Cosmologia Física

Ismael Tereno (IA/FCUL)

Lectures

Monday 14h00-16h00 Zoom

Thursday 14h00-16h00 Zoom

Fenix page

(lecture slides and homework uploaded there, will send the links)

Contact

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Evaluation

Homework (60%) + Presentation (30%) (from a list of topics to be given, no written report required) + Margin (10%)

Program: **introduction**

Cosmology studies the global properties of the Universe

Physical Cosmology uses physics to describe/understand:

- the current state of the Universe,
- its past and future evolution,
- its structures and their large-scale spatial distributions (note: large = grande)

Two courses on physical cosmology in FCUL:

- **Theoretical/Physical/Primordial Cosmology** - *Universo primitivo*
(thermal history, particle physics, field theory)

- **Observational/Astrophysical/Modern Cosmology** - *Cosmologia Física*
(properties of observable astrophysical quantities that allow to evaluate cosmological models → cosmological probes)

Universo primitivo

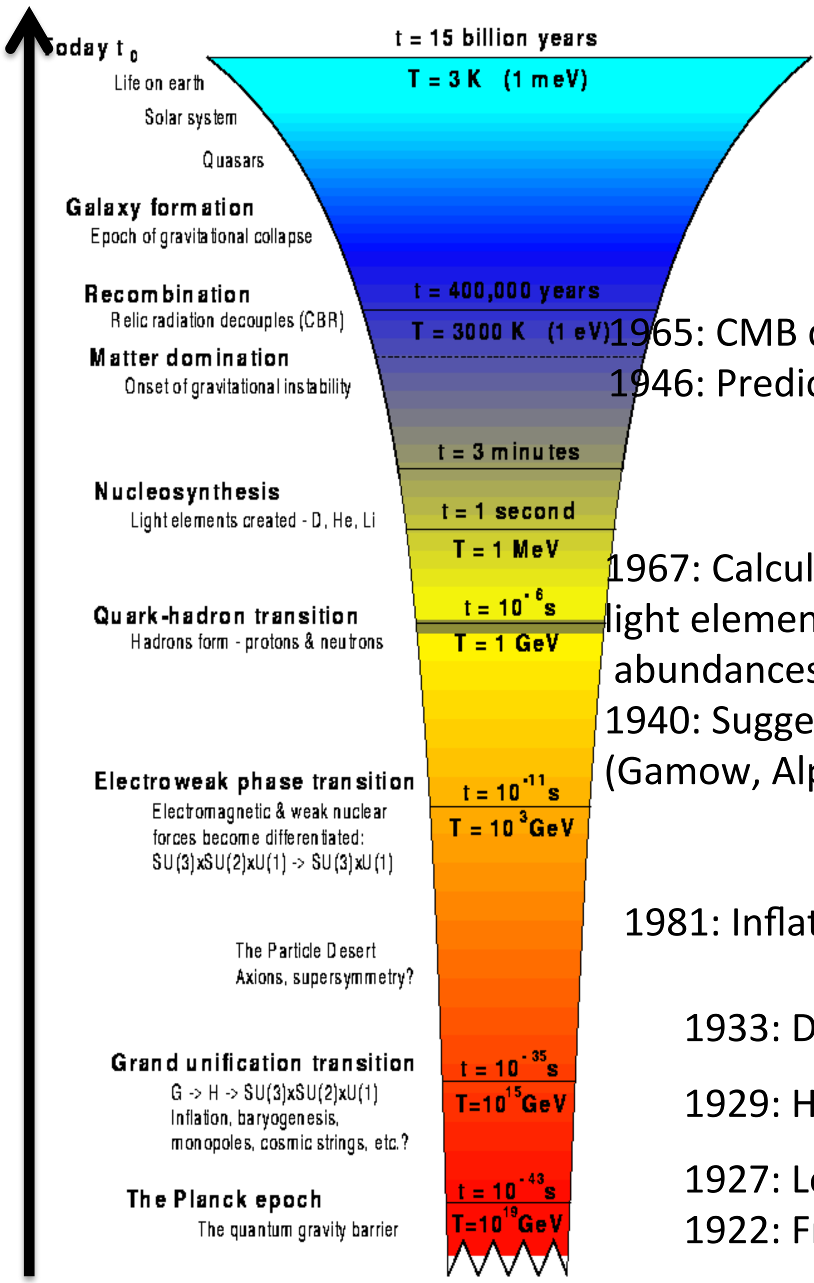
Cosmologia Física

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

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.



Log scale

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)

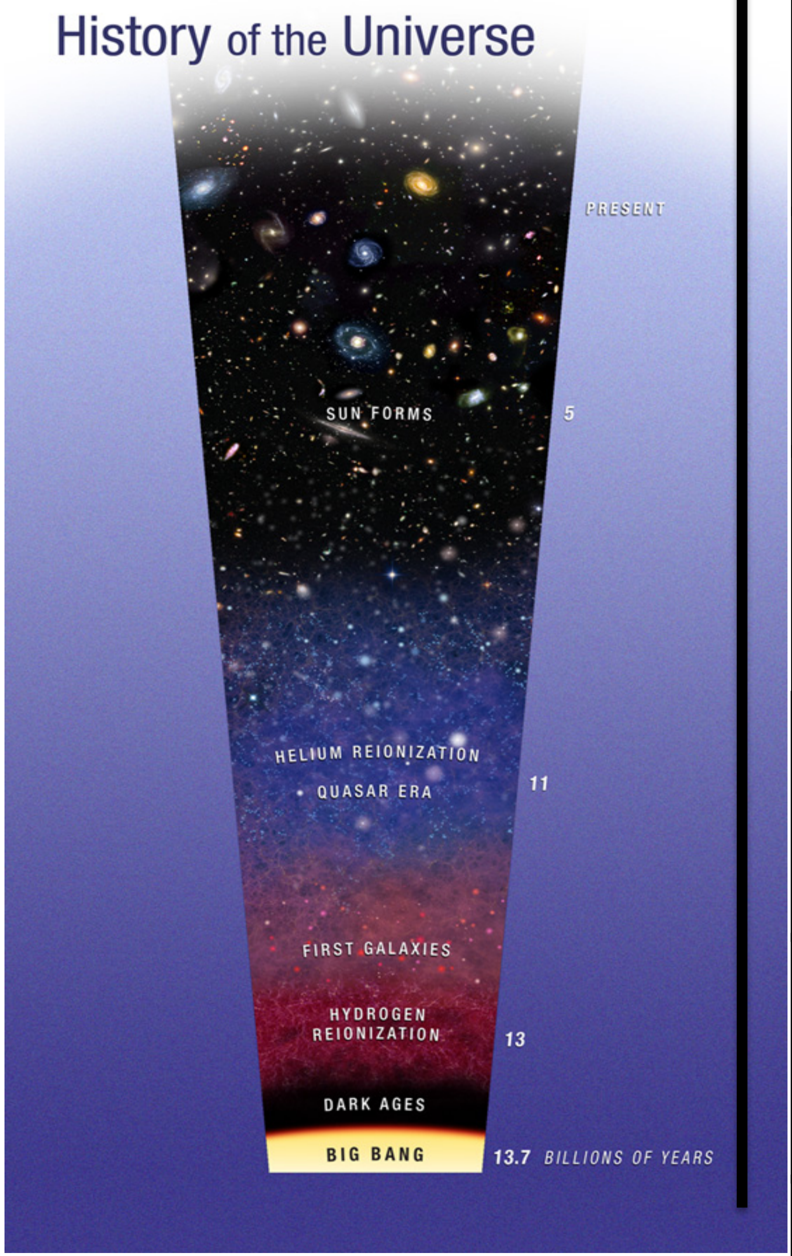
1933: DM proposal (Zwicky)

1929: Hubble law

1927: Lemaitre models
1922: Friedmann models

1915: Theory of GR (Einstein)

Linear scale



2001: H_0 distance ladder (HST Key Proj) (Freedman)
1998: Accelerated expansion (SNIa)

2005: Detection of the BAO peak (SDSS)
2001: LSS updated map (SDSS, 2dFGRS) → SDSS IV (2019)
2000: Cosmic shear (LSS of DM)→DES(2019)→Euclid(2022)
1986: The Great Wall (scale of homogeneity?)
1970: Large-scale structure (first z-surveys of galaxies)

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

1996: z-evolution of Star-formation rate (HDF, Madau)
1988: Galaxy counts (Tyson) (Olbers limit?,confusion limit)
1979: First gravitational lens system
1974: Mass function (Press, Schechter) (NL collapse)
1970: Rotation curves: DM also needed in galaxies (Rubin)

2010: Cosmological HI 21cm (Pen) → SKA (> 2022)
1970s: Discovery of Ly-a forest
1967: GRB discovery
1965: Gunn-Peterson test (the universe is highly ionized)
1963: Discovery of the first quasar (first high-z source)

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 needed)
1990: CMB Black-body (COBE) (Big Bang)

2016: Gravitational waves (LIGO) → LISA (2034)
2002: Neutrino oscillations

Program: **plan**

1. The Homogeneous Universe

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

2. 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)

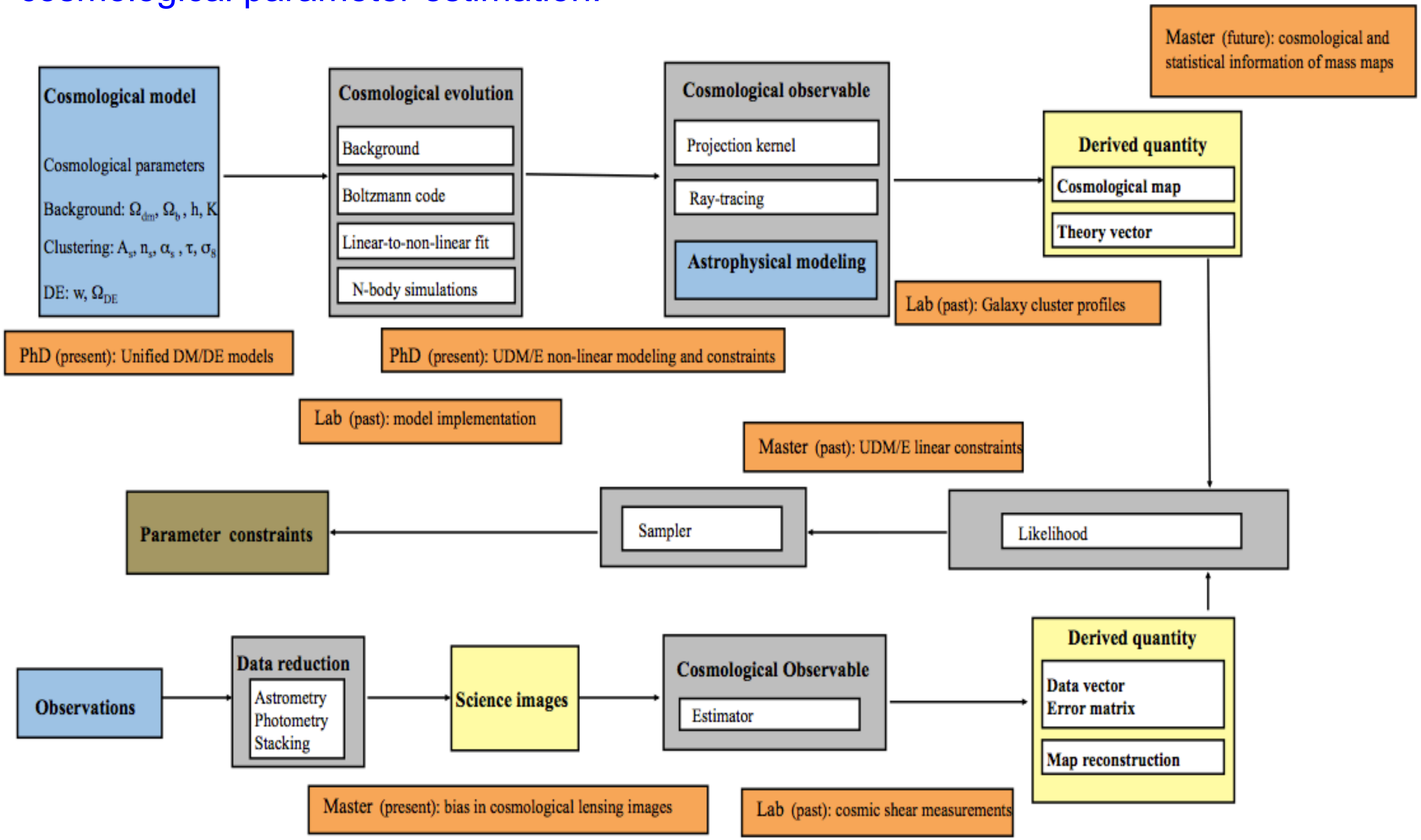
3. The Inhomogeneous Universe

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

4. Testing the Inhomogeneous Universe: *probes of structure*

    gravitational lensing (cosmic shear), galaxy clustering (redshift
    space distortions), CMB anisotropies

The goal of this program is to make a theoretical description of aspects of the cosmological model needed to derive quantities related to observables.
All topics of the program turn out to be elements of a general pipeline for cosmological parameter estimation:



Bibliography

Intermediate level : Main books

- D. Lyth and A. Liddle - *The primordial density perturbation* (2009), Ch. 6-12

- P. Peter and J.P. Uzan - *Primordial Cosmology* (2009), Ch. 3,5,6,7

- Y. Wang - *Dark Energy* (2010), Ch. 1,2 (a quick summary of most topics of the course), Ch. 4-7 (details on the main cosmological probes)

- L. Amendola and S. Tsujikawa - *Dark Energy* (2010), Ch. 1-5, 13,14

Intermediate level : Other books

- S. Weinberg - *Cosmology* (2008), Ch. 1,2,5,6,8,9

- J. Peacock - *Cosmological Physics* (1999), Ch. 15,16

- V. Mukhanov - *Physical Foundations of Cosmology* (2005), Ch. 1,2,6,7,9

- H.Mo, F. van deBosch and S.White - *Galaxy formation and evolution* (2011), Ch. 4-6

- S. Dodelson - *Gravitational Lensing* (2017) (focus on gravitational lensing only)

Simpler (but usually with more details on the homogeneous universe than the main books)

- P. Coles and F. Lucchin - *Cosmology* 2nd ed. (2002), Ch. 1,2,4,10-19

- S. Serjeant - *Observational Cosmology* (2010)

- M. Longair - *Galaxy Formation* 2nd ed. (2008), Ch. 1-8, 11-18

- G. Borner - *The Early Universe - facts and fiction* (2003), Ch. 1,2,4,10,11

- P. Schneider - *Extragalactic Astronomy and Cosmology - an introduction* (2006), Ch. 4,7,8

- B. Ryden - *Introduction to Cosmology* (2006)

More advanced

- S. Dodelson - *Modern Cosmology* (2003) (focus on the inhomogeneous universe theory and tests)

Lecture notes

You can search for some good lecture notes on-line. For example:

Intermediate level
Luca Amendola - *Introduction to Cosmology*
Daniel Baumann - *Cosmology*
Julien Lesgourgues - *Cosmology*

Simpler
Michael Hudson - *Cosmology*
Matthias Bartelmann - *Observing the Big Bang*
Matthias Bartelmann - *Cosmology*

More advanced
Oliver Piattella - *Lecture notes on cosmology*