

KOSMOLOGIA

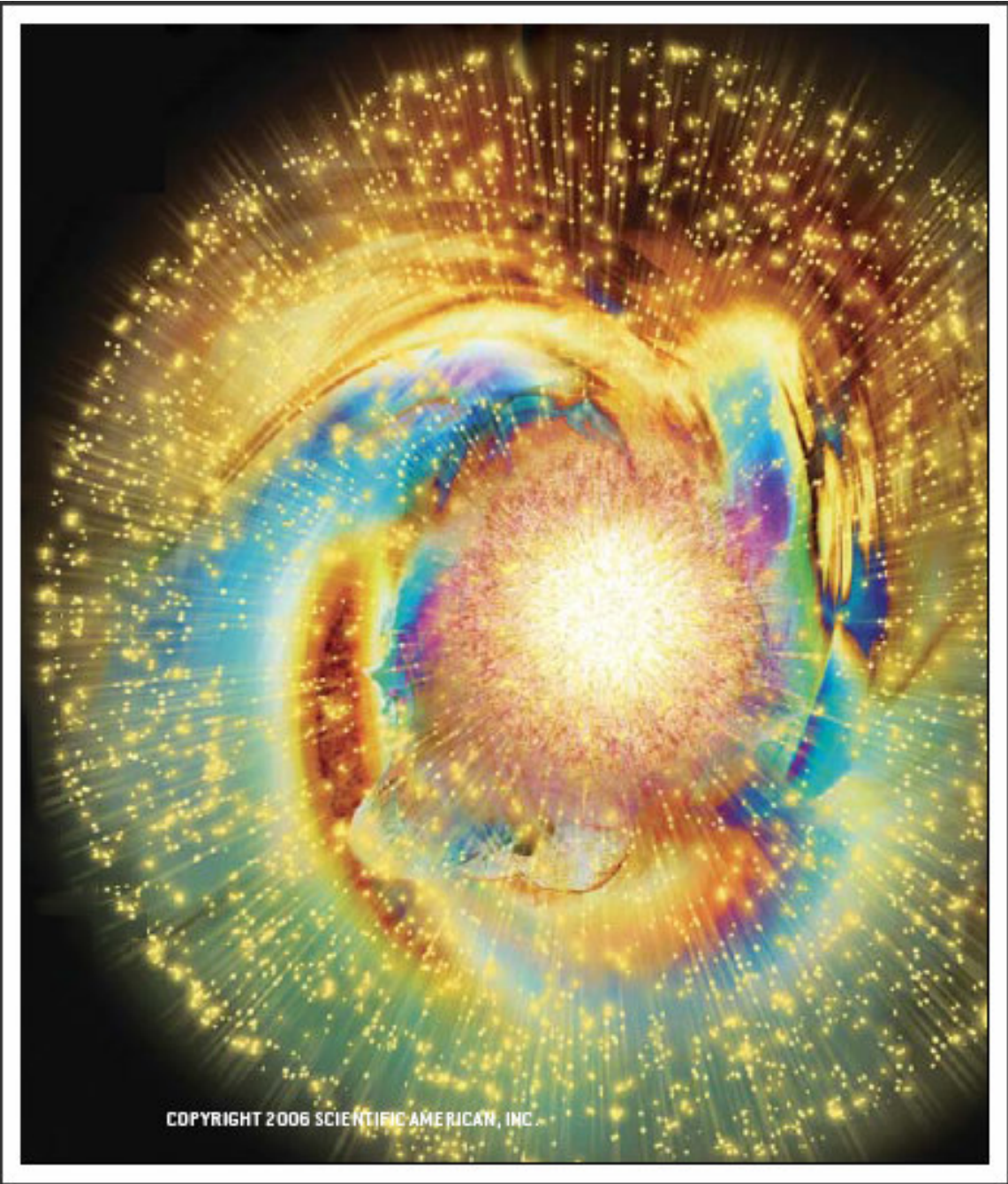
REMIGIUSZ DURKA

Cosmology is the study
of the origin, evolution and future
of our Universe

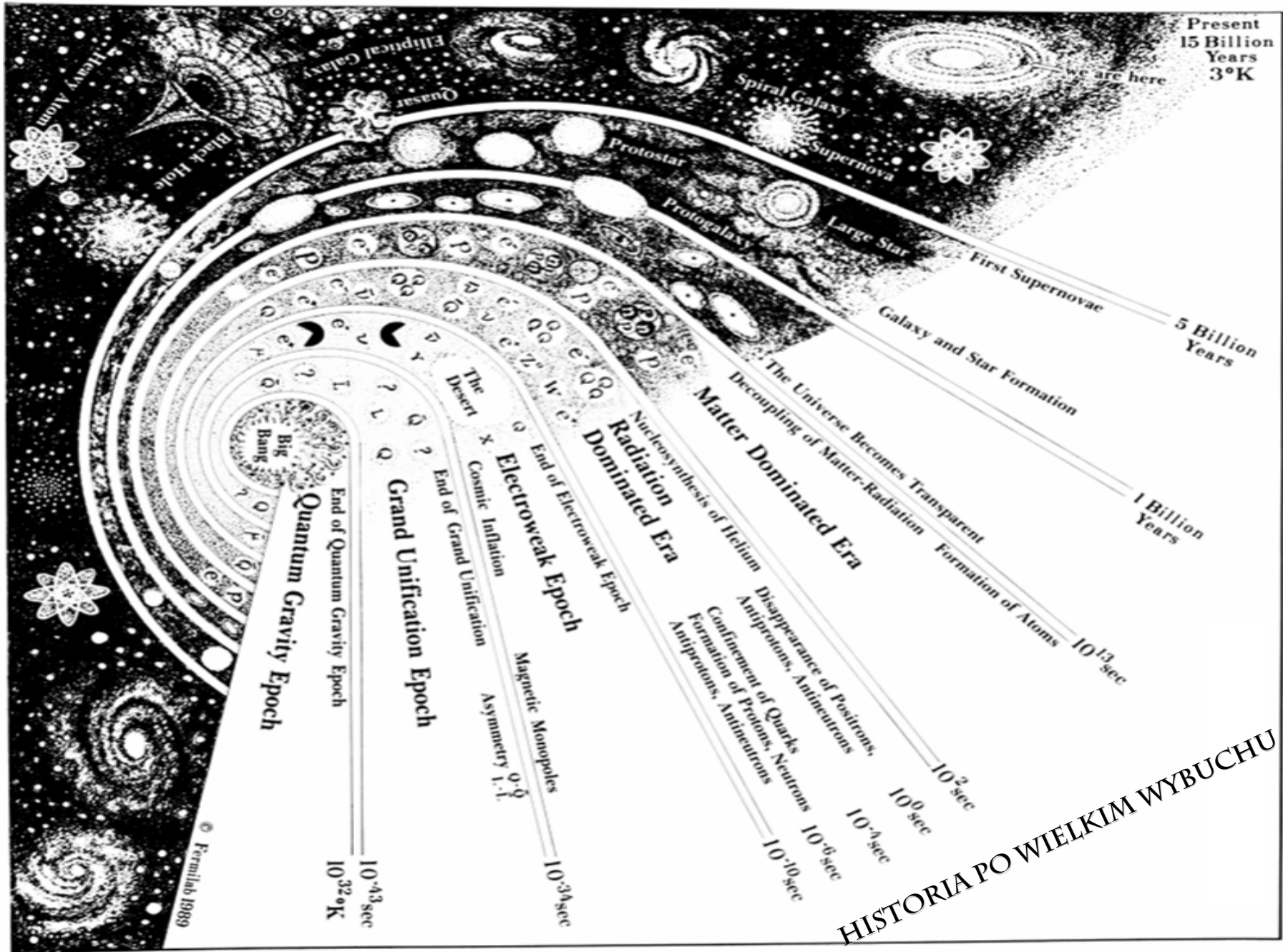
COSMOLOGY MARCHES ON



BIG BANG



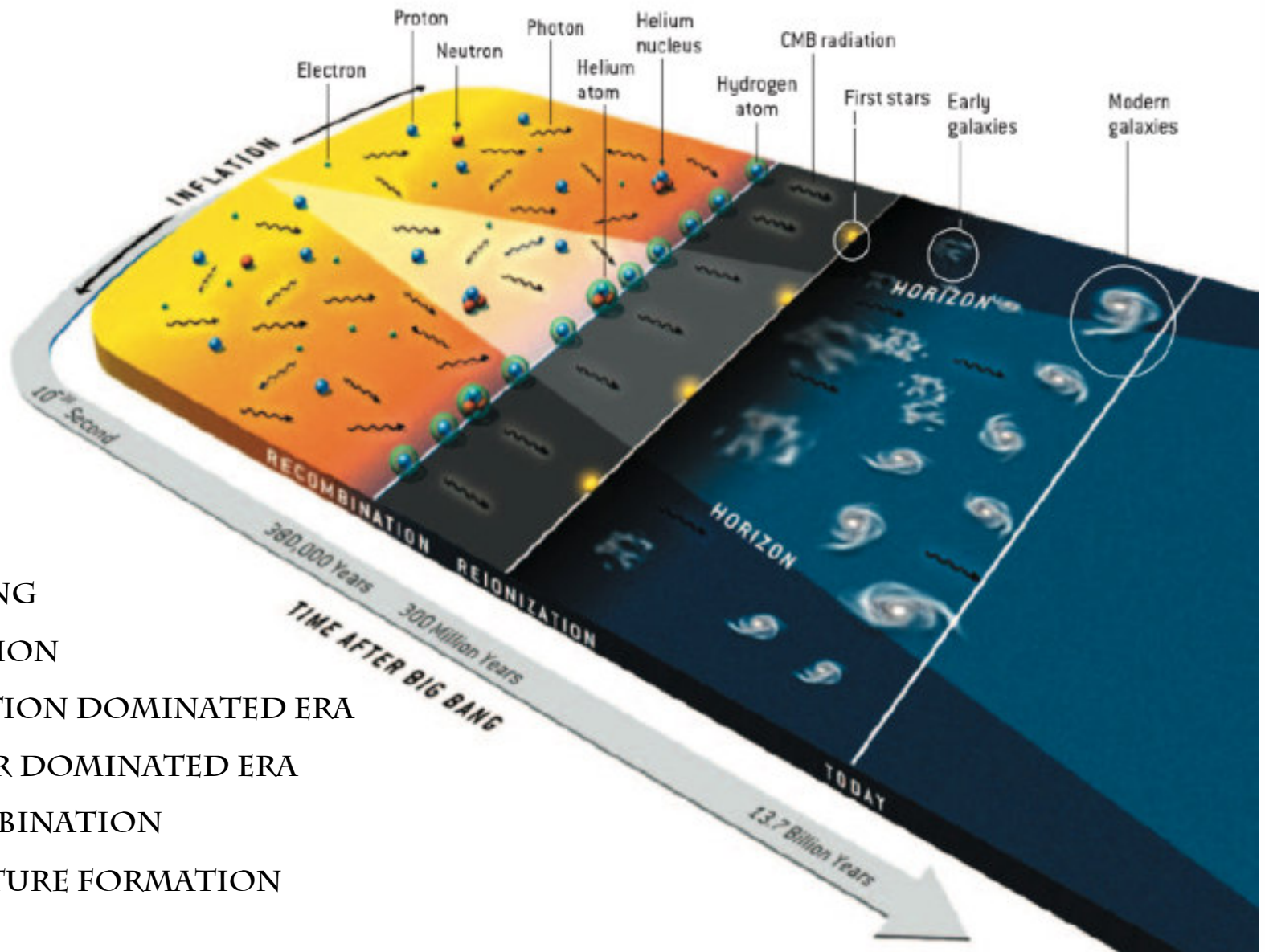
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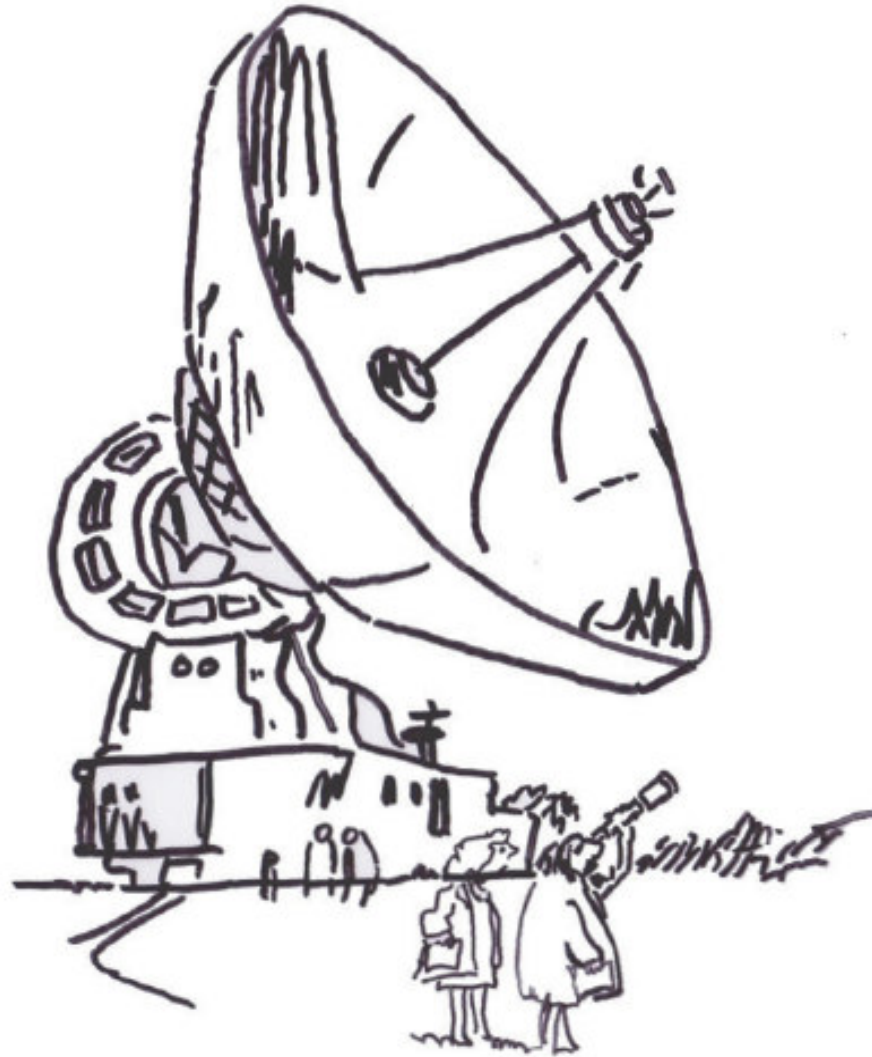
HISTORIA PO WIELKIM WYBUCHU

EWOLUCJA WSZECHŚWIATA



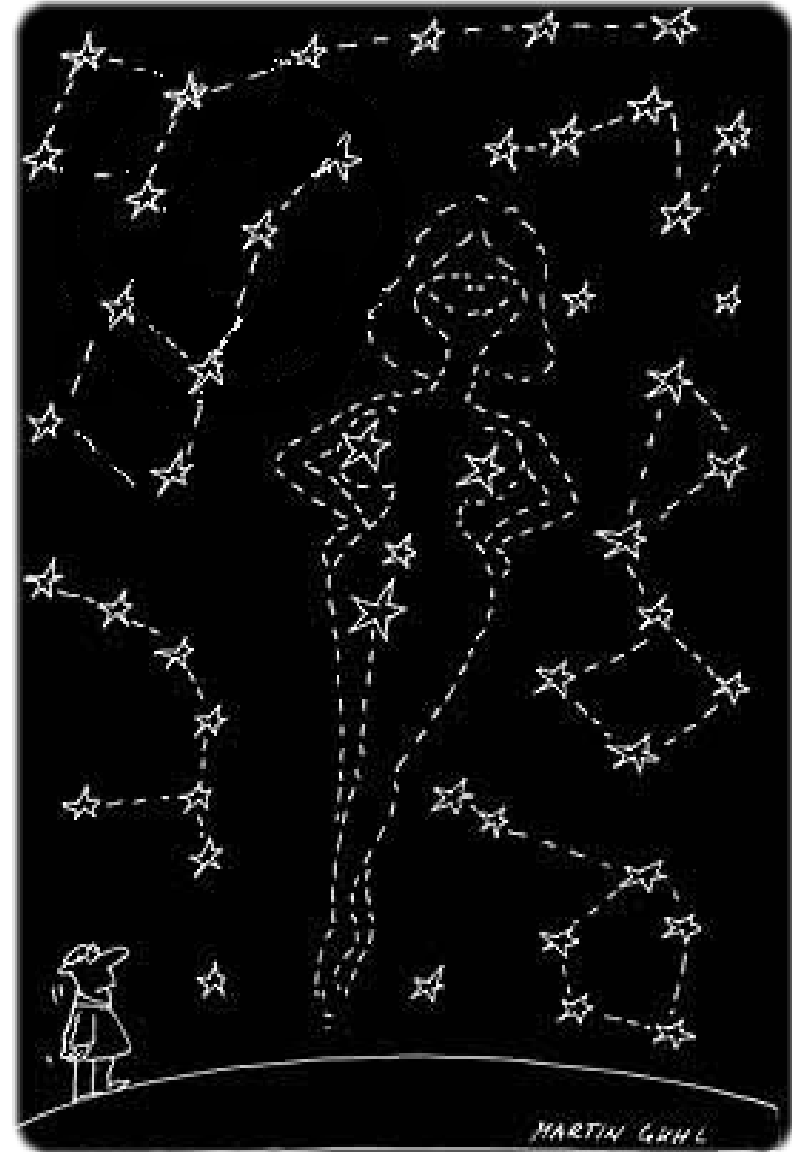
- § BIG BANG
- § INFLATION
- § RADIATION DOMINATED ERA
- § MATTER DOMINATED ERA
- § RECOMBINATION
- § STRUCTURE FORMATION

RZUĆMY OKIEM NA NIEBO



"JUST CHECKING."

CONSTELATIONS

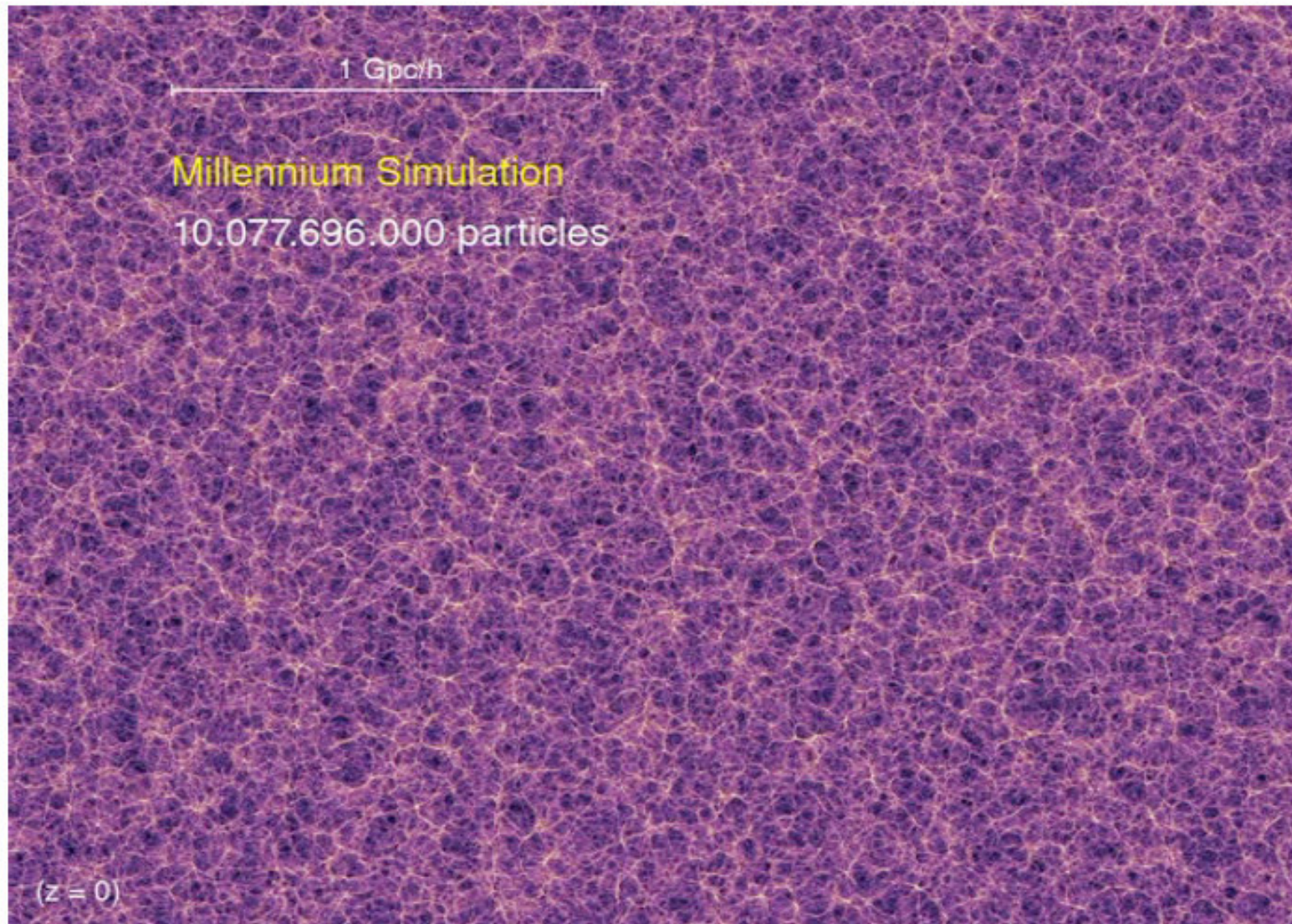


Wszystkie miejsca wyglądają niemal tak samo, gdziekolwiek jesteśmy

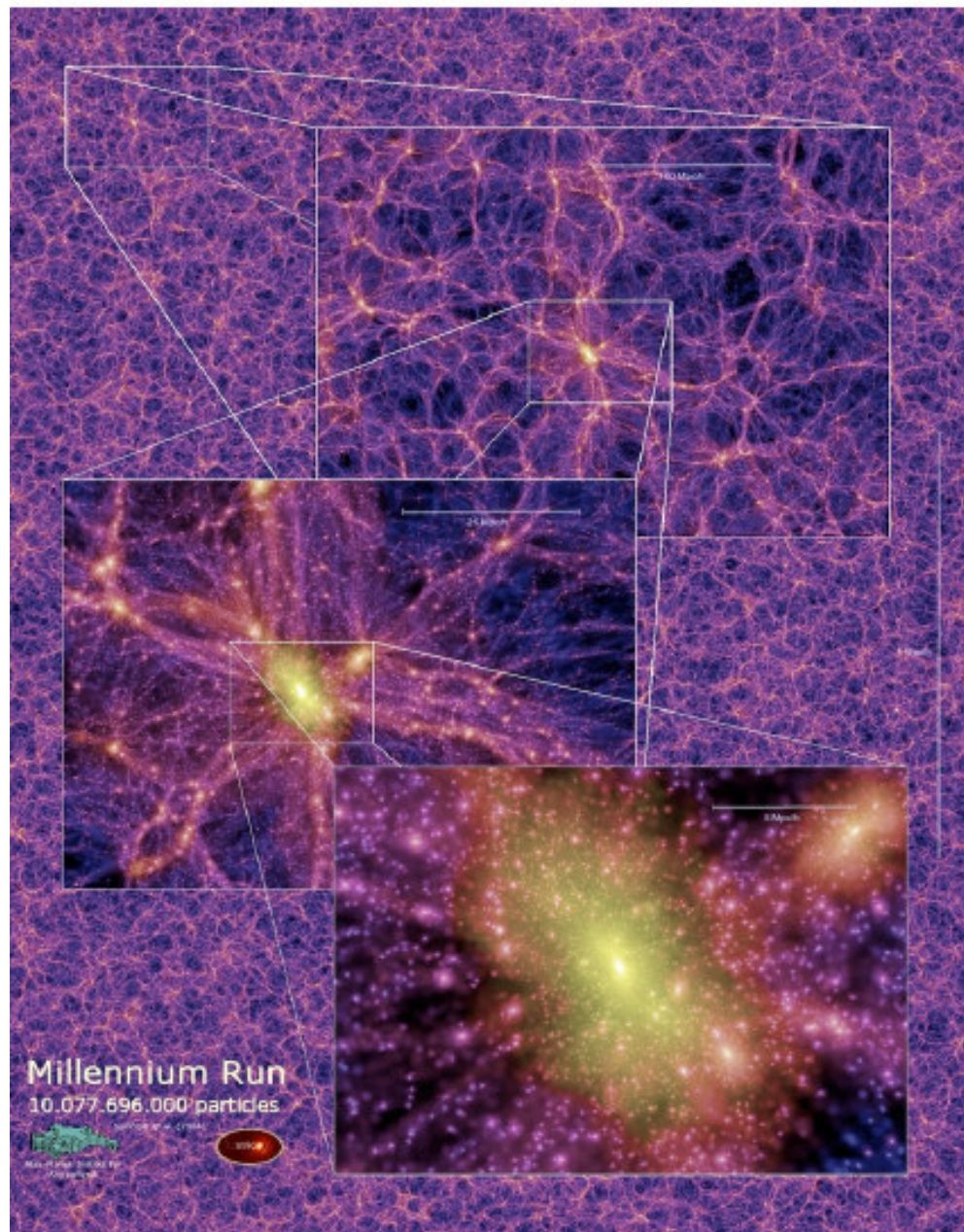


Wszechświat w dużej skali

2005: $N=1024^3 \approx 10^9$



2005: $N=1024^3 \approx 10^9$



June 2008:

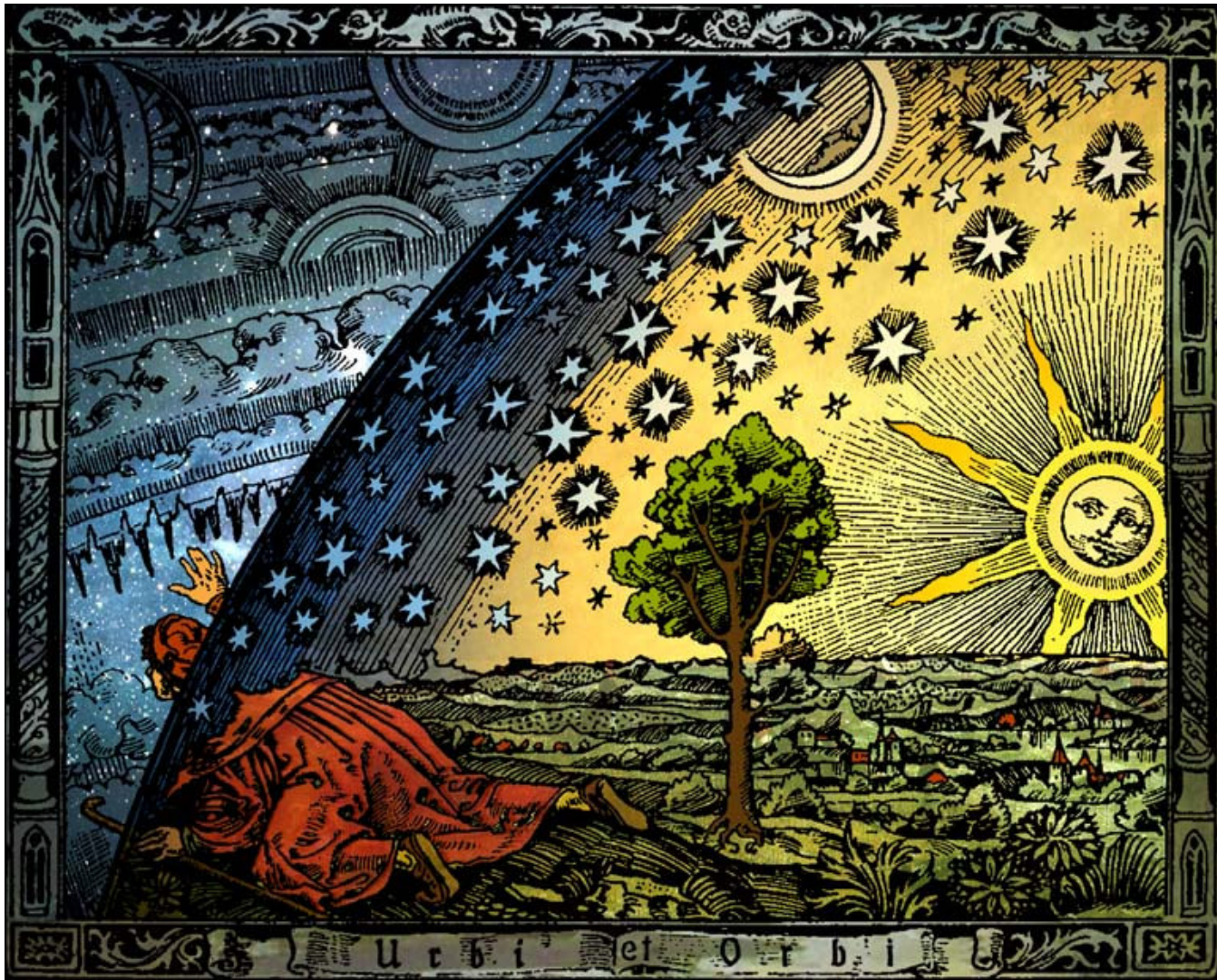


Kosmologiczna Zasada – Wszechświat (biorąc pod uwagę średnią) musi wyglądać tak samo dla każdego, nie ważne gdzie on, ona, ono się znajduje.

Innymi słowy...

Wszechświat jest:

- **Izotropowy**-(to znaczy bez wyróżnionego kierunku)
- **Homogeniczny**-(to znaczy jednorodny, gładki)



HISTORIA

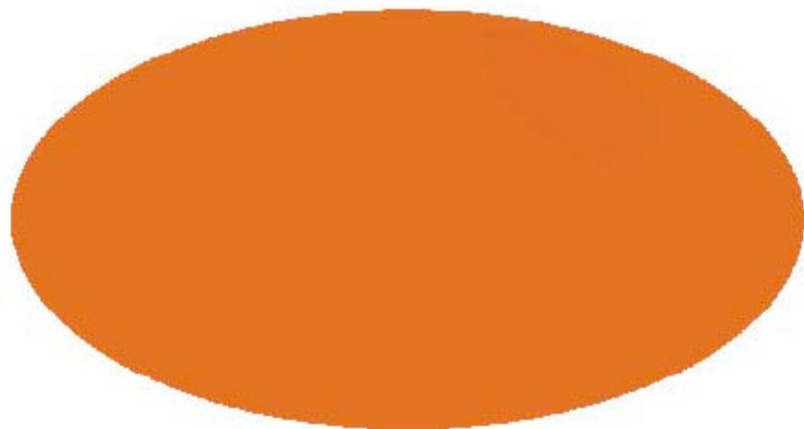
<http://galadriel.ecaetc.ohio-state.edu/tc/sm/>



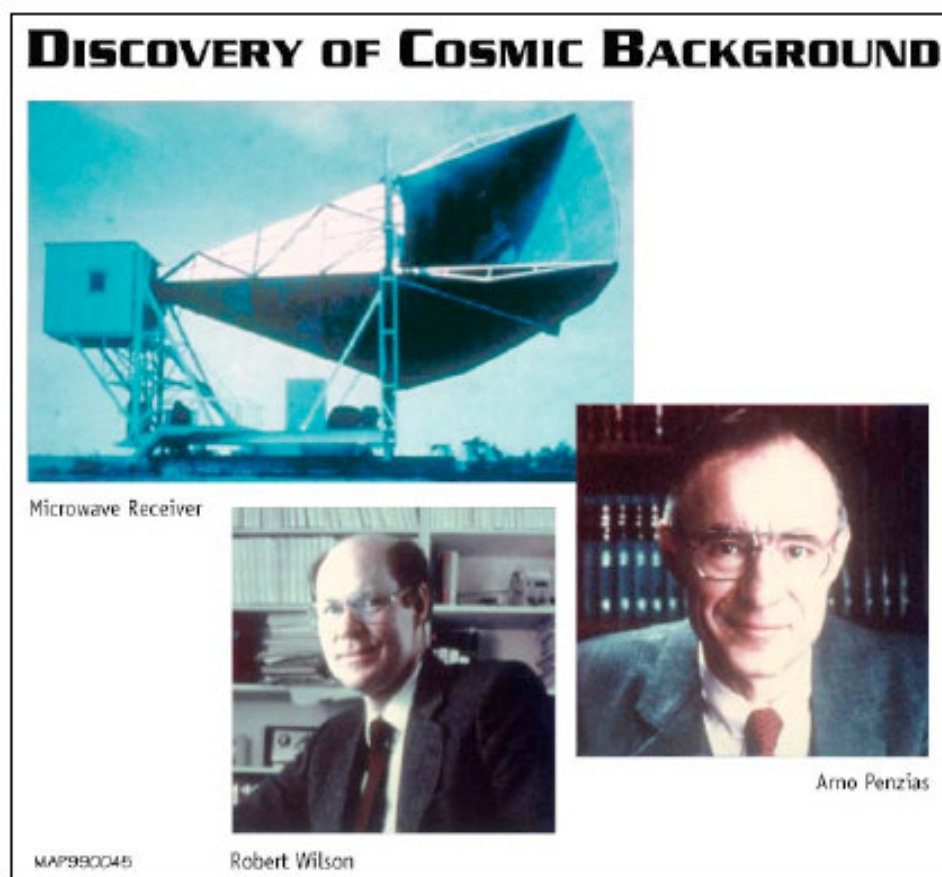
WHERE WE GET THE
COSMIC MICROWAVE BACKGROUND

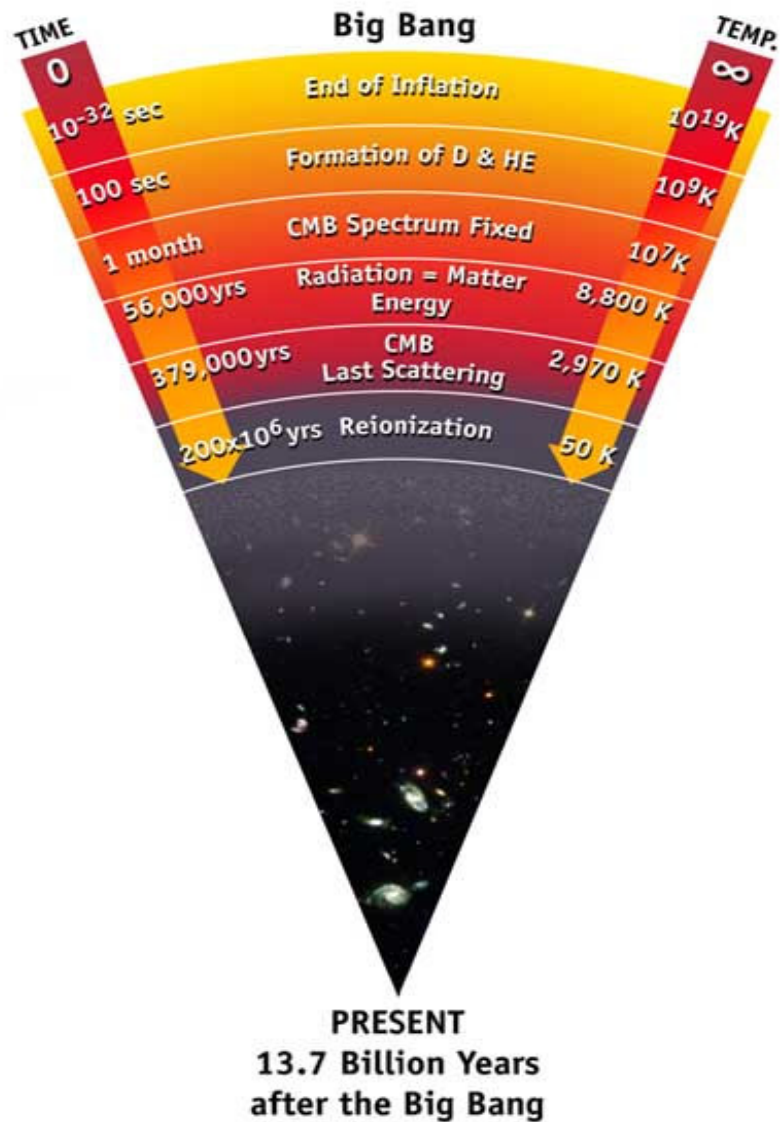
COSMIC MICROWAVE BACKGROUND

- **1948** – emisja ciała doskonale czarnego o temperaturze 5 K przewidziana przez George'a Gamowa.
- **1948**- Fred Hoyle, Thomas Gold and Hermann Bondi publikują teorię Stanu Stacjonarnego.
- **1965** - Penzias & Wilson
(Nobel Prize 1978)

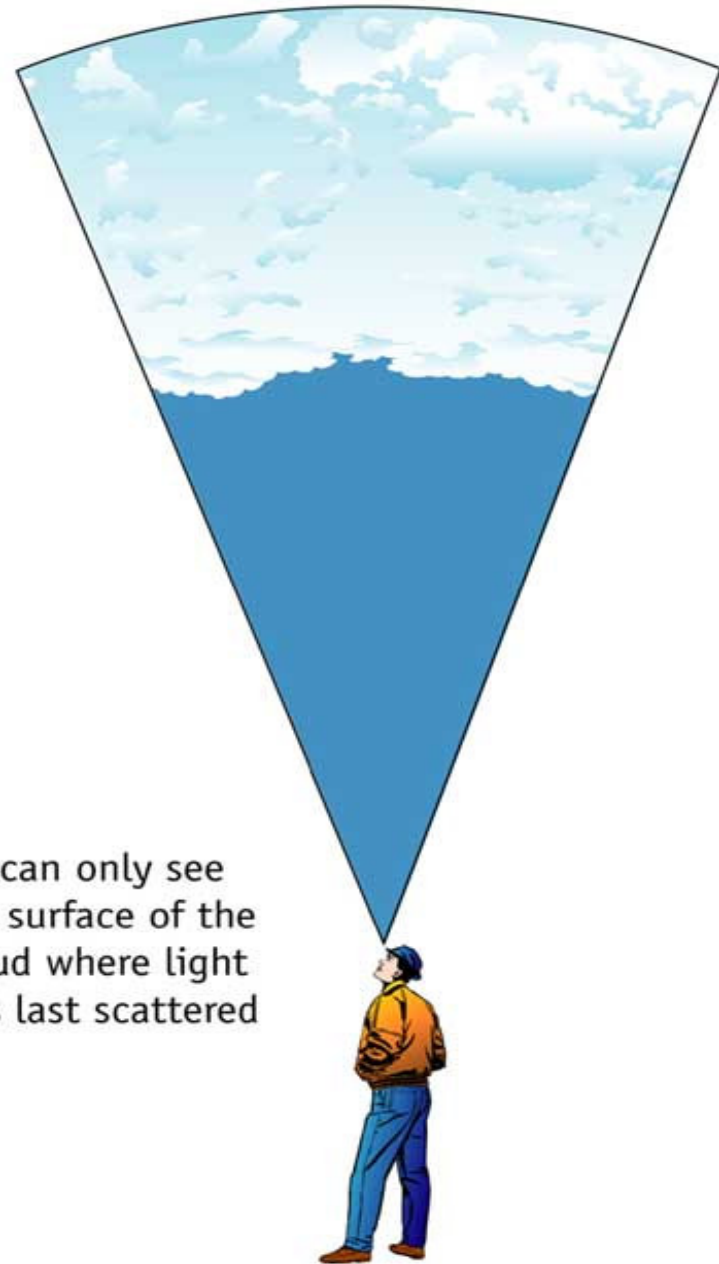


TEMPERATURA 2.7 K



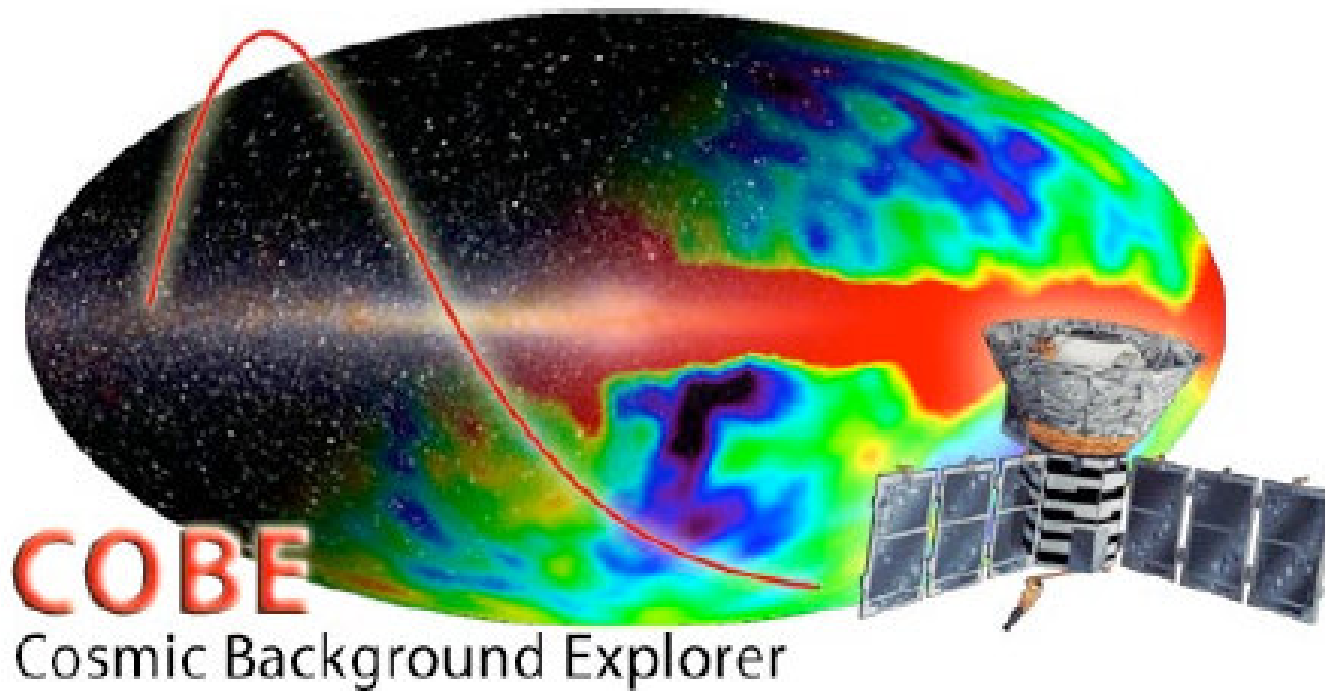


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



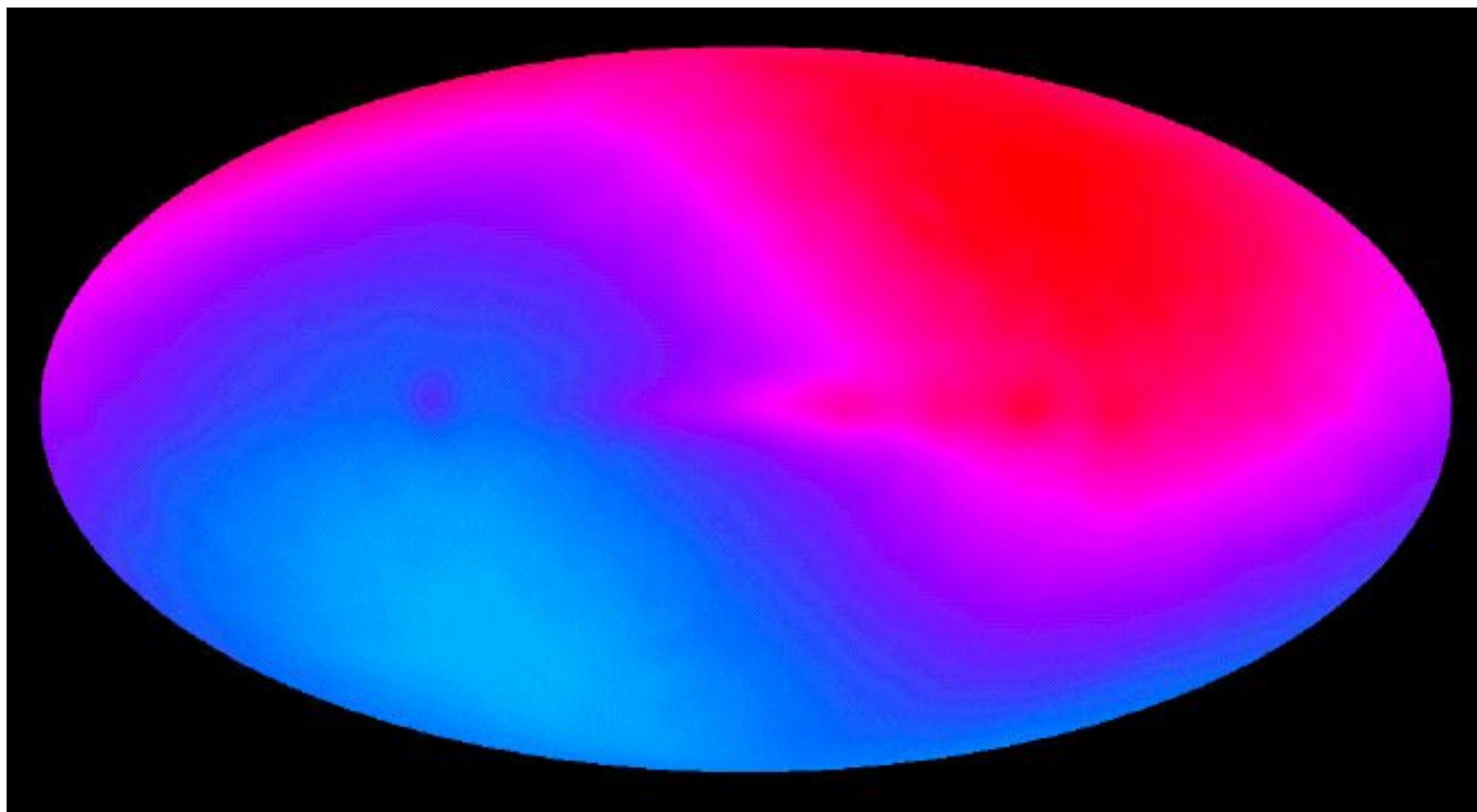
We can only see the surface of the cloud where light was last scattered

COBE (1992)



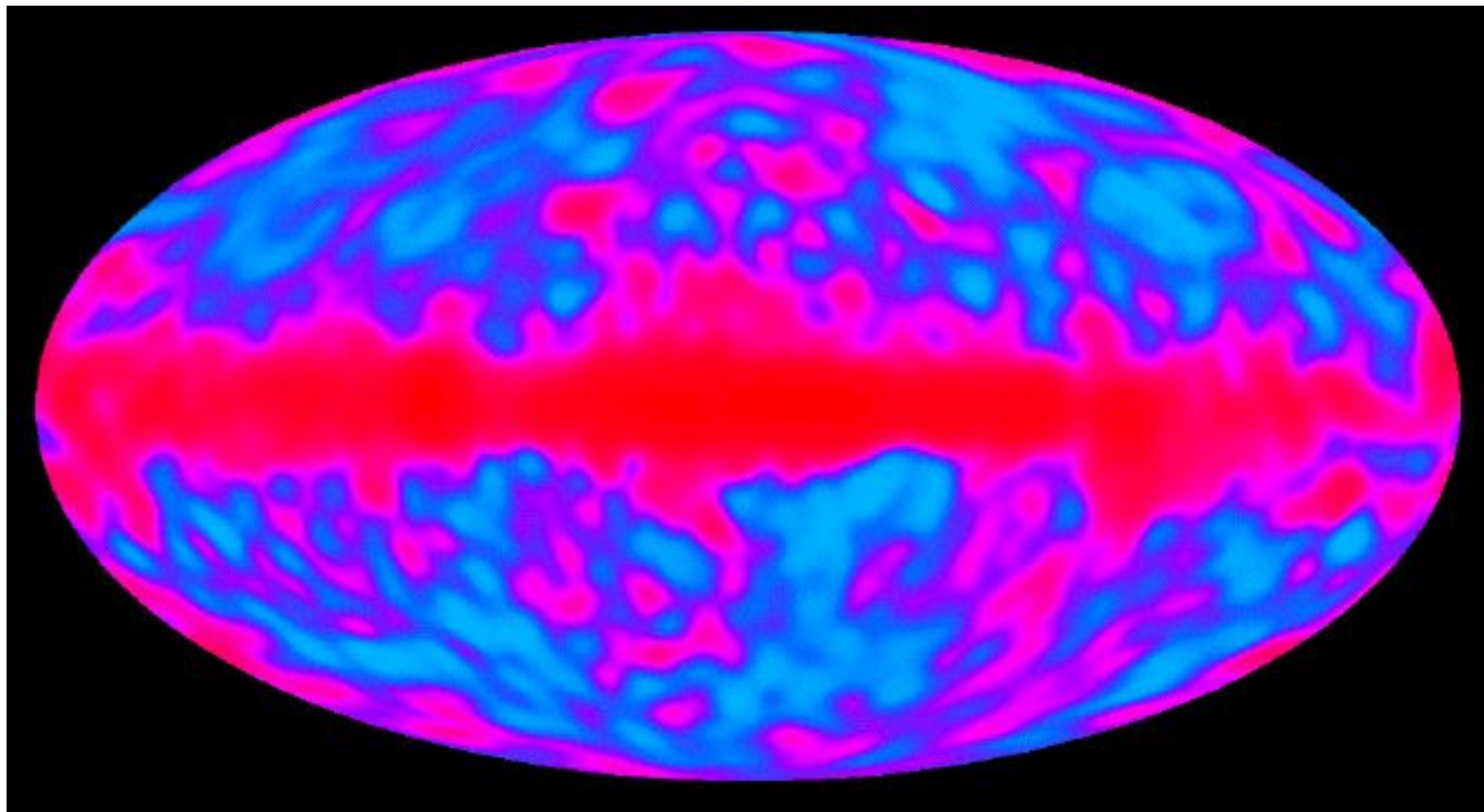
Dwaj dyrektorzy Cobe:
George Smoot i **John Mather** otrzymali Nagrodę
Nobla w fizyce w 2006.

Przez to, że **Ziemia się porusza** w przestrzeni mikrofalowe tło powinno być przesunięte ku czerwieni w jednej części nieba i ku fioletowi w innej.

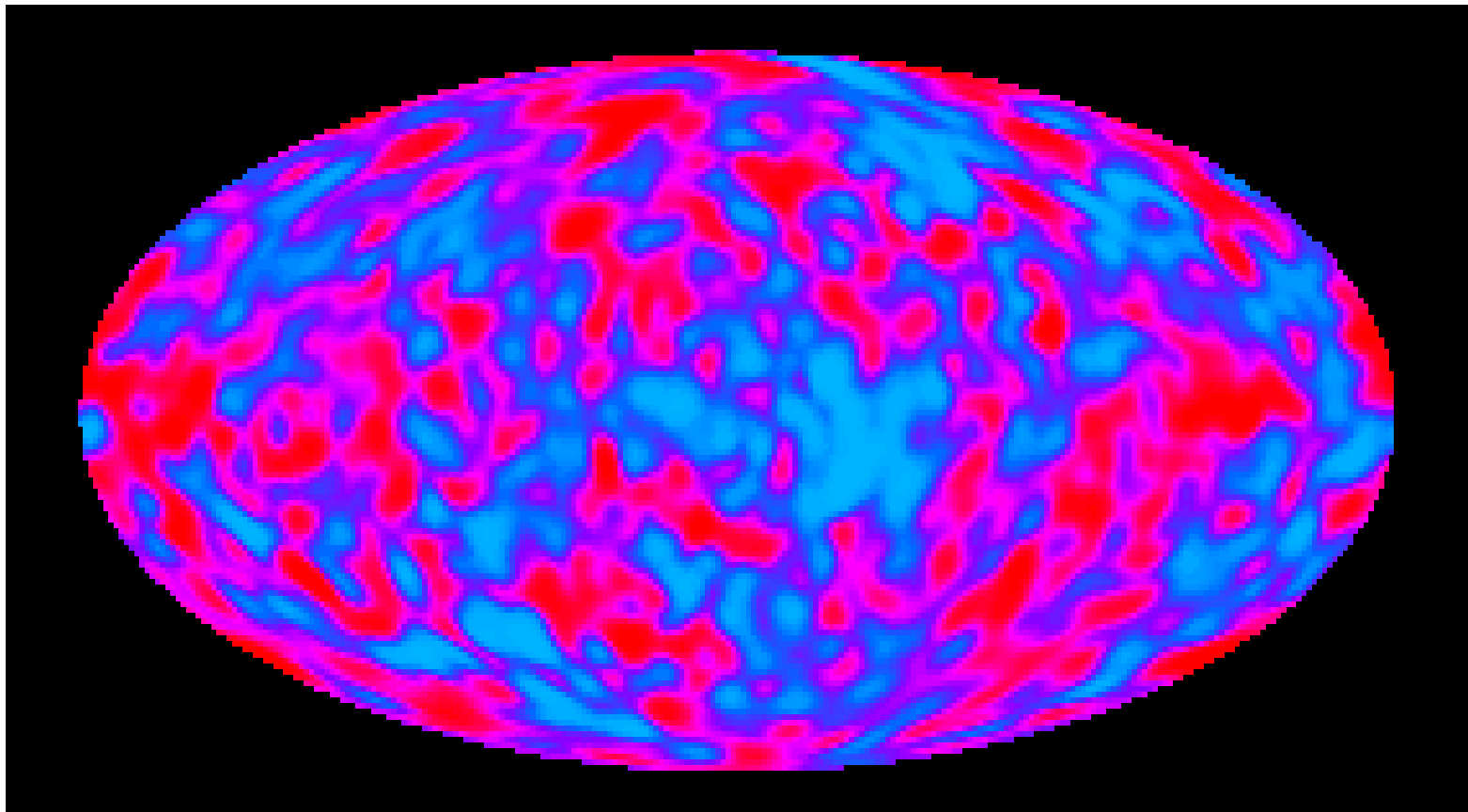


Niebiski oznacza chłodny obszar(uciekanie]; czerwony gorący (przybliżanie)

Kiedy usunie się ruch Ziemi **dystrybucja mikrofalowego tła** na niebie staje się bardziej **zunifikowana**.

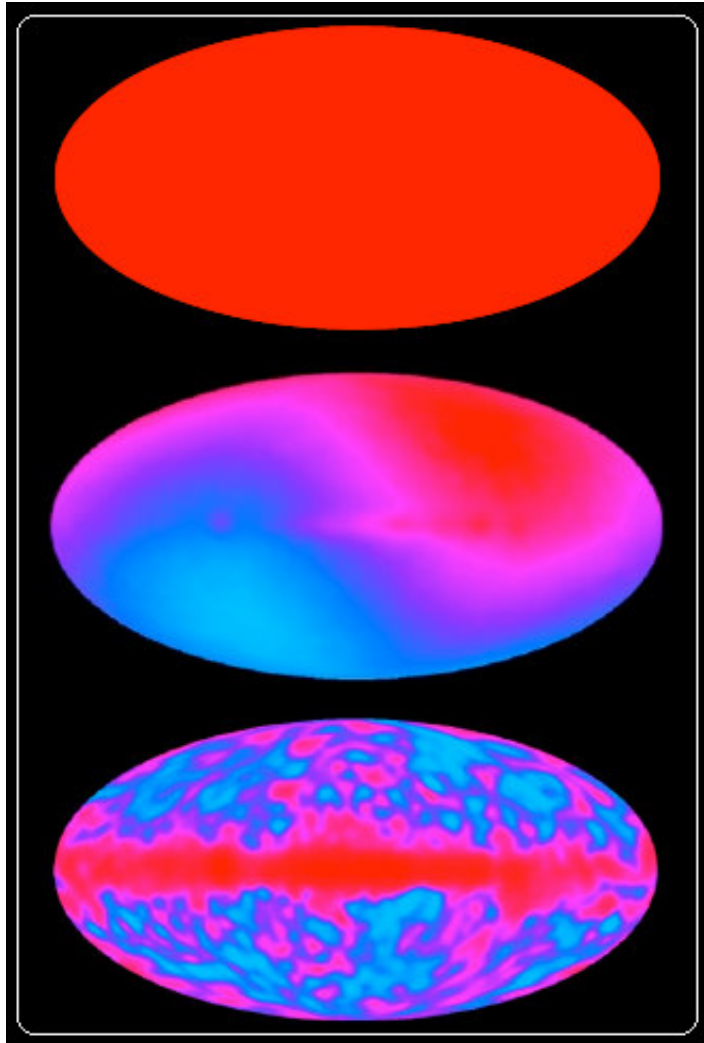


Kiedy usunie się promieniowanie z Drogi Mlecznej pozostała dystrybucja staje się bardzo [ale nie perfekcyjnie] gładka.

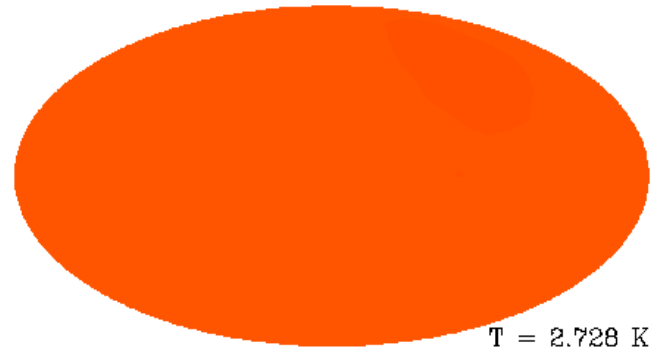


Fluktuacje wynoszą tylko parę części na 10,000!

CMB

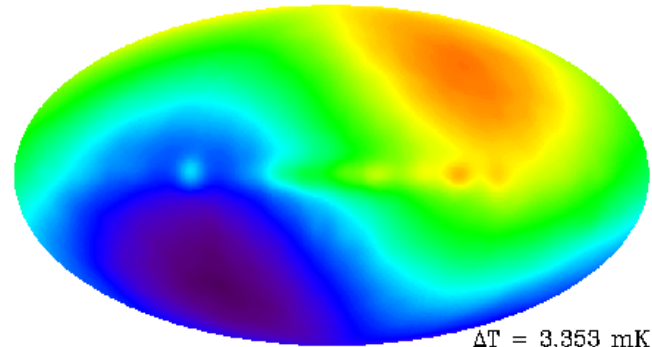


$T=2,726$ K



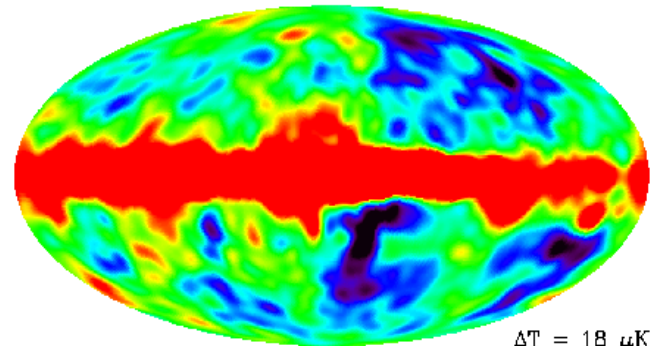
$T = 2.728$ K

$\Delta T \approx \text{mK}$



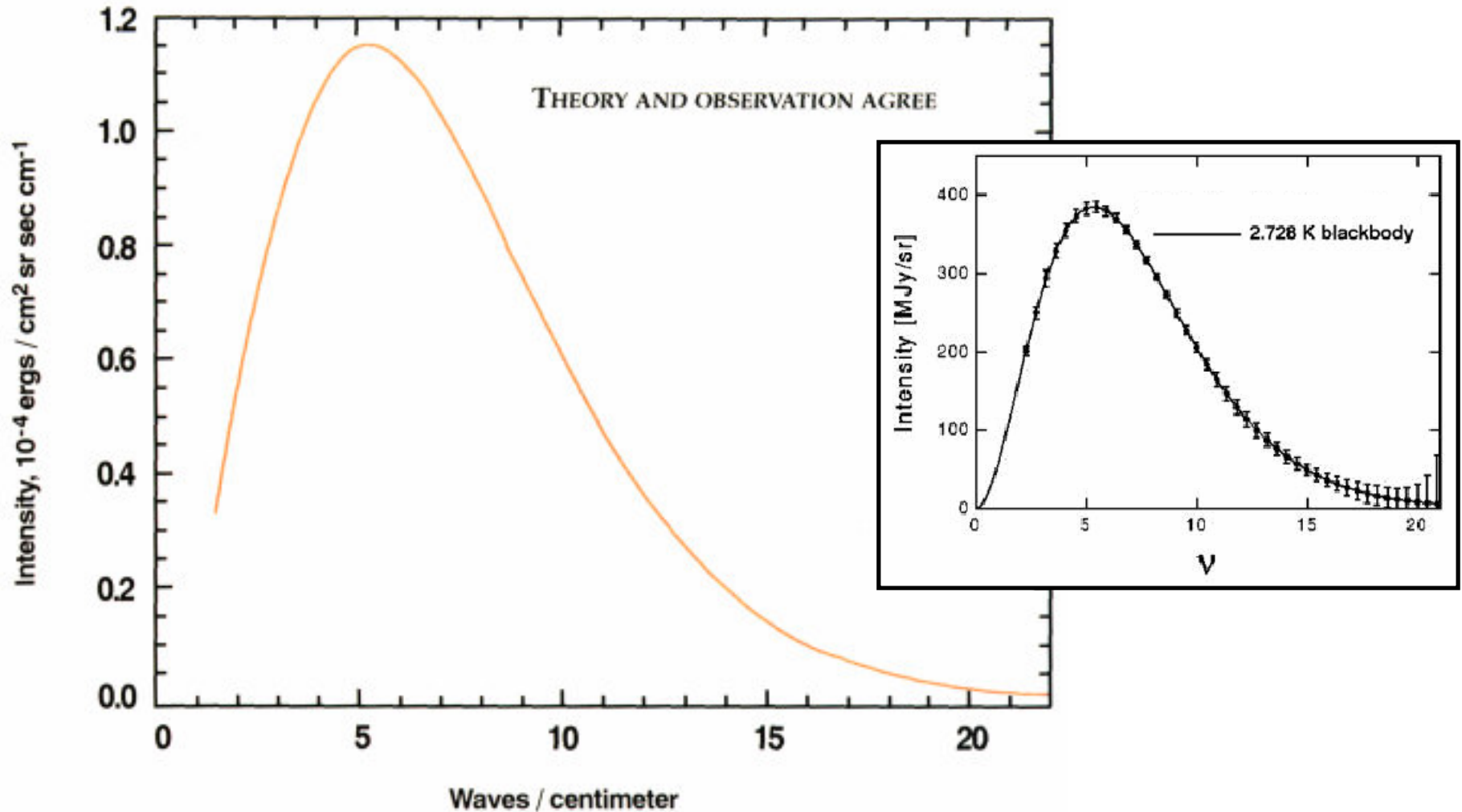
$\Delta T = 3.353$ mK

$\Delta T \approx \mu\text{K}$



$\Delta T = 18$ μK

COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE

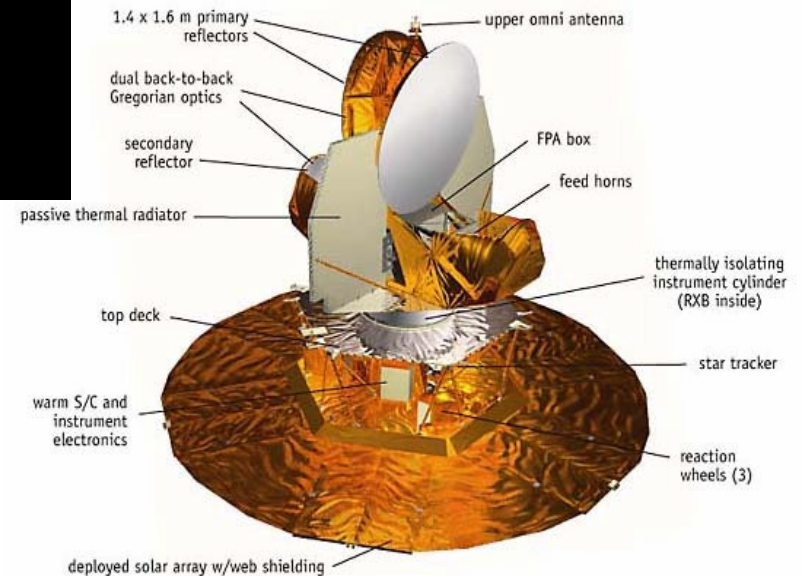
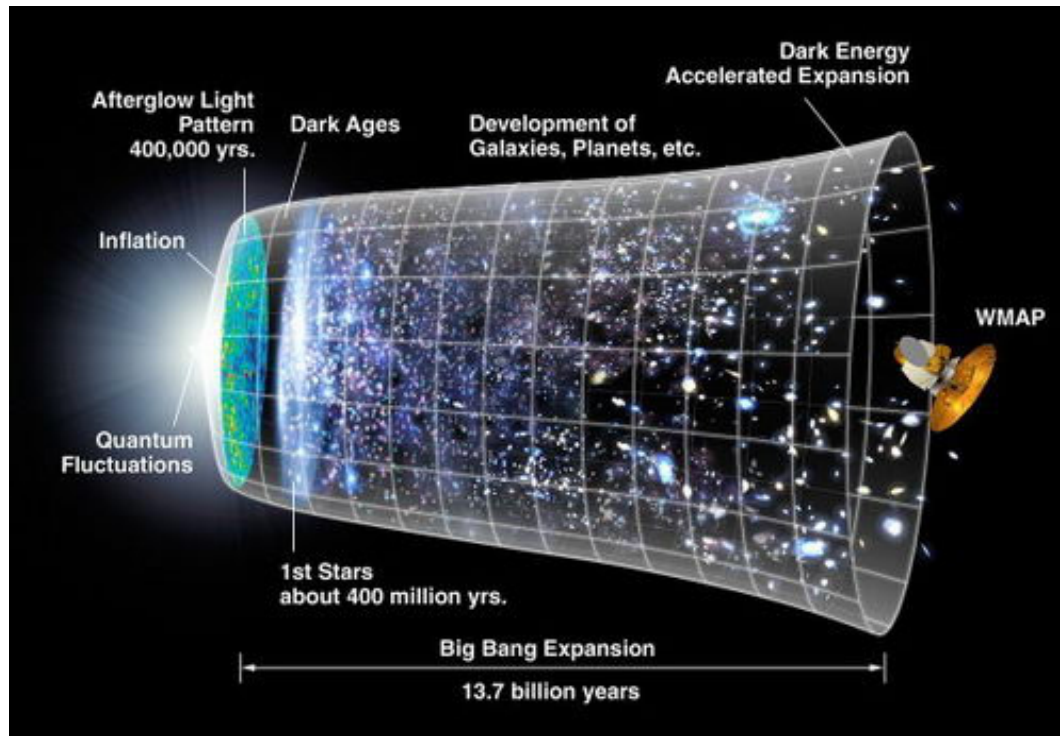


Promieniowanie CMB z COBE i promieniowanie ciała doskonale.

Spektrum jest tak idealne, że błąd jest grubości linii.

2003 WMAP

(*WILKINSON MICROWAVE ANISOTROPY PROBE*)



Odkrycie związane z:

- Kształtem wszechświata,
- Ciemną materią,
- Formowaniem się struktur

KOSMICZNE PARAMETRY ZEBRANE Z WMAP

WMAP Cosmological Parameters

Model: Λ cdm

Data: wmap

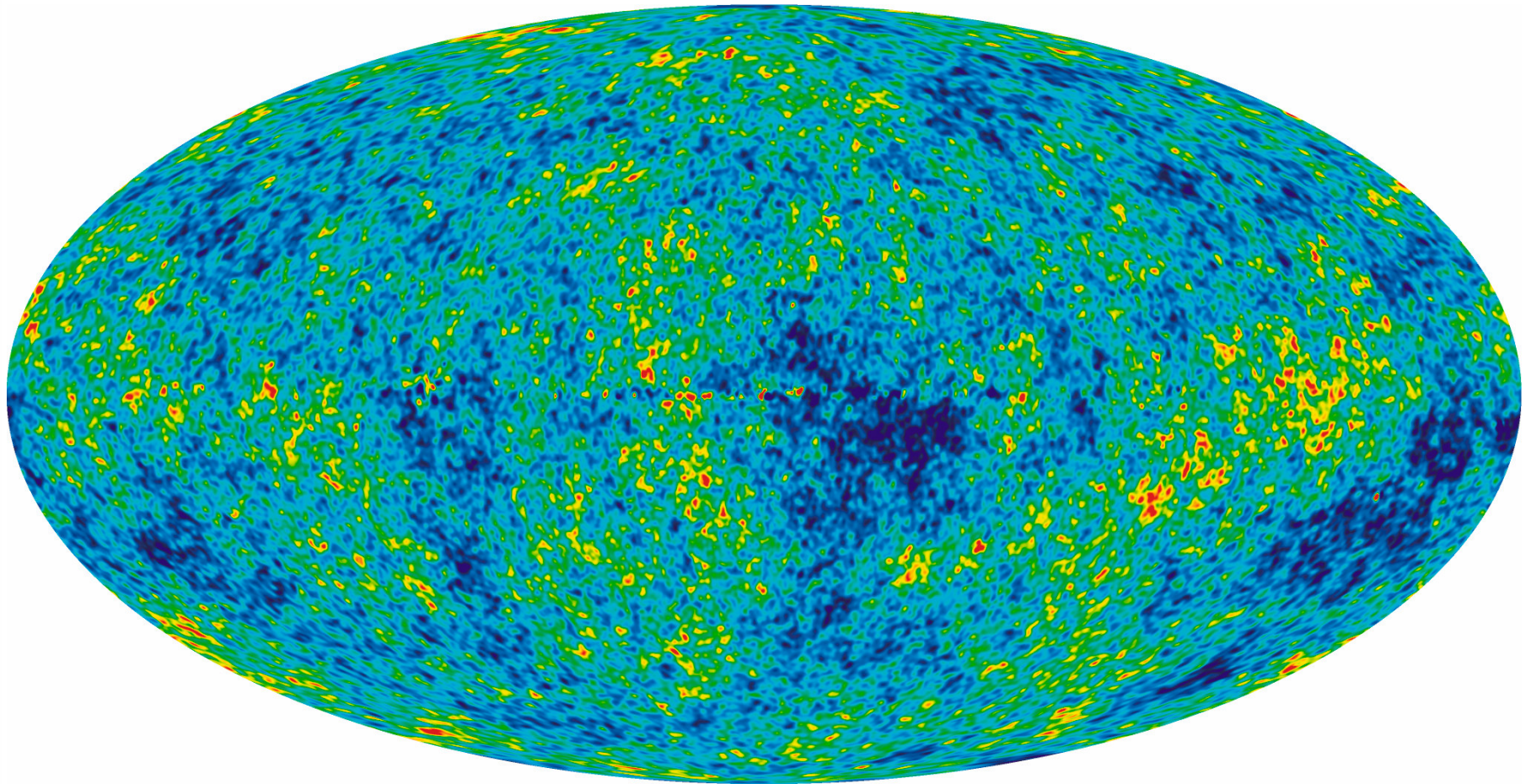
$10^2 \Omega_b h^2$	$2.230^{+0.075}_{-0.073}$
$\Delta_{\mathcal{R}}^2(k = 0.002/\text{Mpc})$	$(23.7 \pm 1.4) \times 10^{-10}$
h	0.735 ± 0.032
H_0	$73.5 \pm 3.2 \text{ km/s/Mpc}$
$n_s(0.002)$	0.951 ± 0.016
$\Omega_b h^2$	$0.02230^{+0.00075}_{-0.00073}$
Ω_Λ	0.763 ± 0.034
Ω_m	0.237 ± 0.034
$\Omega_m h^2$	$0.1265^{+0.0081}_{-0.0080}$
σ_8	0.742 ± 0.051
A_{SZ}	1.00 ± 0.64
t_0	$13.73^{+0.16}_{-0.15} \text{ Gyr}$
τ	$0.088^{+0.029}_{-0.030}$
θ_A	$0.5948^{+0.0021}_{-0.0022} \circ$
z_r	10.9 ± 2.5

Hubbel Parameter

Cosmological Constant

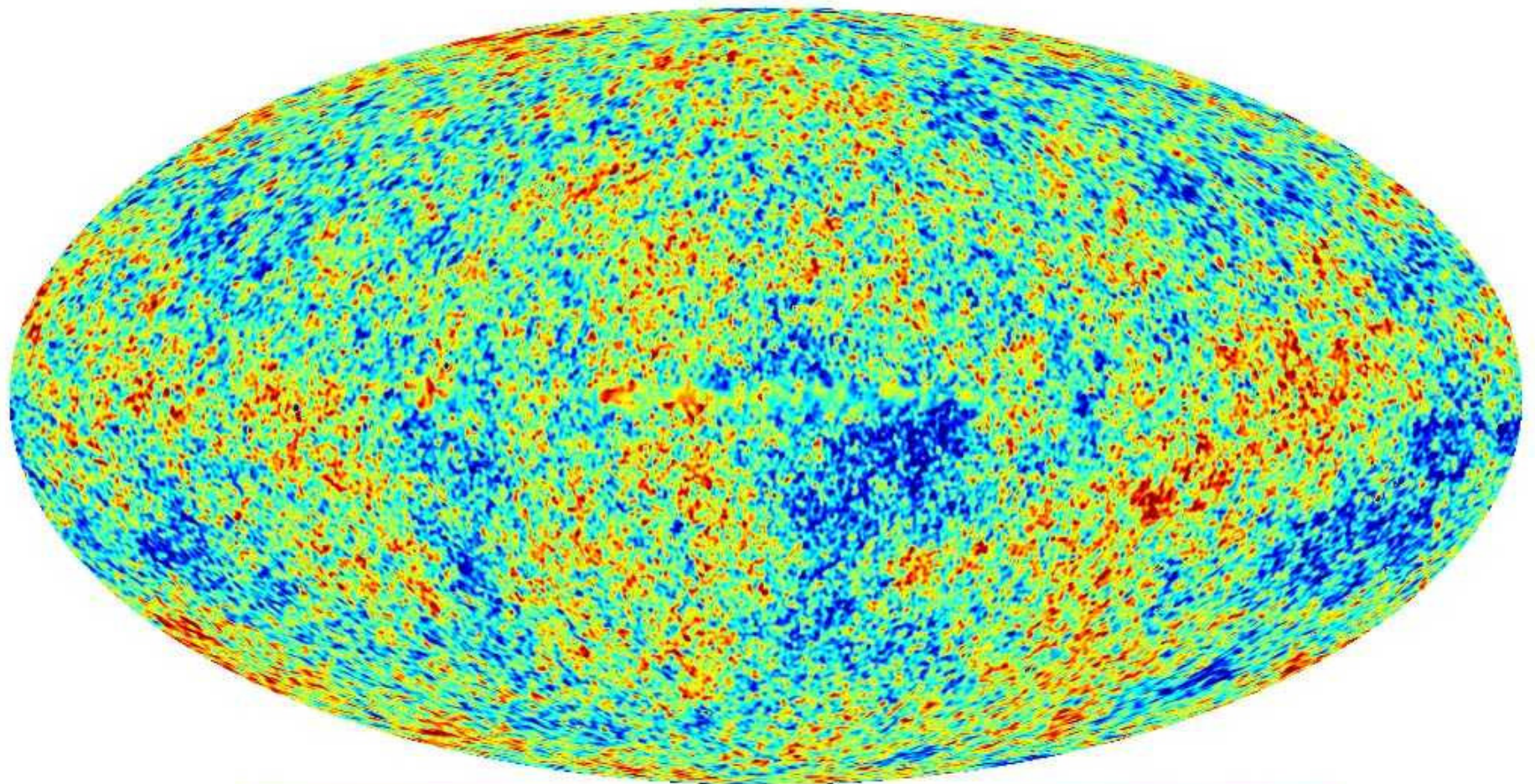
Age of the Universe

COSMIC MICROWAVE BACKGROUND



WMAP (2003)

COSMIC MICROWAVE BACKGROUND

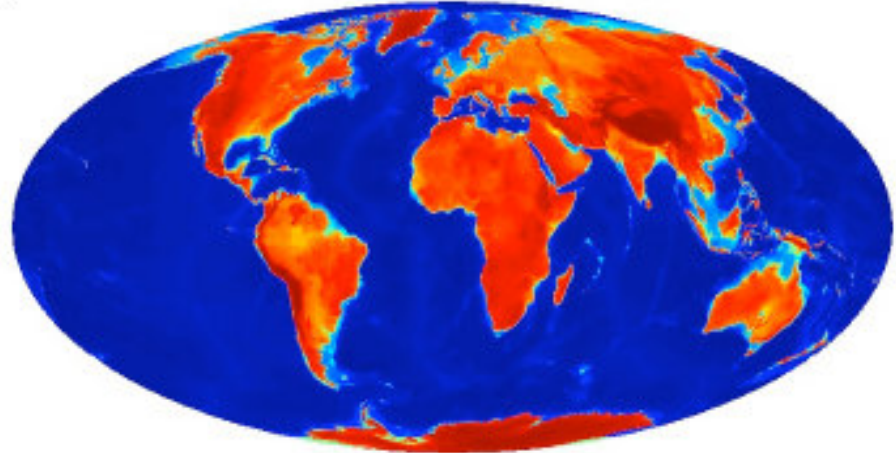
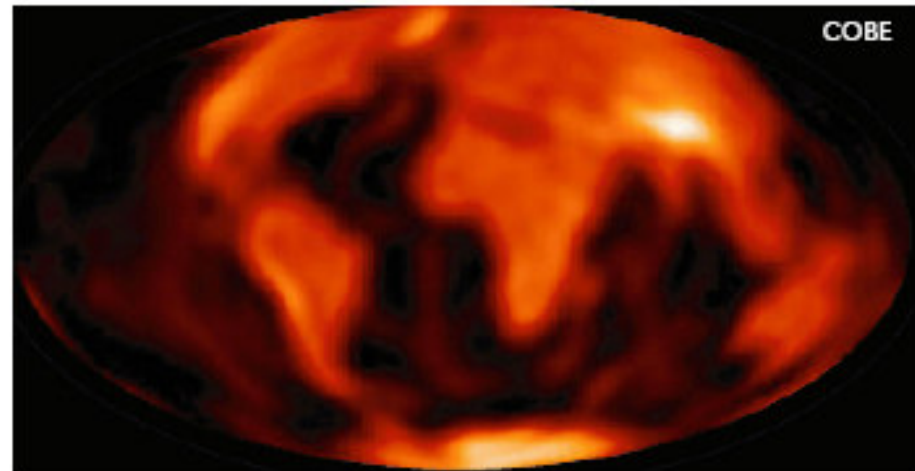


-200 μ K  200 μ K

PLANCK (2008)

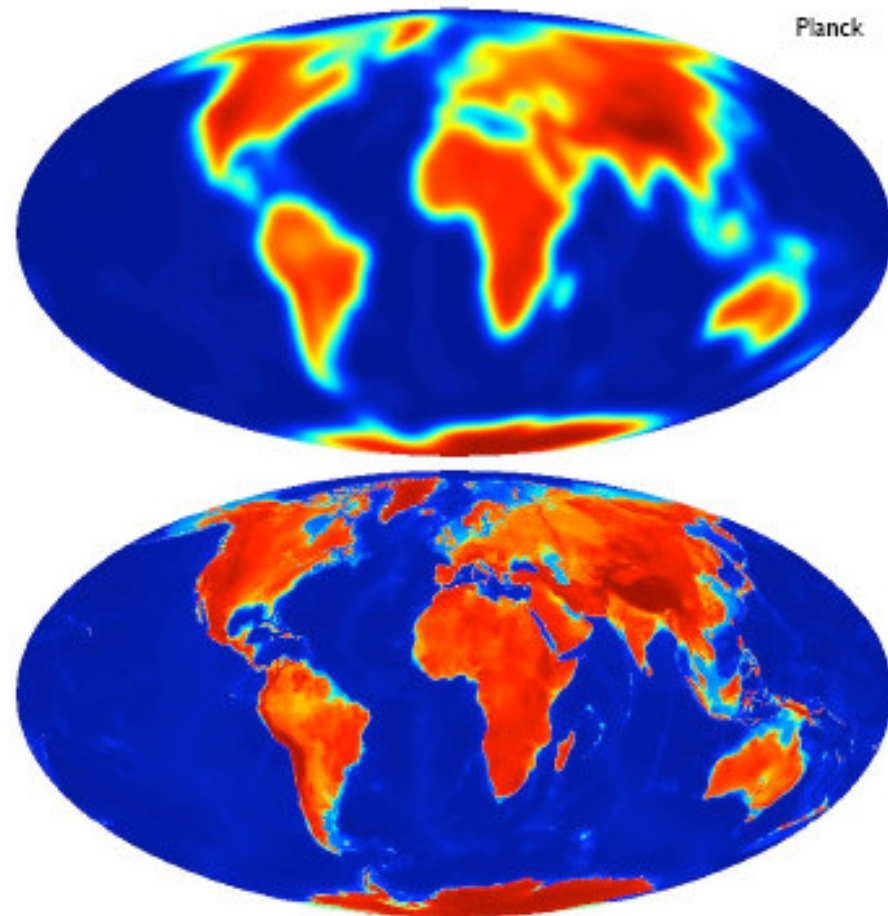
▪ quantifying fluctuations – why Planck in 2007?

- even better precision
- polarisation measure
- gravitational waves
- secondary effects

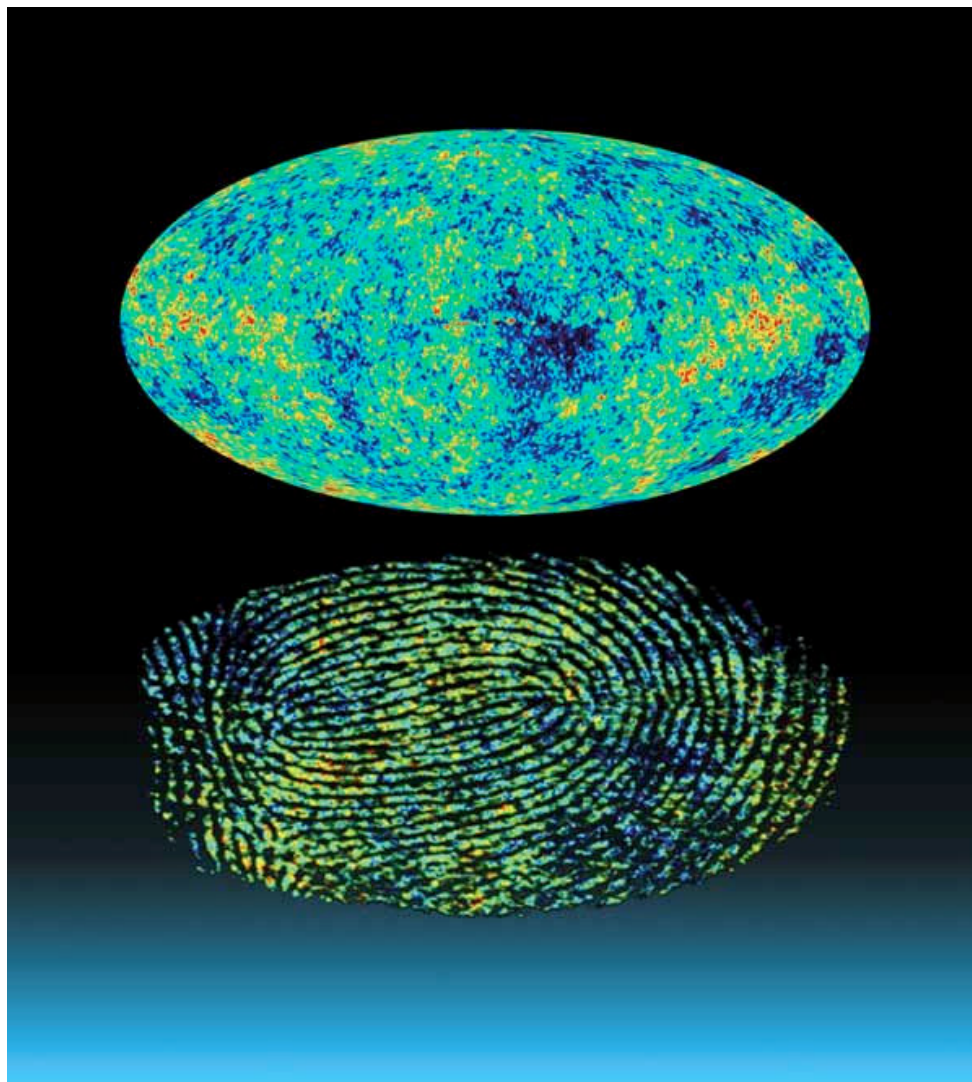


▪ quantifying fluctuations – why Planck in 2007?

- even better precision
- polarisation measure
- gravitational waves
- secondary effects



DALSZE DOCHODZENIE

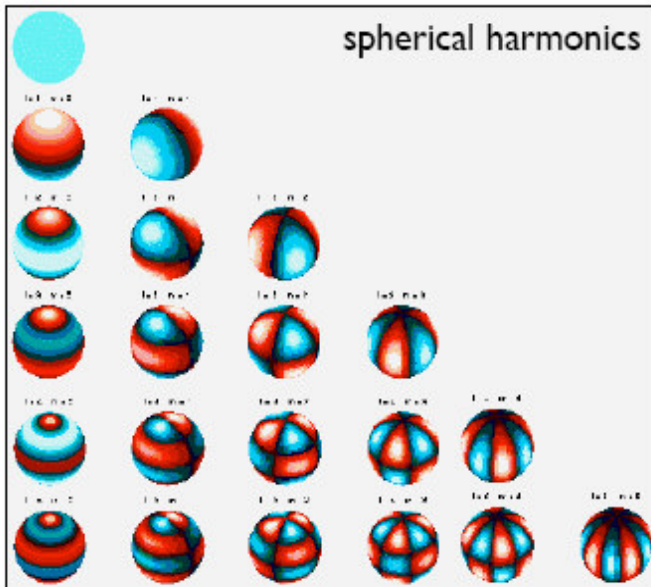


$$\frac{\Delta T}{T}(\vartheta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\vartheta, \varphi)$$

$Y_{lm}(\vartheta, \varphi)$: spherical harmonics

(complete orthonormal set of functions on the surface of a sphere)

$l=0$



-> monopole (not measurable)

$l=1$

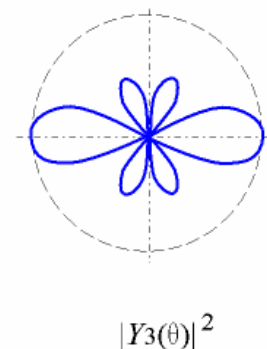
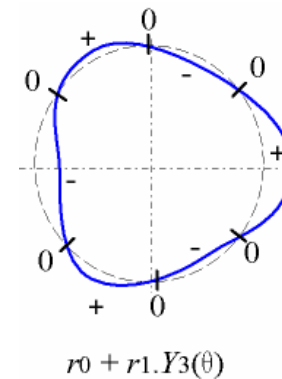
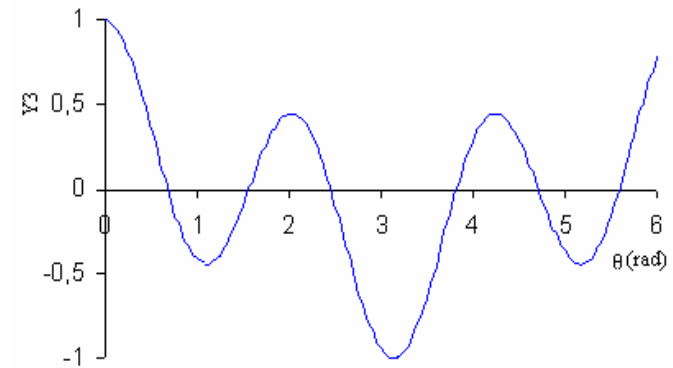
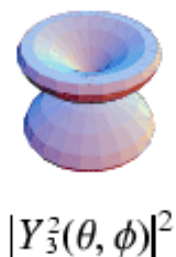
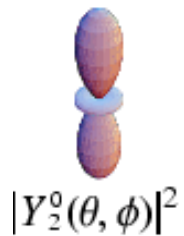
-> dipole (our motion)

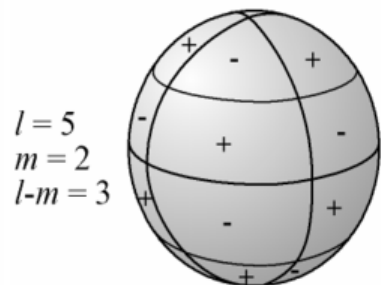
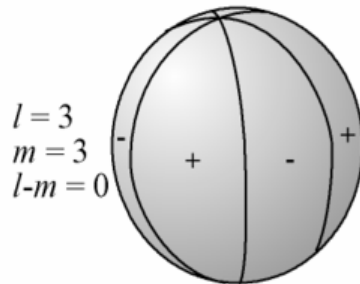
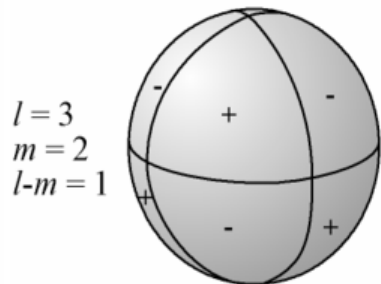
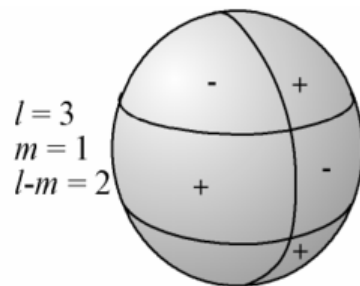
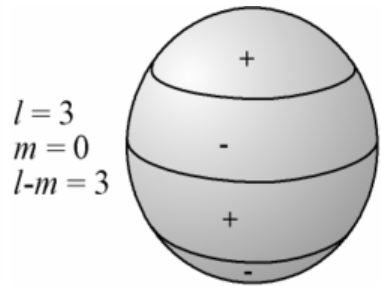
$l>1$

-> anisotropies we're after!

HARMONIJKI SFERYCZNE

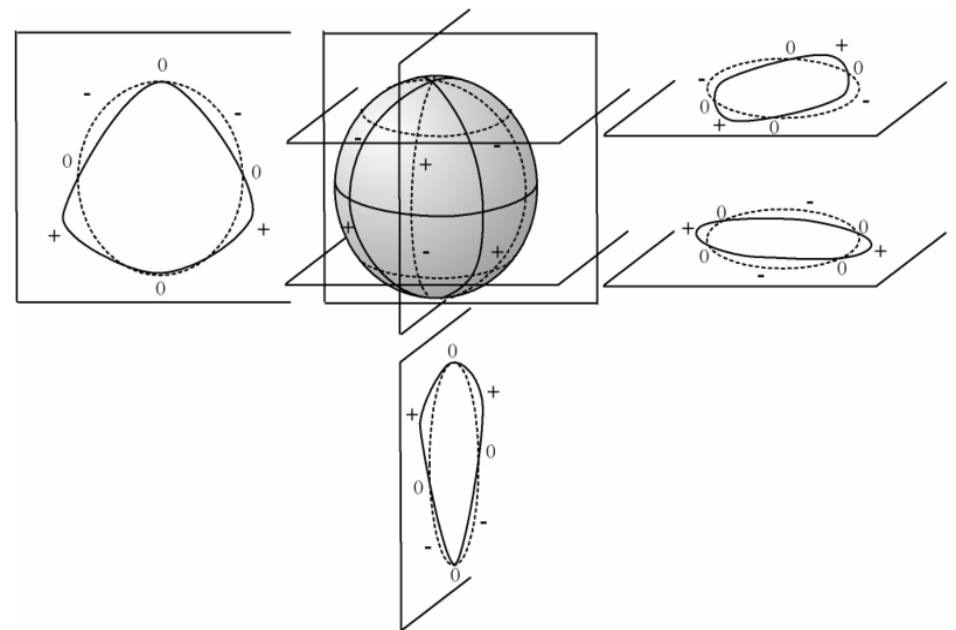
$$Y_l^m(\theta, \phi) = \left[\frac{2l+1}{4\pi} \frac{(l-m)!}{(l+m)!} \right]^{1/2} P_l^m(\cos\theta) e^{im\phi}$$





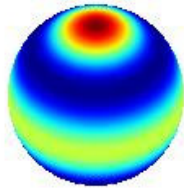
Y_{lm} is equal to 0 along circles (the representative surface intersects the $\rho = \rho_0$ sphere at these circles).

Y_{lm} jest positive and negative between two circles.

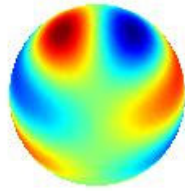


SPHERICAL HARMONICS

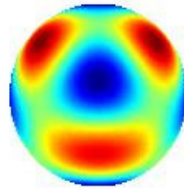
$m=0$



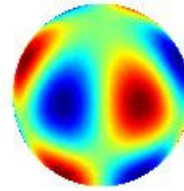
$m=1$



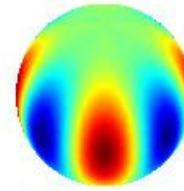
$m=2$



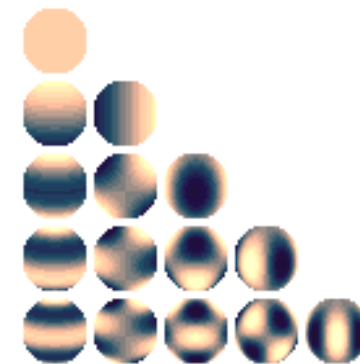
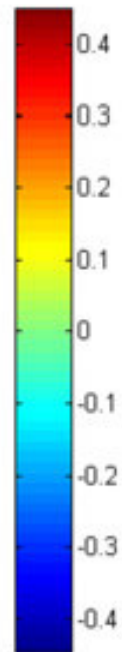
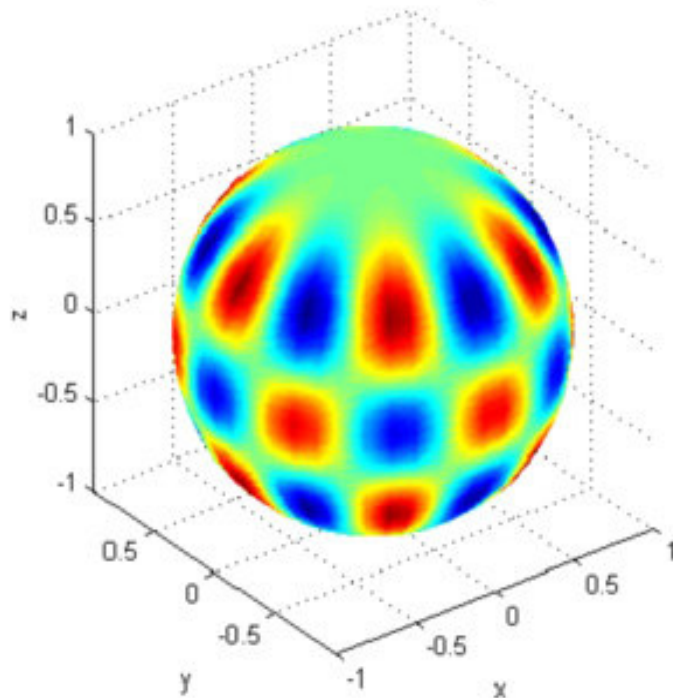
$m=3$



$m=4$



Spherical Harmonic Y_8^6

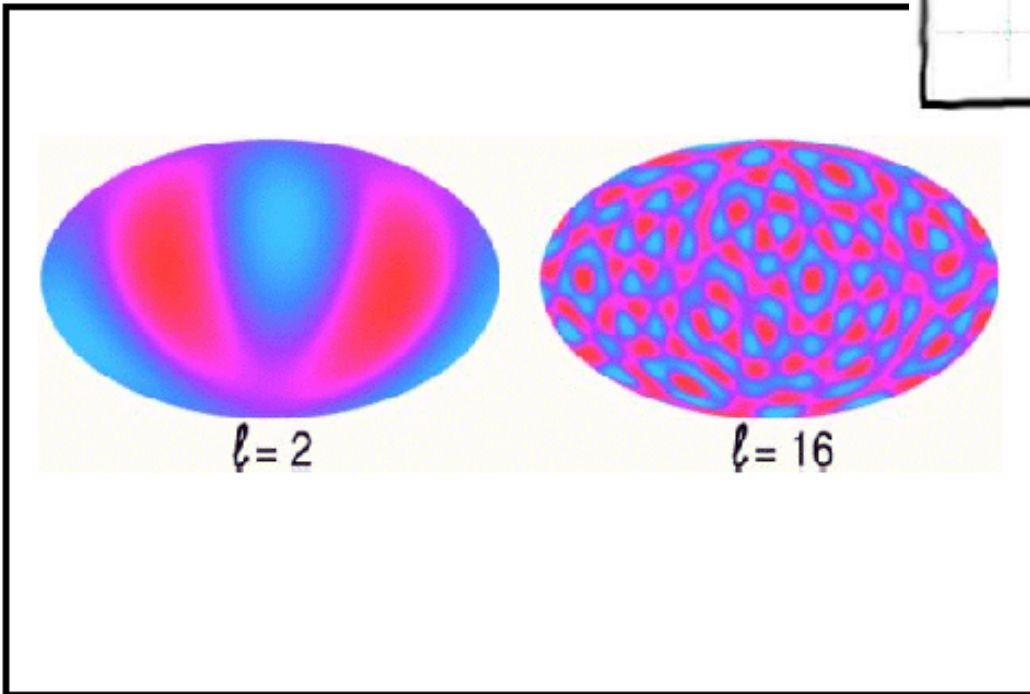
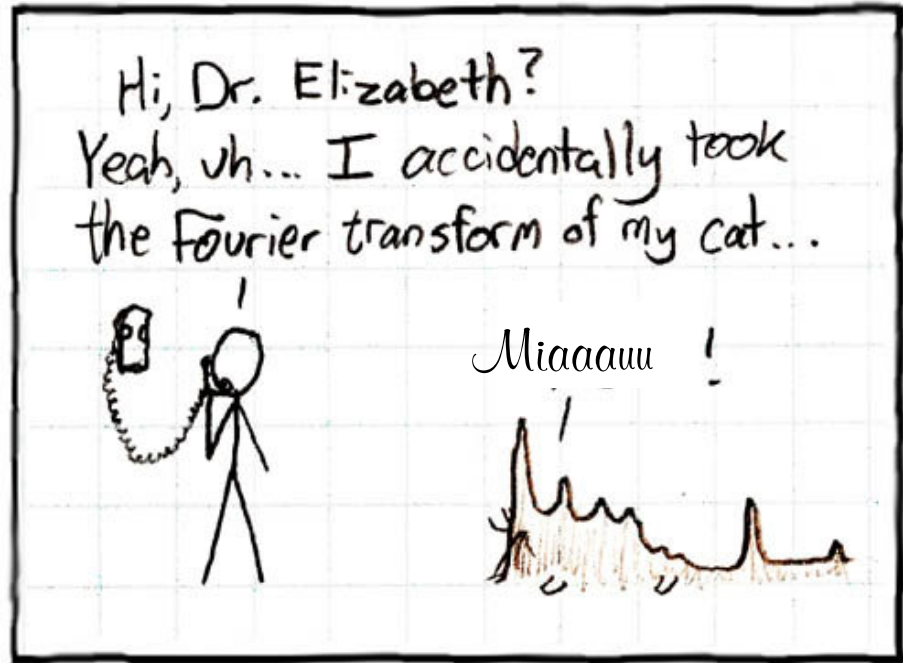


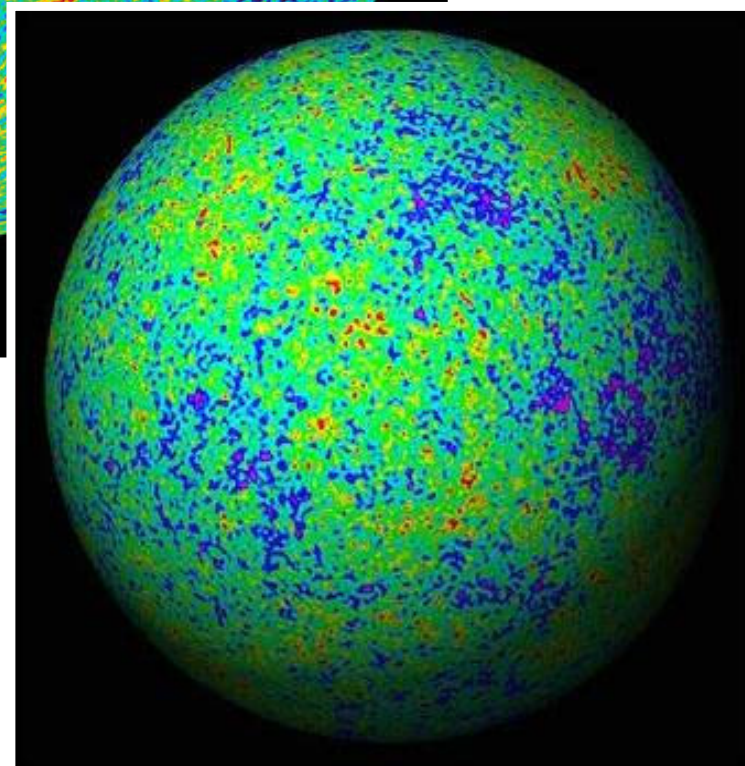
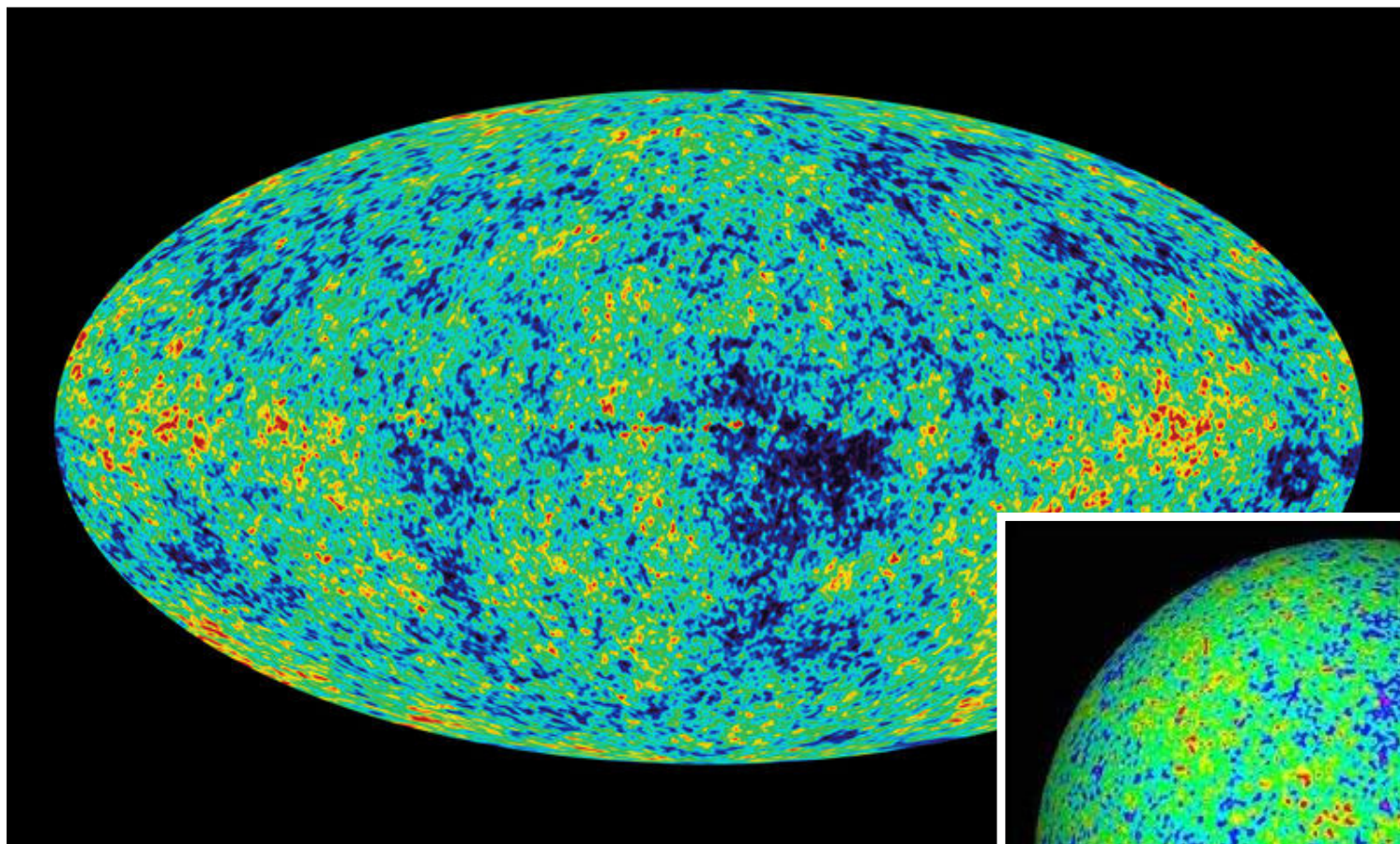
- quantifying fluctuations

$$\frac{\Delta T}{T}(\vartheta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\vartheta, \varphi)$$

rotational invariance

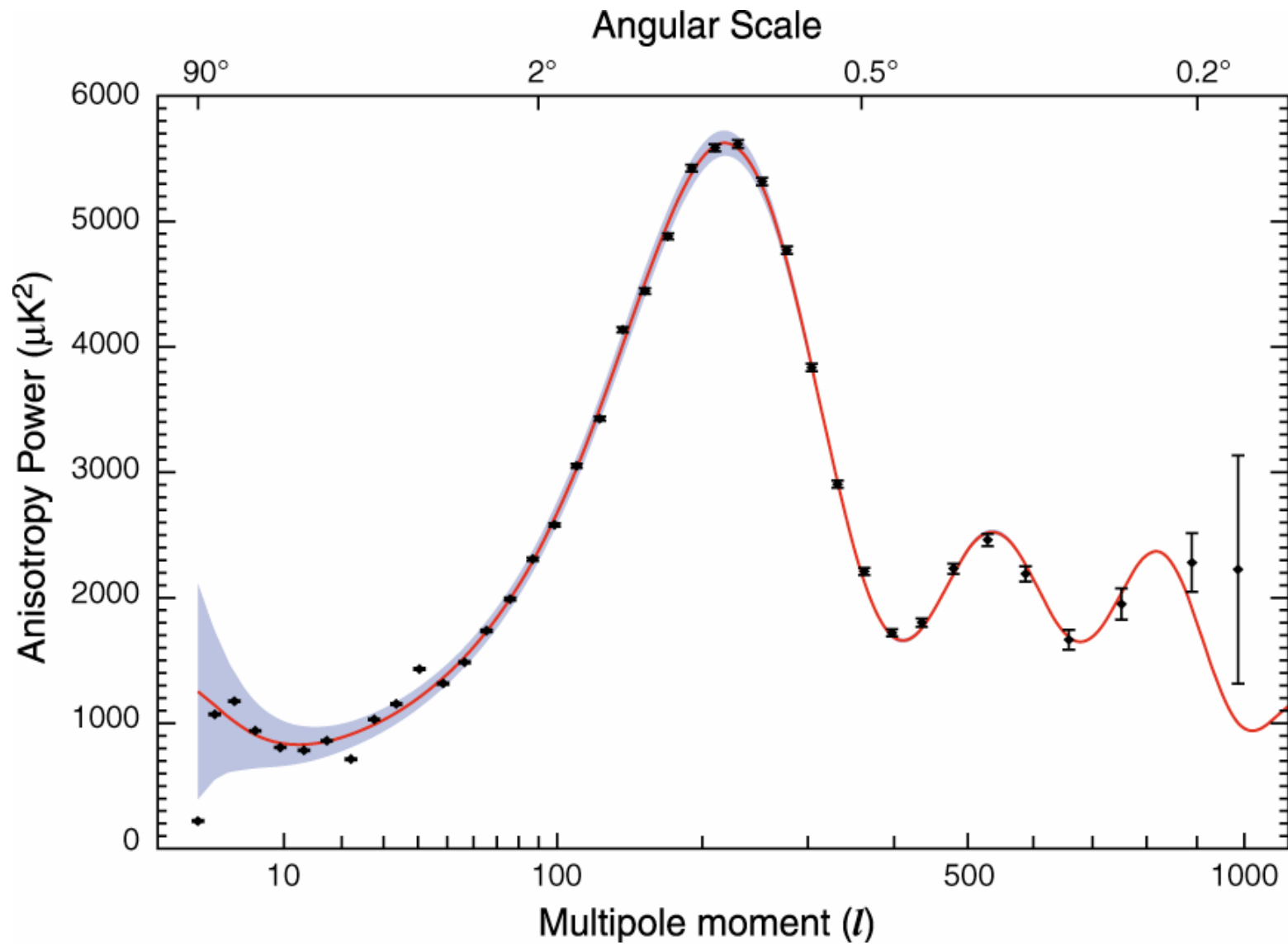
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2$$



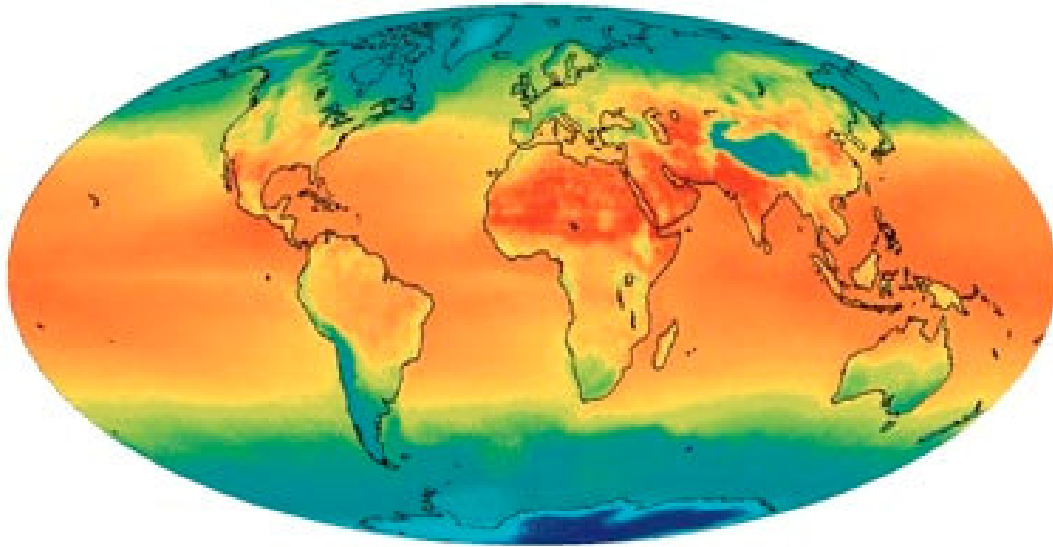


CMB FROM WMAP

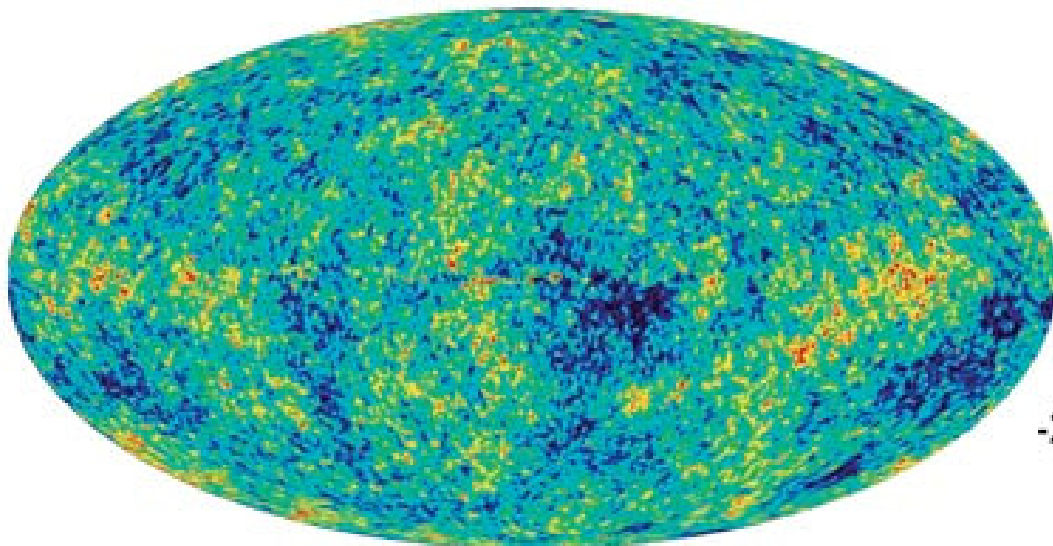
DECOMPOSITION INTO SPHERICAL HARMONICS



TEMPERATURA



Earth
Temperatures



Microwave Sky
Temperatures

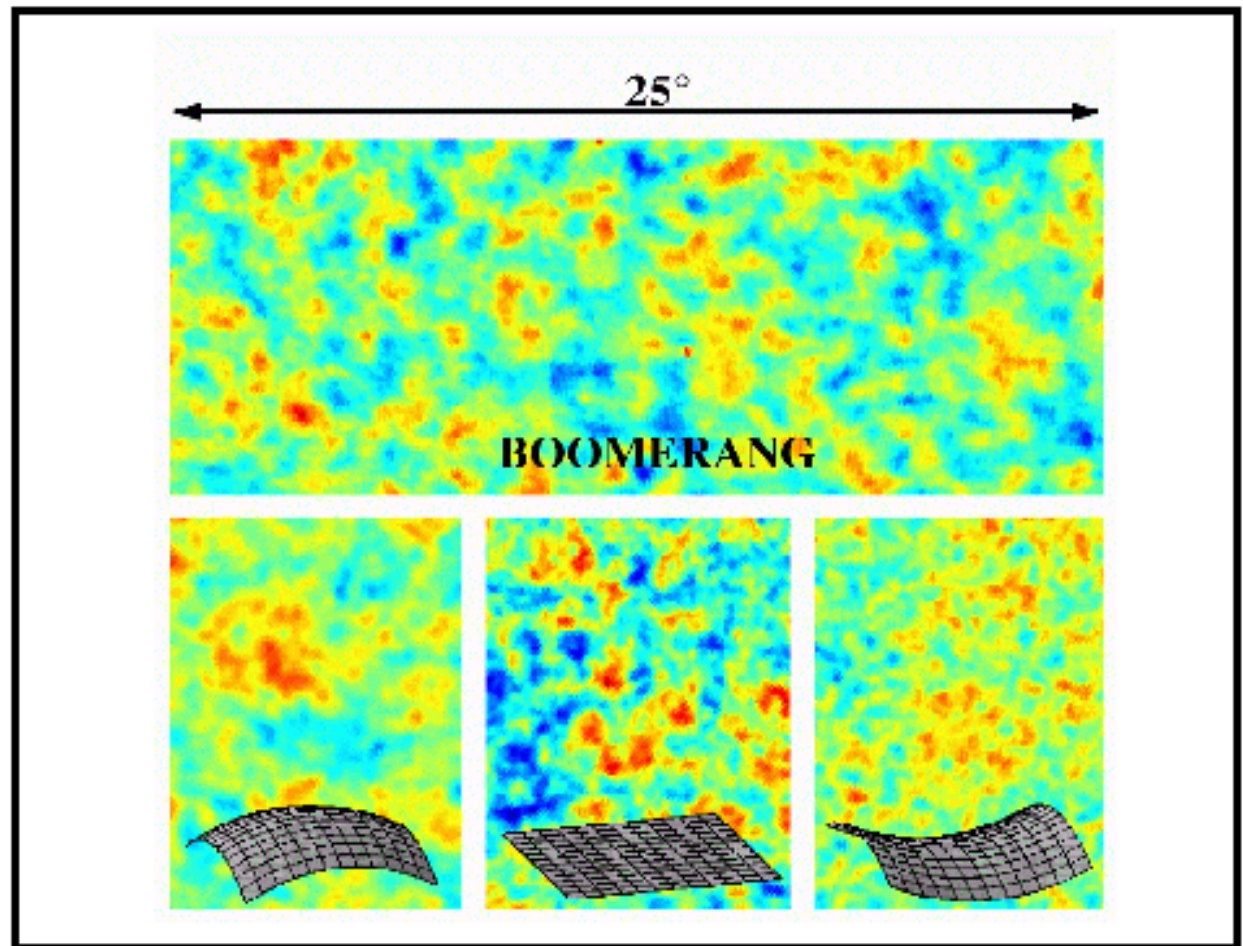


THE SHAPE OF THE UNIVERSE

The microwave background fluctuations also allow us to determine the shape of the universe.

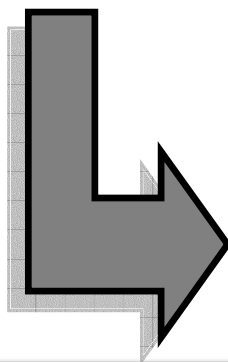
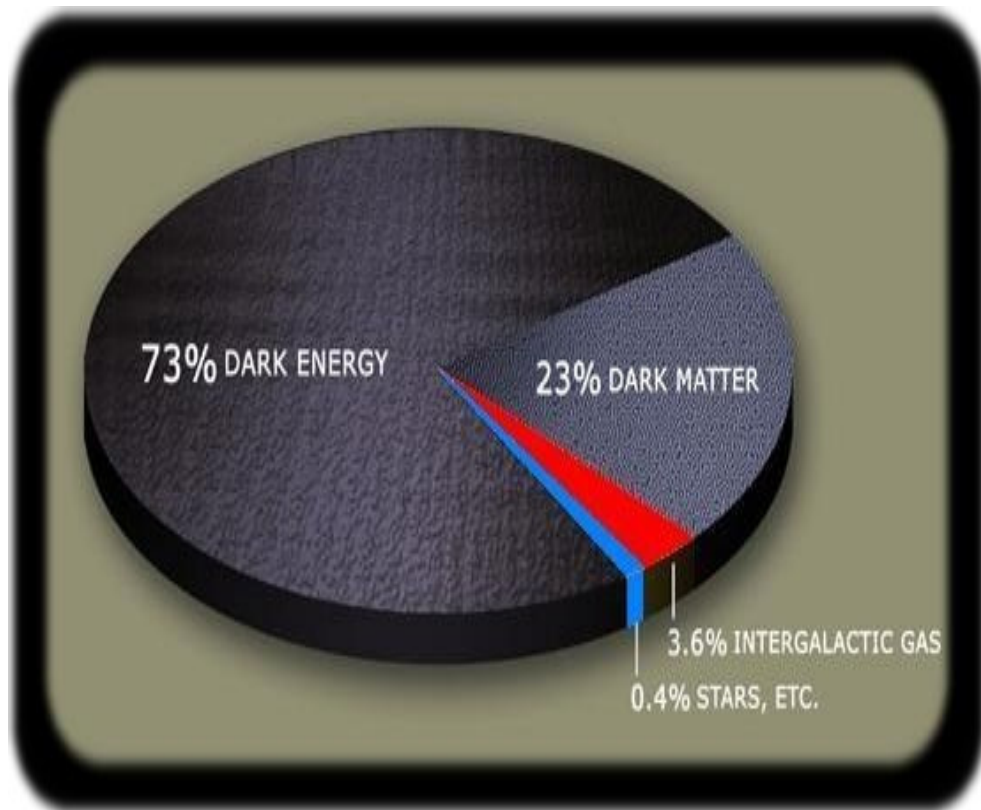
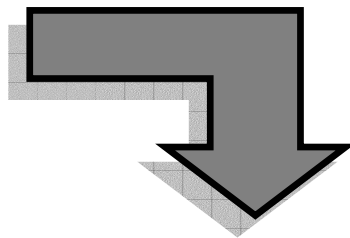
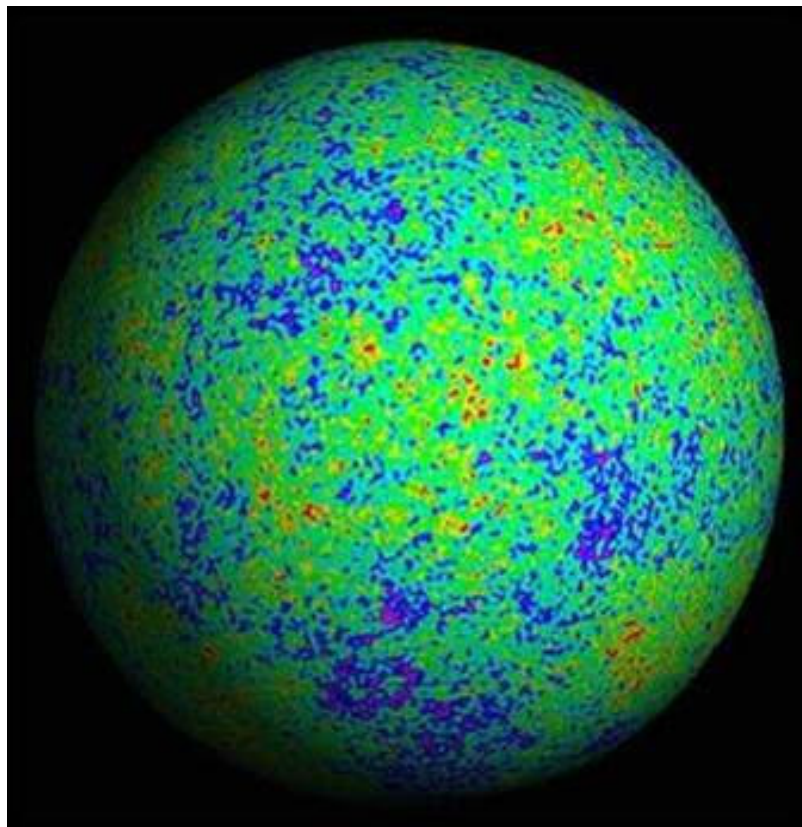
The method is complicated: it has to do with how far apart the positive (and negative) areas appear on the sky.

Theory tells us how far they should be, and we can observe how far apart they are.

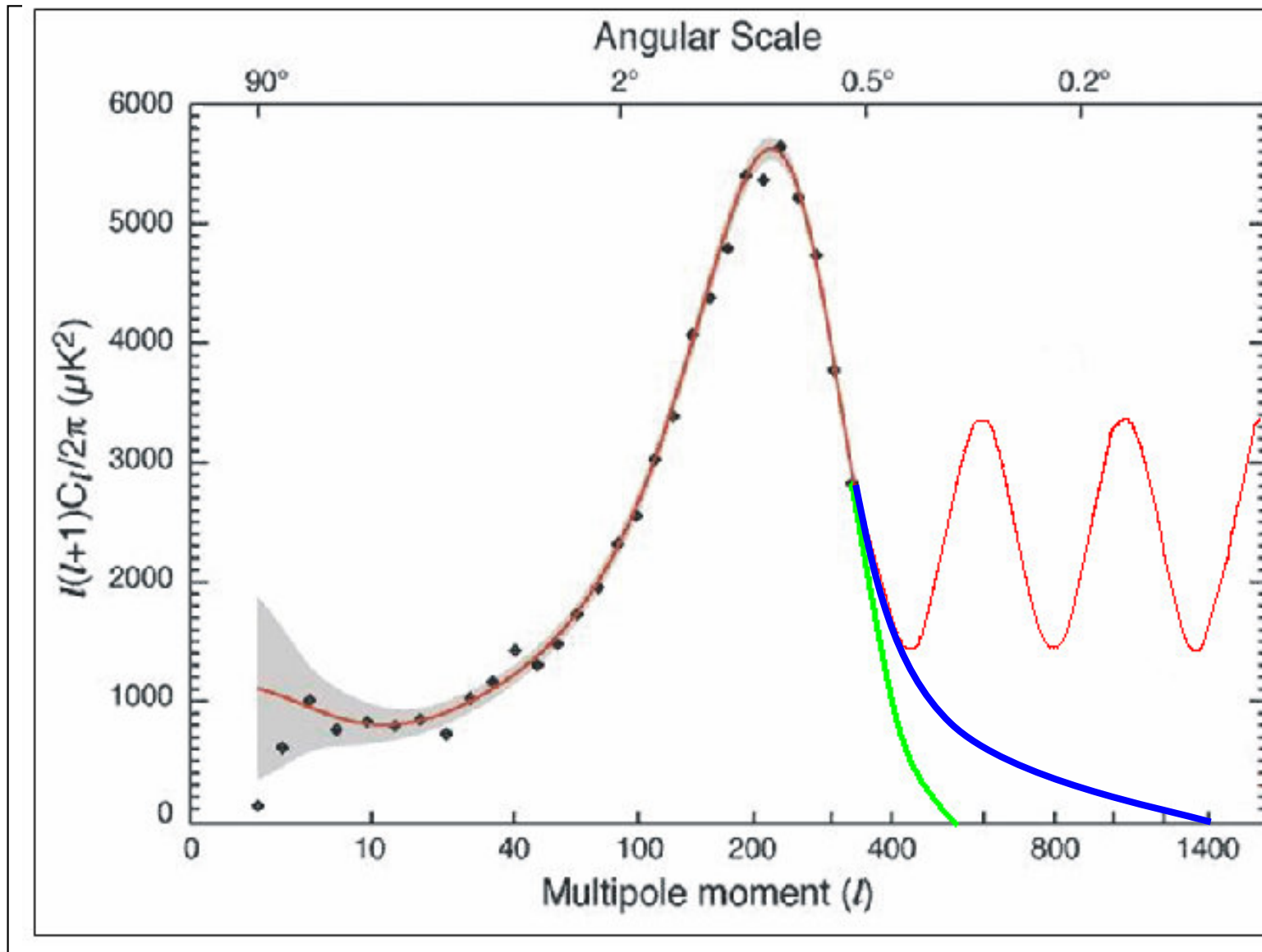


WE OBSERVE THAT THE UNIVERSE IS **FLAT!**

Od **CMB** tdo **Ciemnej Materii**



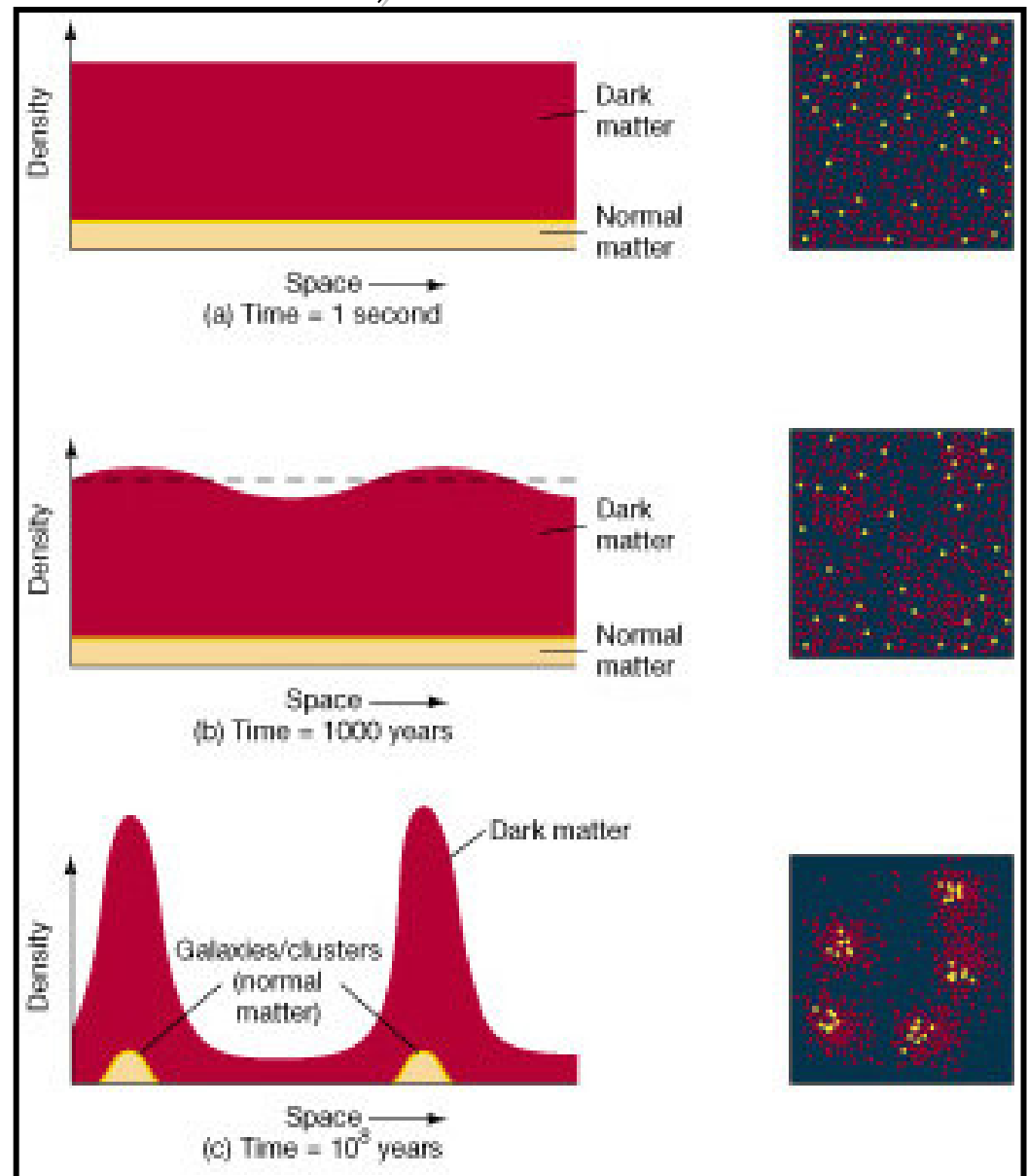
BARYONIC VS. DARK MATTER



FLUKTUACJE

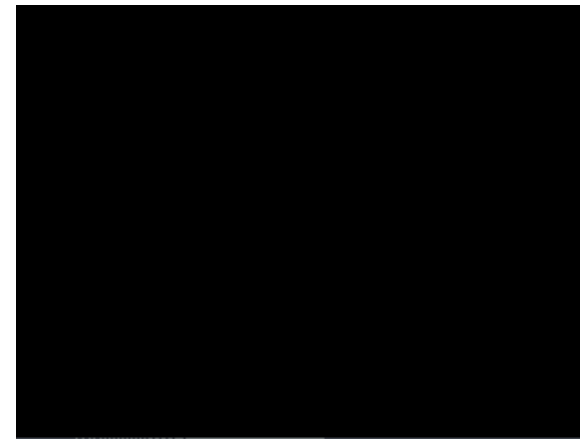
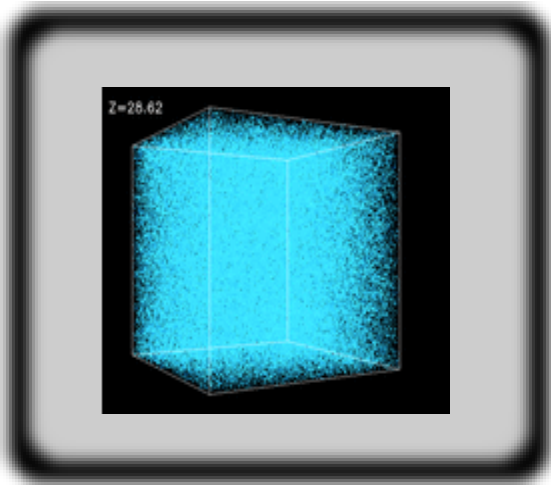
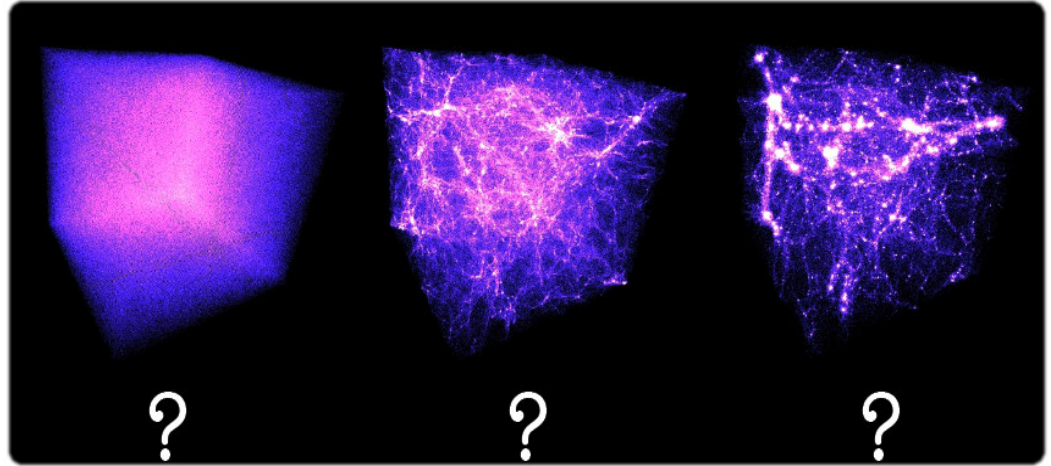
Z czasem bardzo małe fluktuacje gęstości we wczesnym Wszechświecie zostały wzmocnione wiele wiele razy przez grawitację.

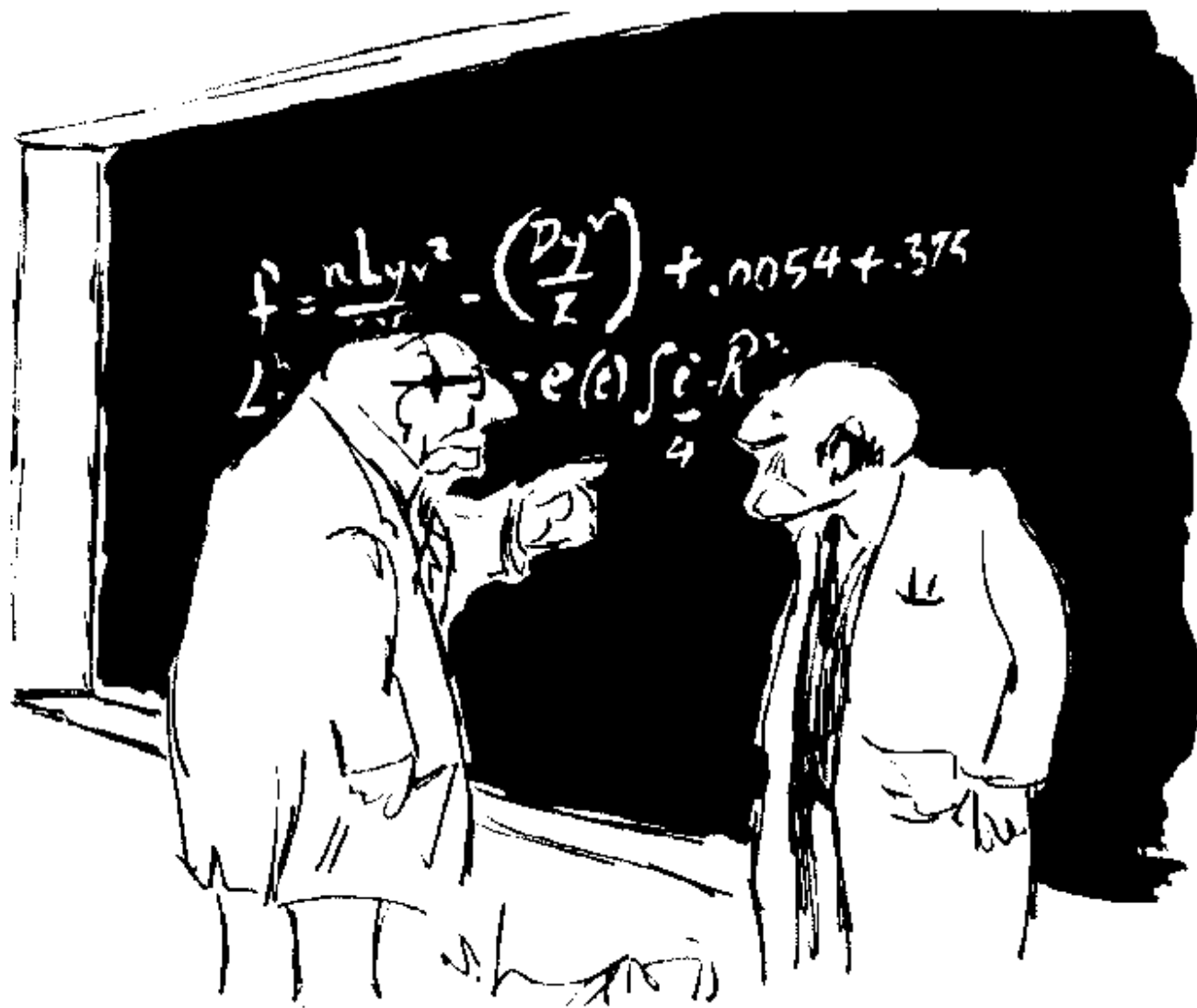
Klastry galaktyk i same galaktyki, które widzimy dzisiaj urosły z tych bardzo małych fluktuacji w mikrofalowym promieniowaniu tła.



NIESTABILNOŚCI

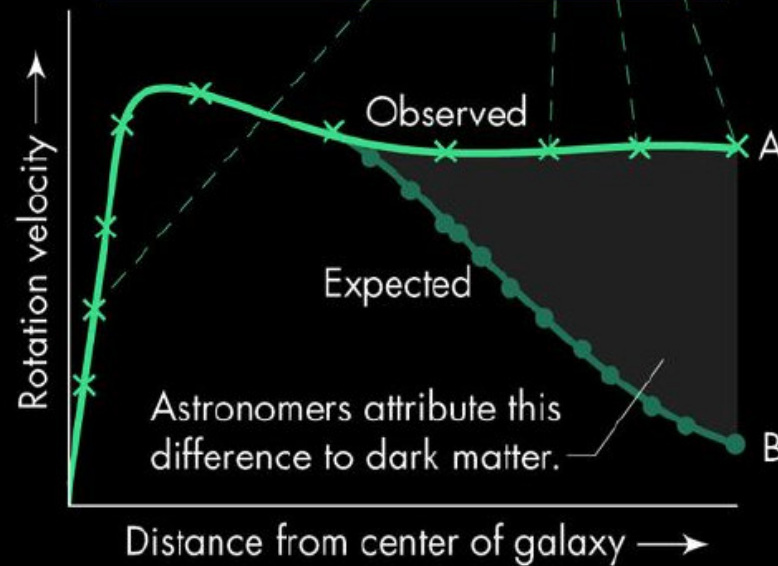
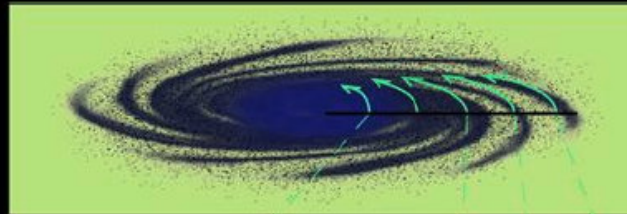
Gorący gaz ochładza się i z pomocą grawitacji zamienia się w galaktyki i klastry galaktyk.





"Does this apply always, sometimes, or never?"

- evidence for dark matter – rotation curves



$$v_{circ}^2(r) = \frac{GM(<r)}{r}$$

\downarrow
 $M = const.$

$$v_{circ}(r) \propto \frac{1}{\sqrt{r}}$$

DARK MATTER

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

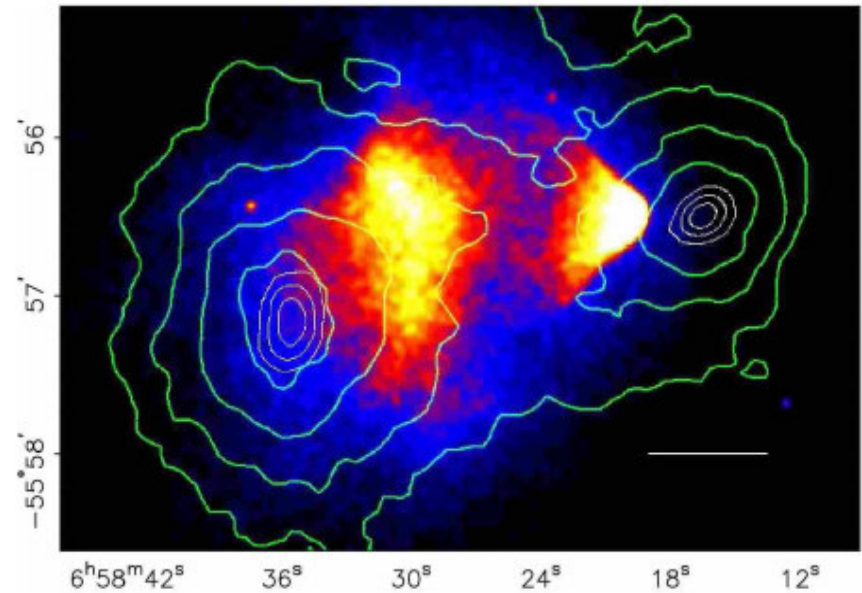
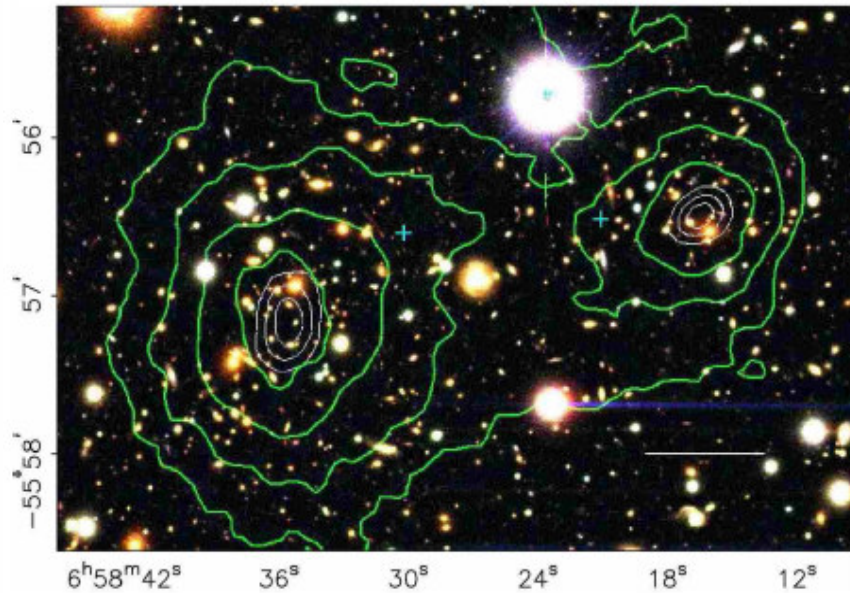
DOUGLAS CLOWE¹, MARUŠA BRADAC², ANTHONY H. GONZALEZ³, MAXIM MARKEVITCH^{4,5}, SCOTT W. RANDALL⁴,
CHRISTINE JONES⁴, AND DENNIS ZARITSKY¹

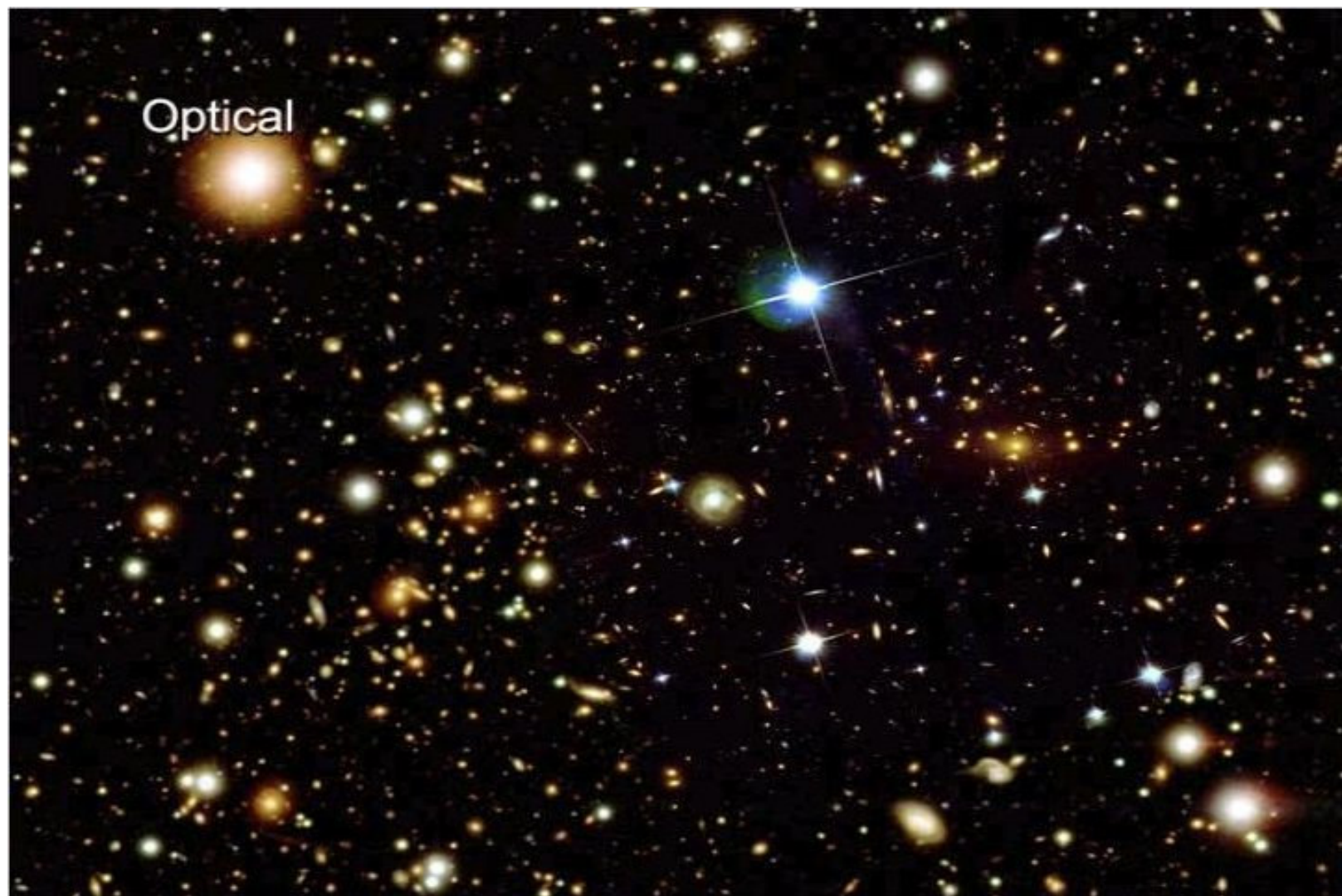
Draft version August 18, 2006

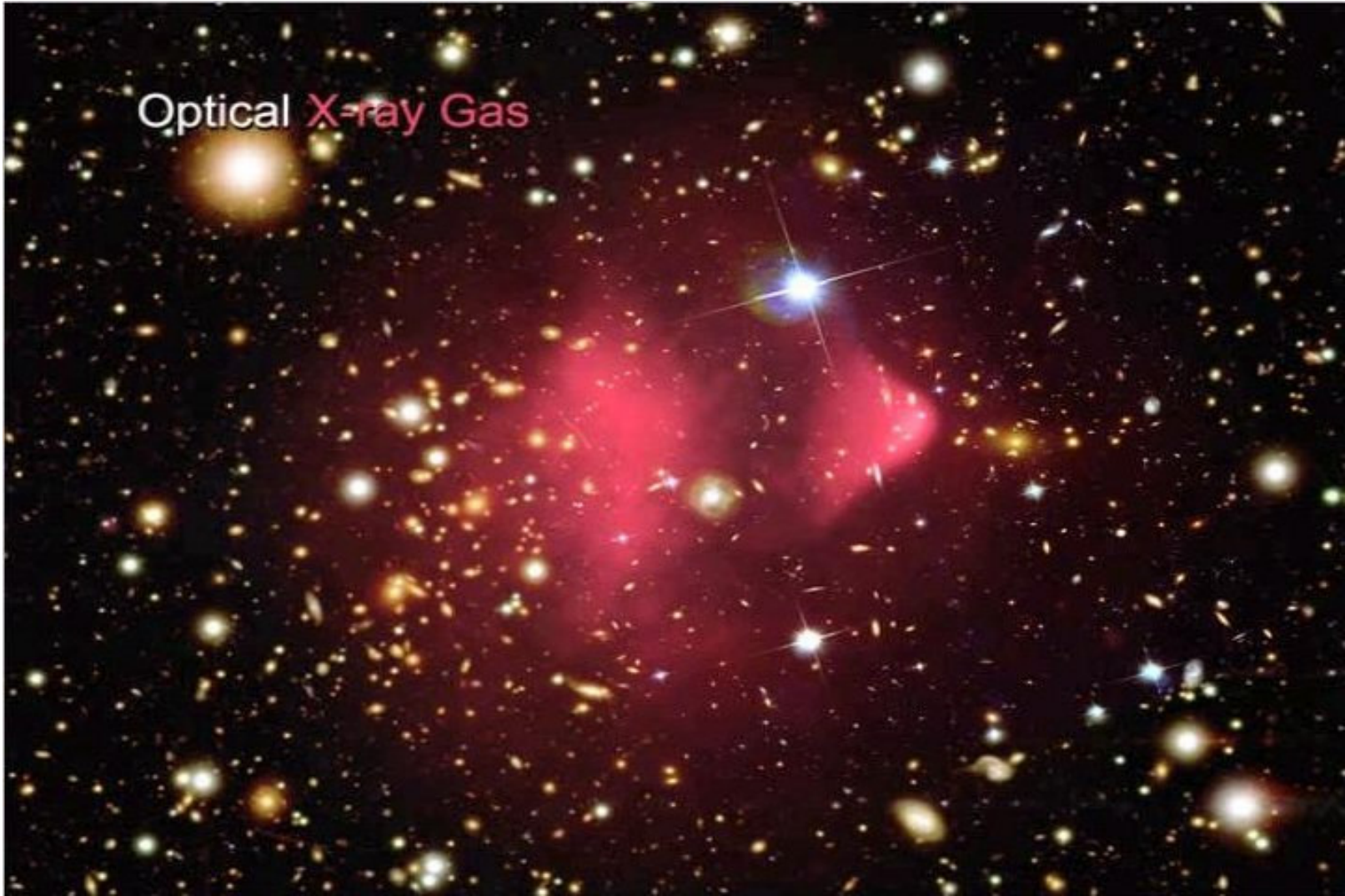


ABSTRACT

We present new weak lensing observations of 1E0657–558 ($z = 0.296$), a unique cluster merger, that enable a direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law. Due to the collision of two clusters, the dissipationless stellar component and the fluid-like X-ray emitting plasma are spatially segregated. By using both wide-field ground based images and HST/ACS images of the cluster cores, we create gravitational lensing maps which show that the gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, but rather approximately traces the distribution of galaxies. An 8σ significance spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law, and thus proves that the majority of the matter in the system is unseen.

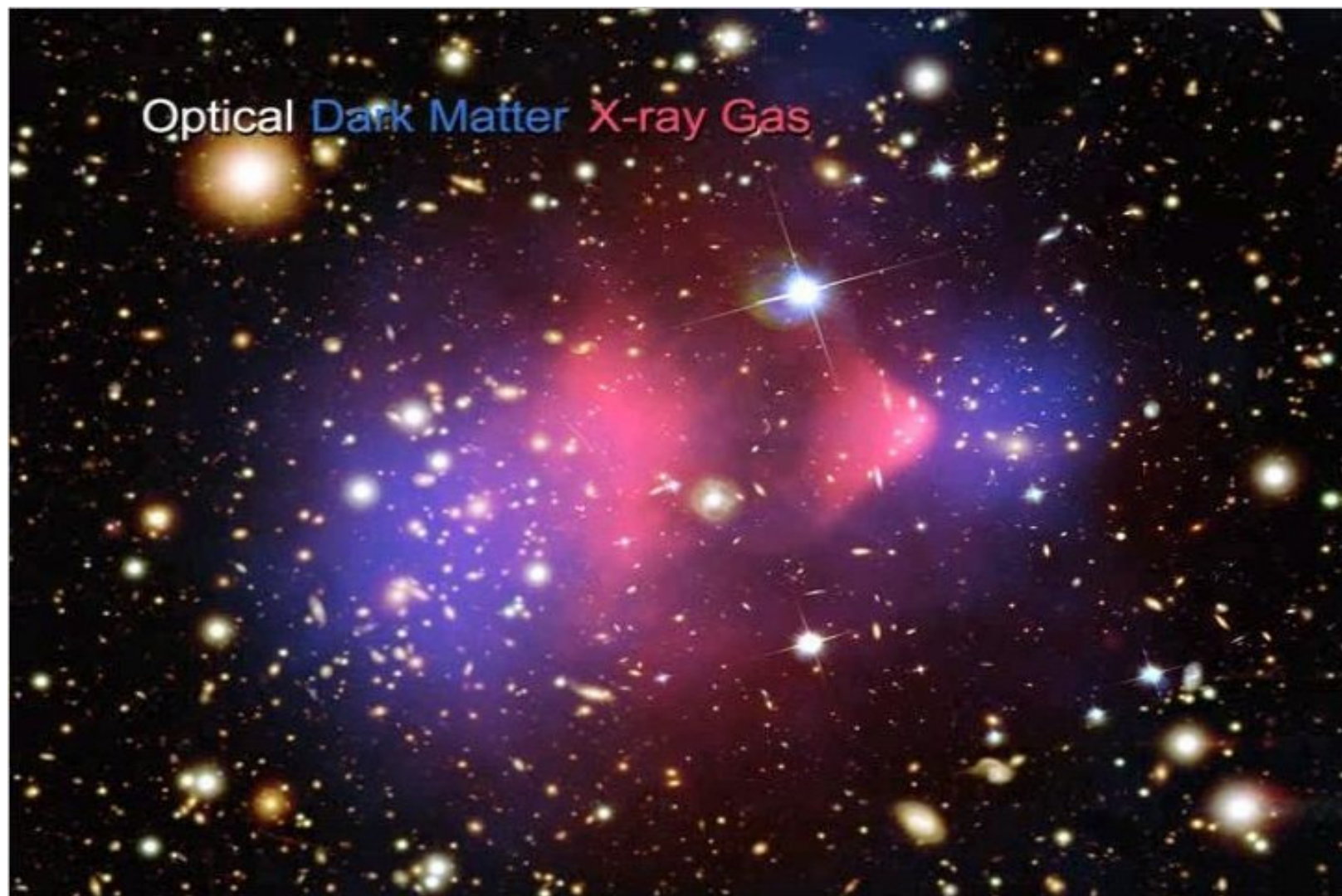






Optical Dark Matter







CIEMNA ENERGIA

EINSTEIN EQUATIONS (1916):

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

FRIEDMAN EQUATIONS (1922):

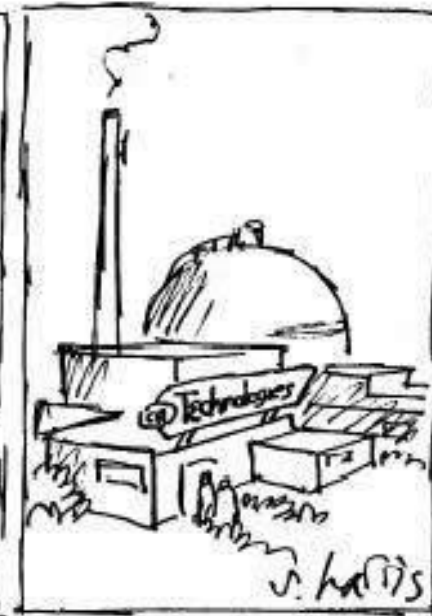
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho + \Lambda}{3} - K\frac{c^2}{a^2}$$

$$3\frac{\ddot{a}}{a} = \Lambda - 4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

BIG SCIENCE



LITTLE SCIENCE



Homogeneous and isotropic
Universe!

IN MORE DETAILS...

$$p \rightarrow p + \frac{\Lambda c^2}{8\pi G}$$
$$\rho \rightarrow \rho - \frac{\Lambda}{8\pi G}$$
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - K\frac{c^2}{a^2}$$
$$3\frac{\ddot{a}}{a} = -4\pi G\left(\rho + \frac{3p}{c^2}\right)$$

The density parameter:

$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G}{3H^2}\rho$$

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_\Lambda - K c^2 a^{-2}$$

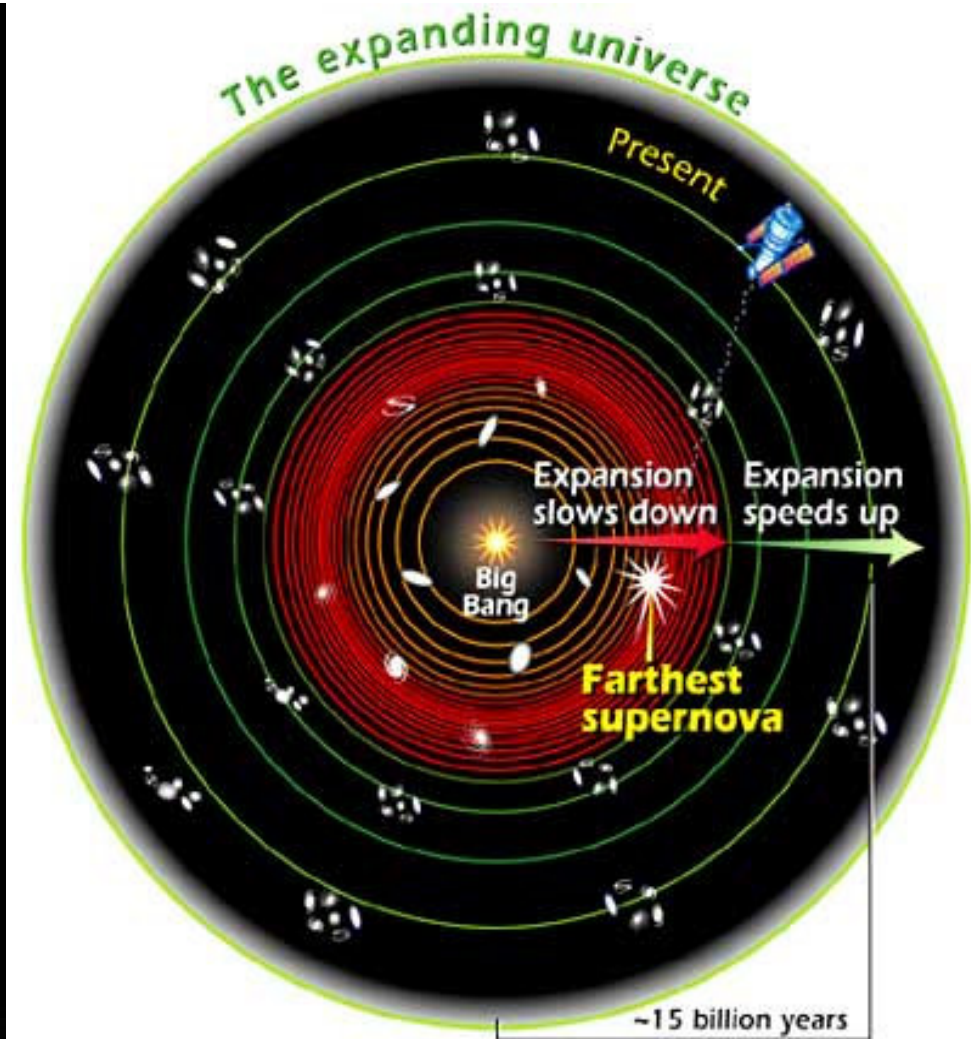
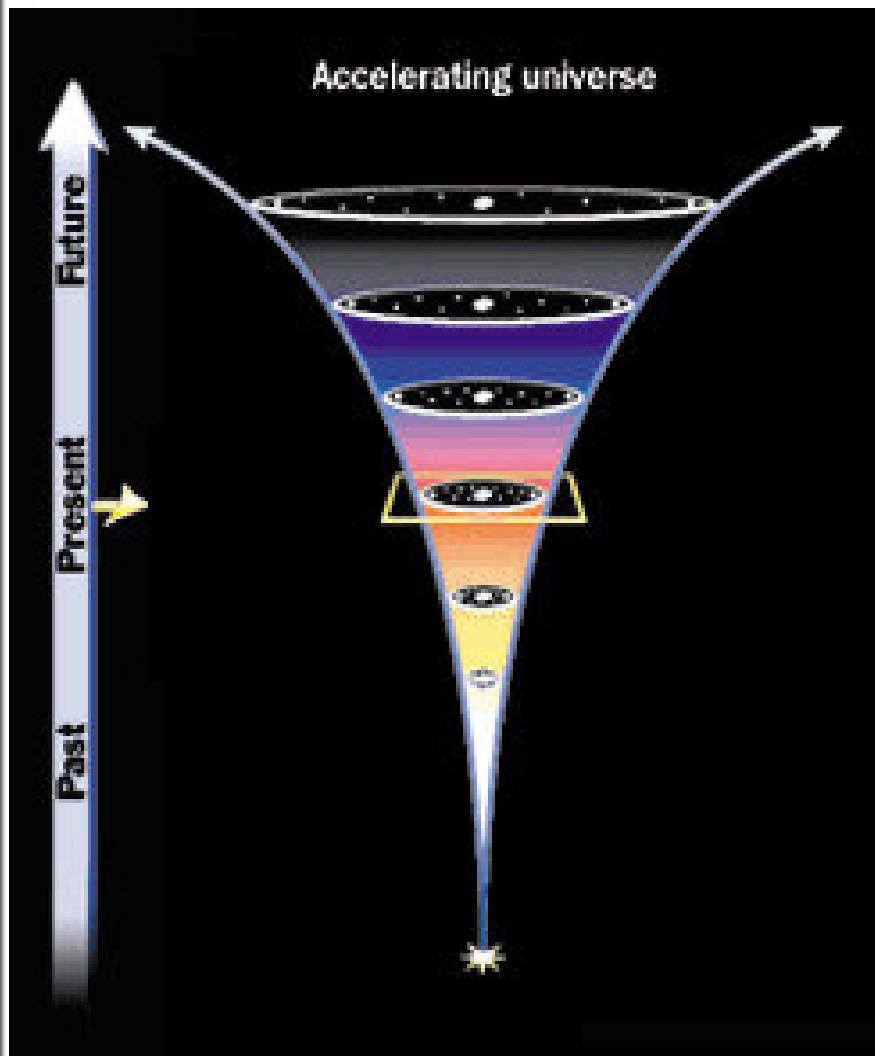
Here we have:

- the radiation density today,
- the matter (dark + baryonic) density today
- vacuum density today (cosmological constant)

Cosmological constant: Λ

- Is this possible in Einstein's General Relativity (GR)?
Yes! : Λ term \rightarrow integration constant \equiv energy of vacuum
 \rightarrow cosmic repulsion
- 1916 : Einstein uses Λ to balance matter \rightarrow static universe
1926 : Hubble discovers expansion
Einstein sets $\Lambda = 0$, says "my biggest blunder"
1998 : acceleration discovered \rightarrow reintroduce $\Lambda \neq 0$
- called "dark energy" (contrast "dark matter")
currently uncertain what it is; vacuum energy ? (6×10^{-10} J/m³)
adds to curvature : currently $\Omega_{\Lambda} = 0.73$ ($\pm 5\%$) \rightarrow dominates!
since ρ_{vac} const \rightarrow unimportant long ago \rightarrow early deceleration
after ~ 6 Gyr, $\rho_{\text{vac}} > \rho_{\text{matter}}$ expansion accelerates (transition seen)
- Future : no recollapse; infinite future; increasingly lonely....

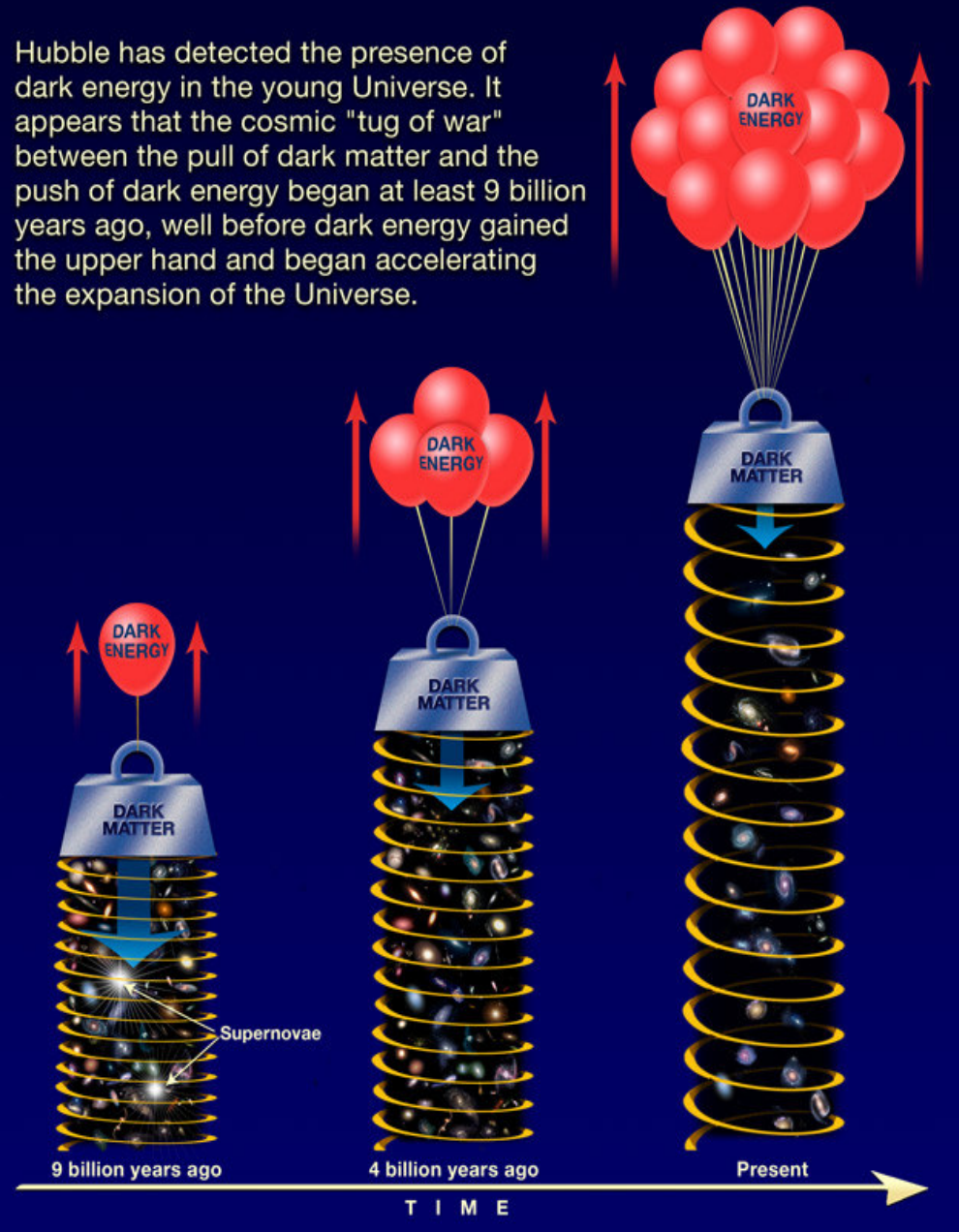
PRZYSPIESZAJĄCY WSZECHŚWIAT!!!



Whatever this pushing force is, we *think* that it is growing stronger as the universe evolves. The more empty space in the universe, the greater the acceleration – as if the vacuum of space has pressure!

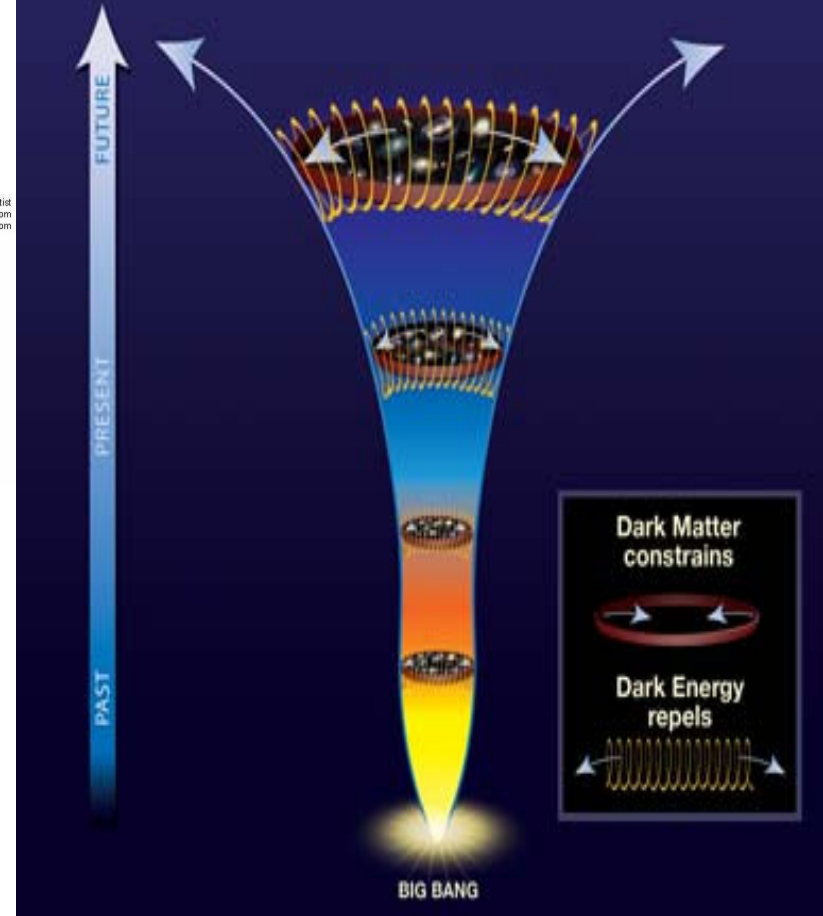
Hubble witnesses a cosmic tug of war

Hubble has detected the presence of dark energy in the young Universe. It appears that the cosmic "tug of war" between the pull of dark matter and the push of dark energy began at least 9 billion years ago, well before dark energy gained the upper hand and began accelerating the expansion of the Universe.



Cosmic tug of war

The force of dark energy surpasses that of dark matter as time progresses.



QUESTIONS?

