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The fate of black hole singularities and the parameters of the standard models of particle physics and cosmology

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ABSTRACT

The implications of a cosmological scenario which explains the values of the parameters of the standard models of elementary particle physics and cosmology are discussed. In this scenario these parameters are set by a process analogous to natural selection which follows naturally from the assumption that the singularities in black holes are removed by quantum effects leading to the creation of new expanding regions of the universe. The suggestion of J. A. Wheeler that the parameters change randomly at such events, leads naturally to the conjecture that the parameters have been selected for values that extremize the production of black holes. This leads directly to a prediction, which is that small changes in any of the parameters should lead to a decrease in the number of black holes produced by the universe. Thus, in this case a hypothesis about particle physics and quantum gravity may be refuted or verified by a combination of astrophysical observation and theory.

This paper reports on attempts to refute this conjecture. On plausible astrophysical assumptions it is found that changes in many of the parameters do lead to a decrease in the number of black holes produced by spiral galaxies. These include the masses of the proton, neutron, electron and neutrino and the weak, strong and electromagnetic coupling constants. Finally, this scenario predicts a natural time scale for cosmology equal to the time over which spiral galaxies maintain appreciable rates of star formation, which is compatible with current observations that $\Omega = .1 - .2$.

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1 Introduction

One of the great puzzles of astronomy and physics is what happens inside of black holes, where general relativity breaks down because of the presence of singularities[1]. That this is not just a problem of mathematical physics is apparent if one reflects on the fact that the rate of formation of black holes in the observable universe is likely to be as high as one hundred per second[1], this may be taken to be the rate at which our ignorance about the universe is increasing due to our not knowing what lies behind all of these event horizons. When one adds quantum physics to the picture the puzzle becomes a crisis, as first realized by Hawking in 1974, because of the problem of the loss of information constituting the quantum state of the star whose collapse formed the black hole[3].

Another basic problem of physics is to understand why the masses and coupling constants of the elementary particles take the values they do. This mystery, which has stubornly resisted solution despite enormous progress in our understanding of the fundamental interactions, is deepened when one tries to understand why so many of the fundamental dimensionless constants that describe the masses and interactions strengths are very large or very small numbers. It is even further deepened when it is pointed out that the fact that our universe is as structured as it apparently is, from the scales of galaxies to the existence of many stable nuclei, and hence stars and chemistry, is based on a series of apparent coincidences relating the values of the fundamental dimensionless parameters of physics and cosmology. For example, if one requires that main sequence stars exist then (as will be outlined shortly) one constrains the values of the following quantities: the proton neutron mass difference, the electron-nucleon mass ratio, α, the strong interaction coupling constant, the neutrino mass[4, 5]. Further requiring that there are type II supernova fixes a relation between the weak interaction and gravitational constant given by eq. (7) below[5, 4] while requiring that there are convective stars fixes a relation between the gravitational constant and the fine structure constant[6, 5] given by eq. (6). With these relations essentially every dimensionless constant associated with the properties of stable matter has been fixed by the requirement that stars with the life cycle of those in our universe exist.

The purpose of this paper is to present evidence for a cosmological con-

[1]This estimate is gotten by multiplying the 10^{12} galaxies believed to be within our horizon by the rate of type II supernovas of about one every forty years per spiral galaxy, and a conservative estimate that between 1/10 and 1/100 of these become black holes[2].

jecture that relates these two puzzles[7]. The conjecture is simple to state, and is a natural outgrowth of ideas which have been contemplated by particle physicists and relativists for many years. As I will describe, it leads to a definite and testable prediction, which is that,

∗ *Almost every small change in the parameters of the standard models of particle physics and cosmology will either result in a universe that has less black holes than our present universe, or leaves that number unchanged.*

After I motivate it, the bulk of this paper will be devoted to presenting evidence in favor of this prediction.

2 Cosmological natural selection

A natural solution to the problem of the fate of black hole singularities, that has been discussed for many years[2], is that quantum effects cause a bounce when densities become extreme (presumably of order of the Planck density) so that the worldlines of the stars atom that have been converging begin to diverge. As there is nothing that can remove the horizon, before, at least, the evaporation time of the black hole, which is at least 10^{54} Hubble times for an astrophysical black hole and therefor, plausibly, beyond the scope of this paper, whatever new region of spacetime is traced by these diverging geodesics remains hidden behind the original horizon. Moreover, any observers in this new region see themselves to be in a region of spacetime which is locally indistinguishable from an expanding cosmological solution with an apparent singularity in the past of every geodesic. Thus, it would make sense to call this process the creation of a new universe that is (at least on scales shorter than 10^{54} Hubble times) causally disconnected from our universe[3].

It may then be conjectured that each black hole of our universe leads to such a creation of a new universe and that, correspondingly, the big bang in our past is the result of the formation of a black hole in another universe.

To have a theory of what determines the parameters of particle physics and cosmology we need add only one equally natural postulate to this picture. It has been suggested a long time ago by Wheeler[8], and perhaps

[2] I learned of it from Bryce DeWitt in 1980, but I do not know who was the first to discuss it.

[3] I will use here the informal expression "universe" to mean a causally connected region of spacetime, bounded by event horizons and excluding any region where the density of energy or curvatures approach Planck scales. Roughly speaking it corresponds to a region in which the laws of classical general relativity may be relied on.

others, that the parameters of physics and cosmology can change at such initiations of universes. Let us make the more specific assumption that *all the dimensionless parameters of the standard models of particle physics and cosmology change by small random increments at such events.*[4]

Then we have the following picture. If we let $\mathcal{P}$ be the space of dimensionless parameters, p, then we can define an ensemble of universes by beginning with an initial value p^* and letting the system evolve through N generations. Let us define a function $B(p)$ on $\mathcal{P}$ that is the expected number of future singularities generated during a lifetime of a universe with parameters[5] p. We may observe that, for most p, $B(p)$ is one, but there are small regions of the parameter space where $B(p)$ is very large. The present values of the parameters must be in one such region because there are apparently at least 10^{18} black holes in our universe.

After N generations the ensemble then defines a probability distribution function $\rho_N(p)$ on $\mathcal{P}$. To give meaning to the postulate that the random steps in the parameter space are small, we may require that the mean size of the random steps in the parameter space is small compared to the width of the peaks in $B(p)$. It then follows from elementary statistical configurations that, for any starting point p^* there is an N_0 such that for all $N > N_0$, $\rho_N(p)$ is concentrated around local maxima of $B(p)$. This is because (from the above restriction on step size) it is overwhelmingly probable that a universe picked at random from the ensemble is the progeny of a universe that had itself many black holes. But, again, because the parameters change by *small* amounts at each almost-singularity this means that it is overwhelmingly probable that a universe picked at random from the ensemble itself has many black holes. Thus, we conclude that *a typical universe in the ensemble (for $N > N_0$) has parameters p close to a local maximum of $B(p)$.*

[4]We may note that this is consistent with our present understanding of string theory and grand unified models of various kinds, as it typically happens in these theories that the parameters of the standard model that describes low energy physics are determined by a particular solution of the more fundamental theory. What we need from such a theory to justify the assumptions made here is that there is a large space of solutions to the fundamental theory leading to different low energy physics, and that generically different solutions differ by small changes in the low energy parameters. It then may be that the fundamental theory will predict that when a region of the universe approaches Planck densities there can be transitions between these different solutions of the fundamental theory. That this may be possible is certainly consistent with what is presently known about string theory.

[5]We may note that even if the universe is open it is very unlikely that the number of black holes produced during its lifetime is infinite. Thus, it is not necessary to make the assumption made in [7] that the universe is closed. This was pointed out by [9]

Thus, the statement $*$ follows from the postulates we have made concerning the fates of stars that collapse to black holes.

We may note that this theory is much stronger than any version of the anthropic principle[6, 4, 5] because it conjectures the existence of an actual ensemble of universes that is generated by a specific process. As a result, it necessarily predicts that a certain property must be satisfied by almost every universe in the ensemble. Furthermore, whether this property is true or false of our universe is determinable from physics and astrophysics at observable scales. Thus, this theory is highly vulnerable to falsification. This property is not shared by any version of the anthropic principle, first because there is no principle that defines the ensemble in question and second because it requires only that there exists in whatever ensemble is conjectured only one universe with a particular property, which is that there is intelligent life[6]. A theory that asks that only one member of an (ill-defined, and possibly infinite) ensemble exist with a particular property can have no predictive power, because it is possible that a member with any set of logically possible properties exist in such an ensemble[7]

The theory presented here makes certain assumptions about physics at the Planck scale which, presumably, may be tested directly at some time in the future when we have a good understanding of that domain. However, note that in order to test the prediction $*$, we need to assume no more about Planck scale physics than was needed to derive that statment. Further, because there are many dimensionless parameters in the standard models of physics and cosmology, and because so many of them are very small or very large, it is easy to imagine that the statement $*$ could easily be

[6]There is a recent proposal of Crane according to which the anthropic principle would become a consequence of the theory discussed here if it happens often enough that intellegent life desires to, and is able to, construct black holes[10]. This makes the anthropic principle a particular hypothesis about cosmological natural selection in the same way that one may discuss the selective advantage of intellegence in biological natural selection. Similarly, Crane's proposal is a scientific proposal, but because life cannot evolve in a universe without galaxies and stars, it is one that cannot be discussed unless and untill the hypothesis $*$ has been substantiated. The above comments then only refer to the anthropic principle prior to such a discussion of Crane's proposal.

[7]To my knowledge, the first proposal that the quark masses and other parameters of the standard model might be explained by a process analogous to natural selection was made by Y. Nambu[12], although the philosopher Charles Sanders Peirce made similar speculations in the late nineteenth century[13]. More discussion of the motivation behind the hypothesis of cosmological natural selection, as well as more about its relationship to the anthropic principle, may be found in ref [11]. The present paper is devoted only to discussion of the testability of the conjecture.

falsified without having to be very specific about the width of the probability distributions around local maximum, its dependence on N or any details of the form of $B(p)$.

Furthermore, because the argument leads to a conclusion only about local maxima of $B(p)$ the prediction $*$ refers to only small changes in the parameters; it is irrelevant whether or not there are parameters of p very different from the present values that lead to more black holes than are produced by our present universe.

In the remainder of this paper I will discuss the evidence for the statement $*$.

3 Evidence for the prediction $*$

As the standard models of physics and cosmology have about 20 parameters, there are as many chances to falsify $*$. At the present time, the situation seems to be the following. i) $N(p)$ is strongly sensitive to every cosmological parameter and to every particle physics parameter that determines the properties of stable matter. ii) No argument has so far been found for a small change in any parameter leading to an increase in the number of black holes produced in the universe. iii) Given reasonable and widely believed assumptions about star formation processes in spiral galaxies there are clear arguments that at least seven distinct small changes in the parameters that determine low energy physics lead to a decrease of $N(p)$. These include changes in each of the four masses of the stable particles: proton, neutron, electron and neutrino and the strengths of the couplings of the electromagnetic, strong and weak interactions.

We begin with point i), the demonstration of the sensitivity of $N(p)$ to the parameters that determine low energy physics. The sensitivity of the $N(p)$ to all parameters of cosmology and particle physics associated with stable matter follows from the circumstance, mentioned in the introduction, that the existence of main sequence stars requires a number of coincidences. Among these are,

1) The existence of stable nuclei, up to at least carbon, requires conditions on $\Delta m = m_{neutron} - m_{proton}$, α and α_S, the strong interaction coupling constant. The requirements are $\Delta m < 18 Mev$, that α not be greater than .1 and that α_S not be weakened more than by a factor of 2 [4, 5].

2) The production of these nuclei in stars requires still stricter limits. An increase in Δm by a factor of 2 from its present value, or an increase

of α_S by 31%, unbounds the deuteron, while an increase in α_S by 13% will bind the diproton and dineutron, all of which would modify drastically the evolution of stars[4, 5]. Further, as first pointed out by Hoyl, that carbon is resonantly produced, and does not resonantly burn to oxygen, requires that the former nuclei have, and the latter not have, a level within narrow ranges[14]. Consequently, the requirement that carbon be produced copiously in stars is likely to put still stronger limits on these values.

That nuclear fusion take place puts additional limits on the parameters including[4, 5]

$$\Delta m \approx 2 m_{electron}, \tag{1}$$

$$\alpha \approx \frac{\Delta m}{m_\pi} \tag{2}$$

and

$$\alpha > \frac{m_{electron}}{m_{proton}} \tag{3}$$

3) Additionally, the requirement that stars that burn hydrogen are stable and that the photon pressures contribute to, but do not dominate, the energy balance of a star leads to[4, 5]

$$\frac{m_{electron}}{m_{proton}} > \alpha^2 50^{-4/3} \tag{4}$$

$$G_{Newton} m_{proton}^2 < \alpha^{12} \tag{5}$$

4) As Carter pointed out, the existence of convective stars requires the more precise relationship that[6]

$$G_{Newton} m_{proton}^2 \approx \left(\frac{m_{electron}}{m_{proton}} \right)^4 \alpha^{12} \tag{6}$$

We may note that this is satisfied up to a factor of 3.

5) The requirement that supernova exist bounds the weak coupling constant on both sides so that the neutrinos produced interact weakly enough to escape the collapsing core but strongly enough so that they may expel the envelope. As pointed out by Carr and Rees, that this be the case implies that[4],

$$G_{Fermi} m_{electron}^2 \approx \left(G_{Newton} m_{electron}^2 \right)^{\frac{1}{4}} \left(\frac{m_{electron}}{m_{proton}} \right)^{\frac{1}{2}}. \tag{7}$$

6) If there is a grand unified gauge group, the unification scale is restricted by the requirement that the proton lifetime exceed the lifetime of main sequence stars to satisfy[5]

$$m_{unification} > \alpha \, (M_{Planck} m_{proton})^{\frac{1}{2}} \left(\frac{m_{proton}}{m_{electron}} \right)^{\frac{1}{2}} \tag{8}$$

7) We may finally note that the existence of main sequence stars puts restrictions on all the main cosmological parameters, as has been often discussed[5].

None of these relations are new, they have all been put forward previously as evidence for the anthropic principle, and their derivations may be found in the cited references[4, 5]. What I would like to do here is to reinterpret each of them as evidence for the prediction $*$. In particular, as the small size of the primordial density fluctuations observed by COBE [15], as well as direct observational limits, seems to rule out the presence of primordial black holes in our universe, the dominant mode of black hole production in our universe is by the collapse of massive stars. As such any change in the parameters that effects the production or evolution of stars, or the process of supernova, is going to effect the number of black holes. This is sufficient to establish the sensitivity of $N(p)$ to all of the parameters appearing in (1)-(8).

Having established the sensitivity of $N(p)$ to the parameters that determine low energy physics, we may go on to discuss the evidence for the conjecture $*$ in the case of these parameters. The evidence that changes in these parameters in many cases descrease the number of black holes produced comes from the following considerations:

i) Black holes would not form copiously were there not galaxies. Therefor any change in the parameters that disrupts the formation of the galaxies will decrease the number of black holes. While we do not currently have a completely successful theory of galaxy formation, it is likely that the early stages involve the condensation of overdense regions by cooling by bremsstrahlung processes. That this can occur puts conditions on S, the photon to baryon ratio, and the scale of $\delta\rho/\rho$, the primordial fluctuations[4, 5]. For instance, it is likely true that the formation of galaxies requires that the decoupling time approximately coincide with the transition from radiation to matter dominated universe, this requires that $S \approx 10^9$, as observed. While it is difficult to make this more specific it is clear that galaxies could not form in a universe with S much larger than this.

That there are electrons to bremsstrahlung requires that

$$\Delta m > -7Mev. \tag{9}$$

so that the universe is primordially mostly hydrogen rather than mostly neutrons. (The right hand side is not zero because we may allow the possibility that if helium were stable some would be produced in the early universe.) We may note that there is only a factor of 10^3 between the cooling times of clouds of $10^{12}M_{solar}$ and the Hubble, time, there are then no cooling mechanisms involving only neutrons that could play a role in galaxy formation at a time much shorter than the present hubble time[8]. Thus, we may conclude that if (9) were not satisfied, the number of black holes would consequently strongly decrease.

Furthermore, that galaxies are much smaller than the radius of the universe at the time of galaxy formation, $R_{formation}$, requires that[5]

$$\frac{\alpha^4}{G_{Newton}m_{proton}^2}\left(\frac{m_{proton}}{m_{neutron}}\right)^{\frac{1}{2}} a_{bohr} << R_{formation} \tag{10}$$

ii) As black holes are the result of the collapse of very massive, short lived stars, it follows that a significant, and likely dominant, mode of black hole formation in our universe is in the continual formation of massive stars in

[8]Rothman and Ellis[9] have studied the proposal of cosmological natural selection and criticized the argument that a neutron universe would be less efficient at forming stars. However their arguments principly apply to the collapse of clouds to stars, whereas my point is that in a neutron universe it is less likely that there would be many cold dense clouds of the type that collapse to form stars. For the case of collapse to galaxies, the electron opacity is unlikely to slow collapse of hydrogen, while the much diminished rate of radiation in a neutron cloud due to coupling to the neutron dipole moments rather than electrons is likely to slow cooling of the primordial clouds that become galaxies. (See [5]. eq. 6.71 for the cooling rate.) Furthermore, the point is not whether there are ways to make the collapse of cold clouds to stars more effecient. These processes in our universe *are* rather inefficient. The point is that the processes that continually form new molecular clouds and catalyze their collapse depend on the delicate tunings of the parameters that provide a universe copious in carbon and supernovas. Thus, it may be possible to change the parameters such as to make a given cold cloud more likely to collapse to form a star, or to make make a given massive star more likely to be a black hole. The problem is that such changes seem in all cases so far studied to disrupt the processes that are apparently necessary to have a constant rate of massive star formation, and hence of black hole formation. The main claim I am making is that this constant rate of star formation results in many more black holes than would the episodic star formation that would result were there not the delicate fine tunings that the present mechanisms seem to require.

spiral galaxies. Thus, if the processes by which the continual process of star formation and hence black hole formation in spiral galaxies were disrupted by some change in the parameters, the number of black holes produced during the lifetime of the universe would significantly decrease, unless the same change led to a compensating increase in the black holes formed during earlier stages of the universe such as in the formation of elliptical galaxies and in the halos of spiral galaxies.

It is then important to note that recent work on spiral galaxies has led many astrophysicists to the conclusion that star formation in spiral galaxies is a self-propagating process whose rate is likely governed by feedback processes at several scales[16, 19, 18] [22, 20, 23]. Disruption of these feedback processes resulting from a change of parameters would then likely lead to a decrease in the rate of black hole production (again, as long as there is no compensating increase from other effects of the change.)

The evidence that self propogating star formation, with a rate governed by feedback processes, contributes significantly or dominantly to the star formation rate of spiral galaxies may be summarized as follows.

1) There is good evidence that the star formation rate in our galaxy and other spiral galaxies is constant over the disk on time scales of 10^{10} years[17]. This is, *a priori*, unlikely without self-regulation because the time scales involved in star formation and in the significant energetic interaction between stars and the interstellar medium range only up to 10^7 years. Other evidence of this kind comes from the fact that after 10^{10} years the dust and gas normally constitute a significant fraction by mass of the disk, between .1 and .5. Finally, the rate of conversion of gas and dust in the disk to stars, which is estimated at $3 - 5 M_{solar}$/year is approximately equal to the rate of return of matter to the medium from stars, which is at least $1-2 M_{solar}$/year[16]. Given the present uncertainties about the rates of mass loss by massive stars and the infall of gas into the disk from the galactic halo, it is then plausible that the disk is in a steady state, with a lifetime of at least a few times 10^{10} years[17]. It is important to note that this cannot be an equilibrium state because of the enormous differences in the temperatures and densities of the different components of the interstellar gas; the galactic disk is therefor a nonequilibrium steady state system driven by gravitational and nuclear potential energy.

2) There are many examples in which star formation is observed being triggered by shock waves from supernovas or the interaction of giant molecular clouds and ionized regions heated by massive stars[16, 18, 19].

3) There is evidence that the ambient warm interstellar medium in many

galaxies is near the critical pressure and temperature for the phase transition between warm (100^oK) atomic clouds and cold (20^oK) dense molecular clouds[20]. Additional evidence that the medium is critical is that there is good evidence that the distribution of the cold clouds in the medium is scale invariant and fractal up to the scales of the spiral arms [21]. Feedback mechanisms involving heating by massive stars have been proposed which would keep the medium at the critical point for this transition [20].

4) There are successful models of the spiral structure that incorporate triggered, propagating star formation, which is regulated by feedback effects[22, 23]. It seems very helpful to incorporate such effects to achieve the generatation of persistant spiral structure over a range of spiral types. Typically, in such models the rate of star formation stimulated by energetic events such as supernova from massive stars dominates over the spontaneous rate. These include the simple cellular automota models of Gerola, Schulman and Seiden[22] and more realistic models involving moving clouds and stars by Elmgreen and Thomasson[23].

The cellular automata models[22] employ directed percolation models in $2+1$ dimensions, where the percolation probability, p is tuned to be near the critical point by feedback effects involving the interstellar medium. Without these feedback effects spiral structure can only be reproduced by tuning p to the percolation fixed point. This model has further successes such as reproducing bursts and oscillations of star formation in small galaxies, which is observed in blue dwarf galaxies, and incorporating a natural explanation of the lack of continual star formation in elliptical galaxies. It then seems likely that idealized as it is, this model isolates the key processes of spiral structure; to the extent that this is the case propagated star formation dominates the star formation rate in spiral galaxies.

It is apparently the case that these percolation models have difficulty reproducing grand design spirals. These symmetric patterns are reproduced by the competing density wave theory, however that appears to have difficulty explaining the persistance of spiral structure in isolated spiral galaxies[23]. The most succesful models, such as that of Elmegreen and Thomasson, incorporate both hydrodynamical and feedback effects (including propogating star formation) and are able to reproduce persistant spiral structure over the whole range of spiral types[23]. It then seems reasonable to conclude that the effects isolated in the percolation models do play a role in real spiral galaxies, but in combination with global hydrodynamical effects.

If, as the evidence seems then to point to, the galactic disk is a nonequilibriium system driven by gravitational and nuclear potential energy which

has evolved to a steady state in which the rate of star formation is governed by feedback loops, one cannot make a simple estimate of the rate of formation of black holes as a function of the fundamental paramters. However another opportunity is available to test the prediction $*$, which is that any change in the parameters that disrupts critical processes in the star formation process will lead to a cessation of that process and a transition to a state in which the rate of star formation, and hence of black hole formation, is drastically reduced. As long as that change does not lead to increases in some other mode of black hole formation, one may conclude that the number of black holes formed by the universe then significantly decreases.

There are two critical processes involved with star formation that can be so disrupted. These are supernovas and the transition from warm atomic gas to the giant molecular clouds. We discuss them in the following two sections.

4 Supernovas, star formation and the Fermi constant

Type II supernovas play a crtical role in this scenario as they are both the events in which black black holes are formed and the triggers for propagating star formation[9]. As a result of the Carr-Rees observation mentioned above[4], that type II supernovas could not occur in a world in which the value of G_{Fermi} was either increased or decreased significantly, we have a candidate for a substantiation of the prediction $*$. Without supernovas there would be no resulting shock wave to trigger star formation and also no material returned to the interstellar medium.

This has three consequences. First, without triggered star formation the scenario discussed in the previous section implies that the rate of star formation, and hence of black hole formation significantly decreases. Furthermore, whatever star formation rate persists in this case, there is less material available for the formation of new stars, as there is no return of matter to the interstellar medium from supernova. Third, those massive stars that are formed are more likely to form black holes, as, without supernova, the envelope would remain bound to the core, resulting in the colapse of the whole massive star to a black hole.

However, while the number of massive stars that, once formed, became black holes would certainly increase in this case, the issue is how many

[9]Type I supernovas are not believed to form black holes [2, 24].

massive stars a universe without supernova would form to begin with. It is certainly plausible that the answer is a great many fewer. The reason is that the formation of very massive stars requires very energetic events which can force the clouds of gas and dust to sufficient densities that gravitational collapse can overcome the thermal and magnetic support of the clouds. The very low effeciency of the star formation process attests to the apparent fact that the rate for this to occur spontaneously is low.

Furthermore, this is in fact most likely to be case for massive stars, because it is correspondingly less likely, in the absense of violent events such as shock waves, for the clouds to collapse sufficiently fast for masses many times the Chandrasekar mass to accrete before the process is reversed by winds driven by processes in the protostar. These processes are quite effecient at halting most cloud collapses shortly after the protostar ignites, as is evidenced both by the fact that most stars that form are small and by the low effeciency of the conversion of the mass of giant molecular clouds into stars. The evidence for there being a bimodal initial mass function[27, 26], as well as for massive stars forming in distinct regions[28] attests to this.

Thus, it is reasonble to conclude that it is likely that the rate of spontaneous formation of massive stars is very small, so that in the absence of supernovas very few of these stars would be formed. This effect may then overwhelm the fact that in such a world more of the massive stars that did form would become black holes.

It may seem novel that important astrophysical processes depend on fine tunings of the parameters of particle physics. It is interesting that it is not hard to find a rather general argument that this may be the case. To give this we will assume that the star formation rate $R(t)$, where we have indicated its possible dependence on time, is the sum of a spontaneous process and a process driven by supernovas so that

$$R(t) = A + BS(t) \tag{11}$$

where A gives the spontaneous rate, $S(t)$ is the supernova rate and B is the number of new stars whose formation is induced by each supernova. We may assume that the supernova rate is given by

$$S(t) = R(t - \tau_{sn}) \int_{m_{sn}}^{\infty} dm D(m) \tag{12}$$

where τ_{sn} is the average time from formation to supernova of a massive star and $D(m)$ is the initial mass function, which is defined so that $D(m)dm$

is equal to the proportion of stars that form with masses between m and $m + dm$. I have here normalized it so that $\int_0^\infty dmD(m) = 1$. We may assume that $D(m)$ is zero below some lower mass cutoff which is less than m_{sn}, which is the minimal mass that results in a supernova. Above this we assume it takes the simple form $D(m) = (\beta - 1)/m_0(m/m_0)^{-\beta}$, where the parameter β is known to be greater than one. One then easily finds that

$$R(t) = A + BR(t - \tau_{sn}) \left(\frac{m_0}{m_{sn}}\right)^{\beta-1} \tag{13}$$

Thus, if the star formation rate is constant, as is observed, we have,

$$R = R(t) = \frac{A}{1 - B\left(\frac{m_0}{m_{sn}}\right)^{\beta-1}} \tag{14}$$

if $A \neq 0$ or

$$B = \left(\frac{m_{sn}}{m_0}\right)^{\beta-1} \tag{15}$$

if there is no spontaneous star formation. Now, both observation and the success of the stochastic models of spiral structure suggest that there is a small spontaneous star formation rate, but that the dominant process is induced star formation triggered by supernova bursts. If this is the case, and if, as we assumed, the star formation rate is constant, this requires that the constant B be tuned so that the equality (15) approximately hold.

As B is the number of star formation events induced by a single supernova, it is sensitive to the energy created by each supernova and hence to the weak coupling constant. This argument shows that, given the assumptions, the value of G_{Fermi} falls into a narrow range that allows a constant rate of induced star formation to dominate the star formation process of the galaxy. To put this another way, the spiral appearance of the galaxies may be regarded as the result of the weak coupling constant being tuned so that (15) approximately holds.

To conclude the argument, it is necessary to check that increases or decreases in G_{Fermi} large enough to suppress type II supernovas do not lead to other mechanisms for black hole formation. One important side effect that must be considered is that the fact that some, but not all, of the baryons are bound into helium depends also on the coincidence (6)[4, 5]. Thus, an increase in G_{Fermi} leads to a world that is all hydrogen primordially, while a decrease will lead to a world that is primordially all helium. It is difficult

to imagine that an all hydrogen world would have drastically different rates of star formation and black hole formation than our universe, but the case of a helium universe is more difficult. One effect would be that all stars would now have lifetimes of 10^{6-7} years. The result could be an increase in the rate of type I supernovas, as there would be a much larger number of white dwarfs formed within the hubble time. However, it is generally believed that type I supernovas do not lead to black holes. A more difficult question, which is so far unresolved, is whether the intitial mass function might increase on the high mass side in a helium world.

This ends the argument that small changes in G_{Fermi} may plausibly lead to decreases of the rate of black hole production in spiral galaxies, in agreement with $*$.

5 Star formation and carbon

The second critical process in spiral galaxies is the cooling of the dense molecular clouds, leading to star formation. A scenario for this process that seems consistent with observations to date is the following[28]. Dense molecular clouds form spontaneously in the interstellar medium as a result of cooling processes involving dust. Star formation then occurs in these clouds by further condensation of small regions of the clouds. The process by which stars are formed from the dense molecular clouds is not very efficient, possibly because the clouds are supported by magnetic fields, so that the overall efficiency of conversion of clouds into stars is about one percent[28, 17]. Because of this, induced processes, in which the collapse of parts of the cloud are catalyzed by shock waves from supernova, make an important contribution to the star formation rate, in addition to whatever spontaneous rate of star formation may exist.

Thus, in addition to supernovas, the processes by which the dense molecular clouds cool and condense are critical for there to be a constant rate of star formation, and hence black hole formation, in spiral galaxies. We may note that both the dominant cooling mechanisms of the clouds and the shielding of the interiors of the clouds to heating from ultraviolet radiation from young stars require the presence of carbon, in the form of dust and in the form of CO, whose transitions provide the dominant cooling. (Furthermore, it is possible that the CO and other molecules are formed on the surface of the dust.) Therefor, we may conclude that any change in the parameters of particle physics that results in carbon nuclei being either un-

stable or not copiously produced in stars will lead to a decrease in the rate of formation of black holes, because there would not be possible a constant rate of star formation over the life of the galaxy.

If we recall the arguments of section 3 we will see that the requirement that the carbon nuclei be both stable an copiously produced puts strong constraints on many of the parameters, from equations (1-8). We may then conclude that small changes in all of these parameters that lead to violations of these relations will result in a decrease in the number of black holes produced by spiral galaxies, and, hence, by our universe.

6 Some further tests of the conjecture

Given the a priori implausibility of the conjecture $*$, it is surprising that it is not possible to discover many changes in the paramters of physics and cosmology that lead to strong increases in the number of black holes produced by the universe. Indeed, as several people have pointed out, there are several candidates for such changes that come immediately to mind. I would like to devote this next to last section of this paper to discussing them and explaining why they do not immediately lead to a refutation of the conjecture $*$. At the same time, in at least two of the cases, there is a possibility that more work will reveal that the conjecture is refuted. These are then clearly important directions for further work.

6.1 Increasing the gravitational constant

One change that might seem to lead to the formation of more black holes is to increase the strength of the gravitational force. Surely by hastening gravitational collapse more black holes will be created.

However, when looked at more closely it is not at all obvious that to increase G_{Newton} will lead to an increase in the number of black holes. The main reason is that the mass of a typical star scales as the same power of $G_{Newton}m_{proton}^2$ as does the Chandrasekar mass, $M_{Chandra} \approx m_{proton}(G_{Newton}m_{proton}^2)^{\frac{3}{2}}$, to which the upper limit for the mass of a stable neutron star is proportional[4, 5]. The reason is believed to be that the process of collapse of a dense core of a giant molecular cloud to a star is halted by energy released by the ignition of nuclear fusion[28], which happens at a mass proportional also to $M_{Chandra}$. Thus, the main effect of increasing G will be to make *all* stars proportionately more massive, but it would not directly change the proportion of stars that become black holes.

Furthermore, if the mass available in a galaxy or in the whole universe to be turned into stars is fixed, then an increase in the mass of each star would lead to a *decrease* in the number of total stars and, if their proportion is unchanged, to a *decrease* in the number of black holes. We may note that as $M_{Chandra}$ increases like the 3/2 power of $G_{Newton}m_{proton}^2$, this effect could be very significant.

Secondly, increasing G significantly will make all stars unstable because (5) is then violated, while even modest increases in G will change stellar evolution significantly because (6) is violated.

A third effect of increasing $G_{Newton}m_{proton}^2$ would be to strongly decrease the lifetime of each kind of star, which is proportional to $(G_{Newton}m_{proton}^2)^{-2}$. However, the collapse times for clouds of dust and gas, on which depend the time scales for the processes of star formation are proportional to $(G_{Newton}^{\frac{5}{2}}$ [9]. This means that an increase in $G_{Newton}m_{proton}^2$ will quickly lead to a situation in which the life time of a massive star, from birth to supernova will be the same as the time scale of star formation. This will disrupt the processes of star formation because no giant molecular cloud would be able to form more than a few stars before it would be disrupted by a supernova, drastically reducing the efficiency for the formation of gas to stars, and hence decreasing the star formation rate.

While these processes are complex enough that it is difficult to draw definitive conclusions, it seems that there is no reason to expect that an increase in $G_{Newton}m_{proton}^2$ will lead to a decrease in the rate of formation of black holes and several pieces of evidence that it would have the opposite effect.

6.2 Increasing the number of baryons

A commonsense way to increase the number of black holes would be to increase the amount of matter available to form stars and black holes. However, as we do not know if our universe is finite or infinite, we do not know if we can speak of a total number of baryons in the universe. But it certainly does make sense to speak of increasing the proportion of matter that is in baryons. If we otherwise keep the history of the universe fixed, this has the effect of decreasing the photon to baryon ratio S.

Decreasing S greatly affects the history of the early universe, necessitating changes in the scenarios for nucleosynthesis and structure formation. Cosmological scenarios in which S is intially much lower, called cold or tepid big bang models[30], have been studied, and it is possible to arrive at the

same proportion of helium as in our present universe[31]. The main issue with such a scenario is whether there are viable scenarios for structure formation, leading to galaxies and hence to black holes.

At the same time, it may not be that S is a free parameter. If it arises instead from CP violating effects in the early universe then S is inversely proportional to the CP violating[5]. To decrease in this case S then requires that CP violating effects are increased. Such a change is unlikely to affect the properties of ordinary matter. Thus, if the problem of structure formation can be solved, this is a candidate for violation of $*$ that deserves further exploration.

6.3 Lowering the upper mass limit for neutron stars

A change that would certainly lead to an increase in the number of black holes would be a decrease in the upper mass limit for neutron stars. This would lower the mass needed to form a black hole, which would result in the formation of more black holes.

The difficulty is that the upper mass limit for neutron stars depends only on the Chandrasekhar mass and the equation of state for nuclear matter[2]. It is certainly possible to lower the upper mass limit by changing from a stiffer to a softer equation of state. However, the physics that dominates the determination of the equation of state for nuclear matter is QCD, which has no free parameters apart from the dimensional QCD scale and the quark masses. A change in these parameters might achieve a softer equation of state, but there will be other effects on the rates of key processes involved in stellar physics. These are likely to strongly effect in other ways the number of stars and black holes produced. In particular, as the present formation of black holes depends on the several coincidences we have already discussed, it is not clear if the equation of state could be softened without disrupting the processes that lead to constant star formation rates in galaxies.

However, it cannot be ruled out that there is a change in some of the parameters of nuclear physics that will soften the equation of state while leaving unaffected the binding of deuterium and the ability of stars to produce carbon copiously. One interesting such possibility is that this might be accomplished by changing the strange quark mass, as it has been conjectured that neutron stars have a significant component of strange matter. Thus, this is a possibility that deserves further exploration.

6.4 Changing the slope of the initial mass function

Another obvious way to increase the numbers of black holes produced would be to increase the proportion of the material of the galactic disk that is made into massive stars, in relation to the proportion that is made into small stars. Such a change would have a two fold effect on the final number of black holes produced, first because more massive stars are made at one time and second because most of the matter that goes into massive stars that supernova is recycled back into the interstellar medium, while a smaller proportion of the matter that goes into smaller stars is recycled. (Although it should be mentioned that the proportion of matter recycled due to steller winds from stars is believed now to be the significant contribution to recycling, dominating over the mass remnants of supernovas. Further, the present rate of recycling of matter is not small, it is estimated to be about 40% in the solar neighborhood[17].)

The proportion of matter going into massive stars is determined by the shape of the initial mass function, which is believed to follow a power law for large masses[25, 26]. Unfortunately, for large masses that are relevant for this question, that power is only poorly measured. Doubly unfortunately, we do not understand the physics that determines what the slope of the initial mass function is. For example, it is not even agreed upon whether there is a single process that produces stars of all masses, or two different processes, one of which produces low mass stars, while the other is predominantly responsible for the production of massive stars[27, 26, 28].

This is then also a subject that deserves further work. There is only one point which might be mentioned, which is that if it is the case, as present evidence seems to suggest, that the rate at which material is formed into stars is matched, in spiral galaxies, by the rate of the return of material from stars to the interstellar medium, then this matching must be sensitively dependent on the slope of the initial mass function. This leads to two possible conclusions, first that changes in the slope of the initial mass function will disrupt this balance, making the continual star formation-and hence black hole formation-of spiral galaxies impossible. The result will either be no star formation as in the elliptical galaxies, or a temporary runaway star formation as in the star burst galaxies.

The second conclusion is that it may be that the relative proportion of low mass and high mass stars is itself determined by some process of self-regulation that effectuates the balence between the rate of mass flow in each direction between stars and the interstellar medium. This is not impossible,

especially if a separate process is responsible for the formation of high mass stars.

For example if the process of self-propogating star formation, through supernova caused shock waves is primarily responsible for the formation of massive stars, as has been proposed[28], then there is a natural feedback process that adjusts the rate of this process to the amount of material available in giant molecular clouds[22, 16, 19] [18]. Too much star formation depletes the interstellar medium, making subsequent supernova shocks less effecient in catalyzing the formation of new stars. But too little star formation results in the collection of more clouds, making subsequent supernova shocks more efficient as catalysts of new star formation. Such a feedback mechanism is, indeed, essential to the models of spiral structure of Gerola, Seiden and Schulman[22].

The point, beyond the simple beauty of such possible mechanisms, is that if this is the case there is no parameter that can be varied to increase the proportion of matter that goes into massive stars and hence black holes. An imagined galaxy that would produce many more black holes in each generation of star formation could not support a constant rate of star formation, hence the overall black hole formation rate would decrease.

6.5 Early production of black holes

Notwithstanding what has just been said, it has sometimes been conjectured that the relative proportion of massive and light stars does change in time, with a higher proportion of massive stars produced at earlier times[27, 26]. A possible reason for this might be that a certain enrichment of the interstellar medium with carbon and other elements is necessary for the mechanisms of the formation of light stars that we see now, which is dominated by cooling of giant molecular clouds involving such metals. We may note that it is only such slow, regulated, mechanisms of star formation that can produce stars predominantly around a solar mass, as the collapse has to be easily reversed soon after nuclear ignition has taken place in the center of the protostar.

At earlier times, before the medium was enriched, it may be that the only available mechaisms for star formation were more violent, with shocks from supernovas playing a more important role. It has then been conjectured that in the early history of a galaxy many more massive stars were formed, in what might have been runaway chain reactions of massive star formation and supernova explosions[32]. The result, beyond the enrichment of the medium to the point that formation of light stars through cooling became

possible, would be that a significant portion of the halos of galaxies may be in relic neutron stars and black holes from this period.

If this is the case then such early processes might make a significant contribution to the total black hole production of a galaxy. Again, this is a question that deserves further exploration.

It has also been suggested that shortly after decoupling there was a burst of massive star formation, which resulted in the formation of a large number of black holes, which would presently constitute a major proportion of the dark matter and inside of which a large fraction of the baryons would be trapped[33]. This possibility is consistent as well with the recent observations[34, 33] that point to a value of $\Omega = .1 - .2$. Such early processes would contribute significantly to the black hole production of a universe and also deserve further exploration in relation to the conjecture $*$.

6.6 The issue of Ω

Finally, there is the question of the density of matter, and the value of Ω. As is well known, theories that Ω is determined by elementary particle physics, such as inflationary models, predict uniformly that Ω should be equal to one. The general argument for $\Omega = 1$ is simply one of scales; if it has any other value then there is a dimensional parameter, $\tau_{universe}$, which is the lifetime of the universe before it either recollapses or becomes very dilute. The fact that this has not yet happenned means that this parameter is at least as great as several times the present age of the universe. The great mystery is then why the laws of elementary particle physics that governed the early universe should produce such a parameter, which is enormously greater than the natural time scales of elementary particle physics. The difficulty of answering this question results in the natural expectation that there is no such parameter, which is only possible if $\Omega = 1$.

It should then be mentioned that the scenario of cosmological natural selection discussed here does provide a natural explanation for $\tau_{universe}$ being several times the present age of the universe. The reason is simply that if such a parameter were fixed by the conjectured process of cosmological natural selection, we would expect it to be not significantly longer than the time scale over which galaxies produced significant numbers of black holes. While the rate of star formation is approximately constant in spiral galaxies, there is evidence that the rate is decreasing on scales of 10^{9-10} years, coming from both the observations of many blue galaxies at high redshifts and models of chemical evolution of the galaxy[17]. If this is the

case then there may be a time on the order of perhaps ten times the current age of the universe at which the rate of formation of black holes has strongly decreased. If this is the case then, on the scenario of cosmological natural selection, we would expect the overall lifetime of the universe to be not significantly greater than this time.

While this is very rough, given present knowledge, we may note that this would result in an Ω presently of not 1, but more likely around .1. It is interesting to note that, while there are not yet conclusive results, the value of $.1 - .2$ is what is claimed by observational astronomers[34, 33] as the most likely value for Ω.

Further, we may note that if the parameters of cosmology and particle physics have been tuned by a random and stochastic process such as cosmological natural selection, it is more likely that the effect that extermizes the production of black holes is produced by tuning several parameters that effect the result equally roughly, rather then tuning one or more of them extremely finely. As the cosmological constant, the neutrino mass, as well as the initial mass density all contribute to Ω, if this scenario is true we should then expect that the value of Ω that maximizes black hole production is achieved through a simultaneous tuning of all these parameters. This would mean that we would expect to see a small cosmological constant, a small neutrino mass, making some contribution to the dark matter, *and* at the same time Ω on the order of $.1 - .2$.

To avoid confusion I should mention that the scenario of cosmological natural selection is compatible with inflation. Indeed as was discussed in [7] it may also explain how it is that the self-coupling of the inflaton field, λ, is tuned to the unnaturally small values requried for inflation. But, especially given that the initial density perturbations are also proportional to the same coupling, the mechanism should tune the value of λ to values small enough to cause sufficient inflation for a universe like ours to be created, but there is no reason for the tuning to be better than this. This again leads to the conclusion that even if there is inflation it did not last long enough to tune Ω presently any closer to one than would be required for the universe to live as long as galaxies produce black holes.

As this differs substantially from the prediction of conventional inflationary models, we may regard the measurement of Ω as a test that distinguishes the theory described here from other possible explanations of how the cosmological parameters came to be so finely tuned.

7 Conclusion

Putting these arguments together, we see that there is good evidence that the following changes in the parameters will lead to a decrease in the number of black holes produced in spiral galaxies in our universe: i) A reversal of the sign of Δm. ii) An increase or decrease in G_{Fermi} large enough to effect the energy and matter ejected by supernovas. iii) An increase in $\Delta m = m_{neutron} - m_{proton}$, the electron mass, the neutrino mass, α or a decrease in α_{strong} large enough to destabalize carbon (or any simultaneous change that has the same effect). In addition to this, the same effect will follow from any (unfortunately unknown) changes in the parameters that result in the coincidence of nuclear levels that are, as noted by Hoyle, necessary for carbon to be copiously produced in stars[14].

In addition to this, it is likely that there are further relations that may be implied by $*$ that may emerge from a more detailed understanding of stellar physics and cosmology. These include bounds that follow from the Carter relation (6) and changes in α and $m_{electron}/m_{proton}$ that effect the rates of critical processes in star formation and evolution as well as relations that could bound S and $\delta\rho/\rho$ that may come from an understanding of galaxy formation. There are, however, some open possibilities which should be further explored, among these are the effect of changing the strange quark mass on the equation of state for nuclear matter and hence on the upper mass limit for neutron stars.

Finally, it should be mentioned that such a cosmological scenario can predict why a natural time scale for the evolution of the universe should be the time over which spiral galaxies continue to copiously produce new stars. This is consistent with present observational suggestions that $\Omega = .1 - .2$. It is then very interesting that a conjecture that ties together the large scale parameters of cosmology with the question of the determination of the parameters of the standard model of elementary particle physics can predict values for Ω different from 1.

In conclusion, the conjecture $*$ leads to, and is verified by, a surprisingly large number of relations among the observed values of the fundamental parameters of particle physics and cosmology. If there were really no relation between the fundamental parameters of elementary particle physics and the rate of production of black holes, it seems that it ought to be easy to discover ways to change the constants to strongly increase the number of black holes. The fact that it seems difficult to do this suggests, at the least, that in spite of the unusual nature of the cosmological scenario that implies it, this

conjecture may be considered to be deserving of further development and testing.

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