Introductory Particle Cosmology

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Lecture 7

Introduction

Mathematical Tools
- Generic Vector Bases
- Basis Change
- Vectors in Curved Geometries
- Tensors, Metric Tensor
- (Riemann) Manifolds
- Connection
- Geodesics and Curvature

General Relativity
- Equivalence Principle
- Einstein Equations

Cosmology
- Cosmological Principle
- FLRW Metric
- Friedmann Equations
- Cosmic Distances
- Cosmological Models

Observation
- CMB
- Structure Formation
- Red-shift/Distance

Standard Model
- Brief History
- Particle Content
- Gauge Principle, CPV, Strong CP
- EW Symmetry Breaking
- Beyond the SM

Particle Cosmology
- Dark Matter (Models + Exp.)
- Dark Energy (Models + Exp)
- Inflationary Models
- Gravitational Waves
- Density Perturbations

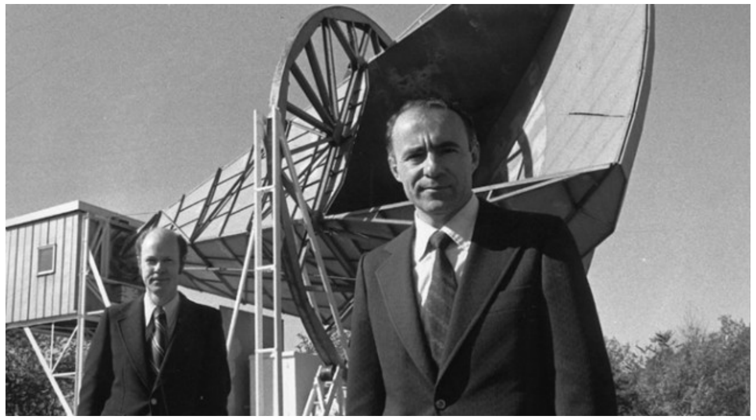
Plan

	Datum	Von	Bis	Raum
1	Di, 17. Apr. 2018	10:00	12:00	05 119 Minkowski-Raum
2	Do, 19. Apr. 2018	08:00	10:00	05 119 Minkowski-Raum
3	Di, 24. Apr. 2018	10:00	12:00	05 119 Minkowski-Raum
4	Do, 26. Apr. 2018	08:00	10:00	05 119 Minkowski-Raum
5	Do, 3. Mai 2018	08:00	10:00	05 119 Minkowski-Raum
6	Di, 8. Mai 2018	10:00	12:00	05 119 Minkowski-Raum
7	Di, 15. Mai 2018	10:00	12:00	05 119 Minkowski-Raum
8	Do, 17. Mai 2018	08:00	10:00	05 119 Minkowski-Raum
9	Di, 22. Mai 2018	10:00	12:00	05 119 Minkowski-Raum
10	Do, 24. Mai 2018	08:00	10:00	05 119 Minkowski-Raum
11	Di, 29. Mai 2018	10:00	12:00	05 119 Minkowski-Raum
12	Di, 5. Jun. 2018	10:00	12:00	05 119 Minkowski-Raum
13	Do, 7. Jun. 2018	08:00	10:00	05 119 Minkowski-Raum
14	Di, 12. Jun. 2018	10:00	12:00	05 119 Minkowski-Raum
15	Do, 14. Jun. 2018	08:00	10:00	05 119 Minkowski-Raum
16	Di, 19. Jun. 2018	10:00	12:00	05 119 Minkowski-Raum
17	Do, 21. Jun. 2018	08:00	10:00	05 119 Minkowski-Raum
18	Di, 26. Jun. 2018	10:00	12:00	05 119 Minkowski-Raum
19	Do, 28. Jun. 2018	08:00	10:00	05 119 Minkowski-Raum
20	Di, 3. Jul. 2018	10:00	12:00	05 119 Minkowski-Raum
21	Do, 5. Jul. 2018	08:00	10:00	05 119 Minkowski-Raum

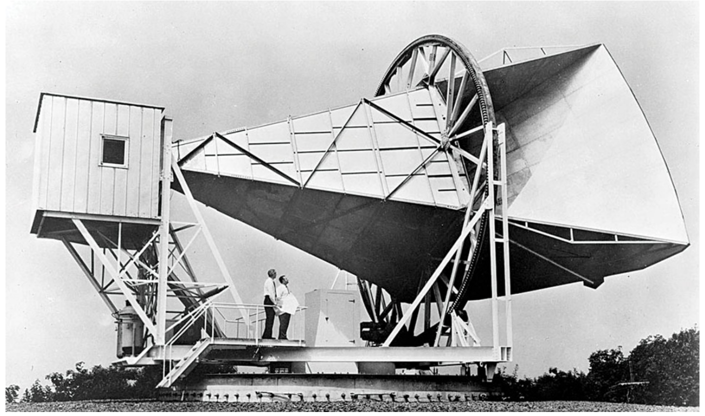
H.Minkowski
(1864-1909)

Physics Dept. Building, 5th Floor

Short History



Arno A. Penzias (1933-)
Robert W. Wilson (1936-)



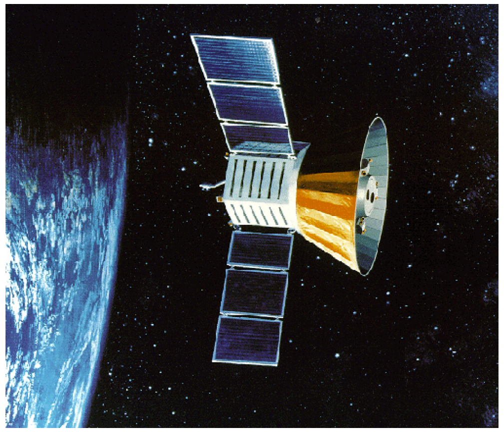
Holmdel Horn Antenna,
New Jersy (USA)

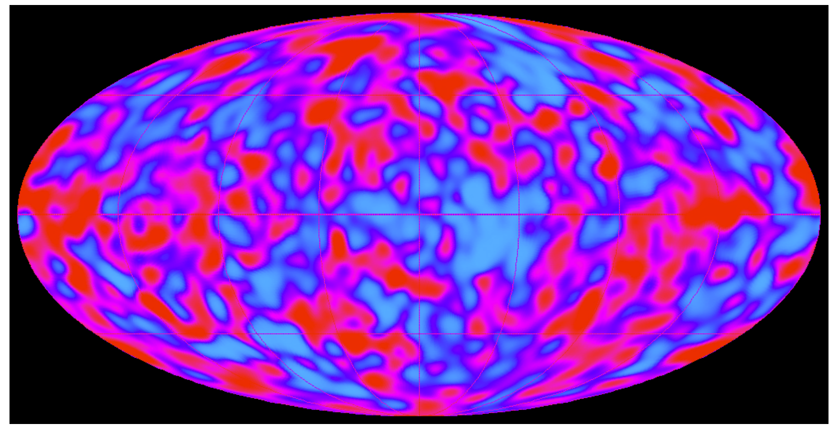
Penzias & Wilson won the Nobel Prize in Physics in 1978 for the discovery of the CMB.
The 15x6x6 horn antenna they developed was build for satellite communications.
After the removal of all the known backgrounds and using cryogenic techniques for lowering the electronics noise, a microwave component remained present in their data.
It looked like coming from every direction and corresponded to a temperature they estimated to be about 3.5K

The discovery confirmed a big-bang prediction by Gamow et al. and was made before Princeton scientists J. Peebles, R. Dicke, and D. Wilkinson, whom were building an antenna exactly for trying to detect the CMB.

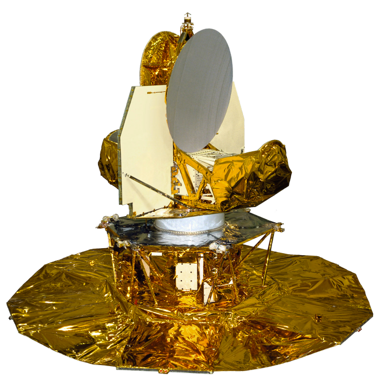
Penzias, A.A.; R. W. Wilson (October 1965). "A Measurement of the Flux Density of CAS A At 4080 Mc/s". Astrophysical Journal Letters. 142: 1149–1154.

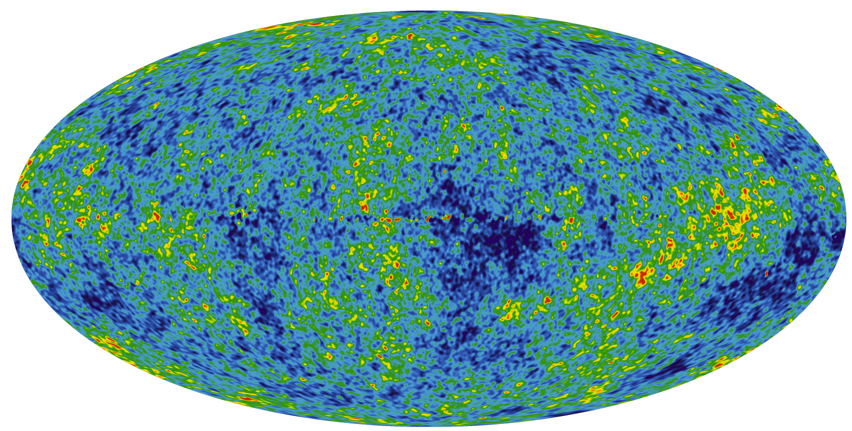
Short History



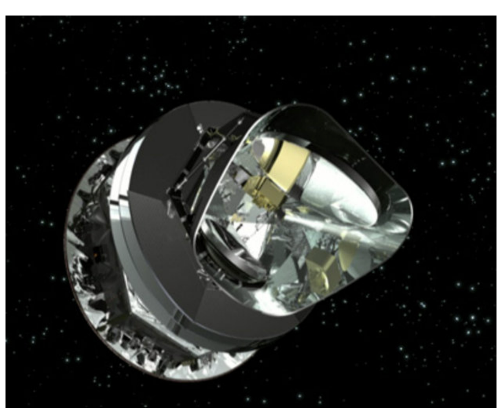


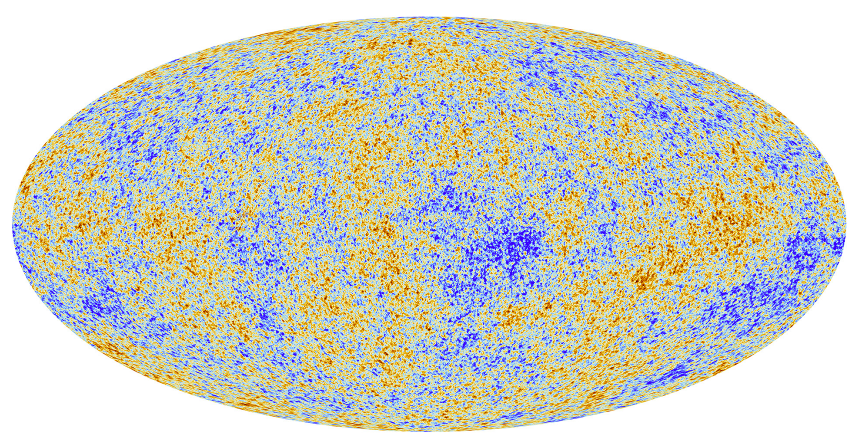
COBE (1992)





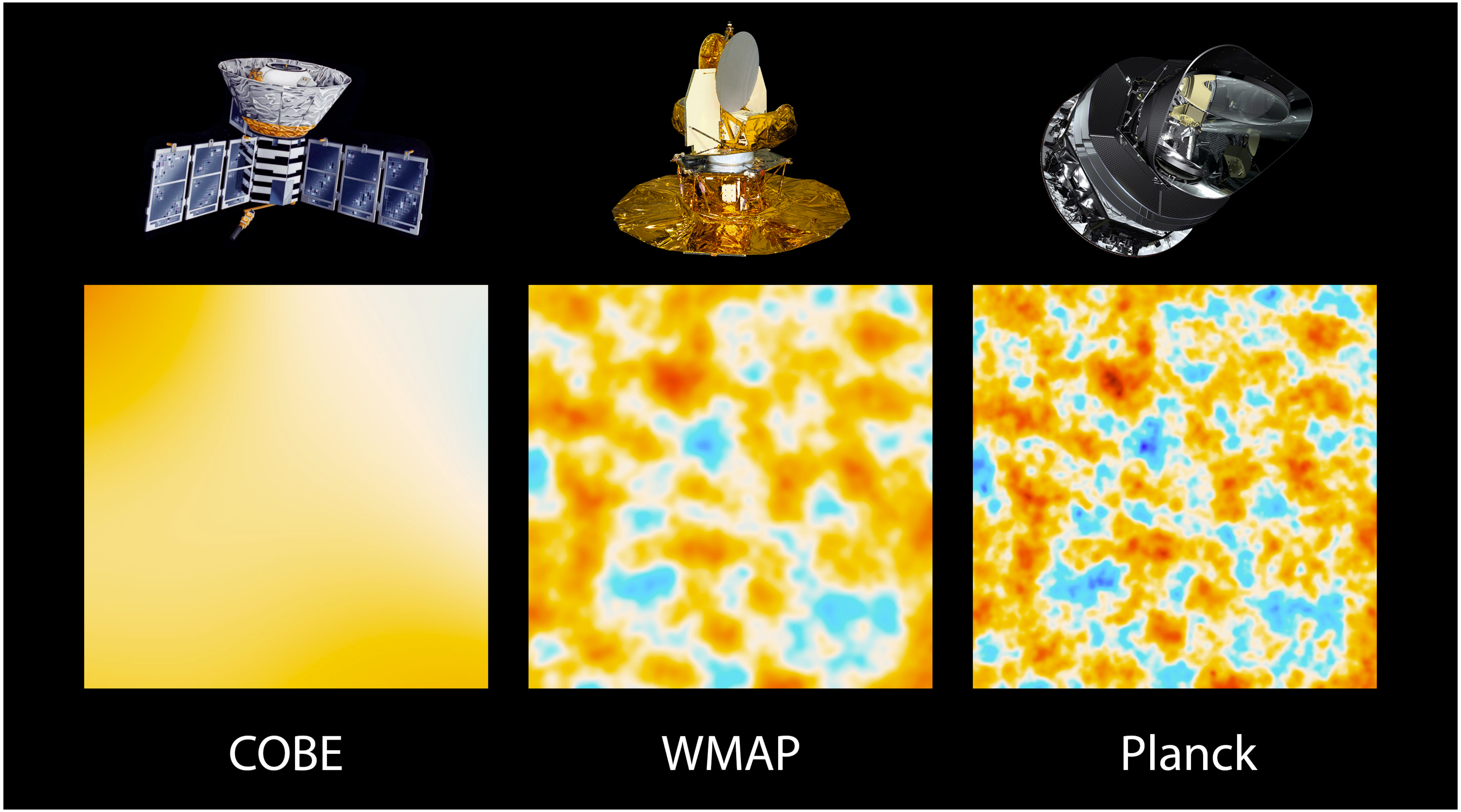
WMAP (2003)

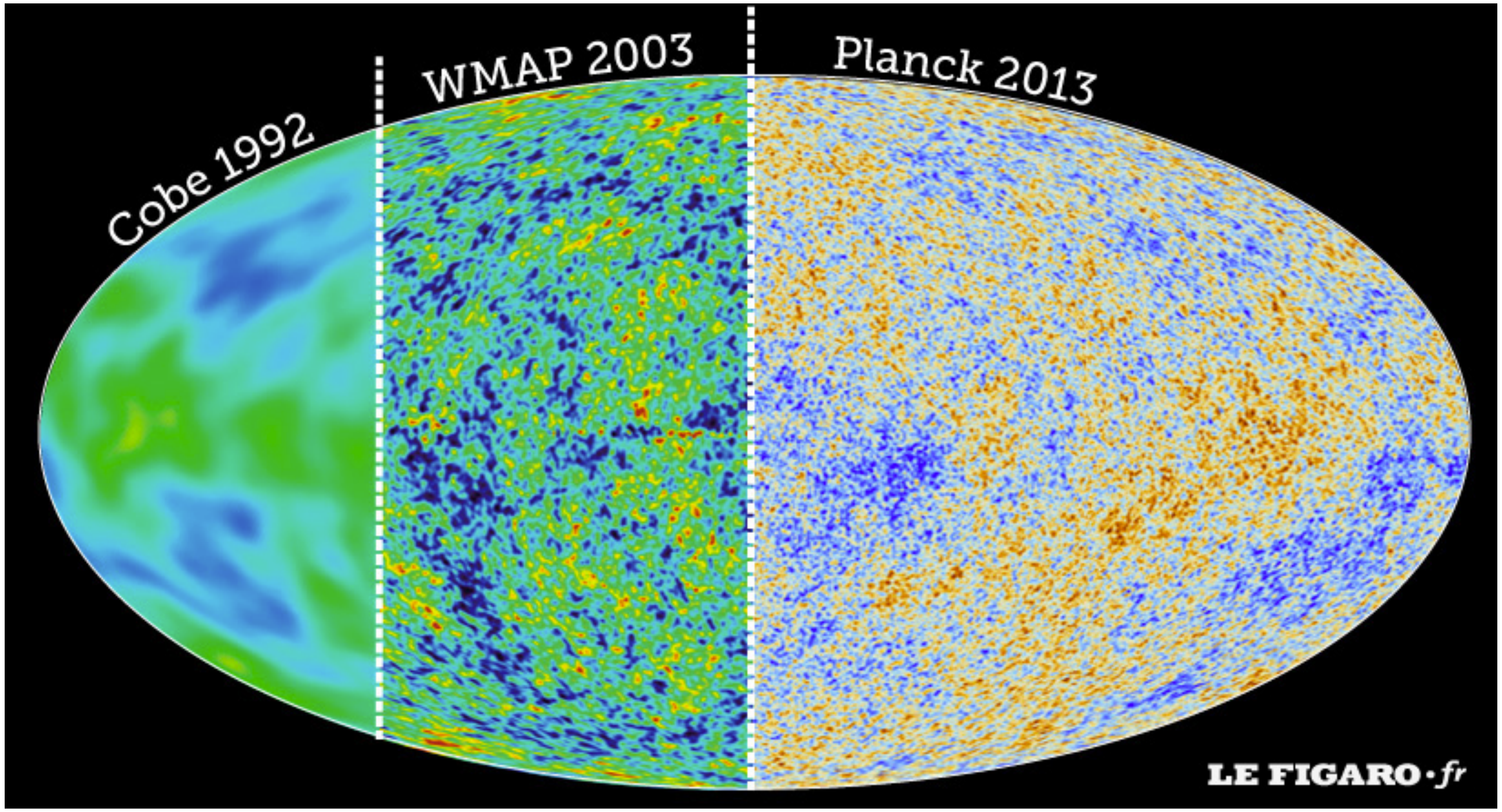




Planck (2013)

Short History



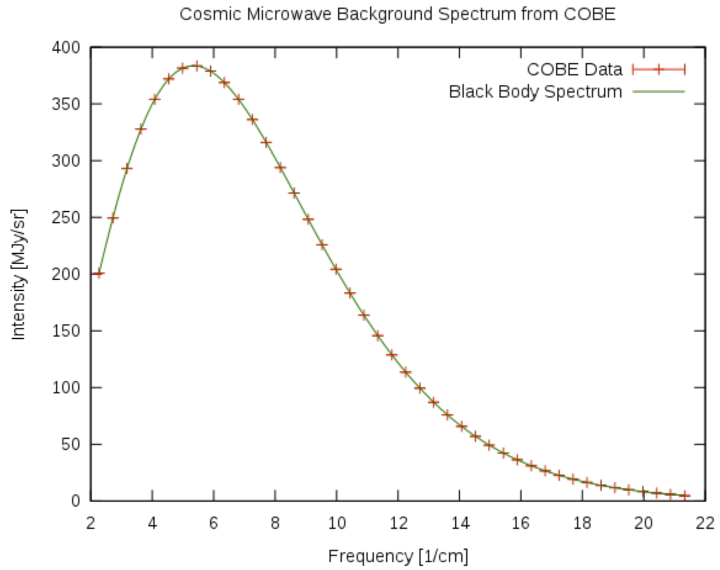


COBE: First detection of anisotropies

Mather (1946-)
Smoot (1945-)

2006 Physics Noble Prize

CMB Black-body spectrum

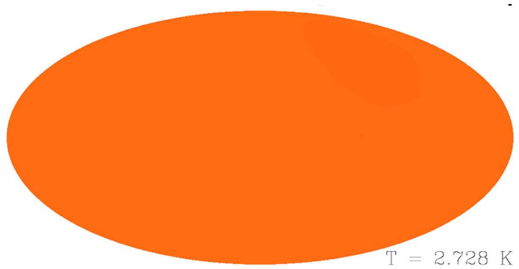


The Cosmic Microwave Background

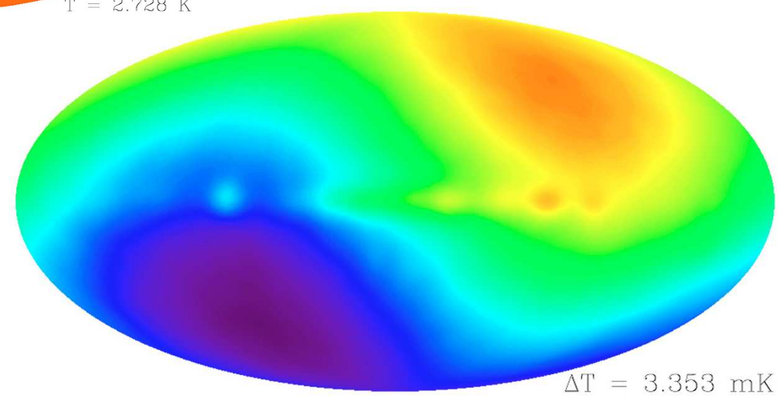
The CMB has cosmological origin: it is the radiation which started to free-stream after recombination.

The today's photon density of the CMB is about 500 photons/cm^3.
It's spectrum is very close to a thermal one with temperature T=2.7K.
These photons traveled 99.7% of the age of the Universe before reaching us.

Scalar and Dipole Subtraction



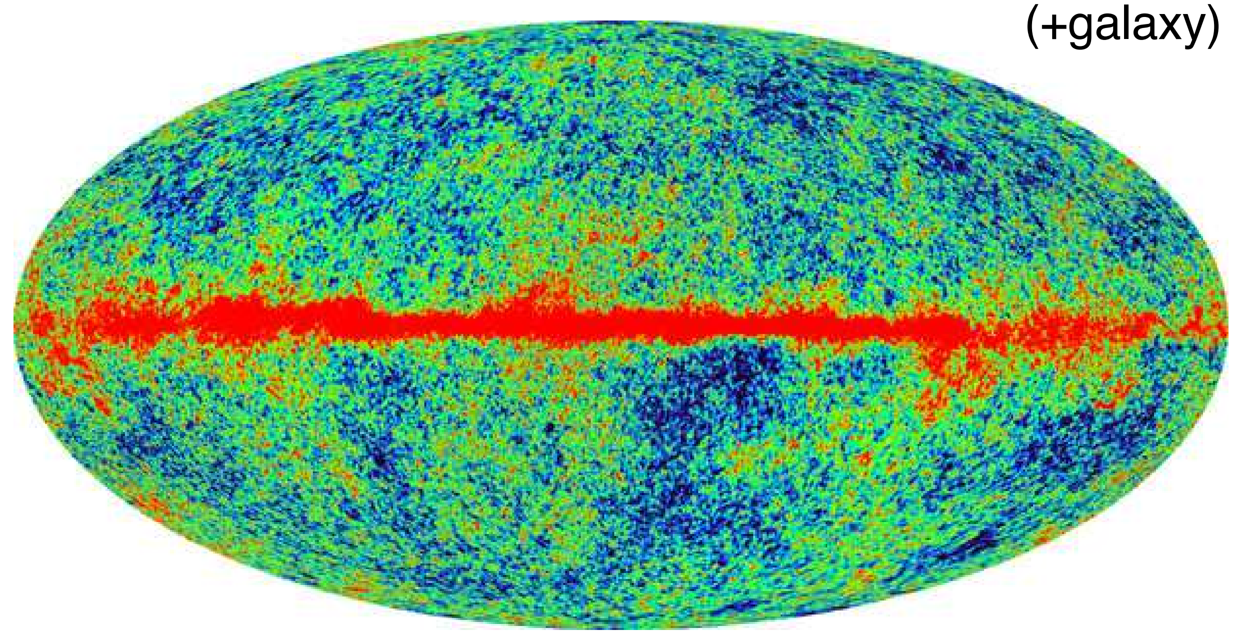
(almost) uniform 2.726K blackbody



Dipole (local motion)

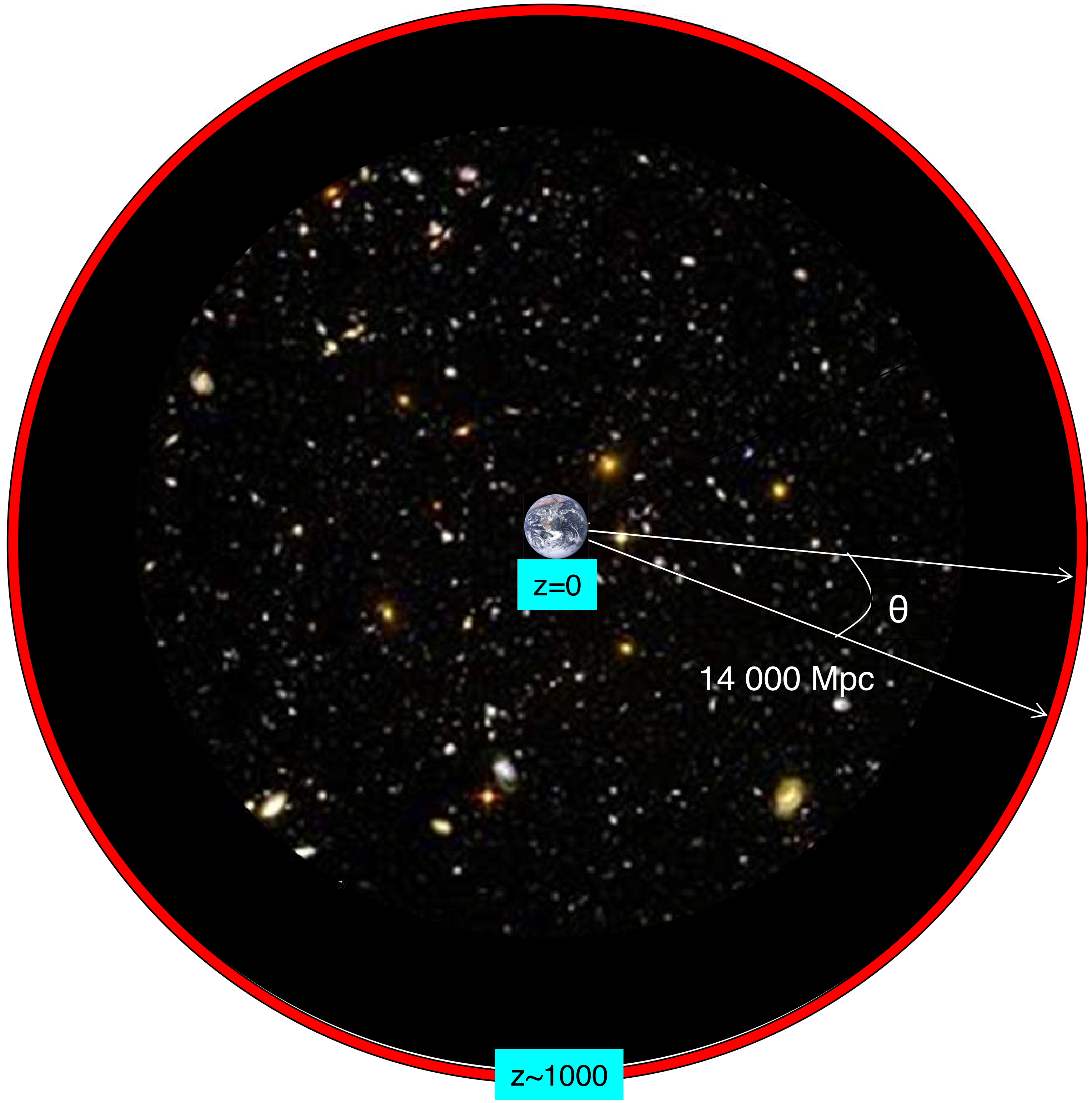
We move at 370km/s wrt the CMB frame!

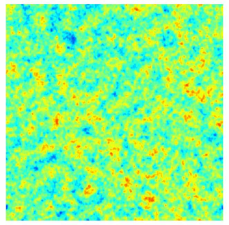
O(10^{-5}) perturbations
(+galaxy)



Source: NASA/WMAP Science Team

Angular Scale (Horizon Problem!)





CMB Fluctuations

Temperature fluctuations around the mean

$$\frac{\delta T}{T_0} = \frac{T - T_0}{T_0}(\theta, \phi)$$

Decomposition in spherical harmonics

$$\frac{\delta T}{T_0}(\theta, \phi) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta, \phi)$$

$$\int Y_{l,m} Y^*_{l',m'} d\Omega = \delta_{l,l'} \delta_{m,m'}$$

$$a_{l,m} = \int Y^*_{l,m}(\theta, \phi) \frac{\delta T}{T_0}(\theta, \phi) d\Omega$$

Angular Power Spectrum

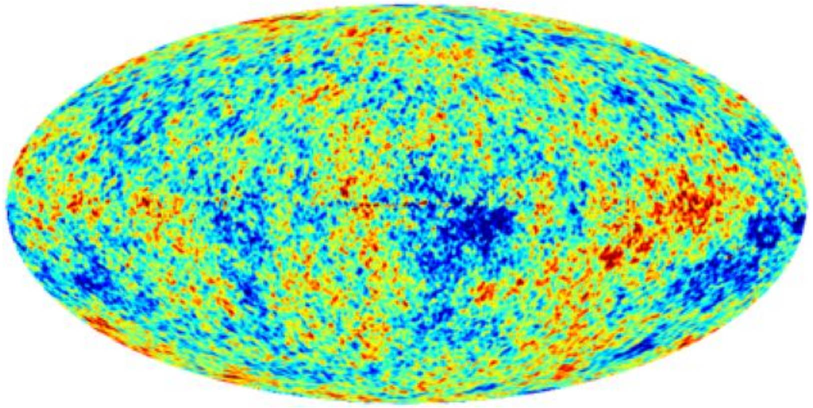
If the direction does not matter $\sum_m |Y_{l,m}|^2 = (2l+1)/4\pi$

$$\langle a_{l,m} a_{l',m'} \rangle = \delta_{l,l'} \delta_{m,m'} C_l$$

Power spectrum

$$C_l = \frac{1}{2l+1} \sum_m \langle |a_{l,m}|^2 \rangle$$

Inflation predicts a Gaussian distribution for the power spectrum coefficients which are therefore Gaussian random variables. If this is true, the correlation functions encode all the information about the fluctuations.



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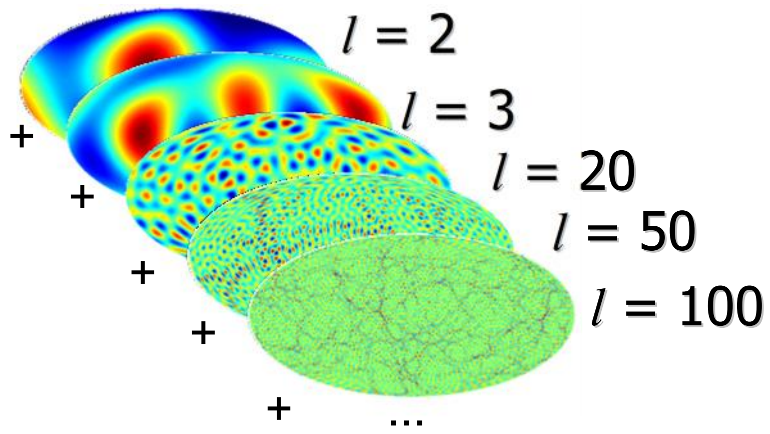


Cosmic Variance

Error in the difference btw theory and measurement

$$\langle (\hat{C}_l - C_l)^2 \rangle = \frac{2}{2l+1} C_l^2$$

This error cannot be eliminated: only 1 realization of the CMB to observe!

This error, or "cosmic variance" is larger at small l (large scales) and represents a fundamental limit on the knowledge of the CMB fluctuations.

CMB Polarization

Thompson scattering $\frac{d\sigma}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$

incoming/outgoing polarization

Converts quadrupole asymmetries in linear polarizations. Expected to be present at the 5% level.

Polarization tensor $p_{ij} = \langle \hat{\epsilon}_i \hat{\epsilon}_J^* \rangle$

Traceless

$$Trp = p_{ii} = \langle \hat{\epsilon}_i \hat{\epsilon}_i^* \rangle = \langle |\epsilon| \rangle = 1$$

Hermitian

$$(p_{ij})^* = p_{ji}$$

Can be decomposed using the Pauli matrices (orthogonal basis for hermitian matrices.)

$$p_{ij} = \frac{1}{2}(I + Q\sigma_1 + U\sigma_2 + V\sigma_3)$$

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad ; \quad \sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad ; \quad \sigma_3 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Q,U,V are the Stokes parameters.

CMB Polarization

Intensity tensor
(in every polarization component)

$$\rho_{ij} = \langle E_i E_j^* \rangle = \frac{1}{2}(J \cdot I + Q\sigma_1 + U\sigma_2 + V\sigma_3)$$

Geometric Invariants

$$J = \delta_{ij}\rho_{ij} = |E_x|^2 + |E_y|^2$$

$$V = \epsilon_{ij}\rho_{ij}$$

Differential Invariants

$$S = \nabla^2 P_E = \partial_i \partial_j \rho_{ij}$$ E-modes

$$P = \nabla^2 P_B = \epsilon_{ik} \partial_i \partial_j \rho_{jk}$$ B-modes

E and B modes are the analogous of the irrotational and solenoidal decomposition of a vector.
In this case, it is a rank-2 tensor which is decomposed.

CMB Polarization

Non-zero cross-correlation spectra

$$\langle T(\hat{n})T(\hat{n}')\rangle = \frac{1}{4\pi}\sum_{l=0}^{l=\infty}(2l+1)C_l^{TT}P_l(\cos\theta)$$

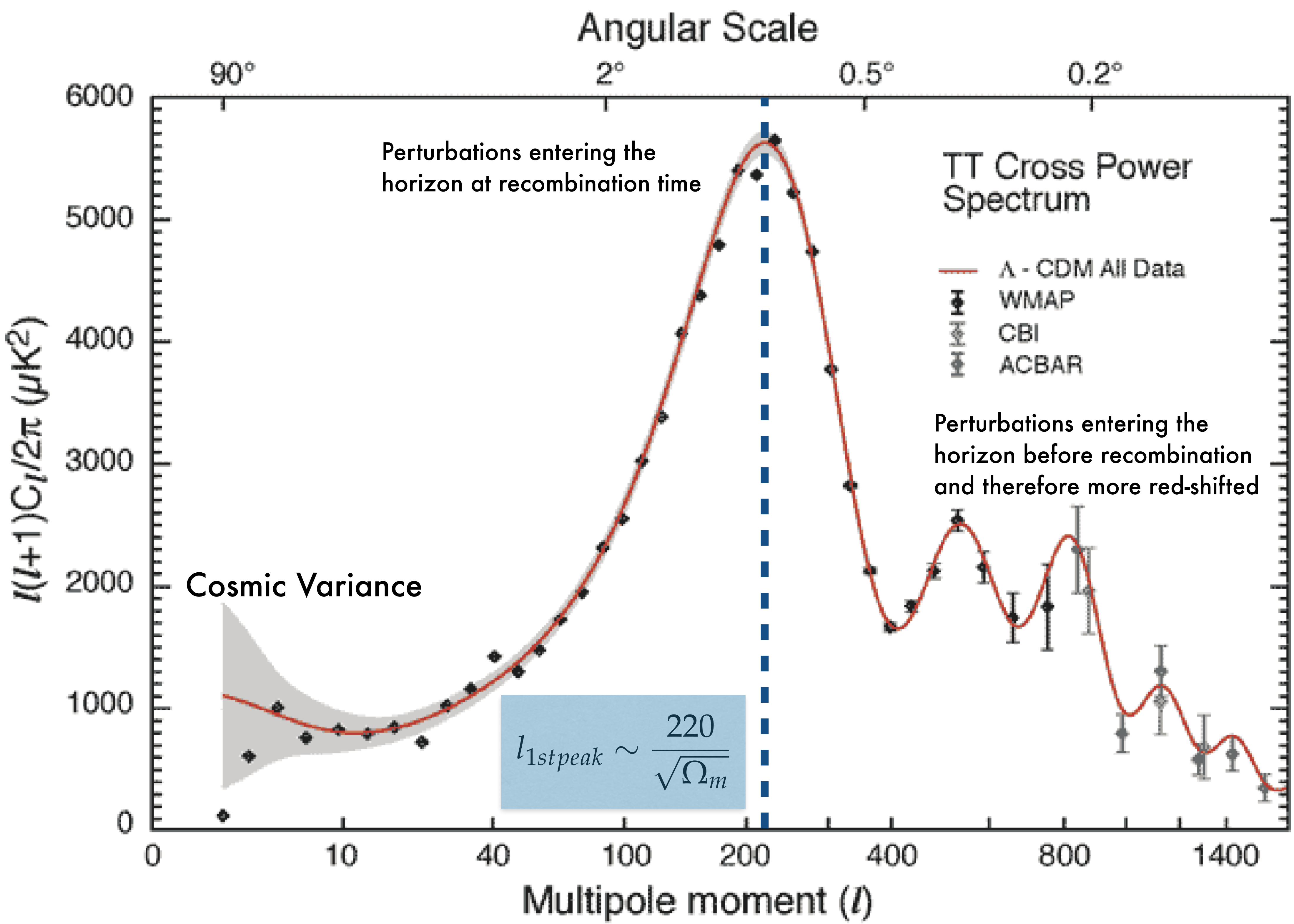
$$\langle T(\hat{n})E(\hat{n}')\rangle = \frac{1}{4\pi}\sum_{l=0}^{l=\infty}(2l+1)C_l^{TE}P_l(\cos\theta)$$

$$\langle E(\hat{n})E(\hat{n}')\rangle = \frac{1}{4\pi}\sum_{l=0}^{l=\infty}(2l+1)C_l^{EE}P_l(\cos\theta)$$

$$\langle B(\hat{n})B(\hat{n}')\rangle = \frac{1}{4\pi}\sum_{l=0}^{l=\infty}(2l+1)C_l^{BB}P_l(\cos\theta)$$

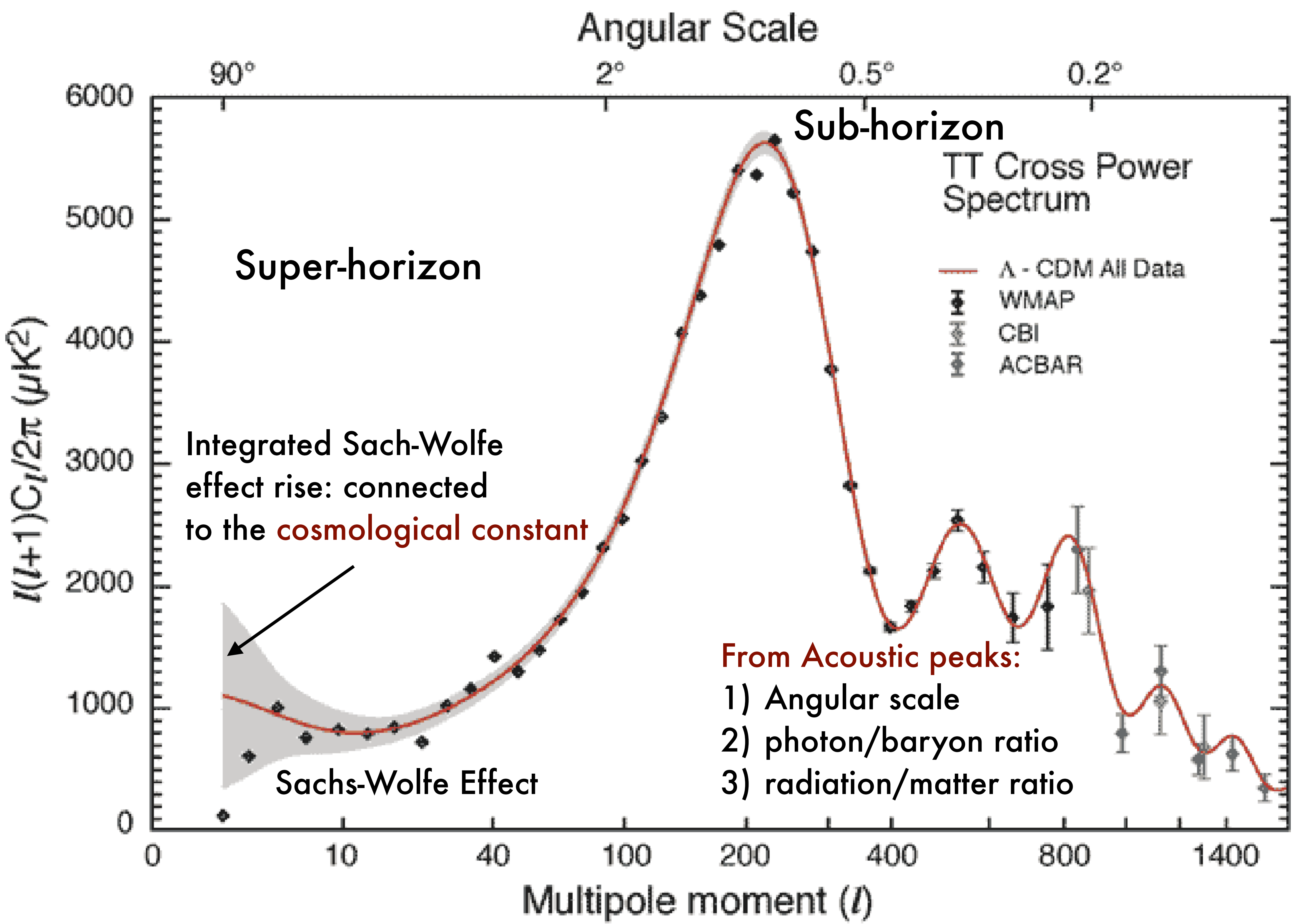
Besides the already defined TT correlations the symmetry (parity) of the EM interaction allows for further 3 cross-correlation terms: TE, EE and BB.

TT Angular Power Spectrum 1

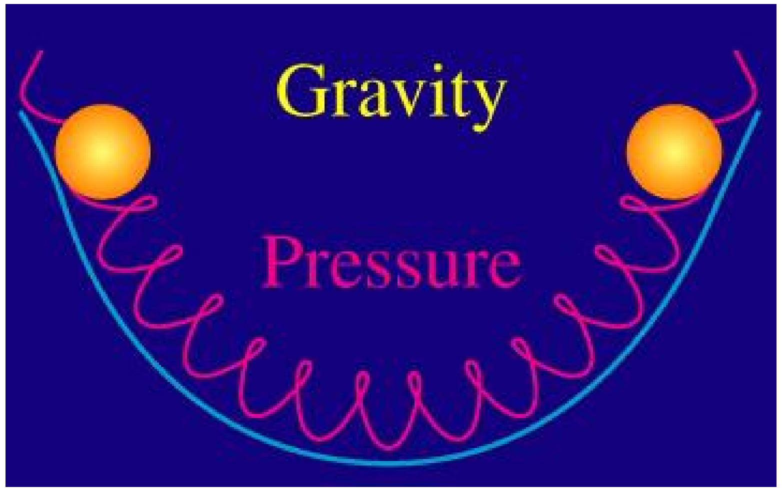


JG|U

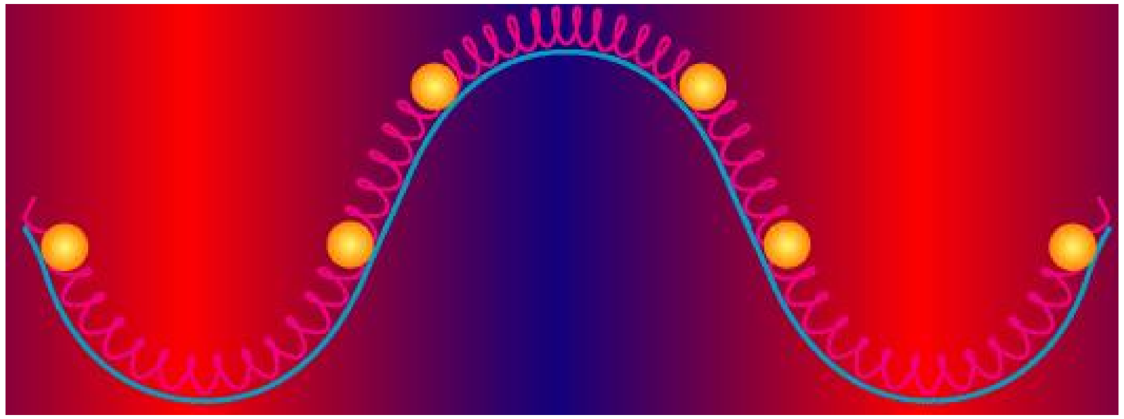
TT Angular Power Spectrum 2



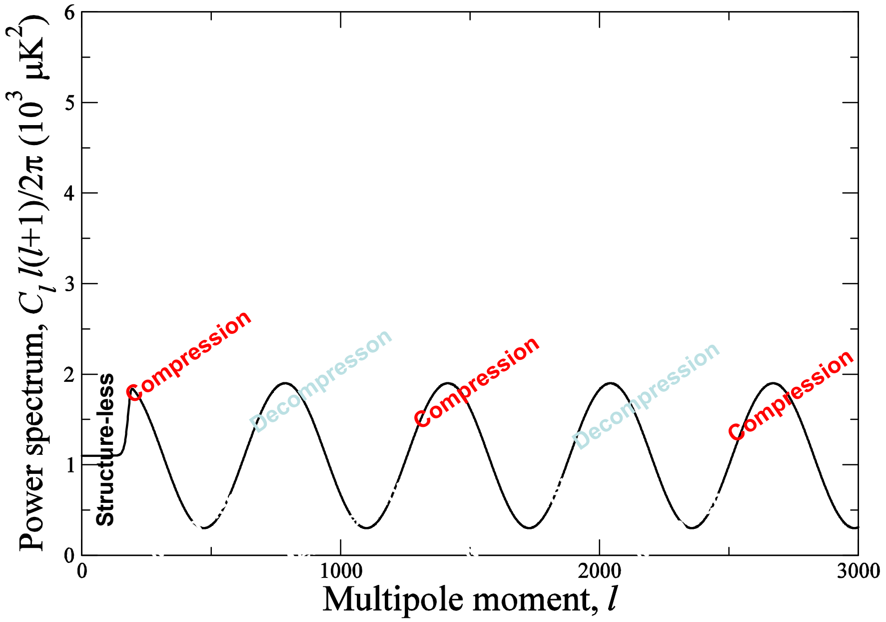
Physics of the TT spectrum



Gravity forms potential wells (Dark Matter ?).
Baryons can be seen as masses attached to springs.
Springs represent the photon pressure.
When the density increases pressure increases, starting oscillations.

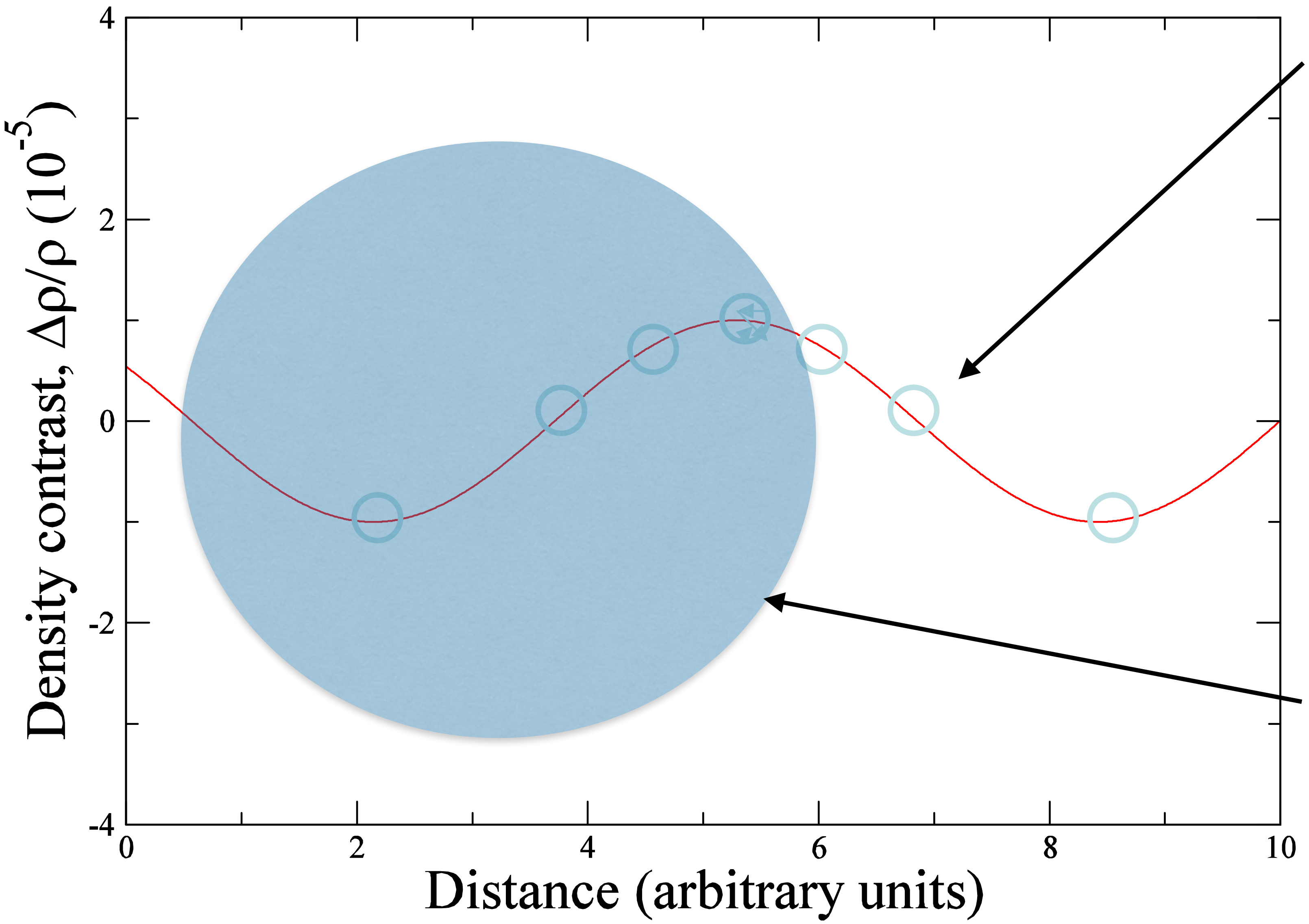


Top of wells –> cold regions
Bottom of wells –> hot regions
Landscape of grav. wells vs photon pressure starts sound waves in the plasma.



The CMB power spectrum (always positive by definition) should look like this.
No oscillations are present at very large scales.

Physics of the TT spectrum

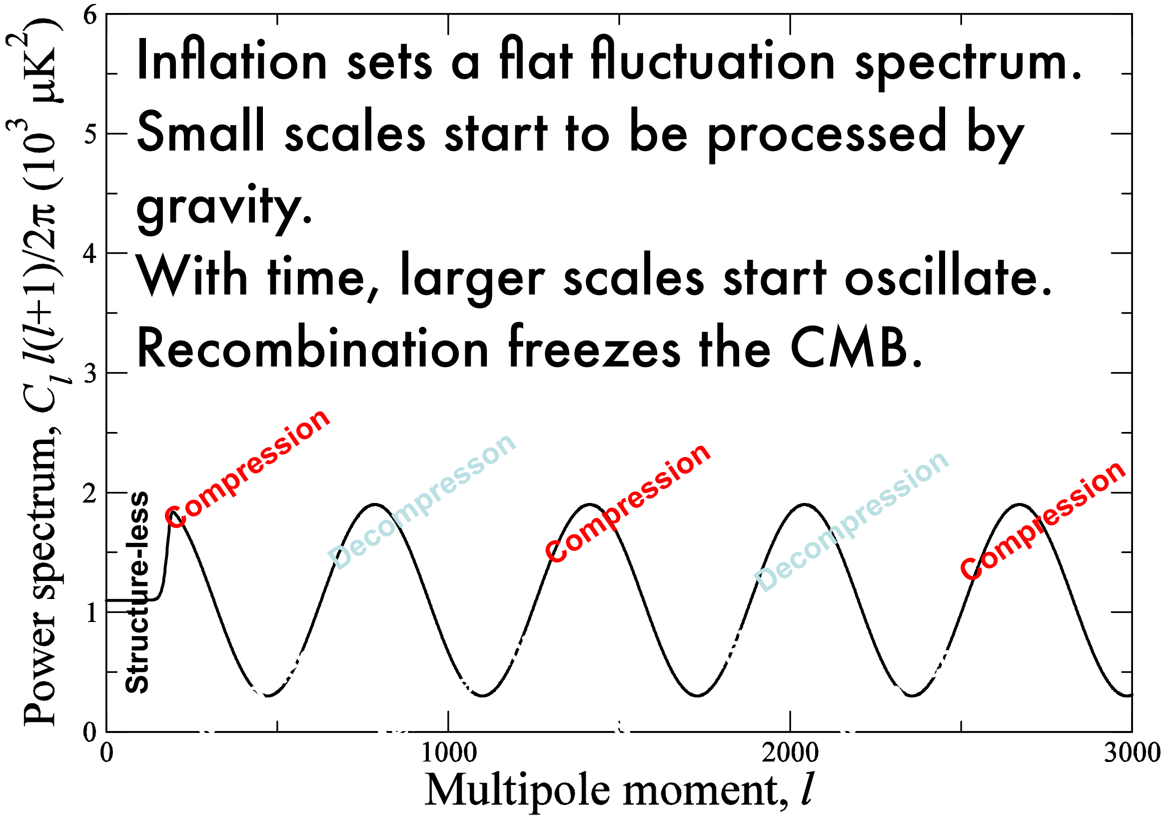


If the horizon (small after inflation) is much smaller that the wavelength of the oscillation, it cannot be detected.

While the horizon grows, more and more oscillation modes enter our "field of view".

Physics of the TT spectrum

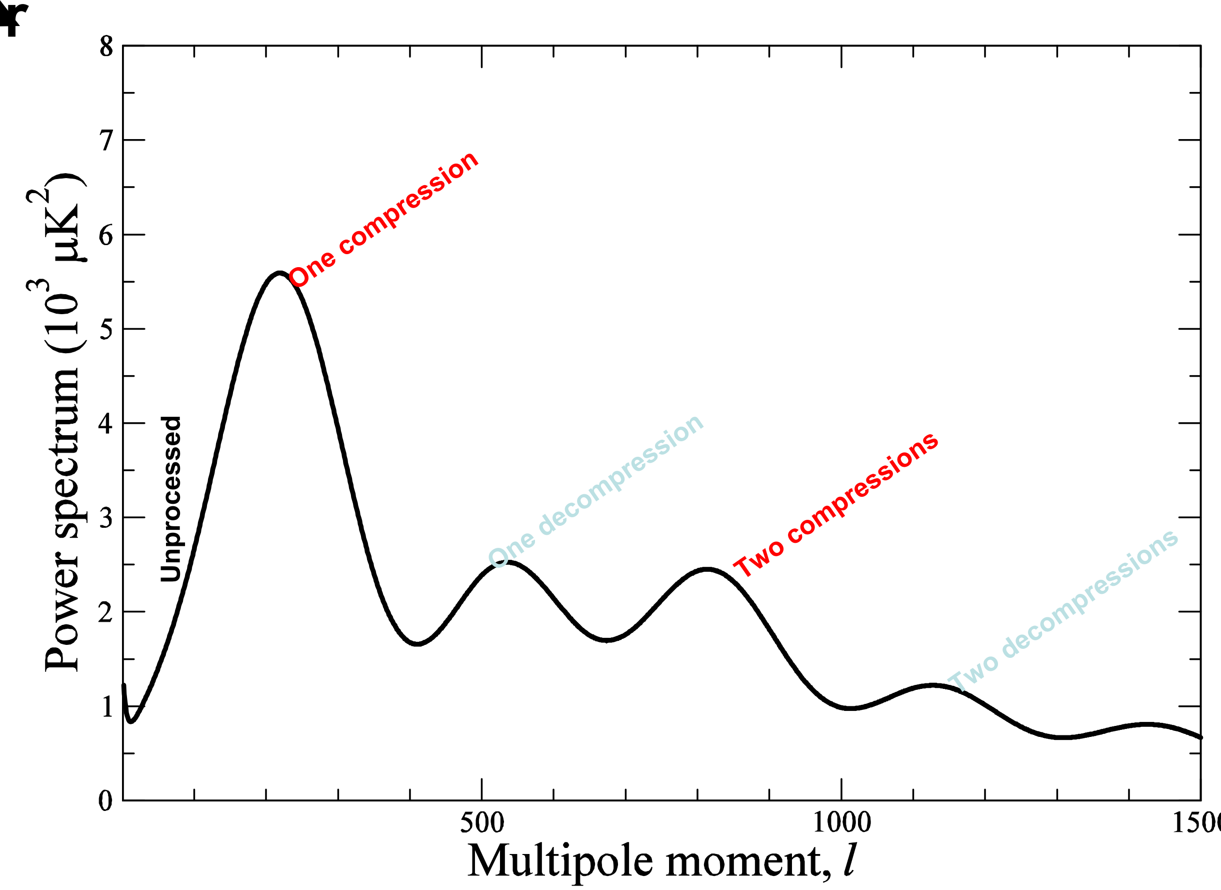
Inflation sets a flat fluctuation spectrum.
Small scales start to be processed by gravity.
With time, larger scales start oscillate.
Recombination freezes the CMB.



What we actually observe is a bit different. This has to do (besides the Silk damping at very small angular scales due to photon diffusion after recombination) with the different amounts of baryons and photons in the plasma.

angular

Remember the spring-mass model.
More baryons —> compression modes are stronger than decompression modes.
Therefore: odd peaks generally larger than even peaks.
<u>The odd-even peak ratio is connected to the baryon/photon ratio in the Universe.</u>



TT Summary

The horizon size at recombination is today at about 1deg which corresponds to and angular scale of l~200. At large scales l<200, gravity/pressure has a weaker effect.

For very small l, like l<50, we can have a picture of the fluctuations generated by inflation.

The predictions from inflation are the following:

1) The fluctuations are Gaussian

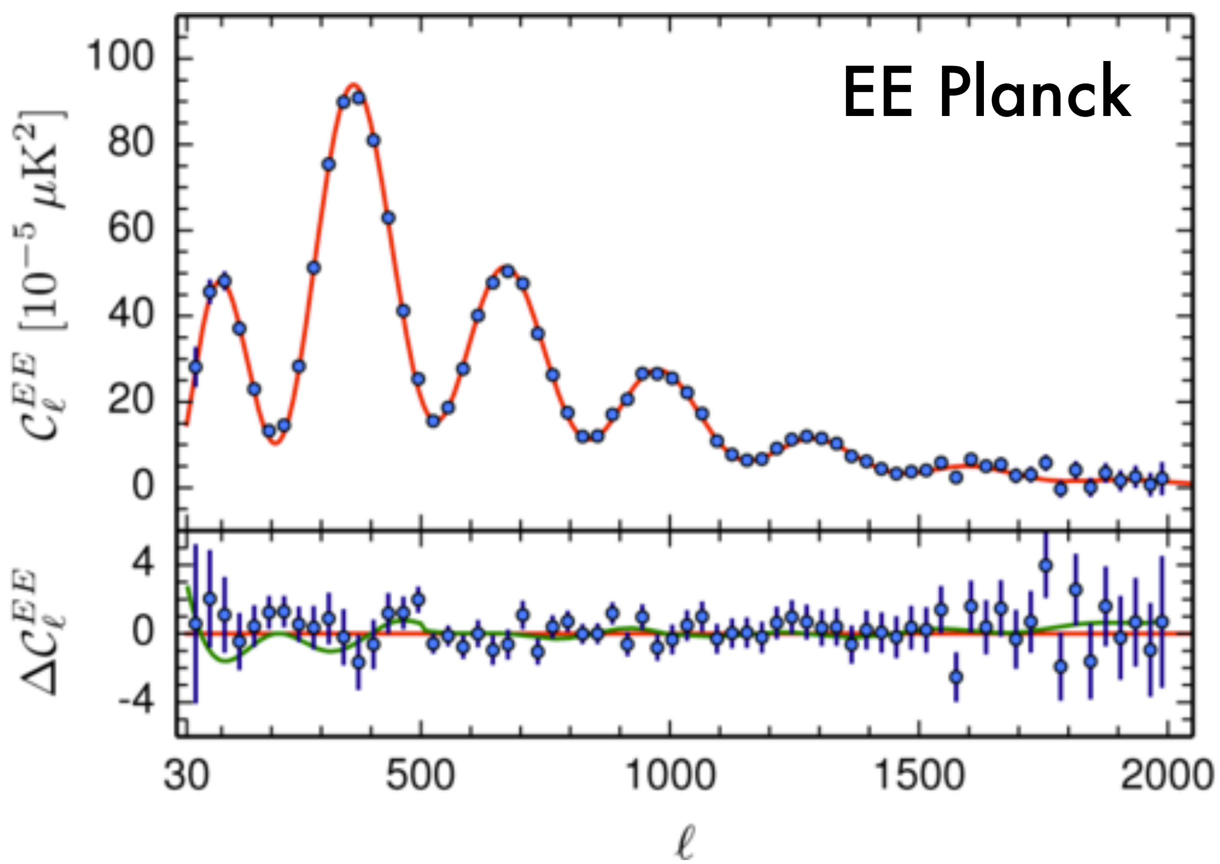
2) The fluctuation spectrum is scale invariant: $P(k) \propto k^n \quad n = 1$

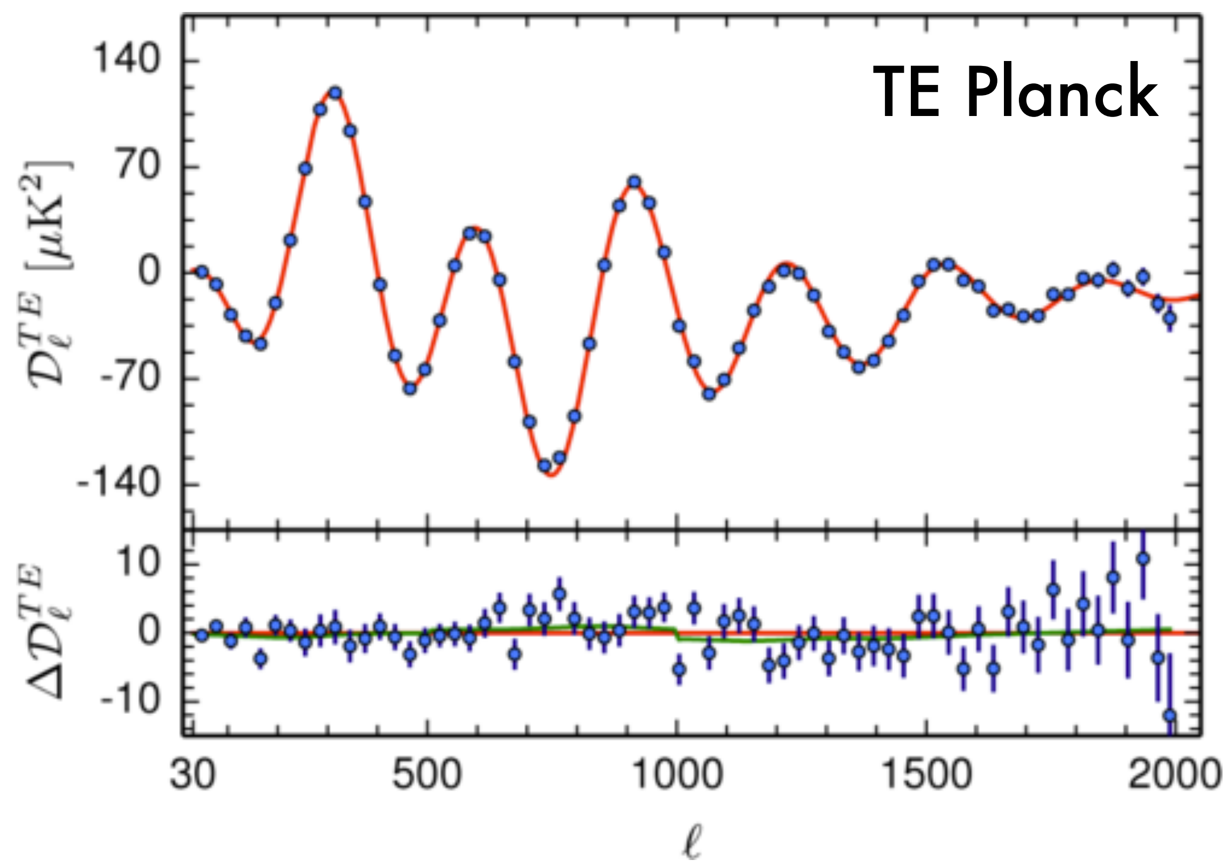
The fluctuations are equally probable on all scales

$$C_l = A \left(\frac{l}{l_0} \right)^{n_s - 1}$$

Fitting this to l<50, we can estimate n_s and A (tilt parameter and amplitude).

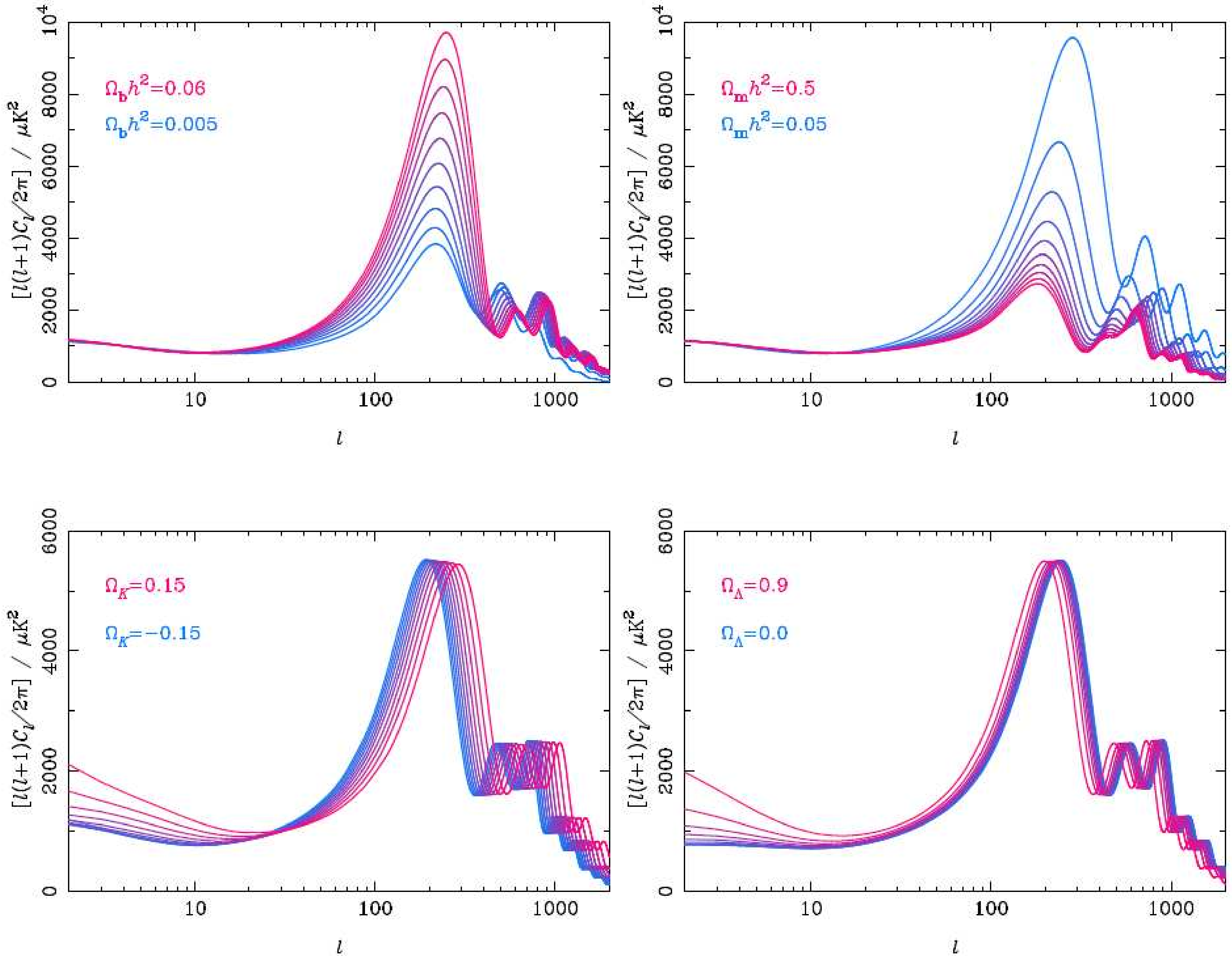
EE and TE Angular Power Spectra





EE and ET polarization spectra can provide information on the reionization era, when hydrogen atoms got ionized again by the activity of the first stars.
The presence of free electrons Thomson re-scattered the CMB.
EE/ET act also as cross-check for TT and it is sensitive to non-standard perturbations like the isocurvature ones (standard perturbations are adiabatic).

Dependence from Cosm. Parameters



https://chrisnorth.github.io/planckapps/Simulator/

Credit: Anthony Challinor

BB Correlation Spectrum

Scalar and tensor perturbations were created during inflation.
The scalar perturbations ultimately lead to structure formation.
Tensor perturbations were created by primordial gravitational radiation resulted from strong variable gravitational fields.

According to inflation, these fields were created by an amplification mechanism called "parametric amplification" which transformed the initial vacuum quantum fluctuations in multi-particle states (the waves).

The measurement of the BB spectrum is considered one of the most important goals of modern experimental cosmology, since it contains relevant information about inflation.

BB correlations are also produced by other effects like gravitational lensing, but these have nothing to do with early-Universe physics.

Data usually set limits on the ratio r=scalar/tensor perturbations amplitude which is generically ~<0.1. <u>r is connected to the energy scale of inflation.</u>
The detection of BB modes is quite a challenge.