⟨Quantum|Gravity⟩Society

How Predictive are Cosmological Theories?

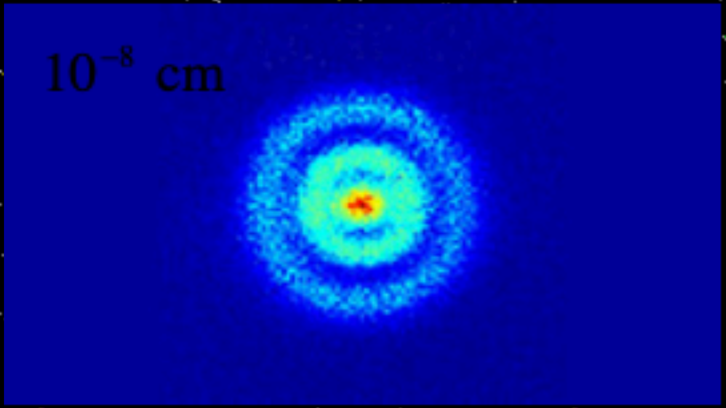
V. Mukhanov

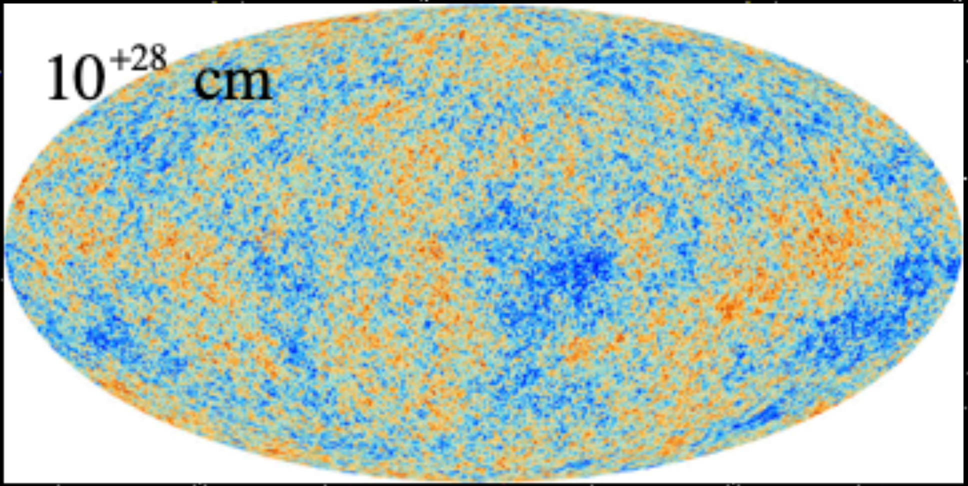
I never understood why the theory of relativity with its concepts and problems so far removed from practical life should for so long have met with a lively, or indeed passionate, resonance among broad circles of the public … I have never yet heard a truly convincing answer to this question.

How predictive are cosmological theories?

V. Mukhanov

ASC, LMU, München





$$\Delta q \times \Delta p \geq \frac{1}{2}\,\hbar$$

There are no (definitely) solved problems,
there are only more or less solved problems

Henri Poincare

The physics, both of the Academy and the Lycaeum,
as they are built, not on observation, but on argument,
have retarded the progress of real knowledge.
Edward Gibbon
The History of The Decline and Fall of the Roman
Empire, Vol. 5

"*In questions of science the authority of a thousand*
is not worth the humble reasoning of a single individual
...the modern observations deprive all former writers of
any authority..."
Galileo (*December* 1612)

Inflation is THE theory only when it is understood as the stage of unbroken accelerated expansion due to the same ingridient which is responsible for quantum fluctuations.

Otherwise it is rubbish without any predictions!!!

In this case it is unbeatable as predictive theory because it allows us to calculated the effect of amplification of quantum fluctuations in completely controlable weak coupling regimes

while most alternatives cannot even compete with "rubbish inflation" in a sense of controlable reproduction of outcome for quantum fluctuations

COSMOLOGY - Theology = $\exp(Ht)$

during at least 70 H^{-1}, but less than 10^6 $H^{-1} \rightarrow$

no any problems with predictions, which could falsify the theory in Popper's sense

What is relevant for predictions?

$-\varepsilon$ energy density

$-p$ pressure

$$1+w \equiv \frac{\varepsilon + p}{\varepsilon} \ll 1$$

during last 70 e-folds $(a = a_f \cdot e^{-N})$

$a)$ $1+w \ll 1$ for $N \gg 1$

$b)$ $1+w \approx O(1)$ for $N \simeq O(1)$

$c)$ $1+w$ is a smooth function of N

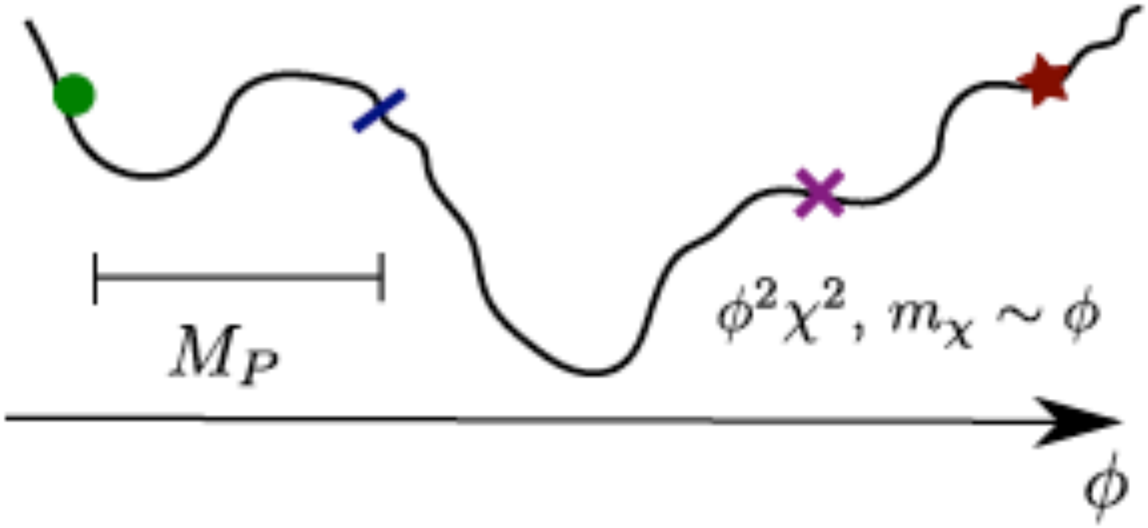
The only purpose of inflationary models relevant for observation is a maping

$$V(\varphi) \quad \text{to} \quad p \approx -\varepsilon$$

and this maping happened to be not crucial for robust predictions but important only for excluding definite potentials $V(\varphi)$, which anyway we will never be able to verify in any other independent experiments

$$V(\tau,\theta) = \frac{12W_0^2\xi}{(4\mathcal{V}_{\mathrm{m}}-\xi)(2\mathcal{V}_{\mathrm{m}}+\xi)^2} + \frac{D_1 + 12e^{-2a_2\tau}\xi A_2^2}{(4\mathcal{V}_{\mathrm{m}}-\xi)(2\mathcal{V}_{\mathrm{m}}+\xi)^2} + \frac{D_2 + \frac{16(a_2A_2)^2}{3a\lambda_2}\sqrt{\tau}e^{-2a_2\tau}}{(2\mathcal{V}_{\mathrm{m}}+\xi)} \qquad (25)$$

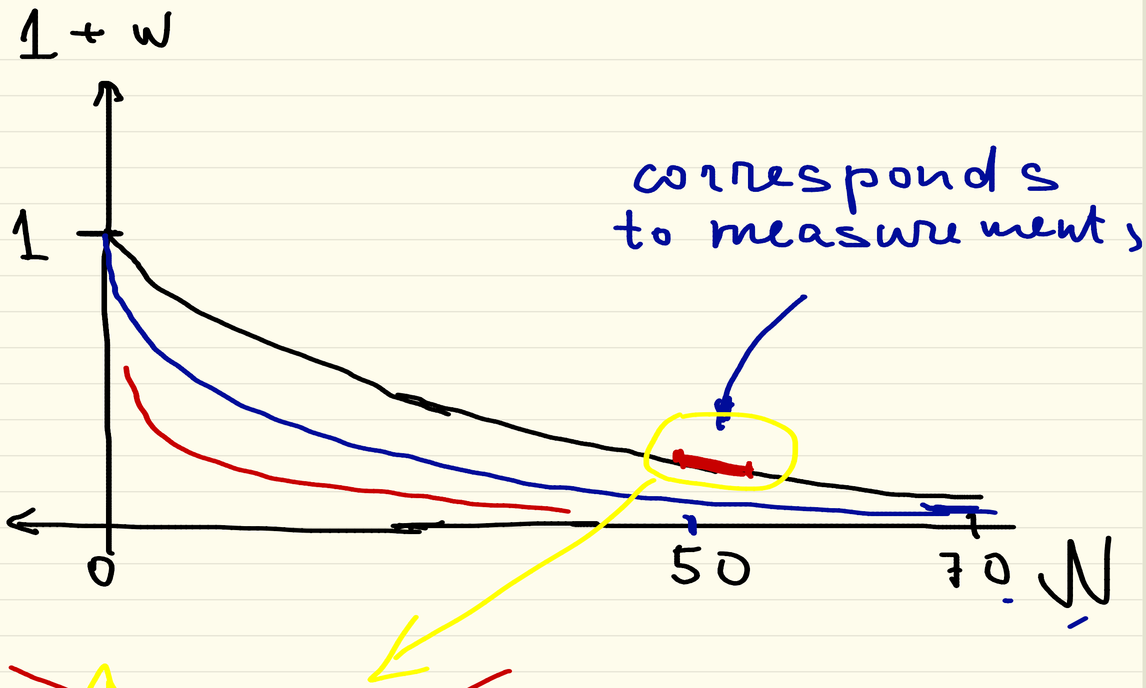
$$+\frac{D_3 + 32e^{-2a_2\tau}a_2A_2^2\tau(1+a_2\tau)}{(4\mathcal{V}_{\mathrm{m}}-\xi)(2\mathcal{V}_{\mathrm{m}}+\xi)} + \frac{D_4 + 8W_0A_2e^{-a_2\tau}\cos(a_2\theta)}{(4\mathcal{V}_{\mathrm{m}}-\xi)(2\mathcal{V}_{\mathrm{m}}+\xi)}\left(\frac{3\xi}{(2\mathcal{V}_{\mathrm{m}}+\xi)} + 4a_2\tau\right) + \frac{\beta}{\mathcal{V}_{\mathrm{m}}^2}\,.$$



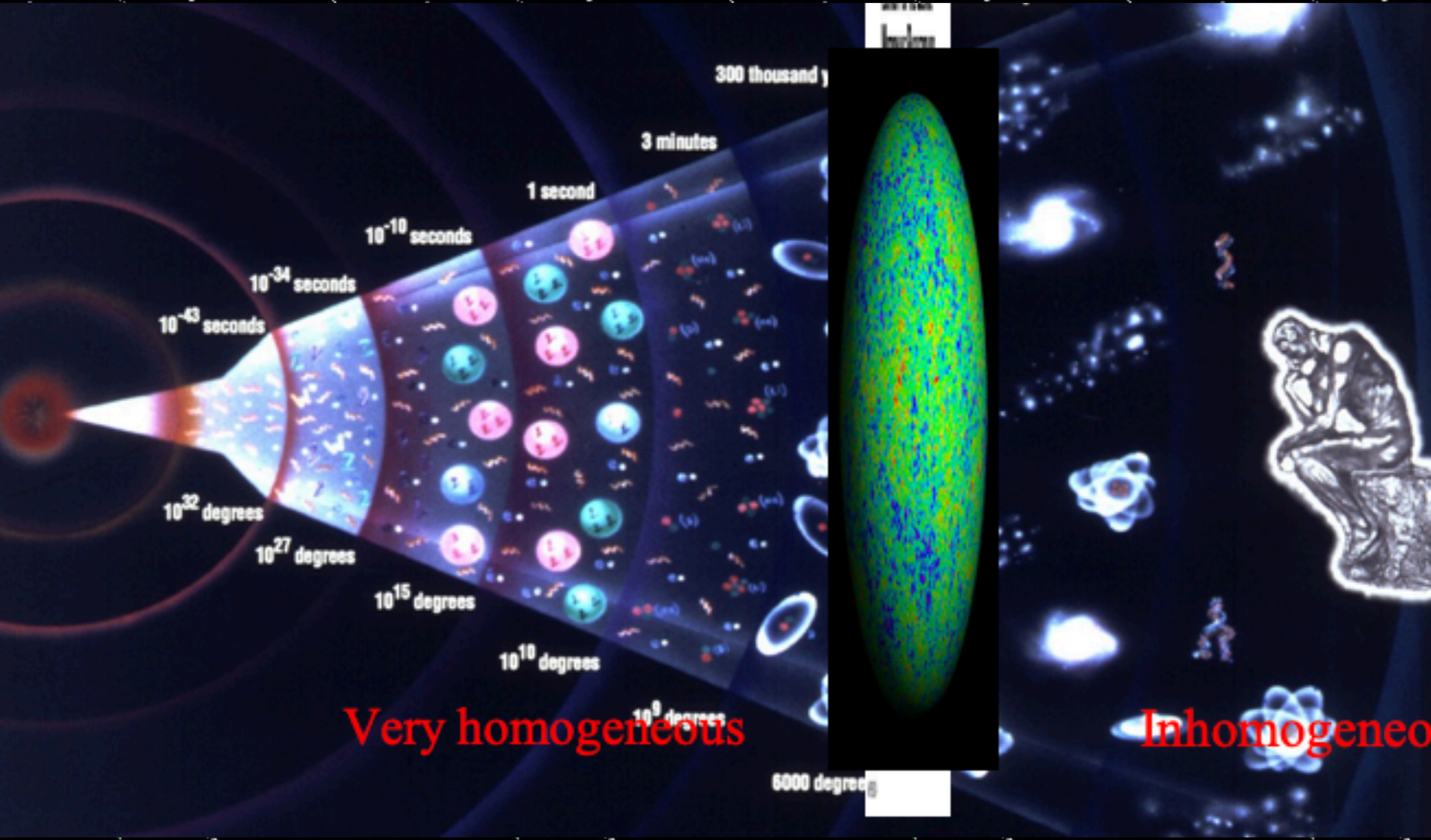
$a)\ 1+w \ll 1$ for $N \gg 1$

$b)\ 1+w \approx O(1)$ for $N \simeq O(1)$

$c)\ 1+w$ is a smooth function of N

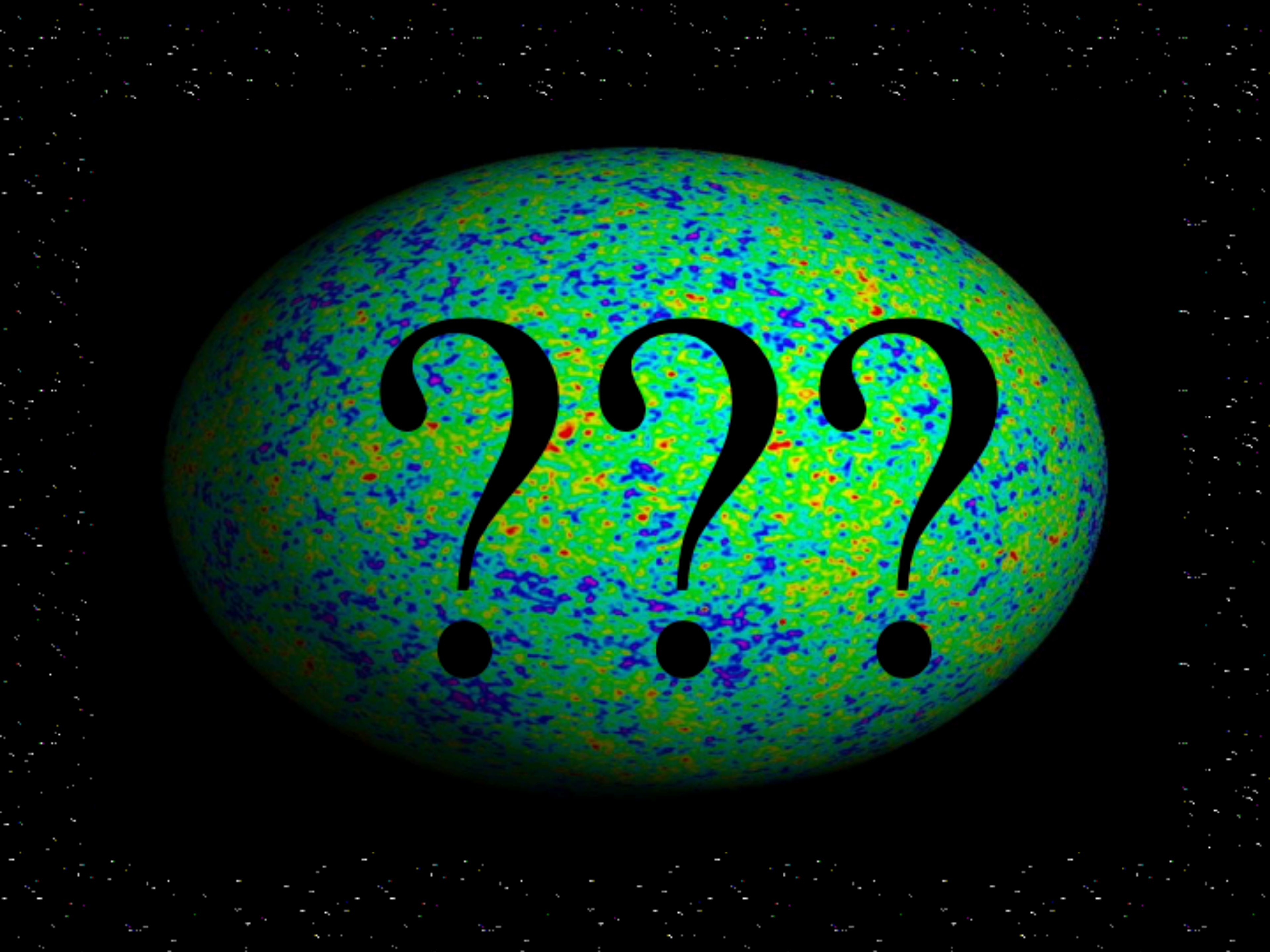


$$\frac{P+\varepsilon}{\varepsilon} = \frac{B}{(N+1)^{\alpha}}$$



Very homogeneous

Inhomogeneo



“Only by their breaking could the divine configurations be perfected”

Kabbalistic text; Ta’alumoth Chokhmah (The Channels of Wisdom)
1629, Joseph Samomon del Medigo of Crete

→ $$\Delta p \Delta x \geq h$$

↓

There always exist unavoidable

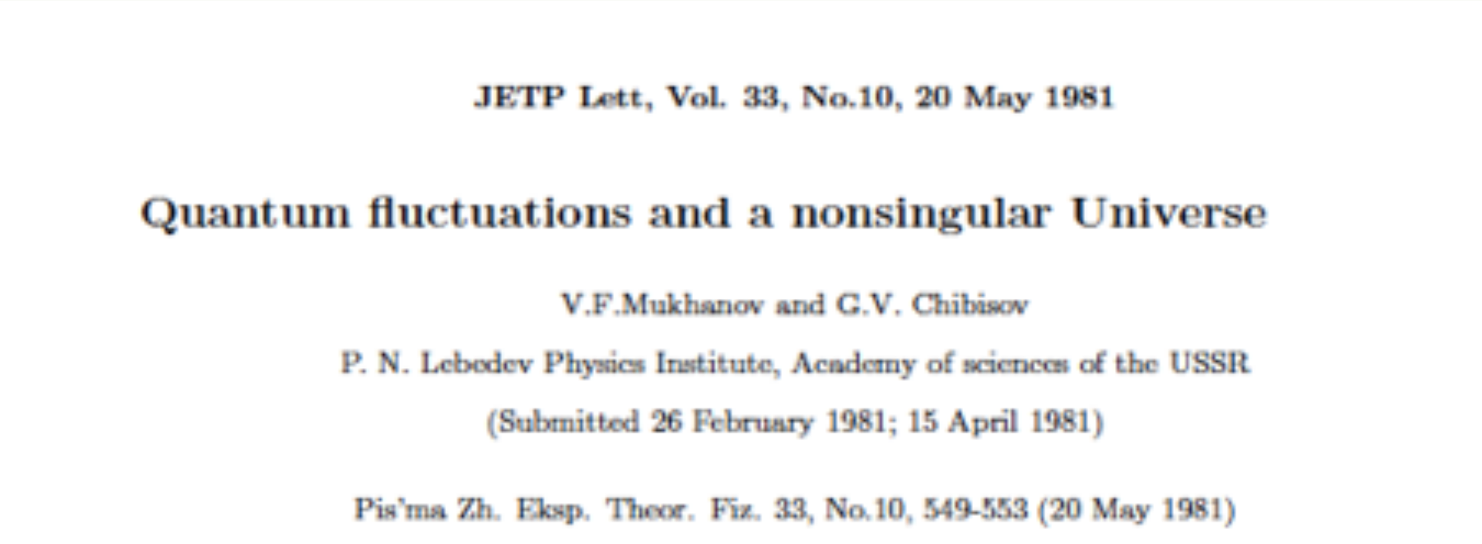
Quantum Fluctuations

Quantum fluctuations in the density distribution are large (10^{-5})

only in extremely small scales ($\sim 10^{-33}$ cm),

but very small ($\sim 10^{-58}$) on galactic scales ($\sim 10^{25}$ cm)

Can we transfer the large fluctuations from extremely small scales to large scales???



JETP Lett, Vol. 33, No.10, 20 May 1981

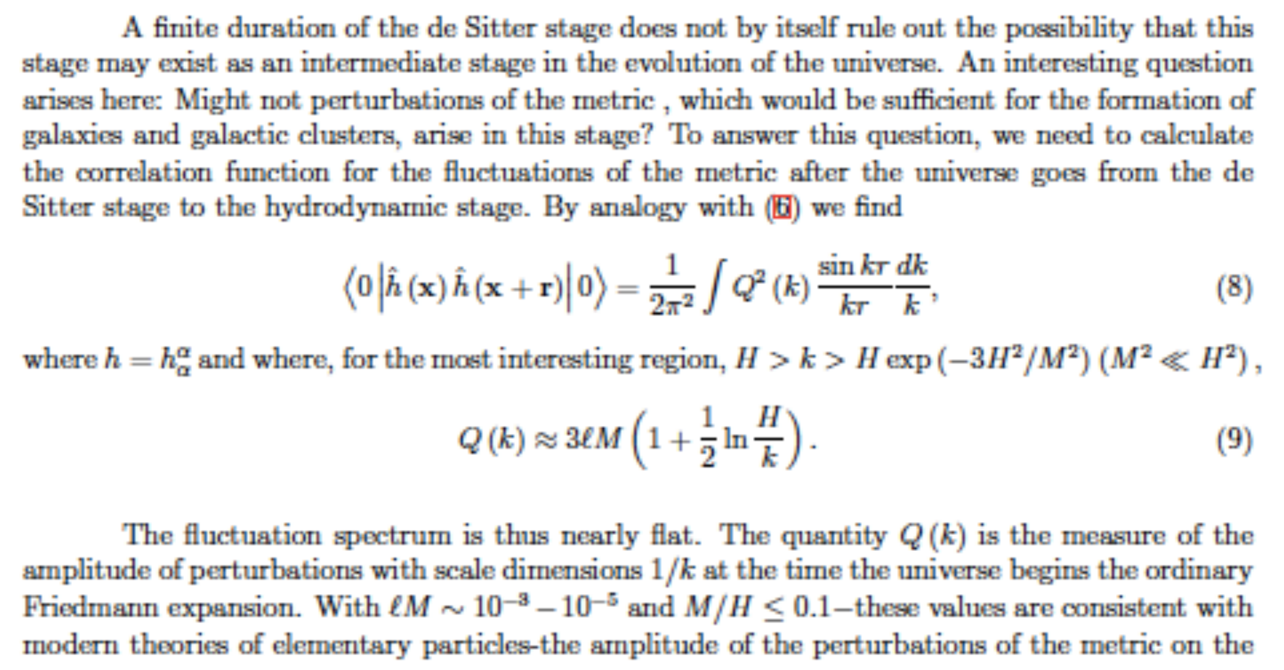
Quantum fluctuations and a nonsingular Universe

V.F.Mukhanov and G.V. Chibisov

P. N. Lebedev Physics Institute, Academy of sciences of the USSR

(Submitted 26 February 1981; 15 April 1981)

Pis'ma Zh. Eksp. Theor. Fiz. 33, No.10, 549-553 (20 May 1981)



A finite duration of the de Sitter stage does not by itself rule out the possibility that this stage may exist as an intermediate stage in the evolution of the universe. An interesting question arises here: Might not perturbations of the metric , which would be sufficient for the formation of galaxies and galactic clusters, arise in this stage? To answer this question, we need to calculate the correlation function for the fluctuations of the metric after the universe goes from the de Sitter stage to the hydrodynamic stage. By analogy with (6) we find

$$\left\langle 0 \left| \hat{h}\left(\mathbf{x}\right) \hat{h}\left(\mathbf{x}+\mathbf{r}\right) \right| 0 \right\rangle = \frac{1}{2\pi^2} \int Q^2\left(k\right) \frac{\sin kr}{kr} \frac{dk}{k}, \tag{8}$$

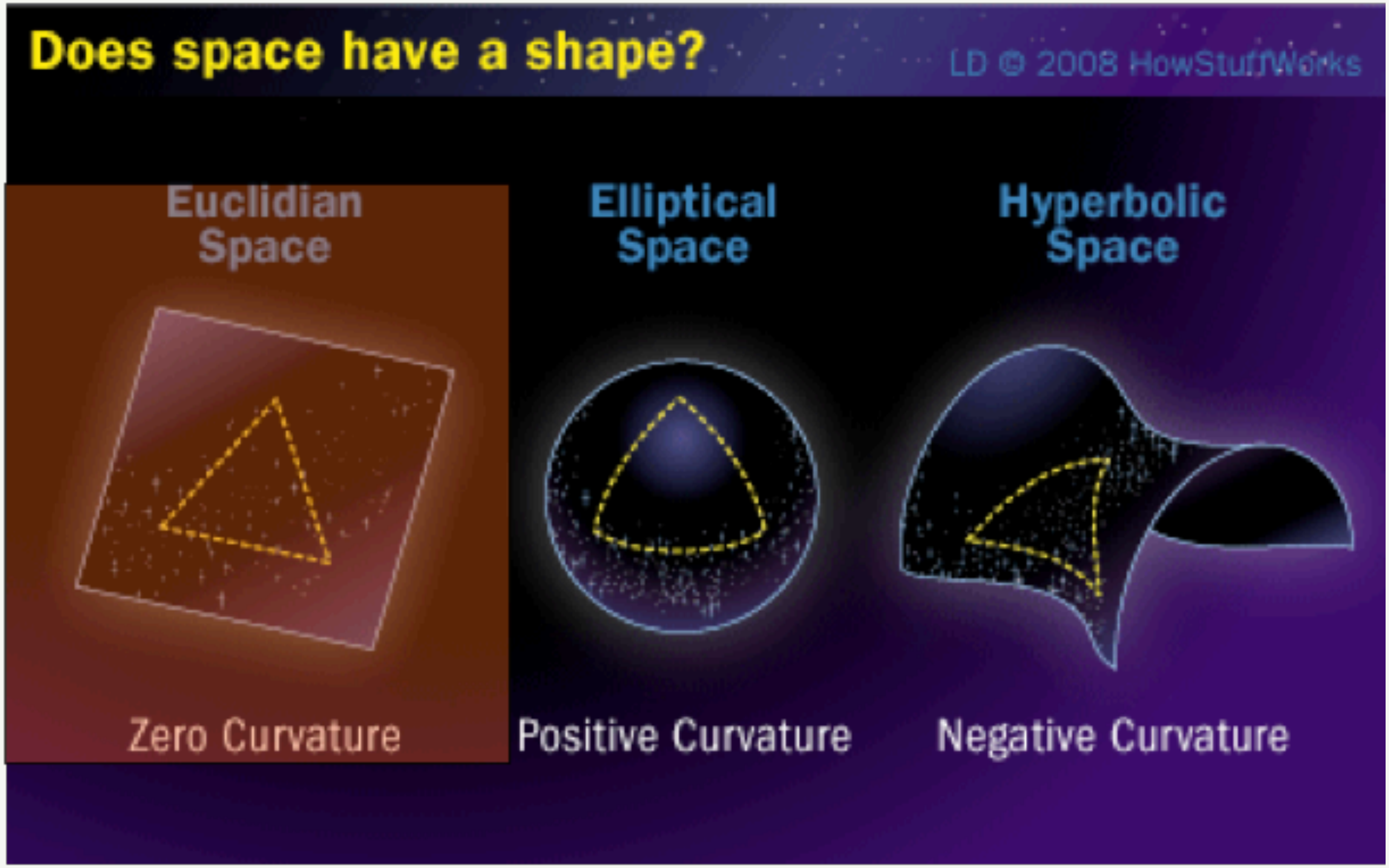
where $h = h_\alpha^\alpha$ and where, for the most interesting region, $H > k > H \exp\left(-3H^2/M^2\right) \left(M^2 \ll H^2\right)$,

$$Q\left(k\right) \approx 3\ell M \left(1 + \frac{1}{2} \ln \frac{H}{k}\right). \tag{9}$$

The fluctuation spectrum is thus nearly flat. The quantity $Q\left(k\right)$ is the measure of the amplitude of perturbations with scale dimensions $1/k$ at the time the universe begins the ordinary Friedmann expansion. With $\ell M \sim 10^{-3} - 10^{-5}$ and $M/H \leq 0.1$–these values are consistent with modern theories of elementary particles-the amplitude of the perturbations of the metric on the

Predictions!!!

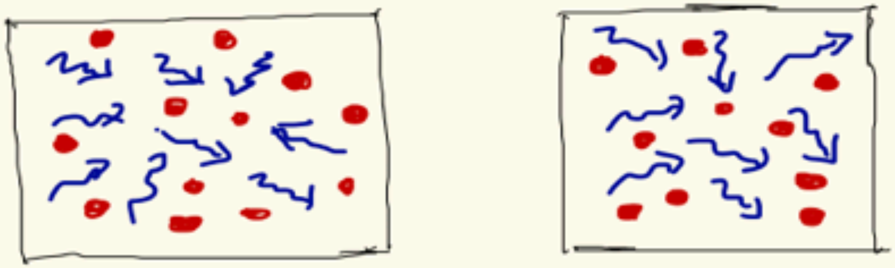
1)



$$\Omega = 1$$

Perturbations (inhomogeneities) are:

2) Adiabatic (MC 1981)

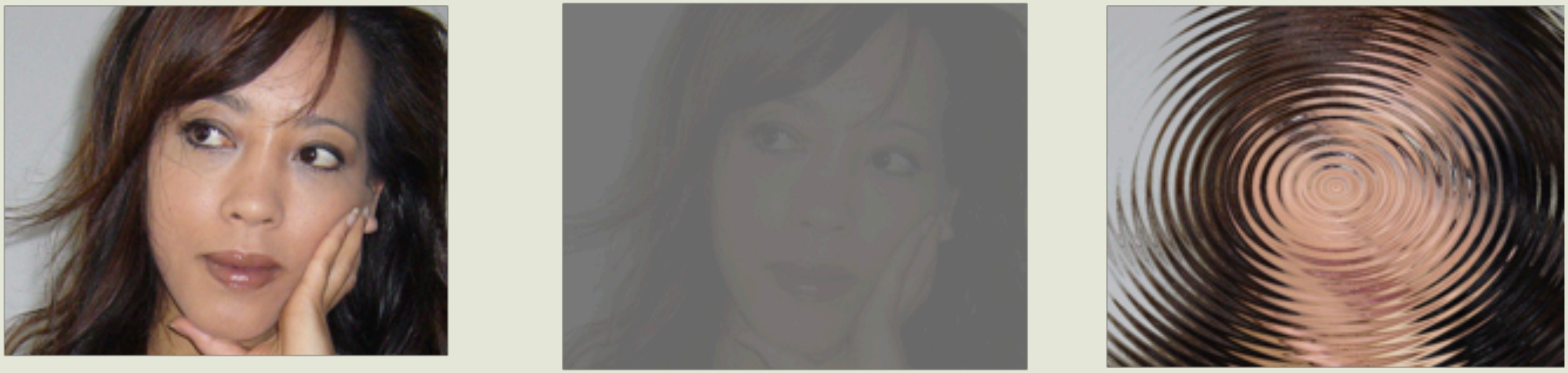


100 photons
50 baryons

98 photons
49 baryons

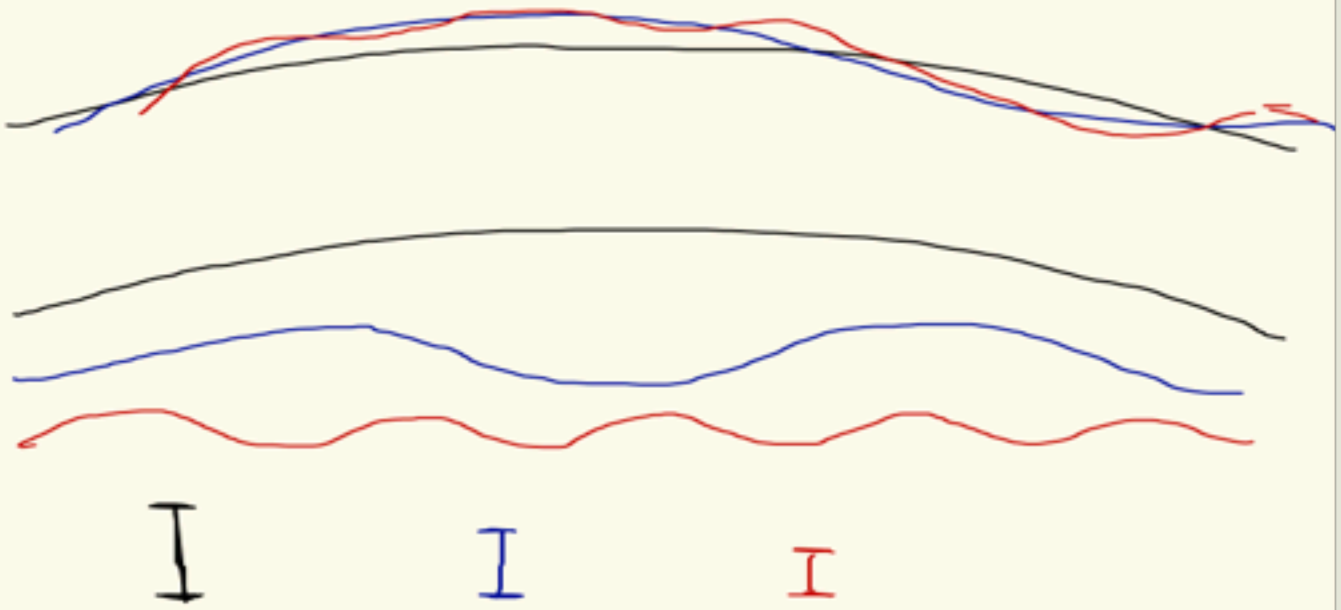
~~49-2=47~~

3) Gaussian (MC 1981)



$\Phi=\Phi_g + f_{NL}\Phi_g^2$, where $f_{NL} = \mathcal{O}(1)$ (MC, 81)

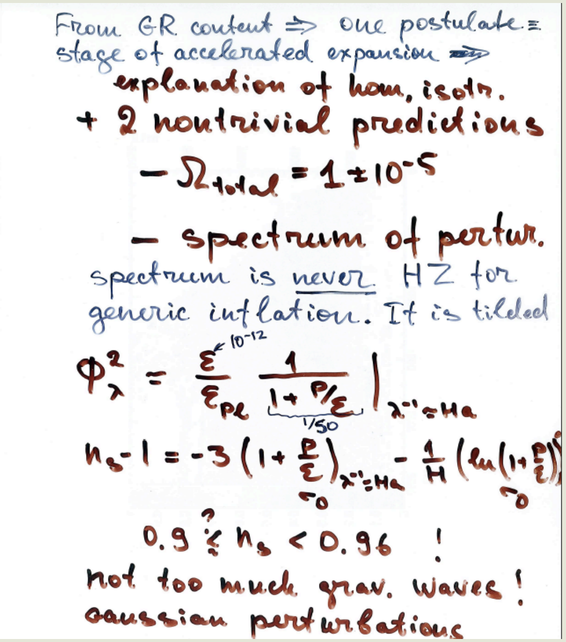
4) have log spectrum (MC 1981)



Amplitude increases by a few percents when scale increases in few times

4) $\Phi \propto \ln(\lambda/\lambda_\gamma) \propto \lambda^{1-n_s}$ with $n_s = 0.96$ (MC, 1981)

The theory always predicts red-tilted spectrum



From GR content ⇒ one postulate ≡
stage of accelerated expansion ⇒
explanation of hom, isotr.
+ 2 nontrivial predictions

$- \Omega_{total} = 1 \pm 10^{-5}$

– spectrum of pertur.

spectrum is <u>never</u> HZ for
generic inflation. It is tilded

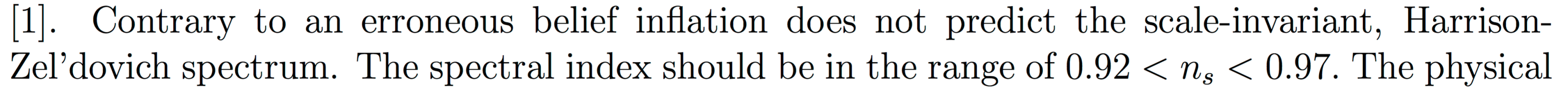
$$\Phi_\lambda^2 \simeq \frac{\overset{10^{-12}}{\varepsilon}}{\varepsilon_{Pl}} \frac{1}{\underbrace{1+p/\varepsilon}_{1/50}}\Bigg|_{\lambda^{-1}=Ha}$$

$$n_s - 1 = -3\Big(1+\underset{\to 0}{\frac{p}{\varepsilon}}\Big)_{\lambda^{-1}=Ha} - \frac{1}{H}\Big(\ln\Big(1+\underset{\to 0}{\frac{p}{\varepsilon}}\Big)\Big)^{\cdot}$$

$0.9 \overset{?}{\lesssim} n_s < 0.96$!

not too much grav. waves!
gaussian perturbations

Cambridge, 2000



[1]. Contrary to an erroneous belief inflation does not predict the scale-invariant, Harrison-Zel'dovich spectrum. The spectral index should be in the range of $0.92 < n_s < 0.97$. The physical

V. Mukhanov, CMB, Quantum Fluctuations
and the Predictive Power of Inflation,
arXiv:astro-ph/0303077 (2003)

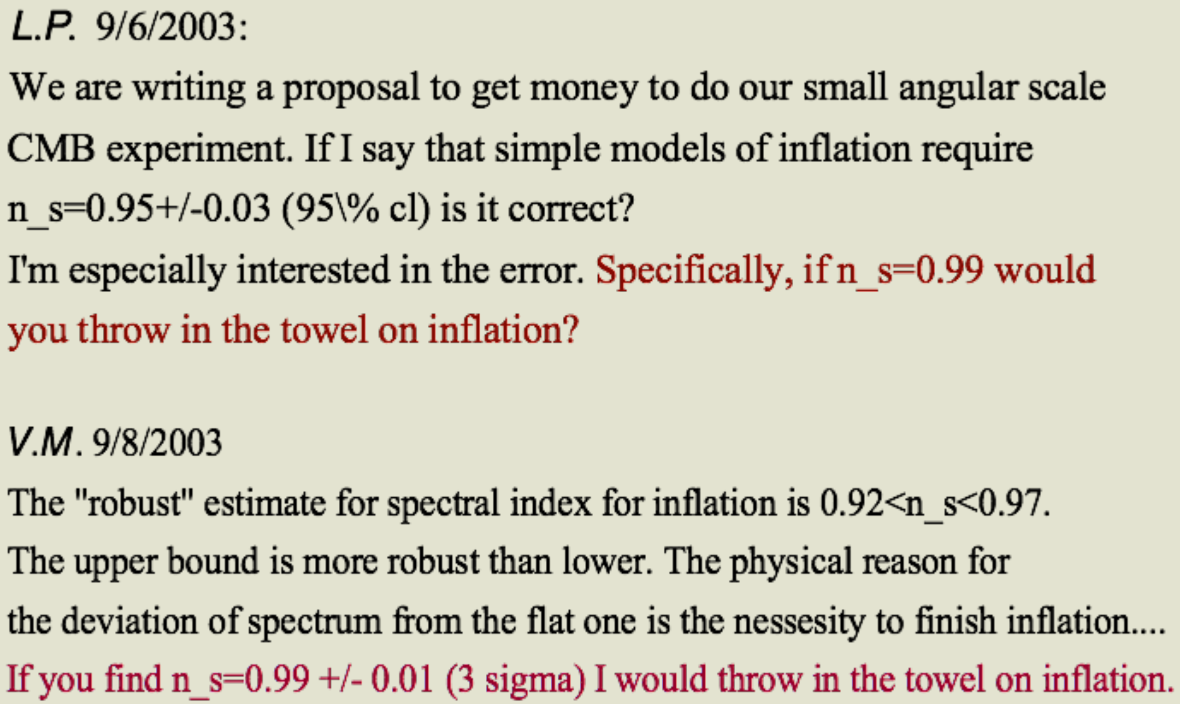
Red-tilted log spectrum (MC, H, 1981-1982) →

$$n_S = 1 - \frac{A}{\ln(B\lambda_{gal} / \lambda_{CMB})},$$

where $A > 1,5$ and $B \simeq 1 - 100$ depending on $50 < N < 55$ →

$$n_S < 0.97$$

irrespective of any particular model!



L.P. 9/6/2003:

We are writing a proposal to get money to do our small angular scale CMB experiment. If I say that simple models of inflation require n_s=0.95+/-0.03 (95\% cl) is it correct?

I'm especially interested in the error. Specifically, if n_s=0.99 would you throw in the towel on inflation?

V.M. 9/8/2003

The "robust" estimate for spectral index for inflation is 0.92<n_s<0.97.

The upper bound is more robust than lower. The physical reason for the deviation of spectrum from the flat one is the nessesity to finish inflation....

If you find n_s=0.99 +/- 0.01 (3 sigma) I would throw in the towel on inflation.

PREDICTIONS

("smoking guns"-nonconfirming any of them would falsify THE theory)

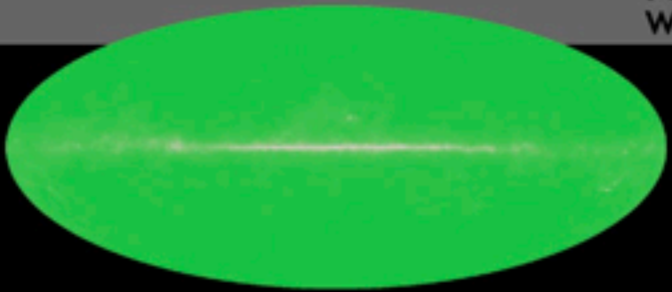
- flat universe
- adiabatic perturbations
- small non-gaussianity ($f_{NL} \sim O(1)$)
- red-tilted spectrum

$$\Phi^2 \propto \lambda^{1-n_S}$$

$$1 - n_S = 3(1+w) - \frac{d \ln(1+w)}{dN}$$

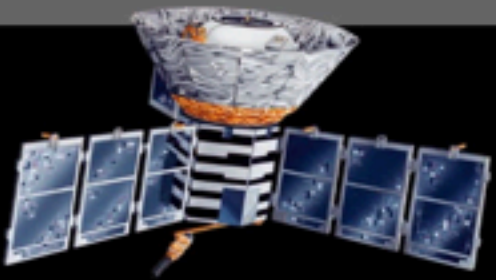
1965

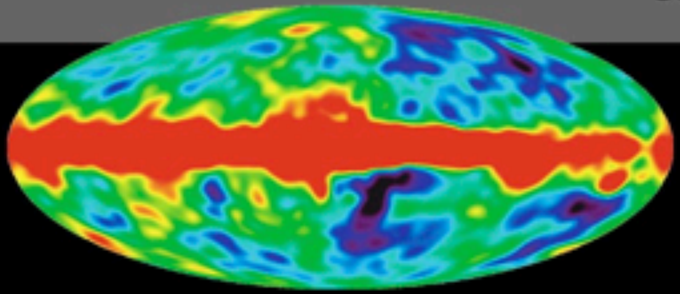
Penzias and Wilson



1992

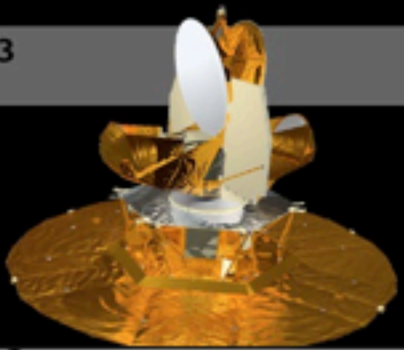
COBE

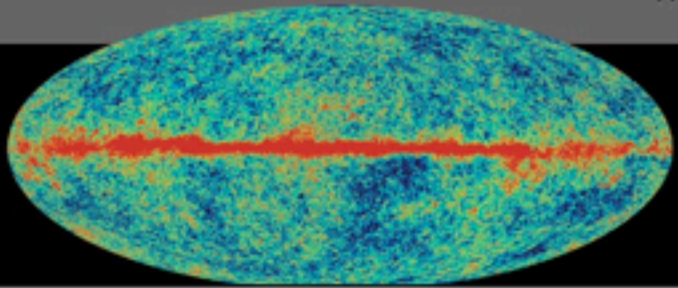




2003

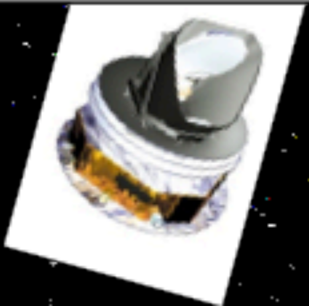
WMAP





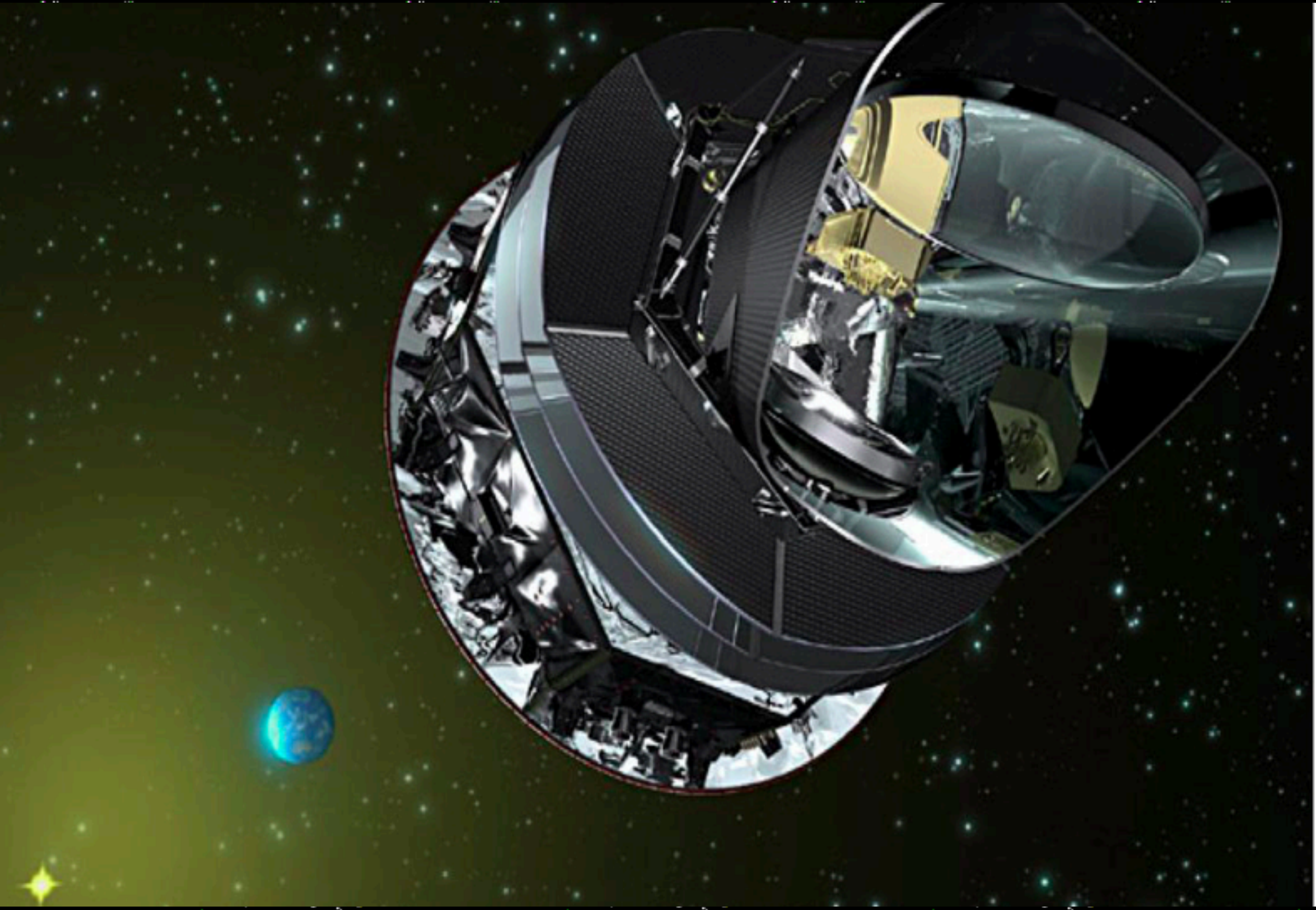
2009

Planck

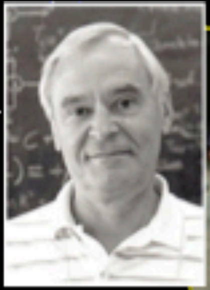


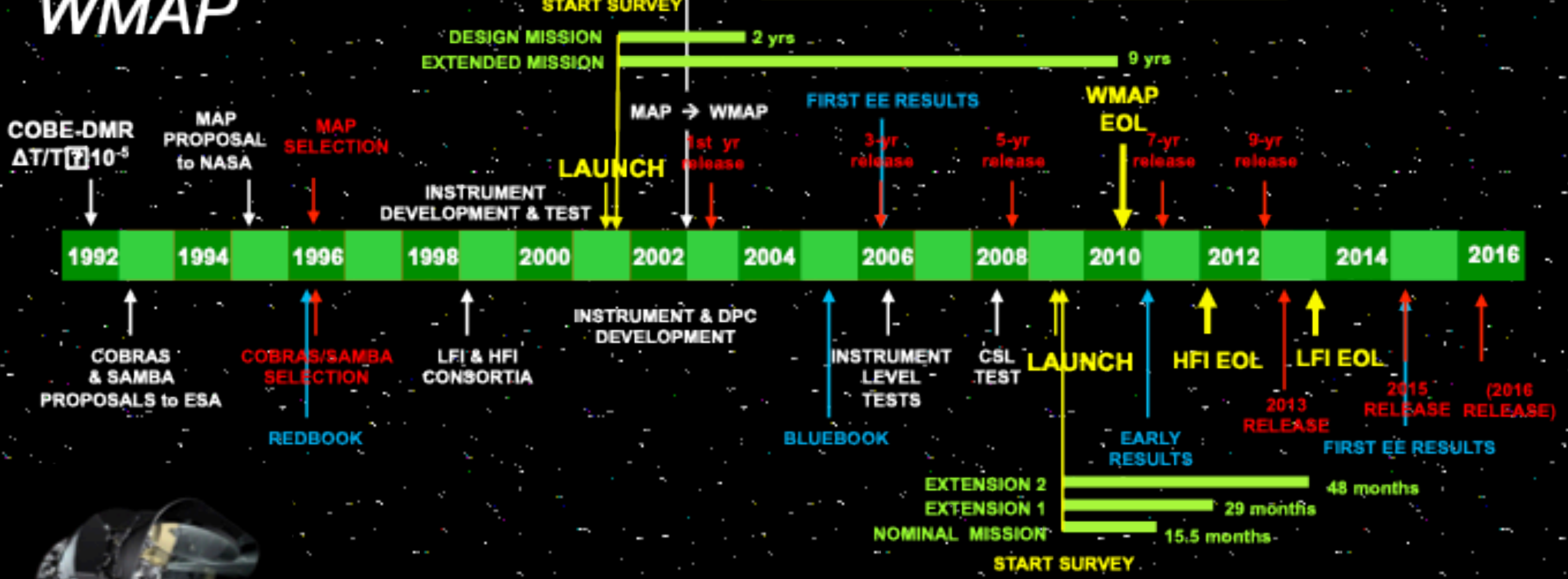
???

End 2012



WMAP





START SURVEY

DESIGN MISSION — 2 yrs

EXTENDED MISSION — 9 yrs

MAP → WMAP

FIRST EE RESULTS

WMAP EOL

COBE-DMR $\Delta T/T$? 10^{-5}

MAP PROPOSAL to NASA

MAP SELECTION

INSTRUMENT DEVELOPMENT & TEST

LAUNCH

1st yr release

3-yr release

5-yr release

7-yr release

9-yr release

1992 | 1994 | 1996 | 1998 | 2000 | 2002 | 2004 | 2006 | 2008 | 2010 | 2012 | 2014 | 2016

COBRAS & SAMBA PROPOSALS to ESA

COBRAS/SAMBA SELECTION

REDBOOK

LFI & HFI CONSORTIA

INSTRUMENT & DPC DEVELOPMENT

BLUEBOOK

INSTRUMENT LEVEL TESTS

CSL TEST

LAUNCH

EARLY RESULTS

HFI EOL

2013 RELEASE

LFI EOL

2015 RELEASE

FIRST EE RESULTS

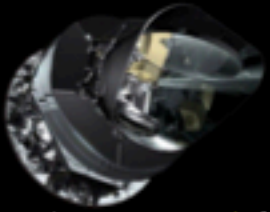
(2016 RELEASE)

EXTENSION 2 — 48 months

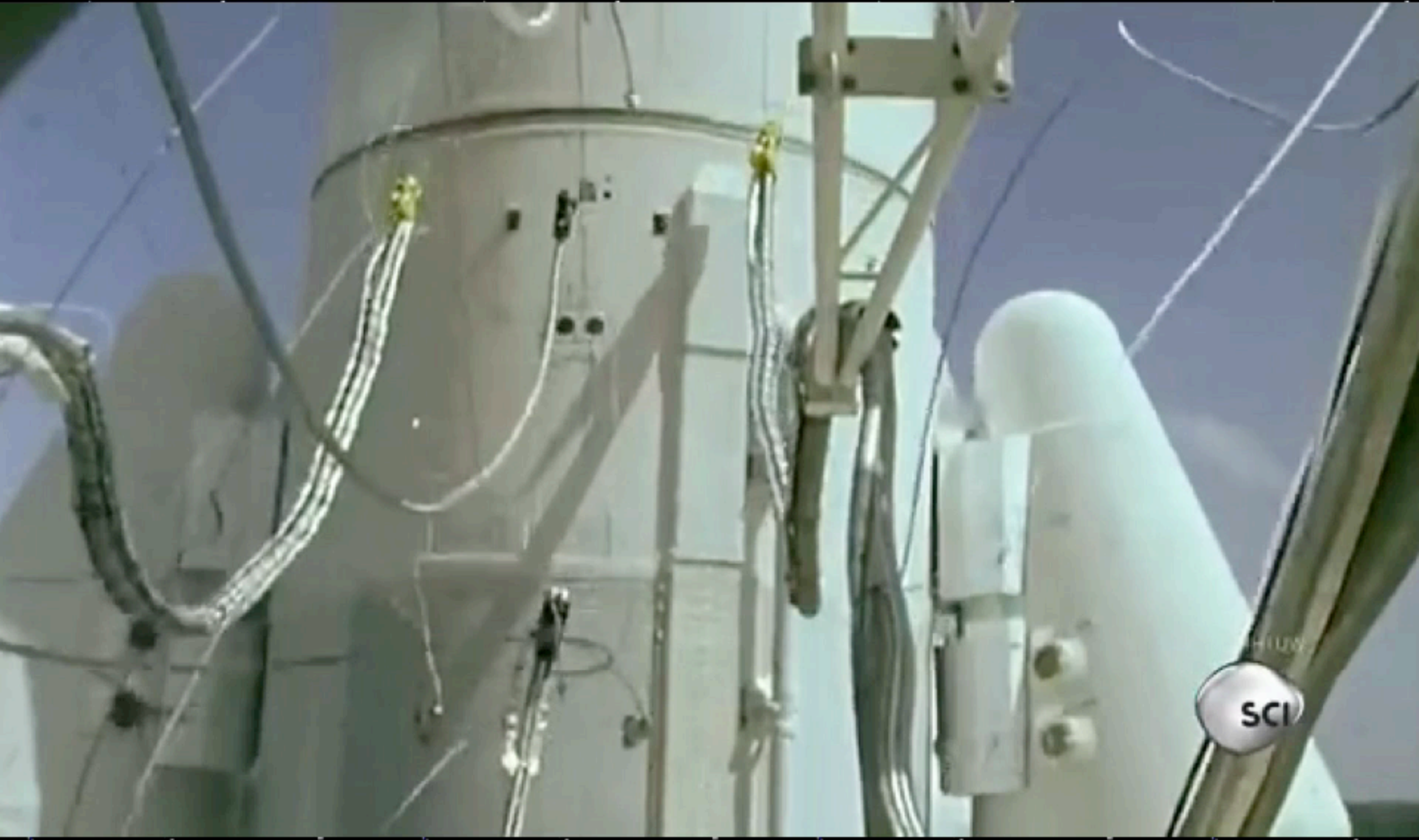
EXTENSION 1 — 29 months

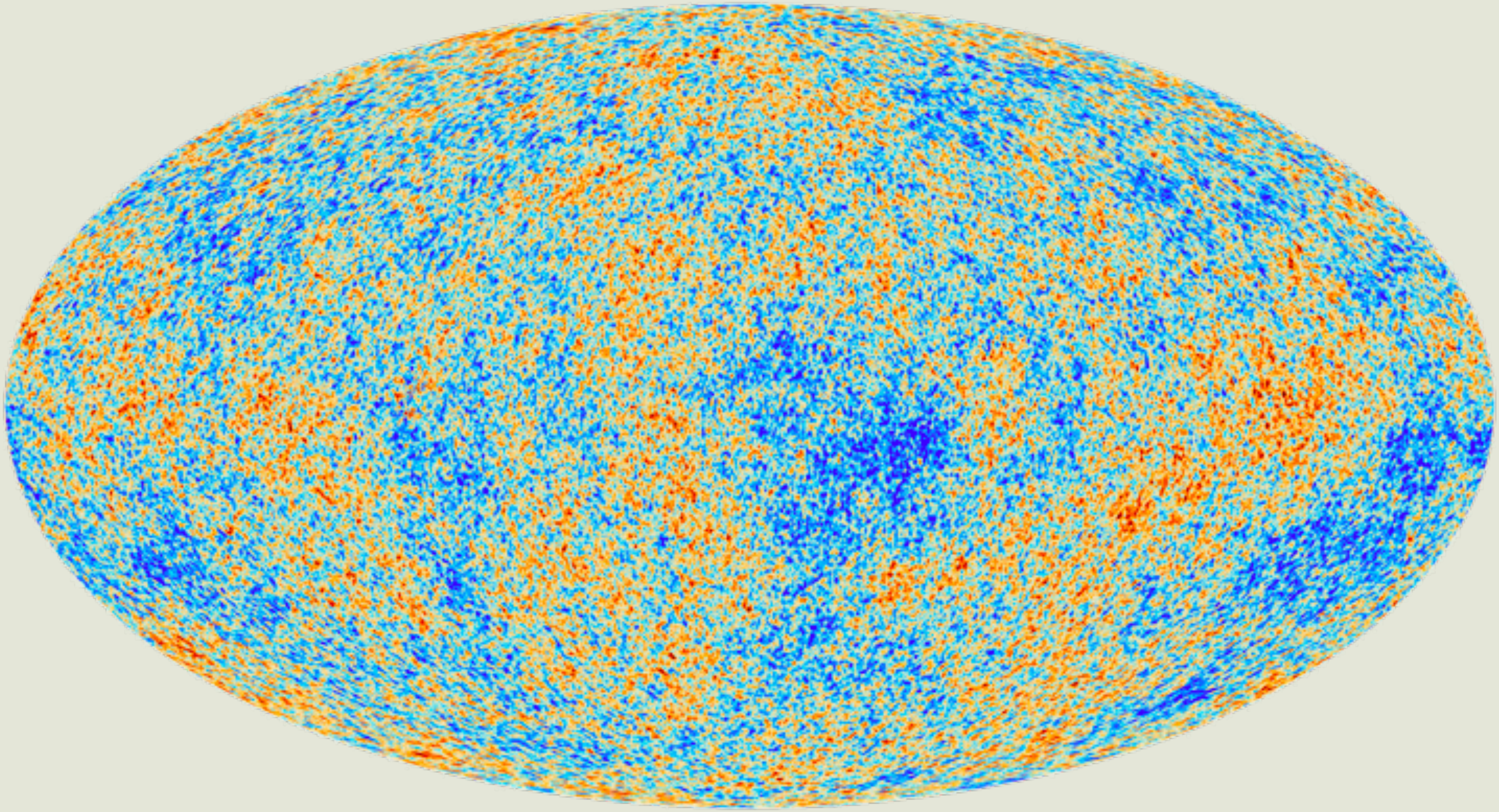
NOMINAL MISSION — 15.5 months

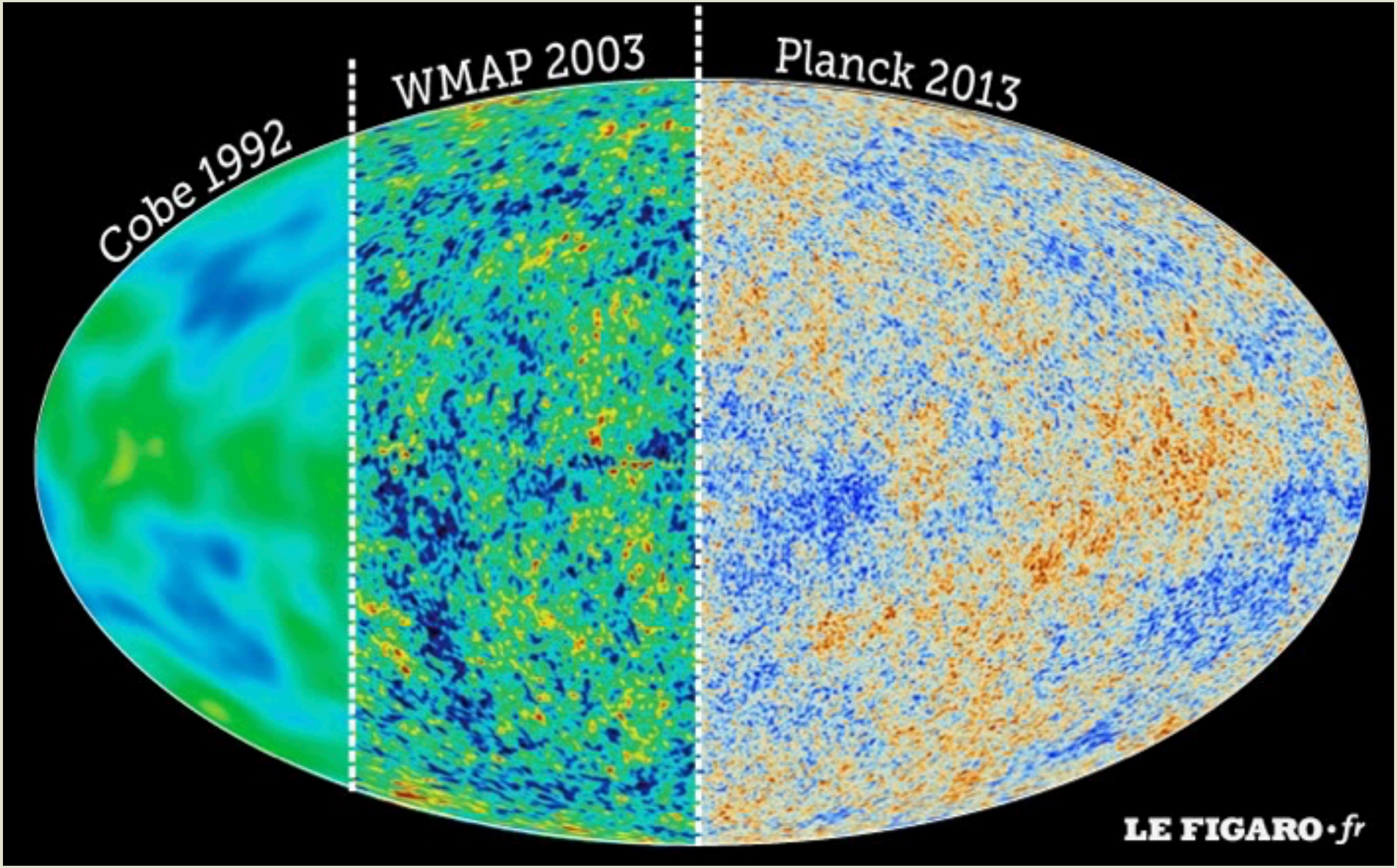
START SURVEY



Planck






Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

PREDICTIONS

1) flat Universe

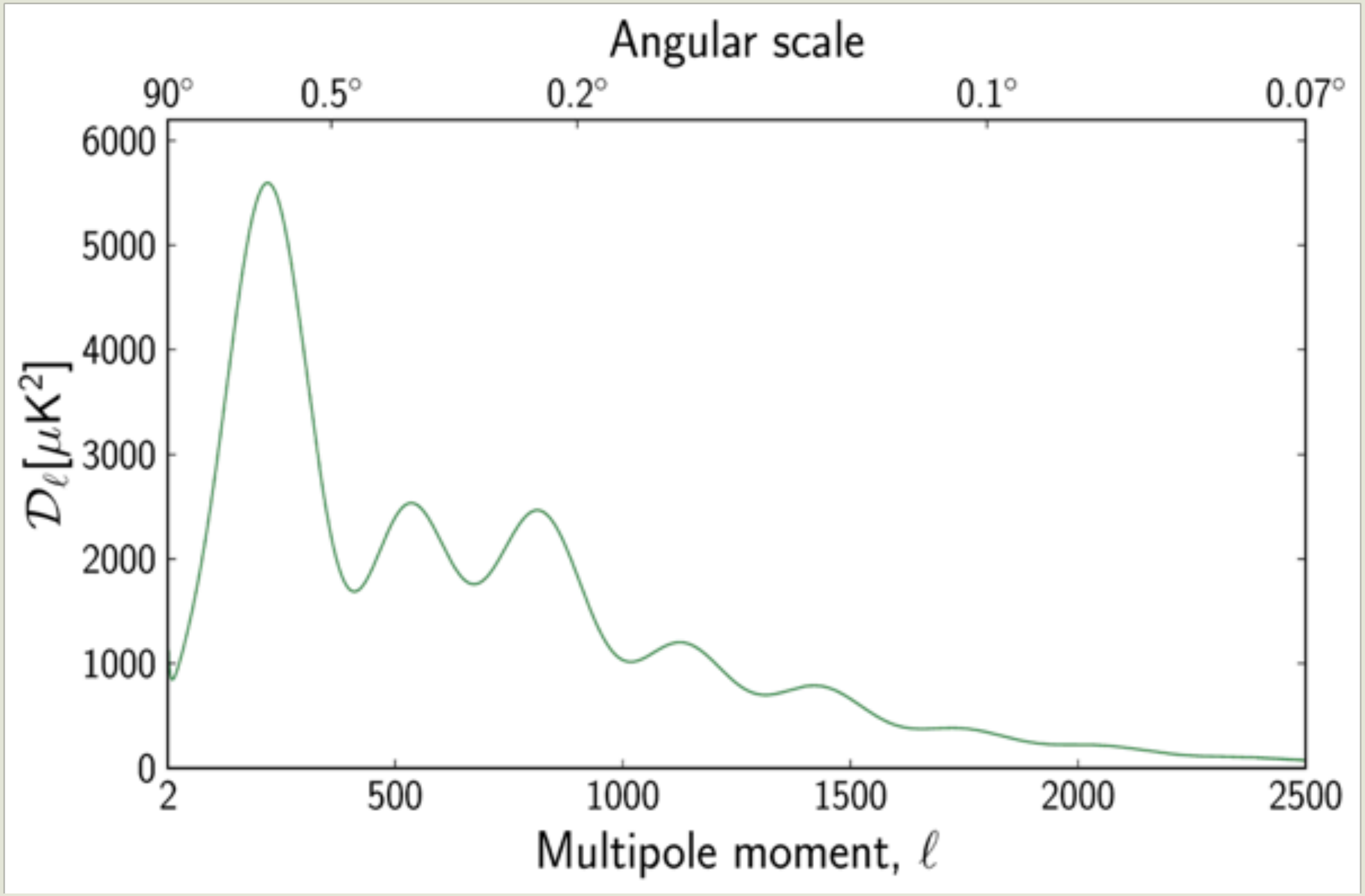
Perturbations are :

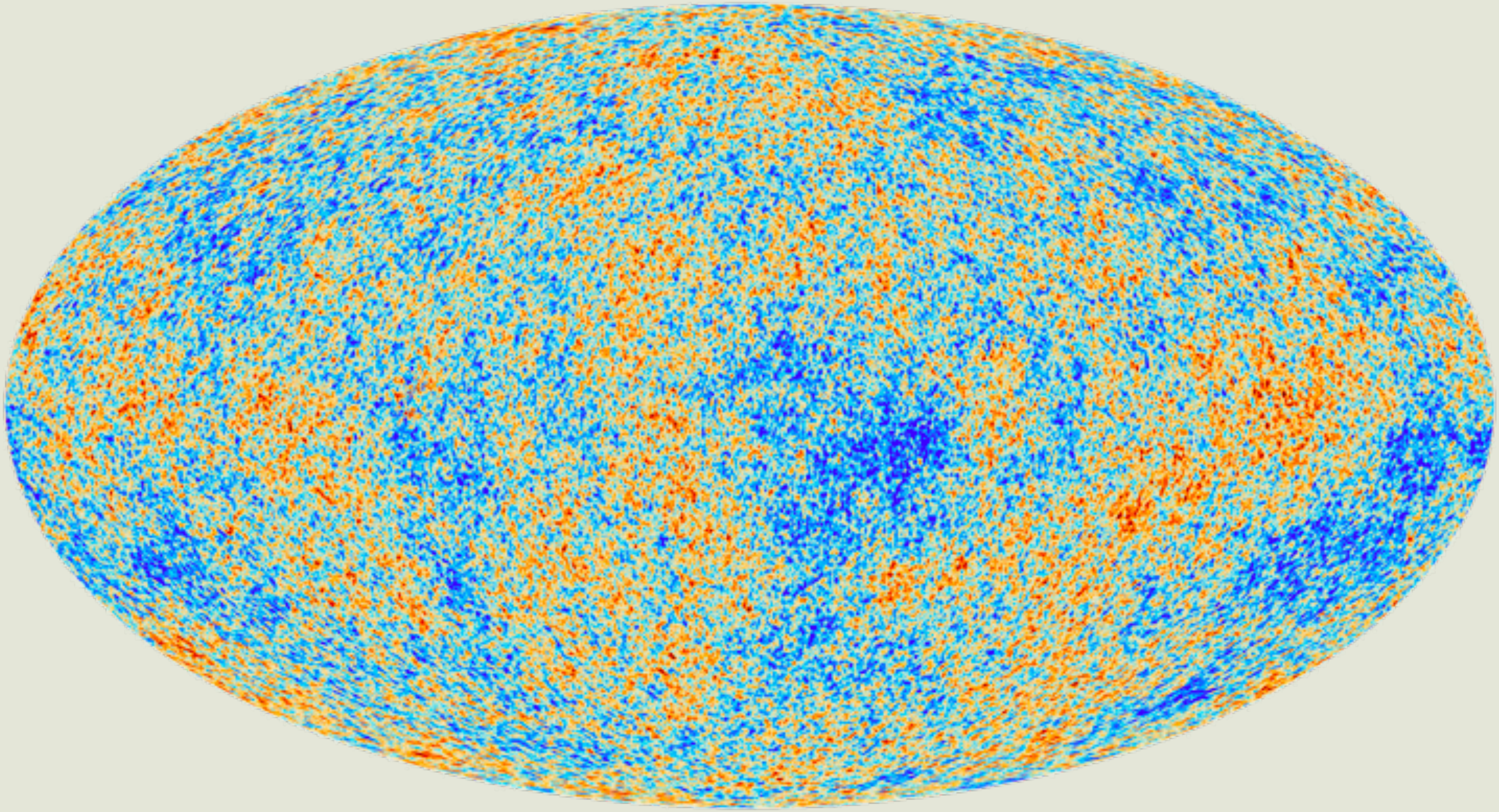
2) adiabatic (MC, 81)

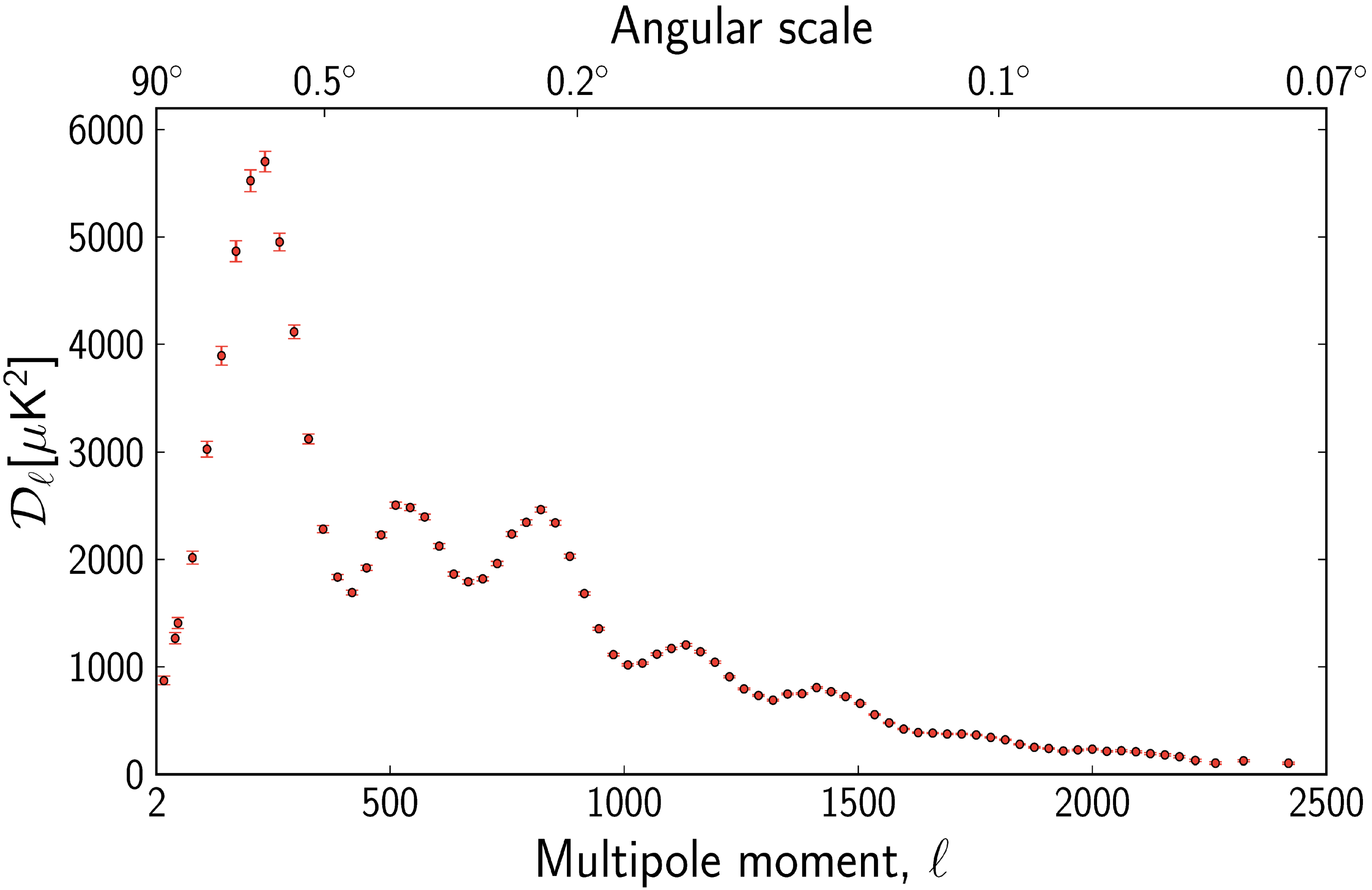
3) gaussian: $\Phi = \Phi_g + f_{NL}\Phi_g^2$, where $f_{NL} = O(1)$ (MC, 81)

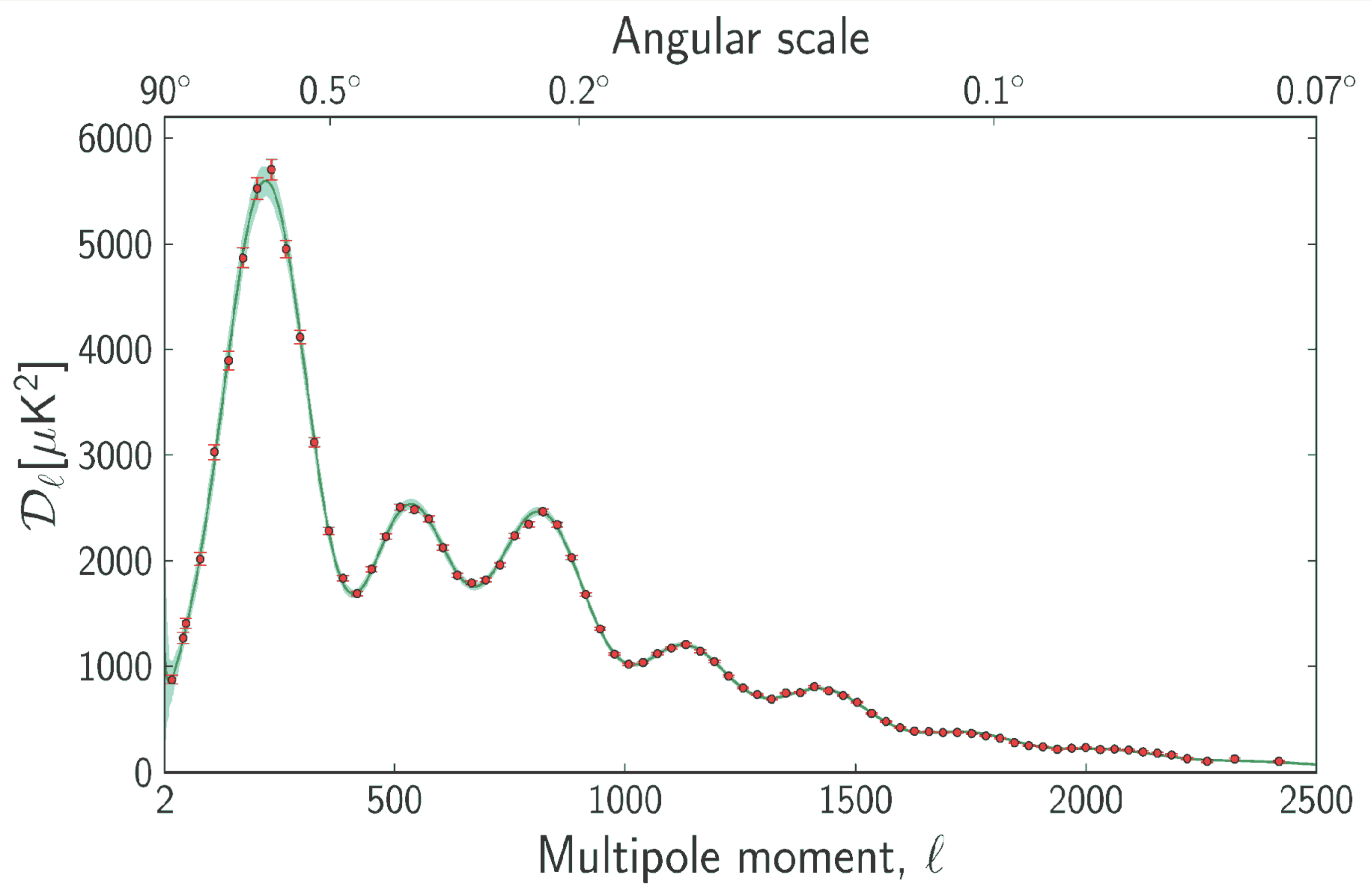
4) spectrum: $\Phi \propto \ln(\lambda/\lambda_\gamma) \propto \lambda^{1-n_S}$ with $n_S = 0.96$ (MC, 81)

with $\Omega_{tot} = 1$ (prediction) and H_0, $\Omega_\Lambda, \Omega_{bar}$ from supernova, deuterium et.cet. we get






Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ


Angular scale
90°
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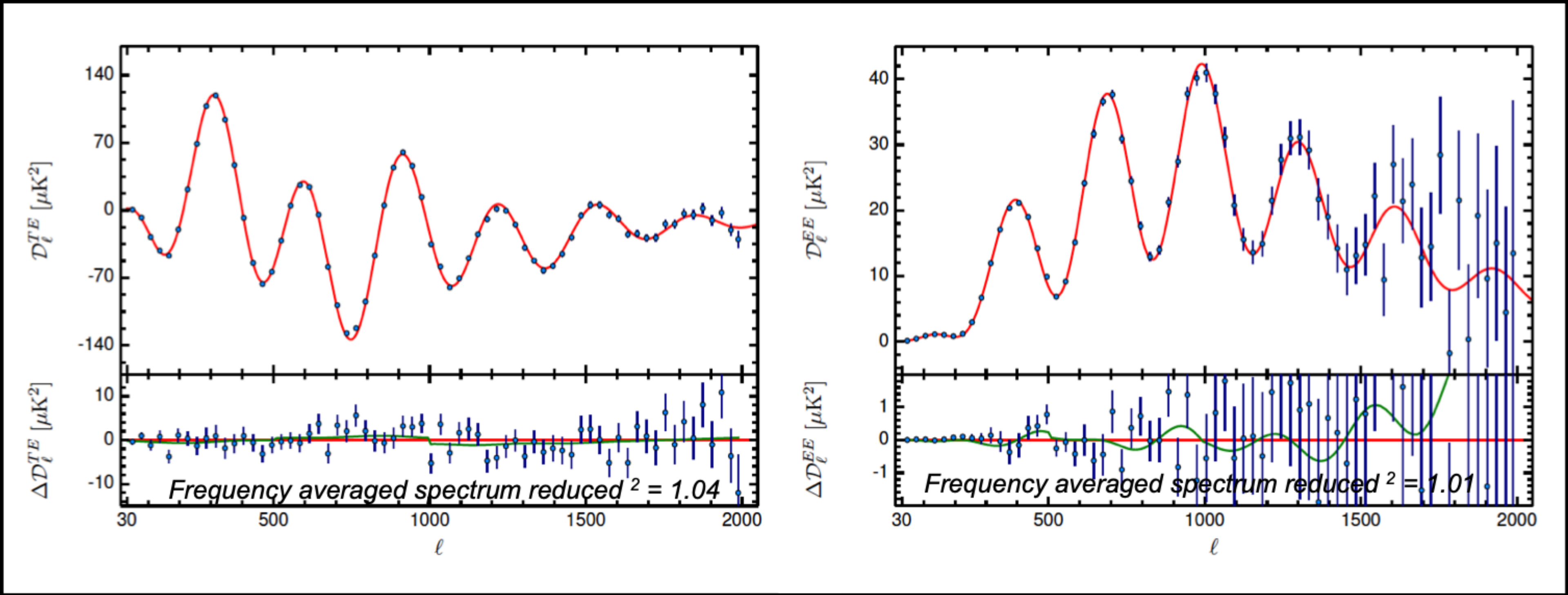
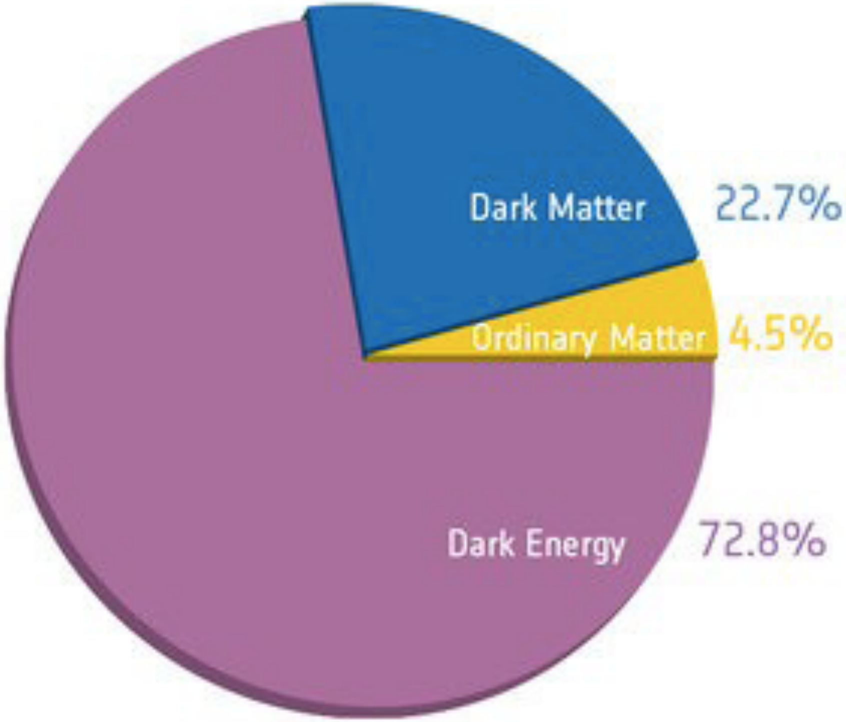
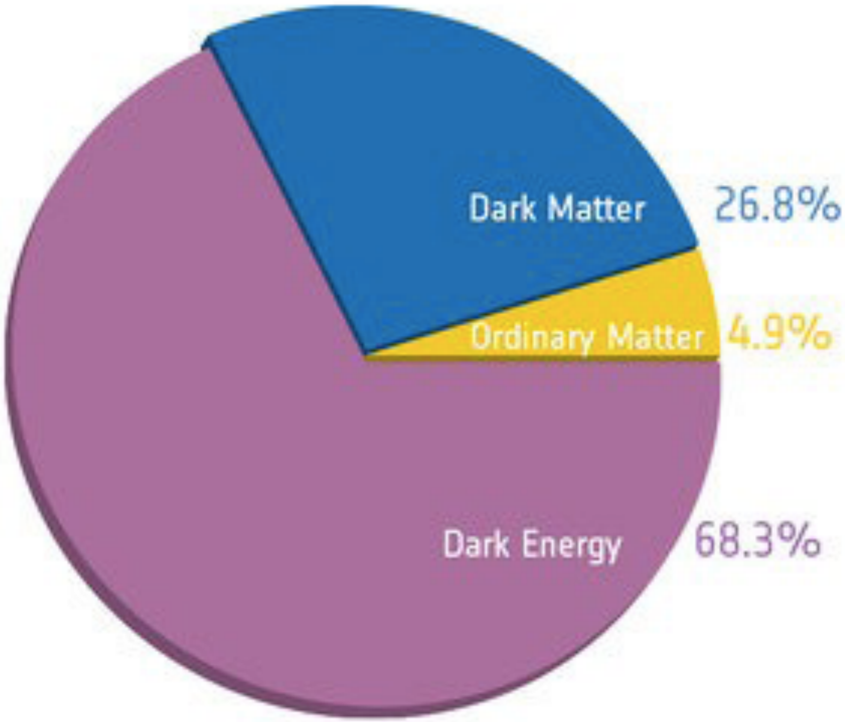
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ

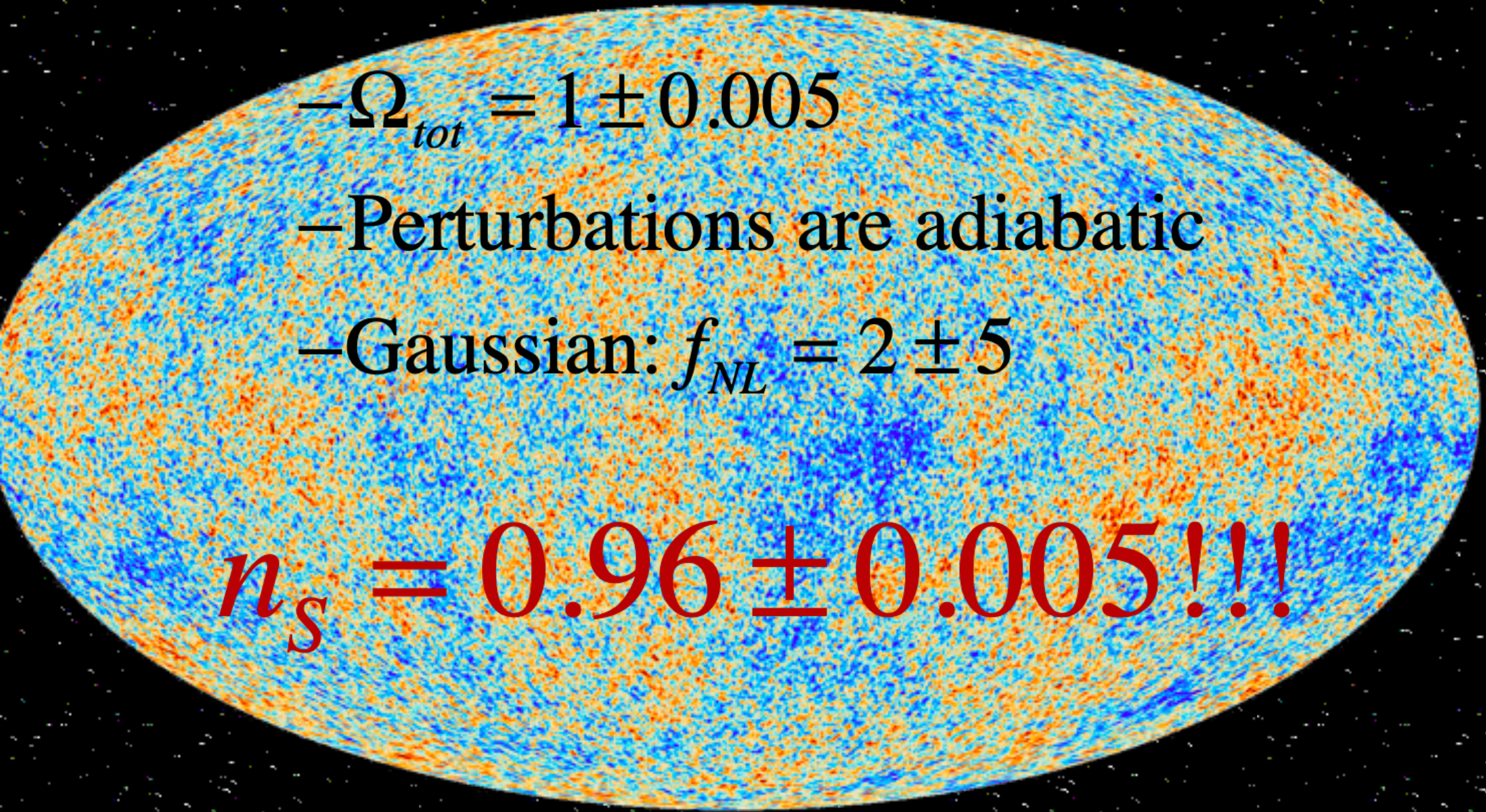

$\mathcal{D}_\ell^{TE}$ [μK^2]
140
70
0
-70
-140
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
-10
Frequency averaged spectrum reduced ^{2} = 1.04
30
500
1000
1500
2000
ℓ
$\mathcal{D}_\ell^{EE}$ [μK^2]
40
30
20
10
0
$\Delta\mathcal{D}_\ell^{EE}$ [μK^2]
1
0
-1
Frequency averaged spectrum reduced ^{2} = 1.01
30
500
1000
1500
2000
ℓ



Before Planck



After Planck



– $\Omega_{tot} = 1 \pm 0.005$

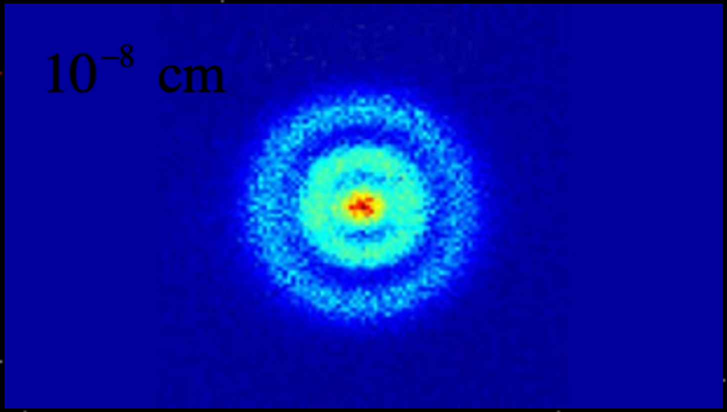
– Perturbations are adiabatic

– Gaussian: $f_{NL} = 2 \pm 5$

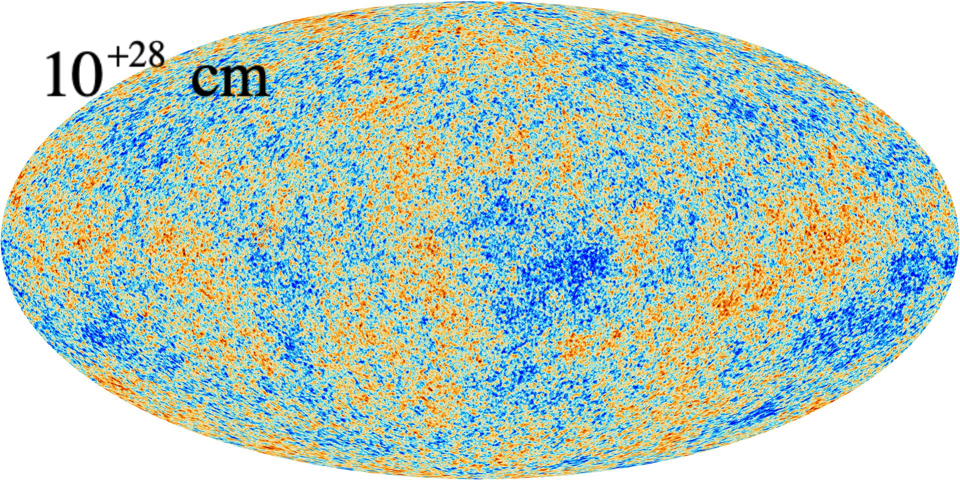
$$n_S = 0.96 \pm 0.005!!!$$

CONCLUSIONS

- General Relativity is valid up to the scales 10^{-27} cm
- We all originated from quantum fluctuations



10^{-8} cm



10^{+28} cm

$$\Delta q \times \Delta p \geq \frac{1}{2}\ \hbar$$

Multiverse?

One Universe?

From the point of view of Physics
both statements are equally
Correct!
Wrong!
because they are not falsifiable

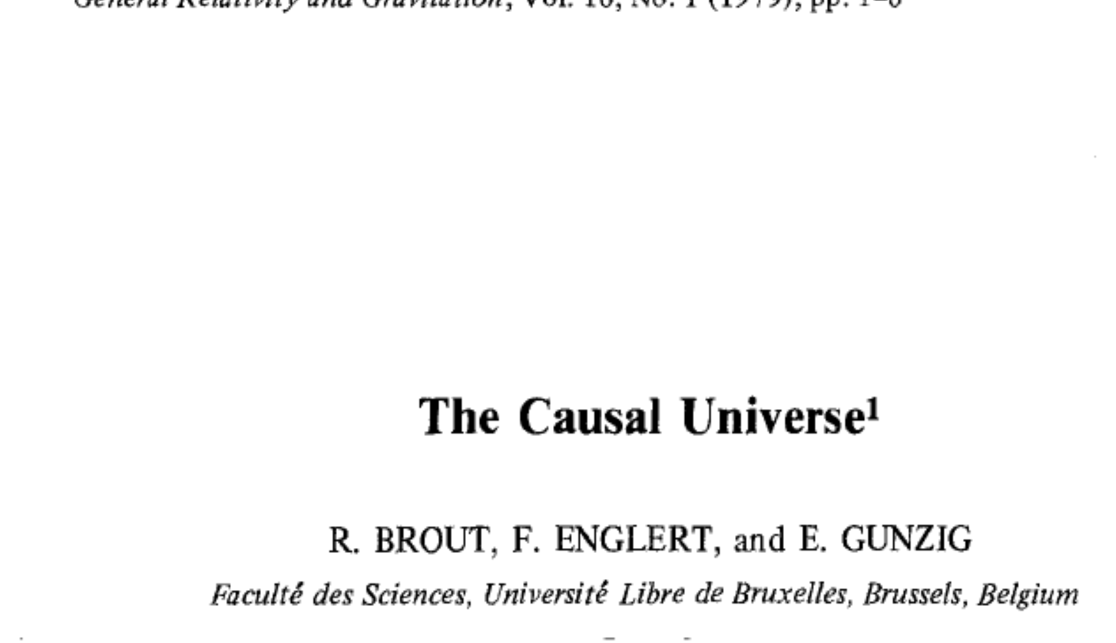
Initial conditions

a) for perturbations

b) for the Universe as a whole

No problem with initial conditions for perturbations!!!
*O*ne can begin with arbitrary inhomogeneities provided that they do not destroy right away the stage of accelerated expansion.
As a result all "garbadge" will be thrown away from the observable horizon and remaining quantum fluctuations will be amplified and produce galaxies (compare to alternatives)

How generic are initial conditions for the Universe and are there any problems with them in inflationary cosmology?

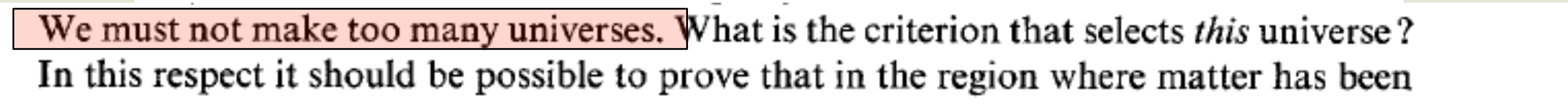


General Relativity and Gravitation, Vol. 10, No. 1 (1979), pp. 1–6

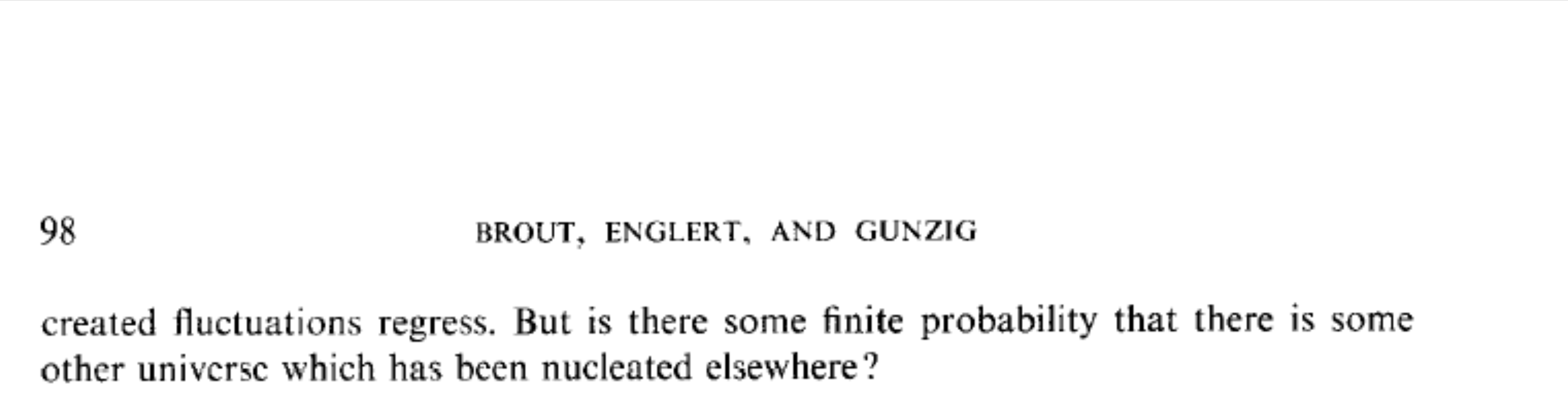
The Causal Universe[1]

R. BROUT, F. ENGLERT, and E. GUNZIG

Faculté des Sciences, Université Libre de Bruxelles, Brussels, Belgium



We must not make too many universes. What is the criterion that selects *this* universe? In this respect it should be possible to prove that in the region where matter has been



created fluctuations regress. But is there some finite probability that there is some other universe which has been nucleated elsewhere?

- Selfreproduction →

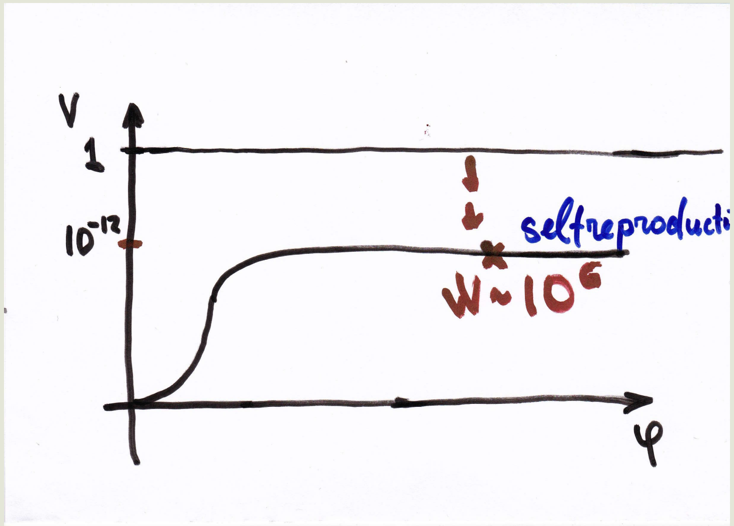
"everything what could happen is happening"

No natural choice of natural measure and even

Boltzman brains:)

- After WMAP-Planck → flat potential →

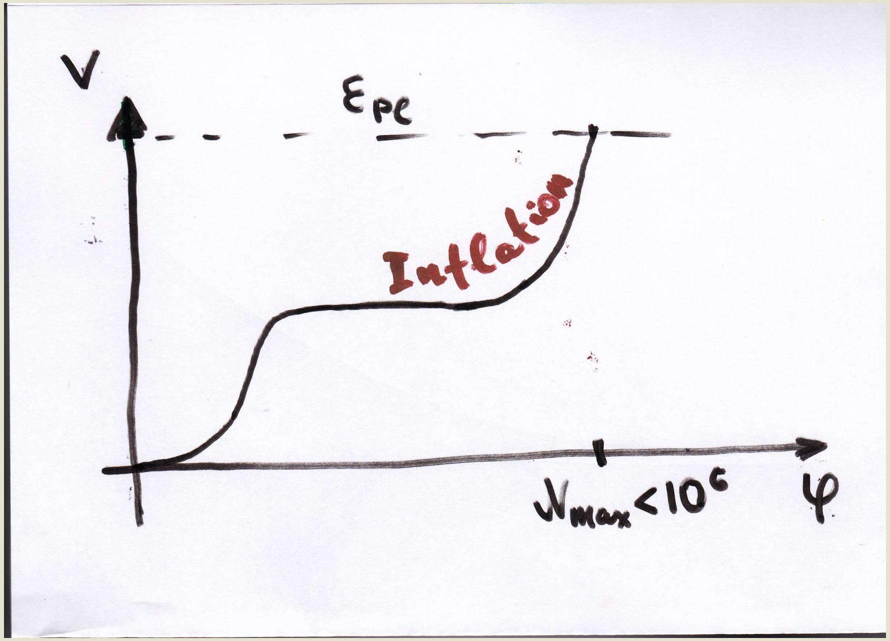
fine tuning is back???



Can we SIMULTANEOUSLY avoid

- *selfreproduction* and its unpredictable Multimess?
- *fine tuning*?

Yes!!!



$$1 + w\left(N\right) \simeq \frac{\beta}{N^{\alpha}} + \frac{1}{3\gamma\left(N_m + 1 - N\right)},$$

$$V\left(\varphi\right) \simeq \frac{\left[1 - \exp\left(-\varphi\right)\right]^2}{\left(\varphi_m - \varphi\right)^a}.$$

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