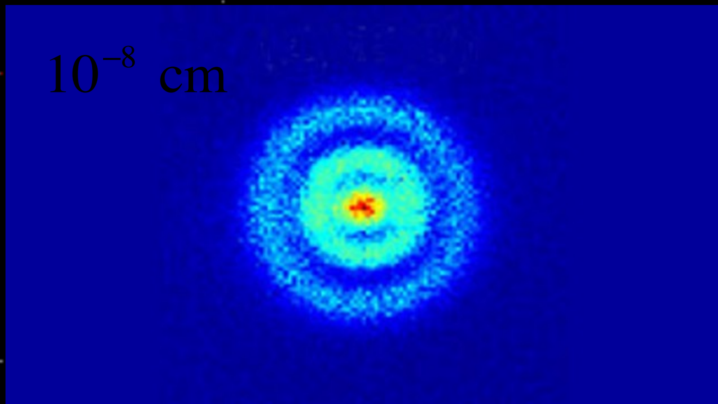
Quantum Universe

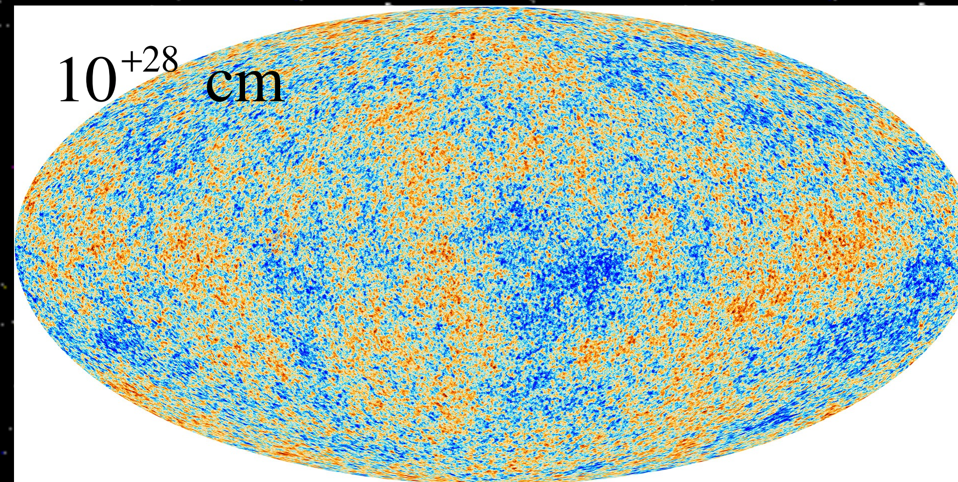
V. Mukhanov

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

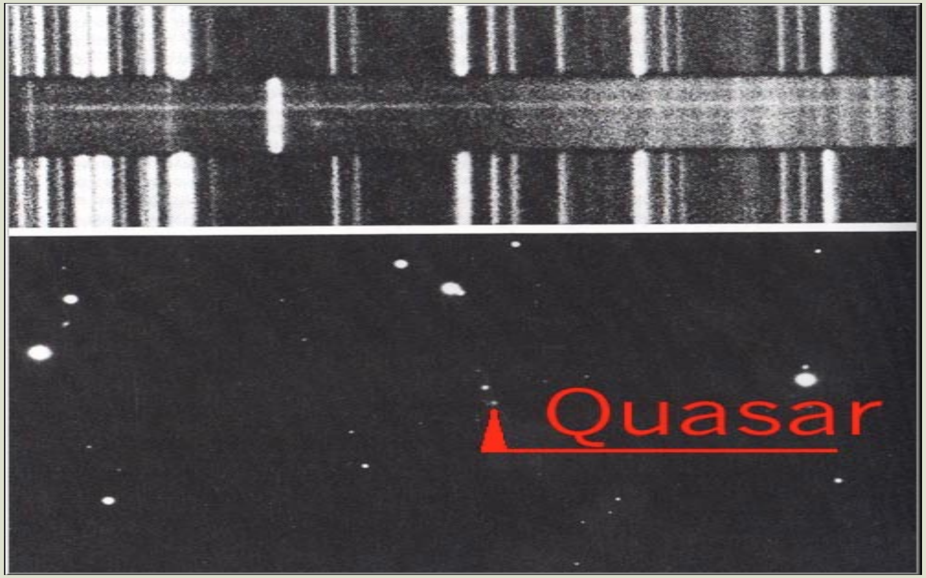




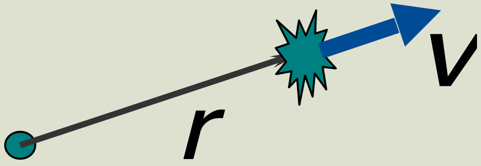
$$\Delta q \times \Delta p \geq \frac{1}{2}\,\hbar$$

Before 1990

- The Universe expands



- Hubble law



$$v = Hr$$

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

There is baryonic matter:

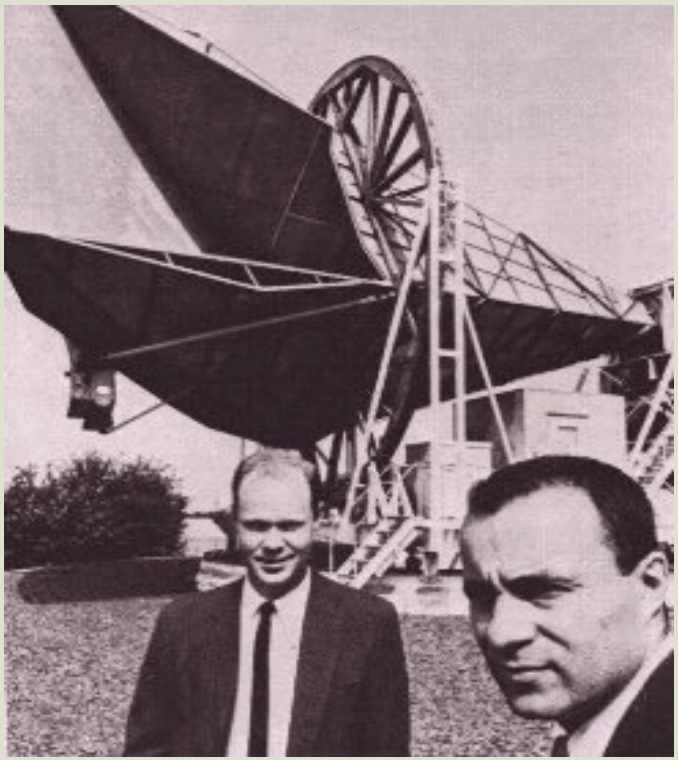
about 25% of ^{4}He, D....heavy elements

Dark Matter???? baryonic origin???

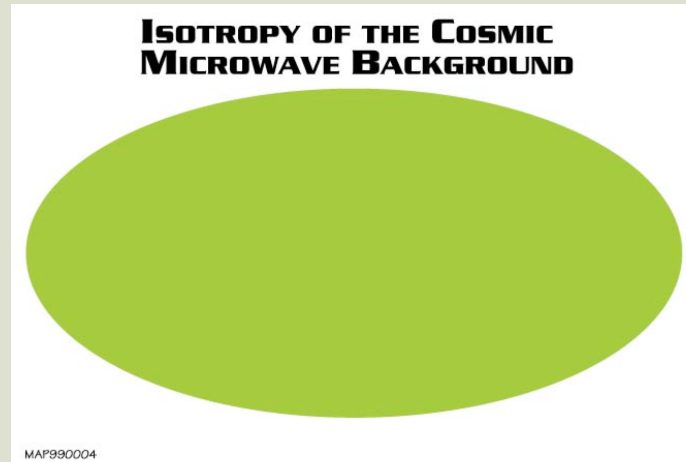
Large Scale Structure: clusters of galaxies!

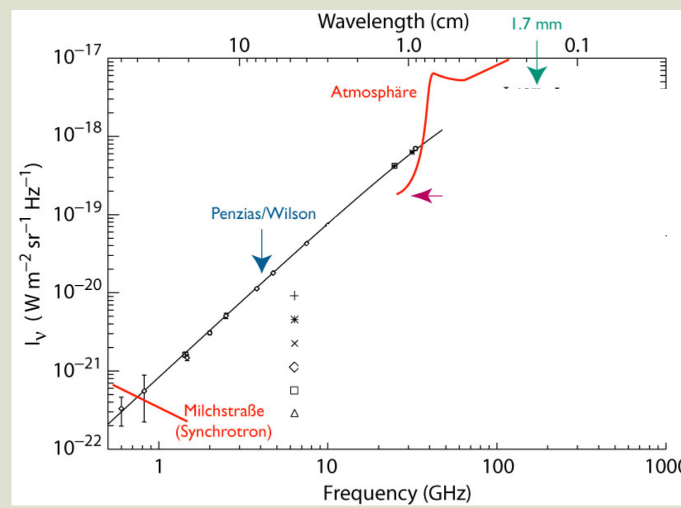
Filaments, Voids??????????????????????

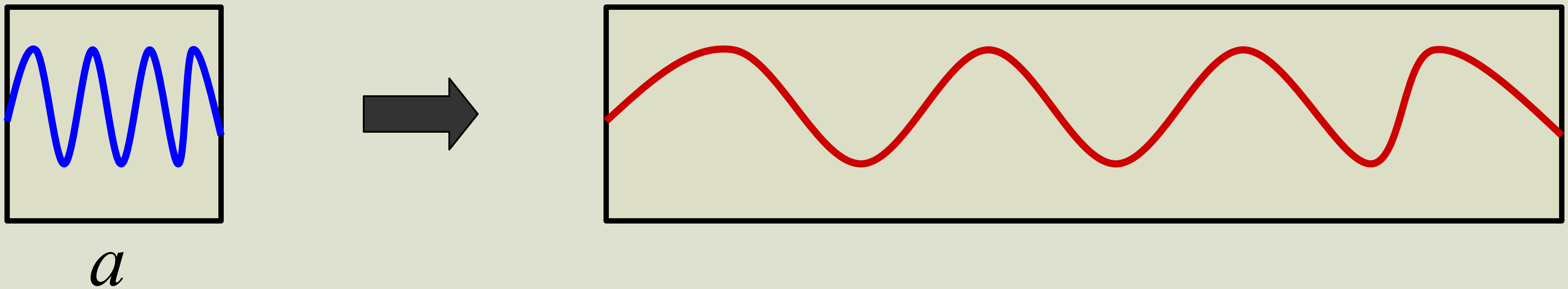
- There exists background radiation with the temperature $T \approx 3K$



Penzias, Wilson 1965

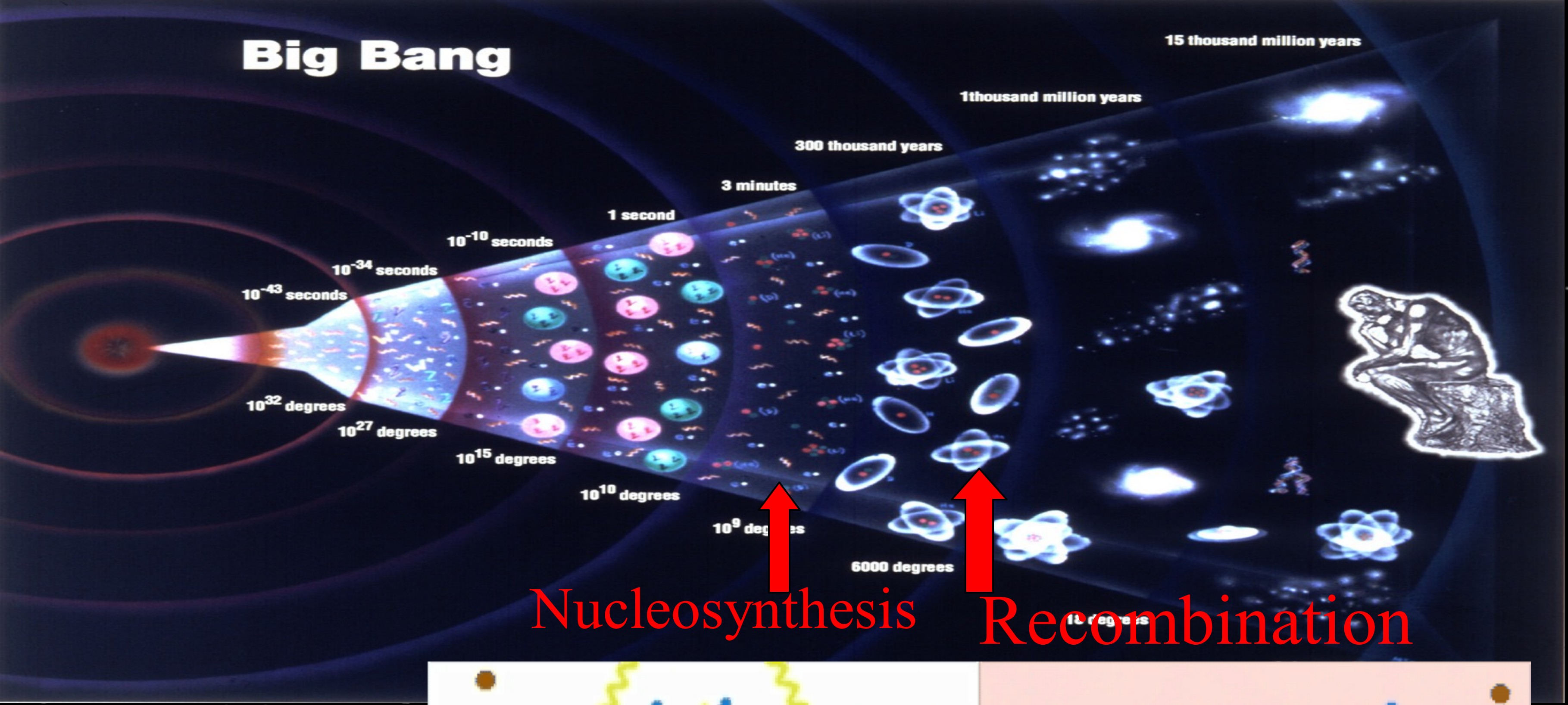


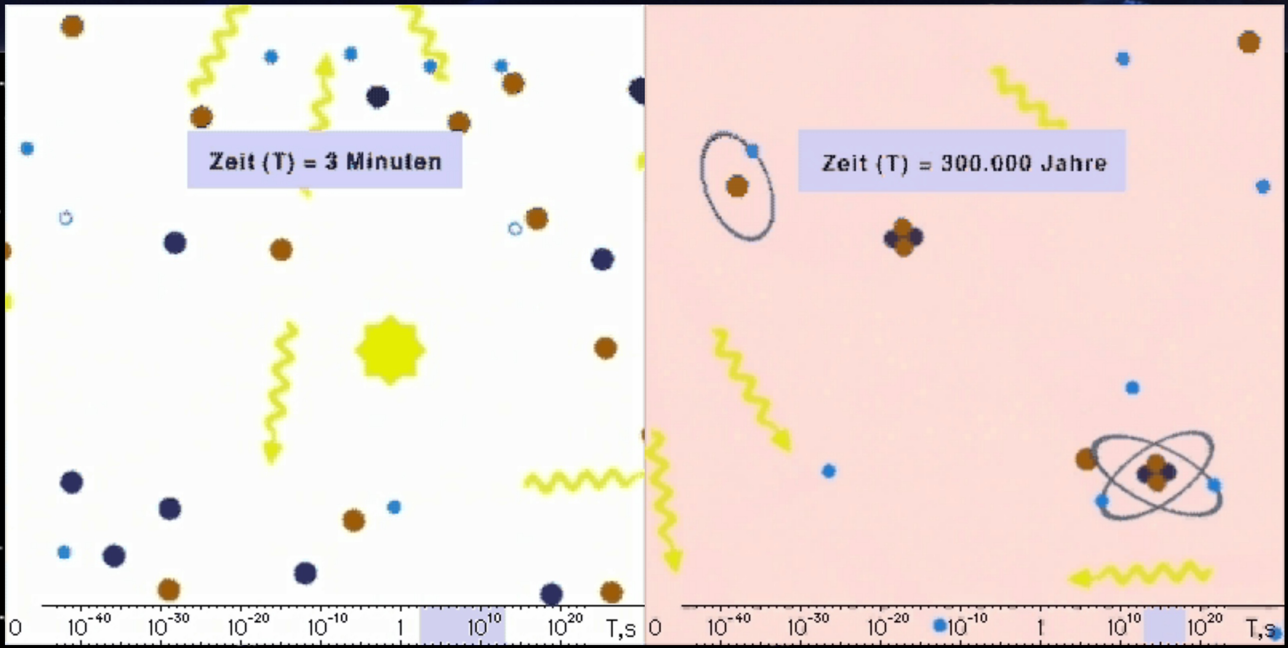


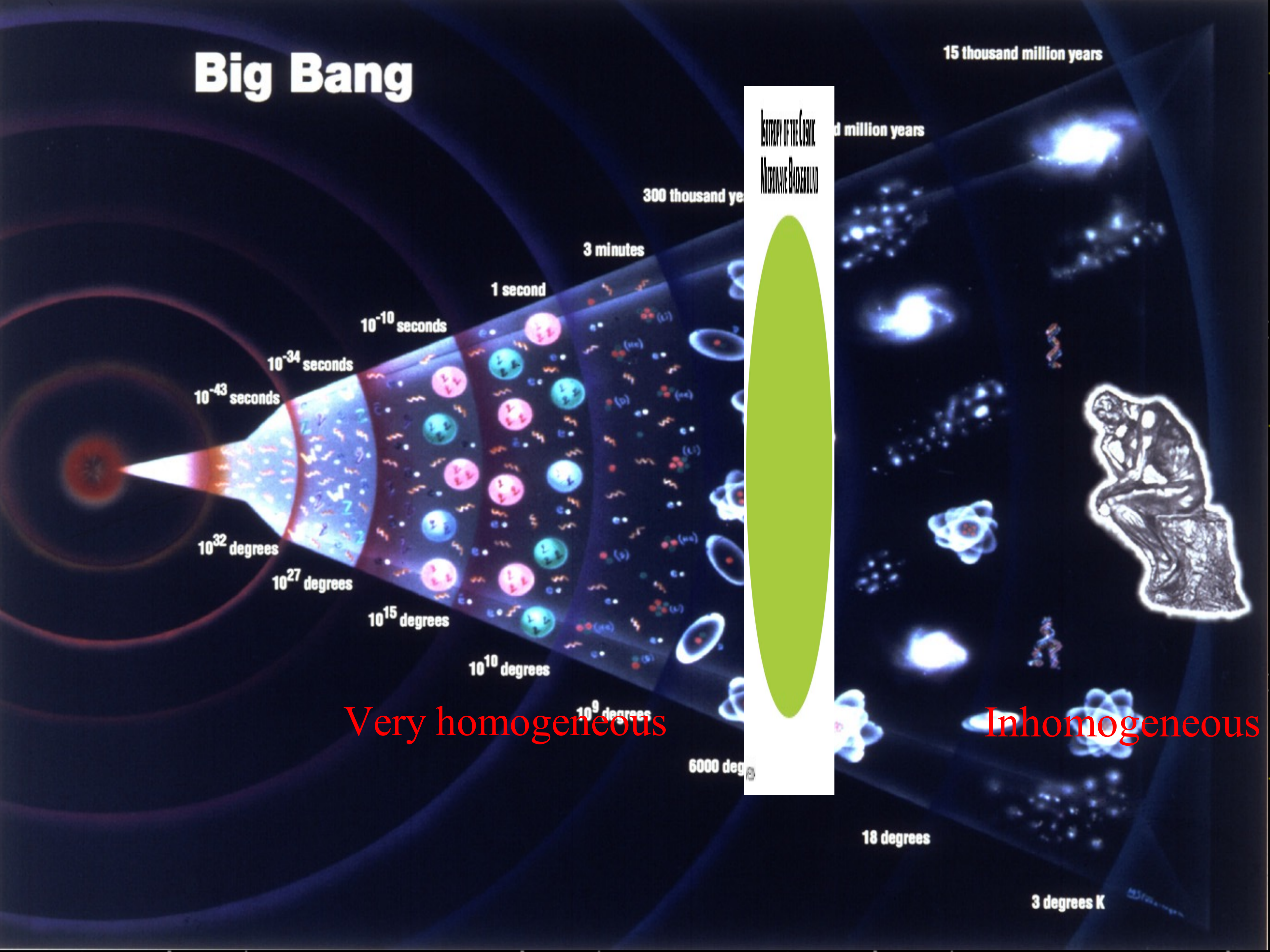


$$\lambda \propto a \quad \Rightarrow \quad T \propto \frac{1}{a}$$

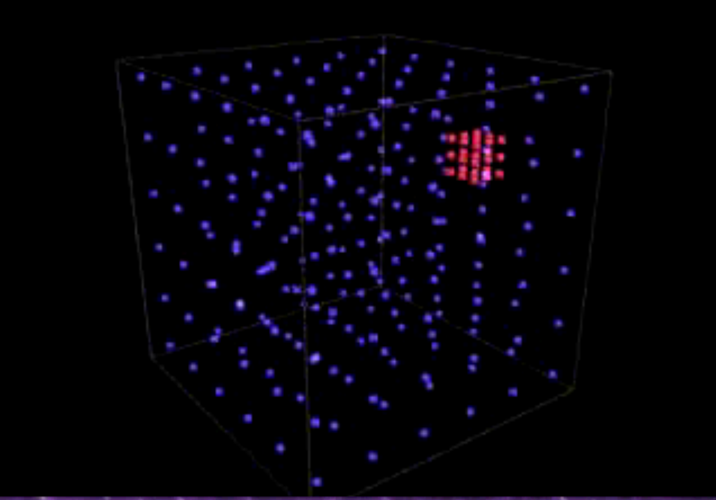
When the Universe was 1000 times smaller its temperature was about $2725°K$

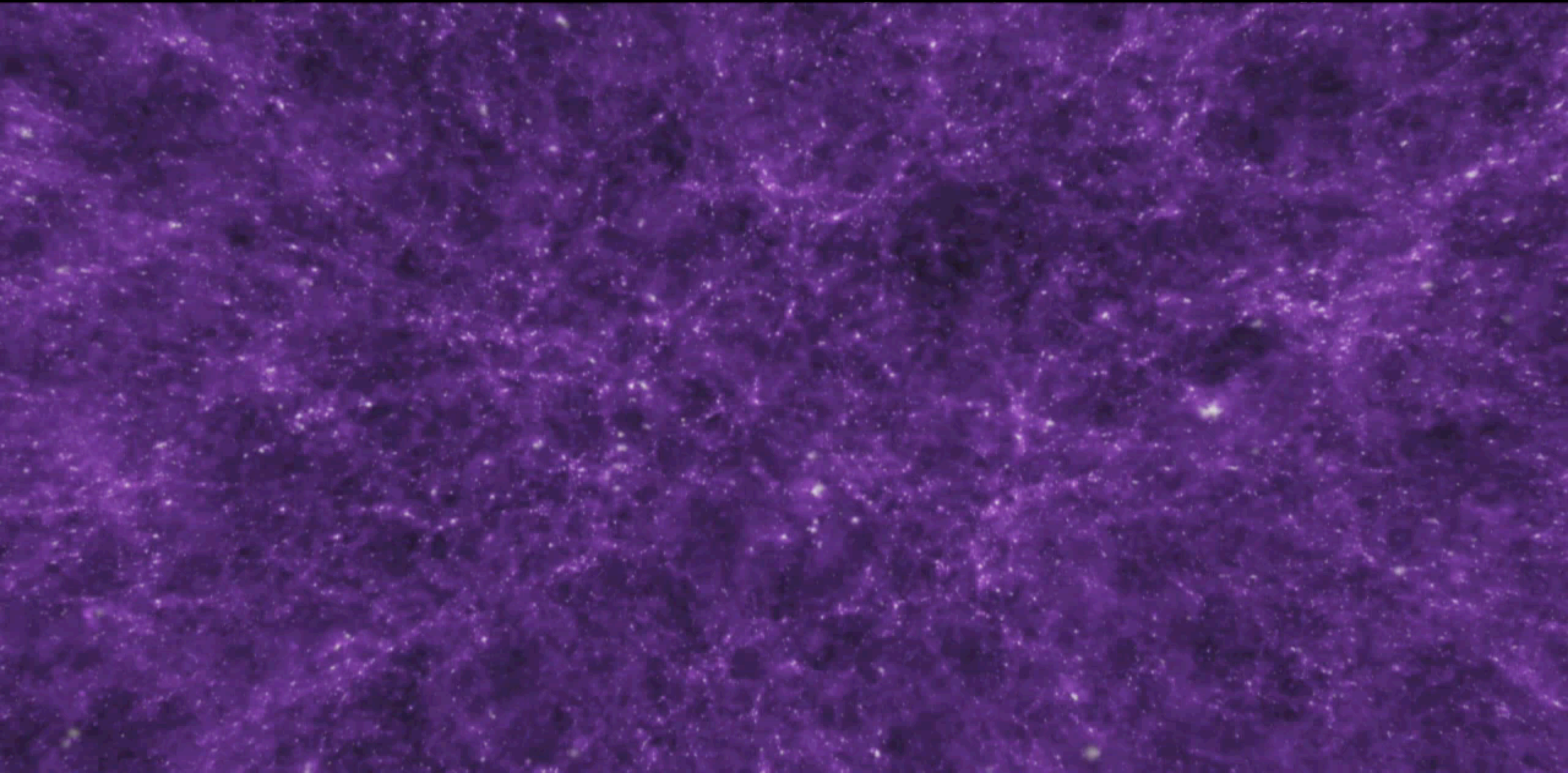

Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10-10 seconds
10-34 seconds
10-43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees
6000 degrees
Nucleosynthesis
Recombination

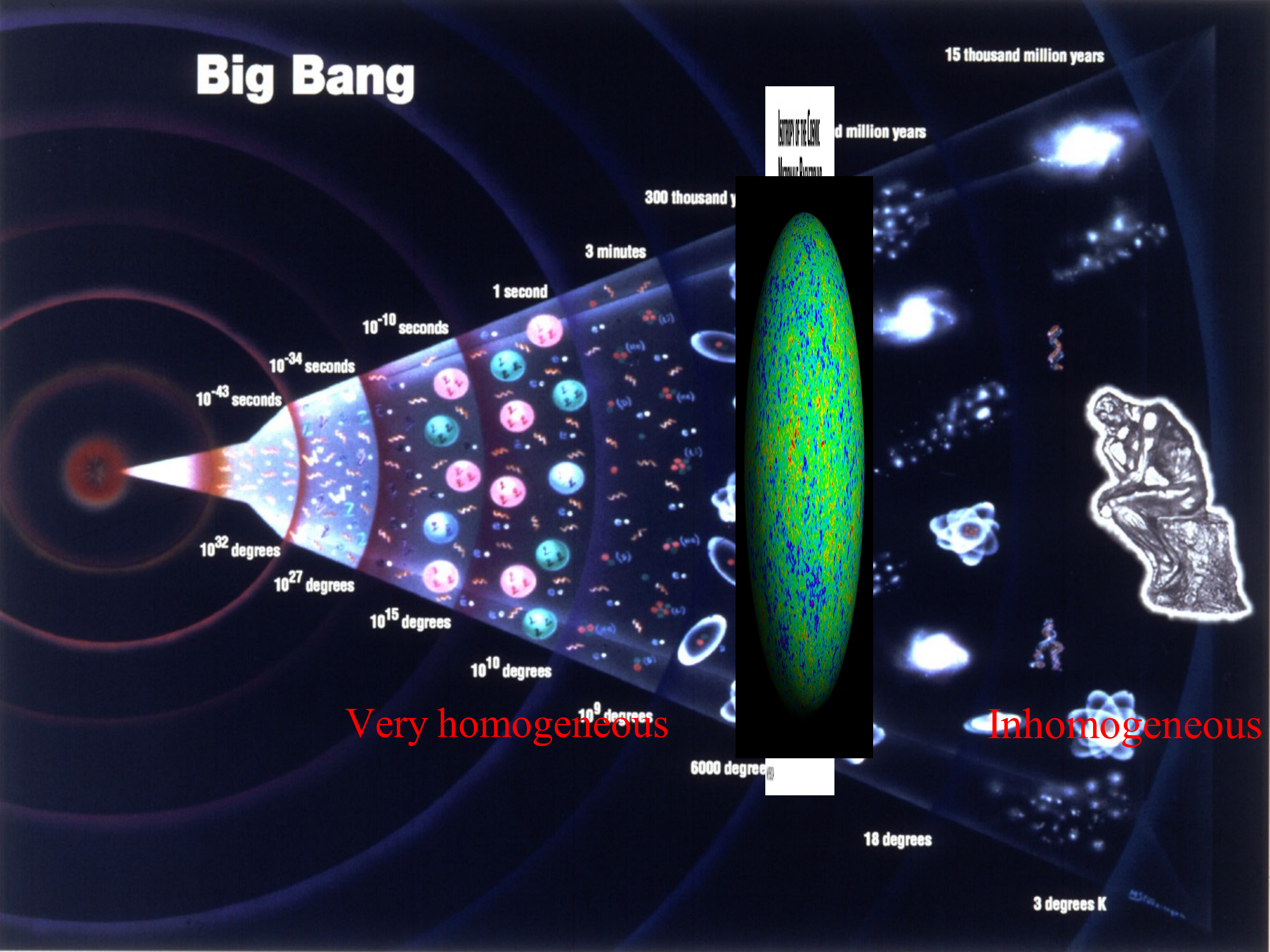

Zeit (T) = 3 Minuten
0 10-40 10-30 10-20 10-10 1 1010 1020 T,s
Zeit (T) = 300.000 Jahre
0 10-40 10-30 10-20 10-10 1 1010 1020 T,s



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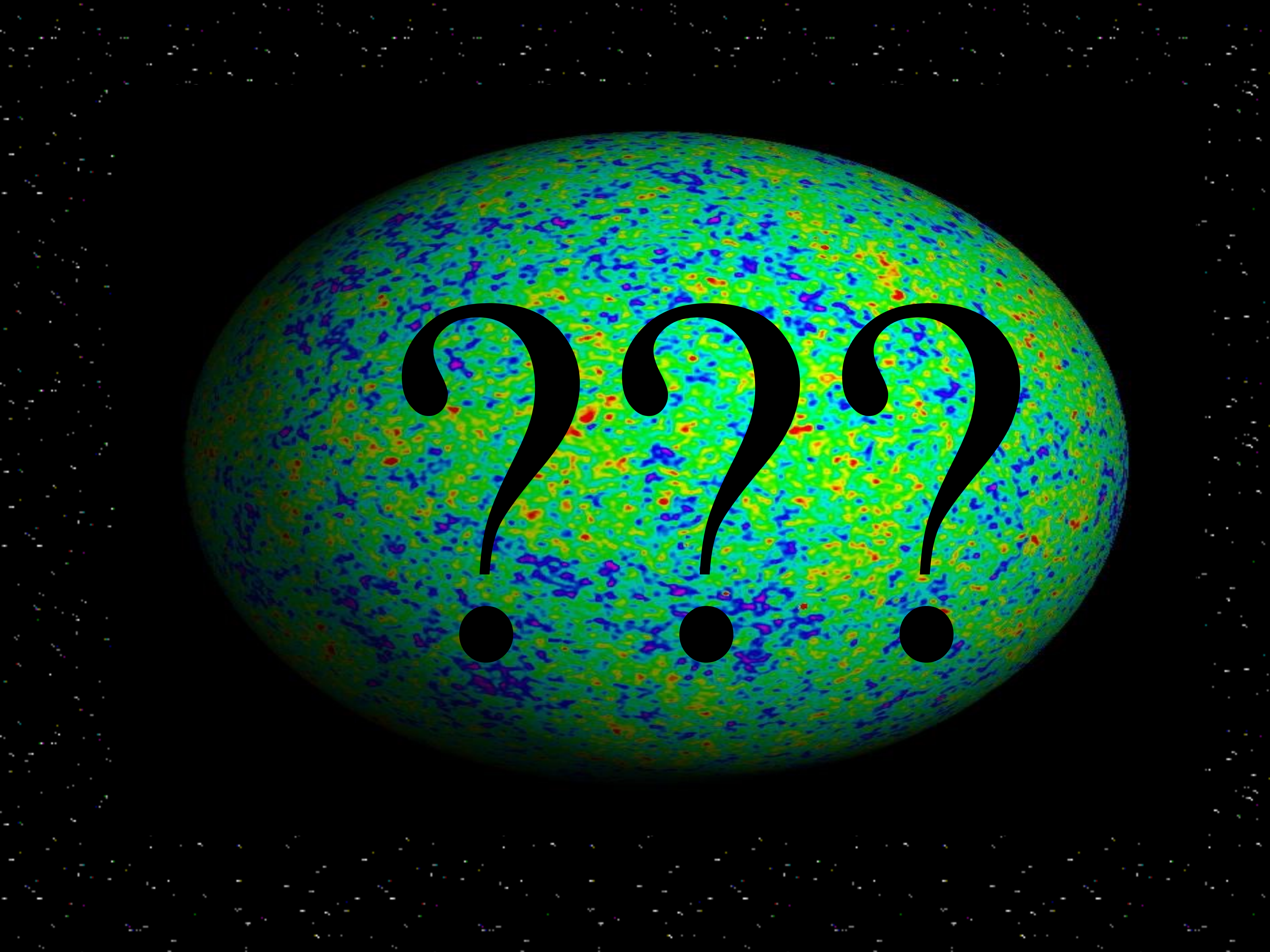
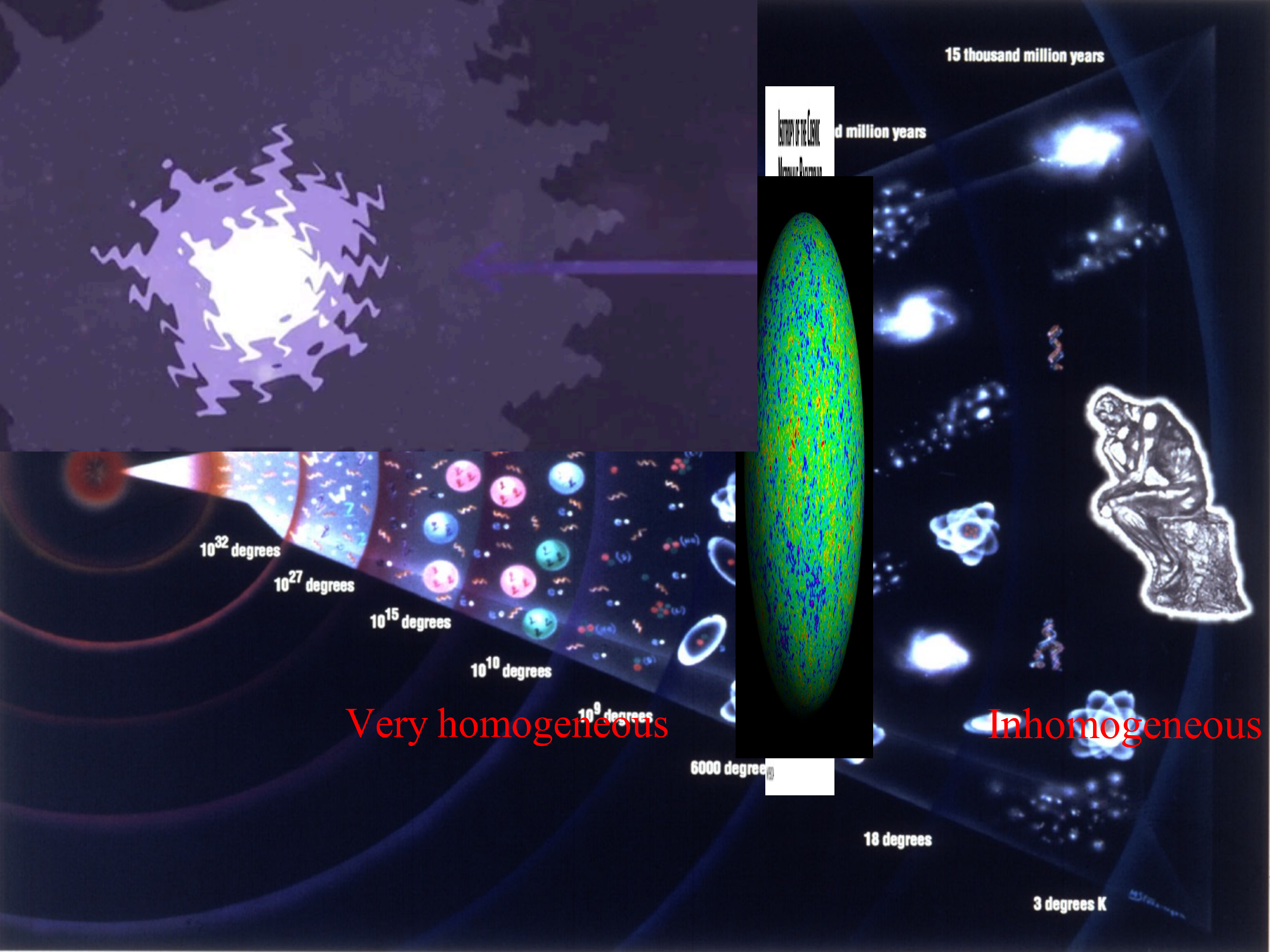
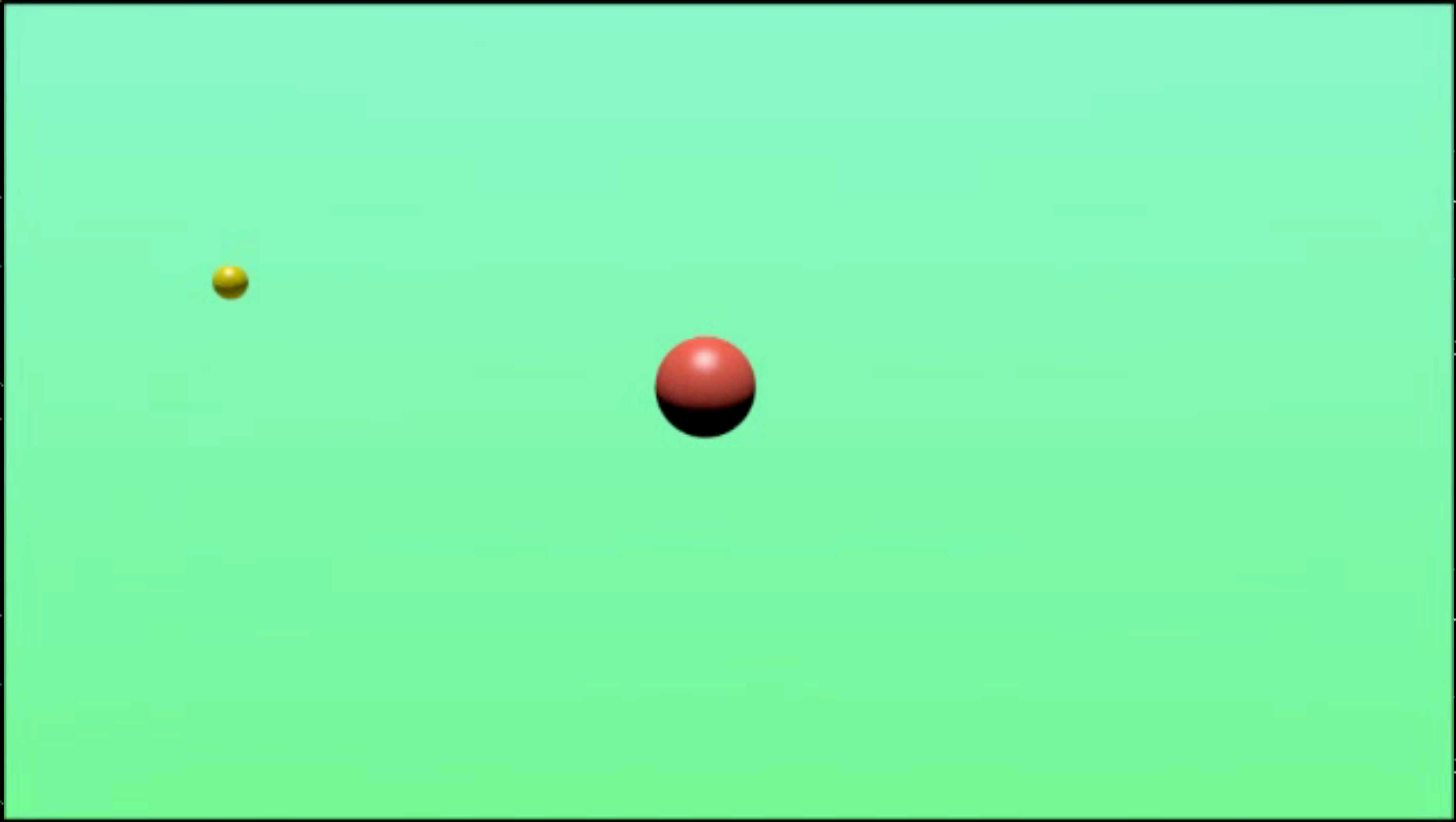
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degree
18 degrees
3 degrees K
Very homogeneous
Inhomogeneous





15 thousand million years
d 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.*

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

Galaxy formation and phonons

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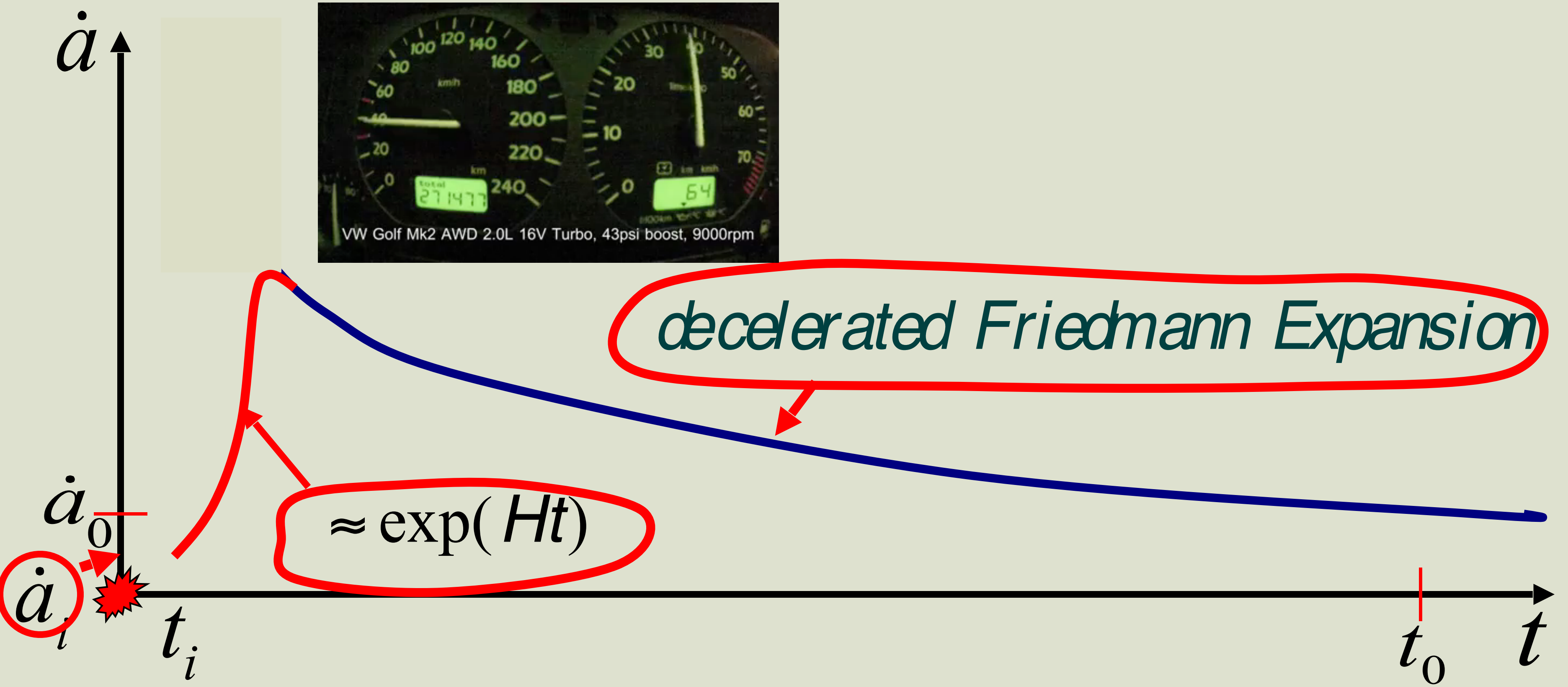
Received 1981 November 25; in original form 1981 August 3

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

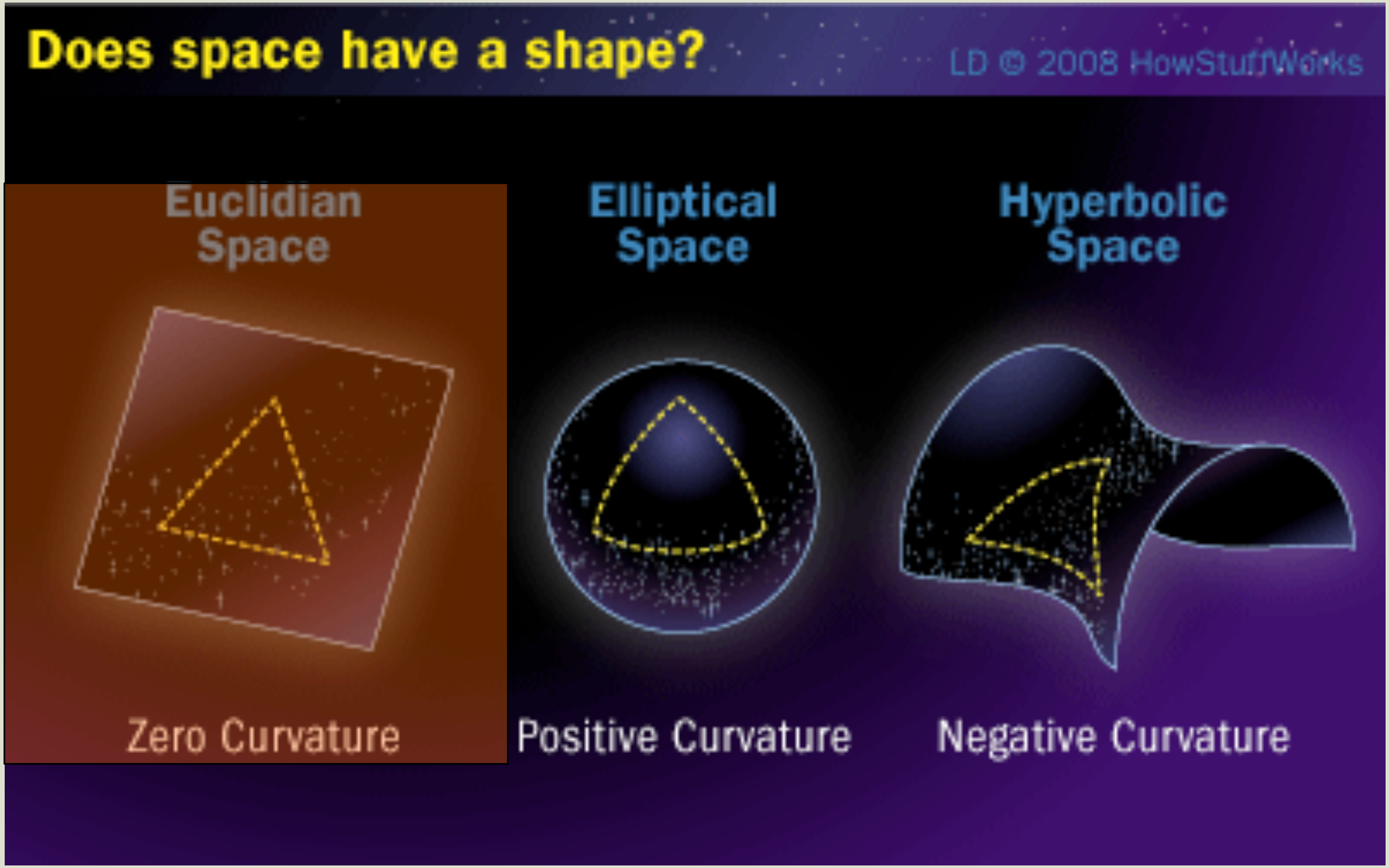
$$\left\langle 0\left|\hat{h}\,(\mathbf{x})\,\hat{h}\,(\mathbf{x}+\mathbf{r})\right|0\right\rangle = \frac{1}{2\pi^2}\int Q^2\,(k)\,\frac{\sin kr}{kr}\frac{dk}{k}, \tag{8}$$

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

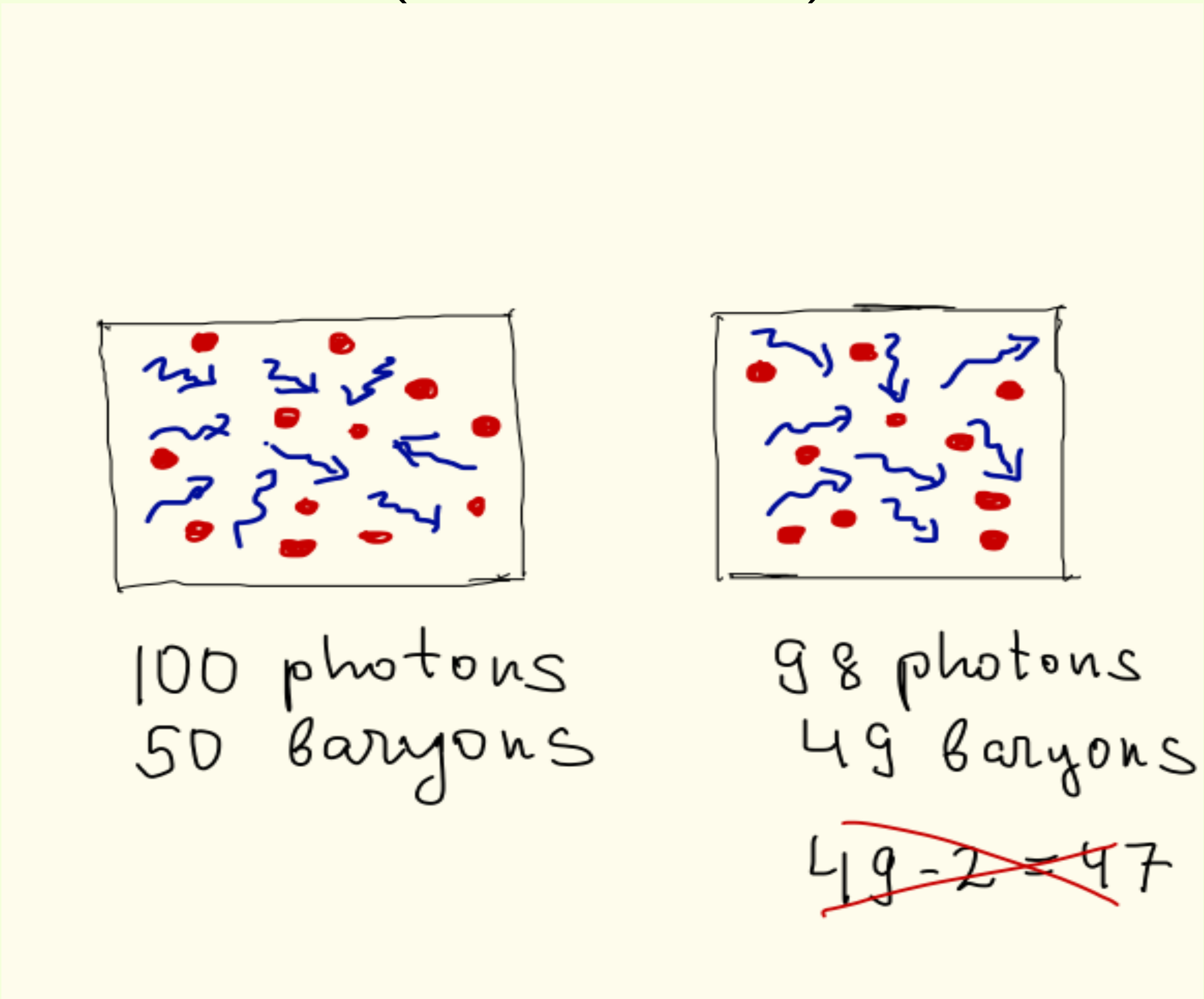
Predictions!!!

1) 

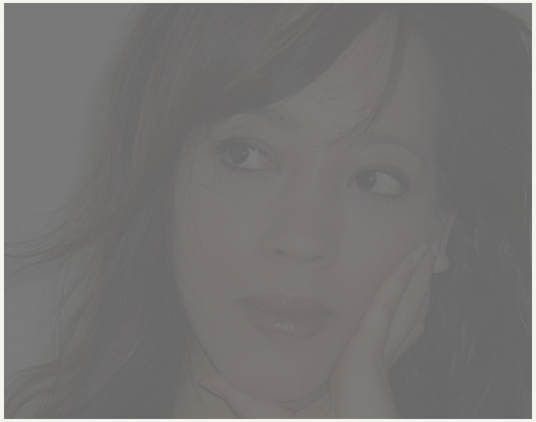
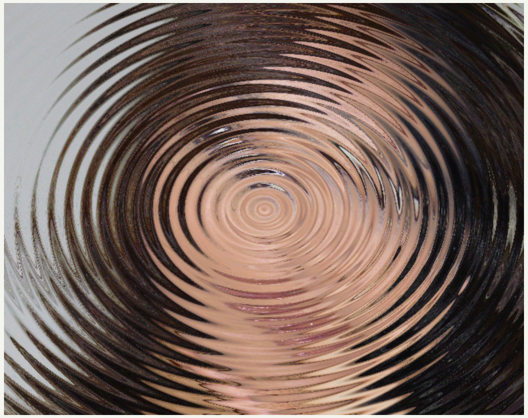
$$\Omega = 1$$

Perturbations (inhomogeneities) are:

2) Adiabatic (MC 1981)

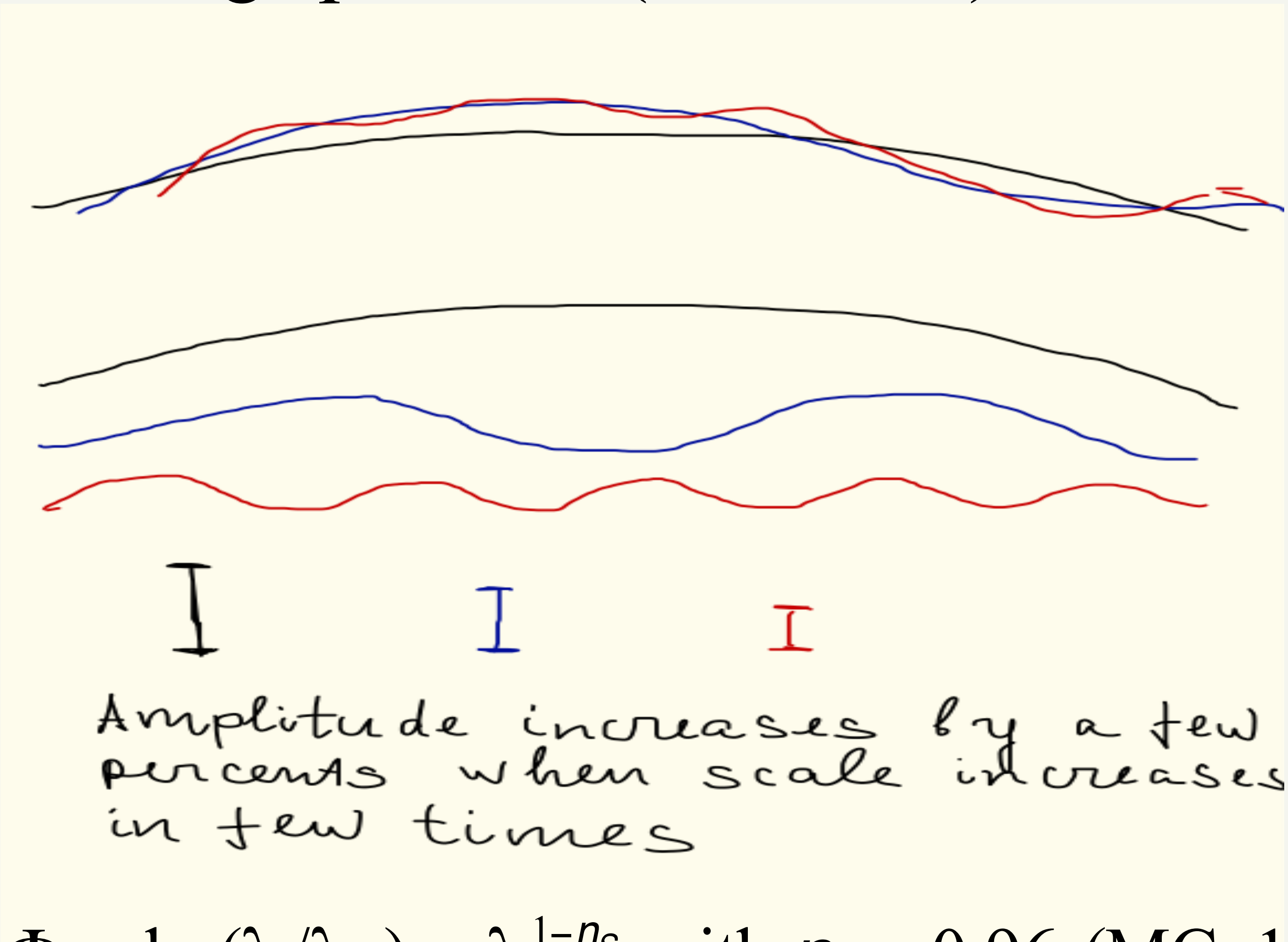


3) Gaussian (MC 1981)

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

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.

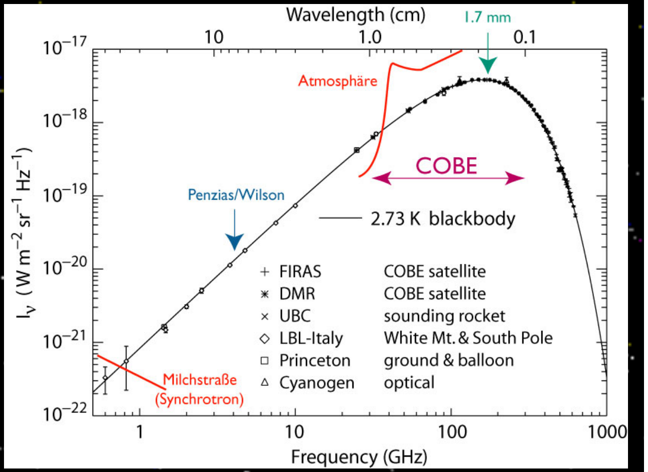
The upper bound is more robust than lower. The physical reason for the deviation of spectrum from the flat one is the nessesity to finish inflation....

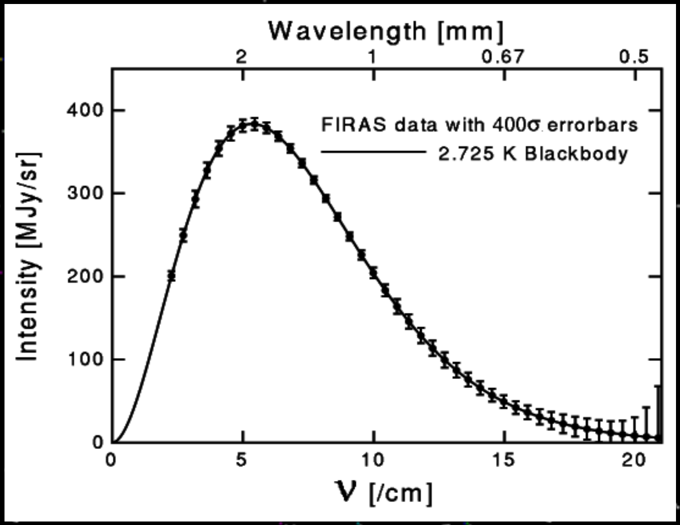
If you find n_s=0.99 +/- 0.01 (3 sigma) I would throw in the towel on inflation.

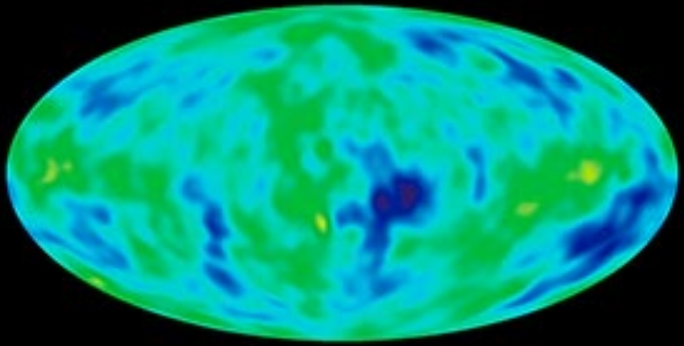
After 90 - present

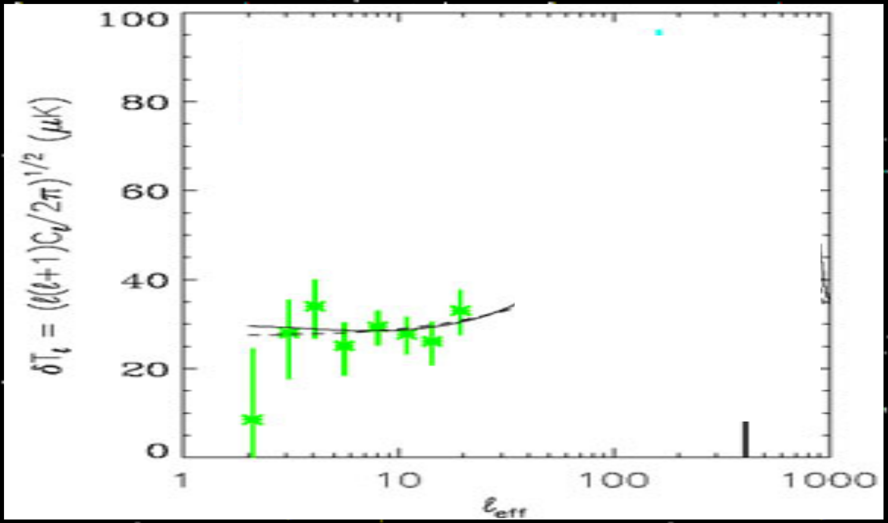
COBE 1992

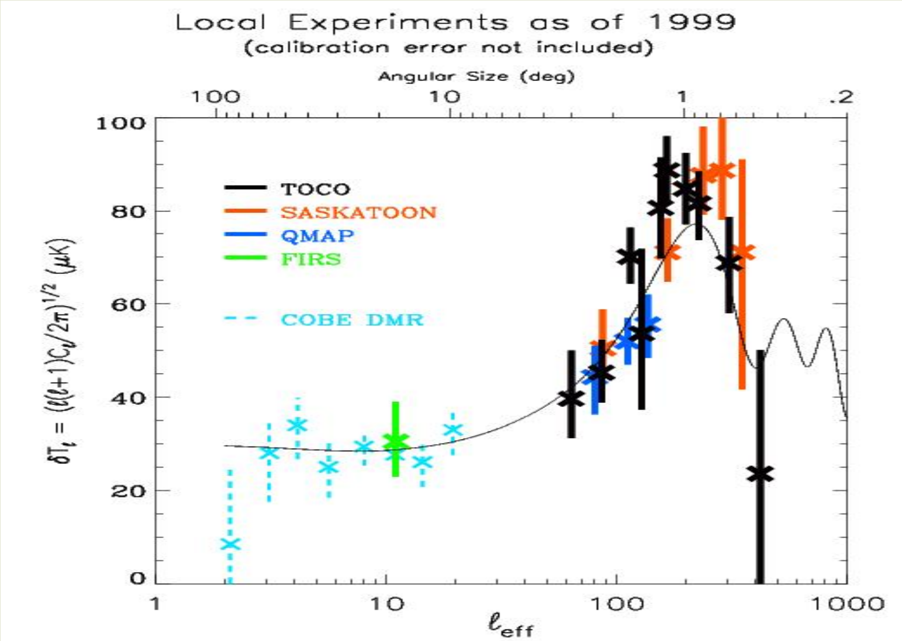

FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

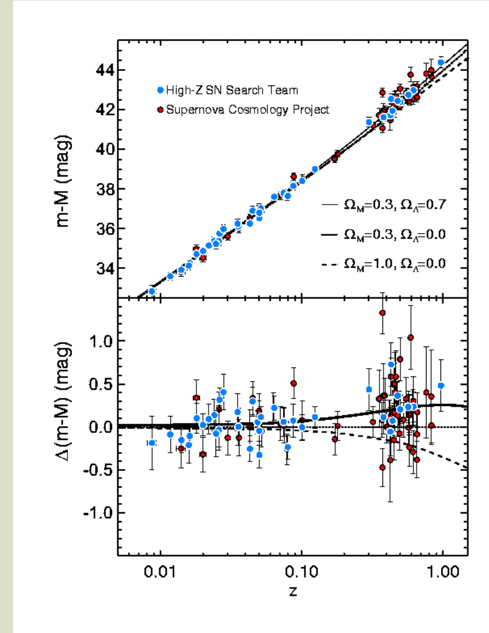

Wavelength (cm)
10
1.0
0.1
1.7 mm
Atmosphäre
COBE
Penzias/Wilson
2.73 K blackbody
+ FIRAS COBE satellite
DMR COBE satellite
UBC sounding rocket
LBL-Italy White Mt. & South Pole
Princeton ground & balloon
Cyanogen optical
Milchstraße (Synchrotron)
I_ν (W m^{-2} sr^{-1} Hz^{-1})
10^{-17}
10^{-18}
10^{-19}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

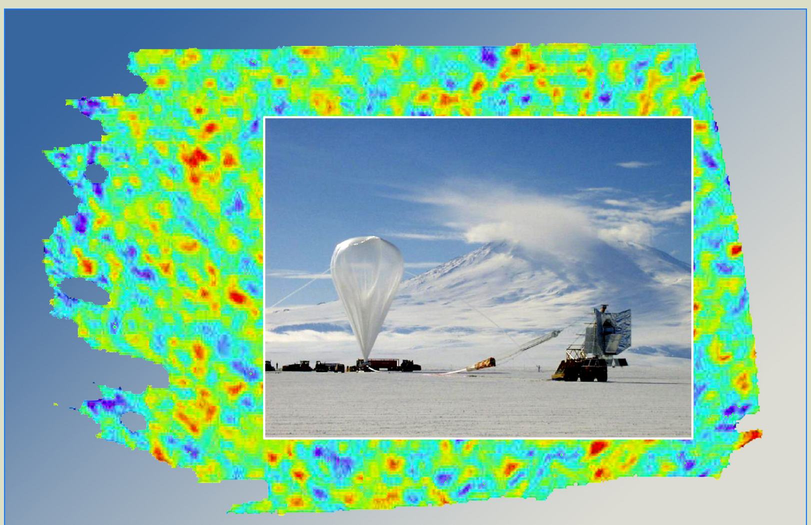

Wavelength [mm]
2
1
0.67
0.5
FIRAS data with 400σ errorbars
2.725 K Blackbody
Intensity [MJy/sr]
0
100
200
300
400
0
5
10
15
20
ν [/cm]

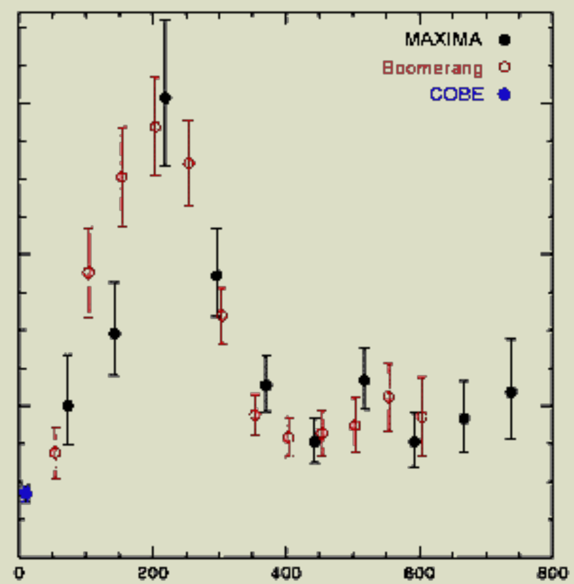


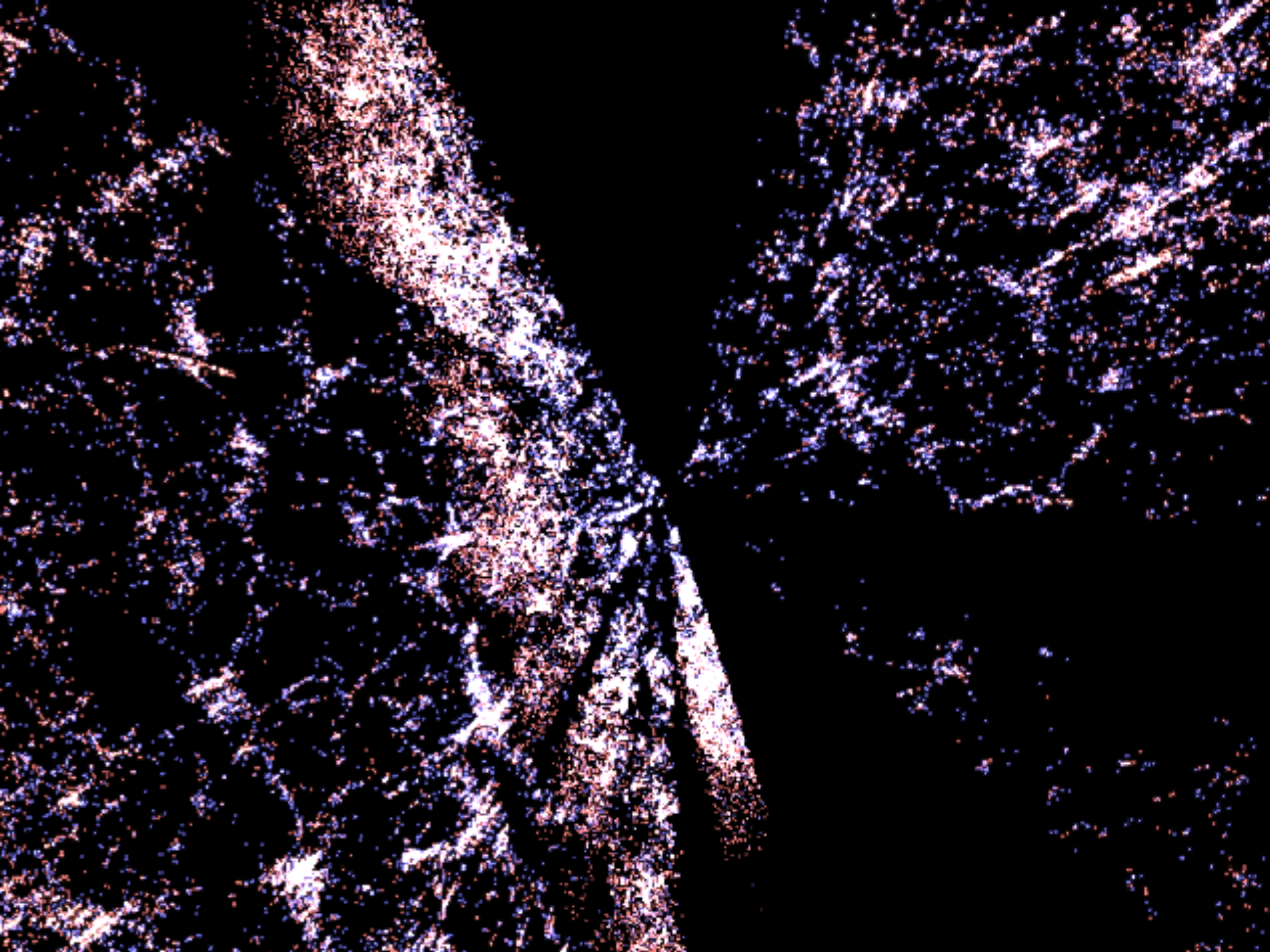

$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
0
20
40
60
80
100
1
10
100
1000
ℓ_{eff}

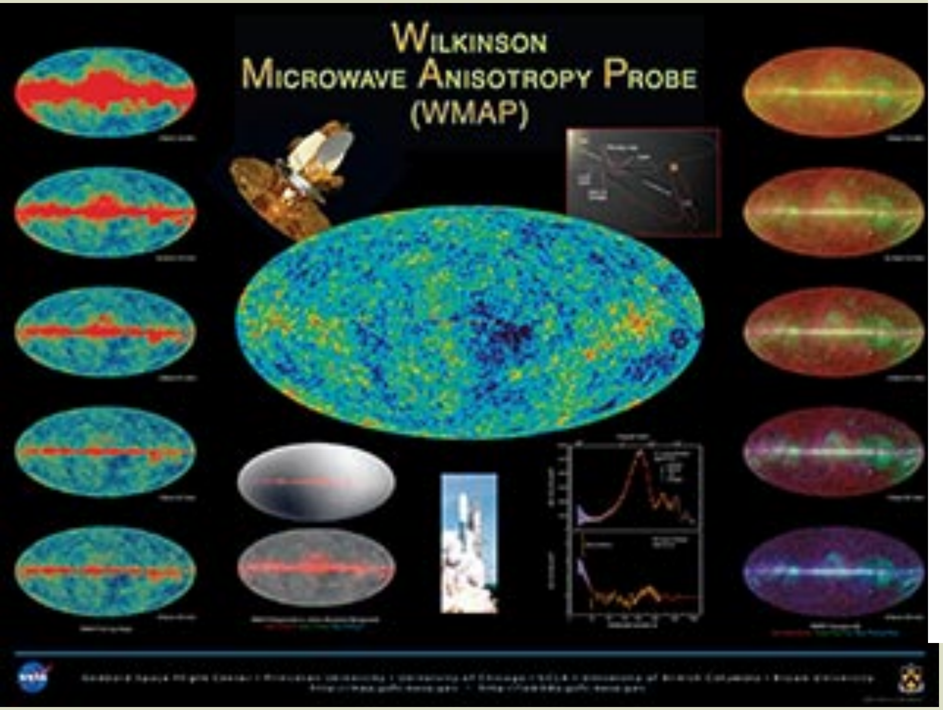

Local Experiments as of 1999
(calibration error not included)
Angular Size (deg)
100
10
1
.2
TOCO
SASKATOON
QMAP
FIRS
COBE DMR
$\delta T_\ell = (\ell(\ell+1)C_\ell/2\pi)^{1/2}$ (μK)
0
20
40
60
80
100
1
10
100
1000
ℓ_{eff}


High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
44
42
40
38
36
34
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)
1.0
0.5
0.0
-0.5
-1.0
0.01
0.10
1.00
z

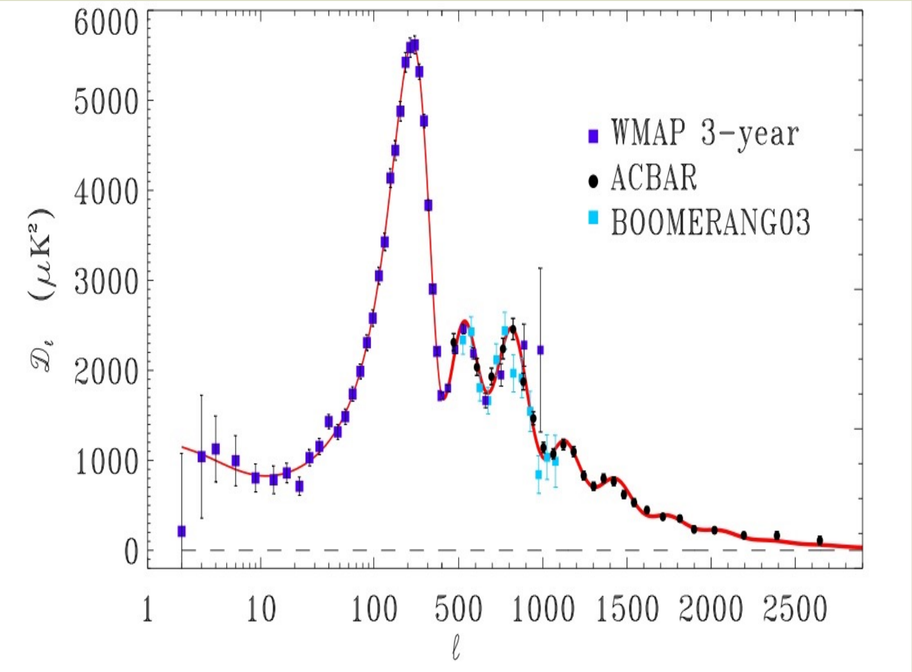



MAXIMA
Boomerang
COBE
0
200
400
600
800

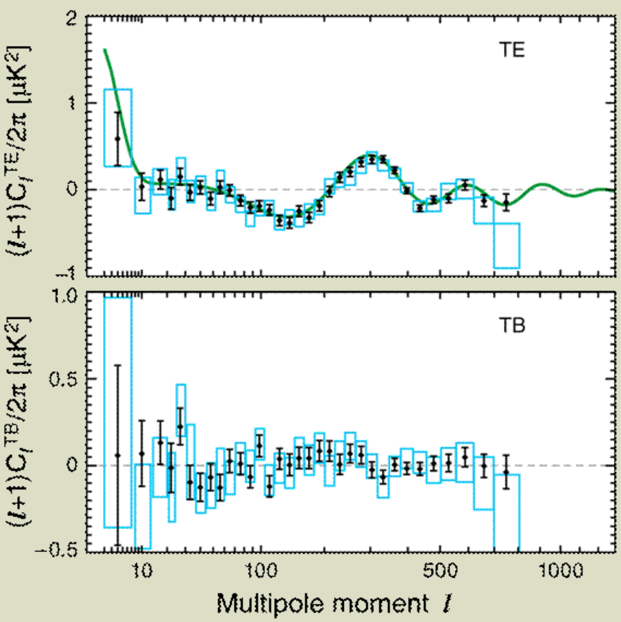




WILKINSON
MICROWAVE ANISOTROPY PROBE
(WMAP)

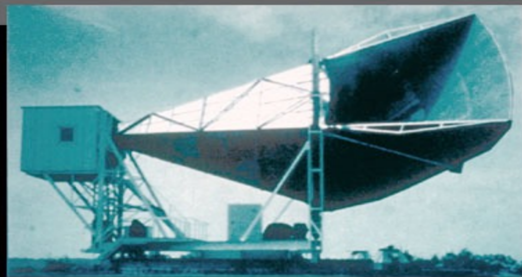


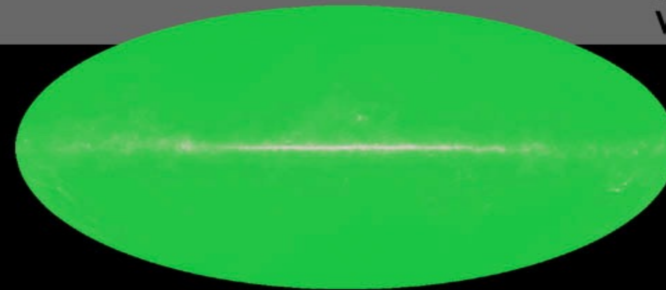
WMAP 3-year
ACBAR
BOOMERANG03
$\mathcal{D}_\ell$ (μK^2)
ℓ



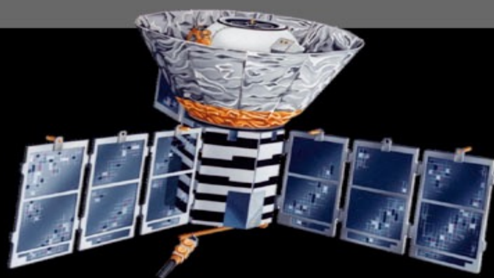
TE
TB
$(l+1)C_l^{TE}/2\pi$ [μK^2]
$(l+1)C_l^{TB}/2\pi$ [μK^2]
Multipole moment l

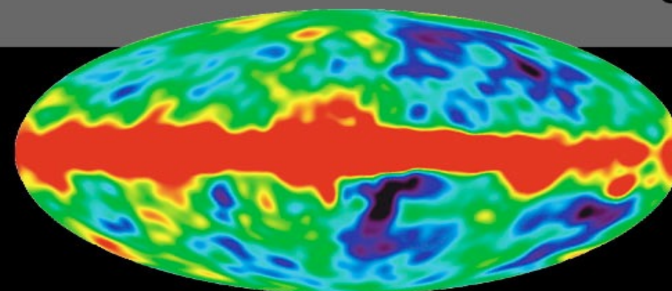
1965 Penzias and Wilson



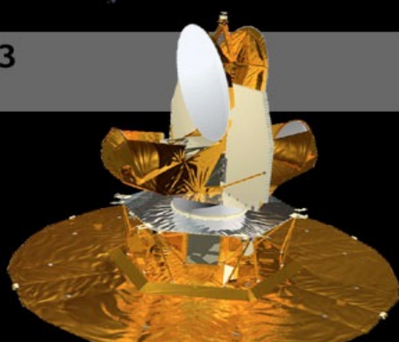


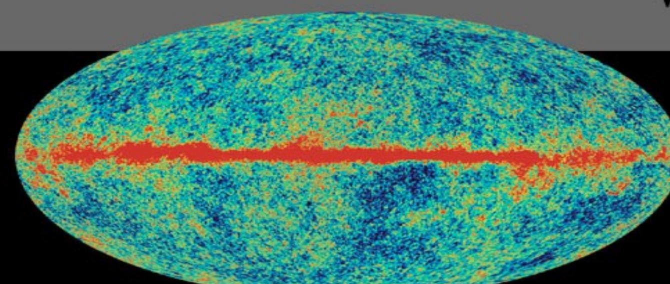
1992 COBE



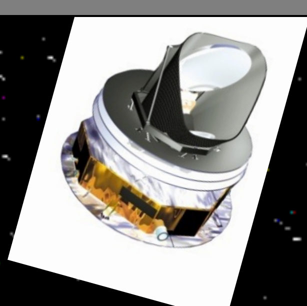


2003 WMAP



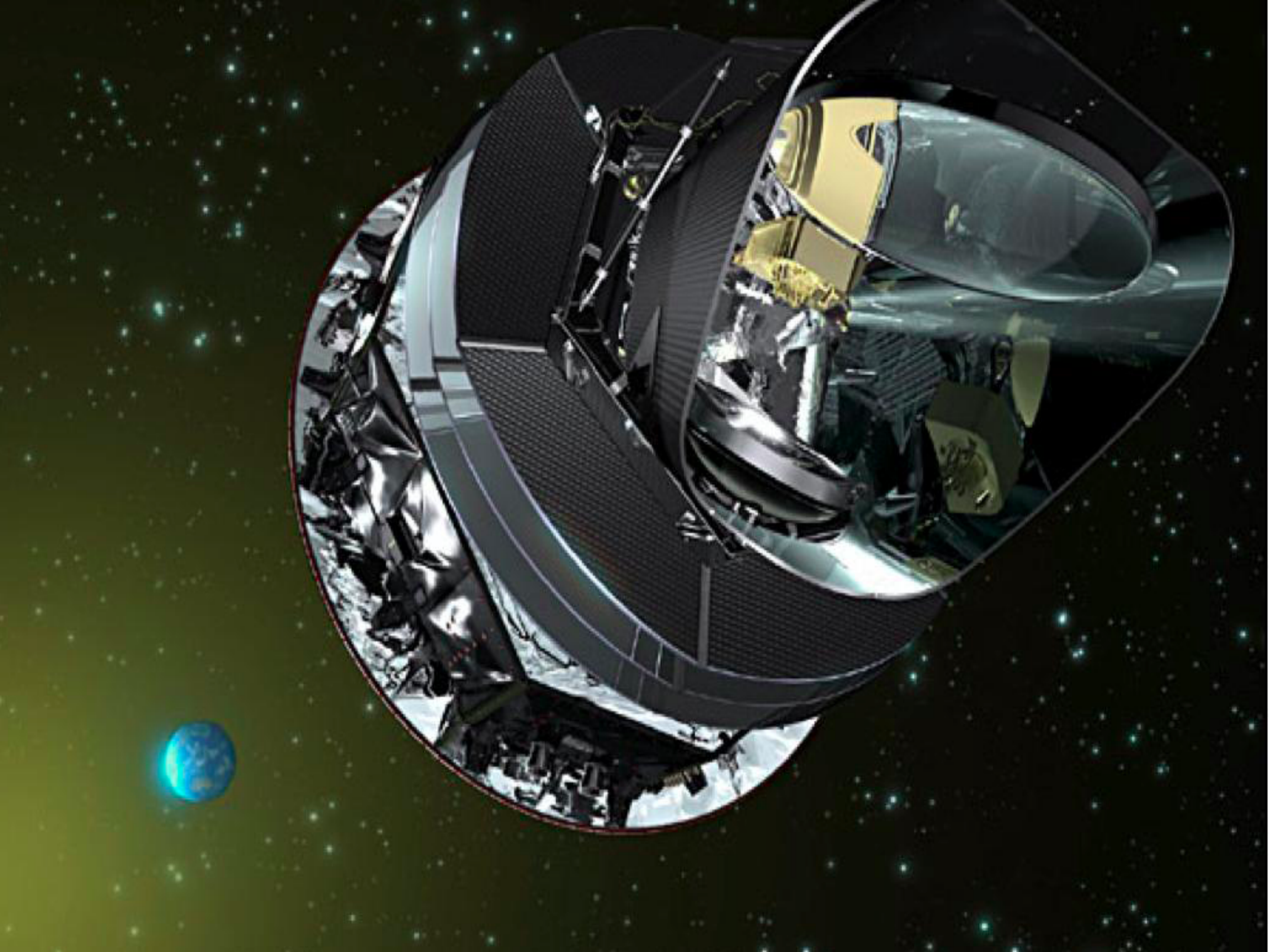


2009 Planck



???

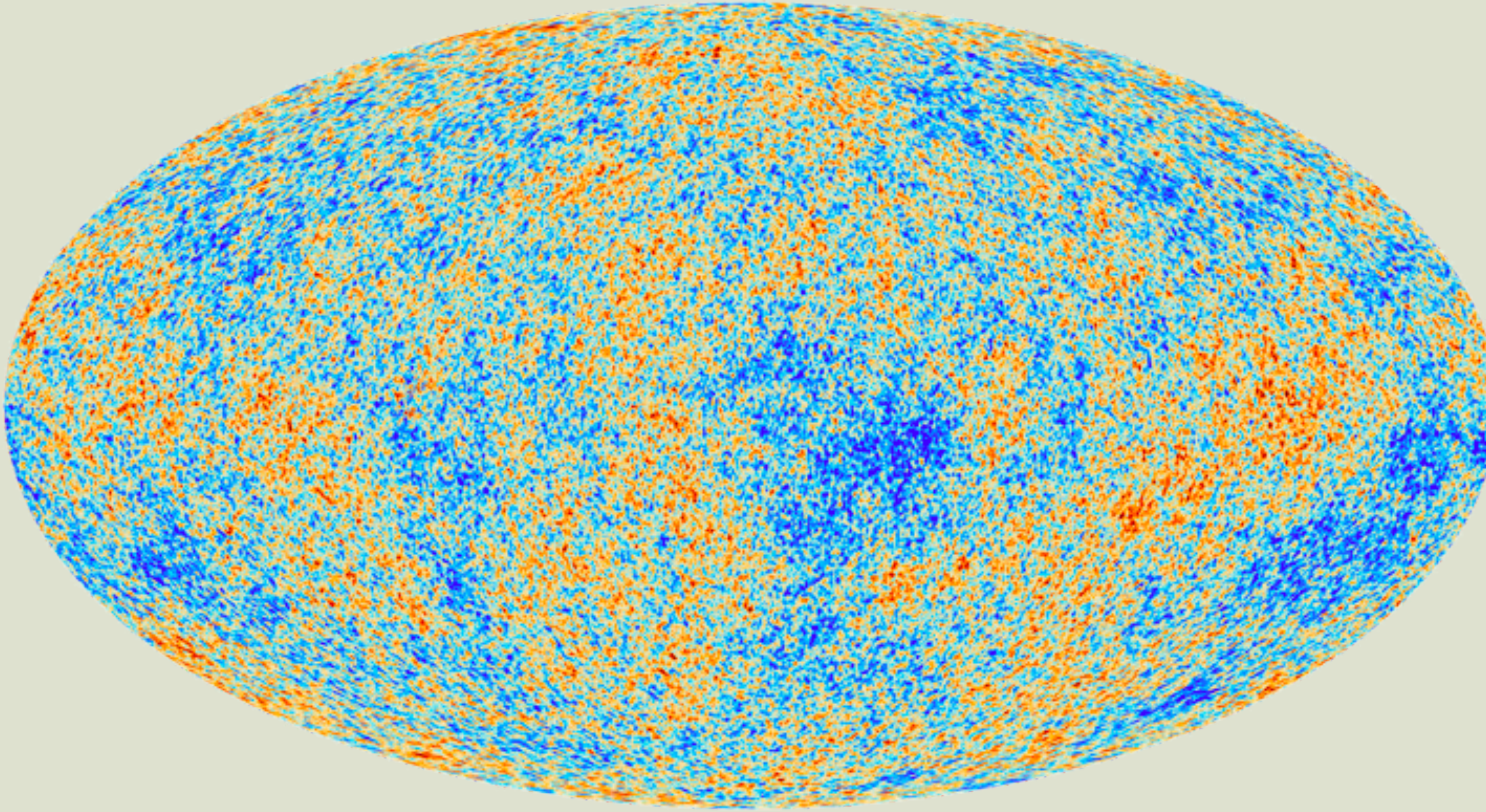
End 2012

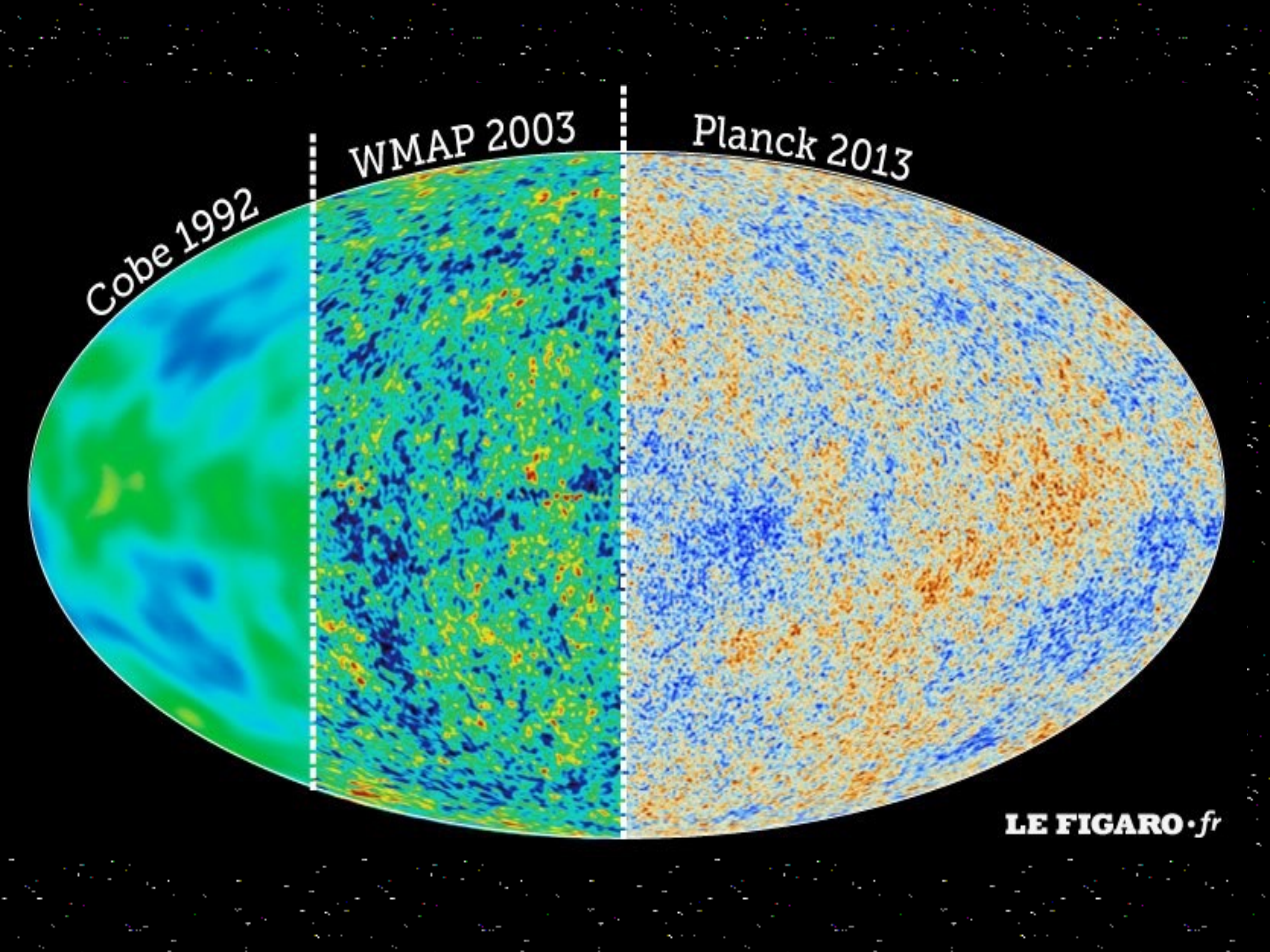


the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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

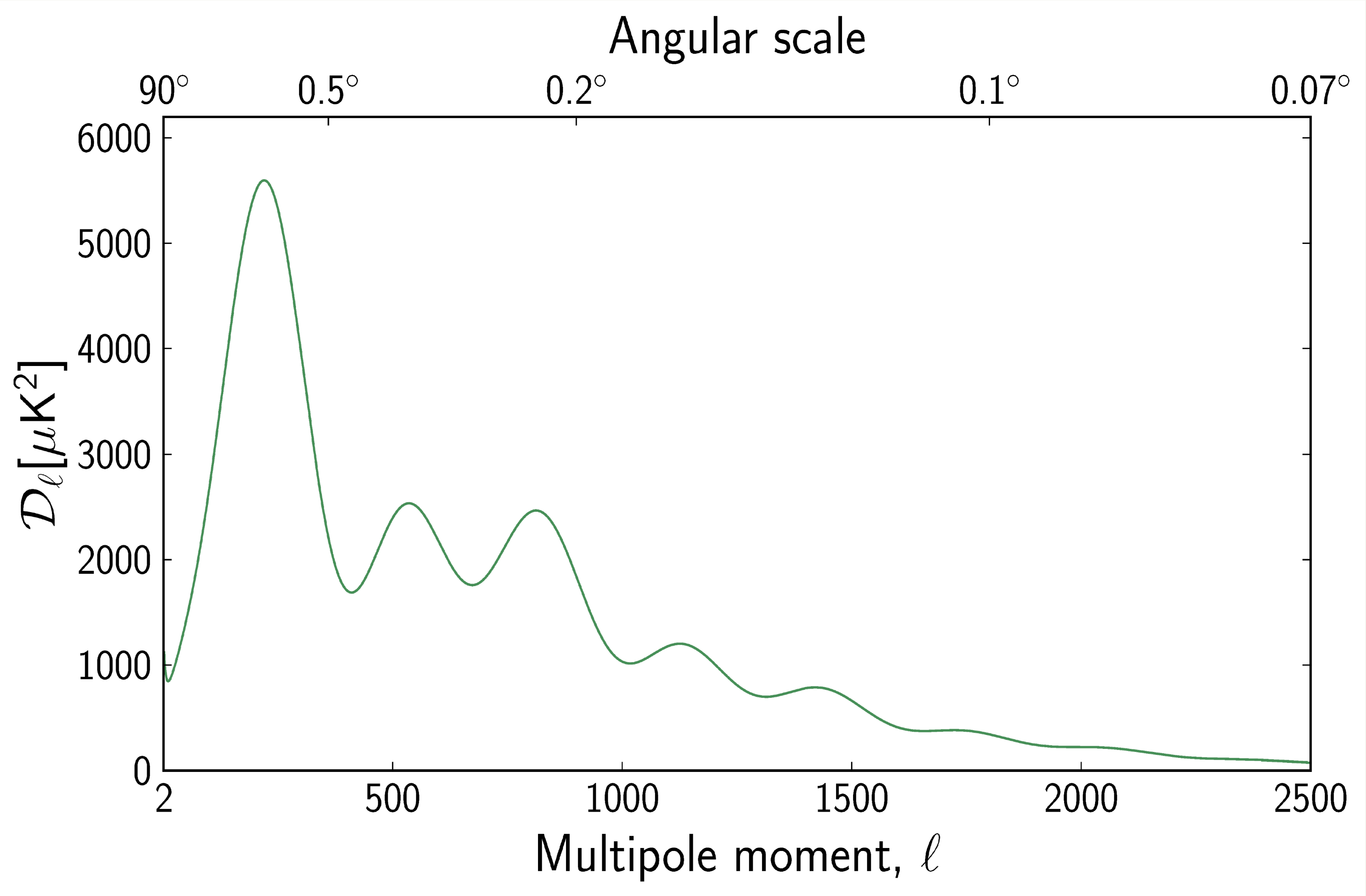
Perturbations are :

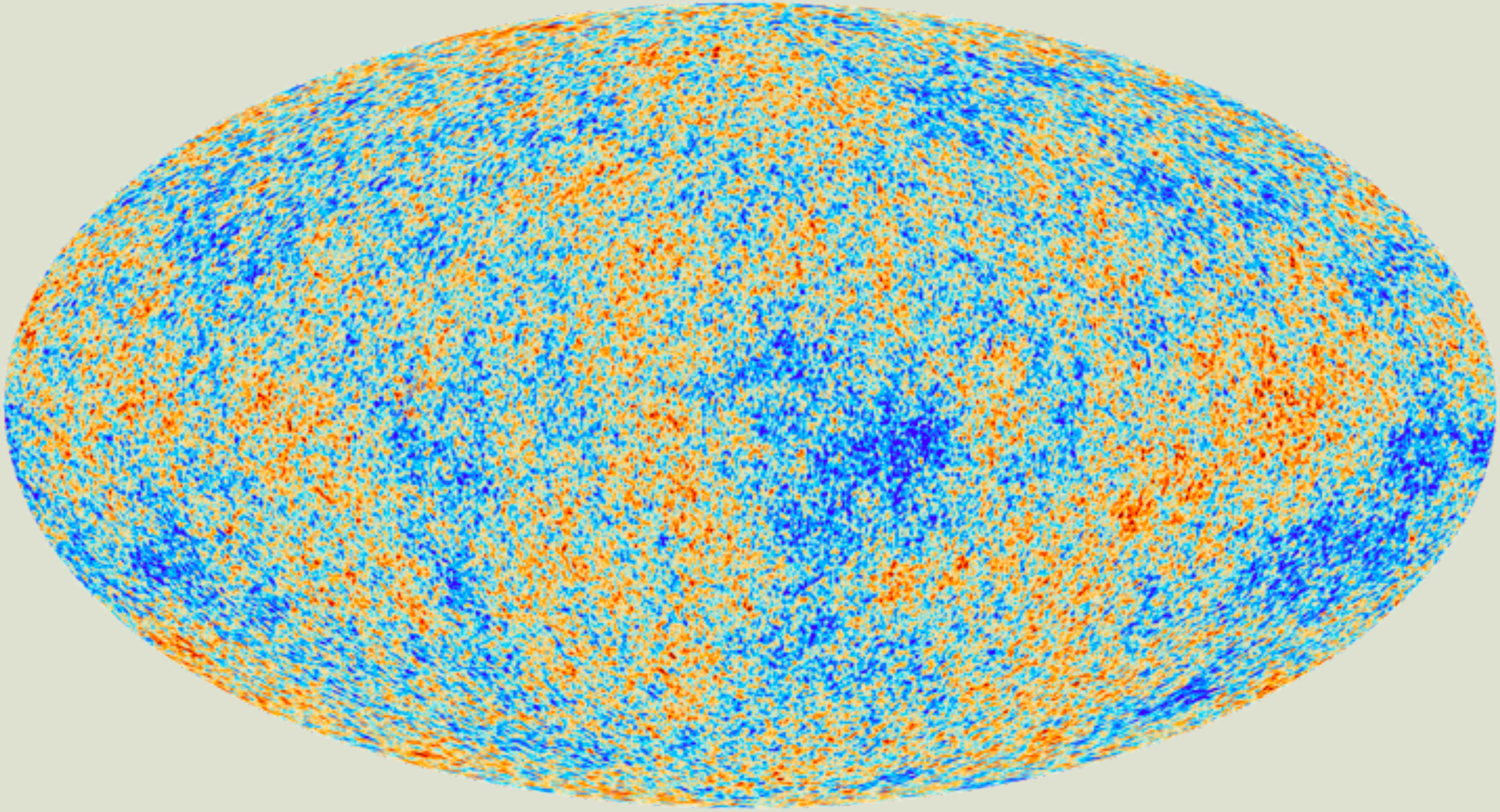
2) adiabatic (MC, 81)

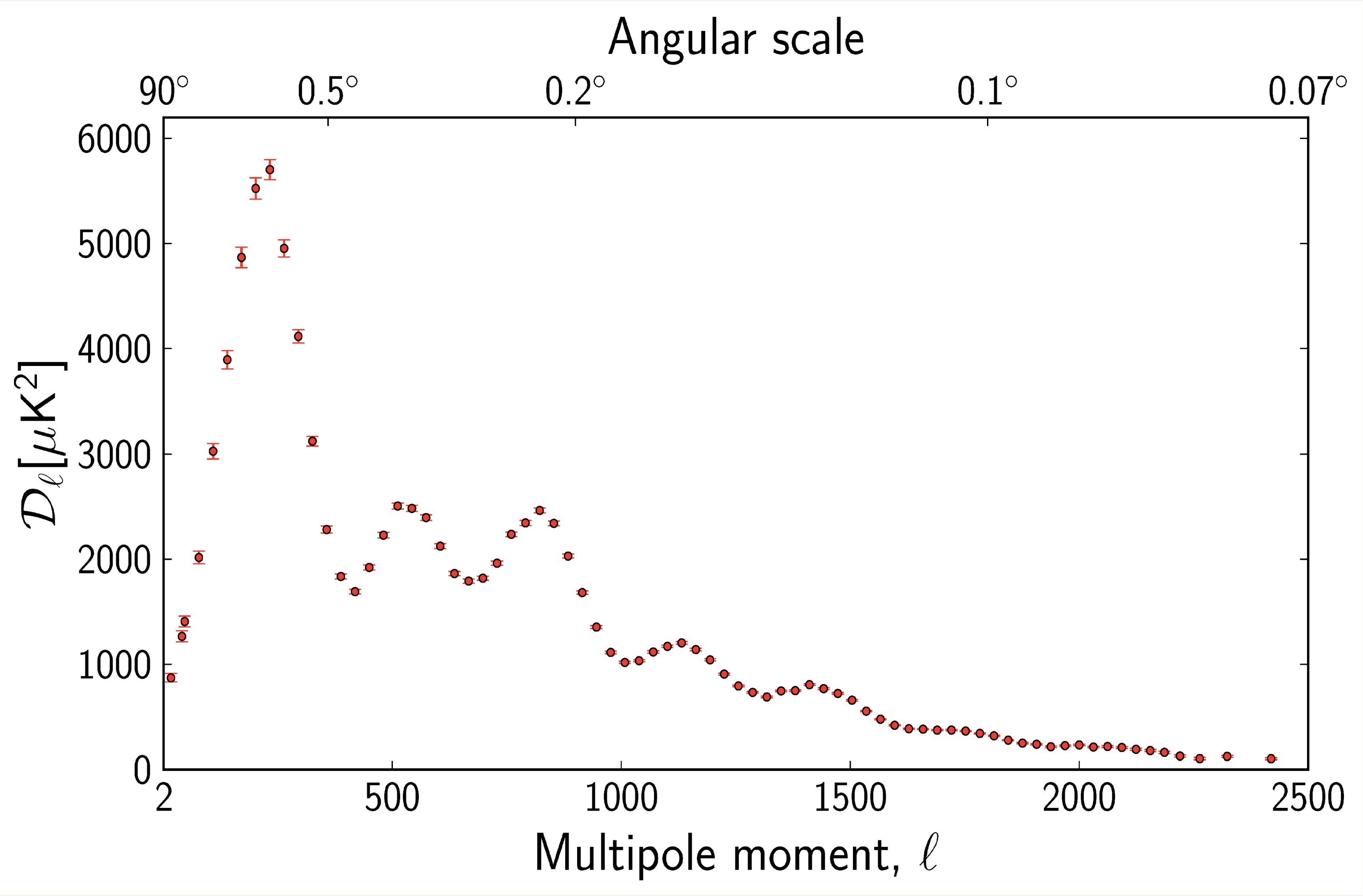
3) gaussian: $\Phi = \Phi_g + f_{NL}\Phi_g^2$, where $f_{NL} = O(1)$ (MC, 81)

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

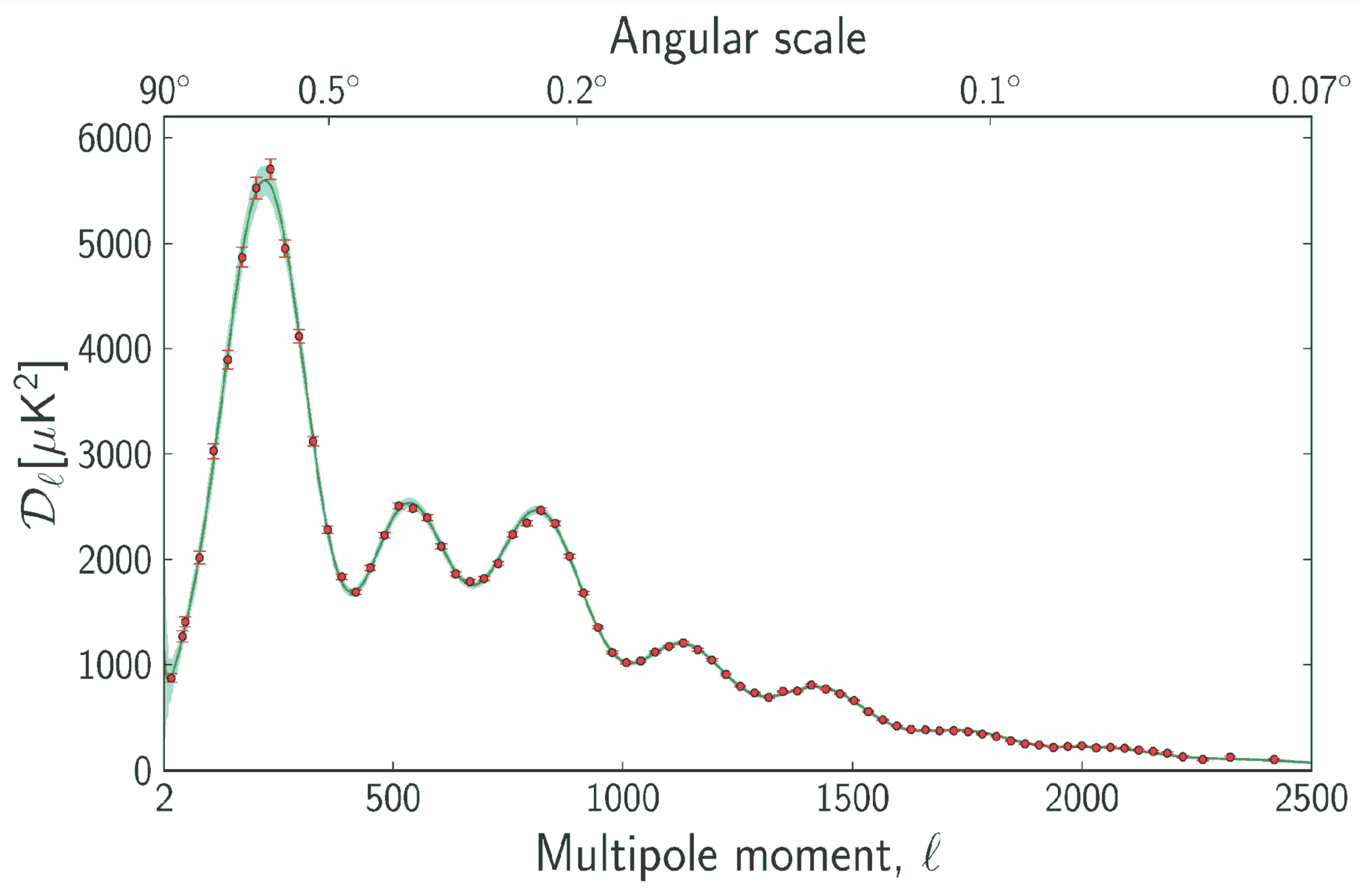
with $\Omega_{tot} = 1$ (prediction) and H_0, $\Omega_\Lambda, \Omega_{bar}$ from supernova, deuterium et.cet. we get



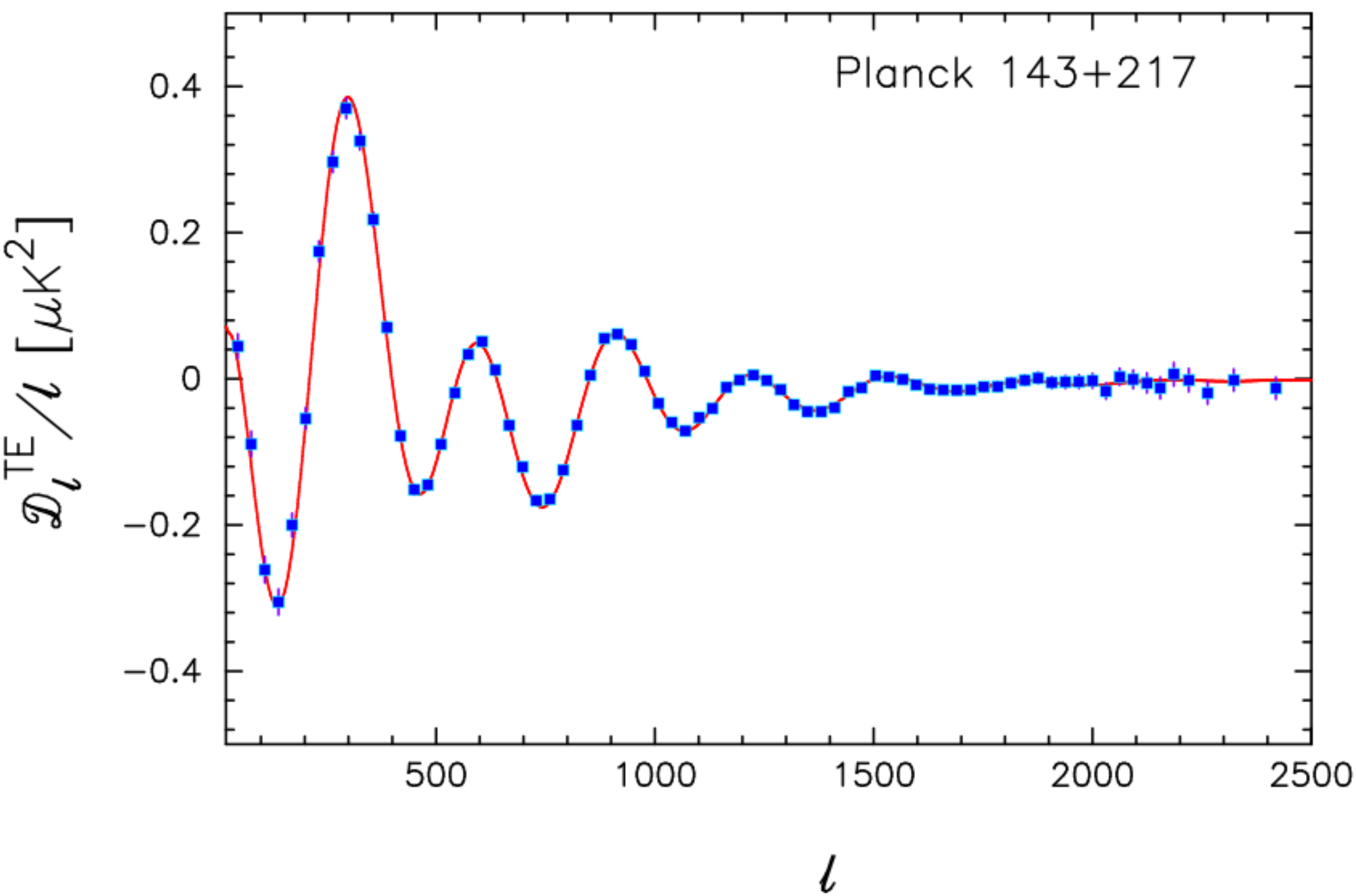




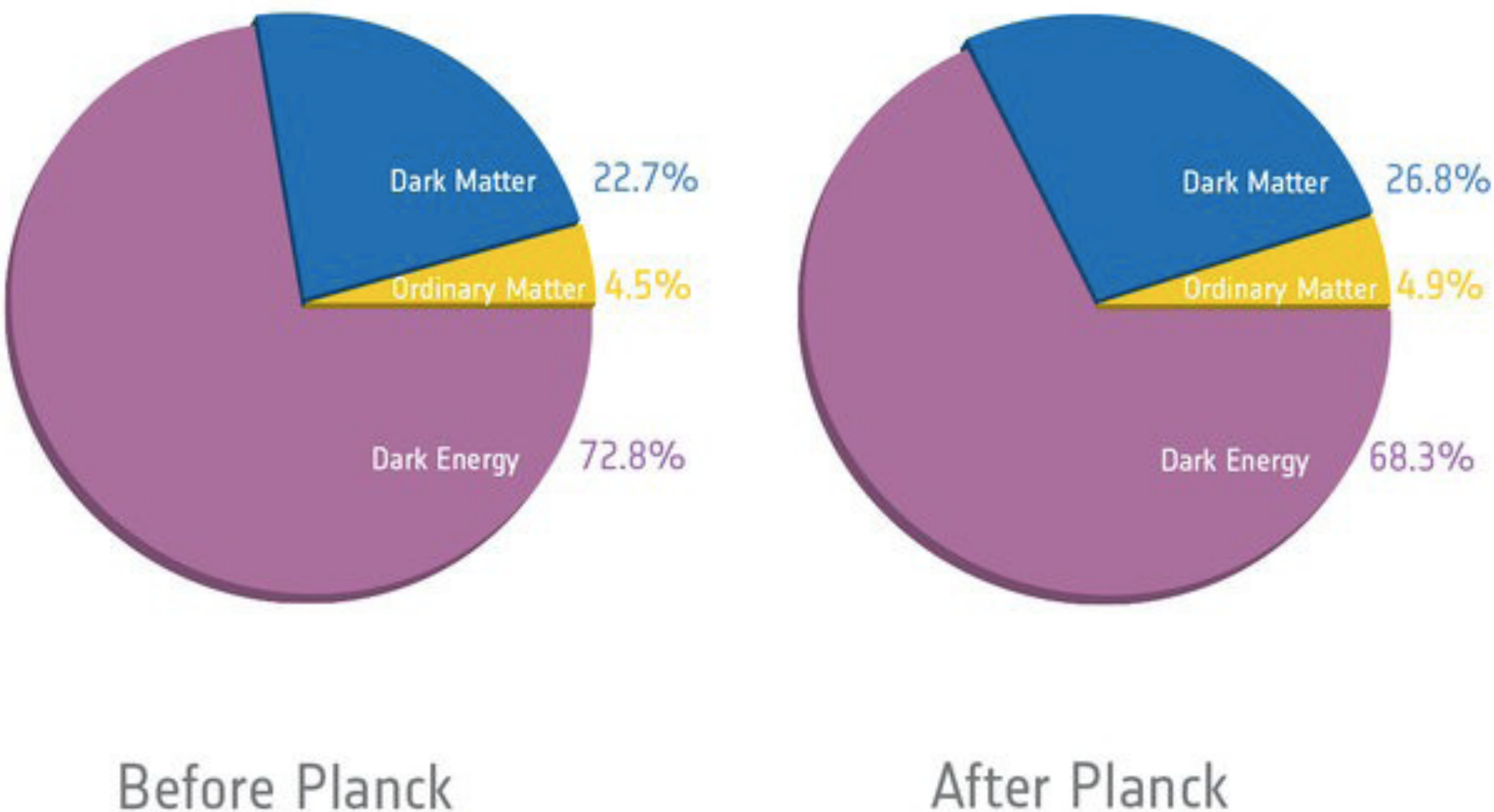
Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ



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



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


Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Before Planck
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
After Planck

- $\Omega_{tot} = 1 \pm 0.0066$
- 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