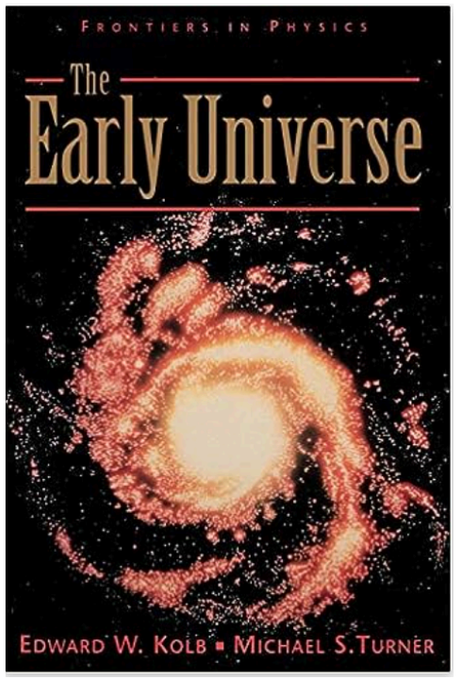
성균관대학교
SUNG KYUN KWAN UNIVERSITY

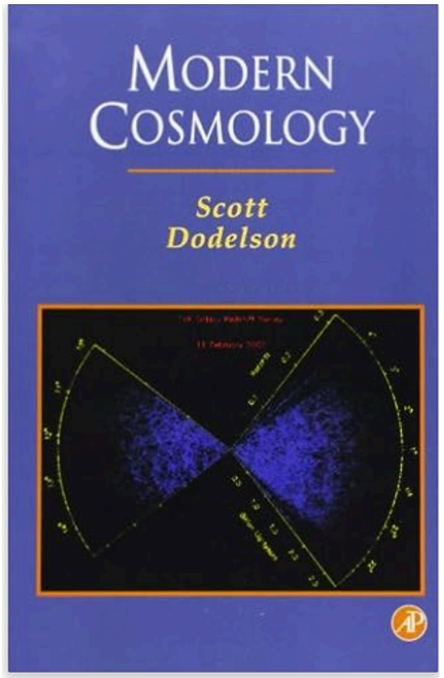
Cosmology I

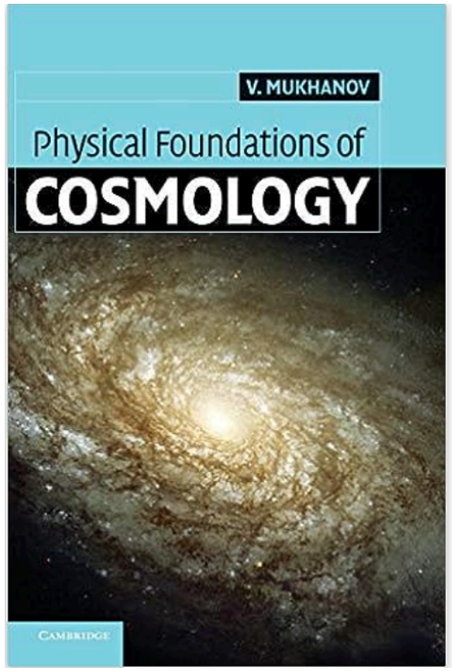
Ki -Young Choi

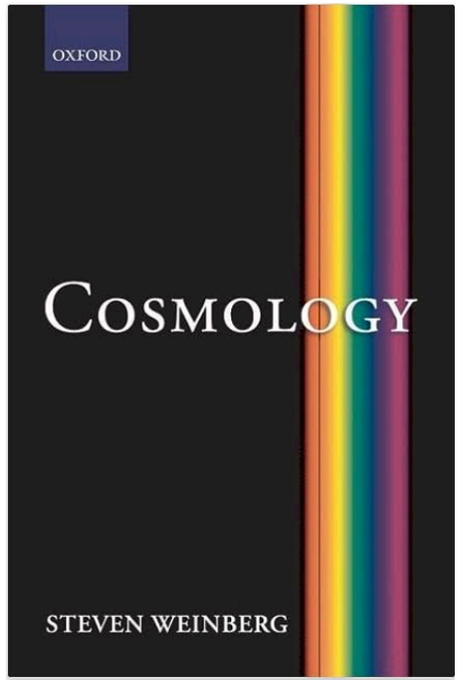


참고문헌


Frontiers in Physics
The
Early Universe
Edward W. Kolb ▪ Michael S. Turner


Modern
Cosmology
Scott
Dodelson


V. Mukhanov
Physical Foundations of
COSMOLOGY
Cambridge


OXFORD
Cosmology
Steven Weinberg

Cosmology: to explain the present observations of the Universe

1. The distribution of the galaxies and their redshift

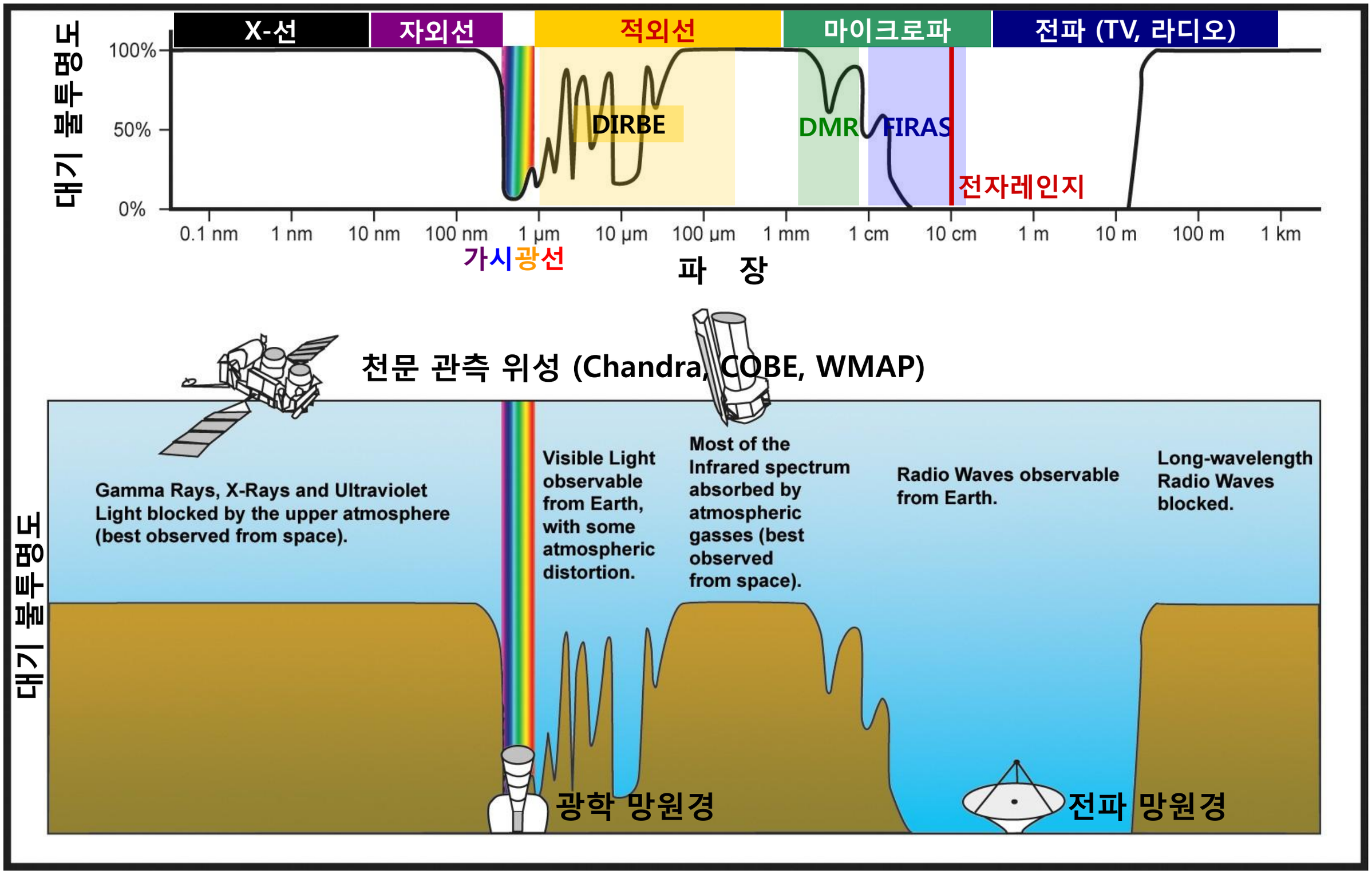
2. Cosmic microwave background radiation (CMB) and its anisotropy

3. The amount of light elements (Big Bang Nucleosynthesis)

Main observational method is Light!

1. The distribution of the galaxies and their redshift

Penzias and Wilson: wavelength of 7.35 centimeters



Unit of distance in astronomy

1 Ly (Light year, 광년): 빛의 속도로 1년 걸리는 거리

빛 속도 x 1 년 = $9.46 \times 10^{12}\,\mathrm{km}$

1 Arcmin = 1 degree / 60

1 Arcsec = 1 Arcmin / 60
=1 degree / 3600

1 pc (parsec) : 약 3.26 광년

~ distance between stars

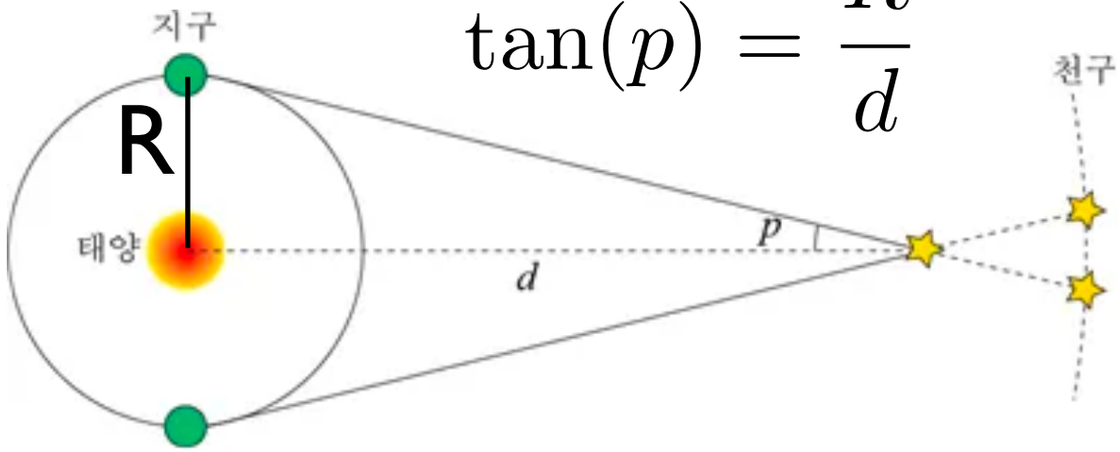
1 kpc = 1,000 pc

~ size of galaxy

1 Mpc = 1,000,000 pc

~ distance between galaxies

$$\tan(p) = \frac{R}{d}$$

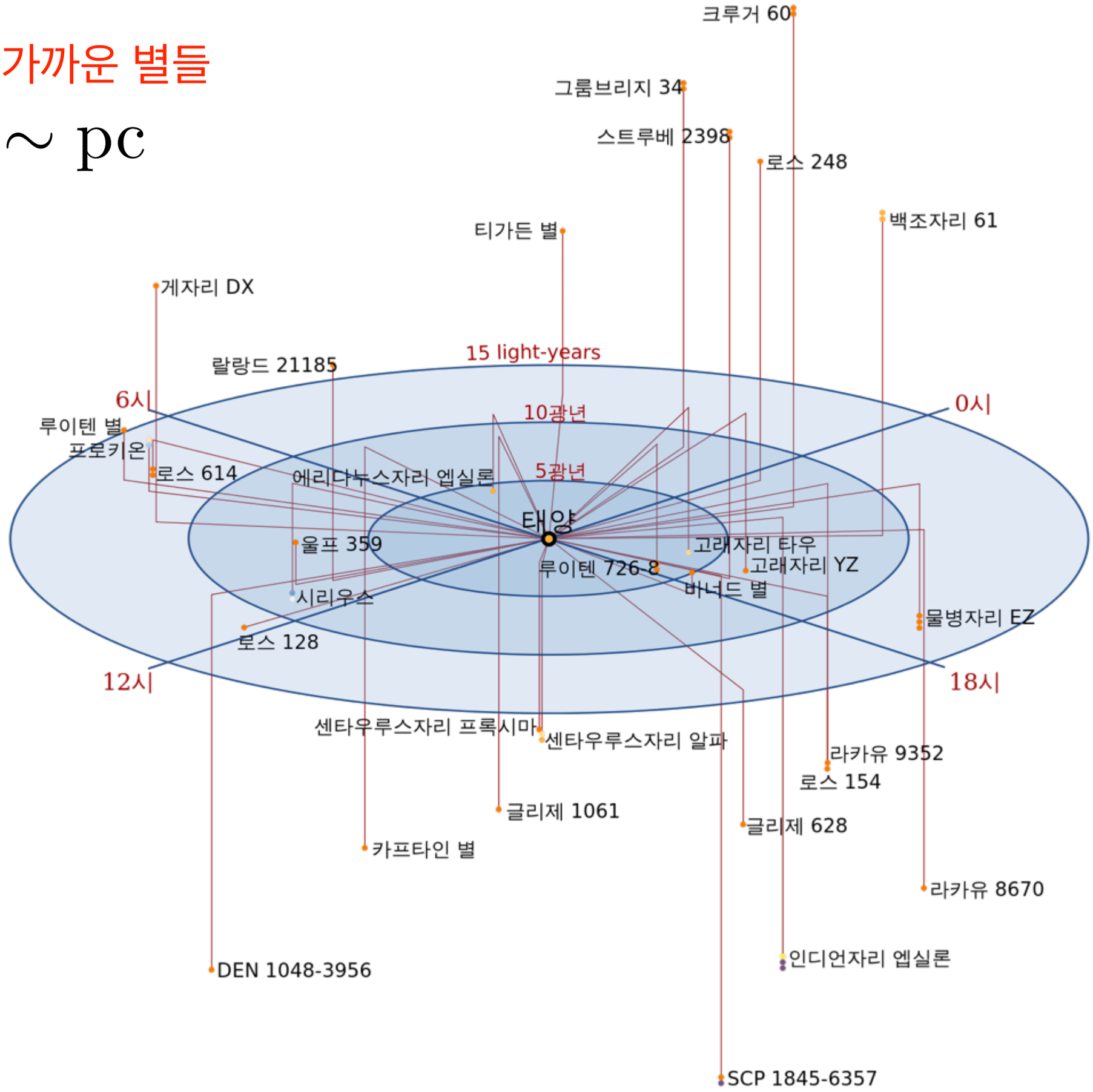


$$d \simeq \frac{R}{p}$$

연주시차(parallex)

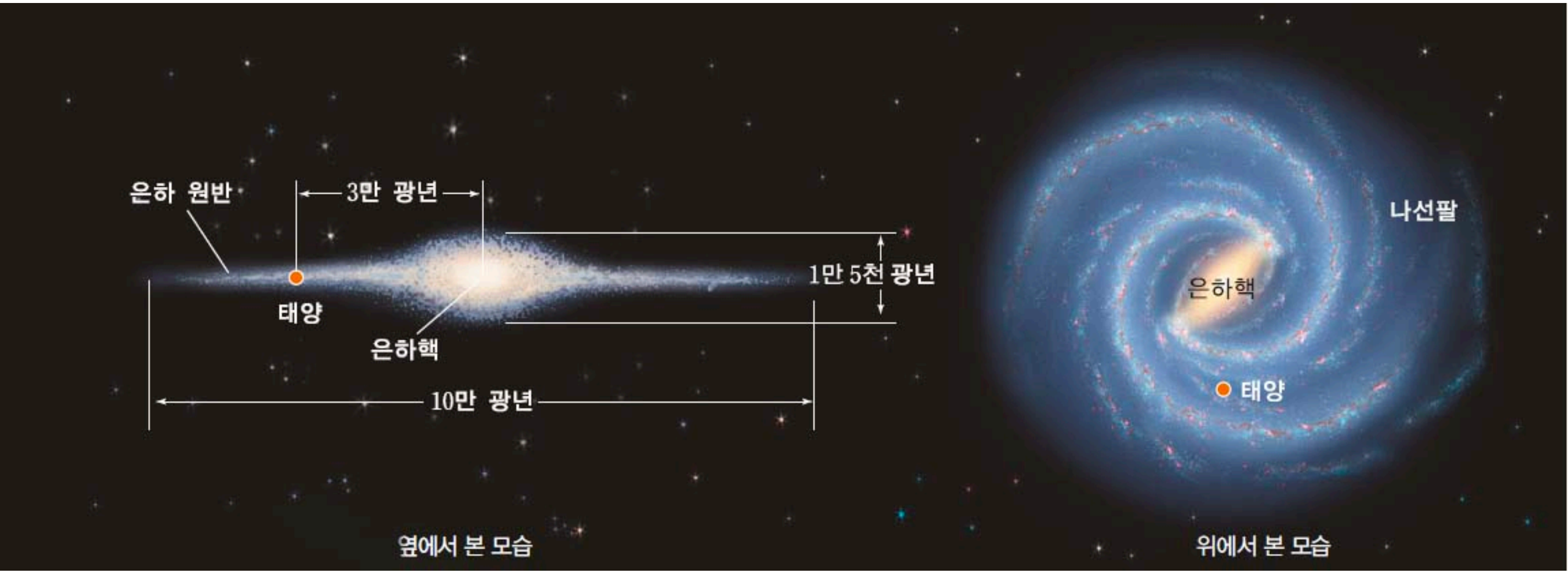
태양에 가까운 별들

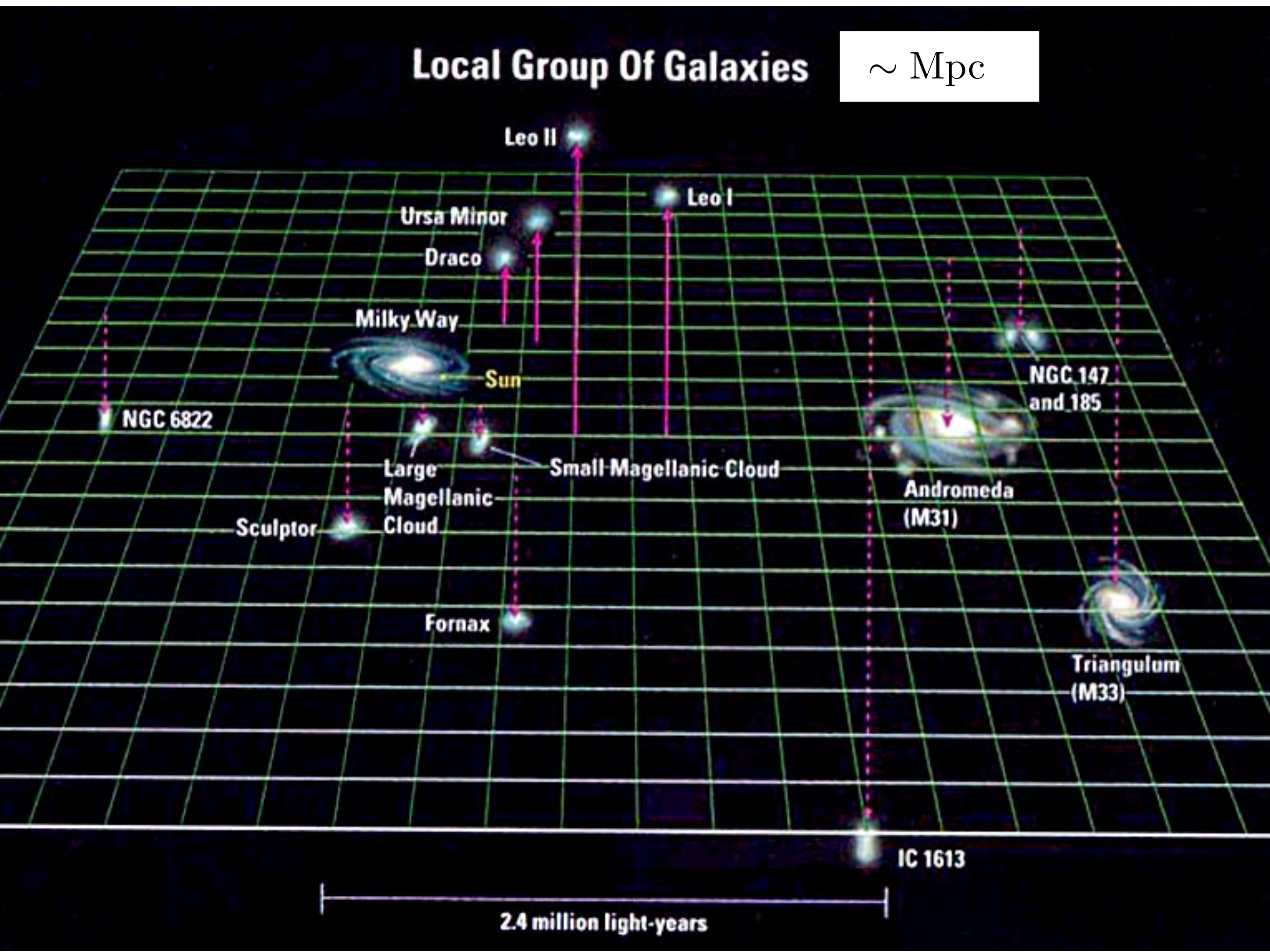
$\sim$ pc



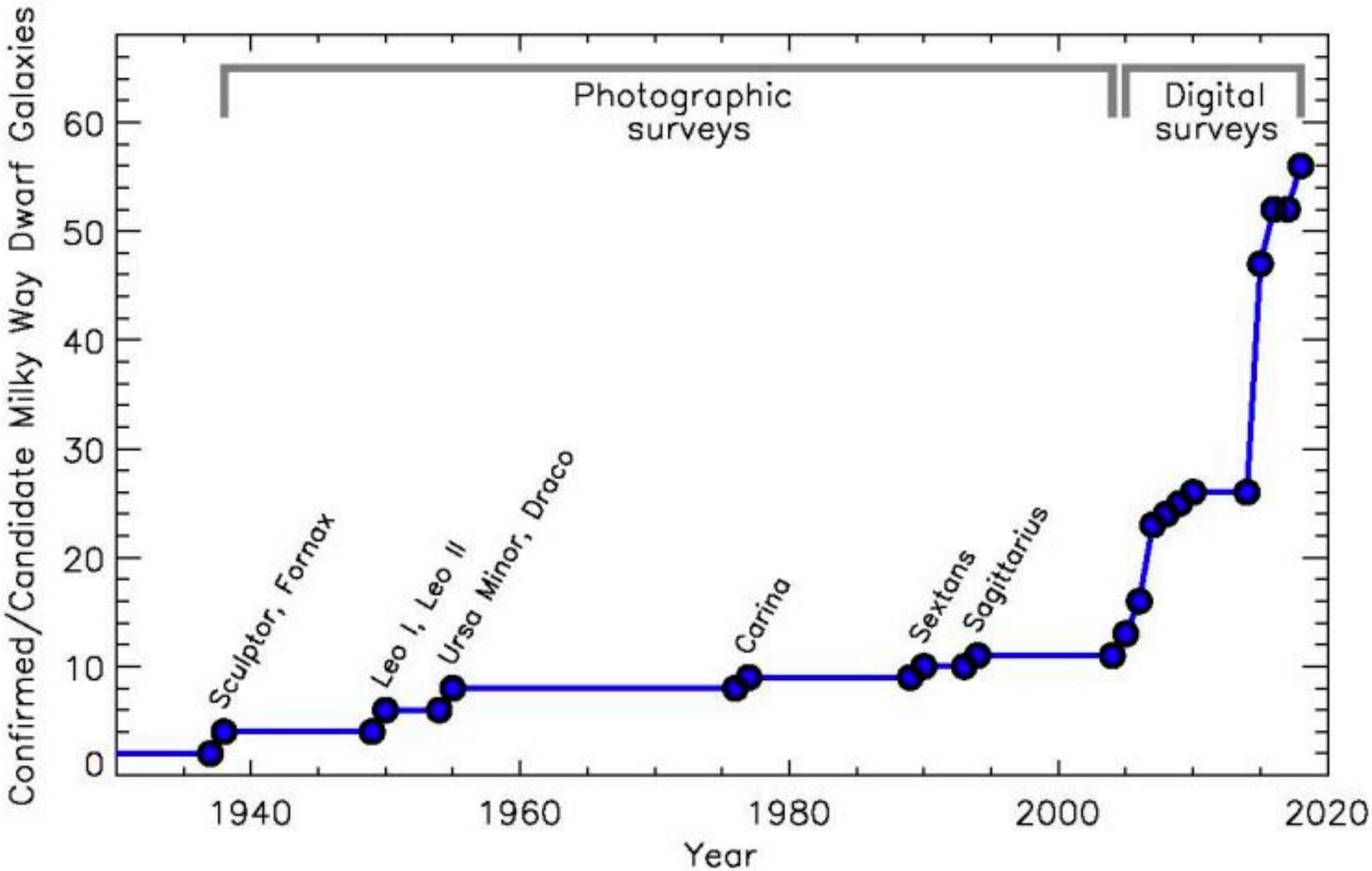
$\sim 10\,\mathrm{kpc}$

우리은하(Milky Way)




Local Group Of Galaxies
~ Mpc
Leo II
Leo I
Ursa Minor
Draco
Milky Way
Sun
NGC 6822
NGC 147
and 185
Large
Magellanic
Cloud
Small Magellanic Cloud
Andromeda
(M31)
Sculptor
Fornax
Triangulum
(M33)
IC 1613
2.4 million light-years

Milky Way satellite galaxies



The major discovery impact of SDSS (from 2005-2010) and DES/Pan-STARRS (2015).

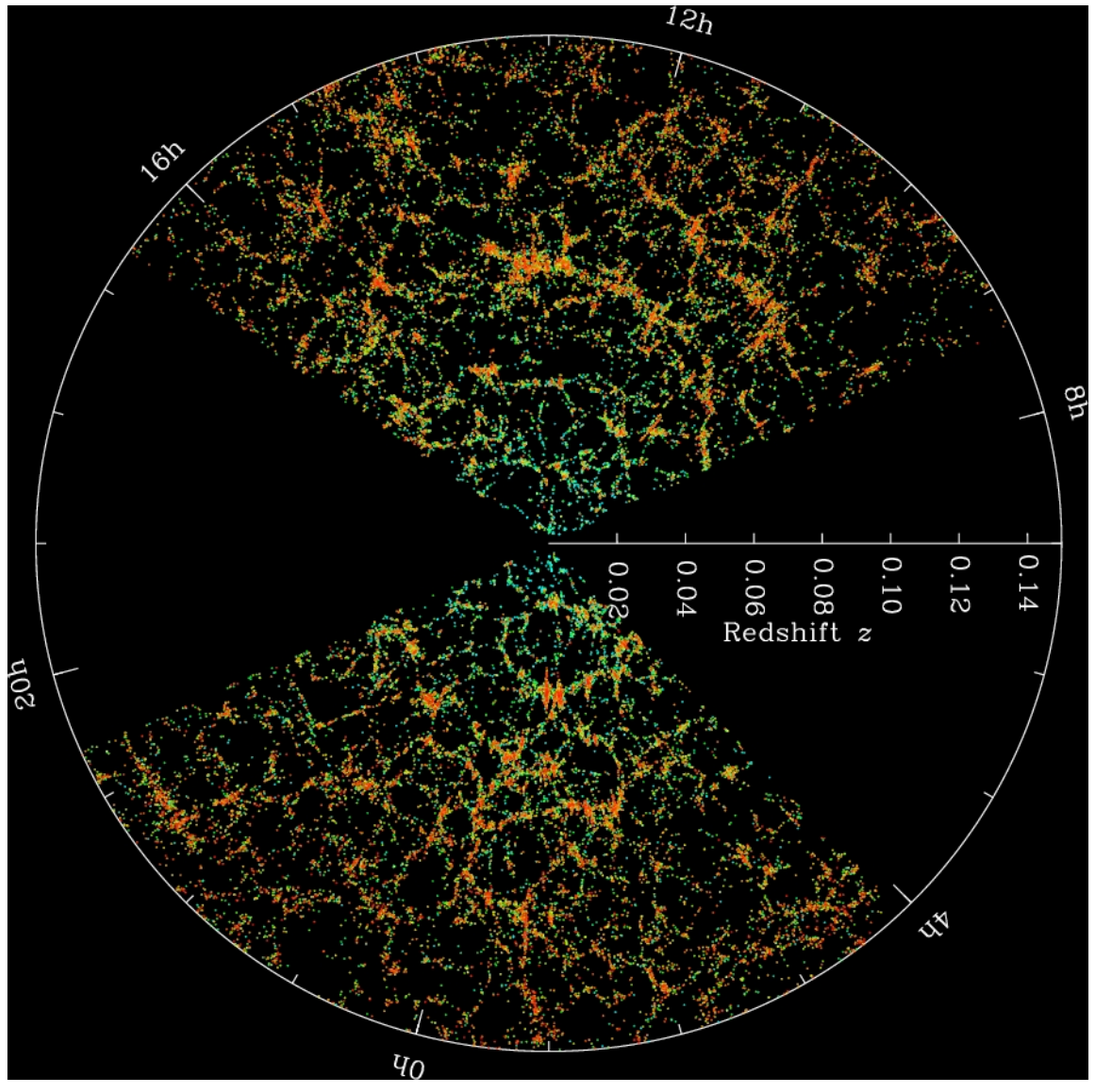
Mapping galaxies in the Universe

https://www.sdss4.org/science/



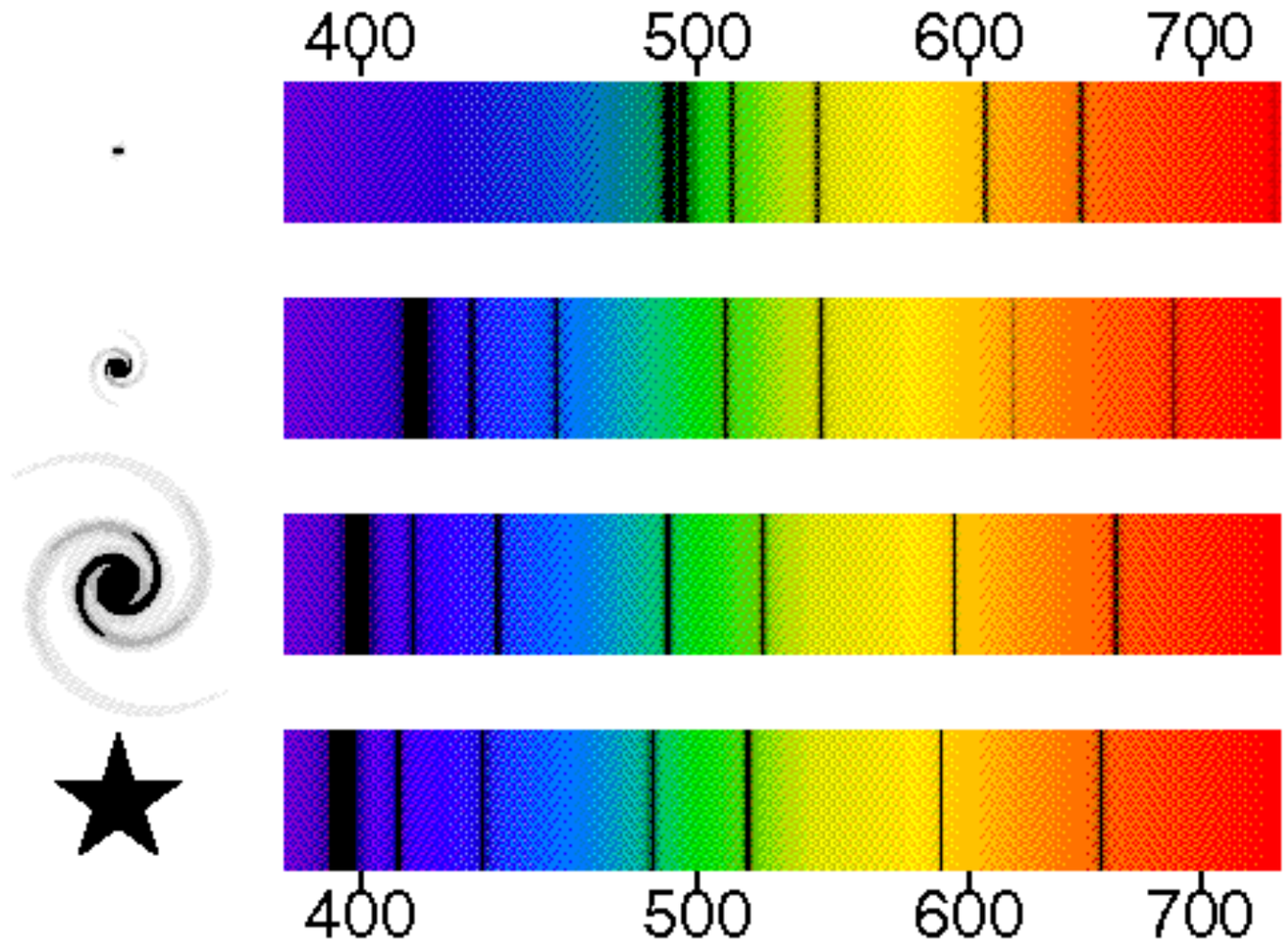
Sloan Digital Sky Survey (SDSS)

https://youtu.be/08LBItePDZw



The SDSS map of the Universe. Each dot is a galaxy; the color bar shows the local density.

분광관측과 적색편이 : redshift



$$1 + z = \frac{\lambda'}{\lambda}$$

λ' observed wavelength

λ emitted wavelength

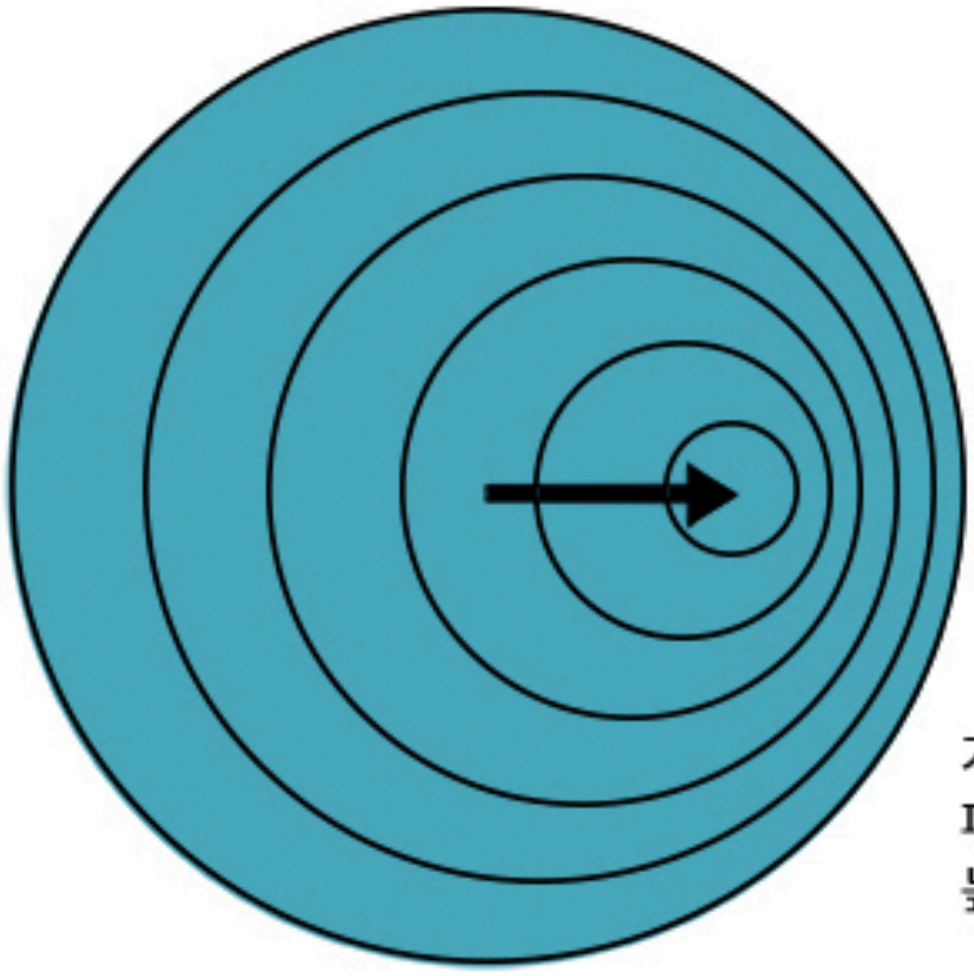
z redshift

도플러효과

음원이 움직일 때

$$\lambda' = \left(1 + \frac{v_s}{v}\right)\lambda$$

멀어지면
파장이 길어지고
낮은 소리가 들린다



$$\lambda' = \left(1 - \frac{v_s}{v}\right)\lambda$$

가까워지면
파장이 짧아지고
높은 소리가 들린다







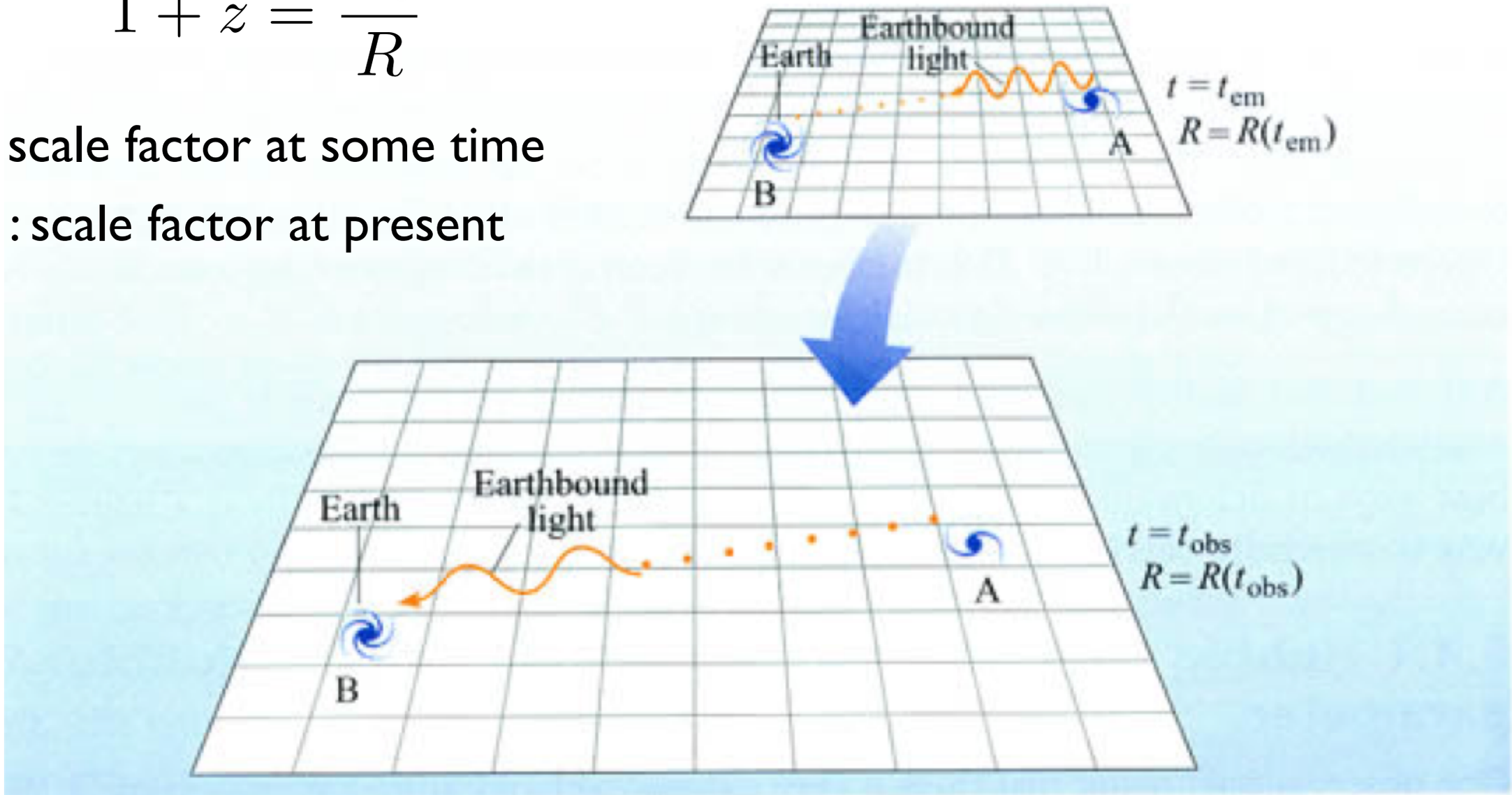
우주의 팽창

우주의 팽창과 적색편이 z

$$1 + z = \frac{R_0}{R}$$

R : scale factor at some time

R_0 : scale factor at present



The redshift is the result of the expansion of the Universe.

z	Light Travel Distance (Billion Light years)	Distance to the object now
0.0000715	0.001	1 million light years
0.1	1.286	1.349 billion light years
0.25	2.916	3.260 billion light years
0.5	5.019	5.936 billion light years
1	7.731	10.147 billion light years
2	10.324	15.424 billion light years
3	11.476	18.594 billion light years
4	12.094	20.745 billion light years
5	12.469	22.322 billion light years
6	12.716	23.542 billion light years
7	12.888	24.521 billion light years
8	13.014	25.329 billion light years
9	13.11	26.011 billion light years
10	13.184	26.596 billion light years

우주의 팽창과 적색편이

: 우주 팽창에 의하여 빛의 파장이 길어짐. 그 비를 적색편이 z 로 나타냄

$$\frac{\lambda_1}{\lambda_0} = \frac{R(t_1)}{R(t_0)} \equiv 1 + z$$

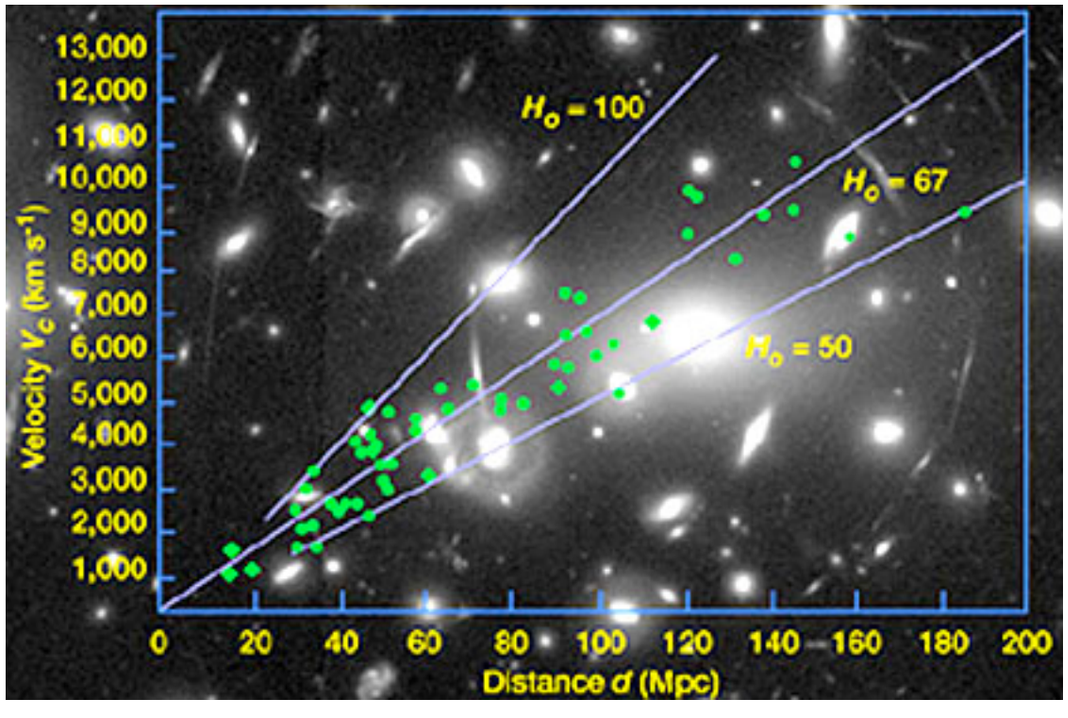
적색편이는 빛이 출발할 때와 현재 공간 크기의 상대적인 비와 같다.

빛의 분광기술은 적색편이를 아주 정확하게 측정할 수 있고, 그러면 원인이 된 빛이 나온 때와 거리를 알 수 있다.

현재 가까운 곳에서 나온 빛은 적색편이가 거의 없으므로 **z=0**. 적색편이가 크다는 것은 그 빛이 거 먼 곳에서 훨씬 더 이전에 만들어져 나왔다는 것을 의미한다.

허블의 법칙

은하들의 적색편이(후퇴속도)와 거리를 비교할 때, 멀리 있는 은하들의 적색편이가 더 크게 관측된다. 거리가 1 Mpc 증가할 때, 그 해당하는 속도가 약 70 km/sec 증가하는 것처럼 보인다. 이 비를 허블상수라고 한다.



허블의 법칙 (1929)

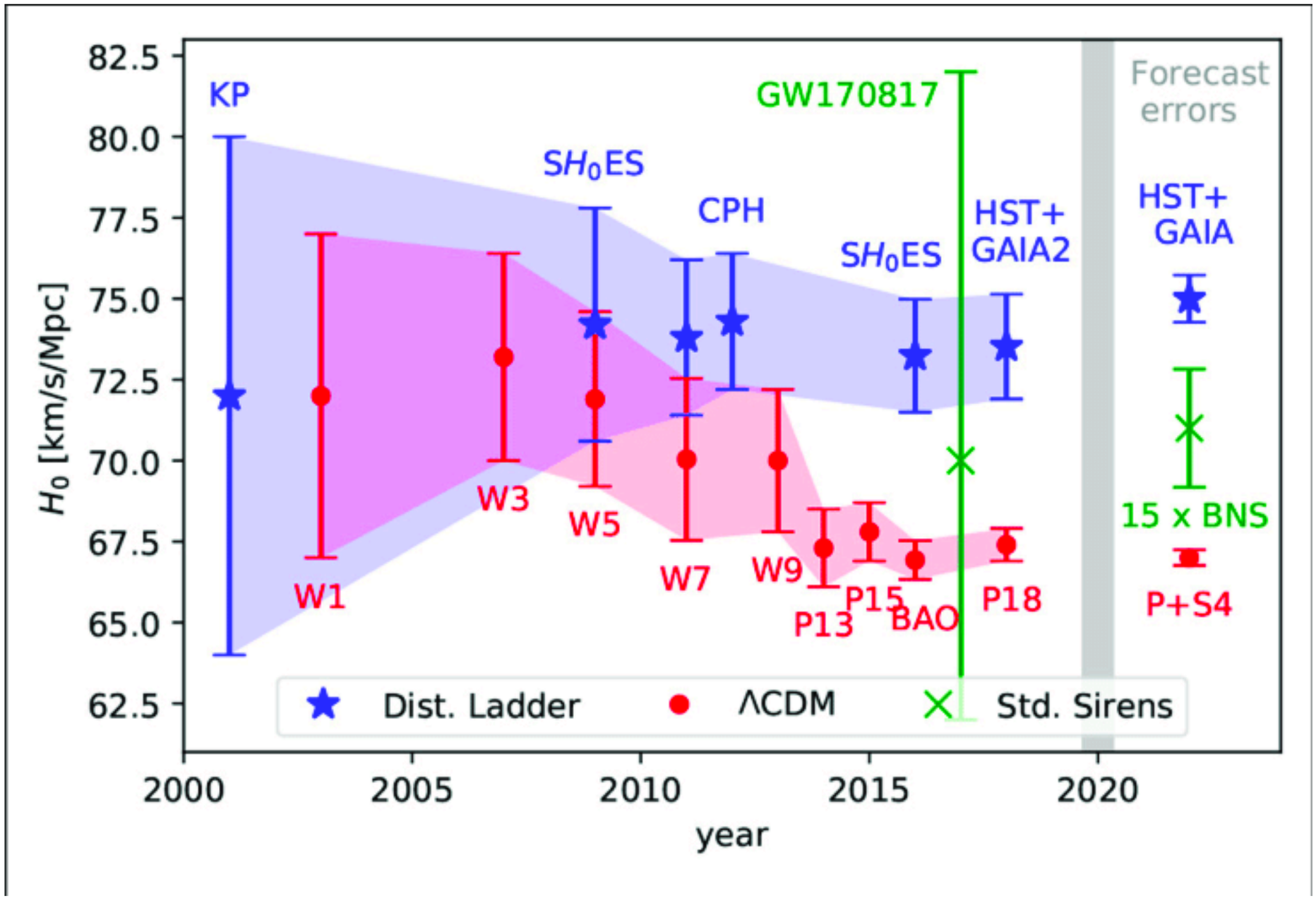
후퇴속도 거리

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

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

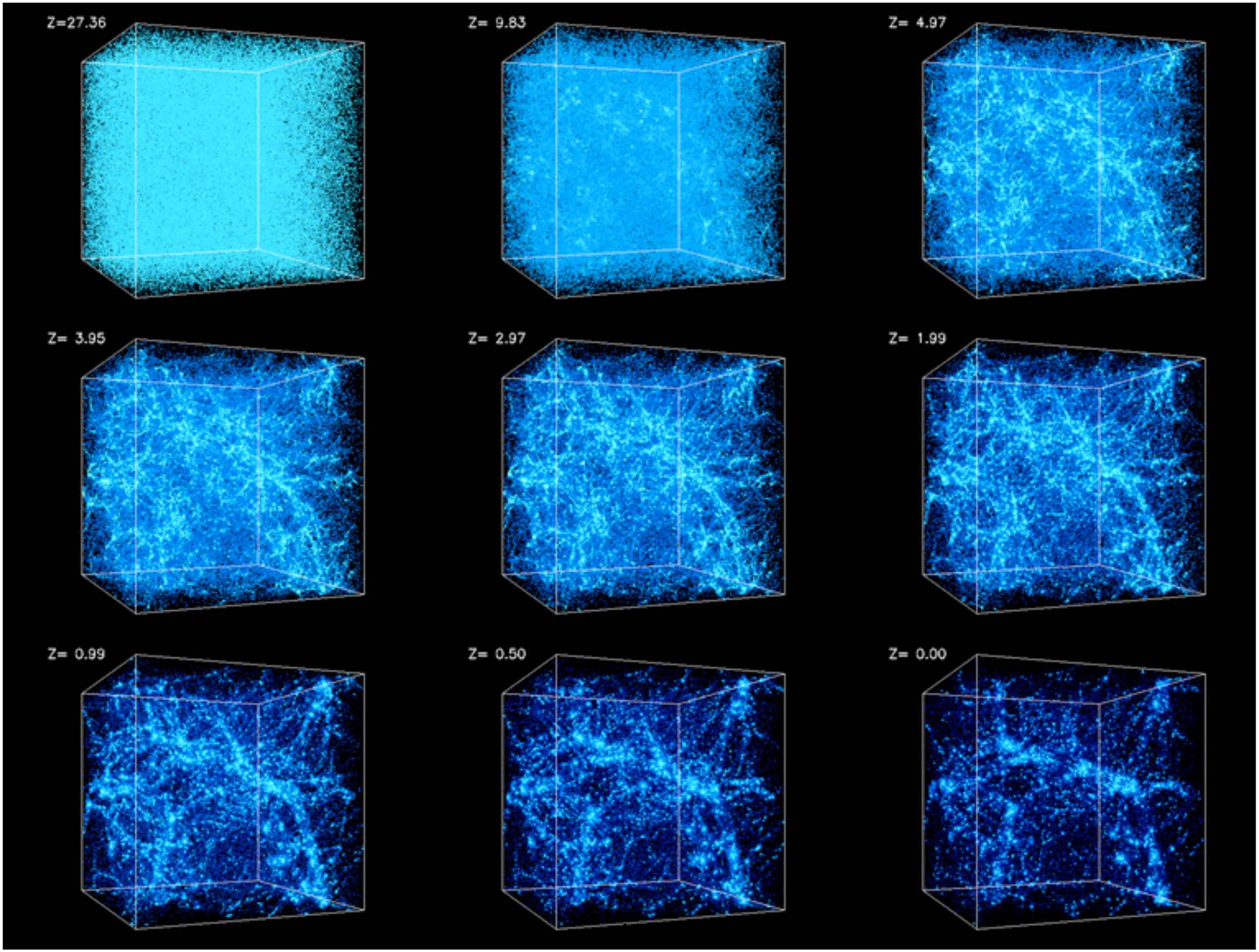
허블상수(변수)

Hubble tension



The Hubble tension (adapted from Beaton et al., 2016; Freedman, 2017, including the first standard sirens measurement following GW170817, Abbott et al., 2017b, Planck 2018, Aghanim et al., 2018 and Hubble Space Telescope (HST) with GAIA DR2, Riess et al., 2018)

- 물질의 진화 : 우주거대구조의 형성 https://youtu.be/8C_dnP2fvxk 43Mpc box



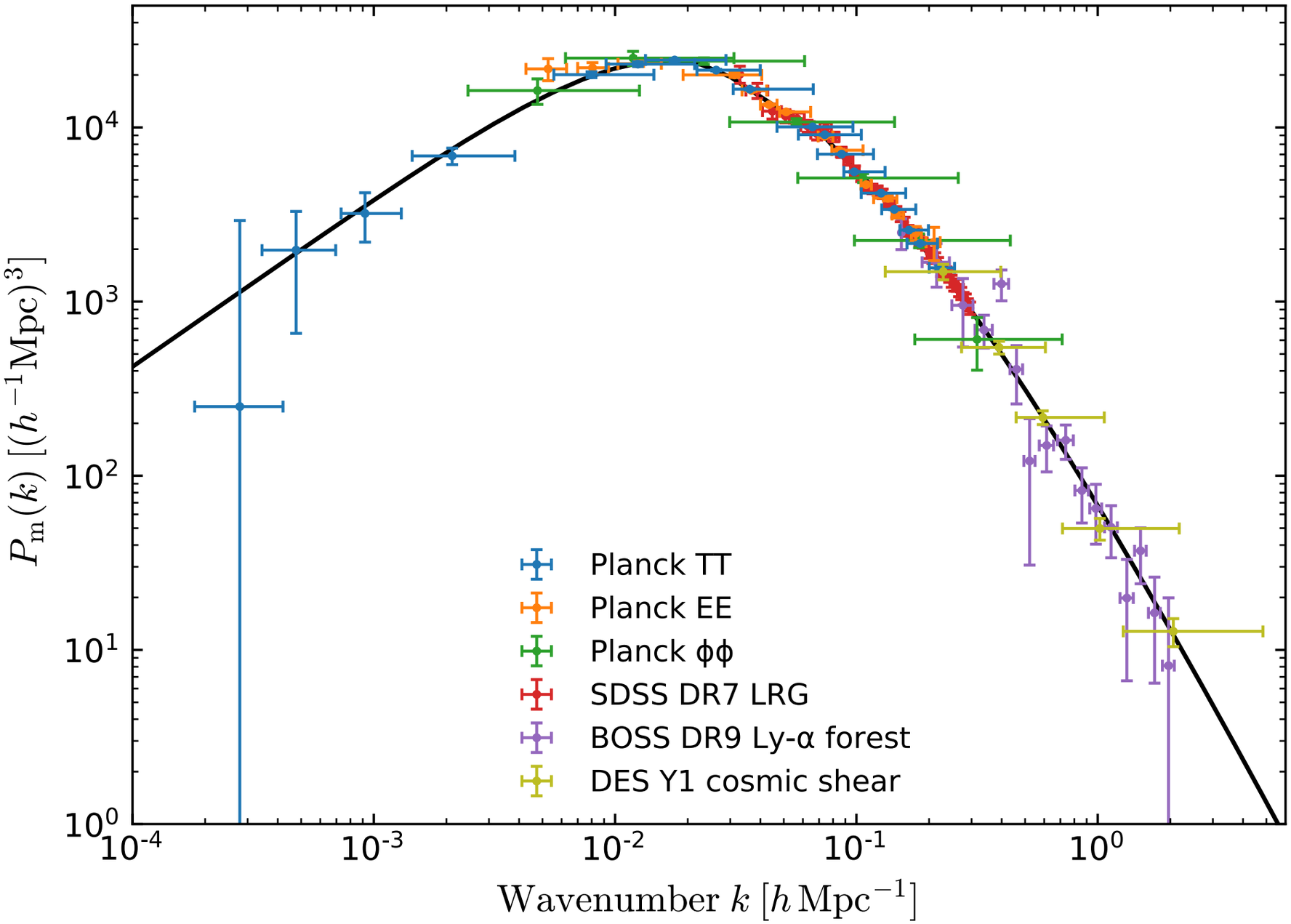
Universe by simulation "Horizon 5"

https://youtu.be/q8R3dfrq6_Y

Matter Power Spectrum

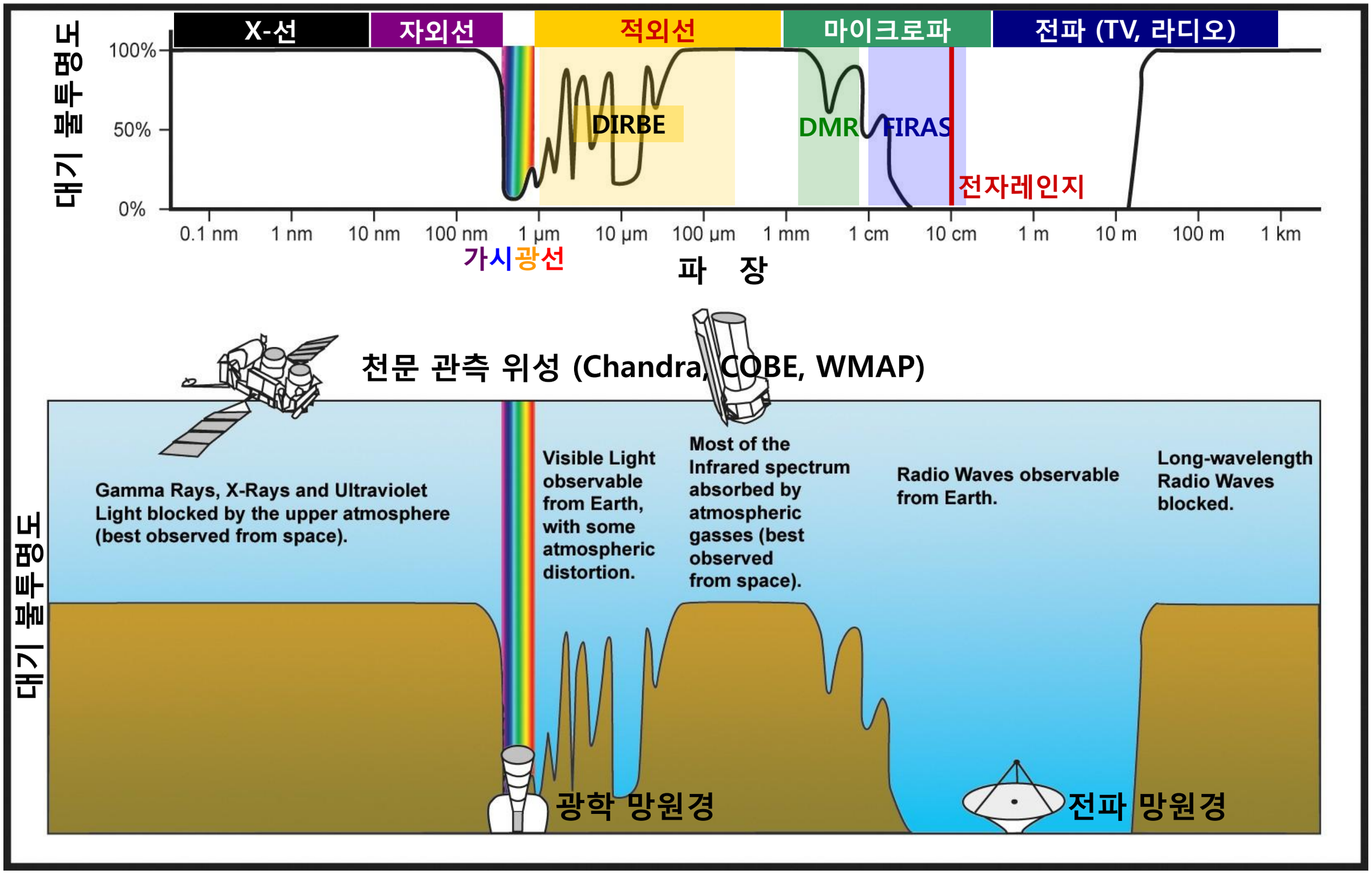
: 스케일에 따른 물질 분포의 정도

[Planck 1807.06205]



2. Cosmic microwave background radiation (CMB) and its anisotropy

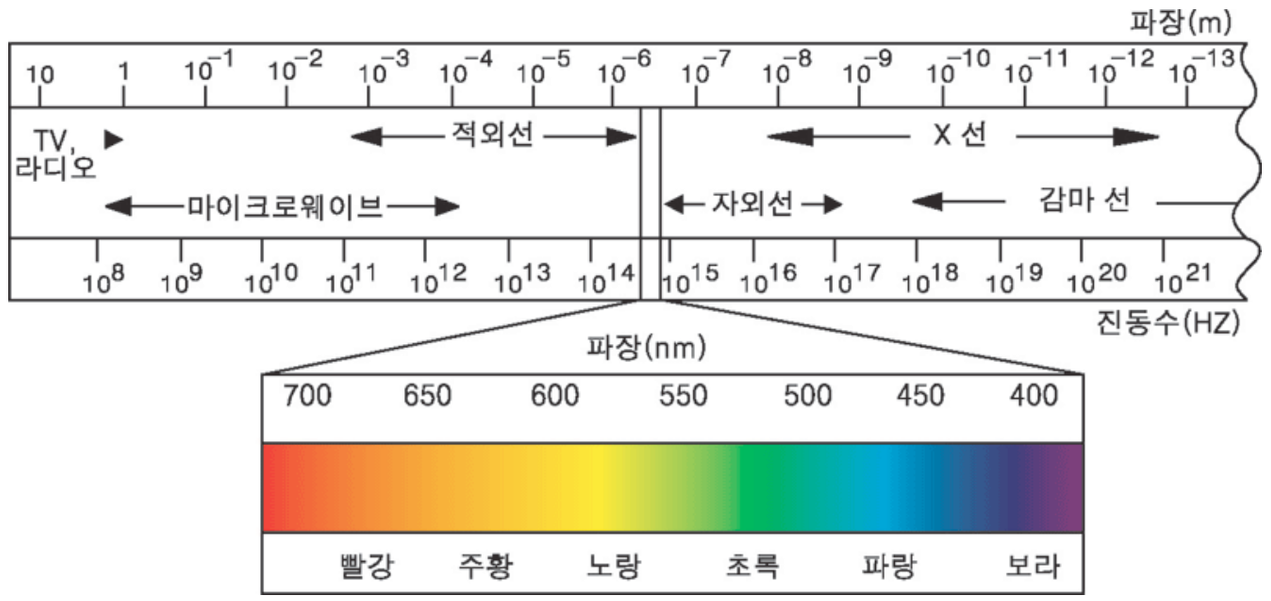
Penzias and Wilson: wavelength of 7.35 centimeters



우주배경복사의 발견



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)



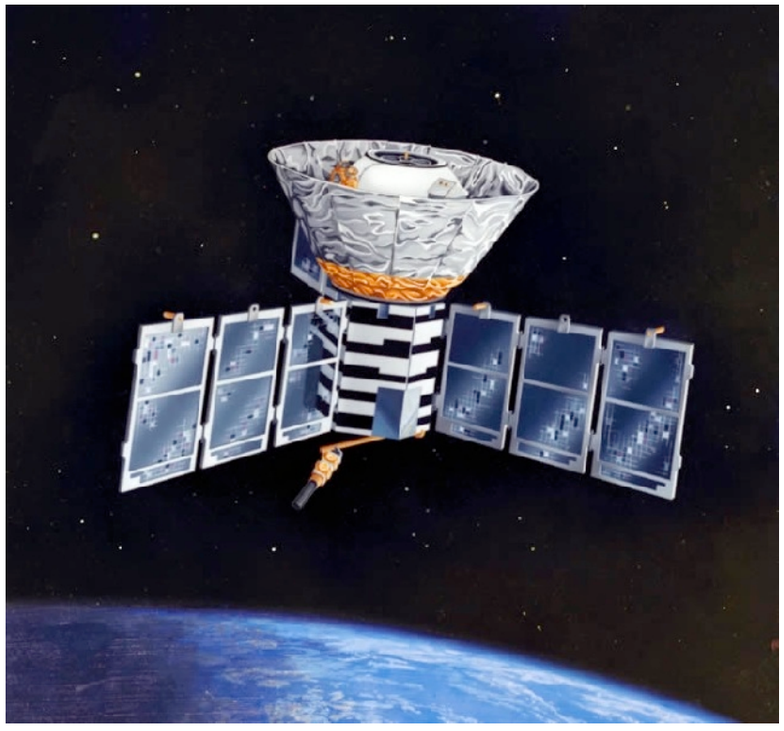
펜지아스와 윌슨은 벨 연구소에서 통신수단으로서 전파를 연구하던 중,
하늘의 모든 방향에서 오는 동일한 세기의 잡음을 발견 (1965)

잡음의 원인은?

: 전자 회로의 문제점, 전기선의 불순물, 안테나의 노후화, 비둘기 똥....

→ 뜨거운 초기 우주에서 떨어져 나온 빛 (1978 노벨상)

- 코비위성 (Cosmic Background Explorer, COBE)



1989년 11월 18일 발사

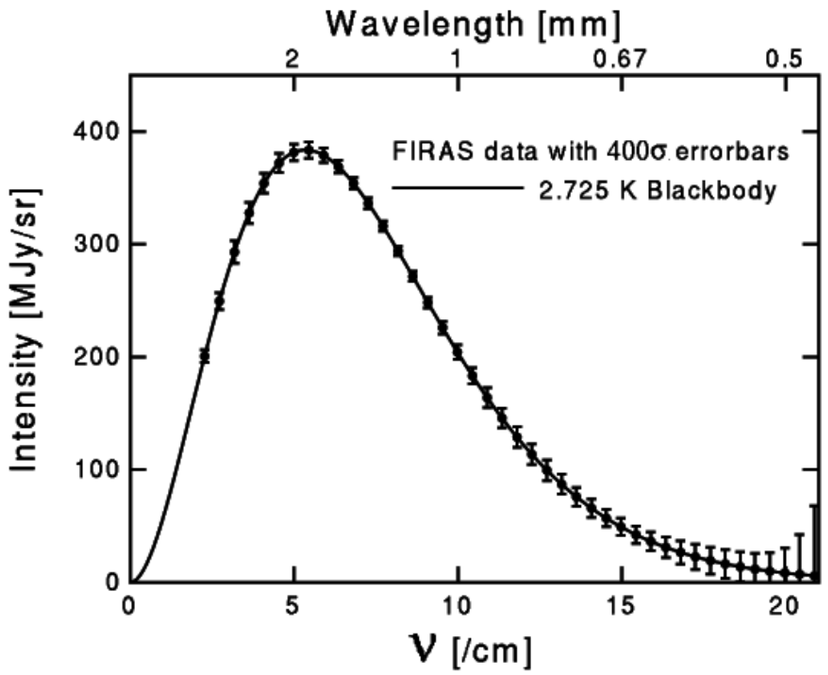
1. 관측된 우주배경복사는 거의 완벽한 플랑크 분포를 따른다. 그 온도는

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

2. 방향에 관계없이 일정한 온도를 나타낸다. 이것은 빅뱅모형의 균일성, 등방성 가정이 옳다는 것을 보이는 것이다.

3. 하지만 $\sim 10^{-5}\,\mathrm{K}$ 에서 온도의 비균질성을 발견

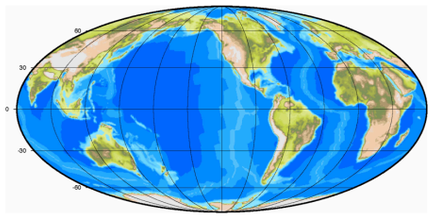
DMR



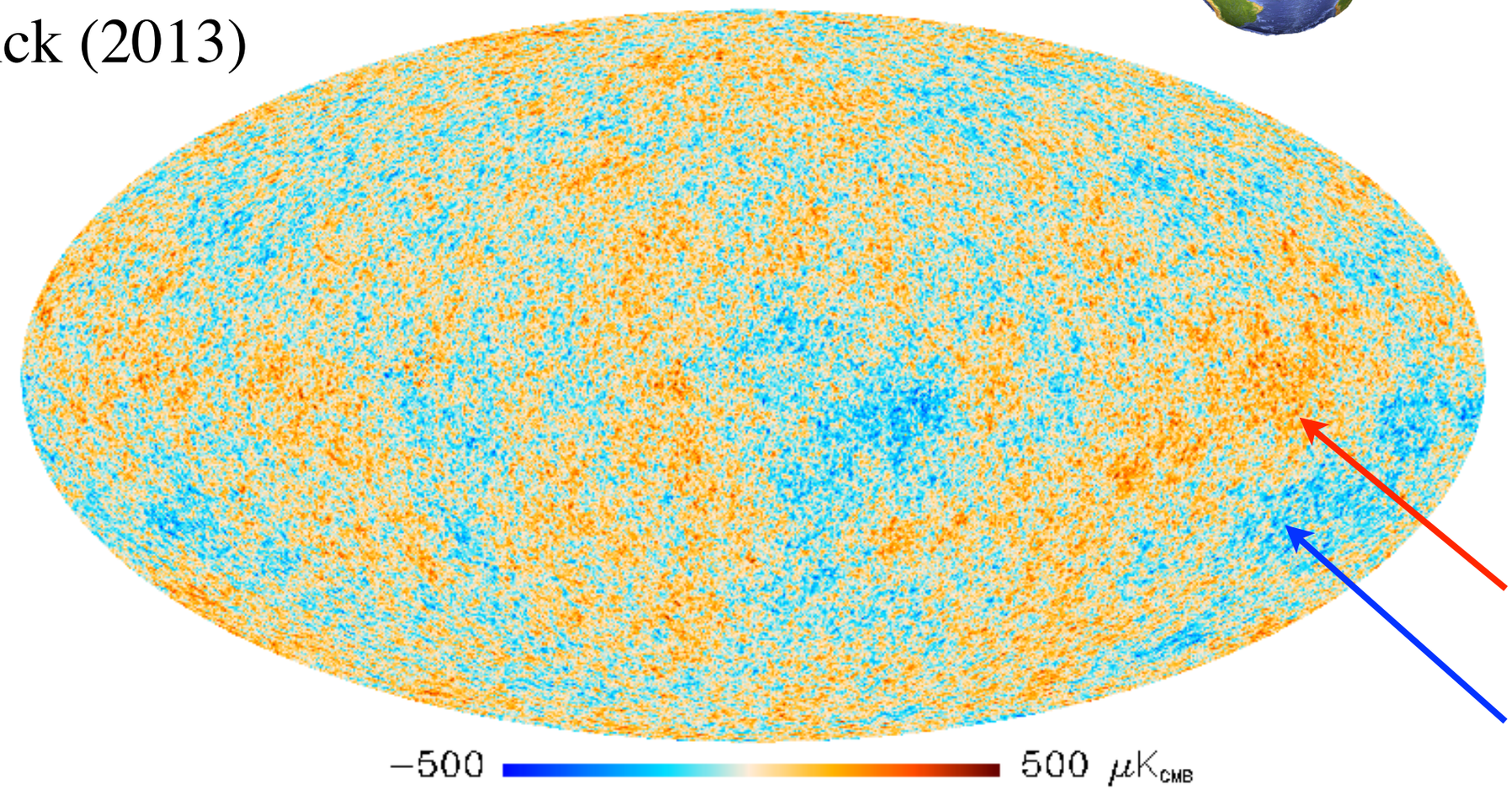
2006 년 노벨상 수상

- CMB 온도 비등방성





Planck (2013)

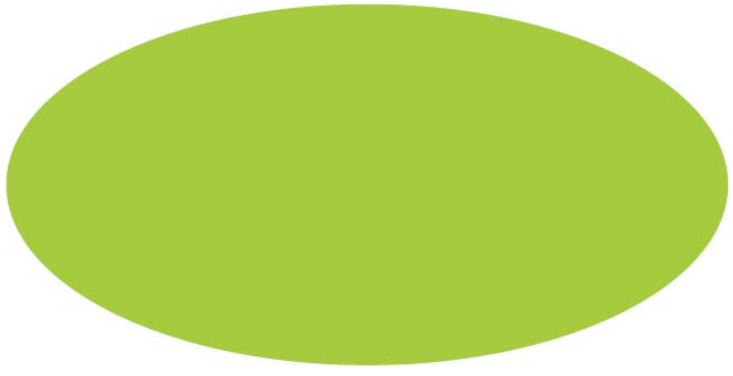


$T_0 = 2.725K$

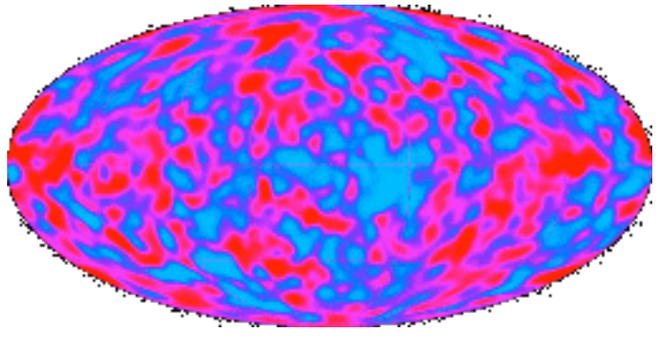
$T_0 + \mathcal{O}(10^{-5})K$

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

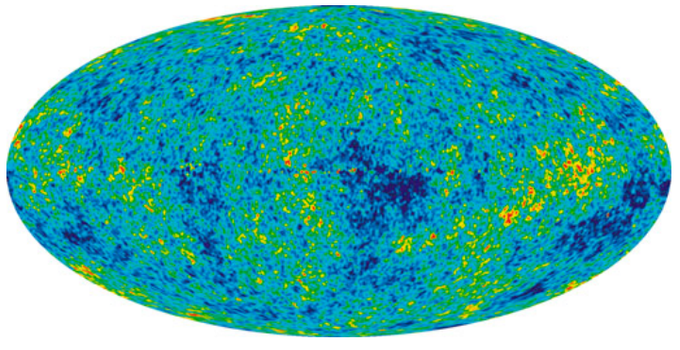
Penzias, Wilson (1965)



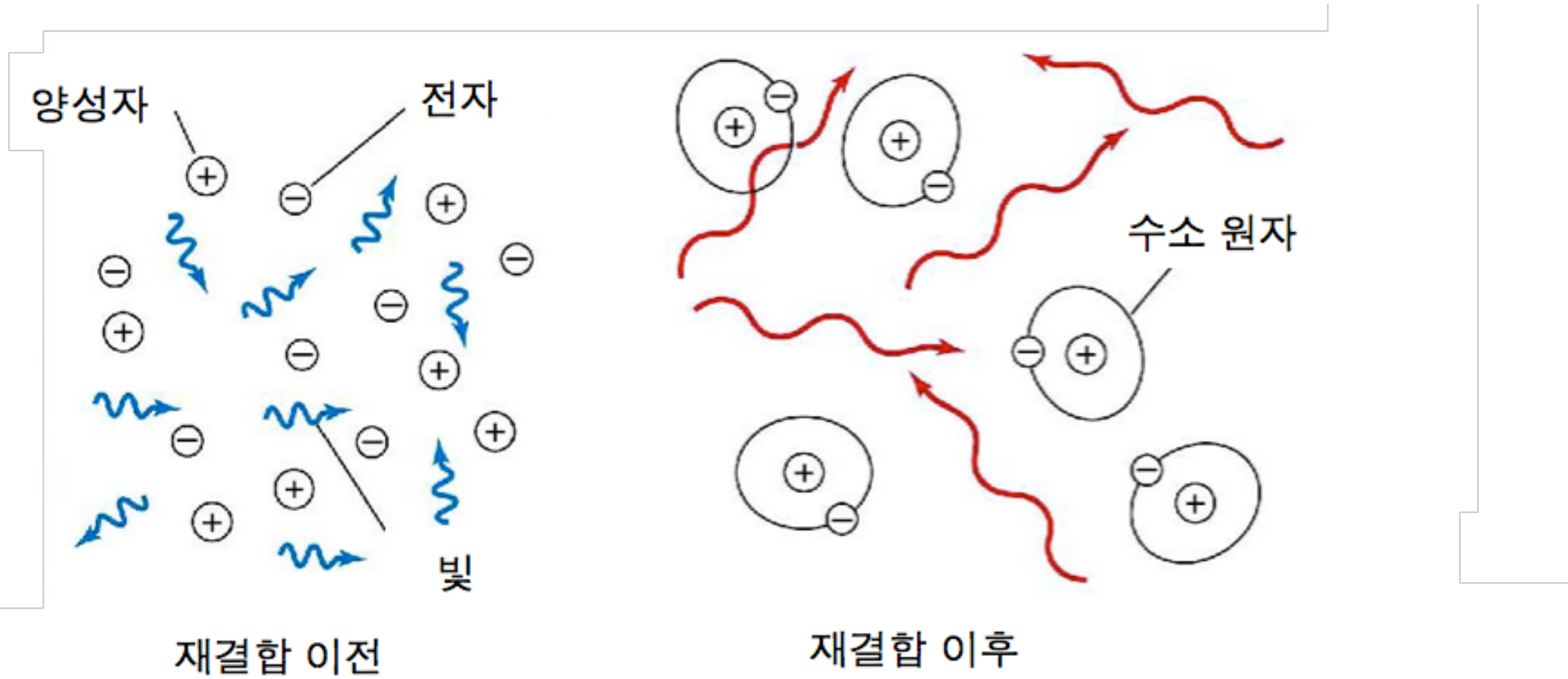
COBE (1992)



WMAP (2007)



- 원자핵과 전자의 재결합 그리고 광자의 분리 (우주 나이 38 만년)
  (Recombination and photon decoupling)



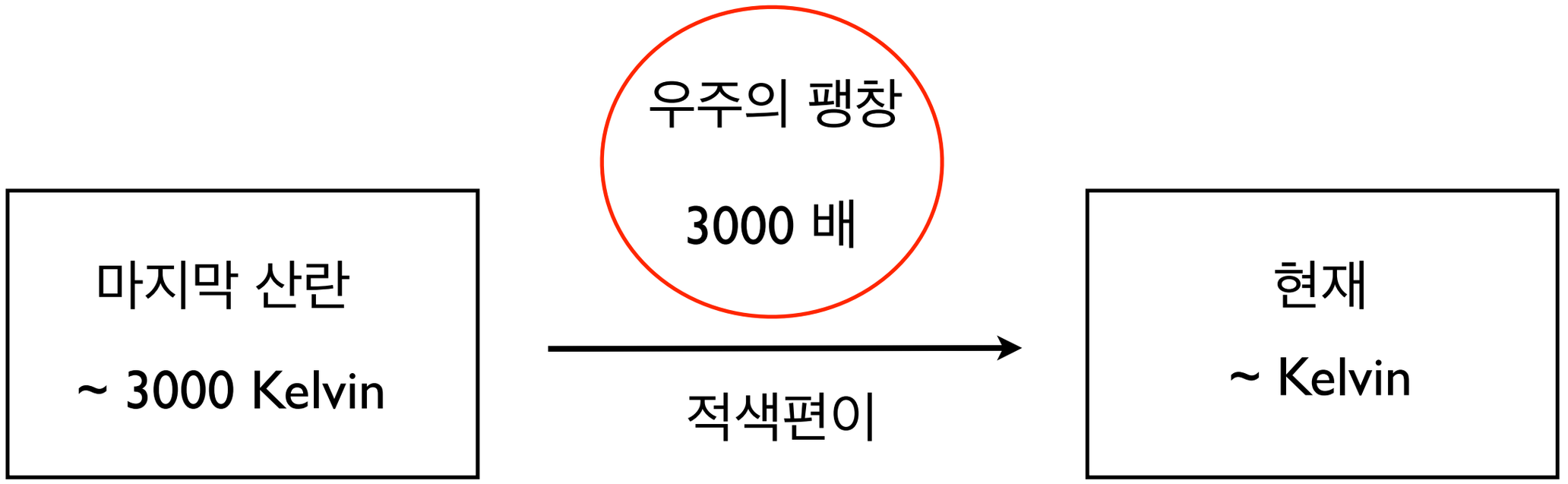
수소 원자핵과 전자의 결합 에너지 13.6 eV : 우주온도 약 3000 도

자유로워진 광자는 아무런 충돌없이 진행하여 현재의 우리 주변을 채우고 있다.

→ 우주 배경 복사

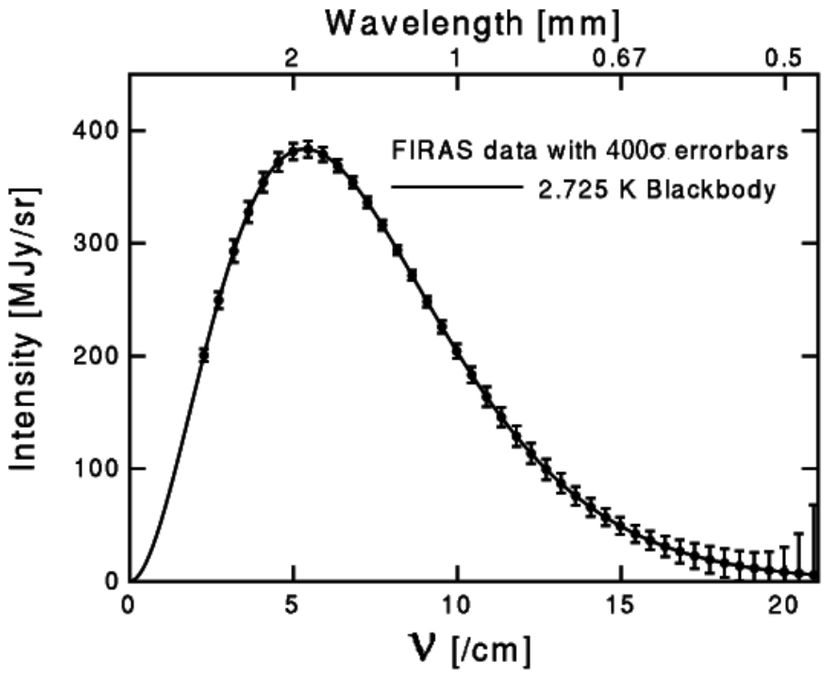
: 우주 팽창에 의하여 온도가 줄어들어 지금 은 2.7 도 정도가 됨
(1948 년, 알퍼와 허먼이 예측하였다.)

팽창하는 우주에서 빛의 마지막 산란과 적색편이 : 우주배경복사

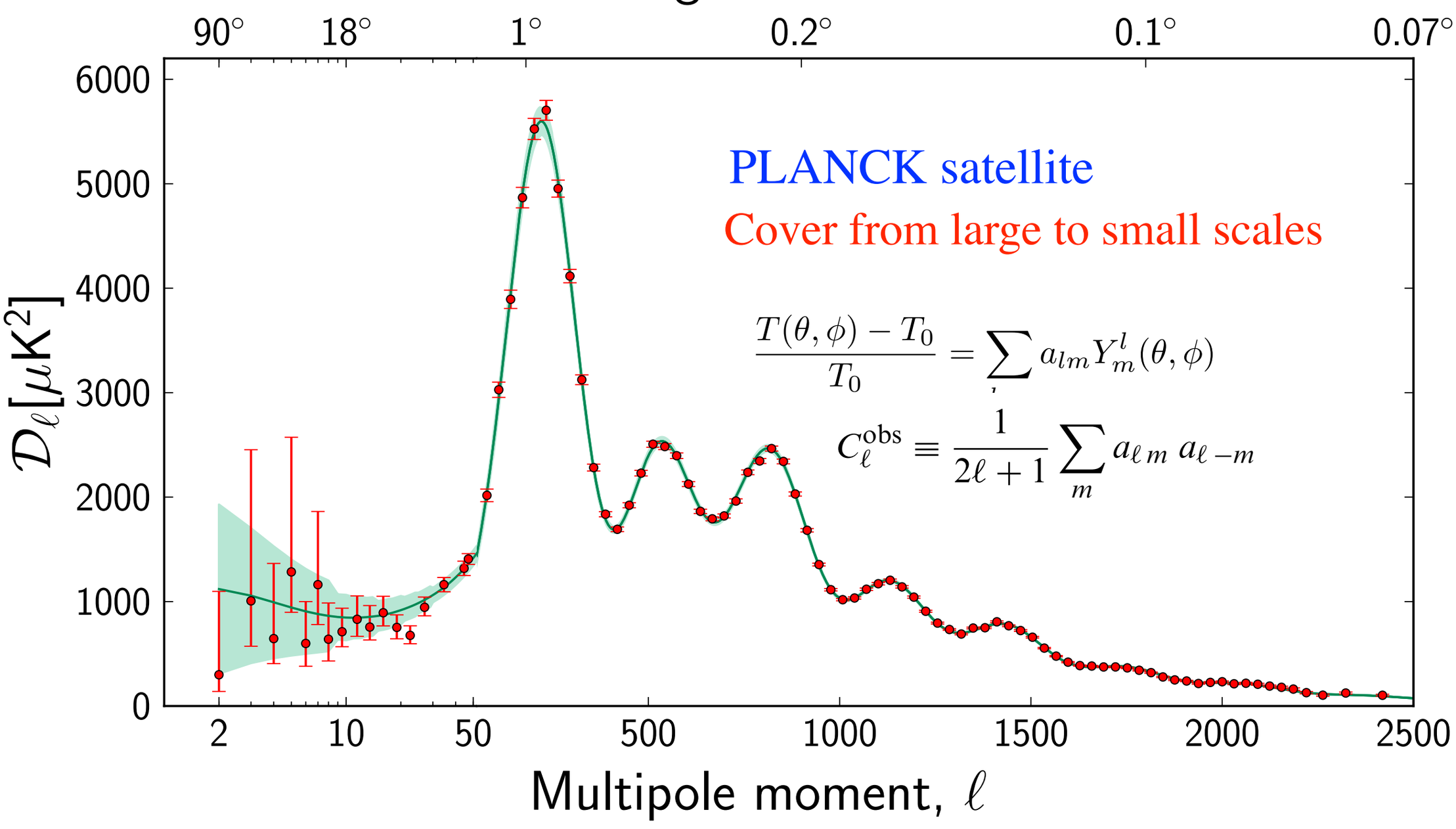


~ micro meter

~ mm

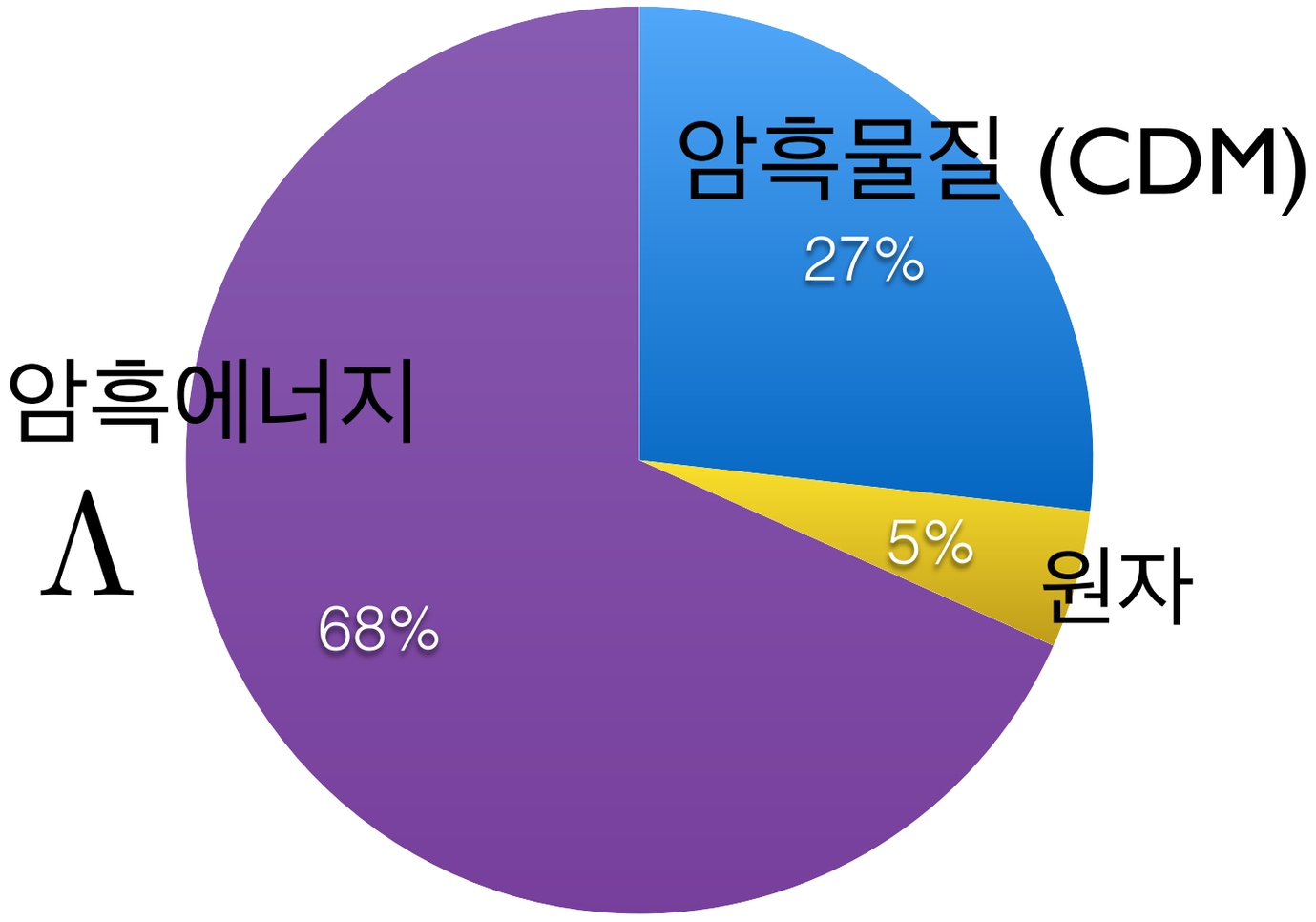


우주배경복사의 온도 음향진동



Composition of present Universe

$$\rho_c = 3H_0^2 M_P^2 = 1.88 \times 10^{-29} \mathrm{g\,cm^{-3}}$$



Radiation : 0.005 %

Neutrinos : less than 5 %

: ordinary baryonic matters

CMB 온도의 비등방성

빛의 온도 분포 = 초기우주에서 빛의 밀도 분포 = 물질의 분포

초기우주의 물질분포의 비등방성 ⟶ 우주거대구조의 형성

물질분포 비등방성의 기원은? 우주 초기의 인플레이션과 양자요동?

3. The amount of light elements (Big Bang Nucleosynthesis)

PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/

GROUP

PERIOD

1 IA												13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 1.0079 H HYDROGEN	2 IIA																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
11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	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				

RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME

Example: 13 IIIA / 5 10.811 / B / BORON

Metal
Semimetal
Nonmetal
1 Alkali metal
2 Alkaline earth metal
Transition metals
Lanthanide
Actinide
16 Chalcogens element
17 Halogens element
18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Ga - liquid
Fe - solid
Tc - synthetic

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)

Copyright © 1998-2003 EniG. (eni@ktf-split.hr)

- The Universe and the formation of the elements

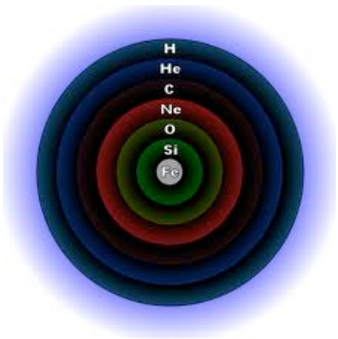


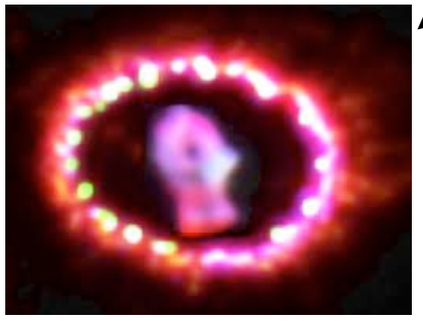
Big Bang

H, He

Stellar fusion

He - Fe





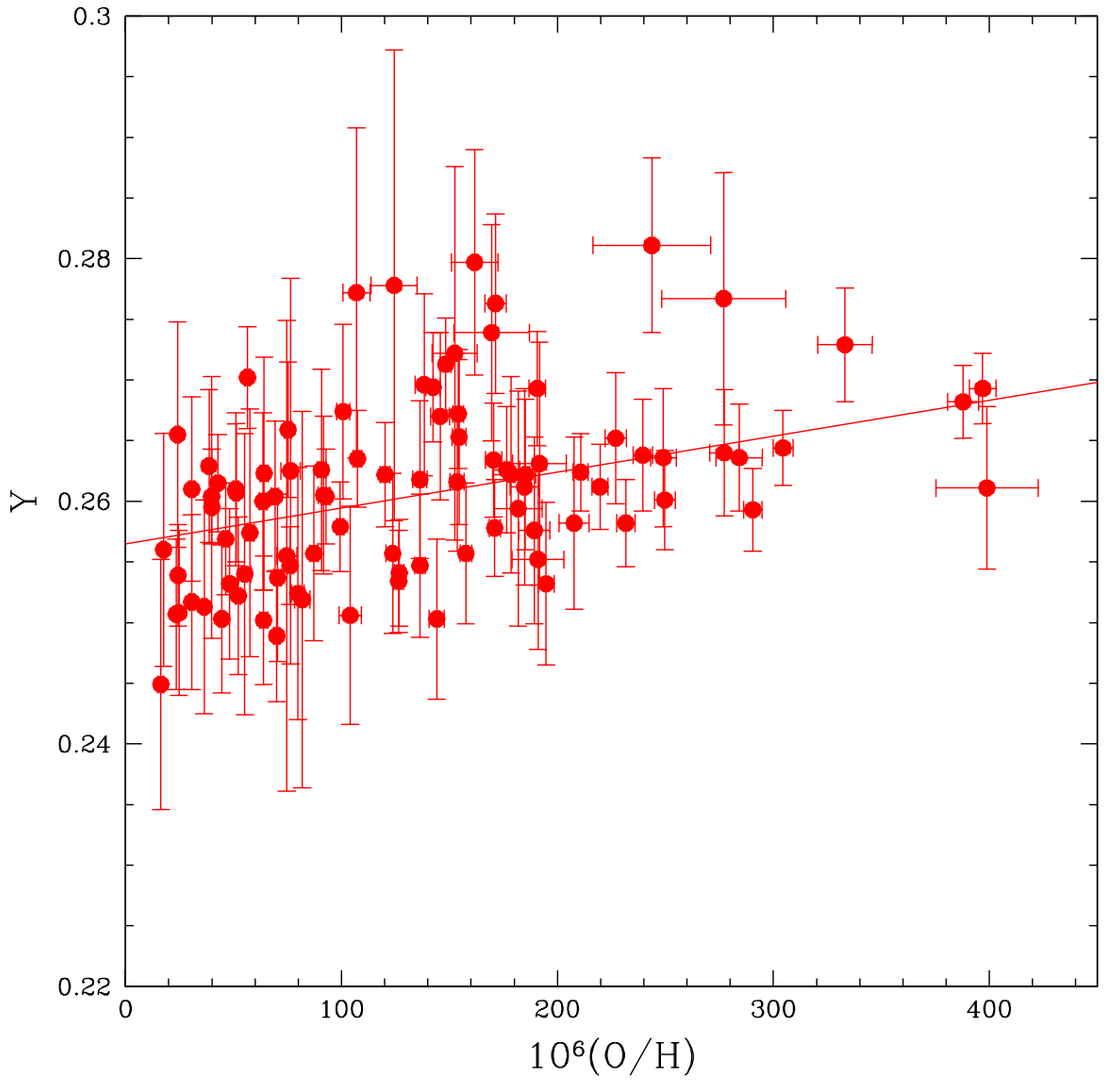
Supernova

Heavier than Fe

The present abundances observed are altered in the astrophysical processes with increase of metals such as C, N, O and Fe.

Helium 4

Observing the spectral line in metal poor extragalactic H II region (clouds of ionized hydrogen).

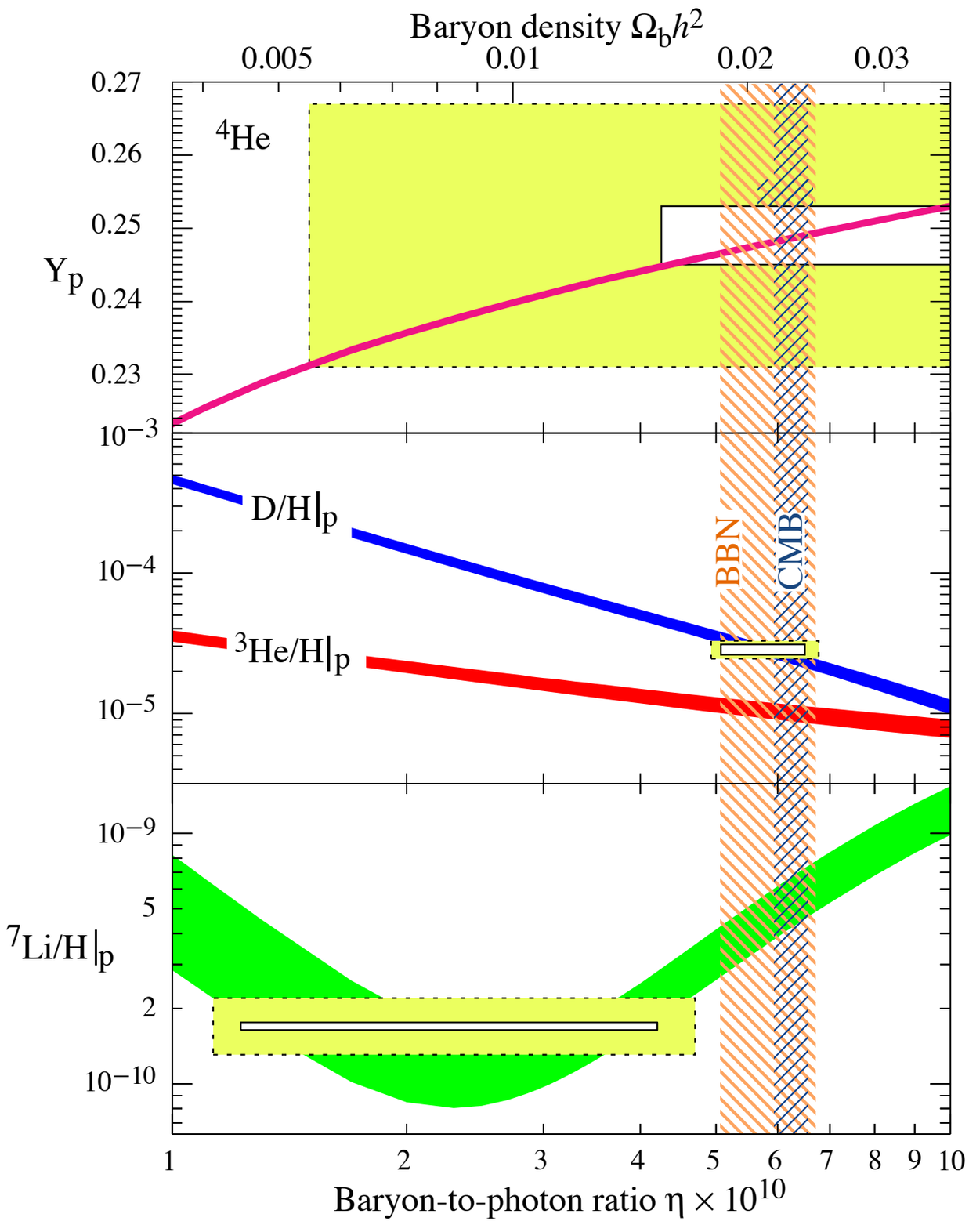


[Steigman, 1208.0032]

$$Y_P = 0.2565 \pm 0.0060.$$

[Steigman, 1208.0032]

• Determination of Baryon density



Box: 2sigma stat, 2sigma stat + syst

The comparison between the observed light element abundances and the theoretical calculation shows that the baryon-to-photon ratio

$$\eta_{10} \equiv \frac{n_b}{n_\gamma} \times 10^{10}$$

must be

$$5.1 \leq \eta_{10} \leq 6.5 \ (95\%\mathrm{CL})$$

It corresponds to Baryon energy density

$$0.019 \leq \Omega_b h^2 \leq 0.024 \ (95\%\mathrm{CL})$$

cf) $\Omega h^2_{\mathrm{lum}} \simeq 0.0024$

It is consistent with independent determination from CMB anisotropy.

$$\eta_{10} = 6.23 \pm 0.17$$