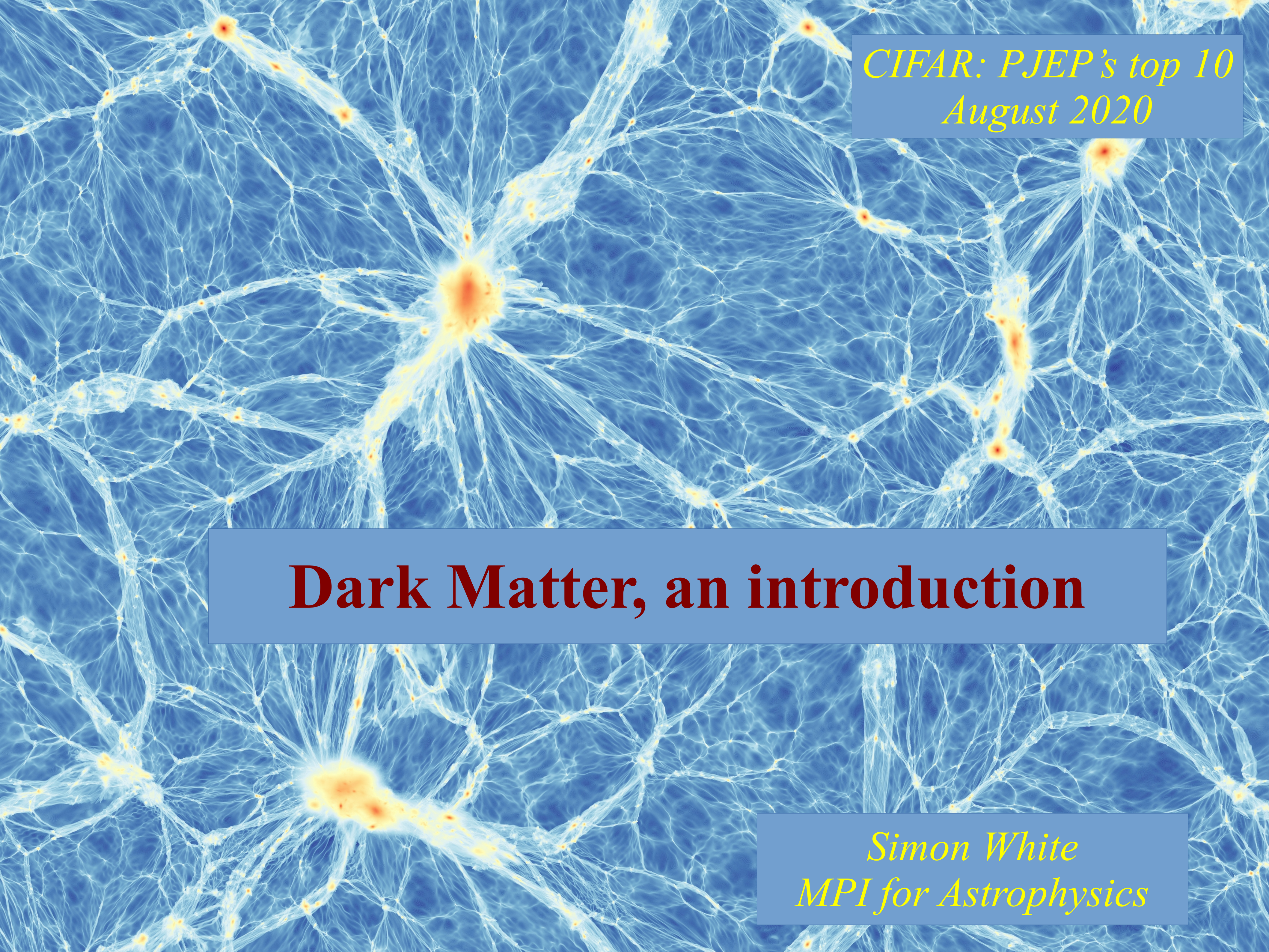

CIFAR: PJEP's top 10
August 2020

Dark Matter, an introduction

Simon White
MPI for Astrophysics

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 vøn Wichtigkeit zu werden verspricht.

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Wie aus der Zusammenstellung in § 3 hervorgeht, existieren im Comahaufen scheinbare Geschwindigkeitsunterschiede von mindestens 1500 bis 2000 km/sek. Im Zusammenhang mit dieser enormen Streuung der Geschwindigkeiten kann man folgende Überlegungen anstellen.

1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

$$\bar{\varepsilon}_k = -\tfrac{1}{2}\,\bar{\varepsilon}_p\,, \tag{4}$$

wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Abschätzung nehmen wir an, dass die Materie im Haufen gleichförmig über den Raum verteilt ist. Der Haufen besitzt einen Radius R von ca. einer Million Lichtjahren (gleich 10^{24} cm) und enthält 800 individuelle Nebel von je einer Masse entsprechend 10^9 Sonnenmassen. Die Gesamtmasse M des Systems ist deshalb

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45}\ \text{gr.} \tag{5}$$

Daraus folgt für die totale potentielle Energie Ω:

$$\Omega = -\frac{3}{5}\,\Gamma\,\frac{M^2}{R} \tag{6}$$

Γ = Gravitationskonstante

oder

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2} \tag{7}$$

und weiter

$$\bar{\varepsilon}_k = \overline{v^2}/2 = -\varepsilon_p/2 = 32 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2}$$
$$(\overline{v^2})^{1/2} = 80\ \text{km/sek}\,. \tag{8}$$

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

This is the first statement of the **concept** of dark matter as we now understand it, as well as the first valid measurement of the relative amounts of mass within and outside galaxies

INTERGALACTIC MATTER AND THE GALAXY

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Received May 18, 1959

ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be 5×10^5 degrees and 1×10^{-4} proton/cm^3, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.

The radial velocity of M31 with respect to the local standard of rest near the sun is -296 km/sec, according to the accurate 21-cm data (van de Hulst *et al.* 1957). With a circular velocity of 216 km/sec near the sun (Schmidt 1958), we find that the centers of M31 and of our Galaxy approach each other with a speed of 125 km/sec. An estimated uncertainty of ± 25 km/sec in the circular velocity near the sun makes this figure uncertain by ± 20 km/sec. The fact that the motion is one of approach is significant. For if the Local Group is a physical unit, the Galaxy and M31 are not likely to have been formed very far from each other, certainly not at a much greater distance than their present separation. This indicates that they must have performed the larger part of at least one orbit around their center of gravity during a time of about 10^{10} years. Consequently, their orbital period must be less than 15 billion years. From this we obtain the total mass of the system as follows. According to Kepler's third law, we have

$$P^2 = \frac{4\pi^2}{GM^*} a^3 \leq 2 \times 10^{35} \text{ sec}^2 , \tag{1}$$

where M^* represents the effective mass at the center of gravity. To obtain a minimum estimate for M^*, we assume that the system has no angular momentum. Then conservation of energy gives, for our Galaxy,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k , \tag{2}$$

where D denotes the present distance of the Galaxy to the center of gravity (480 kpc) and E_t is its present kinetic energy per unit mass. From these equations we obtain

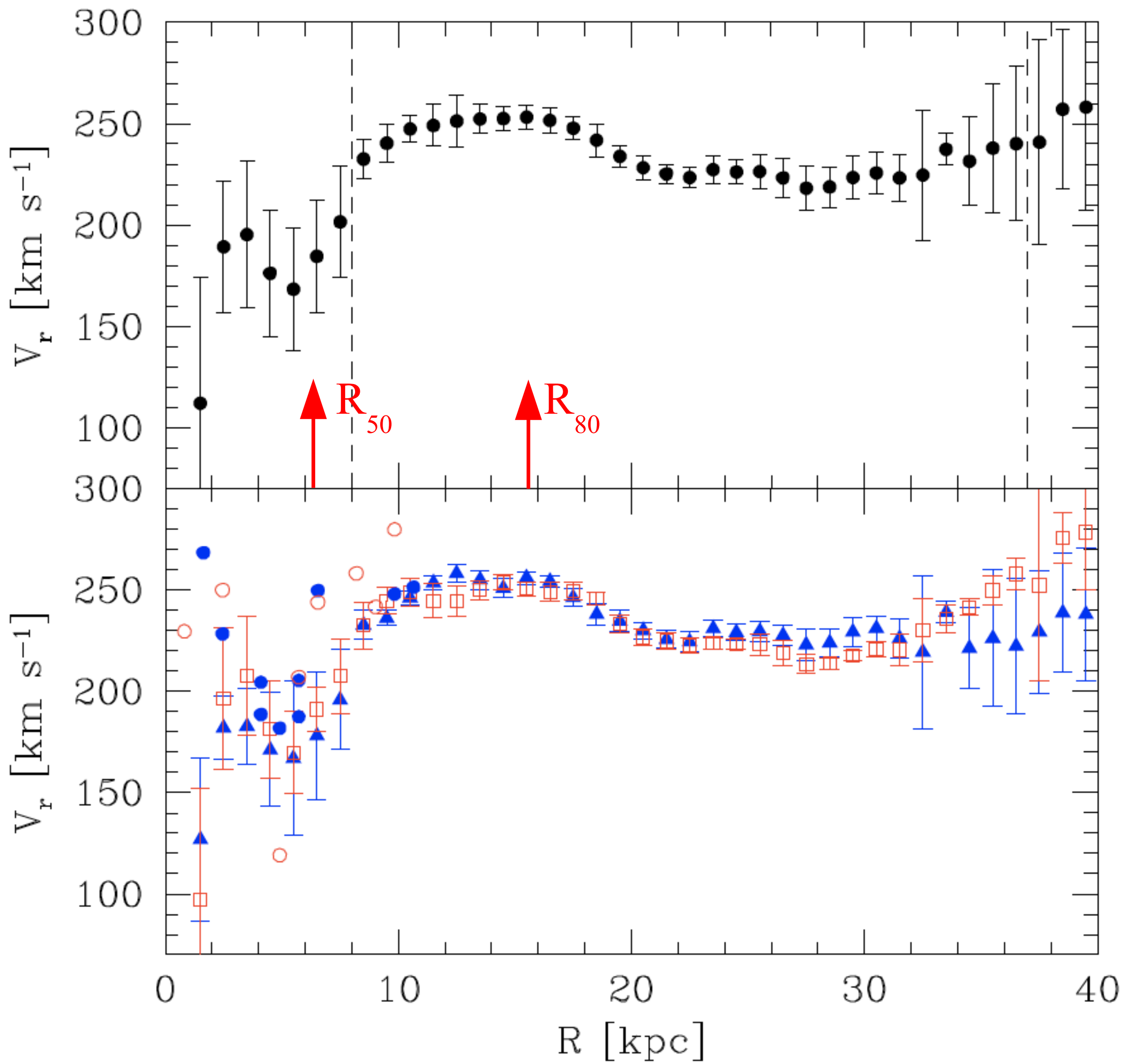
$$\boxed{M^* \geq 1.8 \times 10^{12} m_\odot ,} \tag{3}$$

which is six times larger than the reduced mass of M31 and the Galaxy.

A wide-field H I mosaic of Messier 31

II. The disk warp, rotation, and the dark matter halo

E. Corbelli[1], S. Lorenzoni[1], R. Walterbos[2], R. Braun[3], and D. Thilker[4]



WRST HI survey 2010

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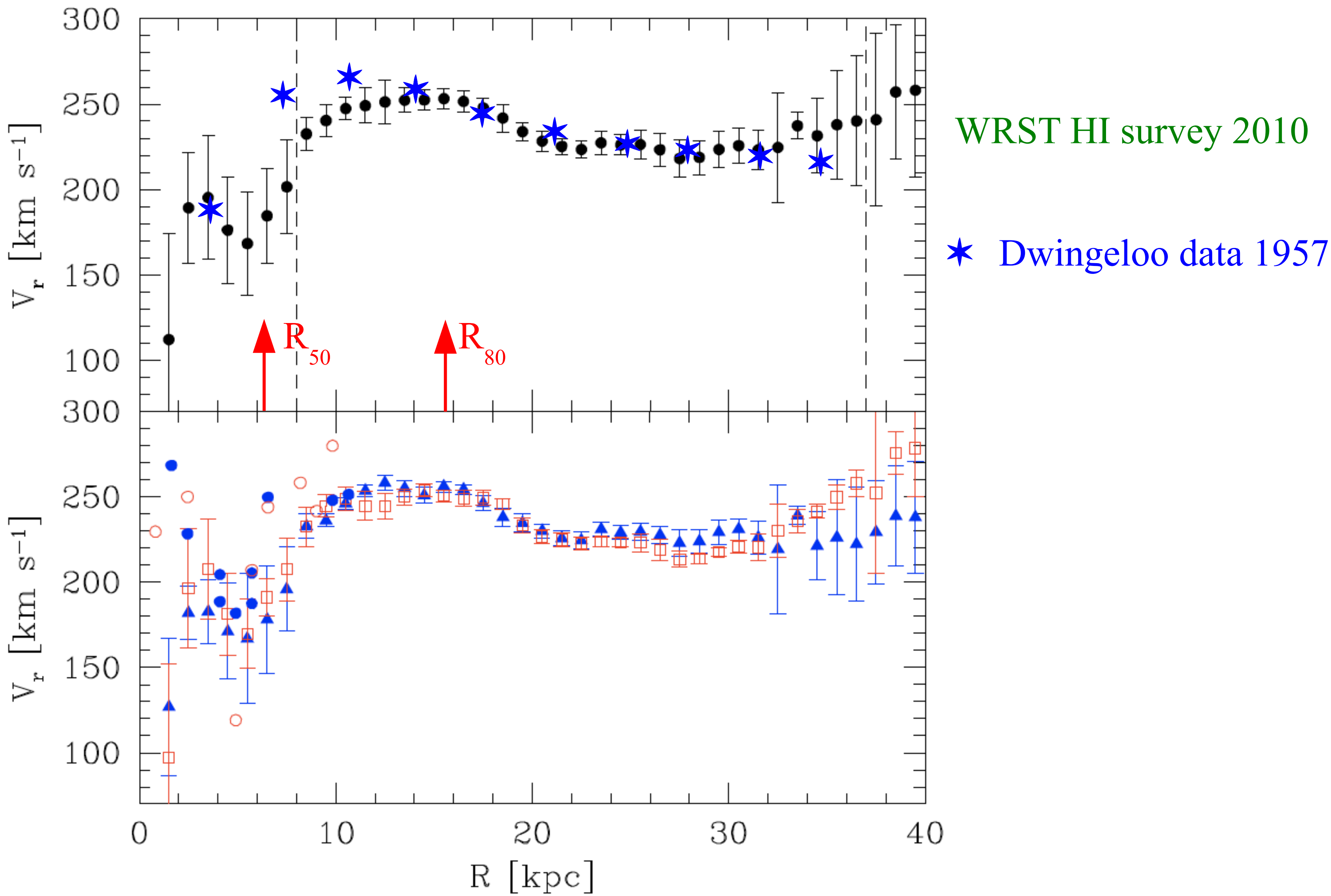


BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

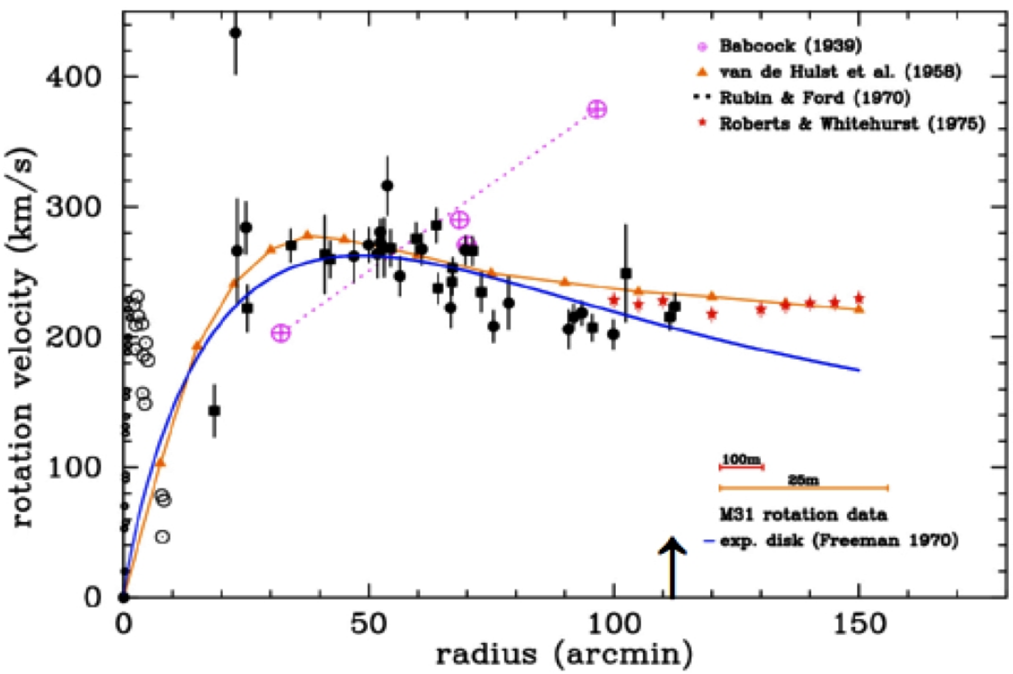
1957 NOVEMBER 9 VOLUME XIV NUMBER 480

COMMUNICATIONS FROM THE NETHERLANDS FOUNDATION FOR RADIO ASTRONOMY AND THE OBSERVATORY AT LEIDEN

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE

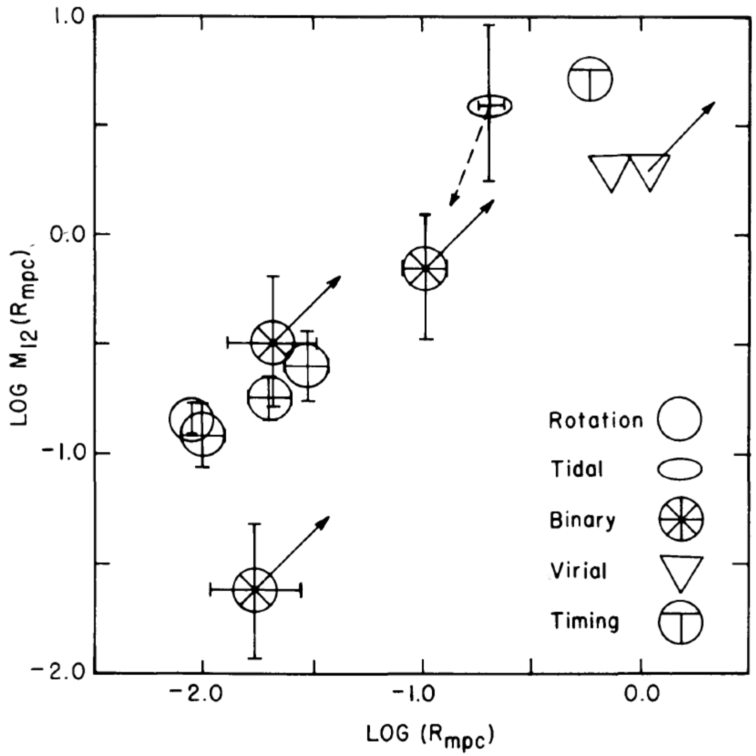
BY H. C. VAN DE HULST, E. RAIMOND AND H. VAN WOERDEN

The atomic hydrogen emission from the Andromeda nebula (M31) was observed with the 25-metre telescope at Dwingeloo; the beamwidth was 0°.6. Line profiles were measured at 20 points of the major axis (Figure 5). The mean error of the brightness temperature measured at one frequency in one direction was 0.2 to 0.3°K except in the frequency range contaminated by galactic foreground radiation. The line was observable to 2°.5 at either side of the centre. The central velocity with respect to the local standard of rest is − 296 km/sec. The velocity of rotation slowly falls from 278 km/sec at 0°.6 from the centre to 221 km/sec at 2°.5

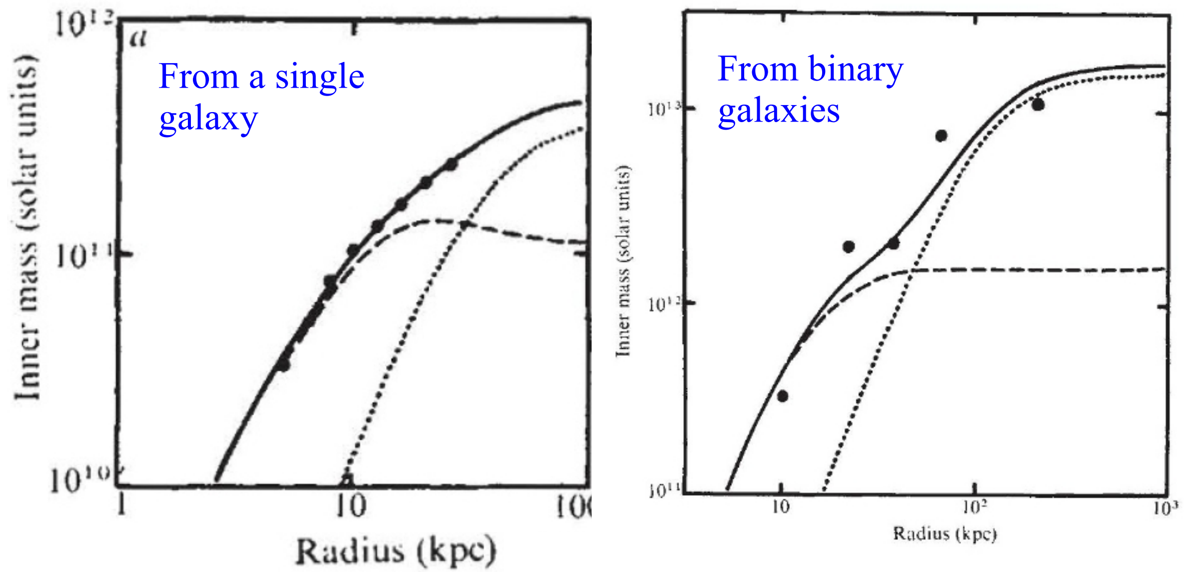


- Discovering flat rotation curve is usually credited to Rubin & Ford 1970 (optical) and Roberts & Whitehurst 1975 (radio)
- The 1957 Dwingeloo curve is at least as good and goes just as far
- In the following BAAN paper M.Schmidt showed variable M/L is needed in M31

J. P. OSTRIKER, P. J. E. PEEBLES, AND A. YAHIL
1974



J.EINASTO, A.KAASIK, AND E.SAAR
1974



- Extended dark matter halos became part of the mainstream in the 1970's

Ann. Rev. Astron. Astrophys. 1979. 17:135–87

MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES[1]

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1 INTRODUCTION

Is there more to a galaxy than meets the eye (or can be seen on a photograph)? Many decades ago, Zwicky (1933) and Smith (1936) showed that if the Virgo cluster of galaxies is bound, the total mass must considerably exceed the sum of the masses of the individual member galaxies; i.e. there appeared to be "missing mass" in the cluster.

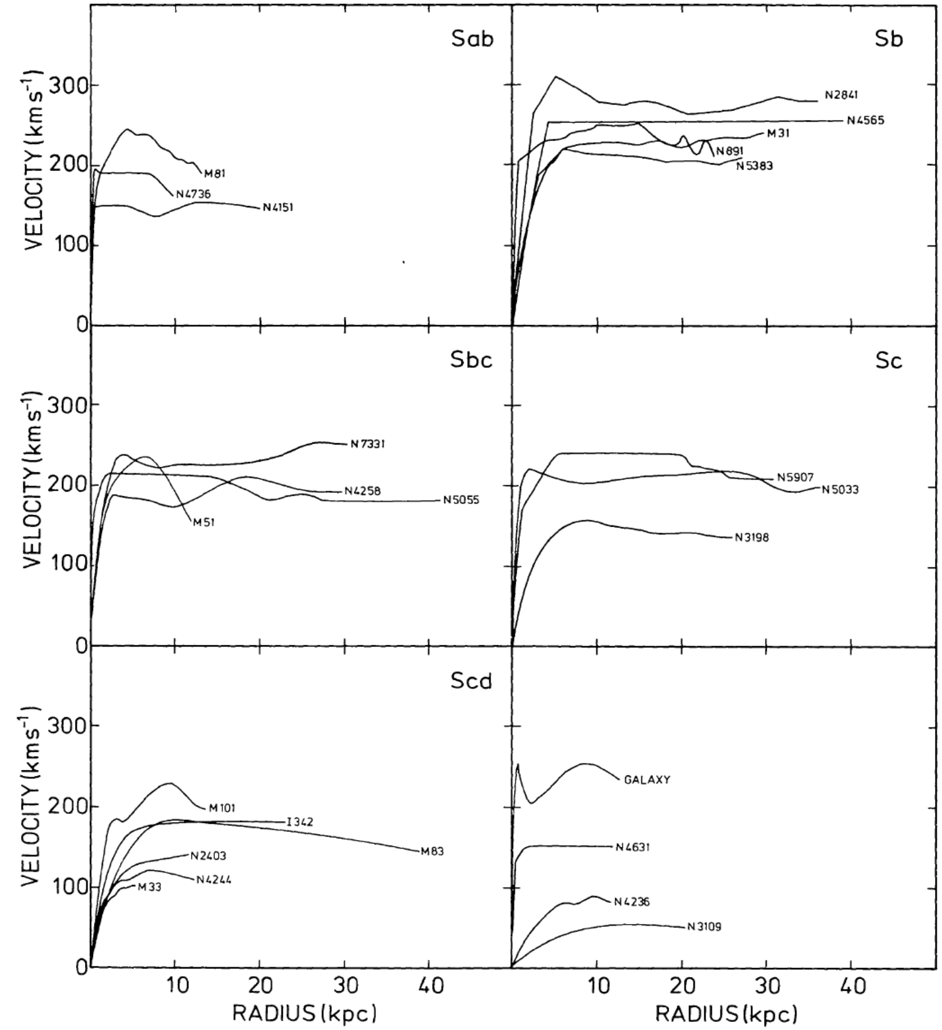


Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

- Extended dark matter halos became part of the mainstream in the 1970's
- Rotation curves were a small part of the justification (9/54 pages in F&G79)
- The rotation curves used were mostly 21cm, rather than optical

The emergence of non-baryonic dark matter

(See "Cosmology's Century", Chapter 7)

Gershtein & Zel'dovich (1966) – cosmology limits the masses of relic ν's from the BB

Marx & Szalay (1972-74)
+ – relic ν's might provide the mass to bind Coma
Cowsik & McLelland (1972-73)

Five papers in 1977 introduced <u>hypothetical</u> WIMPs which could be the dark matter
Hut; Lee & Weinberg; Sato & Kobayashi; Dicus, Kolb & Teplitz; Vysotski, Dolgov & Zel'dovich

Lubimov et al (1980) estimate 30 eV for the mass of ν_e from ^{3}H end-point decay

1981 – 83: Analytic arguments and then simulations demonstrate that **no** known neutral non-baryonic particle (i.e. no neutrino) could match large-scale structure

1983 – 85: Analytic arguments and then simulations show that CDM works better

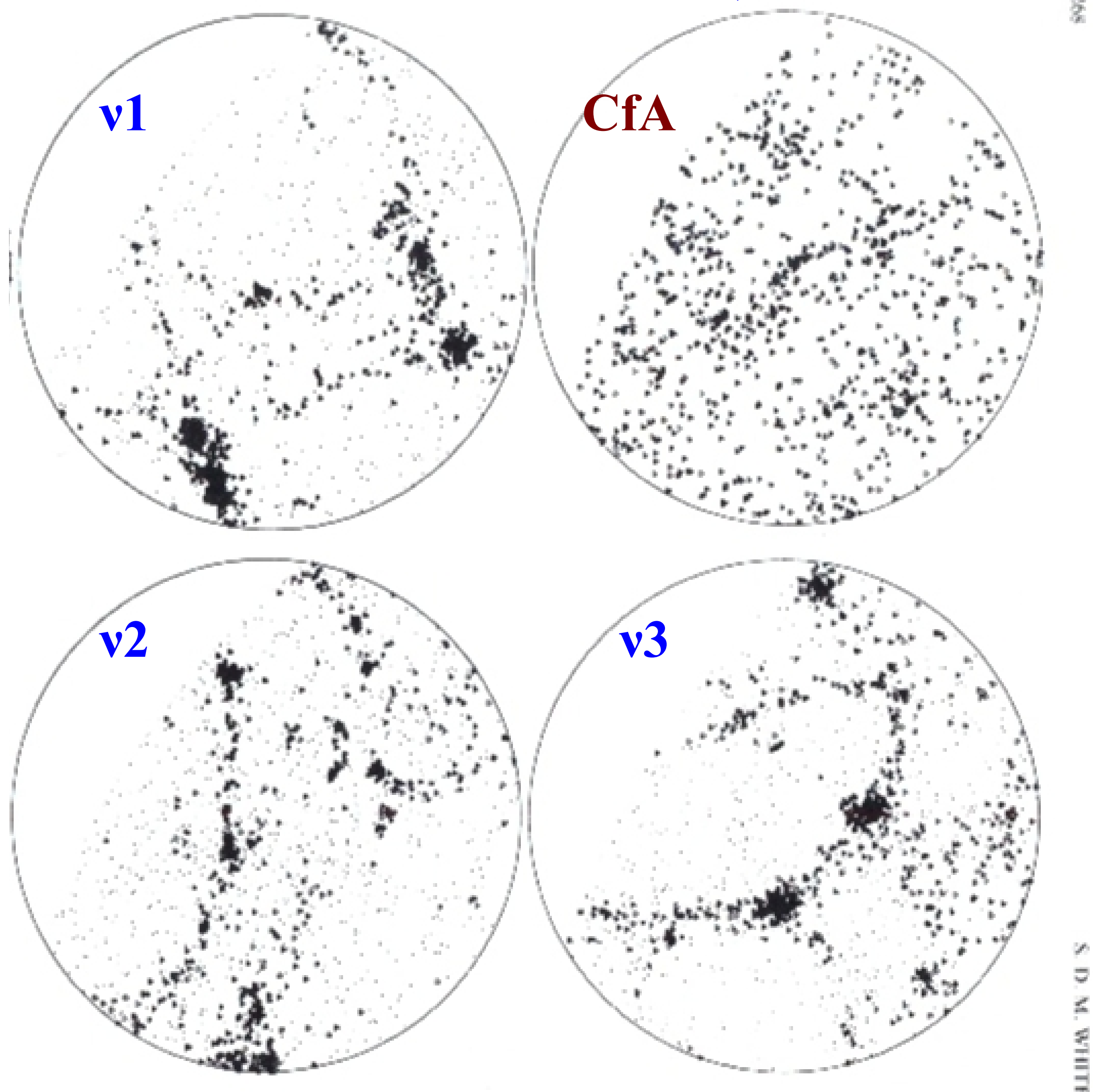
Could massive neutrinos be the Dark Matter?

Simulations assuming dark matter to be made of ν's and galaxies to form only in collapsed regions → LSS incompatible with observation for any cosmological parameters.

This excludes all known particles as possible DM

Direct mass bounds on the τ-neutrino only excluded it in 2006

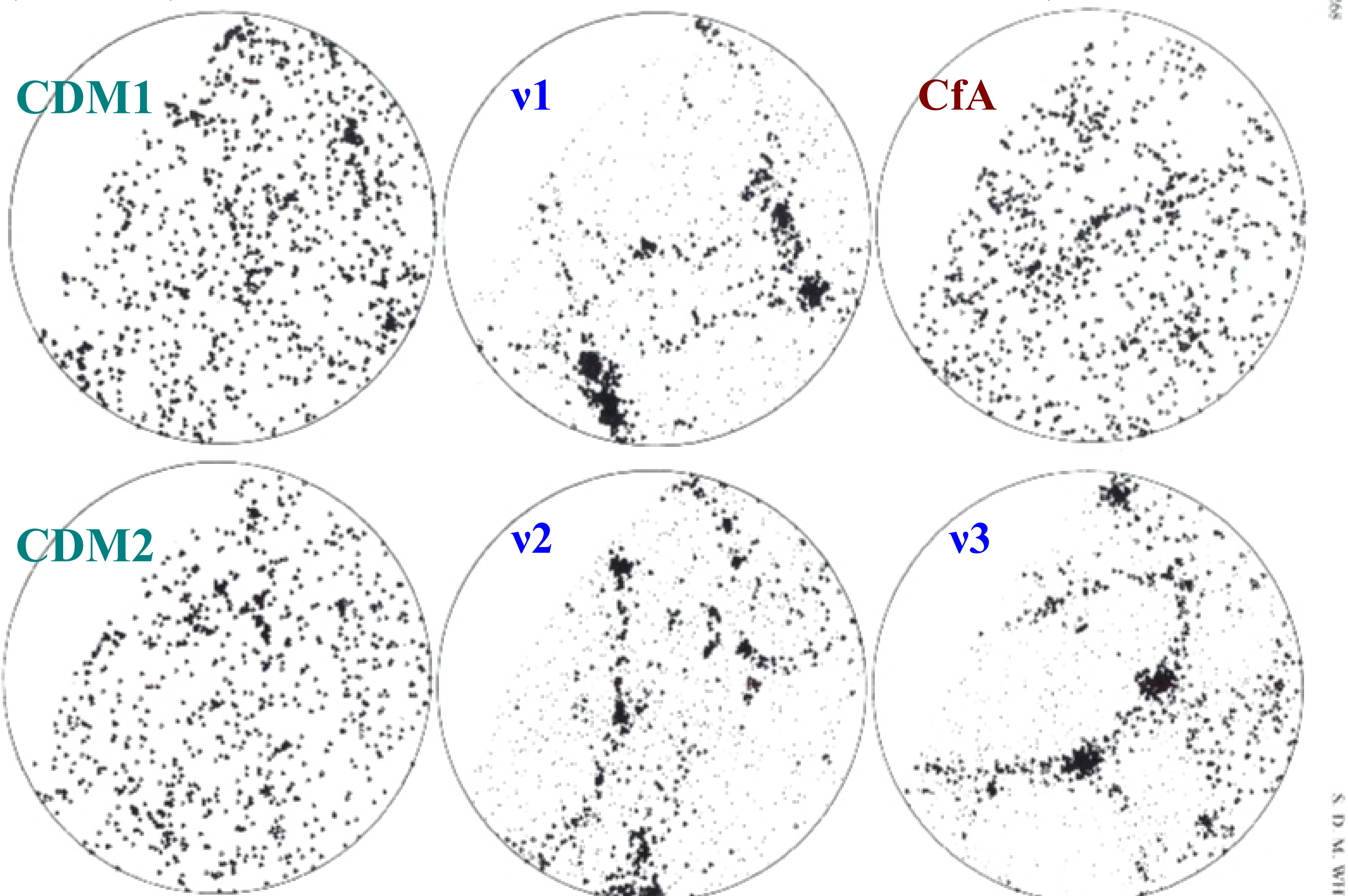
White, Frenk & Davis 1983



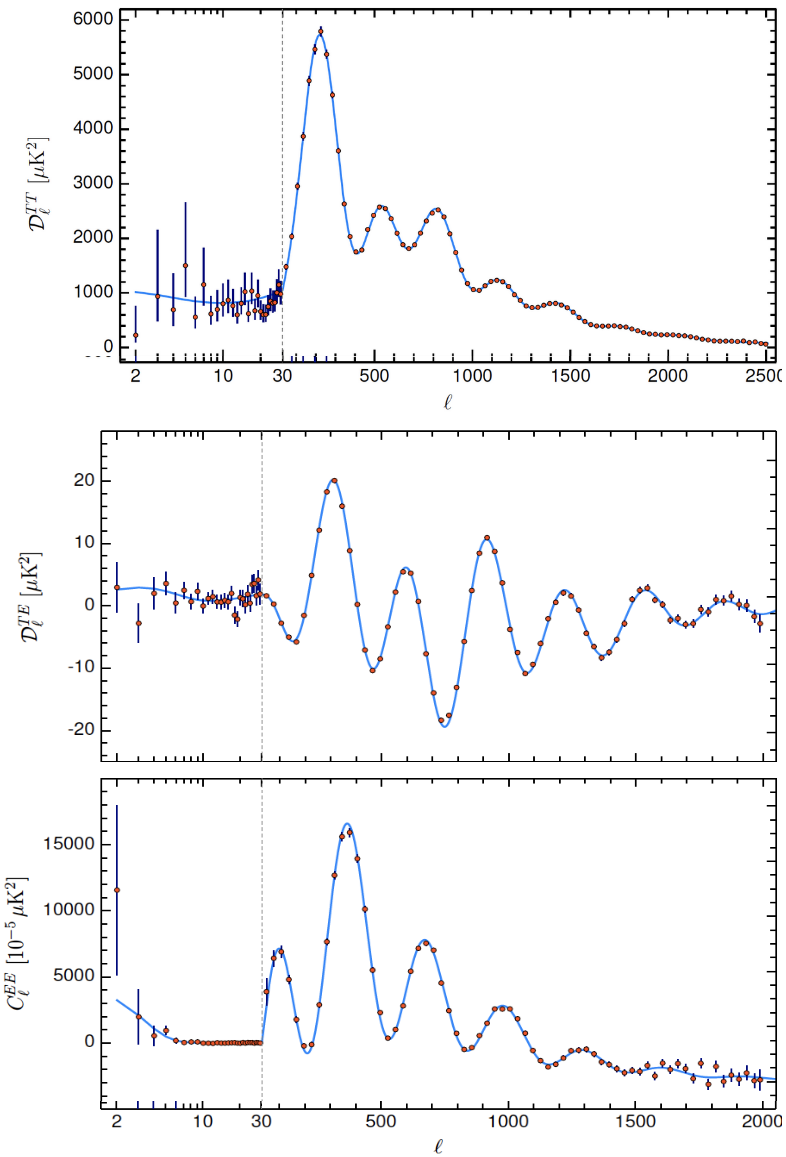
A new kind of particle, Cold Dark Matter, <u>is</u> possible

Davis, Efstathiou, Frenk & White 1985

White, Frenk & Davis 1983



Precise astrophysical evidence for dark matter?



Planck Collaboration 2018

Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061

- Results from a single instrument (Planck/HFI)
- No local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- No measurable primordial non-gaussianity
- Good fit to minimal 6-parameter ΛCDM
- Neutral, stable WIMPs required, but few other constraints on the nature of dark matter

Other astrophysical evidence on dark matter properties

- No confirmed evidence for DM annihilation or decay

  3.5keV line in clusters, γ-ray excess near the Galactic Centre...

- No experimental evidence for interactions with normal matter

  DAMA-Libra?

- No evidence for axion-like energy losses in the Sun, stars or exp'ts

- No evidence for astrophysically significant self-interactions

  Bullet cluster and analogues...

- No evidence for an astrophysically significant Compton wavelength

- Observed small-scale structure $\rightarrow$ $k_{hm} > 20$ h/Mpc, $M_{hm} < 10^8 h^{-1} M_\odot$

  Ly α forest, halos of dwarf galaxies, strong gravitational imaging, perturbations of stellar streams in the halo...