Using neutron stars and primordial black holes to test theories of quantum gravity

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ABSTRACT

Three observational tests of cosmological natural selection, a theory that follows from some hypotheses about quantum gravity, are described. If true, this theory explains the choices of the parameters of the standard model of particle physics. The first, the observation of a pulsar with mass greater than 2.5M⊙, would cleanly refute the theory. The second and third, having to do with primordial black holes and early massive star formation, could do so given likely developments in the near future. However, given present knowledge these arguments do not presently refute the theory. This shows that cosmological natural selection has not so far been refuted, while remaining very vulnerable to falsification by possible observations.

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1 Introduction

It is unfortunate that the Planck scale and unification scale are so remote from what can be probed experimentally that most hypotheses about quantum gravity and the unification of the different interactions are developed without benefit of experimental test. In order to counteract this, one may try to adopt a strategy of searching for hypotheses about fundamental physics whose main merit is that they are testable given present knowledge. One way to do this which has often been pointed out is to use the apparent fact that very high temperatures, densities and energies were experienced, however briefly, in the early universe. Among other things, this has led to the hypothesis of inflation\cite{1, 2}, certain versions of which are going to be well tested in forthcoming observations of the MAP and PLANCK missions.

In \cite{3, 4, 5} a theory aimed at explaining the parameters of the standard model of particle physics was introduced, which assumes the following two hypotheses about fundamental physics:

1. Black hole singularities bounce, leading to new expanding regions of spacetime, one per each black hole.

2. When this happens the dimensionless parameters of the standard model of low energy physics of the new region differ by a small random change from those in the region in which the black hole formed. Small here means with small with respect to the change that would be required to significantly change $B(p)$, the expected number of black holes produced in the classical region of spacetime produced by the bounce. Here $p \in \mathcal{P}$, the space of dimensionless parameters of the standard model.

With the exception of the small in 2), these are not new hypotheses, and have been discussed, for example in \cite{6}. Their conjunction leads to a predictive theory, because, using standard arguments from population biology, after many iterations from a large set of random starts, the population of regions, given by a distribution $\rho(p)$, is peaked around local extrema of $B(p)$. With more detailed assumptions more can be deduced, but this is sufficient to lead to observational tests of hypothesis 1) and 2) because this implies the statement that:

- \textbf{S}: \textit{If } $p$ \textit{is changed from the present value in any direction in } $\mathcal{P}$ \textit{the first significant changes in } $B(p)$ \textit{encountered must be to decrease } $B(p)$.
The conjunction of 1) and 2) thus constitute a theory that if true would explain the values of the parameters of the standard model without recourse to the Anthropic Principle. This theory may be called, “cosmological natural selection.” It should be emphasized that it is completely consistent with our knowledge of fundamental physics. For example, recent work in string theory has revealed that that theory has a large number of stable vacua, or phases, in which the standard model parameters differ. When string theory becomes better understood present knowledge seems to indicate that the likely effect will be not to fix $p$ in $P$ but to replace it with a microscopic parameter $m$ in the space $M$ of string vacua. It should also be mentioned that the possibility of a bounce has been discussed in several different approaches to quantum gravity, including string theory.

Several arguments were made that $S$ is in fact contradicted by present observation. These were found to depend either on confusions about the hypothesis itself or on too simple assumptions about star formation and are thus invalid. Other claims have been made that with present knowledge $S$ is in fact not testable. Here I would like to show that these claims are also false, by explaining why a single observation of an astrophysical object that very well might exist—a heavy neutron star—would refute $S$. After this I describe two more kinds of observations that may be made in the near future which could lead to refutations of $S$. These have to do with more accurate observations of the spectrum of fluctuations in the cosmic microwave background ($CMB$) and the initial mass function for star formation in the absence of carbon.

2 Why a single heavy pulsar would refute $S$.

Bethe and Brown, in introduced the hypothesis that neutron star cores contain a condensate of $K^-$ mesons. For the present purposes their work can be expressed in the following way. Calculations show that there is a critical value $\mu_c$ for the strange quark mass $\mu$ such that if $\mu < \mu_c$ then neutron star cores consist of approximately equal numbers of protons and neutrons with the charge balanced by a condensate of $K^-$ mesons.

1 Other approaches to cosmology which employ phenomena analogous to biological evolution have been proposed, including Davies, Gribbin, Kauffman, Linde, Nambu, Schweber, Thirring and Wheeler. The best developed of these is a series of papers of Linde and collaborators in the context of inflationary cosmology.

2 See especially the appendix of which addresses most of the objections published in and elsewhere.
reason is that in nuclear matter the effective mass of the $K^-$ is renormalized downward by an amount depending on the density $\rho$. Given a choice of the strange quark mass, $\mu$, let $\rho_0(\mu)$ be the density where the renormalized Kaon mass is less than the electron mass. $\mu_c$ is the value of $\mu$ where $\rho_0(\mu)$ is less than the density $\rho_e$ at which the electrons react with the protons to form neutrons. In either case one neutrino per electron is produced, leading to a supernova.

Bethe, Brown and collaborators claim that calculations show that $\mu < \mu_c$ \[12\]. But their calculations involve approximations such as chiral dynamics and may be sufficiently inaccurate that in fact $\mu_c > \mu$. However, the accuracy of the calculations increases as $\mu^{-2}$ as $\mu$ is decreased so, even if we are not sure of the conclusion that $\mu < \mu_c$, we can be reasonably sure of the existence of such a critical value $\mu_c$. Then we may reason as follows. If $\mu < \mu_c$ then, as shown by calculations \[12\] the upper mass limit is low, approximately $1.5 M_\odot$. If $\mu > \mu_c$ neutron stars have the conventional equations of state and the upper mass limit is higher, almost certainly above $2 \ [13]$. Therfore a single observation of a neutron star whose mass $M$ was sufficiently high would show that $\mu > \mu_c$, refuting Bethe and Brown’s claim for the opposite. Sufficiently high is certainly $2.5 M_\odot$, although if one is completely confident of Bethe and Brown’s upper limit of $1.5$ solar masses, any value higher than this would be troubling. Furthermore, this would refute $S$ because it would then be the case that a decrease of $\mu$ would lead to a world with a lower upper mass limit for neutron stars, and therefore more black holes.

Presently all well measured neutron star masses are from binary pulsar data and are all below $1.5 M_\odot$ \[14\]. But an observation of a heavy neutron star may be made at any time.

We may note that this argument is independent of any issue of selection effects associated with “anthropic reasoning”, because the value of the strange quark mass $\mu$ may be varied within a large range before it produces a significant effect on the chemistry\[4\].

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\[4\] Other methods yield less precise estimates\[13\].

\[3\] Skeptics might reply that were $S$ so refuted it could be modified to a new $S'$, which was not refuted by the addition of the hypothesis that $\mu$ is not an independent parameter and cannot be varied without also, say, changing the proton-neutron mass difference, leading to large effects in star formation. It is of course, a standard observation of philosophers of science that most scientific hypotheses can be saved from refutation by the proliferation of ad hoc hypotheses. In spite of this, science proceeds by rejecting hypotheses that are refuted in the absence of special fixes. There are occasions where such a fix is warranted. The present case would only be among them if there were a preferred fundamental theory,
3 How observations of the CMB could refute $S$.

It may be observed that the universe might have had many more primordial black holes than it seems to have were the spectrum of primordial fluctuations, $f(n)$ tilted to increase the proportion on small scales\textsuperscript{10}. Of course, this observation by itself does not refute $S$ directly unless it is shown that the standard model has a parameter that can be varied to achieve the tilt in the spectrum. It does not, but it is reasonable to examine whether plausible extensions of the standard model might. One such plausible extension is to add fields that could serve as an inflaton, so that the theory predicts inflation. Given an extension of the standard model, $E$, that predicts inflation, the spectrum of primordial fluctuations is in fact predicted as a function of the parameters of $E$. Thus, $S$ is refuted if a) some model $E$ of inflation is observationally confirmed and if b) that particular extension of the standard model has some parameter, $p_{inf}$ that can be modified to increase the total numbers of black holes produced, including primordial black holes. Given the accuracy expected for observations of the CMB from MAP and PLANCK, there is a realistic possibility that observations will distinguish between different hypotheses for $E$ and measure the values of their parameters.

In the standard “new” inflationary scenario\textsuperscript{3} there is no parameter that fulfills the function required of $p_{inf}$. There is the inflaton coupling $\lambda$, and it is true that the amplitude of the $f(n)$ is proportional to $\lambda$ so that the number of primordial black holes can be increased by increasing $\lambda$. However, the size of the region that inflates $R$, is given by $R \approx e^{\lambda^{-1/2}}$. This effect overweights the possibility of making primordial black holes. In fact, if the observations confirm that the standard new inflationary scenario is correct, then $S$ is refuted if $\lambda$ is not tuned to the value that results in the largest total production of black holes in the inflated region\textsuperscript{3}. Because of the exponential decrease in $R$ with increasing $\lambda$, this is likely close to the smallest possible value that leads to a sizable constant density of black holes produced in comoving volumes during the history of the universe. This is likely the smallest $\lambda$ that still allows prolific formation of galaxies\textsuperscript{3}.

This seems consistent with the actual situation in which there appears to have been little production of primordial black holes, so that the primary mode of production of black holes seems to be through massive star production, in galaxies that apparently do not form till rather late, given such as string theory, which had strong independent experimental support, in which it turned out that $\mu$ was in fact not an independent parameter, but could not be changed without altering the values of parameters that strongly affect star formation and evolution.
that $\delta \rho/\rho \approx 10^{-5}$. Of course, the observations that favor $\Omega \approx .3$ are also troubling for the standard new inflation which predicts $\Omega$ very near one.

However, there are non-standard models of inflation that have parameters $p_{inf}$ that can be varied from the present values in a manner that tilts $f(n)$ so that more primordial black holes are created than in our universe, without at the same time decreasing $R$. If future observations of the CMB cleanly show that the standard new inflation is ruled out, and only models with such a parameter $p_{inf}$ are allowed, then $S$ will be refuted.

This is a weaker argument than the first one, but given the scope for increases in the accuracy of measurements of the CMB, and hence of tests of inflationary models, it is a realistic possibility that $S$ may be refuted by such an argument.

4 How early star formation could refute $S$.

As shown in [16, 11, 3] there are several directions in $\mathcal{P}$ which lead to universes that contain no stable nuclear bound states. It is argued in [3, 5] this leads to a strong decrease in $B(p)$ because the gravitational collapse of objects more massive than the upper mass limit of neutron stars in our universe seems to depend on the cooling mechanisms in giant molecular clouds, which are dominated by radiation from CO. In a universe without nuclear bound states the upper mass limit for stable collapsed objects is unlikely to decrease dramatically (as the dominant factor ensuring stability is fermi statistics) while without cooling from CO collapsed objects whose ultimate size is above the upper mass limit are likely to be less common.

In the absence of bound states the main cooling mechanism appears to involve molecular hydrogen [17], but there are two reasons to suppose this would not lead to plentiful collapse of massive objects in a world with nuclear bound states. The first is that in such a world there would be no dust grains which appear to be the primary catalysts for the binding of molecular hydrogen. The second is that in any case molecular hydrogen is a less efficient coolant than CO.

This is also a weaker argument than the first, given present uncertainties in our understanding of star formation processes, but as that understanding is likely to become more precise in the near future let us follow it. Could this argument be refuted by any possible observations? In the present universe the collapse of massive objects is dominated by processes that involve nuclear bound states, but we have available a laboratory for the collapse of objects in
the absence of nuclear bound states, which is the universe before enrichment with metals. Indeed, we know that there must have been collapse of massive objects during that period as otherwise carbon, oxygen and other elements would not have been produced in the first place. But given that $CO$ acts as a catalyst for formation of heavy elements, and that the dust formed from heavy elements produced in stars is also a catalyst for molecular binding, there is an instability whereas any chance formation of massive objects leads in a few million years to both an enrichment of the surrounding medium and the production of significant quantities of dust, and these greatly increase the probability for the formation of additional massive objects. Hence, the initial rate of formation of heavy objects in the absence of enrichment does not have to be very high to explain how the universe first became enriched.

This shows that the fact that there was some collapse of heavy objects before enrichment does not refute the argument that the number of black holes produced in a universe without nuclear bound states would be much less than at present. But while it thus doesn’t refute $S$, it doesn’t establish it either. It is still consistent with present knowledge that the production of massive objects in the absence of heavy elements proceeds efficiently under the right conditions, so that there may have in fact been a great deal of early star formation uncatalyzed by any process involving heavy elements.

This could lead to a refutation of $S$ because, in a world without nuclear bound states, many more massive collapsed objects would become black holes than do in our universe, where the collapse is delayed by stellar nucleosynthesis.

The question is then whether a combination of observation and theory could disentangle the strong catalytic effects of heavy elements leading to a strong positive feedback in massive star formation from the initial rate of massive star formation without heavy elements. Although models of star formation with and without heavy elements are not sufficiently developed to distinguish the two contributions to early star formation, it is likely that this will become possible as our ability to model star formation improves. If so then it is also possible that future observations will be able to measure enough information about early star formation to distinguish the two effects. If the conclusion is that the number of black holes formed is greater in world without nuclear bound states than in our own then $S$ would be refuted.
5 Conclusions

The first argument shows that a very likely astronomical observation, the discovery of a pulsar with mass above $2.5M_\odot$ would refute $S$. This shows that the theory of cosmological natural selection is falsifiable at present. The other two arguments each lead to a case in which combinations of theoretical and observational developments that are likely within the next decade could also easily refute $S$. This shows that the vulnerability of $S$ to falsification is very likely to strongly increase in the near future.

If in fact $S$ is not refuted after many more pulsar masses are well measured and the links between theory and observation in inflation and star formation are much improved, and if in the meantime string theory continues to be consistent with a large choice of models and parameters of low energy physics, it will be difficult to avoid taking cosmological natural selection seriously as an explanation of the values of the standard model parameters. Given this, and the fact that even presently it seems to be the most vulnerable to falsification of all the proposals so far made to explain the parameters of the standard model, its predictions deserve further study.

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