Cosmologia Física

Ismael Tereno (IA)

2025

Introduction

The course: a physical model for the Universe

Practical information

Thursday	11h30-12h30	(T)	C8.2.04
Thursday	12h30-13h30	(TP)	C8.2.04
Friday	14h30-15h30	(T)	C8.2.04

Communication: Fénix page and email
Links to lecture notes, homework, and other courses material are given in this page:
https://fenix.ciencias.ulisboa.pt/courses/cfis-2254879305243175/lecture-notes

Contact
email: tereno@fc.ul.pt
office: C8.1.42

Evaluation
Homework: series of exercises
Presentation: of a topic chosen from a list to be given (for example to go in greater depth into a topic from the course). In principle no written report will be required.

Physical Cosmology

describing the physical model of the Universe

Everything

The universe is all of space and time and their contents.

It comprises all fundamental interactions, physical processes and physical constants, and therefore all forms of energy and matter, and the structures they form.

→ two fundamental constraints in the study of the Universe:

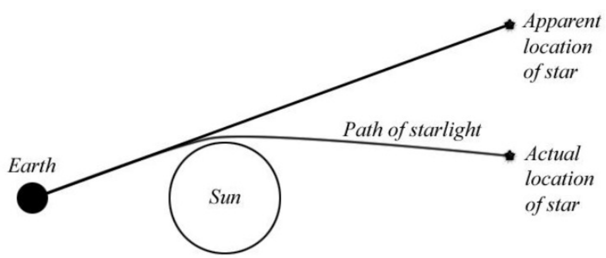
→ finite speed of information propagation → we have only access to part of the Universe - our **lightcone**.

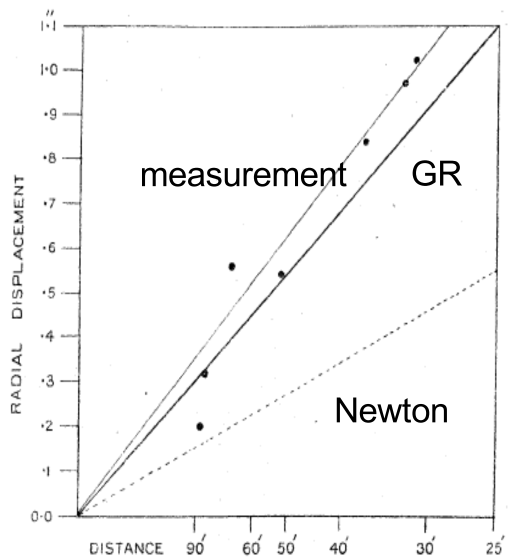
→ we only observe one Universe → we cannot make laboratory experiments, test results in different conditions, or get statistics (possible only under an approximation, the **ergodic hypothesis**) → fundamental limitation – **cosmic variance.**

+ Gravity

is the force that drives the cosmological evolution and describes large-scale interactions, because among the 4 fundamental forces strong and weak forces have short range and the Universe is neutral.

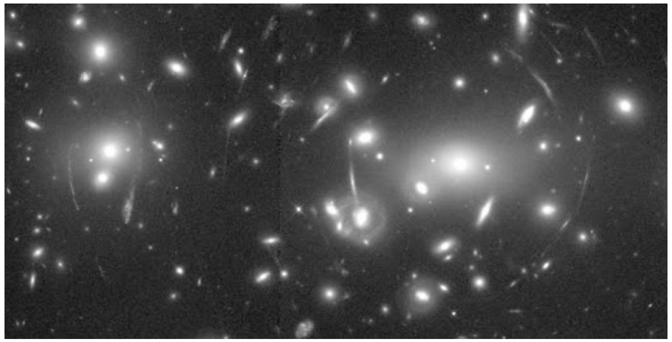
It is tested on various scales:



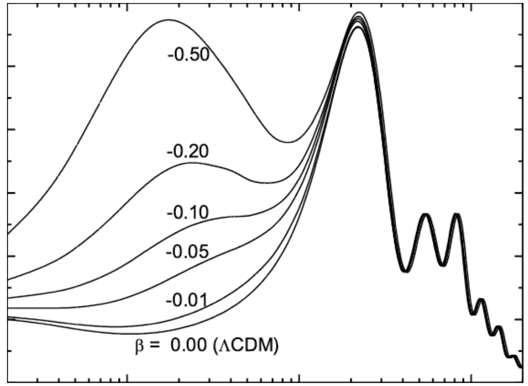


1919

(Eddington)



1987 - today



Gravity is described by **General Relativity**

→ **metric**
→ Einstein equations

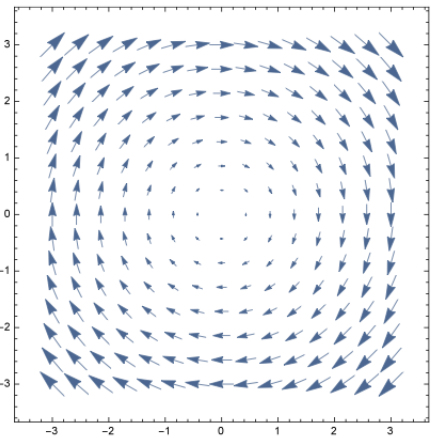
Awarded to **Albert Einstein** "for his services to Theoretical Physics, (and especially for his discovery of the law of the photoelectric effect)." (1/1)

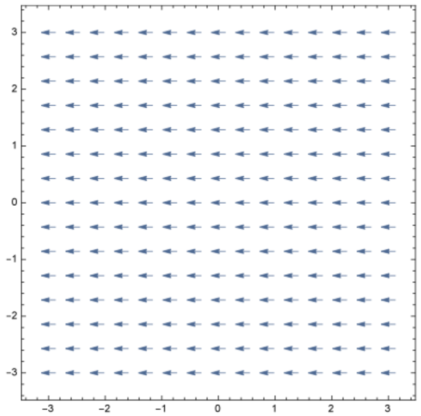
1921

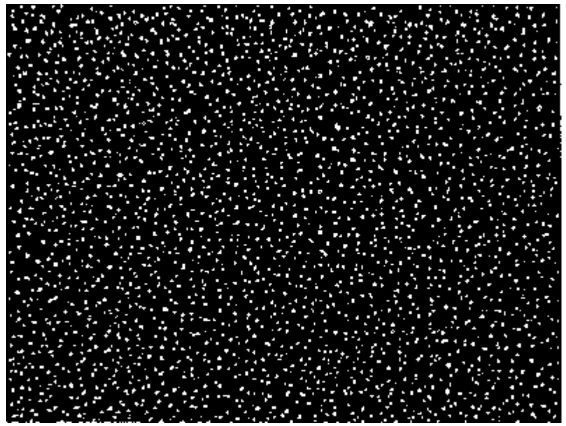
+ Cosmological principle

Isotropy :
the Universe observed in any direction looks the same → rotational invariance

Homogeneity:
the Universe is identical in all points, at each instant → translational invariance





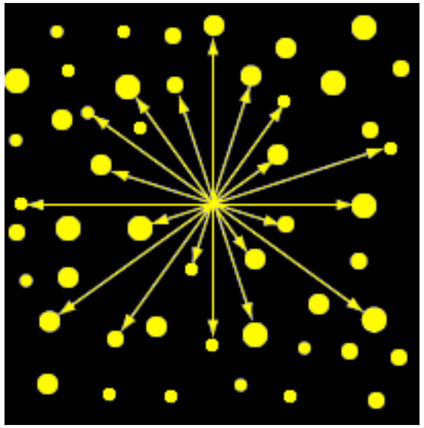


→ metric is Robertson-Walker, **spherically symmetric** with two degrees of freedom: a, K → and two related cosmological parameters: H_0, Ω_K

+ **Olbers paradox**

→ universal loss of luminosity → **redshift**

→ scale factor “a” must **evolve**



+ **Observations of the recession of galaxies**

→ Expansion **Big Bang theory**

→ Thermal history

→ Nucleosynthesis

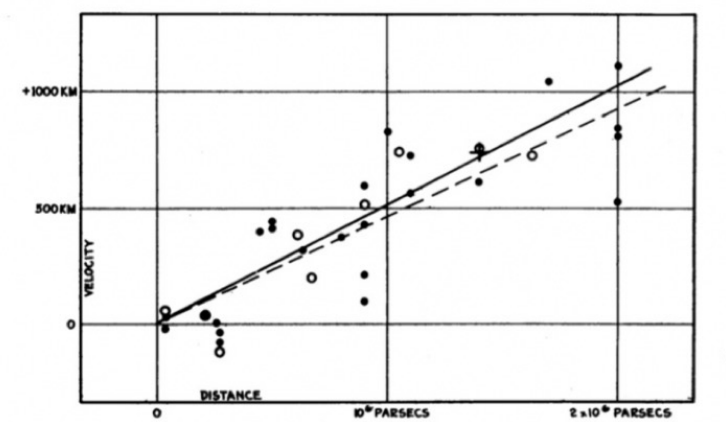


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

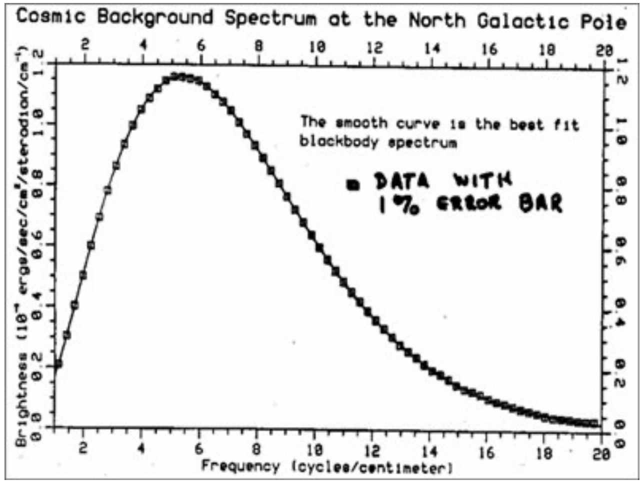
(Hubble)

1929

→ Existence of a universal background radiation:

the **cosmic background radiation**, **CMB** [z ~ 1100]

1965 - 1990



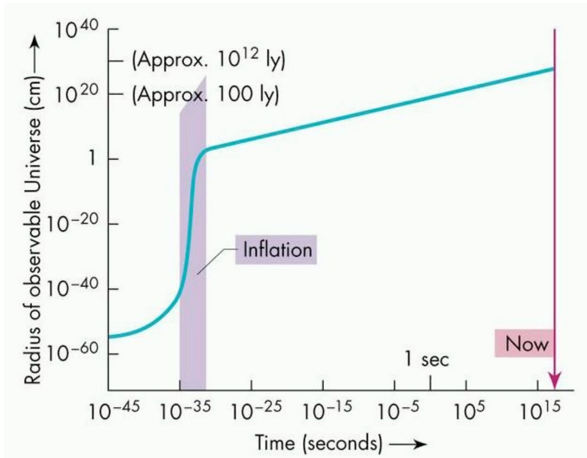
(COBE, 1990)

1978

Awarded to **Arno A. Penzias and Robert W. Wilson** "for their discovery of cosmic microwave background radiation." (1/4 + 1/4)

→ Horizon, flatness and coincidence problems

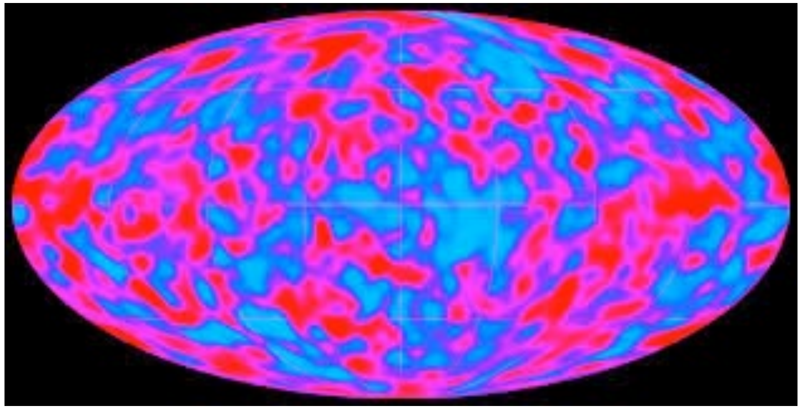
Solved by **Inflation**



+ Observation of anisotropies in the CMB

1992 - 2018

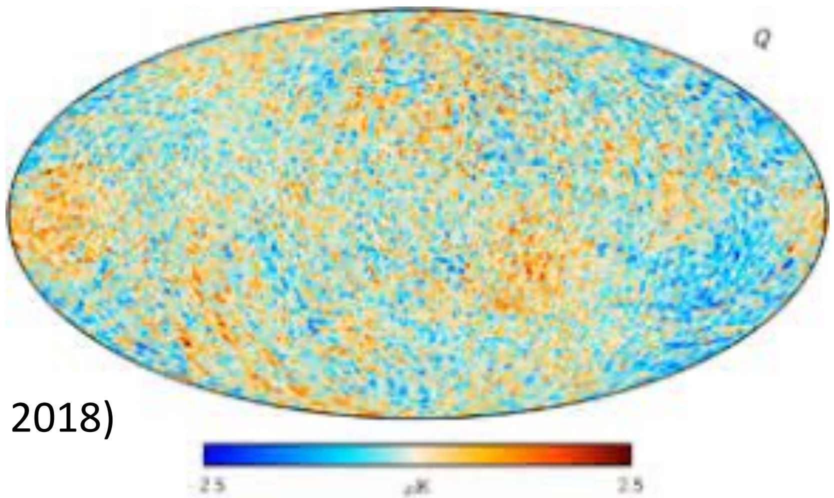
(COBE, 1992)



→ Existence of perturbations to the cosmological principle → found the **seeds of structure**!

→ Problem of the origin of the seeds of structure

Solved by the mechanism
of quantum fluctuations + inflation +
+ gravitational interaction



(Planck, 2018)

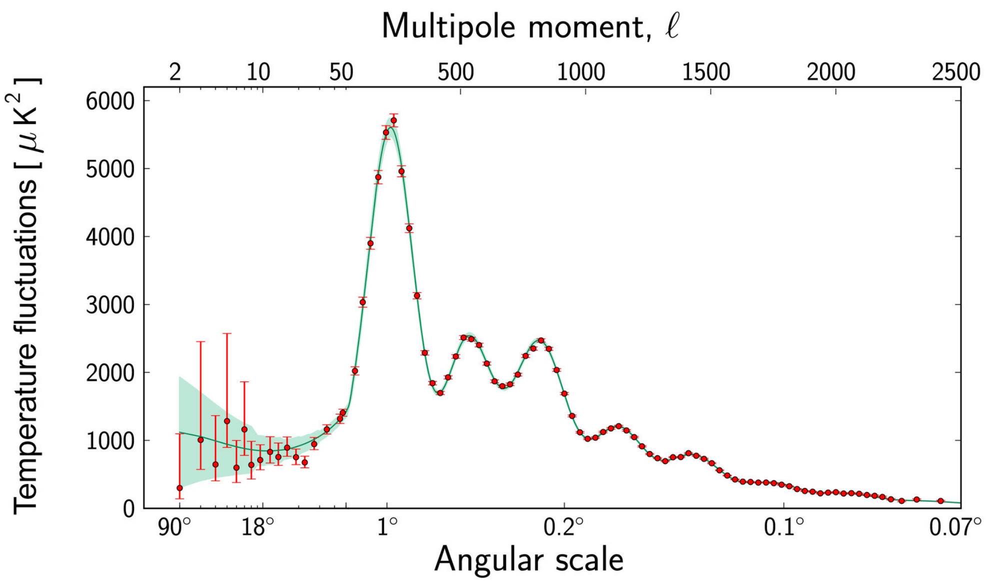
2006

Awarded to **John C. Mather** and **George F. Smoot** "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation." (1/2 + 1/2)

+ Measurement of the anisotropies in the CMB

1992 - 2018

Their amplitude is very small $\delta_T \sim 10^{-5}$



(Planck, 2018)

→ Isotropy confirmed (wide angular bins, i.e., on large angular scales)

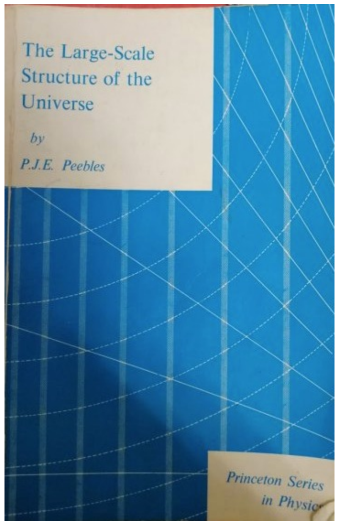
→ indicates very small clustering at z=1100 → δ_b (z=1100) $\sim 10^{-5}$

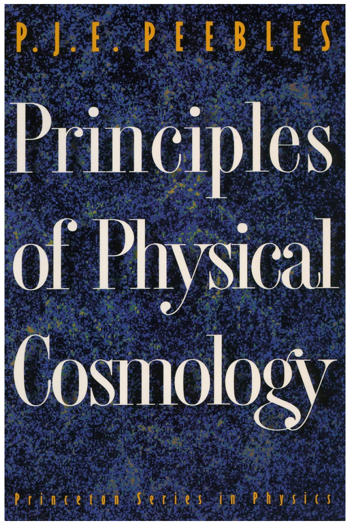
+ Gravitational collapse is slow (δ_b grows only a factor ~10^3 until z=0)

+ Today there are structures with large density contrast δ (large clustering at z=0)

→ Problem of the mechanism of structure formation

Solved by the hypothesis of the existence of an extra component in the cosmological fluid - Dark matter → **CDM model**





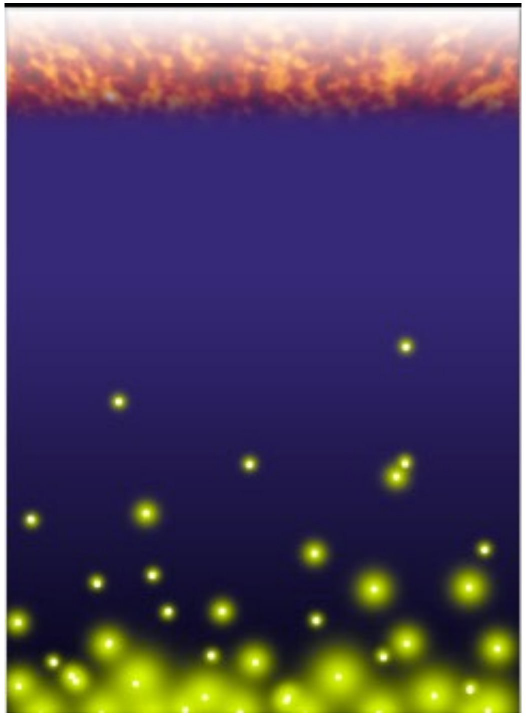
Awarded to **P. James. E. Peebles** ”for theoretical discoveries in physical cosmology” (1/2)

2019

+ Structure formation

Linear (gravitational clustering)

→ There is a very long process of **linear** clustering, during the **dark ages** and beyond. In some points, local gravitational fields start to become strong.



Non-linear (collapse)

→ Formation of **dark matter halos**

Non-linear collapse of baryonic matter on those halos → neutral Hydrogen HI clouds condense and form the first stars, ending the dark ages → **Cosmic Dawn** [z ~ 20]

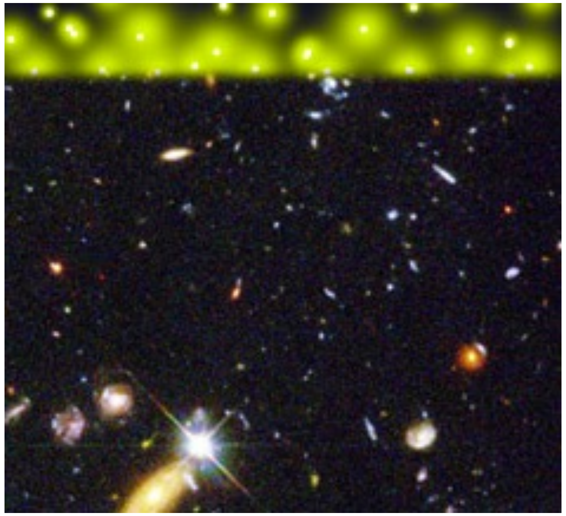
Meanwhile, in some parts (or scales) of the Universe linear structure formation continues its slow process.

+ Galaxy formation

→ The gravitational collapse does not describe all aspects of structure formation.

Non-gravitational effects associated to the baryonic matter start to be important at this stage:

Cooling - the has gas to cool-down to condense. By losing pressure it falls into the center of the halo where it can form stars. Angular momentum conservation during the fall produces a disk → spiral galaxies



Feedback - the quantity of cold gas available decreases by influence of the environment

Mergers - frequent interactions between halos may form elliptical galaxies from primitive spiral galaxies.

The first galaxies [z ~ 15?] led to the **Reionization** era [z ~ 10]

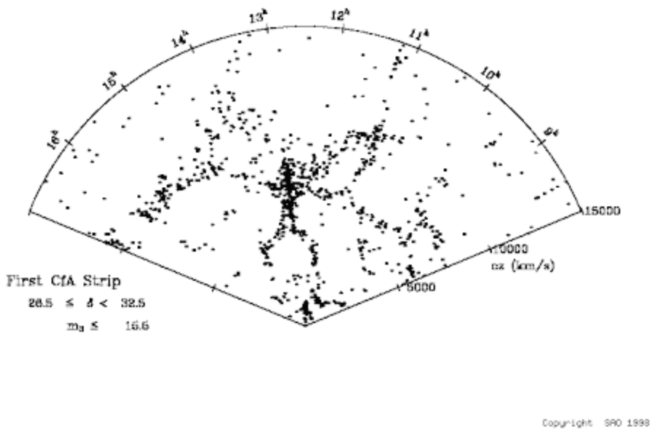
→ New radiation ionizes the HI clouds, forming ionized Hydrogen regions HII - the reionization of the Universe

+ Observation of the LSS of luminous matter in 2D and 3D

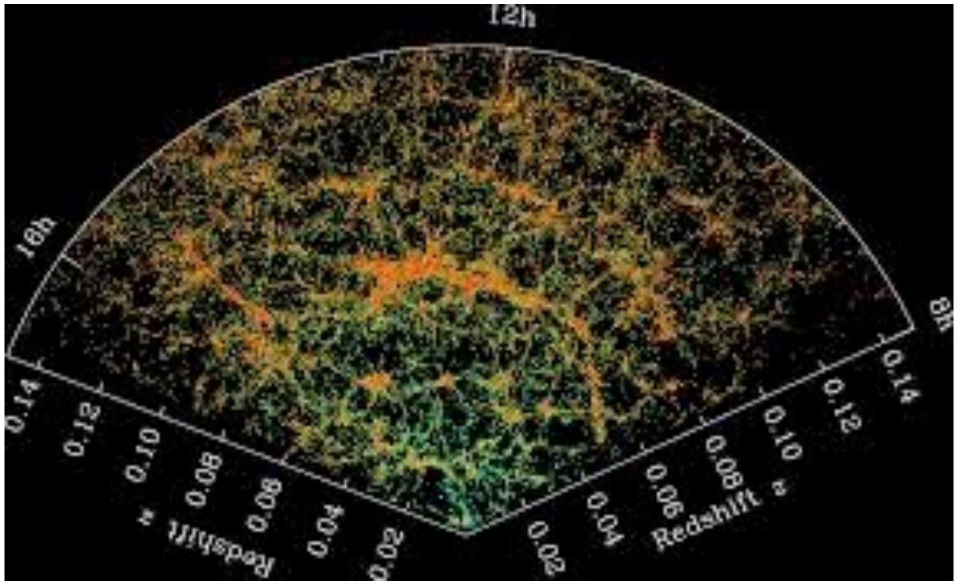
Since the epoch of reionization, galaxies have been forming and evolving, with an intense period of star formation occuring at the **Cosmic Noon** [z ~ 2-3]

Mapping the galaxies positions gives (biased) information on the **cosmic web** - the DM **large-scale structure** of the Universe - by using **galaxy clustering** methods and **redshift space distortions** → find out the details of structure formation

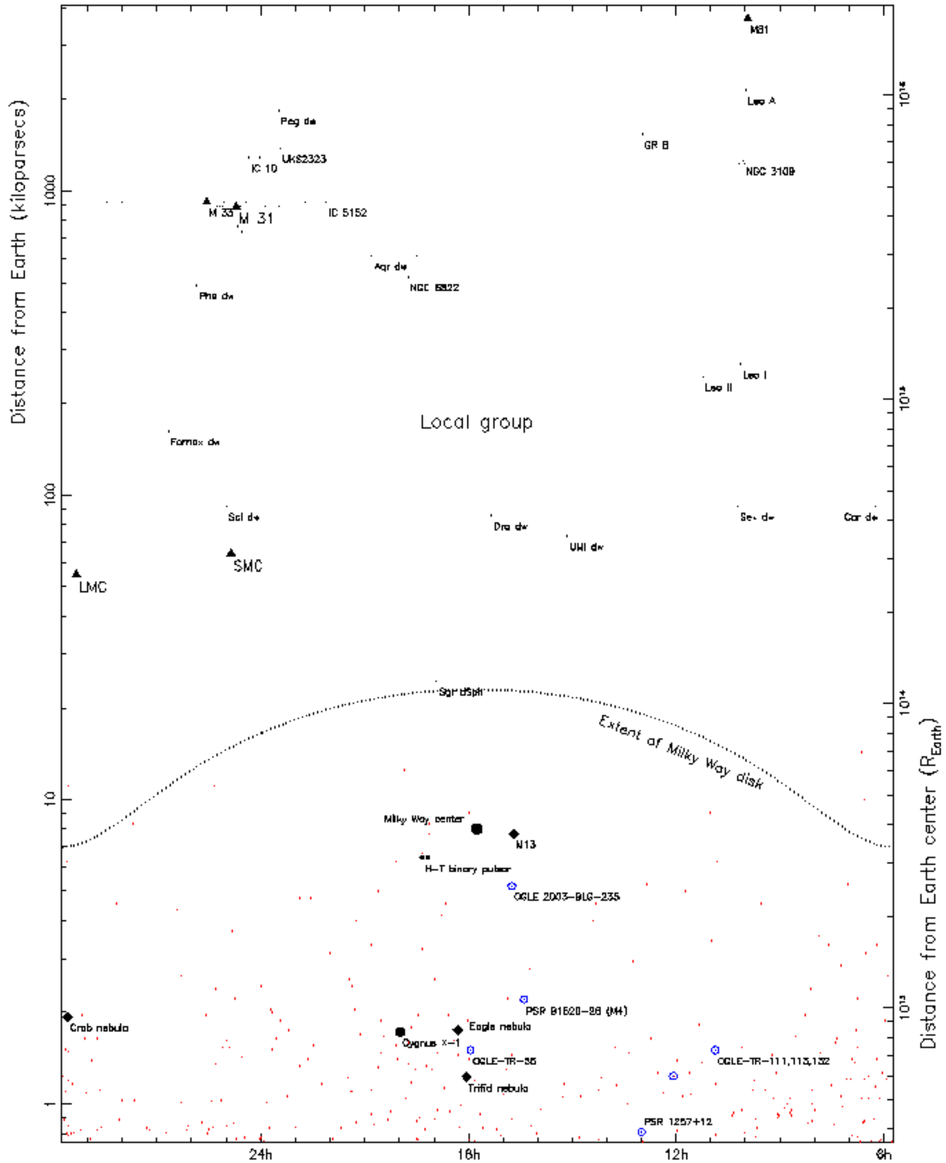
1980 - today

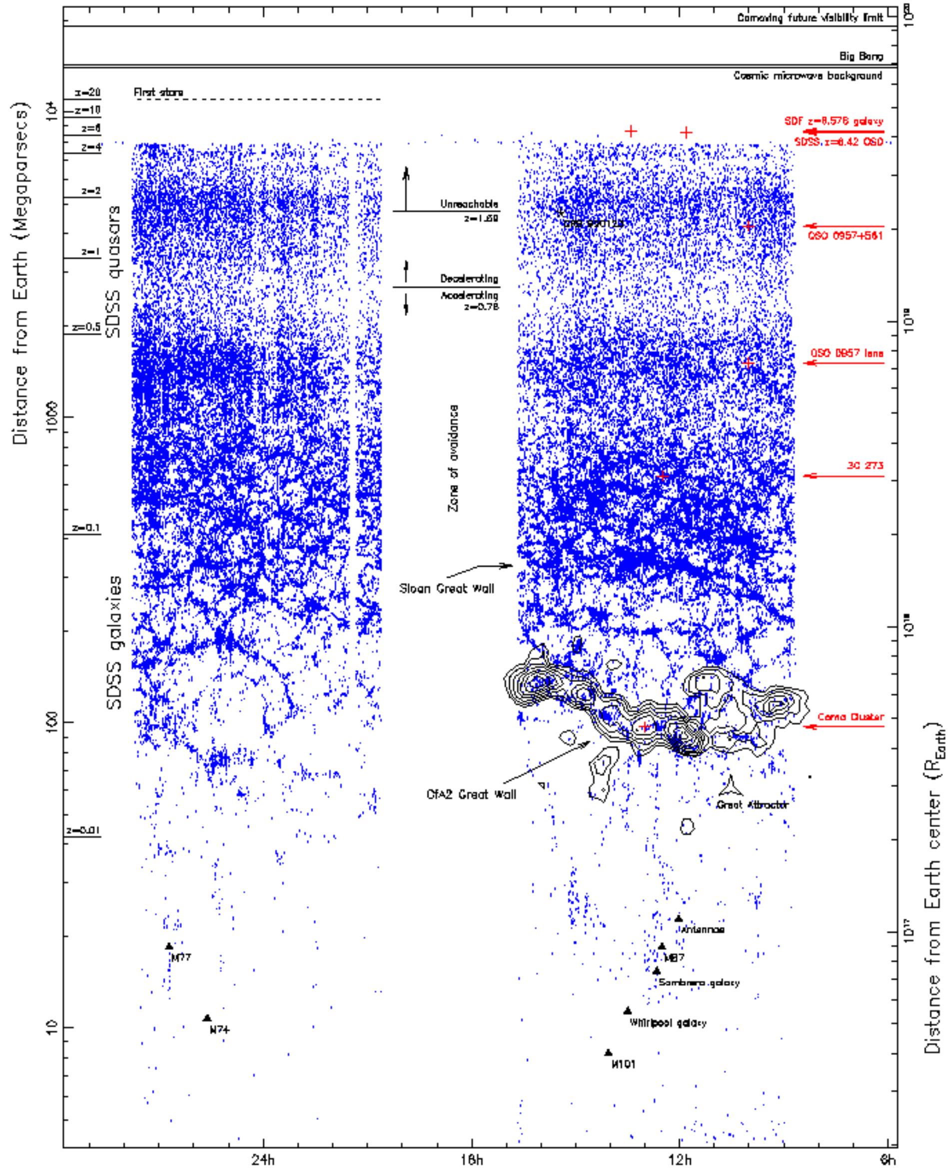


(CfA, 1980)



(SDSS, 2008)



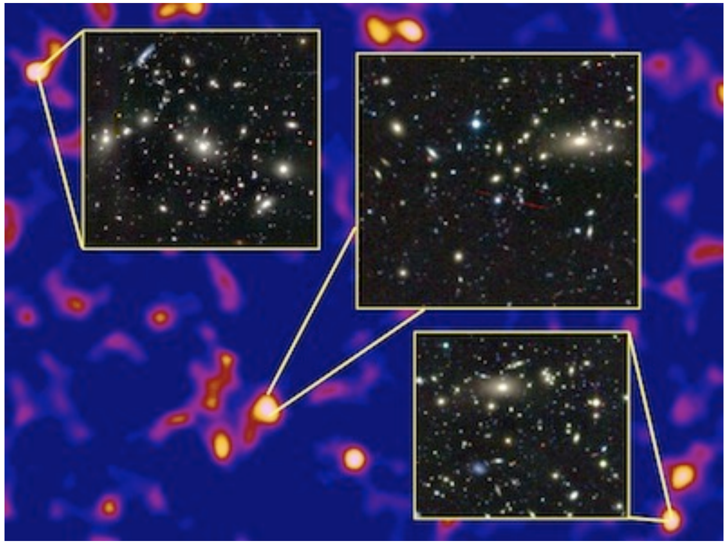


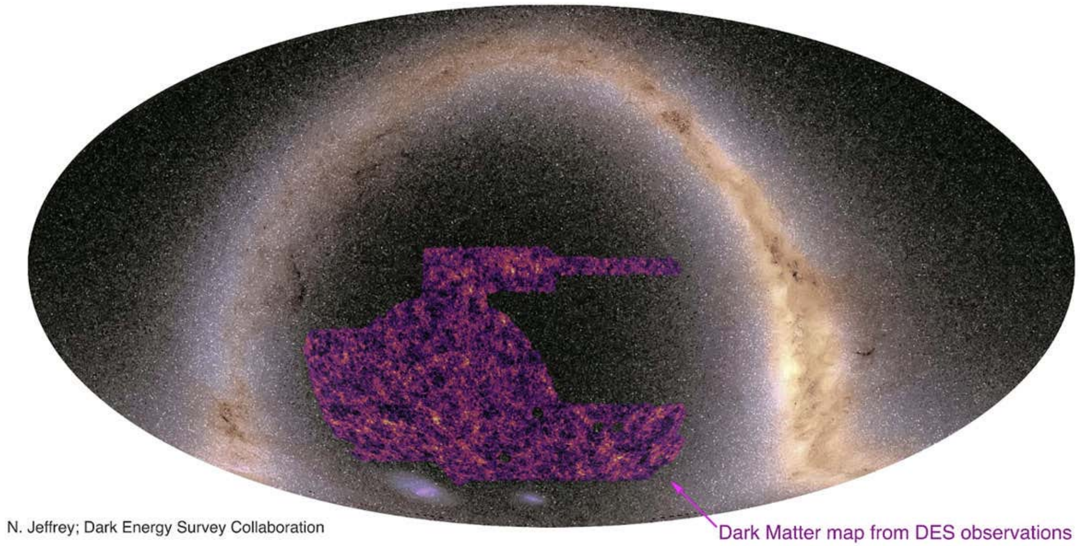
→ Homogeneity confirmed (on large scales)

+ Observation of the LSS of dark matter in 2D and 3D

Mapping the galaxies shapes gives (less biased) information on the **cosmic web** – the DM **large-scale structure** of the Universe - by using **weak gravitational lensing** methods → find out the details of structure formation

2000 - today





(CFHTLenS, 2012)

(DES, 2021)

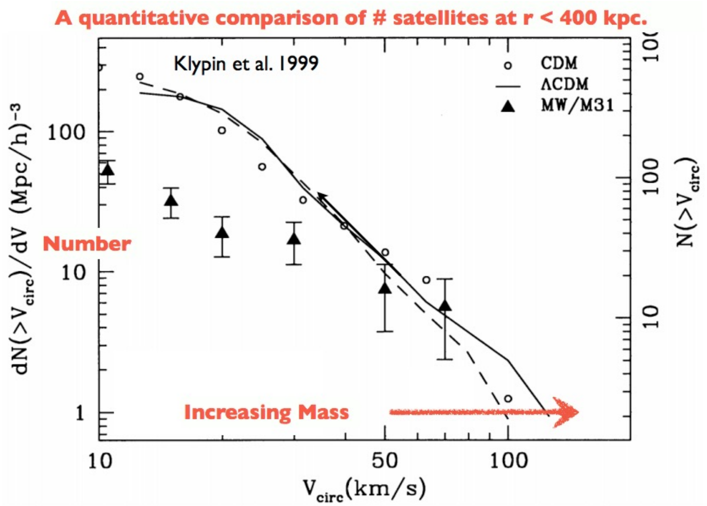
+ **Observations of properties of small-scale structure** (kpc)

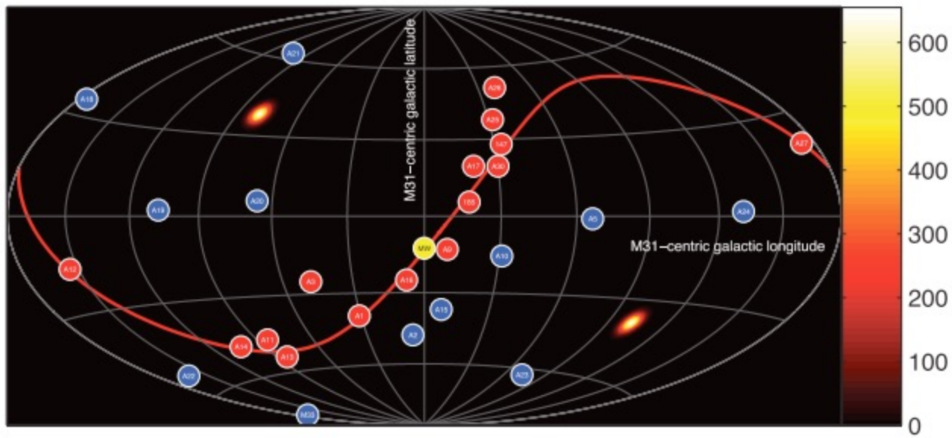
→ Problem of the radial density profile of structures (cusp/core)

→ Problem of lack of structures (satellite galaxies)

→ Problem of the satellite orbital plane - possibly solved in 2022 with new simulations and Gaia 6-dim data (Sawalla et al, arXiv: 2205.02860)

Several problems not yet solved, leading to hypothesis of existence of other types of dark matter (Warm Dark Matter, Interacting DM), interacting DM/baryons in dense environments (Baryon feedback), hypothesis of modifications of GR on galactic scales (MOND)





+ Measurements of distances to SN

Supernovae at all redshifts are fainter (more distant?) than expected from the $d_L(z)$ predicted by the CDM cosmological model

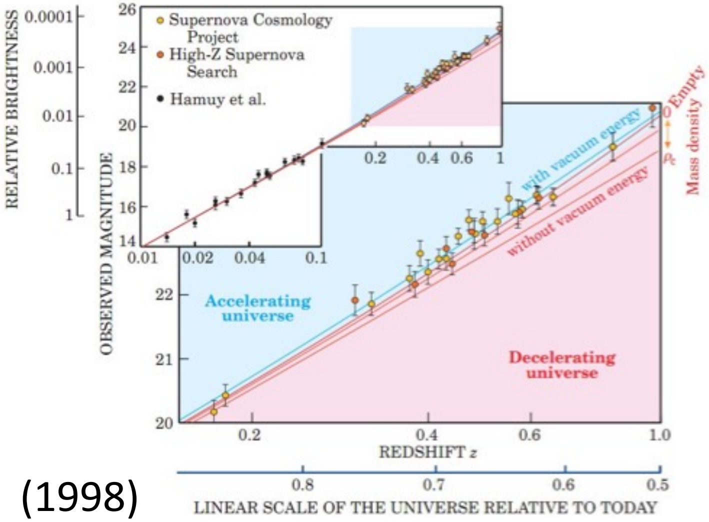
→ The Universe changed from a decelerated expansion to an accelerated one

Solved by assuming the existence of an extra component in the cosmological fluid - Dark energy → **ΛCDM model**

→ Alternatively, the Universe is not accelerating but the theory of gravitation on large scales is not GR, and the measured distances are compatible with that theory

New "**modified gravity**" theory not found yet

1998 - today



(1998)

Awarded to **Saul Perlmutter, Brian P. Schmidt** and **Adam G. Riess** "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." (1/2 + 1/4 + 1/4)

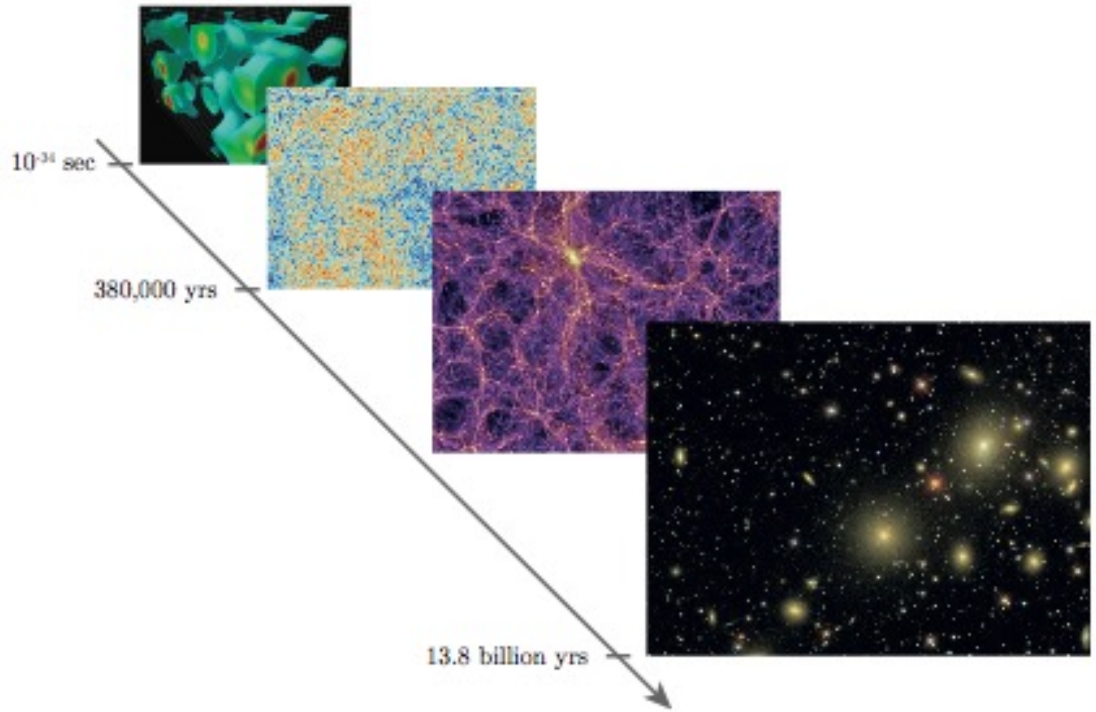
2011

ΛCDM

the standard physical model of the Universe

General Relativity + Big Bang + Inflation + Gravitational clustering + cosmological fluid that includes dark matter of the type cold and dark energy of the type cosmological constant.

This physical model has been the standard model of the Universe since the beginning of the XXIst century and it is known as ΛCDM.



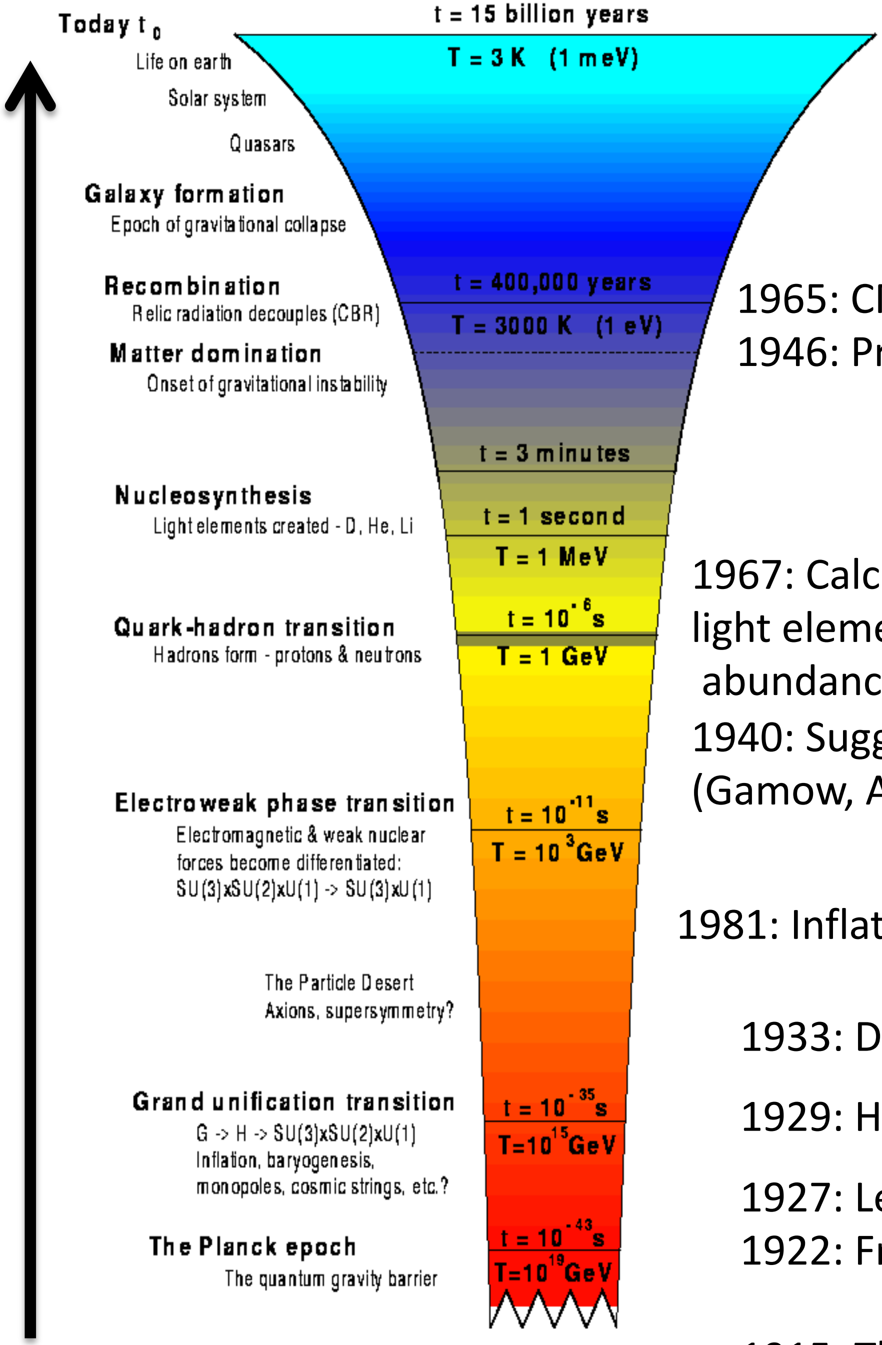
Cosmic timeline

Log scale

Stable particles are the only ones left: photons, neutrinos, protons, neutrons, electrons, DM particles.

During the thermal history, the various species gradually decouple (leave the equilibrium) as their reaction rates become smaller than the expansion rate.

Inflation - mechanism introduced to solve some of the problems of the Big Bang model. It also provides the inhomogeneities initial conditions from quantum fluctuations.



1965: CMB detection (Penzias,Wilson)

1946: Prediction of CMB (Gamow)

1967: Calculations of formation of light elements and observed abundances

1940: Suggestion of nucleosynthesis (Gamow, Alpher, Herman)

1981: Inflation (Guth)

1933: DM proposal (Zwicky)

1929: Hubble law

1927: Lemaitre models

1922: Friedmann models

1915: Theory of GR (Einstein)

Linear scale

Homogeneity

2001: H_0 distance ladder (HST Key Project) (W. Freedman)
1998: Accelerated expansion (SNIa)

LSS

2005: Detection of the BAO peak (SDSS)
2001: LSS map (SDSS, 2dFGRS) → SDSS IV (2019) → DESI (2024)
2000: Weak lensing (LSS of DM) → DES (2021) → Euclid (2027)
1986: The Great Wall (scale of homogeneity?)
1970: Large-scale structure (first z-surveys of galaxies)

Clusters

2006: Bullet Cluster (Chandra, Lensing) (DM observed?)
1996: Nbody simulations (Virgo) (Universal profile NFW)
1993: M_b from clusters is 15% of M_tot (S. White) (DE?)
1982: X-ray cluster mass (Einstein satellite)
1933: Cluster dynamics: DM needed (F. Zwicky)

Cosmic Noon

1996: z-evolution of Star-formation rate (HDF) (P. Madau)
1986: First LSB galaxy
1979: First gravitational lens system
1974: Mass function (Press, Schechter) (NL collapse)
1970: Rotation curves (DM also needed in galaxies) (V. Rubin)

Cosmic Dawn

2024: Luminous early galaxies (record z=14.2) (JWST)
2010: Cosmological HI 21cm (Pen) → SKA (> 2027)
1970s: Discovery of Ly-a forest
1965: Gunn-Peterson test (the universe is highly ionized)
1963: Discovery of the first quasar (first high-z source)

Dark ages

2013: CMB high precision and polarization (Planck)
2003: CMB small scales (WMAP)
2000: CMB 1st peak (Boomerang, Maxima) (Universe flat)
1992: Anisotropies of CMB (COBE) (DM also needed)
1990: CMB Black-body (COBE) (Big Bang)

Primordial

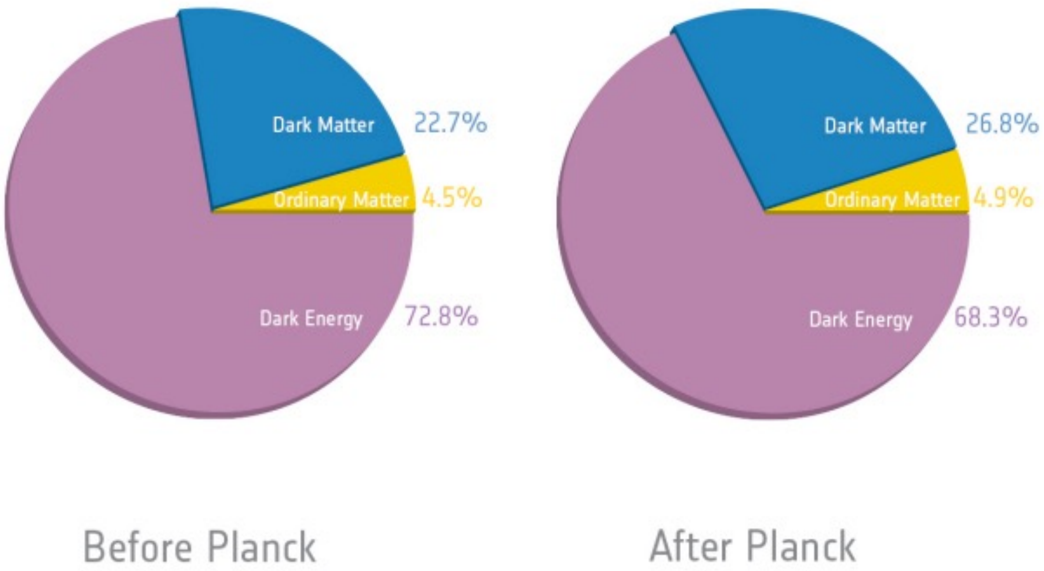
2016: Gravitational waves (LIGO) → LISA (2037)
2002: Neutrino oscillations

ΛCDM parameters

ΛCDM is a complex model. It is a theoretical construction supported by observations.

It includes a variety of physical processes that occur in a variety of epochs, in a variety of scales and contains a large number of free parameters – the **cosmological parameters** - that need to be fixed by the observations.

The values of the cosmological parameters determine the details of the expansion of the Universe and the evolution and formation of its large-scale structures → they determine the "cosmology".



Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

fundamental cosmological parameters

nuisance parameters (of a particular cosmological probe)

derived cosmological parameters

ΛCDM problems

The description of the Universe is far from being finished!

Theoretical development

- Details of the non-linear structure formation are not well understood
- The LSS is not completely described yet (high-order correlations)
- Relativistic effects not completely studied (larger scales)

Observations and interpretation

- Many observations suffer from systematic effects
- Different observations are well fitted by the model predictions but for different and inconsistent parameter values → the Hubble tension
- Many alternative DE models also fit the data
- Test the assumptions (e.g. cosmological principle)

Fundamental concepts

- Nature of dark matter still unknown
- Nature of dark energy still unknown

Plan of the course:
studying the physical model of the Universe

The Homogeneous Universe

geometry, dynamics, age, distances, cosmological parameters,
contents of the Universe (dark matter, dark energy, radiation, baryonic matter)

Testing the Homogeneous Universe: *probes of geometry*

standard candles (SN), standard rulers (BAO), standard abundances,
distance ladder (H0), densities (lensing, dark matter), estimators, biases,
statistical inference (Fisher matrix, MCMC)

The Inhomogeneous Universe

linear spatial perturbations, random fields, structure formation,
power spectra of dark/baryonic matter, non-linear structure

Testing the Inhomogeneous Universe: *probes of structure*

weak gravitational lensing (cosmic shear), galaxy clustering, CMB anisotropies

There is no single textbook covering all aspects of the course at the level intended.
So, the **main resource** are the lecture notes:

I. Tereno - *Cosmologia Fisica lecture notes -*

LECTURE NOTES ~1000 slides

https://fenix.ciencias.ulisboa.pt/courses/cfis-2254879305243175/lecture-notes

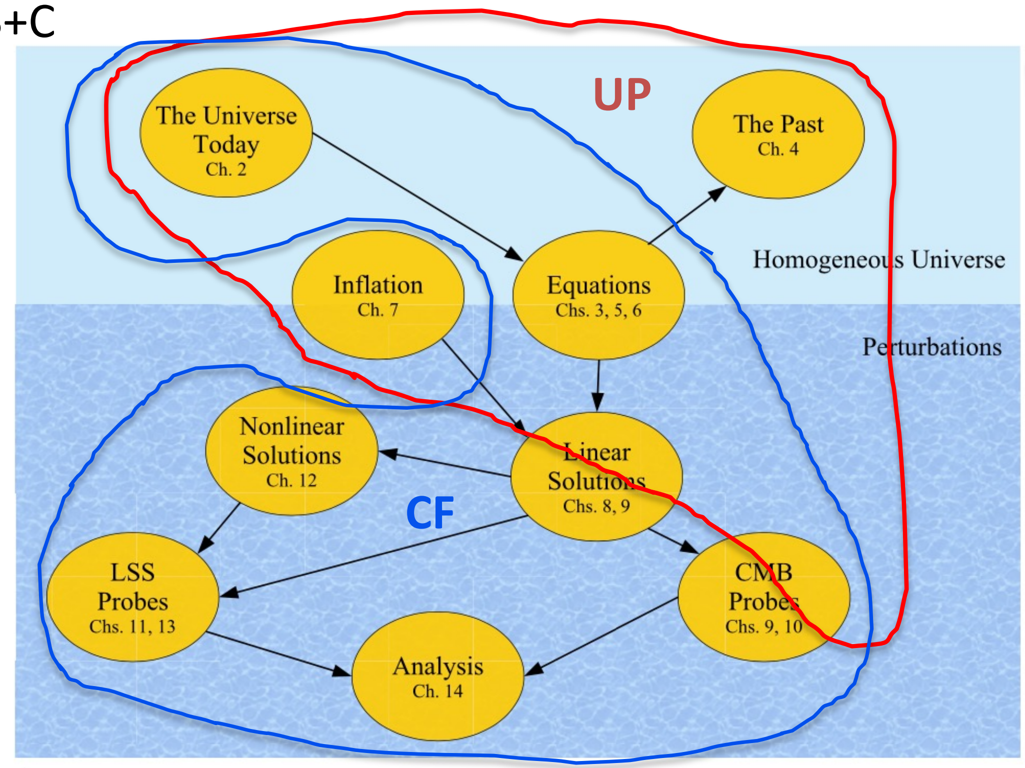
Cosmology sub-divisions A, B, C and how different is this course from Primordial Universe

Primordial Universe

Physical Cosmology

Time	Temperature (K)	Event
	The Quantum Gravity Era	
1×10^{-43} s (Planck time)	1×10^{32}	quantum limit of general relativity
	The Inflation Era	
1×10^{-35} s	1×10^{28}	grand unification symmetry breaking
1×10^{-34} s	1×10^{27}	start of inflation
1×10^{-32} s	1×10^{27}	start of reheating and end of inflation
1×10^{-11} s	3×10^{15}	ew unification symmetry breaking
	The Quark-Lepton Era	
1×10^{-5} s	2×10^{12}	formation of hadrons from quarks
0.1 s	3×10^{10}	neutrinos decouple
1 s	1×10^{10}	neutron to proton ratio freezes out
10 s	5×10^{9}	electron positron annihilation
	The Radiation Era	
3 min	1×10^{9}	nucleosynthesis begins
30 min	4×10^{8}	nucleosynthesis ends
2000 anos	6×10^{4} ($z \approx 10^{4}$)	matter-radiation equivalence
	The Matter Era	
10 mil anos (the plasma epoch)	1×10^{4}	matter is fully ionized
300 mil anos	3.5×10^{3}	electrons and protons recombine
400 mil anos	3.0×10^{3} ($z \approx 1100$)	photon decoupling (last scattering surface)
400 milhoes de anos	($z \approx 15$)	first bound structures form
		formation of intergalactic medium
		first dark halos of galaxies
		first stars (first heavy elements)
		clusters
		filaments and voids
	The Dark Energy Era	
13.6 mil milhoes de anos	2.726	today

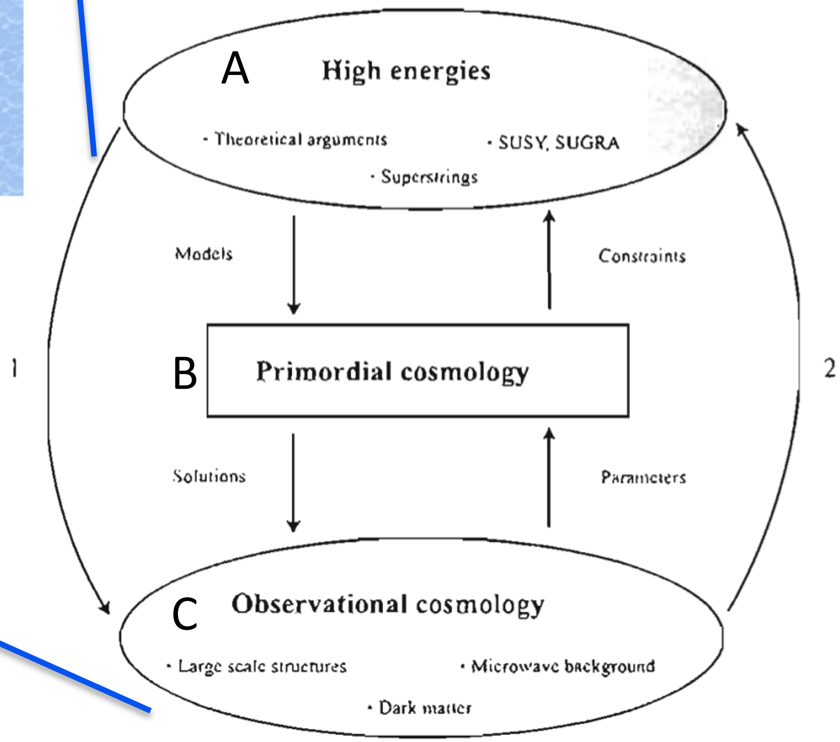
B+C



(from Dodelson and Schmidt)

The 3 sub-divisions of theoretical cosmology

A. Theoretical : field theory, particle physics, dark energy models, modified gravity



B. Theoretical: B0: homogeneous universe (expansion), B1: inhomogeneous universe (structure formation, statistical description)

C. Theoretical: cosmological probes, statistical description, estimators, simulations

(from Peter and Uzan)

Other bibliography

There are many good cosmology **textbooks** that provide good explanations of some aspects, or that go into greater depth in some topics.

- P. Peter and J.P. Uzan - *Primordial Cosmology* (2009) - Ch. 3,5 (homogeneous and inhomogeneous Universe -B-), Ch. 6,7 (cosmological probes -C-), other chapters focus on -A-

- L. Amendola and S. Tsujikawa - *Dark Energy* (2010), Ch. 2,3,4,12 (homogeneous and inhomogeneous Universe –B-), Ch 5,14 (cosmological probes -C-), Ch. 13 (statistical methods -C-), other chapters focus on -A-

- Y. Wang - *Dark Energy* (2010) - Ch. 1,2 (a quick summary of relevant aspects of -B-), Ch. 4-7 (details on the main cosmological probes -C-)

- S. Dodelson and F. Schmidt - *Modern Cosmology* 2nd ed. (2021), the full book gives a very detailed and complete coverage of the inhomogeneous Universe and the theoretical aspects of observational cosmology (more advanced level -B,C-)

- P. Schneider - *Extragalactic Astronomy and Cosmology - an introduction* (2006), Ch. 4,7,8 give a rigorous but less advanced description of the homogeneous Univ, inhomogeneous Univ and cosmological probes (more introductory level -B,C-)

- P. Coles and F. Lucchin - *Cosmology* 2nd ed. (2002), Ch. 1,2,4,10-19 covers most aspects of the course at a less advanced and also more outdated level (-B,C-)

There are also many good **lecture notes** from cosmology courses from universities around the world, that can be found on-line.

- Luca Amendola (B,C)

- Daniel Baumann – detailed calculations (B, some A)

- Tobias Baldauf – theory of observational cosmology (a good resource for the theoretical aspects of C)

- Julien Lesgourgues – detailed description of inhomogeneous Universe (B)

- Hannu Kurki-Suonio - detailed description of inhomogeneous Universe (B)

- Matthias Bartelmann – less advanced level

- Michael Hudson – less advanced level