

Dark Worlds in Astronomy: Exploring the Cosmic Mystery of Dark Matter

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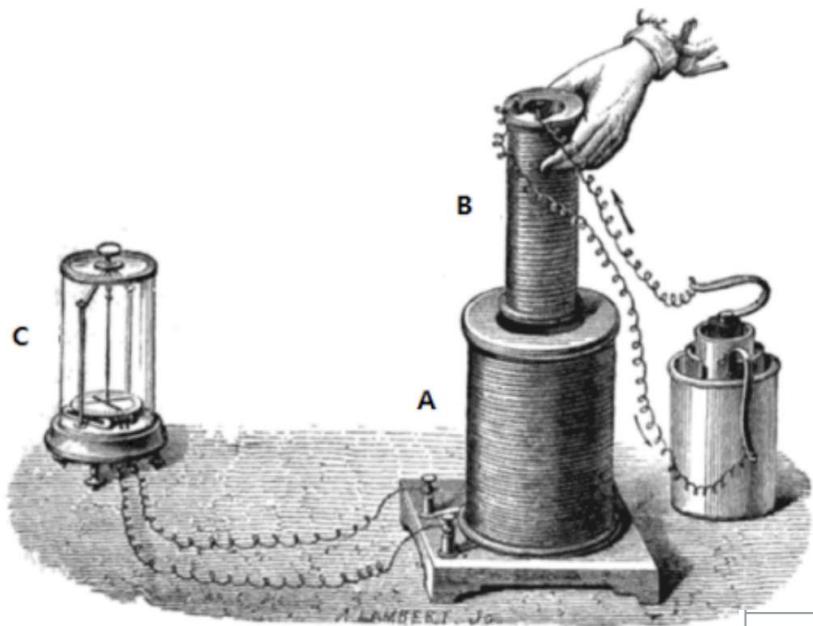


**Lecture Notes
KIAS-SNU Physics2025**

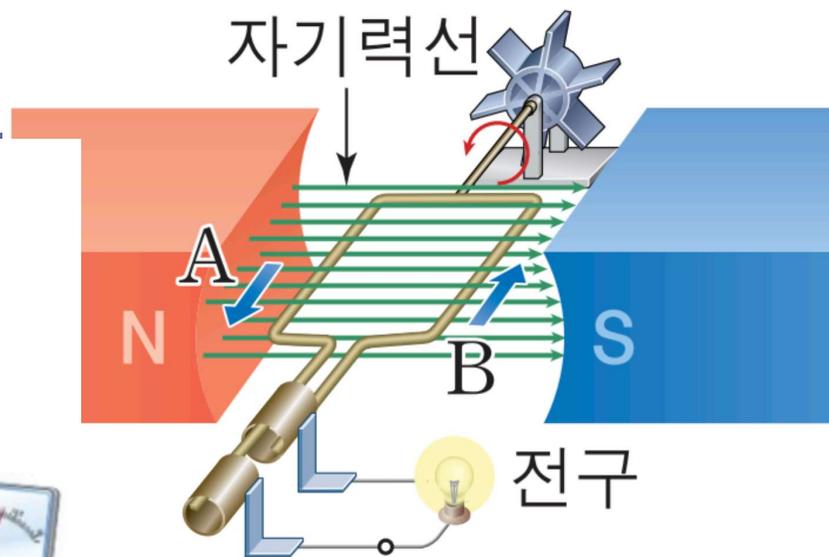
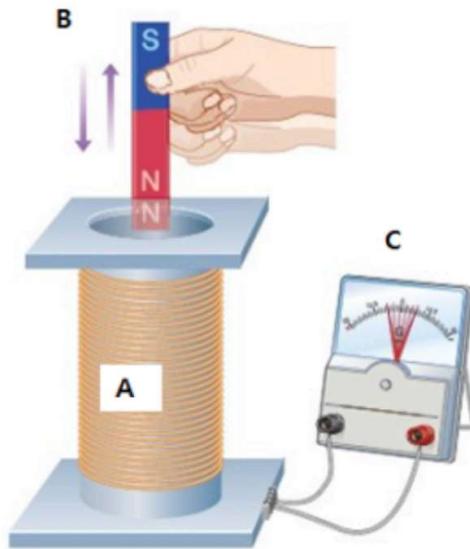
크리스마스에 과학 강연을?



크리스마스에 과학 강연을?



마이클 패러데이의 전자기 유도 실험



발전기의 기본 구성 © ZUM학습백과

패러데이 전자기 유도 법칙:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \iint_S \mathbf{B} \cdot d\mathbf{A}$$

- 패러데이는 전자기 유도와 관련된 자신의 실험을 영국 정부의 재무장관인 윌리엄 글래드스톤에게 보여 주었다.
- 장관이 이렇게 물었다. **“이게 다 어디에 쓸모가 있습니까?”** 정치인들은 동서고금을 막론하고 똑같다.
- 패러데이의 대답은 이랬다. **“어디에 쓰일지는 저도 잘 모르겠습니다만, 아마도 장관께서 여기에 세금을 매길 수 있을 겁니다.”**

크리스마스에 과학 강연을?

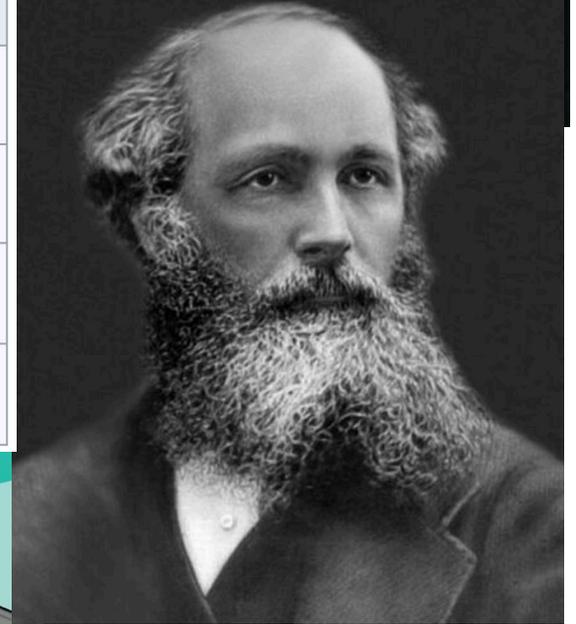


1856년 크리스마스 강연을 하는 마이클 패러데이

➤ Maxwell Equation

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = 4\pi \iiint_{\Omega} \rho dV$	$\nabla \cdot \mathbf{E} = 4\pi\rho$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{1}{c} \frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \frac{1}{c} \left(4\pi \iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S} \right)$	$\nabla \times \mathbf{B} = \frac{1}{c} \left(4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} \right)$

James Clerk Maxwell
(13 Jun. 1831 - 5 Nov. 1879)



Saturn's Rings

The subject of the 1856 University of Cambridge Adams Prize was "*The Motion of the Rings of Saturn*".

Different hypotheses were given regarding the rings, namely that the rings were:

- (i) rigid
- (ii) fluid or partly gaseous, or
- (iii) composed of isolated masses.

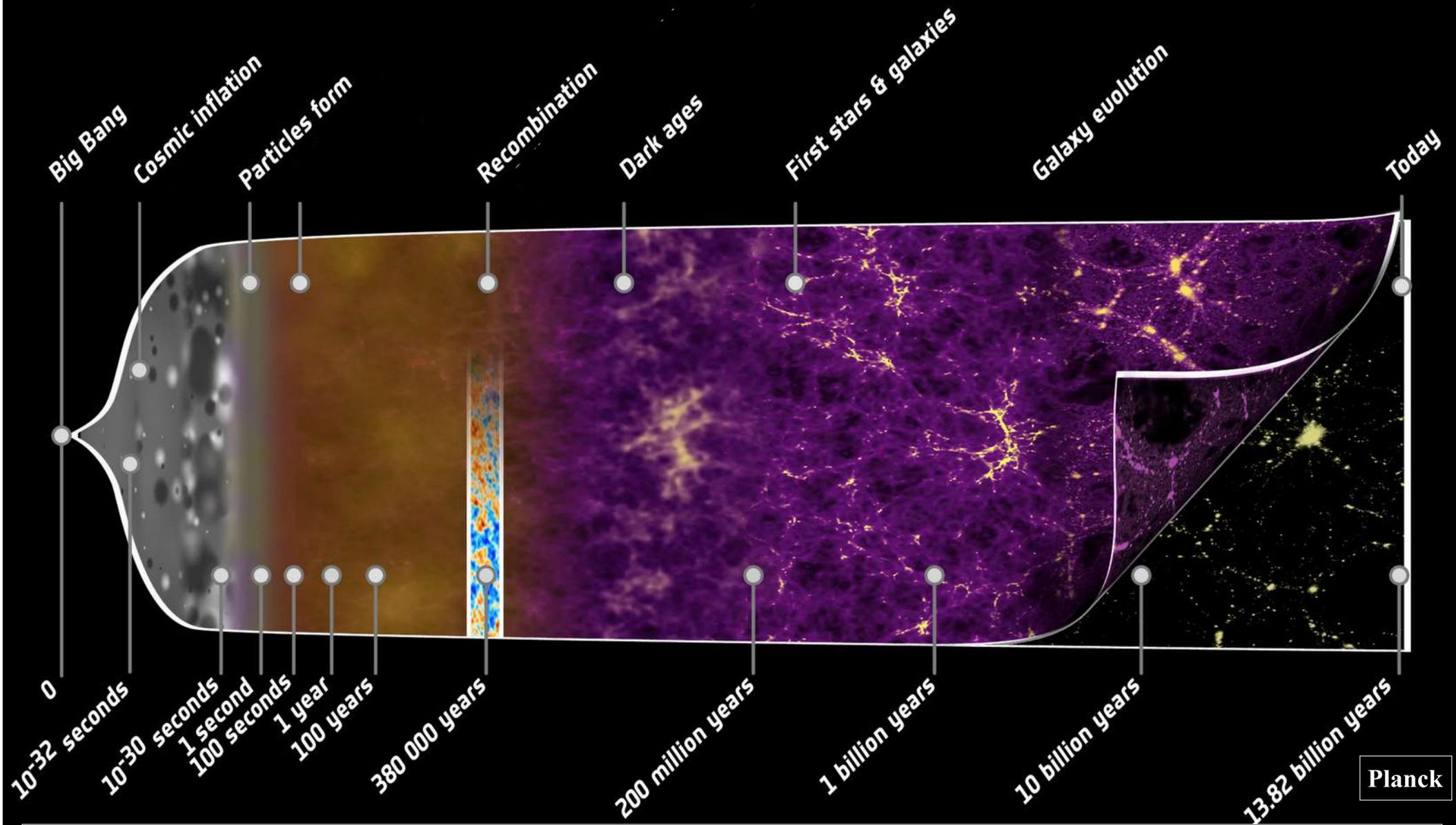
Maxwell and the other candidates were asked which of these hypotheses would be mechanically stable.



Image courtesy of NASA

- Maxwell's essay won the 1856 Adams Prize - demonstrating his powerful ability to analyse a difficult problem mathematically.
- Maxwell is rightly commemorated by having a feature of the Rings of Saturn named after him - the 'Maxwell Gap' within the C ring.

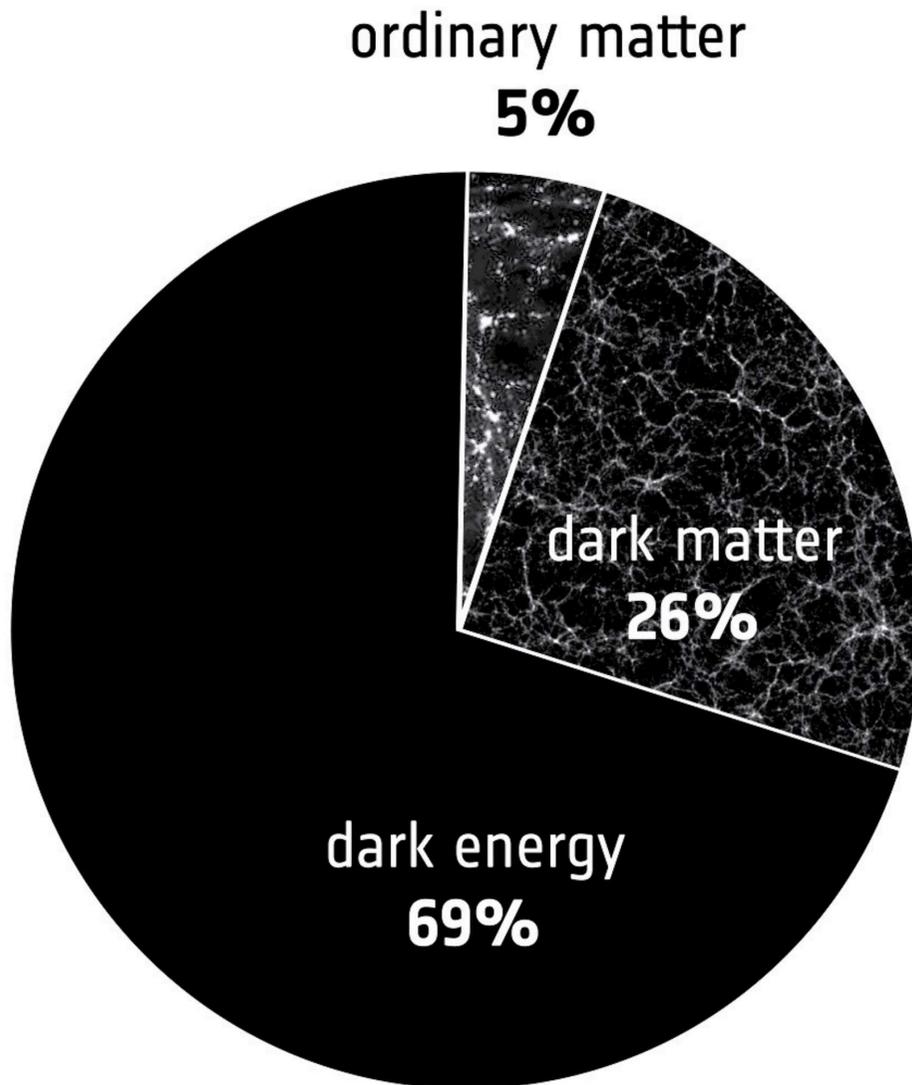
History of the Universe



We think we live in the Universe that can be described by a standard cosmological model.

Standard Cosmological Model

- 우주는 138억년 전에 무한한 크기로 생겨나서 영원히 팽창하게 된다.
- 그 안에는 암흑 에너지, 암흑 물질, 보통의 물질(중입자 또는 baryon), 중성미자 등이 담겨 있고, 큰 규모에서 봤을 때는 균질하고 등방한데, 작은 규모에서는 우주 초기의 밀도 요동에서 성장한 천체들이 자리잡고 있다.
 - => Λ CDM (cosmological constant + Cold Dark Matter) model
- 우주는 본래 무한한데, 우리가 (빛을 통해) 관측 가능한 크기는 빛의 속도가 유한하기 때문에 유한하다. 이 관측 가능한 우주의 크기는 빛이 우주의 나이인 138억년 동안 달리기 시작한 곳까지의 현재 시점에 정의된 거리에 해당하는데, 우주가 팽창하기 때문에 단순히 138억 광년이 아니라 약 470억 광년에 해당한다.



➤ **Dark matter**

- non-luminous, non-baryonic component that interacts gravitationally.
- required to explain a wide range of astrophysical observations that cannot be reproduced by baryons + GR alone.

➤ **Dark energy**

- smooth component with negative pressure with a negative (how much?) equation-of-state parameter $w = p/\rho$.
- required to explain the accelerating expansion of the Universe.

Cosmological Parameters

Q: How many parameters do we need to describe our universe?

Big Bang: Nucleosynthesis/
Cosmic Microwave Background

**Gravitational
Instability:**
Large-Scale Structure/
CMB power spectrum

Inflation:
isotropy/
flatness

**Standard
Cosmological
Model**

Λ CDM

**Cosmological
Constant, Λ
(dark energy):**
accelerating expansion

Cold Dark Matter:
hierarchical structure
formation

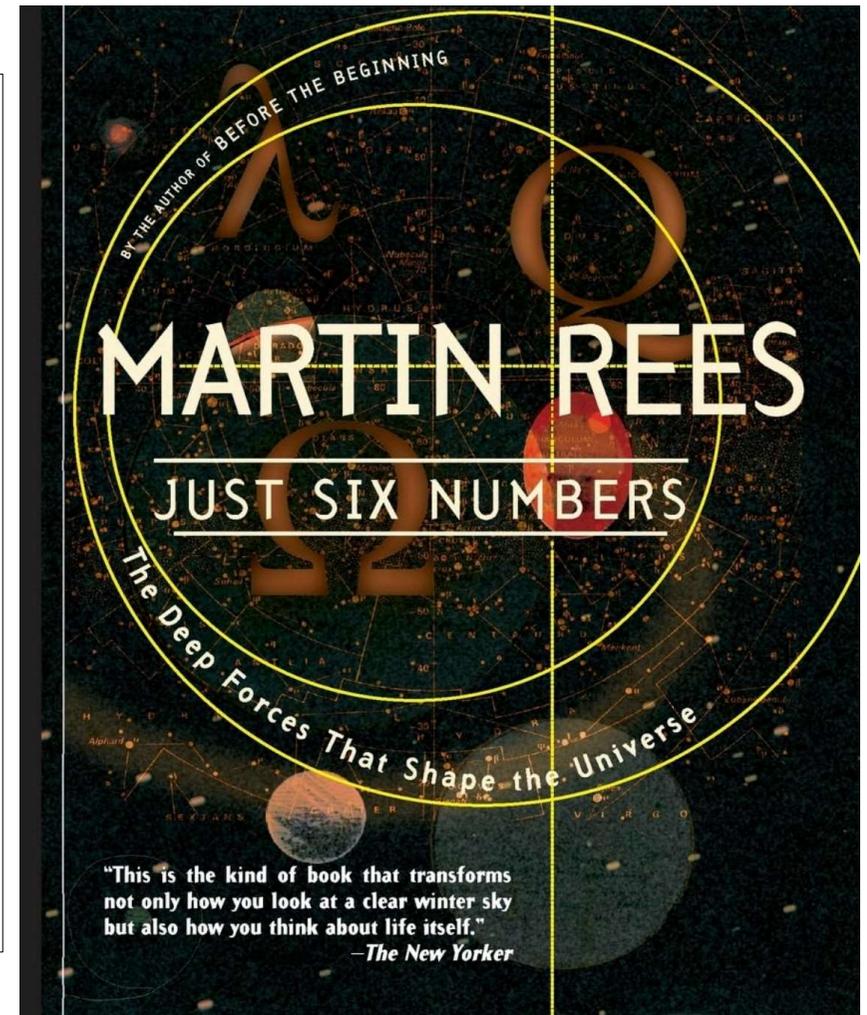
Based on General Relativity

Cosmological Parameters

The Standard Cosmological Model

1. N : strength of the electrical forces that hold atoms together, divided by the force of gravity between them: 10^{36}
2. ϵ : fraction of mass that converts into energy during hydrogen fusion: 0.7%
3. Ω : cosmic mass/energy density: 1
4. Λ : cosmological parameter: >0
5. Q : ratio of the energy needed to break up the most conspicuous structures in the universe (stars, galaxies and galaxy clusters) to their total rest-mass energy: 10^{-5}
6. D : number of spatial dimensions: 3

The fifteenth Astronomer Royal,
Martin Rees, Baron Rees of Ludlow



Cosmological Parameters

Planck+2018

The parameters of the base model

Table 7. Parameter confidence limits from *Planck* CMB temperature, polarization and lensing power spectra, and with the inclusion of BAO data. The first set of rows gives 68 % limits for the base- Λ CDM model, while the second set gives 68 % constraints on a number of derived parameters (as obtained from the constraints on the parameters used to specify the base- Λ CDM model). The third set below the double line gives 95 % limits for some 1-parameter extensions to the Λ CDM model. More details can be found in [Planck Collaboration VI \(2018\)](#).

Parameter	<i>Planck</i> alone	<i>Planck</i> + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_* [Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag} [Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq} [Mpc $^{-1}$]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

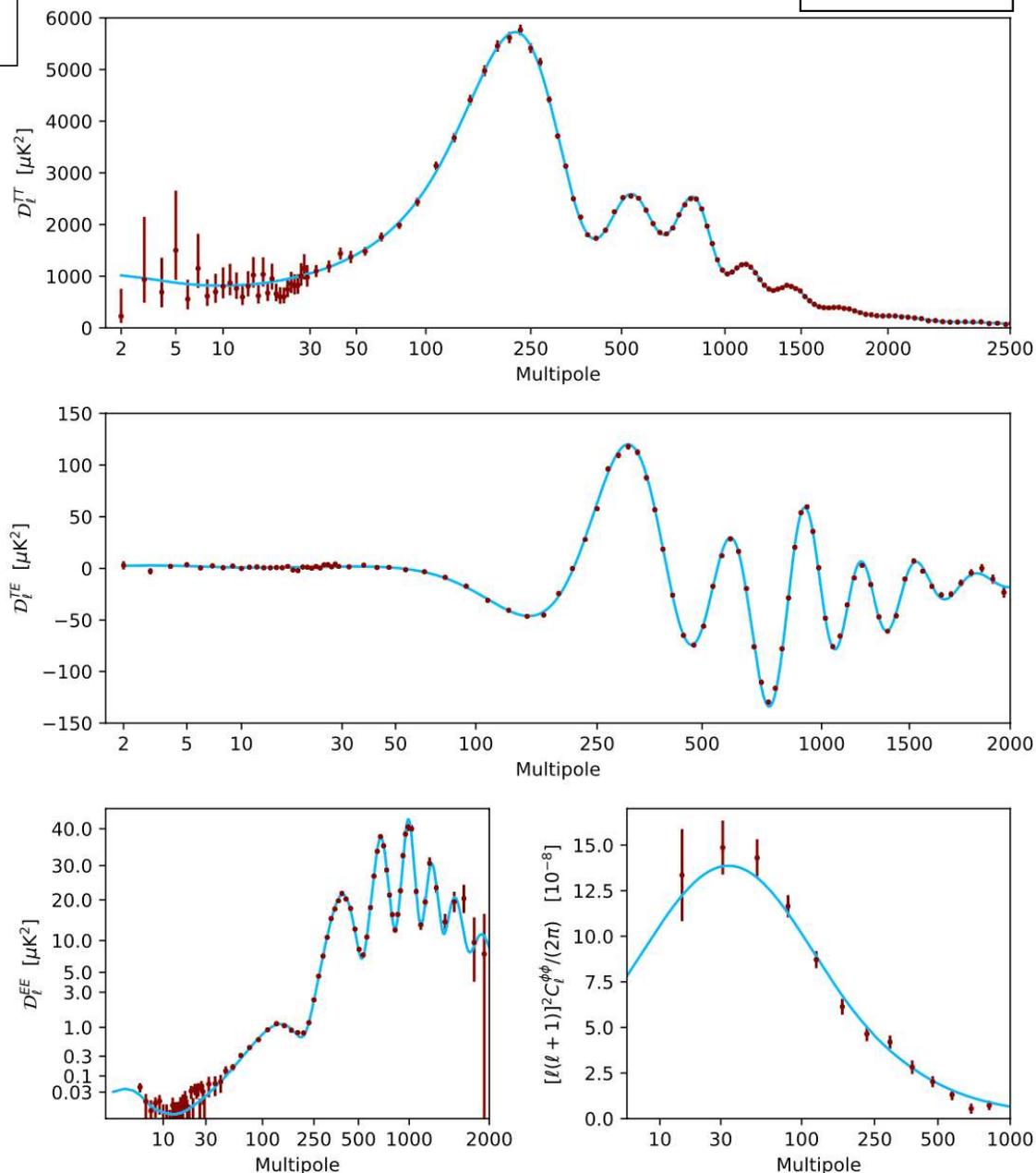


Fig. 9. *Planck* CMB power spectra. These are foreground-subtracted, frequency-averaged, cross-half-mission angular power spectra for temperature (top), the temperature-polarization cross-spectrum (middle), the E mode of polarization (bottom left) and the lensing potential (bottom right). Within Λ CDM these spectra contain the majority of the cosmological information available from *Planck*,

8.7 Cosmological Parameters

8.7.2 The parameters of the base model

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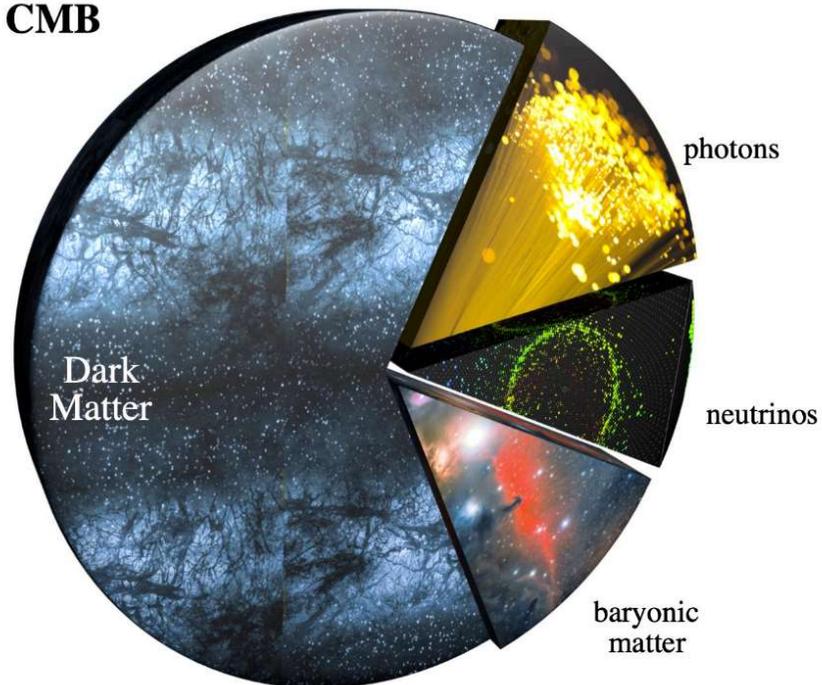
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3.1 Assumptions underlying Λ CDM:

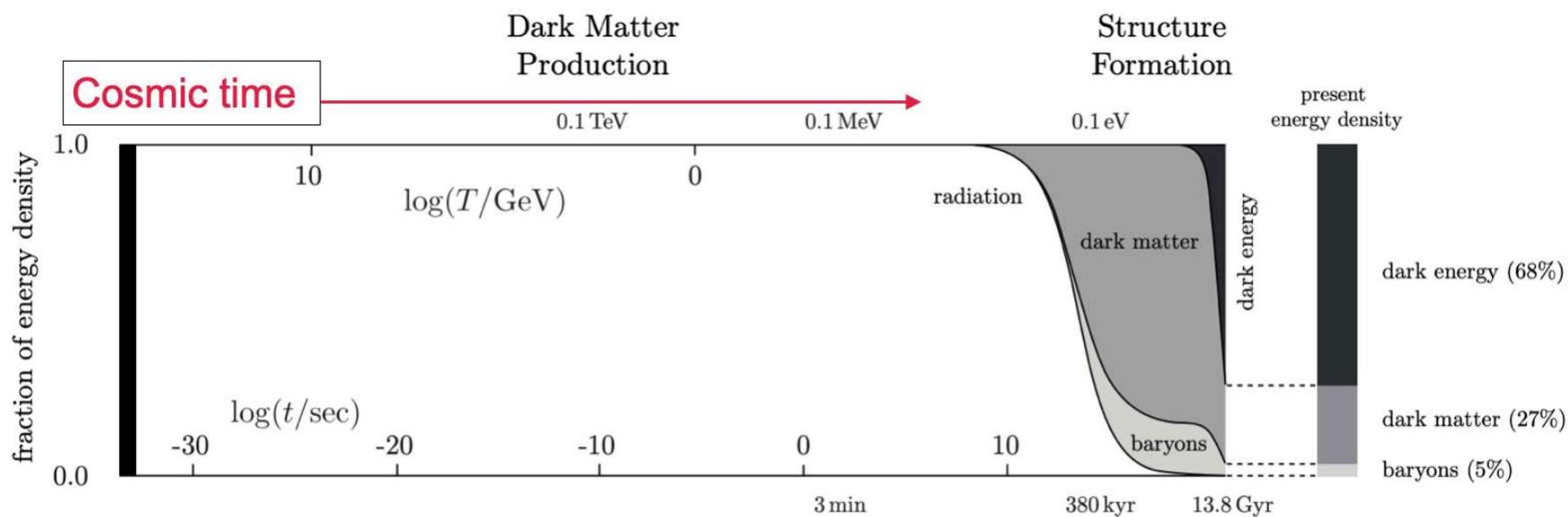
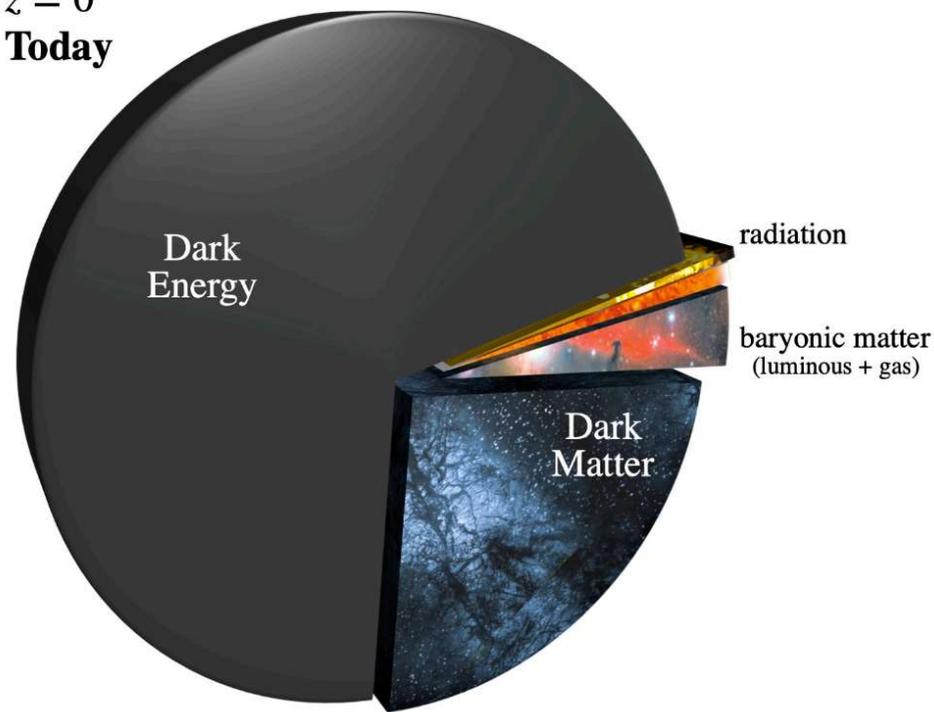
- 1) Physics is the same throughout the observable Universe.
- 2) General Relativity (GR) is an adequate description of gravity.
- 3) On large scales the Universe is statistically the same everywhere (initially an assumption, or “principle,” but now strongly implied by the near isotropy of the CMB).
- 4) The Universe was once much hotter and denser and has been expanding since early times.
- 5) There are five basic cosmological constituents:
 - 1) Dark energy that behaves just like the energy density of the vacuum.
 - 2) Dark matter that is pressureless (for the purposes of forming structure), stable and interacts with normal matter only gravitationally.
 - 3) Regular atomic matter that behaves just like it does on Earth.
 - 4) The photons we observe as the CMB.
 - 5) Neutrinos that are almost massless (again for structure formation) and stream like non-interacting, relativistic particles at the time of recombination.
- 6) The curvature of space is very small.
- 7) Variations in density were laid down everywhere at early times, and are Gaussian, adiabatic, and nearly scale invariant (i.e., proportionally in all constituents and with similar amplitudes as a function of scale) as predicted by inflation.
- 8) The observable Universe has “trivial” topology (i.e., like R³). In particular it is not periodic or multiply connected.

Standard Cosmological Model

$z \simeq 1100$
CMB



$z = 0$
Today



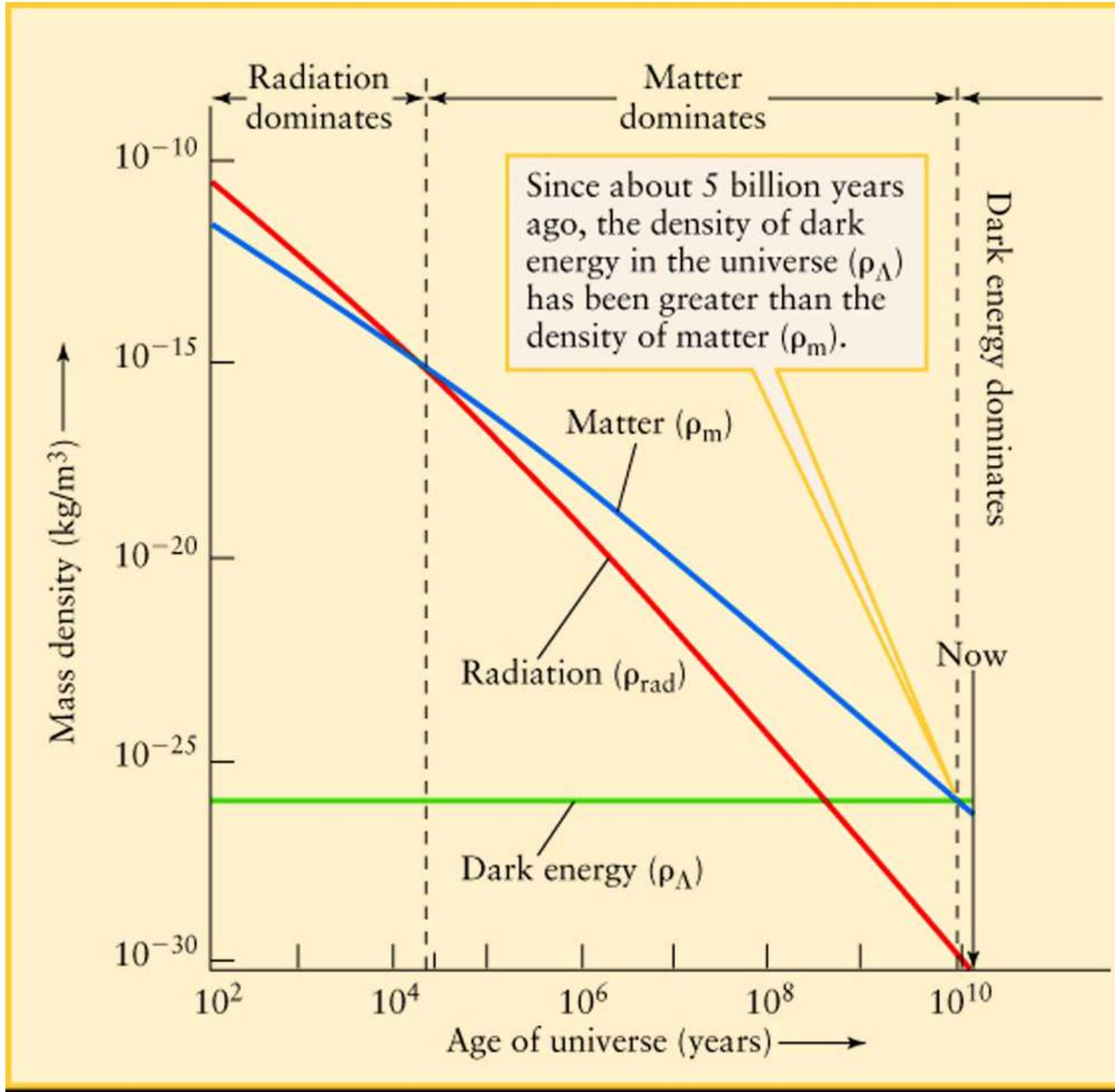
Inflation
(Chapters 2 and 6)

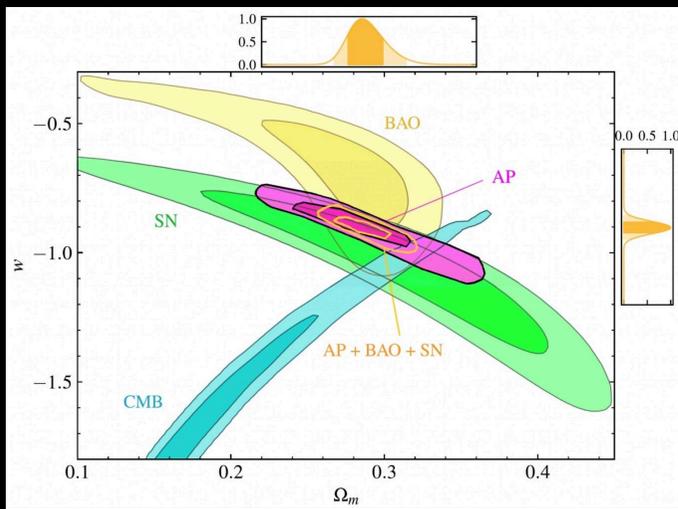
Big Bang
Nucleosynthesis

Cosmic Microwave
Background

Baumann+

The Standard Cosmological Model: Λ CDM





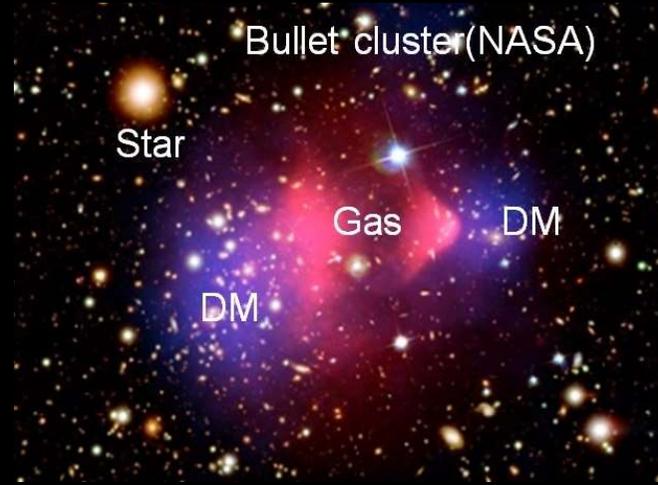
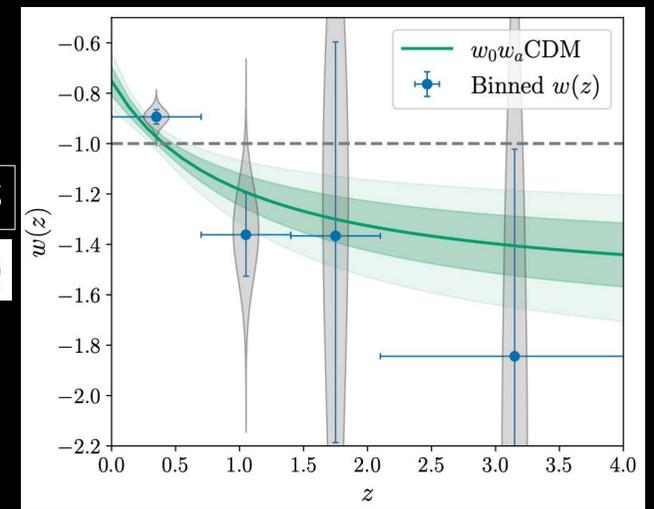
Dong+2023 (4.2 σ difference):

$$w = -0.903^{+0.023}_{-0.023} \text{ and } \Omega_m = 0.285^{+0.014}_{-0.009}$$

$$w(z) \equiv P(z)/(c^2 \rho_{\text{DE}}(z))$$

DESI+2025

$$w(a) = w_0 + w_a(1 - a)$$



**Standard
Cosmological
Model**

Λ CDM

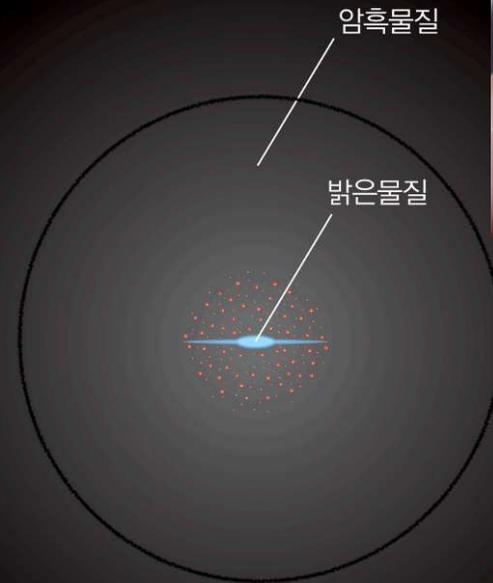
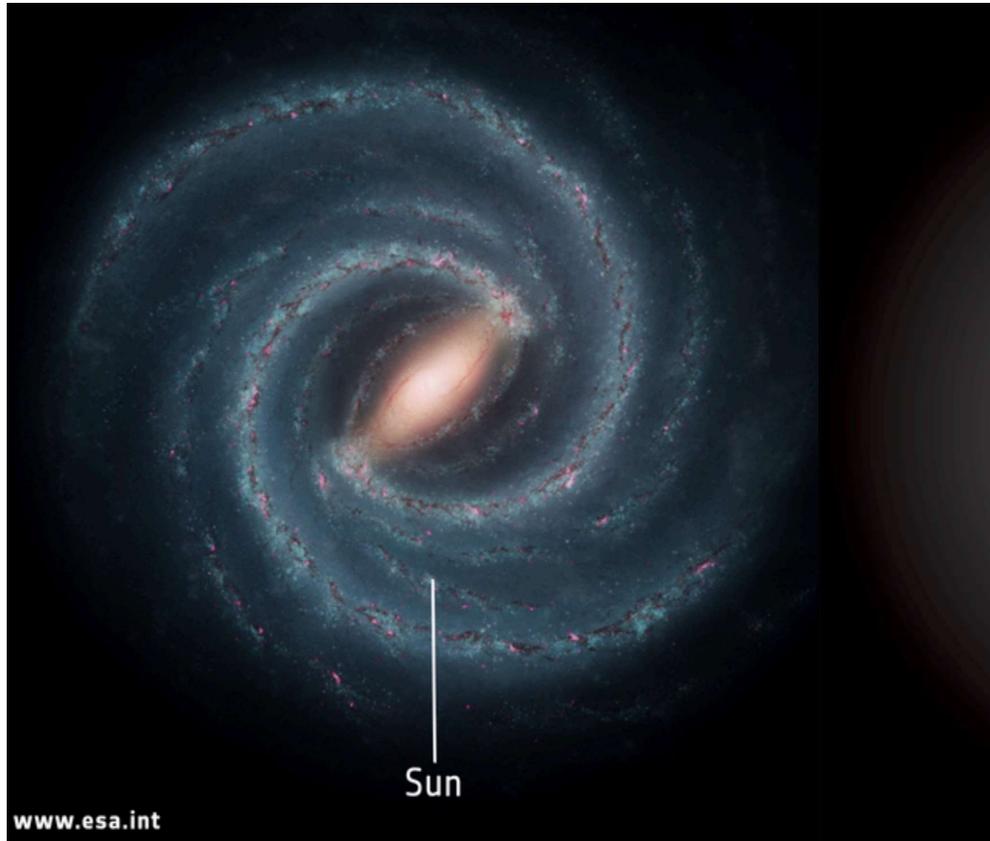
Problems in Λ CDM?

1. **Dark energy is not constant over time any more?**
e.g. **wCDM**
2. **Do we still need dark matter?**
e.g. **MOND, emergent gravity**
3. **Tensions with observations**
 1. **Missing Satellite Problem**
 2. **H_0 tension**
 3. **No direct detection of dark matter on Earth**
 4. **...**

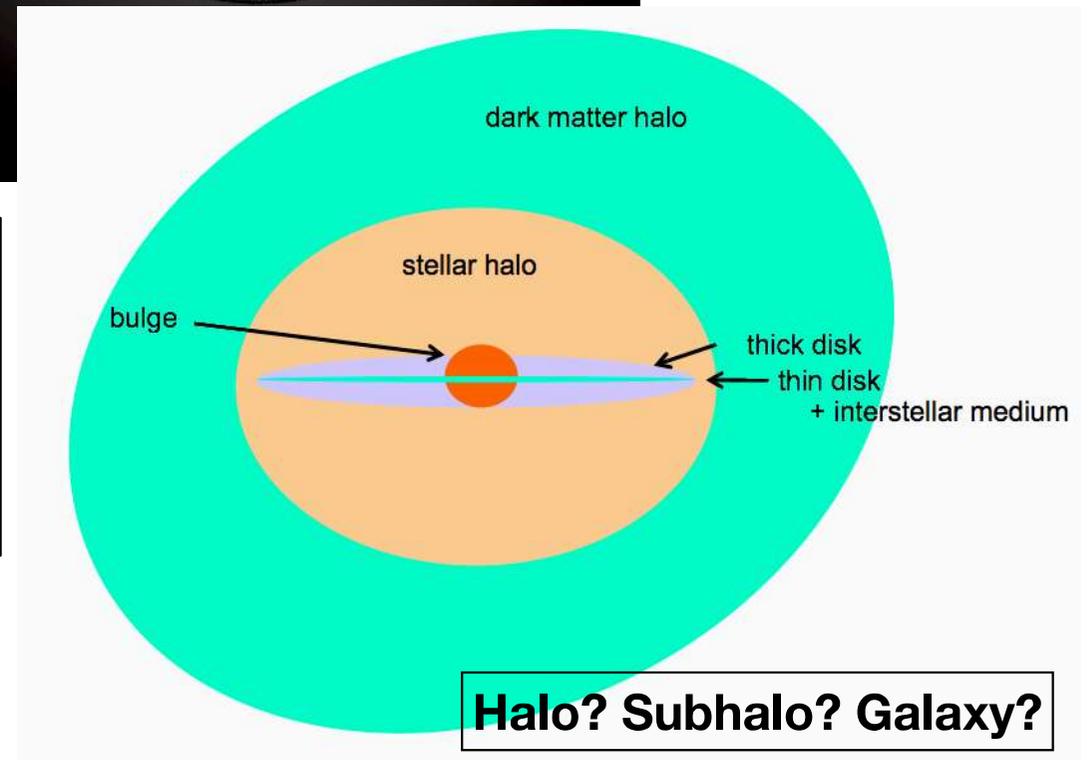
Q: How can we study invisible Dark Components?



Galaxy: A key to study dark components



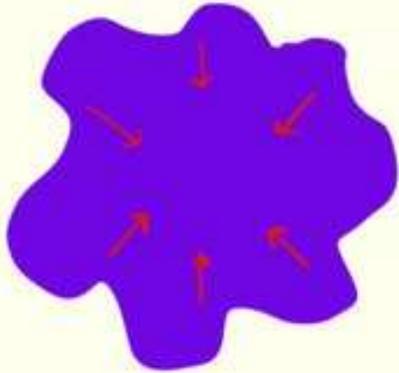
- * In a galaxy (e.g. $M_{\text{total}}(\text{Milky Way}) \sim 1 \times 10^{12} M_{\text{sun}}$)
- * Dark matter: $\sim 94\%$ (mass)
- * Stars: $\sim 5\%$
- * Gas/dust: $\sim 1\%$
- * Black hole: $\sim < 0.1\%$



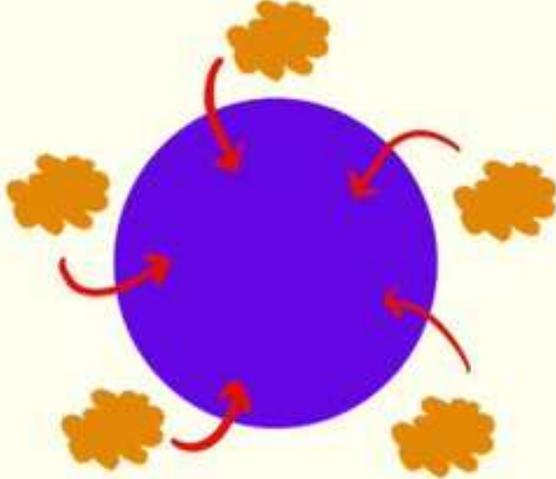
Dark Matter: purple
Gas: orange
Stars: yellow

Theory Of Galaxy Formation

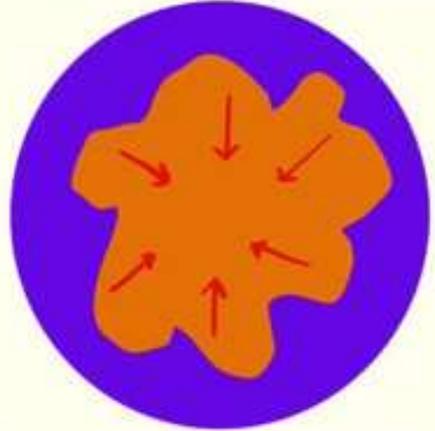
(not to scale)



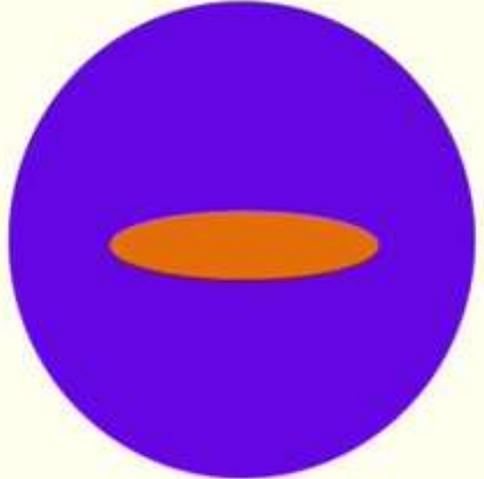
DM Halo collapse



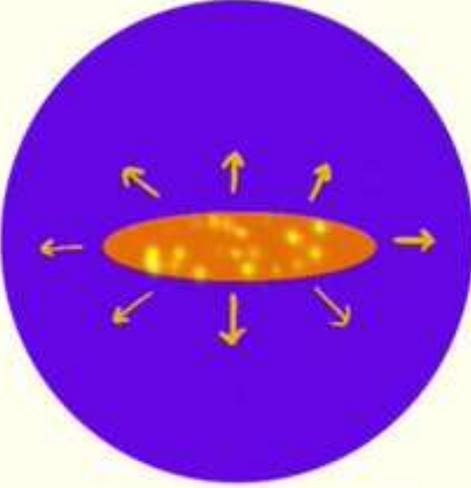
Gas infall & heating



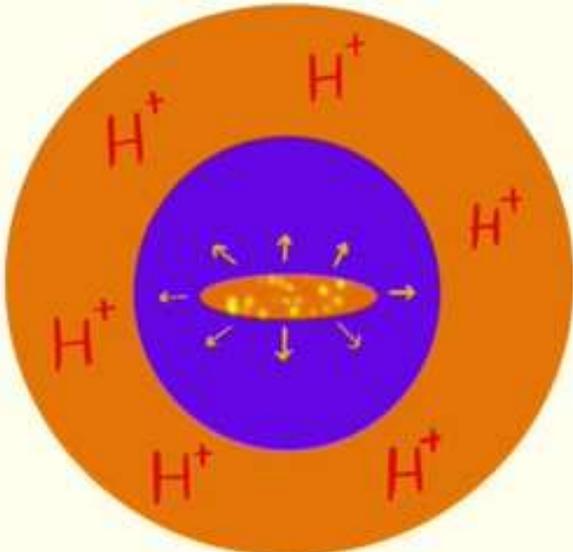
Gas cools + collapses



Dense gas clouds



Star formation + feedback



Ionised Hydrogen

Galaxy Formation Simulations: Small Scales

Gas (Hydrogen)

Dark Matter

Star

Gas

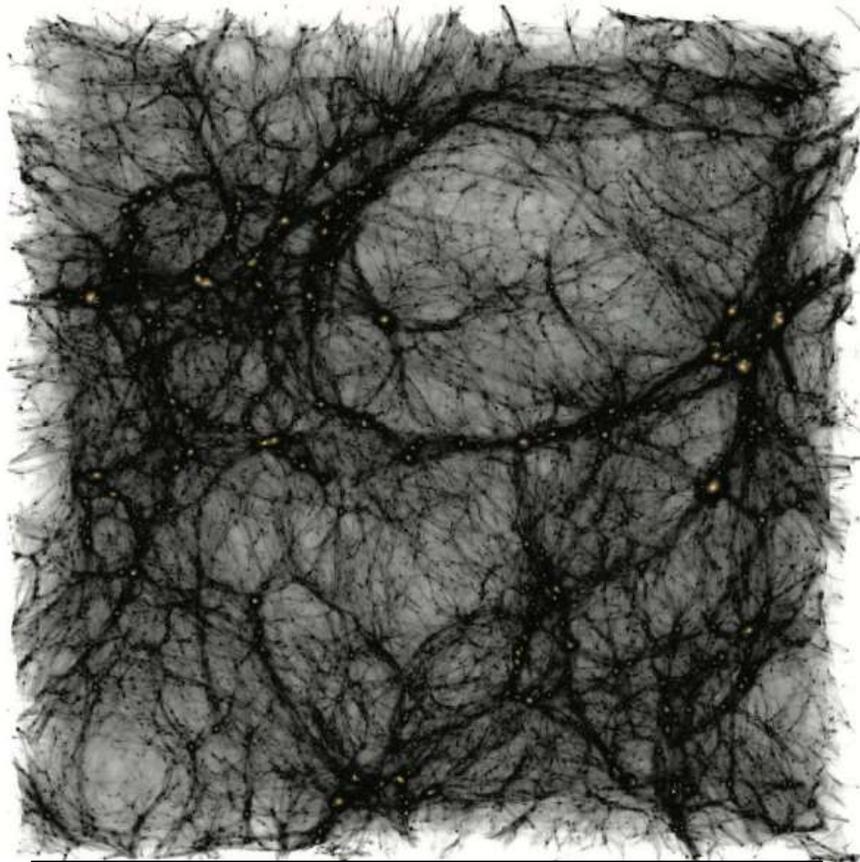
Galaxy Formation Simulations: Large Scales

Horizon Run 5 Simulation – Formation of a Massive Cluster of Galaxies

Korea Institute for Advanced Study
Korea Astronomy and Space Science Institute
Korea Institute of Science and Technology Information
Institut d'astrophysique de Paris
University of Hull
University of Oxford

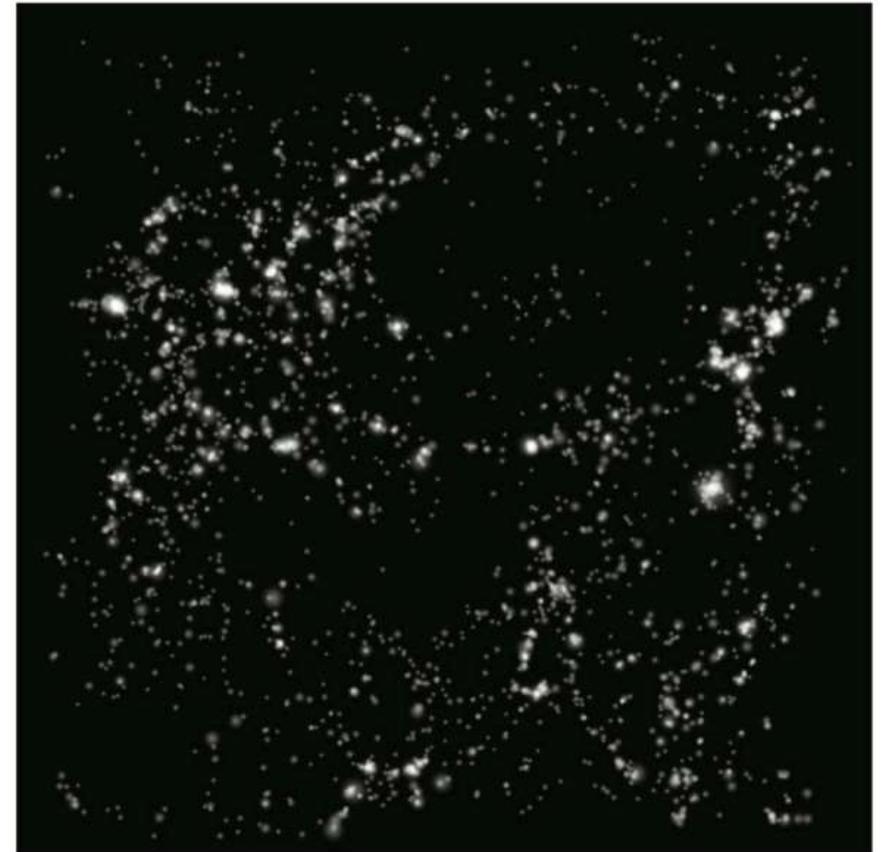
Dark Matter vs. Galaxies

Wechsler & Tinker (2018)



Dark matter distribution (invisible)

Galaxy-halo
connection

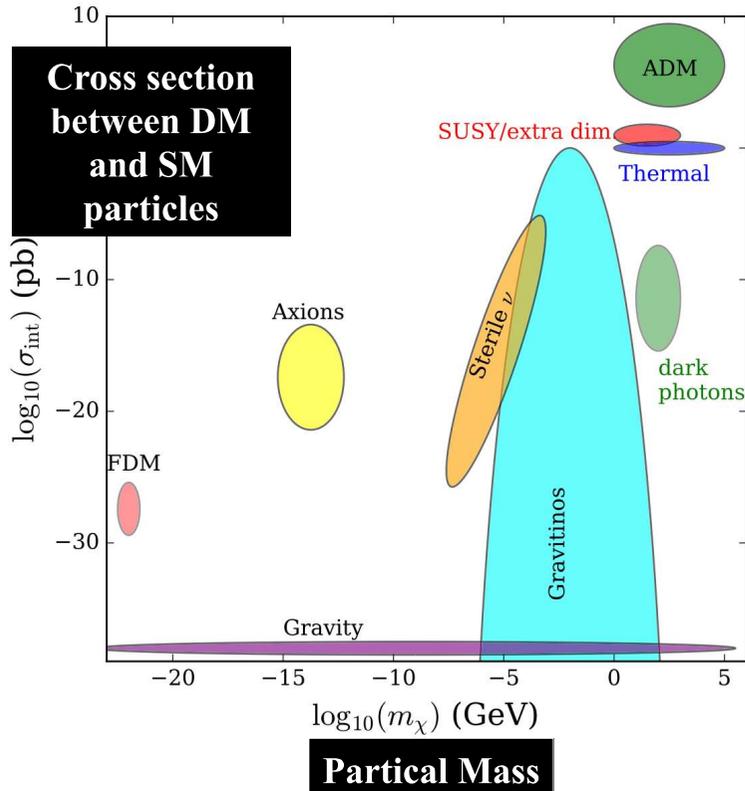


Galaxy distribution (visible)

Q: What is the role of dark matter in the formation and evolution of galaxies?

Dark Matter Studies

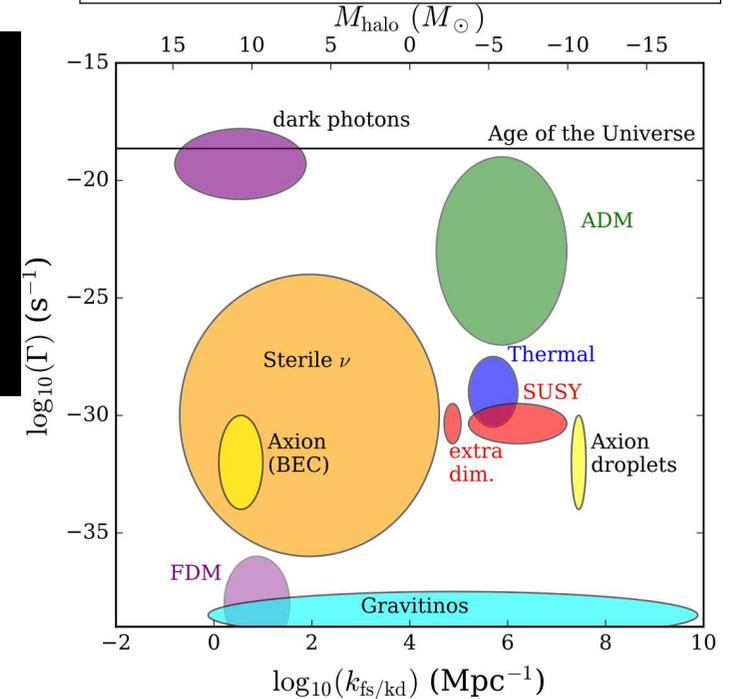
➤ For Particle Physicists



Buckley & Peter 2018

Evolutionary effects on DM halos and cosmology according to a characteristic interaction or decay rate

➤ For Astronomers



Primordial effects in terms of characteristic Free-Streaming Wavenumber

We would like to constrain physical parameters from experiments/observations.

So, we would like to know the nature of dark matter in the end.



Goal of this lecture:

To understand 1) why we need dark matter,
2) what we know about it, & 3) what to do with it!

➤ Part 1: History of Dark Matter

- Ref: Bertone & Hooper 2018, Rev. Mod. Phys. 90, 045002

➤ Part 2: Dark Matter Models

➤ Refs:

- “Dark Matter” by Cirelli+2024 (arXiv:2406.01705)
- “Small-Scale Challenges to the Λ CDM Paradigm” by James S. Bullock and Michael Boylan-Kolchin (2017, Annu. Rev. Astron. Astrophys., 55, 343)

➤ Part 3: Dark Mater Studies in practice

➤ General Refs:

- “Gravitational probes of dark matter physics” by Buckley & Peter (2018, Physics Reports, 761, 1)
- “Dark Matter” by Cirelli+2024 (arXiv:2406.01705)

1. A History of Dark Matter

arXiv:1605.04909 — Bertone & Hooper

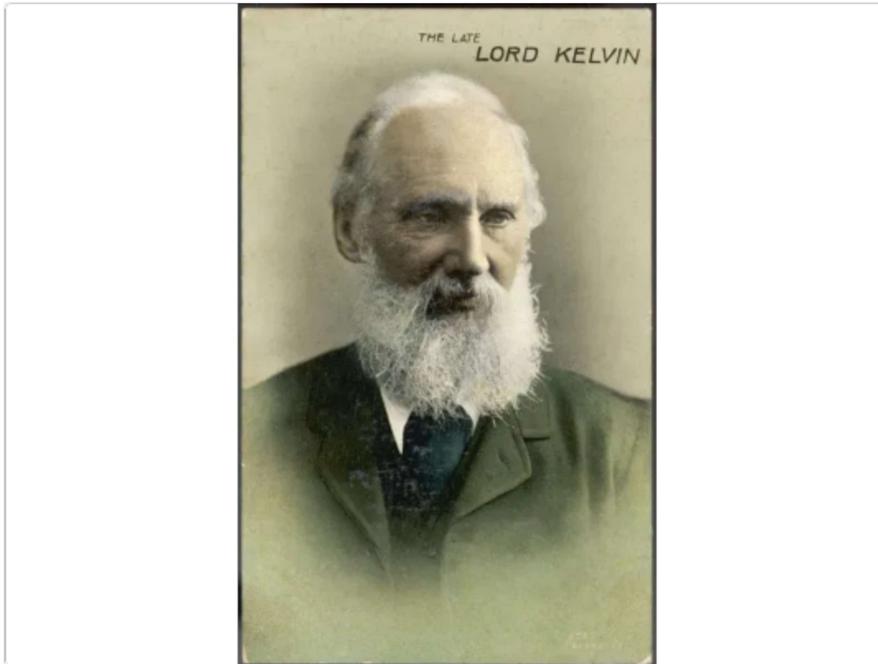
From the 19th Century to the Precision Era

- **Why do need to know the history of dark matter?**
 - *“Those who cannot remember the past are condemned to repeat it.”
- George Santayana*
 - *“Science advances one funeral at a time.” - Max Planck*

I. Prehistory (1884—1932)

Lord Kelvin, Henri Poincaré, and the
Oort Limit

1884: LORD KELVIN'S BALTIMORE LECTURES



William Thomson (Lord Kelvin) was among the first to apply the **Kinetic Theory of Gases** to stellar systems.

- Used stellar velocity dispersions to "weigh" the Milky Way.
- Acknowledged the possibility of "dark bodies" far outnumbering visible stars.
- His estimate of 1 billion stars was remarkably close to current galactic mass models.

1906: "MATIÈRE OBSCURE"

Responding to Kelvin's work in "The Milky Way and the Theory of Gases," Henri Poincaré provides the first linguistic anchor for the field.



The Term

Poincaré coins the phrase "*matière obscure*" (Dark Matter) in the context of Kelvin's dark bodies.

The Finding

He noted that if dark matter existed, it must not be significantly more abundant than visible matter.

The Legacy

This established the "Dark Matter" problem as a quantitative dynamical question.

1922: KAPTEYN AND STELLAR MOTION

Dutch astronomer Jacobus Kapteyn studied the motions of stars perpendicular to the galactic plane.

- Aimed to find the vertical acceleration toward the disk.
- Attempted to reconcile the number of stars with the total vertical force.
- Found no major evidence for dark matter locally (Ratio ~ 1).



My aim in the present paper is simply to get hold of some approximate information about the real structure and motion of the system, and quantitative accuracy has been considered of secondary

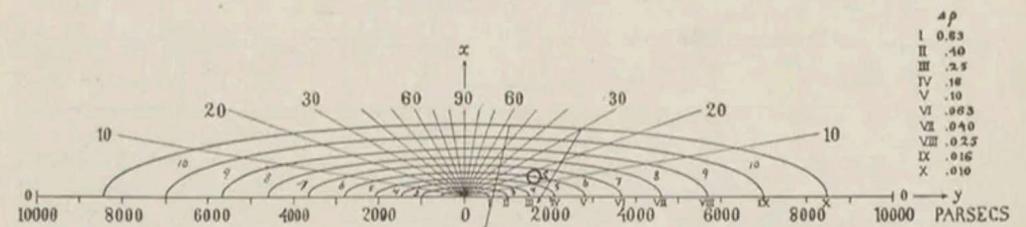


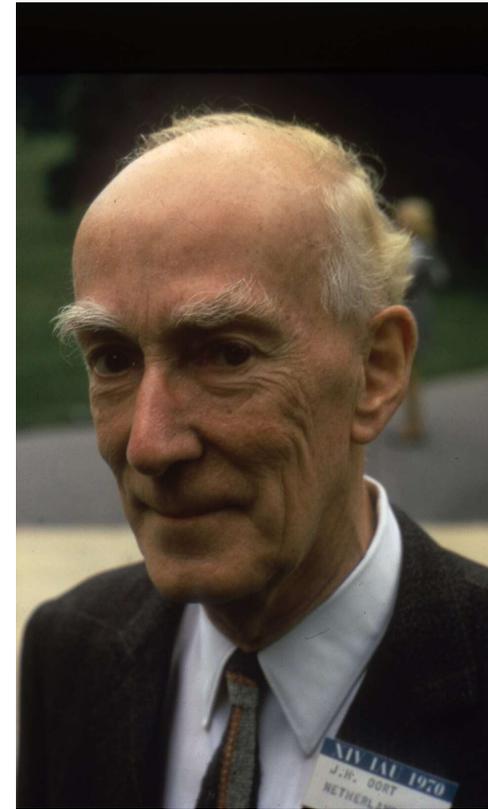
FIG. 1

importance as long as we may hope that the main features are not affected. I trust that this hope will not be disappointed, notwithstanding the many defects—defects that will be duly pointed out—which still attach to the present treatment.

1932: THE OORT LIMIT

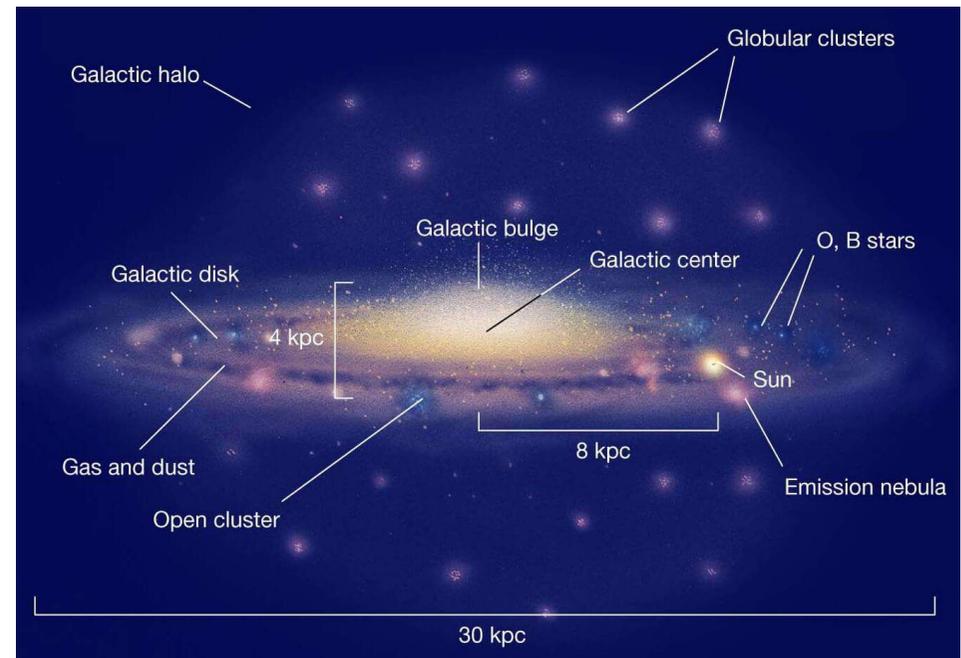
Jan Oort's 1932 study is often cited as the "start" of the dark matter problem, though his findings were complex.

- His analysis indicated that the total density, found from dynamical data, exceeds the density of visible stellar populations by a factor of up to 2. This limit is often called the Oort limit.
- This suggested significant "local" dark matter, later found to be an artifact of star distance errors.

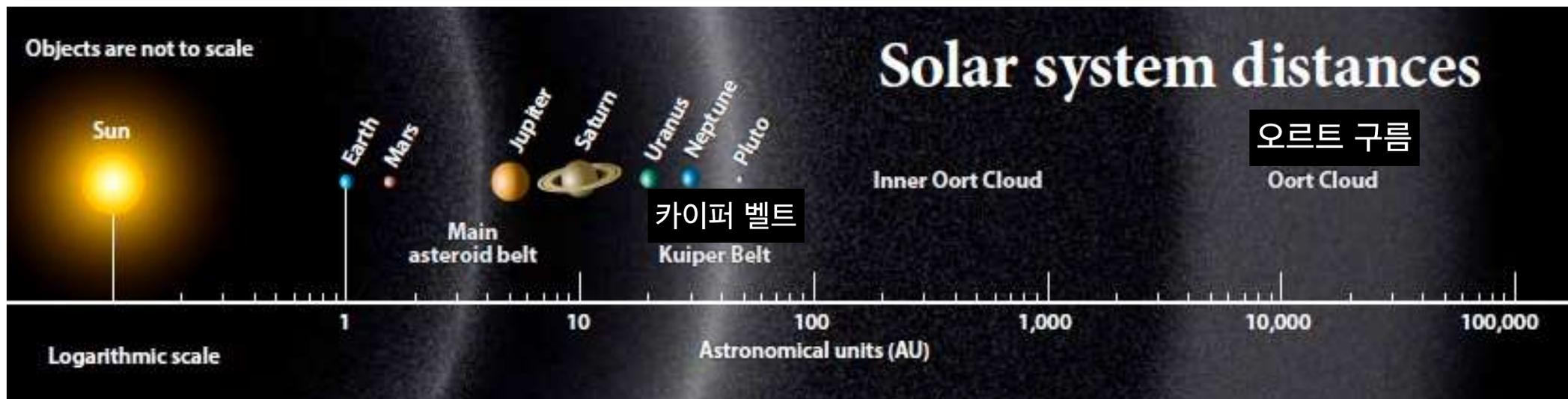


Systematic Error

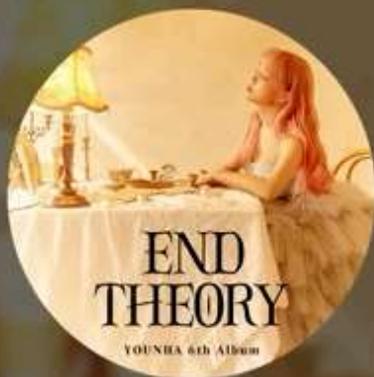
Oort's finding of 2x more dark mass than visible was eventually debunked by better stellar distance calibrations.



Oort Cloud

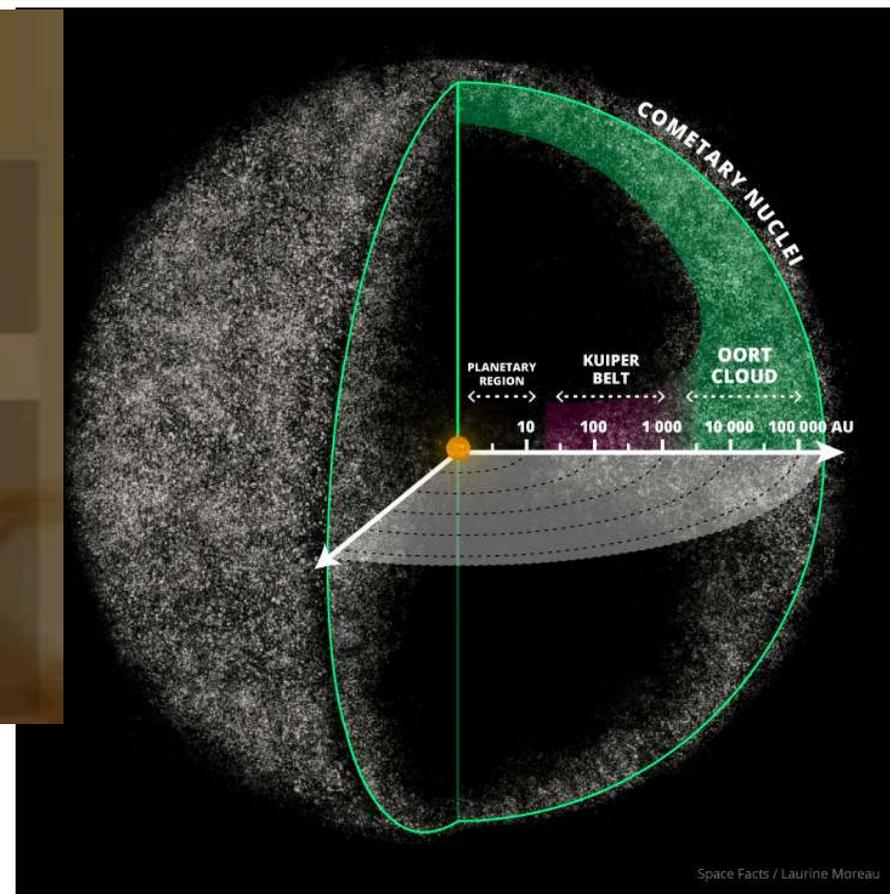


윤하(YOUNHA) - 오르트구름



윤하

오르트구름

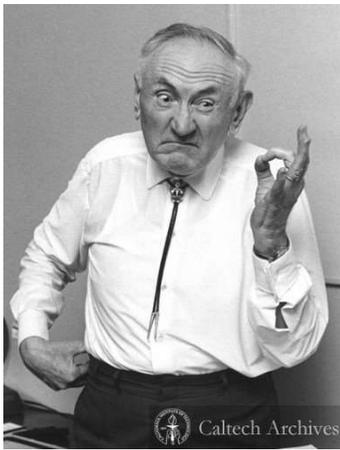


II. The Cluster Crisis (1933—1950)

Fritz Zwicky, Sinclair Smith, and the Virial
Theorem

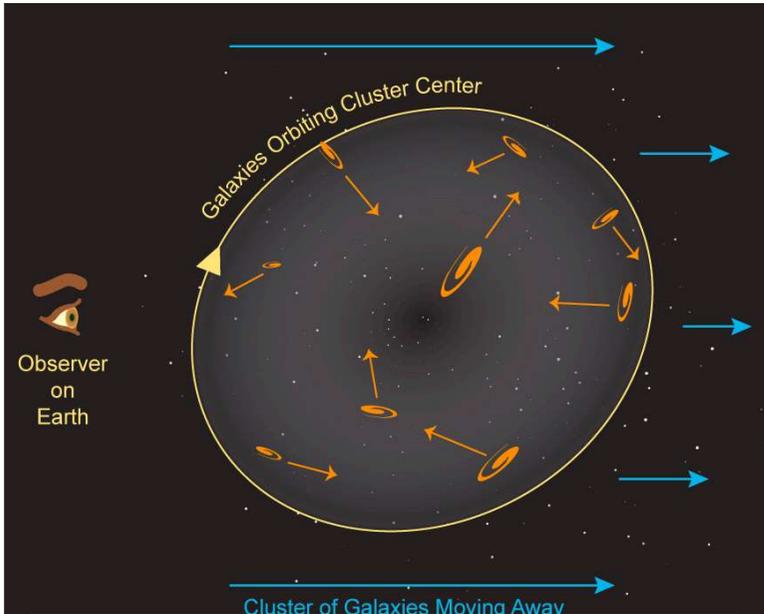


The stunning view of the Coma galaxy cluster, taken by the Dark Energy Camera. The two large galaxies at the center of the cluster are giant ellipticals, namely NGC 4889 and NGC 4874 to its right. (Image credit: CTIO/NOIRLab/DOE/NSF/AURA)



Fritz Zwicky

- Dynamical Mass of Cluster
- Based on the velocity dispersion measurements



Credit: NASA/SSU/Aurore Simonnet

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

Rotverschiebung extragalaktischer Nebel.

119

Scheinbare Geschwindigkeiten im Comahaufen.

$v = 8500$ km/sek	6900 km/sek
7900	6700
7600	6600
7000	5100 (?)

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 86

OCTOBER 1937

NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

Combining (33) and (34), we find

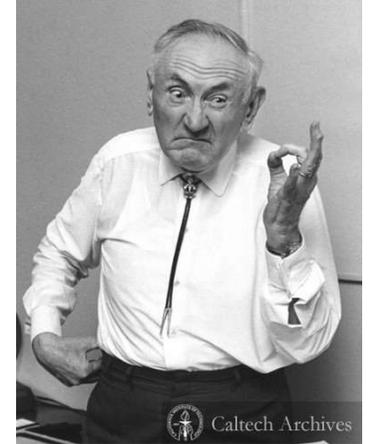
$$\mathcal{M} > 9 \times 10^{46} \text{gr.} \quad (35)$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\bar{M} > 9 \times 10^{43} \text{gr} = 4.5 \times 10^{10} M_{\odot}. \quad (36)$$

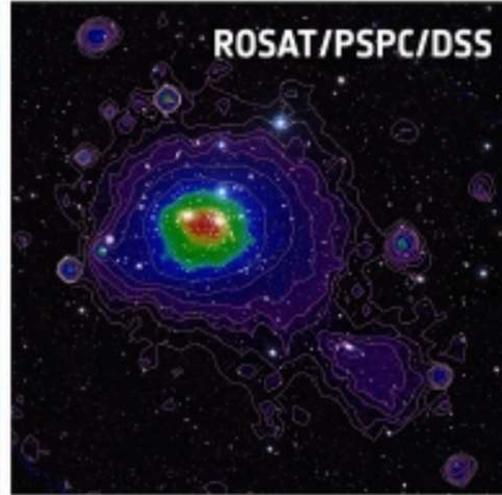
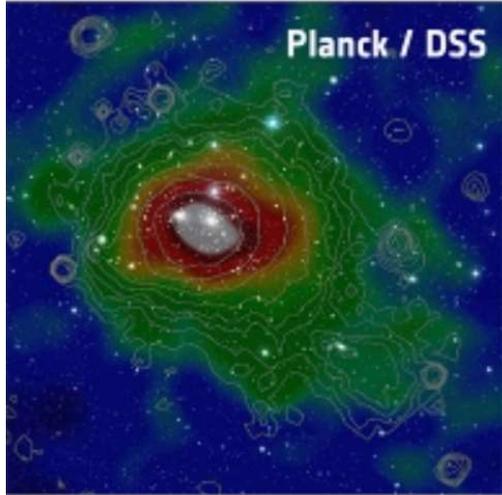
Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass \mathcal{M} , the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500, \quad (37)$$



Fritz Zwicky

THE COMA DISCREPANCY

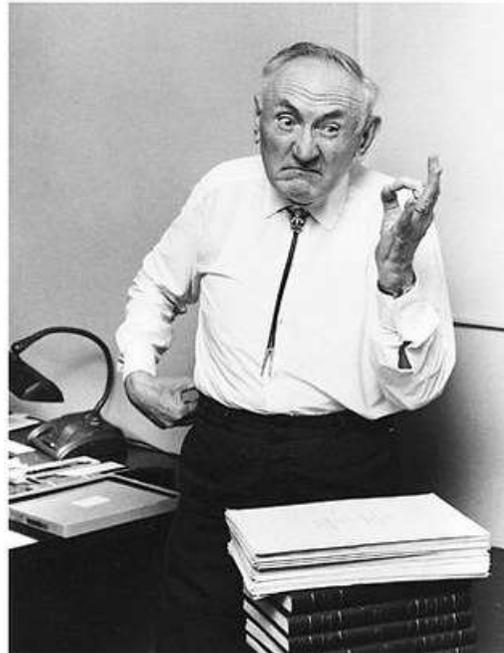


"Dunkle Materie"

Zwicky concluded that galaxies move too fast to be held by their own stars.

He suggested the space between galaxies was filled with "dark matter" in the form of cold gas or dwarf stars.

Note: Zwicky was a "maverick" and his findings were largely ignored by the mainstream for decades.



"Astronomers are spherical bastards. No matter how you look at them, they are just bastards."

- Fritz Zwicky

Coma Cluster in 21c

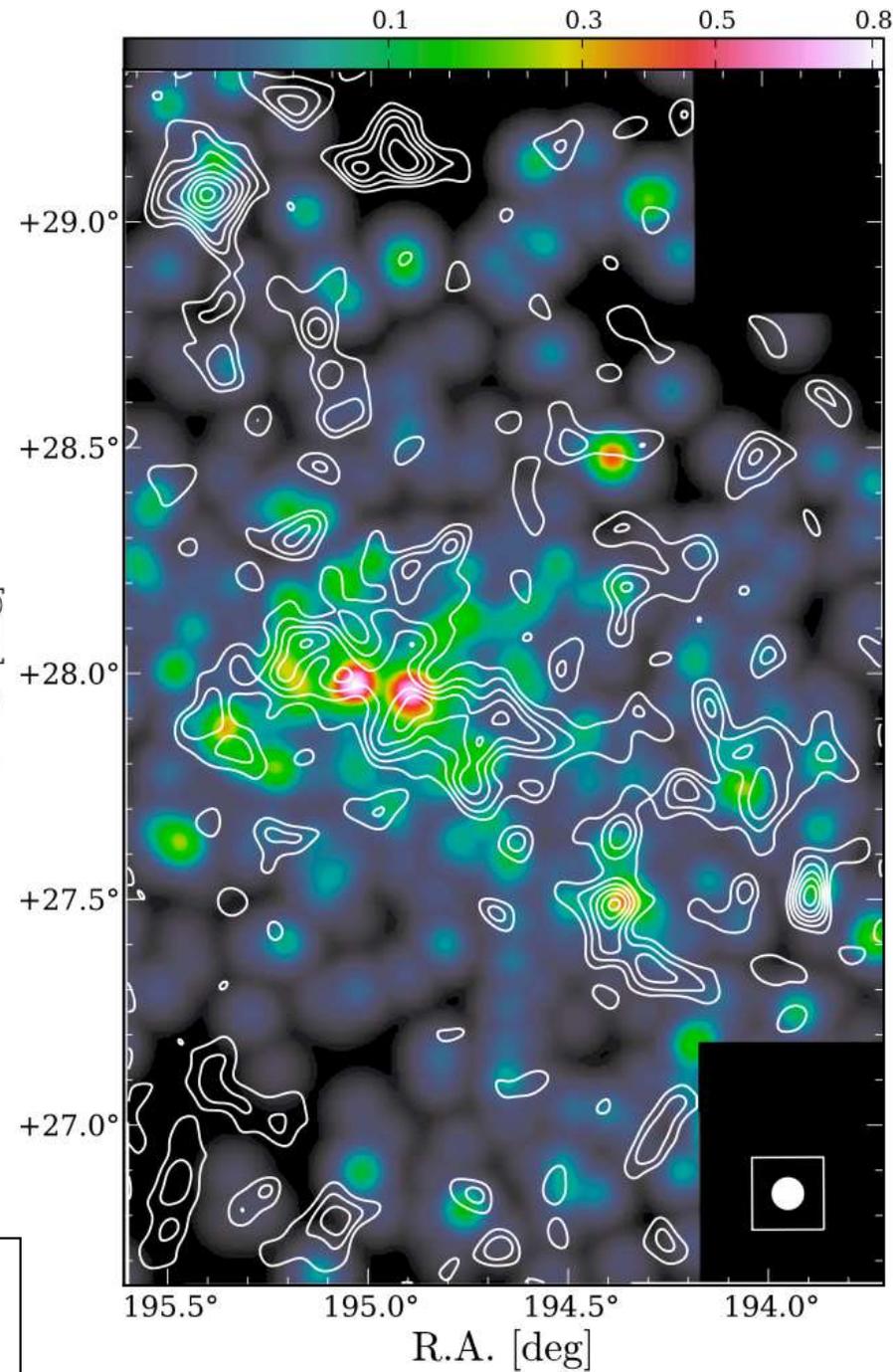
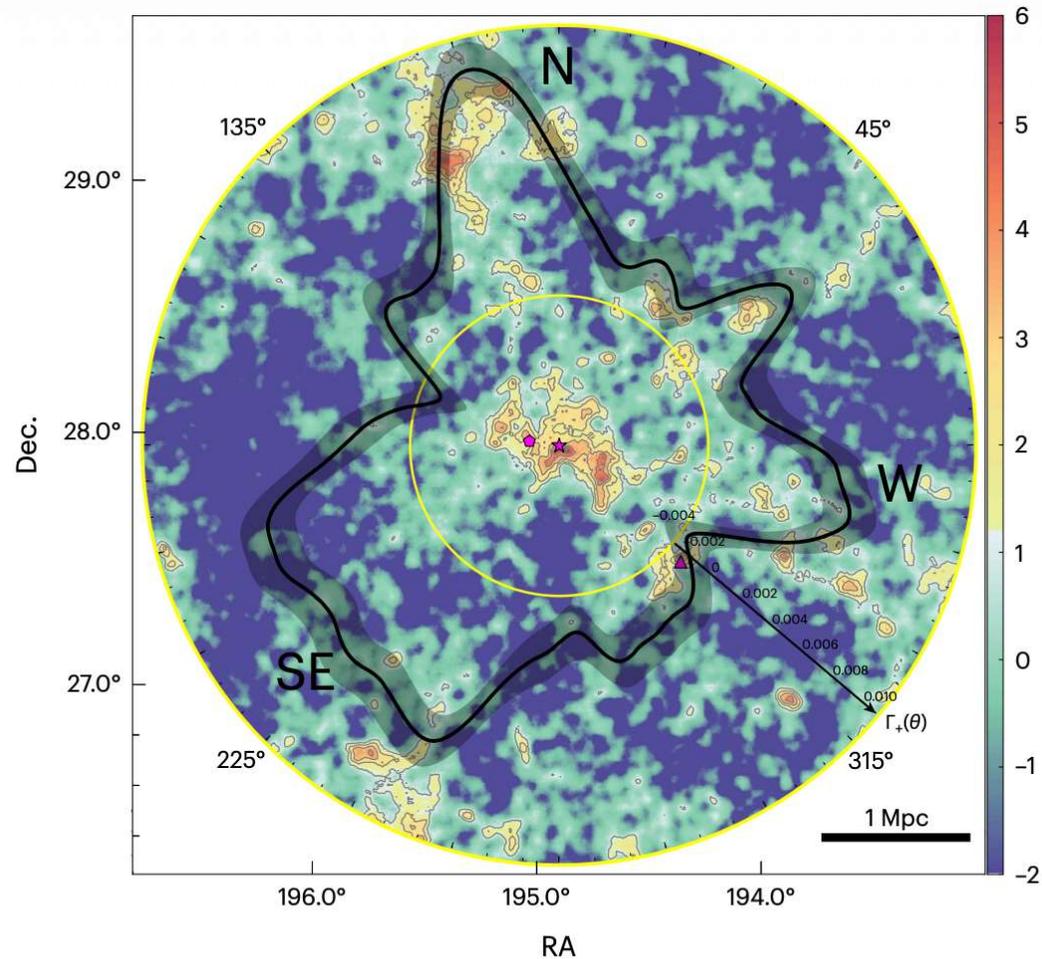


Fig. 1 | Mass reconstruction and matched-filter statistic of the Coma cluster.

Contour: Dark Matter Filaments from Weak Lensing Analysis (KimH+2024)

Contour: Dark Matter from Weak Lensing Analysis, Color: Galaxy Luminosity (Okabe+2014)

1936: VERIFICATION in the VIRGO Galaxy Cluster

The Target

Sinclair Smith studied the Virgo Cluster, much closer and better mapped than Coma.

The Finding

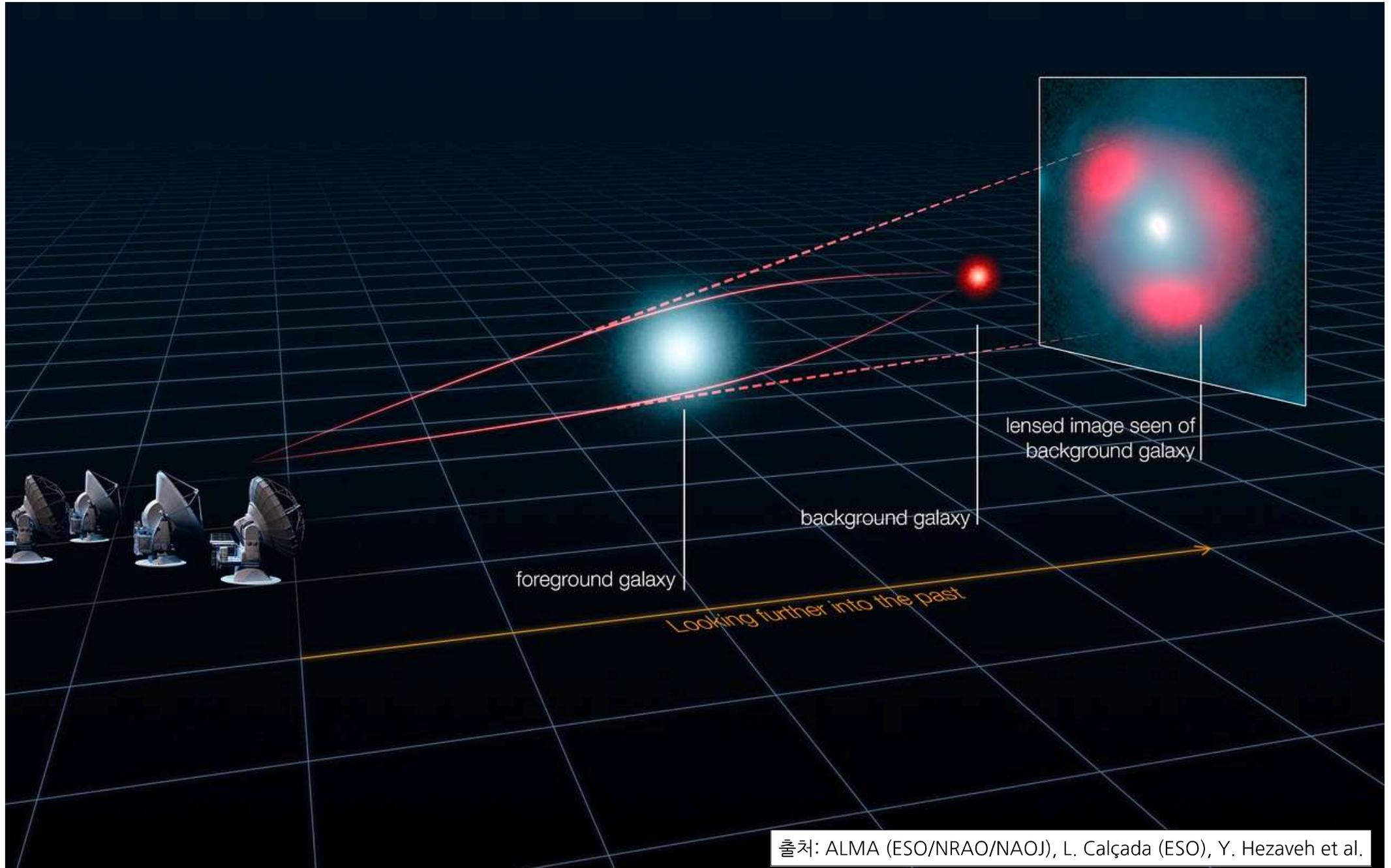
Found a discrepancy of factor ~ 50 . Verified that the cluster mass problem was real.

The Skepticism

Like Zwicky, Smith's work was treated as a curiosity or a sign that clusters were "unbound" and flying apart.



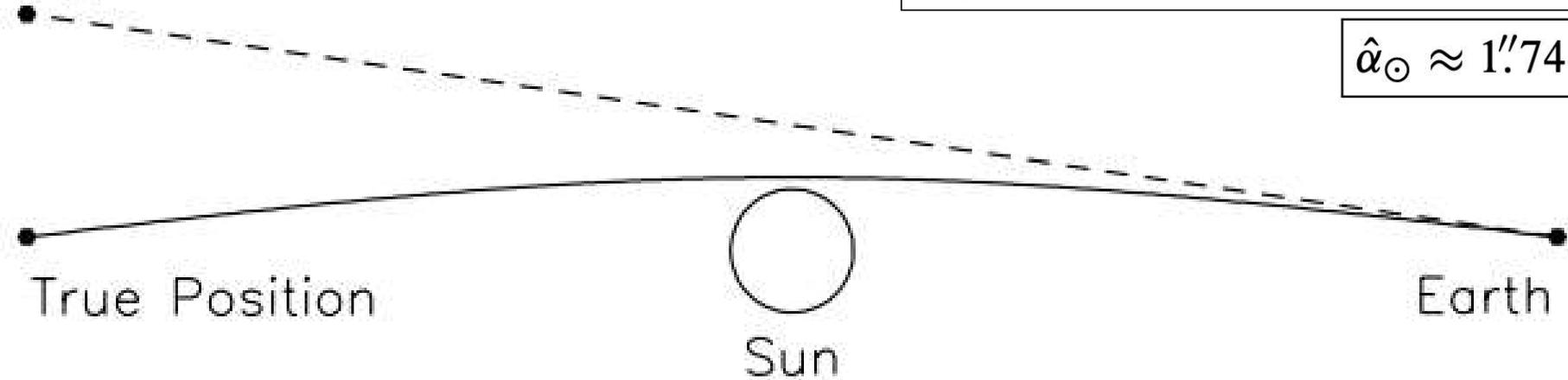
Gravitational Lens



Gravitational Lens

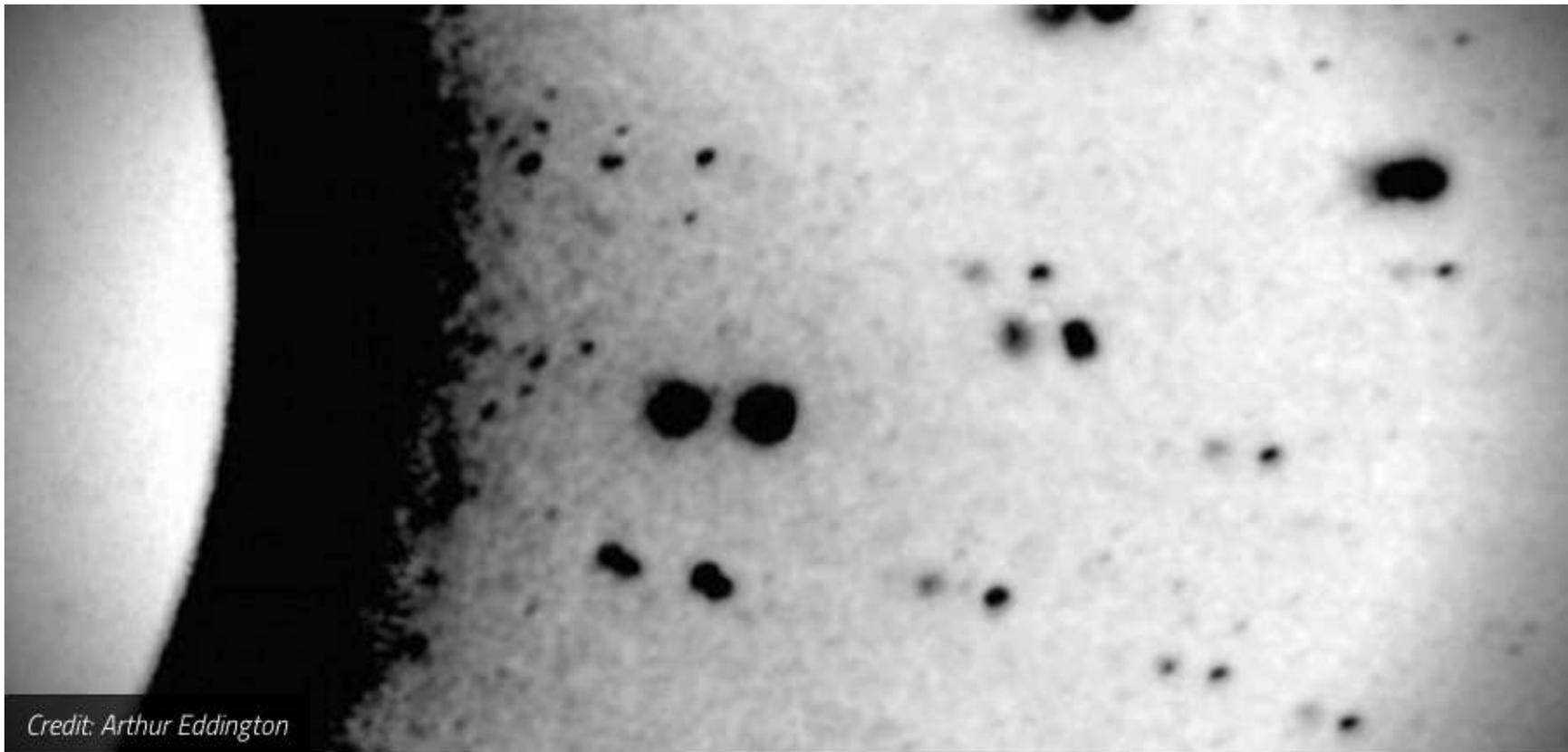
$$\hat{\alpha} = \frac{4 G M}{c^2 \xi} \quad (2.74)$$

Apparent Position



If a point mass M at a distance ξ is deflected by an angle $\hat{\alpha}$

$$\hat{\alpha}_{\odot} \approx 1''.74$$



**Narayan &
Bartelmann (2008)**

Gravitational Lens

- In 1924, the Russian physicist Orest Chwolson: a massive body could deflect the light from a more distant source in such a way that would lead to the appearance of multiple images, or of a ring (Chwolson, 1924)
- In 1936, Einstein himself published a paper on this topic, but concluded that due to the very precise alignment required, “there is no great chance of observing this phenomenon.”
- In 1937, Zwicky argued it would be detectable because the Universe contains massive galaxies and clusters acting as powerful lenses (not stars as Einstein assumed).
- In 1979, Walsh, Carswell & Weymann discovered the first double quasar, QSO 0957+561.

Gravitational Lensing

The first lens system (other than the Sun)?!

➤ **QSO 0957+561, the first double quasar:** In 1979 by Walsh, Carswell & Weymann when the optical identification of a radio source showed two point-like optical sources.

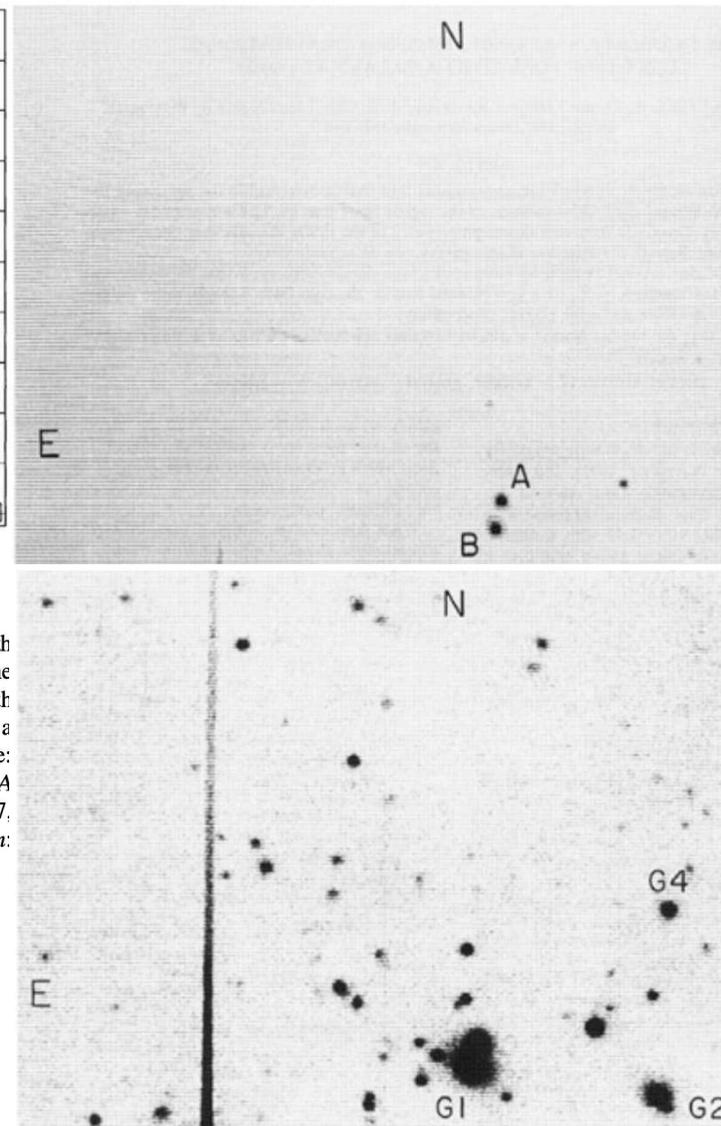
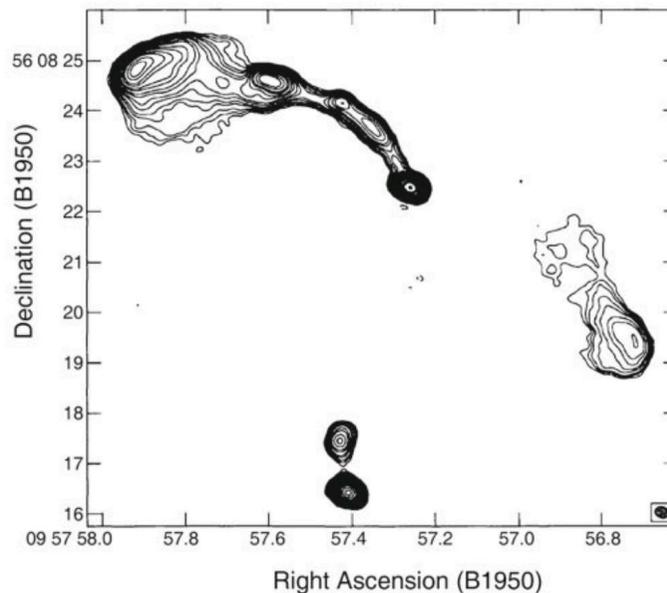
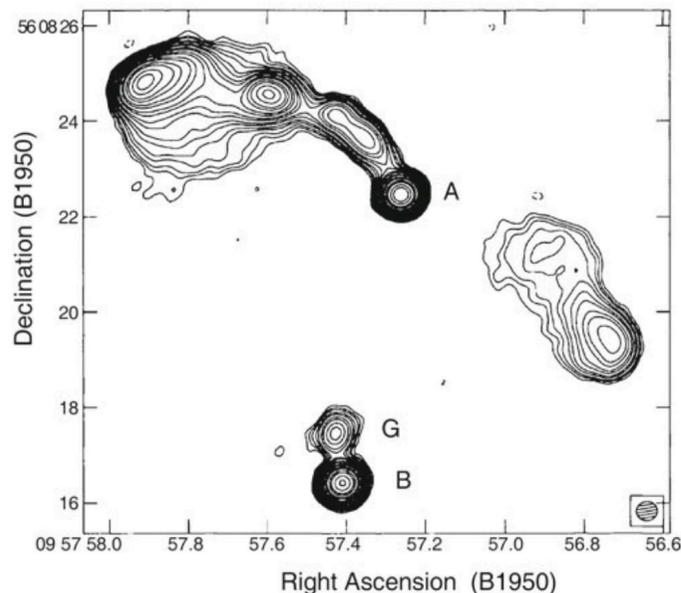


Fig. 3.56 *Top:* optical images of the double quasar QSO 0957+561. The image on the *top left* has a short exposure time; here, the two point-like images A & B of the quasar are clearly visible. In contrast, the image on the *top right* has a longer exposure time, showing the lens galaxy G1 between the two quasar images. Several other galaxies (G2–G5) are visible as well. The lens galaxy is a member of a cluster of galaxies at $z_d = 0.36$. *Bottom:* two radio maps of QSO 0957+561, observed with the VLA at 6 cm (*left*) and 3.6 cm (*right*), respectively.

angular scales, the jet can be observed by VLBI techniques in both images (see Fig. 3.57). On large scales only a single image of the jet exists, seen in image A; this property should be compared with Fig. 3.55 where it was demonstrated that the number of images of a source (component) depends on its position in the source plane. Source: *Top:* P. Young et al. 1980, *The double quasar Q0957 + 561 A,B—A gravitational lens image formed by a galaxy at $z = 0.39$* , *ApJ* 241, 507, p. 508, 509, Fig. 1a,b. ©AAS. Reproduced with permission. *Bottom:*

Gravitational Lensing

The first lens system (other than the Sun)?!

➤ **QSO 0957+561, the first double quasar:** In 1979 by Walsh, Carswell & Weymann when the optical identification of a radio source showed two point-like optical sources.

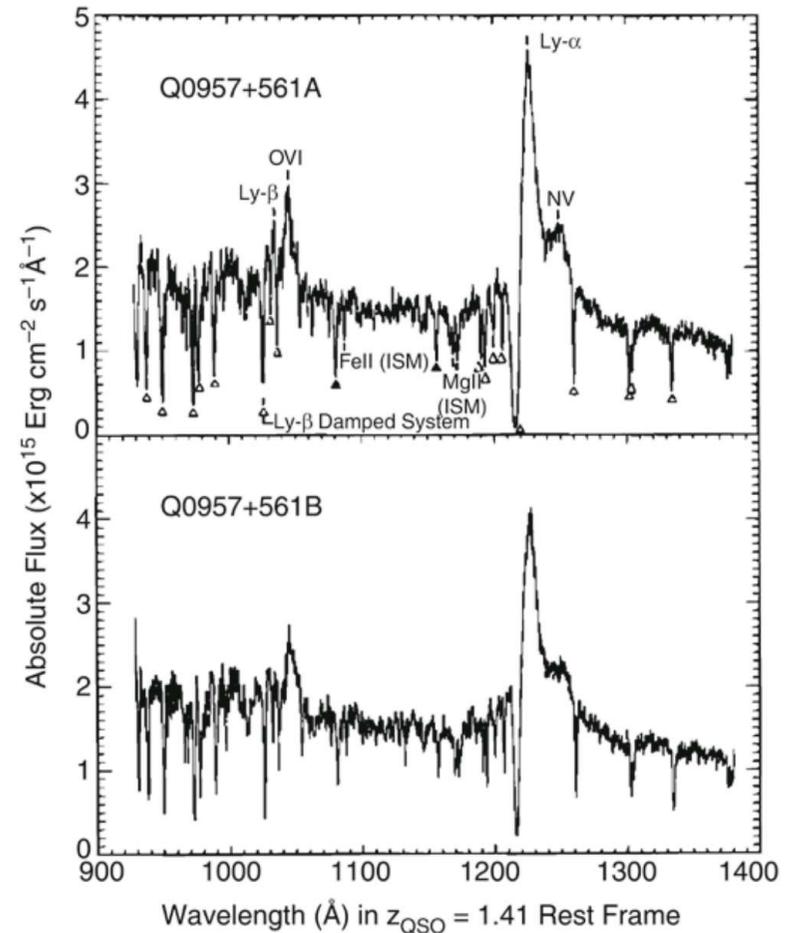
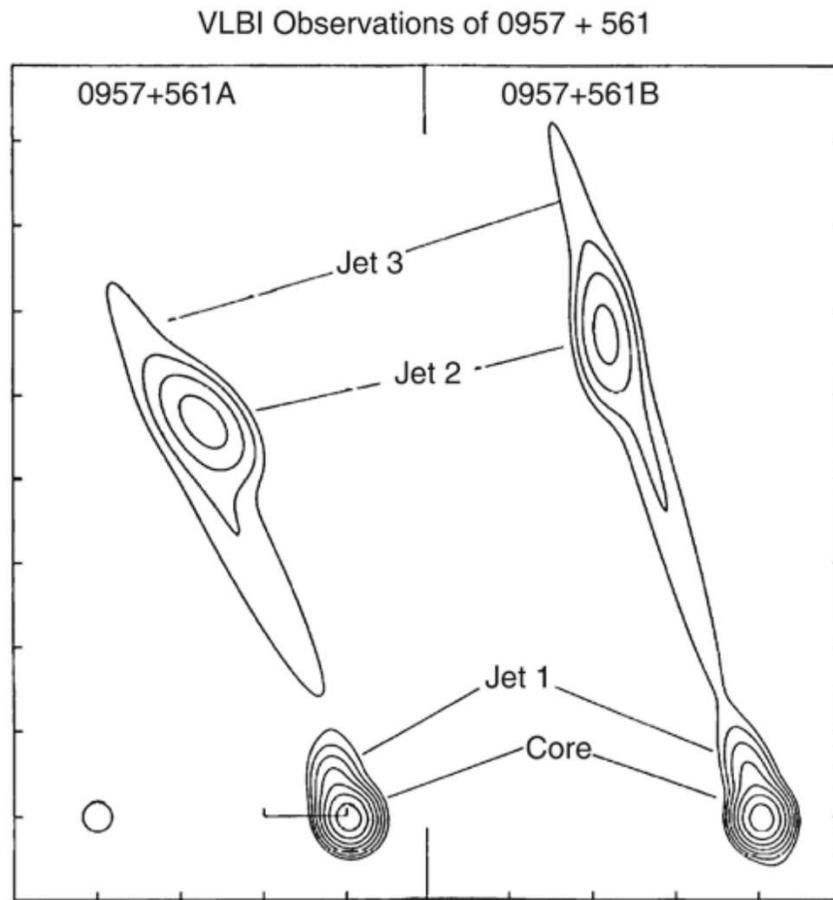


Fig. 3.57 *Left:* milliarcsecond structure of the two images of the quasar QSO 0957+561, a VLBI map at 13 cm wavelength. Both quasar images show a core-jet structure, and it is clearly seen that they are mirror-symmetric, as predicted by lens models. *Right:* spectra of the two quasar images QSO 0957+561A,B, observed by the Faint Object Camera (FOC) on-board HST. The similarity of the spectra, in particular the identical redshift, is a clear indicator of a common source of the two quasar images. The broad Ly α -line, in the wings of which an

NV-line is visible, is virtually always the strongest emission line in quasars. Source: *Left:* M. Gorenstein et al. 1988, *VLBI observations of the gravitational lens system 0957+561—Structure and relative magnification of the A and B images*, ApJ 334, 42, p. 53, Fig. 5. ©AAS. Reproduced with permission. *Right:* A.G. Michalitsianos et al. 1997, *Ly alpha Absorption-Line Systems in the Gravitational Lens Q0957+561*, ApJ 474, 598, p. 599, Fig. 1. ©AAS. Reproduced with permission

Gravitational Lens

- In 1924, the Russian physicist Orest Chwolson: a massive body could deflect the light from a more distant source in such a way that would lead to the appearance of multiple images, or of a ring (Chwolson, 1924)
- In 1936, Einstein himself published a paper on this topic, but concluded that due to the very precise alignment required, “there is no great chance of observing this phenomenon.”
- In 1937, Zwicky argued it would be detectable because the Universe contains massive galaxies and clusters acting as powerful lenses (not stars as Einstein assumed).
- In 1979, Walsh, Carswell & Weymann discovered the first double quasar, QSO 0957+561.
- In 1986, Paczynski: gravitational microlensing by stars could be used to search for compact objects in the “dark halo” of the Milky Way.

The Galactic microlensing effect: The quest for compact dark matter

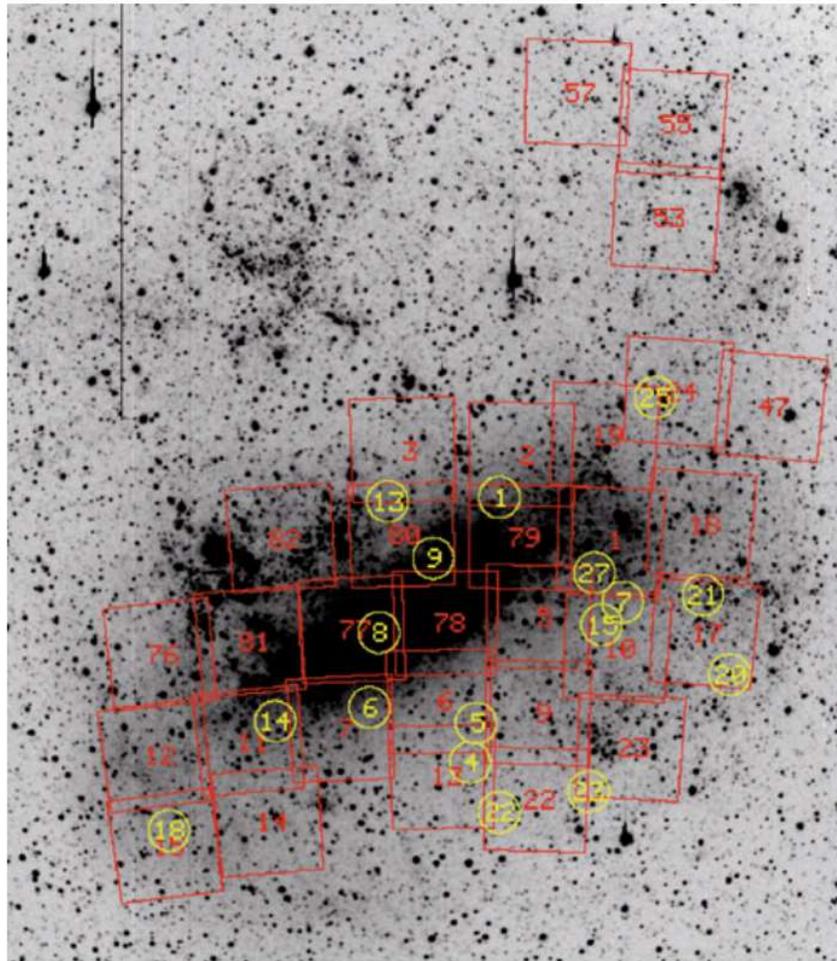


Fig. 2.37 In this $8^\circ \times 8^\circ$ image of the LMC, 30 fields are marked in red which the MACHO group has searched for microlensing events during the ~ 5.5 yr of their experiment; images were taken in two filters to test for achromaticity. The positions of 17 microlensing events are marked by yellow circles; these have been subject to statistical analysis. Source: C. Alcock et al. 2000, *The MACHO Project: Microlensing Results from 5.7 Years of Large Magellanic Cloud Observations*, ApJ 542, 281, p. 284, Fig. 1. ©AAS. Reproduced with permission

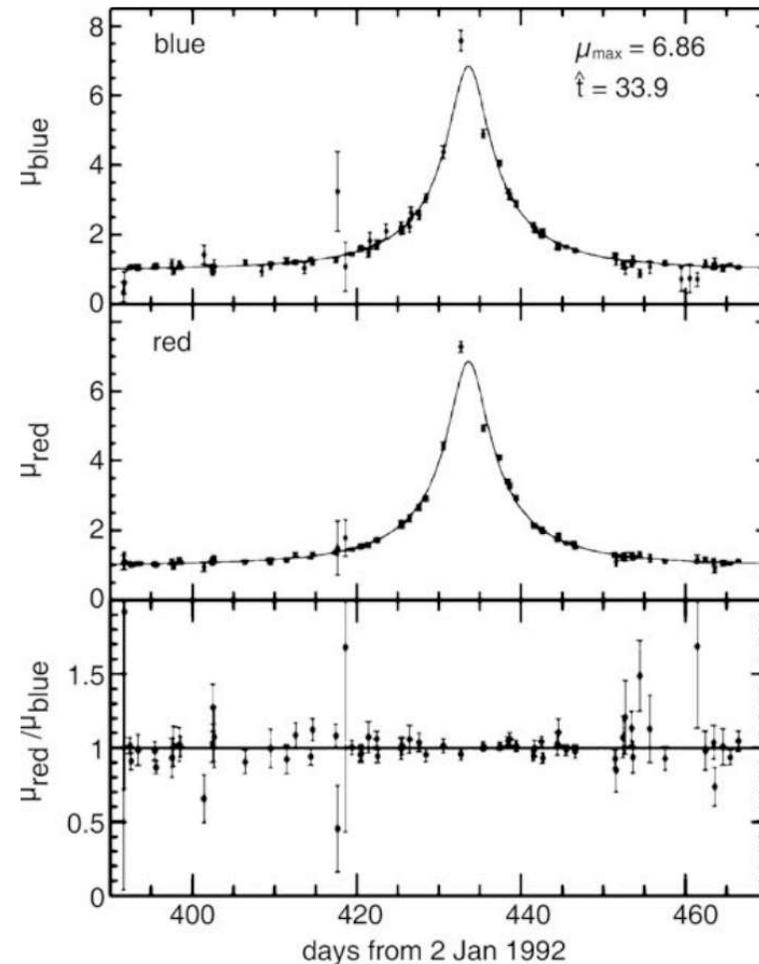


Fig. 2.36 Light curve of the first observed microlensing event in the LMC, in two broad-band filters. The solid curve is the best-fitting microlensing light curve as described by (2.93), with $\mu_{\max} = 6.86$. The ratio of the magnifications in both filters is displayed at the bottom, and it is compatible with 1. Some of the data points deviate significantly from the curve; this means that either the errors in the measurements were underestimated, or this event is more complicated than one described by a point-mass lens—see Sect. 2.5.4. Source: C. Alcock et al. 1993, *Possible gravitational microlensing of a star in the Large Magellanic Cloud*, Nature 365, 621

The Galactic microlensing effect: The quest for compact dark matter

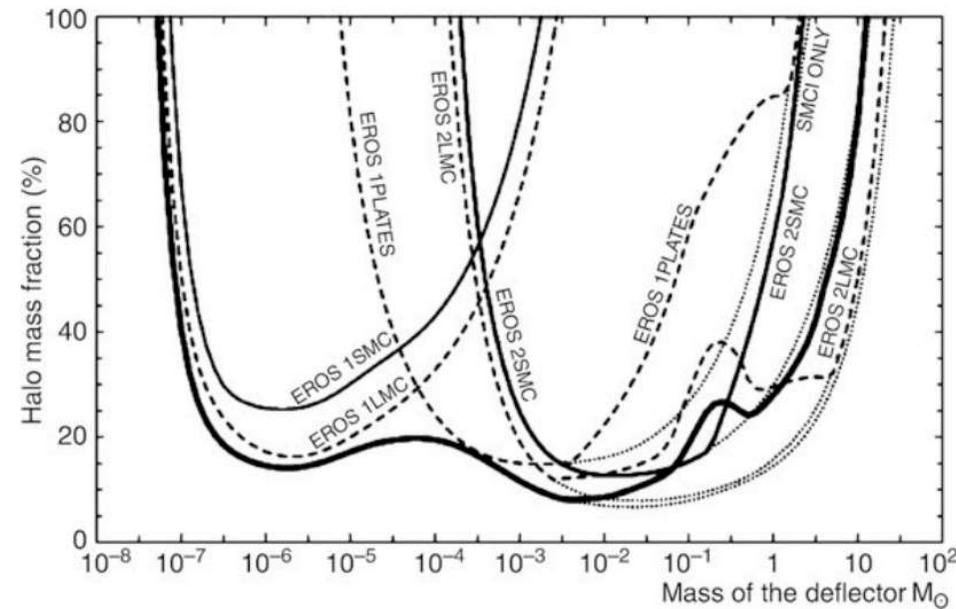


Fig. 2.39 From observations by the EROS collaboration, a large mass range for MACHO candidates can be excluded. The maximum allowed fraction of the halo mass contained in MACHOs is plotted as a function of the MACHO mass M , as an upper limit with 95% confidence. A standard model for the mass distribution in the Galactic halo was assumed which describes the rotation curve of the Milky Way quite well. The various curves show different phases of the EROS experiment. They are plotted separately for observations in the directions of the LMC and the SMC. The experiment EROS 1 searched for

microlensing events on short time-scales but did not find any; this yields the upper limits at small masses. Upper limits at larger masses were obtained by the EROS 2 experiment. The *thick solid curve* represents the upper limit derived from combining the individual experiments. If not a single MACHO event had been found the upper limit would have been described by the dotted line. Source: C. Afonso et al. 2003, *Limits on Galactic dark matter with 5 years of EROS SMC data*, A&A 400, 951, p. 955, Fig. 3. ©ESO. Reproduced with permission

- The absence of lensing events of very short duration then allowed them to derive limits for the mass fraction of such low-mass MACHOs, as is shown above.
- OGLE derived an upper bound of 2% of the dark matter in our Milky Way which could be in the form of compact objects.

The Galactic microlensing effect: The quest for compact dark matter

Variations and extensions

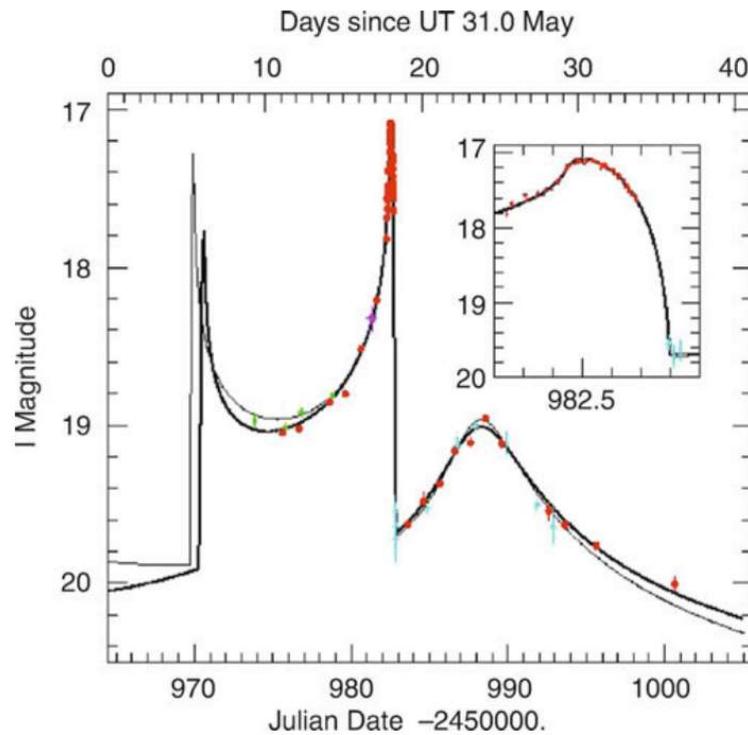


Fig. 2.41 Light curve of an event in which the lens was a binary star. Note the qualitative similarity of this light curve with the second one from the top in Fig. 2.40. The MACHO group discovered this 'binary event'. Members of the PLANET collaboration obtained this

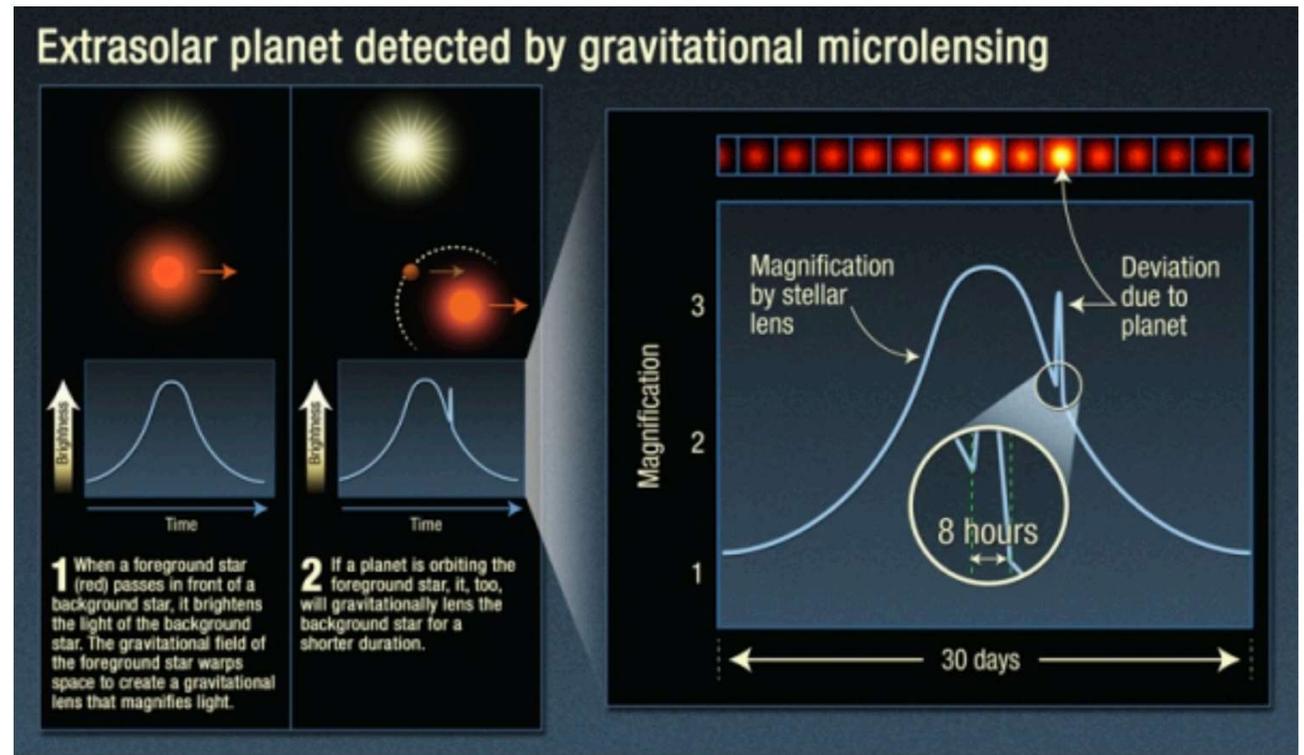
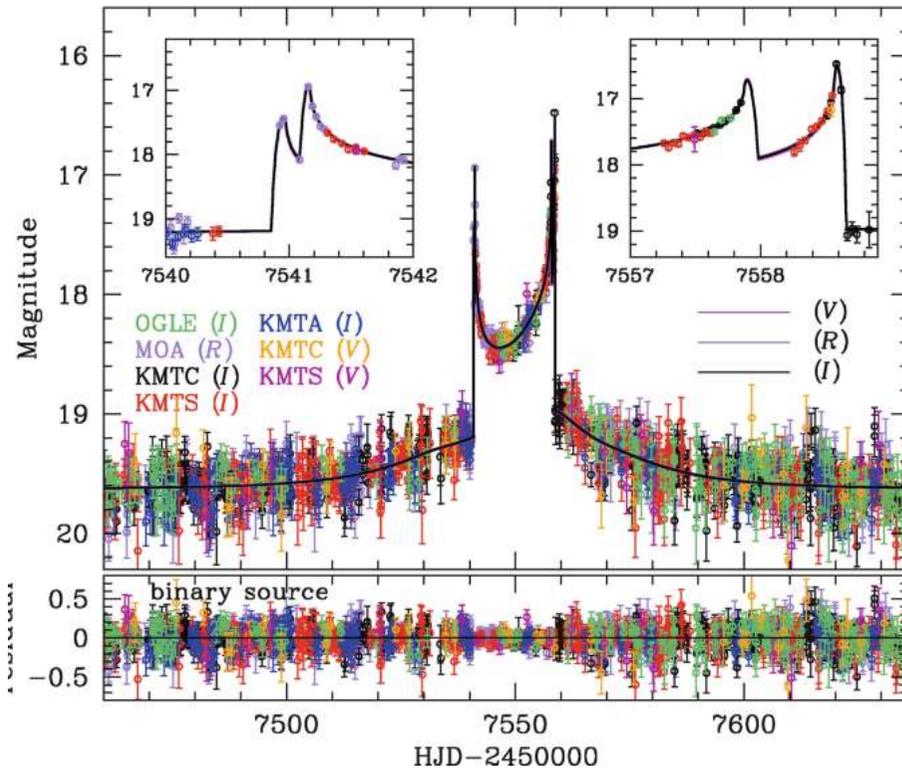


Image: This infographic explains the light curve astronomers detect when viewing a microlensing event, and the signature of an exoplanet: an additional uptick in brightness when the exoplanet lenses the background star. Credit: NASA / ESA / K. Sahu / STScI).

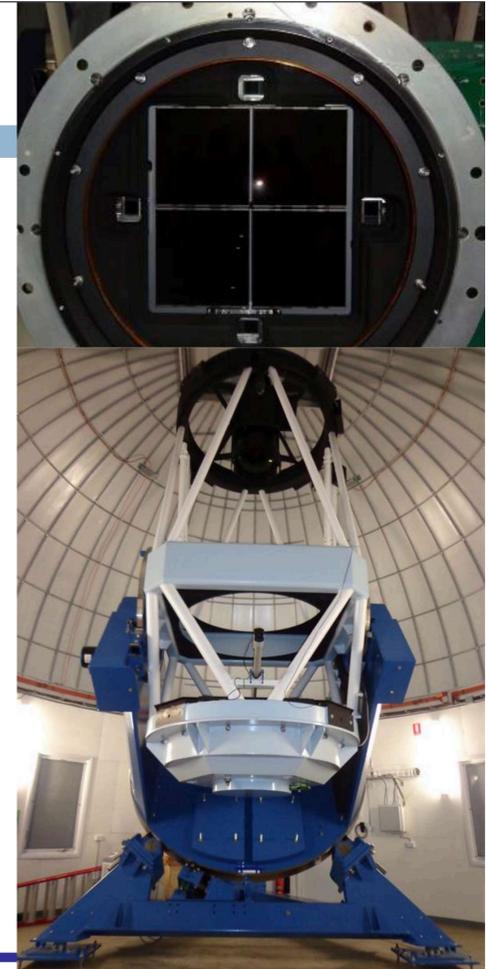
The Galactic microlensing effect: The quest for compact dark matter

Variations and extensions

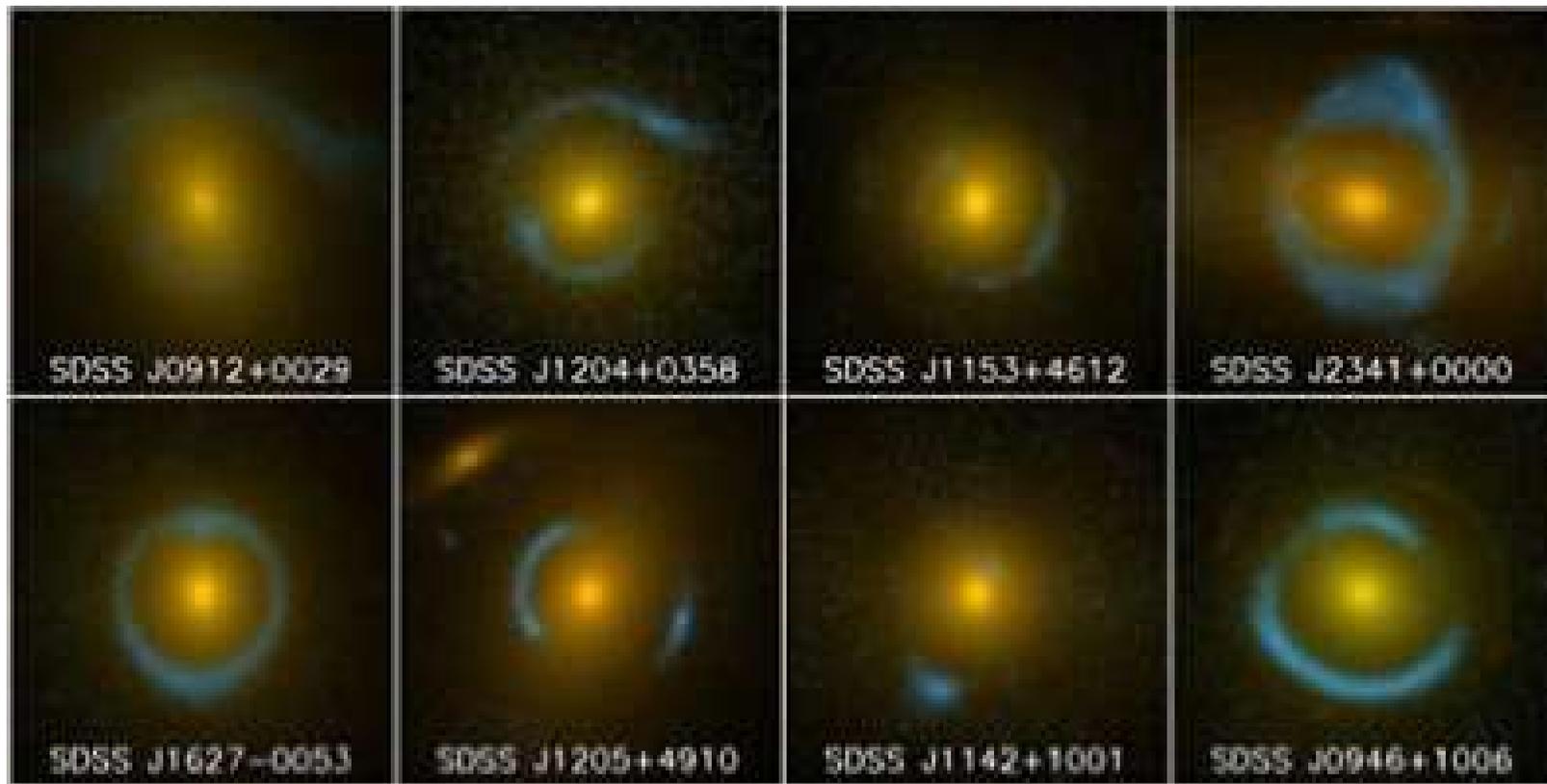
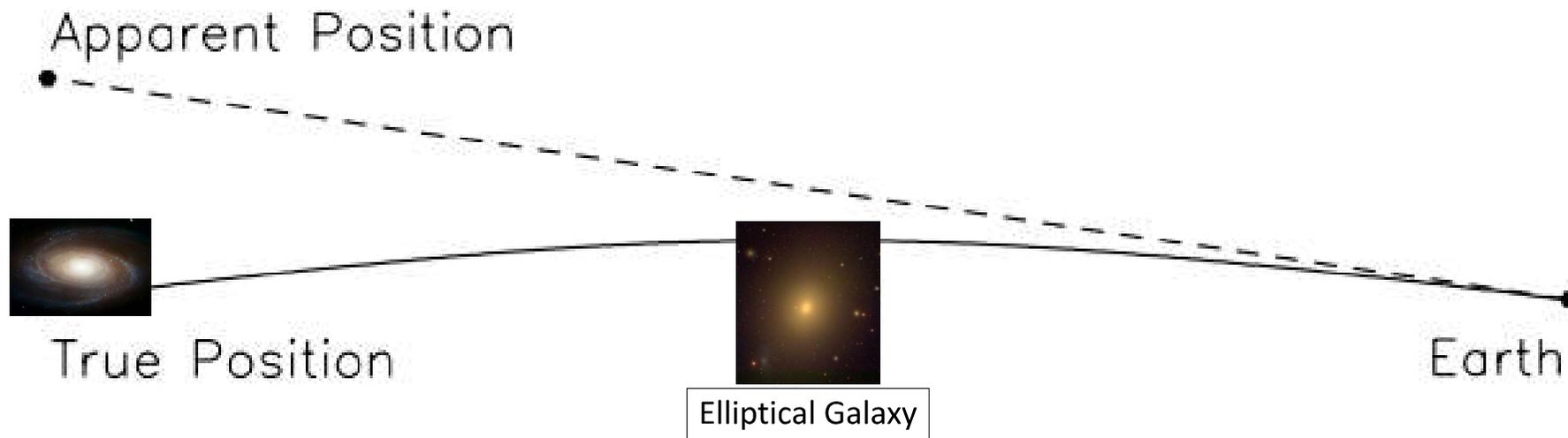


KMTNet Observation System

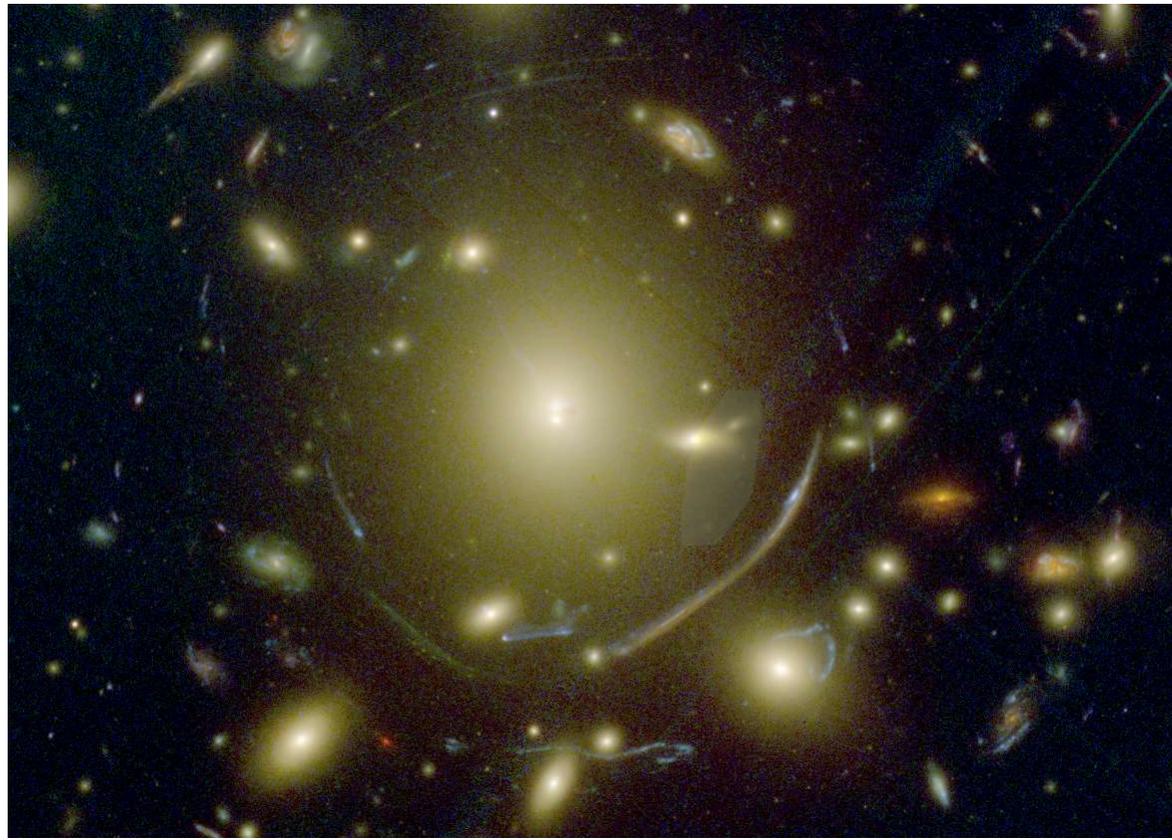
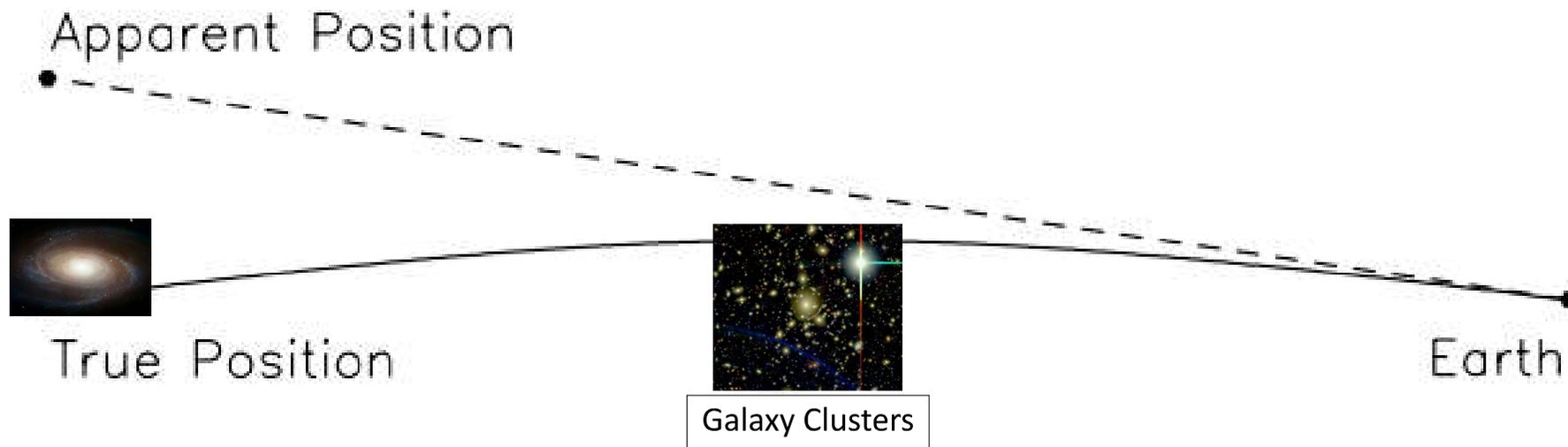
- Korea Microlensing Telescope Network
- Three Identical Observing Systems: CTIO in Chile, SAAO in South Africa, SSO in Australia
- **24-hours Monitoring** of night sky at Southern Hemisphere
- Primary Mirror with 1.6m Diameter
- 4 Chips with 9K x 9K pixels
- 0.4 arcsec/pixel,
- **2°x2° wide-field of view** (FOV)
- * f/3.2



Strong Lens



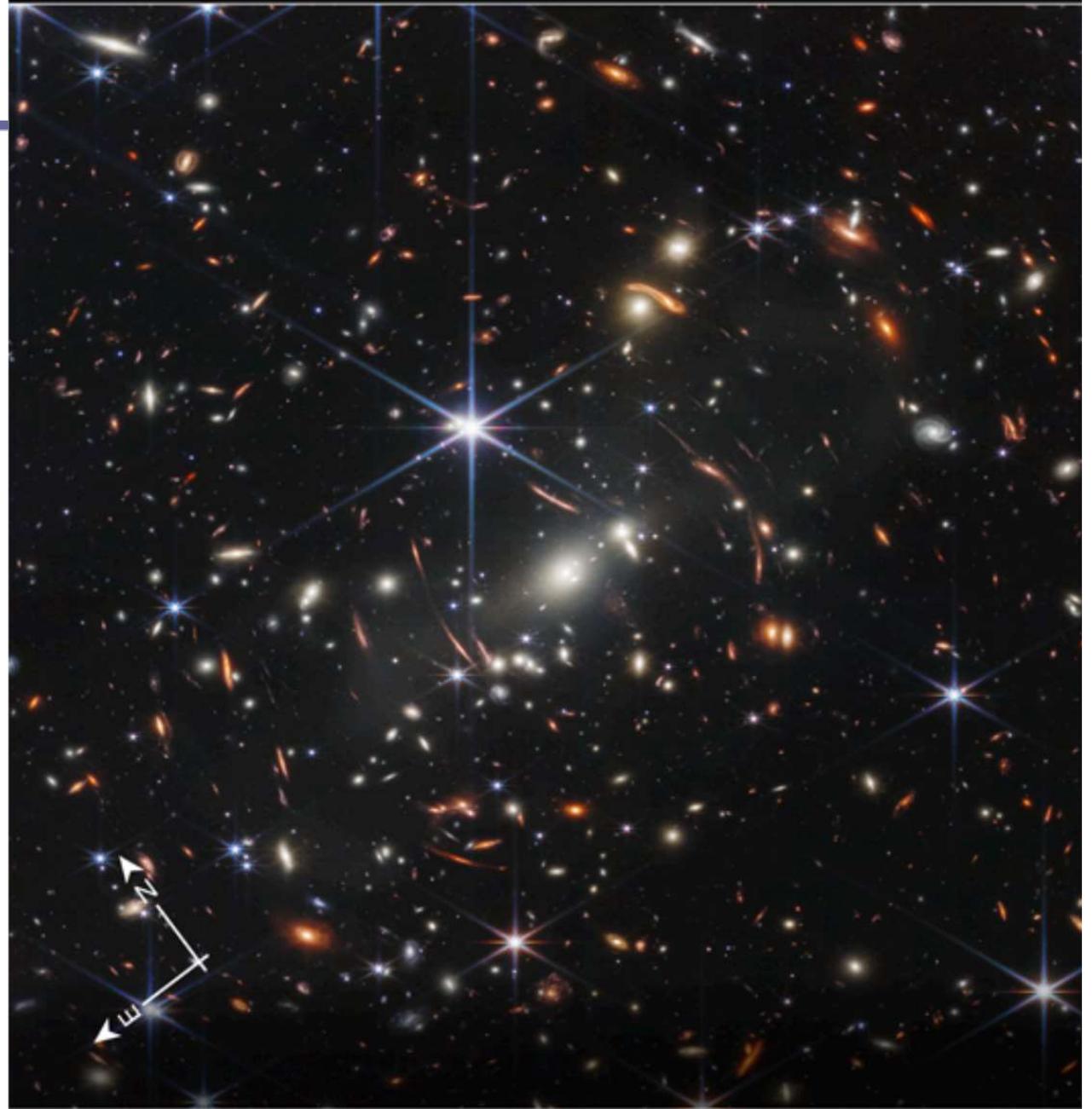
Weak Lens



First Image from JWST

JAMES WEBB SPACE TELESCOPE

DEEP FIELD | SMACS 0723



NIRCam Filters

F090W

F150W

F200W

F277W

F356W

F444W



인류가 만든 최고의 기계!
(비록 13조가 들었지만!)



제임스웹 우주 망원경 최초 영상을 직접 공개하는 미국 바이든 대통령 (2022년 7월 11일)

III. Rotation Curves (1970—1980)

Rubin, Ford, Bosma, and the Halo

Discovery

1970: THE ANDROMEDA REVOLUTION



Vera Rubin and Kent Ford used high-precision spectroscopy of H-alpha regions in the Andromeda Galaxy (M31).

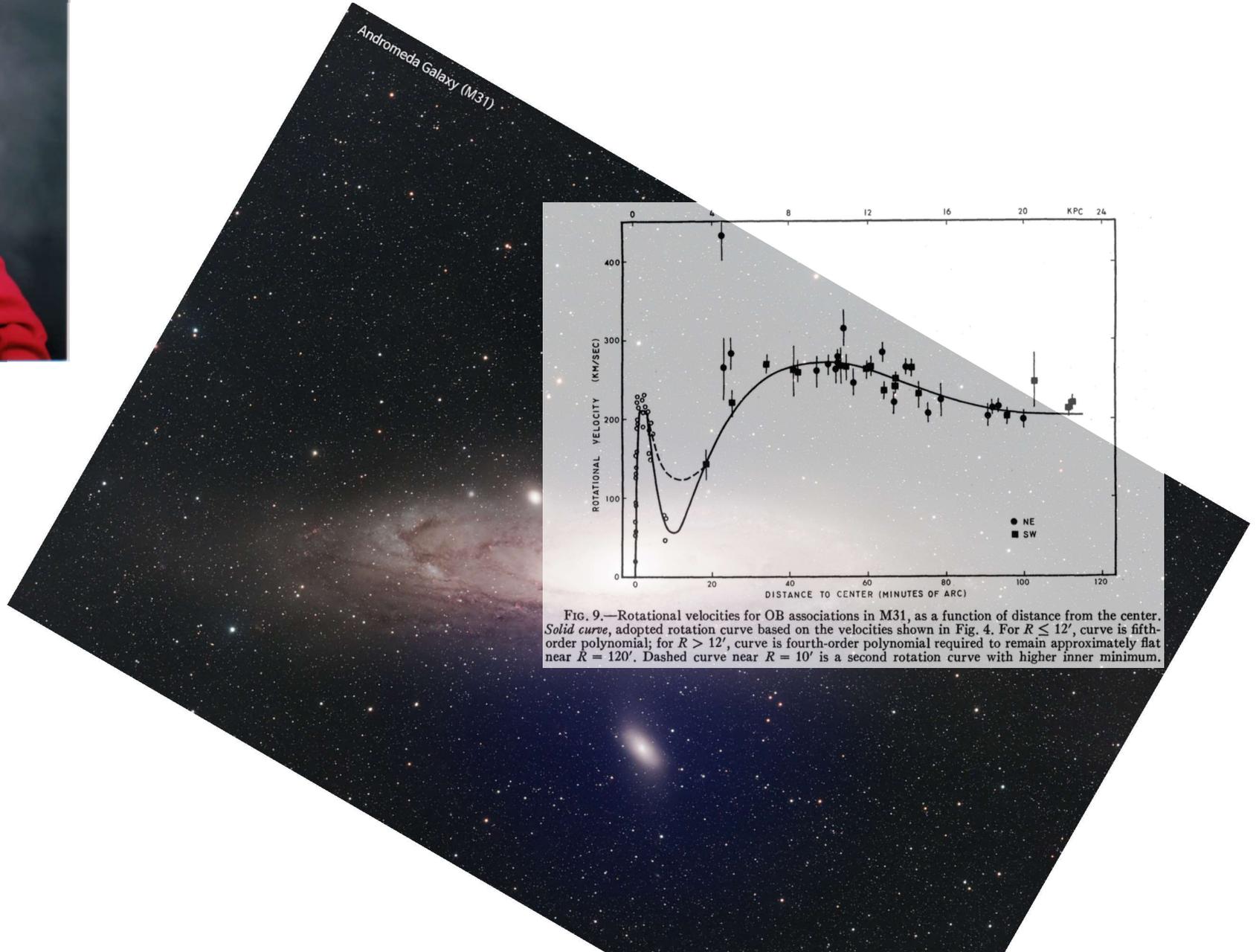


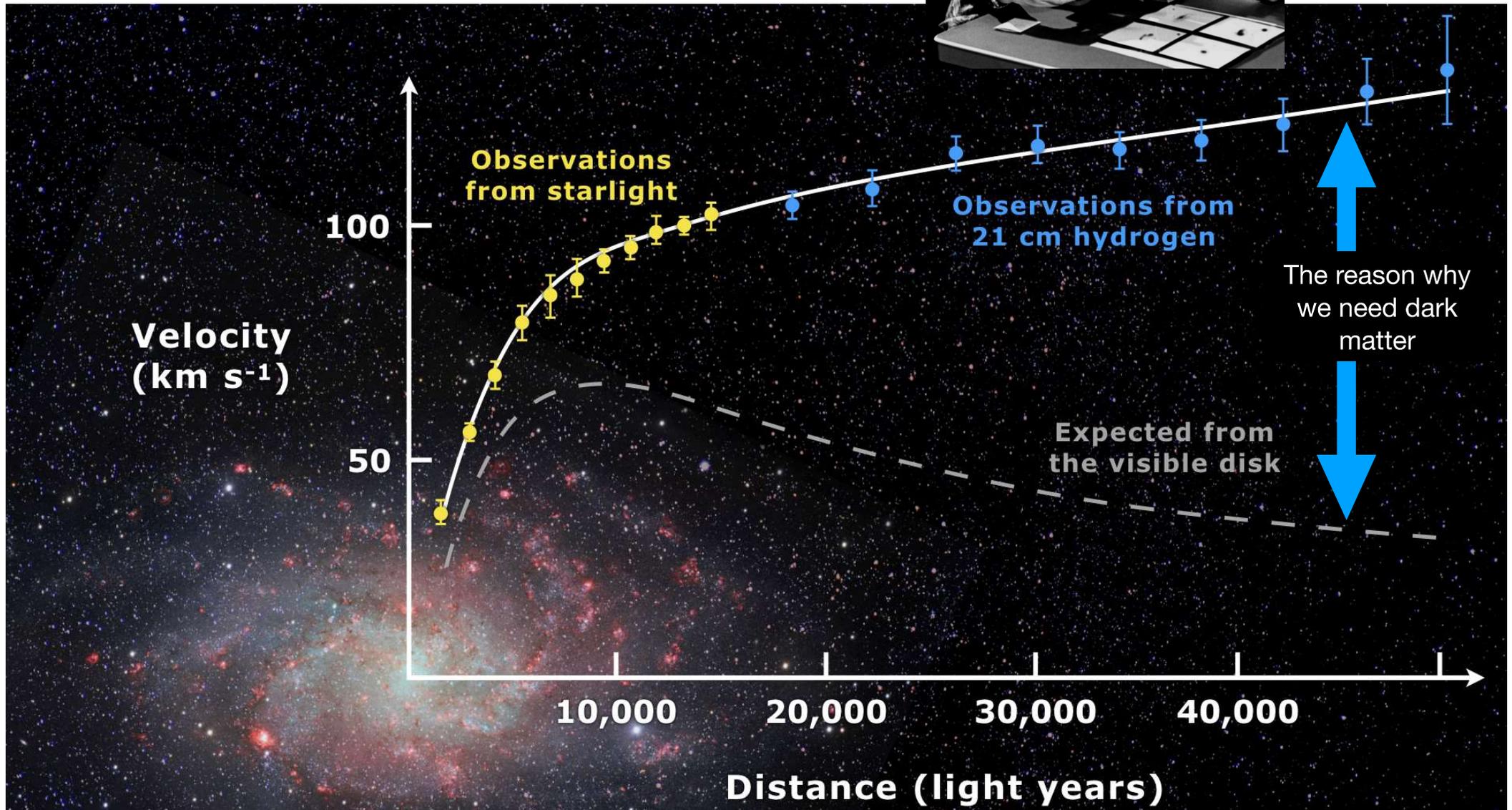
Fig. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately flat near $R = 120'$. *Dashed curve* near $R = 10'$ is a second rotation curve with higher inner minimum.

- Expected: Orbital velocity drops with distance: e.g. $v \propto r^{-1/2}$
- Observed: Orbital velocity remains **Flat**.
- Conclusion: The mass must be distributed in a massive halo.

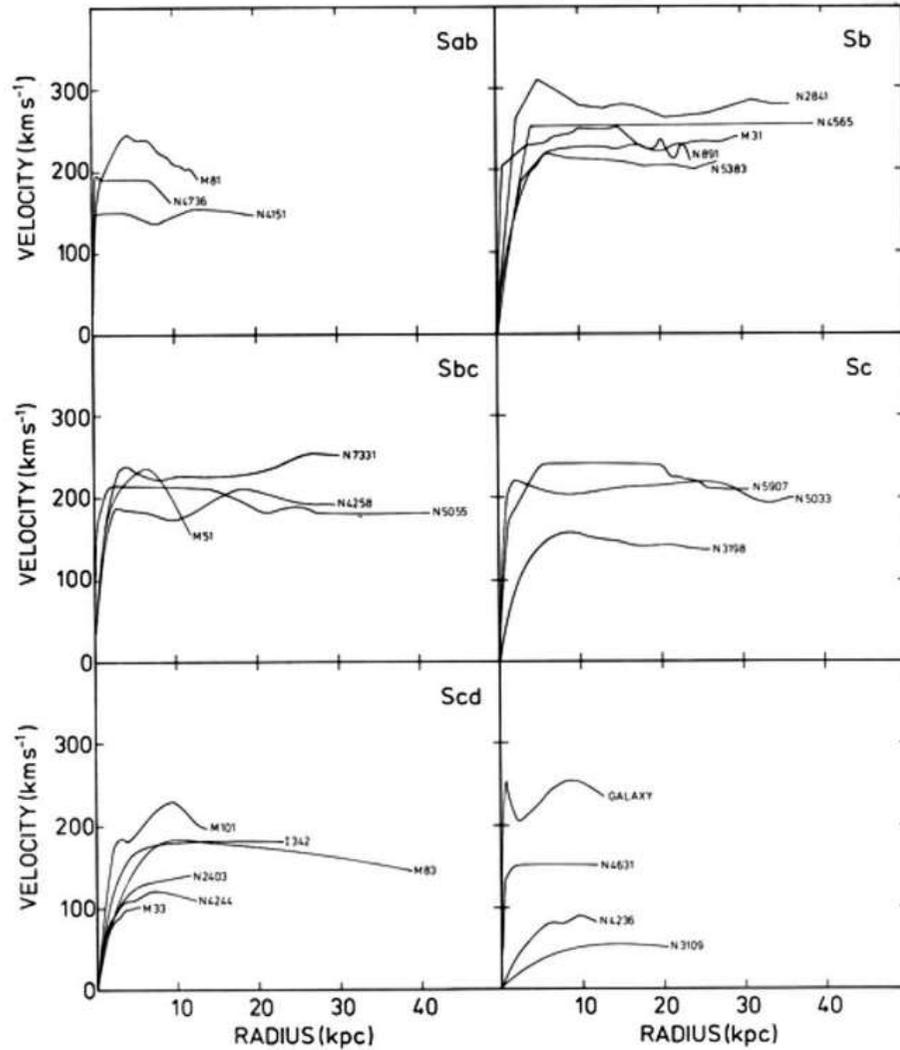
I have met her in 2002, but...



Vera Rubin



1978: RADIO CONFIRMATION



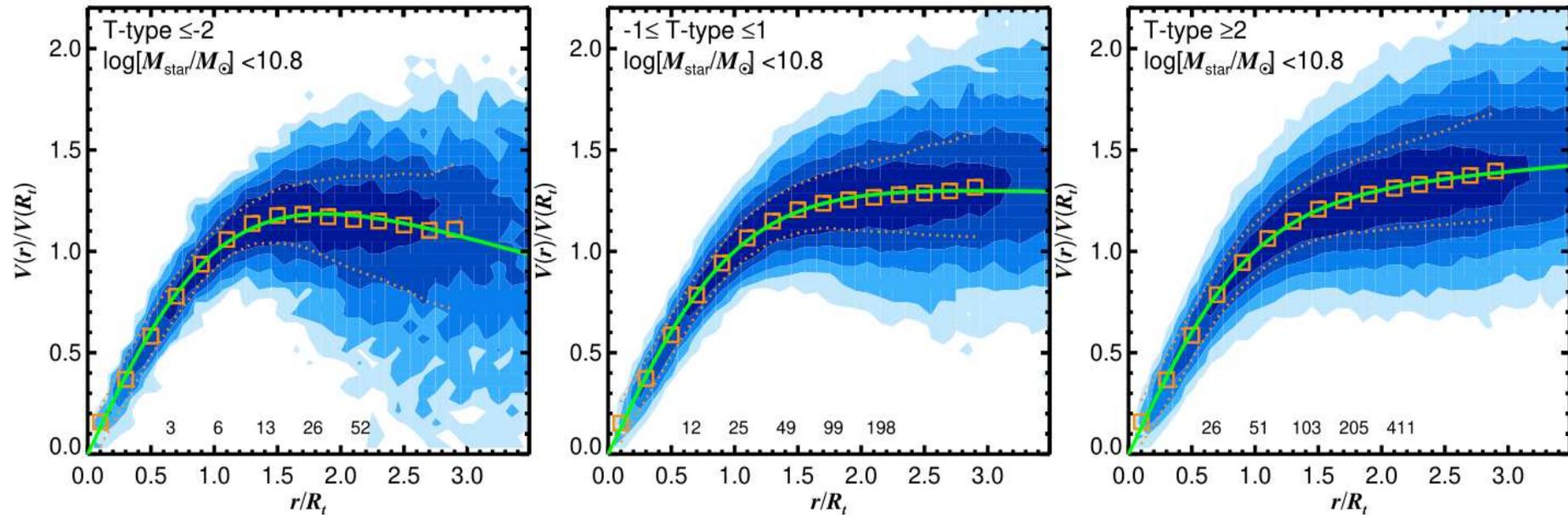
While Rubin used optical stars, Albert Bosma used **Radio Astronomy** (21-cm HI line).

- Gas extends much further than stars.
- Observed dozens of galaxies.
- Proved that flat rotation curves were a **Universal** feature of spiral galaxies.

FIG. 5. The rotation curves of the 25 galaxies. From Bosma, 1978.

Galaxy Rotation Curves in 21c

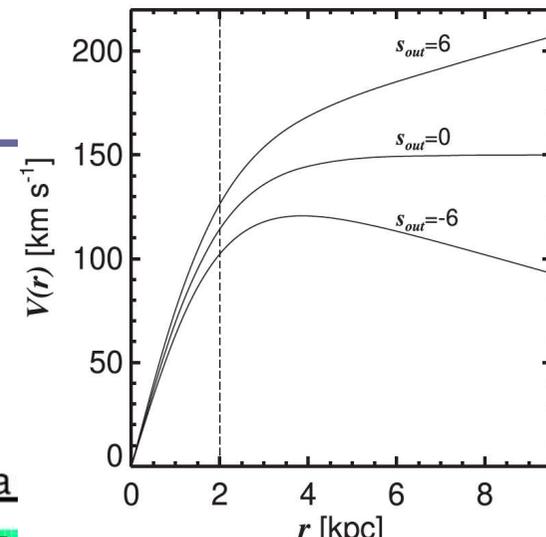
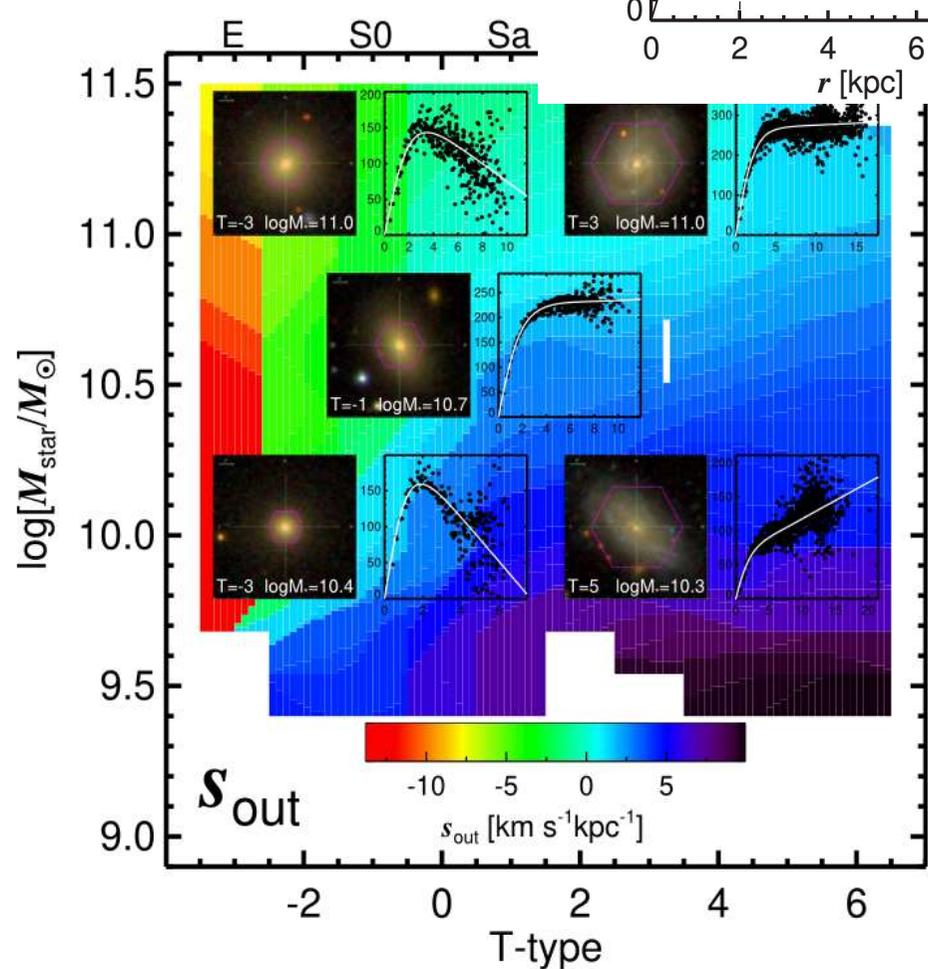
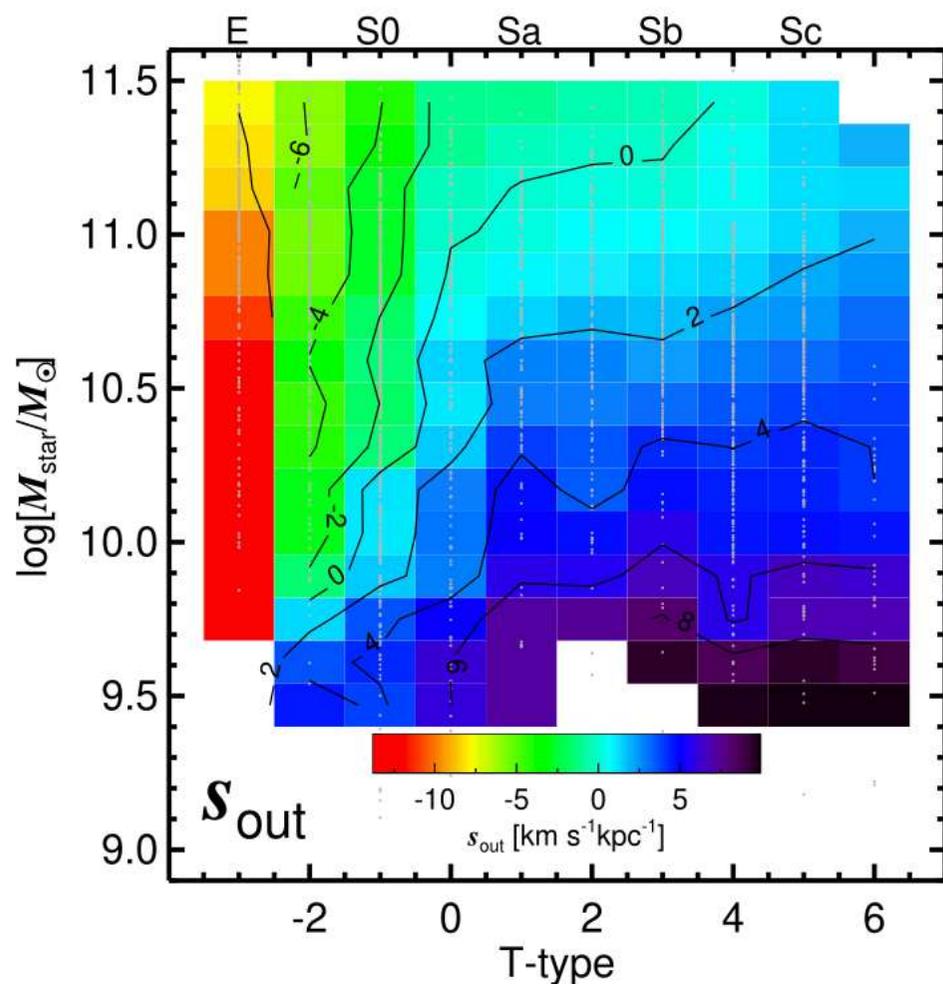
Rotation curves are NOT always flat, why?



➤ Dark matter may play an important role in shaping the rotation curve.

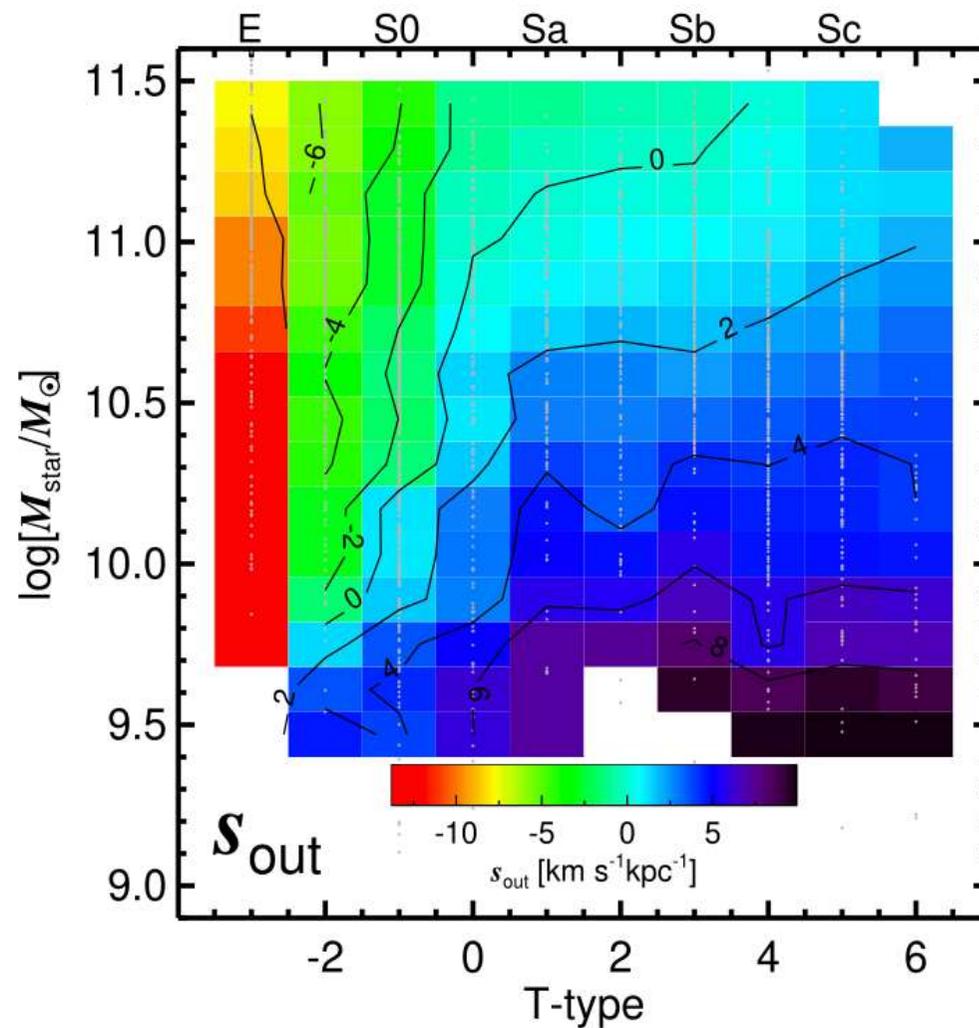
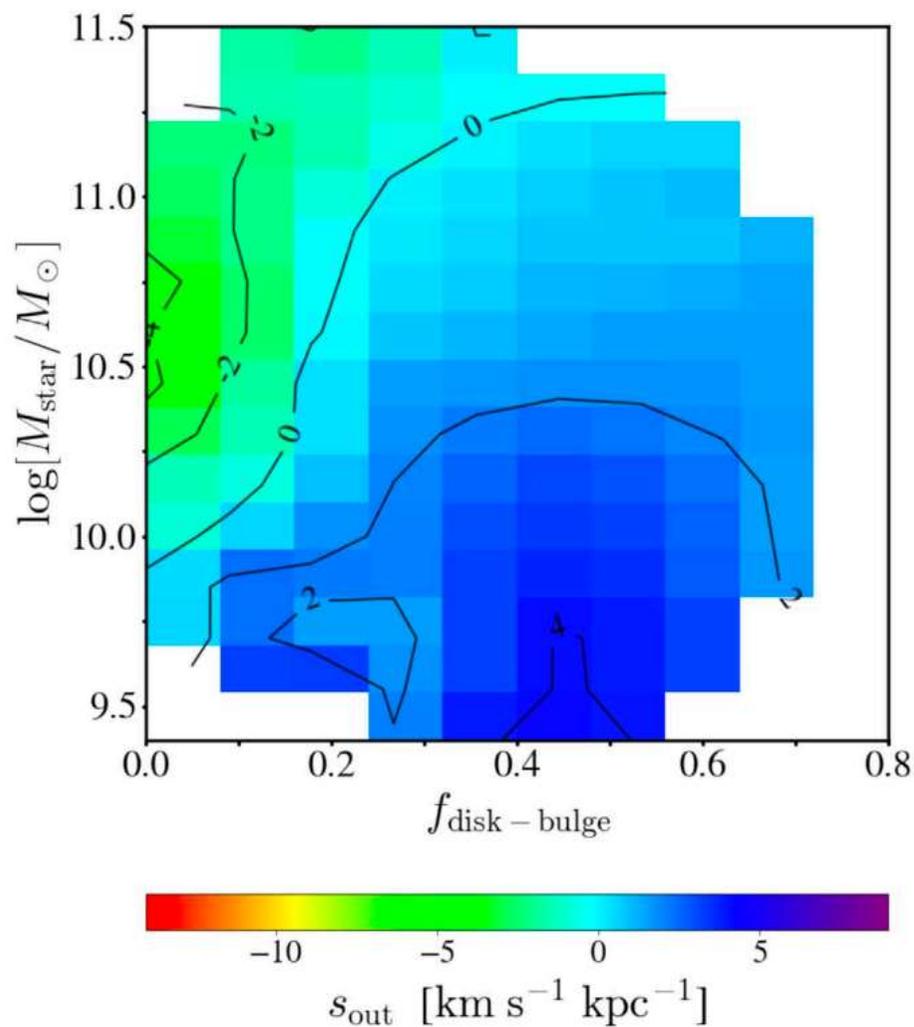
Galaxy Rotation Curves in 21C

A: Let's get some help from simulations.



Q: How to understand this diversity and dependence?

Galaxy Rotation Curves in 21C @ z~0

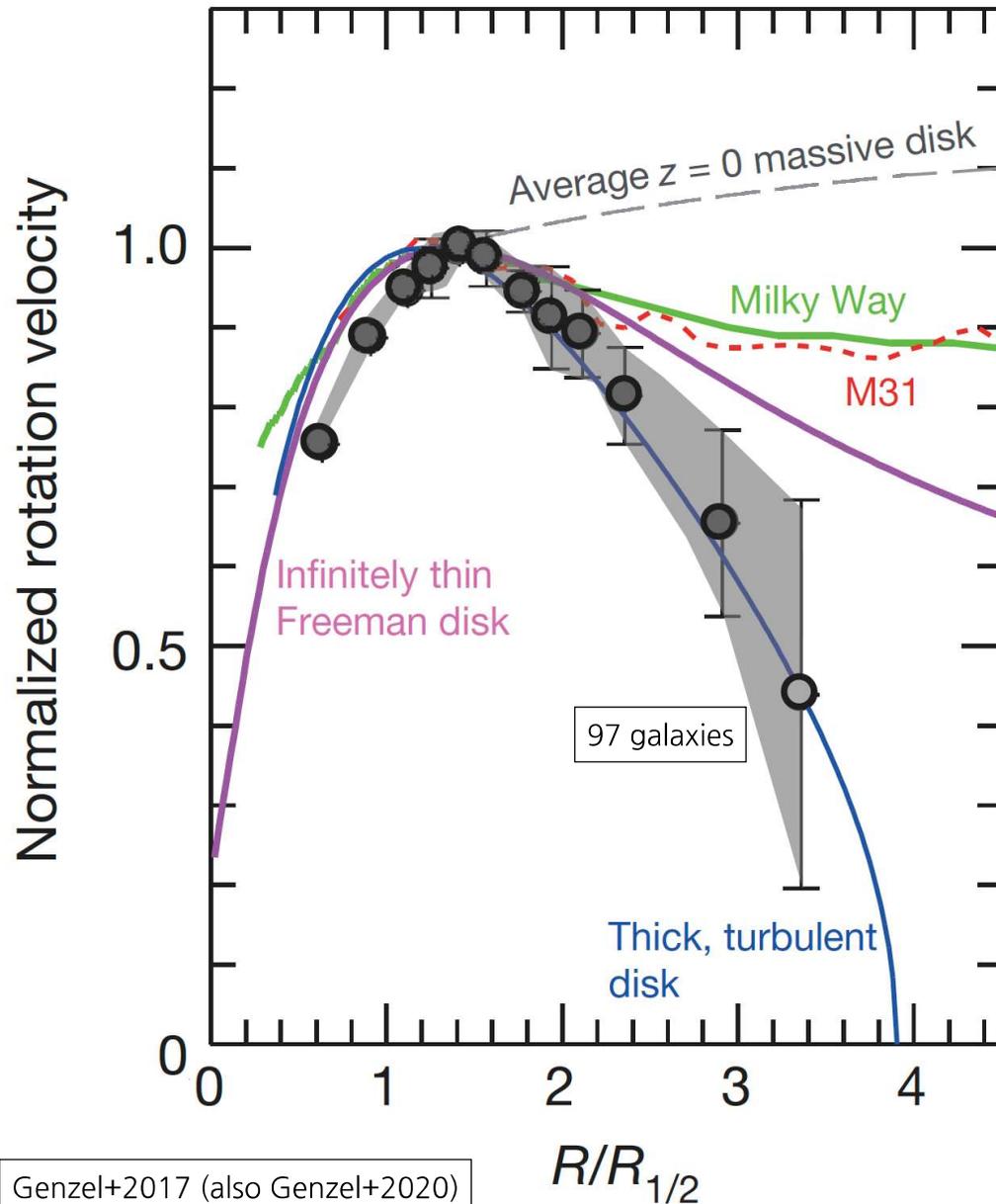


Simulations
(Jeong+2025)

Q: We could reproduce the trend in simulation, but what is Physics behind this? What should I do?

Observations
(Yoon+2021)

On the other hand, **Galaxy Rotation Curves in 21C @ z~1-2**



Genzel+2017 (also Genzel+2020)

➤ Interestingly, in the early universe ($z=0.6-2.6$, 2.5-8 Gyrs old), **the overall rotation curves declines unlike the local galaxies!**

➤ **This means something, what?**

➤ **Lower dark matter fraction for the galaxies in the earlier universe, but why?**

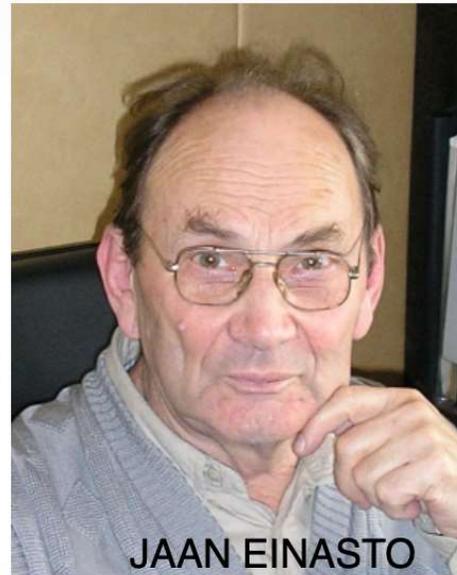
Total mass density of the Universe

Nature 250, 309 - 310 (26 July 1974)

Dynamic evidence on massive coronas of galaxies

JAAN EINASTO, ANTS KAASIK & ENN SAAR

A LONGSTANDING unresolved problem in galactic astronomy is the mass discrepancy observed in clusters of galaxies. The virial mass of the cluster per galaxy and the mass–luminosity ratio are considerably larger than the corresponding quantities for individual galaxies. This discrepancy cannot be a result of expansion or be because of the recent origin of clusters: these ideas contradict our present knowledge of the physical evolution and ages of galaxies. Therefore it is necessary to adopt an alternative hypothesis: that the clusters of galaxies are stabilised by hidden matter.



JAAN EINASTO

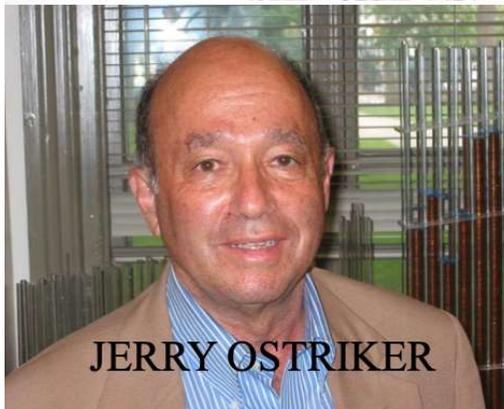


ENN SAAR

According to new estimates the total mass density of matter in galaxies is 20% of the critical cosmological density.

Both papers: $\Omega_m \approx 0.2$

THE SIZE AND MASS OF GALAXIES, AND THE MASS OF THE UNIVERSE



JERRY OSTRIKER

J. P. OSTRIKER
Princeton University Observatory

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

AND

A. YAHIL
University Observatory; and Department of Physics, Tel-Aviv University
Received 1974 May 28; revised 1974 July 15

ABSTRACT 1974 ApJ 194, L1



AMOS YAHIL

Currently available observations strongly indicate that the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc. This means that the total mass per giant spiral is of the order of $10^{12} M_\odot$, and that the ratio of this mass to the photographic light within the Holberg radius, f , is $\sim 200 (M/L)_\odot$. Using this value of f and the luminosity function of surveyed galaxies, we determine a local mean cosmological mass density $\approx 2 \times 10^{-30} \text{ g cm}^{-3}$ corresponding to $\Omega \equiv \rho/\rho_{\text{crit}} \approx 0.2$. The uncertainty in this result is not less than a factor of 3.

Slides from J. Primack

IV. Stability & Halos (1973—1974)

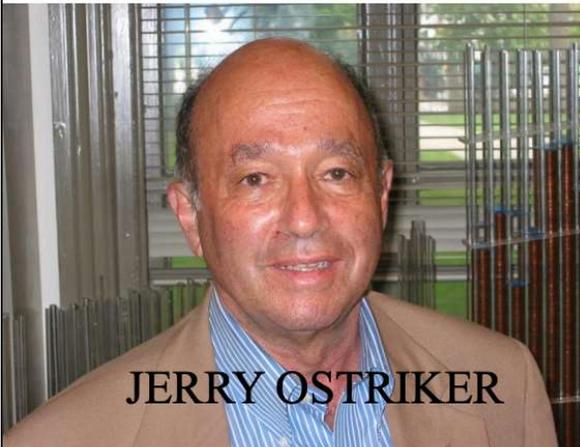
Ostriker, Peebles, and the Theoretical
Necessity

1973: DISK INSTABILITY

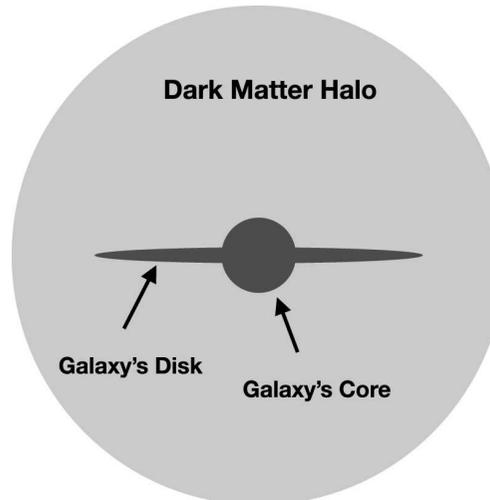
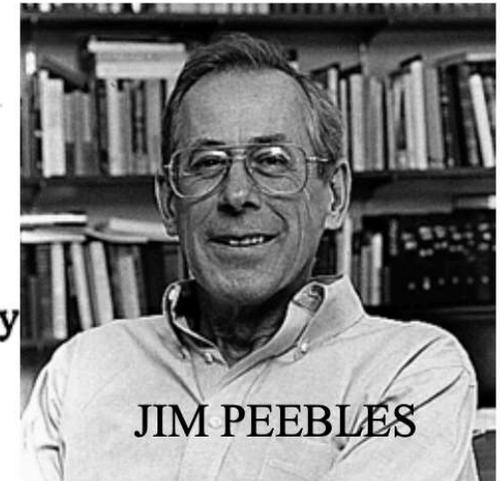
Jeremiah Ostriker and Jim Peebles discovered a critical problem using early computer simulations:

- Galactic disks of stars are naturally unstable and collapse into "bars" very quickly.
- **The Fix:** A massive, non-rotating spherical halo provides the gravity to stabilize the disk.
- This shifted dark matter from an "observational oddity" to a "theoretical requirement."

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*



J. P. OSTRIKER
Princeton University Observatory
AND
P. J. E. PEEBLES
Lyman Observatory, Princeton University
Received 1973 May 29



V. The Particle Turn (1980 — Present)

Cold Dark Matter, WIMPs, and
Axions

Dark Matter: Hot or Cold?

~1980 - Most astronomers are convinced that dark matter exists around galaxies and clusters - but is it Hot or Cold? Theorists usually assumed $\Omega_m=1$, but observers typically found $\Omega_m\approx 0.2$.

The Hot-Warm-Cold DM terminology was introduced by Dick Bond and me in our talks at the 1983 Moriond Conference.

1973 - Marx & Szalay, Cowsik & McClelland: $m_\nu < 100$ eV

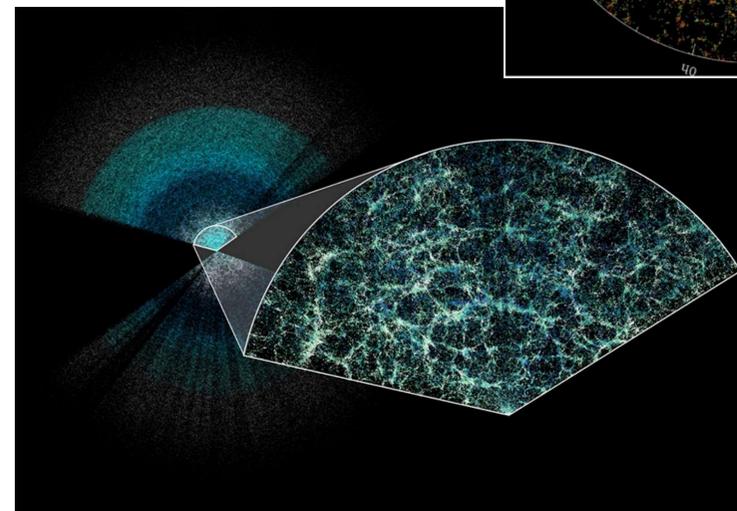
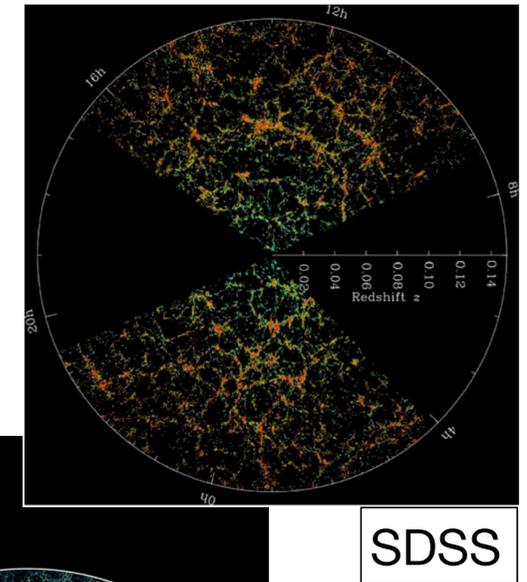
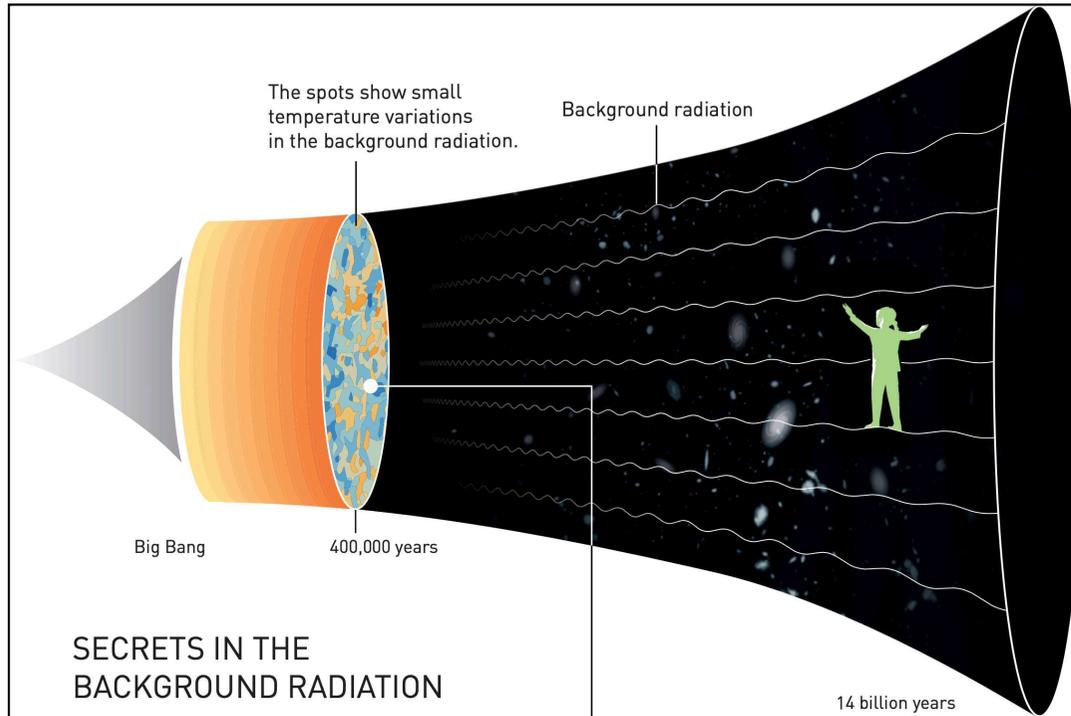
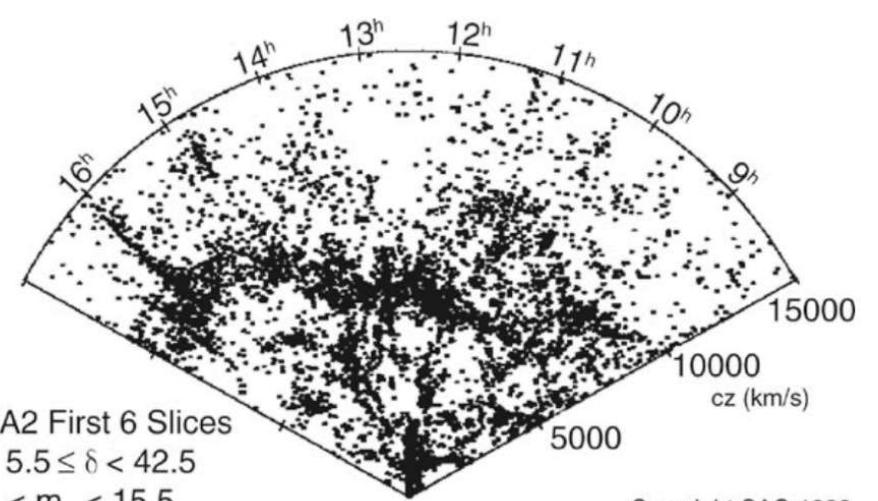
1980 - Zel'dovich group develops Hot Dark Matter (HDM) theory¹

1983 - White, Frenk, Davis: simulation rules out HDM

In ~1980, when purely baryonic adiabatic fluctuations were ruled out by the improving upper limits on CMB anisotropies, theorists led by Zel'dovich turned to what we now call the HDM scenario, with light neutrinos making up most of the dark matter. However, in this scheme the fluctuations on small scales are damped by relativistic motion (“free streaming”) of the neutrinos until $T < m_\nu$, which occurs when the mass entering the horizon is about $10^{15} M_{\text{sun}}$, the supercluster mass scale. Thus superclusters would form first, and galaxies later form by fragmentation. This predicted a galaxy distribution much more inhomogeneous than observed.

¹ E.g., Doroshkevich, Khlopov, Sunyaev, Szalay, & Zel'dovich 1981, NYASA 375, 32; Zel'dovich, Einasto, Shandarin 1982, Nature 300, 407; Bond & Szalay 1982, ApJ 274, 443.

Structure Formation in the Universe



**Q: Anyone saw the Big Bang?
 How do you know there was Big Bang?**

DESI's map of the Universe is the largest to date. The delicate bubble-like structures in the distribution of galaxies—seen in the inset—record vital clues to the expansion history of the universe. Credit: Claire Lamman/DESI collaboration; custom colormap package by cmaestro.

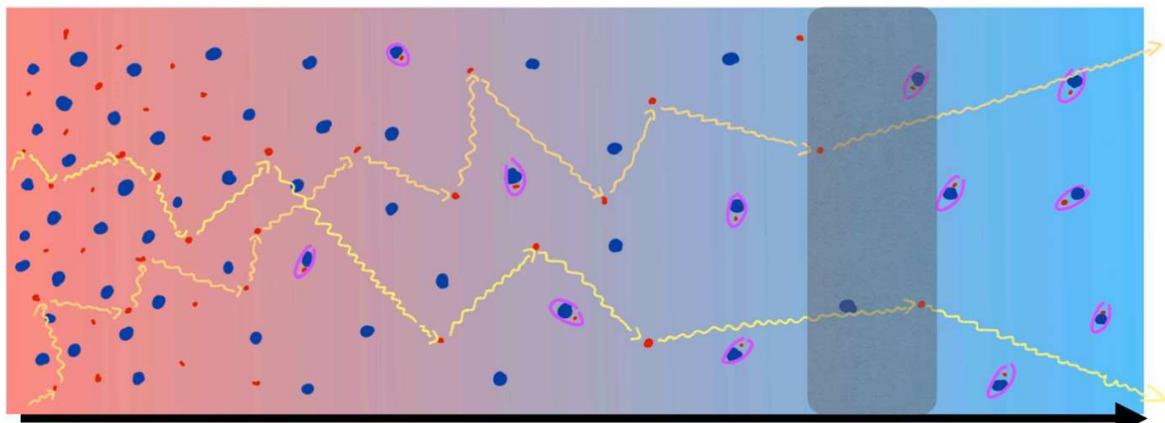
Cosmic Microwave Background (CMB)

-  neutral hydrogen
-  free electrons
-  free protons

-  free electrons
-  free protons



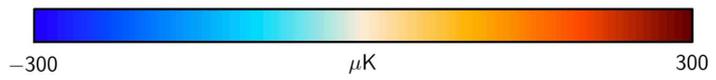
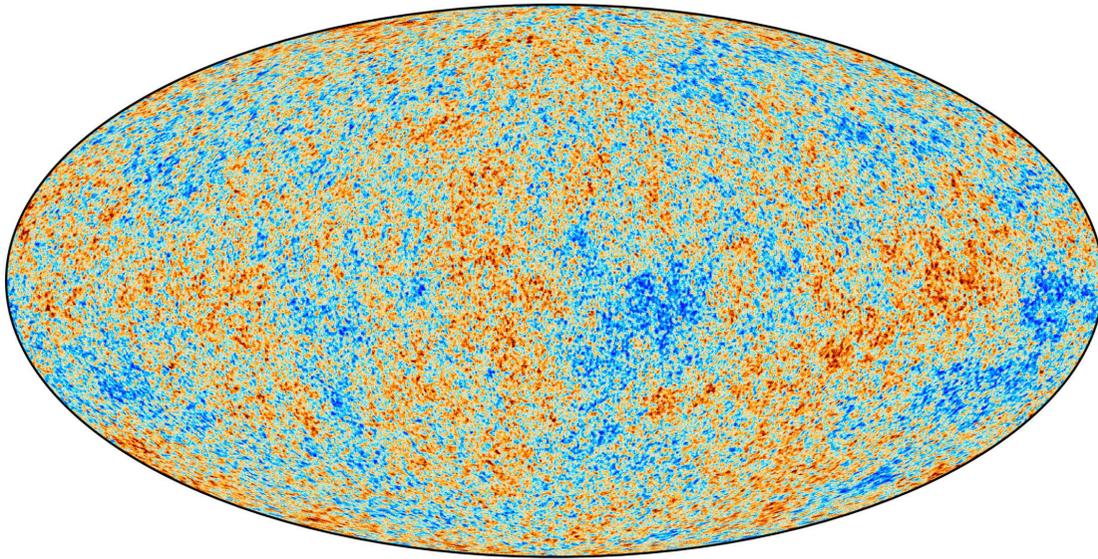
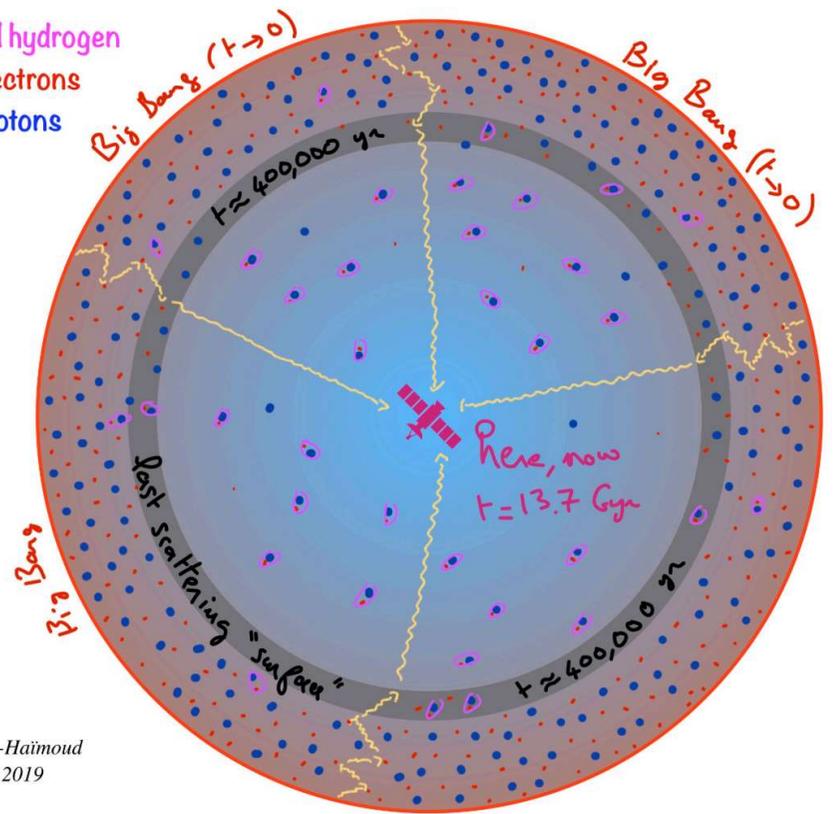
last scattering



Yacine Ali-Haïmoud
NYU, 2019

~400,000 yr Time

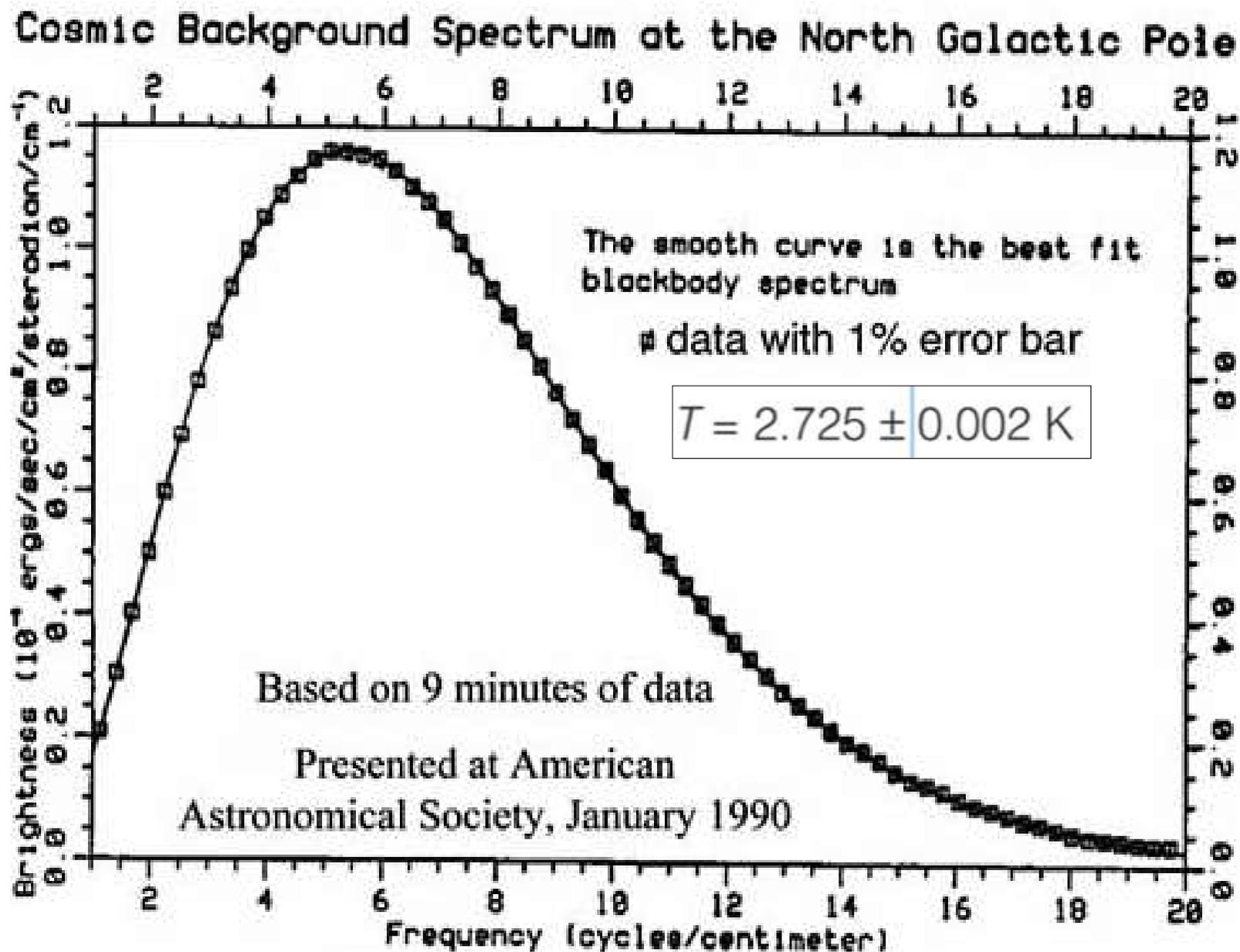
Yacine Ali-Haïmoud
NYU, 2019



Planck

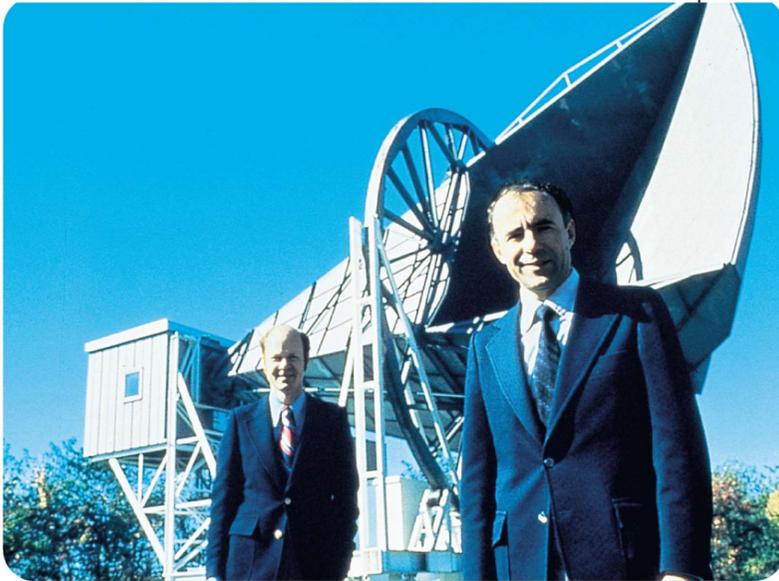
What makes the temperature different?

Evidence for Big Bang - CMB

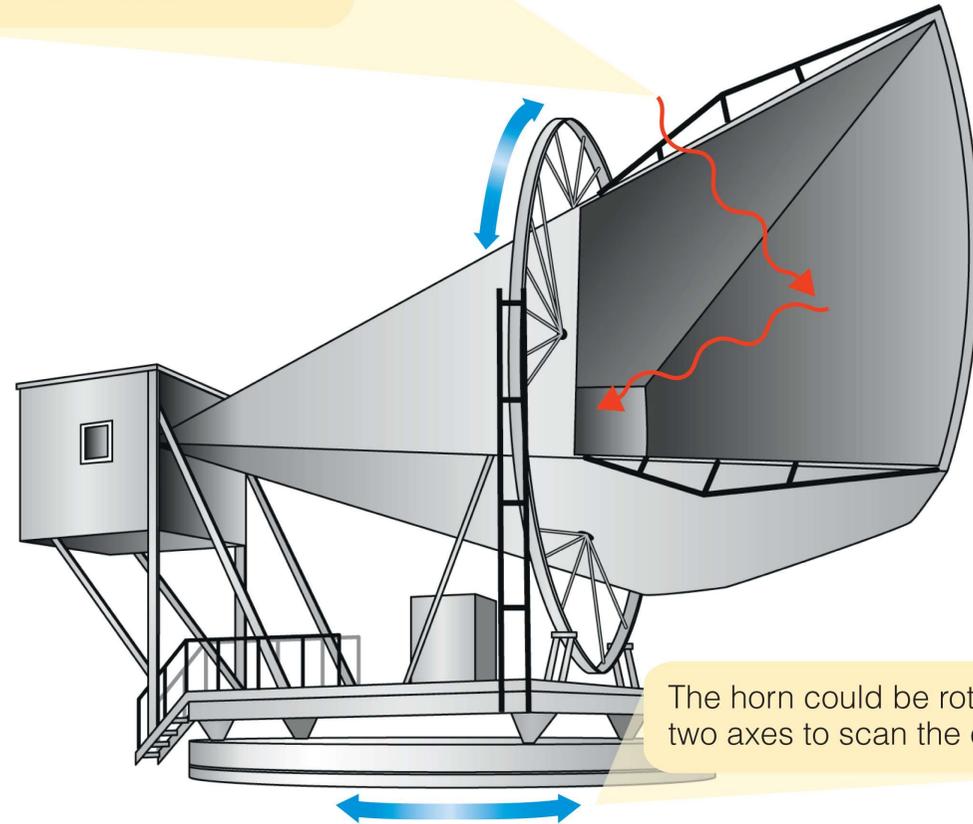


Cosmic background radiation

In 1965, Arno Penzias (right) and Robert Wilson first detected the cosmic microwave background radiation with the horn antenna behind them.



Microwave radiation from the sky enters the horn and is focused into the instrument room.

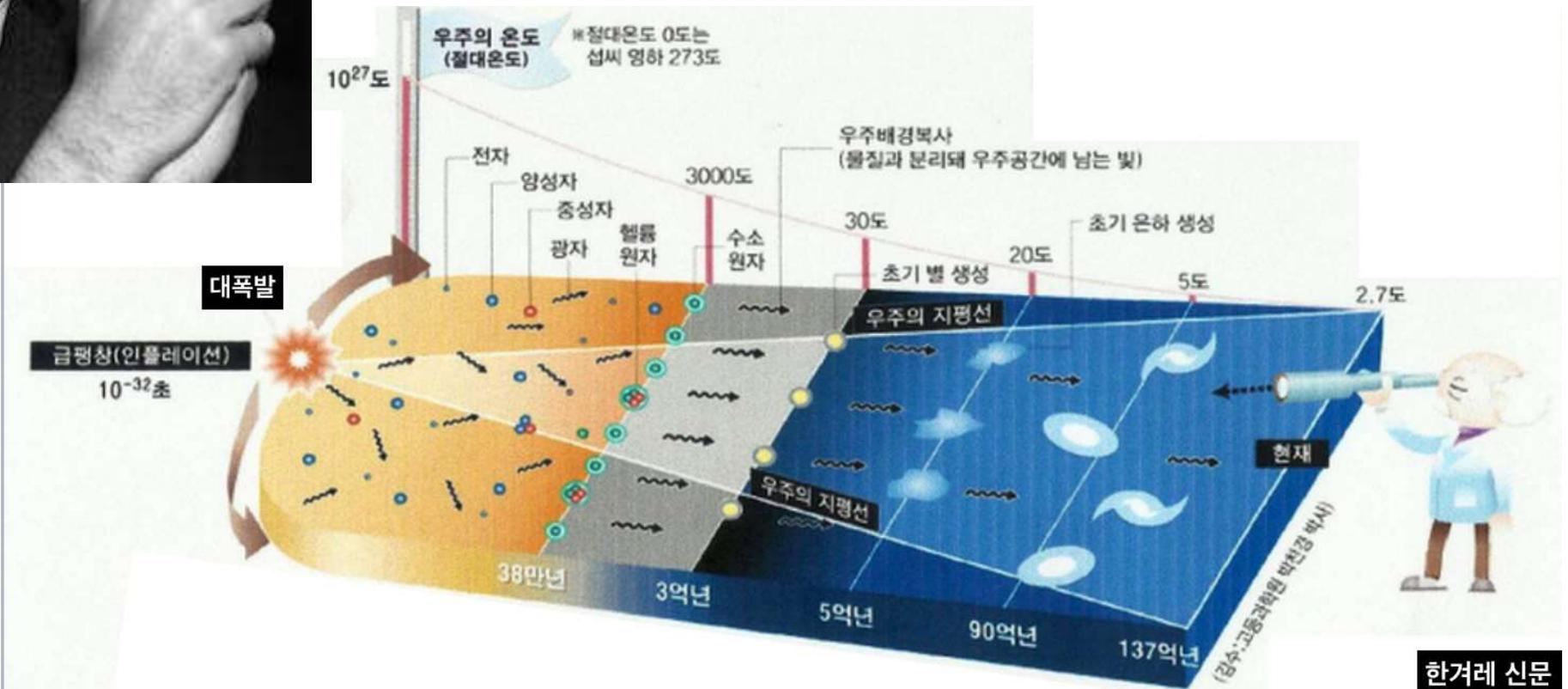


The horn could be rotated about two axes to scan the entire sky.

Cosmic background radiation



Dicke & one of his graduate student



Cosmic background radiation

1965aps...142...413P

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm³ is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. DICKE
P. J. E. PEEBLES
P. G. ROLL
D. T. WILKINSON

May 7, 1965
PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

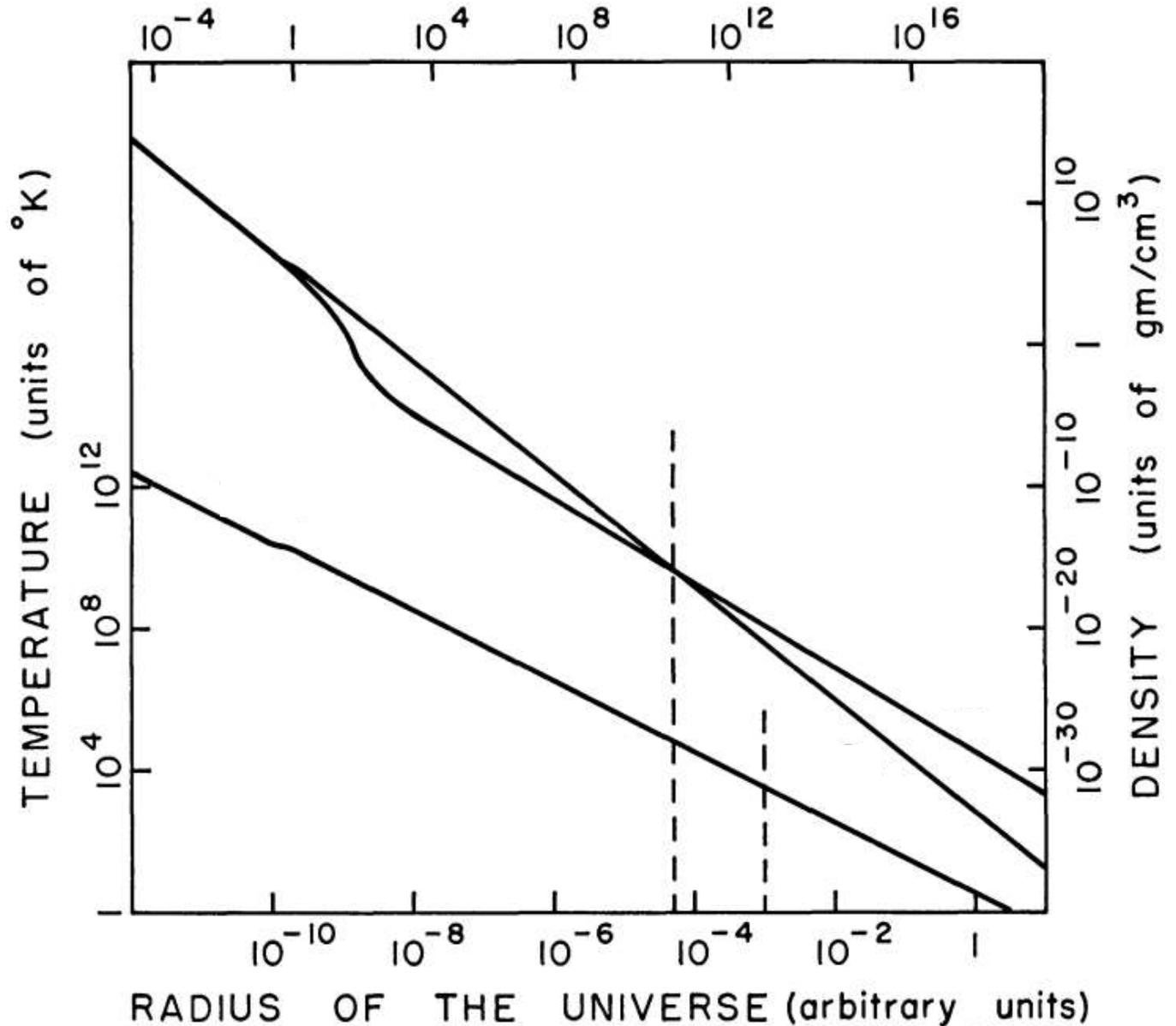
Dicke+

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 ——— 1964, in *Relativity, Groups and Topology*, ed. C. DeWitt and B. DeWitt (New York: Gordon & Breach).
 Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and



Cosmic background radiation

The Nobel Prize in Physics 1978

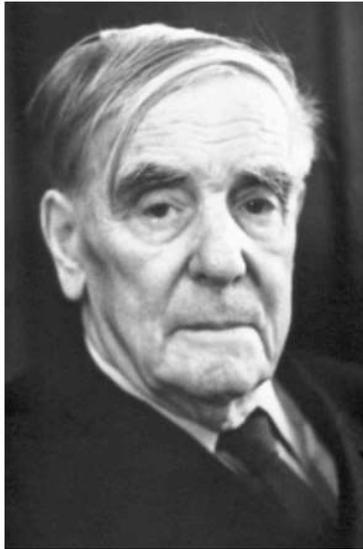


Photo from the Nobel Foundation archive.

Pyotr Leonidovich Kapitsa

Prize share: 1/2



Photo from the Nobel Foundation archive.

Arno Allan Penzias

Prize share: 1/4

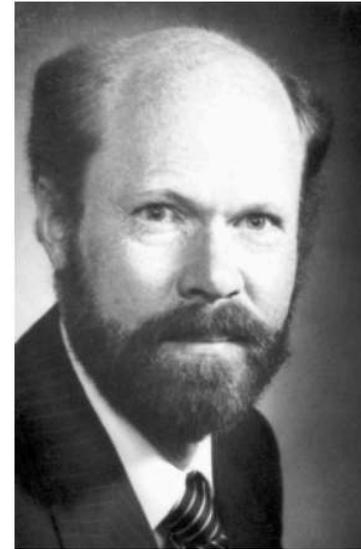


Photo from the Nobel Foundation archive.

Robert Woodrow Wilson

Prize share: 1/4

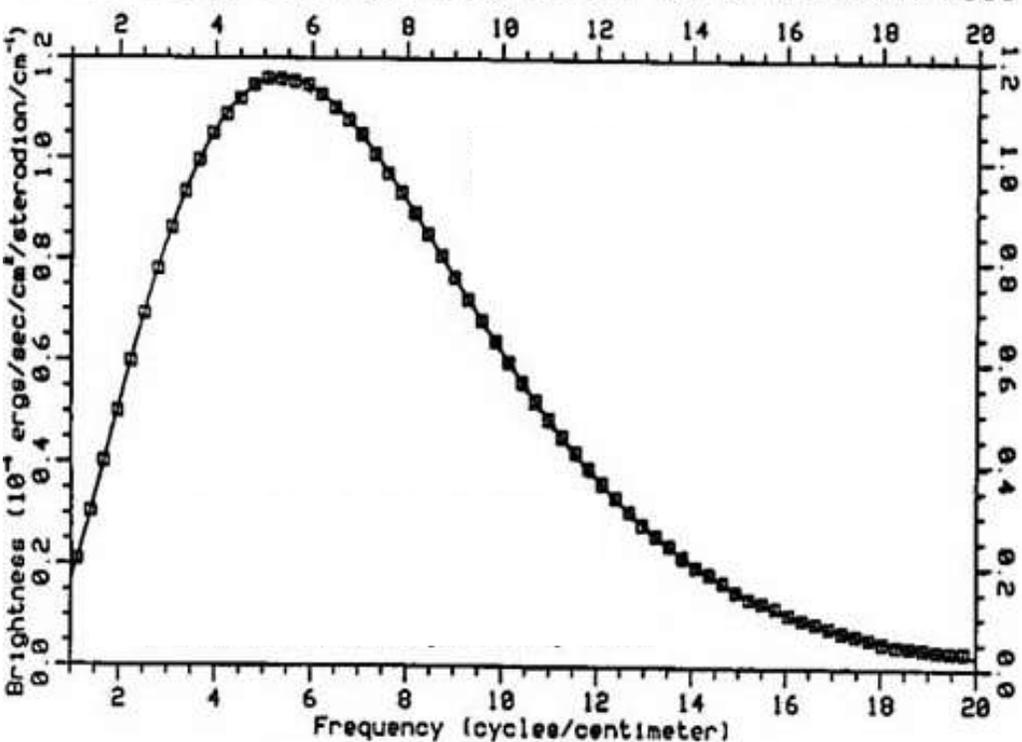
The Nobel Prize in Physics 1978 was divided, one half awarded to Pyotr Leonidovich Kapitsa "for his basic inventions and discoveries in the area of low-temperature physics", the other half jointly to Arno Allan Penzias and Robert Woodrow Wilson "for their discovery of cosmic microwave background radiation."

Wilson's Office at CfA

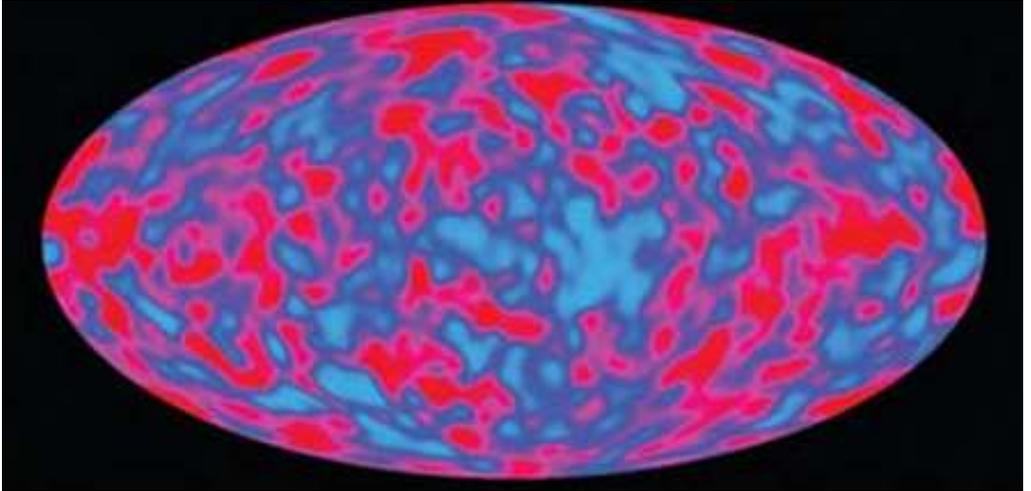


Evidence for Big Bang - CMB

Cosmic Background Spectrum at the North Galactic Pole

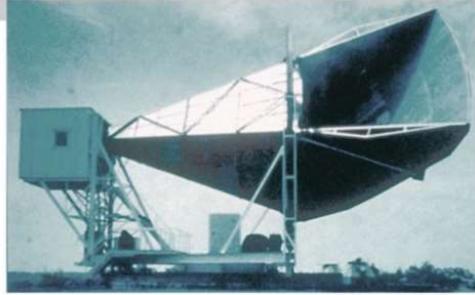


매더 & 스무트 (COBE, 90 → 06)

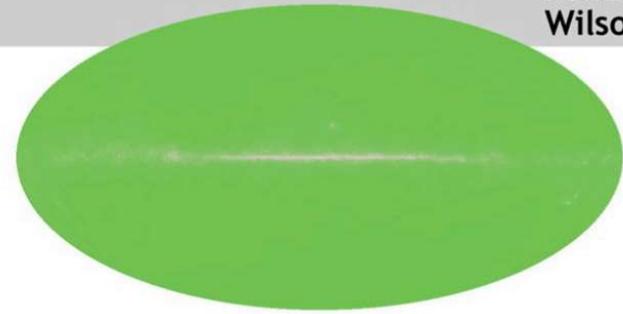


History of CMB Measurement

1965



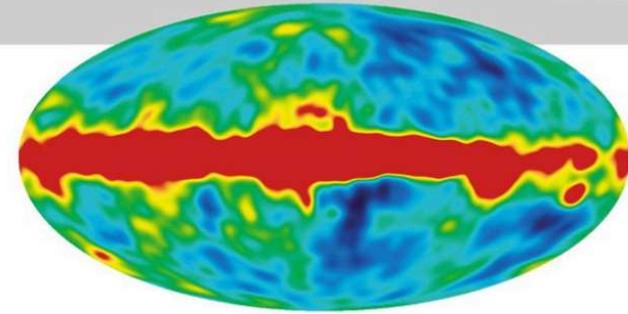
Penzias and Wilson



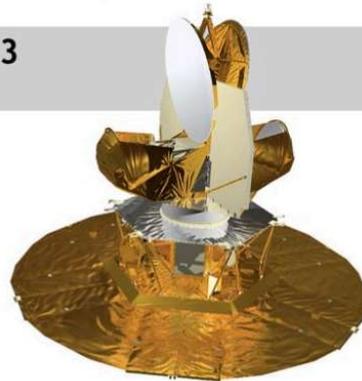
1992



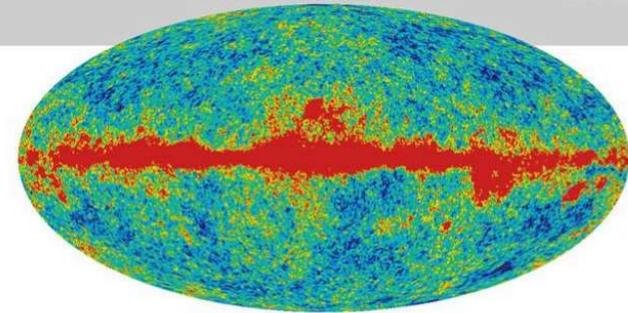
COBE



2003

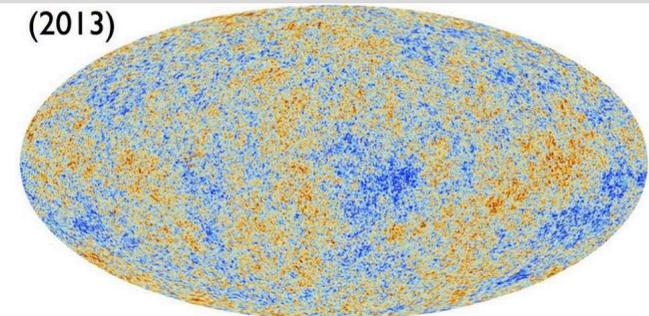


WMAP



Planck

(2013)



An Expanding Universe

Kinematics of the Universe

- Comoving Coordinates \mathbf{x} (vs. Proper/Physical sizes \mathbf{r})

$$\mathbf{r}(t) = a(t) \mathbf{x} . \quad (4.4)$$

- $a(t)$: cosmic scale factor -
 - describe the expansion of the universe
 - dimensionless
 - $a(t_0) = 1$ by definition where t_0 =today

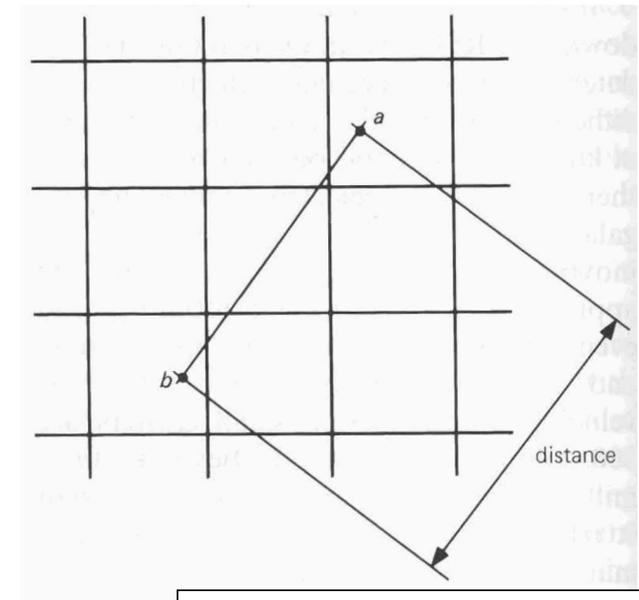
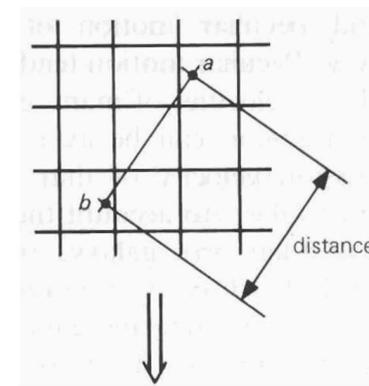
- Expansion rate: $H(t)$ - Hubble parameter

$$\mathbf{v}(\mathbf{r}, t) = \frac{d}{dt} \mathbf{r}(t) = \frac{da}{dt} \mathbf{x} \equiv \dot{a} \mathbf{x} = \frac{\dot{a}}{a} \mathbf{r} \equiv H(t) \mathbf{r} , \quad (4.6)$$

$$H(t) := \frac{\dot{a}}{a} . \quad (4.7)$$

Using the definition of redshift, $z = (\lambda_0 - \lambda_e)/\lambda_e$

$$1 + z = \frac{1}{a} \quad (4.41)$$



Harrison (2000):
Comoving vs. Proper distance

Gravitational Instability

Linear Perturbation Theory

- We would like to describe the growth of density perturbations in the universe.
- For simplicity, we assume that the matter in the universe consists only of dust (i.e. pressure-free matter), with density $\rho(\mathbf{r}, t)$.
- The matter distribution is described as fluid with the velocity of $\mathbf{v}(\mathbf{r}, t)$.

1) Equations of motion

- Continuity equation: $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$, (7.2)

- Euler equation (i.e. momentum equation):

- Here we set $P = 0$ because we consider pressureless matter.

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{\nabla P}{\rho} - \nabla \Phi, \quad (7.3)$$

- Poisson equation: $\nabla^2 \Phi = 4\pi G \rho - \Lambda$. (7.4)

- relative density contrast

$$\delta(\mathbf{r}, t) := \frac{\rho(\mathbf{r}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}, \quad (7.1)$$

- In short, we have:

$$\frac{\partial^2 \delta}{\partial t^2} + \frac{2\dot{a}}{a} \frac{\partial \delta}{\partial t} = 4\pi G \bar{\rho} \delta. \quad (7.14)$$

Gravitational Instability

Linear Perturbation Theory

$$\frac{\partial^2 \delta}{\partial t^2} + \frac{2\dot{a}}{a} \frac{\partial \delta}{\partial t} = 4\pi G \bar{\rho} \delta . \quad (7.14)$$

Remarkably, this equation does not contain

1. derivatives with respect to spatial coordinates
2. coefficients that depend on \mathbf{x}

➤ The solution can have the form of $\delta(\mathbf{x}, t) = D(t)\tilde{\delta}(\mathbf{x})$;
i.e. spatial and temporal dependencies factorize.

➤ $\tilde{\delta}(\mathbf{x})$: arbitrary function of the spatial coordinate

➤ $D(t)$: satisfies the equation of

$$\ddot{D} + \frac{2\dot{a}}{a} \dot{D} - 4\pi G \bar{\rho}(t) D = 0 . \quad (7.15)$$

Gravitational Instability

Linear Perturbation Theory

Example: Einstein-de Sitter (EdS) model

➤ In a special case with $\Omega_m = 1$, $\Omega_\Lambda = 0$, eq (7.15) can be solved explicitly.

$$a(t) = \left(\frac{3 H_0 t}{2}\right)^{2/3} = \left(\frac{t}{t_0}\right)^{2/3}. \quad (4.56)$$

$$t_0 H_0 = 2/3$$

$$\left(\frac{\dot{a}}{a}\right) = \frac{2}{3t}, \text{ and } \bar{\rho}(t) = a^{-3} \rho_{\text{cr}} = \frac{3 H_0^2}{8\pi G} \left(\frac{t}{t_0}\right)^{-2}$$

$$\ddot{D} + \frac{2\dot{a}}{a} \dot{D} - 4\pi G \bar{\rho}(t) D = 0. \quad (7.15)$$

$$\ddot{D} + \frac{4}{3t} \dot{D} - \frac{2}{3t^2} D = 0. \quad (7.18)$$

➤ This equation is easily solved by making the ansatz $D \propto t^q$; each term has the dimension $D/(\text{time})^2$.

$$q(q-1) + \frac{4}{3}q - \frac{2}{3} = 0$$

➤ Solutions: $q = 2/3$ (increasing) and $q = -1$ (decreasing)

$$D_+(t) = \left(\frac{t}{t_0}\right)^{2/3} = a(t) \quad (7.19)$$

➤ **EdS: growth factor = scale factor**

➤ This means that fluctuations were able to grow by a factor ~ 1000 from the epoch of recombination at $z \sim 1000$, from which the CMB photons originate, to the present day.

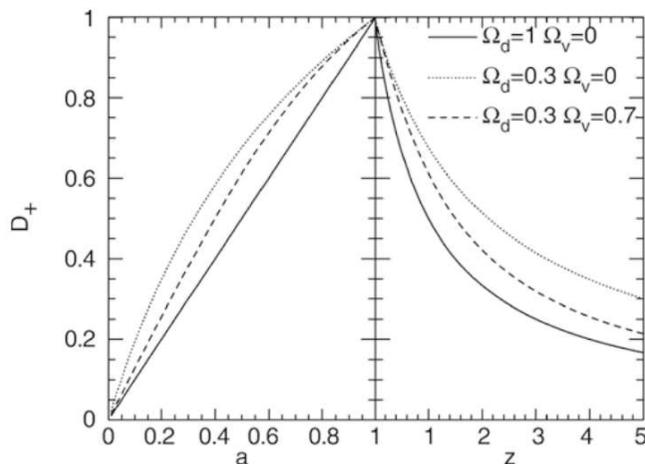


Fig. 7.3 Growth factor D_+ for three different cosmological models, as a function of the scale factor a (left panel) and of redshift (right panel). It is clearly visible how quickly D_+ decreases with increasing redshift in the EdS-model, in comparison to the models of lower density

Gravitational Instability

Q: What is the evidence for dark matter in the universe?

Linear Perturbation Theory

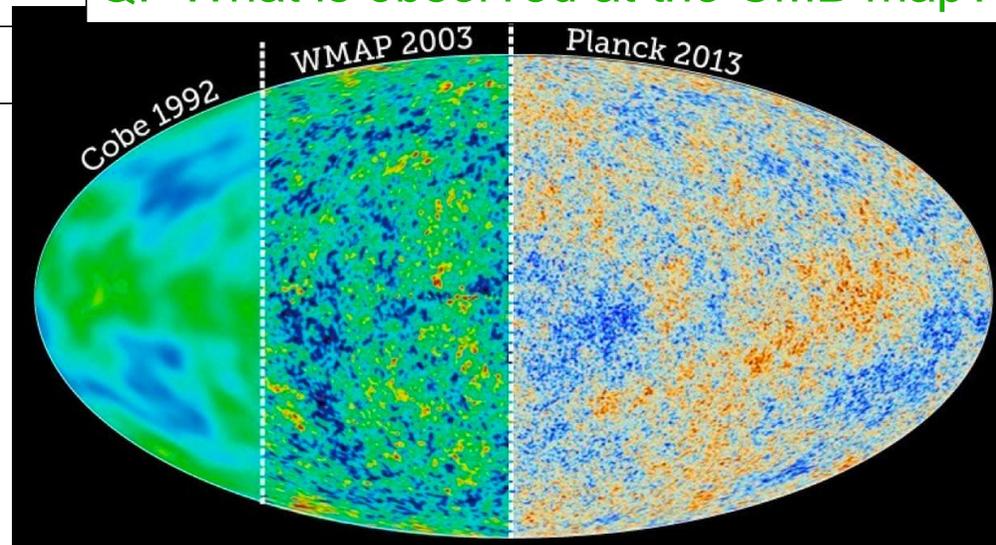
Evidence for dark matter on cosmic scales

At present epoch, the scales of

- galaxy clusters: $\delta \gg 1$
- Superclusters: $\delta \sim 1$
- For EdS:

$$D_+(t) = \left(\frac{t}{t_0}\right)^{2/3} = a(t) \quad (7.19)$$

Q: What is observed at the CMB map?



- According to the change of the growth factor, we expect $\delta \gtrsim 10^{-3}$ at $z = 1000$ so that the fluctuations grow to non-linear structures at the current epoch.
- This means that the CMB fluctuation should be $\Delta T/T \gtrsim 10^{-3}$.
- In reality, $\Delta T/T \sim 10^{-5}$;
these fluctuations cannot grow sufficiently to form non-linear structures. Then what?
- CMB shows the density contrast of baryons!
- Dark matter may have had a higher density contrast at recombination, but the baryons, which are strongly coupled to the radiation field before recombination, are prevented from strong clustering due to the radiation pressure.
- Only after the recombination, the baryons may fall into the potential wells formed by the dark matter.
- This is the important evidence for the existence of dark matter!

우주배경복사와 나

THE ASTROPHYSICAL JOURNAL

VOLUME 142

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NUMBER 4

THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE
AND THE FORMATION OF GALAXIES*

P. J. E. PEEBLES

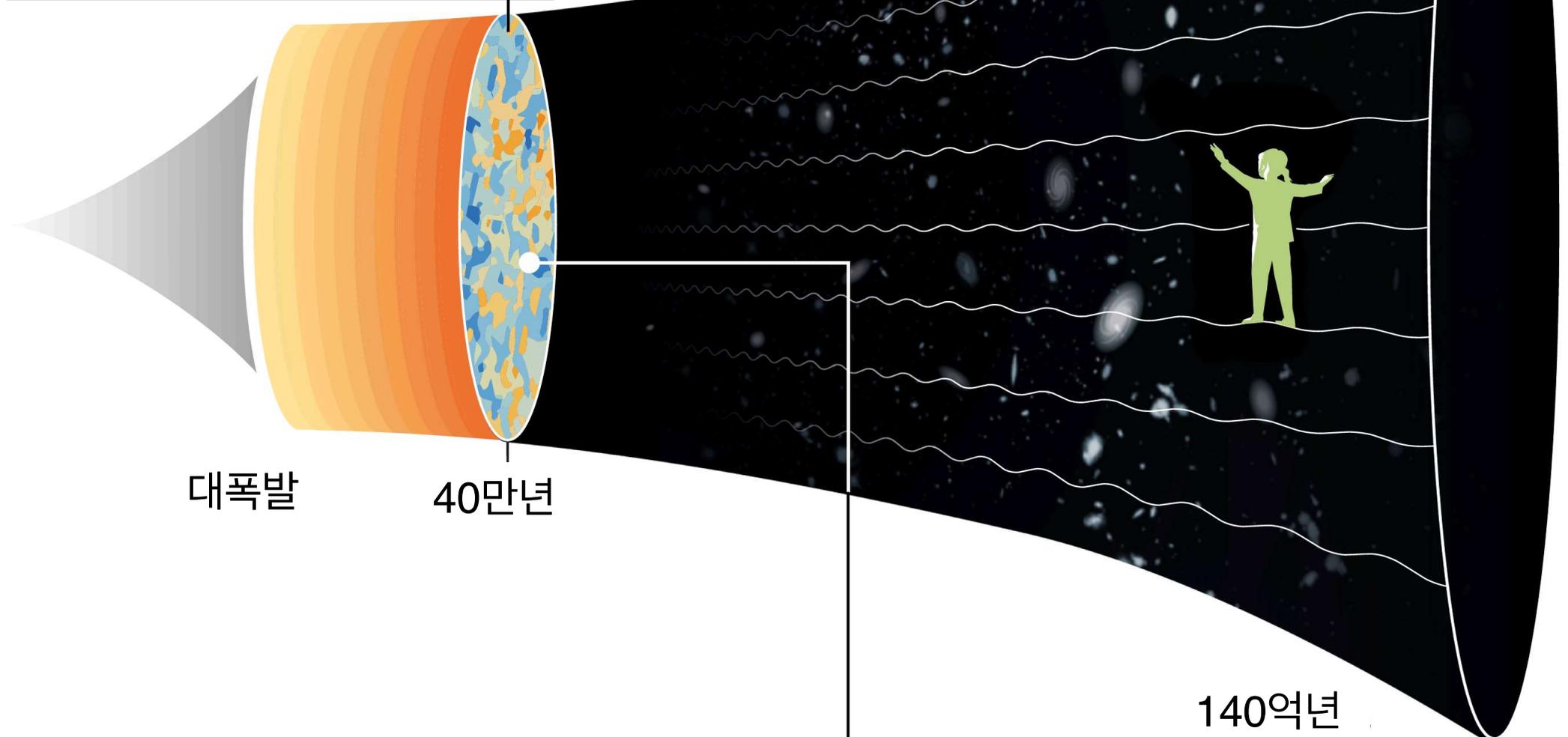
Palmer Physical Laboratory, Princeton University, Princeton, N J.

Received March 8, 1965; revised June 1, 1965

ABSTRACT

A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the Universe. An important property of this radiation is that it would serve to prevent the formation of gravitationally bound systems, whether galaxies or stars, until the Universe has expanded to a critical epoch. There is good reason to expect the presence of black-body radiation in an evolutionary cosmology, and it may be possible to observe such radiation directly.

Background radiation

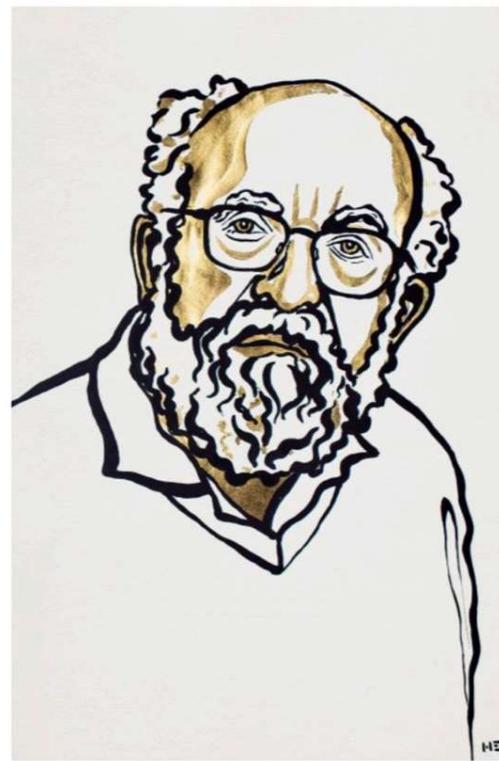


2019년 노벨 물리학상



Ill. Niklas Elmehed. © Nobel Media.

제임스 피블스 (James Peebles)



Ill. Niklas Elmehed. © Nobel Media.

미셸 마요르 (Michel Mayor)



Ill. Niklas Elmehed. © Nobel Media.

디디에 쿠엘로 (Didier Queloz)

- **우주의 진화 및 우주에서 지구의 위치에 대한 이해에 기여**
 - **피블스 (1/2): 물리학적 우주론의 이론적 정립에 기여**
 - **마요르(1/4)/쿠엘로(1/4): 태양과 비슷한 별 주위를 도는 외계 행성을 발견**

We will discuss more about Dark Matter Particle models later.

VI. Precision Cosmology

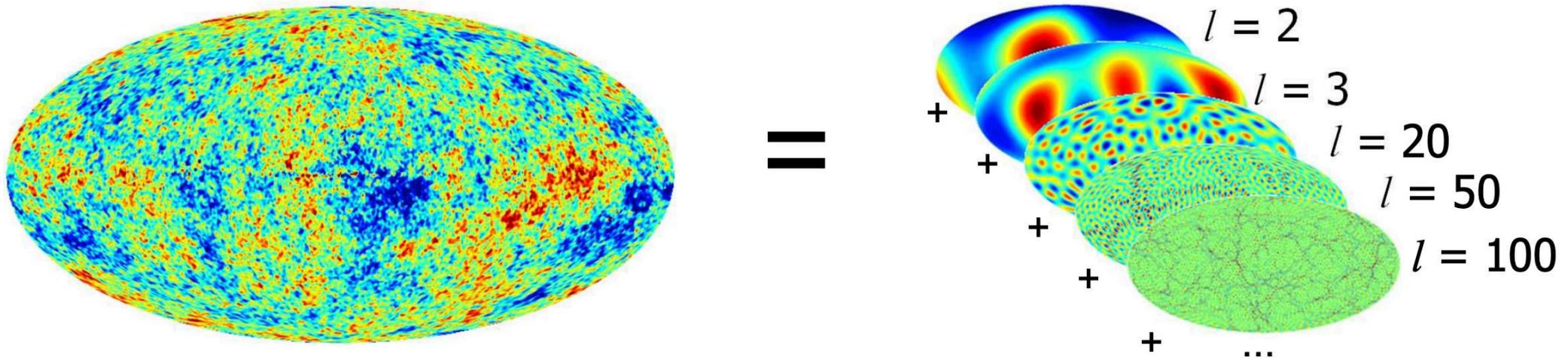
CMB, Bullet Cluster, and Large Scale
Structure

Angular Fluctuations of the Cosmic Microwave Background

Description of the CMB anisotropy

➤ How to quantify the angular distribution of CMB temperature?

1. Correlation function and power spectrum
2. Relative temperature fluctuations: $T(\hat{n}) = [T(\hat{n}) - T_0]/T_0$



➤ Spherical harmonics decomposition of the CMB temperature map

$$T(\hat{n}) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

➤ \hat{n} : unit vector describing the direction on the sphere

➤ $a_{\ell m}$: spherical harmonics coefficients

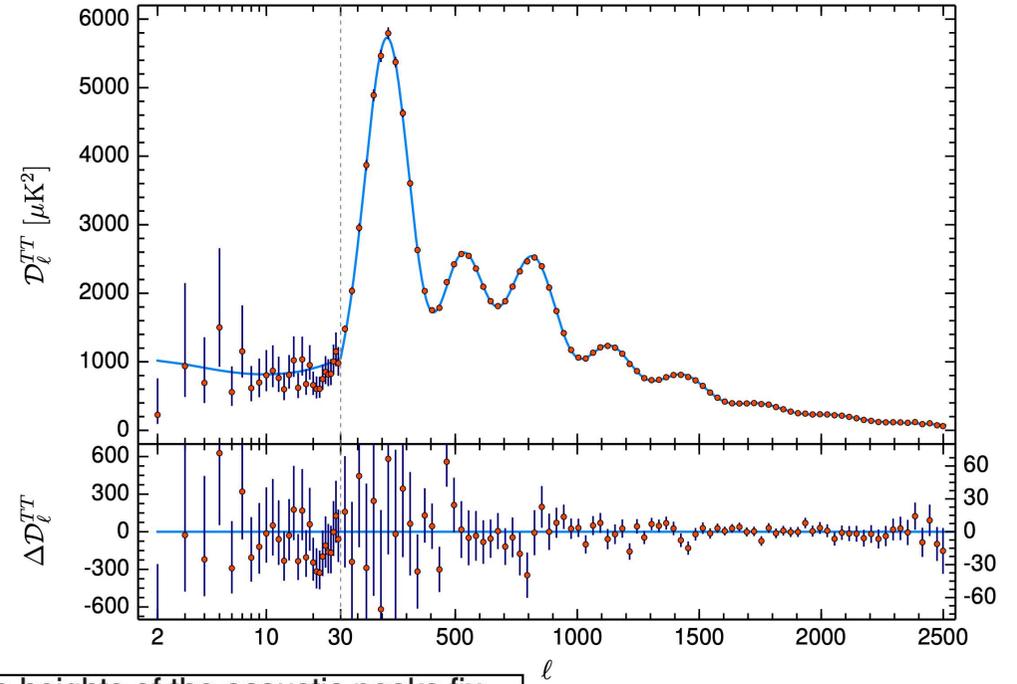
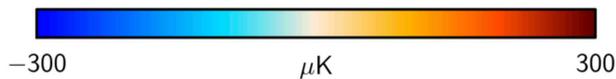
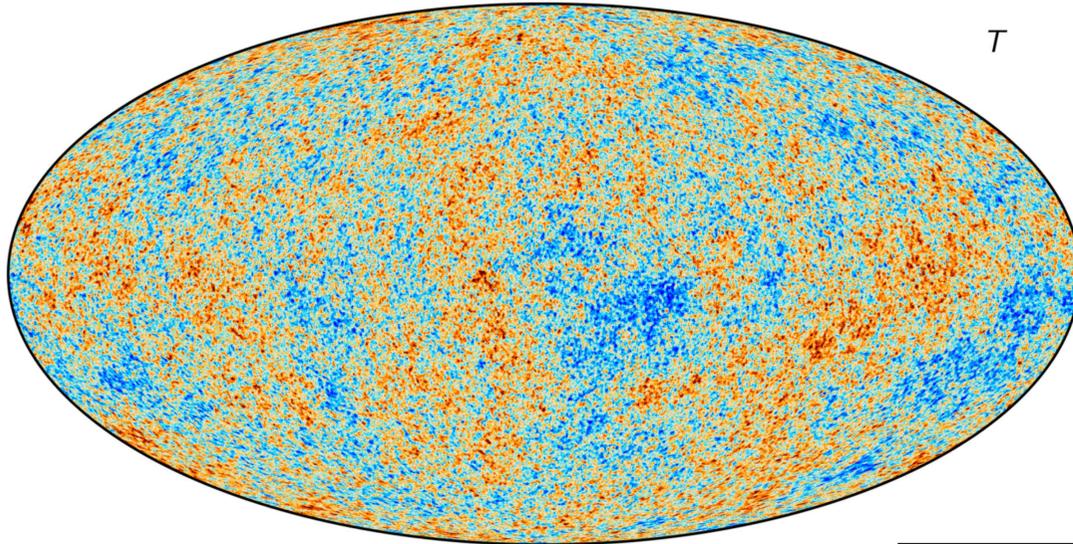
➤ $Y_{\ell m}$: the spherical harmonics themselves (computed with Legendre polynomials)

The expansion coefficients are given by

$$a_{\ell m} = \int_{4\pi} T(\hat{n}) Y_{\ell m}^*(\hat{n}) d\Omega$$

CMB Power spectrum

Planck 2018 results. VI. Cosmological parameters



- The relative heights of the acoustic peaks fix the Ratio of Baryons to Dark Matter.
- Confirmed a universe that is 27% Dark Matter.

$$C(\theta) = \langle T(\mathbf{n}) T(\mathbf{n}') \rangle, \quad (8.35)$$

➤ Correlation Function:

where the average extends over all pairs of directions \mathbf{n} and \mathbf{n}' with angular separation θ .

➤ Power spectrum:

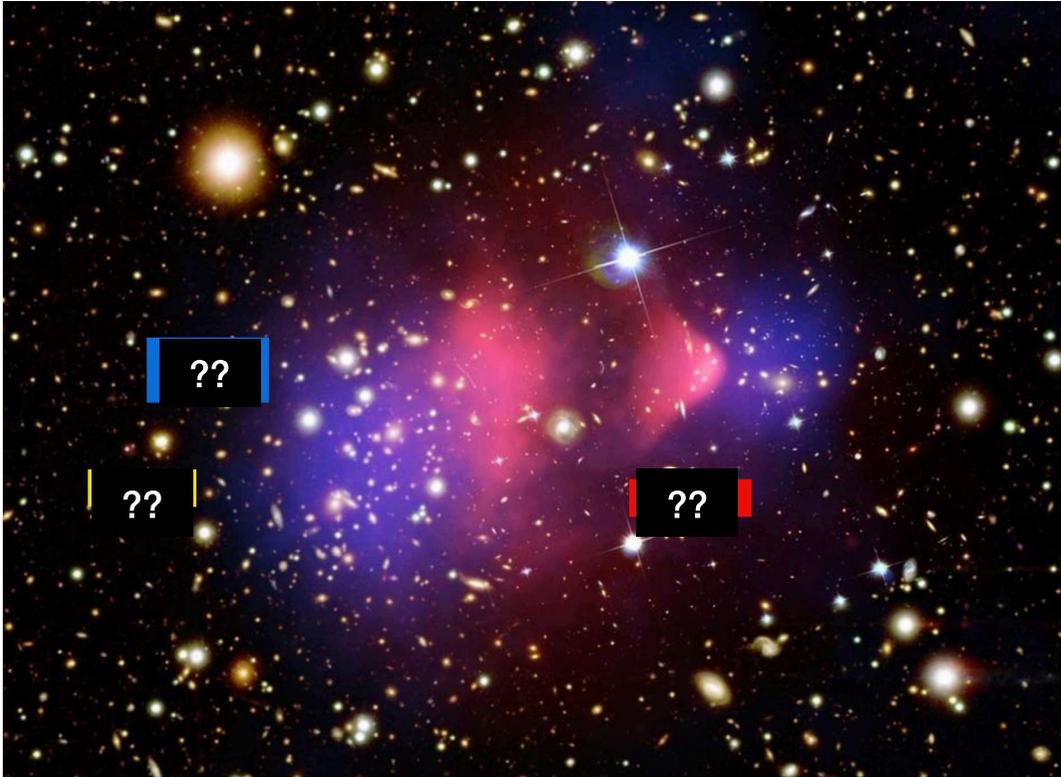
$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

➤ Power spectrum is usually displayed as

$$\Delta_T^2 \equiv \frac{\ell(\ell + 1)}{2\pi} C_\ell T^2$$

Parameter	Planck alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_* [Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag} [Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq} [Mpc $^{-1}$]	0.010384 ± 0.000081

THE "SMOKING GUN"



2006 Breakthrough

A collision of two clusters separated the visible gas from the dynamical mass. Which one is which?

- The mass (detected via lensing) kept moving, while the gas got stuck in the middle.
- Proves that Dark Matter is a **Particle**, not just a modification of gravity.

- Mass of a typical galaxy cluster : 10^{13} - $10^{15} M_{\odot}$
 - Galaxies : 1-2 % (Lin et al. 2003)
 - X-ray emitting Gas : 5-15 % (Vikhlinin et al. 2006)
 - Dark matter : >80% (first suggested by Zwicky 1933)
→ Affect galaxy properties gravitationally and hydrodynamically

Large Scale Structures in the Universe

매일경제

한국이 해낸 세계최대 우주 진화 모의실험

고등과학원, 표준 우주모형 유효성 입증...18억광년 길이 `슬론 장성` 존재 설명

기사입력 2012.11.15 16:52:53



박창범 교수



김주한 연구교수

T = 11.179 Byrs ago

25 Mpc/h

Concluding Summary

Proven Gravity

From Kelvin to Planck, the gravitational evidence for dark matter is overwhelming and consistent.

Non-Baryonic (TBD)

BBN and CMB prove that dark matter cannot be made of atoms or standard matter.

The Missing Link (TBD)

While we know it's there, we have yet to detect the dark matter particle directly in a laboratory.

"The history of dark matter is the story of how we learned that we are a small fraction of the total matter in the universe."