Emergent Universe Scenario and The Low CMB Multipoles

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Workshop on
Gravity and Cosmology

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The Cosmic Microwave Background (CMB)

- The CMB is a prediction of the Big Bang model.

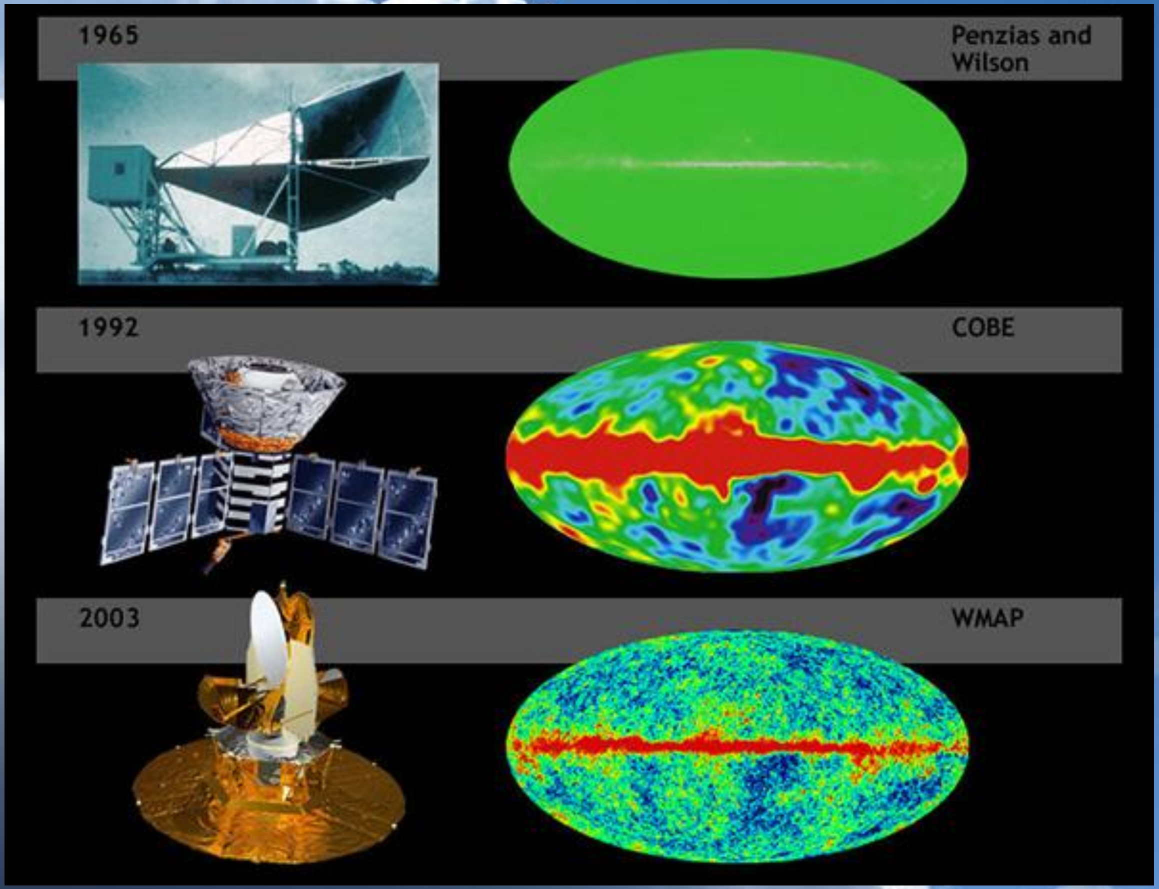
- The CMB is a relic radiation emitted at the time of recombination, when stable atoms formed, permitting the free transit of photons.

- The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old.

- The CMB was first detected by Penzias and Wilson (1965) and it has the spectrum of a blackbody with T = 2.726 K, in all directions of the sky.

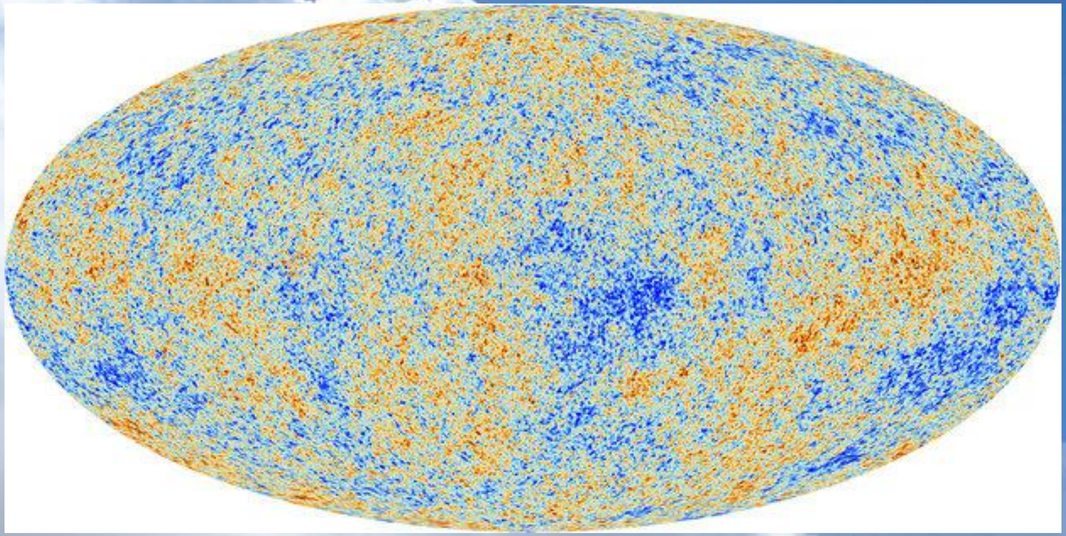
Anisotropies on the CMB

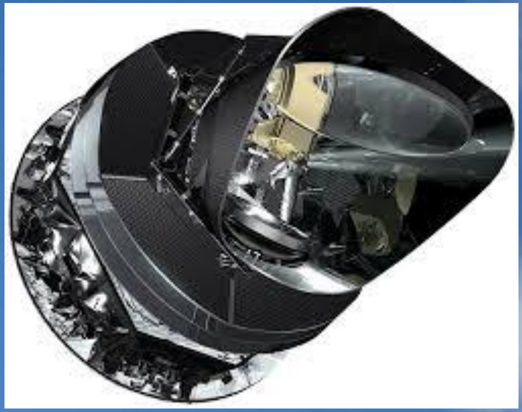
The first hint towards the existence of CMB anisotropy came from the *Relic experiment (1992).*



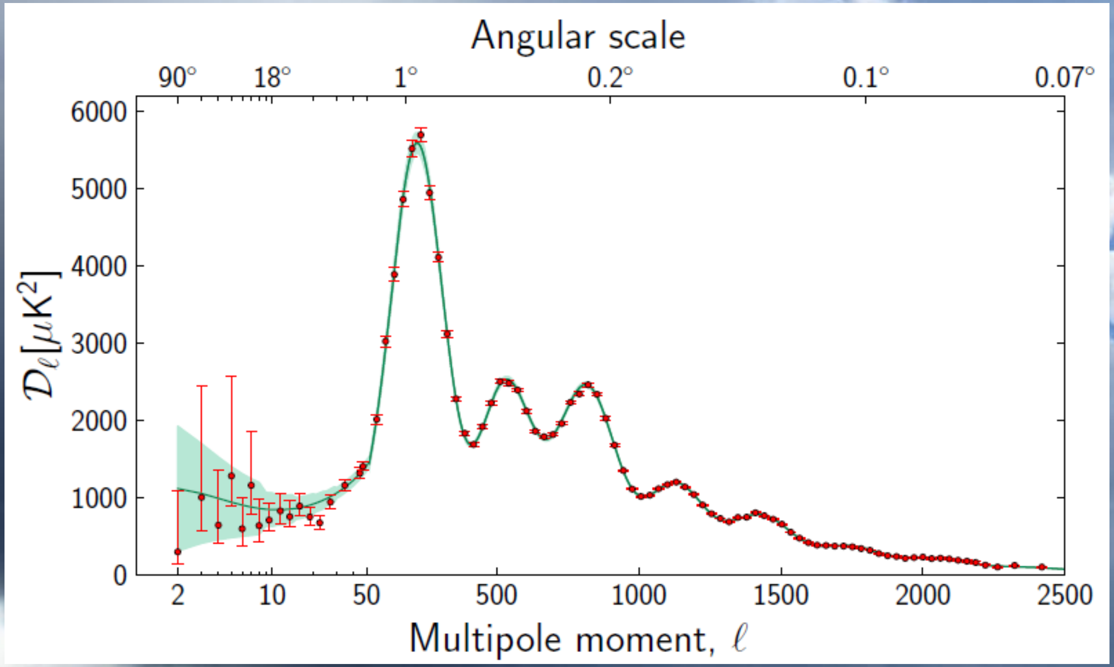
The anisotropy is at the level of $\delta T/T = 10^{-4}$-10^{-5} (once it is eliminated the contribution of the motion of the Earth with respect to the CMB referent frame).

CMB seen by Planck (2013)



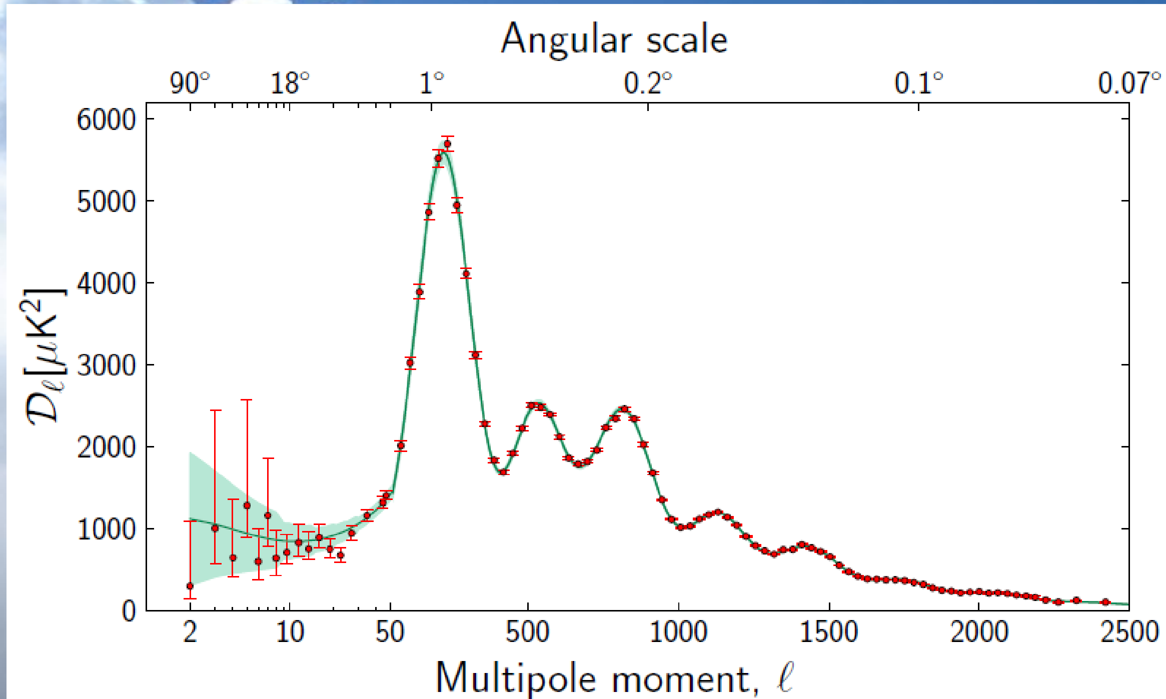


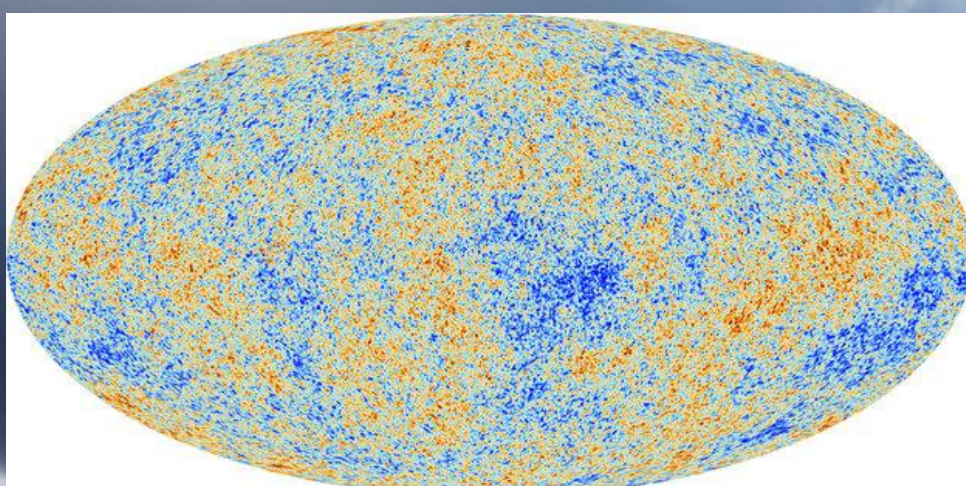
Planck 2013 (ESA)



Temperature power spectrum

Temperature power spectrum of the CMB





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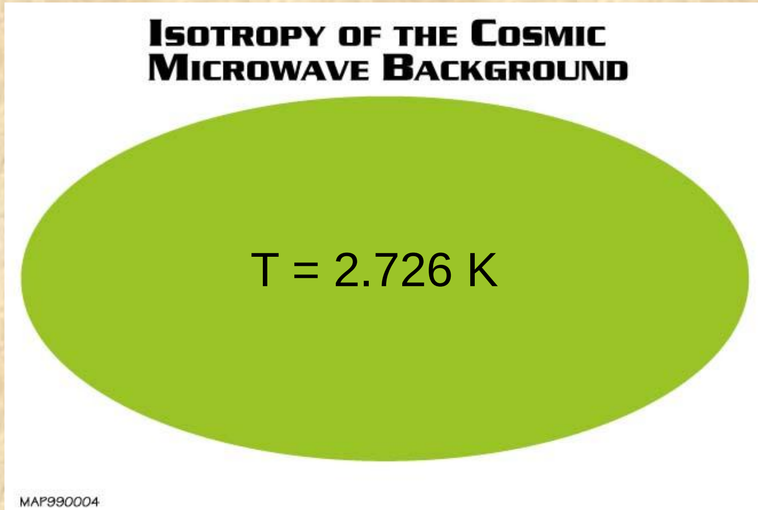
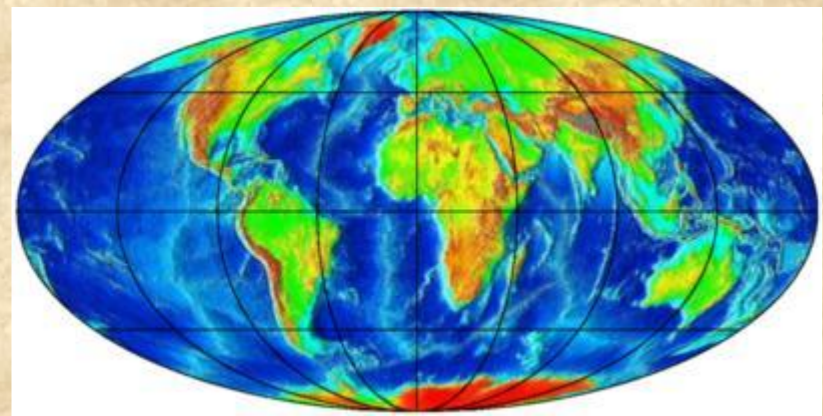
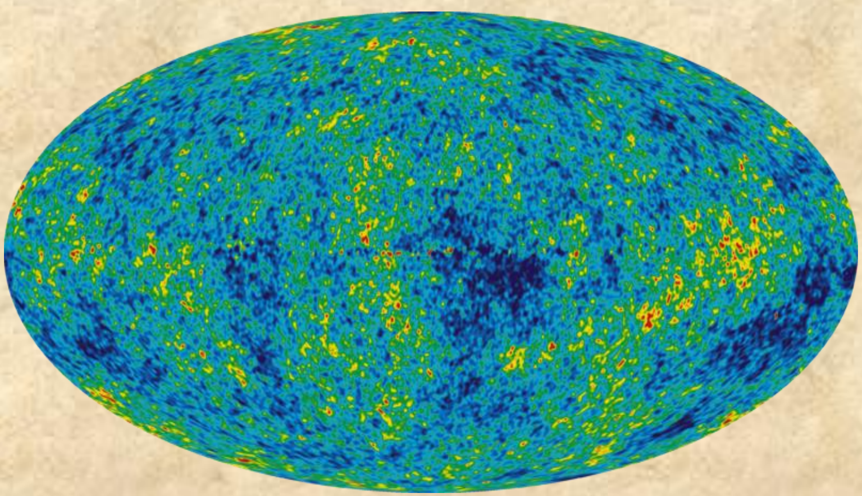
The Horizon Problem



This figure challenges the standard physical.

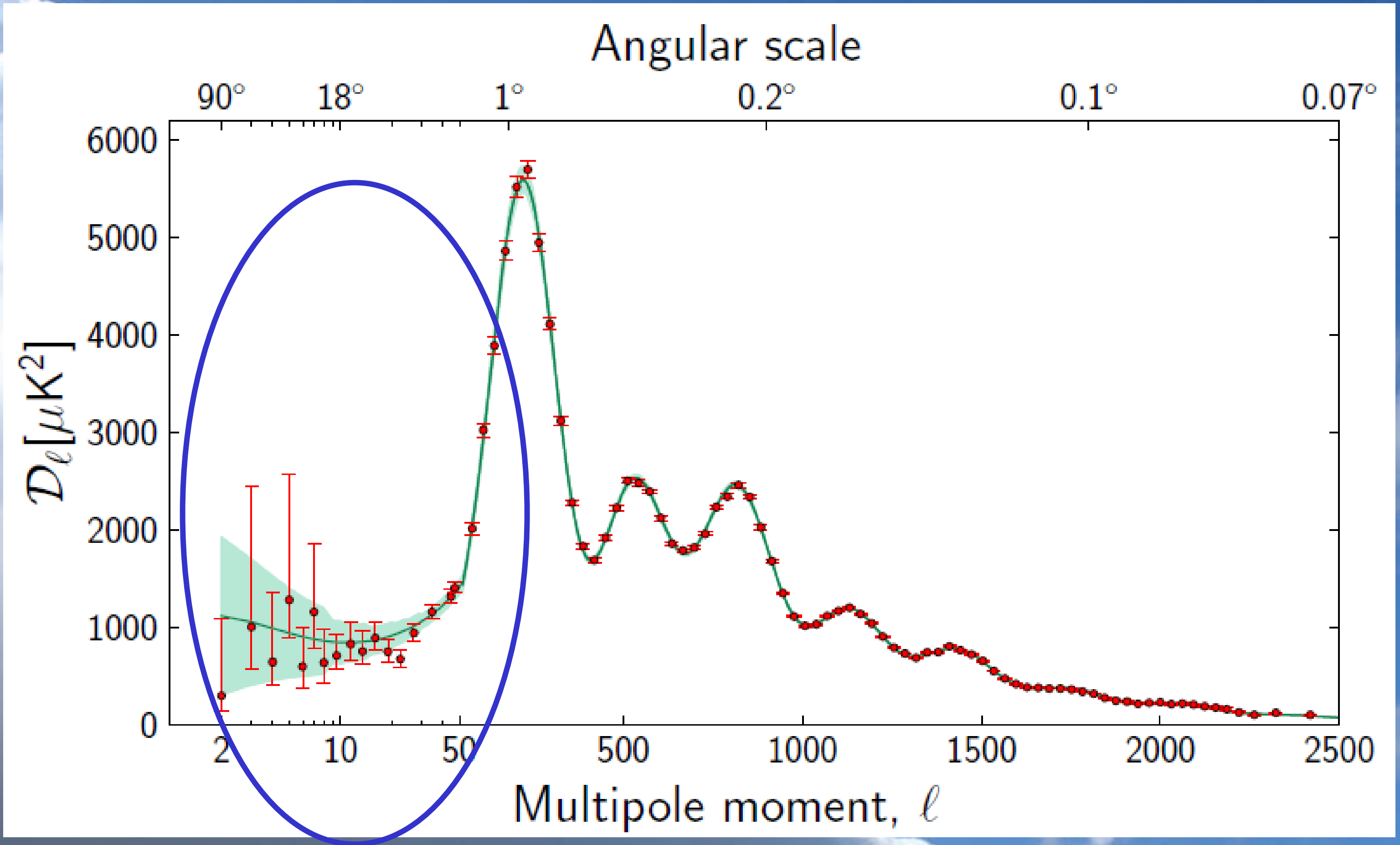
Notice that these ovals are all maps of the entire celestial sphere





$dT/T = 10^{-4}$-10^{-5}

Then, it is hard to understand how these causally disconnected regions ended up with essentially the same temperature

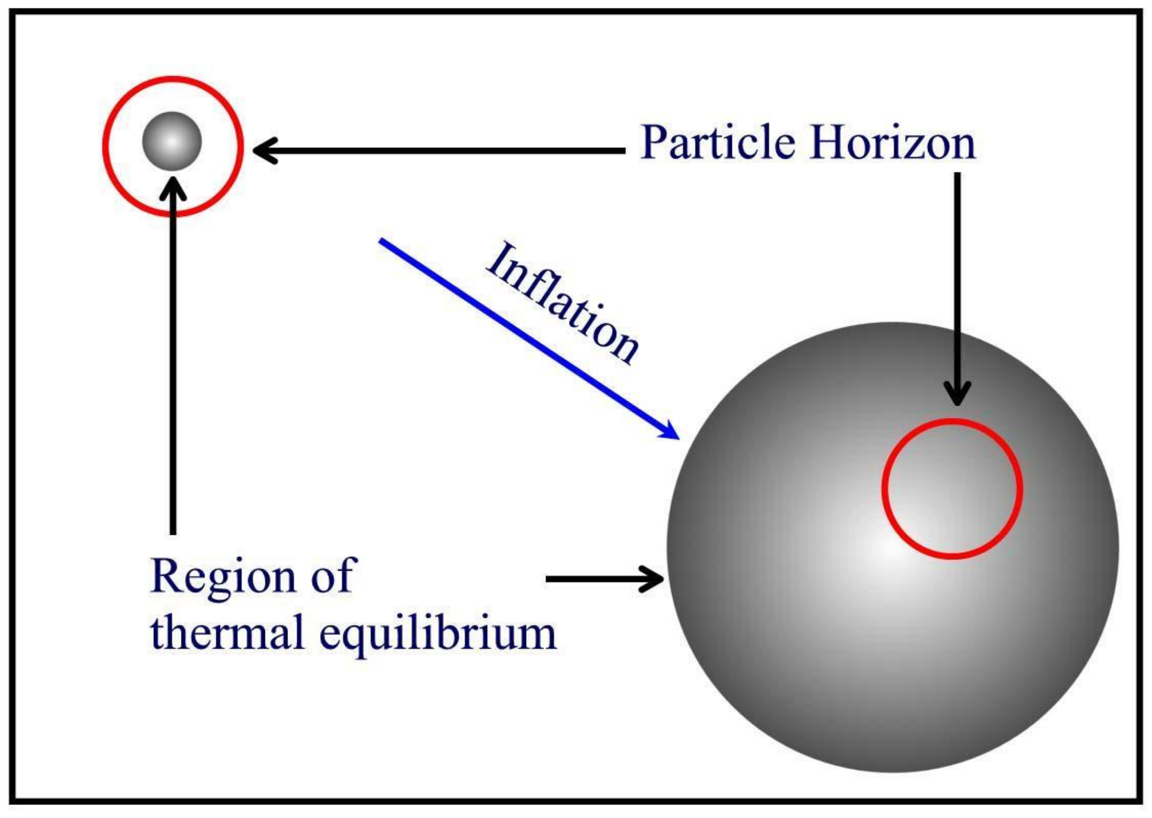


Temperature power spectrum. Points show the Plank data.
(Planck 2013 results. I. Overview of products and scientific results arXiv:submit/0674450)

No causal process could have generated the correlations seen on larger scales than 1^0

Cosmic Inflation

The scheme of inflation is based on the idea that there was an early phase, before the Big Bang, in which the universe evolved through a nearly exponential expansion during a short period of time at high energy scales. (Guth, Linde and Albrecht & Steinhardt ~80´s).



The Horizon $(R \sim 1/H)$

H = Hubble parameter

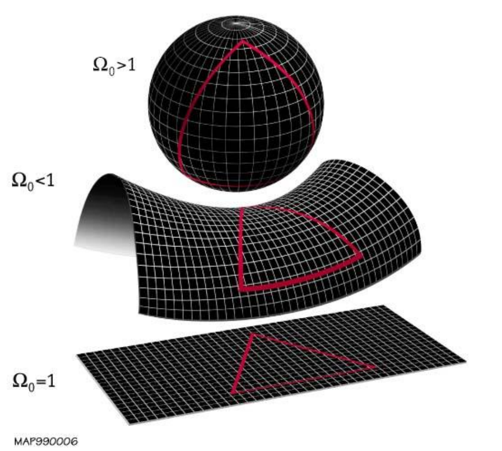
Inflation: standard scenario

Friedman-Lemaître-Robertson-Walker (FLRW)

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

k > 0 Closed universe
k = 0 Flat universe
k< 0 Open universe

$a(t)$ Scale factor



$$S = \int d^4x \sqrt{-g} \left\{ -\frac{R}{16\pi G} + \mathcal{L}_m \right\}$$

Friedmann equation

$$H^2 = \frac{1}{3}\rho - \frac{\kappa}{a^2}$$

$$H \equiv \frac{\dot{a}}{a}$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6}\left(\rho + 3P\right)$$

Energy conservation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + 3H\left(\rho + P\right) = 0$$

The Lagrangian of a minimally-coupled scalar field

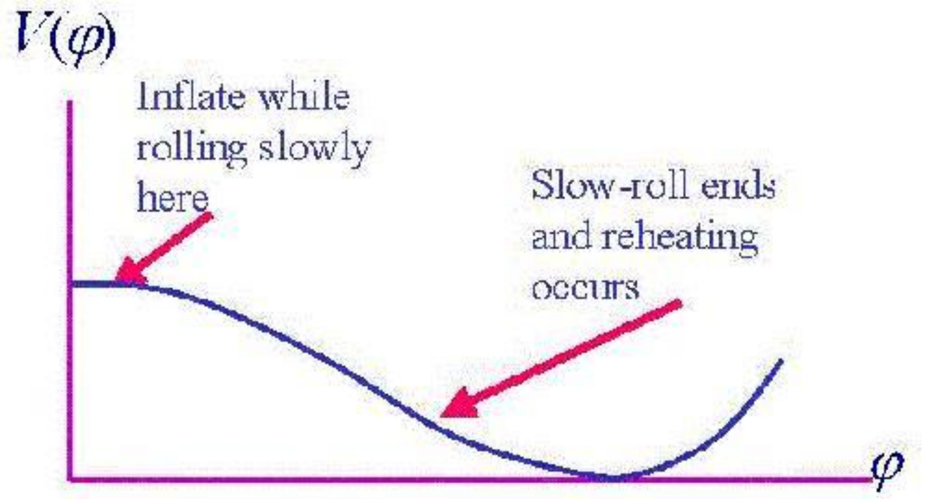
$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi),$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi).$$

Slow-roll inflation

$$H^2 = \frac{1}{3M_P^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$



$$H^2 = \frac{1}{3M_P^2}V$$

Slow-roll condition

$$\dot{\phi}^2 \ll V(\phi)$$

$$\ddot{a} > 0$$

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

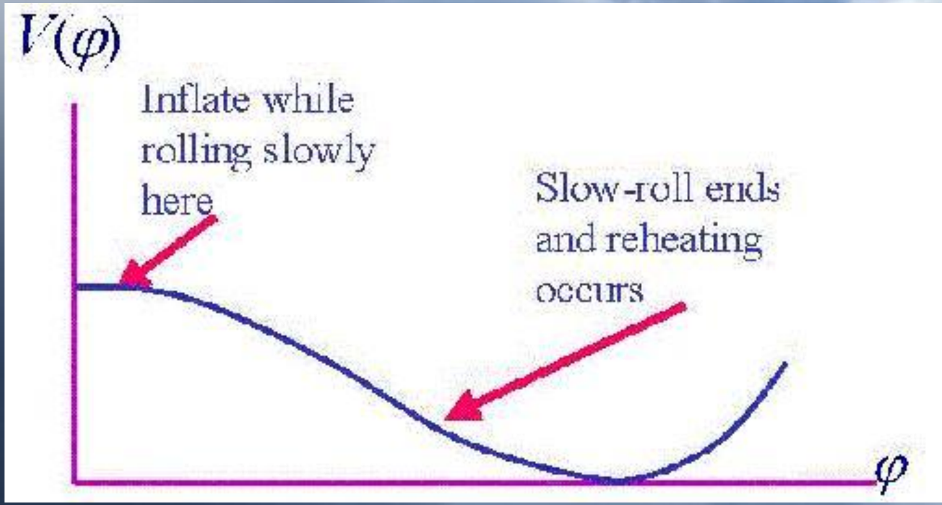
Then, during Inflation the Hubble parameter H is almost constant

Primordial perturbations

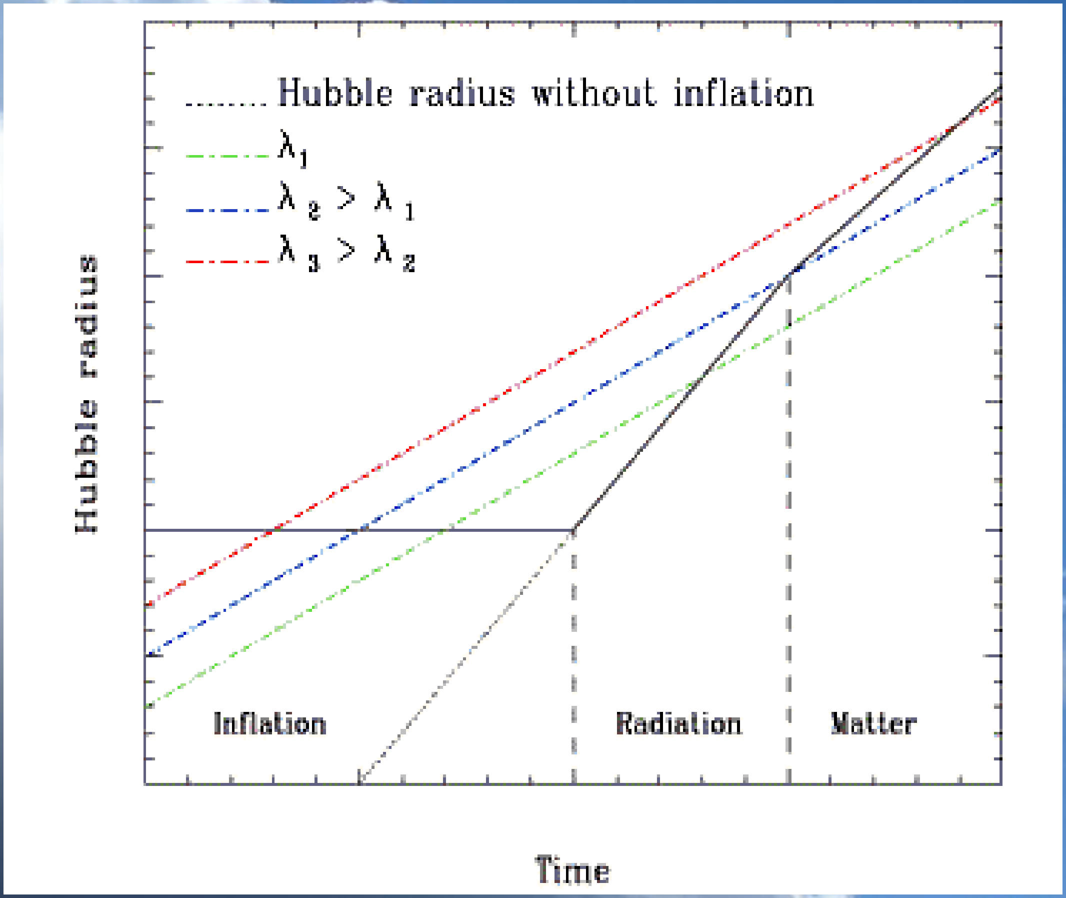
In the standard inflationary Universe quantum fluctuations of the inflaton field give rise to a curvature perturbation.
This curvature perturbation is then the seed for structure formation in the Universe, leaving also their imprint on the CMB.

In particular, for a very flat inflaton potential the quantum fluctuation becomes:

$$\delta\phi(k) = H_k/(2\pi)$$



Notice: **Modes of different scale exit the horizon at different time.** ***Once a given*** **mode exit the horizon its amplitude freeze. This perturbation then reenter the horizon during the post inflationary era.**

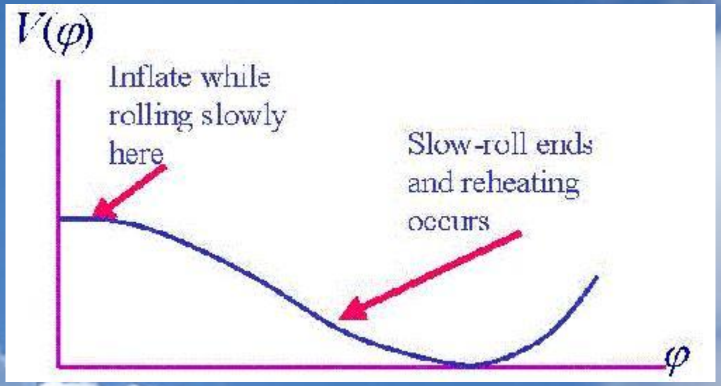


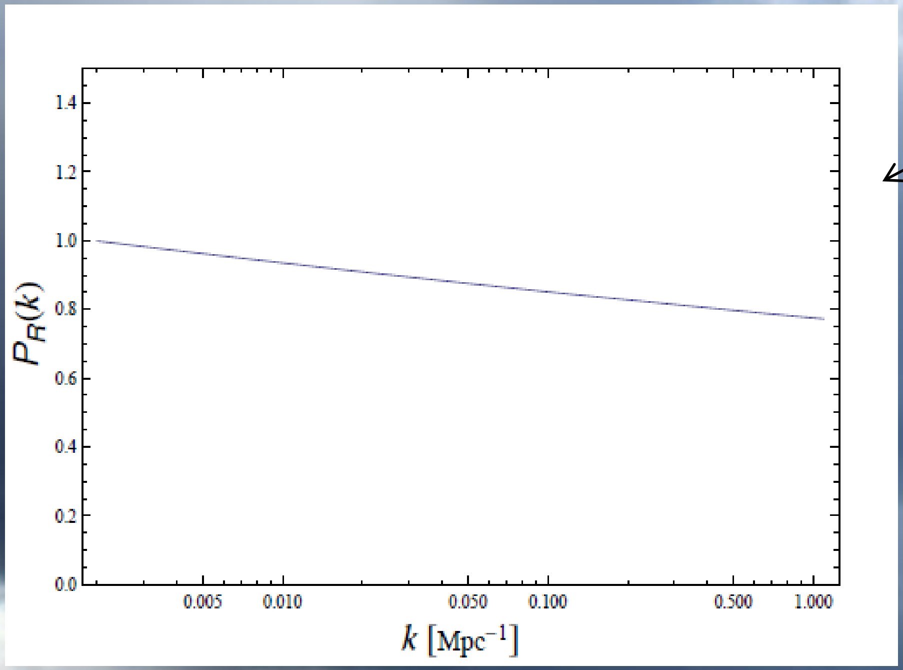
$$\delta\phi(k) = H_k/(2\pi)$$

- Then, perturbation of large scale (small k) have more power that the small scale perturbation.
- Standard slow-roll inflation predicts a slightly red-tilted power spectrum of the primordial perturbation.

$$H^2 = \frac{1}{3M_P^2}V$$

$$\delta\phi(k) = H_k/(2\pi)$$





Primordial perturbation generated during Inflation

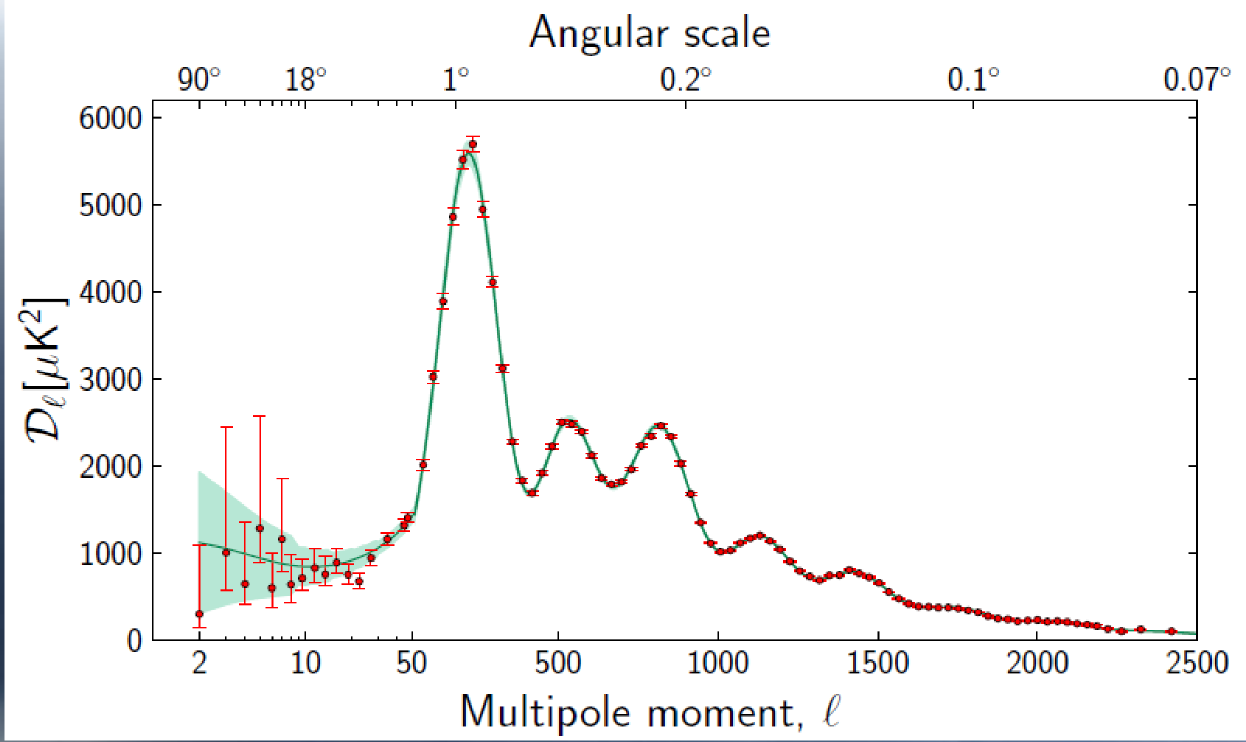
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_s}\right)^{n_s - 1}$$

$n_s < 1$

Planck Collaboration

studied in the companion *Planck* paper Planck Collaboration XVI (2013), the primordial power spectrum $\mathcal{P}_{\mathcal{R}}(k)$, which includes only the adiabatic mode, is modeled using the power law $\mathcal{P}_{\mathcal{R}}(k) = A_s\,(k/k_*)^{n_s-1}$, for which the best fit values are $A_s = 2.20 \times 10^{-9}$ and $n_s = 0.9603$ for a pivot scale $k_* = 0.05\ \mathrm{Mpc}^{-1}$. An extension of this parameterization is

However, there are intriguing observations on cosmic microwave background radiation, suggesting a lack of power at large angular scales (very low multipoles, $l < 40$). These results were first obtained by COBE [22] and WMAP [1] and now are confirmed by Planck [2] and defy the standard model of slow-roll inflation.



Although these results are well within our cosmic variance and statistically their significance is still low, the power deficit is not insignificant. Planck collaboration reported a power deficit in the low multipoles CMB power spectrum of order $5-10\%$ (with respect to the Planck best-fit ΛCDM model [15, 16]) with statistical significance $2.5 \sim 3\,\sigma$.

This situation is interesting because the very low l modes in the CMB spectrum at present time, correspond to very large wavelength modes. Since these modes have been superhorizon sized between inflation and now, they have not been contaminated by the later evolution of the Universe. For this reason we could attribute the new feature observed in the spectrum at low l to physics at the very earliest Universe, perhaps before slow-roll inflation [17].

Some ideas

❑**The hypothesis of *small universe with a compact topology. In this case perturbations* on scales exceeding the fundamental cell size are suppressed.**

❑**Another possibility is hyperspherical topology corresponding to a closed universe.**

❑**The topological approach have some problems with the S-statistic and the matched circle test.**

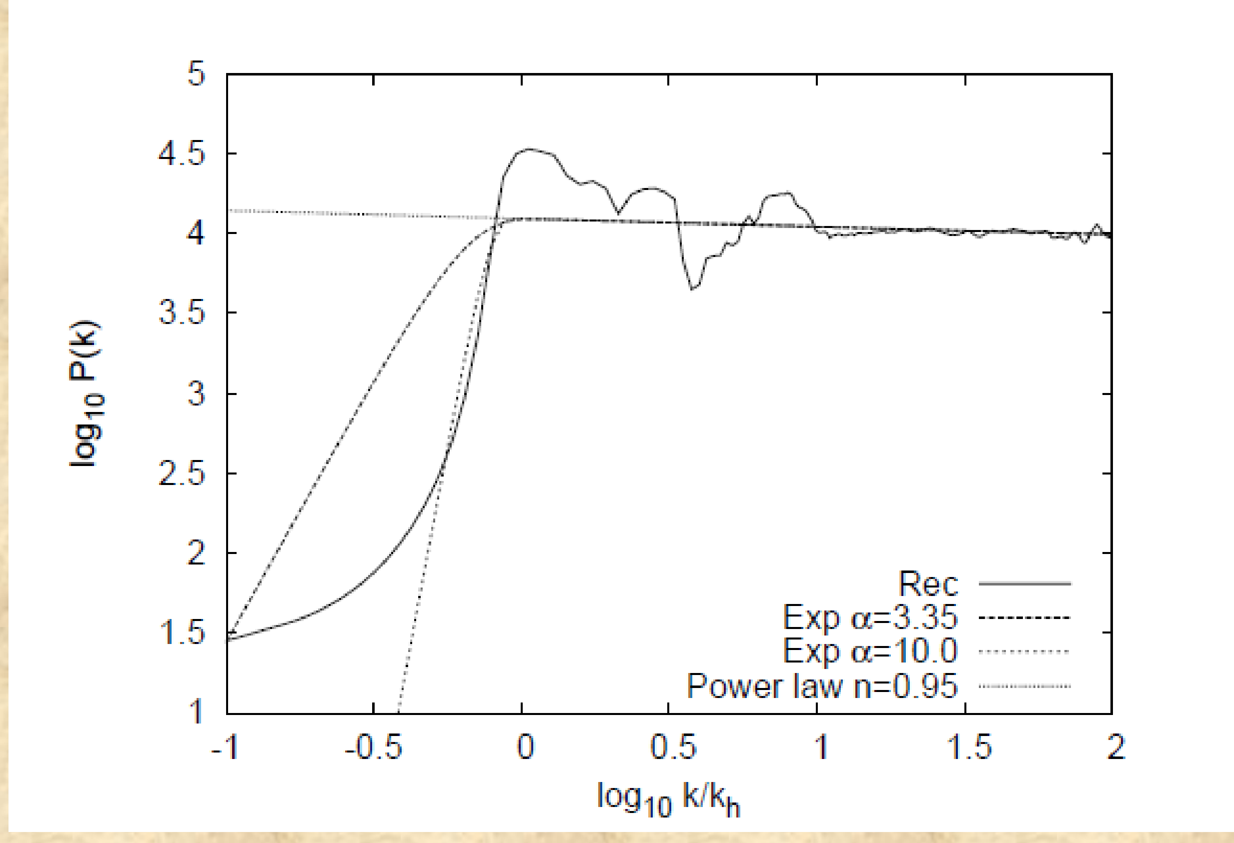
❑**On the other hand, Planck searches yield no detection of the compact topology**

❑**Another approach is introduce a cutoff in the primordial power spectrum. This cutoff is normally introduce by hand, but, linked to:**

- **spatial curvature scale**
- **String physics**
- **fast rolling stage in the evolution of the inflaton field.**

This approach is interesting since it have been claimed that from the observed angular power spectrum it is possible to deconvolve the primordial power spectrum.

The most prominent feature of the recovered primordial power spectrum is a sharp, infrared cutoff on the horizon scale



Primordial power spectrum from WMAP, Arman Shafieloo, Tarun Souradeep
Phys.Rev. D70 (2004) 043523

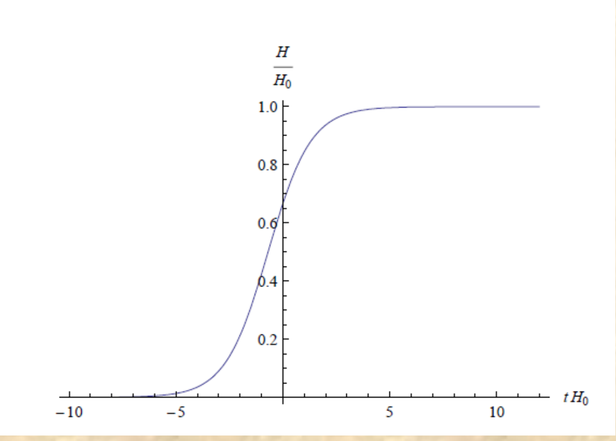
Dhiraj Kumar Hazra, Arman Shafieloo, Tarun Souradeep
Phys. Rev. D 87, 123528 (2013)

Super Inflation approach

At this respect, it has been suggested that the low l power could be related with a period of super-inflation, previous to the standard slow-roll inflationary regimen [38, 39], where the super-inflationary period is characterized by the condition $\dot{H} > 0$. In particular in Ref. [38], this possibility was studied in the context of bouncing universes.

[38] T. Biswas and A. Mazumdar, arXiv:1304.3648 [hep-th].

It is interesting to note, that a super inflationary period is related with any mechanism which attempts to solve the cosmological singularity problem in a semiclassical spacetime description. There are two ways to avoid the singularity problem



1) Non-singular bounce

2) Emergent Universe scenario
(assume that the universe began to evolve from a static state)

Emergent Universe Scenario and the Low CMB Multipoles

Pedro Labraña*

(Dated: December 24, 2013)

Abstract

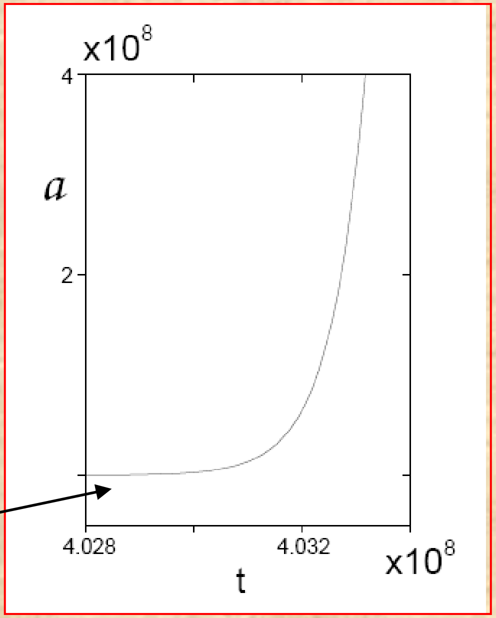
In this work we study super inflation in the context of the Emergent Universe (EU) scenario. The existence of a super inflating phase before the onset of slow roll inflation arises in any Emergent Universe model. We found that the super inflationary period in the EU scenario produce a suppression of the CMB anisotropies at large scale which could be responsible of the observed lack of power at large angular scales of the CMB.

The Emergent Universe scenario

Singularity Theorems: $\begin{cases} k = 0 \text{ or } -1, \\ H > 0 \end{cases}$

- **The universe always existed, but initially the universe is static (Past eternal Einstein static (ES) state)**
- **Something happens and the universe begins to evolve**
- **Inflation**

These models assume that the universe began to evolve from a static state.



Past eternal
universe

VOLUME 90, NUMBER 15 — PHYSICAL REVIEW LETTERS — week ending 18 APRIL 2003

Inflationary Spacetimes Are Incomplete in Past Directions

Arvind Borde,[1,2] Alan H. Guth,[1,3] and Alexander Vilenkin[1]

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[2]*Natural Sciences Division, Southampton College, New York 11968*
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(Received 5 October 2001; revised manuscript received 24 January 2003; published 15 April 2003)

Many inflating spacetimes are likely to violate the weak energy condition, a key assumption of singularity theorems. Here we offer a simple kinematical argument, requiring no energy condition, that a cosmological model which is inflating—or just expanding sufficiently fast—must be incomplete in null and timelike past directions. Specifically, we obtain a bound on the integral of the Hubble parameter over a past-directed timelike or null geodesic. Thus inflationary models require physics other than inflation to describe the past boundary of the inflating region of spacetime.

VOLUME 72, NUMBER 21 — PHYSICAL REVIEW LETTERS — 23 MAY 1994

Eternal Inflation and the Initial Singularity

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(Received 28 October 1993)

It is shown that a physically reasonable spacetime that is eternally inflating to the future must possess an initial singularity.

Vilenkin's arguments shows that null and timelike geodesics are, in general, past-incomplete in inflationary models, whether or not energy conditions hold, provided only that the averaged expansion condition holds along these past-directed geodesics.

$$H > 0$$

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

Any backward-going null (or timelike) geodesic have a finite affine (proper time) length.

The Emergent Universe scenario

However, recently, models that escape this conclusion have been Studied. These models do not satisfy the geometrical assumptions of these theorems.

$$H > 0$$

$$k = 0 \text{ or } -1,$$

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Class. Quantum Grav. **21** (2004) 223–232 PII: S0264-9381(04)67439-9

The emergent universe: inflationary cosmology with no singularity

George F R Ellis[1] and Roy Maartens[1,2]

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Class. Quantum Grav. **21** (2004) 233–249 PII: S0264-9381(04)67591-5

The emergent universe: an explicit construction

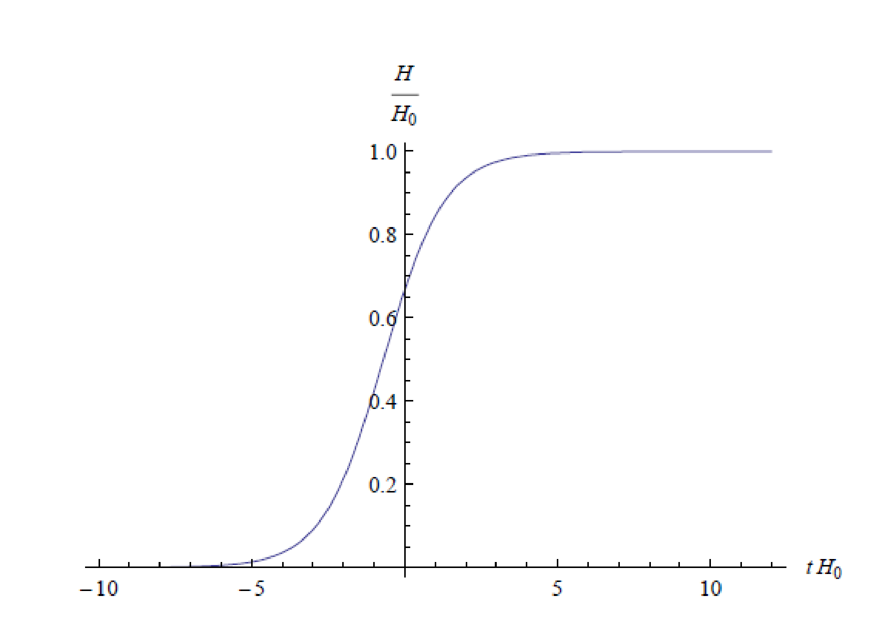
George F R Ellis, Jeff Murugan and Christos G Tsagas

Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7700, Cape Town, South Africa

In the EU scenario, the evolution of the scale factor could be modeled by the following expression, see [65, 66]

$$a(t) \simeq a_0 + A\, e^{H_0\, t} \tag{1}$$

We can note that, a generic characteristic of the EU scenario is the existence of a super inflation phase where $\dot{H} > 0$ before slow-roll inflation. In this model the evolution described in Eq. (1) corresponds precisely to the super inflationary phase of the evolution of the EU, which asymptotically approaches to the de Sitter expansion phase.



$$\delta\phi(k) = H_k/(2\pi)$$

THE PRIMORDIAL PERTURBATION IN EU

The scalar perturbations to the FRW geometry, in the longitudinal gauge, can be written as follow:

$$ds^2 = (1 + 2\Phi)\, dt^2 - (1 - 2\Phi)\, a(t)^2\, d\vec{x}^2, \tag{2}$$

where Φ is the newtonian gravitational potential.

The equation for the perturbations in momentum space is given by

$$v_k'' + k^2\, v_k - \frac{z''}{z}\, v_k = 0\,.$$

where we have used the Mukhanov variable [6, 88]:

$$v_k = a\left(\delta\phi_k + \frac{\phi'}{h}\,\Phi_k\right),$$

where $\delta\phi_k$ is the perturbations in the inflaton field and $'$ is derivative with respect to the conformal time $\eta = \int dt/a$ and we have used units $M_p = (8\pi G)^{-1/2} = 1$. Also, we have defined

$$
\begin{aligned}
z &= \frac{a\phi'}{h}, \\
h &= \frac{a'}{a}.
\end{aligned}
$$

$$a(\eta) = \frac{a_0}{1 - e^{a_0 H_0 \eta}}, \qquad \eta < 0$$

$$v_k'' - (a_0\, H_0)^2 e^{a_0 H_0 \eta} \left(\frac{\left(1 + e^{a_0 H_0 \eta}\right)}{\left(-1 + e^{a_0 H_0 \eta}\right)^2} \right) v_k + k^2 v_k = 0\,,$$

$$v_k(\eta) = \frac{1}{\sqrt{2k}} \left[\frac{e^{-ik\,\eta}}{1 - e^{a_0 H_0 \eta}} \right] \times \tag{9}$$

$${}_2F_1\Bigg(-1 - \frac{ik}{a_0 H_0} - \sqrt{1 - \left(\frac{k}{a_0 H_0}\right)^2}, \; -1 - \frac{ik}{a_0 H_0} + \sqrt{1 - \left(\frac{k}{a_0 H_0}\right)^2}; 1 - 2\frac{ik}{a_0 H_0}; e^{a_0 H_0 \eta} \Bigg),$$

where $2F_1$ is the hypergeometric function.

In the solution (9) we have consider (and appropriately normalized) the solution of Eq. (8) such that in the short wavelength limit, the normalized positive frequency modes correspond to the minimal quantum fluctuations

$$v_k \approx \frac{e^{-ik\eta}}{\sqrt{2k}}, \quad a\,H << k \quad . \tag{10}$$

Follow [35], we consider the spectrum of $Q \equiv v/a$ which becomes constant at late time,

$$P_Q = \frac{k^3}{2\pi^2}|Q|^2 \longrightarrow \frac{H_0^2}{\pi^2}\frac{\chi^2\,\Gamma[x_1]\,\Gamma[x_1^*]}{\Gamma[x_2]\,\Gamma[x_2^*]\,\Gamma[x_3]\,\Gamma[x_3^*]}\,, \tag{11}$$

where we have defined

$$x_1 = 1 - 2\,i\chi \tag{12}$$

$$x_2 = 2 - i\chi - \sqrt{1-\chi^2} \tag{13}$$

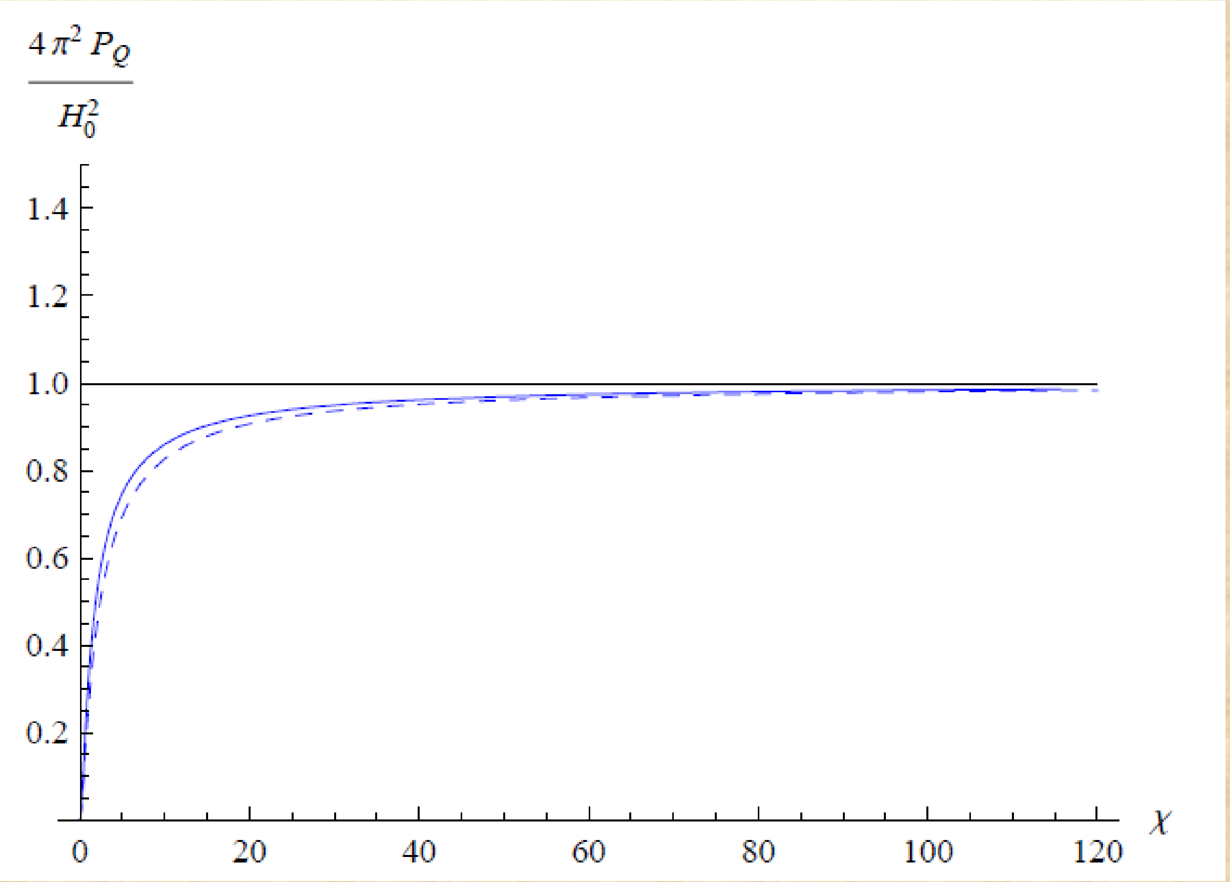
$$x_3 = 2 - i\chi + \sqrt{1-\chi^2} \tag{14}$$

$$\chi = \frac{k}{a_0\,H_0} \tag{15}$$

We can note that in the short wavelengths limit($k >> H_0$) we recovered the standard result of a nearly scale invariant spectrum

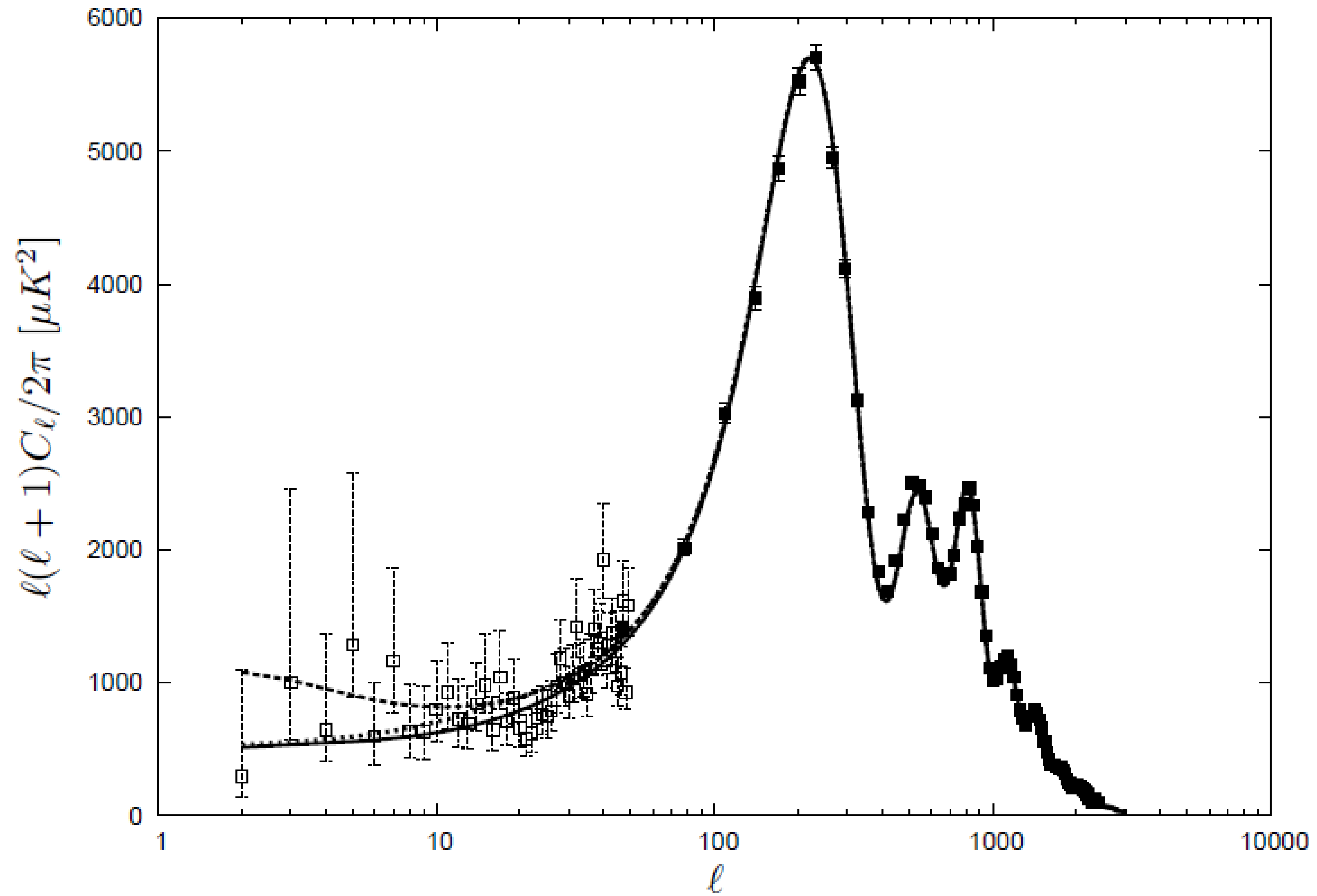
$$P_Q \rightarrow \left(\frac{H_0}{2\pi}\right)^2 \tag{16}$$

At super-horizon scales, the two modes Q_k and Φ_k are related by a k independent rescaling so that the spectrum given by Eq. (11) directly translates into the spectrum of Φ. In Fig. (3) we have plotted the spectrum of P_Q as a function of χ obtained from the analytical calculation Eq. (11), solid line. We can note that there are a suppression of the long wave modes as we expect given the super inflation regimen.



THE EFFECTIVE POWER SPECTRUM

$$\mathcal{P}_\Phi = A\ k^{n_s-1}\frac{\chi^2\,\Gamma[x_1]\,\Gamma[x_1^*]}{\Gamma[x_2]\,\Gamma[x_2^*]\,\Gamma[x_3]\,\Gamma[x_3^*]}\,.$$



In these examples we have consider the following values for the parameters in the case of EU scenario, Eqs. (17, 19), $A = 2.07 \times 10^{-9}$, $n_s = 0.9603$ and $a_0\, H_0 = 0.0002\,\mathrm{Mpc}^{-1}$. In the case of EU scenario with a cutoff Eqs. (18, 19) we consider $A = 2.42 \times 10^{-9}$, $n_s = 0.967$, $a_0\, H_0 = 0.0003\,\mathrm{Mpc}^{-1}$ and $k_{max} = 0.0015\,\mathrm{Mpc}^{-1}$. At this moment we are not doing a best fit calculation of theses parameters, just showing two particular cases and how them produce a suppression of the spectrum at large scales.

Conclusions

In recent cosmological observations, there are intriguing results on cosmic microwave background radiation suggesting a lack of power at large angular scales. This situation is interesting because they may give us clues towards physics at the very early Universe, perhaps before slow-roll inflation. In this context the EU models are an interesting arena to explore pre-inflationary physics and their possible implications to the CMB anomalies.

In this paper we study the primordial perturbations in the context of the EU scenario. In particular we focus in the primordial perturbations generated during the super inflationary phase. We found that the super inflationary period in the EU scenario produce a suppression of the primordial perturbations at large scale which could be responsible of the observed lack of power at large angular scales of the CMB.

Fin