우주가속팽창과 암흑에너지

2011년 노벨물리학상 해설강연

이화여자대학교 물리학과
안 창림

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

The Nobel Prize in Physics 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Observational Evidence from Supernovae for an Accelerating Univ Cosmological Constant

To Appear in the Astronomical Journal

Adam G. Riess[1], Alexei V. Filippenko[1], Peter Challis[2], Alejandro Clocchiatti[3], Alan D Garnavich[2], Ron L. Gilliland[5], Craig J. Hogan[4], Saurabh Jha[2], Robert P. Kirshner[2], B. L M. Phillips[7], David Reiss[4], Brian P. Schmidt[8 9], Robert A. Schommer[7], R. Chris Smith[7 10] Christopher Stubbs[4], Nicholas B. Suntzeff[7], John Tonry[11]

ABSTRACT

We present spectral and photometric observations of 10 type Ia supernovae (SNe redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are deterr methods that employ relations between SN Ia luminosity and light curve shape. Com previous data from our High-Z Supernova Search Team (Garnavich et al. 1998; Schr 1998) and Riess et al. (1998a), this expanded set of 16 high-redshift supernovae anc 34 nearby supernovae are used to place constraints on the following cosmological pa the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., tl energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the Un The distances of the high-redshift SNe Ia are, on average, 10% to 15% farther than in a low mass density ($\Omega_M = 0.2$) Universe without a cosmological constant. Differ curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor e expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current ac of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at tl

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[9]Visiting astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observa the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with tl Foundation.

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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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Accepted for publication in The Astrophysical Journal *LBNL-41801*

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 Type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fit jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia lightcurve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximately by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is non-zero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is $t_0^{\rm flat} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of statistical tests to check for possible systematic errors and biases. We find no significant differences in either the host reddening distribution or Malmquist bias between the low-redshift Calán/Tololo sample and our high-redshift sample. Excluding those few supernovae which are outliers in color excess or fit residual does not significantly change the results. The conclusions are also robust whether or not a width-luminosity relation is used to standardize the supernova peak magnitudes. We discuss, and constrain where possible, hypothetical alternatives to a cosmological constant.

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[8]Space Sciences Laboratory, U.C. Berkeley, California.
[9]Space Sciences Department, European Space Agency.

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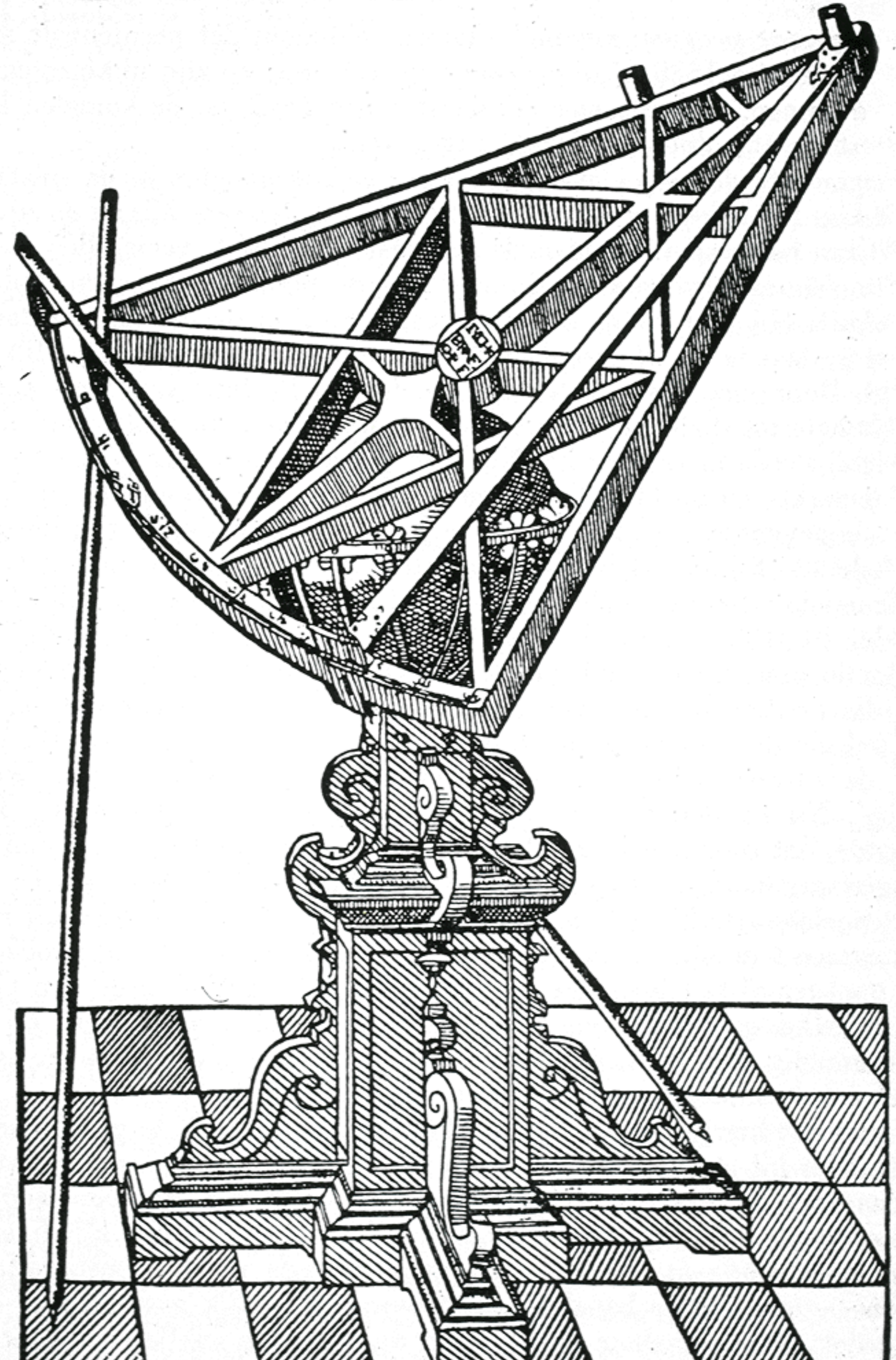
(THE SUPERNOVA COSMOLOGY PROJECT)

우주관측의 역사


EFFIGIES TYCHONIS BRAHE O.F.
ÆDIFICII ET INSTRUMENTORUM
ASTRONOMICORUM STRUCTORIS.
A° DOMINI 1587. ÆTATIS SUÆ 40.



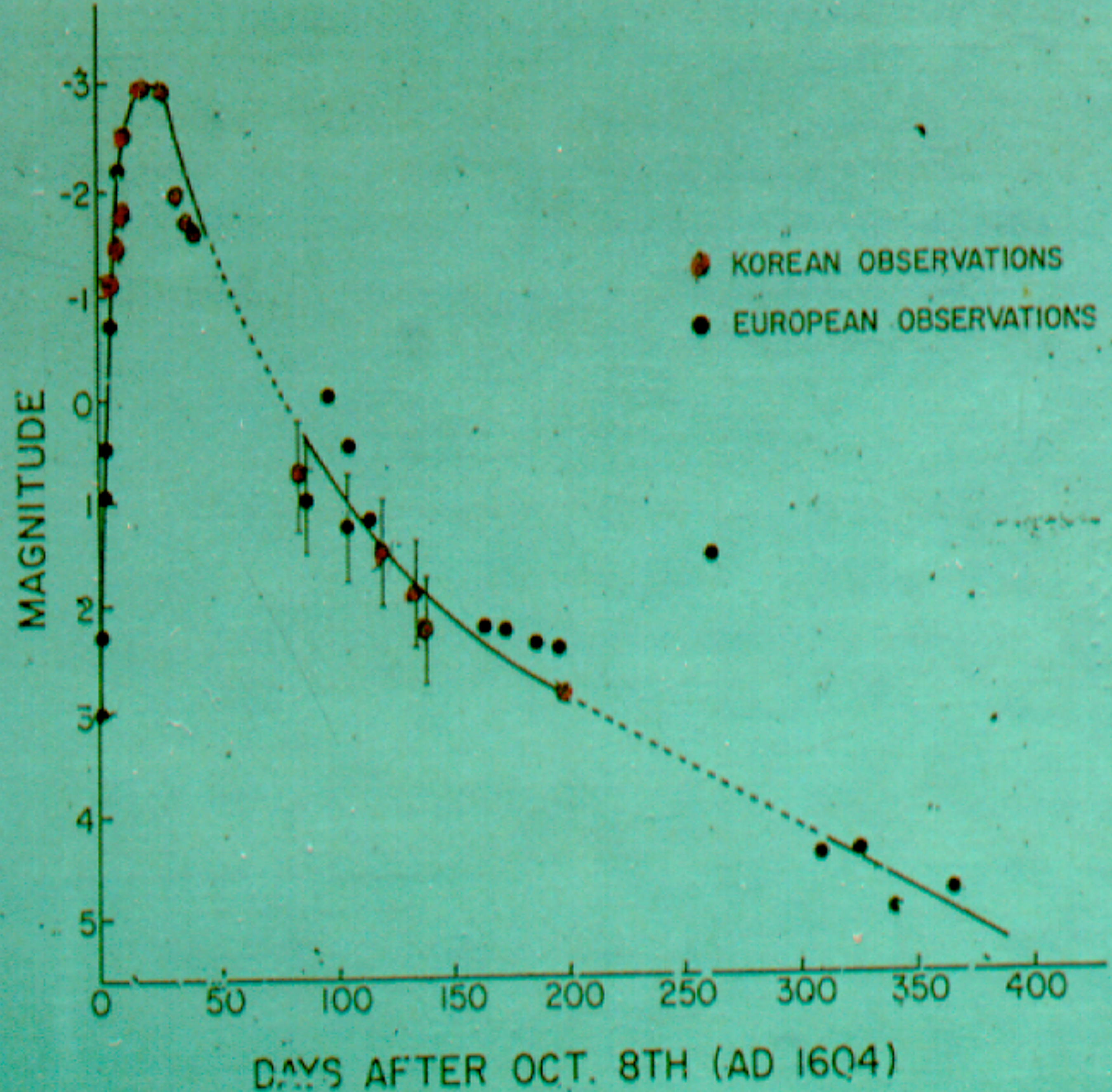
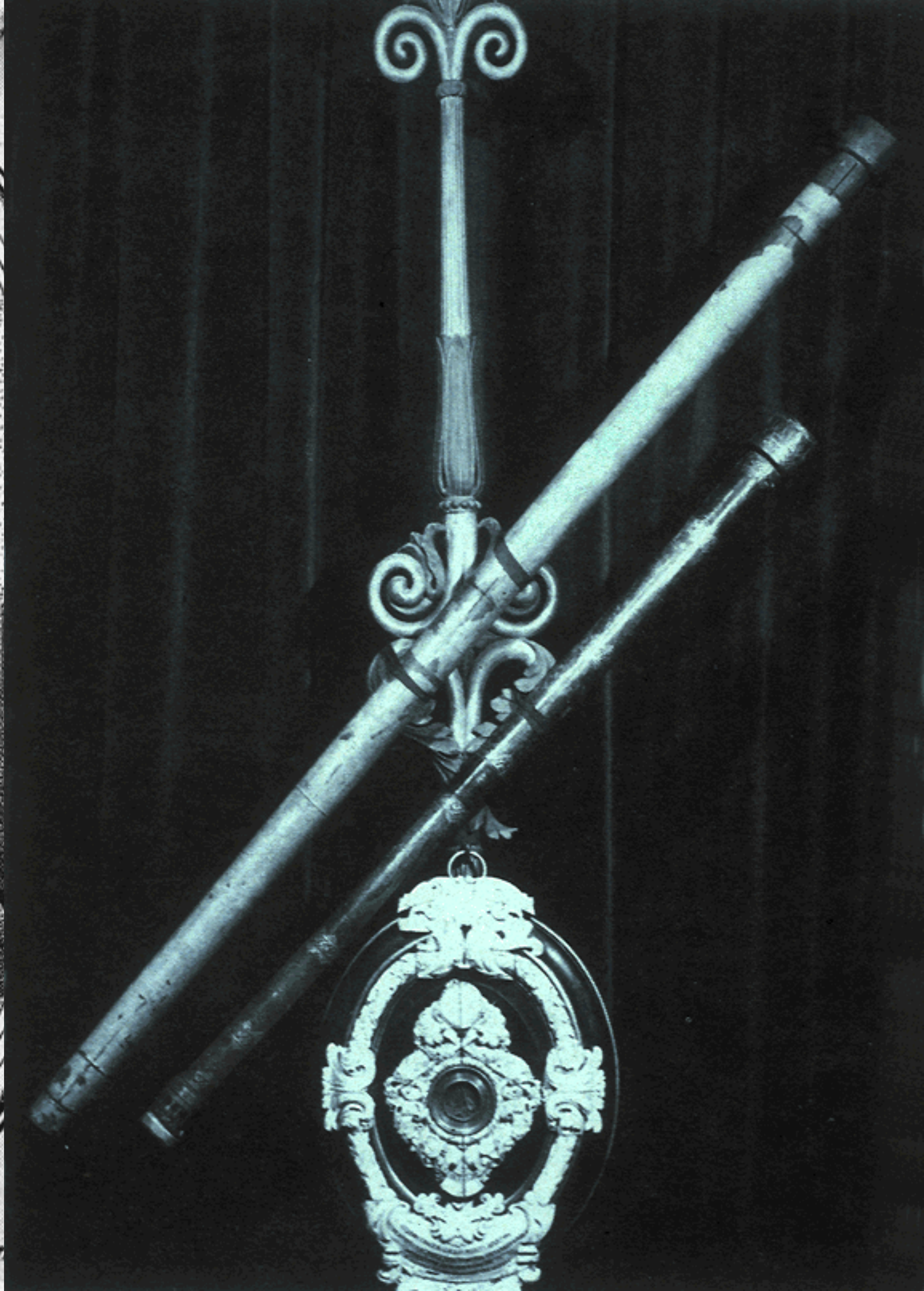
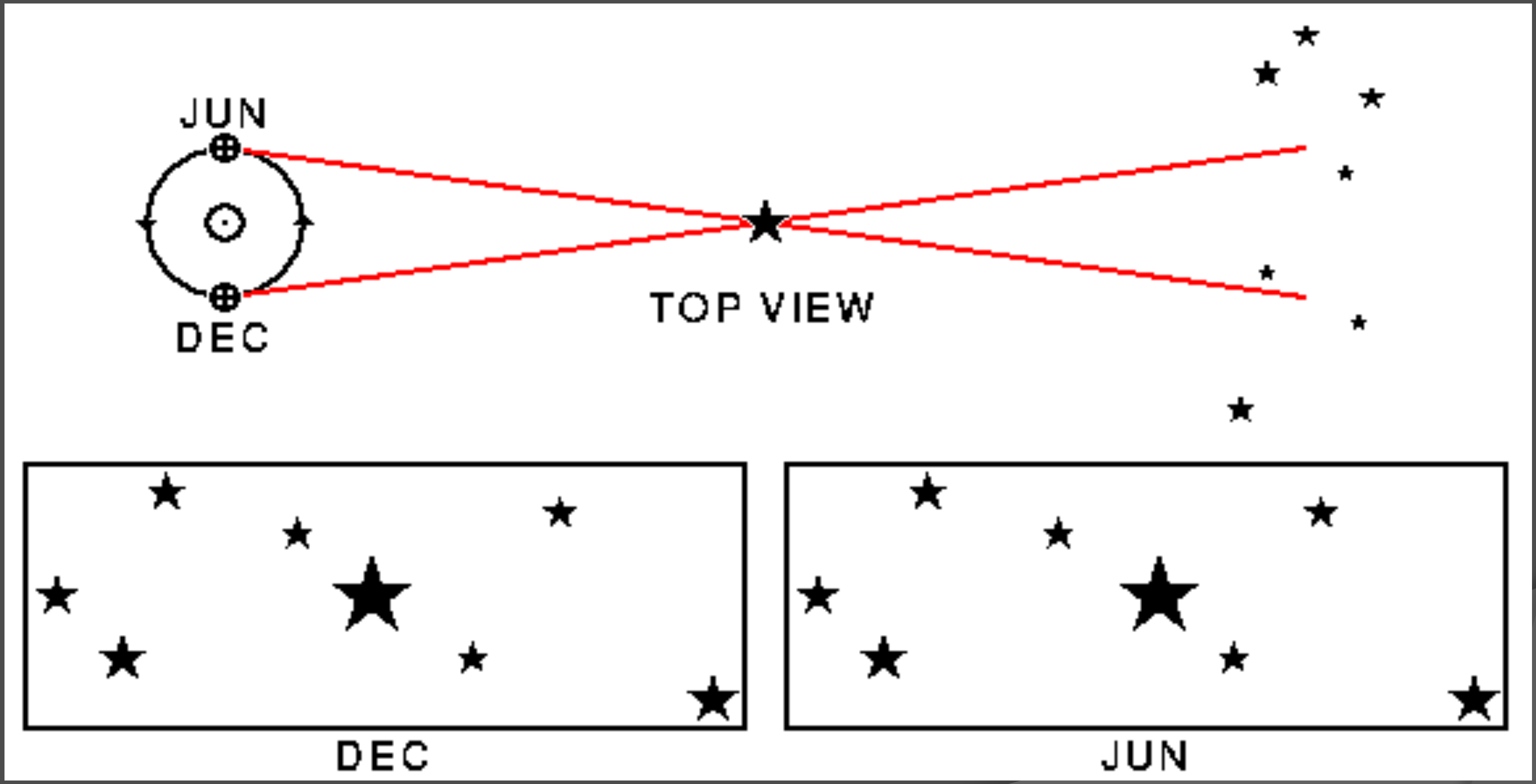

KOREAN OBSERVATIONS
EUROPEAN OBSERVATIONS
MAGNITUDE
-3
-2
-1
0
1
2
3
4
5
0
50
100
150
200
250
300
350
400
DAYS AFTER OCT. 8TH (AD 1604)

그림 3


Galileus Galileus
Octauius Leonus


우주에서 거리를 재는 법

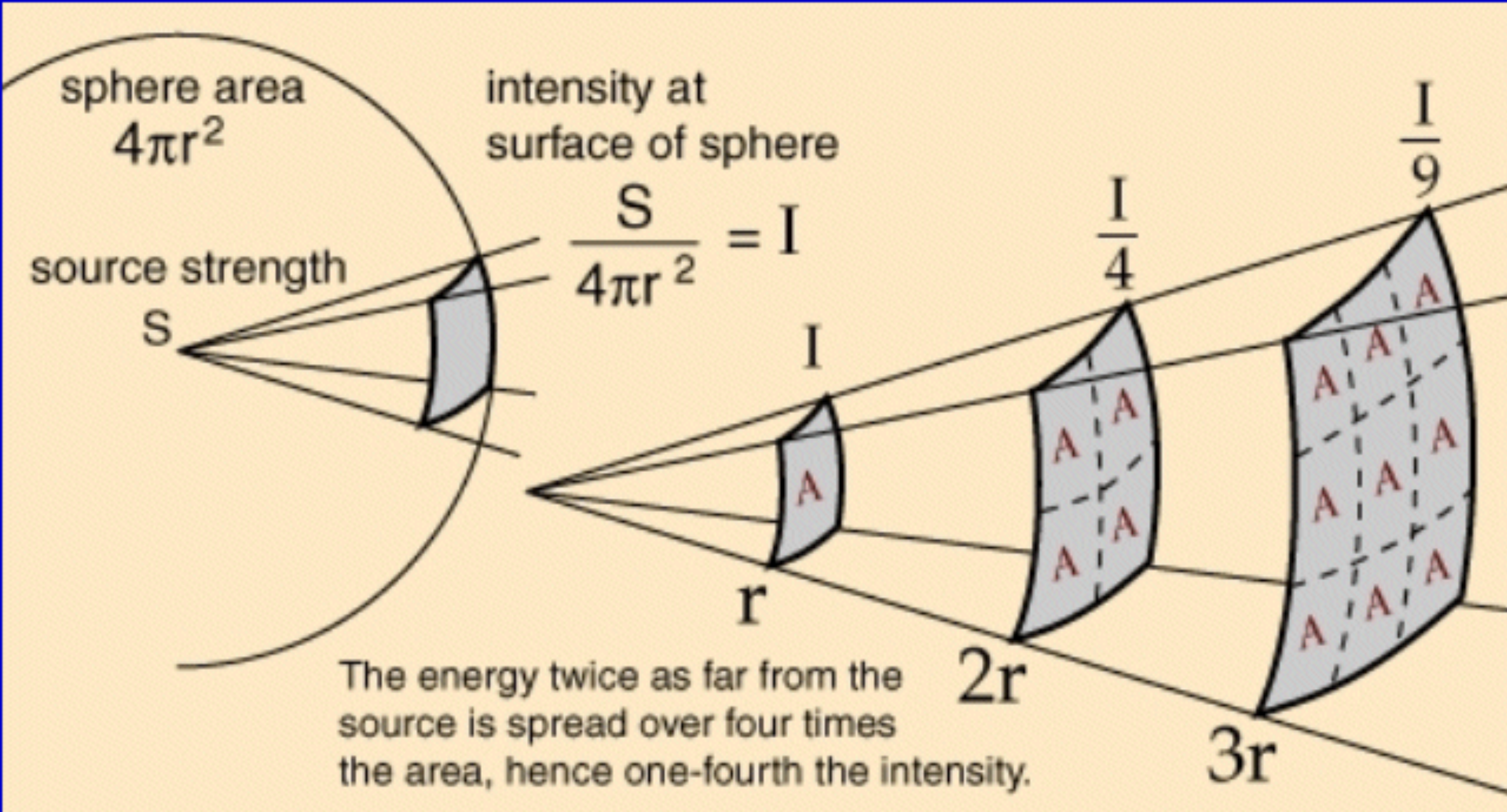
- Parallax (시차법)



절대광도와 상대광도

- 지구에서 보이는 밝기(상대광도)는 거리가 멀수록 거리의 제곱에 반비례하여 희미해짐

- 절대광도/상대광도=거리의 제곱


sphere area
$4\pi r^2$
intensity at
surface of sphere
$\frac{S}{4\pi r^2} = I$
source strength
S
I
$\frac{I}{4}$
$\frac{I}{9}$
A
r
2r
3r
The energy twice as far from the
source is spread over four times
the area, hence one-fourth the intensity.

두 가지 문제점

- 객관적인 밝기의 비교
- 절대광도의 측정

기술의 발전: 사진

- **1839년 발명됨**
- **천문학 발전에 큰 영향**
  - **객관적인 밝기를 기록**
  - **장시간 노출을 통해 아주 희미한 별들도 관측**
  - **관측과 분석의 분리로 자세한 연구가 가능**

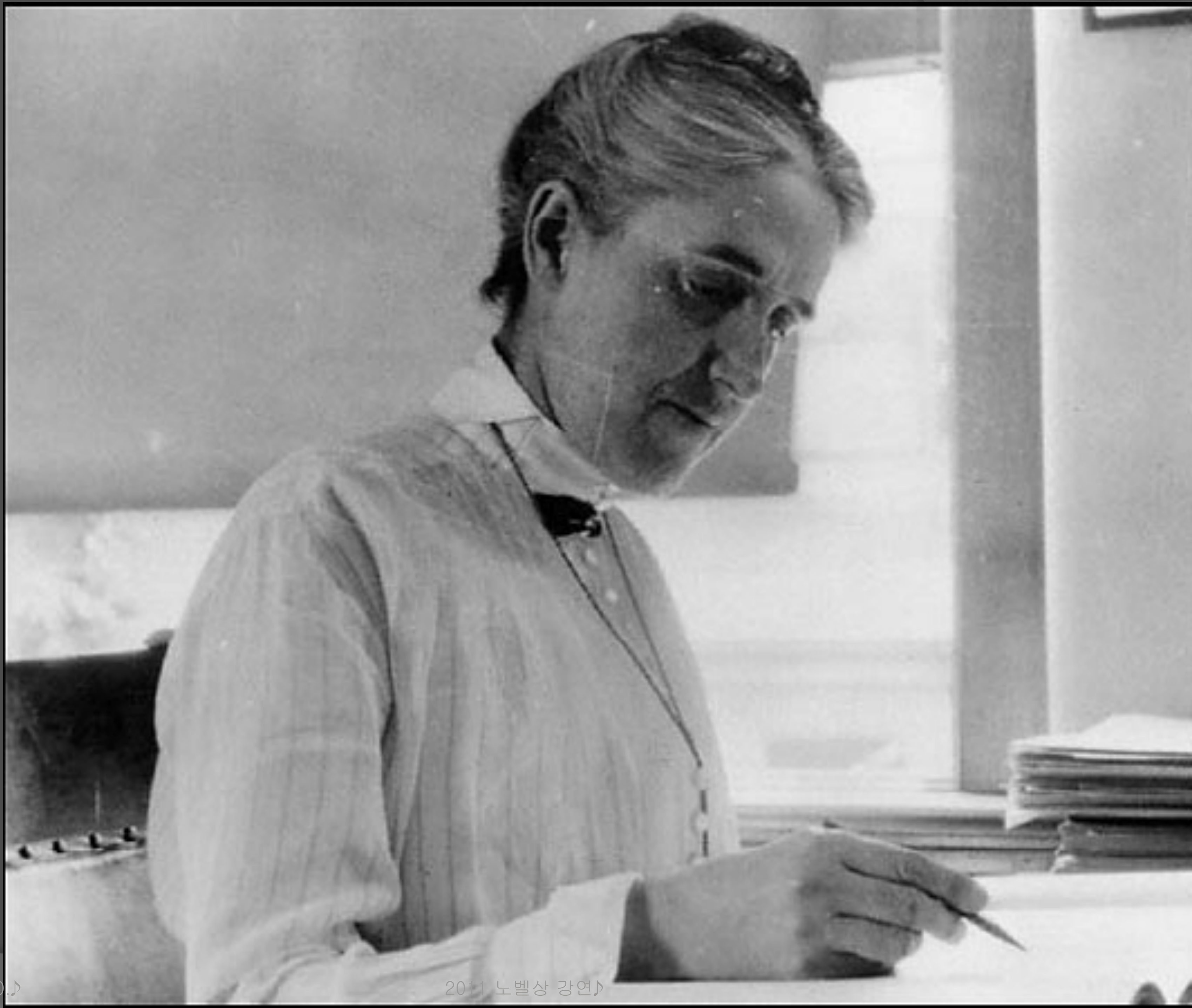
Louis Daguerre♪

사진발명가♪

절대광도의 발견 (Standard candle)

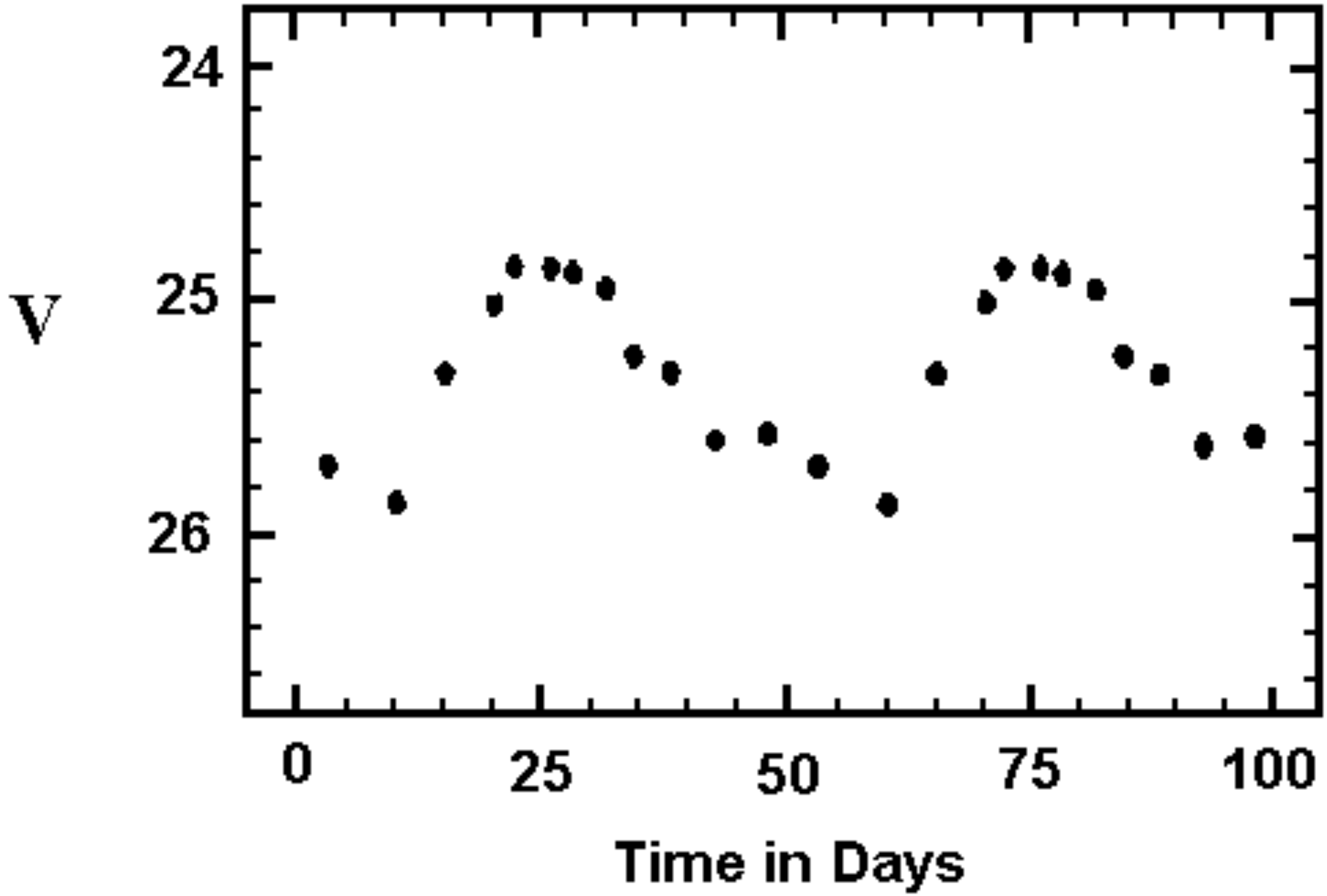
사진 판독 ‘computer’

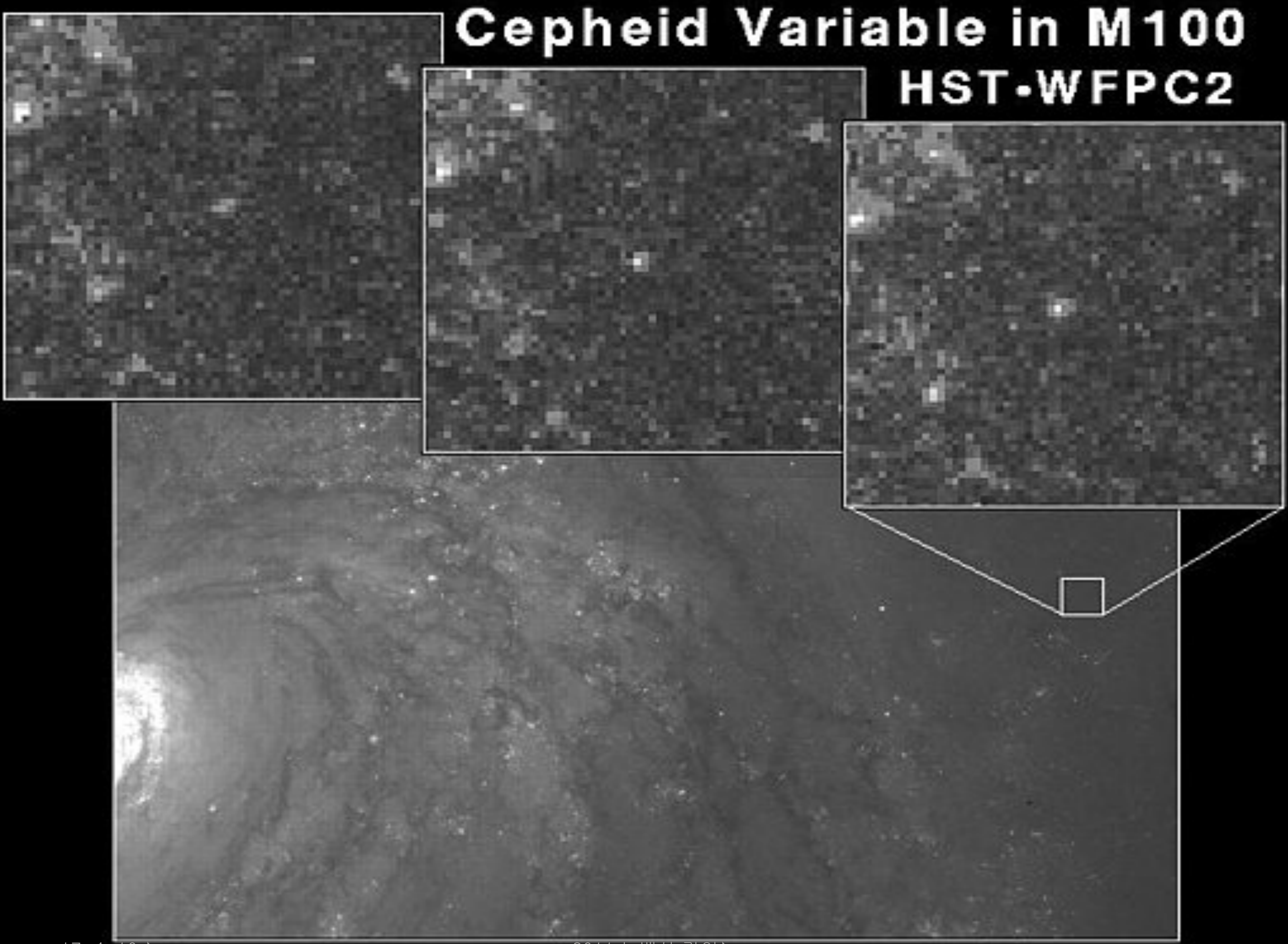
- **희미한 사진들로부터 중요한 천체정보를 읽어내기 위해서는 섬세한 주의력이 필요해져서 여성들의 참여가 시작됨**
- **하바드(Harvard)대학 천문대에서 고용한 많은 여성 ‘computer’들**

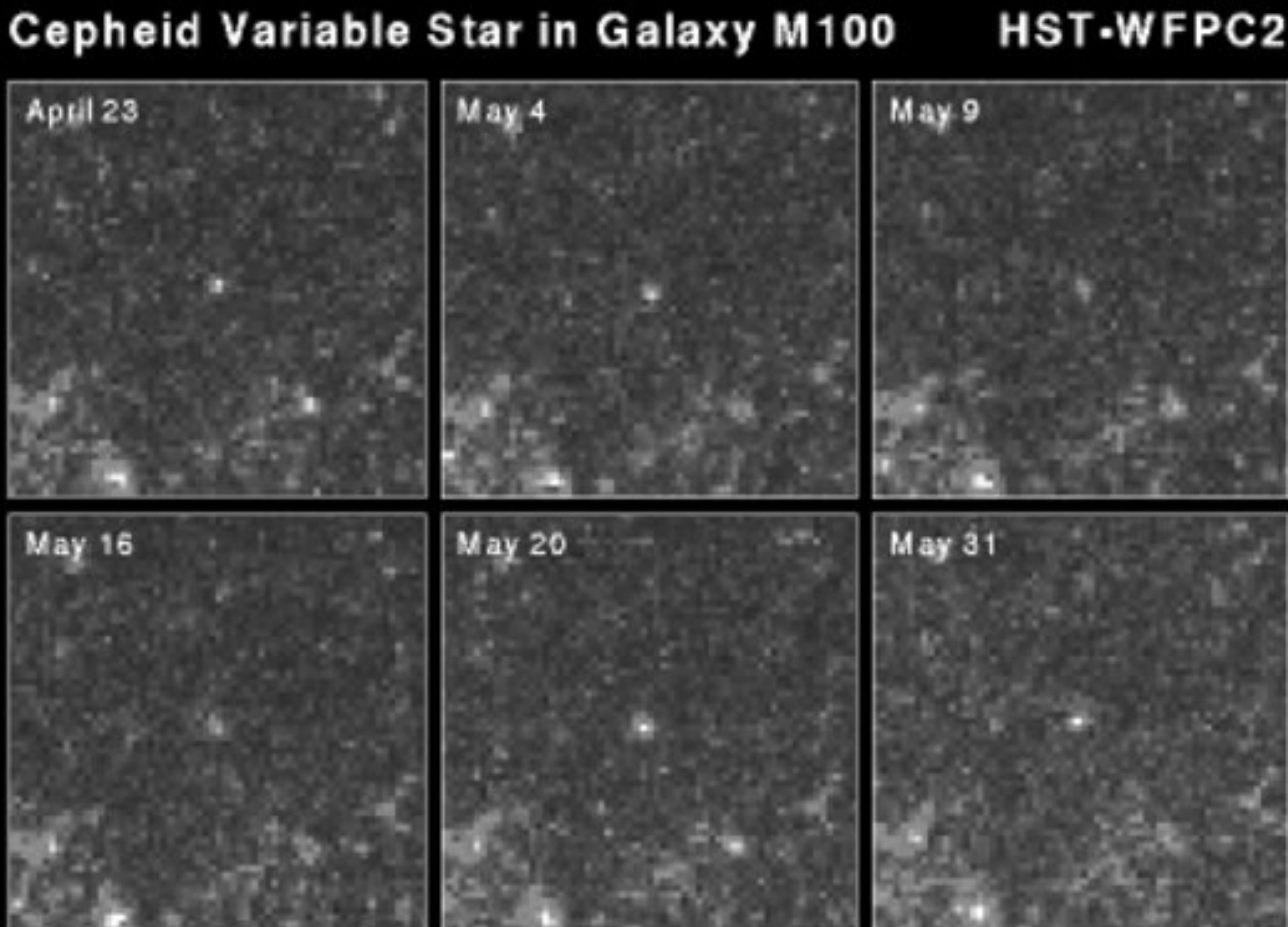


H. Leavitt의 발견

- 小 마젤란 성운의 세페이드변광성
- 지구에서 거의 같은 거리에 있음
- 변광성의 실제 밝기를 비교가능

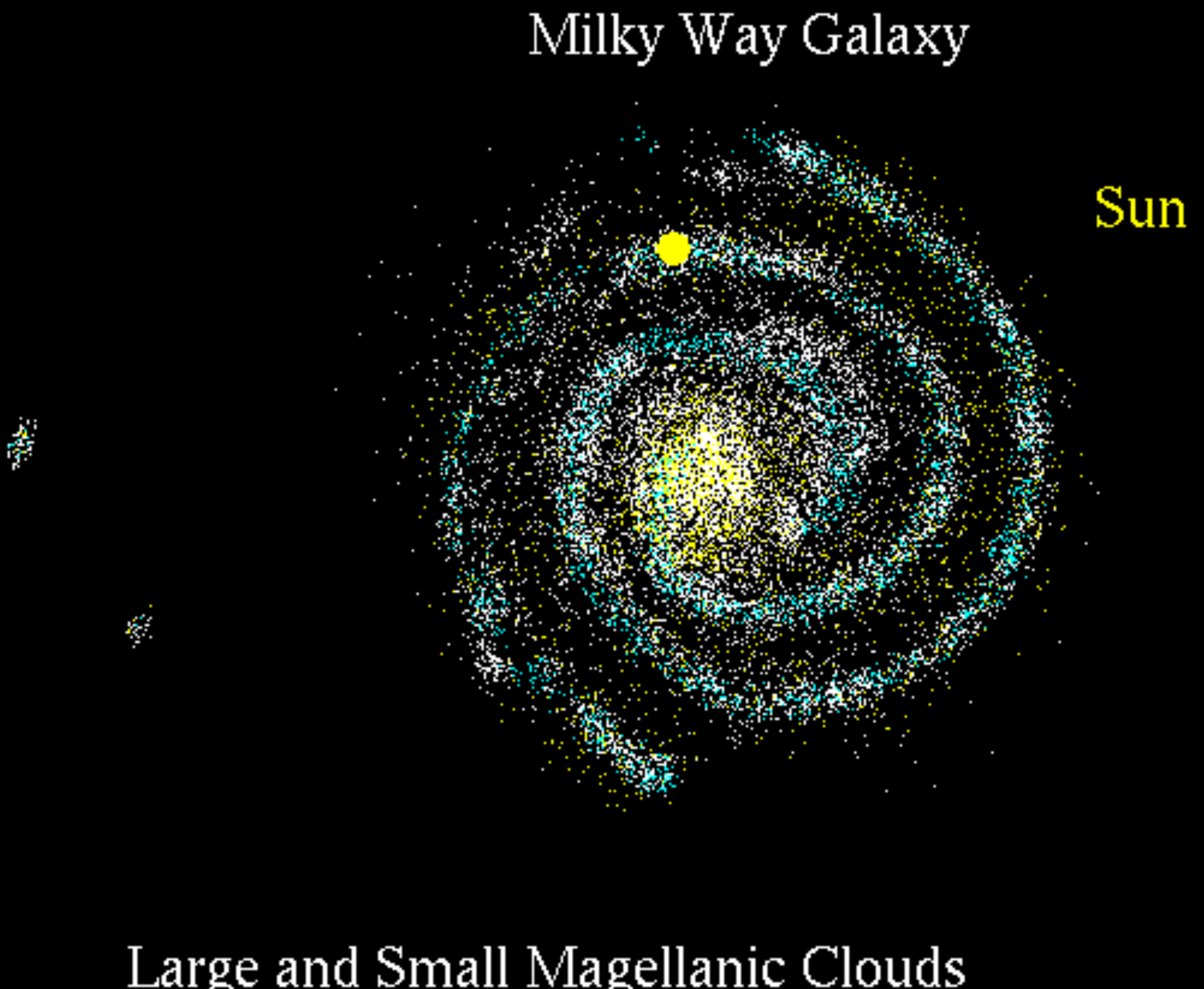

V
24
25
26
0
25
50
75
100
Time in Days

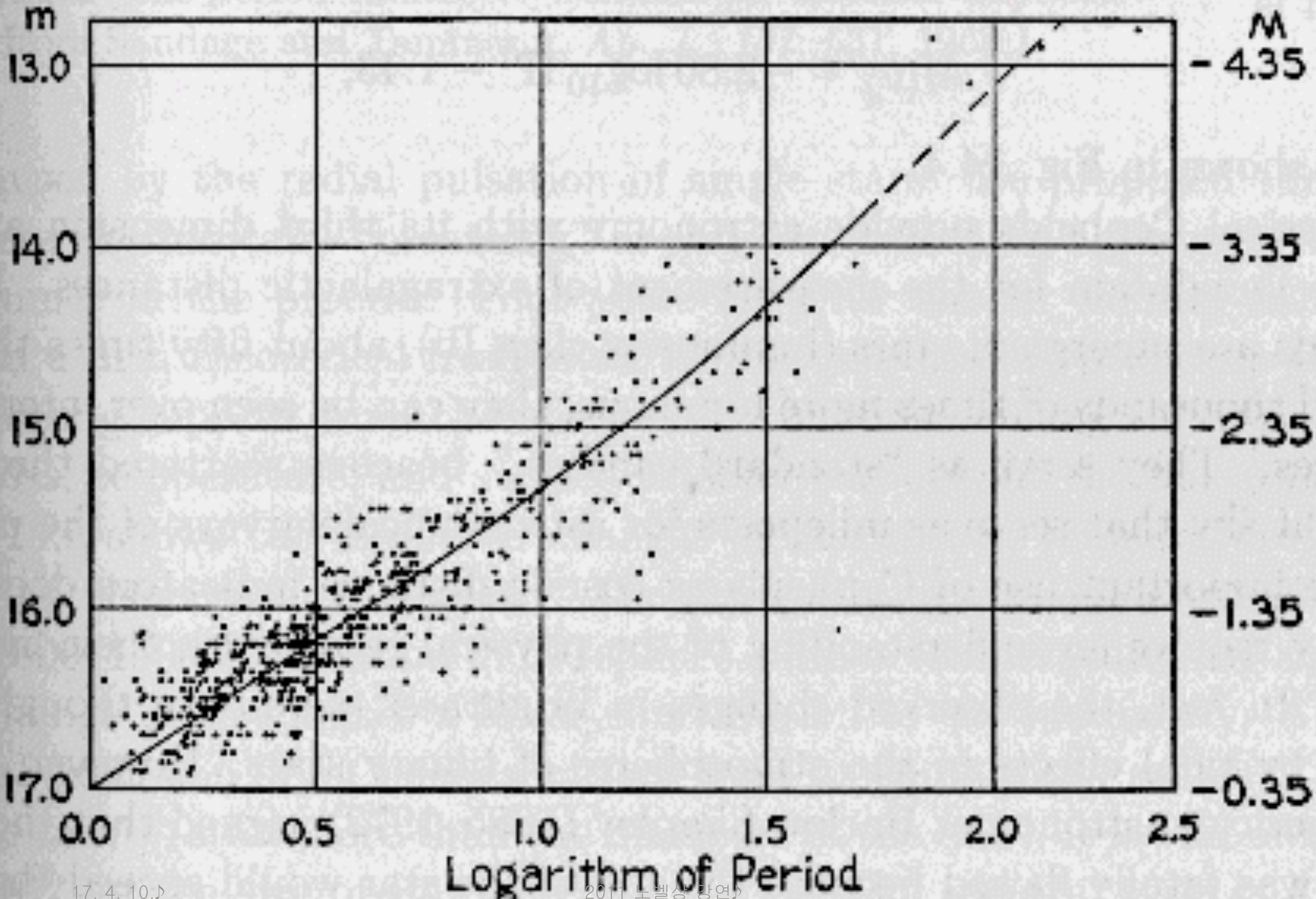

Cepheid Variable in M100
HST•WFPC2


Cepheid Variable Star in Galaxy M100
HST-WFPC2
April 23
May 4
May 9
May 16
May 20
May 31

Magellanic Clouds (남반구)♪

Akira Fujii/David Malin Images

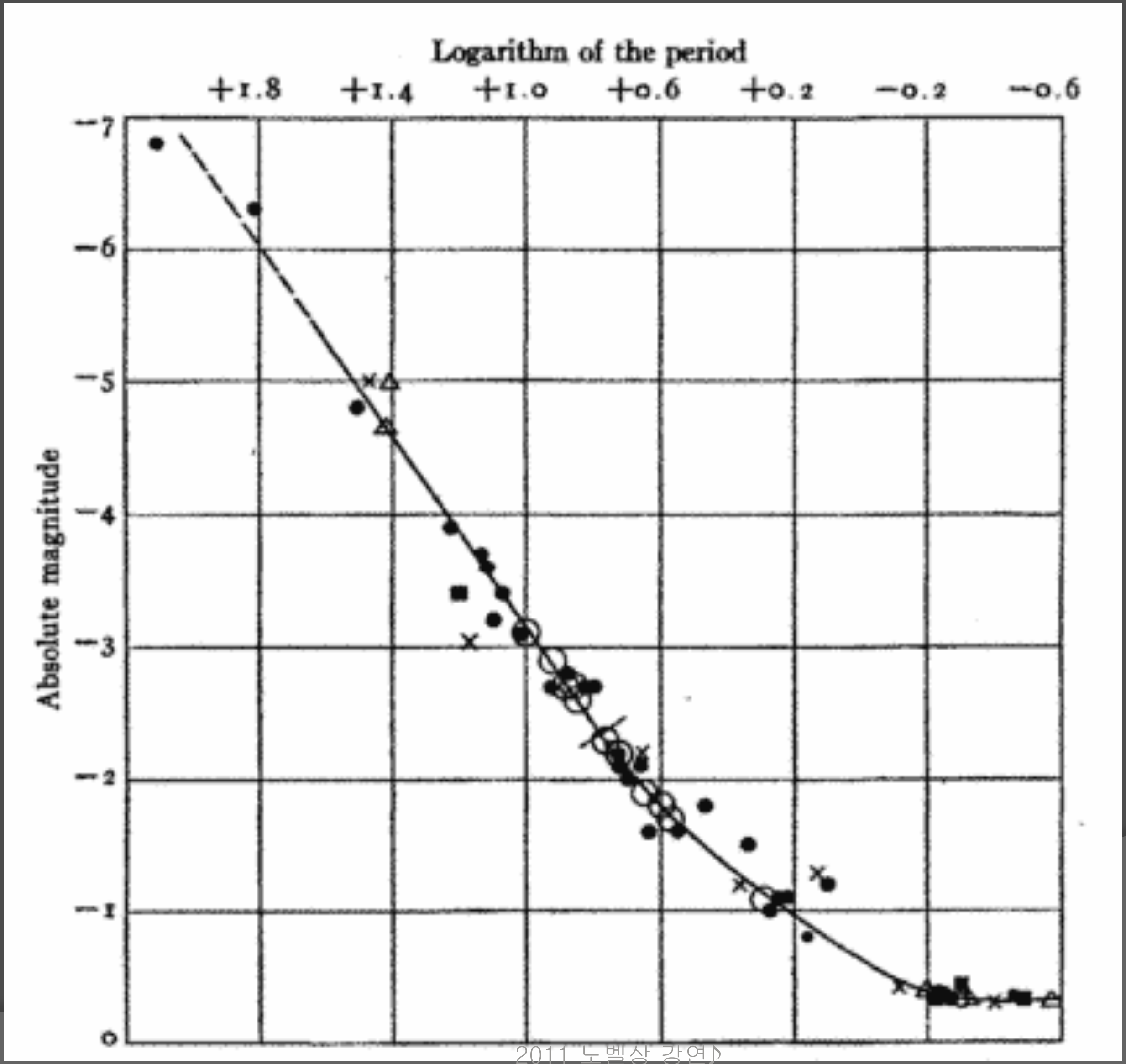

Milky Way Galaxy
Sun
Large and Small Magellanic Clouds


m
13.0
14.0
15.0
16.0
17.0
M
-4.35
-3.35
-2.35
-1.35
-0.35
0.0
0.5
1.0
1.5
2.0
2.5
Logarithm of Period

절대광도 vs. 주기

- 주기와 실제 밝기 (절대광도)의 관계를 입증
- 노벨상을 주려고 했으나 아깝게 이미 사망한 후였음. 달의 분화구, 소행성 등을 그녀의 이름을 따 명명함

절대광도와 주기의 관계



Logarithm of the period
+1.8
+1.4
+1.0
+0.6
+0.2
−0.2
−0.6
Absolute magnitude
−7
−6
−5
−4
−3
−2
−1
0

현대 우주론

Edwin Hubble ♪
(1889–1953)♪

Oxford Rhodes scho
lar♪

Lawyer♪

Boxer♪

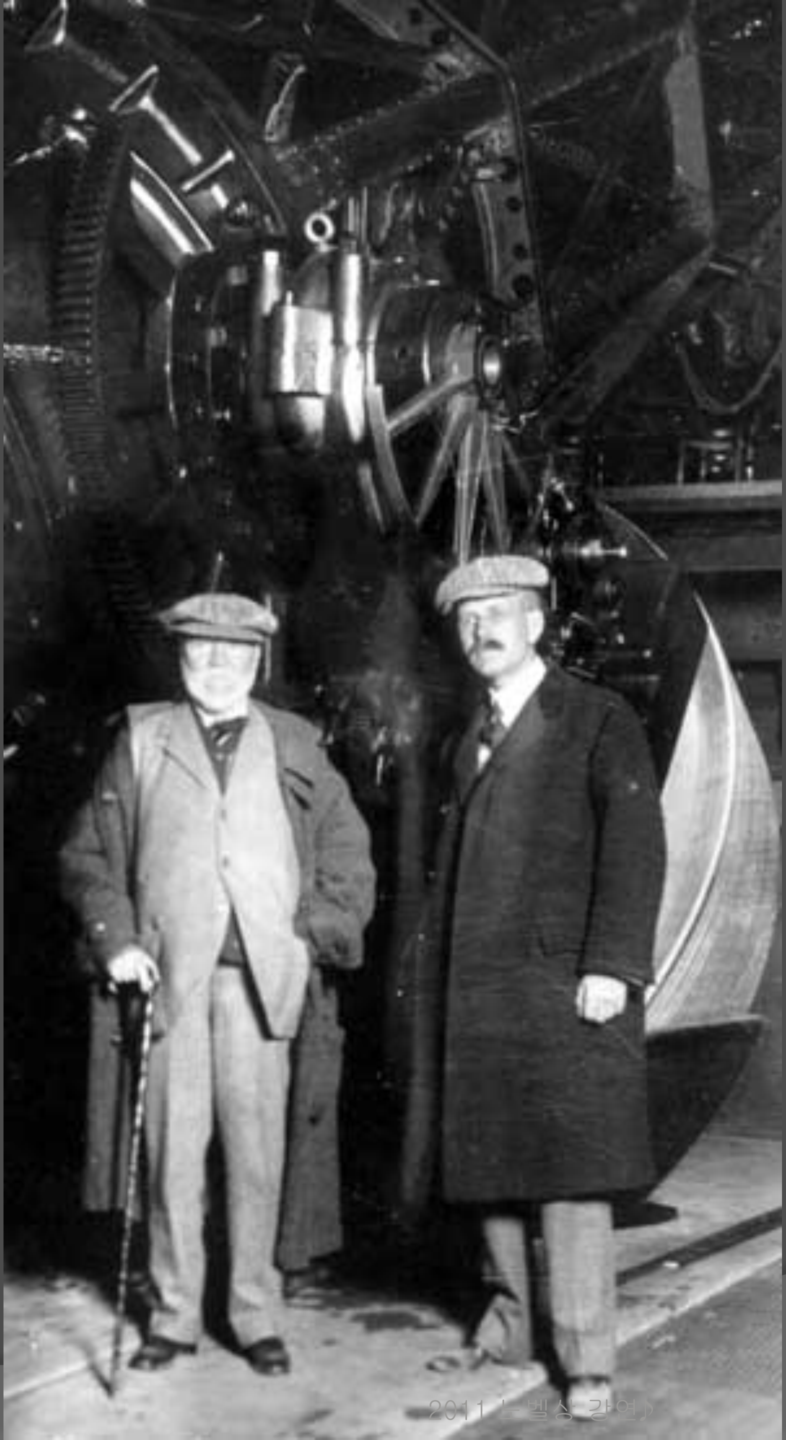
Basketball coach♪

Astronomer♪

"even if I were se
cond-rate or thir
d-rate, it was ast
ronomy that matt
ered." ♪

Edwin Hubble (1889-1953)

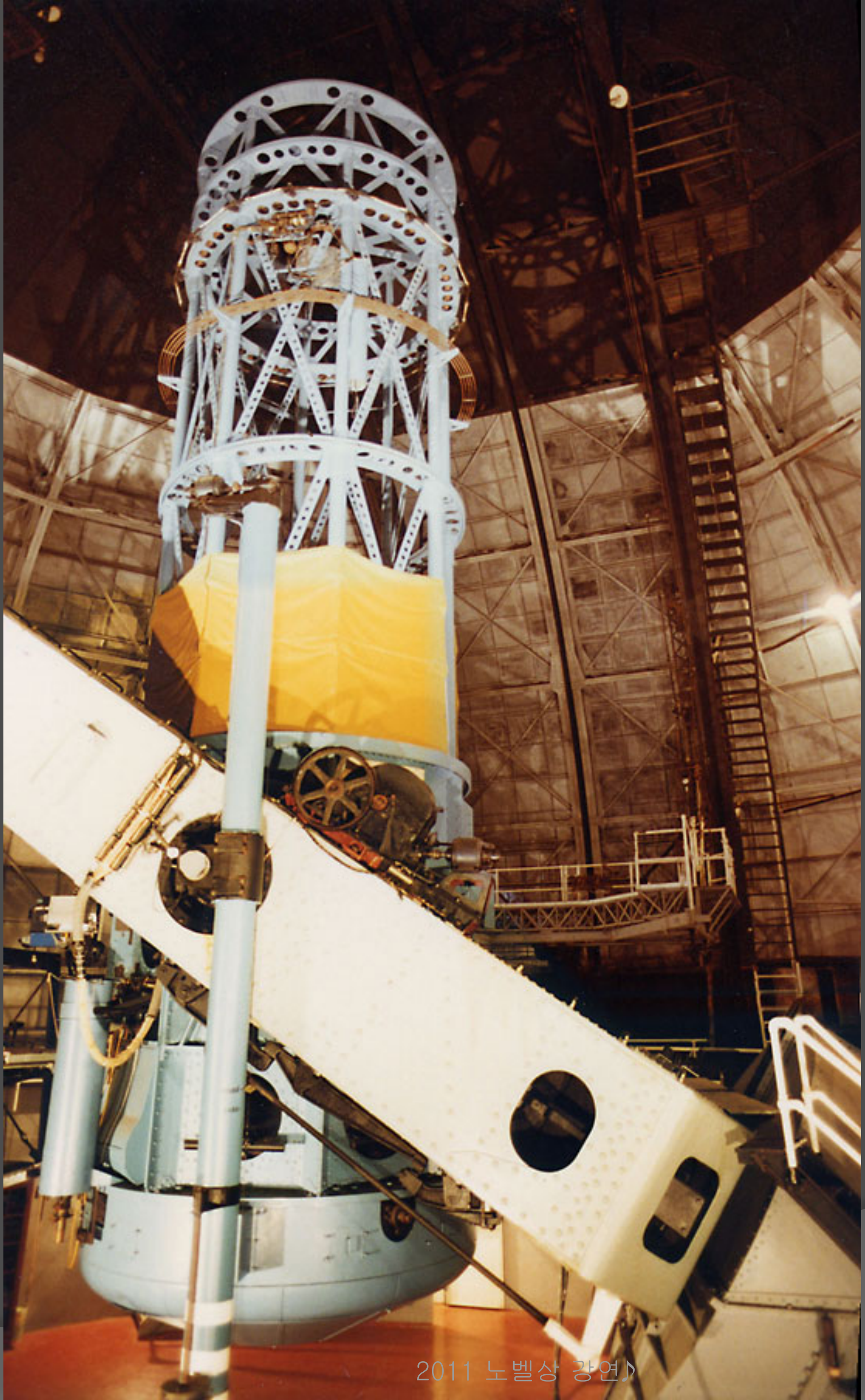
- **Mt. Wilson천문대의 100인치 망원경을 이용하여 현대우주론의 바탕을 마련함**
  - **우주에는 우리 은하계 말고도 많은 은하들이 존재함을 관측을 통해 입증**
  - **허블의 법칙: 빅뱅이론의 기초**
  - **노벨 물리학상을 두 개라도 받아 마땅하나 당시엔 천문학은 물리학으로 의 범주에 넣지 않아 주지 못하다가 룰을 변경한 후 주려고 했으나 이미 사망함**

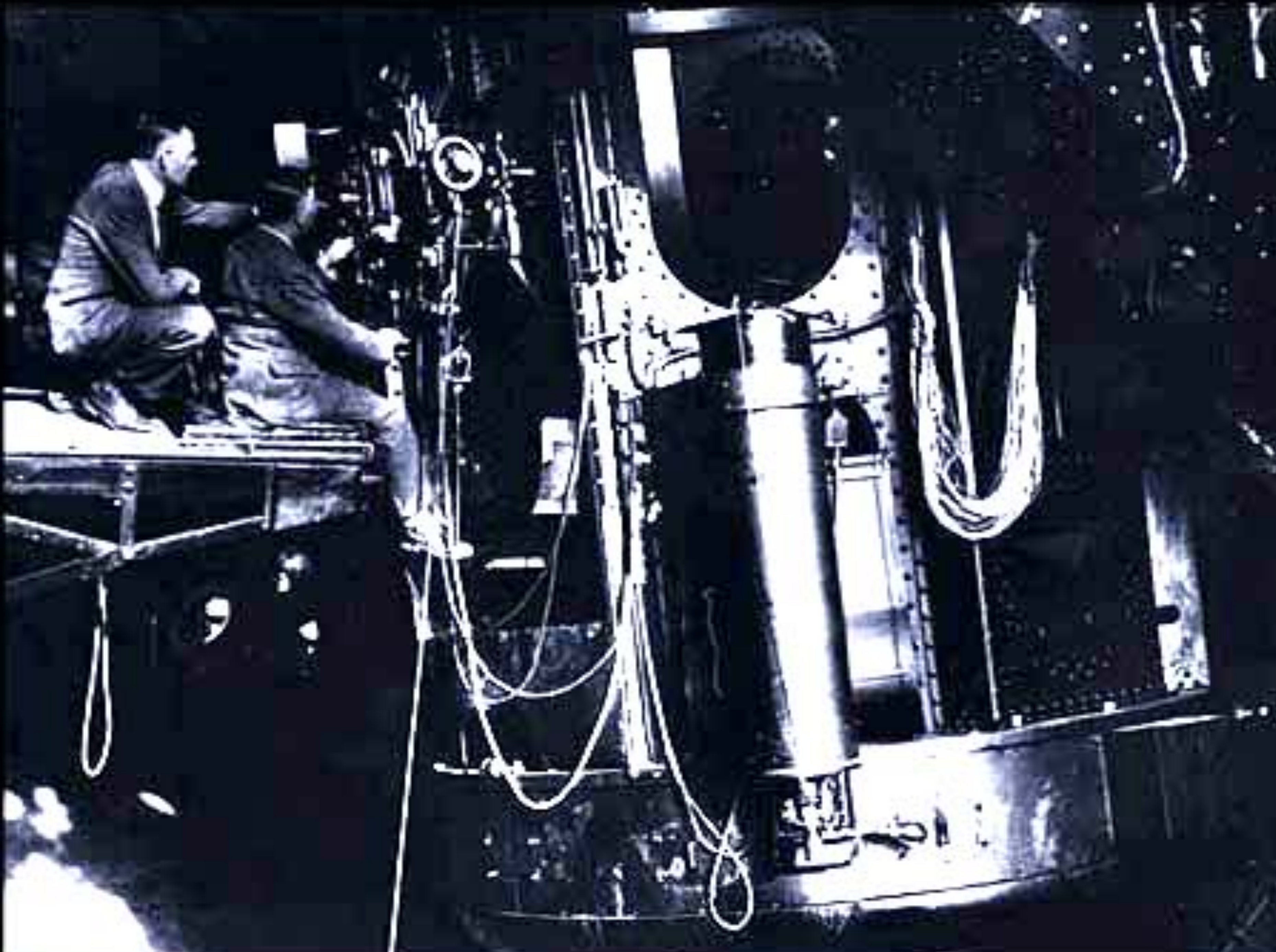


Andrew Carnegie

and

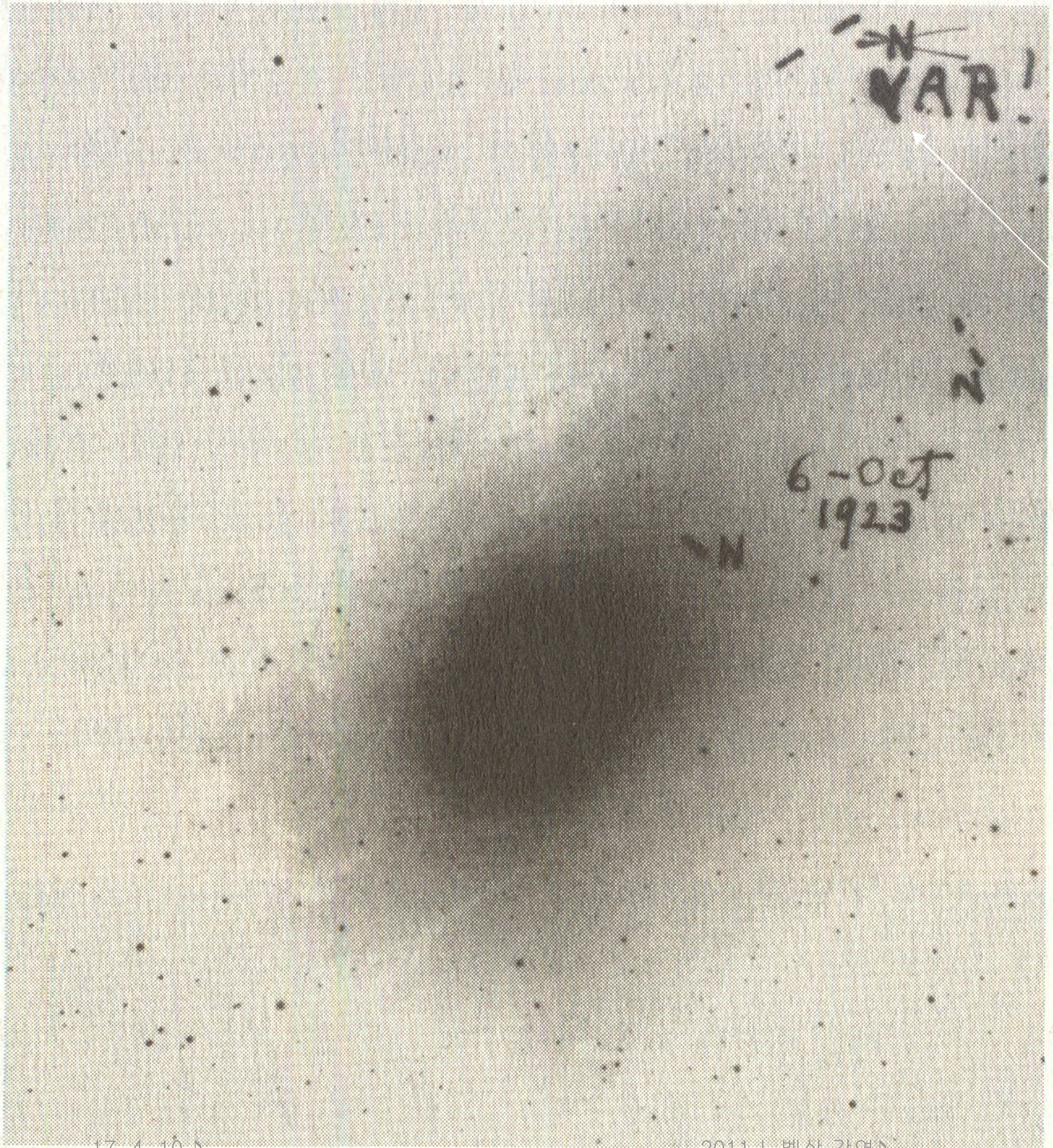
George Hale





Nebula is a galaxy

- 1923년 10월 4-6일 안드로메다 성운에서 세페이드변광성을 발견
- 레빗의 그래프에 대입하여 안드로메다 성운까지의 거리가 90만 광년(실제는 250만광년)임을 발견, 성운이 우리 은하계에서 멀리 떨어진 또 다른 은하계임을 입증함



Nova가 아니라 VAR임을 깨달음

허블의 법칙 (1927)

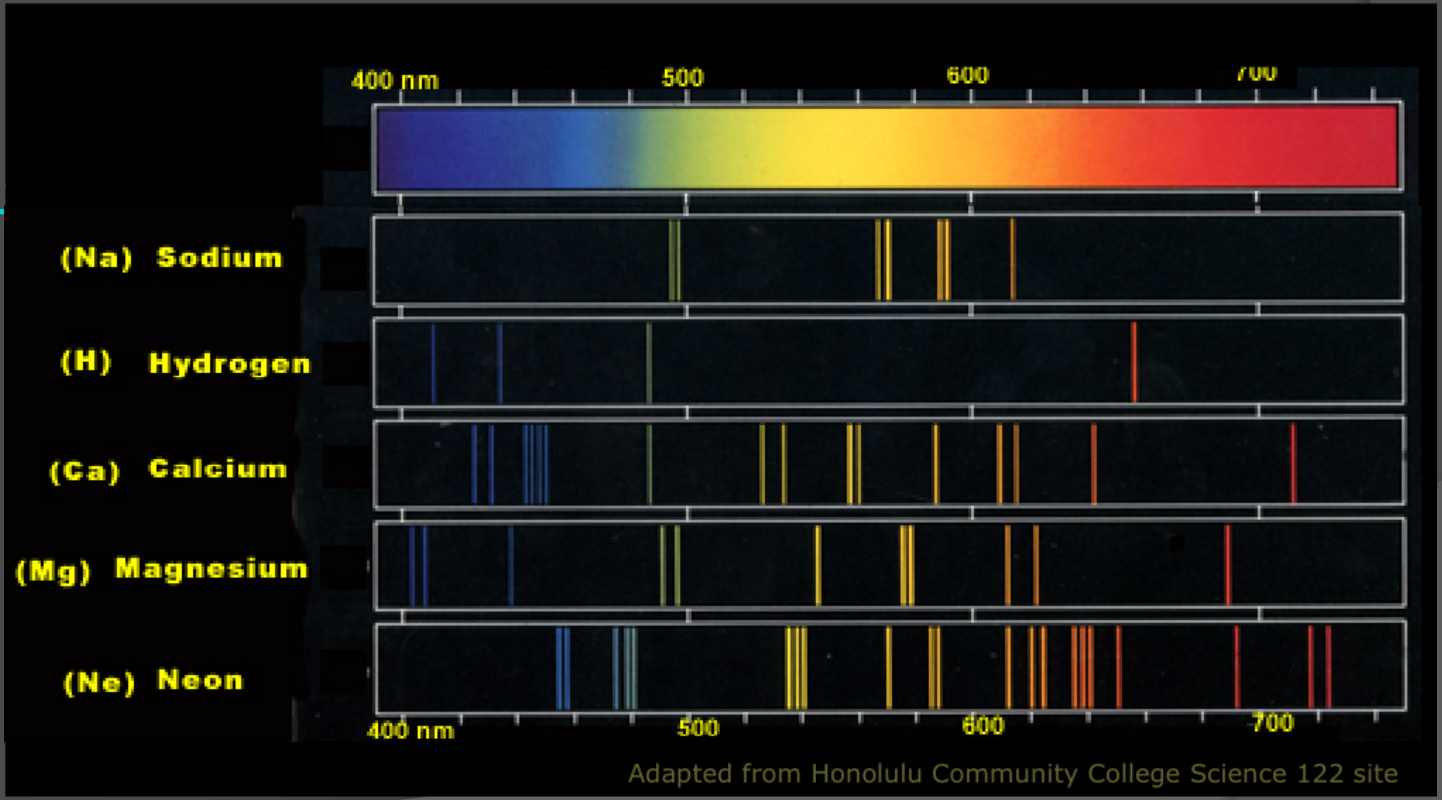
1948년 2월 9일 TIME♪

"one of the most flabbergasting discoveries science has ever made." Aided by a 100-inch telescope, Hubble theorized that the entire visible universe was expanding -- literally exploding. ♪

원자의 스펙트럼

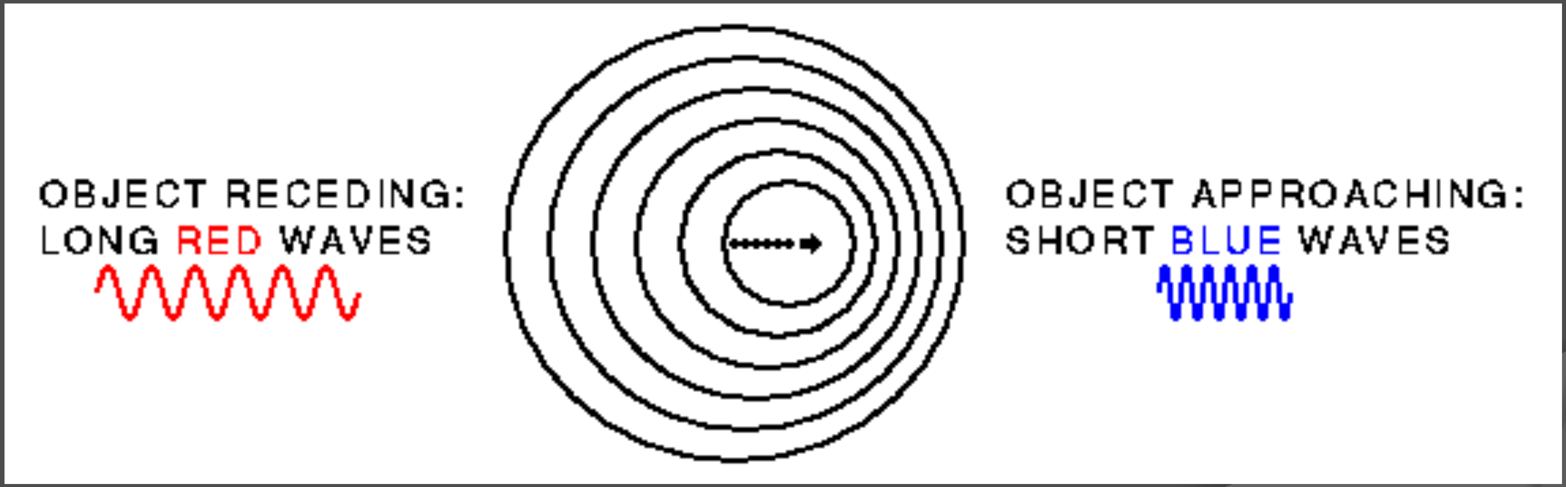
- **원자들은 고유한 주파수들의 빛만을 흡수하거나 방출한다.**

- **원자들**

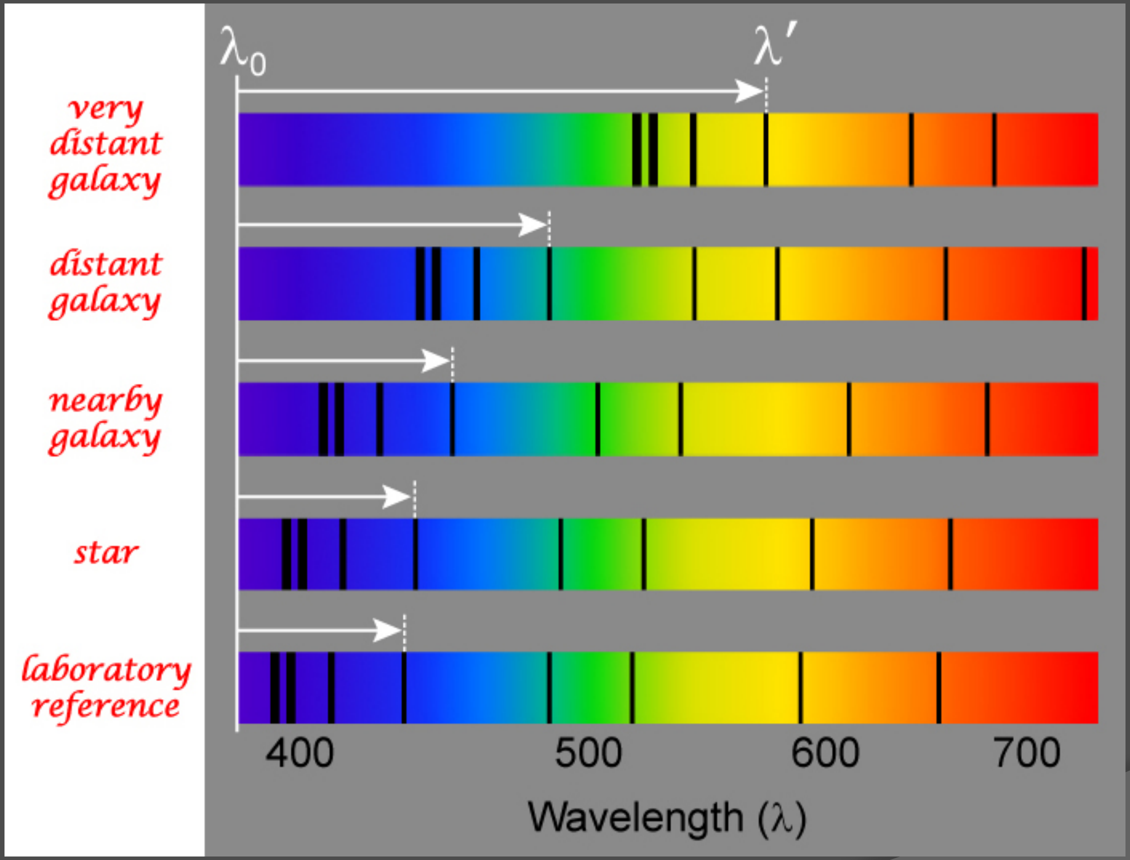


도플러 효과 (Doppler Effect)

- 움직이는 물체에서 나오는 파동의 주파수가 변하는 현상
- 다가오는 물체에서는 주파수가 증가하고 멀어지는 물체는 주파수가 감소한다.

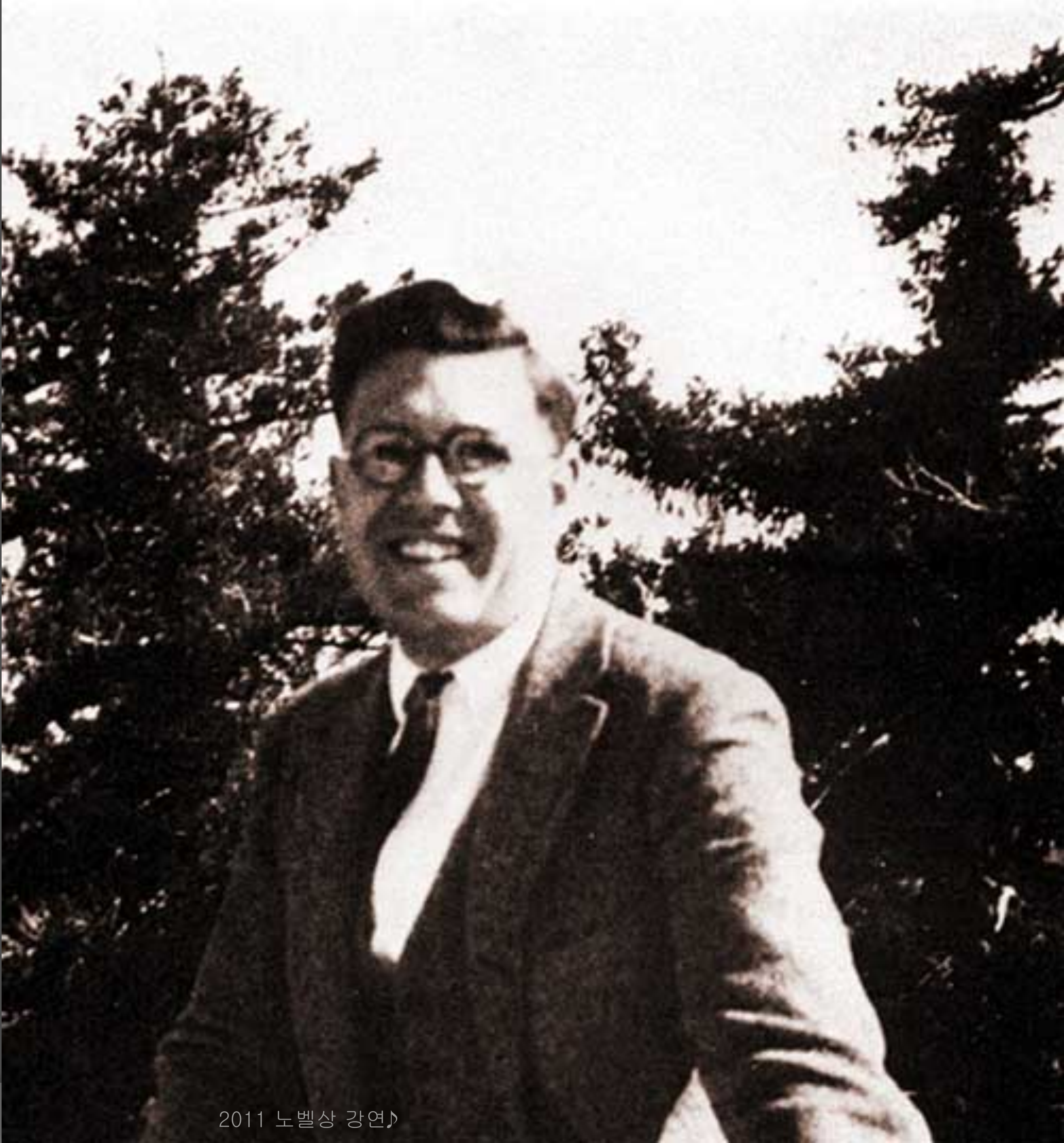


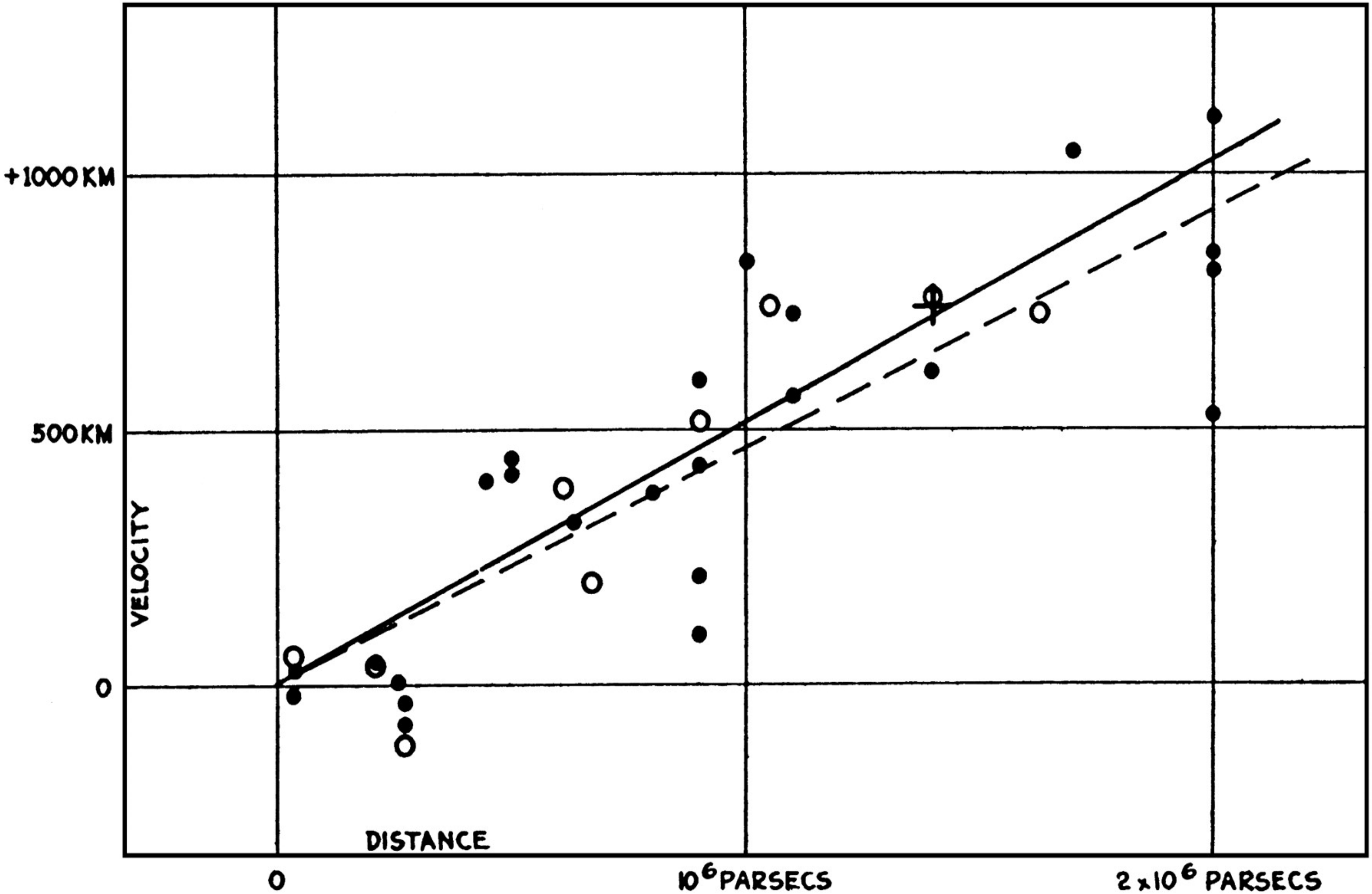
멀어지는 물체는 적색편이



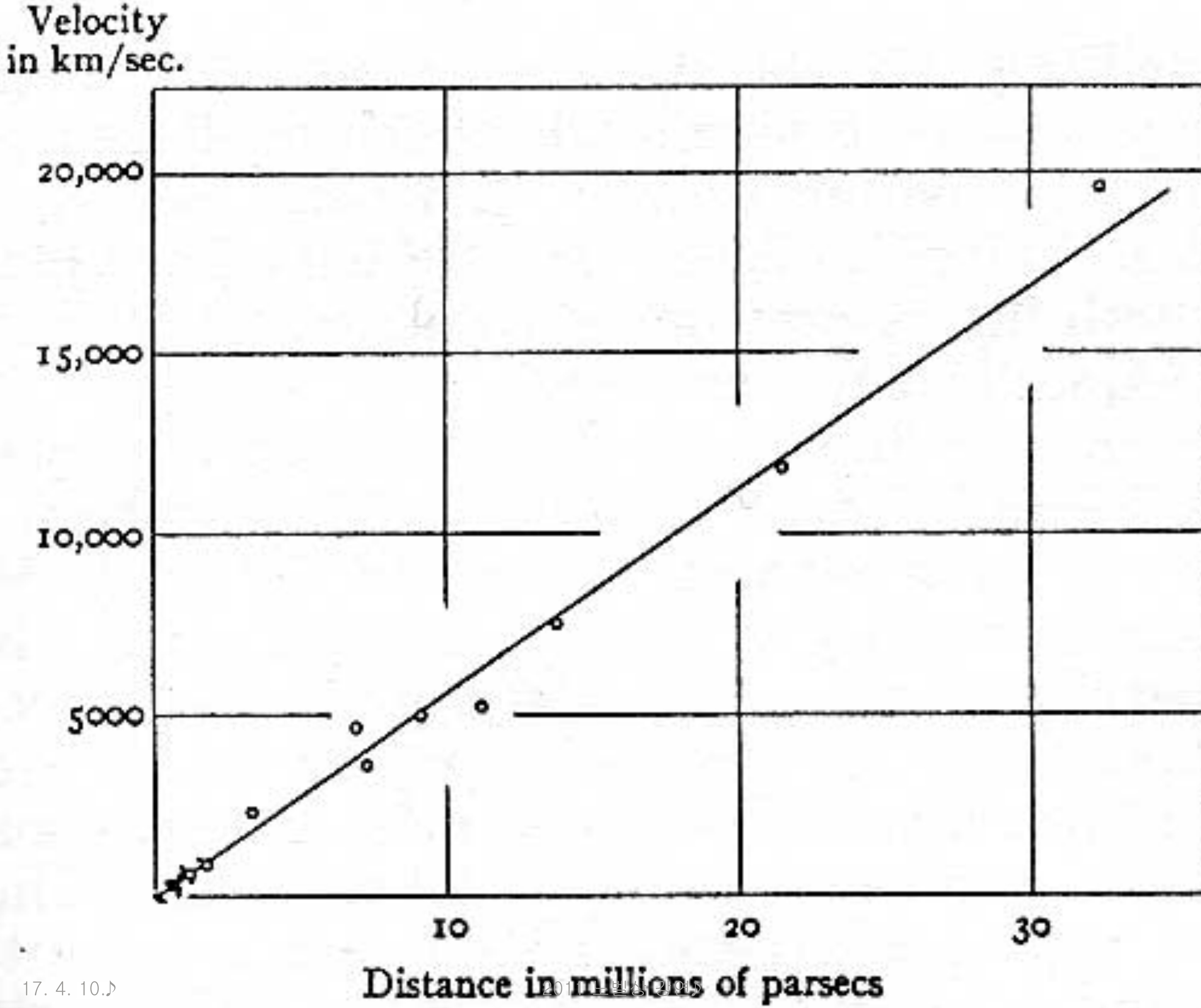
M. Humason

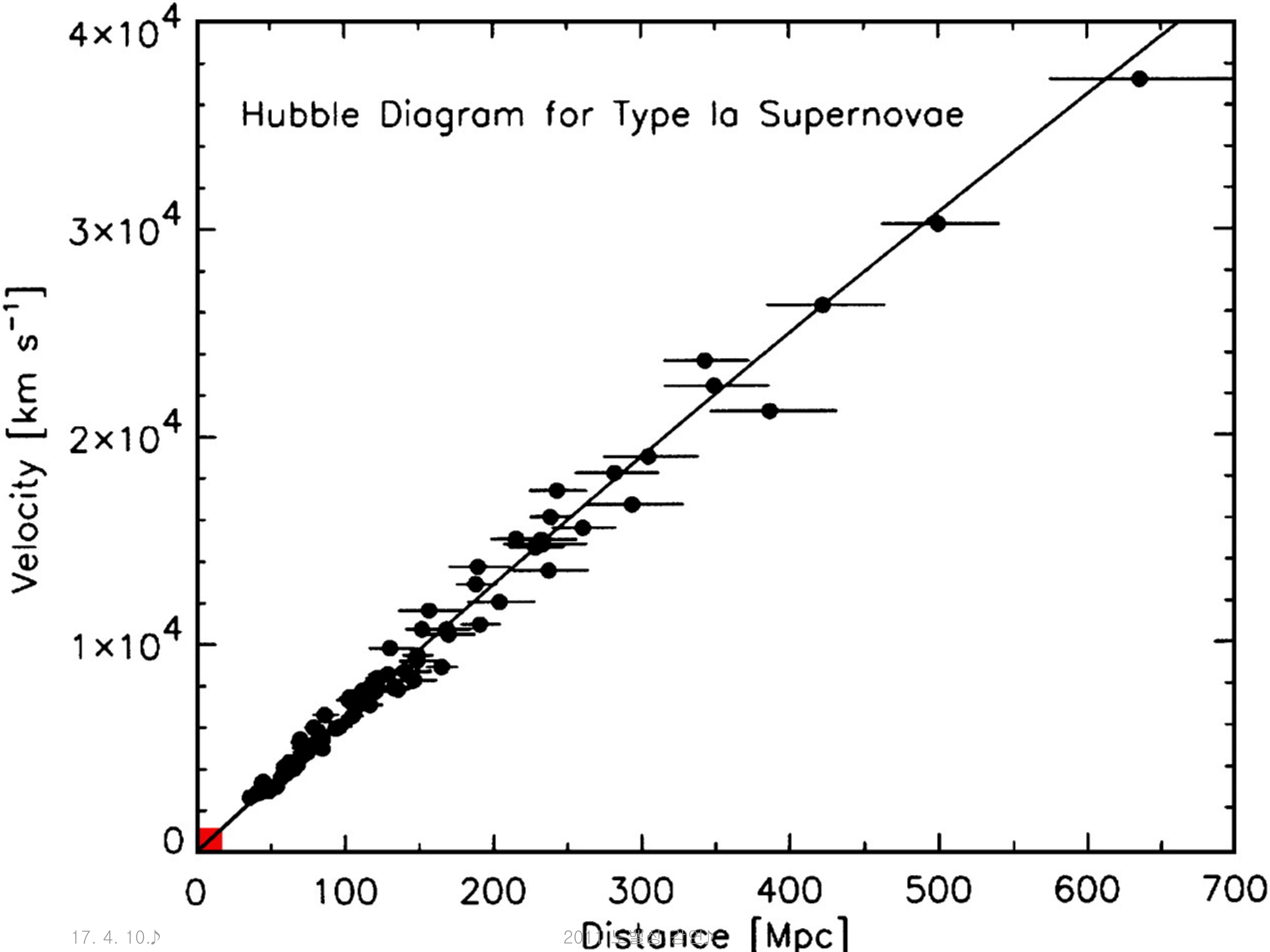
- 천문대 수위
- 허블의 조수
- 은하계의 속도를 재는데 큰 업적

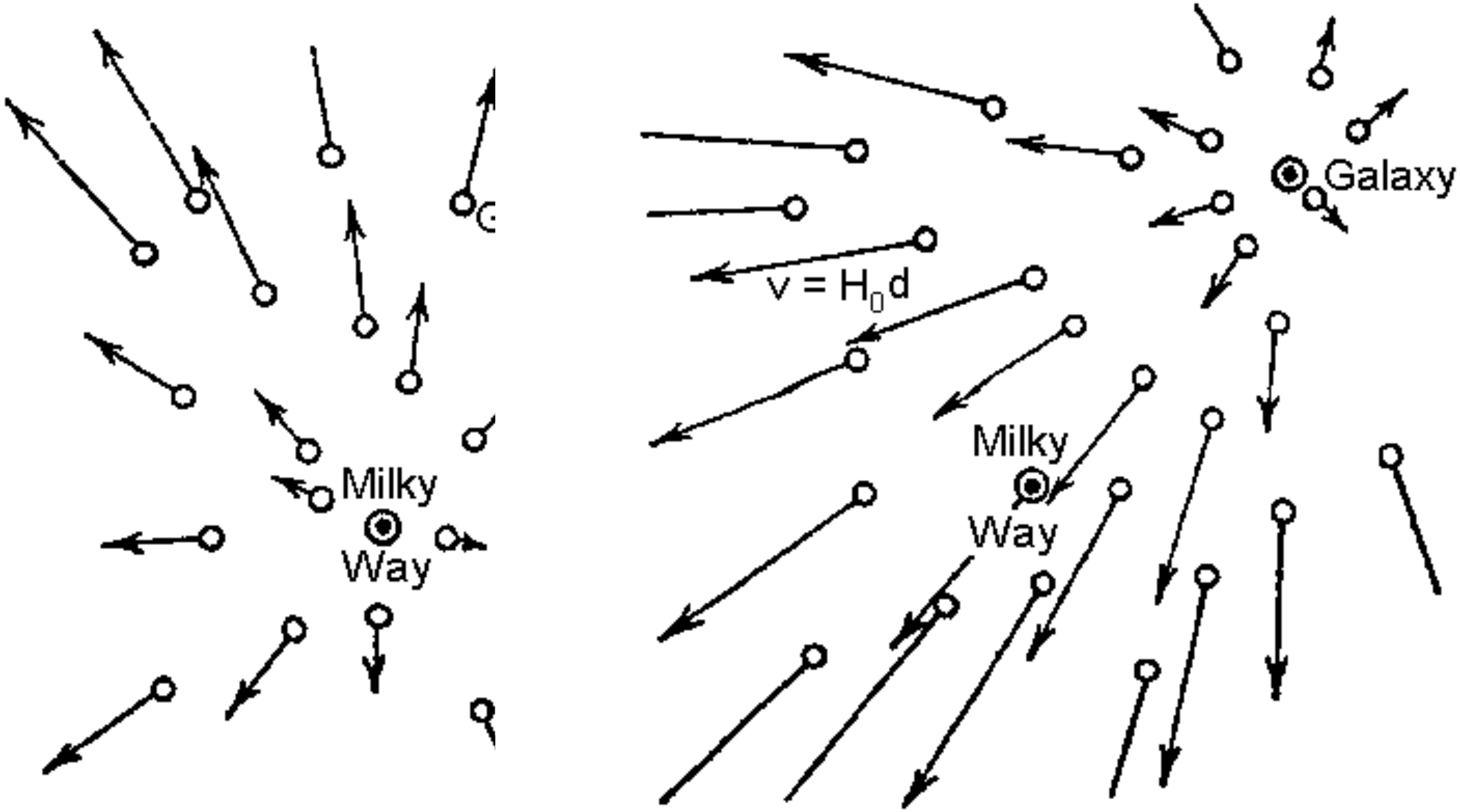



+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2 x 10⁶ PARSECS

1 parsec = 3광년


Velocity
in km/sec.
20,000
15,000
10,000
5000
10
20
30
Distance in millions of parsecs

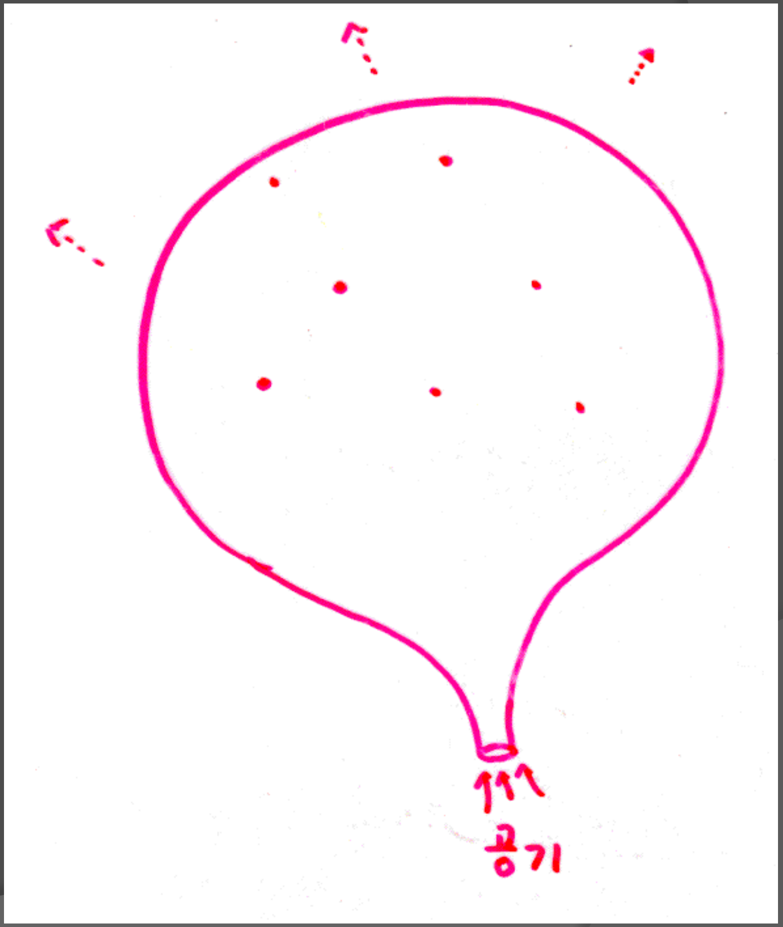

Hubble Diagram for Type Ia Supernovae
Velocity [km s⁻¹]
Distance [Mpc]
0
1×10^4
2×10^4
3×10^4
4×10^4
0
100
200
300
400
500
600
700

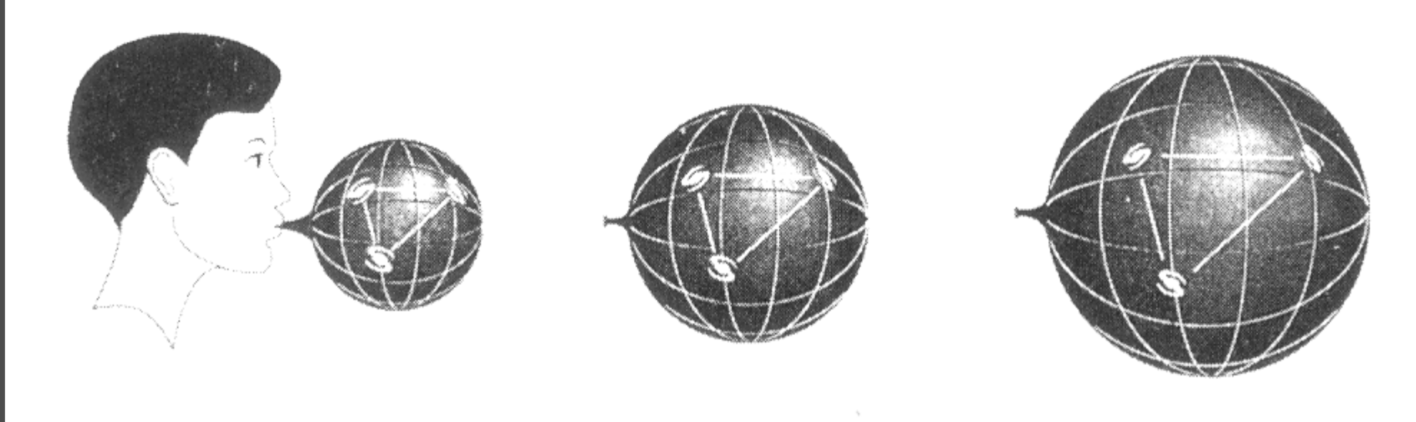


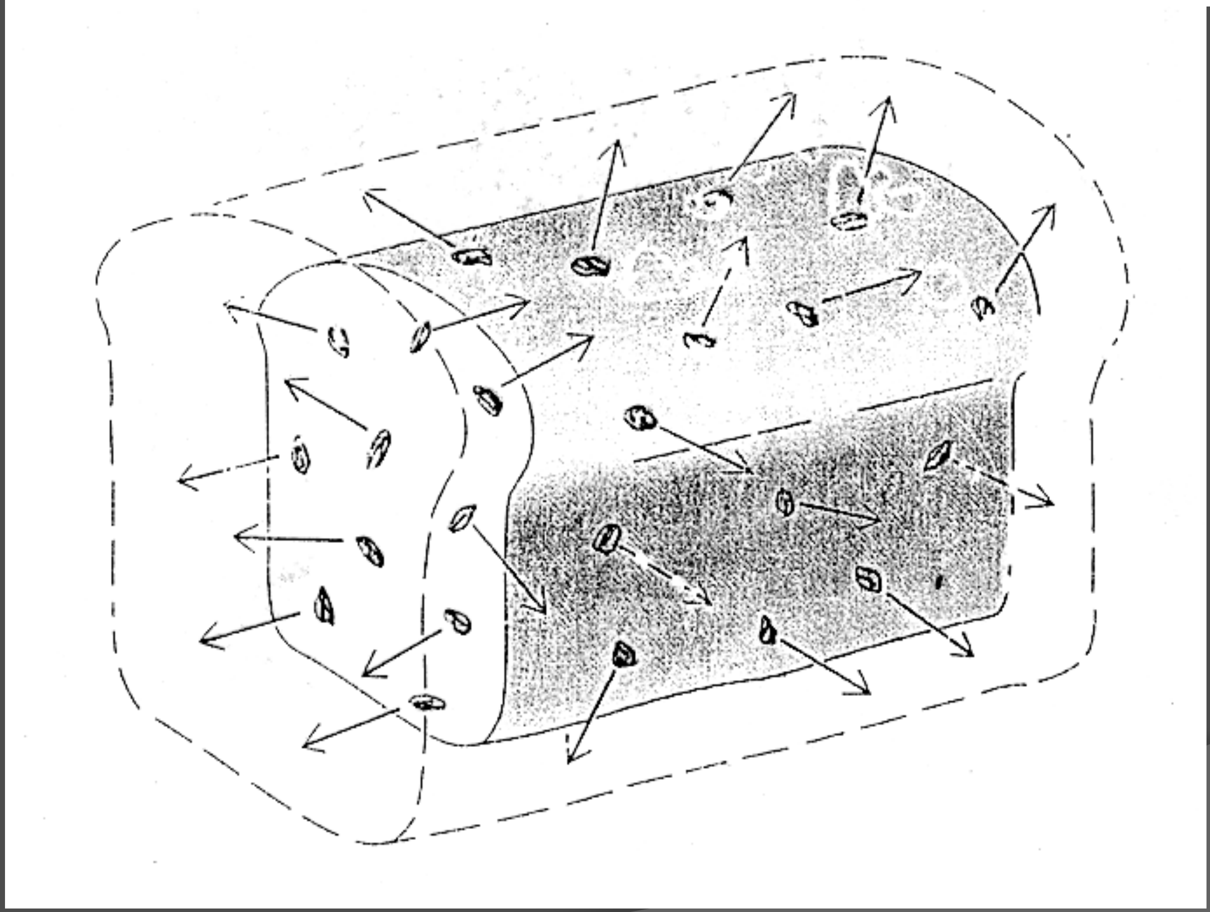
것은 멀어지는 속도가 작기 때문

모두 서로 멀어지기

- **캠퍼스에서 사람들이 모두 서로 멀어지려면?**
- **내가 움직이기 때문이 아니다**
- **캠퍼스자체가 팽창하는 수 밖에 없다!**

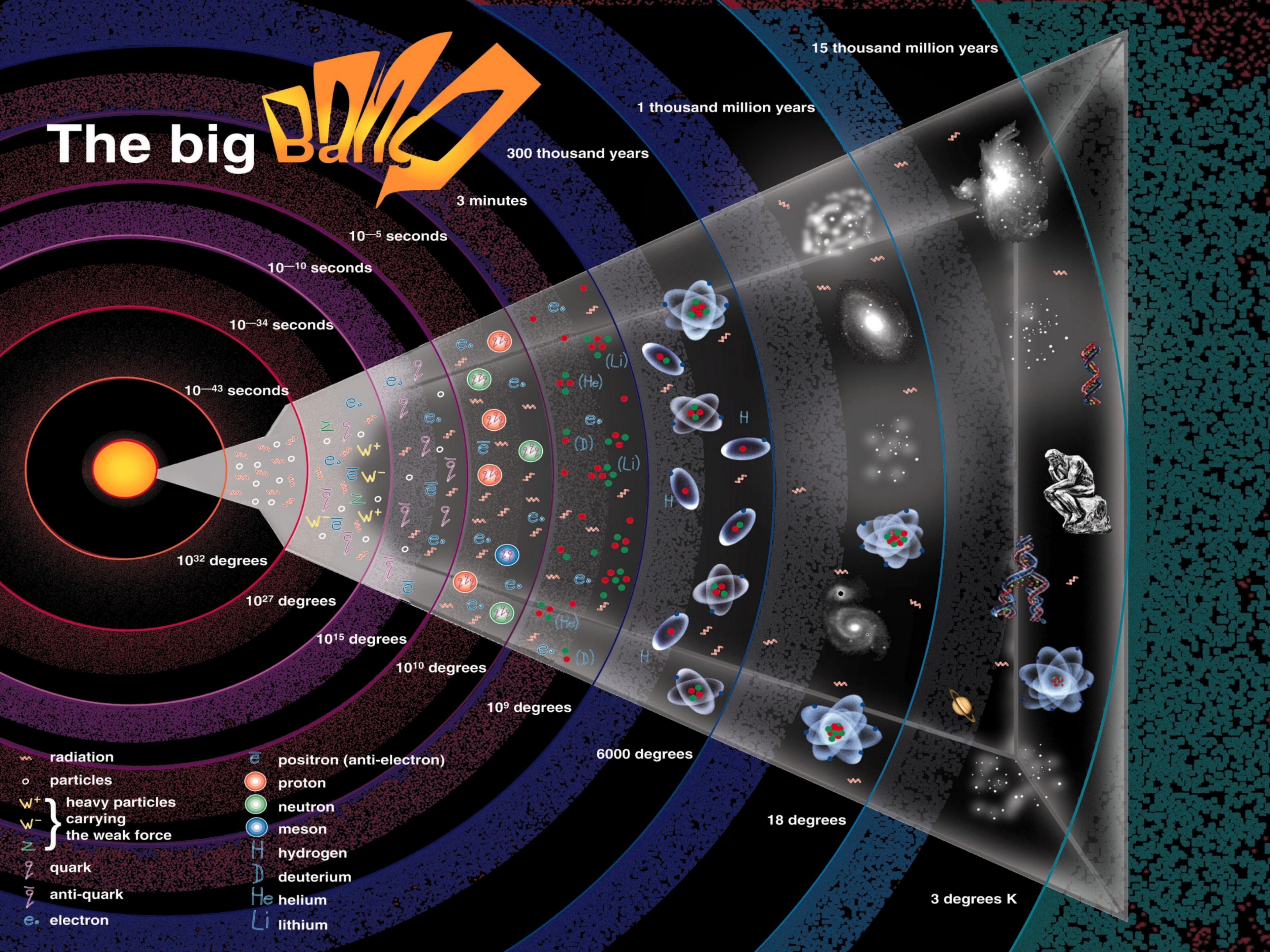






우주의 팽창 및 빅뱅

- 우주가 팽창한다면 오랜 시간전에는 우주가 한 점에 있었다는 의미
- 우주의 시작 (빅뱅, Big Bang)이 존재



The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

아인슈타인의 우주상수

- 중력법칙(일반상대성이론)을 우주에 적용하면 우주가 팽창해야 함.

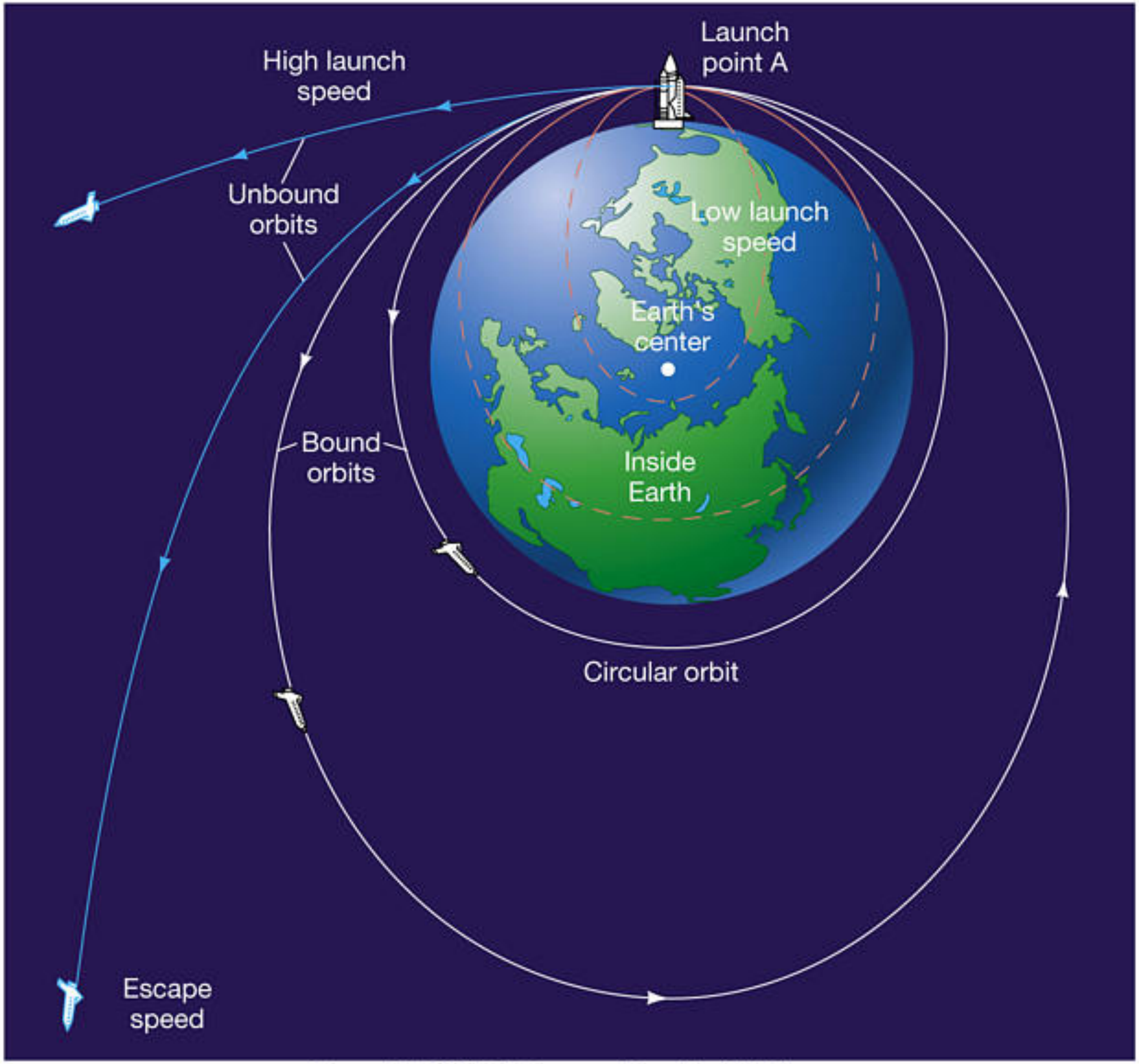
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = T_{\mu\nu} + \Lambda g_{\mu\nu}$$

중력=공간이 휜 정도♪ 물질♪

- 우주는 항상 똑같은 상태를 유지해야 한다고 믿은 아인슈타인은 우주상수를 도입

물질이 많으면
중력이 커지고
우주는 작아진다

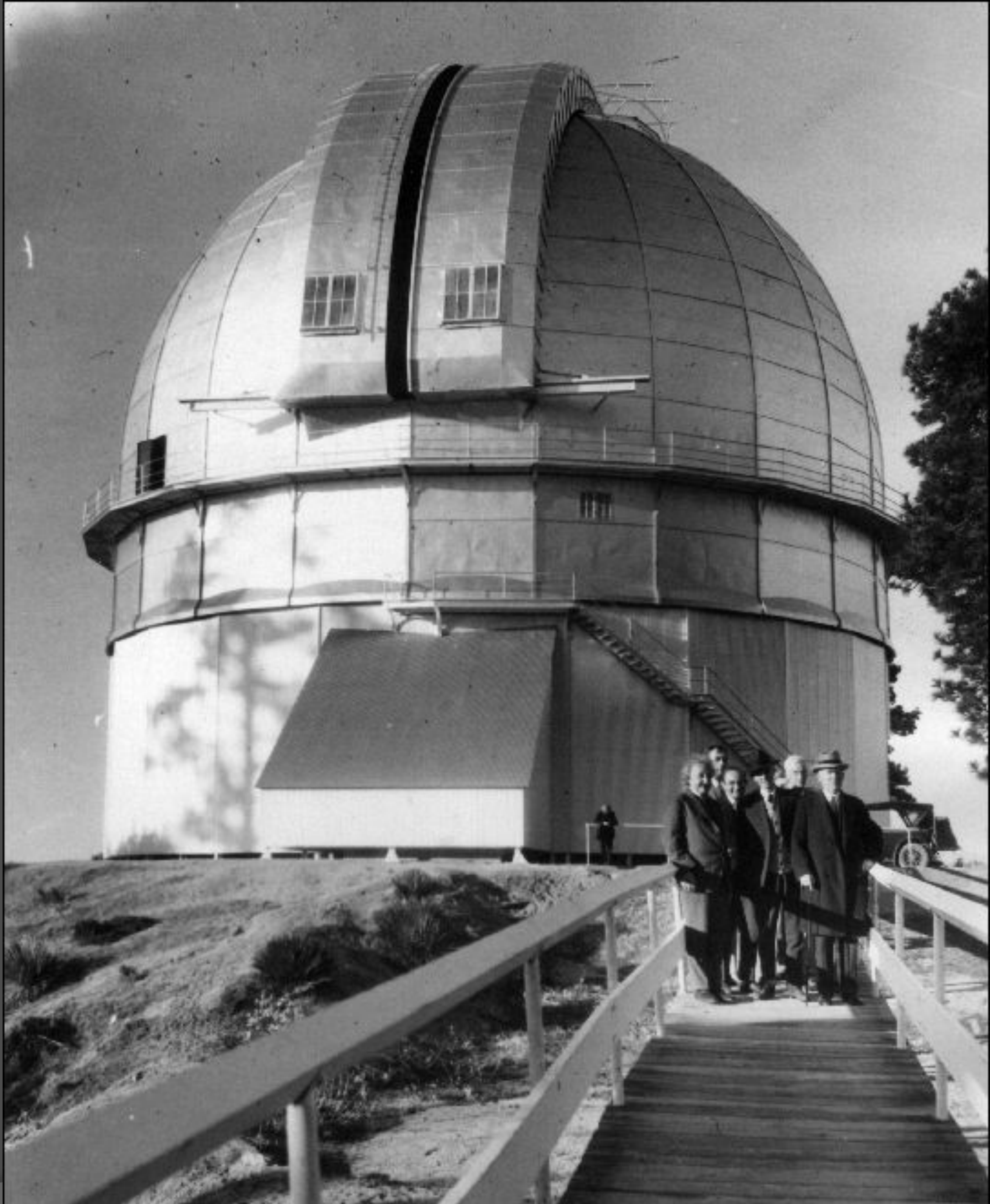
물질이 적으면
중력이 작고
우주는 팽창한다



1931년 1월29일

아인슈타인이

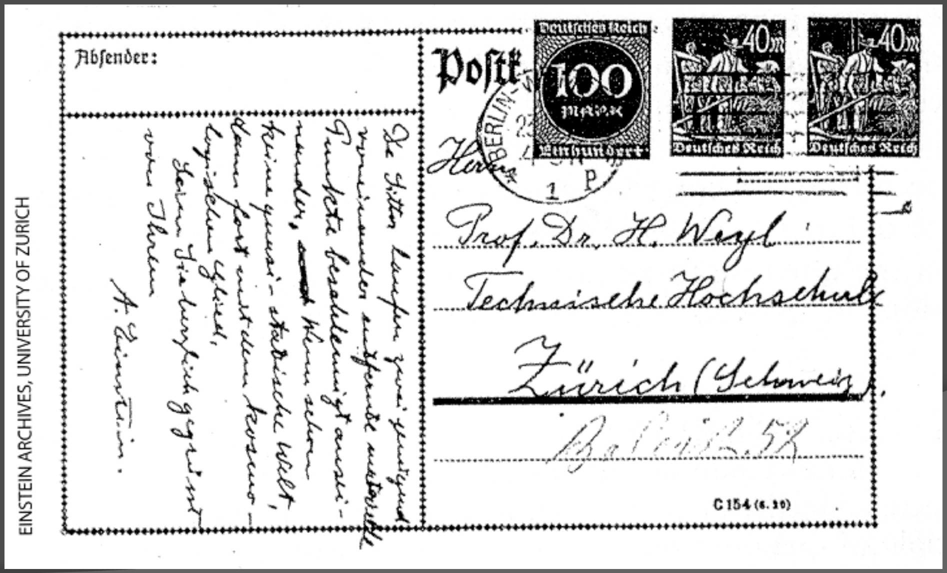
윌슨천문대를 방문



우주상수의 폐기

- **Hubble과 Humason등을 만난 아인슈타인은 우주가 팽창하고 있음을 확인하고 우주상수를 폐기함**

  내인생 최대실수"my biggest blunder!"



THE COMPLETE FIRST SEASON
COMING TO DVD SEPTEMBER 2ND
the BIG BANG THEORY
WWW.BIGBANGTHEORYDVD.COM
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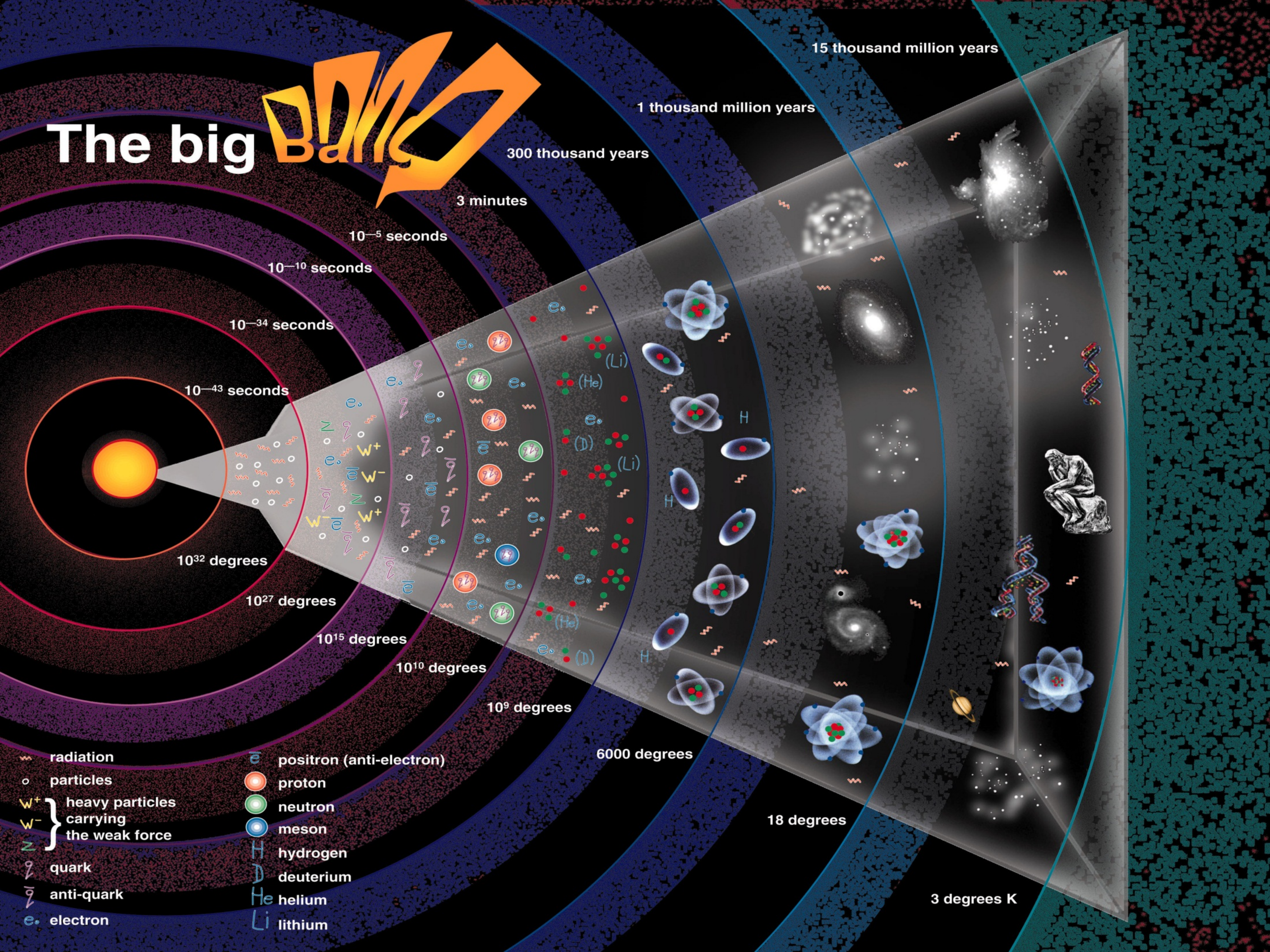
빅뱅이론

- 우주는 한 점에서 시작
- 과학적 증거
  - 우주 배경 복사 등

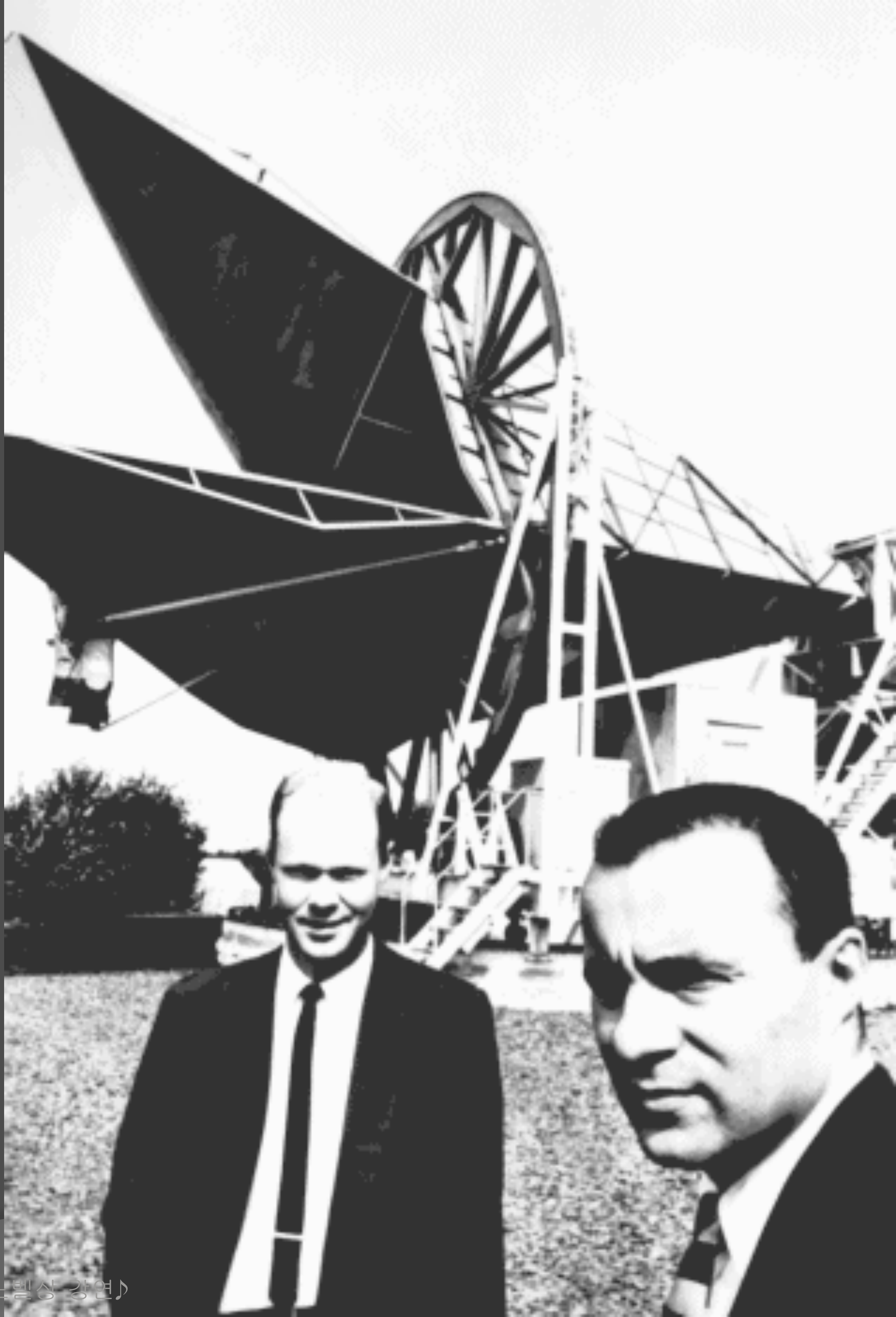
G. Gamow (1904 – 1968)

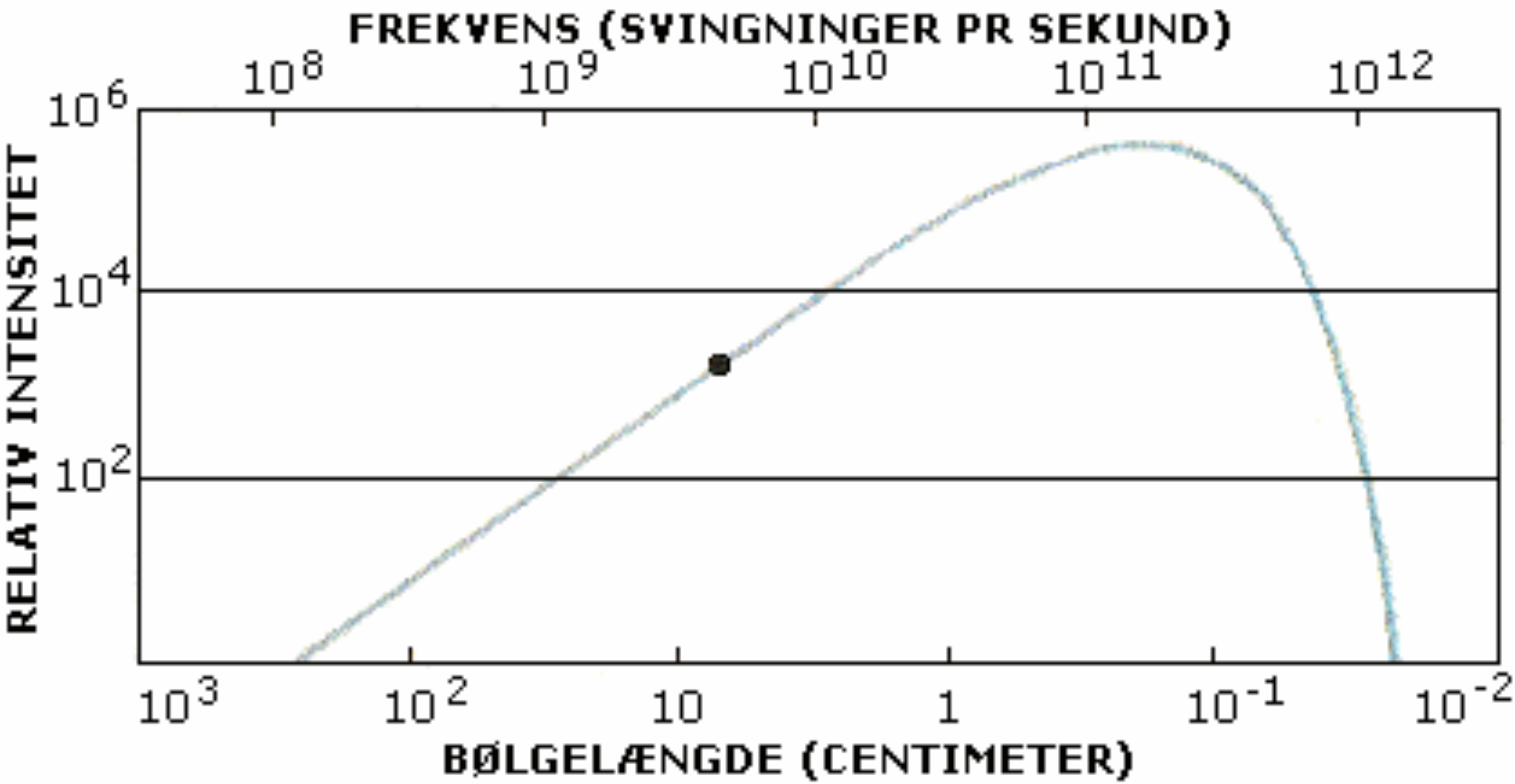
러시아태생의 미국물리학자♪

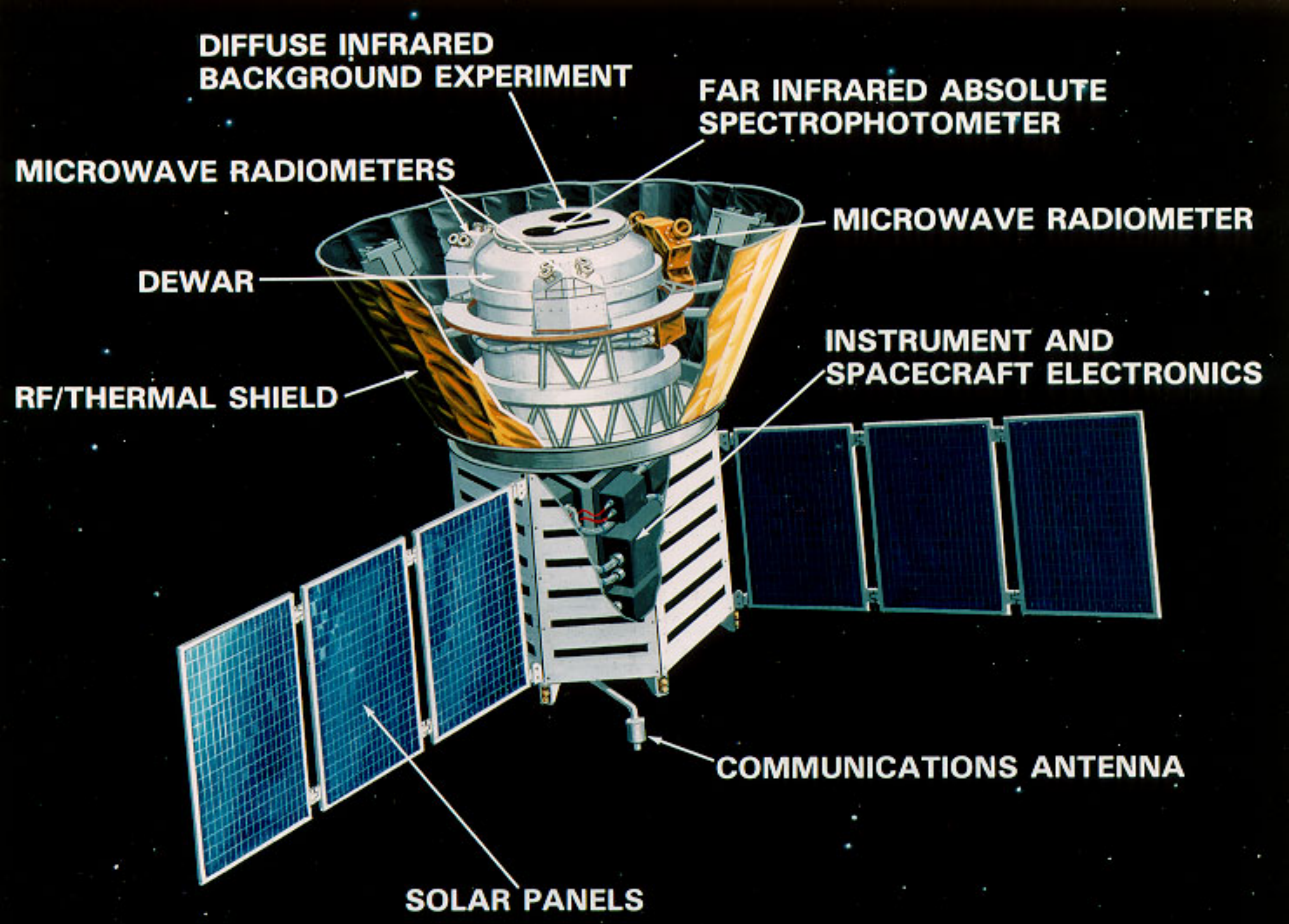

The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
1032 degrees
1027 degrees
1015 degrees
1010 degrees
109 degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

- 미국 벨연구소의 Penzias와 Wilson이 레이다로 최초로 관측♪

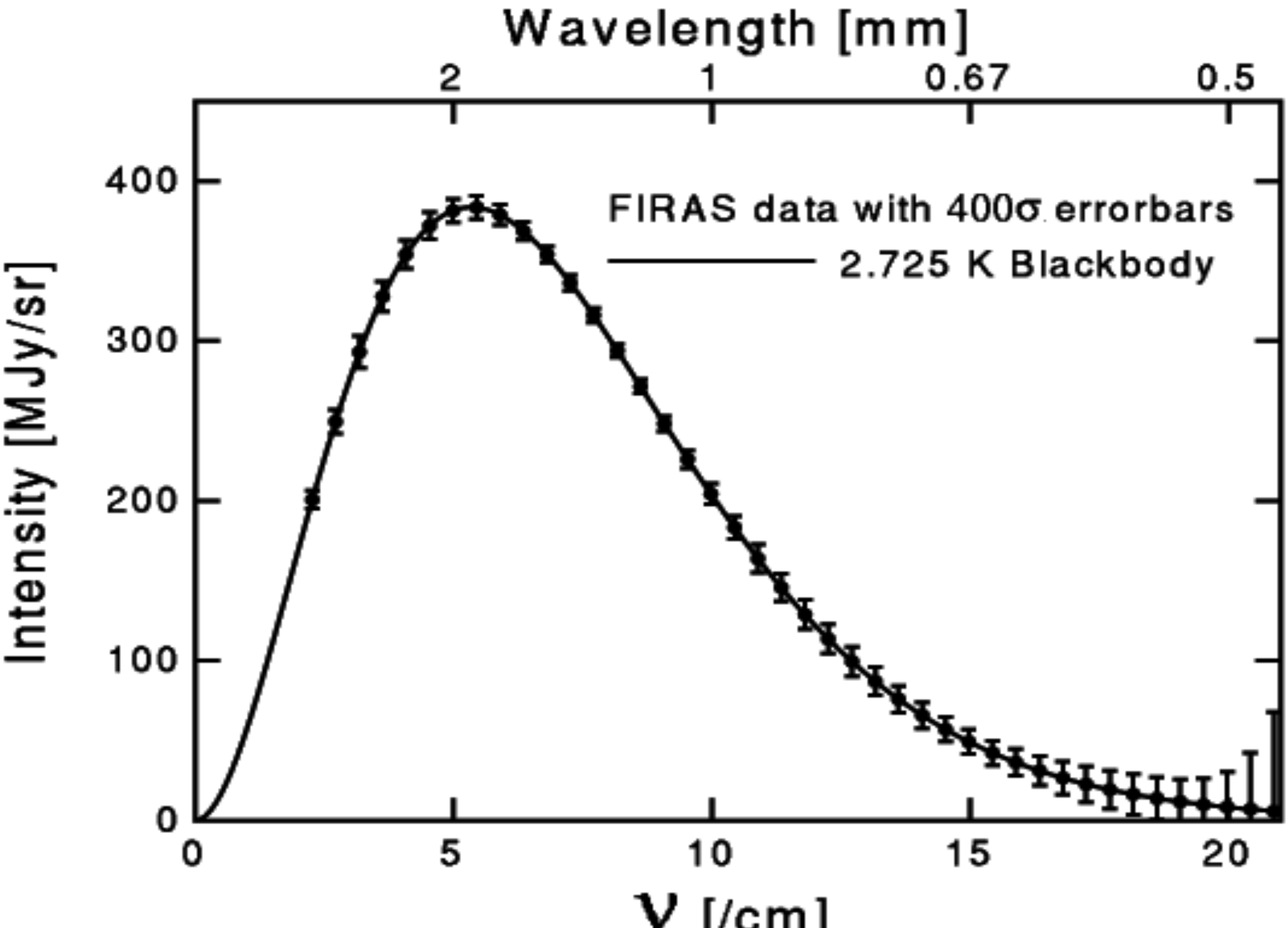
- 최근에는 인공위성 COBE로 정밀관측이 가능해짐♪

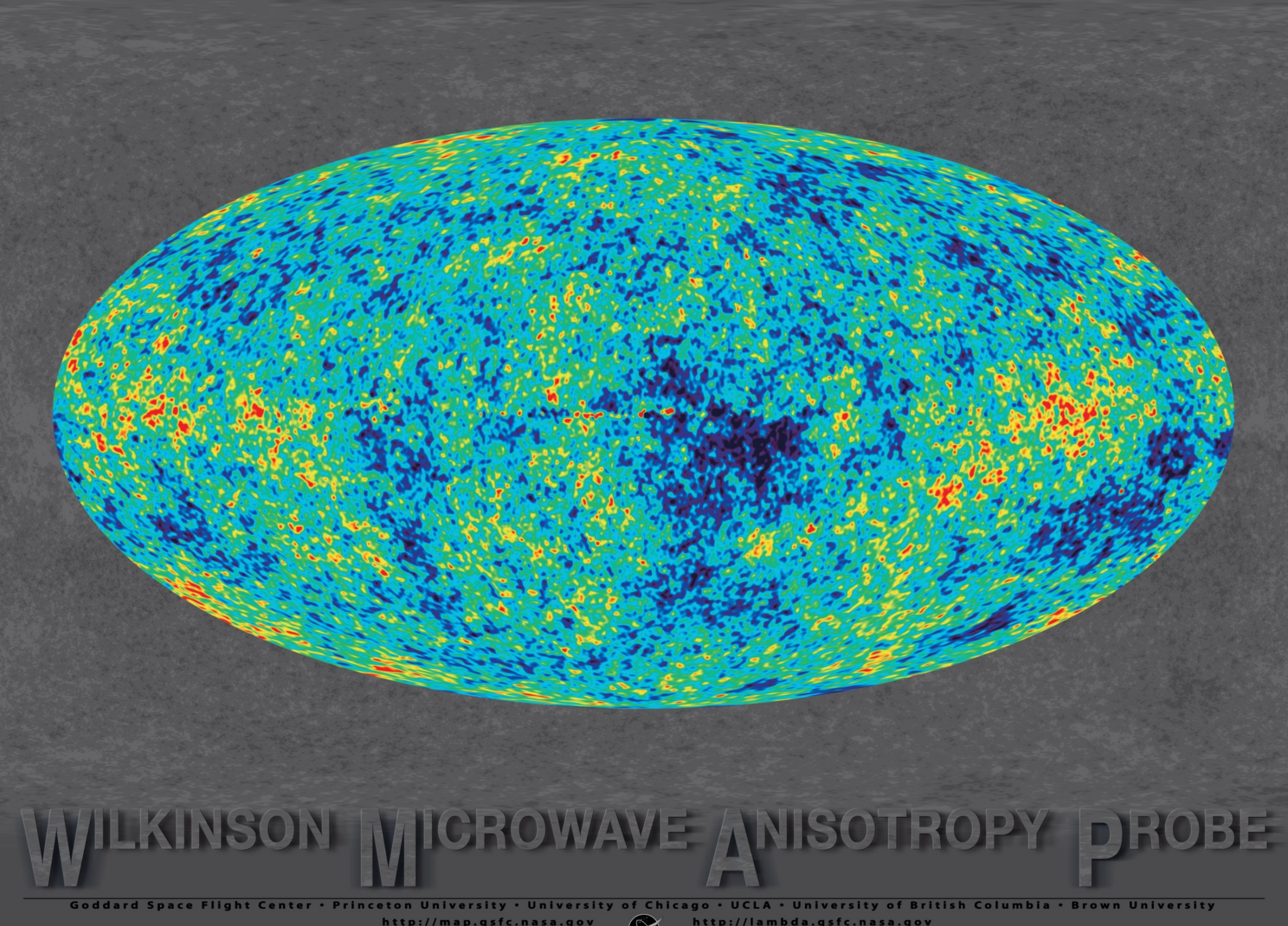



FREKVENS (SVINGNINGER PR SEKUND)
10^8
10^9
10^10
10^11
10^12
RELATIV INTENSITET
10^6
10^4
10^2
10^3
10^2
10
1
10^-1
10^-2
BØLGELÆNGDE (CENTIMETER)


DIFFUSE INFRARED
BACKGROUND EXPERIMENT
FAR INFRARED ABSOLUTE
SPECTROPHOTOMETER
MICROWAVE RADIOMETERS
MICROWAVE RADIOMETER
DEWAR
INSTRUMENT AND
SPACECRAFT ELECTRONICS
RF/THERMAL SHIELD
COMMUNICATIONS ANTENNA
SOLAR PANELS

2006년 노벨물리학상♪


Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]


WILKINSON MICROWAVE ANISOTROPY PROBE
Goddard Space Flight Center • Princeton University • University of Chicago • UCLA • University of British Columbia • Brown University
http://map.gsfc.nasa.gov
NASA
http://lambda.gsfc.nasa.gov

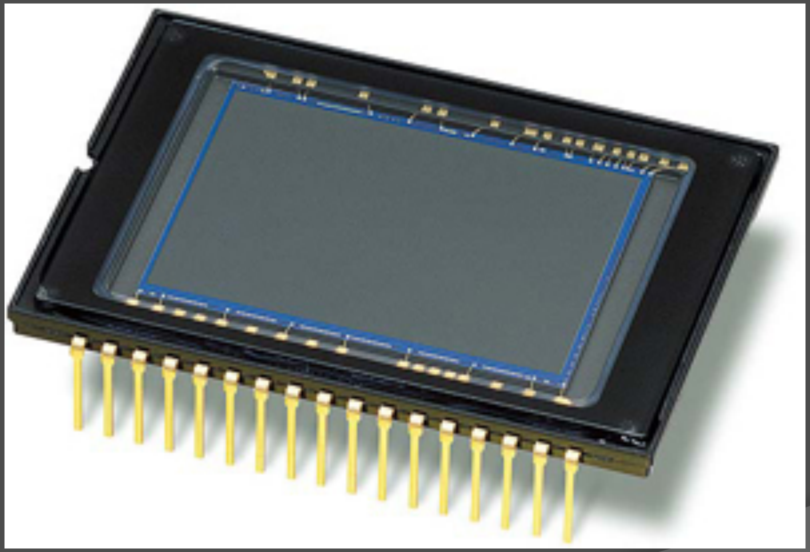
우주의 가속팽창

최첨단 거리관측

- **세페이드변광성을 이용한 방법의 한계**
- **새로운 표준촛불의 필요성**
- **정밀한 광도의 측정**
- **초신성 (Supernova)**

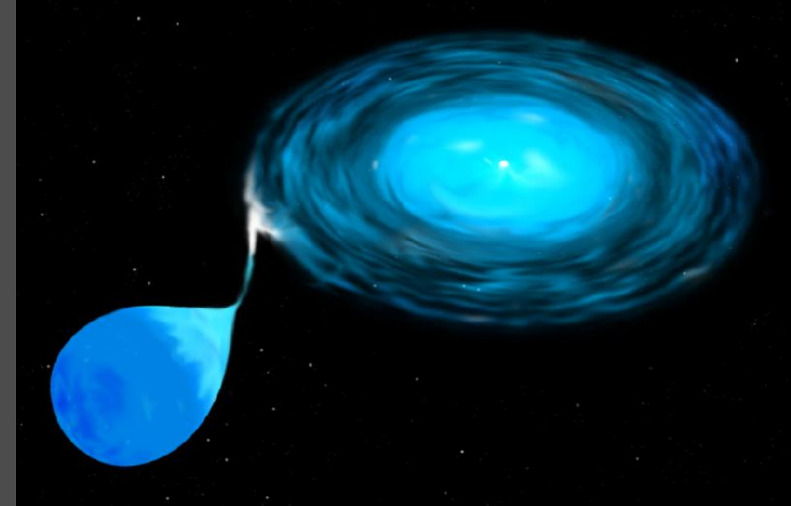
최첨단 밝기측정: CCD

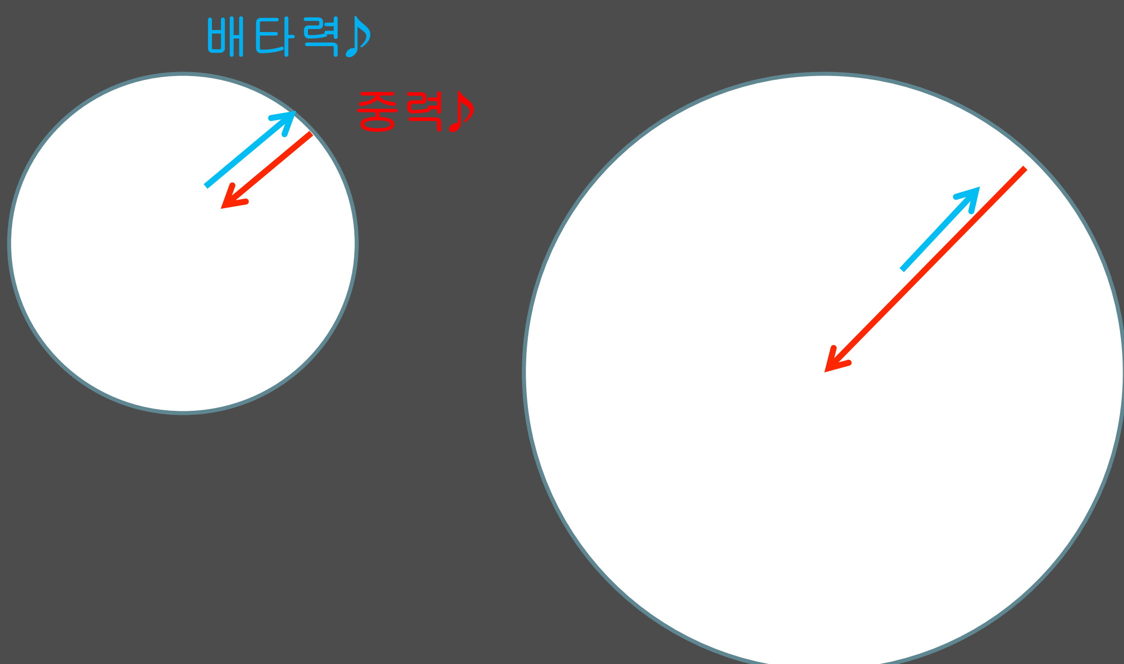
- 필름사진기에서 디지탈사진기로
- 한 개의 광자를 측정할 수 있는 정확성

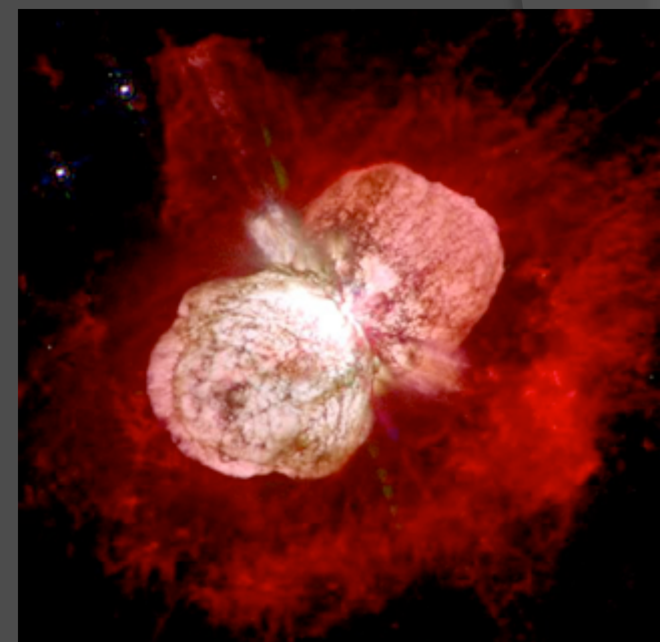


Supernovae Ia

별(백색왜성)이 폭발하면서 생김

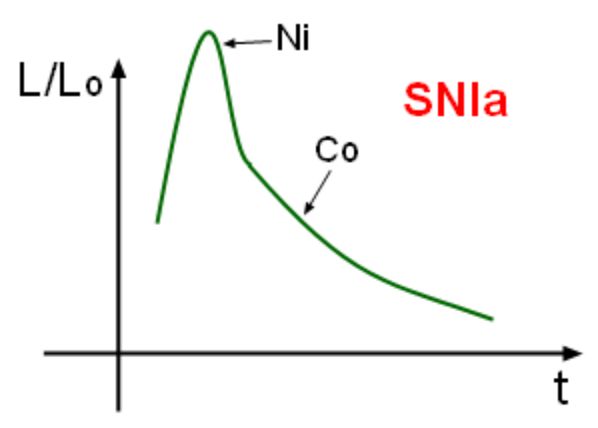




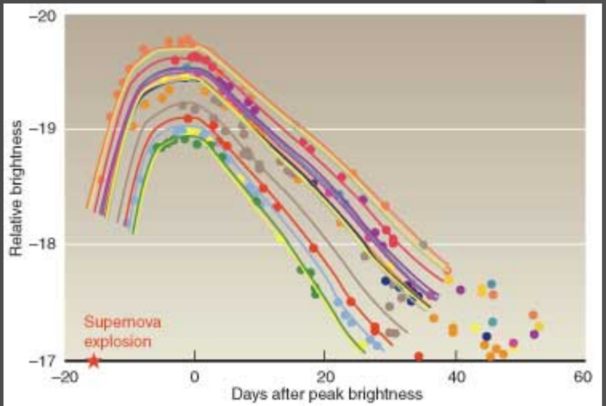


Supernovae Ia

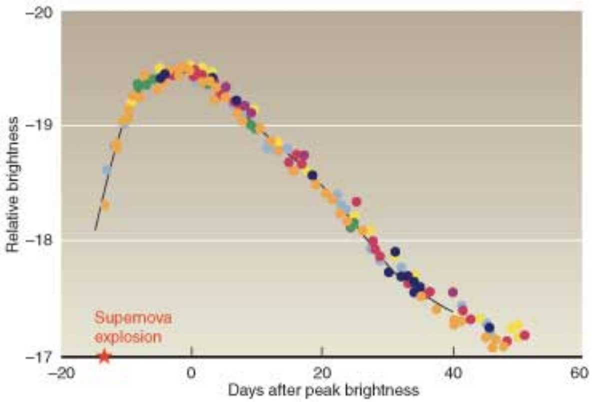
- 특징적인 Light curve



- 폭발이 같은 조건에서만 생기므로 일정한 절대광도를 가짐



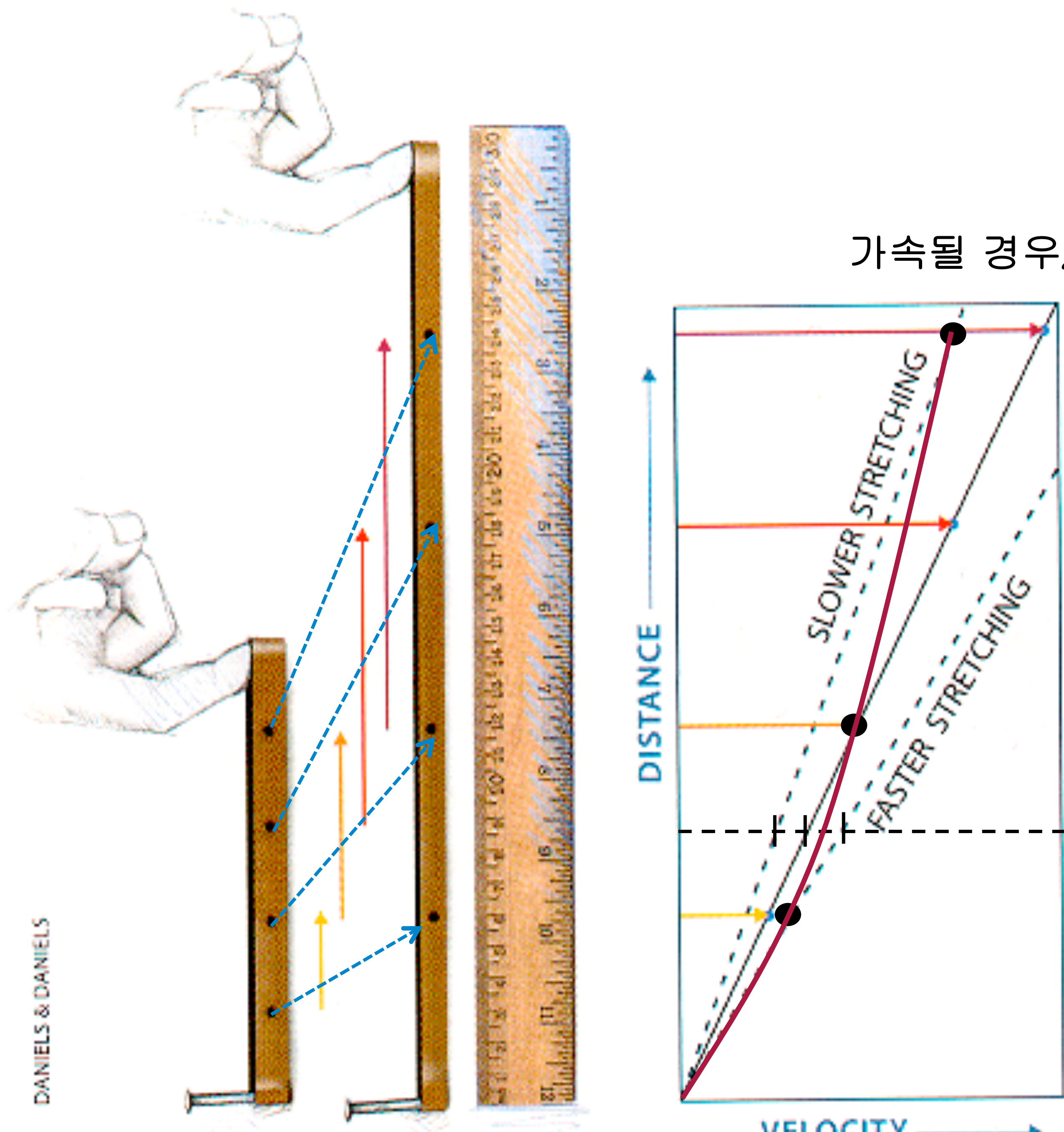
- 정밀한 거리측정가능

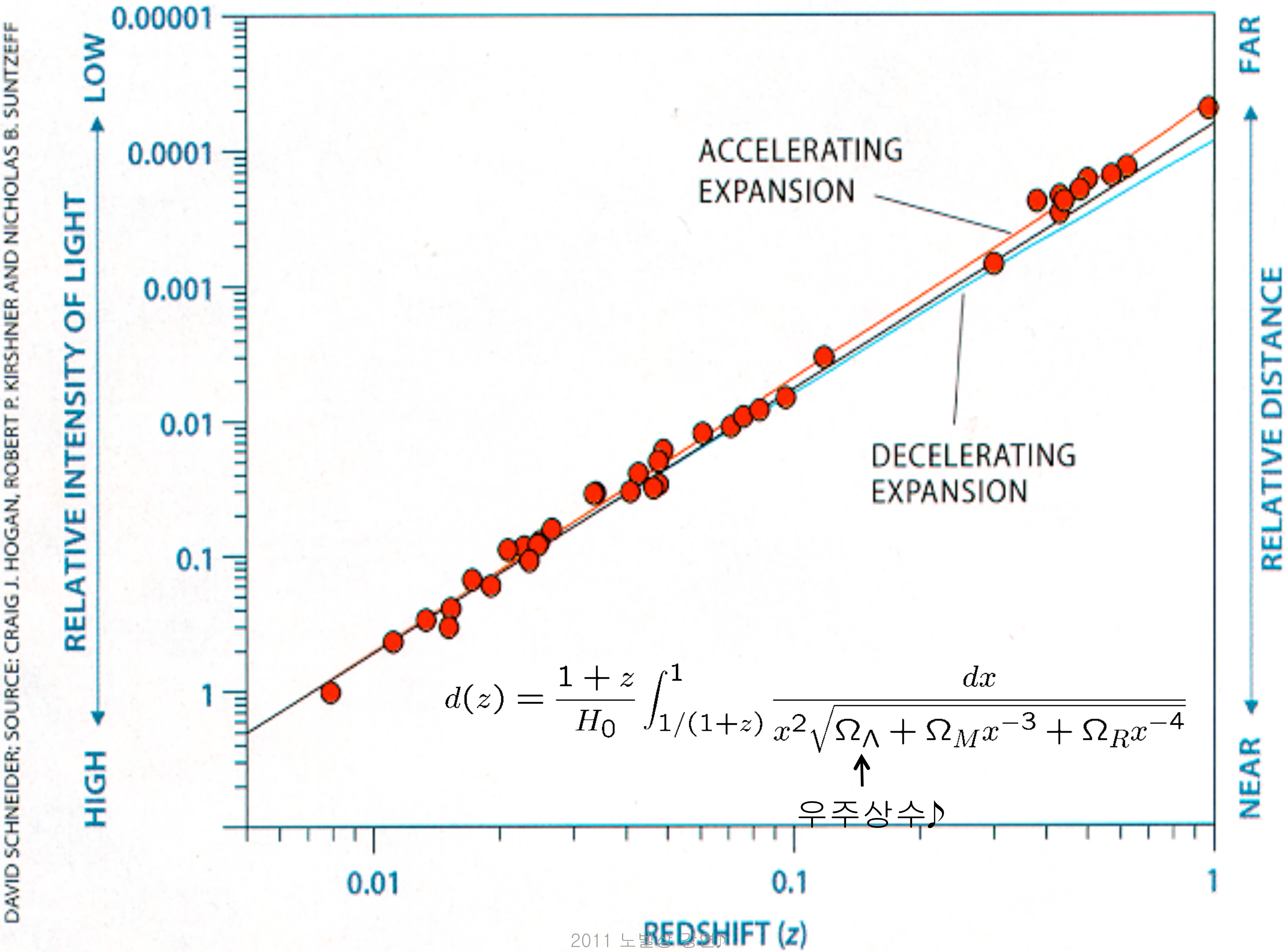


1998년 놀라운 발견

- 우주는 가속팽창을 한다!
- 가속도 = 속도가 더 빨라지는 것
- 팽창속도 자체가 점점 더 커진다.

가속될 경우♪

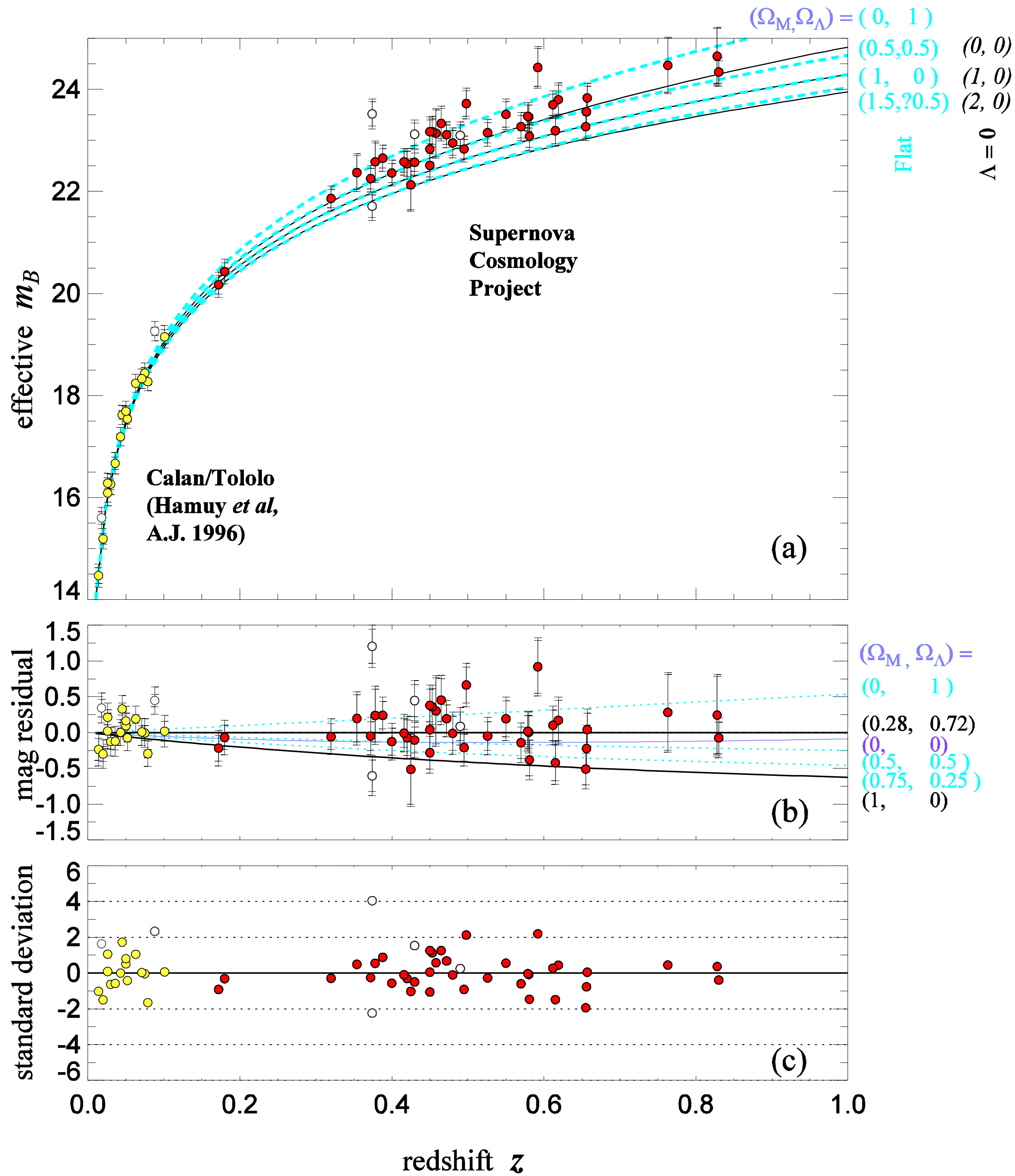

DANIELS & DANIELS
DISTANCE
VELOCITY
SLOWER STRETCHING
FASTER STRETCHING



$$d(z) = \frac{1+z}{H_0} \int_{1/(1+z)}^{1} \frac{dx}{x^2\sqrt{\Omega_\Lambda + \Omega_M x^{-3} + \Omega_R x^{-4}}}$$

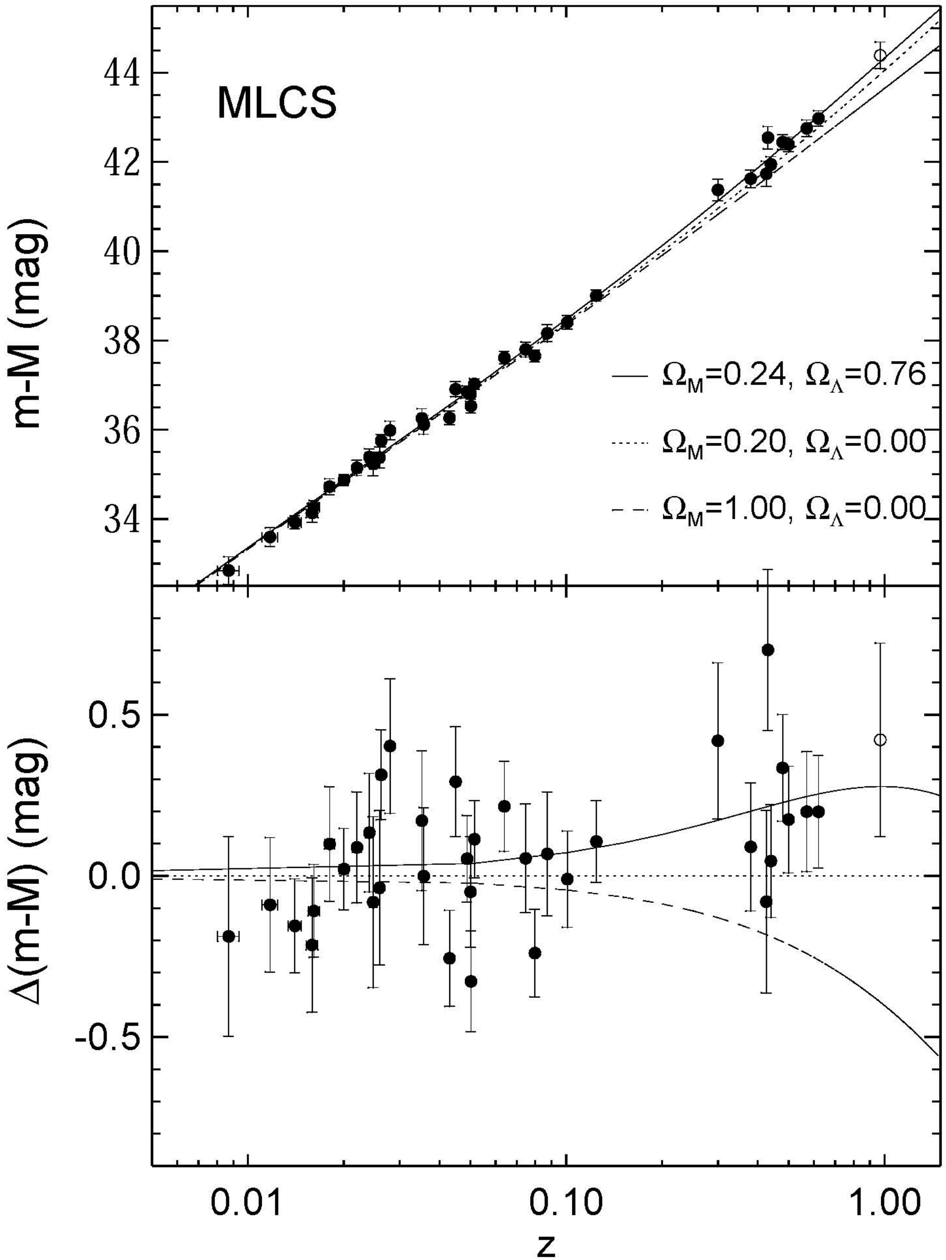
$\uparrow$

우주상수♪

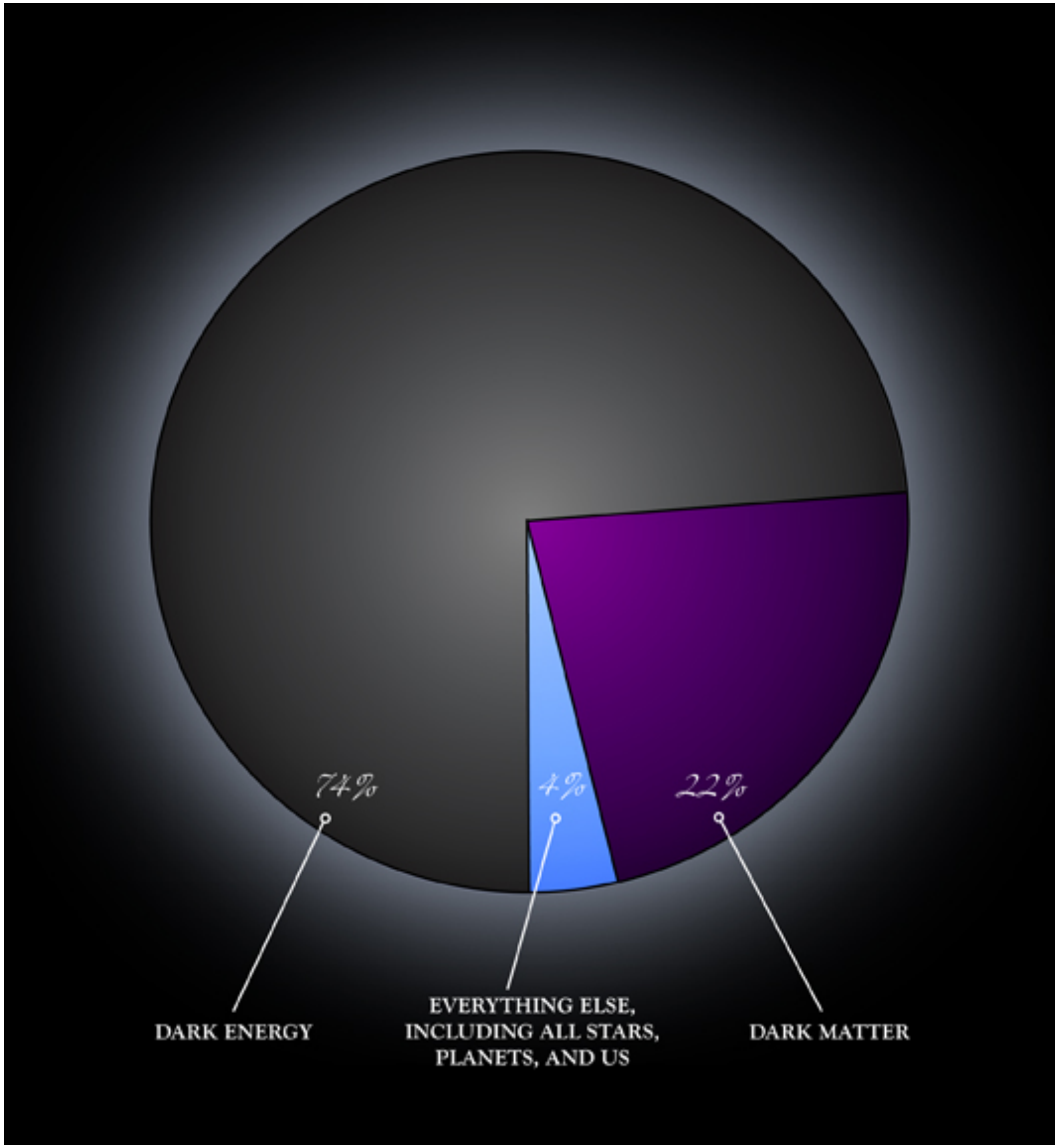


$(\Omega_M,\Omega_\Lambda) = (0, 1)$
(0.5,0.5) (0, 0)
(1, 0) (1, 0)
(1.5,?0.5) (2, 0)
Flat
$\Lambda = 0$
Supernova Cosmology Project
Calan/Tololo (Hamuy *et al*, A.J. 1996)
(a)
effective m_B
$(\Omega_M, \Omega_\Lambda) =$
(0, 1)
(0.28, 0.72)
(0, 0)
(0.5, 0.5)
(0.75, 0.25)
(1, 0)
(b)
mag residual
standard deviation
(c)
redshift z

17. 4. 10.♪



MLCS
m-M (mag)
44
42
40
38
36
34
Ω_M=0.24, Ω_Λ=0.76
Ω_M=0.20, Ω_Λ=0.00
Ω_M=1.00, Ω_Λ=0.00
Δ(m-M) (mag)
0.5
0.0
-0.5
0.01
0.10
1.00
z


74%
4%
22%
DARK ENERGY
EVERYTHING ELSE, INCLUDING ALL STARS, PLANETS, AND US
DARK MATTER

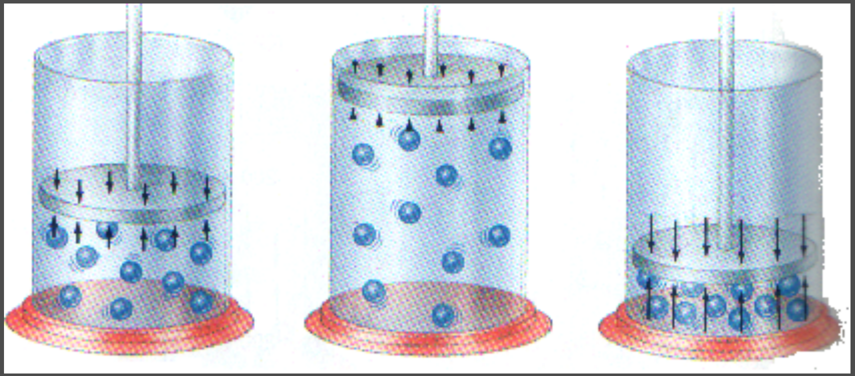
우주가속팽창의 의미

세 가지 가능성

- 우주상수가 결국 존재할 가능성
- 아인슈타인의 중력법칙이 틀렸을 가능성
- 새로운 물질의 존재 가능성
  - 암흑에너지 (Dark Energy)
  - 제5원소 (Quintessence)

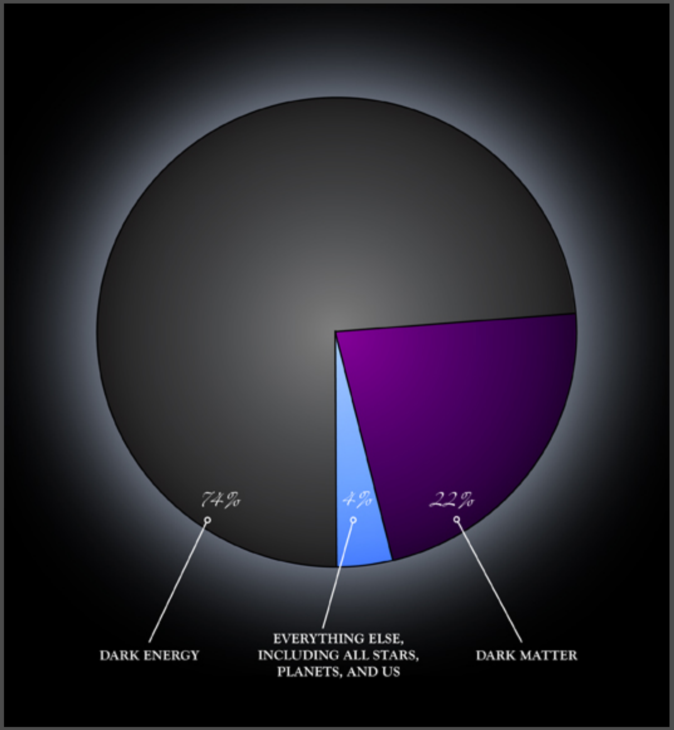
암흑에너지의 특징

- 가속팽창의 조건
- 압력이 음수



- 한번 팽창하면 계속 팽창한다

결론:
새로운 미스터리의 출현



우주에서 인류가 아는 것은 4% 뿐♪