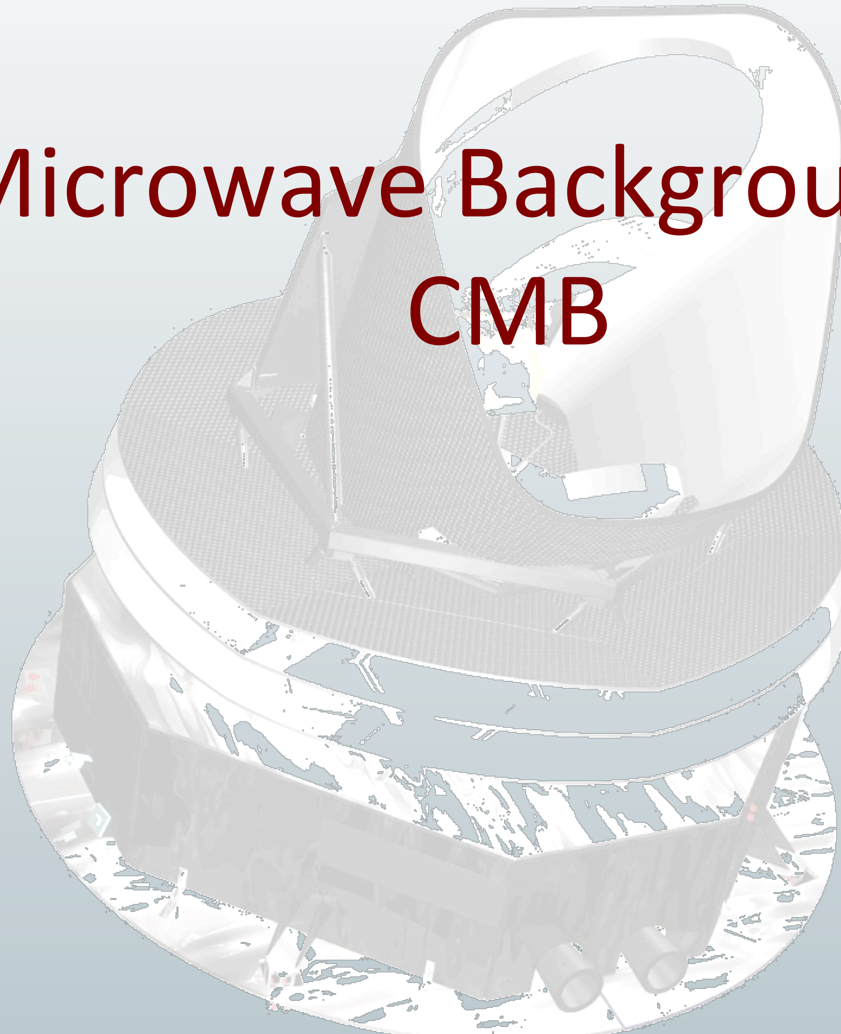
Cosmic Microwave Background Radiation
CMB



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Vth INPE Advance Course on Astrophysics, INPE, September 2013

Lecture 0 - An overview

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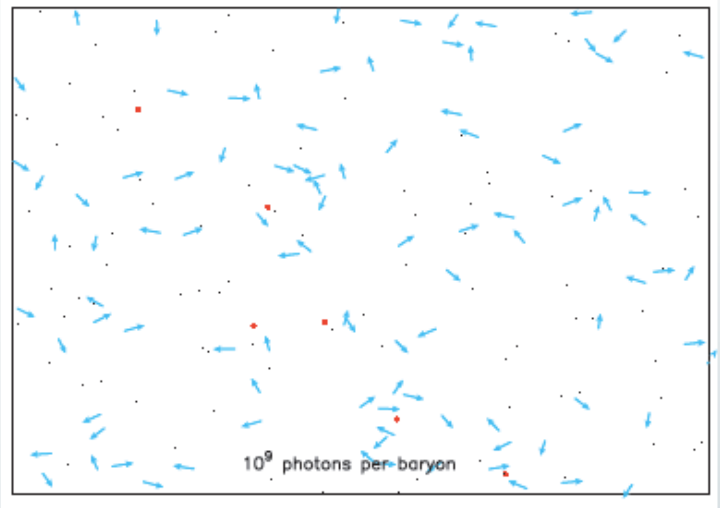
What have we learned so far

For almost 50 years the Cosmic Microwave background (CMB) has been one of most important sources of information about the Universe at large.

- Let's start by reviewing what we have learned so far:
  - The Universe used to be hot and dense - there's no credible alternative to a "big bang"
  - Very early on, it is plausible that the Universe expanded really fast for a short time - something like "inflation" happened
  - There's lots of invisible matter in the Universe - "dark matter"

What is the CMB?

- The oldest light in the Universe - emitted 370,000 years after the Big Bang



- 77% hydrogen, 23% helium, a little deuterium, and a trace of lithium, all ionized, plus “dark” matter (i.e., stuff that has no electromagnetic interactions, only gravity)
  - Mean density of baryonic (normal) matter about **$2.4x10^6$** nuclei per cubic meter

- Matter and radiation were in equilibrium **=>** “blackbody spectrum”
  - T ~ 3000 **K**
  - opaque

What is the CMB?

- Just above 3000 K, a little hotter than a candle flame.
  - No atoms. Everything is banging together so hard that electrons and nuclei can't stay together.
  - Opaque. Light can't travel far without being absorbed by an electron, which then emits more light.
  - Universe is filled with white light

- But Universe is expanding and cooling. A little bit later, a little bit cooler:
  - Hydrogen, helium, and lithium become stable (recombination)
  - Transparent at most wavelengths
  - Light can travel almost without impediment

- What would we see, 13.8 billion years later?
  - We see light coming from a shell of radius 13.8 billion light-years (LSS)
  - Because of expansion, it's highly redshifted
  - No longer a white-hot glow, but a really cold glow that our eyes can't see
  - T = 3000/1100 = 2.7K

Why is the CMB so important?
Simplicity and accessibility

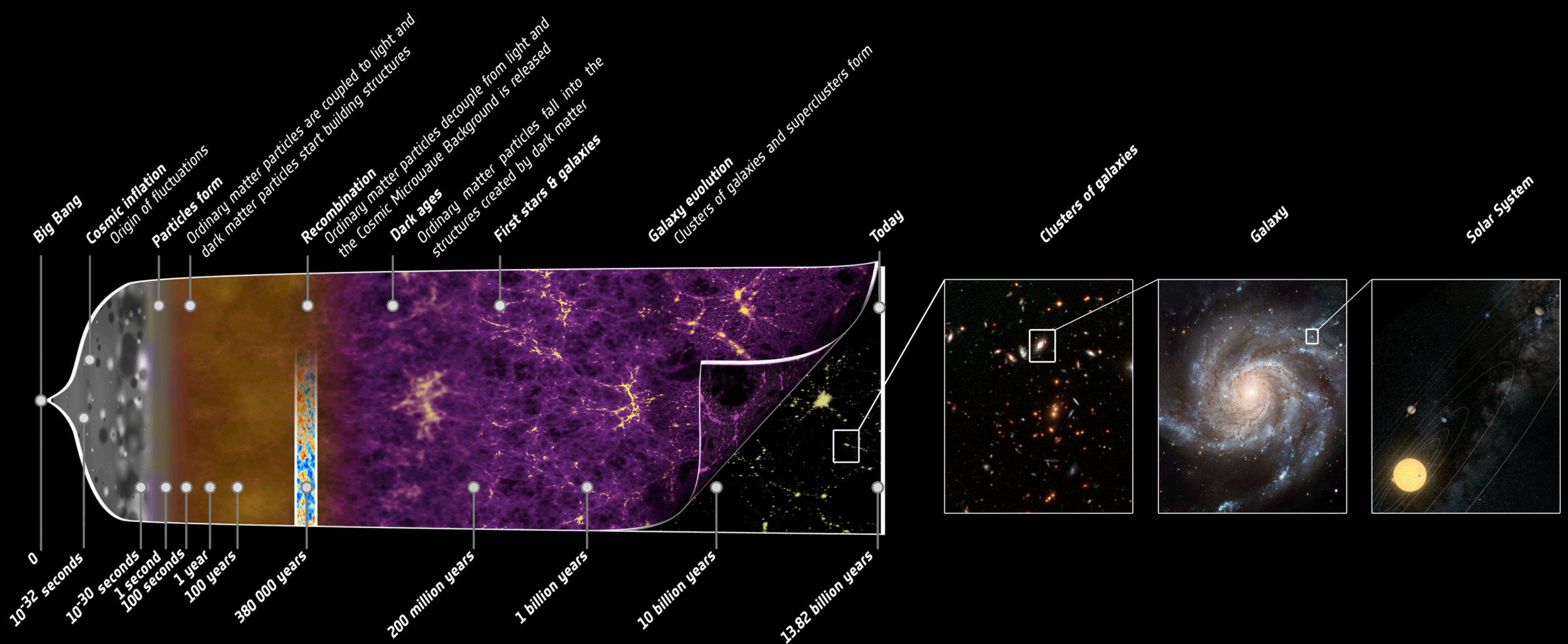
- We see directly what the Universe was like 370,000 years after the Big Bang
- The Universe then was very simple
  - Basic constituents — no chemistry
    - Remember: p+, n, e−, D+, T+, 3He++, 4He++,Li+++, plus “dark” matter. That’s it!
  - Well-understood physical conditions
    - 3000 K
    - High vacuum (2.4 x 10^6 nuclei per m^3)
    - Extremely uniform (~ 1 part in 10^5 – tiny perturbations)

=> Linear regime. “Straightforward” to calculate how matter and radiation behave as a function of many parameters that we would like to know.

- We can calculate what the CMB would look like as a function of how much mass and what type of mass there is, what the overall geometry of the Universe is, how old and how big the Universe is, and so on. Really fundamental, basic things.

We compare with what we observe, and work out all those basic things.

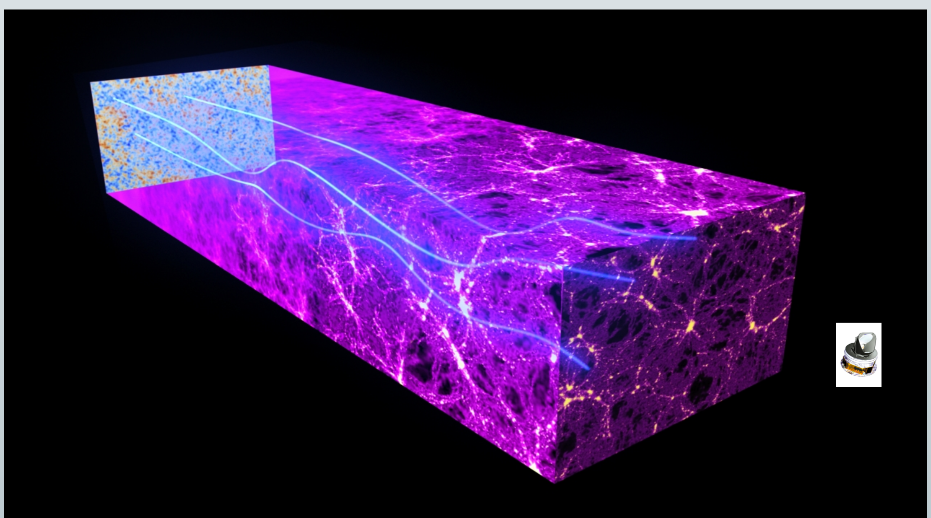
A brief history of the Universe

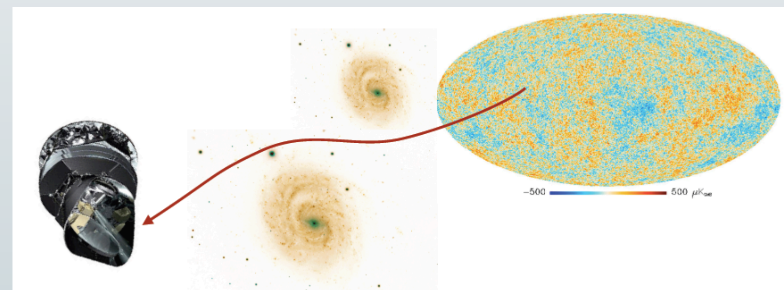


Why is the CMB so important?

- It shows us directly the simple early Universe:
  - Determined by fundamental physical processes that happened 10^{-35} s after the Big Bang
  - Starting point for the further evolution of everything

- As this light travels to us on its 13.8 billion year journey it learns about the intervening parts of the Universe

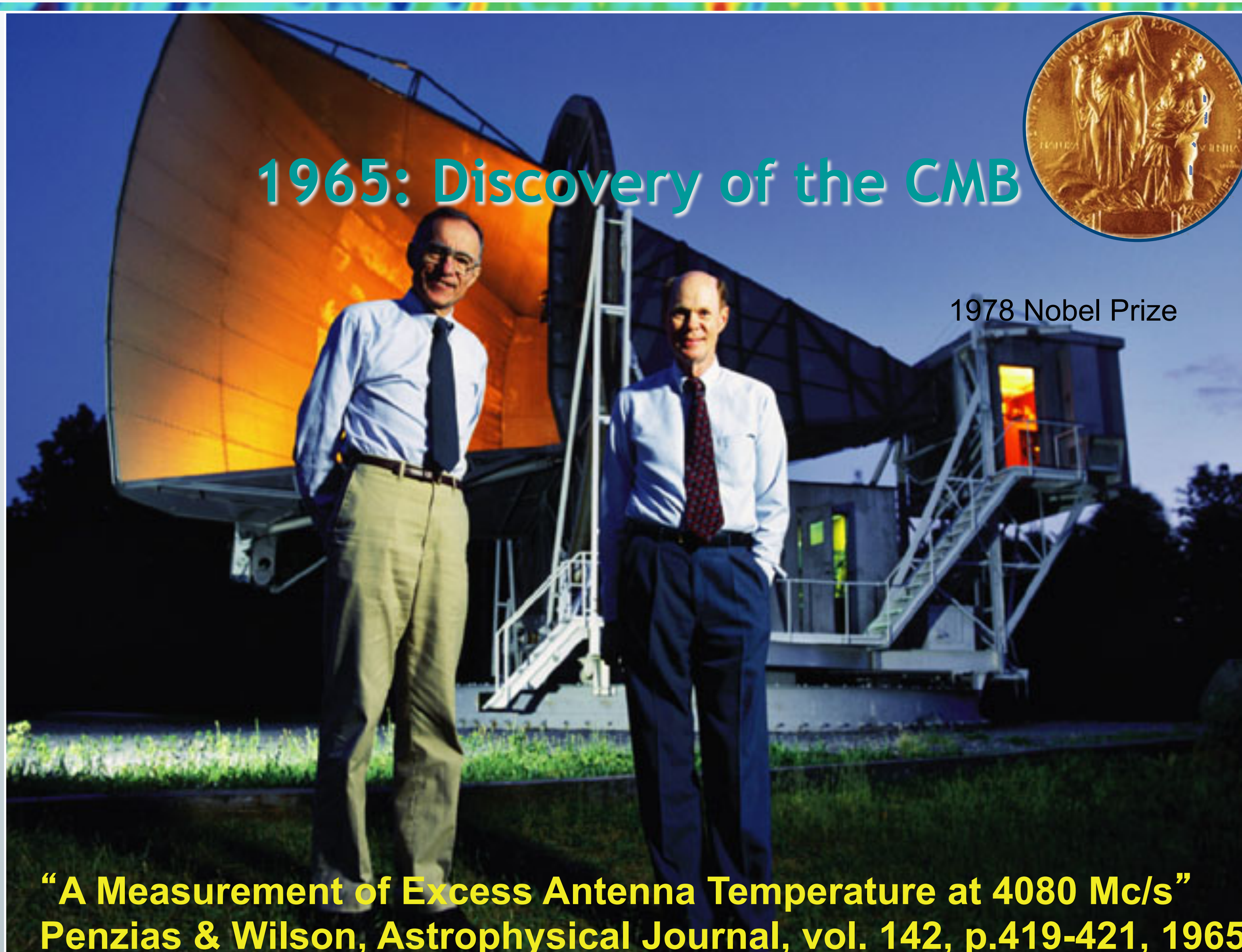




- Matter deflects light (photons) - one of the key prediction of Einstein's theory of GR

- CMB photons were emitted about ~13 Gpc away, and are deflected by all the clumps of matter in the visible Universe (ie. CMB photons are gravitationally lensed by matter)

Discovery of the CMB



Emerging Structure in the Universe

Smooth Gas at t ~ 400,000 yrs

T_0 = 2.725 +/- 0.001 K

Clusters of galaxies at
t ~ 1-2 billion years.
How did this happen?

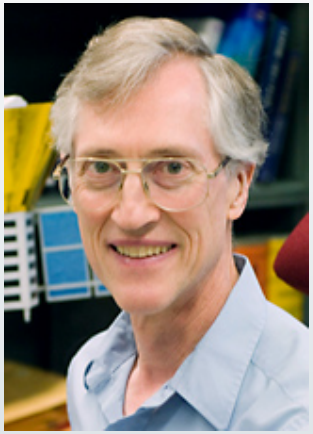
Galaxies & Clusters since t ~ 1-2 Byrs

Smooth gas at
t ~ 400,000 years

?

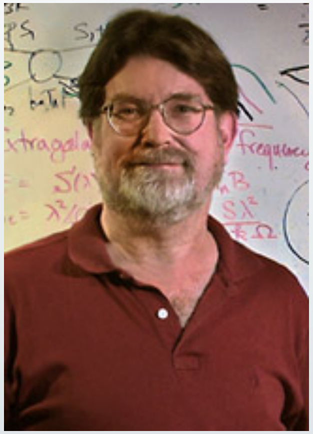
HOW COME?

. . . and then there was COBE …

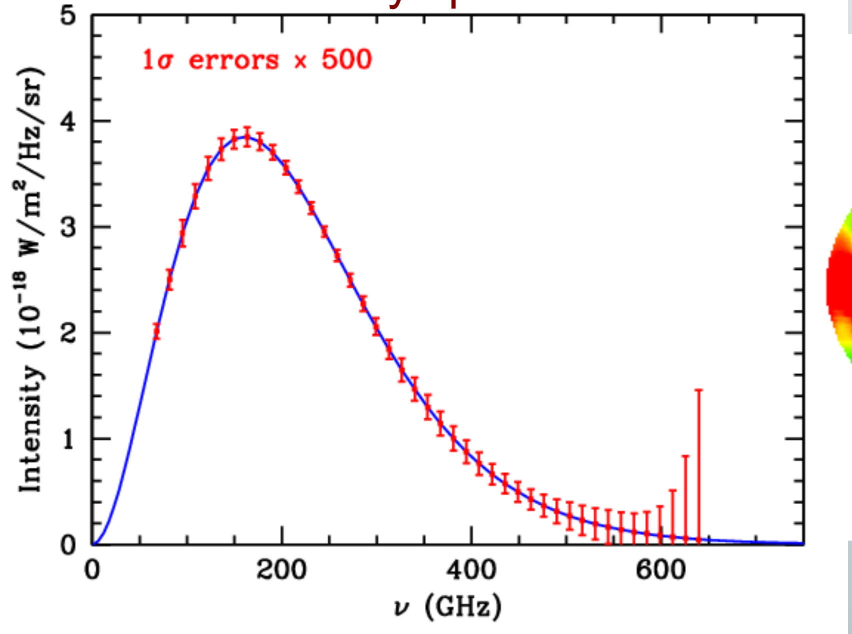


Nobel prize in Physics, 2006, awarded to John Mather and George Smoot

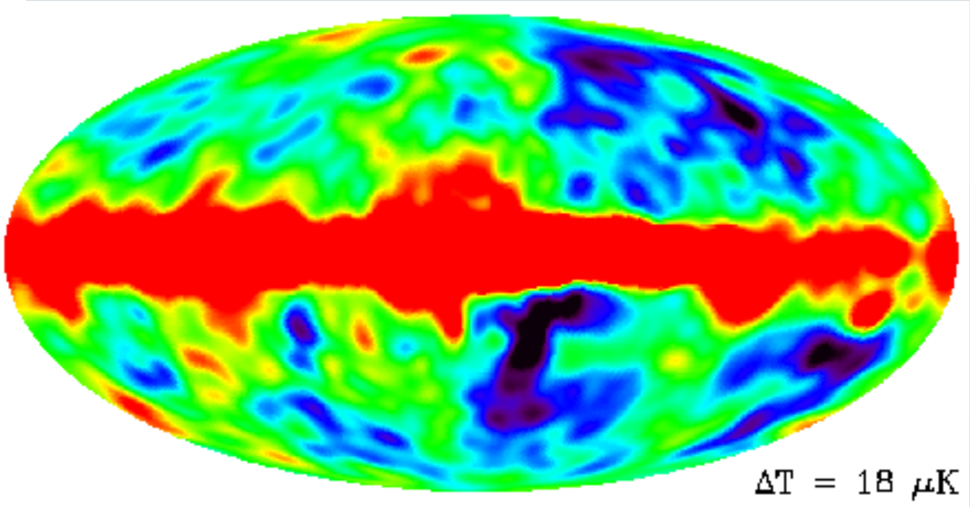
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



Blackbody spectrum



Anisotropy

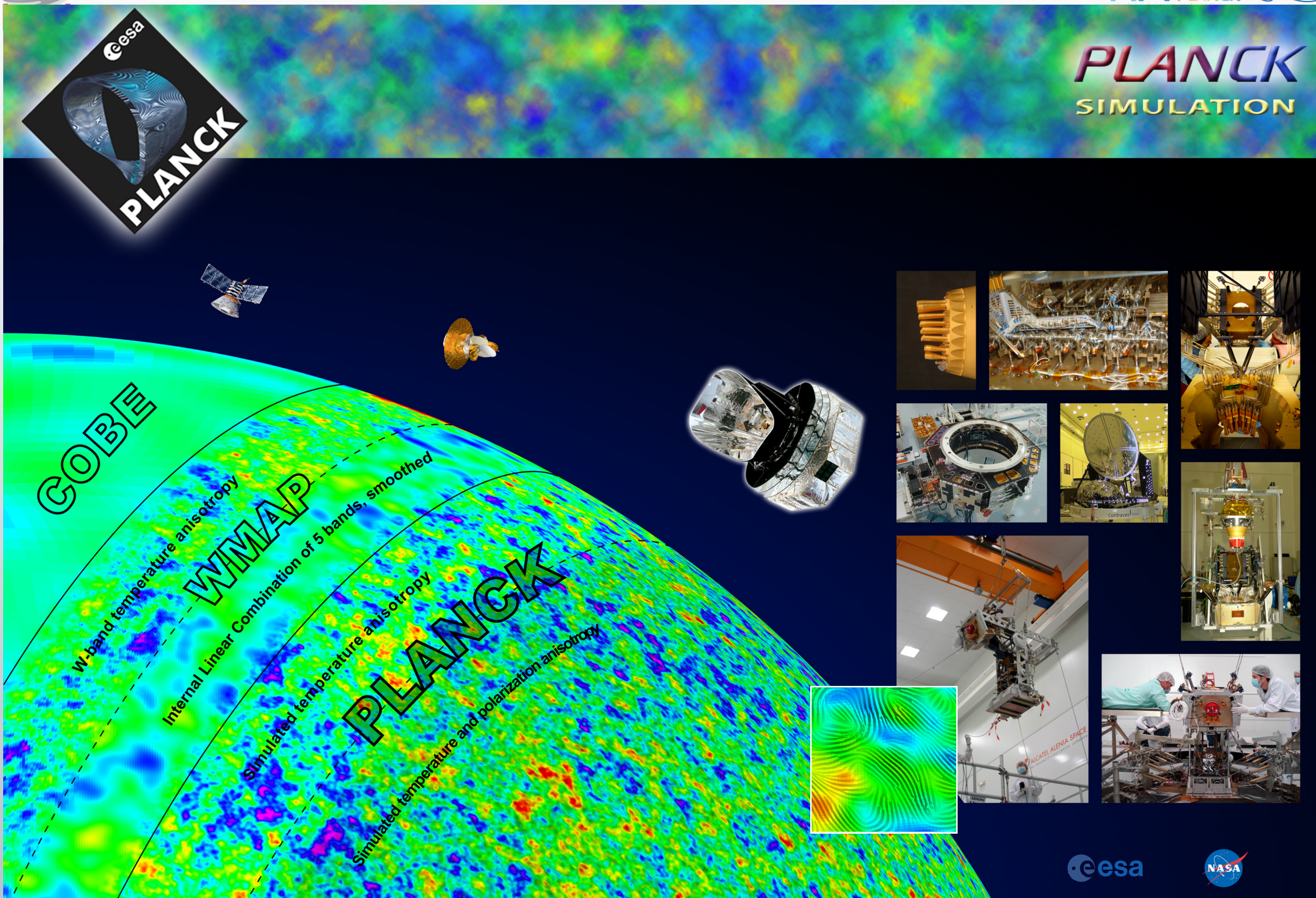


CMB drives a revolution in our understanding of the Universe

- Existence of CMB
  - *One of the pillars of the hot big-bang model (expansion, origin of light elements, &CMB)*
  - *A snap-shot of the universe at the earliest epoch accessible to direct astronomical observation*
- Measurement of the black-body spectrum
  - *$T = 2.725 \pm 0.001$ K, deviations $< 10^{-4}$*
  - *Sets the temperature scale of the Universe*
    - Only cosmological parameter known to better than 1%!
  - *Rules out significant energy injection below $z \sim 10^7$.*
- Measurement of the anisotropy
  - *Shrunk substantially the range of viable cosmological models.*
  - *Gravitational instability in a dark matter dominated Universe formed large-scale structure seen by e.g. 2dF or SDSS.*
  - *The fluctuations are of the form predicted by inflation. (?)*
  - *The large-scale structure of space-time is "simple". (?)*
- Precise normalization of large-scale structure in the universe

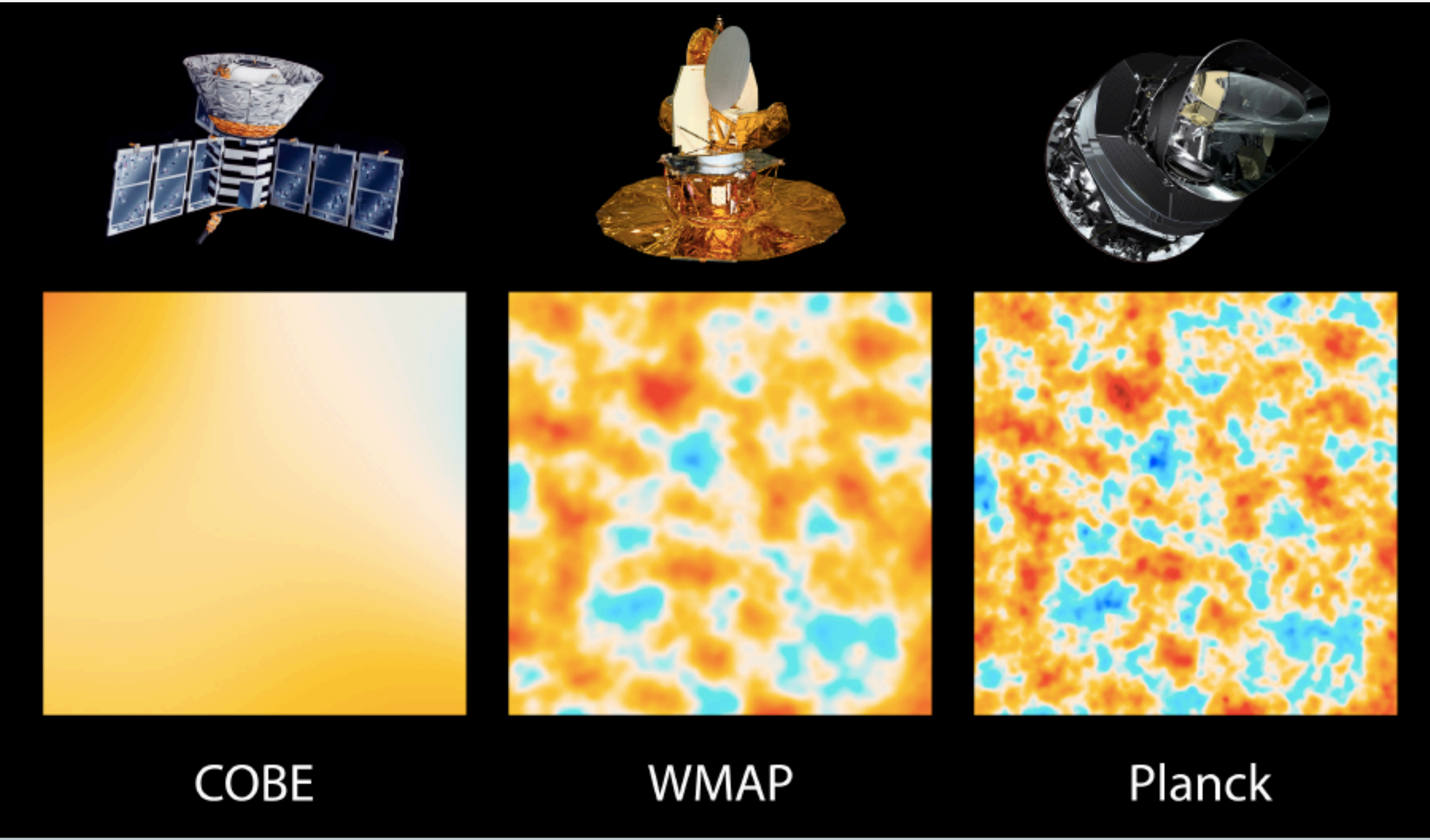
> All right. But apart from the sanitation, the medicine, education, wine, public order, irrigation, roads, the fresh water system, and public health . . .
>
> What have the Romans ever done for us?
>
> Reg, spokesman for the People's Front of Judea

CMB observed by COBE, WMAP, and Planck



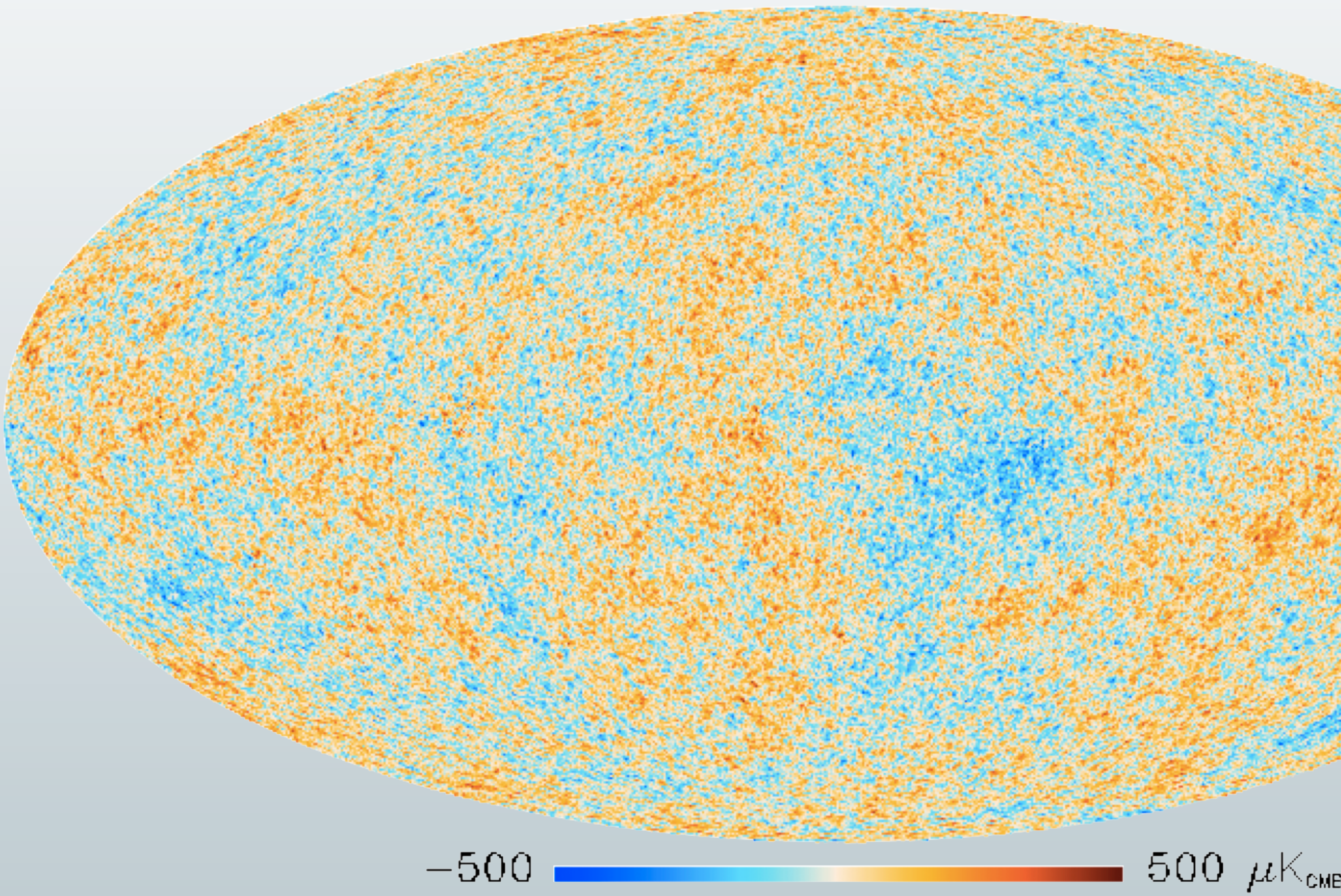
Cosmic Microwave Background Fluctuations

Resolution and Sensitivity

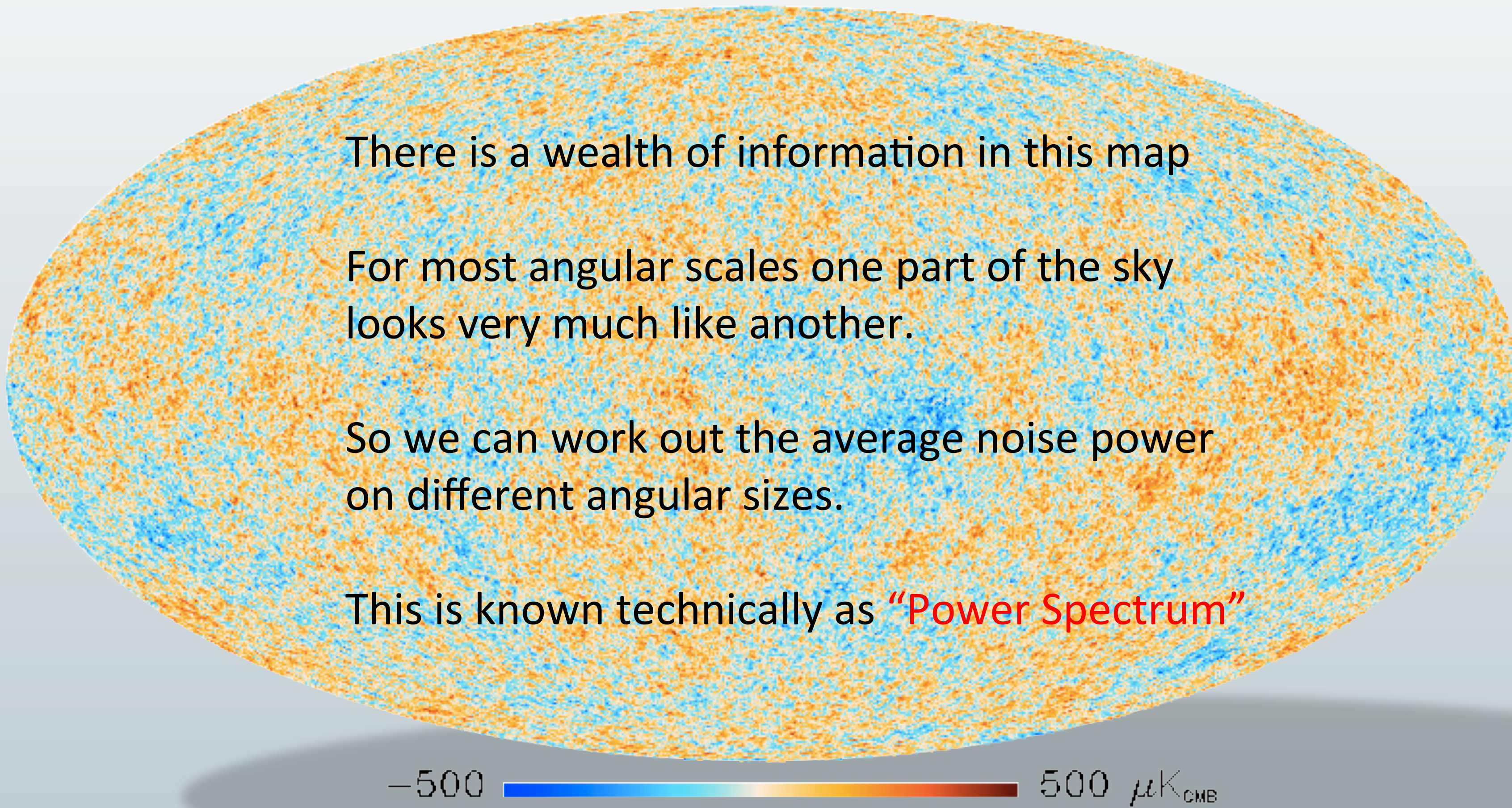


Cosmic Microwave Background Fluctuations

Planck gives us the sharpest and clearest view of this ancient light.



CMB angular power spectrum in words



There is a wealth of information in this map

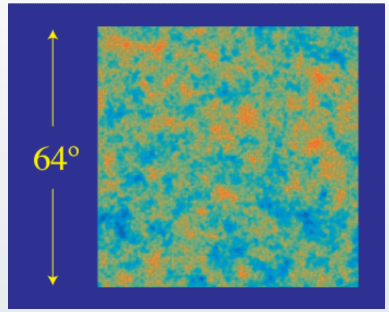
For most angular scales one part of the sky looks very much like another.

So we can work out the average noise power on different angular sizes.

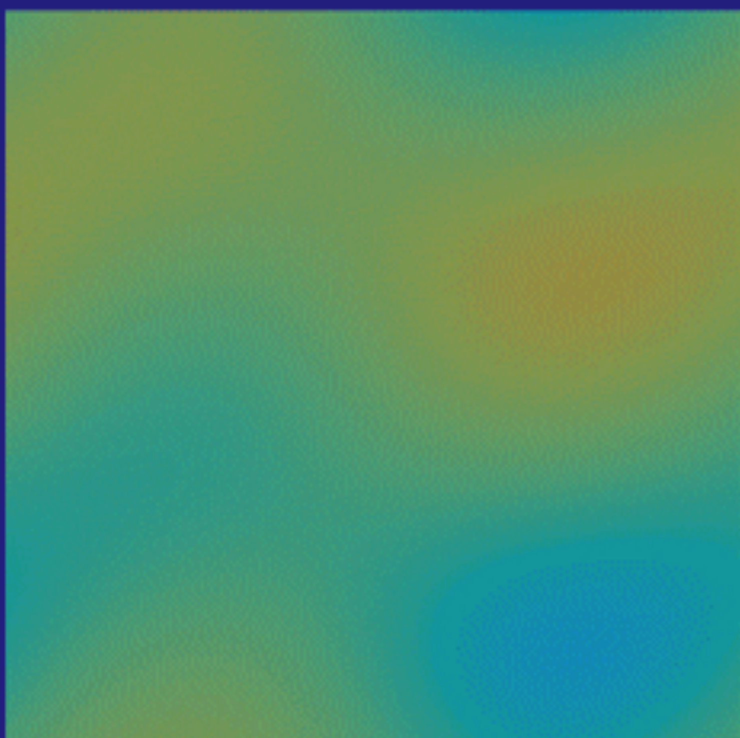
This is known technically as "Power Spectrum"

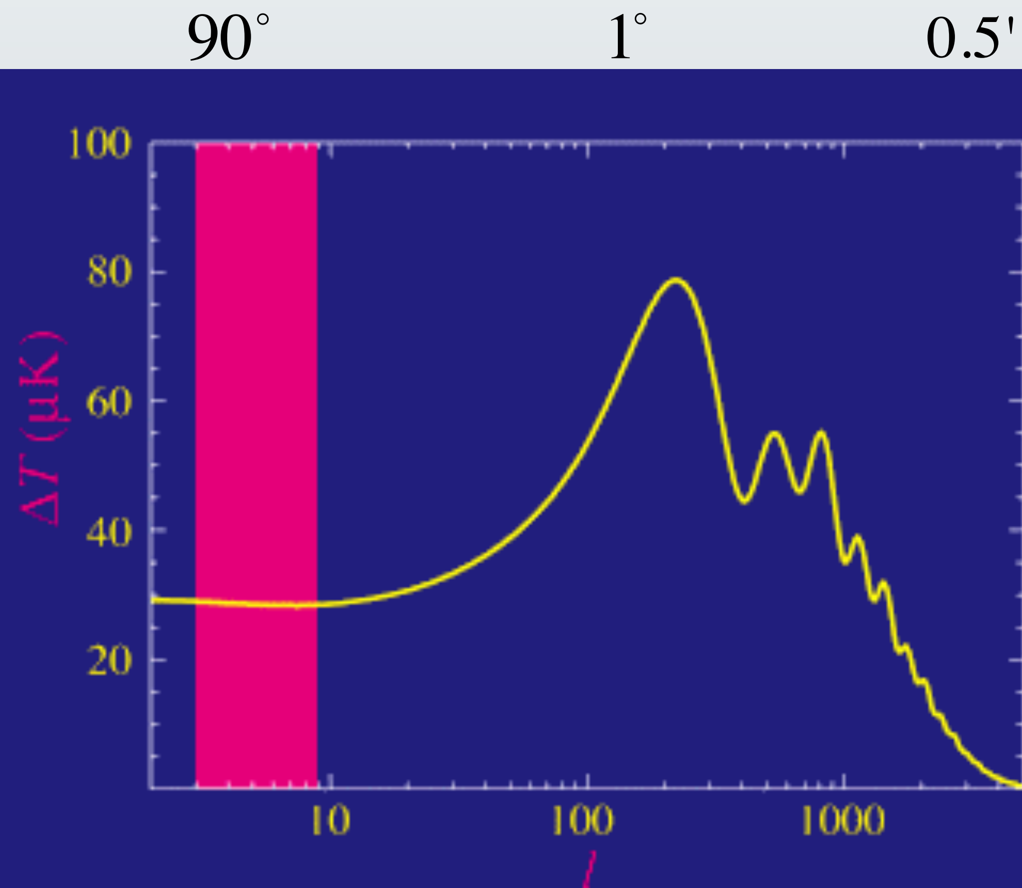
CMB angular power spectrum how does it work?

The angular power spectra tell us how the amplitude of the fluctuations vary with size

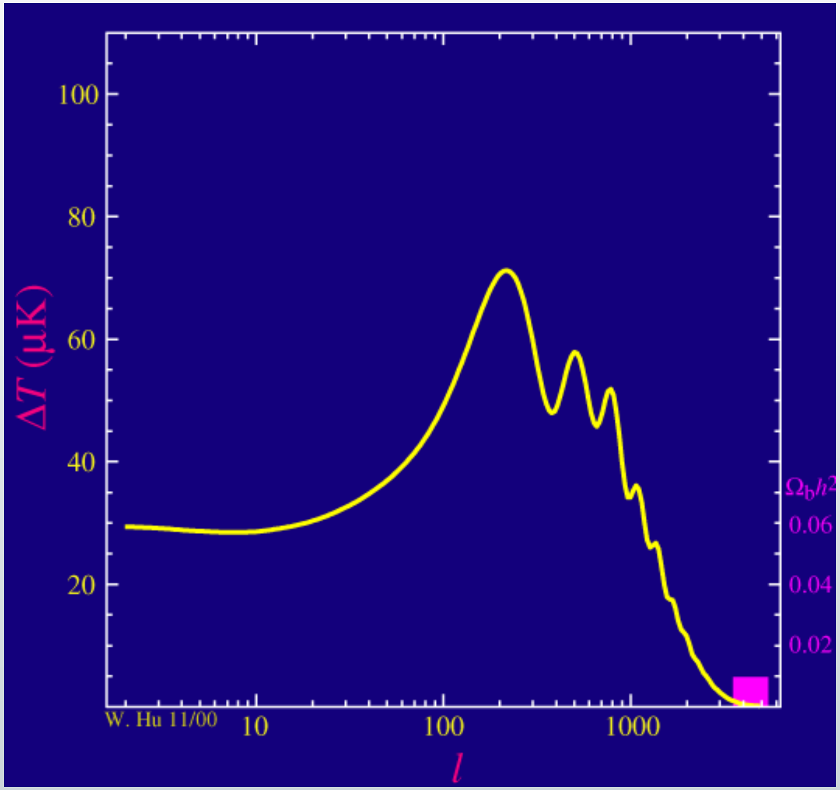


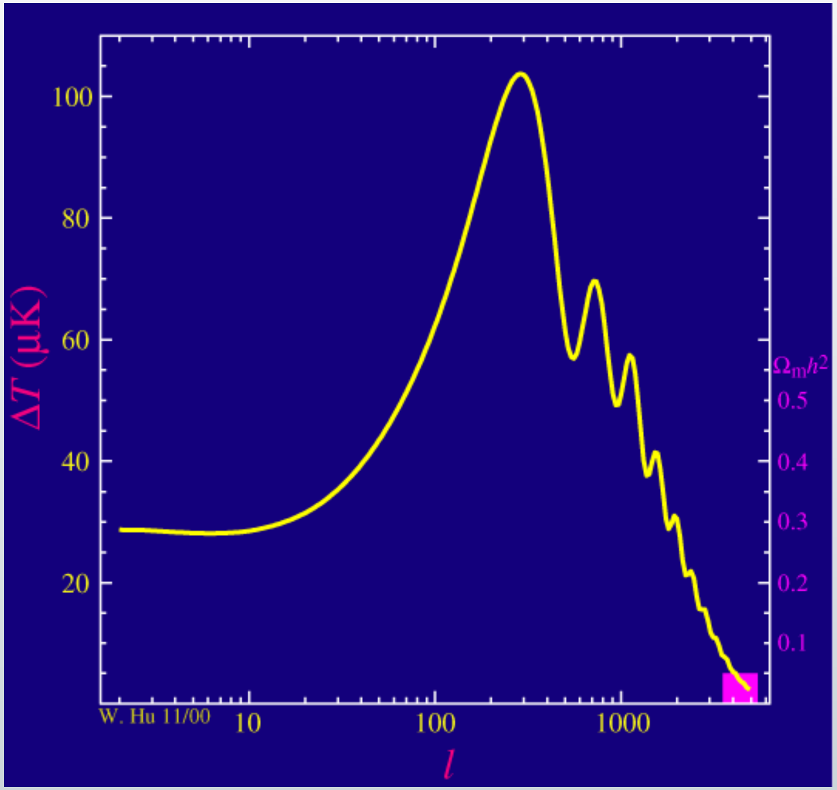
As the pink filter slides from left to right the spots get smaller,
and up to first peak they also get brighter; beyond this point they get smaller and fainter





CMB angular power spectrum
how does it work?

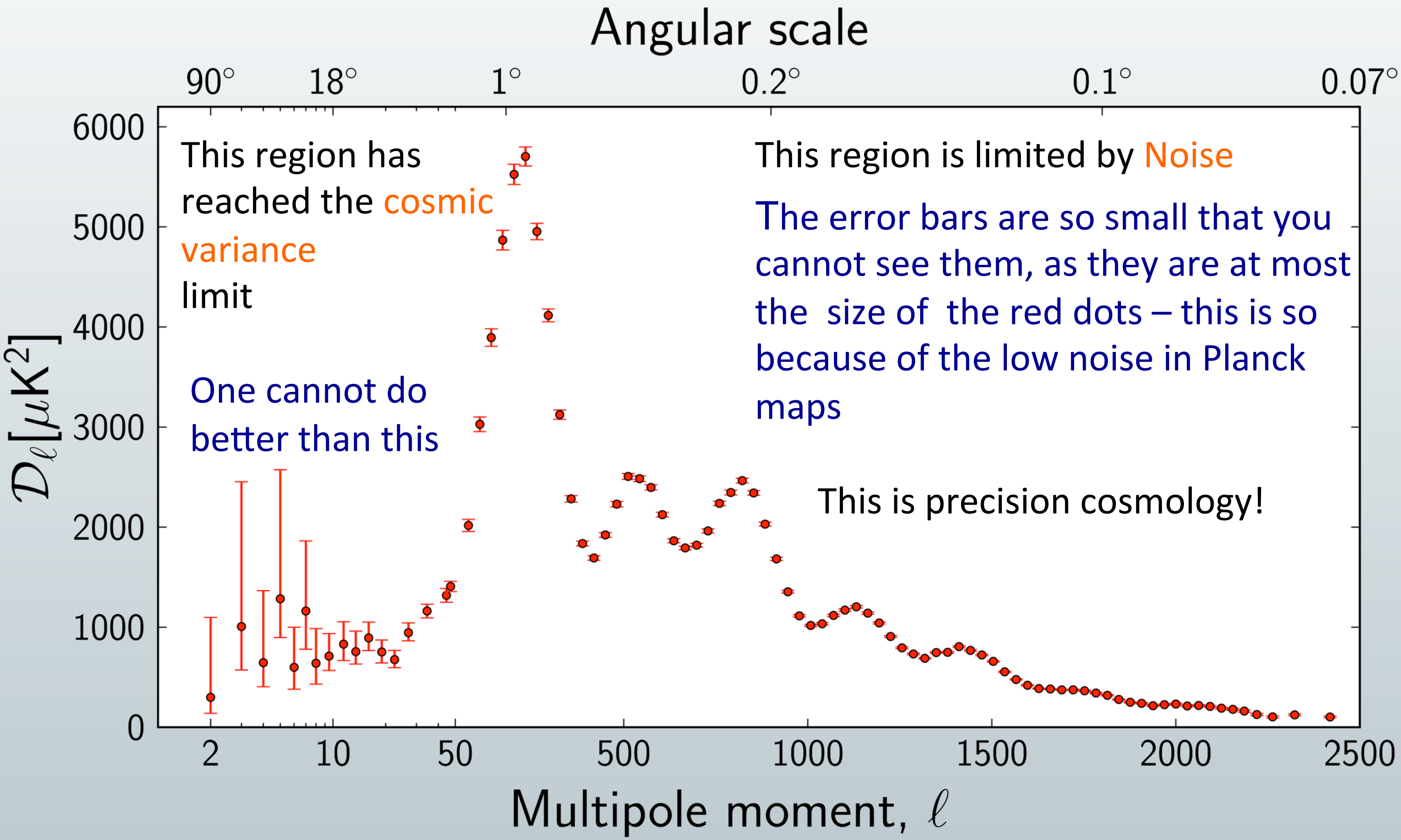




$$\Omega_b h^2$$

$$\Omega_m h^2$$

CMB angular power spectrum what we measure from Planck



This region has reached the cosmic variance limit

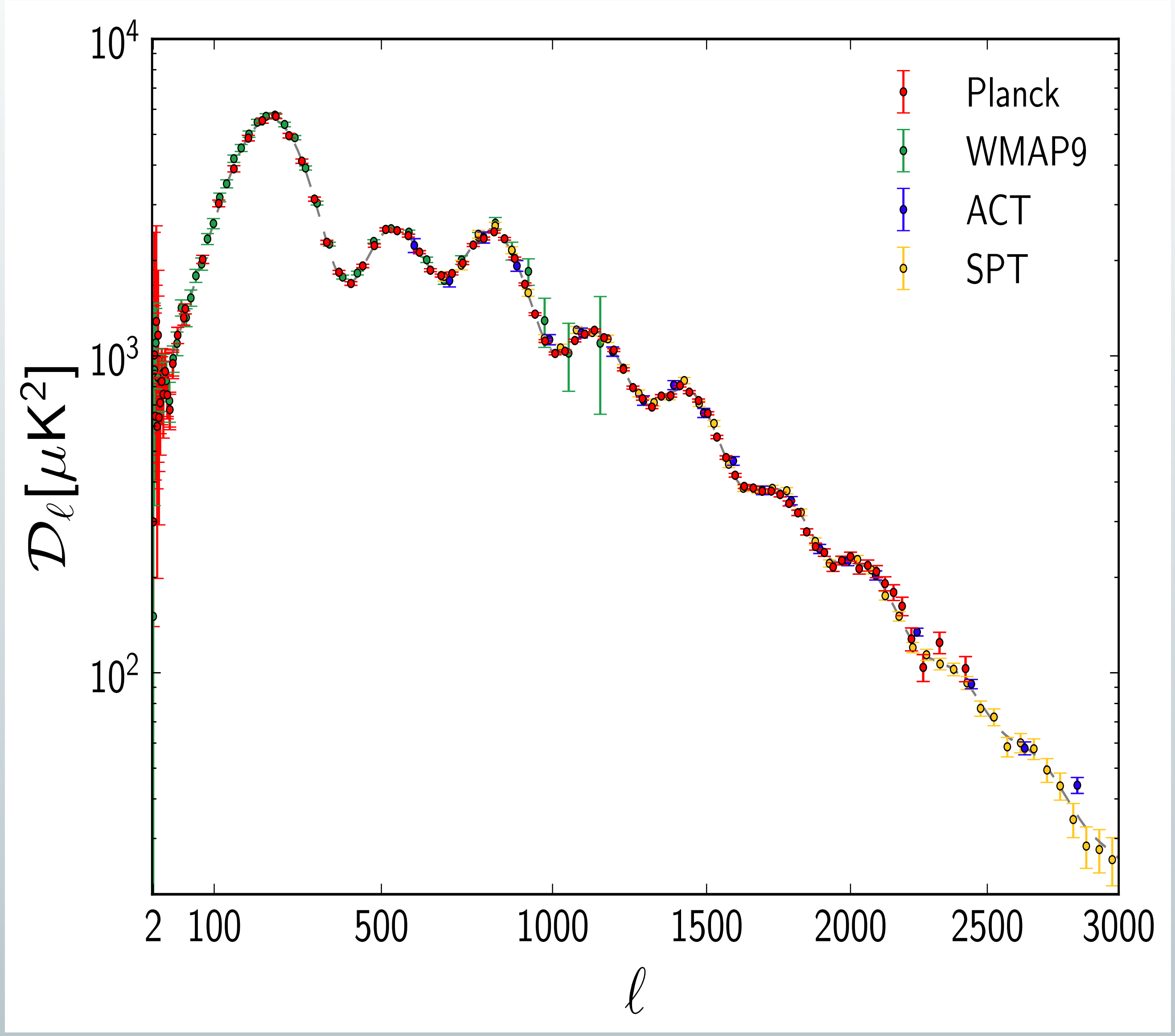
One cannot do better than this

This region is limited by Noise

The error bars are so small that you cannot see them, as they are at most the size of the red dots – this is so because of the low noise in Planck maps

This is precision cosmology!

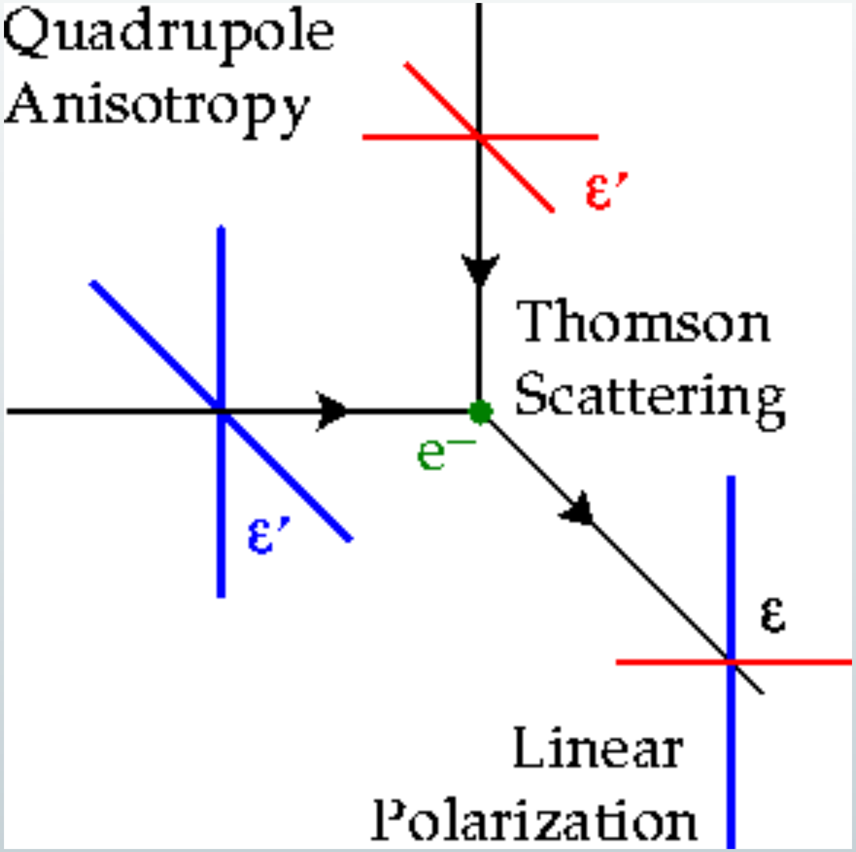
CMB angular power spectrum – Temperature (TT) Planck, WMAP9, SPT,ACT



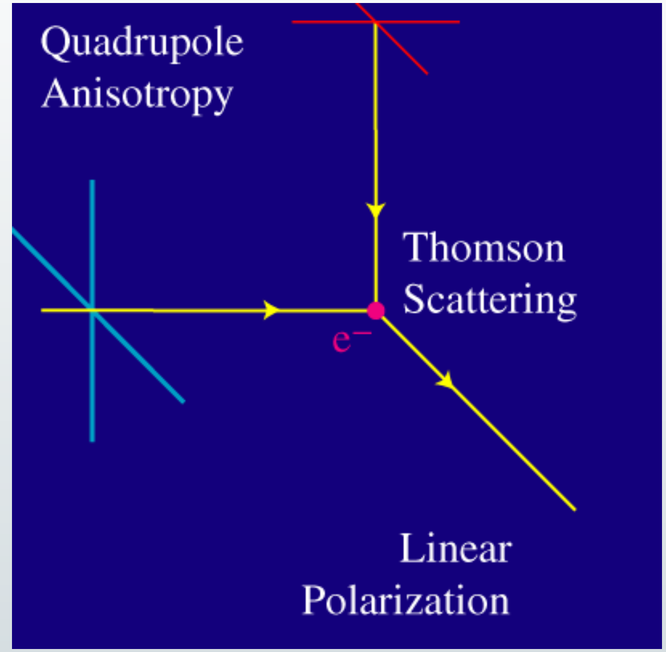
CMB - Polarization

In the presence of anisotropy we expect Thomson scattering to generate (linear) polarization.

Polarization provides a prediction, a cross-check and further information about conditions at last-scattering and reionization.



CMB - Polarization



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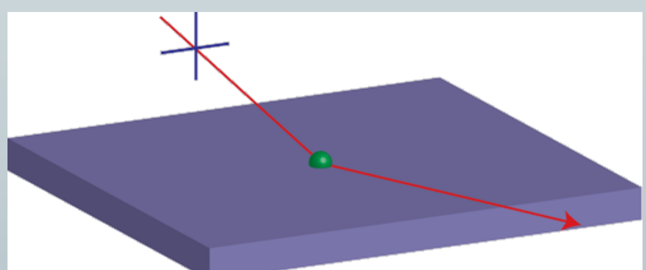
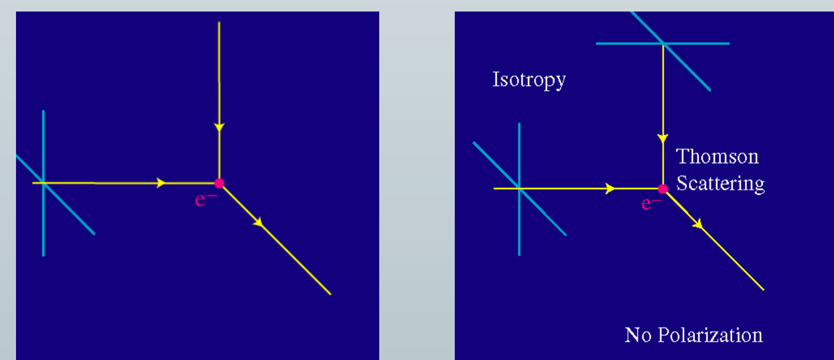
Polarization by reflection

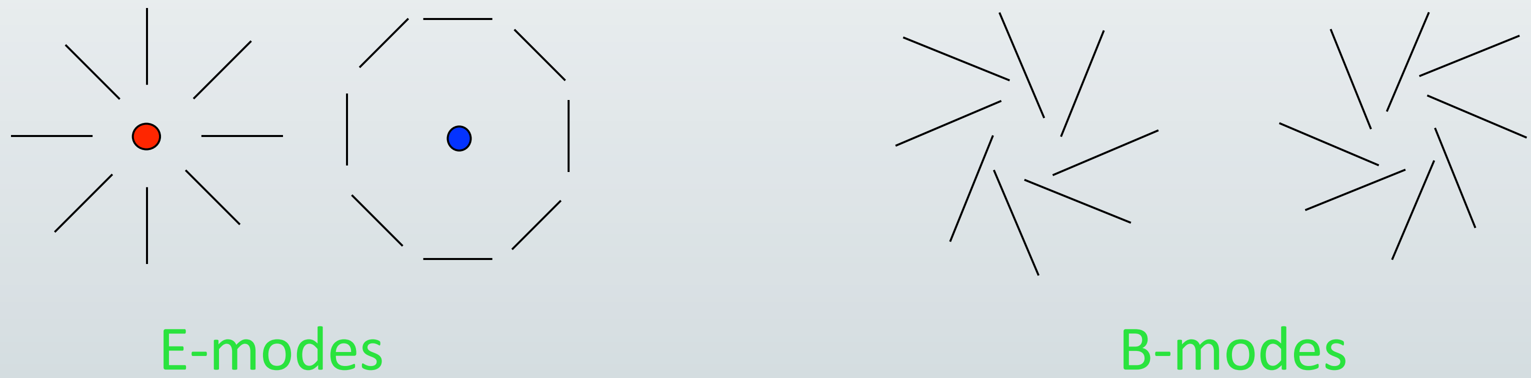


Polarization by Thomson Scattering



E-modes and B-modes

Polarization is made up of two "modes", referred to as E- and B- modes because of their global parity properties.

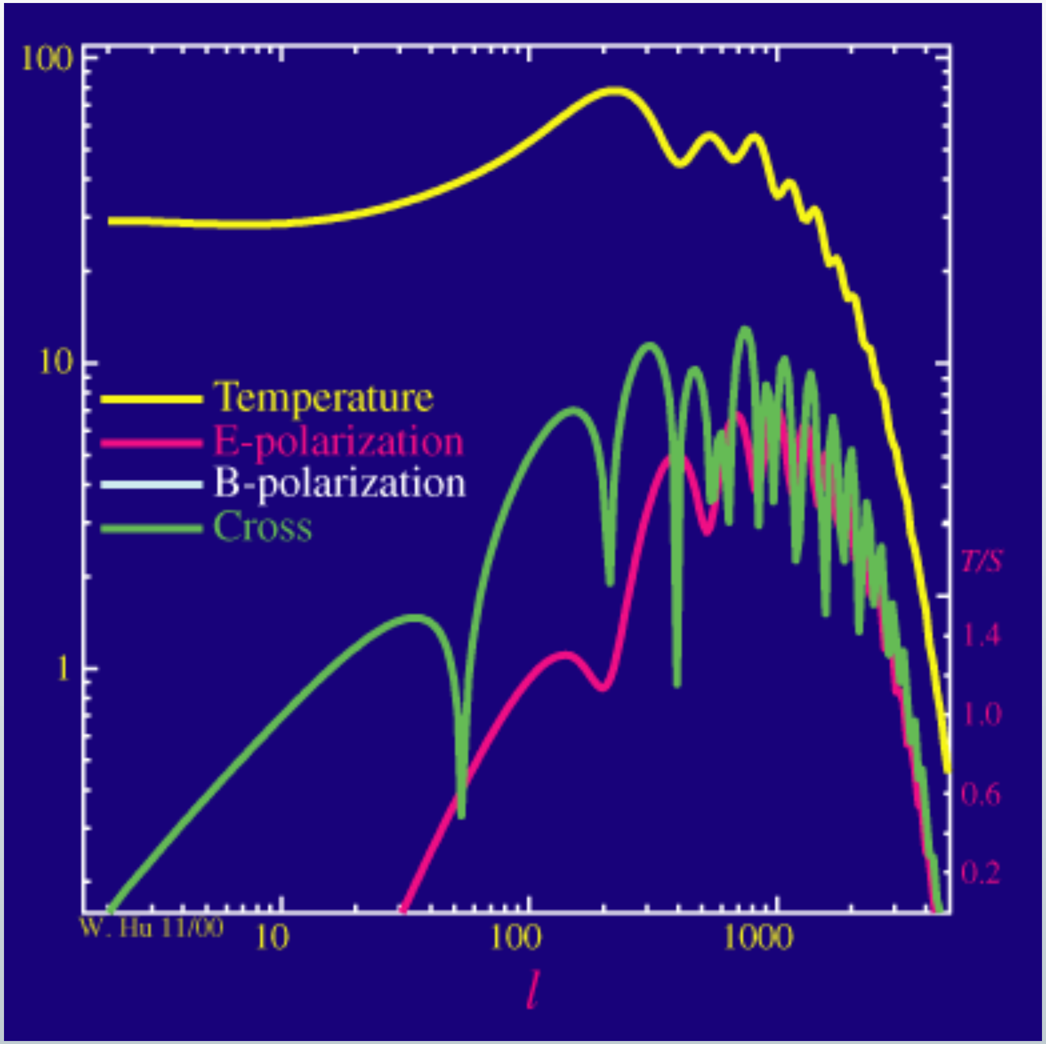


Note that E-modes have no handedness, whereas B-modes do and thus cannot be generated by scalar (density) perturbations.

Hence, B-mode discovery would establish the new source for perturbations - tensor perturbations, i.e. primordial gravity waves.

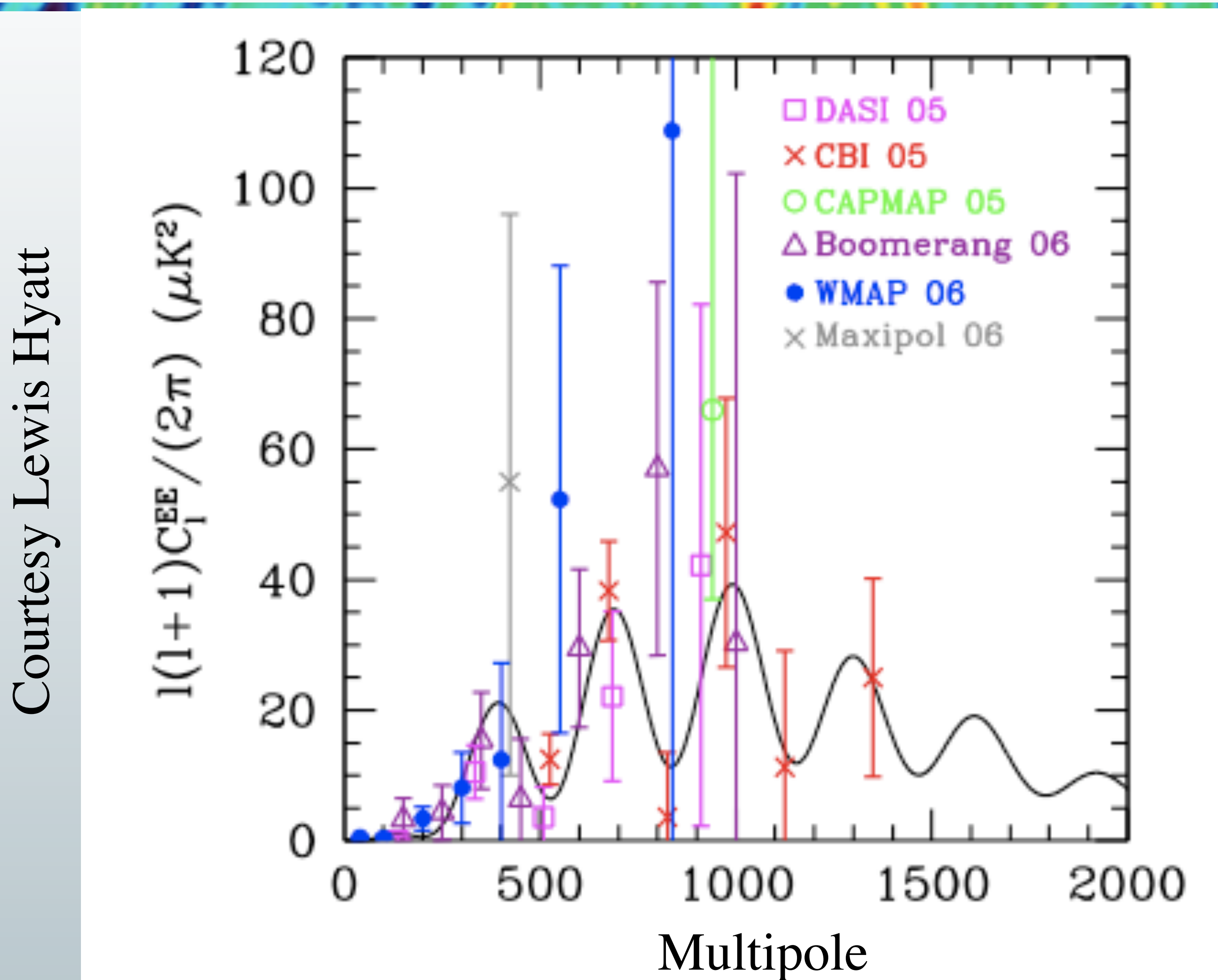
There are those who would call that "a smoking gun of inflation" …

E-modes and B-modes



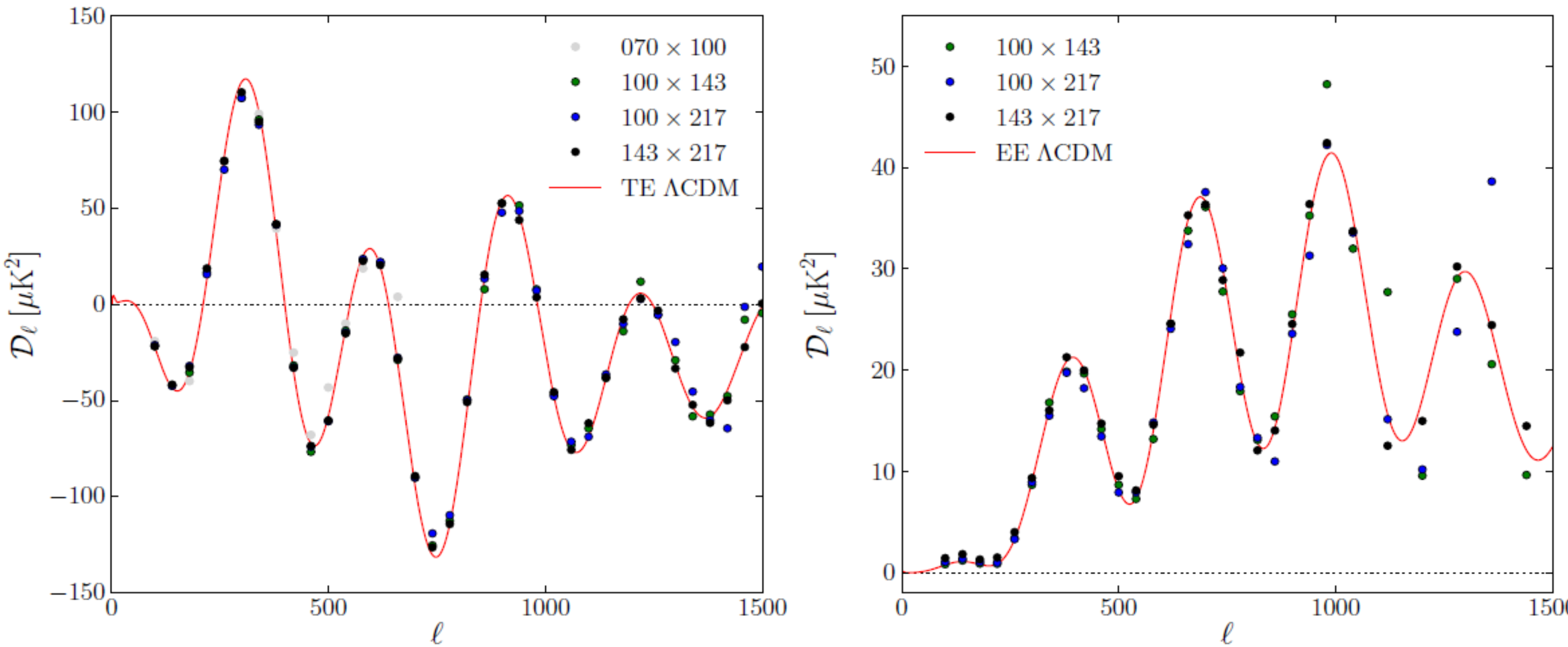
Hu

The world compilation of CMB polarization measurements



Polarization with Planck (preliminary)

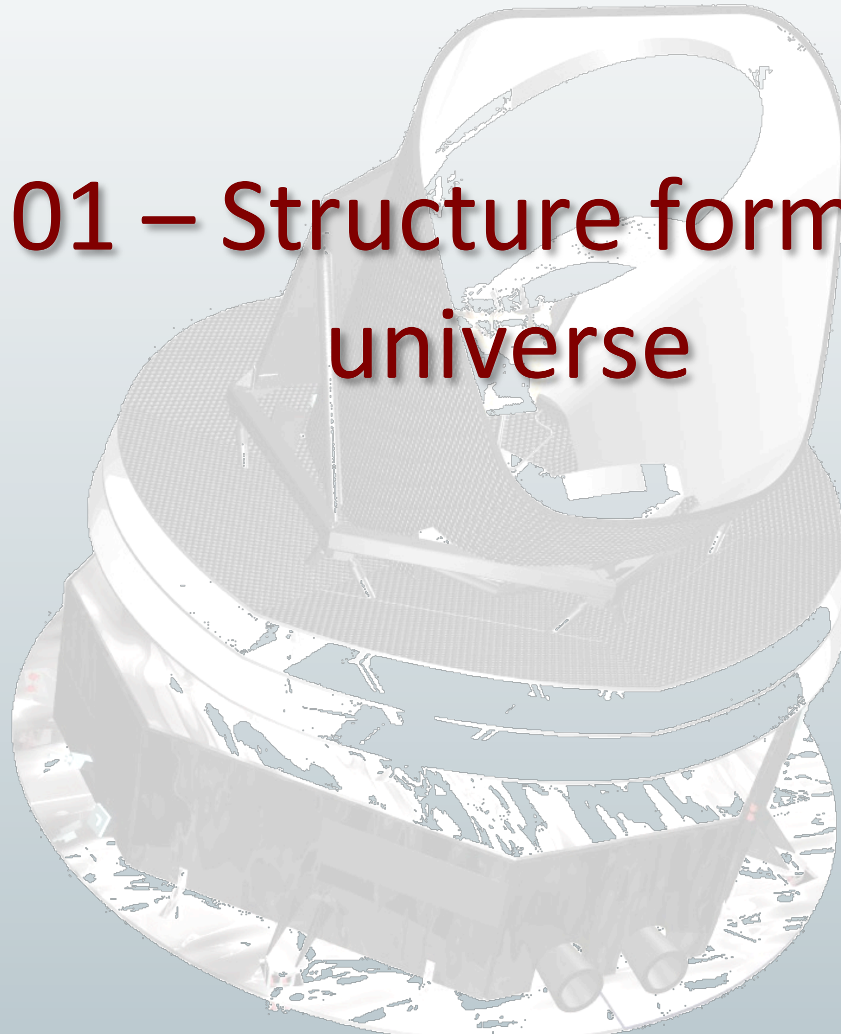
TE and EE Power Spectra (preliminary!) - red line is not a fit to the polarized spectra – it is the TT best fit model



Excellent quality of the data

Foregounds and systematics are not dominant

Lecture 01 – Structure formation in the universe



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Big Bang model

- Homogeneous and isotropic universe which began from a singularity (the primeval fireball) with subsequent cosmological expansion

- The spacetime metric describing the universe is the Friedman-Robertson-Walker:

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right) \right),$$

- Where t is the physical time, a(t) is the scale factor, (r,θ,Φ) are spherical coordinates and k is the curvature constant
- The cosmological expansion is expressed in terms of the scale factor a(t),

(e.g. the spatial dimensions are changed in time by multiplying the spatial comoving coordinate by a(t))

- evolution of a(t) is governed by the Friedman equations which are obtained from General Relativity:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3},$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G(\rho + 3p)}{3} + \frac{\Lambda}{3}.$$

Big Bang model

- The main components of this universe may be described as radiation and matter fluids
- assumes that the radiation is of cosmological origin and this is why it is called `hot'
- provides a tractable framework within which one can try to understand how the structure we see today, like galaxies and clusters of galaxies, originated from small density fluctuations in the early universe
- Critical density - the density necessary for the universe to be flat:

$$\rho_c = \frac{3H^2 - \Lambda}{8\pi G},$$

- Cosmological parameters

- H is the Hubble parameter:

$$H = \frac{\dot{a}}{a},$$

- Deceleration parameter:

$$q = -\frac{\ddot{a}a}{\dot{a}^2},$$

- Density parameter:

$$\Omega = \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2},$$

where we neglected Λ
ρ is energy density
Ω_0 is the density parameter today
$\Omega < 1$ (open), $\Omega = 1$ (flat), $\Omega > 1$ (closed)

Big Bang model

- Neglecting the curvature term and the cosmological constant term and solving the Friedman equations one obtains the following evolution laws for the scale factor :

$$a \propto t^{1/2},\ \rho = \frac{3}{32\pi G t^2}\ \text{(radiation era)}$$

$$a \propto t^{2/3},\ \rho = \frac{1}{6\pi G t^2}\ \text{(matter era)}$$

- Hubble radius- the sphere such that its radius at time t is given by $L_H = c / H$, i.e., it contains all objects that are receding from us with a velocity less than c the speed of light.

(Some authors use the term `Hubble radius' to denote the distance ct rather than the terminology `particle horizon'; they are not strictly the same, although they will agree to within factors of 2 or 3.)

- There are three main epochs in the evolution of the universe of particular interest:
  - the point a_{enter} at which the fluctuations enter the horizon, i.e., the physical size of the fluctuation is equal to the horizon;
  - a_{eq} the time of matter-radiation equality, which occurs when the radiation and matter densities are equal, and
  - a_{rec} the time of recombination, when protons capture free electrons producing neutral atoms and radiation is last scattered.

Big Bang model

- Effects that follow from the FRW metric:
  - The cosmological redshift

$$(1+z) = \frac{a(t_0)}{a(t_i)}$$

where t_i is the time of emission of a photon from an object at redshift z and t_0 is the time at which the photon is seen by the observer (at present epoch).

  - The Hubble expansion law

$$z \sim \frac{v}{c} = \dot{d} = Hd,$$

where d is the proper distance between two objects, v is the recessional velocity, c is the speed of light and H is the Hubble parameter.

The proper distance that light can travel since the beginning of the universe, the particle horizon:

$$d_H \sim 2ct \text{ (radiation era)}$$

$$d_H \sim 3ct \text{ (matter era)}$$

  - The angle-size relation

$$\theta = \frac{L}{a(t_0) r_0 (1+z)^{-1}}$$

where Θ is the angle subtended by an object with proper length L at a distance $r = r_0$ with r the radial coordinate of the FRW metric.

Big Bang model

- At redshifts z>>1, a comoving length, d, subtends an angle θ given by:

$$\theta \sim \frac{d}{2c}\Omega_0 H_0 \text{ (radians)},$$

- in particular the Hubble radius at z>> 1 subtends an angle

$$\theta_H = \left(\frac{\Omega_0}{z}\right)^{1/2} \text{ (radians)}$$

- $\theta_H \approx 1-2^0$ for $z \sim z_{rec} \sim 1000$, where z_{rec} is the redshift at recombination

Big Bang model

- The successes of this model:

  - The observed primordial light element abundances are predicted by primordial nucleosynthesis
  - The observed expansion of the universe (Hubble expansion law)
  - The existence of the Cosmic Microwave Background radiation with a black body spectrum
  - The evolution of radio source counts

- The problems of this model:

  - The horizon problem: the microwave background radiation we receive today on scales separated by more than ~ 1 degree comes from regions which were not in causal contact at the time of the last scattering, so in order to explain its high degree of isotropy, initial conditions must be imposed in the standard model.

  - The flatness problem: $\Omega=1$ is an unstable equilibrium point in the standard model, hence is hard to understand why Ω is close to unity today.

  - The cosmological constant problem: there is empirical evidence that the cosmological constant Λ, is much smaller than expected on dimensional grounds.

  - The monopole problem: in the early universe it is expected that phase transitions produce exotic particles, small black holes and topological defects. In particular grand unified theories (GUT) predict large quantities of monopoles. This is not supported by observations.

Big Bang model

- The structure formation problem: this model has no mechanism to generate the density perturbations that gave rise to the structure on small scales like galaxies, clusters of galaxies, etc. The seed structure need to be imposed as initial conditions rather than produced dynamically.

- The dark matter problem: there is observational evidence that most of the matter in our universe is in the form of non-luminous matter. Some possibilities for this dark matter are non-luminous baryonic matter (e.g.jupiters, brown dwarfs, MACHO's (Massive Compact Halo Objects) formed from an early population of black holes or neutron stars or white dwarfs. The nucleosynthesis constraints on the abundances of baryonic matter imply the existence of non-baryonic dark matter.

  - Possibilities for this dark matter are, e.g., in the form of weakly interacting massive particles (WIMPS) which can be classsified as Cold Dark Matter (CDM) or Hot Dark Matter (HDM) according to their thermal velocities .A candidate proposed for the HDM has been the neutrinos with non-zero mass while for CDM the most popular is the axion; however there is not yet evidence for the existence of WIMPS.

- In order to solve these limitations concepts like Inflation and Topological defect models arose from the combined areas of particle physics and cosmology

Inflation

- Inflation - Solves flatness and horizon problems

- Inflation - consists of a phase of rapid expansion where the scale factor grows faster than the horizon

  - If there is a moment at which the universe goes through a phase-transition (e.g.,associated with symmetry breaking of the grand unified field) then a false-vacuum is generated with the vacuum density energy acting like a cosmological repulsion (equivalent to non-zero cosmological constant Λ). As a consequence there is an exponential expansion of the scale factor inflating the universe by a factor $\approx 10^{28}$, the end of which the vacuum energy density is transformed into matter and radiation

with

$$a(t) \propto e^{Ht},$$

$$H^2 = \frac{8\pi G}{3}\rho_v,$$

where ρ_v is the false vacuum energy density

- In particular Inflation provides a mechanism to generate the seed fluctuations via amplification of quantum irregularities

This scenario predicts a scale-invariant or Harrison Zel'dovich form or closer to it for the fluctuations power spectrum and produces fluctuations distributed according to Gaussian statistics

Topological defects

❖ Topological defects - arise as a natural outcome of phase-transitions in the early universe.

- It provides an alternative mechanism of generation of seed fluctuations
  - In standard theories spontaneous symmetry breaking at a critical temperature T_c , at $t < 10^{-35} s$ (energies $\geq 10^{16} GeV$) at the time where the electromagnetic, weak and strong forces are unified, results in a phase expected to contain topological defects
  - These defects are called monopoles, cosmic strings, domain walls or textures for 0,1,2, and 3 dimensions respectively
  - These defects act as seeds for structure formation via their gravitational effects
  - The generation and evolution of these defects is a non-linear process and therefore the fluctuations they generate are not Gaussian distributed.

- The angular power spectrum of the CMB fluctuations predicted by this model is not supported by observations. However some percentage of fluctuations generated via topological defects (cosmic strings) is expected to contribute to the total anisotropy (isocurvature fluctuations)

Types of fluctuations

- Adiabatic fluctuations: perturbations in the density field, $\delta\rho \neq 0,$ and are predicted by inflation

$$\delta = \frac{\delta n_b}{n_b} = \frac{\delta n_x}{n_x} = \frac{\delta s}{s},$$

where b refers to baryons, x to any other species and s is the entropy density.

- These fluctuations conserve the photon entropy per species x, ie conserve the number per comoving volume of species x:

$$\delta\left(\frac{n_x}{s}\right) = \left(\frac{\delta n_x}{n_x} - \frac{\delta s}{s}\right)\frac{n_x}{s} = 0,$$

and therefore

$$\frac{\delta\rho_x}{\rho_x} = \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}.$$

where ρ_γ is the radiation energy density

- Fluctuations in the temperature of the CMB relates with fluctuations in the matter density by:

$$\frac{\delta T}{T} \sim \frac{1}{3}\frac{\delta\rho}{\rho}.$$

Types of fluctuations

- Isocurvature fluctuations: characterized by $\delta\rho = 0,$ and correspond to fluctuations in the form of the local equation of state, ie perturbation in the entropy per particle of species x:

$$\delta\left(\frac{n_x}{s}\right) \neq 0.$$

- Here perturbations in matter and radiation densities are of opposite sign. It can be shown that an isocurvature mode transforms into an energy density fluctuation once it enters within the horizon, due to pressure gradients.

- Isocurvature fluctuations generate perturbations in the matter component when they enter the horizon and hence produce gravitational potential fluctuations. As, after matter domination, initial entropy perturbations are transferred to the perturbations of the radiation, a significant radiation density fluctuation is then generated.

Power Spectrum and evolution of seed perturbations

❖ An initial power-law spectrum of the density fluctuations, as expected from inflationary scenarios is often assumed, and is in particular predicted by slow-roll inflation

➢ The form assumed is: $$P(k) = Ak^n,$$

where A is the amplitude and n is the spectral index, both to be determined from observations

- n = 1 describes scale-invariant fluctuations - Harrison-Zel'dovich spectrum
  - for n = 1, the variance of the density fLuctuations at horizon crossing, i.e. when the physical size of the fluctuation is equal to the Hubble radius (H = ct), is independent of scale

- The most natural outcome of an inflationary phase at early times is Gaussian, adiabatic fluctuations, with a (or close to) scale invariant spectrum, though it is not the only possibility

In linear perturbation theory each Fourier mode of the perturbations evolves independently of the others.

↓

➢ Can relate the fluctuations at the present epoch, **t0**, with the perturbations when they were generated at time, **ti**, via a linear transfer function, **T(k)**:

$$\delta(k, t_0) \propto T(k)\delta(k, t_i),$$

in terms of the power spectrum:

$$P(k, t_0) = (g(t_0)/g(t_i))^2 T^2(k) P(k, t_i),$$

where **g(t)** is the linear growth law for perturbations above the Jeans length

Power Spectrum and evolution of seed perturbations

- The processing of the power spectrum depends on cosmological parameters like total density of the universe, Ω_0, the Hubble constant, H_0, and the nature of the non-baryonic dark matter

- For a given formula, given the origin and power spectrum of the fluctuations, the quantity and nature of the dark matter and the type of perturbations, one can evolve these fluctuations in an expanding universe (see lecture 1)

- During the growth of a fluctuation there are three main epochs to consider: the point $\mathbf{a}_{enter}$ at which the fluctuations enter the horizon, i.e., the physical size of the fluctuation is equal to the Hubble radius, $\mathbf{a}_{eq}$ the epoch of matter-radiation equality, and $\mathbf{a}_{rec}$ the epoch of recombination.

Models of structure formation

- Baryonic models:

- during the radiation dominated era $a < a_{eq}$ - perturbations on scales larger than the horizon size grow according to $\delta \propto t$, ie, $\delta \propto a^2$

- during the matter dominated epoch they grow according to $\delta \propto t^{2/3}$, ie, $\delta \propto a$

- Matter fluctuations on scales smaller than the horizon size interact with the radiation such that
  - those on scales greater than the Jeans length, $\lambda > \lambda_J$ - where pressure gradients can be ignored, collapse under self gravity,
  - those with $\lambda < \lambda_J$ - where gravity can be ignored, undergo acoustic oscillations.

- The Jeans length is defined by:

$$\lambda_J = 2\pi \left(\frac{v_s^2}{4\pi G\rho} \right)^{1/2},$$

where v_s is the adiabatic sound speed, with corresponding Jeans mass.

Models of structure formation

- Before recombination - the radiation and matter are tightly coupled by Thomson scattering, with Thomson cross-section:

$$\sigma_T = (8\pi e^4)/(3m_e^2) = 0.6652 \times 10^{-24}\ \mathrm{cm}^2.$$

- Matter and radiation act like a single fluid with

$$M_J \sim 9 \times 10^{16}(\Omega h^2)^{-2} M_\odot,$$

where $M_\odot$ is the solar mass.

- After recombination - the adiabatic speed is that of a monoatomic gas, since the photons are no longer coupled to the matter. Then

$$M_J \sim 1.3 \times 10^6 (\Omega h^2)^{-1/2} M_\odot,$$

a mass close to the mass of globular star clusters. Hence,

  - before matter and radiation decouple, adiabatic perturbations on scales smaller than supercluster scales oscillate like sound waves.
  - after recombination the Jeans mass decreases by more than a factor ~ 10^{10} to globular cluster masses.
  - Fluctuations inside the horizon oscillate acoustically and therefore their amplitude is damped with respect to fluctuations outside the horizon producing a turnover in the fluctuation power spectrum.

Models of structure formation

- Imperfect coupling of matter and radiation - lead to a damping of adiabatic fluctuations on smaller scales usually called Silk damping, - in which the photons may move from and into overdensities or underdensities of scale $\lambda < \lambda_D$, carrying matter with them.

This damping is characterised by a length scale and mass given by:

$$\lambda_D = c(At)^{1/2}, \; A \sim \frac{4\pi^2}{6}\frac{1}{\sigma_T n_e c},$$

$$M_D = 9 \times 10^{10} \left(\Omega h^2\right)^{-5/4} M_0, \; (\text{for } z \sim 1000),$$

where n_e is the electron number density, c is the speed of light and σ_T is the Thomson cross-section.

Recombination does not occur instantaneously at z ~ 1000, and so it should be expected that expression 1 is an understimate. The effect of the scattering on a perturbation δT (z) is given by:

$$\int_0^z \frac{\delta T(z)}{T} e^{-\tau(z)} \frac{d\tau}{dz} dz,$$

where τ is the optical depth to Thomson scatterings

Models of structure formation

- The function $e^{-\tau(z)} d\tau/dz$

  is well approximated by a Gaussian with mean $z_{rec} \sim 1100$ independent of Ω and h (150,165) and Δz = 80, but in the context of standard theory of recombination, it can go up to $\Delta z \sim 400$ which corresponds to a proper distance $\Delta L \sim 40h^{-1}$Mpc and to an angular scale $\sim 20'$. The finite thickness of the last scattering surface can erase fluctuations on scales smaller than its width.

➤ The problems of this model

- As the density fluctuations only grow after decoupling, the amplitude $\delta\rho/\rho$ predicted to fit the structure we see today is greater than the upper limit set up by the CMB fluctuations
- Models with $\Omega h^2 \leq 0.1$ give rise to fluctuations in the mass distribution on scales $\sim (10 - 20)h^{-1}$ Mpc, larger than those observed in the distribution of galaxies, assuming that $n \leq 2$. In this case an initial scale invariant spectrum is inconsistent with the low amplitude of the galaxy correlation function observed on large angular scales.
- The desire of satisfying simultaneously the requirements of the inflationary scenario ($\Omega = 1$) and the nucleosynthesis constraints.

Models of structure formation

CDM models

- The gowth of the fluctuations in the baryonic component remains unchanged until the recombination epoch.
- Adiabatic CDM fluctuations which enter the horizon at $a < a_{eq}$, grow according to $\delta \propto \ln a$ suffering a smaller growth as compared with fluctuations outside the horizon
    - This fact gives rise to a characteristic turnover in the fluctuation power spectrum, such that initially scale-invariant perturbations evolve to produce a power spectrum with the asymptotic behaviour:

      $P(k) \propto k$ for $k \to 0$, and, $P(k) \propto k^{-3}$ for $k \to \infty$.
    - The scale corresponding to the transition between these two regimes is the size of the horizon at the time of matter-radiation equality (point of deflection)

      $\lambda = ct_{eq} (a0/a_{eq}) \simeq 10(\Omega h^2)^{-1}$ Mpc
- Fluctuations that enter the horizon at $a > a_{eq}$ grow according to $\delta \propto a$, since they are not coupled to the photons.
    - Since fluctuations in the CDM component begin to grow just as the universe becomes matter dominated, by the end of the recombination the amplitude of the CDM fluctuations are larger than the baryonic fluctuations by a factor $\frac{a_{rec}}{a_{eq}} \sim 21\Omega h^2.$
- The baryons after decoupling from the radiation, at the end of the recombination fall into the potential wells created by CDM fluctuations – amplifying the baryonic fluctuations after recombination.

Models of structure formation

- The CDM components suffer damping of the fluctuations due to the free-streaming of matter particles out the fluctuations. The free-streaming scale is $\lambda_D \sim 1$ Mpc. Fluctuations on scales smaller than 1 Mpc are wiped out, this results in a 'bottom-up' scenario with higher structures forming due to tidal forces and by merging of smaller structures.

- The linear transfer function in adiabatic CDM models has:

$$t(k) = [1 + (ak + (bk)^{3/2} + (ck)^2)^\nu]^{-1/\nu}$$

where $a = 6.4(\Omega h^2)^{-1}$ Mpc, $b = 3.0(\Omega h^2)^{-1}$ Mpc, $c = 1.7(\Omega h^2)^{-1}$ Mpc and $\nu = 1.13$.

➢ The two major problems of this model are:

  - Assuming that light traces mass, simulations show that the correlation function for these models, when compared to the observed correlation implies a $\Omega h \sim 0.2$ (against $\Omega = 1$).
  - The predicted correlation function at large scales is less by a factor of 3 than the observed correlation. Also simulations do not produce giant voids as observed.

- Some of these problems are thought to be solved by considering 'biased CDM models', although consistency with recent CMB observations seem to require antibiased CDM models

Models of structure formation

➢ HDM models

- The growth of the fluctuations is similar to that for CDM models

- Fluctuations on scales smaller than:

$$\lambda_D \sim 40 \left(\frac{m_\nu}{30\,\mathrm{eV}}\right)^{-1} \mathrm{Mpc}$$

are erased due to the neutrino free-streaming.

free-streaming scale is the distance travelled by a neutrino by the present epoch:

$$\lambda_D \sim 5ct_{rn}\frac{a(t_0)}{a(t_{rn})},$$

where t_{rn} is the time separating the relativistic/non-relativistic regimes of the neutrino, when $3kT_\nu \sim m_\nu c^2$.

This damping scale corresponds to scales of superclusters (~ 1015 M_0) and galaxies are formed from fragmentation of large pancake-like structures, in a 'top-down' scenario.

Models of structure formation

- The problems of this model are:

  - This process of structure formation seems to suggest that galaxies are outside clusters in contradiction with observations. This could be solved by incorporating topological defect models as seeds of the structure; as they are not affected by the neutrino free streaming, galaxies could be seeded at $t > t_{rn}$
  - The observed galaxy-galaxy correlation function requires a pancake formation at $z \sim 1$, contradicting the existence of galaxies with $z > 1$ and quasars with $z > 3$.
  - In order to produce galaxies and quasars at high redshifts this model should produce a high level of clustering today and this is not observed. It does not explain the dark halos of galaxies because they cannot cluster at these scales.

- Possible solutions to these problems:
  - neutrinos with $\Omega_\nu h^2 \sim 2$ implying $\lambda_D \sim 5h^{-1}$ Mpc; to assume that clusters trace better the density distribution, diminishing the existing discrepancies with observations
  - existence of additional seeds of structure like topological defects or primordial black holes

Models of structure formation

- MDM models

  - Since adiabatic HDM models fail to explain the observed small-scale structure in the universe, whereas CDM does not seem to reproduce the large-scale structure present in large-scale structure surveys, a mixture of both hot and cold dark matter in conjunction with the baryonic matter seem to be a possible means of balancing the contributions from both components in order to reproduce the observed power spectrum

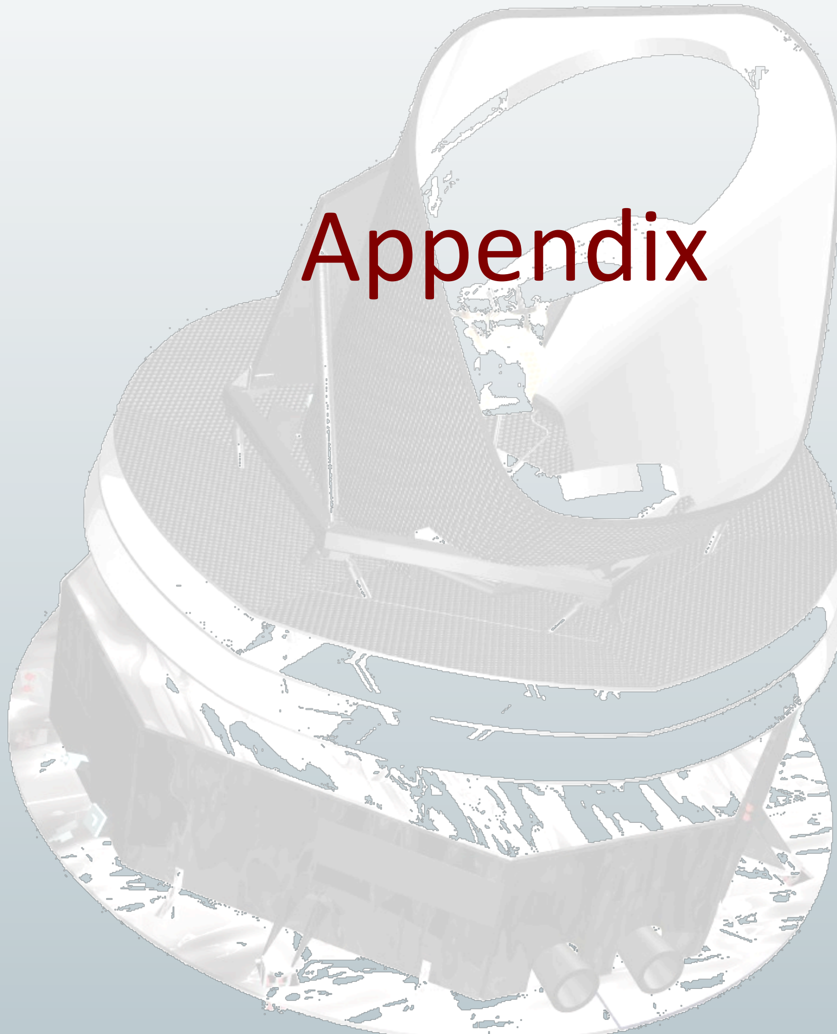
- Currently the CMB observations and in particular the recent Planck results support a

Spatially flat 6-parameter ΛCDM Cosmology

with a Power law spectrum of adiabatic scalar perturbations

In this model, the Universe is spatially flat and is dominated at late times by cold dark matter and mysterious form of `dark' energy that causes the observed accelerated expansion. Evolving on this background are density fluctuations, plausibly generated during an early period of inflation, which are very close to Gaussian and have a nearly scale-invariant power spectrum

Appendix



Graça Rocha
JPL/Caltech
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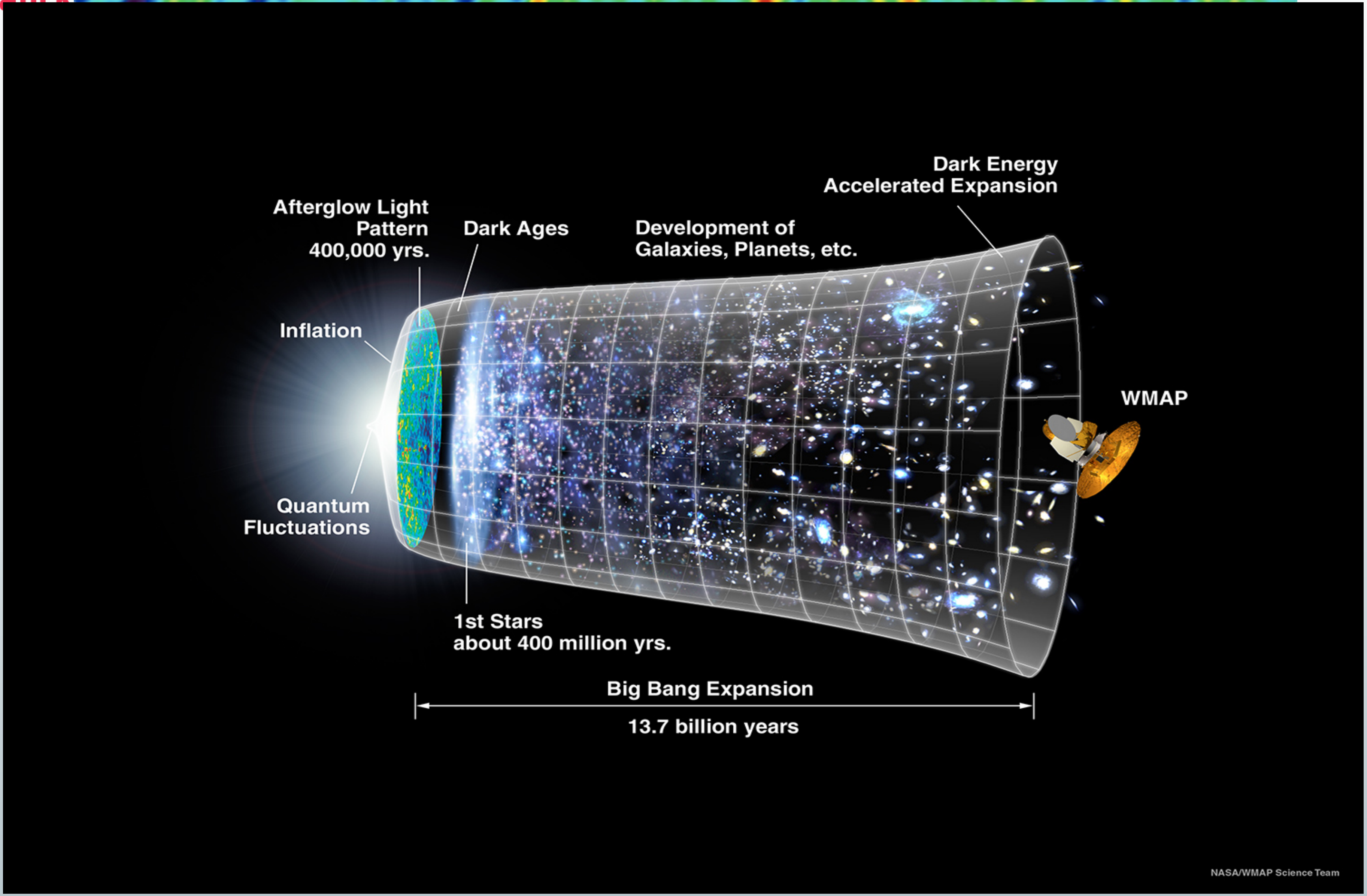
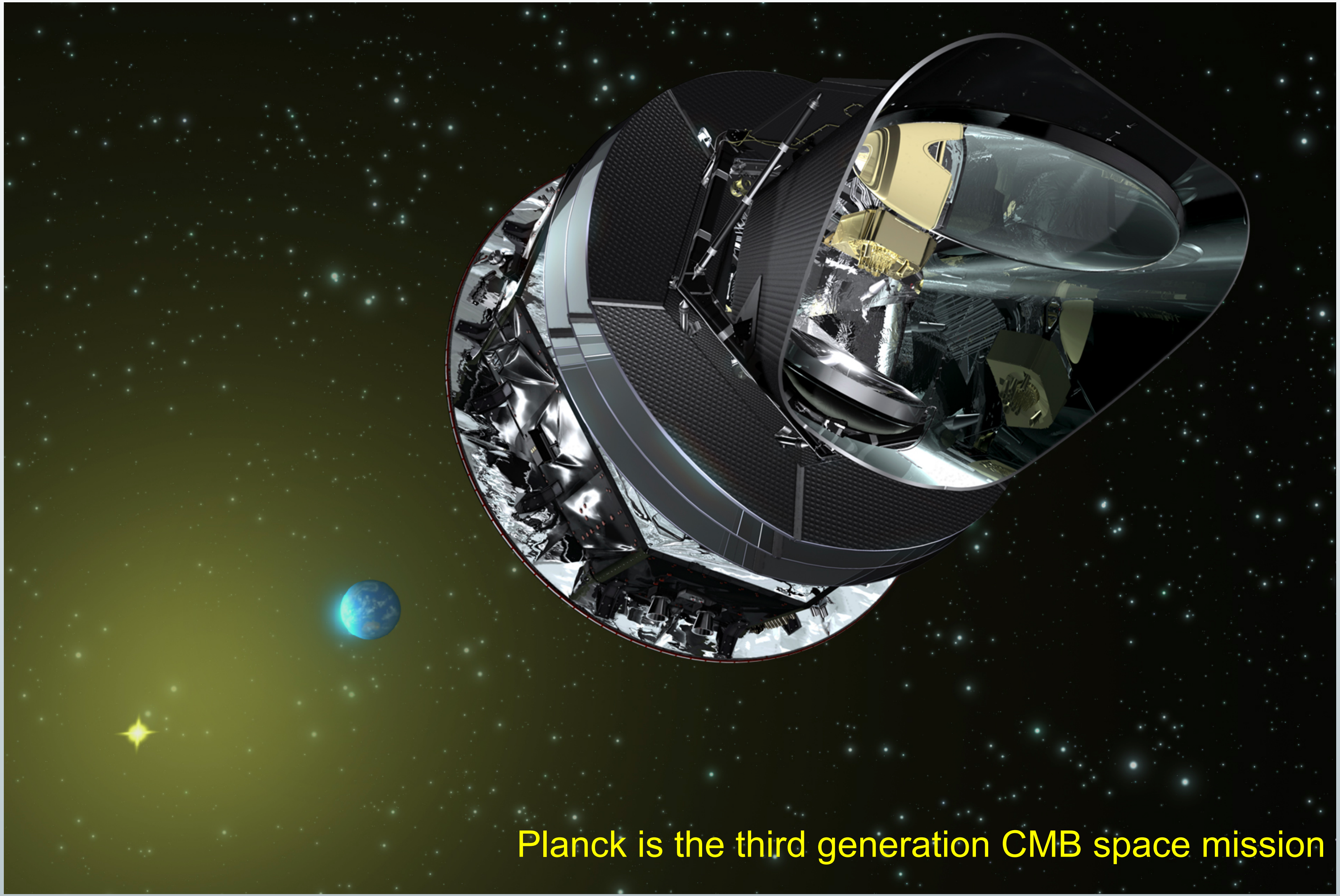
School, S. Paulo, September 2013

CMB Timeline for the Universe

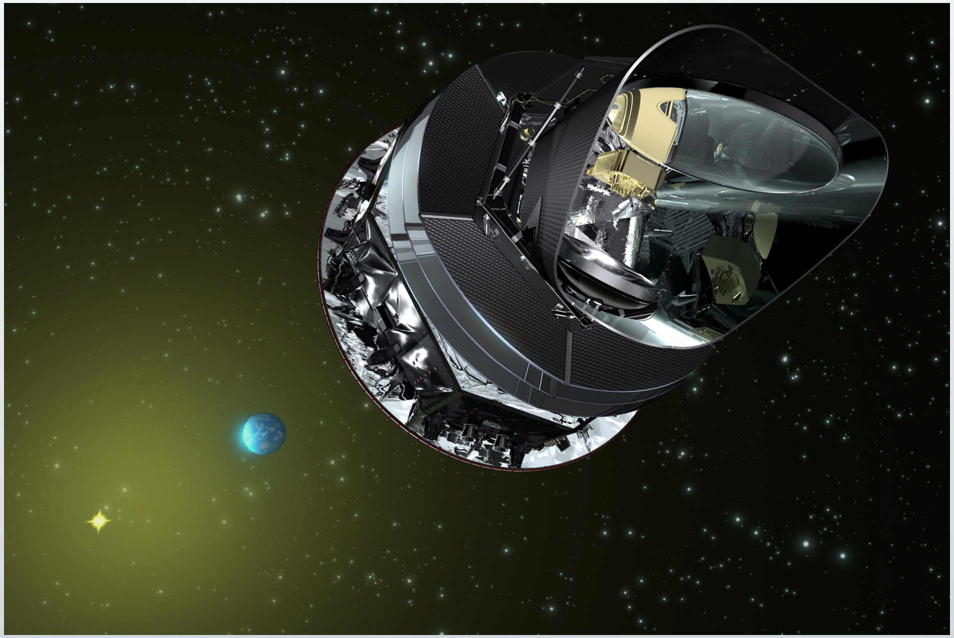


Planck



Planck

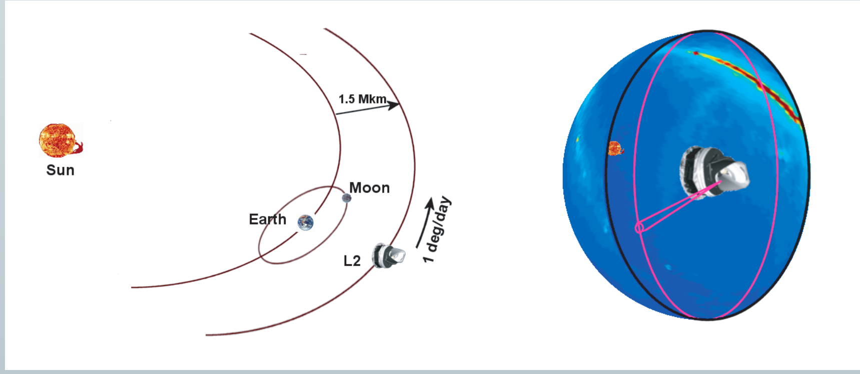
Planck is the third generation CMB space mission



Scientific goal:

Measure the tiny fluctuations
In the temperature of this relic radiation called Cosmic Microwave Background with high accuracy and resolution

Fly at Sun-Earth $\mathbf{L}_2$ point



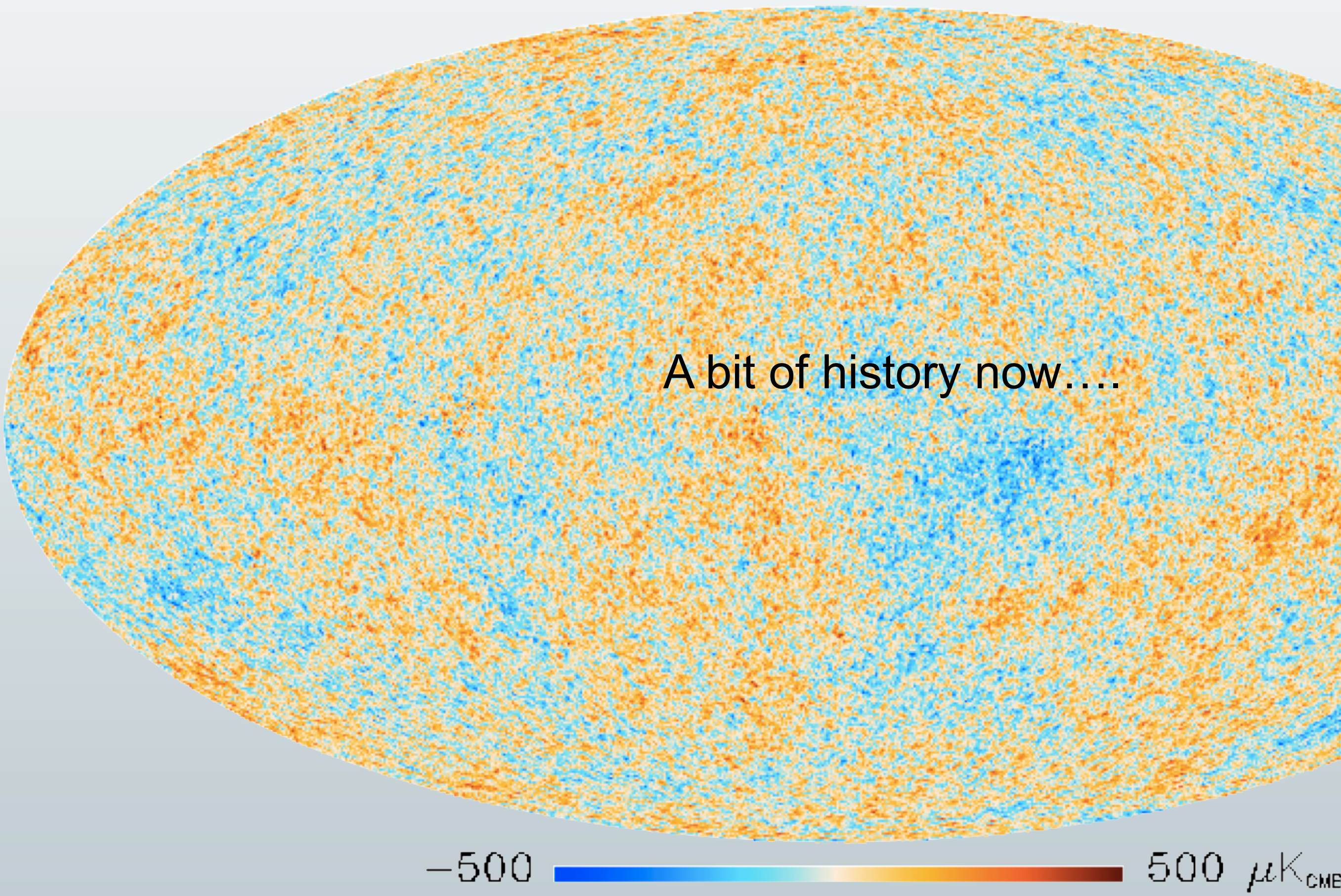
Two instruments:

- Low Frequency Instrument (LFI), 20-K cryogenic amplifiers
- High Frequency Instrument (HFI), 0.1-K bolometers

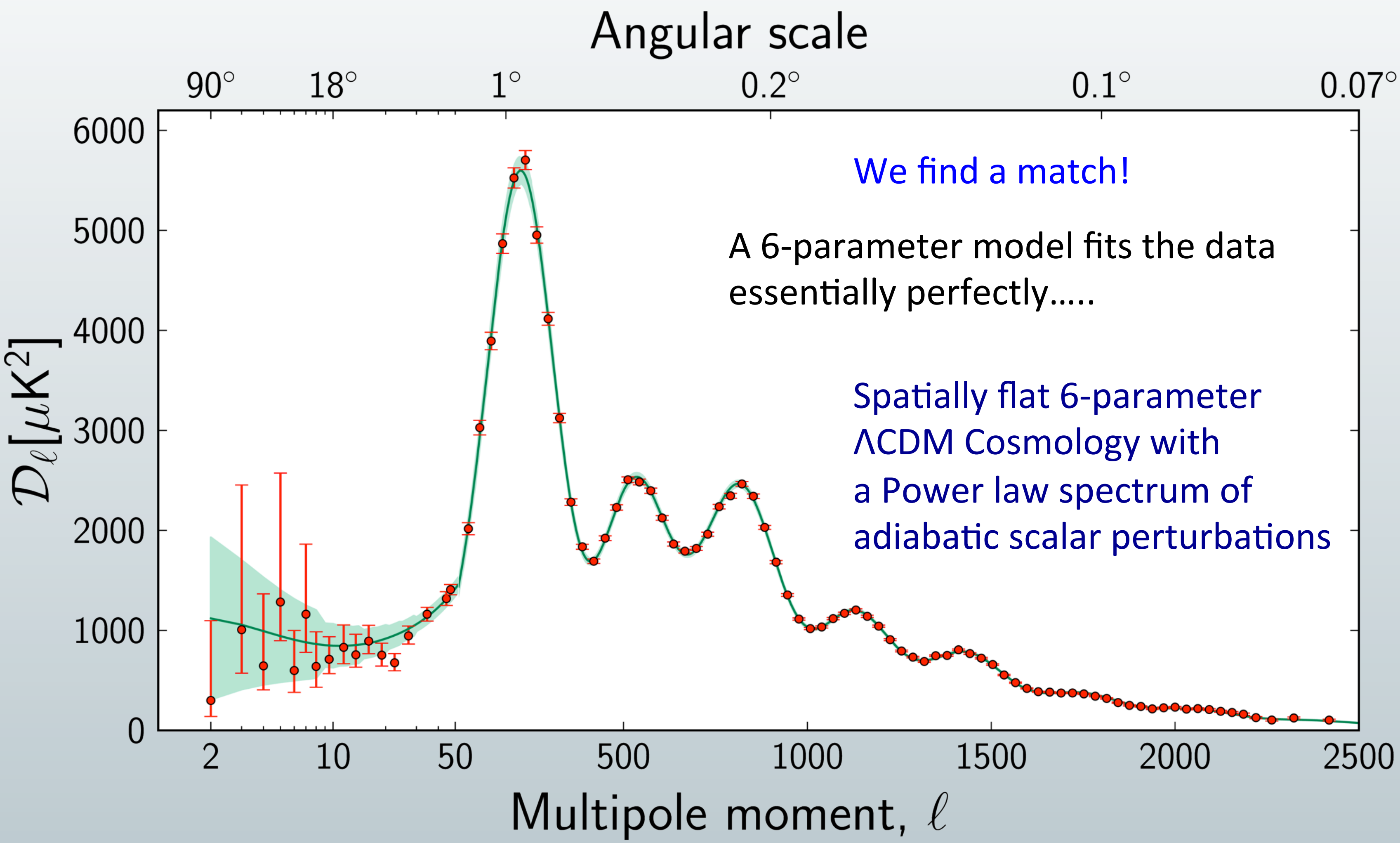
Covers a large number (9) frequencies:
30, 44, 70, 100, 143, 217, 353, 545, 857 GHz

Cosmic Microwave Background Fluctuations

Planck gives us the sharpest and clearest view of this ancient light.



CMB angular power spectrum from Planck measurement vs models



We find a match!

A 6-parameter model fits the data essentially perfectly…..

Spatially flat 6-parameter
ΛCDM Cosmology with
a Power law spectrum of
adiabatic scalar perturbations