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How dark matter came to matter

A history of missing mass, 1930-1974

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4

HOW THE UNIVERSE WENT MISSING IN 1974

When you open a recent textbook on astrophysics you will surely find a treatment of flat rotation curves and the mass discrepancy in galaxy clusters. They are often presented as the cornerstones of our belief in dark matter. The flat rotation curves of galaxies signal the potential existence of mass in the seemingly empty galactic outskirts, and the rapid movement of galaxies within clusters hint that these systems can only exist if they are stabilized by hidden mass. With the power of hindsight it appears to be an obvious fact that these phenomena were *evidence* for dark matter. Yet, as has been illustrated in the previous chapters, historically it was far from *evident* what these observed phenomena signified within the practices from which they emerged. The solutions to the anomalies in galaxies and in clusters were found to be matters of taste, and so was their degree of relevance.

If this was the case, then how did evidence for dark matter take shape? How did it become evident that the rotation of galaxies and the movement of galaxies in clusters signalled an excess of mass? This has been the central question of this dissertation, and after three chapters we have finally come to a point to address it. In this chapter we trace how two independent observations were transformed from being curious anomalies to signifying evidence for the existence of unseen mass. In other words, it aims to understand how flat rotation curves and the problem of mass in clusters *came to matter*: how did they come to indicate the existence of a single type of unseen material that permeated the universe?

This chapter aims to show that dark matter came to matter in 1974. In this year, two papers were published in which rota-

tion curves and measurements of the stability of clusters were brought together to argue for the existence of yet-to-be-observed mass. In what follows we analyze these papers to show: (1) who these authors were; (2) what they did; and, (3) how evidence emerged through their activity. I show that these papers can be understood as part of the new physical approach to the cosmos that arose in the early 1970s: the papers are authored by a new generation of physicist-astronomers that combined different arguments from a variety of distance scales to give a single measure of the mass of galaxies and the universe – one that agreed with the possibility of a closed universe. This chapter then unfolds the parallel development of the current-day dark matter problem and modern cosmology.

4.1 A PRINCETON COLLABORATION

> "There are reasons, increasing in number and quality, to believe that the masses of ordinary galaxies may have been underestimated by a factor of 10 or more."[1]

In October of 1974, a paper appeared from a Princeton-based collaboration of astronomers and physicists that had a central role in dark matter's history. In the centennial issue of the Astrophysical Journal, the paper was listed among the 53 most influential astronomy papers of the 20th century. It marked "a watershed in our understanding of galactic structure, galaxy formation, and cosmology," the nominating review read.[2] The broad impact of the paper was due to the central point outlined in the paper's openings statement: in the paper, the authors argued that galaxies are much larger and massive than previously thought.

The lead author of the influential paper was Jerry Ostriker, a 37-year-old Princeton professor who was making a career as a prolific and outspoken astrophysicist. Ostriker had only recently

1 J. P. Ostriker, P. J. E. Peebles, and A. Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," *Astrophysical Journal* 193 (1974): L1.

2 Scott Tremaine, "Comments on Ostriker, Peebles, & Yahil (1974) "The Size and Mass of Galaxies, and the Mass of the Universe"," *Astrophysical Journal, Centennial Issue* 525C (1999): 1223.

become interested in issues concerning galaxies and cosmology. After obtaining his physics undergraduate degree from Harvard, he had moved to Chicago to do a Ph.D. under the direction of Subrahmanyam Chandrasekhar. Under supervision of Chandrasekhar, famed for his pioneering work on stellar astrophysics, Ostriker started to work on the physics and stability of stars. He finished his Ph.D. in 1964, went on to do a postdoc at the University of Cambridge, collaborating with Donald Lynden-Bell, and in 1965 was hired by the Princeton Department of Astrophysical Sciences. All the while, Ostriker worked on the physics of stars, and on the stability of rotating stars in particular.[3]

The properties of stars and their evolution had been one of the central research topics in astronomy since the 1930s.[4] Yet this focus was shifting in the 1960s, and so was Ostriker's interest. As discussed in the previous chapter, in the late 1960s a new generation of astronomers and physicists started to part ways with Hubble's classical cosmological endeavor – the ever-continuing search for redshifts of galaxies to determine the expansion of the universe and its deceleration. There was a rising "suspicion" of this tradition, Ostriker called it in an interview in 2014.[5] The suspicion had to do with the work of Beatrice Tinsley and others in the late 1960s, who were showing that the brightness of galaxies change as galaxies age. "[A]ll of a sudden we realized galax-

3 D. Lynden-Bell and J. P. Ostriker, "On the stability of differentially rotating bodies," *Monthly Notices of the Royal Astronomical Society* 136, no. 3 (1967): 293. For his work on the stability of rotating stars, see also e.g. J. P. Ostriker and J. W-K. Mark, "Rapidly rotating stars. I. The self-consistent-field method," *Astrophysical Journal* 151 (1968): 1075–1088. In Cambridge, Ostriker also became more exposed to topics in cosmology. Ostriker had a desk in Fred Hoyle's office – who apparently was not coming in due to a feud with others at the institute – and shared the space with radio astronomer Ken Freeman whom later would do influential work on the rotation curves of galaxies. See: Jerry Ostriker, interview with the author, November 10, 2014, Princeton, NJ.

4 Robert Smith for example noted in one of his papers that the "1920s, 1930s, 1940s, and even 1950s, [were] decades in which the properties of stars and their life histories had dominated the interests of astrophysicists in the United States and elsewhere." Smith, "Beyond the Galaxy: The Development of Extragalactic Astronomy 1885-1965, Part 1," 91.

5 Jerry Ostriker, interview with the author, 1 December 2014, Princeton, New Jersey.

Figure 55: Princeton University's Peyton Hall in 1966, where the Department of Astrophysical Sciences has been housed since 1966. Image courtesy of the Trustees of Princeton University.

ies have to evolve," Ostriker recalled.[6] And with this realization, Hubble's classic tests of cosmology were deemed unreliable.

This upheaval in the understanding of galaxies and their role in the universe had gained Ostriker interest too. By the time Ostriker became full professor at Princeton University, in 1971, he had turned his interests towards galaxies and their dynamics. He used his expertise in the evolution of stars to show how stellar processes, of white dwarfs in particular, could influence the total luminosity of galaxies during their lifetime.[7] Ostriker also became interested in extrapolating his research on the stability of

6 Jerry Ostriker, interview with the author, 10 November 2014, Princeton, New Jersey.

7 In 1968, Ostriker had already applied his knowledge of rotating white dwarfs to explain the physical mechanisms behind the recently observed pulsating stars, or "pulsars." See Jeremiah Ostriker, "Possible Model for a Rapidly Pulsating Radio Source," *Nature* 217, no. 5135 (1968): 1227–1228. From the theory of pulsars as rotating neutron stars, he started to work on the production of cosmic rays and x-rays from these sources. See for an overview of this Ostriker's interview with Chris Smeenk: Interview of Jeremiah P. Ostriker by Christopher Smeenk on 2002

rotating stars to galaxies: how do rotating galaxies maintain their stability during their lifetime? Ostriker himself lacked expertise on modeling galaxies, so to address this topic he "walked across the road to talk to Jim Peebles."[8]

Jim Peebles had come from Winnipeg in Canada to Princeton in 1958 to study physics. He started his career focused on particle physics, but eventually came to work with gravitational physicist Robert Dicke. Dicke, we saw in previous chapters, was a main character in the renaissance of general relativity and known for his unique approach to gravity physics in which he devised potential experiments to test different theories of gravity. Under supervision of Dicke, Peebles engaged with physical questions that concerned gravity and the cosmos. This included, for example, determining the thermal history of meteorites to test whether the gravitational constant was changing over time and observational tests of the possible existence of a Mach-like relation between the mass in universe and the fine structure constant.[9]

In 1964 Dicke suggested to Peebles to think about the consequences of an observable background of cosmic microwaves in the sky – a potential leftover of a hot and dense early stage of the universe.[10] A year later such a "cosmic microwave background" was observed. That same year, Peebles used the temperature of the microwave background to calculate the amount of helium created in a dense and hot "primeval fireball," and used this radiation to calculate how gravitational clustering of mass and the

May 14, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

8 Jerry Ostriker, interview with the author, 10 November 2014, Princeton, NJ.

9 P.J.E. Peebles, "The Eötvös experiment, spatial isotropy, and generally covariant field theories of gravity," *Annals of Physics* 20, no. 2 (1962): 240–260; J. Peebles and R. H. Dicke, "The temperature of meteorites and Dirac's cosmology and Mach's principle," *Journal of Geophysical Research* 67, no. 10 (1962): 4063–4070. For more on Robert Dicke and his approach to gravity, see Peebles, "Robert Dicke and the naissance of experimental gravity physics, 1957–1967." As discussed in chapter 3, gravitational physics was mostly a field of obscure mathematics until the mid-50s.

10 See interview with Jim Peebles in Alan P. Lightman and Roberta Brawer, *Origins: the Lives and Worlds of Modern Cosmologists* (Cambridge, MA: Harvard University Press, 1990), 214-231. For a detailed history on the discovery of the cosmic microwave background, see Oliver, ""The lucky start toward today's cosmology"? Serendipity, the "Big bang" theory, and the science of radio noise in Cold War America."

formation of galaxies began.[11] Through his work on the CMB, and by using it as a probe to understand the physical processes in the evolving universe, Peebles was one of the pioneers of the physical approach to cosmology.

In the late 1960s, Peebles became particularly interested in the formation of structure in the universe, or "how matter would tend to gather together in an expanding universe [through] gravitational instability," as he would recall in 2014.[12] Between 1967 and 1970, Peebles published on modeling the formation and evolution of galaxies, clusters of galaxies, and globular star clusters. Another interest of his was the mass density in the universe. Together with a Princeton post-doc, Bruce Partridge, Peebles had calculated the mass density due to galaxies in 1967.[13] A massive 64-page chapter on the contents of the universe was included in his famous textbook *Physical Cosmology*, published in 1971 – also covering Ambartsumian's "stability problem" in galaxy clusters.[14]

When Jerry Ostriker walked into Peebles' office at the Princeton Department of Physics, the young Peebles had just returned from a sabbatical at Caltech and the Los Alamos Scientific Laboratory nuclear research facility. Despite being a Canadian citizen, Peebles had been invited to spend some time at the theory group of Los Alamos.[15] The lab at Los Alamos had been involved in the Vela Satellite Program, a program to launch satellites in orbit to detect potential nuclear detonations in space (see Figure 56). In 1969, it appeared that one of the satellites had detected an energetic flash of gamma radiation of which the origin was unknown (later to be recognized as the first detection of a gamma

11 P. J. E. Peebles, "The Black-Body Radiation Content of the Universe and the Formation of Galaxies.," *Astrophysical Journal* 142 (1965): 1317; Peebles, "Primeval Helium Abundance and the Primeval Fireball."

12 Jim Peebles, interview with the author, 13 November 2014, Princeton, NJ.

13 Peebles and Partridge, "Upper Limit on the Mean Mass Density due to Galaxies."

14 Peebles, *Physical Cosmology*, 64.

15 Jim Peebles, interview with the author, 13 November 2014, Princeton, NJ. As Peebles recalled: "I was Canadian at the time—an alien. So, I wasn't allowed inside the second gate to the complex, but I was allowed inside the first, and was allowed to use their very fancy computers."

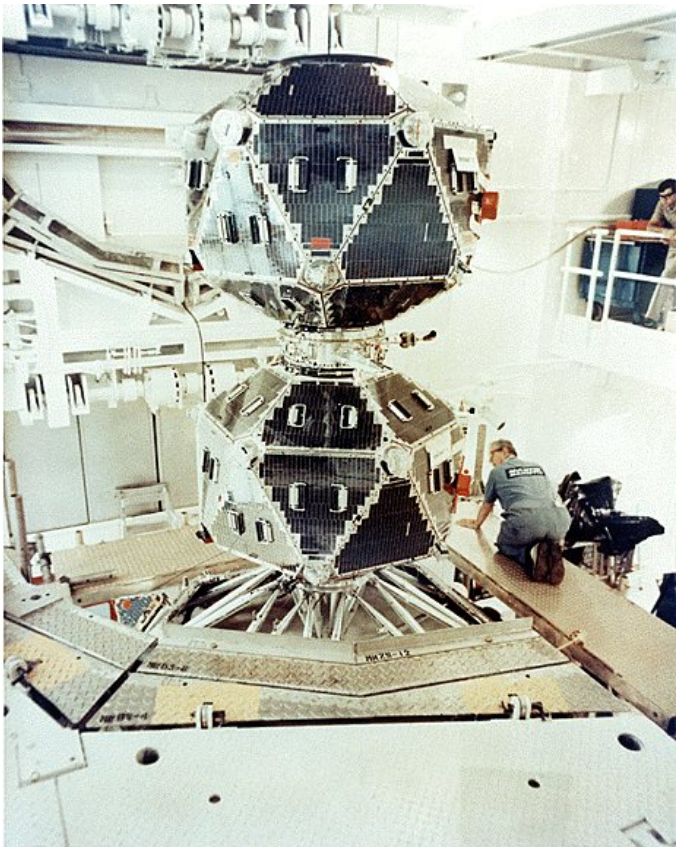


Figure 56: The Vela 5A and 5B satellites, prior to their launch in 1969. These satellites would split after launch, each covering one of earth's hemispheres. On board were x ray, gamma ray, and neutron detectors to detect potential nuclear detonations. The first of the satellites were launched in 1963, as a response to a recent treaty that banned nuclear testing in space and the atmosphere. By 1973, the Vela 5 and Vela 6 satellites had detected 16 events that showed the existence of highly energetic bursts of gamma radiation in the sky. The origin of such bursts are currently attributed to the collapse of matter into black holes. See e.g. Bonnell & Klebesadel (1996). Image courtesy of Los Alamos National Laboratory.

ray burst).[16] Inviting Peebles to discuss the potential cosmological origins of this source was an obvious choice. He took advantage of the occasion to use the lab's advanced computing system – normally used to model nuclear weapons and the propagation of explosions – to do one of the first simulations of the formation and evolution of galaxy clustering in the universe. It showed how a homogeneous distribution of mass would increasingly grow clumpy under gravity.

Peebles' expertise on galaxy formation and numerical simulations had interested Ostriker in a collaboration. Ostriker's idea was simple: to check the stability of a rotating galaxy (a disk of stars), as he had also done with the stability of a rotating star. The philosophy of the project was in line with the work of Tinsley and others: to scrutinize the idea that galaxies are stable unchanging objects and investigate their evolution.[17] "[W]e could readily test [Ostriker's idea] by doing n-body simulation which I knew how to do, so I banged out some n-bodies," Peebles said in an interview.[18] They performed numerical computations containing 150 to 500 mass points in a rotating disk to simulate the Milky Way (see Figure 57). With their model they found that such a rotating disk was "rapidly and grossly unstable."[19] Their simulations showed that only when galaxies had a particular critical ratio of rotational kinetic energy (T_{rot}) to gravitational energy

16 Ray W. Klebesadel et al., "Observations of Gamma-Ray Bursts of Cosmic Origin," *The Astrophysical Journal* 182 (1973): L85.

17 There seemed to have been a more direct link between the interests of Peebles and Ostriker. In a 1969 paper, Peebles had calculated the angular momentum of galaxies, where he noted that actual galaxies were much more oblate than his model had shown. P. J. E. Peebles, "Origin of the Angular Momentum of Galaxies," *Astrophysical Journal* 155 (1969): 393. In a 1984 interview, Peebles recollected the following: "I had written a paper on angular momentum of galaxies. I had obtained what I thought was a pretty reliable estimate of the specific angle of momentum. It required that a good deal of the mass in a spiral galaxy be not in the disk but the halo, because otherwise you didn't have enough angular momentum per unit mass," Interview of Jim Peebles by Martin Harwit on 1984 September 27, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

18 Interview of Jim Peebles by Martin Harwit on 1984 September 27, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

19 J. P. Ostriker and P. J. E. Peebles, "A Numerical Study of the Stability of Flattened Galaxies: or, can Cold Galaxies Survive?," *The Astrophysical Journal* 186 (1973): 467.

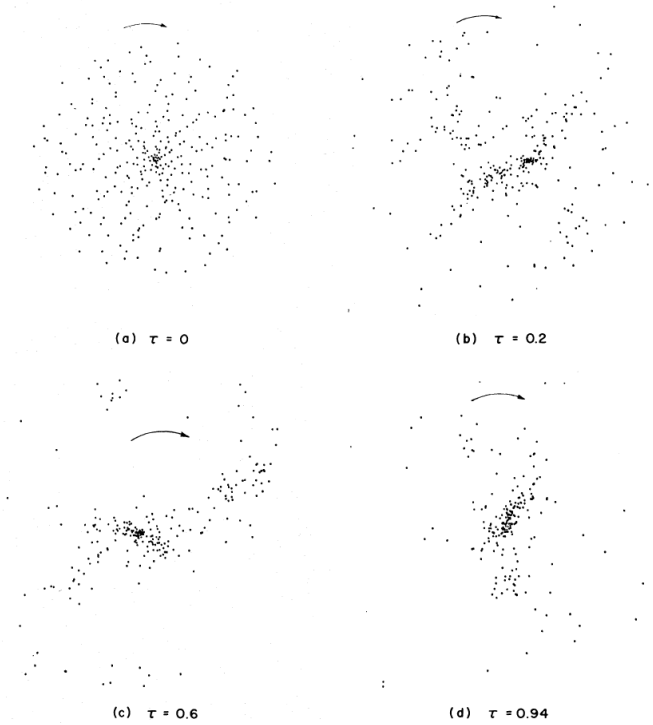


Figure 57: The evolution of a rotating galaxy as modeled by Ostriker and Peebles (1973). It illustrates that a rotating disk of stars is unstable: it does not retain its disk structure when it rotates. The graphs show the positions of "stars" (mass points) projected onto the plane of the galaxy at four instants. The parameter τ is a measure of time. When $\tau = 1$, the outermost particles in the original disk have completed one orbit. In their model of the evolution of a galaxy, Ostriker and Peebles find "(barlike) instabilities" (p. 467) as time increases. Their proposed solution was to have a large percentage of the mass of the system distributed in the spherical component ("halo") instead of the disc. In: J. P. Ostriker and P. J. E. Peebles, "A Numerical Study of the Stability of Flattened Galaxies: or, can Cold Galaxies Survive?," *The Astrophysical Journal* 186 (1973): 474.

(W), they remained stable. Their new stability criterion said that $T_{rot}/W = 0.14$.

The Milky Way galaxy, they knew, did not abide to their new criterion and had too much rotational energy. To make sense of how such a "cold" galaxy like the Milky Way would survive – referring to the fact that they had little heat-like random motions of stars – Ostriker and Peebles added a spherical component of mass to their model. This spherical component, at a radius interior to the disk, would increase the potential energy of the system and could make $T_{rot}/W = 0.14$. If a large part of the measured mass of a galaxy resides in such an "halo", Peebles and Ostriker concluded, the violent instability was suppressed.[20] In August of 1972, Ostriker and Peebles presented their conclusion at the 138th meeting of the American Astronomical Society (AAS) in East Lansing, Michigan. Their abstract read:

> "[Our] arguments lead to the conjecture that more than half of the mass of the galaxy is in the spherical halo, which has a large mass-to-light ratio, its mass most likely residing in extremely numerous M dwarfs."[21]

Their conclusion was controversial. Researchers studying the dynamics of galaxies were reluctant to embrace Ostriker and Peebles' new criterion for stability and the necessity of a halo for stabilization. "[T]he T/W business [was] kind of baloney," according to Allar Toomre, who had previously worked on models of gaseous disks and their stability, introducing the "Toomre stability criterion" in 1964.[22] Richard Miller was also reluctant to accept the need for a stabilizing halo. Miller, an astrophysicist at

20 Note that their conclusion was not that galaxies should be more massive, but that the mass should be distributed more spherical. Ostriker summarized: "the picture we have of the galaxy – *inside* the galaxy – must be wrong, and the spherical component must be a larger fraction of the total. It didn't change the mass of the galaxy at all," Ostriker, in Lightman and Brawer, *Origins: the Lives and Worlds of Modern Cosmologists*, 274.

21 J. P. Ostriker and P. J. E. Peebles, "Is the Mass of the Galactic Halo Greater than the Mass of the Disc?," *Bulletin of the American Astronomical Society* 4 (1972): 317. An M dwarf is a type of low-mass, low-luminosity star.

22 Alar Toomre, Interview with the author, 9 December 2014; Alar Toomre, "On the gravitational stability of a disk of stars," *Astrophysical Journal* 139 (1964): 1217–

the Institute for Computer Research at the University of Chicago, together with Kevin Prendergast, then at Columbia University, pioneered computer models of the dynamics of galaxies in the late 1960s.[23] "The paper of Ostriker and Peebles is based on maintenance of stability in an axisymmetric system," Miller pointed out during a conference in 1973, "but no-one believes that our Galaxy is axisymmetrical."[24] Miller's point was that non-axisymmetric systems might be more stable. He also noted there could exist many other mechanisms that would potentially cause stability in galaxies.[25]

Ostriker and Peebles' numerical work on an invisible halo surrounding galaxies, albeit controversial in the long run, impressed a young Israeli postdoc who attended the AAS meeting in 1972. His name was Amos Yahil, and it was one of the first astronomy conferences that he attended. Yahil, who had studied physics at the Hebrew University in Jeruzalem, had just obtained his Ph.D. in elementary particle physics at Caltech in 1970. Although he was not unsuccessful as a particle physicist, Yahil "wasn't happy with the field."[26] Under guidance of his Caltech acquaintance John Bahcall, Yahil made a switch to astrophysics. Bahcall, who had just been offered a professorship at the Institute for Advanced Study in Princeton, proposed to Yahil to join him as a postdoc there in 1971.

1238. Groningen astronomer Albert Bosma also recalled that "it was not clear whether the criterion really was universal, so it wasn't received very well." Albert Bosma, interview with the author, 24 July 2014, Amsterdam, the Netherlands.

23 R. H. Miller, K. H. Prendergast, and William J. Quirk, "Numerical Experiments on Spiral Structure," *The Astrophysical Journal* 161 (1970): 903.

24 Miller, in Freeman, "The Early History of Our Galaxy: Dynamics (invited Paper)," 137.

25 The conclusion of Ostriker and Peebles remained controversial. In a 1977 review on the topic of galaxy dynamics, Toomre wrote: "the *need* for proper halos has still not been established firmly in our subject–though this is neither to imply that they would be unwelcome, nor to dispute the growing evidence from flat rotation curves (cf Roberts 1975, Krumm & Salpeter 1977)." Alar Toomre, "Theories of Spiral Structure," *Annual Review of Astronomy and Astrophysics* 15, no. 1 (1977): 469. Frank Hohl, of NASA's Langeley Research Center did support that halos could help with stability in galaxy simulations. F. Hohl, "Suppression of bar instability by a massive halo.," *Astronomical Journal* 81, no. 1 (1976): 30–36.

26 Amos Yahil, online interview with the author, 23 May 2020.

In his switch to astrophysics, Yahil used his physics background to engage with one of Hubble's classic cosmological problems: determining the cosmic rate of expansion. In particular, Yahil had learned from Neta Bahcall, astronomy postdoc at Caltech and John's spouse, about the possibility that clusters of galaxies could be used as "standard yardsticks" – objects that have a known luminosity which makes it easy to compute their distance – to help understand the evolution of the universe.[27] But Yahil's attention was quickly drawn to a different cosmological parameter: the mass density of the universe. When he engaged with Neta Bahcall's model for the mass profile of clusters, he was skeptical: where Bahcall had introduced a cut-off point to the mass of clusters in her model, Yahil observed that cluster mass had no sudden cut-off. Instead, he argued, the density of clusters kept falling off inversely squared to its radius – which meant that masses of clusters kept increasing linearly with radius.[28] This idea, Yahil wrote, "can provide serious theoretical constraints on the mass density of the Universe."[29]

After hearing Ostriker and Peebles' talk in 1972, Yahil was inspired to extrapolate his idea of clusters to galaxies: perhaps similar to clusters, galaxies too have no point where their mass suddenly ends. Galaxies might be much more extensive. Shortly after the conference, in the fall of 1972, Yahil sent Jerry Ostriker a draft of his paper on clusters of galaxies in which he had included a tentative paragraph on galaxies, showing that there might be signs that "[galaxy] masses increase linearly with size."[30]

Ostriker, who was on sabbatical in Berkeley that year, was thinking along similar lines. In their 1973 paper on massive galactic "halos", Ostriker and Peebles had argued that a large part of the galaxy resides in a spherical component. In 2014, Ostriker recollected being inspired by the consequences of this idea: "if

27 Amos Yahil, online interview with the author, 23 May 2020; and see Amos Yahil, "The Density Profiles of Rich Clusters of Galaxies," *The Astrophysical Journal* 191 (1974): 623.

28 If the density is inversely related to the square of the radius ($\rho \sim r^{-2}$), and mass grows as density times radius to the third ($M \sim r^3 \rho$), mass increases linearly with radius ($M \sim r$).

29 Yahil, "The Density Profiles of Rich Clusters of Galaxies," 630.

30 Ibid.

the disk doesn't dominate [the mass of a galaxy's] interior, then maybe it doesn't dominate exterior either."[31] Perhaps it could be that the spherical dark component increasingly dominates the mass in the outer edges of a galaxy. It was the start of a collaboration between Ostriker and Yahil, and Ostriker soon arranged a second postdoc position for Yahil, this time at Princeton University.

Inspired by their ideas on extended galaxies, Ostriker and Yahil started to work together on the mass of galaxies. Yahil left for Israel in November 1973, and Ostriker presented an early draft of their research at the 141st American Astronomical Society meeting in Tucson, Arizona, in December of 1973. The abstract stated that they presented "evidence that the total mass of spiral galaxies increases almost linearly with the radius."[32] After Yahil left, Ostriker asked Peebles to join the project – "I agreed to have my name on it," Peebles recollected.[33] Their paper was submitted in May of 1974 and bore the name "The Size and Mass of Galaxies, and the Mass of the Universe."

4.2 "THE SIZE AND MASS OF GALAXIES"

The gist of the four-page paper by the Princetonians was quite straightforward: observations showed that the masses of galaxies are about ten times larger than was previously thought. "[A]vailable evidence", Ostriker, Peebles and Yahil wrote, "indicates that the measured masses of galaxies diverge with increasing distance [...]."[34] The paper substantiated the hunch that both Yahil and Ostriker already had, that the mass of galaxies kept increasing even on its outskirts. They did so by putting together a variety of already-existing observations from different studies that gave a measure of the mass of galaxies.

31 Jerry Ostriker, interview with the author, 2014, Princeton, New Jersey.

32 J. P. Ostriker and A. Yahil, "The mass of galaxies and the density of the universe," *Bulletin of the Astronomical Society, Vol. 6, p. 262* 6 (1974): 262.

33 Interview of Jim Peebles by Martin Harwit on 1984 September 27, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

34 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L1.

TABLE 1

$M(r)$ FOR SPIRAL GALAXIES

Object	#	$\log_{10}(R_{\mathrm{Mpc}})$	$\log_{10}(M_{12})$	Method
1. Galaxy	1	$-2.05\pm?$	-0.84 ± 0.07	Rotation
2. Local giants	3	-2.00 ± 0.10	-0.92 ± 0.14	Rotation
3. Field doubles	20	-1.77 ± 0.20	-1.62 ± 0.30	Binary
4. Virgo doubles	23	-1.68 ± 0.20	$-0.5\ \pm0.3$	Binary
5. Local giants	3	-1.69 ± 0.10	-0.74 ± 0.10	Rotation
6. Local giants	3	-1.52 ± 0.10	-0.60 ± 0.16	Rotation
7. Dwarf spheroidals	3	-1.14 ± 0.04	-0.60 ± 0.55	Tidal
8. Field doubles	9	-0.98 ± 0.11	-0.15 ± 0.32	Binary
9. Dwarf spheroidals	3	-0.69 ± 0.03	$+0.59\pm0.35$	Tidal
10. M81 group	7	$-0.15\pm?$	$+0.30\pm?$	Virial
11. M31 group	6	$-0.22\pm?$	$+0.72\pm?$	Timing
12. Local groups	200	$+0.04\pm?$	$+0.30\pm?$	Virial

Figure 58: Table used by Ostriker, Peebles, & Yahil (1974: L2). It shows the mass of galaxies ($\log_{10} R_{\mathrm{Mpc}}$) measured at increasing radii ($\log_{10} M_{12}$) as determined by different methods by several authors. The entry under # is not explained in the text but seems to indicate the number of galaxies that were involved in determining the values in that row. M_{12} is $10^{12} \times M_{\odot}$, the mass of the sun.

The literature they used was diverse, and represented several orders of magnitude in scale, from kiloparsec to megaparsec. They used twelve measurements of mass in total for their study, and neatly ordered them in the table that is reproduced in Figure 58. At the heart of their paper was a diagram in which all these measurements on different scales were combined. The diagram is reproduced in Figure 59. This logarithmic plot showed the different measurements of galactic mass as a function of the distance to the galactic center, and hence illustrated how galactic mass was related to radius. The diagram, the authors argued, showed that the mass of a galaxy kept increasing as the mass is measured increasingly further away from its center.

It would be wrong to assume that the mass determinations that were used by Ostriker, Peebles and Yahil spoke for themselves. They did not. And that is the central point of this chapter: in Ostriker, Peebles and Yahil's paper existing observations came to function as obvious evidence for unseen mass. To understand this, we will have to discuss the details of this paper and see how the authors tinkered with different arguments, scales and determinations of mass.

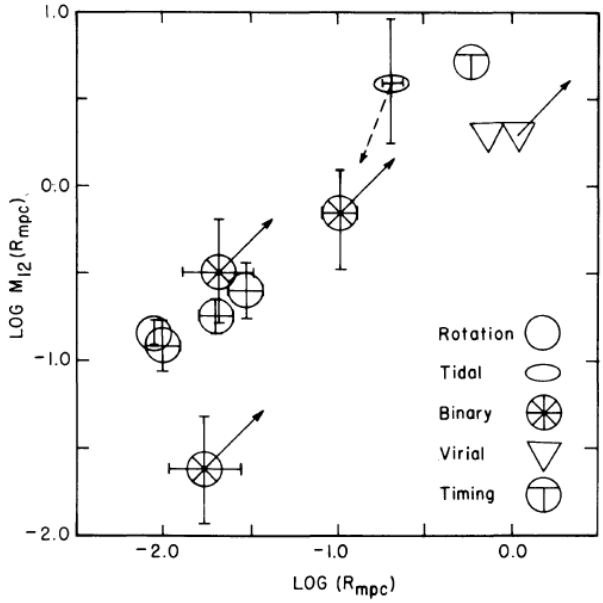


Figure 59: Diagram used by Ostriker, Peebles and Yahil (1974) to illustrate the increase of mass of galaxies with their radius. The mass is given in units of 10^{12} solar masses (2×10^{30} kg) and the radius in Megaparsec (3×10^{22} m). The diagram is a log-log plot. It shows the linear increase of mass with radius "as determined by various methods" (p. L2). These methods are portrayed by the different icons: rotations of galaxies, tidal movement of dwarf galaxies, binary systems of galaxies, groups of galaxies ("virial"), and the timing of approaching galaxies. These measurements all neatly fit in a single diagram. The optically visible mass in galaxies extended to about 10 kpc (0.01 Mpc), "-2.0" in the figure. The solid arrows indicated the value if the Hubble constant was half of what they had assumed (H=50 instead of H=100). The dashed arrow determines where the mass measurement of dwarf systems would be if they would not assume the orbits are circular, but "highly eccentric" (p. L3). From: Ostriker, Peebles & Yahil (1974, L2).

For the smallest scales – that of galaxies (~10 kpc) – Ostriker, Peebles and Yahil obtained their data from radio astronomical measurements of the rotation of galaxies. They used the 1973 study by Morton Roberts and Arnold Rots of three nearby galaxies, M31, M81 and M101. This was the paper in which Roberts and Rots concluded that "the three galaxian rotation curves decline slowly, if at all," and their results signalled a "significant mass density" in the outer edges of these galaxies.[35] Although Roberts and Rots used different mass distribution models and made a distinction between the different structural types of galaxies, Ostriker, Peebles and Yahil used little of these details: three masses are given at 10, 20 and 30 kpc, with 0.12, 0.18 and 0.25 $\times 10^{12}$ solar masses respectively (entries 2, 5, and 6 in Figure 58).[36]

For scales slightly larger than those of galaxies (~30 kpc), the authors used mass measurements of *double systems*: two galaxies rotating around each other. The mass of double systems can be calculated from how fast the galaxies rotate around each other, assuming circular orbits and using Newtonian mechanics. Such calculations had existed for a while, and Ostriker, Peebles and Yahil used studies by Thornton Page and Sidney van den Bergh from the early 1960s (respectively entries 3 and 4 in Figure 58).[37] Interestingly, Page's estimates gave 0.02×10^{12} solar masses for the mass of spiral galaxies, a result that was in opposition with the mass estimates of galactic rotation at the same distance scale. This difference is not addressed in the paper. "[B]asically we thought Page's result was wrong, but we didn't know why," Yahil men-

35 Roberts and Rots, "Comparison of Rotation Curves of Different Galaxy Types," 484.

36 A peculiar detail, is that Ostriker, Peebles and Yahil used different measured radii for the "local giants" (M31, M81 and M101) as that Roberts and Rots did. They e.g. used 10 kpc for what seems to be M81. Why the measurement of this mass would be at 10 kpc and not at 30 as the study of Roberts and Rots indicated, is unclear.

37 Thornton Page, "Average Masses of the Double Galaxies," in *Proceedings of the Fourth Berkeley Symposium on Mathematical Statistics and Probability, Volume 3: Contributions to Astronomy, Meteorology, and Physics. June 20-July 30, 1960.*, ed. Jerzy Neyman (Berkeley, 1961); Sidney van den Bergh, "An Analysis of the Radial Velocities of Galaxies in the Virgo Cluster," *Monthly Notices of the Royal Astronomical Society* 121, no. 4 (1960): 387–391.

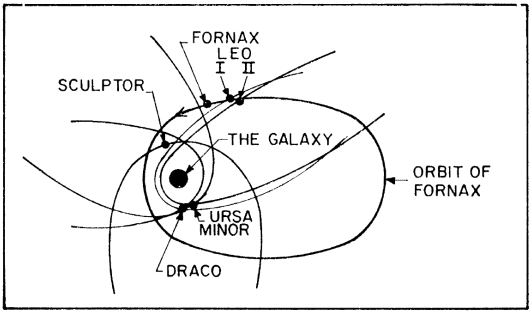


Figure 60: Representation of the probable configuration of dwarf galaxies and their orbits by Paul Hodge in 1966. Ostriker et al. calculated the mass interior to the perigalacticon, the closest point of passage, by using principles of tidal dynamics. Many other details of Hodge's research were irrelevant for Ostriker, Peebles and Yahil, including the specific configuration of dwarf galaxies around the Milky Way given in this image. In: Paul W. Hodge, "Radii, Orbital Properties, and Relaxation Times of Dwarf Elliptical Galaxies," *The Astrophysical Journal* 144 (1966): 872.

tioned in a 2020 interview.[38] Van den Bergh's results on double systems in the Virgo cluster were deemed too high, and Ostriker, Peebles and Yahil "conservatively" removed some data points from his study and recalculated his mass values (0.3×10^{12}).[39] Another data point is based on a selection of data from an unpublished study of Princeton astronomer Bernard Jones (entry 8 in Figure 58).

For yet larger distances, the authors used studies of dwarf galaxies. These are small satellite galaxies in orbit around a larger galaxy. Ostriker, Peebles and Yahil used a study by Paul Hodge, astronomer at the University of Washington, from 1966 (entries 7 and 9 in Figure 58). Hodge's 1966 paper was a study of the properties and orbits of satellite galaxies around the Milky Way, and therefore only a minor part of Hodge's research was of interest

38 Amos Yahil, online interview with the author, 4 May 2020
39 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L2.

to Ostriker, Peebles and Yahil (see Figure 60). Moreover, Hodge's paper only contained estimates of the mass of these dwarf systems themselves, and not those of the galaxy around which they rotate.[40] Ostriker, Peebles, and Yahil calculated the masses using "straightforward tidal theory," by for example assuming that these dwarf systems have circular orbits around the Milky Way.[41] They did not include all these mass determinations in the log-log plot (Figure 59) because half of the dwarf systems had a large uncertainty in distance (entry 7 in the table of Figure 58).

A peculiar argument was used for distances still further beyond the galaxy, at about 700 kiloparsec. The argument, which was introduced by Franz Kahn and Lodewijk Woltjer in 1959, rested on the fact that our closest neighbouring galaxy – the Andromeda Galaxy (M31) – is actually rapidly approaching the Milky Way.[42] Andromeda and the Milky Way are galactic members of what is called the "local group" of galaxies. They are the two main and most massive galaxies in this group, otherwise filled with small galaxies and dwarf systems. This meant that the dynamics of the two galaxies can be treated as a two-body system. In an expanding universe, the galaxies originally were very close together and then moved away from each other during the expansion. The gravitational attraction between the bodies slows them down, eventually reversing the initial expansion. By using the time since the beginning of the expansion and the current observed velocity of approach between the two galaxies, one can calculate the total mass of the system. Peebles had reproduced Kahn and Woltjer's argument in his textbook, and in their paper, Ostriker, Peebles and Yahil used new values for estimated velocities to obtain yet another updated value of the system's mass (entry 11 in Figure 58).[43]

On the largest scales, of about a thousand kiloparsecs, the authors relied on studies of clusters of galaxies (entry 12 in Figure

40 Paul W. Hodge, "Radii, Orbital Properties, and Relaxation Times of Dwarf Elliptical Galaxies," *The Astrophysical Journal* 144 (1966): 869.

41 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L3.

42 F. D. Kahn and L. Woltjer, "Intergalactic Matter and the Galaxy.," *The Astrophysical Journal* 130 (1959): 705.

43 Peebles, *Physical Cosmology*, 81-83.

58). These measurements were reminiscent of the discussions in the early 1960s on the stability of groups of galaxies that we have elaborately covered in chapter 1. In their paper, Ostriker, Peebles and Yahil did not refer directly to the discussions on Ambartsumian's hypothesis, but used calculations by Peebles and Margaret Geller, one of Peebles' doctoral students at the time. In a 1973 paper, Geller and Peebles introduced a new method to apply the virial theorem to small groups of galaxies to determine their masses. The method was statistical and based on the analysis of a whole catalog of galaxies, their velocities and separations.[44] With this method, Geller and Peebles found that there was no statistical evidence that groups of galaxies were flying apart, and arrived at similar numbers for the masses of clusters of galaxies as earlier estimates of Rood and de Vaucouleurs had shown: 2×10^{12} solar masses.[45]

The hodgepodge of mass measurements collected by the authors showed that the mass of a galaxy kept increasing the further away from the galactic center it was measured. "[T]he general trend seen in [Figure 59], of significantly increasing mass with increasing radius, is almost certainly real," they concluded.[46] Even outside the visible part of the galaxies mass was increasing linearly with radius. The total mass of a spiral galaxy was calculated to be about 10^{12} solar masses and their mass-to-light ratio about 200 $M_\odot/L_\odot$, meaning masses of galaxies had previously been underestimated by a factor of 10 and much of their mass should be in a form that is not visible. Such was the conclusion drawn by Ostriker, Peebles and Yahil from their analysis of existing literature.

44 Geller and Peebles, "Statistical Application of the Virial Theorem to Nearby Groups of Galaxies"; One of the potential issues with determining the mass of clusters on the basis of the virial theorem were "projection effect," the accidental inclusion of some background or foreground objects that were not really part of the system. The statistical method of Geller and Peebles was based on sacrificing particular information about the member galaxies for "statistical reliability of the mean mass [of galaxies]" Ibid., 329.

45 Rood, Rothman, and Turnrose, "Empirical Properties of the Mass Discrepancy in Groups and Clusters of Galaxies"; De Vaucouleurs, "Nearby Groups of Galaxies."

46 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe."

4.3 A SOVIET PARALLEL

Two months before the paper by the Princeton group came out, a remarkably similar paper had been published by a group of astronomers and physicists in the Soviet Union. At the W. Struve Astrophysical Observatory near Tartu in the Estonian Soviet Socialist Republic, a paper was drafted early in 1974 which argued that galaxies were surrounded by massive coronas of "hidden matter."[47] The paper used literature similar to that of the Princeton group and came to a similar conclusion. We again discuss the details of this paper to give insight in the conditions under which the hidden matter conclusion was established.

The new astronomy of the 1960s that has been discussed in the previous chapter was hardly only a Western enterprise. With Yurii Gagarin famously becoming the first man in space in 1961, research in astronomy and space science was receiving much attention in the USSR in the 1960s.[48] This excitement was also felt in cosmology. By the mid 1960s, renowned nuclear physicist Yakov Borisovich Zeldovich was gathering a group of young bright-minded physicists at the Institute of Applied Mathematics of the USSR Academy of Sciences to tackle the problems of the cosmos. The influence of Zeldovich's work is hard to overestimate; he hypothesized black holes as the origin of quasars, worked on the formation of galaxies, neutrinos, and many other aspects of cosmic physics.[49] A weekly three-hour seminar held at the Sternberg State Astronomical Institute of the Moscow State University drew in scientists from all around the Soviet Union to discuss astrophysics and cosmology with Zeldovich and his group.[50]

47 Jaan Einasto, Ants Kaasik, and Enn Saar, "Dynamic evidence on massive coronas of galaxies," *Nature* 250, no. 5464 (1974): 3.

48 For an overview of the Soviet Union's efforts during the Space Race, see Asif A. Siddiqi, *Challenge to Apollo: The Soviet Union and the Space Race, 1945-1974* (Washington, DC: National Aeronautics; Space Administration, 2000).

49 Arthur D. Chernin, "Approximating the truth, or the Zeldovich ansatz," in *Zeldovich: Reminiscences*, ed. R.A. Sunyaev (Boca Raton, FL: Chapman & Hall / CRC, 2014), 244.

50 For reflections on Zeldovich's group meetings, see R.A. Sunyaev, "When we were young," in *Zeldovich: Reminiscences*, ed. R.A. Sunyaev (Boca Raton, FL: Chapman & Hall / CRC, 2014); See also J. Maddox, "Differences of

In 1971, one of the Sternberg seminars was given by a forty-two-year-old Estonian astronomer by the name of Jaan Einasto. Einasto, whose family name was invented by his father as anagram of "Estonia" in the 1930s, had come to Moscow to talk about his new model of galaxies.[51] He was not a stranger to Moscow. During his undergraduate years of studying astronomy in Tartu, Einasto often traveled to the Sternberg Institute where one of the leading galactic astronomers, Pavel Parenago, inspired him to work on galaxies and their stellar populations. Starting in 1952, he used his knowledge of stars to make models of galaxies – work that had been done in Tartu for several generations.[52] His work on modeling galaxies and their evolution culminated in Einasto's doctoral thesis (which at the time in Russia was the thesis one wrote to obtain full professorship). On this he came to speak in Moscow in 1971.

Zeldovich, not much acquainted with galactic models, enjoyed Einasto's work and invited him to join the Soviet astrophysics winterschools he organised yearly in the Caucasus mountains. When Einasto came back from the school early 1972, he was looking into a problem in his model for the Andromeda system: the rotation curves of Morton Roberts (1966) were hard to include in models. His data were telling that at the outer edges the mass-to-light ratios were very high, which Einasto found could not be matched with any known population of stars at the periphery of

style in science," *Nature* 329, no. 6142 (1987): 786–787, in the "Soviet Science" special of Nature. Rashid Sunyaev reflects on the meetings as follows: "Many remember the seminars at the Sternberg Astronomical Institute (SAI) in 1965 to 1968, when they were supervised jointly by YaB [Zeldovich], V.L.Ginzburg, and I.S.Shklovskii; when Solomon Borisovich Pikelner was prepared at any minute to step up and explain something to the physicists; when D.Ya.Martynov, S.I.Syrovatskii, B.A.Vorontsov-Vel'yaminov, B.V.Kukarkin, N.N.Pariiskii, Ya.A.Smorodinskii, P.N.Kholopov, A.L.Zel'manov, A.G.Masevich, and M.U.Sagitov sat in the front rows at nearly every seminar; S.A.Kaplan sometimes came in from Gor'kii; the young L.M.Ozernoi, I.D.Novikov, N.S.Kardashev, V.S.Imshennik, V.G.Kurt, Y.N.Efremov, V.F.Shvartsman, and A.M.Cherepashchuk actively participated; E.M.Lifshitz, I.M.Khalatnikov, or A.D.Sakharov occasionally appeared," Sunyaev, "When we were young," 235.

51 See for an autobiographical account of his life and work, Einasto's book: Jaan Einasto, *Dark Matter and Cosmic Web Story* (Singapore: World Scientific Publishing, 2014).

52 Estonian astronomer Ernst Öpik had worked on galaxy models from the 1920s onward; Einasto had learned stellar dynamics from Gregori Kuzmin at Tartu.

Figure 61: The Sternberg Astronomical Institute of Moscow State University in the 1950s. With the main building of Moscow State University in the background. From: http://heritage.sai.msu.ru

galaxies. "[It was] very difficult to explain the rotation velocity of galaxies at large galactocentric distances with known stellar populations," Einasto writes in his autobiographical notes.[53] It was a problem he was unable to address properly until he came to speak about it with a younger colleague at the observatory, cosmologist Enn Saar.

Born as the son of Estonian fishermen, Saar left the Estonian coast to study theoretical physics in Tartu. He was drawn toward theoretical astrophysics, and by 1966 he was estimating cosmological parameters like the deceleration from recently observed quasar distributions. A year later Saar began his doctorate ('aspirant') in general relativity under supervision of Arved Sapar, during which he tried to figure out what effect large density fluctuations like that of galaxy clustering had on theories of the evolution of the universe. (His conclusion: not much). In 1972, after defending his Ph.D., Saar got into a discussion with his senior col-

53 Jaan Einasto, "Cosmology Paradigm Changes," *Annual Review of Astronomy and Astrophysics* 56 (2018): 13.

league Einasto about the problems in modelling the outer edges of galaxies. It was "sort of a difference in attitudes," Saar remembered in an interview: his experience in cosmology made that he saw not much of a problem in extended galaxies. Rather, he told, "[i]t's a normal state of any gravitational body that it has no borders."[54] Maybe there was more than met the eye: For Einasto, Saar's insight meant "abandoning the idea that only known stellar populations exist in galaxies."[55]

Saar's simple suggestion opened the "deadlock" that Einasto was in.[56] Galaxies might not end abruptly and instead have a "corona" of a new population of yet unknown nature. Einasto presented these insights at an invited lecture at the First European Astronomy Meeting in Athens, September 1972. "Massive galaxies may be surrounded by coronae of large mass and dimensions," he reported, and showed how this assumption would better fit Roberts' 1966 rotation curves (see Figure 62).[57] Einasto's report in Athens "did not give rise to special excitement."[58] The lukewarm response Einasto blamed on the lack of evidence, so he set course to find more observations to support his claim.

Prominent astrophysicist Iosif Shklovsky of the Sternberg Astronomical Institute is said to have joked that all astronomical observations in USSR were being done through the American *Astrophysical Journal* – Soviet astronomical instrumentation was often hampered by weather conditions, mechanical problems and a lack of computer technology.[59] Tartu Observatory itself was

54 Enn Saar, interview with the author, 4 April 2017, Tõravere, Estonia. Saar here refers to gravity being inversely proportional to radius.

55 Einasto, *Dark Matter and Cosmic Web Story*, 82.

56 Jaan Einasto, interview with the author, 3 April 2017, Tõravere, Estonia.

57 Einasto, Kaasik, and Saar, "Dynamic evidence on massive coronas of galaxies," 322.

58 Einasto, *Dark Matter and Cosmic Web Story*, 85.

59 Enn Saar, interview with the author, 4 April 2017, Tõravere, Estonia. Observatories in the Soviet Union could not compete with those in the United States, and so was the case for the Tartu Astronomers – Tartu Observatory itself was unable to do significant observations because of the too-bright night sky at their latitude. One of most relevant observatories for cosmologists in the Soviet Union was the Special Astrophysical Observatory in Zelenchukskaya, with their RATAN-600 radio telescope. The radio telescope was aimed at conducting complete surveys of the sky at centimeter wavelengths, and could for example provide information related to the cosmic microwave background. The telescope saw first light

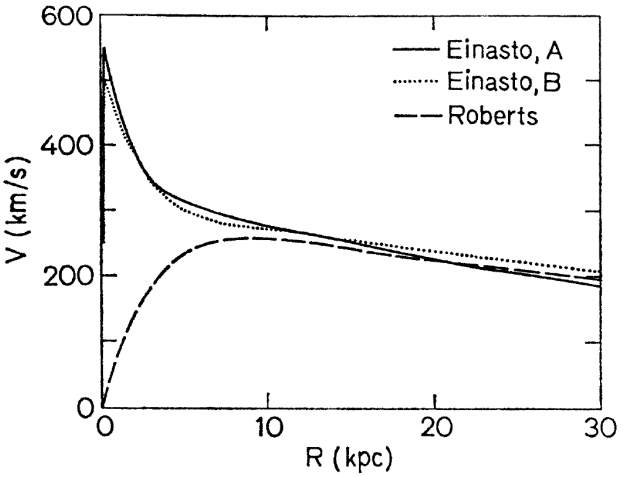


Figure 62: This figure was used by Einasto at the 1972 European Meeting in Astronomy to show how a galactic model with an additional massive cloud would better correspond to the slope of the line found by Roberts. It shows three rotation curves, with V the velocity of galaxies and R the radius. "Einasto, A" is the model without, and model "B" is the model with an added massive spherical component. In: Jaan Einasto, "Galactic Models and Stellar Orbits," in *Proceedings of the First European Astronomical Meeting Athens, September 4–9, 1972* (Berlin: Springer, 1974), 311.

unable to do significant observations because of the too-bright night sky at their latitude. Einasto too depended on studies done abroad with the most advanced telescopes, and he scoured international papers for more data. In particular, he gathered published studies on groups and clusters of galaxies, from which he

in 1974. See e.g. L. M. Gindilis, "The Development of Radio Astronomy at the Sternberg Astronomical Institute of Lomonosov Moscow State University and the Space Research Institute of the USSR Academy of Sciences," in *A Brief History of Radio Astronomy in the USSR. Astrophysics and Space Science Library, vol 382*, ed. S.Y. Braude et al. (Dordrecht: Springer, 2012). Shklovsky wrote that "lack of computer technology has also hampered Soviet instrumentation." For more on Shklovsky's pronounced character, see his collection of anecdotes: (Iosef Shklovsky, *Five Billion Vodka Bottles to the Moon: Tales of a Soviet Scientist* (n.p.: W. W. Norton & Company, 1991), 139.

learned about the long history of the instability problem in clusters from the work of Herbert Rood and Thornton Page, and he looked into data from recent X ray studies of clusters.[60]

It was clear to Einasto that the ionized gas found in clusters was not able to stabilize the clusters, and here his earlier ideas on galaxies became useful. "Another possible way of removing the mass discrepancy is to suppose that the masses of individual galaxies have been underestimated," his draft paper noted.[61] One of the reasons to assume this was the case, he argued, was the "very slow decrease of rotational velocity" of galaxies seen in Roberts' new study – the flat rotation curves.[62]

Einasto, together with Enn Saar, set out to determine the mass distribution at the outer edges of galaxies of both the known stellar population and that of the hypothesized invisible "corona." For this they used Einasto's earlier studies of galaxy rotation, but also added mass determinations at larger radius by using data of 105 pairs of galaxies taken from studies by Thornton Page and Igor Karachentsev.[63] Einasto asked his student Ants Kaasik to join the effort, and do some of the calculations. Einasto, Saar and Kaasik divided the pairs of galaxies into five groups and plotted how the mass of a galaxy depends on radius. The result is pictured in Figure 63 – a figure remarkably similar to the plot that was published a few months later by the Princeton group. It showed that galaxies were surrounded by "a previously unrecognized, massive population" that exceeded the mass of the stellar population by an order of magnitude.[64]

In January of 1974, Einasto presented his, Saar and Kaasik's new results at that year's Soviet astrophysics winterschool. With Mount Elbrus on the background, the highest mountain in Europe, Einasto told about his new idea of galactic coronae. Accord-

60 Herbert J. Rood et al., "The Structure of the Coma Cluster of Galaxies," *Astrophysical Journal* 175 (1972): 627.

61 Jaan Einasto, Ants Kaasik, and Enn Saar, "Dynamical evidence on massive coronas of galaxies," *Tartu Astrofüüs. Obs. Preprint* 1 (1974): 3.

62 Ibid.; Roberts, "Radio Observations of Neutral Hydrogen in Galaxies."

63 Thornton Page, "Spectral Lines and Radial Velocities of Galaxies in Pairs," *The Astrophysical Journal* 159 (1970): 791; Karachentsev, "The virial mass-luminosity ratio and the instability of different galactic systems."

64 Einasto, Kaasik, and Saar, "Dynamical evidence on massive coronas of galaxies," 4.

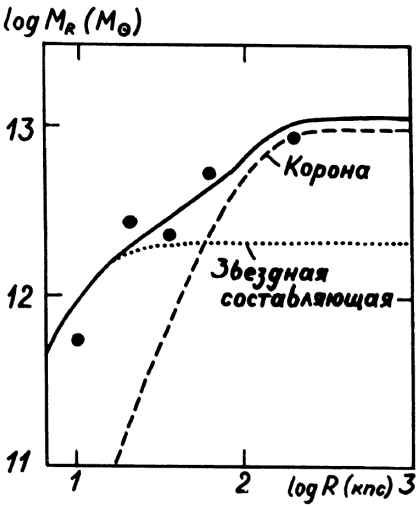


Figure 63: The logarithmic plot of mass as function of radius by Einasto, Kaasik and Saar (1974). The given data is based on the analysis of 105 pairs of galaxies, binned in five groups based on their separation distance. The dashed line gives the mass of the corona (), the dotted line gives the mass of the stellar component (eg). This is the earliest version of the diagram, and appeared in the Soviet "Astronomical Circular" in February of 1974: J. Einasto et al., "Dynamical evidence for the presence of hidden mass in galaxies", *Astronomicheskii Tsircular* 811 (1974): 3.

ing to his recollection it was "as if a bomb had exploded" at the meeting.[65] Zeldovich and his students, trained in quick order-of-magnitude calculations, engaged with the problem directly after the talk. Young astrophysicists of the Sternberg Institute like Igor Novikov and Arthur Chernin checked on-site whether this new population could perhaps be hot ionised gas or neutrinos.[66]

Einasto, Kaasik and Saar quickly wrote a note for a Russian astronomy leaflet that was published in February of 1974.[67] But

65 Einasto, *Dark Matter and Cosmic Web Story*, 90.

66 Jaan Einasto, interview with the author, 4 April 2017, Tõravere, Estonia.

67 J. Einasto et al., "Dynamical evidence for the presence of hidden mass in galaxies," *Astronomicheskii Tsircular* 811 (1974): 3–4.

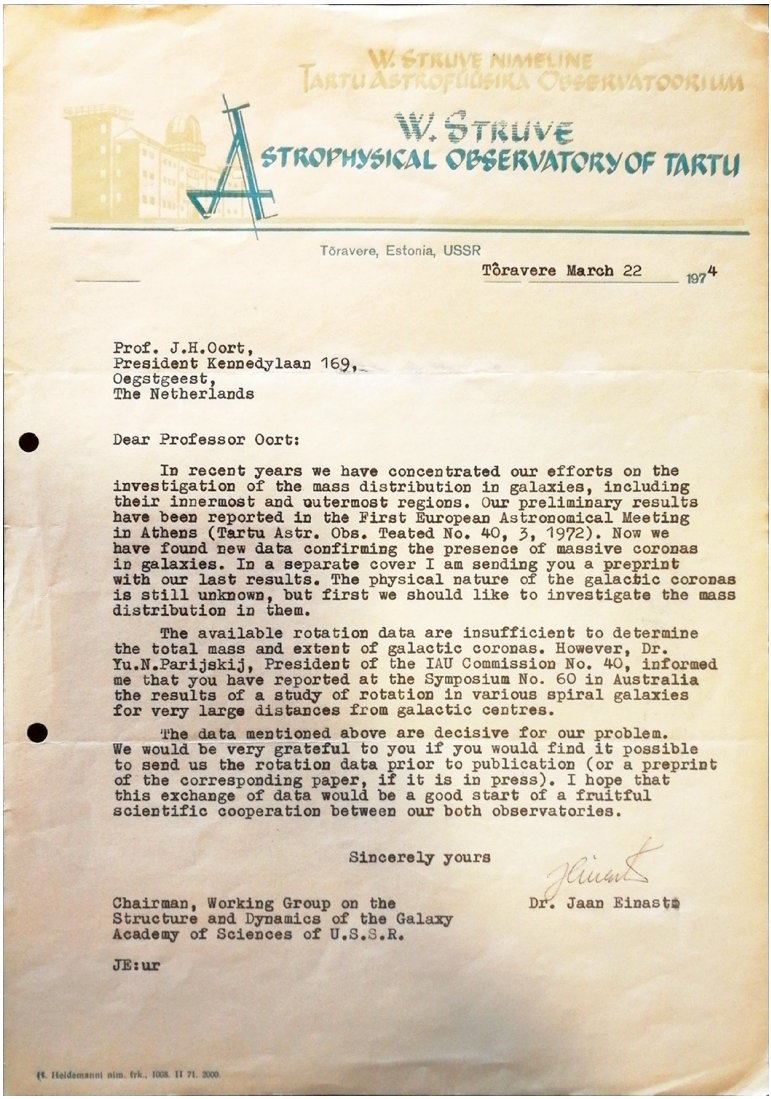
their renowned Soviet colleague suggested them to do otherwise: "Zeldovich insisted this must be published in some really important journal," Einasto remembered later.[68] Following Zeldovich's advice, Einasto and his group decided to send their paper to *Nature*. This was a momentous decision, because in Tartu it had long been the standard to publish in the local astronomical bulletin (*Tartu Astrofüüsika Observatoorium Teated*), and publishing in Soviet astronomy journals was not highly regarded at the observatory.[69] Besides that, international publishing was difficult. "It was a strange idea because we knew it was practically impossible to publish something outside [the Soviet Union]," Enn Saar recollected, referring to how the Soviet intelligence agency thoroughly examined every outgoing communication.[70]

Despite the difficult and lengthy procedure, and without the revisions of the print proof of their paper ever being incorporated, the paper was published in July of 1974. It was Einasto, Kaasik and Saar's first international paper, and the paper's pre-print version was also the very first pre-print they sent across the world (see Figure 64). The abstract to the pre-print read: "Evidence is presented that galaxies are surrounded by massive coronas exceeding the masses of known stars by one order of magnitude [...].[71]

4.4 "THE MASS OF THE UNIVERSE"

In 1974, the groups in Princeton and Tartu argued that galaxies were ten times more massive than had previously been believed, drawing upon the stability problem in clusters of galaxies and the measurements of flat rotation curves. But this was only half of what these authors tried to show. There is yet another aspect to understanding their works: how these authors related their computations to the *mass density of the universe*, Ω – the parameter that cosmologists had recently started to focus on in determining the correct model of the universe.

68 Jaan Einasto, interview with the author, 3 April 2017, Tõravere, Estonia.
69 Jaan Einasto, interview with the author, 30 March 2017, Tõravere, Estonia.
70 Enn Saar, Interview with the author, 4 April 2017, Tõravere, Estonia.
71 Einasto, Kaasik, and Saar, "Dynamic evidence on massive coronas of galaxies," 2.



W. STRUVE NIMELINE
TARTU ASTROFÜÜSIKA OBSERVATOORIUM

W. STRUVE
ASTROPHYSICAL OBSERVATORY OF TARTU

Tõravere, Estonia, USSR

Tôravere March 22 1974

Prof. J.H.Oort,
President Kennedylaan 169,
Oegstgeest,
The Netherlands

Dear Professor Oort:

In recent years we have concentrated our efforts on the investigation of the mass distribution in galaxies, including their innermost and outermost regions. Our preliminary results have been reported in the First European Astronomical Meeting in Athens (Tartu Astr. Obs. Teated No. 40, 3, 1972). Now we have found new data confirming the presence of massive coronas in galaxies. In a separate cover I am sending you a preprint with our last results. The physical nature of the galactic coronas is still unknown, but first we should like to investigate the mass distribution in them.

The available rotation data are insufficient to determine the total mass and extent of galactic coronas. However, Dr. Yu.N.Parijskij, President of the IAU Commission No. 40, informed me that you have reported at the Symposium No. 60 in Australia the results of a study of rotation in various spiral galaxies for very large distances from galactic centres.

The data mentioned above are decisive for our problem. We would be very grateful to you if you would find it possible to send us the rotation data prior to publication (or a preprint of the corresponding paper, if it is in press). I hope that this exchange of data would be a good start of a fruitful scientific cooperation between our both observatories.

Sincerely yours

Dr. Jaan Einasto

Chairman, Working Group on the
Structure and Dynamics of the Galaxy
Academy of Sciences of U.S.S.R.

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Figure 64: Letter of Jaan Einasto to Jan Oort, dated March 22, 1974. The letter included the pre-print of the article by Einasto, Kaasik and Saar. There is no known response of Oort to this inquiry. Leiden University Library Special Collections, Oort Archive, Box 127 A.

Ostriker's group, in particular, emphasized the implications of their work for understanding "the mass of the universe"; if their conclusion was correct, and the masses of galaxies were ten times as high than previously thought, "the mean mass density of the Universe would have been underestimated by the same factor," they wrote in the introduction of their paper.[72] The authors showed this was indeed the case. They determined the cosmic mass density by using their newly calculated mass-to-light ratio for galaxies (200 $M_\odot/L_\odot$) and multiplying it with the emitted light of observed galaxies (i.e. the luminosity function). They found that the density due to galaxies was 2×10^{-30} g cm^{-3}, corresponding to $\Omega \approx 0.2$; this was more than ten times as much as had been recently determined by Jim Peebles' graduate student, Stuart Shapiro, and had earlier been argued by Jan Oort.[73]

In their introduction, the authors summarized the implications of their take on the mass density of the universe:

> [T]he current estimate (Shapiro 1971) for the ratio of gravitational to kinetic energy in the Universe is $\Omega = 0.01$. If we increase the estimated mass of each galaxy by a factor well in excess of 10, we increase this ratio by the same amount and conclude that observations may be consistent with a Universe which is "just closed" ($\Omega = 1$) – a conclusion believed strongly by some (cf. Wheeler 1973) for essentially nonexperimental reasons.[74]

This text, taken from the first paragraph of their paper, shows how critical the authors thought their conclusion was: their measure of mass might show that the universe was "just closed." The closed universe – the universe in which there was enough cosmic mass to curve space-time into a sphere – had dominated cosmological discussions in the 1950s, and was the model favored by the

72 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L1.

73 Shapiro, "The Density of Matter in the Form of Galaxies"; Oort, "Distribution of Galaxies and the Density in the Universe."

74 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe."

likes of Dennis Sciama, Robert Dicke and John Wheeler. Ostriker, Peebles and Yahil indeed referred to a paper by John Wheeler, who was already 63 years old at the time, in which he had once more emphasized the attractive power of a closed universe and "the mystery of the missing mass" that it entailed.[75]

In their paper, Ostriker, Peebles and Yahil suggested that they had found part of this missing mass. The search for the "missing mass" to close the universe was an extra stimulus to put together already existing observations and issues of mass, and create a picture consistent with a closed universe. The authors were even confident enough to note that a tenfold increase in galactic masses "may be consistent" with $\Omega = 1$, despite that their own calculations were still a factor of 5 away from a closed universe ($\Omega = 0.2$ *vs* $\Omega = 1$). Their reasoning, Jerry Ostriker reflected in an interview, was motivated by the general opinion on the closed universe at the time:

> "[People] would say, "we're just discovering more and more matter, and it's going to end up agreeing with $\Omega = 1$" – so, we were very interested that our value was ten times Oort's, but still only a third of what people wanted. It was a question of, kind of, belief – "it should be this." So, that was our motivation. Anybody who was interested in cosmology had a belief that they knew what it was, or it should be, or something or other."[76]

The Princetonians were not the only ones who related their results to the mass of the universe and its preferred value. "If you wrote a cosmological paper then, you had to estimate the mean density," Enn Saar of the Estonian group reflected in 2017, "this was the norm."[77] Just as the Princeton group, the Tartu group related their new findings to the cosmological endeavour of find-

75 John Archibald Wheeler, "The Universe as Home for Man," *American Scientist* 62, no. 6 (1974): 686.

76 Jerry Ostriker, interview with the author, 1 December 2014, Princeton, NJ.

77 Enn Saar, interview with the author, 4 April 2017, Tartu Observatory, Tõravere, Estonia.

ing the correct model of the universe and framed their results in terms of the critical density:[78]

> Evidence is presented that galaxies are surrounded by massive coronas exceeding the masses of known stars by one order of magnitude [...] the total density of matter in the galaxies being 20% of the critical cosmological density.[79]

The U.S. and Estonian groups brought together different arguments to show that galaxies contained a great amount of unseen mass, and the missing mass to close the universe was an important element in their reasoning. The reception of these papers will be discussed in the conclusion of this dissertation. Before that, we attend to the issue of "evidence."

4.5 RECOGNIZING THE EVIDENCE

"We didn't invent any of these arguments," Ostriker reminded me in an interview, referring to the different observations they used to conclude on the existence of unseen mass.[80] The only thing they did is "recognize" that the arguments were evidence for dark matter, as Peebles put it.[81] Indeed, the phenomena of flat rotation curves and the stability problem in clusters had previously been treated independently, and in no case had they unequivocally been interpreted as the existence of dark matter: astronomers had not "recognized" that their observations provided evidence for the existence of dark matter, to use Peebles' terminology.

How, then, can we understand that in 1974 evidence for dark matter *did* take shape? What made that these authors recognized already existing arguments as evidence where others had not? As

78 Remember that Ω was defined as the density relative to the critical density, $\Omega = \rho/\rho_{critical}$. The critical density was approximately $10^{-29}\ gr\ cm^{-3}$.

79 Einasto, Kaasik, and Saar, "Dynamical evidence on massive coronas of galaxies," 2.

80 Jerry Ostriker, interview with the author, 10 Nov 2014, Princeton, NJ.

81 Peebles, *Cosmology's Century: An Inside History of Our Modern Understanding of the Universe*, 272.

already alluded to, these actors had a new way of seeing and engaging with the universe through which the mass measurements of galaxies obtained a novel significance. This section is meant to reflect on this, and will relate the 1974 papers and their authors more precisely to the rebirth of cosmology and the rise of the new type of physical cosmological reasoning in the early 1970s.

To begin with, the authors of the two papers represented the hybrid generation of physicist-astronomers that came up in the late 1960s. Peebles and Yahil both had Ph.D.s in physics, not in astronomy, and Ostriker was an astrophysicist that moved fluently between studies of stars, galaxies and the cosmos. Saar was a theoretical physics graduate, and Einasto worked on the physics of galaxies and through his interaction with Zeldovich obtained insight in many aspects of cosmology. Both groups were addressing the cosmos *astrophysically*, and moved away from the classic search for the universe's deceleration, instead focusing on the mass density of the universe. In this context, masses of galaxies obtained a different relevance than they had in studies of gas in galaxies and the dynamics of galaxy clusters.

To calculate the mass of galaxies, both groups combined a multitude of different methods and techniques from a variety of astronomical subfields. Ostriker, Peebles and Yahil's paper included mass measurements from radio astronomical studies of hydrogen gas in galaxies, double systems of galaxies, tidal dynamics of dwarf galaxies, the viral theorem applied to clusters of galaxies, and "nonexperimental" ideas on the mass of the universe. They also connected their conclusion to Ostriker and Peebles' earlier idea of a "halo" of mass that seemed to be needed to stabilize a rotating galaxy. The paper of the Tartu group built on many of the same sources. In this respect, these two papers resembled the 1974 paper by Gott, Gunn, Schramm and Tinsley that combined many different measures of the mass of the universe (see section 3.6).[82] Just as the Gott et al. paper, the dark matter papers exemplify how cosmology had become a "methodological omnivore":

82 Gott et al., "An Unbound Universe." The paper of Gott et al. was published December 15, two months after the paper of Ostriker, Peebles and Yahil. The paper of Gott et al., using both similar and different measures of mass, came to a different conclusion: that the universe is open, with $\Omega \sim 0.06$.

rather than focusing on a single method or test, the field drove on the convergence of multiple evidential means.

The methodological plurality of the two dark matter papers can be related to how cosmological science around 1970 became dominated by a historical narrative style of reasoning, in which many different aspects of the cosmos were aligned in a single evolutionary picture. In creating such an evolutionary picture of the universe, cosmologists were also challenged to think with a new sense of *scale*: creating a conception of the universe in which small and large structures were fundamentally interconnected, from stars and quasars to galaxies and clusters. The papers of Einasto and Ostriker's groups also illustrate how reasoning happened on a cosmological scales: they put existing observations within a cosmological picture in which a large range of scales mattered, from galaxies (10 kpc) to large galaxy clusters (1000 kpc). Both groups used a diagram with a *logarithmic scale* to be able to synthesize data from three orders of magnitude in distance (Figures 59 & 63 on pages 243 & 254).

Ostriker, Peebles, and Yahil illustrated their sense of scale explicitly. Galaxies, they noted in their paper, were usually assumed to be finite system: it was thought the mass of a galaxy would converge at a certain finite distance. According to Ostriker, Peebles, and Yahil, this assumption of finite galaxies was unproblematic for most astronomers because of a "very important [fact] about astronomical measurements of mass": in classical mechanics, the gravitational field inside a hollows sphere is zero if the mass distribution outside of that sphere is homogeneous – this is sometimes known as the "shell theorem".[83] So, to determine the mass inside a certain radius, an astronomer most of the time needs no knowledge of what exists outside of this radius. "[T]he rotation curve interior to the Sun's orbit [in the Milky Way] gives little information about the disk mass exterior to the Sun ($r > 10$ kpc)," Ostriker, Peebles and Yahil illustrated.[84] For those authors concerned with galaxies as isolated systems, any mass on larger scales was mostly irrelevant.

83 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L1.

84 Ibid.

This "ignorance," Ostriker and his group wrote, would be little cause for concern if masses of galaxies indeed converged; but, as the paper showed, they did not.[85] Only when considering the masses of galaxies as measured on *several different scales* one could see that the mass of galaxies did not converge; instead of converging, the mass of galaxies seemed to diverge, increasing linearly with radius. So, according to Ostriker, Peebles and Yahil, studies of mass that focused on one particular scale did not see that the masses of galaxies diverged, because, for these studies, any mass on larger scales was mathematically irrelevant.

We can understand the formation of evidence for dark matter in the work of these authors through their use of different methods to attend to three orders of magnitudes of distance scales. Where flat rotation curves and the mass discrepancy in galaxy clusters by themselves had alternative interpretations, combining the arguments within a bigger picture and using different methods helped to find a unique explanation. Or, as Peebles commented in an interview:

> "What was the best argument [for not understanding masses in the early 1970s]? None of them. This is a case of no one argument being compelling, because you could think of systematic errors, but so many arguments pointing in the same direction."[86]

The evidence for dark matter in the Soviet and American papers was not a single argument, but the combination of different arguments. A similar point was made by Alar Toomre: "any one of these pieces were somewhat shaky," he remembered, "[but] when you have five pieces all pointing in the same direction. . . ."[87] The ambiguity in the interpretation of the observations that we saw in chapters 1 and 2 was resolved by adding the arguments together. This, again, we can understand as characteristic for reasoning within physical cosmology – the case for the big bang theory of the universe also being an example of how

85 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L1.

86 Jim Peebles, interview with the author, 13 Nov 2014, Princeton, NJ.

87 Alar Toomre, interview with the author, 9 December 2014, Cambridge, MA.

several arguments on different distance and time scales acted together (e.g. helium synthesis, cosmic microwave background, the counts of radio stars), and so was the case presented by Gott, Gunn Schramm, and Tinsley for a low mass density of the universe (Figure 54 on page 223).

In combining several arguments, the two papers sidestepped errors, doubts, and disagreements that surrounded these original arguments individually. They did not discuss any earlier mentioned problems, such as the potentially ill-understood radio astronomical instruments (side lobes) in the measurement of flat rotation curves, or the possibility of galaxy clusters being unstable or otherwise giving wrong measures of mass. The way Ostriker, Peebles and Yahil treated the errors in the data is illustrative here. In the table of their data (see Figure 58 on page 242) they reported errors, and their diagram shows error bars: "the uncertainties, which have been roughly indicated by error bars, are obvious," they wrote.[88] "Roughly" is key here. The exact origin or nature of many of these used error margins are unaccounted for in the paper, especially when compared to the cited literature. Although they gave errors to their data and error bars in their diagram, what method of reporting errors they use is unclear. [89]

The above points are meant to illustrate that the way that evidence emerged for the existence of dark matter can be understood as an example of a new way of engaging with the cosmos. So when Jim Peebles talked of how they had "recognized" previously existing arguments as evidence for dark matter, we should understand him quite literally as *re*cognizing: they "re-knew," appropriating existing knowledge anew in a different context of research where the mass of galaxies had obtained a different significance, and in which the mass density of the universe – and the universe's potential closure – was a topic of central concern. In

88 Ostriker, Peebles, and Yahil, "The Size and Mass of Galaxies, and the Mass of the Universe," L3.

89 No reference to how this uncertainty is constructed is made in the paper other than the following: "The uncertainty of this result, due to inaccuracy in f_s alone [the M/L of spiral galaxies], is clear from the preceding discussion. The total uncertainty, which is not less than a factor of 3, contains an important contribution due to our poor knowledge of j_s [the mean volume emissivity of light from spiral galaxies] as well." Ibid.

this re-appropriation, the Princeton and Tartu groups combined different arguments through which they transformed the interpretation of flat rotation curves and the mass discrepancy in cluster of galaxies: these observations went from ambiguous "matters of taste," as they had been called, to explicit evidence for missing mass.