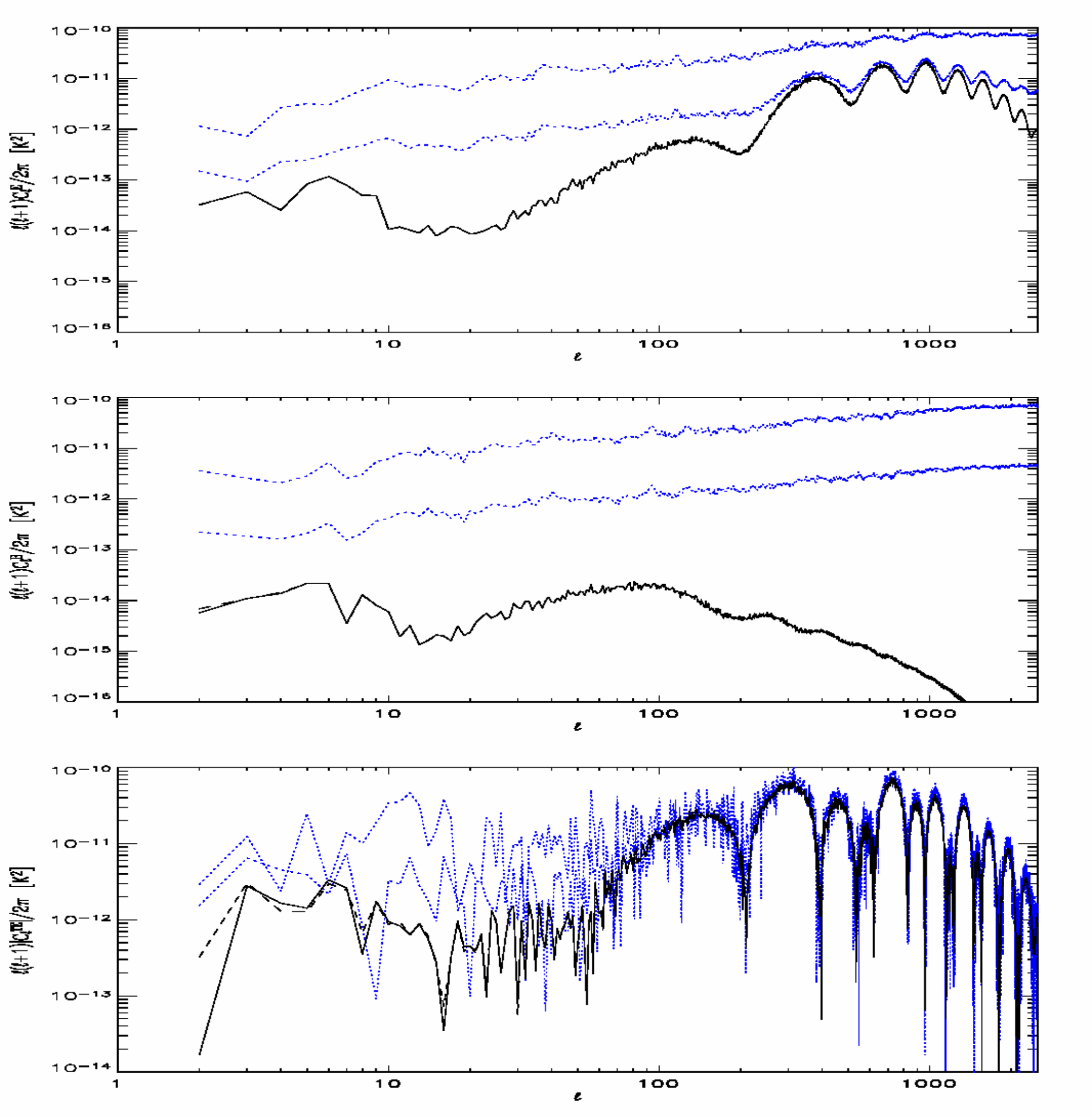
input output

ICA performance



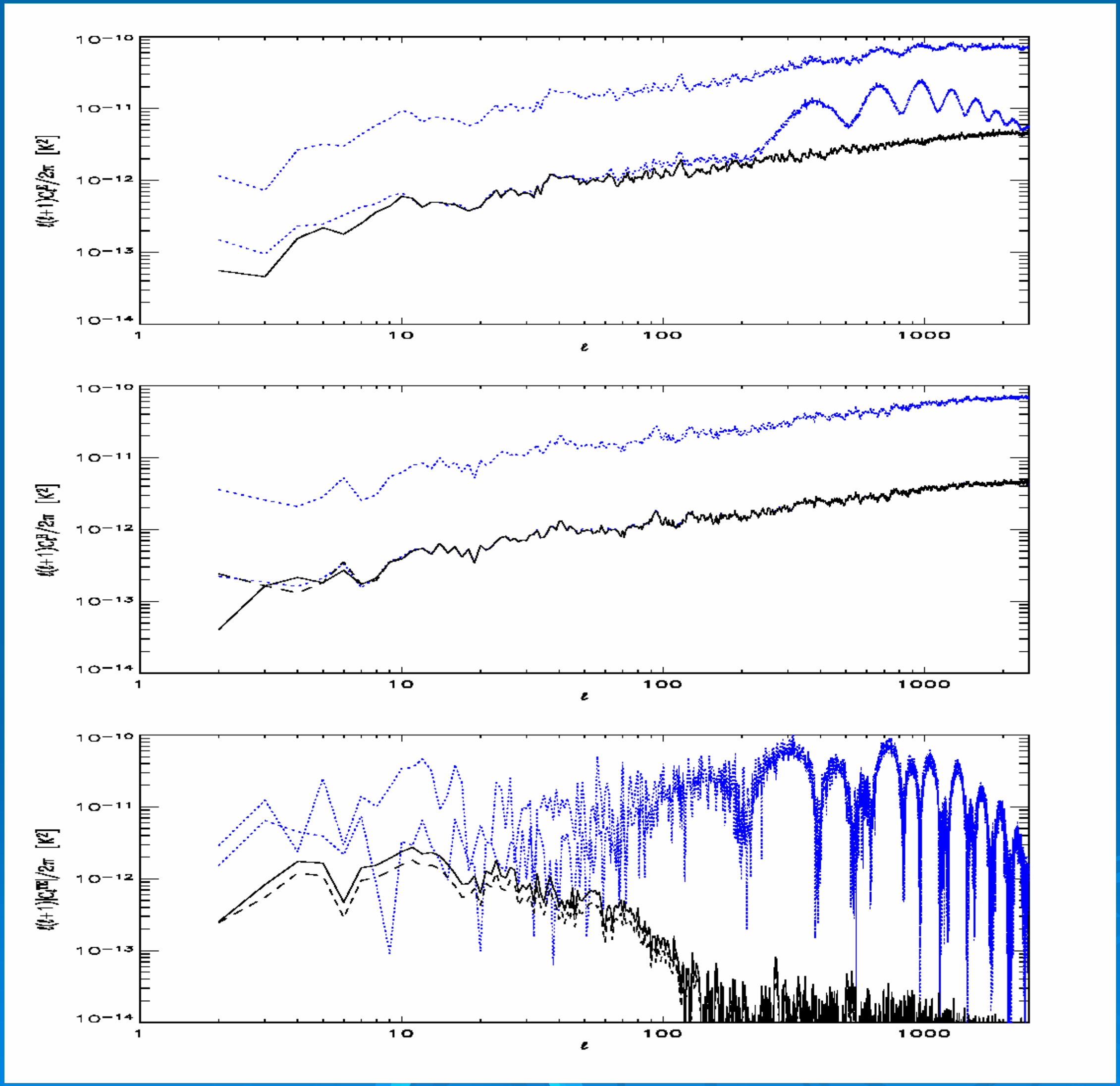
input output

ICA performance



Blue: sky at the two frequencies. Black solid (dashed): CMB output (input)

ICA performance



Blue: sky at the two frequencies. Black solid (dashed): synchrotron output (input)