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KOREA INSTITUTE FOR ADVANCED STUDY

The Standard Model of Cosmology

Ki -Young Choi

18-20th February, 2025

The 1st Gülbahçe School and Workshop for Theoretical Physics

1. Introduction: standard model of cosmology

2. Big Bang Cosmology and problems

3. Cosmic Inflation

4. Cosmic Perturbation

5. CMB and LSS

Standard Model of Cosmology

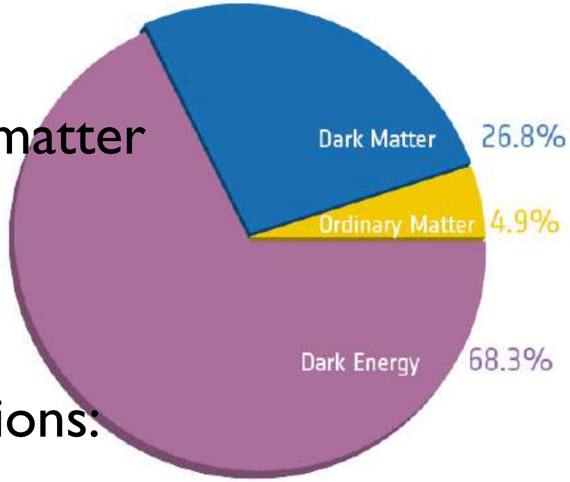
(Lambda-CDM model) **ΛCDM** model

a mathematical model of big bang theory with three major components

with a cosmological constant (Lambda) for dark energy

a cold dark matter (CDM) for non-relativistic dark matter

and ordinary matter, light and neutrino



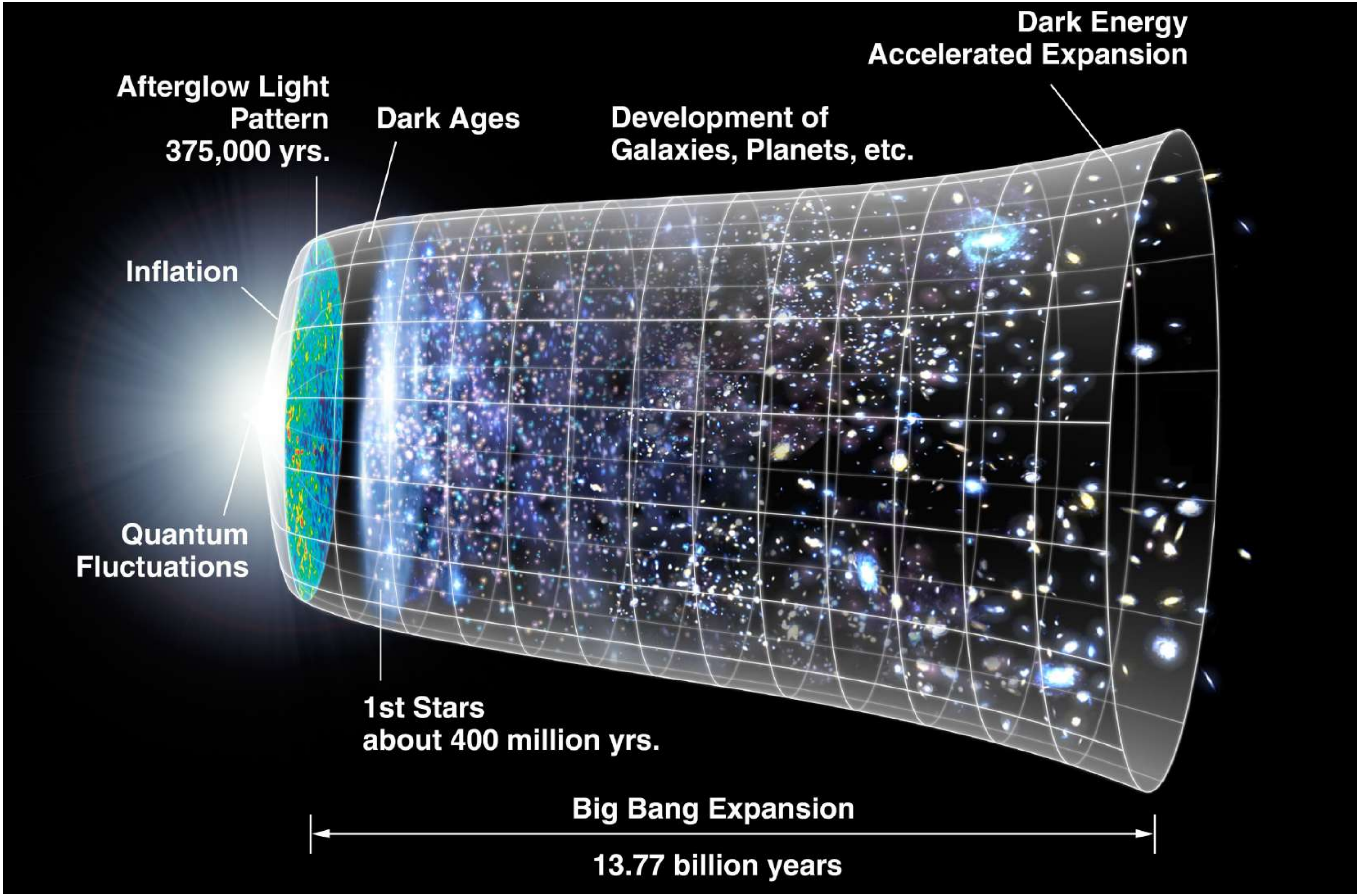
This simple model can explain the cosmological observations:

the existence and structure of the cosmic microwave background (CMB)

the large-scale structure (LSS) formation in the galaxy distribution

the observed abundances of light nuclei such as hydrogen, helium, and lithium

the acceleration of the Universe

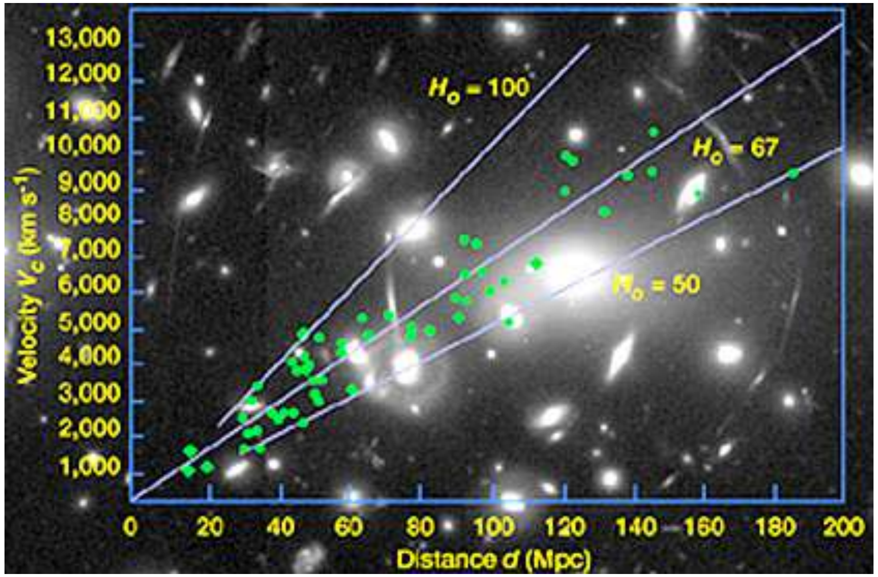


NASA/WMAP Science Team - Original version: NASA; modified by Cherkash

Big Bang Theory

Expanding Universe (not necessarily meaning the initial beginning of Universe)

- From the observation of the distant galaxies
- From the theory of the general relativity
- From the CMB observation, BBN and structure formation



Relation between receeding velocity and distance

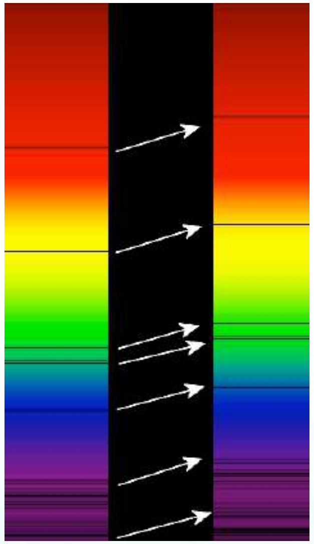
$$v(r) = H \times r$$

$$H = 70(\,\mathrm{km}/\,\mathrm{sec})/\,\mathrm{Mpc}$$

Actually the galaxy is not moving with that velocity!

Redshift

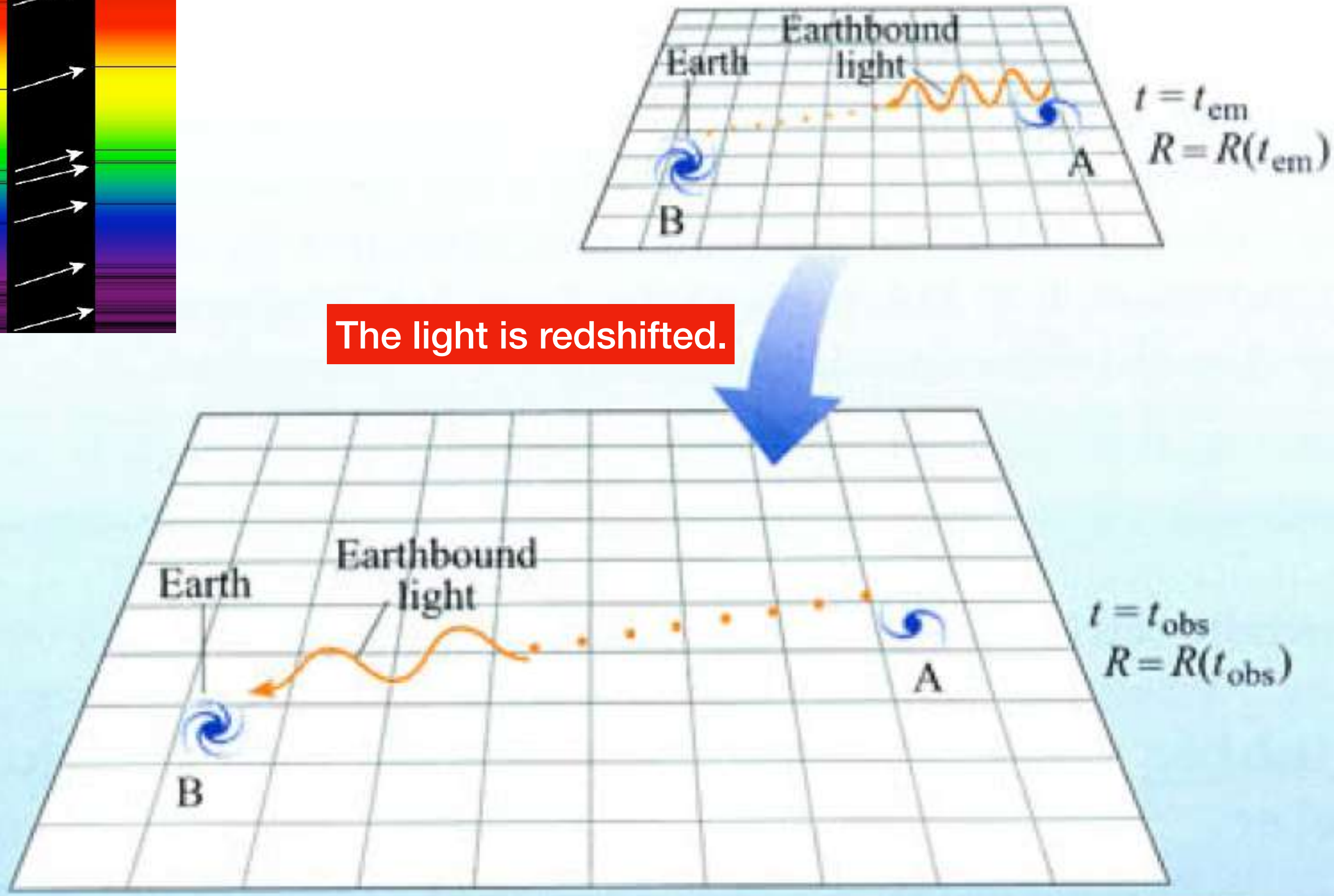
λ



Hubble-Lemaitre Law

*2018 IAU(International Astronomical Unit)

The light is redshifted.

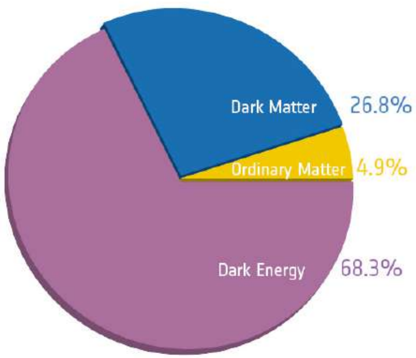


Ki-Young Choi, SKKU

Basic theory: Einstein's General Relativity

Einstein equation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



geometry : metric

$$g^{\mu\nu}$$

matter in the Universe, perfect fluid

$$T^{\mu}_{\nu} = \mathrm{diag}(\rho, -p, -p, -p)$$

• Standard Big Bang model: general relativity

Big bang cosmology assumes that the matter and radiation are uniformly distributed throughout the Universe - Cosmological principle
It is true for large scales of larger than around 100 Mpc for matter distribution and also in the temperature distribution observed in the Cosmic Microwave Background radiation.

The metric for a homogeneous and isotropic space is Friedmann-Robertson-Walker (FRW) metric with line element

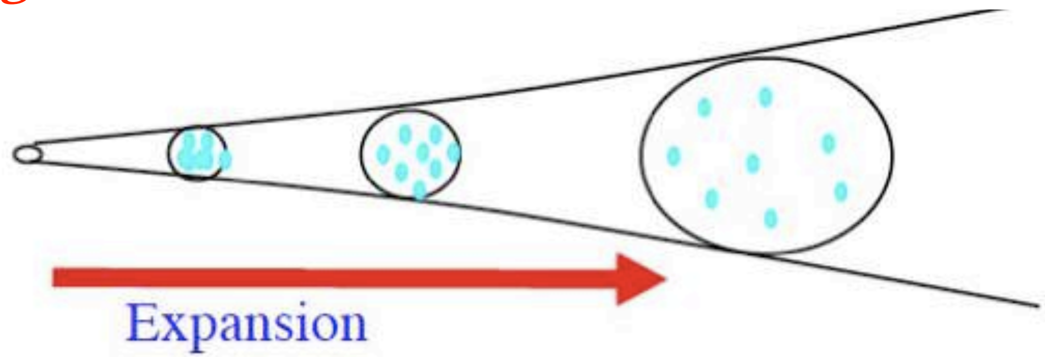
$$ds^2 = dt^2 - R^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin\theta^2 d\phi^2\right\}$$

R(t) : scale factor

k > 0 closed, k = 0 flat, k < 0 open

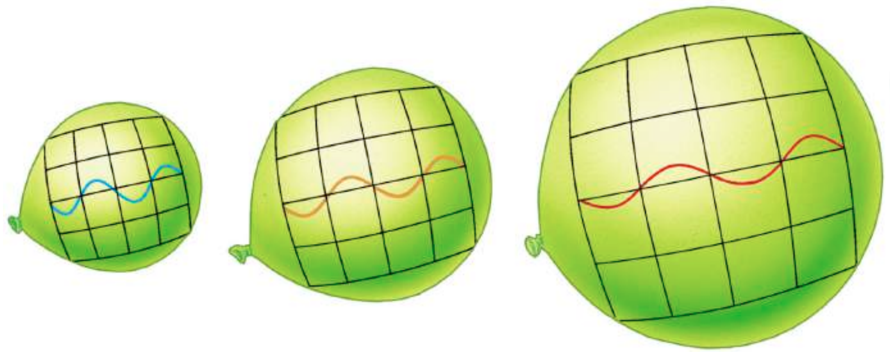
* The assumption of homogeneity and isotropy is understood locally and global properties can be different.

In the expanding Universe



1. The number density decreases. $n(t) \propto \frac{1}{R^3(t)}$

2. The momentum is redshifted. $P(t) \propto \frac{1}{R(t)}$



Relativistic matter $\rho_r \sim E(t)\, n(t) \propto R(t)^{-4}$

Non-Relativistic matter $\rho_m \sim M\, n(t) \propto R(t)^{-3}$

The Standard Model of Particle Physics

Fundamental particles

Higgs 125 GeV

BOSONS

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W⁻	80.39	–1
W⁺ (W bosons)	80.39	+1
Z⁰ Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Evolution of Matter in the Early Universe

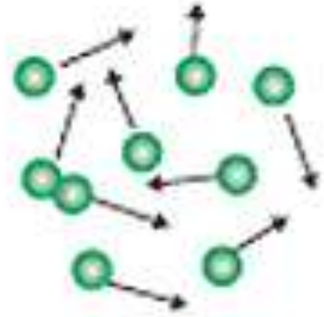
atom, molecule
nucleus
electron

Large Structure Formation

very cold

Dark Energy

galaxy



neutral gas

~ eV
recombination
last scattering
: CMB formation

matter dominated

Radiation dominated

very hot

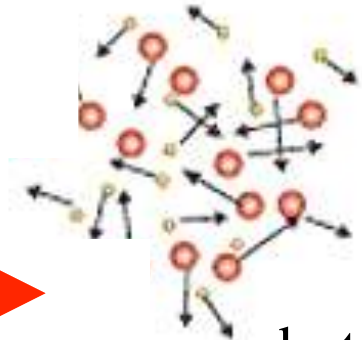
plasma of quark, gluon, and electron,..

thermal equilibrium

plasma of proton, neutron, electron

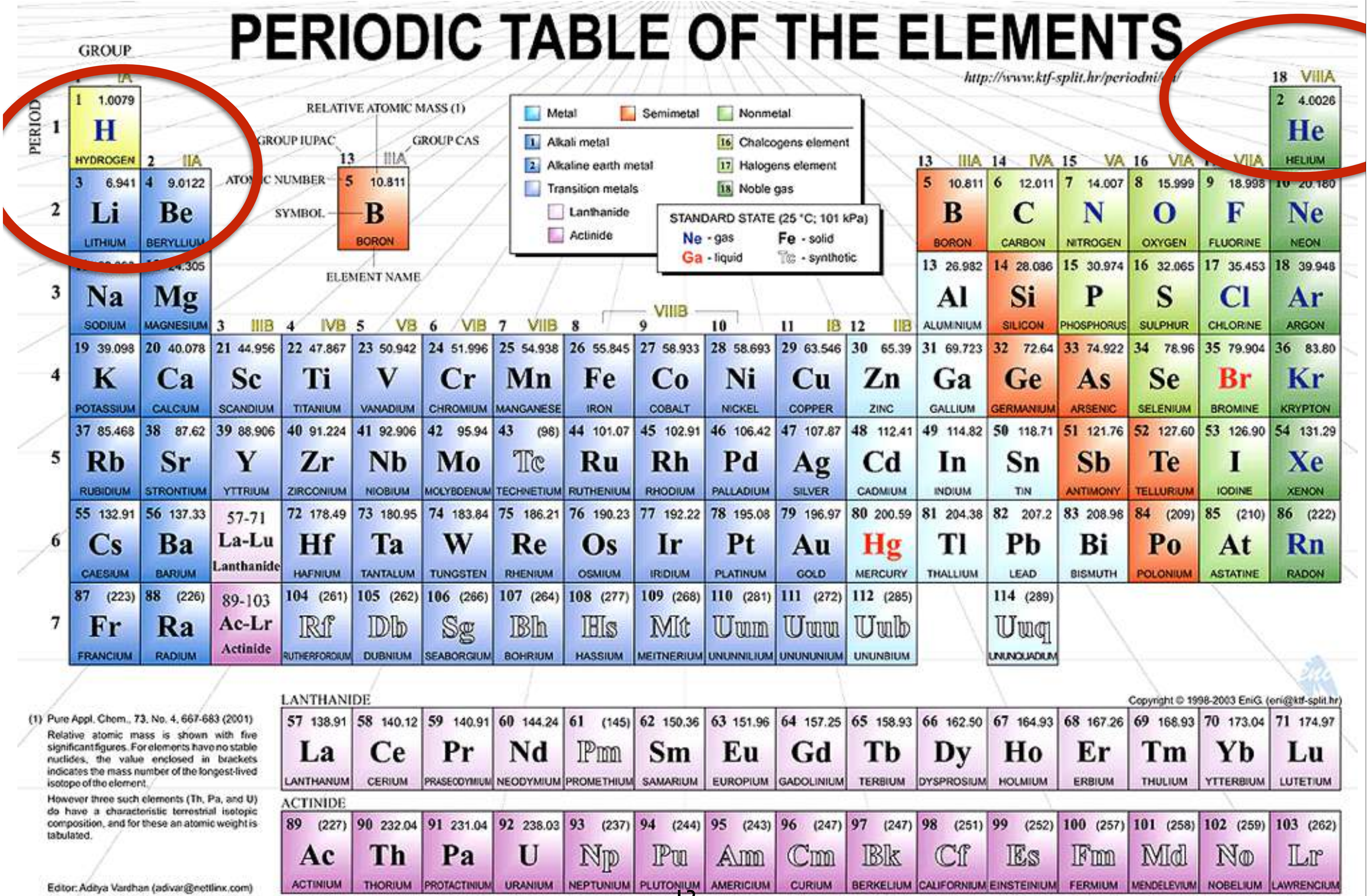
100 MeV
quark-hadron transition

MeV
nucleosynthesis
BBN



photon, electron, light elements

BBN


PERIODIC TABLE OF THE ELEMENTS
http://www.ktf-split.hr/periodni/
GROUP
PERIOD
RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME
5 10.811 B BORON
Metal
Semimetal
Nonmetal
Alkali metal
Alkaline earth metal
Transition metals
Lanthanide
Actinide
Chalcogens element
Halogens element
Noble gas
STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic
1 1.0079 H HYDROGEN
2 4.0026 He HELIUM
3 6.941 Li LITHIUM
4 9.0122 Be BERYLLIUM
5 10.811 B BORON
6 12.011 C CARBON
7 14.007 N NITROGEN
8 15.999 O OXYGEN
9 18.998 F FLUORINE
10 20.180 Ne NEON
Na SODIUM
Mg MAGNESIUM
13 26.982 Al ALUMINIUM
14 28.086 Si SILICON
15 30.974 P PHOSPHORUS
16 32.065 S SULPHUR
17 35.453 Cl CHLORINE
18 39.948 Ar ARGON
19 39.098 K POTASSIUM
20 40.078 Ca CALCIUM
21 44.956 Sc SCANDIUM
22 47.867 Ti TITANIUM
23 50.942 V VANADIUM
24 51.996 Cr CHROMIUM
25 54.938 Mn MANGANESE
26 55.845 Fe IRON
27 58.933 Co COBALT
28 58.693 Ni NICKEL
29 63.546 Cu COPPER
30 65.39 Zn ZINC
31 69.723 Ga GALLIUM
32 72.64 Ge GERMANIUM
33 74.922 As ARSENIC
34 78.96 Se SELENIUM
35 79.904 Br BROMINE
36 83.80 Kr KRYPTON
37 85.468 Rb RUBIDIUM
38 87.62 Sr STRONTIUM
39 88.906 Y YTTRIUM
40 91.224 Zr ZIRCONIUM
41 92.906 Nb NIOBIUM
42 95.94 Mo MOLYBDENUM
43 (98) Tc TECHNETIUM
44 101.07 Ru RUTHENIUM
45 102.91 Rh RHODIUM
46 106.42 Pd PALLADIUM
47 107.87 Ag SILVER
48 112.41 Cd CADMIUM
49 114.82 In INDIUM
50 118.71 Sn TIN
51 121.76 Sb ANTIMONY
52 127.60 Te TELLURIUM
53 126.90 I IODINE
54 131.29 Xe XENON
55 132.91 Cs CAESIUM
56 137.33 Ba BARIUM
57-71 La-Lu Lanthanide
72 178.49 Hf HAFNIUM
73 180.95 Ta TANTALUM
74 183.84 W TUNGSTEN
75 186.21 Re RHENIUM
76 190.23 Os OSMIUM
77 192.22 Ir IRIDIUM
78 195.08 Pt PLATINUM
79 196.97 Au GOLD
80 200.59 Hg MERCURY
81 204.38 Tl THALLIUM
82 207.2 Pb LEAD
83 208.98 Bi BISMUTH
84 (209) Po POLONIUM
85 (210) At ASTATINE
86 (222) Rn RADON
87 (223) Fr FRANCIUM
88 (226) Ra RADIUM
89-103 Ac-Lr Actinide
104 (261) Rf RUTHERFORDIUM
105 (262) Db DUBNIUM
106 (266) Sg SEABORGIUM
107 (264) Bh BOHRIUM
108 (277) Hs HASSIUM
109 (268) Mt MEITNERIUM
110 (281) Uun UNUNNILIUM
111 (272) Uuu UNUNUNIUM
112 (285) Uub UNUNBIUM
114 (289) Uuq UNUNQUADIUM
LANTHANIDE
57 138.91 La LANTHANUM
58 140.12 Ce CERIUM
59 140.91 Pr PRASEODYMIUM
60 144.24 Nd NEODYMIUM
61 (145) Pm PROMETHIUM
62 150.36 Sm SAMARIUM
63 151.96 Eu EUROPIUM
64 157.25 Gd GADOLINIUM
65 158.93 Tb TERBIUM
66 162.50 Dy DYSPROSIUM
67 164.93 Ho HOLMIUM
68 167.26 Er ERBIUM
69 168.93 Tm THULIUM
70 173.04 Yb YTTERBIUM
71 174.97 Lu LUTETIUM
ACTINIDE
89 (227) Ac ACTINIUM
90 232.04 Th THORIUM
91 231.04 Pa PROTACTINIUM
92 238.03 U URANIUM
93 (237) Np NEPTUNIUM
94 (244) Pu PLUTONIUM
95 (243) Am AMERICIUM
96 (247) Cm CURIUM
97 (247) Bk BERKELIUM
98 (251) Cf CALIFORNIUM
99 (252) Es EINSTEINIUM
100 (257) Fm FERMIUM
101 (258) Md MENDELEVIUM
102 (259) No NOBELIUM
103 (262) Lr LAWRENCIUM
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.
Editor: Aditya Vardhan (adivar@nettlinx.com)
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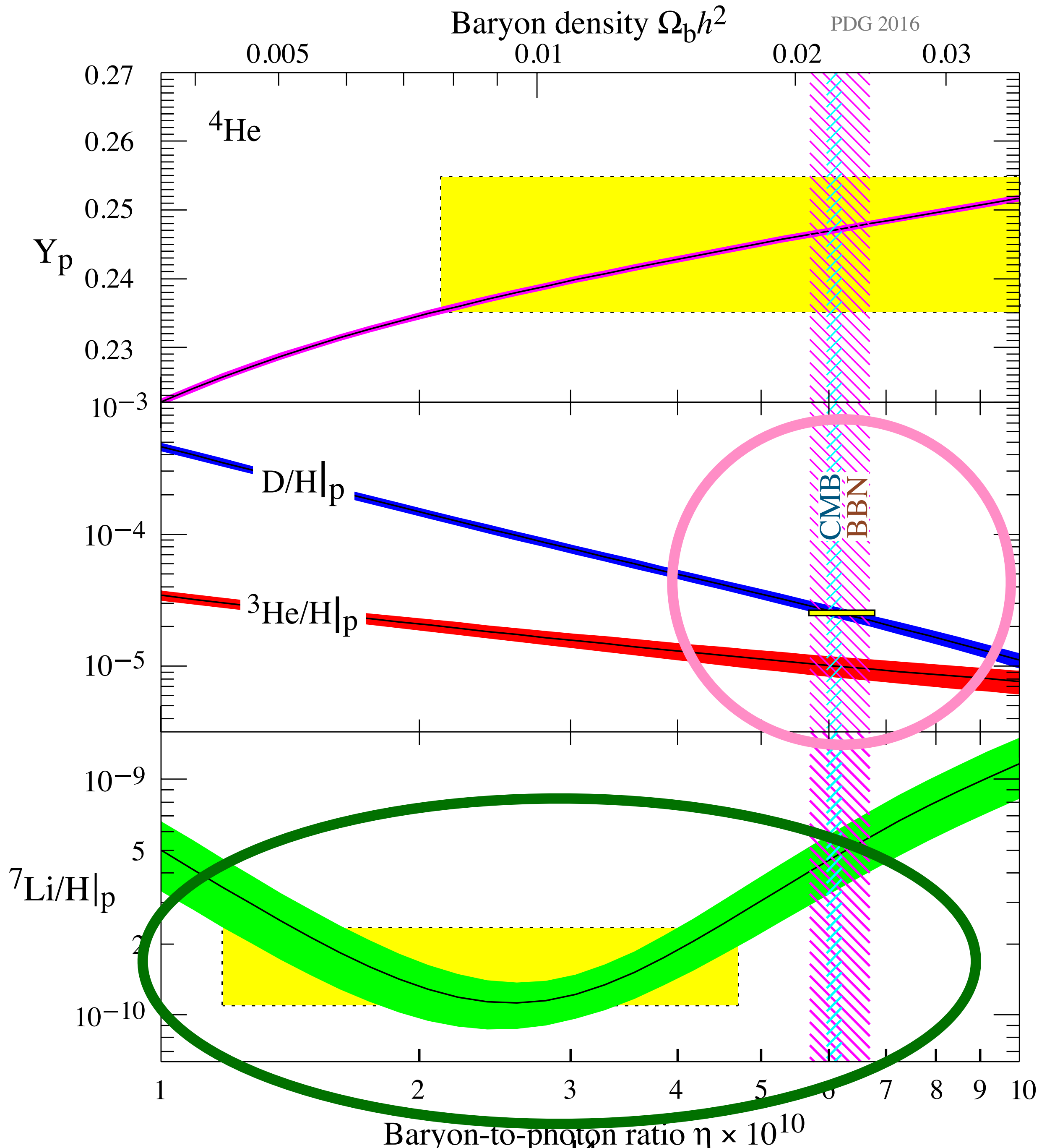
Big Bang Nucleosynthesis



[PDG (2016)]

baryon asymmetry

Lithium problem

CMB

Cosmic Microwave Background

Horn Antenna — Holmdel, New Jersey.
Dr. Robert Wilson (left) and Dr. Arno Penzias (right) in front of the Horn Antenna, 1975.
(Photo Credit: Bell Labs)

Penzias and Wilson found a low, steady, mysterious noise that persisted in their receiver.
100 times intense than expected
and evenly spread over the sky (1965)

Source of noise?

: After checking the equipment, removing pigeons nesting in the antenna and cleaning out the accumulated droppings, the noise remained

→ Radiation left over from the early hot Universe

Nobel Prize 1978

Cosmic Background Explorer (COBE) : 1992 April 23

Launched on November 18, 1989

Nobel Prize 2006

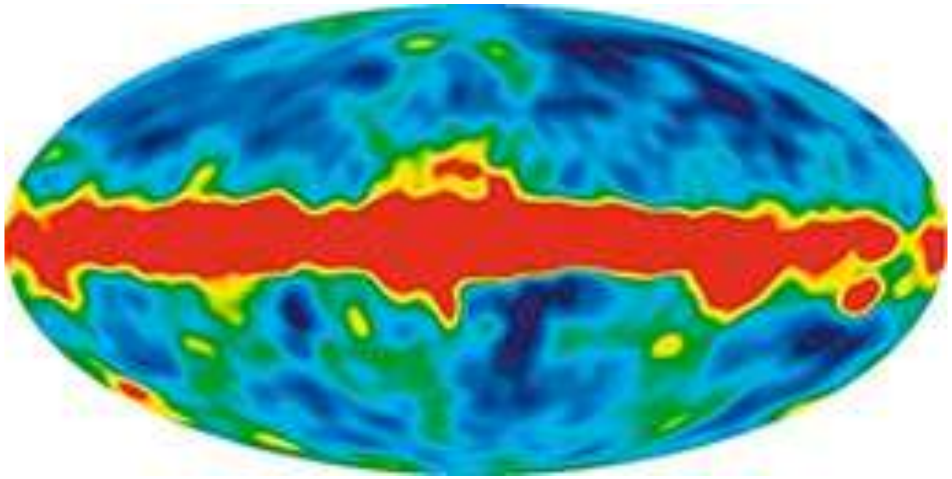
The observed spectrum of CMB radiation agrees closely with the predicted Planck spectrum with temperature

$$T = 2.725 \pm 0.001\, K$$ FIRAS

COBE confirmed that the CMBR is uniform in all directions to nearly 1 part of 50,000, consistent with the homogeneity assumption of the hot big bang model.

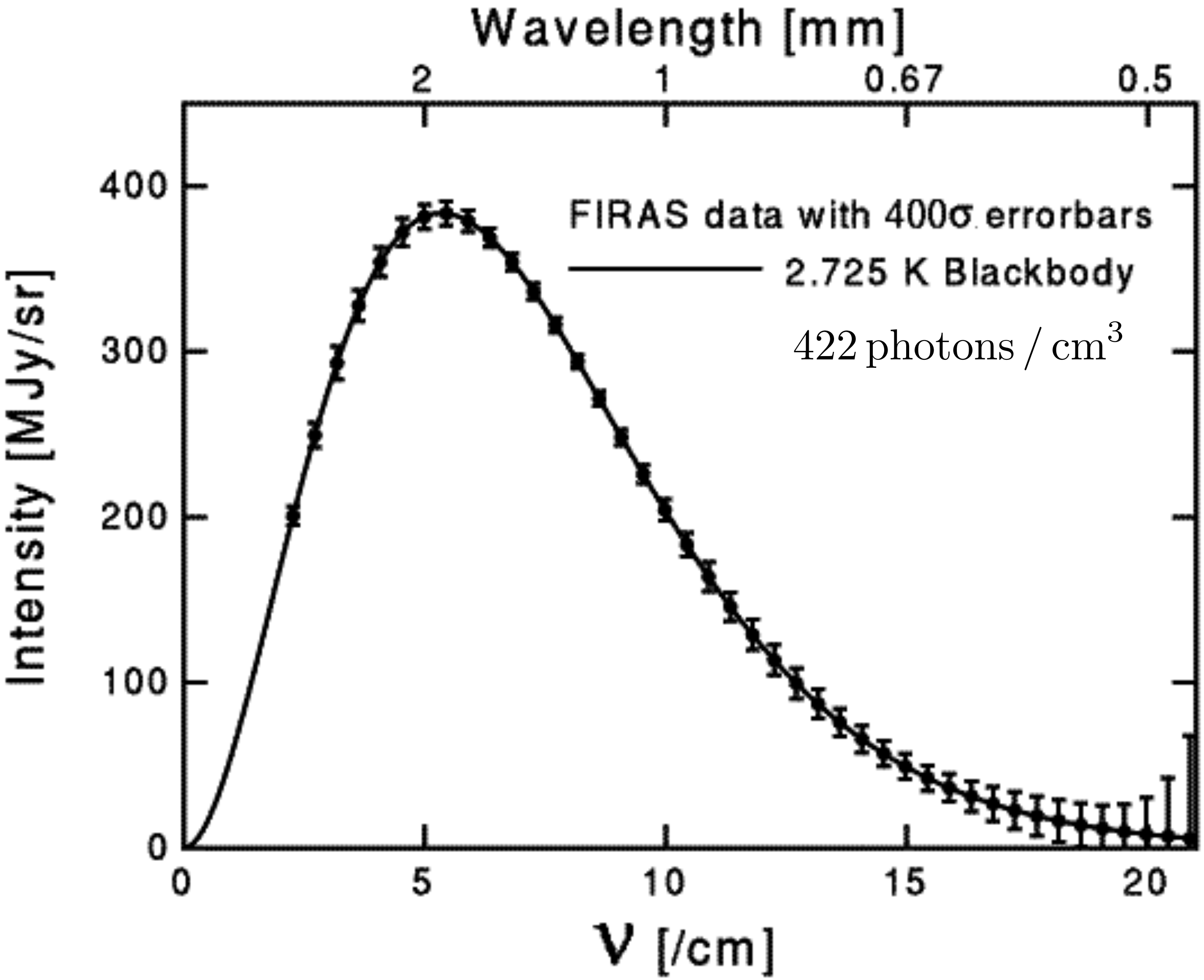
COBE observed the small anisotropy $\sim 10^{-5}$ K

DMR

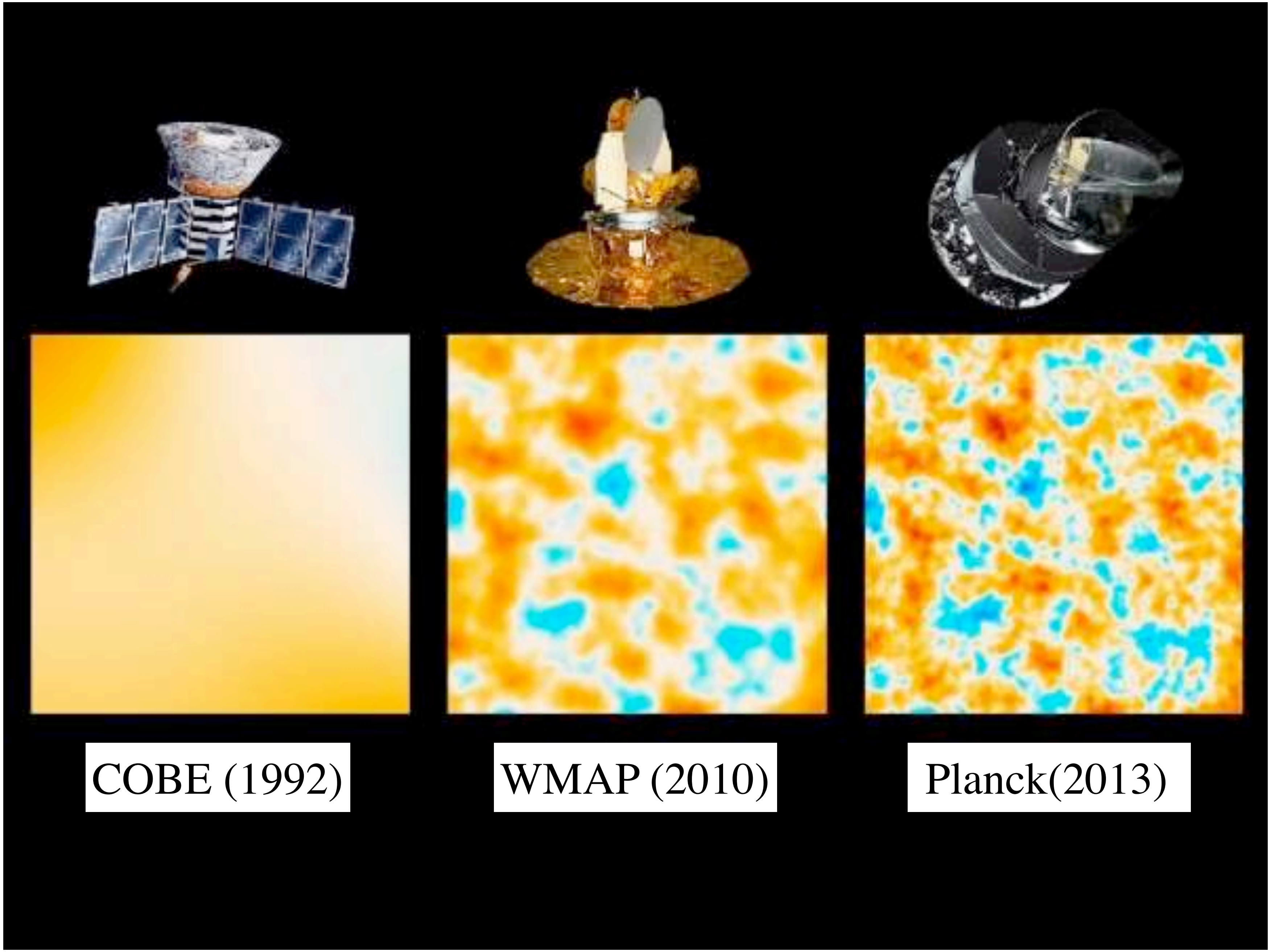


COBE

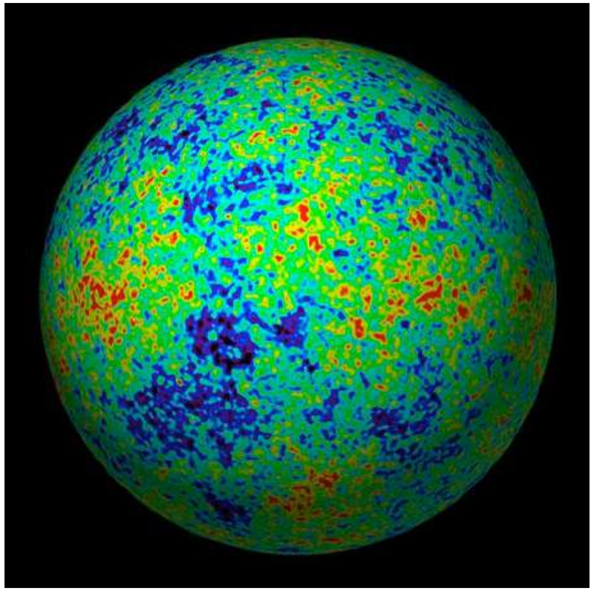
- Black body radiation of CMB with FIRAS data

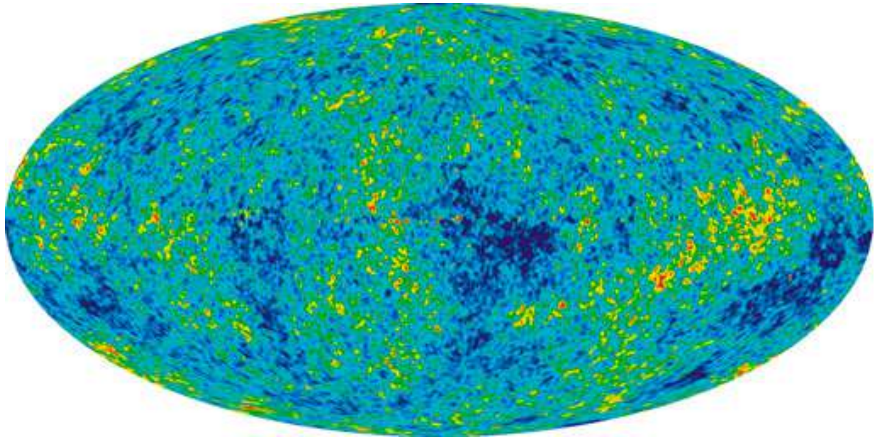


Cosmic Microwave Background satellite



Cosmic Microwave Background Radiation

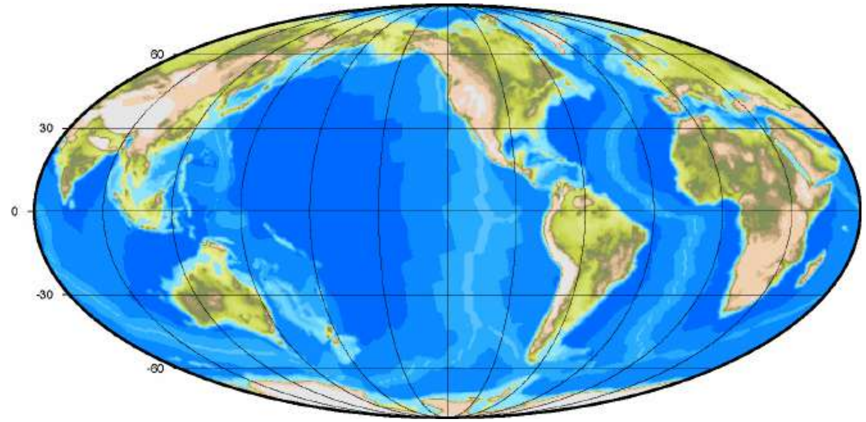




CMB temperature

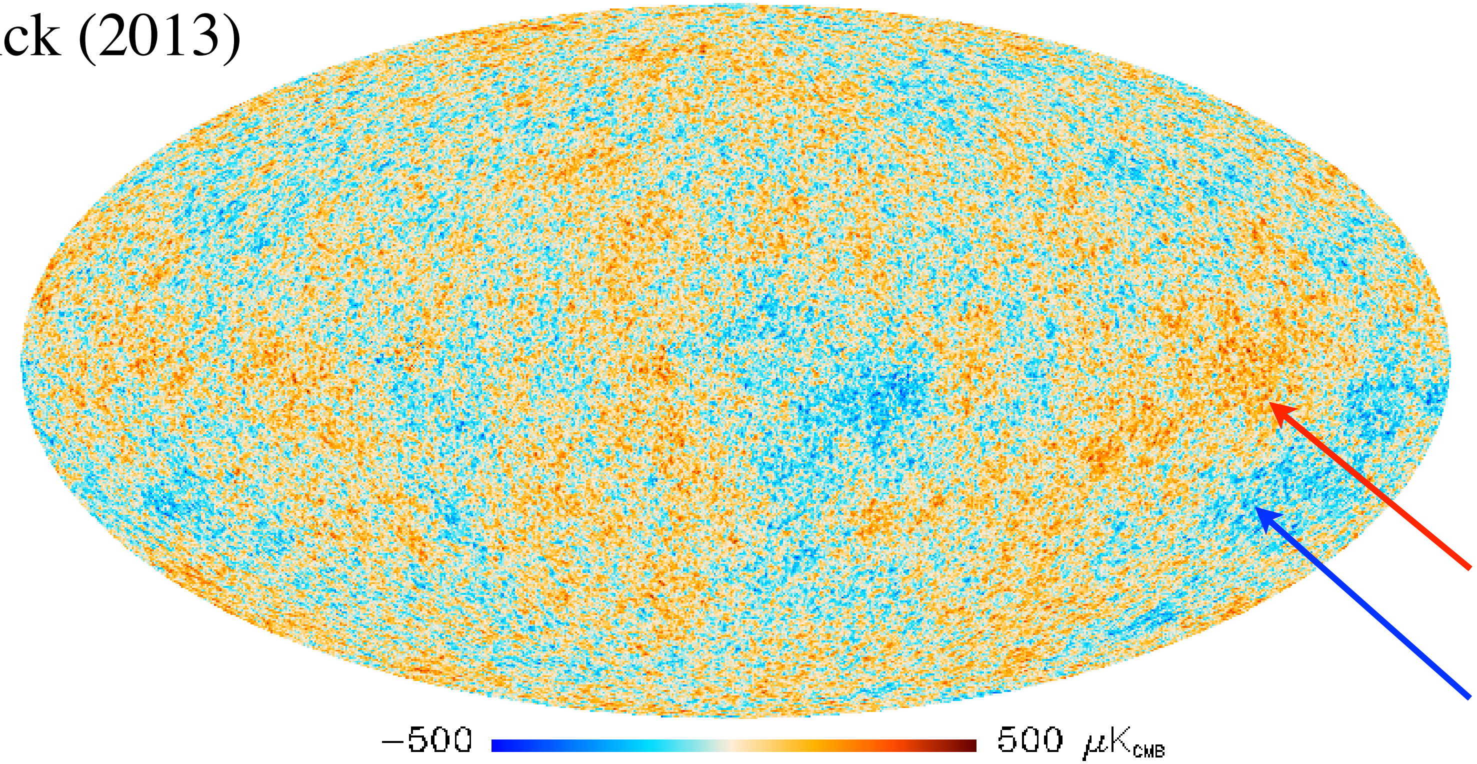
Mollweide projection

Earth



CMB temperature anisotropy

Planck (2013)

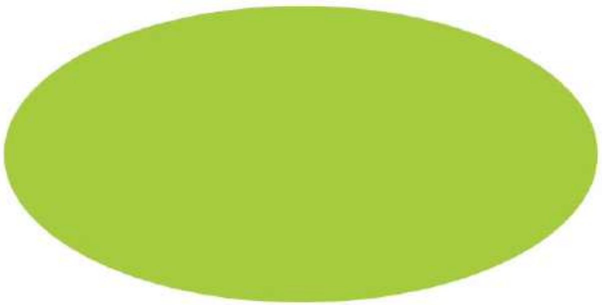


$$T_0 = 2.725K$$

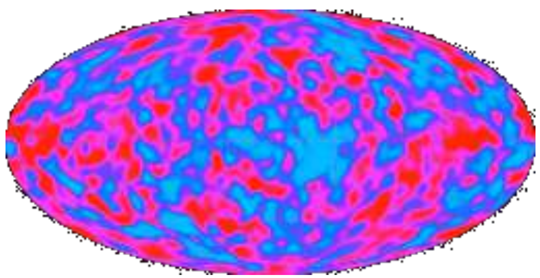
$$T_0 + \mathcal{O}(10^{-5})K$$

$$T_0 - \mathcal{O}(10^{-5})K$$

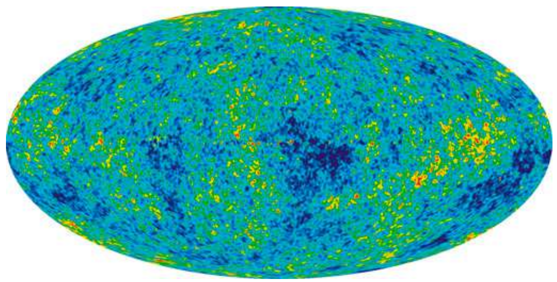
Penzias, Wilson (1965)



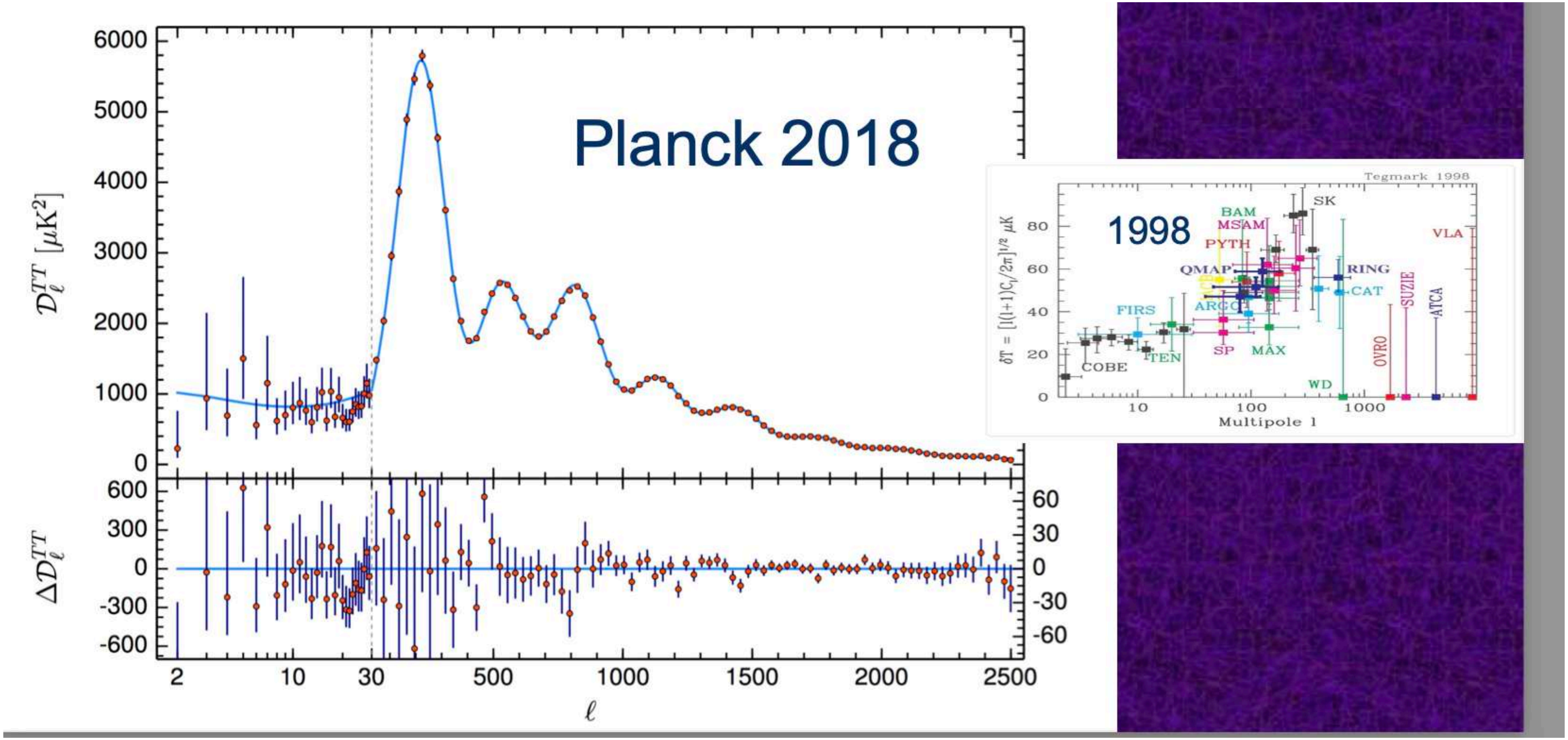
COBE (1992)



WMAP (2007)



Cosmic Microwave Background



Precision Cosmology

Planck 2018

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

Table 2. Cosmological parameter values for the six-parameter base ΛCDM model. Columns 2 and 3 give results for the *Planck* temperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns 6 and 7 include *WMAP* polarization at low multipoles. We give best fit parameters as well as 68% confidence limits for constrained parameters. The first six parameters have flat priors. The remainder are derived parameters as discussed in Sect. 2. Beam, calibration parameters, and foreground parameters (see Sect. 4) are not listed for brevity. Constraints on foreground parameters for *Planck*+WP are given later in Table 5.

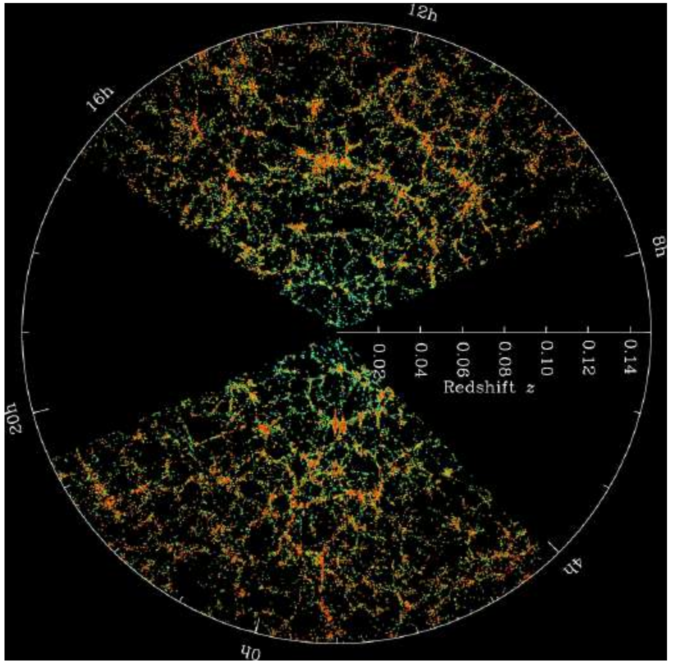
Large Structure Formation

Large Scale Structure Formation

Astronomers observe the structure in the Universe, from stars to galaxies to clusters and superclusers of galaxies.

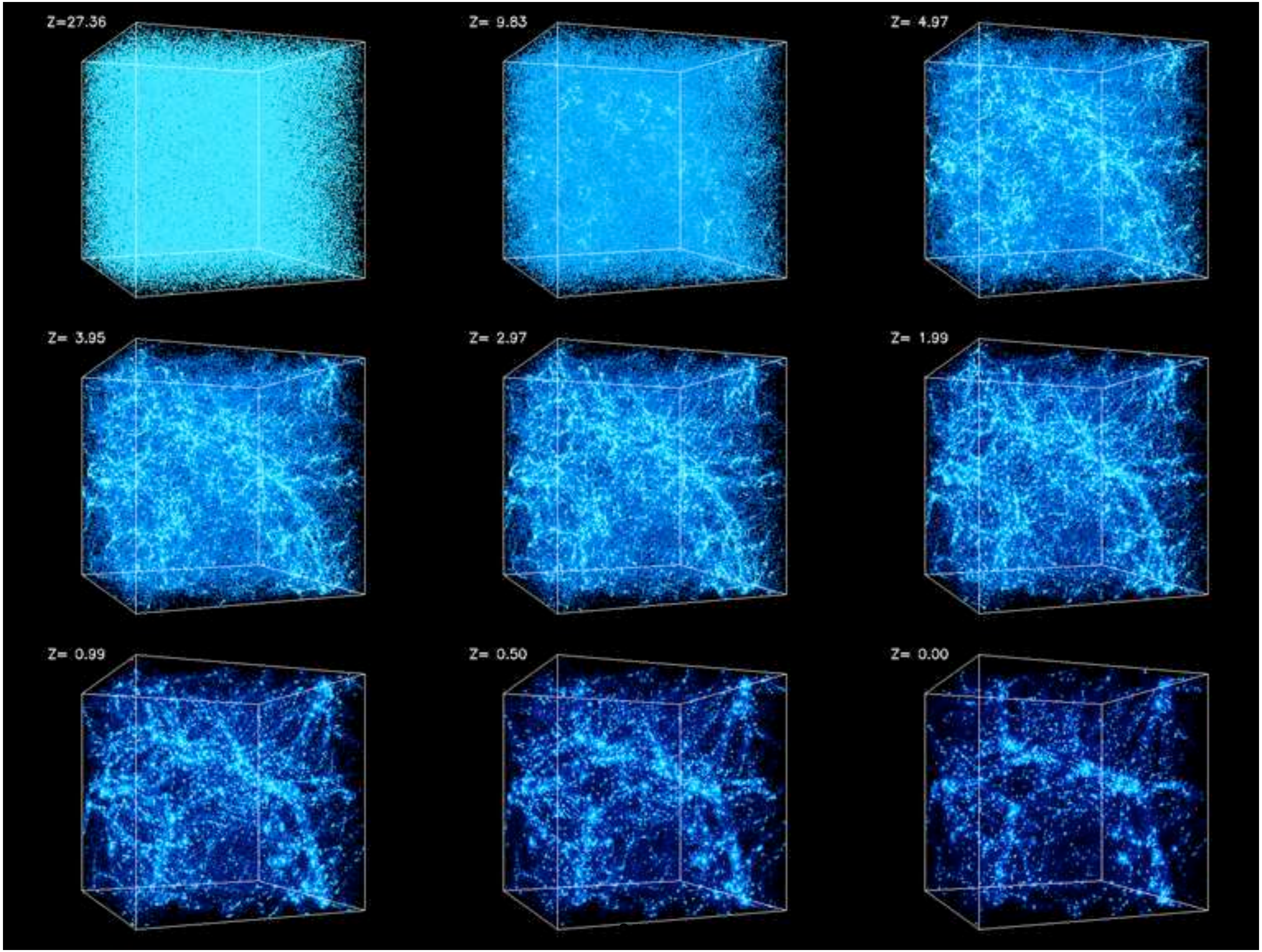
- 2-degree Field (2dF) Galaxy Redshift Survey
- Sloan digital Sky Survey (SDSS)

The matter distribution is most easily probed by observing the galaxy distribution, but with a bias factor between galaxy distribution and dark matter distribution.

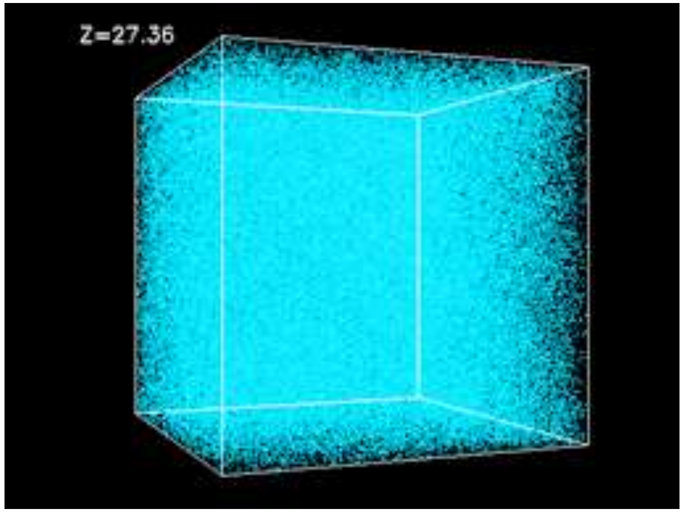


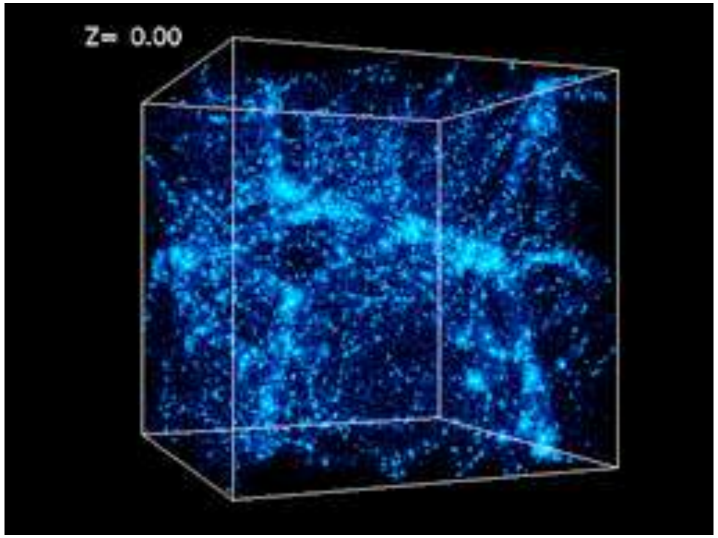
Slices through the SDSS 3-dim map of the distribution of galaxies

- The formation of clusters and large-scale filaments in the LCDM model 43Mpc box



- Dark Matter for the Large scale structure formation





Early Universe

Homogeneous, isotropic

$$\frac{\delta\rho}{\rho} \sim 10^{-5}$$

Present Universe

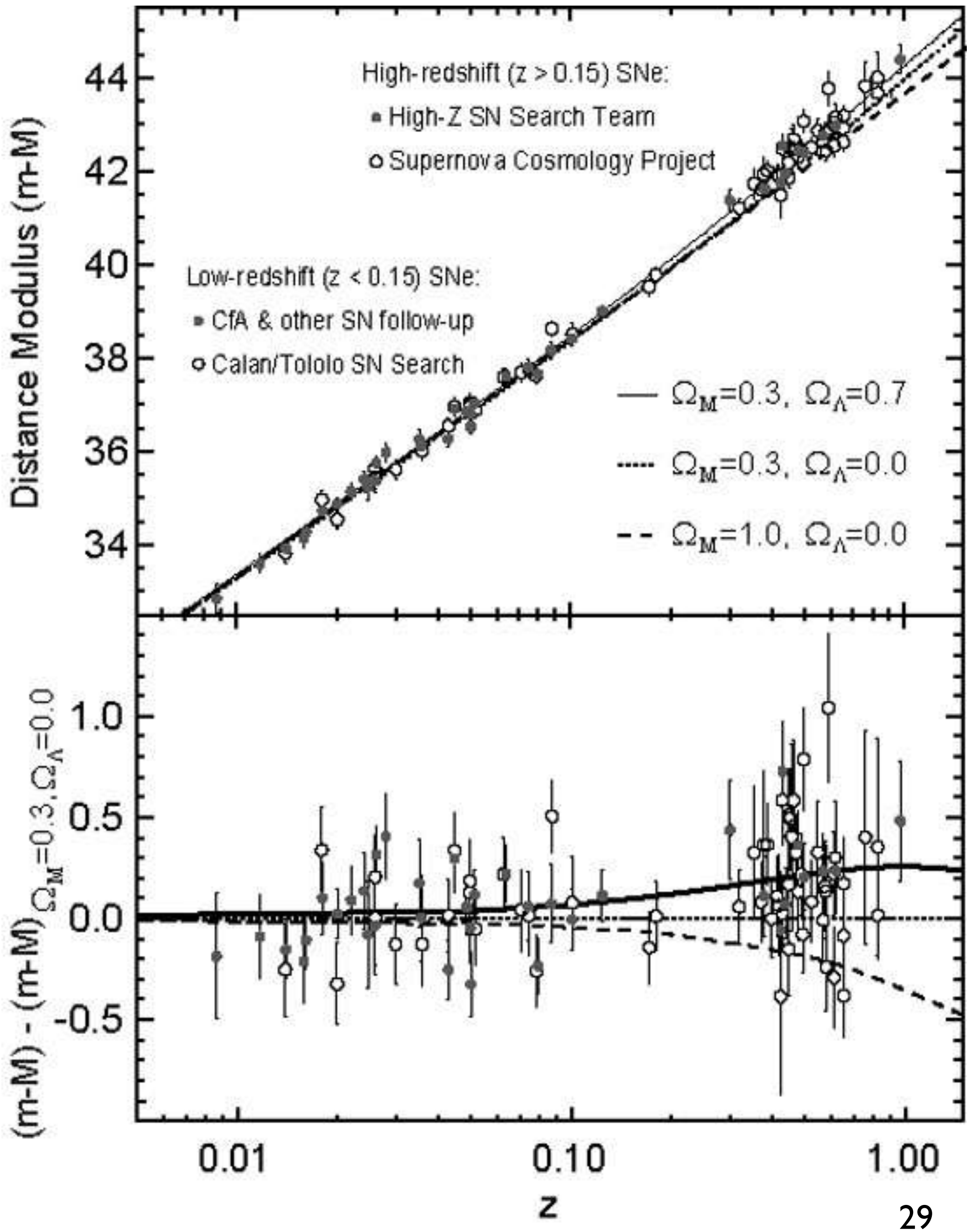
Inhomogeneous, anisotropic

$$\frac{\delta\rho}{\rho} \gtrsim 1$$

By gravitational attraction

Dark Energy

Acceleration of the Universe



In 1998, Perlmutter group and Riess group discovered that
the distant supernovae are fainter than expected

Due to the expansion history of the Universe

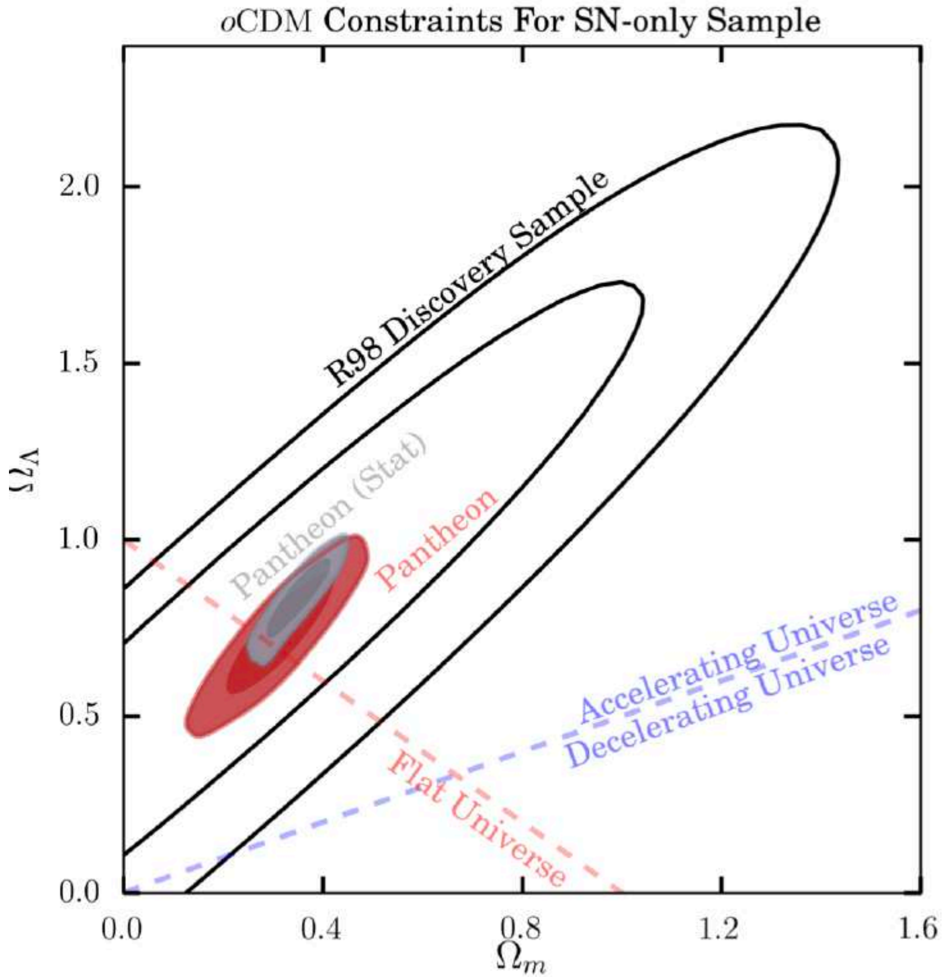
$$\frac{d^2a}{dt^2} = -\frac{4\pi G\rho}{3}a + \frac{\Lambda}{3}a$$

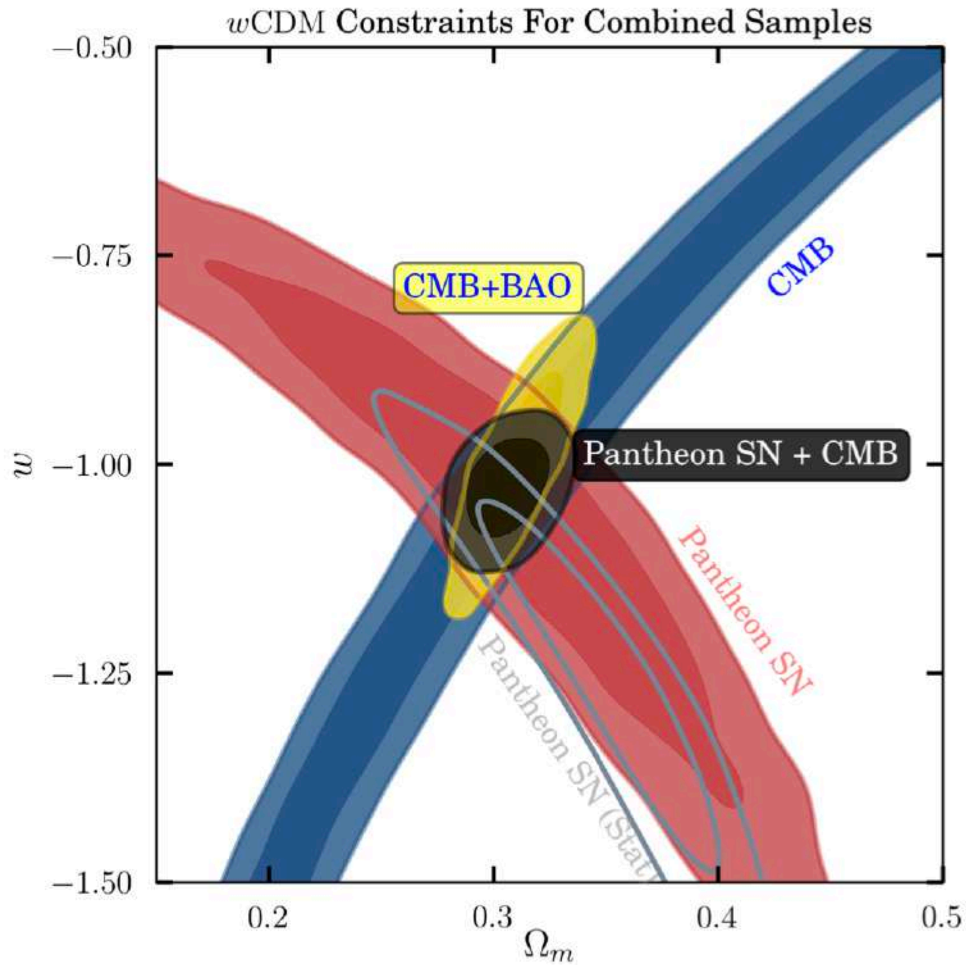
deceleration acceleration

Revival of cosmological constant!

[Riess 2000, Perlmutter & Schmidt 2003]

m - M = 5 Log (DL/10 pc)





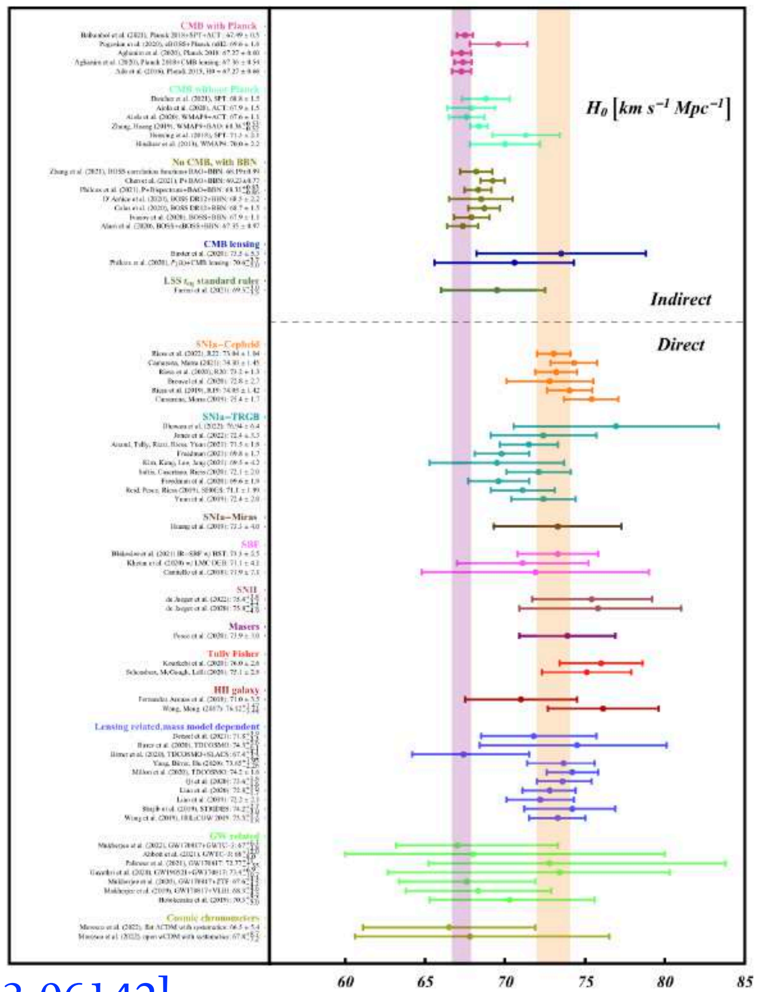
[Pantheon compilation, Scolnic etal, (2018)]

Problems

Hubble Tension

Mismatch of the Hubble expansion parameter at present in between CMB observation and local measurement.

E. Abdalla, G.F. Abellán, A. Aboubrahim et al. *Journal of High Energy Astrophysics 34 (2022) 49–211*



$$H_0 = 67.27 \pm 0.6 \text{ km/s/Mpc at } 68\% \text{ C.L.}$$

Planck CMB data

5-sigma deviation

$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

Local SH0ES measurement

[2203.06142]
E. Abdalla, G.F. Abellán, A. Aboubrahim et al.

S8 Tension

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{1/2}$$

$$\Omega_m \equiv \rho_m/\rho_c$$

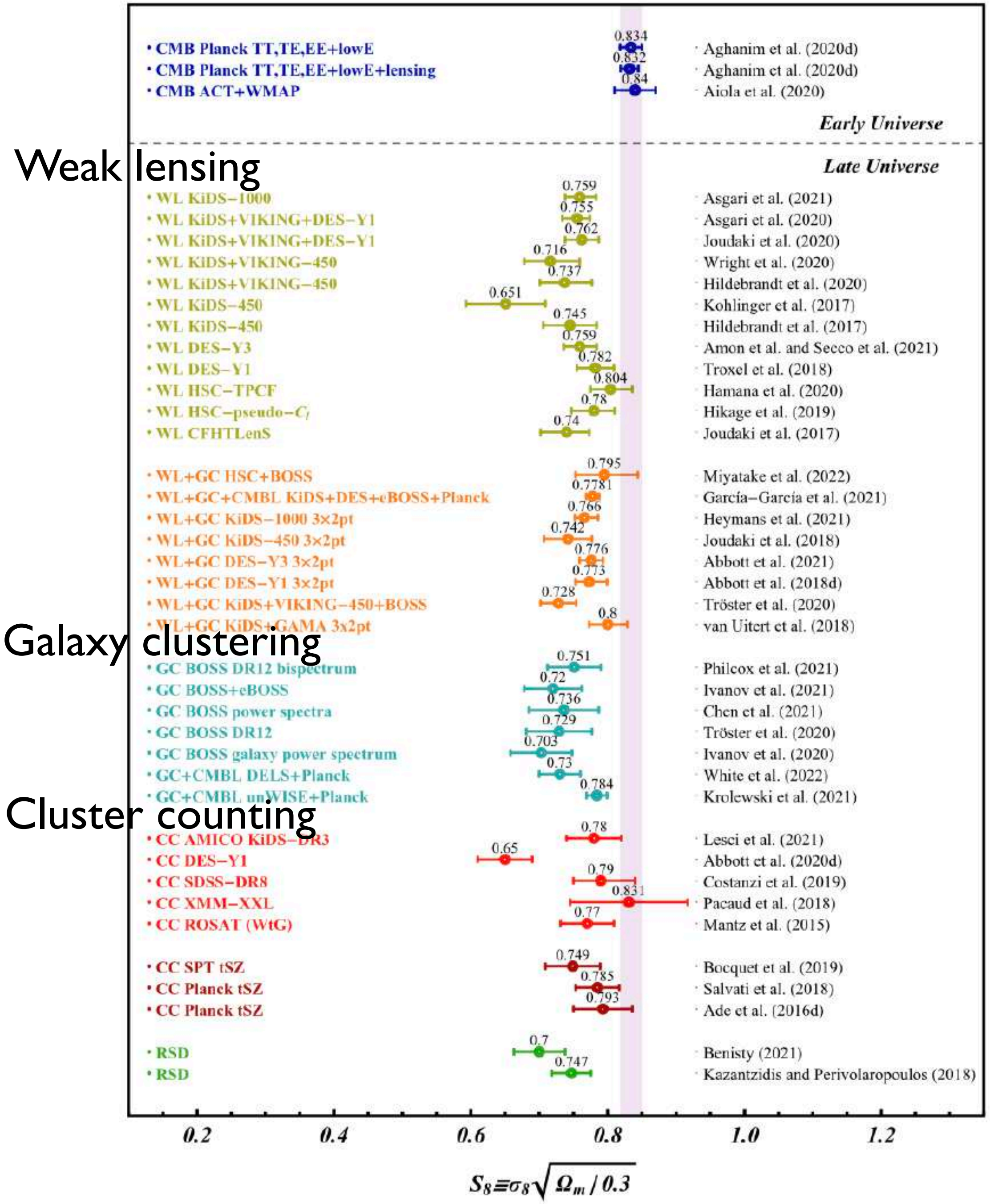
Mismatch of the amplitude of matter fluctuations on the scale of 8 Mpc/h between CMB measurement and LSS survey such as weak gravitational lensing and galaxy clustering.

$S_8 = 0.834 \pm 0.016.$ Planck (CMB)

2-3 sigma deviation

$S_8 = 0.759 \pm 0.024$ KiDS (Weak-lensing)

E. Abdalla, G.F. Abellán, A. Aboubrahim et al. [2203.06142]



[Di Valentino etal, 2008.11285]

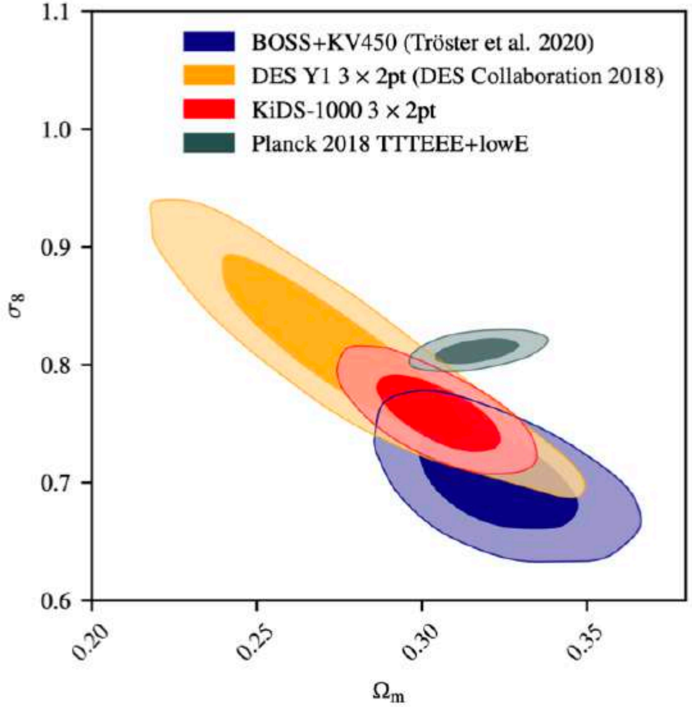
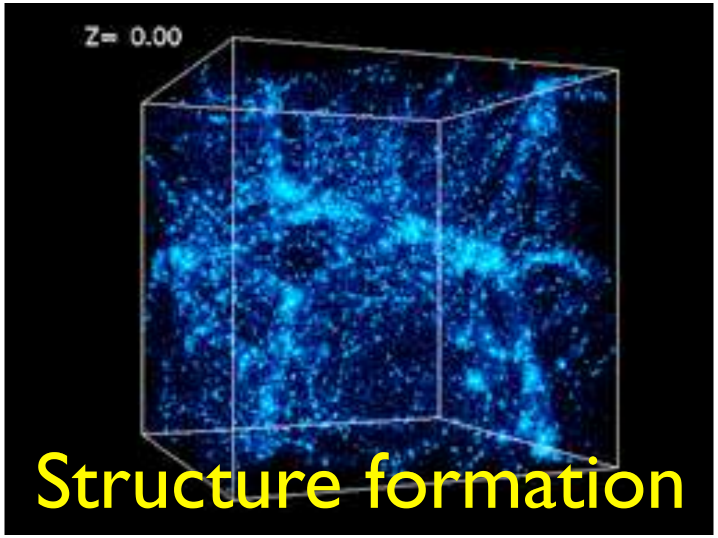
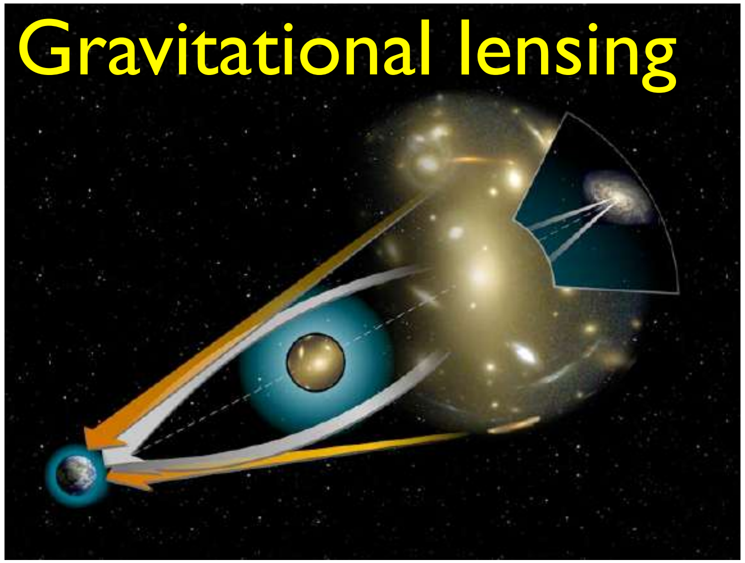


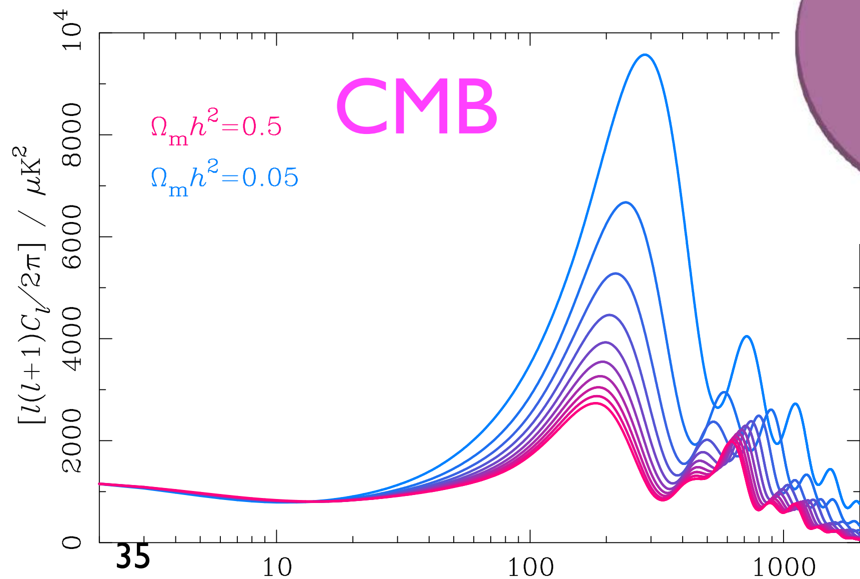
Figure 1: 68% CL and 95% CL contour plots for σ_8 and Ω_m(from Ref.[3]).

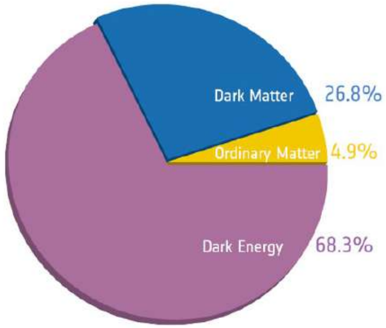
Dark Matter


The bullet cluster
Optical X-ray Gas Dark Matter


Z= 0.00
Structure formation


Gravitational lensing


CMB
$\Omega_m h^2=0.5$
$\Omega_m h^2=0.05$
$[l(l+1)C_l/2\pi]$ / μK^2
10^4
8000
6000
4000
2000
0
10
100
1000


Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%

Evidences for Dark Matter (DM)

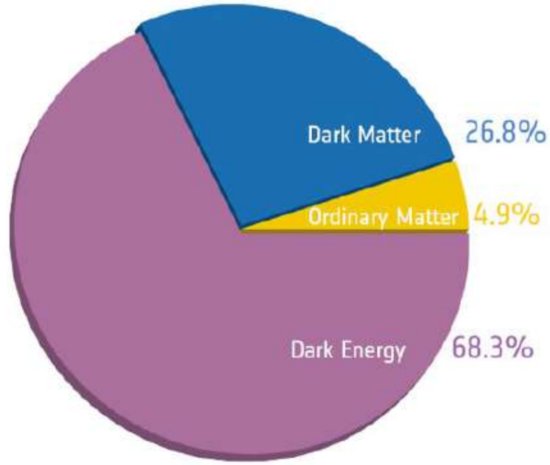
In 1933, F. Zwicky first discovered Dark Matter in the velocity dispersion of galaxies in the COMA cluster.

The discrepancies between visible matter and gravitational matter in different scales.

- Galactic scales : rotation curves of galaxies
- Galaxy cluster scales : distribution of velocities, gravitational lensing, profile of X-ray emission, Bullet cluster
- Cosmological scales : acoustic peaks of CMB, large scale structure formation

All of these observations can be explained by a single component of dark matter.

Dark Matter as a particle must



1. have existed from early Universe up to now and located around galaxies, clusters

➡ be stable or lifetime longer than the age of universe

2. be neutral : NO electromagnetic interaction

➡ Only upper bounds on the self interaction [Harvey et al., 1503.07675]

$\sigma/m < 0.47\ \mathrm{cm}^2/\mathrm{g}$ at 95% CL from cluster collisions

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 27% of the present energy density of the universe

$$\Omega_{\rm DM} h^2 = 0.1186(20)$$ [Planck 2015]

4. cold (or warm) : non-relativistic to seed the structure formation

What is Dark Energy?

- Cosmological Constant
- Vacuum Energy
- Quintessence
- modified gravity
- interacting dark energy
- ....

Topics in the Cosmology

Standard Model

Inflation

Dark Matter (DM)

Big Bang Nucleosynthesis (BBN)

Baryon Asymmetry of Universe (BAU)

Cosmic Microwave Background (CMB)

Large Scale Structure (LSS)

Dark Energy (DE)

Neutrinos

Beyond Standard Model

Thank You!