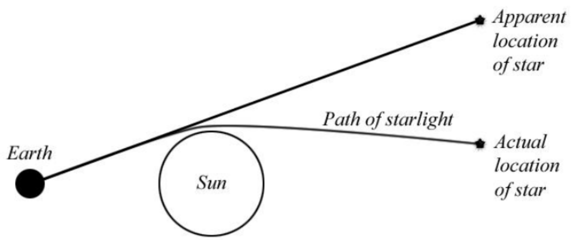
Overview of the cosmological model

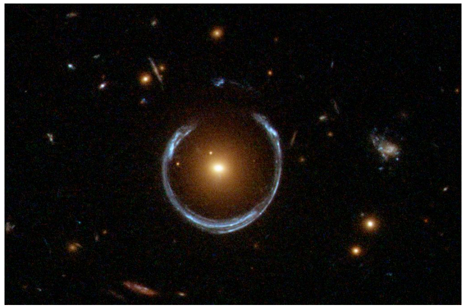
Summary

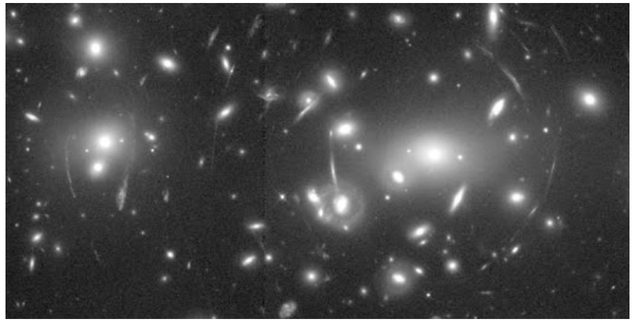
Physical Cosmology: a physical model for the Universe

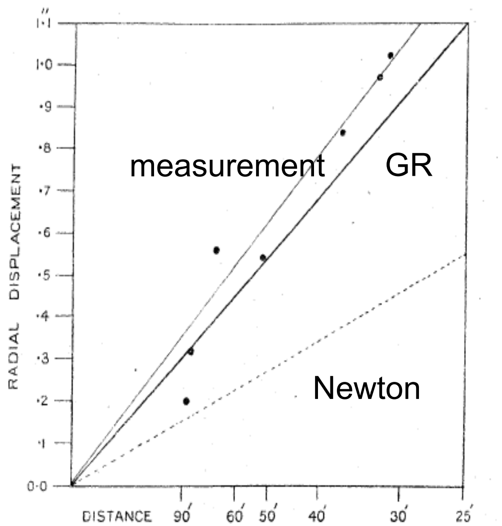
Gravity (**General Relativity**)

Tested on various scales



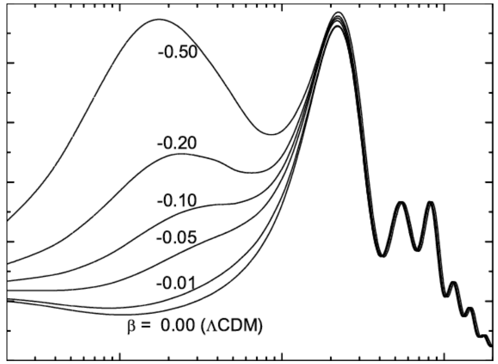






→ metric

→ Einstein equations

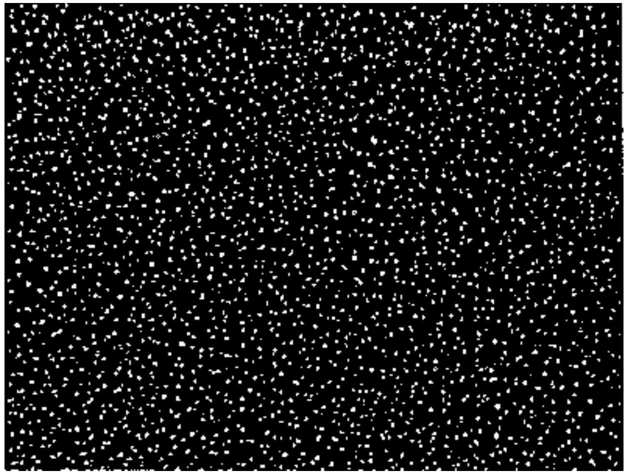


1921

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

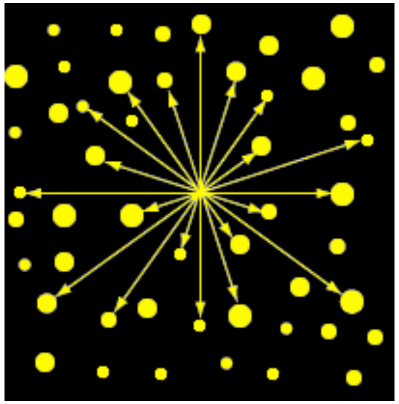
+ Cosmological principle

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



+ Olbers paradox

→ a(t) must vary



+ Observations of the recession of galaxies

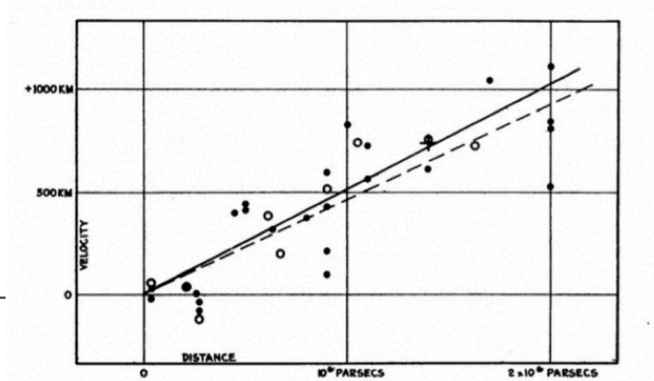
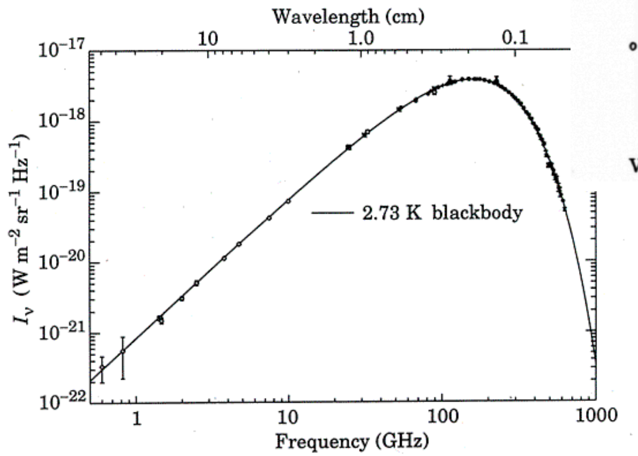


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

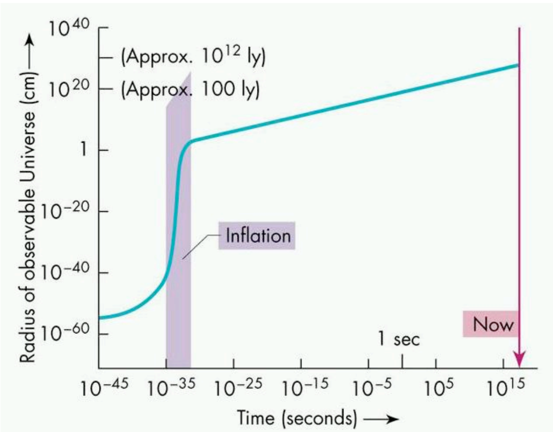
→ Expansion Big Bang

→ Thermal history

→ Existence of a universal background radiation: CMB



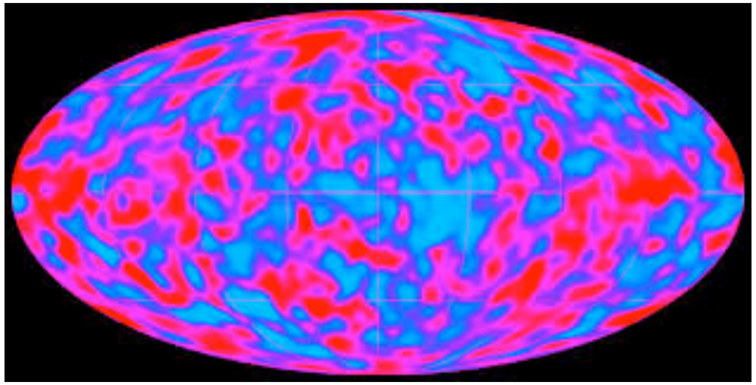
→ horizon, flatness and coincidence problems: solved by the **Inflation** mechanism



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

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**

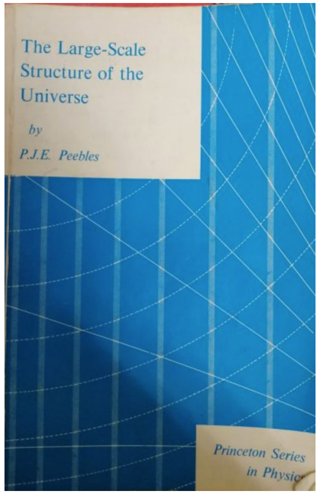
Their amplitude is very small $\delta_T \sim 10^{-5}$ → very small clustering at z=1100 ($\delta_b \sim 10^{-5}$)

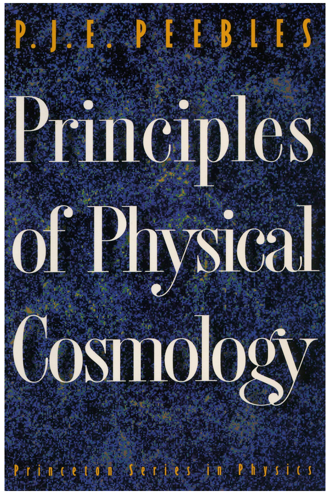
+ Gravitational collapse is small (δ_b grows only a factor $\sim 10^3$ until z=0)

+ 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**





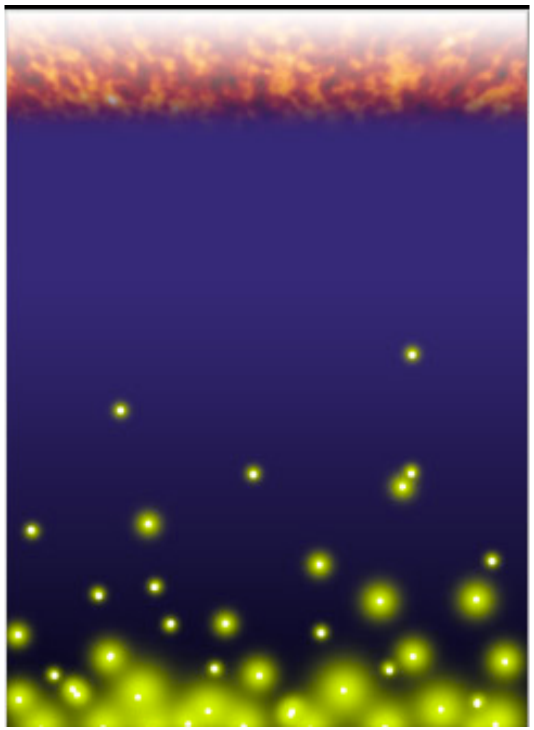
Awarded to **P. James. E. Peebles** "for theoretical discoveries in physical cosmology" (1/2)

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.

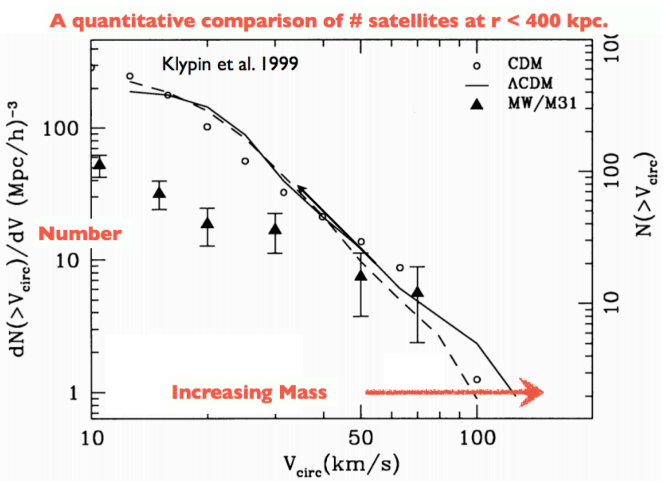
+ **Observations of properties of small-scale structure** (kpc)

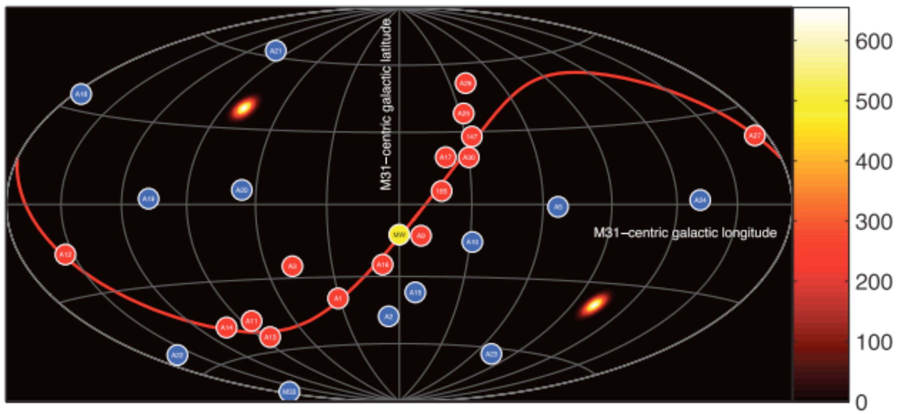
→ Problem of the radial density profile of structures (cusp/core)

→ Problem of lack of structures (satellite galaxies)

→ Problem of the satellite orbital plane

Not yet solved - 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 to GR on 'small scales' (MOND)





+ Measurements of distances to Supernovas

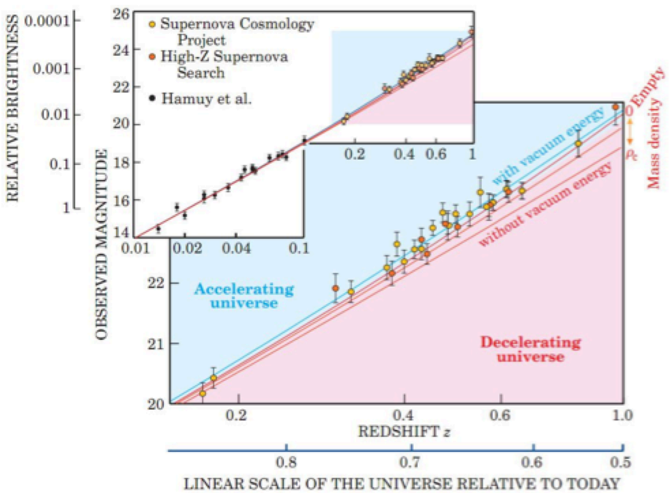
SN at all redshifts are fainter (more distant?) than expected from the $d_L(z)$ predicted by the CDM cosmological model

→ 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

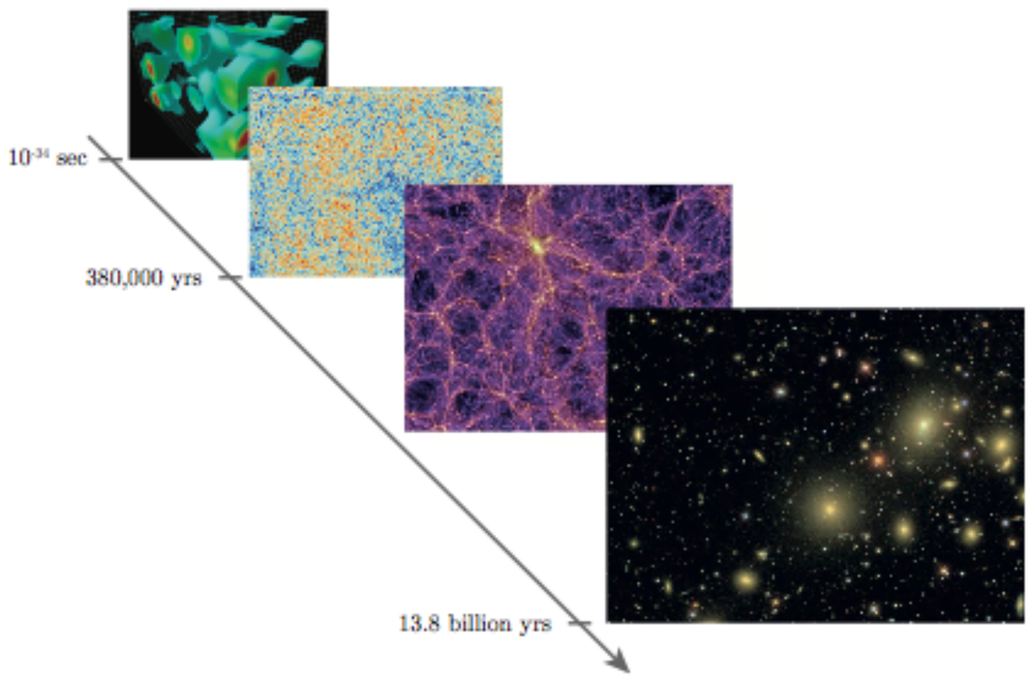


Awarded to **Saul Perlmutter**, **Brian P. Schmidt** and **Adam G. Riess** "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." (1/2 + 1/4 + 1/4)

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 XXIst century and it is known as ΛCDM.

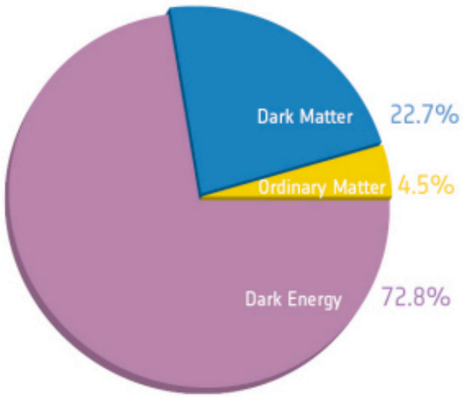


ΛCDM is a complex model

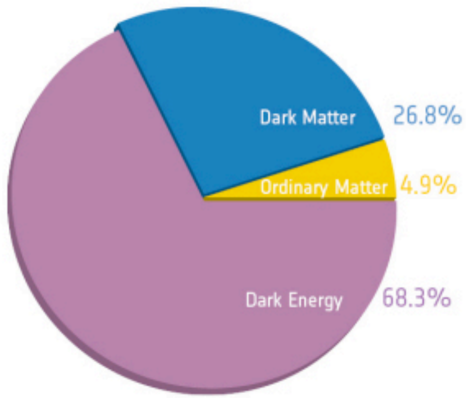
It is a theoretical construction supported by observations.

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".



Before Planck



After Planck

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

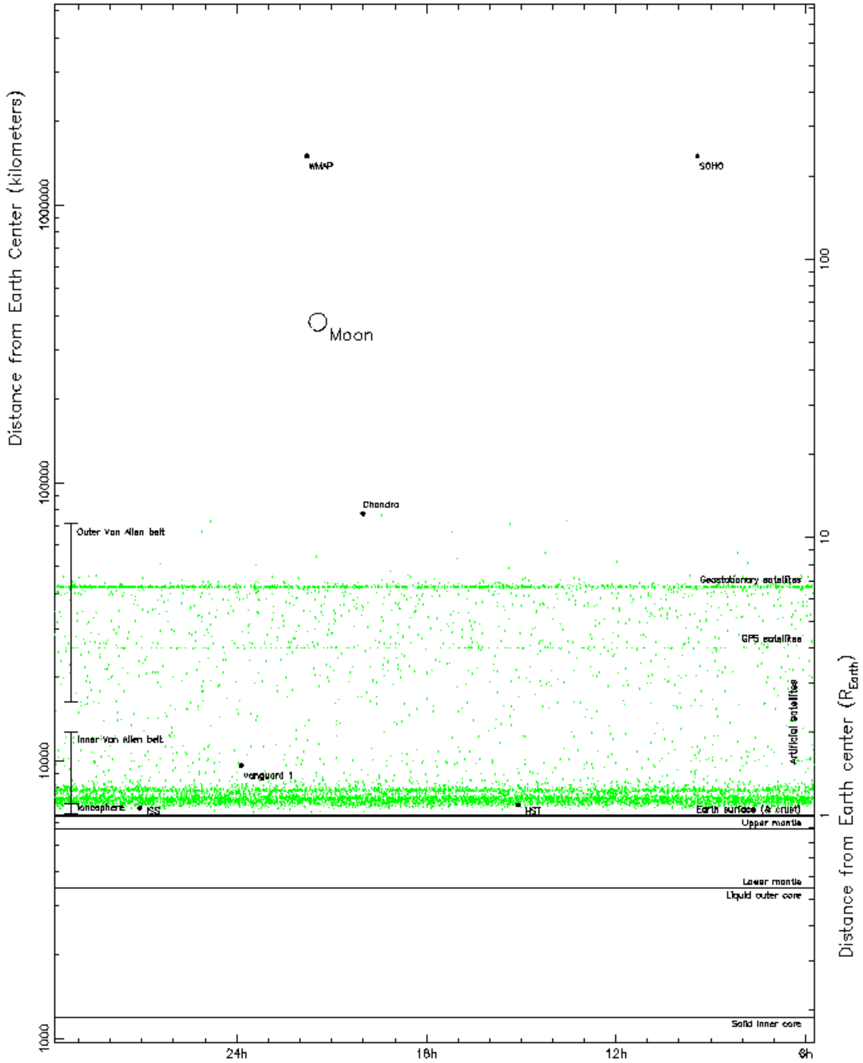
fundamental cosmological parameters

nuisance parameters (of the particular cosmological probe)

derived cosmological parameters

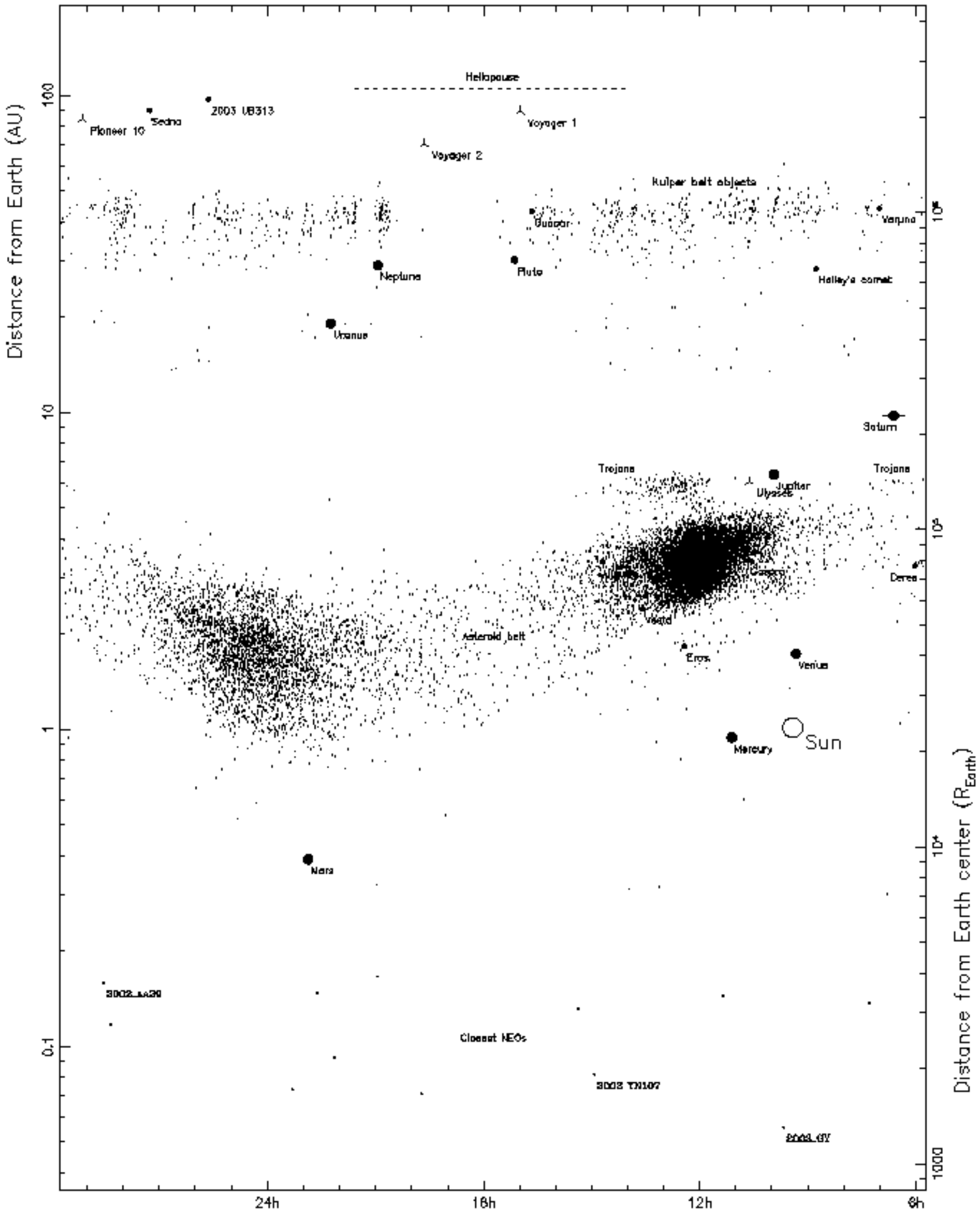
Map of the observed Universe - logarithmic scale and showing the astrophysical objects in their actual coordinates

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



Distance from the centre of the Earth (Km)

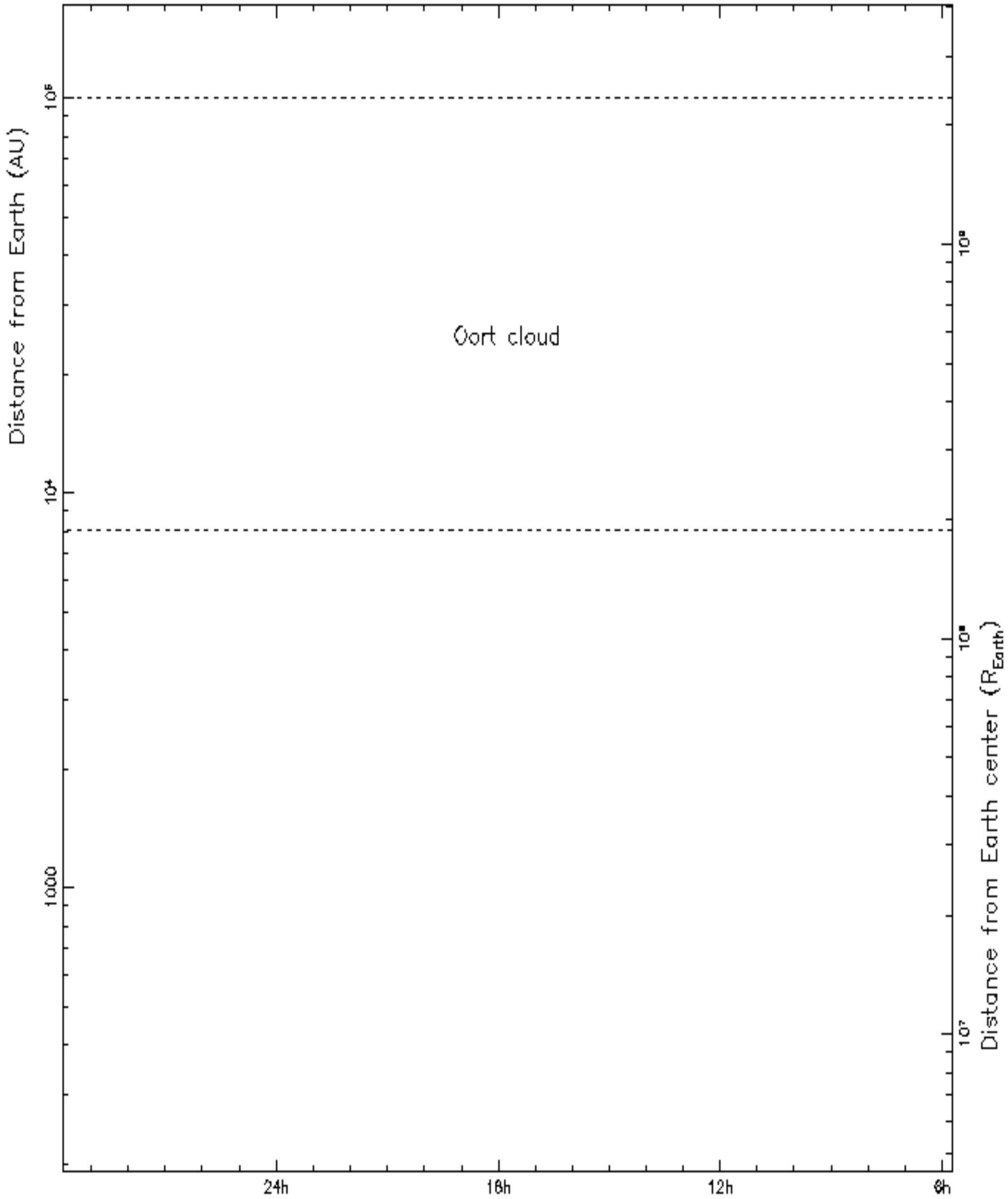
100 - 500 000



Distance from Earth (AU)

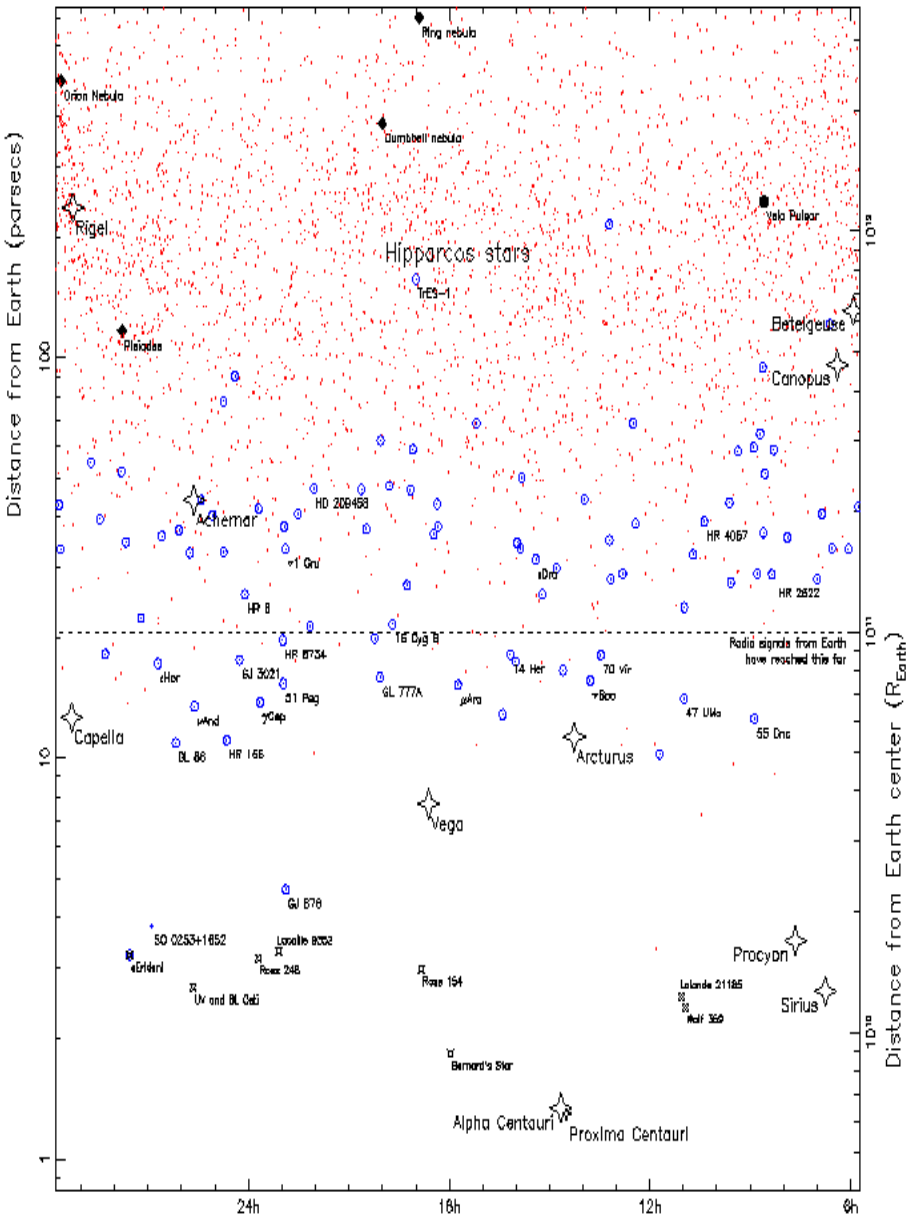
0.05 - 100

(1 AU = 150 000 000 Km)



Distance from Earth (AU)

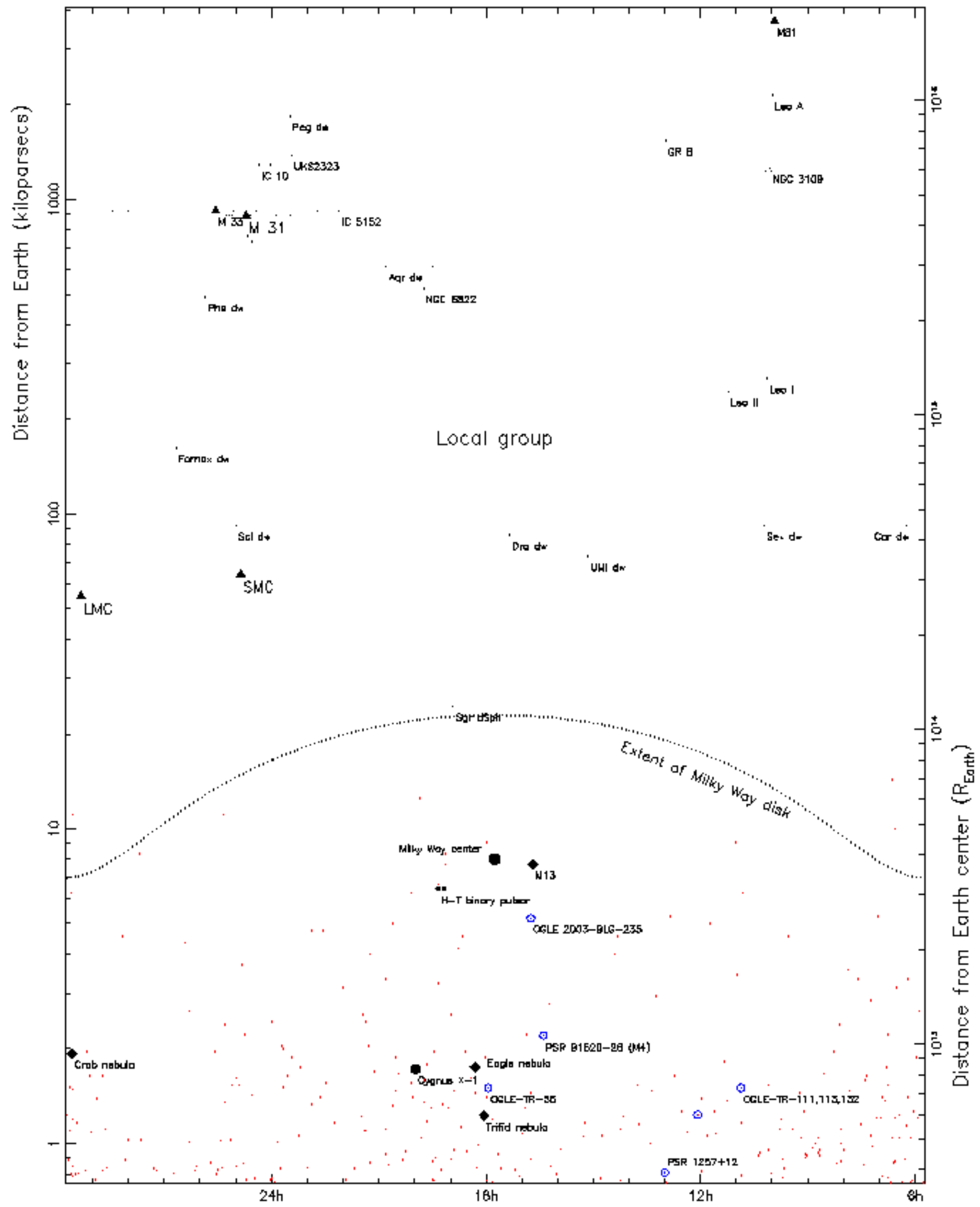
100 - 100 000



Distance from Earth (pc)

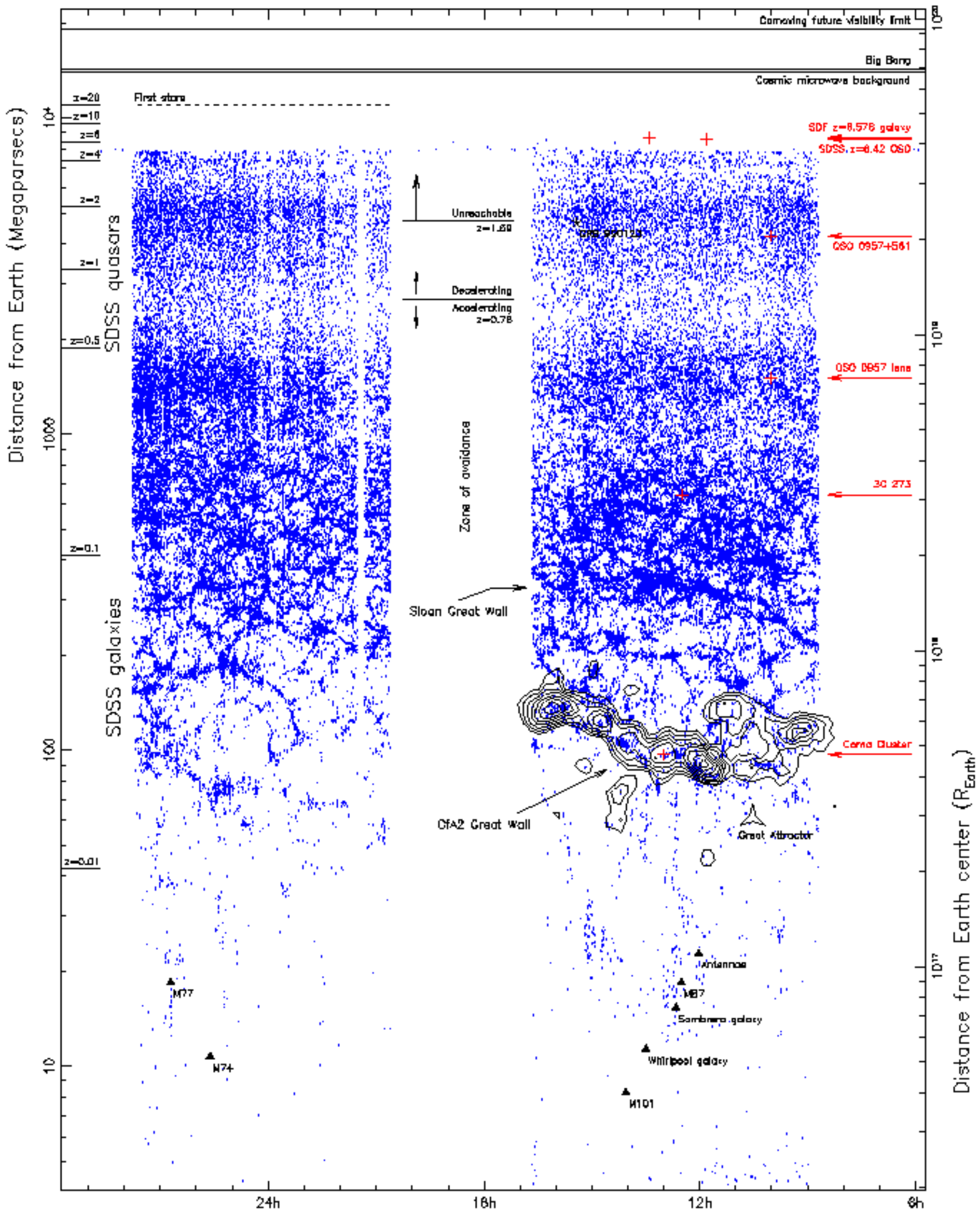
1 - 1000

(1pc = 200 000 AU)



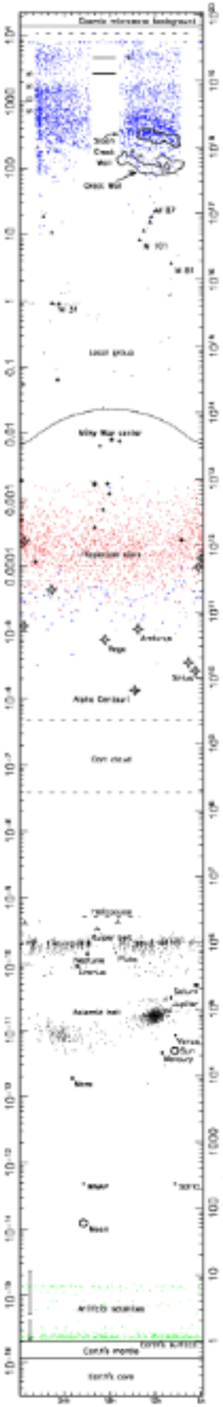
Distance from Earth (Kpc)

1 - 3000



Distance from Earth (Mpc)

5 - 10 000

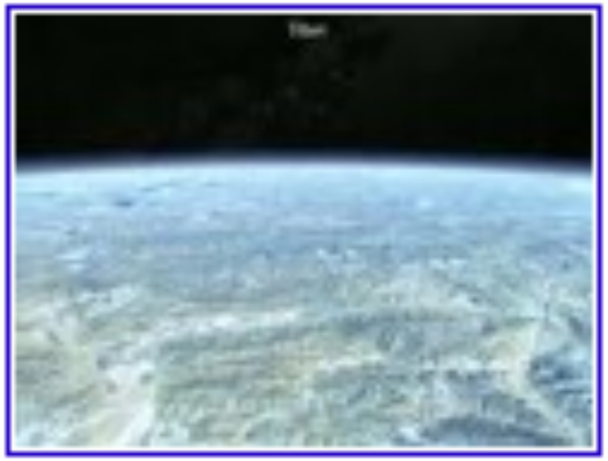


Artistic image of Gott's map (P. Budassi 2015)

Movie of the observed Universe

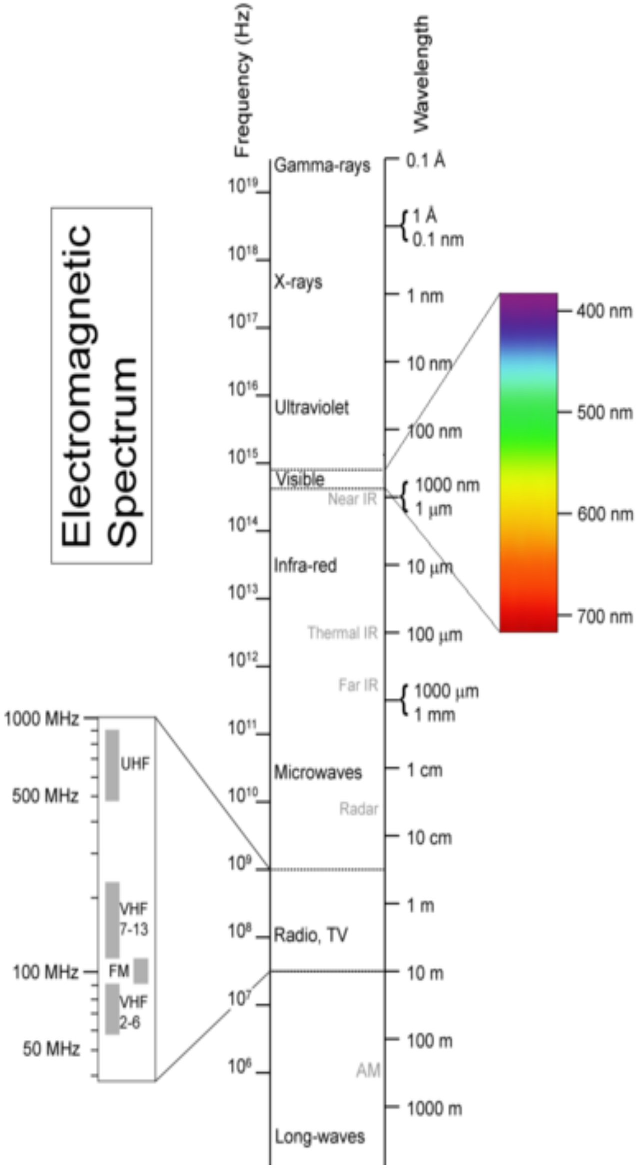
(the Rubin Museum of Art and the American Museum of Natural History)
https://www.youtube.com/watch?v=17jymDn0W6U

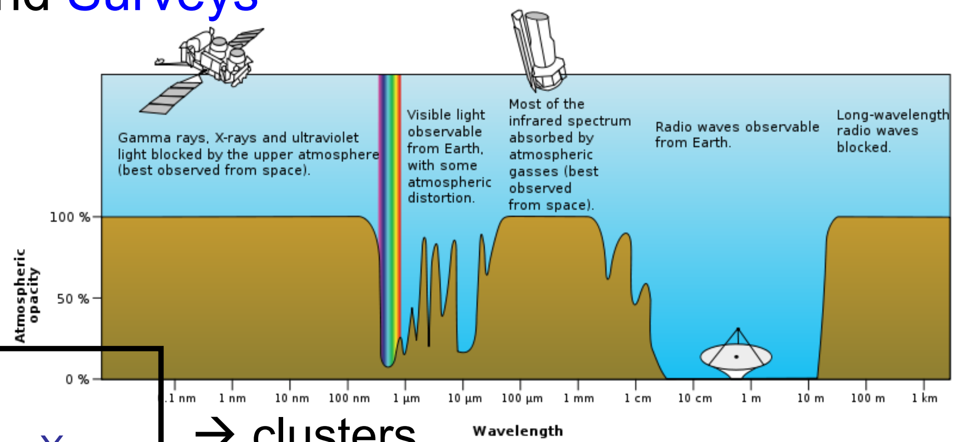
The Known Universe



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

Observatories (ground and *space) and Surveys

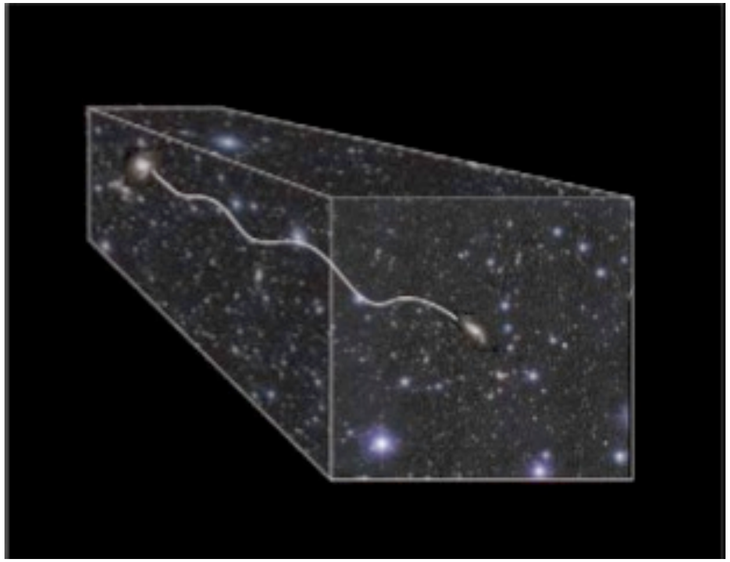


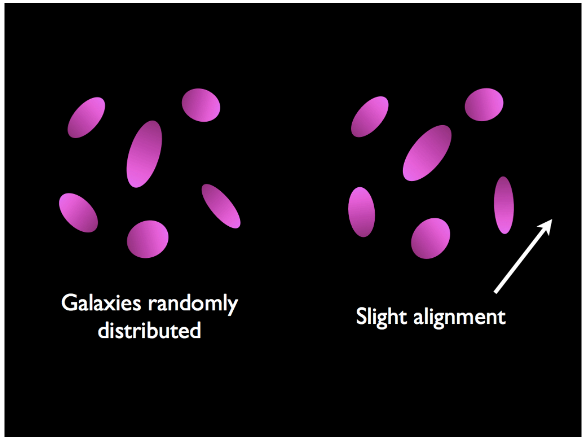


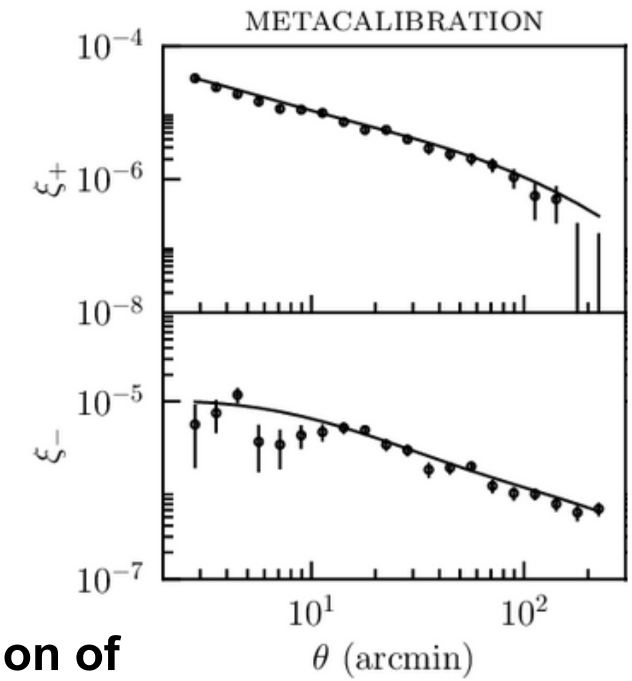
*XMM *Chandra	Xrays	→ clusters
*GALEX	UV	→ star formation
*HST (COSMOS, HDF) VST/VLT (KiDS) Blanco (DES) Sloan (SDSS, BOSS)	Optical	→ galaxies, Ly_α → cosmic shear → galaxy clustering, LSS map
*Spitzer (GOODS) CTIO (2MASS)	NIR	→ distant galaxies → map of nearby galaxies, peculiar velocities
*Herschel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

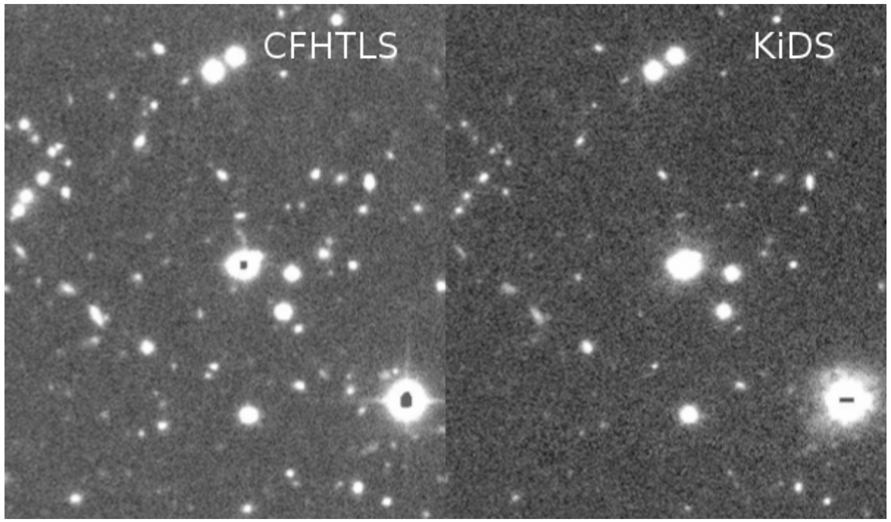
Cosmological probes: **extracting cosmological information from the data**

- Weak Lensing



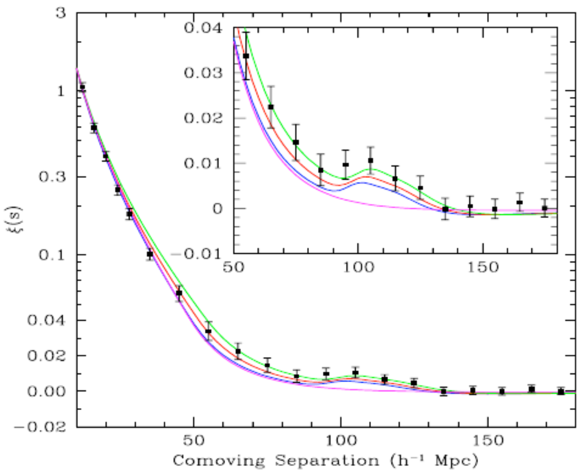


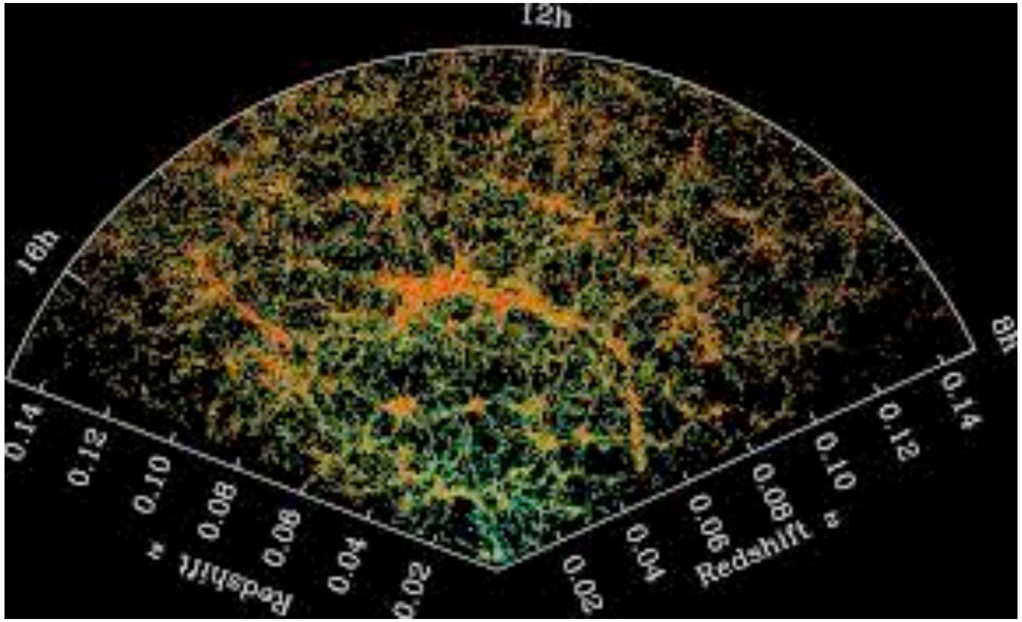




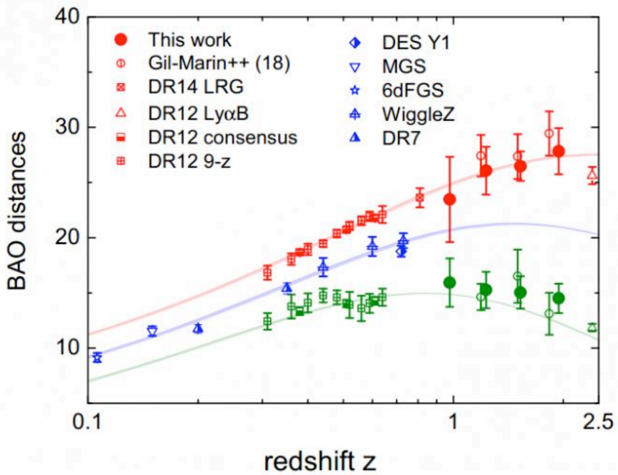
Correlation of ellipticities

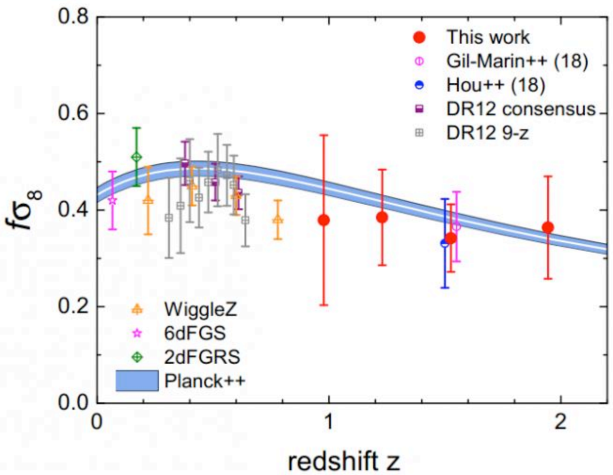
- Galaxy Clustering





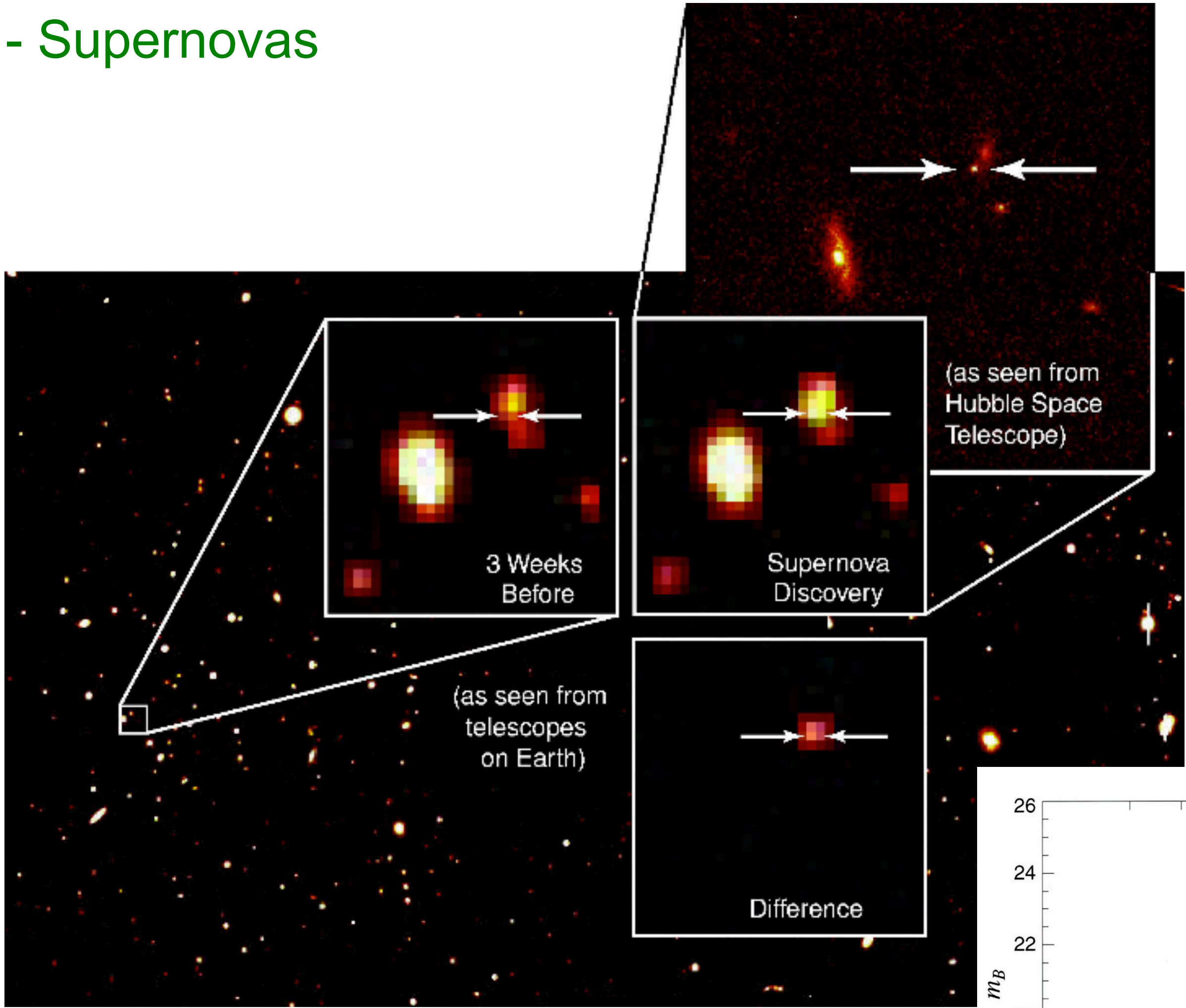
BAO peak

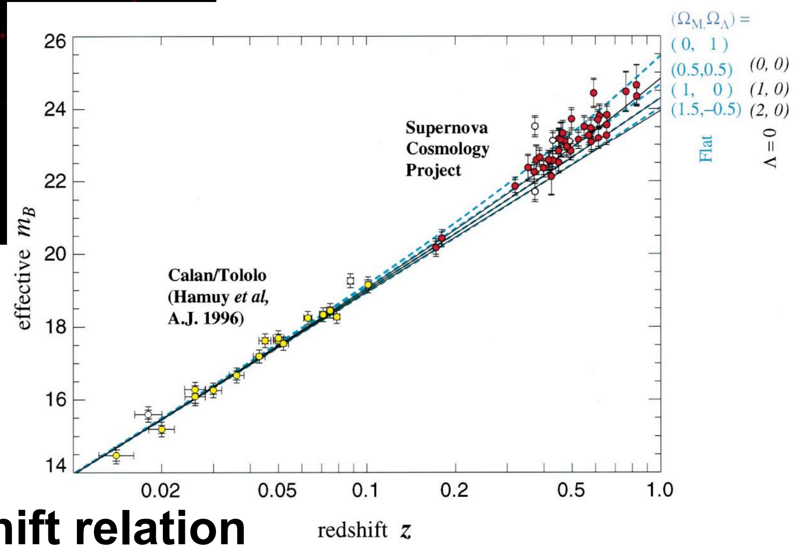




Amplitude of clustering

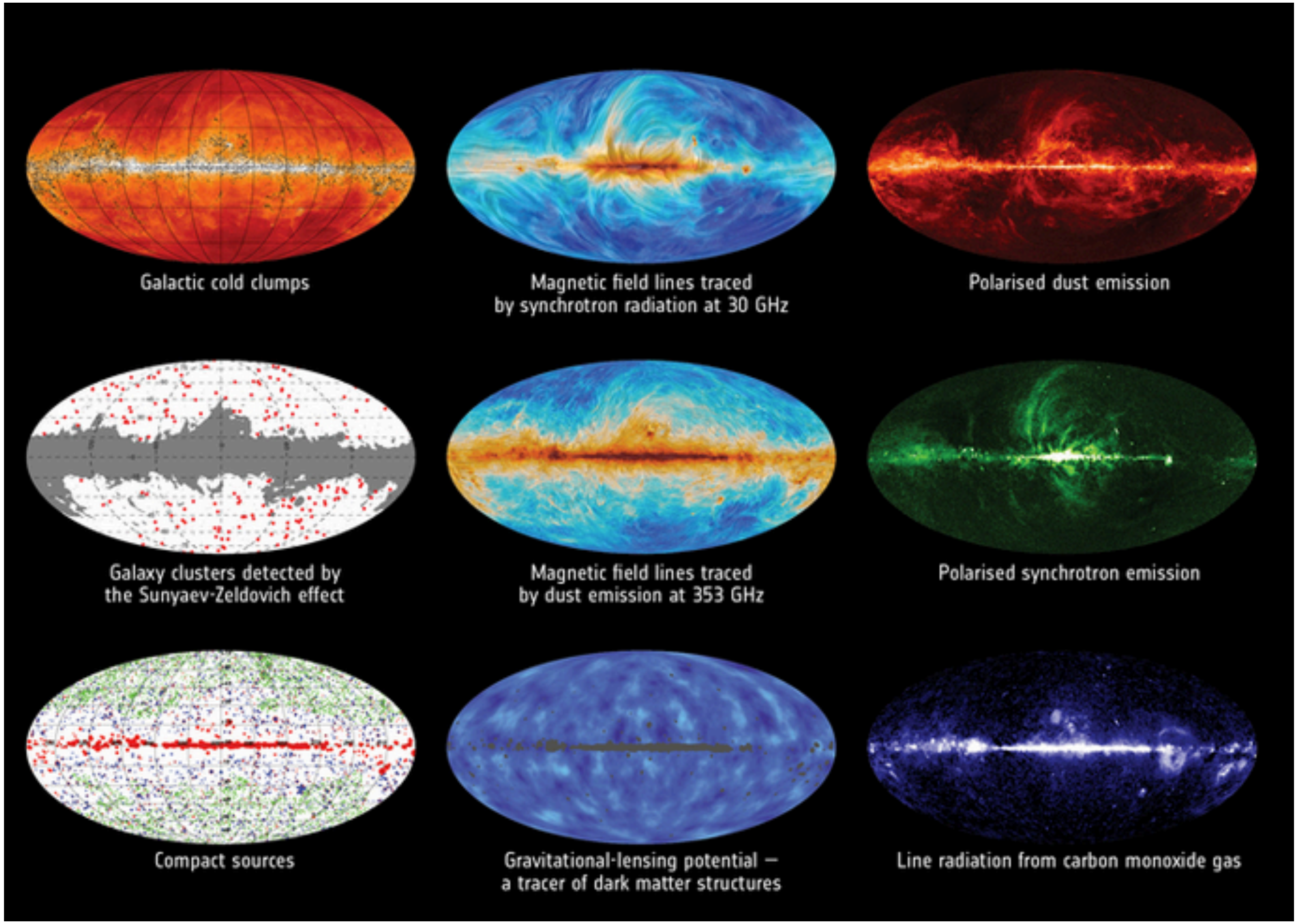
- Supernovas



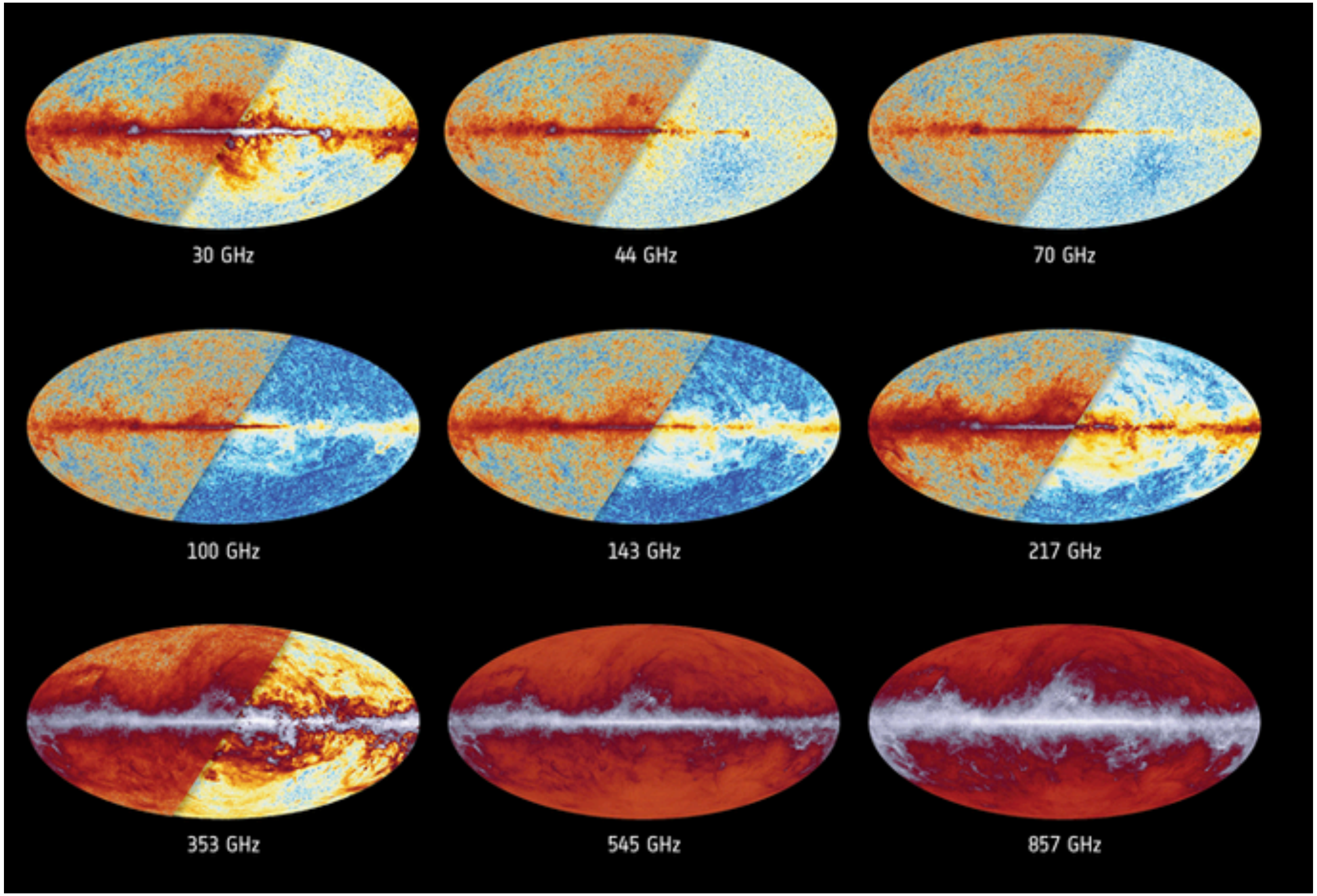


Distance vs redshift relation

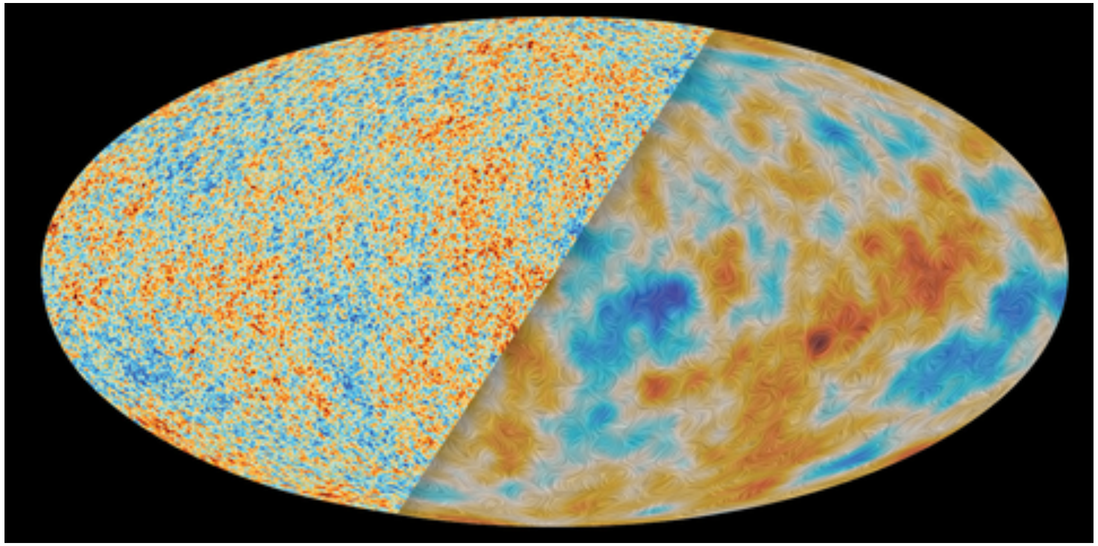
- Cosmic Microwave Background



(Foregrounds)

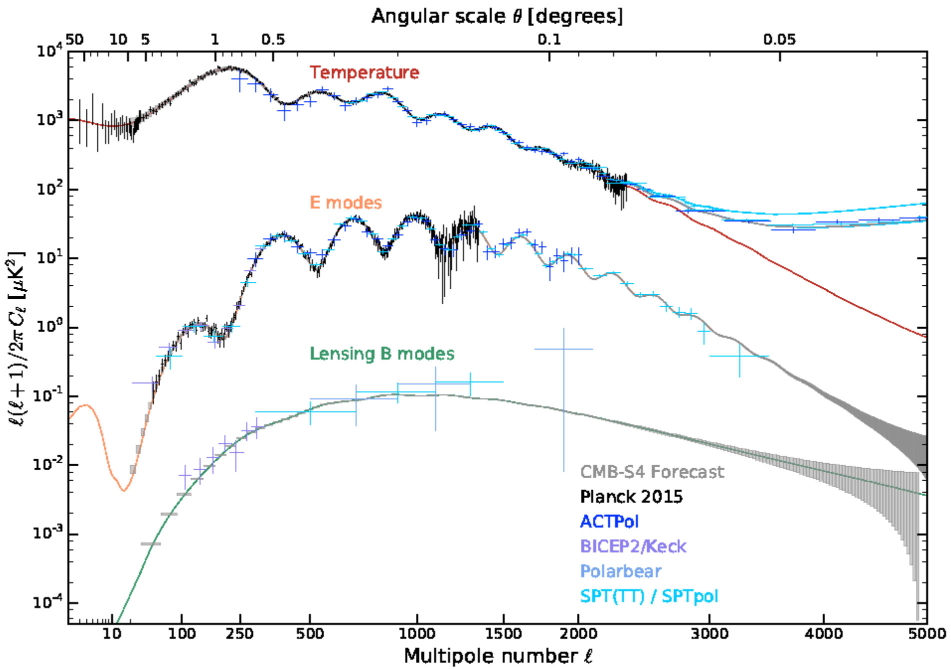


(Cosmological signal in each channel)



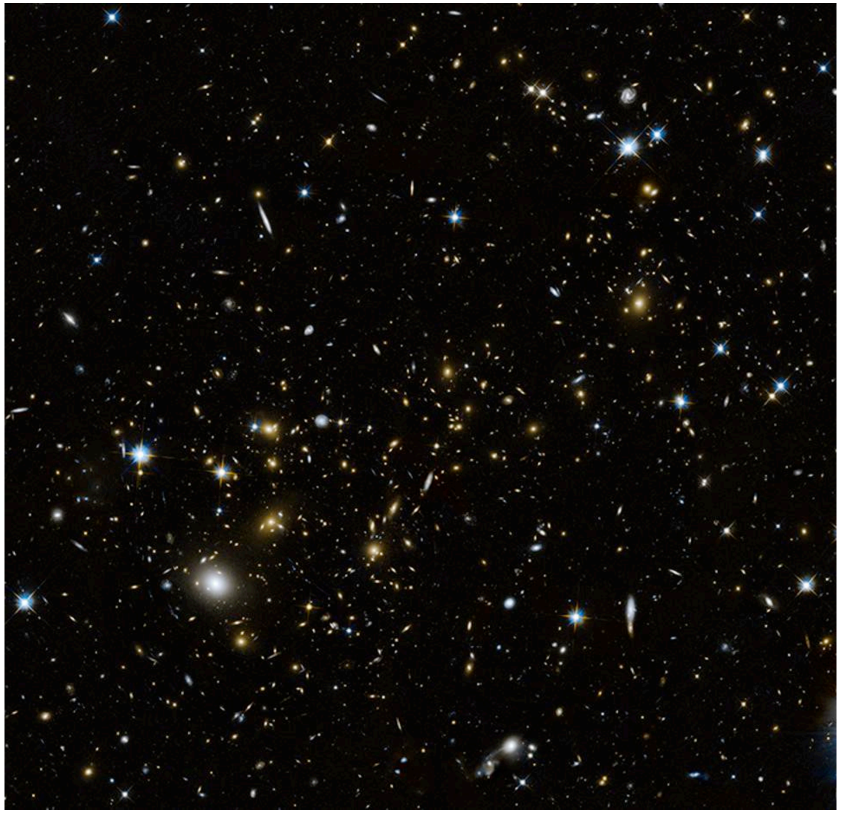
Temperature and polarization maps:

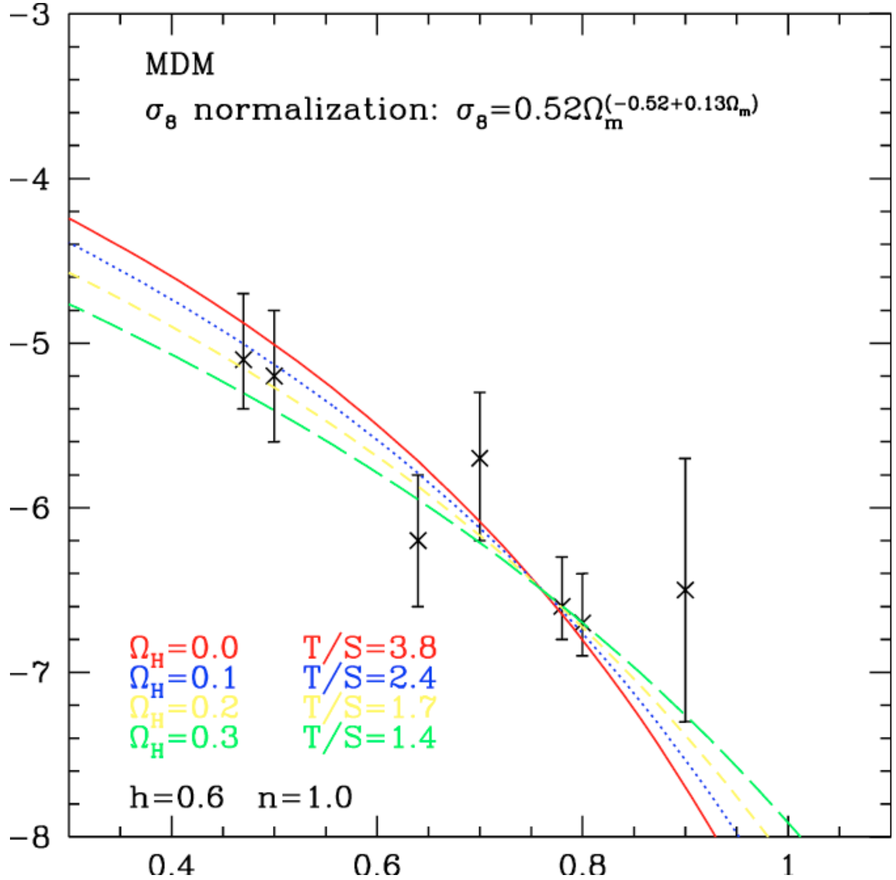
combining 9 frequencies, removing foregrounds, reconstructing the galaxy plane



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 (2022): imaging
(previously named LSST “Large Synoptic Survey Telescope”)

- Nancy Grace Roman space telescope (2025): space
(previously named WFIRST “Wide-Field Infra-Red Survey Telescope”)

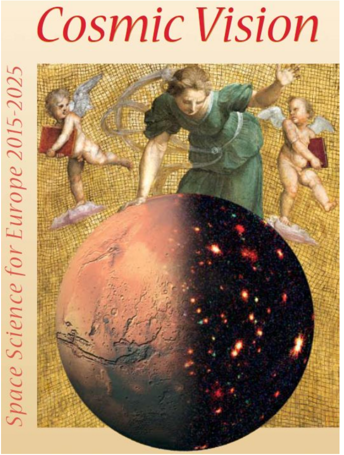
Department of Energy / National Science Foundation

- DESI “Dark Energy Spectroscopic Instrument” (2020): spectroscopic

Explorers Program (NASA)

- SPHEREx “Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer” (2023): space

European program: Cosmic Vision (ESA)



8 space missions

2020 - M1 - Solar Orbiter

2022 - M2 - **Euclid** (PT: *António da Silva, Ismael Tereno)*

2022 - L1 - JUICE "JUpiter Icy moons Explorer"

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

2028 - M4 - ARIEL "Atmospheric Remote-sensIng Exoplanet Large-survey" (PT: *Pedro Machado*)

2031 - L2 - **ATHENA** "Advanced Telescope for High-ENergy Astrophysics"

2032 - M5 - TBD among EnVision, THESEUS "Transient High Energy Sky and Early Universe Surveyor", SPICA "SPace Infrared telescope for Cosmology and Astrophysics "

2034 - L3 - **LISA** "Laser Interferometer Space Antenna"

Nowadays there is much interaction between theory and observations.

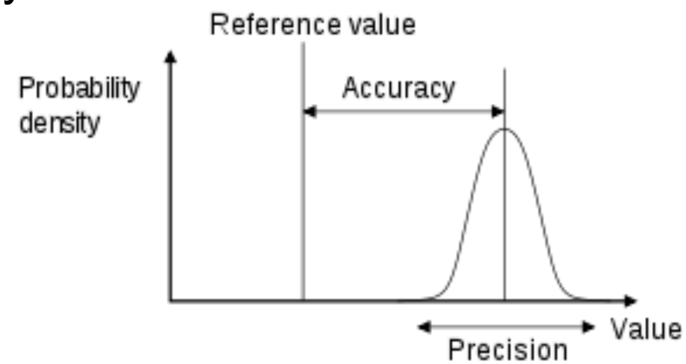
Modern research in cosmology deals with:

- **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