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Is Falsifiability a ‘Blunt Instrument’ for Modern Physics?

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ABSTRACT

Modern (theoretical) physics seems to be in deep crisis today as many of its core aspects are not empirically well-confirmed. Heated exchanges among physicists on the scientific status of physical theories with little or, at best, a tenuous connection to possible experimental tests is highly visible in the popular scientific literature. Some physicists (e.g., Carroll 2014, 2019; Ijjas et al., 2017) argue that science must discard empirical testability as one of its defining properties and the highly explanatory theories of present-day physics should be exempted from experimental testing, while others (e.g., Ellis & Silk 2014) spot in these arguments (for softening the testability or falsifiability requirement for modern physics) a dangerous tendency to undermine science. The philosopher of science who naturally draws most attention in these current debates is Karl Popper (1902-1994). His views, however, are often misrepresented in these debates. The prime objective of this paper is to explain how a more enlightened perspective on the ongoing debates can be obtained by a careful scrutiny of the Popperian criterion of falsifiability. As a first step in achieving this objective we will analyze the two major (conceptual) failures on which the current controversies rest. Our next step will be examining the controversial string theory to see whether the criteria of falsifiability is a ‘blunt instrument’ for determining its scientific status.

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Introduction

Modern (theoretical) physics is facing a serious crisis today as many of its core aspects seem anything but empirically well-confirmed. Heated conversations among physicists on the scientific status of theories with a tenuous connection to possible experimental tests are highly visible in the popular scientific literature. For example, three prominent cosmologists, Anna Ijjas, Paul Steinhardt and Abraham Loeb, argue in the February 2017 issue of *Scientific American* that inflationary cosmology– the long-favoured model for the early universe– has no data to support it and it has gone through so many patch-ups that no experiment can ever disprove it. Interestingly, although inflationary cosmology seems untestable, these cosmologists refuse to abandon it. Instead, they propose that science must change by discarding one of its defining properties, namely, "empirical testability" (Ijjas et al., 2017: 39). In contrast, Alan Guth (2017), one of the originators of inflationary cosmology, together with thirty-two equally prominent other signatories (including five Nobel laureates) express categorial disagreement with the view that inflationary cosmology is beyond testability and draw attention to the impressive empirical success of the standard inflationary models.

Such heated exchanges are not only limited to inflationary cosmology. Particle physicist Hossenfelder (2017) is sceptical about the value of theoretical particle physics. She admits openly that "… we produce a huge number of new theories and yet none of them is ever empirically confirmed. Let's call it the overproduction crisis. We use the approved methods of our field, see they don't work, but don't draw consequences…, we repeat ourselves over and over again, expecting different results…" (Hossenfelder 2017: 316). However, instead of indiscriminately dismissing all this research as useless she observes that "…in the absence of good quality measures the ideas that catch on are the most fruitful ones, even though there is no evidence that a theory's fruitfulness correlates with its correctness" (Hossenfelder 2017: 316).

The crisis in modern physics seems to manifest itself most markedly in debates on string theory. Whereas some critics of string theory point to its cosmologies as stark examples of fact-free physics, high-energy theorists Herman Verlinde and Nima Arkhani-Hamed, argue that fundamental physics and string theory are all about finding the "…Truth with capital T."[1] The current debate about the scientific status of theories with questionable links to experimental tests has motivated certain physicists to turn to the history and philosophy of science. String theorist David Gross, for instance, agrees with philosopher Richard Dawid (2019) on the point that string theory necessitates a novel understanding of scientific rationality– an understanding in which progress can be attained on the basis of theory alone.[2] Cosmologist Sean Carroll (2014; 2019), too, is of the opinion that the criteria for scientific theory-assessment should be weakened as empirical testing of the core hypotheses of modern (theoretical) physics is very difficult to achieve. What is

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[1] Nima Arkani-Hamed, quoted in Blom and Wessel (2017).

[2] David Gross extensively discussed and endorsed Dawid at the 2014 Strings conference in Princeton in his plenary lecture (27 June, 2014, Princeton University) in response to criticism that string theory lacks empirical connections.

more, dismissing the Popperian criterion of falsifiability as a ‘blunt instrument’ (Carroll 2014) Carroll (2014; 2019) argues for an exemption of such highly elegant and explanatory theories of present-day physics from experimental testing. Such proposals from leading contemporary scientists have reignited the controversies regarding the nature of science and the viability of its methodologies (that are not directly dependent on empirical evidence).

Cosmologists George Ellis and Joseph Silk, however, spot in these arguments for softening the testability requirement or weakening the need for empirical testing a dangerous tendency to undermine science. They (Ellis and Silk 2014) make it crystal clear that Popper’s criterion of testability (or falsifiability) needs to be (re)instated to demarcate proper cosmology from unwarranted theorizing because “…a theory must be falsifiable to be scientific” (Ellis and Silk 2014:321). The real issue at stake thus seems to concern the question of how serious the crisis of empirical testing in contemporary physics actually is. Quite unsurprisingly, Karl Popper (1902-1994) draws most attention (either as a friend or as a foe) in these current disputes on theory assessment and methodologies in science. His views, nevertheless, are often misrepresented in these debates. Several scholars who are sceptical about the plausibility of the Popperian criterion of falsifiability appear to have an impoverished notion of falsifiability.

The central objective of this paper is to explain how a more enlightened perspective on the ongoing debate can be obtained by a careful scrutiny of the Popperian criterion of falsifiability as a proposed solution to the problem of demarcation. The paper, divided into three main sections, attempts to achieve its objective firstly, by considering two major (conceptual) failures on which the current scientific-philosophical dialogue rests and secondly, by presenting a short case study of string theory to determine whether the Popperian criteria of falsifiability acts as a ‘blunt instrument’ for the assessment of its scientific status.

A major conceptual confusion provoking scholarly controversies is due to some scientists’ (and philosophers’) utter negligence to the Popperian thesis of two different senses of falsifiability, namely, the logical-technical sense of falsifiability− which Popper (1983) calls ‘falsifiability$_1$’− and the practical-experimental sense of falsifiability− which Popper (1983) calls ‘falsifiability$_2$’. As a result, these scholars tend to interpret the difficulties in obtaining conclusive empirical evidence for the theories of modern physics as a significant weakness of the proposed criterion of falsifiability. How the recent debates among physicists and philosophers rest on a conflated version of the two clearly different senses of falsifiability, viz., falsifiability$_1$ and falsifiability$_2$ (Popper 1983) is reviewed in the first section of this paper.

The other conceptual confusion, discussed in the second section of this paper, is due to the scholars’ obliviousness to the Popperian distinction between two different modes or methods of theory-evaluation or assessment, namely, justification and criticism. It is argued in this section that the worrying demand for abandoning experimental testing of the highly speculative theories of fundamental physics has been generated by confusing the justificatory process of theory-assessment with the characteristically different process of critical examination or criticism.

The third and final section of this paper considers one of the most compelling and controversial cases, namely, the string theory[1] in order to examine the plausibility of the Popperian criterion of falsifiability. It begins with a brief (and non-technical) overview of the origin and early developments of the string theory and proceeds to show how the key insights implied in Popper's arguments are still being grossly misinterpreted. The paper concludes by commenting on whether or not the Popperian criterion of falsifiability acts as a 'blunt instrument' for dealing with the controversies regarding the scientific status of string theory.

Section I: The Popperian Distinction between Falsifiability$_1$ and Falsifiability$_2$

Trouble has been brewing for a while in the community of fundamental physics. For, some "empirically unconfirmed or inconclusively confirmed" (Dawid 2019:1) theories of modern physics, have attained a high degree of trust among their exponents and de facto "treated as well-established theories" (Dawid 2019:1). Consequently, some leading physicists (e.g., Carroll 2014; 2019) are of the opinion that Popper's arguments (and his proposed criterion of falsifiability) are of limited value in explaining what is at stake in the recent controversies about the status of such physical theories.

Popper's (1935; 1963; 1983) proposal is that a theoretical system (say, a conjecture or a hypothesis) is to be considered as scientific *only if* it makes assertions which may clash with observations; in other words, a theoretical system is tested or critically examined by attempts to produce such clashes, i.e., by attempts to refute it. Thus, all real tests are attempted refutations. As testability is the same as refutability it too can be taken as a criterion of demarcation− a criterion proposed by Popper (1935; 1963) for addressing the practical problem of assessing theories and judging their claims. There are, of course, degrees of testability. Some conjectures or hypotheses expose themselves to possible refutations more boldly than others. Accordingly, there are well tested theories, hardly tested theories, and non-testable theories. To borrow Popper's (1963/2013:256) own example, a theory, say T_1, that offers precise numerical predictions about the splitting up of spectral lines of light emitted by atoms in magnetic fields of varying strength is evidently more exposed to experimental refutation than a theory, say T_2, that merely predicts that a magnetic field influences the emission of light. As there are degrees of testability the criterion of demarcation obviously cannot be a very sharp one.[2]

Many scientific theories appear to originate in myths. Popper in his *Logic of Scientific Discovery* cites several examples of myths such as, atomism or the corpuscular theory of light which have eventually become most important for science. Take for instance, Copernicus' idea of placing the sun rather than the earth in the center of the universe. In Popper's (1963/2013:257) view, it was not the result of any new observations but of a new interpretation of old and well-known facts in

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[1] For the purposes of this paper, I use the generic term "string theory" to refer to a broad family of related theories connected with the concept of cosmic strings.

[2] Popper has devoted a whole chapter in *The Logic of Scientific Discovery* to this topic.

light of Platonic and Neo-Platonic (semi-religious) ideas. This crucial idea can be traced back to the 6th book of Plato's *Republic*, where we can see that the sun plays the same role in the realm of visible things as does the idea of the good in the realm of ideas. Just as idea of the good is the highest in the hierarchy of Platonic ideas, the sun, which grants visible things their visibility, vitality, and growth, is the highest in the hierarchy of the visible things in nature. Now if the sun merited a divine status in the hierarchy of visible things, then the only appropriate place for such a star could be the center of the universe. The earth, therefore, is bound to revolve around the sun (Popper 1963/2013:253). It may be a slight exaggeration to say that only Platonic or Neo-Platonic ideas exerted an influence on Copernicus' new interpretation of observational data and shifting of the center of all motion from the earth to the sun. Interestingly enough, Copernicus followed the Arabic method in trigonometry instead of chords used by the Greek astronomers (Koyre/ 1973: 23-24). But there is no doubt that he learned Greek, read Plato and was greatly inspired by Neo-Platonic (and Pythagorean) insights (Koyre/ 1973: 21-24).

What's more important, myths may develop testable components, which in the course of investigation, become fruitful and important for science (Popper 1963). It might also happen that a certain statement belongs to science because it is testable, but its negation turns out to be untestable, and thus needs to be placed below the line of demarcation. The example cited by Popper (1963) is of Planck's formulation of the First Law of Thermodynamics in the form of a negation of an existential statement: *There does not exist any perpetual motion machine*. The corresponding existential statement '*There exists a perpetual motion machine*' would naturally belong below the line of demarcation (Popper 1963/2013:347).

In Popper's (1963) view, what makes a theoretical system admissible to the realm of science (or scientific knowledge) is its openness to tests (or to refutation), and not its conclusive verification or substantial empirical confirmation[1] (as many physicists and philosophers of science still assume). Miller (2006: 86) reiterates this point that "decisive or irrefragable refutation" is not necessary for Popper, but susceptibility to removal is. Only those hypotheses that are empirically refutable or falsifiable can count as scientific. If any of the conjectures (or theoretical systems) clashes with empirical evidence *only then* it is to be rejected (Popper 1963). By implication, then, for Popper, a conjecture or theoretical system may remain accepted until it clashes with and falsified or dislodged by experiential evidence. Importantly, such theories, by not being falsified, neither become partially justified nor become more probable. The epistemological status of all not-yet-refuted hypotheses remains equivalent (Miller 2006: 98); they are all highly imaginary guesses or bold speculations (neither derived from experience nor from any a priori first principles) open to criticism and refutation.

Given that a statement (a theory or a conjecture) has the status of belonging to the empirical sciences *if and only if* it is falsifiable, the next question would be: when is a theory or conjecture

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[1] Hume taught us long ago that no amount of empirical evidence can ever suffice (logically) for even the most circumspect generalization.

falsifiable? Few scientists engaged in the current debates appear to be heedfully aware of the fact that falsifiability in the sense of Popper's demarcation criterion is a purely logical affair. It deals only with the logical structure of statements or of classes of statements and has nothing to do with the question of whether or not certain possible experimental results would be accepted as falsifications. A statement or theory is, according to Popper's (1983) criterion, falsifiable *if and only if* there exists at least one potential falsifier, i.e., at least one possible basic statement that conflicts with it logically.

Popper (1983) characterizes the class of basic statements in such a way that a basic statement describes a logically possible event of which it is logically possible that it might be observed. To borrow his own example, the statement "All swans are white" is falsifiable since it contradicts the following basic statement: 'On the 16th of May, 1934, a black swan stood between 10 and 11 o'clock in the morning in front of the statue of Empress Elizabeth in the Volksgarten in Vienna' (Popper 1983/2000: xx). What is not required here is that the basic statement in question must be true (Popper 1983/2000: xx).

In contrast, the widely-held hypothesis of psychological egoism− all human actions are egotistic, motivated by self-interest− variants of which may be found in behaviourism, psycho-analysis, utilitarianism, or in sociology of knowledge− is not falsifiable (Popper 1983/2000: xx). No example of an altruistic action can refute the claim that there was an egotistic motive hidden behind it. To borrow another example from Popper (1983/2000: xx-xxi): 'There is a ceremony whose exact performance forces the devil to appear.' Such a statement is also not falsifiable, though it is, in principle, verifiable. For, it is logically possible to find a ceremony whose performance leads to the appearance of a human-like form with horns and hooves. Even if a repetition of the ceremony fails to produce the same result there would be no falsification because anybody might argue that some unnoticed aspect of the exact performance of the ceremony has been omitted. Falsifiability in this logical sense (as shown by the above examples) signifies a logical relation between the theory (or hypothesis) in question and the class of basic statements, or the class of events described by them, that is, the potential falsifiers. Falsifiability is relative to these two classes: if one of these classes is given, then falsifiability is simply a logical matter. Falsifiability in this logical-technical sense is referred to by Popper (1983) as 'falsifiability$_1$'. It neither entails that a falsification can in practice be carried out, nor that, if it is carried out, it will be entirely unproblematic.

There is, however, a second sense of 'falsifiable' and 'falsifiability' which needs to be distinguished very clearly from the (above) logical-technical sense in order to avoid gross misunderstanding. The second sense of 'falsifiable' is that the theory (or hypothesis) in question can definitively or conclusively or demonstrably be falsified (Popper 1983/2000: xxi-xxii). While the first sense refers to the logical possibility of a falsification in principle, this second sense refers to a conclusive practical-experimental proof of falsity. One might here of course ask whether an actual falsification is ever so compelling that the theory (or hypothesis) in question be regarded as falsified (and thus as false), or whether there isn't always a way out for saving the theory (or hypothesis) in question.

In the very first edition of *Logik der Forschung* (1935), and also in his earlier *Die beiden Grundprobleme der Erkenntnistheorie* (1979), composed during 1930-33, Popper states very clearly that it is impossible to prove (conclusively) that an empirical scientific theory is false. In this practical-experimental sense, which Popper (1983) calls 'falsifiability$_2$', scientific theories or hypotheses are not (conclusively) falsifiable. Popper (1935) argues further that every theoretical system can in various ways be protected from an empirical falsification. It is not at all difficult to find some way of evading falsification, as for example, by introducing ad hoc an auxiliary hypothesis (Popper 1935/2005: 19-20). As a result, no conclusive disproof of a theory (or hypothesis) can ever be produced and, more importantly, it is not necessary either because "…it is always possible to say that the experimental results are not reliable, or that the discrepancies which are asserted to exist between the experimental results and the theory are only apparent and that they will disappear with the advance of our understanding…" (Popper 1935/2005: 28).

Therefore, from Popper's perspective, a theory which is falsifiable in the former, i.e., logical-technical sense is never falsifiable in this latter practical-experimental sense. This key insight of Popper has gone largely unnoticed in the relevant literature. In his 1935 work we see Popper complainingly refers to the fact that he has been constantly misinterpreted as upholding a criterion based upon a doctrine of 'complete' or 'conclusive' falsifiability (Popper 1935/2005:28). That his views are still being misconstrued is evident in the following comments of Carroll (2014): "…Karl Popper famously suggested the criterion of "falsifiability" − a theory is scientific if it makes clear predictions that can be *unambiguously falsified*…" (italics mine). The recent debates concerning the plausibility of the Popperian criterion of falsifiability (as is visible in popular science outlets) clearly rest on the failure of the scientists to differentiate between the logical-technical sense of falsifiability or 'falsifiability$_1$' and the practical-experimental sense of falsifiability or 'falsifiability$_2$'.

Let's look at the case cited by Popper (1983/2000: xxiii) of the falsification of J. J. Thomson's model of the atom, which led Ernest Rutherford to propose the nuclear model. In Thomson's model of the atom, the positive charge was distributed over the entire space which the atom occupied. Rutherford had accepted this model but the experiments of his students (namely, Hans Geiger and Ernest Marsden) showed that alpha particles which were shot on to a very thin piece of gold leaf were sometimes reflected from the gold leaf, instead of being only deflected. Although the reflected particles were quite rare− approximately one among twenty thousand− they occurred with statistical regularity. Rutherford described this event as the most incredible one of his life− almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back and hit you.

Even though the findings of Geiger and Marsden look incredible, Popper (1983/2000: xxiv) points out, it is not logically impossible that a shot from a giant cannon on to a piece of tissue paper is reflected by it even with a (regular) statistical probability of 1 in 20,000. One cannot, therefore, argue for a strict disproof or conclusive refutation of Thomson's theory (according to which the atoms form a wall like tissue paper). Nevertheless, the said theory was eventually replaced or superseded by the nuclear model of Rutherford. This shows how (empirical) falsification of even a non-definitive character could play a significant role in the history of scientific investigation.

The scientists who accuse Popper for proposing a 'blunt' criterion of (conclusive) falsification and for ignoring the non-conclusiveness of the falsification of scientific theories are blind to this perfectly sharp, unambiguous distinction between falsifiability_1 and falsifiability_2. That's why the difficulties involved in a (conclusive) practical-experimental falsification appear as a weakness (or bluntness) of falsifiability per se– the Popperian criterion of demarcation. Any criticism assuming such an impoverished notion of falsifiability is, in effect, no useful criticism of falsifiability at all.

Relatedly, one of the standard objections (e.g., Lakatos 1978) against Popper is that very few episodes in the history of science actually conform to this Popperian pattern of bold conjectures and rigorous refutations. Popper's criterion of falsification, we need to remember, is a methodological proposal, not a thesis about the history of science. As Miller (2006:96) clarifies, it is a demand and not an empirical thesis or generalization that can be challenged or refuted by citing the scarcity of cases of falsifications in the history of science. All this would have been of little importance today had some prominent scientists not ignored the Popperian insights and argued for relaxing the need for empirical testability.

Section II: The Popperian distinction between the Method of Justification and the Method of Criticism

It is generally claimed that from a rational point of view, the choice between competing scientific (or mathematical or even metaphysical) beliefs or positions is arbitrary because it is logically impossible to act or decide on rational grounds when it comes to such choices. The sceptical argument based on this analysis is called the argument about the 'limits of rationality' or the 'boomerang argument' (Bartley 1964/1999:6). The argument is basically an interpretation of the fact that any view may be challenged with questions as 'how do you know'? or 'give me a reason' or 'prove it' or 'justify it'. Such traditional philosophical questions are authoritarian in structure in the sense that they all beg authoritarian answers. Questions like how do you know or justify your beliefs, or with what do you guarantee your opinions, necessarily call for authoritarian answers. No demand for a justification or guarantee can be met except by providing something authoritative, i.e., something unquestionable that does not need any justification.

When we try to address such challenges by citing further reasons (including those already under review), these reasons may be questioned in turn and so on forever. Usually, though not necessarily, in order to avoid such infinite regress, one adopts certain things like standards, criteria, ends or goals. However, if to defend a position rationally is to offer good reasons in justification of it, then none of these usually adopted halting points would be rationally defensible.

It is Popper who made us realize that philosophers should neither demand nor search for infallible intellectual authorities, but should instead try to develop a way of eliminating (intellectual) errors.

The process of reasoning, Popper (1963) argues, may provide criticism but it can never provide justification. The rational attitude thus consists wholly of openness to criticism as well as of appropriate responses to criticism. This general shift from the traditional, philosophical demand for authoritative justification to the demand for criticism is seen by Bartley (1964/1999: 21) as "a genuine innovation" in philosophy. Popper's is the first non-justificational philosophy of criticism in the history of philosophy. No one before Popper has succeeded in separating the process of justification from that of criticism.

Most philosophical theories about the rational evaluation and criticism of competing views take it for granted that rational character and degree of rationality (i.e., all properties, measures, and tokens of intellectual value or merit), regardless of its nature, are properties that pass from premises to conclusion in the same manner as the property of truth through the relationship of logical deducibility (Bartley 1964/1999: 24-25). Generally, such theories about the assessment and criticism of competing views include (a) some more or less well-defined notion about the nature of whatever property (e.g., truth, probability, empirical character) is to be used in evaluating and criticizing, and (b) the assumption that this property, whatever its character, must be fully logically transmissible like truth and probability. Truth and probability are two of the very few characteristics that do happen to be transmissible from premises to conclusion through the deducibility relationship. Most other evaluational properties are not like them. Nevertheless, due to the profound influence of these two (evaluational) properties over early developments within the justificationist metacontext, it has been uncritically assumed that all other indicators of merit or intellectual respectability (regardless of their logical capabilities) inevitably share the transmissible capacity of truth and probability (Bartley 1964/1999: 26).

Take, for instance, testability as an evaluational property. Unlike truth, the measures of degree of testability are not logically transmissible from premises to conclusion. A hypothesis is testable or falsifiable by the falsification of any of its consequents, and therefore, a hypothesis must possess at least as high a degree of testability as any of its consequents. However, a hypothesis may have a higher degree of testability if, for example, it has other consequents independent of the first. Now, if a hypothesis can possess a higher degree of testability than its consequents, then it's consequents do not inevitably inherit testability through the deducibility relationship (Bartley 1964/1999:25). A high-level, highly testable scientific hypothesis thus does not necessarily bequeath its degree of testability or falsifiability to the lower-level consequents it entails. What is worth noting, Popper's concept of testability, which addresses the familiar problem of rationally assessing or criticizing competing theories, neither entails the deducibility assumption nor is even compatible with it.

The process of testing, Popper (1963) teaches us, is, in principle, infinite. A refutation, according to Popper (1963), does not establish the falsity of a hypothesis or theory; rather it simply leads to the provisional rejection of the hypothesis because it appears to conflict with some other better tested hypothesis or theory. It is also important to note that the view or hypothesis that causes the refutation is itself open to criticism by the testing of its own consequences, and these in turn are criticisable, and so on forever. Our criticism, therefore, is never conclusive; just like the hypotheses we are examining our critical arguments are themselves conjectural. Every falsification may, in its turn, be tested again. In contrast, justificational arguments, leading back to positive reasons, eventually reach reasons which themselves cannot be justified without entailing an infinite regress. The justificationist is thus forced to conclude that such reasons or ultimate presuppositions must in some sense be beyond argument, and, by implication, beyond criticism. According to Popper (1963), it is this uncritical reliance on positive reasons of the orthodox method of justification that poses a serious threat to the rational attitude.

Popper's (1963) method of criticism, i.e., the method of looking for falsifying instances or critical reasons to test a theory or hypothesis contrasts sharply with the traditional method of justification. In his later writings he (Popper 1983/2000: 20-21) explains how 'critical reasons' are to be differentiated from 'positive reasons.' Positive reasons (an appeal to observation, for instance) are offered "…with the intention of *justifying* a theory, or, in other words, of justifying the belief in its truth…" (Popper 1983/2000:20). However, justification− conclusive or inconclusive− is impossible. For, any argument (or positive reasons) put forward to justify, conclusively or inconclusively, the truth (or the acceptability) of a proposition is almost inevitably circular. That is why, Popper replaces "…the question whether we can produce valid reasons (positive reasons) in favour of the truth of a theory by the question whether we can produce valid reasons (critical reasons) against its being true, or against the truth of its competitors..." (Popper 1983/2000: 25).

Critical reasons consist in pointing out "… how, one theory has hitherto withstood criticism better than another…" (Popper 1983/2000:20). Such reasons, evidently, do not justify a theory, because "…the fact that one theory has so far withstood criticism better than another is no reason whatever for supposing that it is actually true…" (Popper 1983/2000: 20). Critical reasons are in no sense ultimate in Popper's view; they are conjectural, infinitely open to re-examination and reconsideration, but can be used to defend (not to justify[1]) our preference for a theory. Such Popper (1983) emphasizes, do not prove that our "…preference is more than conjectural: we ought to give up our preference should new critical reasons speak against it, or should a promising new theory be proposed, demanding a renewal of the critical discussion…" (Popper 1983/2000: 20). Though the process of testing involving critical reasons is infinite, it doesn't lead to any infinite regress because it's aim is not justify any hypothesis with conclusive reasons. This crucial Popperian insight that it is only the demand for proof or justification that generates an infinite regress has not been systematically followed up in the philosophical-scientific literature.

Extending Popper's thesis Miller (1994) defines a critical argument as one in which what is concluded contradicts what is assumed. Put differently, a critical argument can succeed even if it assumes what it seeks to refute. As there is no question of proving or justifying anything, no infinite regress is generated. This is the heart of the difference between justificational and critical arguments or between the method of justification and the method of criticism. An understanding

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[1] Citing reasons for one's preferences may be seen as a method of justification in ordinary language. But it is obviously not the classical, philosophical method of justification that is discussed here.

of this (Popperian) distinction between what Miller (1994) calls a circular or question-begging justificational argument (*a petitio principii*) and a critical argument (*a reductio ad absurdum*) is never more valuable than when we are challenged by the problem of whether or not to abandon or to weaken the need for empirical testing in modern physics. The recent proposal for an exemption of highly speculative theories of modern physics from experimental testing depends on the assumption that theory assessment in science is basically a method of justifying our belief in the truth of such theories by means of some positive reasons. This clearly indicates the scientists' obliviousness to Popper's "genuine innovation" (Bartley1964/1999: 21) that the method of justification can be replaced by the method of non-justificational assessment involving critical reasons, to be exact, reasons instrumental in defending (and not justifying) our preference for any scientific theory. Had the scientists been attentive to this dramatic transition from the various methods of justification to Popper's method of (non-justificational) criticism, they could have dealt with the current controversy about scientific theory assessment more advantageously.

Section III: Is Falsifiability a 'blunt instrument' for String Theory?

The present section attempts to examine the origin and early developments of the much-debated string theory in order to determine whether falsifiability acts as a 'blunt instrument' (Carroll 2014) for evaluation of its scientific status.

Let's first try to understand the basic idea of string theory− often described as a "work in progress" (Greene 2000:18; Schwarz 2000: 3) or a theory under development. In a nutshell, string theory describes the different species of elementary particles as various modes of vibrations of tiny strings. Many theoretical physicists are very excited about its potential for revealing an extraordinarily rich structure with many deep connections to various branches of fundamental mathematics and theoretical physics, while some (e.g., Weinberg 2015:14) are doubtful about its application to the empirical world.

One possible way to grasp the core idea of string theory is to review (albeit briefly) the evolution of scientific ideas about the microscopic structure of the universe during the last century. Historical evidence indicates that in Miletus, over a century before the time of Socrates, the ancient Greeks began to speculate about the fundamental substance of which is world is composed. The pre-Socratics, from Thales to Empedocles, appeared to have thought of the elements as undifferentiated substances, like water or air. A contrasting view, quite closer to modern understanding, was developed by Leucippus and his successor Democritus a little later (Weinberg 2015: 7). All matter, according to Leucippus and Democritus, consists of tiny, indivisible particles that they named atoms− "*uncuttable constituents*" in the truest sense of the ancient Greek (Green 2000:141; italics in original) − moving in empty space.

Scientists continue to hold in some form or other this atomic hypothesis implying the discreet or grained nature of matter for over two thousand years. The scientific accounts of the most fundamental units, obviously, have undergone several revisions. Let's consider the solar-system like atomic model developed by J.J. Thomson, E. Rutherford, N. Bohr and J. Chadwick in the early

1930s. The atoms, according to this model, instead of being the most elementary material constituent, consist of a nucleus, containing protons and neutrons, surrounded by a swarm of electrons. In 1968 when the experimenters at the Stanford Linear Accelerator Center, probed deeper into the microscopic complexity of matter with the help of more advanced technological instruments, they discovered that even protons and neutrons are not fundamental as each consists of three smaller particles, called *quarks*, which are of two kinds, namely, *up-quark* and *down-quark*. A proton consists of two up-quarks and one down-quarks, whereas a neutron consists of two down-quarks and one up-quark.

Meanwhile, a fourth kind of fundamental particle called *neutrino*− which rarely interact with other matter− was detected by Frederick Reines and Clyde Cowan in the mid-1950s after years of painstaking research. Another particle called a *muon*, which is identical to but 200 times heavier than electron, was spotted by physicists studying cosmic rays in the late 1930s. Using ever more powerful technology physicists themselves produced some particles through high-energy collisions which are not constituents of anything they typically encounter. Four more quarks, namely, charm, strange, bottom and up, two other particles with properties similar to the neutrino, namely, muon-neutrino and tau-neutrino, and another even "heavier cousin of electron" (Greene 2000: 8) called *tau* were found. What's more, each of these particles has an anti-particle, i.e., a particle of identical mass but opposite in certain other respects, such as its electric charge. These particles are what Greene (2000:13) calls the "letters" of all matter, which like their linguistic counterparts are devoid of any internal sub-structure. In the words of theoretical physicist Ellis, "…there aren't little subquarks sitting inside the quarks…" (Davies 2000:152). Interestingly, string theory describes quarks as extended objects, made of not any more fundamental constituents but of a little piece of string, the typical size of which, roughly, is something like 10^{-33} centimeters, i.e., one thousandth of one billionth of one billionth of the size of a nucleus (Davies 2000: 152).

The 'Standard Model'− widely accepted in the community of the physicists− provides an extremely successful account of matter particles (e.g., quarks), force particles (e.g., photon) as well as a Higgs particles discovered at the LHC (the Large Hadron Collider) in 2012. This well-established Standard Model− a relativistic quantum field theory describing the strong nuclear, weak nuclear and electromagnetic forces− involves c (the speed of light as it appears in the equation $E = mc^2$) and h (Planck's constant as it appears in the famous equation $E = hf$), but not gravity G (Newton's constant in that famous force equation $F = GmM/r^2$). Hence, the unification of this Standard Model and General Relativity appears to be the most sought-after goal among the physicists who aspire for a unified understanding of fundamental forces and particles (in terms of compelling mathematical principles).

String theory presents an account very different from that upheld by the Standard Model. Michael Green− one of the originators of string theory− describes it as "radically different" (Davies 2000:123) from any of the earlier theories (e.g., Maxwell's theory of electrodynamics, or general relativity or supergravity). All these former theories contain particles (photons, gravitons, quarks) which are point-like objects, having no internal structure, while string theory claims that if the presumed point-particles (of the Standard Model) could be examined with even greater precision, (which means many orders of magnitude beyond our present technological capacity) each would be seen to be made of a single, tiny, oscillating loop of string moving through space (Greene 2000:141), which are not points at all but extended objects[1] (Davies 2000:123).

Apparently, string theory adds a new microscopic layer of a vibrating loop to the previously known scientific development from atoms through protons, neutrons, electron and quarks (Greene 2000:14). It complicates the picture further by claiming that the observed particle-properties are the manifestations of one and the same physical feature: the resonant patterns of vibration of fundamental loops of string. Each of the patterns of vibration of a string appears as a particle whose mass and force charges are determined by the string's oscillatory pattern. For example, the electron is a string vibrating in one way and the up-quark is a string vibrating in another way, and so on. The same idea applies to the forces of nature as well. The force-particles are also connected with particular patterns of string-vibration. In this way, everything, that is, all matter and all forces, is unified under the same rubric of microscopic string oscillations. String theorist Green's metaphorical expression is worth quoting here: "…Just as the different vibrational patterns of a violin string give rise to different musical notes, *the different vibrational patterns of a fundamental string give rise to different masses and force charges*… (italics as in original)" (Davies 2000:143).

Now, to understand why our present-day experiments are unable to investigate directly into the microscopic stringy nature of matter one should first inquire about the length of a typical string loop. It's about what scientists call 'the Planck length', i.e., about a hundred billion billion (10^{20}) times smaller than an atomic nucleus (Greene 2000:141). Even on the scale set by subatomic particles, strings are incredibly miniscule. It is indeed conceivable, in principle, that with the help of sufficiently powerful instruments (an immensely powerful accelerator, for instance) we could directly see this loopy structure inside particles. However, practically, to do experiments which probed energies of 10^{19} GeV− which is approximately ten million billion times more than the energies probed up to the late 1980s in the particle accelerators− the accelerator has to be some million billion times more powerful than any accelerator built till the end of the last century (Davies 2000: 153). The construction of such a powerful accelerator looks not only difficult but inexorably expensive.

The origins of string theory go back to the late 1960s when Gabrielle Veneziano (along with other researchers) were trying to understand various properties of the strong nuclear force emerged from high energy collisions in particle accelerators. This force holds protons and neutrons together inside the nucleus of an atom and also holds quarks and gluons together inside the neutron and proton. Veneziano noted that an esoteric formula devised for purely mathematical pursuits by renowned mathematician Leonhard Eluer, popularly known as the Eular beta-function, could be employed for making some sense of the numerous properties of such strongly interacting particles

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[1] There are intriguing hints in theoretical research that strings may have further sub-structure (Greene 2000:142).

in one fell swoop (Greene 2000: 137). Veneziano's model– describing the quantized motion of a string– was a dramatic departure from previous theoretical models of matter in terms of particles.

Euler's beta-function appeared to be a useful formula but it required an explanation. In 1970 the collaborative works of Yoichiro Nambu, Holger Nielsen and Leonard Susskind suggested that if one models elementary particles as little, vibrating, one-dimensional strings, then their nuclear interactions could be captured accurately by Euler's function. These researchers hypothesized further that if the pieces of strings were small enough, they would look like point-particles and consequently be consistent with experimental data. However, when high-energy experiments (in the early 1970s) penetrated more deeply into the sub-atomic world a number of predictions of the string-model seemed to be in direct conflict with experimental observations.

The point-particle quantum field theory of quantum chromodynamics (QCD) was being developed around that time. As a relativistic quantum theory of strong nuclear force based on point particles (quarks and gluons) it was quite consistent with the Standard Model. When this theory achieved overwhelming success in describing the strong force virtually every physicist, except a few dedicated researchers (e.g., John Schwarz), chose to abandon string theory, to be precise, the string-description of strong nuclear force. Moreover, string theory has various features such as extra dimensions and massless particles, none of which look appropriate for a hadron theory.

Two important implications of Popper's criterion of falsifiability are to be noted at this point. The first one concerns the judgements or decisions of most physicists to give up string theory in favour of the theory of quantum chromodynamics. The conflict between the predictions of the early string-model and the high-energy experimental results in the 1970s, on the one hand, and the experimental evidence found in favour of quantum chromodynamics (around the same time) on the other, are both crucial from Popper's point of view. What do such experimental results show? Such experimental reports, Popper would say, neither entail a conclusive refutation of the early string theory nor imply a guaranteed or conclusive acceptance of quantum chromodynamics. The Popperian argument one could draw from such empirical evidence is not that quantum chromodynamics should be preferred to early string theory, but that string theory (for the time being) should not be preferred to quantum chromodynamics.

The second implication (of Popperian falsifiability) is, the acceptance of quantum chromodynamics by a large number of researchers does not signify anything beyond considering the theory as worthy of further and rigorous scientific investigation. If "…acceptance is so understood…", as Miller (2006:125) explains, then only one can appreciate the key insight of falsifiability, namely, that scientific hypotheses can be accepted (i.e., conjectured) "…even if there is no experimental evidence in their favour…" (Miller 2006:125). No one disputes the fact that the early string model, despite appearing radically different from the previous physical theories, suggested or predicted something about the empirical world. Naturally, it had consequences that could, in some conceivable circumstances, expose themselves as false. In practice it could indeed be very difficult to discover the loopy structure inside particles (which require experiments probing energies of 10^{19} GeV), but at least in principle it is conceivable that the scientists could actually reveal these little loops (Davies 2000: 153). It is this susceptibility to modification (or falsification[1]) in the light of (conceivable) experiments that entitles the early string hypothesis for further scientific investigation (actually carried out by only a few scientists like Schwarz) in spite of not having adequate empirical support at the moment.

One of the crucial problems with string theory was that the theory contained configurations of vibrating string properties like those of gluons and, in addition, it contained some messenger-like particles (with no mass but two units of angular momentum) that did not correspond to anything in the experimental observations of strong nuclear processes (Davies1988:70). Schwarz continued his research for almost a decade and after studying the puzzling messenger-like patterns of string vibration, he and his then collaborator Joel Scherk found that one of the massless particles in string theory has the right properties (zero mass and spin two) that quite precisely match those of the hypothesized quantum-mechanical (messenger) particle which carries the gravitational force– the graviton.[2] At accessible energies, the interactions of the string-theory-graviton appear to agree with the graviton in General Relativity. Massless string modes also include spin-one particles that behave like the particles that are responsible for the forces described by the Standard Model (namely, nuclear and electromagnetic). These facts led Schwarz and Scherk in 1974 to re-introduce string theory as a unified theory of all forces including gravity, not as a theory of hadrons (Schwarz 2000). This implied, in particular, that the typical size of a string L_s is close to the Planck length L_p, 20 orders of magnitude smaller than hadronic strings!

Schwarz and Scherk's 1974 proposal were largely ignored because at that time researchers who worked on General Relativity did not seem to interact much with particle physicists and particle physicists apparently felt no need for considering gravity (Schwarz 2000). Besides, prior attempts to construct a quantum version of General Relativity assuming point-like particles (quantum field theory) had given rise to nonsensical infinite results (such as, nonrenormalizable ultraviolet divergences). This means, as per Schwarz (2000), the theory is inconsistent and needs to be modified at short distances or high energies. By contrast, he and his collaborators already knew from their previous studies that string theory provides finite results (no ultraviolet divergences) and it does this by (a) giving up one of the basic assumptions of quantum field theory, namely, that elementary particles are mathematical points, and by (b) developing a quantum field theory of one-dimensional extended objects, called strings. Although there are very few consistent theories of this type, string theory shows great promise as a unified quantum theory of all fundamental forces including gravity (Schwarz 2000).

During the period from 1984 to 1985, Schwarz along with Michael Green were able to show that there are five distinct but consistent string theories, each of which requires spacetime

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[1] For Popper, no falsification can be conclusive as all test statements are open to dispute. However, as Miller (2006) reminds us, to say that a falsification has not been done conclusively is not to mean that it has not been done carefully or adequately.

[2] Massless particles travel with the speed of light, ***c***. The electromagnetic force is mediated by a massless spin-one particle, called the photon. The force can be either attractive or repulsive. The gravitational force is mediated by a massless spin-two particle, called the graviton. The force is always attractive.

supersymmetry in the ten dimensions− nine spatial dimensions plus time− (Schwarz 2000). In addition, more than a thousand research papers from across the world suggested how numerous features of the Standard Model emerged naturally from the grand theoretical structure of string theory (Greene 2000:139) and, how string theory could offer a more satisfying explanation (than is found in the Standard point-particle Model) for many of these features that had been painstakingly discovered over the course of decades of research. These developments, triggering the first superstring revolution, led many physicists to believe that string theory is a worthy area of research and it is well on its way to fulfilling its promise of being the ultimate unified theory.

Arguably, the most important feature of string theory concerns its incorporation of general relativity. Ordinary quantum field theory does not allow gravity to exist, while string theory necessitates it. It does get modified at very short distances and/or high energies but at ordinary distance and energies it is present in exactly the form proposed by Einstein. This, in Schwarz's (2000:3) opinion, is very significant, because it arises within the framework of a consistent quantum theory. String theory thus could be seen as an attempt at reconciling the general relativity theory and the quantum theory by subsuming them into a broader theoretical framework.

But string theory still awaits an adequate formulation, and cannot yet provide a detailed description of how the Standard Model of elementary particles should emerge at low energies. Vibrating superstrings, multiple, folded, (extra) dimensions of spacetime, and other features of the theory are (so far) inaccessible to experimental tests. As noted, the typical size of the loop of string would be like one thousandth of one billionth of one billionth of the size of a nucleus (roughly). In order to detect this loop-structure inside particles experiments need to probe energies of 10^{19} GeV, some 10 million billion times more the energies achieved till the end of the last century (Davies 2000: 123). Such features− often alleged by the critics to be mere metaphysical speculations− naturally strengthens the impression that string theory is "…unsatisfactorily detached from empirical confirmation" (Dawid 2013:19).

One might, therefore, be curious to ask whether string theory involving such seemingly experimentally inaccessible features deserve to belong to the domain of science at all? Some recent philosophers of science (e.g., Dawid 2013; 2019) tend to highlight the role played by non-empirical criteria[1] in scientific theory assessment. What these scholars assume, consciously or unconsciously, is that the criterion of falsifiability doesn't work in cases like string theory where either technology is not advanced enough to probe energies of 10^{19} GeV or where the theory is yet 'a work in progress'. No matter how speculative and mathematically intricate the theory may appear to be, Popper would say, if it is in principle criticisable or testable, it deserves to be entertained, i.e., to be considered for further scientific examination. Those who are engaged in the highly visible debates over the scientific status of string theory− often dubbed as 'The String Wars' (Dardashti 2019:1) – seem quite unaware of Popper's insightful analysis of two clearly different senses of falsifiability and of two distinct methods of theory assessment (in science).

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[1] For a detailed discussion on string theory and non-empirical theory assessment see Dawid (2013).

Concluding Comments:

String theory appears to provide an interesting and promising framework for constructing an underlying theory that incorporates the Standard Model of particle physics and General Relativity. Scientists like Ellis (Davies 2000:166) thinks that it "…has arrived as a language to discuss fundamental physics, elementary particle physics and relativity physics", while Schwarz (2000) admits that despite much efforts and imaginative proposals, superstring theory is not yet formulated. The debate about whether it will remain forever beyond the possibility of experimental testing is still going on. Though extra dimensions may look problematic to many scholars, some (e.g., Kane 2019: 396) are hopeful that the curled-up dimensions contain lots of information indicating testable predictions for the compactified theories, particularly determining the forces and particles.

The present paper concludes by drawing attention to two points important for the present purposes. The first point concerns the popular assumption that string theory is most strongly criticised for resulting in a wide spectrum of speculative and (hitherto) empirically unconfirmed (or, in some cases may be empirically unconfirmable) new hypotheses. Quite the contrary, Feynman, whose scepticism towards string physics is all too well known, doesn't see any danger in making such bold guesses like nature at its deepest level is unified because "…if something is wrong, we check it against experiment, and experiment may tell us that it's not true…" (Davies 2000:193). The real problem with string theory, Feynman (Davies 2000:194-195) argues, is not that there are no experiments to lead the scientists. In fact, a large number of experimental facts− to be precise, some two dozen numbers associated with the masses of various particles such as quarks− has already been collected by the string theorists but no reasonably good explanations for those facts (say, an account of why are the masses of various particles what they are) hasn't yet been developed by them (Davies 2000: 195). Understandably, Feynman emphasizes more on the explanatory weakness of string theory than on its experimental inaccessibility. The bold speculation that there is some wonderful unifying principle may not be a mere, crazy guess, but Feynman (Davies 2000:196) argues that the statement that there should be some kind of unification bears no indication of what kind of unification the string theorists are proposing. Among the enormous number of possibilities any one (or none) might be right.

The second point relates to Popper's key contribution to the ongoing debate. References to Popper appear quite frequently in the popular scientific literature and in general philosophical discussions. His views, however, are often ignored or clumsily distorted in those debates. Consider one of the most recent works on the issue regarding the status of some fundamental theories of modern physics. The 2019 volume entitled "*Why Trust a Theory: Epistemology of Fundamental Physics*" (edited by Dardashti et.al.) begins with the observation that fundamental physics today faces increasing difficulty in finding "conclusive empirical confirmation of its theories… Some empirically unconfirmed or inconclusively confirmed theories in the field have nevertheless attained a high degree of trust among their exponents and are de facto treated as well-established theories. String theory, cosmic inflation, and to a certain extent the multiverse are particularly noteworthy examples…” (Dardashti 2019: 1). That is why, it is argued in the volume, some leading physicists, philosophers and historians of science strongly feel the current state of physics necessitates a paradigm shift regarding the understanding of scientific theory assessment.

The question is: does anything like “conclusive empirical confirmation” of a scientific theory ever exist? Has it not been shown by Hume long ago that no amount of empirical evidence can ever be sufficient for confirming or justifying even the most circumspect generalization? Has it not been explained by Russell (1918) that no universal hypotheses can be conclusively verified, even in a finite universe because any claim to have inspected the whole universe is itself a statement of universal form. Has it not been clarified by Popper (1963) why no search for “conclusive empirical confirmation” for scientific theories can ever be successful? The answers to these questions are no longer awaited. Thus, the real issue at stake, when discussing the scientific status of string theory, is not whether non-empirical theory assessment should replace the Popperian criterion of falsifiability. To interpret the debate in such terms would be highly misleading. The relevant question is, can the scientists (and philosophers), from the Popperian methodological point of view (i.e., using his criterion of falsifiability) consider string theory (as a work-in-progress theory) worth pursuing? The answer that emerges from the above analysis is yes.

References

Bartley, W. W. III. (1999). Rationality versus the Theory of Rationality. In *Critical Approaches to Science and Philosophy*, ed. M. Bunge, Transaction Publishers.

Blom, T. & Wessel, M. (2017). Deze wetenschappers strijden tegen alternatieve feiten, *De Volkskrant*.

Carroll, S. (2014). Edge essay: What scientific ideas are ready for retirement? Falsifiability. www.edge.org/response-detail/25322

Carroll, S. (2019). Beyond Falsifiability: Normal Science in a Multiverse. In *Why Trust a Theory? Epistemology of Fundamental Physics*, ed. R. Dardashti et al. Cambridge University Press.

Davies, P. C. W & Brown, J. (1988/2000). *Superstrings: A Theory of Everything?* Cambridge University Press (Canto).

Dawid, R. (2013). *String Theory and the Scientific Method.* Cambridge University Press.

Dawid, R. (2019). The Significance of Non-Empirical Confirmation in Fundamental Physics. In *Why Trust a Theory? Epistemology of Fundamental Physics*, ed. R. Dardashti et al. Cambridge University Press.

Ellis, G. F. R (2019). Theory Confirmation and Multiverses. In *Why Trust a Theory? Epistemology of Fundamental Physics*, ed. R. Dardashti et al. Cambridge University Press.

Ellis, G. F. R., & J. Silk. (2014). Scientific method: Defend the integrity of physics. *Nature*, Vol. 516: 321–3.

Greene, B. (2000). *The Elegant Universe.* Vintage Books.

Guth, A., et. al. (2017). A cosmic controversy, *Scientific American*, 316.

Hossenfelder, S. (2017). Science needs Reason to be Trusted, *Nature Physics*, Vol. 13, 316-317.

Ijjas, A., et. al. (2017). Pop goes the Universe, *Scientific American*, 32-39.

Kane, G. L. (2019). String/M-Theories about Our World Are Testable in the Traditional Physics Way. In *Why Trust a Theory? Epistemology of Fundamental Physics*, ed. R. Dardashti et al. Cambridge University Press.

Koyré, A. (1973). *The Astronomical Revolution*, Hermann.

Lakatos, I. (1978). *The Methodology of Scientific Research Programmes*. Edited by J. Worrall & G. Currie. Cambridge University Press.

Miller, D. (1985). *Popper Selections* (eds). Princeton University Press.

Miller, D. (1994). *Critical Rationalism: A Restatement and Defence*, Open Court.

Miller, D. (2006). *Out of Error.* Ashgate Publishing Limited.

Popper, K. R. (1935/2005). *The Logic of Scientific Discovery*, Routledge.

Popper, K. R. (1963/2013). *Conjectures and Refutations: The Growth of Scientific Knowledge*, Routledge & Kegan Paul.

Popper, K. R. (1983). *Realism and the Aim of Science*. Routledge.

Schwarz, J. H. (2000). *Introduction to Superstring Theory*. arXiv: hep-ex/0008017v1 9 August 2000.

Weinberg, S. (2015). *To Explain the World.* Harper Perennial.