# Cosmic Microwave Background: observations, data analysis, results and future expectations

Carlo Baccigalupi

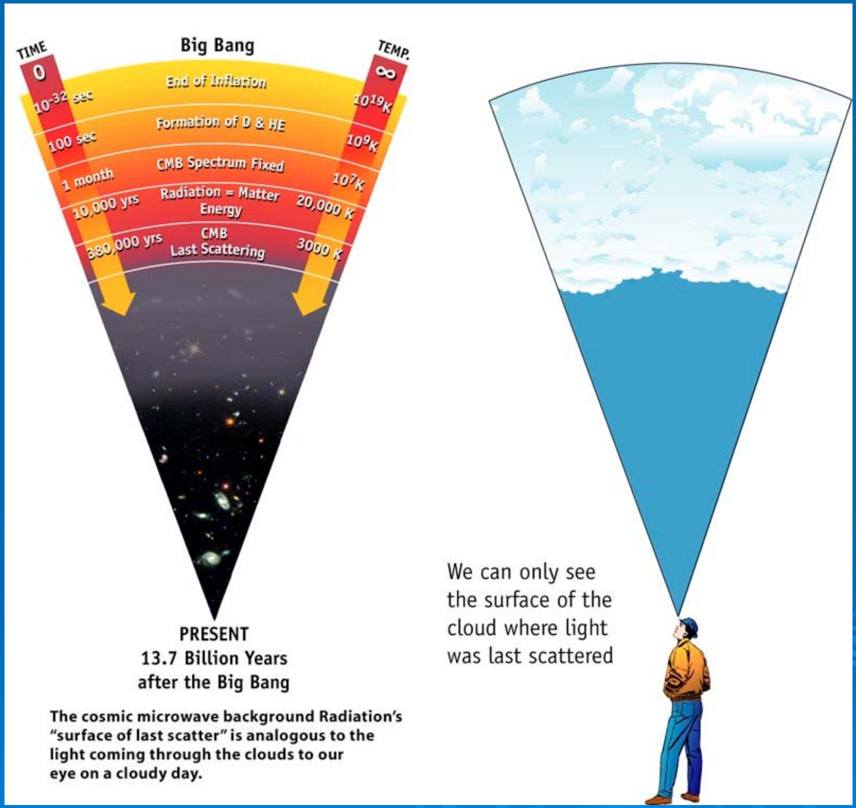
# Outline

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

# 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: $\lambda \gg H^{-1}$
- The 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



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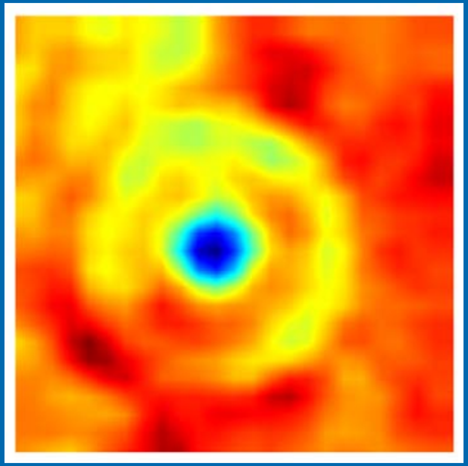
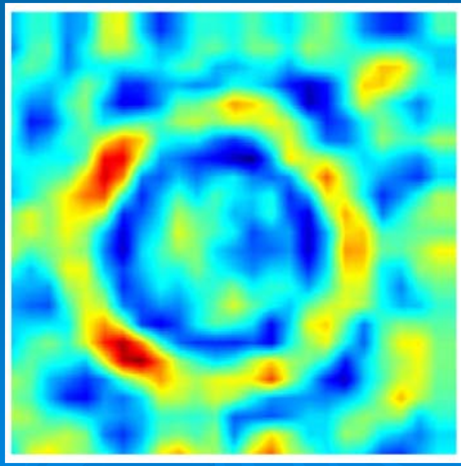




B99

Animation from the NASA WMAP team

# CMB physics: Boltzmann equation

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

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

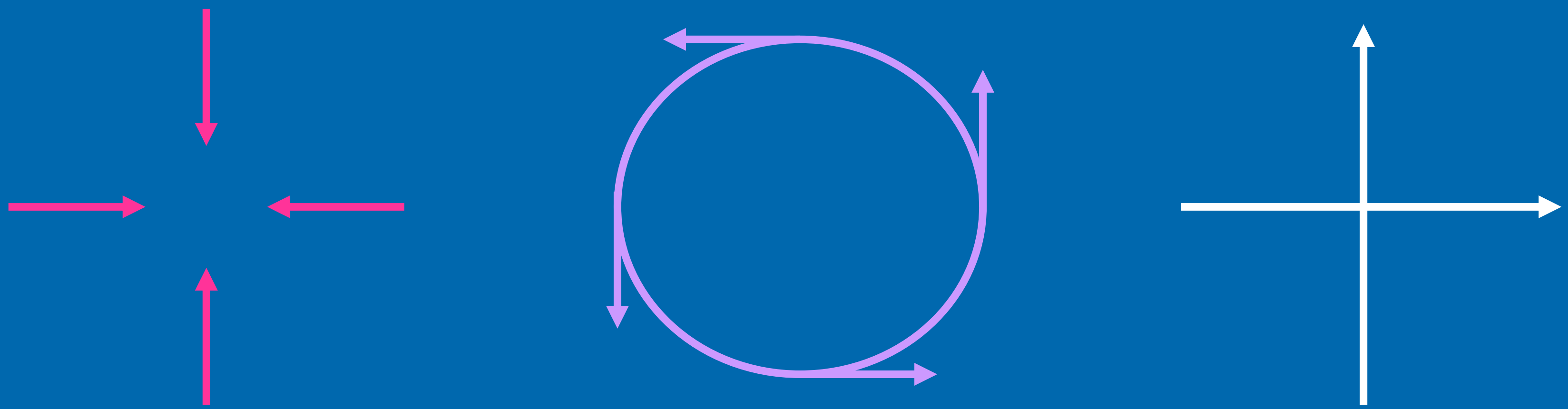
# CMB physics: Boltzmann equation

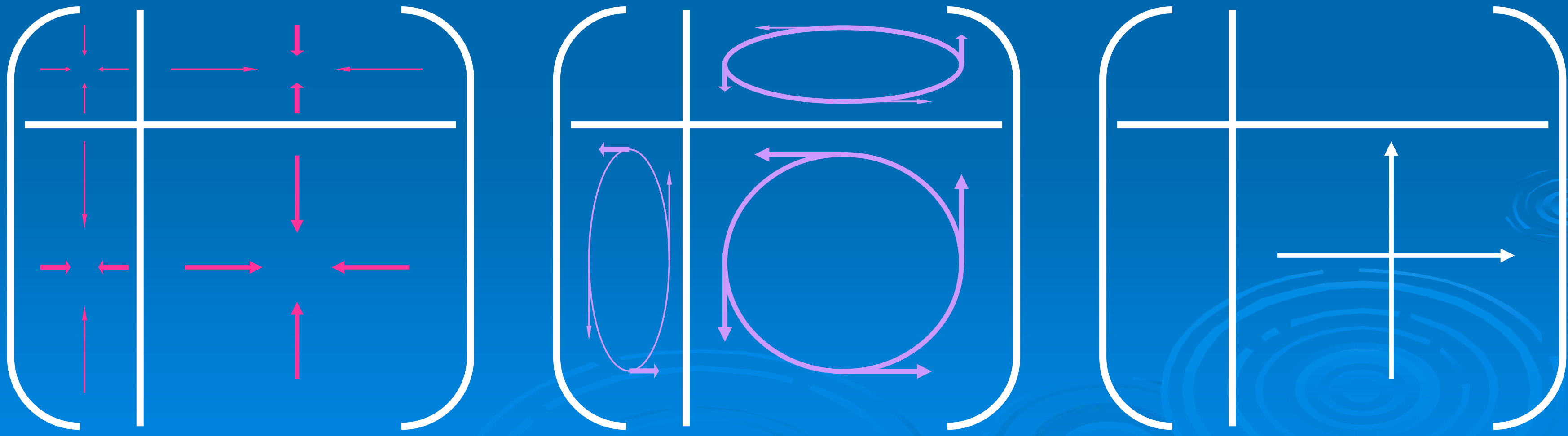
$$\frac{d\ \text{neutrinos}}{dt} = \text{metric} + \text{weak interaction}$$

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

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

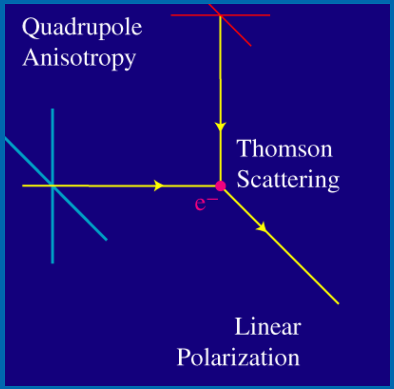
# CMB physics: metric

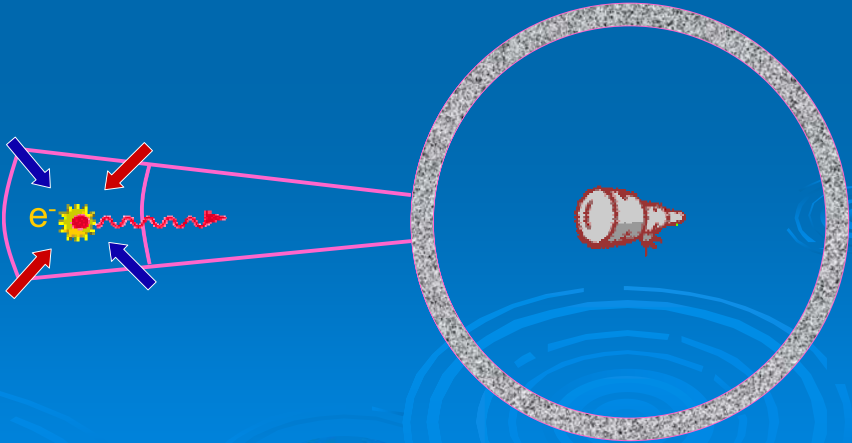




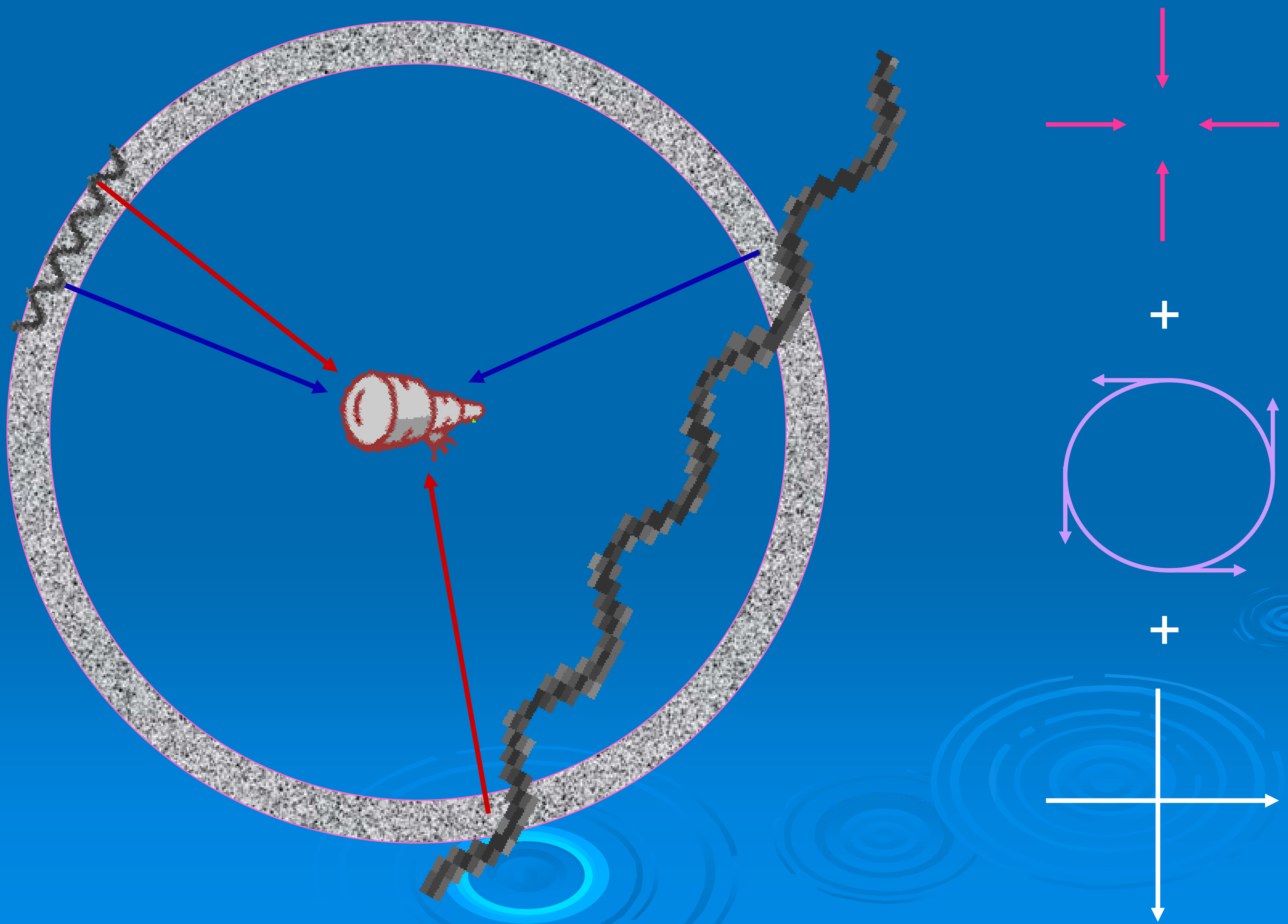
# CMB Physics: Compton scattering

- 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



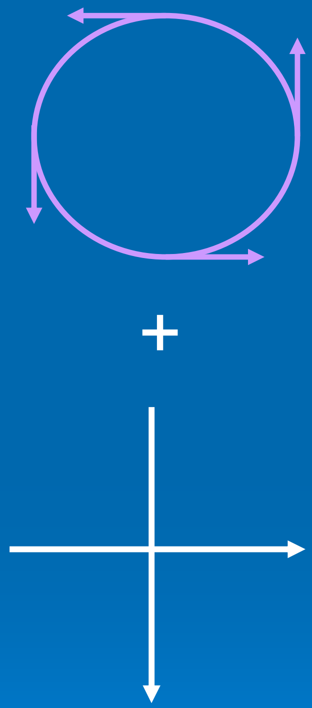



# CMB anisotropy: total intensity

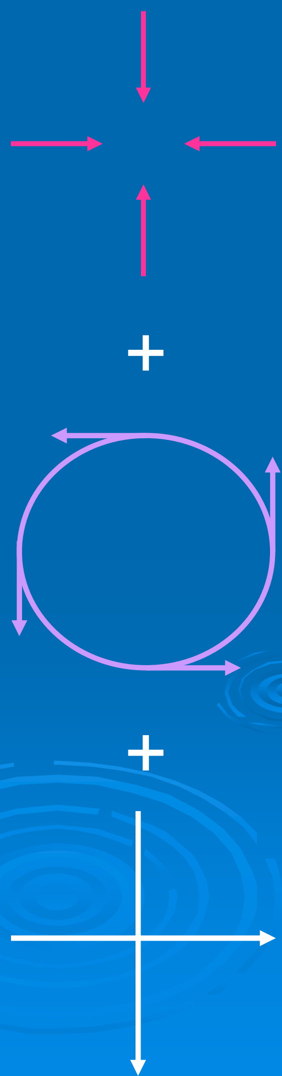


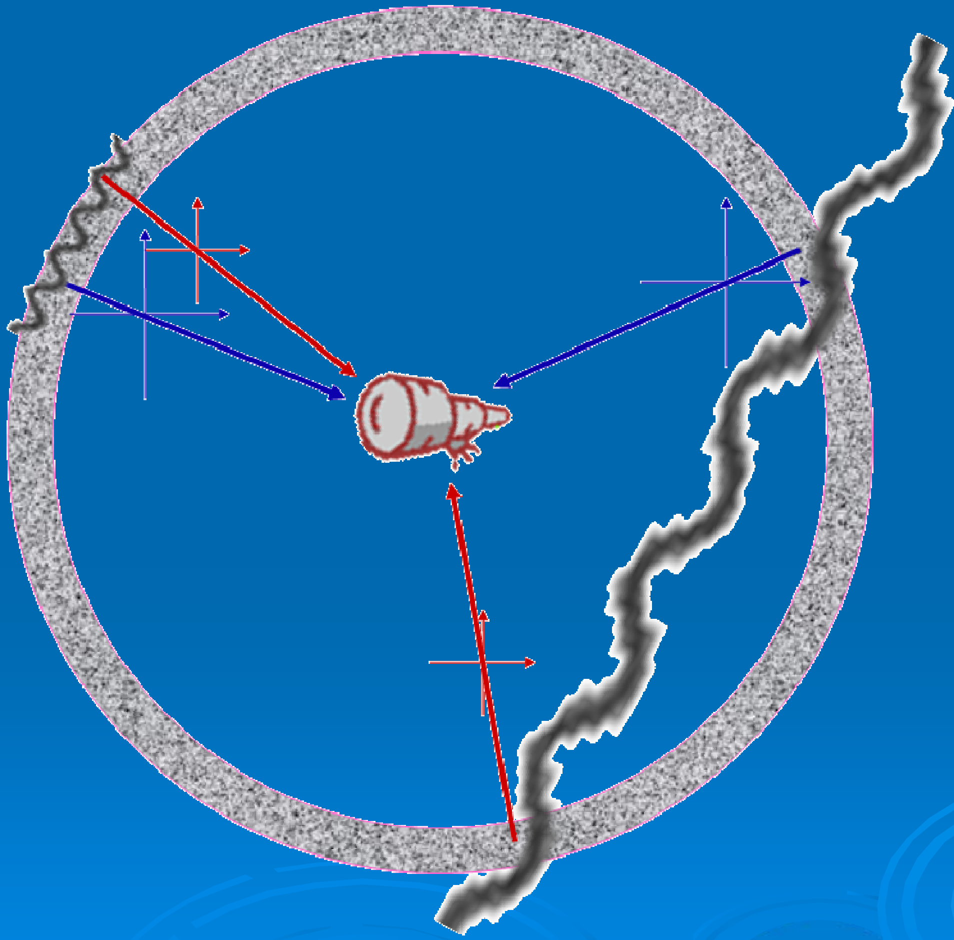
# CMB anisotropy: polarization

Curl (B):

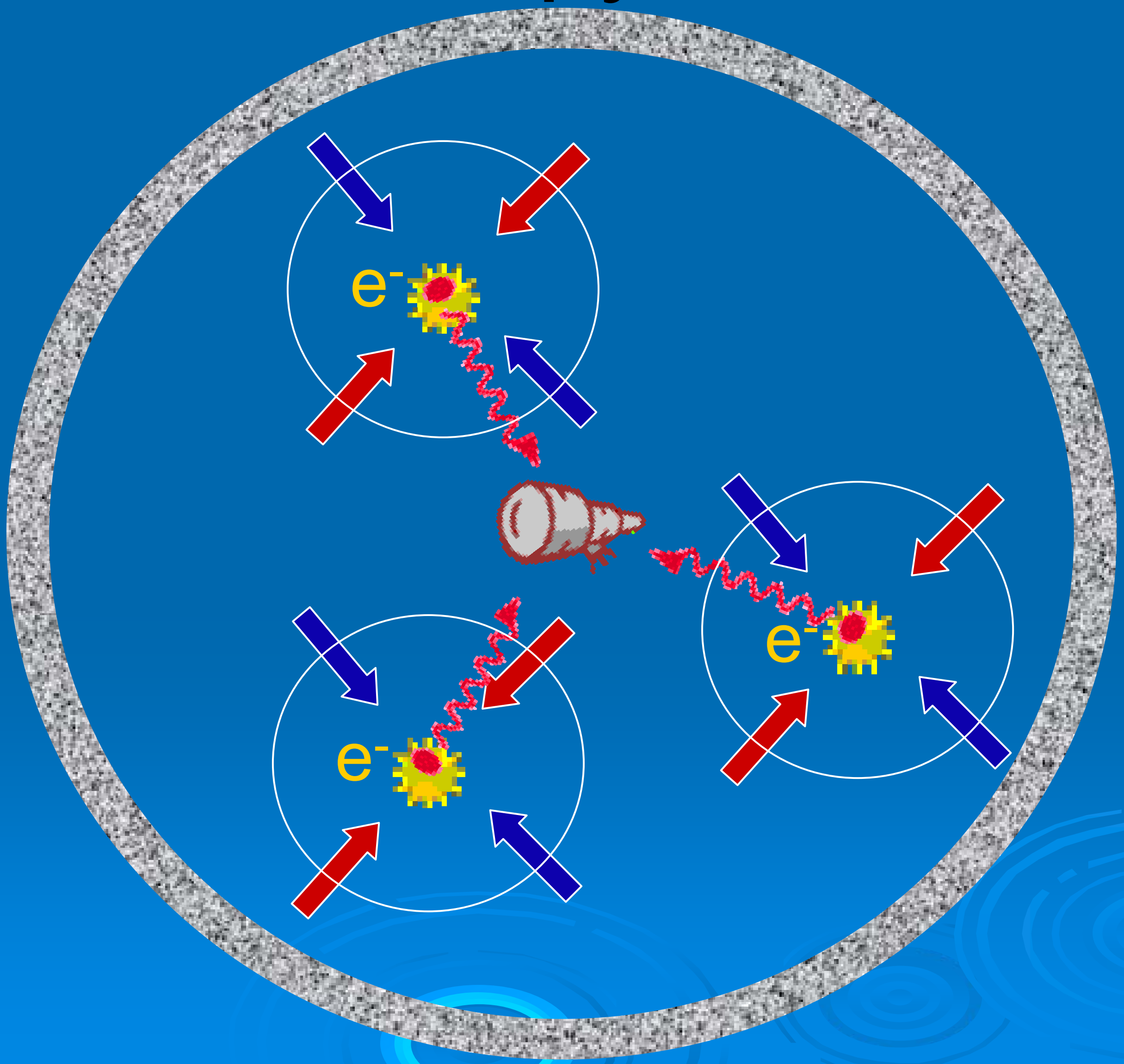


Gradient (E):

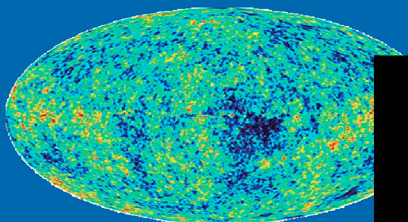


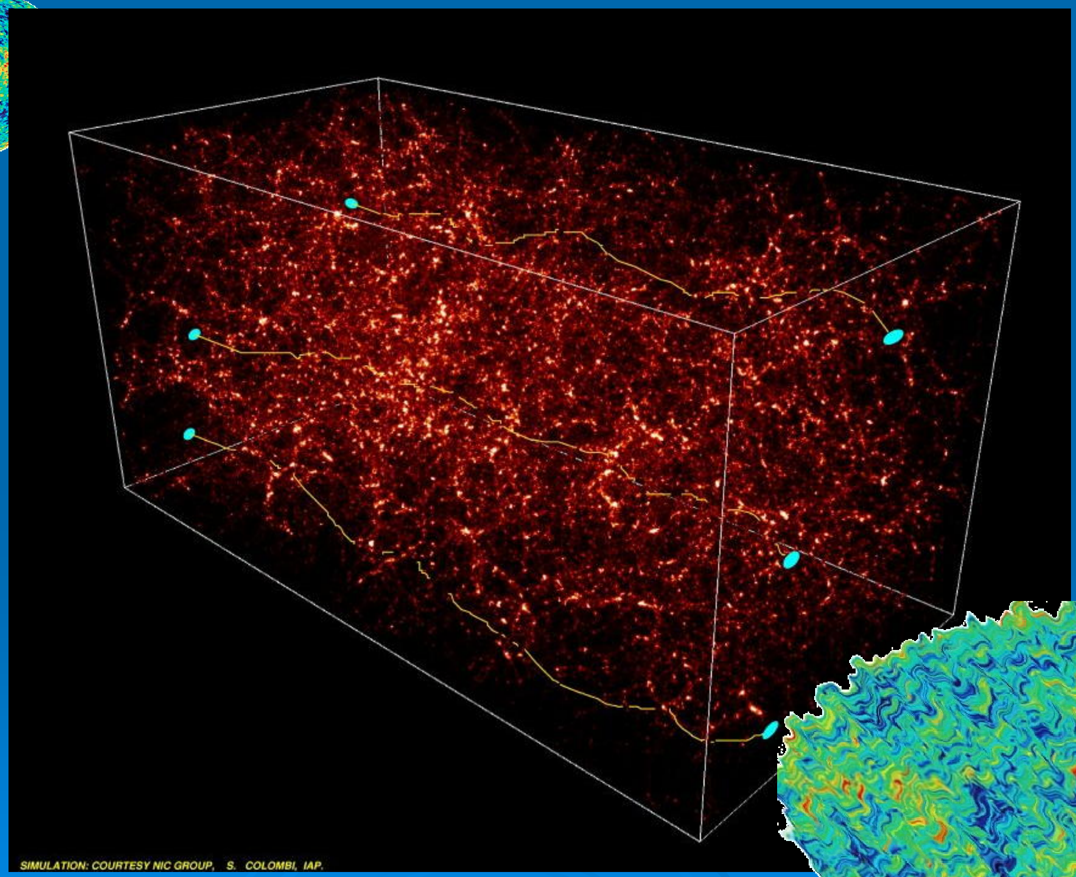


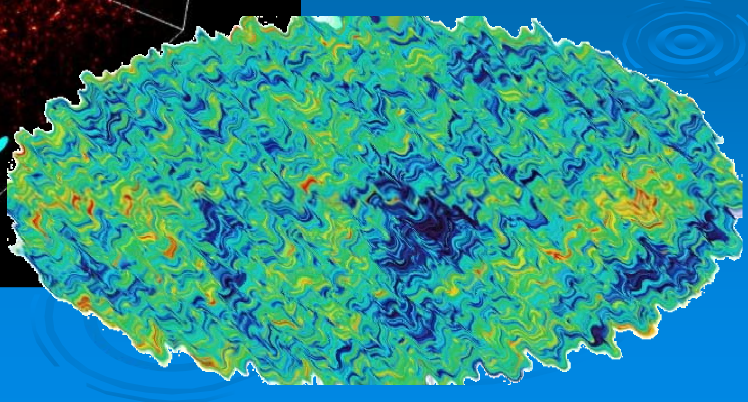
# CMB anisotropy: reionization



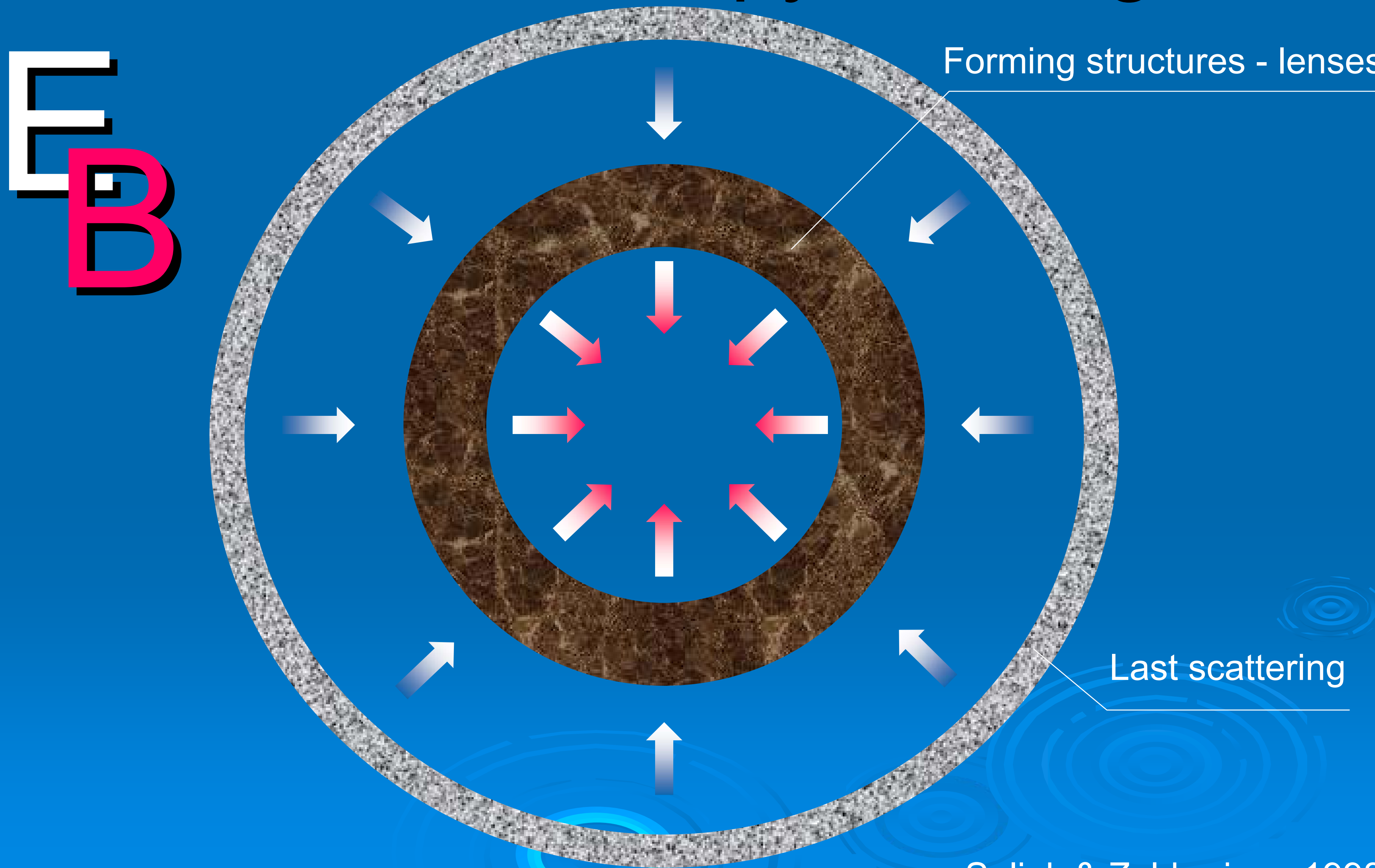
# CMB anisotropy: lensing





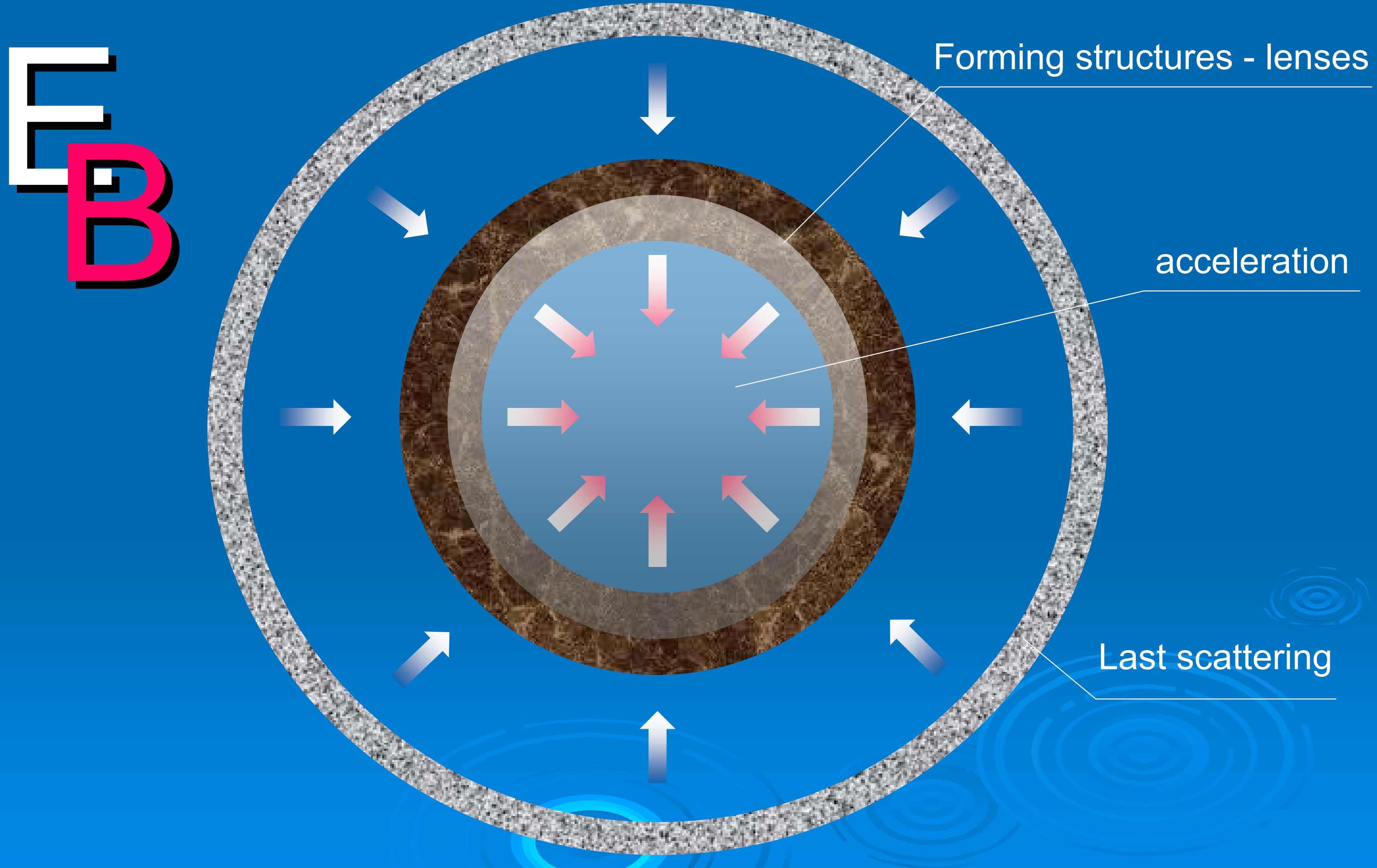



# CMB anisotropy: lensing



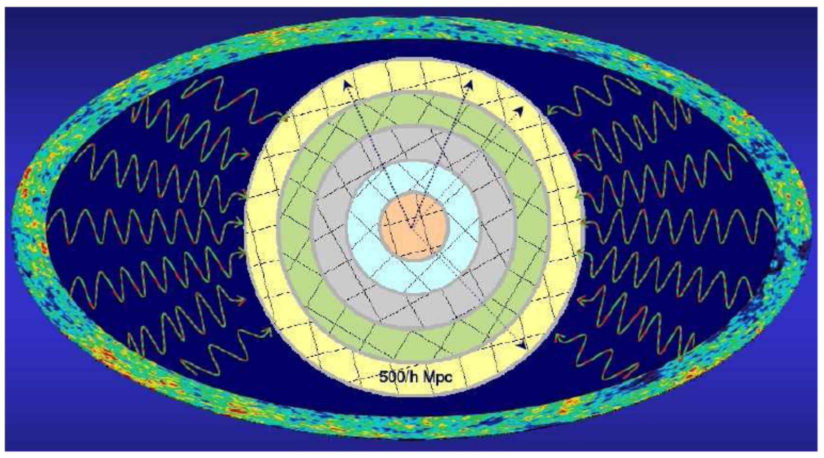

Seljak & Zaldarriaga 1998

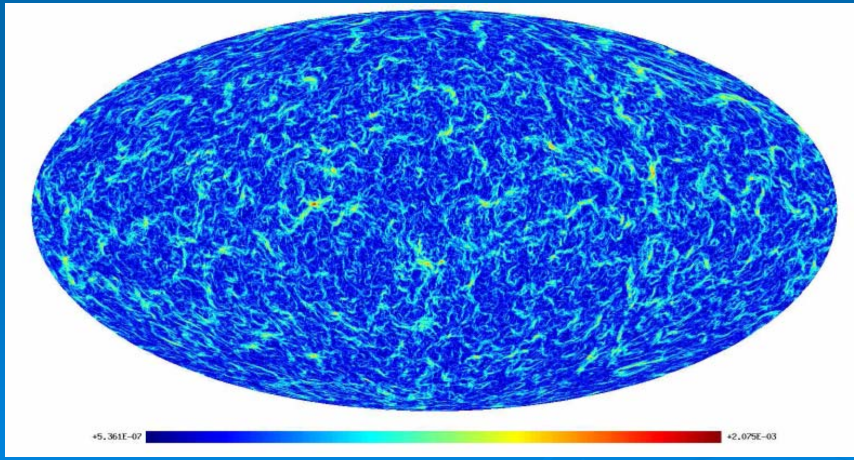
# CMB anisotropy: lensing

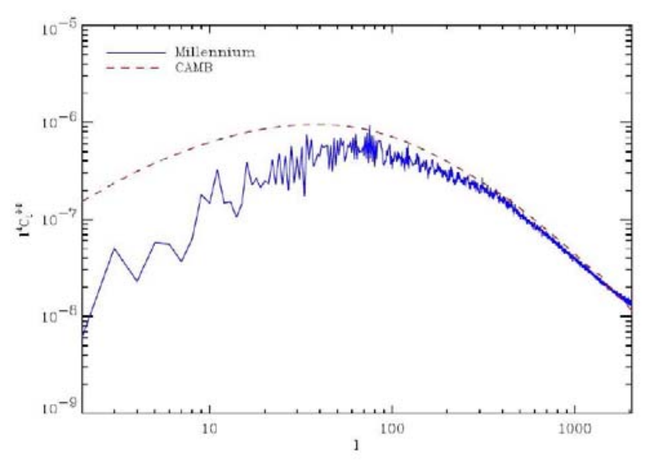


# CMB anisotropy: lensing

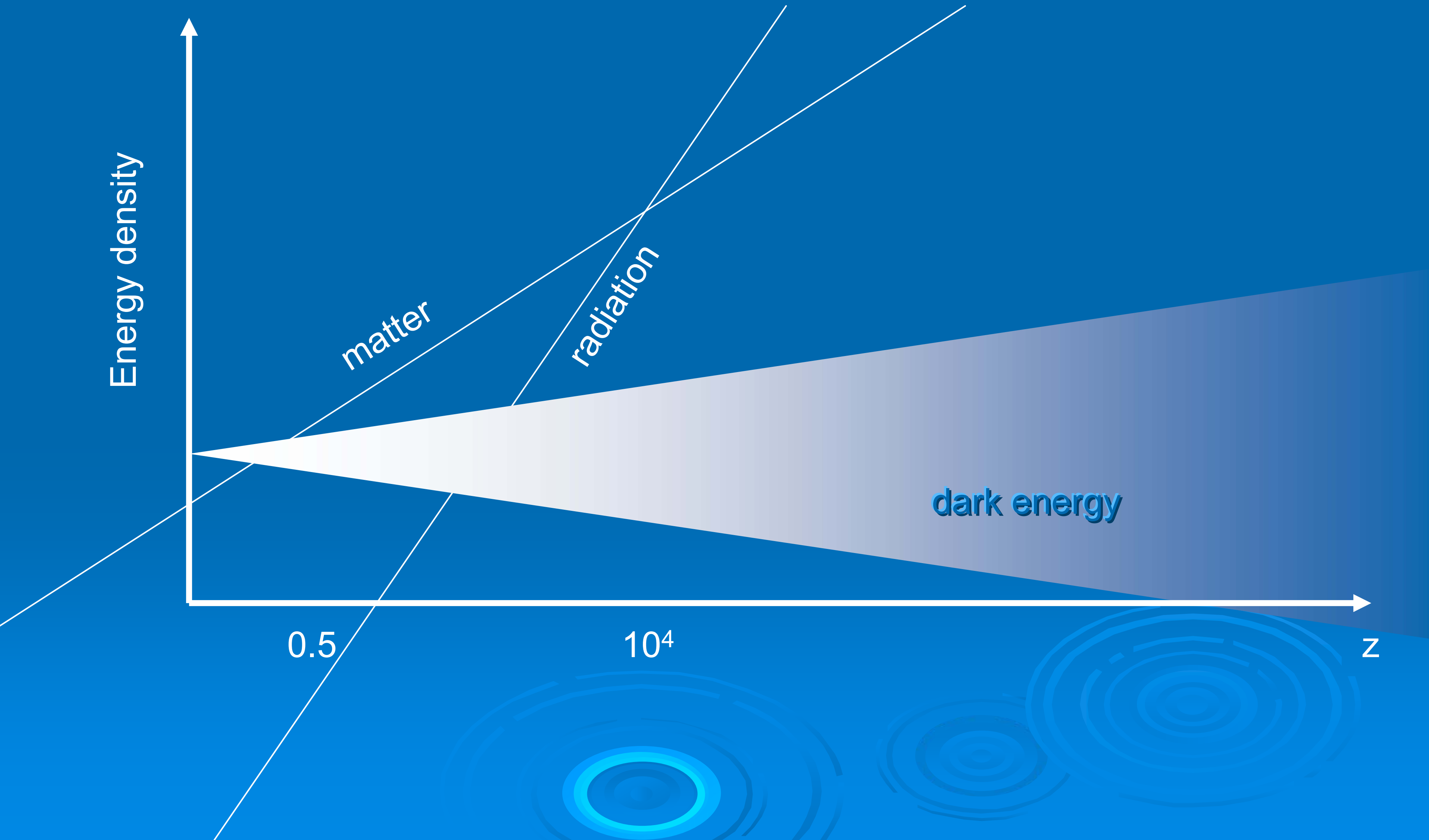
- N-body simulations are exploited for predicting the pattern and full statistics of the lensing distortion, beyond the semi-analytical estimates concerning the power spectrum
- Carbone (PhD thesis), Bartelmann, Baccigalupi, Matarrese, Springel, in preparation



# CMB lensing and dark energy



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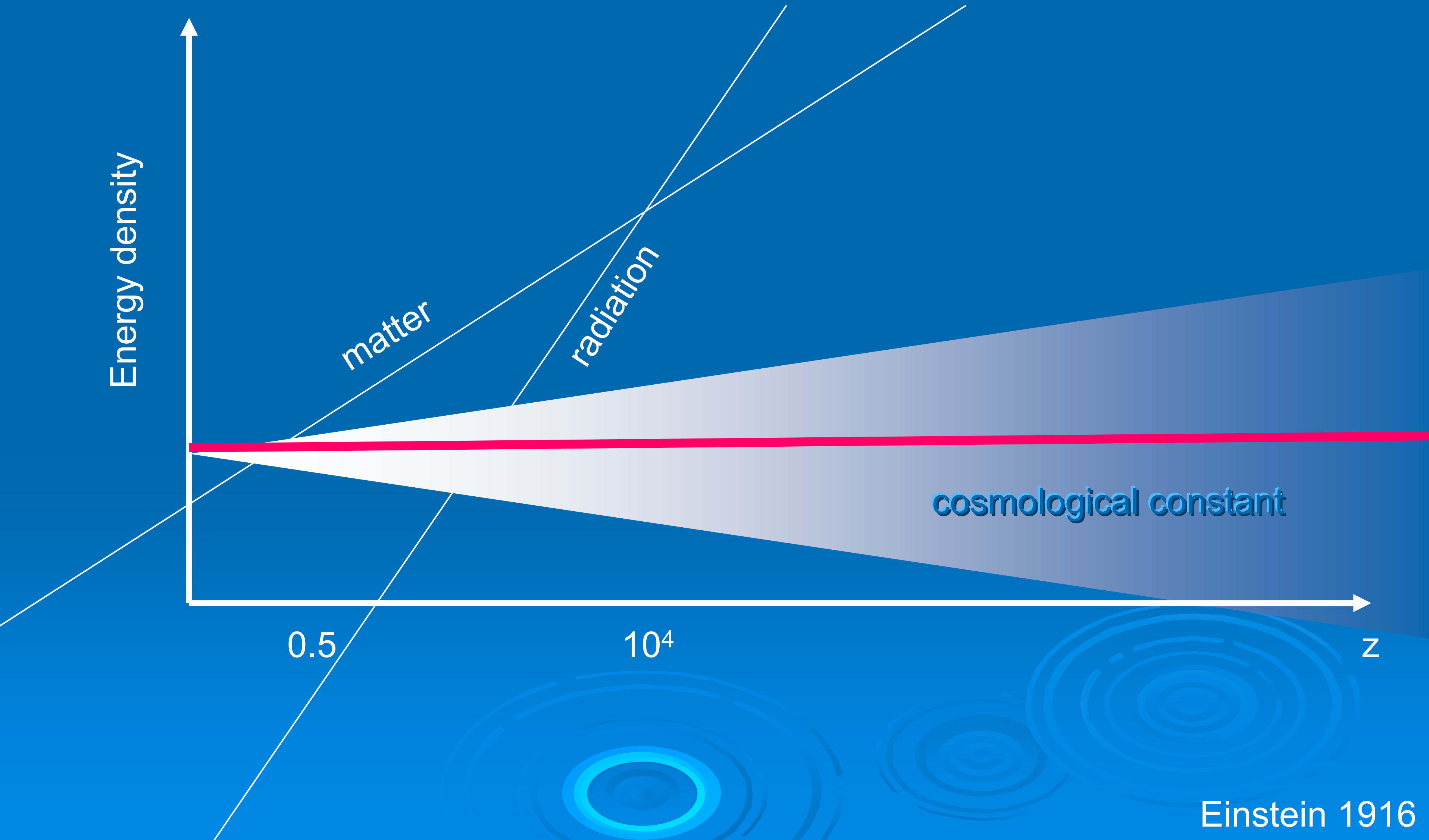
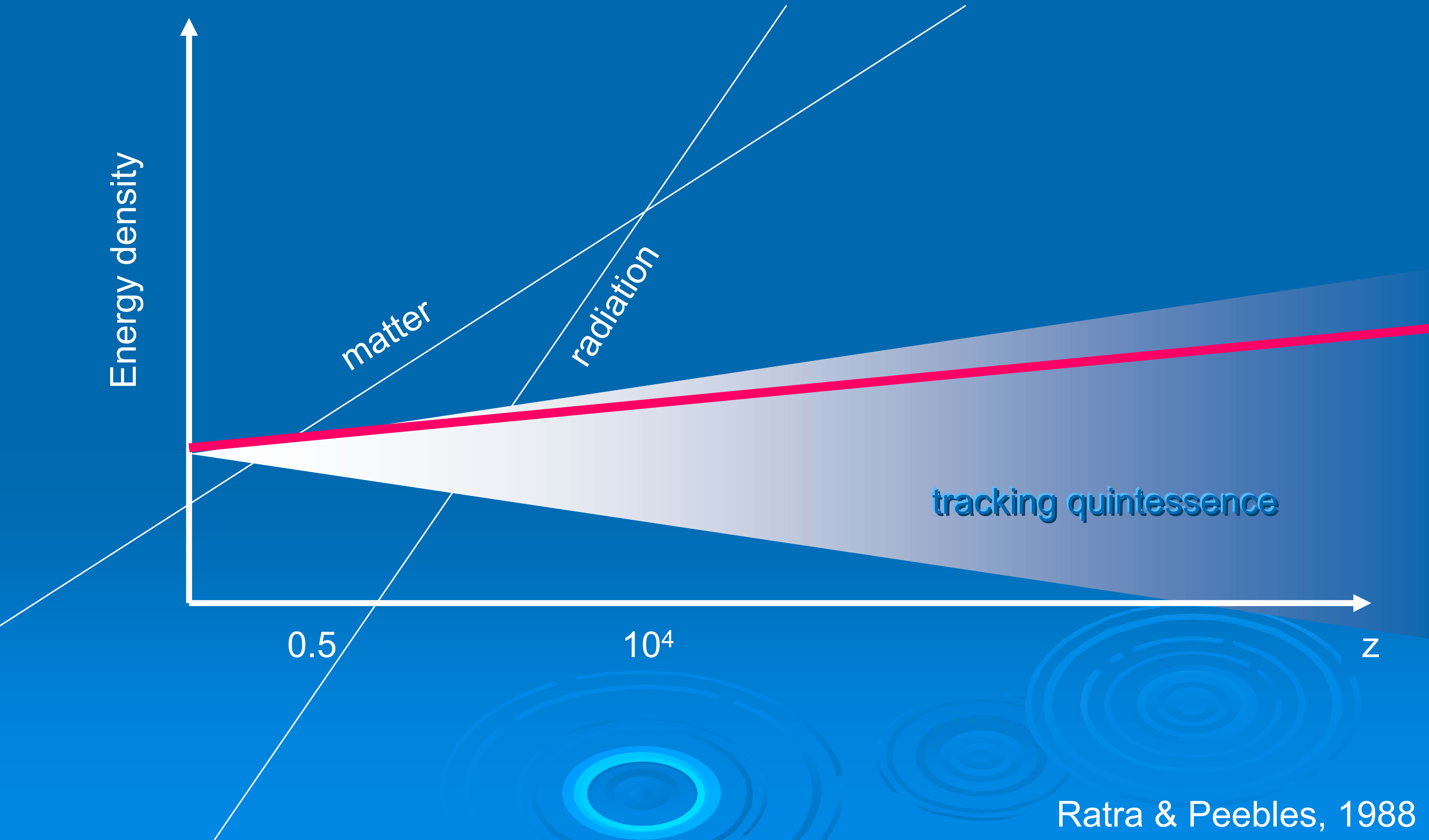


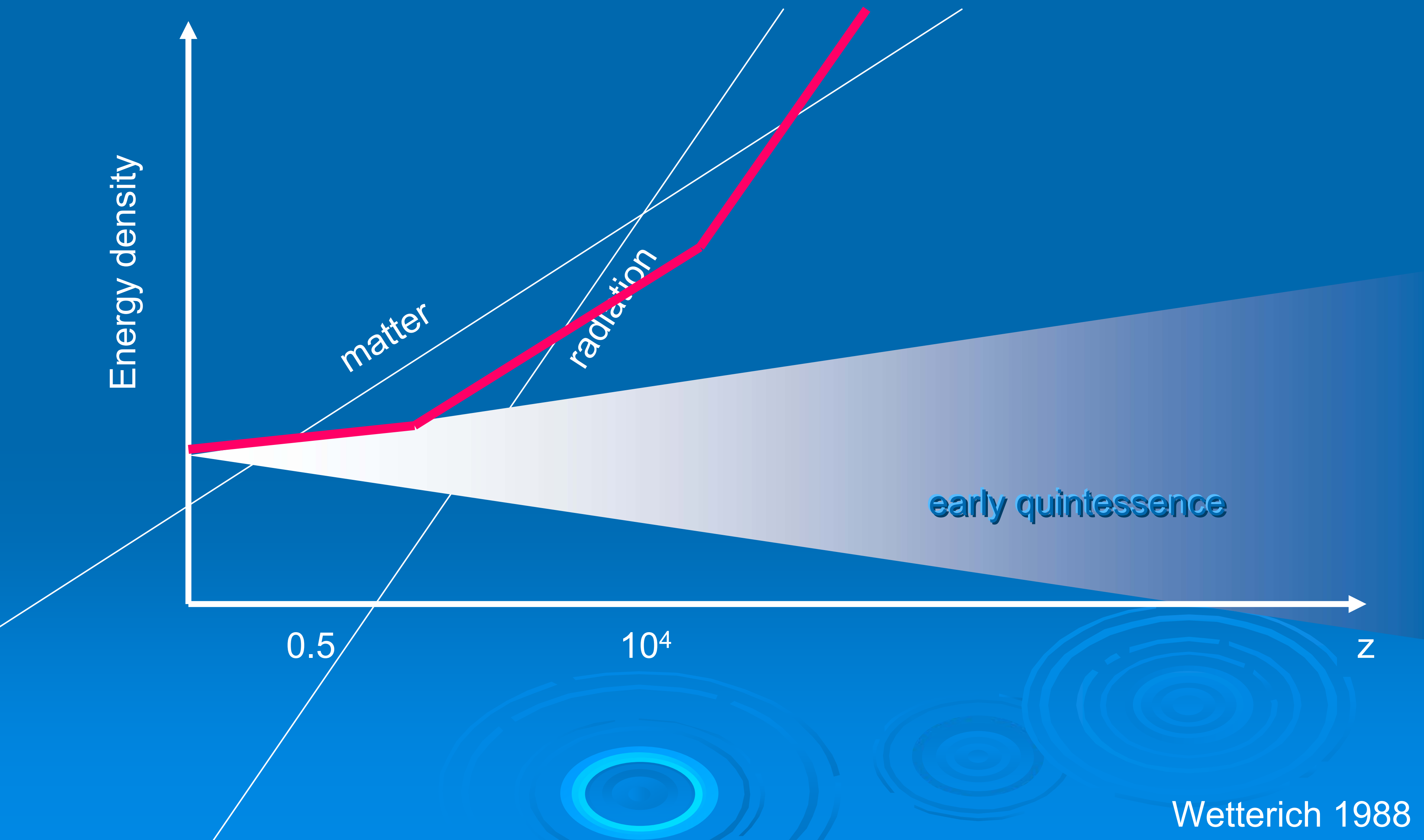

Einstein 1916

# CMB lensing and dark energy



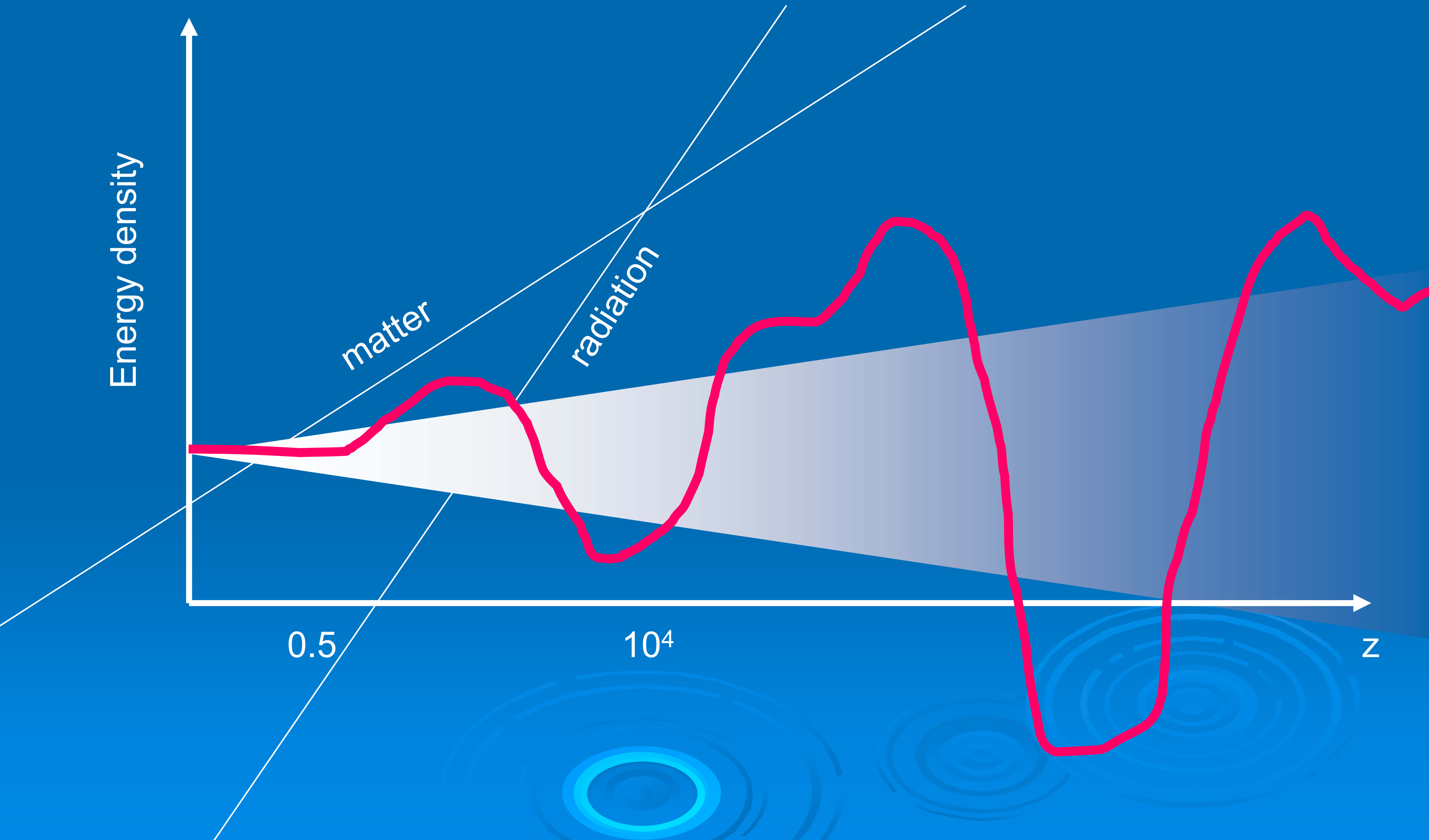

Ratra & Peebles, 1988

# CMB lensing and dark energy




Wetterich 1988

# CMB lensing and dark energy



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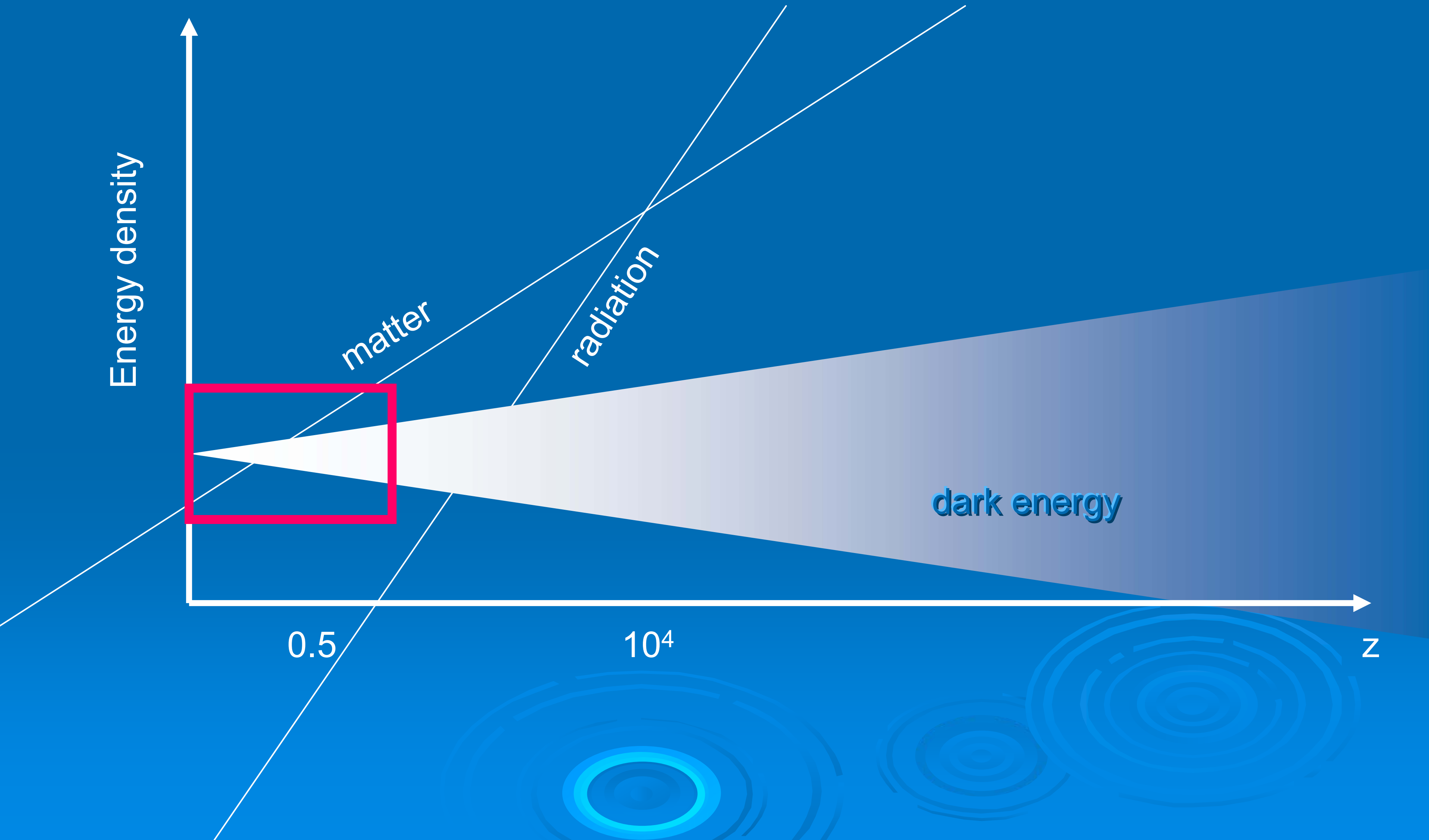

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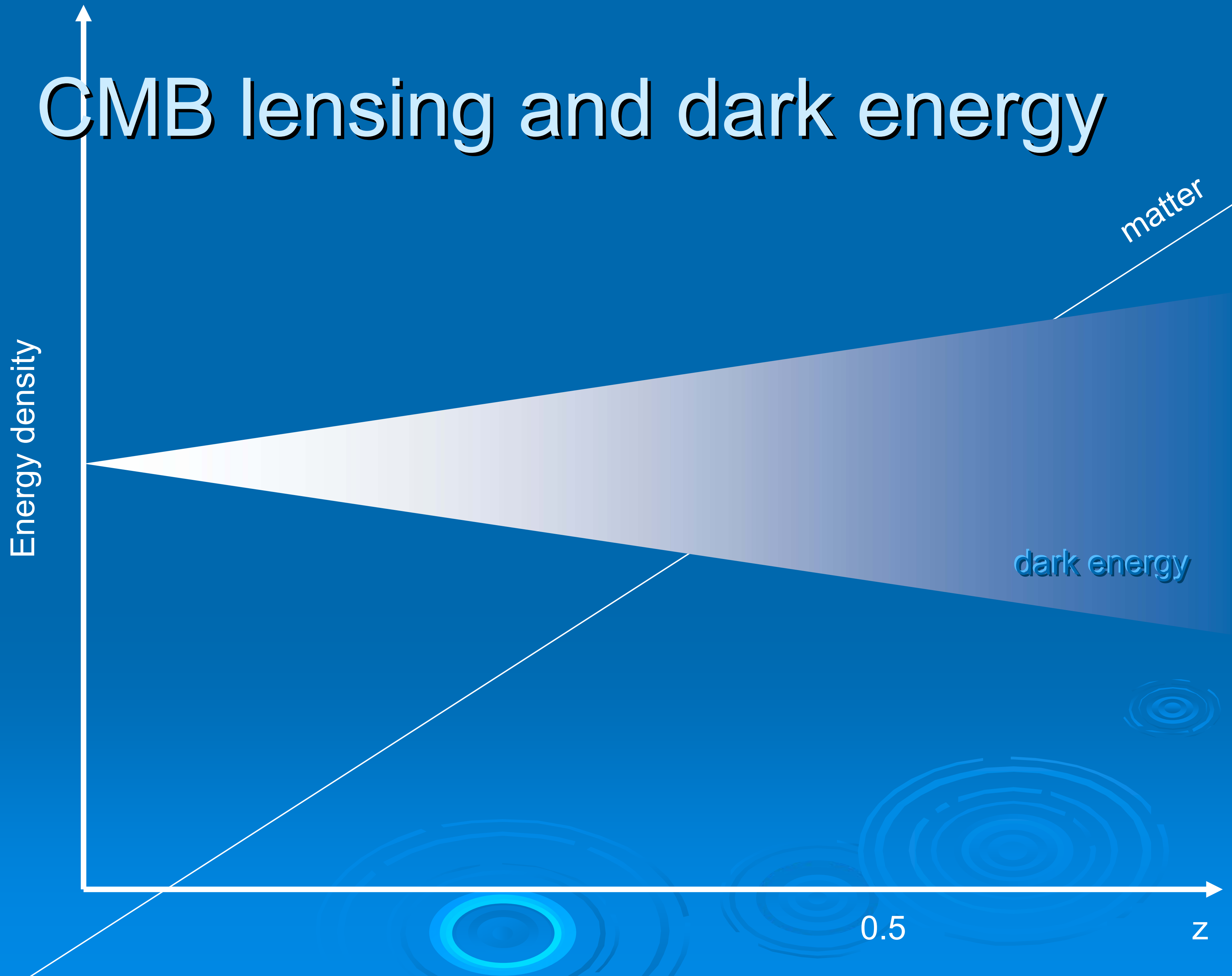

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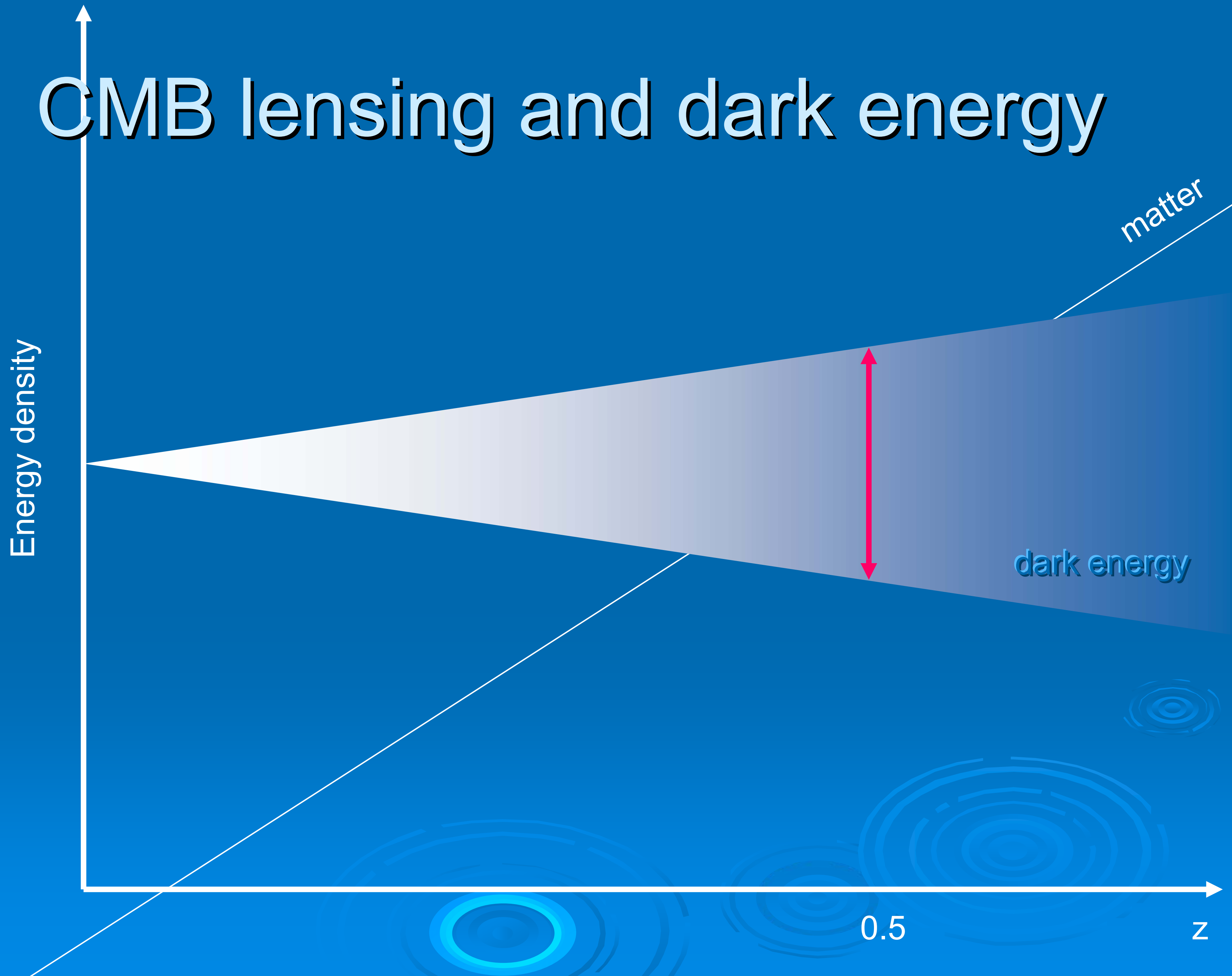
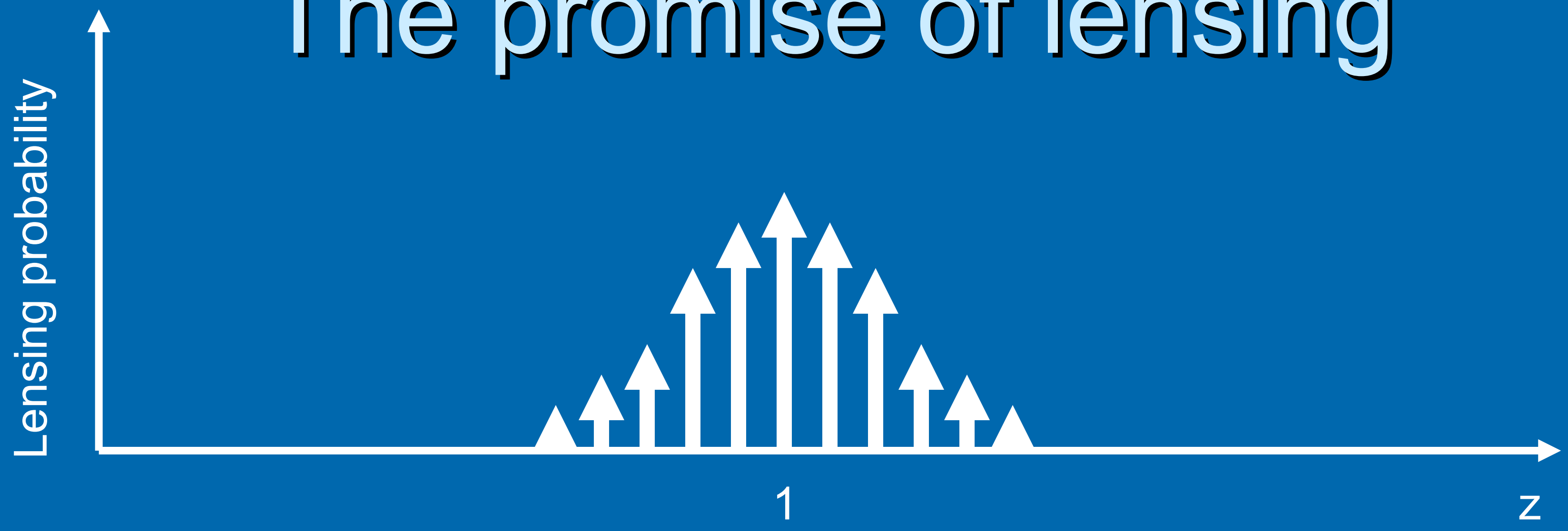
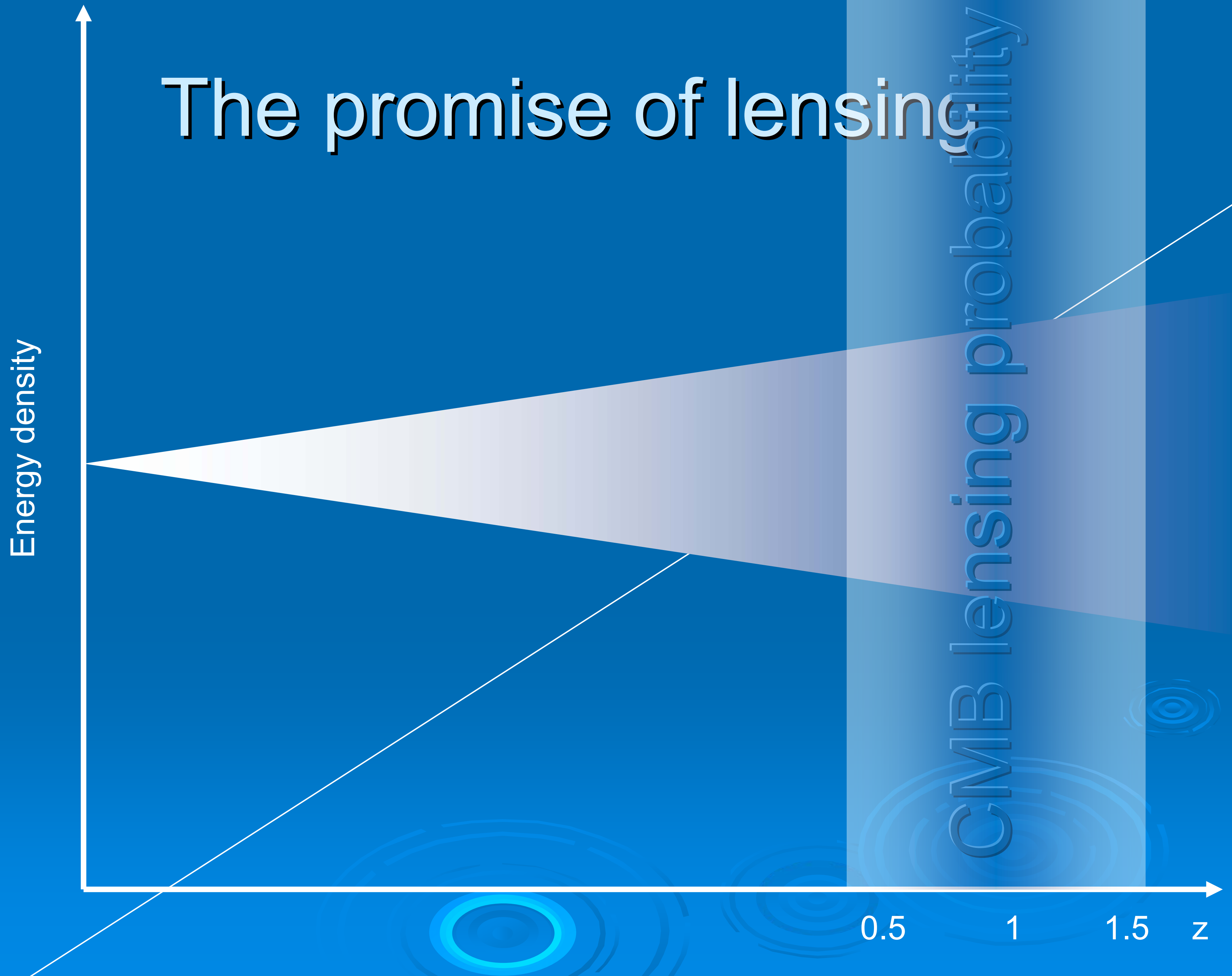


# The promise of lensing




- 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



# Status of the CMB observations and future experimental probes

# CMB anisotropies

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

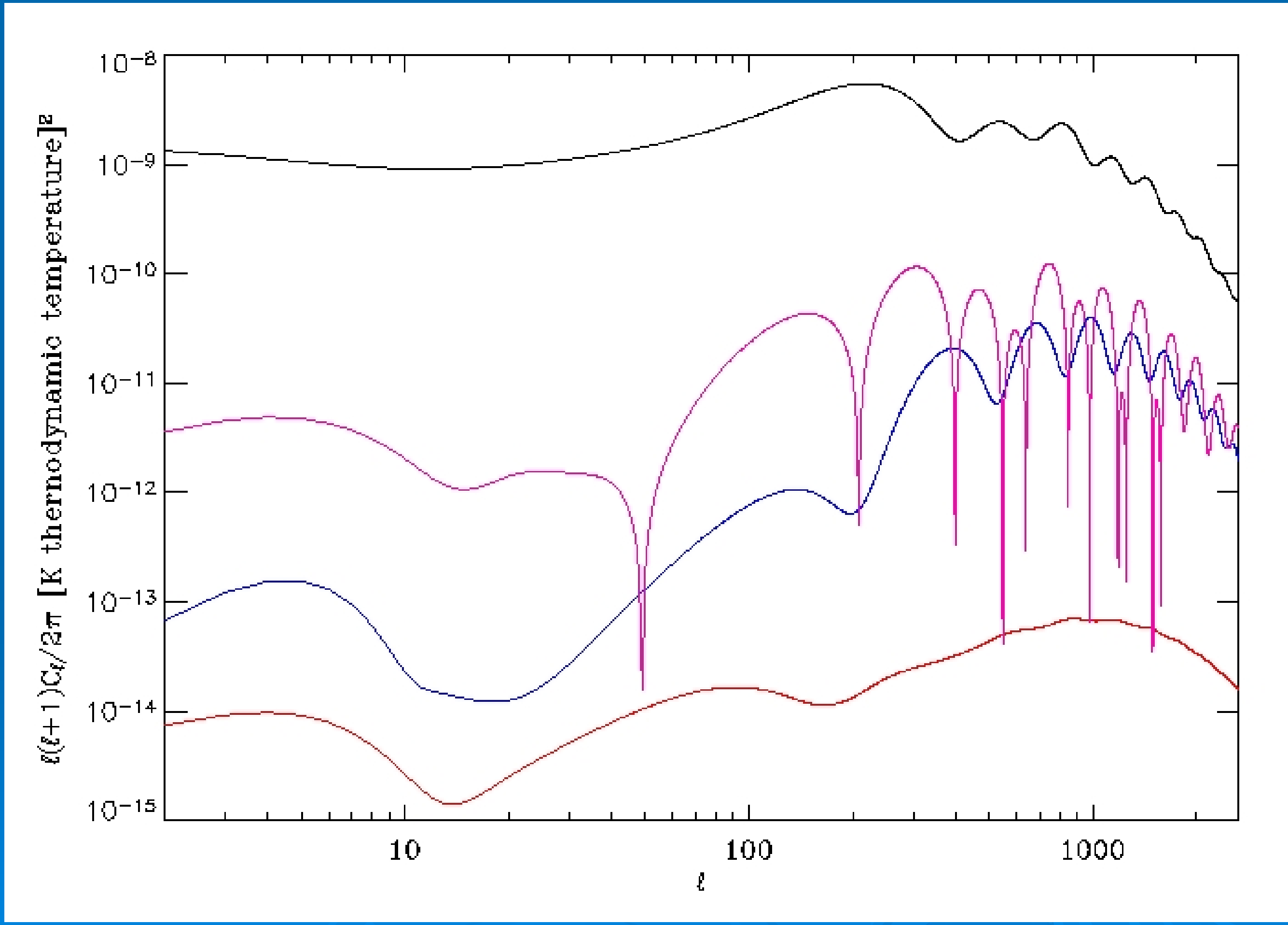
spherical harmonics

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

information compression

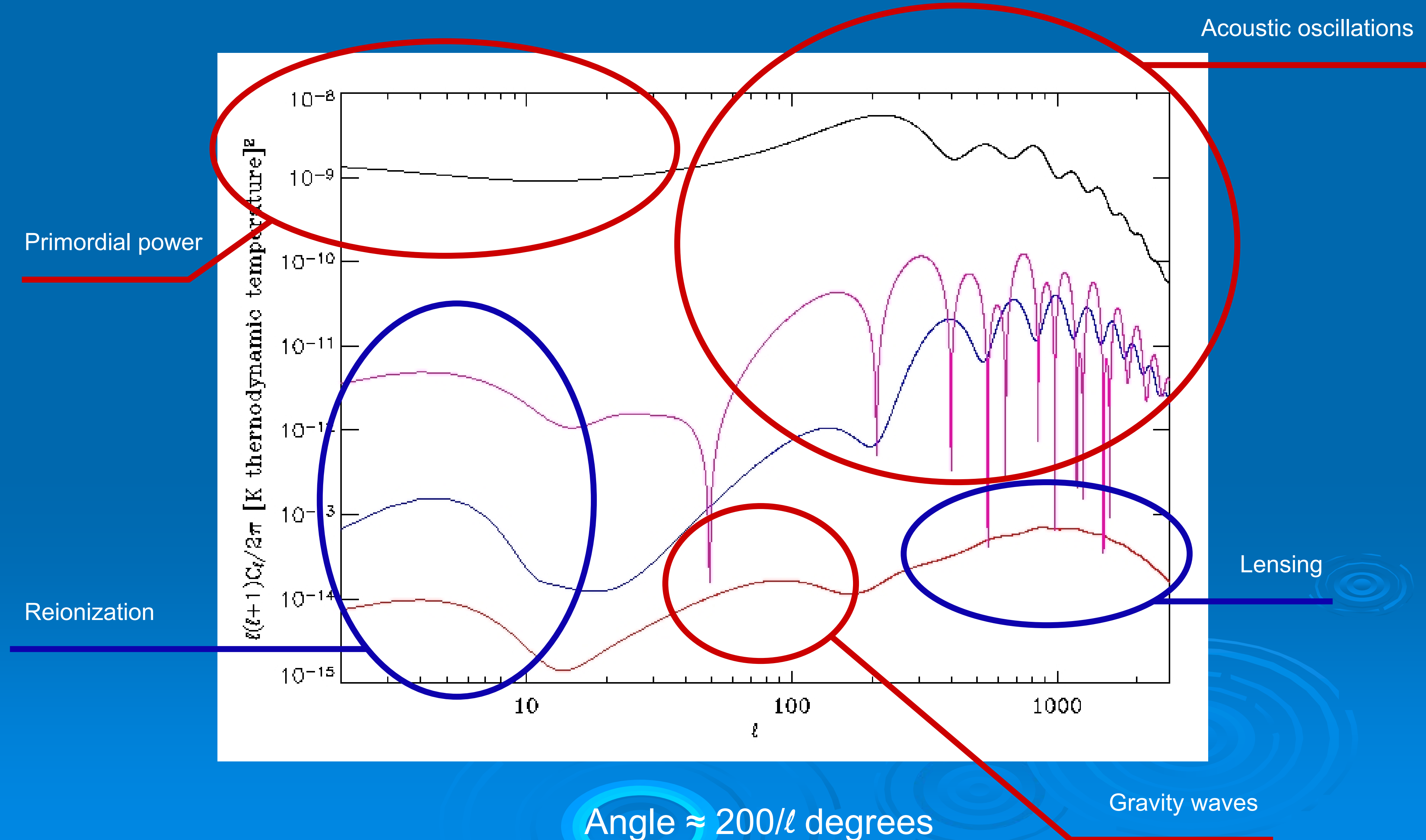
$$C_l = \Sigma_m |a_{lm}{}^{T,E,B}|^2 / 2(l+1)$$

# CMB angular power spectrum



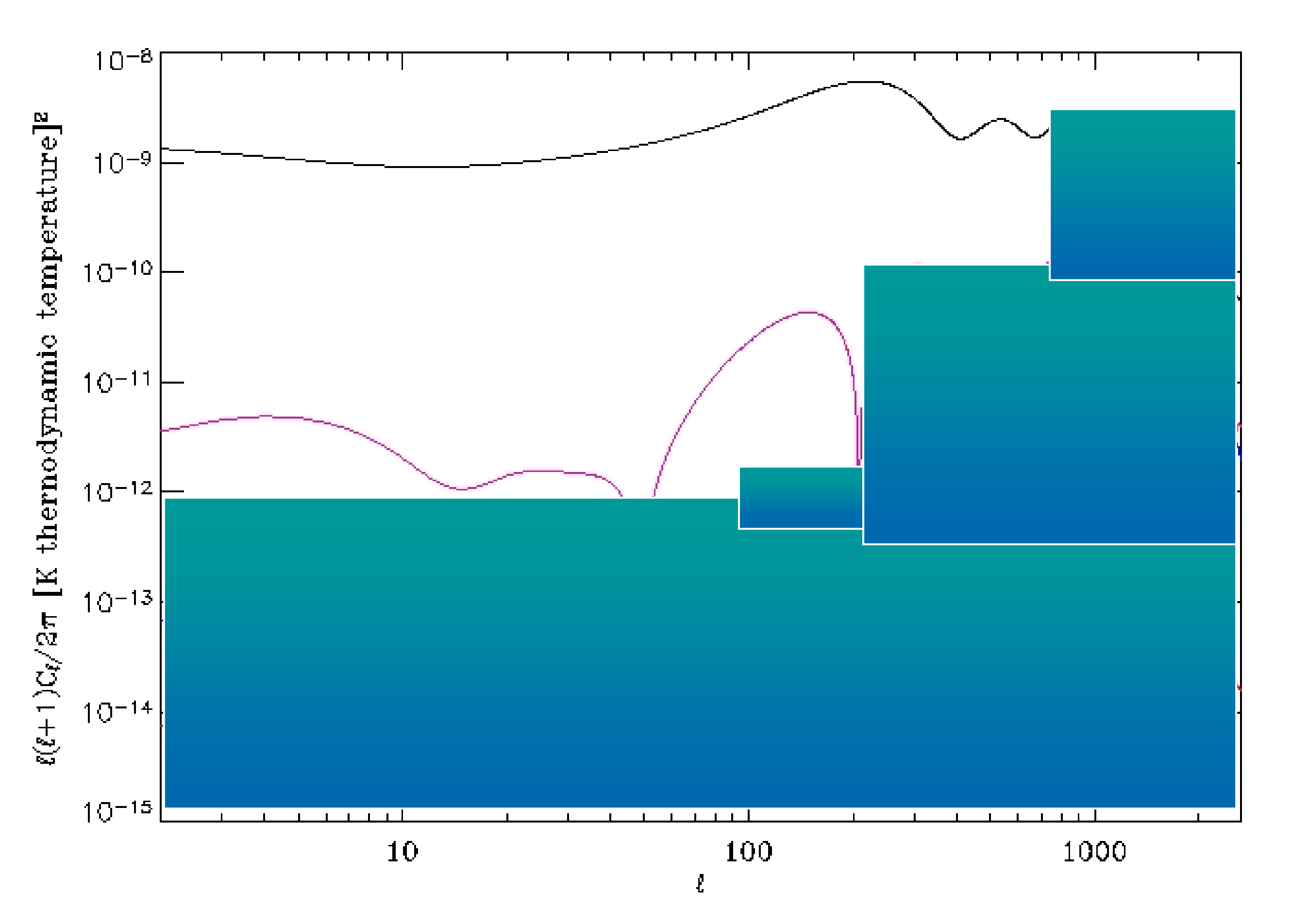

Angle ≈ 200/$\ell$ degrees

# CMB angular power spectrum



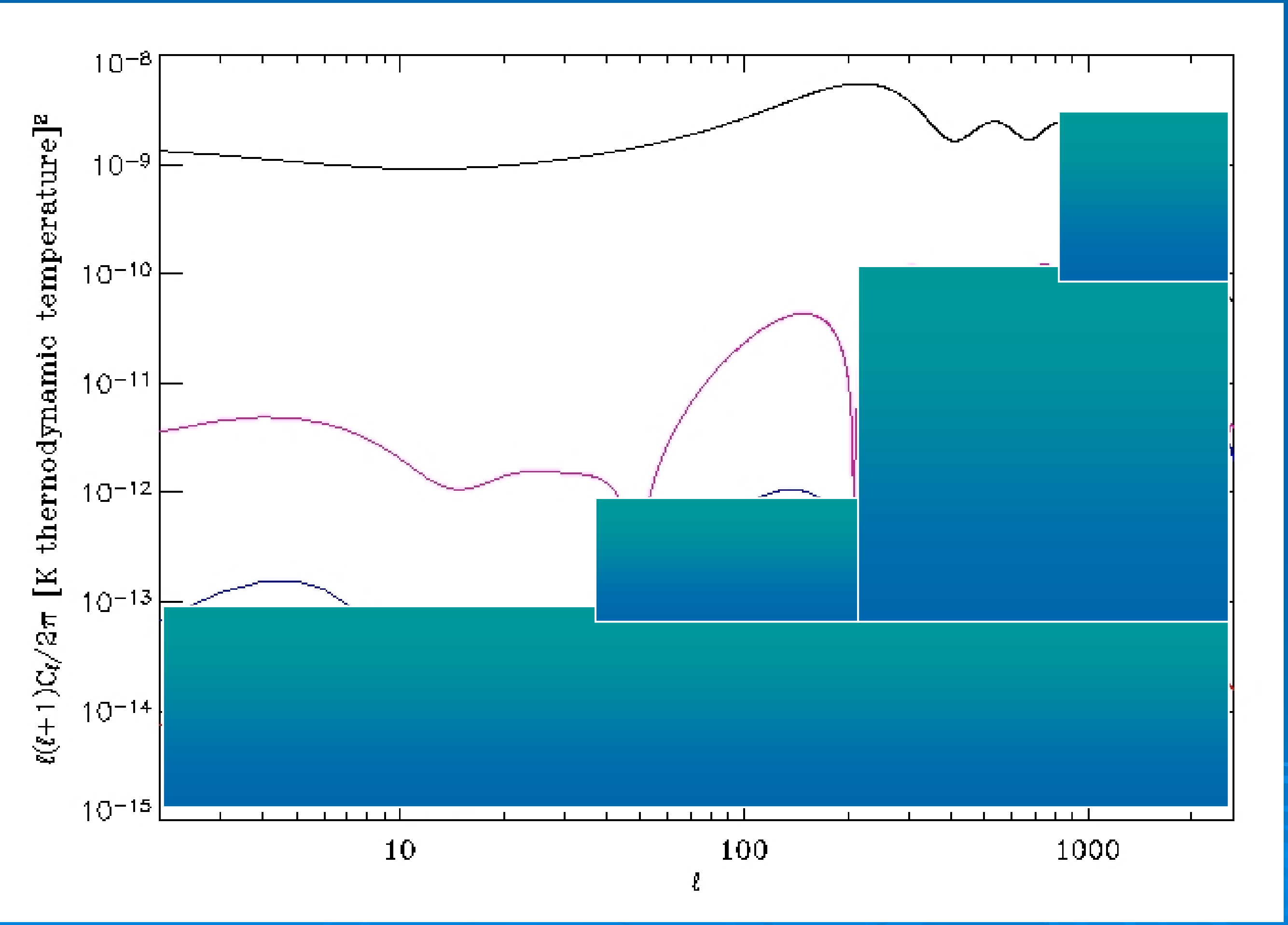

Angle ≈ 200/ℓ degrees

# WMAP first year



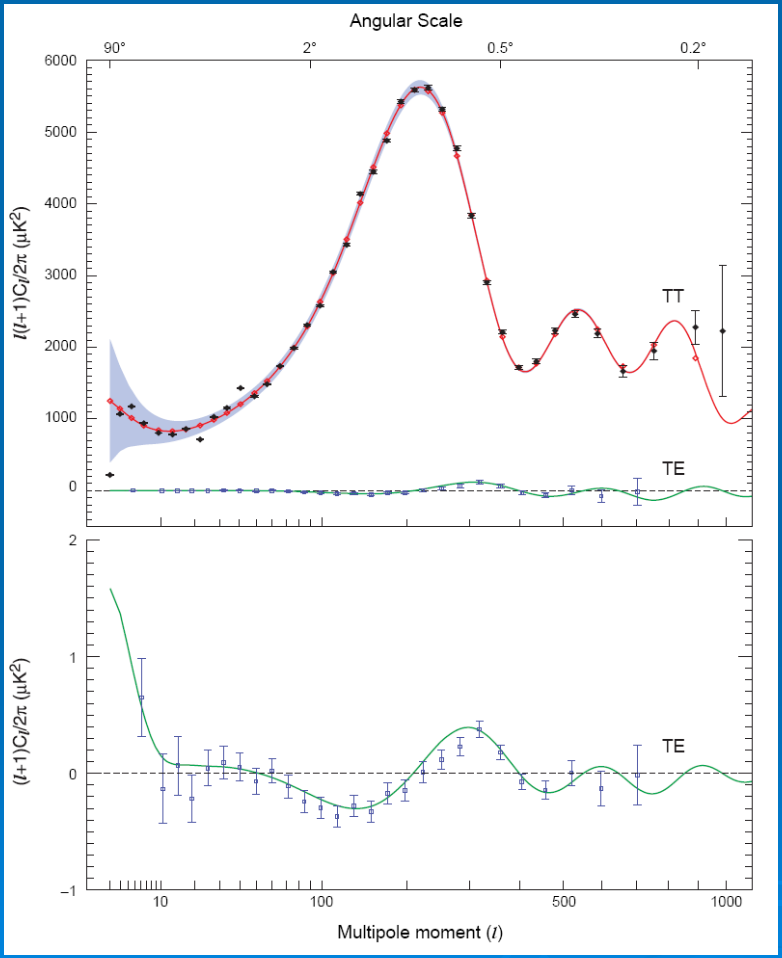

Angle ≈ 200/$\ell$ degrees

# WMAP third year

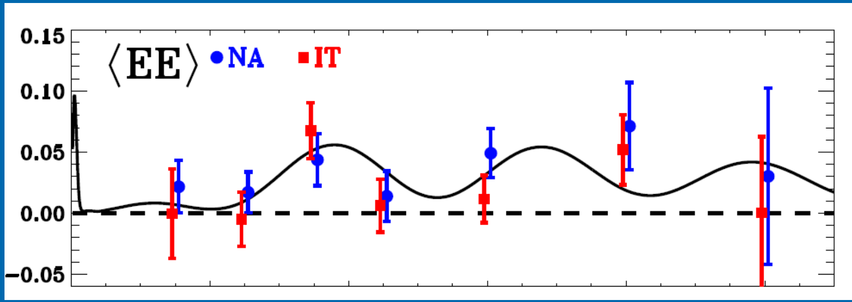



Angle ≈ 200/$\ell$ degrees

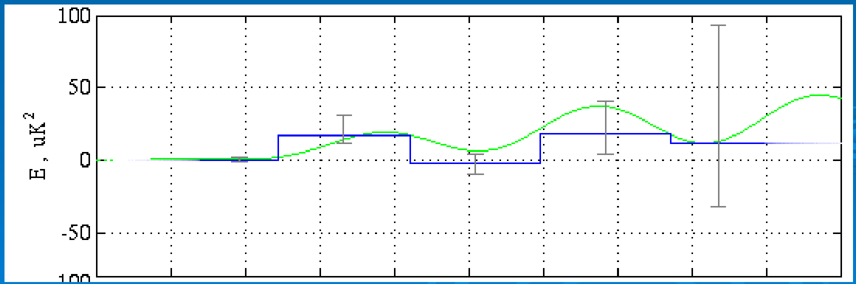
# CMB angular power spectrum




WMAP




boomerang

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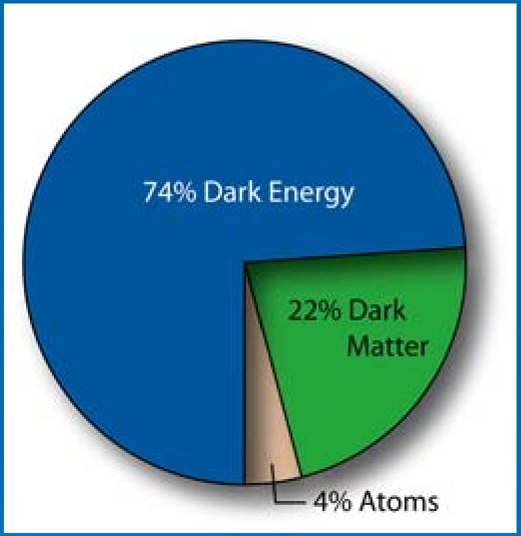
# Cosmological concordance model



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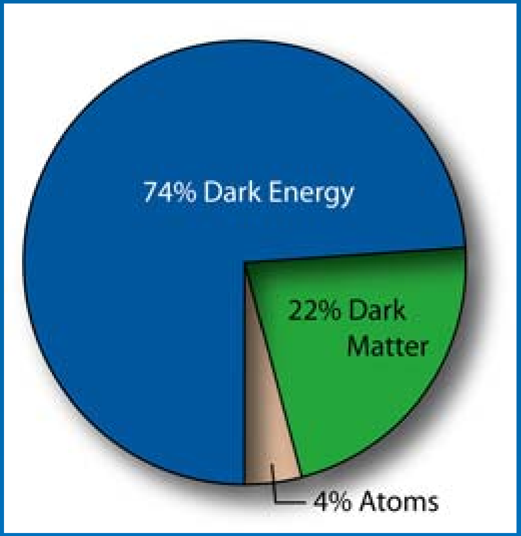


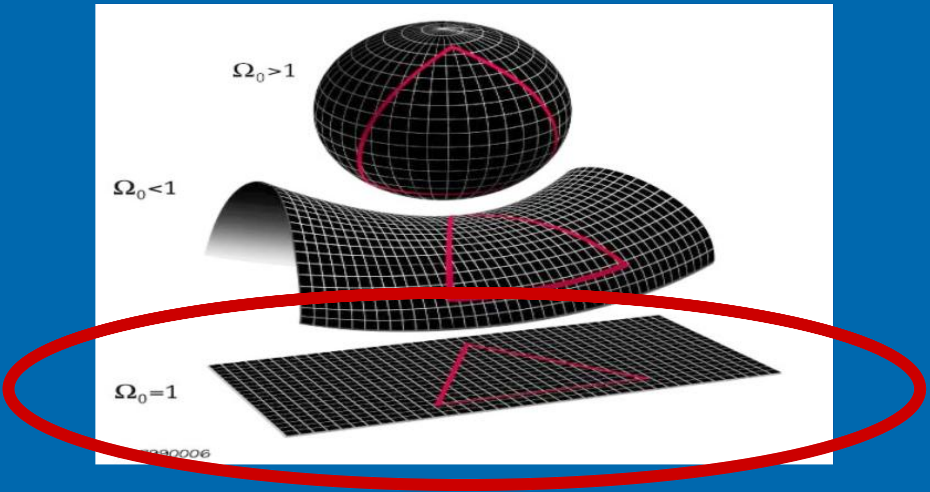

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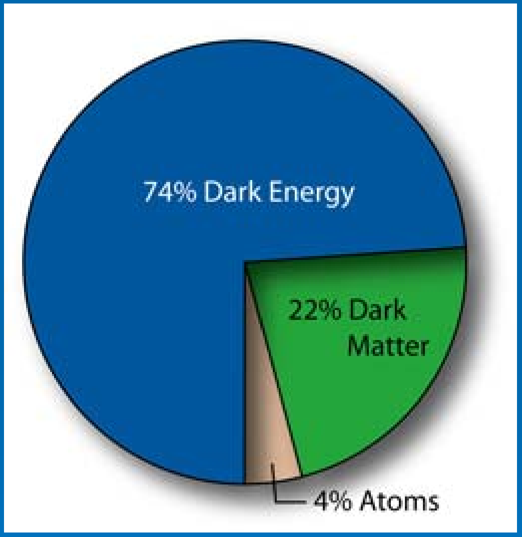
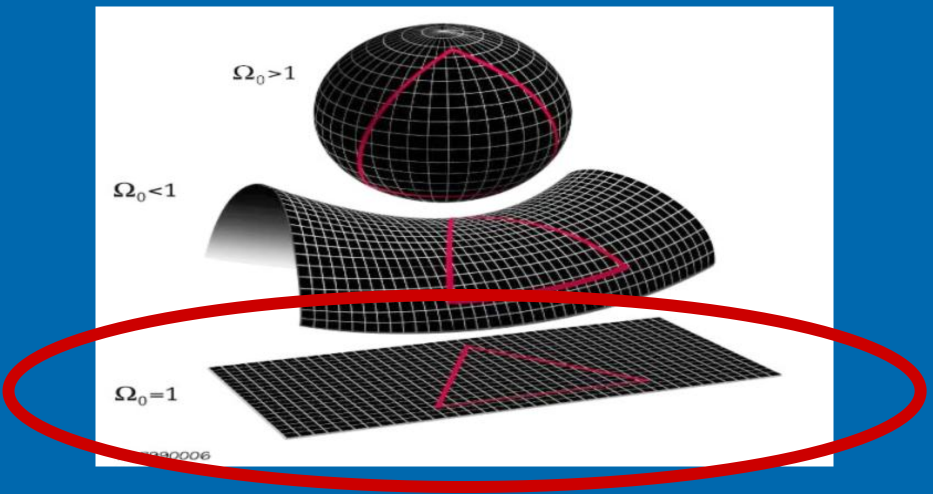
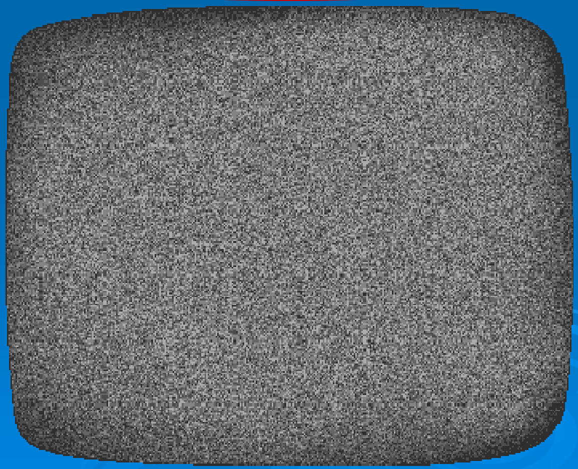
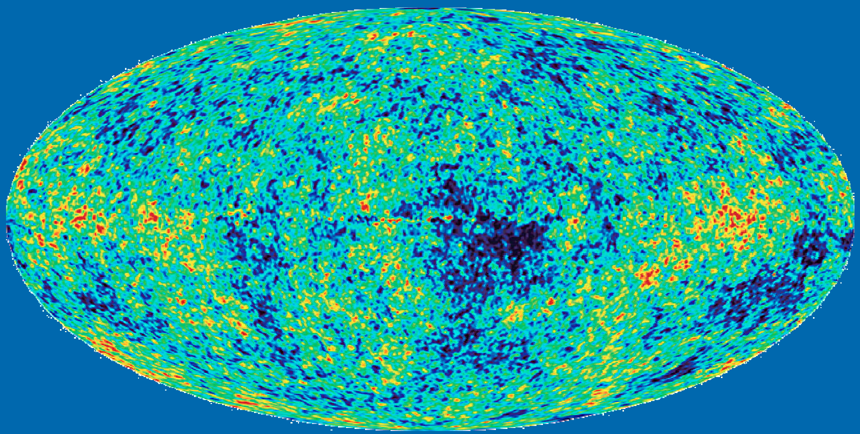


# CMB anisotropy statistics: unknown, probably still hidden by systematics

- Evidence for North south asymmetry (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

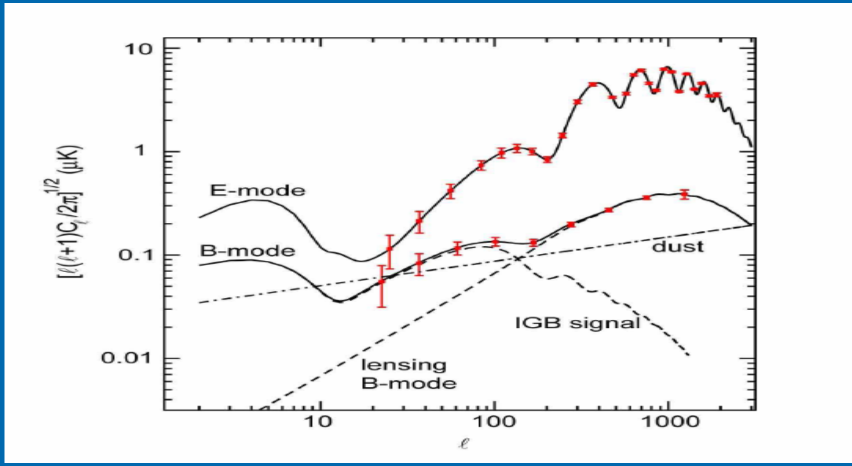


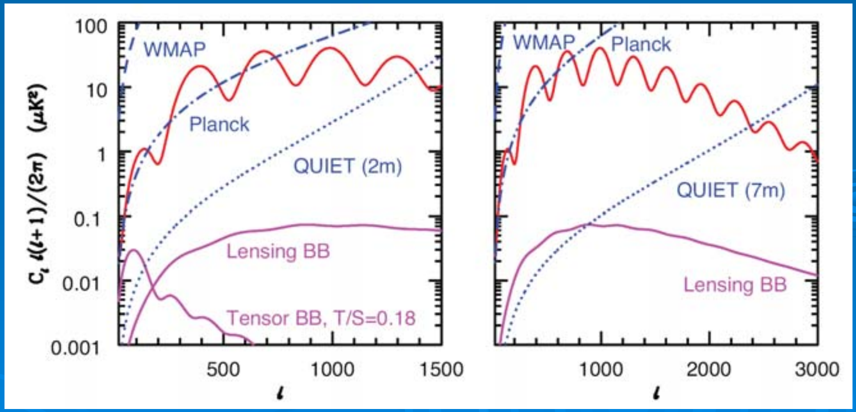
# Other cosmological backgrounds?

- 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 (NASA funded, data analysis people in the US, France, Italy), baloon, same launch time scale as Planck for the north american flight
- QUIET (US, UK), ground based
- Clover (UK, …)
- Brain
- …
- The complete list of ongoinf an planned experiments is available at the Lambda archive lambda.gsfc.nasa.gov

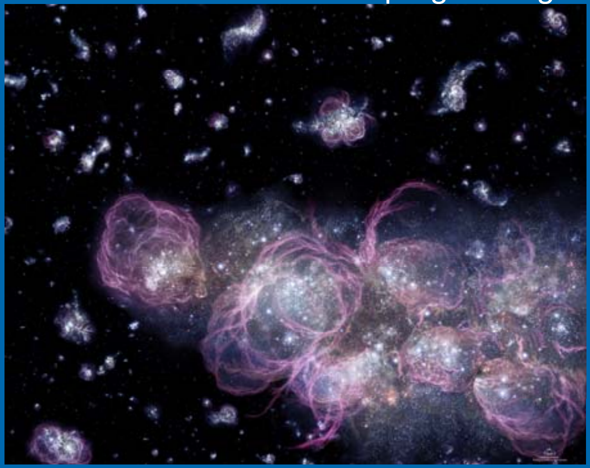


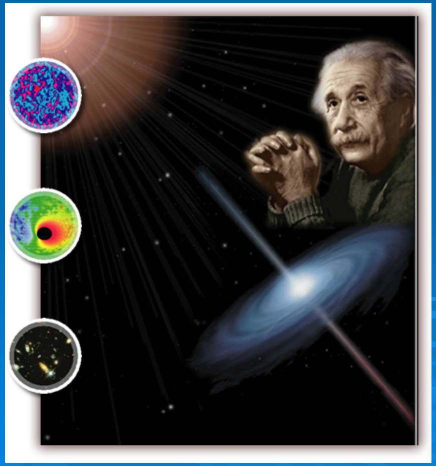



# Cosmic vision beyond Einstein

- 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



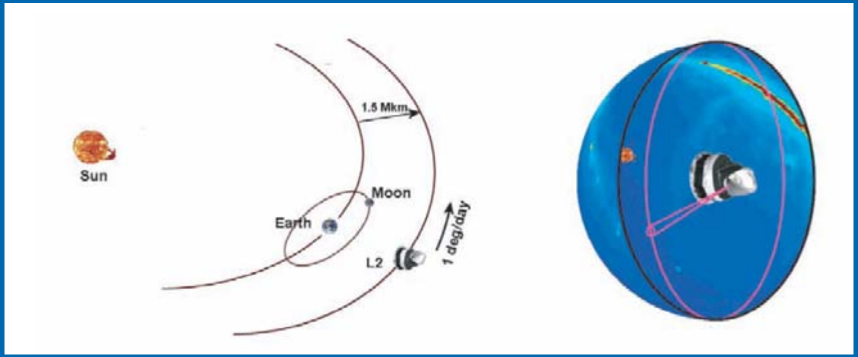


Beyond einstein logo

# Basics of CMB data analysis

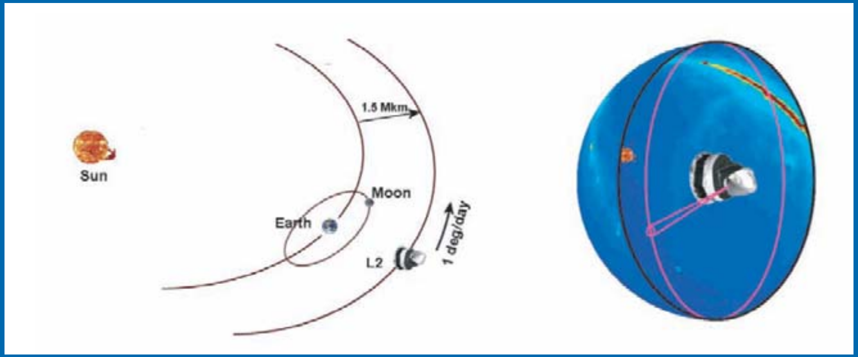
# CMB data analysis: super-zip

- 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

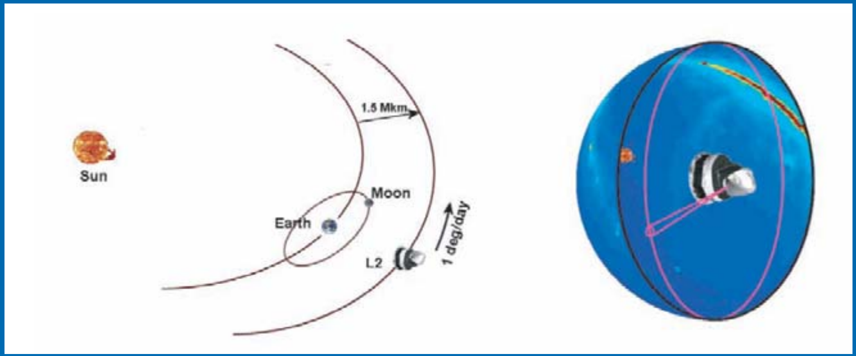



# Super-zip main phases

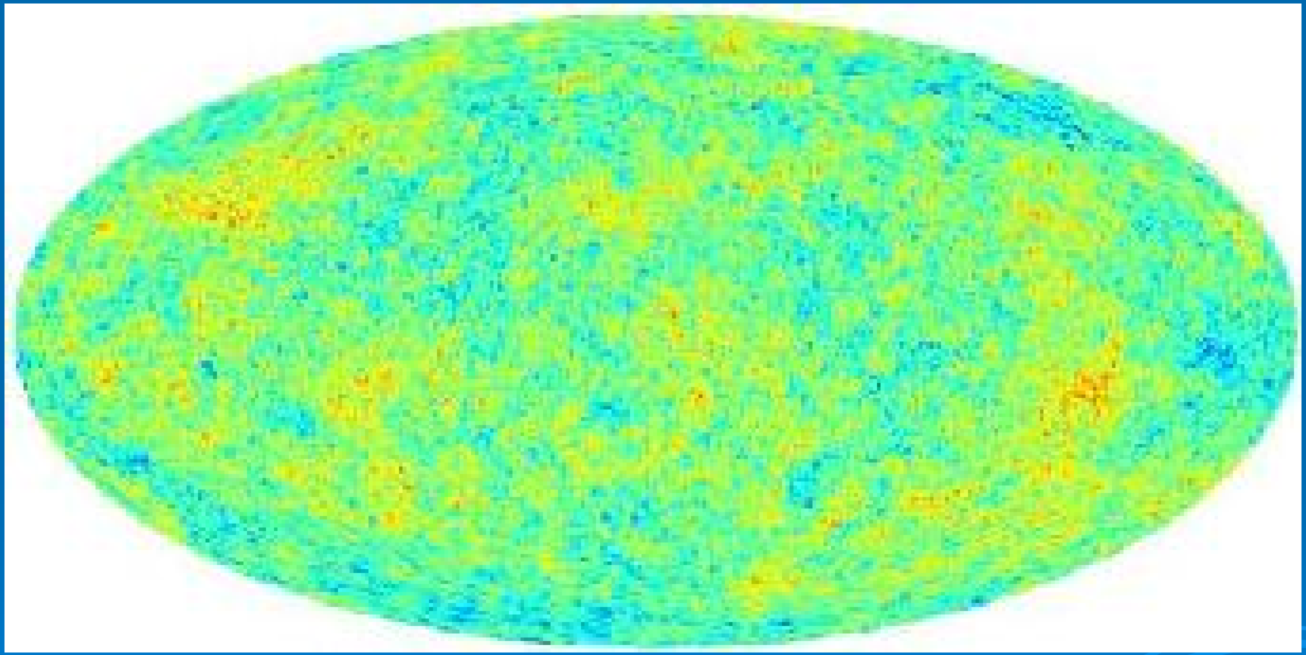
- Time ordered data
- Map-making
- Component separation

# CMB data analysis: time ordered data

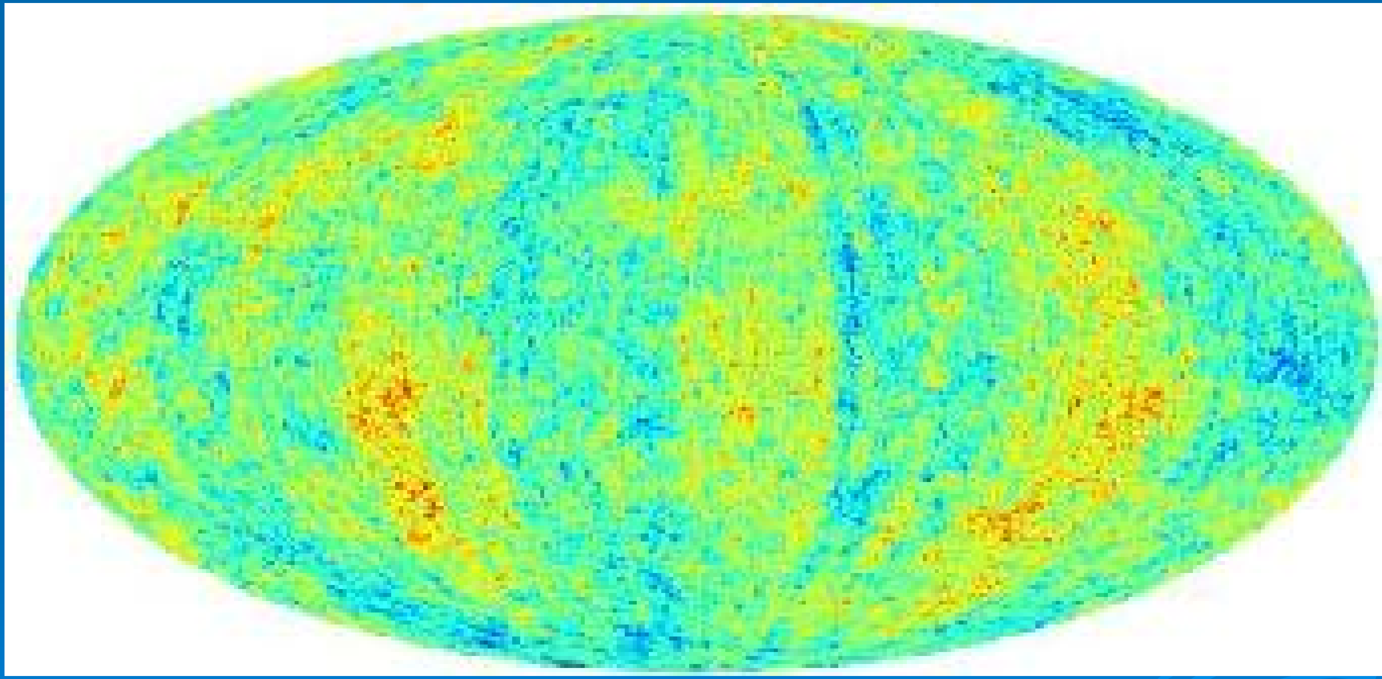
- Beam: at each point, the radiation is collected from a finite solid angle
- Noise: this is the stage where the noise is born
- Calibration: Volts must be converted in CMB units
- …



# CMB data analysis: co-adding map-making



# CMB data analysis: co-adding map-making

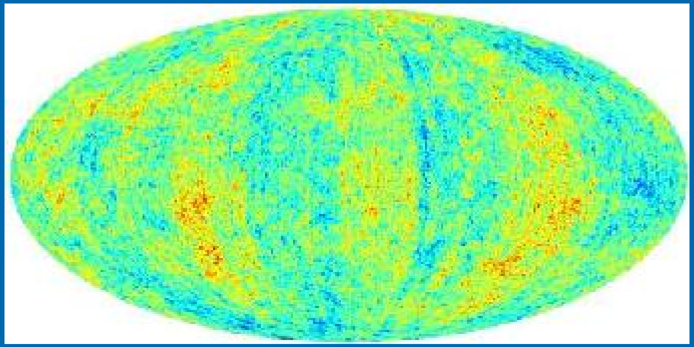


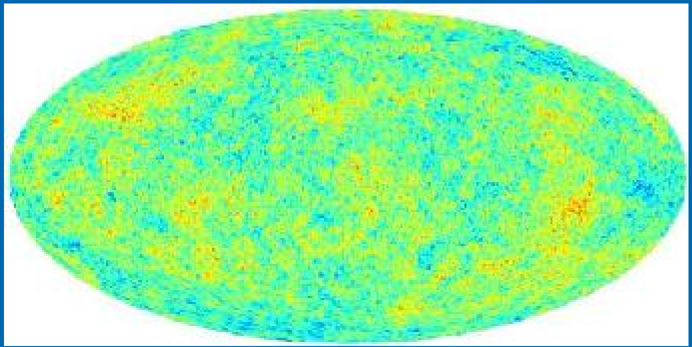
# CMB data analysis: maximum likelihood map-making

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

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

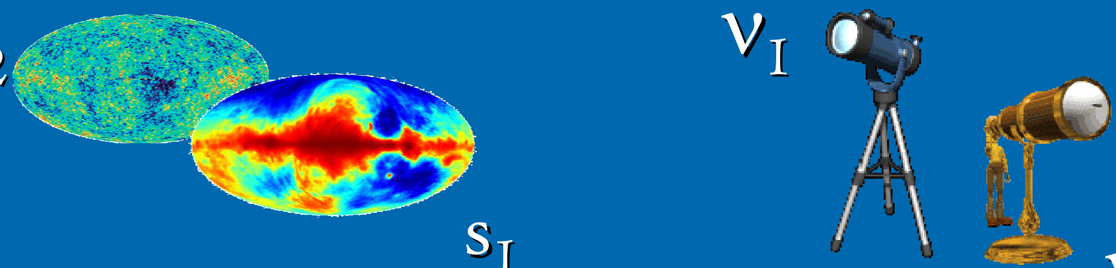
# CMB data analysis: destriping map-making

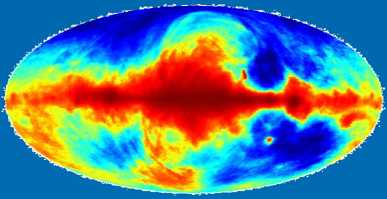
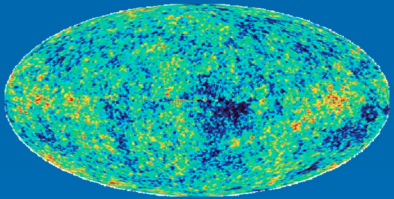


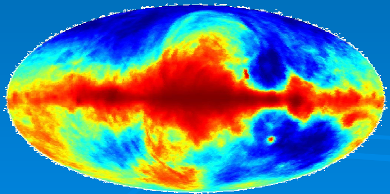
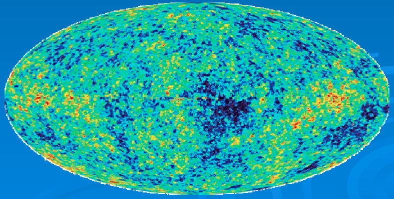


- Exploit redundancy, i.e. points in which different circles intersect, in order to estimate the noise offsets in the intersection points
- Subtract the offsets in order

# CMB data analysis: component separation

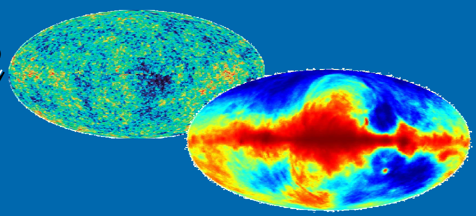



$x_1 = a_{11}$  $+ a_{12}$  $+ n_1$

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

# CMB data analysis: component separation

$s_2$



$s_1$

$\nu_1$

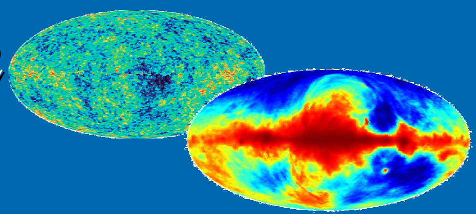
$\nu_2$

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

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

# CMB data analysis: component separation

$s_2$



$s_1$

$\nu_1$

$\nu_2$

$$x = As + n$$

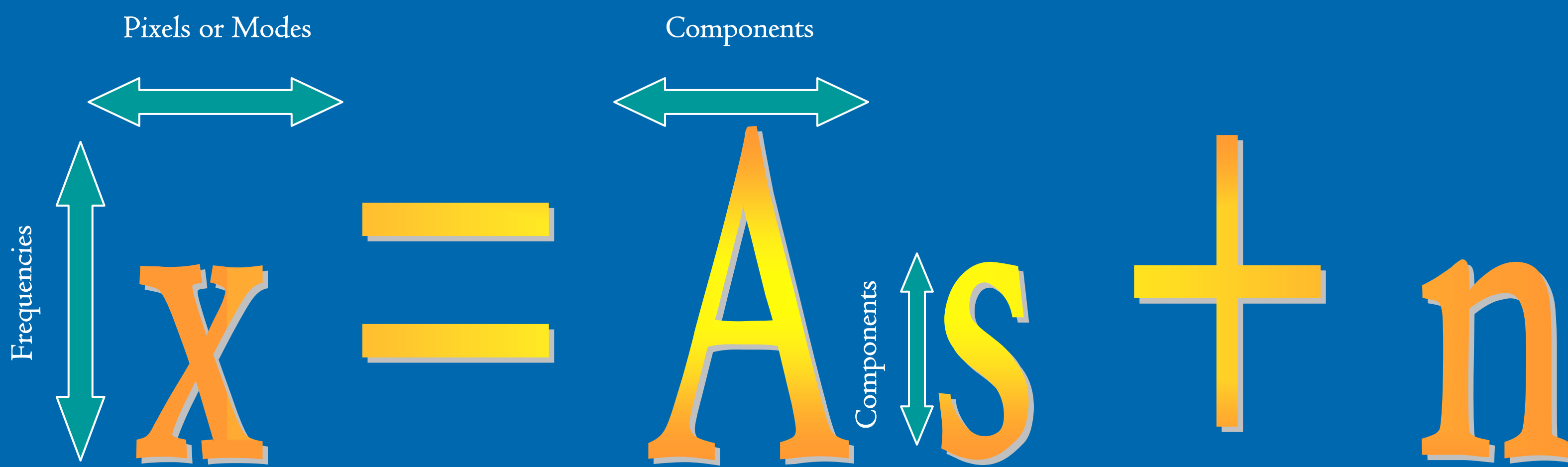
# Invert for s!

# CMB data analysis: component separation

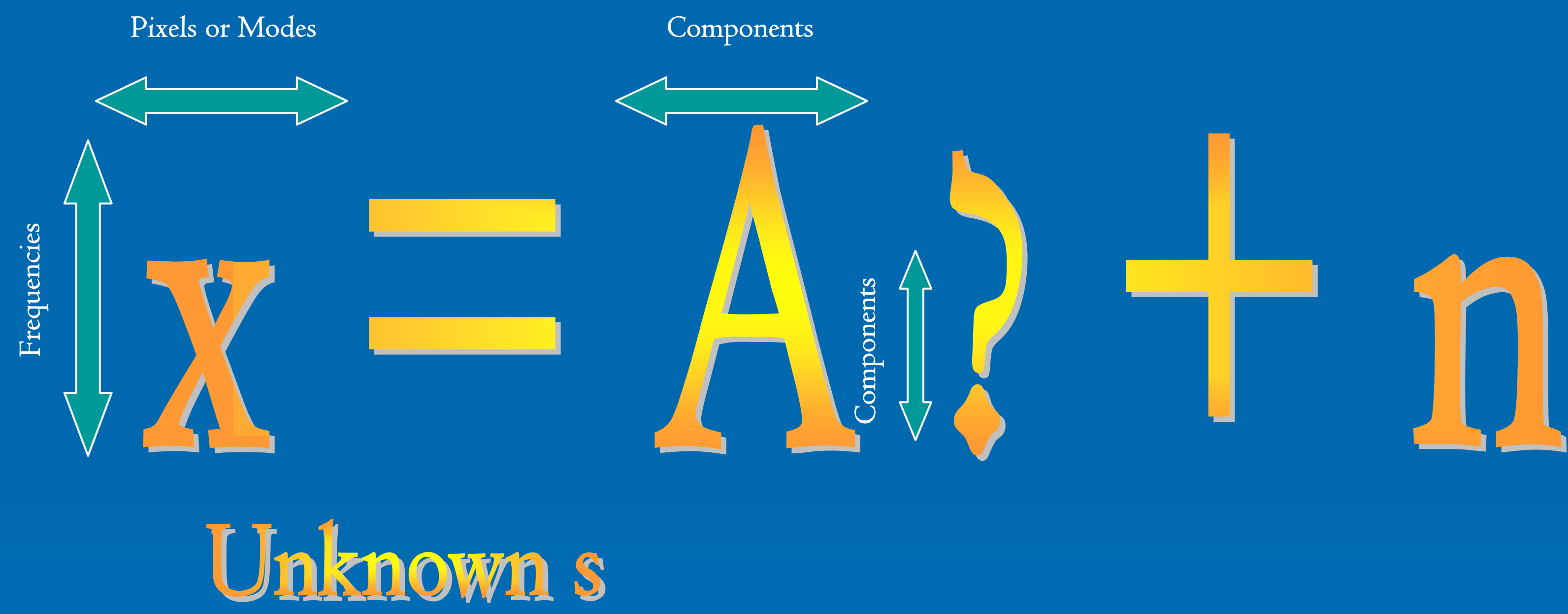
$$x = As + n$$

- 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
- 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

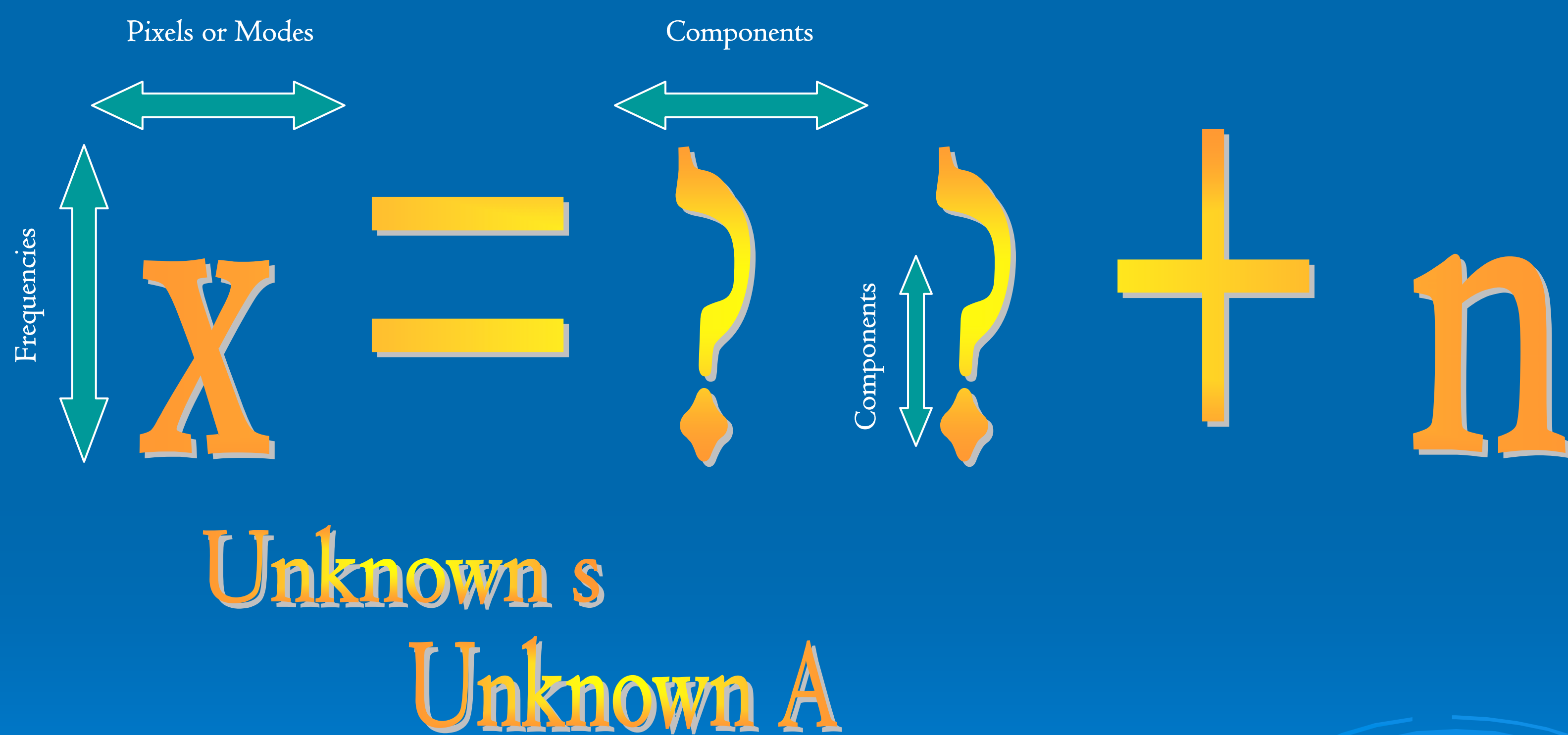
# CMB data analysis: independent component analysis



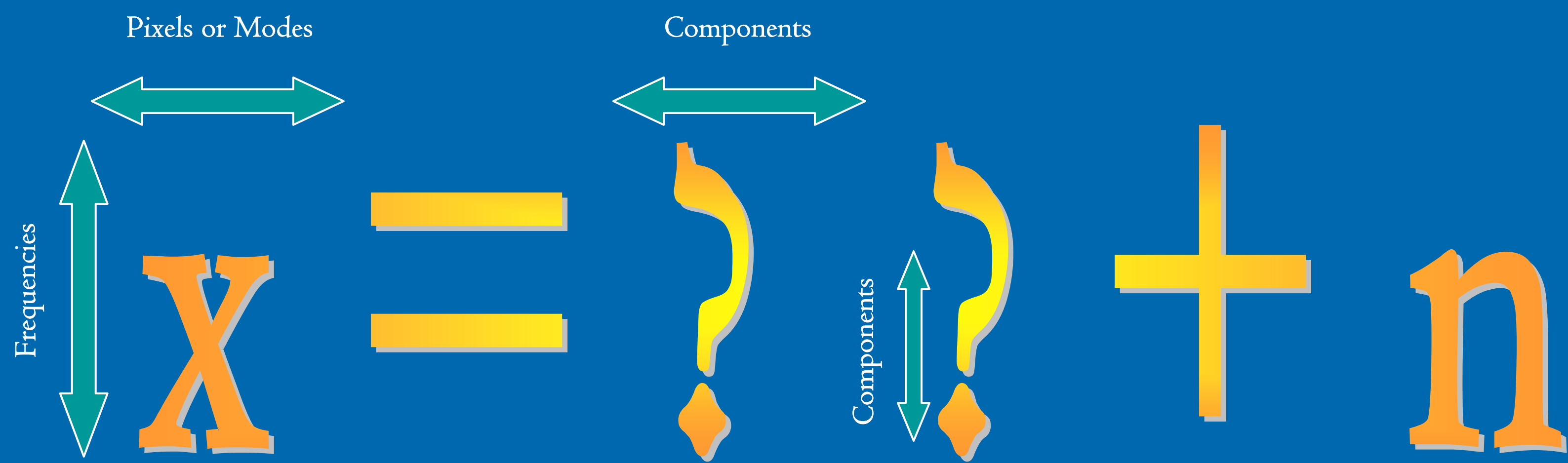
# CMB data analysis: independent component analysis



# CMB data analysis: independent component analysis



# CMB data analysis: independent component analysis




Unknown s

Unknown A

Find s!

# CMB data analysis: independent component analysis

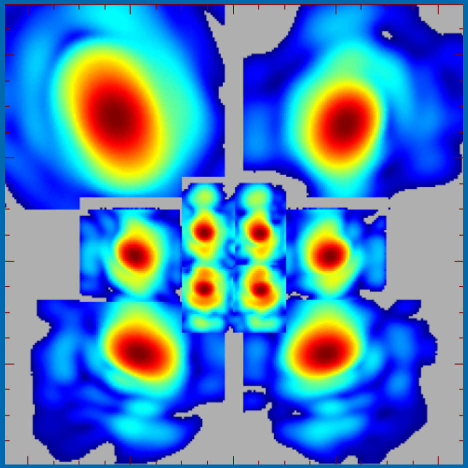

Experience the Magic

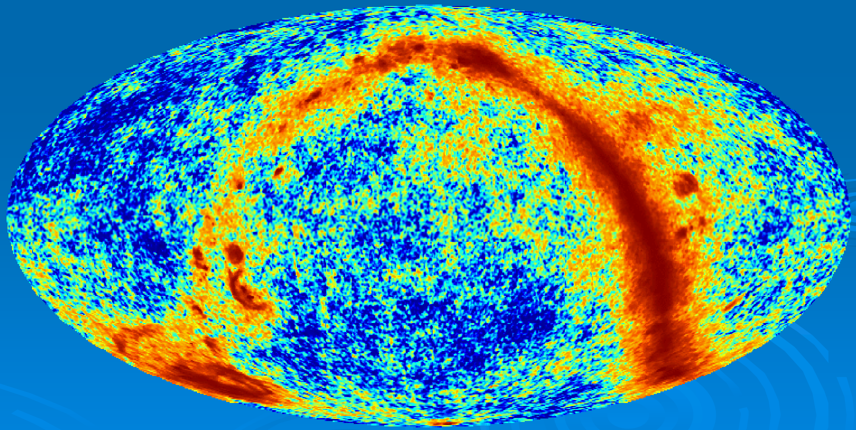
# Challenges for future CMB

# 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 ☹

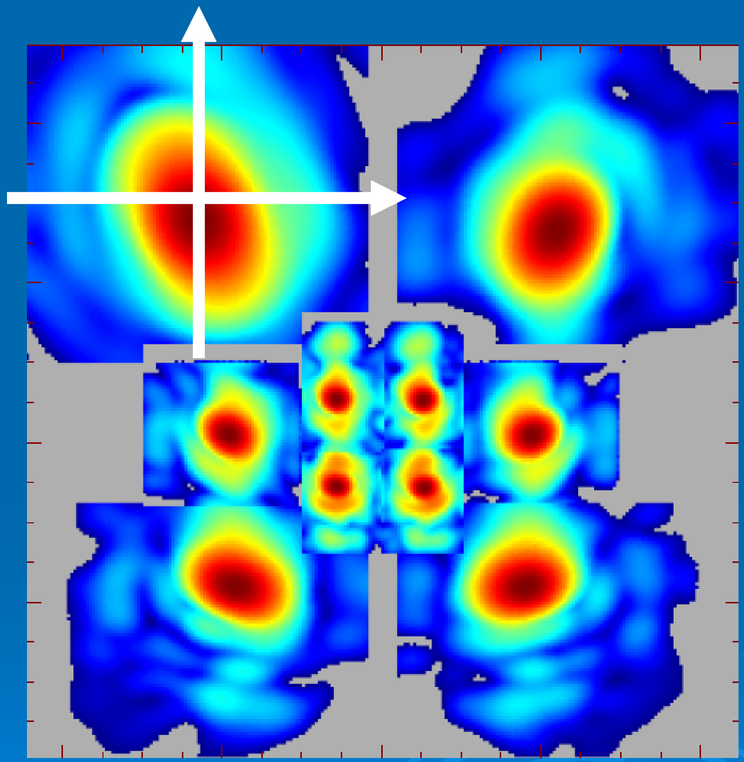
Jarosik et al. 2006





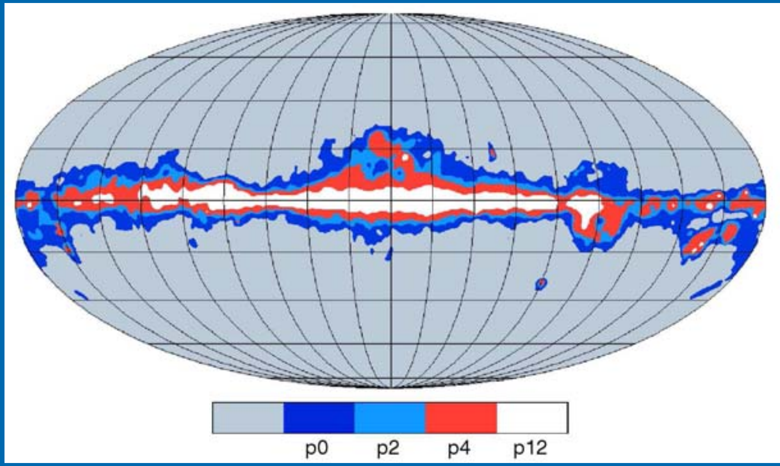
# Challenges for future CMB: systematics from beam shape

- 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

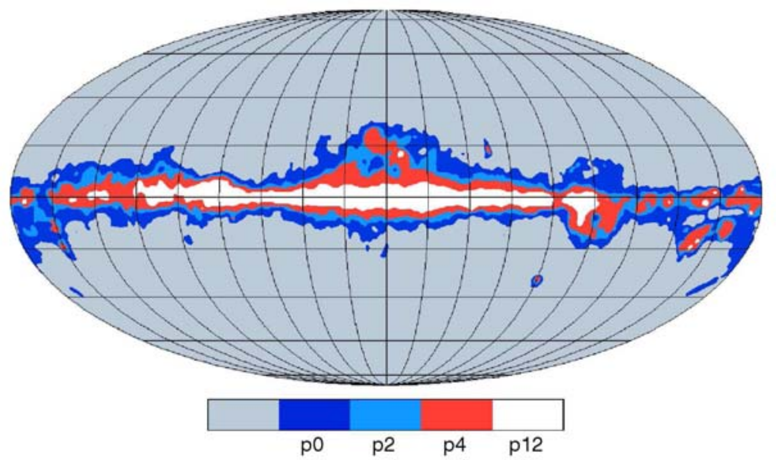
Bennett et al. 2006



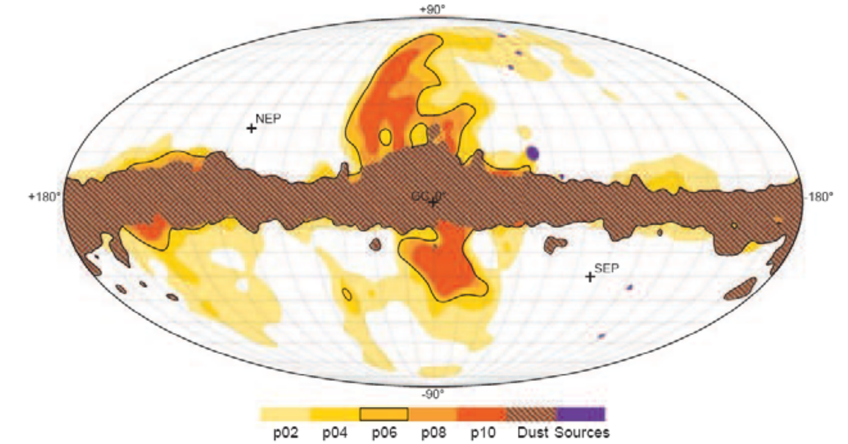

- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB

# Challenges for future CMB: foreground emission

Bennett et al. 2006



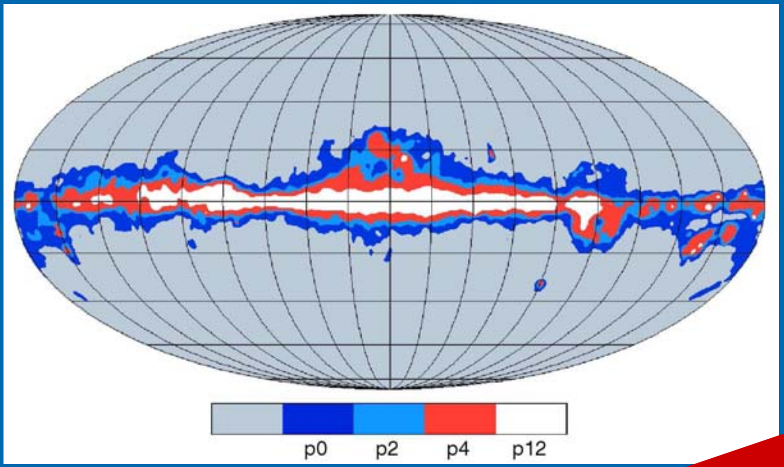

- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB
- In polarization, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB



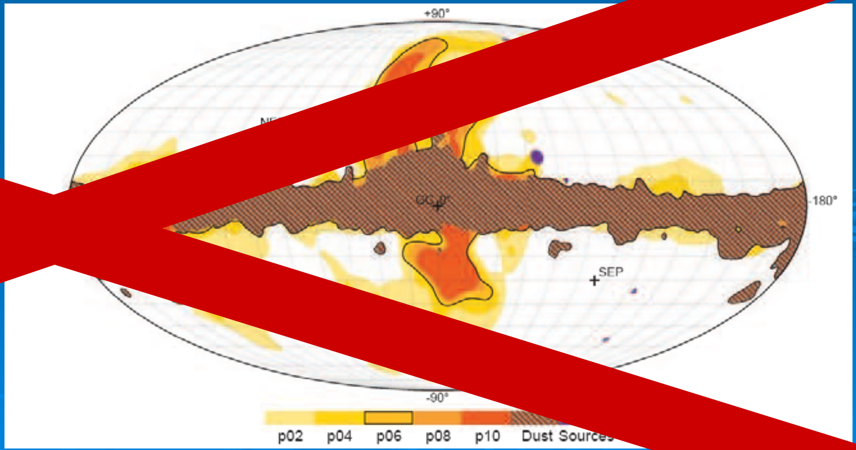

Page et al. 2006

# Challenges for future CMB: foreground emission

Bennett et al. 2006

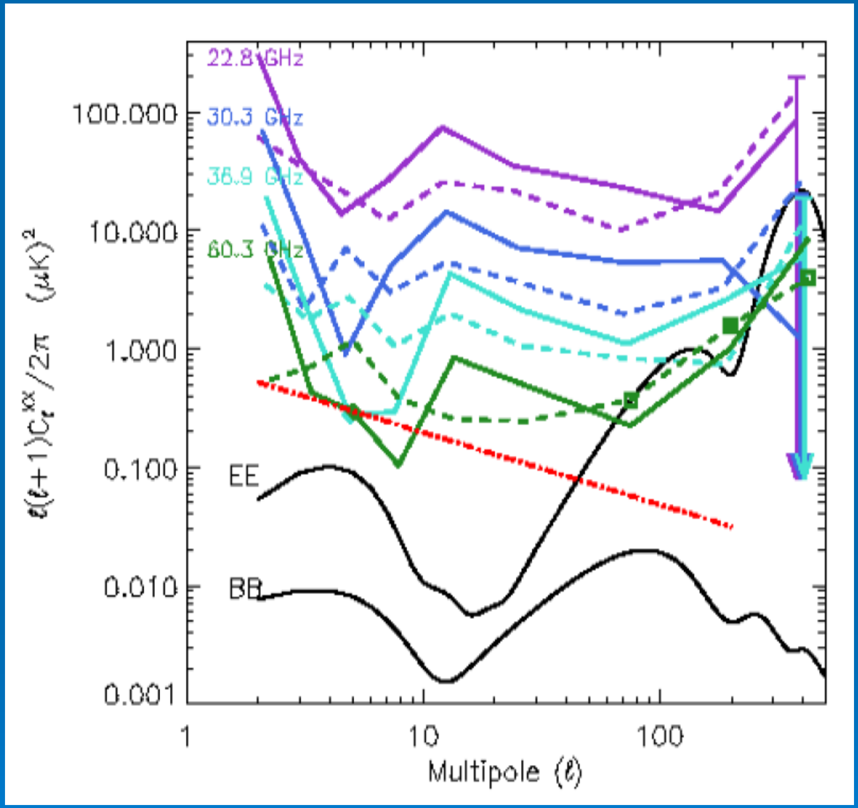



- In total intensity, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB
- In polarization, at frequencies between 60 and 90 GHz, after cutting out the brighest part of the Galactic emission, the sky is dominated by CMB

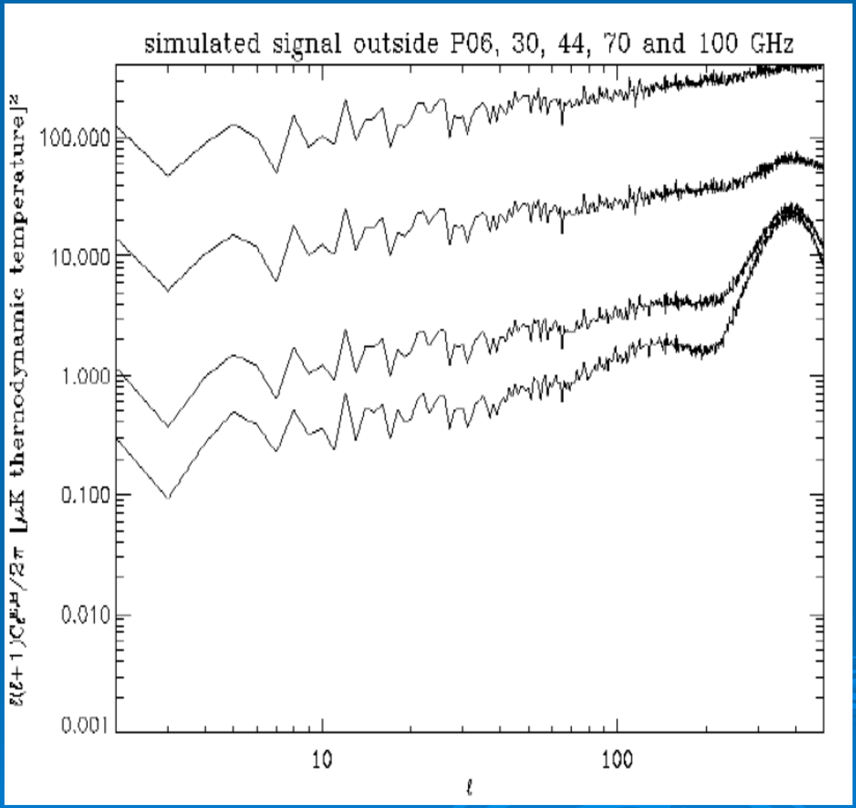



Page et al. 2

# Challenges for future CMB: foreground emission



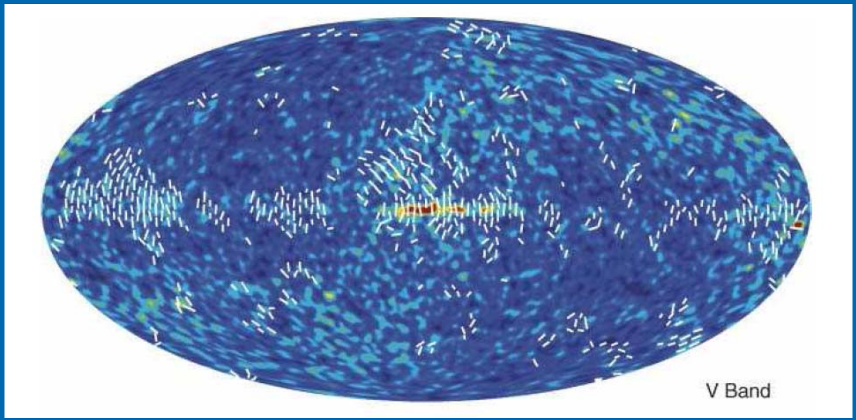

Page et al. 2006



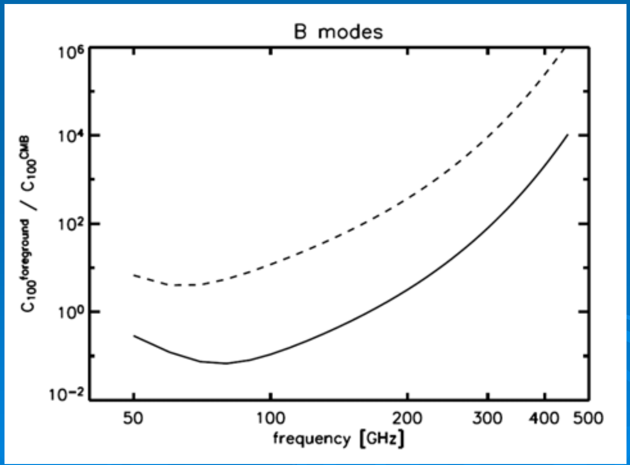

Planck reference sky

# Are there foreground clean regions at all in polarization?

Page et al. 2006

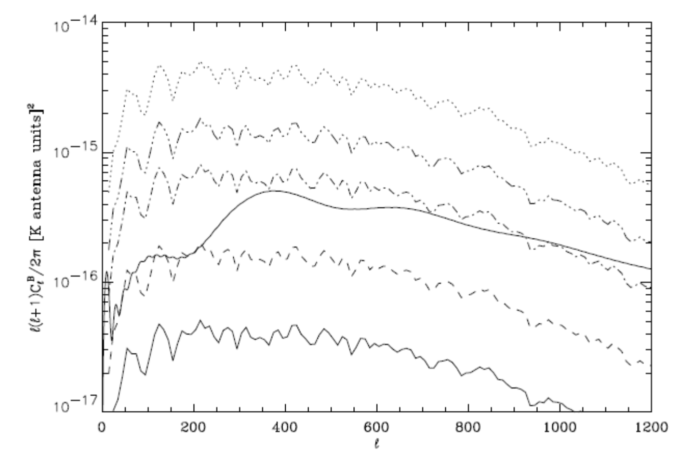


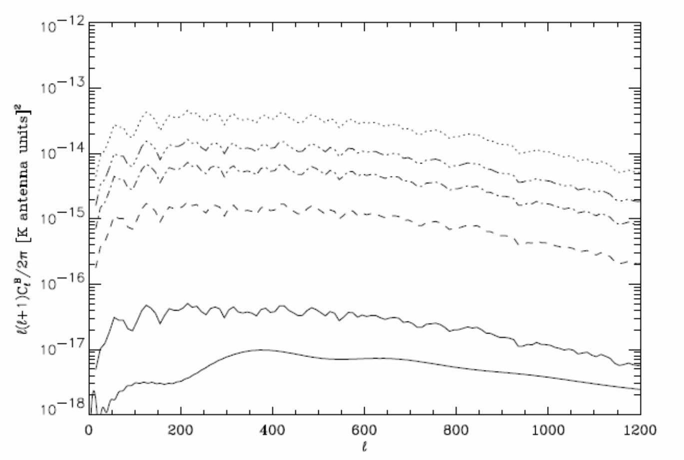

- WMAP has no detection in large sky areas in polarization
- Very naive estimates may be attempted in those areas, indicating that the foreground level might be comparable to the cosmological B mode at all frequencies, in all sky regions

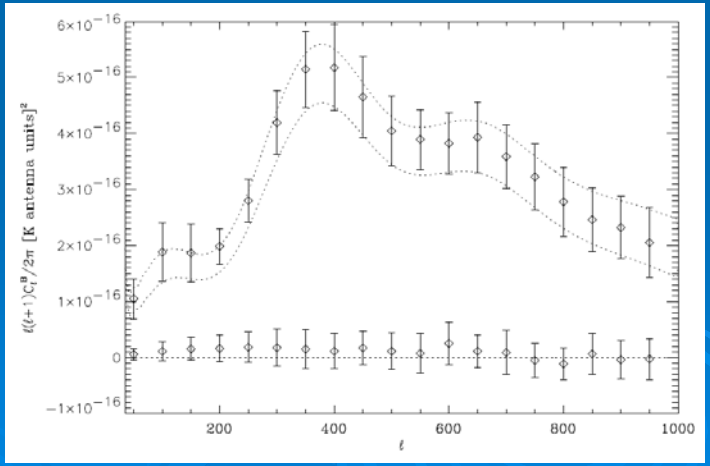


# Shall we ever get rid of foregrounds?

- 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



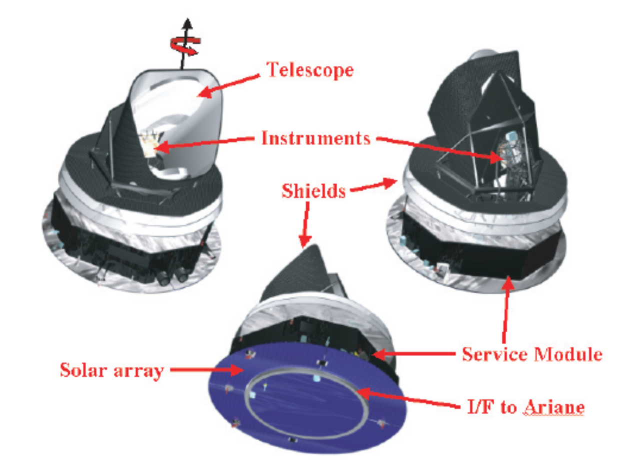

Stivoli et al. 2006

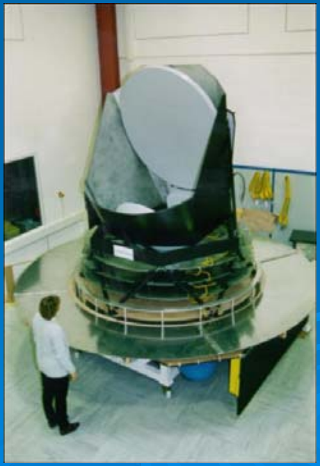
# The science goals of the Planck satellite

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

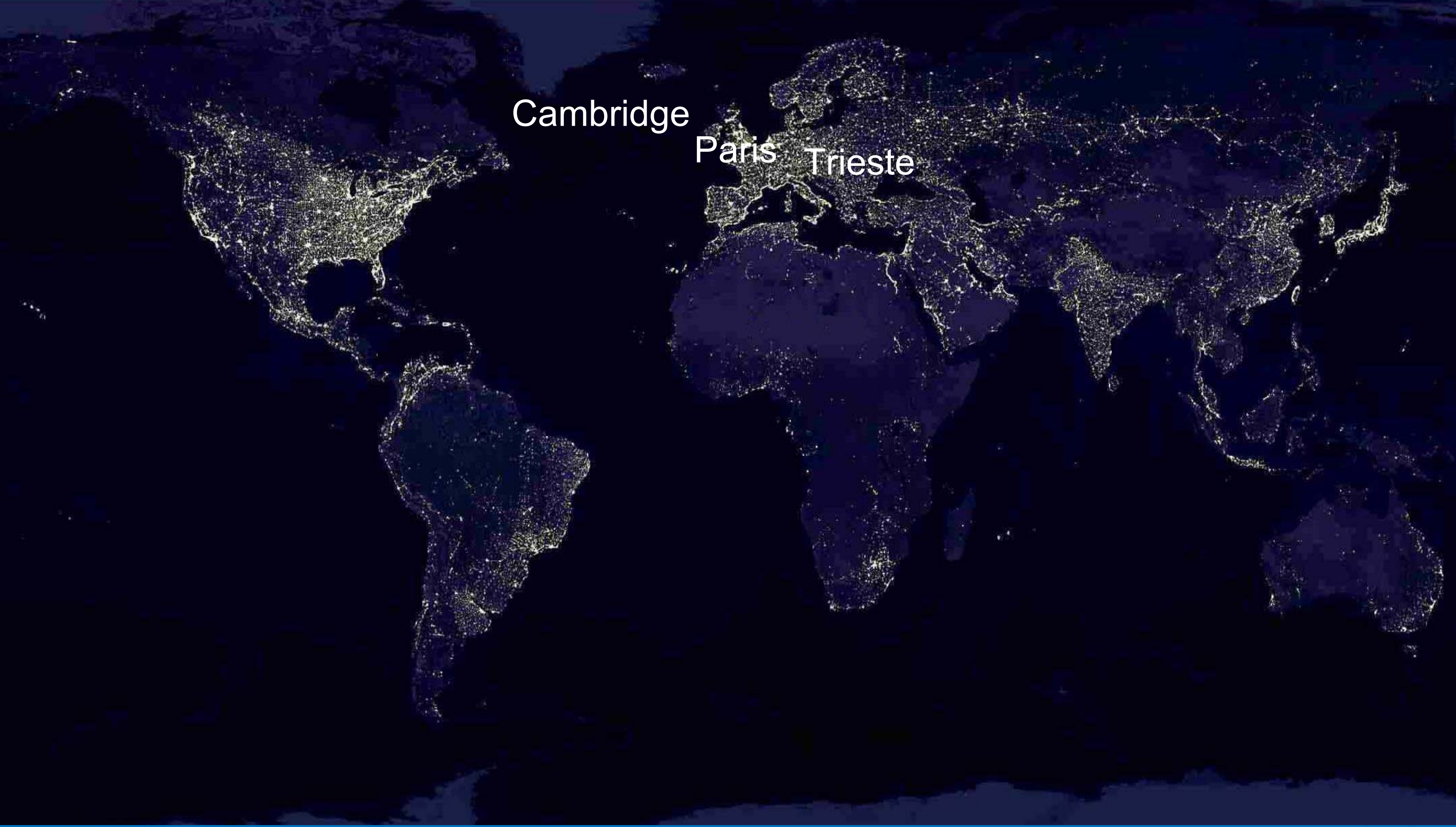
# Planck

- 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)



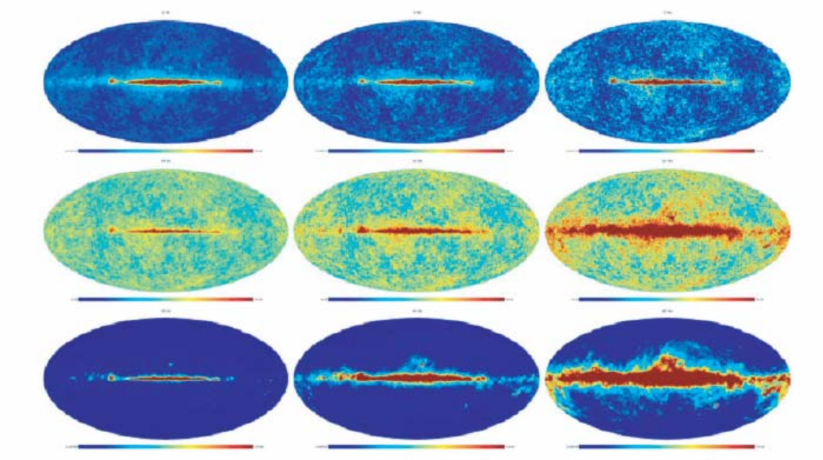

# Planck contributors




# Planck data processing sites

# Planck data deliverables

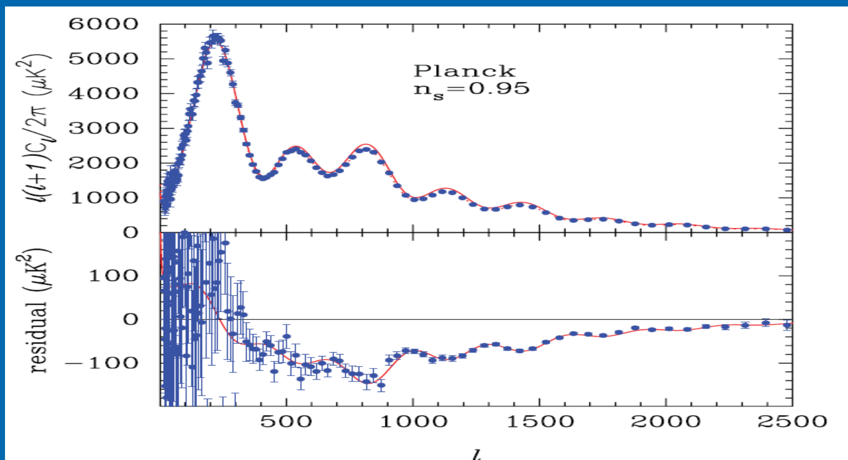
- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33' to 7' between 30 and 143 GHz, 5' at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

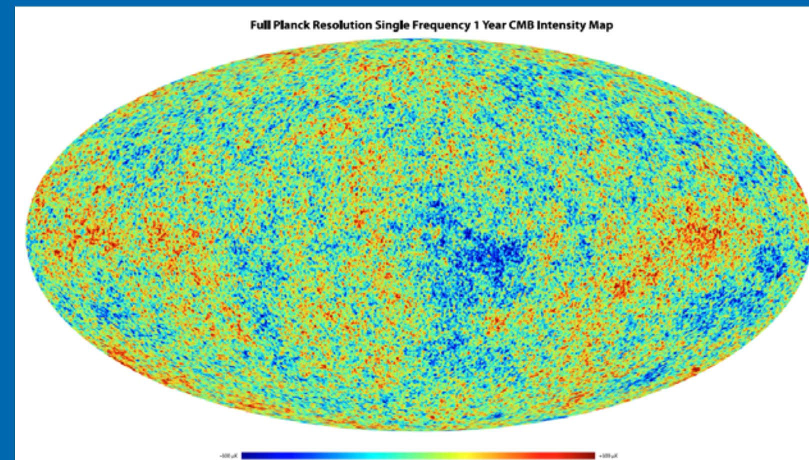


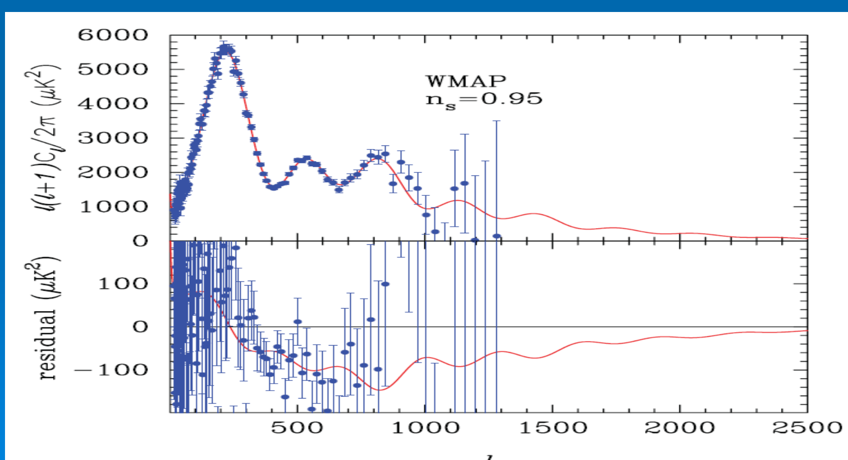
PLANCK GALAXY SURVEYS

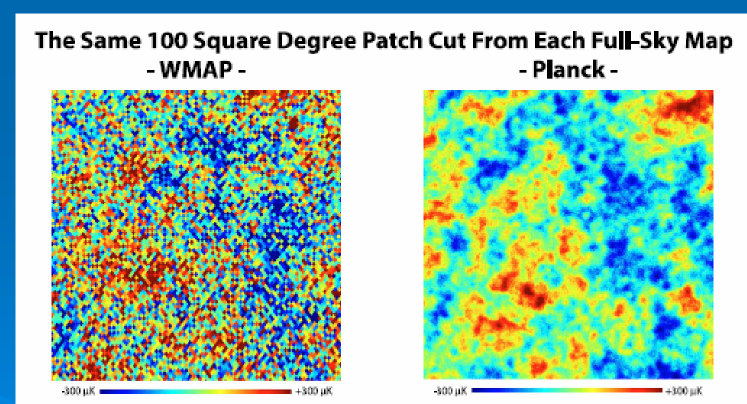
| | FREQUENCY [GHz] | | | | |
|---|---|---|---|---|---|
| | 143 | 217 | 353 | 550 | 850 |
| Confusion limit [mJy, 3σ] | 6.3 | 14.1 | 44.7 | 112 | 251 |
| *Planck* All Sky Survey sensitivity [mJy, 3σ] | 26 | 37 | 75 | 180 | 300 |
| *Planck* Deep Survey sensitivity [mJy, 3σ] | 10 | 18.4 | 49 | 170 | 280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

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

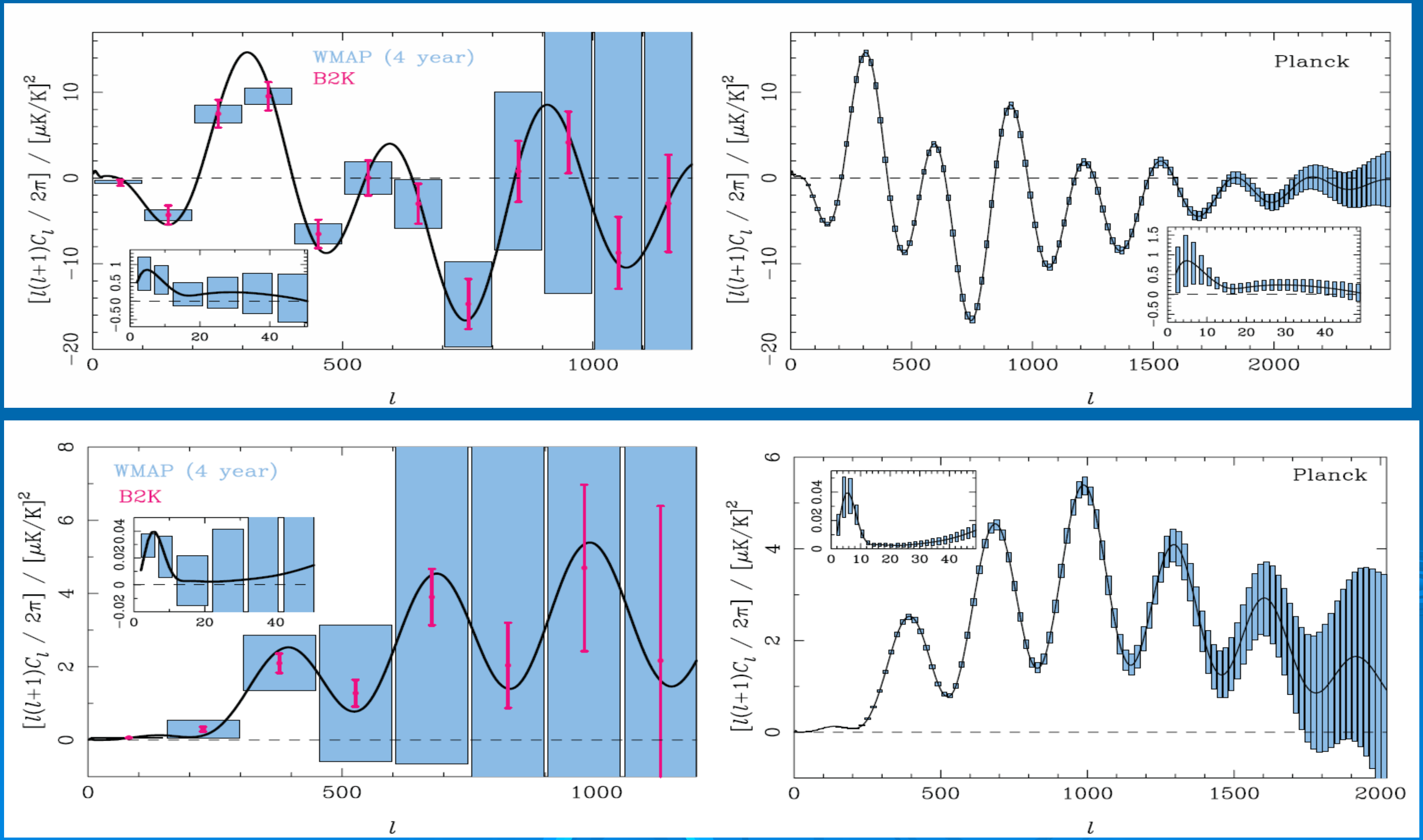


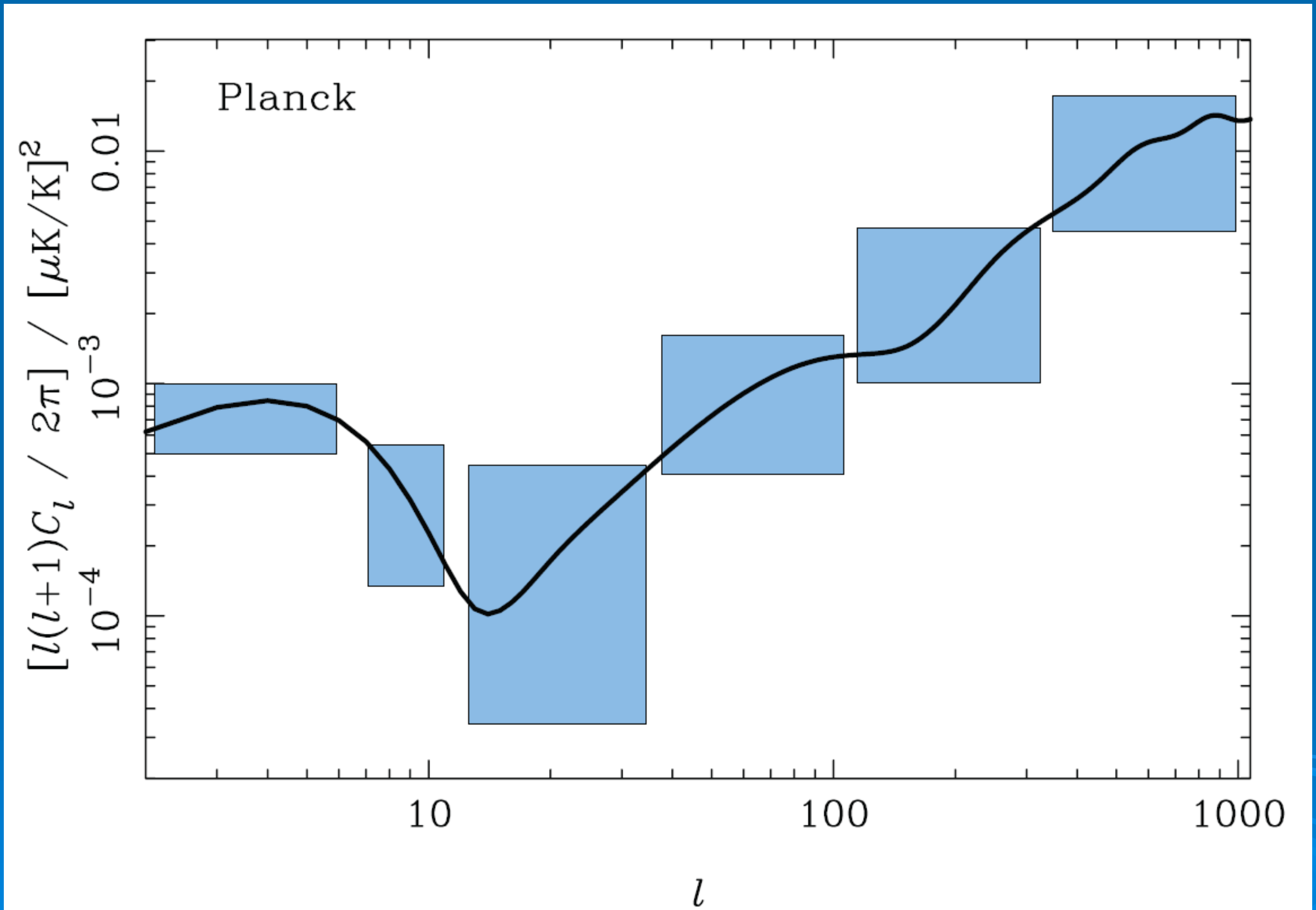



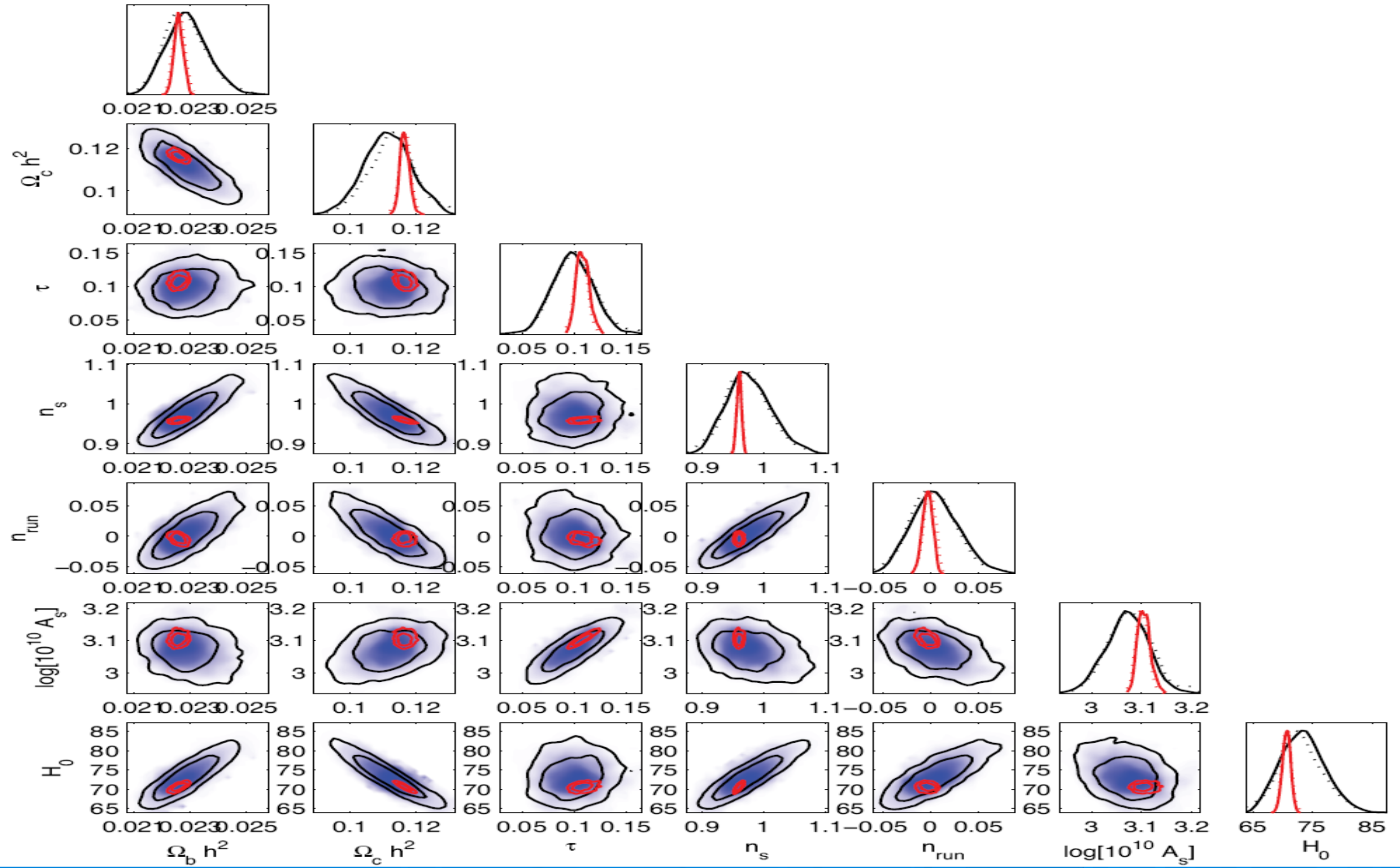
# Planck scientific deliverables: CMB polarization



# 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…

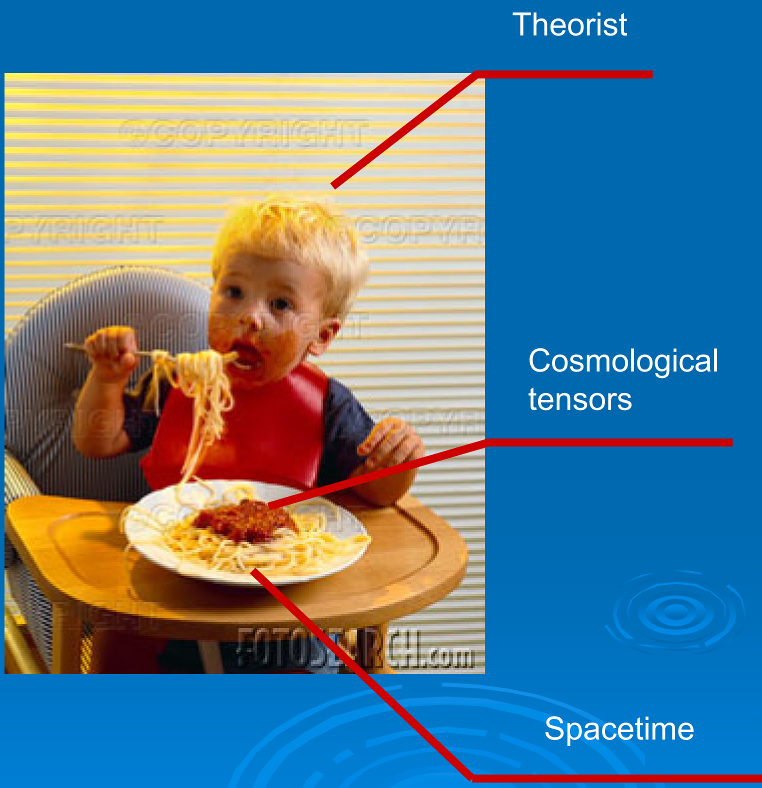
☹

- 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

Theorist

# ☺

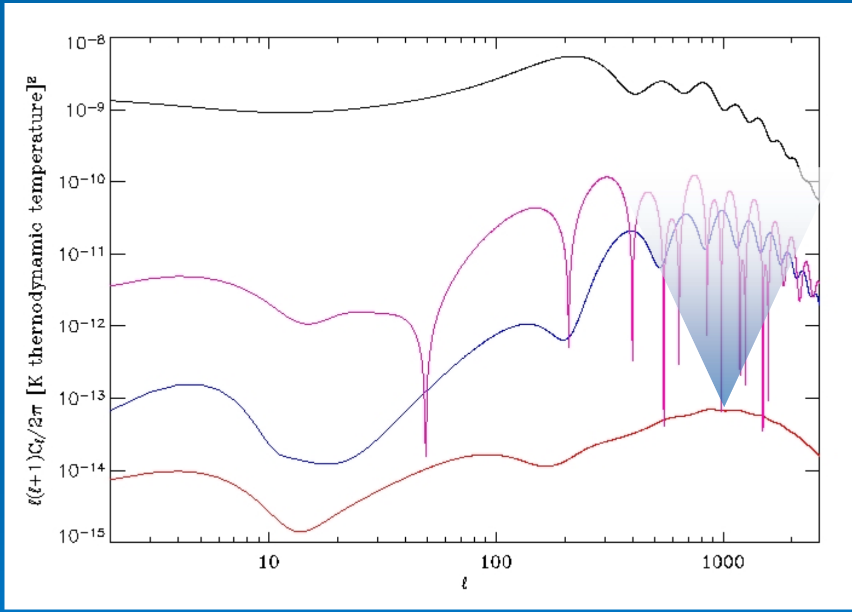
- Modest or controllable foreground emission, systematics under control
- Cosmological gravity waves discovered from CMB B modes! Expected precision down to one thousandth of the scalar amplitude
- Percent measurement of the dark energy abundance at the onset of acceleration, from CMB lensing
- Time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



# Add-on I: CMB lensing and dark energy

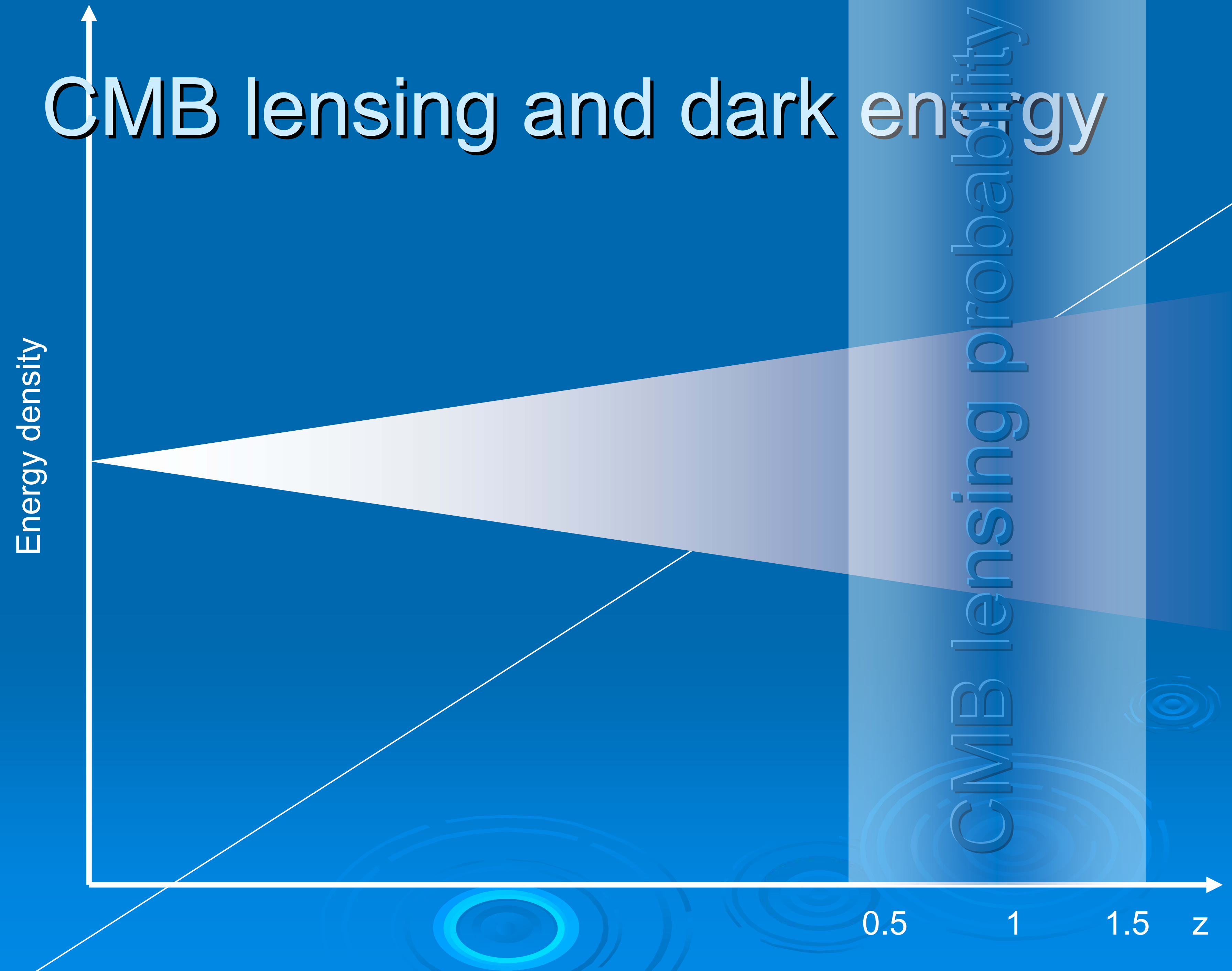
# CMB lensing: a science per se

- 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

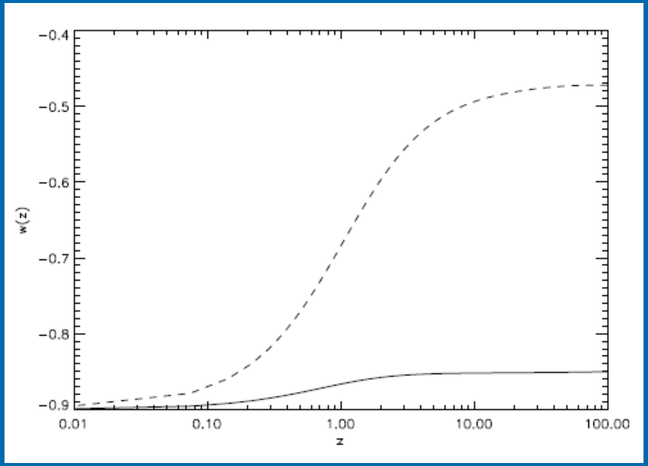


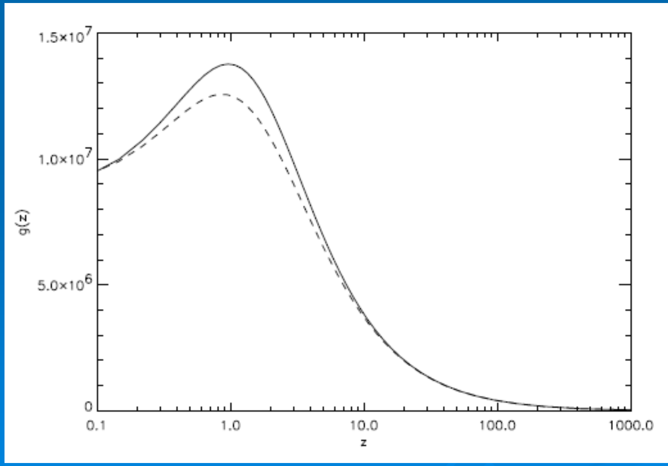
# So let's play…

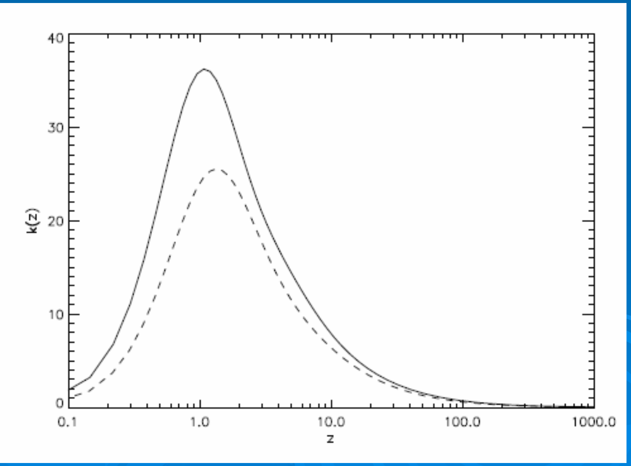
- Upgrade a Boltzmann code for lensing computation in dark energy cosmologies (Acquaviva et al. 2004 experienced doing that with cmbfast, lensing.f has to be substantially changed…)
- Get lensed CMB angular power spectra for different dark energy dynamics
- Look at the amplitude of lensing B modes

# 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



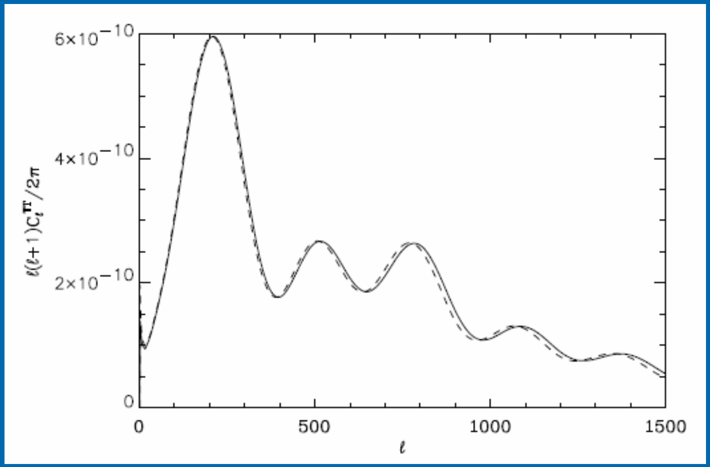



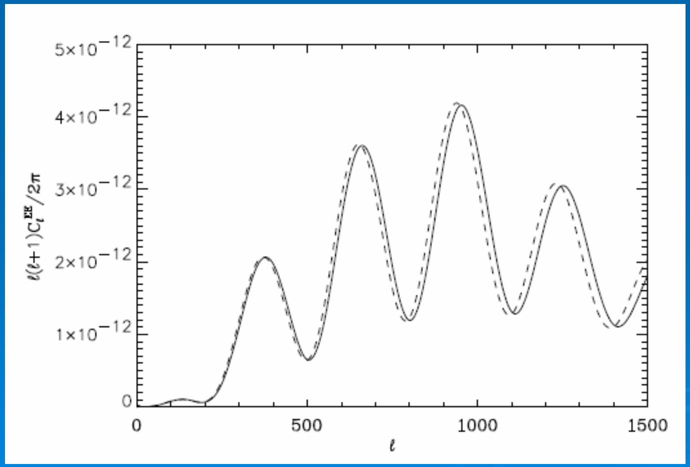



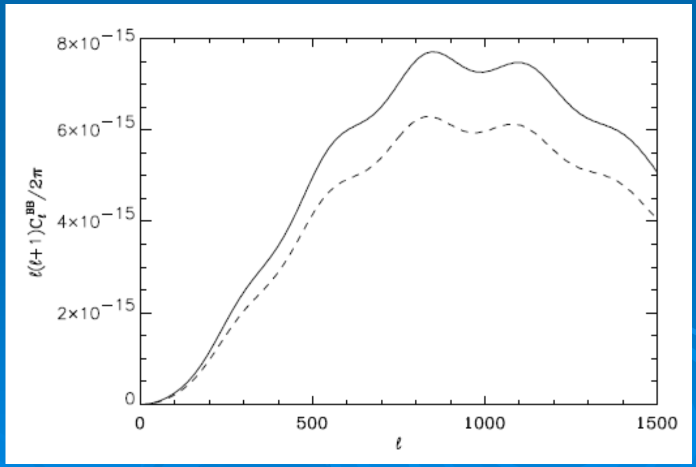

Acquaviva & Baccigalupi 2005

# Play…

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

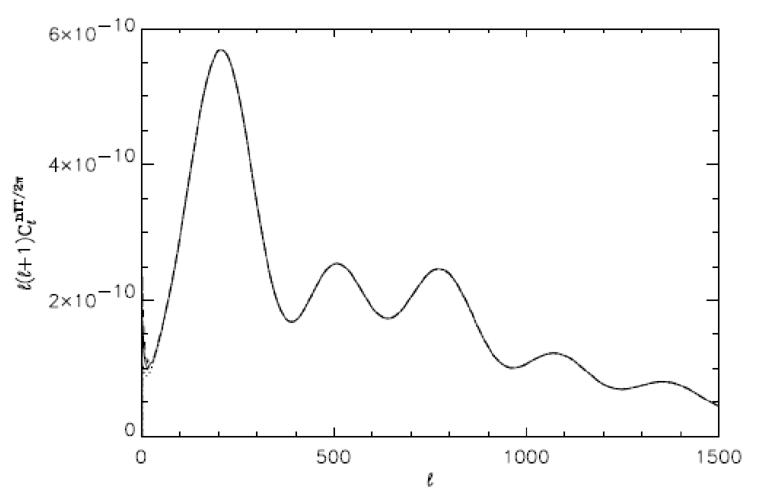


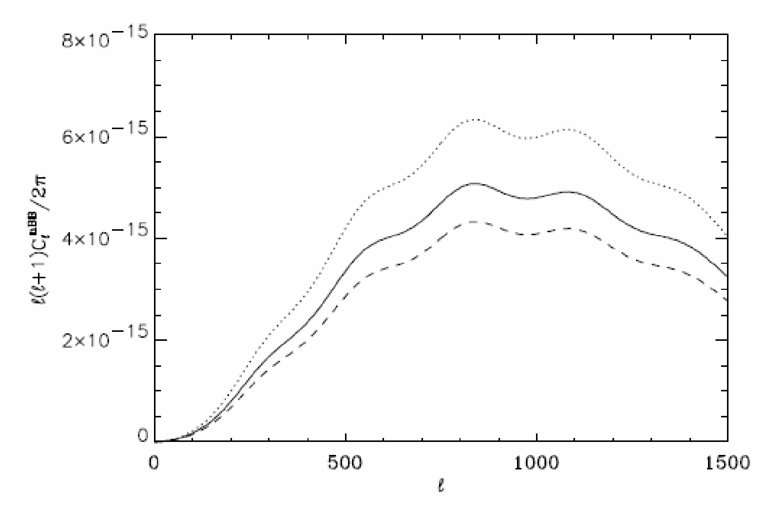




Acquaviva & Baccigalupi 2005

# 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

# Add-on II:
# ICA performance

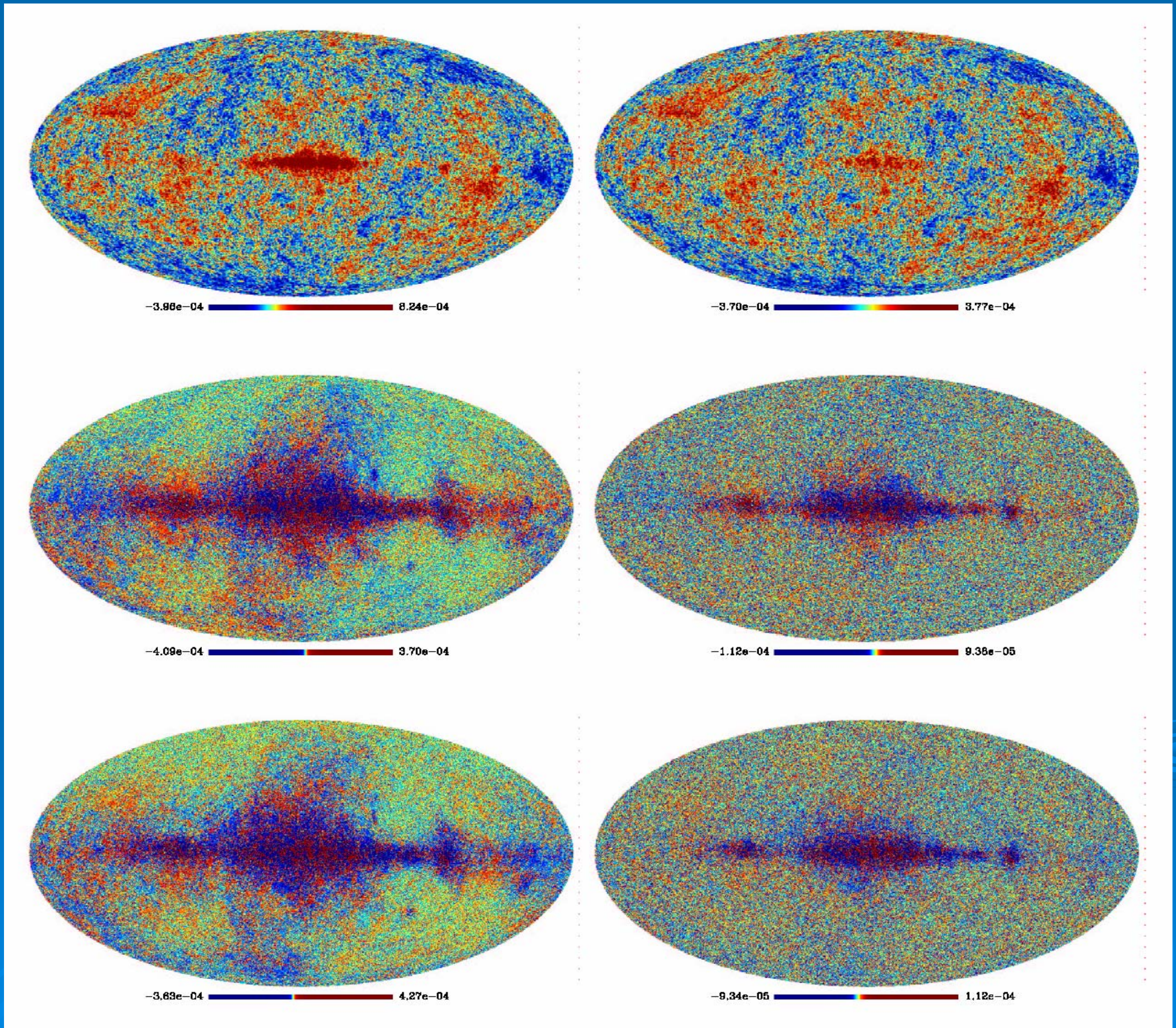
# Independent Component Analysis (ICA)

- 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

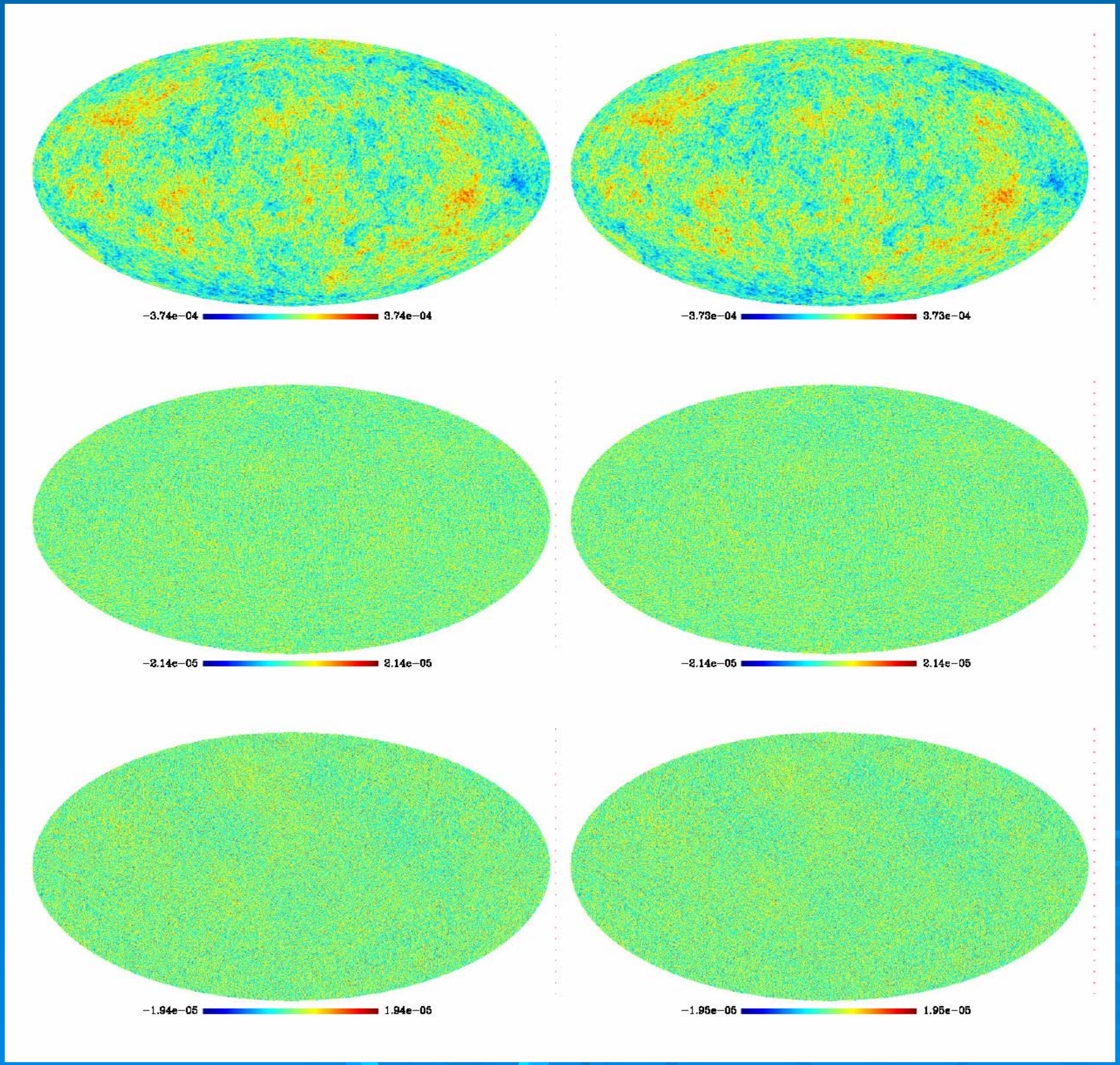
Q

U

50 GHz

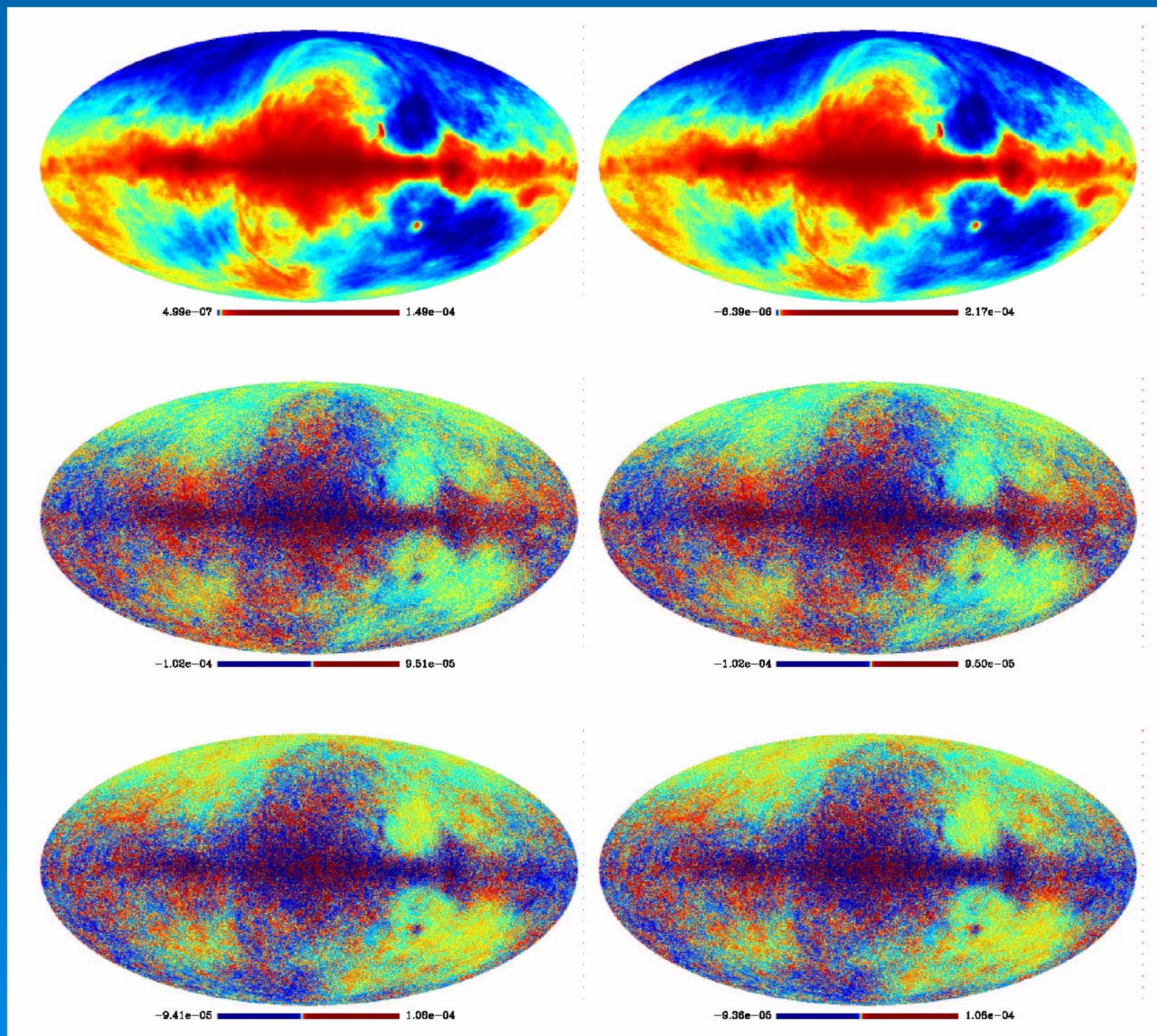
80 GHz

# ICA performance



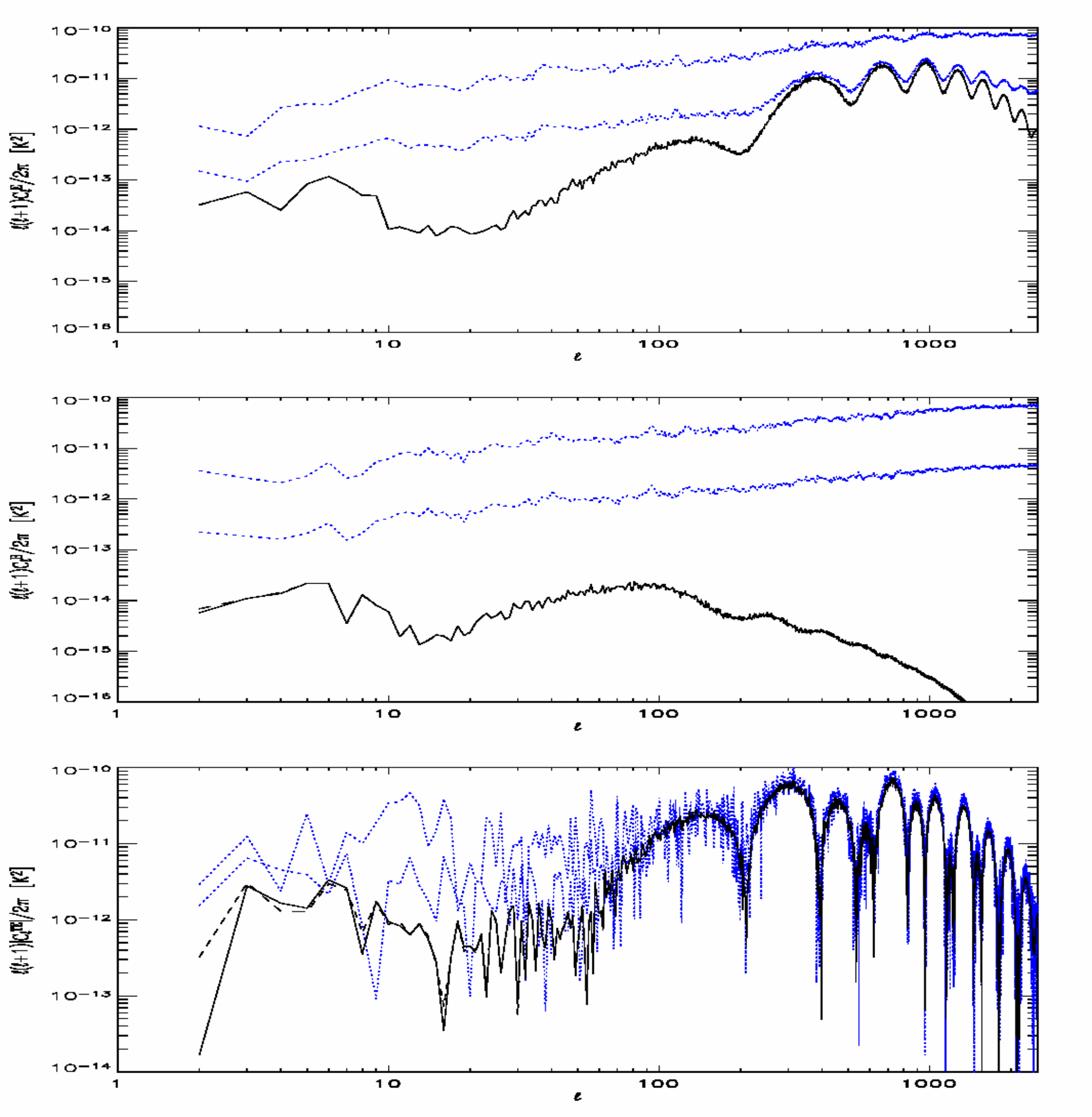

input output

# ICA performance



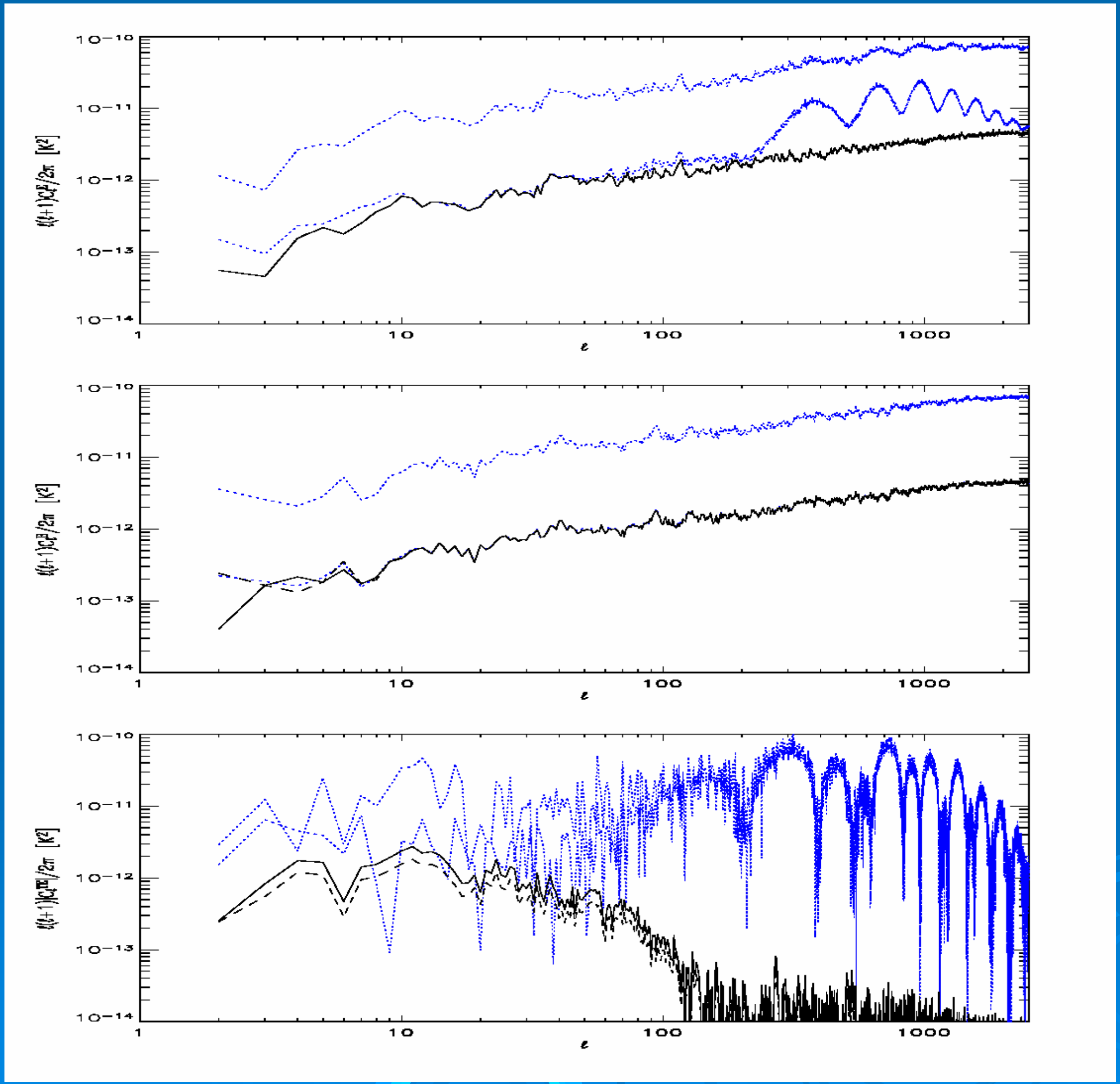

input output

# 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)