Cosmic Microwave Background

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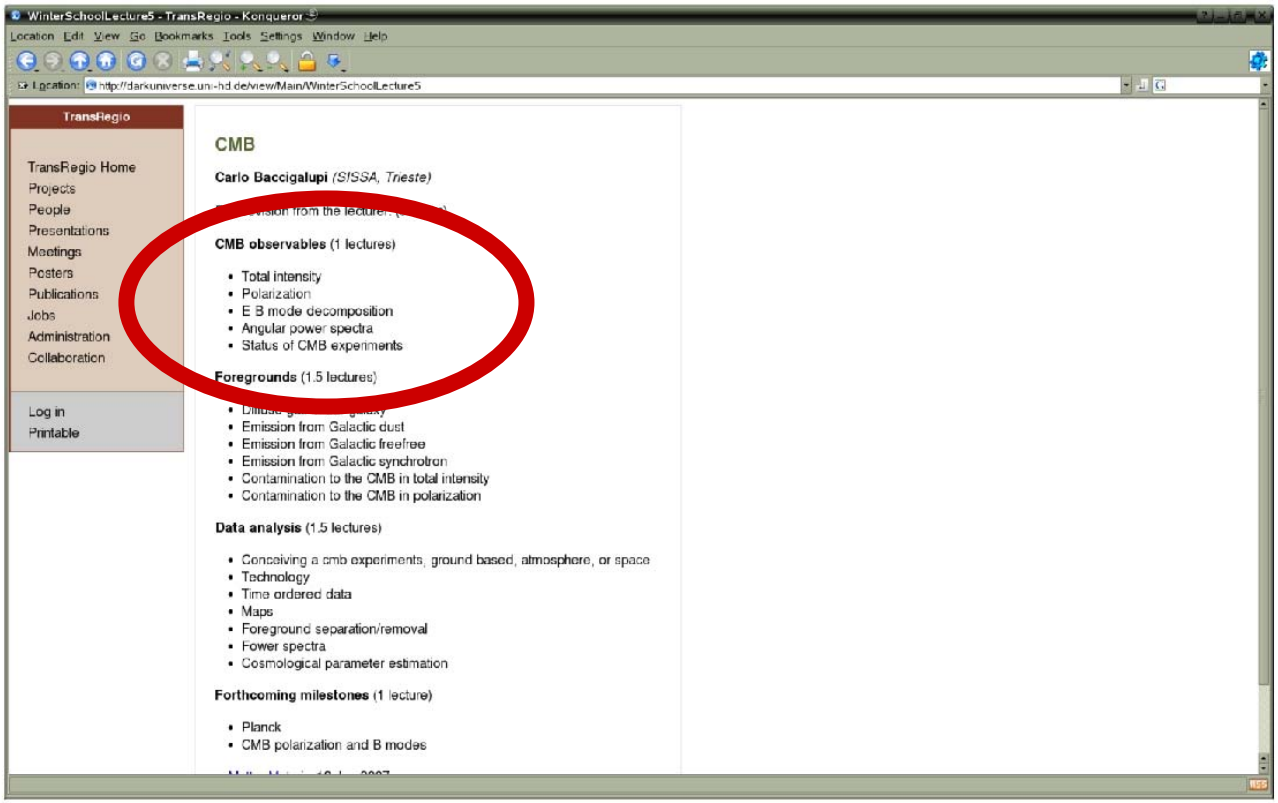
CMB lectures at TRR33, see the complete program at
darkuniverse.uni-hd.de/view/Main/WinterSchoolLecture5
These lectures are available in pdf format at
people.sissa.it/~bacci/work/lectures

CMB observables



Outline

- Generalities and historical remarks
- Cosmological fossils
- Total intensity and polarization: T, E, B
- Angular power spectra
- Status of the CMB observations
- Suggested lectures

Generalities and historical remarks

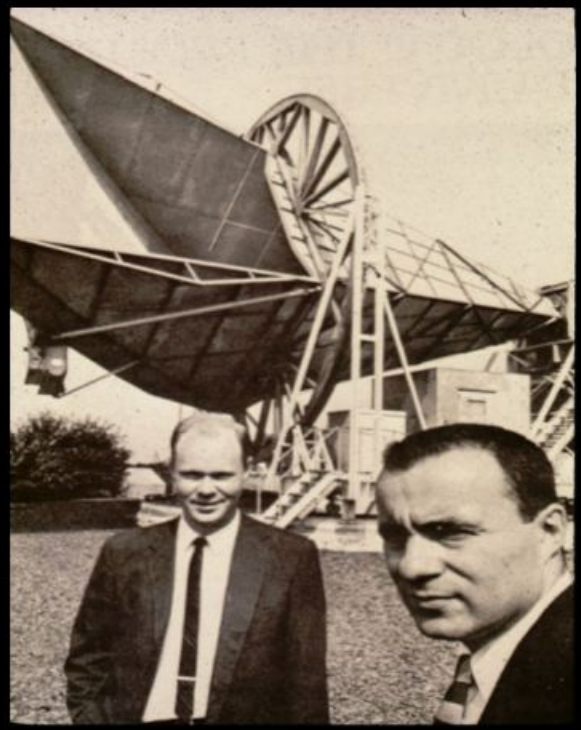
Expanding universe ⇒ CMB

- compression in the early stages of an expanding universe causes lots of radiation arising from thermonuclear explosions
- Reactions are rapid enough to achieve thermalization and a black body spectrum
- It is possible to compute the rarefaction caused by the expansion since that epoch
- The relic radiation is predicted to peak in microwaves, temperature of a few Kelvin, known today as the Cosmic Microwave Background (CMB, Gamow et al. 1948)

George Gamow, three years old in Odessa, Ukraine, 1907

Discovery

Arno Penzias and Robert Wilson



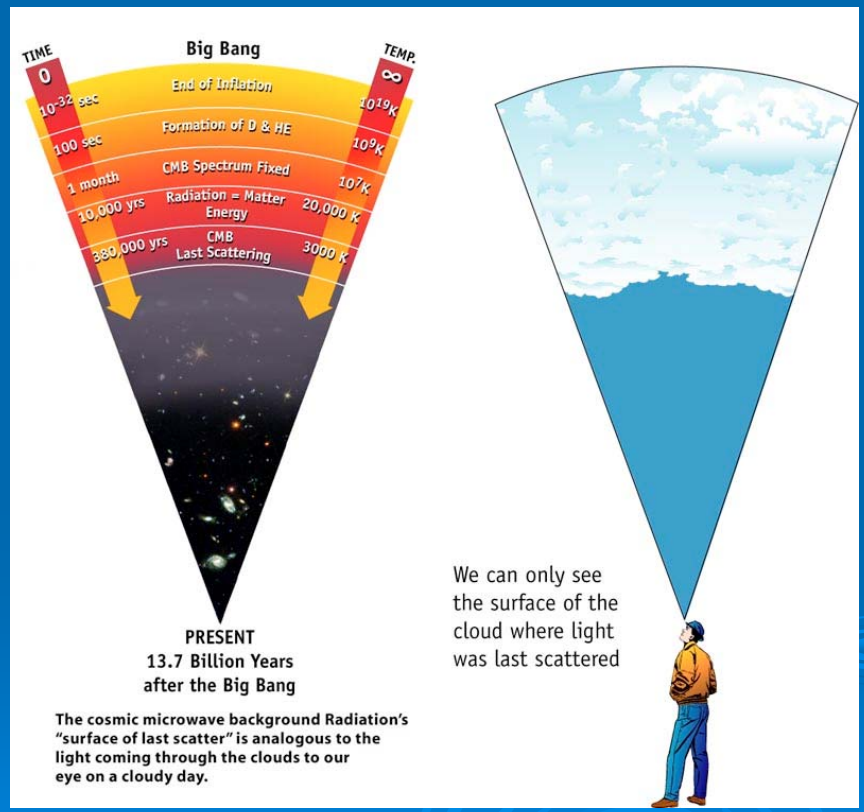
Early 1960s - Penzias and Wilson are hired by Bell Labs to evaluate the performance of the new radio telescope to be used in trans-Atlantic telephone communications.

They find a small, unexplained signal regardless of the direction the telescope is pointed. It is not enough to be a problem, but they are curious.

1964 - They become aware that the noise in their telescope is the cosmic background radiation predicted by the Big Bang theory.

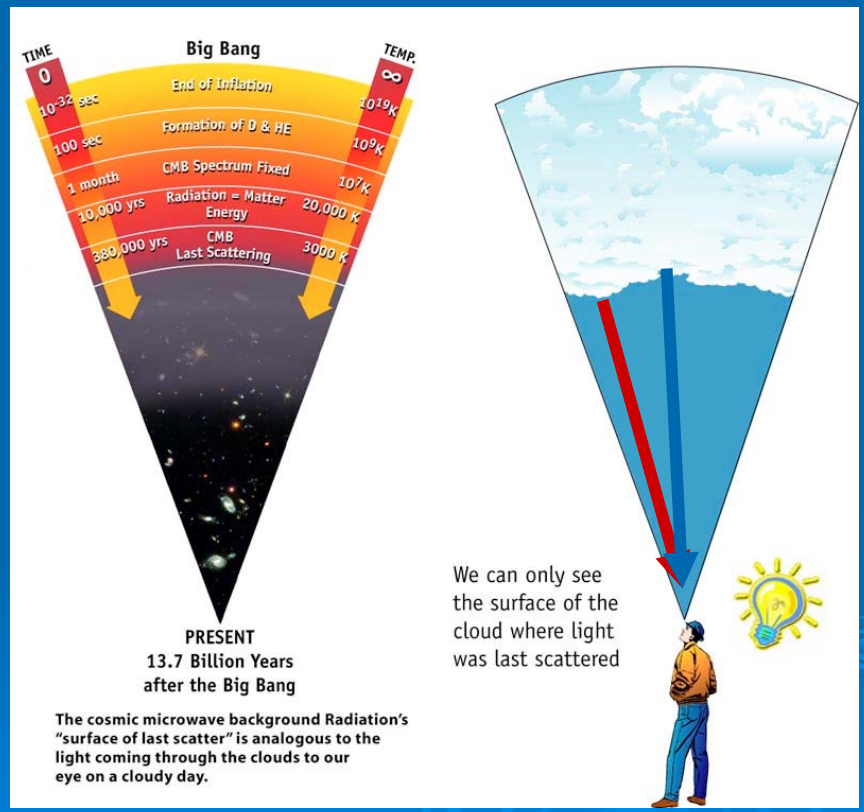
CMB: where and when?

- Opacity: $\lambda = (n_e \sigma_T)^{-1}$ « horizon
- Decoupling: $\lambda \approx$ horizon
- Free streaming: λ » horizon
- Cosmological expansion, Thomson cross section and electron abundance conspire to activate decoupling about 300000 years after the Big Bang, at about 3000 K CMB photon temperature



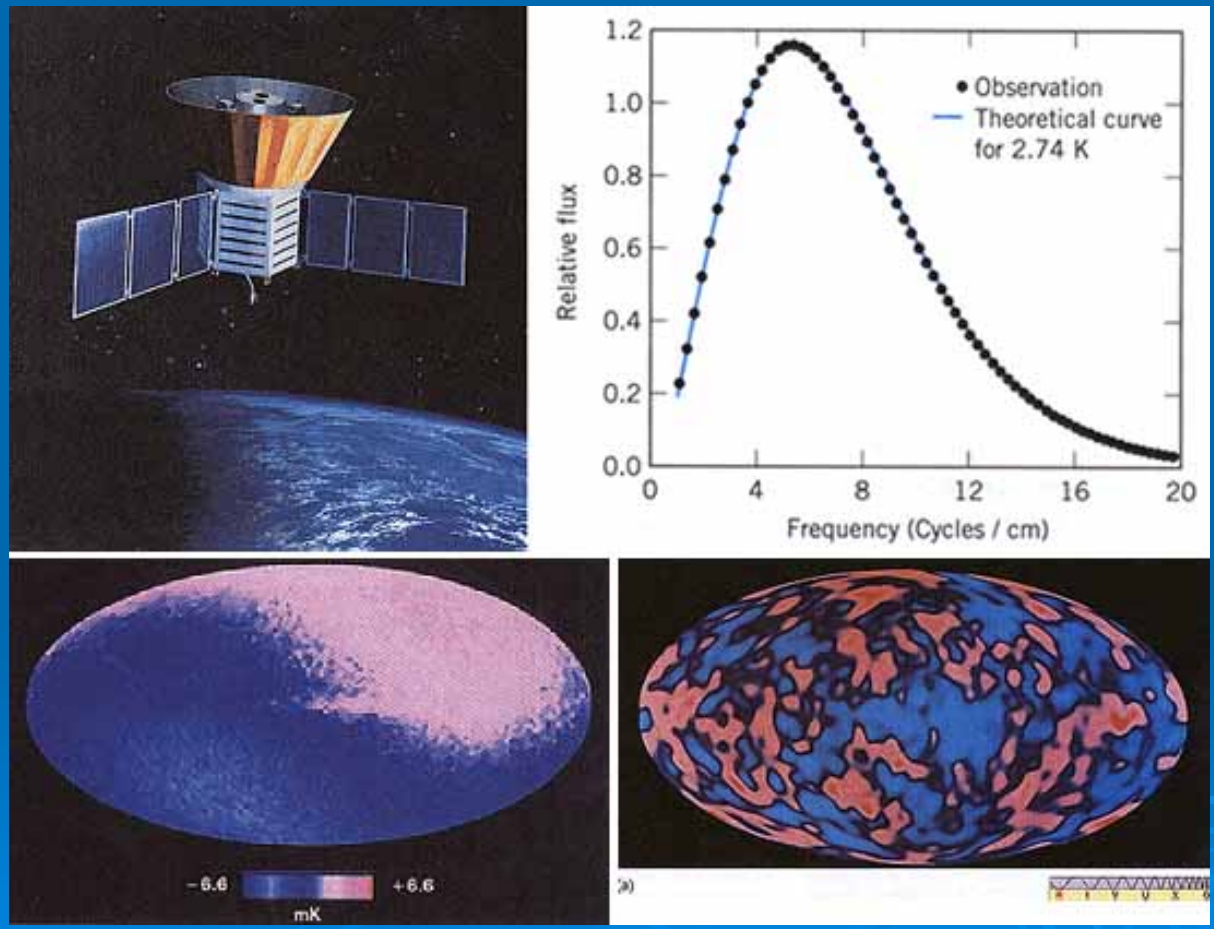
A postcard from the big bang

- From the Stephan Boltzmann law, regions at high temperature should carry high density
- The latter is activated by perturbations which are intrinsic of the fluid as well as of spacetime
- Thus, the maps of the CMB temperature is a kind of snapshot of primordial cosmological perturbations



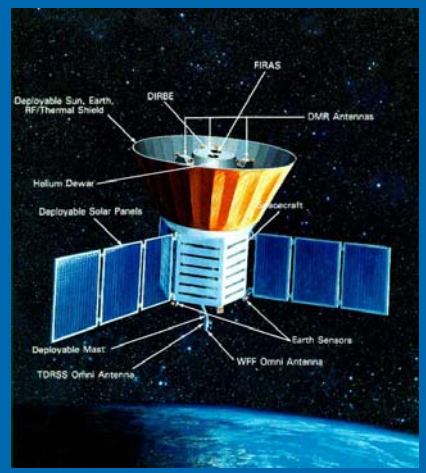
Animation from the NASA WMAP team

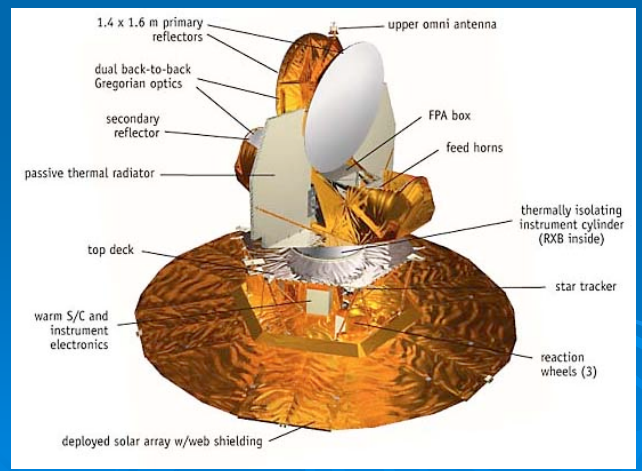
COsmic Background Explorer



From COBE to the Wilkinson Microwave Anisotropy Probe

- About 20 years of insight into one of the most important observables in physics
- Lots of experiments, from ground as well as the stratosphere
- A fantastic technological and data analysis progress, in parallel to theory
- lambda.gfsc.nasa.gov





Animation from the NASA WMAP team

Cosmological fossils

CMB physics: Boltzmann equation

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

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

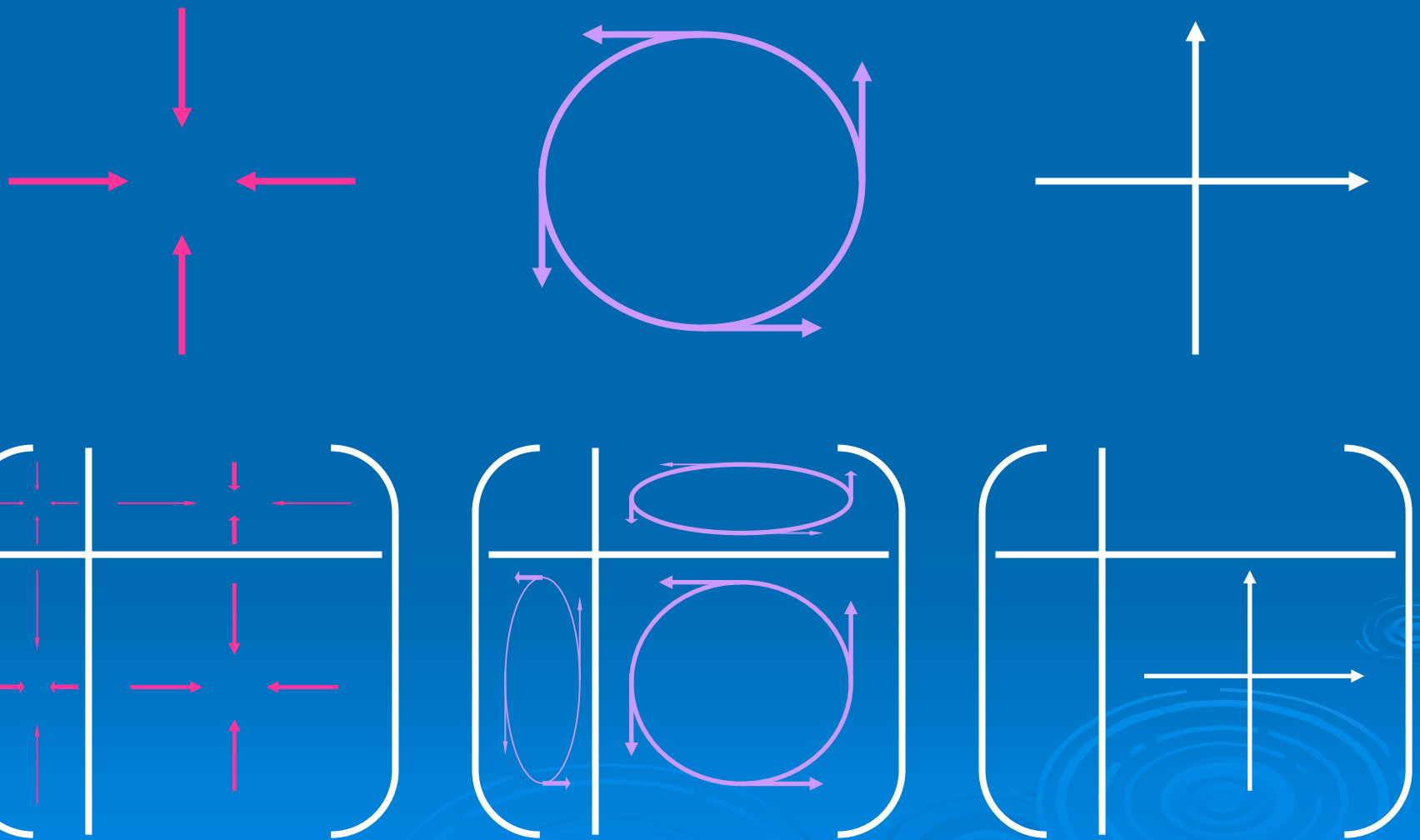
CMB physics: Boltzmann equation

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

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

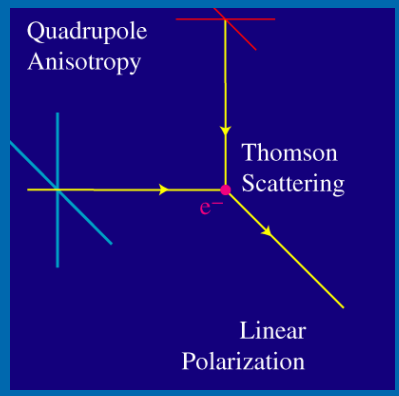
metric = photons + neutrinos + baryons + leptons + dark matter

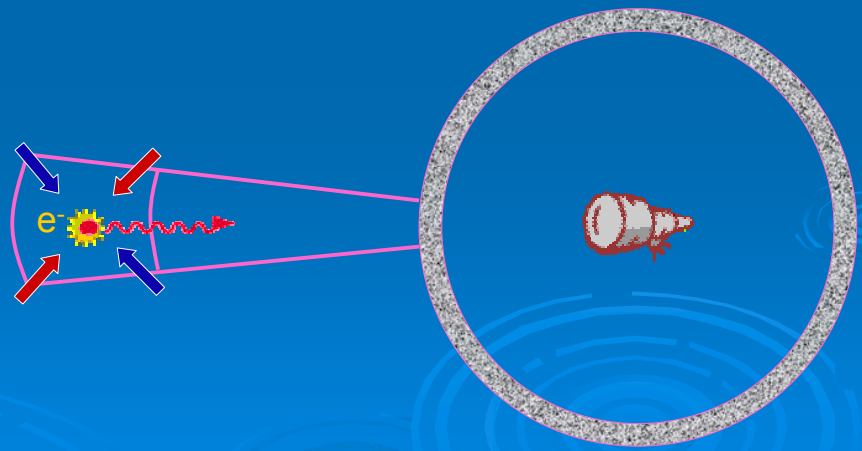
CMB physics: metric



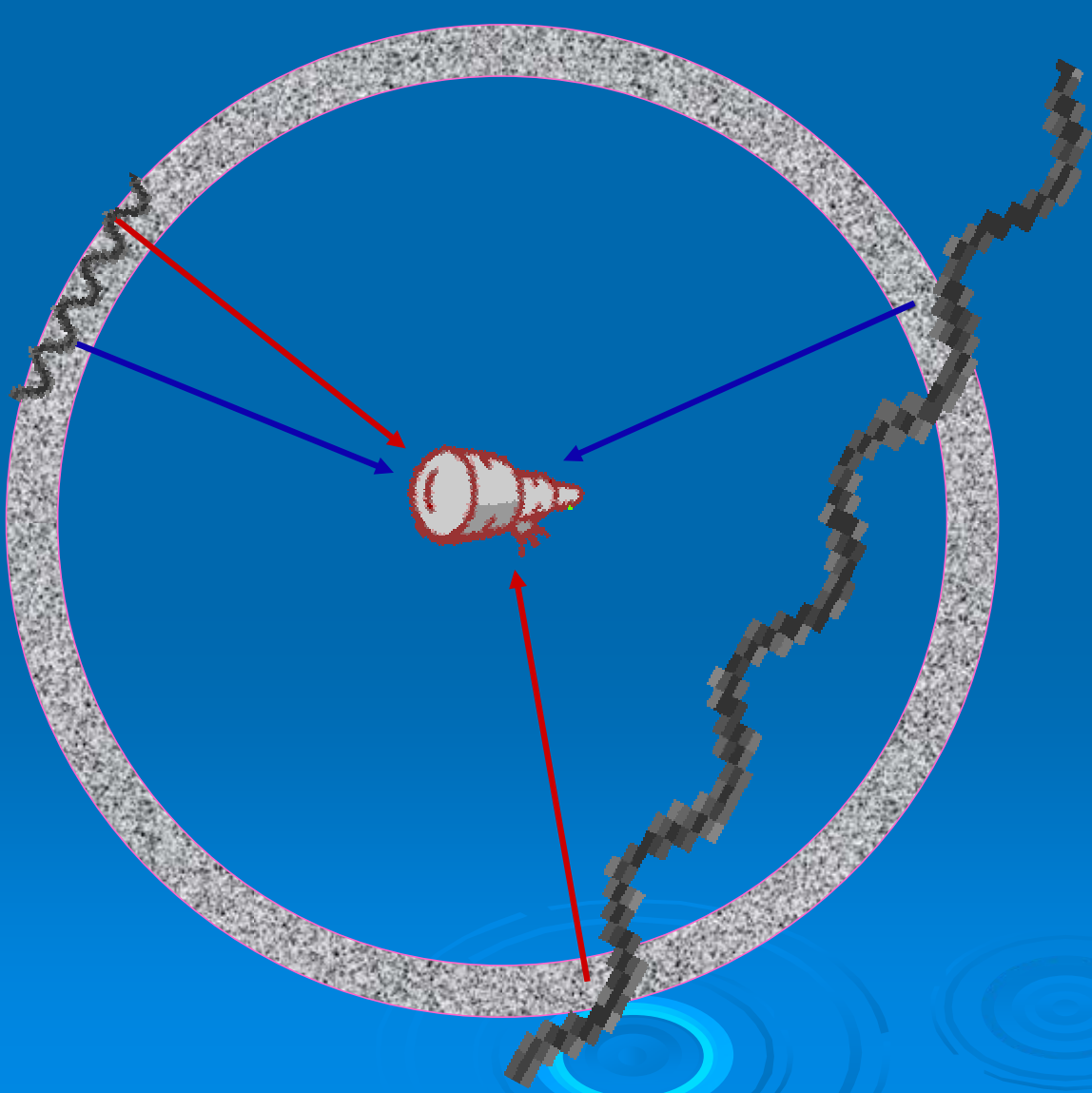
CMB Physics: Compton scattering

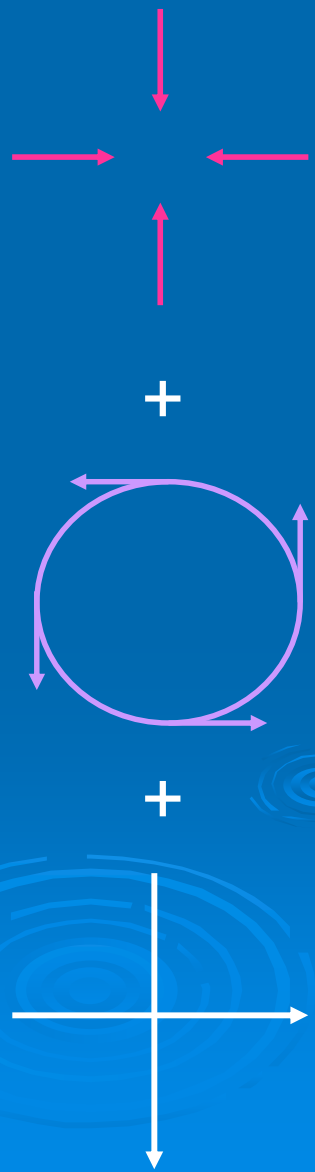
- Compton scattering is anisotropic
- An anisotropic incident intensity determines a linear polarization in the outgoing radiation
- At decoupling that happens due to the finite width of last scattering and the cosmological local quadrupole





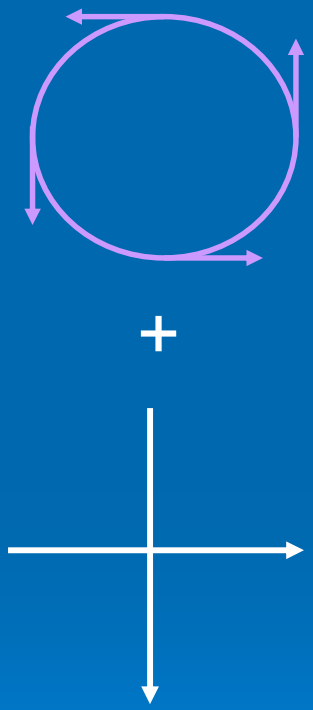
CMB anisotropy: total intensity



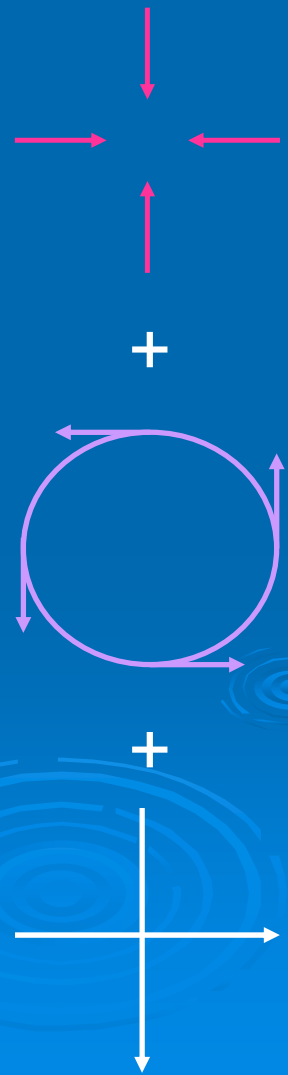


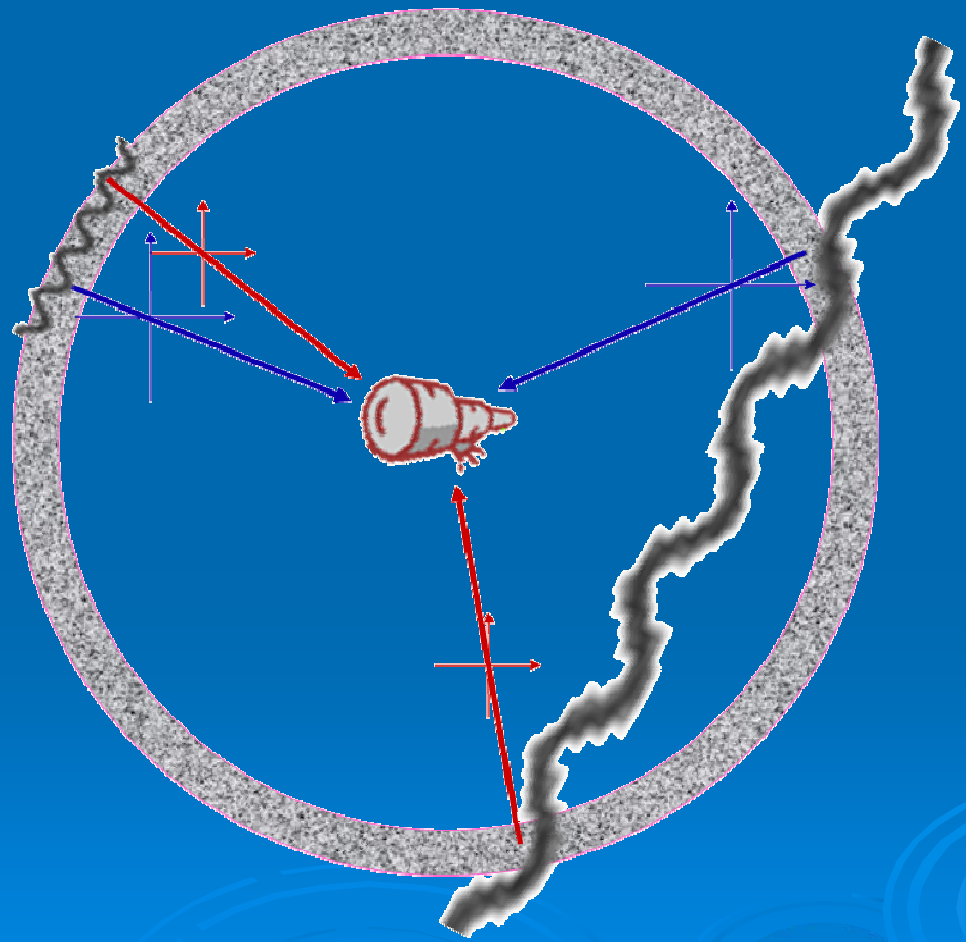
CMB anisotropy: polarization

Curl (B):

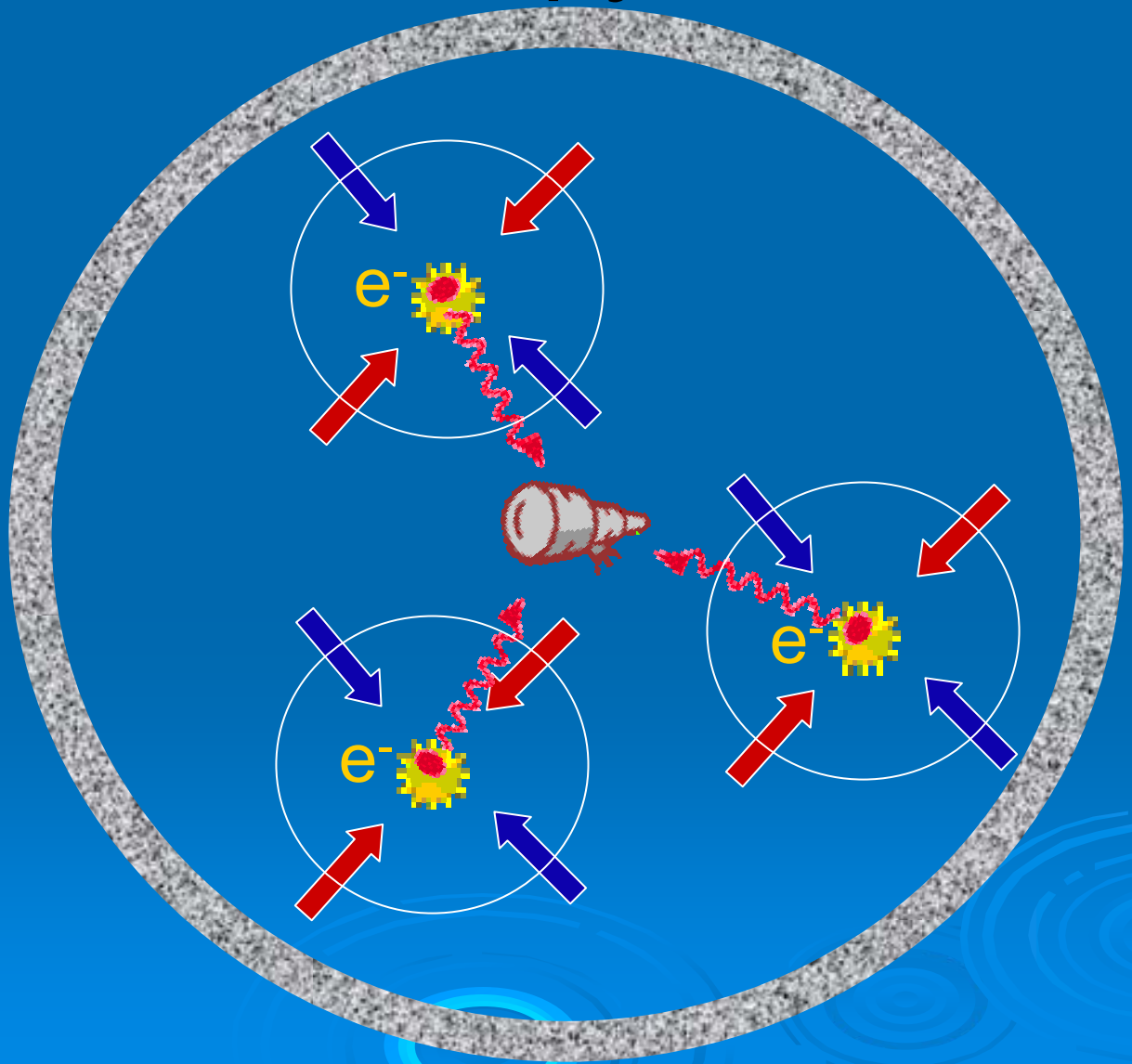


Gradient (E):

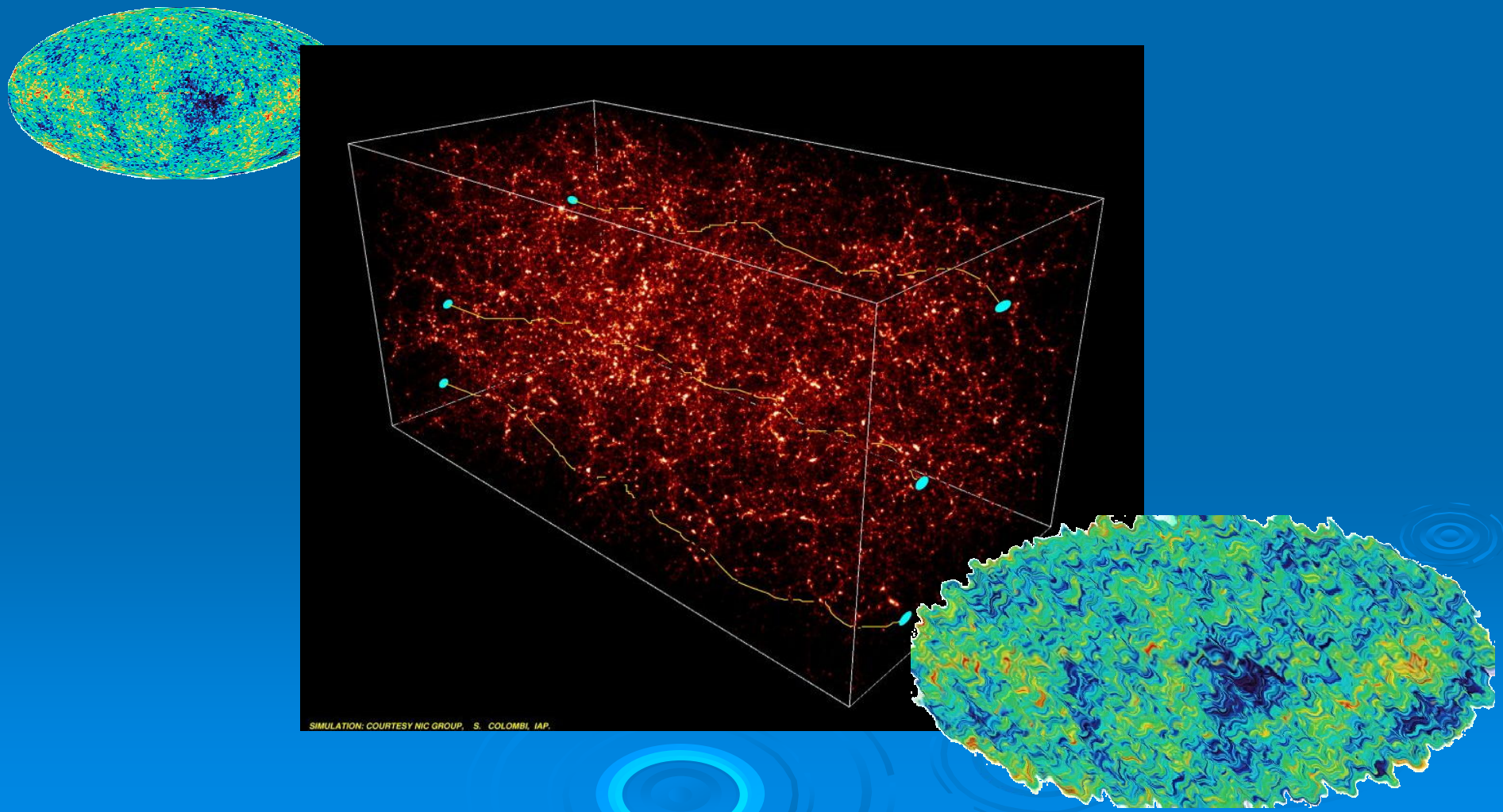




CMB anisotropy: reionization



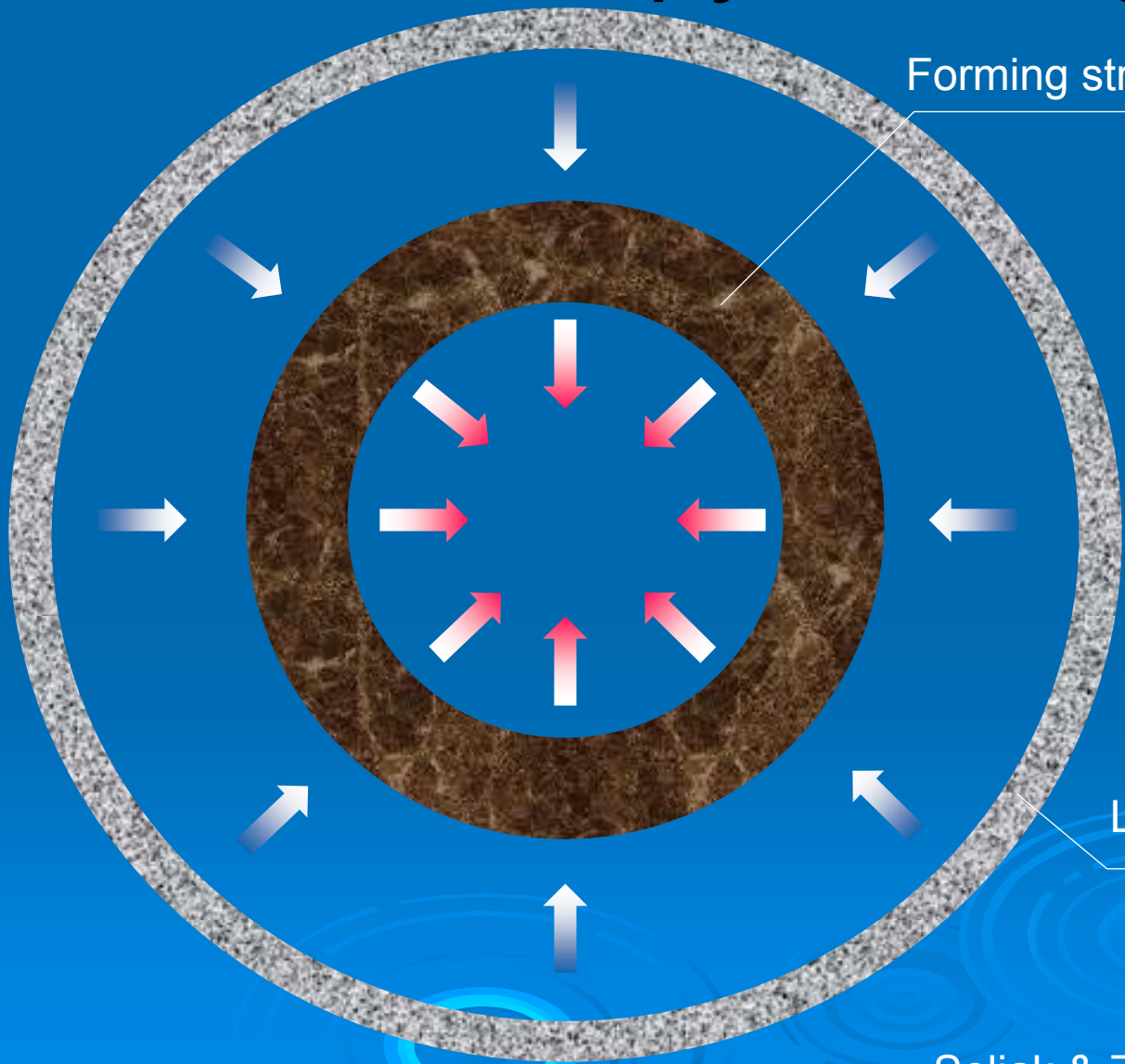
CMB anisotropy: lensing



CMB anisotropy: lensing

E

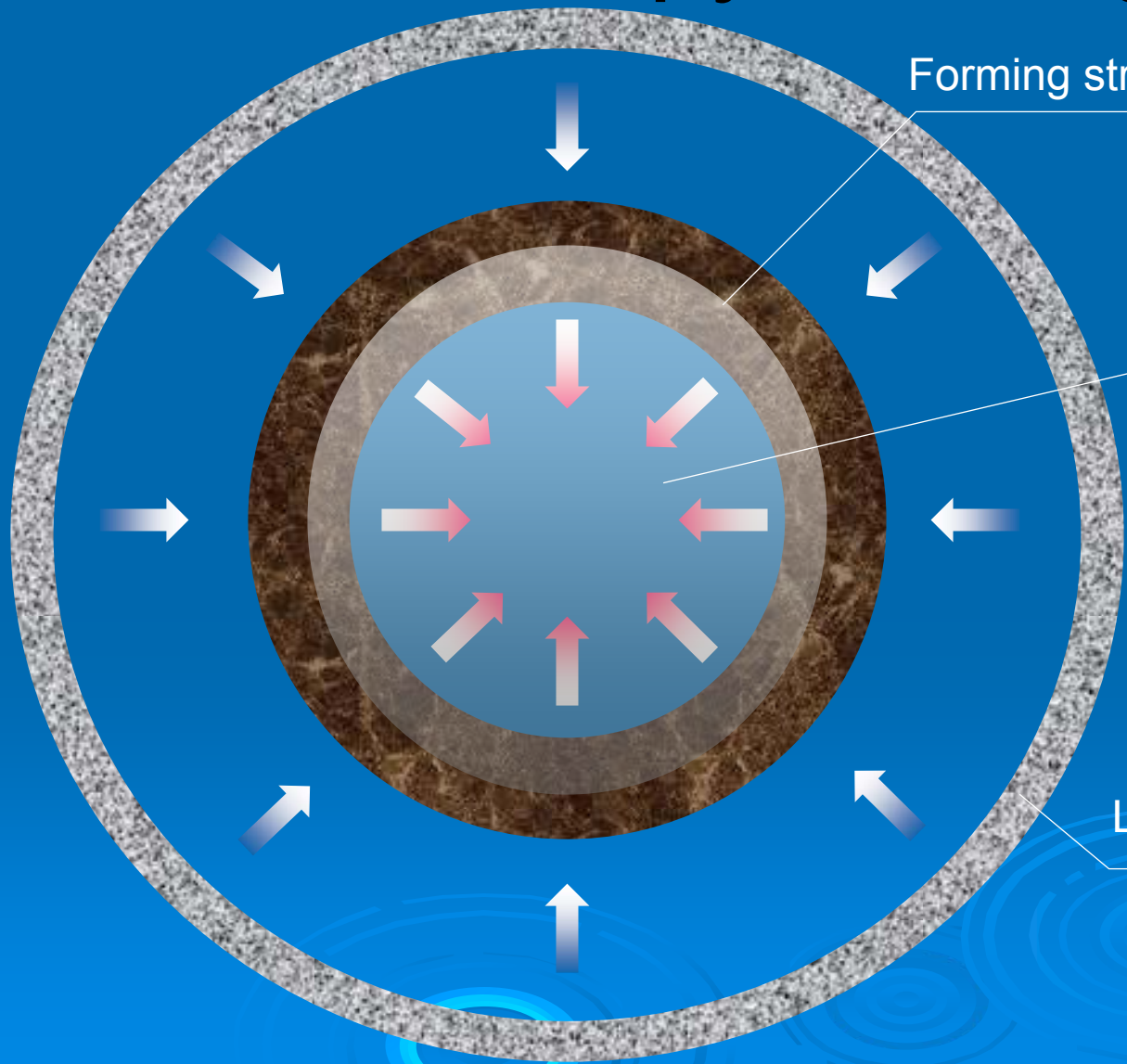
B



Seljak & Zaldarriaga 1998

CMB anisotropy: lensing

E B



Anisotropies

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

spherical harmonics

$X(\theta,\varphi)=\Sigma_{lm}\, a_{lm}^{X}\, Y^{s}_{lm}(\theta,\varphi)$

$X=T,E,B$

$s=0$ for T, 2 for Q and U

E and B modes have opposite parity

Angular power spectrum

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

spherical harmonics

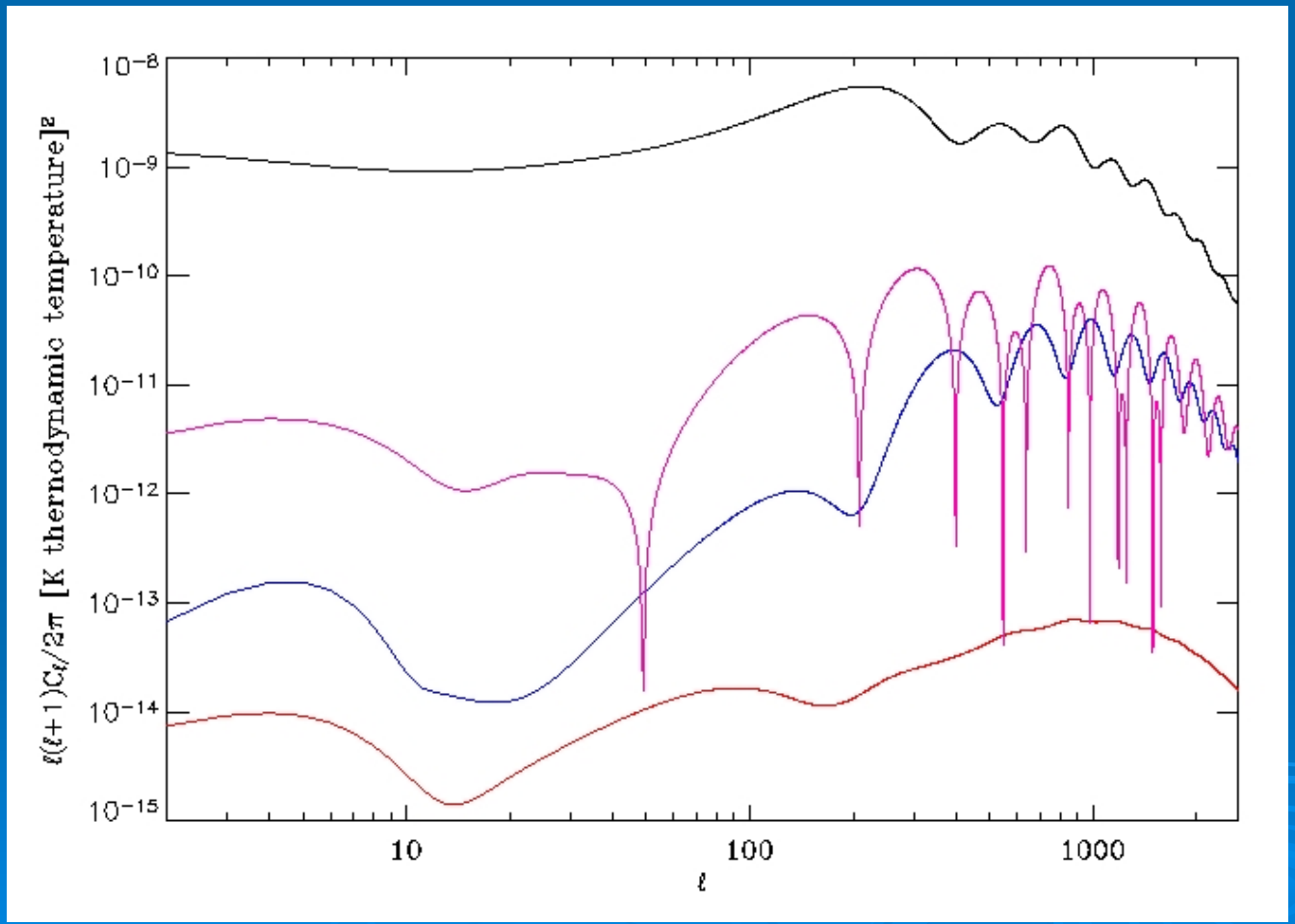
a^X_{lm}, $X=T,E,B$

information compression

$C_l=\Sigma_m [(a_{lm}{}^X)(a_{lm}{}^Y)^*]/(2l+1)$

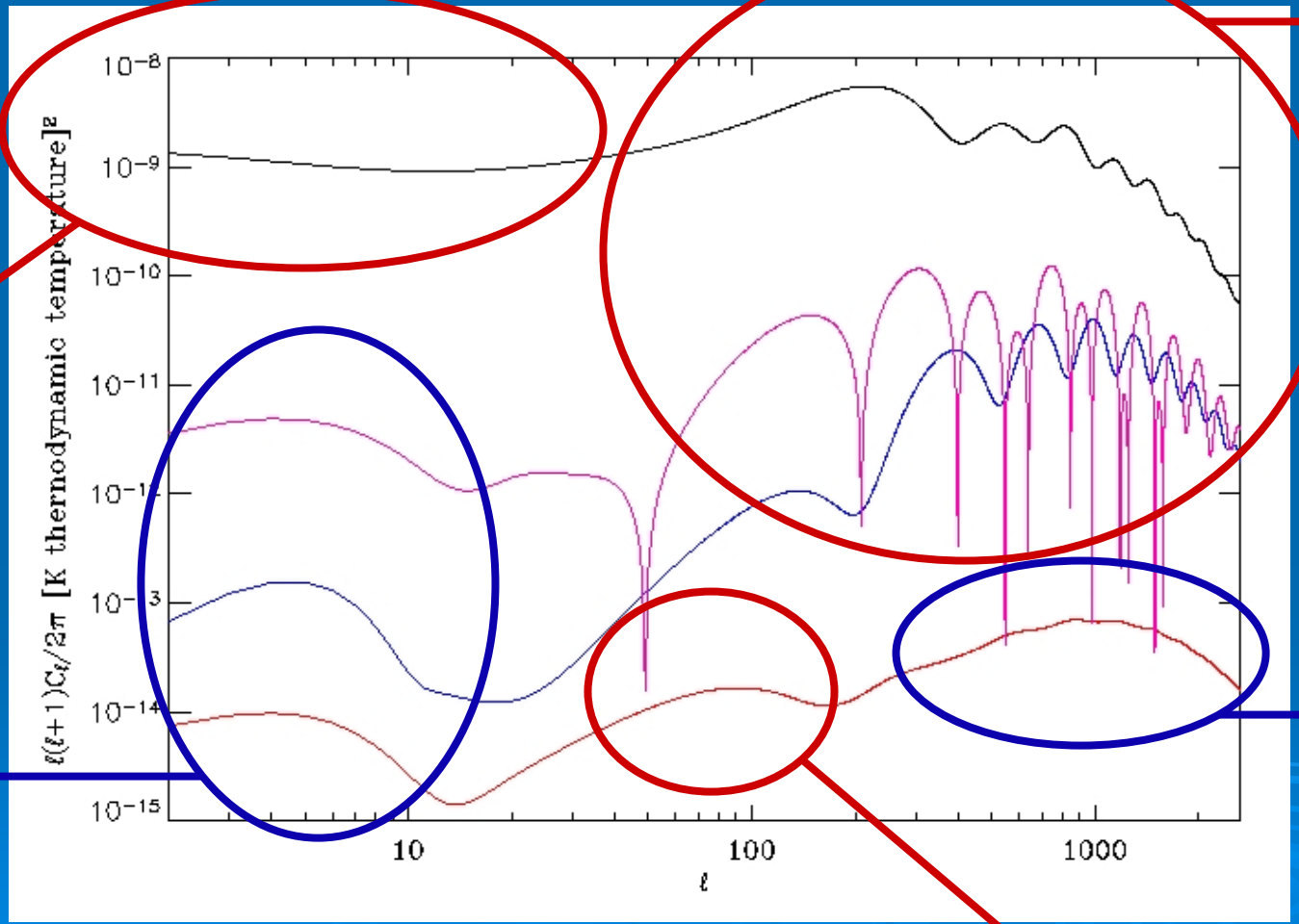
Status of the CMB observations and future experimental probes

CMB angular power spectrum



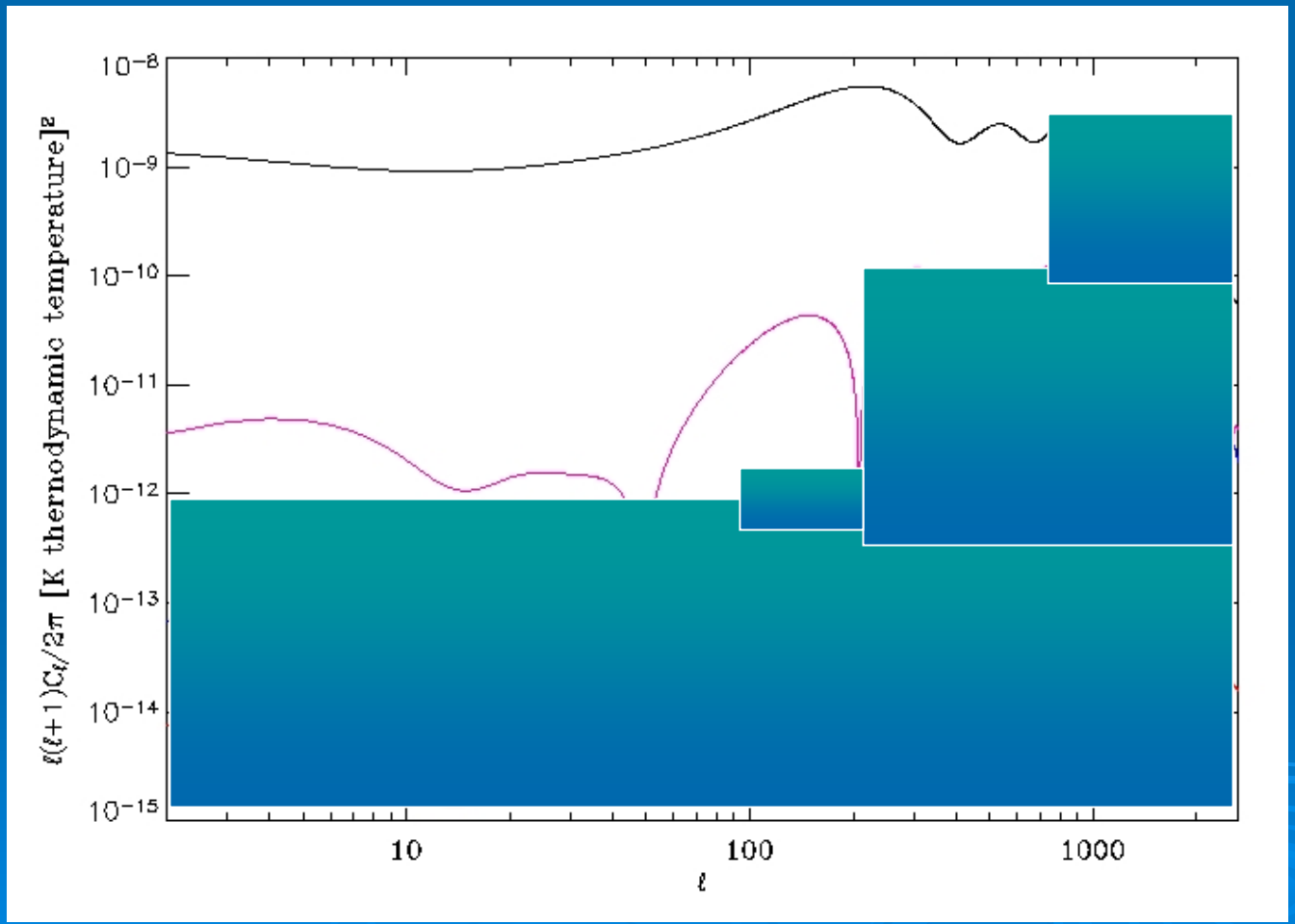
Angle ≈ 200/ℓ degrees

CMB angular power spectrum



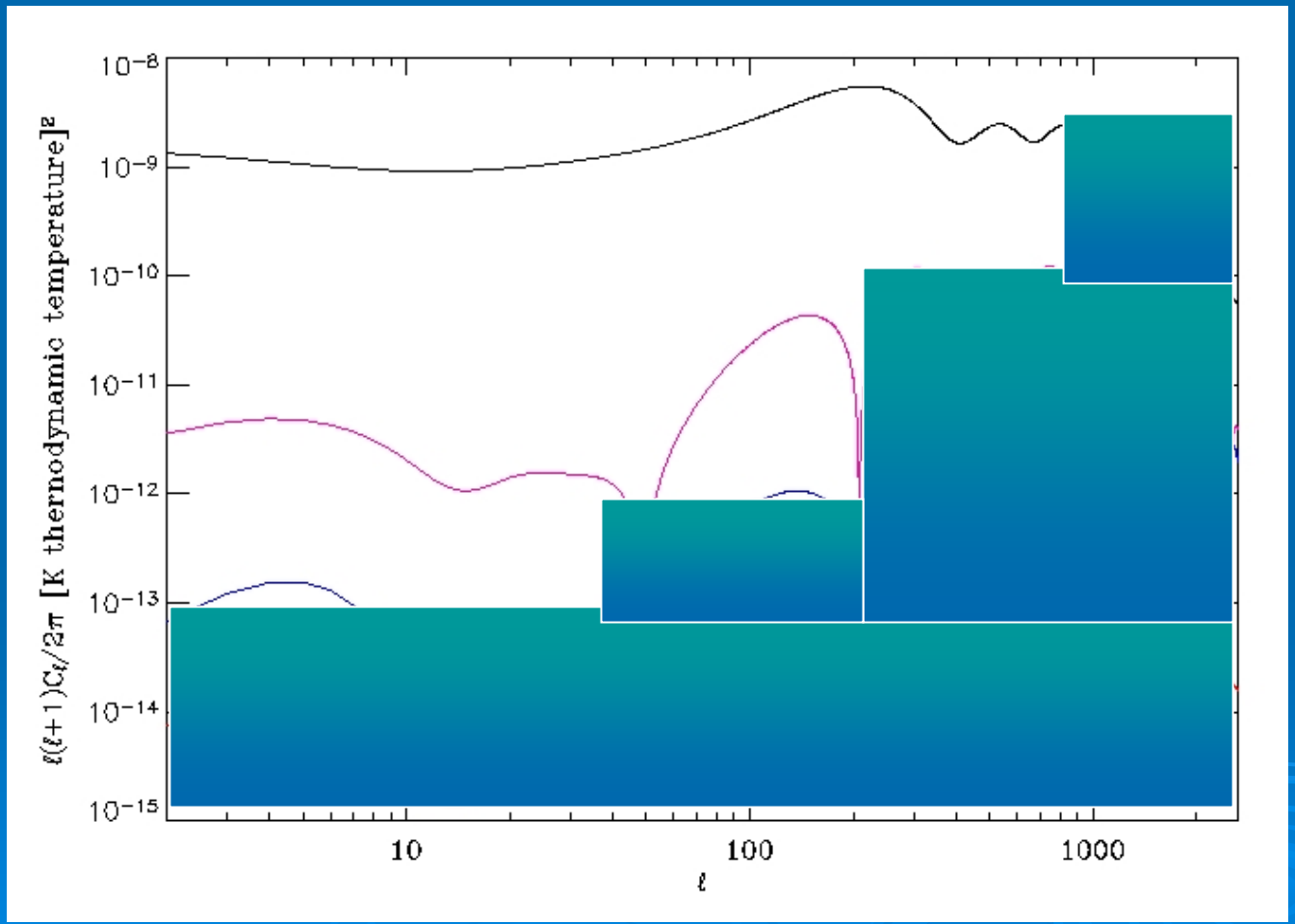
Angle ≈ 200/ℓ degrees

WMAP first year



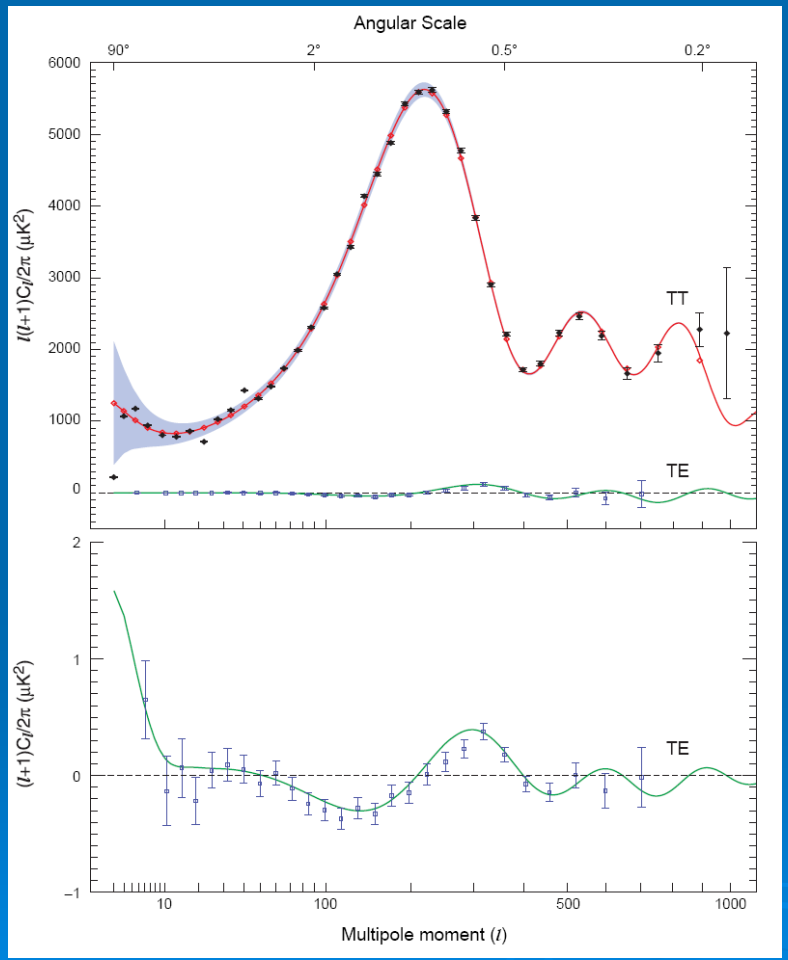
Angle ≈ 200/ℓ degrees

WMAP third year

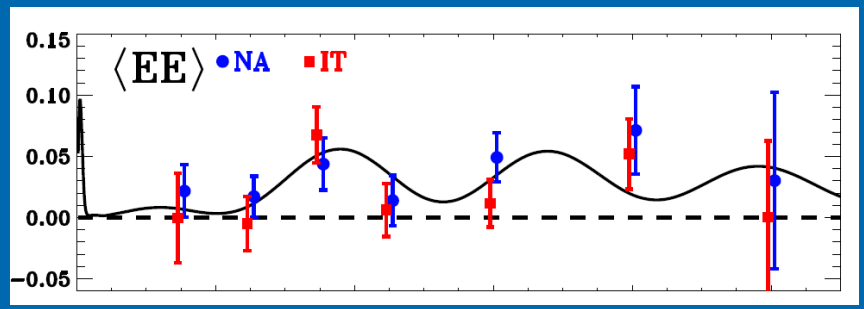


Angle ≈ 200/ℓ degrees

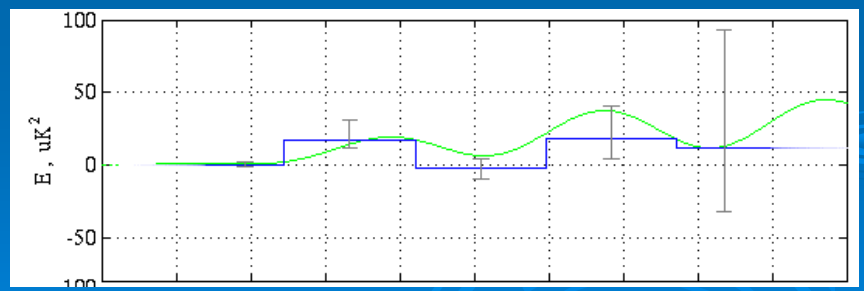
CMB angular power spectrum



WMAP



boomerang



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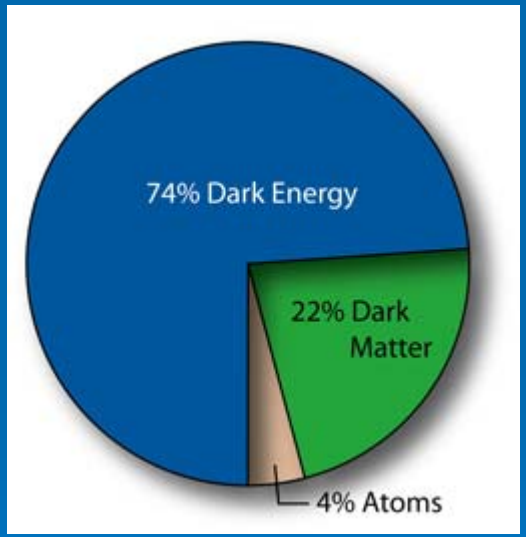
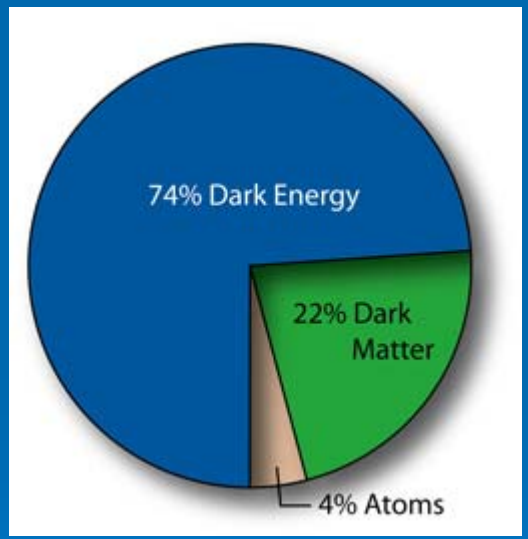
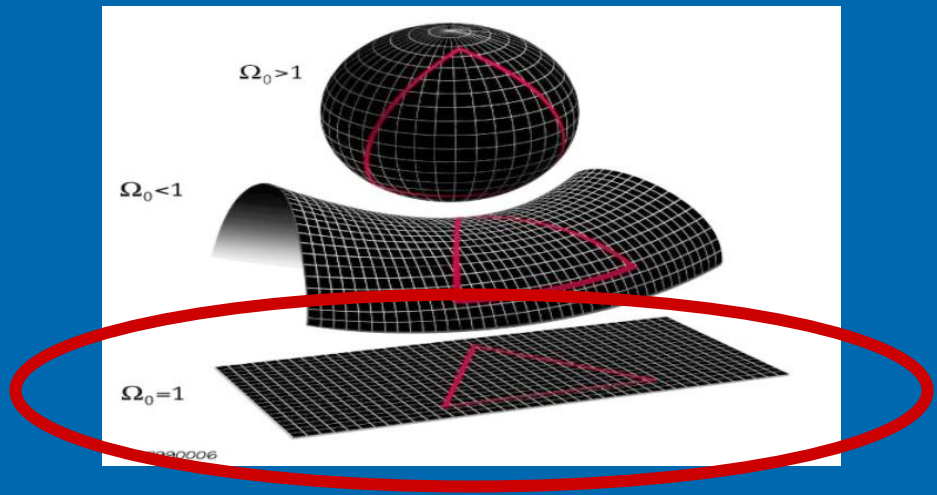
Cosmological concordance model

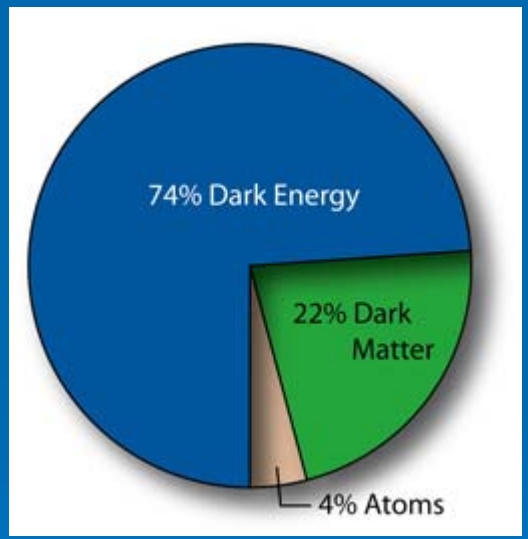


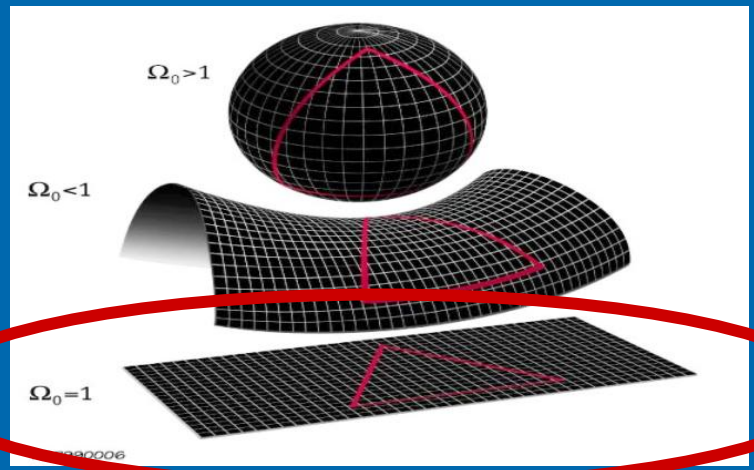
Cosmological concordance model





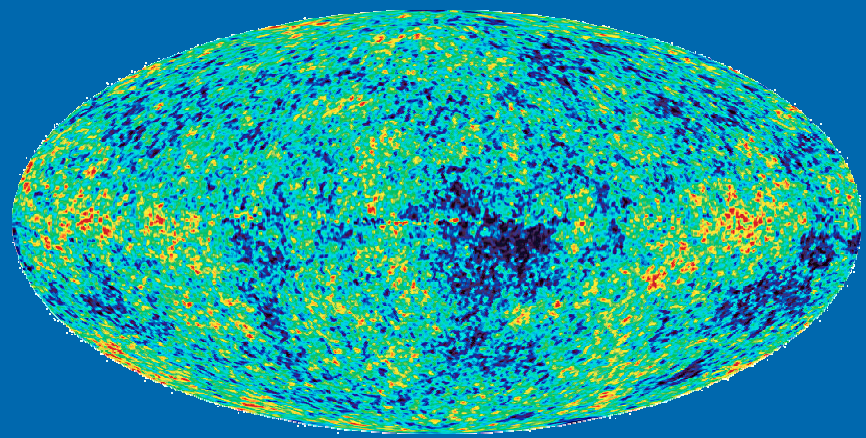
Cosmological concordance model





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



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…
- See lambda.gfsc.nasa.gov

Suggested reading

- Modern Cosmology textbook from Scott Dodelson
- My lecture notes from the course at SISSA, people.sissa.it/~bacci/lectures/
- Cosmological inflation and large scale structure, textbook from Andrew R. Liddle and David H. Lyth
- These lectures are available in pdf format at people.sissa.it/~bacci/work/lectures/