A Non-anthropic Solution to the Cosmological Constant Problem

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Accelerating cosmological expansion is driven by a minuscule vacuum energy density possibly seeking opportunities to decay to a true ground state. Quasar characteristics imply their central engines possess an intrinsic magnetic field compatible with the presence of an electrically charged toroidal dark hole, an eternally collapsing structure lacking an event horizon. The possibility is consistent with the inability of black holes to capture particles in a universe of finite age, Einstein's dismissal of the Schwarzschild metric as unphysical and the implausibility of the various paradoxes invoked by black hole existence. The uncloaked innards of these dark holes would expose immense vacuum accelerations at their cores, inevitably tempered by Planck scale physics. The Unruh effect predicts that intense yet highly localised heating should occur there. As thermal energy gradually amasses and dissipates, radiation would eventually start to escape into the surrounding environment. Virtual from the dark hole perspective, the emissions could not decrease the dark hole's mass: the energy source must instead be the universal vacuum, the likely repository of dark energy. In analogy with core-collapse supernovae, neutrinos should dominate the cooling flows. Red-shifting to low energies upon escape, quantum degenerate haloes should form predominantly around the largest galaxies. This mechanism is promising from the perspective of enabling the future universe to efficiently sustain aquatic life before stars become scarce, offering a biological yet decidedly non-anthropic solution to the cosmological constant problem.

1 Introduction

Despite tremendous interest in the composition, distribution and interactions of dark matter particles, the existence of only one of the candidates presently transcends speculation. This accolade belongs to the neutrino — a fermion which, by virtue of its non-zero mass [1], is capable of gravitational condensation to form quantum degenerate galactic haloes [2]. With cosmological constraints already implying hierarchical neutrino mass eigenstates, the similarity of $kT_{H_2O(aq)}$ and $|\Delta m_{13}|c^2$ is most striking. Neutrino oscillations require physics beyond the Standard Model but renormalisable extensions likely demand the existence of sterile varieties. Intriguingly, these facts could be hinting at the perpetuation of advanced aquatic lifeforms well beyond the stelliferous era [3].

Dark matter was recently overshadowed by the discovery of dark energy, a yet more pervasive and enigmatic phenomenon causing universal expansion to accelerate. Its spatial energy density is some 120 orders of magnitude smaller than quantum physics can comfortably explain [4]. Although dark energy's influence is locally imperceptible it dominates the cosmos already [5,6] and consequently represents a formidable new frontier in cosmology. Parallels can be drawn with theories of cosmic inflation, whose accelerating expansion purportedly terminated as an underlying energy field decayed into high energy particles. Whereas Mercury's orbital peculiarities provided both an impetus for Einstein's development of general relativity and a means of experimentally validating corrections to Newtonian mechanics, dark energy is far more inscrutable. Thus, insights of any kind are potentially valuable and merit careful investigation.

The goal of this work is to revisit the cosmological constant problem following the advancement of a novel model of the universe predicting the future decay of dark energy. This framework happens to incorporate the first scientific hypothesis concerning the long-standing mystery of extraterrestrial silence, yielding testable predictions for particle physics [3]. There is a very real prospect that the future universe might sustain aquatic life for $\sim 10^{25}$ years in certain locales via the annihilation of gravitationally condensed neutrinos within hexagonally close-packed iron (hcp-Fe), a material that dominates the cores of oceanic planets up to $\sim$ 15 $M_\oplus$ [7]. Active neutrinos may well have sufficient mass to maintain liquid oceans since oscillations [8] and cosmological considerations [9] imply that Σm_ν lies in the range 58–230 meV. Moreover, the hcp/fcc boundary in iron's phase diagram conveniently lends itself to planetary thermoregulation almost independently of planet size [3]. Key to the scenario is the finding that the cosmic abundance of neutrinos must first be hugely augmented, implicating the future decay of dark energy primarily to galaxy-engulfing active neutrino halos of a mass approaching 10^{21} $M_\odot$ within ~60 Gyr [10].

This particular line of cosmological investigation has not previously succeeded in venturing any suggestion as to a physical process by which dark energy might decay to neutrinos, an eventuality implied by the propensity of neutrinos to sustain aquatic life with remarkable efficiency [3]. Other avenues of enquiry have similarly failed to pinpoint specific mechanisms for vacuum discharge capable of ending the current phase of cosmic acceleration, although a model of dark energy interacting with a neutrino-like fermion field has been considered [11]. The present approach draws heavily on developments in black hole research and observational cues from the contrasts between active and inactive galactic nuclei. A promising mechanism for dark energy discharge shall be identified here but its quantitative analysis is likely to remain challenging for some time, in large part due to the continuing lack of a theory of quantum gravity and knowledge of physics at the highest energies. The concluding discussion reflects upon the capability of this mechanism to fulfil its cosmological motivations and thereby offer a radical new approach to comprehending the minute energy density of the vacuum.

2 Theoretical motivations

2.1 The physics of biology

Life is reliant on complex biochemical interactions involving only three subatomic particles whose arrangements are stabilised by only two forces: electromagnetism and the strong interaction. The neutron is marginally more massive than the combined rest mass of a proton and an electron, allowing protons and neutrons to coexist without prohibiting the formation of neutron degenerate matter within dense stars. The strong interaction conveniently allows the assembly of heavy atomic nuclei despite intense electromagnetic repulsion between protons. Of the elements up to lead, only three lack unconditionally stable isotopes, yet most possess only one or two stable isotopes. Remarkably minor adjustments to several physical constants could radically shorten the periodic table or rule out chemistry altogether. Space might be populated mainly by neutron stars and black holes. Stars might be incapable of nuclear fusion, too short-lived to support complex evolutionary processes or so dim that planets orbiting within their habitable zones soon become tidally-locked. Supernovae might never scatter the ashes of stars into space, so that their ejecta might form elements necessary for planets and life.

Ascertaining why nature's constants might possess the values they do has been traditionally regarded as the preserve of mathematical physics — yet the approach has met with little success. One should therefore remain open to alternative possibilities. Due to the improbable compatibility of the physical laws with long-term biological evolution the 'anthropic principle' has been advanced. Although the universe existed well before life on Earth commenced, our existence imposes retrospective constraints on the physical laws and the natural constants. However, the anthropic principle does not allow one to conclude that physics would have been any different had chance chemical interactions never led to life on this planet. Furthermore, the Copernican revolution provides a historical precedent that the innate sense of human self-importance does not always provide a reliable foundation for cosmological extrapolation. Moreover, appeals to the precondition of human existence are at odds with a multitude of life-promoting characteristics in nature falling comfortably outside the gamut of the anthropic principle.

Nevertheless, the traditional perception has been that the universe is rather ill-suited to life. The Earth's living organisms only harness some 0.1% of the insolation, in turn amounting to just one billionth of the Sun's total radiation. No star liberates more than 0.008% of its rest mass energy through fusion processes. The Sun burns hydrogen to helium, yet 90% of its hydrogen will remain by the time it becomes a red giant. Planets orbiting low mass red dwarves are never habitable for very long. These considerations seem to paint a picture of a universe largely inhospitable to life. However, there is now reason to believe that impression was premature. Active neutrinos may be capable of internally heating iron-cored oceanic planets on galactic scales, sustaining aquatic life long after the stars have died with impressive efficiency [3, 10]. The fact that a technological species has evolved on this planet provides no plausible explanation for this, and neither does happenstance.

For oceans to be maintained in a liquid state by neutrino annihilation, haloes are required of a mass approaching the threshold for gravitational implosion, some 4∼7 orders of magnitude larger than the mass of a galaxy cluster. Synthesis of the available information points to dark energy decaying at a suitable juncture predominantly to active neutrinos that form dense haloes. This is expected somewhat prior to the disappearance of the last stars capable of cultivating life on orbiting planets — when the universe is approximately five times its present age. Accordingly, the continuity of life need not be endangered and there would be ample time for the evolution of technologically and ethically advanced colonising civilisations before widespread colonisation could be attempted.

The former solar neutrino anomaly was resolved when it was found that neutrinos undergo spontaneous flavour oscillations [1], demonstrating their possession of mass. The diminutive neutrino mass scale closely coincides with the energy scale associated with the temperature of liquid water. Furthermore, it is small enough to ensure that neutrinos can condense under gravity to form galaxy-enveloping structures supported by fermionic quantum degeneracy [3, 10].

The likelihood of a neutrino mutually annihilating with other neutrinos depends on the ambient neutrino concentration, but the probability of a neutrino scattering with nucleons does not. In a dense neutrino halo, annihilation events can be frequent in the presence of hcp-Fe at temperatures compatible with the presence of a 4s electron receptive to some of the annihilation energy [3, 7]. Whilst even high energy neutrinos can travel through light years of lead without scattering, low energy neutrinos are unlikely to emerge from an iron-cored planet without annihilating if the planet is immersed in a sufficiently dense neutrino halo. If, as cues from cosmology and oscillation experiments suggest, the neutrino mass scale lies in the vicinity of ~0.05 eV, a halo density of just one picogram per cubic kilometre can sustain liquid oceans. A neutrino mass just one order of magnitude smaller would be incapable of maintaining liquid oceans, even with assistance from a thick insulative crust of ice.

2.2 Biotic reasoning

Appreciation of the inadequacy of the weak anthropic principle as an explanation for the fine-tuning of physics inspired an investigation into whether dark matter particles might be capable of sustaining aquatic life. This led to the discovery that neutrino annihilation is capable of targeting 4s electrons in hcp-Fe, a phase transition in iron providing a natural thermoregulation mechanism as the 4s electrons transfer to the 3d subshell, assuring that the thermal flux through a subglacial ocean is essentially independent of planetary mass for relatively dense, rocky planets [3, 10].

Being polytropic, a neutrino halo expands upon depletion and, due to the resulting decline in neutrino concentration, the heating capacity eventually falls below that needed to maintain liquid oceans. A sizeable fraction of the halo energy might thereby go to waste. The energy of a neutrino halo approaching the gravitational implosion limit is inversely related to the mass of an individual neutrino. Hence, a smaller neutrino mass might support aquatic life for longer. This likely explains why the neutrino mass scale is at least one order of magnitude lower than required merely for haloes to fully surround a galaxy — reducing their ambient concentration, yet not to the degree that aquatic life cannot be maintained. Although this permits a lengthy aquatic era, the wastage this incurs as the aquatic era ends is not insignificant. This may be mitigated by another consideration, one that is potentially relevant to the current composition of dark matter.

Half the Earth's atmosphere is concentrated at altitudes below 6 km, less than 0.1% of the planet's radius. If the mass of the Earth were somehow abruptly reduced, say to the mass of the Moon, the atmospheric scale height would increase a hundred-fold. Many species, including our own, would soon die of asphyxiation. The gravitational load on the Earth's atmosphere is clearly vital to our minute-by-minute survival. By analogy, if oceanic planets are pictured as inhaling neutrinos and exhaling infrared photons, gravitationally loading an excessively large halo could locally boost the neutrino concentration over galactic scales. This could be very useful at late times when the neutrino halo would otherwise be quite rarefied within the galaxy. An inner halo of relatively low mass, roughly twice the diameter of the contained galaxy but of far greater mass than the galaxy itself, would apply an effective additional load. Ideally, this auxiliary halo would also support its own weight through fermionic repulsion but its constituent particles would be highly inert, virtually immune to all forces except gravity.

The weak interaction maximally violates parity so that right-handed particles and left-handed antiparticles are insensitive to it. Hence, particles resembling conventional neutrinos but having opposite chirality and a somewhat larger mass would be advantageous. Prior to the realisation that such particles could be biologically useful, anomalies in neutrino oscillation experiments were already alluding to the existence of sterile neutrinos at the eV-scale [12, 13]. Furthermore, gravitational lensing data for the Abell 1689 galaxy cluster strongly hinted at the presence of a cloud of degenerate 1.5 eV fermions [14, 15], inconsistent with cosmological constraints on active neutrinos but in keeping with the expectation that eV-scale sterile neutrinos would be well-suited to concentrating active neutrinos on galactic scales [3, 10].

Whilst the discovery of sterile neutrinos has not yet been formally announced and their mass remains loosely constrained, the statistical evidence for their existence already stands at 3.8σ. Active neutrinos may well have sufficient mass to maintain liquid oceans since $58 < \Sigma m_\nu < 230$ meV [16]. Moreover, the hcp/fcc boundary in iron's phase diagram beautifully lends itself to planetary thermoregulation in a manner almost independent of planet size [7, 10]. This picture testifies to the utility of biotic reasoning: a cohesive new approach to cosmology has emerged that dispenses with unsatisfactory anthropic explanations for fine-tuning and yields the first scientific resolutions of the Fermi paradox [3]. Before proceeding to apply similar logic to dark energy decay, attention shall be drawn to some other pertinent considerations.

2.3 Inferences and expectations

The potential sustainment of aquatic life by neutrinos annihilating within iron-cored oceanic planets would be sufficiently efficient as to bear the hallmarks of cosmic design, in turn implying that some coordinated strategy for life could operate at all levels throughout the universe. A swift overview of the envisaged scenario is provided here so as to facilitate expectations concerning the manner and timing of dark energy decay. The model anticipates that, following the decay of dark energy to neutrinos, oceanic planets will be populated by advanced civilisations adept at installing aquatic biospheres free of welfare-endangering perils such as carnivorous predation and avoidable disease. Photosynthesis has oxygenated the Earth's atmosphere but photochemistry would not be possible in subglacial oceans deprived of sunlight. This may not be problematic since many have speculated that complex chemosynthetic lifeforms could have evolved in Europa's dark and relatively anoxic oceans [17, 18].

Habitable planets capable of evading tidal-locking invariably orbit stars within the mass spectrum that terminate their lives as red giants, incinerating or absorbing any potentially habitable planets that may have orbited their progenitors. Given the cosmological context, this may be telling: it could imply that lifeforms incapable of interstellar relocation are deemed too primitive to be granted survival beyond the early universe. More advanced, space-faring civilisations are likely to be skilled geneticists, especially if they have wrested control of their own biology from the clutches of haphazard evolutionary processes whether for purely ethical reasons or in an attempt to safeguard their ongoing survival [3, 19].

Galaxies frequently undergo mergers within galaxy clusters. Potentially introducing alien cultures to one another, collaboration and competition might ensue. If each galaxy spawns roughly one colonising civilisation then the ultimate outcome of a process of galactic mergers is expected to be a supercivilisation which could be confidently entrusted with colonisation [3]. The welfare of post-evolutionary lifeforms inhabiting skilfully designed aquatic biospheres could comfortably exceed that of the Earth's present lifeforms. Hence, the cosmic arrangement may seek to maximise opportunities for more advanced lifeforms subject to the need to first cultivate responsible colonists through natural selection. This impression is reinforced by the fact that formerly habitable orbiting planets would be incinerated during the red giant stage of their host stars, prohibiting the later revival even of dormant microbial organisms interred deep underground.

Statistical modelling of this scenario constrains to within a factor of two or so the rarity of advanced civilisations, not only now but also at other times [3]. This leads to three novel yet related resolutions of Fermi's paradox, all involving the future decay of dark energy to active neutrinos predominantly in galaxy clusters when the universe is ∼5 times its present age. A small fraction of life-cultivating stars will remain active until then, assuring survival for civilisations capable of interstellar relocation. It is striking that the measured energy density of empty space is compatible with this timescale, offering a hitherto elusive explanation for its tiny yet non-zero value where the $\Lambda \approx m_p^4$ guesstimate for the value of the cosmological constant has failed so spectacularly, m_p being the Planck mass. This attempt to calculate the value of the cosmological constant from quantum theory alone has yielded what is notoriously regarded as the *'worst prediction in all physics'*. Note, however, the claim that "although the magnitude of the vacuum energy remains a profound mystery, it seems clear that an understanding of how quantum-mechanical matter behaves in curved spacetime will play an important role in any eventual resolution to the puzzle" [20].

In summary, the universe may keep a tight rein on its available resources, restricting their expenditure except when it supports life — in particular post-evolutionary aquatic life. The temporary, relatively inefficient sustainment of evolutionary life during the early universe can be amortised by the vastly more efficient (∼99%) and lengthy (∼ 10^{25} year) aquatic era. Life is reliant on energy but energy conservation is a cornerstone of physics. Thus, energy cannot be the underlying currency of the universe. However, the universe could be strategically arranged so that entropy-increasing processes are restricted *unless* they either engender (via abiogenesis and evolution by natural selection) or support (via the direct internal heating of oceanic planets) advanced aquatic lifeforms.

2.4 The necessity of dark energy & its timely decay

If neutrinos are capable of efficiently sustaining aquatic life, why did the universe not provide dense neutrino haloes from the outset? Had the question instead been why did the universe not provide habitable planets from the outset, the answer would have been obvious: the primordial elements hydrogen and helium cannot form rocky planets or biomolecules. Answering the original question concerning the biological necessity for dark energy may not be so straightforward.

From a design perspective, a substantial postponement in the widespread provision of habitable environments for life could be a prudent precaution against incompetent colonisation. There may therefore be no urgency associated with the delivery of neutrinos until life-cultivating stars are becoming scarce. If dark energy must decay so that neutrino haloes capable of planetary heating can form then it can represent a temporary repository for the fuel needed by a forthcoming aquatic era. The accelerating expansion of the universe by an incongruously small cosmological constant may well be heralding the future delivery of active neutrinos.

Although some currently regard the cosmological constant as being literally responsible for cosmic acceleration, it requires an inexhaustible energy supply and its minuscule value defies theoretical explanation. Thus, independently of biotic reasoning, dynamical models of dark energy have been favoured. However, that leaves completely open the fate of the cosmic expansion. Biotic reasoning can assist here, offering clear hints concerning the future decay of dark energy, its timing, the particles it will yield and their distribution in space. A mechanism with considerable potential for satisfying all these various expectations shall now be sketched.

3 Gravitational collapse

Annual modulation in the timing of eclipses of Jupiter's moon Io allowed Ole Rømer to infer in 1676 that light travels at a finite speed. In 1783 John Michell argued for the existence of "dark stars", objects of sufficient mass that their escape velocity would exceed the speed of light. The Michelson-Morley experiment of 1887 found that light always travelled at the same speed regardless of the orientation of the apparatus relative to the Earth's passage through space. This spurred Einstein to conceive his 1905 theory of special relativity which ushered in the concept that clocks in relative motion are subjected to time dilation. When relativity was generalised a century ago to include gravitation Einstein showed that matter and energy could also affect the passage of time and indeed the entire network of temporal relationships amongst worldlines populating a spacetime manifold. Prior to this there was no reason to suspect that nature might be capable of evading Michell's dark star expectation. We now understand that gravitational time dilation can grow without limit in general relativity: the proper time along one timelike worldline can cease to advance relative to the proper time along another. Combinations of the constants c, $\hbar$ and G cannot impose any Planck-scale restriction upon time dilation, a dimensionless quantity. It is therefore interesting to consider whether time dilation effects might be sufficient to ensure that gravitationally imploding matter is incapable of vanishing from view and becoming forever lost to the universe.

Supermassive black holes are by now widely thought to inhabit galactic nuclei, their masses occupying the range $10^6 \sim 10^{10}$ $M_\odot$ [21]. A Schwarzschild black hole has a surface area $A_\bullet = 4\pi R_\bullet^2 = 16\pi G^2 M^2/c^4$ which ostensibly governs its growth rate when immersed within a degenerate cloud of matter. In a galaxy hosting a million black holes of stellar mass, their combined area might be ten orders of magnitude less than that of a single supermassive black hole. Thus, if supermassive black holes did exist they would unacceptably sap neutrino haloes of biologically vital energy [3]. A mechanism for the eradication of eternal black holes is known involving the separation of virtual particle pairs via quantum tunnelling effects near the event horizon, the escape of one particle coming at the black hole's expense [22, 23]. However, the timescale for black hole evaporation via Hawking radiation is $5120\pi G^2 M_\bullet^3/\hbar c^4$ so astrophysical black holes require upwards of 10^{67} years to fully evaporate.

Rotating black holes are invariably plagued by the presence of closed timelike curves within their event horizons. The information loss paradox remains another stubborn complication [24] and locations of supposedly infinite mass density, *singularities*, hardly seem physically realistic — for example on energy conservation grounds. In addition, it has long been known that infalling particles, whether following timelike or lightlike trajectories, require infinite time to reach the event horizon of a black hole according to any arbitrarily-moving clock situated anywhere external to the event horizon. As the worldlines within a spacetime manifold must satisfy a global network of temporal interrelationships, black holes cannot grow through particle capture — rendering their dynamical formation implausible too [25–32]. No particle is better suited to the challenge of penetrating a Schwarzschild black hole event horizon than a radially ingoing photon but the metric then informs us that $|dr/dt| = c(1 - 2m/r)$ so that $dr/dt \to 0$ as $r \to 2m$ with attention confined to the regular coordinate region $r > 2m$. Evidently, the photon's motion is halted before it can reach the event horizon at $r = 2m$. It is possible to insert a mirror between the photon and the event horizon at arbitrarily late times and have it reflect back out along a radial geodesic, confirming that it never entered the black hole. Since nothing can be captured through an event horizon, the defining characteristic of a black hole, one can safely infer that gravitational collapse will always be safely arrested by the phenomenon of gravitational time dilation.

Given the enthusiasm for black hole research within modern science it may be difficult to accept that these objects are merely mathematical curiosities. Some further elaboration may thus be warranted. *Any* useful theory of gravity should be capable of predicting the trajectories of test particles in the vicinity of a gravitating point mass. If there is some maximum speed which no particle can exceed then matter straying too near the point mass will inevitably be incapable of escaping. It should therefore come as no surprise whatever that general relativity yields a stationary solution matching this expectation. But whereas Newtonian gravity would predict the existence of dark stars, general relativity departs radically since it predicts that time dilation can grow arbitrarily large even at a finite distance from the point mass responsible. Caution must hence be exercised since the fact that the Schwarzschild metric exists by no means guarantees that the solution is actually attainable through any physical process from realistic initial conditions in a universe of finite age.

Analytical solutions to Einstein's field equations can only be derived in certain idealised situations. The metrics describing the familiar eternal black holes have all been obtained by imposing the condition of stationarity: an assumption prohibiting any temporal evolution of the spacetime geometry, including of course any evolution that might be initially required to obtain the stationary configuration in question. Tracing the full *dynamics* of gravitational collapse in general relativity is hindered by the nonlinearities of the field equations. However, a pioneering work tackled this for the spherically symmetric case of a homogeneous sphere of pressureless matter [33]. If the advancement of proper time along all worldlines satisfies a very obvious constraint [31] this solution is well-behaved and time dilation asymptotically halts the collapse process just prior to event horizon formation. This constraint is compatible only with the exterior perspective on Oppenheimer-Snyder collapse — the interior perspective requiring the physically impossible advancement of proper times along *all* external worldlines. Though aware that neutron degeneracy pressure cannot always resist gravitational collapse, Oppenheimer & Snyder did at least appreciate that "it is impossible for a singularity to develop in a finite time" [33]. Hence, their collapse did not form a Schwarzschild black hole. Accordingly, gravitational collapse is expected to generate "*dark holes*", objects that may superficially resemble black holes in many circumstances but due to their lack of event horizons are free of their various pathologies. Whereas the situation considered by Oppenheimer and Snyder pertained to a particular mass distribution, a straightforward yet general proof now exists that black holes can neither form nor grow based on the inability of the Schwarzschild black hole to capture test particles of any description in a universe of finite age [31]. Furthermore, recent independent studies of dynamical collapse have also confirmed the non-formation of event horizons [27, 32].

Assertions that objects with event horizons exist cannot be verified even in principle [34] although the detection of Hawking radiation could arguably provide a counter-example. Whether or not black holes lie strictly outside the scope of science, nothing can prohibit the collection of evidence that specific black hole candidates *lack* rather than *possess* event horizons. The finite lifetimes ($10^7 \sim 10^8$ years) and the collimated jets of relativistic charged particles produced by quasars strongly suggests that their central engines have an intrinsic magnetic field — probably a dipole created by a spinning electrically charged torus [31, 35]. This interpretation calls into question the physical relevance of the *Principle of Topological Censorship*, a mathematical theorem constructed upon the assumption that trapped surfaces are present within some given spacetime [36] — a condition that no dark hole will satisfy [31] but which also belies the singularity theorems [37–39]. That is likely why, through the accrual of angular moment, dark holes are free to adopt toroidal geometry. The torus can then amass a significant net electrical charge, its rotation inducing a poloidal magnetosphere defending against charge neutralisation from the plasma of an orbiting accretion disk. Toroidal dark holes can explain the formation of relativistic jets of charged particles, the extreme energetics and the finite lifetimes of quasars [35]. Astronomers have found evidence of intrinsic magnetic fields in several black hole candidates, consistent with the absence of event horizons both in galactic black hole candidates [40–42] and in quasars [43]. When evaluating solutions of the field equations, the need to ensure that those configurations can be realistically attained without falling foul of constraints on global relationships has been generally overlooked: their formation must not involve the physically impossible advancement of time along any worldline within the spacetime manifold [31].

4 Dark energy from dark holes

The intersection of quantum mechanics and black hole physics led to the field of black hole thermodynamics. If, however, gravitational collapse is incapable of realistically producing objects endowed with event horizons, it may be more fruitful to consider the implications of quantum physics for dark holes. The complete absence of an event horizon precludes the emission of any Hawking radiation but a closely related process, the Fulling-Davies-Unruh effect [44–48], could be highly relevant to this discussion. Regarded as a fundamental and inescapable consequence of quantum field theory [49], the Unruh effect teaches us that the concept of a particle is observer dependent and that what may seem to exist in one reference frame may not exist at all in another [44]. It predicts that an accelerating detector coupled to a quantum field should perceive empty space to be seething with particles whose temperature is proportional to the acceleration of the detector [50].

According to Einstein's equivalence principle, a uniform acceleration is locally indistinguishable from a constant gravitational field. Hence, Unruh radiation is also expected if the detector/observer is stationary and, due to the presence elsewhere of a gravitating body, space is accelerating. Unruh and Hawking temperatures both share the common form $T = \hbar a/2\pi c k_B$ where T is the temperature of the perceived thermal bath of a vacuum field undergoing relative acceleration a. Although the value of the scaling factor $\hbar/2\pi c k_B$ is minute, $\sim 4\times10^{-20}$ °K$/g$, it is generally accepted that the Unruh effect has already been experimentally confirmed in the observed depolarisation of electrons in storage rings [51, 52]. More sensitive measurements should be possible by exploiting Berry's phase [53].

Black body radiation from nearby galaxy clusters peaks in the X-ray spectrum, betraying the fact that gas there has been intensely heated by gravitational contraction. In the rarefied and hence transparent conditions of the intracluster medium, X-rays provide cooling. In contrast, matter exists in a dense state within stars, making their interior regions opaque to electromagnetic radiation. During core collapse supernovae, stars release large amounts of gravitational binding energy that drive runaway thermonuclear reactions. In such circumstances, cooling occurs almost exclusively through neutrino emission [54]. Even at energies above $2m_ec^2 \approx 1$ MeV at which electron/positron pairs are readily produced, neutrinos continue to dominate supernova cooling processes [55]. Some 10% of the rest mass of a collapsing star can be converted into neutrinos within a ten second interval [56]. The total luminosity during that period is $\sim 10^{46}$ W or $10^{19}L_\odot$, which greatly exceeds the power output of an entire galaxy. Radiated neutrinos are ultrarelativistic, a fact exploited by the Supernova Early Warning Systems to alert optical telescopes of impending supernova activity [57].

Likewise, neutrino escape will represent the main cooling mechanism for dark holes. They will copiously radiate neutrinos during their initial implosion stages but these formative outflows will soon cease as gravitational time dilation mounts, and are of no interest to this discussion. From the perspective of a stationary external observer, the internal vacuum of a dark hole whose collapse is arrested by time dilation will appear to undergo extreme acceleration — and hence, via the Unruh effect, should appear to be extremely hot. Over astronomical timescales, this intense but highly localised heating can deposit considerable thermal energy as heat percolates from the core of a dark hole to its periphery. The ordinarily prohibited proton decay process $p^+ \rightarrow n^0+e^++\nu_e$ might be perceptible to dark hole onlookers whereas in the local frame it appears to be $p^+ + e^- \rightarrow n^0 + \nu_e$. The neutrino-related supernova processes $e^- + p^+ \leftrightarrow \nu_e + n^0$ and $e^+ + n^0 \leftrightarrow \bar{\nu}_e + p^0$ should also be important. Ultimately, via the Unruh effect, temperatures should become so elevated throughout the dark hole that some of the neutrinos generated by the thermal bath would satisfy the dark hole's escape requirements. A state of pseudo-equilibrium might exist in which the neutrino cooling rate approximately balances the power in the Unruh effect.

For an observer accelerating through Minkowski space it has been speculated that the energy in Unruh radiation comes courtesy of the work that maintains the observer's acceleration [20]. Hawking radiation is thought to come at the expense of the black hole which captures negative energy virtual particles, reducing its mass. However, neither explanation satisfactorily explains the origin of the Unruh-related radiation emanating from a dark hole. According to general relativity, distortions of spacetime influence the motions of all objects because gravitation is, like the vacuum, a *global* phenomenon. Energy conservation may therefore be possible if the vacuum represents a quantum gravitational energy reservoir coupling both to gravity (consistent with accelerating cosmic expansion) and quantum mechanics (consistent with the Unruh effect). If indeed the vacuum acts as a dynamical repository for dark energy, the Unruh effect precipitated by extreme accelerations within dark holes may be uniquely capable of tapping into the cause of the accelerating cosmic expansion and eventually halting it.

Although neutrinos could dominate the cooling processes both within core collapse supernovae and dark holes, the dynamics of the latter case would be profoundly influenced by time dilation. Neutrinos escaping from dark holes would necessarily be red-shifted to low energies. This could be most advantageous to aquatic life: if the emerging neutrinos are at most mildly relativistic they could be easily retained by the gravity of the dark hole's host galaxy — thereby forming dense, inhabitable haloes.

4.1 Acceleration scales

In order to quantify the Unruh effect within dark holes there is a need to determine the acceleration of the vacuum due to gravity from the perspective of the surrounding universe. Although the Schwarzschild metric describes a black hole, by Birkhoff's theorem its exterior region can accurately represent the spacetime outside any spherically symmetric mass distribution, including a dark hole. Consider a timelike particle momentarily at rest in Schwarzschild coordinates $x^\lambda = [x^t, x^r, x^\theta, x^\phi]$. The metric reads $d\tau^2 = (1-2GM/c^2r)dt^2$ such that $dt/d\tau = 1/\sqrt{1-2GM/c^2r}$ and the particle's 4-velocity u is simply

$$u = \frac{dx^\lambda}{d\tau} = \dot{x}^\lambda = \left[\frac{1}{\sqrt{1-2GM/c^2r}},\ 0,\ 0,\ 0\right]. \tag{1}$$

To find the particle's acceleration, $a^\lambda = \ddot{x}^\lambda$, the components of the covariant derivative of u are needed. Using the fact that dx^λ is non-zero only for dx^t and making use of the Christoffel symbols of the second kind, Γ^i_{kl} where

$$\Gamma^i_{kl} = \frac{g^{im}}{2}\left(\frac{\partial g_{mk}}{\partial x^l} + \frac{\partial g_{ml}}{\partial x^k} - \frac{\partial g_{kl}}{\partial x^m}\right) \tag{2}$$

this simplifies to

$$du^\lambda = \left[\frac{\partial u^\lambda}{\partial x^t} + u^\sigma \Gamma^\lambda_{\sigma t}\right] dx^t. \tag{3}$$

Since u^t is the only non-zero component of u^λ and $\Gamma^t_{tt} = 0$, it follows that $du^t = 0$. The only non-zero component of $\Gamma^r_{\sigma t}$ is $\Gamma^r_{tt} = GM(1-2GM/c^2r)/r^2$ and so

$$du^r = u^t\,\Gamma^r_{tt}\,dx^t = \left(\frac{GM(1-2GM/c^2r)}{r^2\sqrt{1-2GM/c^2r}}\right)dt. \tag{4}$$

As Γ^θ_{tt} and Γ^ϕ_{tt} are both zero, the covariant derivative sought is $du = [0, GMr^{-2}\sqrt{1-2GM/c^2r}\,dt, 0, 0]$. The proper acceleration of the test particle can now be obtained using the fact that $dt/d\tau = 1/\sqrt{1-2GM/c^2r}$.

$$a^r = \dot{u}^r = \frac{du^r}{d\tau} = \sqrt{1-2GM/c^2r}\left(\frac{GM}{r^2}\right)\frac{dt}{d\tau} = \frac{GM}{r^2}. \tag{5}$$

Hence, the 4-acceleration is $a = [0, GM/r^2, 0, 0]$ and for this momentarily stationary particle the magnitude of the outwardly directed acceleration is $a_s = \sqrt{a.a} = \sqrt{g_{\mu\nu}a^\mu a^\nu} = \sqrt{g_{rr}}GM/r^2$. Since $g_{rr} = (1-2GM/c^2r)^{-1}$,

$$a_s \equiv \frac{d^2r}{d\tau^2} = \frac{GM}{r^2\sqrt{1-2GM/c^2r}}. \tag{6}$$

This acceleration corresponds to that of the vacuum at $x^r = r$, as perceived by remote observers. The Unruh temperature which this acceleration would predict, neglecting for now the influence of time dilation, would be

$$T_u = \frac{\hbar a_s}{2\pi c k_B} = \frac{\hbar GM}{2\pi c k_B r^2\sqrt{1-2GM/rc^2}}. \tag{7}$$

Both a_s and T_u diverge as $r \to 2GM/c^2$, the radius of the event horizon. At $x^r = r$, the time dilation relative to distant objects can be readily derived from the Schwarzschild metric by setting $dr = d\phi = d\theta = 0$ to obtain $d\tau/dt = \sqrt{1-2GM/c^2R}$. Applying this correction factor to T_u, a finite temperature is obtained at the event horizon, T_{hor}. Inversely related to mass, this is the usual Hawking-Unruh temperature of a black hole:

$$T_{hor} = T_u\left(\frac{d\tau}{dt}\right) = \frac{\hbar c^3}{8\pi k_B GM}. \tag{8}$$

Some appreciation of the variation of the matter distribution within a dynamically forming dark hole would be useful. Oppenheimer & Snyder considered the scenario of uniform density [33]. More realistically, one would expect density to decline towards the periphery of a dark hole. The mean density within the event horizon of a black hole decreases quadratically with mass, $\bar{\rho}_\bullet = 3c^6/32\pi G^3 M_\bullet^2$, and with radius, $\bar{\rho}_\bullet = 3c^2/8\pi G R_\bullet^2$. The addition of a mass δM to a Schwarzschild black hole increases its radius by $\delta R = 2G\delta M/c^2$ and hence the density of a thin shell at radius R is $\delta M/4\pi R^2 \delta R = c^2/8\pi G R^2$. This is again inversely quadratic in R, justifying the expectation that the mass density within a dark hole should generally decline with radius and be most concentrated at the core.

When the square root term in (6) is small the acceleration grows large, permitting a simplifying approximation:

$$r \approx \frac{2GM}{c^2} + \frac{c^6}{8GMa_s^2}\,. \tag{9}$$

The coordinate time of a photon falling from a modest distance outside the event horizon to this radius satisfies

$$\Delta t > \frac{2GM}{c^3} \ln\left(\frac{8GMa_s^2}{c^6}\right). \tag{10}$$

In the case of a Planck mass black hole this gives

$$\Delta t \gtrapprox 2 \times 10^{-44} \ln(3 \times 10^{-69} \times a_s^2)\,. \tag{11}$$

If some 10^{18} seconds (30 Gyr) are allowed to elapse after an infalling particle starts its descent, the apparent acceleration of the vacuum at the particle's final location would be approximately $10^{(10^{62})}$ $\times$ the surface acceleration of a neutron star. It is extremely doubtful that such a huge acceleration is physically attainable. Using dimensional analysis, a quantity constructed using the constants c, G and $\hbar$ must be proportional to $c^{7/2}\hbar^{-1/2}G^{-1/2}$ in order to have the same units as acceleration. An estimate for the Planck acceleration, a_p, is therefore given by

$$a_p \sim \sqrt{\frac{c^7}{\hbar G}} \approx 10^{51} g\,. \tag{12}$$

The Planck temperature, T_p, is usually considered to be $T_p = m_p c^2/k_B = \sqrt{\hbar c^5/G k_B^2}$. This tallies with the Unruh temperature for an acceleration of $2\pi\sqrt{c^7/\hbar G}$. However, the Hawking temperature, $\hbar c^3/8\pi k_B G M$, of a Planck mass black hole is normally assumed to be $T_p/8\pi$, yielding a Planck acceleration of $a_p \approx \frac{1}{4}\sqrt{c^7/\hbar G}$. This conforms to the Newtonian acceleration of a Planck mass from a distance matching its Schwarzschild radius. One may quibble over the best definition of a_p but it is apparent that $a_p \ll 10^{10^{62}} g$. Notice also that increments in proper time less than the Planck time, $t_p = \sqrt{\hbar G/c^5}$, are likely to be meaningless and, therefore, time dilations exceeding 10^{60} are essentially infinite within a universe less than 14 Gyr old.

If trans-Planckian accelerations are unattainable in nature then, independently of gravitational time dilation, this consideration alone would prohibit both the formation and growth of black holes. For a black hole of mass $M \gg m_p$, the ratio of the radius at which a stationary particle would experience the Planck acceleration to the radius of the event horizon would be $1 + m_p^2/M^2$. The time dilation at the Planck acceleration radius is given by

$$\frac{d\tau}{dt} = \sqrt{1 - 2GM/rc^2} = \sqrt{1 - \frac{1}{1 + m_p^2/M^2}} \approx m_p/M. \tag{13}$$

The perceived temperature of the Unruh heat bath, T_b, at radius $r > 2GM/c^2$, as reported by observers remote from the Schwarzschild black hole, requires correction for time dilation:

$$\begin{aligned} T_b &= T_u \times \left(\frac{d\tau}{dt}\right) = \left(\frac{\hbar a_s}{2\pi c k_B}\right)\left(\frac{d\tau}{dt}\right) \\ &= \frac{\hbar GM \times \frac{d\tau}{dt}}{2\pi c k_B r^2 \sqrt{1 - 2GM/rc^2}} = \frac{\hbar GM}{2\pi c k_B r^2}\,. \end{aligned} \tag{14}$$

For a given black hole, T_b is a function of radius and declines as $1/r^2$. According to the Stefan-Boltzmann law for an ideal radiator, the radiative power, P_r, is given by the product of the area, $A = 4\pi r^2$, the Stefan-Boltzmann constant, $\sigma = \pi^2 k_B^4/60\hbar^3 c^2$, and the fourth power of the temperature:

$$P_r = A\sigma T_b^4 = 4\pi r^2 \left(\frac{\pi^2 k_B^4}{60\hbar^3 c^2}\right)\left(\frac{\hbar GM}{2\pi c k_B r^2}\right)^4 = \frac{\hbar G^4 M^4}{240\pi c^6 r^6}\,. \tag{15}$$

Evidently, this power is highly localised since $P_r \propto 1/r^6$. Bearing in mind the Shell Theorem, it makes little difference how the mass distribution within a spherically symmetric dark hole declines with radius (whether as $\sim 1/r^2$, $1/r$, $1/\sqrt{r}$ etc) since the radiated power will be almost entirely sustained by quantum activity in the immediate vicinity of its core where the density is maximal and the gravitational acceleration of the vacuum is strongest.

By setting $r = r_s = 2GM/c^2$, the Schwarzschild radius, in (15) one recovers the power obtainable through Hawking evaporation, $P_\bullet(M_\bullet) = \hbar c^6/15360\pi G^2 M_\bullet^2 \approx (M_\bullet/M_\odot)^{-2} \times 10^{-28}$ W. For a 10^{10} $M_\odot$ black hole, this comes to some 10^{-48} W, roughly 98 orders of magnitude short of what aquatic life would need. Even if a dark hole of this mass were composed of a set of concentric spherical shells, each of a thickness comparable to the Planck length ($\sim 10^{-35}$ m) and each radiating the same power, there would still be a shortfall of around 50 orders of magnitude.

The maximum power available from Hawking evaporation occurs when the black hole's mass approaches the Planck scale. The Compton wavelength of a particle of Planck mass is comparable to its Schwarzschild radius, $\hbar/cm_p \approx 2Gm_p/c^2$. Classical physics breaks down at this scale because $\hbar \neq 0$. It is customary in gravitation to work with the reduced Planck mass, $m_p \approx \sqrt{\hbar c/8\pi G}$. A black hole of this mass will be a nebulous, fuzzy object referred to here as a 'reduced Planck particle' (**rpp**). Its radiated power would be roughly $P_{\mathbf{rpp}} \approx 2 \times 10^{49}$ W, though it might be somewhat larger as the Planck power is usually taken to be, $c^5/G \approx 4 \times 10^{52}$ W.

It is generally thought that Planck particles are incapable of evaporating since their high Hawking temperatures preclude the black body radiation of significantly lighter particles. Hence, many imagine them to be quasi-stable remnants of black hole evaporation which is why they are now included amongst the panoply of dark matter candidates [58]. They also represent the most likely outcome of collapse processes that might otherwise result in naked singularities and the violation of cosmic censorship [59]. An **rpp** interred within a dark hole may be invulnerable to evaporation as long as the dark hole continues to exist. Thus, it is conceivable that power might be sustainably radiated at a level approaching $P_{\mathbf{rpp}}$ for spherically symmetric dark holes. Although this is very much an upper limit, it is encouraging that it yields a crude prediction that dark energy decay might terminate just as the last life-cultivating cease to be active.

4.2 Angular momentum injection

The Kerr metric represents a stationary, rotationally symmetric and asymptotically flat rotating black hole. It accommodates angular momentum through an extended singularity located within the plane $z = 0$, lying along the circle $x^2+y^2 = a^2$ in Kerr coordinates. Its radius, $a \equiv J/m$, depends on the angular momentum, J, of the black hole. At extremality, $a \to m$ and $J \to m^2$, the radius of the singularity coincides with that of the two event horizons, $r_\pm = m \pm \sqrt{m^2 - a^2}$. For $a^2 < m^2$ the singularity lies internal to both event horizons.

At high angular momentum, self-gravitating fluids bifurcate from the Maclaurin spheroids, yielding toroidal configurations [60, 61] reminiscent of the prototypical Dyson rings [62]. With analytical solutions confined to relatively simple cases, numerical techniques have now been deployed to better explore the space of axisymmetric configurations [63–67]. The assumption of homogeneity has been relaxed, differential rotation has been allowed and realistic equations of state have been modelled. Qualitatively similar results have been obtained in both Newtonian analyses and general relativity [68–70]. Ergoregions can arise even in the absence of event horizons [71], which may be of some relevance to jet formation in quasars [35].

Since topological censorship does not apply to spacetimes lacking trapped surfaces, the gravitational collapse of a rotating body can result in a toroidal mass distribution, analogous to the circular source of the Kerr geometry although visible to the surrounding universe. Whilst the angular momentum of a Kerr black hole is bounded, $a^2 \le m^2$, there is no such restriction for a dark hole: the major radius of a self-gravitating torus can be arbitrarily larger than its minor radius. The axisymmetric Kerr geometry cannot dissipate rotational kinetic energy via gravitational waves. Moreover, since gravitational waves are incapable of superluminal propagation, any gravitational radiation due to perturbations of the singularity would necessarily remain imprisoned within the event horizon. However, deviations from axisymmetry deep within a dark hole could generate rather strong gravitational waves, and their radiation into space would sap the dark hole's energy and angular momentum.

Suppose a dense ring of radius $r = m$ is quantised by subdivision into a circular arrangement of N particles, each of roughly the reduced Planck mass, such that $N = m/m_p$. Since the ring's circumference is $C_r = 2\pi Gm/c^2$, each reduced Planck particle would then be separated from its two neighbouring particles by a distance

$$\frac{C_r}{N} = \frac{C_r m_p}{m} = \frac{2\pi G}{c^2}\sqrt{\frac{\hbar c}{8\pi G}} = \sqrt{\frac{\pi\hbar G}{2c^3}} \approx \sqrt{\frac{\pi}{2}}\,\ell_p\,. \tag{16}$$

The mean particle separation should decline as J decreases but if separations below the Planck length ℓ_p are unattainable, the idealised circular arrangement may be disrupted, resulting in localised thickening of the ring. It may help to picture the interior of the toroidal dark hole as a dense circular arrangement of knotty density existing at extreme densities approaching the Planck scale. Due to this granularity and its chaotically fluctuating nature, gravitational waves should be produced which dissipate both angular momentum and rotational energy. Ultimately, these losses should result in a topological collapse of the core.

For the purposes of this discussion, we might simply regard the core of a rapidly spinning dark hole as a circular collection of reduced Planck particles. in the case of a toroidal dark hole they would number m/m_p, a huge number. Toroidal dark holes should therefore receive enormously more internal heating via the Unruh effect than purely spheroidal dark holes of the same mass. Thus, the discharge of vacuum energy would be strongly biased towards the most massive and rapidly spinning dark holes of the cosmos — even if such objects are comparatively short-lived in astronomical terms.

Following galactic mergers, the supermassive dark holes introduced by each galaxy are generally expected to coalesce relatively swiftly since they occupy locations of least gravitational potential within their respective host galaxies. Inspiralling supermassive black hole binaries provide prime targets for gravitational wave astronomy [72]. A supergalaxy harbouring an ultramassive remnant dark hole would be the inevitable outcome of hierarchical galaxy mergers. Just as the coalescence of a pair of co-orbiting black holes is able to create a rapidly rotating black hole due to the conversion of orbital angular momentum to rotational angular momentum [73], a pair of coalescing spheroidal dark holes will often combine to produce a more massive dark hole of internally toroidal structure with a dense filamentary core. Violent galactic mergers within galaxy clusters should hence be capable of sporadically inducing episodes of intensively accelerated heating and dark energy discharge until the resulting dark holes lose their toroidal inner structure via the shedding or redistribution of internal angular momentum.

4.3 Discharge timeframes

The details of the physical cooling processes operating within core collapse supernovae are still the subject of ongoing research but it is known that even neutrinos cannot free stream away from an innermost region termed the neutrinosphere. Although the circumstances deep within dark holes will be yet more complex and involve energies well above those probed by any practical particle collider, neutrinos generated there will also be unable to free stream away into space, hindered by the exclusion principle and large interaction cross sections. In order to accurately model these situations, a working theory of quantum gravity will be needed along with an understanding of how matter behaves at near-Planckian temperatures and densities. Also, the influence of strong time dilation must be taken into account, a problem which modern numerical approaches to general relativity still grapple with. Even order of magnitude estimates to the processes involved may currently lie beyond our reach. Nevertheless, it is incumbent upon us to consider the viability of this scenario.

At energies below 1 GeV, electron neutrinos scatter onto neutrons, $\nu_e + n \to e^- + p^+$, with cross section

$$\sigma_n = \frac{(\hbar c\, G_F E_\nu)^2 (g_V^2 + 3g_A^2)}{\pi} \approx 10^{-47} \left(\frac{E_\nu}{1\text{ MeV}}\right)^2 \text{m}^2. \quad (17)$$

The mean free path of a neutrino can be estimated using

$$\lambda_\nu \approx \left(\frac{\rho}{10^{18}\text{kg}\cdot\text{m}^{-3}}\right)^{-1} \left(\frac{E\nu}{10\text{ MeV}}\right)^{-2} \text{ metres}. \quad (18)$$

Within a supernova the neutron number density may be as high as $\rho_n \sim 10^{45}$ m^{-3}. For a typical supernova neutrino energy of 30 MeV, the cross section would be $\sim 10^{-44}$ m^2 and the free path, $\lambda = 1/\rho_n\sigma_n$, may be as short as ten metres. Cooling occurs as neutrinos emerge from a thin shell surrounding a rather constipated, diffusion-limited neutrinosphere. The volumetric luminosity within that spherical escape shell could approach 10^{36} W$\cdot$m^{-3}. Deep within a dark hole, degeneracy is also likely to have a profound impact on the dynamics, for instance blocking neutrino production via the Unruh effect deep within the neutrinosphere.

The limiting mass of a halo of 0.05 eV neutrinos is estimated to be $8 \times 10^{20} M_\odot$ [10], equating to an energy in excess of 10^{68} J. The power due to Unruh radiation from a reduced Planck particle was determined earlier to be $P_{\mathbf{rpp}} \approx 2 \times 10^{49}$ W so it would take some 7×10^{18} seconds to inflate a habitable neutrino halo, roughly 230 Gyr. Encouragingly, this crude and simplistic estimate has the right order of magnitude: dark energy is anticipated to decay before the universe reaches ~ 75 Gyr in age. Pauli blocking and impedance of thermal transport within the time-dilated neutrinosphere will slow the discharge, but episodic input of angular momentum generating ultra-dense rings might easily compensate by hugely accelerating the process, if only briefly.

If, by analogy with Hawking radiation from black holes, the Unruh radiation from deep within supermassive dark holes came entirely at the expense of their dark hole hosts then the lifespan of a supermassive dark hole evaporating at the rate $P_{\mathbf{rpp}}$ would be $\sim Mc^2/P_{\mathbf{rpp}}$. This is just a few hours for a $10^6\ M_\odot$ black hole and no more than a few years for a $10^{10}\ M_\odot$ black hole. The observational evidence for the ongoing existence of supermassive black hole candidates in this mass rnage within galactic nuclei confidently rules out this possibility. It instead points to the dark energy vacuum being the origin of the Unruh radiation which, according to quantum field theory, is mandatory — so much so that it needs no experimental confirmation [49].

Consider now the case of an ultramassive remnant dark hole of a galaxy cluster of a mass $\sim 10^{11}$ M$_\odot$ that ultimately generates a neutrino halo of mass 10^{21} M$_\odot$. The Unruh effect provides the dark hole with intense but localised heating. Over time, thermal energy accumulates and steadily diffuses throughout the dark hole. Once peripheral temperatures are sufficient to permit neutrino escape, a galactic halo can start to form. One can envisage neutrino cooling approximately balancing heating from the Unruh effect until vacuum energy is exhausted. If, instead, one assumes that neutrinos barely escape until dark energy is almost fully depleted, then the mass of the dark hole from the galactic perspective must increase by ten orders of magnitude. From the dark hole's vantage, however, its mass will not have changed since there was no Unruh effect attempting to increase the temperature of its constituent matter.

Ignoring the initial thermal energy of the dark hole, in order that it can eventually form a dense neutrino halo from the thermal energy deposited through the Unruh effect, its particles must attain Lorentz factors, γ, of $\sim 10^{10}$ where γ represents the relativistic mass ratio m/m_0. Temperature is synonymous with kinetic energy and relativistic kinetic energy is proportional to $\gamma m_0 c^2$. The Lorentz factor is closely tied to relativistic temperature according to the relationship, $T = 2(\gamma - 1)m_o c^2/3k_B$. If $\gamma \gg 1$, it follows that $\gamma \approx 3k_B T/2m_o c^2$. Thus, for any given temperature, it is much easier for lighter particles such as neutrinos to attain large Lorentz factors. Consequently, irrespective of temperature, neutrinos should dominate the cooling outflows of dark holes. For a neutrino mass of 0.05 eV, a Lorentz factor of 10^{10} corresponds to a temperature of some 4×10^{12} K, comfortably below the Planck temperature $\sqrt{\hbar c^5/Gk_B^2} \approx 10^{32}$ K. Hence, there is much latitude for dark holes to discharge dark energy by only temporarily adopting internally toroidal matter distributions. Dark holes will of course undergo heating via gravitational contraction during their initial formation, and this energy will contribute to their effective mass, pushing the required Lorentz factors and temperatures for neutrinos to escape somewhat higher. Nevertheless, there seems to be ample scope to accommodate this particular consideration.

5 Discussion

Via the Unruh effect, dark holes may well be capable of tapping into the energy of the vacuum and, in due course, fostering the total discharge of dark energy. A minority of class K stars will continuously host habitable planets until the universe is five times its present age. As the neutrino haloes produced would be capable of efficiently sustaining aquatic life, the model offers a new and biological resolution of the cosmological constant problem. This provides a long-sought alternative to the relatively loose bounds imposed by anthropic arguments [4] which, if neutrinos are well-suited to the task of planetary heating, would be as untenable as the Ptolemaic system. However, this new approach can only explain the value of the present vacuum energy density, not how it might have been tuned to 120 decimal places. That question is akin to asking how the constants of physics in general might have been manipulated to be propitious towards life — something perhaps for string theorists to mull over.

The supermassive dark holes of galaxy clusters are likely to play a prominent role in the decay of dark energy due to their frequent adoption of an internally toroidal structure following violent coalescence events pursuant to galaxy mergers. With circular 'heating elements' operating at temperatures potentially approaching the Planck scale, $T_p \approx 10^{32}K$, these rapidly spinning dark holes would accumulate thermal energy far more rapidly than their counterparts in field galaxies. Such extreme conditions will help combat the intense gravitational time dilation and Pauli-blocking deep within dark holes, in time facilitating a radiative flux from their cores. Eventually, peripheral temperatures should rise sufficiently to provide opportunities for neutrinos to escape completely, albeit after redshifting to low energies as they do so. Dense haloes should thereby form around the remnant galaxies of galaxy clusters — in accordance with the expectation that neutrinos might sustain aquatic life into the distant future [3].

During the initial phase of dark hole heating the neutrino luminosity is likely to remain negligible for billions of years. This is no cause for concern: a lengthy delay would be biologically advantageous, usefully prohibiting the widespread colonisation of the universe until ethically mature civilisations are on hand to undertake such daunting responsibilities. Very loosely, the situation might be likened to the conversion of liquid water within a lake into steam by the vigorous agitation of a single water molecule over a prolonged period. It is not inconceivable that galactic nuclei within galaxy clusters may be currently generating gentle outflows of neutrinos. It may even be that changes in the dynamics of galaxies orbiting within clusters may be perceptible over time.

A promising line of enquiry has been outlined concerning dark energy without any radical departure from the scientific method. Whilst alternative proposals capable of predicting the timing, outcome and mechanism of dark energy decay have not been forthcoming, this scenario dovetails remarkably well with a recently advanced cosmological framework, reinforcing its potential to unravel the composition of dark matter, anticipate the fate of the accelerating cosmic expansion and decipher the mystery of extraterrestrial silence. This same framework offers much scope for understanding why the constants of nature assume the values they do without recourse either to mathematical arguments or anthropic reasoning [74]. Physical fine-tuning influences all aspects of the universe — from the simplest microscopic scales to the most complex macroscopic scales, including multicellular lifeforms, symbiotic ecosystems and the imponderable workings of the human mind. If the fine-tuning of physics cannot be apprehended through mathematical physics alone then alternatives can and should be explored, even if that entails a holistic synthesis of all scientific knowledge. Support has emerged here for the contention within superstring theory that there may exist a vast underlying landscape of physical configurations. A biological resolution of the cosmological coincidence problem, the naïvely surprising similarity between Ω_Λ and Ω_M is also apparent.

Although this dark energy decay scenario must be regarded as tentative for now, it exhibits many compelling features and the remaining uncertainties mainly pertain to timescales. Vacuum discharge by dark holes fulfils the original cosmological expectation that dark energy might decay predominantly to neutrinos of sufficiently low energy as to permit their retention by host galaxies. Whereas black holes have an unhealthy appetite for neutrinos, dark holes are incapable of recapturing the neutrinos they discharge on account of the Unruh effect: those particles belong to a different reality. Dark energy decay should strongly track supermassive, rapidly-rotating dark holes and hence galaxy clusters where collisions between galaxies and supermassive dark holes are commonplace events. There is no reason at present to suppose that significant errors exist in the basic timing constraints based on the measured vacuum energy density, calculated neutrino halo implosion threshold and the necessity of habitable neutrino haloes before the last life-cultivating stars expire. However, much work remains before decay timescales can be confidently calculated. In the meantime, as long as neutrinos continue to bear the hallmarks of cosmic design the efficient sustainment of aquatic life remains a very real possibility and the timely decay of dark energy just before life-cultivating stars die out is a likely outcome of cosmic evolution.

In the field of black hole thermodynamics, the entropy of a black hole is given by $S = kA/4\ell_P^2$. With the entropy of a Sun-like star being $\sim 10^{35}$ $\mathrm{J \cdot K^{-1}}$ [75] a single black hole of some 10^4 solar masses would possess as much entropy as all the stars of all the galaxies within the visible universe. Therefore, the existence of even one supermassive black hole in nature would be catastrophic for a universe attempting to judiciously manage entropy-increasing processes for the benefit of advanced lifeforms [3]. Dark holes may not chime with the scientific orthodoxy of recent decades but they accord with the original 'frozen star' interpretation of stellar collapse and dispense with the theoretical shortcomings of black holes. It is not that the stationary black hole metrics are mathematically invalid, merely that they are unobtainable via physically admissible processes: global constraints on the evolution of spacetime manifolds have been generally overlooked [31]. Although one expects any useful theory of gravity to possess within it a solution resembling that obtained by Karl Schwarzschild in 1916, i.e. a bizarre object describing a point mass surrounded by a region from which light cannot escape, the architect of general relativity did not rush to dismiss it. His considered opinion was offered after decades of careful reflection. That his views on black holes now carry so little weight within academic science is disturbing.

On a far more positive note, it comes as some surprise that particles which are able to propagate unperturbed through light years of lead may be of any potential benefit to life. That sterile neutrinos, their yet more inert counterparts, might provide further assistance also defies intuition. However, if this universe is exquisitely configured to host life, all natural phenomena would ideally have something positive to contribute. It would nevertheless be astonishing if the objects lurking at the heart of each galaxy, which many currently believe to be destructive black holes, can serve as portals to a crucial biological energy resource capable of efficiently sustaining aquatic life far into the distant future. We learnt from special relativity that mass and energy are interrelated, a breakthrough necessary to explain how stars could remain active for billions of years, sufficient time for the Sun to support the evolution of complex organisms. Ultimately, the take-home message from general relativity, if only apparent at present to extraterrestrial civilisations, may be that gravity is benign and free of pathologies precisely because time dilation provides a robust mechanism preventing the formation and growth of trapped surfaces — essential for the discharge of dark energy so that aquatic lifeforms might thrive long after the expiry of the stars, harnessing the full promise of $E = mc^2$. If Einstein were still with us he might regard the current fascination with black holes as a pathological science, further affirmation of his 1920 remark to Marcel Grossmann that the world is a "strange madhouse" [76]. It very much seems there is now a contagious misunderstanding of his theoretical legacy. It may be preventing humanity from collectively converging towards a comprehension of the universe capable of providing much-needed guidance for future policy-making.

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