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## **An inflationary explanation to the initial entropy problem**

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**Abstract:** The early universe was close to thermal equilibrium, as seen in the observed isotropy of the cosmic microwave background (CMB) with temperature deviations of  $\Delta T/T \sim 10^{-5}$ . However, the entropy of the universe has been increasing, consistent with the second law of thermodynamics. These two facts suggest that this state of thermal equilibrium is one of low entropy, at odds with the current understanding of the high entropic content of equilibrium states. Davies has suggested that low initial gravitational entropy may be the explanation of low entropy in the early universe. Penrose's reliance on the initial value of the Weyl curvature tensor does not explain low initial gravitational entropy. Rather, an inflationary model explains how an arbitrary universe could be driven to the 'specialness' of low initial gravitational entropy. The rapid expansion of false vacuum energy, and its decay during reheating, deposited matter and radiation into the universe homogeneously. We suggest that this is a state of low gravitational entropy. This puts the early universe in a low entropy state. Thus in addition to the flatness, horizon, and monopole problems, inflation naturally solves the initial low entropy problem if the low initial gravitational entropy dominates the maximal entropy in other degrees of freedom.

**Keywords:** entropy of the universe; inflation; gravity

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## 1. Introduction

Inflationary scenarios [1,2] have solved the flatness, horizon, and monopole problems, and provide explanations of the origin of structure. Davies has suggested it gives rise to the observed thermodynamic arrow of time [3]. We propose inflationary explanations to the following problems:

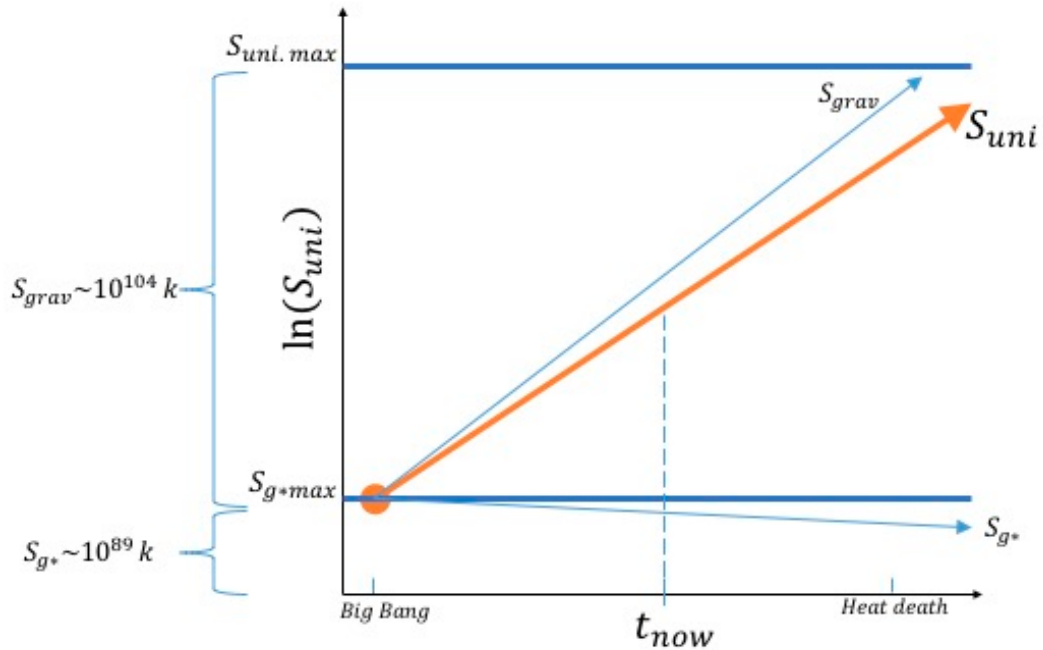
- (1) If the second law entails that the universe began at low entropy and increased its entropy over time, how could it have started off at a state that is fundamentally less probable than a high-entropy one? That is, why did the universe not begin as thermodynamically homogeneous radiation and matter, if this was statistically likely?
- (2) The cosmic microwave background (CMB) photons are close to isotropic, with temperature deviations of  $\frac{\Delta T}{T} \sim 10^{-5}$  [4]. States at thermal equilibrium are at maximum entropy. These observations, coupled with the (necessarily) low-entropy beginnings of the universe, entail that the early universe at thermal equilibrium, was in fact at low entropy. What's missing in our picture of entropy that leads to the conclusion that homogenous and isotropic matter and radiation at thermal equilibrium is somehow far enough from equilibrium to produce stars, life and other entropy-generating structures?

Davies has suggested that during inflation, the universe was 'wound up' to a low-entropy state, with the proceeding evolution a subsequent winding down through free energy dissipation and gravitational clumping. He and Penrose make use of gravitational entropy as critical answers to (2). We improve Davies' model in clarifying the openness of the universe 'system' and implications for  $S_{uni}$  which Davies claims to 'decrease' during inflation.

## 2. Results and Discussion

### 2.1 Gravitational entropy

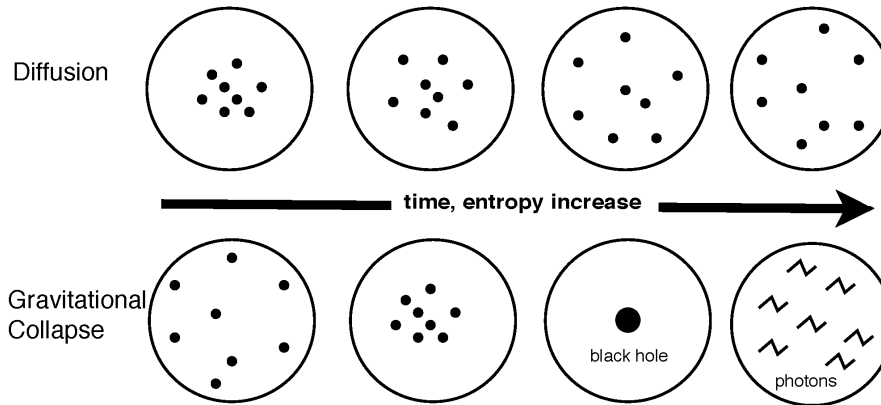
Entropy increases whenever a system gravitationally collapses. This can pose a conceptual hurdle – how can an amount of matter condense into a smaller physical space and yet be associated with a larger number of microstates? When a system gravitationally contracts, matter flung outwards from the accretion disk cannot be ignored. Hence, gravitational clumping represents both a shrinking of the system and an expansion. This analysis includes suns, black holes, and planetary systems. The highest gravitational entropies – as well as the largest contributions to the entropy of the universe, will be found in the supermassive black holes that are theorized to exist at the centre of many galaxies [5]. We postulate that a smooth distribution of matter corresponds to minimal gravitational entropy, that gravitationally collapsed objects such as black holes correspond to high entropy [6], and that a freely expanding photon gas (e.g. from black hole evaporation) corresponds to maximal entropy [7]. The gravitational entropy ( $S_{grav}$ ) of this progression from a smooth distribution of matter, to black holes and then to the photons from black hole evaporation cannot yet be expressed and quantified in an equation of the form  $S_{grav}(t) = f(P(k, t))$ , where  $P(k, t)$  is the time-dependent power in large-scale structure (e.g. [8]). We suggest that gravitational entropy dominates the entropy of other degrees of freedom. This would entail the entropic evolution described in Fig. 1. See [9] for an opposing view on the relationship between gravitational collapse and entropy.



**Figure 1.** (a) The entropy in relativistic degrees of freedom  $g_*$  begins near maximum at reheating and decreases as thermal and mechanical gradients form following gravitational collapse. (b) The total entropy  $S_{uni} = S_{g_*} + S_{grav}$ . We postulate the dominance of gravitational entropy over other degrees of freedom by  $\sim 10^{15}$  [10]. Hence a low initial  $S_{grav}$  and high initial  $S_{g_*}$  represents a low entropy beginning for  $S_{uni}$  which is far from its maximum value initially.

### 2.1.1 Penrose's Weyl Curvature Hypothesis and anthropic reasoning

This surprisingly underdeveloped idea of the entropy associated with gravitational collapse overturns our conception of the high-entropic content of equilibrium states. From these insights, the homogeneity of matter in the early universe suggested by CMB isotropy indicates the potential to generate entropy by gravitational collapse. This explains (2). There have been many proposals to explain (1). Penrose's Weyl Curvature Hypothesis represents a specific version that might broadly be considered an anthropic approach [11,12]. Penrose asserts that the off-diagonal elements of the Weyl conformal tensor are constrained to zero or near zero at initial singularities where  $t \rightarrow 0$ . This would constrain the initial gravitational entropy  $S_{grav}$  of the universe to be low. However Penrose agrees his Weyl Curvature Hypothesis remains unjustified. More generally, anthropic considerations that suggest the observable universe is a low-entropy fluctuation in a larger high-entropy Universe fail to justify why the increasing particle horizon reveals greater numbers of entropy-generating structures. If we do exist in a low-entropy fluctuation, we should expect these fluctuation to be close to the minimum required for conscious observers (fig. 3). If what is required for conscious observers is a structure the size of the Milky Way, then the rest of the universe should be at high entropy.



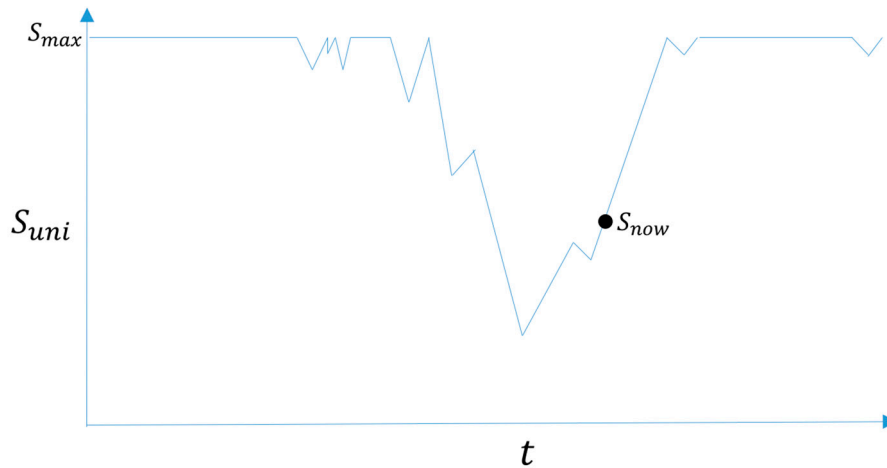
**Figure 2.** In a kinetically-dominated system like a perfume bottle in a room (top), low entropy is when the perfume is in the bottle. High entropy is when the perfume is homogeneously distributed throughout the room. In a gravitationally-dominated system (bottom) a homogeneous distribution of matter corresponds to low gravitational entropy, while collapse into a black hole corresponds to higher entropy, and the evaporation of the black hole into relativistic particles that will not clump, corresponds to maximal entropy.

However, as the particle horizon increases, observations of the newly visible parts of the universe indicate cosmic homogeneity and a greater numbers of low-entropy structures than what is minimally necessary to explain our existence. The cosmic low entropy fluctuation is much more widespread than it needs to be [13]. From these considerations a fluctuation this large cannot be explained through anthropic reasoning since its rarity exceeds what can be reasonably expected from a stochastic process that generates conscious individuals.

We must look for another explanation of low initial entropy in (1). If gravitational entropy is the missing piece of our entropic puzzle in (2), then constraints associated with the distribution of matter and radiation at the time of reheating could provide appropriate boundary conditions for the initially low gravitational entropy of the universe.

## 2.2 Entropy of the observable universe

The entropy literature makes a distinction between ‘system’ and ‘environment’ when determining the rate at which the entropy of the *system* is increasing  $\frac{dS_{sys}}{dt}$  and the rate at which *total* entropy is increasing  $\sigma$ . If the rate at which entropy is being produced by the system is the same as that which is being exported into the environment, then steady state of entropy is assured. The Earth is such a system, with an import and production of entropy due to solar radiation, and an export of entropy via radiation at  $\sim 300$  K. The entropy of a sufficiently large region of the universe is simpler. Due to the large-scale homogeneity of the universe, any representative ‘sample volume’ (e.g. the size of the observable universe) can be used, without needing to refer to import and export into an environment, since these rates are identical for scales greater than  $\sim 100$  million light years. Hence, for our sample volume, entropy import and export undo each other, and all that is left to consider is its entropy  $S_{uni}$  and entropy produced  $\frac{dS_{uni}}{dt}$ . While this might amount to the universe being considered ‘closed’ thermodynamically, Davies suggests that the



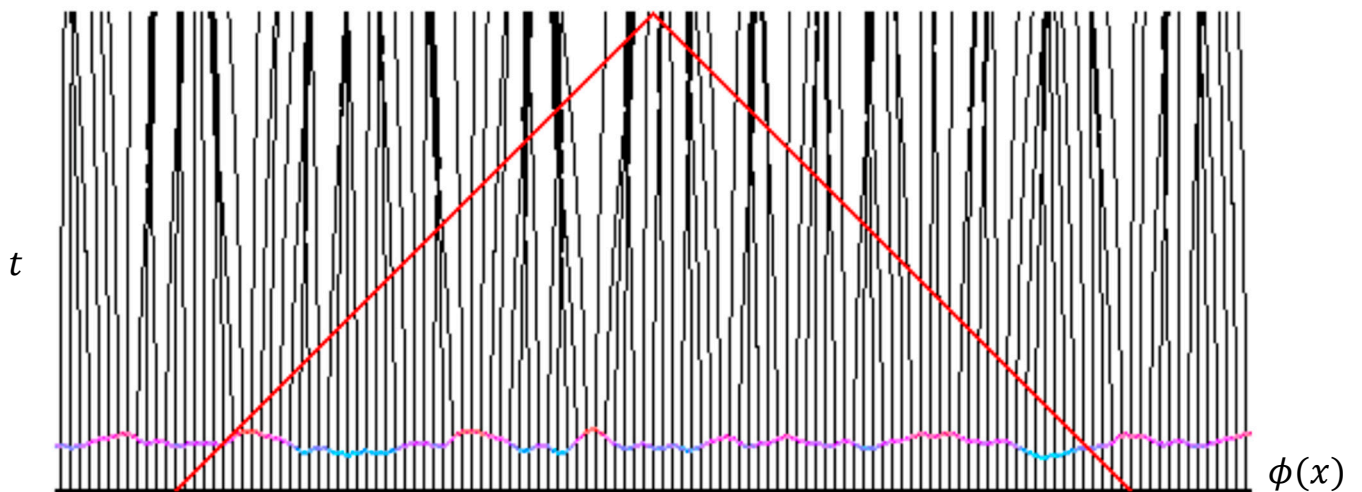
**Figure 3.** The entropic history of the universe if  $S_{uni}$  at present was a low entropy fluctuation amount many. We would then be in the process of closing down this low entropy fluctuation via gravitational collapse and the dissipation of free energy.

universe is in fact open to ‘external’ gravitational fields, whereas the second law applies only to closed systems. In an inflationary scenario, the ‘external’ field for Davies is the repulsive gravitational force of the inflaton field that drives inflation. For some physicists, this may amount to a Creator-like, external presence that induces the thermodynamic arrow of time through inflation. We argue that the false vacuum potential is not ‘external’ in any way, but permeates our inflationary bubble. Hence, it is internal to the universe and does not render the universe an open system.  $S_{uni}$  is not allowed to jump out of equilibrium as Davies suggests, though a time-dependent  $S_{max}$  could increase and open an entropic ‘gap’ that is being subsequently wound down. This conceptual use of a time-dependent  $S_{max}$  is utilised when Davies postulates a ‘lag’ between an exponentially expanding universe during inflation and a thermalising hydrogen material whose previously equilibrated state couldn’t keep up with the rising  $S_{max}$ . Hence Davies argues that an entropy gap is formed that gravitational collapse is currently trying to close. The use of a time-dependent  $S_{max}$  is misleading. A gap due to varying  $S_{max}$  must be defined such that there is extractable free energy from the gap. For instance, decoupling between neutrinos and photons reveals no extractable free energy. Though both exist homogeneously, they do not interact and cannot be used thermally to increase entropy and ‘equilibrate’ further. Hence, though there is a temperature difference between the decoupled fluid,  $S_{max}$  is maintained. More generally, the postulate of a time-dependent  $S_{max}$  relies on the counterfactual that if decoupled fluids *could* equilibrate, then  $S_{max}$  could be reached. Such a reliance on counterfactuals flies in the face of scientific discourse. As such, we suggest the use of  $S_{max}$  as the maximum entropy the universe will ever reach, at heat death.

### 2.3 Physics of inflation

Inflation describes a period of exponential spatial expansion of the Universe  $\sim 10^{-43}$ - $10^{-36}$  seconds after the Big Bang. It originally served to solve the monopole problem encountered by grand unified theories (GUT’s), but also solved several problems in cosmology – including the flatness and horizon problems. This exponential expansion is driven by the inflaton field – a metastable false vacuum which sits at a higher energy density than its minimum; a ‘true’ vacuum. Inflation is driven by the false vacuum decay to a lower energy state by a smooth ‘roll’ down its potential hill. Inflationary growth is similarly ended

once this decay ceases and the true vacuum is reached. The false vacuum decay is the source of all matter and energy in the universe. Once this roll down the potential slope is completed, the inflaton field oscillates around its minimum value. There are several options as to what might happen next. The first suggestion was that the inflaton field is characterised by a number of elementary particles that decay independently as described by perturbative decay theory [14]. This is incorporated into the inflaton potential  $V(\phi)$ . False vacuum, similar to the energy density in a cosmological constant has a ‘negative pressure’ which gives rise to a repulsive gravitational field, meaning that by definition the inflaton energy does not and cannot gravitationally clump. Secondly, the inflaton field is homogeneous everywhere. These give rise to the contention that appropriate determination of the inflaton field  $\phi$  and the process of reheating, such that the field is homogeneous, could result in a decay into matter and radiation that is ‘smooth’, without inhomogeneities or isotropies. That is, dumping the entirety of the false vacuum entropy thermally rather than gravitationally allows for a natural constraint on  $S_{uni}$  such that its low initial gravitational entropy, and hence low initial entropy, is entirely expected.  $S_{uni}$  does not need to decrease as Davies suggests, and the second law holds. The vacuum energy density is subject to quantum fluctuations, and these give rise to gravitational structures and voids seen in Fig. 4.



**Figure 4.** A space-time diagram that details structural collapse due to density fluctuations  $\delta\rho$  in the inflaton potential. It reveals how gravitational entropy begins low initially (subject to quantum fluctuations), and how these fluctuations lead to structures and voids (merging and diverging worldlines respectively [15]).

### 3. Conclusions

Low initial gravitational entropy is a promising solution to the universe’s initial entropy problem. Davies’ inflationary model features some incoherencies that can be clarified to a more plausible model where the universe exists as a closed system and the second law holds for  $S_{uni}$ . Alone, low initial gravitational entropy only shifts the blame of statistically improbable low entropy, to gravity. If constraints associated with the physics of inflation provide natural limits to the distribution of matter in the early universe, the initial entropy problem is solved without shifting blame to another parameter (e.g. the Weyl Curvature).

## Conflicts of Interest

The authors declare no conflict of interest.

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