How dark matter came to matter

A history of missing mass, 1930-1974

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HOW THE UNIVERSE GAINED ITS WEIGHT

This thesis has up to now dealt with two ways in which invisible mass entered astronomical discourse: through flat rotation curves and the mass discrepancy in galaxy clusters. We traced the waxing and waning of discussions on these types of matter and showed that, at least until the mid-1970s, the reality of both kinds of unseen mass was not established. It turned out that the observations that are currently considered evidence for the existence of dark matter were not understood as evidence right away. The way these problems *did* turn into evidence for dark matter was facilitated by a new way of engaging with the cosmos in the early 1970s, and this transformation in cosmological thinking is the topic of the current chapter.

The aim of this chapter is threefold. Firstly, it sets out to offer yet another window on the discontinuities in astronomical research between 1930 and 1970, this time focusing on theories and theorists of the cosmos. How does one do a science of the universe? And how has this norm been changing? This chapter focuses on a fundamental transformation in cosmological practice between 1950 and 1970, in which cosmology went from describing *how* the universe is – and ought to look like – to explaining *why* the universe is the way it is. To illustrate this transformation, the chapter follows several changes in which parameters, observations, philosophies, and questions that were at stake in cosmology in these decades.

The chapter argues that, by 1970, a new generation of scientists was engaging with the cosmos, and cosmology was reborn as *physical* cosmology: an approach dominated by studying the physics of cosmic phenomena and relating these phenomena to the evolutionary history of the universe – from the synthesis of

elements and galaxy formation to gravitational collapse and the cosmic microwave background. Two parts of this change in cosmological practice are highlighted: a shift from the dominance of metaphysical debates between adherents of different theories of the universe, to the consensus of a physical big bang picture of the universe; and, a shift from Hubble's search for the deceleration of cosmic expansion, to a search for the mass density of the universe. This then is the first meaning of the chapter's title: showing how the universe gained weight as a well-respected physical science in the early 1970s.

Besides tracking a fundamental conceptual and practical discontinuity in cosmology, another aim of this chapter is to highlight a *continuity* in cosmological thinking. Although there was a shift away from the philosophical and methodological debates that characterized cosmology in the 1950s, there was one particular philosophical preference for a cosmological model that remained dominant in cosmological discussions until at least the mid-1970s: the preference for a spatially closed universe. The origins of this model are discussed and traced back to Einstein and his, and others', take on Mach's principle. It is shown that this philosophical idea became a benchmark cosmological model that still reverberated in the reborn physical cosmology of the 1970s.

The third aim of the chapter is to show that, by 1970, cosmology had also gained weight in a second way: the *mass* of the universe became a central parameter to assess the ultimate fate of the cosmos. I argue that, in the rebirth of cosmology, the mass of the universe obtained a new significance as a tool to determine the correct model of the universe. Determining the mass density of the universe became a central aim of cosmological practice in the second half of the 1960s. What is crucial to this thesis' narrative, is that the combination of a preference for a closed universe and the search for the mass density of the universe resulted in the establishment of a new hypothesized object: the *missing mass* to close the universe. We show that this missing mass became a new motif in cosmological research from the late 1960s onward.

This chapter builds on many authoritative works that have been written on the history of cosmology in the twentieth cen-

tury.[1] These works have particularly focused on the theoretical developments that brought about the emergence of the big bang cosmological paradigm in the 1960s. The current chapter, instead, centers on studying the changes in how cosmology was practiced; it does not survey the theories cosmologists have proposed, but highlights several important parts of the field's history that show that what it meant to *do* cosmology – and *who* was doing it – radically changed in the 1960s.

In toto, this chapter does four different things: (1) illustrate the history of cosmology and its methodological foundations in the 1950s; (2) discuss the relation between cosmology and the revival of research on general relativity in the late 1950s, including its relation with Mach's principle; (3) indicate the fundamental conceptual and institutional changes in the practice of astronomy during the 1960s, which signals cosmology's "rebirth"; and, (4) show that by the 1970s, mass had obtained a central significance in cosmology and the concept of missing mass – the mass to close the universe – was established.

3.1 COSMOLOGICAL FOUNDATIONS

Edwin Hubble changed the face of the cosmos with his papers on the redshift of galaxies in the 1920s and early-1930s. The first time we encountered Hubble's work was in the context of the work on the distribution of galaxies, and the second time because of the impulse it gave to the study of galaxies and their rotation, but we have yet to comment on the cosmological significance of his work. Hubble's observations showed that the reces-

1 For broader conceptual overviews of the history of cosmology in the twentieth century, see in particular John David North, *The Measure of the Universe: A History of Modern Cosmology* (Oxford: Clarendon Press, 1965), Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, Smeenk, "Approaching the Absolute Zero of Time: Theory Development in Early Universe Cosmology," Kragh, *Conceptions of cosmos: from myths to the accelerating universe: a history of cosmology*, and Longair, *The Cosmic Century*. For personal perspectives, see e.g. B. Bertotti et al., eds., *Modern Cosmology Retrospect* (Cambridge: Cambridge University Press, 1990); Peebles, *Cosmology's Century: An Inside History of Our Modern Understanding of the Universe*. For a popular, yet meticulously researched book, see Overbye, *Lonely Hearts of the Cosmos: the Scientific Quest for the Secret of the Universe*.

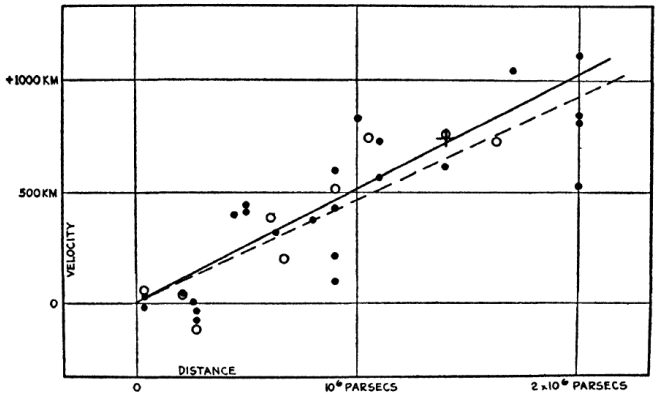

Figure 45: The velocity-distance relation as presented by Hubble in 1929. The radial velocities of 18 objects is plotted against distance. The black dots and full line represent the nebulae individually; the open circles and broken line represent the nebulae when grouped together. The recession velocity of galaxies was shown to increase linearly with distance. In: Edwin Hubble, "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae," *Proceedings of the National Academy of Sciences* 15, no. 3 (1929): 172.

sion velocity of a galaxy was increasing with distance. The diagram of his original 1929 study is shown in Figure 45. With this diagram Hubble made cosmology an empirical study. "Hubble's work helped to breed among astronomers and mathematicians of his day the confidence to discuss and ultimately attempt to explain the entire history of the universe," historian of astronomy Robert Smith characterized Hubble's work.[2] Hubble empirically grounded "relativistic cosmology."

Relativistic cosmology was the approach rooted in Einstein's effort to treat the entire universe with his relativistic field equations.[3] In a paper from 1917, Einstein showed that the entire cosmos could be described geometrically, as the curvature of space-

2 Robert W. Smith, "Edwin P. Hubble and the Transformation of Cosmology," *Physics Today* 43, no. 4 (1990): 58.

3 Albert Einstein, "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie," in *Albert Einstein: Akademie-Vorträge* (n.p.: Wiley, 1917).

time. Although Einstein, and his Dutch colleague Willem de Sitter, initially introduced (and preferred) static cosmological models, Russian theorist Alexander Friedmann, Belgian astronomer and abbey Georges Lemaître introduced *dynamical* models of the universe in which space could expand or contract.[4] Their work formed the theoretical backbone of the redshift-distance relation: "The receding velocities of extragalactic nebulae are a cosmical effect of the expansion of the universe," Lemaître wrote in 1927.[5] Hubble's observational work helped to establish this evolutionary model of the universe: through his work the expanding universe had become a reality by the mid-1930s.[6]

"[T]hrough the efforts of Hubble and others, the practice and the very nature of the enterprise of cosmology had themselves been transformed," Smith wrote about the first three decades of the 20th century.[7] The transformed *nature* of cosmology was the universe's re-description in terms of the geometry of spacetime and its expansion; the transformed *practice* of cosmology was the new observational cosmological program that was set up by Hubble to measure this cosmic curvature. By determining the velocity of galaxies further into space, possible deviations from linearity in the Hubble diagram could be measured. These deviations would indicate how the expansion of the universe was decelerating. This showed how the Einsteinian universe was curved,

4 A. Friedmann, "Über die Krümmung des Raumes," *Zeitschrift für Physik* 10, no. 1 (1922): 377–386; G. Lemaître, "Note on De Sitter's Universe," *Journal of Mathematics and Physics* 4, nos. 1-4 (1925): 188–192.

5 G. Lemaître, "Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques," *Annales de la Société Scientifique de Bruxelles* 47 (1927): 58; translated in G. Lemaître, "A Homogeneous Universe of Constant Mass and Increasing Radius accounting for the Radial Velocity of Extra-galactic Nebulae.," *Monthly Notices of the Royal Astronomical Society* 91, no. 5 (1931): 489.

6 For the early cosmological models of Einstein and de Sitter and the origins of relativistic cosmology, see: Pierre Kerszberg, *The Invented Universe: The Einstein-De Sitter Controversy (1916-17) and the Rise of Relativistic Cosmology* (Oxford: Oxford University Press, 1989). Hubble himself never admitted his observations were proof of an expanding universe. For more on Hubble's formulations and role in the establishment of the expanding universe hypothesis, see Kragh and Smith, "Who discovered the expanding universe?" For a detailed exposé on Hubble and relativistic cosmology, see Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, chapters 1 and 2.

7 Smith, "Edwin P. Hubble and the Transformation of Cosmology."

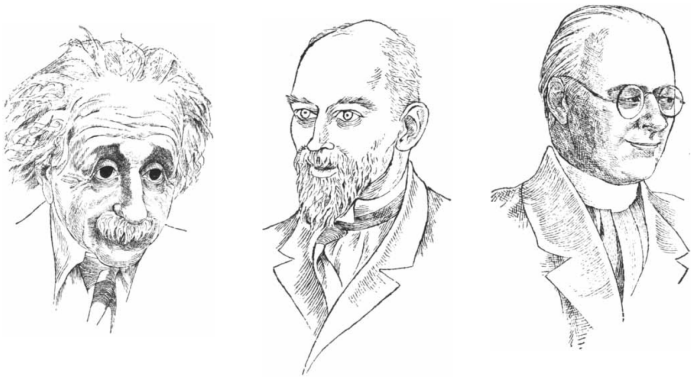

Figure 46: Drawing of "contributors to modern cosmology" as depicted in a popular article by Gamow in Scientific American (1956). From left to right, Albert Einstein, Willem de Sitter and Georges Lemaitre. Drawings by Bernadette Bryson. George Gamow, "The Evolutionary Universe," *Scientific American* 195, no. 3 (1956): 137.

and helped to determine the correct cosmological model (see box "Models of the Universe").

Hubble's way of doing cosmology became paradigmatic. The approach was centered on refining the Hubble diagram, and this was also the central aim of the 200-inch Hale telescope at Palomar mountain that saw first light in 1949. By 1949, Lemaître and physicist George Gamov had connected relativistic cosmology to the hypothesis of a "primeval atom" – a very dense and hot initial stage from which the universe expanded.[8] Gamov had connected relativistic cosmology with nuclear physics in the 1940s, but, by the 1950s, relativistic cosmology was still mainly understood in terms of the Friedmann-Lemaître picture: as a model (or set of models) in which the dynamics of Einstein's field equa-

8 Note that the idea of an expanding universe did not intrinsically involve the hypothesis of a cosmic origin, or what was known as Lemaître's "primeval-atom" hypothesis. This idea was mainly celebrated by Lemaître and Gamov, but it was no integral part of relativistic cosmology at that time. For more on Gamov's approach to cosmology and his influence on forming the big bang picture, see: Alexandre Bagdonas and Alexei Kojevnikov, "Funny Origins of the Big Bang Theory," *Historical Studies in the Natural Sciences* 51, no. 1 (2021): 87–137.

Models of the Universe

According to the Friedmann-Lemaître picture, there were three ways in which the universe could be curved: negative curvature ($k = -1$) which meant the universe was spatially "open", positive curvature ($k = 1$) which was a spatially "closed" universe, or a special model which had no intrinsic curvature (spatially "flat"). The curvature determined how the universe would evolve, and could be determined by measuring the deceleration of the universe (q_0) in the Hubble diagram (see box "Relativistic Cosmology").

Curvature	*Model*	*Evolution*	*Deceleration*
$k = -1$	Open	Ever-expanding	$0 \leqslant q_0 < 1/2$
$k = 0$	Flat	Ever-expanding	$q_0 = 1/2$
$k = 1$	Closed	Collapse	$q_0 > 1/2$

Table 1: The three parameters that distinguish different types of models of the universe, for a universe that has no pressure component and no contribution of the cosmological constant (i.e. "matter-dominated"; $\Lambda = P = 0$).

tions describe the expansion of the universe (see box "Relativistic Cosmology").

Partially due to the fruits of post-war observational programs in astronomy, the early 1950s knew increased attention to cosmological issues. Reason for this we have encountered earlier in this thesis, and include a new estimate of the rate of expansion of the universe – the Hubble constant, H_0 – by Baade in 1952, and later by Humason, Mayall and Sandage in 1956, increasing the age of the universe by a factor of three.[9] In the 1950s, radio astronomers agreed on the extra-galactic nature of observed radio sources, making these bright sources of cosmic relevance. So did new cat-

9 Baade, W. In 28. Commission des nebuleuses extragalactiques. In *Transactions of the International Astronomical Union VIII* (Cambridge: Cambridge University Press, 1954), 397–399); Humason, Mayall, and Sandage, "Redshifts and magnitudes of extragalactic nebulae."

alogues of galaxies appear from surveys of unprecedented size done by the Lick and Palomar observatories.[10] This information could help refine the Hubble diagram. Despite these developments, good and relevant cosmological observations were still considered scarce and hard to obtain in the 1950s.[11] Indeed, empirical novelties were only partially responsible for the increased attention to cosmological research in the period. A large part of the increasing volume of work and publications on cosmology was due to a clash between two theories of the cosmos: relativistic cosmology and the steady state theory of the universe.

Relativistic Cosmology

The general dynamics of a relativistic universe, as it was discussed by Friedmann, Lemaitre, Robertson and others from the 1930s onward, was governed by the *expansion rate* of the universe. This rate is described by the scale factor, R, with R_0 being its present value. The scale factor describes how the universe expands, that is, how the scale of the universe – the separation of two frames of reference – changes with time. The Hubble parameter, that relates the relative recession velocity of galaxies to their distance, can be expressed in terms of the rate of change of the scale factor: $H_0 = \dot{R}_0/R_0$.

The equations that governed an expanding universe, as they were formulated by Friedmann in the 1920s and expanded upon by others, had the following form:

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2}) + \frac{1}{3}\lambda \qquad (14)$$

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} + \frac{1}{3}\lambda - \frac{kc^2}{R^2} \qquad (15)$$

10 M. L. Humason, N. U. Mayall, and A. R. Sandage, "Redshifts and magnitudes of extragalactic nebulae.," *The Astronomical Journal* 61 (1956): 97; Martin Ryle, "Radio Galaxies," *Scientific American* 195, no. 3 (1956): 204–221; Shane and Wirtanen, "The distribution of extragalactic nebulae"; Abell, "The National Geographic Society-Palomar Observatory Sky Survey."

11 Smith, "Beyond the Galaxy: The Development of Extragalactic Astronomy 1885-1965, Part 1."

Here G and c are, respectively, the gravitational constant and light speed. The cosmological constant λ indicates a repulsive force exerted by the vacuum in the universe. For our purposes it is sufficient to know that it became common to argue that $\lambda = 0$. The same held for the pressure P. The quantity k is a constant that gives the curvature of space. Finally, ρ signifies the mass density of the universe. The Friedmann equations are completely determined by two observable parameters: the rate of expansion (H_0), and the rate of deceleration of the expansion, given by the deceleration parameter q_0.

$$q_0 = -\frac{\ddot{R}_0 R_0}{\dot{R}_0^2} \tag{16}$$

The deceleration tracks how much the Hubble constant changes over time. The value of q_0 can be determined from the Hubble diagram. With q_0, and knowing H_0, one could determine the curvature k of the universe, and whether the universe will expand forever or contract again.

The expanding relativistic model had been criticized in various ways, but with the formulation of the steady state theory in 1948 it obtained its most concrete form. The theory was introduced in two different forms by three Cambridge physicists: one by Hermann Bondi and Thomas Gold, and another by Fred Hoyle, as an attempt to resolve a discrepancy between the relativistic theory and observations.[12] This discrepancy mainly consisted of a mismatch between the time-scales of the relativistically predicted age of the universe, and the much larger estimated age of the Earth.[13] Bondi, Gold, and Hoyle also had serious reservations about the unphysical and unscientific nature of the idea of a

12 H. Bondi and T. Gold, "The Steady-State Theory of the Expanding Universe," *Monthly Notices of the Royal Astronomical Society* 108, no. 3 (1948): 252–270; F. Hoyle, "A New Model for the Expanding Universe," *Monthly Notices of the Royal Astronomical Society* 108, no. 5 (1948): 372–382.

13 After the revision of the Hubble constant by Baade in 1952, the mentioned time-scale problem became less problematic for relativistic cosmology, although it did

cosmic origin, which, although not unanimously agreed upon by relativists, was implied by an expanding universe. "The big-bang idea," Hoyle said during a 1949 talk on BCC Radio, "seems to me to be in the philosophical [sic] a distinctly unsatisfactory notion, since it puts the basic assumption out of sight where it can never be challenged by a direct appeal to observation."[14] In addressing his discontent with the theory, Hoyle had given it its new name: the big bang theory.[15]

The steady state alternative of Hoyle, Bondi and Gold was a universe that on the large scale is steady and unchanging. It was infinite of age with a constant average density. This solved both the time-scale difficulty and the need for an initial big bang origin. Yet, to reconcile their ideas with the observed expansion of the universe, steady state theorists hypothesized a "continuous creation of matter."[16] So, a mechanism was needed in the steady state model through which new matter was created in the universe such that its density stayed constant during the expansion. The idea was met with skepticism by many relativists. The friction between the steady steady model and relativist cosmology turned into the dominant polemic of 1950s cosmology.

3.2 DEDUCTION OR EXTRAPOLATION? (1949 - 1955)

Steady state theorists had challenged the physical foundations of relativistic cosmology. The resulting debate between these parties dominated cosmological practice in the 1950s, and showed the absence of a unanimously accepted theory, method or practice that defined what a science of the cosmos looked like. This is illustrated by the many reviews, textbooks and popular articles that addressed the conundrum of theorizing the cosmos – all having a

not fully disappear. See e.g. Hermann Bondi, *Cosmology* (Cambridge: Cambridge University Press, 1952), 140.

14 Fred Hoyle, script of his 1949 lecture at the BCC, Fred Hoyle: An Online Exhibition, St. John College Cambridge.

15 On the origin of the name "big bang," see e.g. Helge Kragh, "Big Bang: the etymology of a name," *Astronomy & Geophysics* 54, no. 2 (2013): 28–2.

16 Hoyle, "A New Model for the Expanding Universe," 273.

Figure 47: Fred Hoyle at BBC Radio 4 "Desert Island Discs" in 1954. Credit: BBC.

different angle of approach.[17] At the same time, as Helge Kragh has emphasized, these debates show the fundamental philosophical character of cosmological practice in the 1950s.[18]

The very nature of cosmology as a proper science of the universe was at stake in the debate between steady state theory and relativistic cosmology. How do you study the cosmos, and what methods should guide this inquiry? Because of the friction between the groups of theorists, such philosophical questions started to be elaborately discussed in the 1950s. The different methodological positions in this debate were often divided into

17 F. Hoyle, *The Nature of the Universe* (New York: Harper & Brothers, 1950); Bondi, *Cosmology*; G. C. McVittie, *Cosmological Theory*, 2nd (London: Methuen & Co. Ltd. 1952); W. H. McCrea, "Cosmology," *Reports on Progress in Physics* 16, no. 1 (1953): 321–363; T. Gold, "Cosmology," *Vistas in Astronomy* 2 (1956): 1721–1726; George Gamow, "The Evolutionary Universe," *Scientific American* 195, no. 3 (1956): 136–156; Harold P. Robertson, "The Universe," *Scientific American* 195, no. 3 (1956): 72–81.

18 Helge Kragh has reviewed the details of these discussions in his 1996 book: Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, 219-251. Much of the tensions of the methodological debates in 1950s cosmology are rooted in early debates from the 1930s. See e.g.: George Gale and John Urani, "Milne, Bondi, and the 'Second Way' to Cosmology," in *The Expanding Worlds of General Relativity*, ed. Hubert Goenner et al. (Boston: Birkhäuser, 1999).

two camps by the involved theorists. Steady state theorist Bondi wrote about "extrapolating" versus "deductive" attitudes in cosmology; mathematician William McCrea of London's Royal Holloway College wrote about "astrophysical" and "deductive" attitudes; and relativist George McVittie, former student of Arthur Eddington and head of the University of Illinois Observatory, identified them as "empiricist" and "rationalist" approaches.[19] These two styles were argued to roughly coincide with the two theories of the cosmos: steady state theory represented the deductive approach while relativistic cosmology was based on the extrapolation of general relativity theory. We will see that a strict division in approaches might not do historical justice to all theorists, but the dichotomy the actors introduced does highlight the prevailing major methodological tensions and emphasizes the philosophical concerns of cosmologists in the 1950s.

The split between "deductive" and "extrapolating" approaches chiefly concerned what primacy one would award to physical principles. In 1932, Edward Milne formulated an extension of Einstein's famed principle of relativity – the idea that all frames of reference know the same laws of nature. Milne's extended principle held that not only the laws of nature but the universe itself must appear to have the same structure to every observer.[20] This idea has since been known as the "cosmological principle." In more contemporary terms, the principle holds that the matter distribution in the universe is homogeneous and isotropic on large scales.[21] The cosmological principle quickly turned into a central element of attempts to formulate theories of the structure of the universe. However, the prominence given to the principle

19 Bondi, *Cosmology*, 5; McCrea, "Cosmology," 332; G. C. McVittie, *Fact and Theory in Cosmology* (New York: Macmillan, 1961), 12.

20 E. A. Milne, "World Structure and the Expansion of the Universe," *Nature* 130, no. 3270 (1932): 10.

21 As with many physical concepts, the exact formulation of the cosmological principle differed between authors. Dennis Sciama formulated the cosmological principle as "[e]ach particle always sees an isotropic distribution of particles around it." D. W. Sciama, "Observational aspects of cosmology," *Vistas in Astronomy* 3 (1960): 312. McVittie put it slightly differently: "[t]he development of the universe appears to be the same for each observer of an equivalent set, every one of whom assigns co-ordinates by the same method." (McVittie, *Cosmological Theory*, 96.

in building and justifying these theories differed widely.[22] That is: should the principle serve as an addendum to theoretical exploration, or does this principle form the very condition of possibility for a science of the universe?

For Bondi and Gold, the cosmological principle explicitly served the latter goal. In their 1948 paper, they reasoned that the cosmological principle is a logical necessity for the universe to be intelligible at all, as it ensures the universal applicability of physical laws such as Newton's laws of motion. Given that physical laws are tested locally, on Earth, Bondi and Gold argued that there is no reason to assume that they could not differ throughout the universe. Then, in pursuing a science of the cosmos, one should provide grounds on which it can actually be assumed that the local physical laws hold everywhere the same. A system of cosmology should be principally concerned with this, Bondi and Gold wrote; it should be able to justify the "unrestricted repeatability of all experiments."[23] For them, relativistic cosmology lacked a way to guarantee this unrestricted repeatability.

The steady state theorists found the grounds on which to justify the universal application of known physical laws in what they called the "perfect cosmological principle."[24] Their extension of the cosmological principle said that on the largest scales, the universe looks the same on every position in both space *and* time. To avoid any dependencies of physical laws, in future and past, one should not only assume that the universe looks the same everywhere, but also that it is unchanging. Hence, as Bondi put it, one should "postulate that position in space and time is irrelevant"; this way, physical laws on Earth would be universally applicable.[25] Without the perfect cosmological principle, "cosmology," Bondi and Gold wrote, "is no longer a science."[26] Because of the way they prioritized *a priori* principles, these steady steady

22 In a review of cosmology in 1953, McCrea wrote: "All the theories to be discussed require their models to conform to the cosmological principle (CP), though we shall see that they do so for somewhat different reasons." McCrea, "Cosmology," 326.

23 Bondi and Gold, "The Steady-State Theory of the Expanding Universe," 252.

24 Ibid., 254.

25 Bondi, *Cosmology*, 11.

26 Bondi and Gold, "The Steady-State Theory of the Expanding Universe," 255.

theorists were identified as rationalist or deductivist by the likes of McVittie and other relativists.

For Hoyle's version of the steady state theory things worked a bit differently. He worked on a relativistic extension of Einstein's field equations, and did not share Bondi and Gold's worries about the validity of physical laws. Hoyle emphasized that formulations of these laws in terms of fields would mean that their validity is guaranteed everywhere. In a similar fashion he disagreed about the role of the perfect cosmological principle. He remarked in 1949: "[i]t is believed that the wide [perfect] cosmological principle should follow as a consequence of primary axioms of the field form [...] and should not appear itself as a primary axiom."[27]

Despite Hoyle's different attitude, he was still often grouped with Bondi and Gold in having a deductive approach to cosmology. This was because Hoyle's justification of a steady state theory in 1948 hinged primarily upon the introduction of continuous creation of matter.[28] This initial assumption was often criticized on being an "arbitrary alteration" of the field equations.[29] There was no experimental evidence for such an alteration, so there would be no reason to abandon the fundamental principles of energy conservation in favor of Hoyle's idea of the creation of matter. Hoyle, involved in studies of stellar nucleosynthesis, was no less concerned with observations than were the proponents of relativistic cosmology. His disagreement with relativistic cosmology, however, does seem to have been considered a matter of principle.

The claim of having a deductivist or rationalist approach to cosmology was not restricted to steady state theorists. In the 1930s, Edward Milne's introduction of a kinematic relativistic world model – a description of the universe without a need for Einstein's full gravitational theory – based on deductive reasoning

27 F. Hoyle, "On the Cosmological Problem," *Monthly Notices of the Royal Astronomical Society* 109, no. 3 (1949): 371.

28 Hoyle, "A New Model for the Expanding Universe."

29 Heckmann, O. In Stoops, *La Structure Et l'Évolution de l'Univers: Rapports Et Discussions*, 76.

from a set of principles[30] Lemaître even traced rationalist philosophical attitudes in cosmology back to Leibniz.[31] During the 1950s, however, this approach began to be discussed programmatically and more explicitly. This happened as steady state theorists used their methodological convictions to defend their theory. In his 1952 textbook on cosmology, Bondi wrote that "it is a dangerous habit of the human mind to generalize and to extrapolate without noticing that it is doing so."[32] Thomas Gold more specifically warned against uncritical extrapolation of known physical laws: "[n]o prejudices about physical principles must be used there when they would be based merely on the acquaintance with a much smaller scale of the physical world."[33] In these discussions, the division of approaches to cosmology started to take shape.

While the steady-state theorists explicitly discussed their methodologies, relativistic cosmologist did this much less. Their approach was formulated mainly as a response to the steady state theory. The cosmological principle was also less central in relativistic cosmology. The principle was used as an additional criterion for obtaining special solutions of the field equations, not as an axiomatic statement. Influential cosmologists in the 1950s advocating an approach to cosmology that opposed that of Bondi and Gold included McVittie, and astronomer and philosopher Herbert Dingle. Especially the latter was fierce in his response to the steady state theorists. In 1956, Dingle, former president of the Royal Astronomical Society, wrote that "[s]ome cosmologists have returned to the discredited practice of inventing arbitrary general principles, with no justification except that they seem 'right,' and fitting phenomena to the requirements of the

30 See:Edward Arthur Milne, *Relativity, Gravitation and World-Structure* (Oxford: The Clarendon Press, 1935).

31 In 1958 Lemaître stated: "As far as I can see, the inclination to rely on an a priori principle is related to Leibnitz [sic] philosophical attitude which made him to believe that there is some esthetical design in the Universe or even that the Universe is determined as being the best possible one" G. Lemaître, "The Primeval Atom Hypothesis and the problem of the Clusters of Galaxies," in *La structure et l'évolution de l'univers*, ed. R. Stoops (Bruxelles: Institut International de Physique Solvay, 1958), 2.

32 Bondi, *Cosmology*, 6.

33 Gold, "Cosmology," 1721.

principles," referring to the steady state theorists and the perfect cosmological principle.[34]

Most relativists were similarly, but in a less pronounced way, in pursuit of what some were calling an "empirical" methodology. German cosmologist Engelbert Schücking and astronomer Otto Heckmann, for example, found that "[a] theory constructed on a sound foundation of empirical data ought not to be discarded unless [...] new facts turn up that cannot be fitted into the framework of this theory."[35] The theory to which Schücking and Heckmann referred here is Einstein's theory of general relativity. For relativistic cosmologists, the legitimacy of Einstein's theory was given priority over cosmological principles.

3.3 RELATIVITY'S RENAISSANCE & MACH'S PRINCIPLE (1955 - 1962)

"As of the present no one model can lay exclusive claim to being the best representation of the actual universe," Caltech cosmologist and mathematician Howard Robertson summarized in 1956.[36] Yet, in the second half of the 1950s this changed, and relativistic cosmology gained more support. Some of these developments were observational, like the counts of radio sources of galaxies that first appeared in 1955: Martin Ryle and Peter Scheuer, radio astronomers in Cambridge, used these counts to argue that the density of galaxies in the past was bigger than it is today, showing that the universe could not be in a steady state.[37] The development that we will discuss in more detail is how the growth of research on the theory of general relativity increased support for relativistic cosmology. The revival of work on general relativity was another driver behind the development of

34 Herbert Dingle, "Cosmology and Science," *Scientific American* 195, no. 3 (1956): 234.

35 Engelbert L. Schucking and Otto Heckmann, "World Models," in *La structure et l'évolution de l'univers*, ed. R. Stoops (Bruxelles: Institut International de Physique Solvay, 1958), 149.

36 Robertson, "The Universe," 81.

37 M. Ryle and P. A. G. Scheuer, "The Spatial Distribution and the Nature of Radio Stars," *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 230, no. 1183 (1955): 448–462.

interest in cosmological issues, and its involvement gives another perspective on how extra-empirical matters dominated 1950s cosmology – also in the relativistic approach.

Although the flourishing modern era of gravitational wave astronomy and black hole physics would seem to suggest otherwise, research on the physics of gravity has been waxing and waning throughout the twentieth century. Whereas the subject bloomed shortly after Einstein's introduction of the theory of general relativity, historian Jean Eisenstaedt has argued that from the mid-1920s to the 1950s gravitational physics knew a low-watermark period of stagnated research activity.[38] Only in the mid-1950s the tide turned for gravity's relative weight in physics research – a period Physicist Clifford Will dubbed the "renaissance of general relativity."[39] Alexander Blum, Roberto Lalli and Jürgen Renn have shown that this period was characterized by the rise of dedicated conferences, community formation and the recognition of the general relativity's "untapped potential" as a physical theory.[40] By the late 1950s an integrated research field of gravitational physics arose and caused a "global transformation in the character of [general relativity]," they argued.[41] This transformation, we will show now, implied a change in the relationship between cosmology and relativity. In particular, the growth of the authority of general relativity increased support for a relativity-based extrapolating attitude to cosmological research.

Steady state theorists, often trained in relativity, joined in meetings on gravitational physics, and brought the discussion on how to approach cosmology to the attention of gravity scholars.

38 Jean Eisenstaedt, "La relativité générate á l'étiage: 1925 - 1955," *Archive for History of Exact Sciences* 35 (1986); Jean Eisenstaedt, "Trajectoires et Impasses de la Solution de Schwarzschild," *Archive for History of Exact Sciences* 37 (1987); Jean Eisenstaedt, "The Low Water Mark of General Relativity, 1925 - 1955," in *Einstein and the History of General Relativity*, ed. D. Howard and John Stachel (Boston: Birkhäuser, 1989).

39 Clifford M. Will, *Was Einstein right? Putting general relativity to the test.* (n.p.: Basic Books, 1986); Clifford M. Will, "The Renaissance of General Relativity," in *The New Physics*, ed. P.C.W. Davies (Cambridge: Cambridge University Press, 1989).

40 Alexander Blum, Roberto Lalli, and Jurgen Renn, "The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-time," *Isis* 106, no. 3 (2015): 618.

41 "Editorial introduction to the special issue "The Renaissance of Einstein's Theory of Gravitation"":98.

One of the most influential scholars in the new field of gravitational physics that responded to this issue was Princeton professor John Wheeler. During one of relativity's renaissance most famous meetings – the 1957 Chapel Hill conference – Wheeler expressed his view on how to approach cosmology. He commented on the work of steady state theorist Thomas Gold by stating that "one should not give up accepted ideas of wide applicability such as general relativity but should investigate them completely."[42] Wheeler's take on cosmology dominated the discussions on relativity and cosmology in the late 1950s: an approach to cosmology that centered around the extrapolation of general relativity.

This view became more ingrained as confidence in the potential of the theory of general relativity kept increasing; evidenced, for example, by extensive work on the possible existence of gravity waves.[43] By the early 1960s, the general opinion was that general relativity was fundamentally true and that this needed little debate. Venerable physicist and Princeton colleague of Wheeler, Robert Dicke, wrote that "[specialists] take it as axiomatic that general relativity is correct in all its details and that one must compute with this theory."[44] Dicke was one of the few people researching alternatives to Einstein's theory. The confidence in relativity's correctness had consequences for how cosmology was perceived to be done. In 1962, Wheeler reflected on the transformation that the status of general relativity had recently undergone:

> Increasing numbers of investigators share the conviction that Einstein's 1915-1916 analysis of the curvature of space by energy is a unique theory, of unrivalled scope and reasonableness, against which no objection of principle or observation has ever been

42 Wheeler, in Cécile DeWitt-Morette and Dean Rickles, "The Role of Gravitation in Physics," in *Report from the 1957 Chapel Hill Conference* (n.p.: Edition Open Sources, 1957), 129.

43 See for an overview Alexander Blum, Roberto Lalli, and Jürgen Renn, "Gravitational waves and the long relativity revolution," *Nature Astronomy* 2, no. 7 (2018): 534–543, especially pp. 539-540.

44 R. H. Dicke, "Remarks on the Observational Basis of General Relativity," in *Gravitation and relativity*, ed. Hong-Yee Chiu and William F. Hoffman (New York: W.A. Benjamin, Inc, 1964), 1.

> sustained, and out of which one should now try to read the deeper meaning and consequences. Among these consequences some of the most interesting have to do with the dynamics of the universe.[45]

Between 1955 and 1963, the relation between cosmology and relativity transformed. Where Einstein's former research assistant Peter Bergmann wrote in 1957 that cosmology was "not intimately connected" with other aspects of relativity that most theorists were working on, this sentiment had changed by the early 1960s.[46] General relativity was a supplying a new "rationale" for practicing cosmology, as Wheeler put it in 1962.[47] The increasing confidence in the theory of relativity made cosmological research relevant and urgent: cosmology became both a product of and the testing grounds for the theory of general relativity.

At the moment that the success of general relativity theory became a rationale for doing cosmology, the climate changed around the steady state versus big bang theory debate. As the steady state theory challenged general relativity theory through its dismissal of relativistic cosmology, the latter began to be favored. Helge Kragh similarly reflected that relativistic cosmology's increasing status in the late 1950s is "probably related to the simultaneous revival of interest in the general theory of relativity."[48] One of the criticisms of the steady state theorists was that they had been unable to formulate a formulation of the theory in terms of Einstein's theory of gravity – to which it eventually should also abide. Kragh pointed out that, in response to these criticisms, Hoyle's, McCrea's, and later versions of the steady state theory were being designed to conform to the mathematics of general relativity through Einstein's field equations.[49] In this way too, the increase in authority of Einstein's gravita-

45 John Archibald Wheeler, "The Universe in the Light of General Relativity," *Monist* 47, no. 1 (1962): 40.

46 Peter G. Bergmann, "Summary of the Chapel Hill Conference," *Reviews of Modern Physics* 29, no. 3 (1957): 352.

47 Wheeler, "The Universe in the Light of General Relativity," 75.

48 Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, 318.

49 Kragh, "Steady State Cosmology and General Relativity: Reconciliation or Conflict?," 398.

tional theory was reflected in how cosmology was ought to be done.

According to McVittie, avid defender of relativistic cosmology, the general relativity point of view was "that scientific cosmology should be based on the laws of physics as we know them from experiment and observation rather than on hypotheses and principles laid down a priori."[50] This was the approach that McVittie had called the "empirical" approach, and this became the dominant way to call the method of relativistic cosmology. But how "empirical" was this approach really? One could be quite skeptical of McVittie's remarks on the method of relativistic cosmology. That is, the less empirical and more *philosophical* foundations of Einstein's theory itself also kept lingering within cosmology.

The identification of relativistic cosmology as "empirical" in approach is confusing. First of all because steady state theorists were very "empirical," in the sense that they provided concrete testable predictions, as Bondi often reiterated, and were keen on addressing empirical findings, like Hoyle and his work on the abundances of elements. Secondly, to describe general relativity theory's methodological underpinning as "empirical" would be quite incorrect.[51] "[T]he origins of General Relativity are mainly philosophical rather than observational", Robert Dicke reflected in 1961.[52] The theory was deductively constructed on the basis of basic principles – even Einstein himself called it a "principle-theory."[53]

There was one principle on which the theory of general relativity was based that was particularly debated; this was the idea

50 G. C. McVittie, "Rationalism versus Empiricism in Cosmology," *Science* 133, no. 3460 (1961): 1232.

51 For a comprehensive overview of the genesis of general relativity, see: Jürgen Renn, ed., *The Genesis of General Relativity*, Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 2007). For an in-depth discussion of Einstein's methodology and its development, see: Jeroen van Dongen, *Einstein's Unification* (Cambridge: Cambridge University Press, 2010).

52 R. H. Dicke, "Mach's Principle and Equivalence," in *Proceedings of the International School of Physics Enrico Fermi XX: Evidence for Gravitational Theories. Held between June 19 and July 1 in Verenna, Italy.*, ed. C. Møller (n.p.: Academic Press, 1962), 4.

53 Albert Einstein, "What is the Theory of Relativity?," in *Ideas and Opinions* (New York: Bonanza, 1954), 228. Einstein's reasoning was based on the equivalence between inertial and gravitational mass, which he dubbed the "equivalence principle." See also Van Dongen, *Einstein's Unification*, especially pp. 49-51.

known as "Mach's principle." This principle was a recurring subject in discussions during the renaissance period in the 1950s. The fact that this principle was again fiercely discussed in the context of general relativity and cosmology in the 1950s, just as it had during the 1910s in debates between Einstein and de Sitter, sheds light on how relativistic cosmology, just as the steady state theory, had deep ties with philosophical ideas and principles.[54]

Ernst Mach's famed principle was reminiscent of the Austrian physicist and philosopher's elaborate criticism of Newton's absolute notions of space and motion. Nearing the end of the 19th century, Mach had argued that mechanics is not based on absolute, but on the *relative* position and movement of bodies.[55] This relationist view had far-reaching implications for Mach's notion of inertia. He presented a particular argument for understanding the inertia on a rotating sphere like the Earth. We know that on the surface of a rotating sphere (e.g. the earth), one experiences inertial forces like that of the centrifugal force. But because there is no absolute rotation, he argued, an observer on the surface of a sphere should notice no physical difference in either having the sphere rotate with respect to distant objects, or having distant objects rotate around the sphere. With Mach's insights, "the principles of mechanics" could be so understood "that even for relative rotations centrifugal forces arise."[56] Because of this reasoning, Mach suggested there to be a relationship between local

54 Many elaborate studies have been done on Mach's Principle, its general importance and its role in the theory of general relativity. See specifically: Julian B. Barbour and Herbert Pfister, eds., *Mach's Principle: from Newton's Bucket to Quantum Gravity* (Boston: Birkhauser, 1995). The writing of a longue durée history of the principle seems to have not yet been attempted. For debates on Mach's Principle in the 1910s, see Einstein's correspondences in József Illy, A. J. Kox, and Michel Janssen, eds., "Introduction to Volume 8," in *The Collected Papers of Albert Einstein, Vol. 8a* (Princeton: Princeton University Press, 1987).

55 On Mach's method of historical source criticism, see Sjang ten Hagen, "History and physics entangled: Disciplinary intersections in the long nineteenth century" (University of Amsterdam, 2021), chapter 3.

56 Ernst Mach, *The Science of Mechanics: A Critical and Historical Account of Its Development*, 6th ed. (La Salle, Illinois: The Open Court Publishing Company, 1960), 284.

inertial forces (e.g. on Earth), and the distant celestial bodies. This is what Einstein in 1918 dubbed "Mach's principle."[57]

Einstein was profoundly influenced by Mach's ideas on inertia; for a long time he was concerned with having a theory of gravity that fully abided by Mach's mandate.[58] As relativity revived in the 1950s, so did these concerns. The principle came to have a wider interpretation, and more generally was understood as the idea that the local inertial frame depends on, or, in a stronger form, is determined by the mass distribution of the universe. In this sense, the adjective "Machian" was used for any connection between local dynamics and the structure of the universe.[59] During the renaissance of general relativity, many physicists took Mach's principle to be fundamental to gravity theories.

Dennis Sciama, graduated in 1953 from Cambridge under supervision of Paul Dirac, was central in the revival of work on Mach's principle. His doctoral work resulted in a novel take on the "origin of inertia", in which he proposed a Machian-like long-range interaction with distant matter (see Figure 48).[60] Mach's principle was put high on the list of the newly developing research agenda of gravitational physics. Referring to

57 Albert Einstein, "Prinzipielles zur allgemeinen Relativitätstheorie," *Annalen der Physik* 360, no. 4 (1918): 16.

58 For the role of Mach's principle in the development of general relativity, see e.g. Carl Hoefer, "Einstein's struggle for a Machian gravitation theory," *Studies in History and Philosophy of Science Part A* 25, no. 3 (1994): 287–335; Jürgen Renn, "The Third Way to General Relativity: Einstein and Mach in Context," in *The Genesis of General Relativity*, ed. Michel Janssen et al. (Dordrecht: Springer Netherlands, 2007); Julian B Barbour, "Einstein and Mach's Principle," in *The Genesis of General Relativity*, ed. Michel Janssen et al. (Dordrecht: Springer Netherlands, 2007); Dennis Lehmkuhl, "Why Einstein did not believe that general relativity geometrizes gravity," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 46 (2014): 316–326; and, Michel Janssen, ""No Success Like Failure...","," in *The Cambridge Companion to Einstein*, ed. Michel Janssen and Christoph Lehner (Cambridge: Cambridge University Press, 2014).

59 There were many different and more technical definitions of Machian ideas. See Goenner (1970) and references therein for examples of the use of "Mach's principle" and "Machian" in the 1950s and 1960s: Hubert Goenner, "Mach's Principle and Einstein's Theory of Gravitation," in *Ernst Mach: Physicist and Philosopher*, ed. Robert S Cohen and Raymond J Seeger (Dordrecht: Springer Netherlands, 1970). For a pre-1950s definition of Mach's principle, see e.g. H. P. Robertson, "Relativistic Cosmology," *Reviews of Modern Physics* 5, no. 1 (1933): 62–90.

60 D. W. Sciama, "On the Origin of Inertia," *Monthly Notices of the Royal Astronomical Society* 113, no. 1 (1953): 34–42.

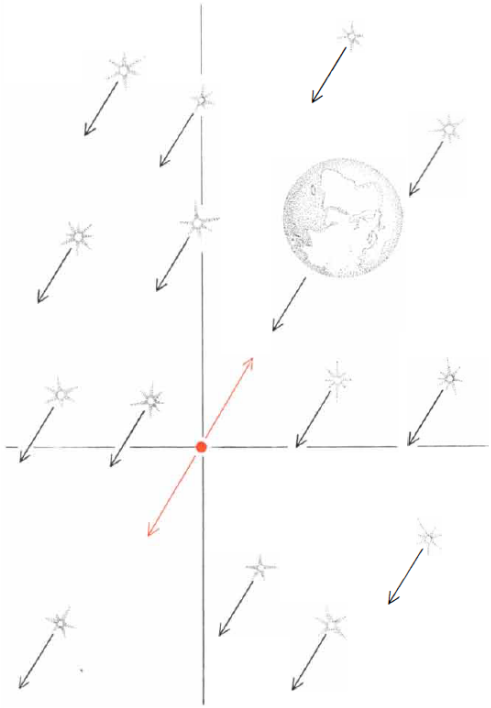

Figure 48: Image used to convey Dennis Sciama's interpretation of Mach's principle in a 1957 popular science article. The relativity of motion allows for two interpretations of the situation: in the rest frame of the earth, a falling body (center dot) is accelerating towards the earth with respect to the earth and the stars; in the rest frame of the body, the earth and the stars are accelerated with respect to the body. This is pictured in the image (accelerations given by the black arrows). In the rest frame of the body, an inertial force is needed to compensate for the gravitational attraction of the earth because the net force should be zero (arrows at the dot). In Sciama's view of Mach's principle, all (inertial) forces must have their physical origin in actual matter, hence, in his words, "the gravitational attraction of the earth, and the force due to the rest of the mass in the universe (colored [central] arrows) balance each other exactly. This suggests a method for measuring the mass of the universe." In: Dennis Sciama, "Inertia," *Scientific American* 196, no. 2 (1957): 109.

Sciama's work, Wheeler orated at the Chapel Hill conference in 1957 that one of general relativity's important open problems was "spelling out Mach's principle in a better-defined way."[61] Robert Dicke was similarly concerned with Mach's ideas. He wrote about their importance on many occasions in the late 1950s and early 1960s, and was influential in discussing experiments on testing Mach's principle through possible mass anisotropies in the universe.[62] In 1961, Dicke and Princeton student Carl Brans proposed what came to be known the Brans-Dicke theory of gravitation, to come into accordance with Machian ideas.[63]

In cosmology too, Mach's principle was of great importance during the 1950s. It served as a foundation for both steady state and relativistic cosmology. Mach's principle formed a central motivation for the steady state theorists' "Perfect Cosmological Principle"; that is, when there exists a Machian connection between the cosmic distribution of mass and local inertia, a different mass distribution in the earlier universe might imply different local laws of physics. The steady state theorists tried to avoid such a possibility with their reasoning: "If the uniformity of the universe is sufficiently great none of these difficulties arise," steady state theorist Bondi wrote in his 1952 textbook.[64]

Relativistic cosmology's relation with Mach's principle had deeper and more complex historical ties. In Einstein's cosmological paper of 1917, he had emphasized that inertia should follow

61 John Archibald Wheeler, "The Present Position of Classical Relativity Theory and Some of its Problems," in *The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference*, ed. Dean Rickles and Cécile DeWitt-Morette (n.p.: Edition Open Sources, 1957), 46.

62 See e.g. Robert H Dicke, "New Research on Old Gravitation," *Science* 129 (1959): 621–624; Dicke, "Mach's Principle and Equivalence." If the universe looked different in two opposing directions, Mach's principle seemed to dictate that, in these directions, inertia might work differently. For experimental test see e.g. G. Cocconi and E. E. Salpeter, "Upper Limit for the Anisotropy of Inertia from the Mössbauer Effect," *Physical Review Letters* 4, no. 4 (1960): 176–177, and R. H. Dicke, "Experimental Tests of Mach's Principle," *Physical Review Letters* 7, no. 9 (1961): 359–360. For a historical overview of Dicke's important work, see Phillip James Edwin Peebles, "Robert Dicke and the naissance of experimental gravity physics, 1957–1967," *The European Physical Journal H* 42, no. 2 (2017): 177–259.

63 C. Brans and R. H. Dicke, "Mach's Principle and a Relativistic Theory of Gravitation," *Physical Review* 124, no. 3 (1961): 925–935.

64 Bondi, *Cosmology*, 12.

from a body's gravitational interaction with all the other masses in the universe. In any model of the universe, he reasoned, a mass at sufficient distance from all the other masses should have its inertia fall to zero. Einstein tried different ways of implementing this Machian condition. He found it most satisfactory to use it as a selection criterion: the relativistic model that can realize the Machian condition is the correct one. For Einstein, this model was a universe that is *spatially closed* (see box "Models of the Universe" on page 179).[65] During a series of lectures at Princeton University in 1921, Einstein spelled out his epistemological preference for a closed universe explicitly:

> [T]his idea of Mach's corresponds only to a finite universe, bounded in space [...]. From the standpoint of epistemology it is more satisfying to have the mechanical properties of space completely determined by matter, and this is the case in a closed universe.[66]

Whether or not adding the assumption of a closed universe would make general relativity truly Machian was, and still is, disputed.[67] What cannot be disputed is that the preference for a

65 As both Chris Smeenk and Carl Hoefer have spelled out, Einstein first tried to use Mach's statement as a boundary condition to the field equations. Later, in his 1917 cosmology paper, he had turned away from this perspective. Instead, he used the fact that a spatially closed universe has no boundary region. Einstein noted: "[f]or if it were possible to regard the universe as a continuum which is finite (closed) with respect to its spatial dimensions, we should have no need at all of any such boundary conditions." Albert Einstein, "Cosmological Considerations in the General Theory of Relativity," in *The Collected Papers of Albert Einstein. Volume 6: The Berlin Years: Writings, 1914-1917 (English translation supplement)* (Princeton, NJ: Princeton University Press, 1987), 427. See: Christopher Smeenk, "Einstein's Role in the Creation of Relativistic Cosmology," in *The Cambridge Companion to Einstein*, ed. Michel Janssen and Christoph Lehner (Cambridge: Cambridge University Press, 2014); Carl Hoefer, "Einstein's Formulations of Mach's Principle," in *Mach's Principle: from Newton's Bucket to Quantum Gravity*, ed. Julian B Barbour and H. Pfister (Boston: Birkhauser, 1995). For an in-depth discussion of Einstein's 1917 paper, see Cormac O'Raifeartaigh et al., "Einstein's 1917 static model of the universe: a centennial review," *The European Physical Journal H* 42, no. 3 (2017): 431–474.

66 Albert Einstein, *The Meaning of Relativity* (Dordrecht: Springer Netherlands, 1922), 108.

67 For more information on whether general relativity is Machian see e.g. Dicke, "Mach's Principle and Equivalence," Barbour and Pfister, *Mach's Principle: from Newton's Bucket to Quantum Gravity*, and other references found in footnote 58.

closed universe became broadly shared. Having a universe that is closed was by John Wheeler even seen as an integral part of Einstein's theory of relativity. In 1958, Wheeler considered the following to be the meaning of the term "Einstein's Relativity":

> In speaking about Einstein's theory [...] we mean not only the system of differential equations associated with his name, but also two further points, the present tentative arguments for which he gives in his book [*The Meaning of Relativity* (1922)]:
>
> (1) The universe is closed;
>
> (2) No "cosmological" term is to be added to the field equations.[68]

Tied together with Mach's principle, another philosophical principle, or, say, extra-theoretical idea, was taken on when doing relativistic cosmology: the idea that the universe should be closed. Although relativistic cosmology had been argued to be "empiricist," and the big bang hypothesis in the late 1950s was appearing more and more "victorious," in the words of Kragh, this did not mean the relativistic approach had swept away every *a priori* principle.[69] Cosmology in the 1950s was deeply philosophical in all of its approaches. Yet, as the field developed, these methodological concerns and the interest in Mach's principle appeared decreasingly explicit in cosmological discussions.

3.4 A COSMIC WATERSHED (1960 - 1970)

What it meant to do cosmology fundamentally changed in the 1960s. During this decade, the astronomical discipline was flooded with expected and unexpected observations that bore great cosmological significance. New phenomena started to dominate research, and they changed what were legitimate questions to ask in cosmology; this drove the philosophical discussions of

68 John Archibald Wheeler, "Meaning of the Term, "Einstein's Theory"," in *La structure et l'évolution de l'univers*, ed. R. Stoops (Bruxelles: Institut International de Physique Solvay, 1958), 98.

69 Kragh, "Steady State Cosmology and General Relativity: Reconciliation or Conflict?"

the 1950s to the background. Here, seven examples are given of these transformations in cosmological thinking and doing.

Some of the developments that had a large impact on cosmology in the 1960s have already been discussed in previous chapters, and this includes how extra-galactic astronomy flourished near the end of the 1950s. New catalogues of galaxies based on the surveys of the Palomar and Lick observatories in the late 1950s made it possible to better understand galaxies and their large scale distribution.[70] Upon inspection, the plates of the Palomar survey showed signs of explosive phenomena, galaxy clusters, galaxies breaking up or in collision, and peculiar systems that were ejecting gas. Similarly, the optical identification of radio sources from the Cambridge radio catalog showed the existence of radio galaxies, which possibly indicated large energetic activity in galaxies and their histories.[71] This triggered interest in evolutionary scenarios to account for galaxy formation.

Secondly, radio galaxies also invigorated research in observational cosmology as it had been set up by Hubble. Hubble, who had died in 1953, was succeeded in his attempt to determine the deceleration of the universe by Allen Sandage, a Caltech graduate that had been taken under Hubble's wing in 1949. Because of their distance – radio galaxy 3C 295 was at the furthest distance measured yet of z=0.46 (speeding away at 46% of the light speed) – these objects promised to be great measuring sticks for the deceleration. In 1961, Sandage used them as a standard candles to probe the Hubble diagram deeper into space then it had ever before (see Figure 49). Sandage was optimistic about the ability of the 200-inch Hale telescope to measure q_0 and to discriminate between different cosmological models – steady state or any of the models of relativistic cosmology. He also pointed out that as-

70 These catalogues included Zwicky et al., *Catalogue of galaxies and of clusters of galaxies, Vol. I*; B. A. Vorontsov-Velyaminov, A. A. Krasnogorskaya, and V. P. Arkhipova, *Morphological Catalogue of Galaxies. Part I-V* (Moscow: Moscow State University, 1962); and, Arp, "Atlas of Peculiar Galaxies."

71 For the radio catalogues see Edge et al., "A survey of radio sources at a frequency of 159 Mc/s."; A. S. Bennett and F. G. Smith, "The Preparation of the Revised 3C Catalogue of Radio Sources," *Monthly Notices of the Royal Astronomical Society* 125, no. 1 (1962): 75–86. See also D. W. Sciama, *Modern Cosmology*, 1st ed. (Cambridge: Cambridge: University Press, 1971), 49-82.

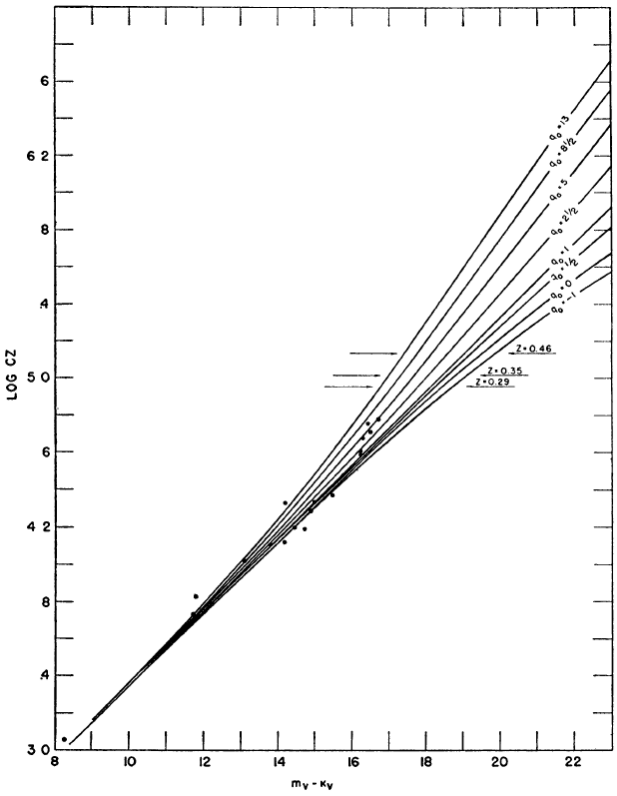

Figure 49: The redshift-magnitude relation as determined by Sandage. The points show the redshift of 18 galaxies. The three arrows show sources of which the magnitudes were speculative, including the radio galaxy 3 C 295 at redshift z=0.46 – the furthest known object at the time. The lines are the expectation based on different values of the deceleration parameter, q_0 (from -1 to 13). These are the different "world models." In the steady state case, q_0 should be -1. His data was suggesting that $q \sim 1$. Note that Sandage uses magnitudes of galaxies to probe their distances. The reliability of magnitudes as distance measures were soon to be contested. In: Allan R. Sandage, "The Ability of the 200-inch Telescope to Discriminate Between Selected World Models.," *The Astrophysical Journal* 133 (1961): 367.

tronomers were drawing theory and observation closer together: "[r]enewed interest in the cosmological problem is evidenced by the number of recent papers which treat the fitting of observational data to predictions of the theory."[72]

Thirdly, in 1963, the optical identification of one of the Cambridge radio sources also led to the introduction of a whole new class of objects, the influence of which on astronomy is hard to overestimate: the quasi-stellar radio source; the name that stuck was "quasar." The history of its detection has been well-documented, and we have already encountered part of it in previous chapters.[73] Around 1960, Allen Sandage and radio astronomer Thomas Matthews found that some of radio sources in the catalogs had bright blue stellar counterparts. Matthews and Sandage, and head of the Caltech astronomy department, Jesse Greenstein, worked on optically studying these.[74] So did newly arrived staff-member Maarten Schmidt. Schmidt recognized a large redshift in the spectra of this "star": it was no nearby stellar object, but a enormously distant source that "would be about 100 times brighter optically than the luminous galaxies," Schmidt concluded.[75] Within a year, nine other of such quasars were found. The study of the distribution of these quasars could again help address Hubble-type cosmology, and see whether the universe was different in the past than it is today. At the same time quasars could help to find new galaxies to determine the deceleration parameter even more precisely and further the project of Sandage and others.

But, and this is the fourth point, quasars were much more than a beacon that could be used for classic cosmological tests. Most of all, quasars caused a shift *away* from the Hubble-type cosmology. Their brightness and distance implied an explosive energy

72 Allan R. Sandage, "The Ability of the 200-inch Telescope to Discriminate Between Selected World Models.," *The Astrophysical Journal* 133 (1961): 356.

73 See e.g. Overbye, *Lonely Hearts of the Cosmos: the Scientific Quest for the Secret of the Universe*, especially pp. 67-84.

74 Thomas A. Matthews and Allan R. Sandage, "Optical Identification of 3C 48, 3C 196, and 3C 286 with Stellar Objects.," *Astrophysical Journal* 138 (1963): 30; Jesse L. Greenstein and Thomas A. Matthews, "Red-Shift of the Unusual Radio Source: 3C 48," *Nature 1963 197:4872* 197, no. 4872 (1963): 1041–1042.

75 Schmidt, "3C 273 : A Star-Like Object with Large Red-Shift," 1040.

release of unknown nature: it was calculated to be more than 10^{60} ergs, which is the energy contained in the rest mass of a million solar masses.[76] As an immediate response to the quasar discovery, and to address the puzzling energy release, the first of a very successful series of "Texas Symposia on Relativistic Astrophysics" was held in 1963, in Dallas. Here astronomers, astrophysicists, cosmologists, gravitational physicists, and nuclear physicists participated to discuss the nature of quasars. The theoretical requirements needed for an outburst of such enormous energy had "so far ruled out nearly all of the explanations and theories put forward to explain such extraordinary events", the invitation to the symposium read.[77]

Gravitational physicists became involved in searching for a mechanism of gravitational collapse that might cause such outbursts of energy. The search was spearheaded by John Wheeler. He noted at the Texas symposium that "attention has turned to gravitational collapse as a mechanism by which in principle a fraction of the latent energy of matter much larger than 1 percent can be set free."[78] Proposed mechanisms included the formation of objects that we now understand as neutron stars and "black holes" – a term Wheeler coined in 1967.[79] The conference illustrates that the quasar observation drew physics and astronomy, and physicists and astronomers, yet closer together. At the dinner of the First Texas Symposium, Thomas Gold, known for his work on the steady state theory, made this quite clear: "[e]veryone is pleased, the relativists [...] who are suddenly experts in a field they hardly knew existed; the astrophysicists for having enlarged their domain, their empire, by the annexation of another subject – general relativity."[80] This was the start of what Wheeler's student Kip Thorne called the "golden age" of relativity, and Blum,

76 See e.g. Sciama, *Modern Cosmology*, 61.

77 Robinson, Schild, and Schucking, *Quasi-Stellar Sources and Gravitational Collapse: Proceedings of the 1st Texas Symposium on Relativistic Astrophysics*, v.

78 B. K. Harrison et al., *Gravitation Theory and Gravitational Collapse* (Chicago: University of Chicago Press, 1965), 1.

79 Interview of John Wheeler by Kenneth W. Ford (Session IX) on 1994 March 4, Niels Bohr Library Archives, American Institute of Physics, College Park, MD USA.

80 T. Gold, "After-Dinner Speech," in *Quasi-Stellar Sources and Gravitational Collapse: Proceedings of the 1st Texas Symposium on Relativistic Astrophysics*, ed. Ivor Robinson,

Lalli and Renn dubbed relativity's "astrophysical turn."[81] And the combined efforts of astronomy and physics, which the organizers of the Second Texas symposium themselves called "exotic astrophysics", drew a large audience. Where at the first occasion of the symposium some 300 scientists attended, four years later, in 1967, the third symposium knew more than 600 participants.[82] A new branch of cosmological research was born.

There was another unexpected detection in the mid-1960s that rivalled the quasar in its long-term effects on cosmology; that of the cosmic microwave background radation (CMB). The impact of this detection on cosmology is well known, and its history and subsequent reception has been discussed in several papers and books.[83] In 1964, two radio astronomers at Bell Labs, in Holmdel, New Jersey, observed a low-energetic background radiation in tests to improve the range of Bell Company's "Telstar" communication satellite. The astronomers, Arno Penzias and Robert Wilson, had found an excess radiation at a temperature of about 3 degrees Kelvin with their 20-foot (6 meter) horn reflector antenna.[84] The explanation of this signal noise was provided by a group of physicists a few miles north of Holmdel, in Princeton, where Robert Dicke and his co-workers had just initiated a search for the existence of such a low-energy radiation. If the universe knew a dense and hot early state, Dicke hypothesized, leftover ra-

Alfred Schild, and Engelbert L. Schucking (Chicago: University Of Chicago Press, 1965), 470.

81 Kip S. Thorne, *Black holes and time warps: Einstein's outrageous legacy* (London: W.W. Norton, 1994), 285-299; Blum, Lalli, and Renn, "Gravitational waves and the long relativity revolution," 541-542.

82 André Mercier, "Report of the Third Texas Symposium on Relativistic Astrophysics," *Bulletin on General Relativity and Gravitation* 14 (1967): 1–10. For how these big changes affected how general relativity was practiced between 1950 and 1970, see David Kaiser, "A psi is just a psi? Pedagogy, Practice, and the Reconstitution of General Relativity, 1942-1975," *Studies in History and Philosophy of Modern Physics* 29, no. 3 (1998): 321–338.

83 Kendrick Oliver, ""The lucky start toward today's cosmology"? Serendipity, the "Big bang" theory, and the science of radio noise in Cold War America," *Historical Studies in the Natural Sciences* 49, no. 2 (2019): 151–193; Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, especially pp. 344-355; Kragh, *Conceptions of cosmos: from myths to the accelerating universe: a history of cosmology*.

84 The temperature of a signal is a measure of its intensity; it refers to the temperature needed for a black body to produce the same intensity radiation.

diation of this state, of about 3 Kelvin, must still be around. The papers of both groups, the detection and interpretation, appeared in print in 1965.[85] They were not just a strong confirmation of the big bang picture of the universe; the papers showed that there existed an early universe that one could investigate and understand in terms of known physics – the features of this "relict" radiation, as some called it, could be studied to probe the evolution and structure of the universe.[86]

Around the same time, another probe of the early universe was being studied: the abundance of cosmic helium. The calculations of the synthesis of elements in stars, as done in the famed 1957 paper of Burbidge, Burbidge, Hoyle and Fowler (B^2HF), had not been able to reproduce the observed amount of helium. In 1964, Fred Hoyle and his Cambridge colleague Roger Tayler showed that, to produce the observed amount of helium (of about 25% of the visible mass), one needed a "high-temperature, high-density phase" of the universe.[87] Jim Peebles, student of Robert Dicke in Princeton and co-author of the CMB paper, used the observed cosmic background radiation to infer the temperature and density in the early universe and calculated the resulting helium abundance to be about 27-30%.[88] The success of these calculations reinforced a big bang cosmology, brought into existence a field of research in "big bang nucleosynthesis," and again showed how current observations could be connected to physical mechanisms in the beginning of the universe.[89]

A last demonstration of the rapidly changing astronomical concerns in the 1960s was the increasing focus on questions of the origin and evolution of galaxies in the universe. The topic of galaxy

85 R. H. Dicke et al., "Cosmic Black-Body Radiation.," *Astrophysical Journal* 142 (1965): 414–419; A. A. Penzias and R. W. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s.," *Astrophysical Journal* 142 (1965): 419–421.

86 S. S. Gershtein and Ya. B. Zel'dovich, "Rest Mass of Muonic Neutrino and Cosmology," *Journal of Experimental and Theoretical Physics Letters* 4 (1966): 120.

87 F. Hoyle and R. J. Tayler, "The Mystery of the Cosmic Helium Abundance," *Nature* 203, no. 4950 (1964): 1110.

88 P. J.E. Peebles, "Primeval Helium Abundance and the Primeval Fireball," *Physical Review Letters* 16, no. 10 (1966): 410–413.

89 For a short review of the origins of big bang nucleosynthesis, see Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, 338-442.

evolution began to be methodically addressed in dedicated conference sessions in the 1960s. "The study of evolution of galaxies is now in an early stage of development comparable to that of the study of stellar evolution in 1935", Thornton Page wrote, summarizing such a conference in 1964.[90] Research on the physics that drove galaxies to change developed quickly. Particularly influential was the work of New Zealand astronomer Beatrice Tinsley, at Texas at the time, who used numerical computations to model the evolution of stars and gas in galaxies. In her work, she showed that the brightness of galaxies can rapidly change during their lifetime and therefore it was unreliable to determine distances to galaxies based solely on this brightness.[91] The evolutionary picture of galaxies emphasized what the study of galaxies could mean for cosmology as the initial conditions of galaxies were closely tied to those of the universe.

In 1970, the National Research Council reported to U.S. Congress that "the rapid pace of discovery in astronomy and astrophysics during the last few years has given this field an excitement unsurpassed in any other area of the physical sciences."[92] During the 1960s, a surge of newly observed and theorized cosmic phenomena changed the face of cosmology: active galactic nuclei, radio galaxies, quasars, the CMB, big bang nucleosynthesis, the evolution of galaxies, but also the development of high-energy astrophysics and the discovery of pulsars in 1967. These phenomena drew many different branches of astronomy into the domain of cosmology; astronomy and astrophysics experienced a *cosmological turn*.[93] In this "new turn of events," Dennis Sciama

90 Page, "The Evolution of Galaxies," 804.

91 Beatrice M. Tinsley, "Evolution of the Stars and Gas in Galaxies," *The Astrophysical Journal* 151 (1968): 547. See also: Sandra Faber, "Beatrice Tinsley," *Physics Today* 34, no. 9 (1981): 110.

92 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 1: Report of the Astronomy Survey Committee* (Washington, DC: National Academies Press, 1972), 55.

93 The notion of a "cosmological turn" is related, although distinct, from what Blum et al. call "the astrophysical turn of general relativity" (Blum, Lalli, and Renn 2018, 8). They introduce this term to signify the refocusing of the research agendas of relativists because of the astronomical discoveries of the 1960s. What I try to describe here with a cosmological turn is aimed to be more inclusive: it is the change during the 1960s, in which *astronomical* practices more generally – and

wrote in 1967, "cosmology [was] becoming astrophysical."[94] Indeed, the events of the 1960s redetermined the objects of interest for both physicists and astronomers, and blurred the boundaries between physics and astronomy.

3.5 A HYBRID GENERATION AND REBORN COSMOLOGY

Another boundary that became blurred was between the physicists and astronomers themselves. The new cosmic phenomena that started to dominate the interest of astronomers and physicists in the 1960s was accompanied by transformations in the institutional landscape of astronomy. Specifically, physicists were starting to flood astronomy in the late 1960s and early 1970s. By the early 1970s, astronomy had many more, and very different practitioners compared to earlier decades.

The demand for graduate astronomers in the mid-1960s was high: "today there are not enough astronomers either to satisfy the demands of the space program or to keep pace with expanding university requirements."[95] The launch of *Sputnik One* and the resulting Space Race produced an unparalleled growth in the number of staff and students working in astronomy. By 1970, the number of degrees awarded in astronomy had increased tenfold as compared to a decade earlier. And the number of awarded astronomy degrees grew at an accelerated rate. Where between 1920 and 1960 the number of astronomy Ph.D.-degrees awarded grew around 4% every year, between 1960 and 1970 this rose to a 20% annual increase (see Figures 50 & 51); this was twice the growth rate of that in related sciences.[96] And the manpower increase not only held for students. The total number of personnel

not just relativity scholars – turned towards understanding the structure and evolution of the universe.

94 Dennis Sciama, "Cosmology before and after quasars and the cosmic black-body radiation [Book Review]," *Scientific American* 217, no. 3 (1967): 31.

95 National Research Council, *Ground-based Astronomy: A Ten-year Program* (Washington, D.C. National Academies Press, 1964), 26.

96 Bernard Lovell, "The Effects of Defence Science on the Advance of Astronomy," *Journal for the History of Astronomy* 8, no. 3 (1977): 168.

employed in the field of astronomy, both technical and scientific, almost tripled in the 1960s.[97]

Besides an absolute increase in manpower, the background of people that worked in astronomy also changed. The field became increasingly populated by physicists. While in 1966, 26 percent of the astronomy personnel with Ph.D.s had received their doctorates in physics, by 1970 this had increased to 45 percent. In 1970 it was projected that it took only two more years until there were more people with Ph.D.s in physics working in astronomy, than people with Ph.D.s in astronomy.[98] Although the funding channels were stagnating in astronomy, the discipline was doing relatively well compared to physics in the early 1970s. David Kaiser has shown that American physics after the Second World War knew an explosive growth in manpower. Yet, from 1965 onward the number of available physics jobs stopped growing as steeply as the rise in freshly trained physicists – by 1968, nearly 1000 physicists were competing for only 253 advertised jobs.[99] The employment crisis in physics made that physicists were bound to search for other career paths. So while 30% of the young physics Ph.D.s failed to secure a job, the demand for astronomers was essentially equal to its supply, the National Research Council noted.[100]

The big increase in astronomers had practical repercussions. Between 1967 and 1970, a third of the astronomer Ph.D. recipients found that their research was restricted by the lack of availability of observing time on telescopes.[101] While observational capacities were lacking, work on theoretical problems was widely avail-

97 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 2: Report of the Panels* (Washington, D.C. National Academies Press, 1973), 327.

98 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 1: Report of the Astronomy Survey Committee*, 55-56; National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 2: Report of the Panels*, 332.

99 David Kaiser, "Cold War requisitions, scientific manpower, and the production of American physicists after World War II," *Historical Studies in the Physical and Biological Sciences* 33, no. 1 (2002): 151.

100 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 2: Report of the Panels*, 333-339. For details on the case of manpower in American physics after World War II, see Kaiser, "Cold War requisitions, scientific manpower, and the production of American physicists after World War II."

101 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 2: Report of the Panels*, 349.

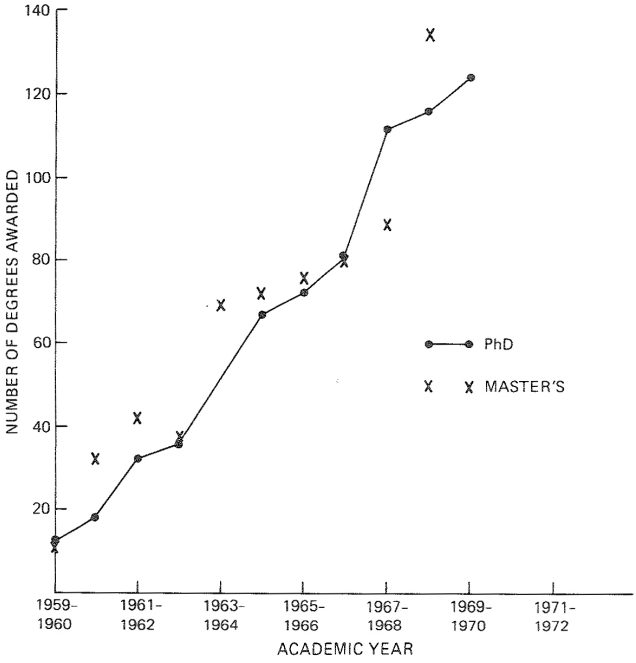

Figure 50: The number of advanced degrees in astronomy awarded in the United States between the academic years 1959/1960 and 1969/1970. Source: National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 1: Report of the Astronomy Survey Committee* (Washington, DC: National Academies Press, 1972), 56.

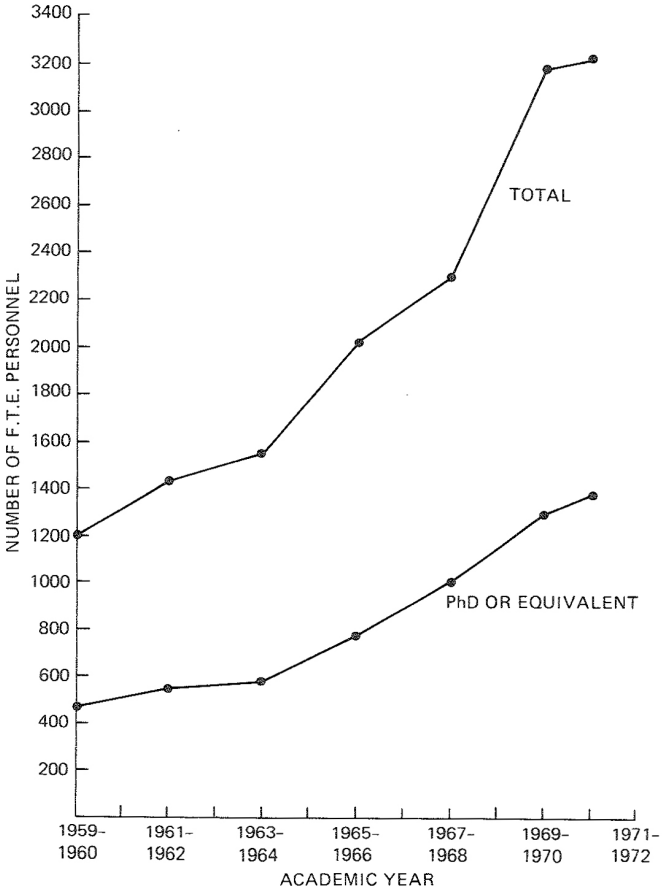

Figure 51: The number of personnel in astronomy given in F.T.E. in the United States between the academic years 1959/1960 and 1969/1970. Source: National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 1: Report of the Astronomy Survey Committee* (Washington, DC: National Academies Press, 1972), 57.

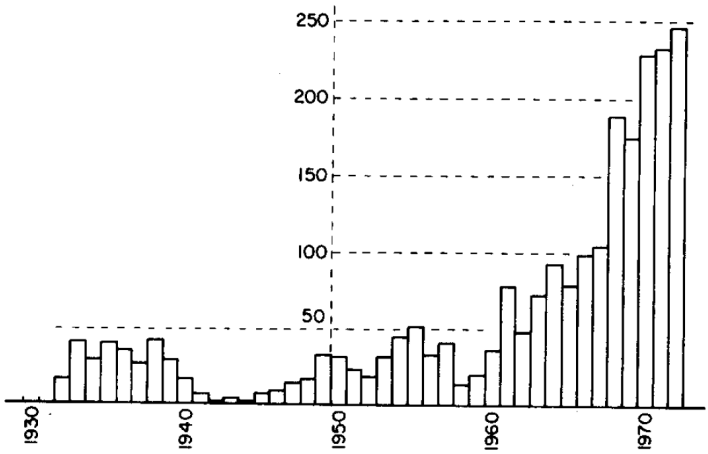

Figure 52: Histogram of published articles on cosmology. The vertical axis shows the (absolute) number of articles listed each year under the subject classifications "cosmology" and "cosmogony" in the abstracting and indexing service *Physics Abstracts*. In: Michael P. Ryan and L. C. Shepley, "Resource Letter RC-1: Cosmology," *American Journal of Physics* 44, no. 3 (1976): 223.

able. By 1970, "theoretical astrophysics" was the research subject that enjoyed most interest of professional astronomers, according to the National Research Council.[102] During these developments the number of publications on the topic of cosmology almost increased tenfold between 1960 and 1973 (see Figure 52).

The boundaries between astronomy and physics blurred, also institutionally. An increasing number of *astronomy* Ph.D. degrees were being awarded by "physics and astronomy" departments: "in 1960 only 8% of the degrees were from physics or physics and astronomy departments, while in 1975 about one third of the Ph.D. degrees were awarded by such departments."[103] In physics

102 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 1: Report of the Astronomy Survey Committee*, 60.

103 National Research Council, *Astronomy and Astrophysics for the 1970's: Volume 2: Report of the Panels*, 372.

it was also acknowledged that the two fields were conceptually growing closer: "[n]ever before have so many parts of physics directly concerned astrophysicists; seldom before have astronomical phenomena so stirred the imagination of physicists", the hefty 1972 Bromley report on the state of physics in the U.S. read.[104] According to the report, astrophysics and relativity had become top physics research priorities, closely following particle physics and nuclear physics – a "Physics of the Universe," they called this direction of research.[105]

This notion had already been used elsewhere. In the academic year of 1968, Jim Peebles started a course at Princeton University's Department of Astrophysical Sciences titled "Physics of the Universe: Origin and Evolution." It was the first course on cosmology at the Department of Astrophysical Sciences in Princeton, and the new approach to the cosmos was well described by this name.[106] "A survey of the classical (ca. 1930) and modern lines of evidence leading to a physical picture of the origin and evolution of the large-scale structure of the universe," the course description read.[107] Peebles' course included discussions on galaxy distribution, the deceleration of the universe, galaxy formation, helium abundance, the cosmic microwave background, and quasars. And Peebles was not alone in trying to teach a new generation of students cosmology. A wealth of new books from the early 1970s pursued a physics of the cosmos. These included influential textbooks like Steven Weinberg's *Gravitation and Cosmology* (1972), Hawking and Ellis' *The Large Scale Structure of Space-Time* (1973), Misner, Thorne and Wheeler's *Gravitation* (1973), Sciama's *Modern Cosmology* (1971), and Zeldovich and Novikov's *Relativistic Astrophysics, Vol. 1: Stars and Relativity* (1971). These books again show the boundary-crossing character of cosmology: every single author of these books was a physicist by training, and many

104 Physics Survey Comittee, *Physics in Perspective: Volume 1* (Washington, DC: National Academies Press, 1972), 73.

105 Ibid., 256.

106 Princetons' Department of Astronomy was renamed Department of Astrophysical Sciences in 1962.

107 Princeton University: The Graduate School Announcement 1968-1969, p. 62.

of them discuss astronomical observations, cosmological theory, and gravitational physics.[108]

National and international astronomical associations were also quick to respond to the new interests and manpower that were making astronomy flourish. In 1969, the American Astronomical Society set up the High Energy Astrophysics Division (which soon came to be chaired by Joe Silk in 1972). Similarly, the American Physical Society initiated the Division of Cosmic Physics in 1970 – renamed as Division of Astrophysics in 1983. Also in 1970, the International Astronomical Union created both the commissions of Cosmology (with Jim Peebles as vice-president) and of High Energy Astrophysics (with Martin Rees as vice-president).[109] When the 1970s came to a start, a new community and generation of hybrid physicist-astronomers was in place that studied the physics of the universe.

With a new community of researchers, its deepened connection with physics, and the wealth of new cosmological phenomena, cosmology fundamentally transformed between the 1950s and the early 1970s. This was a "rebirth of cosmology," philosopher Jacques Merleau-Ponty and astronomer Bruno Morando argued in 1976.[110] Sciama similarly called it a "renaissance."[111] The achievements of cosmology, "especially in the last few years," Sciama wrote in 1971, "constitute a revolution in our knowledge and understanding of the Universe with no parallel in the whole recorded history of mankind."[112] In the 1950s, renowned radio astronomer Martin Ryle had been notoriously skeptical of the whole cosmological enterprise: "[c]osmologists always lived in

108 See also Kaiser, "Whose Mass is it Anyway? Particle Cosmology and the Objects of Theory," 547.

109 Virginia Trimble, "HEAP 50 at 50," American Astronomical Society, July 8, 2020. https://www.youtube.com/watch?v=q4MwJ8SxTTk; International Astronomical Union, "Past Commissions," October 27, 2020. https://www.iau.org/science/scientific_bodies/past_commissions

110 Jacques. Merleau-Ponty and Bruno Morando, *The Rebirth of Cosmology* (New York: Alfred A. Knopf, 1976).

111 D. W. Sciama, "The recent renaissance of observational cosmology," in *Relativity and gravitation, Based on the proceedings of an International Seminar on Relativity and Gravitation, held at Technion City, Israel, July, 1969.*, ed. Charles G. Kuper and Asher Peres (New York: Gordon & Breach, 1971).

112 Sciama, *Modern Cosmology*, vii.

a happy state of being able to postulate theories which had no chance of being disproved."[113] Yet in 1974, Ryle was awarded the Nobel Prize for his radio-astronomical work and invention of the aperture synthesis technique that had been of "crucial significance" for cosmology.[114] It was the first time the prestigious prize was awarded for astronomical research. Ryle's Cambridge colleague, Malcolm Longair, portrayed the shift in the status of cosmology:

> Because of the increased confidence in the hot [Big Bang] model and the larger number of real facts about the universe, topics which in the past were questions of pure speculation have become susceptible to detailed quantitative analyses which can be checked against the observations.[115]

The big bang model now had many quantitative aspects that could be checked – from the temperature of the CMB to the abundance of light elements. The speculative days of cosmology were over when the 1970s began, and little traces were left of the great philosophical discussions of the 1950s. Early textbooks like the one of McVittie (1956) had vividly discussed the nature of scientific laws, and Bondi (1952) devoted whole sections to the cosmological principle, the problem of inertia, and the differences between physics and cosmology. Textbooks of the early 1970s avoided such explicit philosophical discussions. As Cambridge physicists Stephen Hawking and George Ellis wrote in their 1973 textbook: "we shall take the local laws of physics that have been experimentally determined, and shall see what these laws imply about the large scale structure of the universe."[116] Both had been

113 Ryle quoted in Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*, 309.

114 "Press Release: The 1974 Nobel Prize in Physics". Nobelprize.org. Nobel Media AB 2014. Web. 30 Jan 2018. For more on the curious relationship between the Nobel prize and the astronomical sciences, see Helge Kragh, "The Nobel Prize System and the Astronomical Sciences," *Journal for the History of Astronomy* 48, no. 3 (2017): 257–280.

115 Longair, "Observational cosmology," 1125-1248.

116 S. W. Hawking and G. F. R. Ellis, *The large-scale structure of space-time.* (Cambridge: Cambridge University Press, 1973), 1.

students of Dennis Sciama who had been partially responsible for reviving work on Mach's principle in the 1950s. But Sciama too changed his ways. While in the 1950s, Sciama wrote a popular book that was themed around Mach's principle – titled *The Unity of the Universe* (Sciama 1959) – his 1970 popular book barely mentioned Mach. Instead, he emphasized that "[t]he first question must be: can [the great flood of new observations] be understood in terms of the known laws of physics?"[117] Mach's principle, considered in great extent by pre-1960s textbooks, was mostly disregarded from explicit discussion in cosmology and relativity from 1970 onward.

The tendency among the new pupils in gravitation and cosmology was clear: the phenomena came first, not the principles. Many researchers abandoned explicit reflection on extra-theoretical ideas and principles. Yet, as we will see, in practice researchers still related to these ideas, and, in this way, the vivid methodological discussions of the 1950s did have their repercussions in cosmological research of the 1970s. Similar to how cosmology became a hybrid environment of astronomers and physicists, a hybrid of approaches to cosmology was adopted that included connecting to extra-theoretical ideas and principles.

3.6 MISSING MASS

The rebirth of cosmology changed what parameters and features of the universe were at stake and should be studied. This change is best reflected in the responses to Sandage's continuation of the classical cosmological search for the Hubble diagram. "Cosmology," he wrote in a 1970 popular article, was still a "search for two numbers": the Hubble constant, and the deceleration parameter.[118] Yet his search for the deceleration parameter, and Hubble's cosmological program, came under heavy criticism in the early 1970s. In his work, Sandage had assumed that the brightness of distant (old) galaxies were similar to those that were close (young). With this assumption he could determine their rel-

117 Sciama, *Modern Cosmology*, 101.

118 Allan R. Sandage, "Cosmology: A search for two numbers," *Physics Today* 23, no. 2 (1970): 34–41.

ative distances. However, from the work of Tinsley and others it had appeared that galaxies evolved, and so did their brightness. The brightness of a galaxy turned out to be a very bad measure of its distance, and the consequence was that most of the data points that Sandage had used in his Hubble diagram were unreliable. "Now I think it's wrong," Sandage said in a 1974 interview, "I think my [q_0] value's wrong. I think it's wrong because in the six billion years that it's taken light to come, these things have changed, the absolute luminosity, so we don't know the distance."[119]

The response to Sandage's work reflects a general change of sentiment in the new generation of cosmologists: "Let's call cosmology not just finding the value of q_0, but understanding how things originate in the universe and how they evolve," Tinsley said in an interview in the 1970s.[120] Tinsley's argument was in line with the general shift away from classical cosmology and toward a *physical* cosmology, and its focus on an evolutionary narrative consisting of many physical processes, parameters and phenomena.

With the rise of physical cosmology, instead of q_0 a new parameter became more dominant in discussions on the future of the universe: the universe's mass density. The mass density of the universe had become a true observable during the late 1960s because of better knowledge of the distribution of galaxies and the new estimates of intergalactic mass from the many high-energy space-based astronomical experiments (see chapter 1). In the work of the new generation of cosmologists the mass density was slowly taking over from q_0 as the way to determine which of the cosmological models is correct: open, flat or closed (see box "Mass Density of the Universe"). "Finding the density is something which is very much easier [than determining q_0]," Tinsley said in an interview, "it's based on essentially local data in a cos-

119 Interview of Allan Sandage by Paul Wright on 1974 May 16, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

120 Interview of Beatrice Tinsley by David DeVorkin on 1977 June 14, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

Mass Density of the Universe

In a matter-dominated universe, without pressure and a cosmological constant, the deceleration of the universe is related to the mass density of the universe:

$$\rho_0 = \frac{3H_0^2}{4\pi G} q_0 \tag{17}$$

In the early 1970s it became common to address the mass density of the universe through the dimensionless parameter Ω, which is the density relative to the "critical density," $\Omega = \rho/\rho_{critical}$. The critical density was the density of a flat universe, defined as:

$$\rho_{critical} = \frac{3H_0^2}{8\pi G} \tag{18}$$

The mass density and the deceleration were therefore related as:

$$\Omega = 2q_0 \tag{19}$$

Just as for q_0, the value of Omega implied whether the universe was open ($\Omega < 1$), closed ($\Omega > 1$) or flat ($\Omega = 1$) (see Figure 53).

mological sense [...]."[121] Cosmology shifted from being about the curvature of the universe, to being about its mass density.

There was a second way this mass density came to matter in the 1960s. There existed clear preconceptions about the shape of the universe. As discussed in Section 2, Mach's principle had left a strong imprint on the way relativistic cosmology was done. The principle was "conceived as the requirement that the universe be closed", as Wheeler had put it just before the "Golden Age" of relativity took off.[122] Nearing the end of the 1960s, a closed universe was still a much-preferred model for many cosmolo-

121 Interview of Beatrice Tinsley by David DeVorkin on 1977 June 14, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

122 Wheeler, "The Universe in the Light of General Relativity," 74.

	OPEN	CRITICAL	CLOSED
DENSITY PARAMETER Ω $\frac{\text{ACTUAL DENSITY}}{\text{CRITICAL DENSITY}}$	$\Omega < 1$	$\Omega = 1$	$\Omega > 1$
DECELERATION PARAMETER q_0 DECELERATION $\frac{\text{DISTANCE}}{(\text{VELOCITY})^2}$	$q_0 < \frac{1}{2}$	$q_0 = \frac{1}{2}$	$q_0 > \frac{1}{2}$
GEOMETRY OF SPACE	HYPERBOLIC (NEGATIVE CURVATURE)	FLAT (ZERO CURVATURE)	SPHERICAL (POSITIVE CURVATURE)
FUTURE OF THE UNIVERSE	PERPETUAL EXPANSION	PERPETUAL EXPANSION	EVENTUAL COLLAPSE
			

Figure 53: Models of the universe as depicted in a popular article by Gun, Gott, Schramm and Tinsley in 1976. "Open and closed models of the universe are distinguished mainly by the average density of matter and by the value of the cosmic deceleration." J. Richard Gott et al., "Will the Universe Expand Forever?," *Scientific American* 234, no. 3 (1976): 69.

gists and relativists. "*Philosophically*, there might be a preference," Wolfgang Rindler, a leading physicist in research on general relativity, wrote in 1967, "the choice $k = 1$ [a positively curved universe] might appear desirable. It implies closed space sections that would, in some sense, validate Mach's principle according to which the totality of matter in the universe and nothing else determines the local inertial frames."[123] Rindler, as a gravitational physicist, echoed Einstein's 1922 argument for a closed universe.

The preference for a closed universe, Einstein's original Machian cosmos, still resonated in the thinking of many of the early generation of relativity scholars and physical cosmologists in the 1960s. This included the thinking of Dennis Sciama, who in the early years had been a supporter of the steady state theory,

123 Wolfgang Rindler, "Relativistic Cosmology," *Physics Today* 20, no. 11 (1967): 29-30, emphasis in original.

but by the 1960s came to prefer a closed big-bang universe on the basis of Mach's principle. In an 1978 interview he said:

> [...] the Einstein-de Sitter model is the one where the total energy of the universe is zero, the kinetic energy and the negative gravitational potential energy just balancing. Well, if you think that kinetic energy manifesting inertia is due to gravitation, then you might intuit that the most Machian way of having one made by the other would be if there's equal amount of energy, which would give you uniquely the Einstein-de Sitter model, I still have a secret hope that that might turn out so, but it may well not.[124]

Others that advocated a closed universe were John Wheeler, who still regarded a closed universe as an essential part of Einstein's relativity theory. His Princeton colleague Robert Dicke too endorsed a closed universe. Dicke had been an avid supporter of a universe that was oscillating: a cyclic universe that, after expansion, would collapse and "bounce" back again. This bounce had been mathematically discussed by Russian theoretical physicists in 1963.[125] The idea had even sparked Dicke's initial interest in finding the cosmic microwave radiation, and he and his team referred to the idea in the paper accompanying the discovery.[126] His preference for the oscillating model was because of his struggle with the idea that all the mass in the universe would have been created in one instance. In his scenario (which had no further theoretical support), every bounce would add a bit of mass to the universe. "It was the only way you could generate all that matter, from my viewpoint," Dicke said in an interview in the 1980s.[127] Dicke's oscillating universe could only exist if the universe was closed.

124 Interview of Dennis Sciama by Spencer Weart on 1978 April 14, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

125 E. M. Lifshitz and I. M. Khalatnikov, "Investigations in relativistic cosmology," *Advances in Physics* 12, no. 46 (1963): 185–249.

126 Dicke's group justify the search for leftover radiation from a hot state of the universe by their interest in "closed oscillating models": Dicke et al., "Cosmic Black-Body Radiation.," 415.

127 Interview of Robert Dicke by Alan Lightman on 1988 January 19, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA. For

> [I]f one tentatively accepts the result that q_0 is of order unity [$\Omega \geqslant 1$], then one is forced to the conclusion that the mass density of about $2 \times 10^{-29} g/cm^3$ must be found somewhere outside the normal galaxies. But where?[128]

Having a closed universe demanded that the mass density of the universe was above the critical value (see box "Mass Density of the Universe"). In the 1960s, this demand featured in many studies that estimated the mass density of the universe. "One would particularly like to know whether there is enough mass to close the universe", Dicke's juniors at Princeton, Jim Peebles and Bruce Partridge wrote in 1967.[129] But, as Peebles and Partridge showed, and as had already been known since Oort's estimate of the mass density of the universe in 1958, the mass in galaxies is much too low to "close the universe."[130] There existed a crucial discrepancy between observations and a spatially closed cosmological model: the measured value of the mass density of the universe was typically around the order of 10^{-31} gr. cm^{-3}, two orders of magnitude lower than the mass needed for a closed universe ($\rho_c \sim 10^{-29}$ gr. cm^{-3}).[131] Indeed, "the predicted density,"

more on the history of the oscillating universe model, see Helge Kragh, "Continual fascination: The oscillating universe in modern cosmology," *Science in Context* 22, no. 4 (2009): 587–612.

128 Steven Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, vol. 41, no. 4 (New York City, NY: John Wiley & Sons, Inc. 1972), 478.

129 P. J. E. Peebles and R. B. Partridge, "Upper Limit on the Mean Mass Density due to Galaxies," *The Astrophysical Journal* 148 (1967): 713.

130 Ibid.; Oort, "Distribution of Galaxies and the Density in the Universe."

131 See e.g. Ibid.; Peebles, *Physical Cosmology*; Stuart L. Shapiro, "The Density of Matter in the Form of Galaxies," *The Astronomical Journal* 76 (1971): 291–293; Thomas W. Noonan, "The Mean Cosmic Density from Galaxy Counts and Mass Data," *Publications of the Astronomical Society of the Pacific* 83 (1971): 31; Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*; G. R. Burbidge, "Intergalactic Matter and Radiation (Survey Lecture)," in *External Galaxies and Quasi-Stellar Objects, Proceedings from IAU Symposium no. 44 held in Uppsala, Sweden, 10-14 August 1970*, ed. David Stanley Evans, Derek Wills, and Beverly J. Wills (Dordrecht: D. Reidel, 1972), 493. The critical density is $\rho_c = \frac{3H^2}{8\pi G} \sim 10^{-29}$ gr. cm^{-3}. In 1965, two Caltech graduate student, Jim Gunn and Bruce Peterson, showed by using the recently discovered quasars by Maarten Schmidt, and the lack of absorption in their spectra, that the universe had not enough neutral hydrogen to be closed. See: James E. Gunn and Bruce A. Peter-

John Wheeler wrote, arguing from the assumption of Einstein's closed model of the universe, "exceeds by a factor between 10 and 100 the density that one is able to find in the dust and stars of galaxies."[132] The issue was well-known. Harvard theoretical physicist Steven Weinberg stated the following in his 1972 textbook on cosmology:

It was known as the "missing matter," the mass needed to close the universe; the preference for a closed universe was a theoretical reason to assume there is much more mass then met the eye. The missing mass problem became a staple theoretical consideration in cosmology nearing the end of the 1960s.[133] Work on the missing mass problem thrived because of a development that has been discussed earlier in this thesis: the search for intergalactic matter. George Field, whom we discussed in chapter 1, was one of the central figures in the search for intergalactic matter. In an interview, Field reflected finding the missing mass was a central part of his research: "If we had been extremely fortunate, we would have found matter which would have sufficed to close the universe."[134] It was the "magic density."[135] When there was a claimed detection of a hot intergalactic medium by one of the rocket experiments in 1968, even *Time Magazine* wrote about the "Mystery of the Missing Mass."[136]

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son, "On the Density of Neutral Hydrogen in Intergalactic Space.," *Astrophysical Journal* 142 (1965): 1633–1636.

132 John A. Wheeler, "Our Universe: The Known and the Unknown," *The Physics Teacher* 7, no. 1 (1969): 29.

133 That extra mass was needed to have a closed universe was an idea that one can already find in the 1930s, before q_0 became the dominant cosmological parameter. In his 1933 paper, Zwicky mentioned it was not unreasonable to assume that "dunkle (kalte) Materie" could make the universe have a critical density. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln," 122-123. Howard Robertson more explicitly referred to it in a popular piece: "for the mean density of matter in such a [closed] model exceeds that contained as luminous matter in the nebulae by a thousand-fold and, although it is conceivable that the universe contains this much dark matter, we have as yet no independent justification for assuming that it does" (Robertson 1933, 24).

134 Interview of George Field by Richard Hirsh on 1980 July 14, Niels Bohr Library Archives, American Institute of Physics, College Park, MD USA.

135 Field, Rees, and Sciama, *The Astronomical Significance of Mass Loss by Gravitational Radiation*, 192.

136 *Time Magazine*, "Mystery of the Missing Mass."

The detection of the mass was not confirmed, but the aim of finding the missing mass persisted well into the 1970s. In 1970, Jim Peebles chaired a session at the first general assembly meeting of the IAU "Commission on Cosmology" titled "Open or Closed Universe, Missing Masses, Gravitational Radiation and Black Holes."[137] In a 1972 review George Field wrote that "[t]he main interest in IGM [inter-galactic matter] stems from the evidence that galactic matter constitutes only a small fraction of the critical cosmological density of matter [...]."[138] And so did Geoffrey Burbidge, who discussed the "problem of the so-called 'missing mass"' in a survey lecture.[139] Finding the missing mass to close the universe would ultimately vindicate Mach's principle that was so vigorously pursued in earlier decades, yet this reason behind preferring a closed universe did seldom enter in discussions. Although its origin was little regarded, the philosophical preference for extra mass did have real implications for astrophysical and cosmological observational programs. Research was set to uncover potential yet-unseen intergalactic matter and to explore how to theoretically accommodate such a finding. Or, as Wheeler wrote in 1969, "it would be difficult to cite any topic in astrophysics more challenging to the investigator than the search for the missing matter!"[140]

The preference for a closed universe, and the missing mass needed to close it, went hand-in-hand with the rise of physical cosmology, its new generation of cosmologists, and their search for the mass density of the universe. We already saw how the theme appeared in the thinking of Tinsley and Peebles, but also Dennis Sciama's student, Martin Rees discussed the "missing matter" required to have a closed cosmological model. He connected it to understanding the future and eventual collapse of the universe this missing mass would entail. This what was at stake: knowing the density of the universe equalled knowing its destiny. The missing mass was needed to help the universe col-

137 Commission 47: Cosmology. (1971). *Transactions of the International Astronomical Union*, 14(2), 242–243.

138 George B. Field, "Intergalactic Matter," *Annual Review of Astronomy and Astrophysics* 10, no. 1 (1972): 227-228.

139 Burbidge, "Intergalactic Matter and Radiation (Survey Lecture)."

140 Wheeler, "Our Universe: The Known and the Unknown."

lapse again. This was the reason Rees framed his work as an "eschatological study."[141] Rees, like the generation of Sciama and Wheeler, assumed the missing mass was there, but it was not long before the younger generation started to doubt this assumption. In 1974, four young cosmology scholars at Caltech and the University of Texas also picked up the issue of the missing mass in an influential study of the mass density of the universe. They wrote:

> Where [can] the missing mass be hiding if it is demanded, on theological or other grounds that $\Omega \geqslant 1$?[142]

In the paper, Richard Gott, Jim Gunn, David Schramm and Beatrice Tinsley reviewed much of the physics of the universe that could help decide its ultimate fate: mass limits from the statistics of groups and clusters, observations of intercluster gas, dust and other materials, and the big bang origin of helium and deuterium (see Figure 54).[143] The authors dismissed Sandage's "classic techniques" in favor of the physical arguments that had started to dominate in the new physical approach to cosmology.[144] "We were sort of young Turks wanting to upset the establishment," David Schramm, said in an interview with science writer Dennis Overbye. "One of the motivations was to show that the best way to solve cosmology was not through the Hubble diagram."[145] Their paper was a strong plea against the closed model of the universe, and it showed that the density of the universe was no more than a tenth of the value required for closure ($\Omega \sim 0.06$). But even in this leading publication that indicated

141 Rees, *The Collapse of the Universe: an Eschatological Study*.

142 J. R. Gott et al., "An Unbound Universe," *The Astrophysical Journal* 194 (1974): 550; J. Richard Gott received a Ph.D. in 1973, Jim Gunn in 1966, David Schramm in 1971, and Beatrice Tinsley in 1966.

143 Although they also referred to the problem of mass in clusters, they used the recent work of Gott to argue that these masses were probably incorrect and due to the wrong attribution of cluster membership. See Gott, Wrixon, and Wannier, "A Study of Three Groups of Galaxies: Plausible Explanation of the Virial Mass Discrepancy."

144 Gott et al., "An Unbound Universe," 552.

145 Overbye, *Lonely Hearts of the Cosmos: the Scientific Quest for the Secret of the Universe*, 179.

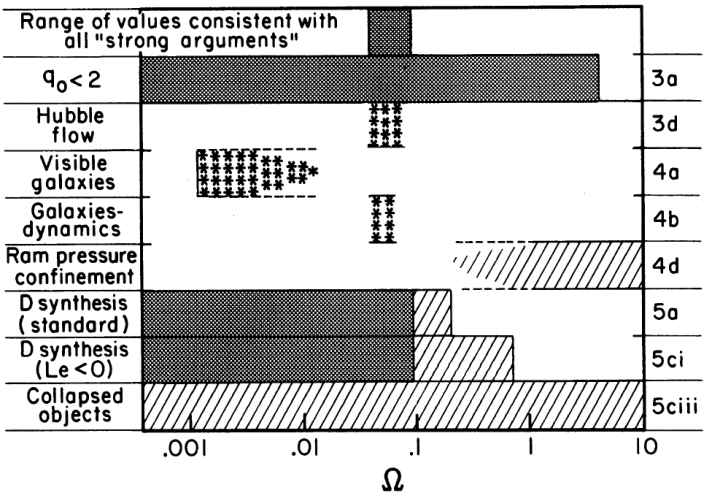

Figure 54: Summary of the constraints on Ω that Gott, Gunn Schramm and Tinsley gave in their 1974 article. The different arguments are given on the left of the diagram. Dark shadings are the allowed values of the arguments that they considered strongest; diagonal lines are from weaker arguments. The starred regions show the contribution of galaxies to Ω. Hazy boundaries showed that it concerned only weakly determined limits. In: J. R. Gott et al., "An Unbound Universe," *The Astrophysical Journal* 194 (1974): 550.

what physical cosmology stood for, philosophical preferences on what the universe ought to be lingered. The missing mass to close the universe was a concept well-embedded in the new cosmological thinking of the 1970s.

3.7 CODA

One of the central points of this chapter was to show how a new notion of invisible mass entered in astronomical discussions: the missing mass to close the universe. Before reflecting on how the notion of missing mass entered the new cosmological canon, a few more words need to be spent on characterizing what the

exact transformation, or "rebirth," of cosmology is that we have traced.

In a straightforward way, the rebirth of cosmology was the shift from classical to physical cosmology. Classical cosmology was a study of the redshift, brightness and distribution of galaxies to describe the universe as it is, and this way of doing cosmology was represented by Hubble's quest to determine the universe's rate of expansion and its deceleration. This work was continued by Allen Sandage. The methodological underpinning of this picture was portrayed well by Berkeley statisticians Jerzy Neyman and Elizabeth Page in 1958:

> "Because of their tremendous distances, our means of studying galaxies are extremely limited. Essentially, all one can do is to look at galaxies, or at their photographs, taken with smaller or larger telescopes, study their spectra, measure their brightness, and count their images on photographs of the sky."[146]

The transformation that we have traced was a shift away from understanding cosmos as a system that needed observing, and towards the universe as a physical mechanism that needed explaining. In place of the sterile picture, a physical conception of the universe had formed. In this conception, cosmology was no longer just about devising a hypothetical cosmological theory or measuring H_0 or q_0 but now included understanding a whole range of physical processes – from nucleosynthesis to gravitational collapse.

We can characterize the key part of the this new physical approach to the universe as *historical*: the different physical mechanisms and phenomena like quasars, the microwave background and the abundance of light elements all needed to fit within a single historical narrative, from the big bang until today. This new style of doing cosmology was a kind of *paleontology*: the physics could be "played back", deciphering the processes as part of a grand historical narrative. During the 1973 IAU Symposium on

146 Jerzy Neyman and Elizabeth L. Scott, "Statistical Approach to Problems of Cosmology," *Journal of the Royal Statistical Society. Series B (Methodological)* 20, no. 1 (1958): 2.

galaxies in Canberra, Australia, Jim Peebles himself described the methodology of cosmology in historical terms:

> "(1) form an opinion of the relevant 'observed' phenomena; (2) draw up a list of presumed processes and/or laws of physics; (3) *ask whether one can trace back in time from the phenomena according to the processes without running into a situation that appears contrived or contradictory.*"[147]

The idea of identifying cosmology as a historical science is not new. The details of this idea have recently been worked out nicely by historian and philosopher of science Jacob Pearce. Pearce has shown how a historical style of reasoning became "entrenched" in twentieth century cosmology, addressing it as a "move to explaining objects of scientific knowledge in terms of their historicity."[148] He emphasized how "fossils", "remnants" and "relics" came to dominate cosmological work from the 1970s to now. Where Pearce focuses mainly on the CMB as a defining moment for "cosmic paleontology," in this chapter we have traced the shift in this way of thinking to the period between 1950 and 1970: the physics of the CMB, quasars, the mass of the universe, galaxy evolution, and the abundances of elements all became pieces of a historical puzzle, and at the same time acted as paleontological tools to probe the history of the universe even further.[149]

However, two things which this chapter has shown about the transformation in cosmology are not immediately captured in

147 P. J. E. Peebles, "Properties and Distribution of Galaxies in Relation to Their Formation and Evolution: Theoretical Situation," in *The Formation and Dynamics of Galaxies: Proceedings from IAU Symposium no. 58 held in Canberra, Australia, August 12-15, 1973.*, ed. John R. Shakeshaft, vol. 58 (Dordrecht: Reidel, 1974), 56, emphasis in original. In his talk, Peebles compared cosmological work on galaxy formation to a *uniformitarian* approach in geology.

148 Jacob Pearce, "The unfolding of the historical style in modern cosmology: Emergence, evolution, entrenchment," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 57 (2017): 18; Pearce has shown the roots of this historical style can be largely recognized in the work of Gamov. There are good reason to credit Gamov for having a "proto" physical cosmology, yet the developments of the 1960s largely happened without Gamov being of major influence.

149 Ibid., 27.

terms of a shift towards historical reasoning. The first is that modern cosmological practice not only involved drawing together different time scales, but also a vast amount of different *distance* scales. The distance scales that were relevant for understanding the evolution and structure of the universe included those of microwave radiation, helium, stars, quasars, galaxies, clusters and the curvature of space-time. This is a point that we also addressed in chapter 1, in connection to Ambartsumian's hypothesis on the origin of galaxies.

The second point is that the new form of reasoning focused on *explaining* rather than on purely *describing* the universe. This, indeed, was the novel "physics" part of cosmology, that emphasized understanding mechanisms behind the existence of cosmic objects and phenomena. It fundamentally changed what it meant to "know" the universe. If, as argued by historian of science Alexandre Koyré, Newton, Leibniz and others had made the cosmos into a sterile "uncreated nothingness," an indefinite and infinite realm of distant stars that was decoupled from human experience, the reborn science of the cosmos in the 1970s can be understood as remaking the universe into a tangible, knowable and created everything: a timeline of events that started with the big bang and could be probed by observations and understood by physics.[150]

There is another point to make here. Understanding physical cosmology as driven by a historical narrative style of reasoning helps us to recognize the reborn cosmology as a "methodological omnivore"; rather than focusing on a single method or test (e.g. finding q_0), the field started to converge multiple evidential means. This notion is taken from the work of philosopher Adrian Currie, who used it to describe the historical sciences.[151] It suits our point well. The new omnivorous nature of cosmology is nicely portrayed by the several methods used to determine the

150 Alexandre Koyré, *From the Closed World to the Infinite Universe* (Baltimore, MD: The Johns Hopkins Press, 1957), 2.

151 Adrian Currie, "Marsupial lions and methodological omnivory: function, success and reconstruction in paleobiology," *Biology & Philosophy* 30, no. 2 (2015): 187–209.

mass density of the universe by Gott, Gunn, Schramm and Tinsley in Figure 54.

Moreover, although in the 1970s cosmology became a respected subject to be studied empirically, it also remained permeated with extra-theoretical considerations. It became a hybrid of what McVittie had called "rationalist" and "empiricist" approaches; or, in more appropriate terminology, a mixture of extra-theoretical principled reasoning and observation-based extrapolation of known physics. Besides the closed universe preference, another example of an extra-theoretical idea would be the "anthropic principle" that began drawing attention in the 1970s.[152] The omnivorous character also surfaces in research on contemporary hot topics. Particularly in discussions on the merits of inflation theory, the almost dialectic tension between extrapolating and deductive strategies in cosmology resurfaces, as is clear in a recent controversy published in *Scientific American*.[153] Similarly, non-empirical arguments are still widely used in discussions surrounding the multiverse.[154]

Now to come back to contributing to the historical narrative of this thesis: the essential part of this chapter was to illustrate the establishment of the notion of *missing matter*. First we recognized that the "mass of the universe" had obtained a new significance as a physical parameter to determine the right cosmological model around 1970. Observations were giving a low cosmic mass density, and given that the closed universe model was preferred by many cosmologists and functioned as a benchmark model, this led to the the existence of potential missing mass to close the universe. At the same time that the universe was found,

152 The notion was introduced by Brandon Carter, a student of Dennis Sciama in Cambridge, in 1973. See B. Carter, "Large Number Coincidences and the Anthropic Principle in Cosmology," in *Confrontation of cCsmological Theories with Observational Data: Proceedings from IAU Symposium no. 63 held in Krakow, Poland, September 10-12, 1973*, ed. M.S. Longair, vol. 63 (Dordrecht: D. Reidel, 1974). Similar reasoning can already be recognized in the work of Dicke, see Helge Kragh, "The Road to the Anthropic Principle," in *RePoSS: Research Publications on Science Studies*, vol. 7 (Aarhus: Centre for Science Studies, University of Aarhus, 2010).

153 Ijjas, Steinhardt, and Loeb, "Pop Goes the Universe."

154 See e.g. Helge Kragh, "Contemporary History of Cosmology and the Controversy over the Multiverse," *Annals of Science* 66, no. 4 (2009): 529–551.

when it became a palpable physical object of study, its majority went missing.

This missing mass was a new motif to search for unseen mass in the universe, and it is on this background that we should understand how two measurements of mass, in galaxies and clusters, were synthesized and used as evidence for the existence of dark matter.