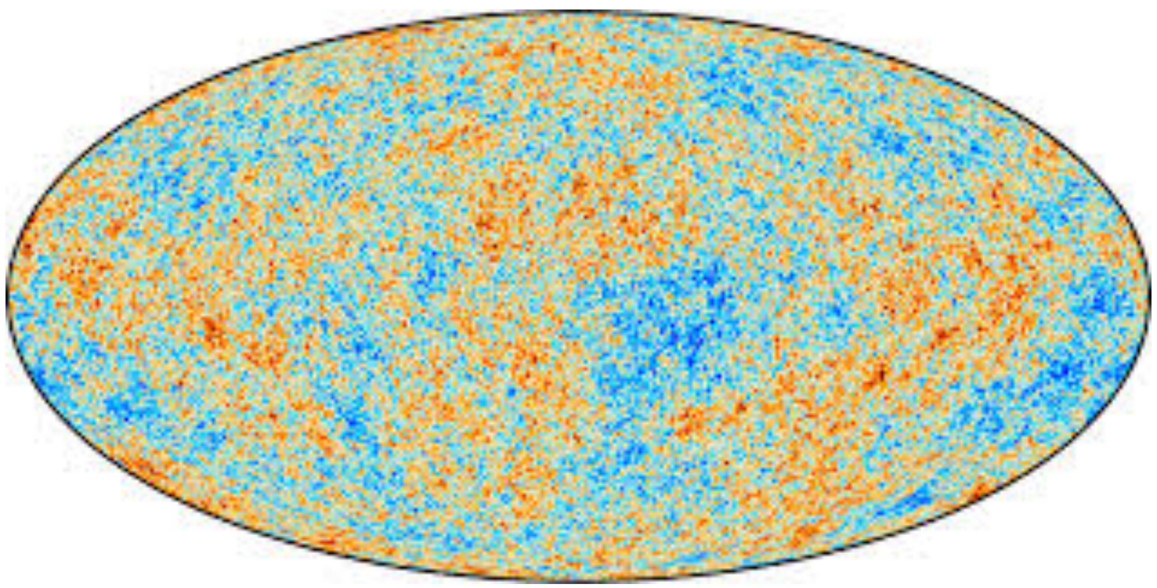
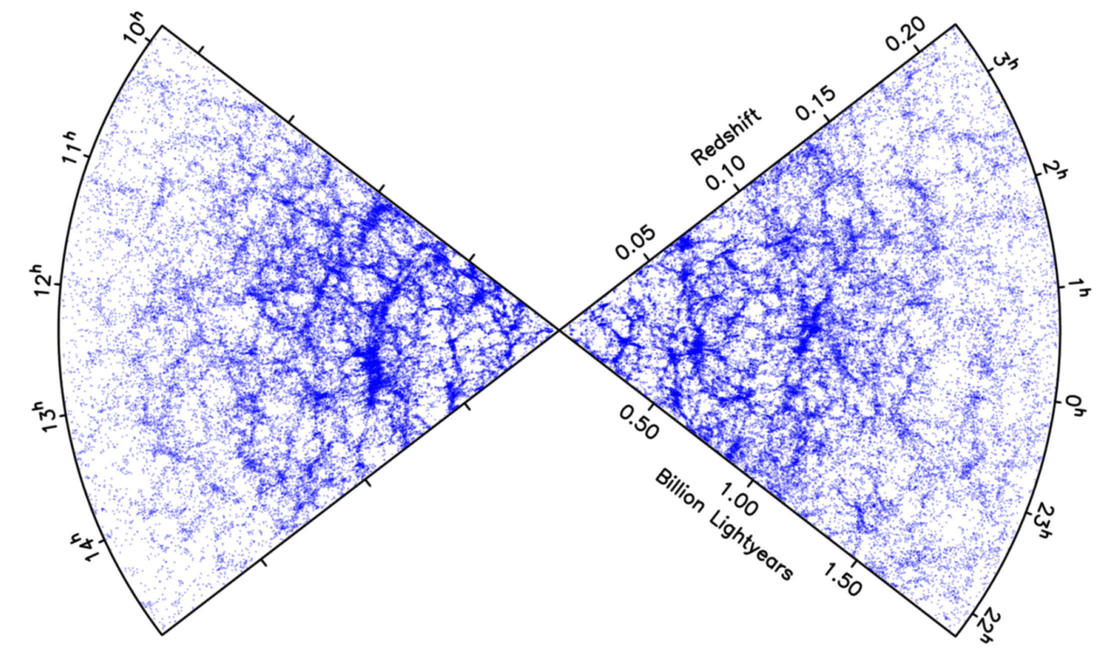
First lecture AST5220 / AST9420 “Cosmology II - Formation of structures in our Universe”



The temperature fluctuations in the Cosmic Microwave Background (CMB) from Planck



Distribution of galaxies in our Universe as seen in galaxy surveys

Hans Winther
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Spring 2021

Todays lecture

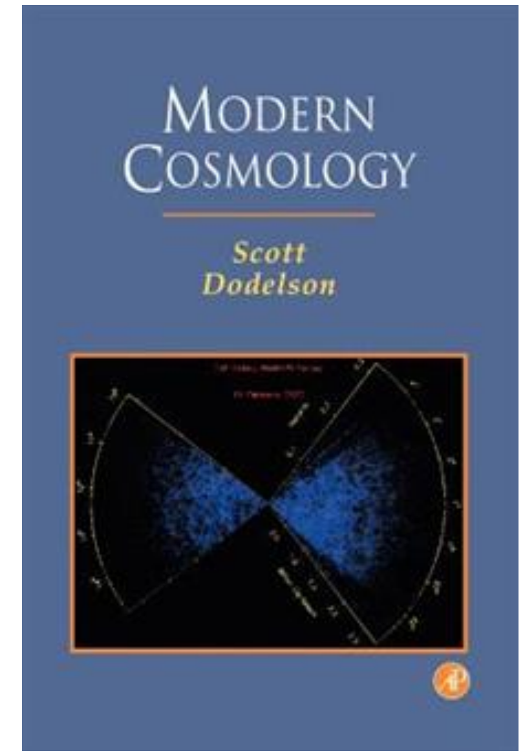
- Practical information: Lectures, curriculum, the numerical project and the exam.
- We will give you an overview of what the course is about and how it is structured.
- A bit about the cosmological observables we are going to learn how to compute predictions for in this course: the **cosmic microwave background radiation** and the **clustering properties of galaxies**
- A bit about the project this course revolves around: make your own Einstein-Boltzmann solver.
- If time we will softly start on an short introduction to *the perfect theory* - **The General Theory of Relativity**

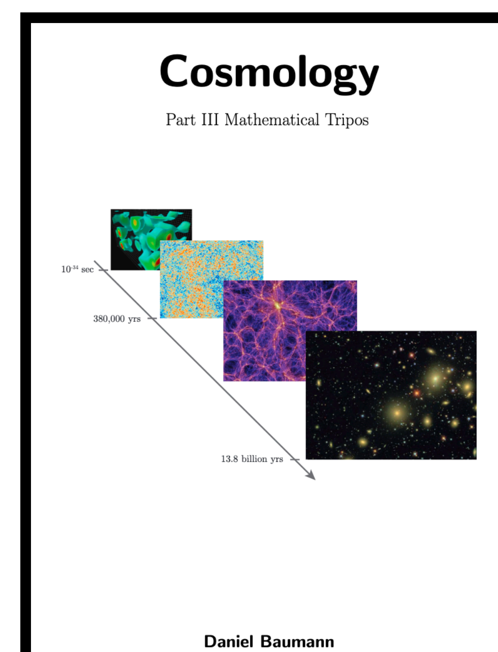
Practical information

- Lectures: 2 x 2 hours per week for 16 weeks. **Wednesday: 1415-1600** and **Thursday: 1215-1400**
- The lectures will be given by Hans Winther (h.a.winther@astro.uio.no).
- Most lectures for going through theory. Some will be used for problems and some for help with the numerical part of the project
- Unfortunately we have to do this online for the first week, but we will hopefully move on to live lectures as soon as possible. But videos from lectures **will be made available** in case you can't come, are quarantined or don't want to attend live lectures.
- **Exam:** Project accounts for 30% of grade and 70% of grade from normal exam. This semester it will be an **oral exam** on May 31st (we will get back with more info on this later on).

Curriculum

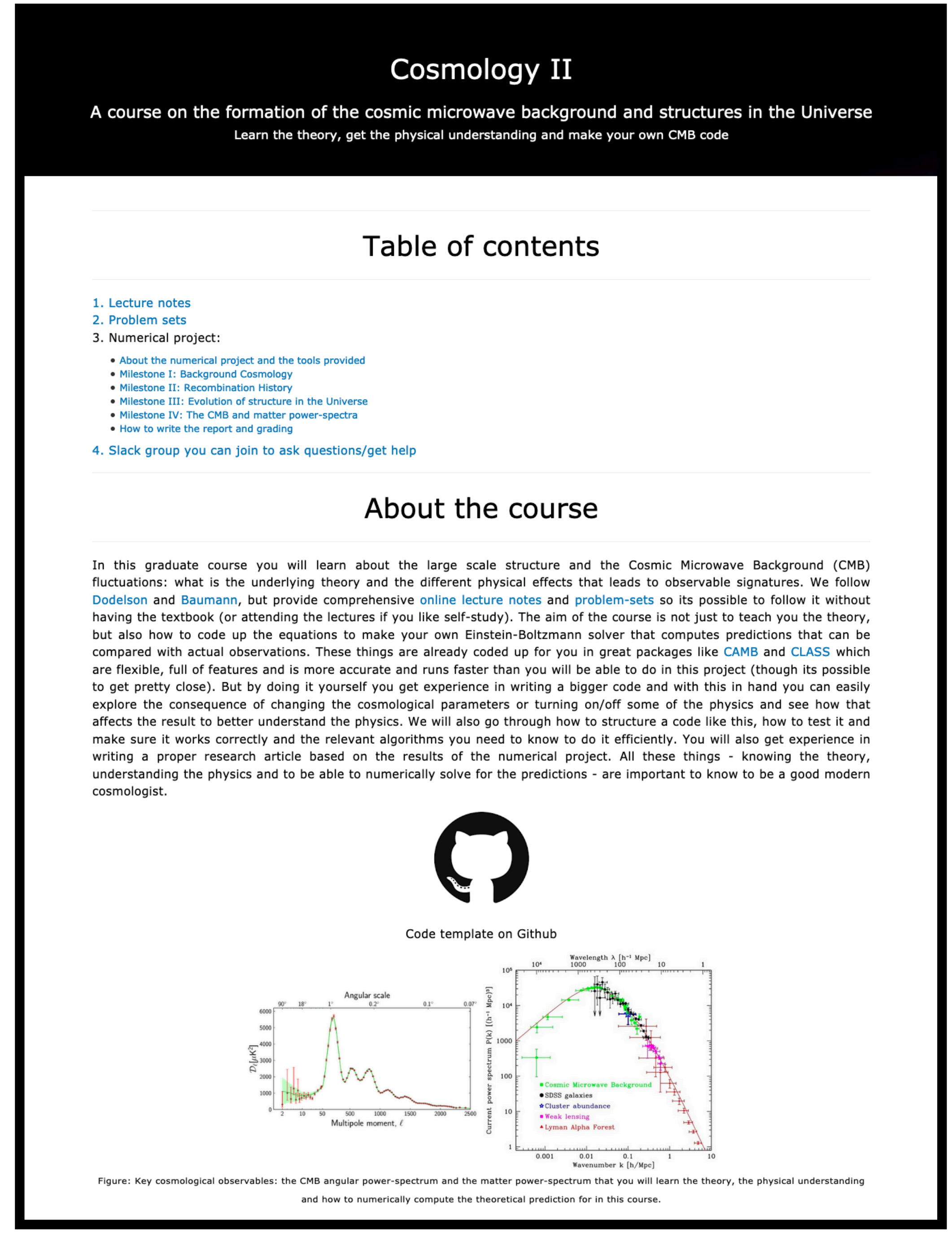
- We will for the most parts use Scott Dodelson's "Modern Cosmology" - this covers pretty much all of the material in this course
- Another "book" that will be very useful is Daniel Baumann's "Cosmology Part III Mathematical Tripos" (free PDF available on my website)
- For the project the paper "How to compute the CMB spectrum" by Peter Callin is useful
- Lecture notes covering most of the course is also available on my website https://cmb.wintherscoming.no/ together with a list of additional literature that might also be useful





Curriculum

- You can find a lot of information about the course on my website
- Has lecture notes, problem sets, info about the textbooks/papers used, the numerical project, links to the code template on GitHub, …
- All **important messages** about the course will be given on the UiO website https://www.uio.no/studier/emner/matnat/astro/AST5220/v21/index.html
- There is also a discussion forum on **https://astro-forum.utenforuio.no/** where you can ask question to me or each other, discuss problems etc (completely anonymous if you want). The website also has a link to a Slack page you can use if you prefer this (though this is not official due to privacy issues with Slack and open to **anybody**).


Cosmology II

A course on the formation of the cosmic microwave background and structures in the Universe

Learn the theory, get the physical understanding and make your own CMB code

Table of contents

About the course

In this graduate course you will learn about the large scale structure and the Cosmic Microwave Background (CMB) fluctuations: what is the underlying theory and the different physical effects that leads to observable signatures. We follow Dodelson and Baumann, but provide comprehensive online lecture notes and problem-sets so its possible to follow it without having the textbook (or attending the lectures if you like self-study). The aim of the course is not just to teach you the theory, but also how to code up the equations to make your own Einstein-Boltzmann solver that computes predictions that can be compared with actual observations. These things are already coded up for you in great packages like CAMB and CLASS which are flexible, full of features and is more accurate and runs faster than you will be able to do in this project (though its possible to get pretty close). But by doing it yourself you get experience in writing a bigger code and with this in hand you can easily explore the consequence of changing the cosmological parameters or turning on/off some of the physics and see how that affects the result to better understand the physics. We will also go through how to structure a code like this, how to test it and make sure it works correctly and the relevant algorithms you need to know to do it efficiently. You will also get experience in writing a proper research article based on the results of the numerical project. All these things - knowing the theory, understanding the physics and to be able to numerically solve for the predictions - are important to know to be a good modern cosmologist.

Code template on Github

Figure: Key cosmological observables: the CMB angular power-spectrum and the matter power-spectrum that you will learn the theory, the physical understanding and how to numerically compute the theoretical prediction for in this course.

https://cmb.wintherscoming.no/

About the course

- If you have had Cosmology I you have gone through how a smooth Universe evolves (but if not don't worry - we will go through this from scratch) and what we can learn about our Universe from studying this expansion.

- The aim of the course is to take the next step and teach you the basics on how structures form in the Universe. We want to understand how structures in the matter content and the cosmic microwave background radiation forms and evolves.

- This will involve learning to combine a lot of interesting theory (some new and some that you might have seen in previous courses) like General Relativity, thermodynamics / statistical mechanics, quantum field theory, perturbation theory, Fourier transforms, gaussian random fields. We will cover all the theory we need so if some of this is new don't worry!

- The course focus on three main things: 1) **learn the theory** 2) **understand the physics** that is going on 3) be able to numerically **compute the predictions**

A very rough overview of Cosmology

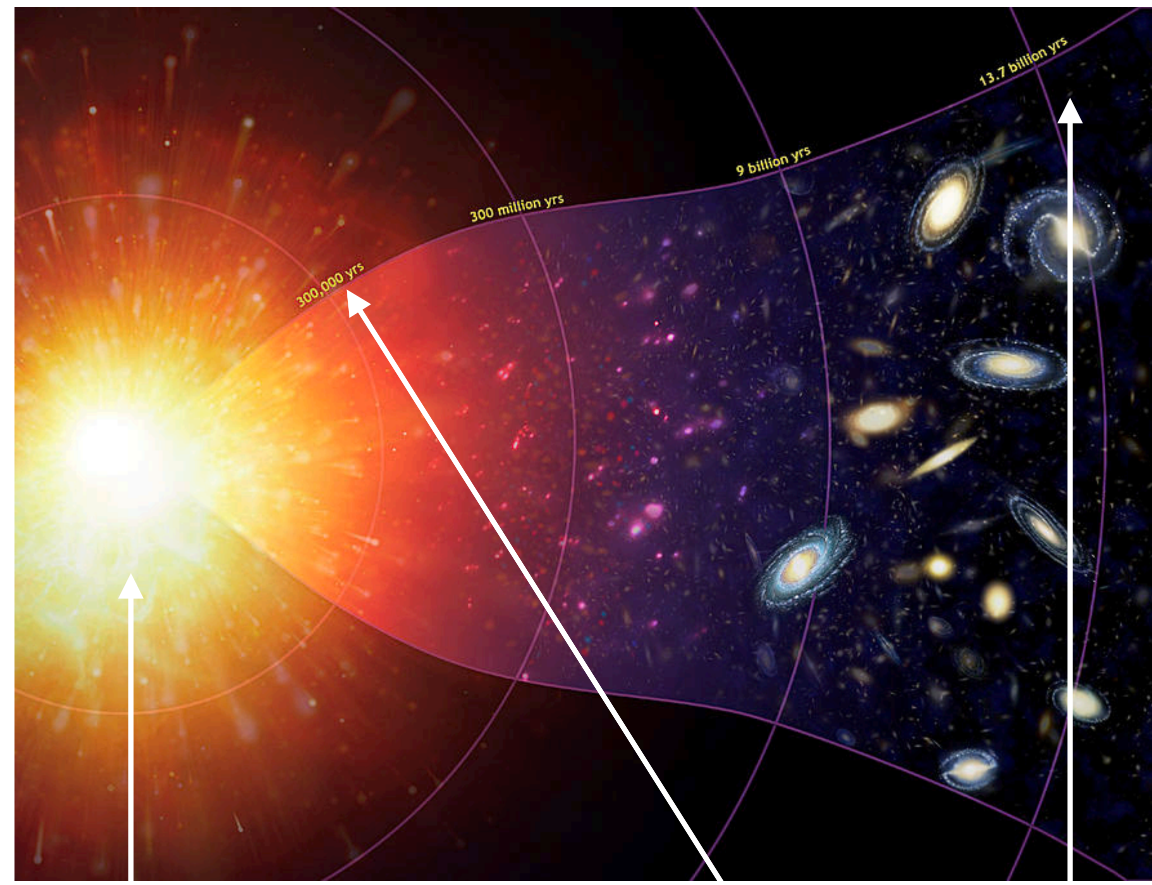
A very rough overview of Cosmology
The Big Bang Model

- The Universe expands today
  - so it must have previously been smaller
  - and very early I must have been very small

- When matter is compressed, it heats up
  - so the Universe must have been very hot early on (a plasma)

- High-energy photons destroys atoms
  - Only elementary particles may have existed very early
  - Protons and neutrons and later atoms was only possible to form as the temperature got low enough

- Important epochs in the history of the Universe:
  - **Inflation** - rapid expansion of space (a fraction of a second after the Big Bang)
  - Big Bang nucleosyntesis - protons and neutrons forms (after ~15 min)
  - **Recombination** - the temperature drops below 3000K and its possible to make hydrogen for the first time (~380.000 years)
  - **Today** - we are here observing the Universe (~14 billions years)



The Universe loads. Inflates

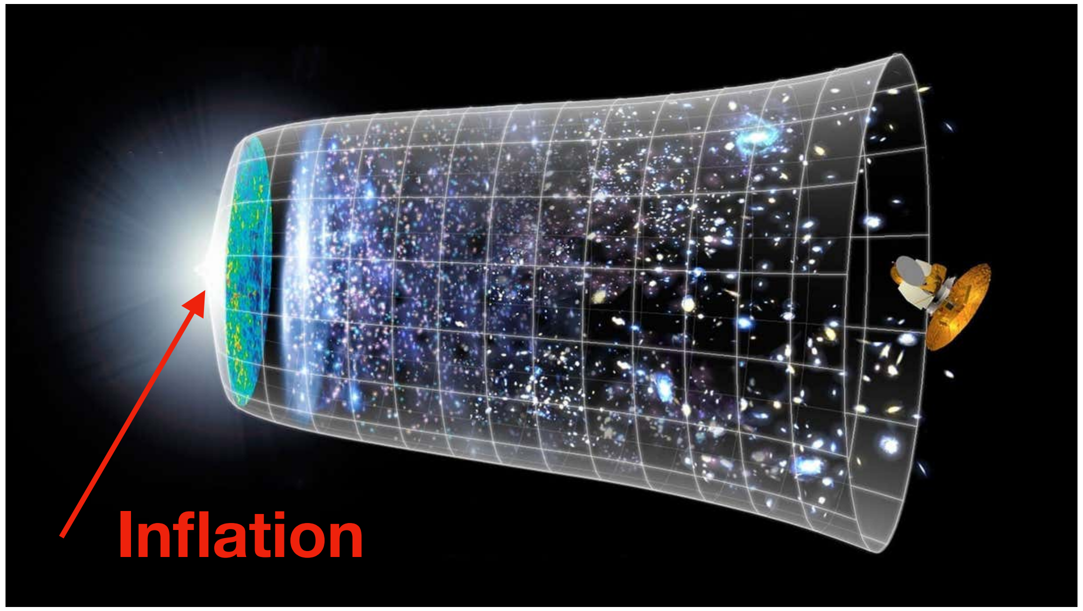
Recombination The CMB is released

We are here observing

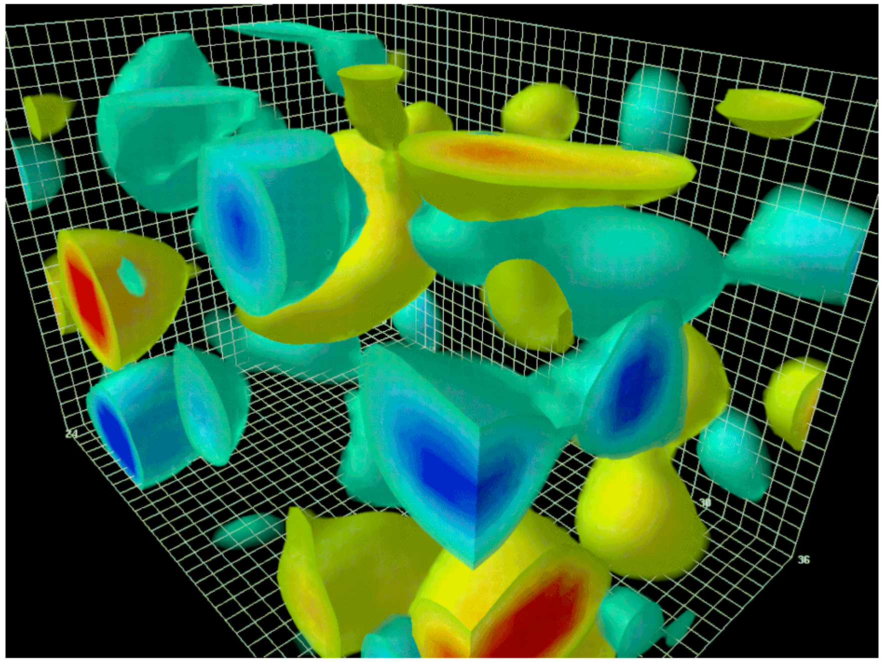
A very rough overview of Cosmology
Inflation

- We observe that the Universe is
  - very close to flat
  - homogenous and isotropic (looks the same everywhere and in all directions)

- Why? Best idea so far is inflation
  - Short period of exponential expansion
  - The size of the Universe increase by a factor ~10^{23} during ~10^{-34} seconds
  - All pre-inflation structure are stretched out



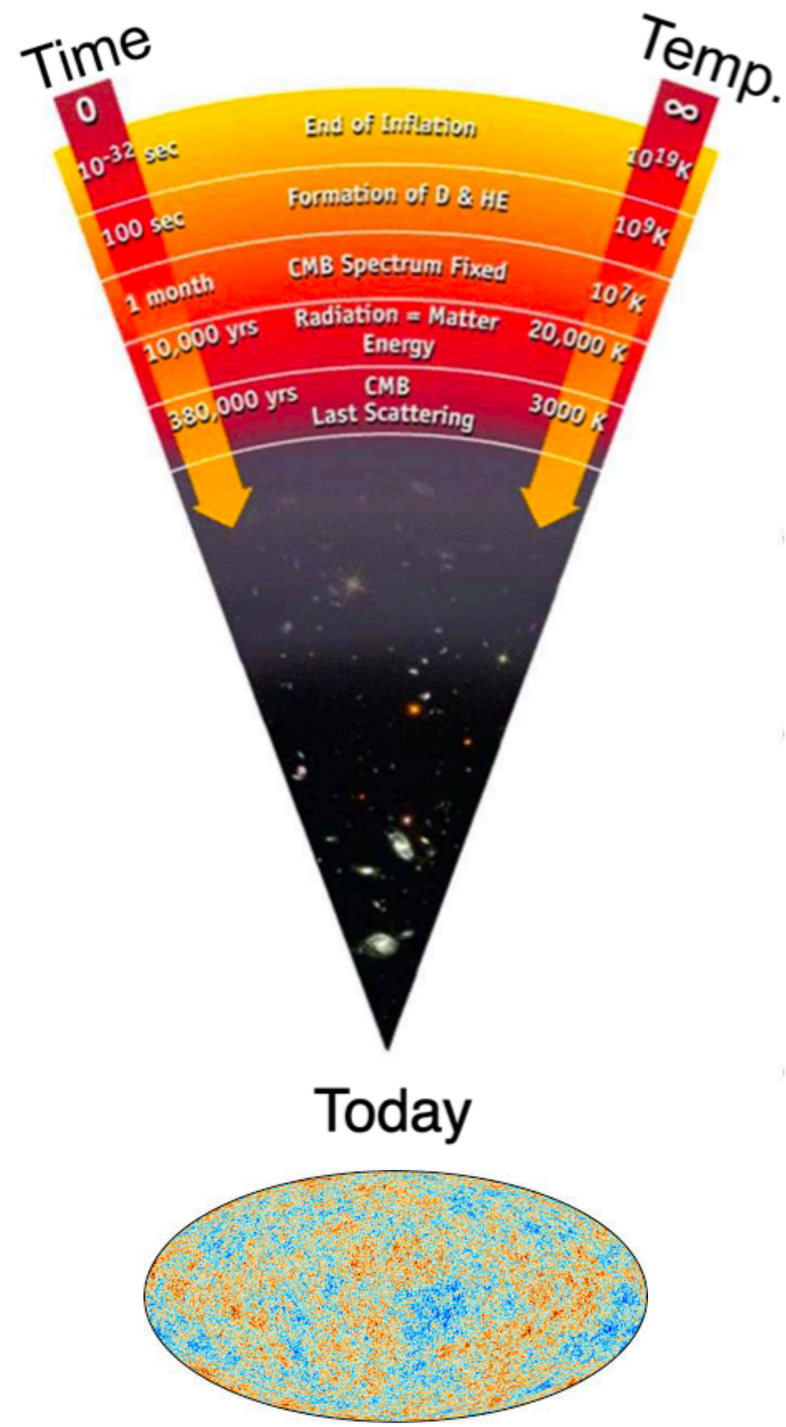
- Leaves the Universe filled with a smooth plasma of photons and elementary particles with some tiny fluctuations created by quantum fluctuations during inflation that gets stretched to macroscopic scales



- These tiny fluctuations will be the seed for structures. Our job in this course is to propagate these initial conditions forward till today!

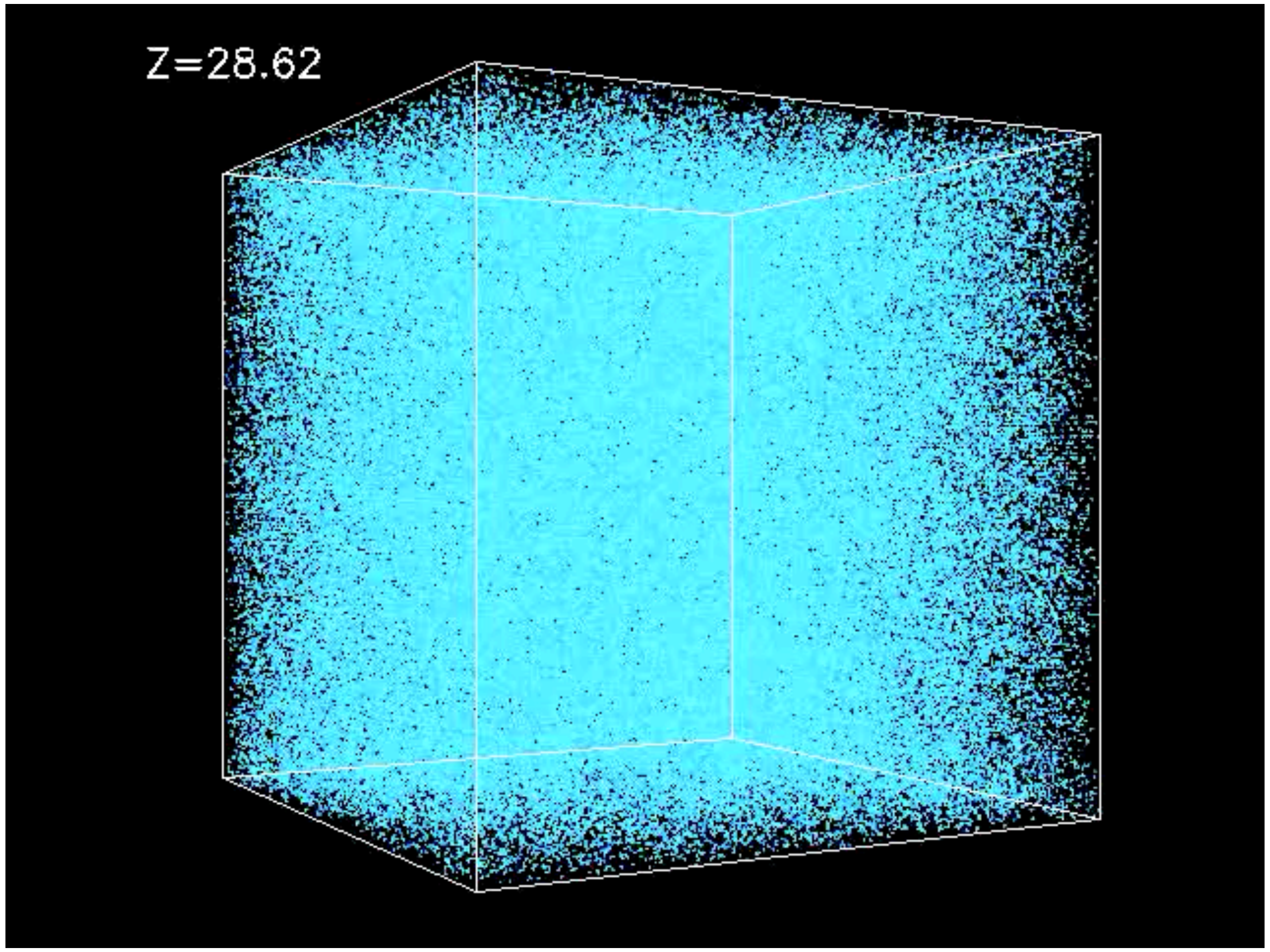
A very rough overview of Cosmology
The Cosmic Microwave Background

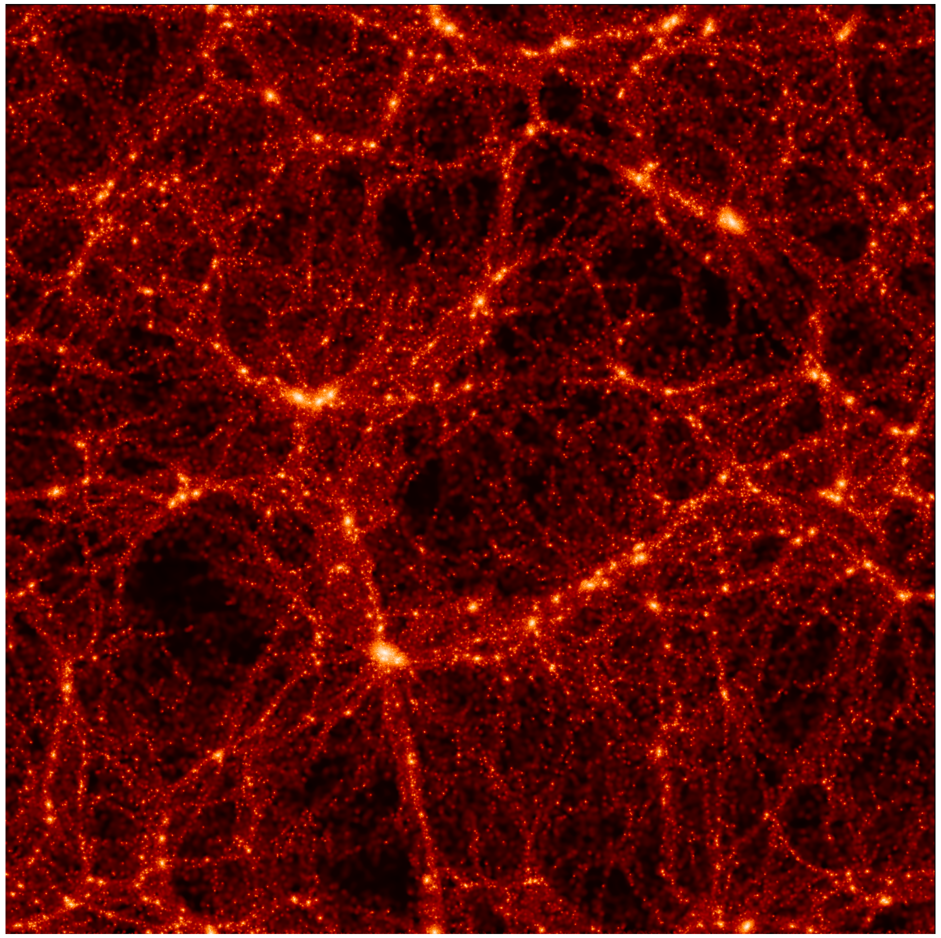
- The Universe started off as a hot gas of photons and free electrons
  - Frequent collisions so thermodynamics equilibrium
  - Photons could only move a few meters before scattering off free electrons
  - The Universe was opaque
- The gas expanded with the Universe and cooled
- Once the temperature fell below 3000 K electrons and protons formed neutral hydrogen
- With no free electrons in the Universe photons could move freely through the Universe towards us today
- The small temperature fluctuations in the photons that was present then is basically what we observe as the **cosmic microwave background**



A very rough overview of Cosmology
Gravitational collapse

- After the CMB is released the photons free streams through the Universe while ordinary matter starts to form bigger and bigger structures via gravitational collapse leading to the web of structures we see today





The cosmic web today with huge dark matter halos holding galaxy clusters, filaments and big voids

A very rough overview of Cosmology Us Today Observing the Universe

- Today we are here observing the sky and can see all kinds of structures from stars to galaxies to large galaxy clusters and the cosmic microwave background.

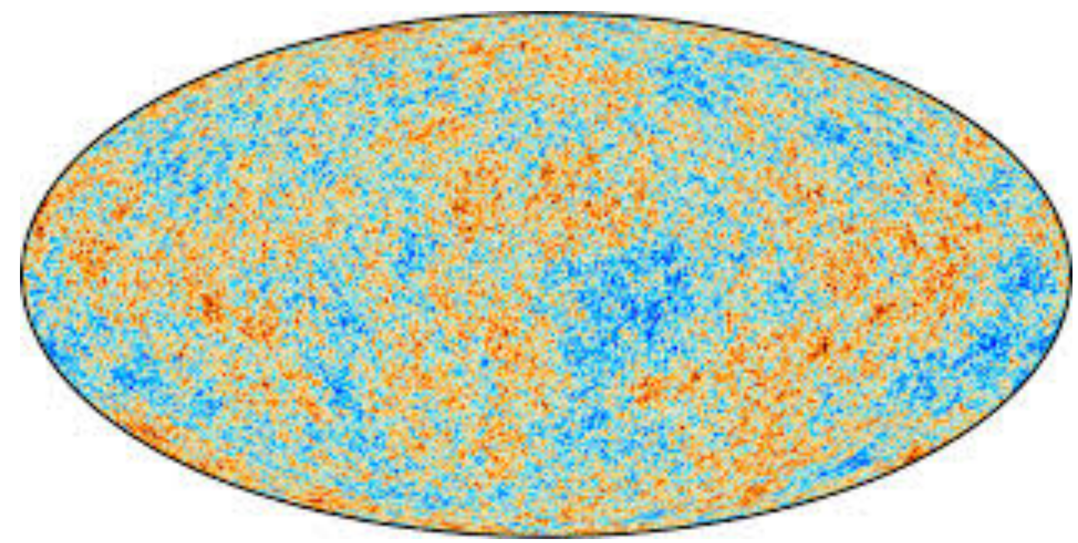
- The theory we will go through in this course will allow us to understand how the large scale structure of the Universe (smaller structures are more complicated and needs much more physics - the large is fairly simple) form.

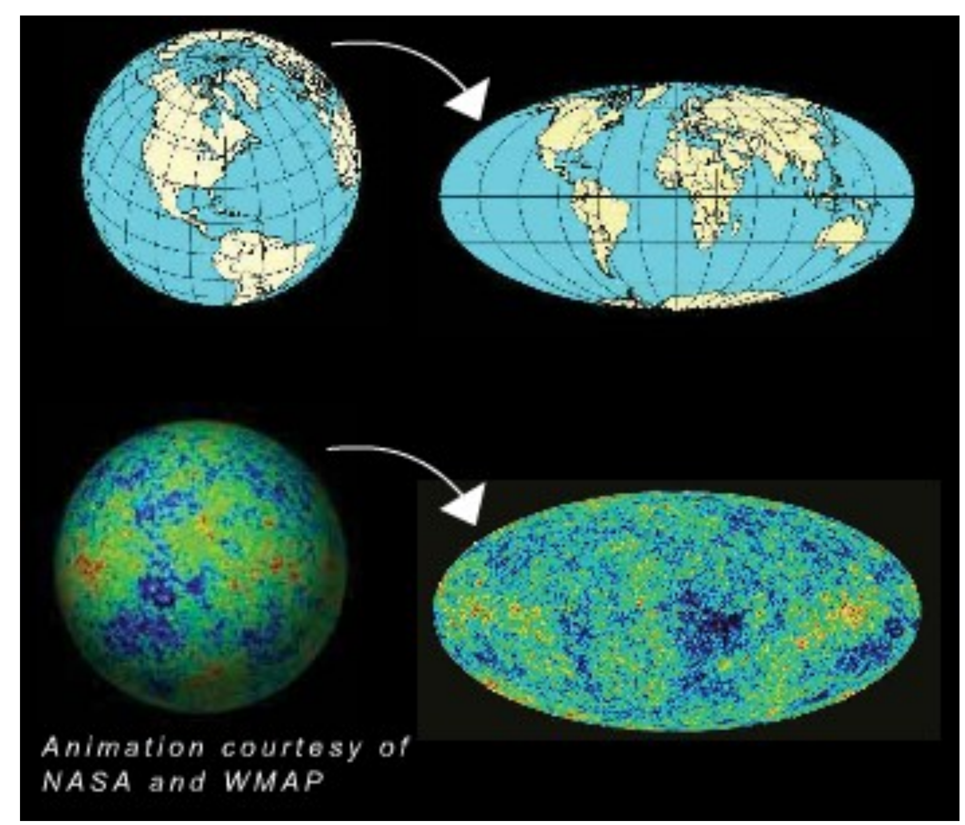
- The end boss of this course is to understand two key observables that contains most of the information: the **CMB power-spectrum** and the **matter power-spectrum** **(**for PhD students we will also go cover **neutrinos** and the **polarisation properties of the CMB)**

- We will just very briefly review these things now just so you have an idea of what we want to understand.

Temperature map of the cosmic microwave background

- A CMB telescope is really just an expensive TV antenna
- You direct the antenna in some direction, and measure a voltage
  – The higher the voltage, the stronger the incident radiation
  – The stronger the incident radiation, the hotter the CMB temperature
- You scan the sky with the antenna, and produce a map of the CMB temperature
- **<u>Result:</u>** the temperature is extremely Uniform with T = 2.7255 K in all directions. Subtracting off the mean gives us a map of small fluctuations.
- Often displayed in the Mollweide projection



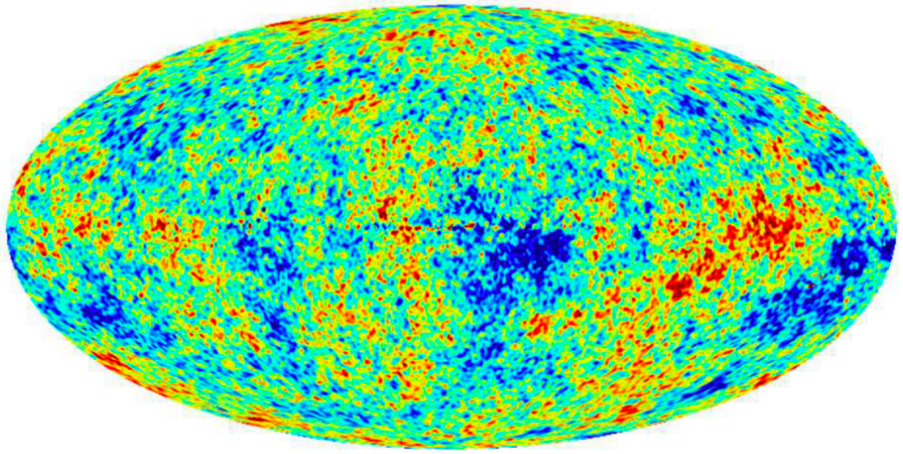


Temperature map of the cosmic microwave background

- Different physical effects affect different physical scales so it's useful to split the map into well-defined scales

- Any function on a sphere can be expanded in so-called **spherical harmonics**. This is the sphere equivalent of a **Fourier series**

$$T(\hat{n}) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$



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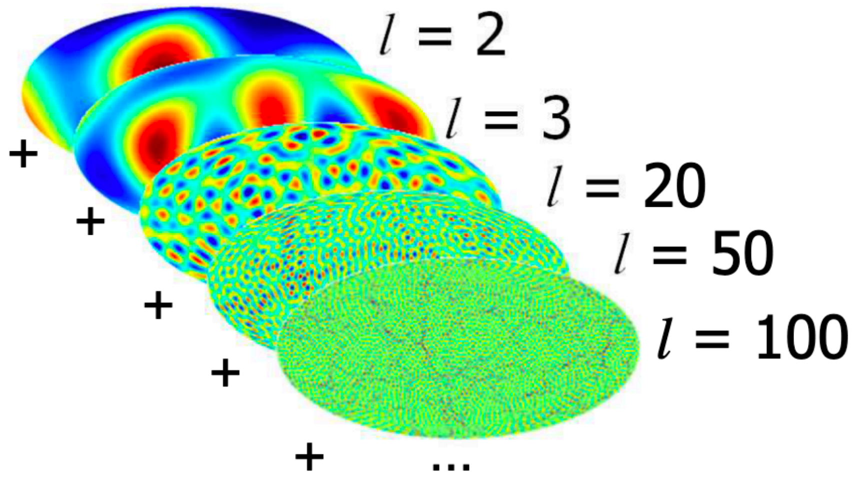


Fluctuations with angular extent theta corresponds to $\ell \sim \dfrac{180^\circ}{\theta}$

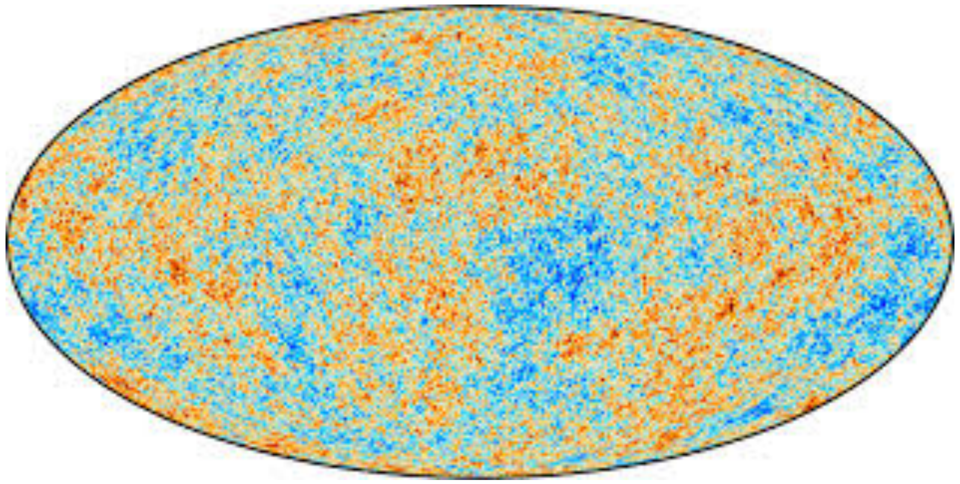
The CMB power-spectrum

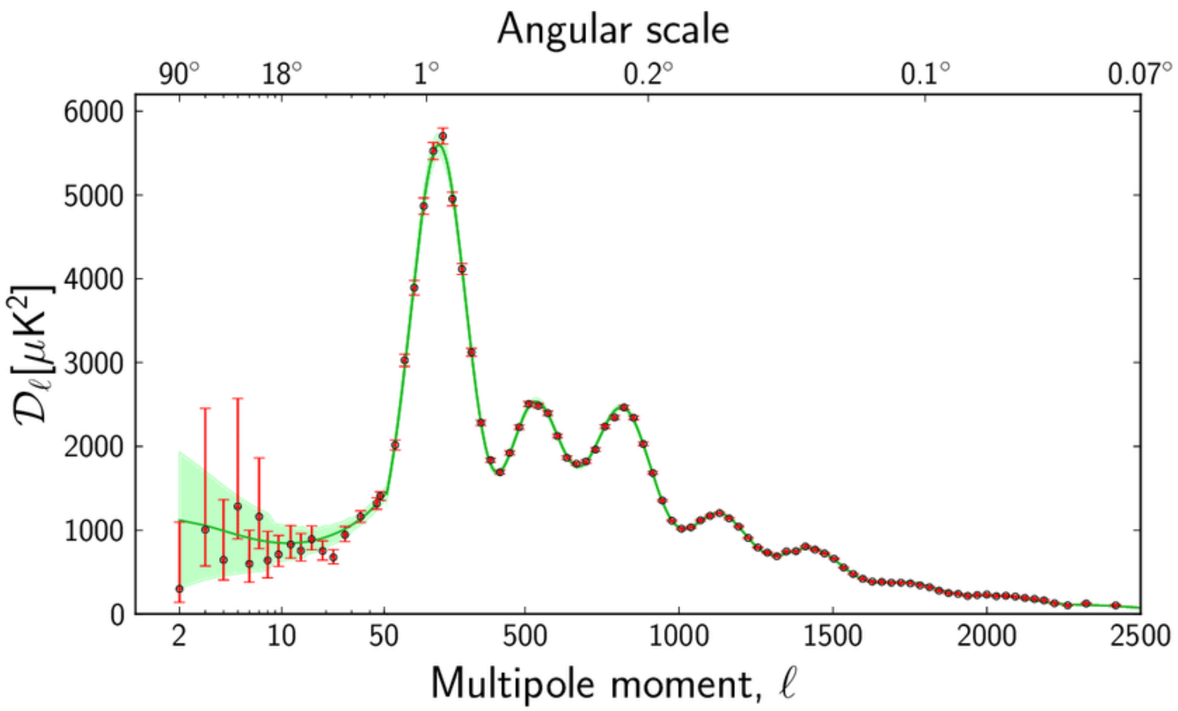
- We cannot predict exactly what the CMB temperature should be in any given direction as its generated by a stochastic process in inflation. We can only say something about correlations on different scales for which the simplest quantity is called the power-spectrum. **<u>This is what we can predict!</u>**

- **The CMB power-spectrum** is the square of the coefficients corresponding to a certain angular scale ell

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

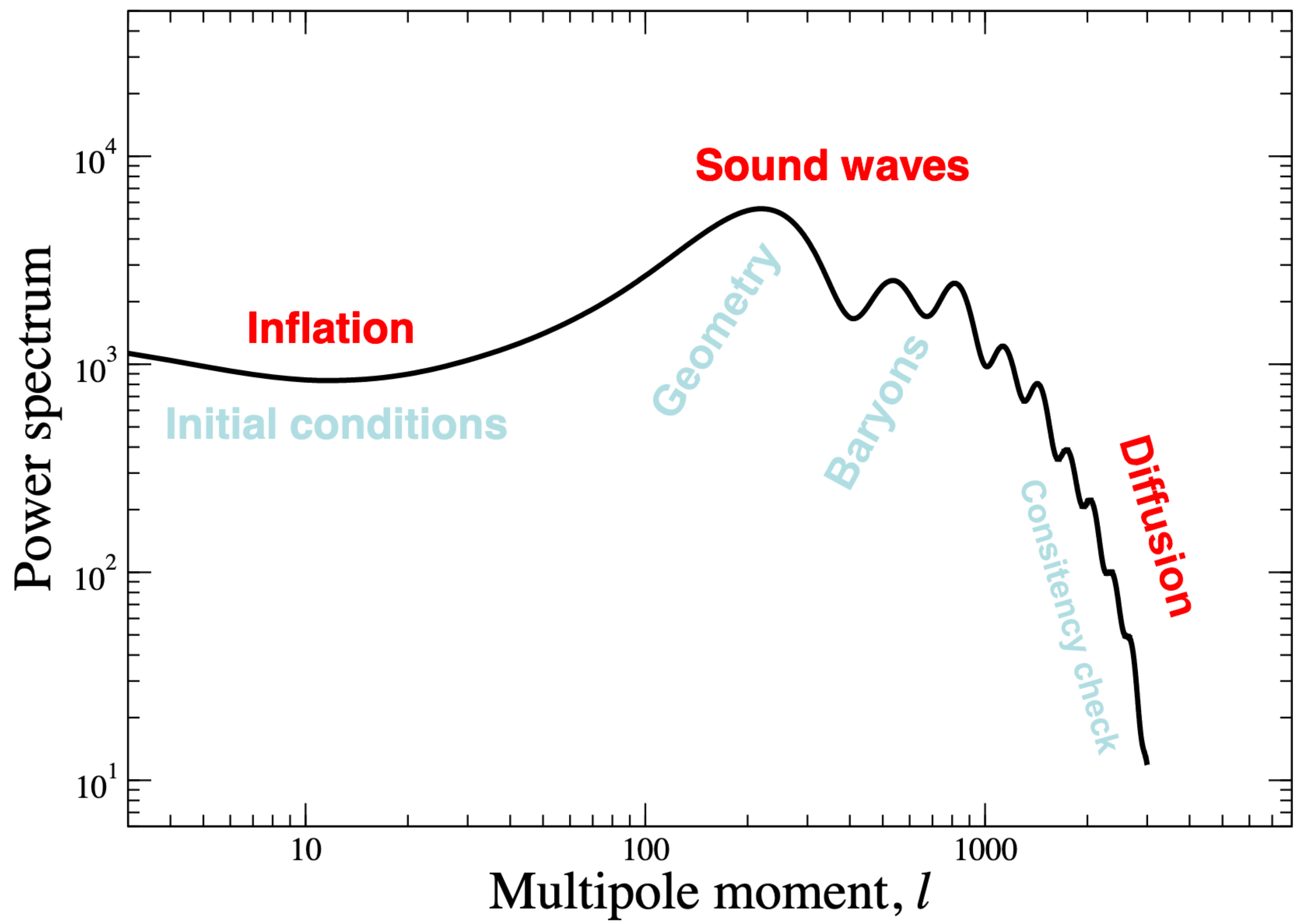
- Roughly think of this as how big the temperature fluctuations are as a function of angular scale. The peak at l ~ 200, roughly means the typical blobs in the CMB maps has a size of ~1 degree.





The CMB power-spectrum

- Different physics acts on different scales and the CMB power-spectrum can tell us a lot about the physics that takes (took) place in our Universe.
- We will learn how to compute this theoretical prediction and what comparing this to observations can teach us.
- For example where the first peak is tells us about the **geometry** of the Universe, the second and third peak about the amount of **normal matter** (baryons) to **dark matter** and much more



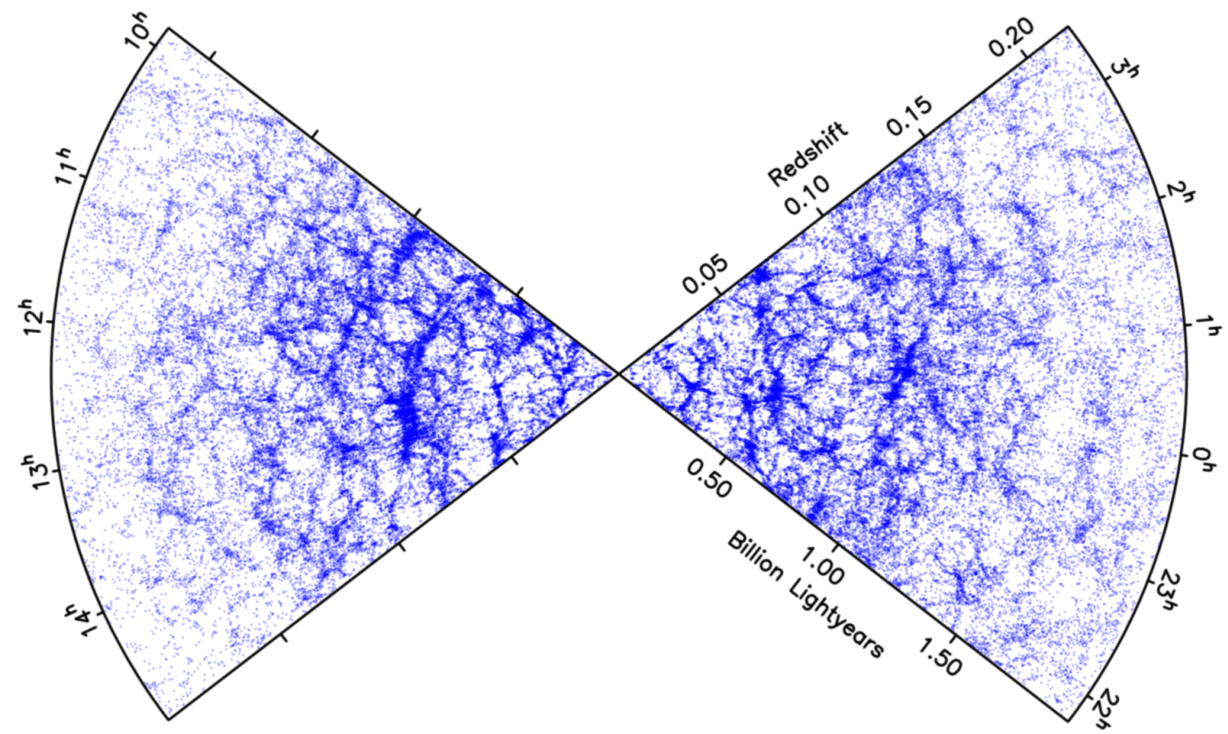
The galaxy density field

- Galaxy surveys maps out the positions of millions of galaxies across the sky

- From positions of galaxies we can compute the 3D density field.

- As for the CMB its useful to split this into well-defined scales (a **Fourier series**)

$$\rho_{\text{galaxy}}(\overrightarrow{x}) = \sum a_{\overrightarrow{k}} e^{i\overrightarrow{k}\cdot\overrightarrow{x}}$$



A 2D representation of the 3D galaxy field from a galaxy survey

The matter power-spectrum

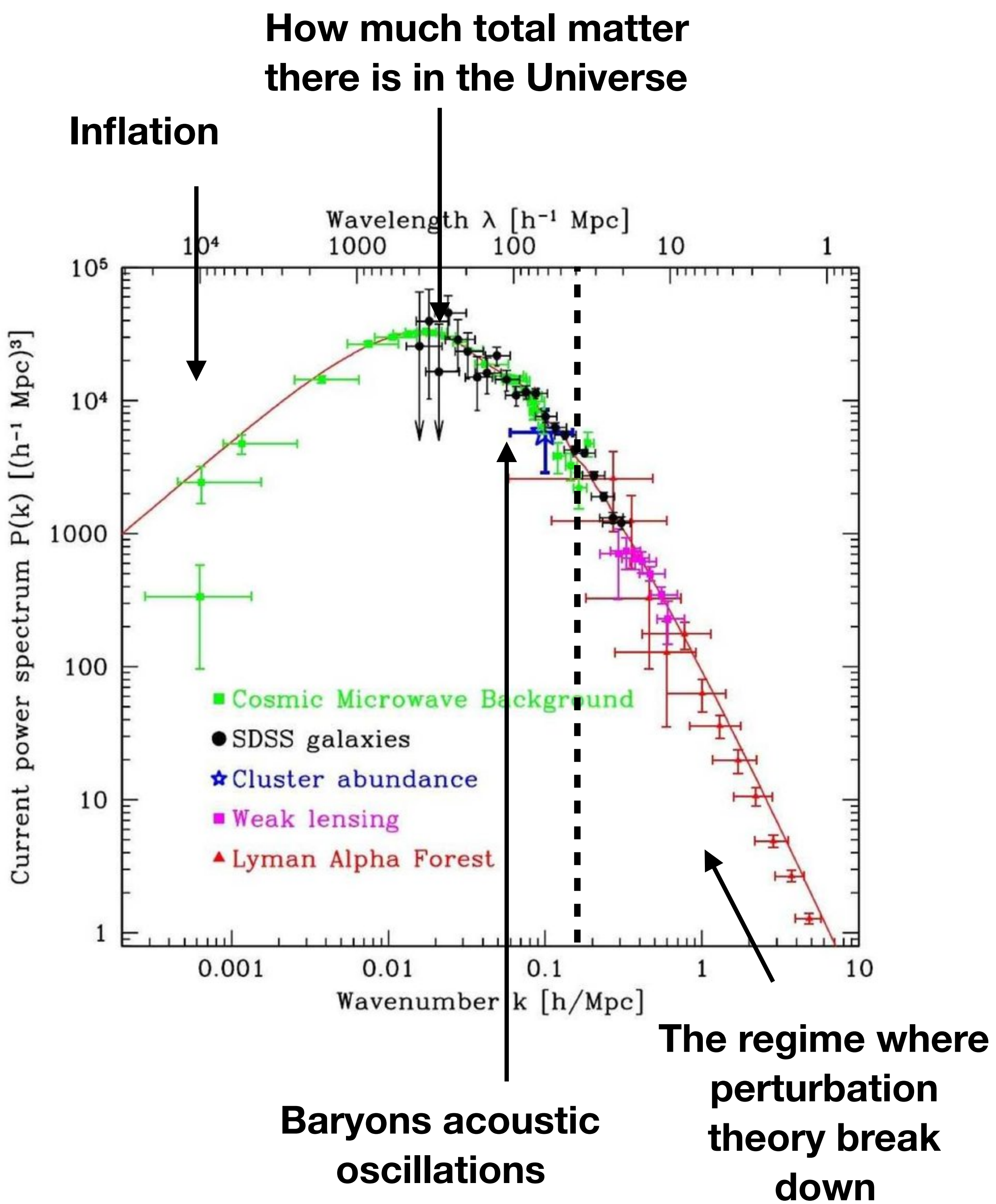
- Again we cannot predict where a galaxy should form, but we can predict the **statistical properties** (correlations of clustering on different scales) the simplest of which is the **matter power-spectrum**

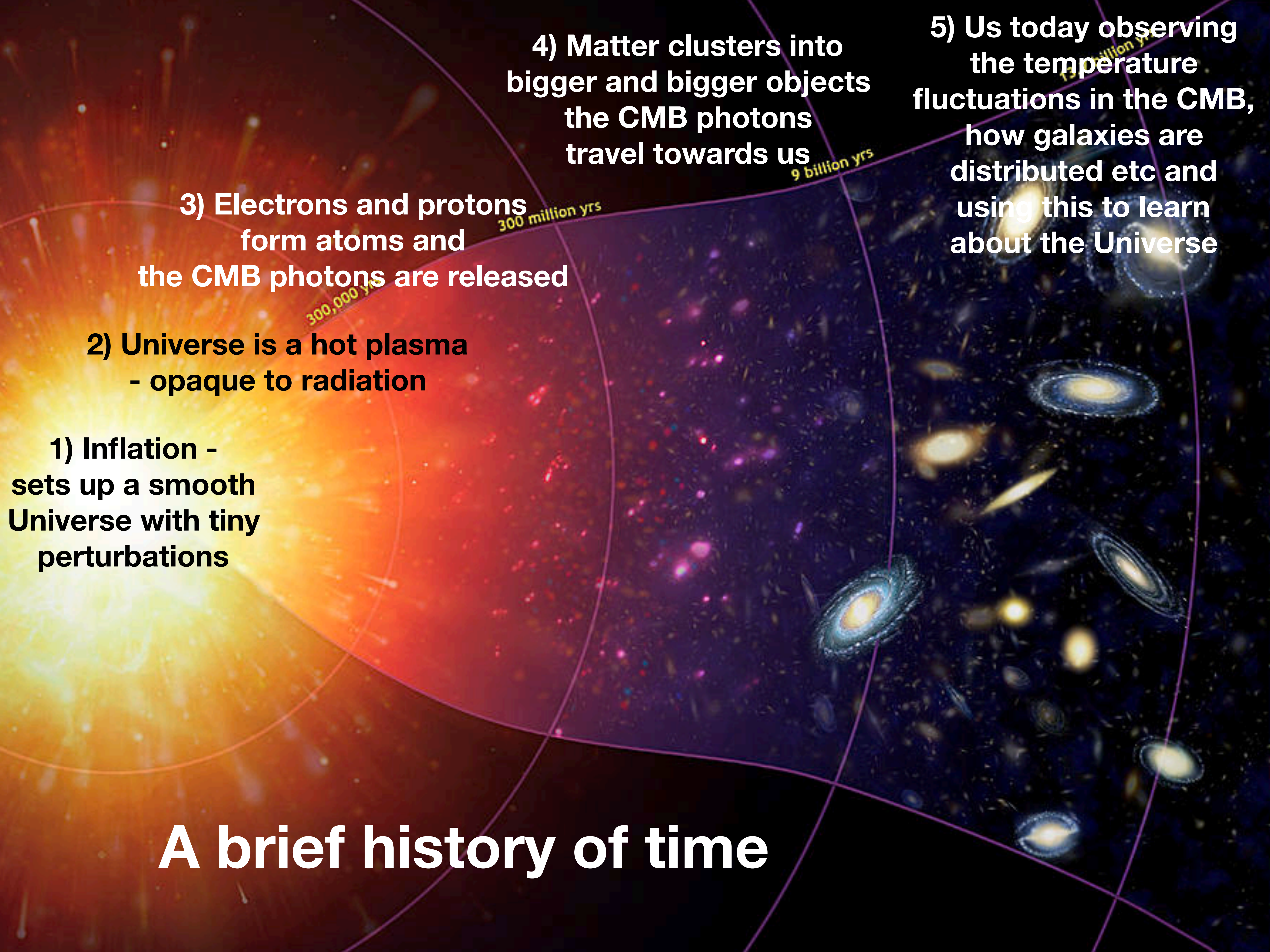
- The matter power-spectrum is the square of the Fourier coefficients

$$P(k) = \sum_{|\vec{k}|=k} |a_{\vec{k}}|^2$$

- It roughly tells us how much galaxies are clustered as a function of scale

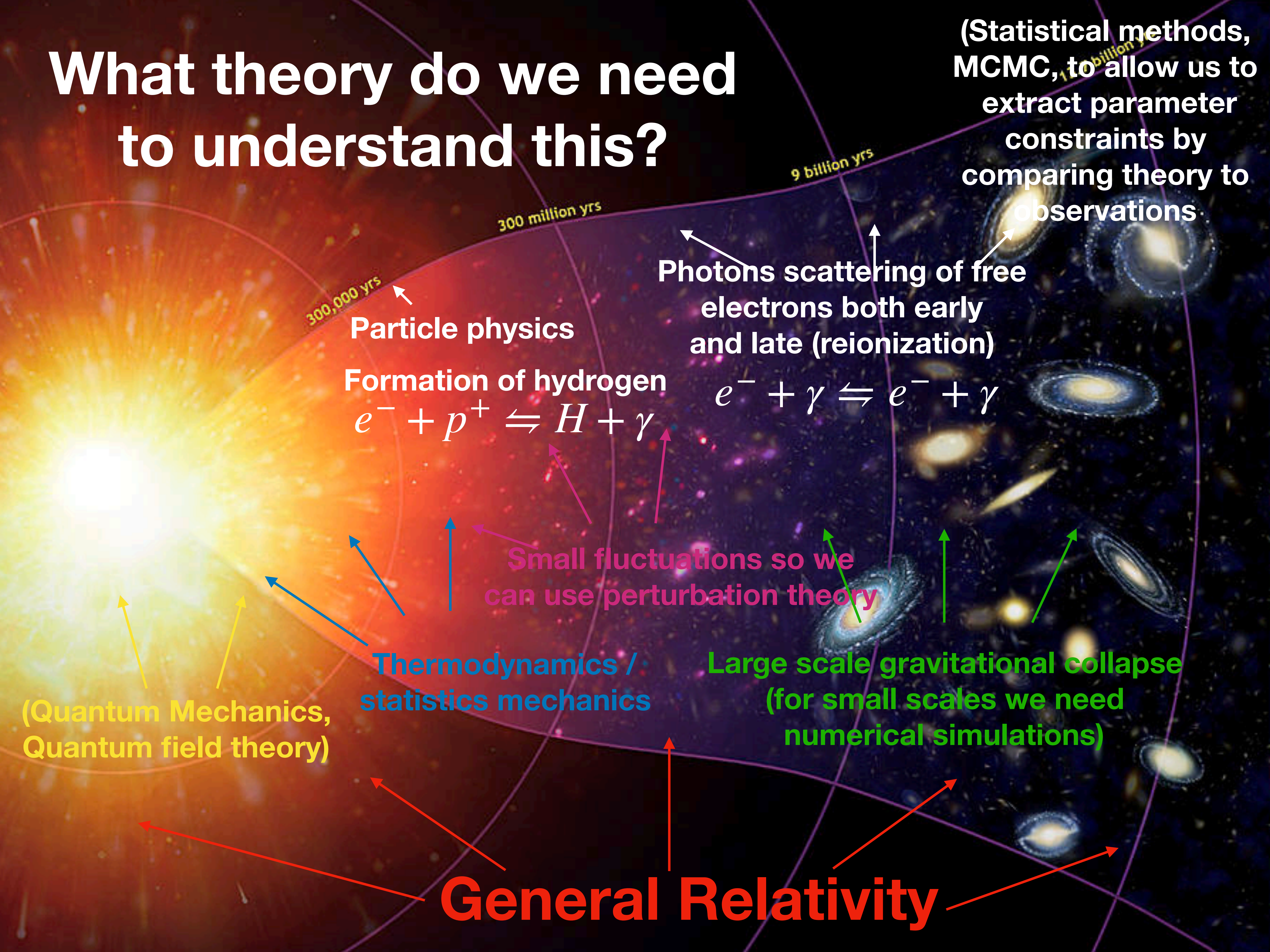
- We will in this course learn how to compute this theoretical prediction and what comparing this to observations can teach us about our Universe.





A brief history of time
1) Inflation - sets up a smooth Universe with tiny perturbations
2) Universe is a hot plasma - opaque to radiation
3) Electrons and protons form atoms and the CMB photons are released
4) Matter clusters into bigger and bigger objects the CMB photons travel towards us
5) Us today observing the temperature fluctuations in the CMB, how galaxies are distributed etc and using this to learn about the Universe
300,000 yrs
300 million yrs
9 billion yrs

What theory do we need to understand this?



(Statistical methods, MCMC, to allow us to extract parameter constraints by comparing theory to observations

Particle physics

Photons scattering of free electrons both early and late (reionization)

$$e^- + \gamma \leftrightharpoons e^- + \gamma$$

Formation of hydrogen

$$e^- + p^+ \leftrightharpoons H + \gamma$$

Small fluctuations so we can use perturbation theory

Thermodynamics / statistics mechanics

Large scale gravitational collapse (for small scales we need numerical simulations)

(Quantum Mechanics, Quantum field theory)

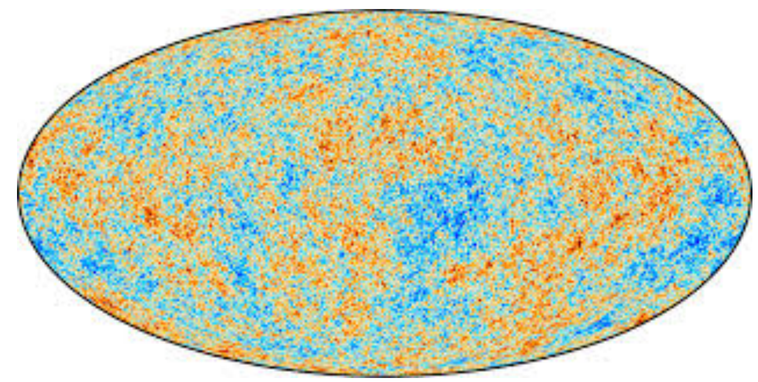
General Relativity

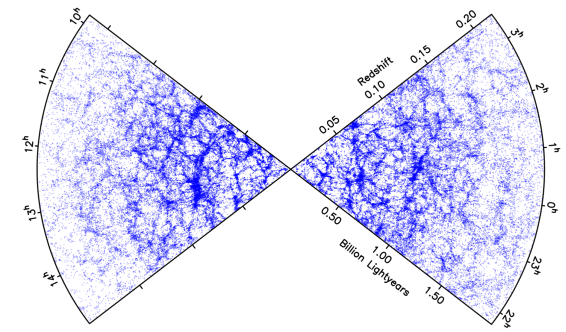
The Project

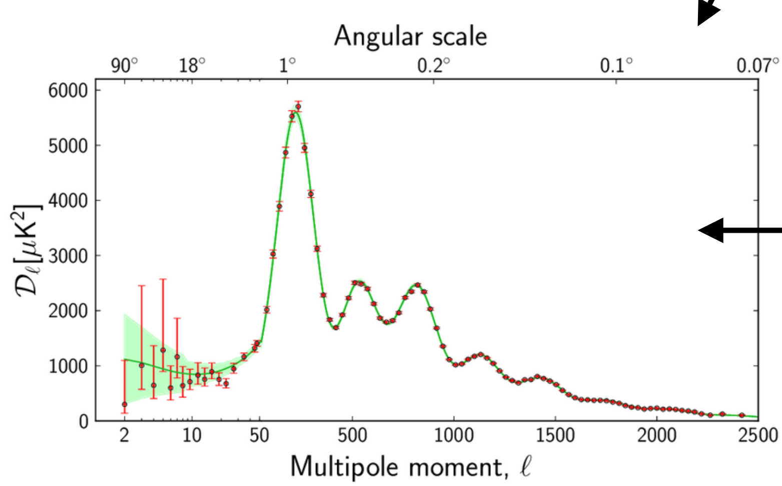
- **<u>Aim:</u>** to produce a code to go from cosmological parameters to theoretical predictions that can be compared to actual observables.

- However computing the observables is only one part. We also want to **<u>understand</u>** the results based on the **<u>physics</u>** we know is taking place. This will be just as important.

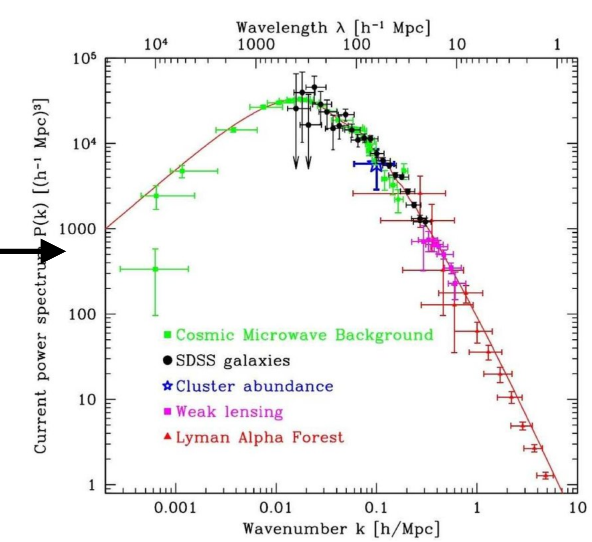
Observations







Theory
(your code)



Statistical observables from observations compared to theoretical predictions

The Project

- In the lectures we go through the theory - and the physics needed to understand the results - and derive the equations we will implement and solve numerically.
- Project divided into four milestones that we need to reach the end goal: how to compute key statistical observables in cosmology related to formation of structures like the **CMB angular power-spectrum** and the **matter power-spectrum** that can be compared to actual observations.
- You will implement these equations, run the code, produce results and write it up.
- New this year is that the report will be written up as an **actual research paper** using the LaTeX template for the Astronomy & Astrophysics journal (available on the website) so you get experience with writing a proper paper.
- You hand in every milestone and gets feedback after each one, but the final result will be one big paper. We will get back to how this works later on.
- **Free choice** of programming language, but we mainly provide templates and help for C++. **Strongly recommended** you use this. Fortran templates from past years and Python templates are also available if you absolutely insist on using these languages, but then you are mostly on your own.
- Master students can ignore helium in recombination and neutrinos altogether. PhD students must include this and also compute the prediction for the polarisation of the CMB. This is the main difference between AST5220 and AST9420

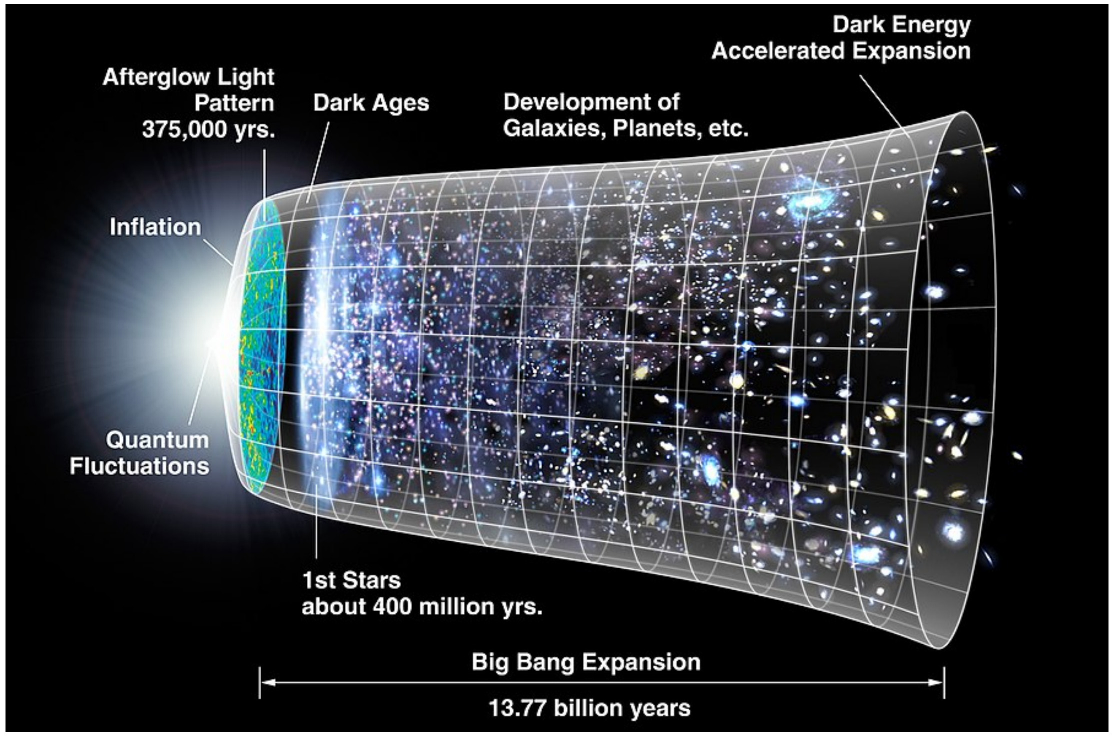
Milestone I: Background Cosmology

- Covers what you need to understand how the Universe as a whole (a smooth Universe) evolves.

- We will start by giving you the basic operational knowledge of working with **General Relativity** in cosmology. What is a **tensor**, the **metric**, **curvature** and how do we evaluate **Einstein's equations?**

- We will then go through the basics of background cosmology: redshifts, distances, times, density parameters, how different energy forms evolve and derive the **Friedmann equations** (so Cosmology I, but derived from scratch).

- **Project:** implement the Friedmann equations and compute the conformal time and the age of the Universe. A minor task to get you familiar with the code, how to solve differential equations and write the report.



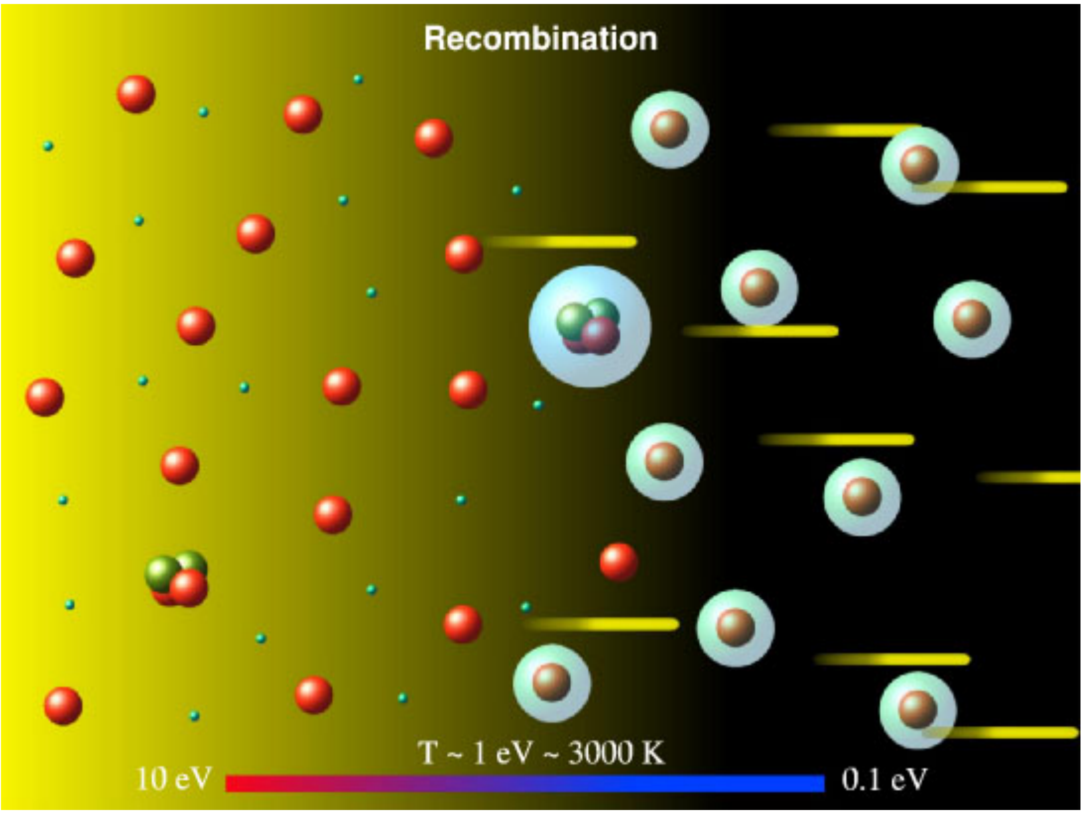
Milestone II: Recombination History

- Covers what you need to know about **statistical mechanics** and **thermodynamics** (in and our of equilibrium) in an expanding Universe.

- We will review some basic equilibrium thermodynamics and introduce the **Boltzmann formalism** allowing us to go beyond equilibrium and deal with all the different matter species and the interactions between them as dictated by quantum field theory.

- We will then go through the thermal history of the Universe leading up to the key event for us which is when electrons and protons formed atoms and the cosmic microwave background was released.

- **Project:** solve the Boltzmann equation for electrons and atoms (hydrogen and helium) which will give us the number density of free electrons and atoms as function of time. This will tell us when the CMB was released and the quantities we compute (optical depth) will play an important role in the next milestones.



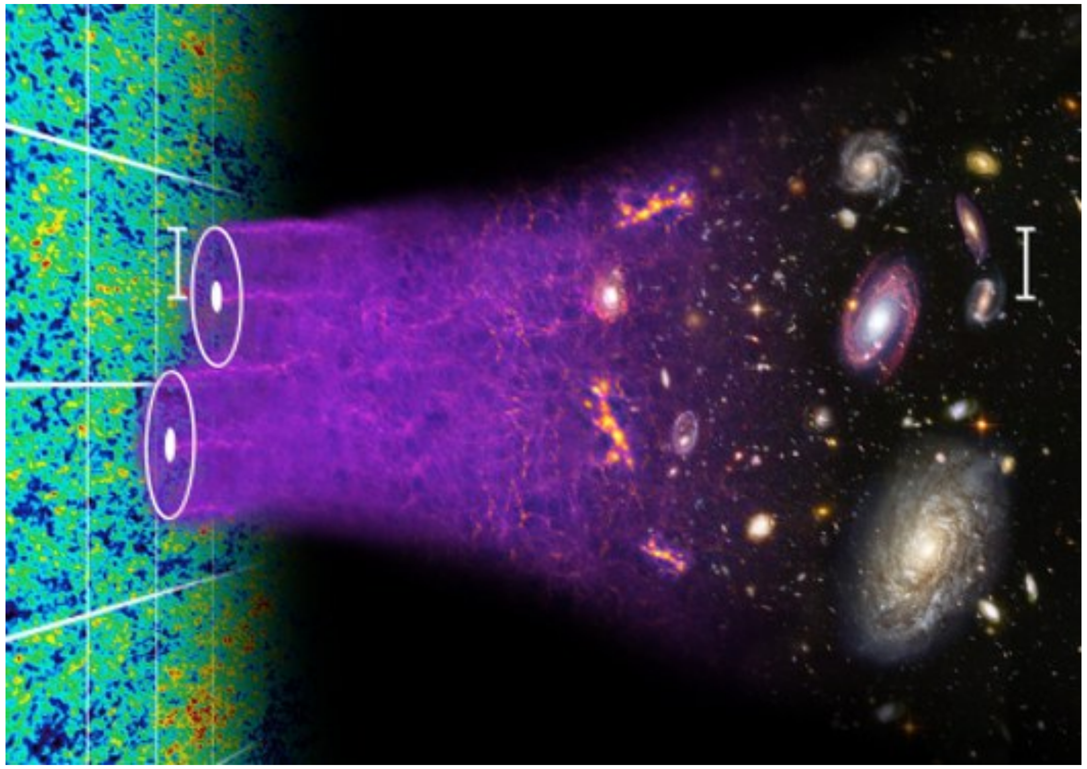
Milestone III:
Evolution of structures in the Universe

- We finally go beyond the smooth Universe and introduce **perturbations** to both the metric and the matter species.

- We will compute the evolution equations - the **Einstein-Boltzmann equations** - for all species (**baryons**, **dark matter**, **photons**, **massless neutrinos**) and the metric (**gravitational potentials**) including relevant interactions between the different species based on known physics.

- We will also give a brief introduction to inflation and its key predictions which is what will give us the **initial conditions** for our equations.

- **Project:** we will solve this system of ~20 coupled differential equations describing perturbations of baryon and dark matter density and velocity, photon temperature perturbations and metric perturbations from the early Universe till today.



Milestone IV:
The CMB and matter power-spectra

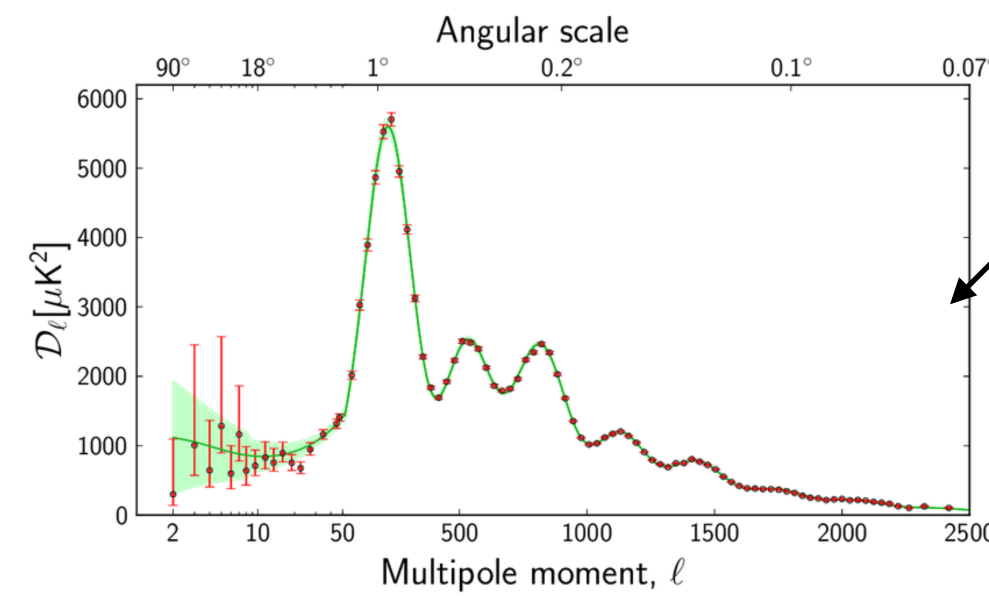
- We will go through how to connect the perturbations we have computed to the key statistical observables: the **CMB power-spectrum** and the **matter power-spectrum**.

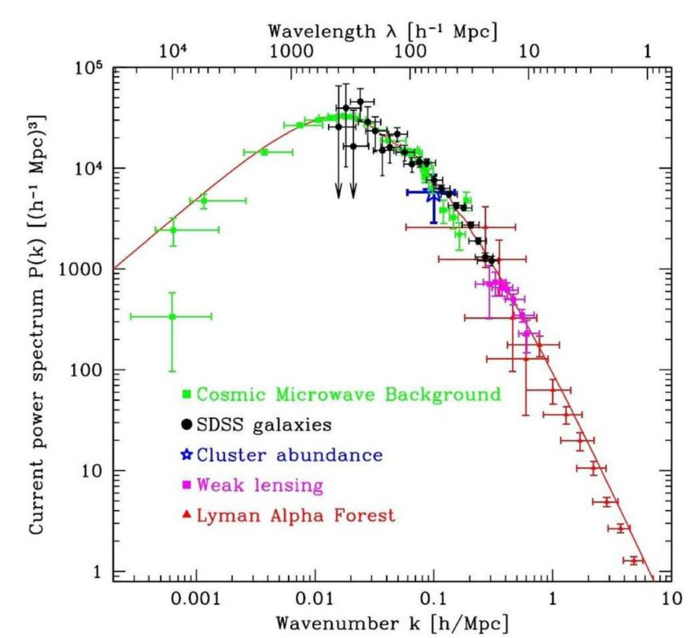
- We will go through a key technique, line of sight integration, for computing and also understanding the CMB spectrum and we will try to understand the features in the spectra and how they change with varying cosmological parameters.

- **Project:** we will put all the pieces together from the previous milestones (we do a few integrals based on stuff we already have computed) and compute the theoretical predictions for the CMB angular power-spectrum and the matter power-spectrum and **compare these with real observations**.

Cosmological parameters

$$\{\Omega_b, \Omega_{\rm CDM}, \Omega_\Lambda, h, T_{\rm CMB}, N_{\rm eff}, A_s, n_s\}$$





Due dates for the project

- Tentative due dates for the project this year (check website for any changes):
- Milestone I: **Deliver by 19. February 2021**
- Milestone II: **Deliver by 19. March 2021**
- Milestone III: **Deliver by 23. April 2021**
- Milestone IV: **Deliver by 28. May 2021**
- **Ask me for help** if you are stuck - don’t wait till the last minute - and we will try to sort it out together. And help each other if you can, just don’t copy. You guys are not good enough to cheat well so I will spot it and its too much of a hassle for me having to deal with reporting that so for my sake please don’t.
- Extensions are given in special circumstances. A few days is often fine, but longer extensions are more problematic as it might put you behind schedule. But if you see you will have trouble making a deadline please get in touch as soon as possible and we will sort something out. It usually works out!

How to study this course?

- A big part of this course is the project. That is a lot of work and most people focus mainly on that. Doing this (mainly writing up the report and trying to understand the results) will help you understand the material better.
- However this only accounts for 30% of the grade. To succeed in the final exam you will have to study a lot yourself to make sure you understand all the theory we cover in the lectures.
- The main focus in the exam will be to test if you have the basic theoretical knowledge and are able to do simple calculations and most importantly to get the physical understanding of the results we derive.
- To help with this I will give some problem sets every week if you are interested in that. There are also problems in Dodelson (end of each chapter) and in Baumann. We won't have time to go through most of these problems in class, but if interest we will do some problem sessions now and then.
- If you want any changes to how we do the teaching you have to let me know. We are not that many this year so it's much easier to change things up.

Questions?
Suggestions?
Requests?
Thoughts?

Next lecture: "**A Crash Course in General Relativity**" …or "**How to teach you how to work with the most complicated and beautiful theory we have in just 3 hours**" (it will be fine)