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: „discussion 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 astronomical observations and experiments. However there are still aspects of cosmic structure that it cannot predict (eg structure of galaxies)
Lectures take place at:

Wednesday: 13-15 - room HCl G3

Thursday: 12-14 - room HPV G5

Weekly exercise Classes - Two groups:

Friday at ETH: 15-17 - room HCl F2
                 15-17 - room HCl F8

Requirement: GR recommended
Course Guidelines


Teaching Assistants (For Friday exercise classes):
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Exercise sheets, lectures slides and textbook section numbers available on website. Exercises sheets will be uploaded on wednesdays and are due the following Wednesday.

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):

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

S. Dodelson - Modern Cosmology (Academic Press)
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
- 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

1929: Hubble (with new technology):
-- 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) (using only 24 nearby galaxies - two different fitting lines relate to two different ways to correct for solar motion). Slope is *Hubble Constant* $H_0$ (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: 
\[ \langle v^2 \rangle \sim \frac{GM_{cl}}{R_{cl}} \]

The Coma Cluster of Galaxies
Zwicky measured 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

Rotational velocity (newtonian gravity assuming spherical potential): $v_{\text{rot}}^2 = GM/R$
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 describing 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 $\sim 1/10^5$ (DeltaT/T $\sim$ 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....