

A HIERARCHY OF COSMIC COMPACT OBJECTS — WITHOUT BLACK HOLES

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We make the case for the existence of a, hitherto unknown and unobserved, hierarchy of ever more compact cosmic objects in the universe. This hypothesis is based on (i) the assumption of “elementary” particle sub-constituents on several levels below the presently known, inspired by Glashow’s “blooming desert” [S. Glashow, *The Future of Elementary Particle Physics*, in Proceedings of the Cargese Summer Institute, Cargese, France, July 9–29, 1979, Plenum Press 1980], (ii) the existence of nearly scale-invariant density fluctuations in the early universe, *e.g.* as predicted by inflationary models [A. Guth, *Phys. Rev.* **D23**, 347 (1981), J.M. Bardeen, P.J. Steinhardt, M.S. Turner, *Phys. Rev.* **D28**, 679 (1983)], (iii) our own previous theoretical work showing that a class of objects considerably more compact than previously thought possible in astrophysics can exist [J. Hansson, F. Sandin, *Phys. Lett.* **B616**, 1 (2005)]. We also give several independent arguments strongly pointing towards the non-existence of black holes. Some brief suggestions on observational signals due to the hierarchy, both in collected astronomical data and in possible future observations, concludes the paper.

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In our point of view it is extremely naive to assume a huge unpopulated “desert” in the immense region separating the scale of the standard model in particle physics ($\sim 10^{-18}$ m), presently our most fundamental *tested* description of nature [5], and the grand unified (GUT) [6, 7] ($\sim 10^{-31}$ m) and/or superstring [8, 9] ($\sim 10^{-35}$ m) scale. The difference in size between a superstring and an atom is roughly the same as the difference between an atom and the solar system, and the question on the existence of atoms was just being resolved only 100 years ago. Also, historically no extrapolations of then reigning theories, as far into the unknown as the one leading

to the hypothetical “desert” have been successful. Instead, successive layers of substructure have been found as shorter and shorter distances have been probed experimentally. Inspired by Sheldon Glashow [1] who coined the term “desert” only to then renounce it, we envisage a fertile “blossoming desert” landscape teeming with substructure at all scales, awaiting to be discovered in the future. “Today we cannot exclude the possibility that micro-unicorns might be thriving at a length scale of 10^{-18} cm” [10].

Also, many models of cosmic inflation in the very early universe give “fractal-like” [11] (scale-invariant) density fluctuations [2, 3]. It is known that the density fluctuations in the early universe act like “seeds” for gravitational structure formation, once the fluctuations are there, gravity does the rest. The difference between over-density and under-density regions will automatically increase due to the expansion of the universe, contracting gravitationally bound systems and diluting gravitationally unbound (expanding) systems. Gravitationally overdense regions act like “mini-universes” of positive curvature, expanding to a maximum size and then recollapsing. The larger the density contrast and the smaller the size, the shorter the “mini-universe” lifetime and the smaller its total mass.

The two preceding paragraphs implicate that gravitationally induced structures should exist on all length scales, at least those being stable. We have previously shown [4] that “preon stars” can exist, and are stable¹. There is nothing magical about neutrons making them the last in line as constituents of cosmic compact objects, as previously believed. But then there can be nothing magical about preons either. If the “desert” of particle physics in reality is populated by particles and sub-structure on many scales, it must be possible for even more compact objects than preon stars to exist, as stability will be assured in some corner of parameter space. (The details will only alter the *abundance* of those objects, *i.e.* their number density in a given volume of the universe.)

If we plot the known observed classes of gravitational structure, a representative sample of which is shown in Fig. 1, we see that they always stay well away from the region of black holes². Our qualitative prediction for the hierarchy of cosmic compact objects is shown in Fig. 2. As can be seen, it does not include black holes.

There are, in fact, several independent hints, which when taken together strongly point towards the conclusion that black holes can never actually form. (See also [15].) In classical general relativity there is the “cosmic

¹ Preons are theoretically suggested sub-constituents of quarks and leptons [12, 13].

² Already in 1969, G. de Vaucouleurs observed a universal density-radius relation for gravitational structures, $\log(\rho) = -21.7 - 17(\log(R) - 21.7)$ (in cgs-units). “This leads one to view the Hubble parameter as a stochastic variable, subject in the hierarchical scheme to effects of local density fluctuations on all scales” [14].

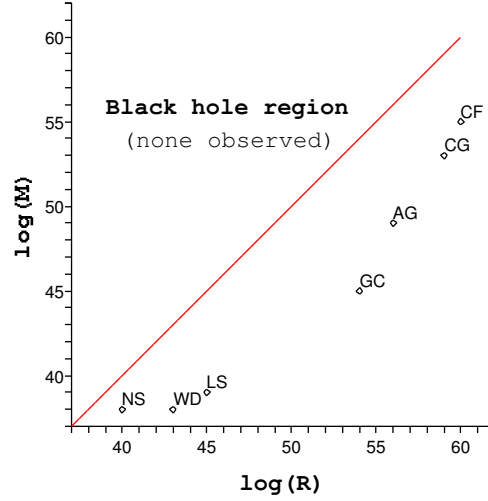


Fig. 1. “The Universe on a line” — including known, representative gravitational structures in the universe. NS — neutron star, WD — white dwarf, LS — large star, GC — globular cluster of stars, AG — average galaxy, CG — cluster of galaxies, CF — cosmic filament/supercluster of galaxies. Gravitationally bound objects larger than white dwarfs are included for completeness, they are not compact, *i.e.* they are not held up exclusively by degeneracy pressure from their quantum constituents. Masses and sizes are expressed in dimensionless units $M = m/m_{\text{Planck}}$ and $R = r/r_{\text{Planck}}$, where m and r are characteristic masses and radii of the objects, while $m_{\text{Planck}} = \sqrt{\hbar c/G}$ and $r_{\text{Planck}} = \sqrt{\hbar G/c^3}$ are the fundamental mass and distance expected from a quantum theory of gravity.

“cosmic censorship” conjecture [16, 17], that singularities are always shrouded from the outside world by event horizons. We propose a much stronger cosmic censorship conjecture: when fundamental microscopic physics is taken into proper account it prevents the very formation and existence of black holes. Some of the clues supporting our conjecture are:

1. Traditionally [18], the existence of black holes inevitably causes a loss of quantum coherence, and hence a breakdown of the basic principles of quantum mechanics, essentially due to Hawking radiation [19]. One can just as easily turn the argument around: As quantum mechanics is a much more fundamental description of nature than general relativity (which is merely a classical theory) the very same chain of arguments, run backwards, implies that black holes can never exist or form as it would violate quantum mechanics.

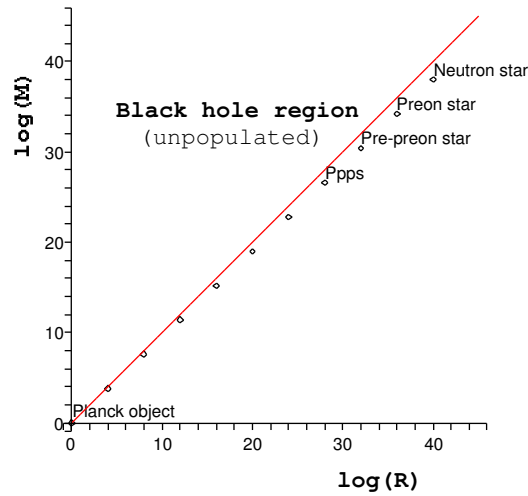


Fig. 2. A mass-radius plot of the hierarchy of cosmic compact objects. These objects are held up by quantum mechanical degeneracy pressure from the “fundamental” constituents (in parenthesis) relevant at their scale: Neutron stars (neutrons), Preon stars (preons), Pre-preon stars (pre-preons), . . . , Planck objects (possibly superstrings). The stable objects are shown with their maximum mass and minimum size, *i.e.* for their maximum density, and are separated by regions of unstable configurations (like between white dwarfs and neutron stars). The actual data-points are thus the end-points of the stable branch in question. Also inserted is the region for Schwarzschild, non-rotating, black holes. (The region for a rotating, Kerr, black hole is somewhat less restrictive.) Masses and sizes are expressed in dimensionless units as in Fig. 1. The only object bordering on becoming a black hole is the Planck-object itself. According to string theory, and also other candidate theories for quantum gravity, this is related to a fundamental minimum length in nature, a further increase in energy will *not* resolve smaller scales, due to string duality [9]. The indicated self-similar plot shown will be altered by the exact nature of density fluctuations in the early universe, and the “elementary” constituents relevant on that scale, including their detailed interactions. If the normal scenario of inflation remains intact, it will dilute all objects originating above the inflation energy scale (*e.g.* Planck-objects) to unobservable levels in our present universe.

2. In a semi-classical, Newtonian quantum gravity we can use the mathematical identity (if $e^2/4\pi\epsilon_0 \rightarrow GmM$) of the Coulomb field and the Newtonian gravitational field (mass = gravitational “charge”) to calculate the smallest allowed radius of a quantum gravitational Bohr-model, for the limiting case that all the mass-energy, mc^2 , of an in-

falling test-particle becomes binding energy, *i.e.* is radiated away in gravitons during infall, making it impossible for the object to accrete more mass-energy. It turns out that the gravitational “Bohr-radius” of any object is of the order of the Schwarzschild radius in this case (for any M as quantum theory is universal), hinting that black holes will not form in the “old” quantum theory of Bohr, especially as all other radiative mechanisms but gravity here have been neglected. (Seen in the language of gravitational field lines, the gravitational radiation effect will be larger the denser the field lines, as the gradient then increases, but as the area of a spherical shell increases in step with how the field lines decrease in r , the effect is independent of the size of the presumptive black hole. So even a very large black hole with an arbitrarily small actual density and horizon curvature is prohibited.)

3. In analogy with the position of the electron in a hydrogen atom, Fig. 3, the position of the event horizon for a black hole will become fuzzy when more exact quantum mechanical effects are taken into consider-

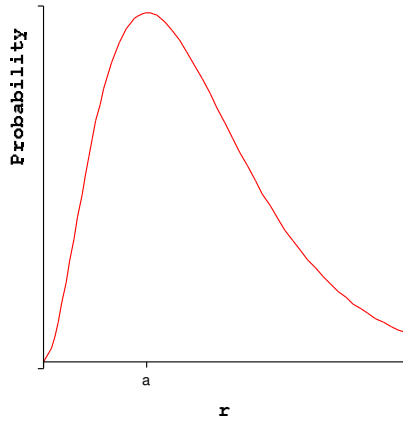


Fig. 3. The probability density for the position of the electron in a hydrogen atom. In the ground state (as shown) it only depends on the radial distance, r , from the atomic nucleus. The height of the curve at a given r gives the probability that the electron is in that (infinitesimal) interval. The probability peaks at the Bohr-radius, a , the radius of the innermost circular orbit in the “old” semi-classical Bohr model. For the position of the event horizon of a black hole an analogous relation must hold. A problem is that all parts of the gravitational field in general relativity cannot be represented by a simple potential, unlike the case for the Coulomb potential in the hydrogen atom. Neither the Bohr-radius in the hydrogen atom nor the classical event horizon radius for a black hole are of any fundamental importance in a truly quantum mechanical treatment.

ation. The Bohr radius for the hydrogen atom, and the Schwarzschild radius for a black hole, both dissolve when subject to a more fundamental quantum mechanical treatment. The “one-way membrane” of classical black holes gets penetrated, and on a microscopic scale, dissolves completely. Seen another way, particles can always quantum mechanically “tunnel” back through the event horizon. In a like manner, the purely geometrical, classical picture of point- (Schwarzschild) and ring-singularities (Kerr) must dissolve when quantum mechanics is taken into account, as simultaneously precise location and motion (zero!) is forbidden. But as black holes are *defined* by the very presence of an event horizon and/or a singularity, we see that the black hole itself cannot exist.

4. Quantum field theory and string theory arguments fare no better as they presuppose the existence of a classical black hole spacetime geometry, in which the fields/strings propagate, being only small perturbations to the background geometry. What one would need, but which so far is absent, is a derivation of black hole-like solutions from first principles in a non-perturbative theory of quantum gravity. According to our conjecture, such solutions will never be found. (Unless quantum mechanics itself is drastically altered.)
5. It is quite possible that radiation, both gravitational and from particle physics (known and undiscovered), will always “bleed off” sufficient mass-energy to keep any region of size R below the mass necessary even for the onset of classical collapse to a black hole, $M < Rc^2/2G$ ³. It is known that the total energy emitted in *e.g.* the formation of a neutron star in a supernova explosion is almost exclusively carried away by neutrinos. There may well be “neutrino-like” sub-species on the undiscovered “elementary” particle levels, playing the same role in collapse. Such mechanisms could ensure that $M < Rc^2/2G$ on all scales. (This could for example make it possible for one, or several, “light” preon star(s) to form from a very massive normal star, possibly population III [4].) As an analogy, consider boiling water: if we pump in a very large amount of energy, the water will not attain a very large temperature, instead it will boil away in a finite time. If in the analogy we replace boiling \rightarrow radiating, water \rightarrow mass-energy, temperature \rightarrow gravitational redshift, we get the gravitational case. For a different viewpoint also reaching this conclusion, see [15].

³ This is strictly only valid for a static, spherically symmetric mass distribution. The relation serves just the purpose to illustrate our point. The exact criterion for dynamical gravitational collapse in general relativity is non-trivial, and unsolved in the general case.

6. Even if we presuppose the existence of a classical black hole, infalling quantum mechanical “particles” (both matter and radiation) behave like waves when unobserved. For particles asymptotically falling in from infinity, the quantum mechanical description will initially be an infinitely long harmonic wave. Even though this will be altered when approaching the black hole, part of their probability amplitude will always be outside the classically defined event horizon, *i.e.* there will always be a finite probability that the particle has *not* fallen through the horizon. In fact, the same applies for all the particles that supposedly built up the black hole. According to quantum mechanics, even nature itself can never tell if the criterion $M = Rc^2/2G$ has been fulfilled, and thus does not know if it is “supposed” to form a horizon and start collapsing the interior. Because quantum mechanical “particles” are not just simply microscopic pebbles, quantum mechanical black holes can never form.

7. It may even be that gravity is only a macroscopically induced, non-fundamental interaction, as proposed by Sakharov [20]. In that case, black holes are ruled out as gravity is absent on microscopic scales, and the classical event horizon and singularity must be defined with infinite, microscopic precision.

Maybe the most important part of suggesting a novel picture of the world is to be able to test, and potentially falsify it via experiments and/or observations.

A first realization is that the observational verification of *any* compact objects smaller and much more dense than neutron stars would be a direct “smoking gun” proof of physics beyond the standard model (especially in the mass-region $M < 10^{12}$ kg excluded for hypothetical, presently existing primordial black holes [21]). Also, such primordial remnants, together with any sub-constituent “neutrino-like” radiation, would be potentially observable messengers from the very early universe, contrasted with today’s situation where we cannot see further back than to a redshift of $z \sim 1100$, or 400 000 years after “time zero” according to the presently favoured cosmological model.

There will be effects in structure formation as *(i)* dark matter is generated in successive steps with smallest/lightest objects first, *(ii)* the particle degrees of freedom keep changing, and the average density of any region in the universe will be scale-dependent in a hierarchical cosmology as already noted in [14], which changes the expansion rate and dynamics of the universe, especially at early stages, *(iii)* structure forms from many more tiny

stable⁴ “seeds” than traditionally believed which means more power for small scales in the normal hierarchical “bottom-up” scenario of structure formation in which smaller aggregates successively build up larger structures through gravitational clumping.

Also, there will be quite unique gravitational lensing effects. The very small and extremely dense objects in the hierarchy will produce gravitational femto-, pico-, ...lensing events [22]. Any such observations would be a confirmation of our model, while their absence could be used to refute it.

There would also in principle be deviations from the expected cosmic microwave background radiation spectrum for very high multipoles, but in practice it will be undetectable.

Perfect scale-invariance means that density fluctuations will have equal strength on all scales. In the early universe compact objects will successively freeze-out when the characteristic energy, due to expansion of the universe, falls below the relevant scale of the “elementary” constituents in question. The lightest compact objects will freeze-out first, and so on, up to Preon stars which freezes out last. Whatever is left (the final freeze-out) will not create primordial compact objects, but will become baryonic matter. If we, just for the sake of argument, assume the “democratic” principle that the total mass in each epoch of freeze-out is the same⁵, we get the following relation for the number density, n_i , of compact object class i in the present universe, $n_i = (m_h/m_i)n_h$, where m_h = mass of hydrogen atom, m_i = typical mass of compact object class i , n_h = mean number density of hydrogen in present universe $\sim 10^{-7}/\text{cm}^3$. (For Planck objects, $m_h/m_{\text{Planck}} \simeq 10^{-19}$, which would be the most abundant compact object unless the inflationary phase dilutes this to unobservable levels. For sub-constituent energy scales below the inflationary scale the formula for n_i can be taken as a very rough guesstimate of the number density of hierarchy objects.) In our case, the bulk mass of the universe also departs more rapidly from thermal equilibrium than in the traditional model, *one* of three conditions needed to explain the matter/antimatter asymmetry in the Universe [23].

⁴ Our compact objects are unaffected by the Hawking radiation which evaporates traditionally conjectured small primordial black holes before they become effective in structure formation.

⁵ It is possible to deduce a model for primordial density fluctuations where this is fulfilled exactly: as the abundance of smaller objects naturally is higher in a fractal-like distribution, coupled with the fact that the density is larger for earlier epochs, it can be made to exactly compensate for their lighter masses. However, as such a fine-tuned model in all probability would not be realized in the real universe, it is of limited value. An analogous relation also holds for normal (non-dark) visible matter: the total mass in free hydrogen (playing the role of our compact “planck-object” for normal matter) is of the same order of magnitude as that gravitationally bound in stars in the universe.

As the number of compact object classes due to the scale-invariant freeze-out in Fig. 2 is about ten, we get that dark matter should be roughly an order of magnitude as abundant as ordinary baryonic matter, as is observed in astrophysical data. The normal big-bang constraint on total matter does not apply to the very compact hierarchy objects, as they have decoupled long before the expansion (cooling) of the Universe and primordial nucleosynthesis converts gravitationally non-trapped “exotica” into normal baryonic matter.

To summarise, the main points in this article are:

1. An assumption that there exist sub-constituents on many levels between the standard model (of particle physics) scale and the level of grand unified theories and/or superstring theory.
2. The sub-constituents give rise to a hierarchy of stable cosmic compact objects. Each new sub-constituent level giving rise to objects lighter, but more dense than the previous scale.
3. Black holes never form. Compact objects on the Planck-scale are equal to the sub-constituents themselves, terminating the hierarchy. Here, the compact object for the first time approaches the border delineating compact objects from black holes.
4. The hierarchy has observational consequences, *e.g.* in astrophysical structure formation and gravitational lensing. In addition, there surely are several potential phenomena and observational effects which have escaped the author.

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