Theoretical Cosmology

What is COSMOLOGY?

-The study of the Universe as a whole, namely as the collection of its matter/energy components and its constituent phenomena

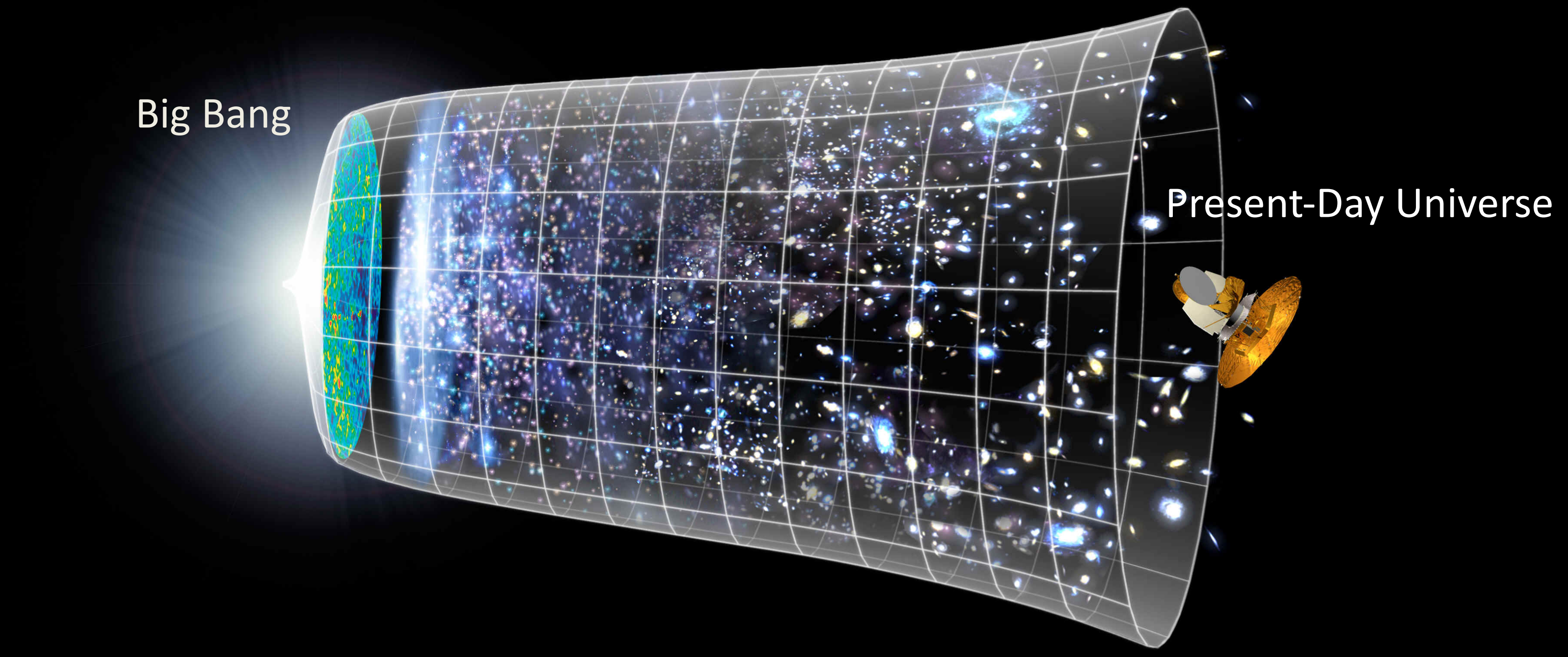
Consequence: Cosmology is a multi-disciplinary science (astrophysics, gravitational physics, particle physics, nuclear physics etc..)

-The „Greek Root" definition: a „dialogue on the Universe" -→ *suggests we should be open minded in our inferences, not dogmatic.*
Indeed Ancient Greeks were the first cosmologists of the western world
(the first philosophers, such as Democritus or Parmenides, proposed different cosmological models). Cosmology is present in all advanced civilizations of the past.

-We study Modern Cosmology or „Physical Cosmology", namely a cosmology that is quantitative and falsifiable , and based on our modern knowledge of physical laws.
-General Relativity constitutes the backbone of the current cosmological model.

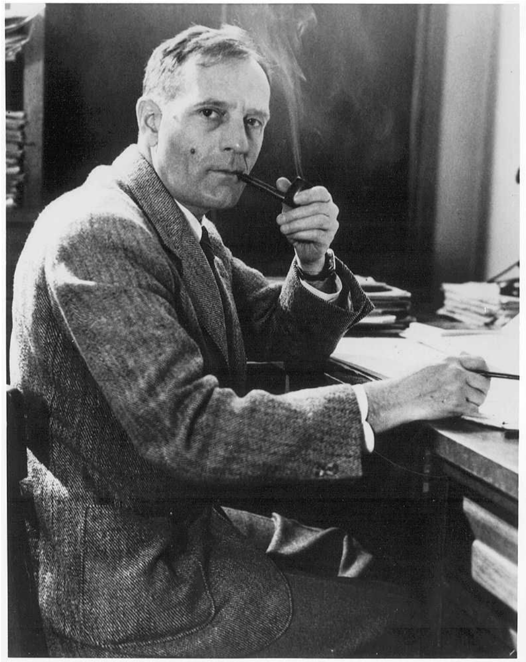
-The prevailing cosmological model is such because it satisfies several tests set forth by astrononical observations and experiments. However there are also phenomena that it cannot explain satisfactorily and others that it can explain only by introducing new physics

- Expansion from an initially dense, hot state.
- Expansion cools matter and energy content. Currently expansion is accelerating
- Initial state not completely uniform. Small inhomogeneities cool and grow via gravitational instability during expansion becoming the galaxies and clusters of galaxies that we see today.

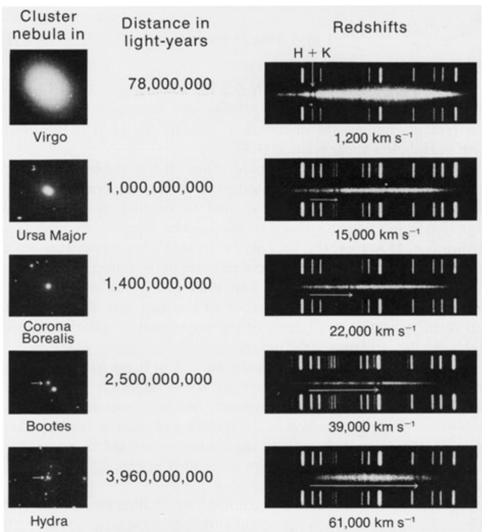


NASA/WMAP Science Team

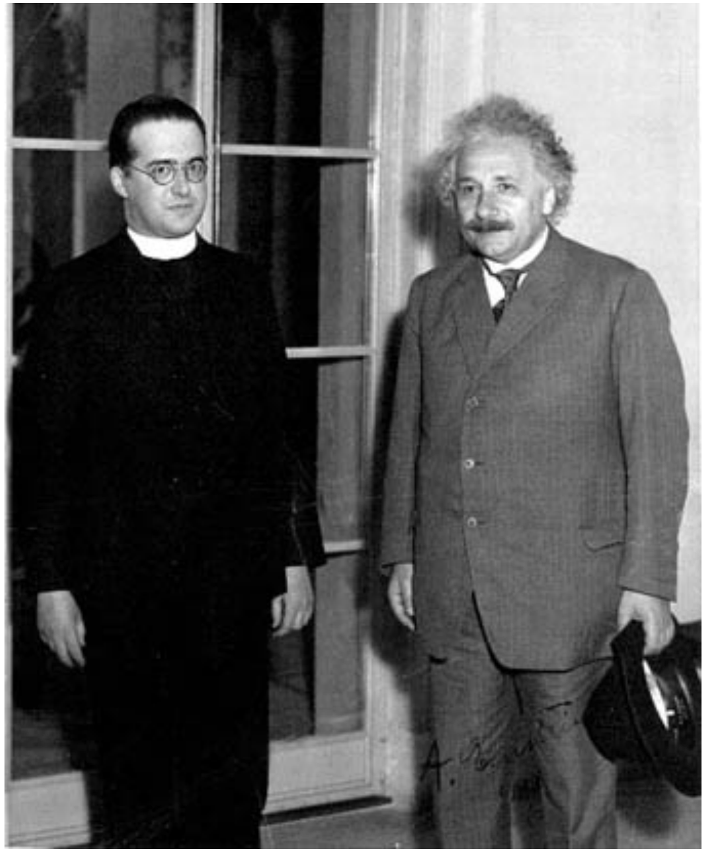
A bit of recent history: the birth of Modern Cosmology



Hubble



Hubble + technology (1920s)
-- Determines spiral nebulae are external galaxies
-- Determines galaxies are receding from each other, and increasingly faster for greater distances (Hubble law) – $v_r = Hd$



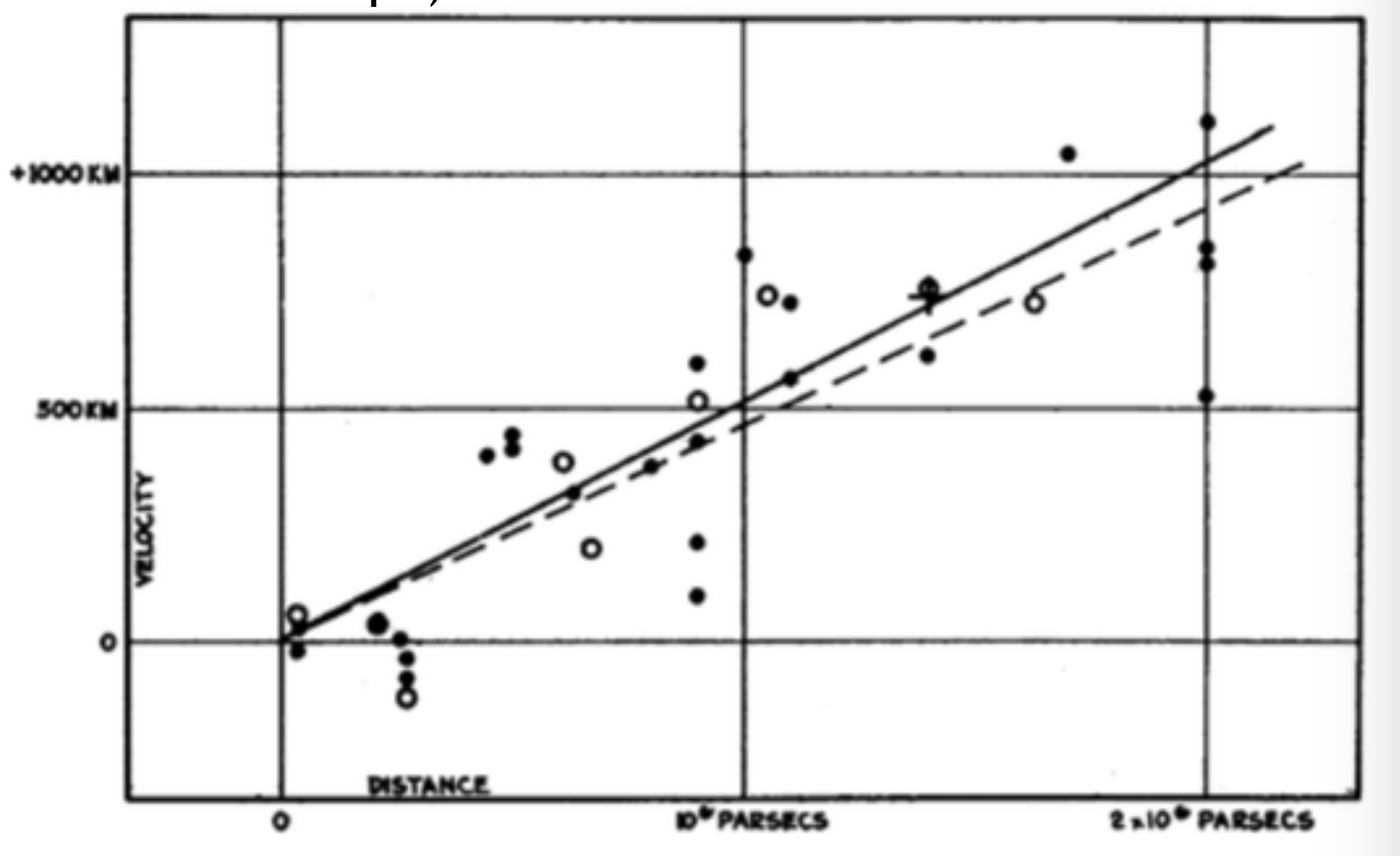
The Theory : Einstein (GR) and Lemaitre (Big Bang/primeval atom model) – also in the 1920s

Later Alpher, Bethe and Gamov develop quantitative model for thermal history of Universe and origin of elements (H, He)

The original Hubble Diagram (1929)

" A relation between distance and radial velocity among extra-galactic nebulae"

(using only 24 nearby galaxies - two different fitting lines relate to two different ways to correct for solar motion). Slope is *Hubble Constant* Ho (500 km/s/Mpc here, today we know it is ~70 km/s/Mpc)



Another new revolutionary notion: Dark Matter

Fritz Zwicky in 1933
at Caltech

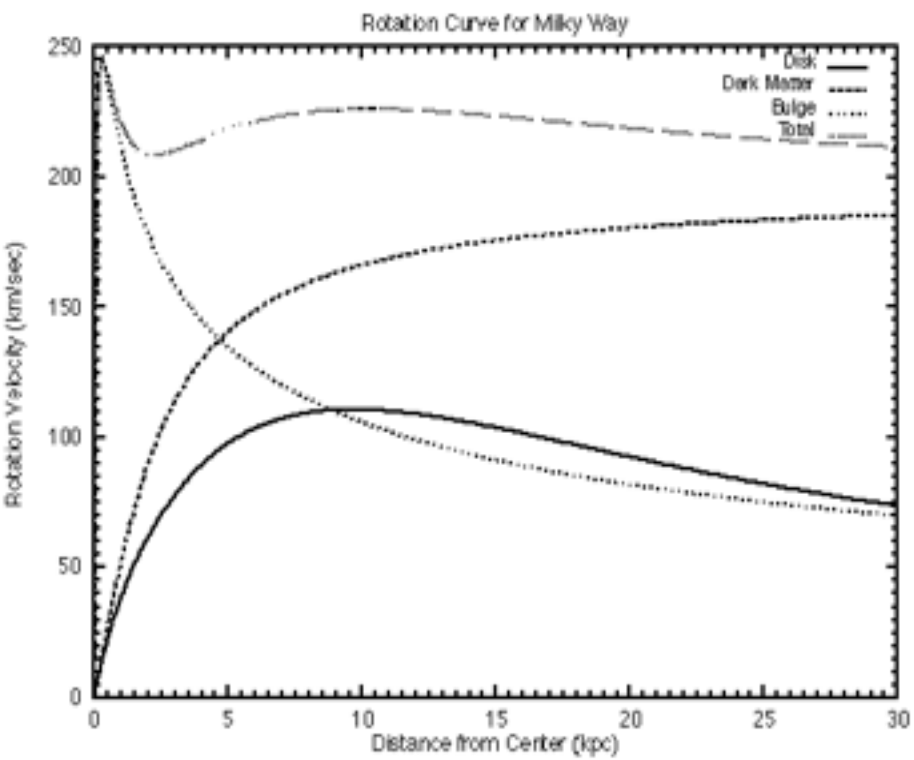
Virial theorem:
$\langle v^2 \rangle \sim GM_{cl}/R_{cl}$

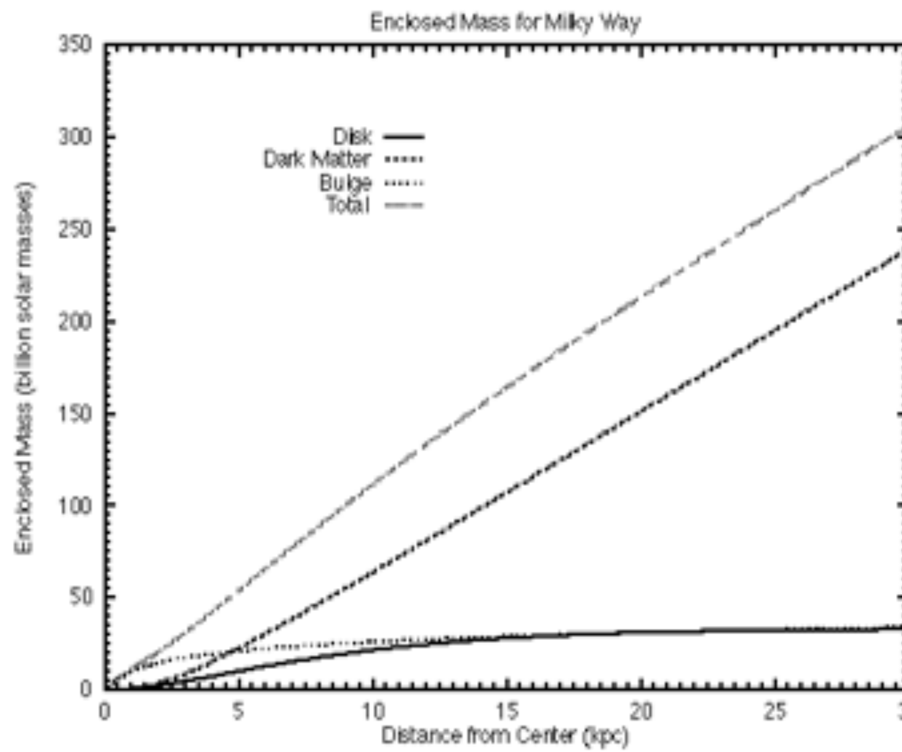
The Coma Cluster of Galaxies
Zwicky meausured the motion of many galaxies in Coma and used the virial theorem to find that there is 400 times more mass than it is visible --> *Dunkle Materie!*

The need for Dark Matter: the rotation curves of galaxies

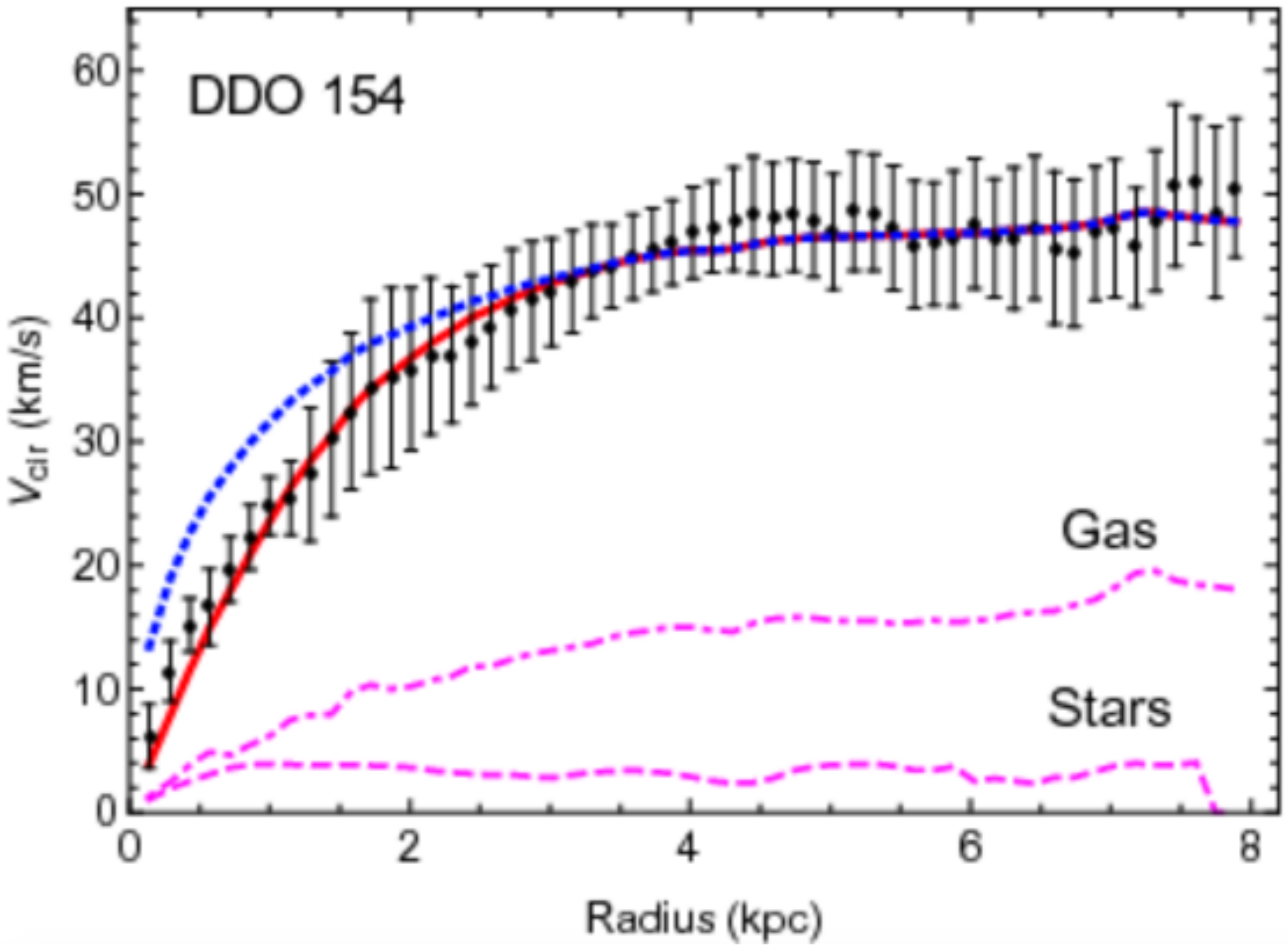
Pioneering work from Vera Rubin in the 70s: first establish that rotation speed remains nearly constant at large radius —-> *need for extended dark matter halo*

Rotational velocity (newtonian gravity assuming spherical potential): $v_{rot}^2 = GM/R$



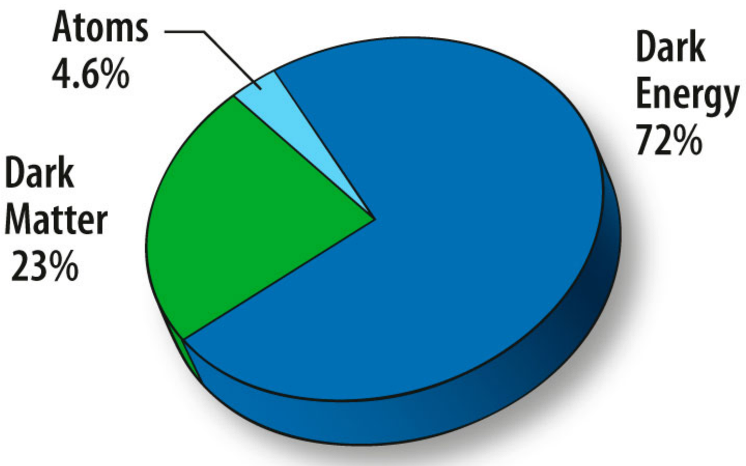


Dwarf galaxies: most numerous and mostly dark matter

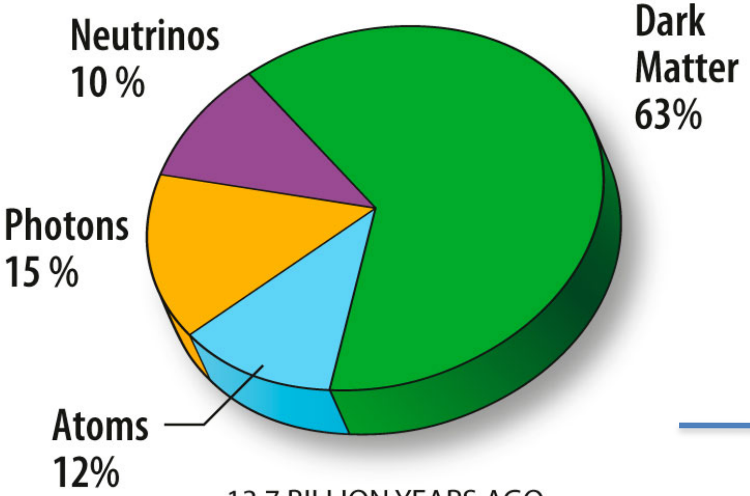


The constituents of the Universe; today and then

(i.e. what contributes to the stress-energy tensor in Einstein's field equations)



TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

~ 1% is in neutrinos (photon density and other sub-atomic particles density is negligible)

Dark energy (simplest form is cosmological constant originally introduced by Einstein) produces accelerated expansion – it has a negative pressure

Dark matter has to be mostly non-baryonic because we can place limits on the baryon content of the Universe

→ Time corresponding to the emission of the cosmic microwave background (CMB), the relic radiation from the Big bang

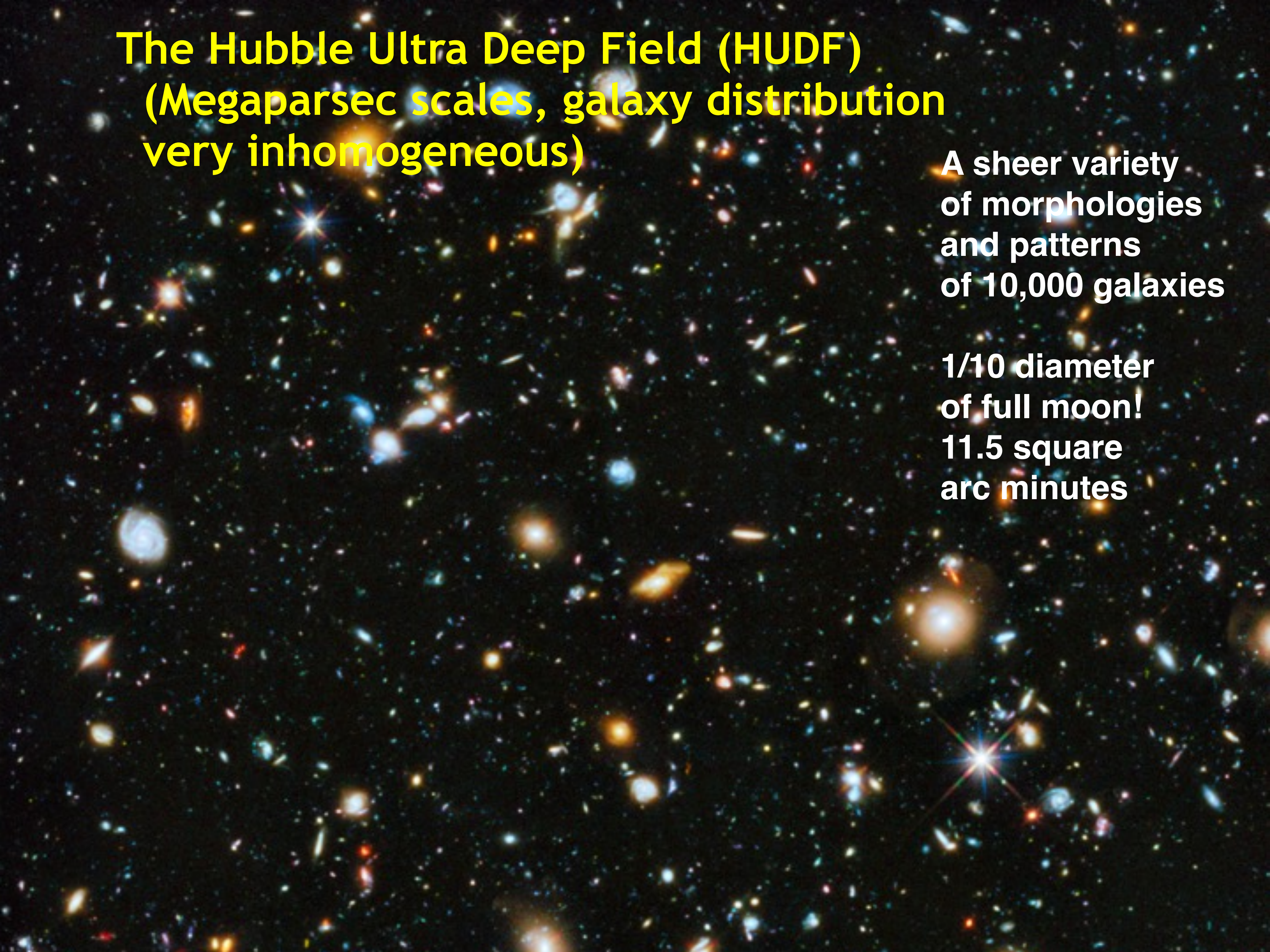
The founding notion: the cosmological principle

Cosmological Principle: Universe is homogeneous and *isotropic*
It is the starting point of modern cosmology
Statement verified on large enough scales

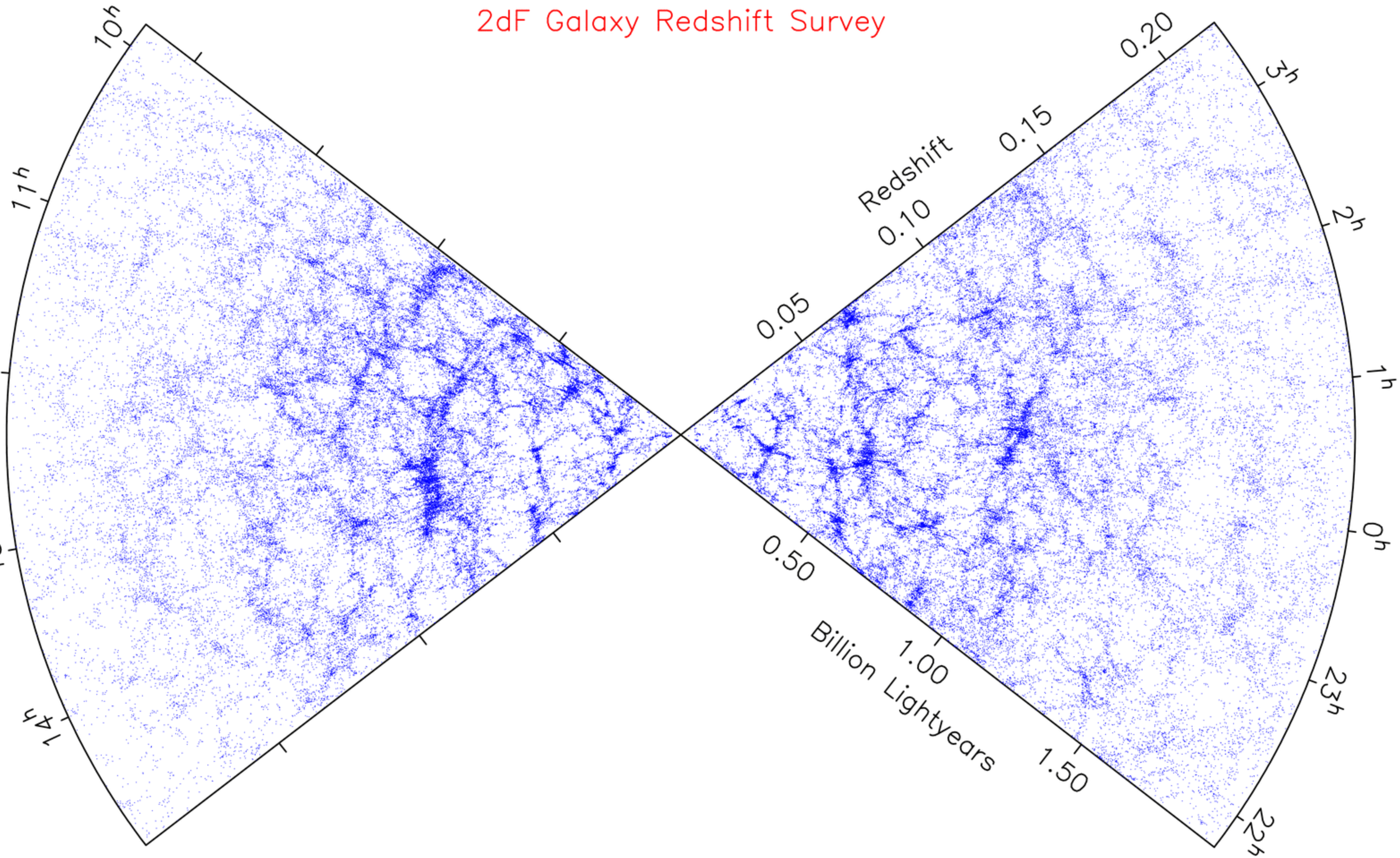
We will use the cosmological principle to derive the fundamental equations That relate the dynamics of the Universe with its matter/energy content and geometry.

The first step will be to determine a metric that satisfies the cosmological principle.
The dynamical equations (Friedmann equations) will then be derived from Einstein's field equations for the proper *metric d*escribing a Universe with a time dependent spatial scale (expanding or collapsing) assuming an appropriate form of the stress-energy tensor to describe the matter/energy content.

Surprisingly, one can obtain the first of the Friedmann equations working with newtonian gravity, again owing to the cosmological principle. Of course in this case there is no natural notion for how to identify the geometrical meaning Of the equation because there is no notion of spacetime in newtonian gravity.


The Hubble Ultra Deep Field (HUDF)
(Megaparsec scales, galaxy distribution
very inhomogeneous)
A sheer variety
of morphologies
and patterns
of 10,000 galaxies
1/10 diameter
of full moon!
11.5 square
arc minutes

......and on Gigaparsec scales (Gpc)

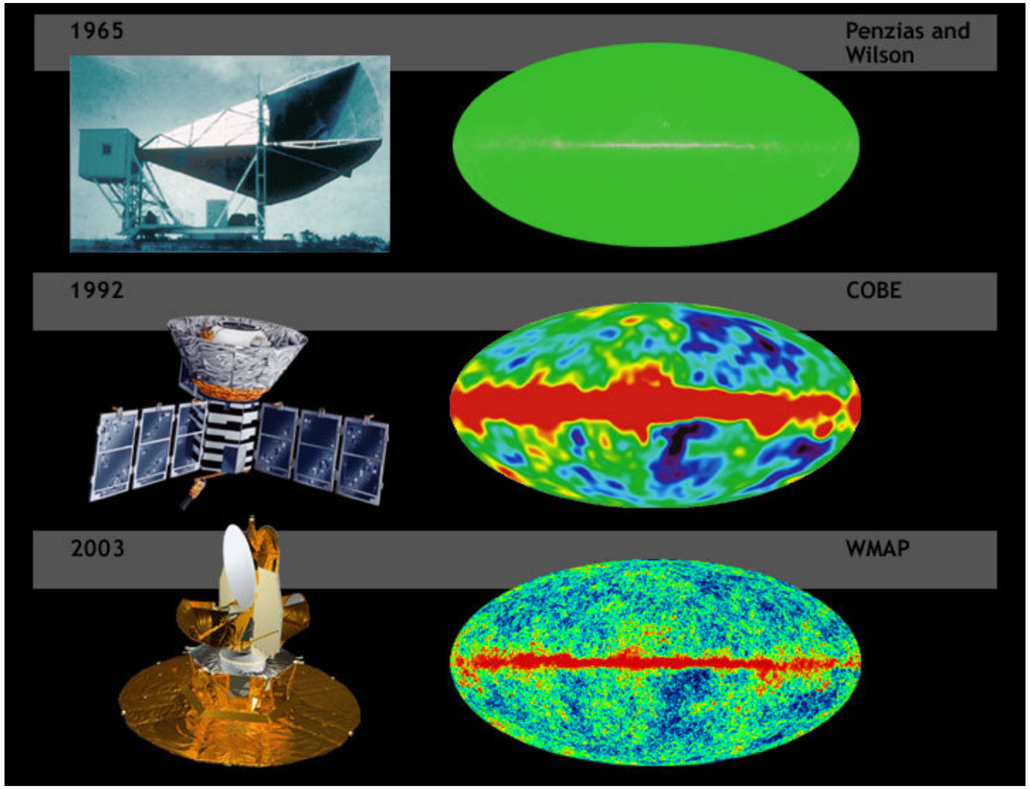


The cosmic microwave background (CMB) radiation:

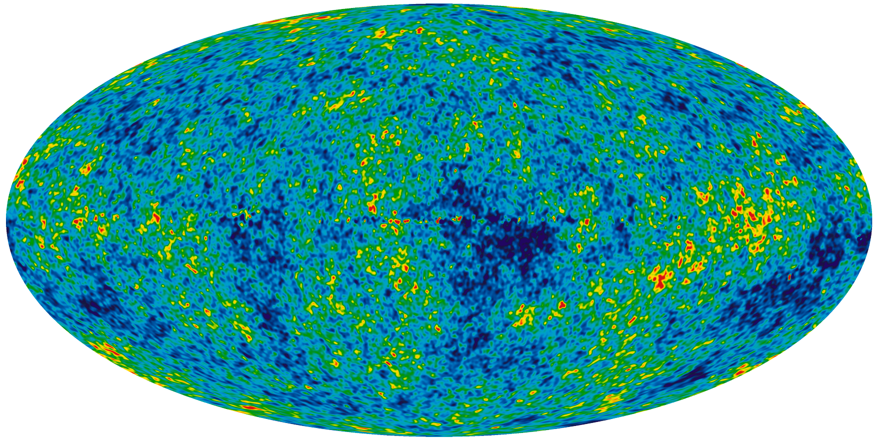
a relic of the Big Bang in support of the cosmological principle

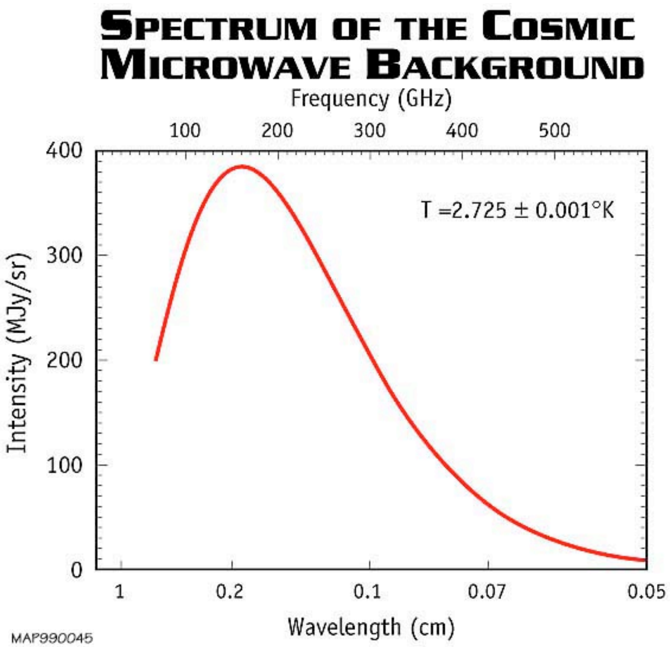
but also evidence of the initial inhomogeneities present in the

early Universe (at the time of last scattering)

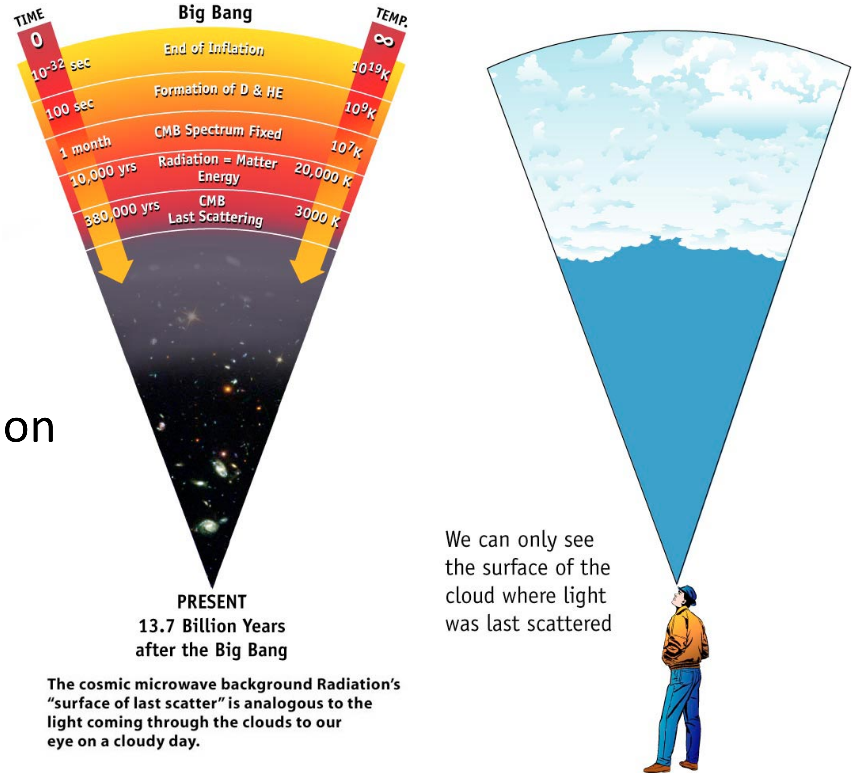


Temperature fluctuations after subtraction of Galactic foreground contamination (7yr WMAP data) – amplitude of spots ~ $1/10^5$ ($\Delta T/T$ ~ a few μK)





Blackbody spectrum of CMB (at a resolution of mK)



Angular power spectrum of temperature fluctuations