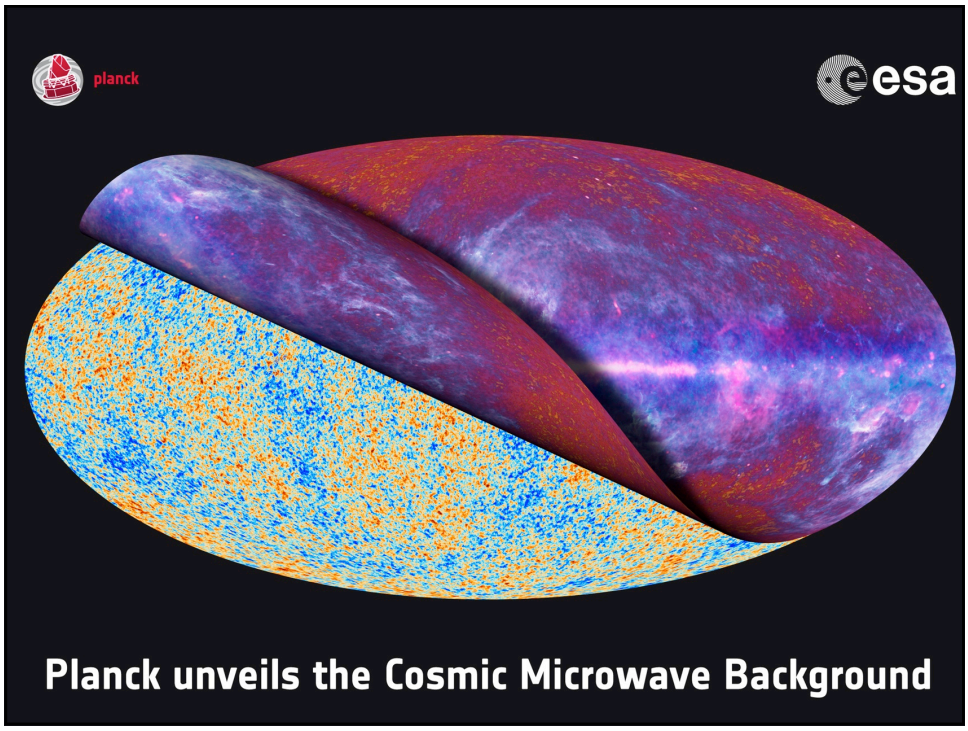


planck esa

Lecture 1: Cosmology and the Cosmic Microwave Background

J. Tauber
Planck Project Scientist
European Space Agency

Cosmology

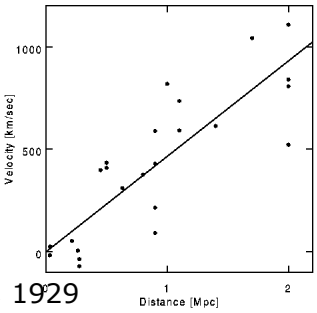
- Describes our Universe at large scales
- The current model is based on
  - Observations
  - The general theory of relativity
  - Fundamental high energy theories
  - The inflationary hypothesis
- The model depends only on a small number of parameters

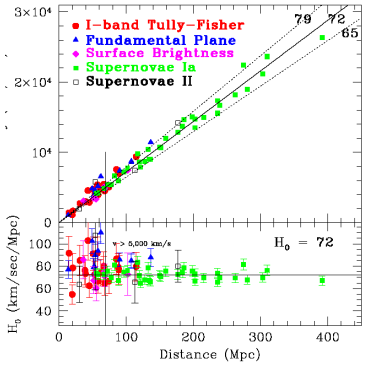
Observational pillars

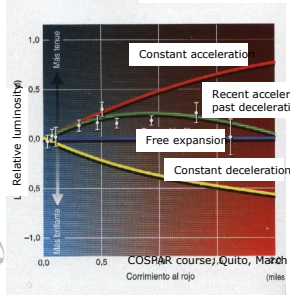
- The expansion of the Universe
- The abundances of light elements
- The structure and dynamics of luminous matter
- The age of the Universe
- The Cosmic Microwave Background

The expansion of the Universe

Edwin Hubble, 1929







The observation of distant Supernovas indicates that the expansion of the Universe is accelerating.
The origin of acceleration is referred to as Dark Energy.

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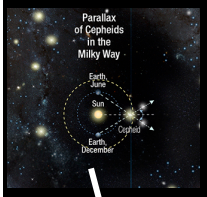
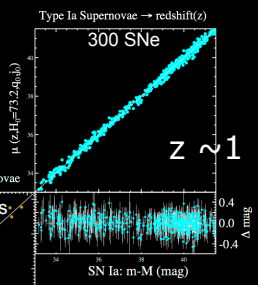
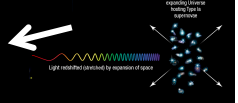
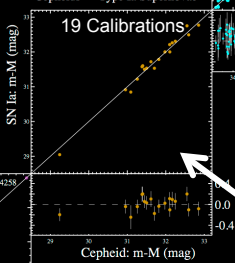
The local measurement of H_0

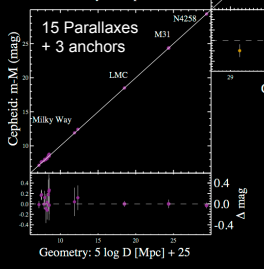


Riess 2016









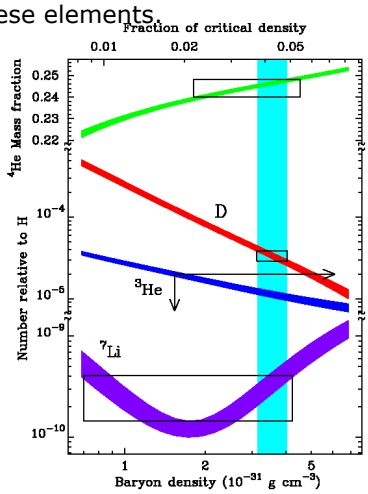
H_0=73.24 +/- 1.74, Km s^{-1} Mpc^{-1}

2.4% total uncertainty

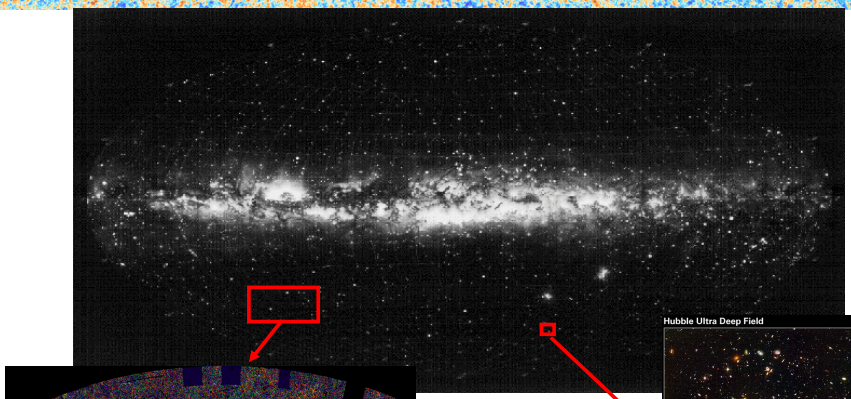
The abundance of light elements

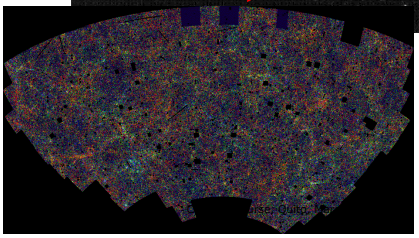
The production of heavy elements was initially thought to take place in stars. Abundance measurements (He, D) indicated that this could not be the case. Gamow showed that a very hot and dense phase of the Universe was needed to produce these elements.

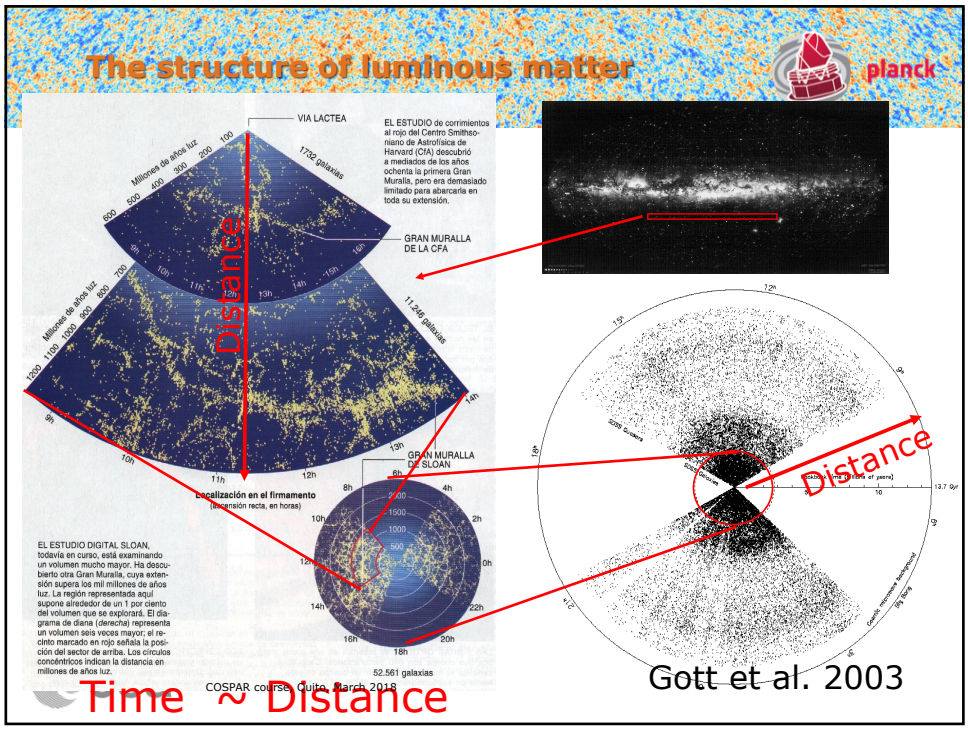
George Gamow
Primordial nucleosynthesis

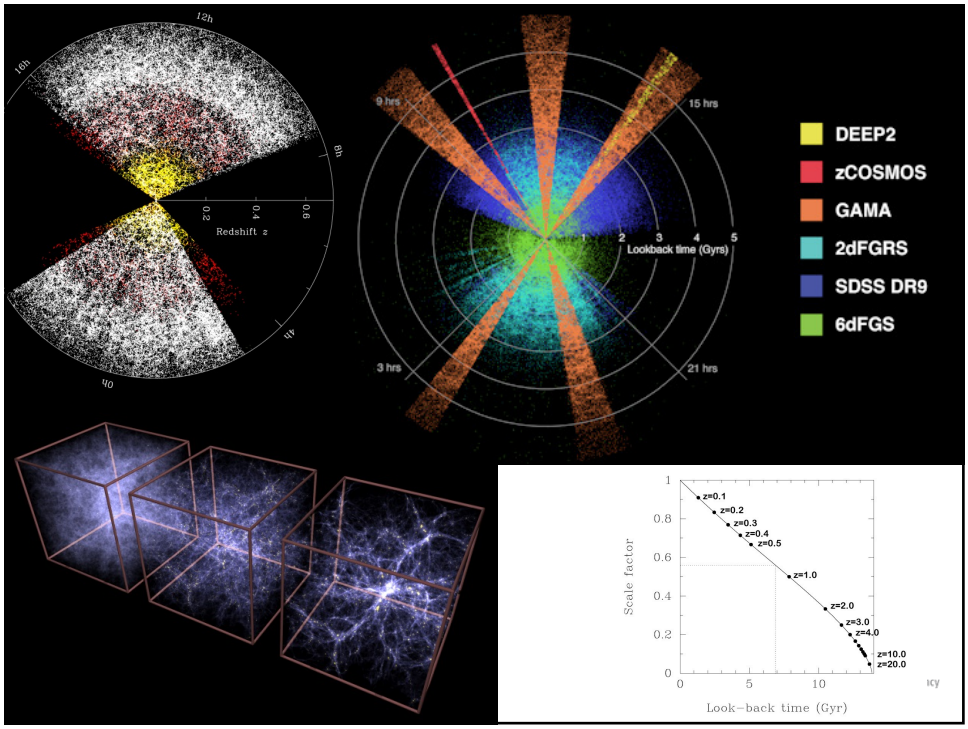


The structure of luminous matter

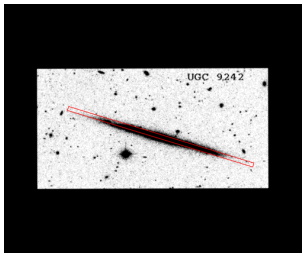


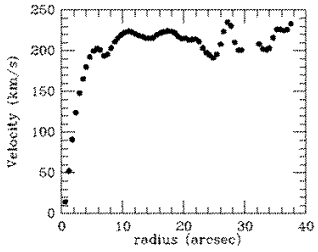



The structure of luminous matter
planck
VIA LACTEA
EL ESTUDIO de corrimientos al rojo del Centro Smithsoniano de Astrofísica de Harvard (CfA) descubrió a mediados de los años ochenta la primera Gran Muralla, pero era demasiado limitado para abarcarla en toda su extensión.
1732 galaxias
GRAN MURALLA DE LA CFA
Distance
11.246 galaxias
GRAN MURALLA DE SLOAN
localización en el firmamento
(ascensión recta, en horas)
EL ESTUDIO DIGITAL SLOAN, todavía en curso, está examinando un volumen mucho mayor. Ha descubierto otra Gran Muralla, cuya extensión supera los mil millones de años luz. La región representada aquí supone alrededor de un 1 por ciento del volumen que se explorará. El diagrama de diana (derecha) representa un volumen seis veces mayor; el recinto marcado en rojo señala la posición del sector de arriba. Los círculos concéntricos indican la distancia en millones de años luz.
52.561 galaxias
Distance
Time ~ Distance
COSPAR course, Quito, March 2018
Gott et al. 2003


Redshift z
Lookback time (Gyrs)
9 hrs
15 hrs
3 hrs
21 hrs
DEEP2
zCOSMOS
GAMA
2dFGRS
SDSS DR9
6dFGS
Scale factor
Look-back time (Gyr)
z=0.1
z=0.2
z=0.3
z=0.4
z=0.5
z=1.0
z=2.0
z=3.0
z=4.0
z=10.0
z=20.0

Dynamics of luminous matter

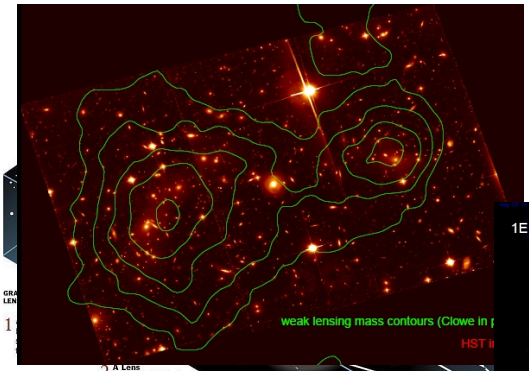


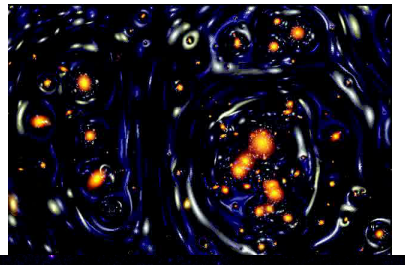


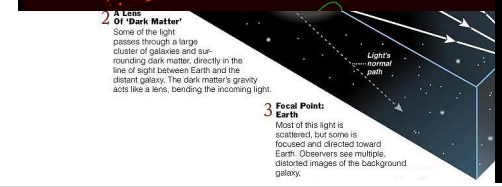
The rotation curves of spiral galaxies demonstrate that there is matter which does not emit light even though it interacts gravitationally.
This is Dark Matter.

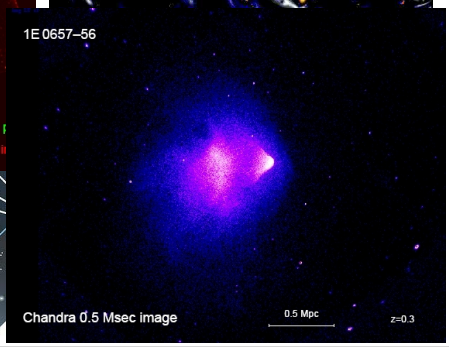
Other evidence for dark matter

1. Lensing



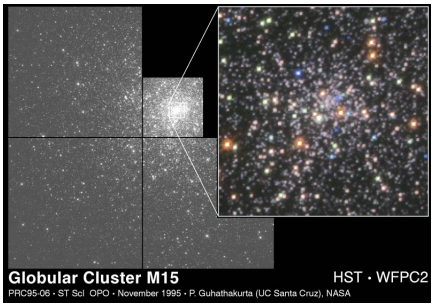






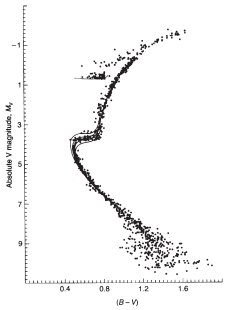
The age of the Universe

The expansion of the Universe implies an age of ~14000 million years



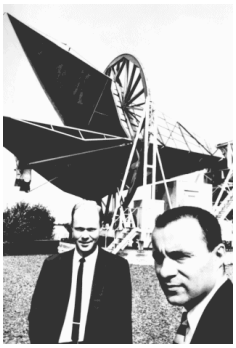
Globular clusters have an age between 12000 and 18000 million years.

The Ages of the Oldest Globular Clusters:

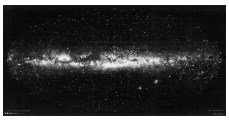


Bolte (1997) :
$T_0 = 15 \pm 2.4\ (\text{stat})^{+4}_{-1}\ (\text{syst})$ Gy
Chaboyer (1998) :
$T_0 = (11.5 \pm 1.3)$ Gy

The Cosmic Microwave Background



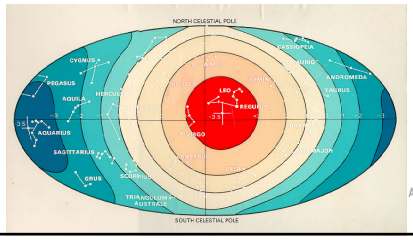
Discovery of a signal of equal intensity across the sky – cosmological origin



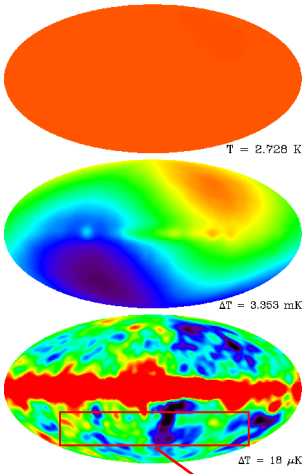
Penzias & Wilson 1965

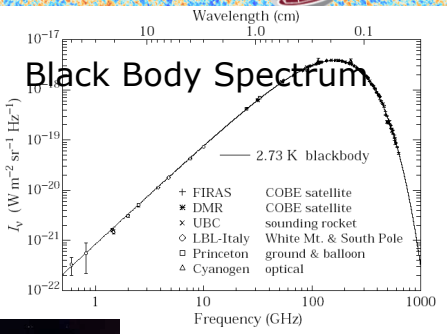
The Dipole

U2 experiment 1970's



The Cosmic Microwave Background





T ~ 2.7 K = -270.3

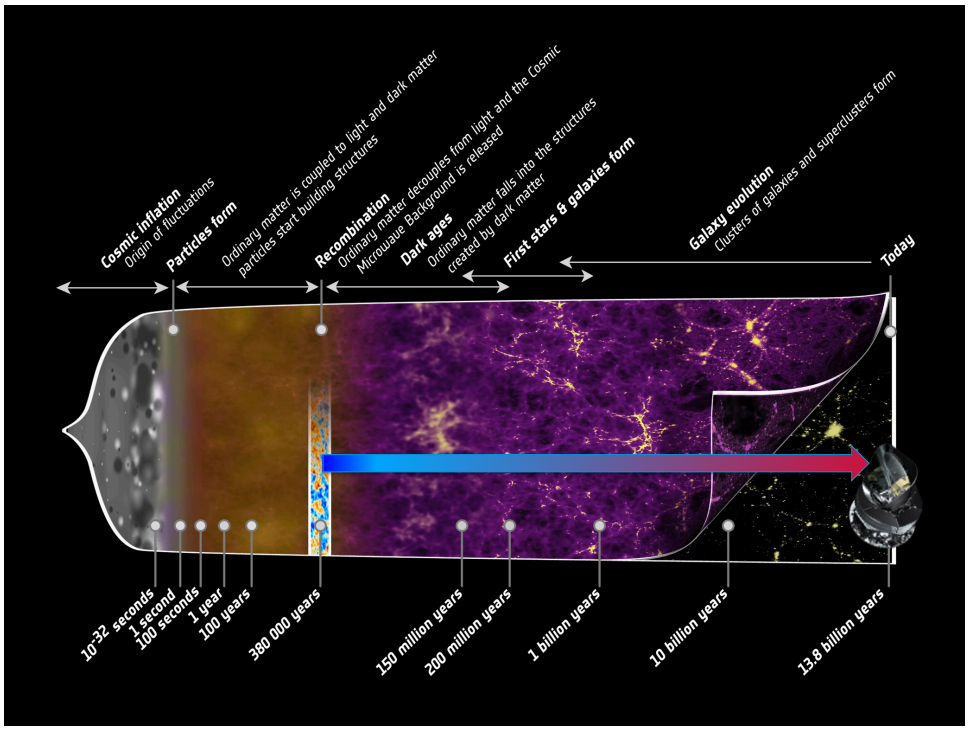
COBE

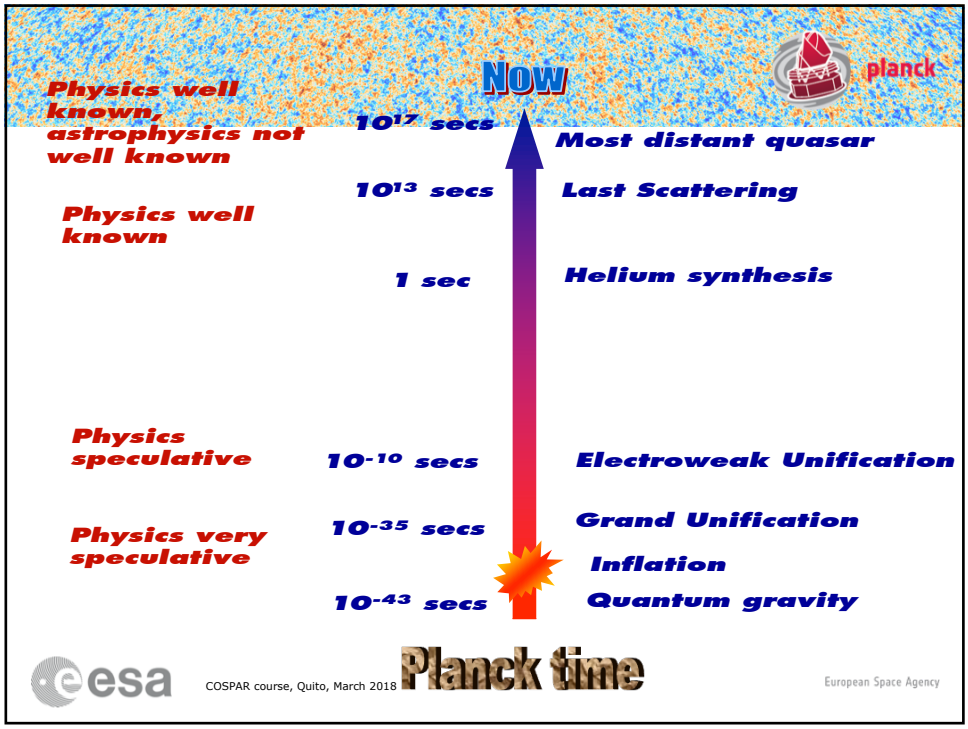
1992

These small fluctuations in the temperature of the CMB are the origin of luminous structure

Summary: the "Hot Big Bang"

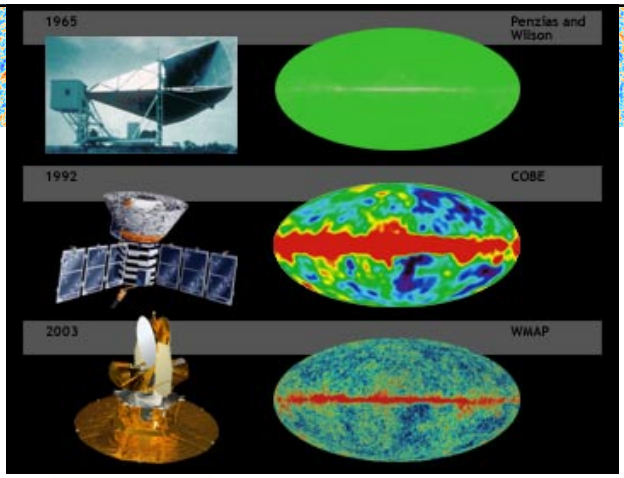
- Assumption: Causality and physics are the norm everywhere
- In its infancy the Universe was hot, dense, and compact
- Since that time the Universe is expanding, gradually cooling and becoming less dense
- Today – as before - the Universe is homogeneous and isotropic at large scales
- At small scales there is structure caused by local non-linear physics, which has evolved from a featureless plasma
- A special beginning is required: inflation

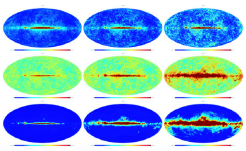

Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter is coupled to light and dark matter
particles start building structures
Recombination
Ordinary matter decouples from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter falls into the structures created by dark matter
First stars & galaxies form
Galaxy evolution
Clusters of galaxies and superclusters form
Today
10-32 seconds
1 second
100 seconds
1 year
100 years
380 000 years
150 million years
200 million years
1 billion years
10 billion years
13.8 billion years


Now
planck
Physics well known, astrophysics not well known
10^17 secs
Most distant quasar
10^13 secs
Last Scattering
Physics well known
1 sec
Helium synthesis
Physics speculative
10^-10 secs
Electroweak Unification
10^-35 secs
Grand Unification
Physics very speculative
Inflation
10^-43 secs
Quantum gravity
Planck time
esa
COSPAR course, Quito, March 2018
European Space Agency

A recipe to understand the Universe

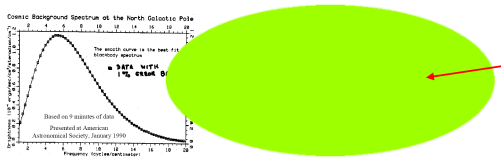
- The Universe was a rather simple object soon after the Big Bang
- The Cosmic Microwave Background gives us a picture of what it was like at that time
- The large-scale properties of our Universe can be boiled down to about a dozen numbers
- The evolution of these properties can be predicted
- Using the CMB can measure these numbers with unprecedented accuracy



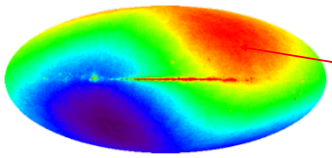


Planck: 3rd Generation CMB space experiment

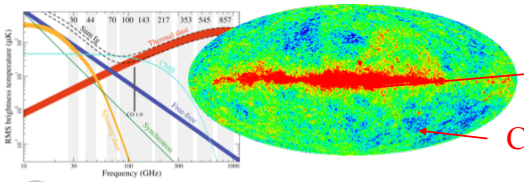
The sky as seen by a CMB experiment, e.g. Planck



CMB, T ~ 2.7 K



Dipole, ΔT ~3 mK



Milky Way, ΔT ~1 mK

CMB anisotropies, ΔT ~50 μK

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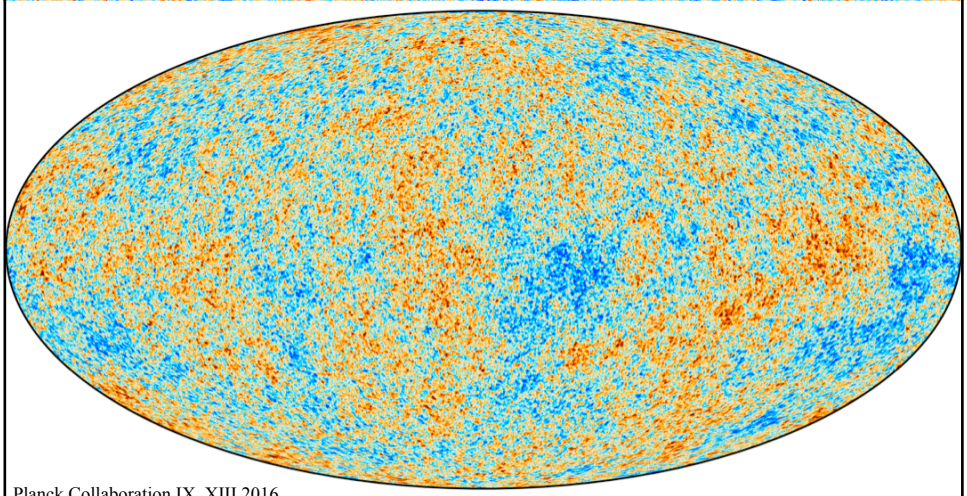
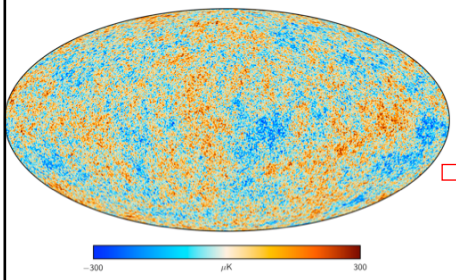
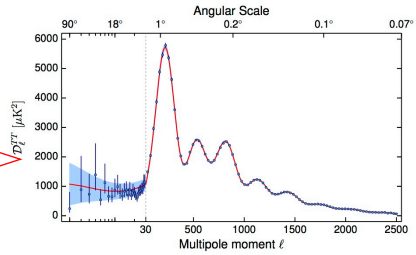
The temperature anisotropies of the Cosmic Microwave Background



Planck Collaboration IX, XIII 2016

Theoretical angular power spectrum of the CMB (ΛCDM)



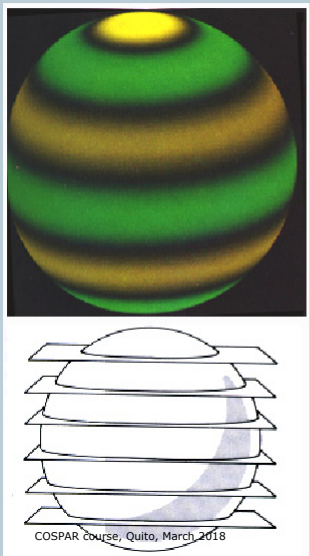


$$\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta,\varphi)$$

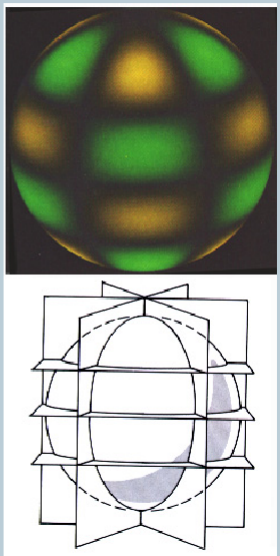
$$C_l = \langle |a_l^m|^2 \rangle$$

Spherical Harmonics

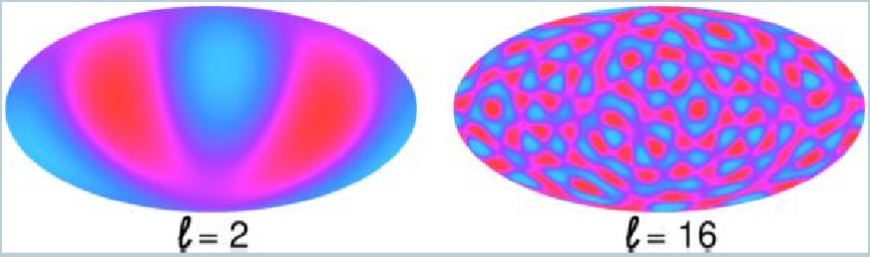
l = 6, m = 0



l = 6, m = 3



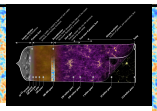
Spherical Harmonics

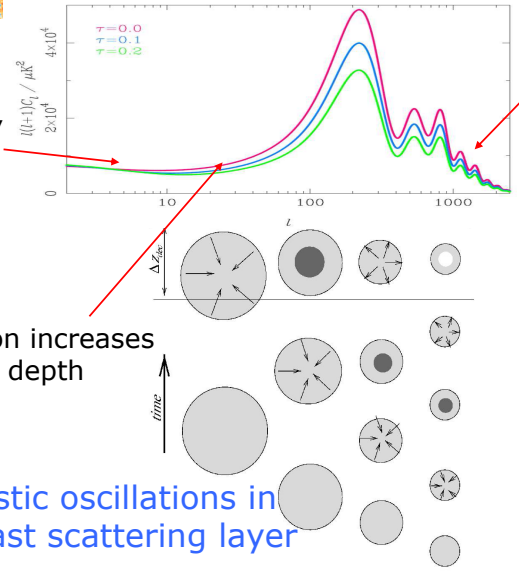


Map with C_l nonzero only for l = 2

Map with C_l nonzero only for l = 16

Physics at the time of recombination



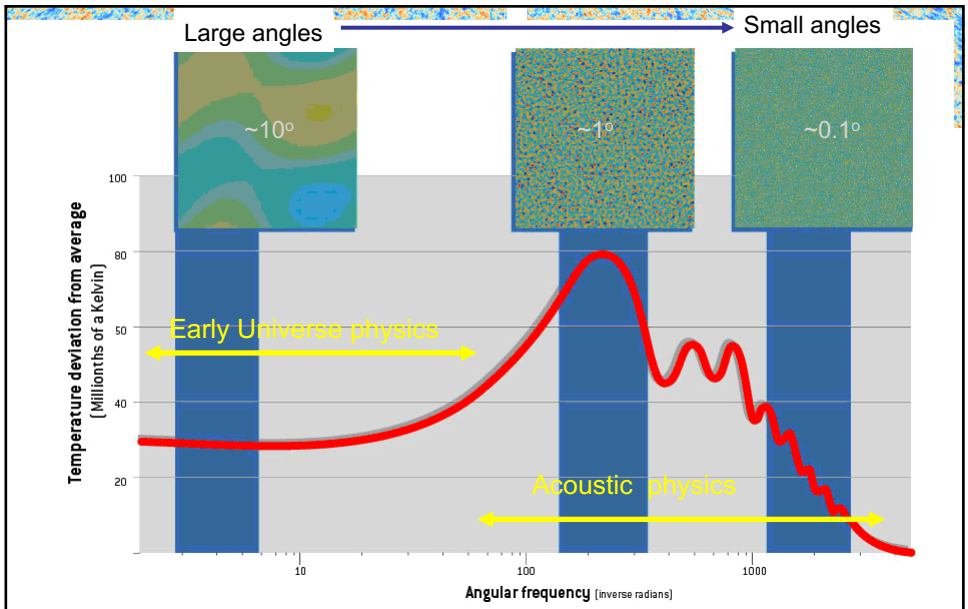


At the largest angular scales, the spectrum of primordial fluctuations is preserved

Photon diffusion damps the signal amplitudes at small angular scales

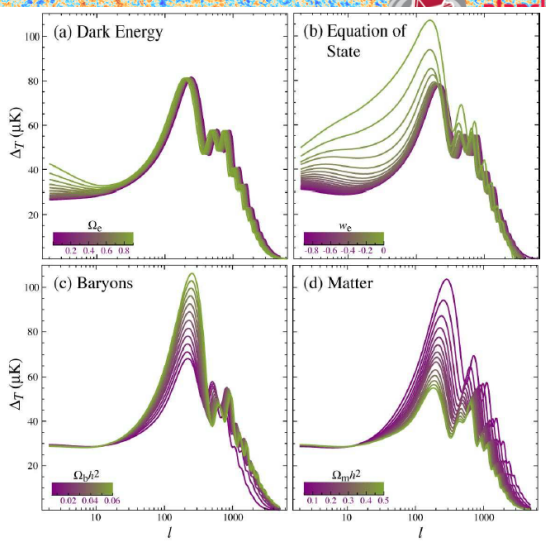
Reionisation increases the optical depth

Acoustic oscillations in the last scattering layer

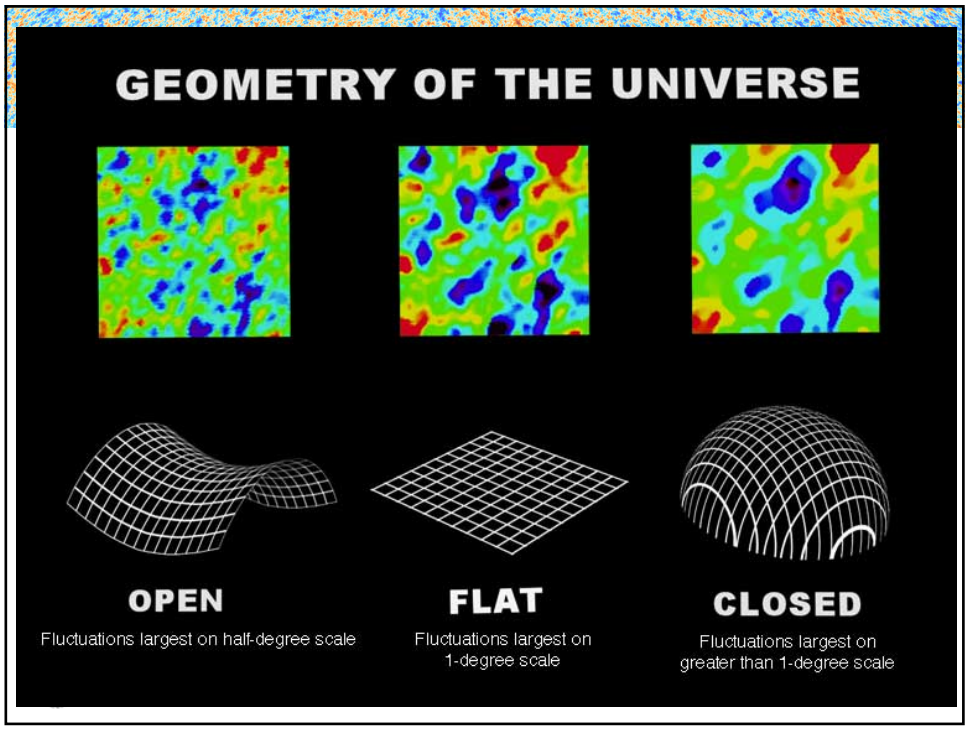


The angular power spectrum of the temperature and polarisation anisotropies can be used to extract the value of fundamental cosmological parameters

The shape of the power spectrum depends sensitively on the value of cosmological parameters



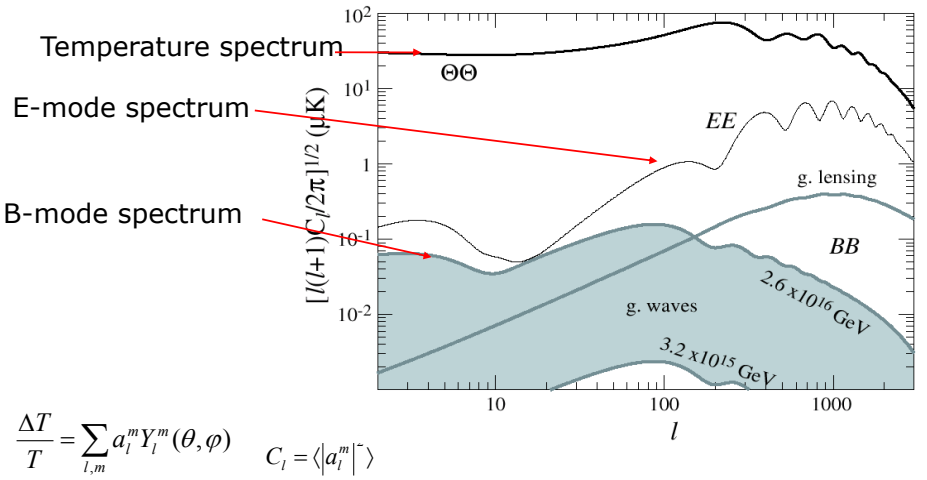
Hu 2002



Main Cosmological Parameters

- H_o Hubble constant (present expansion rate)
- q Deceleration parameter
- t_0 Age of the Universe
- Ω_o Cosmological total density parameter
- Ω_b Baryon density
- Ω_c Cold dark matter density
- Ω_χ Massive neutrino density
- Ω_Λ Dark energy density (Cosmological constant)
- w Dark energy Equation of state
- n_s Spectral index of scalar perturbations
- Q Amplitude of fluctuation spectrum
- r Ratio of Gravitational wave to density perturbations
- τ_r Residual optical depth due to reionisation
- σ_8 Mass fluctuations on 8 Mpc scale

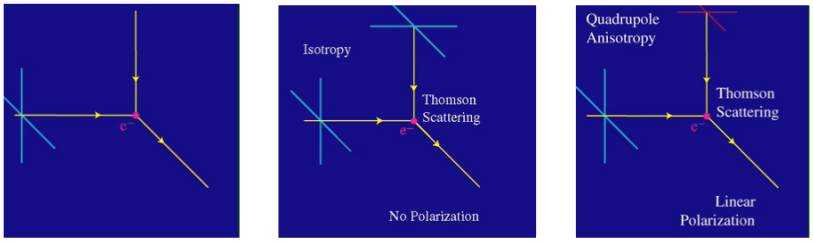
Theoretical angular power spectrum of the polarised CMB



$$\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta,\varphi) \qquad C_l = \langle |a_l^m|^2 \rangle$$

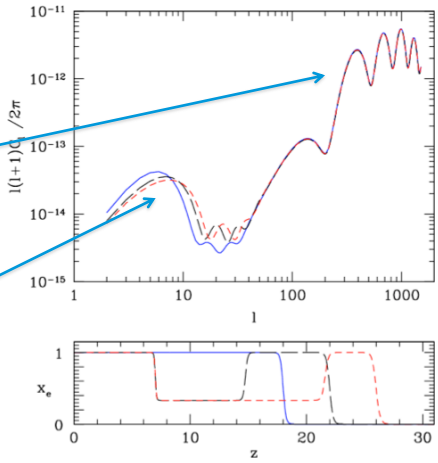
CMB polarisation at the time of recombination

1. The CMB is "released" at the epoch of last *scattering*
2. Thomson scattering polarises light
3. If radiation is homogeneously distributed, then on the average there is no polarisation
4. If there is a (quadrupolar) asymmetry in the radiation field, then some polarisation is generated
5. Quadrupole anisotropies of radiation can be generated during recombination by photons diffusing into gravity wells



CMB E-mode polarisation

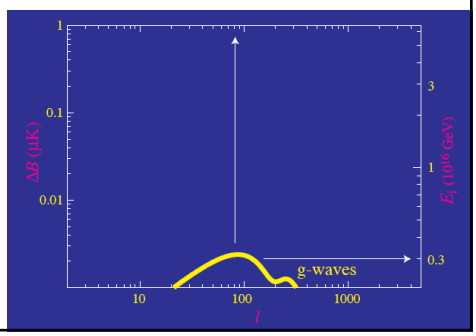
1. Scattering can only produce E-mode polarization
2. CMB E-mode polarisation by scattering occurs at two epochs:
   a. At the end of recombination
      - Small angular scales
      - Follows acoustic structures
   b. At the beginning of structure and star formation ("reionization", z>10)
      - Large angular scales
      - Typically parametrized by one parameter (τ)



Primordial gravitational waves

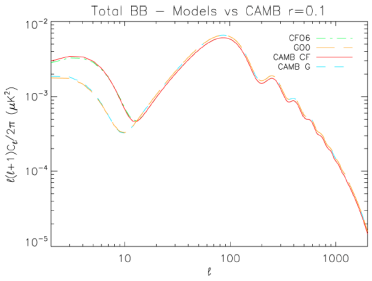
1. Inflation predicts near scale invariant spectrum of gravitational waves (pgws)
   a. Amplitude proportional to the energy scale (squared)
2. Pgws imprint tensor-mode fluctuations on matter at the end of inflation
   a. These fluctuations persist into the recombination era where they appear at <degree scales
3. Interaction with the radiation quadrupole generates **B-mode polarisation**

Note: pgws also generate signals On TT and EE !

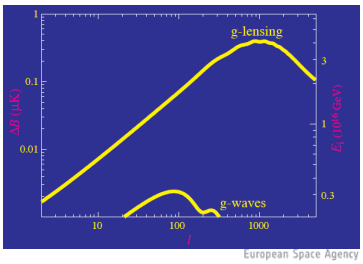


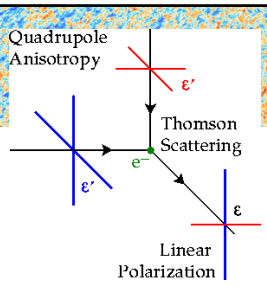
More B-modes

1. During reionization there is some re-scattering of the large-scale B-modes

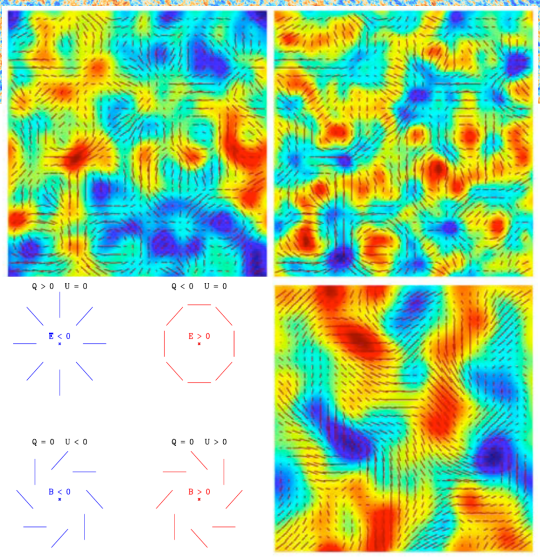


2. Gravitational lensing transforms E-modes into B-modes



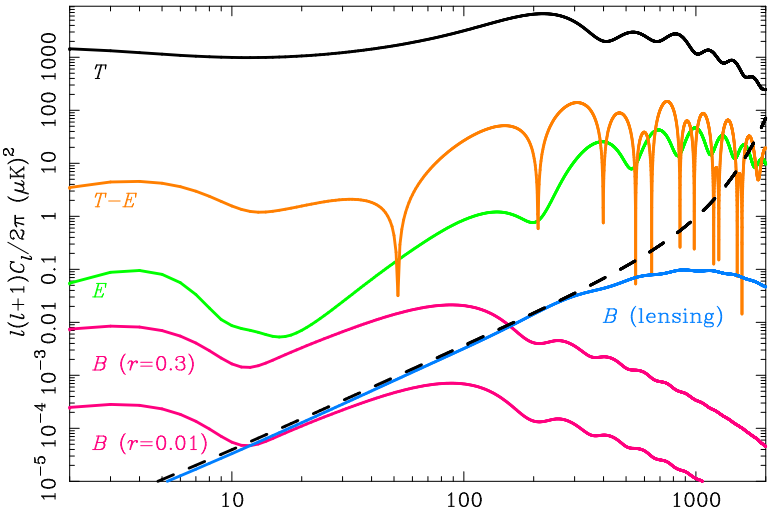


1. Polarisation is generated in the last scattering layer
2. Primordial gravitational waves can only produce B-modes
3. Reionisation also adds a polarised B-mode signal – at large angular scales
4. Weak lensing produces an additional perturbation



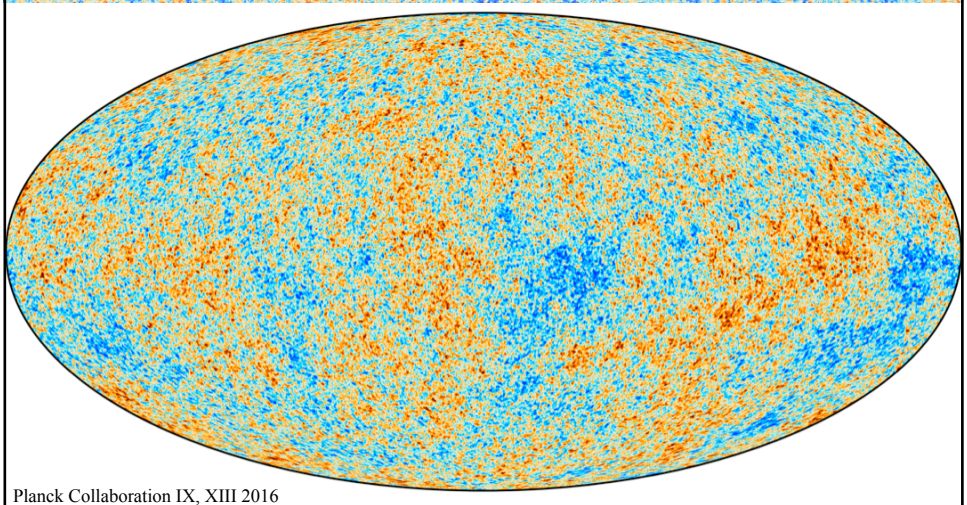
Polarisation physics summary

Summary



esa Reminder: foregrounds.

The temperature anisotropies of the Cosmic Microwave Background



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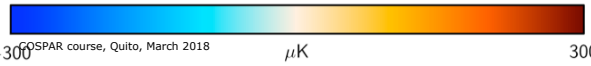
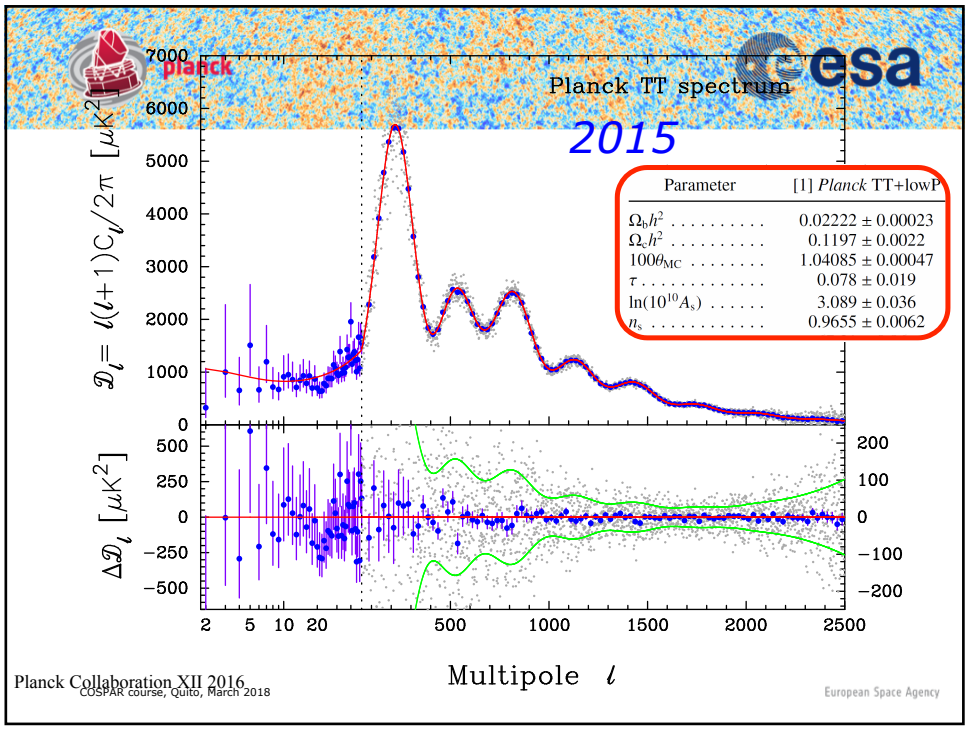
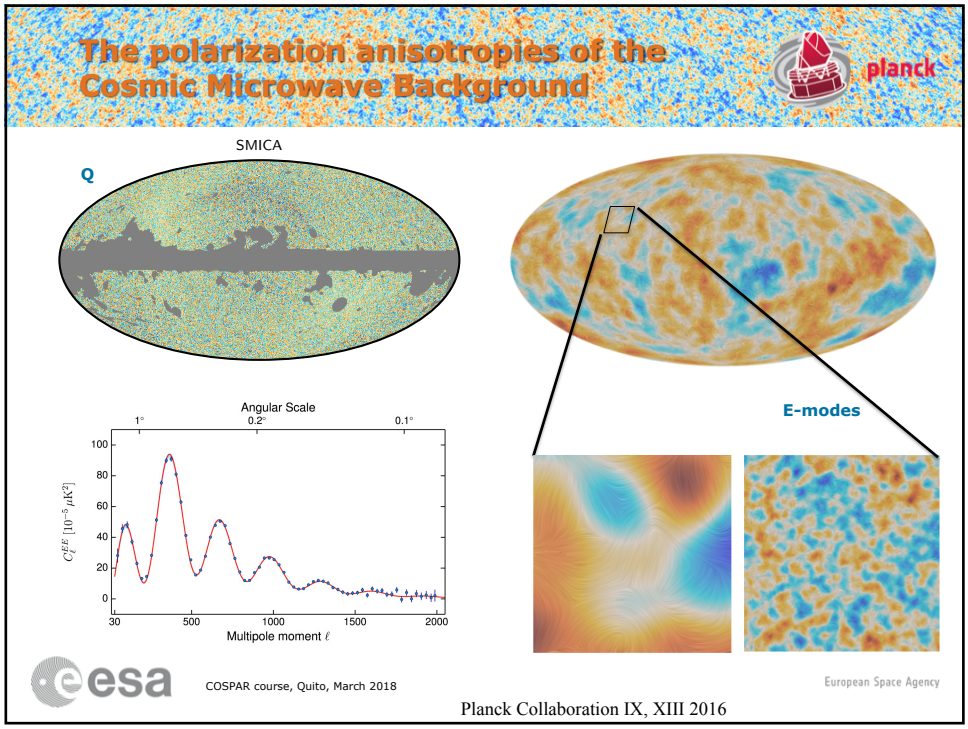


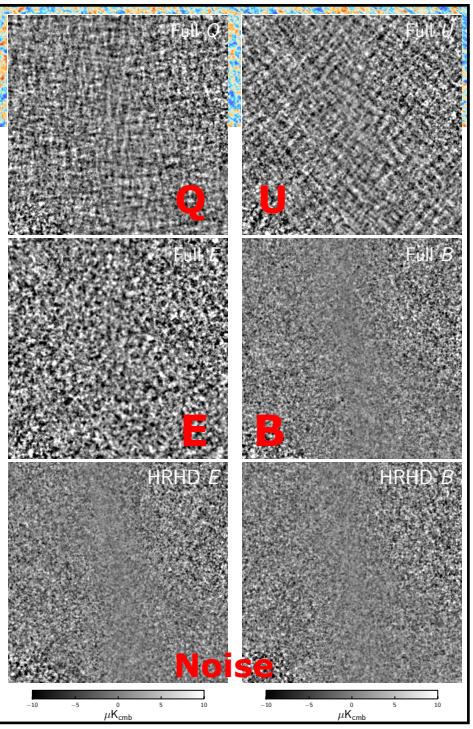

planck
esa
Planck TT spectrum
2015
Parameter [1] Planck TT+lowP
$\Omega_b h^2$ . . . . . 0.02222 ± 0.00023
$\Omega_c h^2$ . . . . . 0.1197 ± 0.0022
$100\theta_{MC}$ . . . . . 1.04085 ± 0.00047
τ . . . . . 0.078 ± 0.019
$\ln(10^{10} A_s)$ . . . . . 3.089 ± 0.036
n_s . . . . . 0.9655 ± 0.0062
$\mathcal{D}_l = l(l+1)C_l/2\pi$ [μK^2]
$\Delta\mathcal{D}_l$ [μK^2]
Multipole l
Planck Collaboration XII 2016
COSPAR course, Quito, March 2018
European Space Agency


The polarization anisotropies of the Cosmic Microwave Background
planck
SMICA
Q
E-modes
Angular Scale
Multipole moment ℓ
esa
COSPAR course, Quito, March 2018
European Space Agency
Planck Collaboration IX, XIII 2016

Polarized CMB

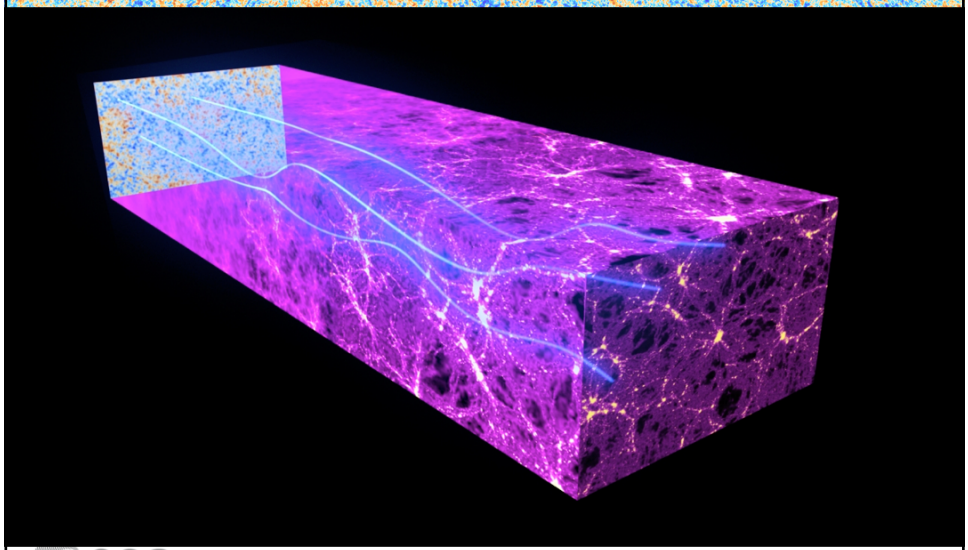
Zooming into a 20x20 deg patch (NEP) shows:

- Characteristics (+ and x) patterns for U and Q maps
- High signal-to-noise for E-modes
- Very low signal-to-noise for B-modes



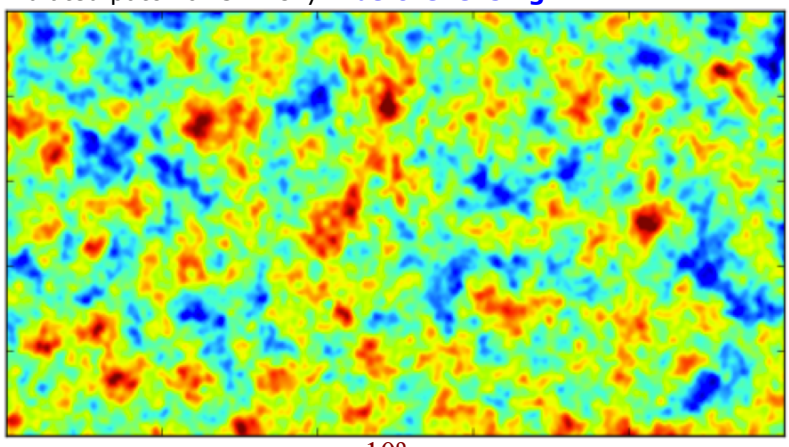
Lensing of the CMB

planck



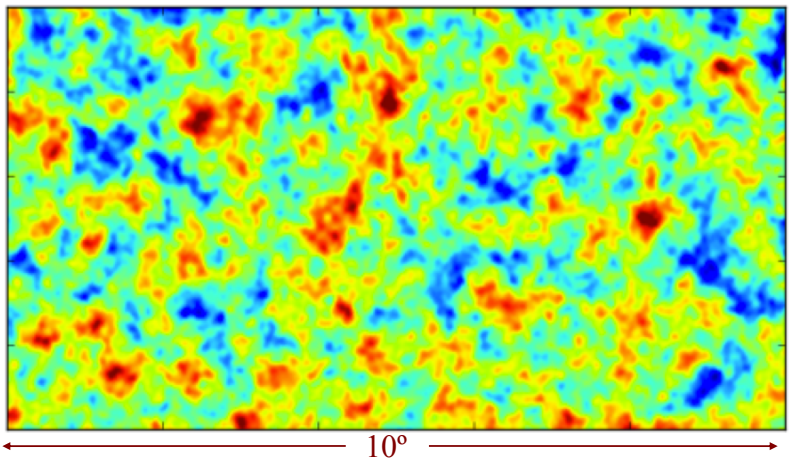
Gravitational lensing of the CMB

A simulated patch of CMB sky – **before lensing**

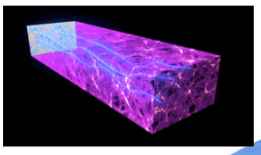


Gravitational lensing of the CMB

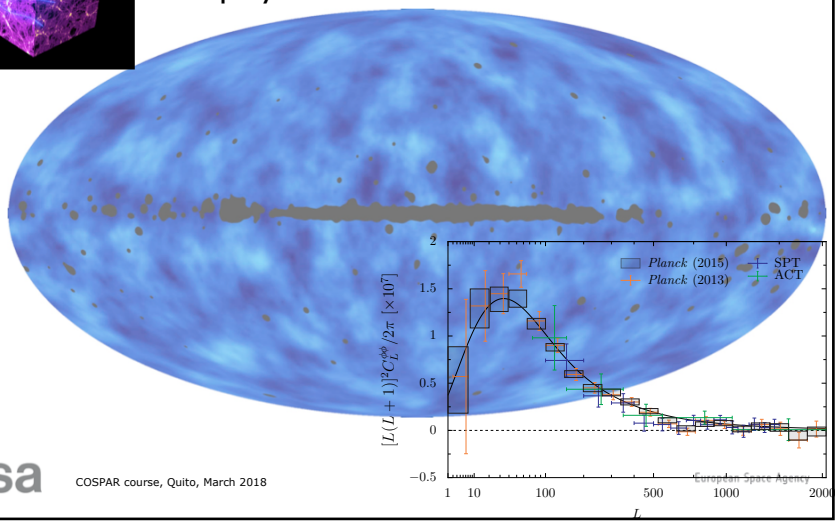
A simulated patch of CMB sky – **after lensing**



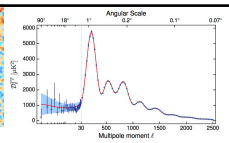
The integrated mass of the Universe



CMB lensing gives us a measure of physics at late times



The six-parameter ΛCDM model



- A six-parameter "vanilla" ΛCDM model is sufficient to explain the data
- The 2015 ΛCDM model is consistent with the 2013 ΛCDM model
- The ΛCDM 2015 model based on temperature is consistent with that based on polarization
  - Remaining systematic effects have little influence on parameters
- The full (temperature+polarization) ΛCDM model improves significantly uncertainties over the temperature-only model

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	−0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	−0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	−0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	−0.1

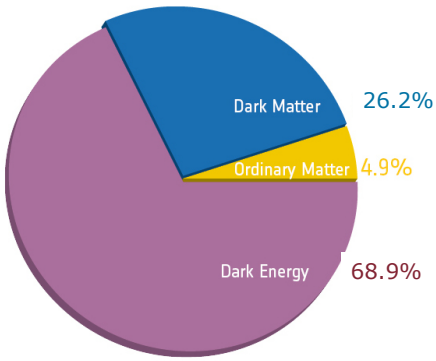
Planck Collaboration XIII 2016

The new recipe of the Universe

Uncertainties

- Dark matter to ~1.1%
- Baryonic matter to ~0.7%
- Dark energy to ~1.2%
- Age to 26 million yrs
- Hubble constant to <1%

n_s ~ 0.965 (to ~0.5%)
Age of the Universe: 13.8 Gyr
Hubble constant: 67.5 km s^{-1}/Mpc



Planck 2015 results

The 2015 CMB model
(based on Planck TT+lowP+lens) [68% rel unc]

Characteristics of the Universe

- The amount of normal matter in the Universe: 4.84% [2%]
- The amount of cold dark matter in the Universe: 25.9% [4.2%]
- The amount of dark energy in the Universe: 69.2% [1.7%]
- The age of the Universe: 13799 million years [0.3%]
- The speed of expansion of the Universe: H_0 ~67.8 km/s/Mpc [1.3%]
- The curvature of the Universe: it is flat ! (to < 0.55%)
- The epoch of reionization is later than previously thought: $z_{re} \sim 8.8^{+1.7}_{-1.4}$

Properties related to very early physics

- The spectral index of fluctuations at large scales: n_s ~0.968 [0.6%]
- Fluctuations are gaussian to high accuracy
- The amplitude of primordial gravitational waves: r < 0.11 (r < 0.09 incl. Bicep2Keck)

No evidence for new physics

- Mass of neutrinos Σm_ν < 0.67 eV, N_{eff} ~3.13 [13%]
- Abundances of light elements fully consistent with BBN
- The equation of state of dark energy w = -1.006 ±0.045 (Planck + SN)

Planck Collaboration XIII, XVII 2016

Polarisation & inflation

1. Diagnostics of inflation
   a. spectral index
   b. r =Tensor/Scalar
      = 0.1 (E_{inf}/2x10^{16} GeV)^4

   [Lyth 1984, GUT motivated inflation]

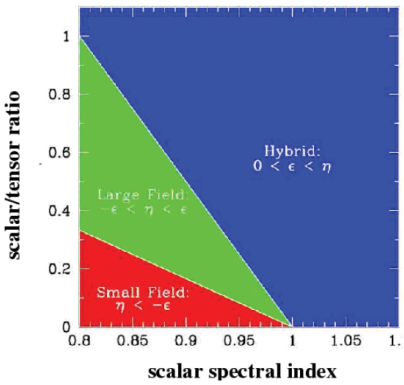
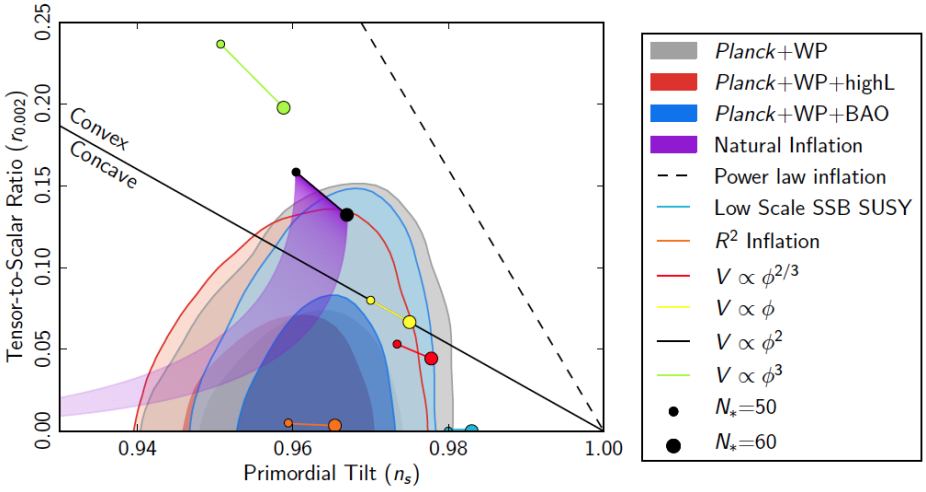


FIG 2.10.—The three classes of inflationary models discussed in the text, delineated in the plane of the tensor-to-scalar ratio r (Eq. 2.14) versus scalar spectral index n_S (adapted from Kinney, Melchiorri and Riotto, 2001)

Implications on inflation models



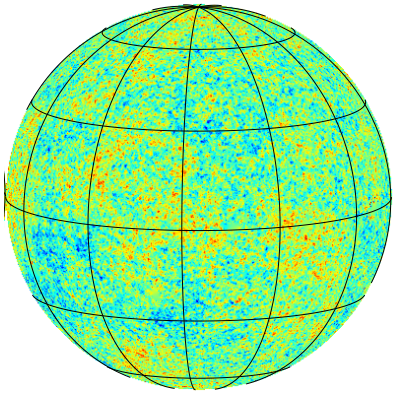
Non Gaussianity in the CMB

Inflation predicts nearly perfectly Gaussian fluctuations

$$\frac{\Delta T}{T} \approx 10^{-5}$$

$$\frac{\Delta T}{T} + f_{NL}\left(\frac{\Delta T}{T}\right)^2$$

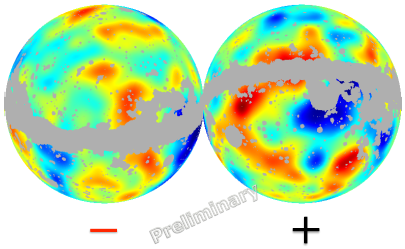
$$\left(\frac{\Delta T}{T}\right)^2 \approx 10^{-10}$$



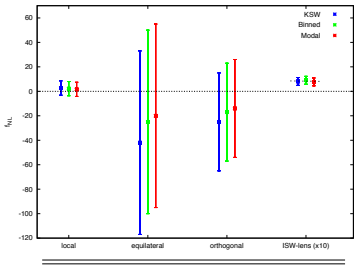
Non-gaussianity and other anomalies

1. No real signs yet of primordial non-gaussianities
   a. Consistency with passive evolution of adiabatic, gaussian, nearly-scale-invariant, primordial seeds
   b. Significant constraints on inflationary models
2. The "low-ell deficit" in the power spectrum persists
3. Large-scale anomalies seen by WMAP and P2013 persist
   a. a-posteriori bias ?

Shape and method	f_{NL}(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**



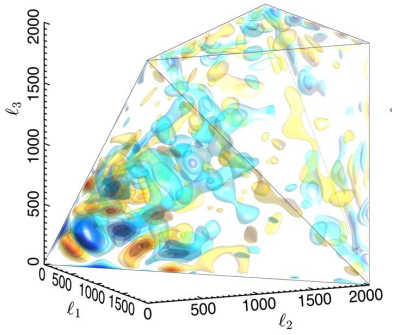
Non-gaussianity of the CMB



f_{NL}

Local	Equilateral	Orthogonal
2.7 ± 5.8	−42 ± 75	−25 ± 39
WMAP: 37±20	51±136	-245±100

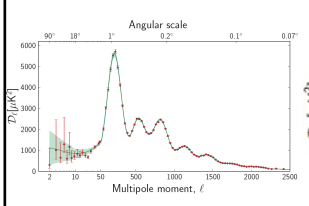
SMICA bispectrum

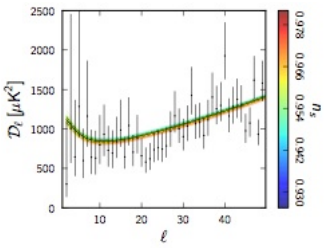


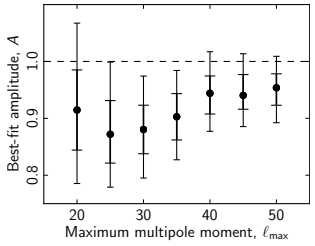
1. *No evidence for non-gaussianity (excepting anomalies at low ell)*
2. The simplest inflation models are favoured (single-field slow-roll…)
3. Multi-field models are not detected but not ruled out
4. Ekpyrotic/cyclic models are under pressure

Anomalies

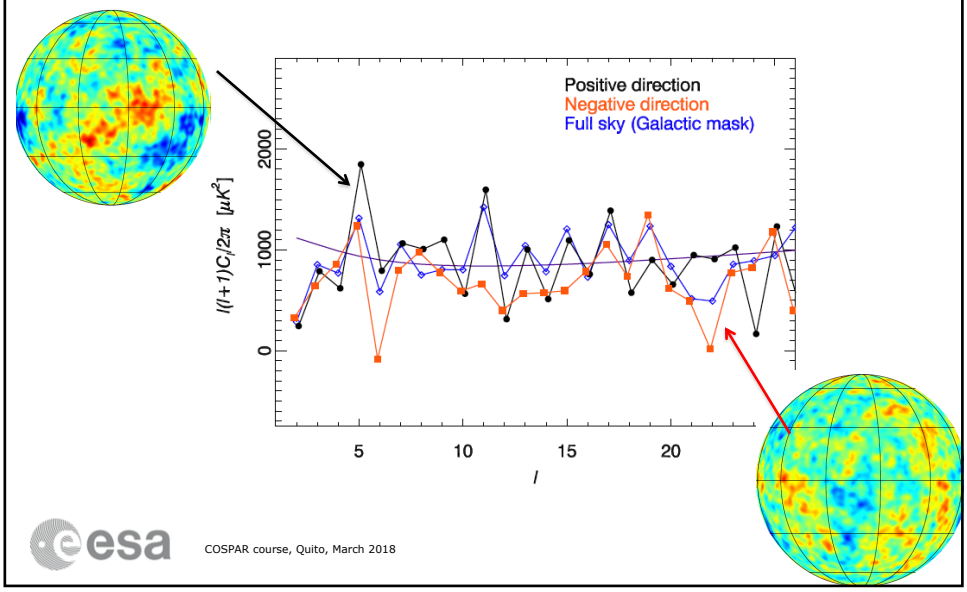
1. Most WMAP large-scale anomalies persist (individually of low significance)
   a. Low quadrupole & octopole
   b. Cold Spot
   c. Hemispheric asymmetry
   d. Alignments, phase correlations, etc
2. Low multipole power deficit







Isotropy: the hemispherical asymmetry

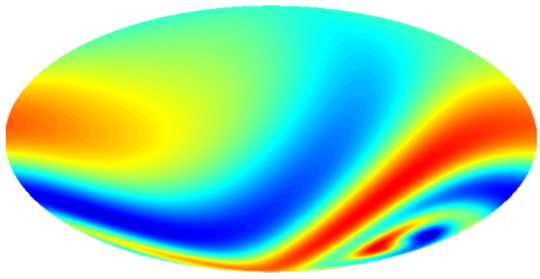


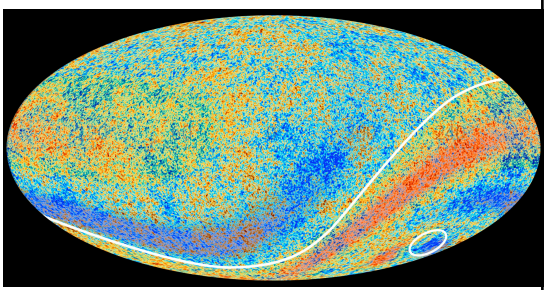
Bianchi model ?

No significant detection of multiply-connected topologies

An anisotropic (Bianchi VIIh) model fits some of the anomalies rather well, but is quite unphysical

Still searching for a model which explains the anomalous features…

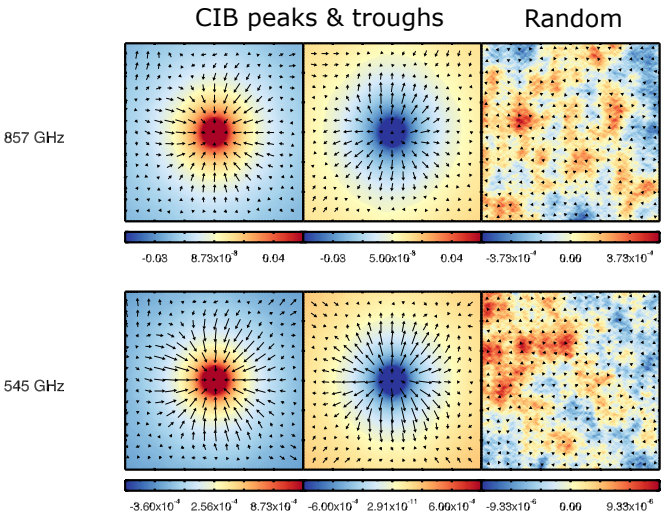




Imaging the lensing deflection

The locations of 20000 peaks and troughs in the "CIB" are stacked in the lensing map.

The deflection by lensing due to mass is directly imaged…



Summary of CMB results

1. The 6-parameter "vanilla" ΛCDM model fits the data very well – no need for additional physics
2. The estimated parameters are constrained to ~1%
3. Hubble constant lower than expected
4. Curvature very tightly constrained
5. No evidence for more than 3 types of neutrinos
6. No evidence for non-gaussianity
7. New constraints for inflationary models: single-field slow-roll inflation is preferred
8. Confirmation of WMAP anomalies; deficit of power at large angular scales
9. High-significance measurement of CMB lensing and CMB-CIB cross-correlation

Many other results !

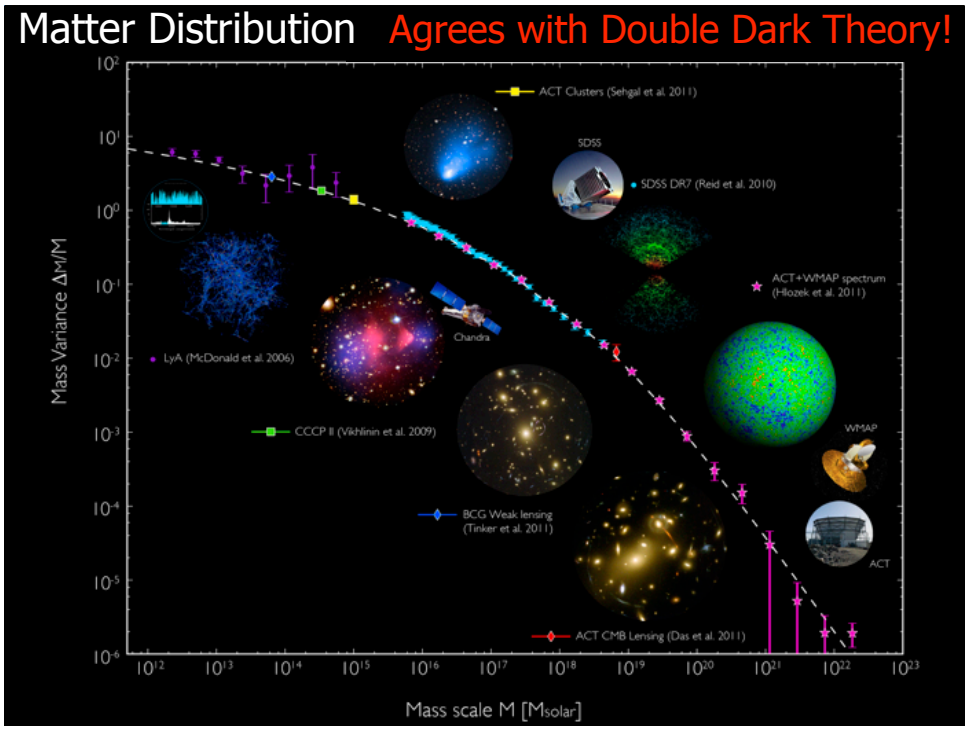
1. Constraints on strings and other defects
2. Integrated Sachs-Wolfe effect
3. Diffuse Sunyaev-Zeldovich emission
4. Detection of CMB Doppler aberration and modulation
5. Galaxy clusters
6. Extragalactic science: radio, IR galaxies
7. Galactic science: dust, CO, etc
8. Zodiacal emission
9. …

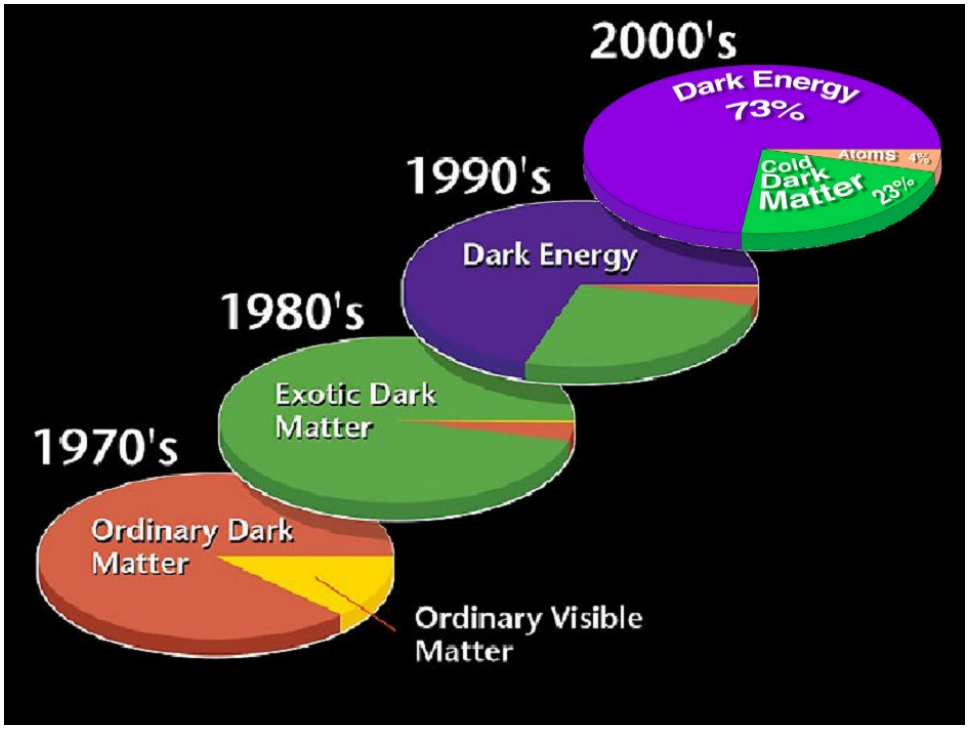
Modern cosmology

- Concordance
  - Many observational lines converge towards a single coherent picture

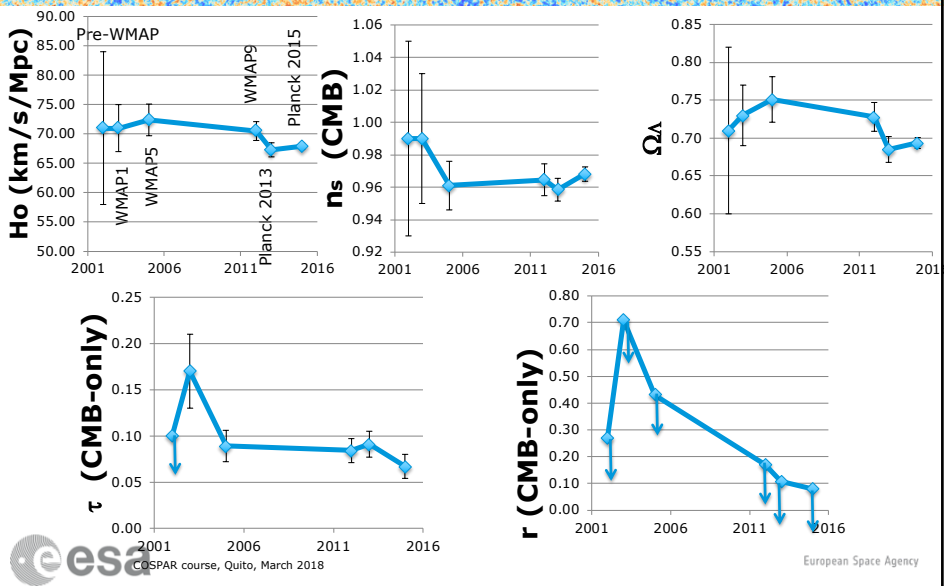
$$\Lambda\text{CDM}$$

- Precision
  - We can measure the parameters of our model with precision of order 1%


Matter Distribution
Agrees with Double Dark Theory!
ACT Clusters (Sehgal et al. 2011)
SDSS
SDSS DR7 (Reid et al. 2010)
ACT+WMAP spectrum (Hlozek et al. 2011)
Chandra
LyA (McDonald et al. 2006)
CCCP II (Vikhlinin et al. 2009)
BCG Weak lensing (Tinker et al. 2011)
WMAP
ACT
ACT CMB Lensing (Das et al. 2011)
Mass Variance Δm/M
Mass scale M [Msolar]


2000's
Dark Energy 73%
Atoms 4%
Cold Dark Matter 23%
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter

CMB-only progress in ΛCDM



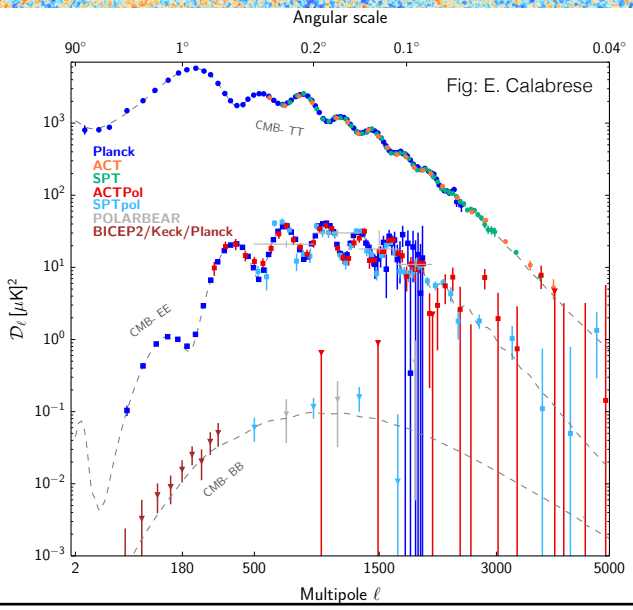
Fundamental questions are still open...

- What is the nature of dark matter ?
- What is dark energy ?
- Why do we live at a time when expansion starts to accelerate ?
- Did inflation occur ?
- What made inflation happen ?
- .....

Summary

- Planck provides a very complete view of both the near and the very distant Universe
- It will remain for many years a unique source of data to address a wide range of problems, from cosmology to astrophysics
- The Planck Legacy Archive already provides all the data that Planck has acquired
  - *Every cosmologist and astronomer will find something useful in it*
  - *USE IT !!!*
- *These are exciting times for cosmology*

CMB status 2016




Thank you
COSPAR course, Quito, March 2018