Cosmologia Física

Ismael Tereno (IA)

2023

Welcome

The course

Lectures

Monday 11h00-13h00 C8.2.02

Monday 14h15-16h00 C8.2.03

Fénix page

Links to the lecture slides and homework will be given in this single page:

https://fenix.ciencias.ulisboa.pt/courses/cfis-847504421685273/lecture-notes

Contact

email: tereno@fc.ul.pt
office: C8.1.29

Evaluation

Homework (60%)   ~ 5 series of exercises ~ every 2-3 weeks

Presentation (30%)   20 minutes
(from a list of topics to be given, no written report required)

Margin (10%)

Replacements

António da Silva (if needed)

Diogo Castelão (PhD student for cosmology software)

The teacher

Cosmological gravitational lensing: the deflection of (galaxy) light in the Universe can be observed → discover the dark matter structures in the Universe and also other properties of the Universe (dark energy, behavior of gravity on large scales)

A matéria que não se via

A MATÉRIA negra, invisível mesmo para os telescópios poderosos, é um dos grandes mistérios da ciência — apesar de se supor que constitui 90 por cento da massa do Universo, nada se sabe sobre a sua composição ou distribuição. Da resolução deste enigma ficar-se-á a saber o destino do Universo. Se irá expandir-se para sempre ou se, como um elástico depois de puxado ao máximo, irá contrair-se devido à força de gravidade da matéria ou, ainda, se irá oscilar como uma bola de pingue-pongue entre a expansão e a contracção.

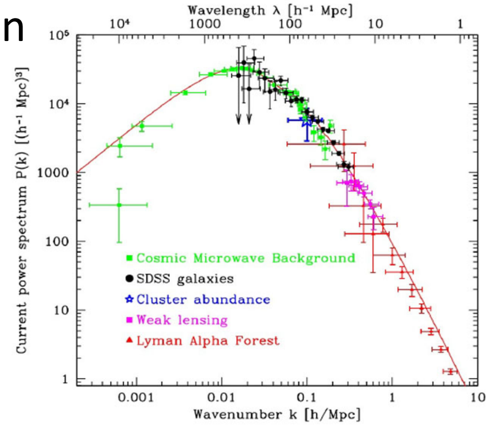
Uma equipa de 13 cientistas internacionais (liderada por Yannick Mellier, do Instituto de Astrofísica de Paris) obteve o primeiro mapa da distribuição da matéria escura numa larga secção do espaço.

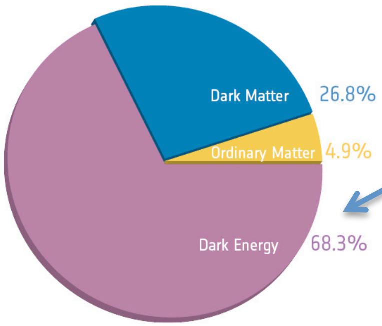
A simulação aqui publicada foi elaborada em computador a partir de imagens de 200 mil galáxias distantes. Os discos azuis alongados são as galáxias distantes e os filamentos vermelhos e brancos a matéria escura. As imagens das galáxias aparecem alongadas, de forma paralela aos filamentos de matéria escura, devido à força de gravidade destes. Ao medir as distorções na luz emitida pelas galáxias, pôde "ver-se" a matéria escura. •

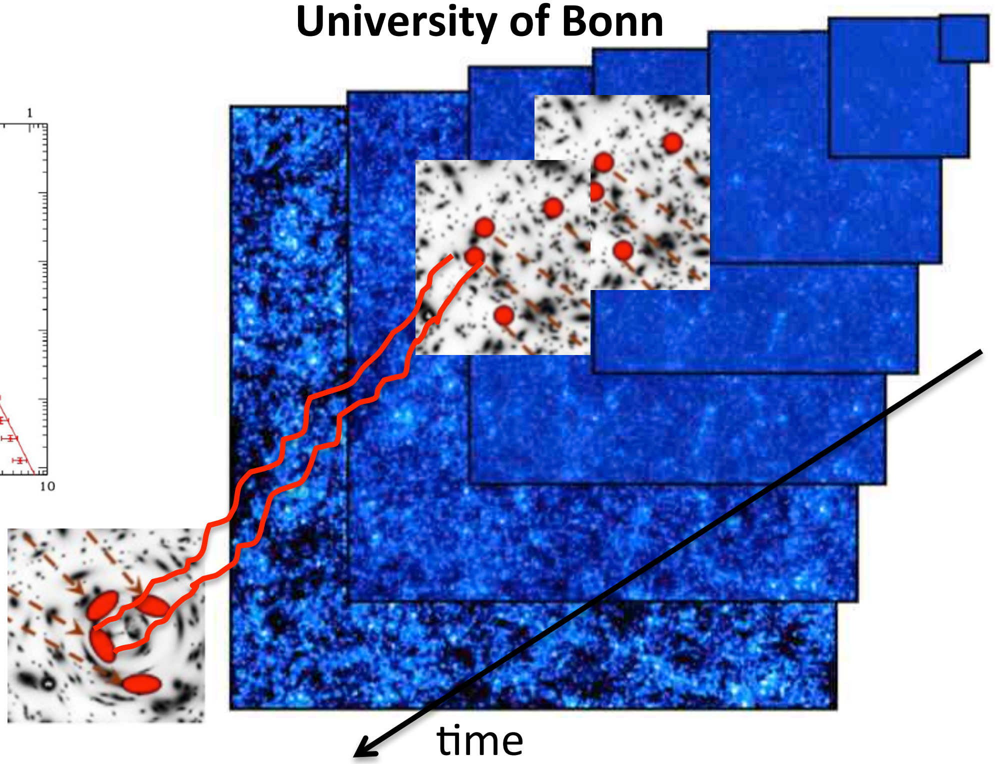
(2000)

Institut d'Astrophysique de Paris

Argelander Institut fuer Astronomie, University of Bonn

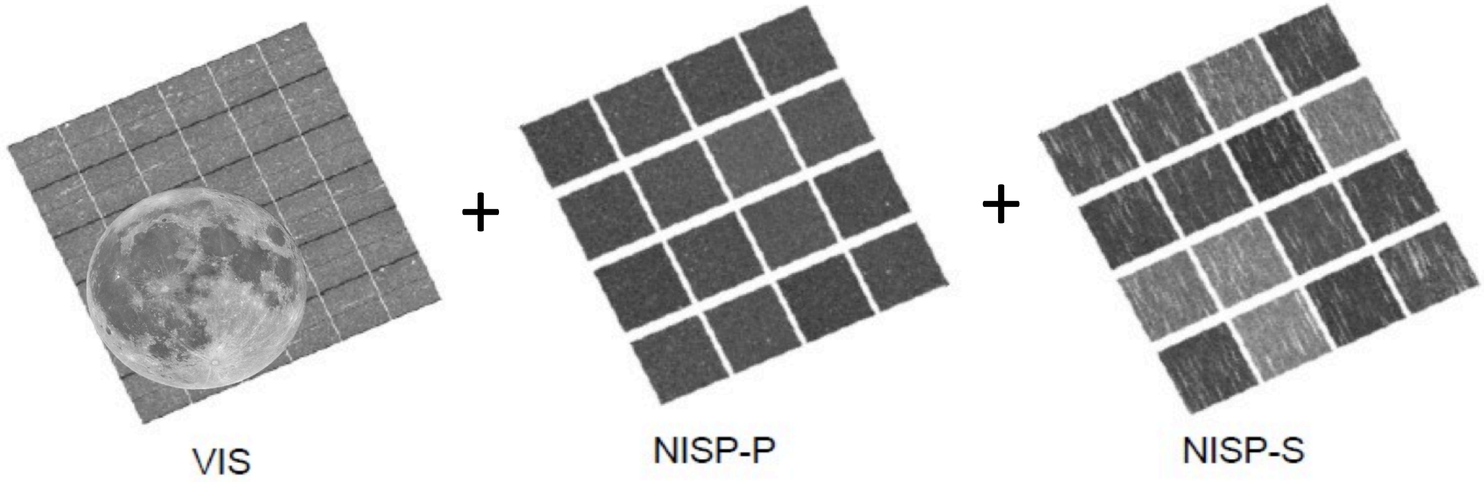






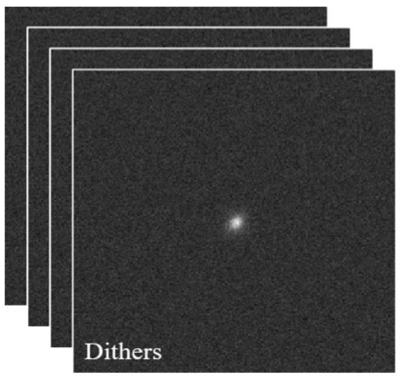
Euclid space mission:

a sequence of 45 000 observations over the sky during 6 years



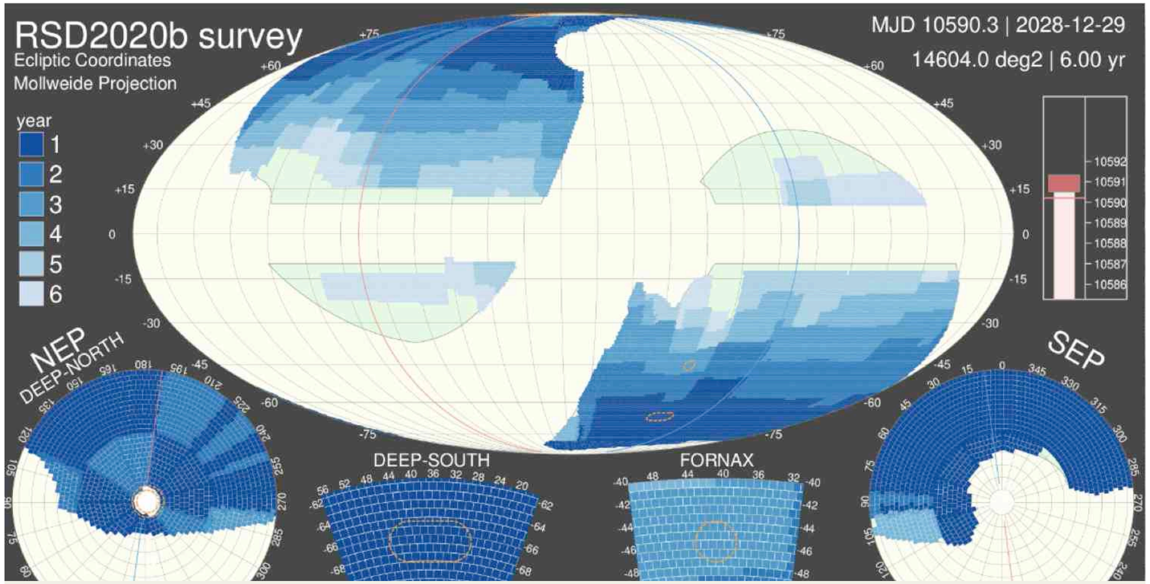
Lead of the Survey Operations Support Team

x 4



→ 1 Euclid Observation = 1h 15'

~ 20 observations / day



https://www.youtube.com/watch?v=R5Q85AbP2nY

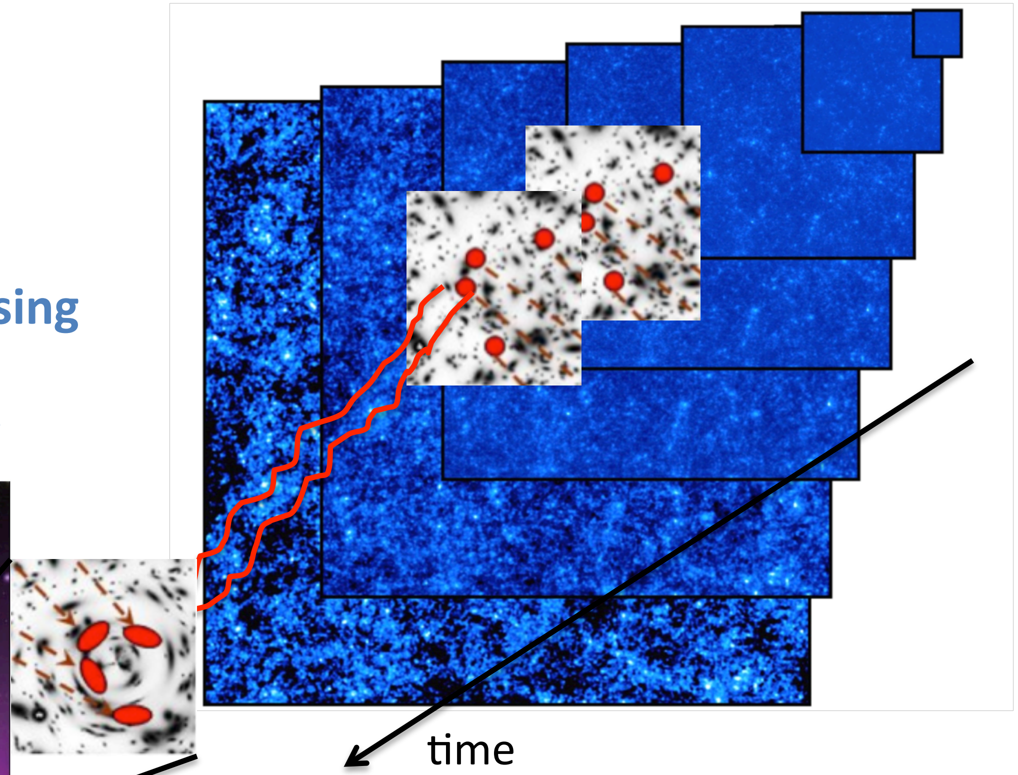
Euclid photometric survey:

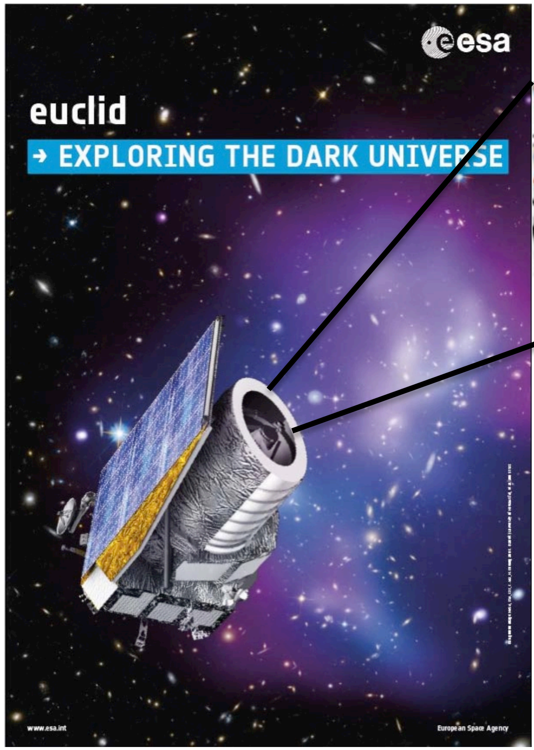
weak gravitational lensing of distant galaxies

Euclid finds source galaxies
(far in the Universe, z > 0.7 - 2.0)

that are subject to gravitational lensing

and observes their distorted images





to infer the dark matter structures (the lenses) at various distances (different epochs in the evolution of the Universe)
→ discover the properties of dark energy.

Euclid Preparation XXIX: Forecasts for 10 different higher-order weak lensing statistics

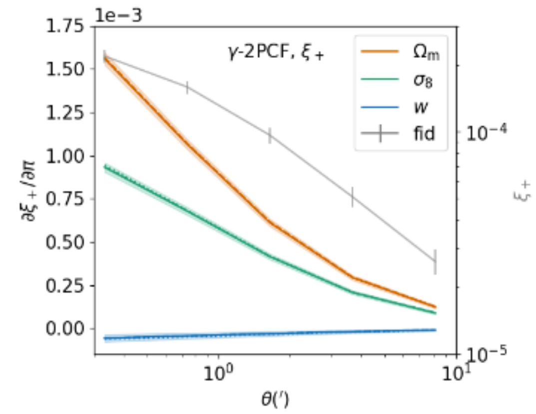
Euclid Collaboration*: V. Ajani[1,2], M. Baldi[3,4,5], A. Barthelemy[6], A. Boyle[7], P. Burger[8], V. F. Cardone[9,10], S. Cheng[11], S. Codis[7], C. Giocoli[4,5], J. Harnois-Déraps[12], S. Heydenreich[8], V. Kansal[7], M. Kilbinger[1], L. Linke[8], C. Llinares[13,14], N. Martinet[15], C. Parroni[10], A. Peel[16], S. Pires[7], L. Porth[8], I. Tereno[13,14], C. Uhlemann[12], M. Vicinanza[10], S. Vinciguerra[17], N. Aghanim[18], N. Auricchio[4], D. Bonino[19], E. Branchini[20,21], M. Brescia[22], J. Brinchmann[23], S. Camera[24,25,19], V. Capobianco[19], C. Carbone[26], J. Carretero[27,28], F. J. Castander[29,30], M. Castellano[10], S. Cavuoti[31,32], A. Cimatti[33], R. Cledassou[34,35], G. Congedo[36], C.J. Conselice[37], L. Conversi[38,39], L. Corcione[19], F. Courbin[16], M. Cropper[40], A. Da Silva[13,41], H. Degaudenzi[42], A. M. Di Giorgio[43], J. Dinis[41,13], M. Douspis[18], F. Dubath[42], X. Dupac[38], S. Farrens[1], S. Ferriol[44], P. Fosalba[30,29], M. Frailis[45], E. Franceschi[4], S. Galeotta[45], B. Garilli[26], B. Gillis[36], A. Grazian[46], F. Grupp[47,48], H. Hoekstra[49], W. Holmes[50], A. Hornstrup[51,52], P. Hudelot[53], K. Jahnke[54], M. Jhabvala[55], M. Kümmel[48], T. Kitching[40], M. Kunz[56], H. Kurki-Suonio[57,58], P. B. Lilje[59], I. Lloro[60], E. Maiorano[4], O. Mansutti[45], O. Marggraf[8], K. Markovic[50], F. Marulli[3,4,5], R. Massey[61], S. Mei[62], Y. Mellier[63,53], M. Meneghetti[4,5], M. Moresco[3,4], L. Moscardini[3,4,5], S.-M. Niemi[64], J. Nightingale[61], T. Nutma[49,65], C. Padilla[27], S. Paltani[42], K. Pedersen[66], V. Pettorino[1], G. Polenta[67], M. Poncet[34], L. A. Popa[68], F. Raison[47], A. Renzi[69,70], J. Rhodes[50], G. Riccio[31], E. Romelli[45], M. Roncarelli[4], E. Rossetti[71], R. Saglia[48,47], D. Sapone[72], B. Sartoris[48,45], P. Schneider[8], T. Schrabback[73,8], A. Secroun[74], G. Seidel[54], S. Serrano[30,75], C. Sirignano[69,70], L. Stanco[70], J.-L. Starck[7], P. Tallada-Crespí[76,28], A.N. Taylor[36], R. Toledo-Moreo[77], F. Torradeflot[76,28], I. Tutusaus[78], E. A. Valentijn[65], L. Valenziano[4,5], T. Vassallo[45], Y. Wang[79], J. Weller[48,47], G. Zamorani[4], J. Zoubian[74], S. Andreon[80], S. Bardelli[4], A. Boucaud[62], E. Bozzo[42], C. Colodro-Conde[81], D. Di Ferdinando[5], G. Fabbian[82,83], M. Farina[43], J. Graciá-Carpio[47], E. Keihänen[84], V. Lindholm[57,58], D. Maino[85,26,86], N. Mauri[33,5], C. Neissner[27], M. Schirmer[54], V. Scottez[53,87], E. Zucca[4], Y. Akrami[88,89,90,91,92], C. Baccigalupi[93,94,45,95], A. Balaguera-Antolínez[81,96], M. Ballardini[97,98,4], F. Bernardeau[99,63], A. Biviano[45,94], A. Blanchard[78], S. Borgani[45,100,95,94], A. S. Borlaff[101], C. Burigana[97,102,103], R. Cabanac[78], A. Cappi[4,104], C. S. Carvalho[14], S. Casas[105], G. Castignani[3,4], T. Castro[45,95,94], K. C. Chambers[106], A. R. Cooray[107], J. Coupon[42], H.M. Courtois[108], S. Davini[109], S. de la Torre[15], G. De Lucia[45], G. Desprez[42,110], H. Dole[18], J. A. Escartin[47], S. Escoffier[74], I. Ferrero[59], F. Finelli[4,103], K. Ganga[62], J. Garcia-Bellido[88], K. George[6], F. Giacomini[5], G. Gozaliasl[57], H. Hildebrandt[111], A. Jimenez Muñoz[112], B. Joachimi[113], J. J. E. Kajava[114], C. C. Kirkpatrick[84], L. Legrand[56], A. Loureiro[36,92], M. Magliocchetti[43], R. Maoli[17,10], S. Marcin[115], M. Martinelli[10,9], C. J. A. P. Martins[116,23], S. Matthew[36], L. Maurin[18], R. B. Metcalf[3,4], P. Monaco[100,45,95,94], G. Morgante[4], S. Nadathur[117], A.A. Nucita[118,119,120], V. Popa[68], D. Potter[121], A. Pourtsidou[36,122], M. Pöntinen[57], P. Reimberg[53], A.G. Sánchez[47], Z. Sakr[123,124,78], A. Schneider[121], E. Sefusatti[45,95,94], M. Sereno[4,5], A. Shulevski[49,65], A. Spurio Mancini[40], J. Steinwagner[47], R. Teyssier[125], J. Valiviita[57,58], A. Veropalumbo[85], M. Viel[93,94,45,95], I. A. Zinchenko[48]

(Affiliations can be found after the references)

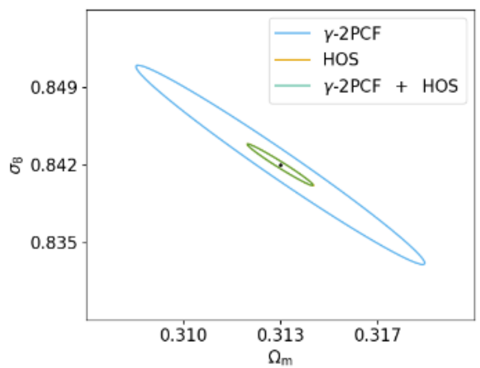
ABSTRACT

Recent cosmic shear studies have shown that higher-order statistics (HOS) developed by independent teams now outperform standard two-point estimators in terms of statistical precision thanks to their sensitivity to the non-Gaussian features of large-scale structure. The aim of the Higher-Order Weak Lensing Statistics (HOWLS) project is to assess, compare, and combine the constraining power of 10 different HOS on a common set of *Euclid*-like mocks, derived from N-body simulations. In this first paper of the HOWLS series we compute the non-tomographic (Ω_m, σ_8) Fisher information for one-point probability distribution function, peak counts, Minkowski functionals, Betti numbers, persistent homology Betti numbers and heatmap, and scattering transform coefficients, and compare them to the shear and convergence two-point correlation functions in the absence of any systematic bias. We also include forecasts for three implementations of higher-order moments, but these cannot be robustly interpreted as the Gaussian likelihood assumption breaks down for these statistics. Taken individually, we find that each HOS outperforms the two-point statistics by a factor of around 2 in the precision of the forecasts with some variations across statistics and cosmological parameters. When combining all the HOS, this increases to a 4.5 times improvement, highlighting the immense potential of HOS for cosmic shear cosmological analyses with *Euclid*. The data used in this analysis are publicly released with the paper.

Key words. Gravitational lensing: weak – Methods: statistical – Surveys – Cosmology: large-scale structure of Universe, cosmological parameters

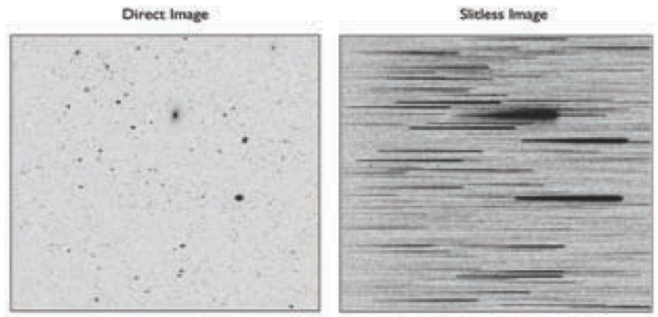


Statistics	individual		
	$\delta\sigma_8/\sigma_8$	$\delta\Omega_m/\Omega_m$	FoM
2nd order statistics			
γ-2PCF	0.75%	1.17%	2.56×10^5
κ-2PCF	1.13%	1.88%	1.40×10^5
HOS (Gaussian)			
κ-PDF	0.42%	0.70%	4.96×10^5
Peaks	0.45%	0.70%	4.28×10^5
MFs	0.35%	0.74%	2.60×10^5
BNs	0.72%	1.27%	9.82×10^4
Pers. BNs	0.32%	0.60%	6.95×10^5
Pers. heat.	0.56%	0.86%	3.44×10^5
ST	0.39%	0.63%	4.95×10^5
All HOS	0.16%	0.27%	4.96×10^6
HOS (non-Gaussian)			
HOM	0.25%	0.65%	6.12×10^5
$\langle M_{ap}^3\rangle$	0.73%	1.56%	2.50×10^5
$\langle M_{ap}^n\rangle$	0.14%	0.27%	2.13×10^6

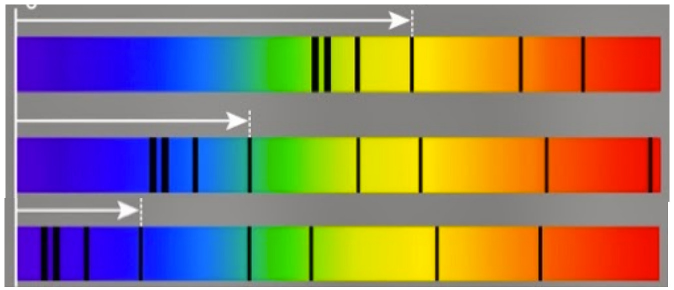


Euclid spectroscopic survey:

galaxy clustering of distant galaxies

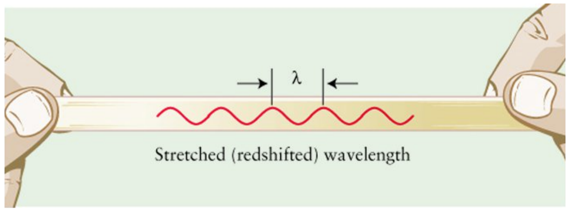


Euclid measures the **spectra** of the galaxies
(far in the Universe, z > 0.7 - 2.0)

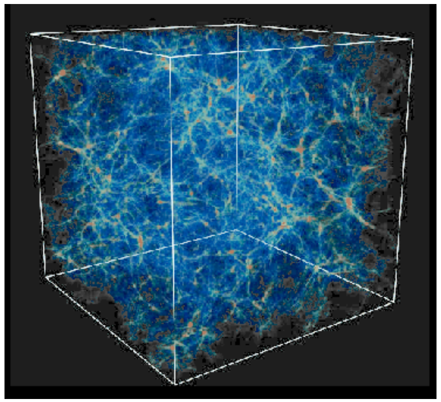


whose frequencies are shifted (the **redshift**)

by the **expansion** of the Universe
(and peculiar velocities)



to determine their
precise distances
(**3D positions**)



The combination of position (GC) and light propagation (WL) information allows us to test gravity.

Euclid launch

next summer!

Portugal is very involved in this mission

CCB, Lisbon, 2016

The students

	54506	Afonso Mexia Gorjão
	54497	Alexandre Miguel Baptista Branco
	54526	Bruno Alexandre Alves Lourenço
	49380	Bruno Manuel Teixeira Carrazedo
	59464	Carlota Maria Pinto da Luz
	60385	Daniel Filipe Dias Capela
	54512	David Júlio da Silva Pereira
	54502	Duarte Gerardo Branco
	54507	Gabriel Inácio Róis
	54524	Guilherme Holbeche Beirão Caldeira Monsanto
	54501	Henrique Duarte Costa
	54513	Inês Moroso Alexandre Serra
	51112	João Oliveira Sena
	54525	Maria Eduarda Manfrinato Pimentel
	13387	Pedro Alexandre Ruivo
	54503	Pedro dos Santos Gil
	51140	Rafael Santos Orelhas
	54498	Rita Matias Oliveira dos Reis
	61282	Selina Maria Ortner
	53224	Simão Marques da Silva Nunes
	61276	Thomas Bode

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

Two courses on physical cosmology in FCUL:

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

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

Universo primitivo

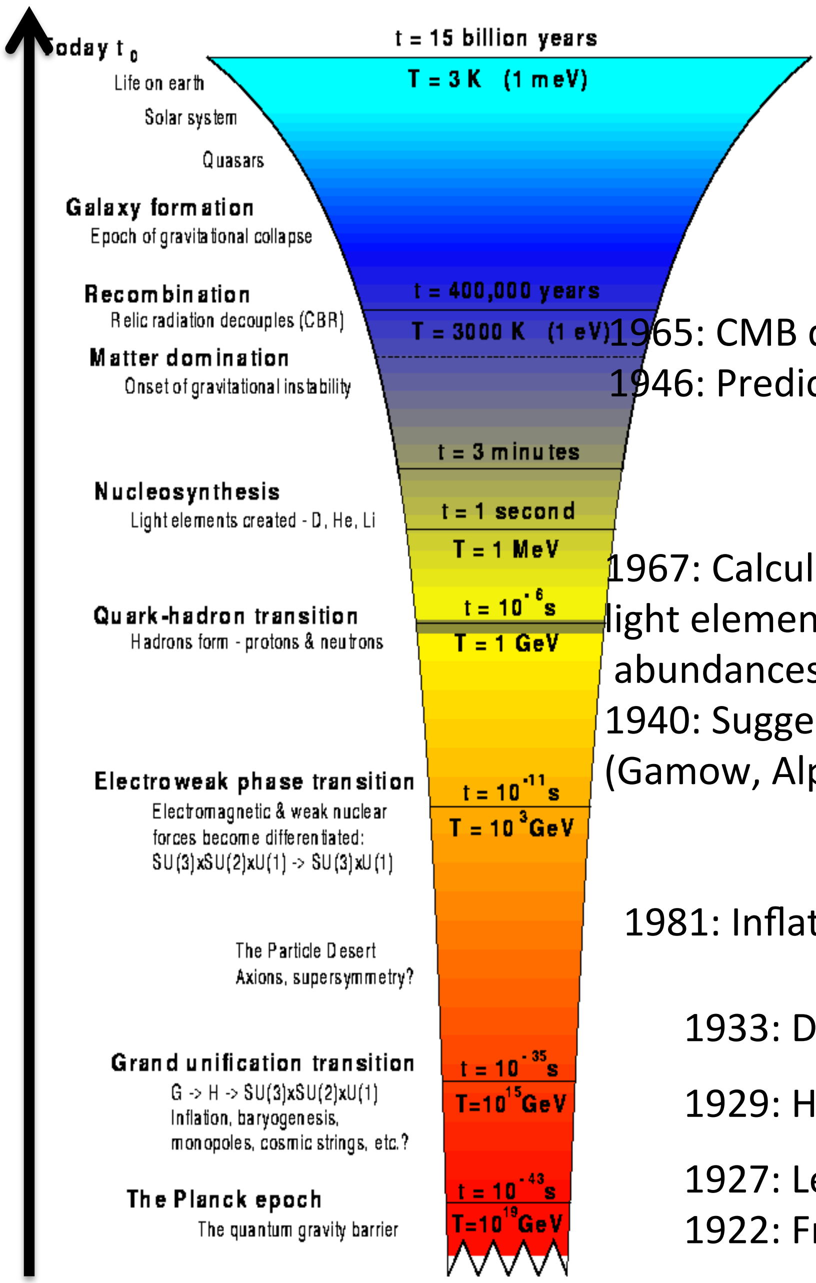
Cosmologia Física

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)

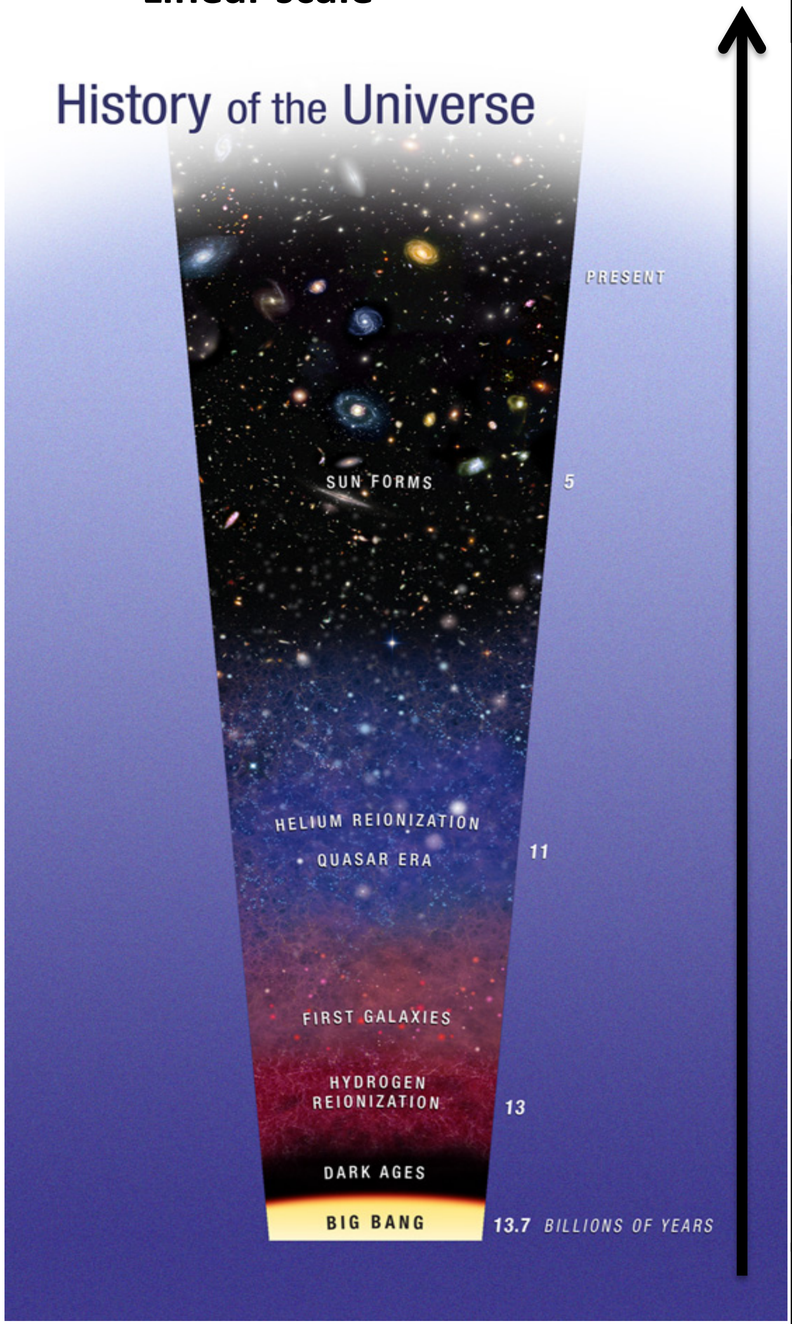
1929: Hubble law

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: Weak lensing (LSS of DM) → DES (2019) → Euclid (2023)
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 (> 2027)
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 (2037)
2002: Neutrino oscillations

Program: **contents**

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

COSMOLOGIA FÍSICA 2023

LECTURE NOTES

Introduction
00: A physical model for the Universe (Feb 13)

Fundamental concepts
01: The zeroth order Universe (Feb 13)
02: The metric and its degrees of freedom
03: The cosmological fluid
04: The background evolution
05: The energy density budget
06: The density contrast random field
07: Statistical properties of the density contrast field
08: Parameterization of the density contrast field

Structure formation
09: Newtonian perturbed fluid equations
10: Dark matter linear clustering
11: Baryonic matter linear clustering
12: Non-linear clustering
13: Perturbations in general relativity
14: The Einstein-Boltzmann equations

Cosmological observations
15: Cosmological probes
16: Supernova surveys
17: Statistical inference
18: Cosmological parameter estimation
19: Cosmic microwave background
20: Galaxy clustering
21: Gravitational lensing
22: Weak gravitational lensing

Cosmology software
23: CLASS (numerical computation of cosmological functions)
24: MontePython (statistical inference)

HOMEWORK

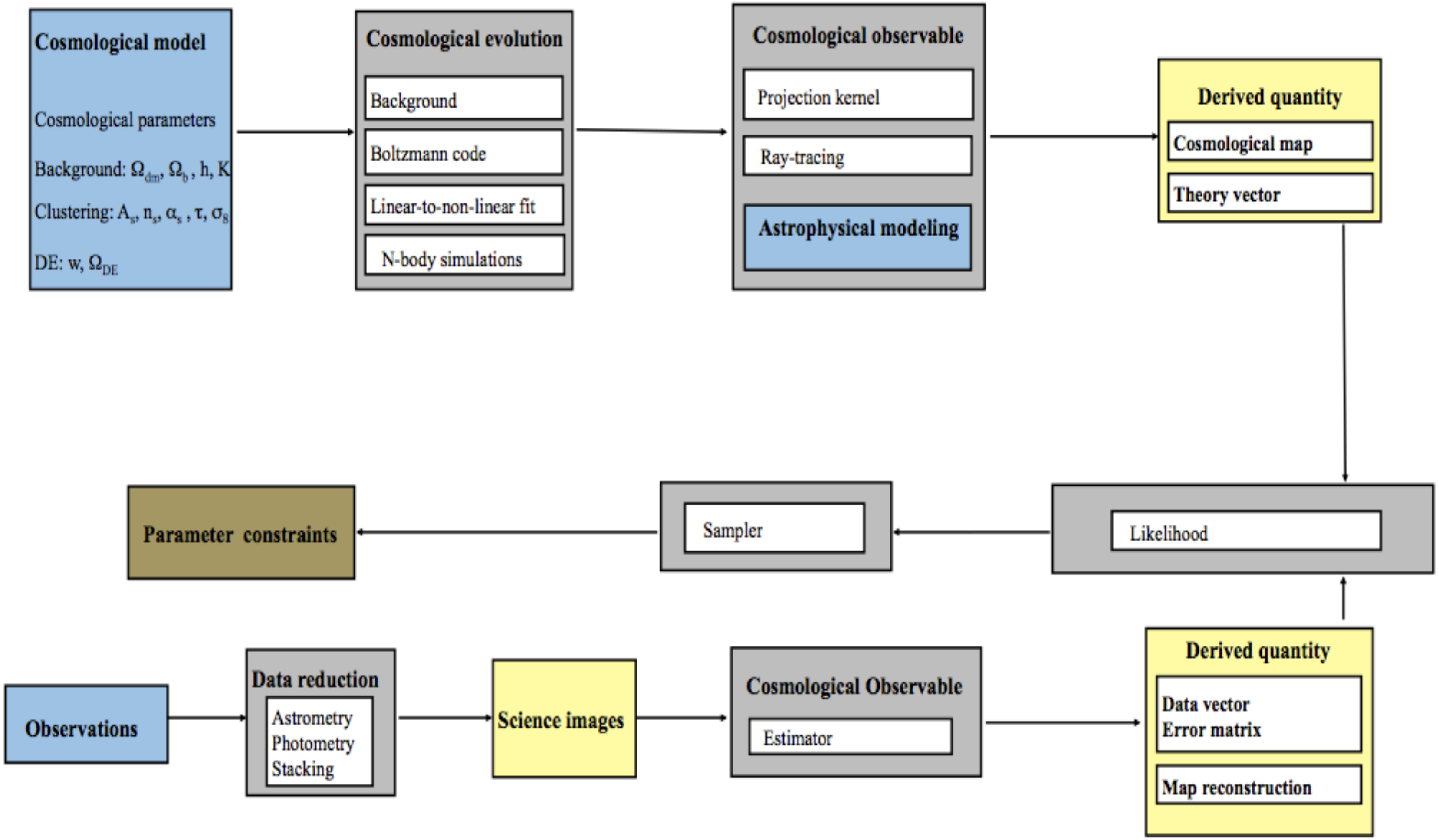
HW1: due Mar 6
HW2
HW3
HW4
HW5

TOPICS for the final presentations

List of topics

https://fenix.ciencias.ulisboa.pt/courses/cfis-847504421685273/lecture-notes

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



Bibliography

Main resource:

- I. Tereno - Cosmologia Fisica slides (~1000 pages)

Books of 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

Bibliography

Books of 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 de Bosch and S.White - *Galaxy formation and evolution* (2011), Ch. 4-6

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

Books of advanced level

- S. Dodelson and F. Schmidt - *Modern Cosmology* 2nd ed. (2021) (focus on the inhomogeneous universe theory and tests)

Books of introductory level

(they usually have more details on the homogeneous universe than the more advanced 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)

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*

Advanced level
Oliver Piattella - Lecture notes on cosmology

Introductory level
Michael Hudson - *Cosmology*
Matthias Bartelmann - *Observing the Big Bang*
Matthias Bartelmann - *Cosmology*

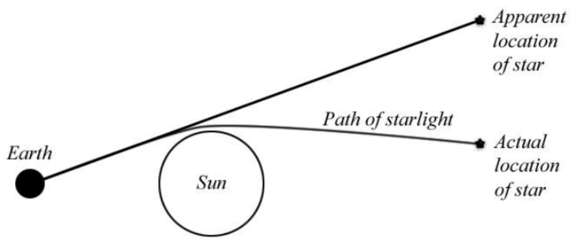
Introduction

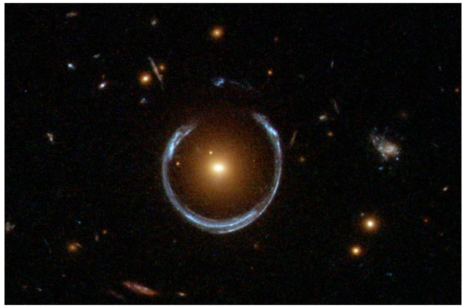
A physical model for the Universe

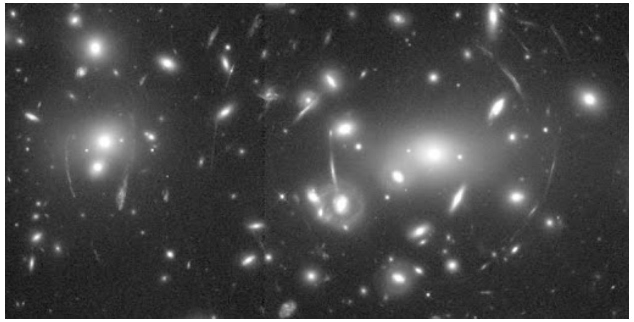
Physical Cosmology: a physical model for the Universe

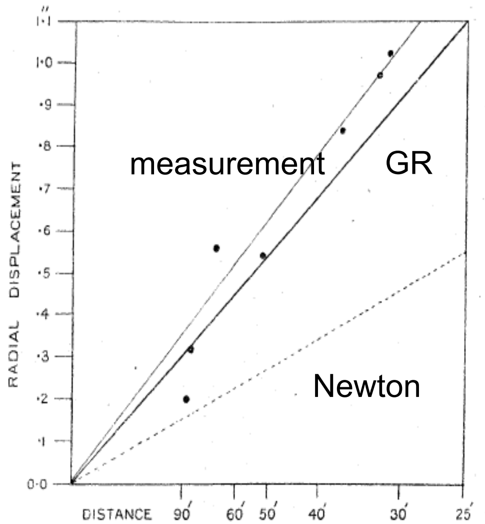
Gravity (**General Relativity**)

Tested on various scales



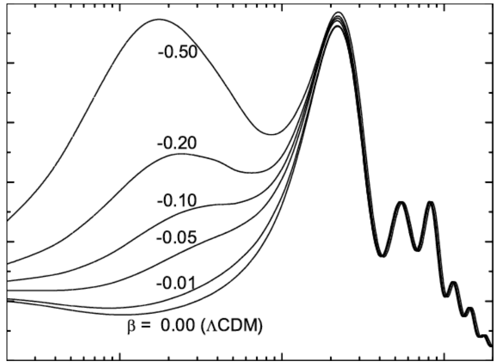






→ metric

→ Einstein equations

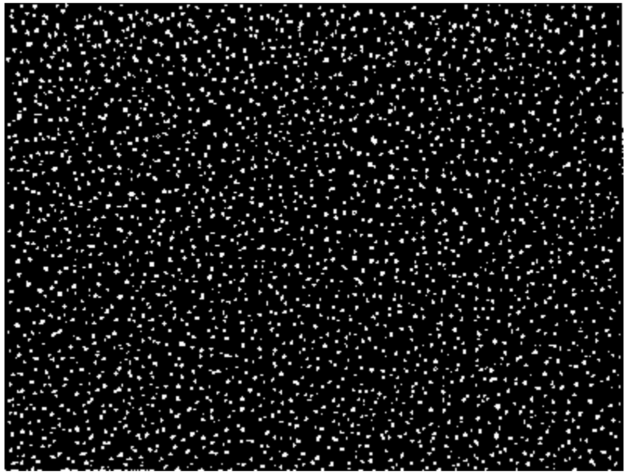


Awarded to **Albert Einstein** "for his services to Theoretical Physics, (and especially for his discovery of the law of the photoelectric effect)." (1/1)

1921

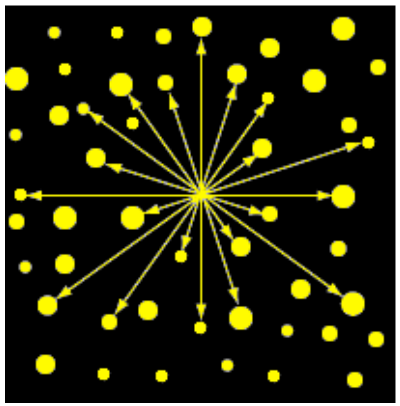
+ **Cosmological principle**

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



+ **Olbers paradox**

→ scale factor a must evolve

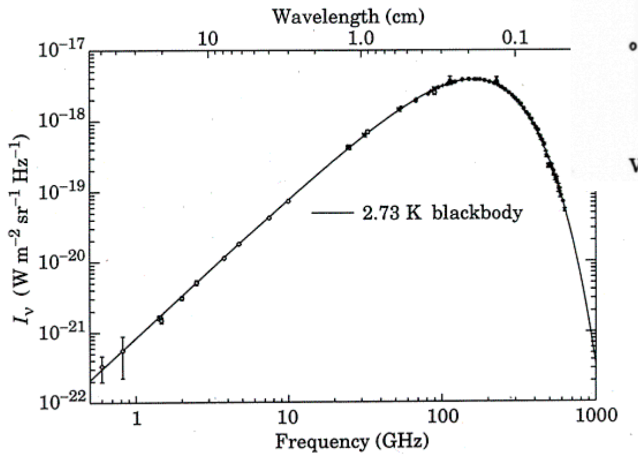


+ **Observations of the recession of galaxies**

→ Expansion   Big Bang

→ Thermal history

→ Existence of a universal background radiation: CMB



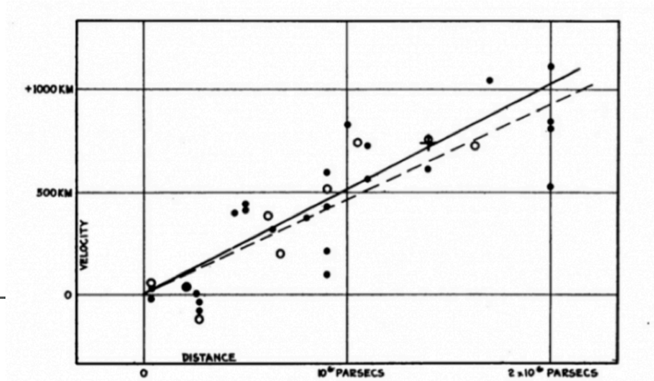
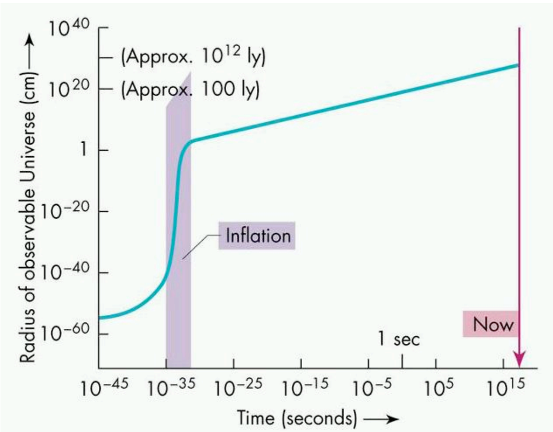


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

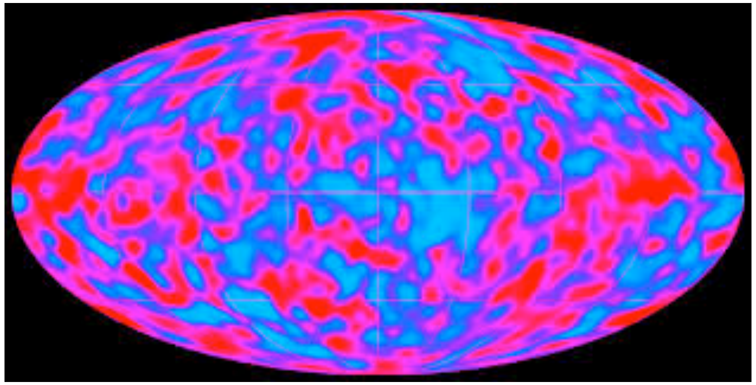
→ horizon, flatness and coincidence problems: solved by the **Inflation** mechanism



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

1978

+ Observation of anisotropies in the CMB



→ Existence of perturbations to the cosmological principle

→ Problem of the origin of the perturbations

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

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)

2006

+ Measurement of the anisotropies in the CMB

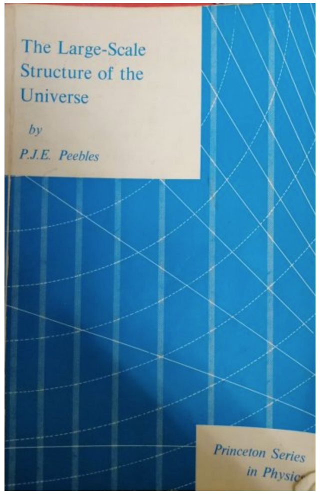
Their amplitude is very small $\delta_T \sim 10^{-5}$ → very small clustering at z=1100 ($\delta_b \sim 10^{-5}$)

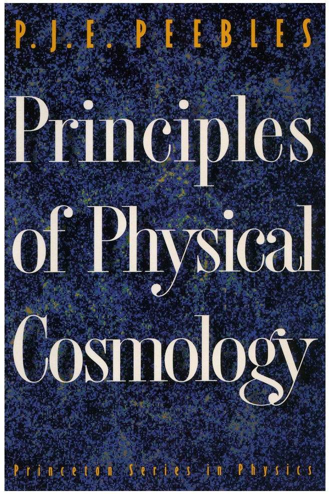
+ Gravitational collapse is small (δ_b grows only a factor $\sim 10^3$ until z=0)

+ 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**





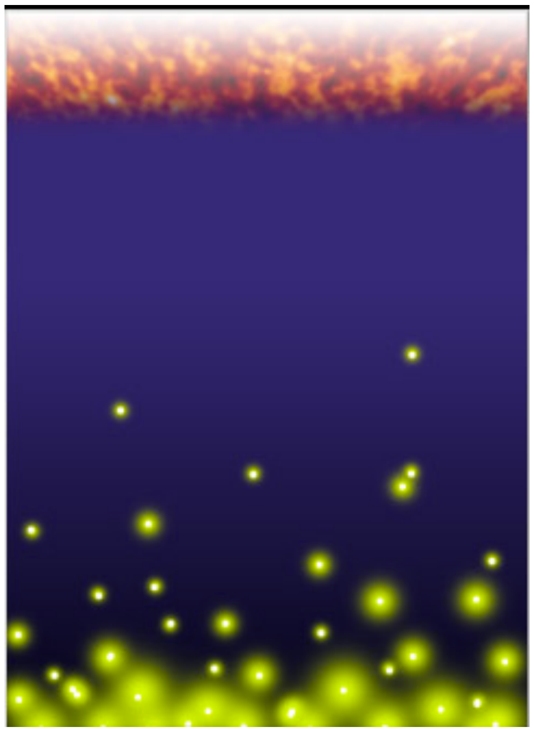
Awarded to **P. James. E. Peebles** ”for theoretical discoveries in physical cosmology” (1/2)

2019

+ **Non-linear gravitational collapse**

→ Formation of dark matter halos and collapse of baryonic matter on those halos (neutral Hydrogen HI clouds that condense and form the first stars)

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



+ 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, losing pressure 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.

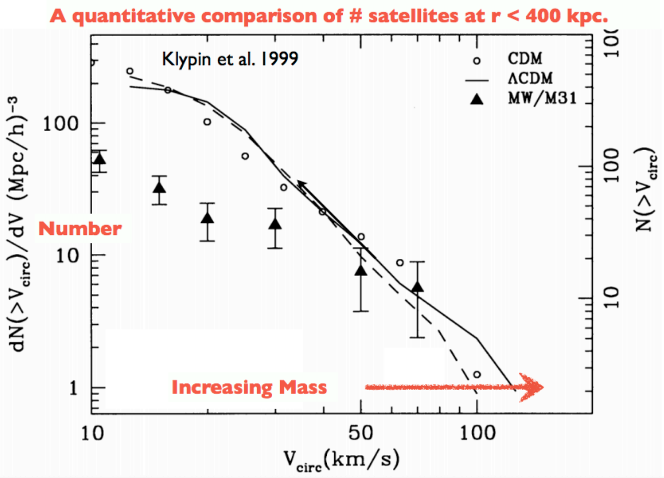
+ **Observations of properties of small-scale structure** (kpc)

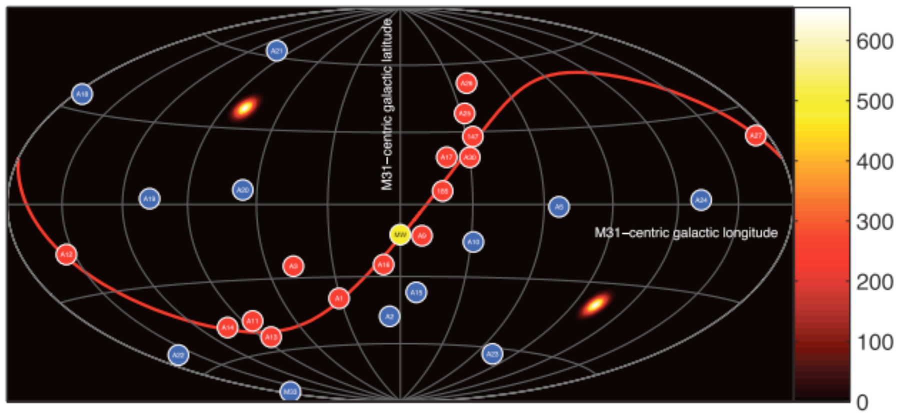
→ Problem of the radial density profile of structures (cusp/core)

→ 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 Supernovas

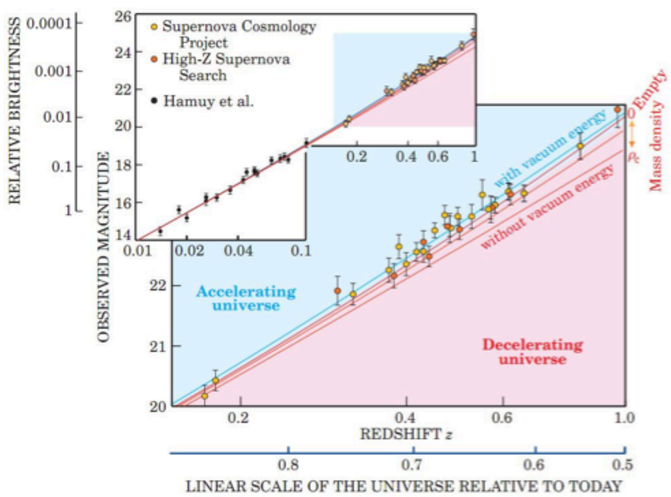
SN at all redshifts are fainter (more distant?) than expected from the $d_L(z)$ predicted by the CDM cosmological model

→ 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**

→ The theory of gravitation on large scales is not GR

New "modified gravity" theory not found yet

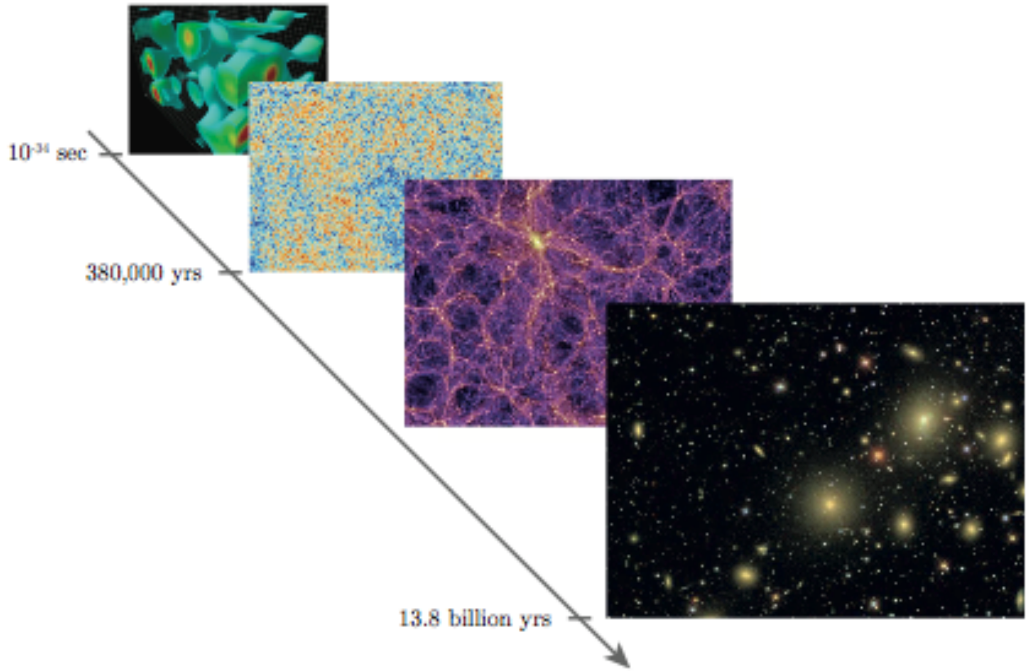


Awarded to **Saul Perlmutter**, **Brian P. Schmidt** and **Adam G. Riess** "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." (1/2 + 1/4 + 1/4)

2011

In Summary: 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 XXI^st century and it is known as ΛCDM.

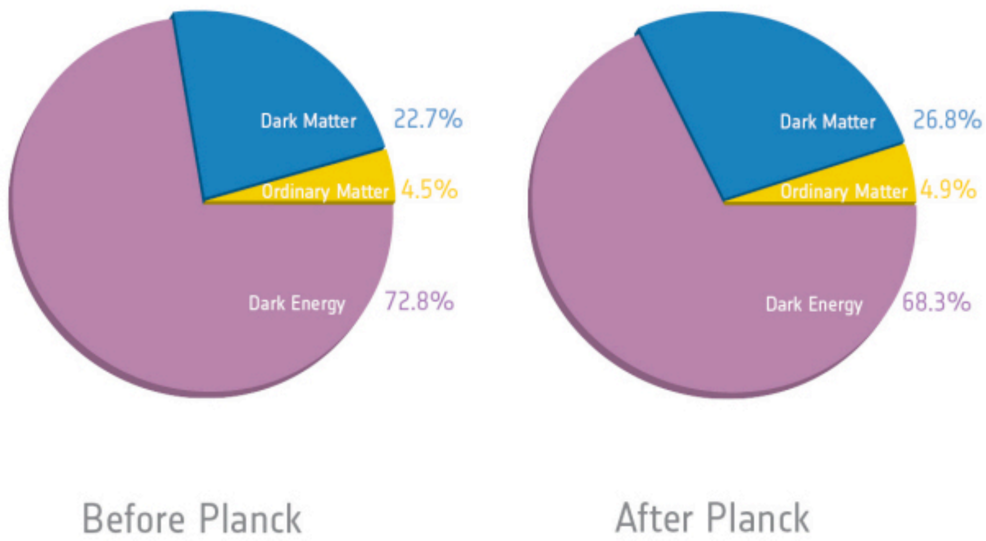


ΛCDM is a complex model

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 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		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	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

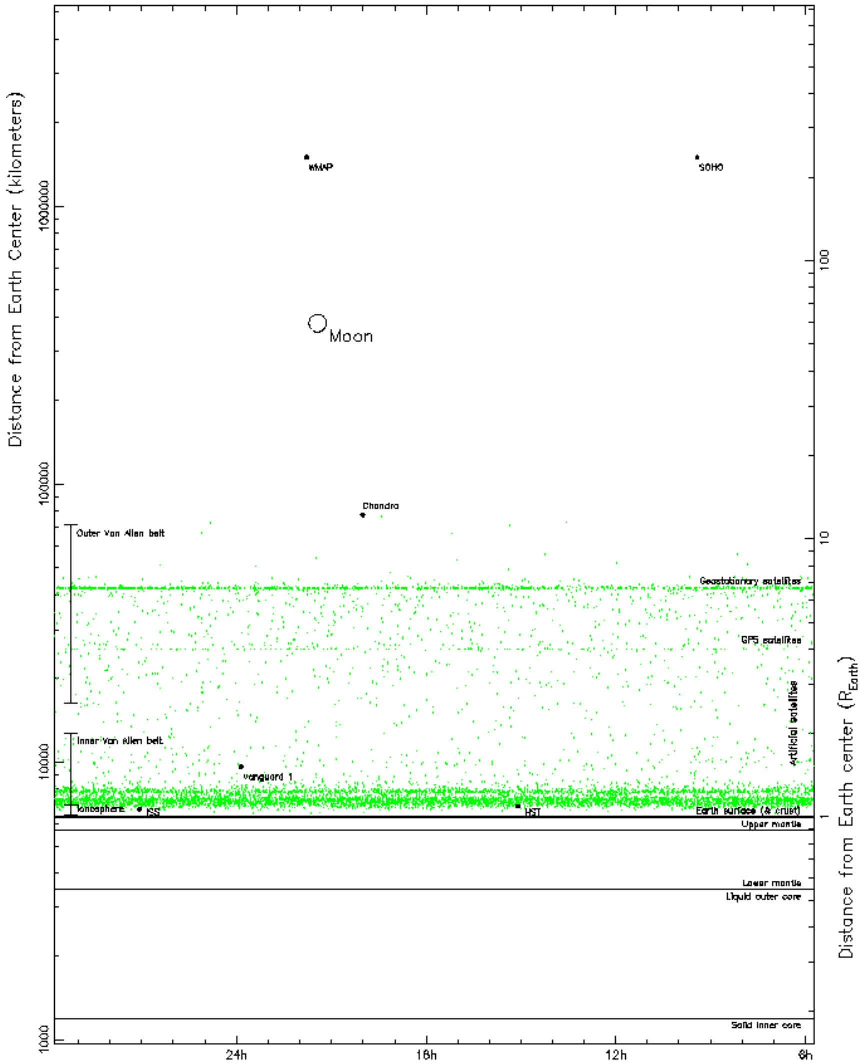
fundamental cosmological parameters

nuisance parameters (of the particular cosmological probe)

derived cosmological parameters

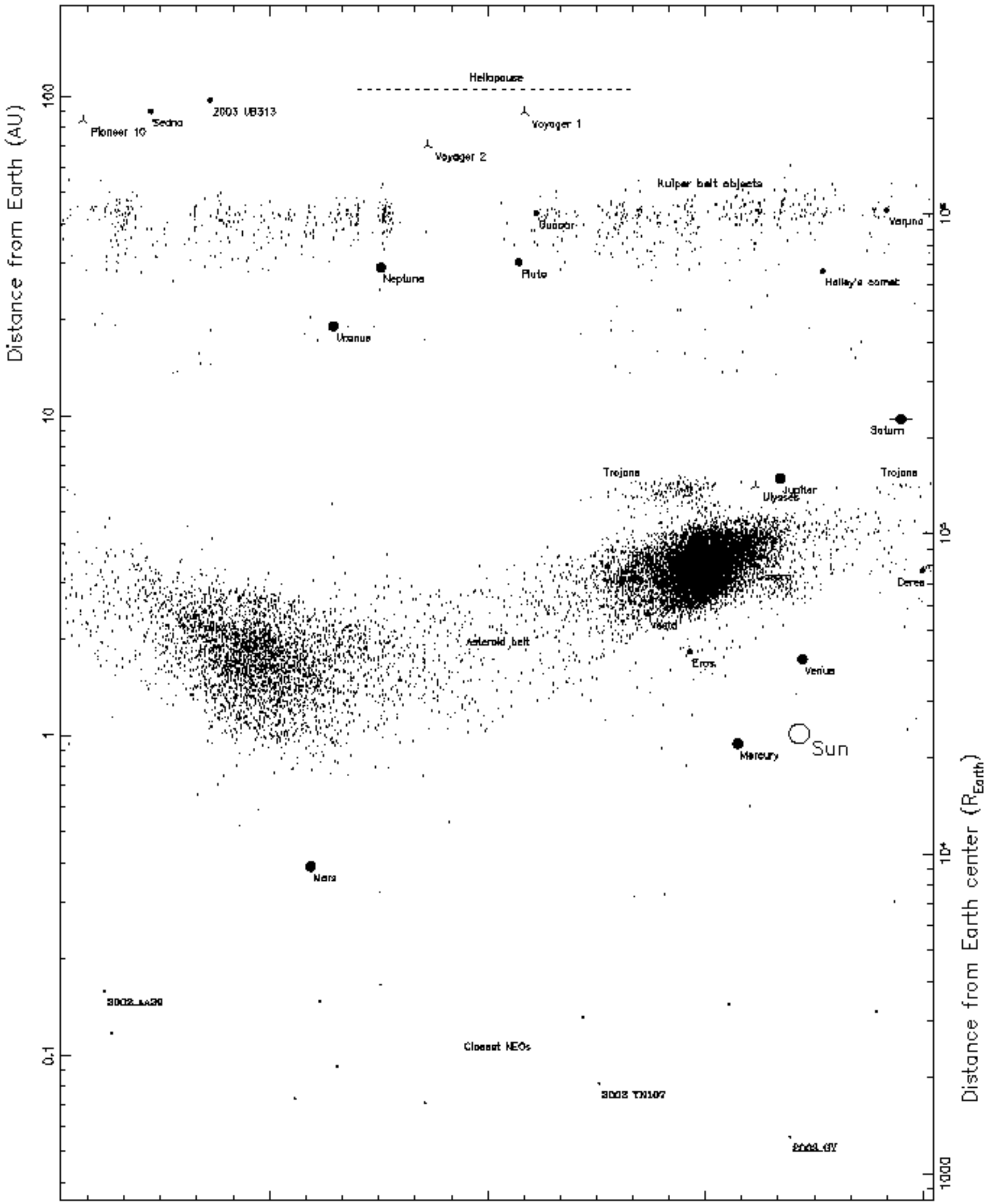
Map of the observed Universe - logarithmic scale and showing the astrophysical objects in their actual coordinates

(Gott et al. 2005) http://www.astro.princeton.edu/universe/



Distance from the centre of the Earth (Km)

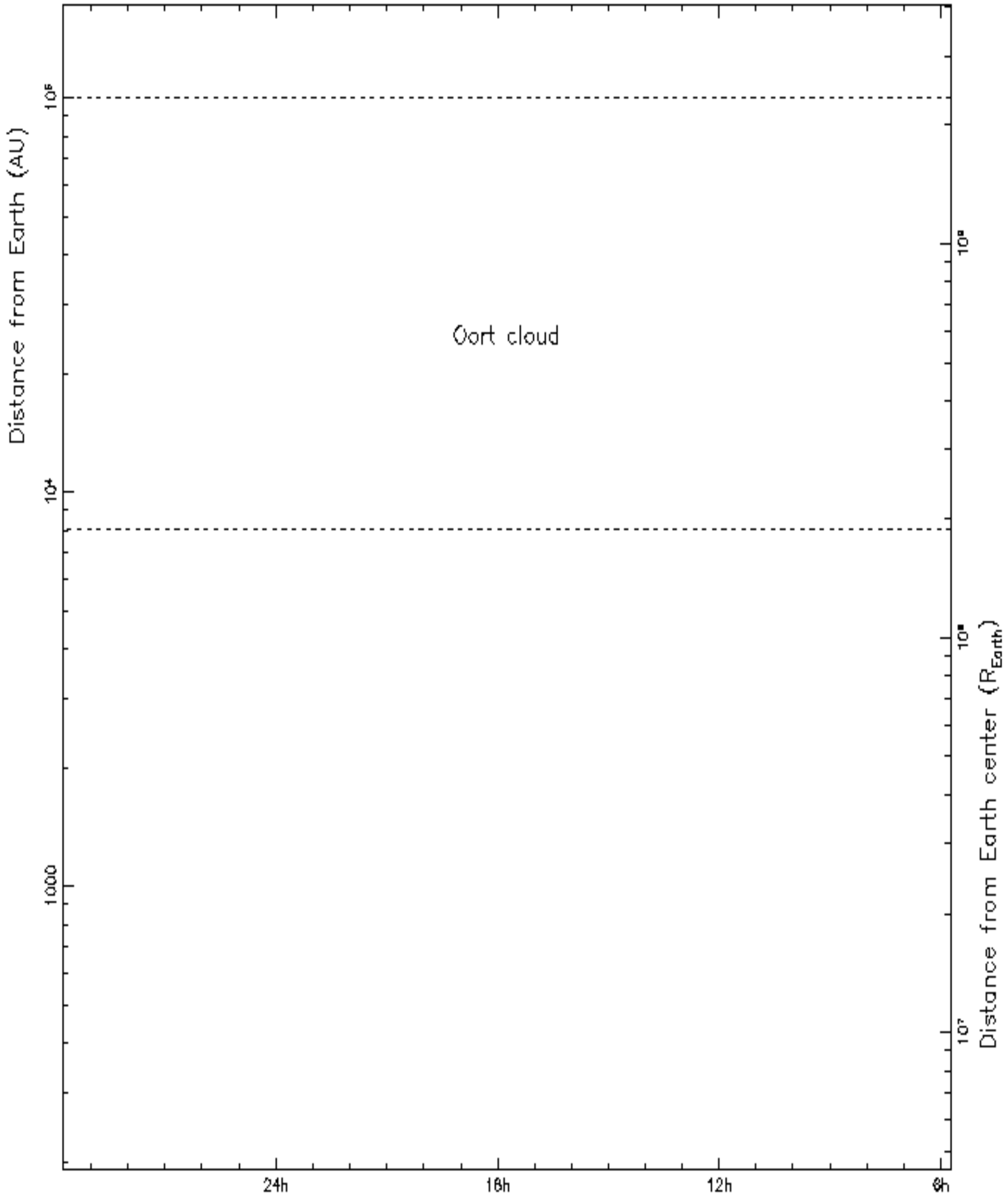
1000 - 500 000



Distance from Earth (AU)

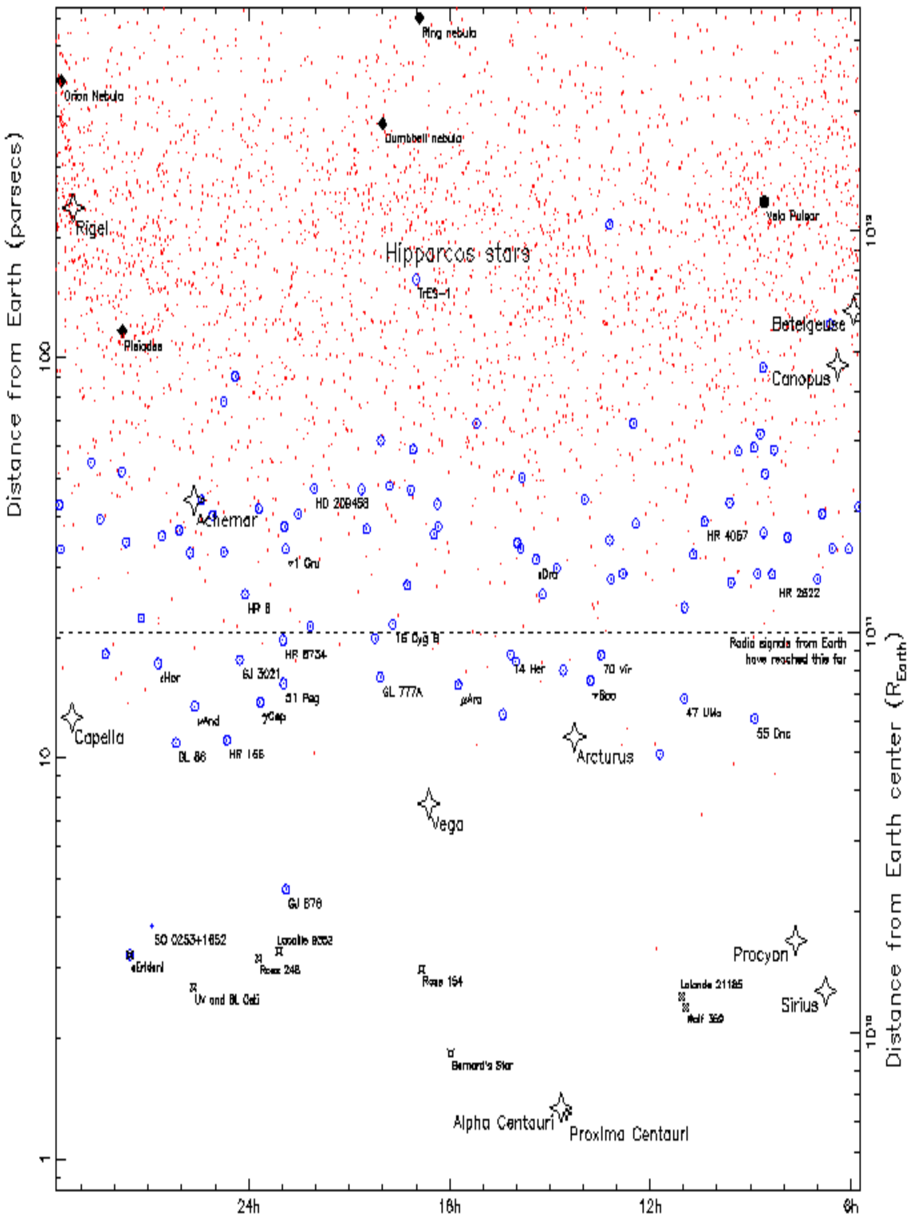
0.05 - 100

(1 AU = 150 000 000 Km)



Distance from Earth (AU)

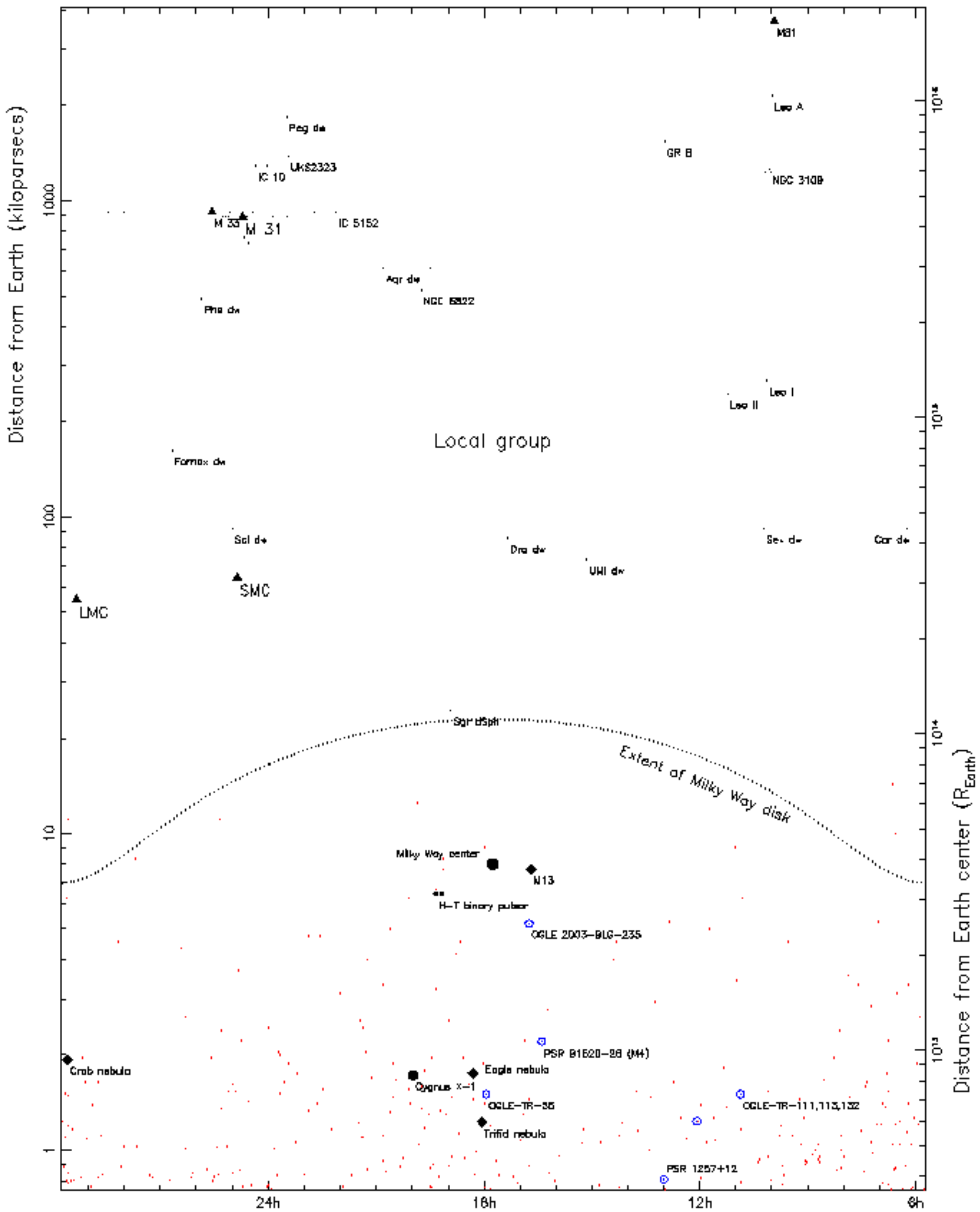
100 - 100 000



Distance from Earth (pc)

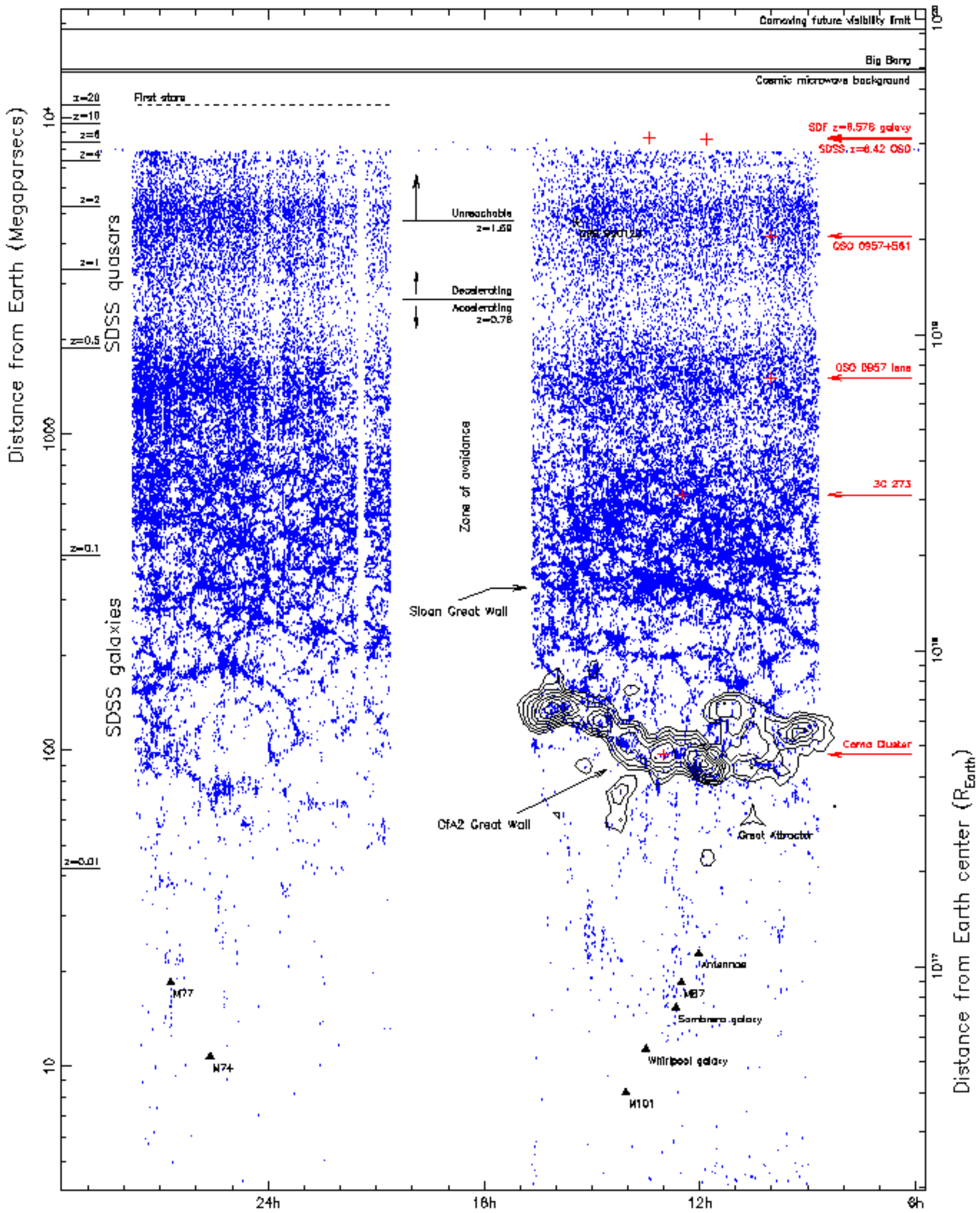
1 - 1000

(1pc = 200 000 AU)



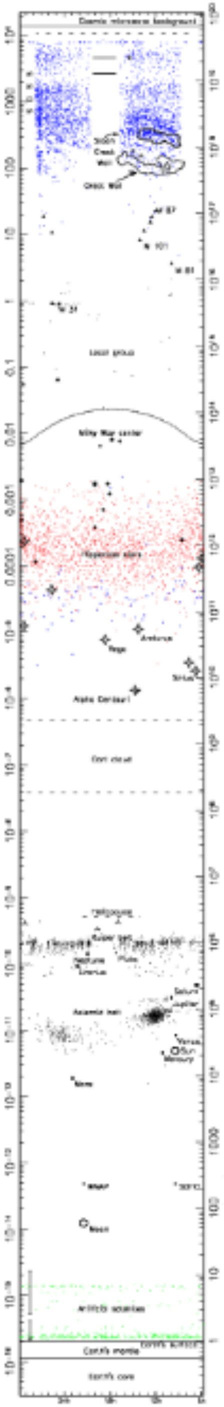
Distance from Earth (Kpc)

1 - 3000



Distance from Earth (Mpc)

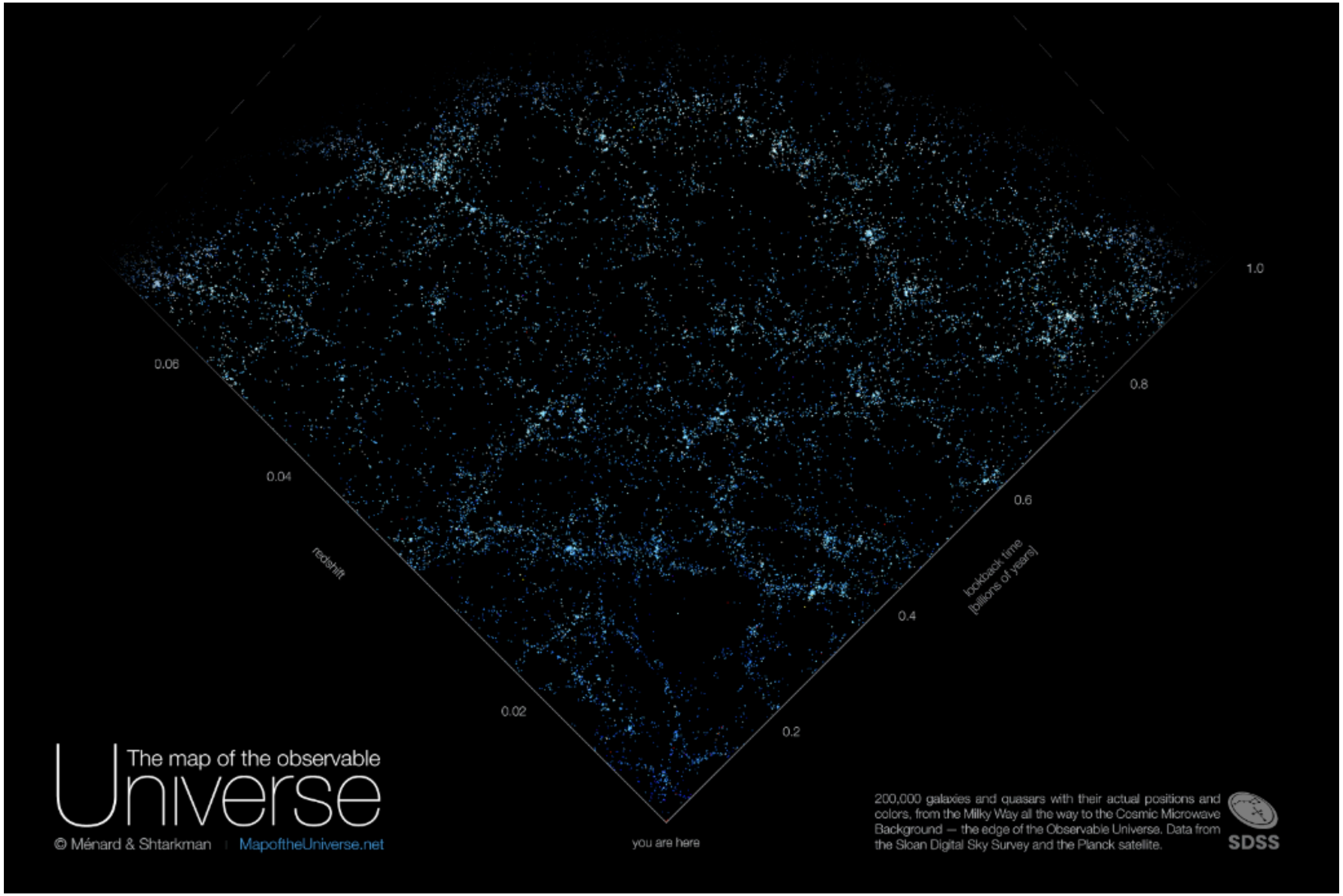
5 - 10 000



Artistic image of Gott's map (P. Budassi 2015)

New map of the observed Universe - logarithmic scale, showing 200 000 galaxies from the SDSS archive in their actual coordinates.

(Ménard & Shtarkman, Nov 2022) http://mapoftheuniverse.net/



Distance from the Milky Way

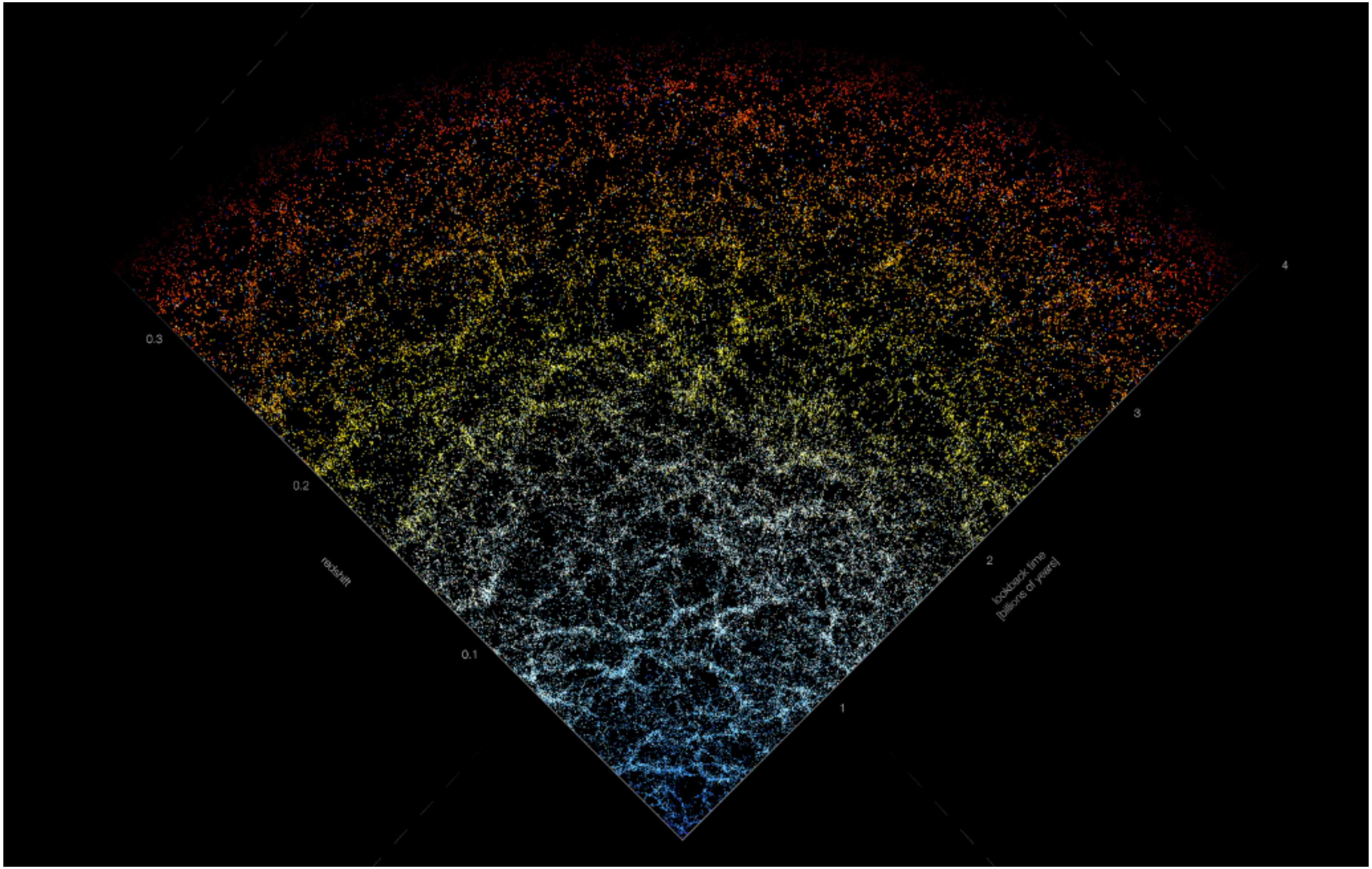
0 - 1 Gyr

z = 0 - 0.07

Distance from the Milky Way

0 - 4 Gyr

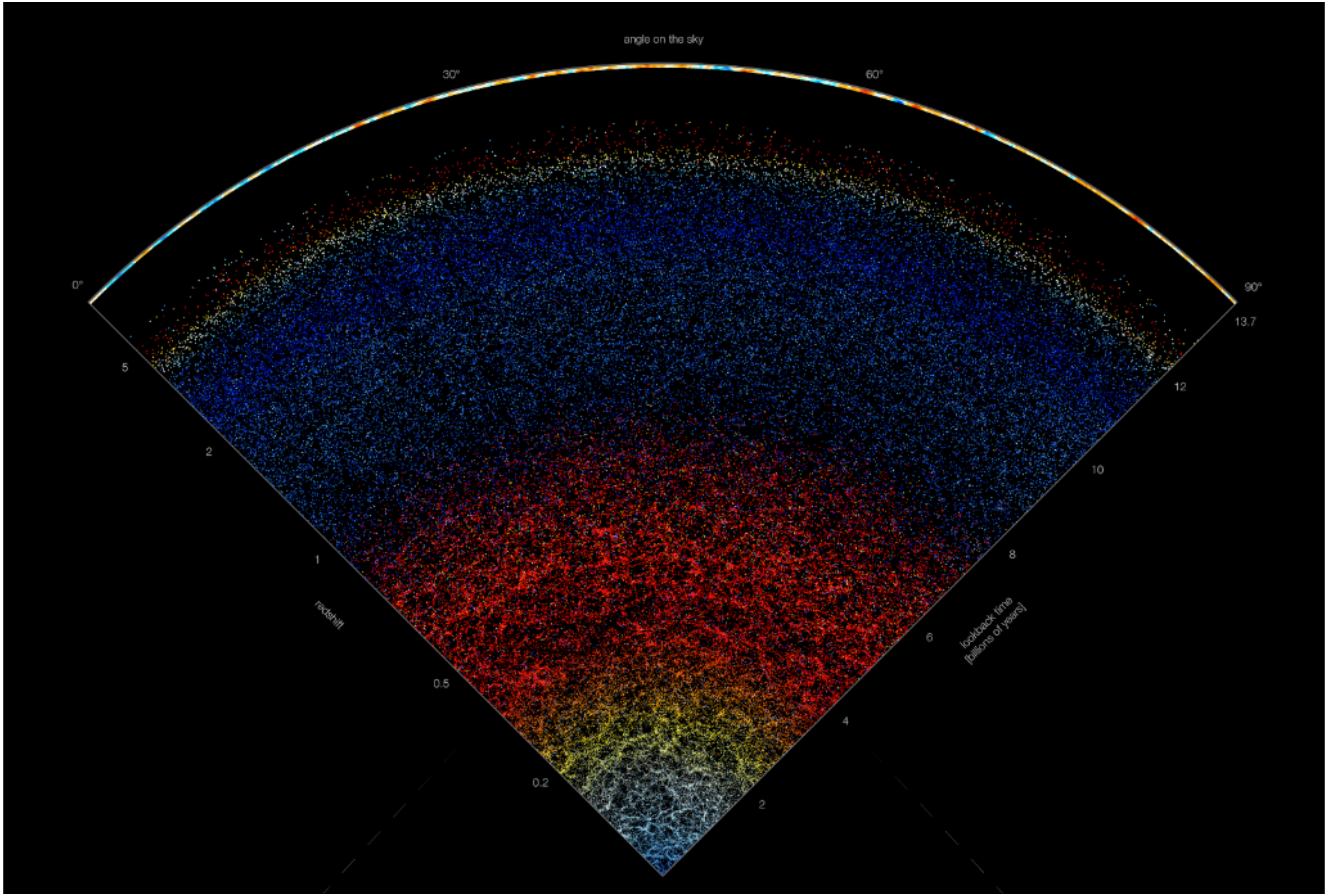
$z = 0 - 0.3$



Distance from the Milky Way

0 - 13.7 Gyr

z = 0 - 1000

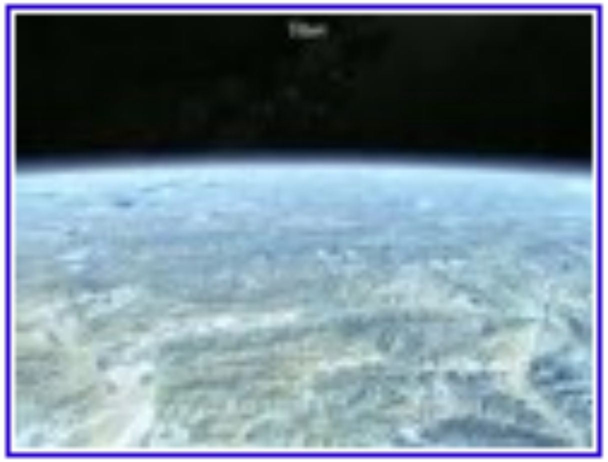


Movie of the observed Universe

(The Rubin Museum of Art and the American Museum of Natural History)

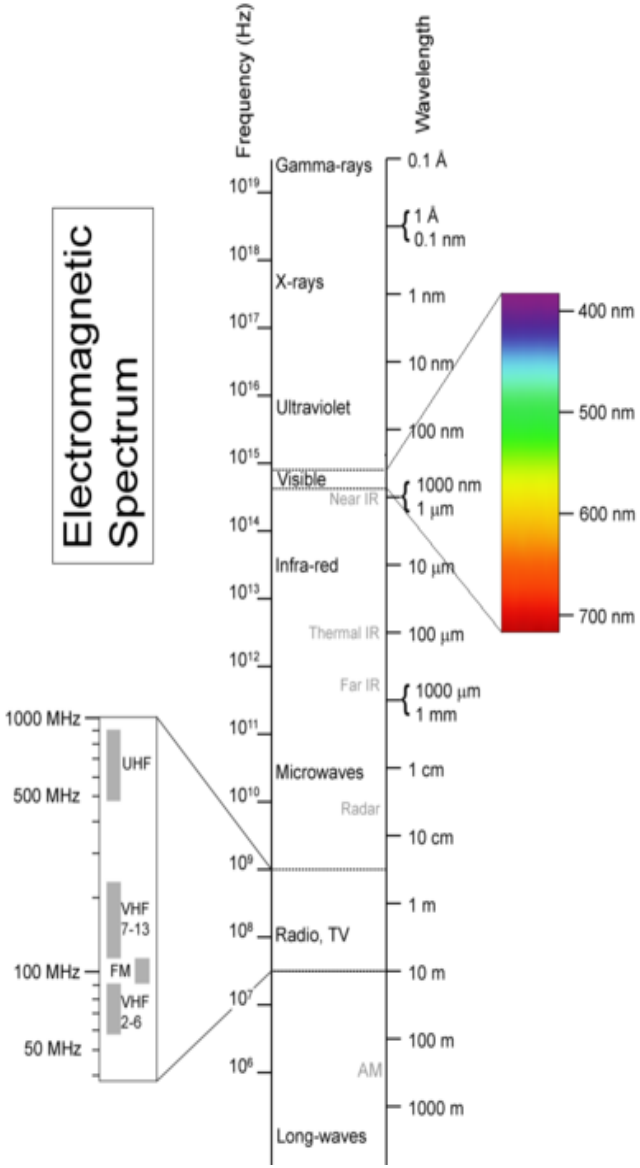
https://www.youtube.com/watch?v=17jymDn0W6U

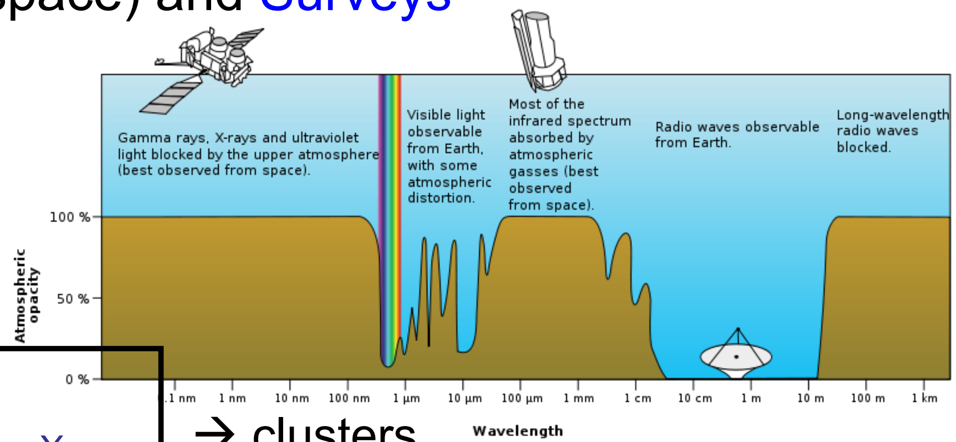
The Known Universe



How are these data obtained
and
how are they used to find the parameter values?

Current Observatories (ground and *space) and Surveys

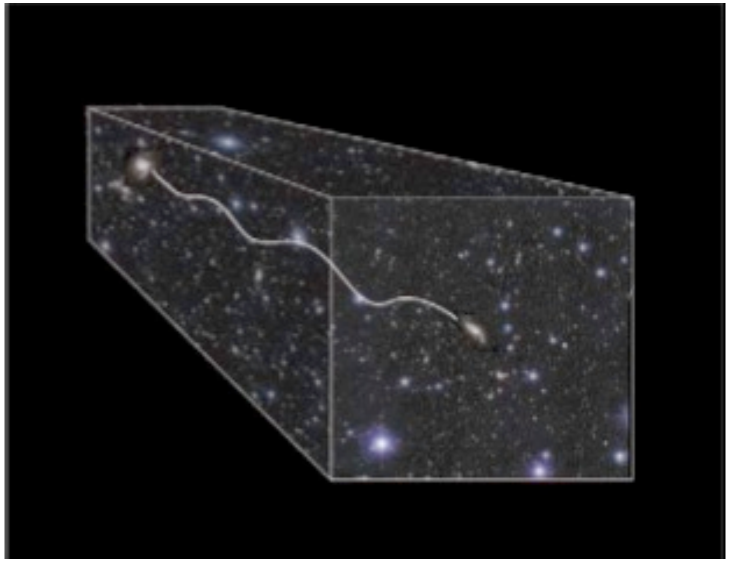


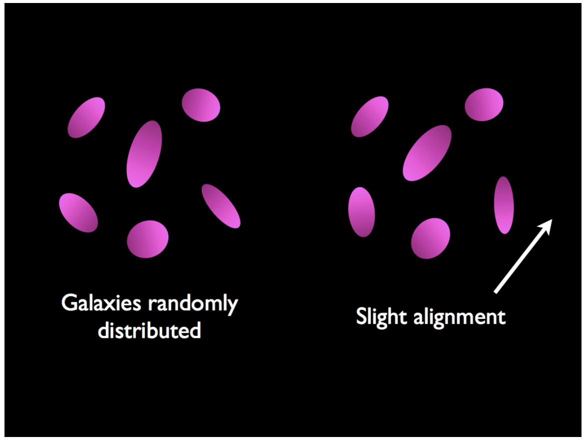


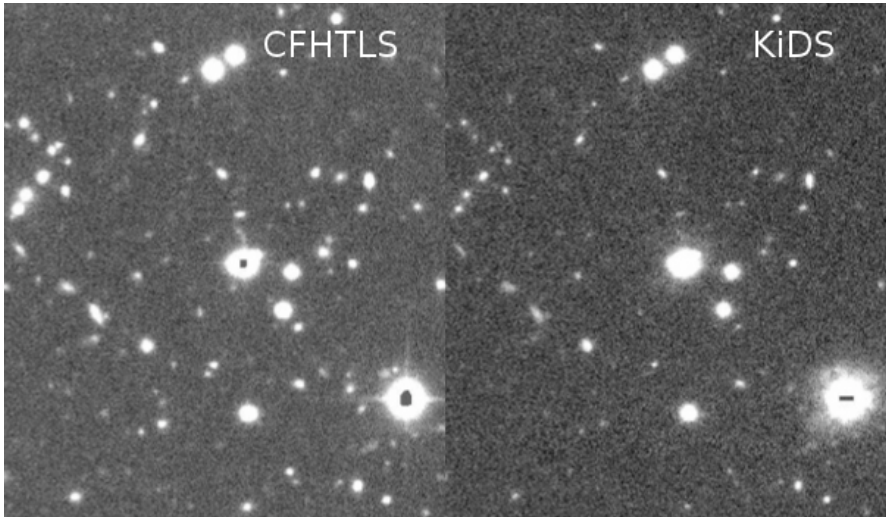
*XMM *Chandra — Xrays	→ clusters
*GALEX — UV	→ star formation
*HST (COSMOS, HDF, etc) VST/VLT (KiDS) Blanco (DES) Sloan (SDSS, BOSS) — Optical	→ galaxies, Ly_α → cosmic shear → galaxy clustering, LSS map
*JWST *Spitzer (GOODS) CTIO (2MASS) — NIR	→ distant galaxies → map of nearby galaxies, peculiar velocities
*Herschel ALMA — FIR / Submm	→ distant galaxies
ACT , *WMAP, *Planck — MW	→ CMB, SZ clusters
LOFAR, VLA — Radio	→ Reionization, 21cm

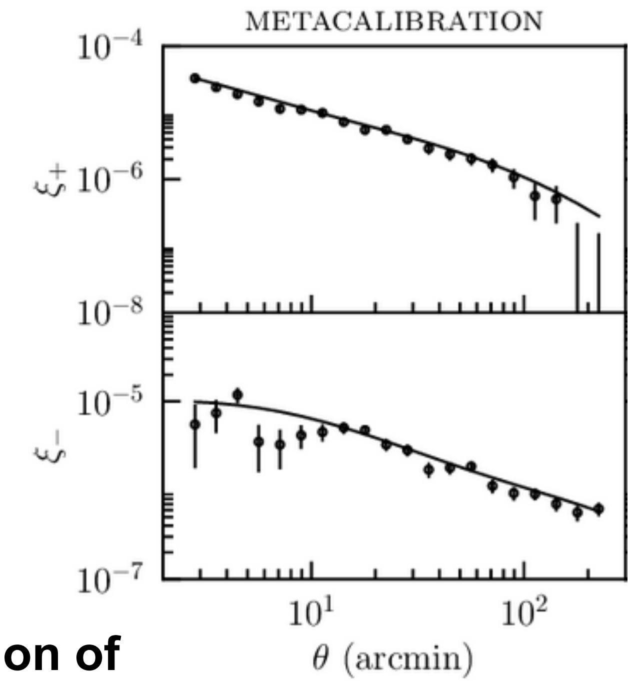
Cosmological probes: **extracting cosmological information from the data**

- Weak Lensing



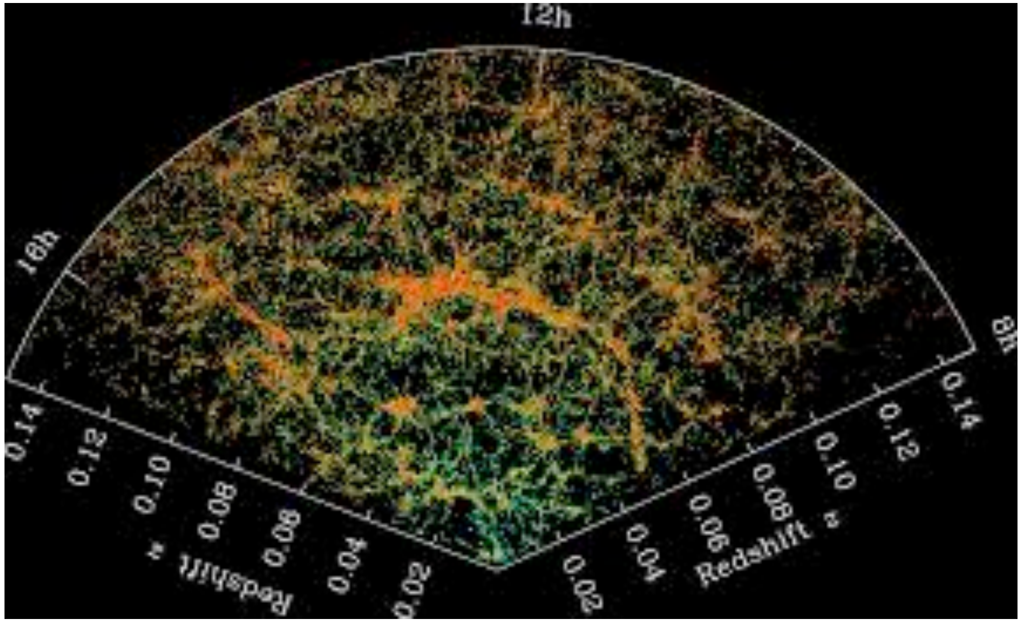


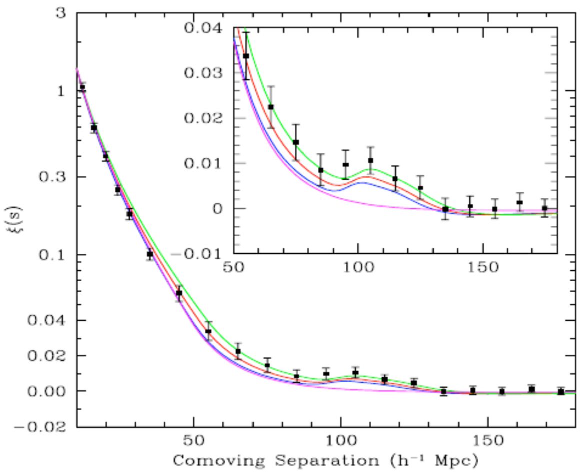




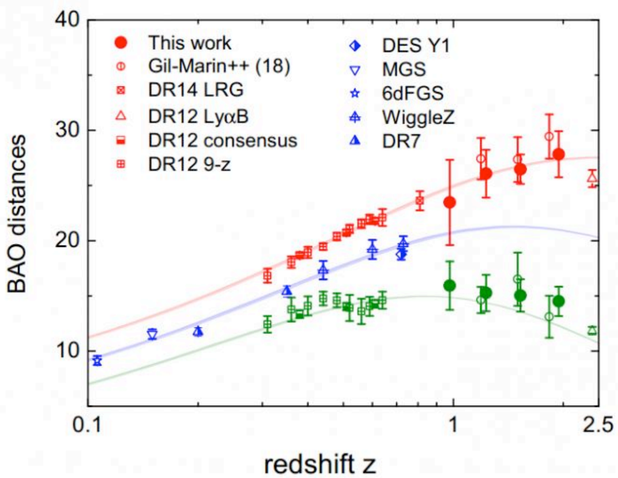
Correlation of ellipticities

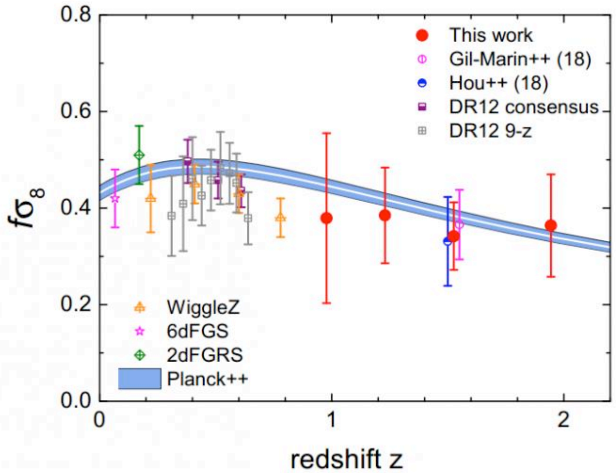
- Galaxy Clustering





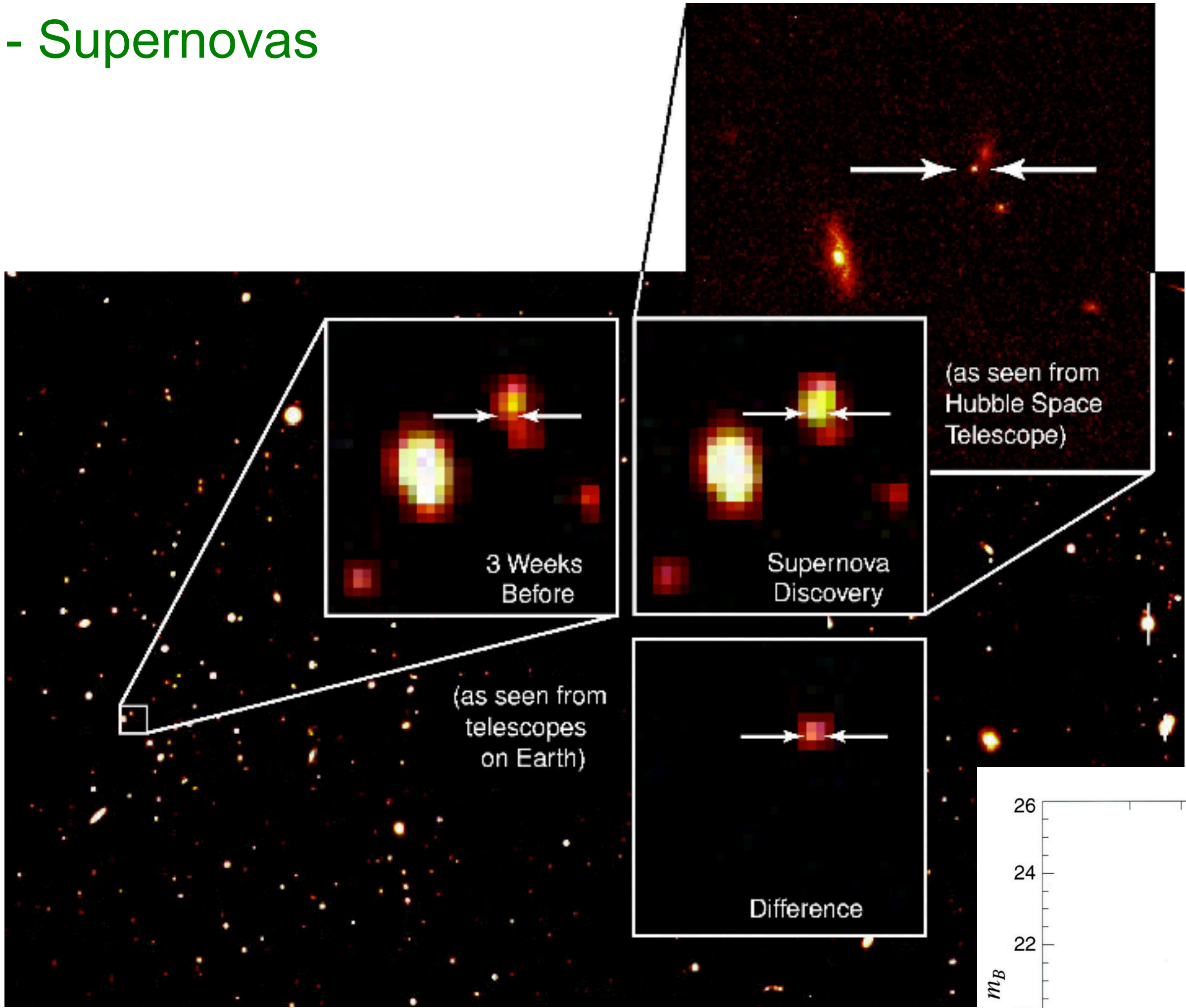
BAO peak

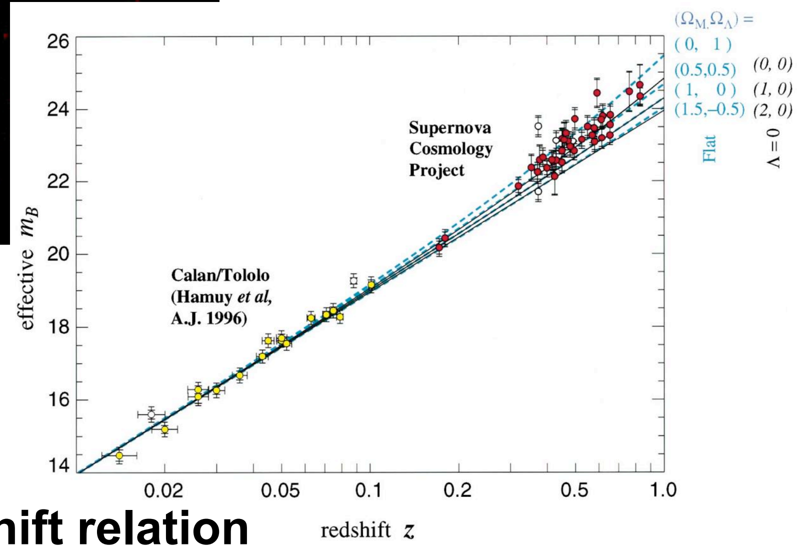




Amplitude of clustering

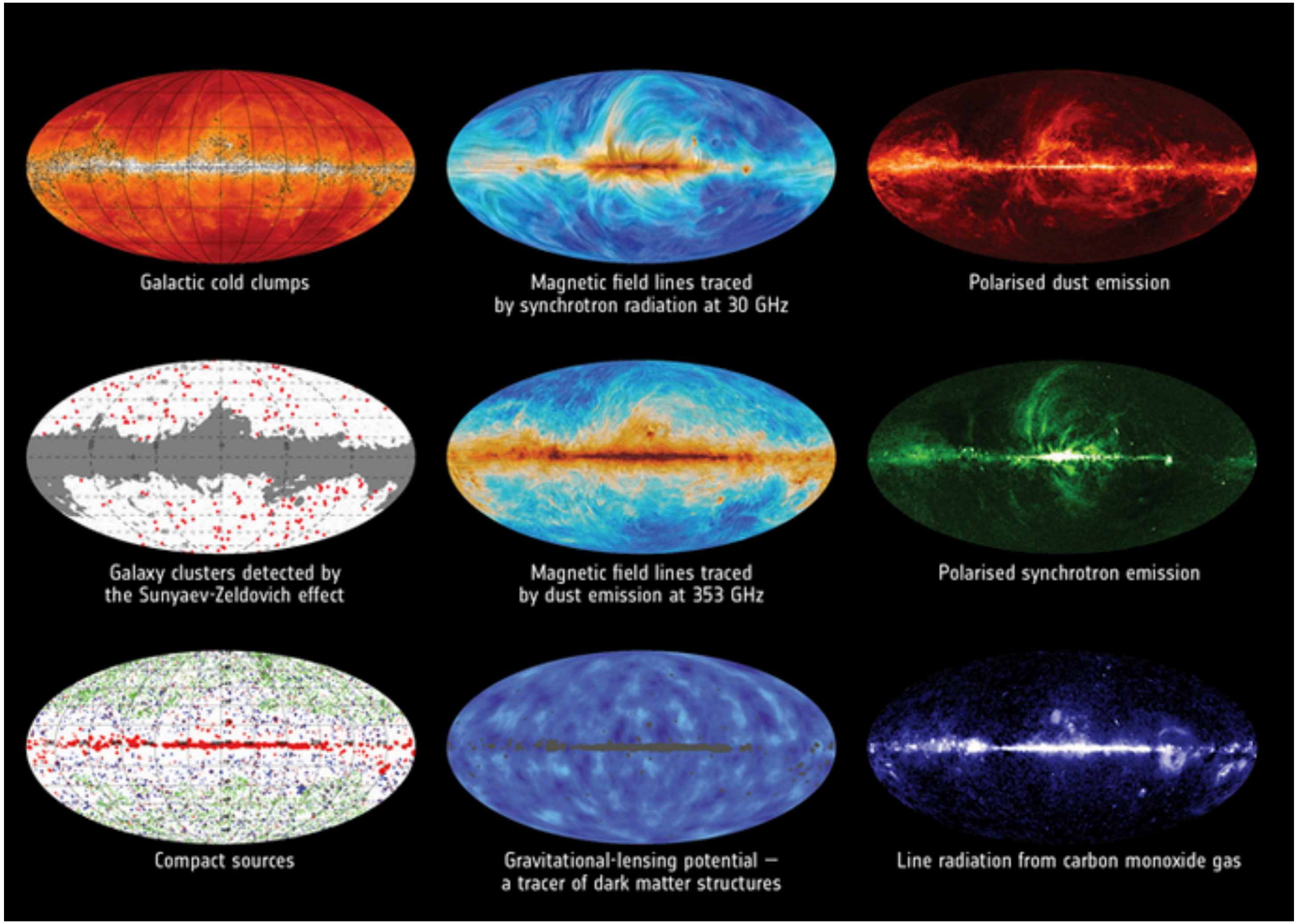
- Supernovas



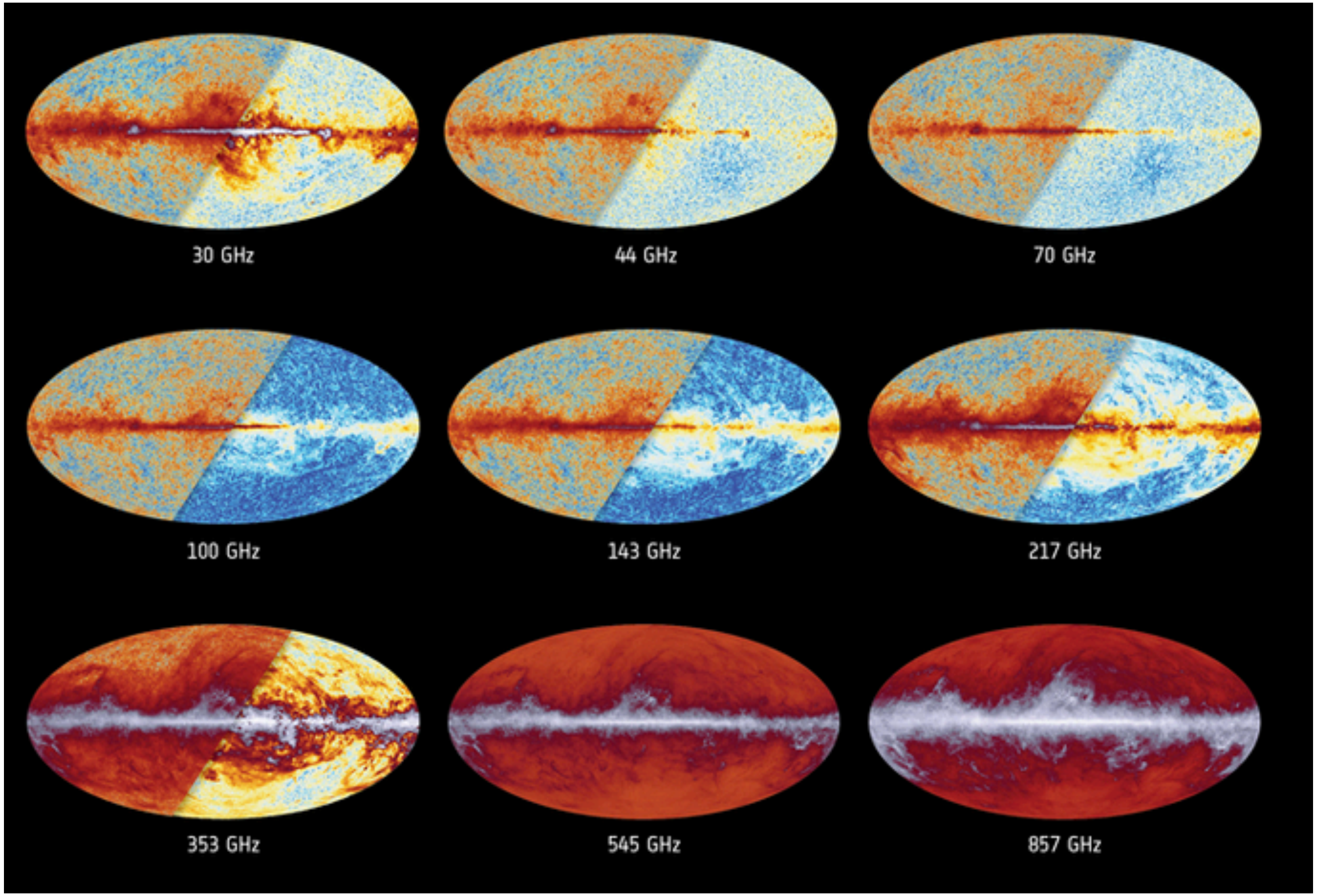


Distance vs redshift relation

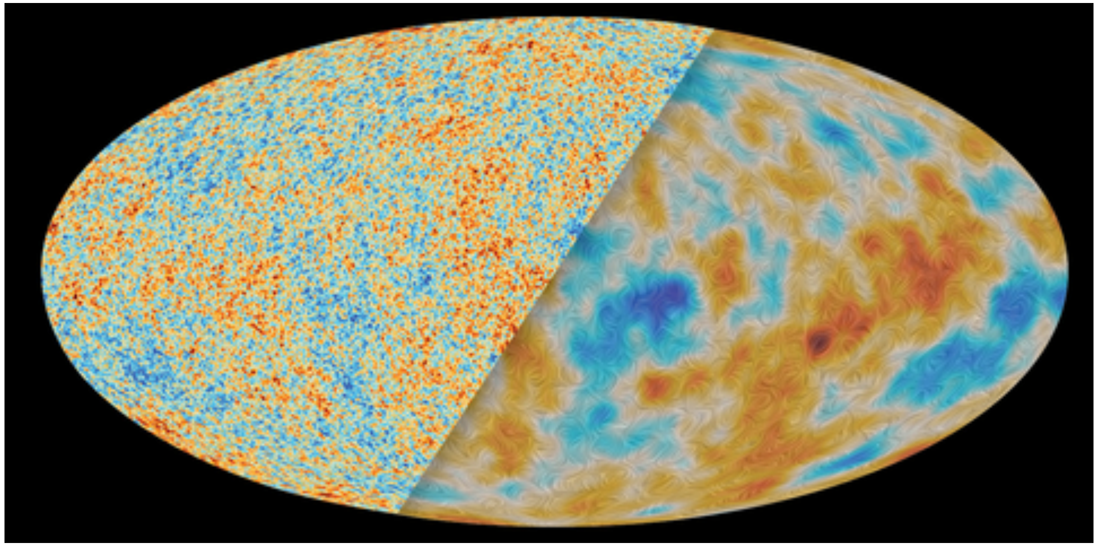
- Cosmic Microwave Background



(Foregrounds)

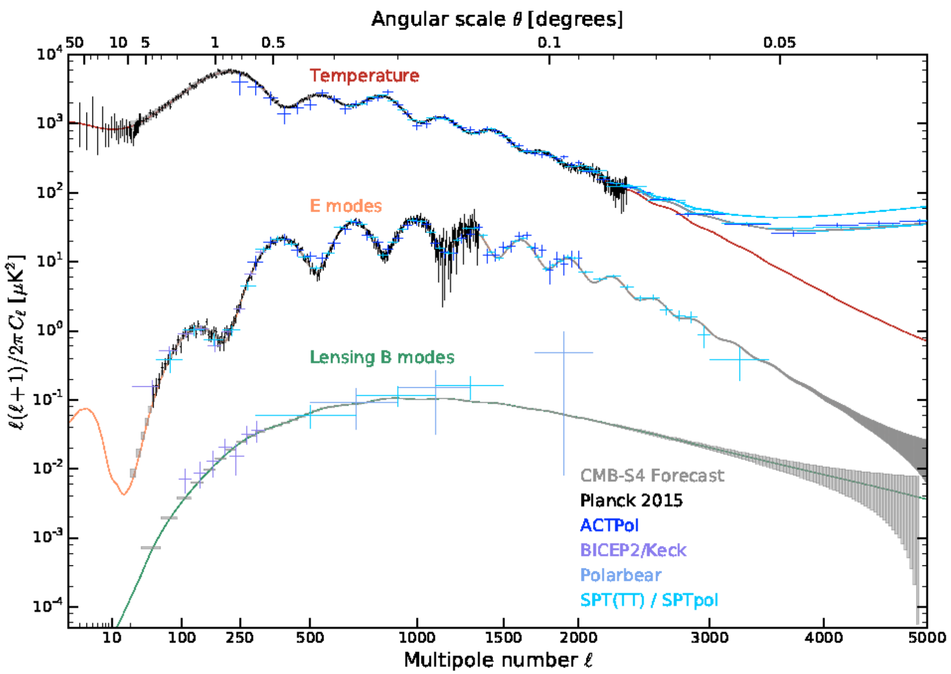


(Cosmological signal in each channel)



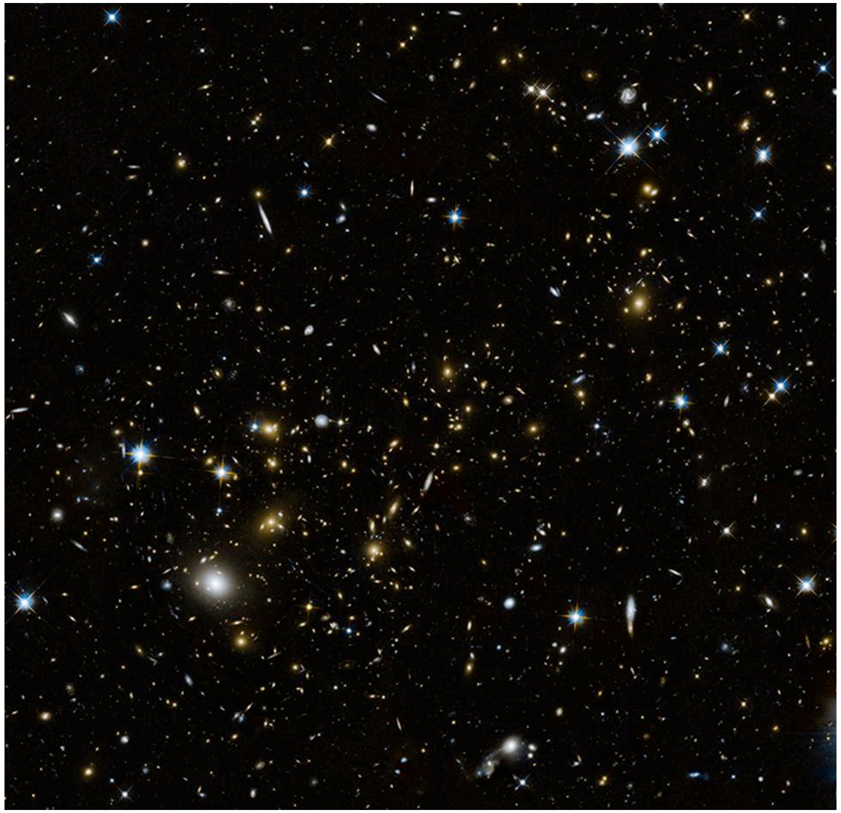
Temperature and polarization maps:

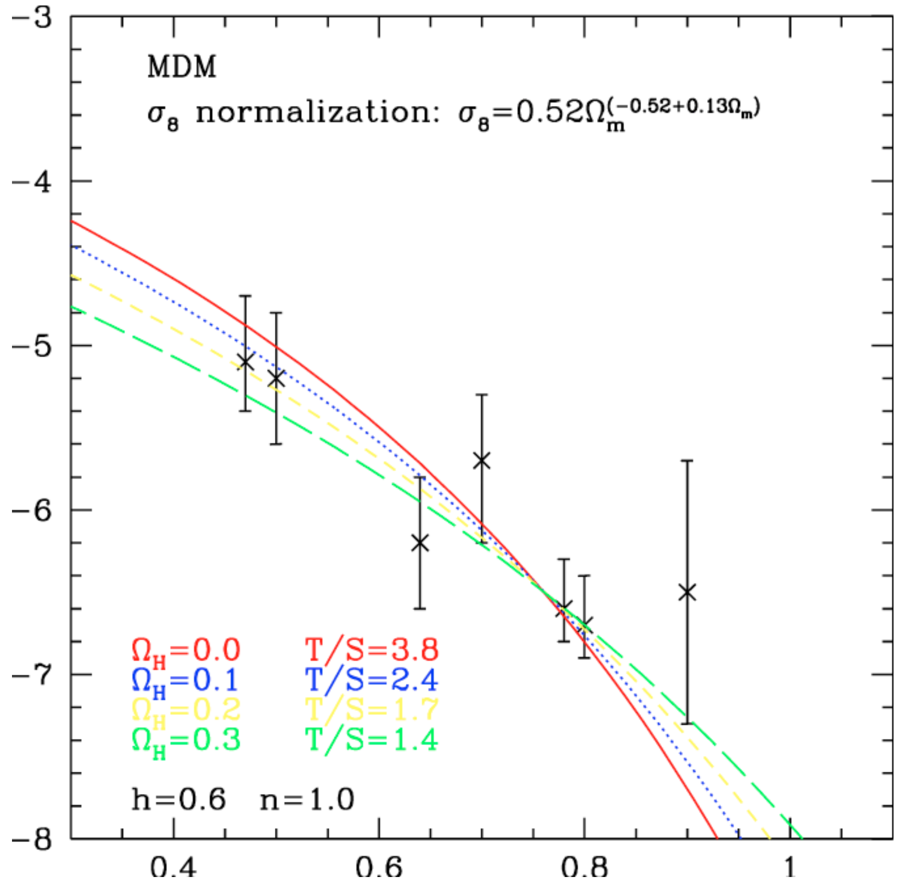
combining 9 frequencies, removing foregrounds, reconstructing the galaxy plane



Temperature correlation
Polarization correlation

- Clusters of galaxies





Cluster abundance (mass function)

and many other cosmological probes:

- Lyman alpha (probes the intergalactic medium)
- 21 cm maps (probes neutral hydrogen)
- Redshift drift (direct measurement of the expansion)
- Time-delays from double images (probes the geometry of space)
- …

In the near future: new cosmological observations already planned in the European and American programs will obtain *maps of the extra-galactic sky on different bands, at different redshifts, using telescopes of different apertures and field-of-views.*

American programs:

National Research Council Decadal Survey 2020

- Vera C. Rubin observatory (2024): ground (imaging)
(previously named LSST "Large Synoptic Survey Telescope") will conduct the LSST survey ("Legacy Survey of Space and Time")

- Nancy Grace Roman space telescope (2027): space
(previously named WFIRST "Wide-Field Infra-Red Survey Telescope")

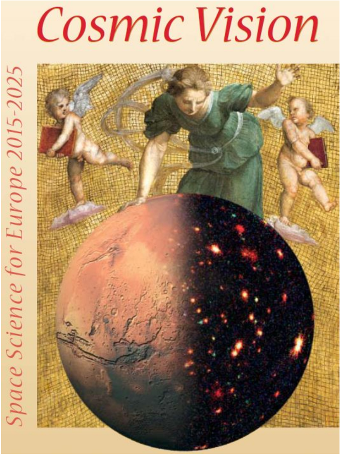
Department of Energy / National Science Foundation

- DESI "Dark Energy Spectroscopic Instrument" (2020): ground (spectroscopic)

Explorers Program (NASA)

- SPHEREx "Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer" (2025): space

European program: Cosmic Vision (ESA)



8 medium and large space missions

2020 - M1 - Solar Orbiter

2023 - M2 - **Euclid** (PT: *António da Silva, Ismael Tereno)*

2023 - L1 - JUICE "JUpiter Icy moons Explorer"

2026 - M3 - PLATO "PLAnetary Transits and Oscillations of stars" (PT: *Nuno Santos*)

2029 - M4 - ARIEL "Atmospheric Remote-sensIng Exoplanet Large-survey" (PT: *Pedro Machado*)

2031 - M5 - EnVision (Venus mission)

2034 - L2 - **ATHENA** "Advanced Telescope for High-ENergy Astrophysics"

2037 - L3 - **LISA** "Laser Interferometer Space Antenna"

Nowadays there is much interaction between theory and observations.

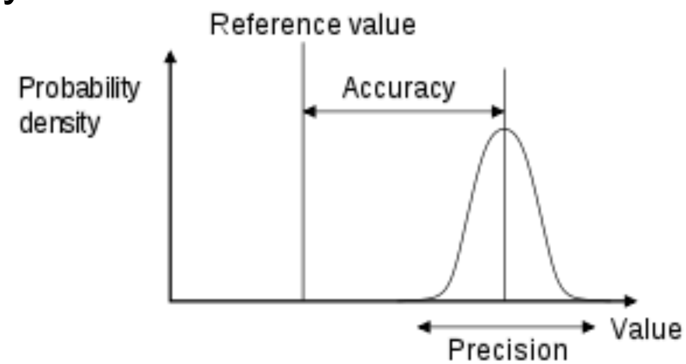
Modern research in cosmology deals with:

- **Testing cosmological models**

Compute theoretical predictions of ΛCDM or alternative models for various observables

Find an explanation for the tensions that exist between various observations (such as different values of H_0 when obtained from local measurements or from CMB observations; different value of σ8 from CMB and LSS measurements). Does it come from experimental systematic effects of is it an evidence for the need for a new model (or new physics) ?

Determine the values of the cosmological parameters with increasing precision and accuracy



- **Make theoretical improvements to ΛCDM**

Build new models of dark energy

Characterize the relation between dark and baryonic matter, introducing more baryonic effects in the description of structure formation (interface cosmology-astrophysics)

- **Explain new observed effects**

The acceleration of the expansion is caused by dark energy or can it be predicted by a new gravitational theory of large scales (modifications to General Relativity)?

The small-scale anomalies (cusp/core problem and lack of galaxy satellites) are an evidence against cold dark matter?

The CMB anomalies (multipoles alignment, cold spot) are systematic effects or fundamental physics?

The Lithium problem (nucleosynthesis predicts more primordial Lithium than it is observed)

- **Caracterize systematic effects that contaminate the observations**

  Intrinsic alignments of galaxies affect gravitational lensing

  Unknown SN absolute magnitudes affect SN distance measurements

- **Define and derive the properties of new observables and estimators**

  Intensity mapping (21 cm)

  Signal-to-Noise properties of different estimators of the same observable

  Estimate the gravitational lensing signal from measured ellipticities

- **Detect new effects predicted by the ΛCDM model**

  Primordial gravitational waves

  CMB polarization

- **Plan and build new cosmological surveys**

    Future space missions

- **Understand the nature of the ΛCDM assumptions**

    What is dark energy (and does it really exist?)

    What is dark matter (and does it really exist?)

    Did inflation really happen?

    Test the cosmological principle

- **Understand the beginning of the Universe**

    Problem of the initial singularity

    Quantum gravity