On the Gravitization of Quantum Mechanics 2: Conformal Cyclic Cosmology

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Abstract The 2nd Law of thermodynamics was driven by the Big Bang being extraordinary special, with hugely suppressed gravitational degrees of freedom. This cannot have been simply the result of a conventional quantum gravity. Conformal cyclic cosmology proposes a different picture, of a classical evolution from an aeon preceding our own. The ultimate Hawking evaporation of black holes is key to the 2nd Law and requires information loss, violating unitarity in a strongly gravitational context.

There are aspects of the gravitization of quantum theory that are on a vastly different scale from those described in the companion article (*Quantum State Reduction*), namely cosmology. Figure 1 depicts the entire history of the universe, according to current conventional cosmology. It is a space-time picture—as most of my pictures will be here—with the passage of time taken in the upward vertical direction. Horizontal sections through the picture would represent spatial dimensions, but to get everything into the picture visually, I have suppressed two of the spatial dimensions (as is a usual practice). In order not to prejudice the issue of whether the universe is spatially closed or not (unknown at present), I have been a bit vague about what is going on at the back of the picture, as this issue will play no role in what I wish to say.

It will be noticed that there is an early phase of rapid expansion, which slowed down after a while (during a period of some 10^{10} years!), but subsequently this expansion rate started to increase again, to become the period of exponential expansion that we see beginning in the upper part of the picture. Such an ultimate exponential

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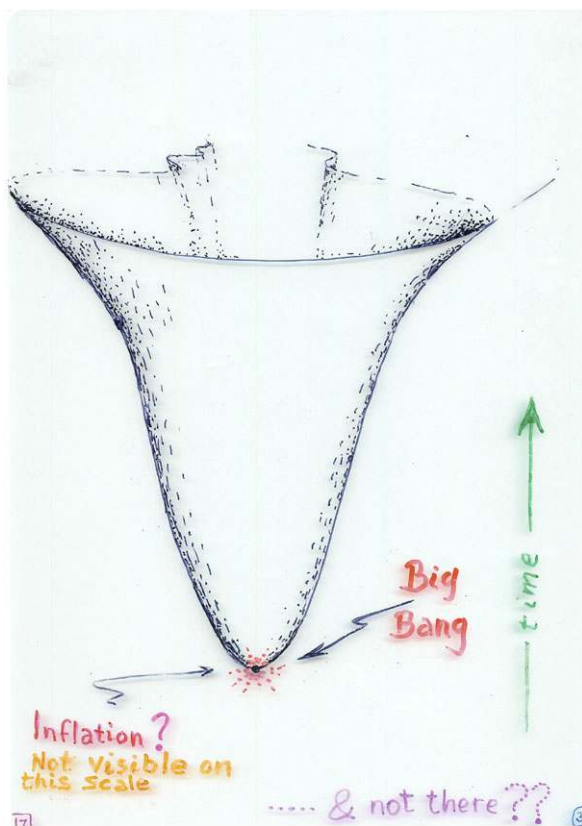
expansion is actually a clear prediction of many solutions of the Einstein equations with positive cosmological constant Λ, the term that Einstein introduced (admittedly largely from a wrong reason) in 1917, although the tiny non-zero value that Λ is found actually to have (initially by the 1998 measurements of distant supernovae made by Perlmutter, Schmidt and their associates) was not anticipated. The observations remain perfectly consistent with this Λ-interpretation; yet many cosmologists try to look for other interpretations, using the (in my view somewhat inappropriate) terminology "dark energy" for the source of the repulsion.

Our current temporal location is somewhere around 3/4 of the way up the picture of Fig. 1. At the bottom we find the *Big Bang*, shown as an initial point, representing what is taken to be the temporal origin of the universe. This is a singularity in its space-time structure, whose physical description is normally argued to require a detailed theory of quantum gravity.

There is one part of modern cosmology that I have not represented in this picture, which is *cosmic inflation*. This is proposed to have occurred within an extremely early period, between (say) 10^{-35} s and 10^{-32} s after the Big Bang. There are *two* reasons that I have not represented this in Fig. 1, the first being that on the scale that the picture is drawn, you would not be able to see the inflationary phase at all, as it would all be happening well within the black spot at the bottom of the picture. The

Fig. 2 A *very* powerful magnifying glass!

second reason, which I shall be coming to shortly, is that I do not actually believe that inflation ever occurred!

Setting aside my severe doubts, at the moment, let us try to see what inflation would look like in this picture. To see it at all, we would need a *very* powerful magnifying glass (Fig. 2). What we would see (Fig. 3) would be an exponential expansion, very much like the exponential expansion that is beginning to take place, on a hugely larger scale, at the current epoch of the history of the universe (compare Fig. 1). There are various reasons that most cosmologists appear to believe that inflation necessarily *did* take place—some good reasons, some not so good.

The main *good* reason has to do with a detailed and somewhat remarkable feature of the generation of the tiny spatial variations in the cosmic microwave background (CMB), namely that they were (very closely) *scale invariant* and this could be explained by the basically self-similar exponential expansion of an early inflationary phase. We recall that the CMB is a ubiquitous electromagnetic radiation that comes to us from all directions in space, having an almost precisely thermal spectrum, of temperature $\sim$2.7 K which is (when corrected from effects arising from the Earth's motion through it) *uniform* over the entire sky to about one part in 10^5. The *not*-so-good reasons for believing in inflation are that it is supposed to explain this uniformity in various respects, it being argued that a random irregular initial configuration in the

Big Bang could be "stretched flat" to produce such uniformity as a result of such an early exponential expansion.

Why is this early enormous inflationary expansion *not* a good reason to explain this uniformity? I do not want to go into the details of this here, but see Penrose [8] for the central argument. The basic problem has to do with the issue of what to expect for a "randomly chosen" initial state. Such a state cannot be expected to be smoothed out in the way intended, simply as a result of dynamical processes that are based on time-symmetric field equations, as are those of the "inflaton field" underlying the dynamics of inflation. This is basically a consequence of the *second law of thermodynamics* (abbreviated 2nd Law), in a gravitational context, as we shall be seeing.

As is well known, this law tells us, roughly speaking, that the randomness of the universe—i.e. *entropy*—increases with time. Equivalently, as we go back in time, this entropy *decreases*, so that the Big Bang must have been an exceedingly special state. In what way was it special? Well, the exceedingly closely *thermal* nature of the CMB tells us that the matter and radiation must have been in a very *high* entropy state in the early universe (at last scattering, at least). This seems like a paradox, but the clue to the particular way in which the entropy *was* actually initially exceedingly low lies in that other most evident feature of the CMB, namely its very closely *uniform* nature over the whole sky, indicating a very spatially uniform early matter distribution.
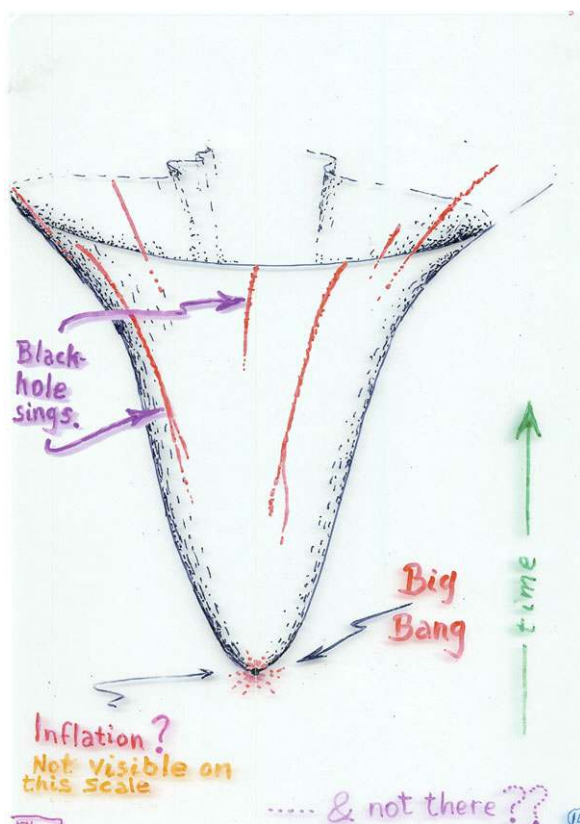
Without this spatial uniformity we would not have had a low entropy initial state, and there would have been no 2nd Law! The spatially uniform initial state must have been an initial condition. It could not have come about via ordinary physical processes acting in accordance with the 2nd Law, because this would have represented an enormous *reduction* in the entropy. i.e. a severe violation of the second Law.

Why does this spatial uniformity represent low entropy? Again this might at first seem to be a paradox, as a gas in a box in its highest entropy state—i.e. thermal equilibrium—would be expected to spread uniformly throughout the box as the entropy *increases*. But when we bring *gravity* in we get a vastly different picture because the universally attractive nature of gravity provides us with a strong tendency for matter to *clump*, leading to the high entropy states being highly *non*-uniform. Thus, we see that with regard to the *gravitational* degrees of freedom, the entropy was indeed exceedingly low at the state, since entropy is gained in gravitating systems by the increase in clumpiness as gravitation takes over—leading to galaxies and stars, finally resulting in stupendous entropy increases as *black holes* are formed. It is in the remarkable *absence* of such clumpiness in the initial state (in particular, the absence of "white holes", the time-reverses of black holes) that the extreme lowness of the initial entropy resides.

The singularities in black (or white) holes involve enormously *high* entropy, which may be thought of as the extreme thermalization of gravitational degrees of freedom at black-hole singularities. These degrees of freedom were what were patently *not* activated in the early universe-and, simply by the 2nd Law their exceedingly high-entropy input could not have been removed by inflation. In Fig. 4 I have improved upon Fig. 1 by including the singularities in the black holes. We can now see how the 2nd Law operates, overall, in our universe, where the initial singularity (the Big Bang) was an exceptionally *low*-entropy singularity, to start things off, whereas the black-hole singularities were states of extraordinarily *high* entropy. Moreover, in each case it is in the *gravitational* degrees of freedom that are driving the whole entropy story. The over-riding role of gravitation, in this story can be ascertained from the Bekenstein-Hawking black-hole entropy formula, which tells us how enormous the entropy in black holes must be. Accordingly, this formula can also be used to estimate the extraordinary specialness of the Big-Bang state, as opposed to the extremely high-entropy potential possibilities in black (or white) holes. We conclude (taking into consideration only the region of space-time lying within our own past light cone-i.e. within our particle horizon) that the probability of such a state coming about purely by chance is: 1 part in something like $10^{10^{124}}$ (where the upper exponent "124" includes a dark-matter contribution to the material content of the universe). This figure makes clear how enormously far from random the initial state must have been.

This is essentially the situation that we are presented with in the universe that we perceive, basically from observation. It makes clear that there is a profound mystery to be addressed, and it is one that is essentially untouched by bringing in an inflationary phase to the very early universe. The mystery lies in the fact that the gravitational degrees of freedom (and apparently *only* these degrees of freedom) are manifestly time-asymmetrically represented in these singular temporal boundaries to space-time. This mystery is left essentially untouched by considerations of inflation, since inflation is supposed to be driven by a postulated field—the *inflaton* field—whose dy-

namical equations are time symmetrical. (For more discussion of this point, see Penrose [9], §28.4–§28.7.) Of course, Einstein's equations are also time-symmetrical, so we can see no resolution in classical general relativity. The singularities, on the other hand are normally perceived to be things that must be addressed by *quantum* gravity, and for many years I had taken the view that this profound time-asymmetry in space-time singularity structure must be a result of the changes to the framework of quantum mechanics that would be engendered by the putative scheme that I am here calling "gravitization of quantum mechanics" (see bottom of Fig. 4 in the companion paper *Quantum State Reduction*).

However, my current views on this issue have very significantly shifted rather recently [10–12] and I shall give here a very brief account of my current viewpoint, which I refer to as "conformal cyclic cosmology" (CCC). The first step is to re-examine the geometry of Fig. 1 from a *conformal* perspective, by adopting two mathematical tricks (Fig. 5). These tricks are basically ones that have been familiar to me since the 1960s (see Penrose [7]), and they can always be applied in the case of the homogeneous isotropic Friedmann-Lemaître-Robertson-Walker (FLRW) models. For such models which expand out to infinity in the remote future, a conformal rescaling of the metric, can be applied to "squash down" the infinite future, so that it becomes a *finite future boundary* ℐ to the space-time (regarded as a conformal
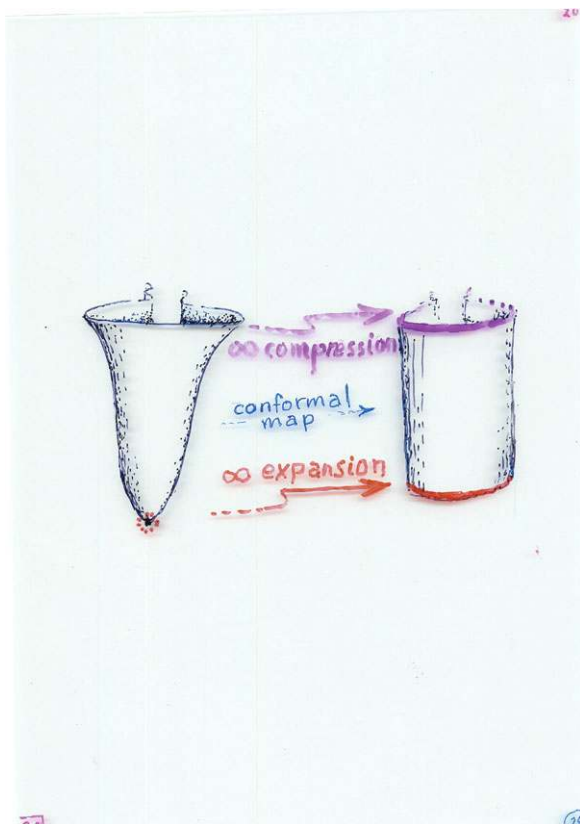
manifold) where $\Im$ is a smooth (conformal) 3-surface, which is *null* (lightlike) if the cosmological constant Λ vanishes, and is *spacelike* if $\Lambda > 0$. This is a useful trick for studying the asymptotic behavior of massless fields, which can be then examined as finite geometric or algebraic quantities at $\Im$. The other (opposite) trick is to "expand out" the big bang of these cosmological models by another conformal rescaling of the metric, so that it becomes a (normally spacelike) *finite past boundary $\mathcal{B}$ to $\mathcal{M}$*. Both $\mathcal{B}$ and $\Im$ are useful for understanding cosmological horizons, where the spacelike nature of $\mathcal{B}$ tells us there are particle horizons and where a spacelike $\Im$ leads to *event* horizons. (Note: I use the uncapitalized "big bang" for these initiating explosions, in cosmology generally, and the capitalized "Big Bang" for that particular occurrence that, according to current cosmology, started our own universe some 1.4×10^{10} years ago.)

Figure 5 illustrates these procedures, where both mathematical tricks are being adopted together, so we have two conformal boundaries to a space-time $\mathcal{M}$, with $\Im$ representing the (infinite) "end-point" $\mathcal{M}$'s exponentially expanded future infinity (spacelike, since $\Lambda > 0$), and with $\mathcal{B}$ representing $\mathcal{M}$'s big-bang origin (also space-like). There is, however, an important distinction between the logical status of these two boundaries. There are general theorems (see Friedrich [1]) that tell us that under very general circumstances, when $\Lambda > 0$, we can expect a smooth spacelike $\Im$ to ex-

**Fig. 6** *Aeons* of conformal cyclic cosmology (CCC)
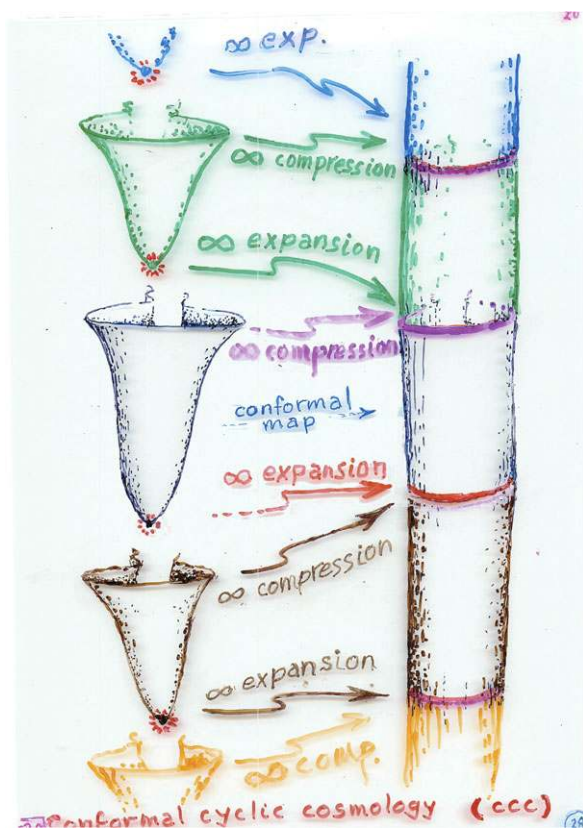
ist as future conformal boundary. On the other hand, the existence of a conformally smooth past boundary $\mathcal{B}$ to $\mathcal{M}$ represents a hugely strong condition on the nature of $\mathcal{M}$'s big bang. Indeed, Tod [13] has proposed that the very existence of such a smooth past boundary $\mathcal{B}$ is a plausible proposal for the mathematical restriction on the Big Bang of our own universe, expressing the necessary huge restriction on the initial gravitational degrees of freedom that gave us our 2nd Law in the way that it appears to have occurred.

My CCC proposal adopts Tod's very elegant point of view, but goes further in suggesting that there was actually a conformal *continuation* of our own Big Bang $\mathcal{B}$ to a previous universe phase *prior to* $\mathcal{B}$, whose conformal infinity joined smoothly to $\mathcal{B}$. Moreover, CCC also maintains that "beyond" our $\Im$, there will be a smooth conformal continuation to the big bang of another universe phase. This is to continue indefinitely in both temporal directions. Thus, CCC proposes that what current cosmology refers to as "the entire history of the universe" (but without any early inflationary phase) is just one *aeon* of a succession of such aeons, that continues indefinitely in both temporal directions (Fig. 6).

In this scheme, although there is never any "inflation", as such, in any of the aeons, the exponential expansion in the *remote future* of each aeon plays a role that would, in many respects, be very similar to that of an inflationary phase occurring in the
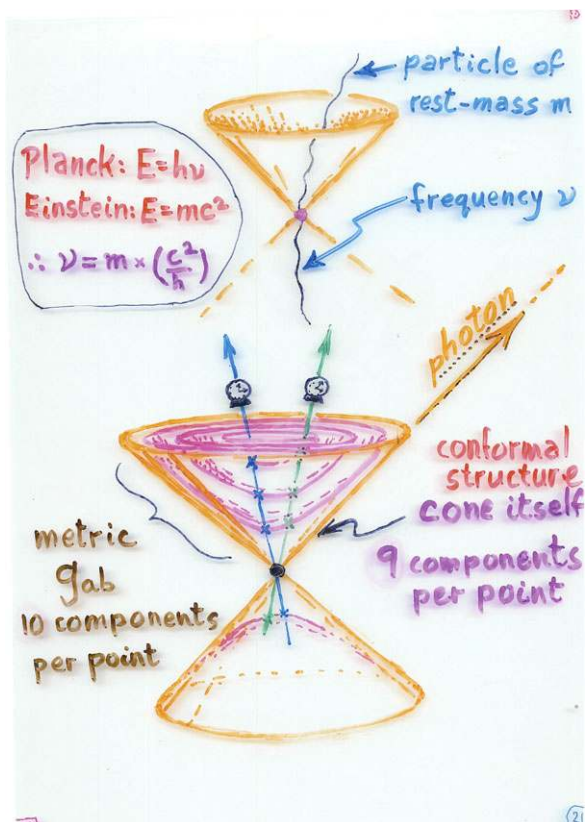
Fig. 7 *Light cones* (null cones) in special and general relativity
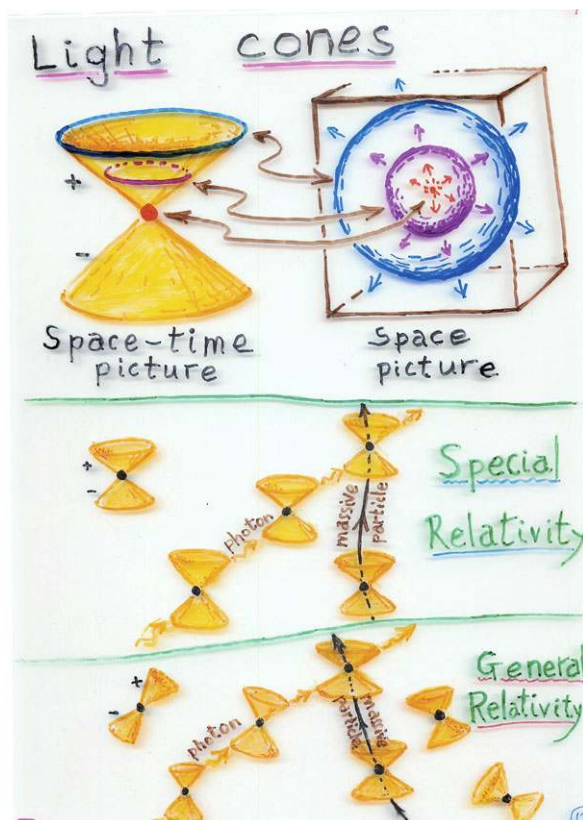
succeeding aeon. As I shall be explaining shortly, it is possible for information in each aeon to pass through into the succeeding one, and will influence the spatial variations in the CMB of that aeon. Thus, we see that in CCC there is indeed a kind of "inflation" entering into the structure of each aeon, but rather than occurring very soon after a big bang, it occurs before the big bang of that aeon and, according to CCC, it was the remote-future exponential expansion in the previous aeon that leads to effects-such as a scale-invariant early input-that would be, in many respects, similar to those of inflation. This idea of placing the inflationary phase *before* our Big Bang is close to one put forward previously by Gasperini and Veneziano [2].

In order to get a better picture of the role of these conformal rescalings, let us first address the important role of *light cones* (or, more correctly, *null* cones, when we are really considering structures in the tangent spaces) at the various points of space-time; see Fig. 7. As is familiar in relativity theory, these represent the space-time directions of world lines of (idealized classical) photons. The causality structure of space-time is defined by them, in that massive particles must have their world-lines constrained to be directed *within* the cones and massless particles, *along* the cones. The metric structure of space-time is largely determined by these cones, but not entirely. They actually determine space-time's *conformal* structure—in other words the metric tensor g_{ab} up to proportionality—this being given by 9 independent compo-

nents per point, which are the independent *ratios* of the 10 metric components at each point.

The full metric, upon which Einstein's general relativity depends, requires all 10 components, and for this we need something to determine the *scale* of the metric. Although it is fairly usual to think of metrics in terms of *distances*, it is more appropriate not to specify distance measures directly, but to use *time* measures, as this is closer to the underlying physics. Indeed, Nature provides us with an excellent notion of primitive *clock* through the combination of the two most important basic equations of 20th century physics, Planck's $E = h\nu$ and Einstein's $E = mc^2$, which along a stable particle's world line gives us a precisely determined frequency $\nu = m \times (c^2/h)$, where m is the rest-mass of the particle (top of Fig. 8). The "ticks" of various identical clocks through a space-time point define, at that point, the degree of *crowding* of the hyperboloidal surfaces (bottom of Fig. 8) there which, in addition to the light-cone structure, defines the full metric of the space-time. In Fig. 9, I have added the crowdings of these (infinitesimal) surfaces to the light-cone structures that we had previously in Fig. 7. This gives a representation of the full metric that is the structure needed for full general relativity.

We observe from Fig. 8 that massless particles such as photons play no role in accessing the scale of the metric, since their world-lines never encounter even the first
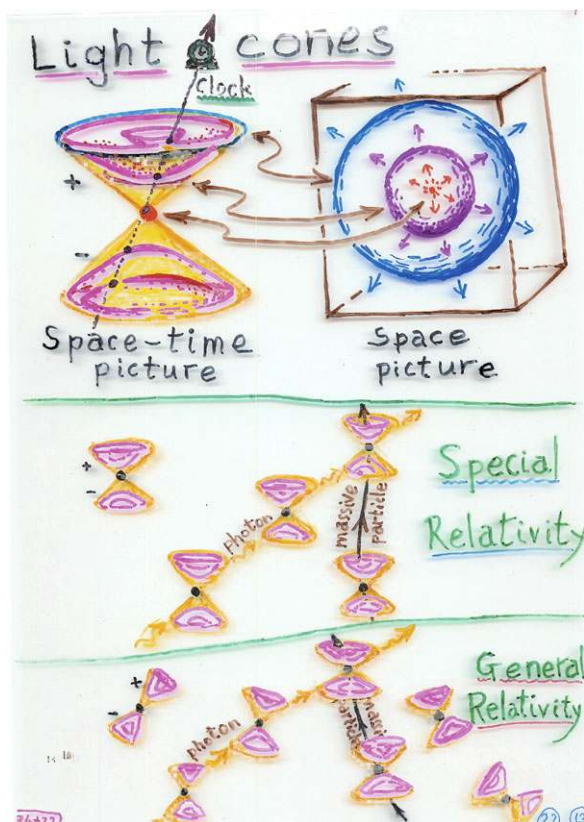
of the hyperboloidal surfaces. Accordingly, massless particles alone cannot be used to
determine the space-time metric, and appear to need only the conformal (light-cone)
structure for their dynamics. This is made a little more precise, in the case of pho-
tons, by the fact that the Maxwell equations are completely invariant under conformal
rescalings, where not only are the free Maxwell equations invariant, but so also is the
way that the Maxwell field is influenced by its sources. The same actually applies to
the (classical) Yang-Mills equations (of strong or weak interactions), provided that
we are not concerned with the masses of the various particles involved.

It is, indeed, with the physics that directly involves *mass* in one way or another
that we find breaking of conformal invariance. We see from Fig. 8, that it is particles
with *rest-mass* that seem to be needed in order to build a clock, and without rest-mass
we appear to have a basically conformally invariant physics. The other obvious place
where the full metric g_{ab} is needed, rather than just the conformal structure, is in
the *gravitational* theory of Einstein's general relativity. Here the crucial role of mass
lies in the fact that mass is the source of the gravitational field (analogous to electric
charge being the source of the electric field).

Now, near the "Big Bang", perhaps at a time a good deal earlier than the "Higgs
time" when the temperature of the universe was so extreme that particles' rest-masses
became irrelevant, their energies far exceeding the mass-energy of the Higgs particle,

then the relevant physics was that of *massless* particles. Accordingly, one might well expect that the conformal invariance of rest-mass-free physics would be appropriate to describe what was going on near the Big Bang. With gravitational degrees of freedom hugely suppressed (which is what we appear to find in the neighborhood of the Big Bang) a conformal picture does appear to be an appropriate one and, if so, we can extend this description right back to the initial (conformal) 3-surface $\mathcal{B}$—and perhaps to even behind it, into the remote future of the previous aeon.

This brings us to the question of what the very remote future of an aeon might actually be like. The first issue to address is the presence of numerous black holes in that aeon, since they all have singularities within them that act as future space-time boundaries for observers unfortunate enough to fall in through their horizons. These boundaries, however, are conformally a complete mess, and there is no way that they could be considered to be conformally extended into the future in a smooth way—for the clear reason that (in time-reversed form) such extendibility was taken as a criterion for the *low*-gravitational-entropy nature of the Big Bang, in accordance with Tod's proposal. However, since we are looking into the very far future indeed, we need to take into account that when the expansion of the aeon cools it down to a temperature lower, even, than the Hawking temperatures of the largest (and therefore coldest) supermassive black holes, the black holes will *then* be the "hottest things around" and will gradually lose their energy—and therefore mass—by Hawking radiation. This mass-loss continues, the hole getting hotter as it gets smaller, until the hole itself disappears with a final "pop" (which, though a substantial explosion in ordinary terms, is pretty insignificant on the astrophysical/cosmological scale). See Fig. 10, which also illustrates the "trapping" character of the hole's horizon, according to the light-cone geometry of Fig. 7.

In view of the sort of sizes of some supermassive black holes, already observed (around 2×10^{10} solar masses) we must expect that time scales of the order of 10^{100} (a googol) years, or more, may well be needed for the final disappearance of all black holes. Almost the entire mass-energy of these black holes will be released in the form of exceedingly low-energy photons, and we may anticipate that by far the major contribution to the contents of the universe-at least in terms of particle numbers-will be in photons. Photons are massless, and subject to conformally invariant laws so that, as was the case for the contents of the very early universe, conformal physics will dominate, and can accordingly be extended to the future conformal boundary $\mathfrak{I}$.

For the philosophical standpoint of CCC to hold more strictly, however, we do need to address the issue of the ultimate (conformally non-invariant) presence of particles of *finite* rest-mass, most seriously "rogue" electrons, that escape from galaxies (and are thus not swallowed by their supermassive black holes), to roam freely throughout the vast almost empty reaches of our universe-aeon's very remote future. Electrons (and their anti-particles, the positrons) are the most serious problem for CCC's massless philosophy because one might imagine that protons and other more massive charged particles could ultimately decay to less massive ones, and that conceivably there is a massless neutrino among the three versions known (still an observational possibility). Assuming charge conservation to be an absolute law (and if it were not, we would have a difficulty with the photon itself acquiring mass), then we would be ultimately stuck with the least massive charged particles, namely electrons

Fig. 10 Hawking-evaporating black hole
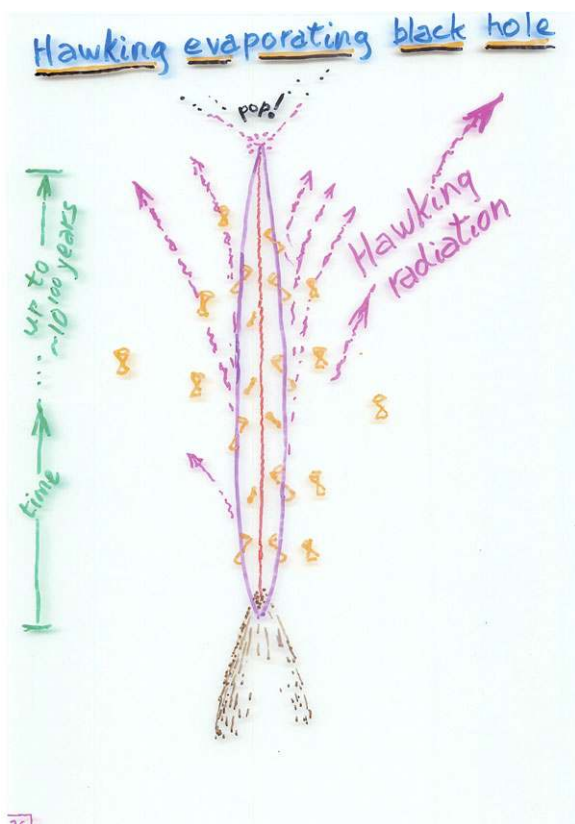
and positrons. Present-day observations (particularly in relation to pair annihilation) assures us that no massless charged particles exist now, so the remaining possibility for eliminating all rest-mass in the very remote future of each aeon, appears to be the ultimate evaporation of rest-mass.

That rest-mass might ultimately evaporate away, over periods that might well be far longer than even the $\sim 10^{100}$ years needed for the disappearance of all black holes (by perhaps some kind of eventual inverse Higgs process) is perhaps not unreasonable, in the presence of a positive Λ, in view of the fact that the Poincaré group—for which rest-mass is a Casimir operator—would have to be replaced by the de Sitter group, when $\Lambda > 0$, for which rest-mass is *not* a Casimir operator and so not necessarily absolutely conserved for a stable particle.

Finally, I address two important questions raised by CCC. The first is the issue of the 2nd Law, in the context of a cyclic universe. In fact CCC can accommodate this Law provided that one adopts what I have always regarded as the reasonable stance with regard to "black-hole information loss", namely that Hawking, in his powerful original analysis [4] was correct in arguing that there is indeed a loss of information—or, as I would prefer to put it, a *loss of degrees of freedom*—in the black-hole evaporation process. These degrees of freedom would eventually be "swallowed" by the singularity, which represents a future boundary to the space-time internal to the black

Fig. 11 Black-hole evaporation: entropy zero re-set

hole. It seems that many (most?) physicists—and including Hawking himself in his later reversal of his earlier position [5]—would take the view that the loss of unitarity (**U**) that would be entailed by this "information loss" is unacceptable, so they try to argue that this information is somehow regained in subtle correlations outside the hole. However, my own position (see Fig. 11) has long been that **U** cannot in any case be a firm law in the context of quantum gravity or, rather, that the gravitization of quantum mechanics must inevitably involve **U**-violation in some form (see Fig. 4 of companion paper *Quantum State Reduction*).

The loss of degrees of freedom results in a "collapsing down" of the phase space (see Fig. 12), into a space of lower dimension, and the evolution curve gets correspondingly projected into this lower-dimensional space. This is not the way that phase space is normally treated in physics, where standard procedure would be to take the phase space as a *given thing*, and the description of the dynamics of the system in question would be given entirely in terms of a particular evolution curve, representing the history of the system, lying within that *fixed* phase space. But when the phase space itself gets smaller, as a result of the particular evolution that is taking place, we have a new situation, not part of standard physics, and this is what is expressed in Fig. 12.
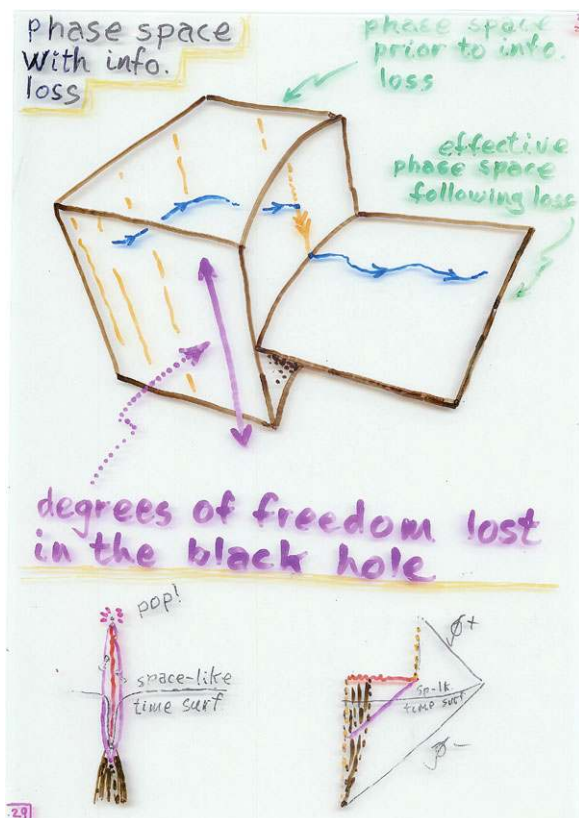
This strange situation is softened somewhat when we realize that the loss of degrees of freedom is not something "abrupt", because there is a (very long) period of ambiguity, during the lifetime of the evaporating black hole, concerning the issue of "when" the degrees of freedom are considered to have disappeared. This comes about because there is much choice about how one might wish to draw the spacelike surface on which the relevant degrees of freedom are to be determined; see bottom two figures in Fig. 12 (both of which represent the same history of an evaporating black hole, the second being a conformal diagram). We may choose to use a spacelike surface that works its way down, when inside the horizon to before the singularity is formed (represented by the broken line), and if we stick to such spacelike surfaces until the hole is gone, then the disappearance is indeed abrupt, but it might be felt that a more natural description would be to use horizontal lines in the left-hand figure, in which case the disappearance would be considered to be extremely gradual, spread out over the entire history of the evaporating hole. Since what happens within the horizon has no effect on the external physics, we see that these ambiguities are really completely irrelevant to the external evolution of the system. Accordingly, in the projection represented in the top part of Fig. 12, there is a great deal of choice about when it is considered that the projection has taken place.

Although this is actually a reduction in phase-space *dimension*, The issue with regard to entropy is the *volume* reduction involved. Each degree of freedom accounts for two dimensions of phase space, these two dimensions, taken together, being measured in units of *action*, the dimension of Planck's constant. In quantum mechanics, we have a natural measure of phase-space volumes, where we can take $\hbar = 1$, so phase-space volumes of different dimension can be compared. Boltzmann's definition of entropy S, namely $S = k \log V$, where V is the volume of the coarse-graining region of the phase space volume relevant to the system under consideration (and k is Boltzmann's constant) simply has a constant subtracted from it when the degrees of freedom disappear. This results in a *renormalization* of the definition of entropy, that takes place when a black hole evaporates away.

It is this re-setting of the zero of entropy, which continues until all the Black holes are gone (over a period of some 10^{100} years) that allows the entropy to be reduced to the small value needed, so that when the aeon's $\Im$ is reached, the entropy value is back down to the low value needed to start off the succeeding aeon (where we recall the enormous entropy values in black holes, easily dominating the entropy values from all other physical processes). We must not think of the renormalization of entropy that occurs when a black hole disappears as a *violation* of the 2nd Law. The entire Hawking evaporation process is fully consistent with the 2nd Law; indeed, it can be considered to be *driven* by it, but the loss of phase-space volume from the destruction of degrees of freedom by the black-hole singularities allows the 2nd law to be *transcended*, rather than violated. Following the crossover into the next aeon, there is the potential for new degrees of freedom to be activated, in the gravitational degrees of freedom that become available, and things can start all over again. It is a subtle point, but it appears to be this that allows the 2nd Law to operate throughout the continuing succession of aeons, in the picture that CCC presents (see Penrose [12]).

The second important question concerning CCC that I wish to raise here is that of *observational* consequences of this proposal. The most clear-cut signal that I have been able to think of would be the result of collisions of the supermassive black holes that we would expect to inhabit galactic centres, in the aeon prior to ours. Each such collision would result in a stupendous release of energy in the form of gravitational waves, which would be effectively instantaneous on the scale of things under consideration. These gravitational waves would continue out to the $\Im$ of that aeon and, according to the equations of CCC would continue as an impulse of energy conveyed to the initial form of *dark matter* that, according to CCC's equations, is necessarily created at the birth of the succeeding aeon (namely ours), and would make its mark on the slight temperature variations that we see in the CMB. In fact, the expectations of CCC are that the major contribution to the temperature variations in the CMB on a small scale would indeed be due to causes of this nature. Each such black-hole encounter would provide a circular "ripple" in the CMB around which the temperature variance would be rather low, and the average temperature would be raised or lowered slightly (raised for particularly distant sources and lowered for relatively near ones). There appears to be some definite evidence that such signals are actually present in our CMB, as revealed in the WMAP data; see Gurzadyan and Penrose [3] and Meissner et al. [6]). It is to be hoped that when the somewhat more precise data from the Planck satellite becomes publically available, it will be possible to ascertain whether or not these findings are confirmed at this more refined level.

Fig. 13 Questioning
(**a**) Λ-entropy
(**b**) Λ-temperature
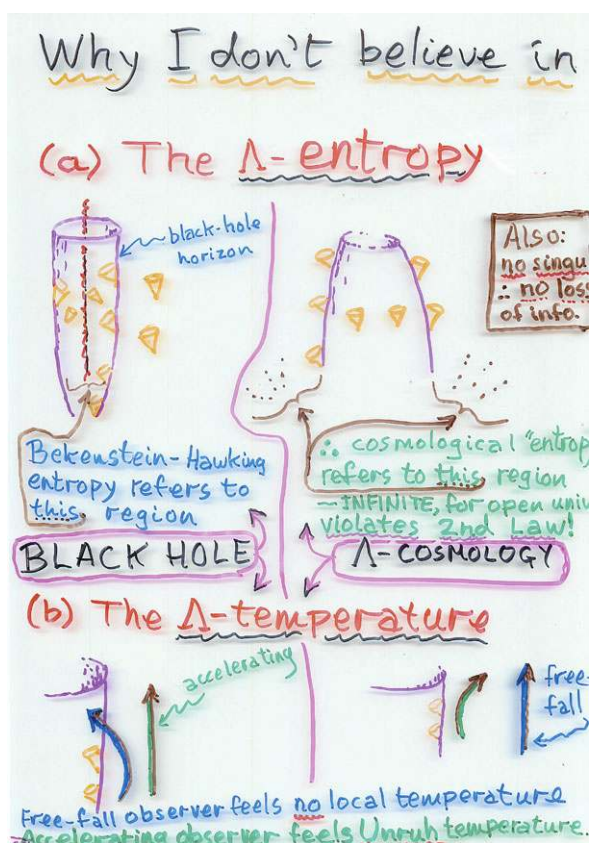
We see that CCC provides a completely different picture of the physics that is appropriate at the Big Bang from that which has been suggested by current investigations into quantum gravity. According to CCC, the relevant physics can be studied by means of entirely *classical* equations, these being derived from a study of conformal invariance and, from a natural-looking assumption concerning the relation between the pre- and post-crossover conformal factors, as we pass from aeon to aeon (see Penrose [12], Appendix B and Gurzadyan and Penrose [3], Appendix A). Remarkably, in view of the viewpoint that has held for many decades that the Big Bang represents the ideal laboratory for examining the effects of quantum gravity, the picture presented by CCC is utterly different, where the classical dynamics of massless fields holds sway, instead.

In Fig. 13, I raise a final further question thrown up by the presence of a positive Λ in a quantum context. It appears to be a common belief (see Gibbons and Perry 1978, Gibbons and Hawking 1993) that the cosmological horizons that arise in cosmologies with $\Lambda > 0$ are directly analogous to those of a black hole and, accordingly, there ought to be a cosmological temperature and entropy analogous to the Bekenstein-Hawking entropy and the Hawking temperature of a black hole. I have difficulties with accepting the reality of either of these cosmological notions. In the case of the cosmological entropy there is the problem that if the analogy is taken completely

seriously, we must carefully examine the space-time regions to which this entropy value is to be assigned. In Fig. 13(a), we see that the relevant region with regard to the black hole is that lying within the horizon, which is what lies to the "future" of the horizon, namely that region towards which the future cones at the horizon point. For the cosmological horizon, this would refer to the *outside* of the horizon of an observer's world-line. In the case of a spatially infinite universe, this is almost the entire universe, so that the "entropy density" for this entire region would be zero, despite the fact that the cosmological entropy is often considered to be particularly huge—and dominating the final entropy for the universe as a whole. For a closed universe, this entropy density would depend on the spatial extent of the universe, which seems to make little physical sense.

In the case of the "cosmological temperature" (Fig. 13(b)), whether or not such an (albeit absurdly tiny) temperature is to be considered as "real" depends on what vacuum is chosen and, in turn, this depends on which space-time coordinates are used. Perhaps a reasonable approach might be to consider the temperature to be the result of an "Unruh effect" due to the acceleration in the world line of an observer. This would presumably be zero if that world line is that of one of the "fundamental observers" of conventional cosmology, since these lines are geodesics, and do not experience any acceleration.

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