Theoretical Cosmology:Course Guidelines

Prof. Lucio Mayer and Prof. Jaiyul Yoo
Course website:https://www.ctac.uzh.ch/en/ast513/

Teaching Assistants (lead exercise classes on Friday):
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Exercise sheets, lectures slides and textbook section numbers available on website.
Exercises sheets will be uploaded on Fridays. Are due on following Friday.

Occasionally the Friday Exercise class will cover extra topics, for example on Astronomical notions (example next week – notion of standard candles for cosmic distance measurements).

Textbooks (copies of material not available online provided during classes):

S. Carroll – Lectures on General Relativity (**http://arxiv.org/abs/gr-qc/9712019**) + textbook "An Introduction to General Relativity: Spacetime and Geometry")

H. Mo, F. van den Bosch, S. White (Cambridge) - Galaxy Formation and Evolution

S. Dodelson – Modern Cosmology (Academic Press)

Lectures take place at:

Wednesday: 13-15 – room **HCI G3**

Thursday: 12-14 – room **HCI G7**

Weekly exercise Classes -Two groups:

Friday at ETH: 15-17 – room HCI F2
15-17 –room HCI F8

Requirement: GR recommended

Course Structure

Part I - The Unperturbed State of the Universe

Introduction: dynamics of expanding Universe and its matter/energy content
The FRW metric and Friedmann equations
The Thermal History of the Universe (Hot Big Bang model)
Decoupling and thermodynamics or relic particles
Nucleosynthesis and Recombination
Introduction to Inflationary Theory

Part II – The Perturbed State of the Universe

Relativistic Perturbation Theory
Perturbed Boltzmann Equation
Inhomogeneities
Anisotropies
Primordial Perturbations from Inflation
Newtonian Perturbation Theory
Cosmological Probes (extra topic)
Conclusions

Theoretical Cosmology

What is COSMOLOGY?

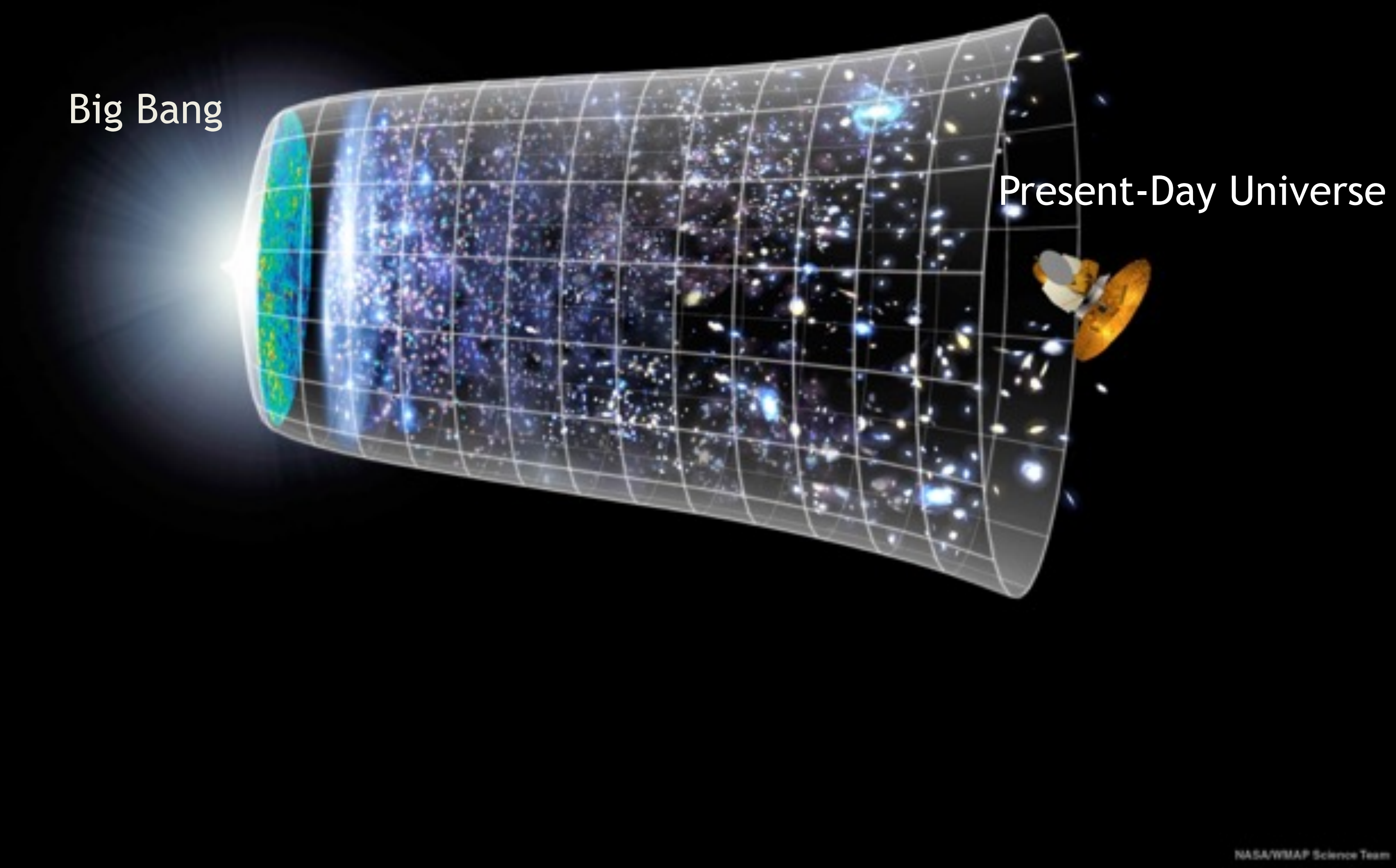
-**The study of the Universe as a whole**, namely as the collection of its matter/energy components and its constituent phenomena, and of its evolution.
Cosmology is thus a multi-disciplinary science (involves astrophysics, relativistic gravitational physics, particle physics, nuclear physics etc..)

-The origin of the word from Ancient Greek: „discourse on the Universe“
Suggests we should be open minded in our inferences, not dogmatic.
Ancient Greeks were the first cosmologists of the western world
(= the first philosophers, such as Democritus or Parmenides, who 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 testable with experiments. It is based on our modern knowledge of physical laws. This course focuses on the physical foundations of cosmology.
General Relativity constitutes the backbone of current cosmological theory

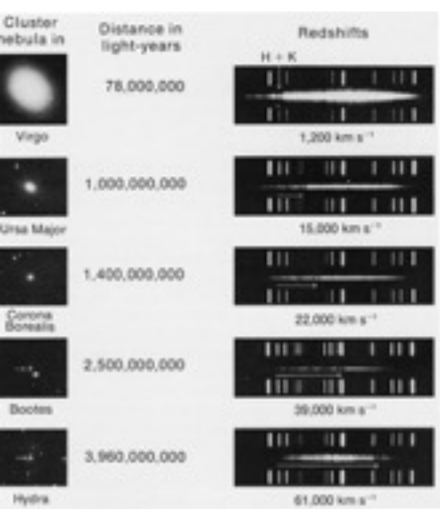
-The prevailing cosmological model **(LambdaColdDarkMatter)** satisfies several tests set forth by astrononical observations and experiments. However there are still aspects of cosmic structure that cannot be predicted (internal structure of galaxies)

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



The birth of Modern Cosmology: the notion of an Expanding Universe

Hubble



1929: Hubble (with new telescope):
-- Determines spiral nebulae are external galaxies
-- Determines galaxies are receding from each other, and increasingly faster for greater distances (Hubble law) – $v_r = Hd$

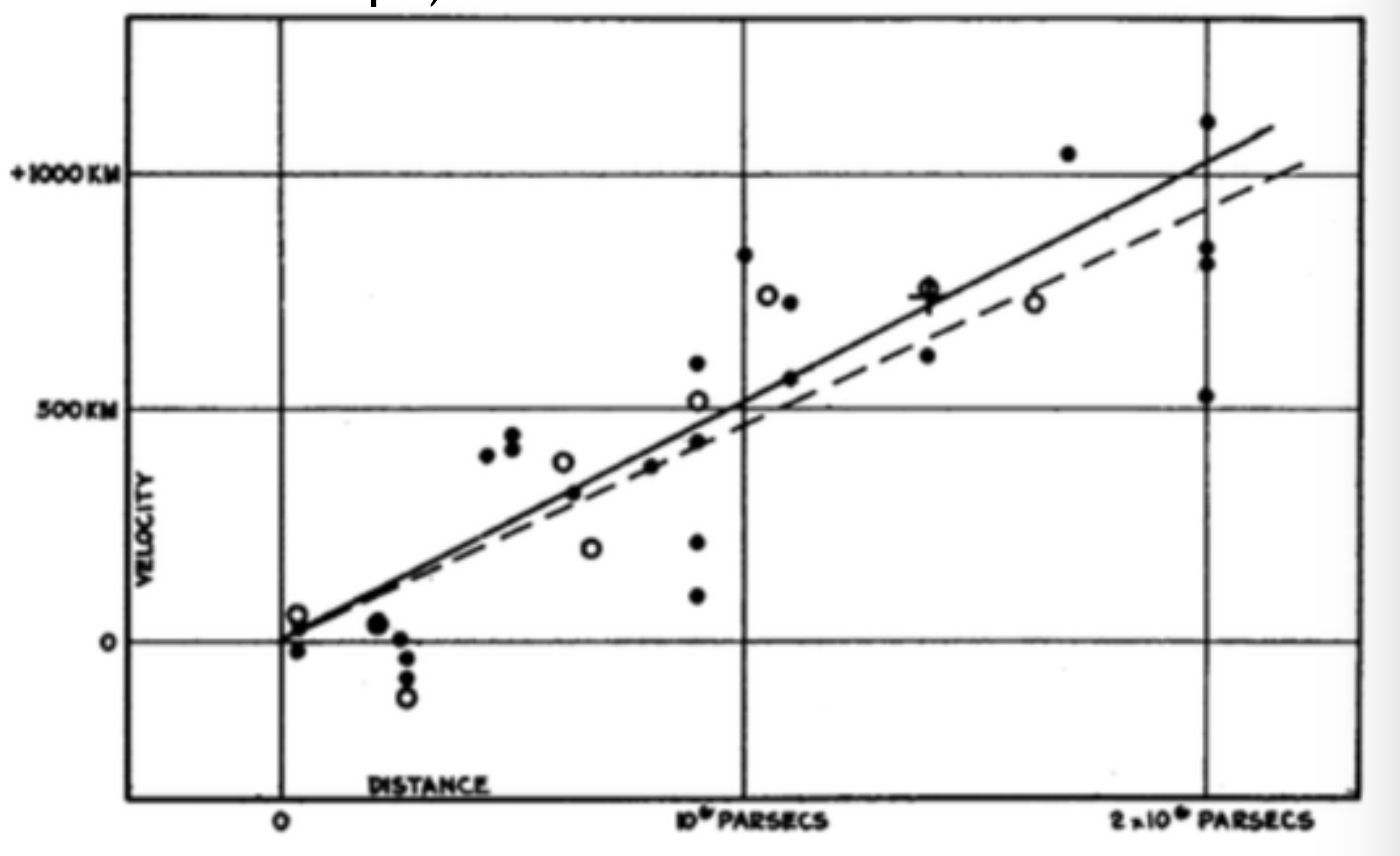
The Theory : Einstein (GR, 1915), then Friedmann (dynamical equations) Lemaitre (expanding solution, Big Bang/primeval atom model) in the 1920s

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

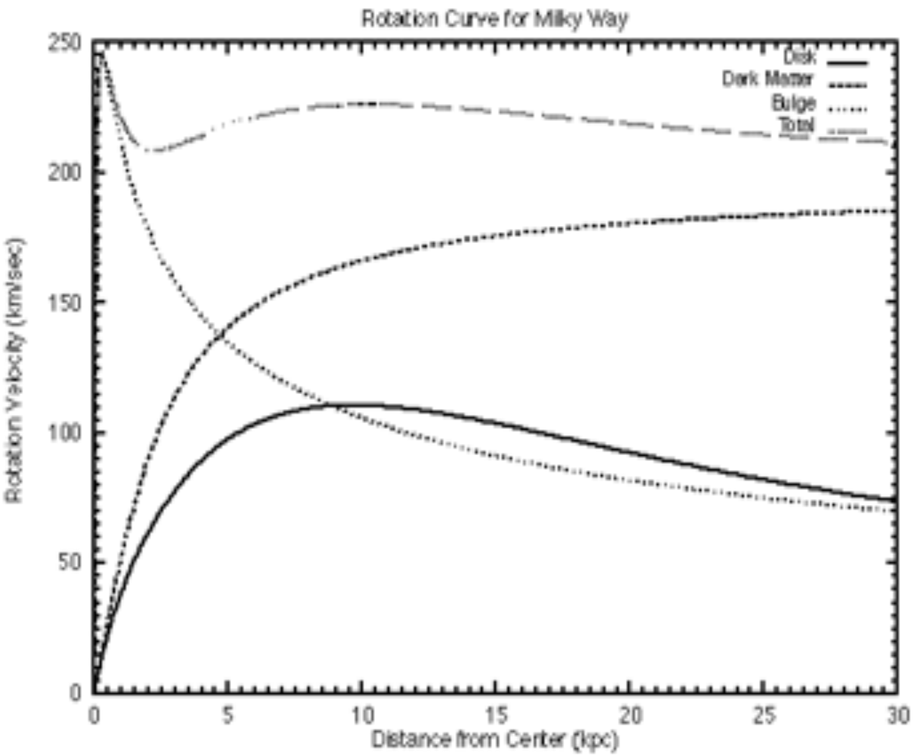
The Coma Cluster of Galaxies
Zwicky meausured the motion of many galaxies in Coma and used the virial theorem to find that there is 400 times more mass than it is visible --> *Dunkle Materie!*

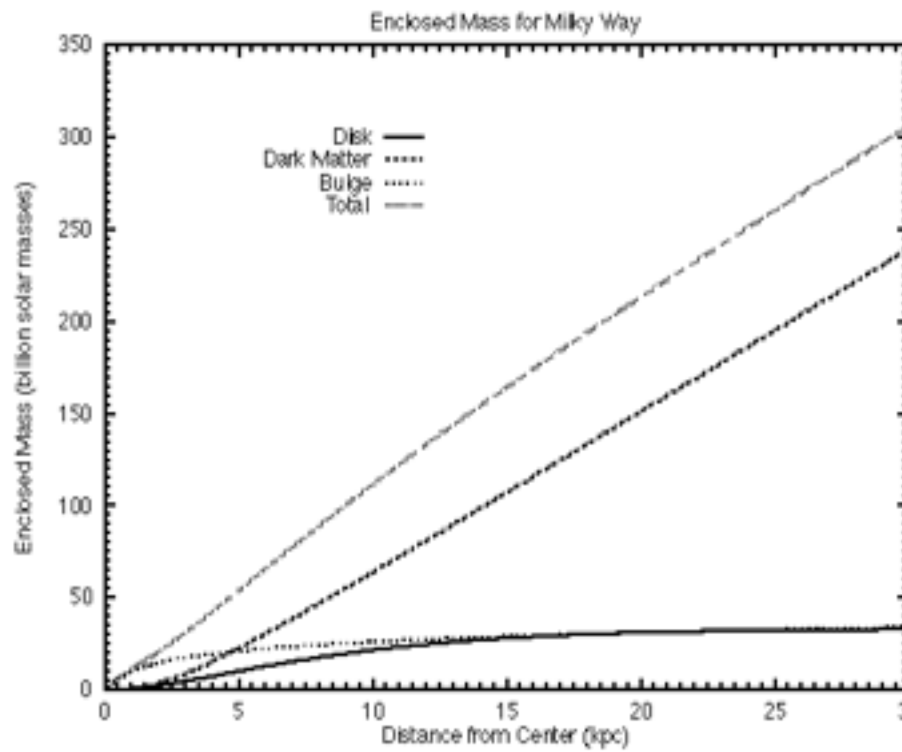
Virial theorem:
$\langle v^2 \rangle \sim GM_{cl}/R_{cl}$

The need for Dark Matter: the rotation curves of galaxies

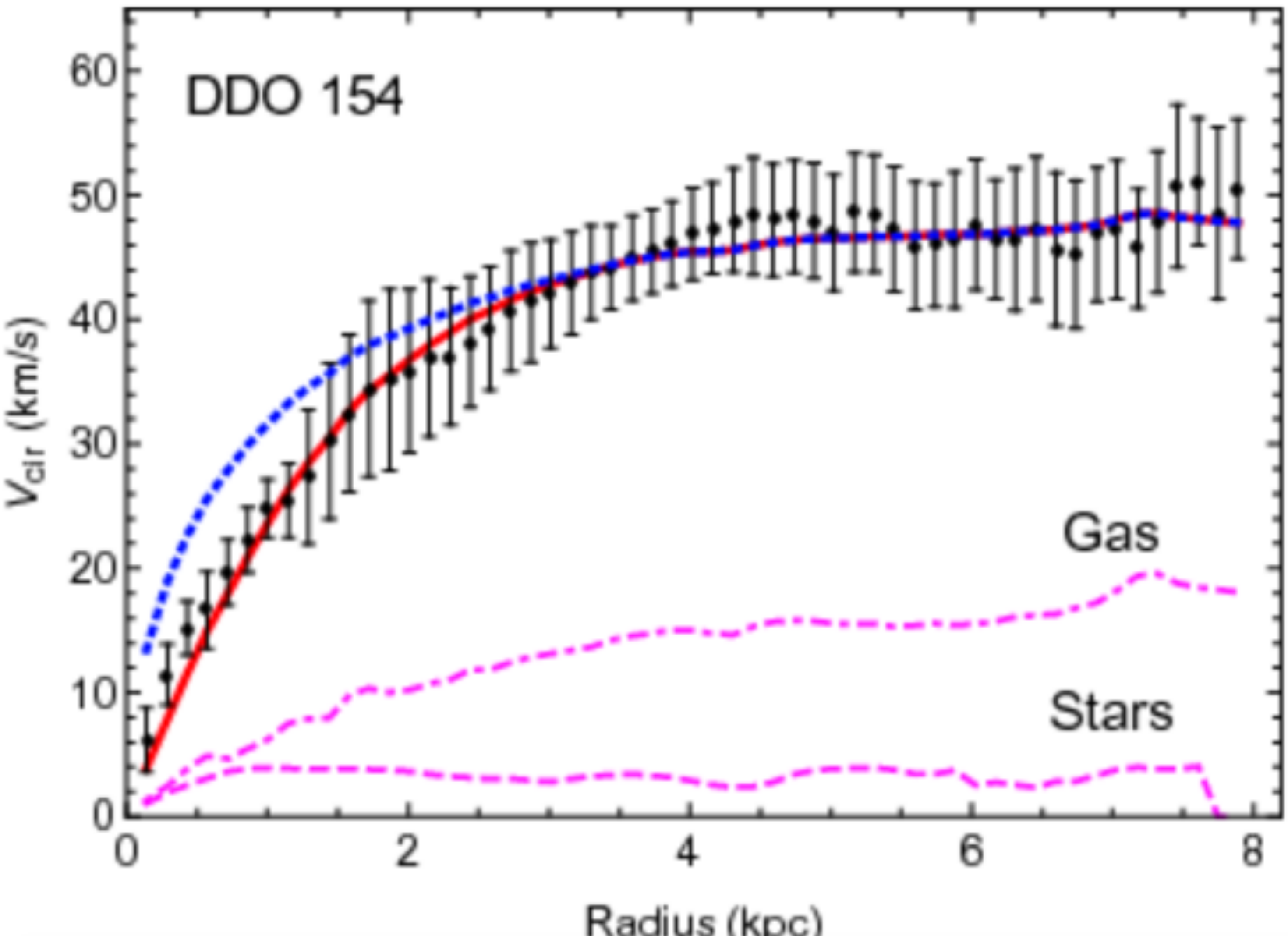
Pioneering work from Vera Rubin in the 70s: first establish that rotation speed remains nearly constant at large radius —-> *need for extended dark matter halo*

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

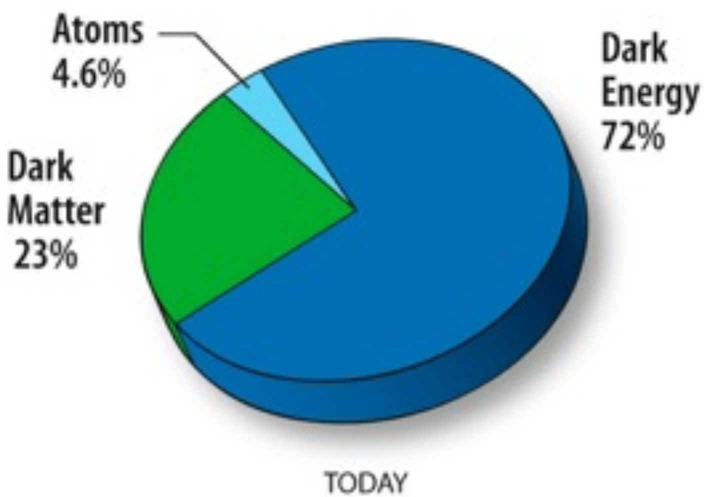


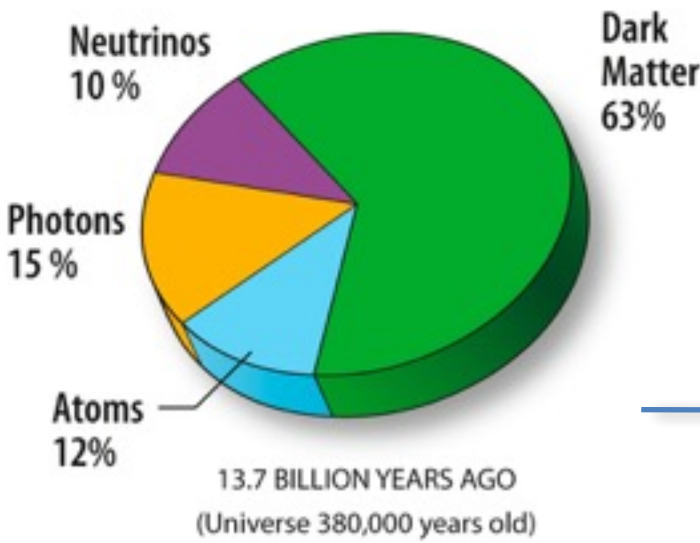


Dwarf galaxies: most numerous and mostly dark matter



The constituents of the Universe; today and then





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

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

Dark matter non-baryonic because we can place limits on the baryon content of the Universe (baryons, eg stars or Interstellar gas, detected In some band of the electromagnetic spectrum plus constraints from nucleosynthesis)

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

The founding notion: the cosmological principle

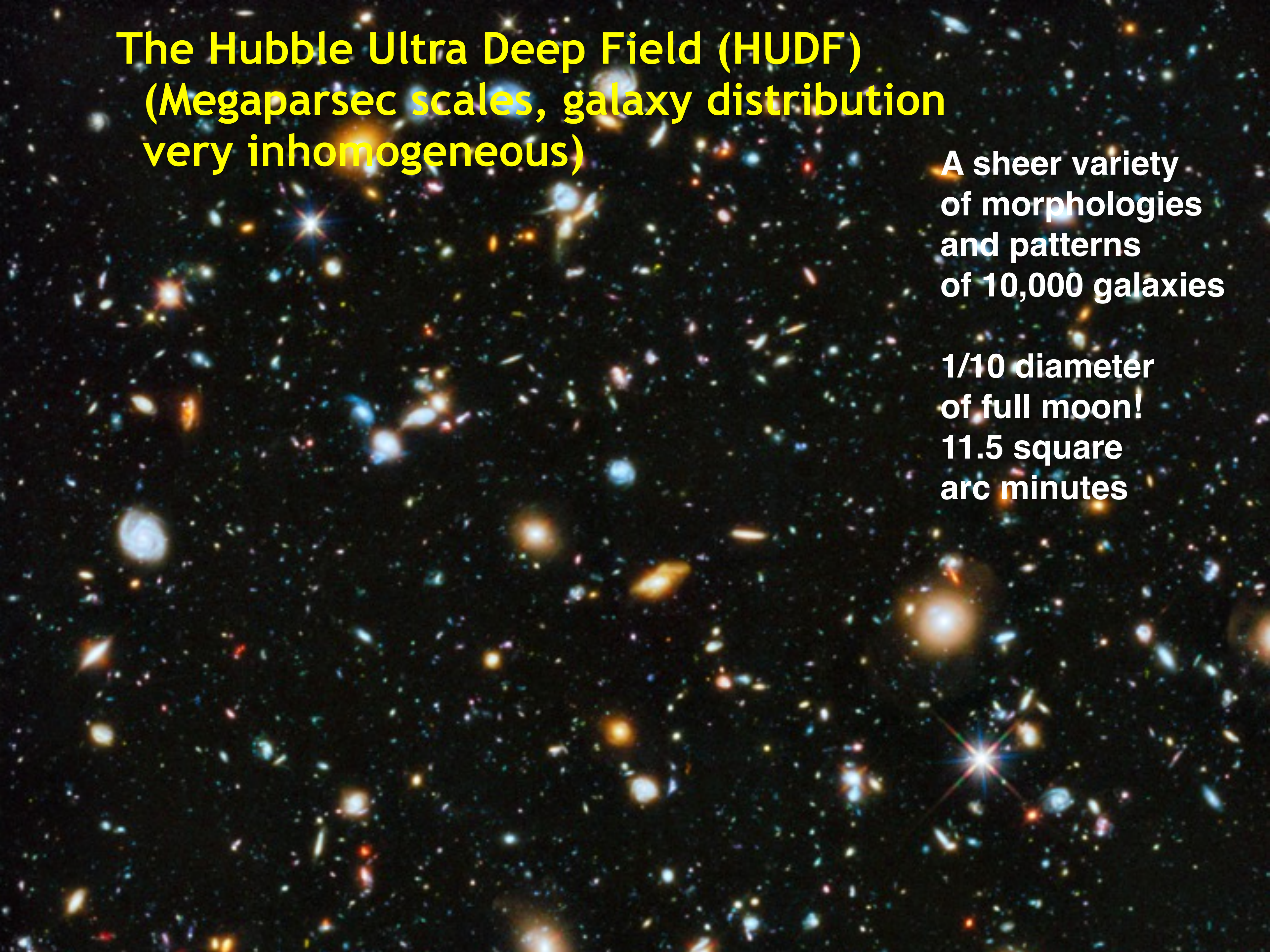
Cosmological Principle: Universe is homogeneous and *isotropic*
It is the starting point of modern cosmology
Statement verified on large enough scales

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.

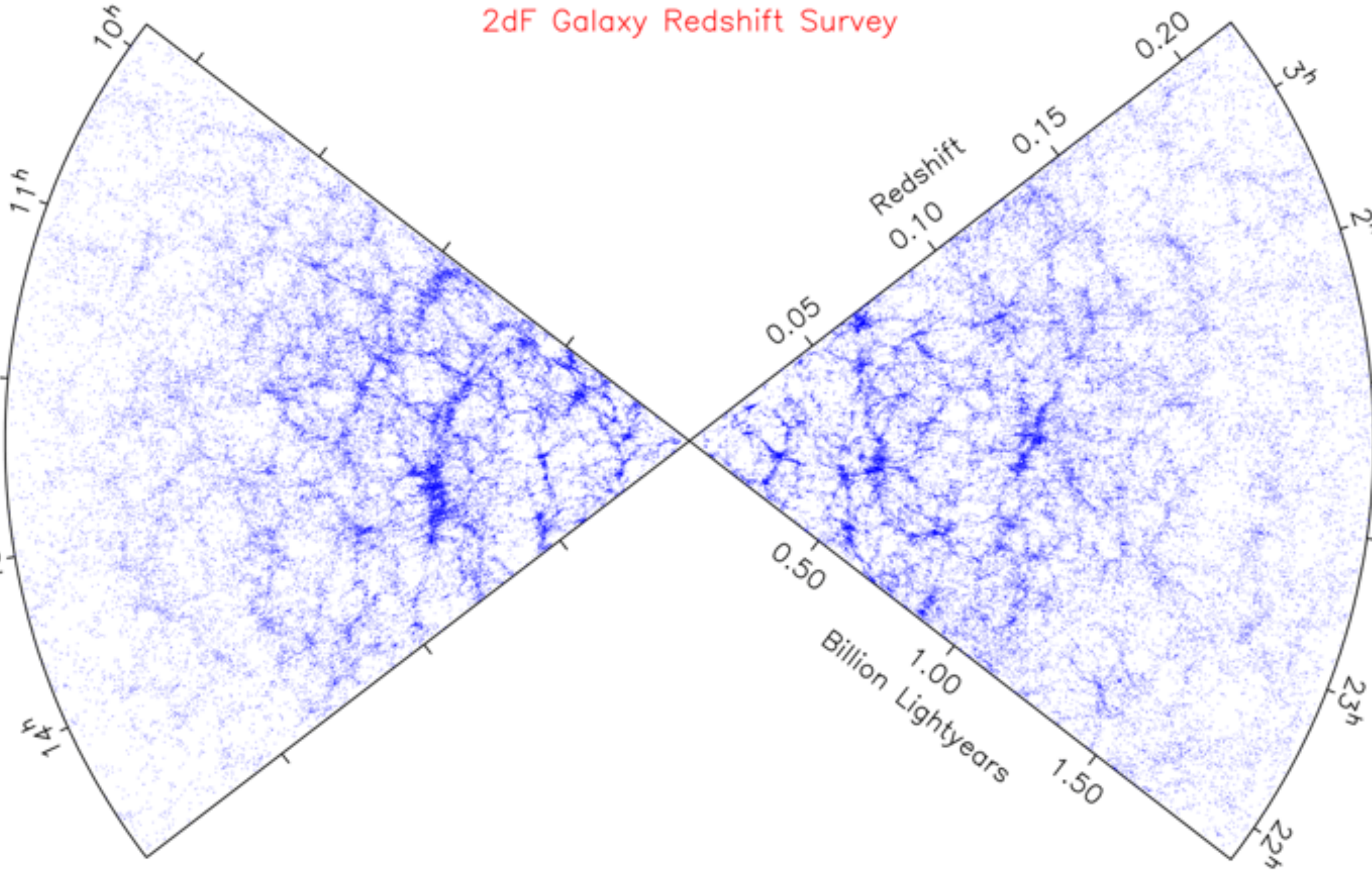
The Hubble Ultra Deep Field (HUDF)
(Megaparsec scales, galaxy distribution very inhomogeneous)



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)

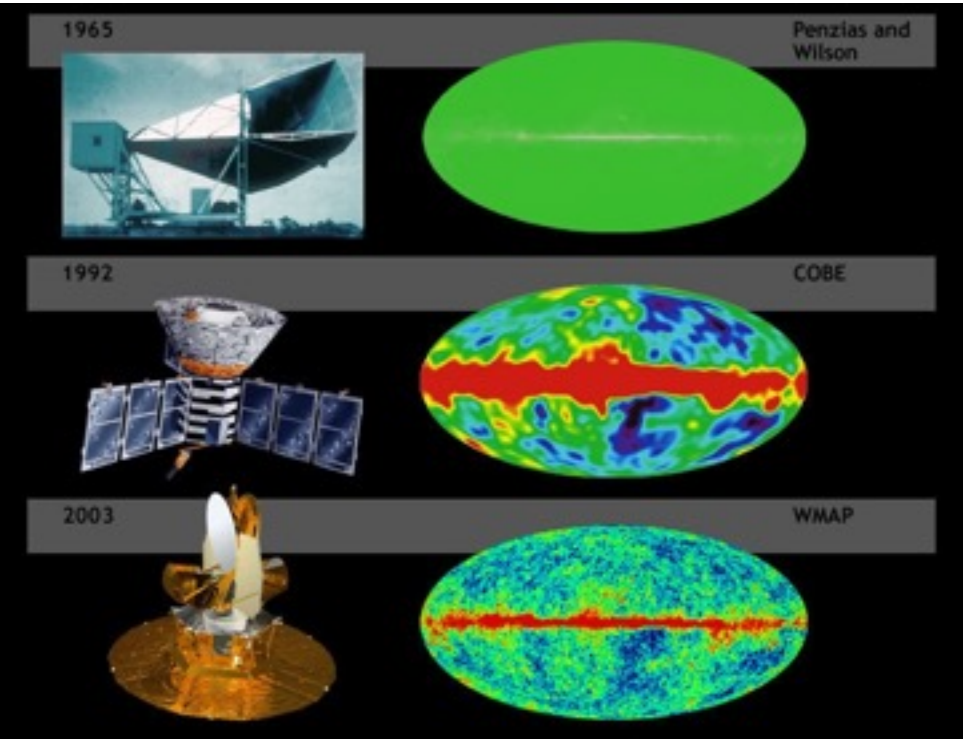


The cosmic microwave background (CMB) radiation:

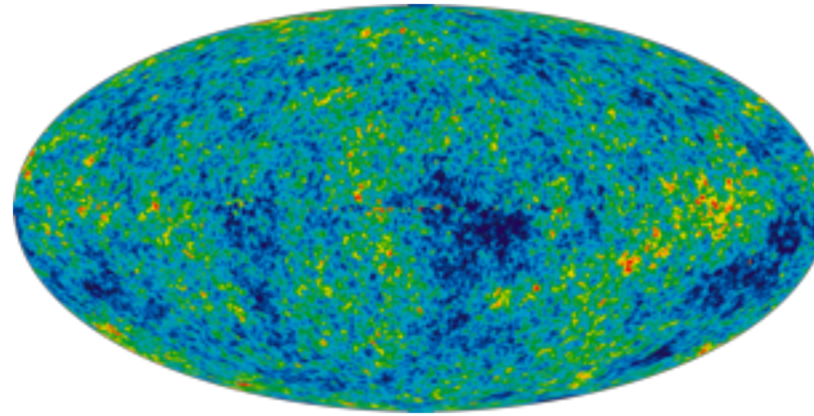
relic of the Big Bang supports strongly the cosmological principle

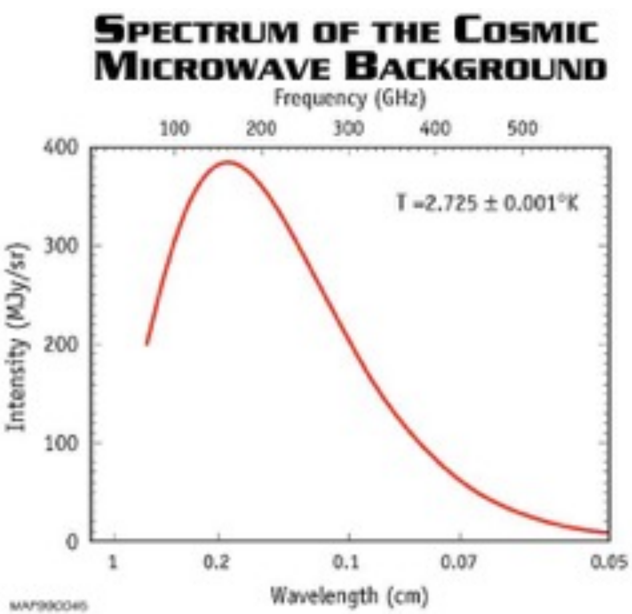
but also evidence of the initial inhomogeneities present in the

early Universe (at the time of last scattering, 380.000 years after the Big Bang)

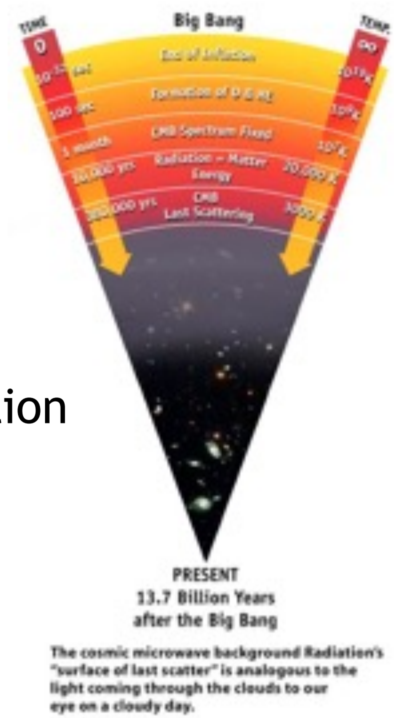


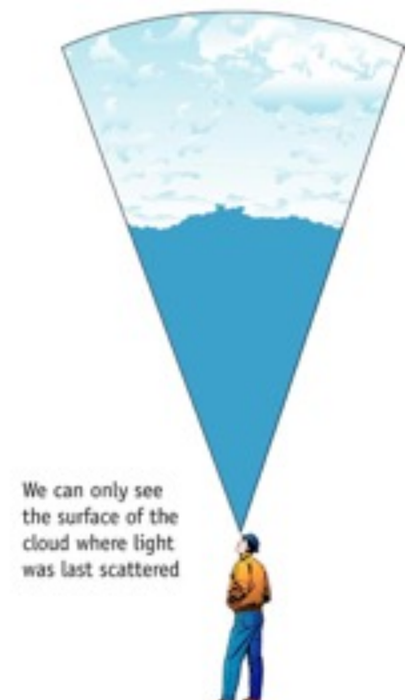
Temperature fluctuations after subtraction of Galactic foreground contamination (7yr WMAP data) – amplitude of spots ~ $1/10^5$ (DeltaT/T ~ a few mK)



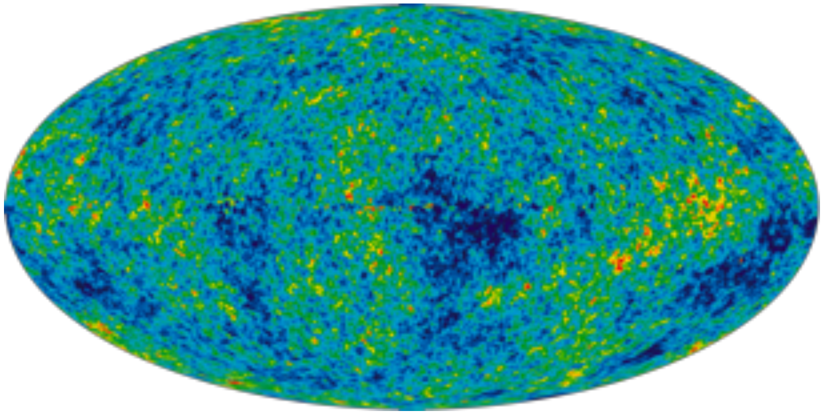


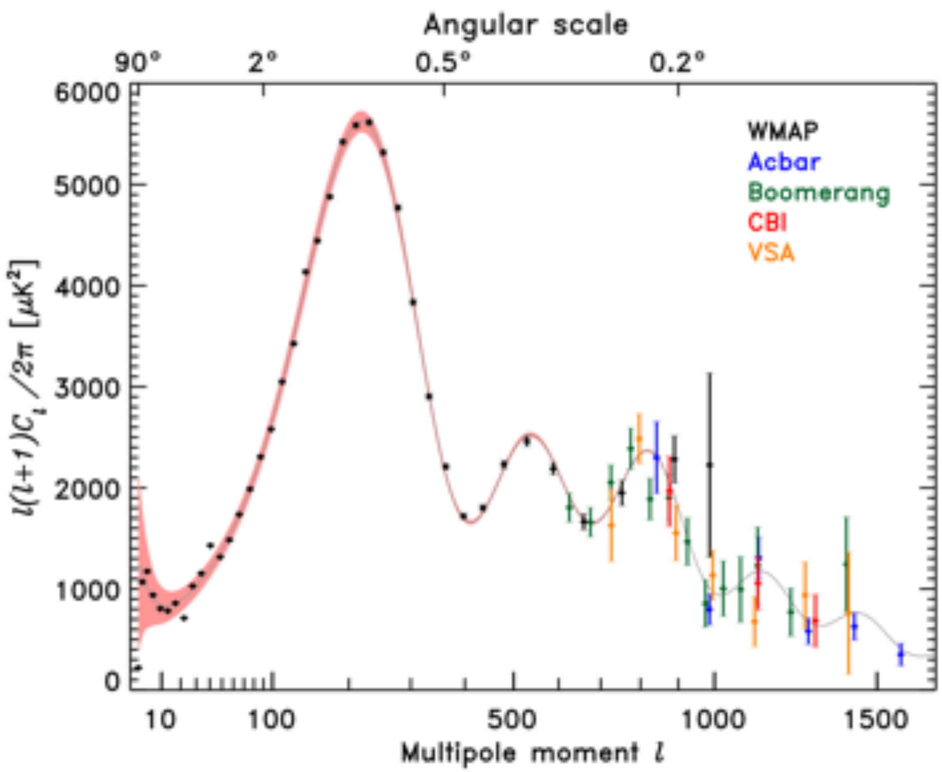
Blackbody spectrum of CMB (at a resolution of mK): uniform Temperature of 2.73 K





Angular power spectrum of temperature fluctuations





And now to a newtonian treatment of a dynamical (eg non-static) Universe....