Dark Matter Physics

Alejandro Ibarra
Technische Universität München

Summer Institute 2016
Xi-Tou
August 2016

Outline

Lecture 1: Evidence for dark matter.

Lecture 2: Dark matter production. Indirect detection.

Lecture 3: Indirect detection (cont.), direct detection, collider signals

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Questions welcome!

Dark matter has been detected

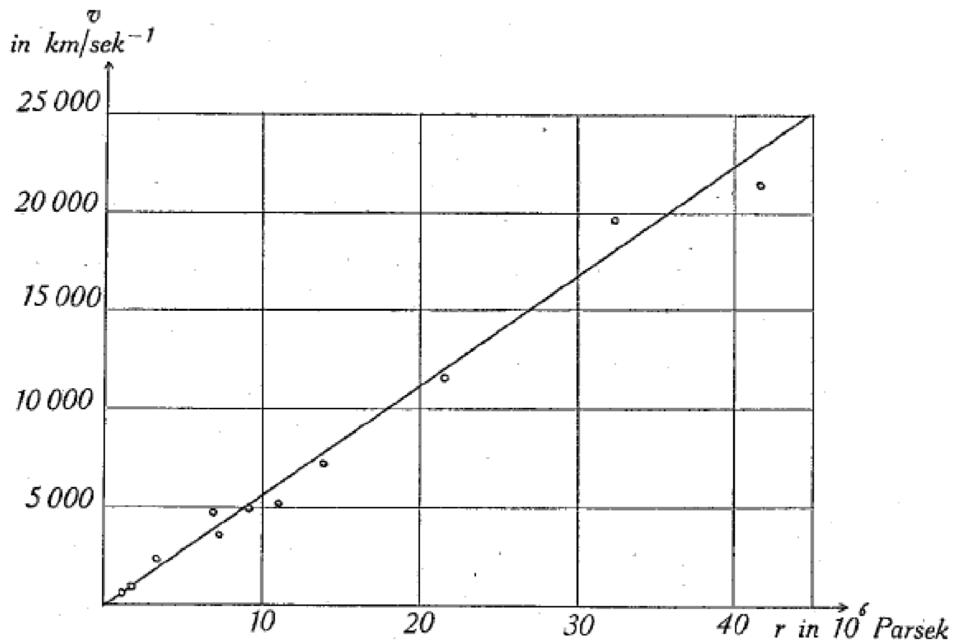
v
in km/sek⁻¹
25 000
20 000
15 000
10 000
5 000
10
20
30
40
r in 10⁶ Parsek

Fig. 2.

Evidence from galaxy clusters

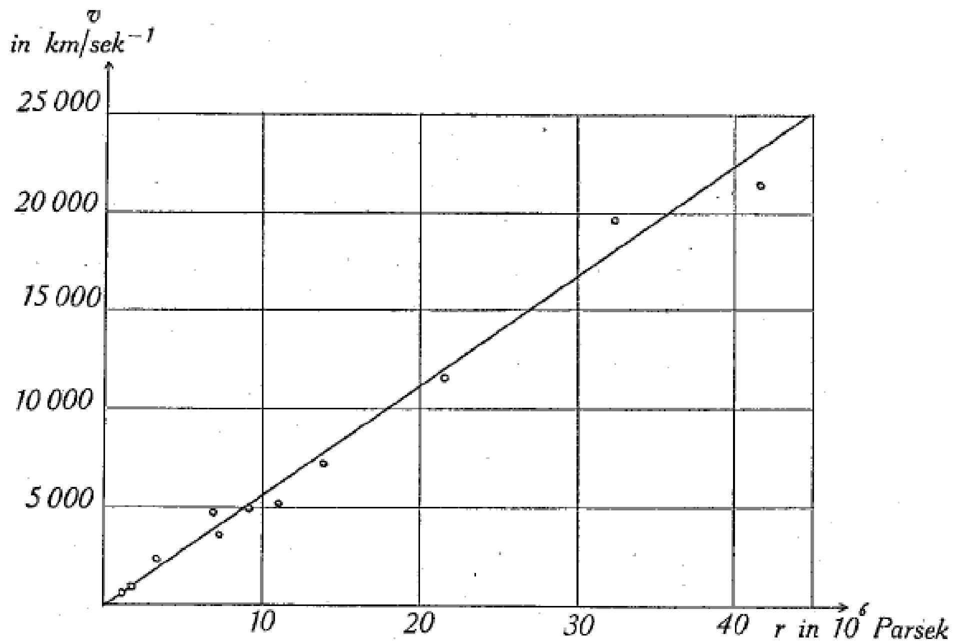

Fig. 2.

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.

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

F. ZWICKY

1- Apply the virial theorem to determine the total mass of the Coma Cluster

For an isolated self-gravitating system,

$$2K + U = 0$$

$$K = \frac{1}{2} M \langle v^2 \rangle \qquad U = -\frac{\alpha G M^2}{\mathcal{R}}$$

$$M = \frac{\langle v^2 \rangle \mathcal{R}}{\alpha G}$$

$$\mathscr{M} > 9 \times 10^{46} \mathrm{gr}$$

2- Count the number of galaxies (~1000) and calculate the average mass

$$\overline{M} > 9 \times 10^{43} \mathrm{\ gr} = 4.5 \times 10^{10} M_{\odot}$$

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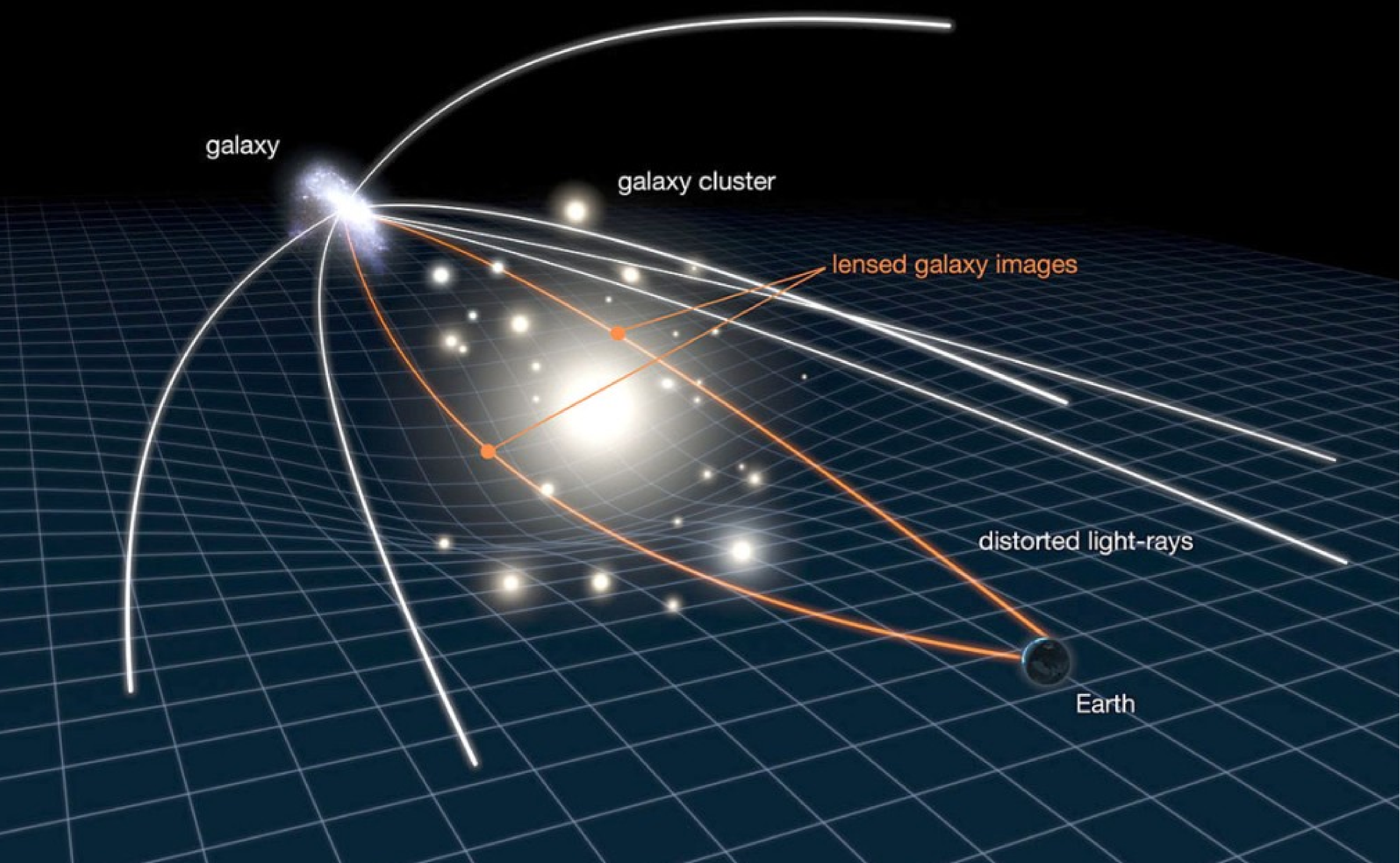
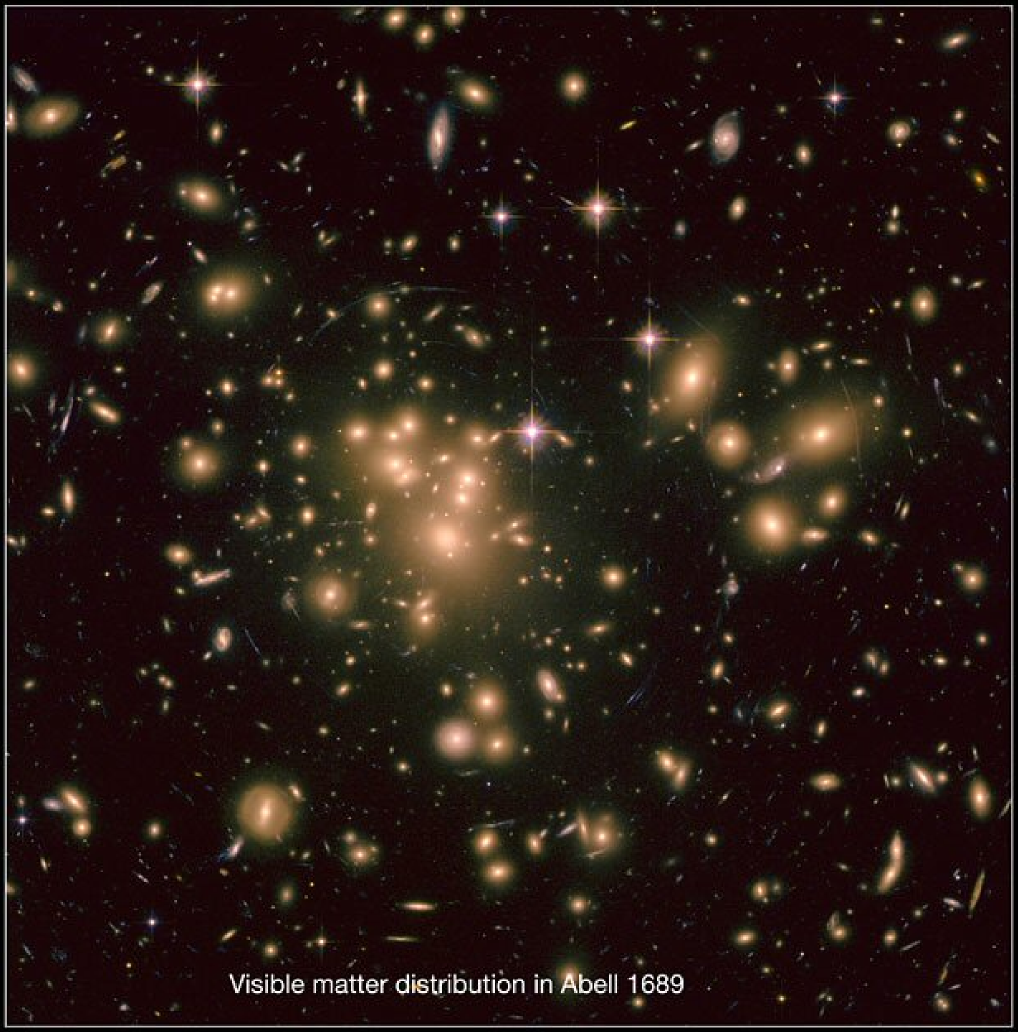
Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view 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

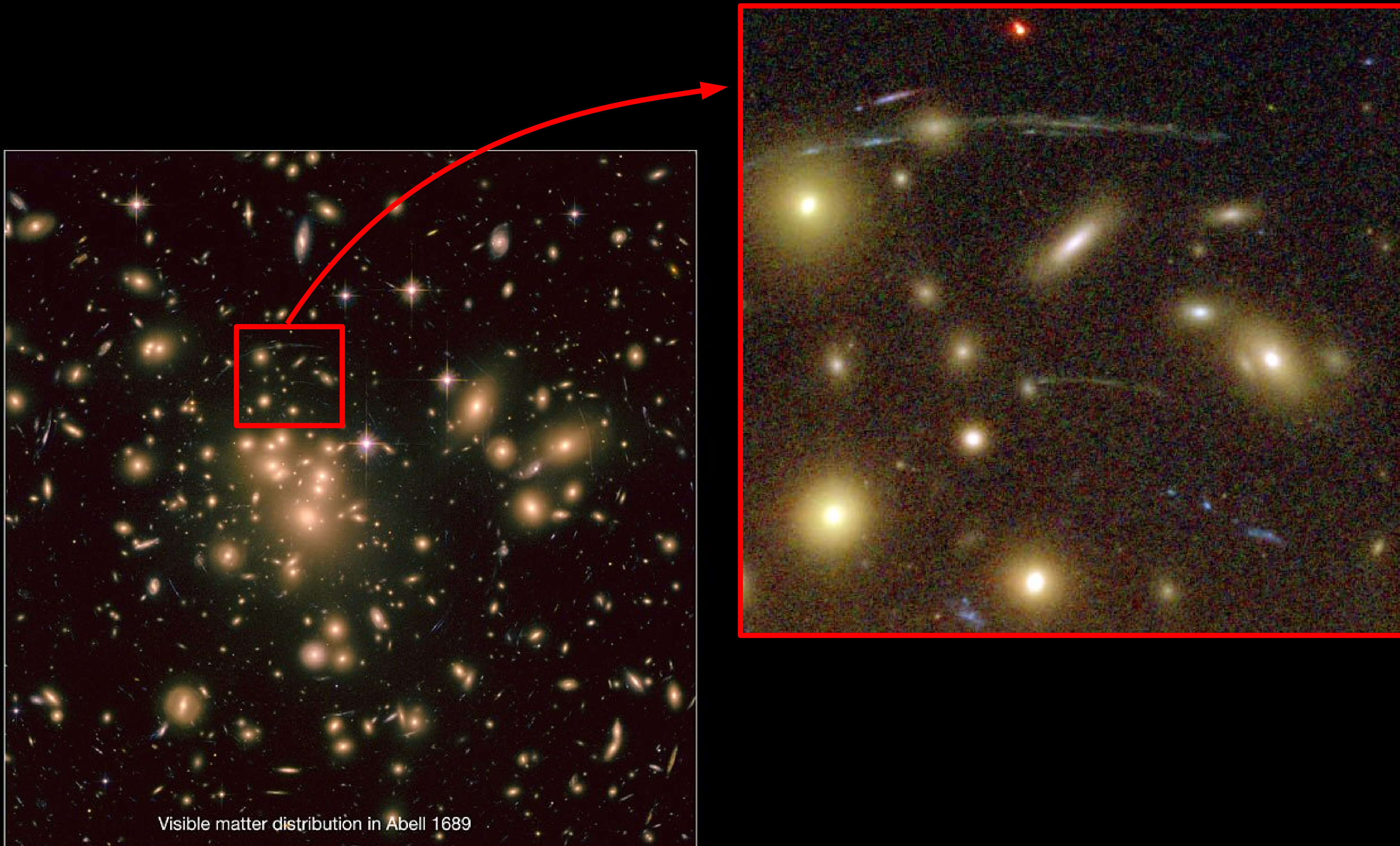
$$\gamma = 500 , \tag{37}$$

A modern technique: gravitational lensing

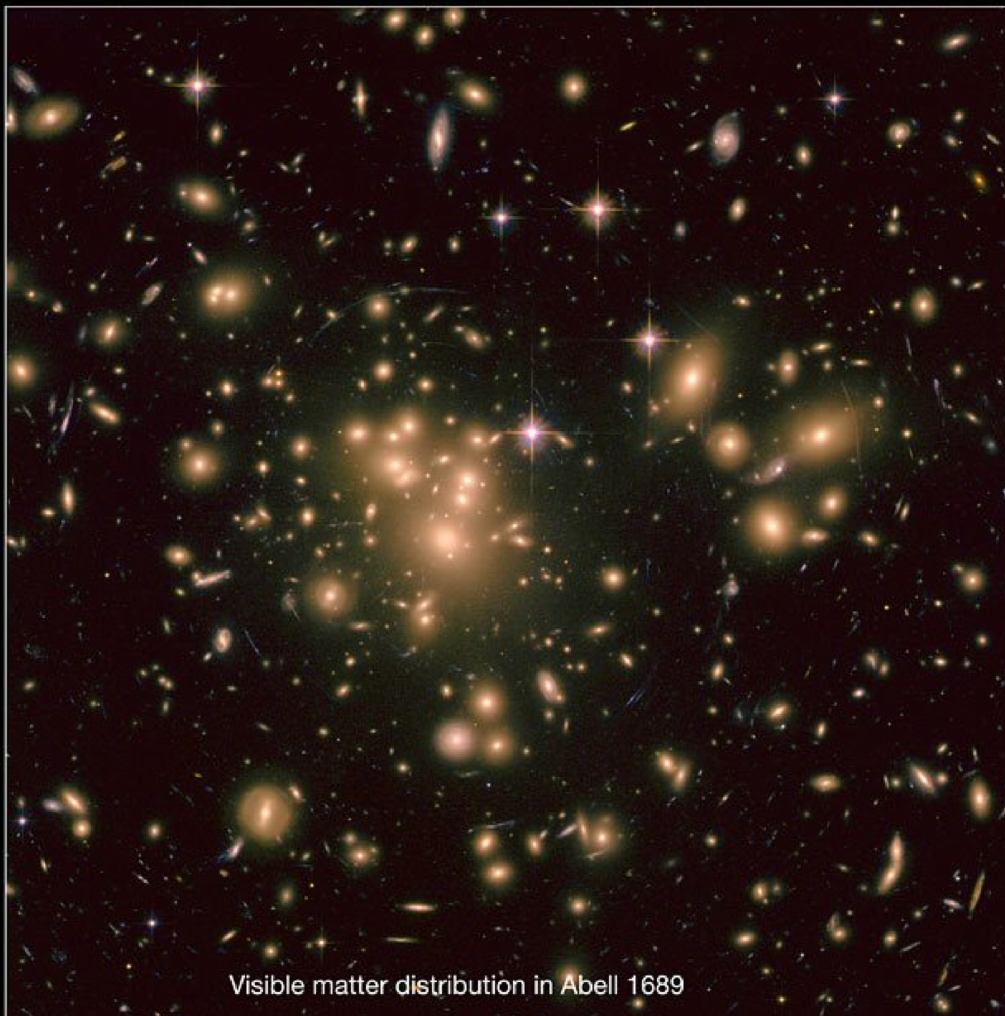


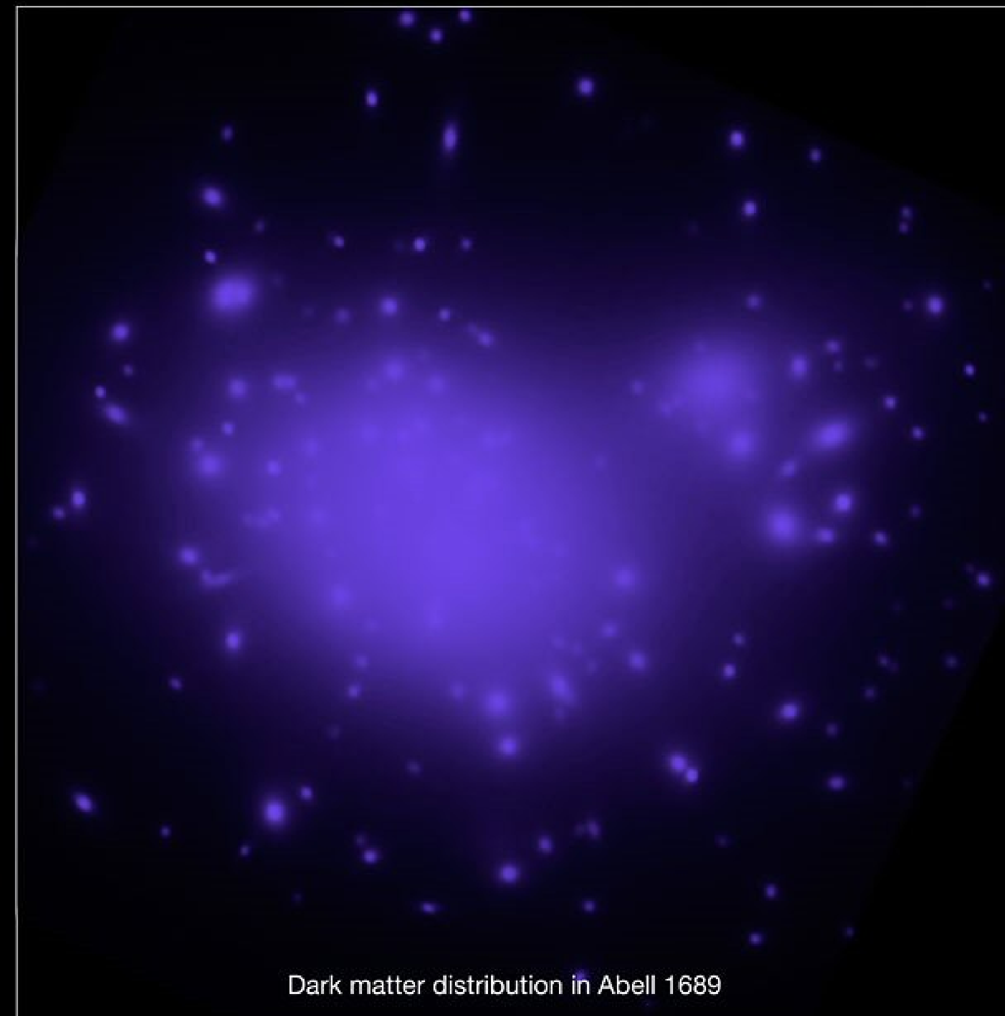


Abell 1689



Abell 1689


Visible matter distribution in Abell 1689


Dark matter distribution in Abell 1689

Abell 1689

Evidence from galaxies

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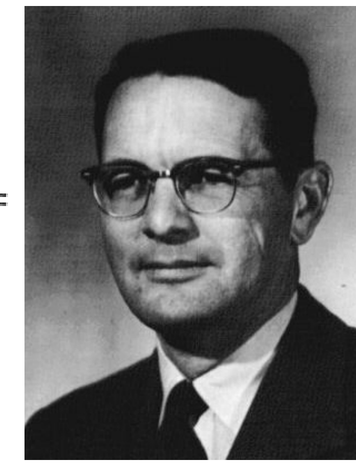
ASTRONOMY

LICK OBSERVATORY BULLETIN

NUMBER 498



THE ROTATION OF THE ANDROMEDA NEBULA*

BY

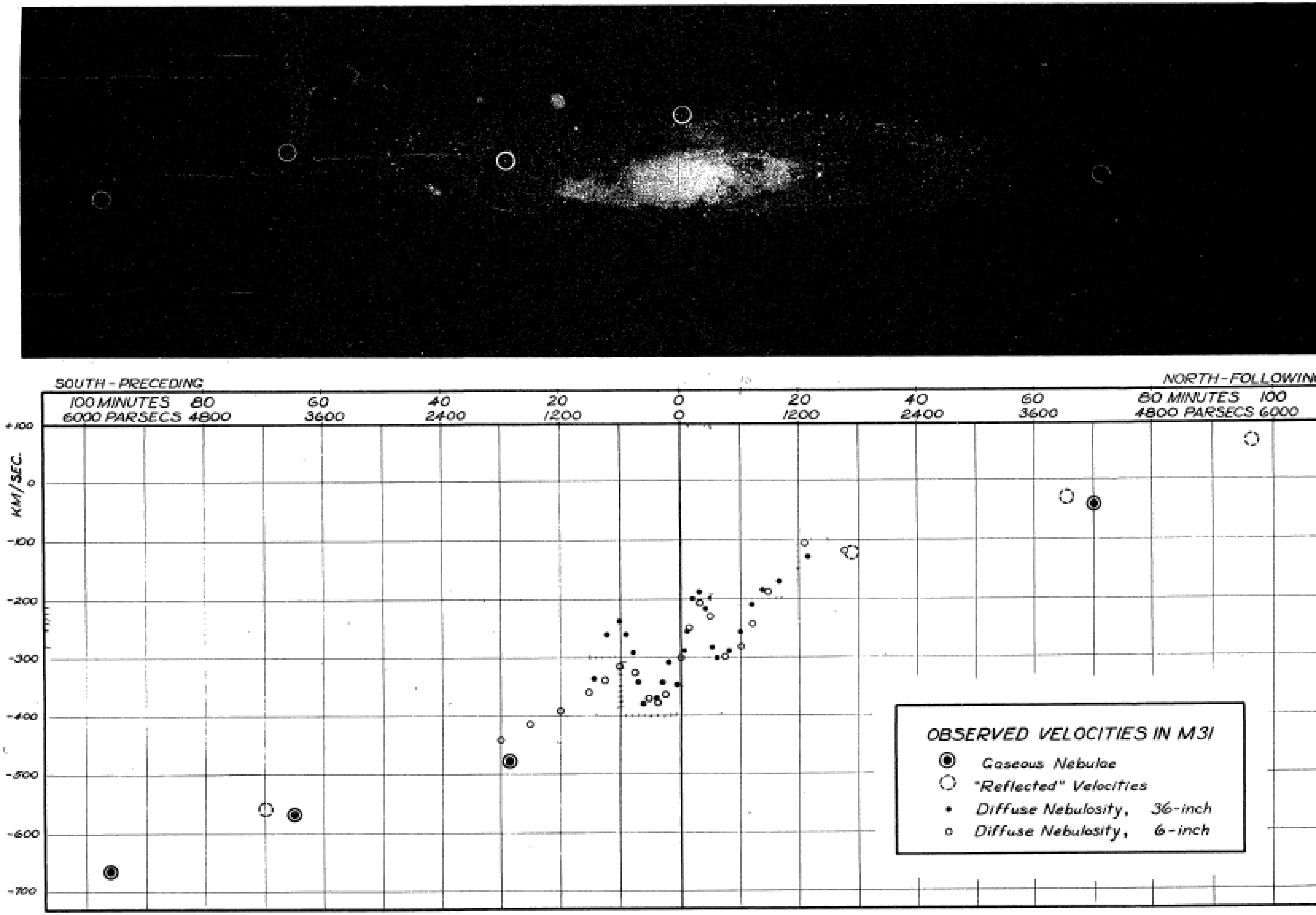
Horace W. Babcock

I. Introduction

One of the important problems of astronomy is the determination of the internal motions of the extra-galactic nebulae. An analysis of such motions for a single system of this kind should lead to a knowledge of the total mass within it, and of the distribution of this mass. When such studies have been made for many of the spirals, correlation of the various dynamical characteristics with nebu-

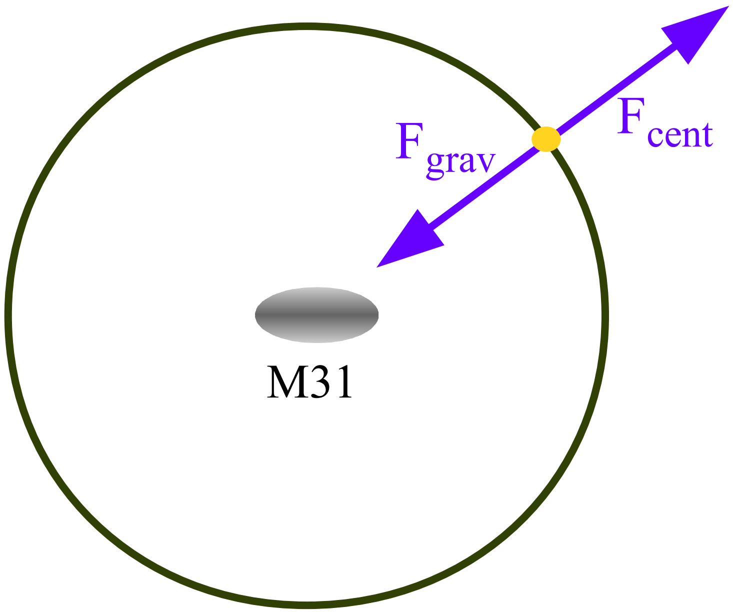
The inclination gives it the apparent outline of an ellipse, as seen on the celestial sphere, and from an estimate of the ratio of axes of this ellipse (about 3 or 4 to 1), Hubble has given 15° as the approximate inclination of the equatorial plane of the spiral to the line of sight. He also found that the major axis of the apparent ellipse lies in position angle 36°.7. The unresolved central region measures about 10′ by 30′, and at the center is the bright

Mount Hamilton, California,
March 31, 1939.
Issued October 30, 1939.



The Andromeda Nebula, with observed velocities plotted below. Smoothed mean velocities of the unresolved central portion are represented by small dots for observations with the Crossley reflector, and by small open circles for observations with the 6-inch mirror. In the photograph, the bright-line emission nebulosities are encircled, and their velocities, with the exception of the one on the minor axis, are plotted as ringed dots. (Photograph by Mayall)

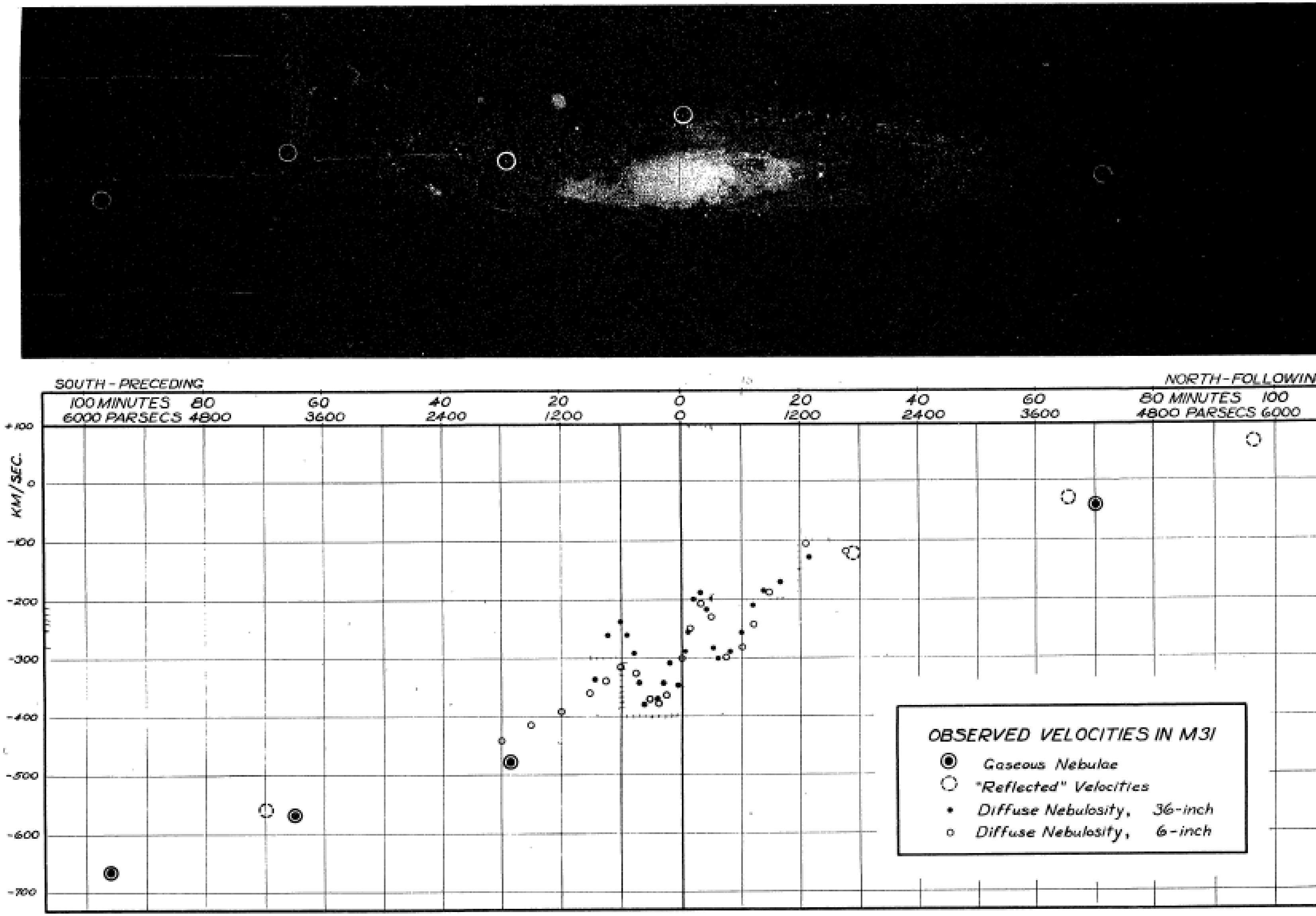
Expectations from Newtonian theory



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$m\frac{v(r)^2}{r} = \frac{GMm}{r^2}$$

$$v(r) = \sqrt{\frac{GM}{r}}$$



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and for this there seems to be no possibility of improvement at present.

The coefficients for the mass-luminosity relation given

TABLE 5

MASS-LUMINOSITY RELATIONS IN M31

x (distance from nucleus)	0′	0′.5	15′	50′	80′
Mass of column (⊙)		11000	7900	4100	2200
Volume (cu. psc.)		5400	5300	4500	2400
Mass density (⊙/cu. psc.)		2.1	1.5	0.9	0.9
Log I (Redman and Shirley)	(2.00)	1.29	0.10	9.44	9.00
I	(100)	19.5	1.26	0.276	0.100
Luminosity density (⊙/cu. psc.)		1.25	0.0827	0.021	0.0144
M/L	0.001 (Hubble)	1.6	18	43	62

in the table evidently indicate little more than orders of magnitude. The mass densities are especially uncertain in the central core, where they are probably too small, so that the corresponding mass-luminosity coefficients near the nucleus may be considered minimum values. Nevertheless, the great range in the calculated ratio of mass to luminosity in proceeding outward from the nucleus suggests that absorption plays a very important rôle in the outer portions of the spiral, or, perhaps, that new dynamical considerations are required, which will permit of a smaller relative mass in the outer parts.

VIII. COMPARISON OF THE GALACTIC SYSTEM AND M31

Current theories of galactic rotation indicate that the

strate that, in a wide region around the sun, circular velocities of the stars decrease with distance from the center.

The Andromeda Nebula and the Galaxy have many well-known features in common, but one outstanding discrepancy between the two systems has hitherto been in their diameters. The spiral arms of M31 can hardly be traced to a radius of more than 1°.6 or 6 kiloparsecs. Beyond this radius, no stars, comparable to the brighter stars in the vicinity of the sun, have been reported, although Hubble has discovered some outlying globular clusters[10] which lead him to suggest that the radius of the nebula, as outlined by these objects, may possibly be as great as 3½°. This large figure is supported by the photo-electric measurements of Stebbins and Whitford.[19]

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ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21

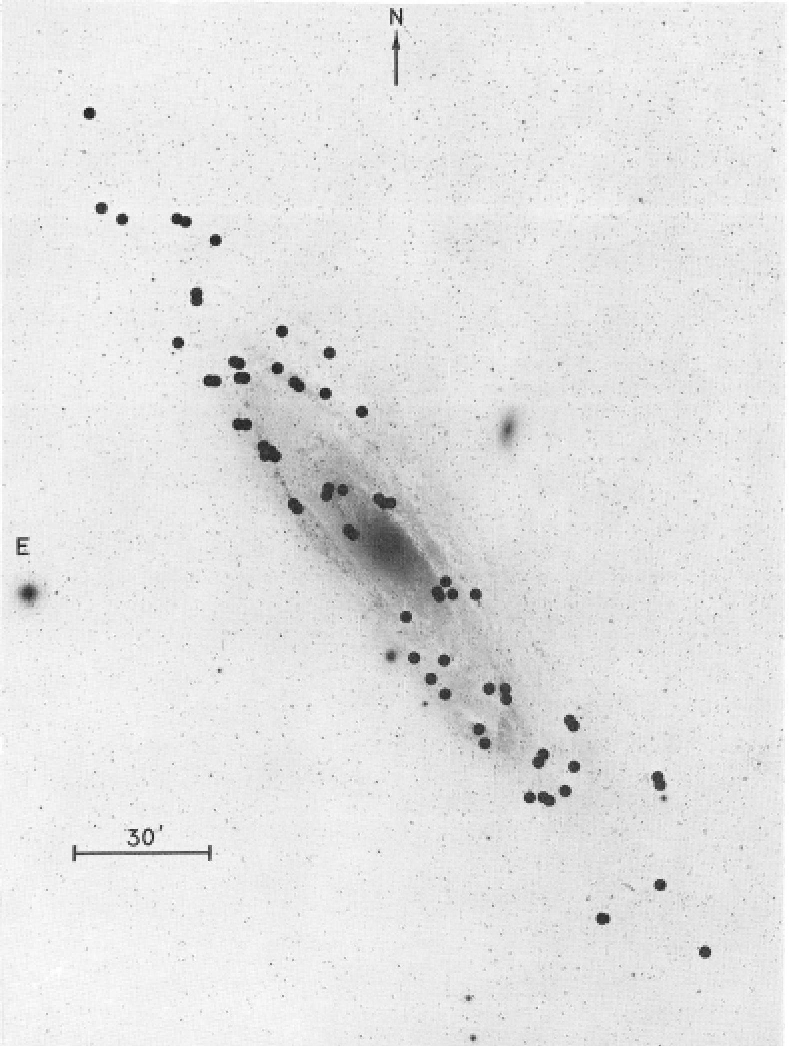
ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm^{-1}. Radial velocities, principally from Hα, have been determined with an accuracy of ± 10 km sec^{-1} for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

For the region interior to 3 kpc where no emission regions have been identified, a narrow [N II] λ6583 emission line is observed. Velocities from this line indicate a rapid rotation in the nucleus, rising to a maximum circular velocity of $V = 225$ km sec^{-1} at $R = 400$ pc, and falling to a deep minimum near $R = 2$ kpc.

From the rotation curve for $R \leq 24$ kpc, the following disk model of M31 results. There is a dense, rapidly rotating nucleus of mass $M = (6 \pm 1) \times 10^9\, M_\odot$. Near $R = 2$ kpc, the density is very low and the rotational motions are very small. In the region from 500 to 1.4 kpc (most notably on the southeast minor axis), gas is observed leaving the nucleus. Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11}\, M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

The optical velocities, $R > 3$ kpc, agree with the 21-cm observations, although the maximum rotational velocity, $V = 270 \pm 10$ km sec^{-1}, is slightly higher than that obtained from 21-cm observations.



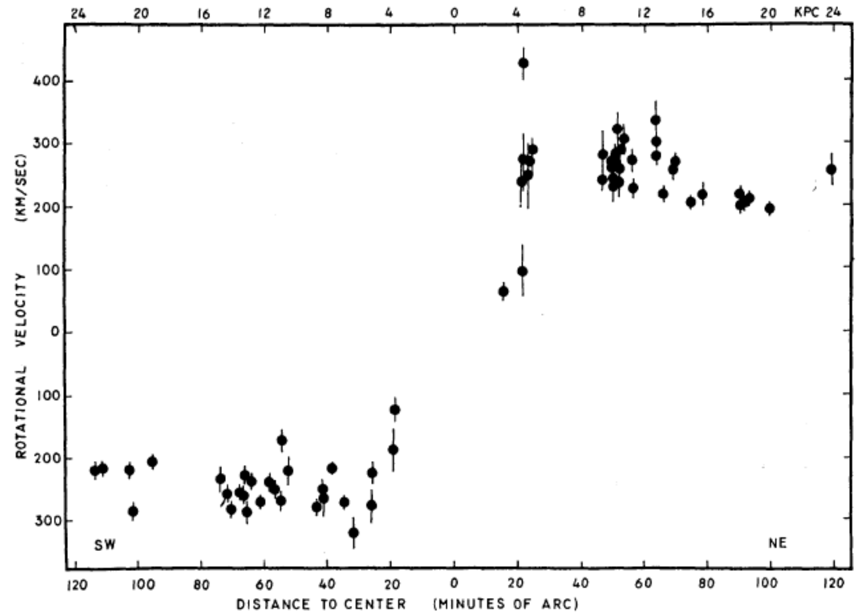


FIG. 3.—Rotational velocities for sixty-seven emission regions in M31, as a function of distance from the center. Error bars indicate average error of rotational velocities.

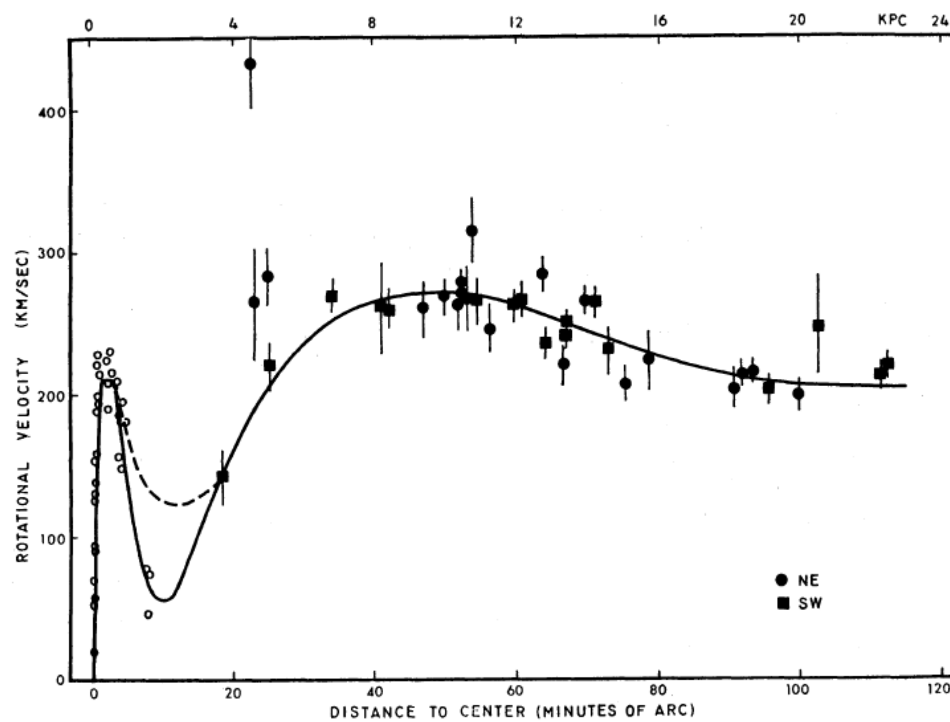
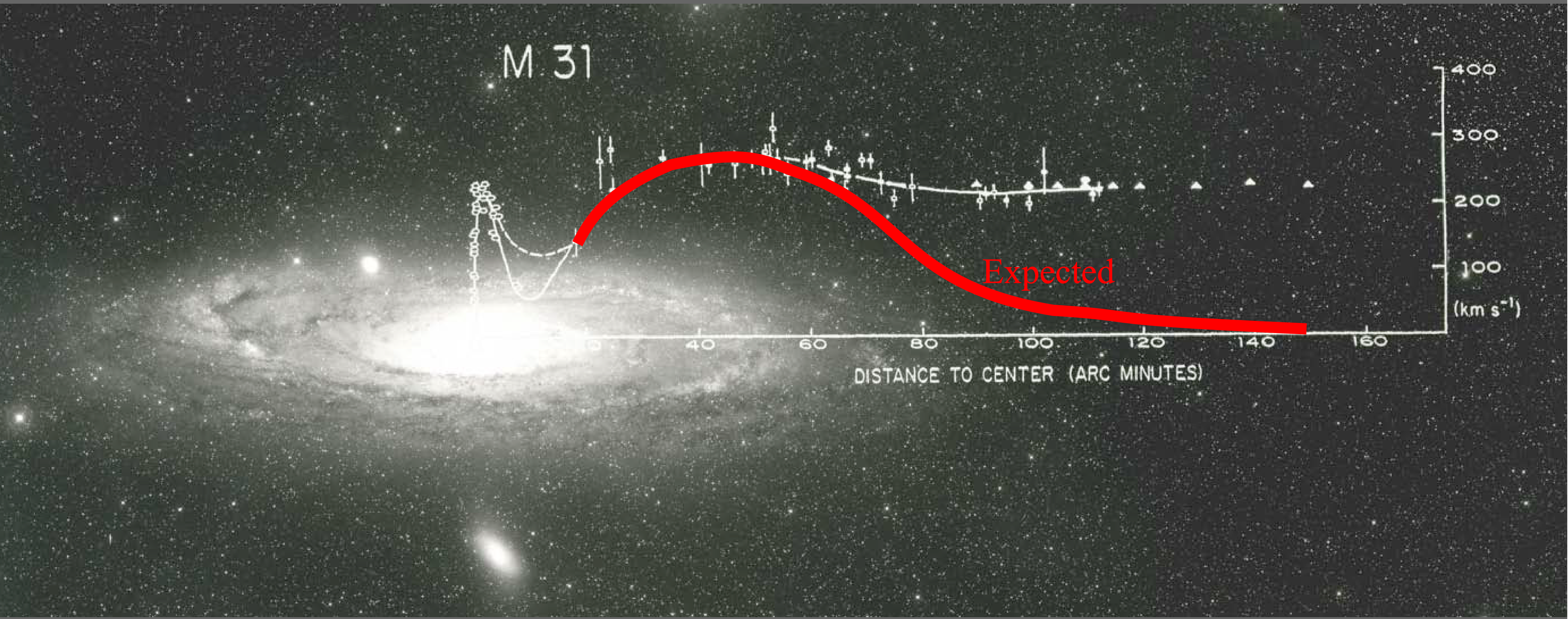
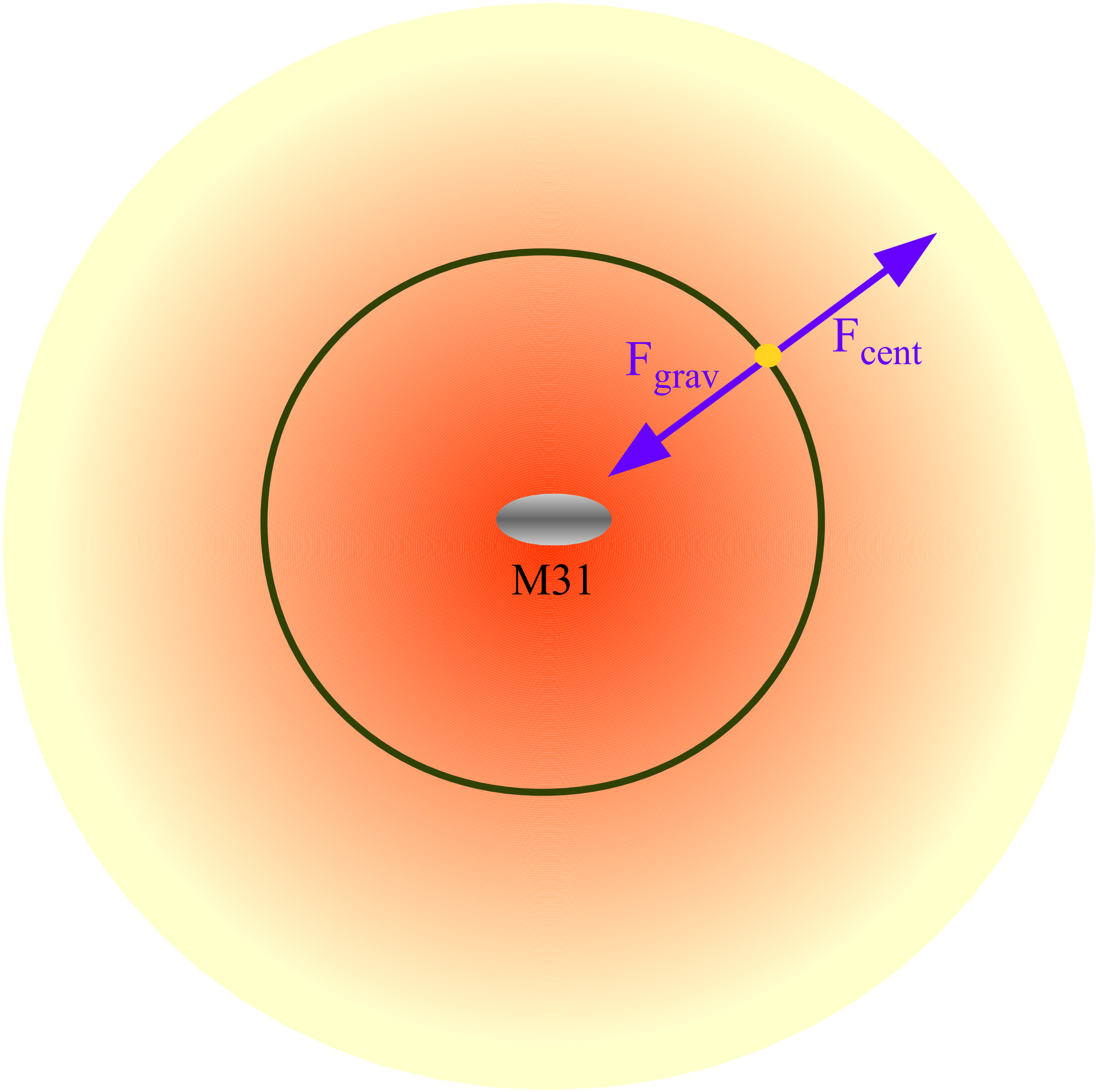


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately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



M 31
400
300
200
100
(km s⁻¹)
40
60
80
100
120
140
160
DISTANCE TO CENTER (ARC MINUTES)
Expected

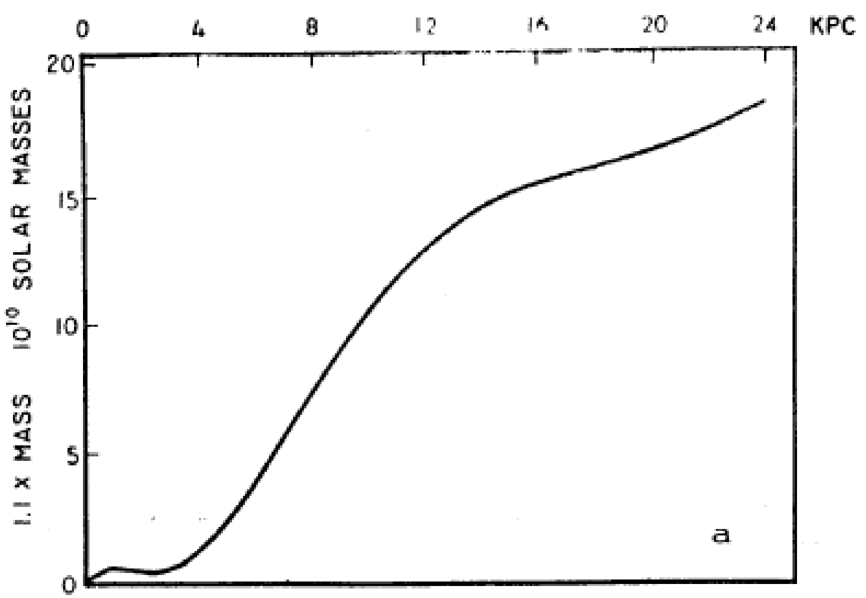
Something else inside M31?



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$m\frac{v(r)^2}{r} = \frac{GM(r)m}{r^2}$$

$$v(r) \sim \text{constant} \Rightarrow M(r) \sim r$$



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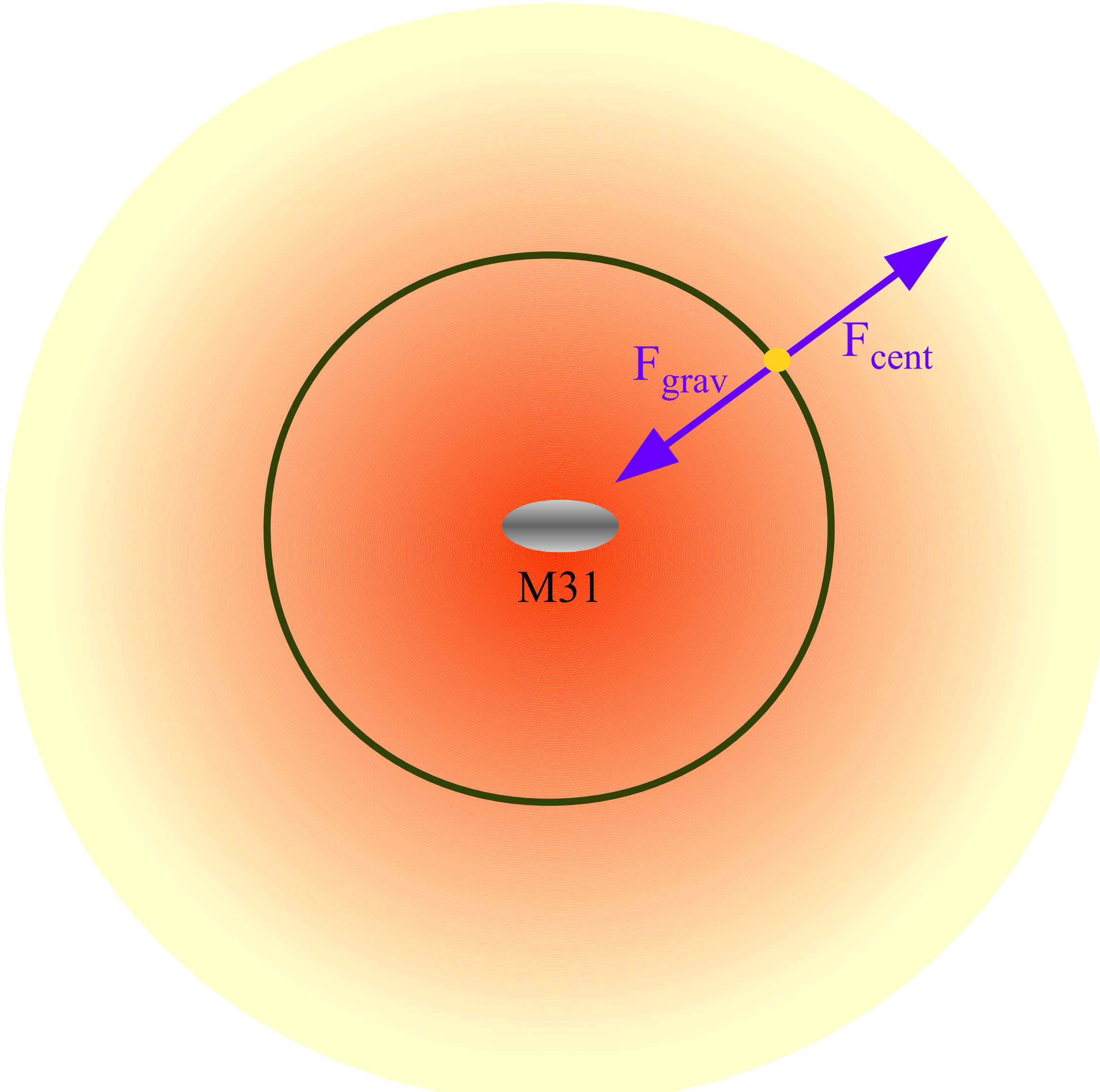

$$\vec{F}_{\rm cent} = \vec{F}_{\rm grav}$$

$$m\frac{v(r)^2}{r} = \frac{GM(r)m}{r^2}$$

$$v(r) \sim \text{constant} \Rightarrow M(r) \sim r$$

$$\begin{aligned} M(r) &= \int_V d^3r' \rho(r') \\ &= 4\pi \int_0^r dr' r'^2 \rho(r') \end{aligned}$$

$$M(r) \sim r \Rightarrow \rho(r) \sim \frac{1}{r^2}$$

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ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

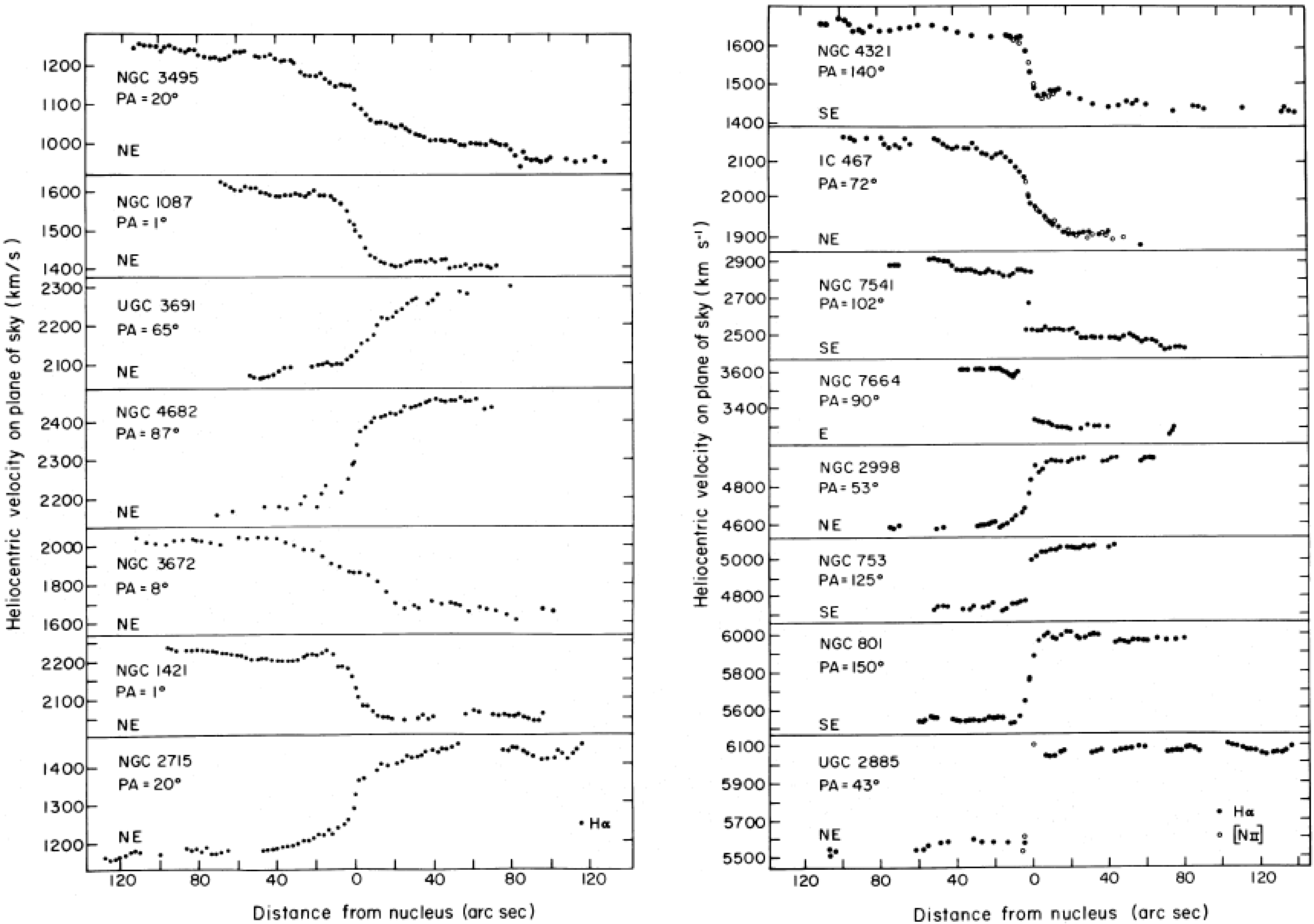
VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

ABSTRACT

For 21 Sc galaxies whose properties encompass a wide range of radii, masses, and luminosities, we have obtained major axis spectra extending to the faint outer regions, and have deduced rotation curves. The galaxies are of high inclination, so uncertainties in the angle of inclination to the line of sight and in the position angle of the major axis are minimized. Their radii range from 4 to 122 kpc ($H = 50$ km s^{-1} Mpc^{-1}); in general, the rotation curves extend to 83% of $R_{25}{}^{i,b}$. When plotted on a linear scale with no scaling, the rotation curves for the smallest galaxies fall upon the initial parts of the rotation curves for the larger galaxies. All curves show a fairly rapid velocity rise to $V \sim 125$ km s^{-1} at $R \sim 5$ kpc, and a slower rise thereafter. Most rotation curves are rising slowly even at the farthest measured point. Neither high nor low luminosity Sc galaxies have falling rotation curves. Sc galaxies of all luminosities must have significant mass located beyond the optical image. A linear relation between log V_{max} and log R follows from the shape of the common rotation curve for all Sc's, and the tendency of smaller galaxies, at any R, to have lower velocities than the large galaxies at that R. The significantly shallower slope discovered for this relation by Tully and Fisher is attributed to their use of galaxies of various Hubble types and the known correlation of V_{max} with Hubble type.

The galaxies with very large central velocity gradients tend to be large, of high luminosity, with massive, dense nuclei. Often their nuclear spectra show a strong stellar continuum in the red, with emission lines of [N II] stronger than Hα. These galaxies also tend to be 13 cm radio continuum sources.

Because of the form of the rotation curves, small galaxies undergo many short-period, very differential, rotations. Large galaxies undergo (in their outer parts) few, only slightly differential, rotations. This suggests a relation between morphology, rotational properties, and the van den Bergh luminosity classification, which is discussed. UGC 2885, the largest Sc in the sample, has undergone fewer than 10 rotations in its outer parts since the origin of the universe but has a regular two-armed spiral pattern and no significant velocity asymmetries. This observation puts constraints on models of galaxy formation and evolution.


Heliocentric velocity on plane of sky (km/s)
NGC 3495
PA = 20°
NE
NGC 1087
PA = 1°
NE
UGC 3691
PA = 65°
NE
NGC 4682
PA = 87°
NE
NGC 3672
PA = 8°
NE
NGC 1421
PA = 1°
NE
NGC 2715
PA = 20°
NE
• Hα
Distance from nucleus (arc sec)
Heliocentric velocity on plane of sky (km s⁻¹)
NGC 4321
PA = 140°
SE
IC 467
PA = 72°
NE
NGC 7541
PA = 102°
SE
NGC 7664
PA = 90°
E
NGC 2998
PA = 53°
NE
NGC 753
PA = 125°
SE
NGC 801
PA = 150°
SE
UGC 2885
PA = 43°
NE
• Hα
○ [NII]
Distance from nucleus (arc sec)

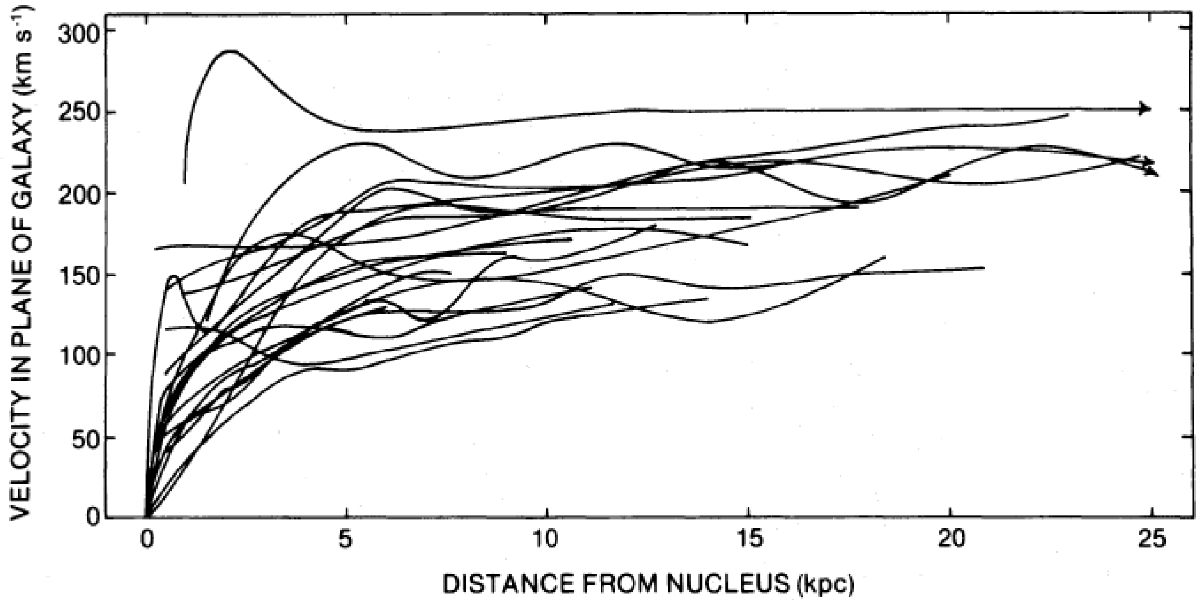


FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter at any *R*.

VIII. DISCUSSION AND CONCLUSIONS

We have obtained spectra and determined rotation curves to the faint outer limits of 21 Sc galaxies of high inclination. The galaxies span a range in luminosity from 3×10^9 to 2×10^{11} $L_\odot$, a range in mass from 10^{10} to 2×10^{12} $M_\odot$, and a range in radius from 4 to 122 kpc. In general, velocities are obtained over 83% of the optical image (defined by 25 mag arcsec^{-2}), a greater distance than previously observed. The major conclusions are intended to apply only to Sc galaxies.

1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc's (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large *R* as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large *R*. The integral mass is increasing at least as fast as *R*. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.

Inescapable?

Inescapable?

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A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

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Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I consider the possibility that there is not, in fact, much hidden mass in galaxies and galaxy systems. If a certain modified version of the Newtonian dynamics is used to describe the motion of bodies in a gravitational field (of a galaxy, say), the observational results are reproduced with no need to assume hidden mass in appreciable quantities. Various characteristics of galaxies result with no further assumptions.

In the basis of the modification is the assumption that in the limit of small acceleration $a \ll a_0$, the acceleration of a particle at distance r from a mass M satisfies approximately $a^2/a_0 \approx MGr^{-2}$, where a_0 is a constant of the dimensions of an acceleration.

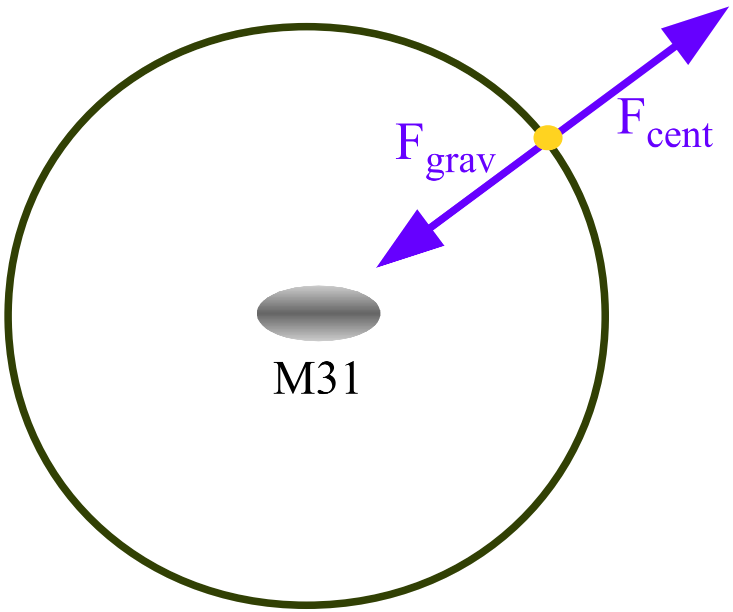
I have considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0)\mathbf{a} = \mathbf{F}, \tag{1}$$

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

replacing $m_g \mathbf{a} = \mathbf{F}$.

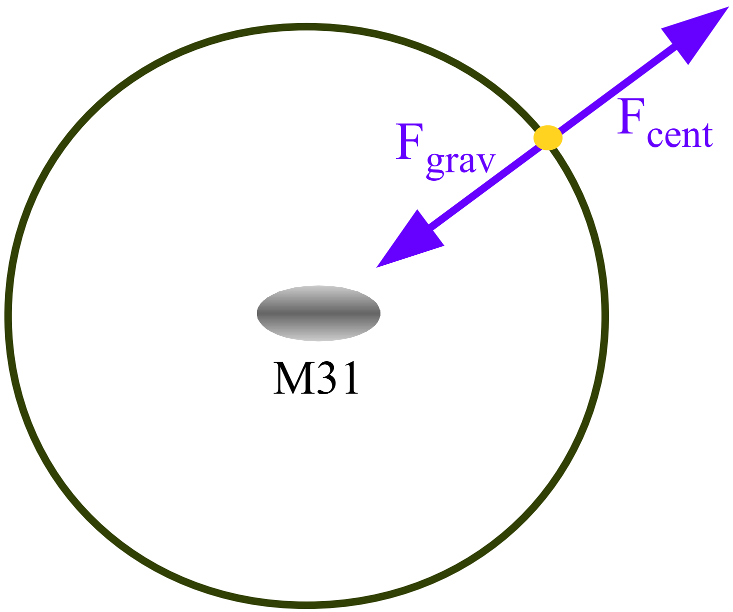
Velocities in the MOND framework



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$F = \begin{cases} ma & \text{if } a \gg a_0 \\ m\dfrac{a^2}{a_0} & \text{if } a \ll a_0 \end{cases}$$

Velocities in the MOND framework



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$F = \begin{cases} ma & \text{if } a \gg a_0 \\ m\dfrac{a^2}{a_0} & \text{if } a \ll a_0 \end{cases}$$

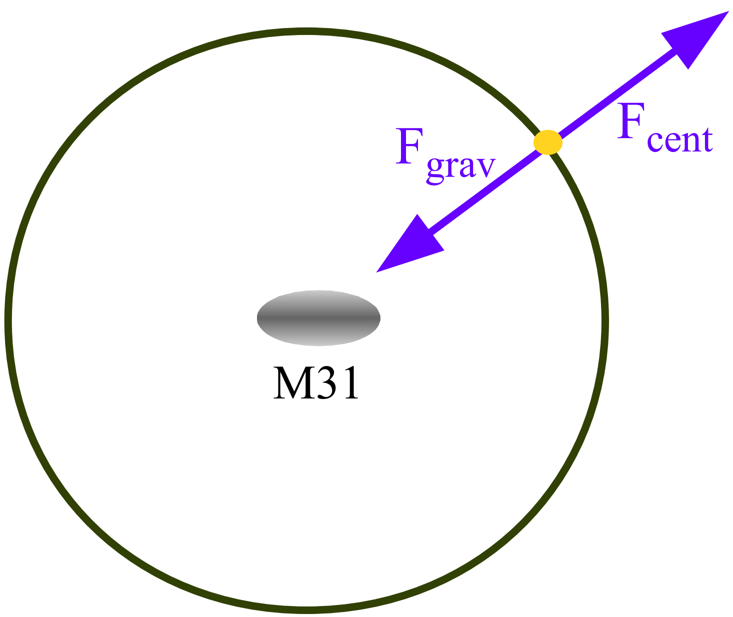
For large acceleration

$$ma(r) = \frac{GMm}{r^2}$$

$$m\frac{v(r)^2}{r} = \frac{GMm}{r^2}$$

$$\boxed{v(r) = \sqrt{\frac{GM}{r}}}$$

Velocities in the MOND framework



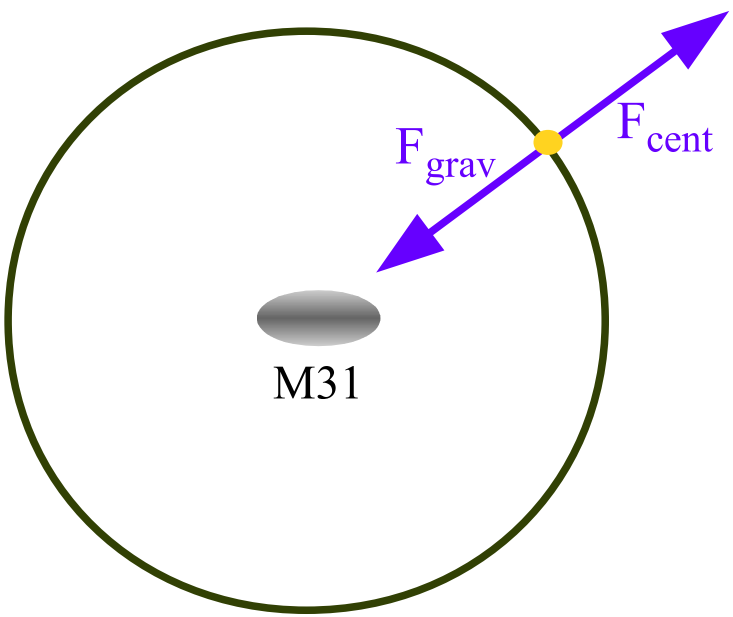
$$\vec{F}_{\rm cent} = \vec{F}_{\rm grav}$$

$$F = \begin{cases} ma & \text{if } a \gg a_0 \\ m\dfrac{a^2}{a_0} & \text{if } a \ll a_0 \end{cases}$$

For small acceleration (expected at large distances).

$$m\frac{a(r)^2}{a_0} = \frac{GMm}{r^2}$$

Velocities in the MOND framework



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For small acceleration (expected at large distances).

$$m\frac{1}{a_0}\left(\frac{v(r)^2}{r}\right)^2 = \frac{GMm}{r^2}$$

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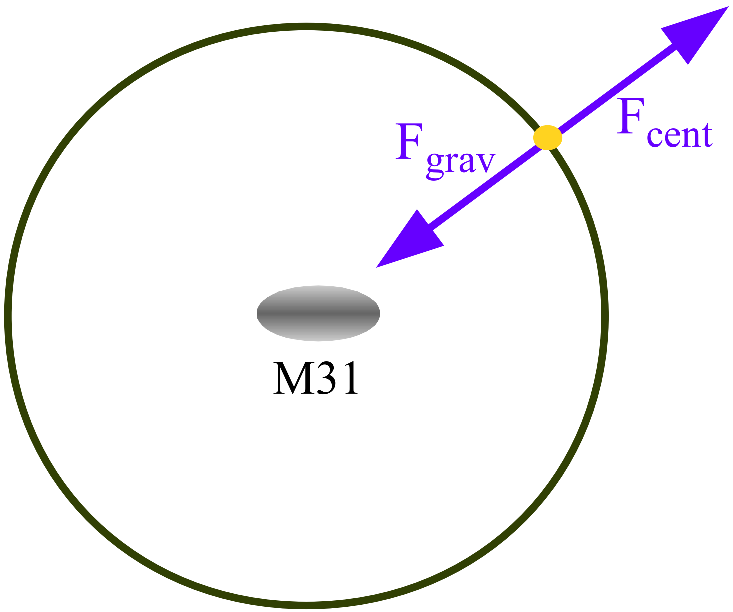

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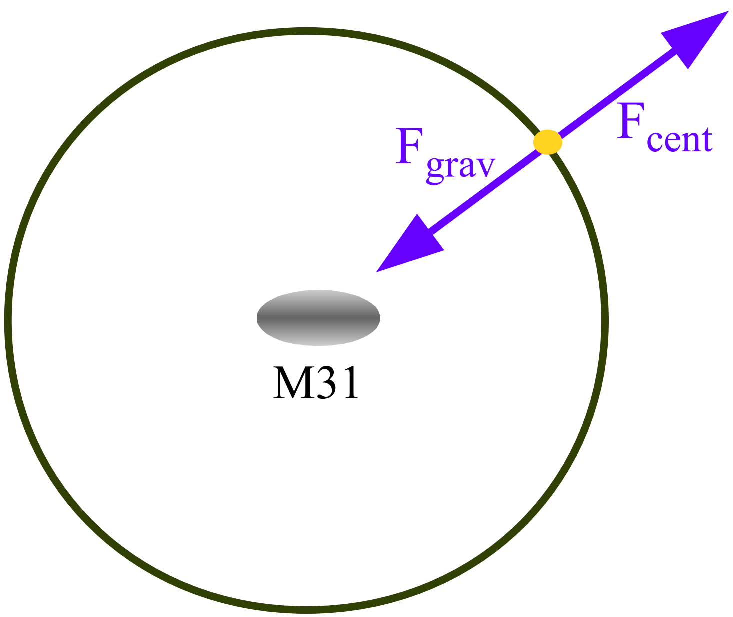
Velocities in the MOND framework



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$F = \begin{cases} ma & \text{if } a \gg a_0 \\ m\dfrac{a^2}{a_0} & \text{if } a \ll a_0 \end{cases}$$

Velocity at large distances from the center:

$$v(r) = (GMa_0)^{1/4}$$

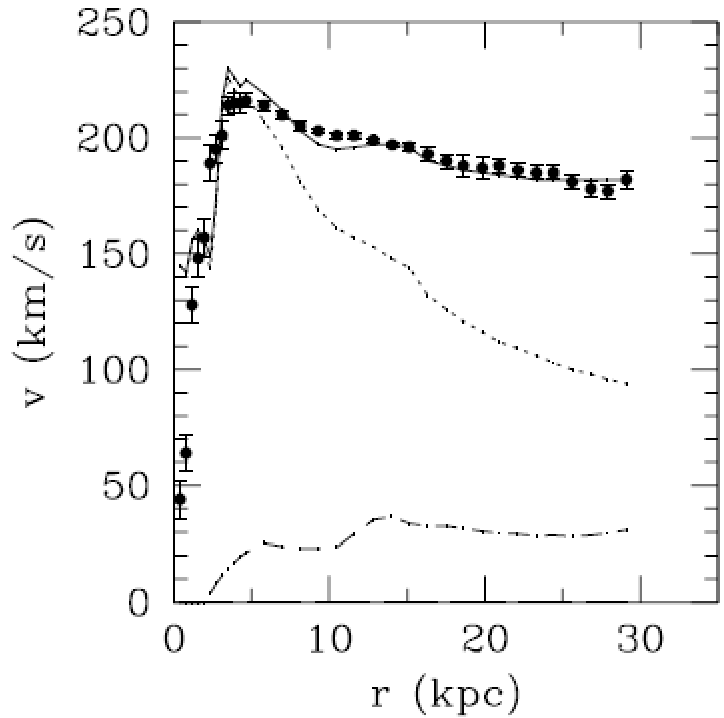
I have considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0) \boldsymbol{a} = \boldsymbol{F}, \tag{1}$$

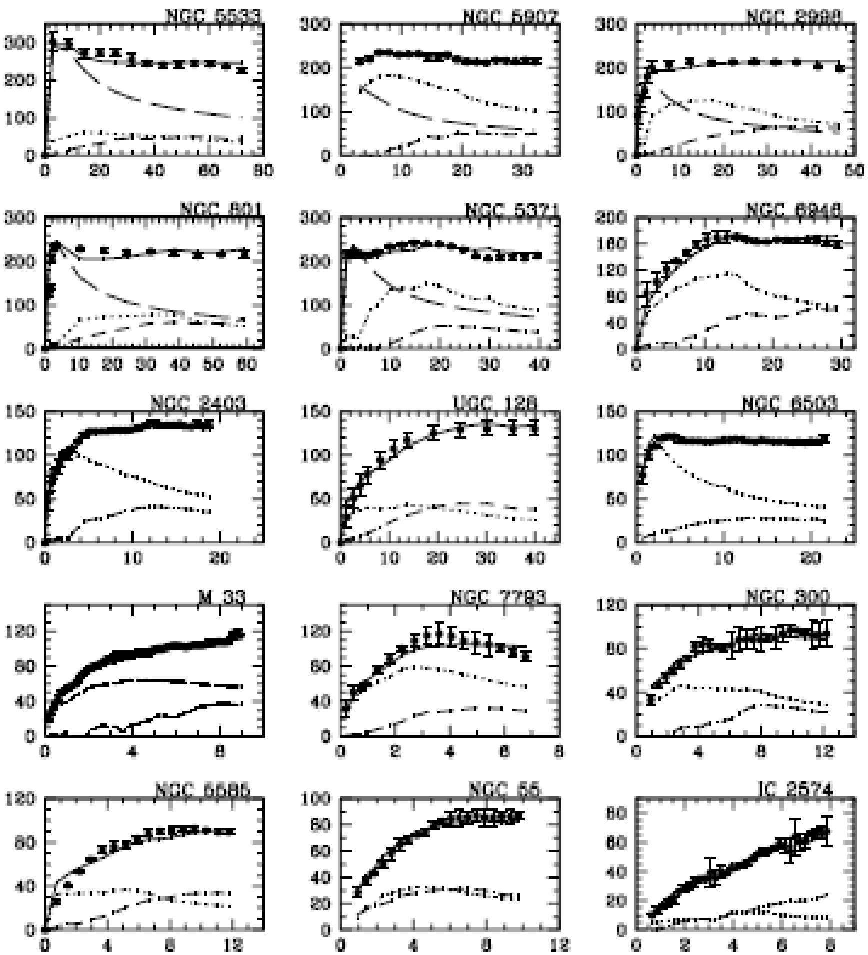
$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

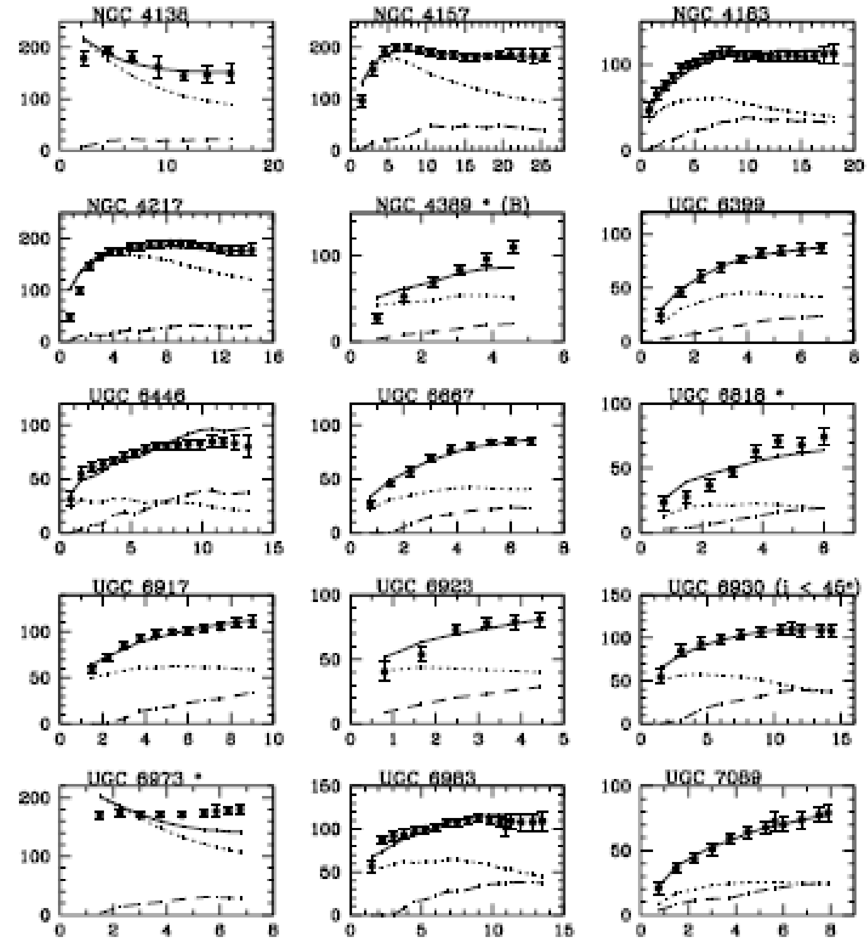
replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

$$a_0 \simeq 10^{-8}\,\mathrm{cm\,s^{-2}}$$

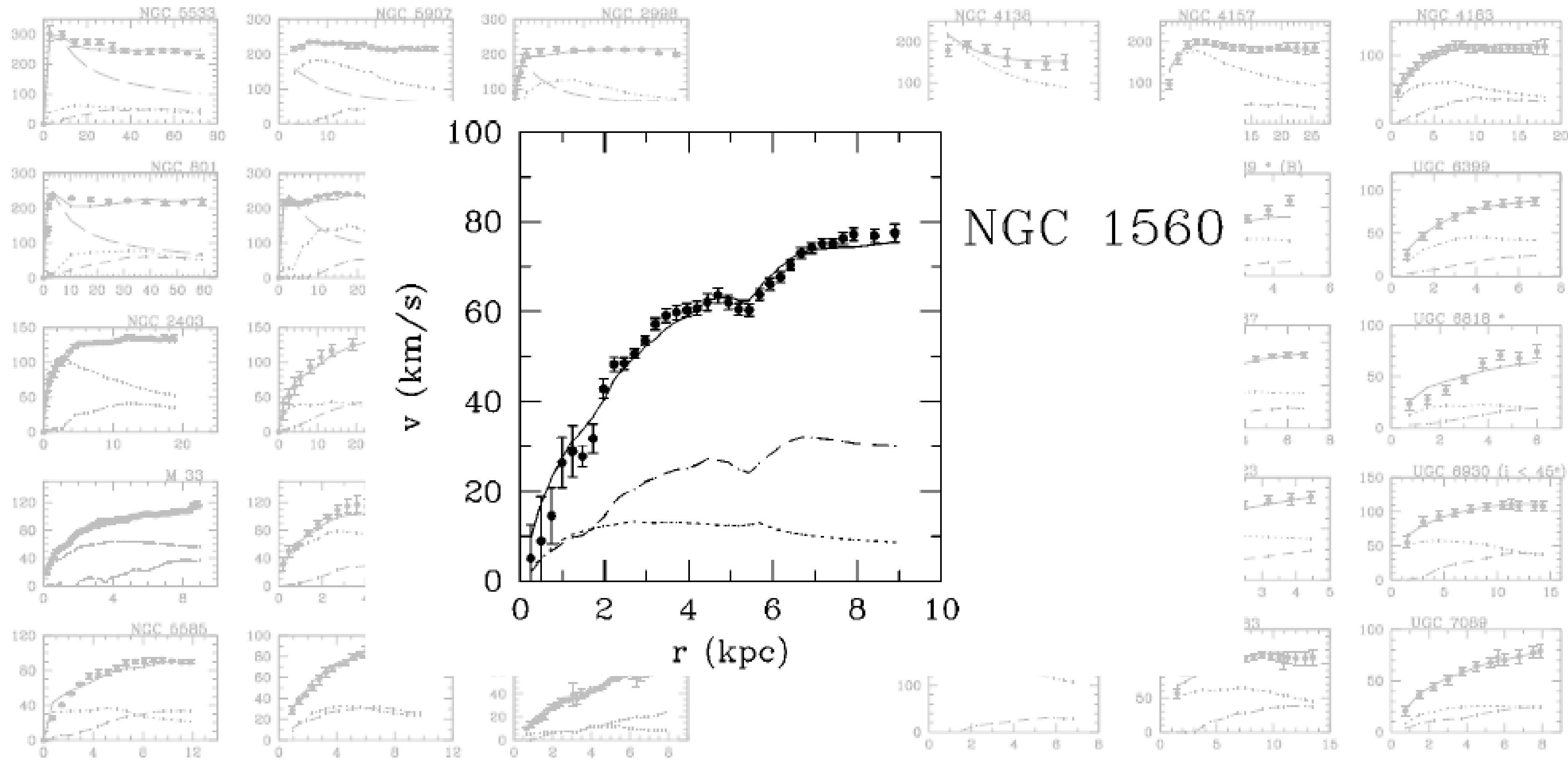


NGC 2903



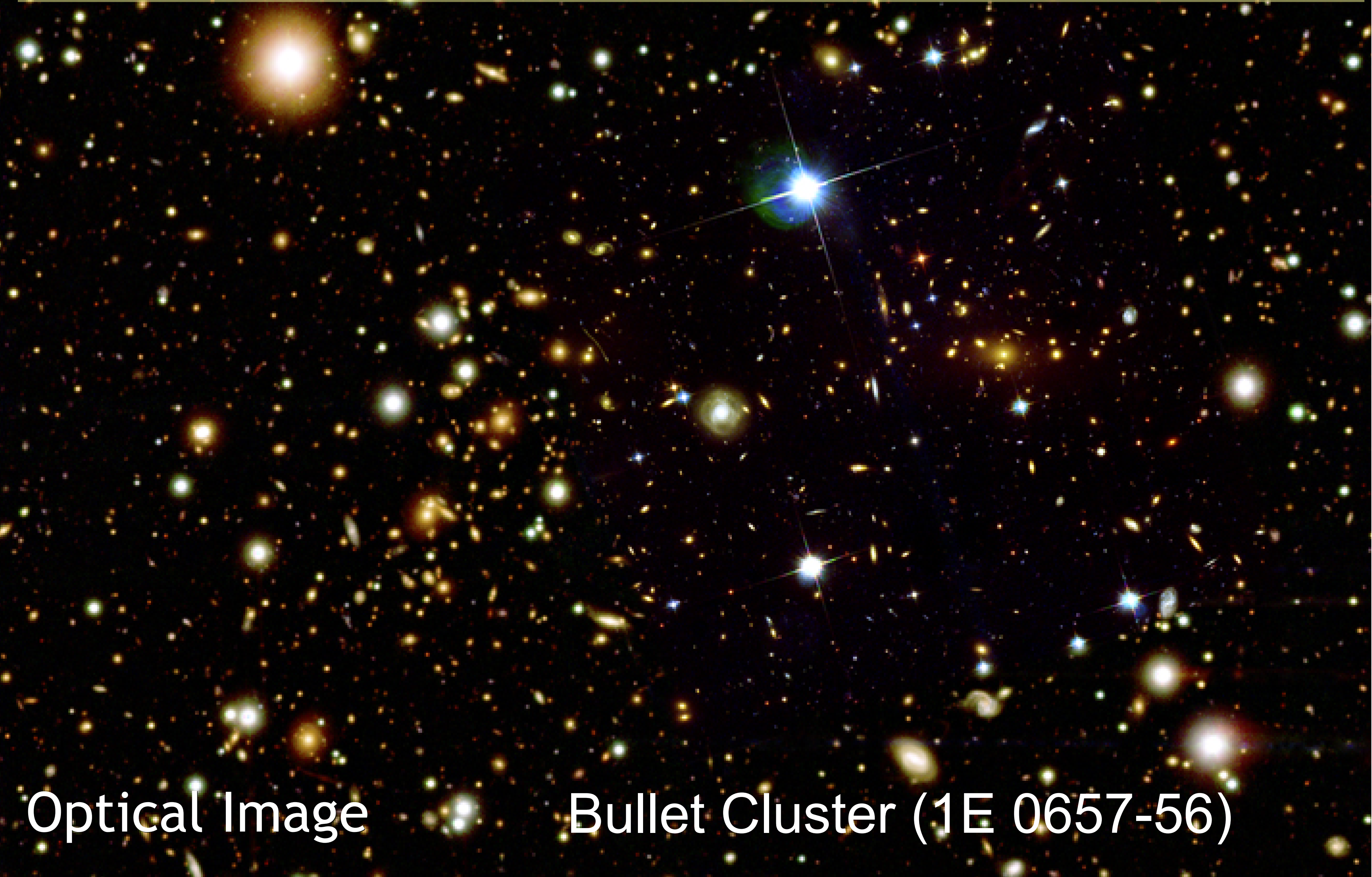


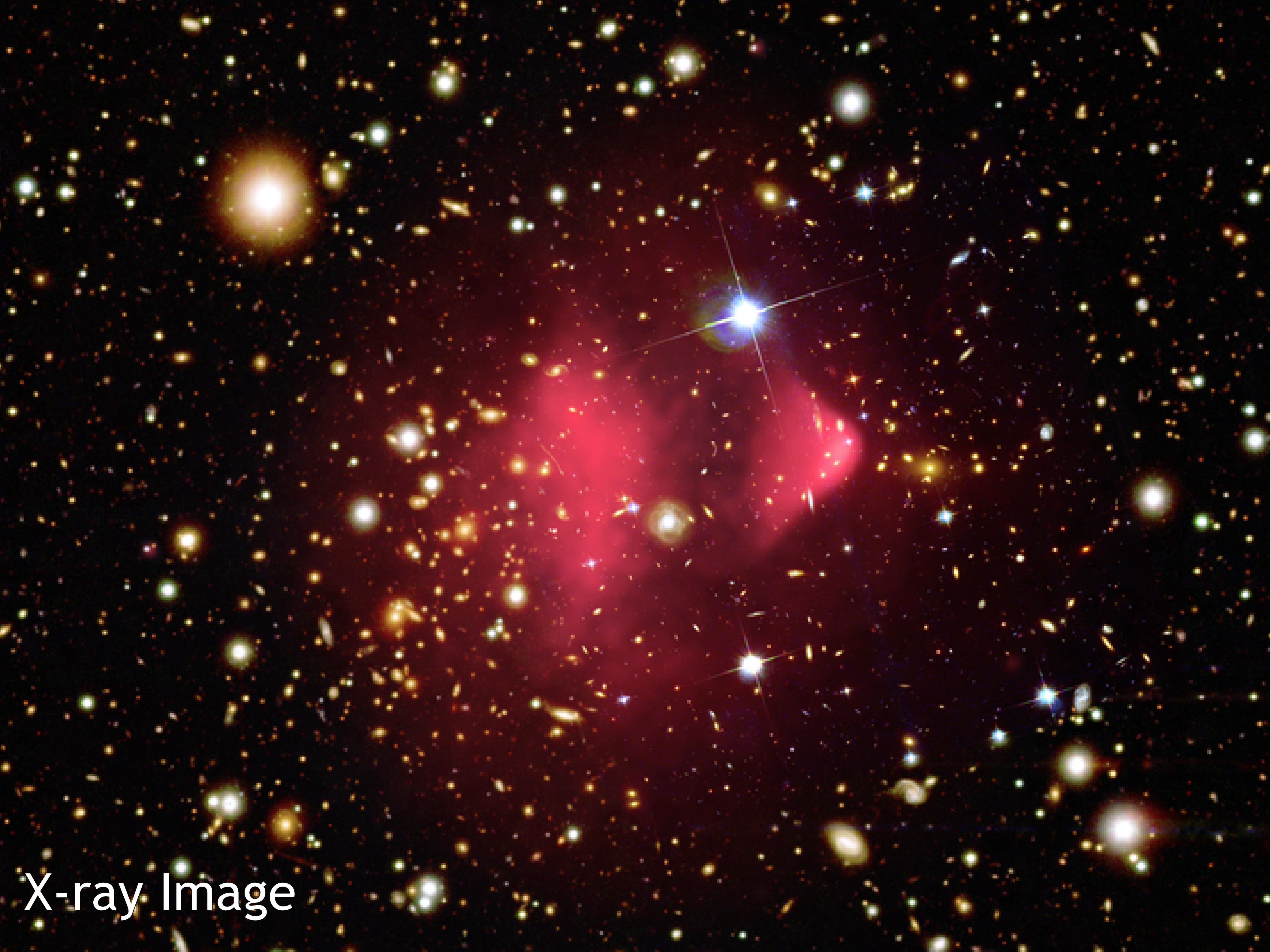
Sanders, McGaugh



Sanders, McGaugh

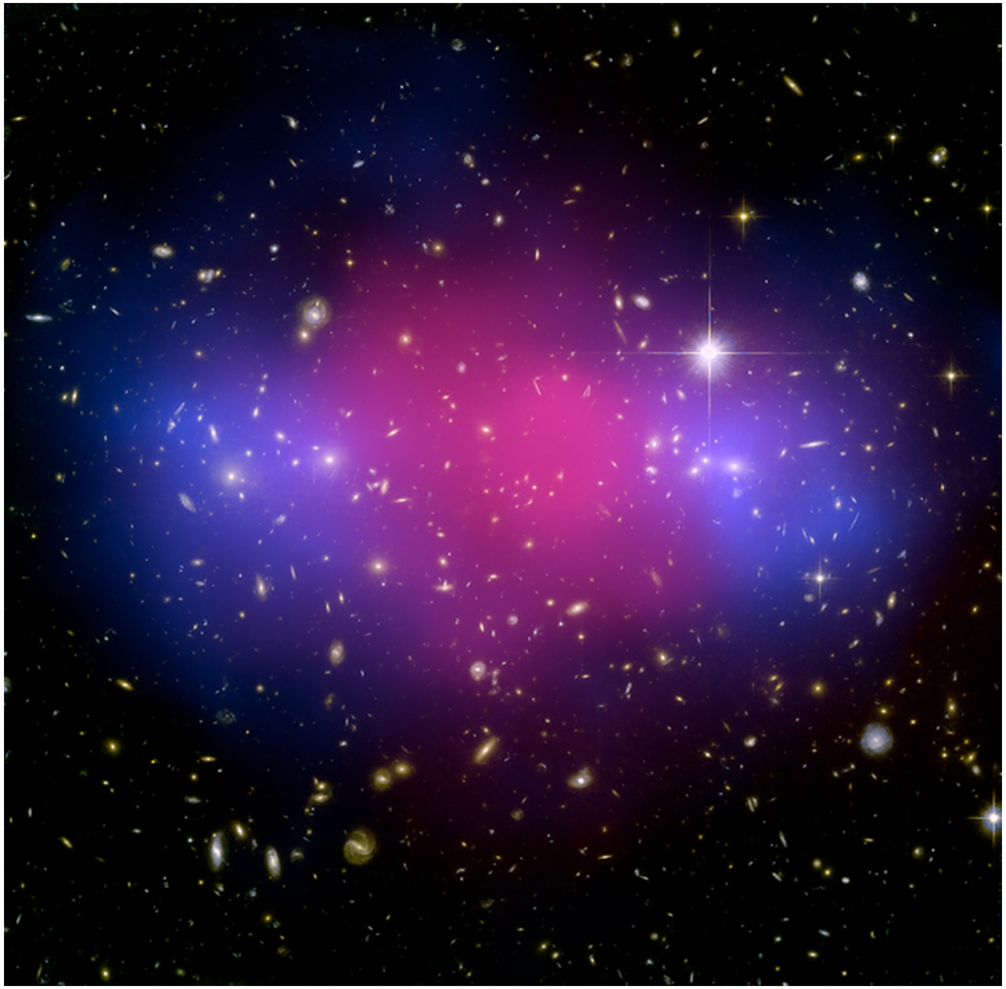
“A direct empirical proof of the existence of dark matter”
Clowe, *et al*., Astrophys.J.648:L109-L113,2006.



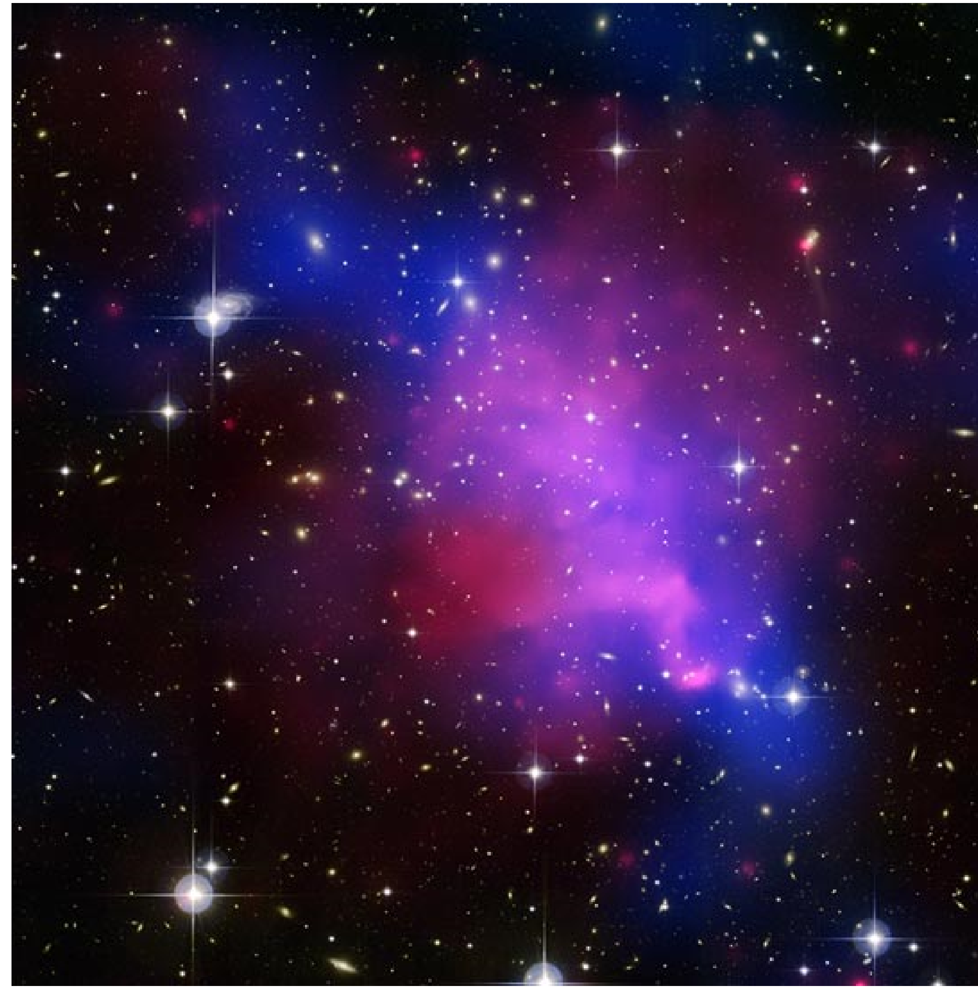

X-ray Image


Weak lensing Image


Composite Image



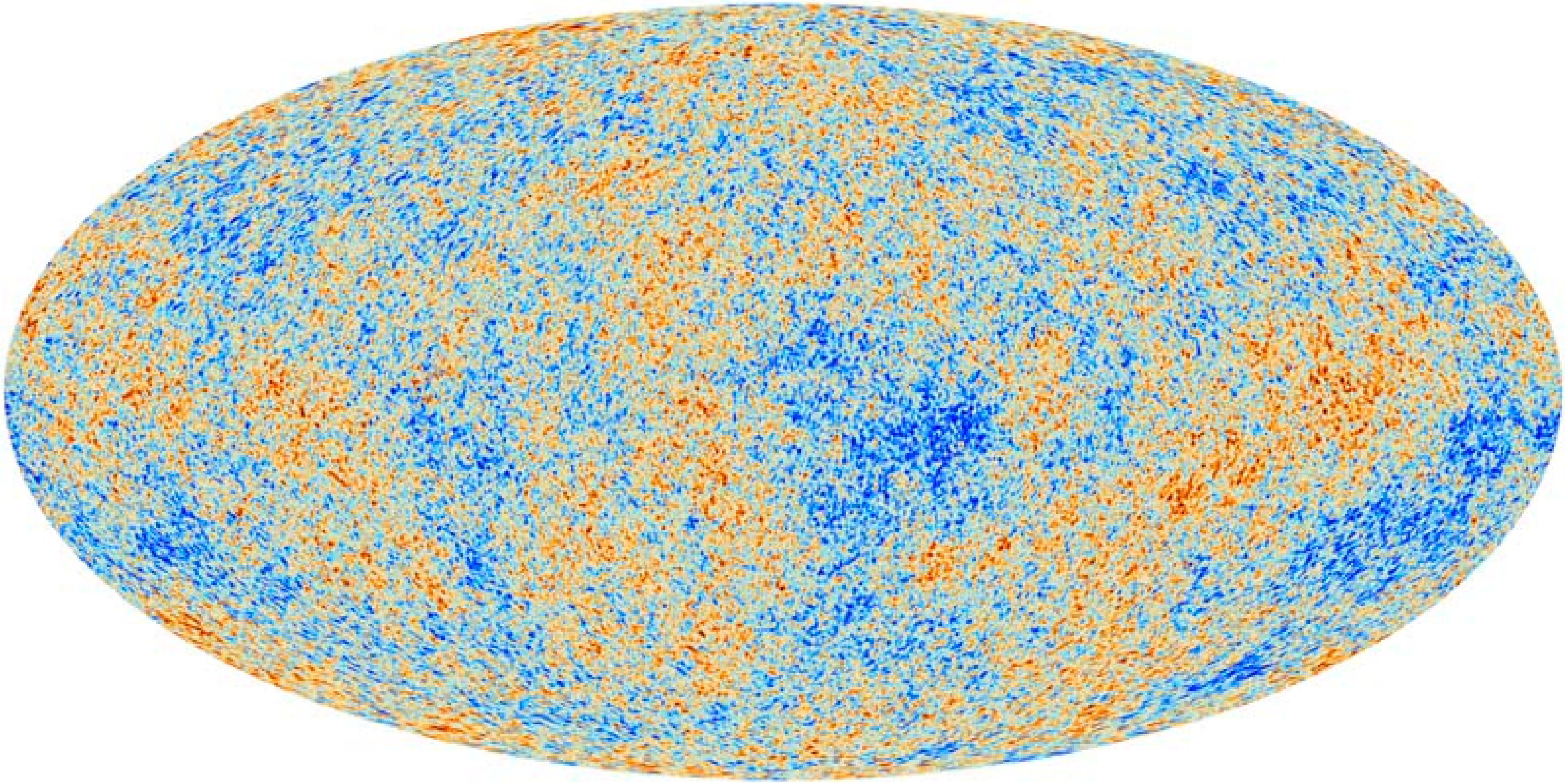
MACS J0025.4-1222



Abell 520

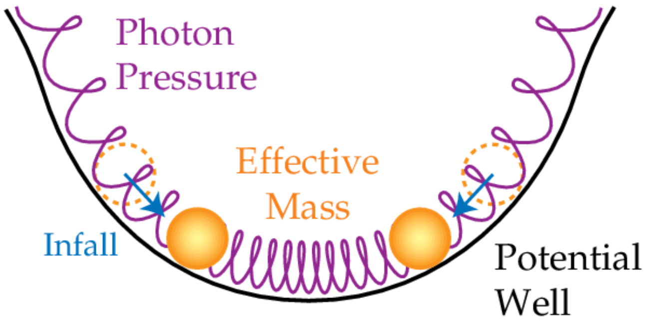
Evidence from the Universe at large

Cosmic microwave background anisotropies

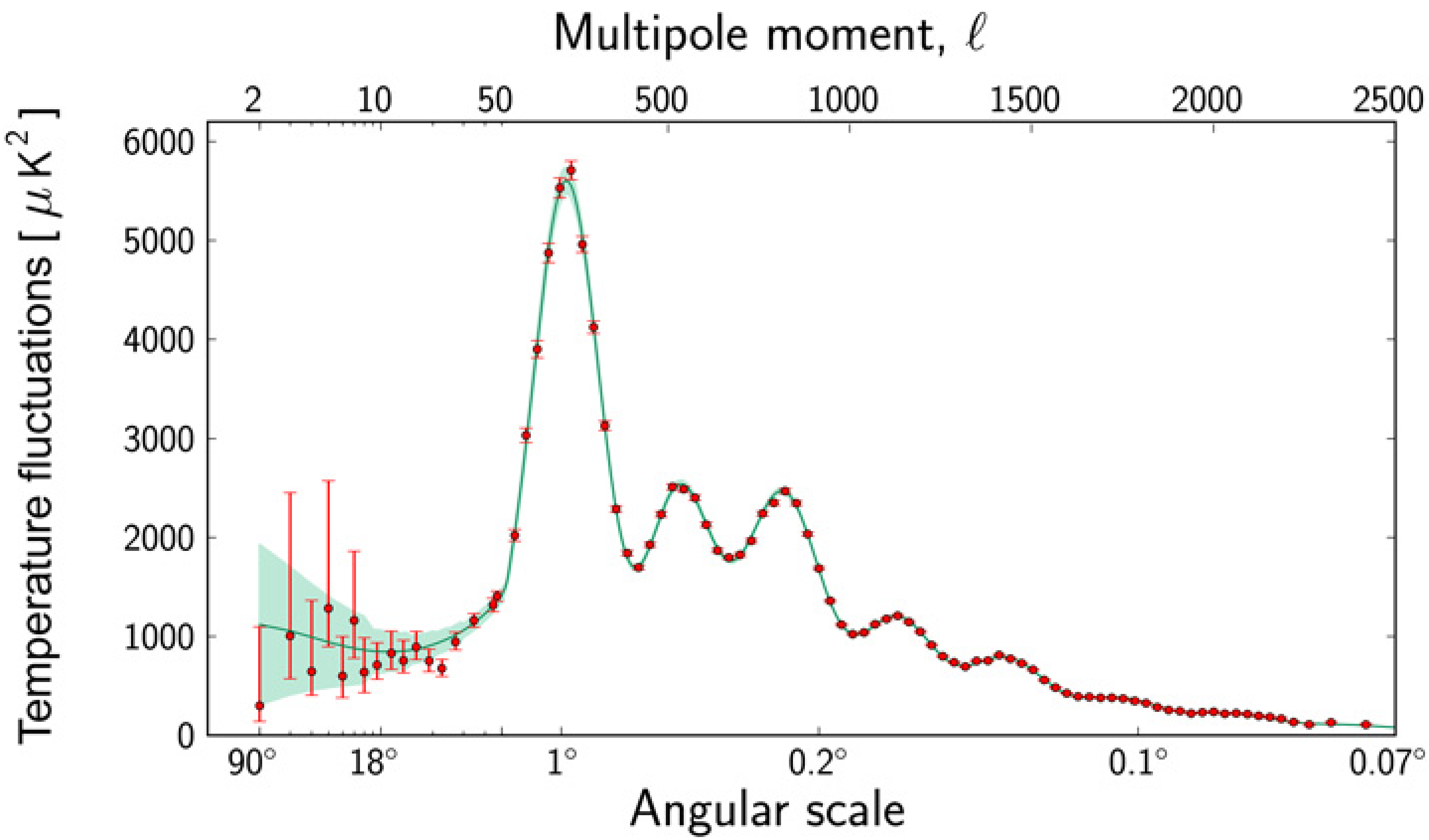


Planck Mission

CMB angular power spectrum

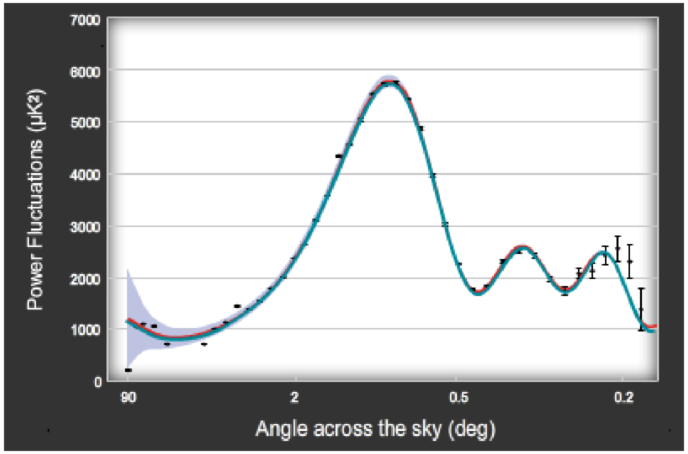


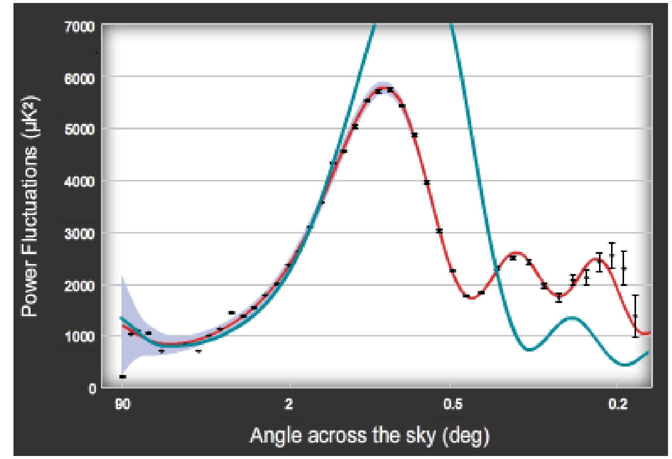
Credit: Wayne Hu



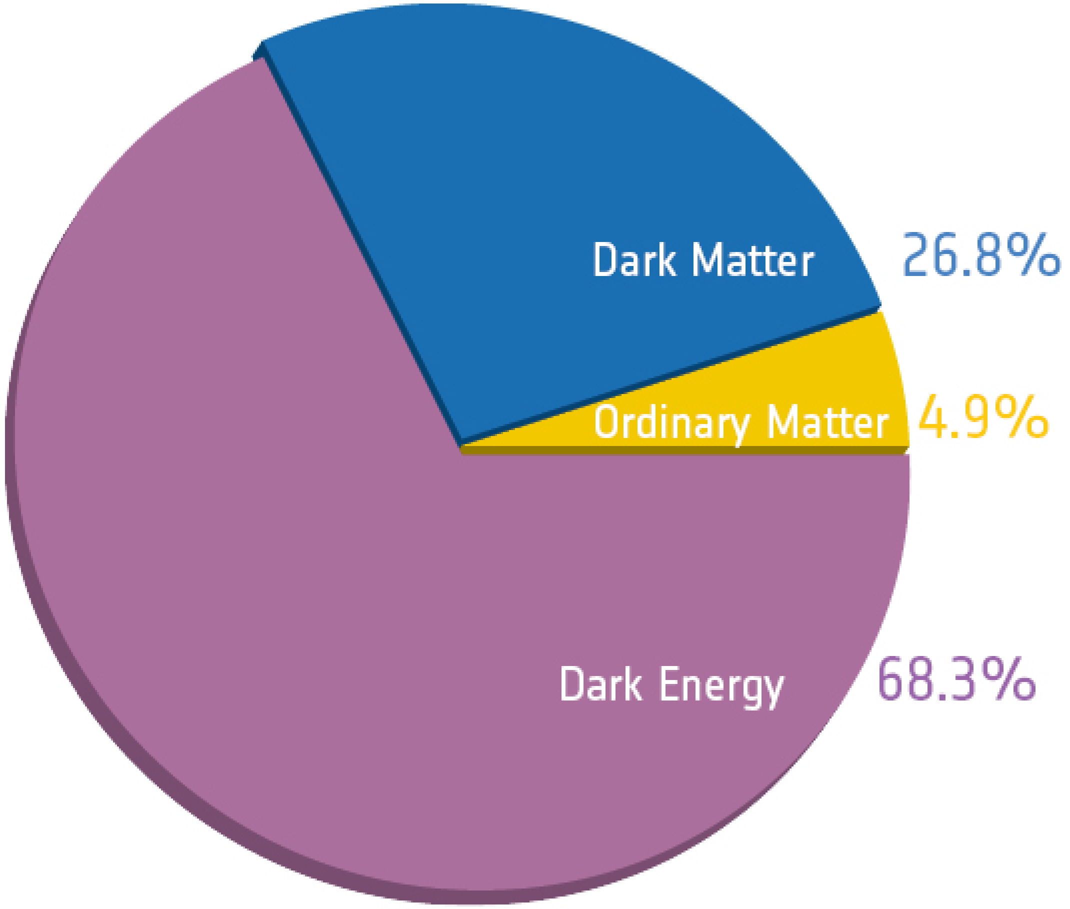
Planck Mission

http://lambda.gsfc.nasa.gov/education/cmb_plotter/





The cosmic pie



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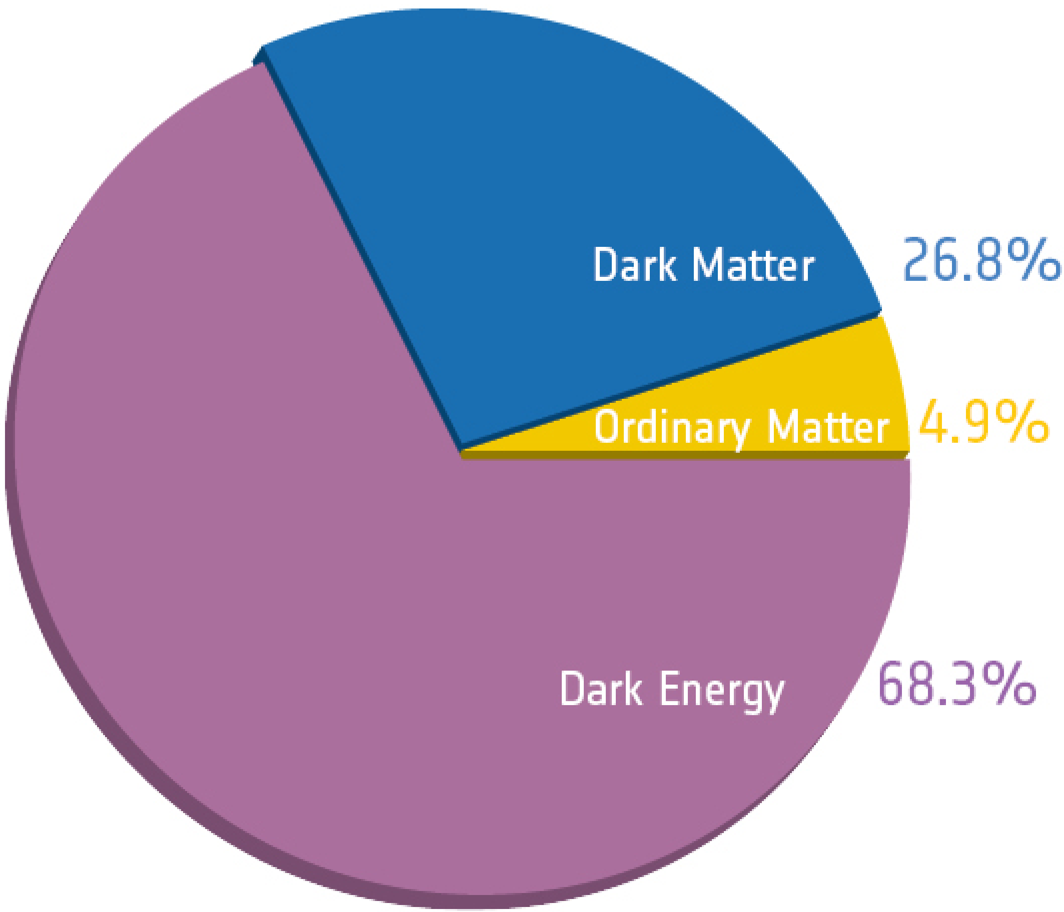
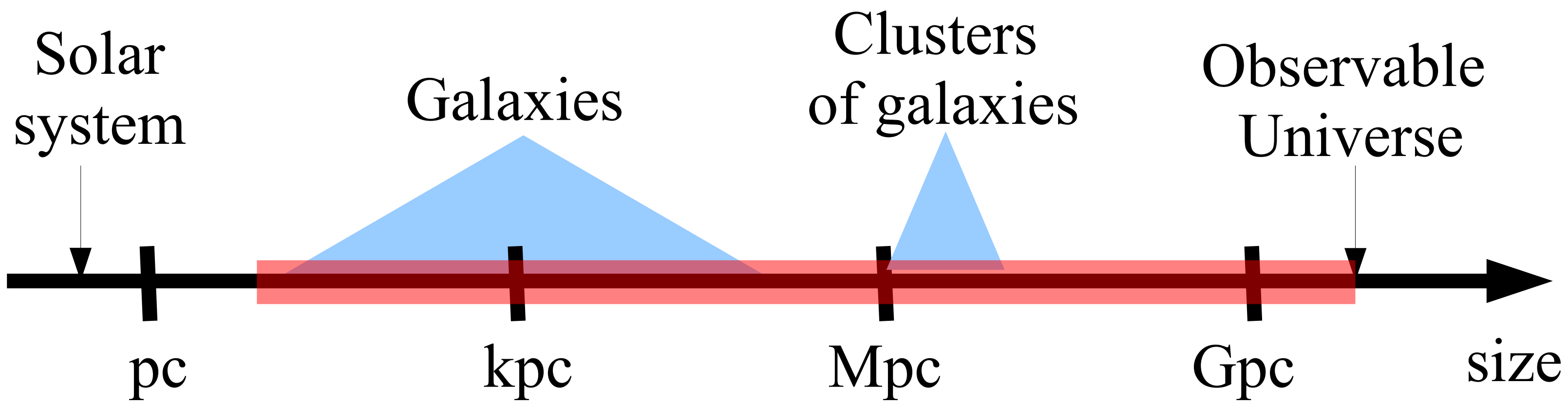


$$\Omega_{\rm DM} h^2 \approx 0.12$$

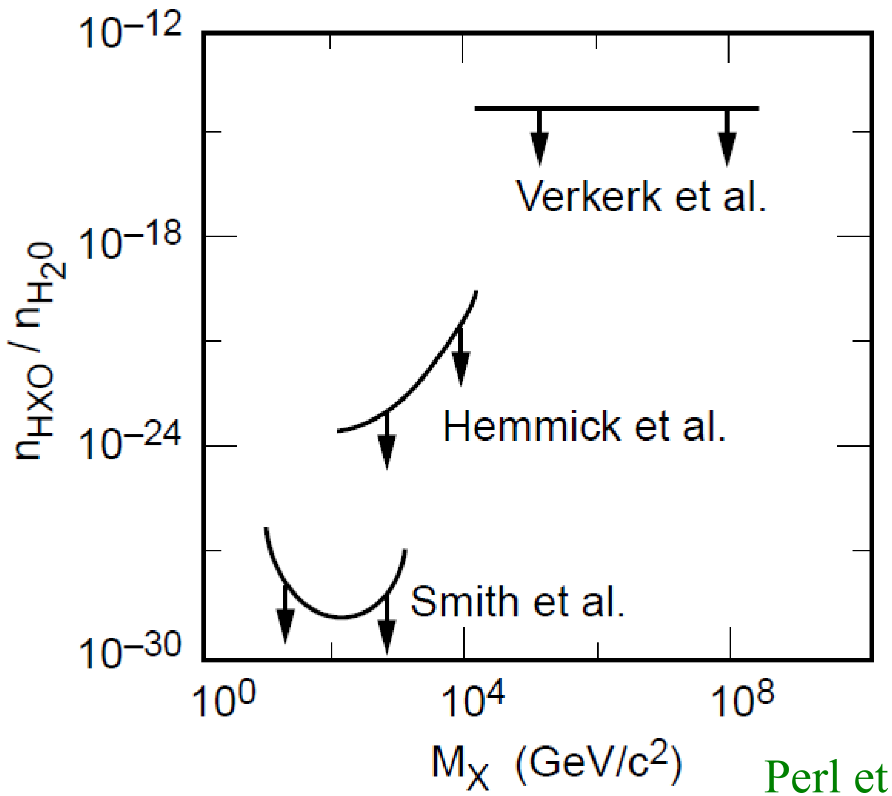
There is evidence for dark matter in a wide range of distance scales



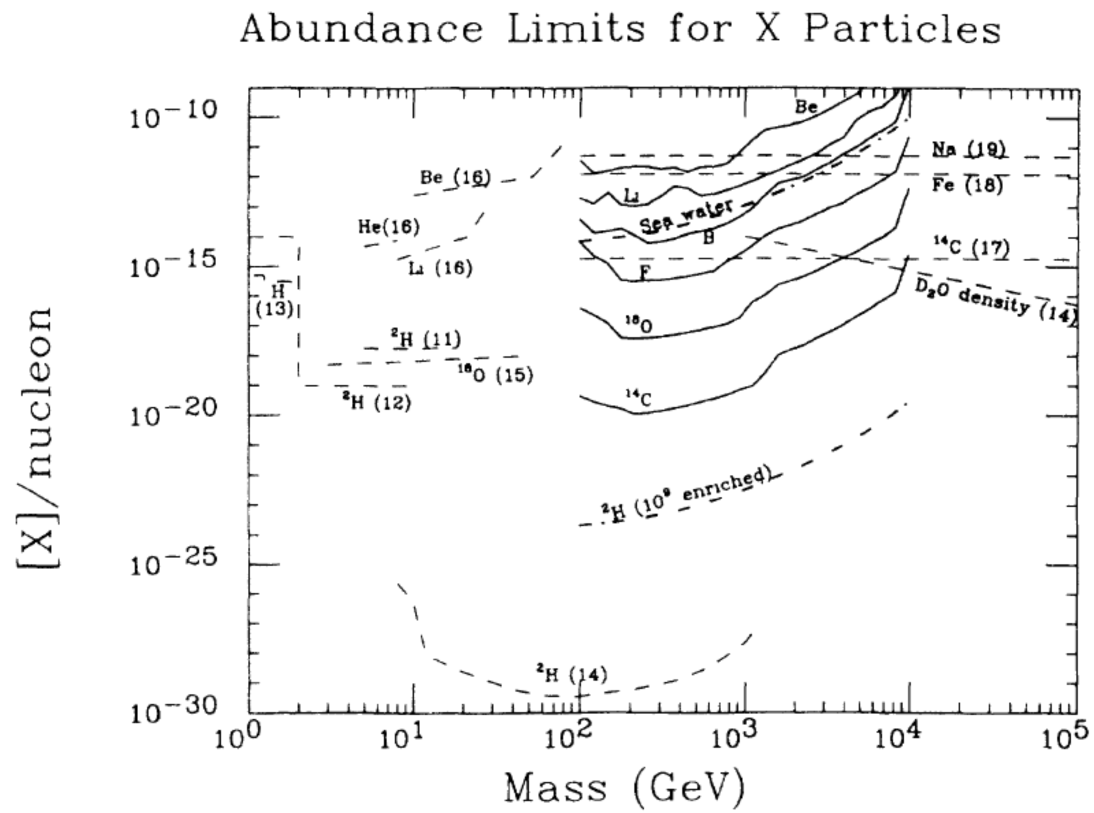
What do we know about dark matter?

1) It is dark. No electric charge.

- If it has positive charge, it can form a bound state X^+e^-, an "anomalously heavy hydrogen atom".
- If it has negative charge, it can bind to nuclei, forming "anomalously heavy isotopes".

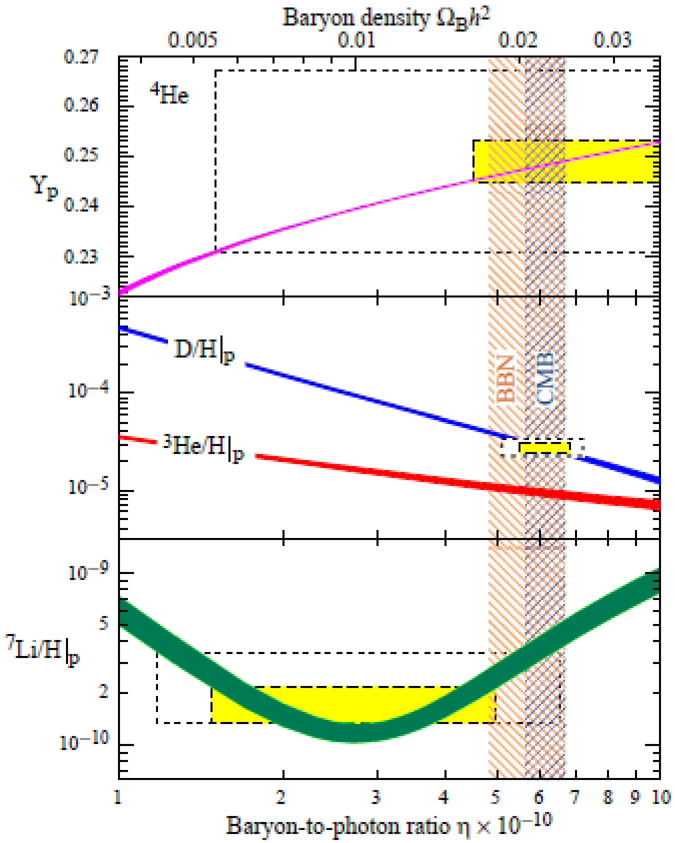


Perl et al.

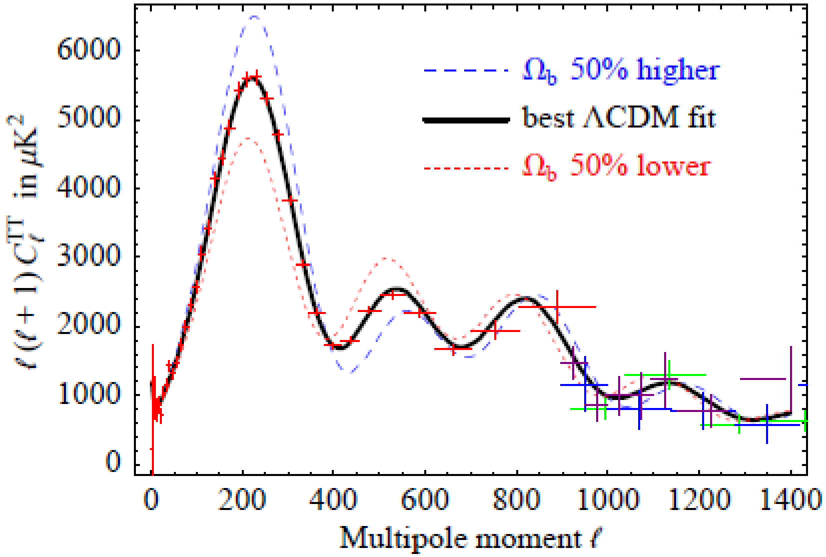


2) It is not made of baryons.

Primordial nucleosynthesis

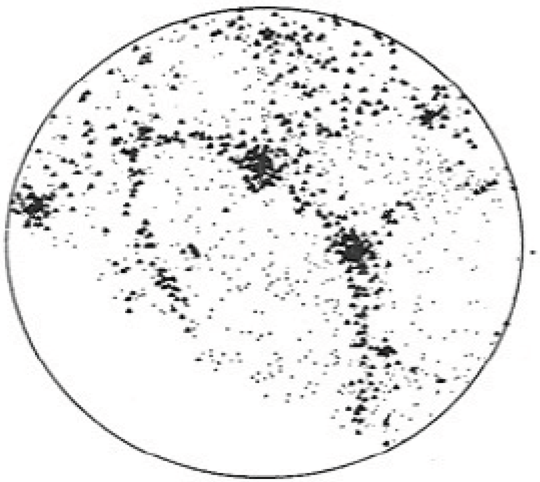


Cosmic Microwave Background radiation



3) It was “slow” at the time of the formation of the first structures.

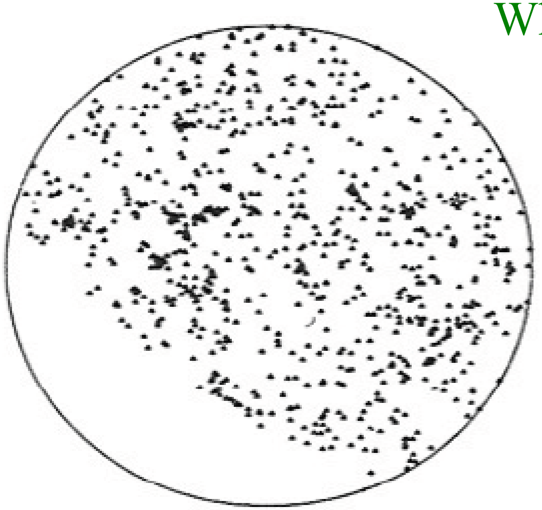
White'86



HDM

Hot Dark Matter

Relativistic



CDM

Cold Dark Matter

Non-relativistic

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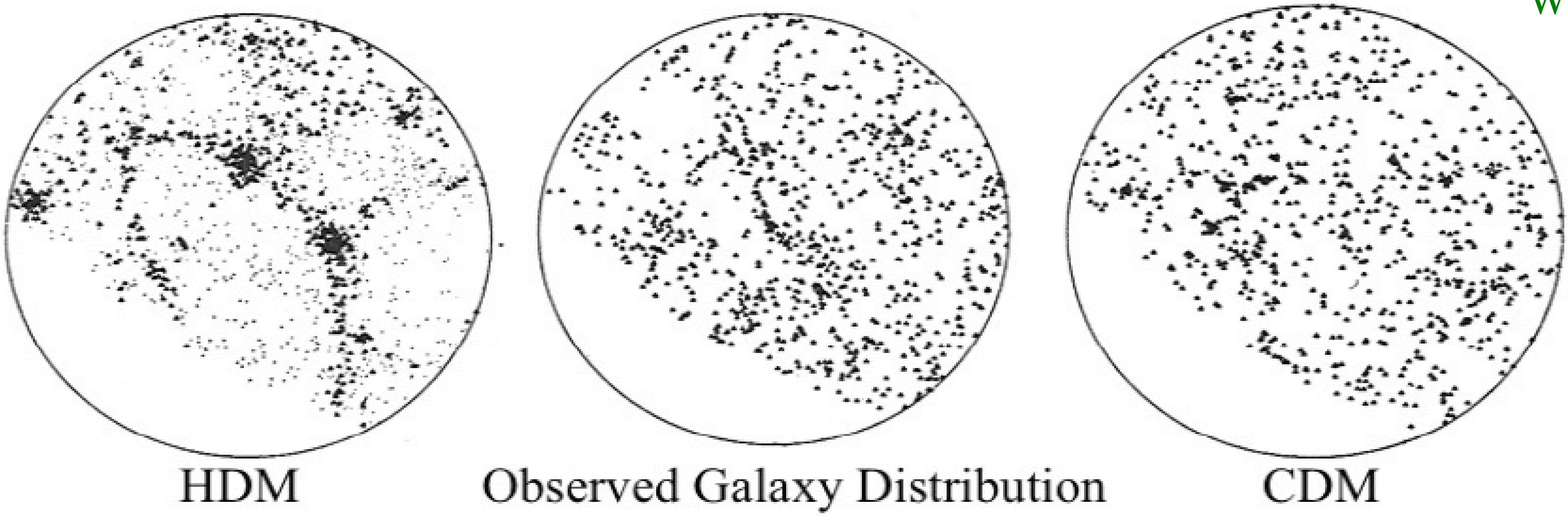
White'86



Hot Dark Matter
Relativistic

Cold Dark Matter
Non-relativistic

3) It was "slow" at the time of the formation of the first structures.

THE ASTROPHYSICAL JOURNAL, **274**:L1–L5, 1983 November 1
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CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

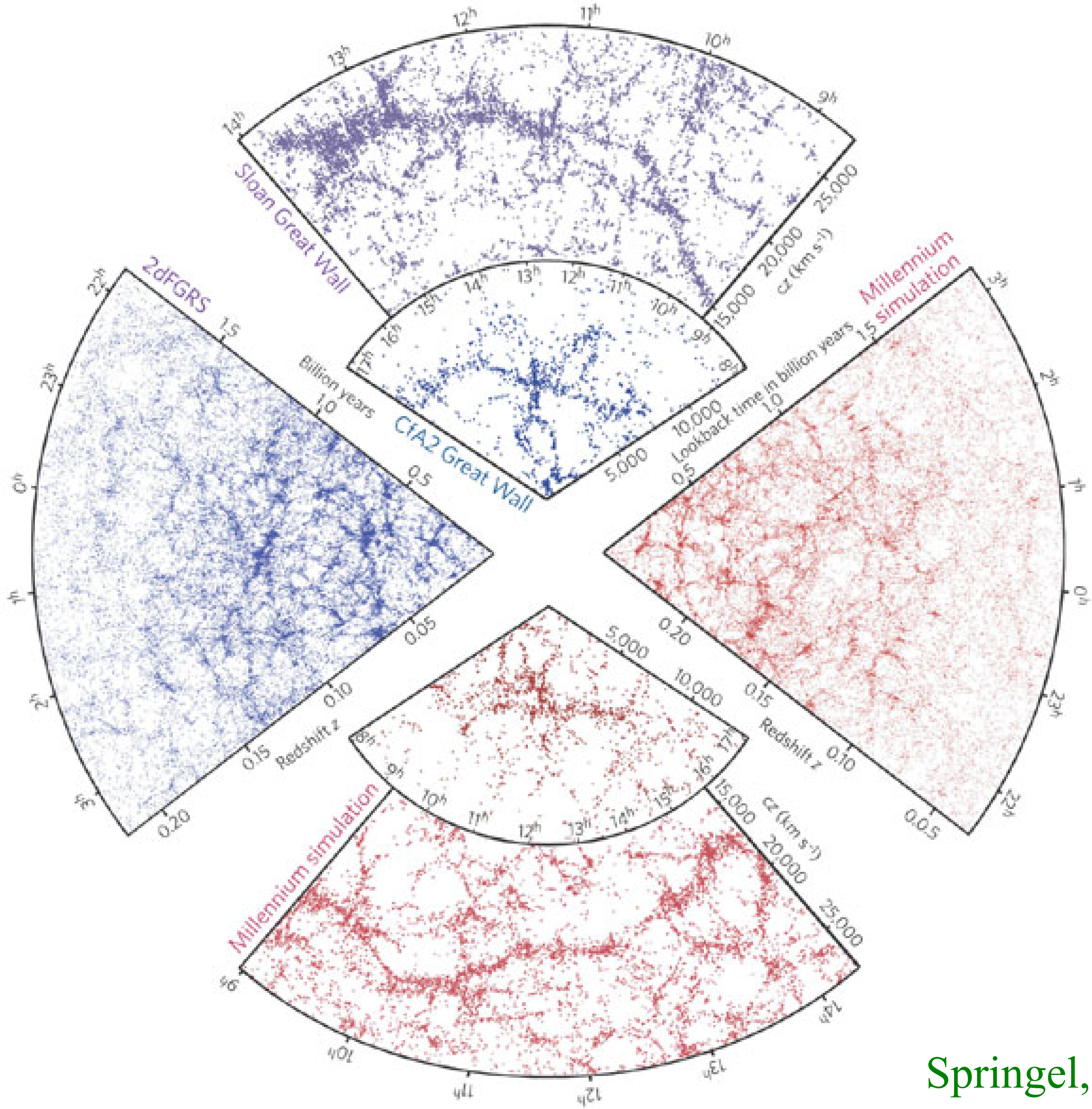
SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.

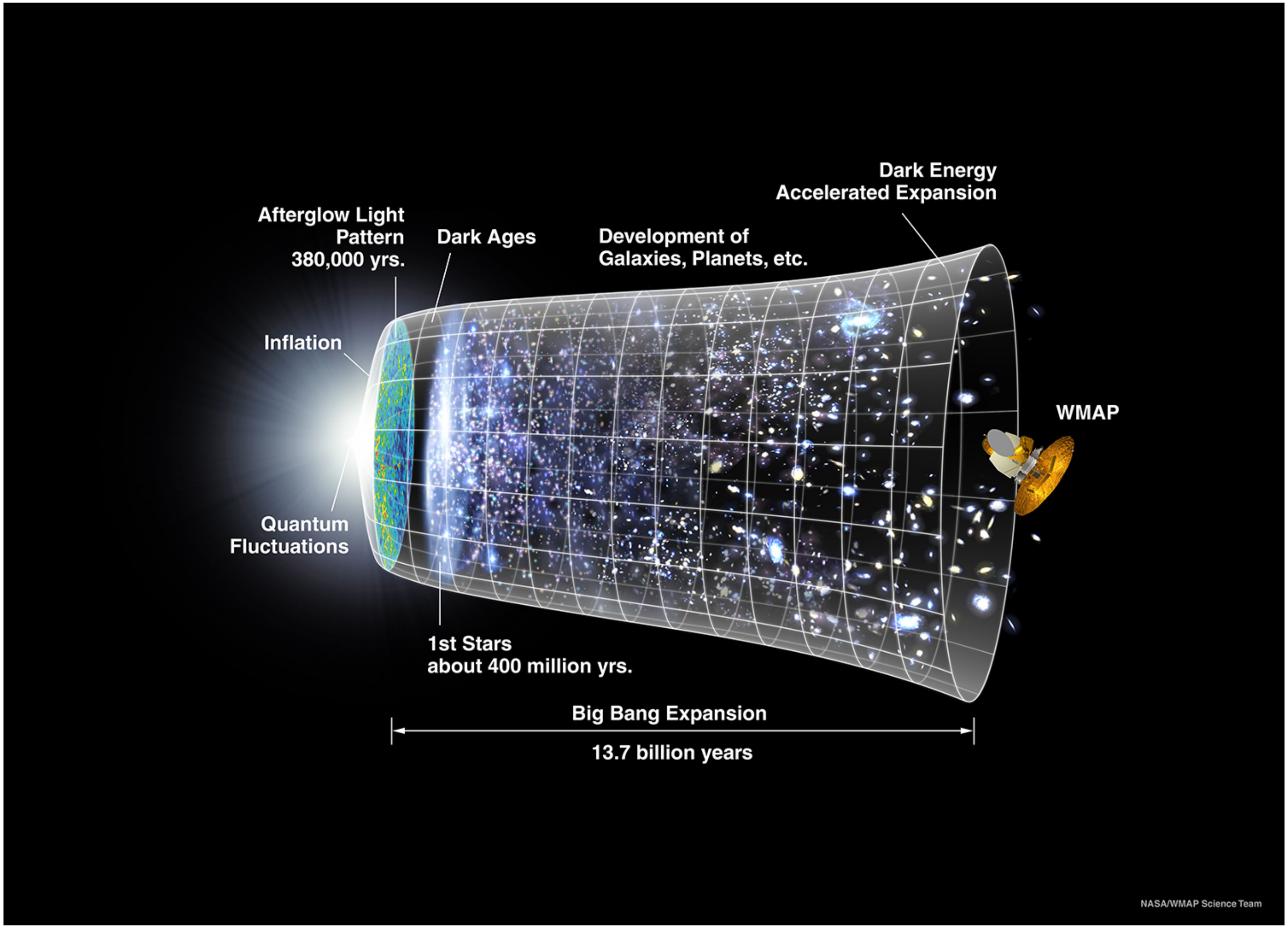
Subject headings: cosmology — galaxies: clustering — neutrinos

3) It was "slow" at the time of the formation of the first structures.



Springel, Frenk, White

4) It exists today.



To summarize, observations indicate that the dark matter is constituted by particles which have:

- No electric charge, no color.
- No baryon number.
- Low velocity at the time of structure formation.
- Lifetime longer than the age of the Universe.

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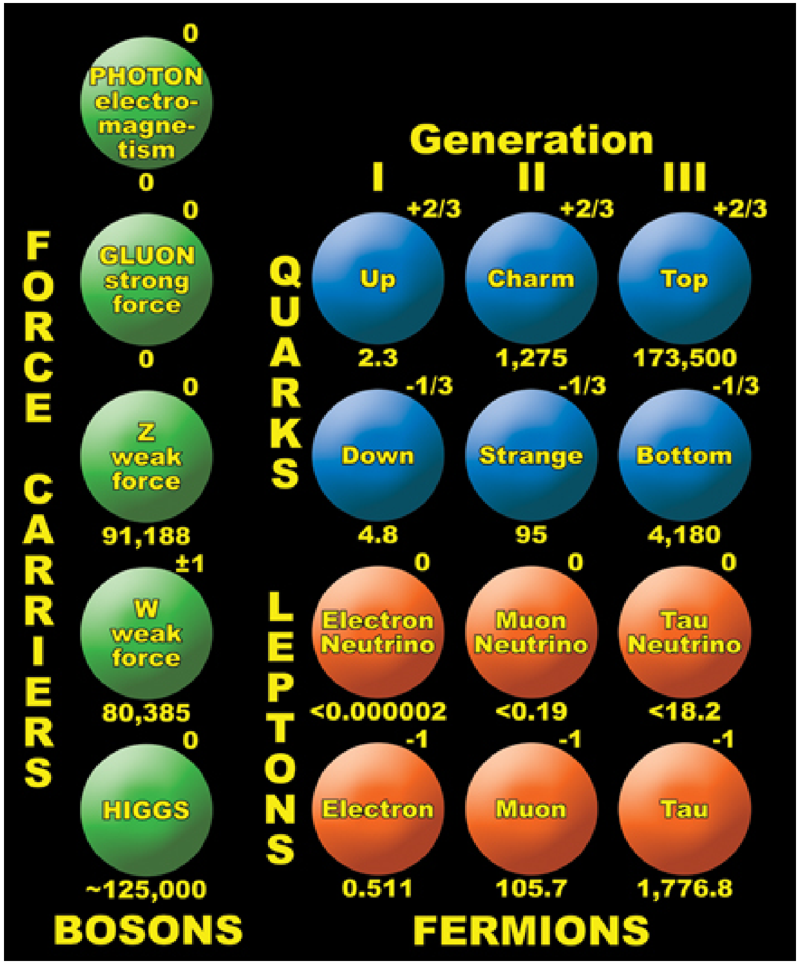

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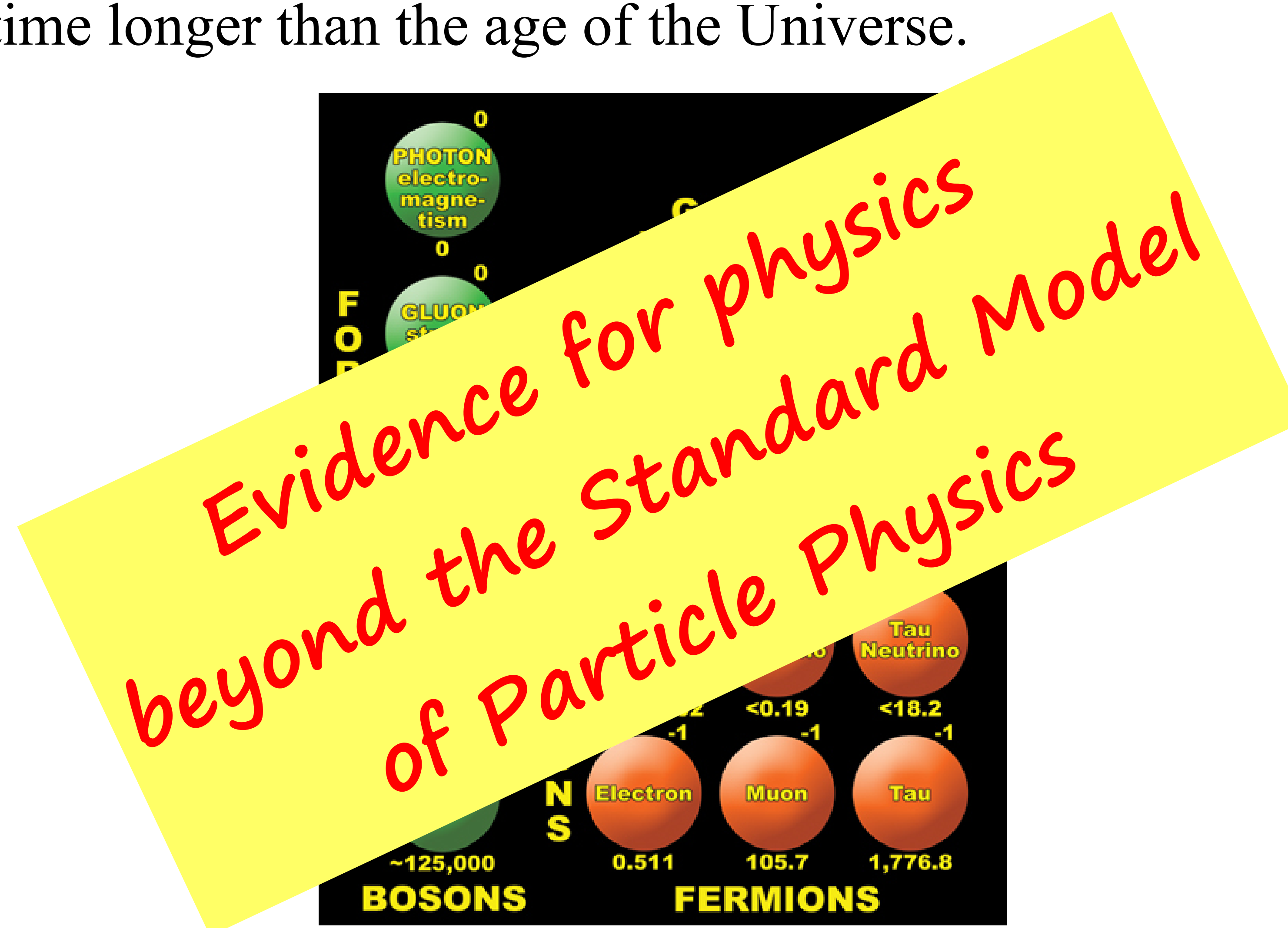

What do we know about dark matter, from the particle physics point of view??

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^\pm$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

Citation: K. Nakamura et al. (Particle Data Group), JPG 37, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

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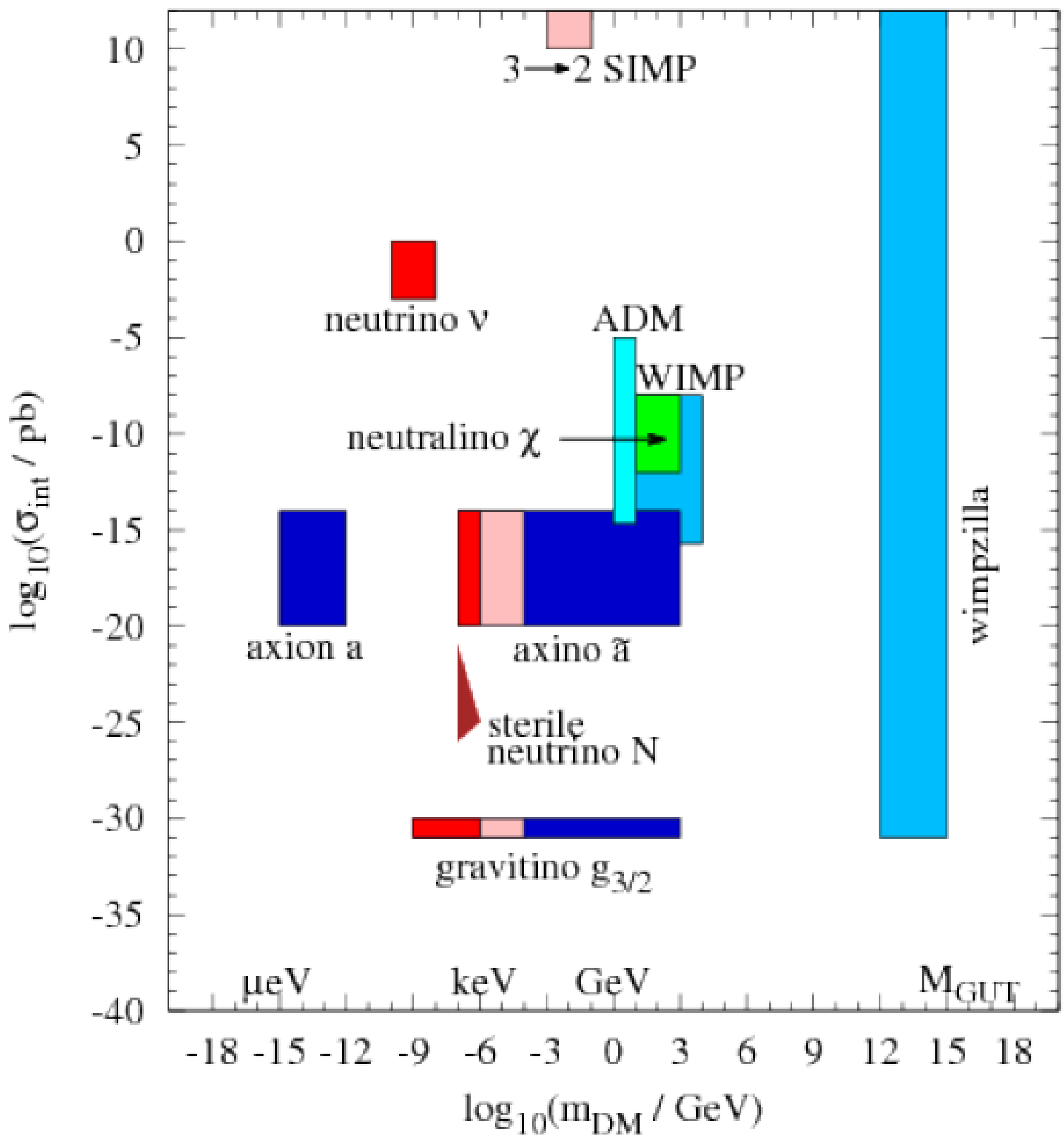
DARK MATTER

$J =$?

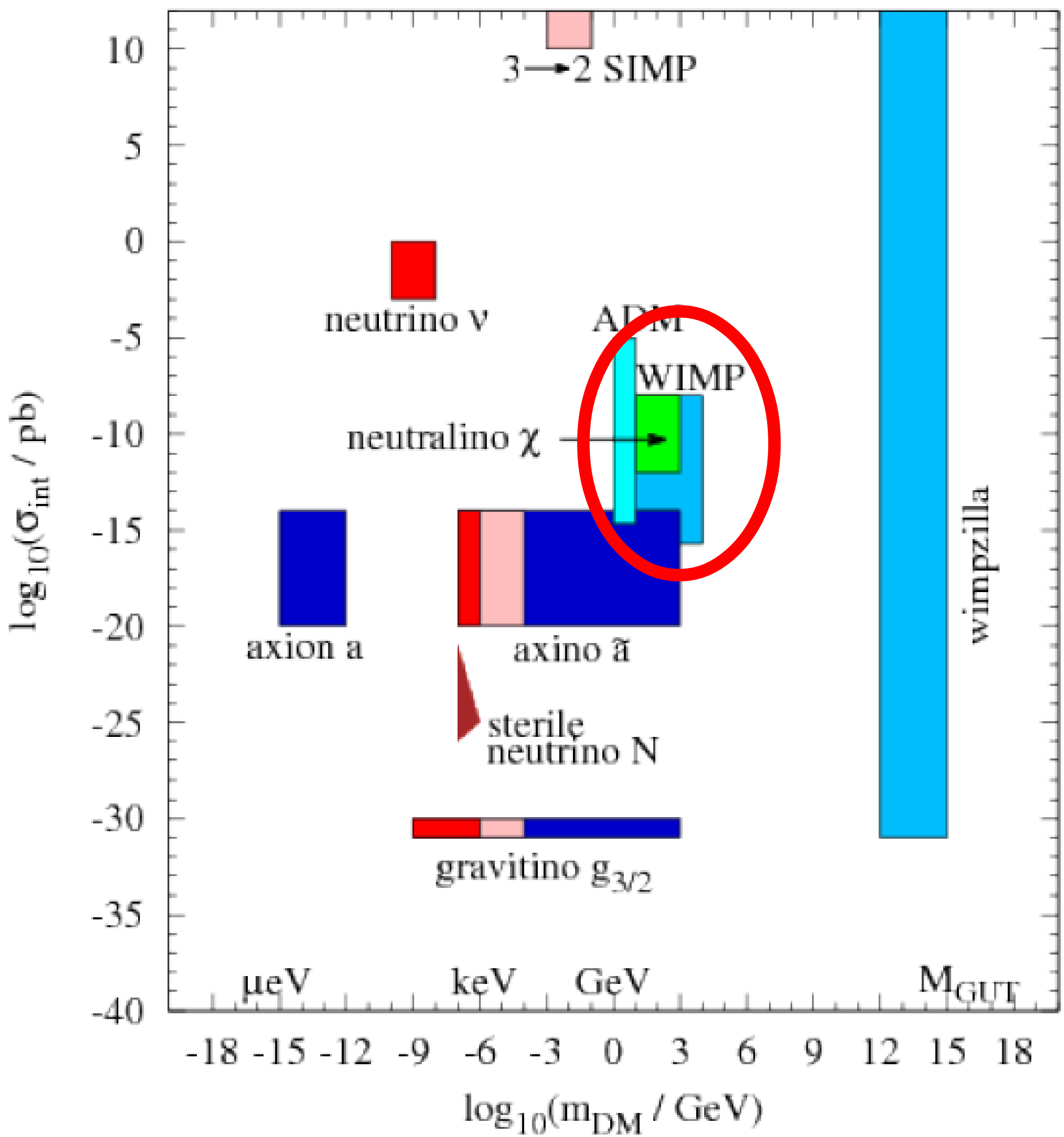
Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

Goal for the 21st century: identify the properties of the dark matter particle

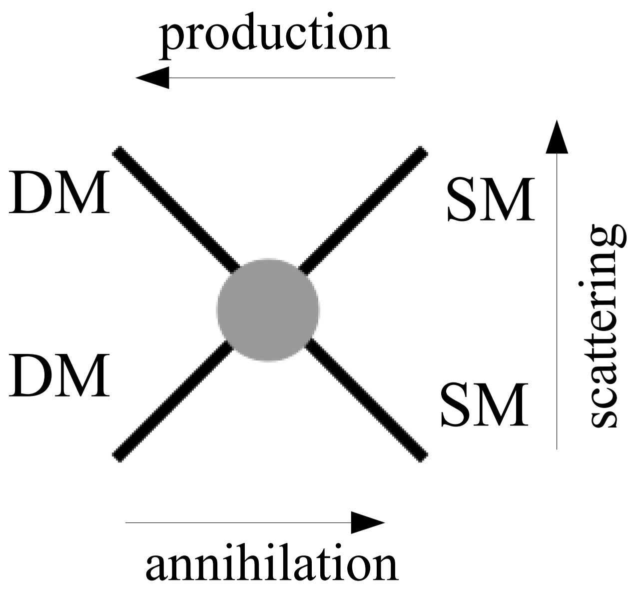


3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
axion a
axino ã
sterile
neutrino N
gravitino $g_{3/2}$
wimpzilla
μeV
keV
GeV
M_{GUT}
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)



3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
axion a
axino ã
sterile
neutrino N
gravitino $g_{3/2}$
wimpzilla
μeV
keV
GeV
M_{GUT}
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)

The freeze-out mechanism



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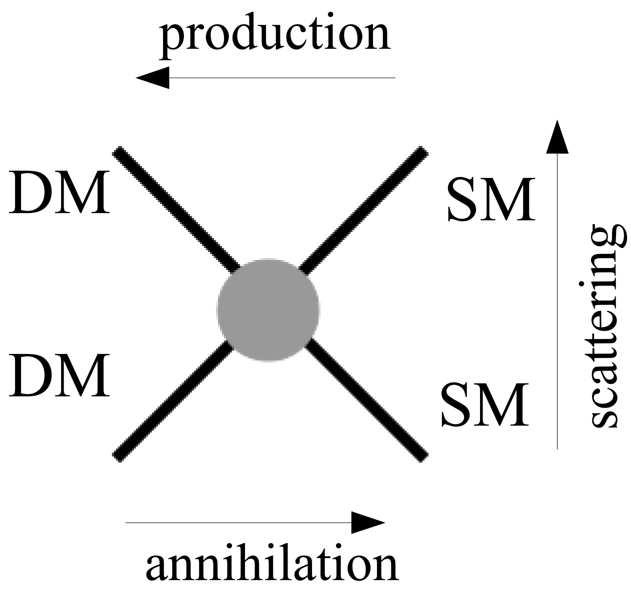
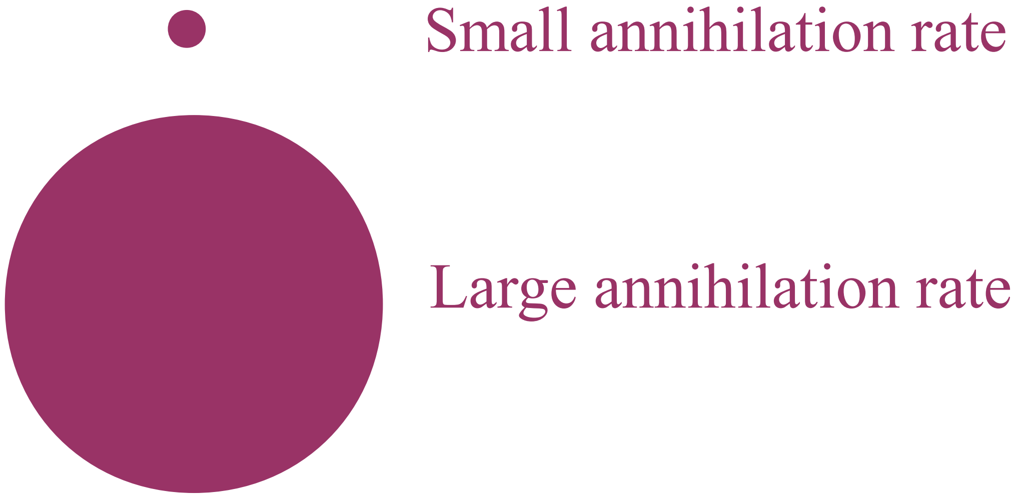
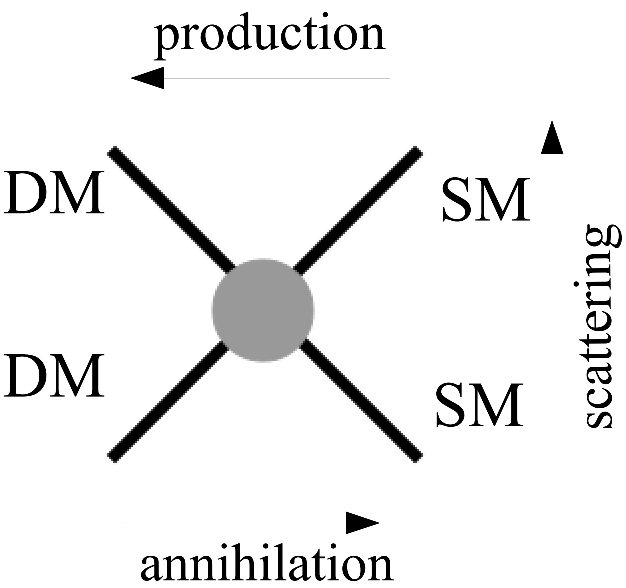


The probability of interaction is controlled by the cross-section



The freeze-out mechanism

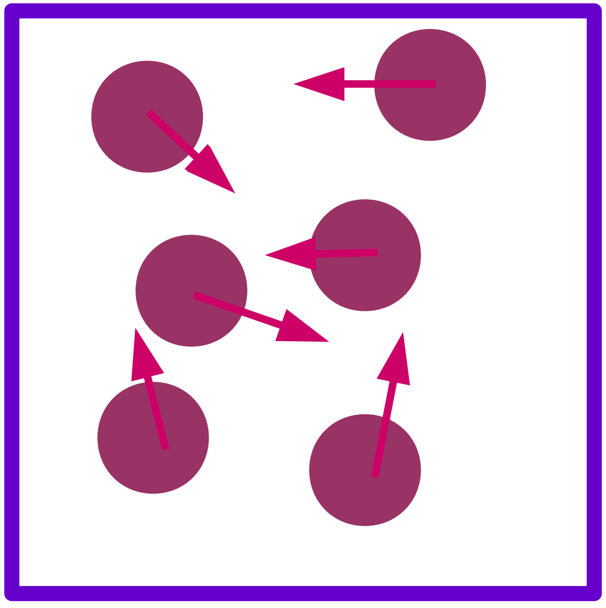


The probability of interaction is controlled by the cross-section

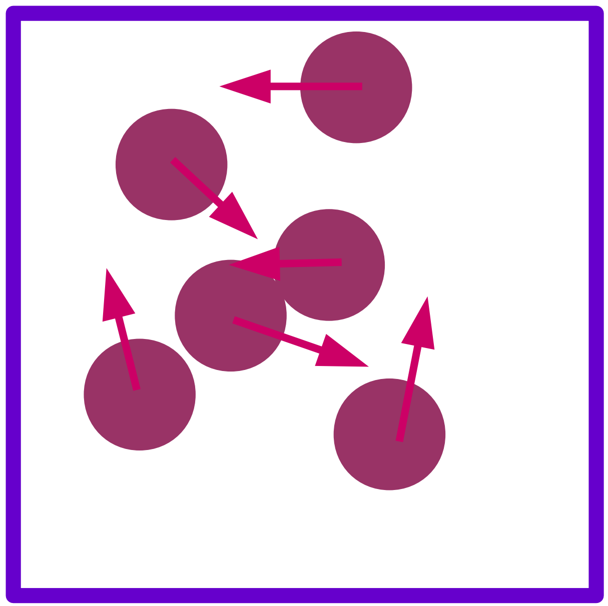
At very high temperatures, dark matter particles are annihilated and regenerated at the same rate.

However, at low temperatures, the Standard Model particles do not have enough kinetic energy to regenerate DM particles.

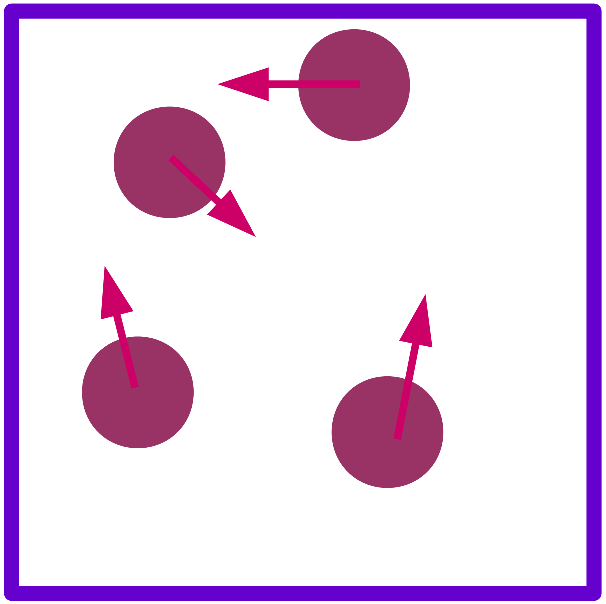
Dark matter population in a static Universe



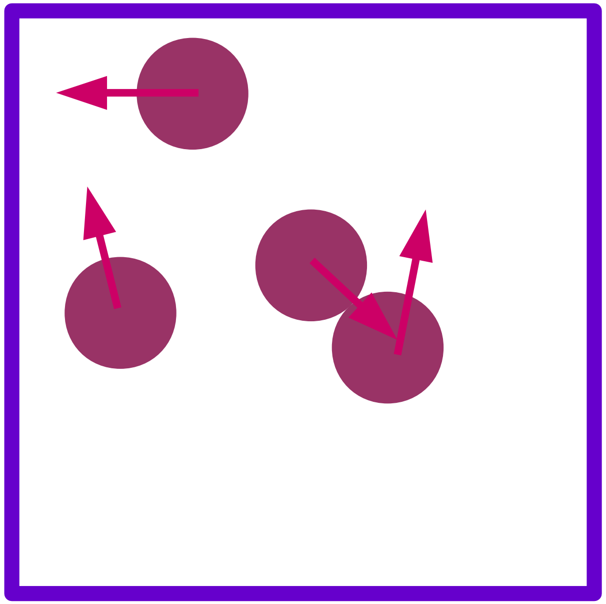
Dark matter population in a static Universe



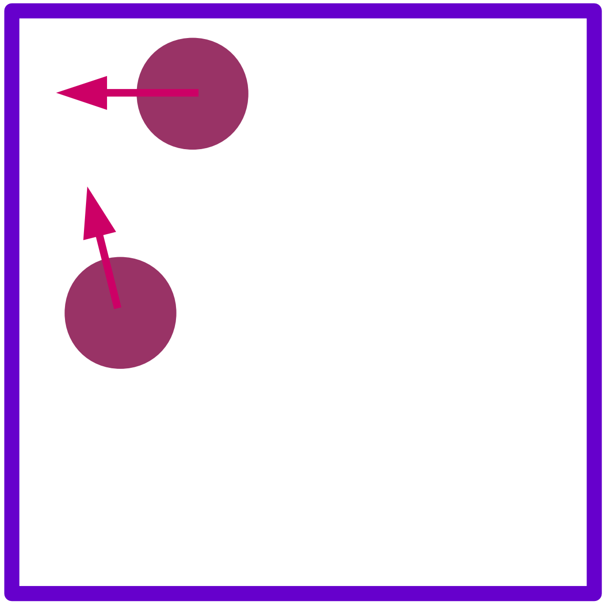
Dark matter population in a static Universe



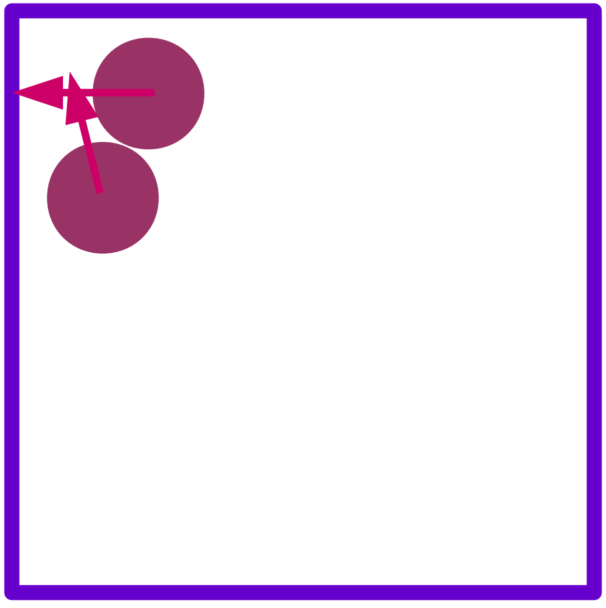
Dark matter population in a static Universe



Dark matter population in a static Universe



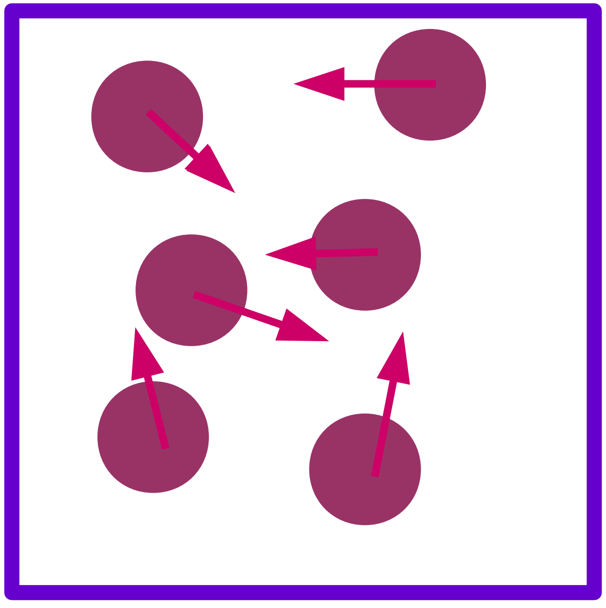
Dark matter population in a static Universe

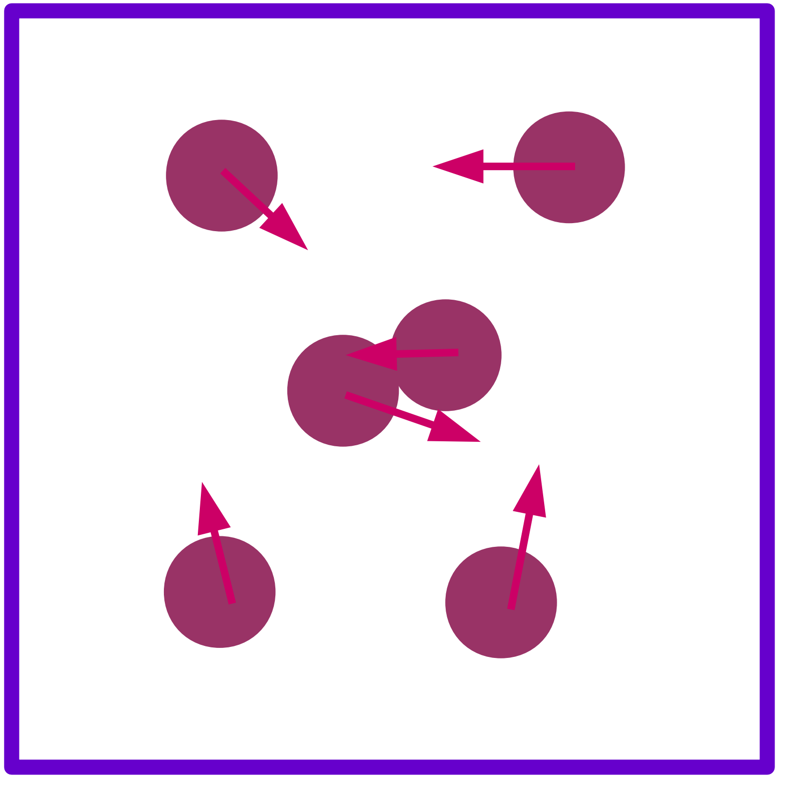


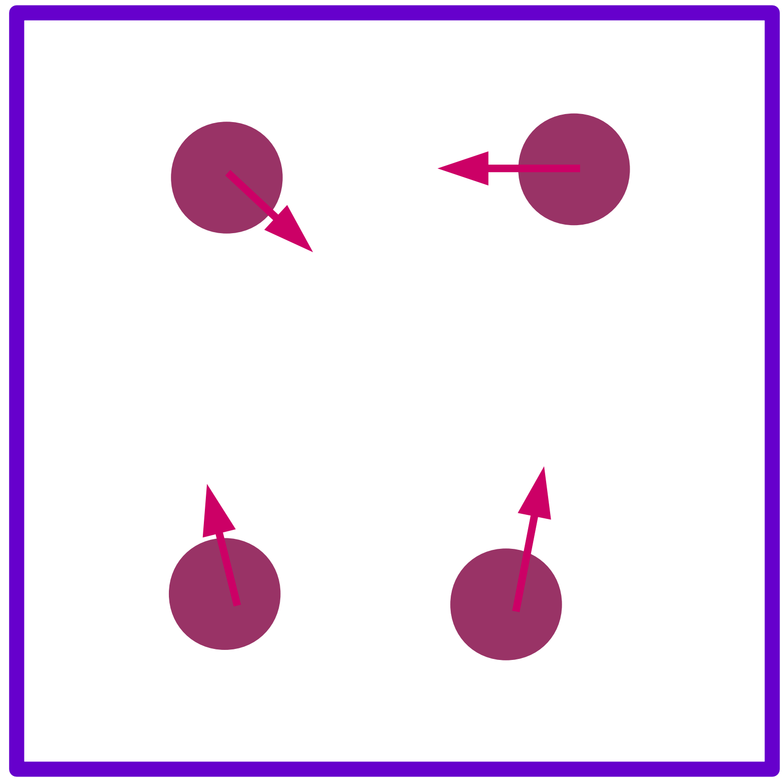
Dark matter population in a static Universe

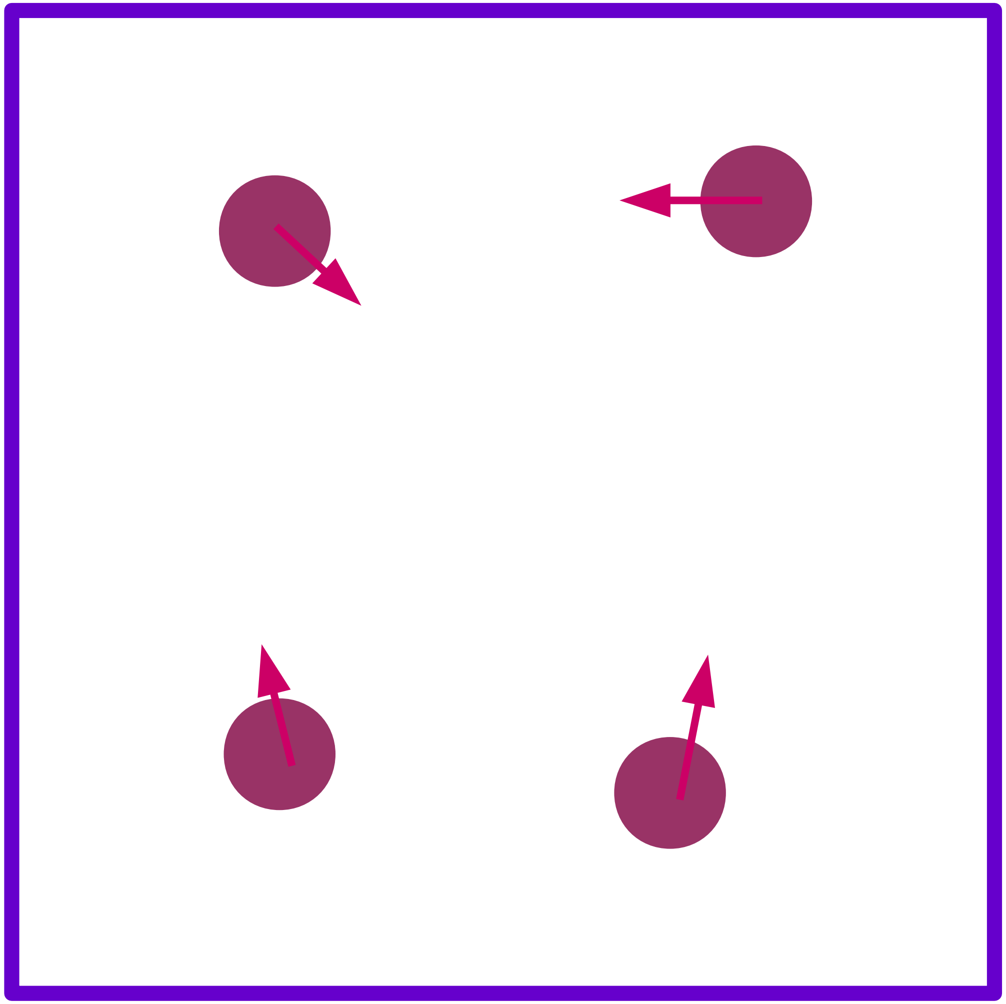
No DM particles at the end!

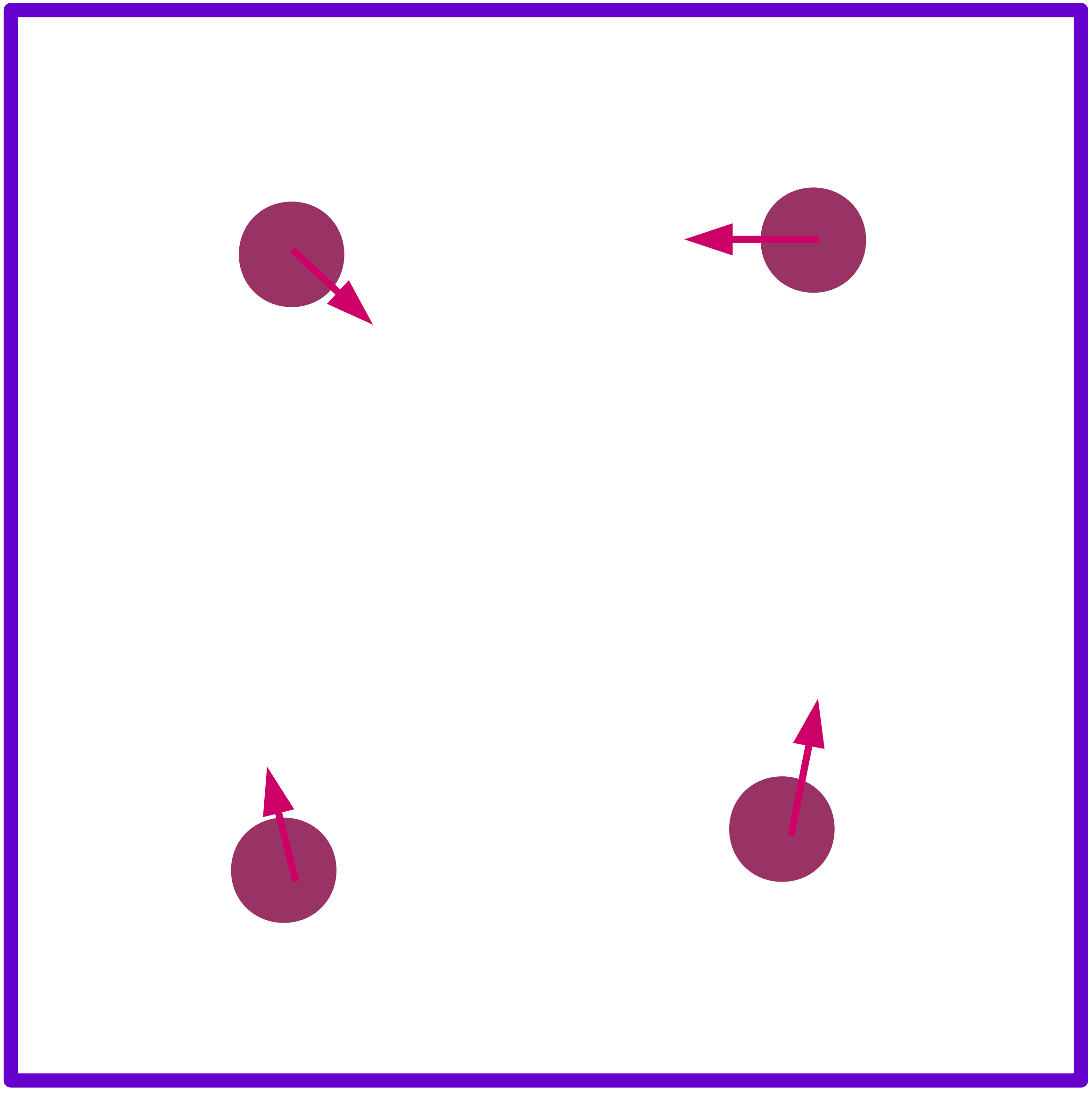
Dark matter population in an expanding Universe





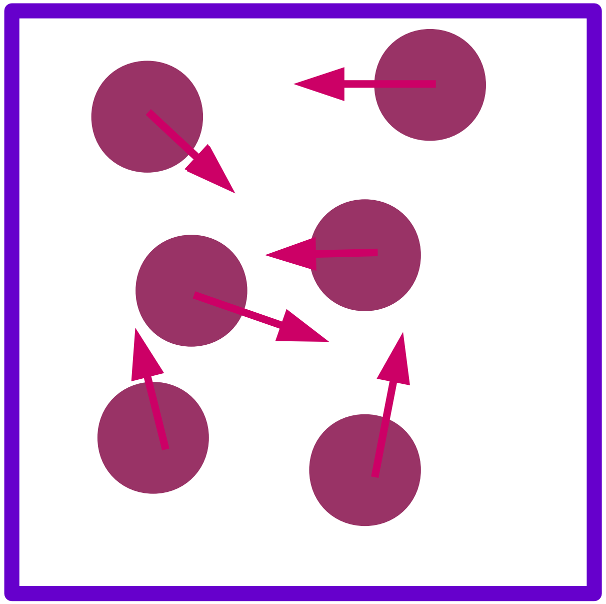




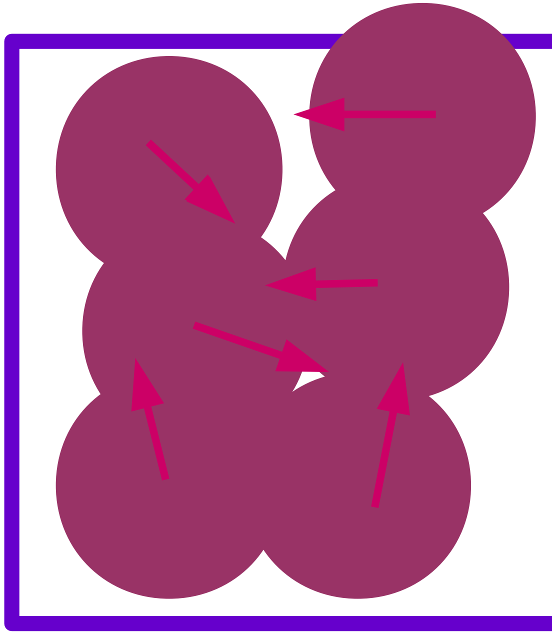


Dark matter particles can no longer annihilate.
The number of dark matter particles "freezes-out"

The *relic abundance* of dark matter particles depends on their annihilation cross section and on their velocity



The *relic abundance* of dark matter particles depends on their annihilation cross section...



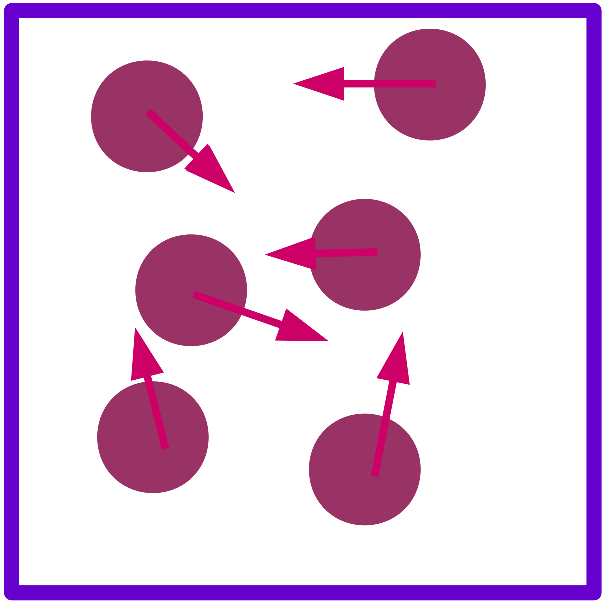
Large annihilation cross section → Small relic abundance

Small annihilation cross section → Large relic abundance

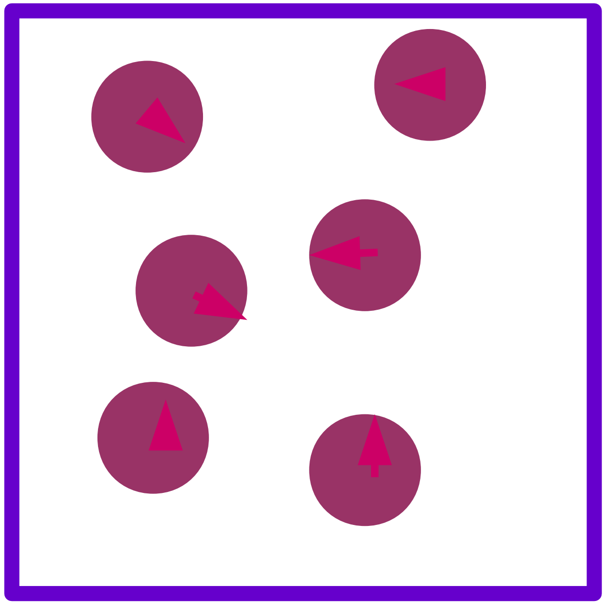
The *relic abundance* of dark matter particles depends on their annihilation cross section...

Large annihilation cross section → Small relic abundance
Small annihilation cross section → Large relic abundance

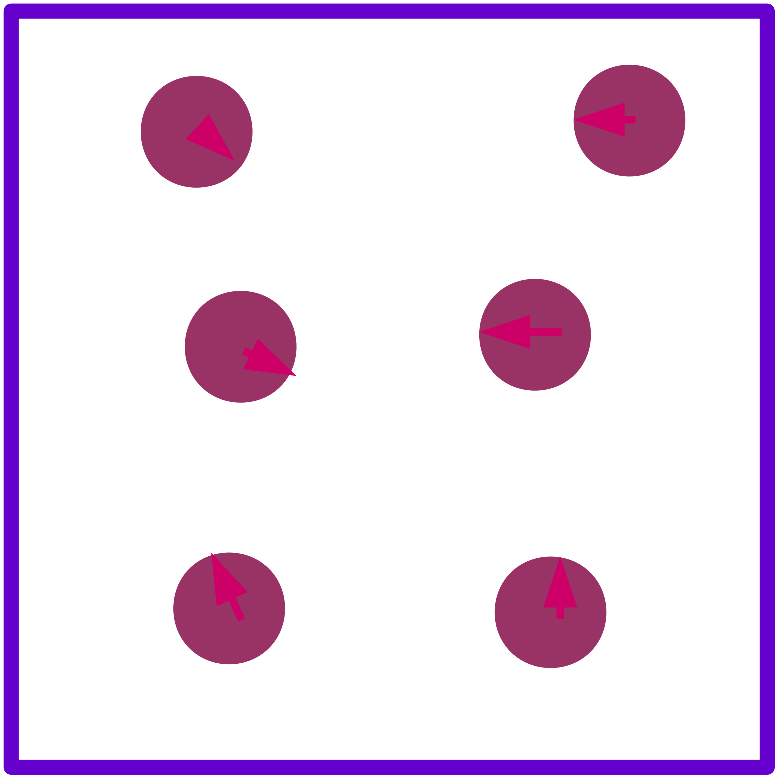
… and on their velocity



… and on their velocity



… and on their velocity



Large velocity → Small relic abundance

Small velocity → Large relic abundance

$$\Omega_{\mathrm{DM}} h^2 \propto \frac{1}{\langle \sigma v \rangle}$$