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UNIÓN EUROPEA
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CEFCA

A historical perspective of Cosmology

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[CEFCA]

Benasque, September 16th 2019

OUTLINE

- The birth of Cosmological Sciences: the *Great Debate,* General Relativity applied to the entire universe, and the discovery of the Hubble flow
- Predictions for nucleosynthesis, measurement of abundances in the *Primeval Fireball*
- Challenges of the model: the need for *Inflation* and dark matter
- The search for angular anisotropies in the Cosmic Microwave Background
- Large Scale Structure surveys and the current picture of the universe

The first days of Cosmology ...

The first days of Cosmology ...

The first days of Cosmology ...

“Our” Milky Way

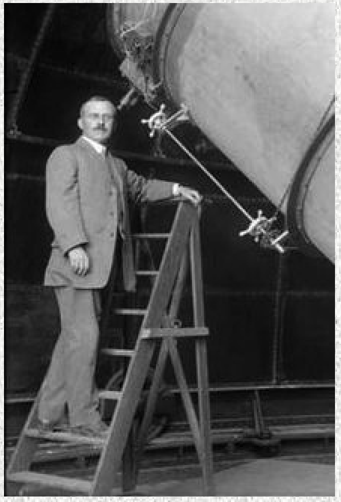
Our neighbor galaxy Andromeda (M31)

M33 as seen in a photometric plate in 14o cm Mount Palomar telescope

The first days of Cosmology ...

Shapley

Curtis



In1920 the *Great Debate* on the nature/structure of our Universe took place between Shapley and Curtis:

- Shapley defended that the entire universe was composed of stars similar to our Sun,

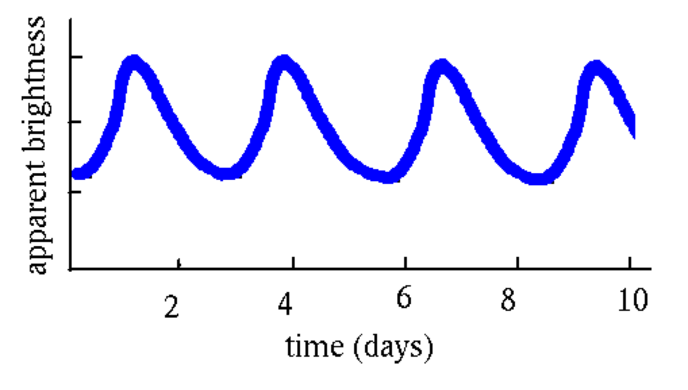
- while Curtis argued that there existed *nebulae,* hosting as many stars as those to be found close to the Sun. He named those nebulae *"universe islands"* *…*

This controversy was solved in 1923 when E. Hubble measured Cepheid stars in Andromeda, our twin galaxy, using their luminosity period to infer a distance which was ~ 100 larger than any distance considered until then …

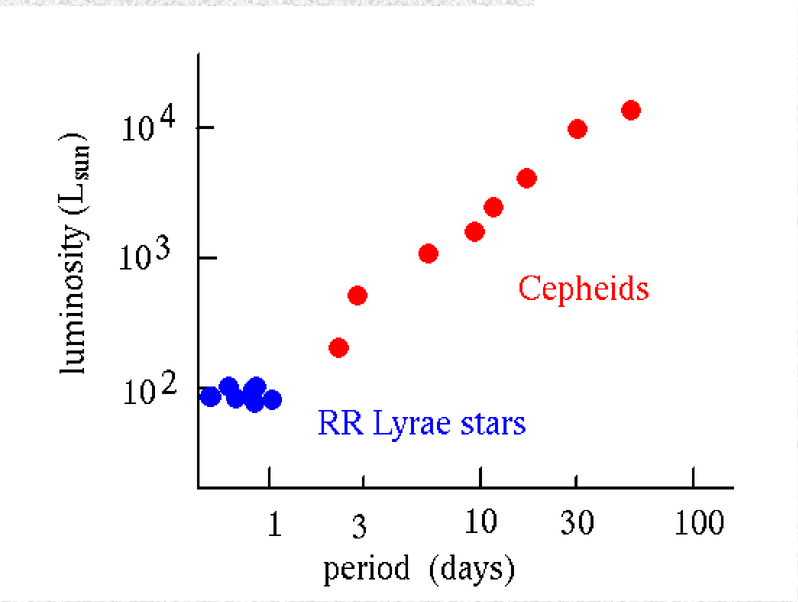
Cepheids are variable stars whose brightness period depends on their luminosity, and this relation had been calibrated for nearby cepheids. By measuring the period and the flux of distant cepheids it was then possible to measure distances to those objects …

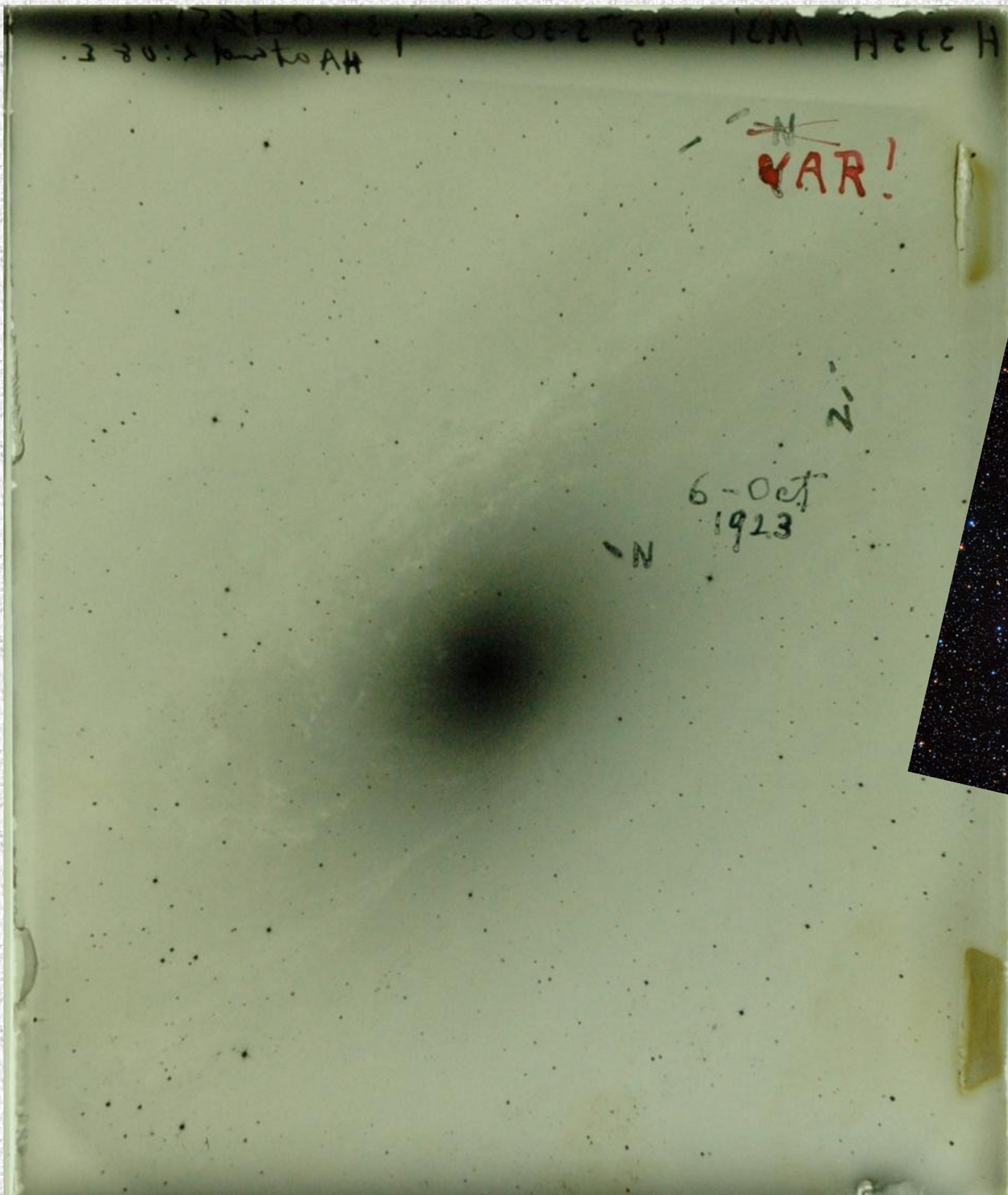
Energy flux ~ Luminosity / Distance^2

Energy flux



E.Hubble

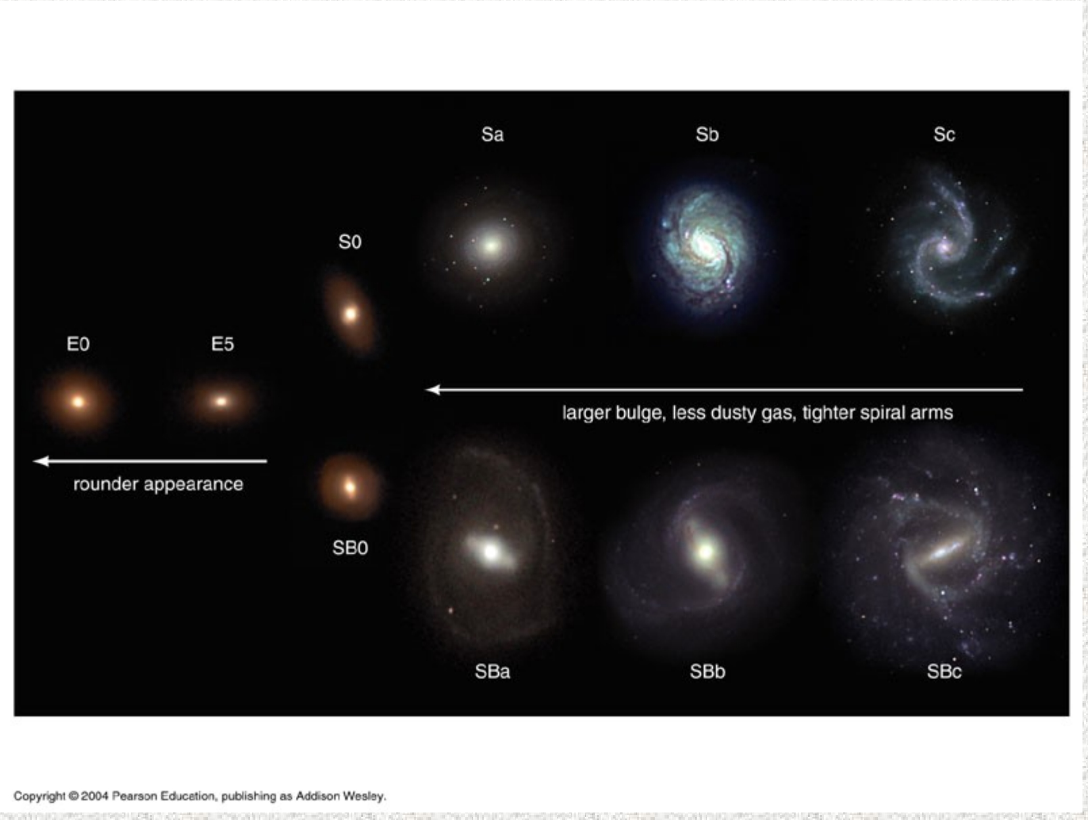




Hubble's photometric plate of M31/Andromeda from 1923

… those nebulae were in reality “galaxies” …

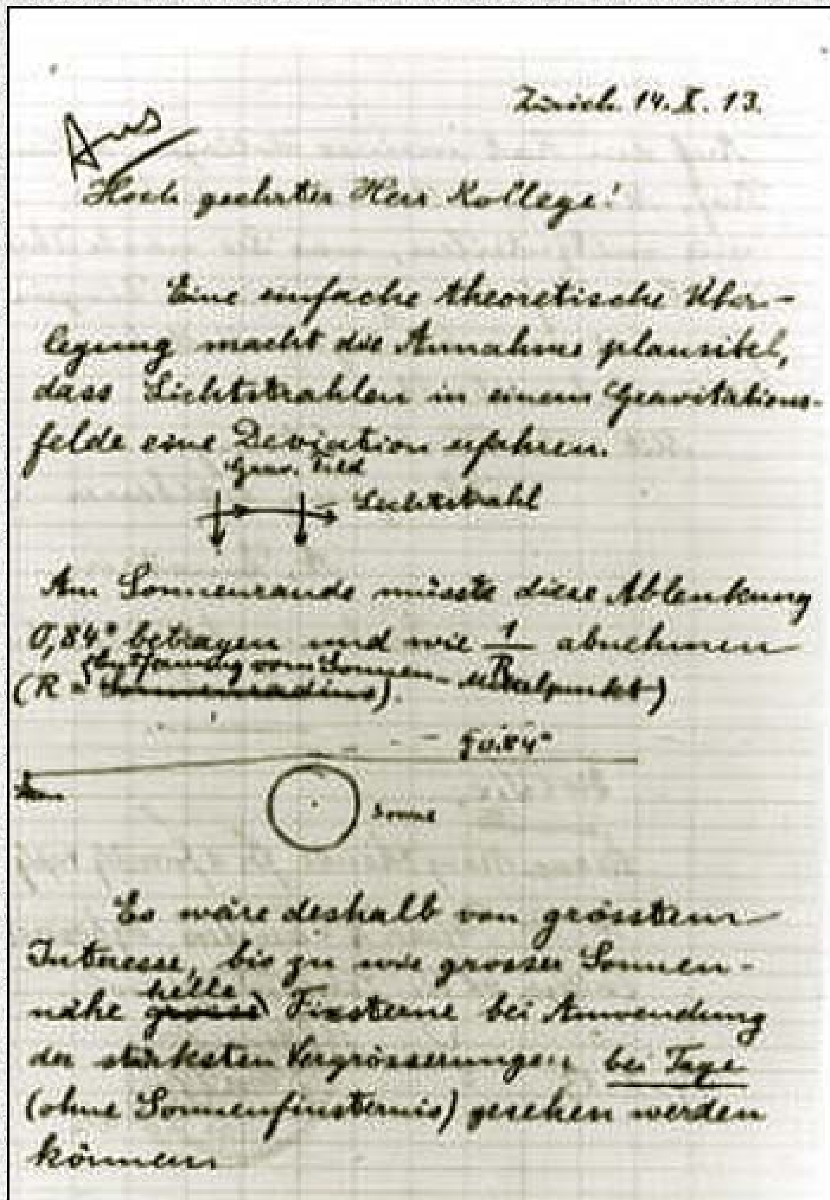
… each hosting about 1e8 – 1e10 stars …



The first days of Cosmology ...

In 1915, Albert Einsten publishes his “*Allgemeine Relativitaetstheorie*” (General Theory of Relativity), a generalization of his ideas of time, space, and inertial observers to the presence of gravity via the *Equivalence Principle,* by which there is way to distinguish locally the effects of gravity on an observer from the effects that such observer would suffer if s/he were found in an accelerated frame …

The first days of Cosmology ...



Zürich. 14. X. 13.

Aus

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld

Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = ~~Sonnenradius~~ Entfernung vom Sonnen-Mittelpunkt).

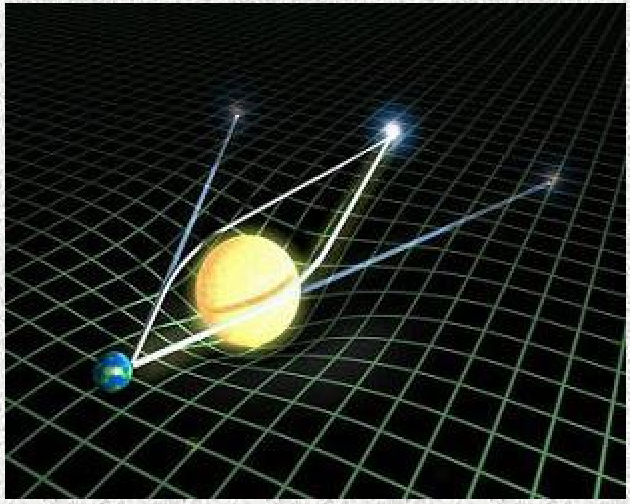
0.84"

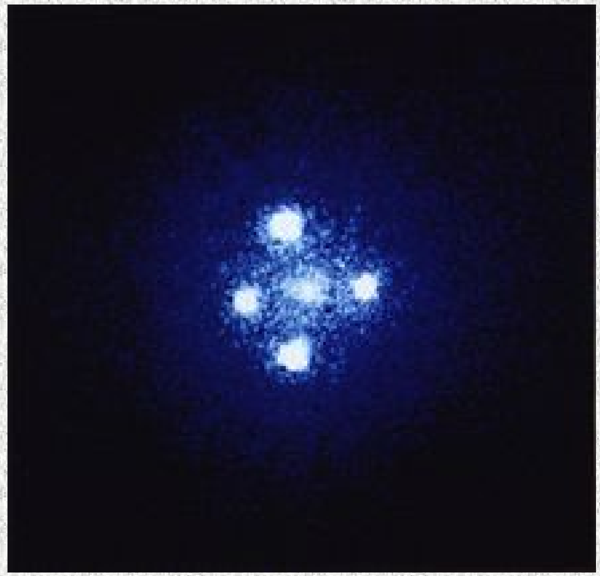
Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

The first days of Cosmology ...

This theory makes predictions about the **deflection** of **light** in the presence of intense gravitational fields, the **precession** of Mercury's perihelion, the **gravitational redshift**, etc … The first observational confirmation takes place in 1919 (Arthur Eddignton's measurement of star light deflection induced by the Sun during an eclipse)





The first days of Cosmology ...

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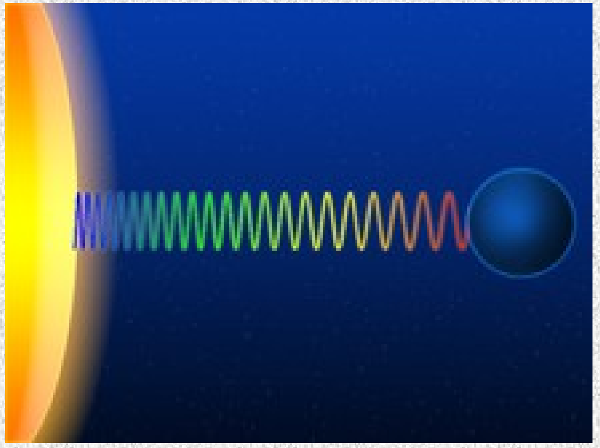
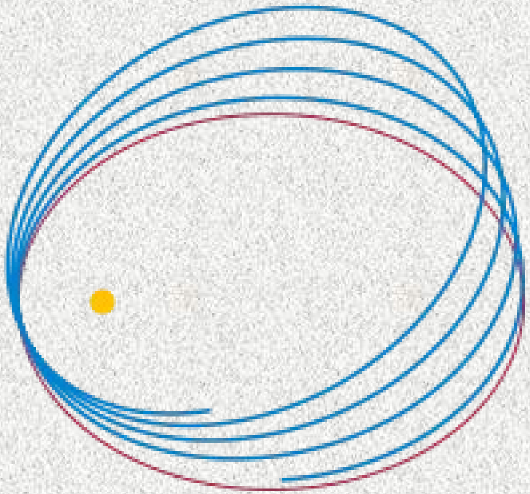
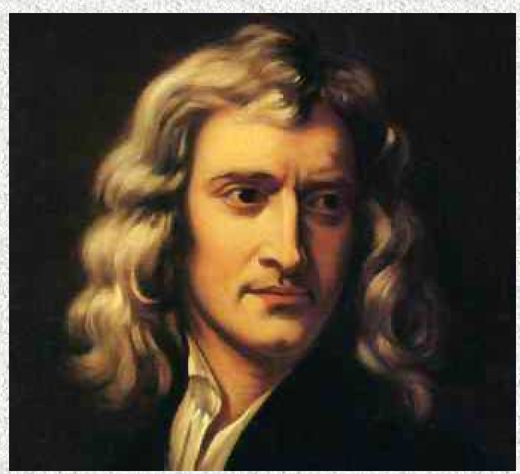




The first days of Cosmology ...

When Einstein's GR equatios were applied to the entire universe as a whole, it was obtained that the universe would not be stable, since mass/energy in it would make the universe collapse. This opposed clearly Newton's idea of an **eternal**, **everlasting** universe …

That is why he added a **cosmological constant** that would act as a **repulsive** force counteracting gravity …



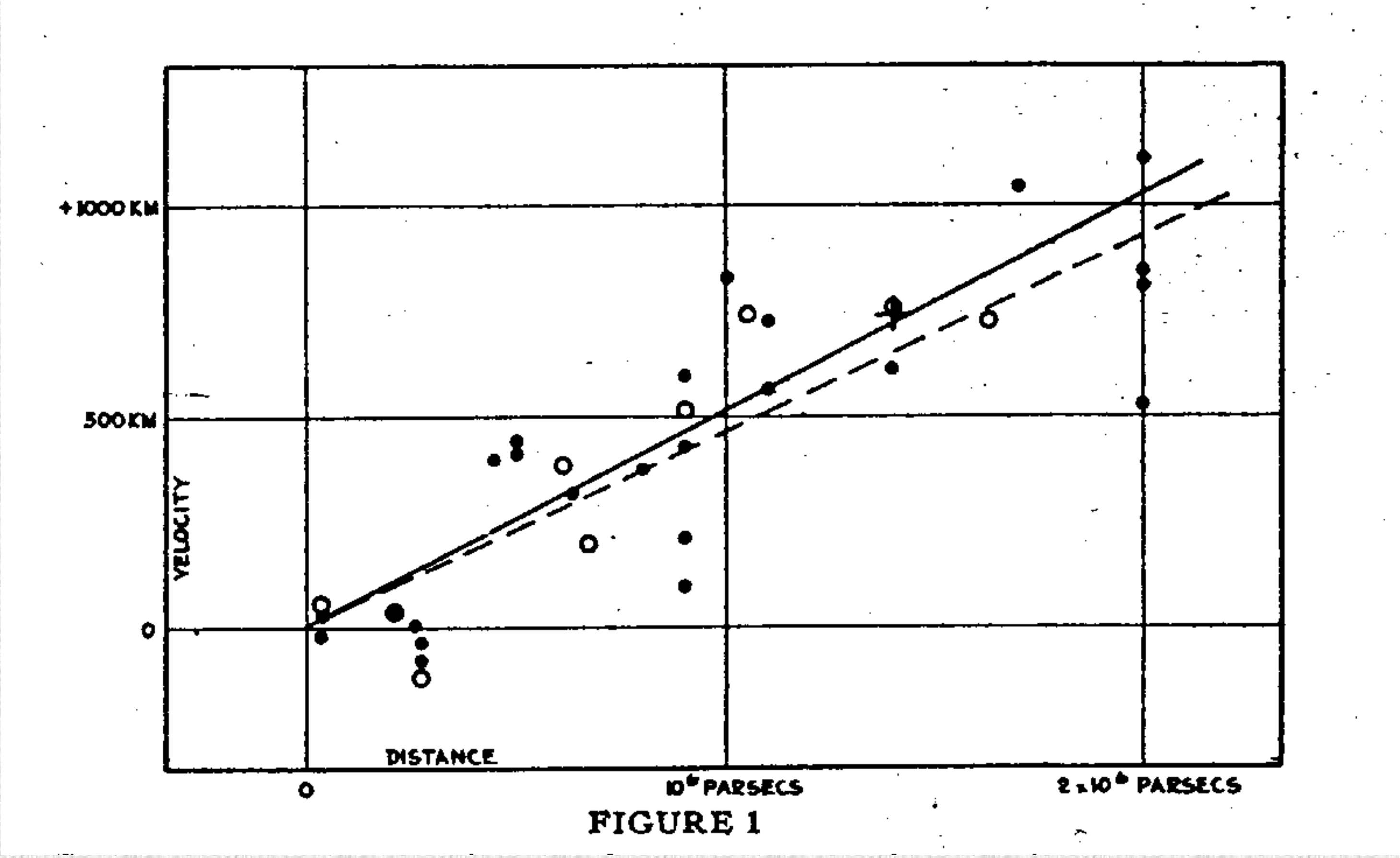
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometric part

Energetic part (mass + radiation)

However, in the second half of the 1920s, astronomer ,**Edwin Hubble** *confirmed* that the so-called *nebulae* were receding from us, the faster the further they were …

E.Hubble



A. Friedmann

Einstein then remember that back in 1922 he had reviewed a paper by a Soviet physicist called **Alexander Friedmann,** who had proposed an **expanding** universe as the result of Einstein's GR equations applied to the entire universe ***:***

a(z) = 1 / (1+z), z := redshift

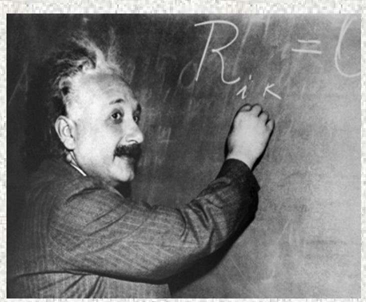
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

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

$$ds^2 = -c^2dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Scale factor

Spatial part of the metric

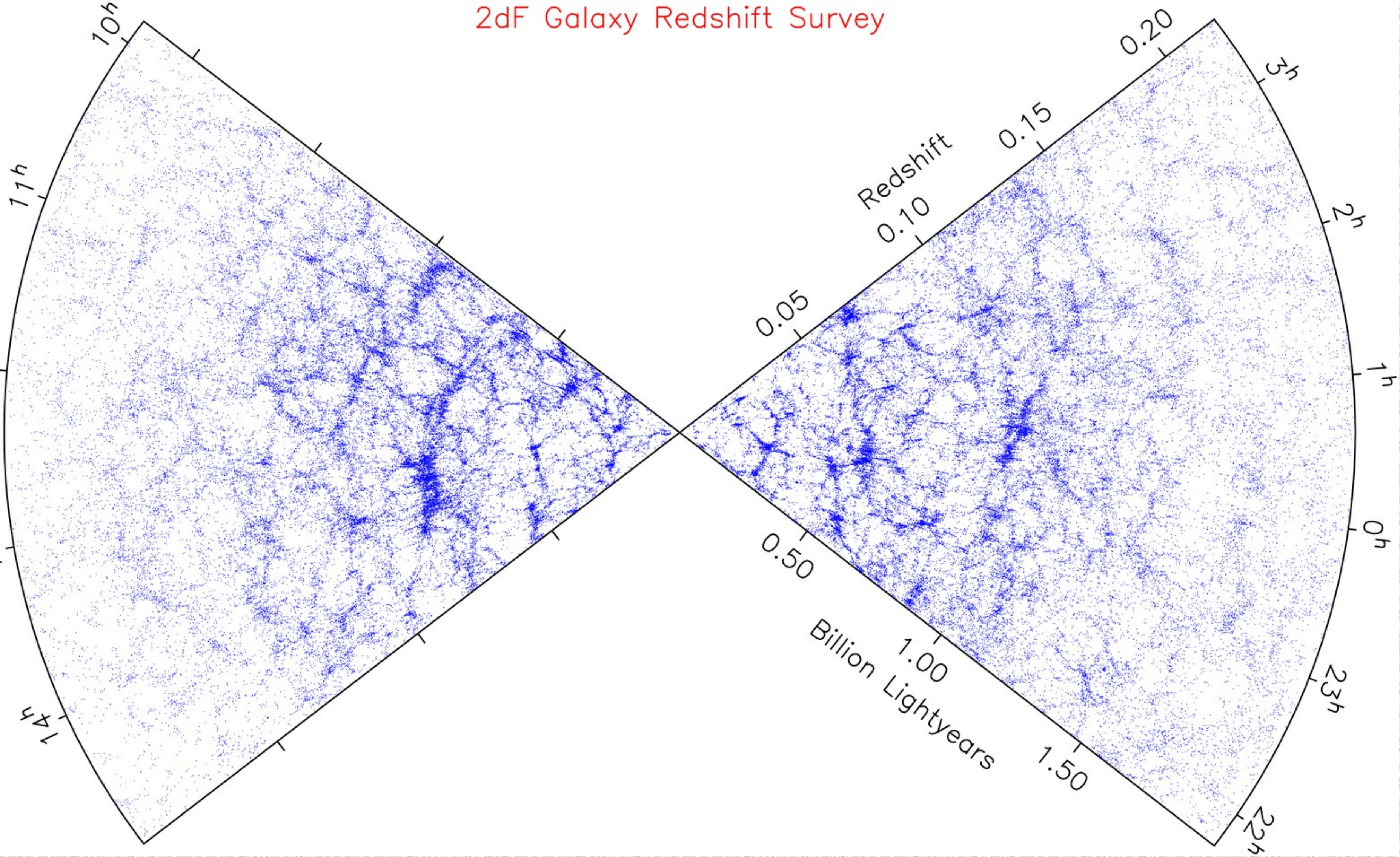


Einstein slowly recognised his mis-conceptions about an eternal, ever-lasting universe, and the solution (cosmological constant) he had proposed …

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

This theory simplifies and asumes that ***no observer in the universe is priviledged above any other, any observer is absolutely equivalent to any other, and thus must witness exactly the same physics …***

COPERNICAN COSMOLOGICAL PRINCIPLE OF HOMOGENEITY AND ISOTROPY



2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50

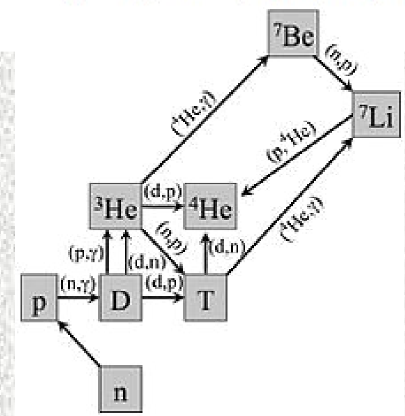
Predicting cosmic chemical abundances in the fireball model ….

This theory can be used a ***time machine*** in our universe…

Predictions for an expanding universe: nucleosynthesis

In an early enough epoch, the dynamics of the universe is ruled by radiation and relativistic species (since for those $\rho \sim a(z)^{-4}$, whereas for non-relativistic species $\rho \sim a(z)^{-3}$). The physics after WWII had developed enough to understand the reaction rates involving electrons, positrons, neutrons, protons, radiation and neutrinos ...

$$\frac{df_X}{dt} = \mathcal{C}[f_X]\,, \quad X = \gamma,\ \nu,\ e^-,\ p\,, n,\ \ldots$$

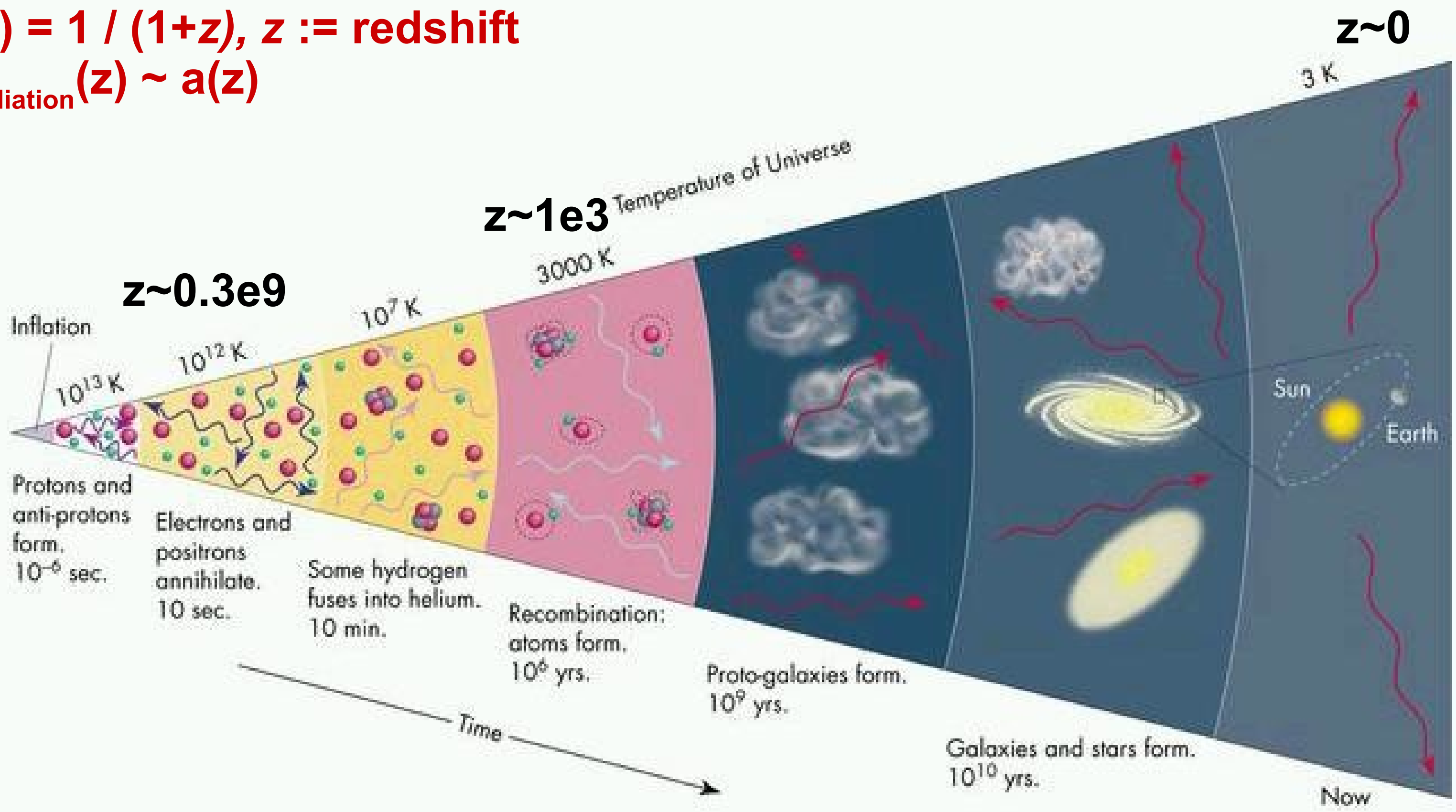


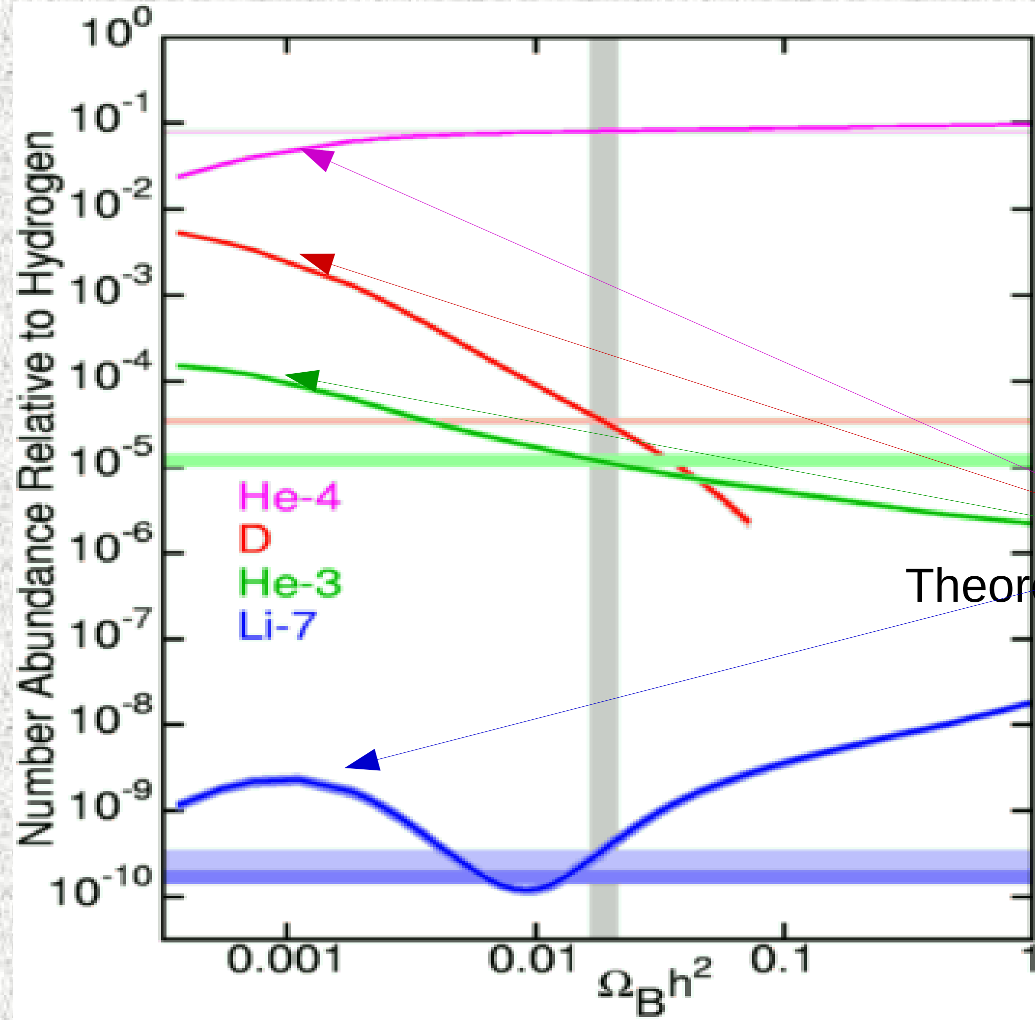
This was done by Gamow and Alpher in 1948, predicting the reaction channel and the relative abundances of the nuclei of ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Li, and ^{7}Be (***primordial nucleosynthesis***) – it was also predicted the existence of a radiation bath filling the entire universe, with the spectral form of a black body …

If one starts at T~1 GeV *(z~4e9)*, one must solve the **Botzmann** equations relating protons, neutrons, electrons, positrons, neutrinos, and photons, and account for the **decoupling** of **neutrinos**, the **electron-positron annihilation**, the **neutron decay into protons**, and the synthesis of deuterium, tritium, before giving rise to helium and heavier species... In all these processes it is crucial to compare the **time-rate for each reaction** to the **age/expansion rate** of the **universe** ...

$a(z) = 1 / (1+z)$, z := redshift

$T_{radiation}(z) \sim a(z)$



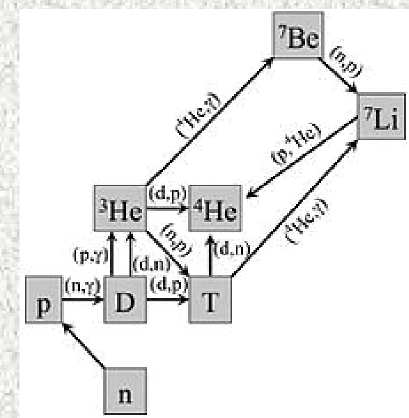


Baryonic energy density in units of critical density

Gamow

Alpher

Theoretical predictions



From Ned Wright, UCLA

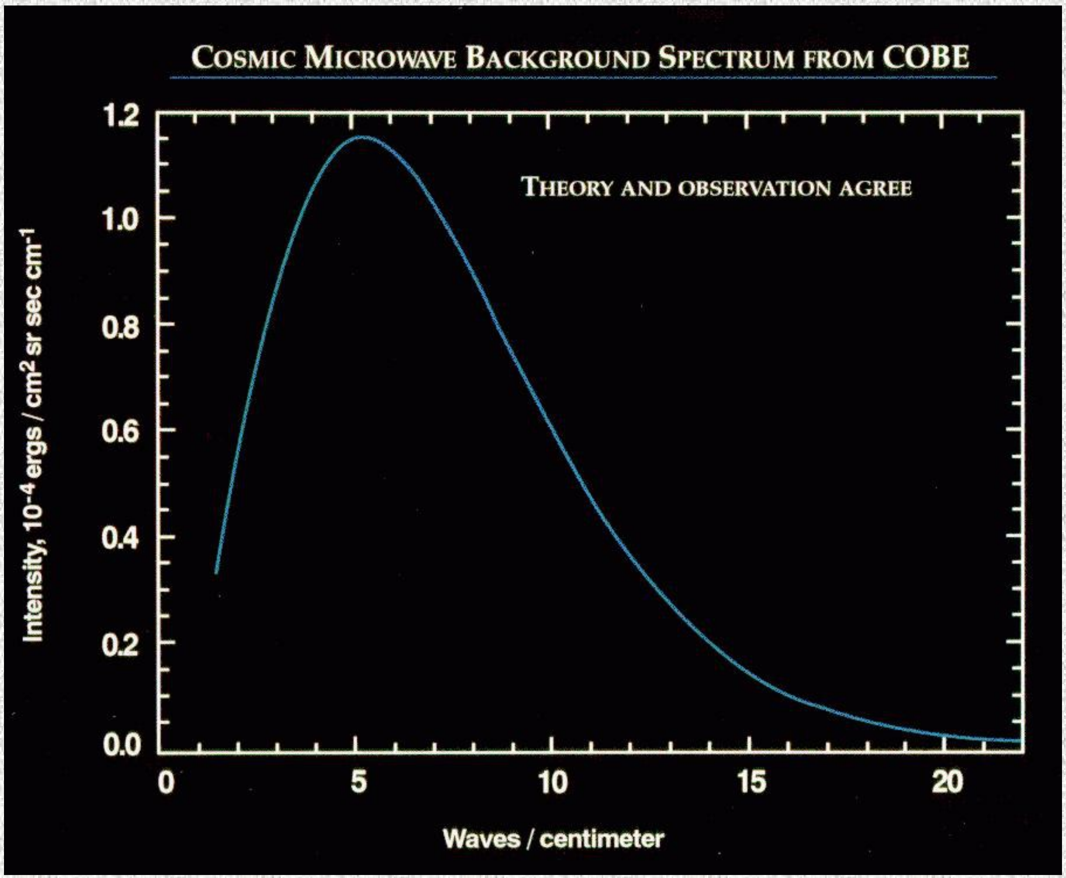
PRIMORDIAL NUCLEOSYNTHESIS

An isotropic radio signal was accidentally found by Bell Laboratories operators Penzias and Wilson in 1964 (who were eventually awarded with the Nobel Prize). Such signal was close to 3 K in antenna temperature, and was *remarkably isotropic …*

This way the **Cosmic Microwave Background was discovered and identified …**

Penzias and Wilson (1964)

On top of being isotropic, this radiation component should be **thermal**, i.e., its spectrum should be a **black body,** relic of the Big Bang as predicted by Gamow and Alpher and others later. The **isotropic** character would be another manifestation of the **Copernican** Principle



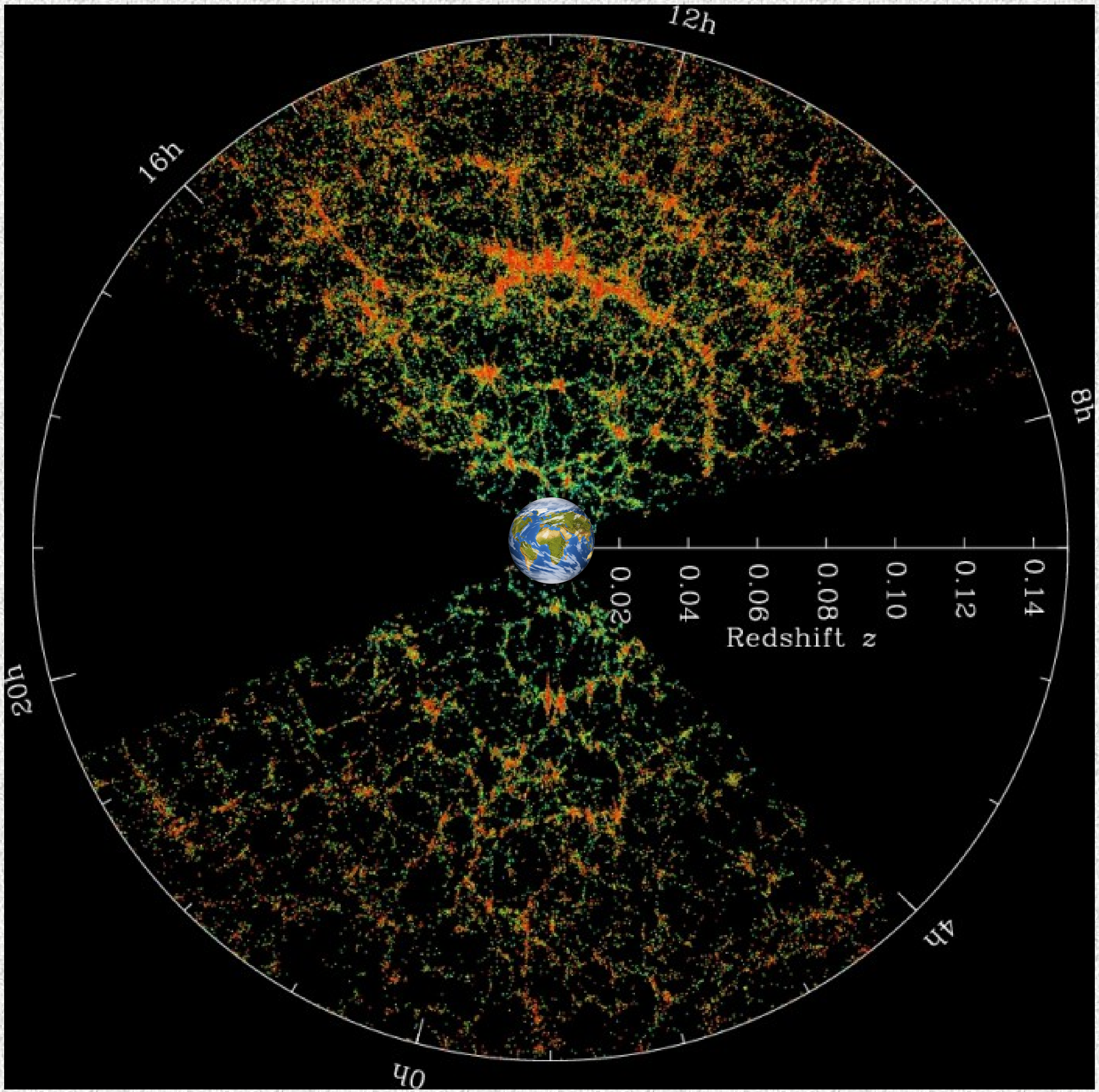
Challenges of the cosmological paradigm

- How can the universe be homogeneous and isotropic?
- The problem of dark matter

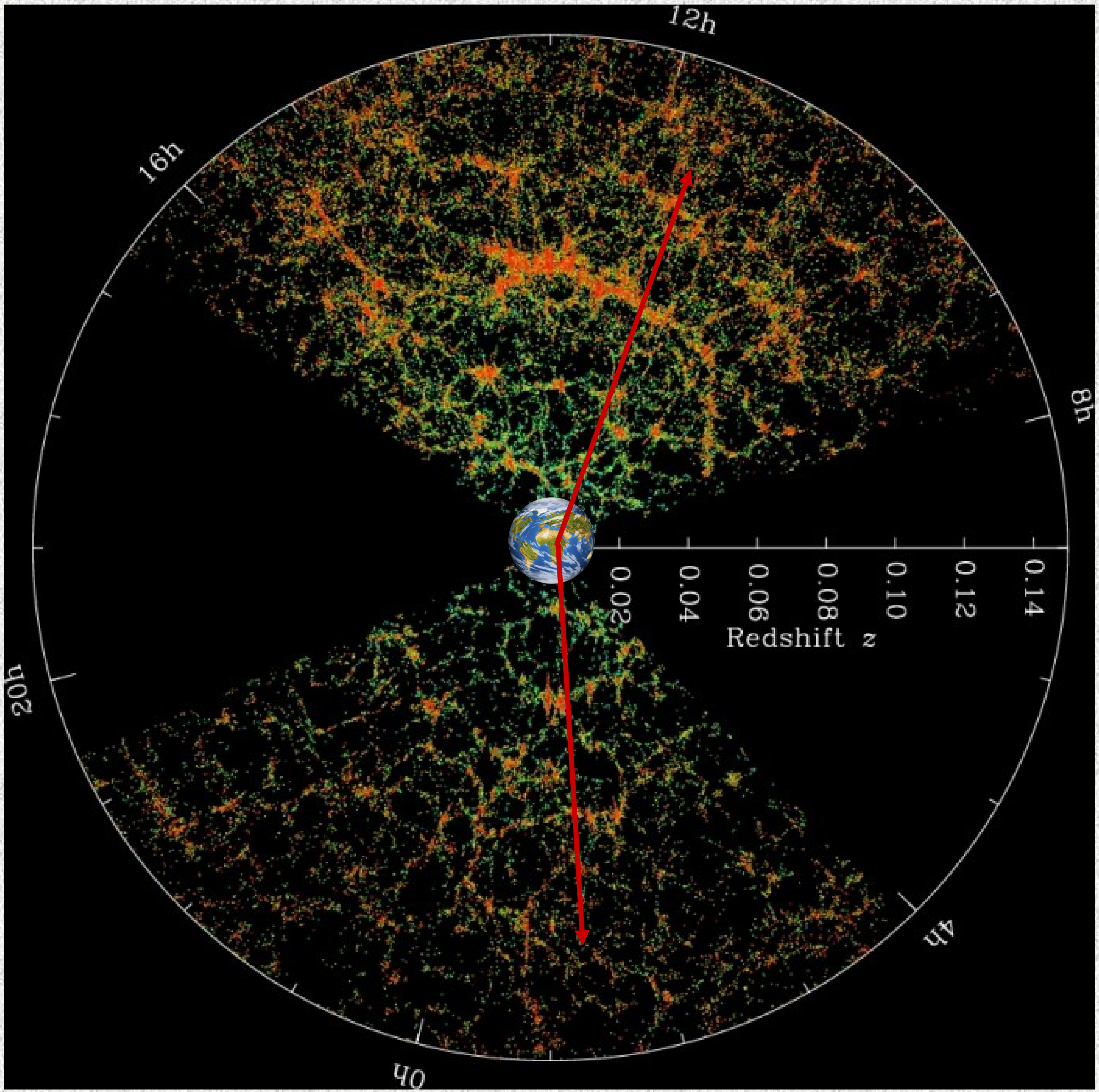
Implications of the cosmological principle …

(the need for Inflation)

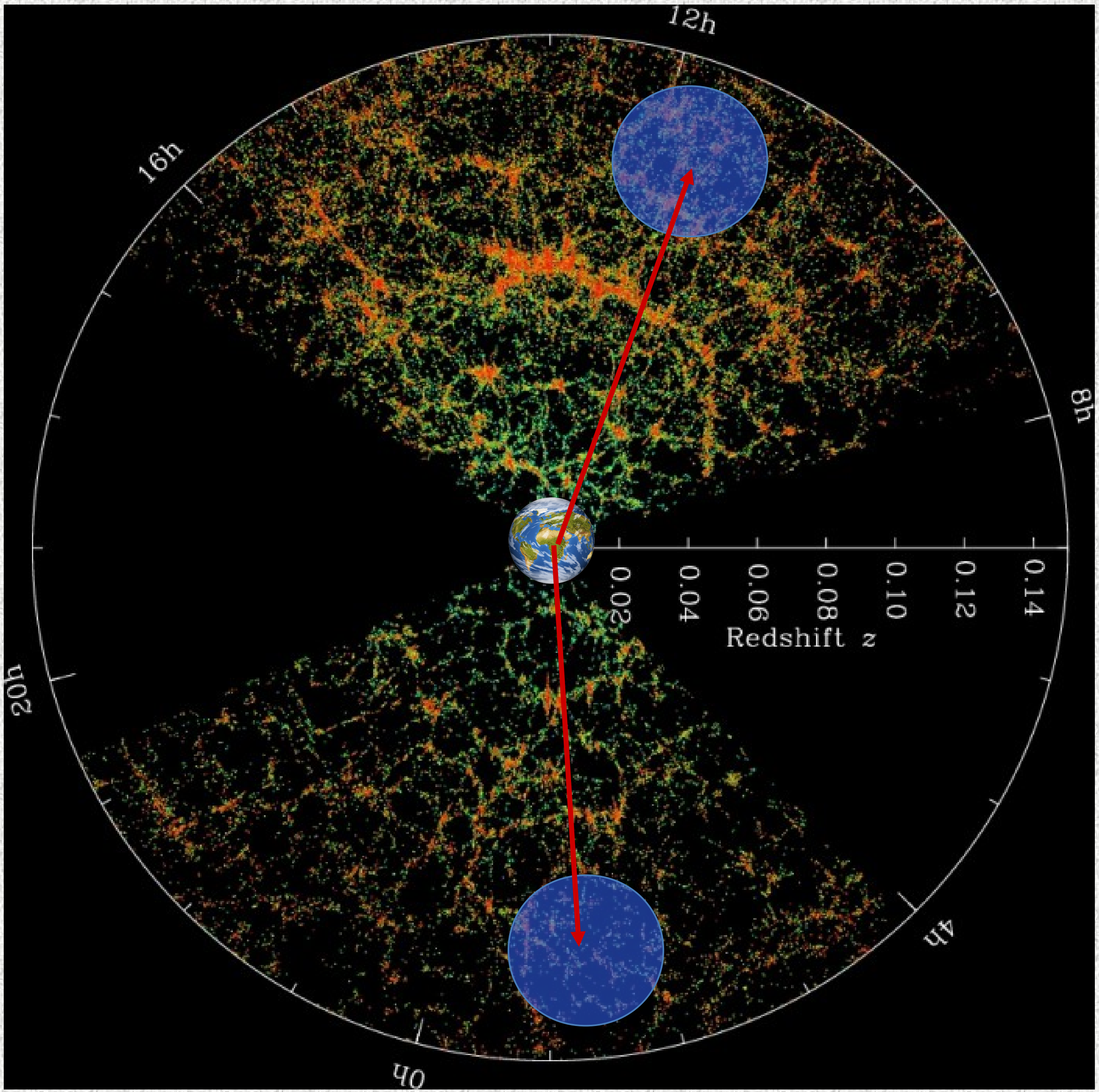
Sloan Digital Sky Survey (SDSS, 2002 – 2012), with about ~1 million spectra in the local universe …



What can we say when looking at very distant regions of the universe?

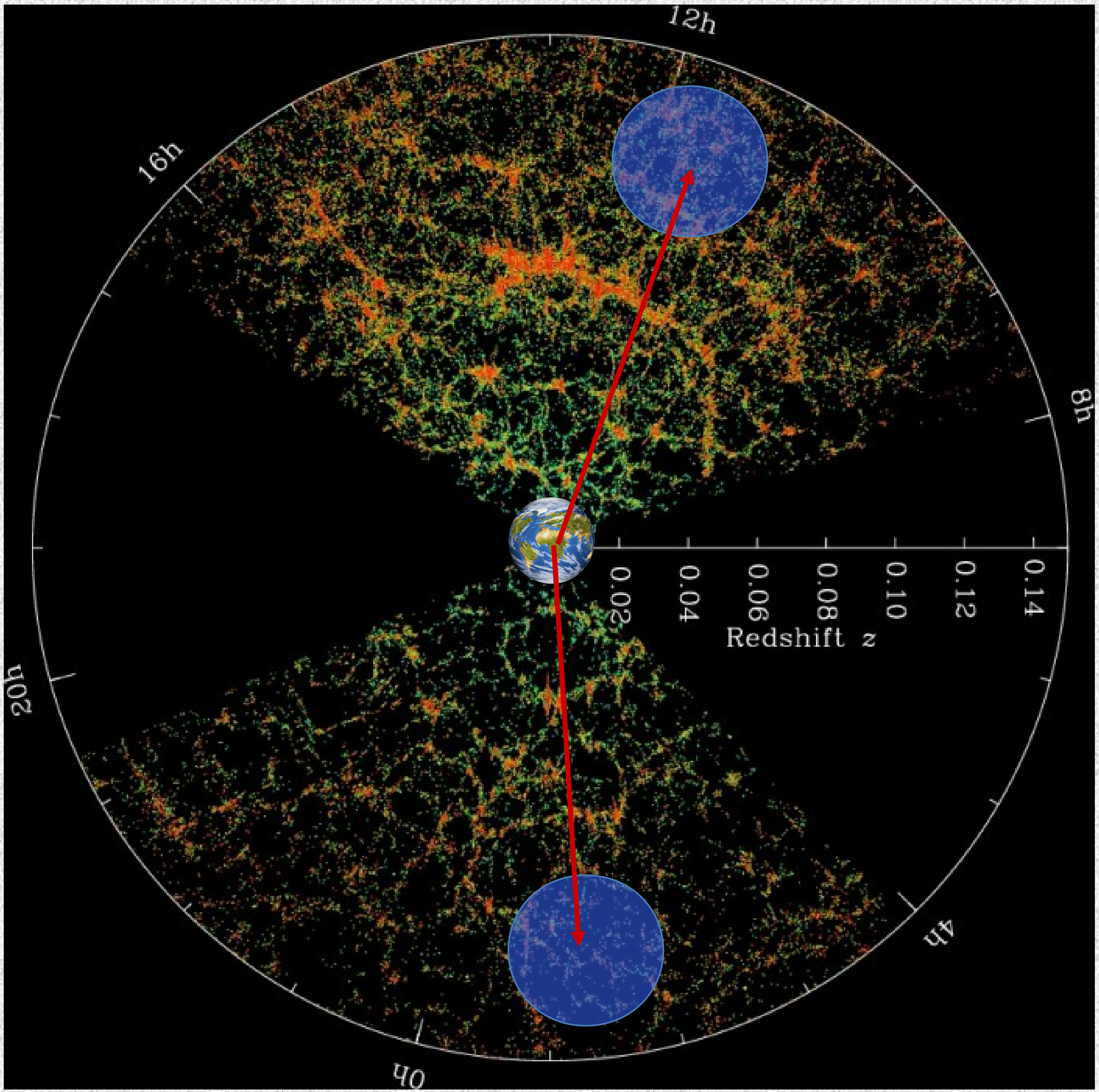


The **further** those regions are, the **younger** they were as we observe them …



The **further** those regions are, the **younger** they were as we observe them …

… despite how **distant** they may be, they look very ***similar***, (i.e., the number and spatial clustering of galaxies is extremely similar)



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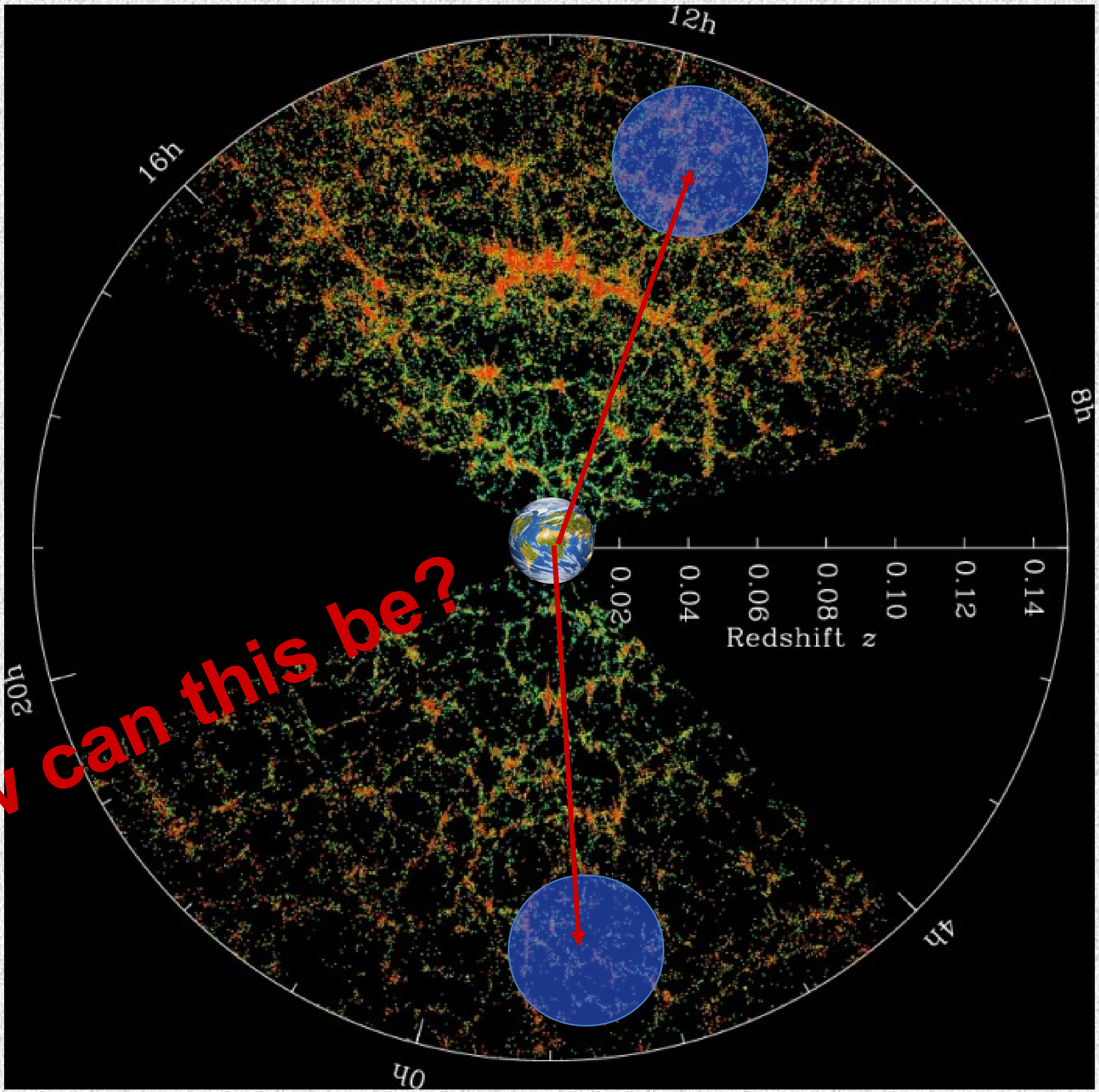
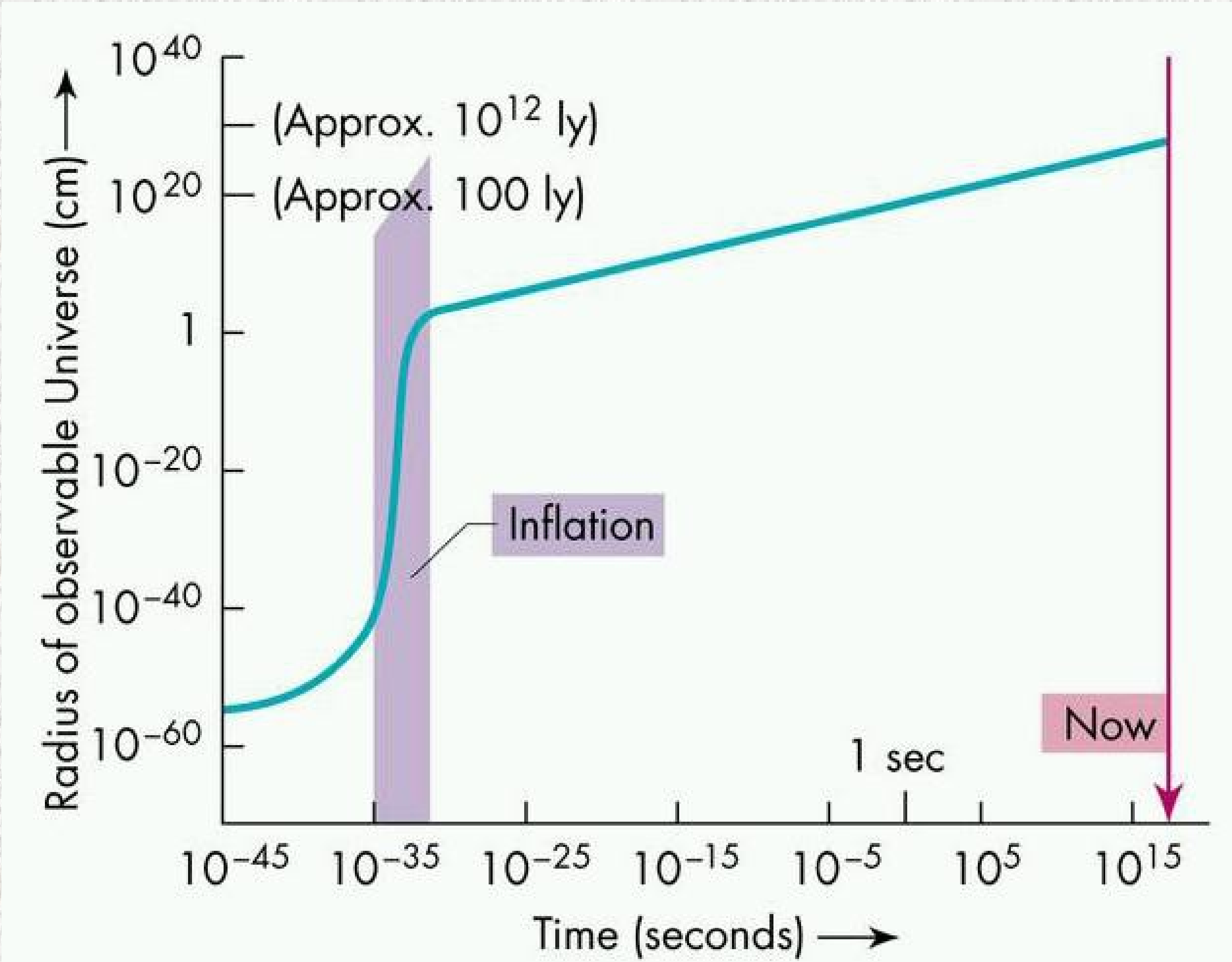


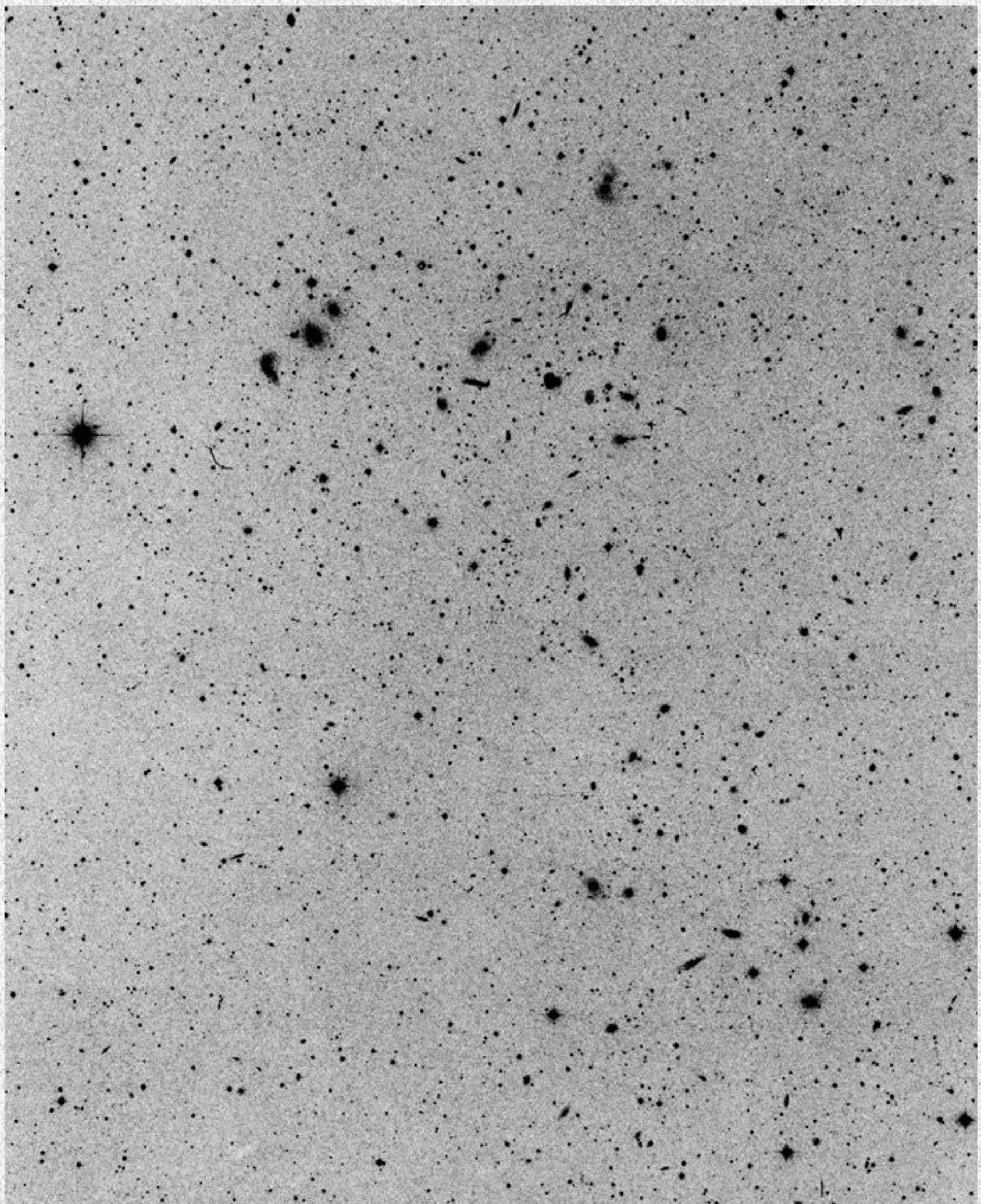
Proposed solution at the beginning of the 1980s:

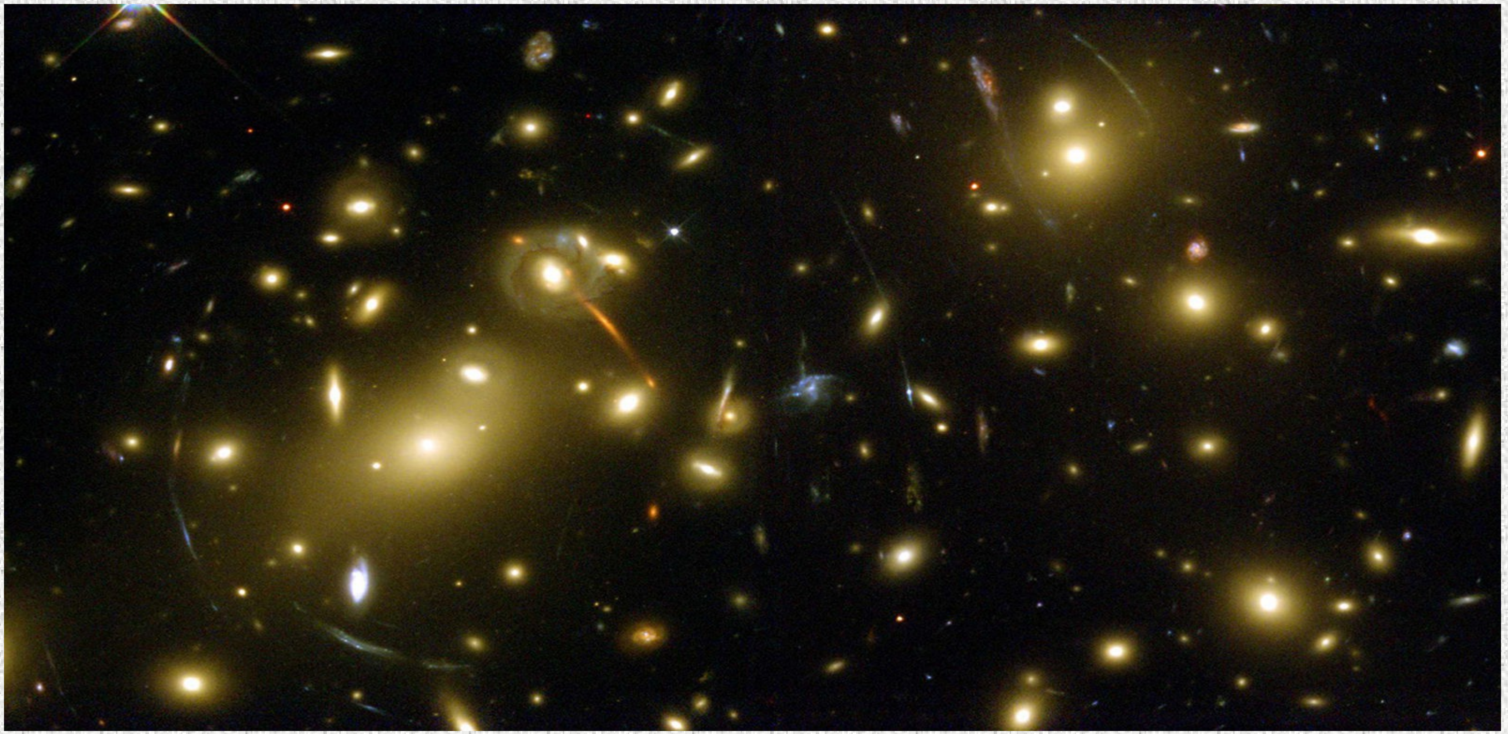
An inflationary epoch, during which the universe expansion is such that *nearby* regions lose causal contact (i.e., near observers lose each other out of sight)



Age of the universe

The problem of dark matter





Galaxy cluster

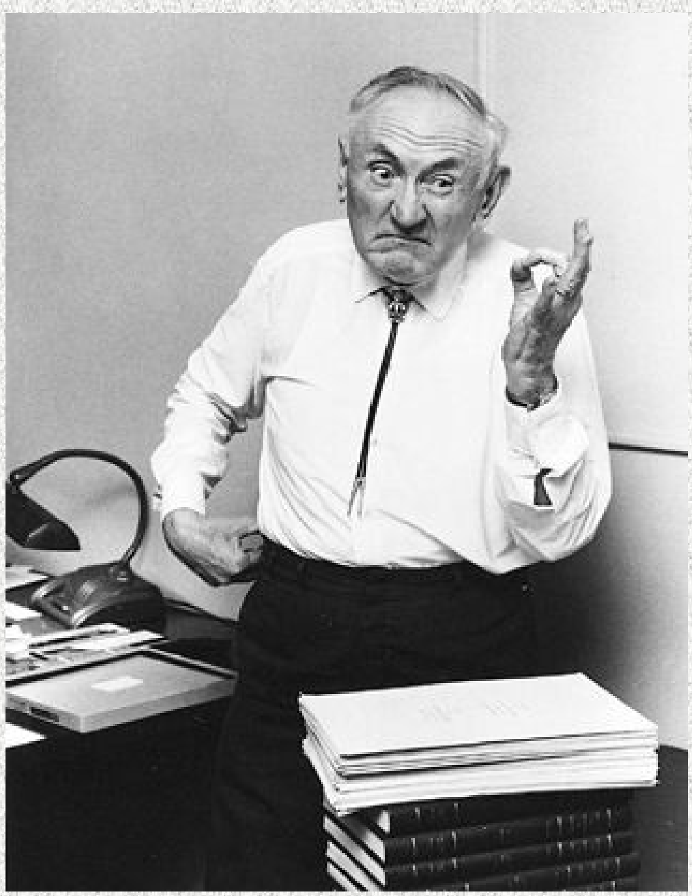
Fritz
Zwicky

$$\frac{1}{2} M_{tot} v^2 = +\frac{1}{4} G \frac{M_{tot}^2}{R_{tot}}$$

$$M_{tot} \simeq 2 \frac{R_{tot} v^2}{G}$$

Mass that is “seen” ≠ Mass that is “deduced”

Masa that is “seen” < Mass that is “deduced”



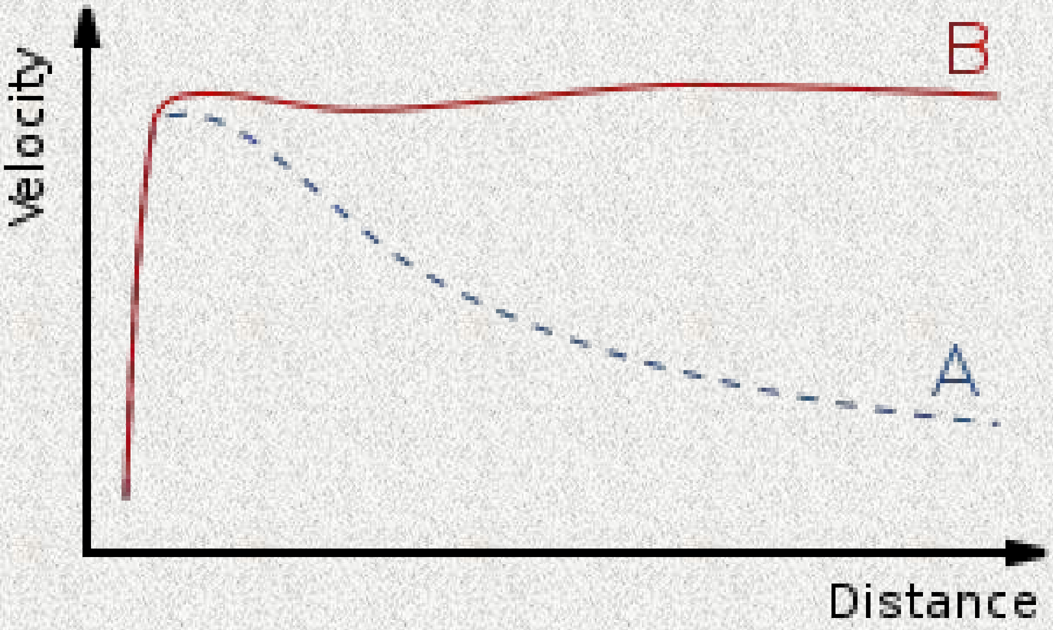
$$M_{seen} \sim 0.1 \times M_{deduced}$$

$$M_{deduced} \sim 10^{14\text{-}15}\ M_{sol}$$

$$\frac{1}{2} M_{tot} v^2 = +\frac{1}{4} G \frac{M_{tot}^2}{R_{tot}}$$

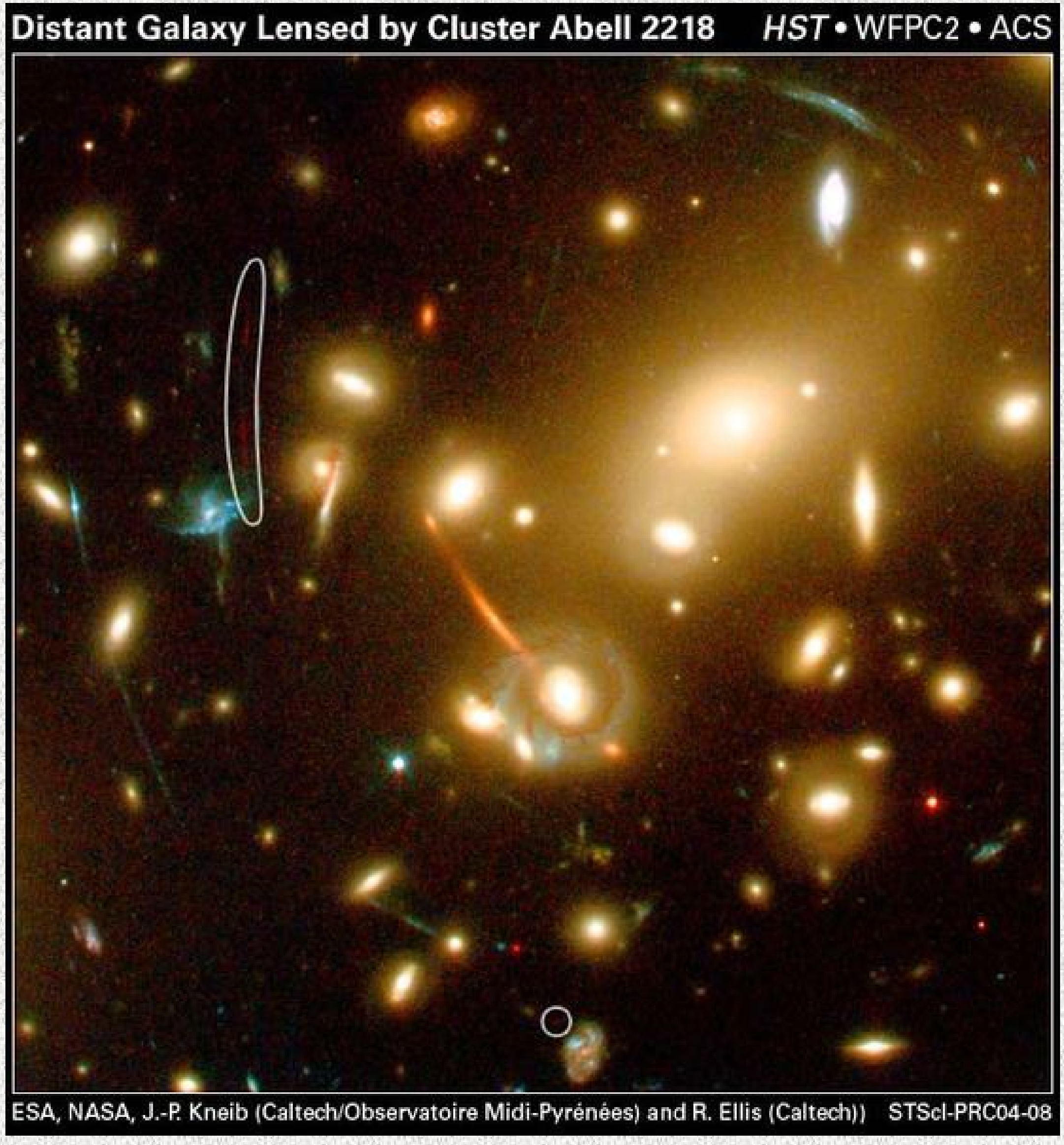
$$M_{tot} \simeq 2 \frac{R_{tot} v^2}{G}$$

When measuring **rotation curves** of **stars** and **HI** in spiral galaxies, one finds a pattern that is incompatible with all mass being visible … a dark **halo** of **invisible** matter is **required**!

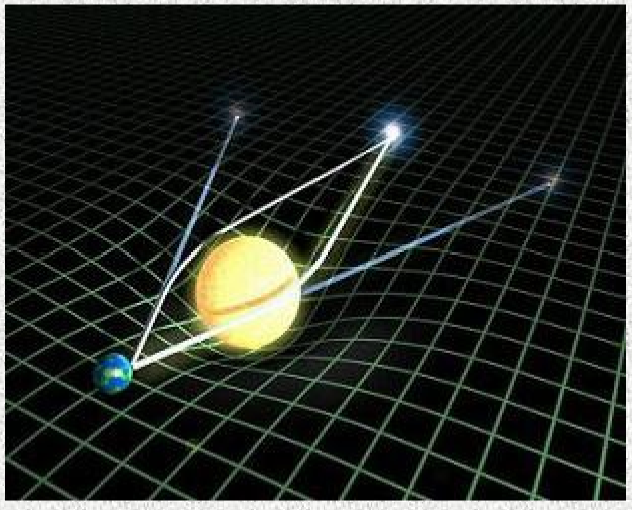


This is the *measured* rotation curve …

And this is the theoretical expectation ..



These **gravitational lens** arcs **demand** an amount of **mass** inside the galaxy cluster that **excedes** by ~a few the amount of mass that can be **assigned** to luminous matter …



The search for angular anisotropies in the CMB

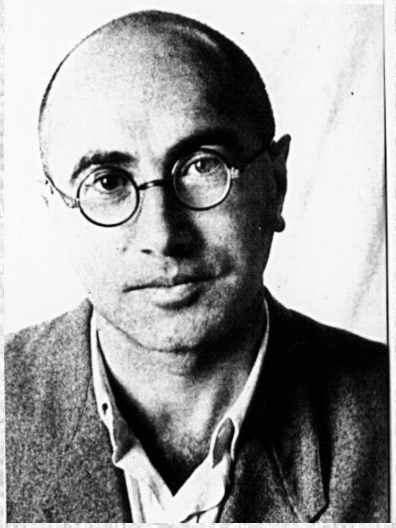
$$\frac{df_X}{dt} = \mathcal{C}[f_X]\,, \quad X = \gamma,\ \nu,\ e^-,\ p\,, n,\ \ldots$$

Given the Copernican principle, **anisotropies** in the **energy distribution** should be ***small***, and thus the **Boltzmann equation can be linearised**, significantly **simplifying** the problem and enabling high-accuracy predictions … This is called **linear cosmological perturbation theory** …

Thus, the statistical properties of the angular anisotropies of the CMB intensity and polarization were predicted by Zel'dovich and Sunyaev in the USSR, and Peebles in the US (1970+)

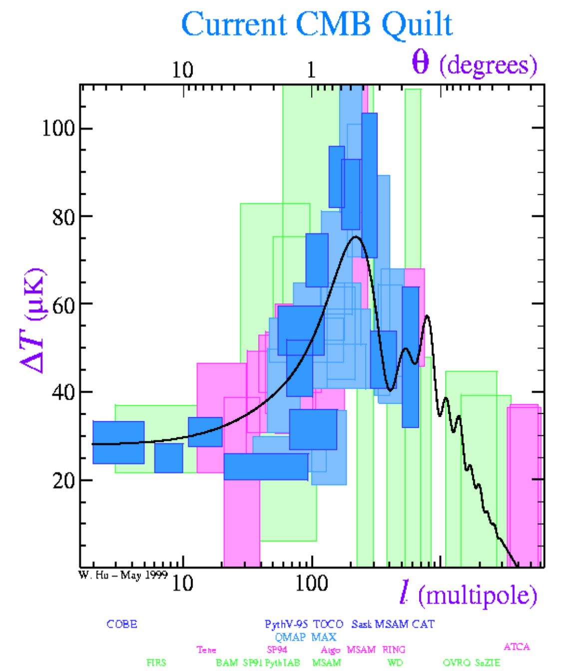
$$T_{CMB}(\hat{\mathbf{n}}) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta,\phi) \;\; ; \;\; C_l^{TT} = \langle a_{l,m} (a_{l,m})^* \rangle$$

Zel'dovich



Sunyaev

$l(l+1)C_l/2\pi$



LONG STORY SHORT: Radiation is trapped/glued via Thomson scattering to electrons (and baryons), and since baryons tend to fall in potential wells (sourced by dark matter), and radiation cannot be compressed arbitrarily, there are sound oscillations in this primeval plasma that lasts as long as most electrons are in the media (i.e., they have not recombined). The largest scale of this acoustic oscillation is the sound horizon

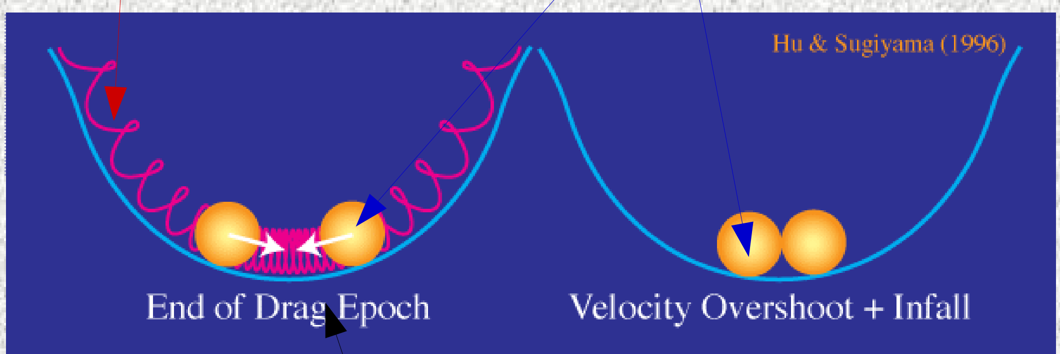
($c_s\, t_{recombination}$ ~ c/sqrt(3) $t_{recombination}$) .

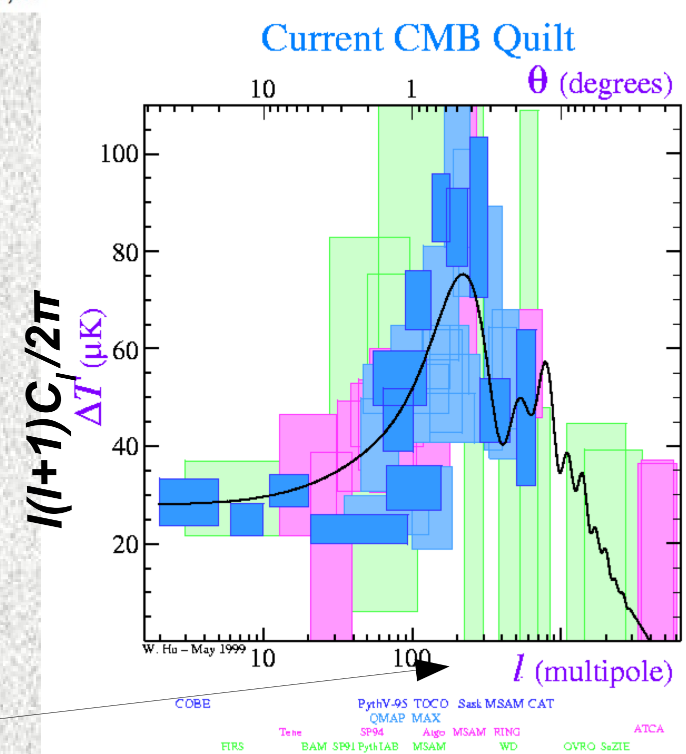
These are the so called **Baryonic Acoustic Oscillations**

$$T_{CMB}(\hat{\mathbf{n}}) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta,\phi) \quad ; \quad C_l^{TT} = \langle a_{l,m} (a_{l,m})^* \rangle$$

Radiation

Matter

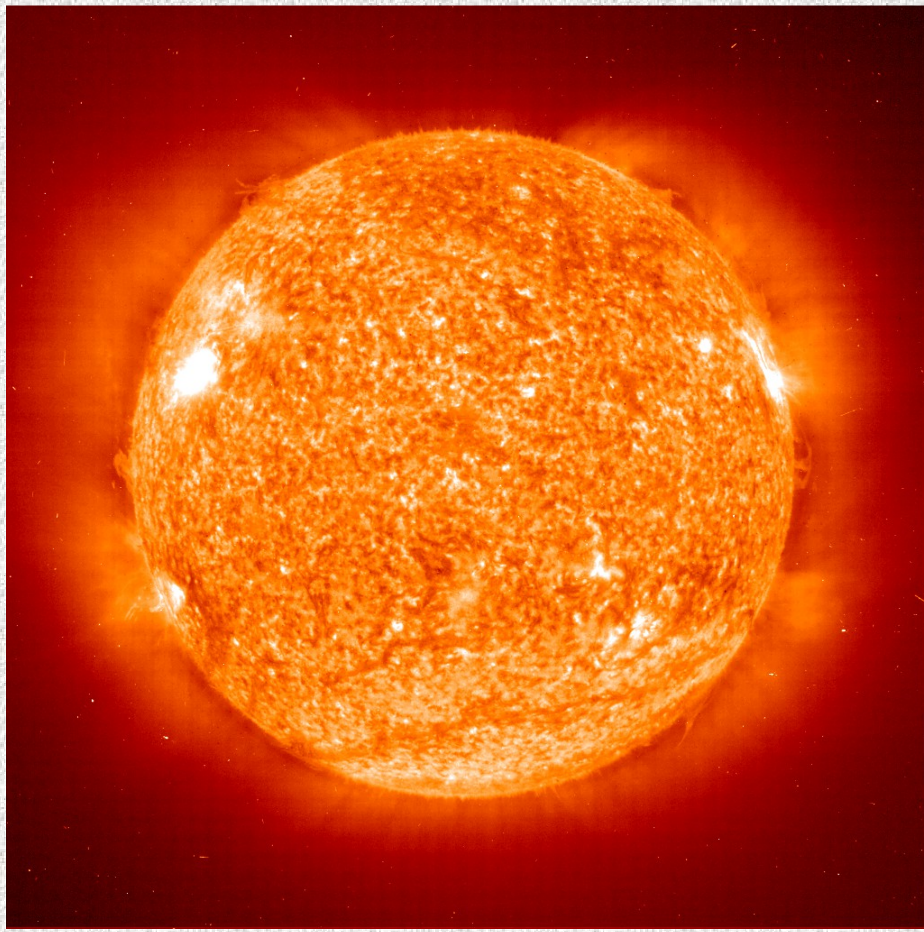




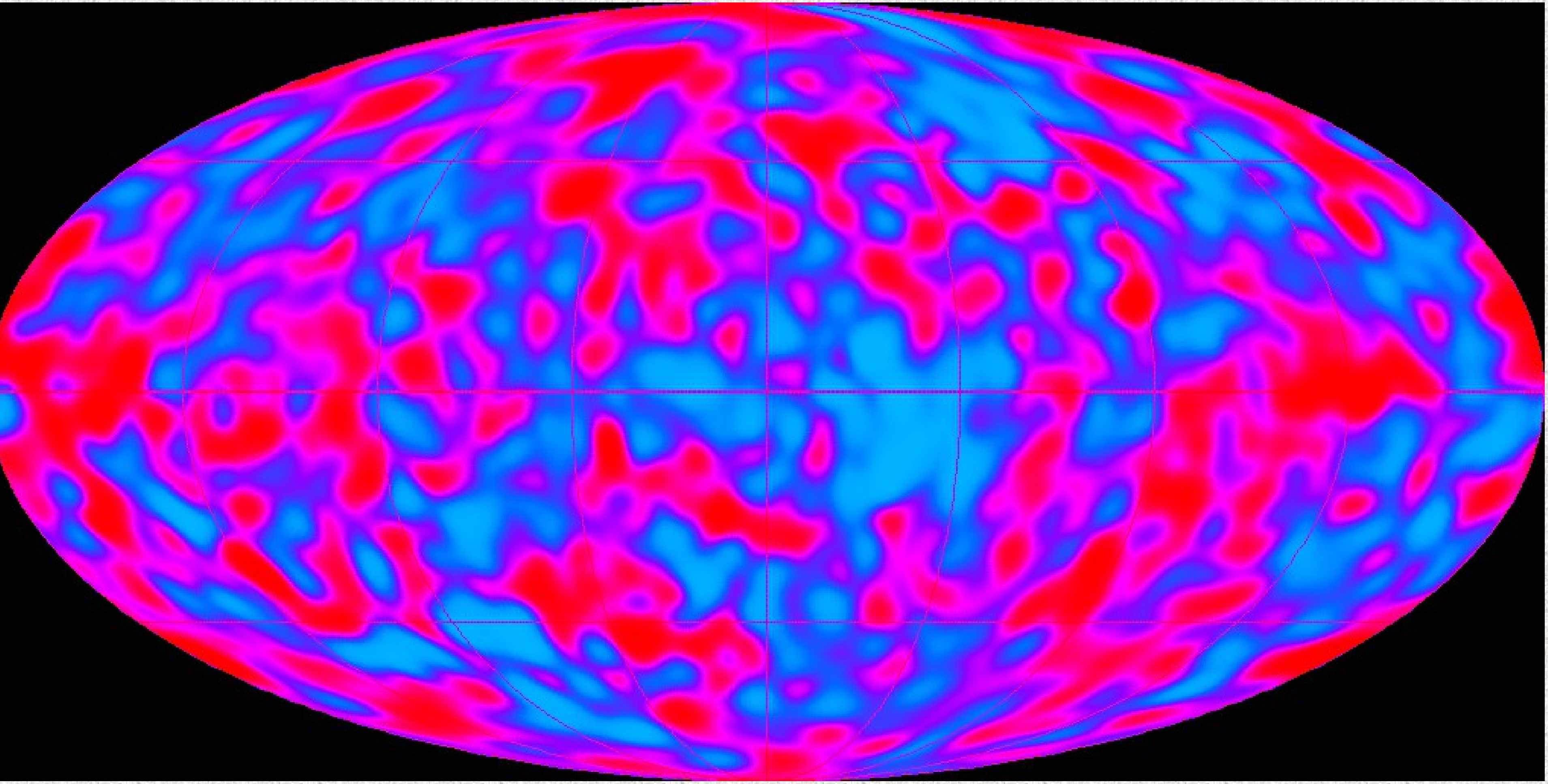
From W.Hu

Size of gravitational potential wells

These computations were close in time to those yielding the nucleo-genesis inside stellar atmospheres …

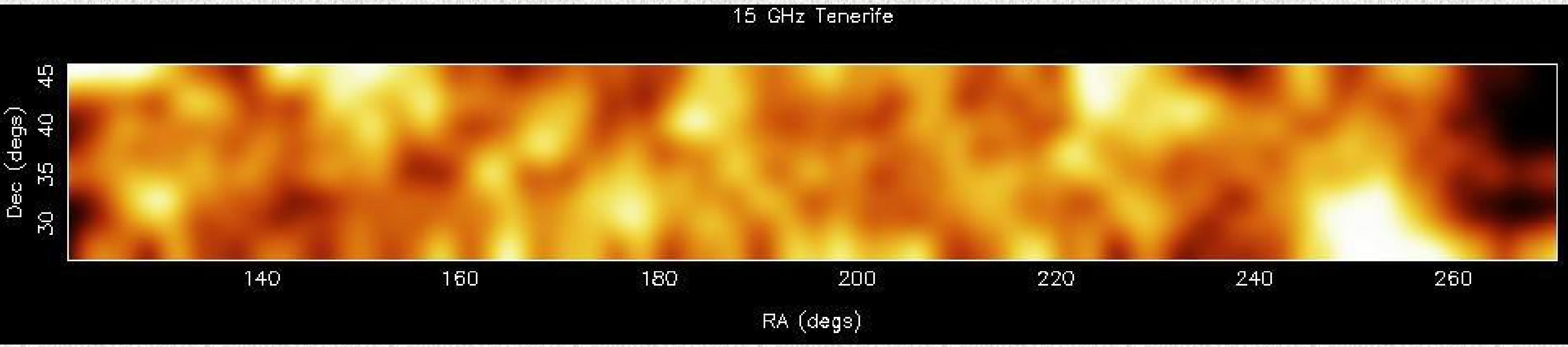


It was in 1992 when NASA's satellite **COBE** detects by **first time the CMB intensity fluctuations**, while also measuring its black-body spectrum with exquisite precision (~3e-5)

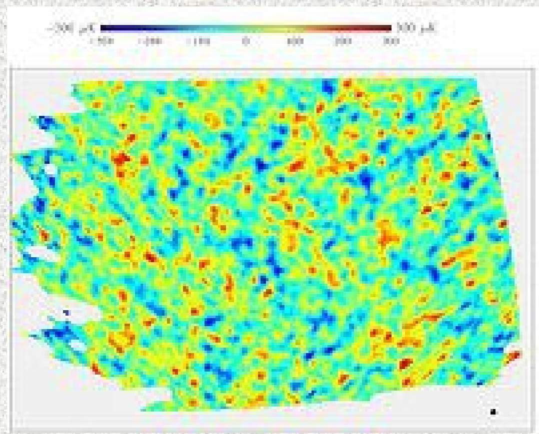


COBE's angular resolution was close to ~ 8 degrees, while the Moon's diameter is about 0.5 degrees.

Shortly after 1992 more and more experiments were providing new CMB maps, of improving quality over the years …

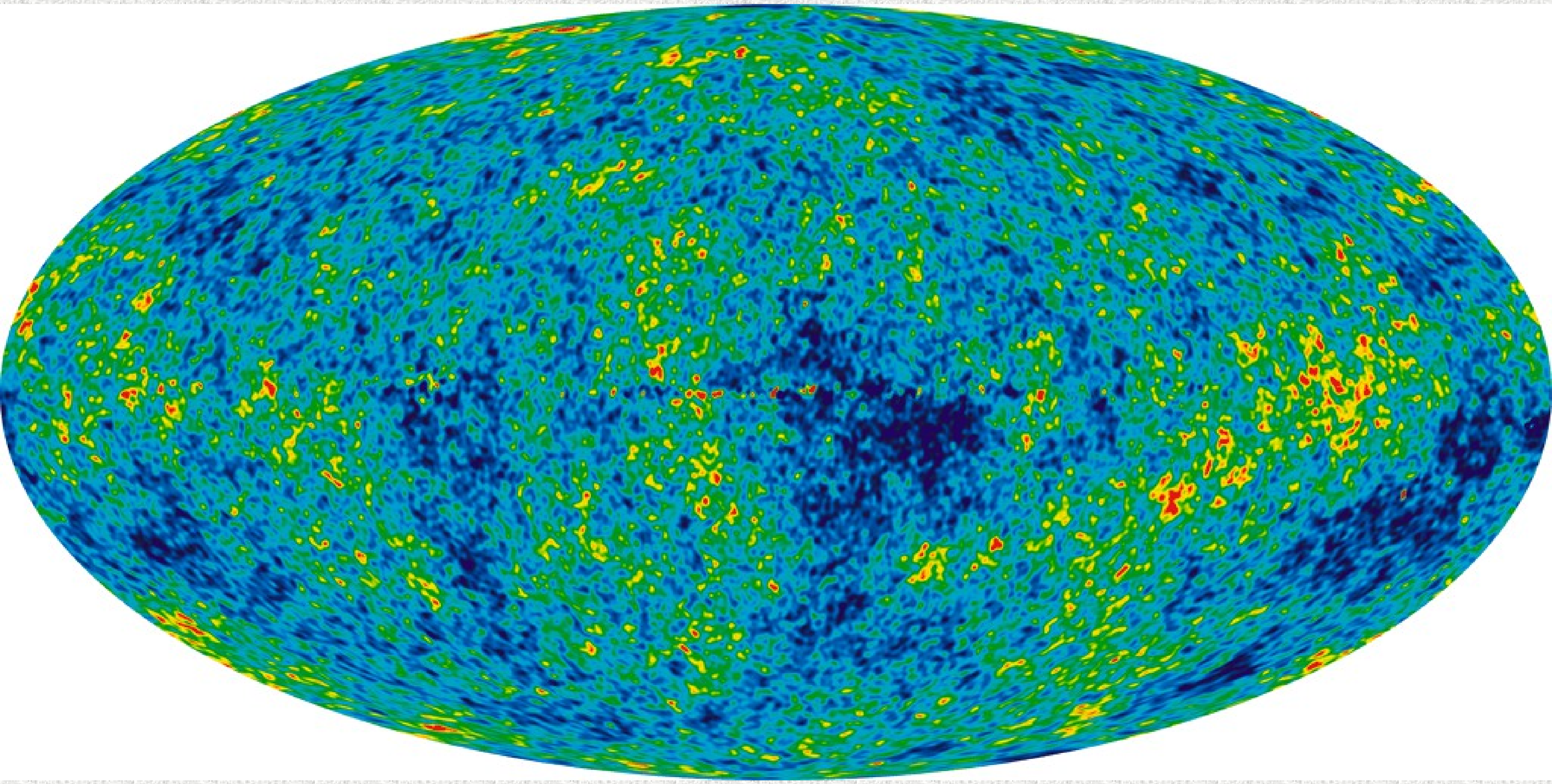


Tenerife experiment (1994)

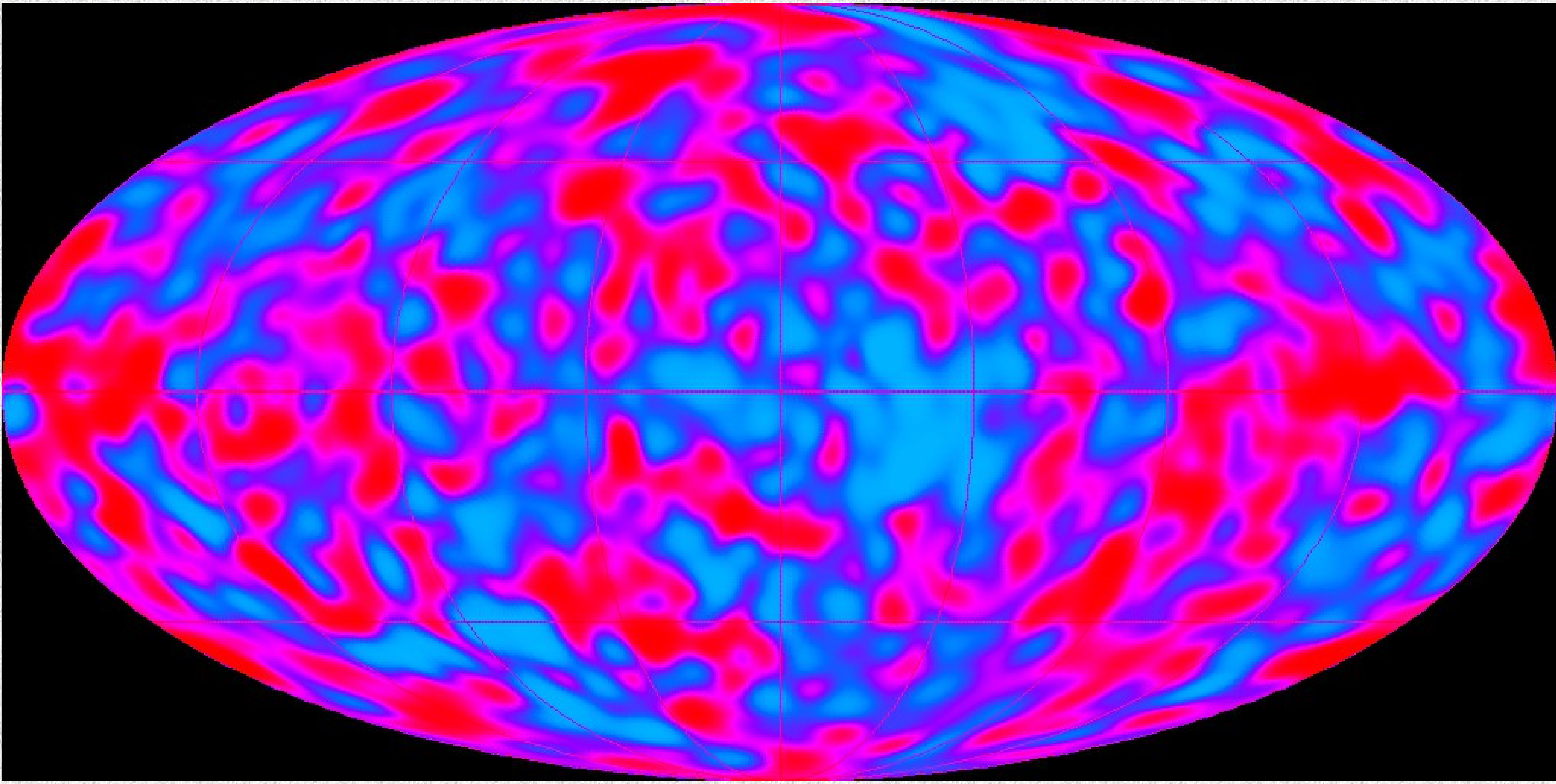


Boomerang experiment (2000)

From 2003 up to 2010, NASA's satellite **WMAP has produced high-quality all-sky maps:**

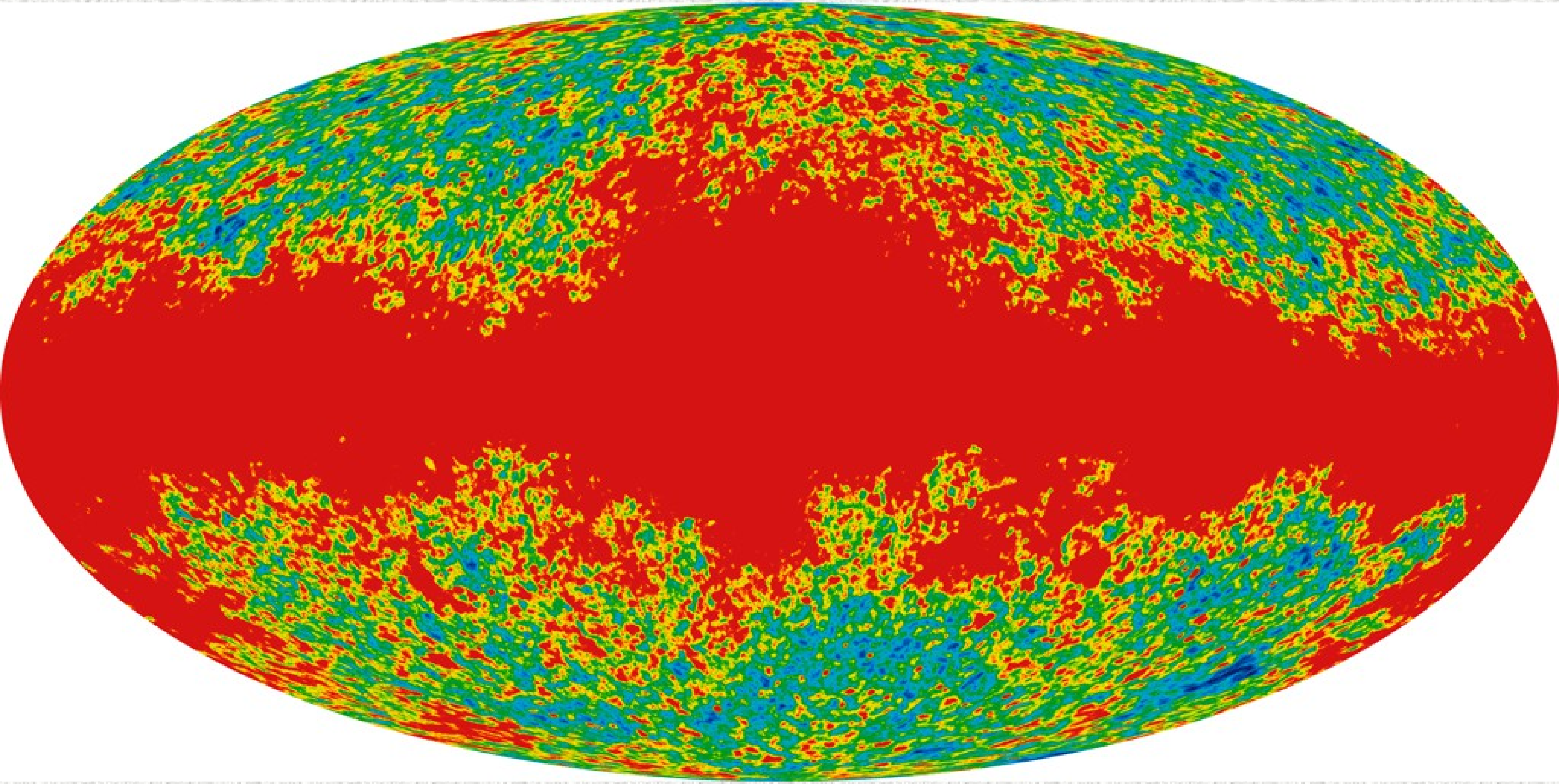


COBE (1992)



Is it so easy to measure the CMB anisotropies?

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
The CMB is a **black body** and thus its **brightness temperature** should be **constant** and **independent** of the **observing** frequency (**unlike contaminants**!)



WMAP, 23 GHz

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
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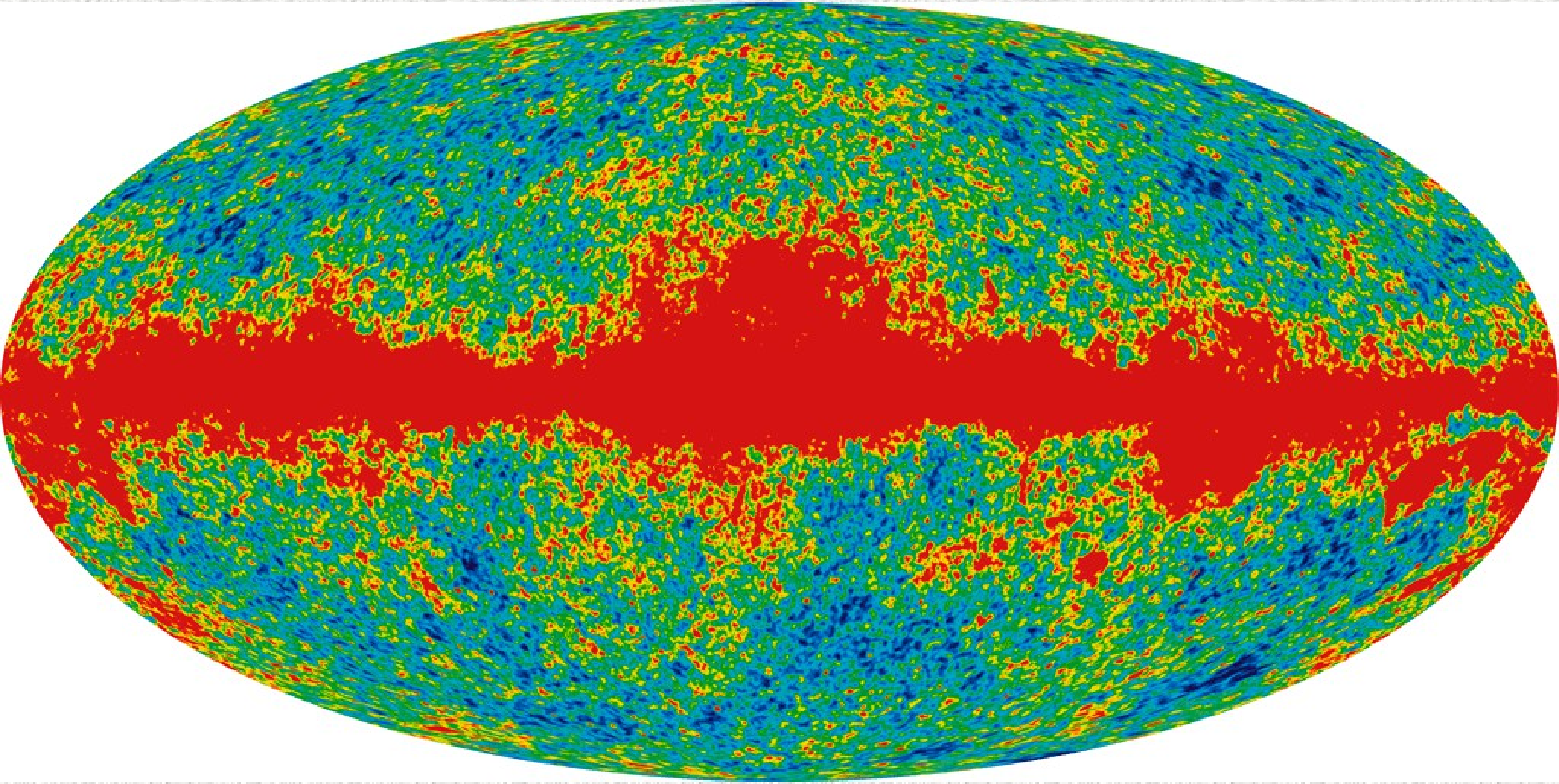
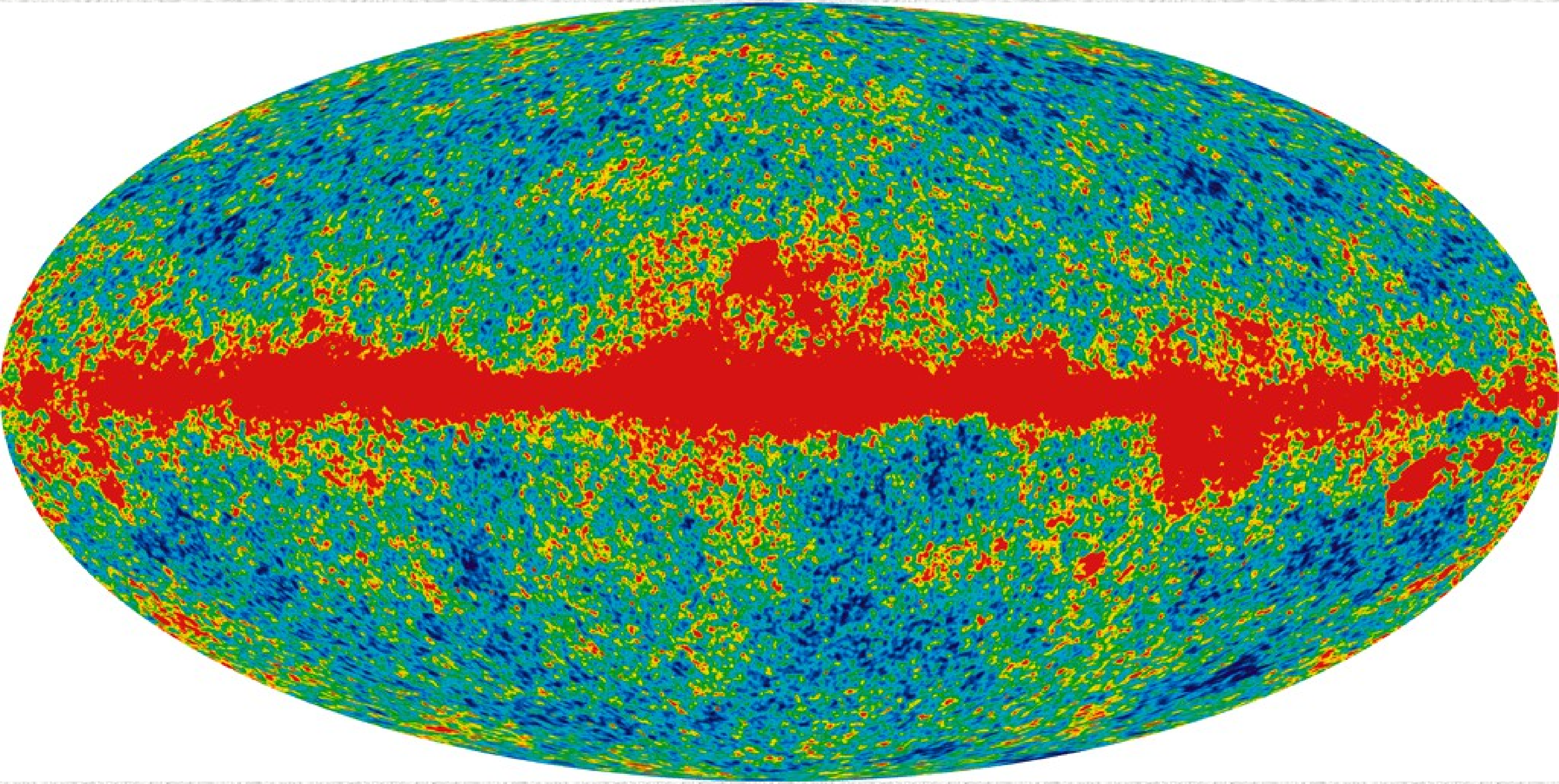


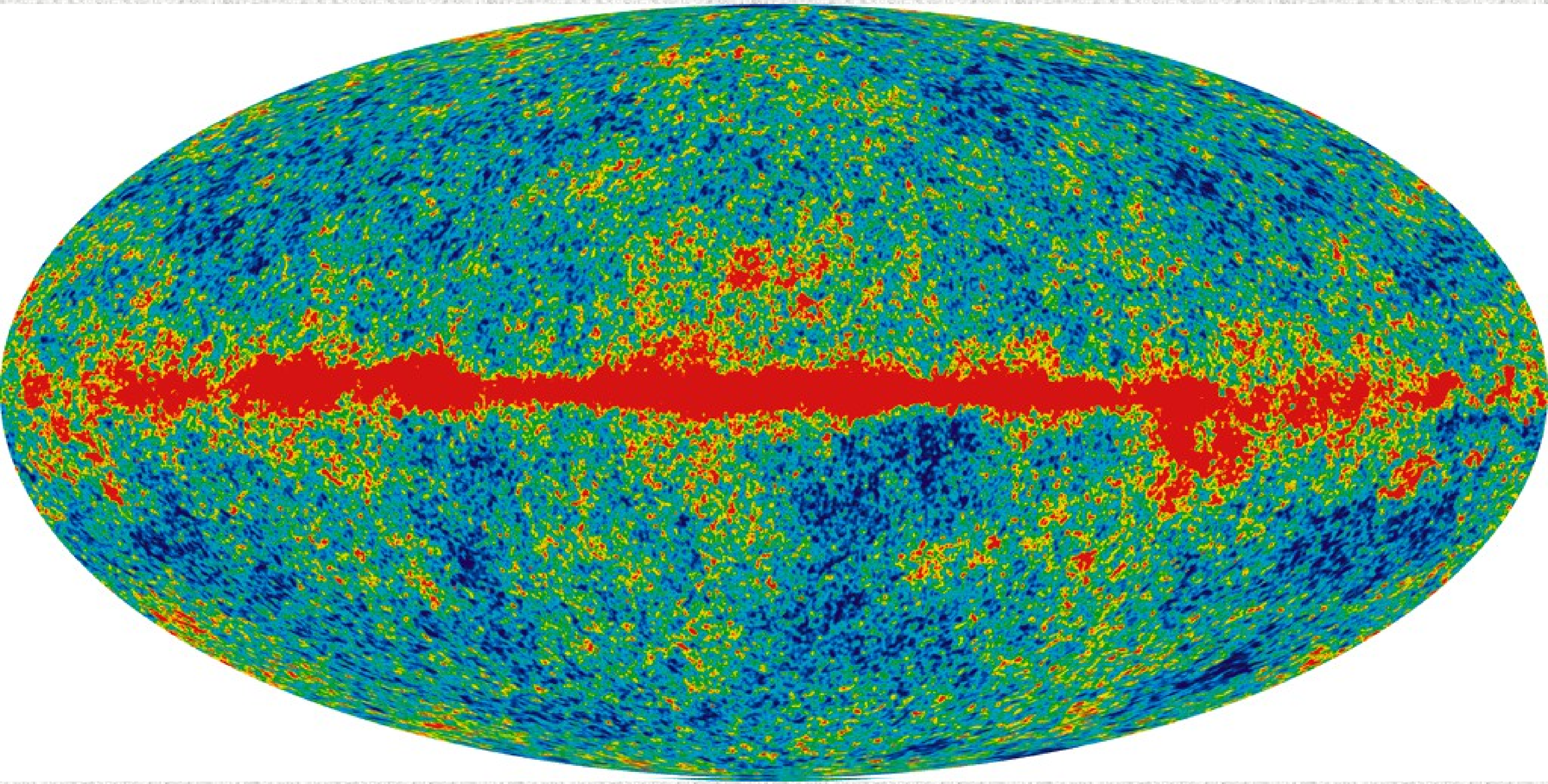
WMAP, 33 GHz

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
The CMB is a **black body** and thus its **brightness temperature** should be **constant** and **independent** of the **observing** frequency (**unlike contaminants**!)



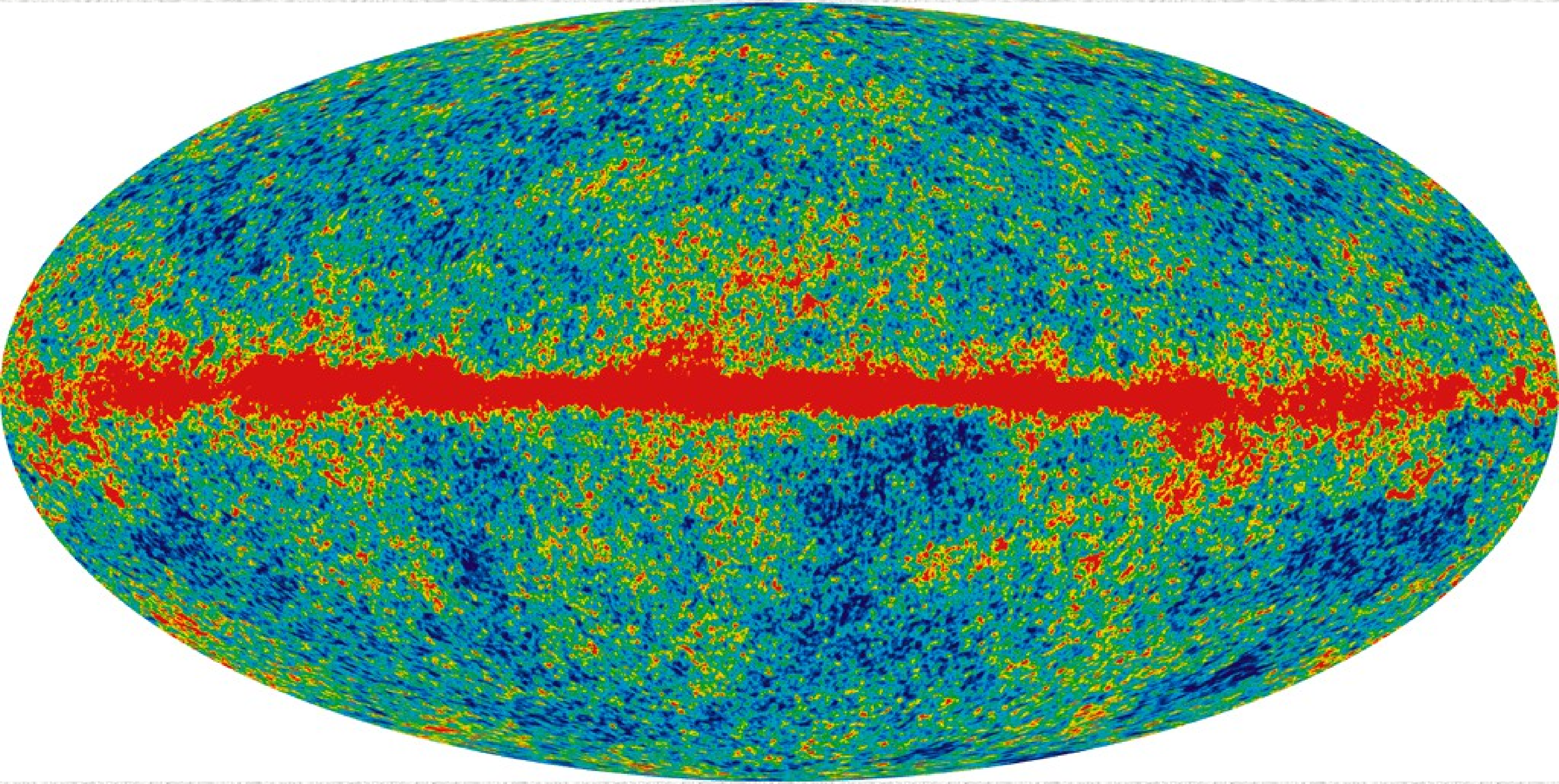
WMAP, 41 GHz

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
The CMB is a **black body** and thus its **brightness temperature** should be **constant** and **independent** of the **observing** frequency (**unlike contaminants**!)



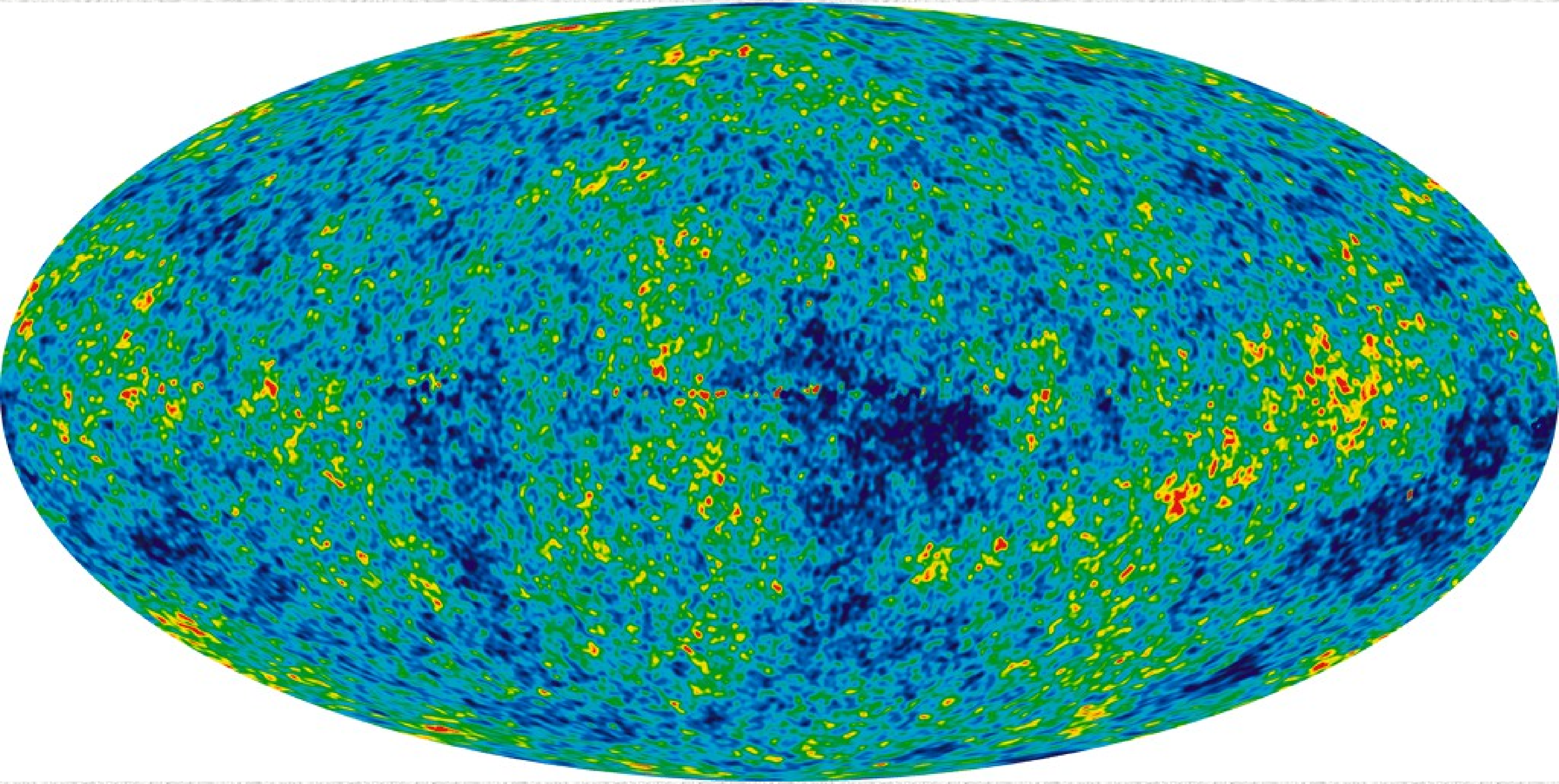
WMAP, 61 GHz

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
The CMB is a **black body** and thus its **brightness temperature** should be **constant** and **independent** of the **observing** frequency (**unlike contaminants**!)



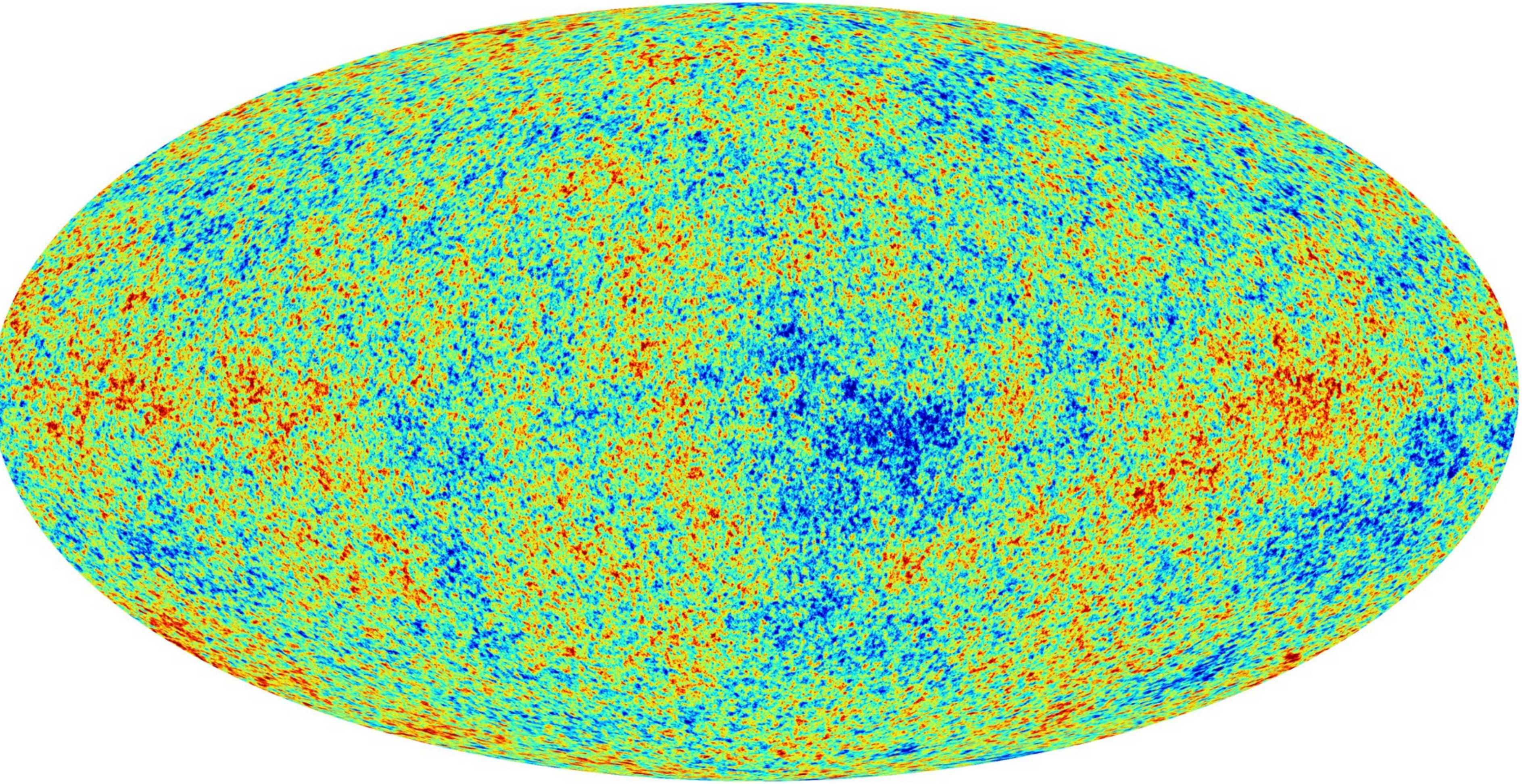
WMAP, 94 GHz

In order to **isolate** the **CMB**, one needs to **subtract** the emission from the **Milky Way** + other extragalactic sources!
The CMB is a **black body** and thus its **brightness temperature** should be **constant** and **independent** of the **observing** frequency (**unlike contaminants**!)

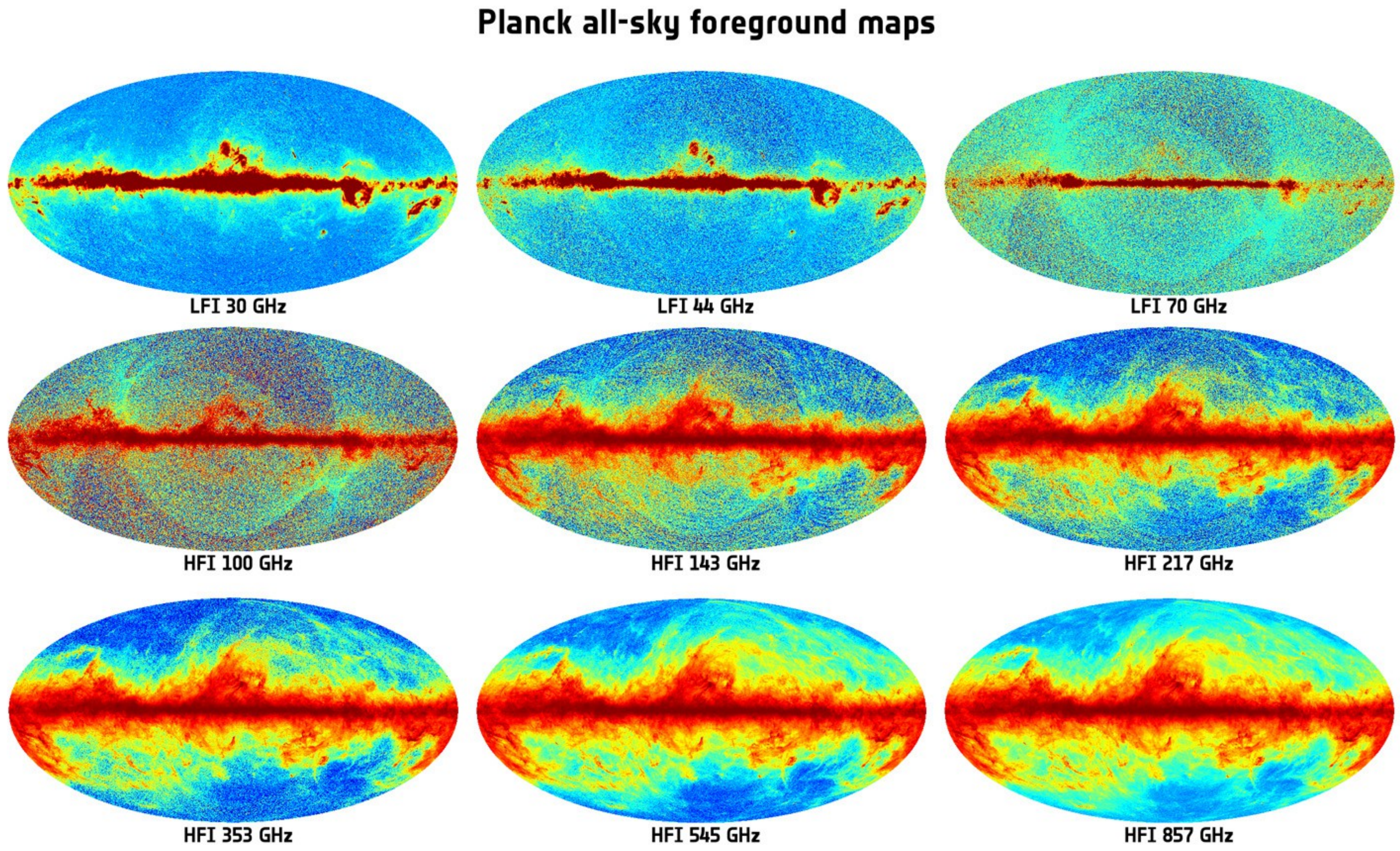


CMB "*limpio"*

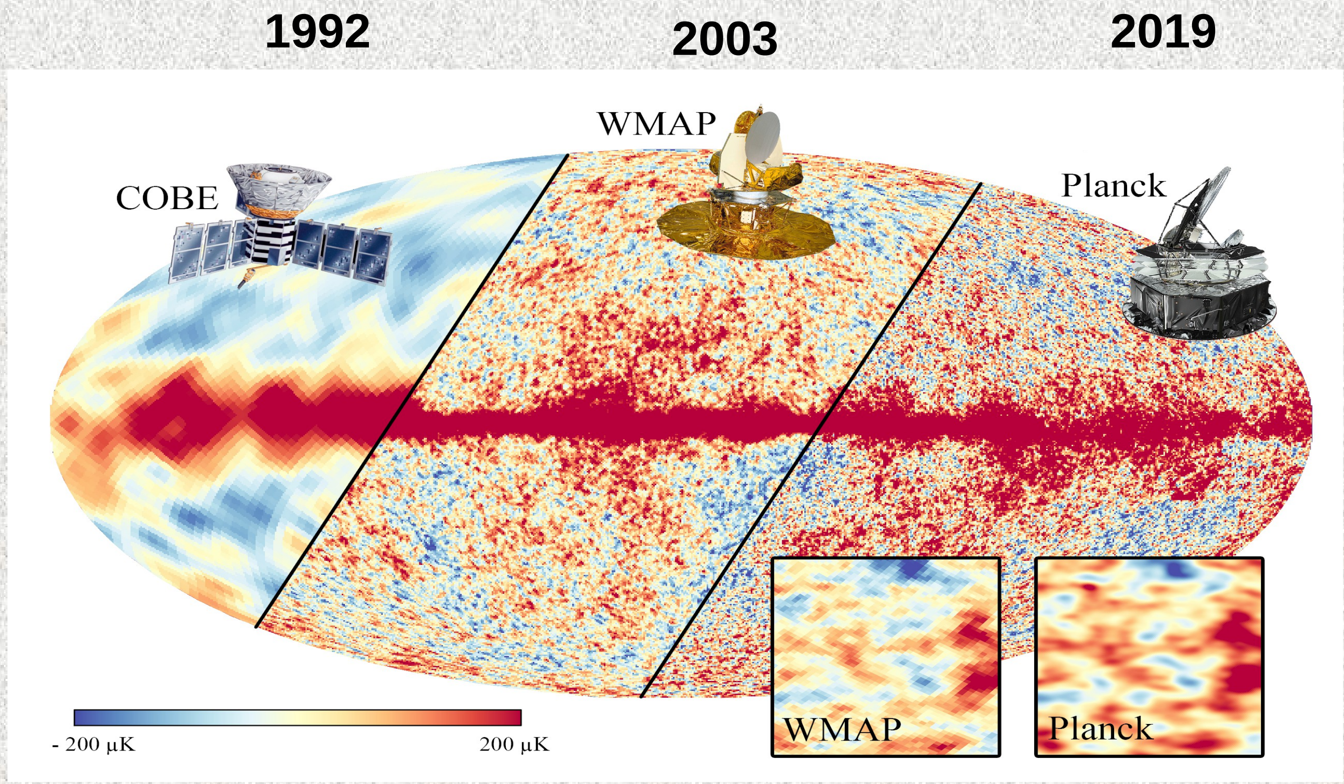
Finally, from 2009 up to 2018, ESA's mission ***Planck*** **has generated the highest quality all-sky maps of the CMB … I**



Thanks to the high number of channels (9), *Planck* is able to **accurately clean** galactic and extra-galactic **foregrounds/contaminants** …



Historical context of CMB research

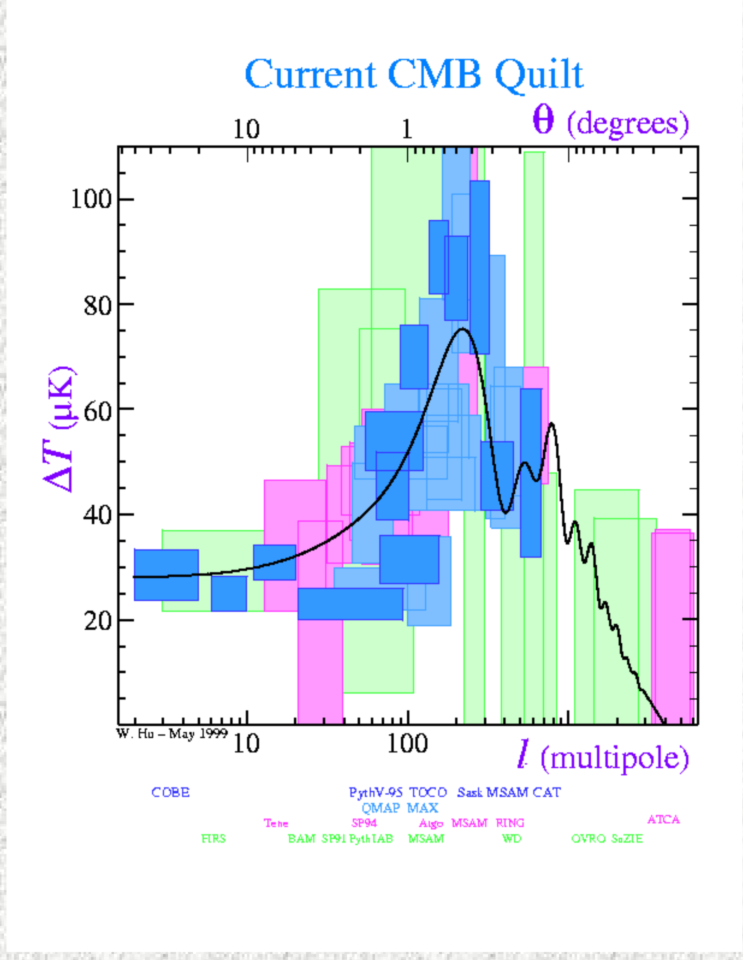


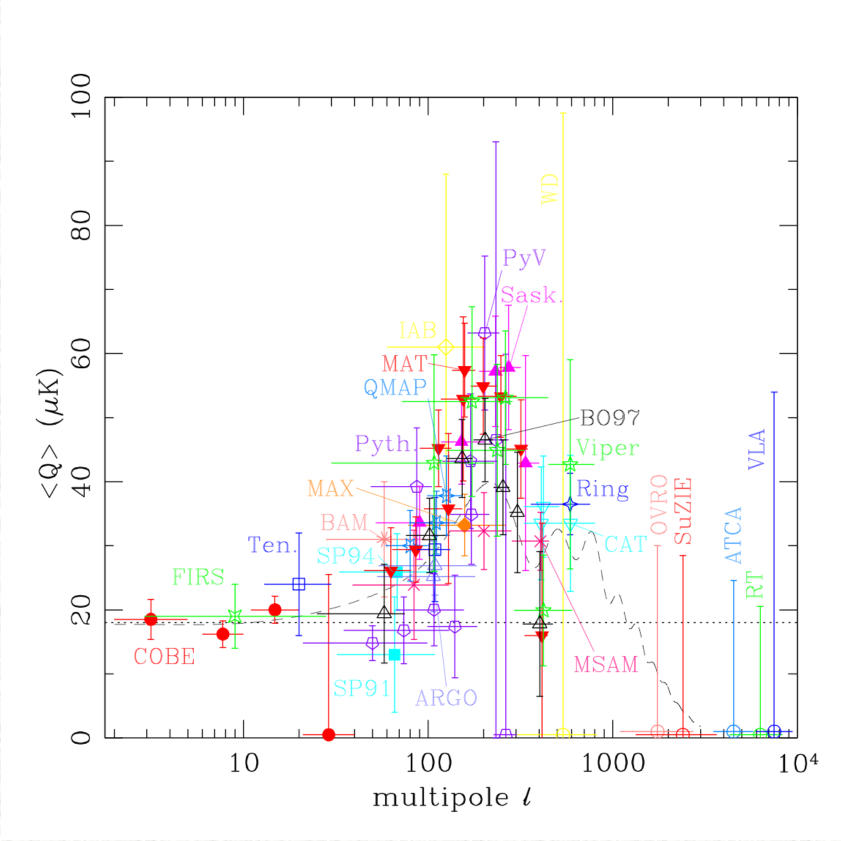
During the last **20 years**, rapidly improving observations of the CMB have provided a more **accurate** descriptions of the epoch of **cosmological recombination** …

Measuring CMB anisotropies allows **comparing data with theoretical predictions** …

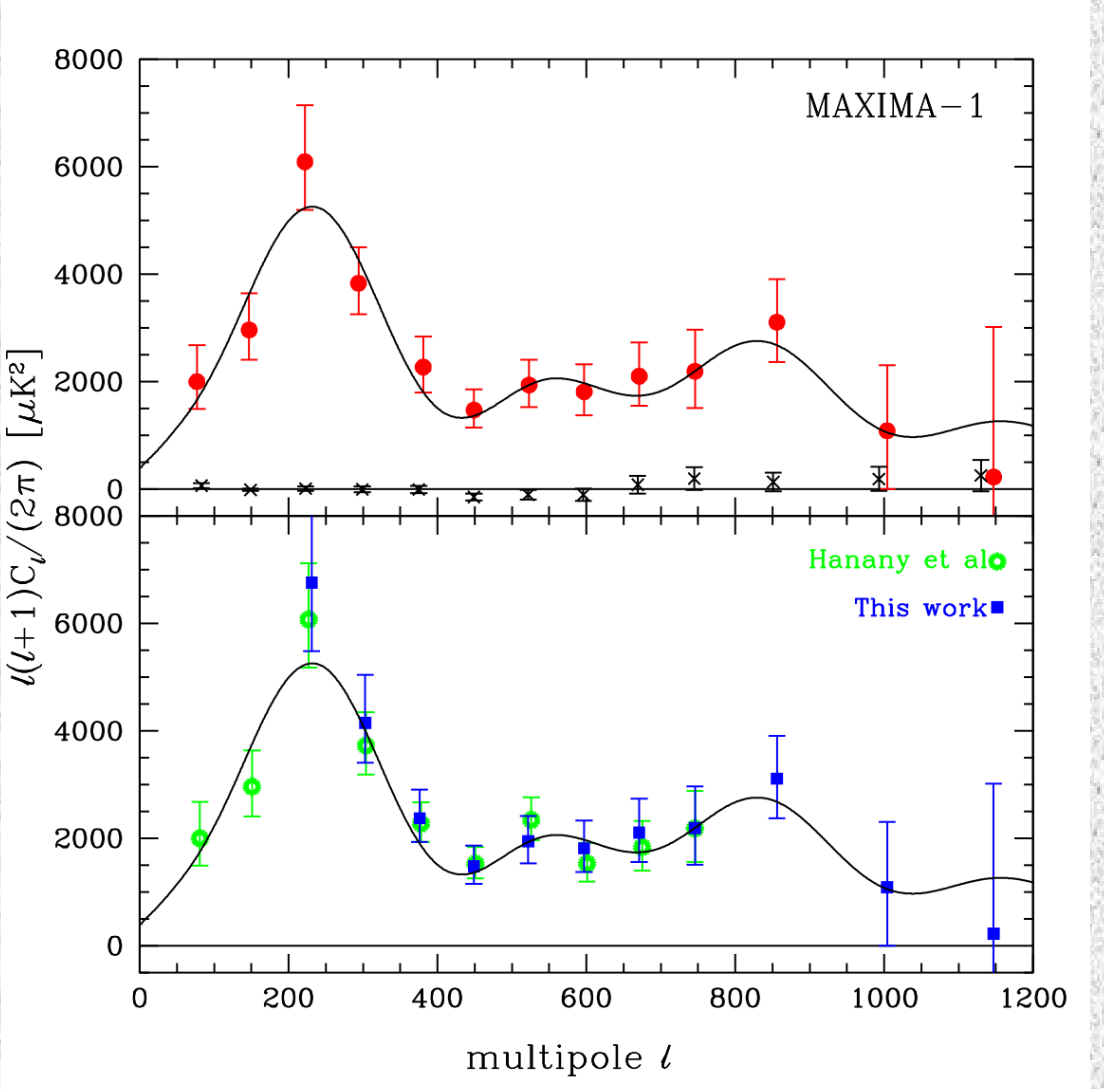
At the end of the 1990s, this was the situation:

1998



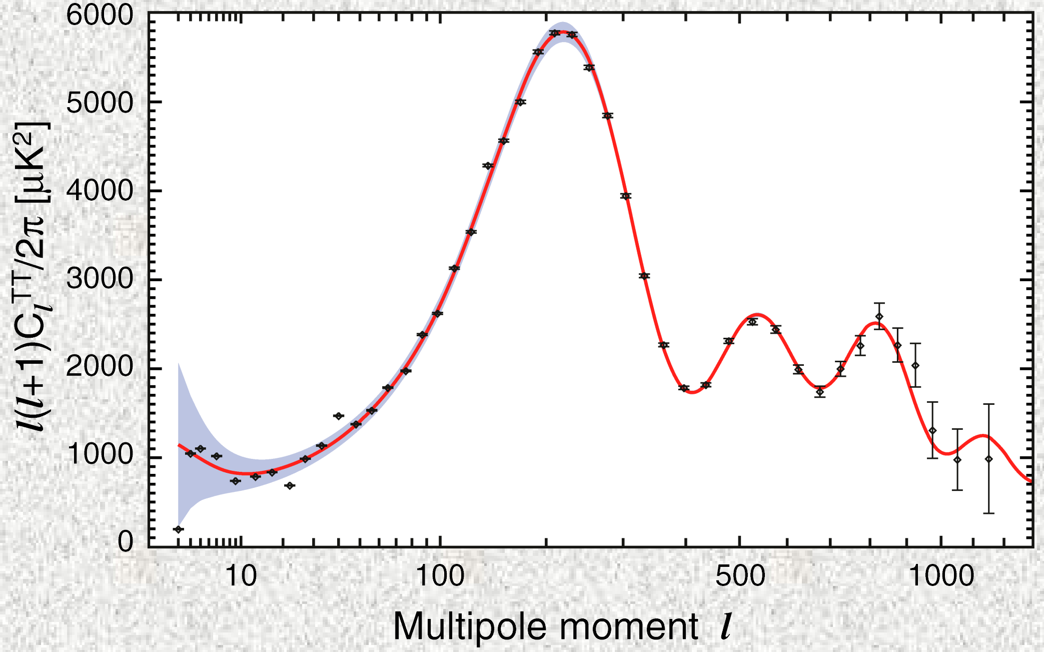


In the years 1999 – 2001, the first acoustic peaks becomes visible …

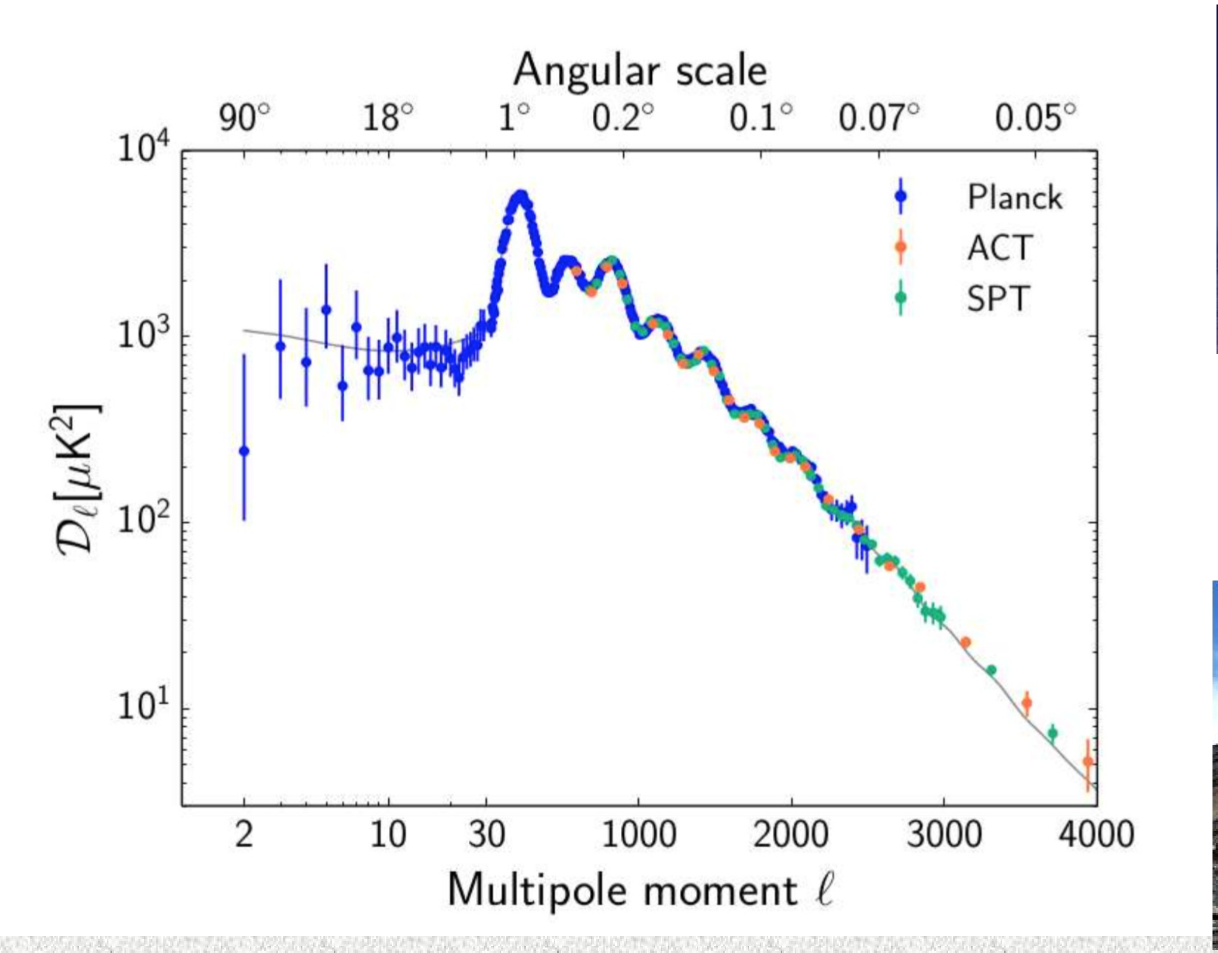


WMAP, in 2003 – 2010, provided the first **high-precision measurement** of **cosmological parameters** defining the acoustic peak structure (**baryon density** during recombination, initial amplitude of potential fluctuations, scale dependence of those fluctuations), together with the **geometry** of the universe …

2010

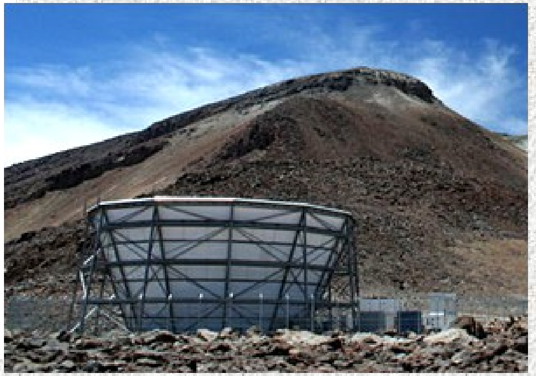


Planck, 2015

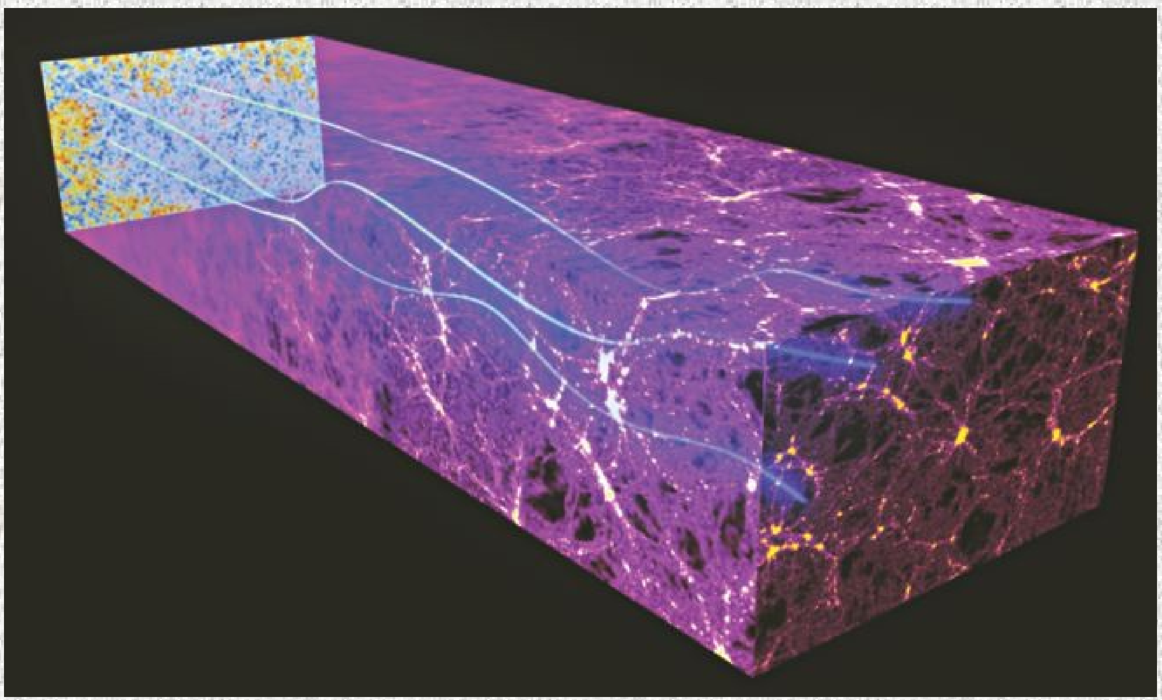


South Pole Telescope

Atacama Cosmology Telescope



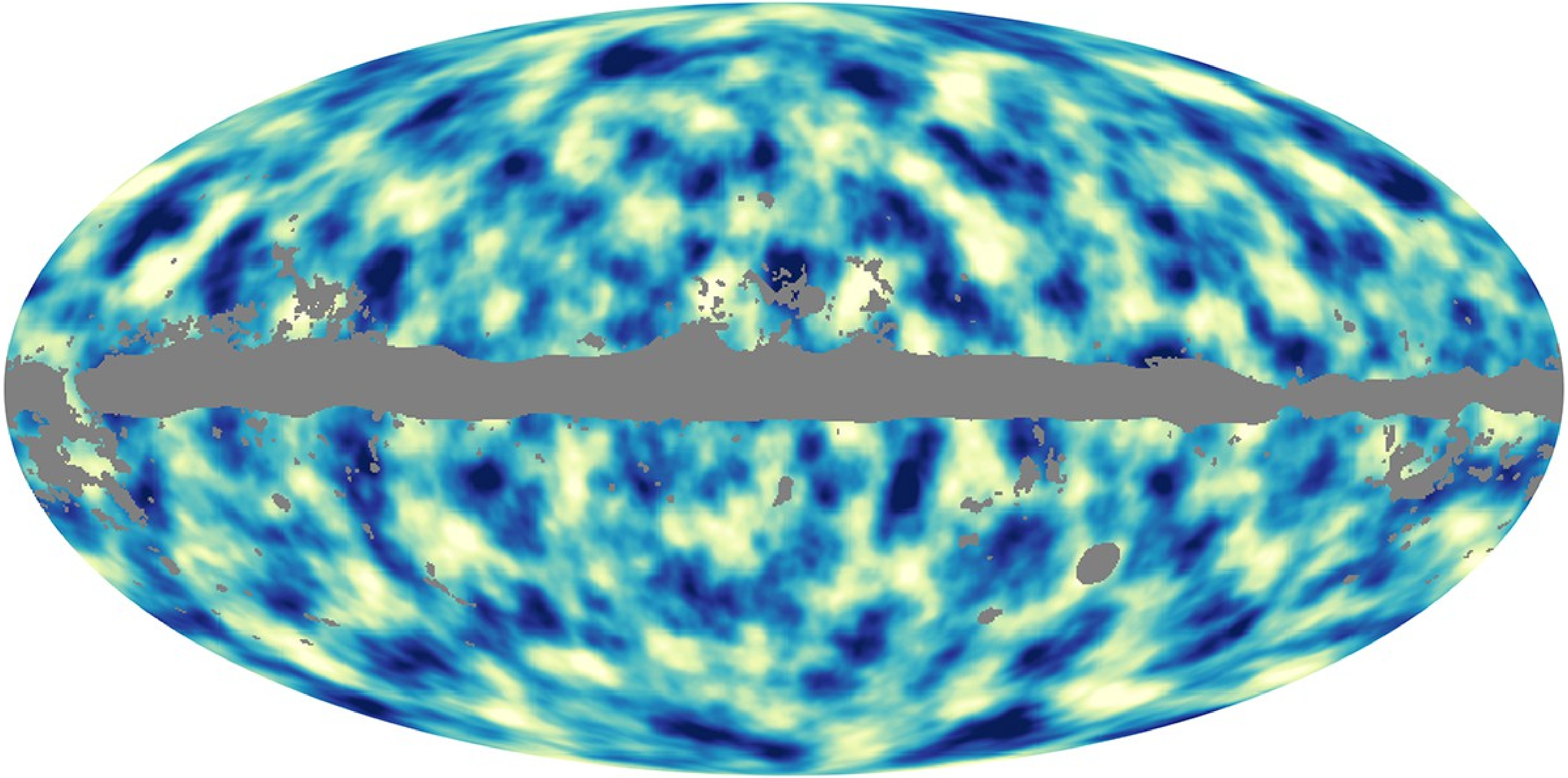
Gravitational lensing of CMB anisotropies



ESA

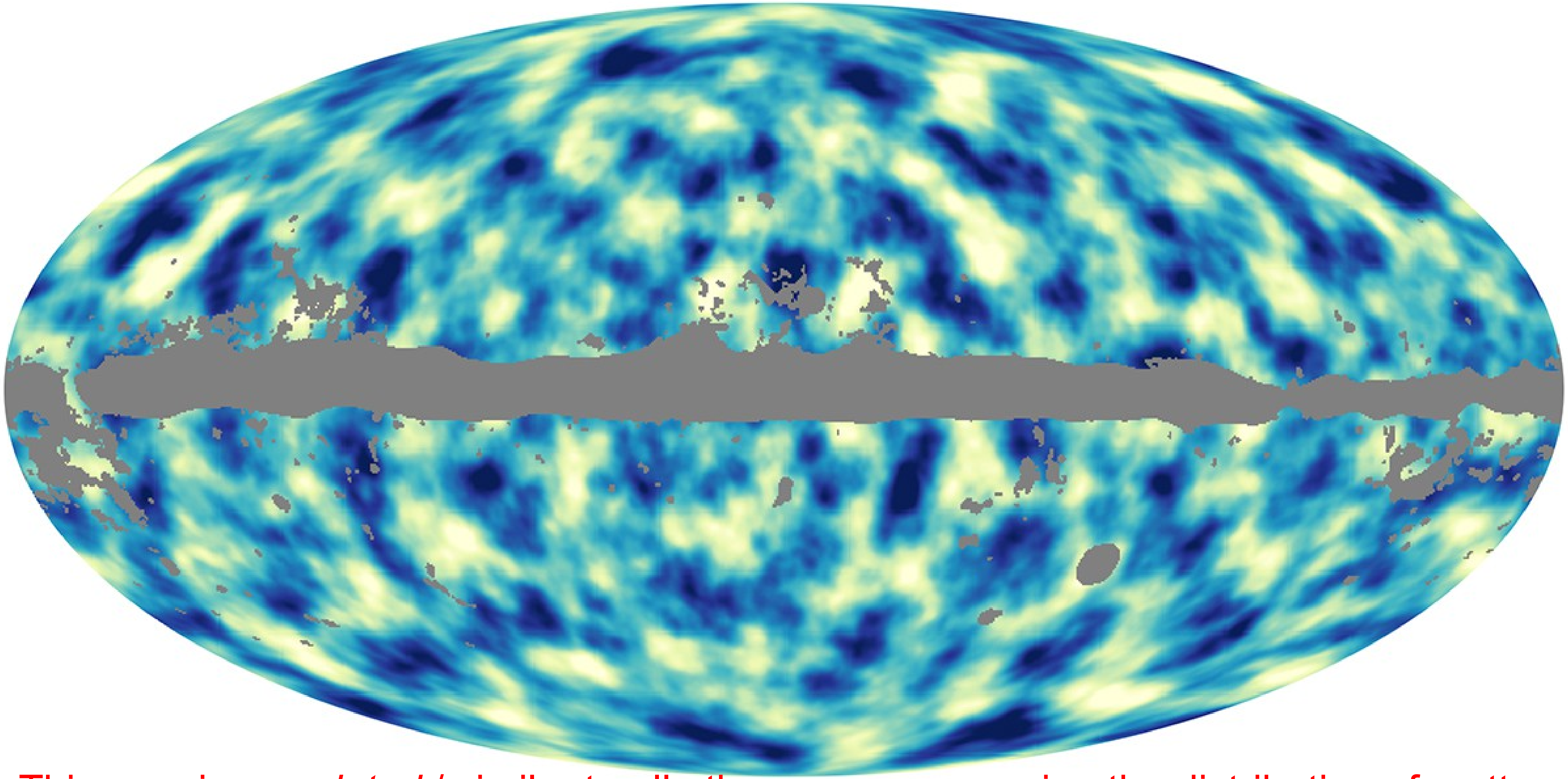
+ many other **secondary** angular anisotropies induced on the CMB at late epochs, enabling **cross-correlation** studies of CMB maps with Large Scale Structure surveys

MAP OF PROJECTED GRAVITATIONAL WELLS



ESA

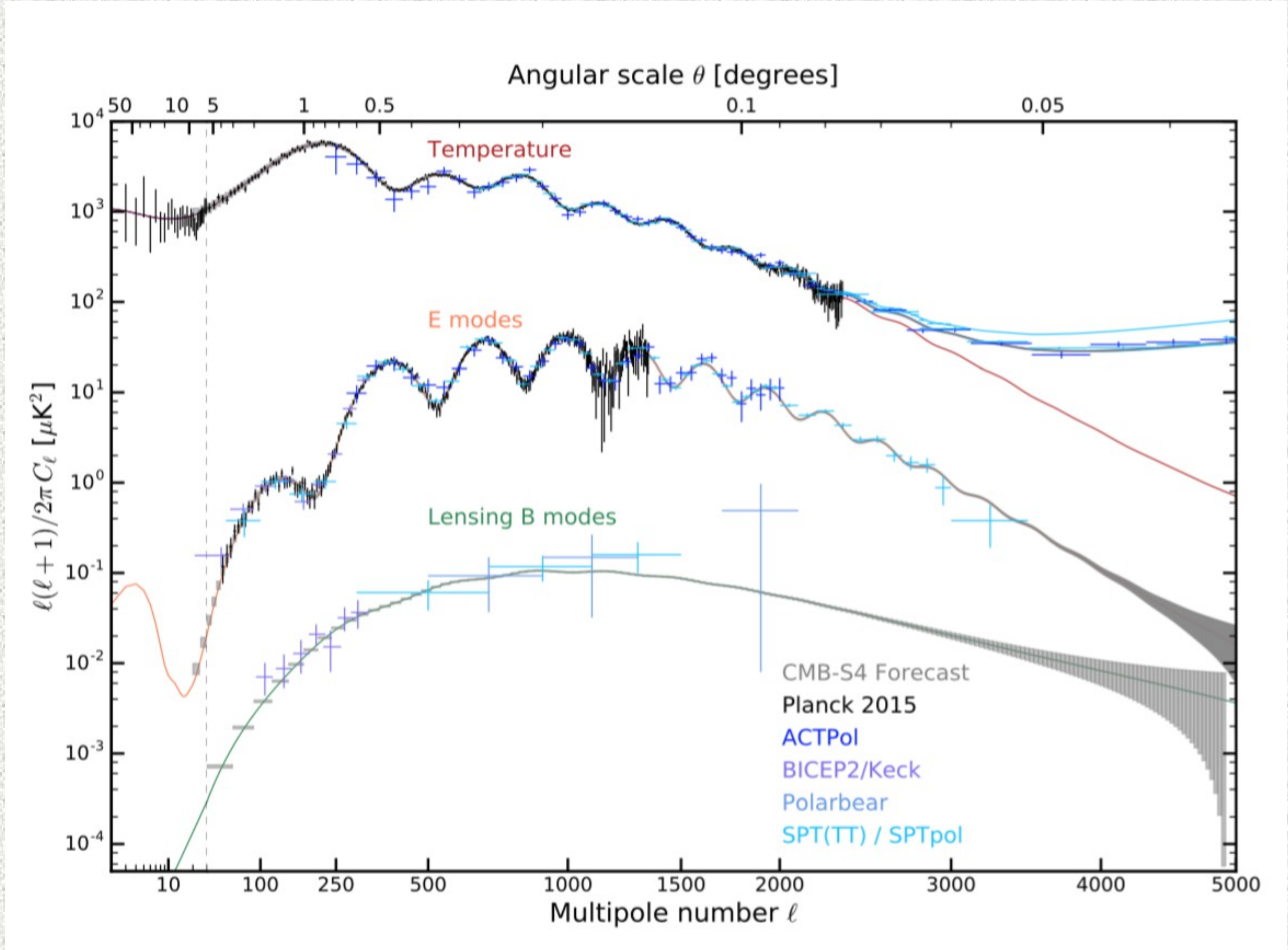
MAP OF PROJECTED GRAVITATIONAL WELLS



This map is *correlated* / similar to all other maps expressing the distribution of matter at large scales (from galaxies and quasars) that we have built so far …

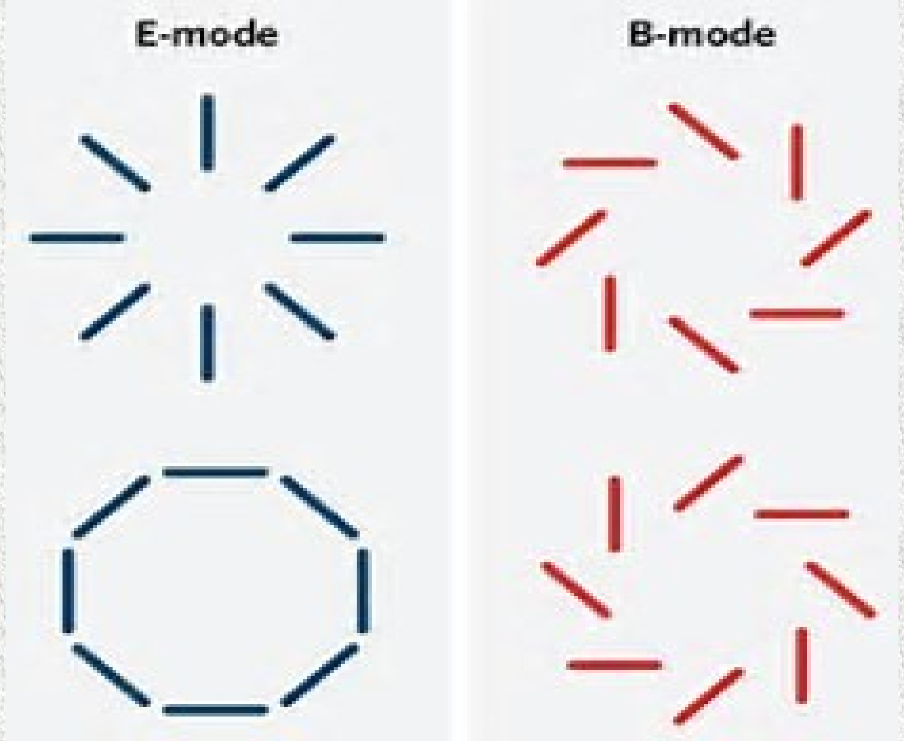
ESA

Current CMB observational status...



Science Book, Stage IV

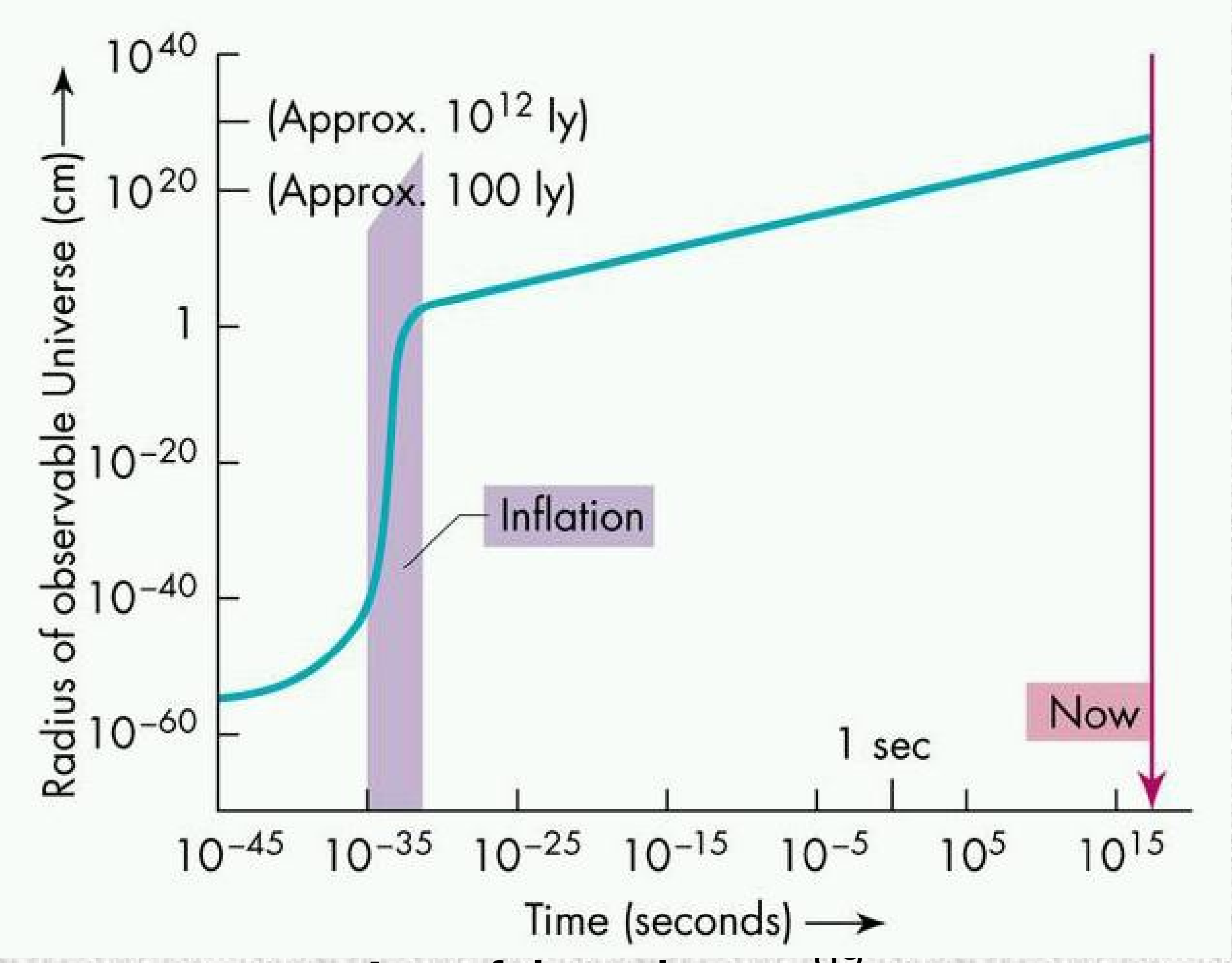
Stage IV CMB experiments



There is just **one mecanism** able to generate **B-type primordial polarization** in the CMB: via **gravitational waves sourced in the inflationary epoch...**

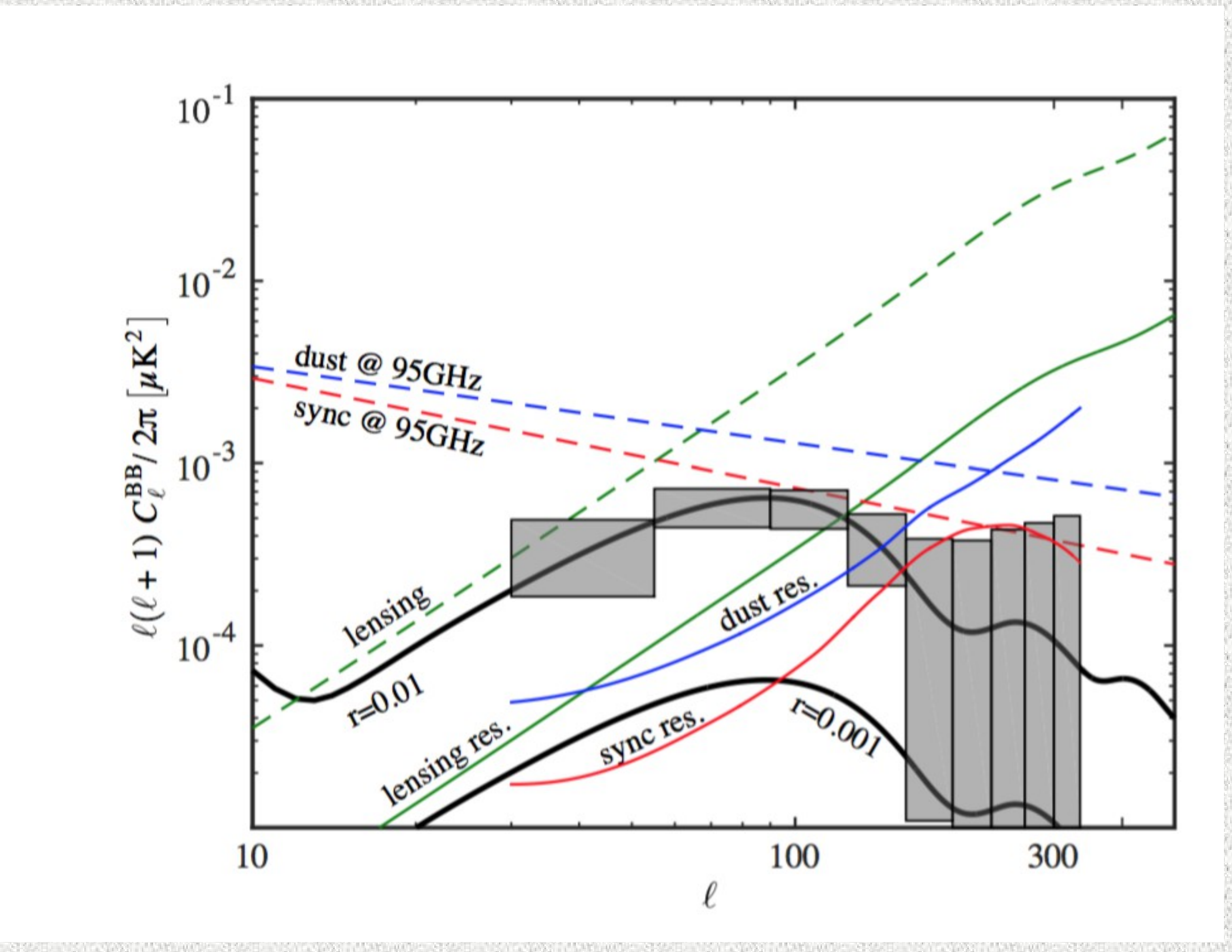
Proposed solution at the beginning of the 1980s:

An inflationary epoch, during which the universe expansion is such that *nearby* regions lose causal contact (i.e., near observers lose each other out of sight)



Age of the universe

Stage IV CMB experiments

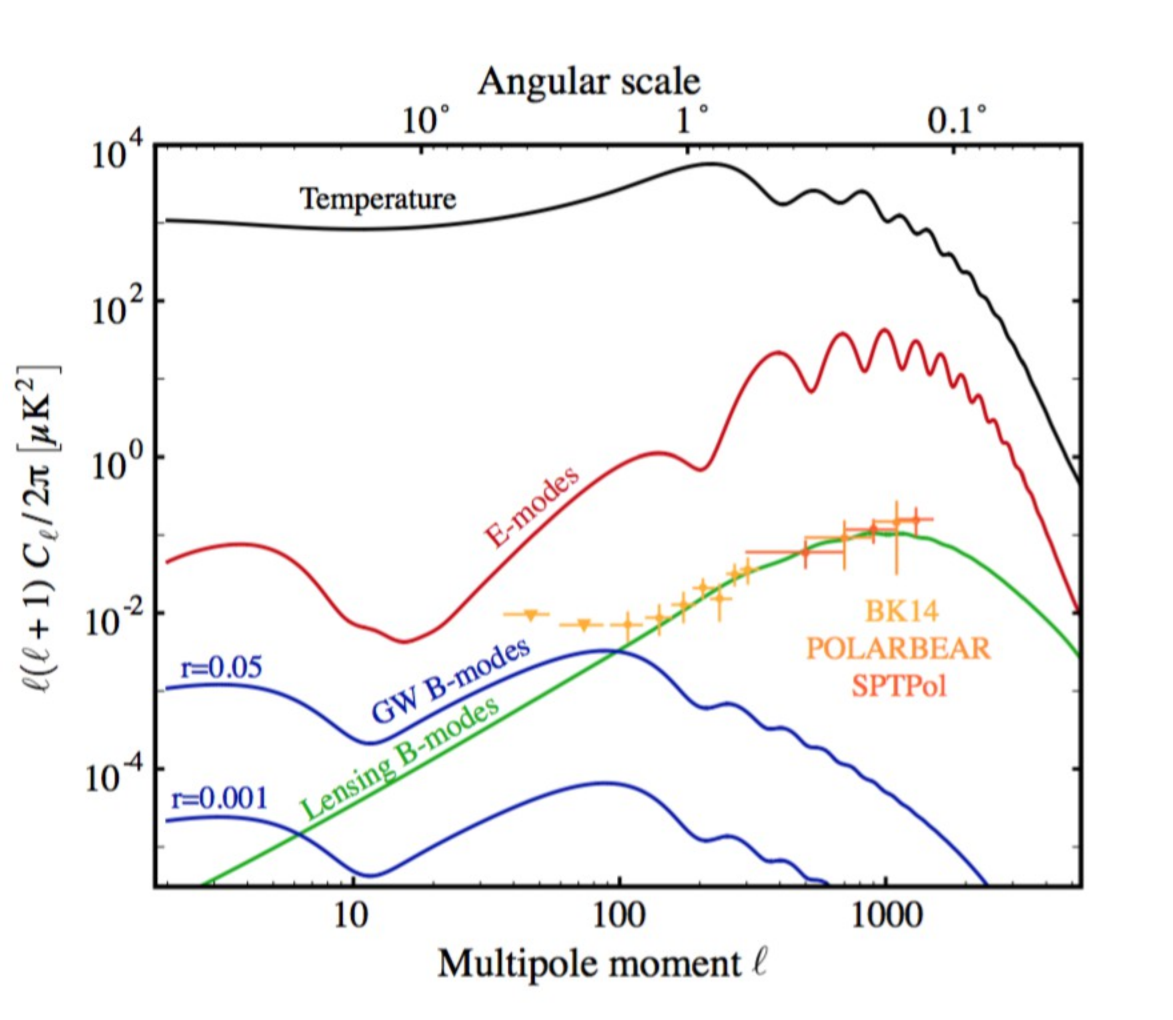


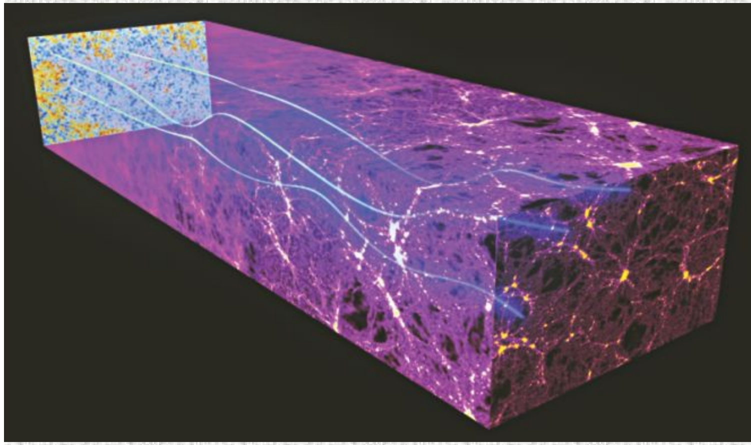
Science Book, Stage IV

The goal is having an error in ***r*** of about **0.001** (al **95%** C.L.).

We would thus access energy scales at the level of $\mathbf{10^{16}}$ **GeV**, **12** orders of magnitude above the **LHC** limit …

Stage IV CMB experiments





Science Book, Stage IV

Stage IV CMB experiments

Stage IV CMB experiments

These experiments are targetting the following open questions:

What is the **energy scale of Inflation?** (This should correspondd to the energy scale of Great Unification Theories, GUT)

How many **relativistic** species exist during the epoch of cosmological recombination? Is there any evidence of other **light relics** (axions/gravitinos/sterile neutrinos)?

What's the nature of **dark matter**? Did dark matter **decay** during recombination/reonization?

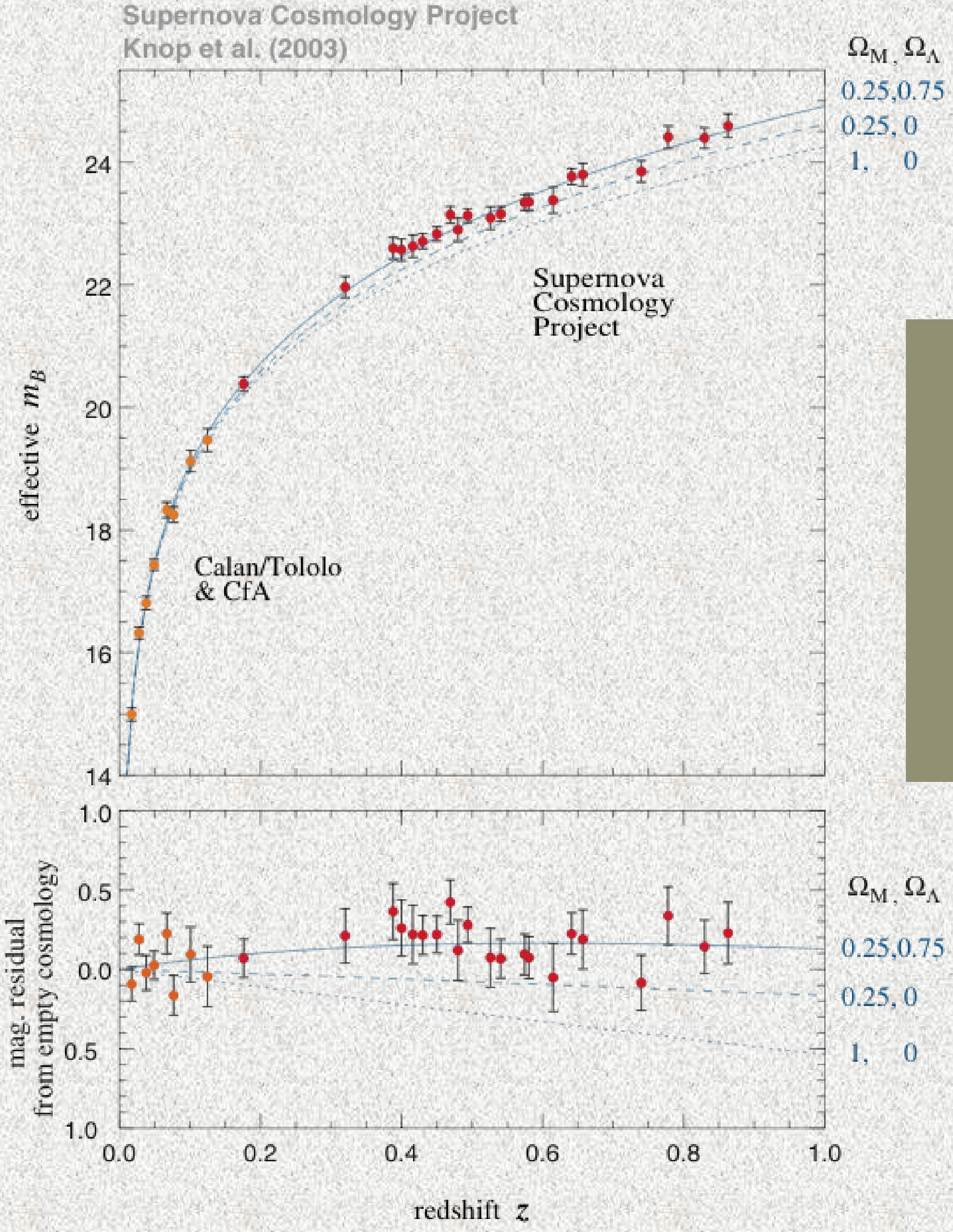
What's the total **mass** of **neutrinos**?

What's **dark energy**? How does it **vary** with **time**? Can it be rephrased as a **correction** to GR?

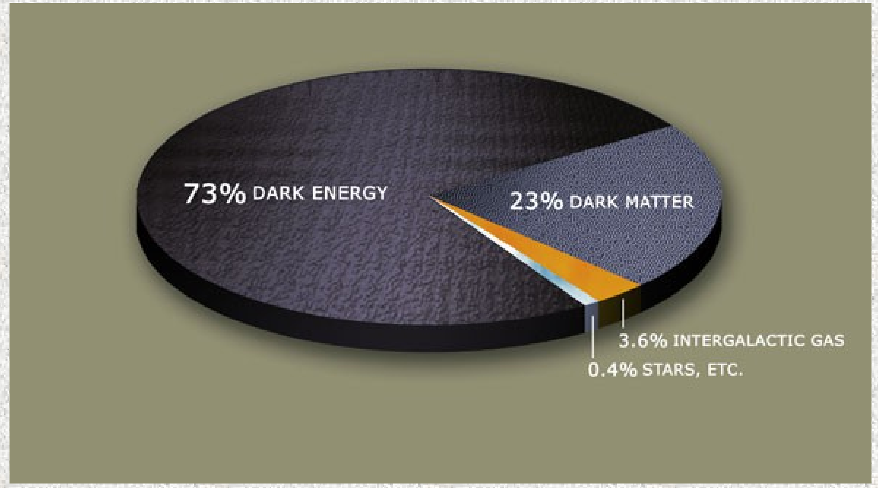
The SN project (~1998)

Type Ia Super novae can be considered as standard candles (after some *“renormalization”):* they all release a very similar amount of energy since they arise from the collapse of a white dwarf into a neutron star.

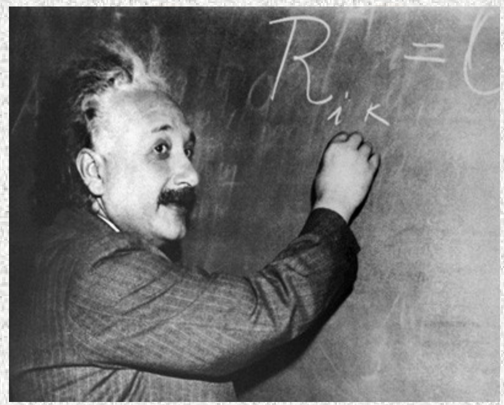
They can be used to measure the luminosity distance at different redshifts / z



Energy budget of the universe



One possible (and seemingly likely) explanation is
Einstein's constant …

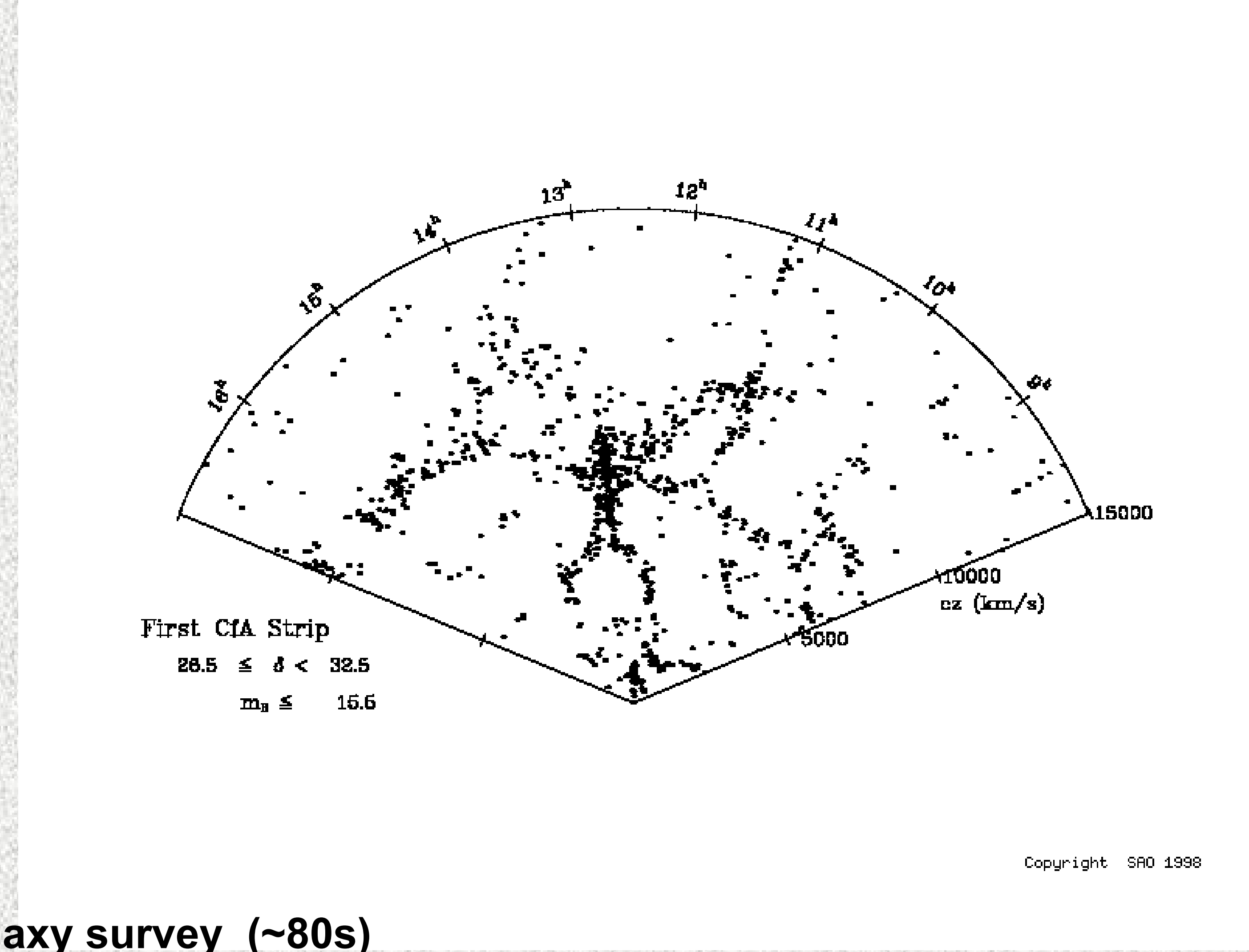


$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

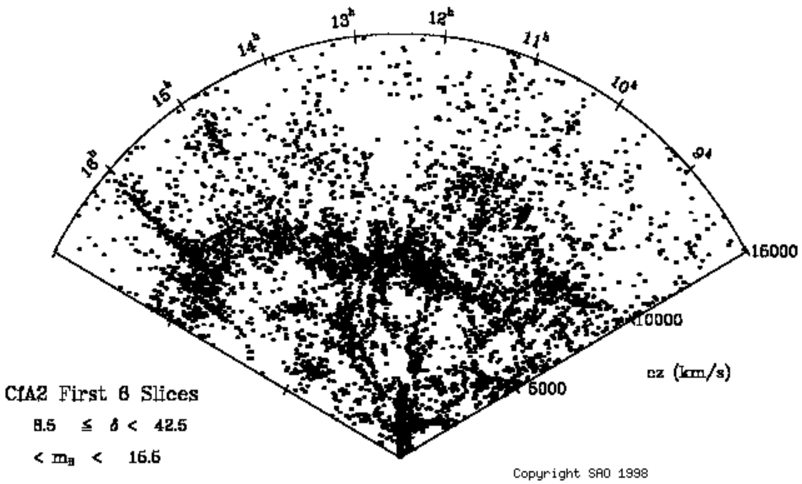
… although we may be facing a more exotic, complex type of repulsive energy (e.g., quintessence), or even something totally different, like a breakdown of GR on cosmological scales …

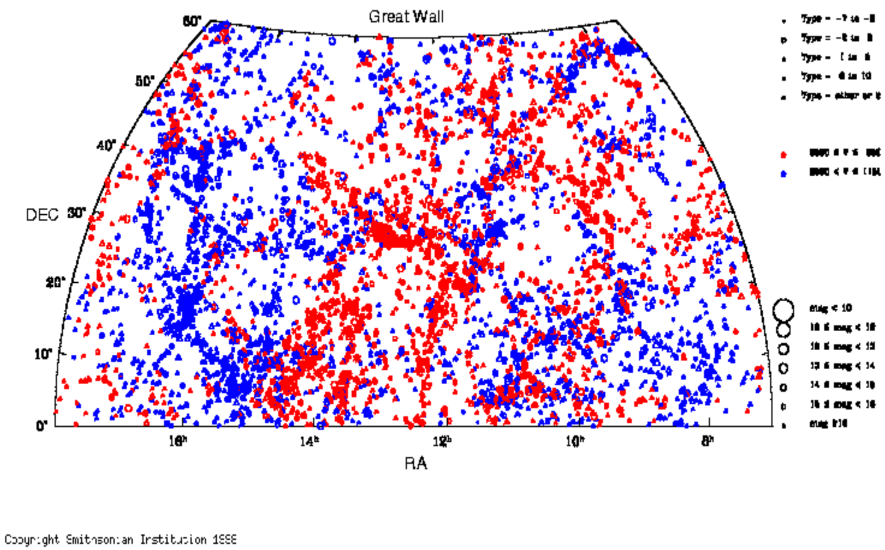
The exploration of the Large Scale Structure

First attempts to obtain galaxy spectra *systematically*

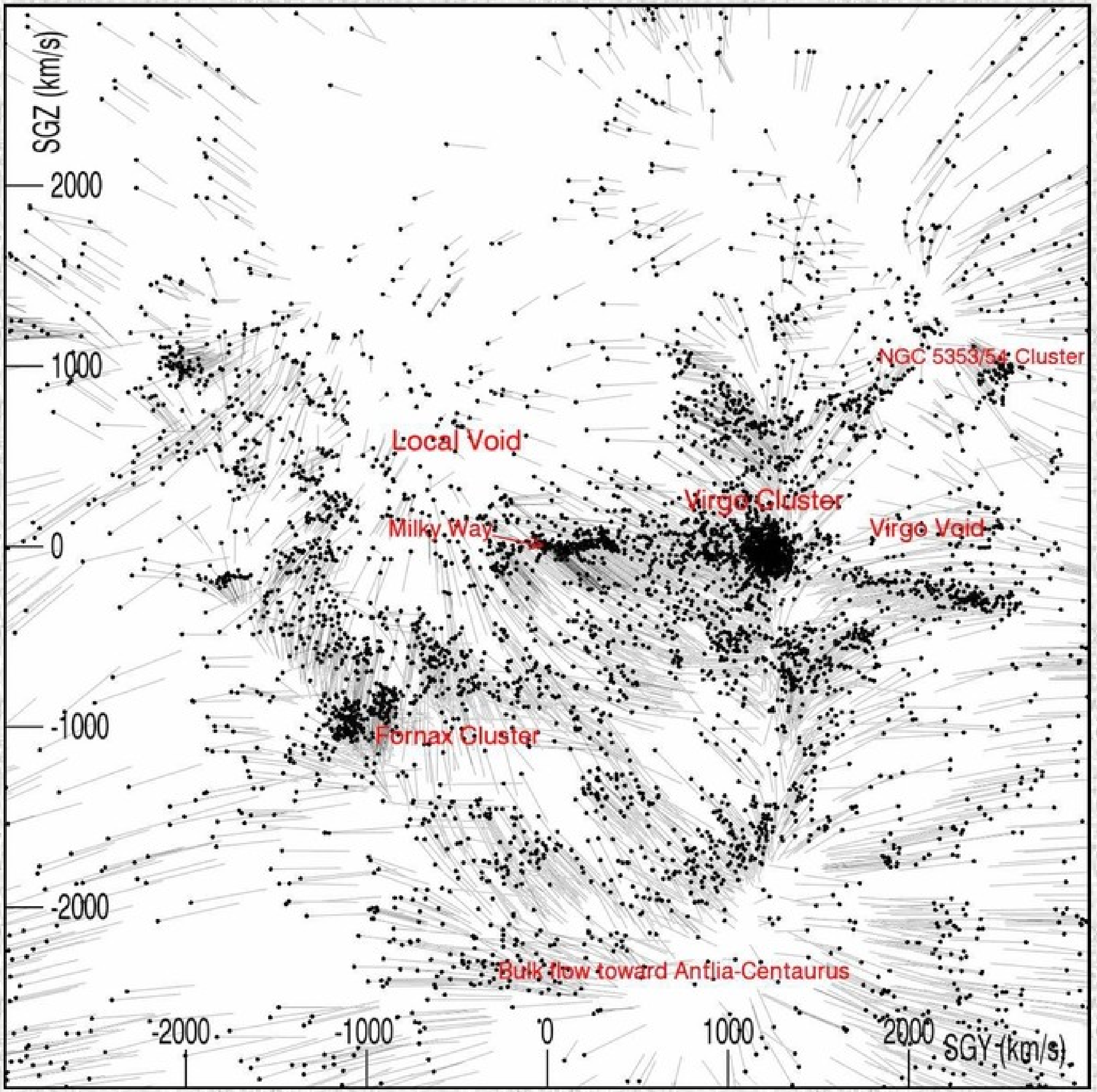


CfA galaxy survey (~80s)

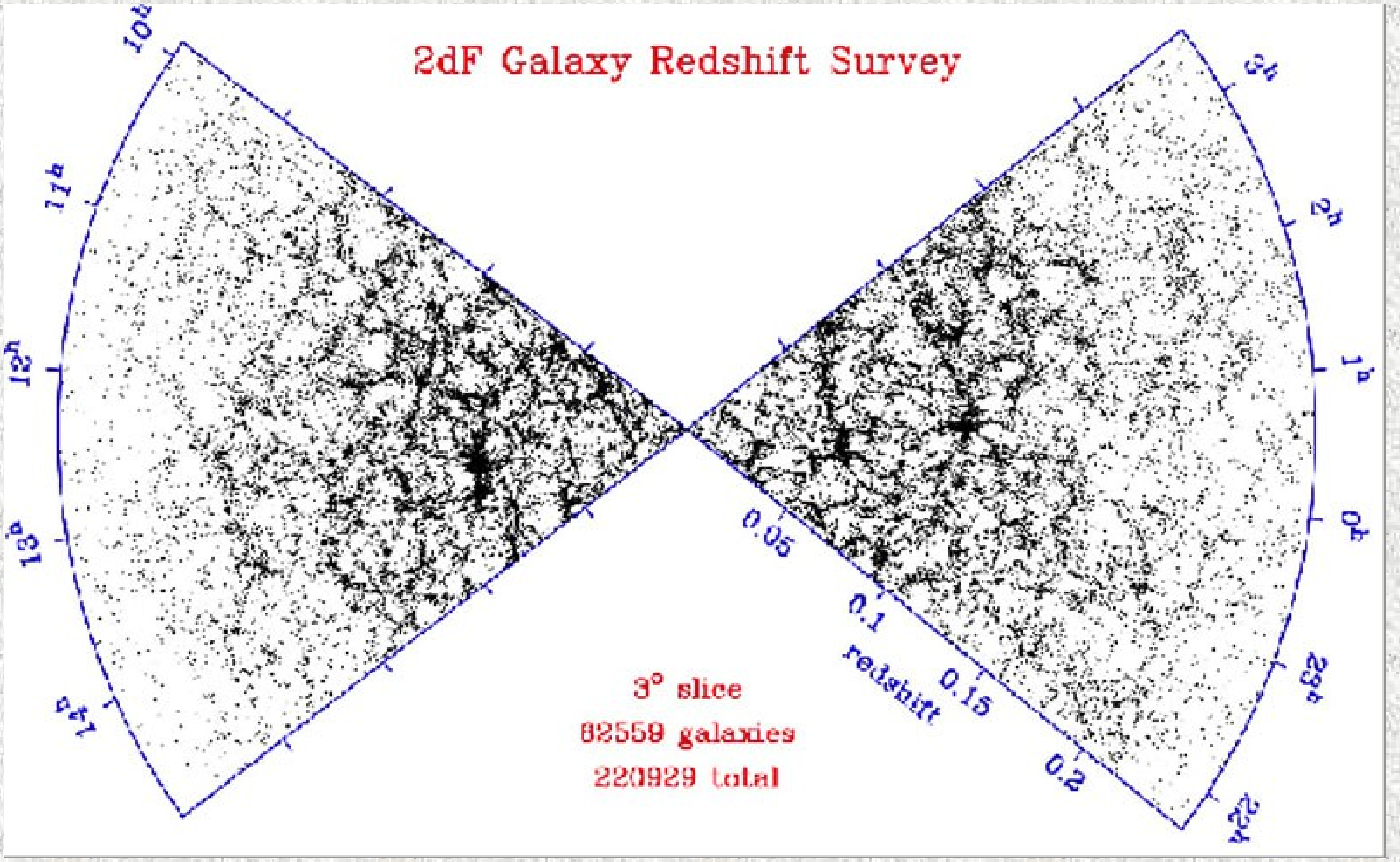

16^h
15^h
14^h
13^h
12^h
11^h
10^h
9^h
15000
10000
5000
cz (km/s)
CfA2 First 6 Slices
8.5 ≤ δ < 42.5
< m_B < 15.5
Copyright SAO 1998


Great Wall
DEC
60°
50°
40°
30°
20°
10°
0°
16h
14h
12h
10h
8h
RA
Copyright Smithsonian Institution 1998

CfA survey

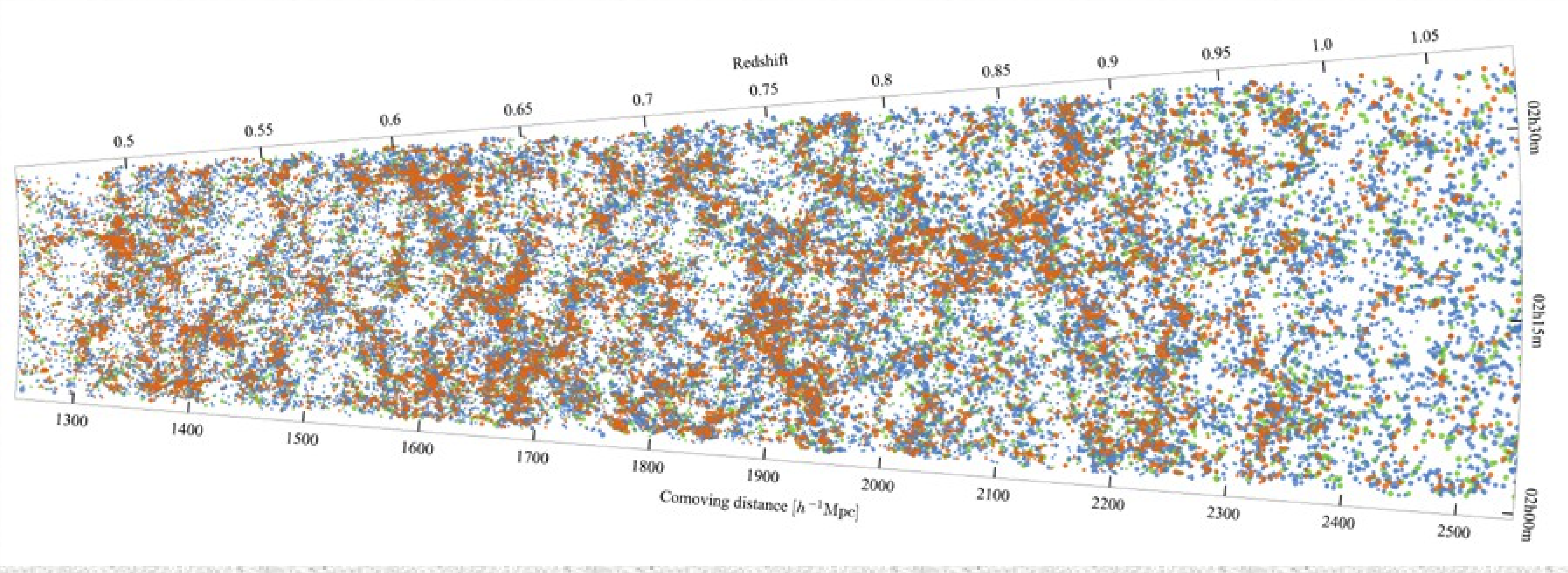


Cortois et al,
2013



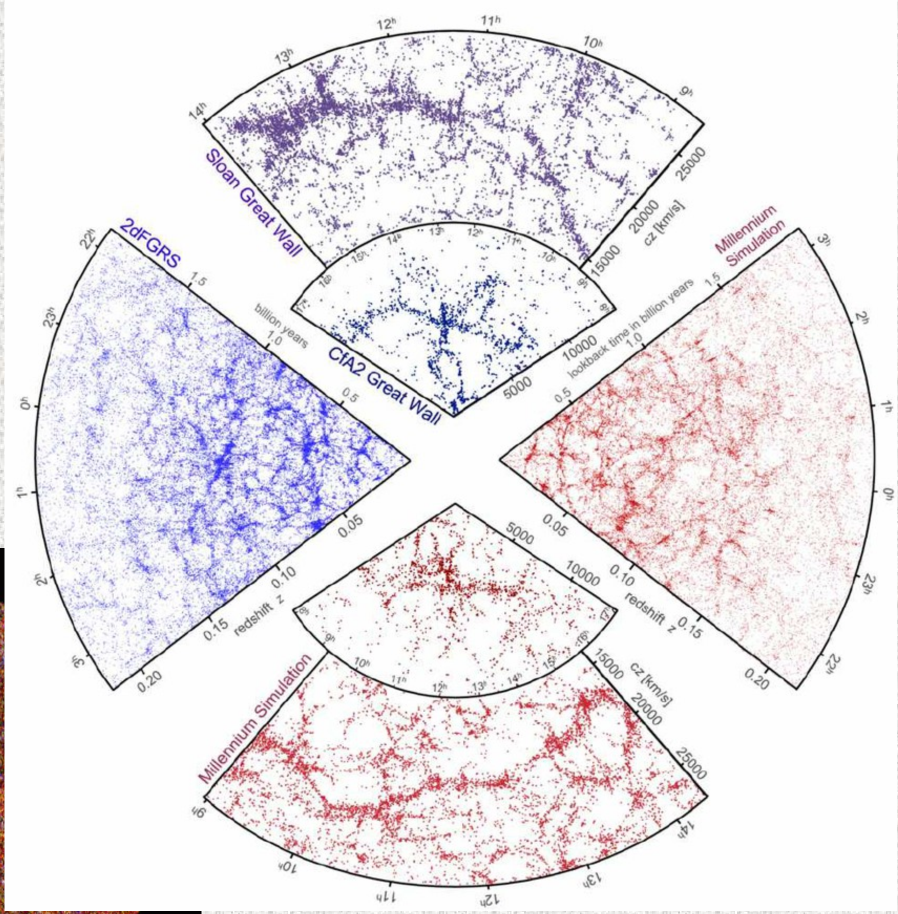
Beginnings of XXIst century

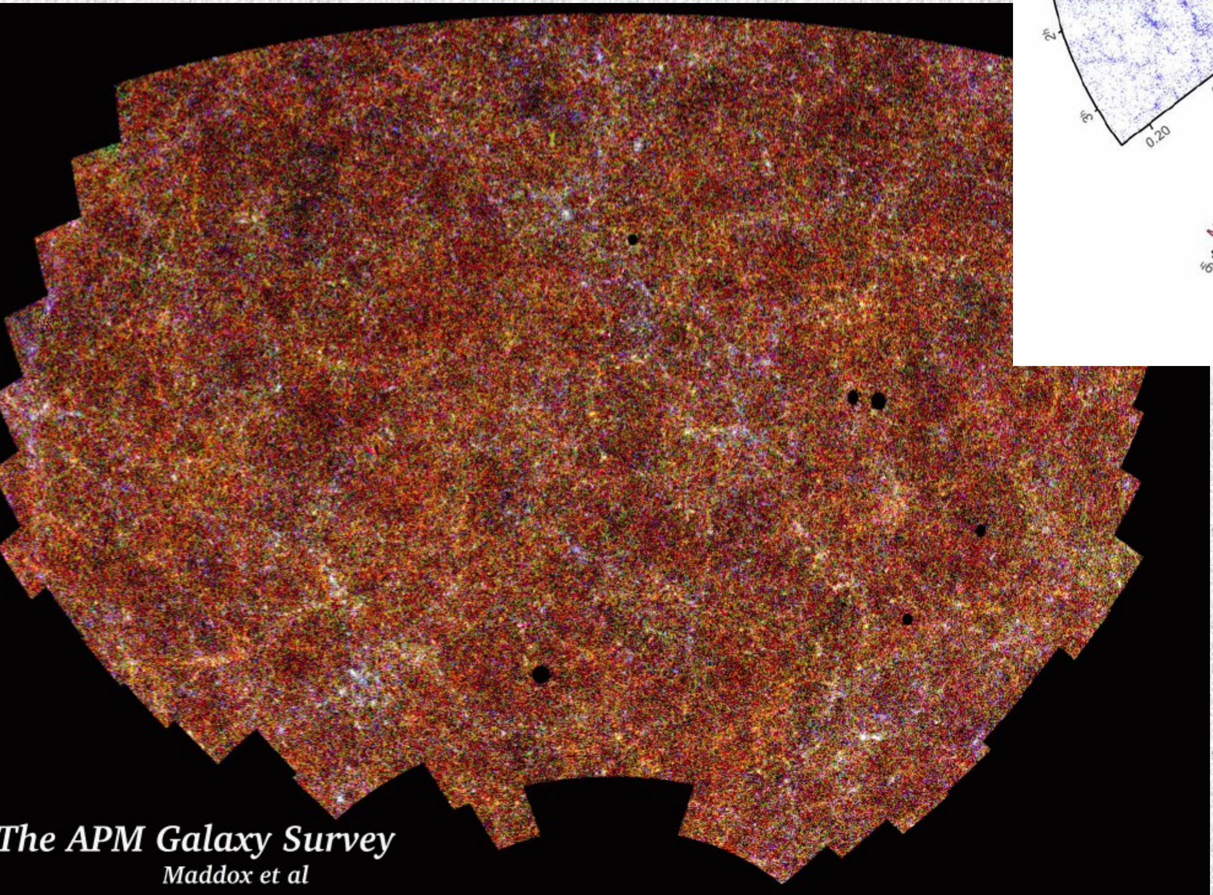
VIPERS

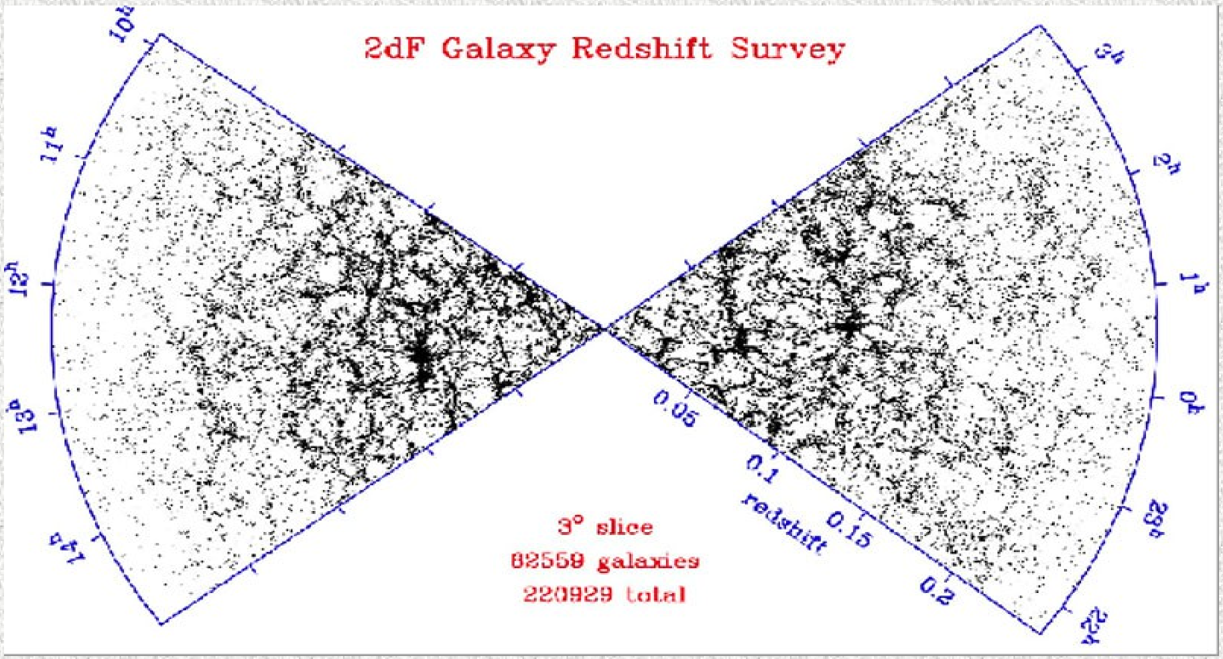


Second decade of XXI century

Galaxy surveys







The universe we see is composed by galaxies (light), whose motion and evolution is sourced by **gravity**

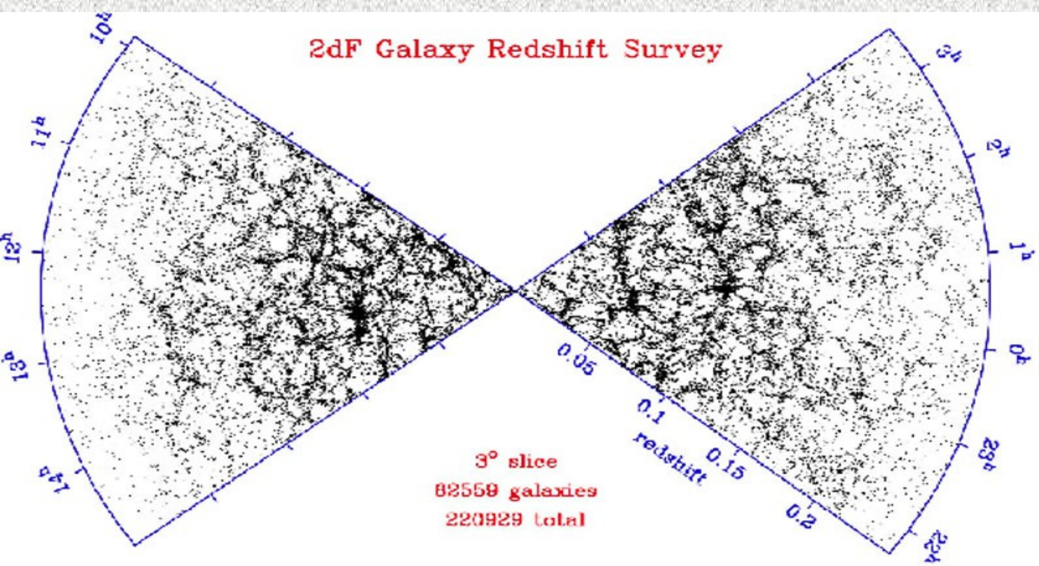
The evolution of the Large Scale Structure of the universe **can be described** with our **theory of Gravity** (GR) + some **ingredients** (its main constituents: matter, radiation, other fields/particles) + **initial conditions** (how much matter, radiation, relativistic species, non-Gaussianity, etc)

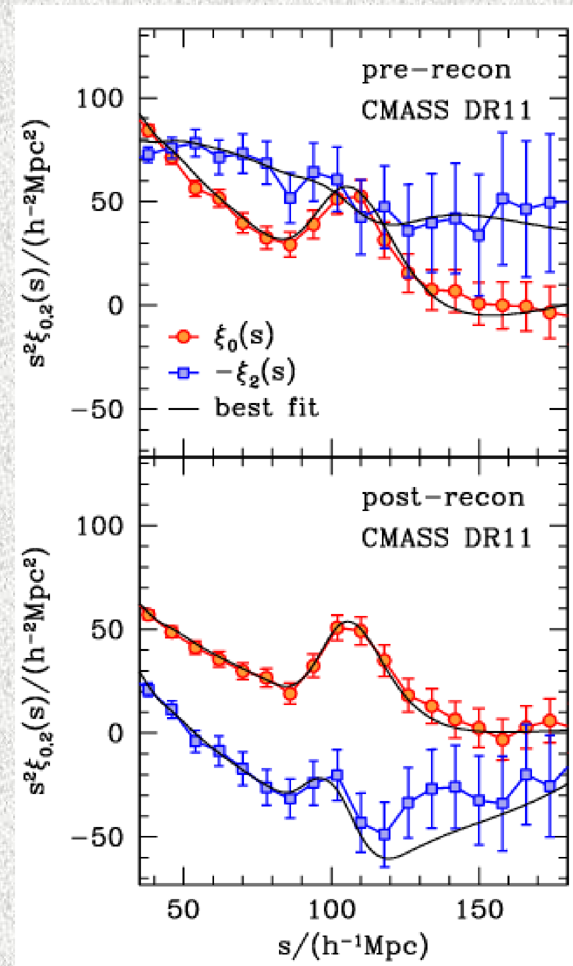
By studying the spatial distribution of galaxies on the large scales and its evolution we may learn about these three different fronts …

For instance: **the two-point correlation function**

Probability of finding a galaxy pair at (x, y) ~ (1 + ξ[x-y]) , ξ[x-y] is the two-point **correlation function**

From Sloan BOSS survey





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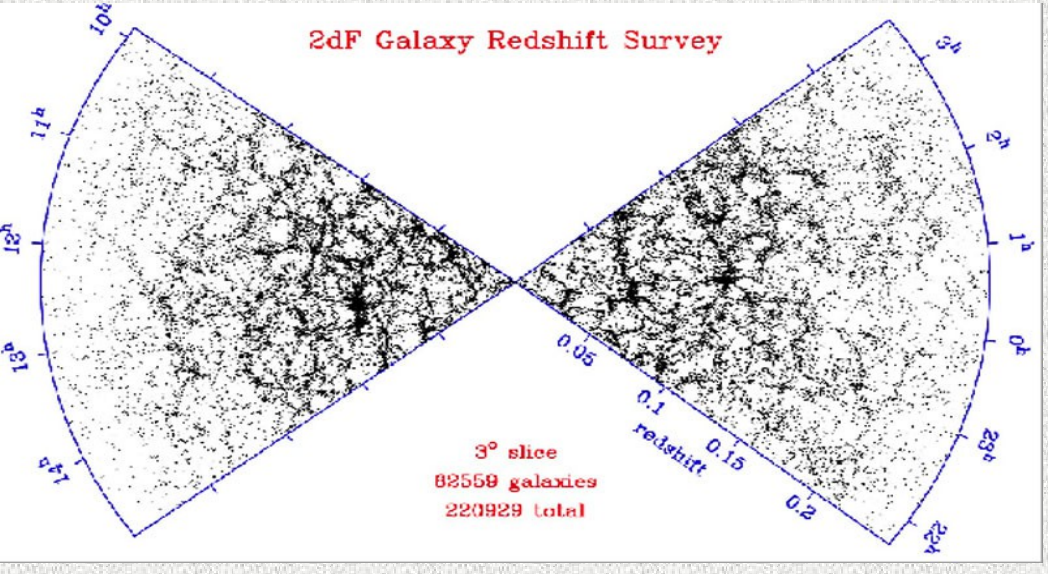
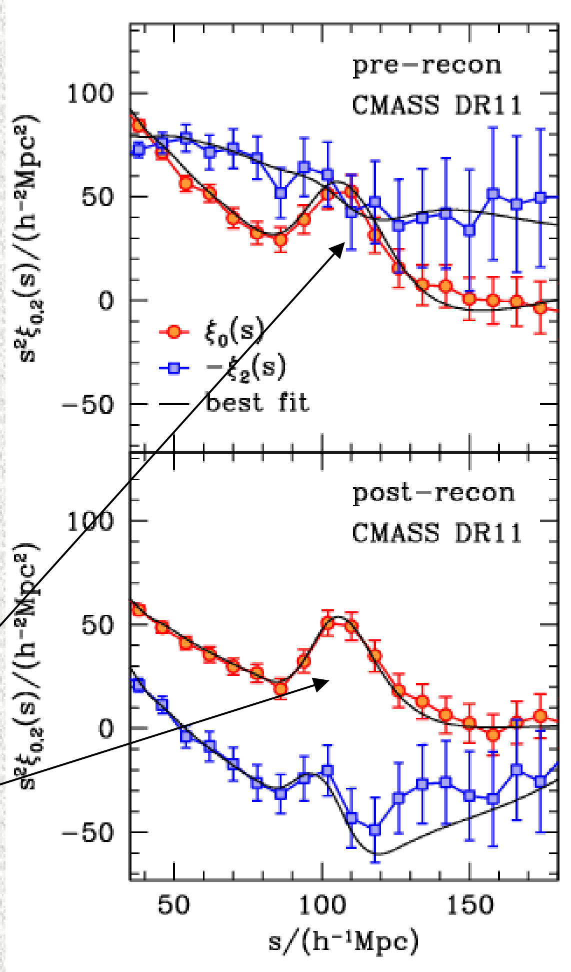




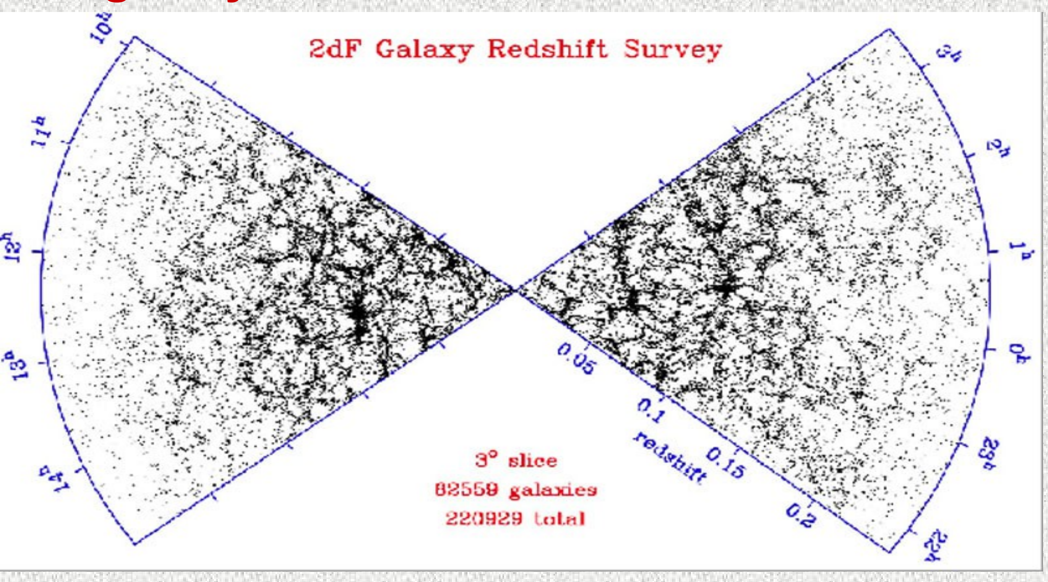
This probability excess is due to the **baryonic acoustic oscillations (BAOs)** generated in the primordial universe (see next talk

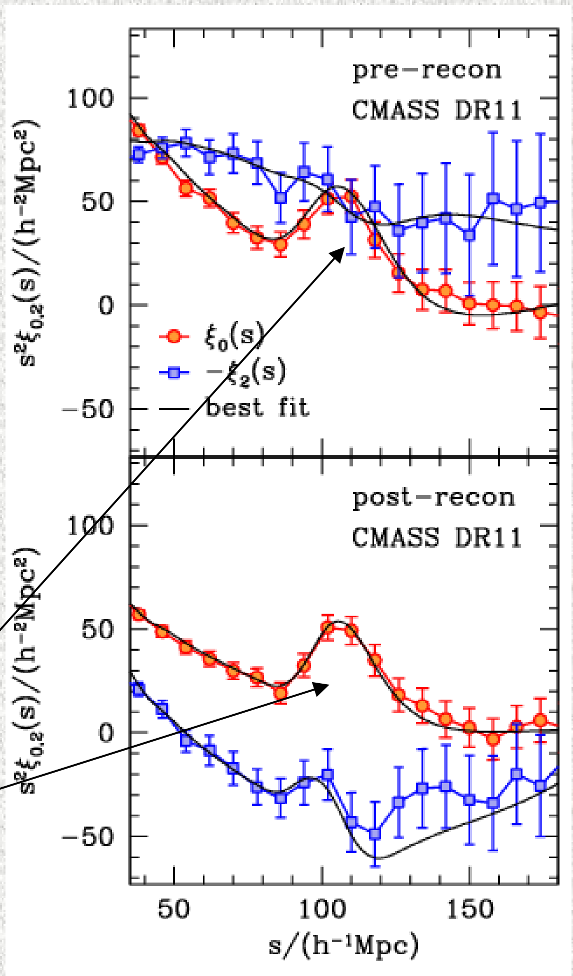
For instance: **the two-point correlation function**

Probability of finding a galaxy pair at (x, y) ~ (1 + ξ[x-y]) , ξ[x-y] is the two-point **correlation function**

From Sloan BOSS survey

It is also possible to compute 3-, 4-, and n-point correlation functions, and thus characterise more precisely the probability distribution function of the galaxy field in our universe

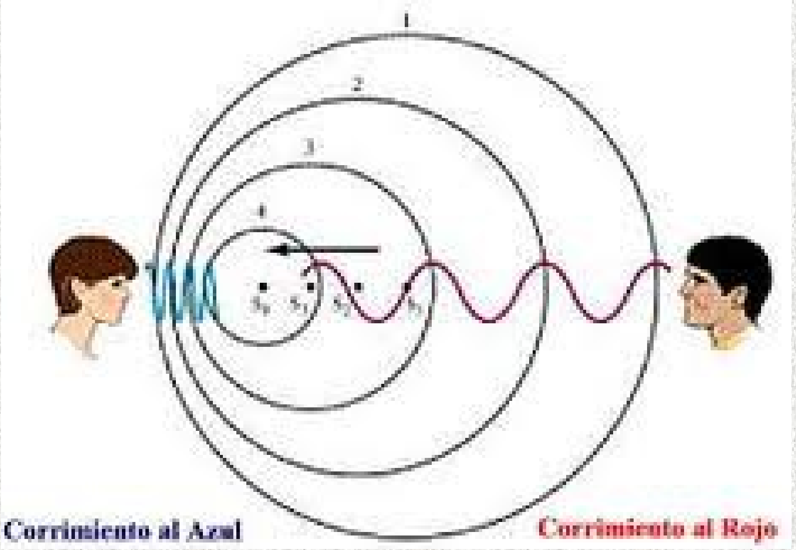




This probability excess is due to the **baryonic acoustic oscillations (BAOs)** generated in the primordial universe (see next talk

Apparent redshifts induced by gravity

$$v = H_o \times d$$

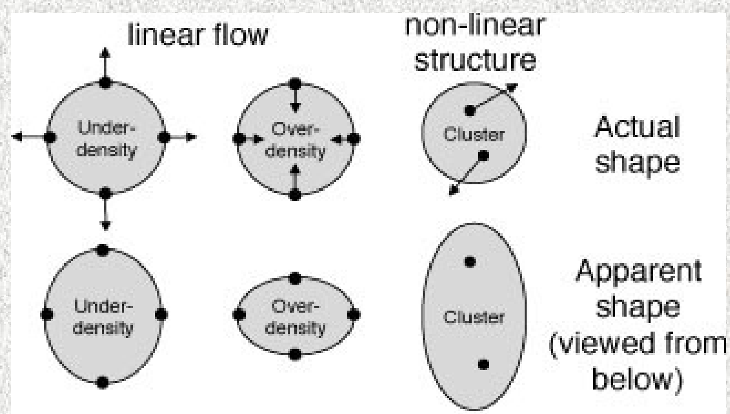


If a galaxy moves **towards us** pulled by the **attraction** of an intermediate body between the galaxy and ourselves, **we will assign** to this galaxy a **distance** that will be **shorter** than the real one …

On the contrary, if such galaxy is **receding from us** due to gravity, then we will assign a **larger** distance than to we would assign if it were at rest wrt us.

Gravity induced distortion in the (apparent) spatial distribution of galaxies

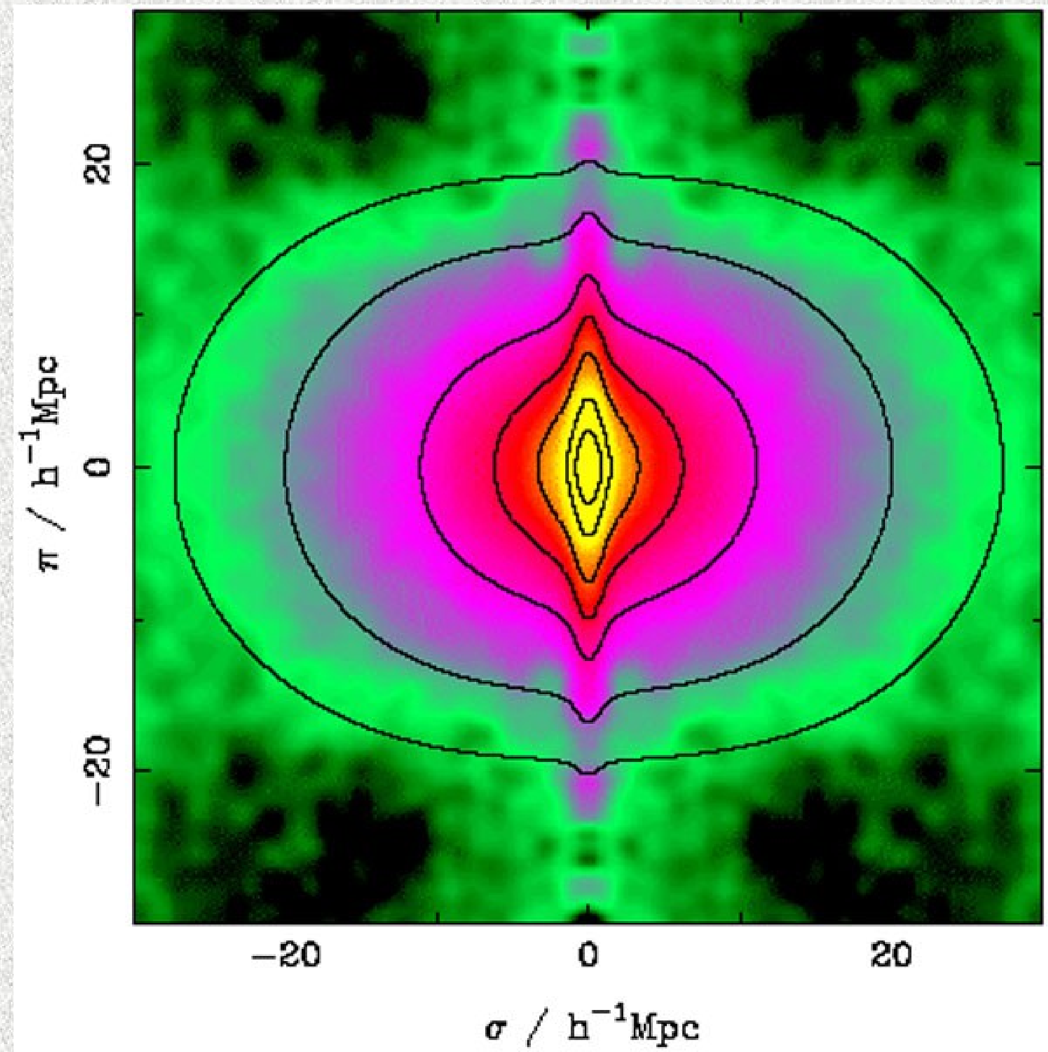
Since there is no priviledged direction, matter should cluster **spherically**. However, due to the **peculiar velocity/redshift** induced by gravity, the appearance of galaxy clustering in redshift space appears distorted: **redshift space distortions**



$$v = H_o \times d$$

2dF

z = zHubble + zpec



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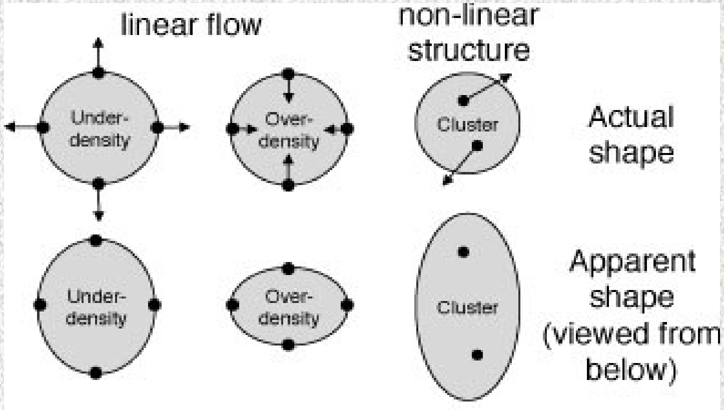

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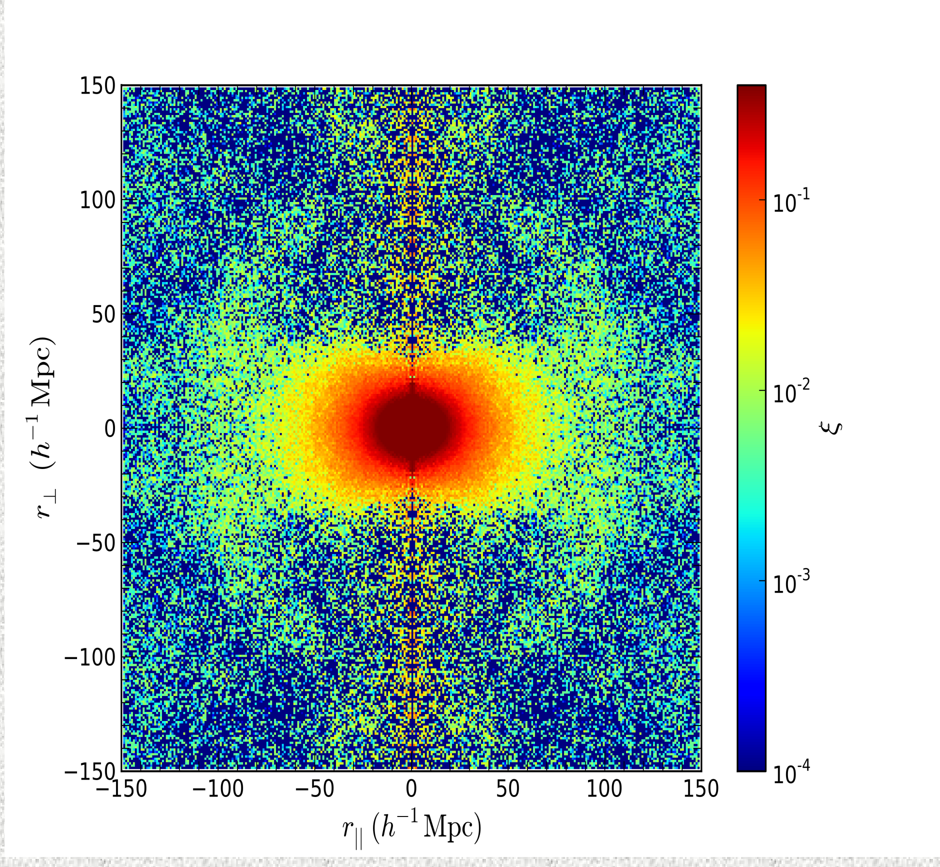
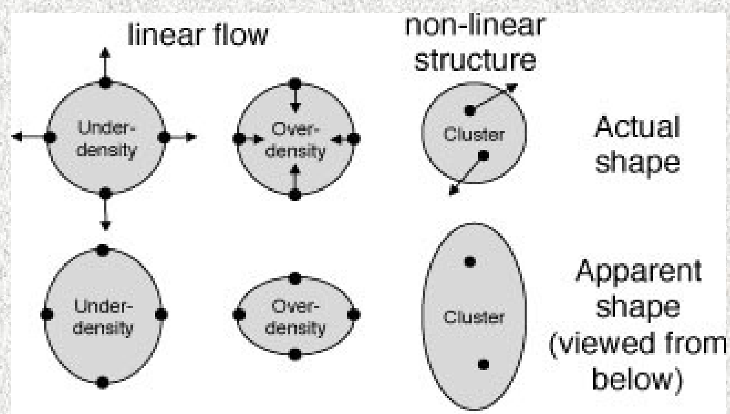


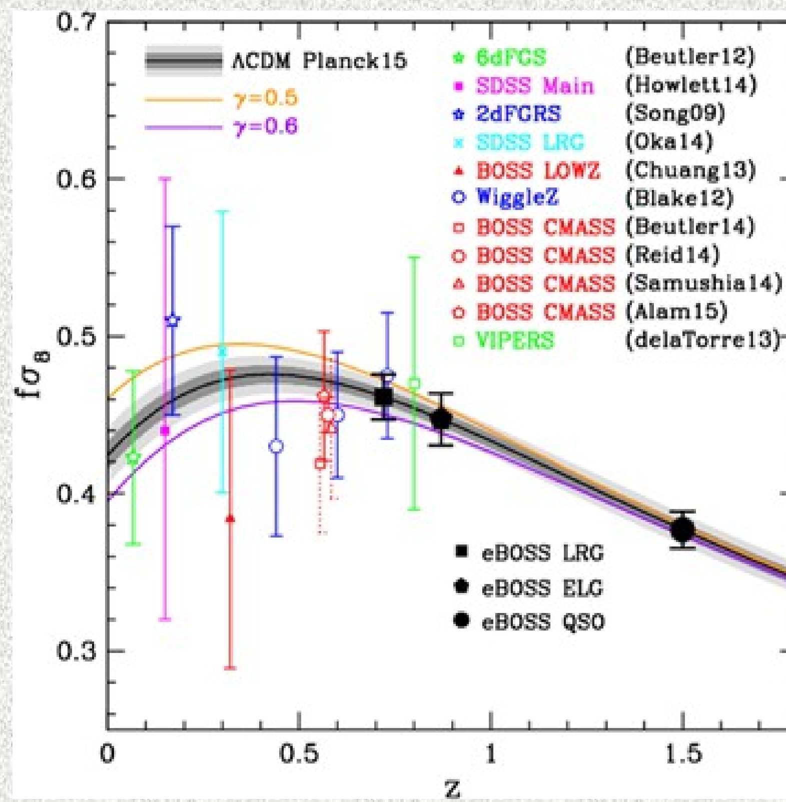
Sloan/BOSS DR11

Distorsión de la distribución espacial de galaxias por la gravedad

z = zHubble + zpec

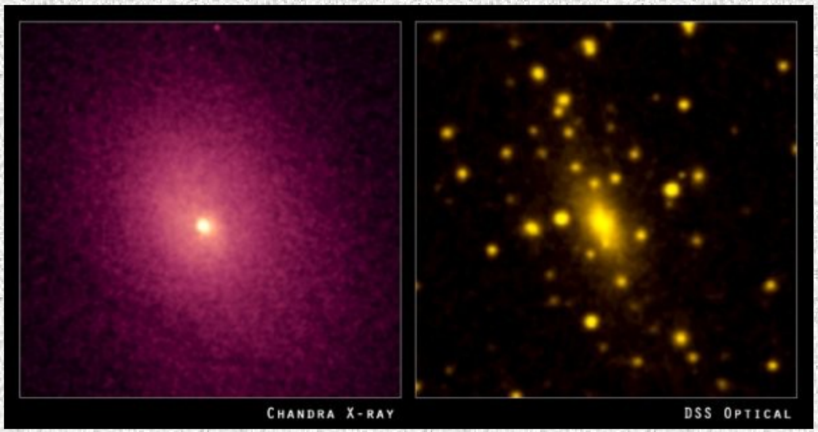
Since there is no priviledged direction, matter should cluster **spherically**. However, due to the **peculiar velocity/redshift** induced by gravity, the appearance of galaxy clustering in redshift space appears distorted: **redshift space distortions**





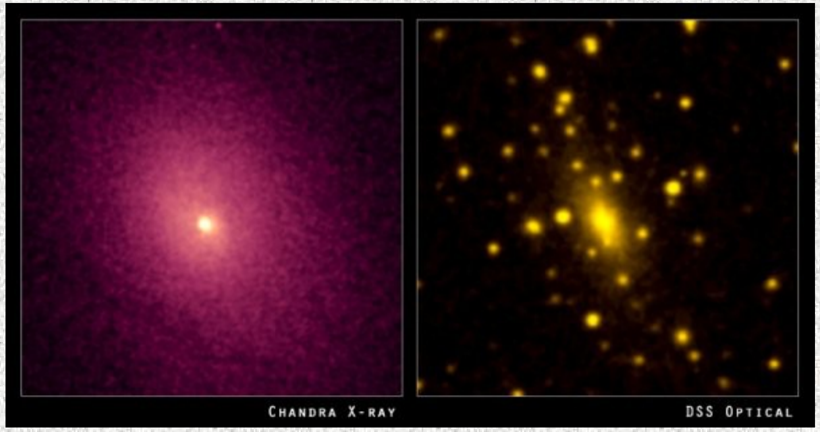
BOSS collab.

Cosmological relevance of galaxy clusters

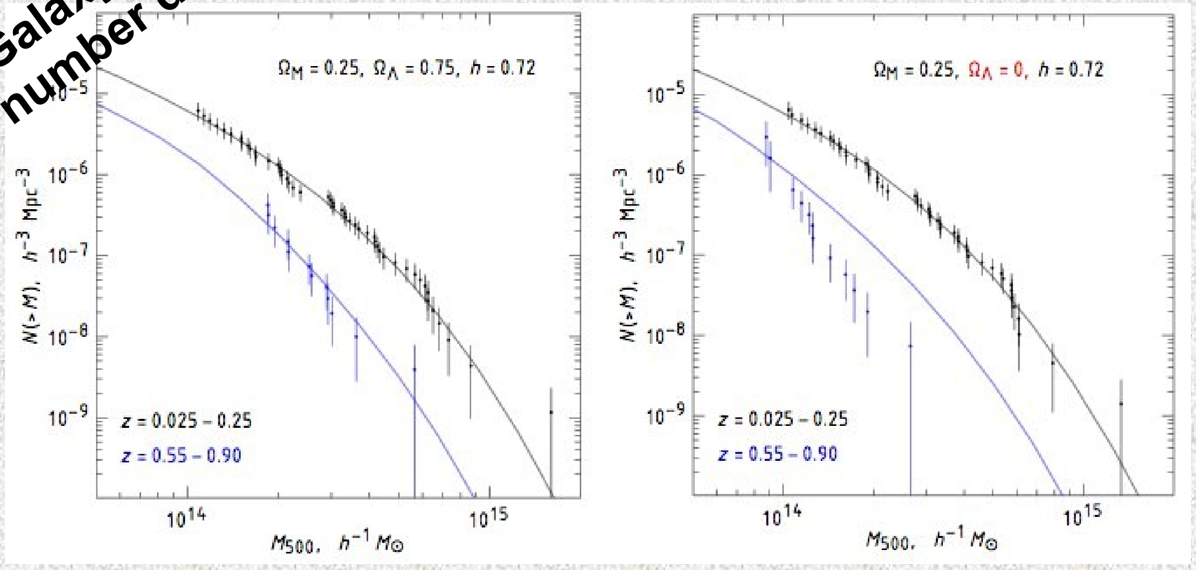


Galaxy clusters constitute the **most massive**, **self gravitating structures** in the universe. They are visible/detectable in different wavelength ranges (optical, IR, X-ray, sub-millimeter), and their **abundance** in **different** cosmological **epochs** provide information about the **initial conditions** and the parameters **conditioning** the **evolution** of the universe (such as **matter density**, **expansion rate**, etc)

Cosmological relevance of galaxy clusters

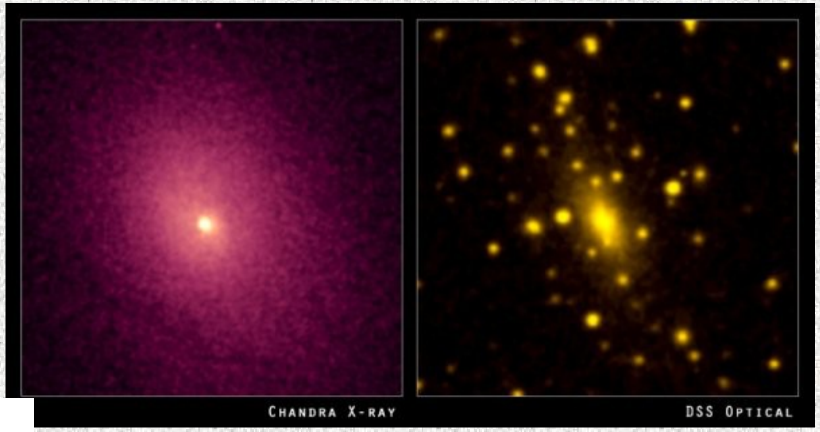


Galaxy cluster number density

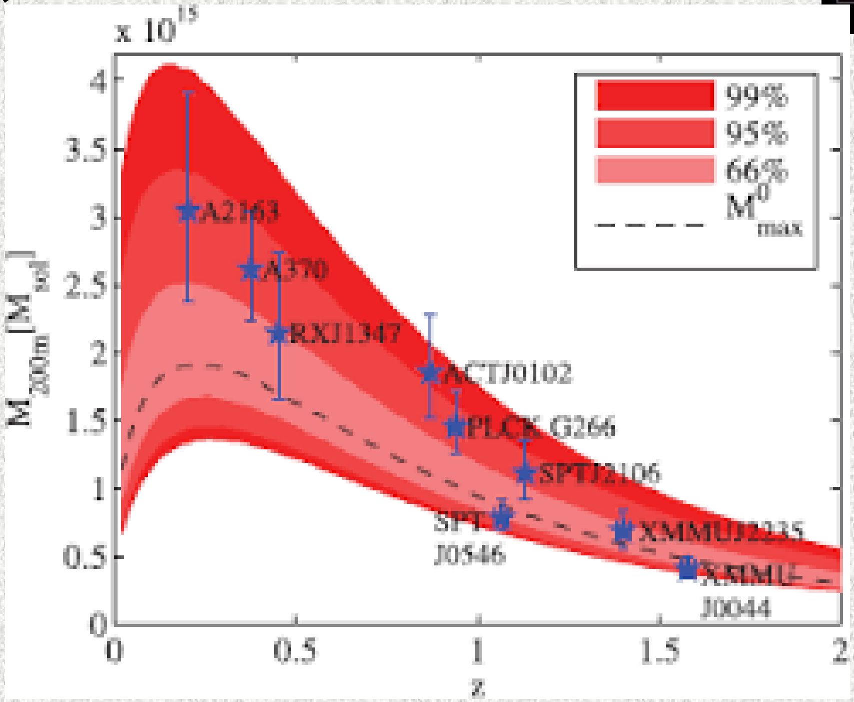


Mass

Cosmological relevance of galaxy clusters

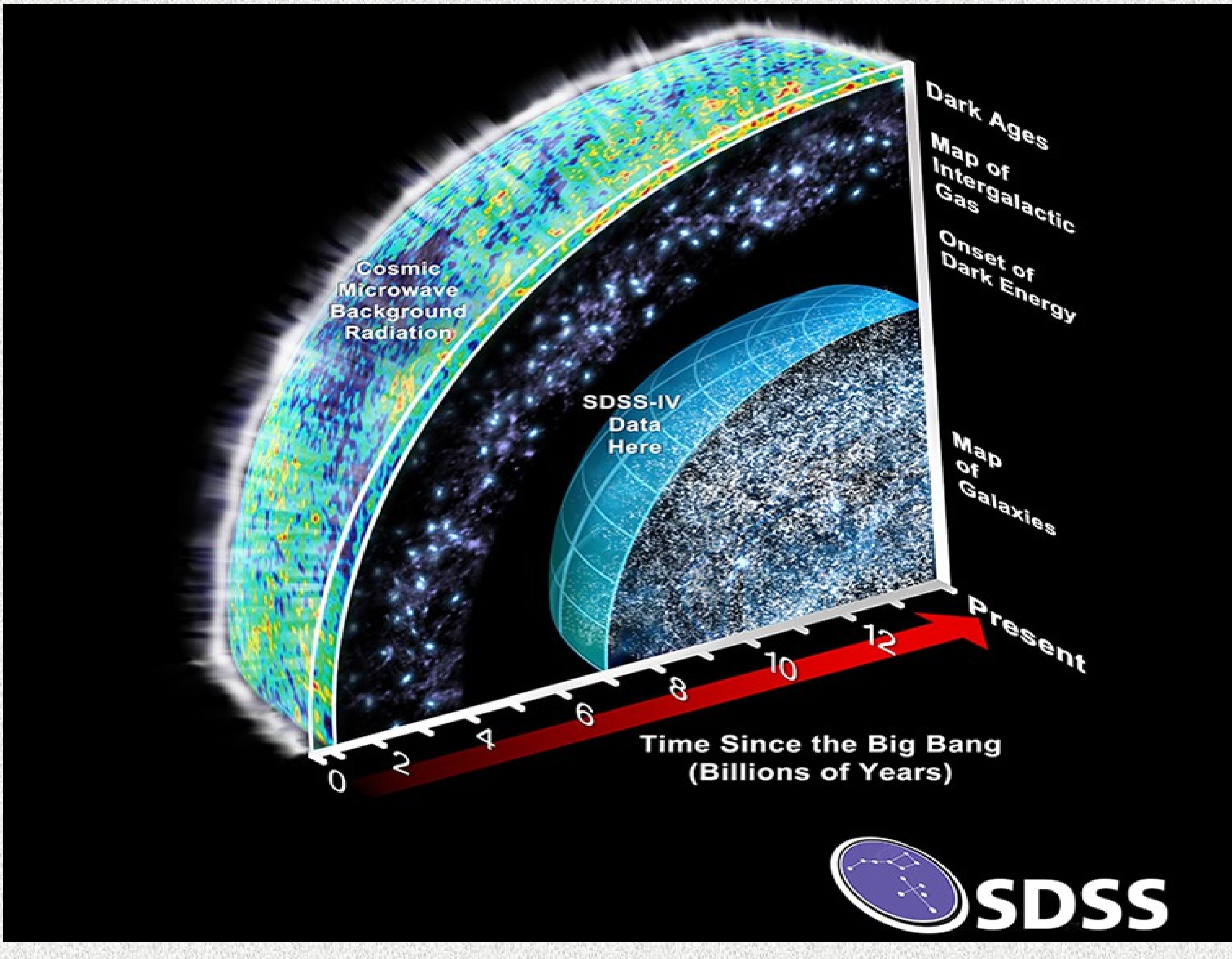


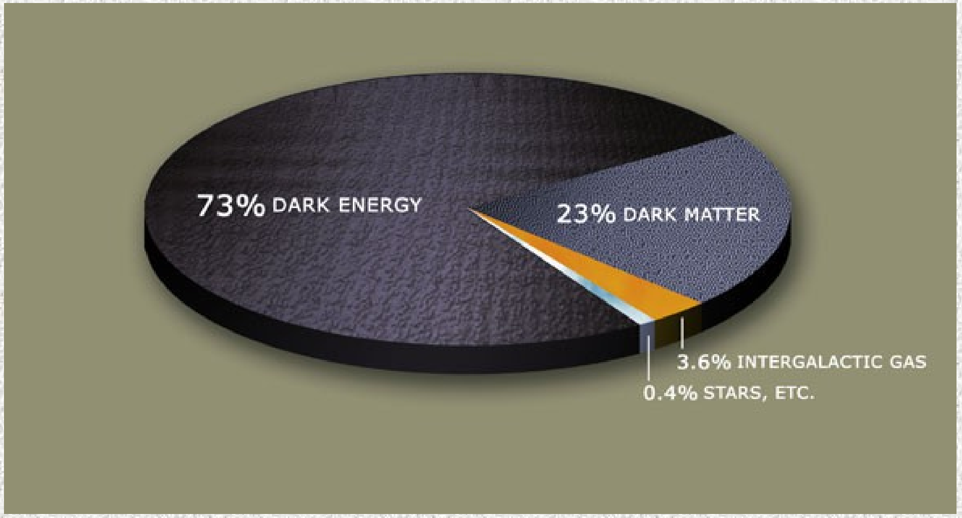
Mass of most massive galaxy cluster



Época cosmológica

Filling "*un-explored*" cosmological volumes ...





- Nature of dark sector (dark matter and dark energy)
- Did inflation occur? Can we measure B-modes? Other parameters ? (non-Gaussianity?)
- Relativistic particles (neutrino masses)
- Constraints on Modified Gravity (extensions to GR)