Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

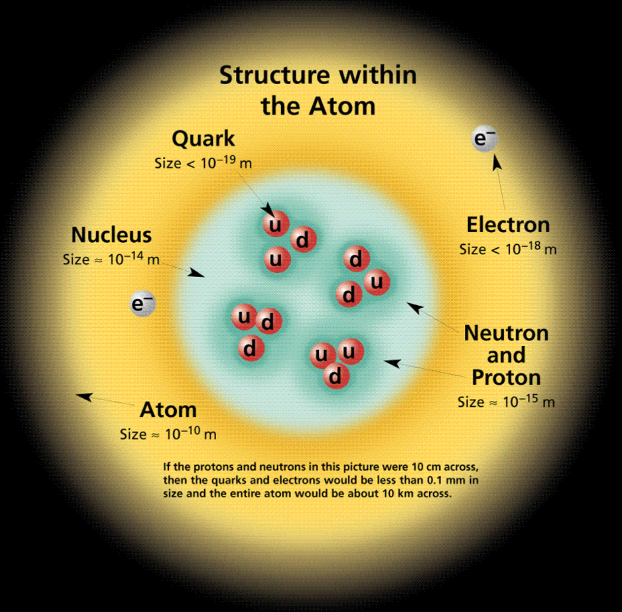
Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
Strength relative to electromag for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

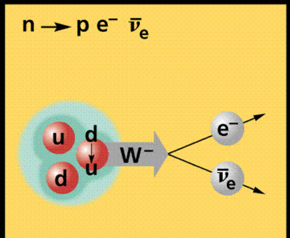
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

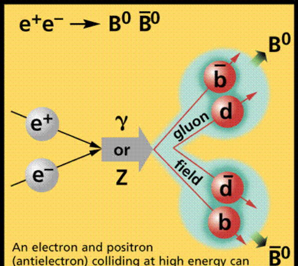
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

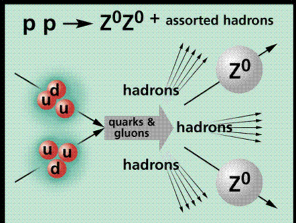
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

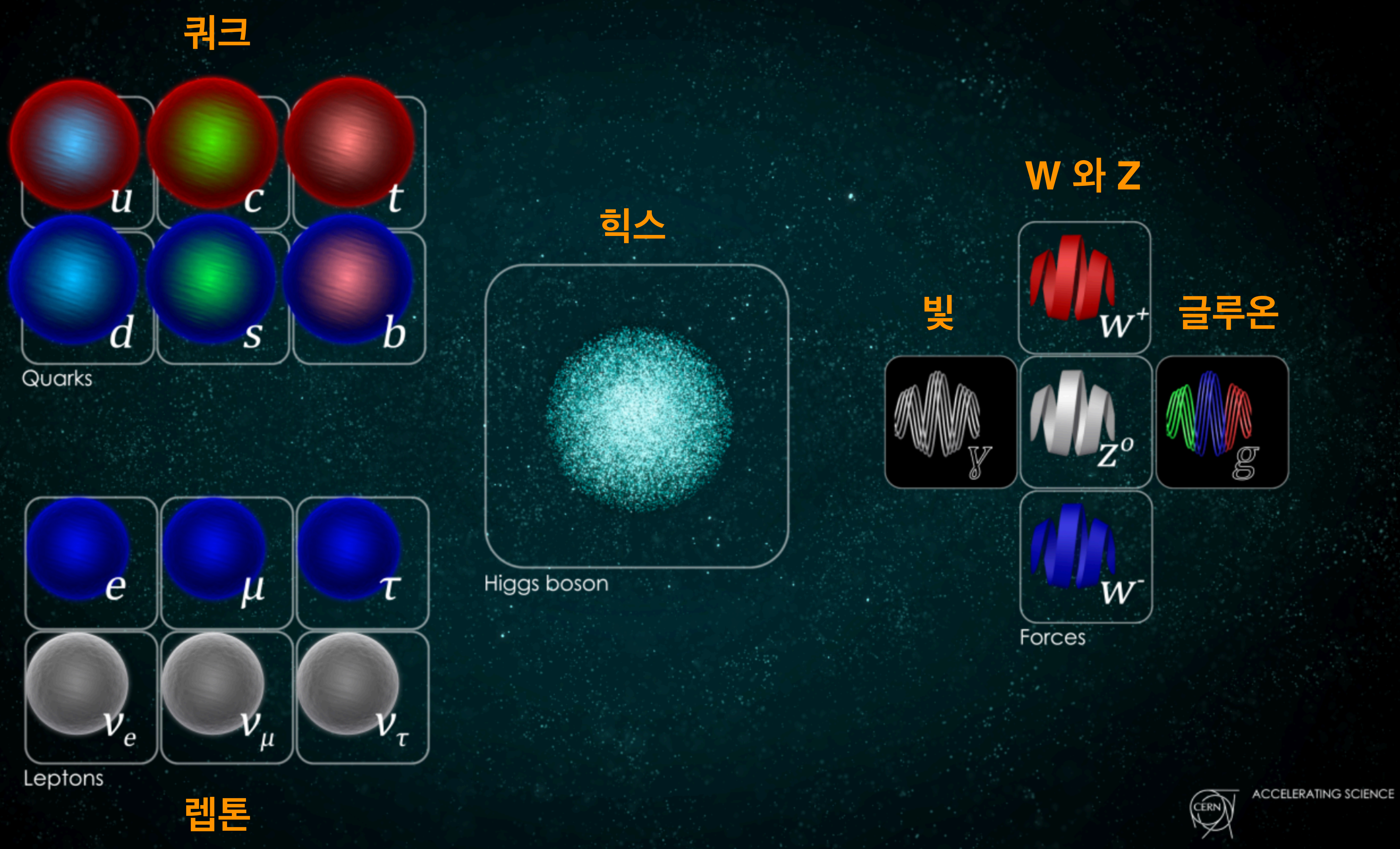
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

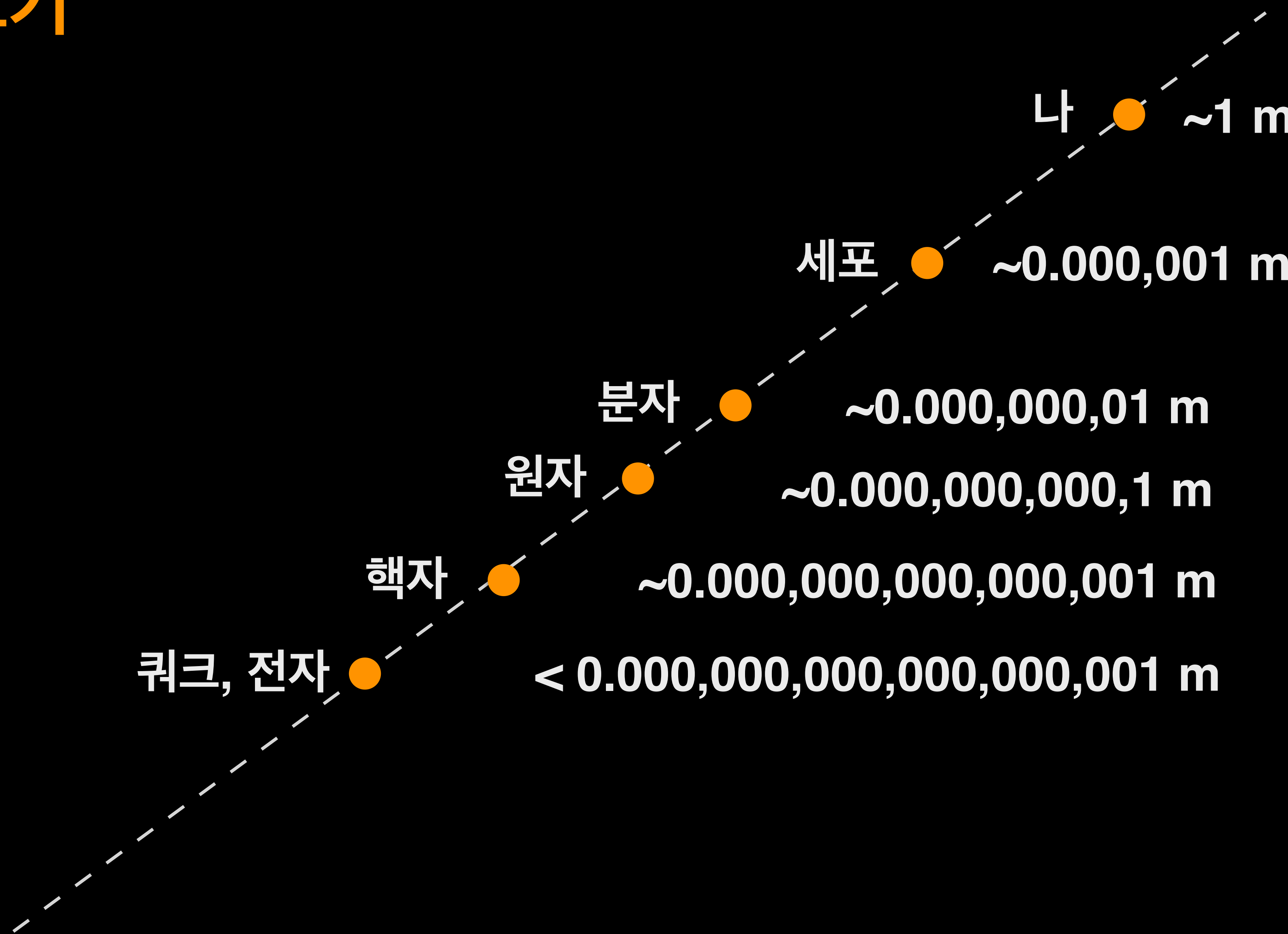
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

물질을 구성하는 입자들

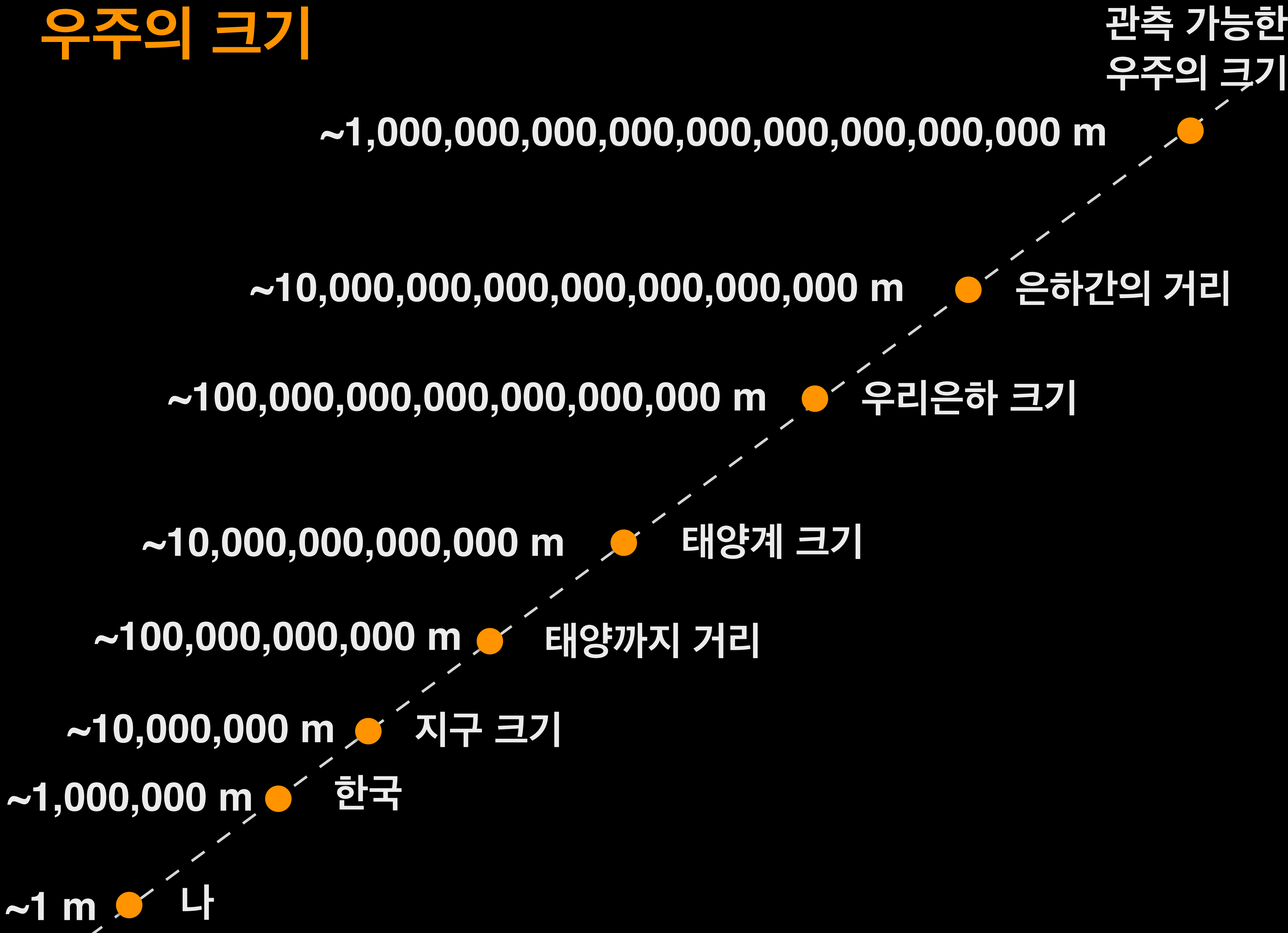

쿼크
u
c
t
d
s
b
Quarks
e
μ
τ
νe
νμ
ντ
Leptons
렙톤
힉스
Higgs boson
W 와 Z
빛
글루온
W+
γ
Z0
g
W-
Forces
CERN
ACCELERATING SCIENCE

우주의 크기



● 플랑크 길이 ~0.000,000,000,000,000,000,000,000,000,000,000,01 m

우주의 크기


관측 가능한
우주의 크기
~1,000,000,000,000,000,000,000,000,000 m
~10,000,000,000,000,000,000,000 m
은하간의 거리
~100,000,000,000,000,000,000 m
우리은하 크기
~10,000,000,000,000 m
태양계 크기
~100,000,000,000 m
태양까지 거리
~10,000,000 m
지구 크기
~1,000,000 m
한국
~1 m
나

입자천체물리학

~1,000,000,000,000,000,000,000,000,000 m ● 관측 가능한 우주의 크기

나 ● ~1 m

10^{62}

● 플랑크 길이 ~0.000,000,000,000,000,000,000,000,000,000,000,01 m

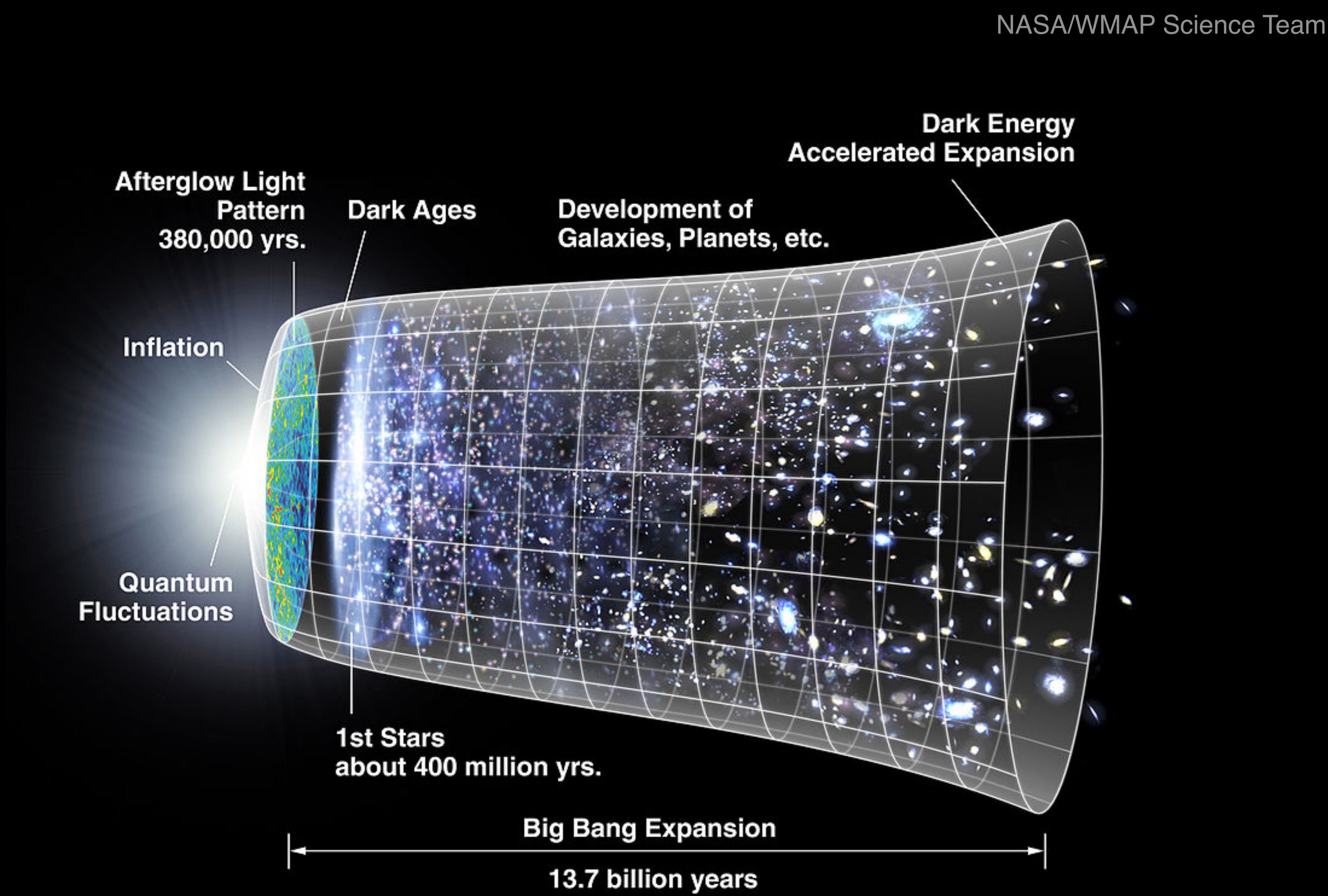
암흑우주

KAIST 물리학과
유 종 희

2019. 7. 17
KAIST 입자천체물리 대중강연

밤하늘 (칠레 고산지대)

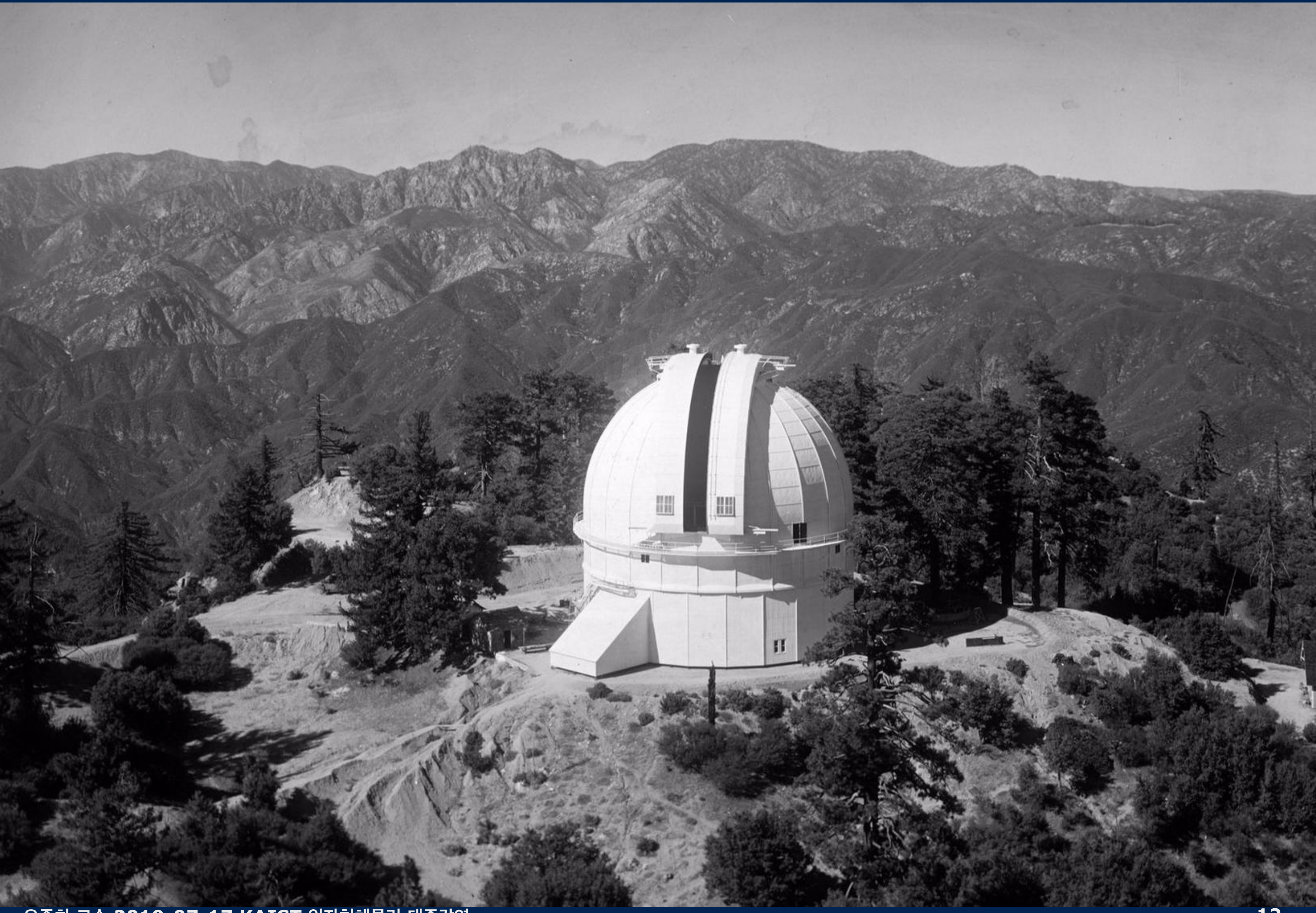
우주의 역사



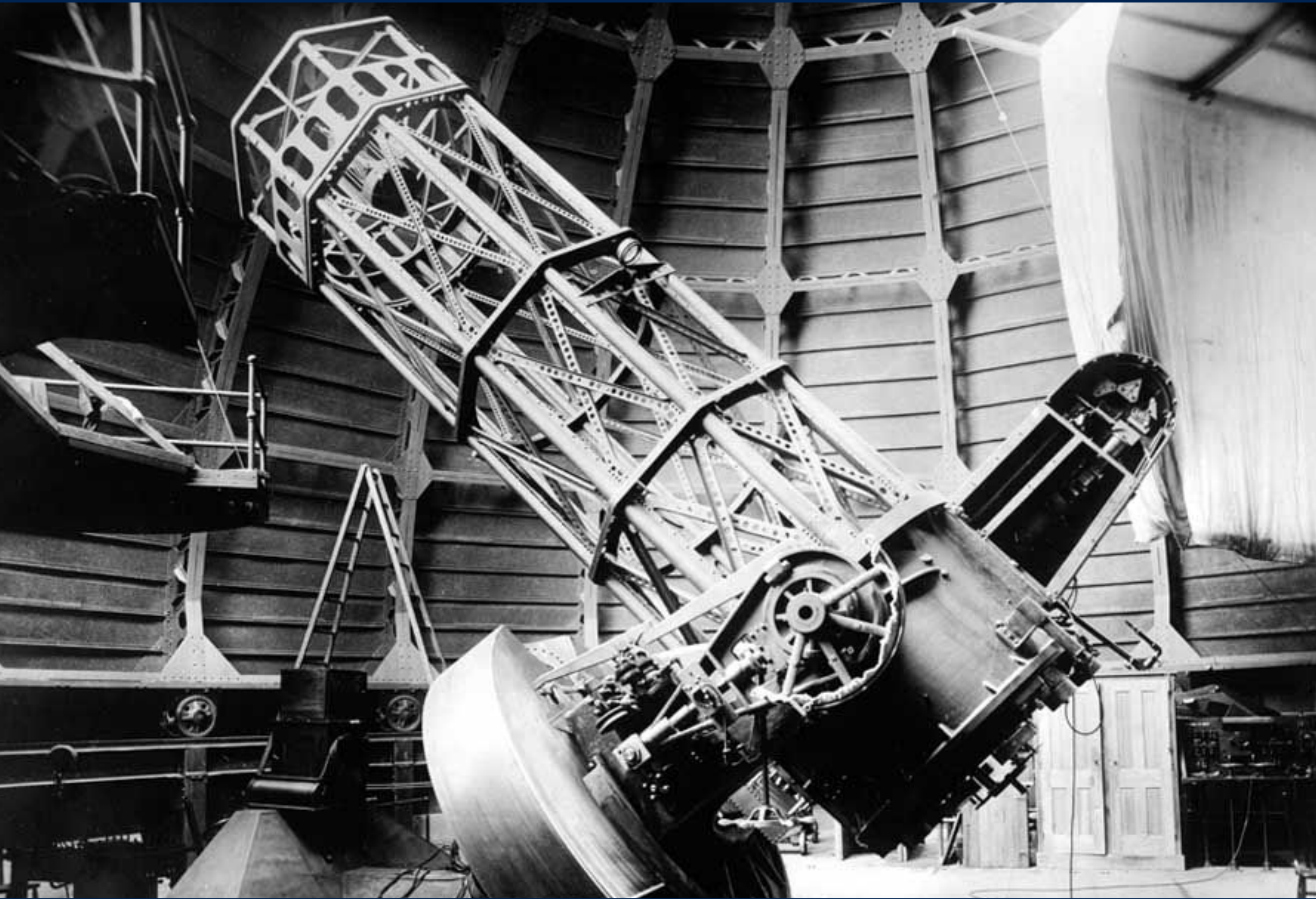
NASA/WMAP Science Team
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

PyroBB youtube

미국 캘리포니아 윌슨산 천문대

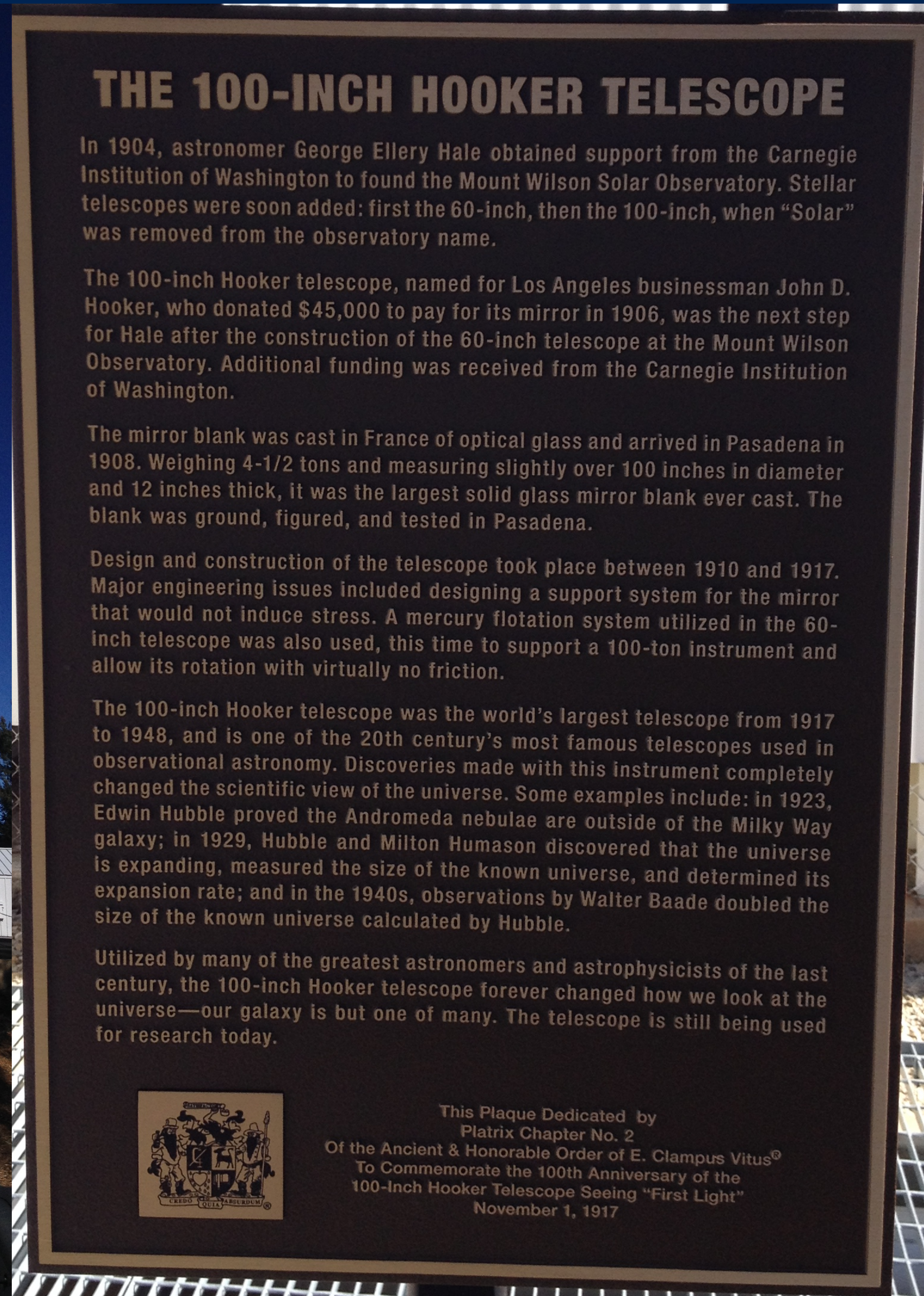


윌슨산 천문대 100인치 망원경

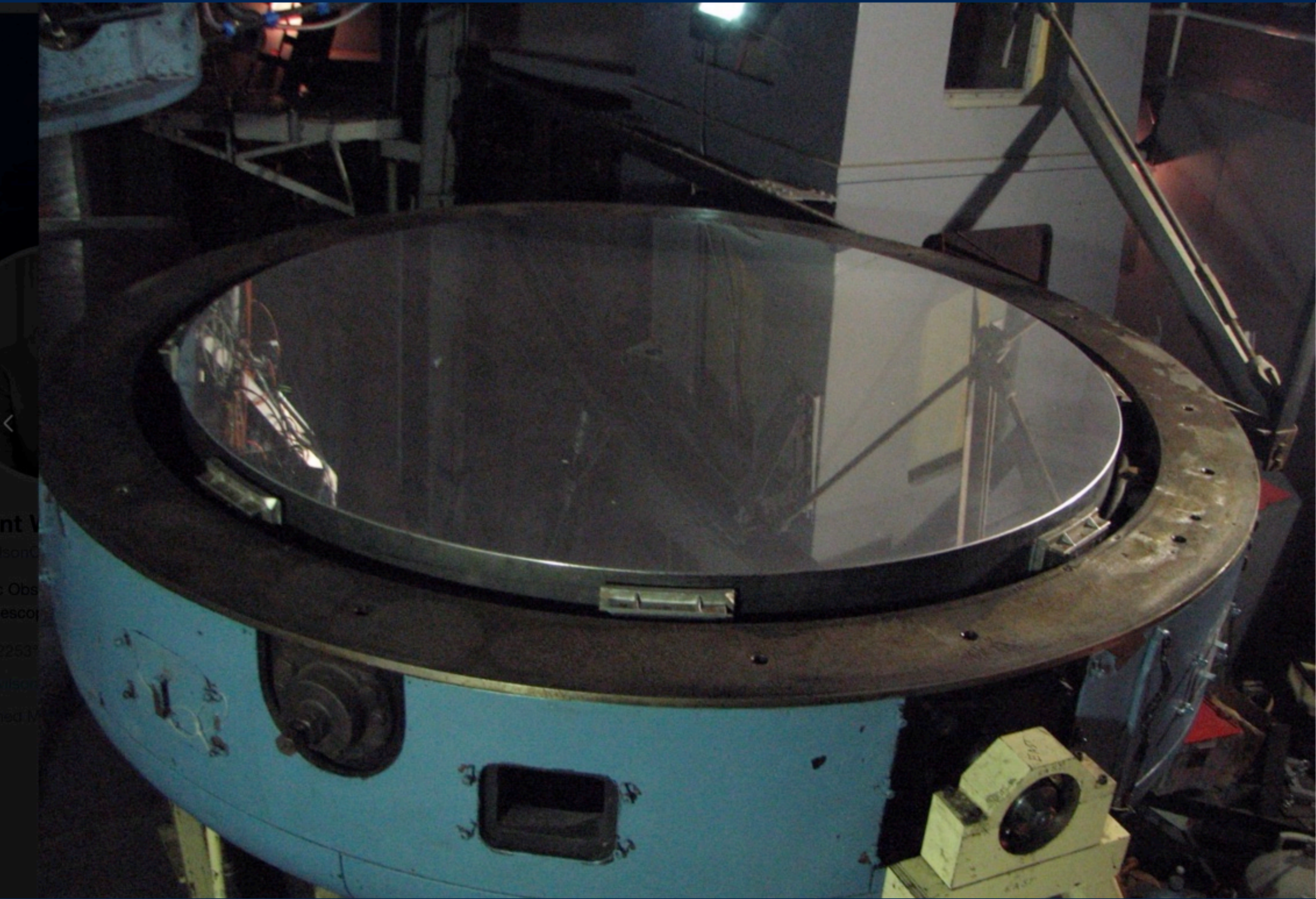


100년전 윌슨산 교통 수단

윌슨산 천문대

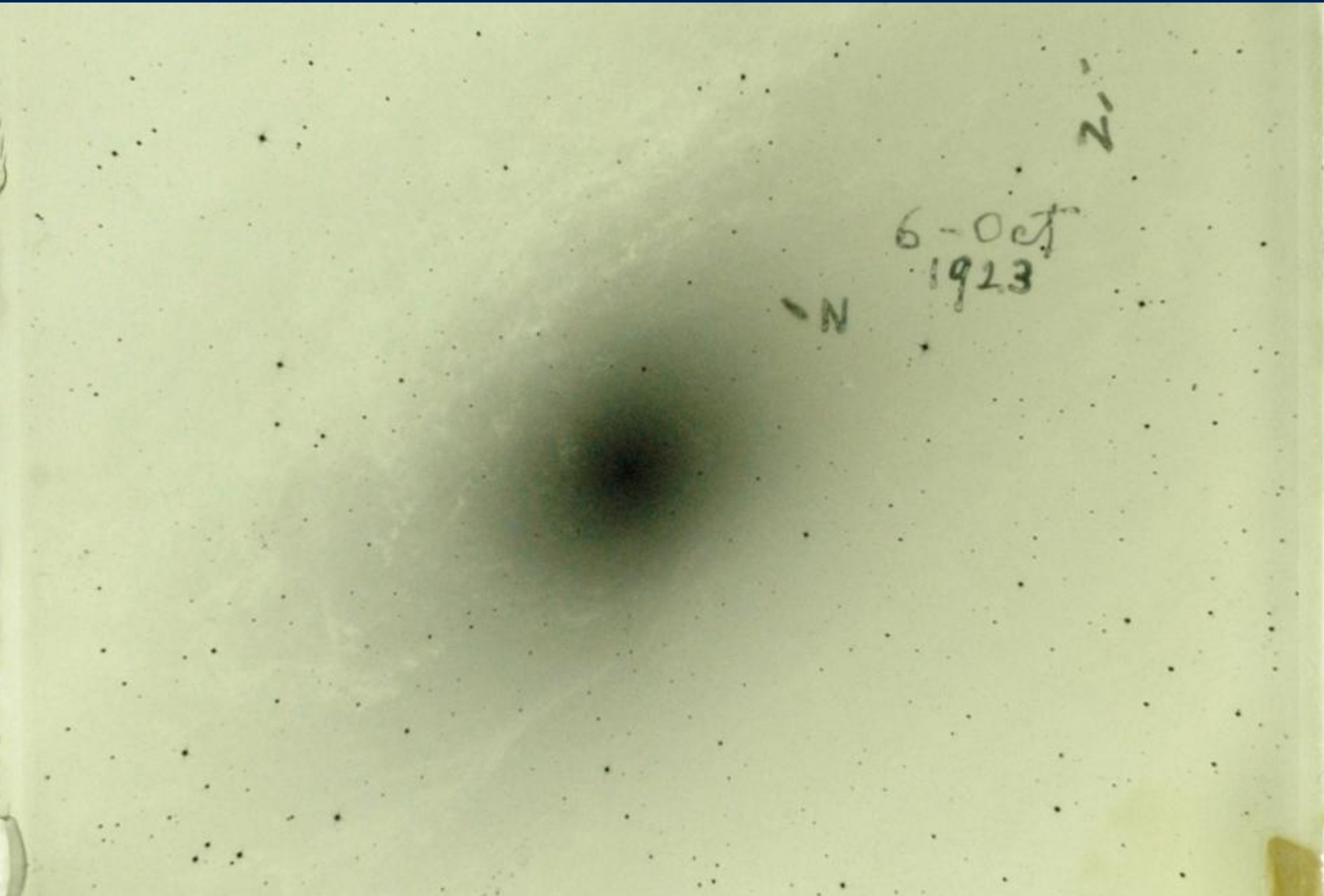

THE 100-INCH HOOKER TELESCOPE
In 1904, astronomer George Ellery Hale obtained support from the Carnegie Institution of Washington to found the Mount Wilson Solar Observatory. Stellar telescopes were soon added: first the 60-inch, then the 100-inch, when "Solar" was removed from the observatory name.
The 100-inch Hooker telescope, named for Los Angeles businessman John D. Hooker, who donated $45,000 to pay for its mirror in 1906, was the next step for Hale after the construction of the 60-inch telescope at the Mount Wilson Observatory. Additional funding was received from the Carnegie Institution of Washington.
The mirror blank was cast in France of optical glass and arrived in Pasadena in 1908. Weighing 4-1/2 tons and measuring slightly over 100 inches in diameter and 12 inches thick, it was the largest solid glass mirror blank ever cast. The blank was ground, figured, and tested in Pasadena.
Design and construction of the telescope took place between 1910 and 1917. Major engineering issues included designing a support system for the mirror that would not induce stress. A mercury flotation system utilized in the 60-inch telescope was also used, this time to support a 100-ton instrument and allow its rotation with virtually no friction.
The 100-inch Hooker telescope was the world's largest telescope from 1917 to 1948, and is one of the 20th century's most famous telescopes used in observational astronomy. Discoveries made with this instrument completely changed the scientific view of the universe. Some examples include: in 1923, Edwin Hubble proved the Andromeda nebulae are outside of the Milky Way galaxy; in 1929, Hubble and Milton Humason discovered that the universe is expanding, measured the size of the known universe, and determined its expansion rate; and in the 1940s, observations by Walter Baade doubled the size of the known universe calculated by Hubble.
Utilized by many of the greatest astronomers and astrophysicists of the last century, the 100-inch Hooker telescope forever changed how we look at the universe—our galaxy is but one of many. The telescope is still being used for research today.
This Plaque Dedicated by
Platrix Chapter No. 2
Of the Ancient & Honorable Order of E. Clampus Vitus®
To Commemorate the 100th Anniversary of the
100-Inch Hooker Telescope Seeing "First Light"
November 1, 1917

100인치 망원경



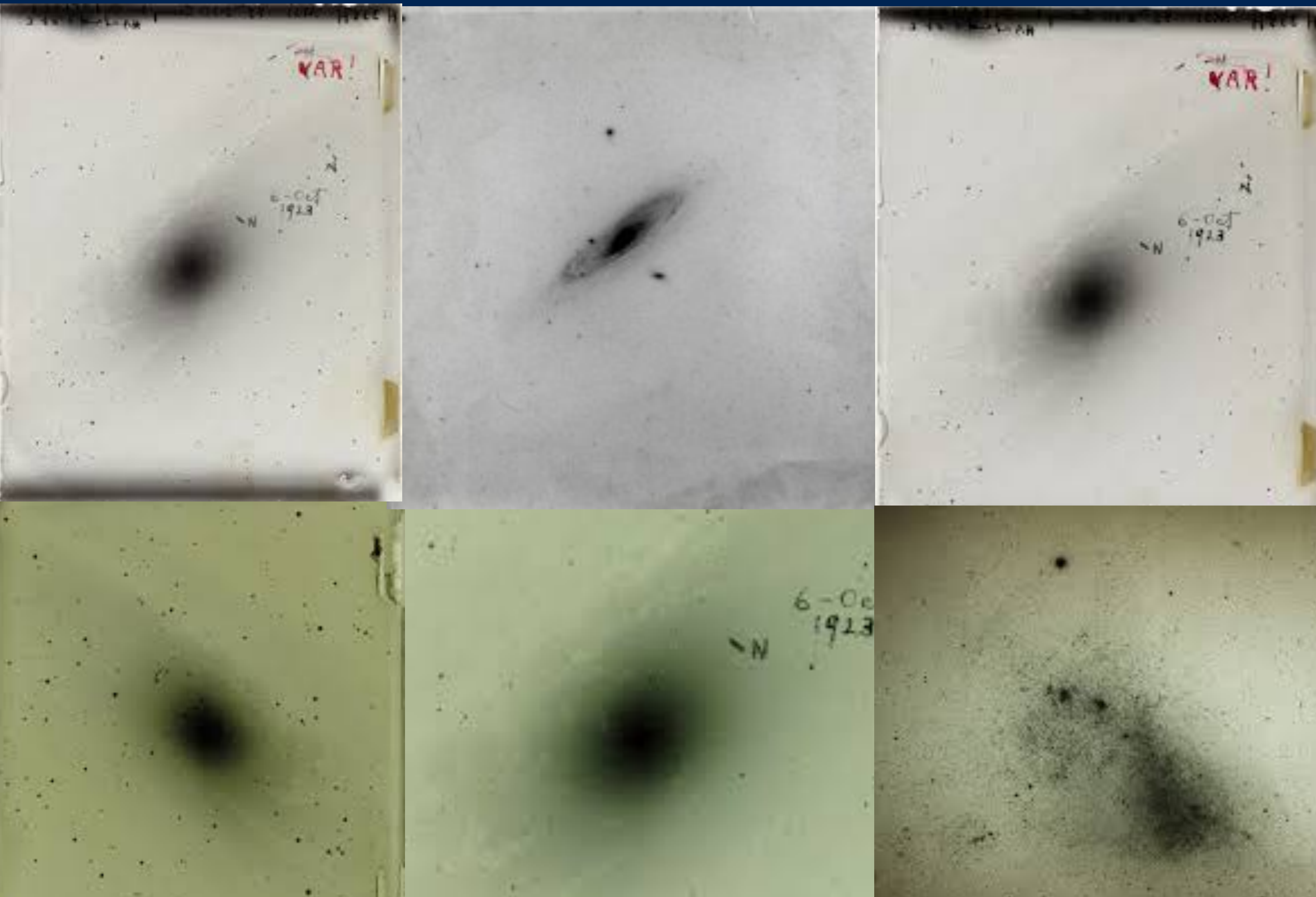
100인치 망원경

100인치 망원경으로 관측된 성운

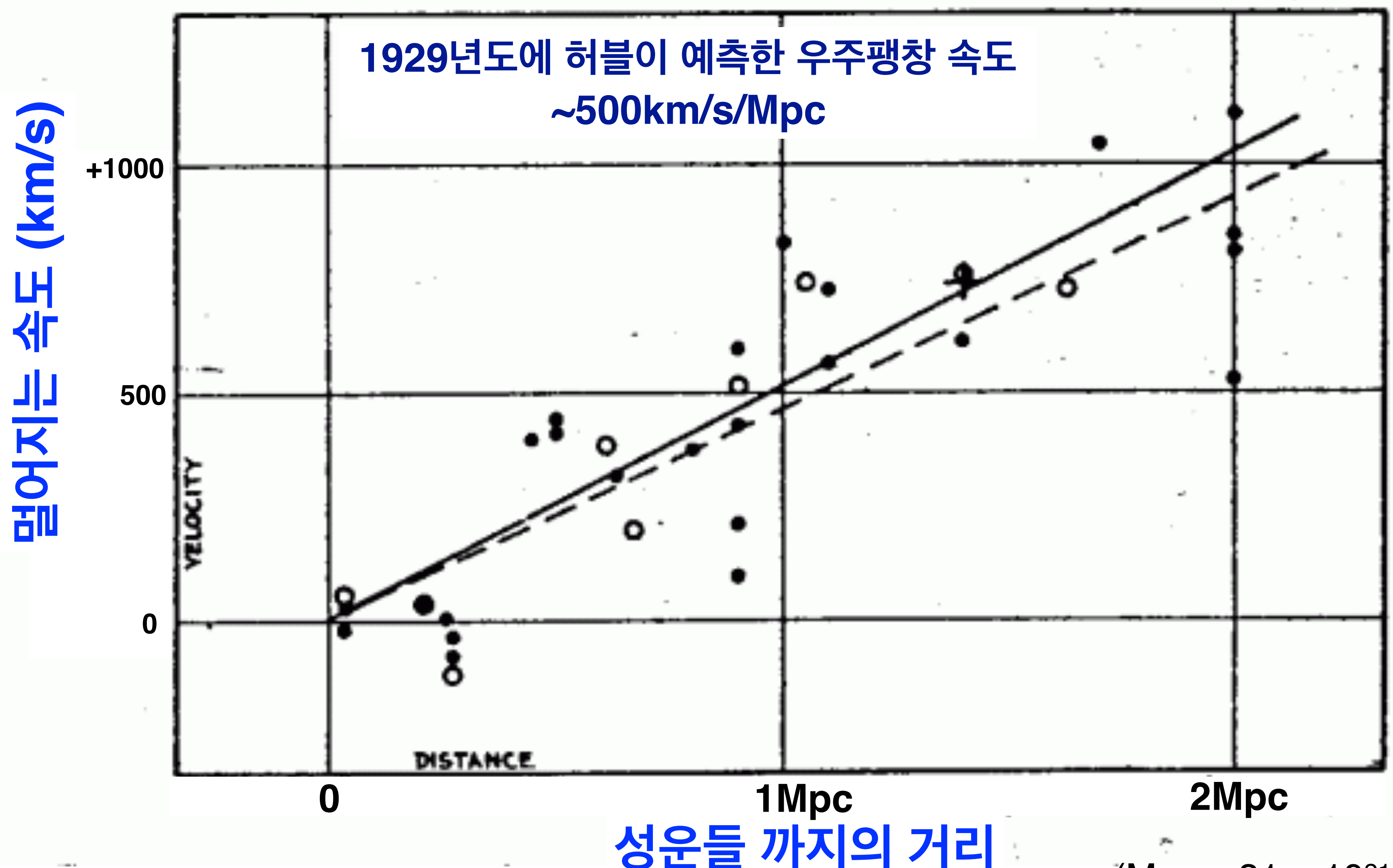


100인치 망원경으로 관측된 성운들

KAIST

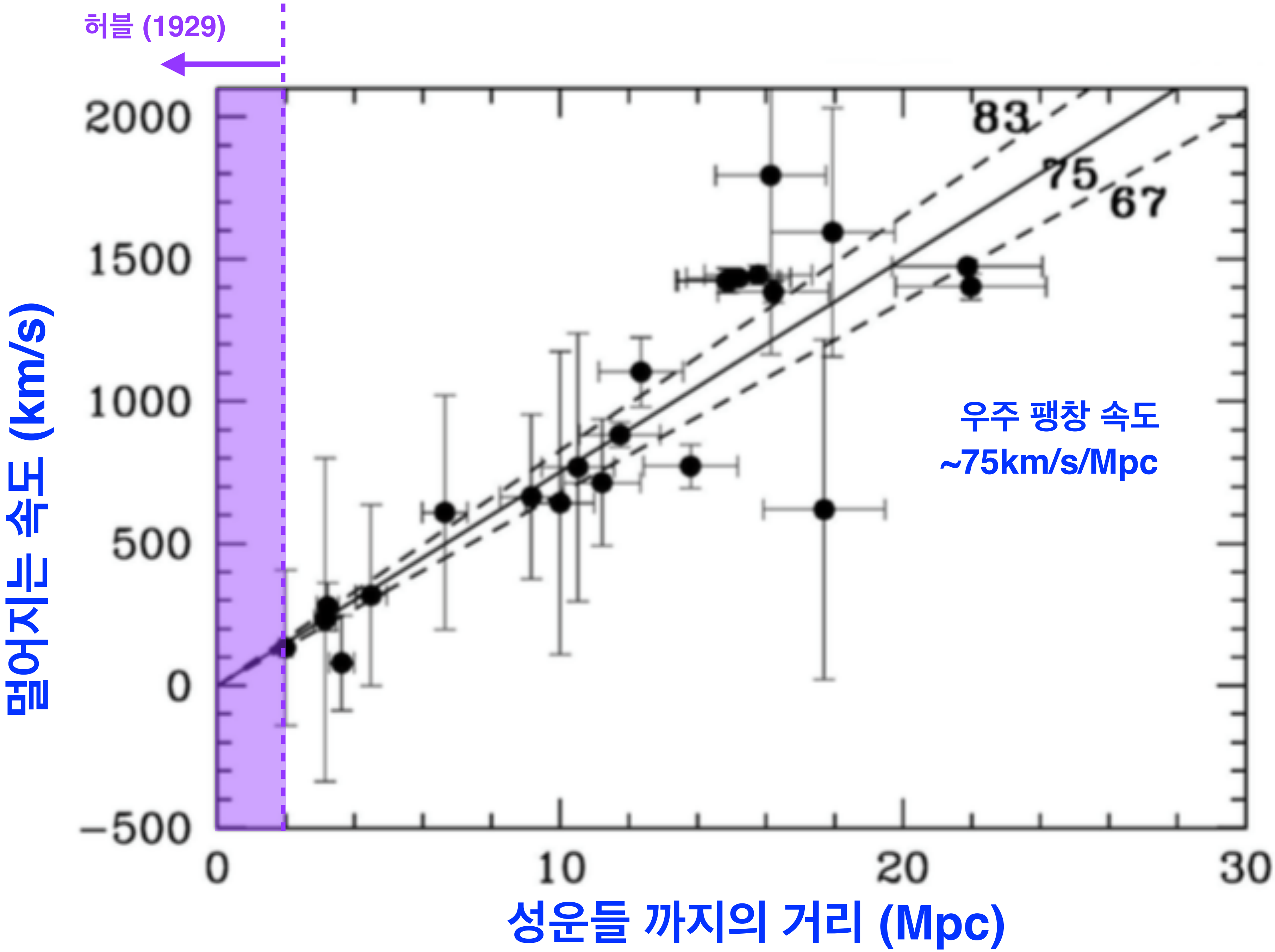


성운들이 멀어지는 속도와 거리 관계 도표 (허블 1929)

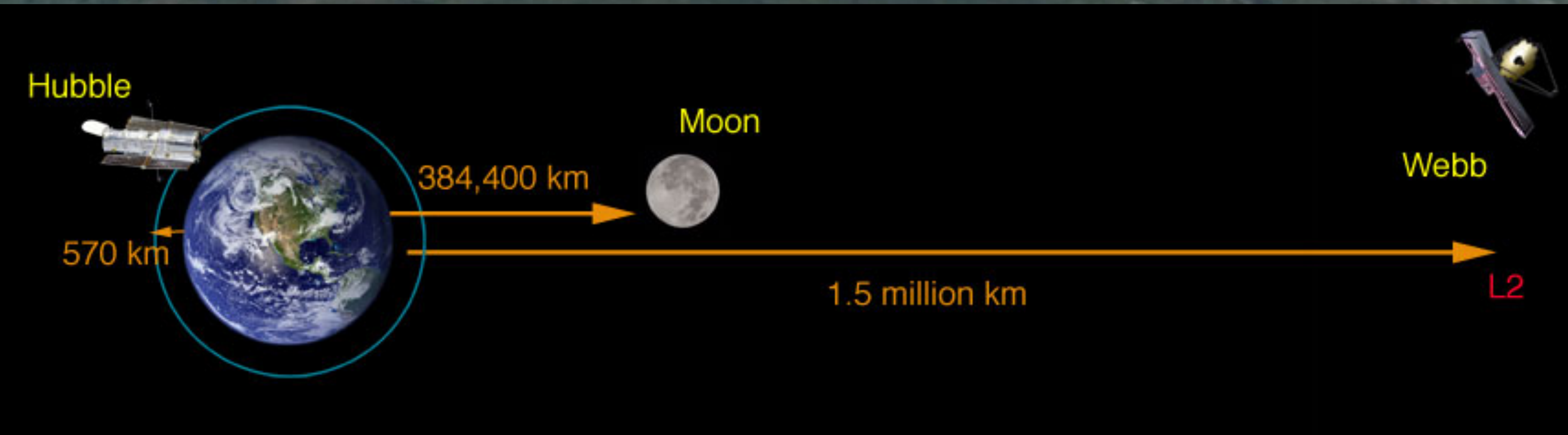


(Mpc = 31 × 10^{21} m)

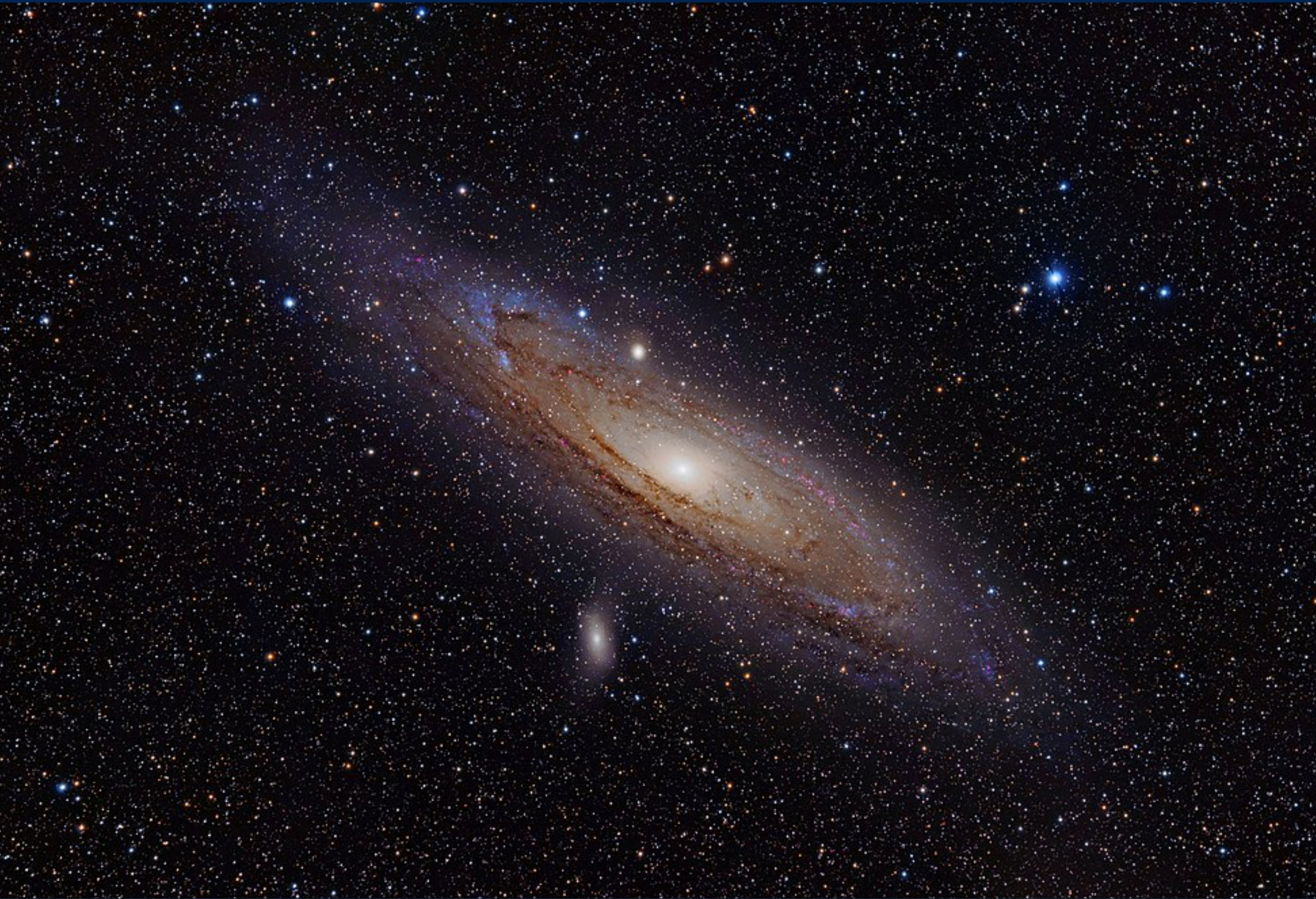
허블 도표 (개선된 측정 결과)



허블 망원경

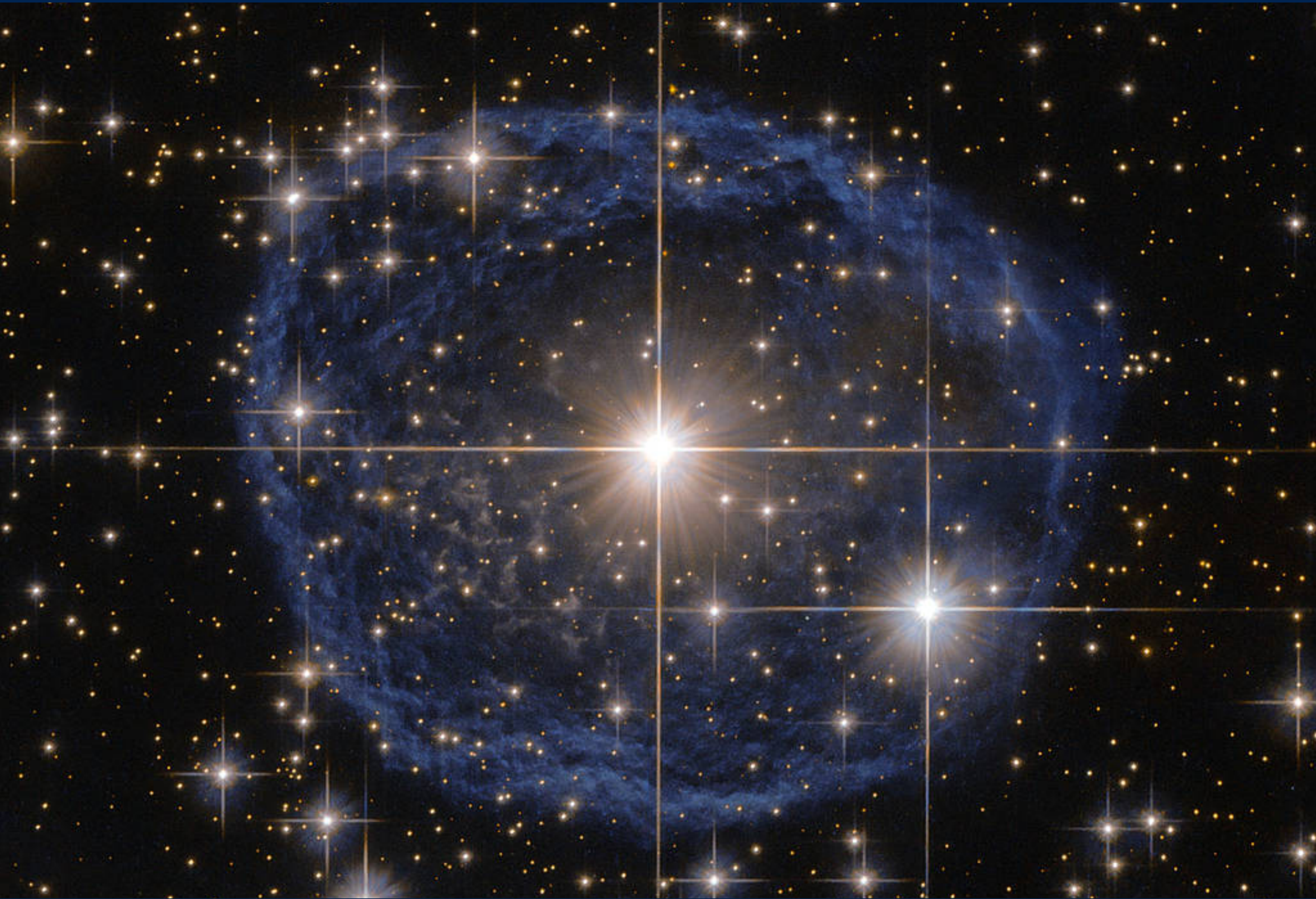


Andromeda (Messier 31, M31, NGC224)

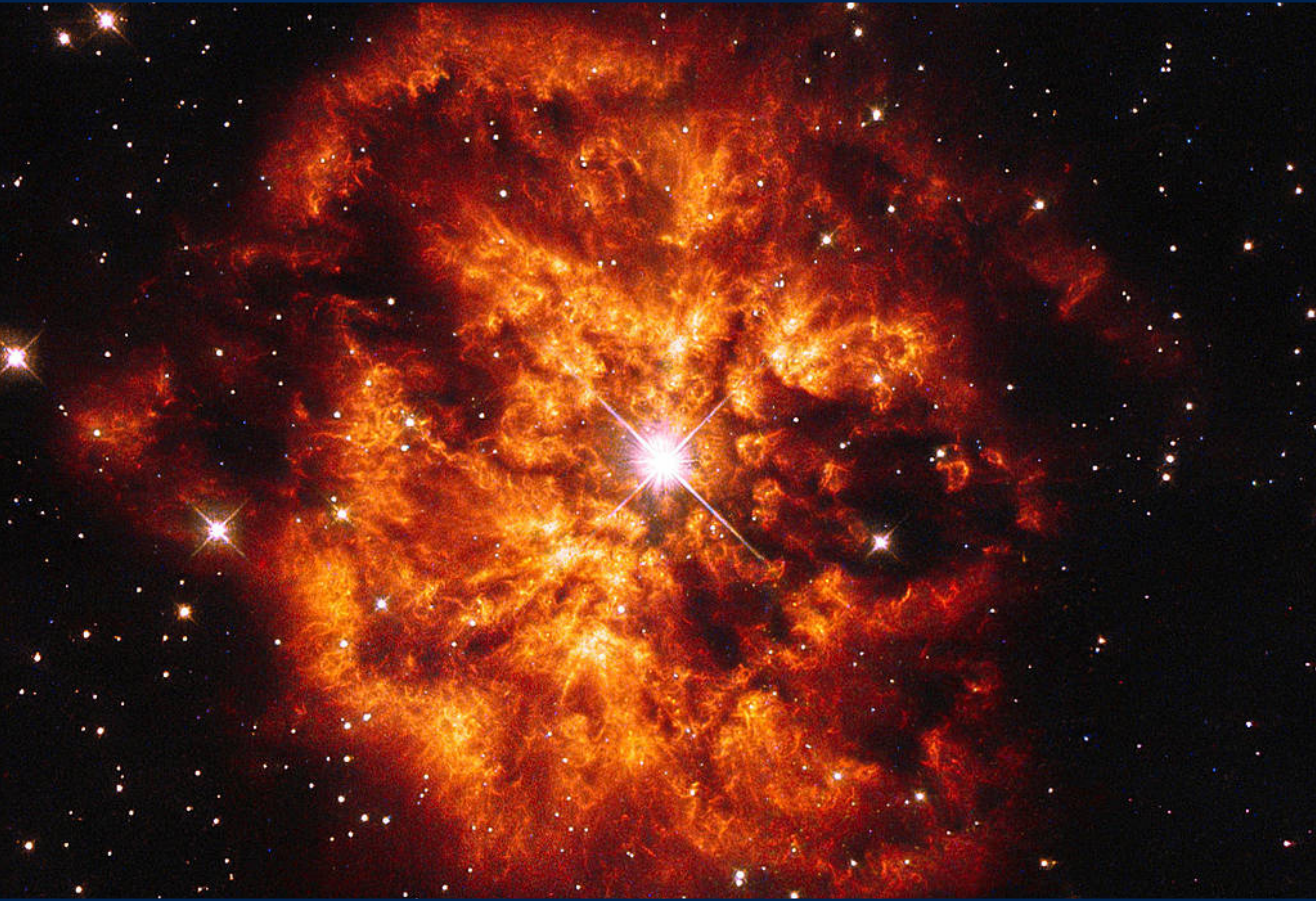


Planetary Nebula (Hen 2-437)

Wolf-Rayet Star (WR 31a)

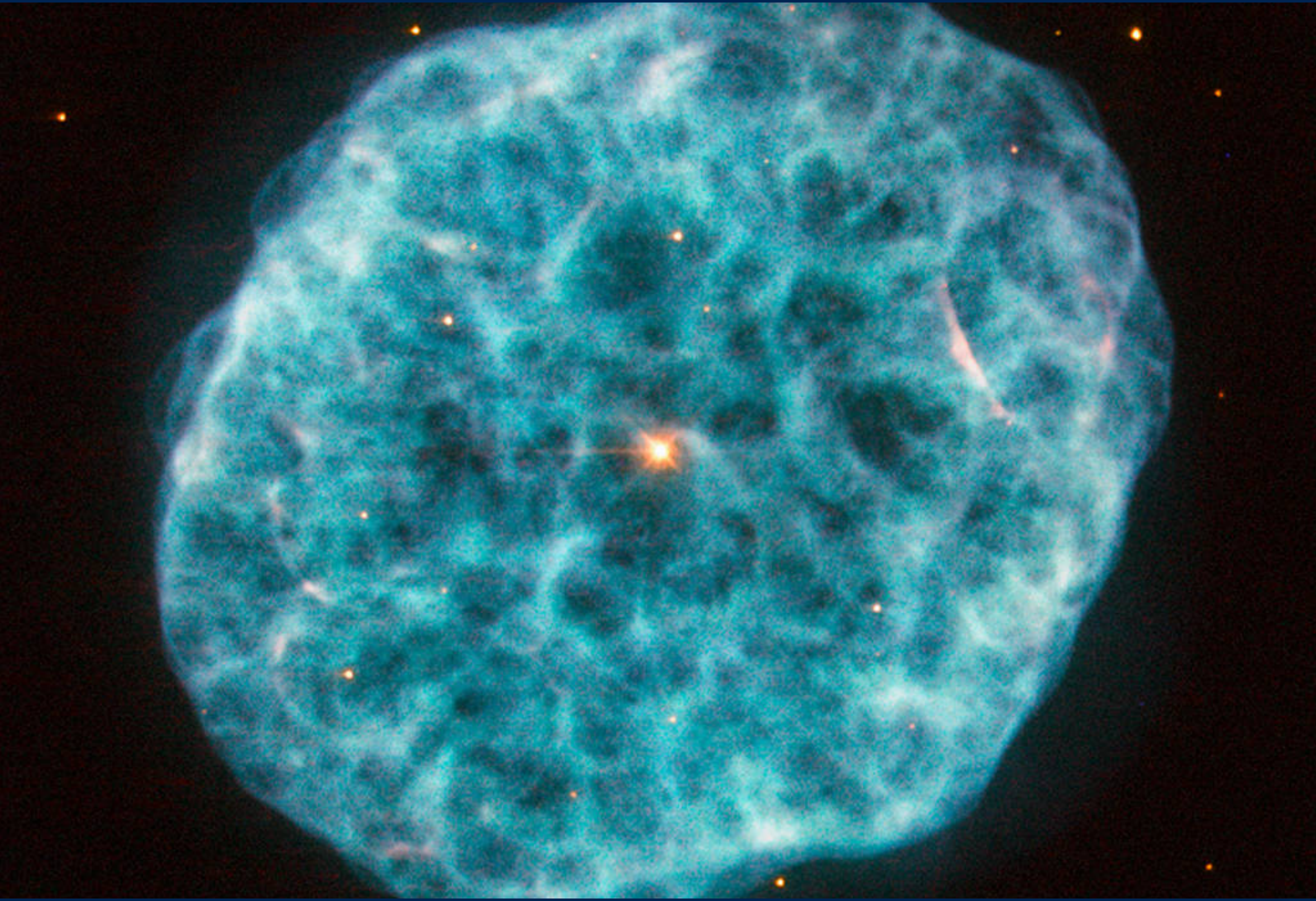


Cosmic Pairing Star Hen 2-427 (WR 124 at M1-67)



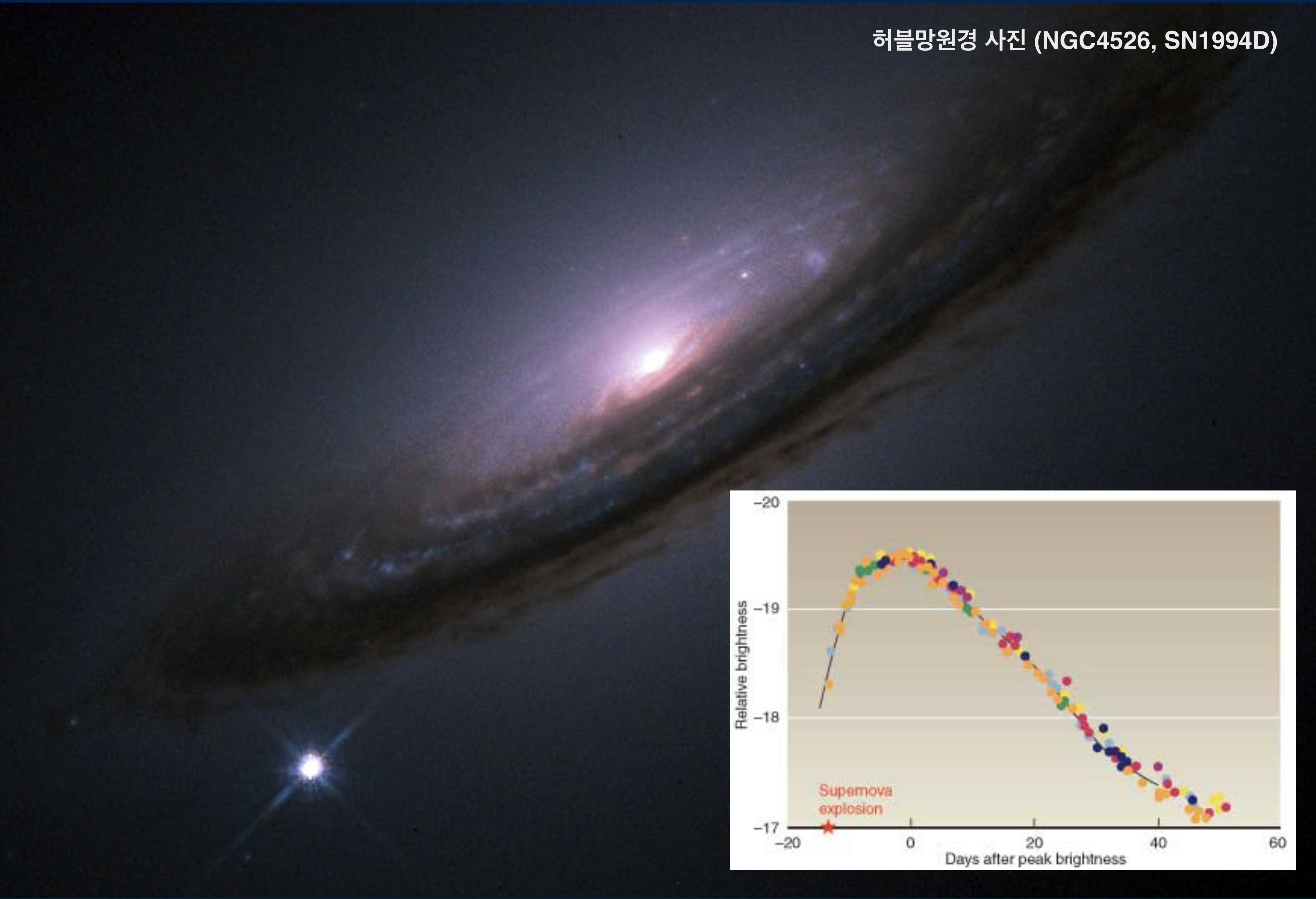
NGC 6818 (Planetary Nebula)

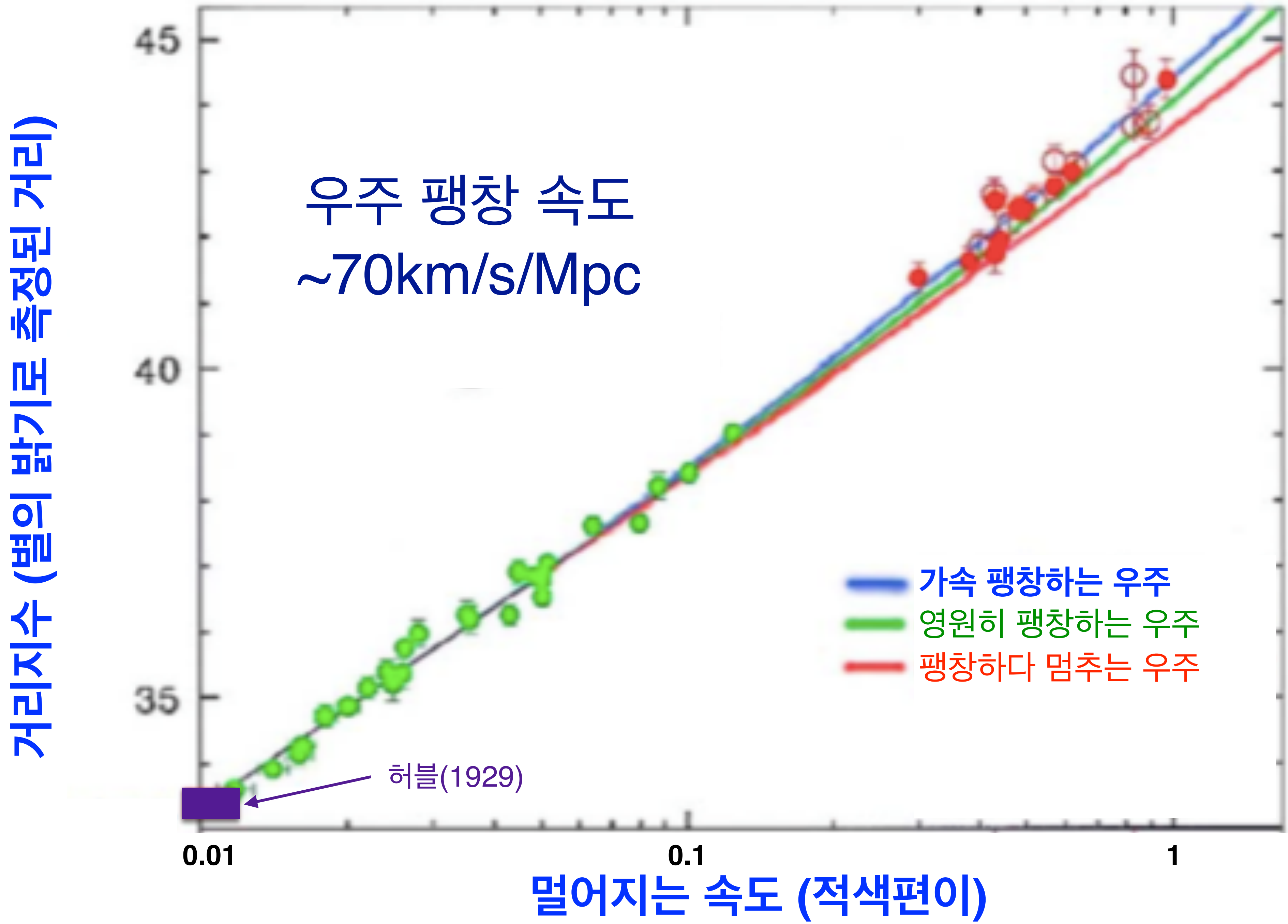
NGC 1501 (Planetary Nebula)



1a형 초신성

허블망원경 사진 (NGC4526, SN1994D)




우주 팽창 속도
~70km/s/Mpc
45
40
35
가속 팽창하는 우주
영원히 팽창하는 우주
팽창하다 멈추는 우주
허블(1929)
0.01
0.1
1
거리지수 (별의 밝기로 측정된 거리)
멀어지는 속도 (적색편이)

불꽃놀이

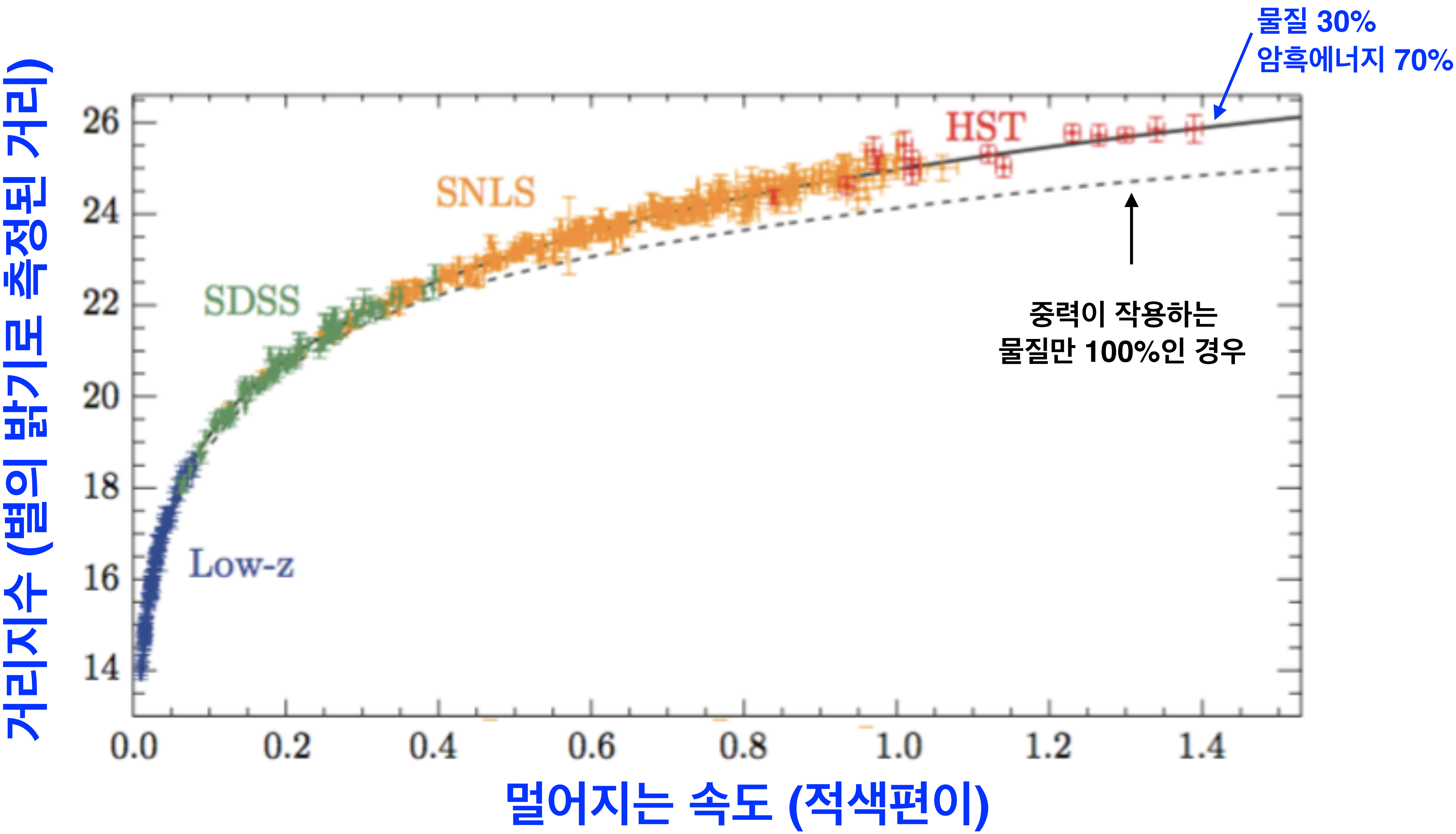
PyroBB youtube

공간 에너지 암흑 에너지

$$G = [8\pi g]T + X$$

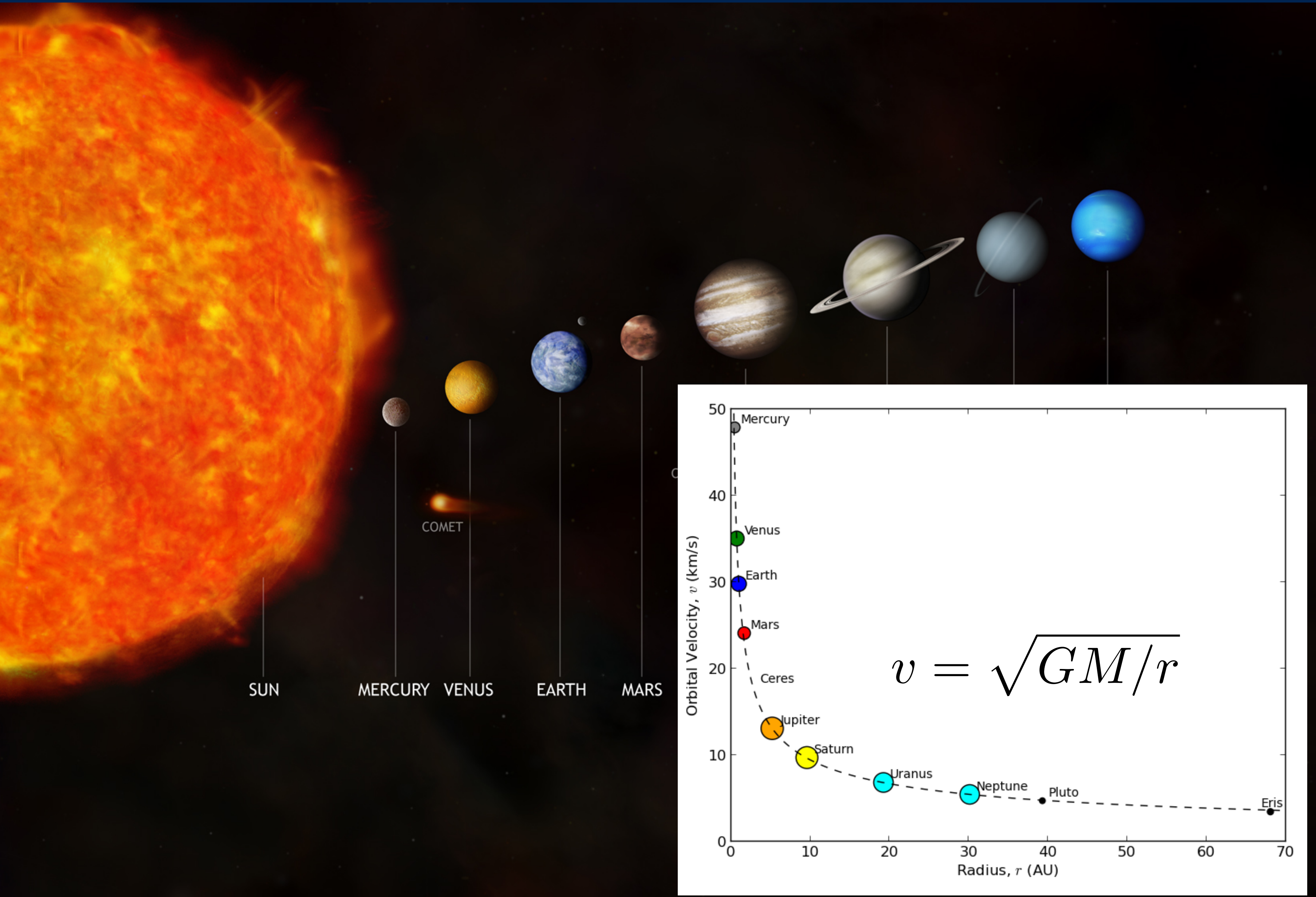
[우주 공간이 **가속** 팽창하는 힘] = [물질에 작용하는 중력에 의한 힘] + [물질에 **암흑에너지**가 작용하는 힘]

서로 당기는 힘 서로 밀어내는 힘

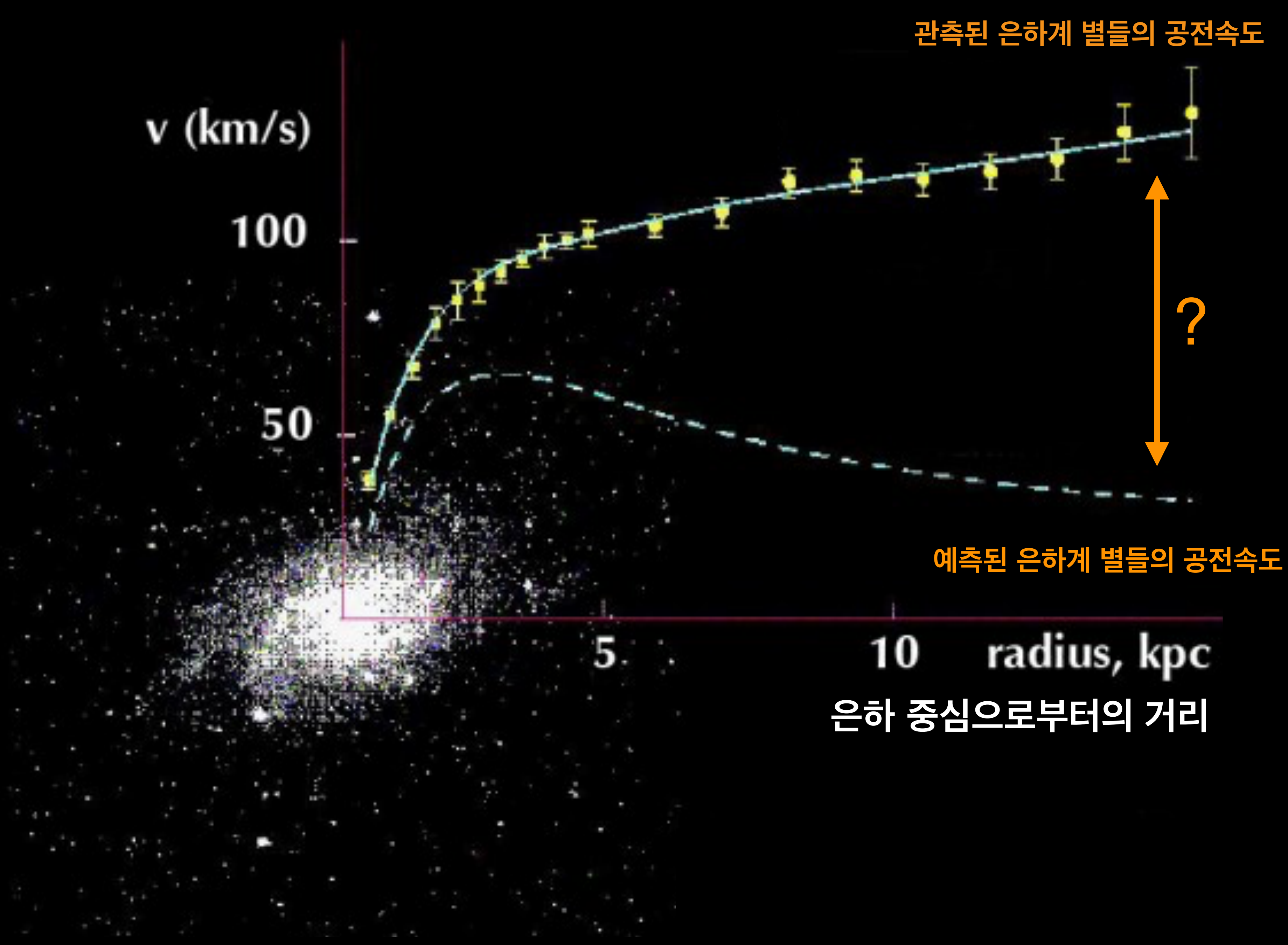


우주를 구성하는 총 에너지의 70%는 암흑 에너지
30%만 중력이 작용하는 물질

태양계 행성의 공전속도

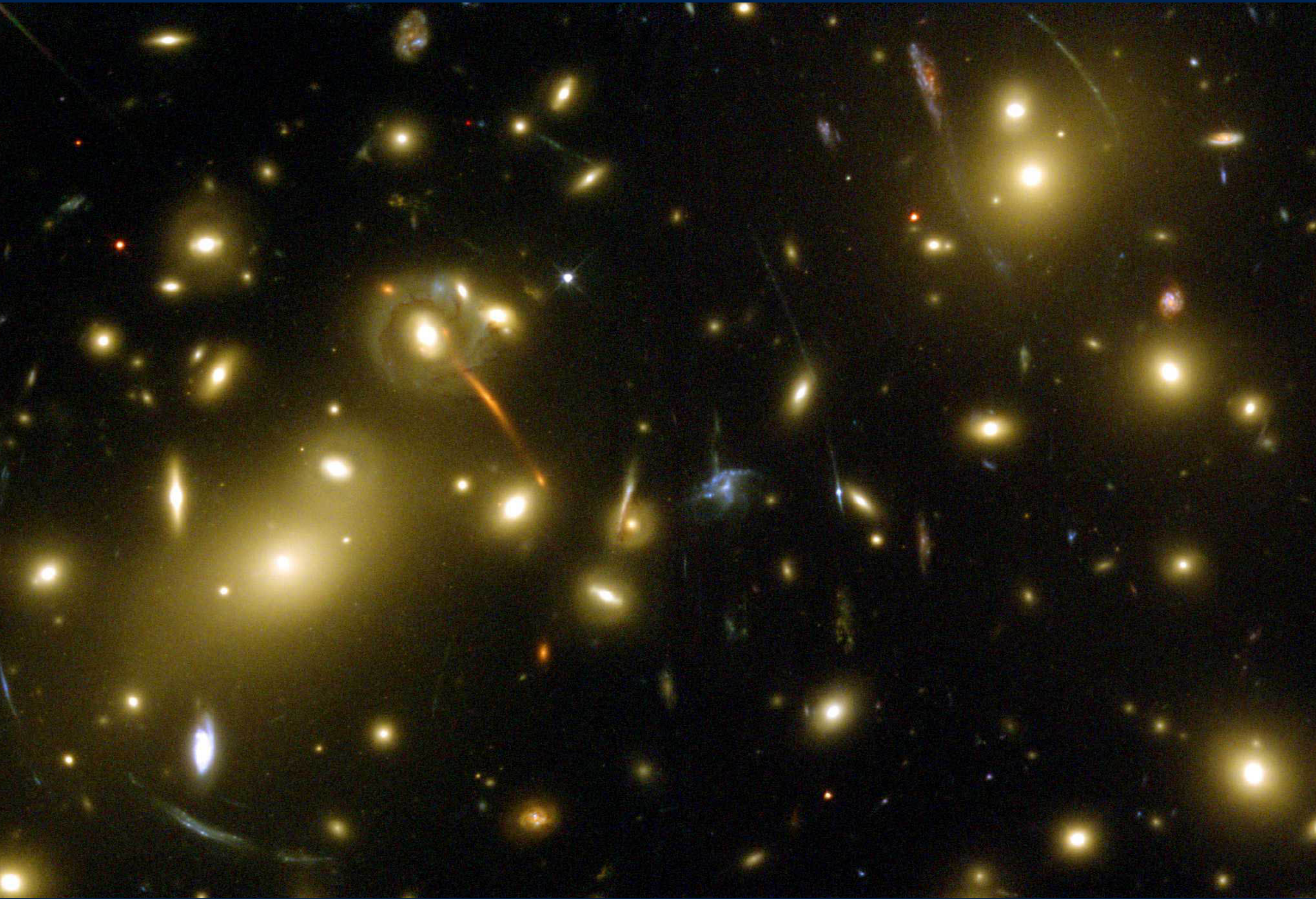

COMET
SUN
MERCURY
VENUS
EARTH
MARS
Mercury
Venus
Earth
Mars
Ceres
Jupiter
Saturn
Uranus
Neptune
Pluto
Eris
Orbital Velocity, v (km/s)
Radius, r (AU)
0
10
20
30
40
50
60
70
$v = \sqrt{GM/r}$

은하계 별들의 공전속도

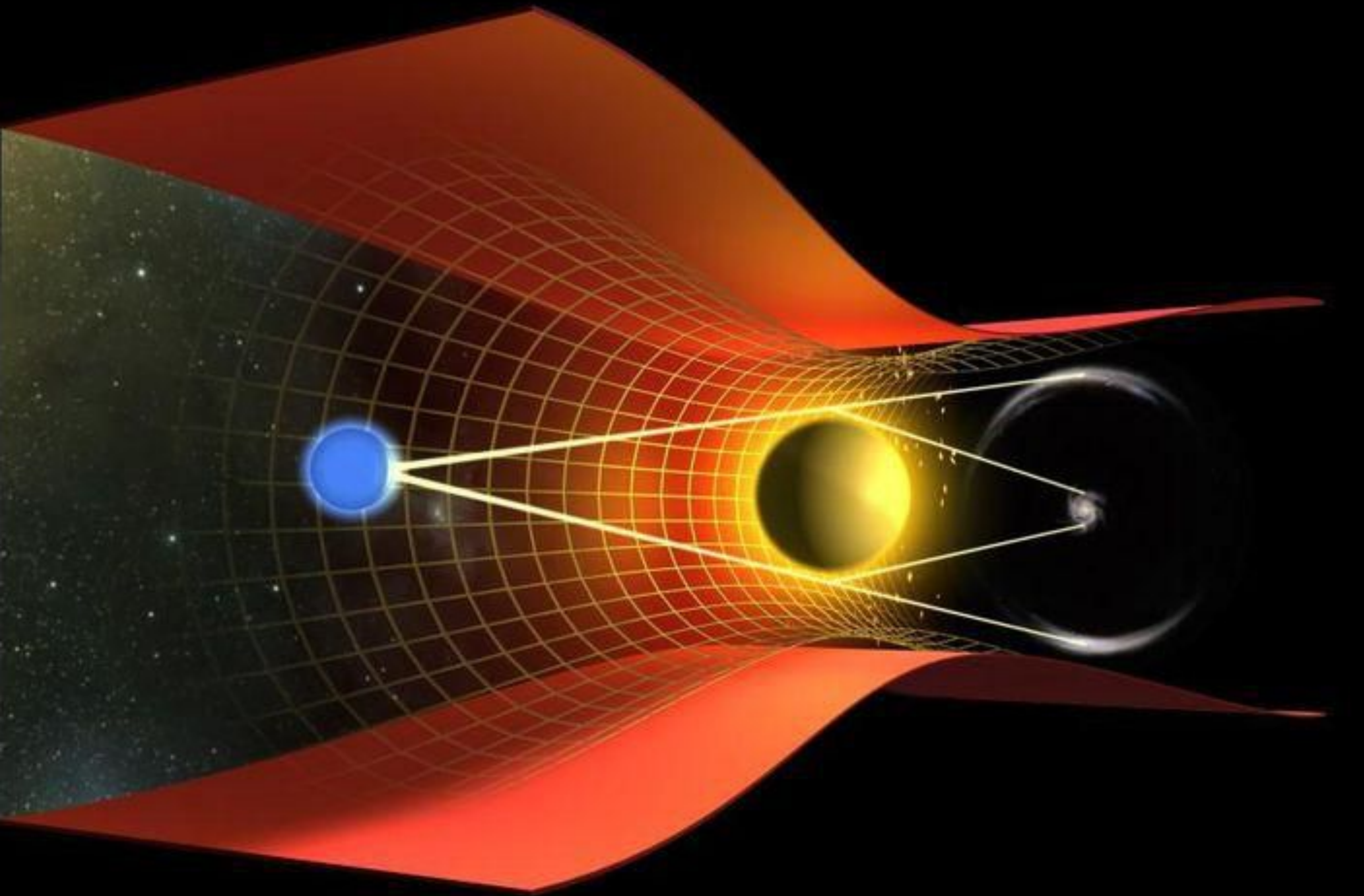


관측된 은하계 별들의 공전속도
v (km/s)
100
50
?
예측된 은하계 별들의 공전속도
5
10
radius, kpc
은하 중심으로부터의 거리

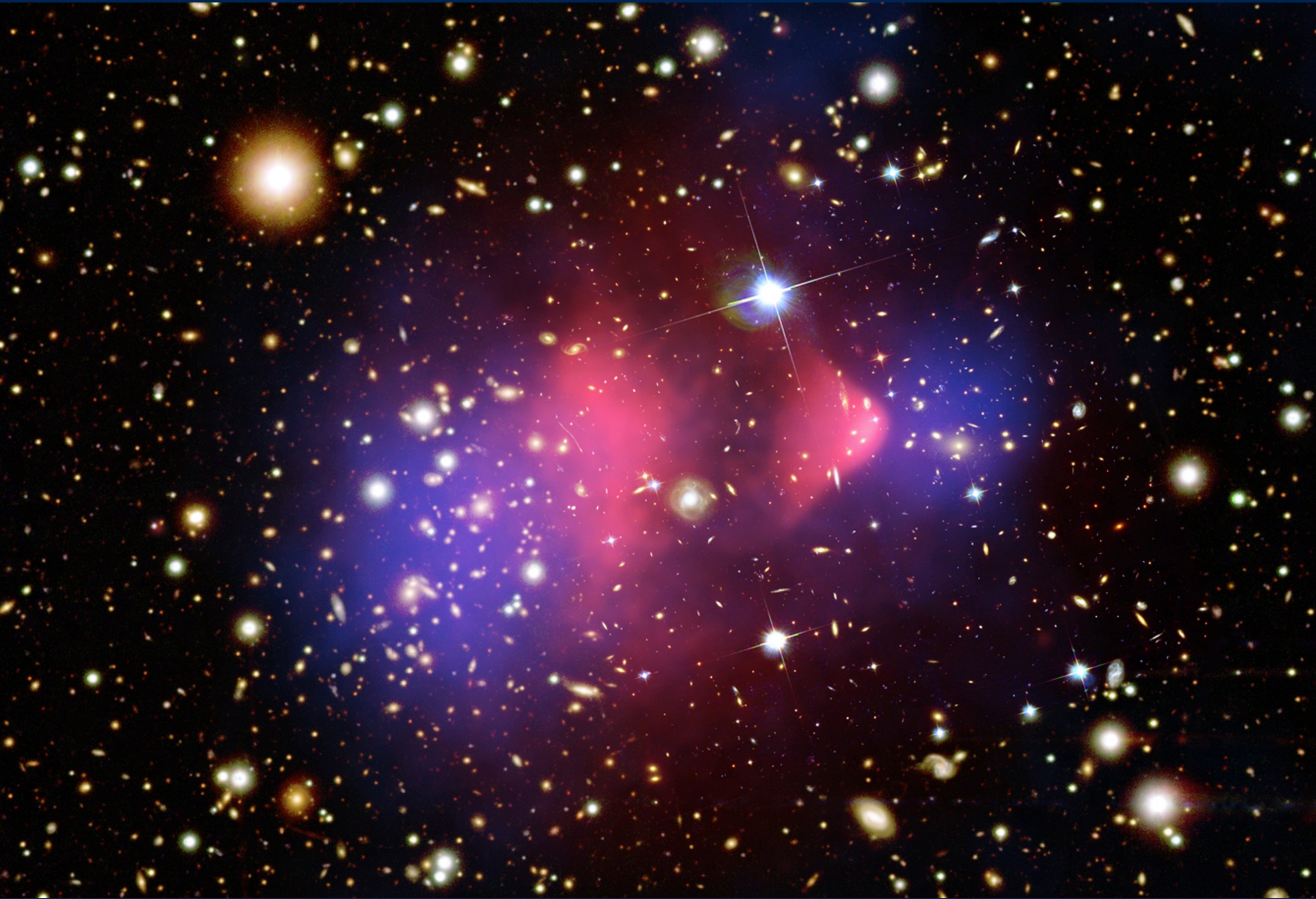
중력렌즈 효과



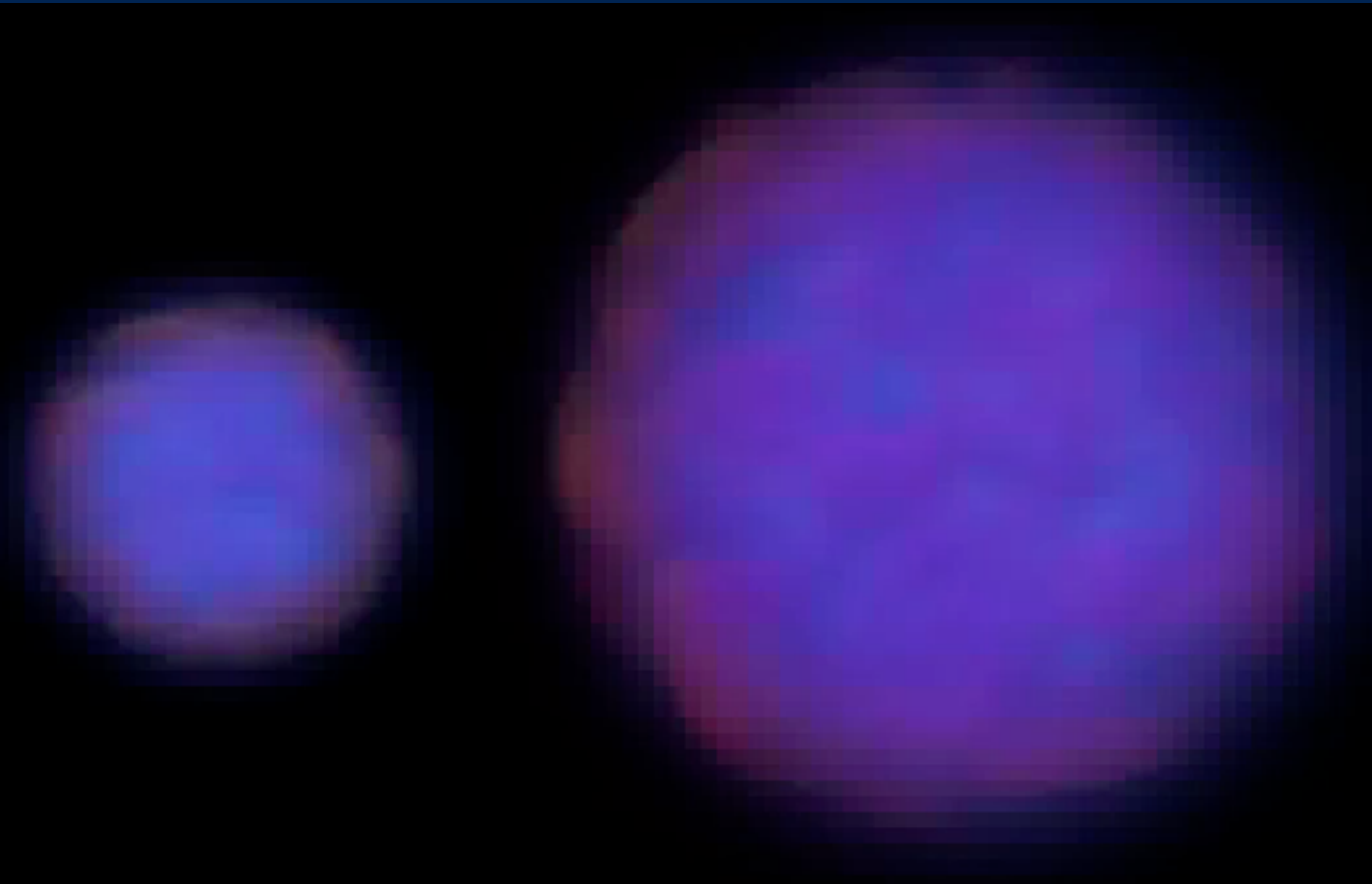
중력렌즈 효과



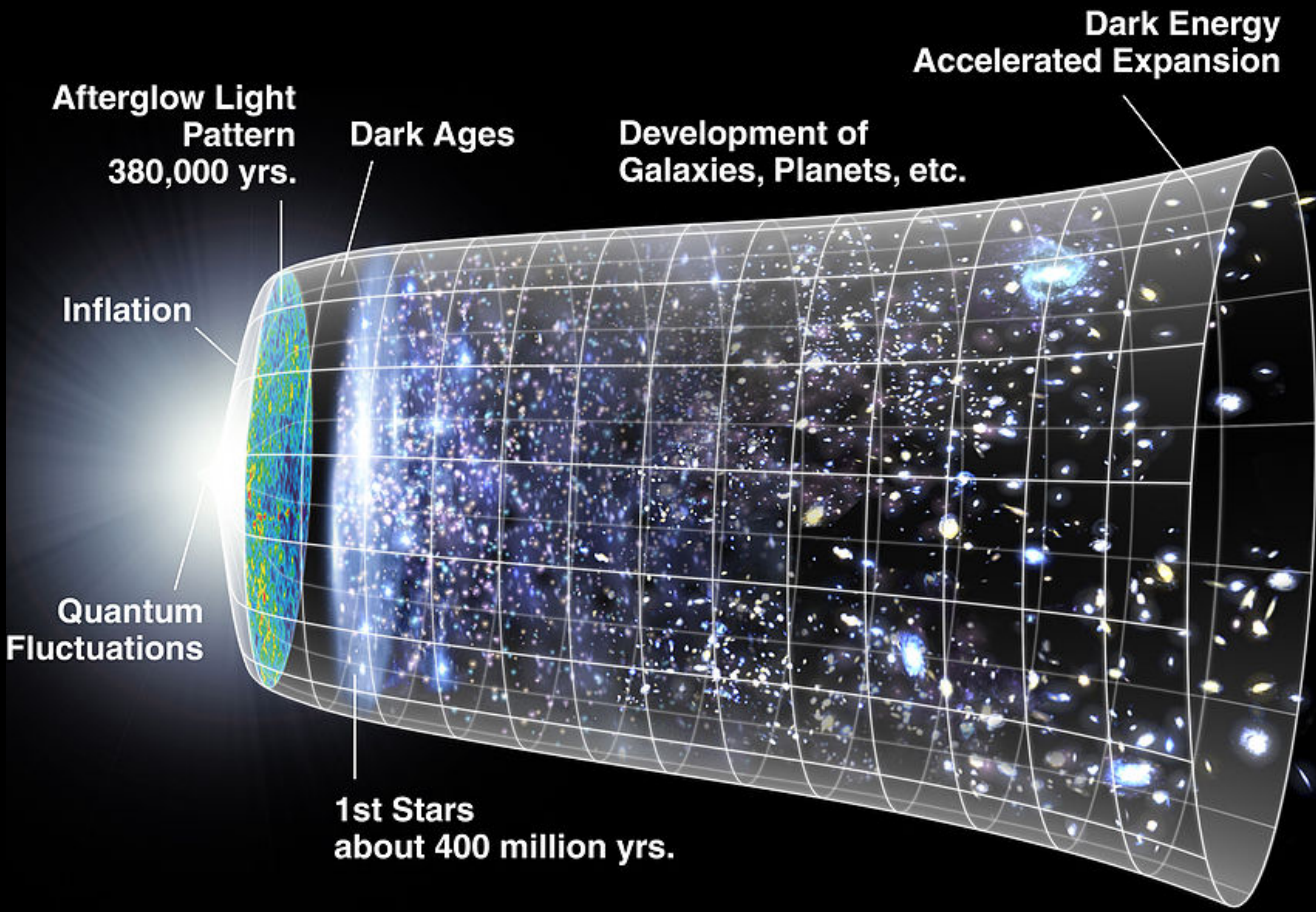
은하성단의 충돌



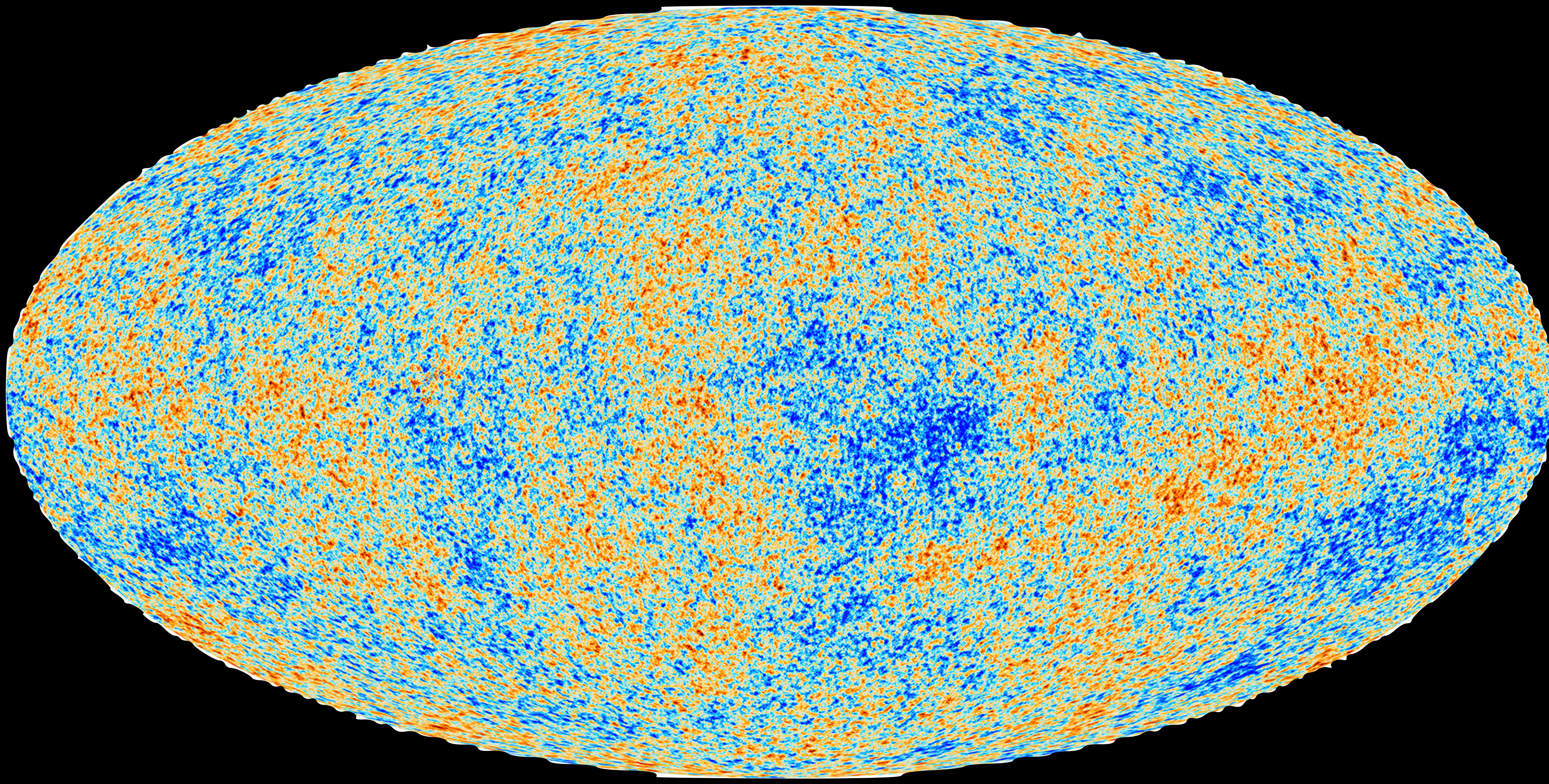
은하성단의 충돌


NASA/CXC/M.Weiss

우주 배경복사의 잔무늬들

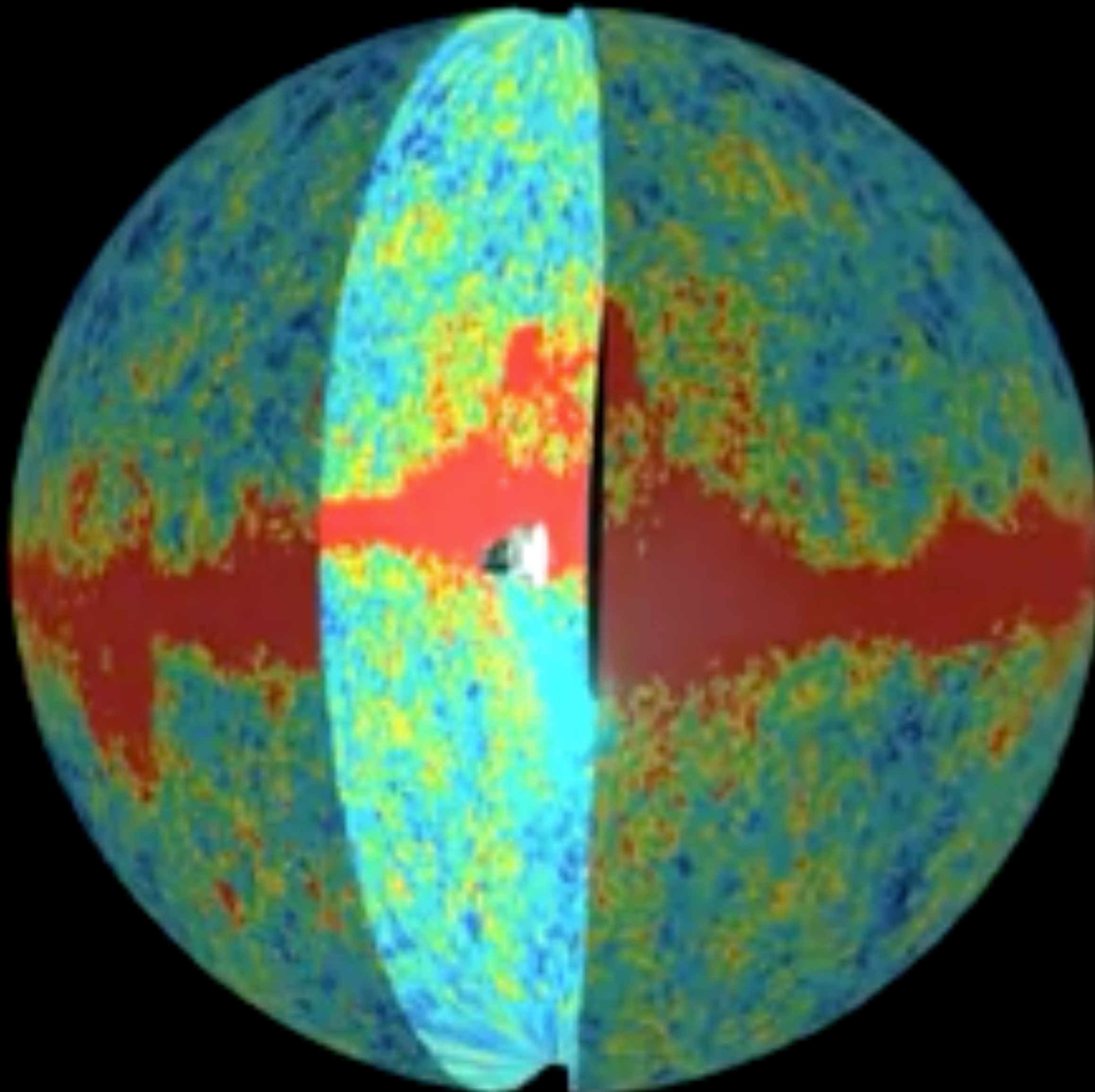


우주의 온도를 정확하게 측정한 지도

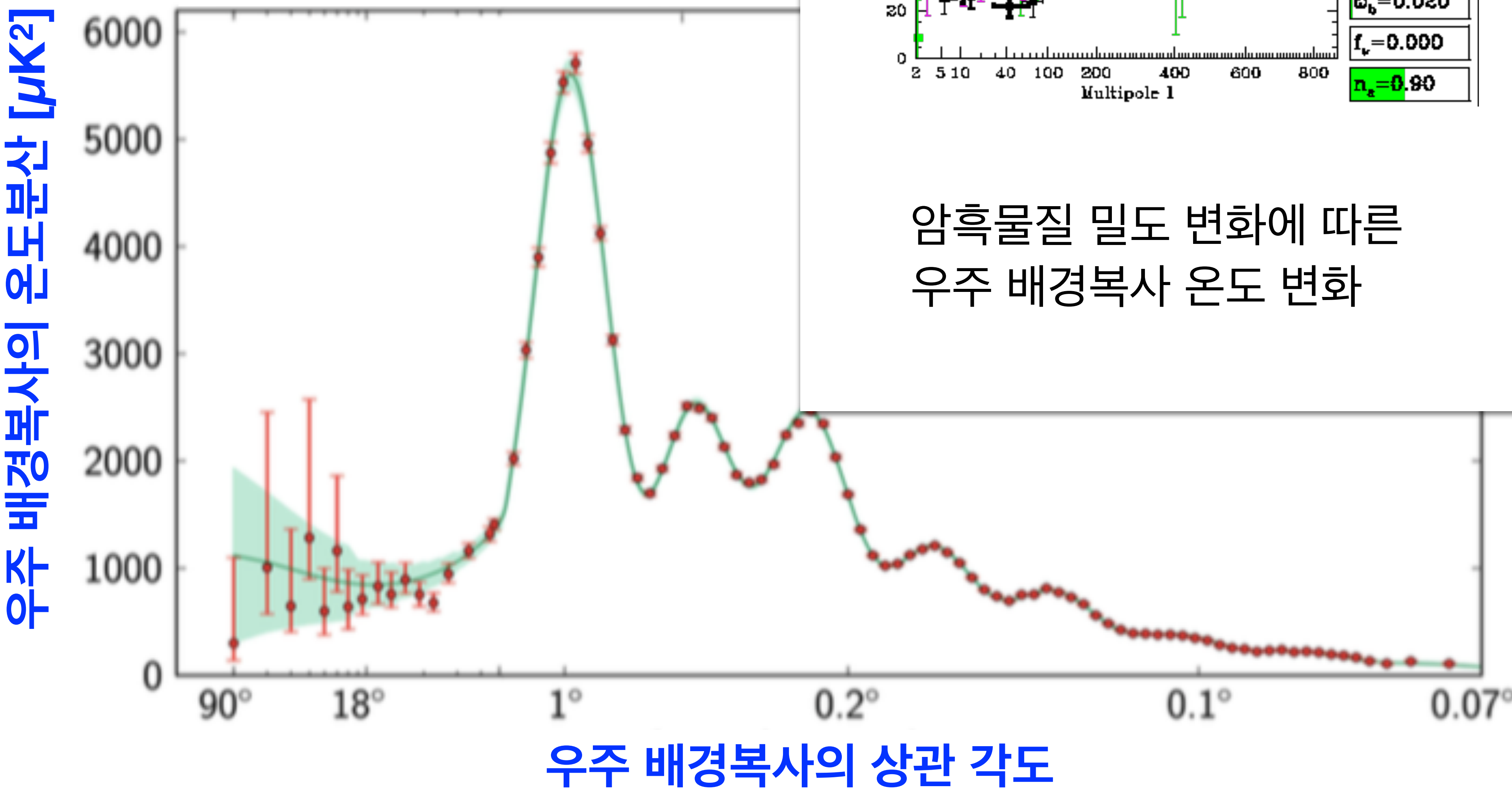


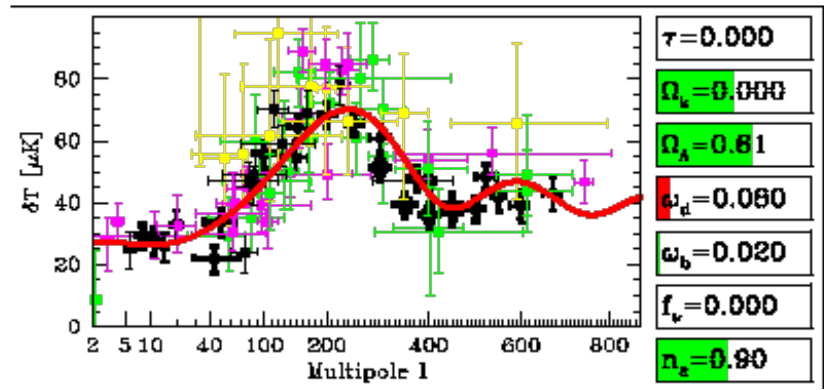
대폭발 약 4십만년 후에 만들어짐

플랑크 과학위성 (유럽 우주국)



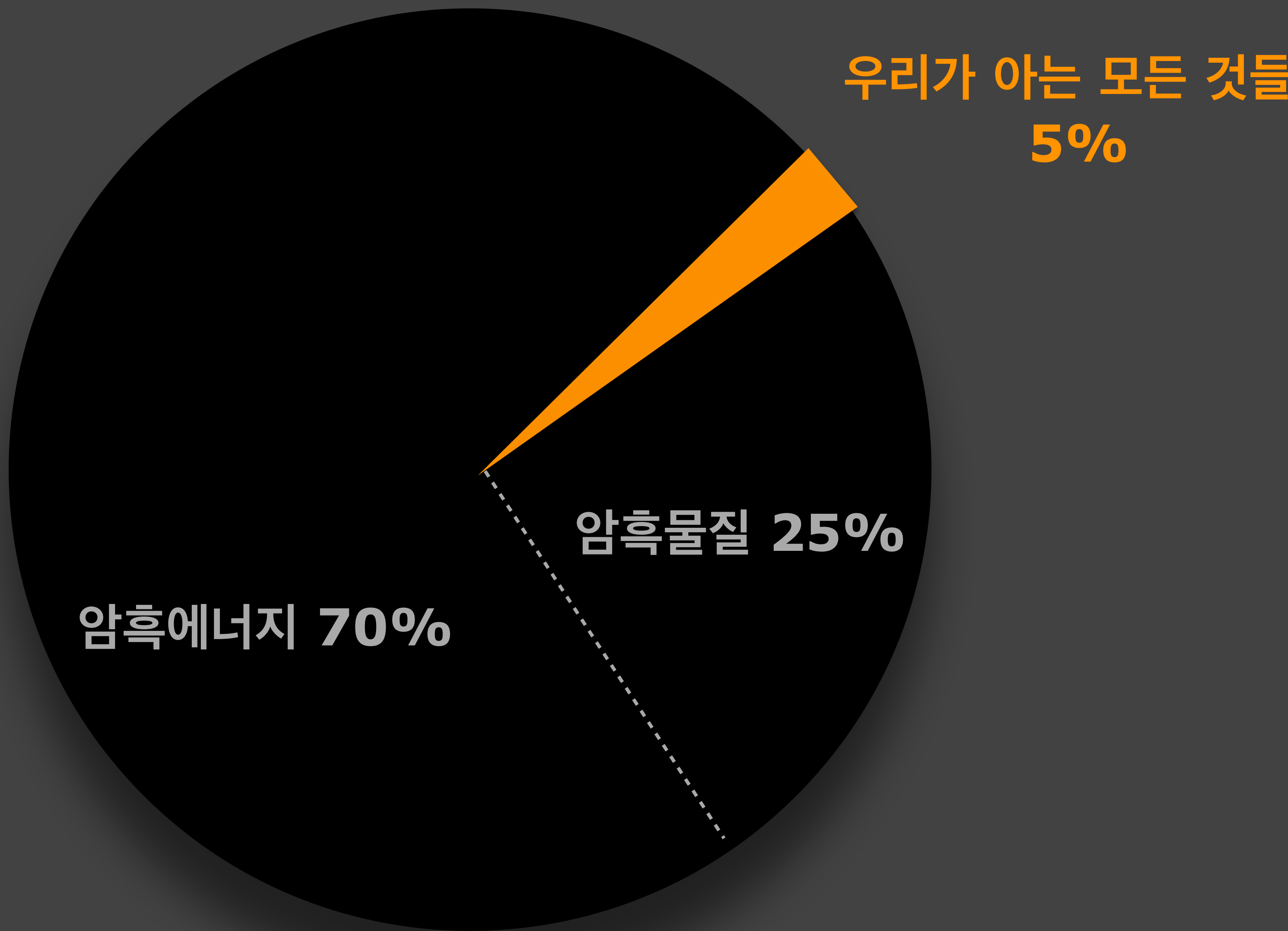
Planck satellite located at L_2 Point (1,500,000km)





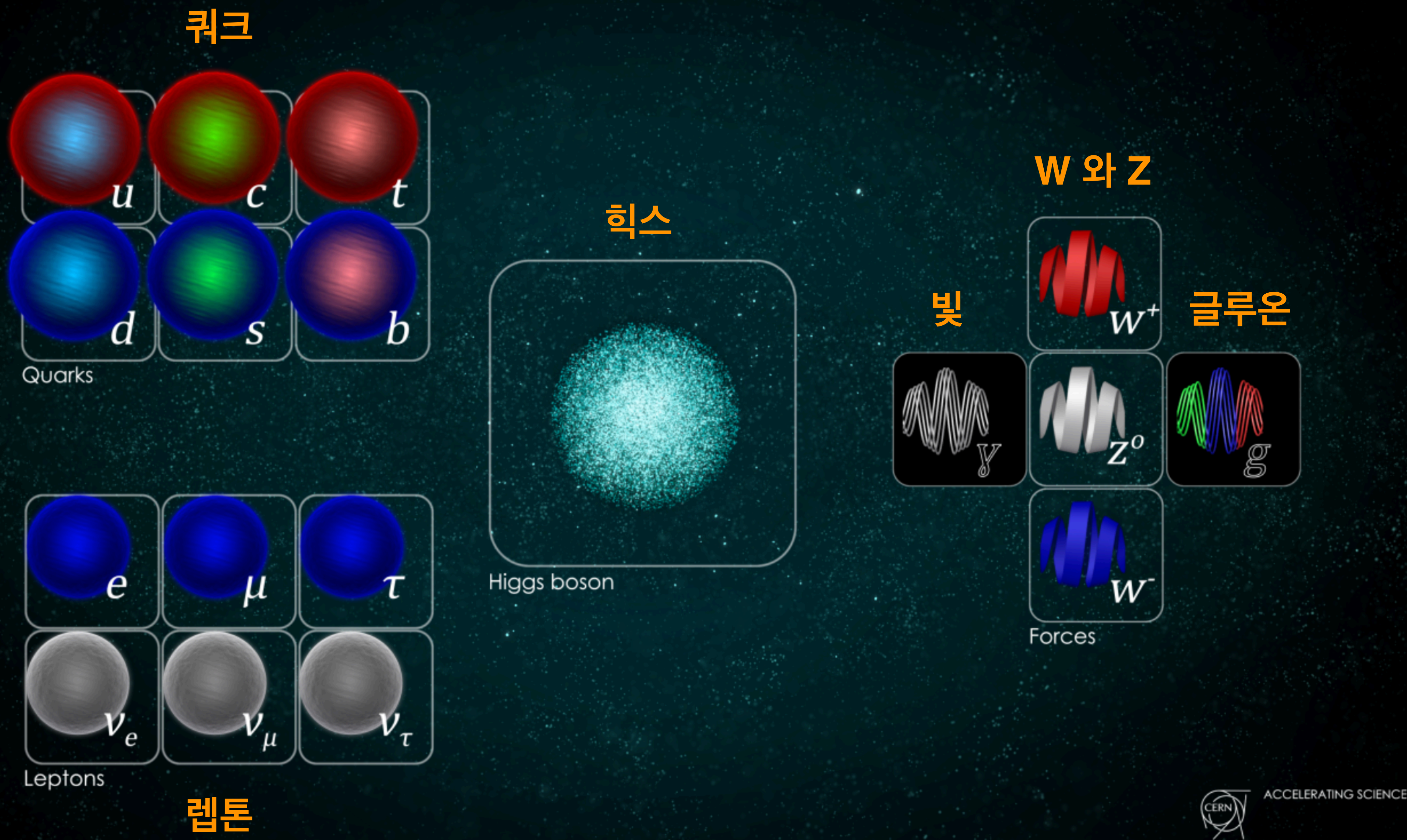
암흑물질 밀도 변화에 따른
우주 배경복사 온도 변화

https://lambda.gsfc.nasa.gov/product/map/dr4/pub_papers/sevenyear/basic_results/wmap_7yr_basic_results_reprint.pdf



우주의 95% 무엇인지 전혀 모름

물질을 구성하는 입자들


쿼크
u
c
t
d
s
b
Quarks
e
μ
τ
ν_e
ν_μ
ν_τ
Leptons
렙톤
힉스
Higgs boson
W 와 Z
빛
글루온
W+
γ
Z0
g
W-
Forces
CERN
ACCELERATING SCIENCE

암흑우주

95%