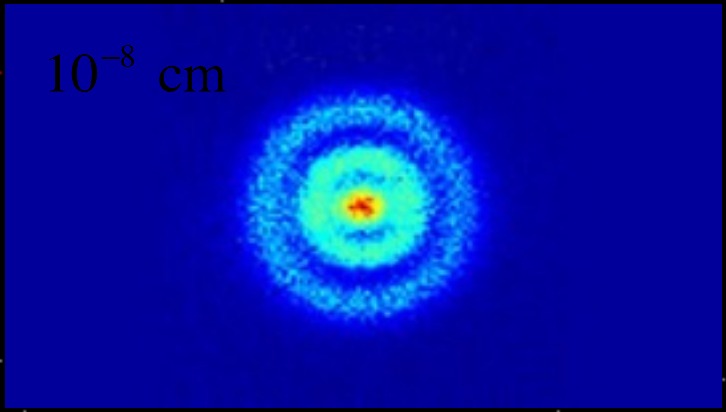
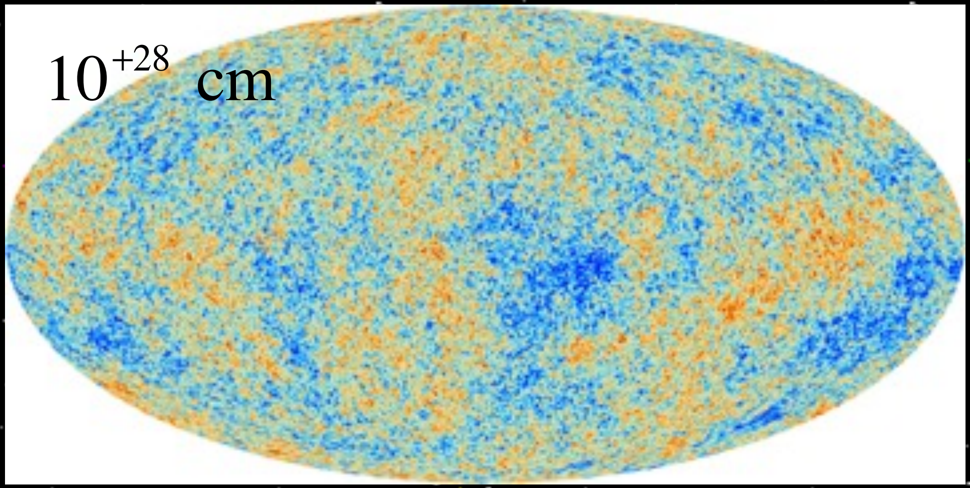
Quantum Universe

V. Mukhanov
ASC, LMU, München

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





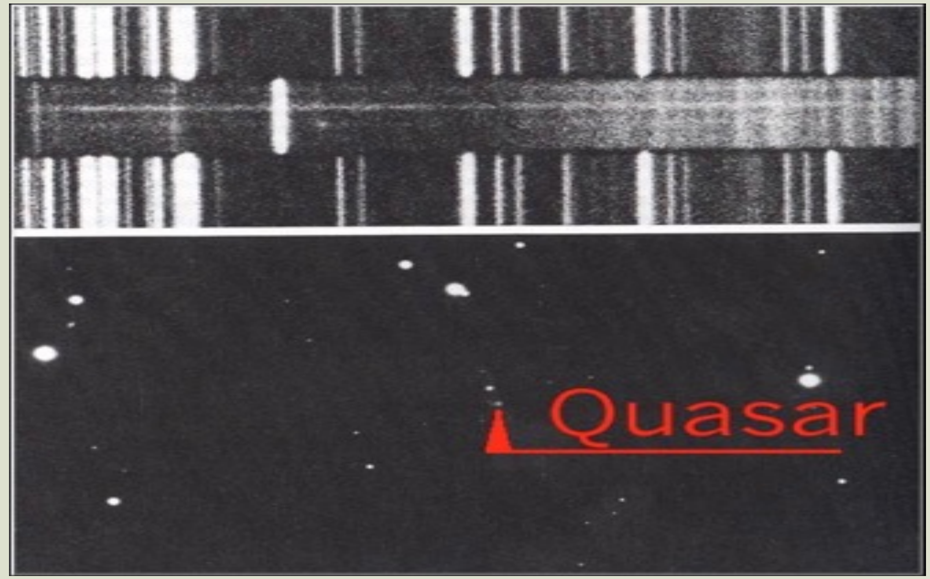
$$\Delta q \times \Delta p \geq \frac{1}{2}\,\hbar$$

Before 1990

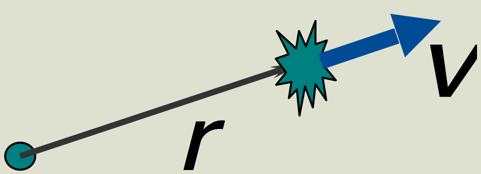
“Only by their breaking could the divine configurations be perfected”

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

- The Universe expands

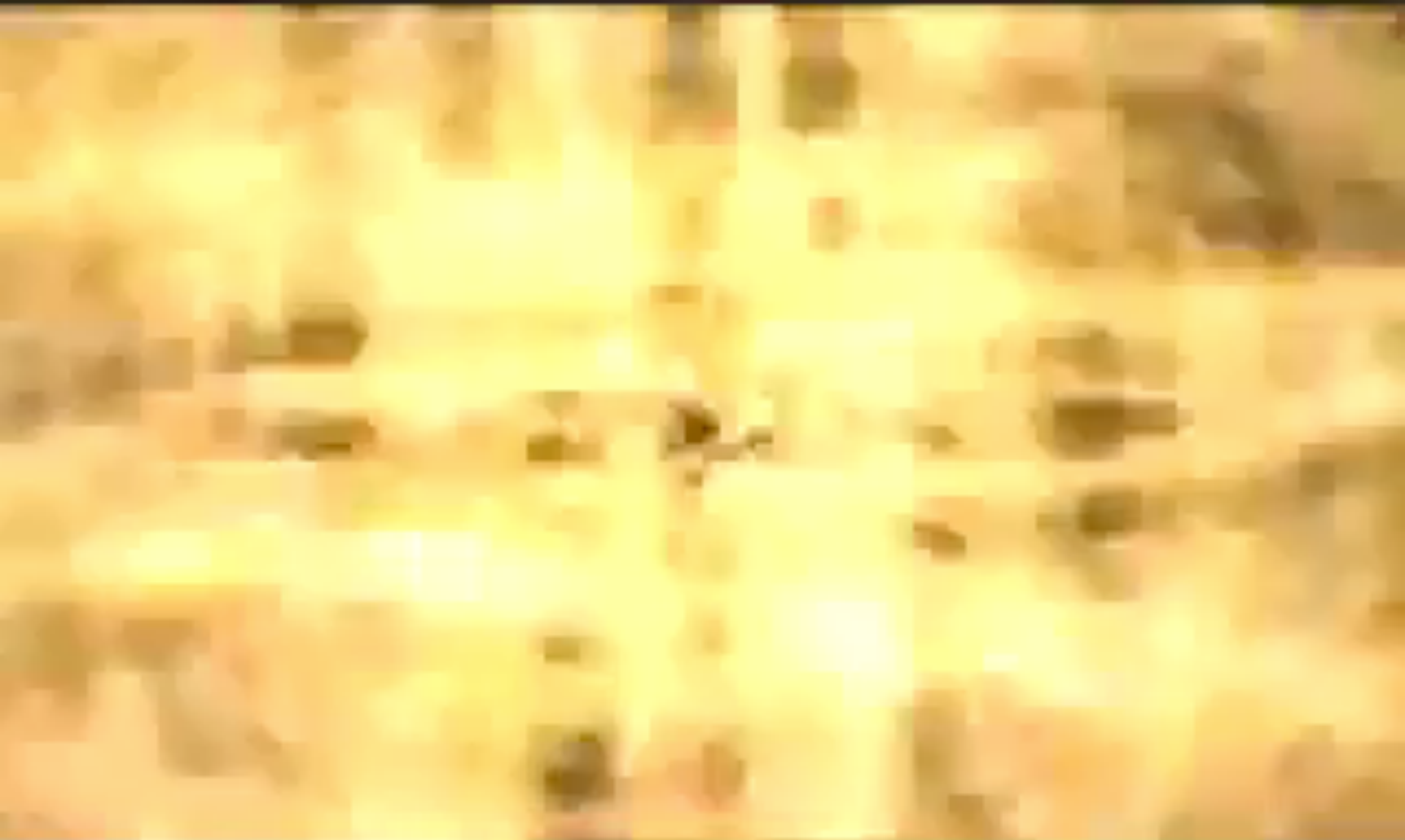


- Hubble law



$$v = Hr$$

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



There is baryonic matter:

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

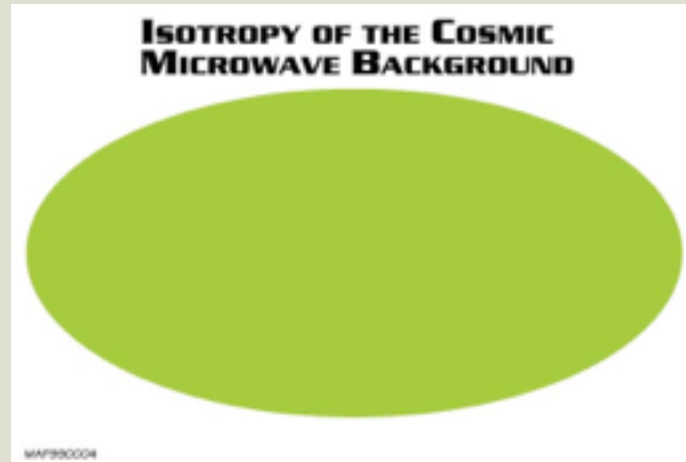
Dark Matter???? baryonic origin???

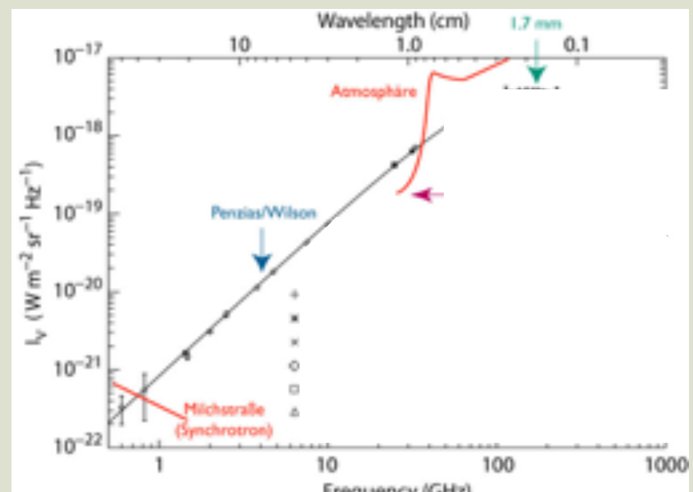
Large Scale Structure: clusters of galaxies!

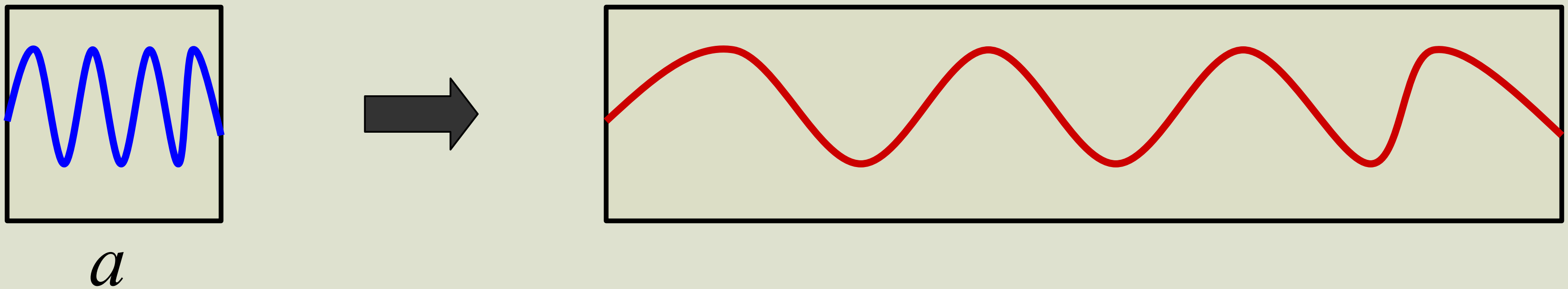
Filaments, Voids??????????????????????

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

Penzias, Wilson 1965



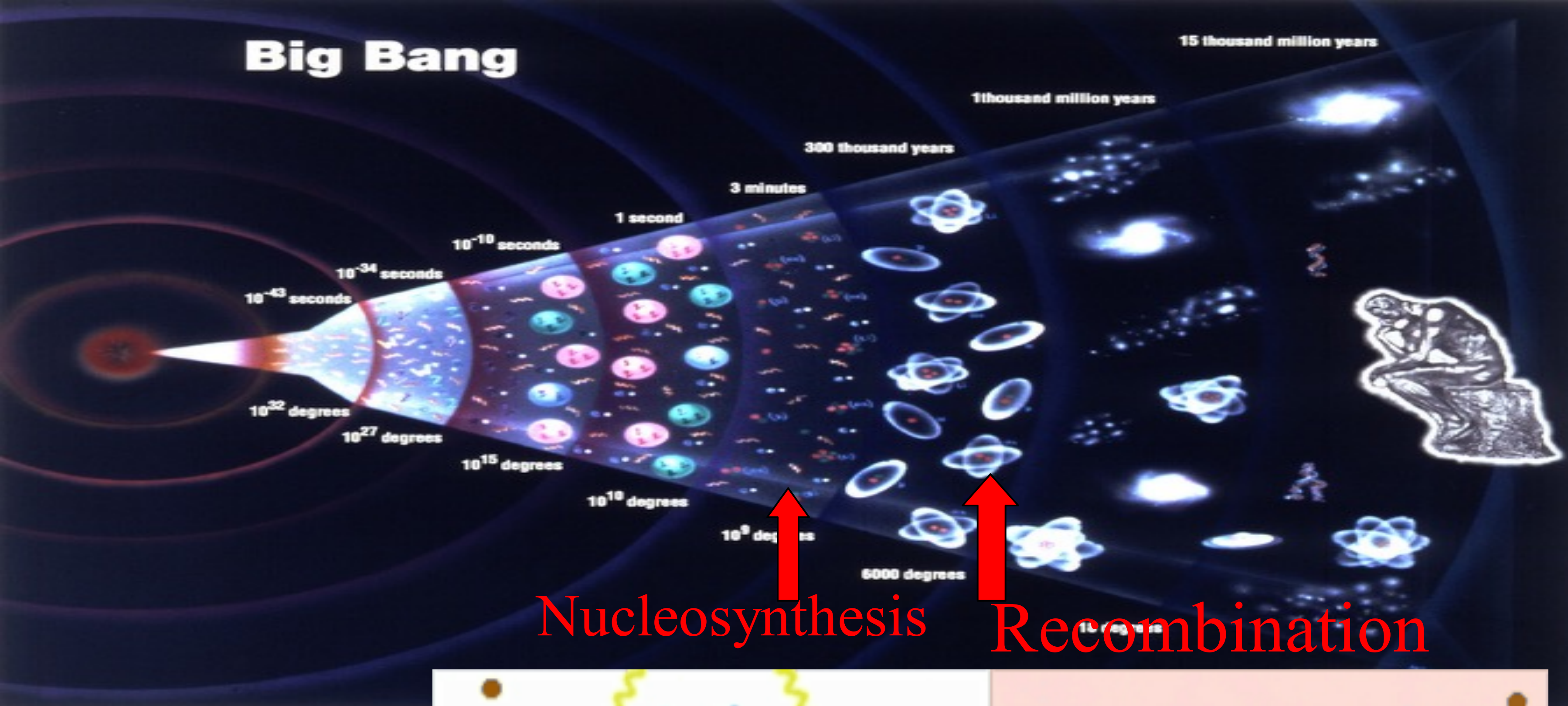


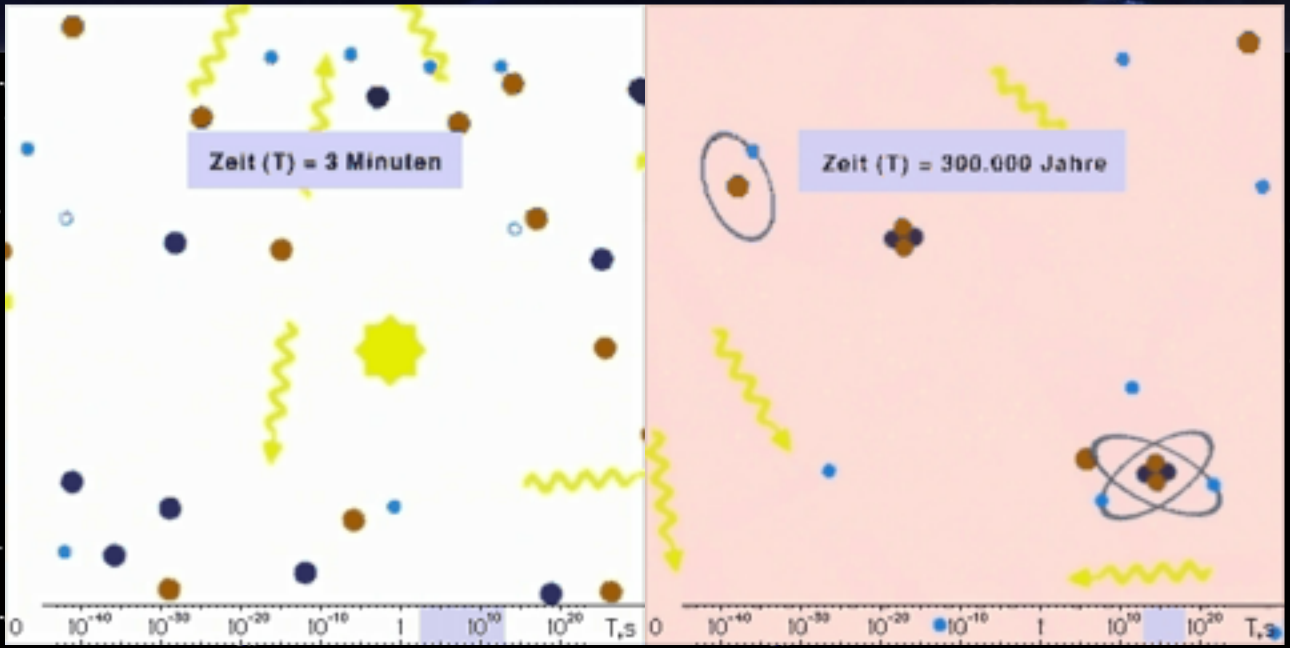


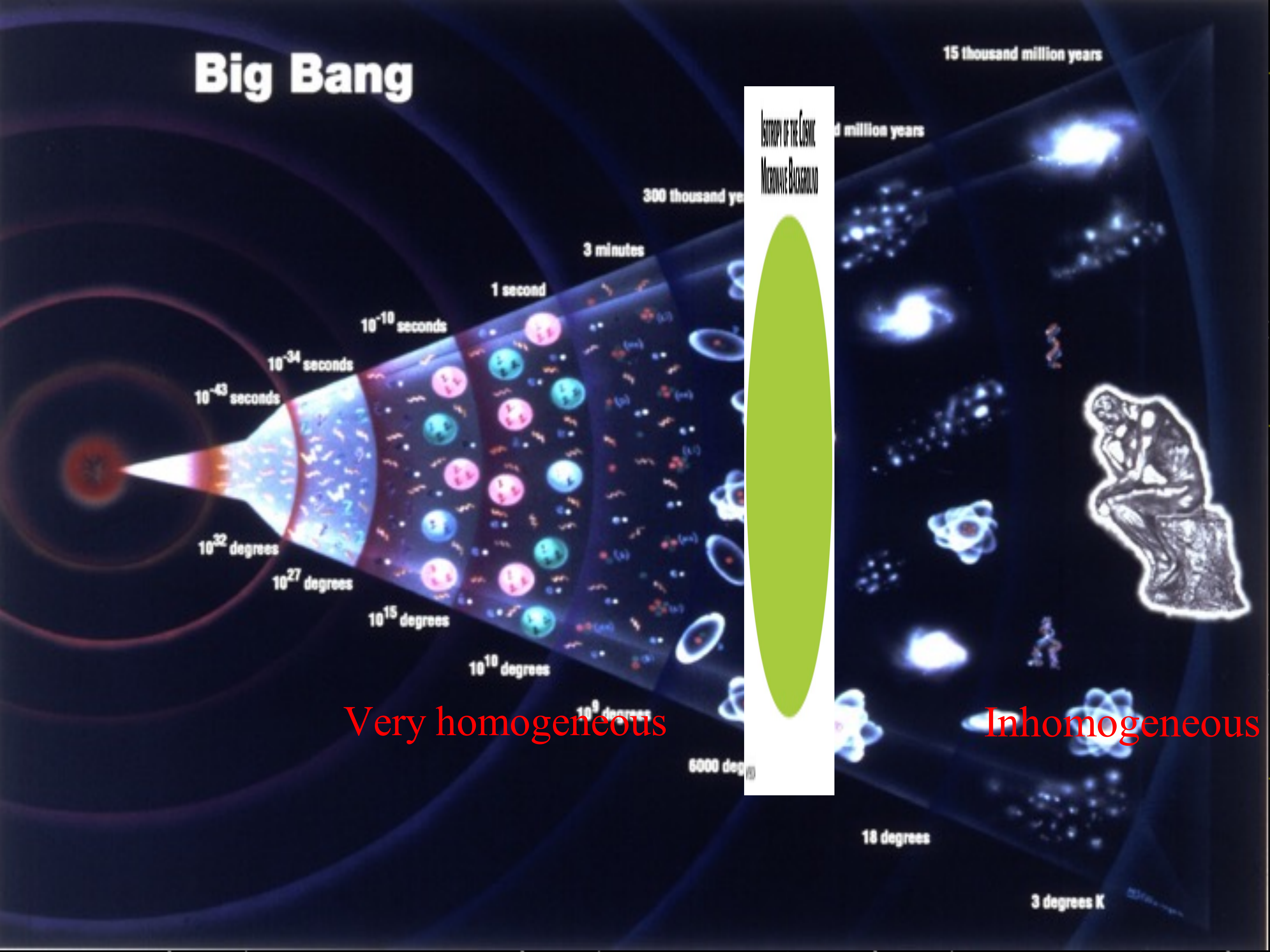
$$\lambda \propto a \quad \Rightarrow \quad T \propto \frac{1}{a}$$

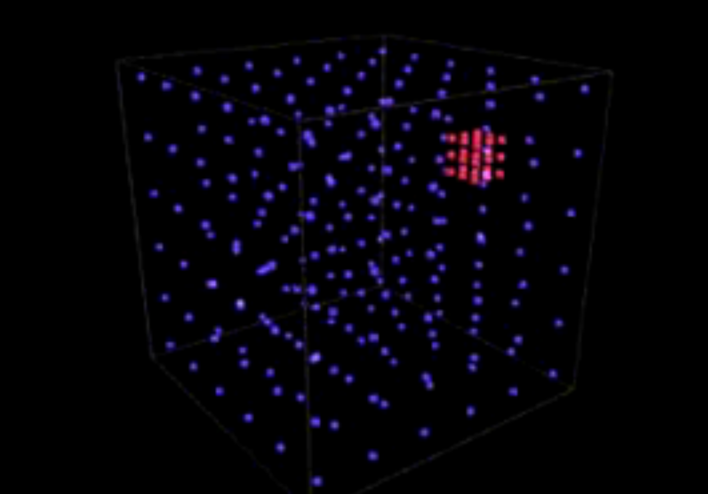
When the Universe was 1000 times smaller

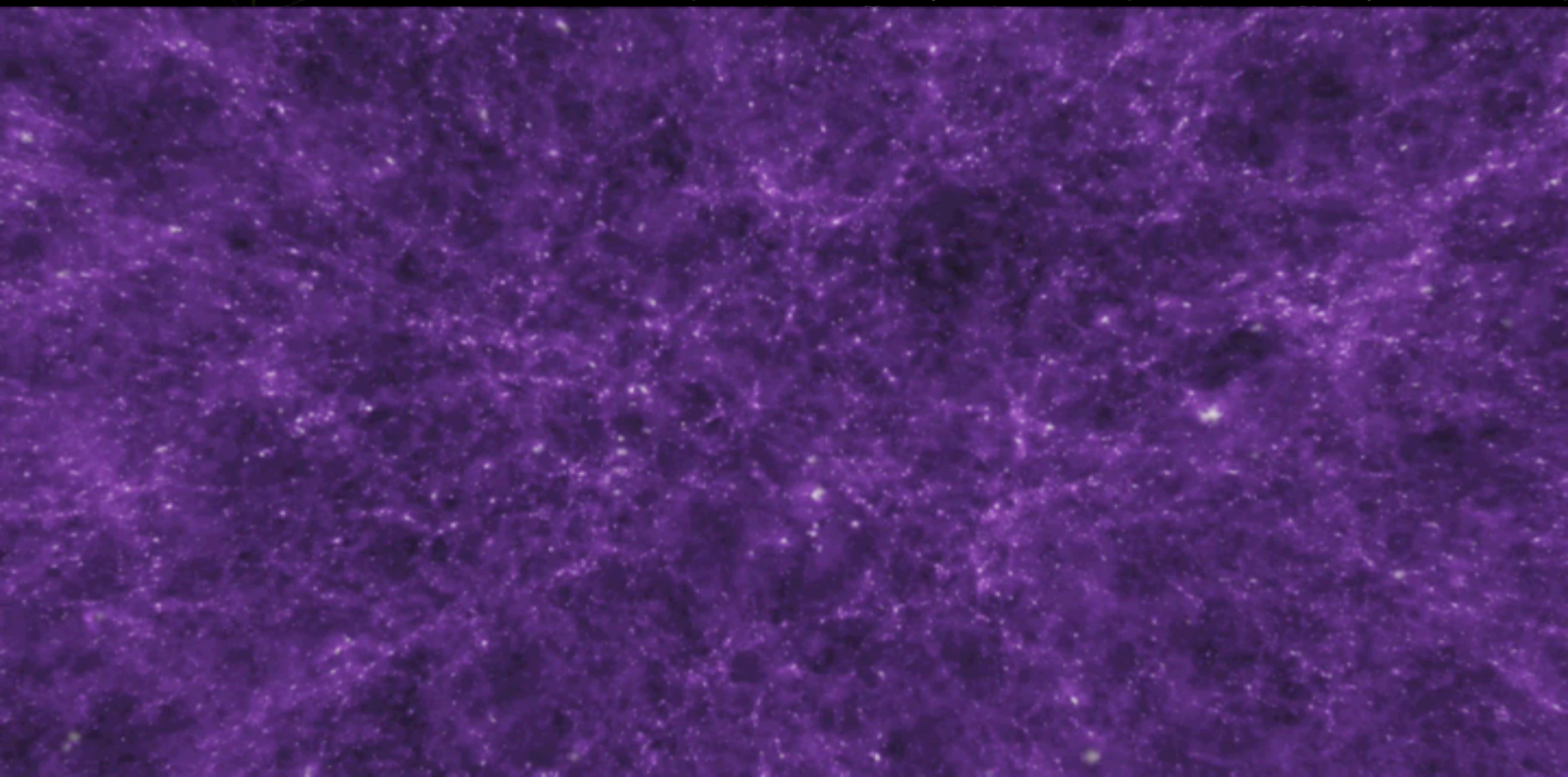
its temperature was about $2725°K$

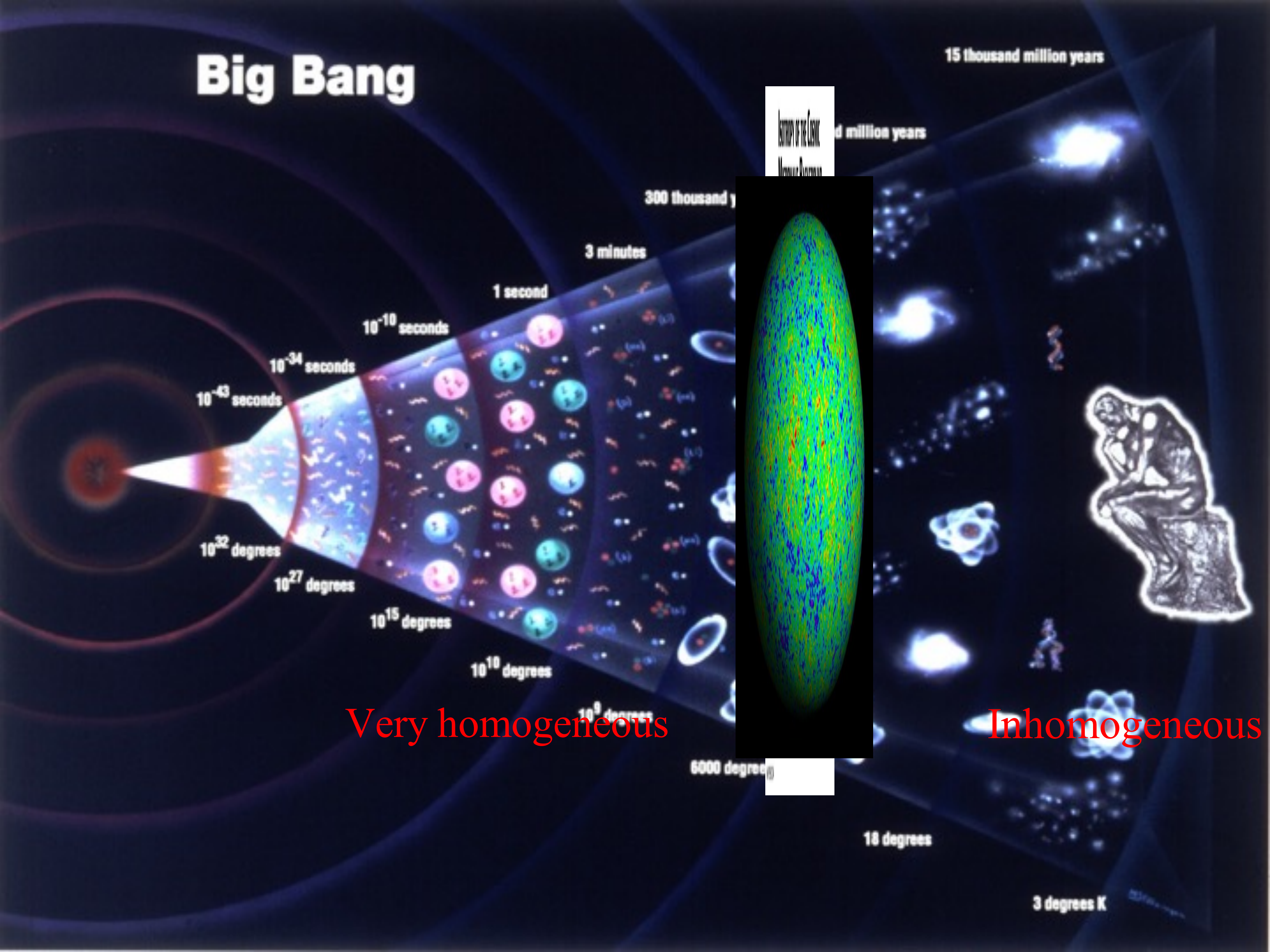

Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^-10 seconds
10^-34 seconds
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
6000 degrees
Nucleosynthesis
Recombination


Zeit (T) = 3 Minuten
Zeit (T) = 300.000 Jahre
T,s

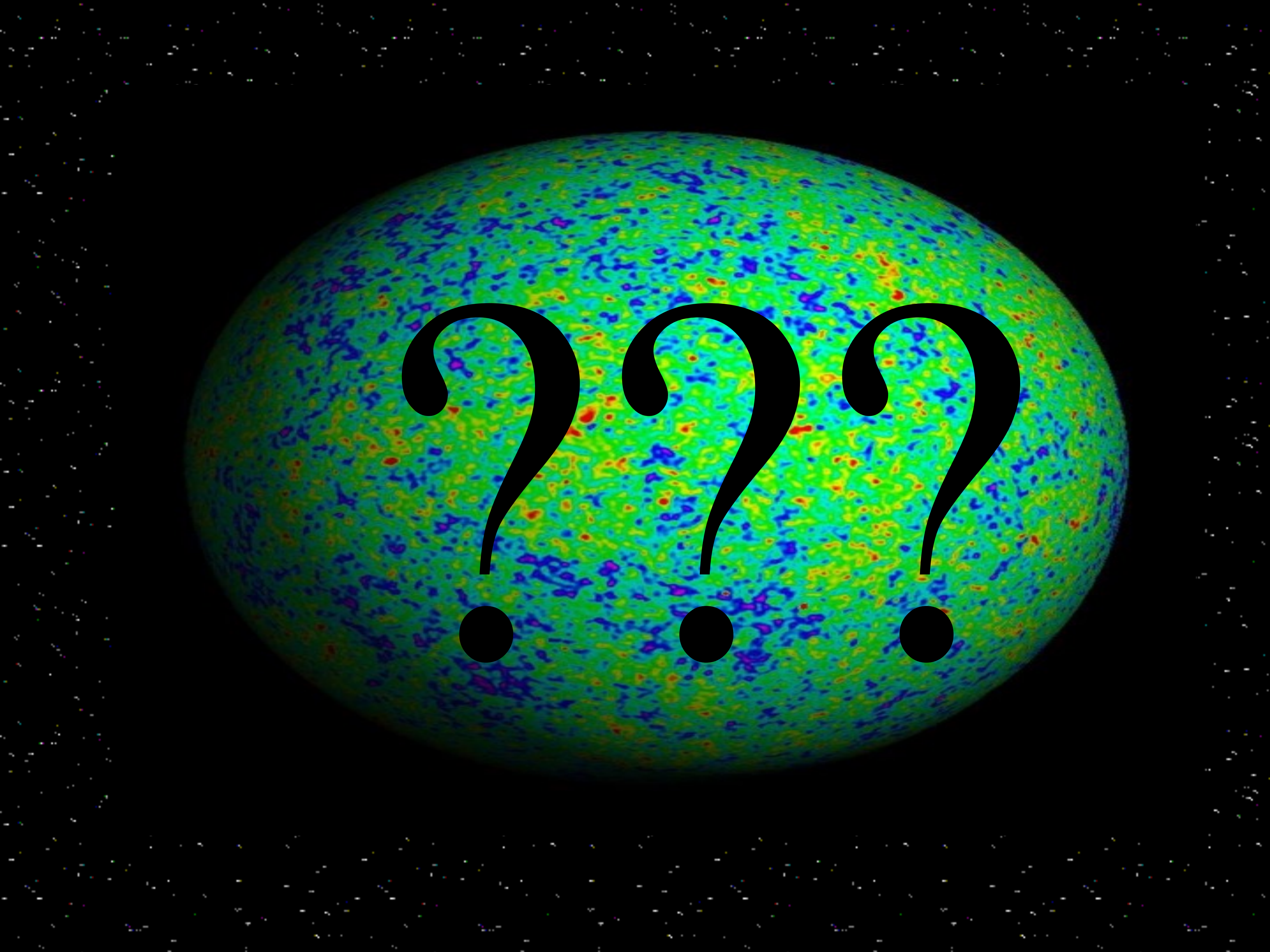

Big Bang
15 thousand million years
million years
300 thousand ye
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 deg
18 degrees
3 degrees K
Isotropy of the Cosmic Microwave Background
Very homogeneous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

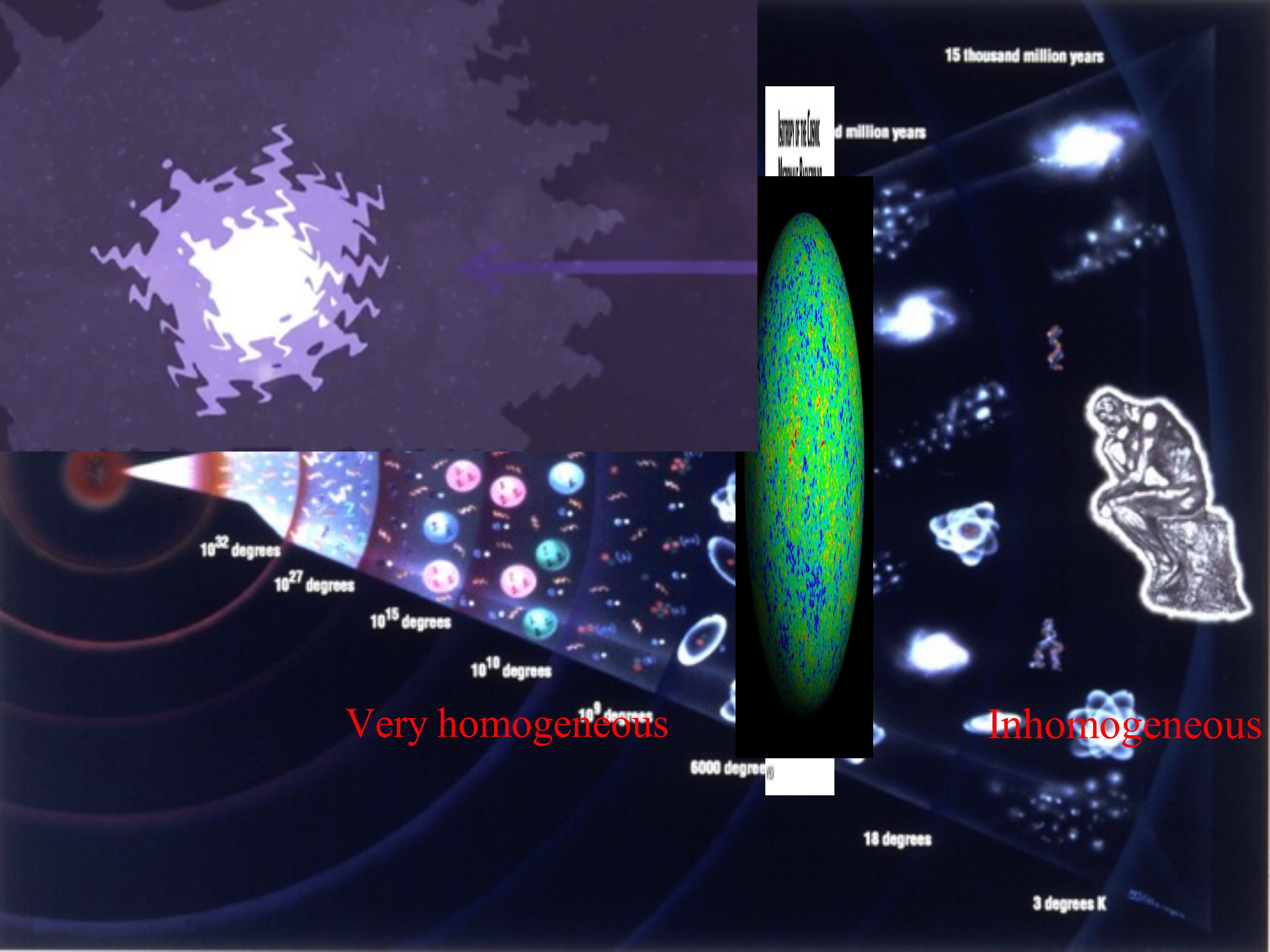


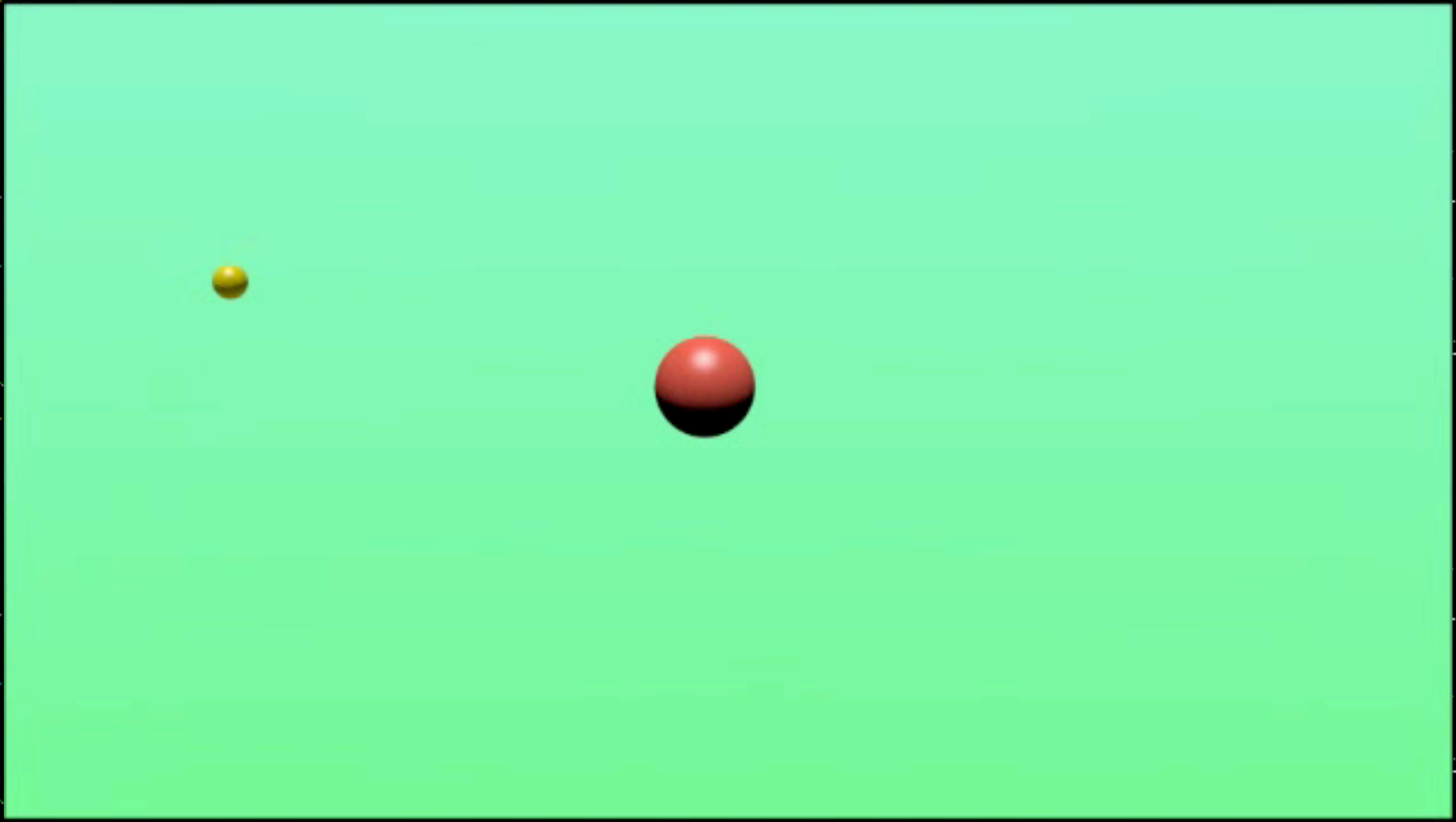




Big Bang
15 thousand million years
million years
300 thousand
3 minutes
1 second
10^-10 seconds
10^-34 seconds
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degree
18 degrees
3 degrees K
Very homogeneous
Inhomogeneous




15 thousand million years
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



$$\Delta x\, m \Delta v \geq \hbar$$

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

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???

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

Galaxy formation and phonons

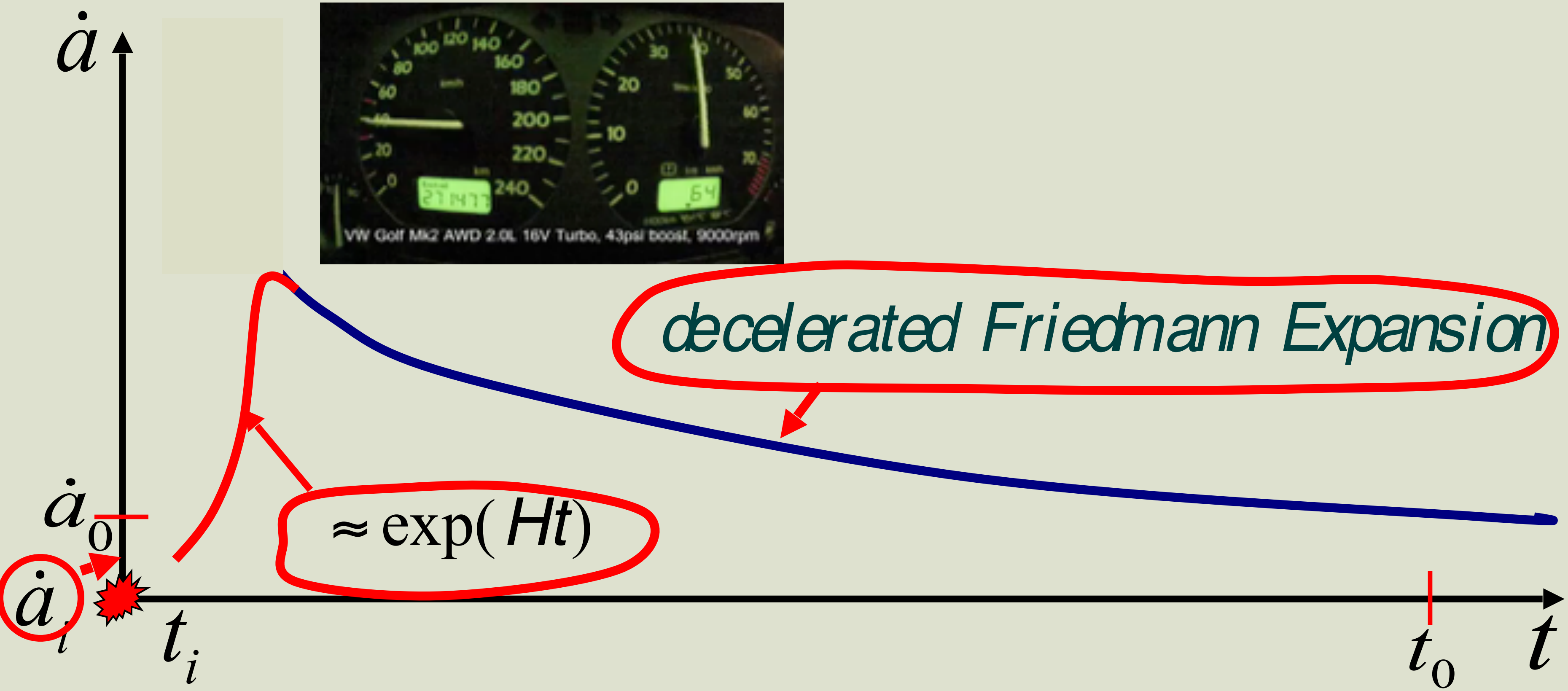
G. V. Chibisov and V. F. Mukhanov *Theoretical Department of P. N. Lebedev Physical Institute, USSR Academy of Sciences, Leninsky Prospect, 53, Moscow 117934, USSR*

Received 1981 November 25; in original form 1981 August 3

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.



ANNALS OF PHYSICS 115, 78–106 (1978)

The Creation of the Universe as a Quantum Phenomenon

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

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

Received July 7, 1977

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

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

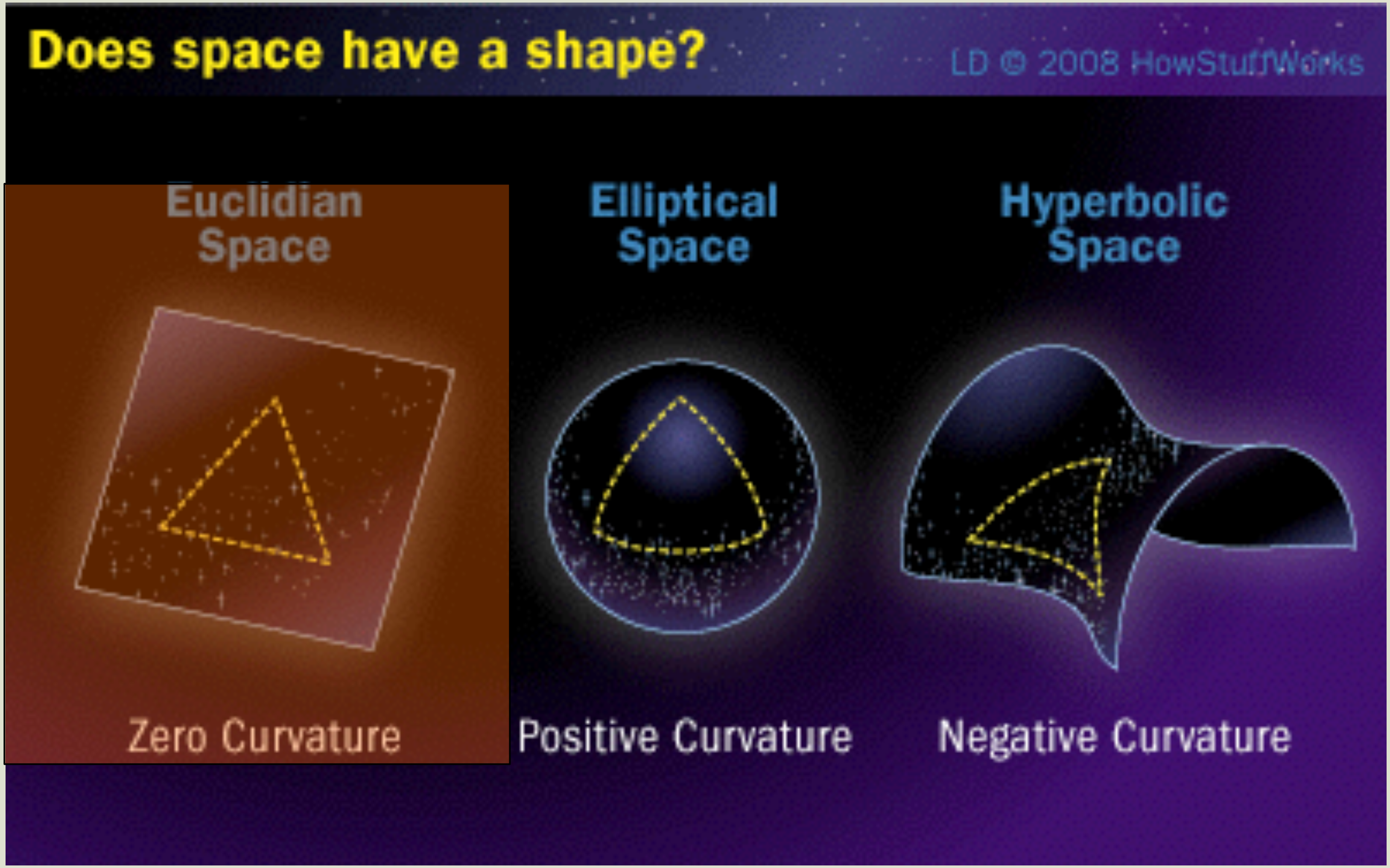
where $h = h^\alpha_\alpha$ and where, for the most interesting region, $H > k > H\exp\left(-3H^2/M^2\right)\left(M^2 \ll H^2\right)$,

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

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!!!

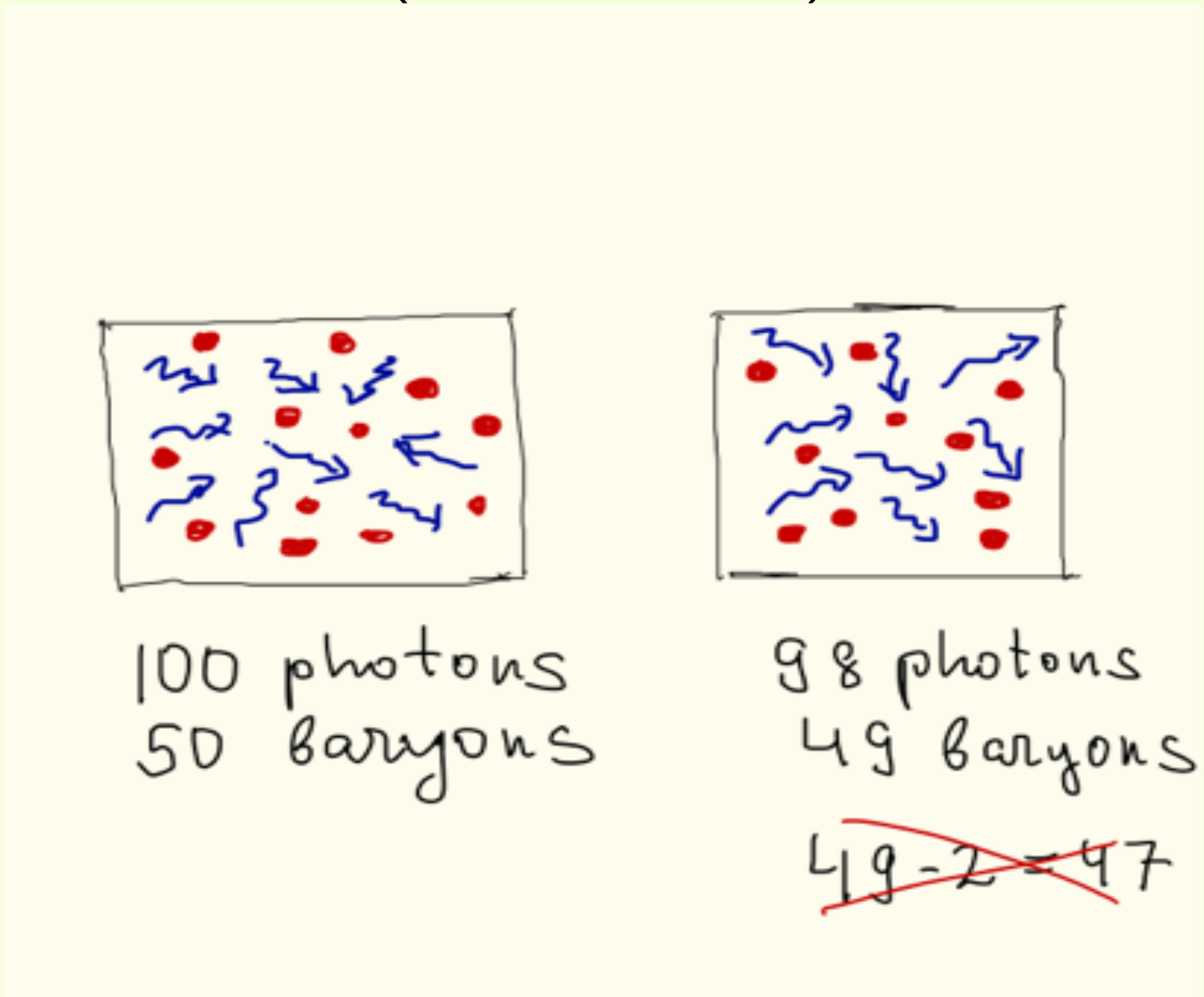
1)



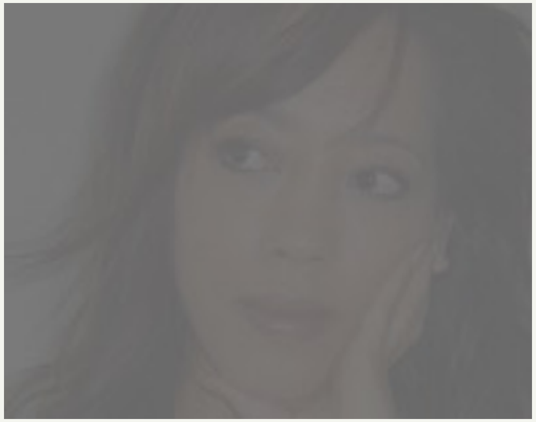
$$\Omega = 1$$

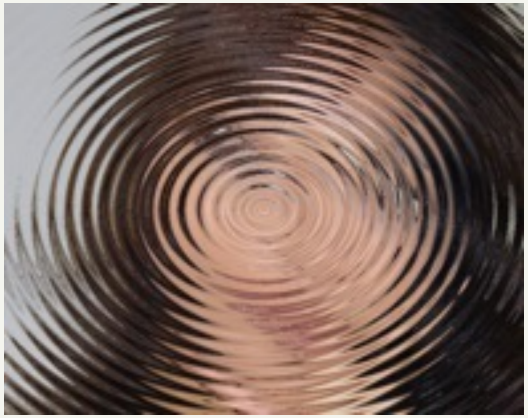
Perturbations (inhomogeneities) are:

2) Adiabatic (MC 1981)



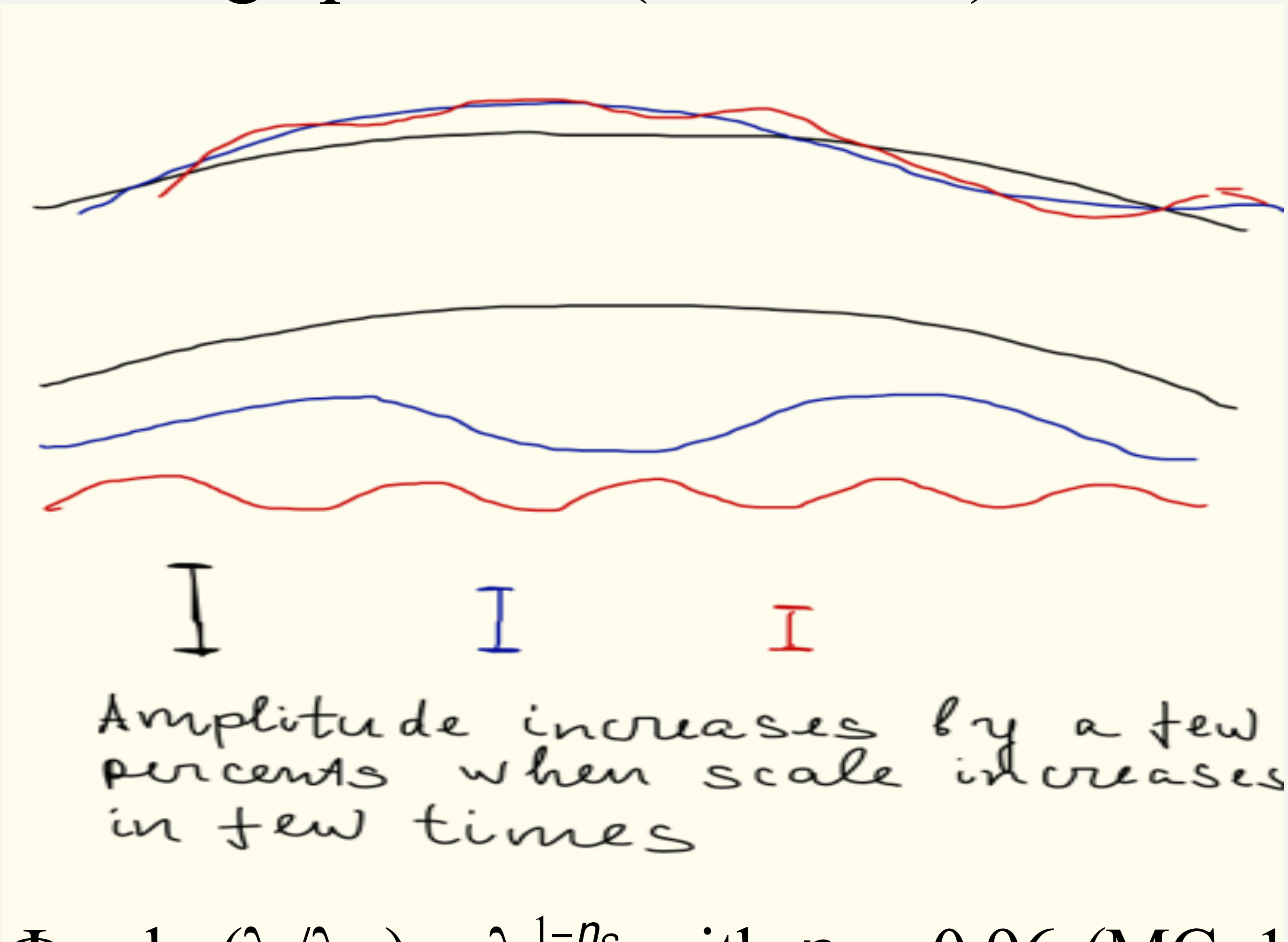
3) Gaussian (MC 1981)





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

4) have log spectrum (MC 1981)



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

L.P. 9/6/2003:

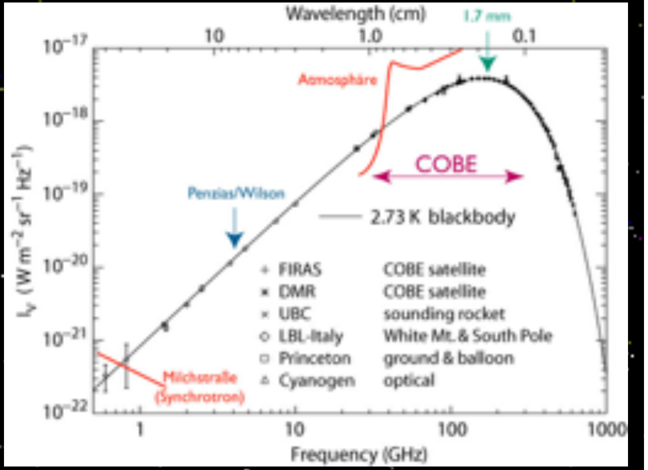
We are writing a proposal to get money to do our small angular scale CMB experiment. If I say that simple models of inflation require n_s=0.95+/-0.03 (95\% cl) is it correct?
I'm especially interested in the error. Specifically, if n_s=0.99 would you throw in the towel on inflation?

V.M. 9/8/2003

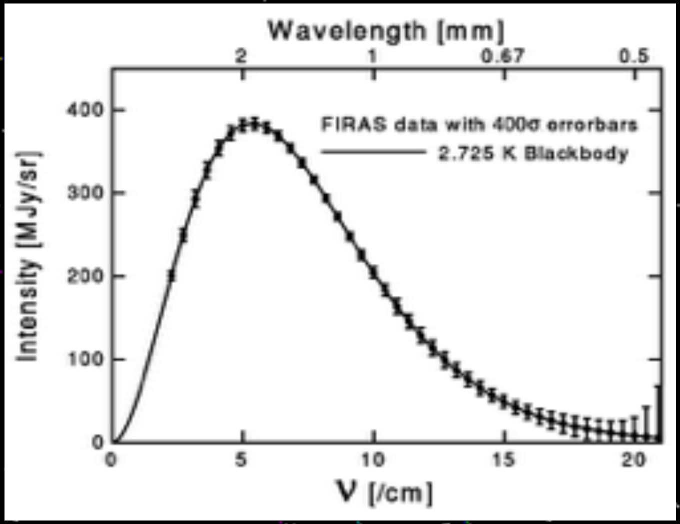
The "robust" estimate for spectral index for inflation is 0.92<n_s<0.97.
The upper bound is more robust than lower. The physical reason for the deviation of spectrum from the flat one is the nessesity to finish inflation....
If you find n_s=0.99 +/- 0.01 (3 sigma) I would throw in the towel on inflation.

After 90 - present

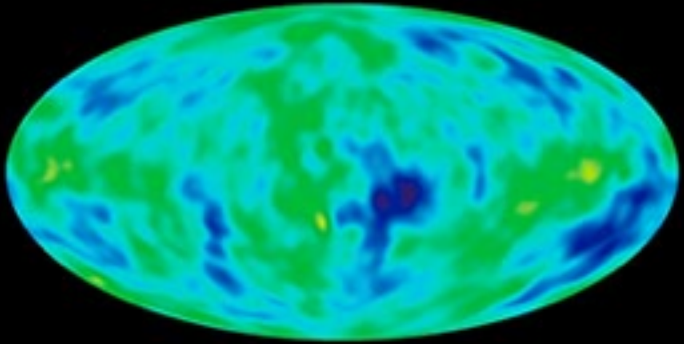
COBE 1992

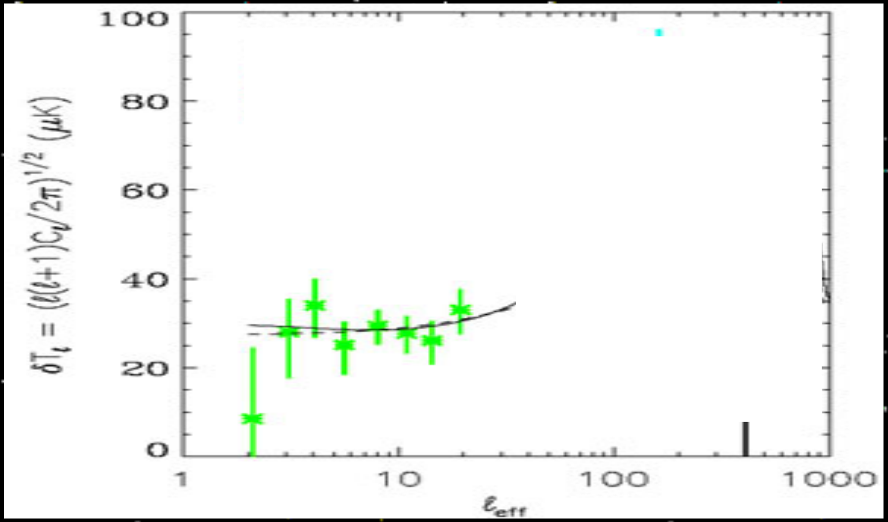


Wavelength (cm)
10
1.0
0.1
1.7 mm
Atmosphäre
COBE
Penzias/Wilson
2.73 K blackbody
FIRAS COBE satellite
DMR COBE satellite
UBC sounding rocket
LBL-Italy White Mt. & South Pole
Princeton ground & balloon
Cyanogen optical
Milchstraße (Synchrotron)
I_ν (W m^{-2} sr^{-1} Hz^{-1})
Frequency (GHz)

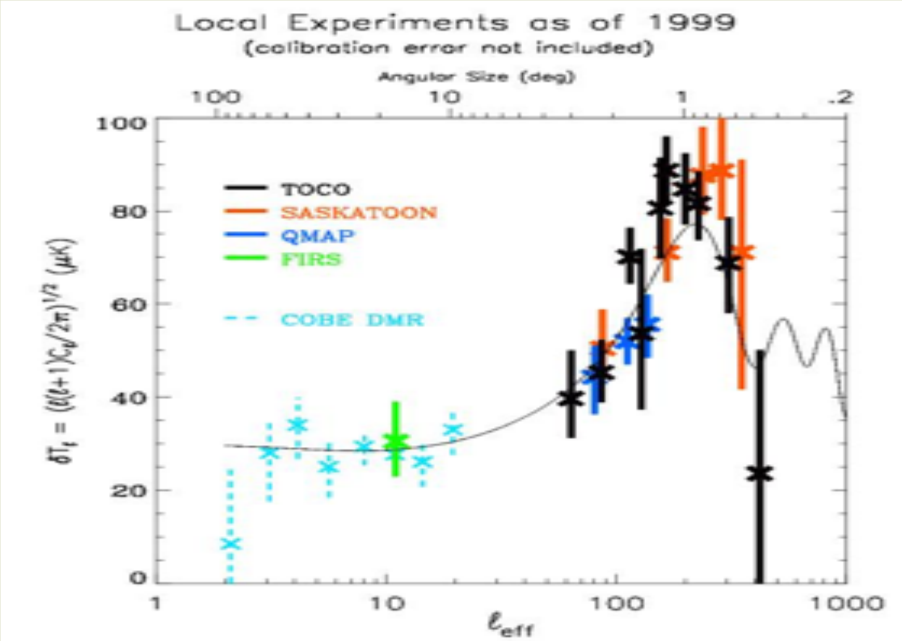


Wavelength [mm]
FIRAS data with 400σ errorbars
2.725 K Blackbody
Intensity [MJy/sr]
ν [/cm]

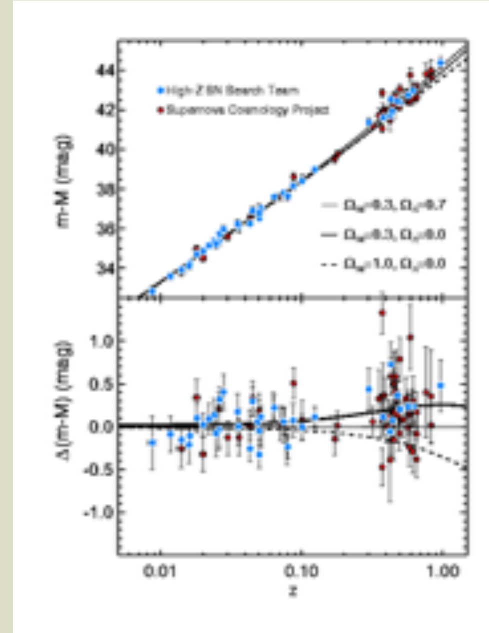




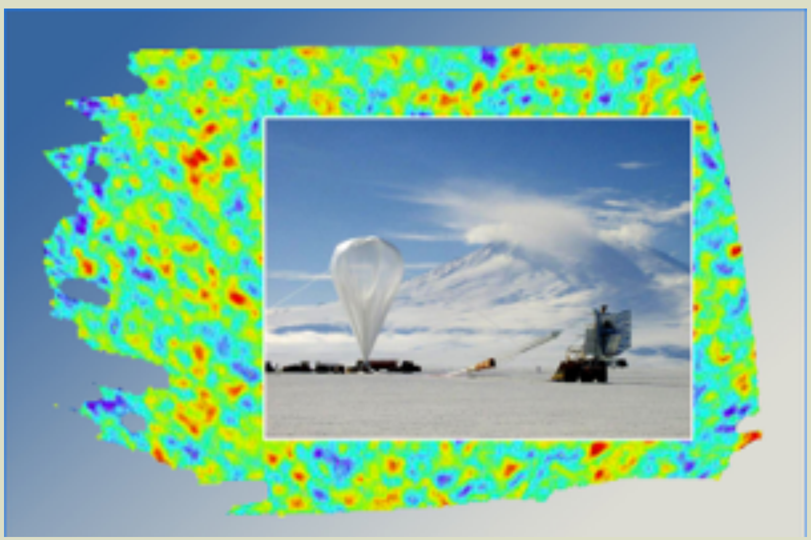
$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
ℓ_{eff}

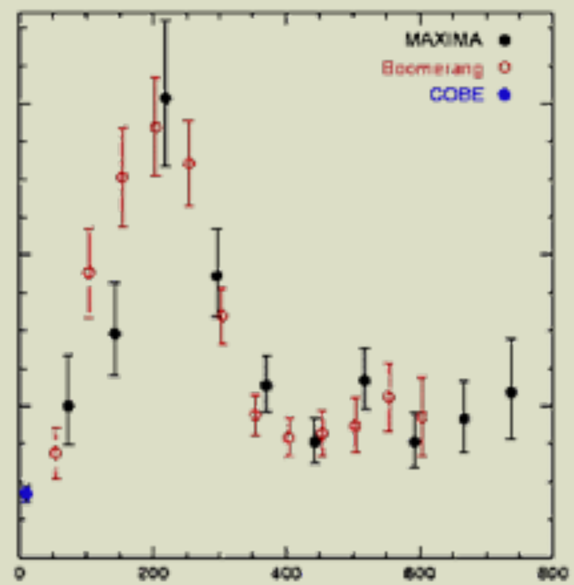


Local Experiments as of 1999
(calibration error not included)
Angular Size (deg)
100
10
1
.2
TOCO
SASKATOON
QMAP
FIRS
COBE DMR
$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
0
20
40
60
80
100
1
10
100
1000
$\ell_{\rm eff}$

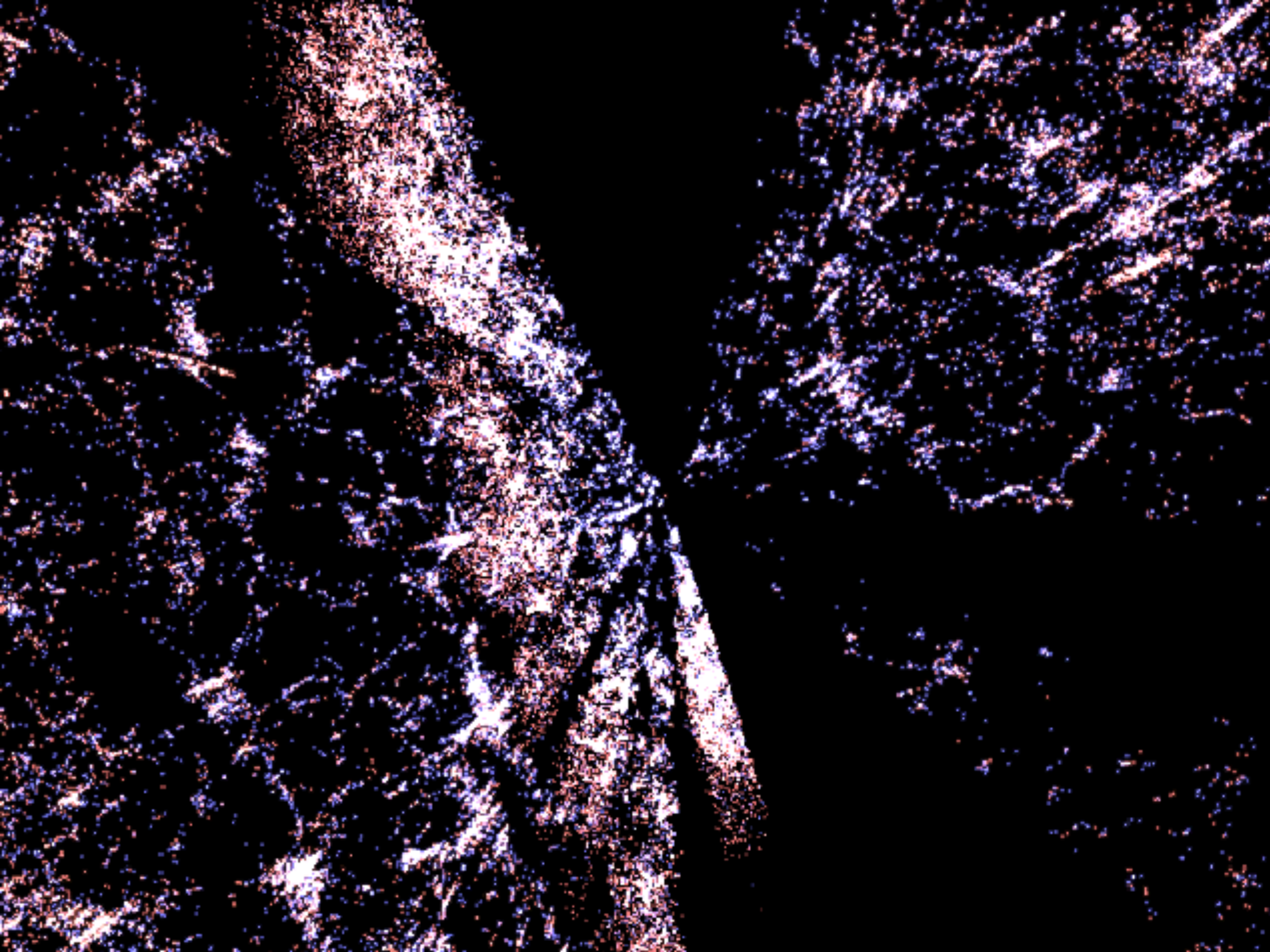


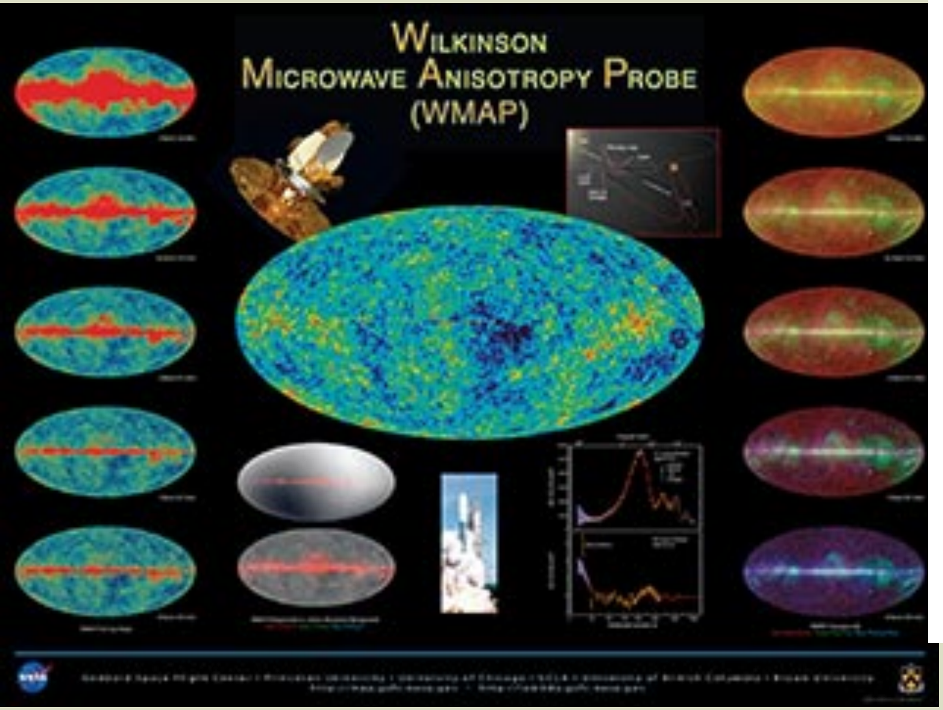
High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
0.01
0.10
1.00
z

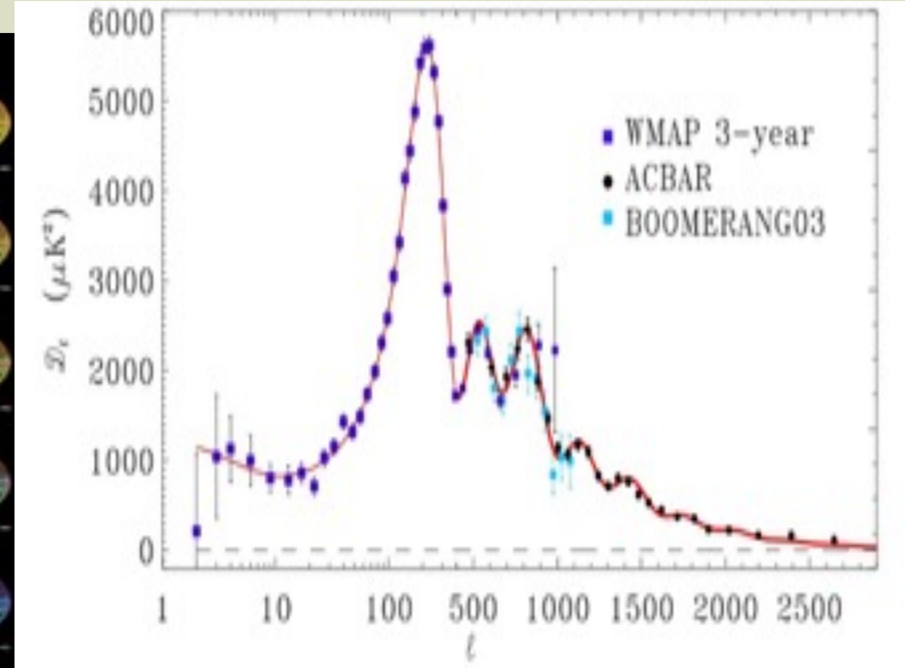


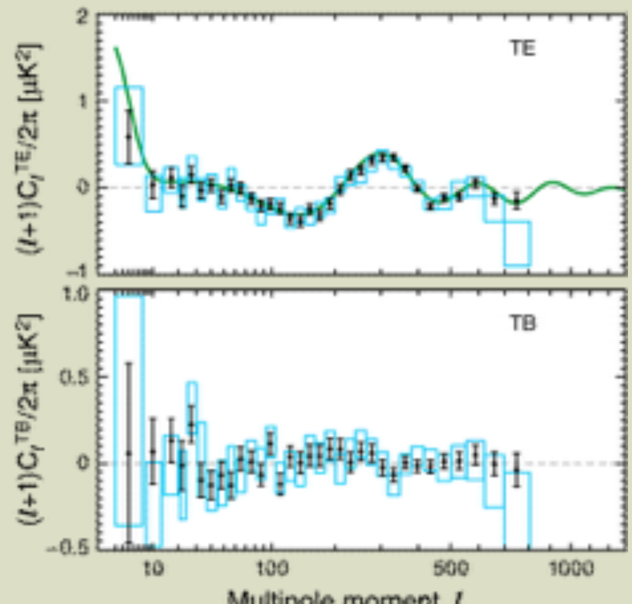


MAXIMA
Boomerang
COBE
0
200
400
600
800



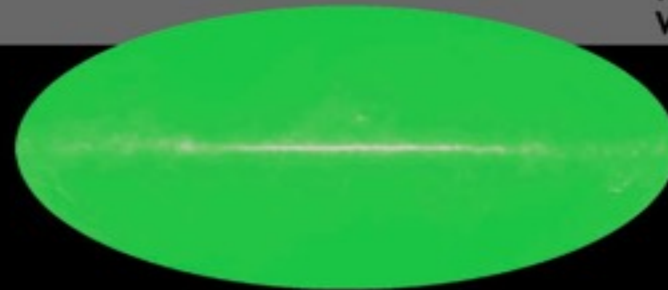

WILKINSON
MICROWAVE ANISOTROPY PROBE
(WMAP)


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ (μK^2)
WMAP 3-year
ACBAR
BOOMERANG03
1
10
100
500
1000
1500
2000
2500
ℓ


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

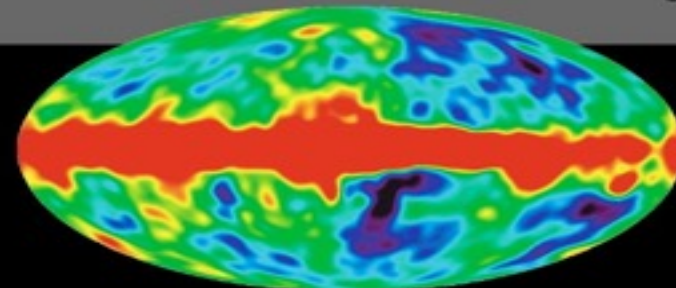
1965

Penzias and Wilson



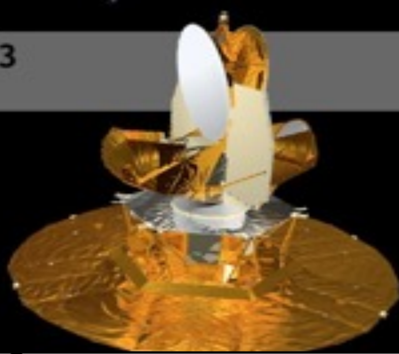
1992

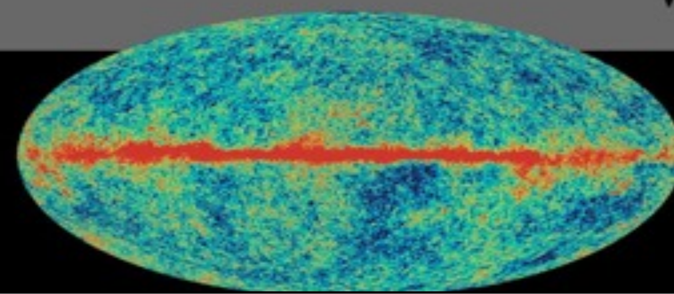
COBE



2003

WMAP



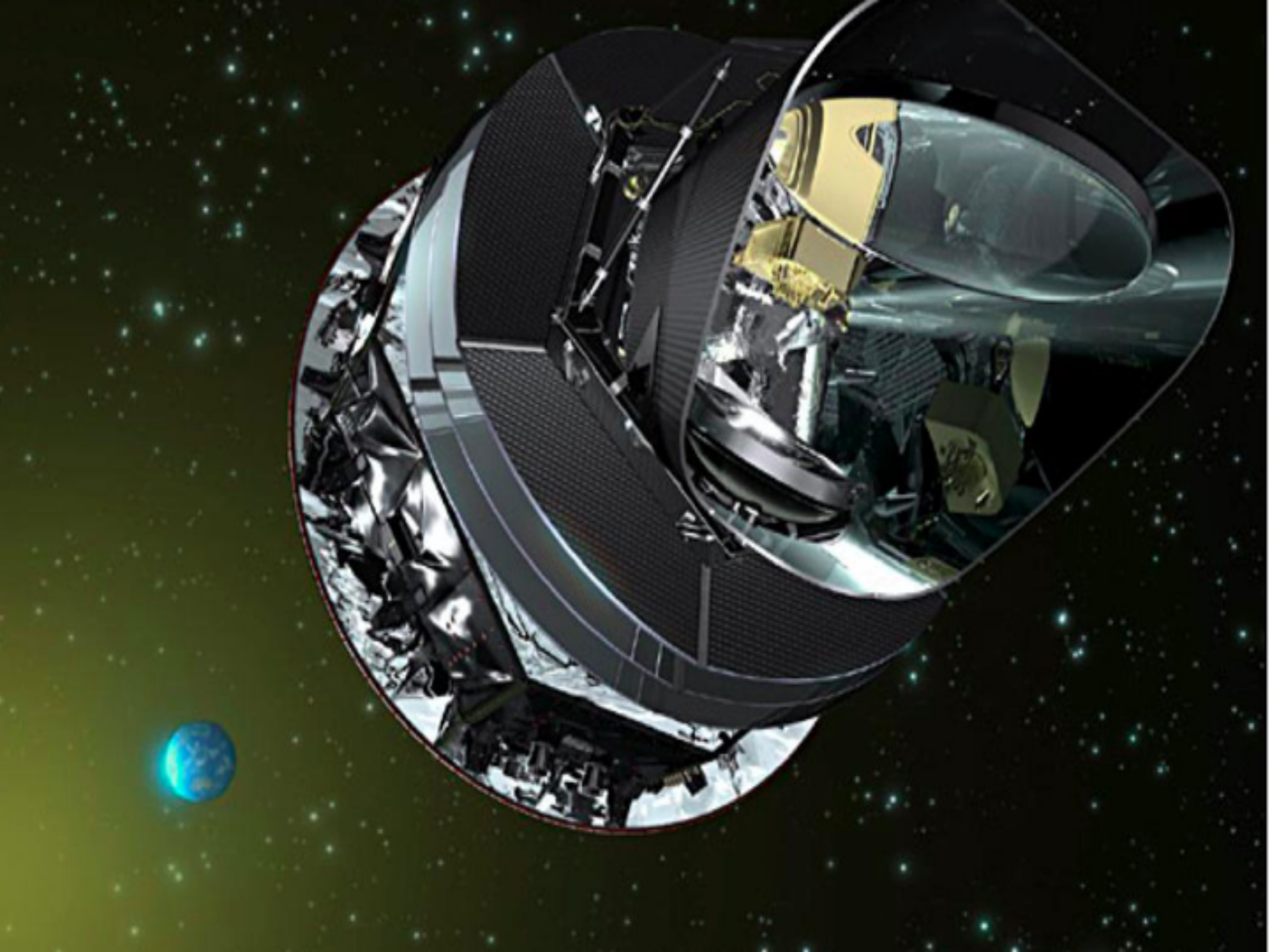


2009

Planck

???

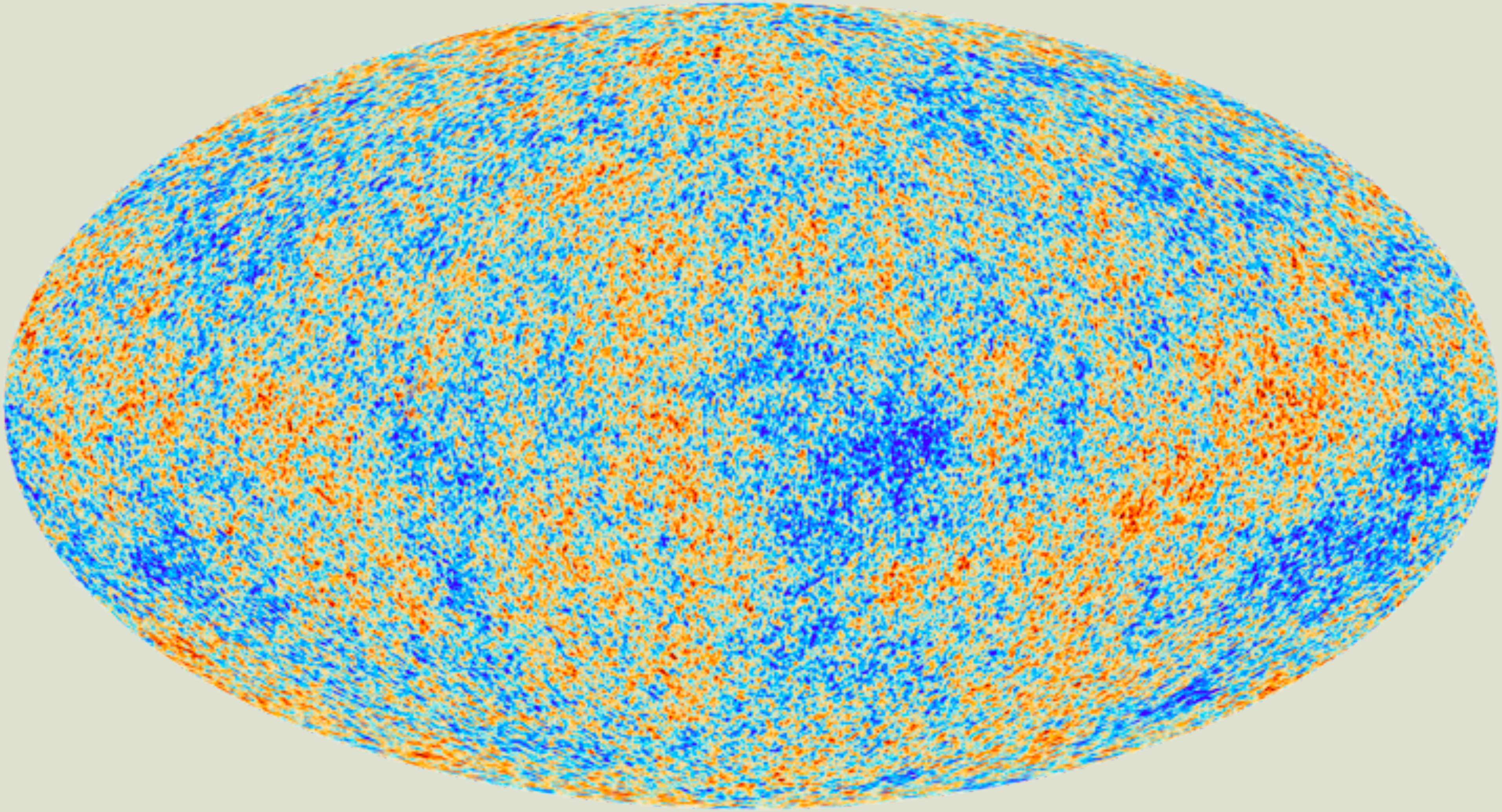
End 2012

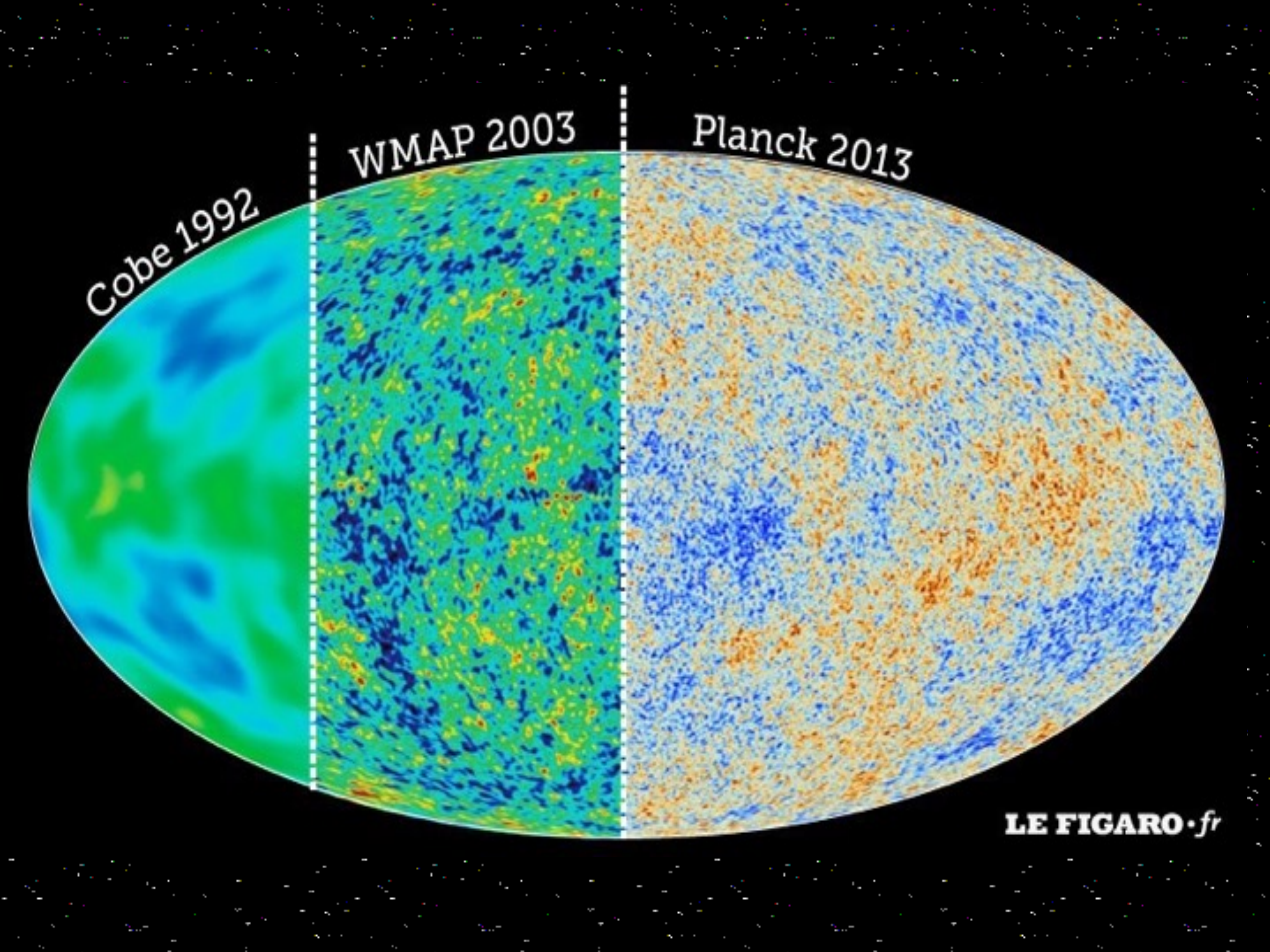


the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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.


SCI




Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

PREDICTIONS

1) flat Universe

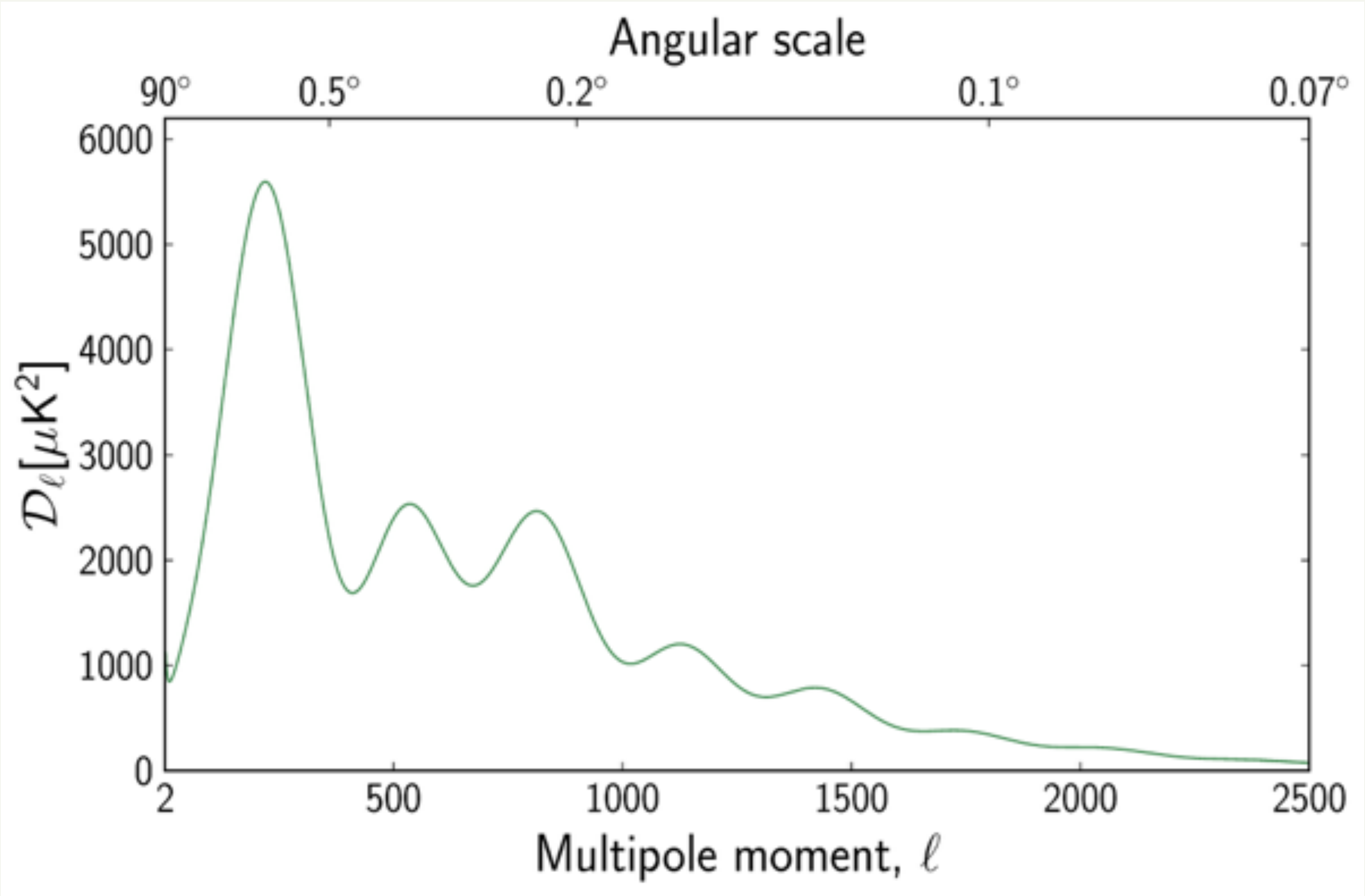
Perturbations are :

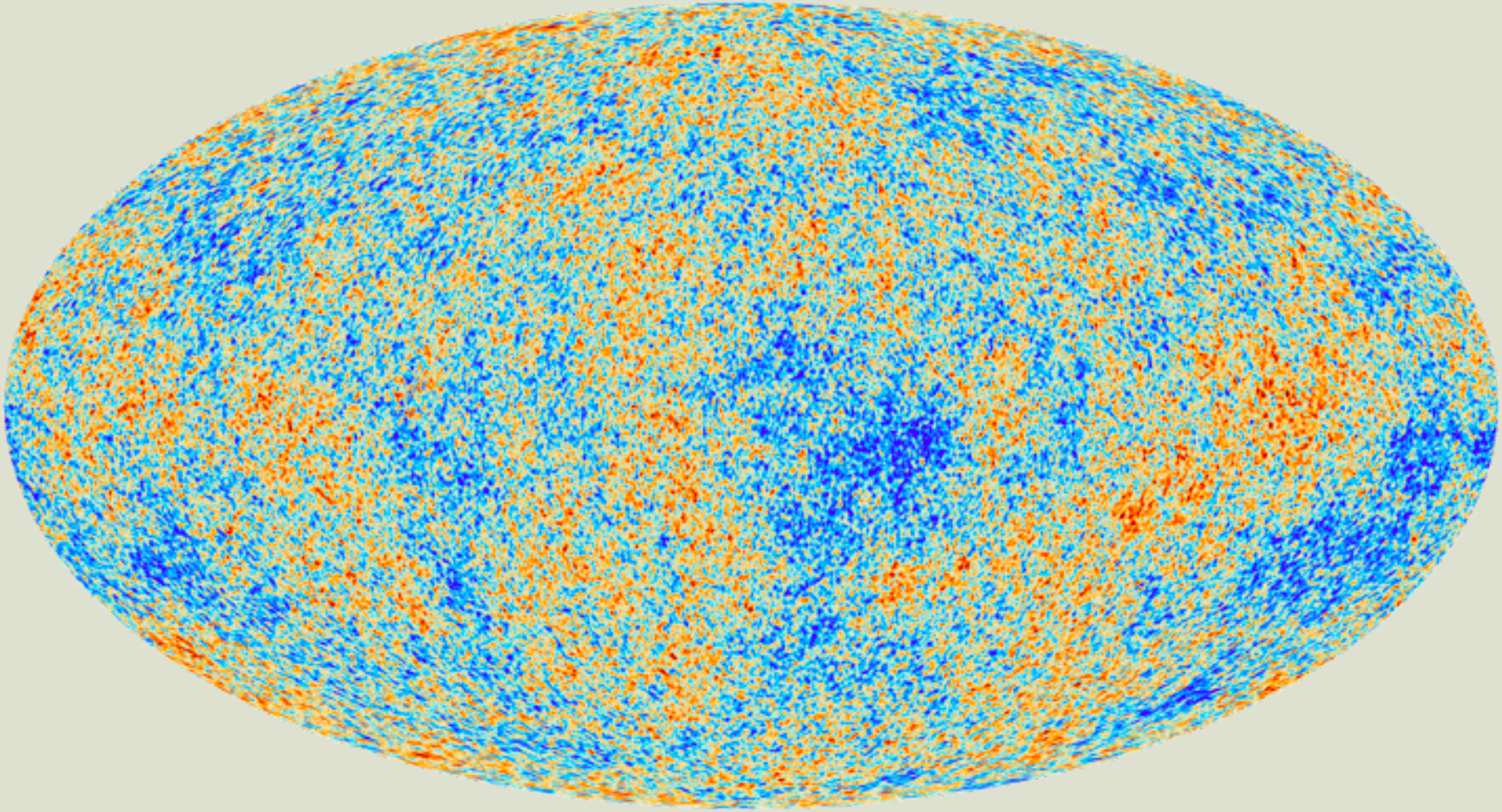
2) adiabatic (MC, 81)

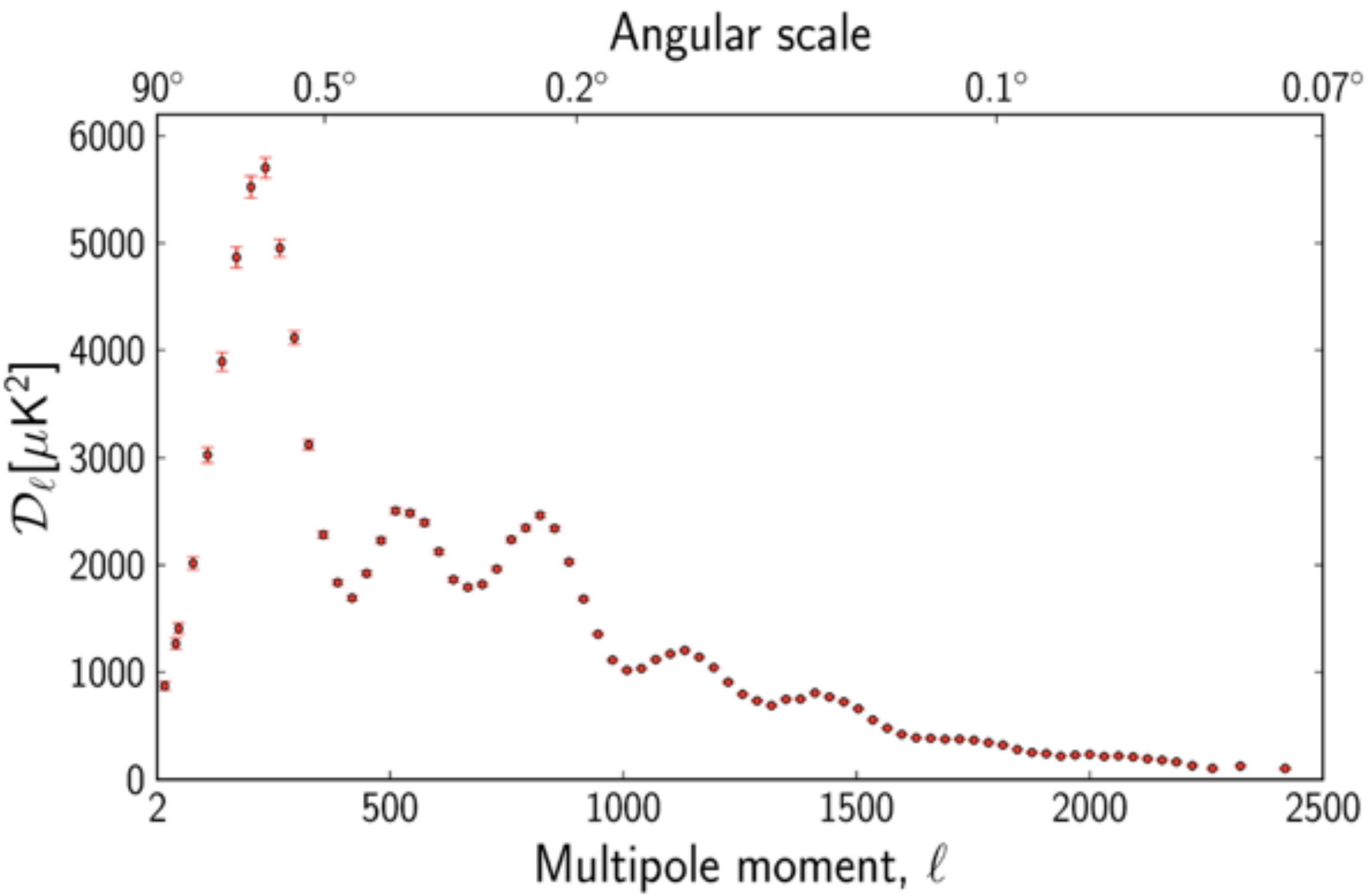
3) gaussian: $\Phi = \Phi_g + f_{NL}\Phi_g^2$, where $f_{NL} = O(1)$ (MC, 81)

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

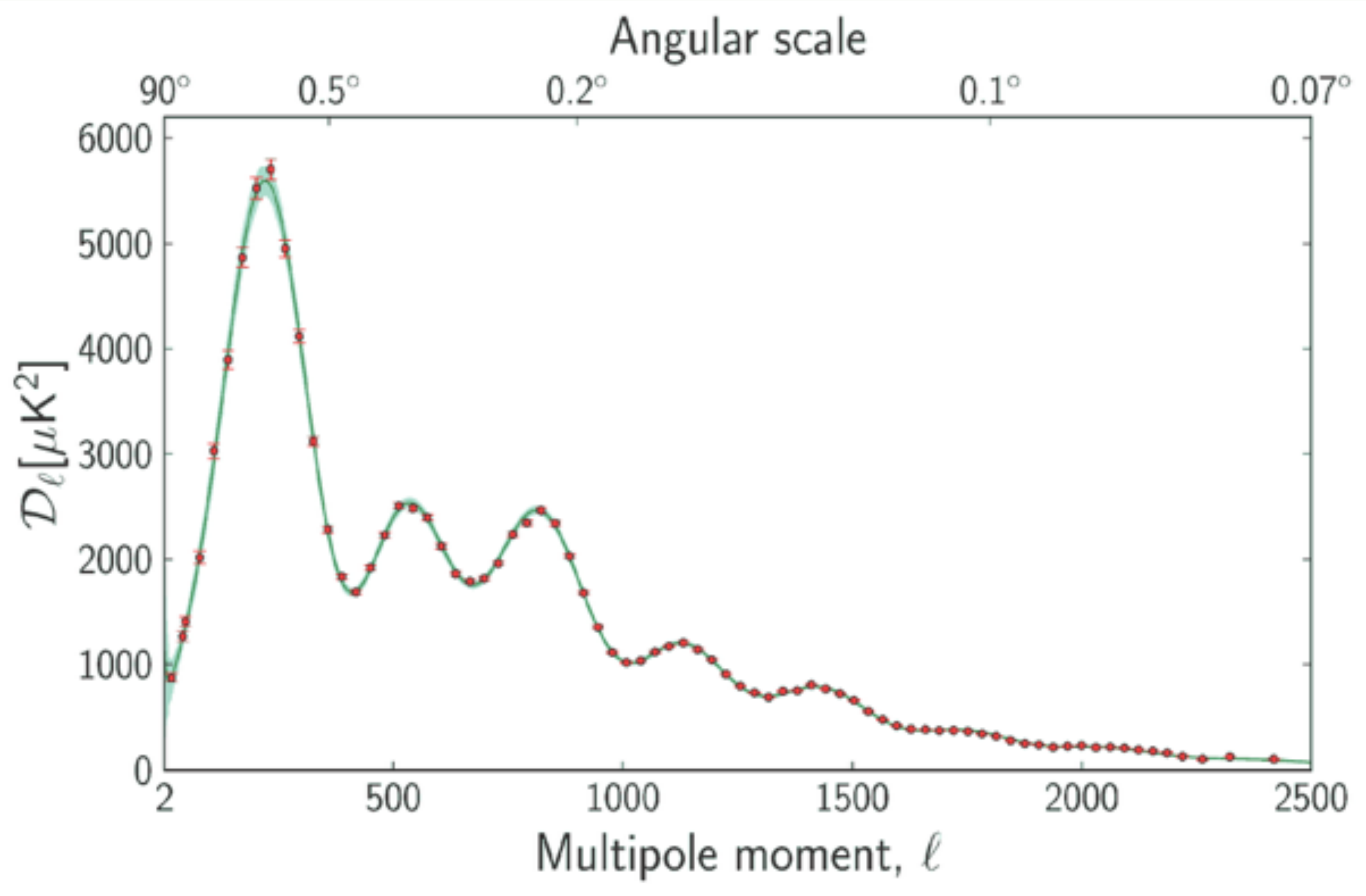
with $\Omega_{tot} = 1$ (prediction) and H_0, $\Omega_\Lambda, \Omega_{bar}$ from supernova, deuterium et.cet. we get

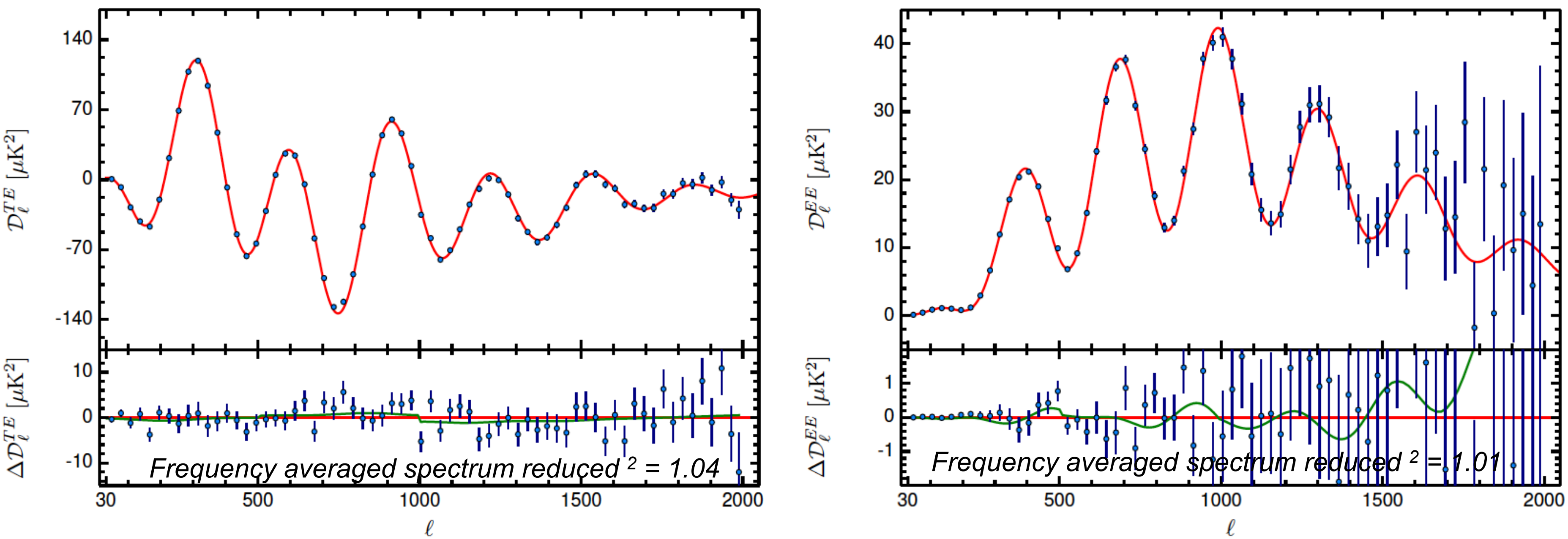




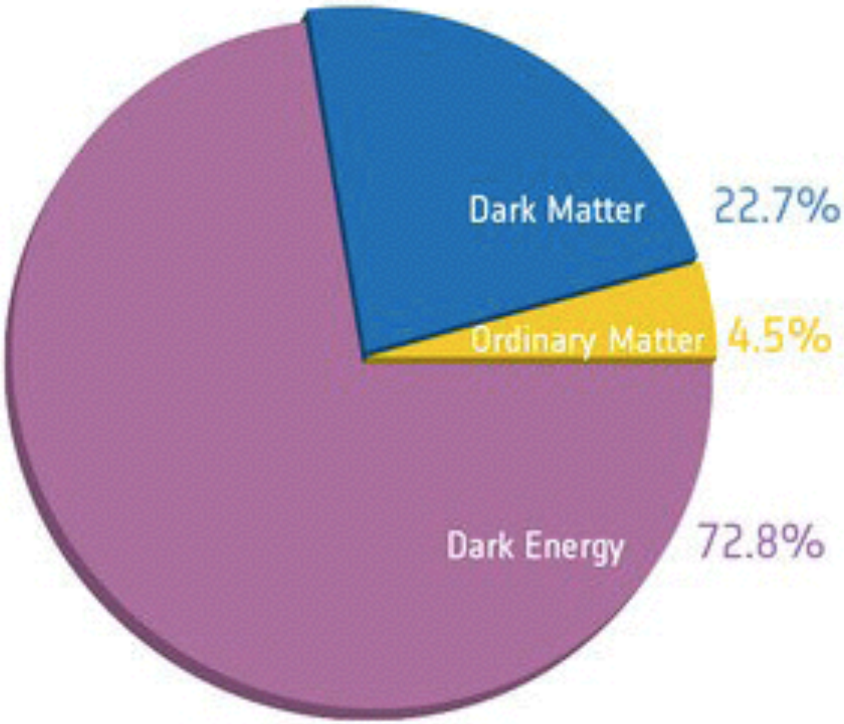


Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ

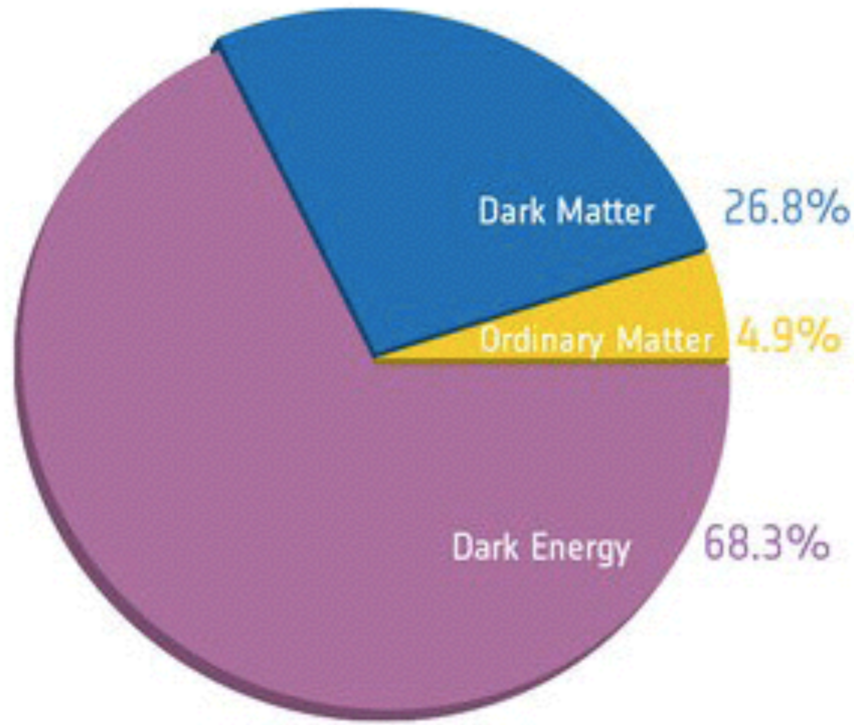

Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ



$\mathcal{D}_\ell^{TE}$ [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

$-\Omega_{tot} = 1 \pm 0.005$

$-$adiabatic pert.!!!, less than 1% from cosmic strings, entropy et.cet.

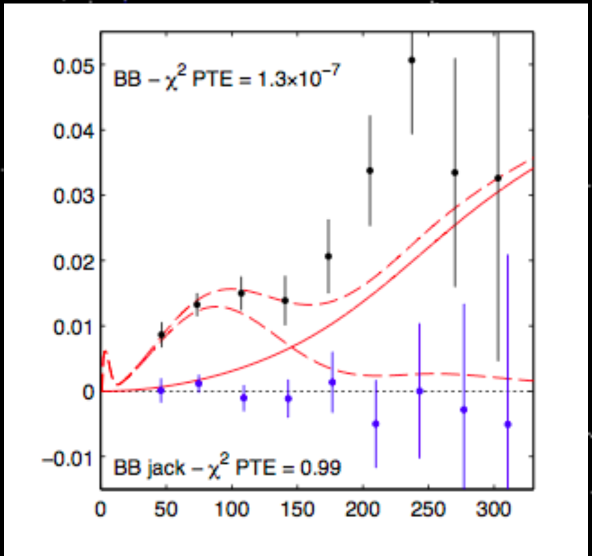
$-$gaussian: $f_{NL} = 0.5 \pm 5.2$

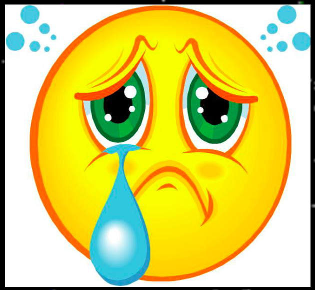
$-n_S = 0.96 \pm 0.0040$

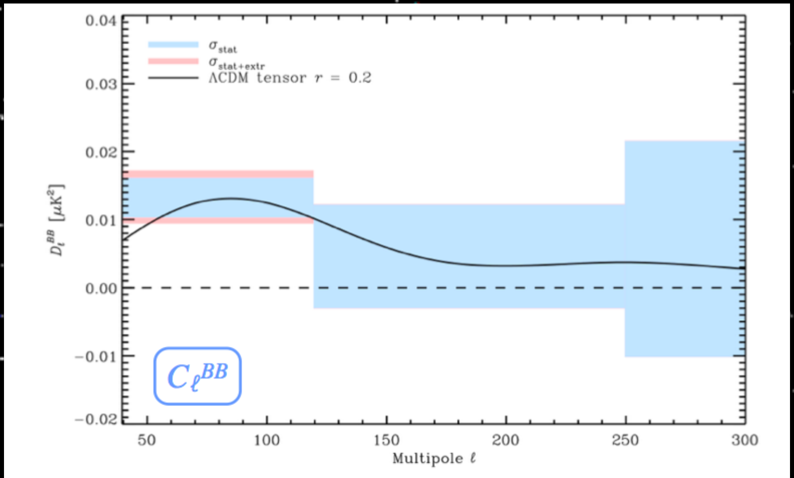
CONCLUSIONS

–*NONPERTURBATIVE* GR is valid from 10^{-27} cm to $10^{28} cm$

–We all originated from quantum fluctuations


BB – χ^2 PTE = 1.3×10^{-7}
BB jack – χ^2 PTE = 0.99
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300




σ_{stat}
$\sigma_{stat+extr}$
ΛCDM tensor r = 0.2
D_ℓ^{BB} [μK^2]
Multipole ℓ
C_ℓ^{BB}
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
50
100
150
200
250
300

- 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.

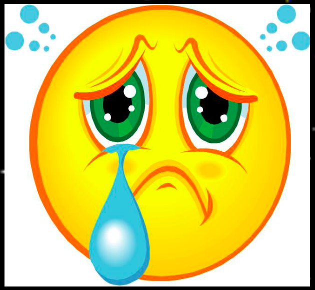
Von Marlene Weiß

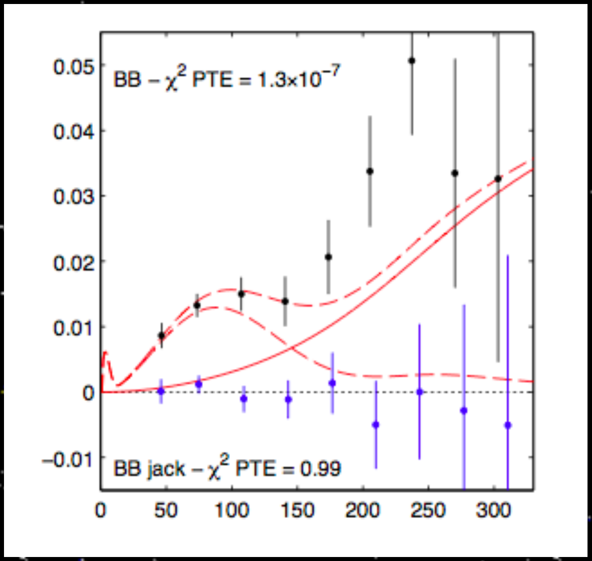
Wer meint, die Welt erklären zu können, indem er am kleinen *n* schraubt, bekommt es mit Viatcheslav Mukhanov zu tun. "Vollkommener Unsinn", schimpft der an der Uni München aktive russische Physiker, "die Zeitschriften sind voll davon, aber es bleibt trotzdem Unsinn!"

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

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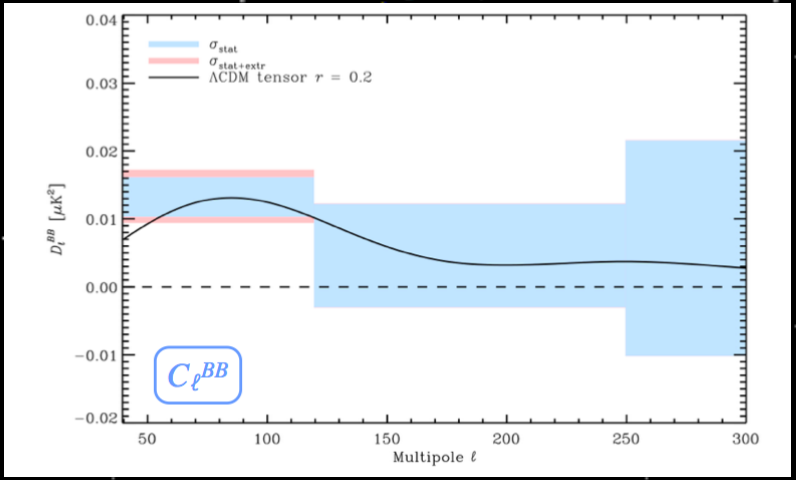
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