"The Poor Man's Accelerator", or how the Primordial Universe Became a Testing Ground for Particle Physics.

Abstract

Among physicists and cosmologists, it is common practice to refer to the "cosmic laboratory" to describe how the study of the universe offers important insights into the inner constitution of matter. Yakov Zel'dovich, for instance, famously claimed that the "universe is the poor man's accelerator." The goal of this paper is to clarify the relationship between cosmology and particle physics by examining a case of crucial importance in connecting these fields: how cosmologists of the 1970s were able to limit the number of lepton families from the measure of the cosmic abundance of helium-4. My claim is that knowledge of the primordial universe enables cosmologists to conceive it as a natural experiment for testing hypotheses of particle physics, thereby supporting the analogy between the universe and particle colliders that is at the foundation of a recent area of cosmological research.

Keywords: cosmology; particle physics; experimentation; scientific method; cosmological collider

1 Introduction

In an article published a few months after his death, the eminent Soviet cosmologist Yakov Zel'dovich wrote: "'The Universe is the poor man's accelerator' is the motto of this new direction of science [i.e. cosmology]" (Zel'dovich

1988, 29). This declaration highlights the growing interplay between cosmology and particle physics over the previous decade and reflects Zel'dovich's belief that cooperation between these fields would intensify in the future. But did he really mean that observations of the universe could, at least in principle, serve as a tool to constrain particle physics hypotheses when sufficiently powerful (and therefore expensive) particle accelerators are unavailable? Should we take this motto at face value or see it as nothing more than a catchy slogan?

I will first argue that Zel'dovich's statement was not mere speculation about the future of science but was grounded in evidence from the past. During the 1970s, collaboration between cosmologists and particle physicists had already yielded a major breakthrough: cosmologists established an upper limit on the number of leptons based on models of primordial nucleosynthesis and the measurement of the abundance of helium-4 (^{4}He) in the universe. I claim that this case represents the first success of a novel approach to using observations of the universe as the outcome of a natural experiment conducted by the universe itself. Thus, I maintain that comparing the universe to a particle accelerator is not merely a figure of speech but a meaningful analogy.

Why is it so important to discuss Zel'dovich's views and to examine whether cosmology's method is partly experimental? Not because experimentation would enjoy any intrinsic epistemic superiority over "purely observational" methods – a claim that has been convincingly refuted by (Boyd and Matthiessen 2024) – but because clarifying the epistemic status of evidence in cosmology affects how we evaluate it and how we conceive new research programs. Understanding cosmology's methodology as a complex articulation of different statistical, observational, historical, experimental approaches enables us to account for how cosmologists and other scientific communities can jointly tackle the challenges of contemporary physics.[1] In our case, recognizing that cosmologists do employ experimental reasoning (even when studying

1. My claim is therefore a reply to Hacking saying that "the method of the science is the same as that of astronomy in hellenistic times. Model, observe, and remodel in such a way as to save the phenomena." Hacking 1989, 577–578

a singular system whose initial conditions cannot be modified) shows that their methodology partially overlaps the one used by particle physicists: the prediction of novel phenomena, the testing of hypotheses through observable consequences and the exploration of high-energy regimes to uncover new entities. This does not erase the difference between cosmology and laboratory sciences: but it explicates how these two fields collaborate and why this collaboration is successful. Even more important may be that understanding this collaboration can help design and evaluate future research programs. I will argue here, for instance, that Zel'dovich's view of the universe as a particle accelerator provides a fruitful framework at the foundation of the recent "Cosmological Collider Physics" program dedicated to the search for non-standard particles (Arkani-Hamed and Maldacena 2015).

In section 2, I describe how cosmologists were able to constrain the number of lepton families. I argue that this achievement was recognized by contemporary scientists as a pivotal moment in the history of cosmology. In section 3, I examine the nature of the relationship between cosmology and particle physics, which is often vaguely articulated by scientists themselves. I show that this association can be understood in two distinct ways, depending on the perspective of the community approaching it: as a source of novel predictions for particle physicists or as an historical interpretation of astronomical data as 'relics' from the primordial universe for cosmologists. I will also suggest a third approach: the limitation of the number of leptons can be seen as an experimental reasoning based on viewing the current universe as the result of a natural experiment that occurred in the early universe. My goal is not only to argue that it is possible to compare the universe with a particle accelerator but also to show that this analogy provides the most comprehensive and illuminating way to understand how cosmology has constrained the Standard Model of particle physics. In section 4, I contend that Zel'dovich's views on the future of science were largely well-founded and that the comparison between the universe and a particle collider is still relevant for today's fundamental physics.

2 A case-study: the cosmological upper limit for the number of leptons

The discovery of the muon neutrino in 1962 and the tau in the mid-1970s raised new questions for particle physics during the last quarter of the twentieth century. As Steven Weinberg recalled, during the 1970s, "there were some questions that arose in particle physics like the number of neutrino species, which suddenly for the first time were taken seriously because a new generation of leptons had just been discovered, and we wondered how many more there were" (Lightman and Brawer 1990, 457). Since each neutrino type corresponds to a lepton type, the question of the number of neutrino species is equivalent to the question of the number of families of leptons. Unexpectedly, this question found its first answer in the field of cosmology at the end of the 1970s, more than a decade before experimental particle physics could address this question. The goal of this section is to recount the story of how the science of the universe became relevant to this question of the science of elementary particles.

Our story begins with a crucial article by Fred Hoyle and Roger Tayler, published in *Nature* in 1964: "The Mystery of the Cosmic Helium Abundance." In this paper, Hoyle and Tayler showed:

> There has always been difficulty in explaining the high helium content of cosmic material in terms of ordinary stellar processes. The mean luminosities of galaxies come out appreciably too high on such a hypothesis. The arguments presented here make it clear, we believe, that the helium was produced in a far more dramatic way. Either the Universe has had at least one high-temperature, high-density phase, or massive objects must play (or have played) a larger part in astrophysical evolution than has hitherto been supposed. (Hoyle and Tayler 1964, 1110)

This "high-temperature, high-density phase" of the universe is what we now call the hot Big Bang. Because Hoyle was a supporter of the rival steady-state theory, he introduced the hypothesis of massive, hypothetical objects –

a proposition that failed to convince the majority of his contemporaries. During the late 1960s, it became widely accepted that the cosmic abundance of helium could only be explained by a primordial nucleosynthesis, i.e., nuclear fusion in the primordial universe.

The second part of our story logically follows the first: in 1967, Hoyle, Robert Wagoner, and William Fowler published a comprehensive article titled "On the Synthesis of Elements at Very High Temperature" in the *Astrophysical Journal*. This paper greatly extended the analysis of Hoyle and Tayler's earlier work by examining the detailed mechanisms of production for elements such as deuterium, tritium, helium, lithium, beryllium, boron, carbon, nitrogen, and oxygen (see figure 1). One notable feature of their analysis is its consideration of isotopes, including one that is central to our story: ^{4}He, a helium atom with two neutrons and two protons in its nucleus. This isotope has a key characteristic: its relative abundance does not decrease after production (see figure 2). As a result, ^{4}He serves as a probe for element production mechanisms: if a hypothetical mechanism produces more ^{4}He than observed, it must be ruled out (Wagoner, Fowler, and Hoyle 1967, 42).

The third part of the story occurred two years later. In 1969, the Soviet physicist Viktoriy Shvartsman published an article titled "Density of Relict Particles with Zero Rest Mass in the Universe", first in the *ZhETF Pis ma Redaktsii* and later in the *Soviet Journal of Experimental and Theoretical Physics Letters*. In this paper, Shvartsman demonstrated that the number of neutrino species directly influences the density and speed of the primordial nucleosynthesis and, consequently, the abundance of helium:

> The point is that the presence of a chemical potential in ν_e ($\bar{\nu}_e$) leads not only to an increase in their density, but also to a direct change in the dynamics of the reaction (A). This can cause cancellation of the indicated mechanism and lead to an arbitrarily low helium content.[2] (Shvartsman 1969, 186)

The final chapter of this story brings all the earlier pieces together. In

2. Here, Shvartsman refers to Wagoner, Fowler, and Hoyle's 1967 paper.

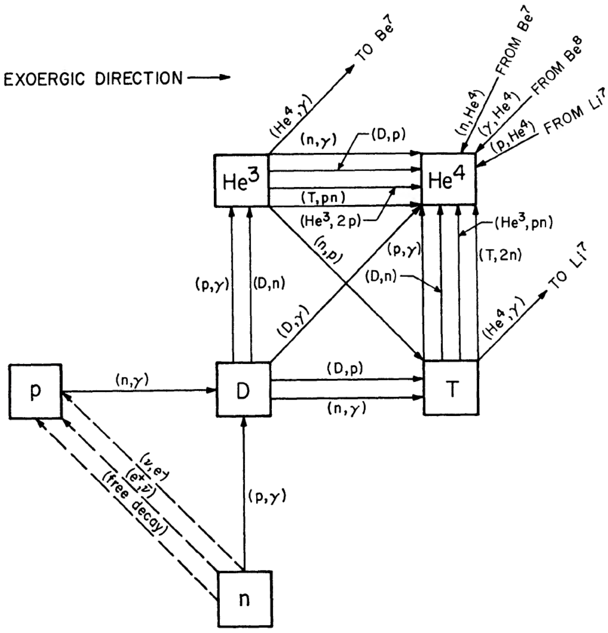

Figure 1: Details of the reactions among light nuclei. Unlike current conventions, the number of the isotope is indicated on the upper-right of the element symbol. Source: (Wagoner, Fowler, and Hoyle 1967, 18).

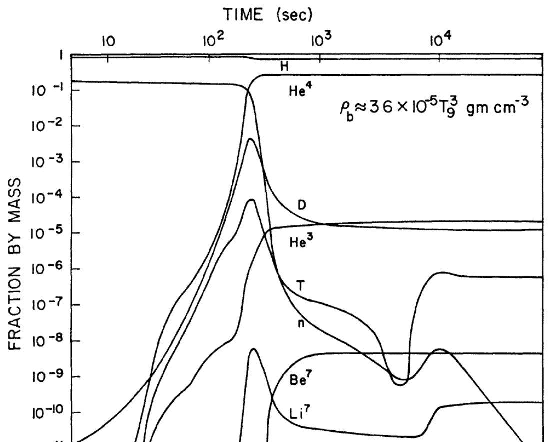

Figure 2: Evolution of cosmic element abundances in an expanding universe. Source: (Wagoner, Fowler, and Hoyle 1967, 20).

1977, Gary Steigman, David Schramm, and James Gunn published the article "Cosmological Limits to the Number of Massive Leptons" in *Physics Letters*, establishing an upper limit on the number of lepton types: seven (two massless, five massive) or fewer. If there were more than seven, the universe's expansion rate during the primordial nucleosynthesis would increase, altering the neutron-to-proton ratio and resulting in excessive production of ^{4}He:

> An increased expansion rate ($\xi > 1$) forces the weak interactions out of equilibrium at a higher temperature and, thus, leads to a higher neutron-to-proton ratio. The primary effect of an increased neutron-to-proton ratio is to increase the abundances of deuterium, helium-3, and helium-4. Since ^{4}He is produced but not easily destroyed in the course of galactic evolution, the observed ^{4}He abundance provides an upper limit to the primordial abundance and, hence, provides a limit to the speed-up of the expansion. From the chain: "new" leptons $\rightarrow$ increased density $\rightarrow$ speed-up $\rightarrow$ increased ^{4}He abundance, we may obtain an upper limit to the number of unknown leptons. (Steigman, Schramm, and Gunn 1977, 203)

This is how cosmologists answered a question posed by particle physicists: linking the number of lepton families to the dynamics of the primordial nucleosynthesis and thus to the current abundance of ^{4}He, which can be directly measured. The story ends with a laboratory experiment: in the late 1980s, the Large Electron-Positron (LEP) collider at CERN began operations and examined the production of the Z boson. The experiments performed at the LEP are exemplary of particle physics. They consisted in accelerating particles (in this case, electrons and positrons) to a velocity close to the speed of light and making them collide, leading to their mutual annihilation. The energy released in these events materialized as new particles, such as Z bosons, which subsequently decayed into other elementary particles registered by large particle detectors. The resulting patterns of detection were then analyzed as a "signature" or a "signal" of the transient particles produced in the collision from which physicists infer their properties. This is how, in 1990, analyses of the Z boson's invisible decay width confirmed the number of three neutrino species (Decamp et al. 1990).[3]

This remarkable anticipation by cosmologists of experimental results from the largest lepton collider ever built marked a pivotal moment in the collaboration between particle physics and cosmology. As David Schramm observed in an interview:

> *Do you remember the motivating factors for your work on limiting the types of neutrinos from the helium abundance?*
>
> Yes. I think in many ways that work was the birth of this whole connection between particle physics and cosmology, because it was the first time when we were able to take something from cosmology and make a statement relevant to particle physics. (Lightman and Brawer 1990, 440)

One could think that Schramm, being one of the main actors of this story, could be biased and would give too much weight to his own achievment But Schramm's reflections are echoed by Dennis Sciama, who had no part in this success and yet emphasized how these results contributed to the recognition of cosmology as a mature science:

> I don't think contempt is too strong a word in those early days, among physicists.
>
> That changed, bit by bit, as the new era came in and particle physics ideas became important. Things changed when, for example, the physicists realized that cosmologists could do much better than the particle physicists at restricting the number of neutrino types. All that came in later. Then the physicists had to admit that maybe the cosmologists have got something. (145–146)

Notice that both Schramm and Sciama describe the connection between cosmology and particle physics in broad and vague terms. Even Weinberg,

3. A fourth family of leptons is theoretically possible but would need to be either very heavy or decoupled from the Z boson.

who worked extensively in both fields, remained vague when discussing the status of their relation:

> I don't remember who was the first person to realize that that was a question for which cosmological evidence gave sensitive limits. There were a lot of events like that. For instance, there are cosmological bounds on the mass of the neutrino. I don't know why it all happened at about the same time, but it was just the nature of the problems that particle physicists were considering that they suddenly realized that cosmology could be of help to them. (Lightman and Brawer 1990, 457)

The next section examines in greater detail the nature of Steigman, Schramm, and Gunn's success in order to clarify the relation of cosmology and particles physics. Was it a successful prediction? Or a successful inference from fossil data? Or should we consider the observation of the abundance of ^{4}He as the result of a natural experiment performed in the early universe?

3 Novel prediction, historical analysis or natural experiment?

In this section, I argue that there are different compatible approaches to the cosmological determination of an upper limit on the number of families of leptons described in the previous section. First, from the point of view of particle physicists, this result could be regarded as a novel prediction to be later tested in particle accelerators. Second, for cosmologists, it was a successful historical analysis of a measurement – the cosmic abundance of ^{4}He – as a "fossil" from an earlier stage of the universe. Third, I suggest framing Steigman, Schramm and Gunn's research as a case of experimental reasoning, in which the universe was genuinely used as "the poor man's accelerator", a tool to investigate the inner constitution of matter. I argue that my approach is supported by the analogy between the causal characteristics of the primordial nucleosynthesis and laboratory experiments and that it explains how reasoning about the early stage of the universe was able to assume the same role as a particle accelerator experiment. Furthermore, this approach integrates the points of view of both particle physicists and cosmologists and determine in what extent each of them is legitimate.

3.1 A cosmological prediction

If you were a particle physicist of the 1970s, why would the result of Steigman, Schramm, and Gunn be of any interest to you? Because it constrained a parameter that had previously been free to vary. How was this constraint established? In a simplified account, this constraint was implied by the conjunction of two elements: the current observation of the abundance of ^{4}He and a set of equations (a model) governing primordial nucleosynthesis. According to this account, the value of the parameter "number of lepton species" was determined by using the measurement of another parameter, "cosmic abundance of ^{4}He", alongside equations that link these two parameters. This kind of reasoning is typical of scientific predictions, and the fact that particle physicists tried – and succeeded – to verify that the number of lepton families was indeed less than seven indicates that they regarded it as such.

It can even be argued that this cosmological constraint on particle physics models is a paradigmatic case of *novel* prediction because it satisfies the three main criteria for defining the *novelty* of a piece of evidence with respect to a theory. In the debate on the respective merits of prediction and accommodation, it is usual to distinguish three ways to characterize how a prediction is novel.[4] The first is *temporal novelty* and applies when a phenomenon is described theoretically before being discovered experimentally. For a particle physicist who considers the experiments at the LEP as direct measurements of the number of lepton species, the fact that Steigman, Schramm,

4. This classification goes back to Alan Musgrave (1974): it has been reused in several works and has shaped the debate since then. See for instance (Mayo 1991; Earman 1992; Leplin 1997; Hitchcock and Sober 2004; Howson and Urbach 2006; Douglas and Magnus 2013; Barnes 2023).

and Gunn's article was published thirteen years before the announcement of these measurements means that their claim regarding the number of leptons was temporally novel. Hence, it can be seen as a novel prediction anticipating the future results of their own field.

The second approach to novelty is *heuristic novelty* or *use-novelty*. This definition, introduced by Élie Zahar (1973) and later reformulated by John Worrall (2014), is as follows. Given a theory $T(f)$ where f is a free parameter (or a set of free parameters), we can use evidence K to fix the value $f = f_0$ and transform $T(f)$ into a predictive model $T(f_0)$. The evidence e is novel with regard to $T(f)$ (and thus T predicts e) if e is a consequence of $T(f_0)$ and e does not belong to K. In other words, T predicts e if e has not been used to fix the free parameters of the model $T(f)$ that allow us to deduce e. In our case, e is the upper limit on the number of leptons, T is the theory of primordial nucleosynthesis, and K includes all the evidence needed to fix the free parameters (e.g., the speed of nucleosynthesis), such as the cosmic abundance of ^{4}He, but not e. We can therefore conclude that the number of lepton families is use-novel with respect to the theory of primordial nucleosynthesis (and more broadly, the Big Bang theory). It was thus a genuinely novel prediction, explaining why the Big Bang theory gained confirmatory support from the experiments of the LEP collider in 1989. These measurements were an independent source of confirmation for e, which was transferred to T because T had predicted it.

The last way to define the novelty of a predicted fact is *theoretical novelty*. According to this approach, a phenomenon P is predicted by a theory T if no alternative theory t' exists that can account for P – or account for P as well as T. This definition also applies to our case study. As shown in the quotations of Schramm, Sciama, and Weinberg given in the previous section, particle physicists were impressed not only by cosmology's ability to constrain the number of leptons but also by the fact that this constraint arose from cosmological considerations at a time when no particle physics reasoning could achieve the same. The model of the primordial nucleosynthesis was the first to deduce anything about the number of lepton families, making this result theoretically novel.

In summary, according to any definition of what constitutes a novel prediction, particle physicists were entitled to view the result of Steigman, Schramm, and Gunn as a prediction from another field relevant to their own research. However, the situation appears different when viewed from the perspective of cosmologists. For them, this result was a successful historical analysis of the abundance of ^{4}He as a fossilized trace of an earlier state of the universe.

3.2 Cosmology as a historical natural science

There is a general agreement that, since the refutation of steady-state cosmology and the advent of the Big Bang theory, cosmology should be regarded as a historical science, because we have access to only one exemplar of its object – the universe – and this exemplar is evolving.[5] As a result, cosmologists began extensively using the historical style of reasoning after the discovery of the Cosmic Microwave Background (CMB), as noted by Pearce:

> Peebles noted that the CMB seemed "to be a major fossil find" (Peebles 1971, 190). However, post-CMB detection, cosmologists actively went looking for new fossils. For Peebles, the task of cosmologists became "to ask under what conditions, what possible histories of the Universe, we would expect to find a closely thermal Fireball spectrum, and under what conditions we would not" (Peebles 1971, 190). (Pearce 2017, 29)

In our case study, the "fossil" was not the CMB but the cosmic abundance of ^{4}He. Yet, the reasoning remains the same: from these data, cosmologists asked the question: "under what possible history of the universe could we expect to find the observed cosmic abundance of this isotope?" As discussed in the previous section, the fact that ^{4}He is not easily destroyed after its production makes it a good fossil of the processes of nuclear reactions in the early universe. Consequently, cosmology – or at least some research in this

5. See (Pearce 2017, 30) for a comprehensive list of references on historical approaches to cosmology. See also the more recent works of (Yao 2023) and (ELDER 2025).

field – can be characterized as what the philosopher of geology Cleland has called "historical natural sciences" (Cleland 2001, 2011). According to Cleland, the methodology of these sciences (e.g., geology, evolutionary biology, archaeology) differs from the classical experimental method:

> Experimental scientists focus on a single (sometimes complex) hypothesis, and the main research activity consists in repeatedly bringing about the test conditions specified by the hypothesis and controlling for extraneous factors that might produce false positives and false negatives. Historical scientists, in contrast, usually concentrate on formulating multiple competing hypotheses about particular past events. Their main research efforts are directed at searching for a smoking gun, a trace that sets apart one hypothesis as providing a better causal explanation (for the observed traces) than do the others. (Cleland 2001, 989)

This account seems to accurately represent how cosmologists themselves arrived at the conclusion that there were no more than seven families of leptons.[6] They first formulated multiple hypotheses about helium production in the universe: they compared different models of primordial nucleosynthesis under varying conditions, including different numbers of lepton families. Then they identified the cosmic abundance of ^{4}He as a "smoking gun" – a trace left by the causal processes that occurred in the primordial universe. Using this measurement, they treated ^{4}He as a "fossil", i.e., a signature in the late universe of this causal past in order to discriminate between competing models. Even though this measurement was not sufficient to eliminate all competing hypotheses[7] it had enough evidential power to refute all models of primordial nucleosynthesis that assumed more than seven lepton families.

At this point, the reader might feel slightly confused. My analysis does not seem to clarify the relationship between particle physics and cosmology

6. Note that Cleland herself, in her 2001 paper, uses the cosmic microwave background as an example of fossil used in historical reasoning.

7. But one can wonder if the perfect "smoking gun" setting apart only one hypothesis and eliminating all others is nothing but an ideal.

but rather muddles it further. On the one hand, I have argued that particle physicists were entitled to view the conclusion of Steigman, Schramm, and Gunn as a novel prediction. On the other hand, I have shown that, for cosmologists, this conclusion was the result of a historical analysis of astronomical measurements. How can these two accounts be reconciled? In what follows, I argue that an elegant way to bridge these two approaches is to depict the work of Steigman, Schramm, and Gunn as experimental reasoning that treats primordial nucleosynthesis as a natural experiment – thus drawing a genuine comparison between the universe and a particle accelerator.

3.3 The primordial nucleosynthesis as a natural experiment

To reconcile how particle physicists and cosmologists view the upper limit of lepton families, we can first observe that they would all agree that Steigman, Schramm, and Gunn's result can be formulated as the following counterfactual statement: "If there were more than seven families of leptons, then the cosmic abundance of ^{4}He would be higher than it is." Because there is no way to account for a greater abundance of ^{4}He than what we measure today, this counterfactual has for consequence that its antecedent is refuted: there are no more than seven lepton families. The logic and semantics of counterfactuals represent an extensive and debated philosophical issue (Starr 2022). One approach to interpreting such a counterfactual statement is to view it as describing a possible intervention, as defined by James Woodward:

> (IN) An intervention I on X with respect to Y (for the purposes of determining whether X causes Y) is an exogenous causal process that completely determines the values of X in such a way that if any change occurs in the value of Y, it occurs only in virtue of Y's relationship to X and not in any other way. (Woodward 2003, 91)

Woodward's move is to use the notion of experimentation, defined as an intervention, to provide an account of what sentences like "X causes Y" mean.

This is what makes Woodward's interventionist account both a conception of causality and a specific view of scientific experimentation. This view is not radically different from other celebrated accounts of scientific experimentation (Hacking 1983; Ackermann 1988; Gooding, Pinch, and Schaffer 1989; Harré 2002; Radder 2003; Franklin and Laymon 2021): it distinguishes experimentation and observation by the specific causal structure of experimental systems and the specific epistemic access that this structure grants to scientists. But Woodward's account of experimental interventions is particularly well-suited to our case because it explicitly accommodates *natural experiments* as genuine experiments:

> (IN) is framed entirely in terms of notions like cause and correlation and makes no reference to human beings or what they can or cannot do. [...] Processes that do not involve human action or design will qualify as interventions as long as they have the right causal/correlational characteristics. Indeed, the important and philosophically neglected category of "natural experiments" typically involves the occurrence of processes in nature that have the characteristics of an intervention but do not involve human action or are not brought about by deliberate human designs. (Woodward 2003, 94)

In other words, I is an intervention if there is a causal path going from I to X to Y with no alternative path from I to Y.[8] This condition represents the core of the interventionist account of causality, as reformulated by Woodward himself (Woodward 2007, 75):

(I1) I causes X.

(I2) I acts as a switch for all the other variables that cause X.

(I3) Any directed path from I to Y goes through X.

8. For a critical discussion of this approach, see (Reutlinger 2012; Kistler 2013; Frisch 2014).

(I4) I is independent of any variable Z that causes Y and is on a directed path from I to Y that does not go through X.

If we endorse this interventionist account, the aforementioned counterfactual – "if there were more than seven families of leptons, then the cosmic abundance of ^{4}He would be higher than it is" – should be interpreted as follows: there is only one causal path going from I, a process that completely determines the value of X (the number of lepton families), to Y (the cosmic abundance of ^{4}He). Any change in the value of the cosmic abundance of ^{4}He would therefore be explainable only in virtue of Y's relationship to X (the number of lepton families) and not through any other mechanism. The existence of this causal path was the main object of to Steigman, Schramm, and Gunn's article. They articulated their argument as a clear causal chain: "From the chain: 'new' leptons → increased density → speed-up → increased ^{4}He abundance, we may obtain an upper limit to the number of unknown leptons." (Steigman, Schramm, and Gunn 1977, 203) But is this causal chain the only path from I (the process changing the number of leptons) to Y (the cosmic abundance of ^{4}He)? This was the focus of the remainder of their article: to demonstrate that "the standard Big Bang model for the universe implies a correspondence between the number of lepton types and the abundance of helium" (Steigman, Schramm, and Gunn 1977, 204). Their goal was to show that changing the number of leptons would not impact any variable related to the cosmic abundance of helium beyond the factors already incorporated into their causal chain. It is because such a "correspondence" exists that we can trace the abundance of helium back to the number of leptons: it would be impossible for this abundance to remain unchanged with more than seven lepton families (see figure 3). Consequently, the causal and correlational characteristics of the primordial nucleosynthesis of ^{4}He satisfy Woodward's definition of an experimental intervention. This explains how Steigman, Schramm and Gunn could perform their counterfactual reasoning.

Obviously, the number of lepton types in the early universe was not determined by human intervention. The causal process that set this number at seven or below falls into the "philosophically neglected category of natural experiments". Following Woodward's definition of intervention, we can thus

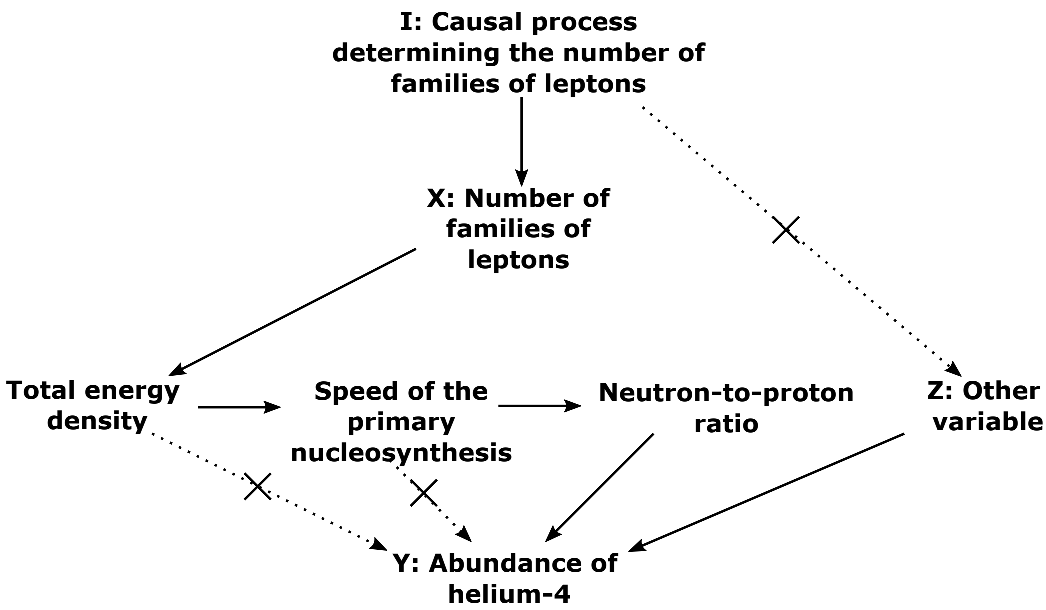

Figure 3: The causal path that Steigman, Schramm and Gunn isolated in the model of primordial nucleosynthesis to fix an upper limit to the number of lepton families. The existence of only one causal path is what makes any process fixing the number of lepton families an experimental intervention according to Woodward's conditions (I1)-(I4).

approach the universe during primordial nucleosynthesis as a genuine natural experiment – one used to investigate the inner constitution of matter and constrain models of particle physics.

A potential objection to our analysis is that the observation of the cosmic abundance of ^{4}He cannot be considered the result of an actual natural experiment, as we have not observed the causal process I determining the number of lepton families in the primordial universe. Ideally, if we possessed multiple universe exemplars, each varying only in the number of lepton families, we could characterize this as a genuine intervention and develop a severe test of whether the number of lepton families causes cosmic helium abundance. However, it is crucial to note that neither cosmologists nor particle physicists were primarily concerned with empirically verifying this causal relationship. Instead, Steigman, Schramm and Gunn first established, based on prior knowledge of the dynamics of the primordial nucleosynthesis, the existence of a causal path connecting the number of lepton families to the abundance of helium, and subsequently used this path to constrain the number of leptons. In a sense, they reversed Woodward's account of experimentation: rather than attempting to determine whether X causes Y, they used the established causal relationships in standard Big Bang cosmology to gain insights into X. Consequently, they did not need to directly observe the causal intervention I on X, but merely to conceptualize a logically possible intervention on X – that is, to describe the primordial nucleosynthesis process if only the number of lepton families were to change.[9] Therefore, it is not necessary for the intervention involving lepton family number change to have been actually implemented to be considered a genuine intervention. The primordial nucleosynthesis process can still be viewed as a genuine natural experiment because we possess sufficient knowledge to determine that, had

9. Reutlinger demonstrated that Woodward's causality account must incorporate logically possible interventions as genuine interventions to apply to any counterfactual statement (Reutlinger 2012, 791). He suggests that Woodward's intervention notion becomes dispensable, potentially collapsing into possible world semantics or leading to inadequate counterfactual evaluation. Discussing these claims falls outside the scope of this paper, as our primary focus is on scientists' reasoning style. Moreover, it remains possible that the number of lepton families could *physically* change, rendering the discussed intervention not merely conceptually but physically plausible.

only the "number of family types" parameter changed, the observed abundace of ^{4}He would have been different.

A second objection might be that the case we are interested in has not much in common with what is usually referred to as "natural experiments". For instance, when Anderl looks at cases of experimentation in astrophysics, she searches for the natural analogue to randomized controlled trials (RCTs), in which two statistically comparable groups differ by only one independent variable (Anderl 2016). This is obviously impossible in cosmology where we have access to only one single universe. But all experiments are not RCTs: actually, many of the most celebrated experimental successes in physics, such as Millikan's oil drop experiment or Eddington's measurement of stellar light deflection by the Sun (Boyd 2021), do not fall in this category. They still qualify as experiments because scientists rely on a specific causal and correlational structure to have access to specific states or variables of a system that they are interested in, and which are usually not accessible. In this broader epistemic sense, cosmology's use of the early universe can indeed be considered experimental: it involves identifying and interpreting the observable consequences of well-characterized causal mechanisms operating under extreme conditions. Our case is precisely one where the natural experiment is comparable not to a RCT but to another kind: the experiments performed by physicists in large-scale particles colliders like the LEP.[10] The reasoning of cosmologists who infer the number of lepton species from the abundance of ^{4}He closely parallels that of particle physicists who inferred the existence of three lepton families from the Z boson's invisible decay: just as more than five lepton species could not adequately reproduce the observed ^{4}He abundance, more than three lepton species could not account for the Z boson's measured decay width in the LEP detectors. Zel'dovich's comparison between the universe and a particle accelerator is thus grounded in a structural and functional analogy: cosmologists possess sufficient knowledge about the primordial universe's causal characteristics to employ it as particle physicists use their particle accelerators.

A third objection to our analysis construing the universe as a natural ex-

10. I would like to thank an anonymous reviewer for pointing that to me.

periment is that no experimental intervention seems physically possible, or even conceptualizable, regarding the universe as a whole. Hacking famously claimed that "galactic experimentation is science fiction, while extra-galactic experimentation is a bad joke" (Hacking 1989, 559), arguing that the method of astronomical sciences is completely detached from the experimental methods of other natural sciences. Cleland's aforementioned view is also that one should not conflate the method of historical natural sciences with the experimental method. However, these claims rest on the assumption that any intervention requires human manipulation of a system. This presupposition, and the resulting astrophysical anti-realism, has been challenged by numerous authors who provided compelling examples and accounts demonstrating how astrophysics relies on experimental methods and reasoning ((Morrison 1990; Shapere 1993; Sandell 2010; Anderl 2016; Leconte-Chevillard 2021; Boyd 2023)). However, the question of experimentation in cosmology differs from that in astrophysics. If cosmology is the science of the universe, then, as it seems that "if you wish to include the entire universe in the model, causality disappears because interventions disappears – the manipulator and the manipulated lose their distinction" (Pearl 2009, 419). Does the notion of intervention break down when applied to the universe as a whole? Indeed, Woodward himself framed his definition of an intervention as an "exogenous" causal process, which raises the question: what could be exogenous to the entire universe? As Woodward argued:

> Consider the claim that (U) the state S_t of the entire universe at time t causes the state S_{t+d} of the entire universe at time $t + d$. On an interventionist construal, this claim would be unpacked as a claim to the effect that under some possible intervention that changes S_t, there would be an associated change in S_{t+d}. Although I don't claim that it is obvious that the relevant interventionist counterfactuals make no sense or lack determinate truth values, it seems uncontroversial that a substantial amount of work would have to be done to explain what these counterfactuals mean. (Woodward 2007, 93)

Yet, it is difficult to make sense of Pearl's and Woodward's restrictions. As Reutlinger pointed out, one could easily imagine a logically possible intervention that changes only the value of variables describing a particle in a Newtonian universe – its mass, velocity or position – while leaving all other particles' variables unchanged:

> For instance, the velocity of a particle is changed by the intervention event i in a possible Newtonian world w. Such an intervention event i could be the influence of an 'additional' counterfactual particle that does not exist in the actual universe. That is, the intervention on a closed system can be understood as a possible world, in which a hypothetical environment (including the 'additional' particle) interacts with a system that is actually closed, i.e. a system that has no environment in the actual world (Woodward's universe). I see no reason why such an intervention should be logically impossible (albeit maybe physically impossible) – and that is all Woodward requires. (Reutlinger 2013, 279)

The case of Steigman, Schramm, and Gunn's 1977 article provides an excellent empirical illustration of such reasoning. Instead of imagining an "additional particle" as in Reutlinger's example, their intervention involved adding new lepton families until the cosmic helium abundance diverged from what is actually measured in our universe. Matthias Frisch offered a similar response to Pearl's prohibition of endogenous intervention:

> Formally, an intervention is represented by removing the equation $x_i = f_i(pa_i, u_i)$ from the model and replacing it with some x_i. Pearl calls such an intervention an "atomic intervention", which can be denoted by "$do(X_i = x_i)$" or "$do(x_i)$" (Pearl 2009, 70). Any more complex intervention that forces several variables to have fixed values can be represented in terms of a set of atomic interventions. Although one might think informally of interventions as requiring that a system have an environment from which the intervention is to be performed, this informal conception is

> not part of Pearl's do-calculus. Thus, contrary to Pearl's own worry, it makes perfect sense to ask, on his own account, how the values of variables would change under an intervention into a model of the universe as a whole. The $do(x)$ operation does not require that we assume that the causal structure on which it is performed be embedded into a larger environment represented in part by exogenous intervention variables. (Frisch 2014, 95)

In our case, the $do(\cdot)$ operation is applied to the number of lepton families, setting it to more than seven, with the causal structure being the causal path from this variable to helium abundance as described by the universe's model during primordial nucleosynthesis. As Frisch pointed out, there is no logical reason why Pearl's definition of intervention would preclude interventions on the universe as a whole. The condition that an intervention should be an exogenous causal process is thus ungrounded, even within the interventionist conceptions of its defenders.

Therefore, it seems reasonable to interpret Steigman, Schramm, and Gunn's reasoning as an instance of experimental reasoning. Primordial nucleosynthesis can be described as an experiment because they leveraged our understanding of the causal structure of this process to predict the consequences of altering the number of leptons. Moreover, interpreting the cosmic abundance of ^{4}He as the outcome of a natural experiment provides a useful framework for understanding why cosmologists and particle physicists might assess the upper limit differently. As Woodward himself noted, his interventionist account "requires that causal claims should be interpretable as predictions about the outcomes of hypothetical experiments" (Woodward 2003, 105). Particle physicists were therefore justified in viewing the cosmologists' claim – that the number of lepton families determined the cosmic abundance of helium – as a prediction. Because laboratory experiments were the standard in their field, they conceptualized this claim as a prediction of the outcome of a hypothetical laboratory experiment. The efforts to transform this hypothetical experiment into a tangible one ultimately led to the development of the LEP collider. However, the situation was different for cosmologists, who approached the natural experiment from a retrospective perspective. For them, the objective was to identify an observable parameter unequivocally linked to the process of the primordial nucleosynthesis. Consequently, their reasoning was historical: they chose to use the abundance of ^{4}He as a relic of the past universe, recognizing that there was a single causal path connecting the number of leptons to this observable parameter.

In other words, Steigman, Schramm, and Gunn's reasoning could be construed both as a novel prediction and as a historical analysis because it conformed to the structure of an intervention as defined by (IN). The causal and correlational characteristics of (IN) enabled both interpretations to be valid and compatible. Hence, Zel'dovich's assertion that the universe is the "poor man's accelerator" should not be read merely as a catchy slogan; it aptly described how cosmologists had acquired sufficient knowledge of the causal processes in the primordial universe to reinterpret observations of the current universe as the results of a natural experiment that could not have yielded the same results if the Standard Model of particle physics were different. Thus, the analogy between the universe and particle accelerators is genuine: both can serve a similar role in reasoning by helping discriminate among competing hypotheses or models of particle physics. In the next section, I argue that this analogy has become even more pertinent since Zel'dovich first proposed it.

4 The cosmological collider

As mentioned above, Zel'dovich's claim that the universe is the "poor man's accelerator" was rooted in past science but also forward-looking. He observed:

> It should be pointed out that cosmology is now applying highly hypothetical fundamental physics that has not been confirmed by any experiment. We are extrapolating physical laws to energies 10^{15} times larger than those achieved in the most powerful accelerators. A new branch of science is born: the application

> of astronomical knowledge to find (or at least to constrain) the fundamental laws of physics in regions inaccessible to direct experiment. We are in the position of the paleontologists, with only fossils or remnants to study directly. (Zel'dovich 1988, 29)

This statement illustrates how cosmology's historical style of reasoning can take on the role of laboratory experiments, as discussed in the previous section, if cosmologists can identify processes with the appropriate causal characteristics in the early universe. As Zel'dovich emphasized, this perspective on the universe as a particle accelerator is indispensable for testing very high-energy physics. For instance, modern particle accelerators, such as the Large Hadron Collider, achieve collision energies as high as 13 TeV (13×10^3 GeV), an extraordinary feat. However, this is still very far from the Grand Unified Theory (GUT) scale of 10^{16} GeV, making it unlikely that any future collider could reach such energies. The only alternative, therefore, is to study natural experiments in the early universe to probe this regime of physics.

This is precisely the goal of what is known as "Cosmological Collider Physics." This emerging field began in 2015 with a paper published on arXiv by Nima Arkani-Hamed and Juan Maldacena. Their work echoes Zel'dovich's ideas and aligns with the analysis in the previous section:

> Inflationary cosmology provides us with a natural high-energy accelerator. The late universe represents the detector output of this accelerator. The presence of new particles, beyond the inflaton, leads to subtle imprints on the cosmological primordial fluctuations. (Arkani-Hamed and Maldacena 2015, 48)

Arkani-Hamed and Maldacena's proposal relies on the idea that during the (hypothetical) inflationary era – which expanded the universe's scale factor by more than 10^{22} before 10^{-34} seconds after the Big Bang – quantum fluctuations were stretched to cosmological scales. These fluctuations are observable today in the anisotropies of the CMB and in the distribution of galaxies. Exotic particles – those beyond the Standard Model – that existed in the early universe would have left imprints on the primordial fluctuation spectrum, particularly in the form of non-gaussianities. These non-gaussianities thus serve as signatures, allowing researchers to infer the mass and spin of such particles, much as collider physicists do from scattering data. Arkani-Hamed and Maldacena explicitly build their research program on the analogy between these signatures and those found in a particle collider: "In a hadron collider we look at jets or patterns of energy deposition on the detector. In cosmology we similarly look for patterns in the distribution of galaxies or in the cosmic microwave background." (Arkani-Hamed and Maldacena 2015, 1) Thus, Zel'dovich's analogy is not merely descriptive but also heuristic and methodological: without a structural and functional analogy between the Universe and a particle accelerator, cosmological collider physics would have been impossible to conceive.

While the initial paper by Arkani-Hamed and Maldacena has not been published in a peer-reviewed journal, it has spurred an on-going research program[11]. Only time will tell if this program will be successful, but it is already evident that it fulfills Zel'dovich's vision of exploring new physics through the early universe, conceived as a natural counterpart to man-made particle colliders. Moreover, cosmological collider physics extends Zel'dovich's vision: it does not merely test existing hypotheses about particle physics but also aims to discover new particles from empirical data. In other words, the inflationary universe is seen not only as an experiment for hypothesis testing but also for exploration, a critical function of experimentation. If cosmological collider research or any other program leveraging cosmological causal processes succeeds in investigating high-energy physics, it will underscore the profound utility of the analogy between natural and man-made particle accelerators for advancing fundamental physics.

5 Conclusion

In this article, I argued that the collaboration between cosmology and particle physics emerged from the constraints on the number of lepton families established by Steigman, Schramm, and Gunn in 1977. While other episodes

11. See, for example, (Chen, Ebadi, and Kumar 2022) or (Sohn et al. 2024).

have been crucial to this collaboration, this work was the first to utilize the primordial nucleosynthesis as a substitute for a particle accelerator. Using Woodward's notion of intervention, I showed that the analogy between cosmologists' use of the universe as a natural experiment and particle physicists' use of accelerators is well-founded. In both cases, the systems under scrutiny exhibit the causal characteristics necessary to infer fundamental properties of matter, and in both cases they can be used to test models of particles physics and to discover unknown entities or interactions.

Recognizing this experimental aspect of cosmology is essential for two reasons. First, it reveals that cosmology is not methodologically monist but pluralist. As Yao (Yao 2025) notes, knowledge about Big Bang nucleosynthesis has been gained through multiple interacting strategies – interpreting relics, extrapolating physics, predicting phenomena, and so on. As shown in section 3, these methods interact to provide an epistemic access to the early universe best described as a natural experiment. Hence, contrary to Cleland's sharp opposition between historical and experimental sciences, cosmology should be thought (and taught) as a combination of methods that one usually find in different fields. Second, regarding cosmology as a source of natural experiments highlights its contemporary scientific importance. In the current state of theoretical physics, where laboratory experiments are either unavailable or unfeasible for the foreseeable future, recognizing cosmology's role in providing natural experiments to test or explore new physics can help foster the cooperation between physicists and cosmologists.

To sum up, developing a detailed philosophical account of natural experiments is crucial not only for understanding the epistemic history of cosmology but also for addressing the methodological challenges of contemporary empirical science.

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