Quantum Universe

V. Mukhanov
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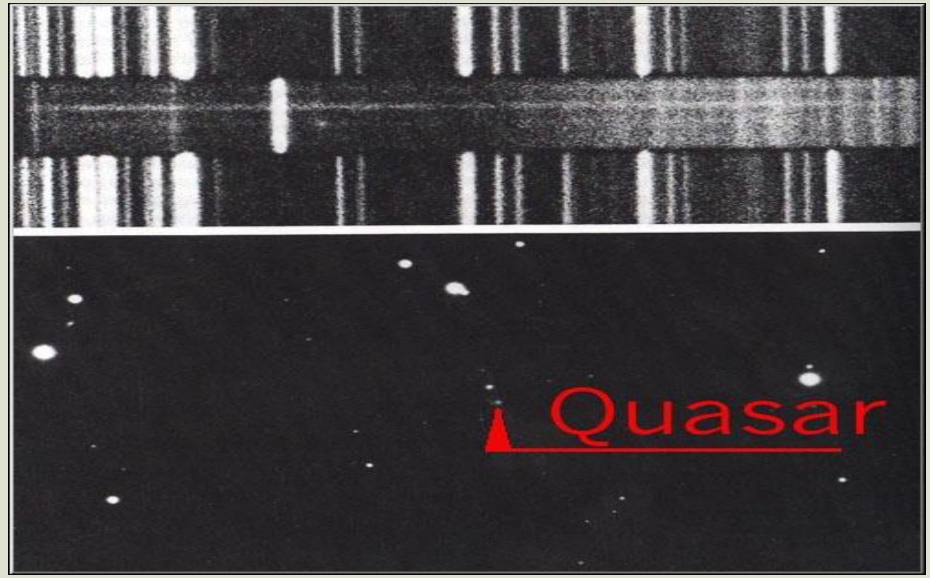
The efforts to understand the universe is one of the very few things that lifts human life a little above the level of farce...

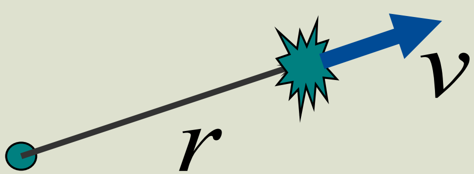
S. Weinberg, 1977

Before 1990

The Universe expands



Hubble law



$$v = Hr$$

$$t \approx \frac{r}{v} = \frac{1}{H} \approx 13{,}7\, bil.\, years$$

There is baryonic matter:

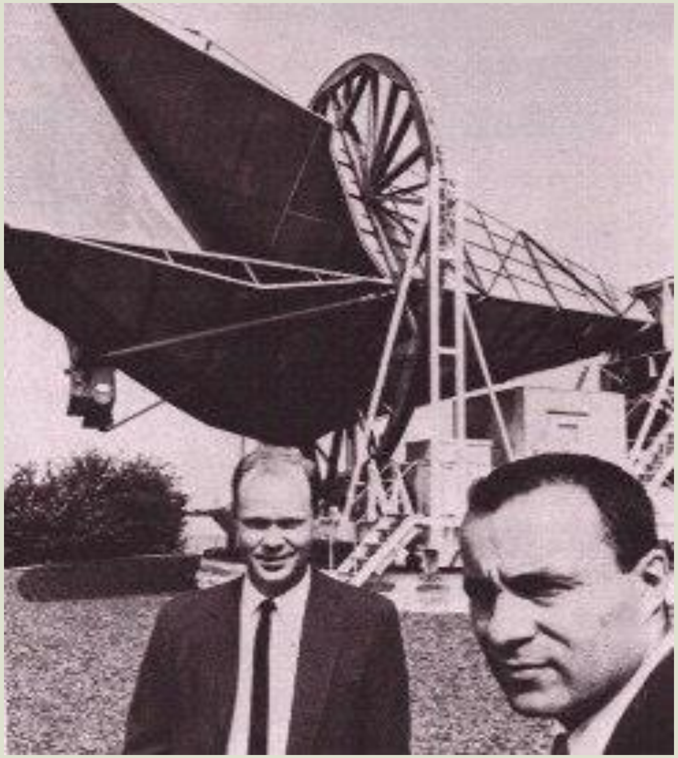
about 25% of ^{4}He, D....heavy elements

Dark Matter???? baryonic origin???

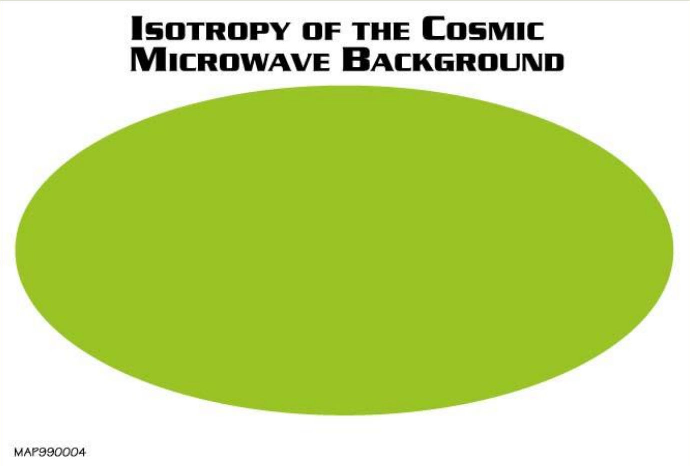
Large Scale Structure: clusters of galaxies!

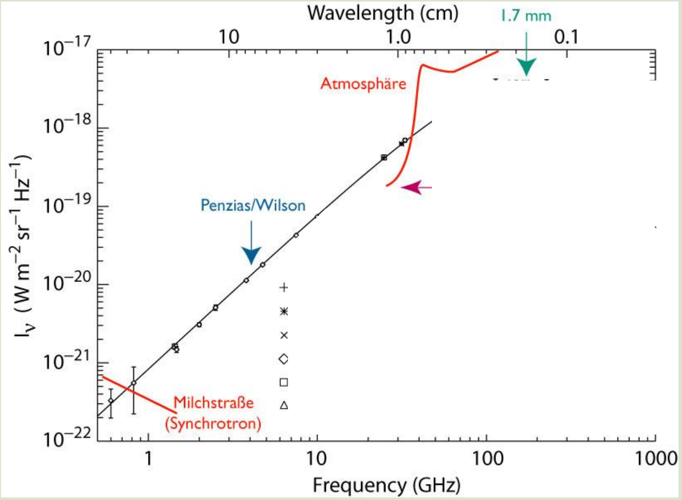
Filaments, Voids??????????????????????

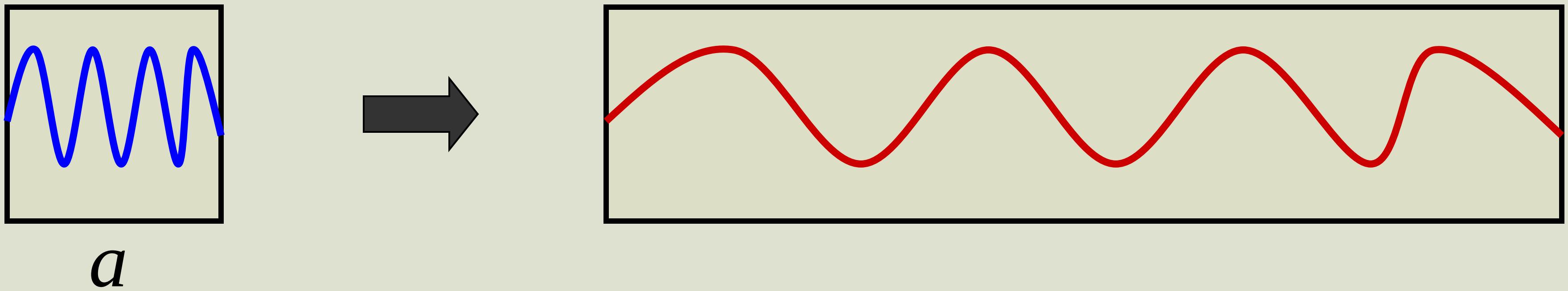
- There exists background radiation with the temperature T » $3K$



Penzias, Wilson 1965



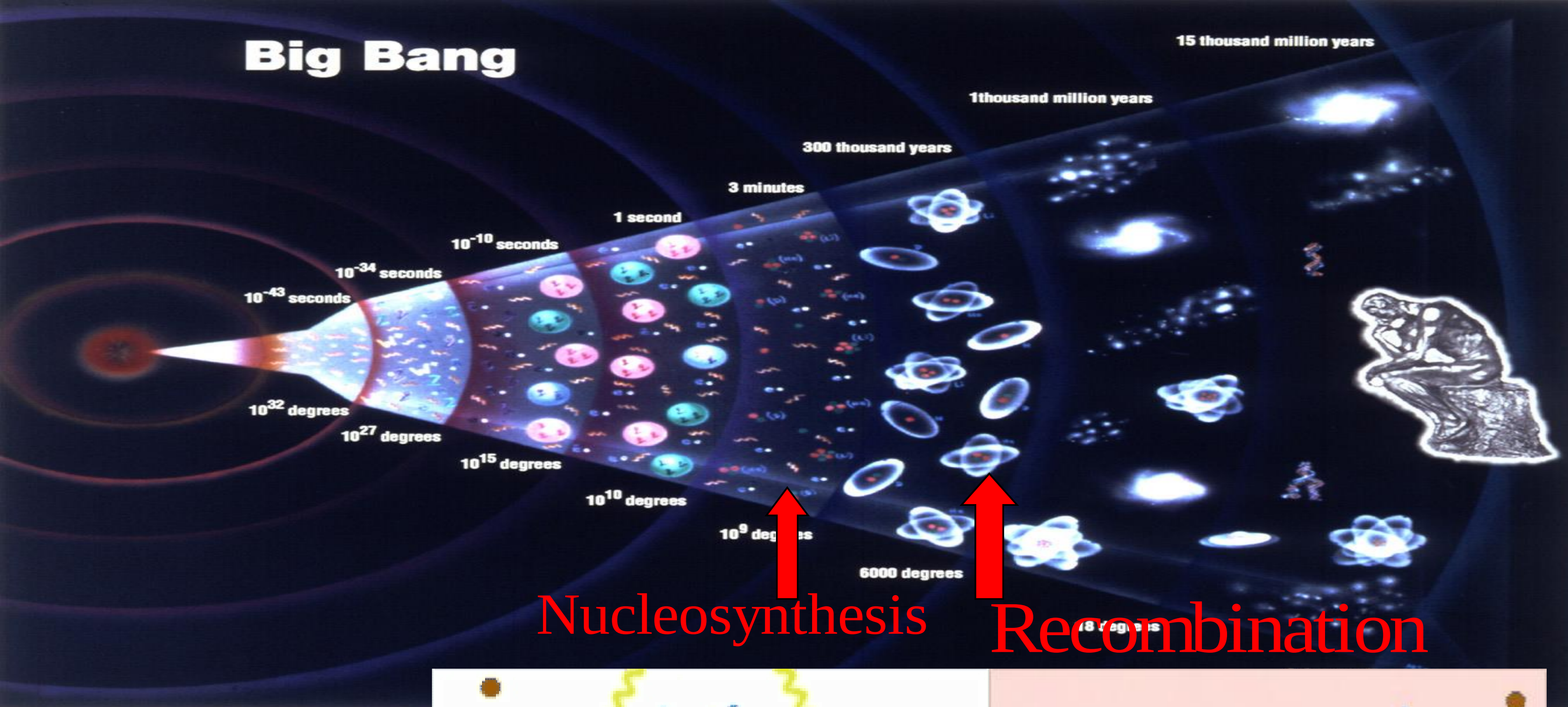




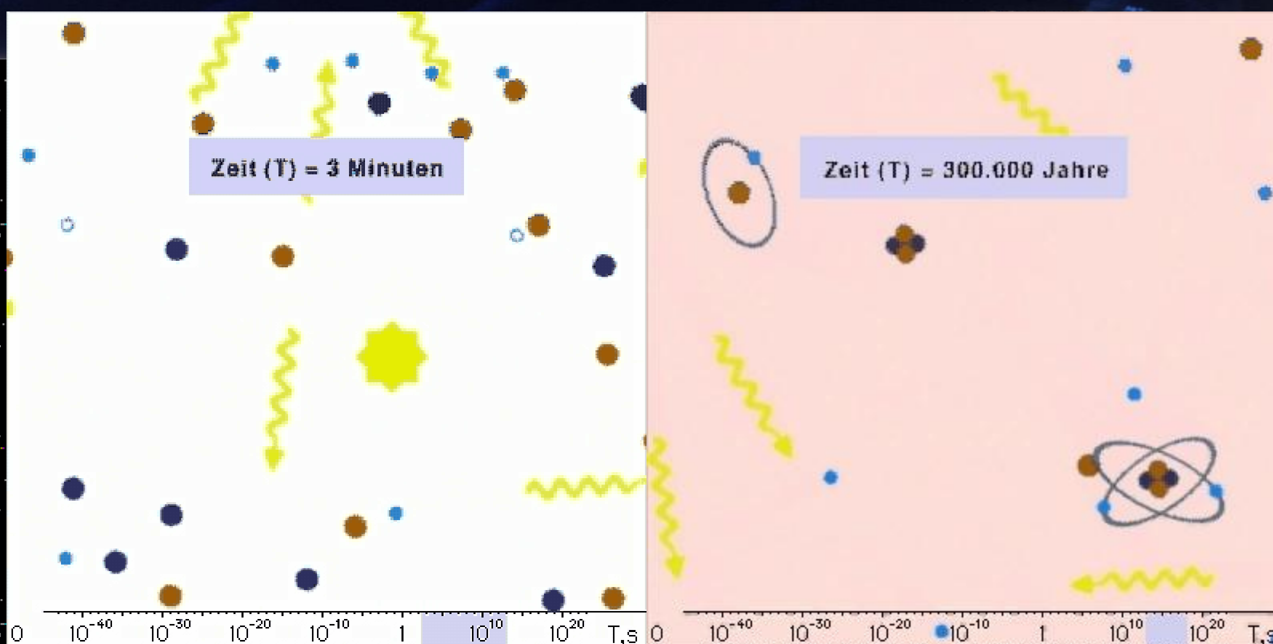
$$\lambda \propto a \quad \Rightarrow \quad T \propto \frac{1}{a}$$

When the Universe was 1000 times smaller

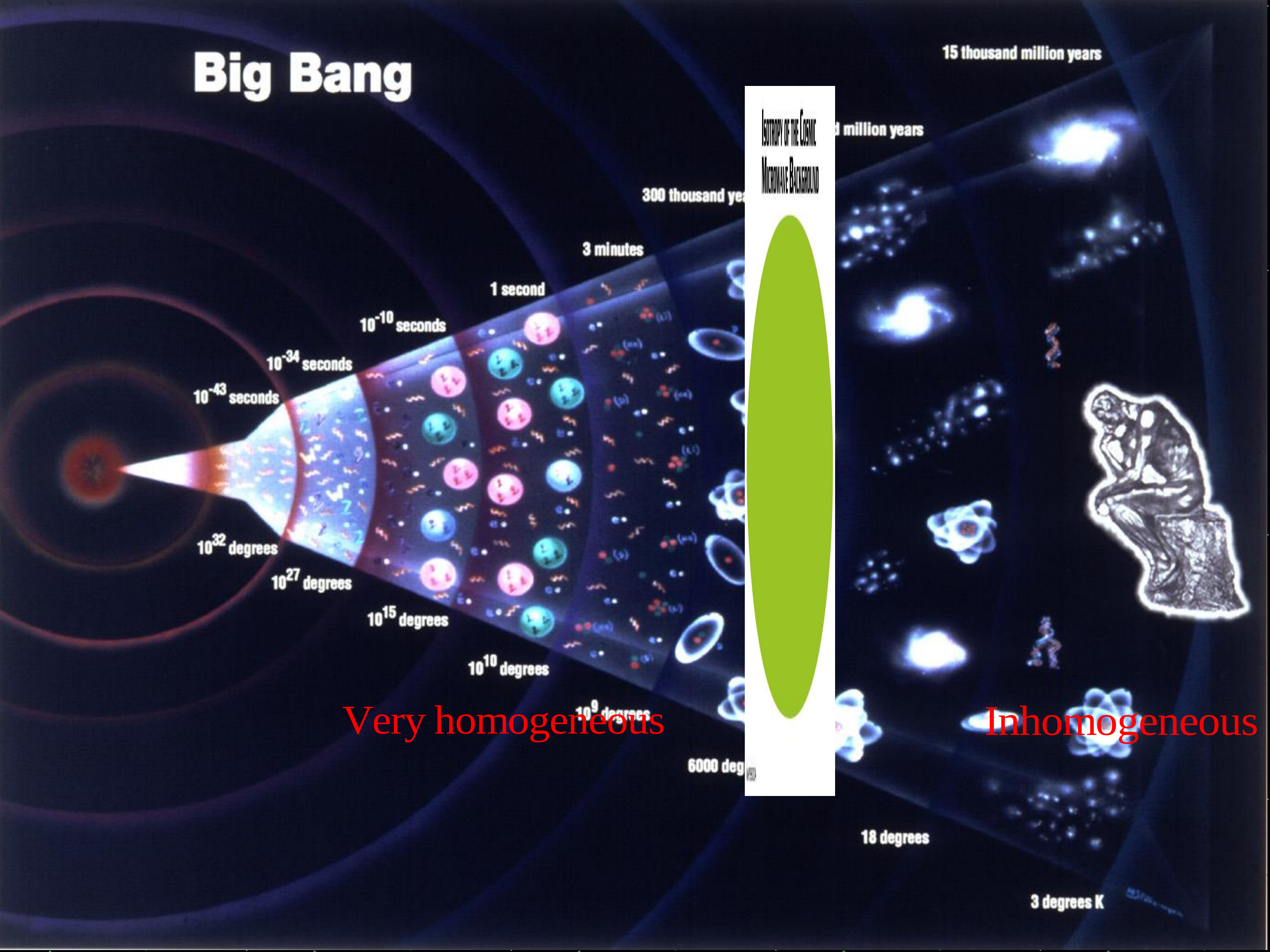
its temperature was about $2725°K$

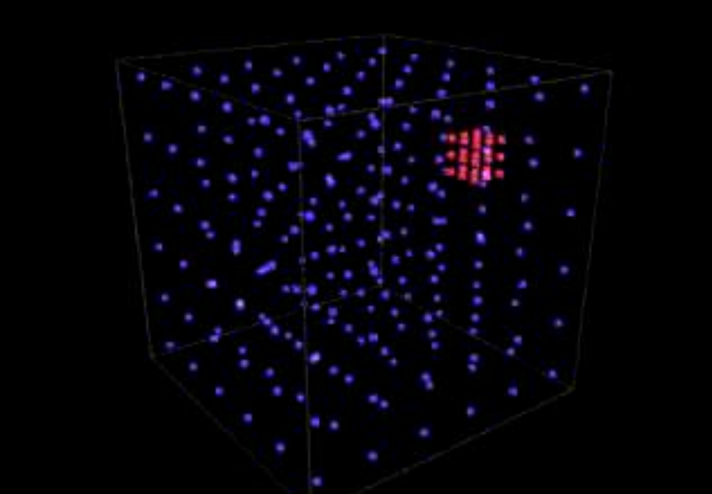


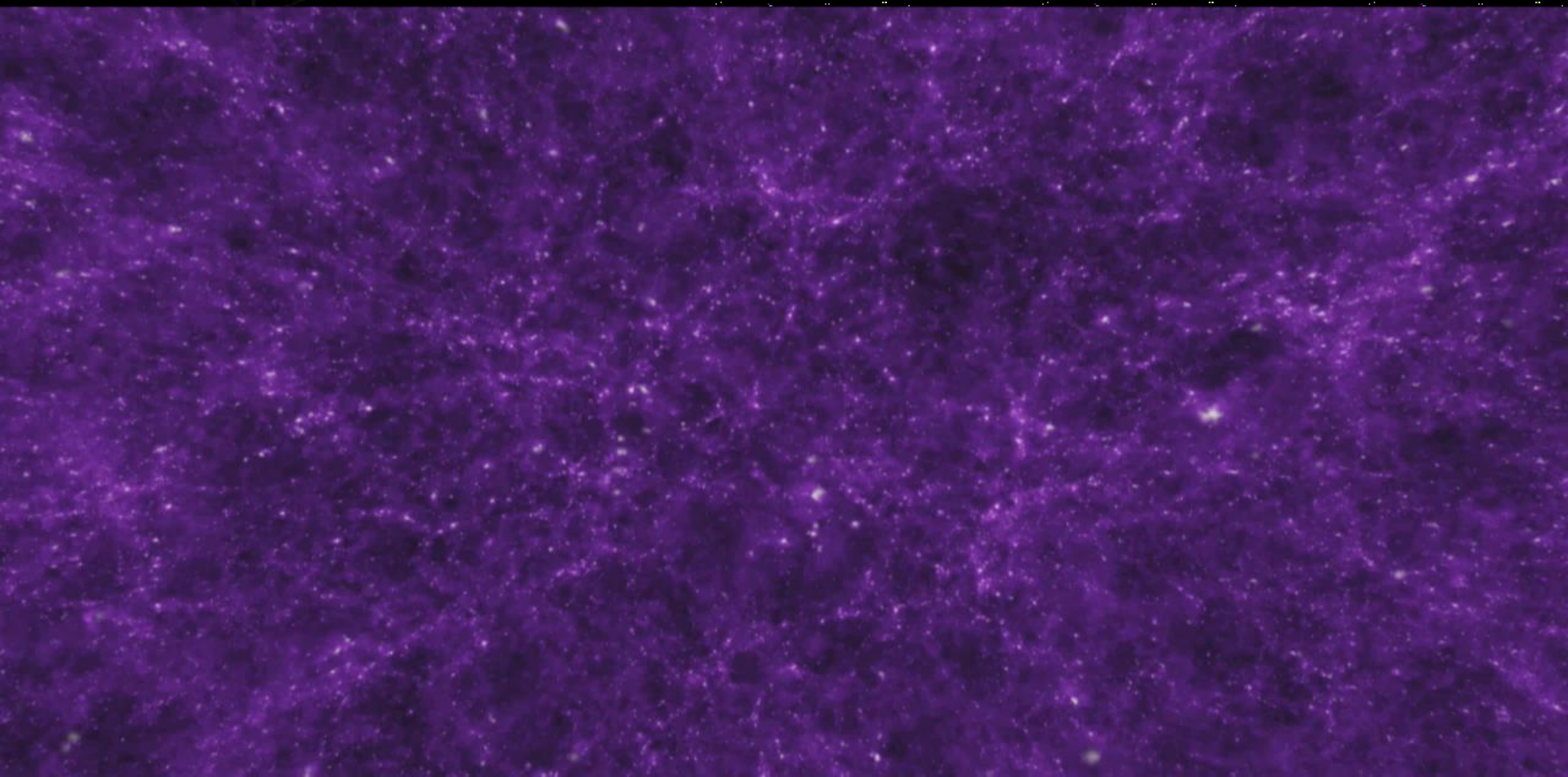
Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10-10 seconds
10-34 seconds
10-43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees
6000 degrees
Nucleosynthesis
Recombination

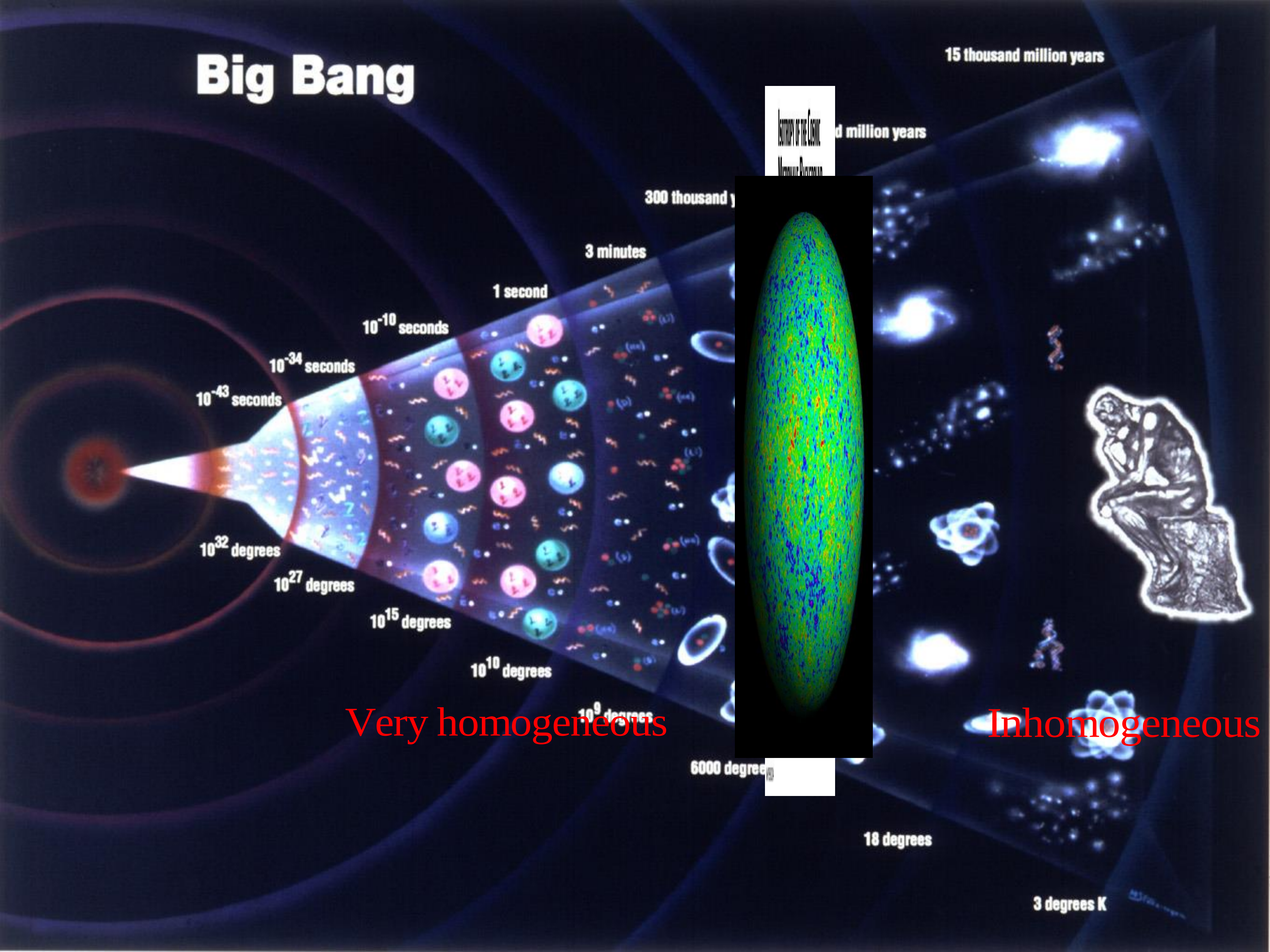


Zeit (T) = 3 Minuten
0 10-40 10-30 10-20 10-10 1 1010 1020 T,s
Zeit (T) = 300.000 Jahre
0 10-40 10-30 10-20 10-10 1 1010 1020 T,s


Big Bang
15 thousand million years
Isotropy of the Cosmic Microwave Background
million years
300 thousand ye
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
Very homogeneous
Inhomogeneous
6000 deg
18 degrees
3 degrees K







Big Bang
15 thousand million years
d million years
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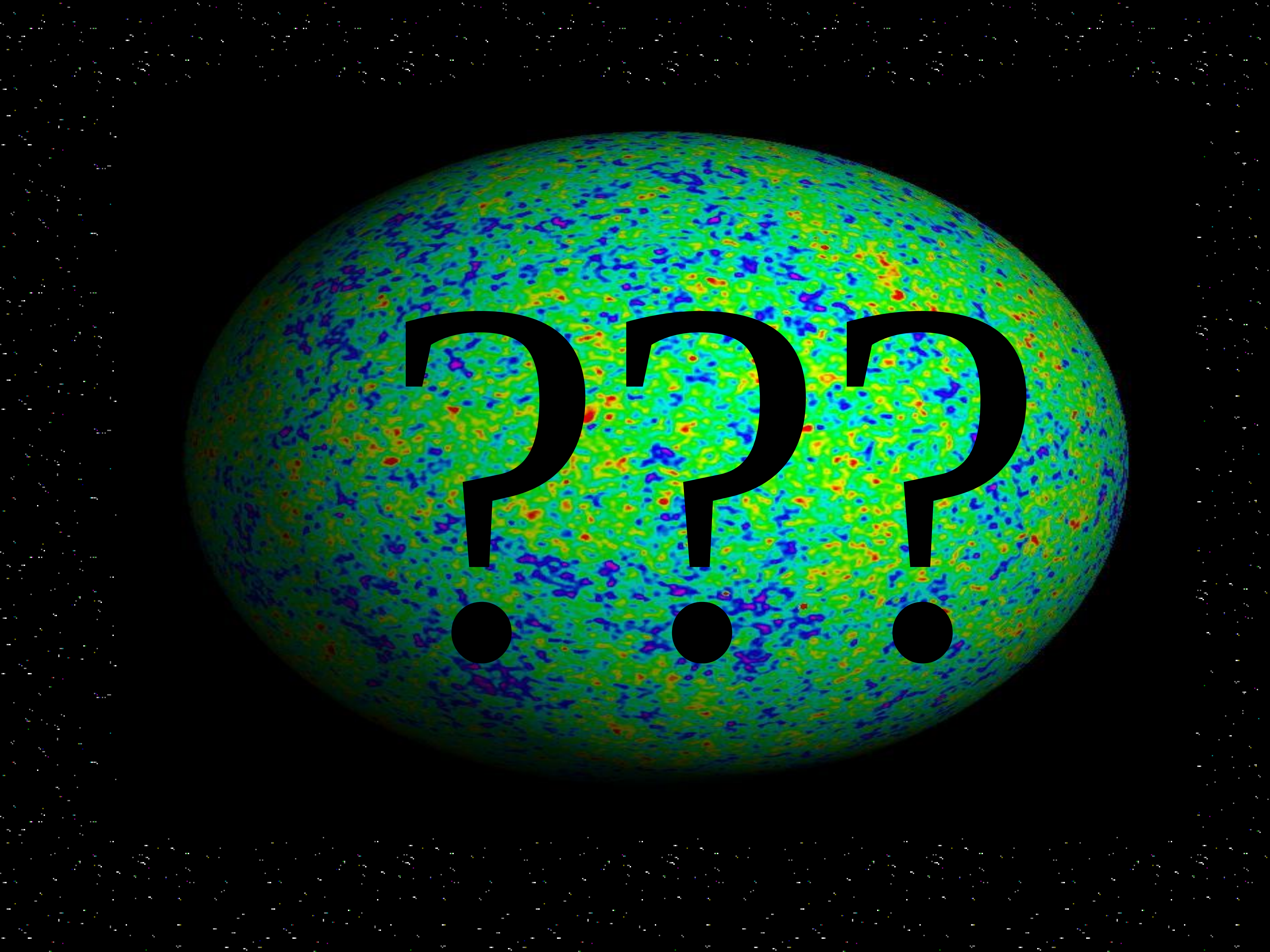
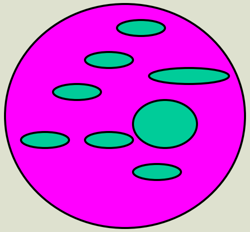
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degree
18 degrees
3 degrees K
Very homogeneous
Inhomogeneous



$$\Delta p \Delta x \geq h$$

There always exist unavoidable

Quantum Fluctuations



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

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

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

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

Chibisov, G. V. & Mukhanov, V. F., 1980. *Lebedev Phys. Inst. Preprint No. 162.*

Mon. Not. R. astr. Soc. (1982) **200**, 535–550

Galaxy formation and phonons

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4 Phonons

The quantization procedure for density inhomogeneities in terms of a real field is well known. For this we must replace the field variable ϕ by the appropriate operator in the quadratic Lagrange function. This is found in the Appendix from the Einstein–Fock action (see formula (A.21)) to be

$$\hat{L} = \int (\hat{\mathscr{L}}_{\mathrm{a}} + \hat{\mathscr{L}}_{\mathrm{ph}}) \sqrt{\gamma}\, d^3\bar{\bar{x}} = -\frac{1}{\ell^2} \int (a'^2 - \kappa a^2 + \ell^2 \epsilon_0 a^4) \sqrt{\gamma}\, d^3\bar{\bar{x}} + \frac{1}{2}$$

$$\times \int \left(\hat{\phi}'^2 - \bar{\bar{c}}_{\bar{\bar{s}}}^2 \gamma^{\alpha\beta} \frac{\partial \hat{\phi}}{\partial \bar{\bar{x}}^\alpha} \frac{\partial \hat{\phi}}{\partial \bar{\bar{x}}^\beta} + \frac{\underline{\underline{z}}''}{\underline{\underline{z}}} \hat{\phi}^2 \right) \sqrt{\gamma}\, d^3\bar{\bar{x}}. \tag{4.1}$$

$$\phi'' - \bar{\bar{c}}_{\bar{\bar{s}}}^2 {}^{(3)}\Delta\phi - \frac{\underline{\underline{z}}''}{\underline{\underline{z}}} \phi = 0, \quad \underline{\underline{z}} = \frac{a}{\alpha} \left(\frac{2\beta}{3\bar{\bar{c}}_{\bar{\bar{s}}}^2} \right)^{1/2} = \frac{a}{\bar{\bar{c}}_{\bar{\bar{s}}}} \left(\frac{\bar{\bar{w}}}{\epsilon - \kappa/\ell^2 a^2} \right)^{1/2}. \tag{3.5}$$

6.2 MODEL WITH A QUASI-VACUUM STAGE

The case when $\bar{p} + \epsilon \ll \epsilon$ is realized for the vacuum equation of state $\bar{p}_{\bar{v}} = -\epsilon_{\bar{v}}$ (see, e.g.,

Thus the calculations of this section clearly demonstrate the possibility in principle of obtaining the conditions for galaxy formation by means of the initial vacuum fluctuations.

$a(t \sim \bar{t})/t$. Thus the role of the vacuum polarization stage for galaxy formation is to connect the galactic scales causally with the Planck scale where the quantum fluctuations are dominant.

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)

Adopting a perturbation of the curvature scalar as a physical variable, we find the corresponding action in the form[6]

$$\delta S_b = \frac{1}{2}\int d^4x \left[\phi'^2 - \nabla^\alpha\phi\nabla_\alpha\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right], \tag{5}$$

where $\phi = 1/\sqrt{18\,(4H^2 - M^2)}\; a\delta R/M\ell$, and $\ell = (8\pi G/3)^{1/2} = 4.37 \times 10^{-33}$ cm is the Planck length.

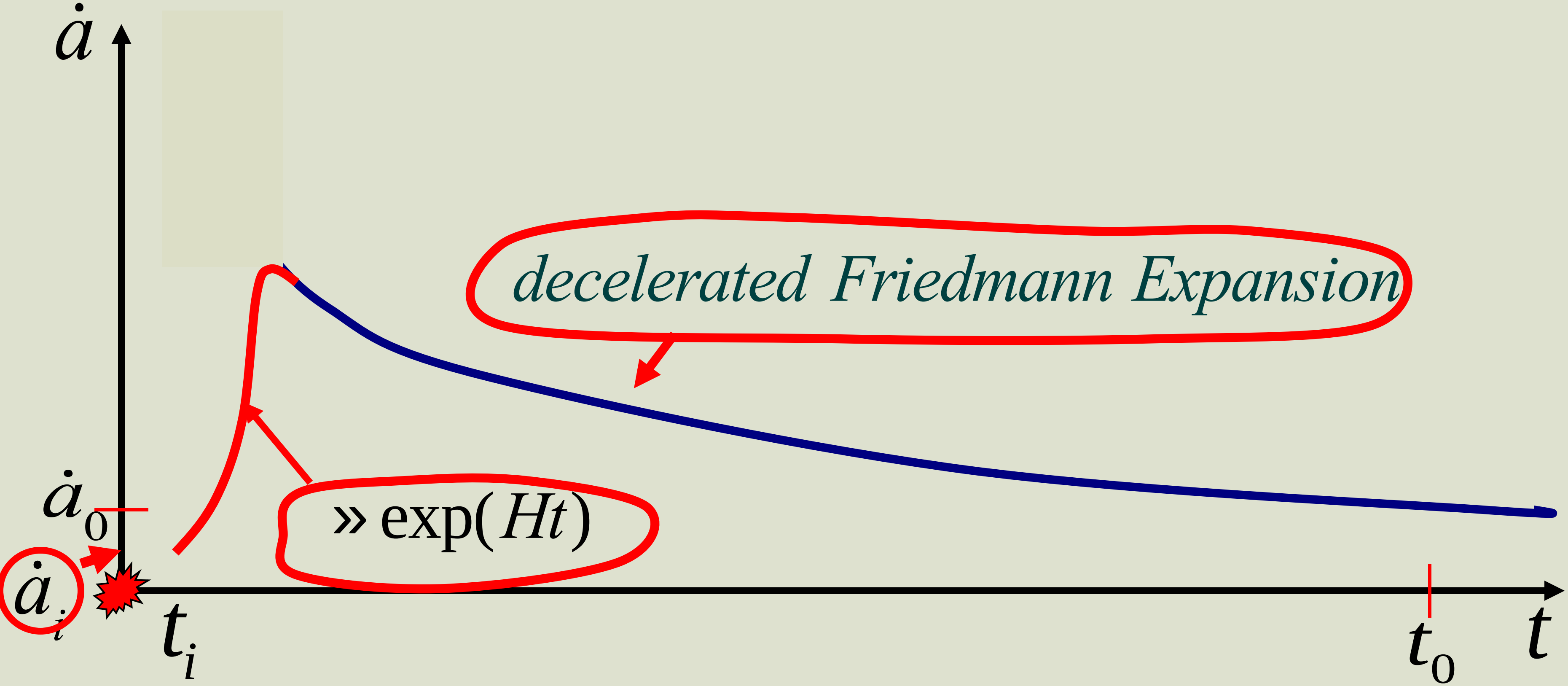
A finite duration of the de Sitter stage does not by itself rule out the possibility that this stage may exist as an intermediate stage in the evolution of the universe. An interesting question arises here: Might not perturbations of the metric , which would be sufficient for the formation of galaxies 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

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

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

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

The fluctuation spectrum is thus nearly flat. The quantity $Q\,(k)$ 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



$\dot{a}$
decelerated Friedmann Expansion
$\dot{a}_0$
$\approx \exp(Ht)$
$\dot{a}_i$
t_i
t_0
t

Inflation —

— theology =

$\approx e^{Ht}$

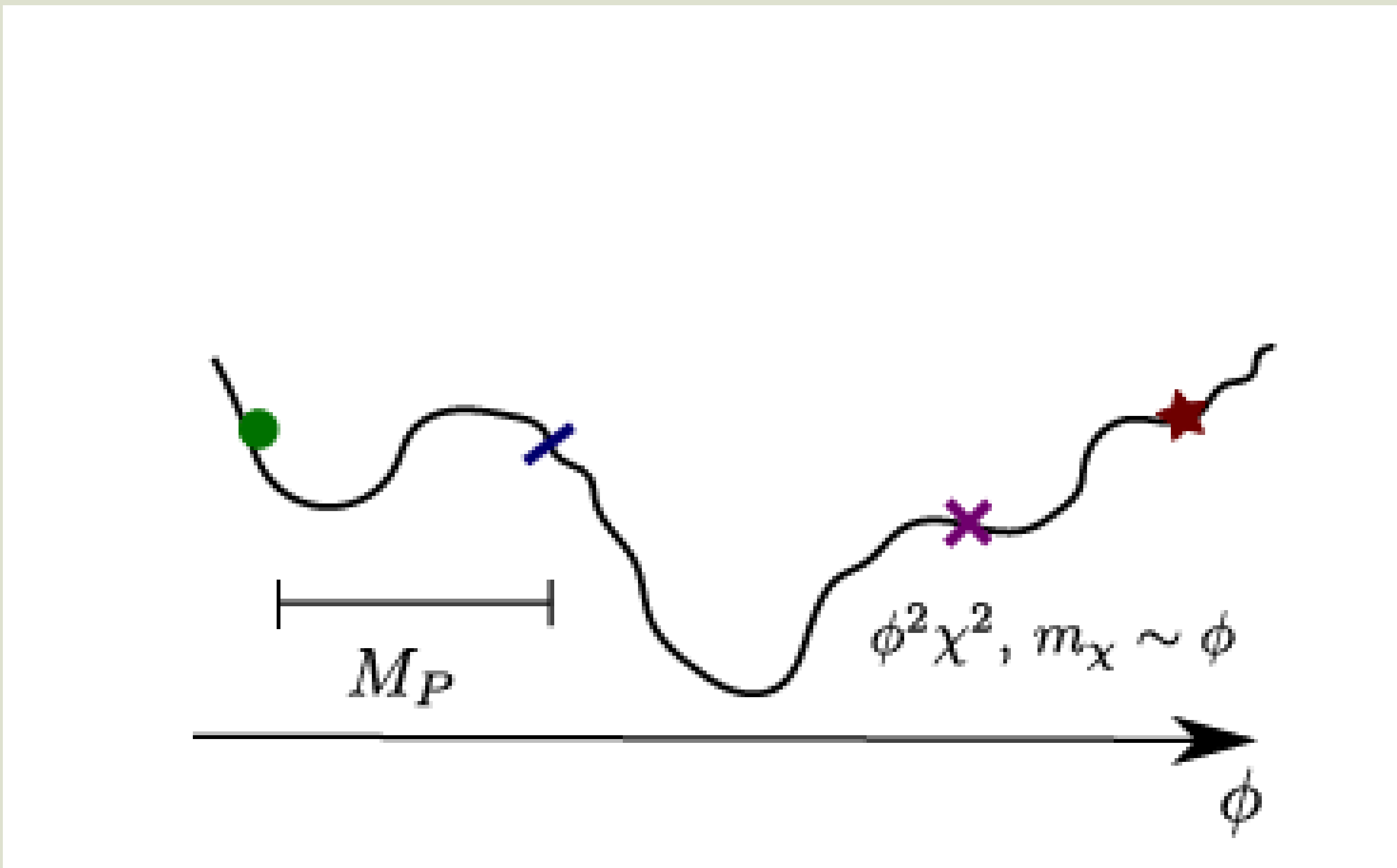
during at least

$t \sim 70 H^{-1}$

$V(\varphi) \Longrightarrow p \approx -\varepsilon$

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

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

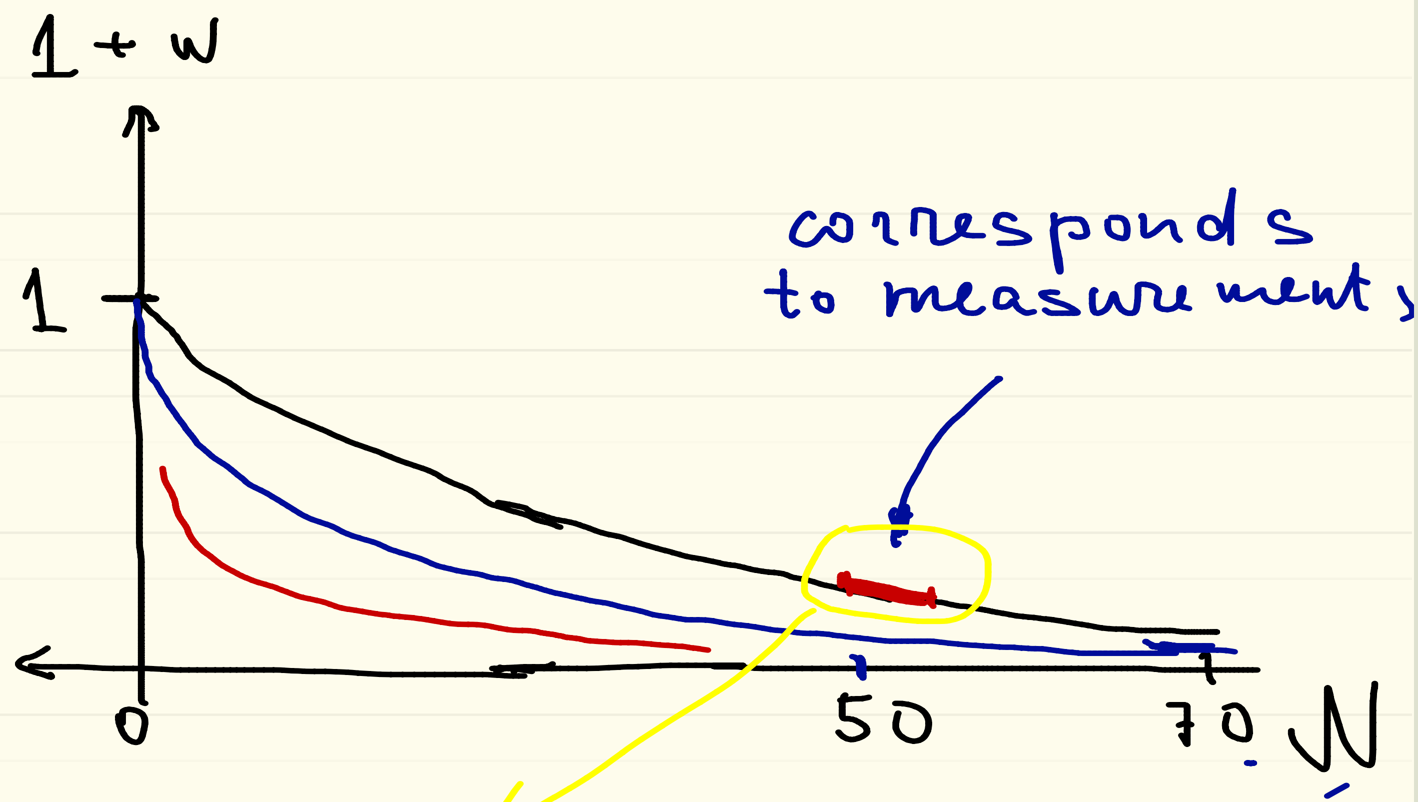


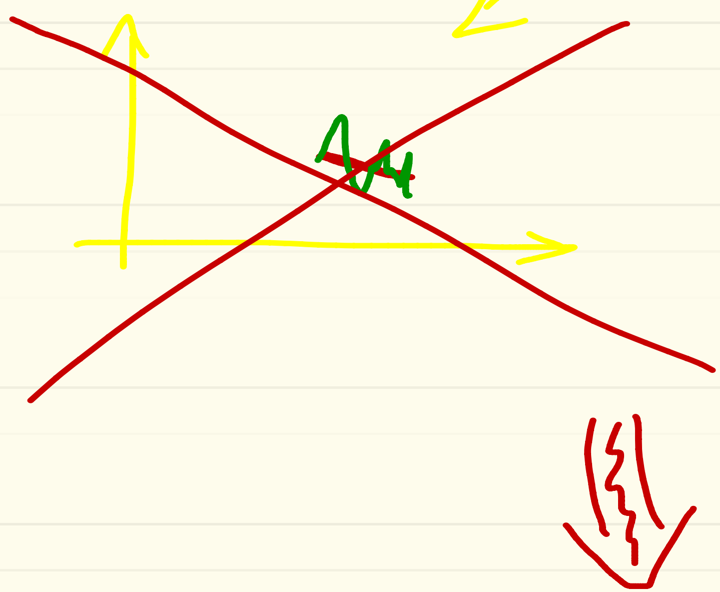
- What is relevant
  - ε – energy density
  - p – pressure

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

during last 70 e-folds

$$a = a_f e^{-N}$$





$$\frac{p + \varepsilon}{\varepsilon} = \frac{\beta}{(N+1)^{\alpha}}$$

PREDICTIONS

1) flat Universe

Perturbations are :

2) adiabatic (MC, 81)

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

4) spectrum: $F \; \mu \; \ln (/ / /_g) \; \mu \; /^{1-n_S}$ with $n_S = 0.96$ (MC, 81)

5) Gravitational waves (Starobinsky, 79)

5) Gravitational waves (Starobinsky, 79)

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.

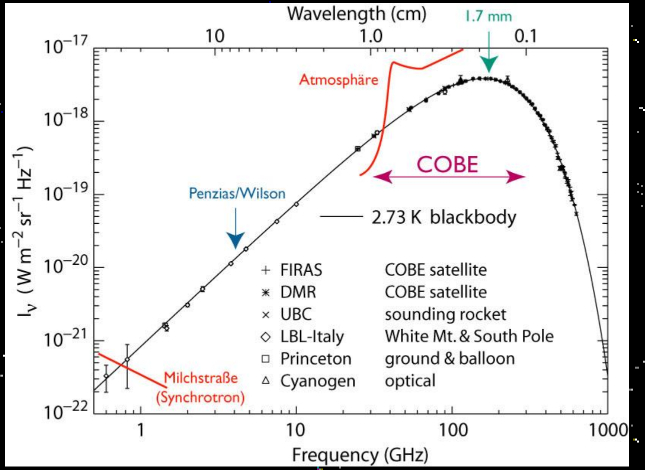
The upper bound is more robust than lower. The physical reason for the deviation of spectrum from the flat one is the nessesity to finish inflation....

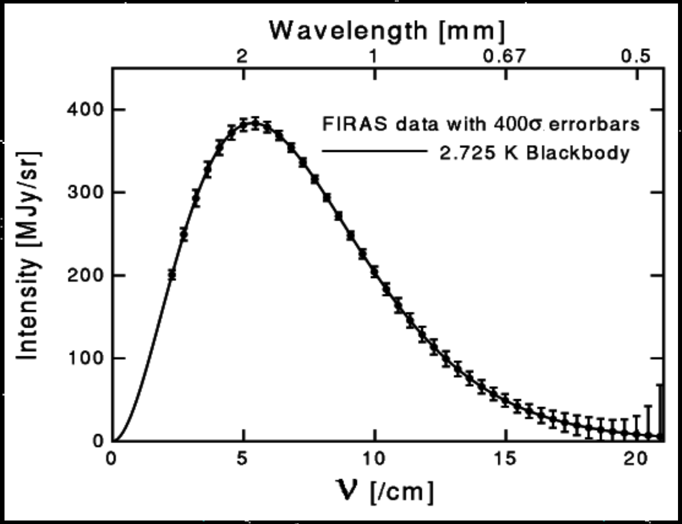
If you find n_s=0.99 +/- 0.01 (3 sigma) I would throw in the towel of inflation.

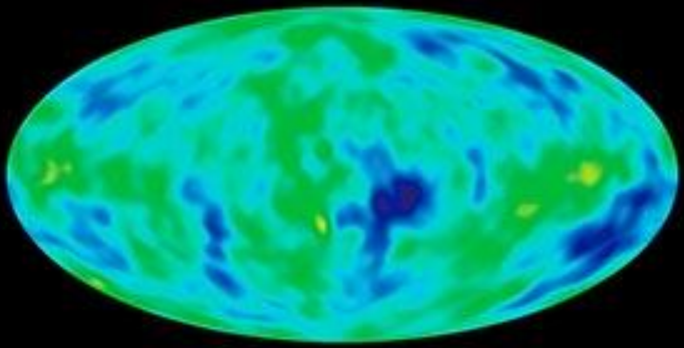
After 90 - present

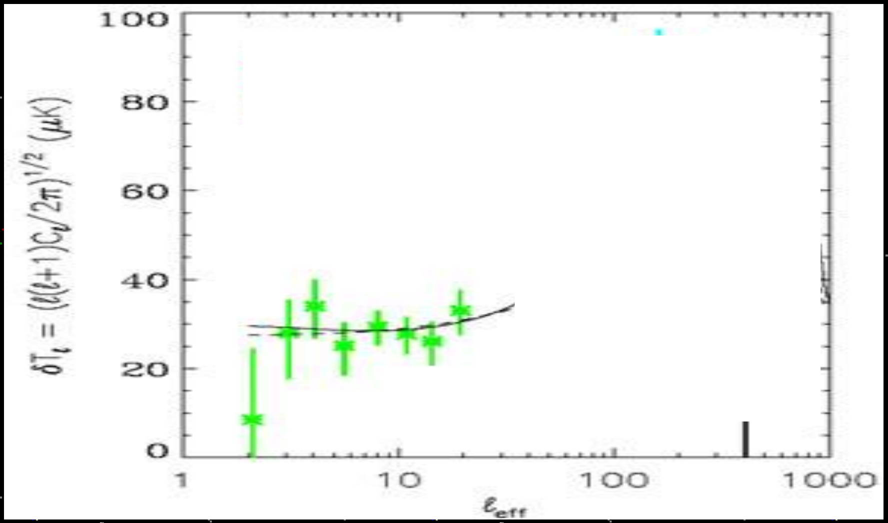
COBE 1992

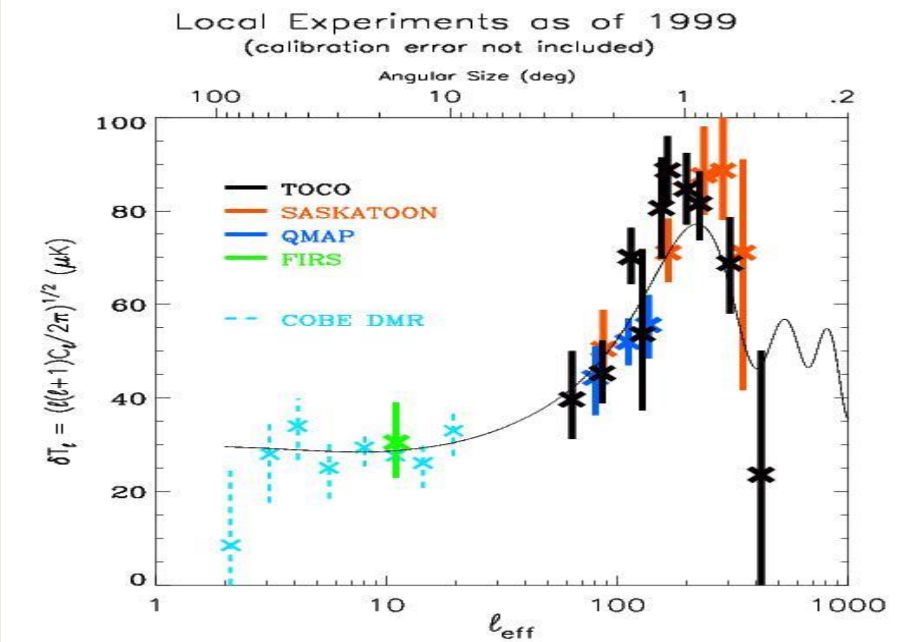

FIRAS
DIRBE
DMR Antennas
Helium Dewar
Deployable Solar Panels
Deployable Mast
TDRSS Omni Antenna
Earth Sensors


Wavelength (cm)
1.7 mm
10
1.0
0.1
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
I_ν (W m^{-2} sr^{-1} Hz^{-1})
Atmosphäre
COBE
Penzias/Wilson
2.73 K blackbody
+ FIRAS COBE satellite
DMR COBE satellite
UBC sounding rocket
LBL-Italy White Mt. & South Pole
Princeton ground & balloon
Cyanogen optical
Milchstraße
(Synchrotron)
1
10
100
1000
Frequency (GHz)

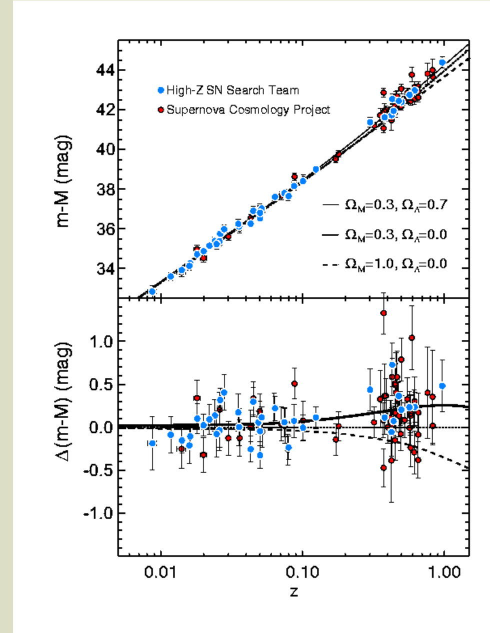

Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]



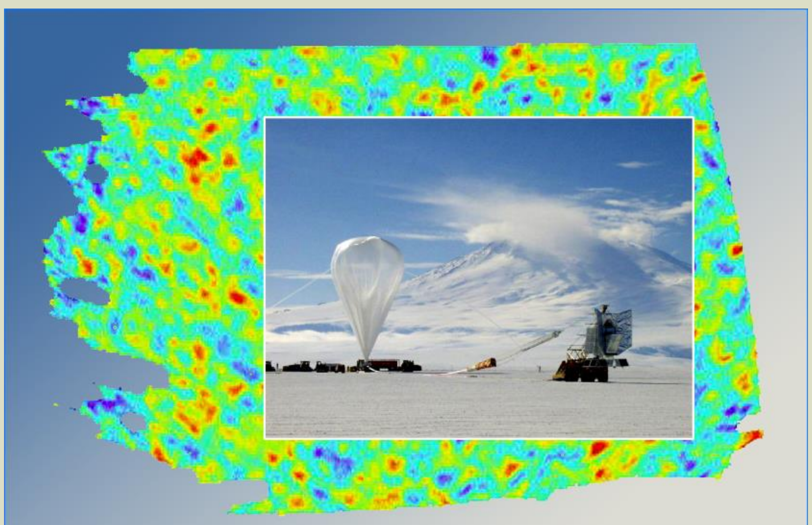

100
80
60
40
20
0
$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
1
10
100
1000
ℓ_{eff}

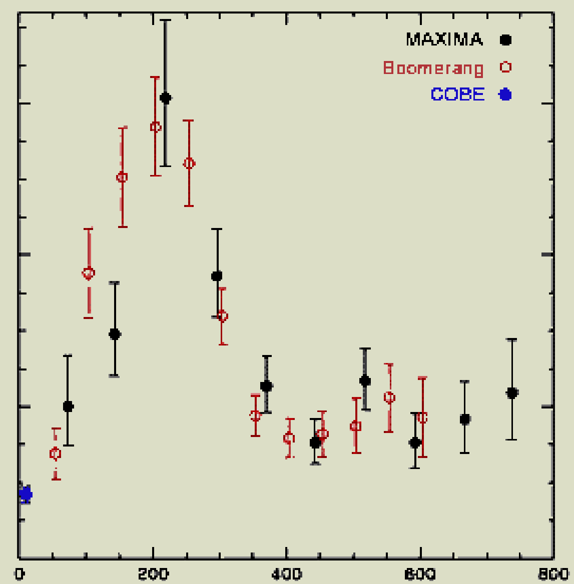


Local Experiments as of 1999
(calibration error not included)
Angular Size (deg)
100
10
1
.2
100
80
60
40
20
0
1
10
100
1000
TOCO
SASKATOON
QMAP
FIRS
COBE DMR
$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
ℓ_{eff}

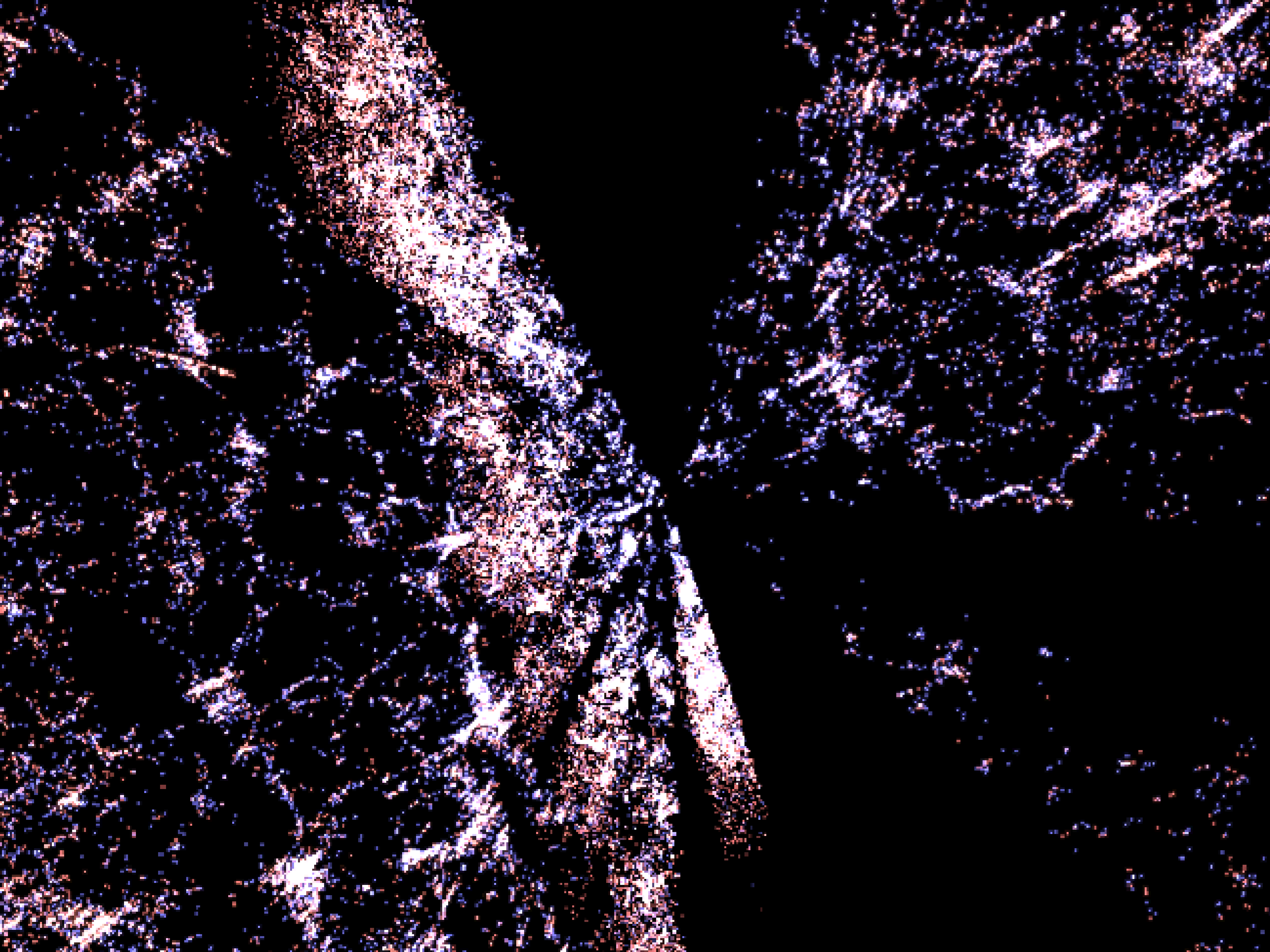


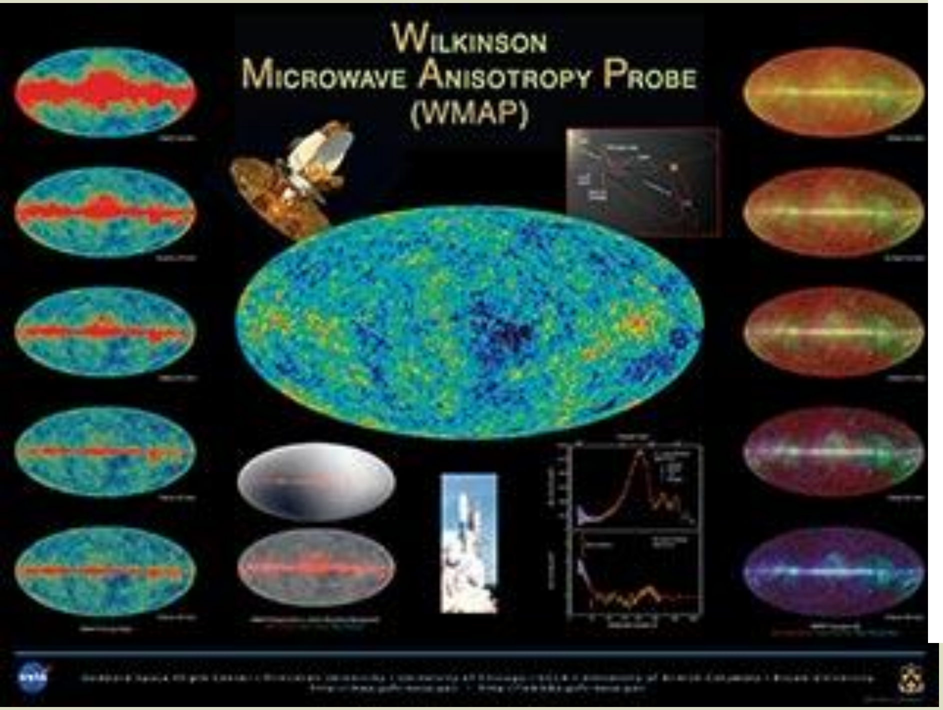
High-Z SN Search Team
Supernova Cosmology Project
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
44
42
40
38
36
34
Δ(m-M) (mag)
1.0
0.5
0.0
-0.5
-1.0
0.01
0.10
1.00
z

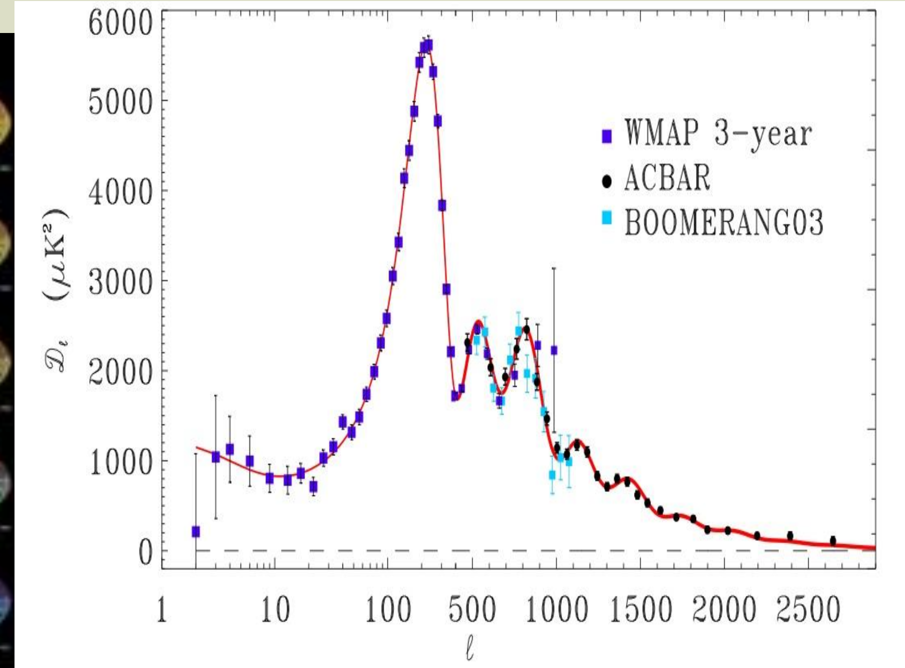


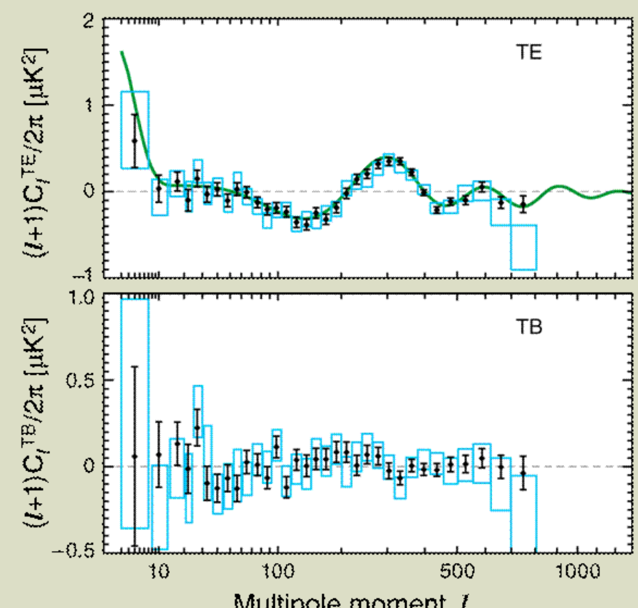


MAXIMA
Boomerang
COBE
0
200
400
600
800

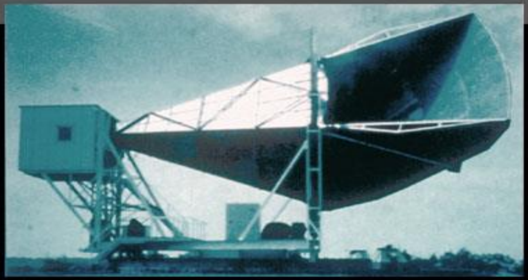


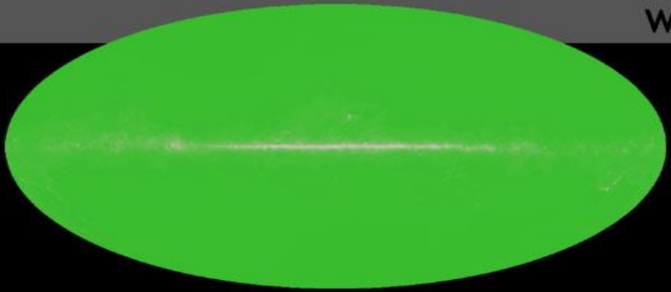

WILKINSON
MICROWAVE ANISOTROPY PROBE
(WMAP)


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ (μK²)
WMAP 3-year
ACBAR
BOOMERANG03
1
10
100
500
1000
1500
2000
2500
ℓ

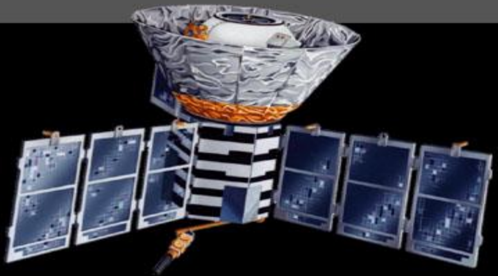

TE
$(l+1)C_l^{TE}/2\pi$ [μK²]
2
1
0
−1
TB
$(l+1)C_l^{TB}/2\pi$ [μK²]
1.0
0.5
0
−0.5
10
100
500
1000
Multipole moment l

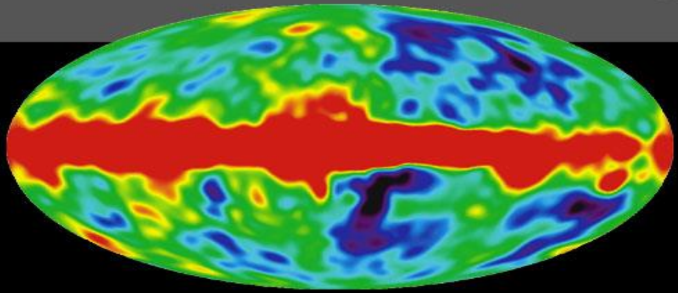
1965 Penzias and Wilson



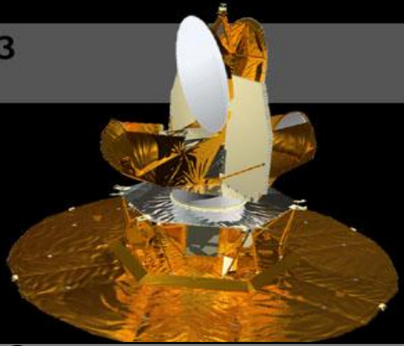


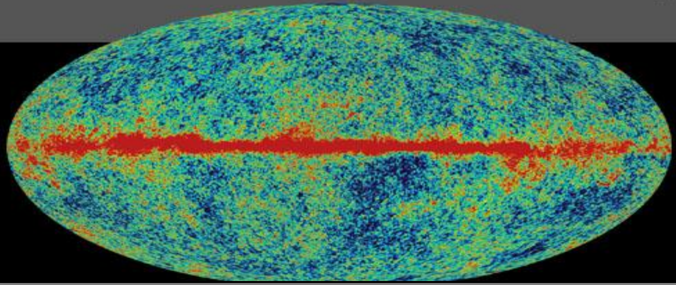
1992 COBE



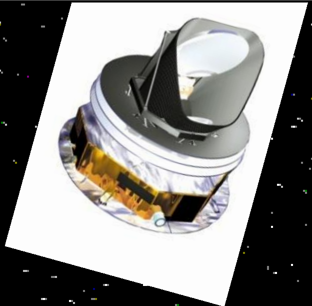


2003 WMAP



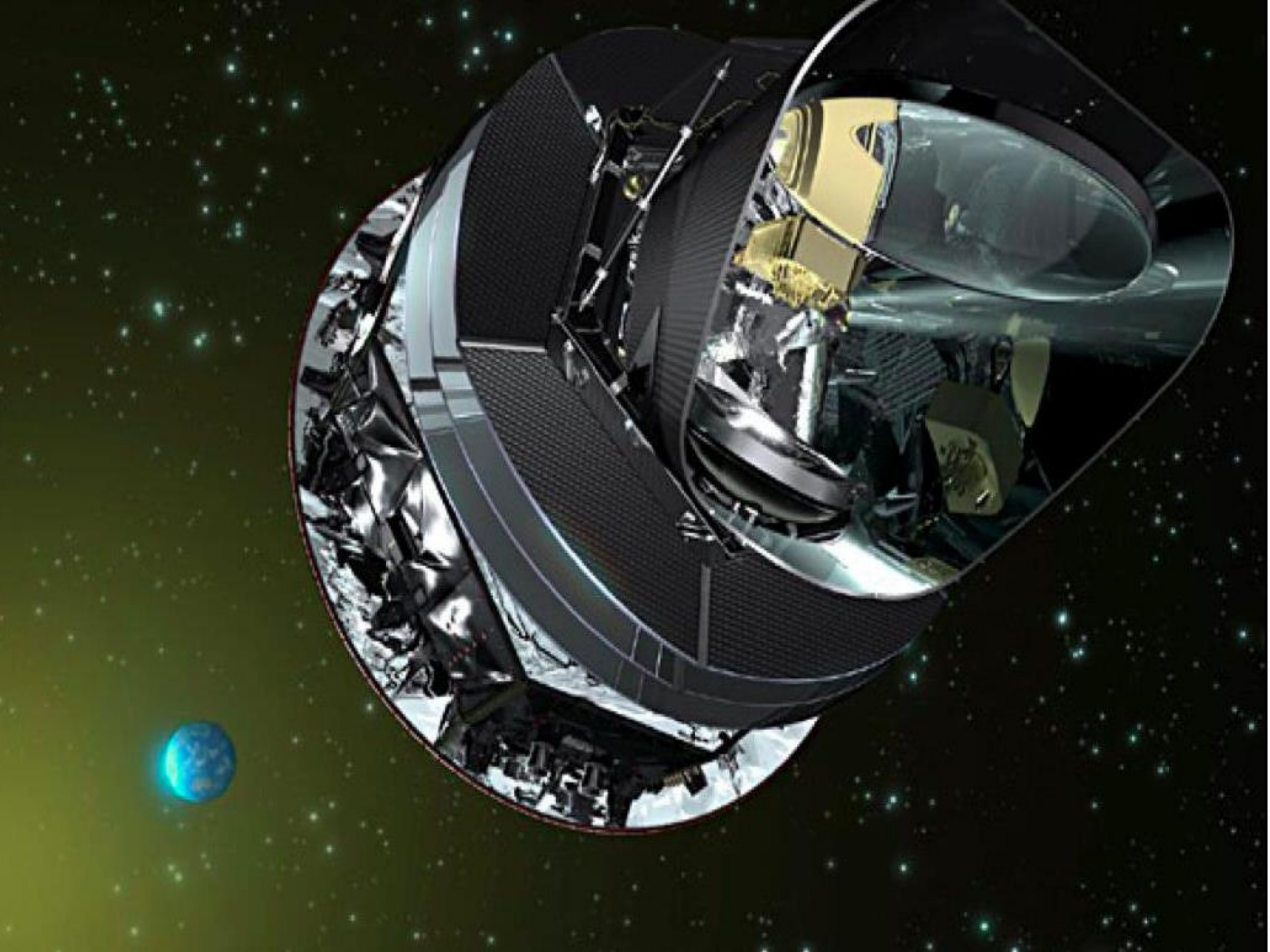


2009 Planck



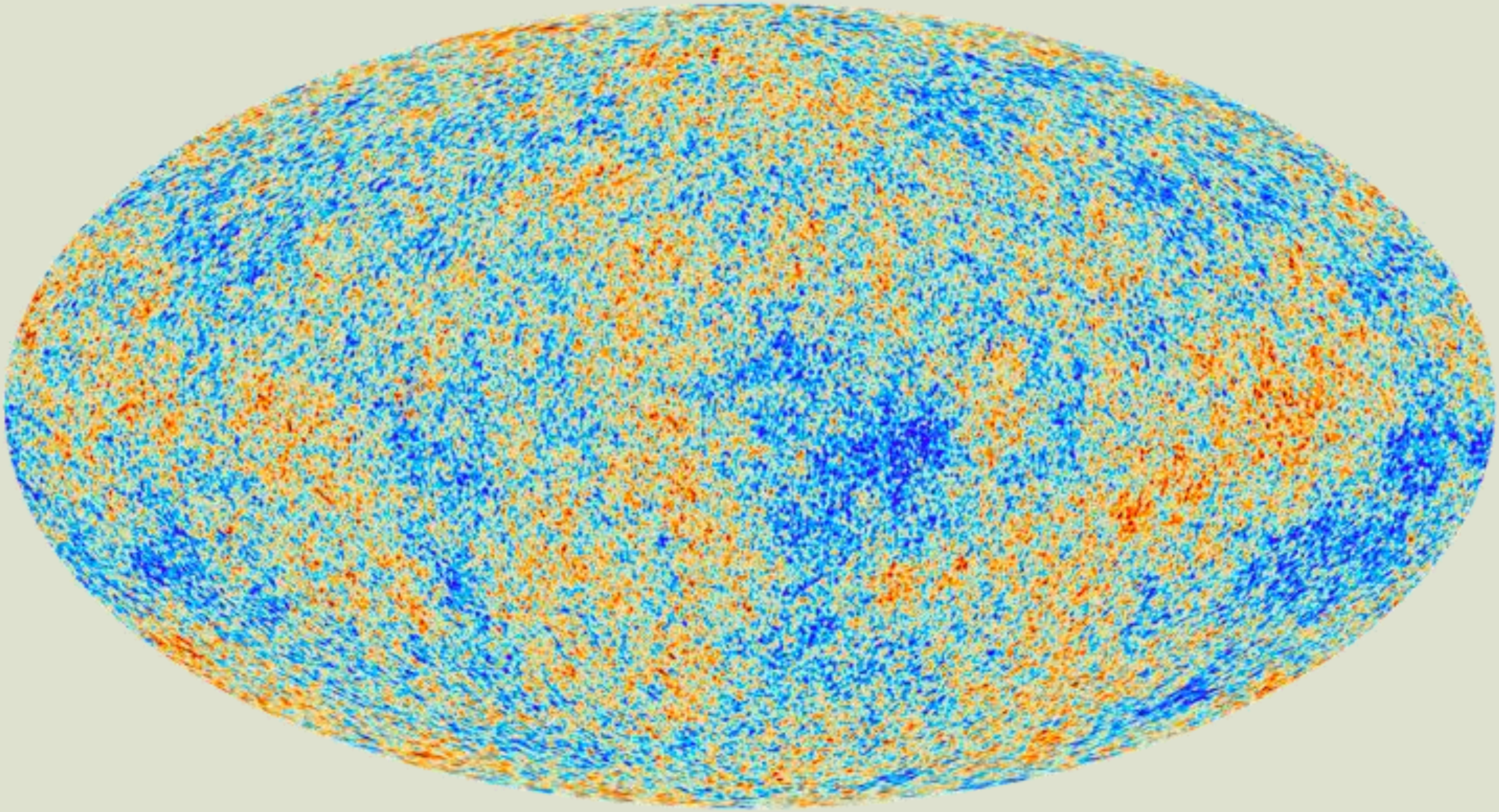
???

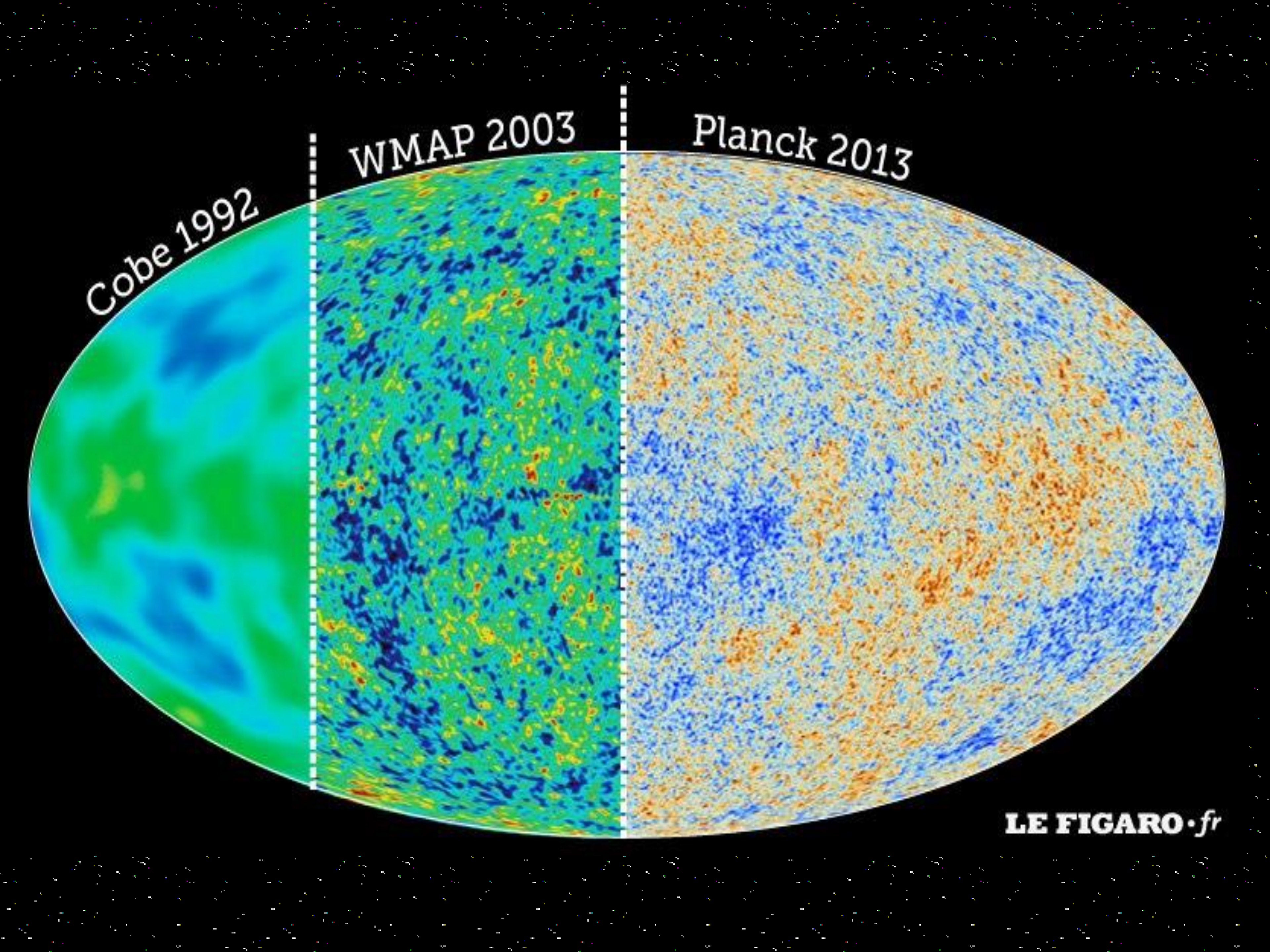
End 2012



the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.




Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

Ground-based:

ABS, ACBAR, ACT, AMI, APEX, APEX-SZ, ATCA
BICEP, BICEP2, BIMA, CAPMAP, CAT, CBI, Clover,
COSMOSOMAS, DASI, FOCUS, GUBBINS, Keck Array,
MAT, OCRA, OVRO, POLARBEAR, QUaD, QUBIC, QUIET,
RGWBT, Sakaatoon, SPT, TOCO, SZA, Tenerife, VSA

PREDICTIONS

1) flat Universe

Perturbations are :

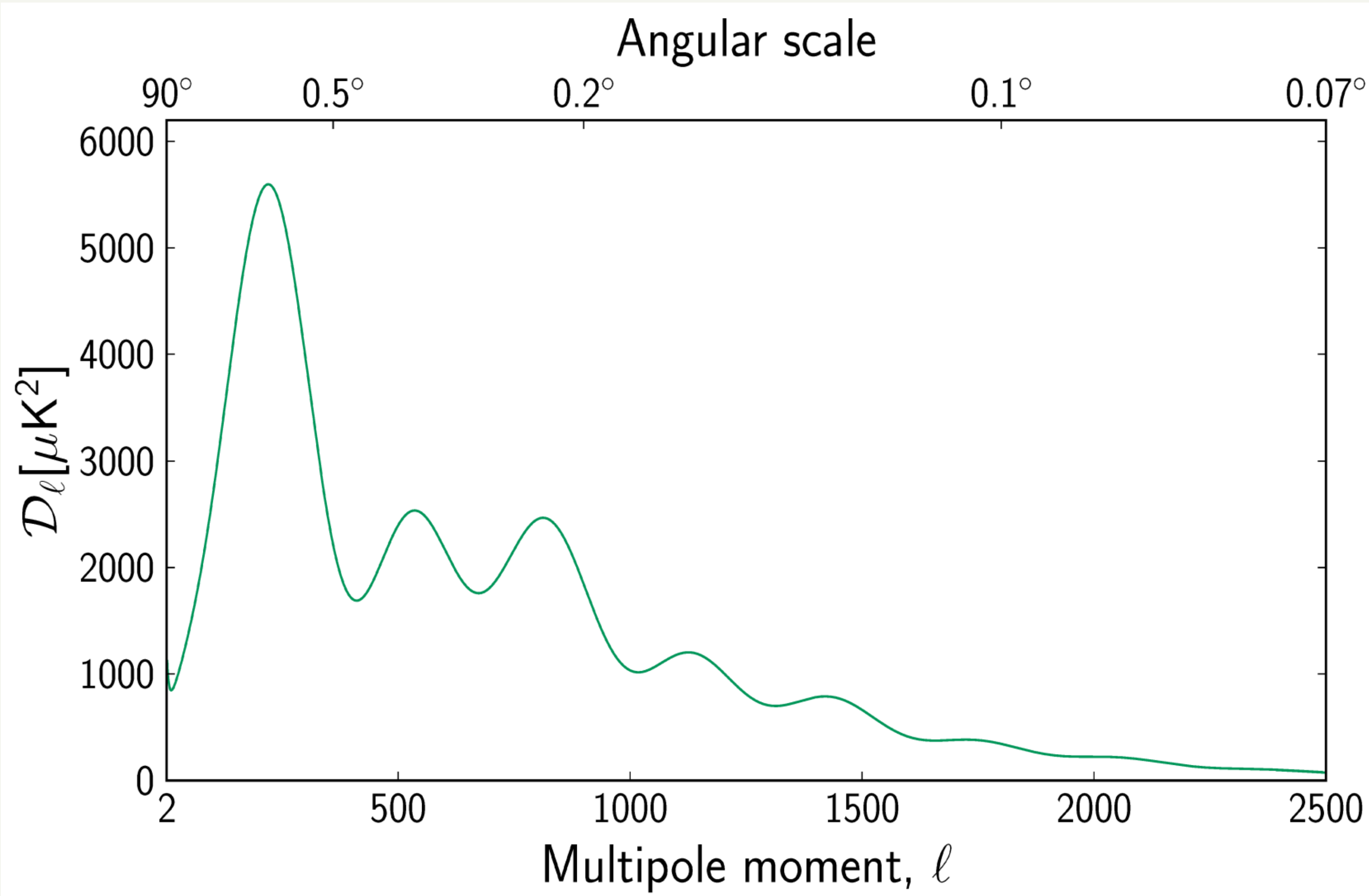
2) adiabatic (MC, 81)

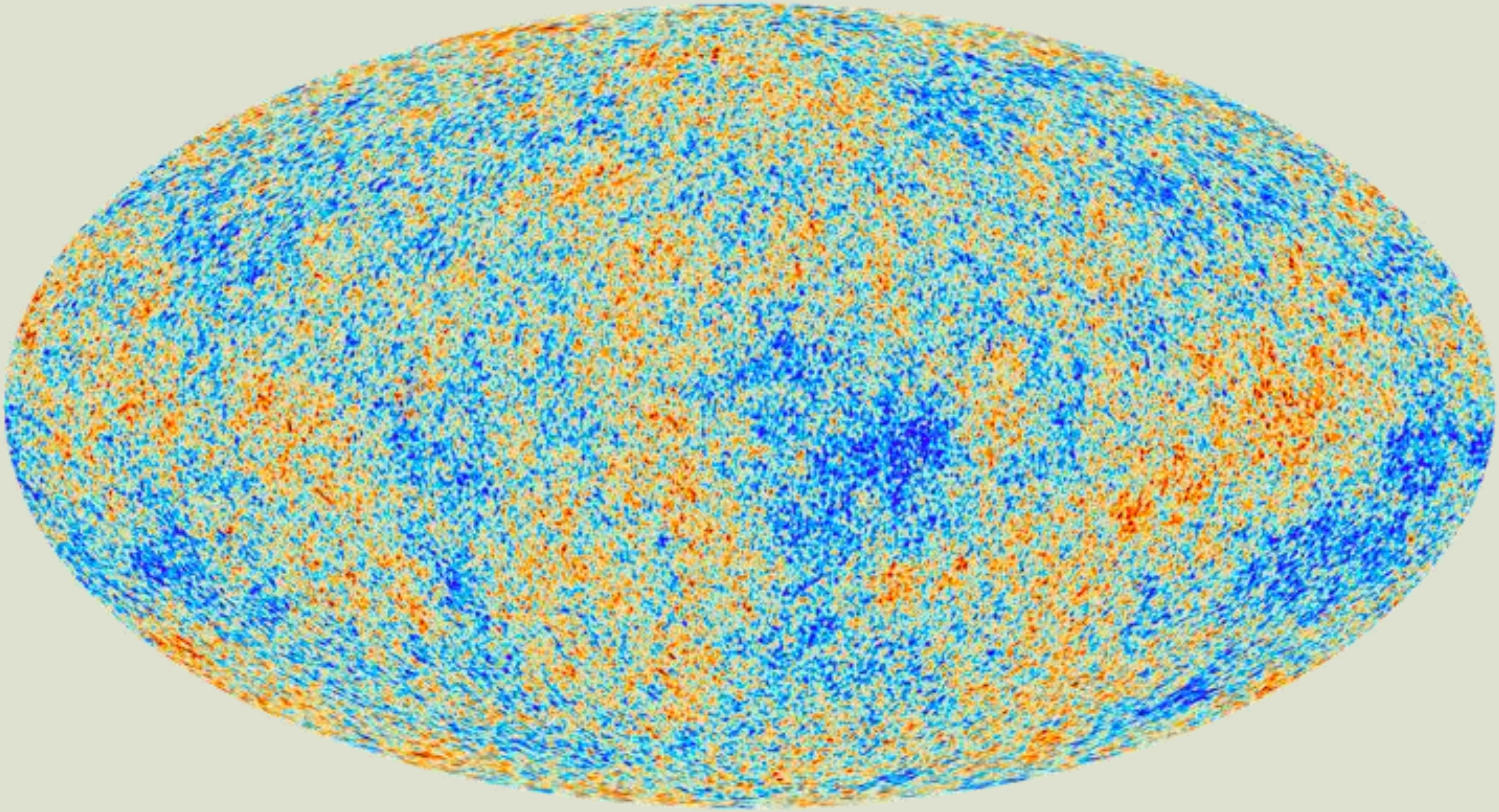
3) gaussian: $F = F_g + f_{NL} F_g^2,$ where $f_{NL} = O(1)$ (MC, 81)

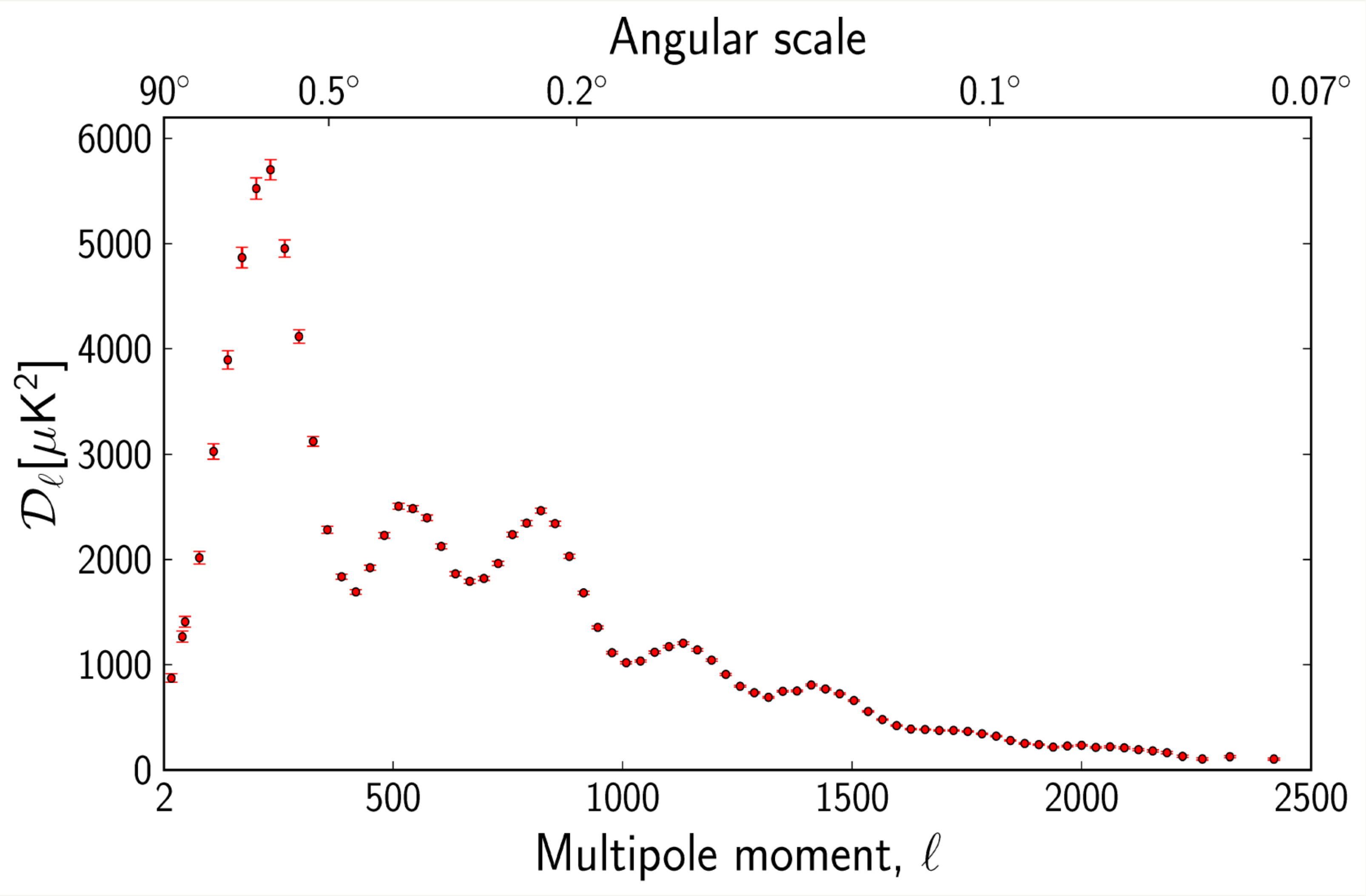
4) spectrum: $F \; µ \; \ln(/ \, // _g) \; µ \; /^{1-n_S}$ with $n_S = 0.96$ (MC, 81)

5) Gravitational waves (Starobinsky, 79)

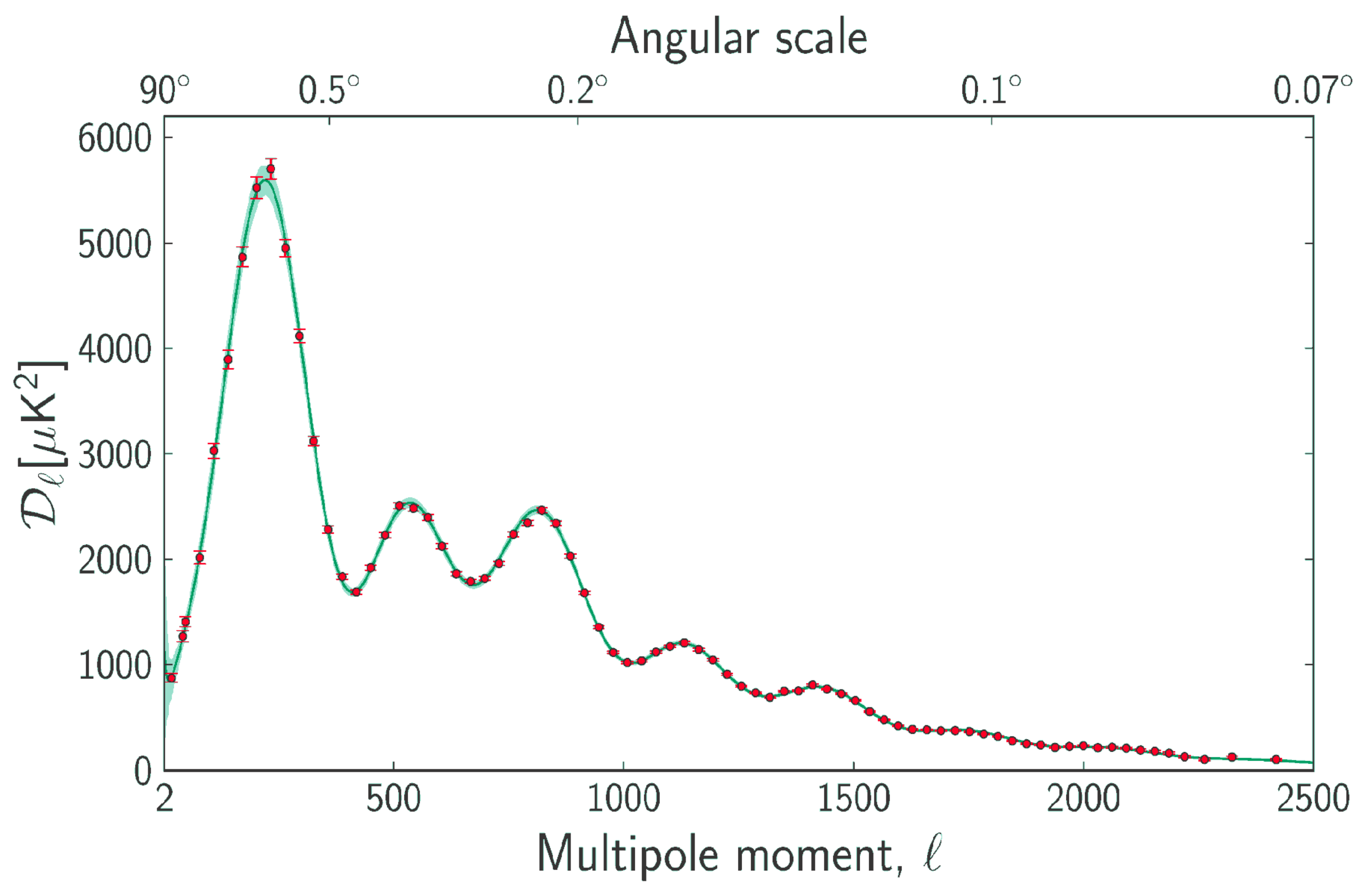
with $\Omega_{tot} = 1$ (prediction) and H_0, Ω_Λ, Ω_{bar} from supernova, deuterium et.cet. we get



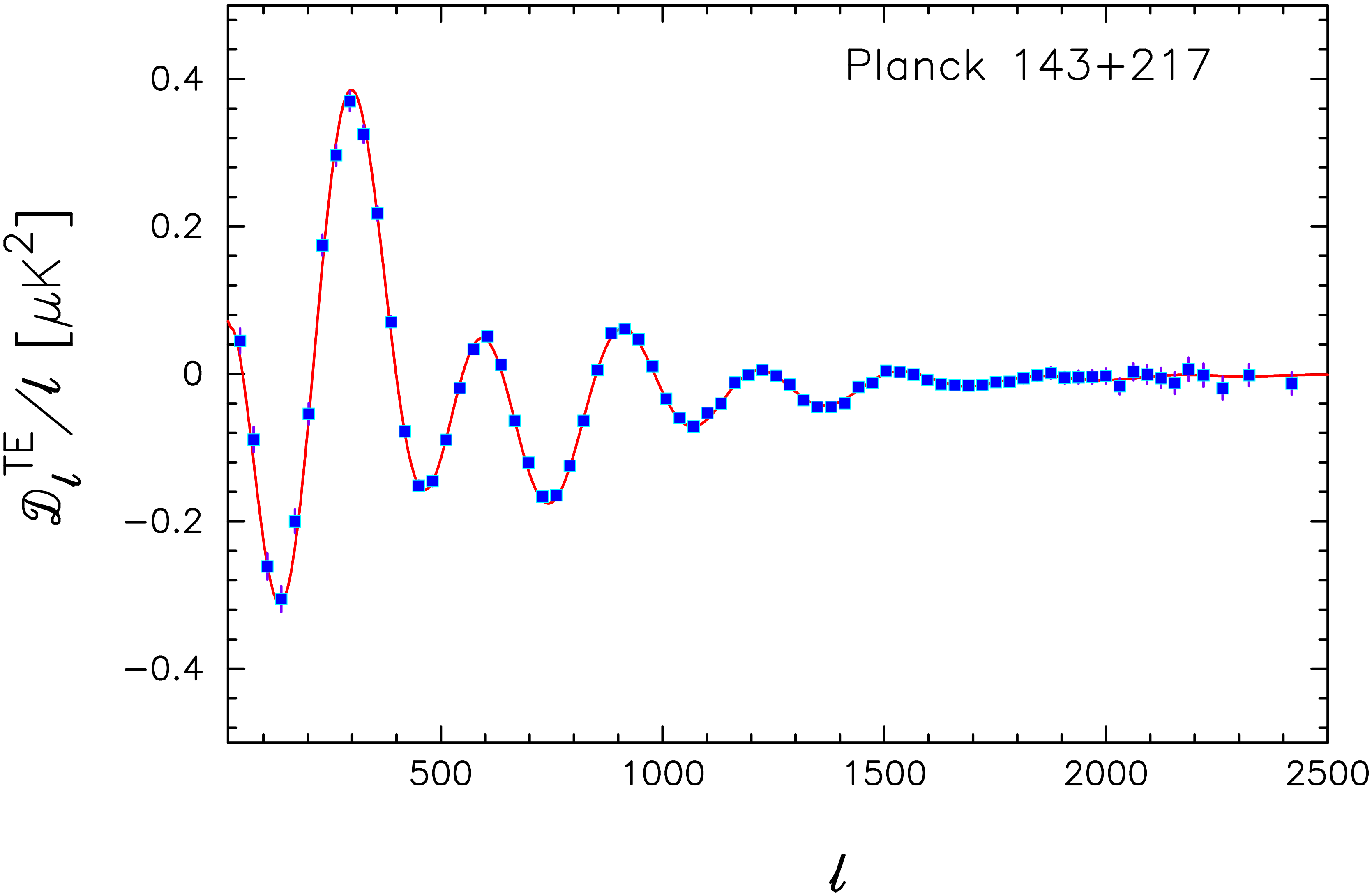




Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ



Angular scale
90°
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



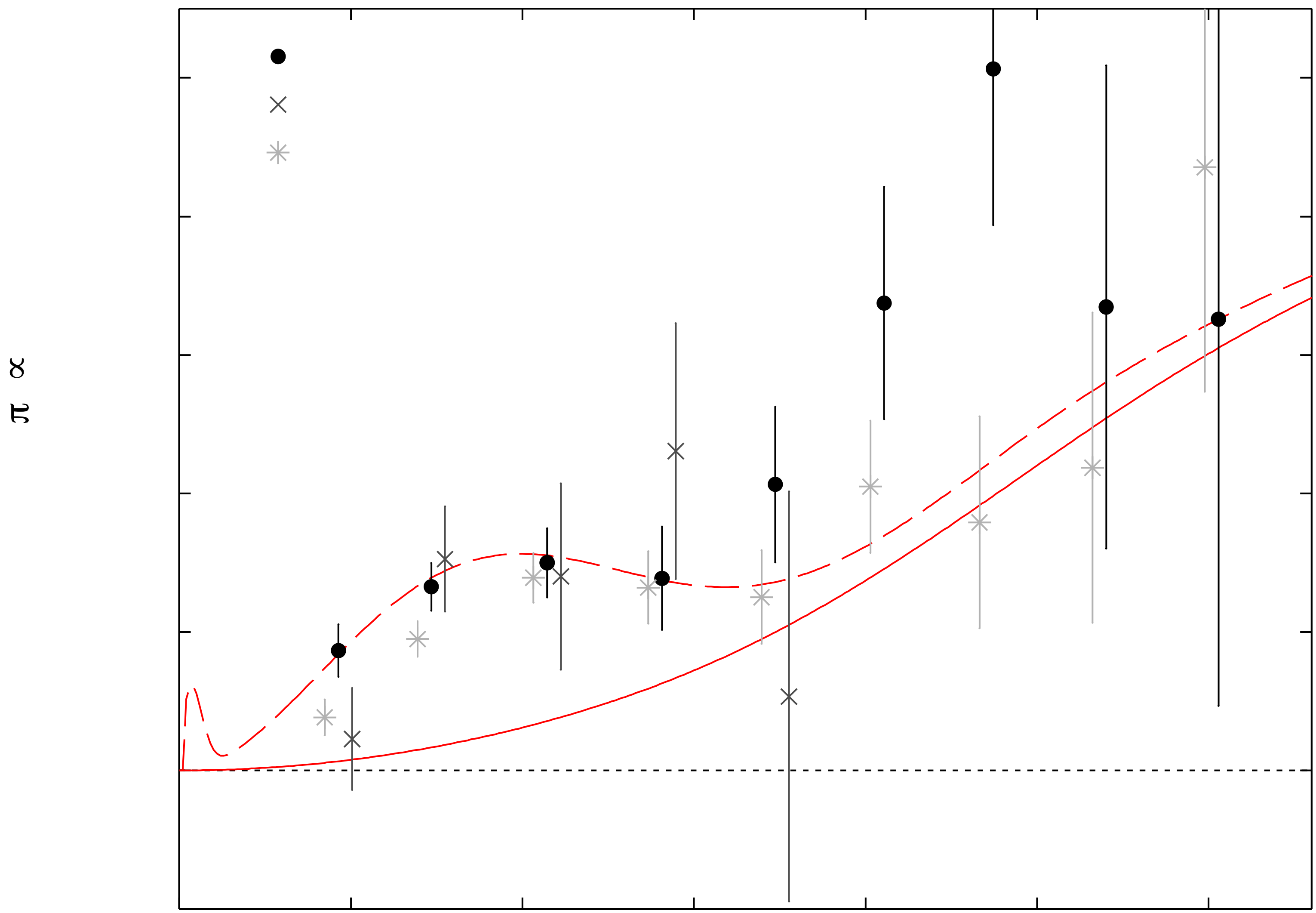
Planck 143+217
$\mathcal{D}_\ell^{TE}/\ell$ [μK^2]
0.4
0.2
0
−0.2
−0.4
500
1000
1500
2000
2500
ℓ

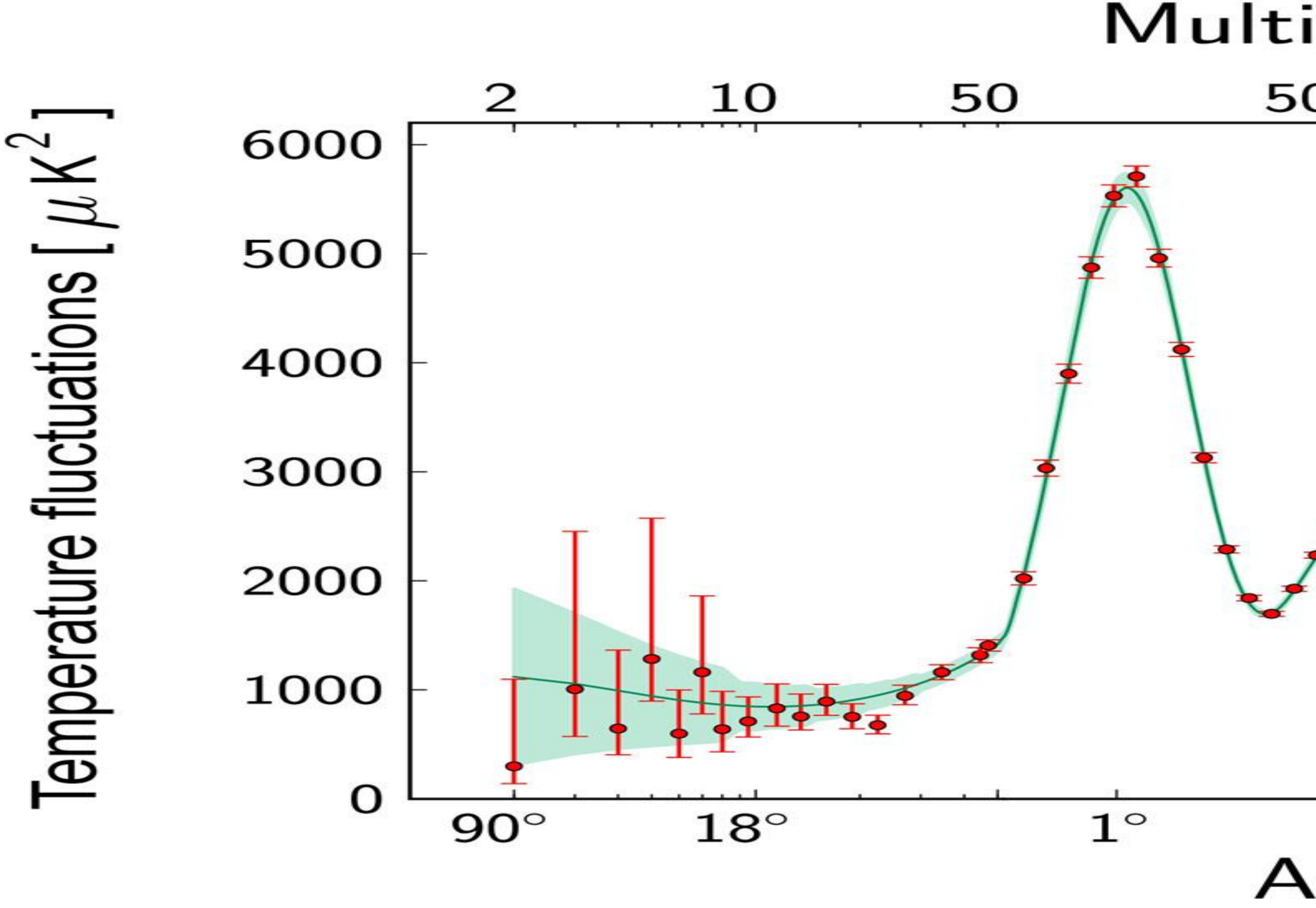
- $W_{tot} = 1 \pm 0.0066$
- adiabatic pert.!!!, less than 1% from cosmic strings, entropy et.cet.
- gaussian: $f_{NL} = 2.5 \pm 5.8$
- n_S =0.9585 $\pm$ 0.0070

CONCLUSIONS

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

BICEP disaster





Multi
2
10
50
50
6000
5000
4000
3000
2000
1000
0
Temperature fluctuations [μK2]
90°
18°
1°
A

- Theory is right
- Planck is right
- BICEP2 is right

T + P ✓ T + B ✓

P + B ✓

But

~~T + P + B~~

Therefore P + B ⇒ catastrophy for theory

29. April 2014 10:54 Entstehung des Universums

Risse in der Urknall-Theorie

Forschungsstation am Südpol: Hier meinen Physiker Signale aus den ersten Sekundenbruchteilen nach dem Urknall gemessen zu haben. Viele Kollegen sind noch nicht überzeugt. (Foto: REUTERS)

Signale aus der Geburtsstunde des Universums: Mitte März jubelte ein Forscherteam über eine bahnbrechende Messung von Gravitationswellen. Möglicherweise haben die Physiker sich zu früh gefreut.

Von Marlene Weiß

Diskutieren
Versenden
Drucken
Feedback

Wer meint, die Welt erklären zu können, indem er am kleinen *n* schraubt, bekommt es mit Viatcheslav Mukhanov zu tun. "Vollkommener Unsinn", schimpft der an der Uni München aktive russische Physiker, "die Zeitschriften sind voll davon, aber es bleibt trotzdem Unsinn!"

Auch wer sonst nichts von seinem Vortrag kürzlich am Max-Planck-Institut für Astrophysik in Garching bei München verstanden hat, eines dürfte jedem Zuhörer klar geworden sein: Das kleine *n* in den Formeln über den Beginn des Universums, auch "spektraler Index" genannt, sollte man in Ruhe lassen, wenn man sich nicht mit Mukhanov anlegen möchte.

Das sind schlechte Nachrichten für all die Fachleute, die Mitte März jubelten, als es hieß, man habe mit einem Teleskop am Südpol Signale aus den ersten Sekundenbruchteilen nach dem Urknall gemessen: Vielleicht war der Jubel verfrüht, das Ergebnis widerspricht anderen Messungen.

Spuren von Gravitationswellen, die vor 13,82 Milliarden Jahren entstanden sein

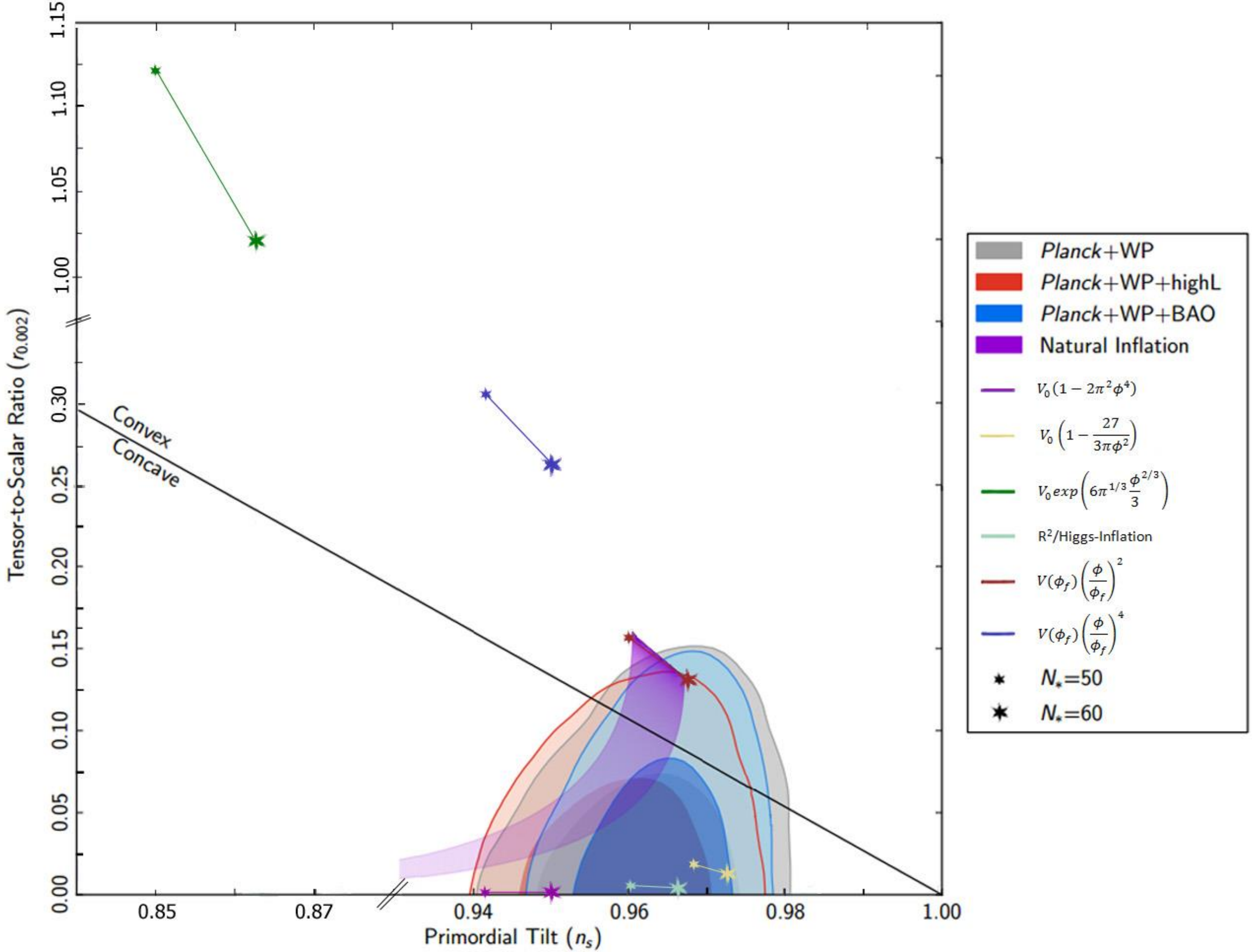
Who thinks he can explain the world by screwing the small n, it gets to do with Viatcheslav Mukhanov. "*Perfect nonsense,*" *complains the active at the University of Munich Russian physicist*, "*the magazines are full of it, but still it remains nonsense*!"

This is bad news for all the professionals who cheered in mid - March, when it was announced that they had signals from the first split seconds measured with a telescope at the South Pole after the Big Bang : *Perhaps the jubilation was premature, the result contradicts other measurements*.

BS: Well, if it turns out that the relic gravitational waves at the level of a few percent is not there, and we have to wait for PRISM....

would this mean that the theory of inflation will remain unconfirmed for years?

AD: Yes remain unconfirmed in the sense that alternative models remain relevant. However, in the theory of inflation there is an element that has no real alternatives. It mechanism for the generation of perturbations calculated Mukhanov and Chibisov, - strengthening the vacuum quantum fluctuations scalar field. Another mechanism nobody offered and all alternative models use it.



1.15
1.10
1.05
1.00
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Tensor-to-Scalar Ratio ($r_{0.002}$)
0.85
0.87
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
$V_0(1-2\pi^2\phi^4)$
$V_0\left(1-\frac{27}{3\pi\phi^2}\right)$
$V_0\,exp\left(6\pi^{1/3}\frac{\phi^{2/3}}{3}\right)$
R^2/Higgs-Inflation
$V(\phi_f)\left(\frac{\phi}{\phi_f}\right)^2$
$V(\phi_f)\left(\frac{\phi}{\phi_f}\right)^4$
N_*=50
N_*=60