Evolution of Cosmic Structure
Lecture 1: Overview of cosmic structure

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Key features

No definitive textbook – slides, notes, lectures.

Introduction to Cosmology by Ryden may be useful for the first several lectures
Galaxies in the Universe by Sparke and Gallagher may be useful for the later part of the course.

Many other galaxy formation textbooks at various levels.
Introduction to galaxy formation and evolution by Cimatti, Fraternali and Nipoti
Galaxy formation and evolution by Mo, van den Bosch and White

Year 3: The course will be assessed 80% by the final exam and 20% by assignments.
Year 4: The course will be assessed 100% by the final exam.

Exam is in-person closed book.

Science and philosophy

Cosmology and galaxy formation have consistent framework that will be the focus of the course. But there are many unknown questions. The framework may be wrong. We have many biases.

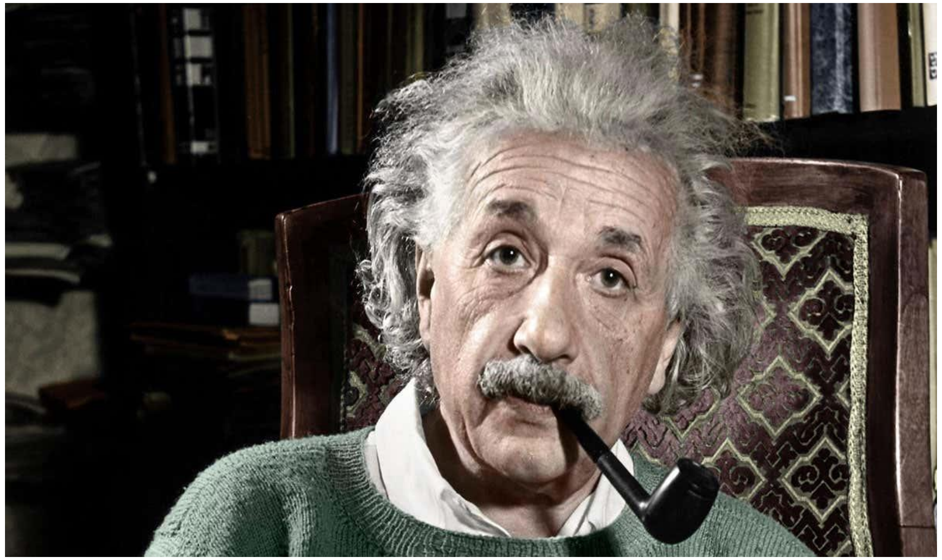
"It's very difficult to find a black cat in a dark room. Especially when there is no cat."

Beware of the limits of data

Beware of accepting 'received truths'

Beware of confirmation bias

Don't destroy creativity with knowledge



Most stars are found in galaxies

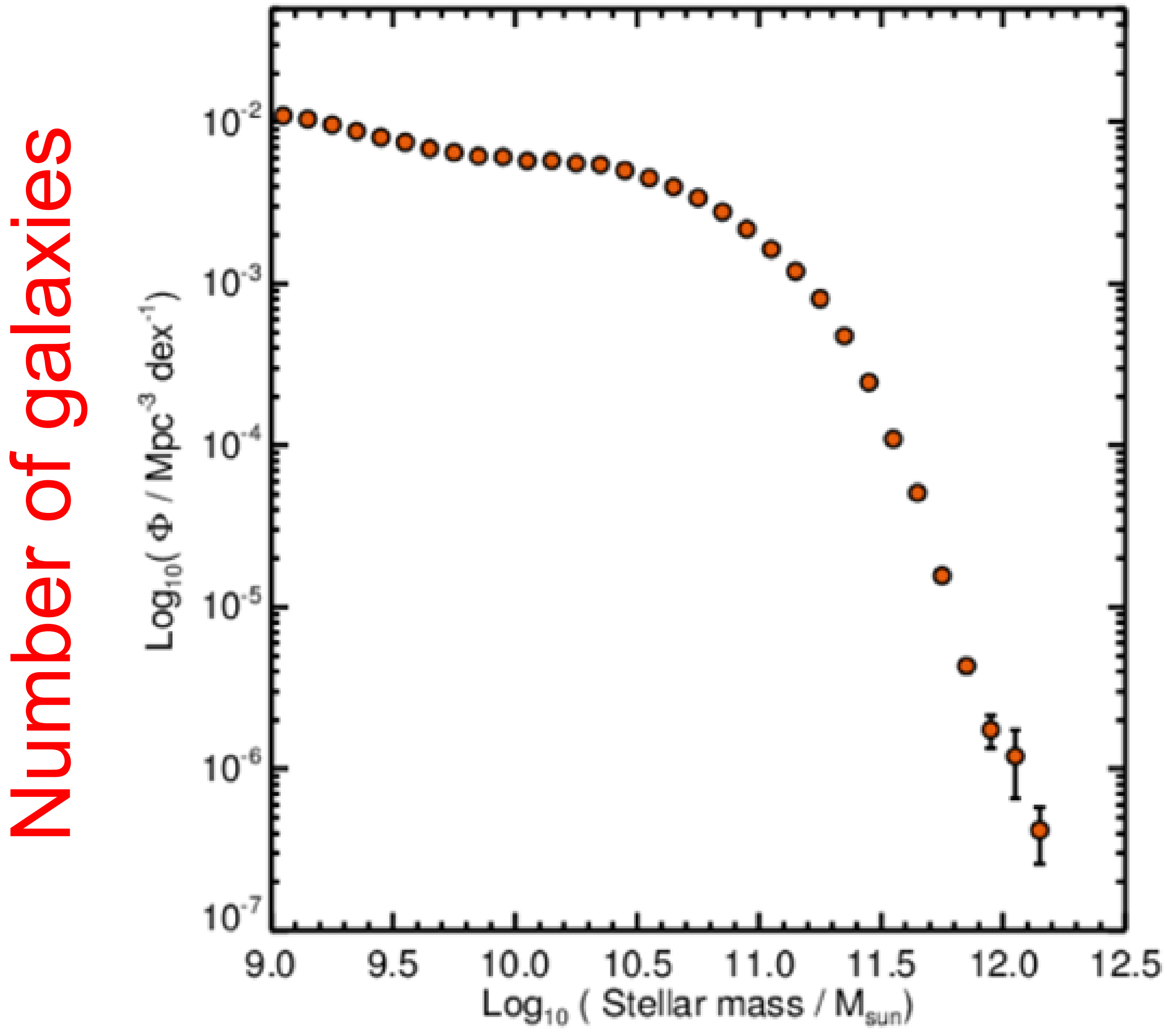
Galaxies can be diverse in structure

Milky Way (NGC 6744)

Large
Magellanic Cloud

M87

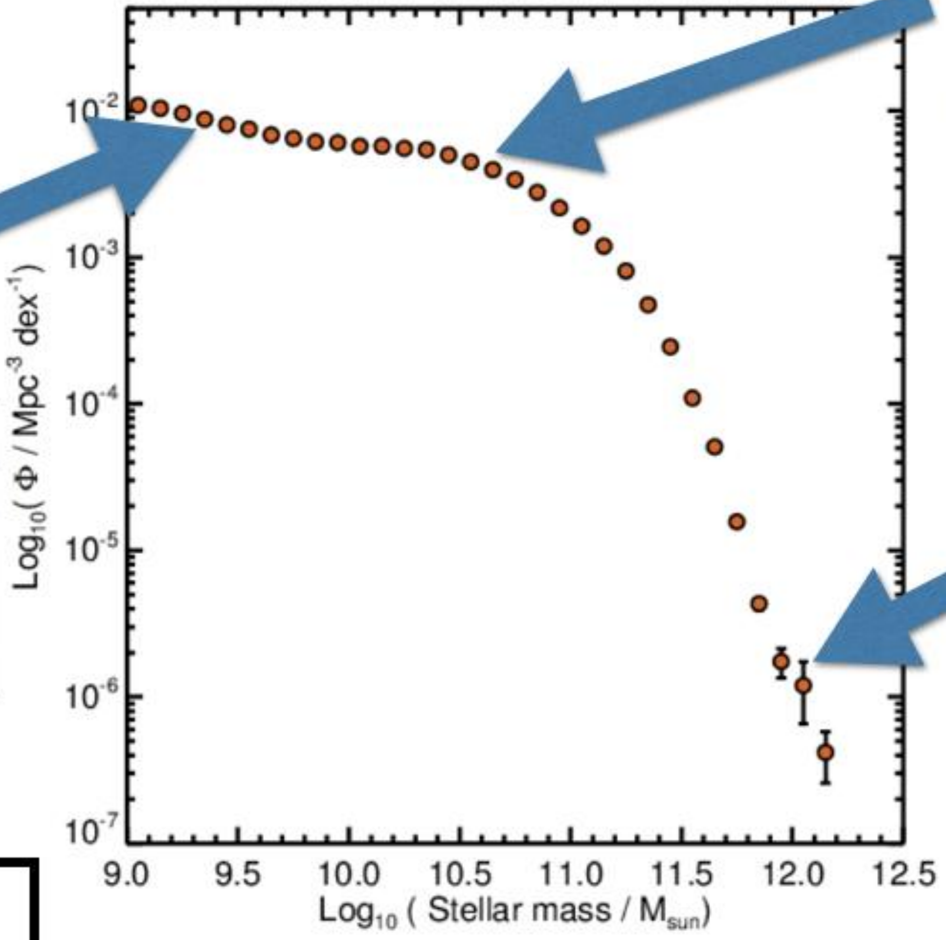
How are they distributed in mass ?



(McGee et al. 2014a) Total galaxy mass

Milky Way (NGC 6744)

Large
Magellanic Cloud



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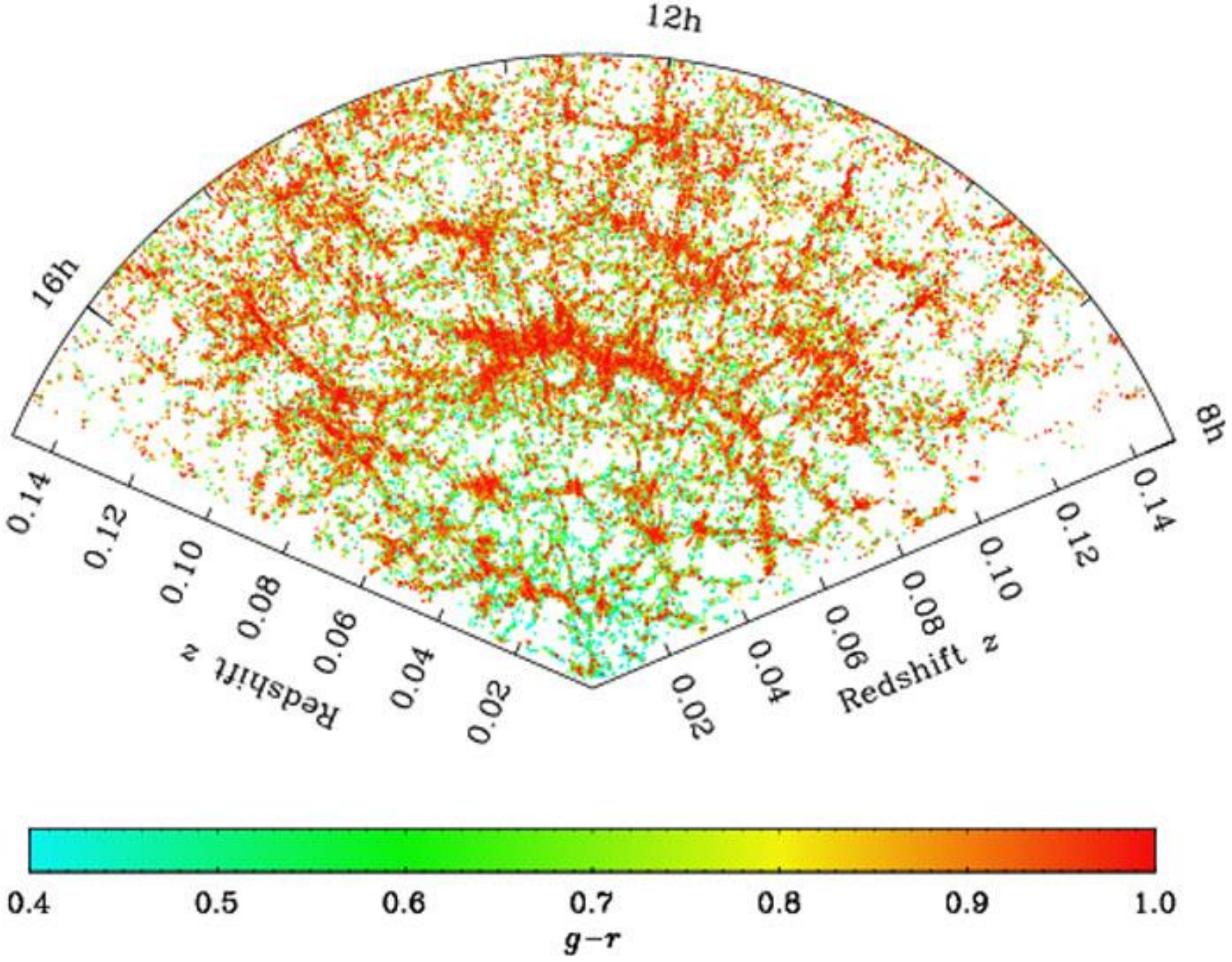
How can we understand this distribution?

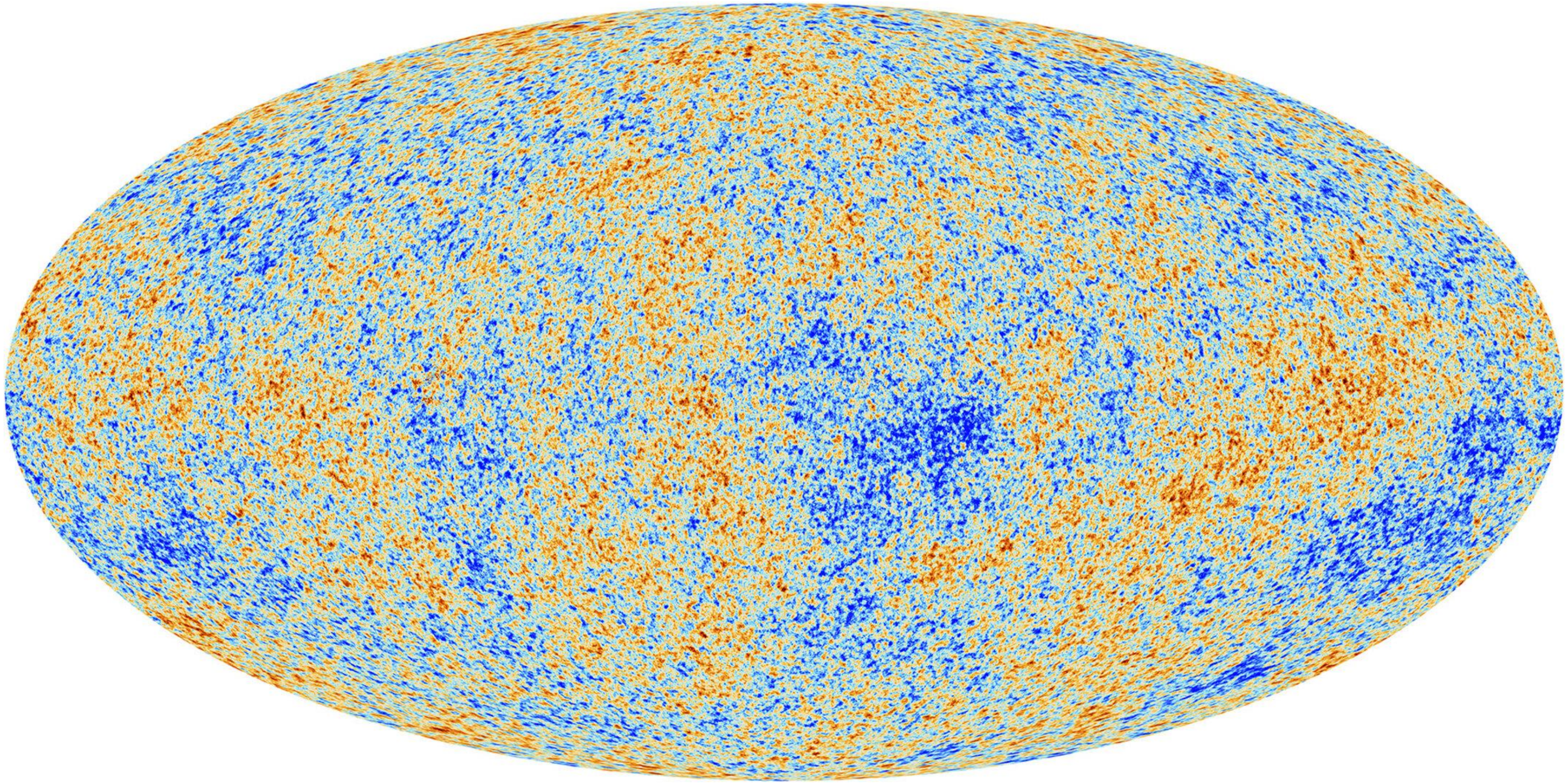
(McGee et al. 2014a)

Galaxies are not randomly scattered

Vast large-scale structure from redshift surveys

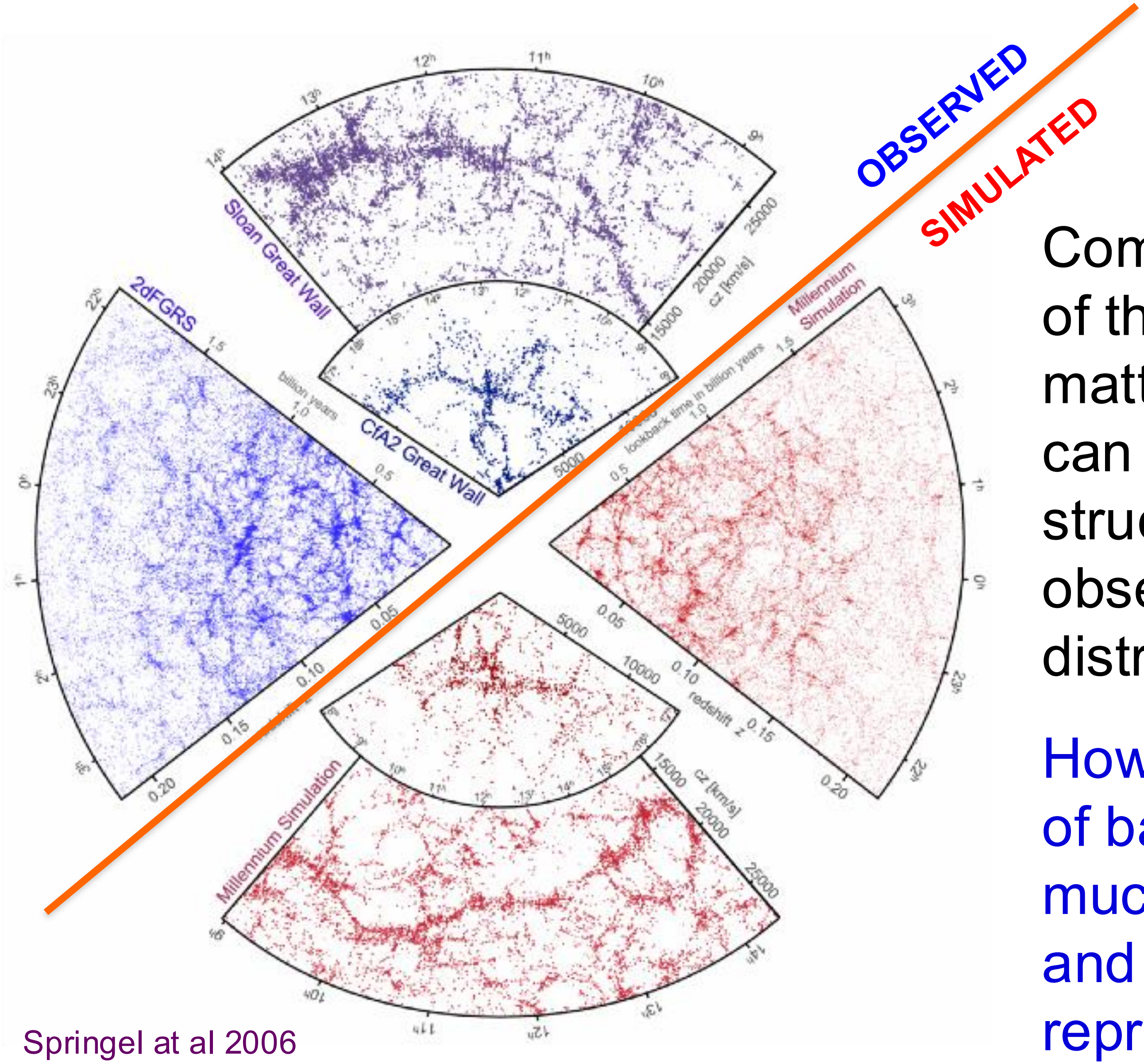


The earliest structure in the Universe



Cosmic microwave background fluctuations from WMAP, originating from $z \sim 1000$. Fractional amplitude is only $\sim 10^{-5}$.
For comparison, a galaxy has a density $>10^{7}$ times the universal mean.

The evolution of structure

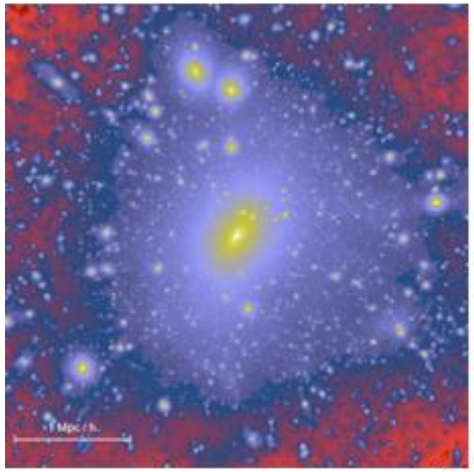


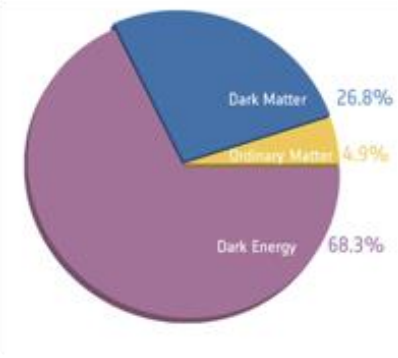
Computer simulations of the clumping of dark matter under gravity can produce large scale structure similar to that observed in the galaxy distribution

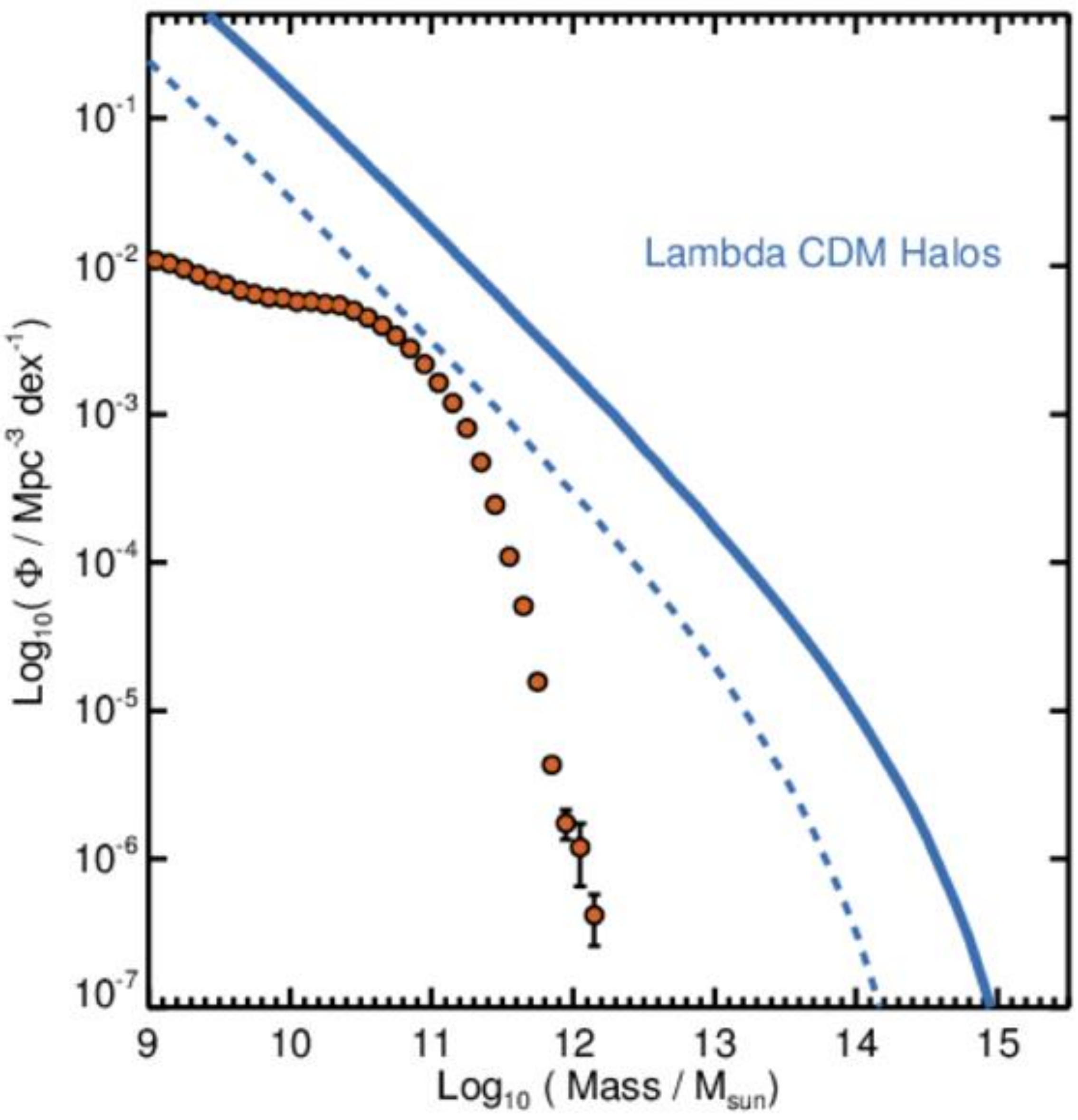
However, the behaviour of baryonic matter is much more complex and challenging to reproduce.

Springel at al 2006

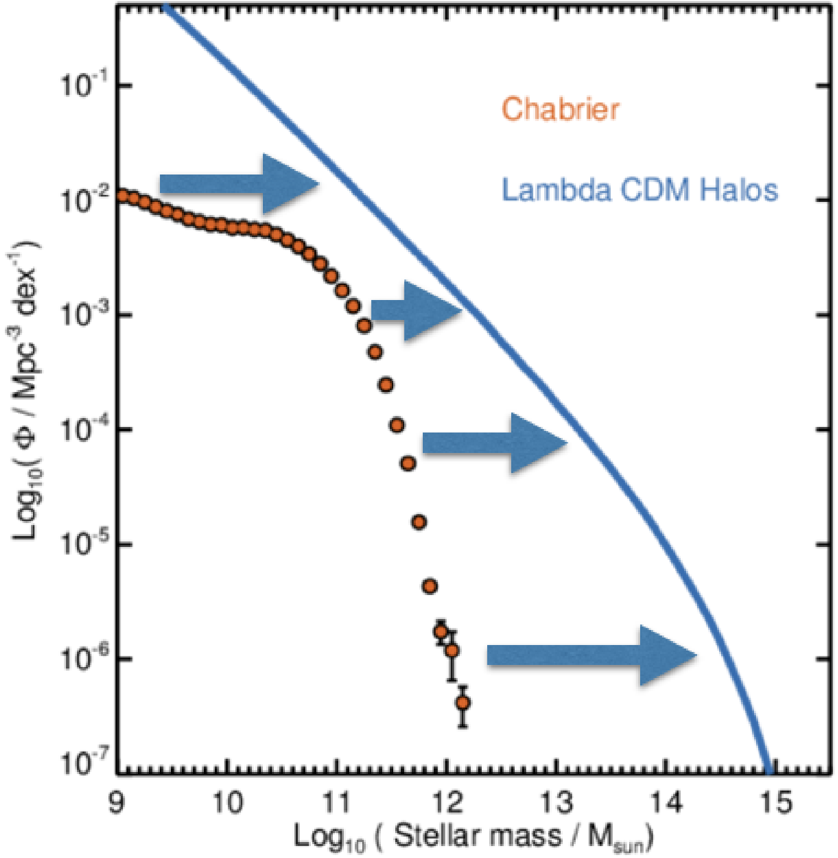
How much stellar mass in halos?

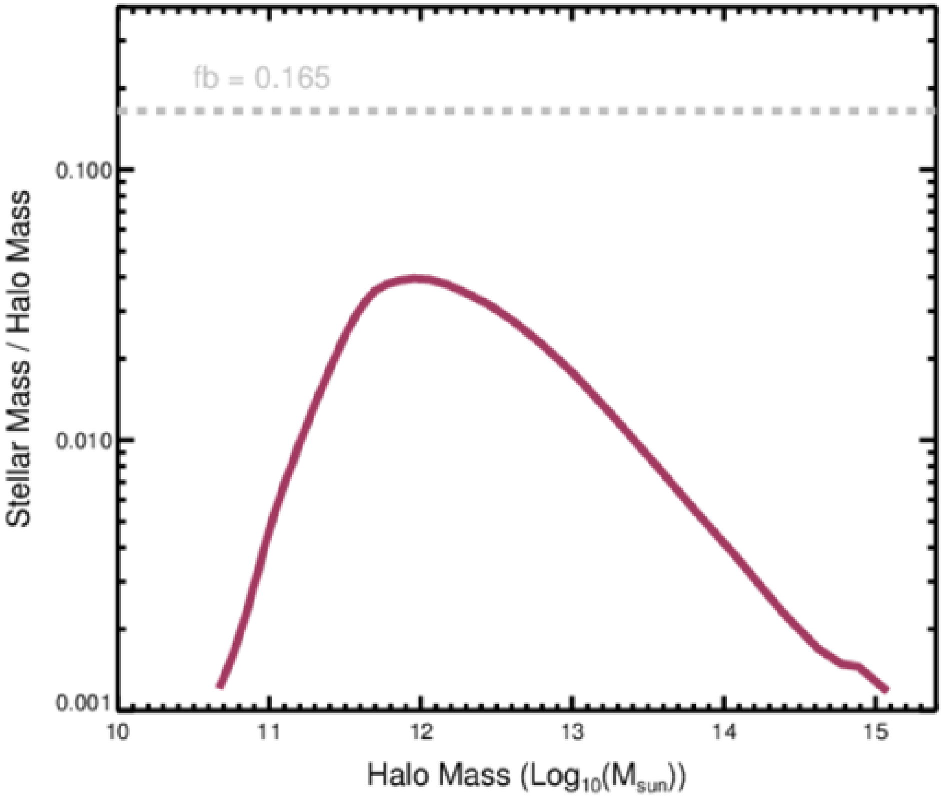






(McGee et al. 2014a)





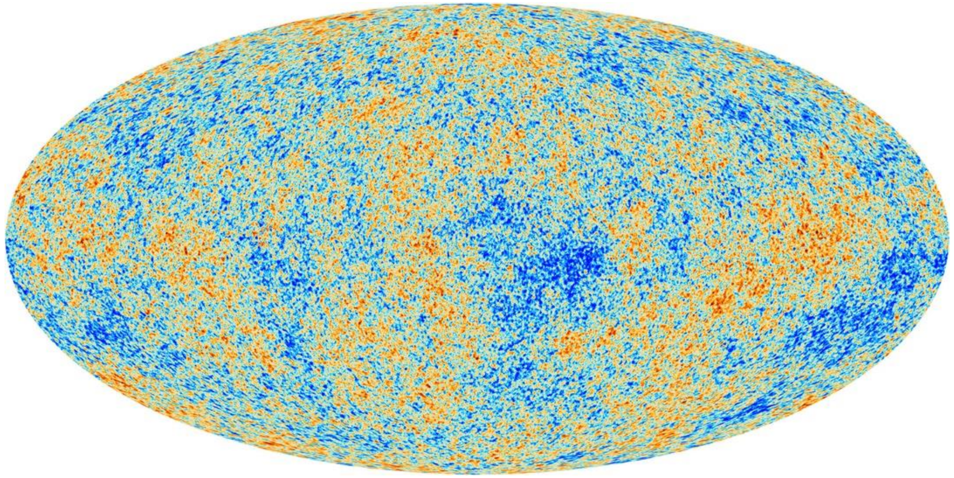
(McGee et al. 2014a)

M_*/M_{halo} *maximises* at 3.5% at halo masses of $\sim 10^{12} M_\odot$

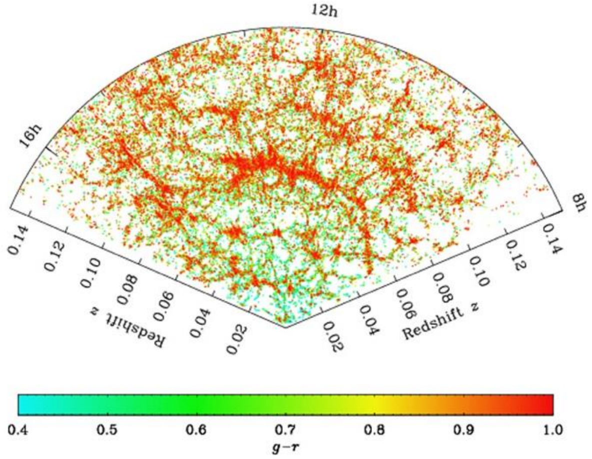
This is *much* less than the global baryon fraction ~ 17%

Conversion of halo baryons to stars has maximum efficiency ~20 to 30% and is much smaller at higher and lower halo mass

How do we get from the CMB to chairs (or galaxies)



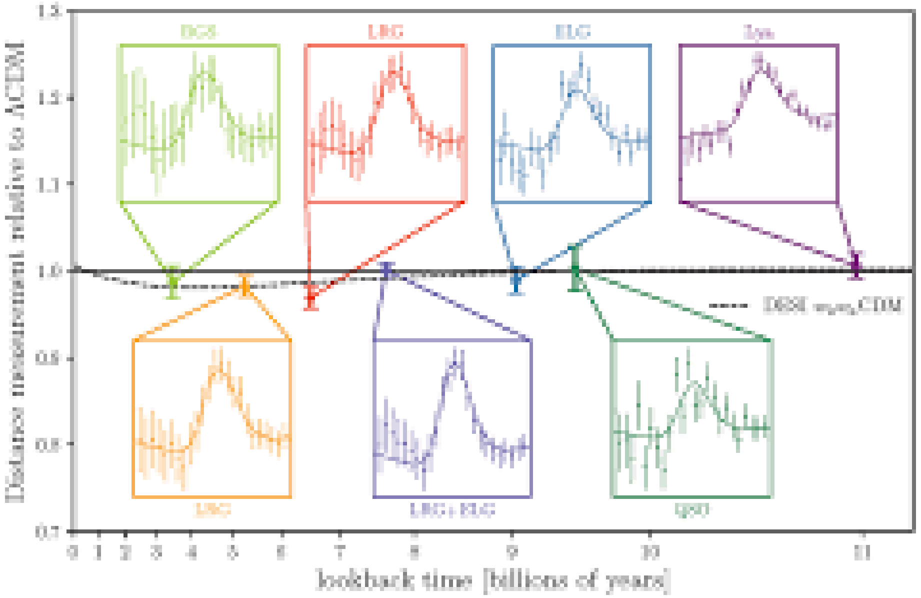
This module
happens here



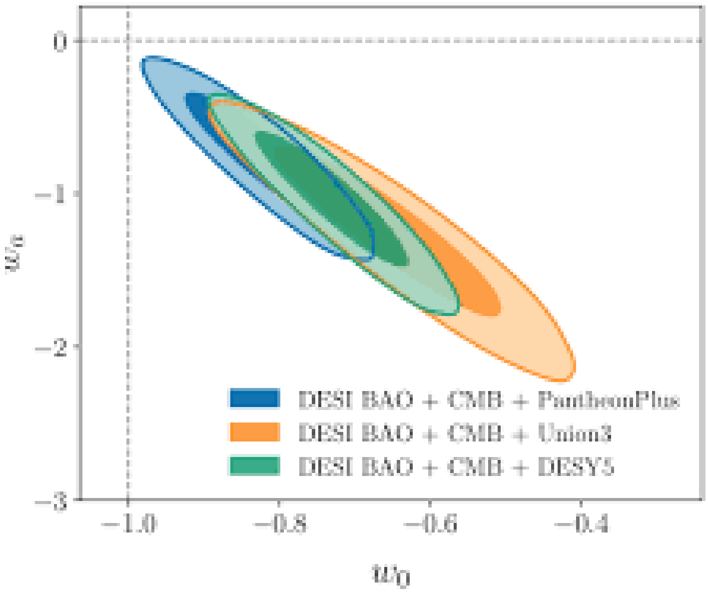
Our picture is that the rich structure at the present epoch has developed from these tiny initial perturbations primarily through gravitational clustering.

Modern Studies of Large-Scale Structure

DESI experiment at Mayall Telescope, Arizona

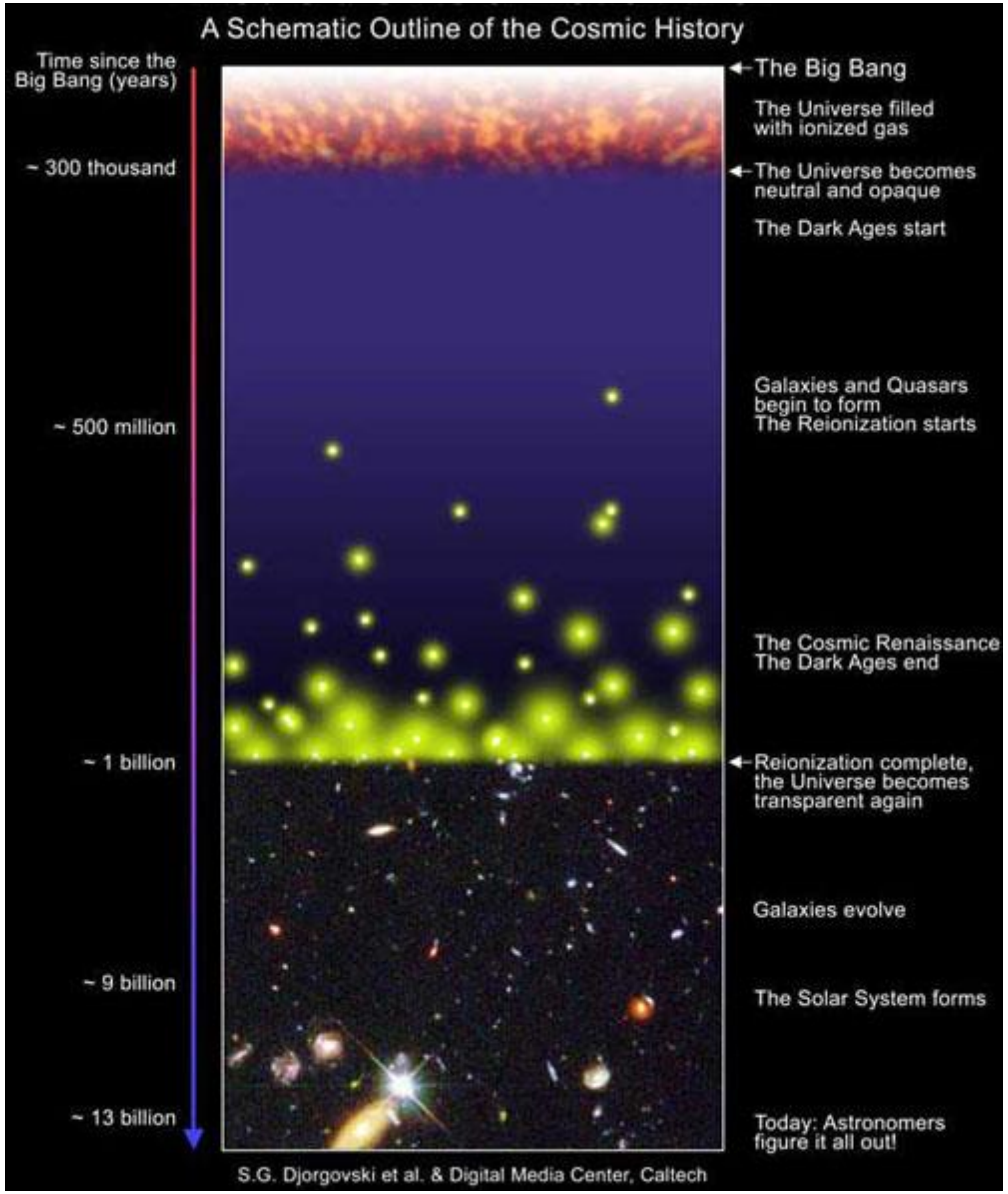


Baryonic Acoustic Oscillations measured at different redshifts -> corresponding to lookback time



Inferring properties of dark energy. Present day equation of state (x-axis) and time-dependence (y-axis)

The *Evolution of Cosmic Structure* course



Our aim is to try to follow the development of structure in the Universe from the formation of the CMB through to the present.

We will study the diversity of structures which form on scales of galaxies and above.

Our perspective will be on the evolution of the Universe.

Course Content

Introduction – Overview [1 lecture]
Universe before decoupling [2 lectures]
Linear growth of perturbations [2 lectures]

Background and linear growth

Galaxy clustering and peculiar velocities [2 lectures]
Non-linear evolution of structure [2 lectures]
Numerical studies of structure formation [1 lecture]

Observational probes of linear growth and non-linear evolution

Observations of the distant Universe [2 lectures]
Reionisation [1 lecture]
Galaxy formation and galaxy properties [3 lectures]
Host galaxies of supernovae [1 lecture]

Galaxy Formation and Evolution across cosmic time

Groups and clusters of galaxies [2 lectures]
Fate of the Universe/Galaxies [1 lecture]

Galaxy groups, clusters and our fate

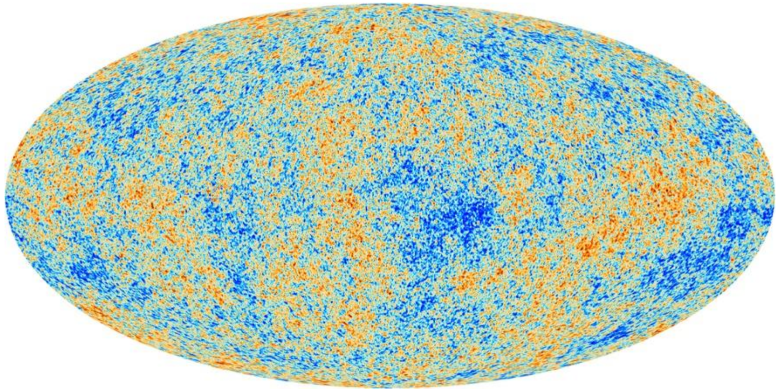
Entropy in the Universe

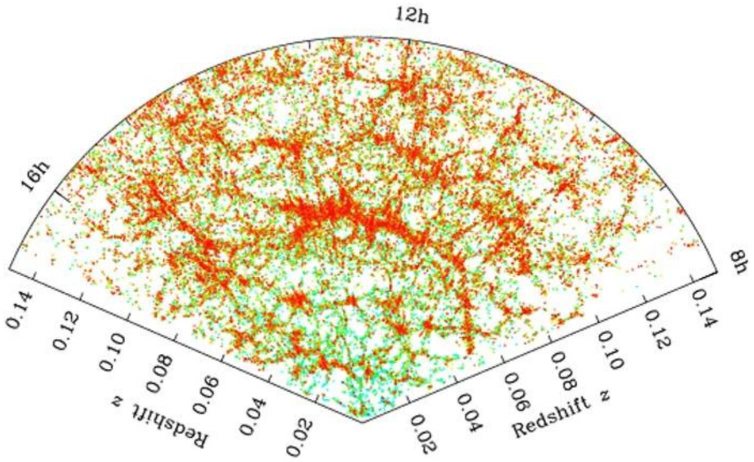
Second law of thermodynamics: $dS_{Universe} \geq 0$

Entropy increasing

Entropy in the Universe

Entropy increasing

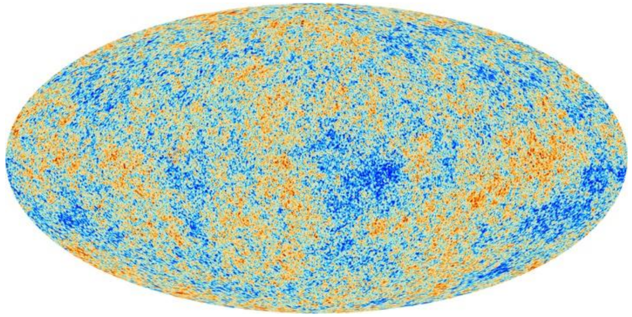


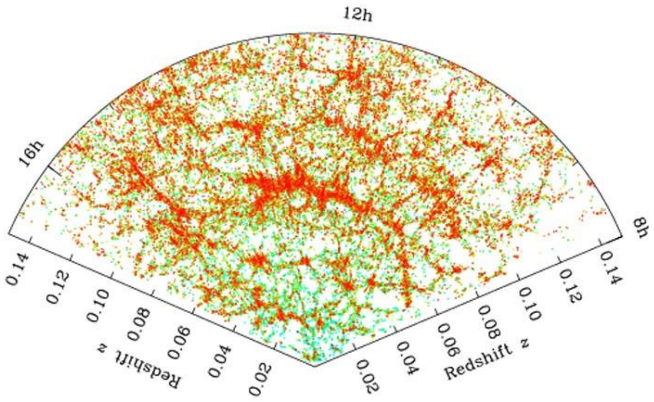


Entropy in the Universe

Entropy increasing

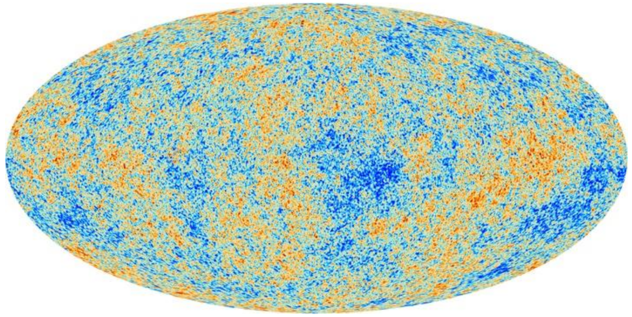
Solution: The gravity between particles in the Universe can’t be ignored. So, unlike the coffee cup, the thermal equilibrium of the CMB is a *very* low entropy state.

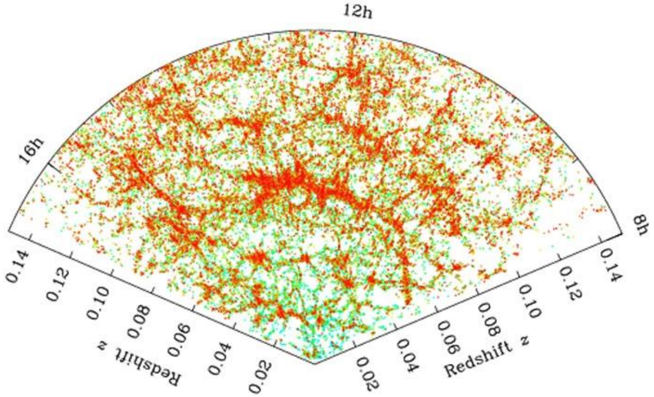




Entropy in the Universe

Entropy increasing





The highest entropy state is within a black hole. $S_{BH} \sim M_{BH}^2$

$$r_s = 2GM/c^2$$

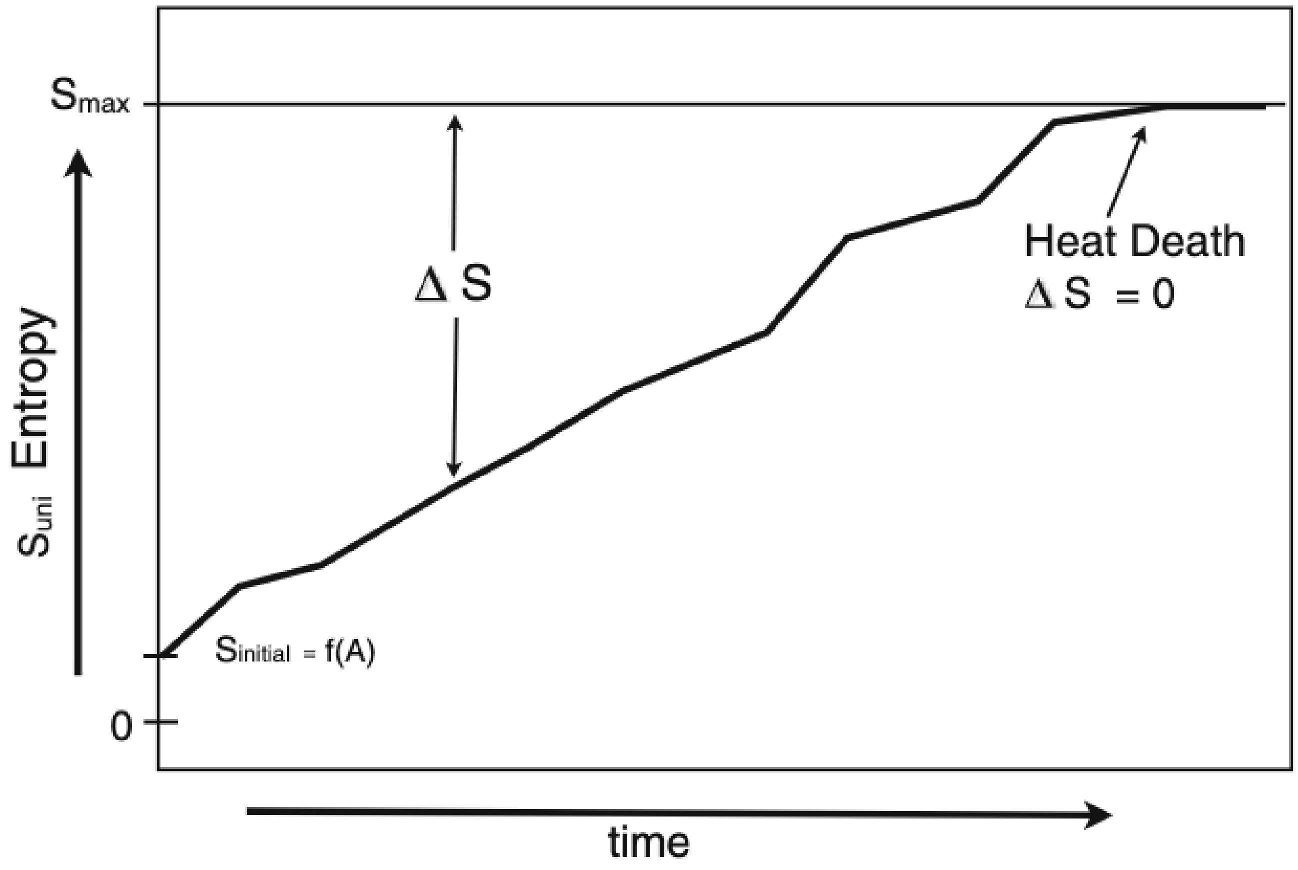
$$A = 4\pi r_s^2 = 4\pi \left(\frac{2GM}{c^2}\right)^2 = \frac{16\pi G^2 M^2}{c^4}$$

$$S = \frac{kc^3}{4G\hbar} A$$

$$S = \frac{kc^3}{4G\hbar} \cdot \frac{16\pi G^2 M^2}{c^4} = \frac{4\pi k G M^2}{\hbar c}$$

$10^{104} k$ in entropy in black holes today. $10^{89} k$ in CMB photon.

Unsolved problem: Why is the entropy of the Universe so low at the beginning?



Some possible solutions:

1. Maybe it wasn't low at the beginning, but we are a low-entropy fluctuation region of the Universe – would break the cosmological principle.
2. We just 'accept it' without asking why.
3. Or the Big Bang is not the beginning (e.g., Cyclic Cosmology, Gurzadyan and Penrose)