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Gravitationally Induced Quantum Superposition Reduction With Large Extra Dimensions

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Abstract
A gravity-driven mechanism ("objective reduction") proposed to explain quantum state reduction is analyzed in light of the possible existence of large extra dimensions in the ADD scenario. By calculating order-of-magnitude estimates for nucleon superpositions, it is shown that if the mechanism at question is correct, constraints may be placed on the number and size of extra dimensions. Hence, measurement of superposition collapse times (*e.g.* through diffraction or reflection experiments) could represent a new probe of extra dimensions. The influence of a time-dependent gravitational constant on the gravity-driven collapse scheme with and without the presence of extra dimensions is also discussed.

Keywords: Quantum state collapse, large extra dimensions, gravitational state superposition, measurement problem

1 Introduction

Since the Copenhagen interpretation of quantum mechanics, the issues of state vector collapse and the measurement problem have negated a full mathematical description of the theory. From the notion of hidden variables or "incompleteness" [1, 2, 3] to the range of "Many Worlds"/"enriched realities" hypotheses [4, 5, 6], the quest for a dynamical reduction model has been thus far merely academic (see [7] for a comprehensive review of proposed collapse models).

This paper will consider a gravitationally-driven collapse model based on the work of Diósi [8] and Penrose [9, 10, 11] in light of the possible existence of large extra compactified dimensions in the ADD framework [12]. This model is shown to behave as a probe of extra dimensions, in that very distinct collapse signatures can result for compactification scales of different sizes. Strict constraints may thus be placed on the size and number of extra dimensions if the model is taken to be correct.

2 Gravitationally-induced collapse: Objective reduction (OR)

Gravity has also been pinpointed as a possible cause of superposition collapse, with the earliest proposal put forth at least as far back as the mid-1960s through the 1980s [13, 14, 15]. Within the past 20 years, this "philosophy" has also been addressed by Diósi [8], Ghirardi *et al.* [16], and Pearle and Squires [17]. Although the framework of Diósi and Penrose are distinct, both draw a similar conclusion concerning the collapse mechanism. For a review of four gravity-driven decoherence models including these two, the interested reader is directed to [18]. Additionally, a resurgence of work involving the Schrödinger-Newton equations [19, 20] has sought to further the investigations of gravity's role in state vector evolution.

The focus of this paper will be on the discussion in Penrose [9, 10, 11], which like the aforementioned citations proposes that quantum superpositions should not just be though of as occurring in the Hilbert space of wavefunctions. A collapse inevitably occurs because of some interaction with the environment, and thus it seems reasonable to believe that each possible outcome (eigenstate) of the superposition is itself continually interacting with the environment. Thus, there must be some physical interpretation or physical correlate of the superposition.

A novel experiment to measure such a macroscopic superposition has been proposed, involving the reflection from a mirror of a single photon which has passed through a partially-transmitting filter. The mirror is thus in such a physical superposition of distinct states, corresponding to the reflected and transmitted photon eigenstate [21]. Alternatively, it has recently been suggested that such a mechanism could serve as a driving mechanism for cosmogenic neutrino oscillation [22], hearkening back to the notion of flavor-dependent violations of the equivalence principle.

Suppose the possible physical correlates are described by wavefunctions $|\psi_1\rangle$ and $|\psi_2\rangle$. Normally the superposition state would be described by $\alpha|\psi_1\rangle + \beta|\psi_2\rangle$. However, if such a physical correlate superposition occurs, then this inevitably has an impact on the background spacetime geometry, since it seems likely that the possible outcome states have conformational differences between one another. The actual superposition state is described by the entangled wavefunction $\alpha|\psi_1\rangle|\mathcal{G}_1\rangle + \beta|\psi_2\rangle|\mathcal{G}_2\rangle$, where the states $|\mathcal{G}_i\rangle$ represents the spacetime curvature associated with $|\psi_i\rangle$. This superposition of geometries creates an ill-definition of the time-like Killing vector, $\partial/\partial t$, since each state will induce slightly different curvatures. This curvature instability is ultimately what leads to the collapse.

Following Penrose's prescription in [9], the difference between curvature configurations is best measured as the energy difference between them, which can be approximated as the difference in free-fall vectors integrated over a hypersurface of constant time,

$$\Delta_G \approx \int_\Sigma (a_1 - a_2) \cdot (a_1 - a_2)\ d^3x \tag{1}$$

Noting that $a_k = -\nabla_k^2 \phi = -4\pi G \rho$, Equation (1) can be simplified to

$$\Delta_G \sim G \int\int \frac{[\rho_1(x) - \rho_2(x)][\rho_1(y) - \rho_2(y)]}{|x - y|}\ dx\ dy \tag{2}$$

Clearly Δ_G depends on the density distributions of each "eigenstate", and furthermore the form of Equation (2) indicates that the important consideration is the self-energy of the *difference* in conformations of each.

$$\Delta_G \sim G \int\int \frac{\rho(x)\rho'(y)}{|x - y|}\ d^3x\ d^3y \quad , \tag{3}$$

an expression which amounts to an equivalent of Penrose's in the limit where the individual eigenstate correlates/conformations have the same gravitational self-energy.

Hence, for two states separated by a distance Δr which is greater than their own spatial extent, this can be approximated as

$$E_\Delta \sim \frac{Gm^2}{\Delta r} \tag{4}$$

The collapse time of the spacetime superposition is determined by the uncertainty relation [8, 9]

$$T_c \sim \frac{\hbar}{E_\Delta} \quad , \tag{5}$$

and thus is inversely proportional to the gravitational energy of the system (calculated in either Diósi's original or Penrose's alternate formalism). In effect, the value T_c can be thought of as a "decay time" or half-life for the unstable superposition.

Penrose has used the relations in Equations (4) and (5) to determine the "collapse time" for various states ranging from simple quantum states (*e.g.* nucleons) to more mesoscopic objects like specks of dust. For a nucleon of mass 10^{-27} kg whose superpositions are separated by the strong interaction scale of 10^{-15} m, it can be shown that $T_c \sim 10^{15}$ seconds (or about 10^7 years). Hence, this object will remain superposed for a practically indefinite amount of time, insofar as laboratory experiments are concerned. This value is completely reasonable, since neutron diffractions patterns are observed for a range of energies (see *e.g.* Reference [23]).

Similarly, Penrose estimates the decay times for more macroscopic objects such as specks of dust, water droplets, and even cats to show that T_c rapidly dips to small order of magnitudes, providing again a "match" for observation (*i.e.* that macroscopic objects effectively do not maintain measurable superpositions).

3 Large extra dimensions and TeV-scale gravity

In 1998, a revival of Kaluza and Klein's spacetime theory with compactified dimensions was introduced to explain the hierarchy problem [12]. Instead of a single dimension of Planck scale compactification radius, the novel framework proposed that there exist n extra flat spatial dimensions (LEDs) of "large" radius R_n into which only gravitation may propagate (no standard model fields). It is assumed that there is only one unification scale – that of the electroweak scale, $m_{EW} \sim 1$ TeV, and that the absurdly large gravitational scale in the usual four dimensional space $M_{Pl} \sim 10^{16}$ TeV is a perceived artifact of the true nature of gravity in a higher-dimensional space[1]

The relationship between the traditional Planck scale and the actual gravitational unification scale can be shown to be of the form

$$M_{Pl}^2 \sim R_n^n M_{4+n}^{2+n} \ , \tag{6}$$

up to factors depending on the geometries of the manifolds. Demanding that $M_{4+n} \sim 1$ TeV, the size of the extra dimensions is found to be constrained by the relationship

$$R_n \sim 10^{\frac{32}{n}-19} \text{ meters} \tag{7}$$

The relationship in (6) can be re-written in terms of the gravitational couplings in 4- and 4+n dimensions as (6) that

$$G_{4+n} \sim G_4 R_n^n \ , \tag{8}$$

[1]The actual value of M_{Pl} in the literature varies between 10^{15} and 10^{16} TeV. This effectively results in an order-of-magnitude difference in the scale size of the extra dimensions, but does not significantly impact the calculations herein or elsewhere.

again up to geometric factors. A more formal derivation of the exact relationship between G_4 and G_{4+n} can be derived any number of ways (*e.g.* using Gauss' law [12]), but for the present analysis the above relationship will suffice.

The upshot of this new behavior of gravity in the extra dimensions is a departure of classical Newtonian laws on scales $r < R_n$. Instead of the usual $1/r$ potential, the field generated by a mass m is now determined by

$$|\phi_{4+n}(r)| \sim \frac{G_{4+n}m}{r^{n+1}} \tag{9}$$

and thus the potential energy between two like masses is

$$|V_{4+n}(r)| \sim \frac{G_{4+n}m^2}{r^{n+1}} \tag{10}$$

again assuming $r < R_n$.

The possibility of such TeV-scale gravity is a very intriguing one at present, since future accelerators such as the LHC or Tevatron will be able to probe precisely these collision energies. Also, curious behavior in the cosmic ray flux spectrum shows a distinctive "knee" around energies of 1 TeV, suggesting that some variety of unexplained mechanism is at work in this region [25, 26]. Current table-top gravity experiments have ruled out extra dimensions (that is, deviations from the inverse-square law) to a scale of about 200 μm [27], which would correspond to between $n = 2$ and 3 in Equation (7).

4 OR in a TeV gravity framework

If the spatial separation of the superposed mass states is small, then due to the explicit gravity dependence of Equation (4) the existence of LEDs would clearly affect the collapse time[2]. The meaning of the integral in Equation (1) remains unchanged, and only the functional form of the potential changes. Thus, it can be surmised that

$$\Delta E_{G,n} \sim \frac{G_{4+n} m^2}{(\Delta r)^{n+1}} \tag{11}$$

which as in [9] can give an order-of-magnitude estimate for the superposition lifetime, analogous to Equation (5).

Table 1 shows estimated collapse times T_c for the OR mechanism, assuming the existence of ADD LEDs. The data is calculated assuming a gravitational unification scale $M_{4+n} \sim 1$ TeV. A discussion of alternate values of M_{4+n} follows at the end of this section, with the rationale being to place bounds on possible deviations from the collapse time predictions in Reference [9]. As noted in [12], it is most the value of M_{4+n} which will be observed as marking the transition to new gravitational interactions (and not via measurements of R_n).

The general conclusion which can be drawn from these figures, however, is multifold. First, if one assumes that Penrose's mechanism is correct, it places heavy constraints on the possible size of extra dimensions. If nucleon superpositions have exceedingly short lifetimes due to the much stronger na-

[2] That large extra dimensions should affect gravity-driven decoherence mechanisms such as those discussed herein was originally suggested in [24]. However, this was anecdotal and no calculations accompanied the idea.

ture of ADD gravity below large R_n (*e.g.* for $n = 2$ and $n = 3$), then it would be virtually impossible to observe coherent neutron diffraction patterns. The cases $n = 4$ and $n = 5$ are interesting, because certainly such short times could be easily observed in a laboratory setting.

Since they have not, it is likely that there must be $n > 5$ extra dimensions with $R_n \leq 10^{-12}$ m. Furthermore, as previously mentioned direct measurements of sub-millimeter gravity ($1/r^2$ deviations) have thus far placed a cap of 200 μm on the possible size of extra dimensions [27] (ruling out $n = 4$), thus this limit is well below these bounds. Alternatively, if the superposition lifetimes are on the order of a few seconds to a few years ($n = 5$ through $n = 7$), it might be possible to devise an experiment to observe this collapse. A more recent result has reduced this limit to 100 nm [28].

As the number of dimensions increases beyond $n = 7$, the scale size becomes on the order of the supposed state separation of 10^{-15} m, and thus "regular" Newtonian gravitation will take over. The range $n \geq 6$ is a particularly interesting regime, since the physical size of the dimensions shrinks very slowly at this point. Instead of decreasing by order-of-magnitude jumps for each n, the scale size "lingers" in the femtometer region. Indeed, as $n \rightarrow \infty$, it can easily be seen that $R_n \rightarrow 10^{-19}$ m.

4.1 Yukawa type gravitational potential

It should be acknowledged that as the compactification scale becomes on the order of the state separation (or lower), the simple approximation begins to break down, and thus the figures may not be completely valid. In fact, one would ideally expect the collapse times to return to the original prediction at a faster rate with an energy function of the form $V_4(r > R_n) + V_{4+n}(r < R_n)$, where the former represents the usual Newtonian potential on the "brane", and the latter in all $4 + n$ dimensions.

In this spirit, a better approximation for the potential in the cases $n \geq 8$ would be the Yukawa-type function

$$V(r) \sim \frac{G_4 m^2}{r} \left(1 + 2ne^{-r/R_n}\right) \tag{12}$$

for toroidal compactifications, which provides subtle corrections to the usual Newtonian potential energy in the case $r > R_n$ [29]. This gives $T_c \sim 2 \times 10^{14}$ seconds for $n = 8$, and 5×10^{14} seconds for $n = 9$ – marginally different from Penrose's prediction of $T_c \sim 10^{15}$ seconds, but most likely difficult to measure.

4.2 Variation of gravitational unification scale

What if the new Planck scale M_{4+n} is not 1 TeV, but is either slightly bigger (or even slightly smaller)? That is, if the scale is $M_{4+n} \sim 10^{\gamma}$ TeV (for any integer γ), the scale relationship can be written more generally as

$$R_n \sim 10^{\frac{32-2\gamma}{n} - 19 - \gamma} \text{ meters} \tag{13}$$

In this case, it can be shown that the collapse times will be related to the originals by a factor of $10^{(2+n)\gamma}$. However, for larger values of M_{4+n} the femtometer compactification scale will be reached quicker, thus giving less "parameter space" for reasonable collapse times.

Table 2 shows the estimated collapse times for the cases $\gamma = 1$ and $\gamma = 2$ (*i.e* $M_{4+n} \sim 10$ TeV and 100 Tev, respectively). The transition to regular gravity occurs around $n = 6$ ($\gamma = 1$) and $n = 4$ ($\gamma = 2$) extra dimensions, with a $T_c \sim 10^{15}$ seconds and 10^{11} seconds for each case. The predictions are still experimentally testable, in principle, since the collapse times on the order of 10^7 seconds could be observable in the experiments discussed in [21].

If the compactification scale is just shy of the TeV range ($\gamma < 0$), then the Newtonian transition limit occurs at higher n. However, since current accelerator experiments probe in the 100 GeV energy range, extra dimensions signatures would likely have seen as quantum gravity effects or missing energy in such beam events.

4.3 States with $\Delta r > R_n$

For the larger "states" considered by Penrose, the existence of extra dimensions would barely affect the collapse time since the scale size drops quickly for small n. A drop of water 100 nm whose superposed states are separated by its radius would only show differing collapse times from Penrose's predictions for $n = 2$ extra dimensions. This would give a $T_c \sim 0.01$ seconds, versus 1 hour predicted in [9]. Reiterating the results reported in [27], though, $n = 2$ has effectively been ruled out. Since $n = 3$ dimensions are on the nanometer scale, any LED-enhanced OR effects would be for objects smaller than this.

One could again apply the Yukawa potential of Equation (12) for the values where $\Delta r > R_n$, but in most cases this yields effectively negligible corrections to the usual Newtonian case.

4.4 Time variation of the gravitational constant

The notion of time-dependent compactification radii $R_n(t)$ in the ADD framework could yield some interesting "early universe" effects if the OR mechanism is to be believed (see [35] for a general overview, although this reference precedes the notion of "large" extra dimensions by 15 years; [36] offers a more "modern" perspective on the issue). A review of the current literature indicates that at most $\dot{G}_4(t)/G_4(t) < -10^{-11}$ yr^{-1} [37].

From Equation 8, this implies $\dot{R}_n(t) > 0$, since the unification scale is constant. That is, the compactification scale is growing. If the radii were less than the femtometer range in the past, then there should be no significant deviations from Newtonian gravity for the cases considered herein (although the mechanism itself will be affected by the different value of $G_4(t)$ at earlier times). However, if the radii $R_n(t)$ are growing, then this suggests that superposition collapse could be adversely affected in the far future.

If it is assumed gravity has been a TeV-scale phenomenon for the entire existence of the Universe, then it can be deduced from Equation (8) that a time-dependent Newtonian constant would behave as $G_4(t) \sim R_n^{-n}$, and thus

$$\frac{\dot{R}_n(t)}{R_n(t)} = -\frac{1}{n}\frac{\dot{G}_4(t)}{G_4(t)} \quad . \tag{14}$$

The simplest exponential solution of these equations indicates that the compactification radius has increased by only 1-10% over the history of the Universe (10^{10} years) for the number of dimensions of interest, and depending on the choice of bound for $\dot{G}_4(t)/G_4(t)$. As a result, the collapse times would not be appreciably different from their present values. However, an exponential solution is not realistic, since it implies that the compactification radius would have some non-zero value at the beginning of the Universe ($t = 0$).

Alternatively, it has been proposed that the gravitational constant might evolve according to a power law of the form $G(t) \sim t^{-\beta}$, where the exponent $\beta < 0.1$ [38], which corresponds to the bound $\dot{G}_4(t)/G_4(t) < -10^{-11}$ yr^{-1}. In this case, the LEDs would behave as $R_n(t) \sim t^{\beta/n}$, with the requirement that at the present epoch (t_p), $R_n(t_p)$ is equivalent to the value given by Equation 7. So, the LEDs expand from a trivial size at the time of the Big Bang to their present size today, in such a way that

$$\frac{\dot{R}_n^n(t)}{R_n^n(t)} = \frac{\beta t^{-1}}{n} \quad . \tag{15}$$

This shows extremely rapid expansion of the extra dimensions in the early Universe. The dependence on n also implies that a smaller number of LEDs will grow faster. Smaller earlier dimensions imply that less quantum systems would be influenced by the Penrose-Diósi mechanism, but that more systems in the future will come under its influence.

Figure 1 shows the relative variation in LED size as a function of time ($R_n(t)/R_n(t_p)$), from 1000 years after the Big Bang until the present epoch, assuming $\dot{G}(t)/G(t) = -10^{-11}$. In this prescription, a single LED would have been only 20% its present size at this very early age, but a larger number of LEDs would only have grown a minimal amount.

The changing size of the compactification radius does not change the collapse time *within* that scale, $\Delta r < R_n$, since in that region the gravitational coupling is still G_{4+n}. Since the LEDs would have been even smaller further in the past, this indicates that most early Universe dynamics would have been governed by the rules of quantum mechanics in the absence of extra dimensions. However, the collapse times will be different because *regular* gravity is stronger than in the present epoch. This can be see from the fact that $\dot{T}_c(t)/T_c(t) = -\dot{G}(t)/G(t)$, since $T_c(t) \sim 1/G(t)$ from Equation (5). So, a decreasing value of $G(t)$ correlates to an increasing value of $T_c(t)$. In this case, if $G(t) \sim t^{-\beta}$, then $T_c(t) \sim t^{\beta}$. When $R_n < 10^{-15}$ m at an earlier epoch, the nucleon collapse time will be shorter than its present value by a factor of $(t/t_p)^{\beta}$.

It is also a fascinating consequence that if the extra dimensions continue to grow, gravity-driven collapse will become more important for macroscopic systems far in the future. So, since collapse times might have been shorter in the past due to stronger regular gravity, and will be shorter again in the future due to larger R_n, there must be a *maximum* value for the collapse which will be achieved at some point in the future. It should finally be noted that variation of the gravitational constant impacts *any* gravity-driven collapse mechanism (*e.g.* see [18]), irrespective of the existence of extra dimensions.

5 Conclusions and future directions

The rough calculations presented herein suggest that observable deviations in quantum superposition behavior could potentially be observed in a world with extra compactified dimensions. This implies either serious problems for the objective reduction mechanism, or alternatively strict constraints on the possible size of extra dimensions. Should extra dimensions exist, it is apparent that due to the stronger nature of gravity at scales $r \ll R_n$, the collapse time of quantum superpositions becomes exceedingly small, and thus in such a scenario the "size" of the quantum regime is also limited. This should have a major impact on any observational prediction which stems from such a model, including the mirror reflection experiment proposed in Reference [21].

The neutrino oscillation mechanism discussed in [22] lends itself nicely as a potential test-bed for the OR mechanism with extra dimensions, since the interaction scale of the neutrinos should be even smaller than the femtometer strong interactions considered herein (albeit the much smaller rest mass will scale the effects accordingly).

Furthermore, a novel application of the gravitationally-induced collapse mechanism can be found in References [30, 31, 32], which posits that "conscious instances" are merely orchestrated reductions of quantum superpositions of entangled microtubulin protein conformation states. If the interaction distances are at or below the compactification scale of any extra dimensions, this "Orch-OR" could greatly impact the theory and potentially invalidate it [34].

Finally, there is no reason to believe that ADD is the correct theory of extra dimensions. The most popular competing theory – that of Randall and Sundrum [39] (RS) – may well have its own poignant implications for superposition collapse in the OR framework, and all the observational phenomenon which result. The expected deviations from non-relativistic Newtonian gravity in the RS framework is of the form

$$V(r) = \frac{G_4 m^2}{r}\left(1 + \frac{1}{k^2 r^2}\right)$$

where k is the graviton mode, presumed to be on the order of the Planck scale. These corrections would be extremely small even for $r \sim 10^{-15}$ m, and thus may not result in any "observable" signature in the Penrose scheme.

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n	R_n (m)	T_c (s)
2	10^{-3}	10^{-9}
3	10^{-9}	10^{-5}
4	10^{-11}	10^{-2}
5	10^{-13}	10^{1}
6	10^{-14}	10^{7}
7	4×10^{-15}	10^{11}
8	1×10^{-15}	10^{15}

Table 1: Gravity-driven collapse times for nucleon superposition with unification scale $M_{4+n} \sim 1$ TeV, assuming a hard spherical model with spatial separation $\Delta r \sim 10^{-15}$ m. The collapse time approximation approaches the regular Newtonian value for $n = 8$ since $\Delta r \sim R_n$.

	$\gamma = 1$		$\gamma = 2$	
n	R_n (m)	T_c (s)	R_n (m)	T_c (s)
2	10^{-5}	10^{-5}	10^{-7}	10^{-1}
3	10^{-10}	1	10^{-12}	10^{5}
4	10^{-13}	10^{5}	10^{-14}	10^{11}
5	10^{-14}	10^{9}	—	—
6	10^{-15}	10^{15}	—	—

Table 2: Gravity-driven collapse times for nucleon superposition with unification scale $M_{4+n} \sim 10$ TeV and $M_{4+n} \sim 100$ TeV, assuming a hard spherical model with spatial separation $\Delta r \sim 10^{-15}$ m.

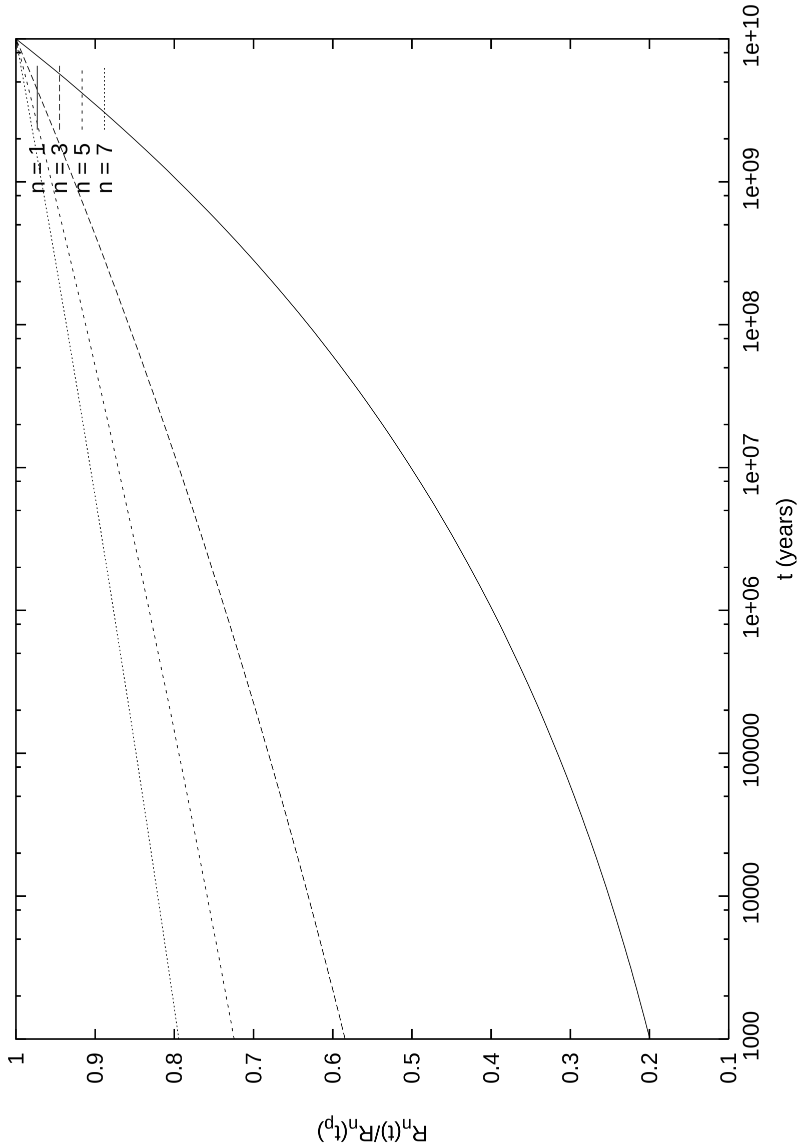

Figure 1: Relative variation of compactification radius $R_n(t)/R_n(t_p)$ from $t = 1000$ years after the Big Bang to the present epoch ($t_p = 10^{10}$ years, assuming a power law dependence on the gravitational constant, $G_4(t) \sim t^{\beta}, \beta = -0.1$.