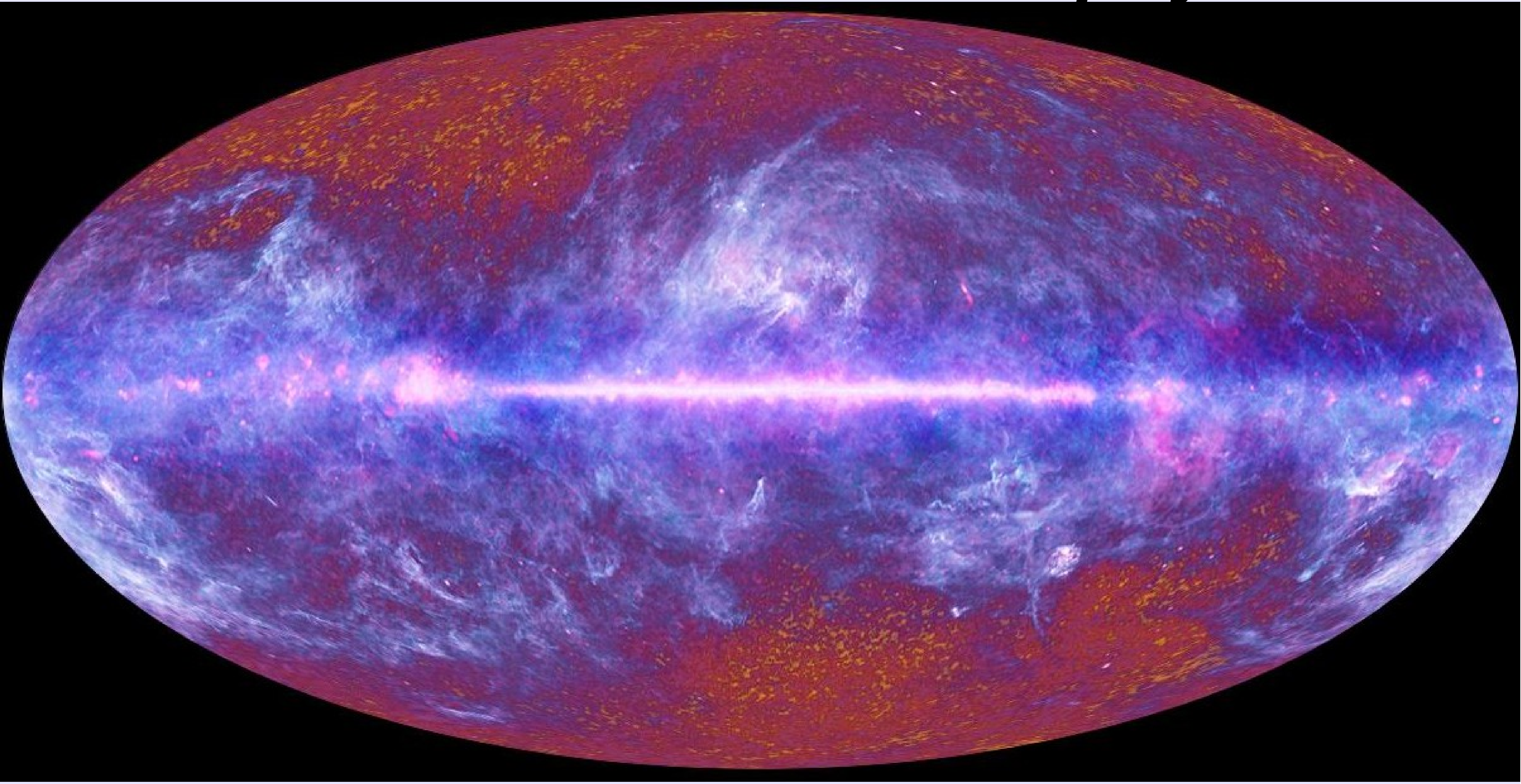
Introduction to the CMB physics



Grupo de Gravitação e Cosmologia,Vitória, UFES
Hermano Velten
23/09/2013

Let's start remembering Hubble's work

Edwin Hubble

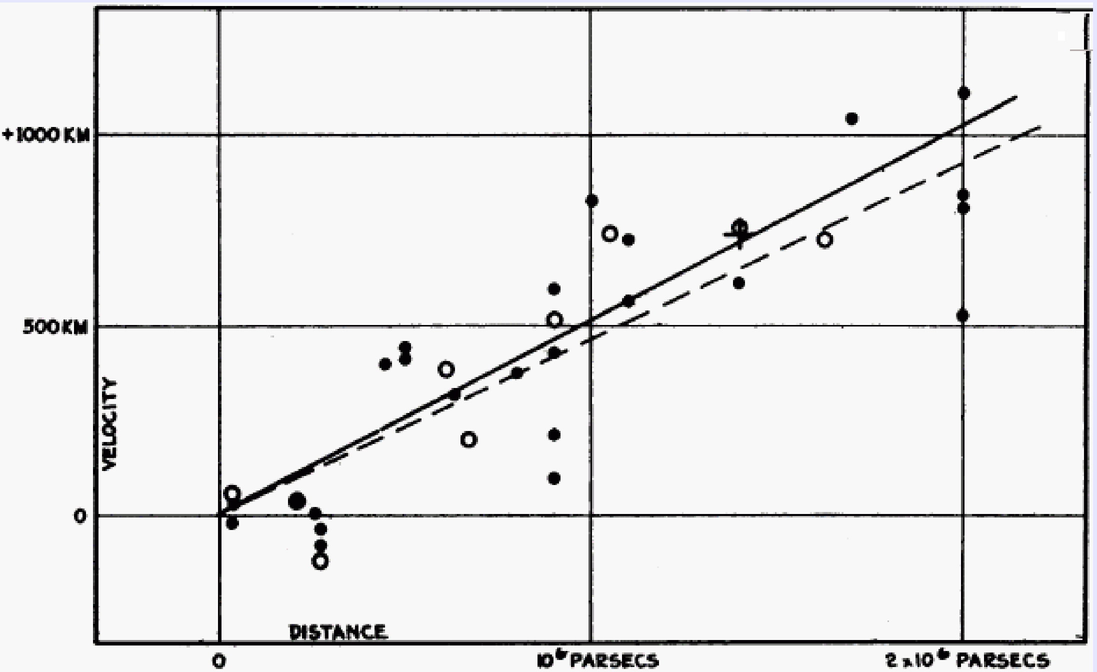


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

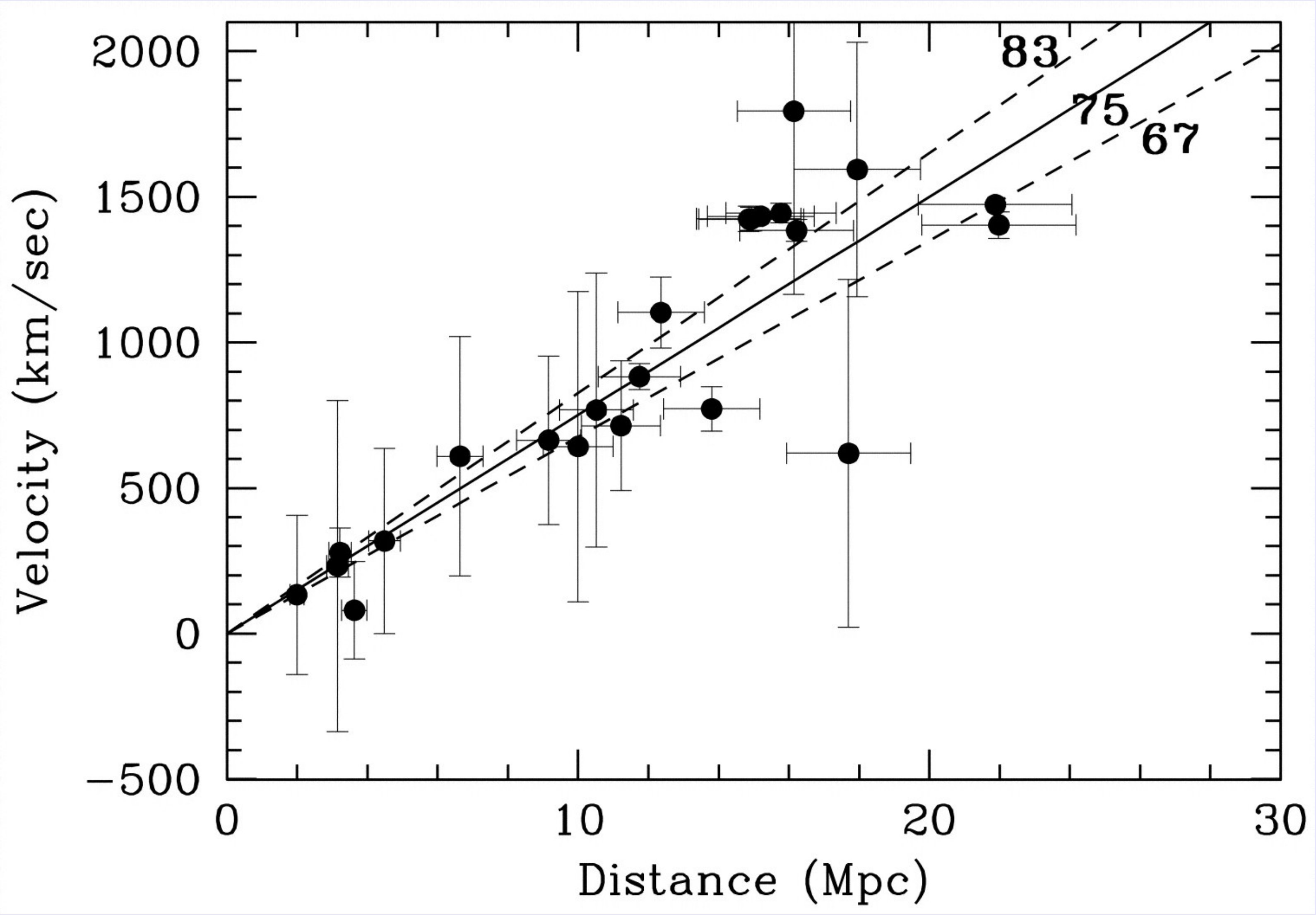
For each galaxy he could identify a known pattern of atomic spectral lines (from their relative intensities and spacings) which all exhibited a common redward frequency shift by a factor 1+z. His fundamental discovery was that the velocities of distant galaxies he had studied increased linerly with distance

$$v = H_0 r$$

This is the Hubble's law (1929)

Main message: The Universe is expanding following the Hubble's flow

Hubble law (recent data)



Freedman et al. (2001), The Astrophysical Journal 553, 47

Let's continue remembering basic definitions

The redshift (z) can be seen as a measure of time or distance. It is a new variable related to the expansion parameter (a), the scale factor.

$$1 + z = \frac{a_0}{a}$$

The emitted wavelenght of the radiation from a distance source (a galaxy, for example) is shifted when it its observed (today)

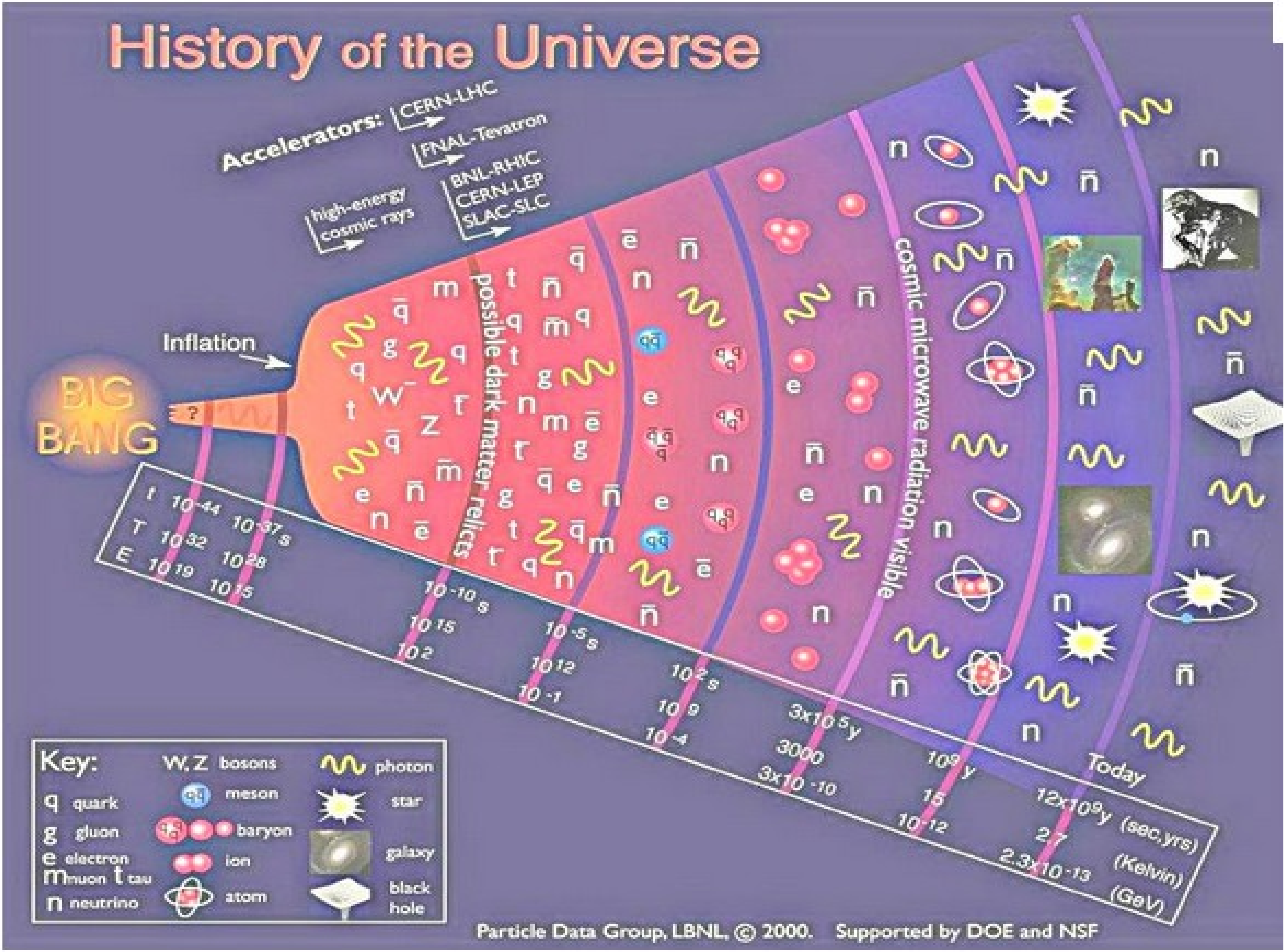
$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e}.$$

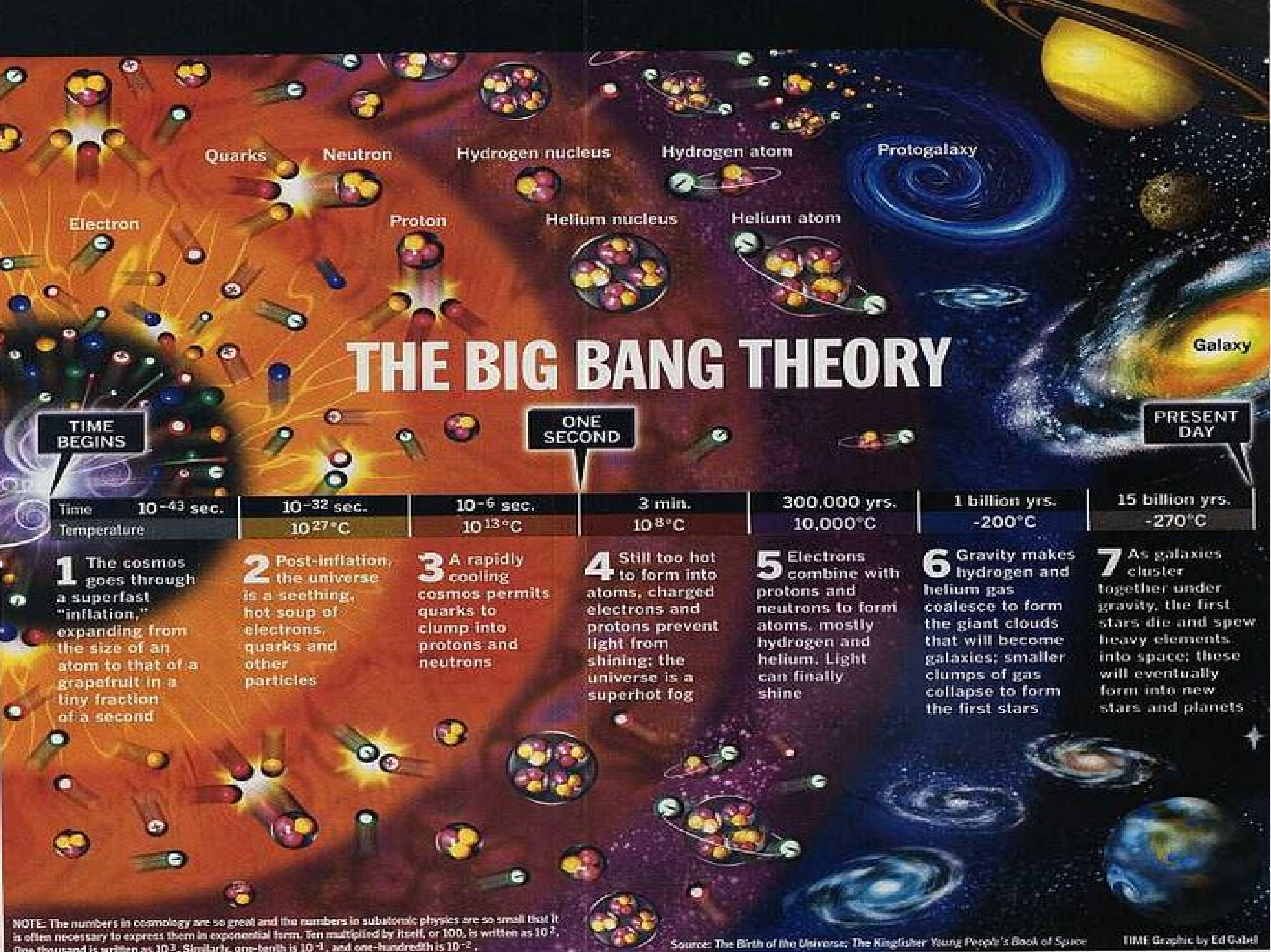
The wavelenght from Andromeda M31 is blue-shifted!

Some astronomical numbers

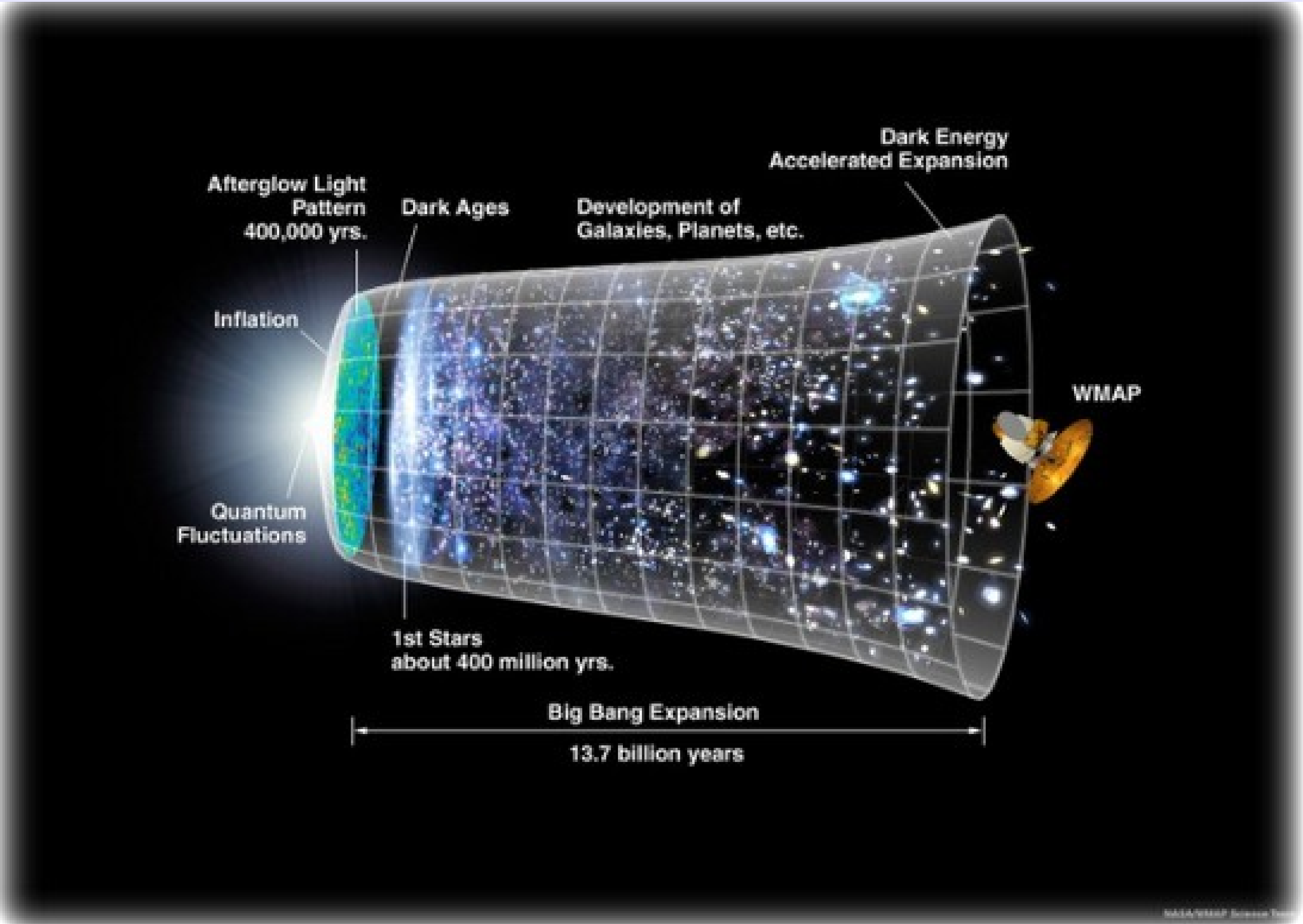
- Distance is usually measured in Parsecs: 1parsec= 3.09 x 10^{16} m
- One light year = 9.46 x 10^{15} m
-

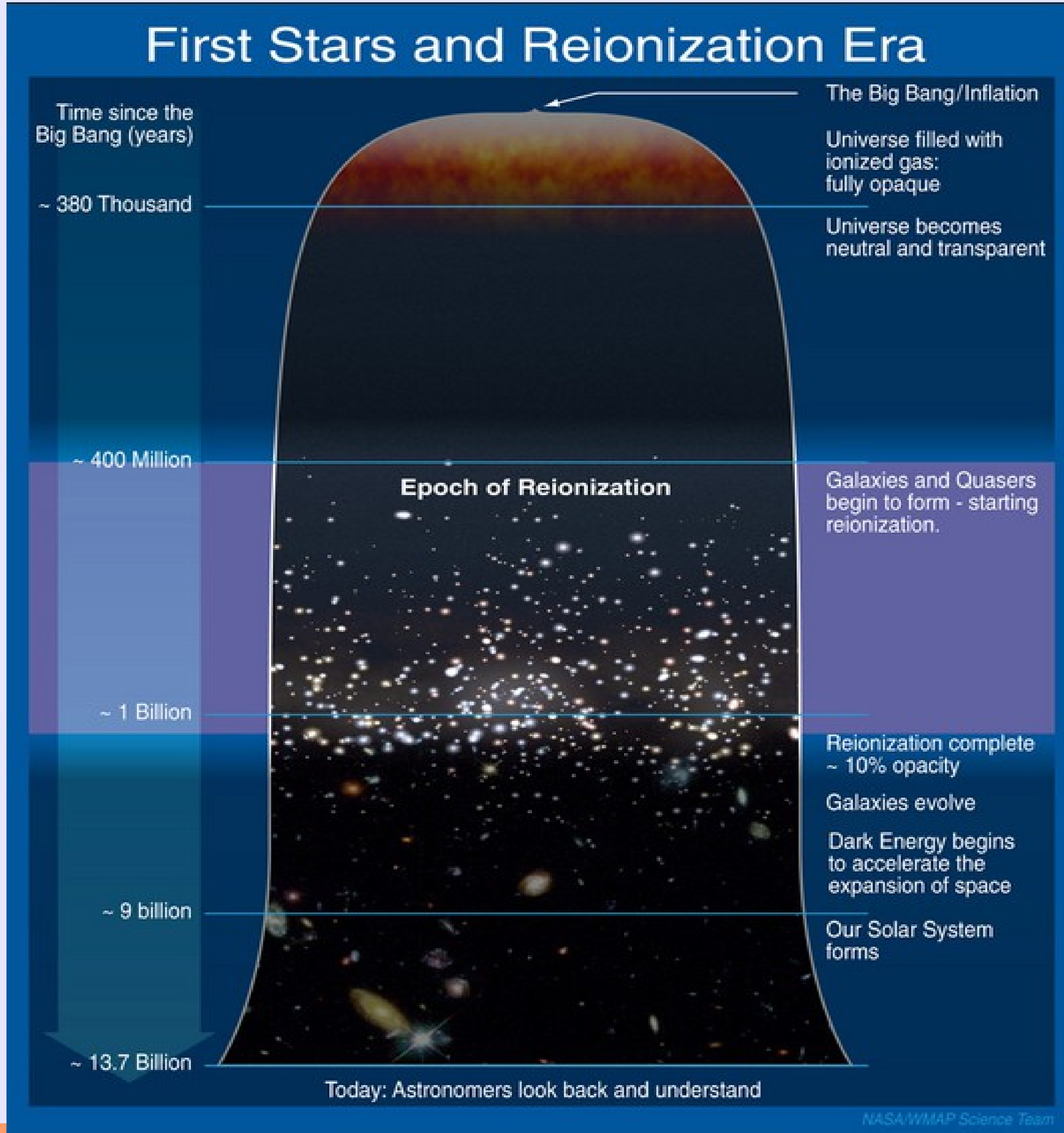
Distance to the nearest star (α Centauri) 1.3 pc
Diameters of globular clusters 5–30 pc
Thickness of our Galaxy, the ‘Milky Way’ 0.3 kpc
Distance to our galactic centre 8 kpc
Radius of our Galaxy, the ‘Milky Way’ 12.5 kpc
Distance to the nearest galaxy (Large Magellanic Cloud) 55 kpc
Distance to the Andromeda nebula (M31) 770 kpc
Size of galaxy groups 1/h Mpc
Thickness of filament clusters 5/*h* Mpc
Distance to the Local Supercluster centre (in Virgo) 17 Mpc
Distance to the ‘Great Attractor’ 44/h Mpc
Size of superclusters 50/*h* Mpc
Size of large voids 60/*h* Mpc
Distance to the Coma cluster 100/*h* Mpc
Length of filament clusters 100/*h* Mpc
Size of the ‘Great Wall’ > 60 × 170/*h^{2}* Mpc2
Hubble radius 3000/*h* Mpc

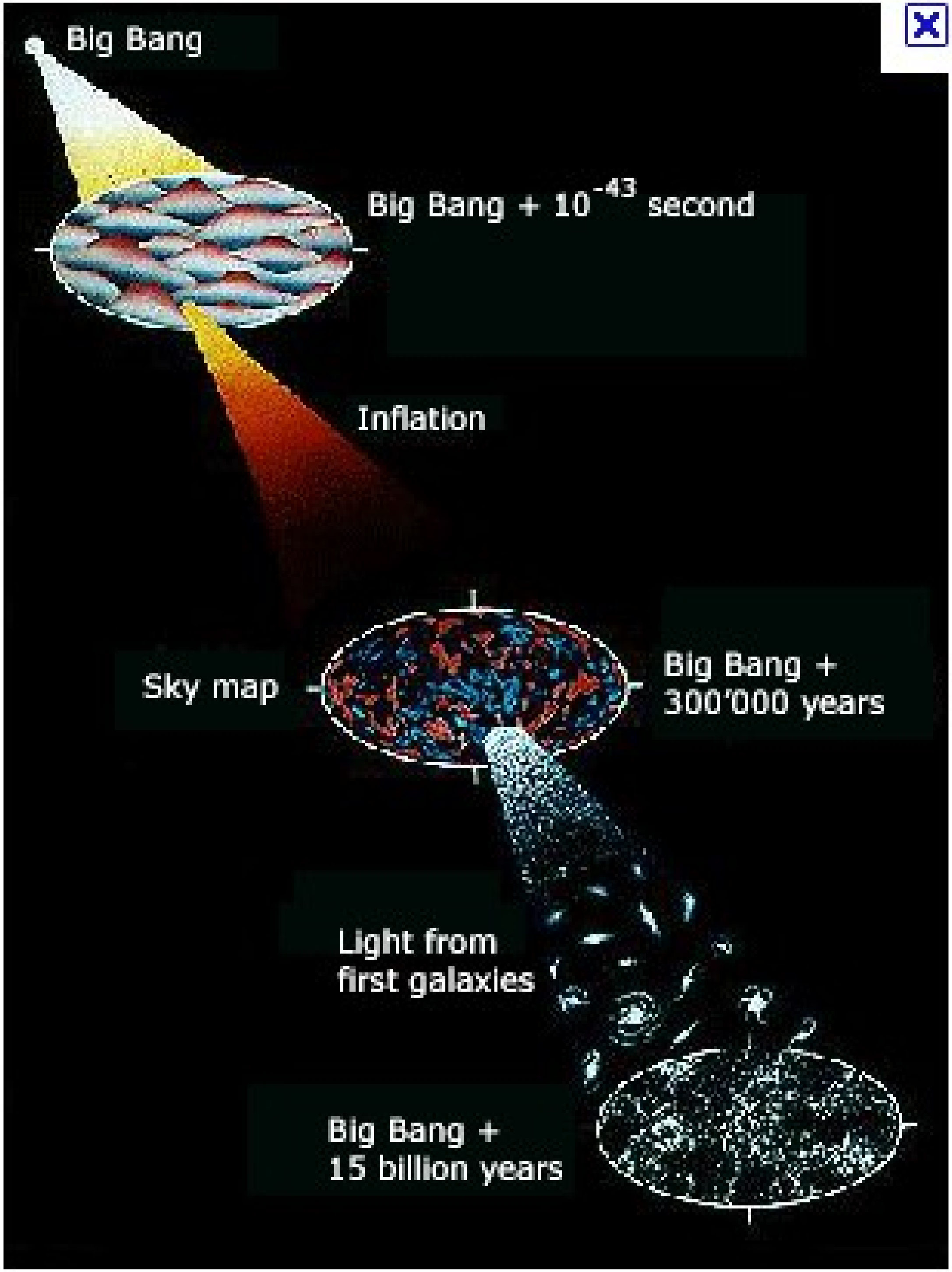

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



THE BIG BANG THEORY
Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time: 10^{-43} sec. | 10^{-32} sec. | 10^{-6} sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature: 10^{27}°C | 10^{13}°C | 10^{8}°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining: the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10^{2}. One thousand is written as 10^{3}. Similarly, one-tenth is 10^{-1}, and one-hundredth is 10^{-2}.
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasers begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team



- Quantum fluctuations present at the primordial matter/fields distribution.Seeds for galaxy formation

- One has Inflation during ~60 e-folds
- Microscopic fluctuations became macroscopic.

- Matter-Radiation equality: z~3000

- The LSS (z~1000): level of inhomogeneity is around 0.00001!!

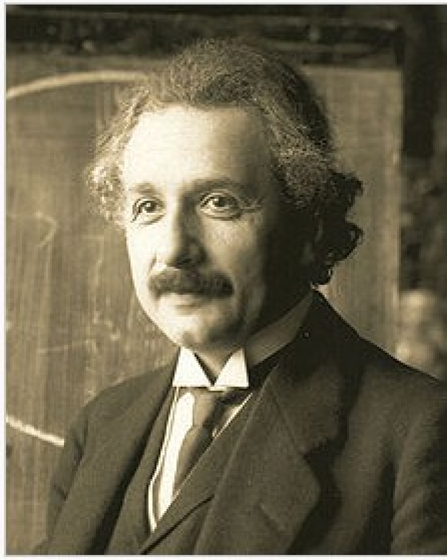
- Structure formation Epoch: from 200.000 yrs untill today!

- Reionization at 1Gy or z~15. End of the Dark Ages.
- Observable range for Supernovae z<1.5

Let's continue remembering basic definitions

FLRW metric

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$



Albert Einstein, 1921

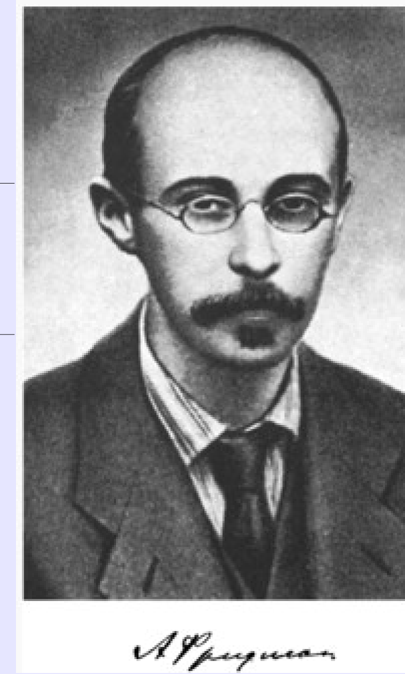
1915

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\dot\rho + 3\frac{\dot a}{a}(\rho + p) = 0$$

1922

Alexander Friedman



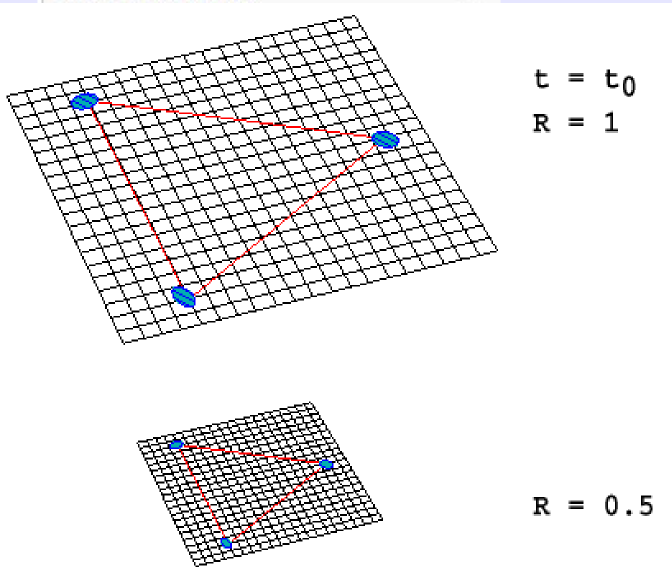
$$H^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

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

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

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

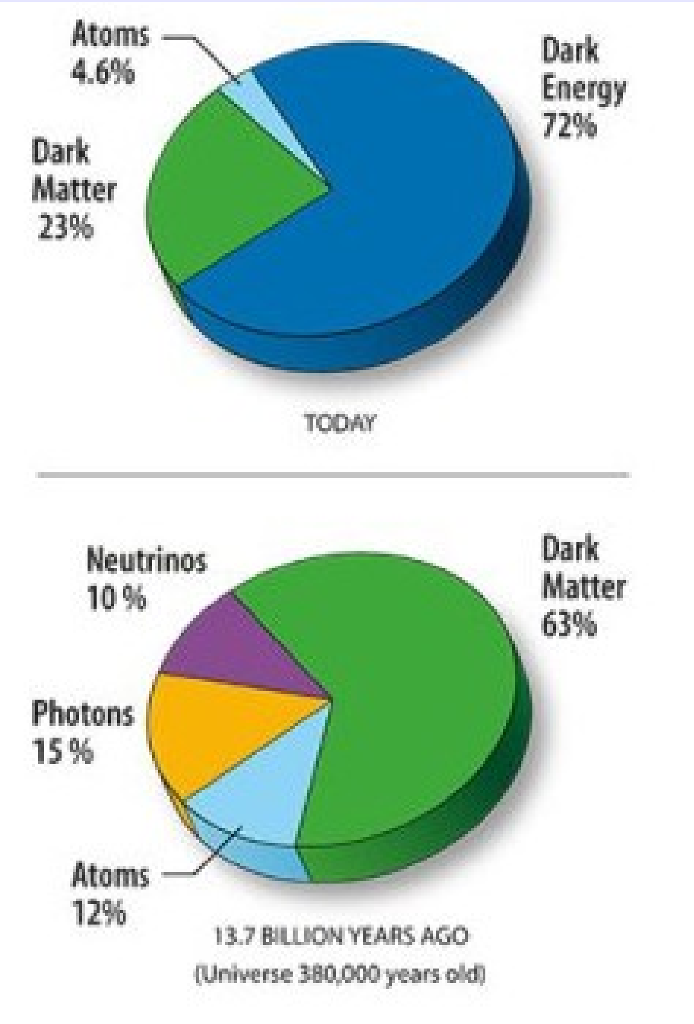
$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$



$$\dot\rho_r + 4\frac{\dot a}{\rho_r} = 0 \Rightarrow \rho_r = \rho_{r0}a^{-4},$$

$$\dot\rho_m + 3\frac{\dot a}{\rho_m} = 0 \Rightarrow \rho_m = \rho_{m0}a^{-3}$$

Matter content of the Universe

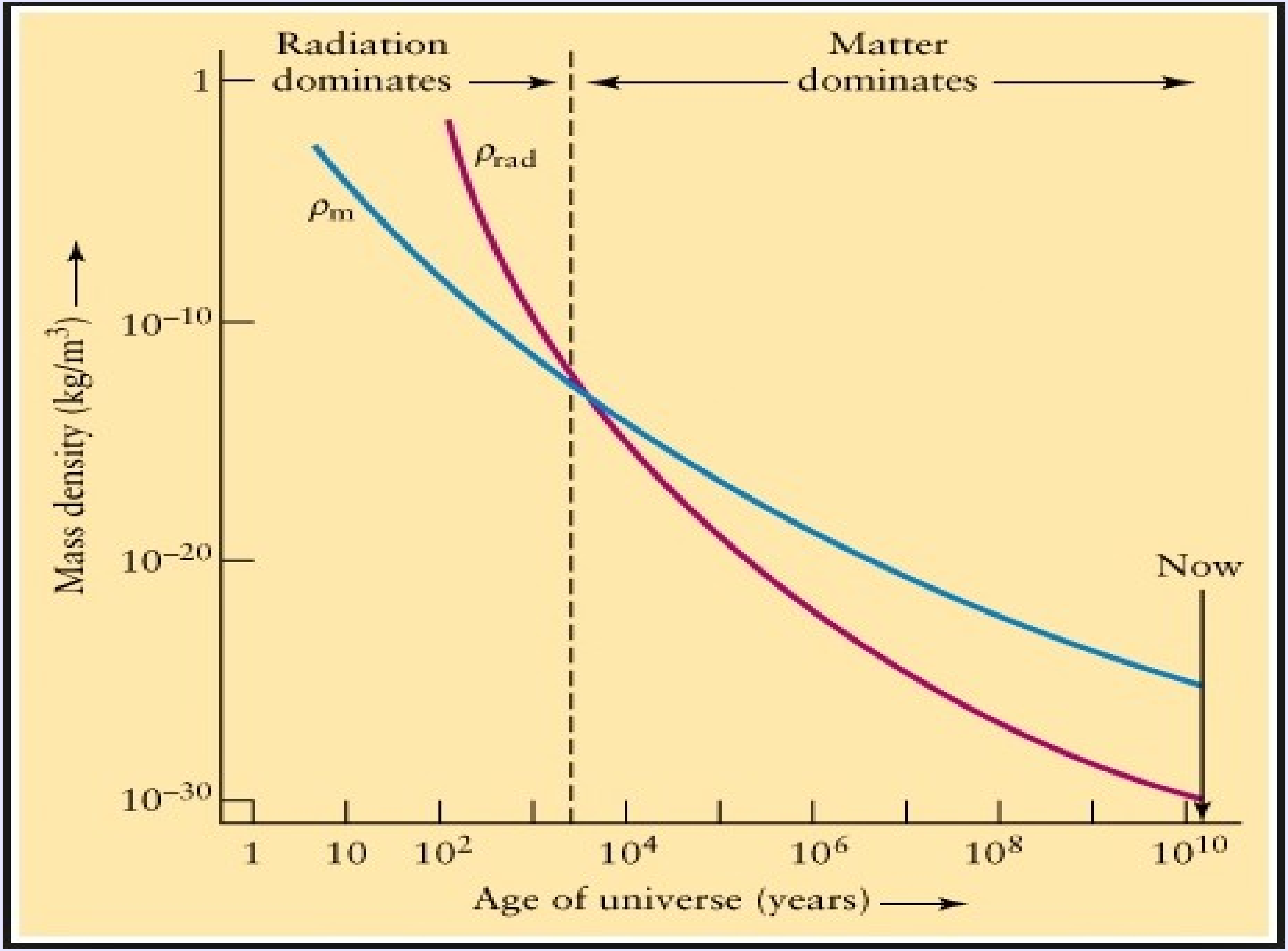


Standard description:

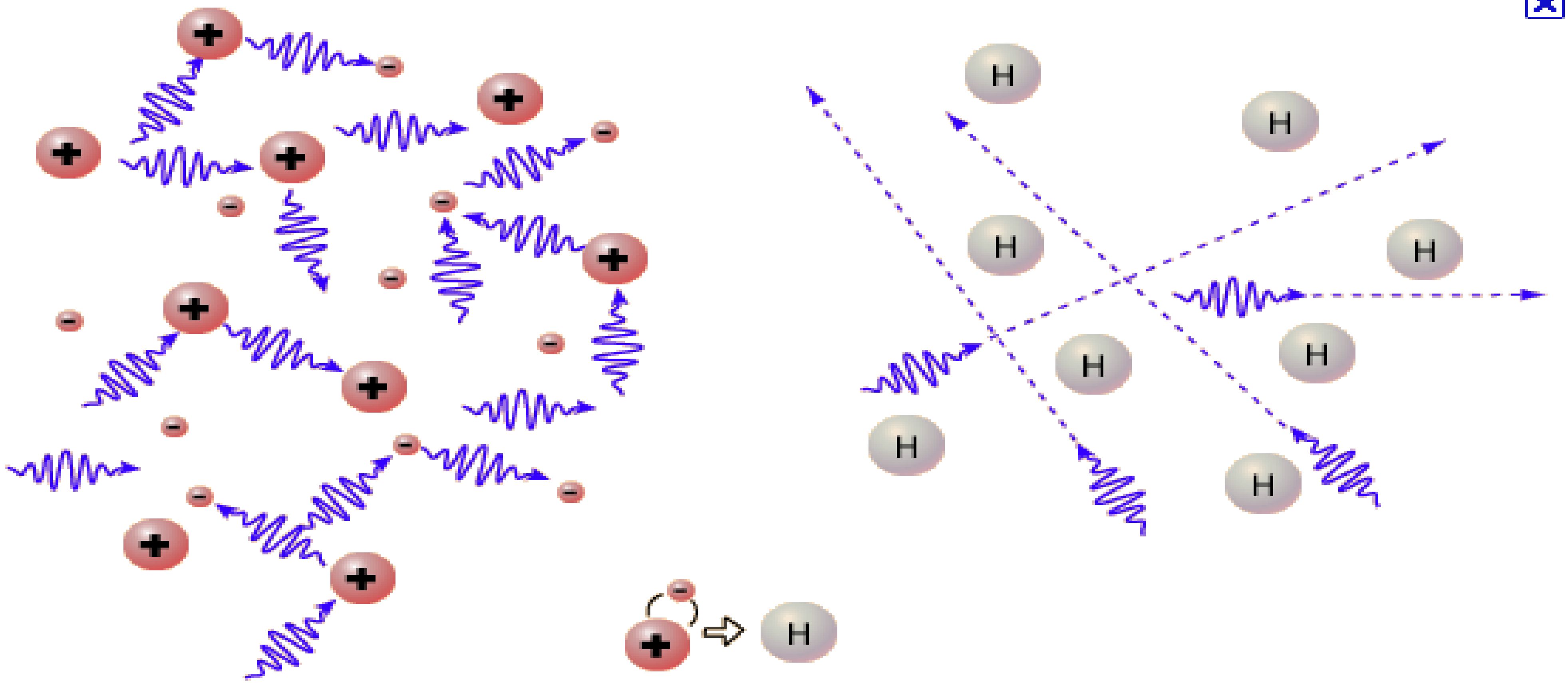
- Baryoninc Matter (~5%)
- Neutrinos & Photons (~0.08%)
- Cold Dark Matter (p=0)(~25%)
- Dark Energy (Lambda?)(~70%)

$$H^2 = H_0^2 \{\Omega_{Bar} + \Omega_{Pho} + \Omega_{Neu} + \Omega_{DM} + \Omega_{DE}\}$$

$$H^2 = H_0^2 \left[\frac{\Omega_{b0} + \Omega_{dm0}}{a^3} + \frac{\Omega_{r0}}{a^4} + \Omega_\Lambda\right]$$


Radiation
dominates
Matter
dominates
ρ_{rad}
ρ_m
1
10^{-10}
10^{-20}
10^{-30}
Mass density (kg/m^3)
Now
1
10
10^2
10^4
10^6
10^8
10^{10}
Age of universe (years)

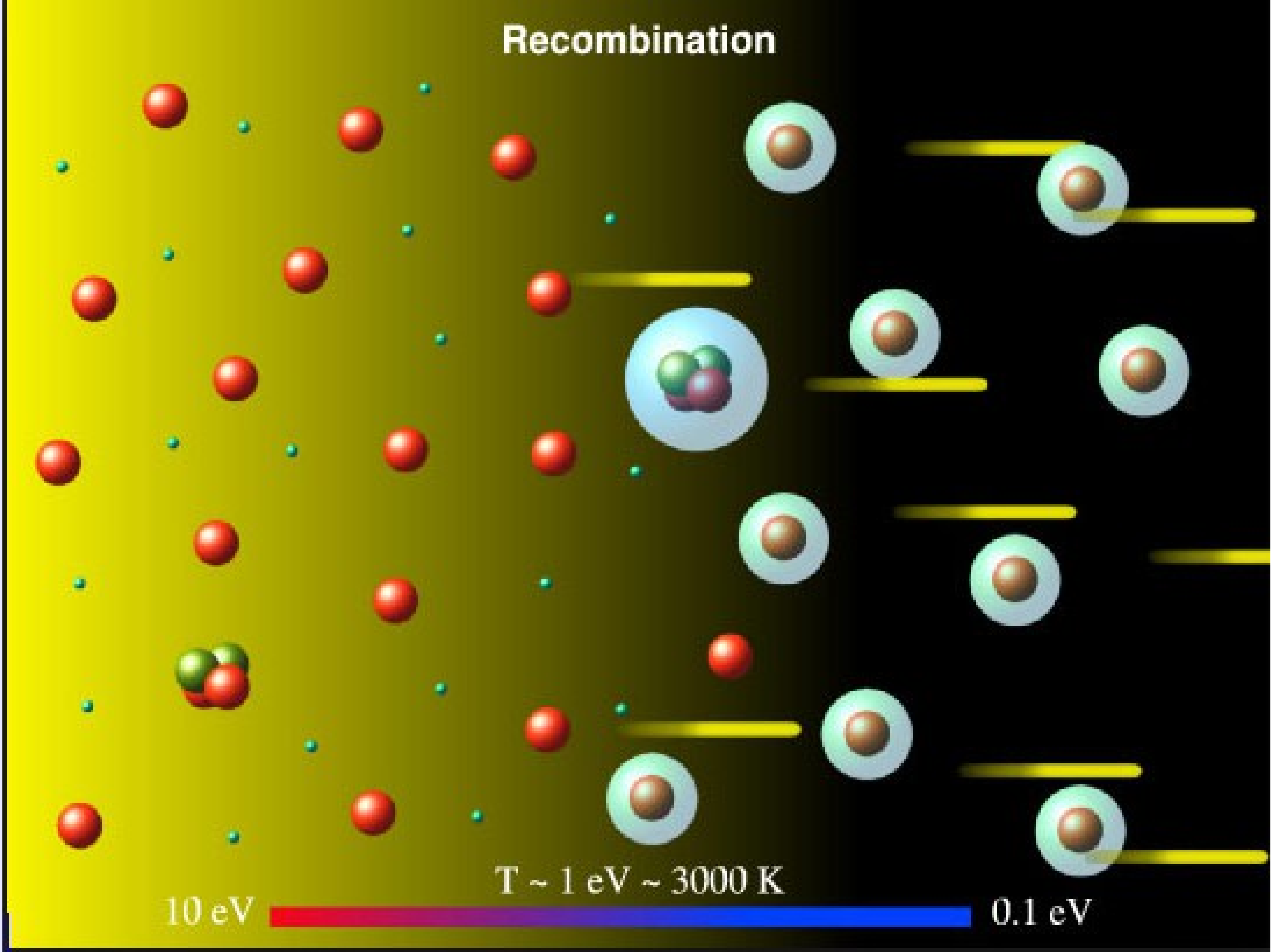
What happens at the Last Scattering Surface (LSS) Recombination and Decoupling (the origin of the CMB)



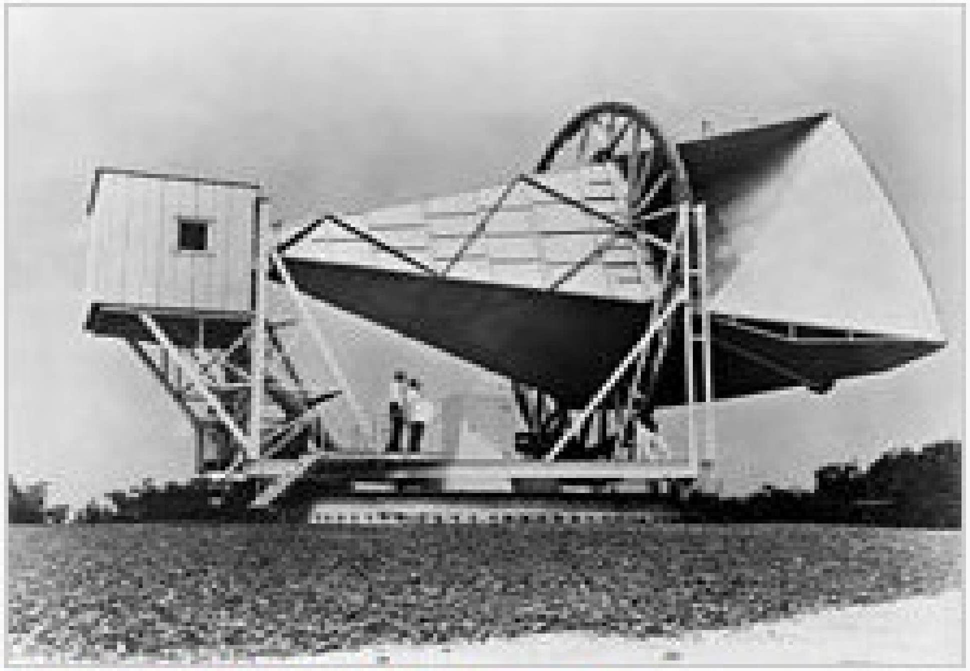
At high temperatures, a hot plasma of charged particles interacts strongly with the radiation. That effectively confines it in the interior of stars and in the early universe.

Below about 3000K, protons and electrons can combine into neutral hydrogen.

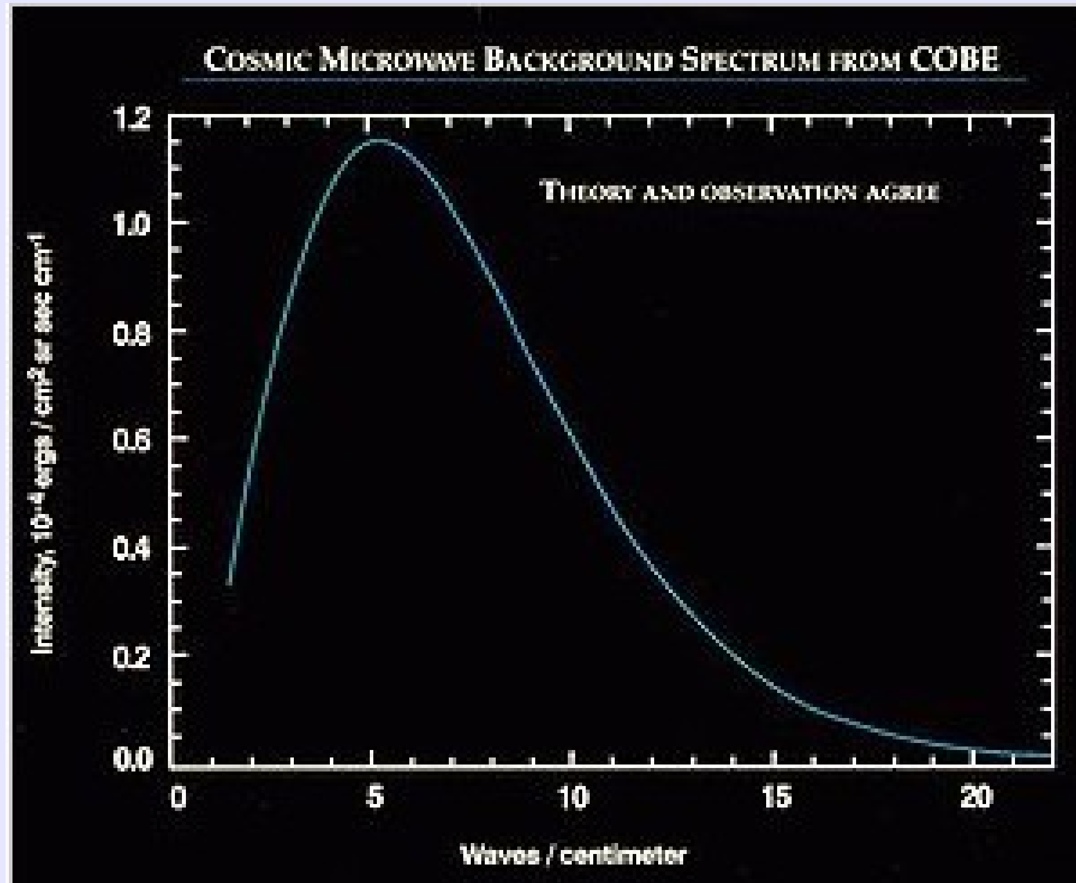
Photons can travel large distances in the neutral hydrogen, so the confinement is effectively broken. Photons can move freely throughout the space.


Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV

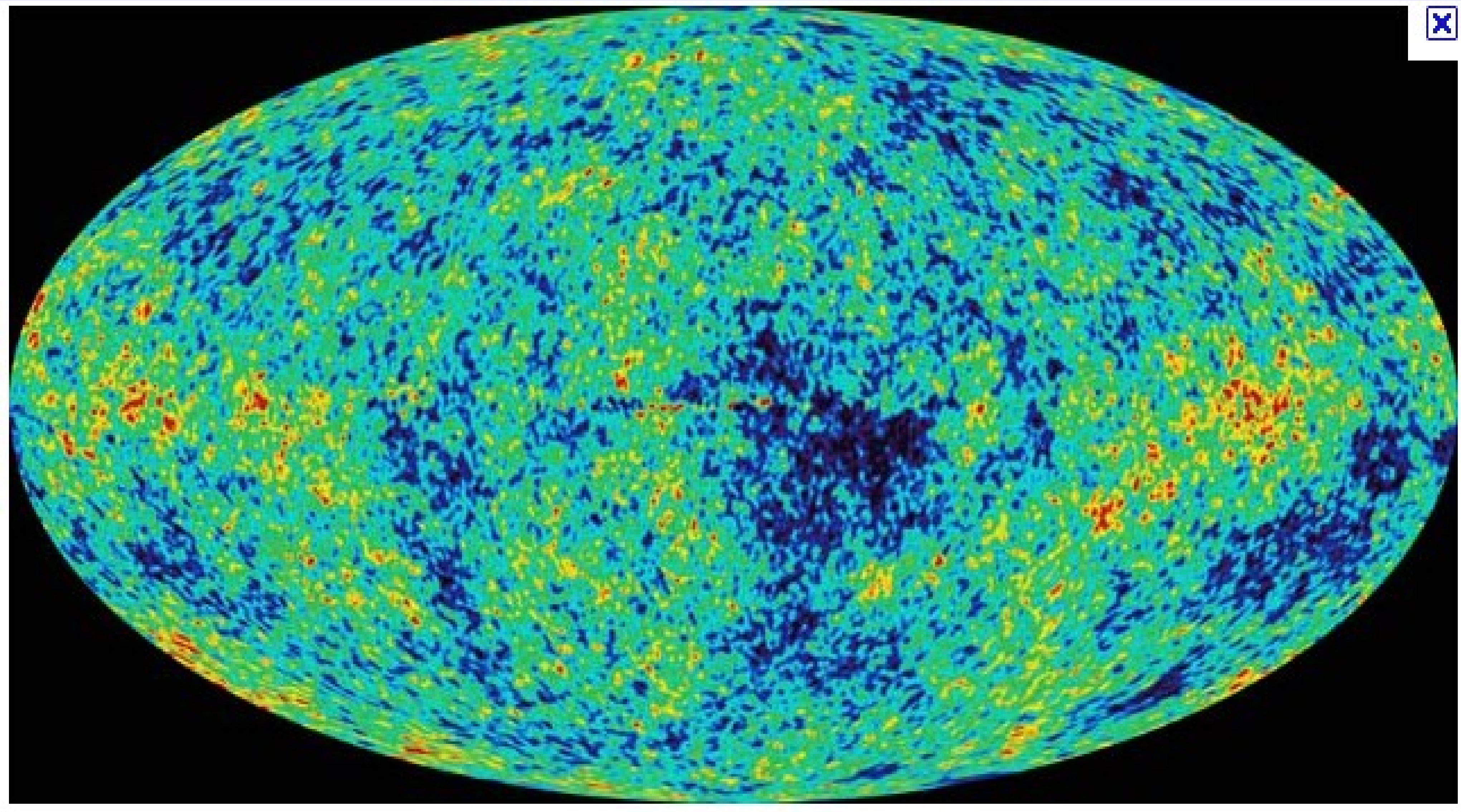
The cosmic microwave background (CMB) radiation



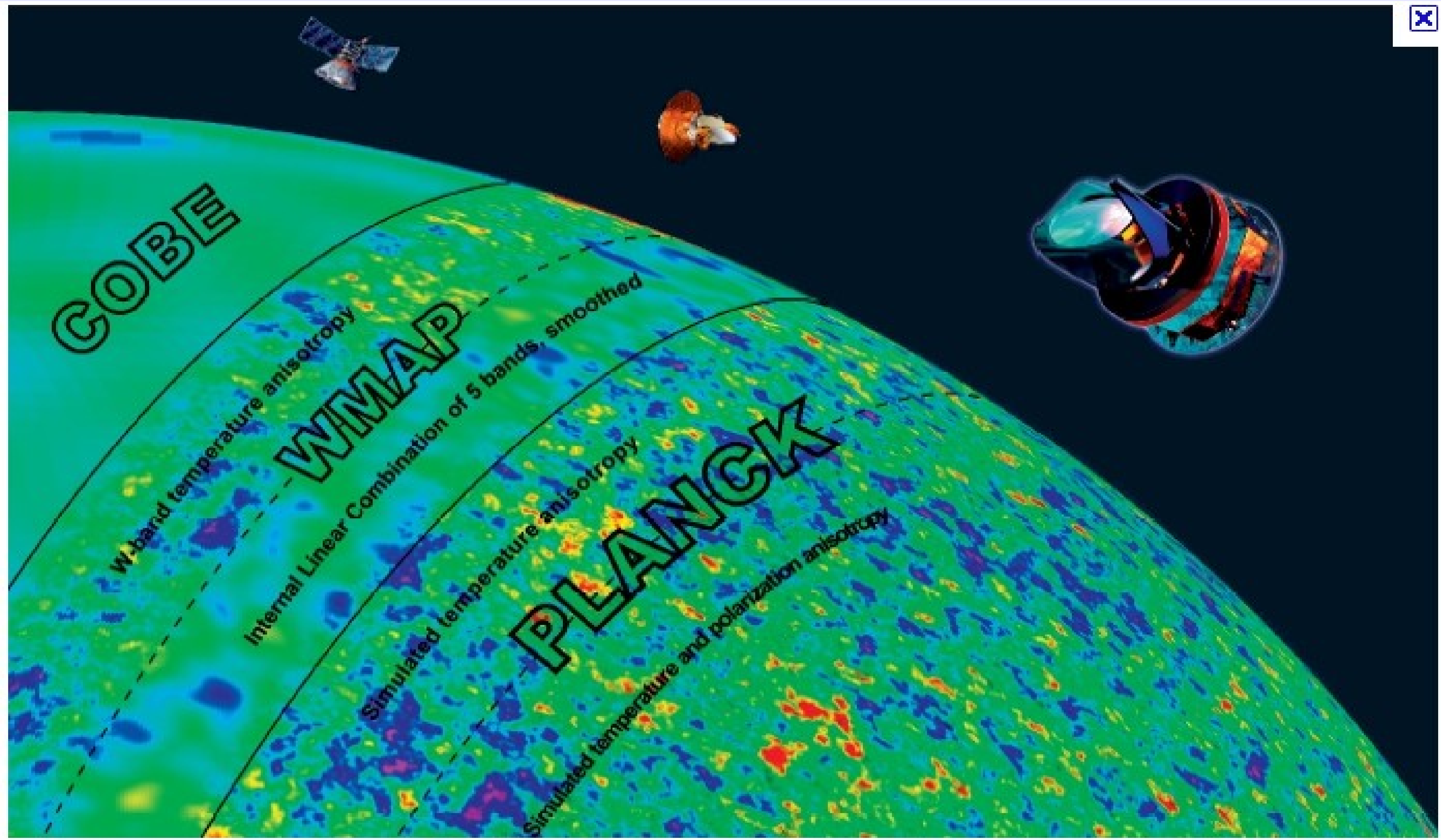
The Holmdel Horn Antenna on which Penzias and Wilson discovered the cosmic microwave background.

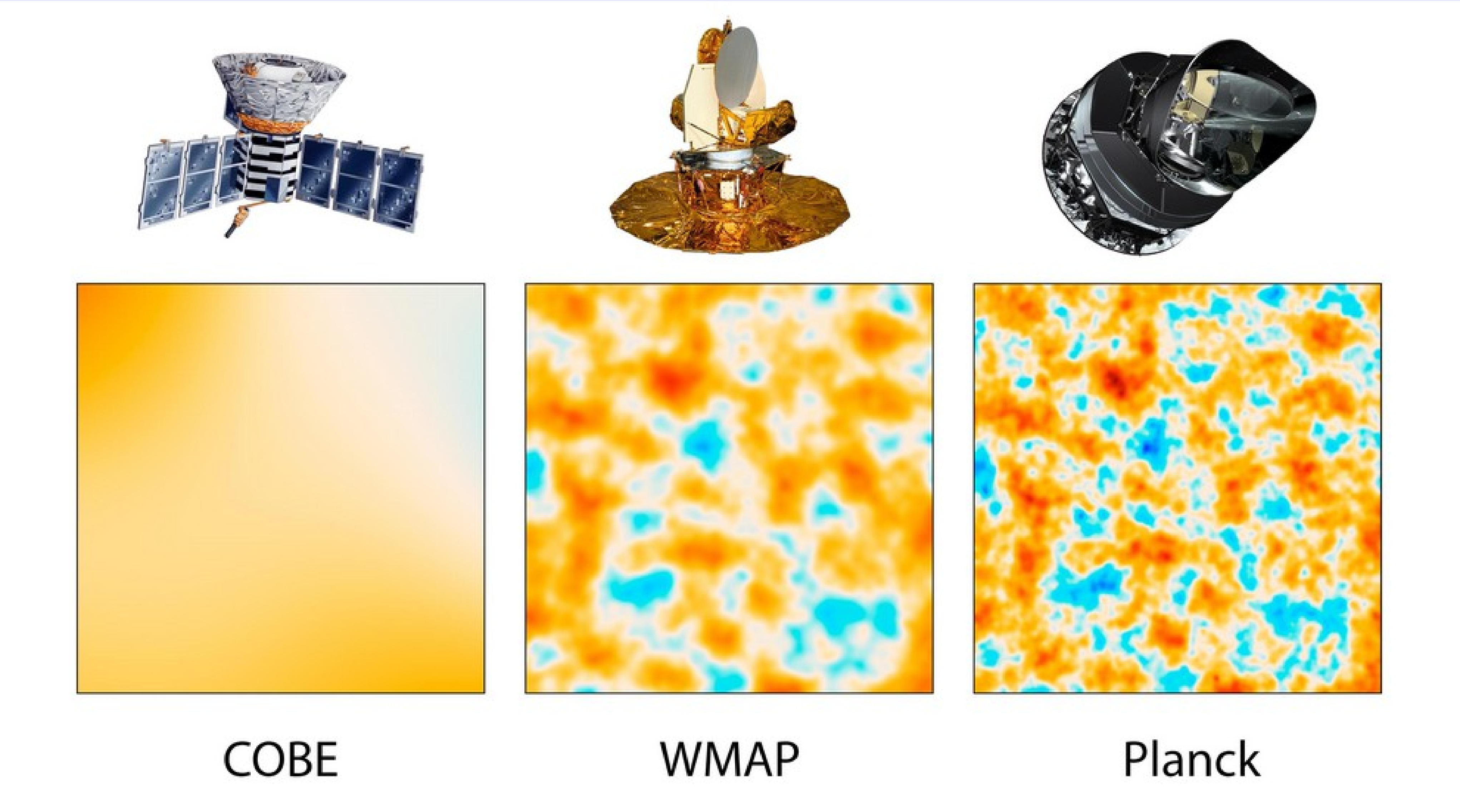


A "thermal picture" of the radiation that fills the Universe
Fluctuations of order ~ 0.00001 K



Evolution of the observations 1990ths, 2000ths, 2010ths




COBE
WMAP
Planck

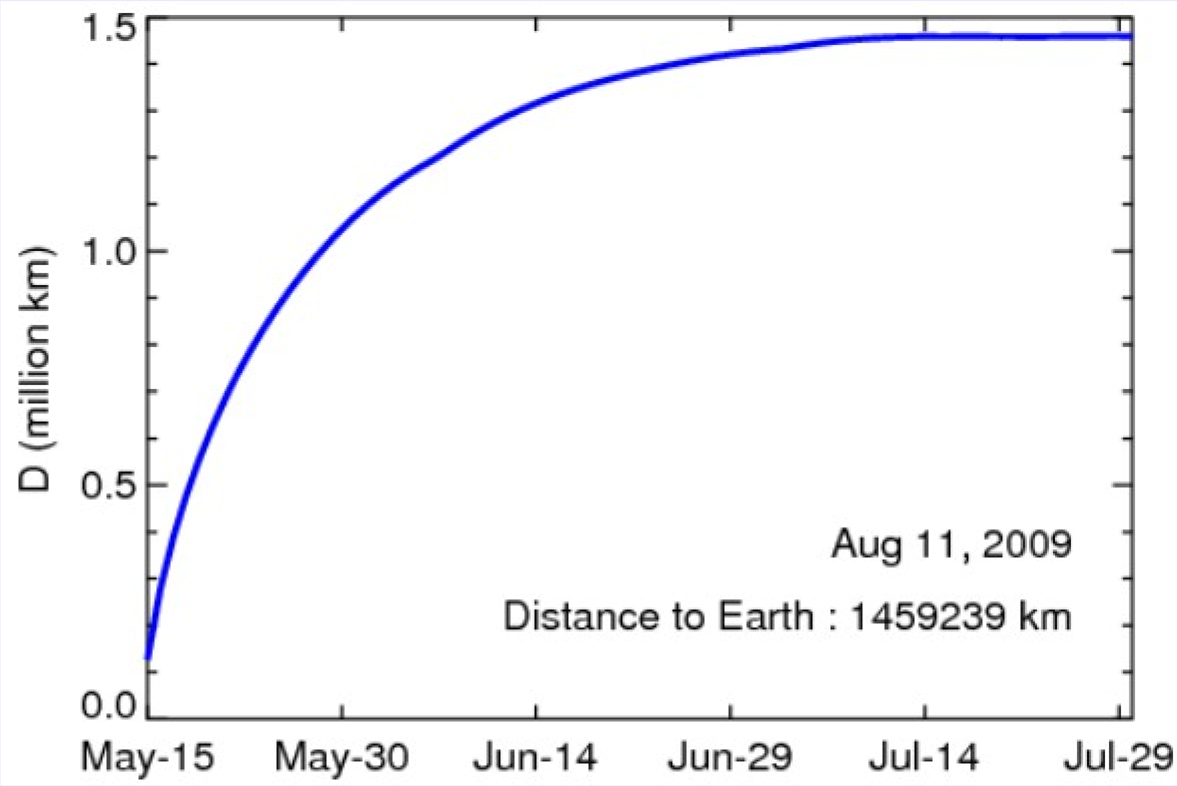
Planck satellite – European Spatial Agency

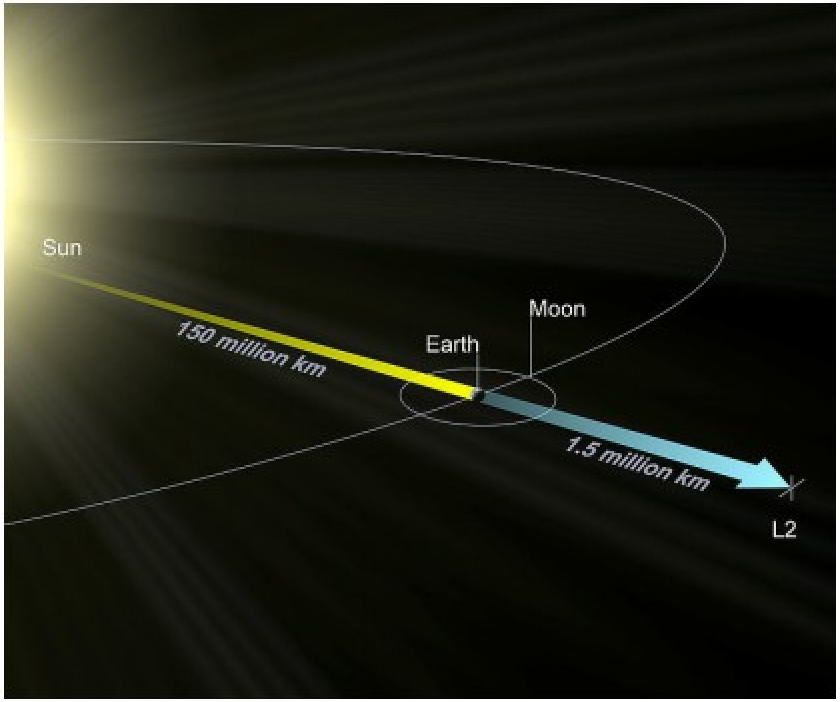
Flight to Kourou, French Guiana

CSL (Liege) 18th February 2009

Launch day: Kourou, French Guiana, 14th May 2009.

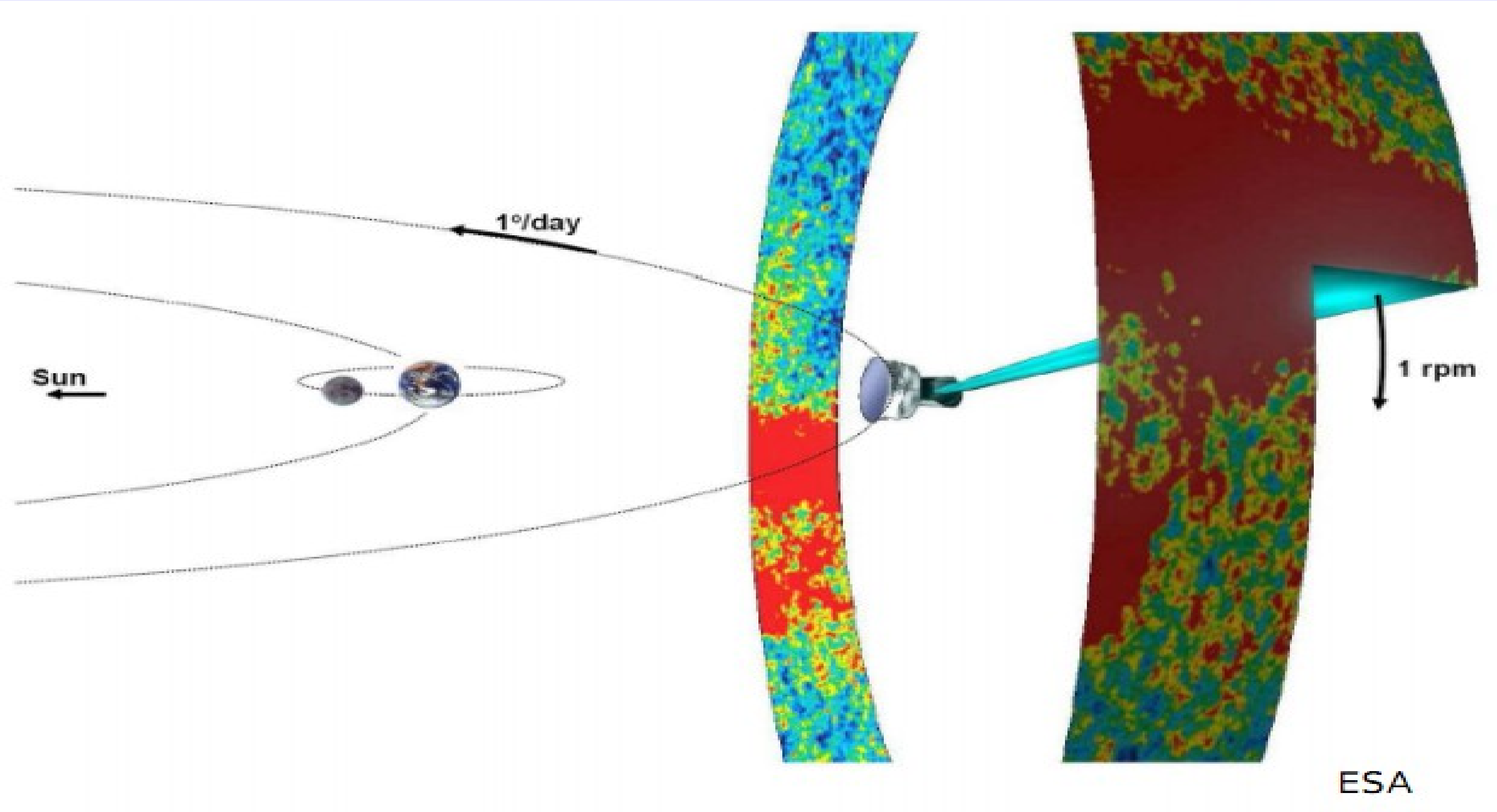
The travel


D (million km)
1.5
1.0
0.5
0.0
May-15
May-30
Jun-14
Jun-29
Jul-14
Jul-29
Aug 11, 2009
Distance to Earth : 1459239 km

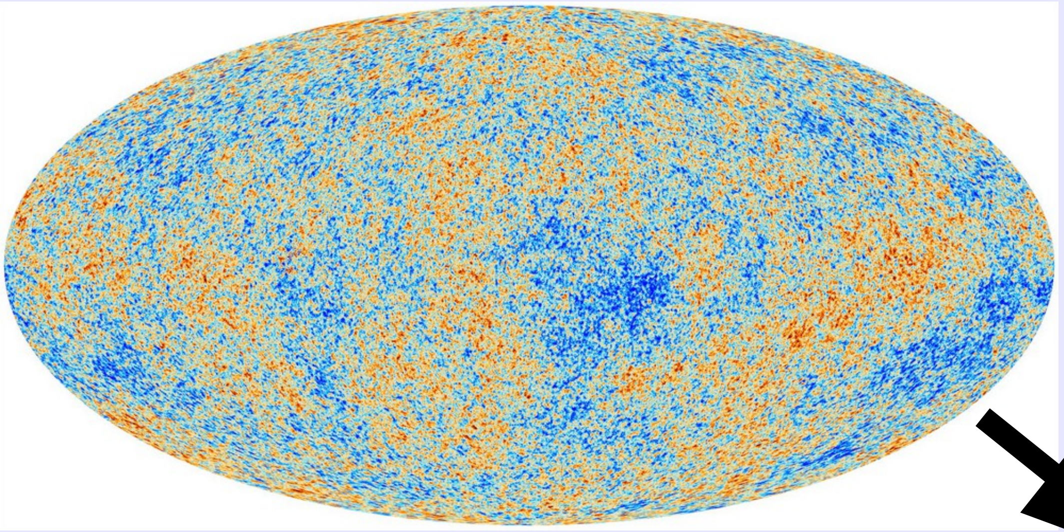

Sun
150 million km
Earth
Moon
1.5 million km
L2

Scanning strategy

- Planck builds up a map from a series of “rings” – spinning at 1 rpm.
- One survey of the sky roughly every six months.

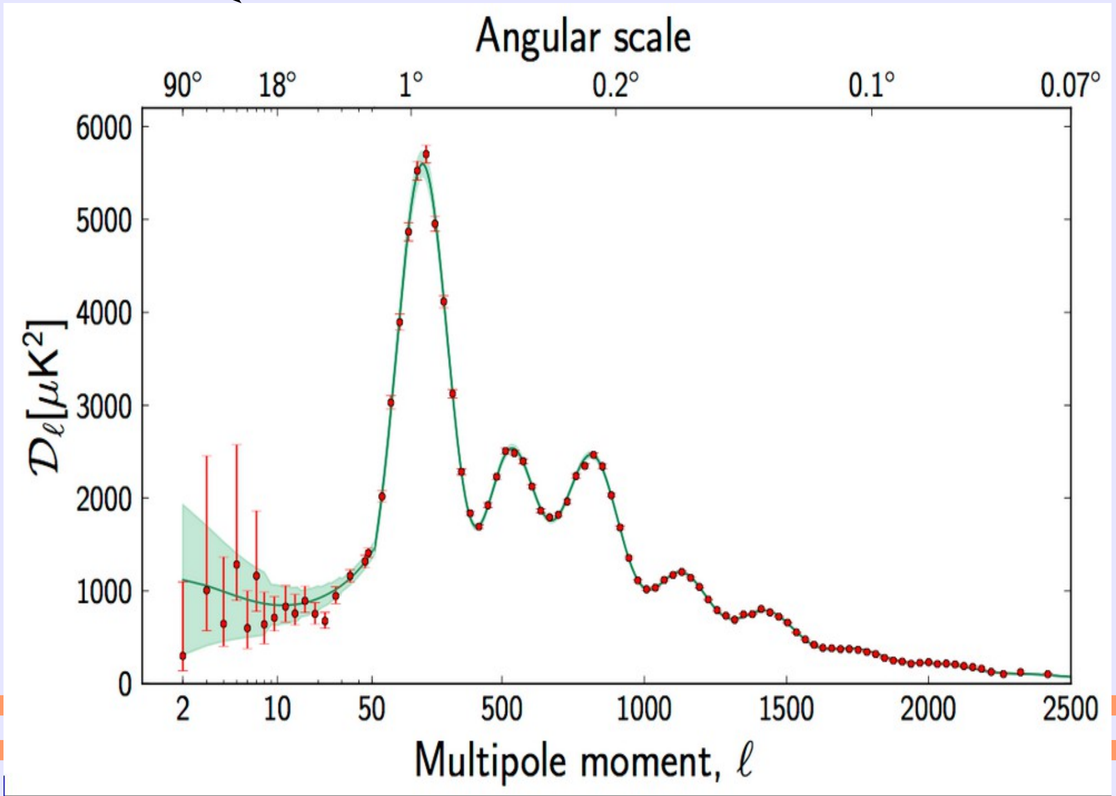


Temperature anisotropies



The information of photons coming from all directions is projected using spherical harmonics

The TT power spectrum



Thus we have a map of the temperature anisotropies! How to compare this observation with theory?

The angular Power Spectrum: to expand the distribution of temperature (T) as a sum over spherical harmonics.

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

$$C_l \equiv \langle |a_{lm}|^2 \rangle$$

$$C(\vartheta) = \left\langle \frac{\Delta T}{T}(\hat{\boldsymbol{n}}_1)\frac{\Delta T}{T}(\hat{\boldsymbol{n}}_2) \right\rangle$$

$$\vartheta \simeq 60^\circ / l$$

$$C(\vartheta) = \frac{1}{4\pi}\sum_{l=2}^{\infty}(2l+1)C_l P_l(\cos\vartheta)$$

The theory of structure formation in more details

The growth of structures

The Jeans Mechanism (1902) – small fluctuations in a static background. There was no evidence for a expanding Universe! Usefull to understand formation of planets and stars. It is easy to implement the effects of Expansion.

Perturbations in Newtonian Cosmology – hydrodynamical approximation. It provides the main qualitative aspects of the structure formation process.

Perturbations in General Relativity – the full treatment. Scalar, Vetorial and Tensorial perturbations (the latter occurs only in the relativistic context) .

Newtonian theory of cosmological perturbations

The following set of equations defines the Newtonian Cosmology

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{u}) = 0\,,$$

$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u}.\vec{\nabla}\right)\vec{u} = -\vec{\nabla}\Psi - \frac{\vec{\nabla}p}{\rho}\,,$$

$$\nabla^2 \Psi = 4\pi G \rho\,,$$

The solutions are:

$$\rho = \frac{\rho_0}{a^3}\,, \quad \vec{u} = H\vec{r}\,, \quad \vec{g} = -\frac{4}{3}\pi G \rho \vec{r}\,.$$

We will introduce small fluctuations around the background quantities

$$\rho = \rho_0(t)\left[1 + \delta(\vec{r}, t)\right]$$

$$p = p_0(t) + \delta p(\vec{r}, t)$$

$$\Psi = \Psi_0(\vec{r}, t) + \varphi(\vec{r}, t)$$

$$\vec{u} = \vec{u}_0(\vec{r}, t) + \vec{v}(\vec{r}, t)$$

Perturbed equations

We Fourier-transform the first order quantities as

$$\delta f\left(\vec{r},t\right) = \delta f\left(t\right)\, e^{-\frac{i\vec{k}.\vec{r}}{a}}$$

where k is the wavelenght of the perturbation.

$$\dot{\delta} = -\frac{i\vec{k}.\vec{v}}{a}$$

$$\dot{\vec{v}} + \frac{\dot{a}}{a}\vec{v} = -\frac{i\vec{k}}{a}\varphi - v_s^2\frac{i\vec{k}}{a}\delta$$

$$-\frac{k^2}{a^2}\varphi = 4\pi G\rho\delta,$$

Combining the above equations we end up with

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} + \left\{\frac{k^2 v_s^2}{a^2} - 4\pi G\rho\right\}\delta = 0,$$

Cosmological Perturbation Theory in the Synchronous vs. Conformal Newtonian Gauge

Chung-Pei Ma and Edmund Bertschinger

Synchronous gauge — $ds^2 = a^2(\tau)\{-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\}\,.$

$h_{ij} = h\delta_{ij}/3 + h_{ij}^{\parallel} + h_{ij}^{\perp} + h_{ij}^{T}.$ $h \equiv h_{ii}$

We will be working in the Fourier space k in this paper. We introduce two fields $h(\vec{k},\tau)$ and $\eta(\vec{k},\tau)$ in k-space and write the scalar mode of h_{ij} as a Fourier integral

$$h_{ij}(\vec{x},\tau) = \int d^3k e^{i\vec{k}\cdot\vec{x}} \left\{\hat{k}_i\hat{k}_j h(\vec{k},\tau) + (\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij})\, 6\eta(\vec{k},\tau)\right\}\,, \quad \vec{k} = k\hat{k}\,.$$

Note that h is used to denote the trace of h_{ij} in both the real space and the Fourier space.

Conformal Newtonian gauge —

$$ds^2 = a^2(\tau)\left\{-(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i\right\}\,.$$

Einstein Equations and Energy-Momentum Conservation

Synchronous gauge —

$$
\begin{aligned}
k^2\eta - \frac{1}{2}\frac{\dot{a}}{a}\dot{h} &= 4\pi G a^2 \delta T^0{}_0(\mathrm{Syn})\,, \\
k^2\dot{\eta} &= 4\pi G a^2 (\bar{\rho}+\bar{P})\theta(\mathrm{Syn})\,, \\
\ddot{h} + 2\frac{\dot{a}}{a}\dot{h} - 2k^2\eta &= -8\pi G a^2 \delta T^i{}_i(\mathrm{Syn})\,, \\
\ddot{h} + 6\ddot{\eta} + 2\frac{\dot{a}}{a}\left(\dot{h}+6\dot{\eta}\right) - 2k^2\eta &= -24\pi G a^2 (\bar{\rho}+\bar{P})\Theta(\mathrm{Syn})\,.
\end{aligned}
$$

Conformal Newtonian gauge —

$$
\begin{aligned}
k^2\phi + 3\frac{\dot{a}}{a}\left(\dot{\phi}+\frac{\dot{a}}{a}\psi\right) &= 4\pi G a^2 \delta T^0{}_0(\mathrm{Con})\,, \\
k^2\left(\dot{\phi}+\frac{\dot{a}}{a}\psi\right) &= 4\pi G a^2 (\bar{\rho}+\bar{P})\theta(\mathrm{Con})\,, \\
\ddot{\phi} + \frac{\dot{a}}{a}(\dot{\psi}+2\dot{\phi}) + \left(2\frac{\ddot{a}}{a}-\frac{\dot{a}^2}{a^2}\right)\psi + \frac{k^2}{3}(\phi-\psi) &= \frac{4\pi}{3} G a^2 \delta T^i{}_i(\mathrm{Con})\,, \\
k^2(\phi-\psi) &= 12\pi G a^2 (\bar{\rho}+\bar{P})\Theta(\mathrm{Con})\,,
\end{aligned}
$$

The conformal Newtonian potentials ϕ and ψ are related to the synchronous potentials h and η in k-space by

$$\psi(\vec{k},\tau) = \frac{1}{2k^2}\left\{\ddot{h}(\vec{k},\tau)+6\ddot{\eta}(\vec{k},\tau)+\frac{\dot{a}}{a}\left[\dot{h}(\vec{k},\tau)+6\dot{\eta}(\vec{k},\tau)\right]\right\},$$

$$\phi(\vec{k},\tau) = \eta(\vec{k},\tau)-\frac{1}{2k^2}\frac{\dot{a}}{a}\left[\dot{h}(\vec{k},\tau)+6\dot{\eta}(\vec{k},\tau)\right].$$

The label "Syn" is used to distinguish the components of the energy-momentum tensor in the synchronous gauge from those in the conformal Newtonian gauge. The variables θ and Θ are defined as

$$(\bar{\rho}+\bar{P})\theta \equiv ik^j\delta T^0{}_j\,, \qquad (\bar{\rho}+\bar{P})\Theta \equiv -(\hat{k}_i\hat{k}_j-\frac{1}{3}\delta_{ij})\Sigma^i{}_j\,,$$

and $\Sigma^i{}_j \equiv T^i{}_j - \delta^i{}_j T^k{}_k/3$ denotes the traceless component of $T^i{}_j$. When the different components of matter and radiation (i.e., CDM, HDM, baryons, photons, and massless neutrinos) are treated separately, $(\bar{\rho}+\bar{P})\theta=\sum_i(\bar{\rho}_i+\bar{P}_i)\theta_i$ and $(\bar{\rho}+\bar{P})\Theta=\sum_i(\bar{\rho}_i+\bar{P}_i)\Theta_i$, where the index i runs over the particle species.

The conservation of energy-momentum is a consequence of the Einstein equations. Let $w \equiv P/\rho$ describe the equation of state. Then the perturbed part of energy-momentum conservation equations

$$T^{\mu\nu}{}_{;\mu} = \partial_\mu T^{\mu\nu} + \Gamma^\nu{}_{\alpha\beta} T^{\alpha\beta} + \Gamma^\alpha{}_{\alpha\beta} T^{\nu\beta} = 0$$

Synchronous gauge —

$$\begin{aligned}
\dot{\delta} &= -(1+w)\left(\theta + \frac{\dot{h}}{2}\right) - 3\frac{\dot{a}}{a}\left(\frac{\delta P}{\delta\rho} - w\right)\delta\,, \\
\dot{\theta} &= -\frac{\dot{a}}{a}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta P/\delta\rho}{1+w}\,k^2\delta - k^2\Theta\,,
\end{aligned}$$

Conformal Newtonian gauge —

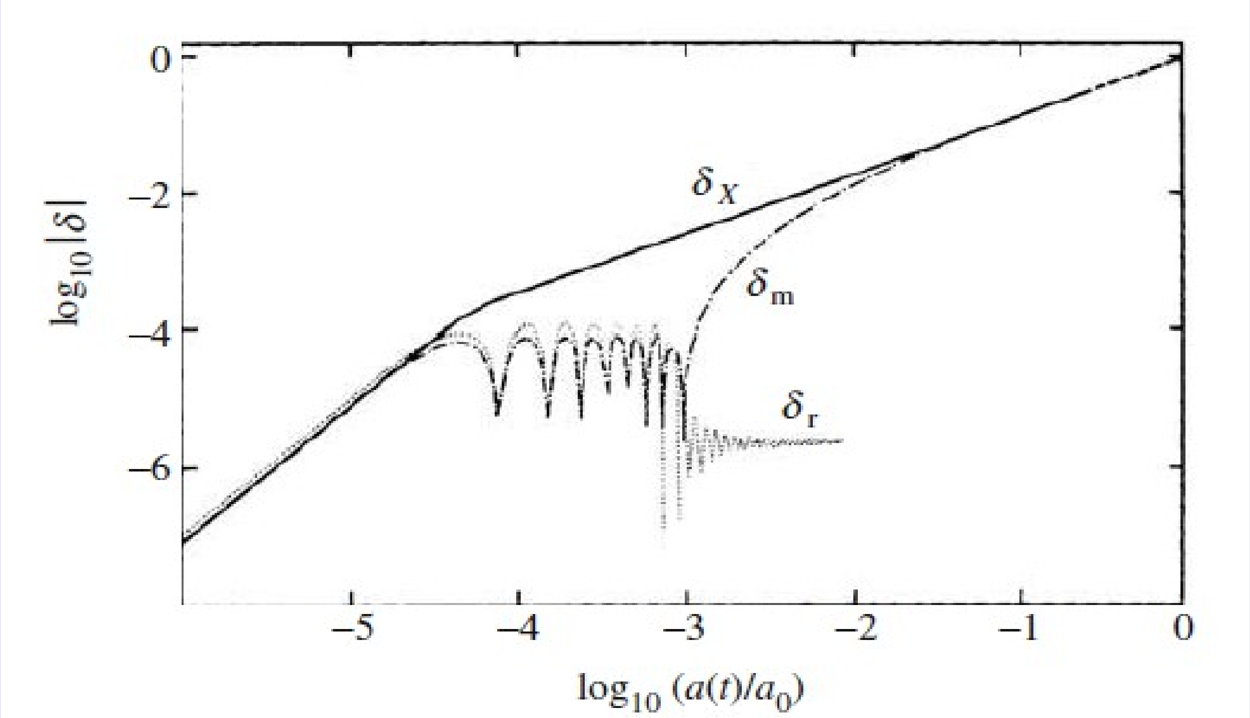
$$\begin{aligned}
\dot{\delta} &= -(1+w)\left(\theta - 3\dot{\phi}\right) - 3\frac{\dot{a}}{a}\left(\frac{\delta P}{\delta\rho} - w\right)\delta\,, \\
\dot{\theta} &= -\frac{\dot{a}}{a}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta P/\delta\rho}{1+w}\,k^2\delta - k^2\Theta + k^2\psi\,.
\end{aligned}$$

The Meszaros effect

At the matter-radiation equality (z~3000) Dark Matter structures start to grow linearly w.r.t scale factor. Before this, they grow is suppressed (Actually they grow logarithimic).

However, baryons (known kind of matter) are coupled to radiation until z~1000.

After the decoupling (z~1000), baryons follow the dark matter gravitational potential wells (dark halos) to succesfully form structures we observe today.



Power spectrum of the matter fluctuations Transfer Functions T(k)

Time

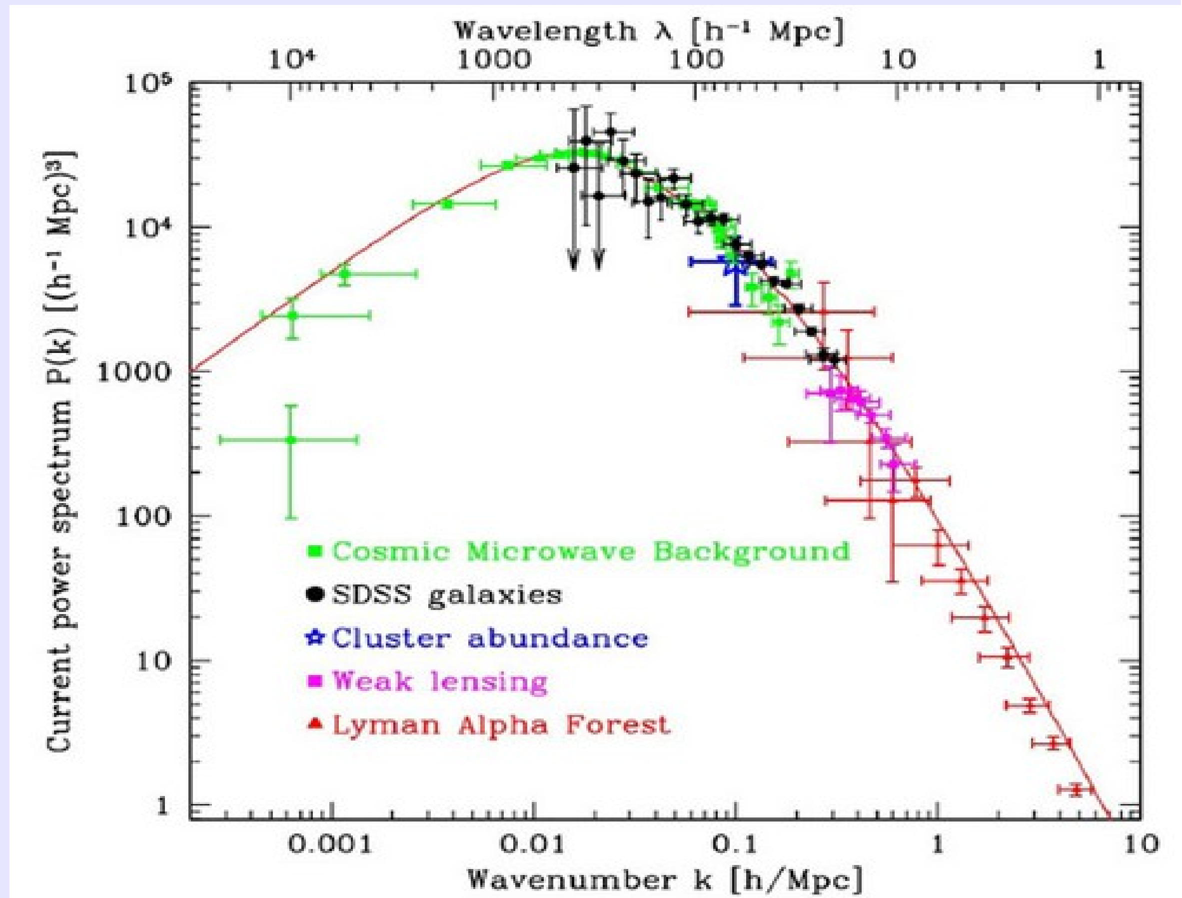
Just after Inflation

z=0 (Today)

The Initial Power Spectrum

$$P(k) = |\Delta_k|^2 \propto k^n$$

The Harrison–Zeldovich power spectrum has $n = 1$



T(k) modifies the shape of P(k).

$$\Delta_k(z=0) = T(k)\, f(z)\, \Delta_k(z)$$

The Sachs-Wolfe formula

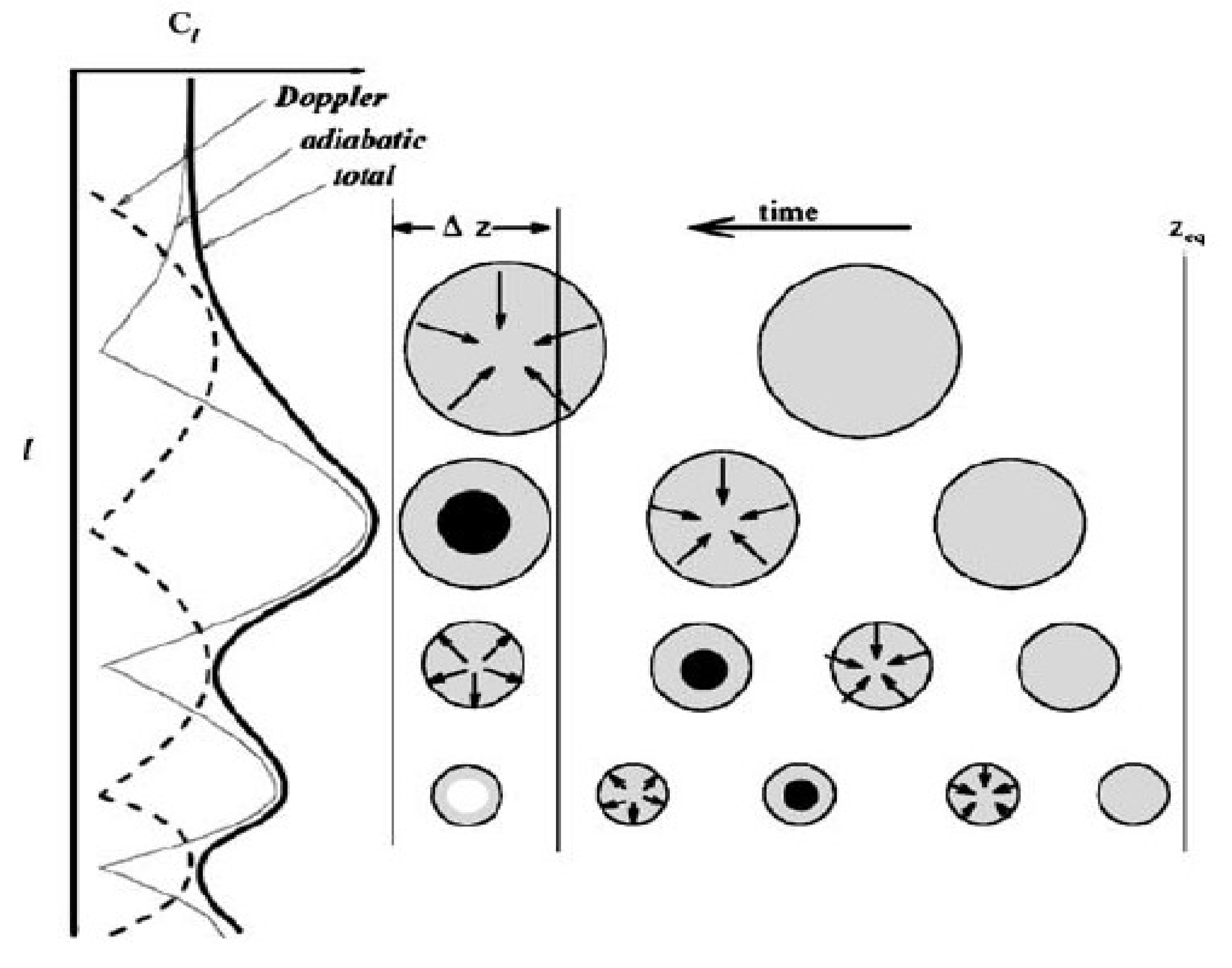
$$\frac{\delta T^{esc}}{T}(\vec{e}) = \left[\frac{\delta T_\gamma}{T} + \phi - \vec{e}.\vec{v}_\gamma\right]_{dec} + \int_{\eta_{dec}}^{\eta_0} d\eta \frac{\partial}{\partial \eta}(\phi + \psi)$$

$$\frac{\delta T^{ten}}{T}(\vec{e}) = -\frac{1}{2} e^i e^j \int_{\eta_{dec}}^{\eta_0} d\eta \frac{\partial}{\partial \eta} h_{ij}$$

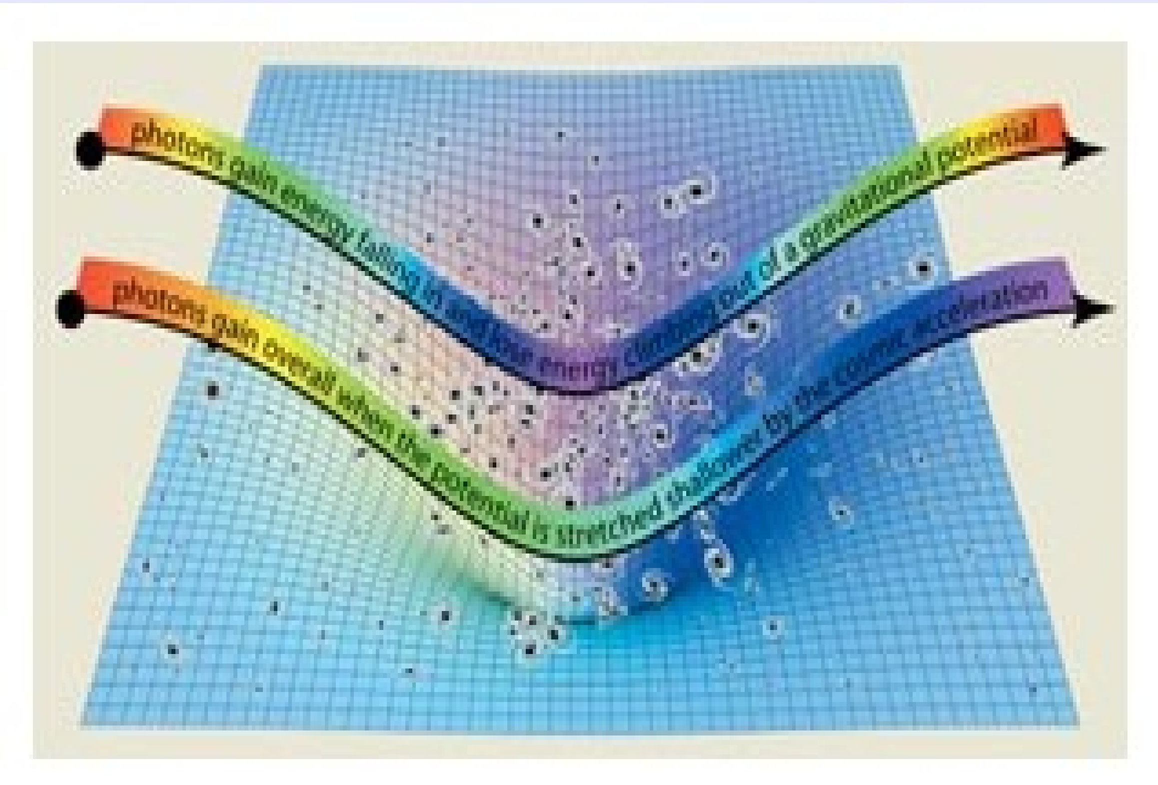
Thus, the observation of a hot spot might be due to:
i) a higher temperature at the moment of the last scattering;
ii) a higher gravitational potential (on super horizon scales ϕ is negative);
iii) or, due to a relative motion of the last scattering surface toward the observer

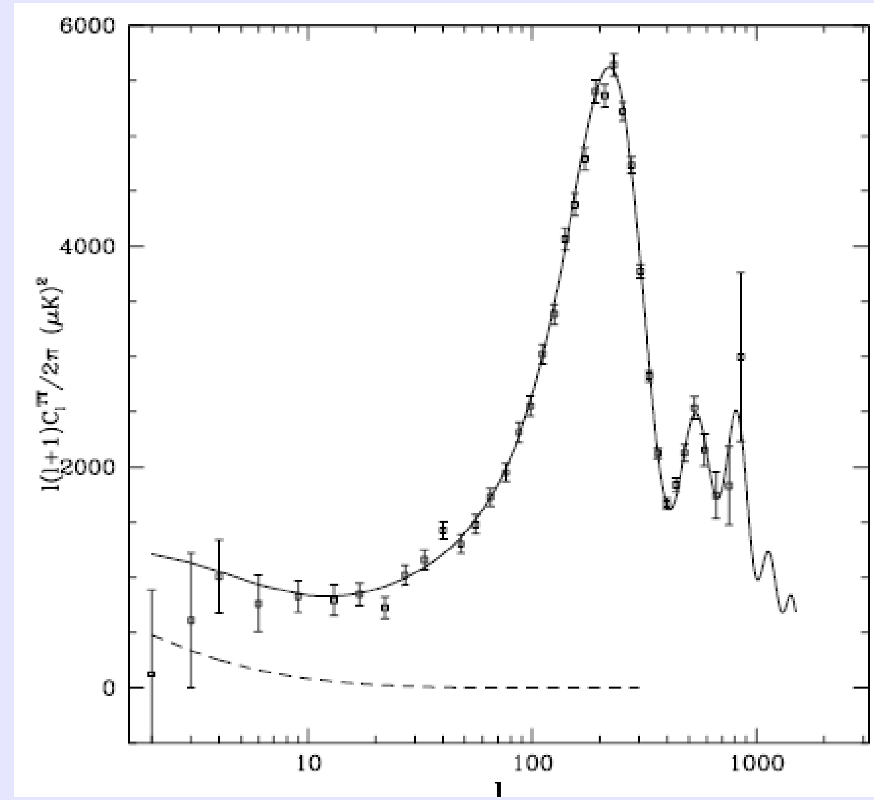
The last term is the ISW effect.

The main contribution to the CMB spectrum comes from the gravitational potential



The integrated Sachs-Wolfe effect





$$S_i = \left(\frac{\Delta T}{T}\right)_{ISW} = 2\int_{\eta_r}^{\eta_0} d\eta \frac{\partial \psi_i}{\partial \eta}\left[(\eta_0 - \eta)\,\hat{\eta}, \eta\right],$$

Gravitational potential

Conformal time

Overview: The strucuture formation process. What should we learn?

1) Small (quantum) fluctuations at the primordial stages are the seeds of cosmic structures.

2) General relativity is "weak" to form baryonic structures. We need to consider DM potential wells at the decoupling to succesfully form galaxies.

3) Cosmic microwave background gives a picture of the situation at the time of decoupling. A lot of physics involved on CMB.