# The Logic of Cosmology Revisited

Chris Smeenk
University of Western Ontario, Philosophy

## 1 Introduction

In the last few decades, cosmology has become a central research area in fundamental physics. One reason for this shift in status is practical: although a variety of experimental results support the Standard Model of particle physics, the accelerators needed to test extensions of the Standard Model are beyond our technological and economic reach. In the big bang model, extrapolating backwards in time leads to higher temperatures and energies, and as a consequence the early universe serves as the "poor man's accelerator." Physicists have increasingly relied on observational cosmology to provide an indirect source of evidence regarding high energy physics. A second reason for the shift in status is the vast increase of observational and theoretical sophistication within cosmology. In the early 60s, cosmology was characterized as a field with only two and a half facts, with some justification;[1] today, by contrast, the big bang model is supported by a number of different lines of evidence, and cosmology is a field rich with new observations and further possibilities for observational work. The role of cosmology in contemporary physics is not limited to tightening the observational straightjacket on theorists' imaginations; instead, a number of proposals for new fundamental physics have been inspired by problems in cosmology. This opens up the prospect of discovering laws of physics in cosmology. But can observational cosmology replace experimental practice as the basis for discovering and justifying new laws, or is the method of physics inappropriate for the study of a unique object, the universe?

This shift in the status of cosmology lends new urgency to philosophical questions regarding the nature of our knowledge in this field. Cosmology is typically defined as the study of the large-scale structure of the universe and its evolution over time. But is the universe as a whole an appropriate object for scientific inquiry? Kant argued that attempts at scientific cosmology inevitably lead to antinomies because there is not an actual object corresponding to the idea of the "universe." A deracinated Kantian skepticism regarding cosmology still thrives in some parts of the intellectual landscape, although it is much less prevalent than it was over 50 years ago when Milton Munitz first turned to philosophy of cosmology. Munitz (1951) clarified how Kant's arguments in the Antinomies miss their mark when it comes to the theoretical understanding of the universe as a physical system provided by relativistic cosmology. Even among those willing to grant the legitimacy of scientific cosmology, the unusual nature of the object of study is usually taken to imply that cosmology must have a distinctive method or logic. For example, it is often argued that the uniqueness of the universe rules out a clean division between "laws" and "initial conditions" in cosmology, and, as a consequence, that cosmology is a merely descriptive, historical science rather than nomothetic science. Even this more modest position is apparently in conflict with contemporary research, in that cosmologists clearly do aim to discover and vindicate new fundamental laws in cosmology. The conflict encourages a more careful consideration of the arguments in favor of the modest position, as well as contemporary scientific practice.

Below I will take up this conflict somewhat indirectly, by considering the account of scientific method in cosmology offered by Munitz. The central issue in philosophy of cosmology is teasing out the methodological implications of the uniqueness of the universe, and below I will offer my own positive account based on a critical analysis of Munitz (1962)'s careful treatment of the problem. This problem is intertwined with two other themes in Munitz's work that will be particularly important below.

First, Munitz wrote at a time when two rivals to relativistic cosmology, Milne's kinematical relativity and the steady state theory of Bondi, Gold, and Hoyle, were defended primarily on the grounds of their methodological superiority. These pronouncements regarding methodology drew philosophers into the fray, and Munitz's early work (Munitz 1952, 1954) exposed the unacceptable rationalism of both approaches. Such explicit philosophical discussions have almost entirely disappeared from contemporary cosmology; instead there is a sense that the mid-century debates have been set aside as cosmology became a properly empirical science. However, important methodological assumptions are implicit in the approach contemporary cosmologists take to their field. (Although I will not make the case here, there is a troubling streak of rationalism in contemporary cosmology, similar in some ways to the rationalism Munitz identified, in the treatment of fine tuning problems in early universe cosmology.)

A second major theme in Munitz's work is the exploration of the observational and conceptual limits of cosmology (see, in particular, Munitz 1986). His discussion combines an appreciation of technical aspects of relativistic cosmology with a pragmatic account of the structure of scientific theories. Below I will focus on the limitations imposed by horizons on any attempt to determine global properties of cosmological models, and on the limitations in our current understanding of the initial singularity in big bang models due to the need to incorporate quantum effects. I do not have space here to discuss Munitz's pragmatism in any detail. As a result, I also will set aside a third major theme, which Munitz almost certainly regarded as the most important: namely, his case for "Boundless Existence" based on his pragmatic account of intelligibility and the existence of conceptual horizons in cosmological models.

Before turning to these philosophical issues, I will first provide a brief orientation to relevant technical aspects of relativistic cosmology. Then in §3 I take up two senses in which there are important horizons in contemporary cosmology, before turning to the main task of the paper in §4: reconsidering Munitz's discussion of the uniqueness of the universe and its implications for the logic of cosmology.

## 2 Global Properties in Cosmology

Einstein (1917) is often described as the first step in physical cosmology, and as a paper that launched an entirely new scientific field. Although such claims are guilty of neglecting the long history of cosmological thought prior to 1917, Einstein does deserve credit for introducing a strikingly new conception of cosmology – namely, as the study of exact solutions of the field equations of general relativity, which give global descriptions of spacetime as a whole.[2] In this section I will briefly review some aspects of this conception of cosmology, laying the groundwork for the discussion of its methodological consequences below.

Einstein's introduction of his cosmological model – his "unexpected lunge for totality," in Torretti (2000)'s memorable phrase – was not motivated by pressing scientific questions regarding the global structure of the universe. Einstein's paper appeared during a period that has been called the "second astronomical revolution" due to the variety of new ideas and new instruments introduced in the period 1900-30; crucial tasks on the astronomers' agenda included determining the architecture of the Milky Way and the nature of the so-called "spiral nebulae," later recognized as galaxies. Theorists had also proposed mechanisms for the formation of the solar system and the Milky Way. But these lines of research focused on the origin and structure of objects within the universe, not on global properties of the universe. Few scientists considered applying physical theories to the universe as a whole, although there were intermittent debates regarding paradoxes that arose when this was attempted using Newtonian mechanics. Einstein (1917) highlighted these paradoxes to cast his new gravitational theory in better light,[3] but they did not spur Einstein's interest in cosmology. Einstein turned to cosmology because he was convinced that one of the principles that had guided his search for a new gravitational theory was at stake.

Mach's Principle was one of the key insights that had helped Einstein to discover general relativity. Although Einstein himself gave different, often conflicting, formulations of the principle, roughly speaking it holds that inertial properties of bodies should be due to relations with other bodies, not with a background "absolute space." Given its central role in his thinking, Einstein was shocked to discover that Mach's Principle may not hold in his theory (as formulated in Einstein 1916). One threat to the principle arose from the need to stipulate boundary conditions in order to solve the field equations; from Einstein's point of view, this was implicitly allowing a vestige of "absolute space" to creep back into general relativity, despite his best efforts to build a theory without such background structures. Einstein's "lunge for totality" was part of an ingenious solution to this problem: he avoided stipulations regarding boundary conditions by doing away with boundaries! He proposed a cosmological model with compact spatial sections, each of which represents the state of the universe at a given instant; like the Earth's surface, each spatial section is finite yet unbounded. This ingenious model is not a solution of the field equations in Einstein's original formulation; it was, however, a solution to a new set of field equations including the infamous "cosmological constant" term (Einstein 1917).

The first cosmological model was born of entirely theoretical concerns, but relativistic cosmology developed into an active field due to suggestive connections between the properties of cosmological models and observational discoveries. In particular, Hubble's observations of a linear relationship between redshift and distance was in qualitative agreement with a red-shift effect in a second cosmological model introduced by Willem De Sitter. Such results encouraged a number of scientists to adopt Einstein's conception of cosmology as the study of exact solutions to his field equations of general relativity. These solutions describe the universe in its entirety, as a single "object" at least in the mathematical sense (in modern notation, as a model $< M, g_{ab}, T_{ab} >$).[4] In the early days of relativistic cosmology, scientists speculated about the possibility of fixing global features of the cosmological model based on astronomical observations; Einstein, for example, estimated the "radius of the universe" in his model based on observations of the local density of matter. But these speculations proved to be quite naïve. Einstein's field equations (hereafter, EFE) state a *local* relationship between matter-energy density and spacetime curvature that is compatible with a bewildering variety of *global* structures. As we will see below, cosmologists can have little hope of observationally establishing global properties without the help of strong assumptions that limit the space of models under consideration. But first it will be useful to discuss one significant example of a "global" property of cosmological models.

Several of the cosmological models discovered in the 1920s appeared to harbor a "singularity." The Friedman-Lemaître-Robertson-Walker (FLRW) models describe a uniform, evolving universe; the scale factor $R(t)$ representing the spatial distance between freely falling objects varies with cosmic time $t$, with its precise behavior fixed by EFE for a given type of matter. Extrapolating these evolving models backwards in time leads to the "singularity" as $t \to 0$, in the sense that the various quantities, such as the spacetime curvature, blow up in the limit. Making this rough idea more precise and turning it into a workable definition of "spacetime singularity" turned out to be a surprisingly intricate conceptual and technical issue that has yet to be fully resolved.[5] Here I will argue briefly that "singularities" are best thought of as truly "global properties" of the spacetime.

The case of spacetime singularities is different than other cases of "singularities" in physics, such as shock waves in fluid dynamics. In the latter case, one can locate the shock wave, the surface where pressure and other quantities "blow-up" or are ill-defined, with respect to the background spacetime; but in the case of general relativity, the "blow-up" of the gravitational field cannot be directly used to "locate" the singular points — there is no other fixed background against which to locate them. Furthermore, it is typically assumed that the metric $g_{ab}$ defined and differentiable everywhere in spacetime; *ex hypothesi* there are no singular points in spacetime. As a result, there is no straightforward way to describe a singularity as a property of a particular region of spacetime.

There are also difficulties facing more sophisticated attempts to give a local analysis of spacetime singularities. One might start with the intuition that a singularity corresponds to a "missing point" or "tear" in spacetime, whose presence is indicated by an incomplete geodesic – a curve that "runs out" abruptly. This idea can be made precise for a manifold $M$ equipped with a Riemannian metric, a non-degenerate, symmetric tensor $h_{ab}$ that is positive definite. A compact manifold includes all the points that it possibly can, in the sense that the manifold cannot be embedded as a proper subset of another manifold. For a space with a Reimannian metric there is a clear link between geodesic incompleteness and "missing points" provided by the notion of a Cauchy sequence. A Cauchy sequence is a set of points $p_i$ such that for any given positive $\epsilon$, $\exists I(\forall j, k > I : d(p_j, p_k) < \epsilon)$, where $d$ is the distance function obtained from $h_{ab}$. If every Cauchy sequence converges to some $p \in M$, the space is Cauchy complete, and also compact; moreover, for the Riemannian case a theorem guarantees that a Cauchy *incomplete* space has incomplete geodesics. Missing points can be naturally added to the space via a "boundary construction," provided by an isometric imbedding of the Cauchy incomplete space into a complete space. The boundary points in the complete space correspond to equivalence classes of non-convergent Cauchy sequences in the original space that (roughly speaking) approach the boundary point. This nice correspondence between incomplete geodesics and "missing points" breaks down for a pseudo-Reimannian metric (as in general relativity), since zero-length null curves confound any attempt to define a positive distance function (and Cauchy sequences). Misner (1963)'s "counter-example to almost everything" nicely illustrates that the connection between geodesic completeness and compactness doesn't carry over to relativistic spacetimes: the general-purpose counter-example is a compact solution that nonetheless contains incomplete geodesics. One might still try to introduce boundary points by analogy with the Riemannian case, as equivalence classes of incomplete geodesics.

There are a number of different ways of constructing boundary points in general relativity. However, they all have various counterintuitive consequences for some of the cases to which they have been applied (see Clarke 1993; Curiel 1999). Geroch et al. (1982) conclude a discussion of these counterintuitive consequences with the following remark: "Perhaps the localization of singular behavior will go the way of 'simultaneity' and 'gravitational force'." Following Geroch et al. (1982)'s advice, we should construe "singular" as an adjective characterizing the global structure of a spacetime rather than as a property of a particular region. On this view, various large-scale properties of the spacetime merit the label "singular" applied to the spacetime as a whole, even though there is no way to identify "missing points" or local regions which display pathological behavior.

Physicists have differentiated various global properties of spacetime related to its causal structure, which can be roughly characterized as specifying the extent to which various causal features characteristic of Minkowksi spacetime hold globally (see Geroch and Horowitz 1979, for a clear introduction). Singular spacetimes are then classified by which of these properties fail to hold. For example, a globally hyperbolic spacetime possesses a Cauchy surface, a null or spacelike surface $\Sigma$ intersected exactly once by every inextendible timelike curve. In a spacetime with a Cauchy surface, EFE admit a well-posed initial value formulation: specifying appropriate initial data on a Cauchy surface $\Sigma$ determine a unique solution to the field equations (up to diffeomorphism). This is properly understood as a global property of the entire spacetime; although submanifolds of a given spacetime may be compatible or incompatible with global hyperbolicity, it cannot be directly treated as a property of local regions which is then "added up" to deliver a global property. Specifying the causal structure of spacetimes precisely is one of the crucial components of the singularity theorems. These theorems establish that the singularities in the FLRW models are not an artifact of the symmetry of the models, as Einstein and others had assumed; instead, the singularities are a generic feature of spacetimes satisfying a number of plausible, physically well-motivated assumptions. But the list of assumptions of the theorems also include specifications of the global causal structure of the spacetime; the discussion of the singularity theorems provoked both the effort to define singularities more precisely and the careful classification of global causal structure.

In sum, Einstein introduced the very idea of a cosmological model to save Mach's principle, a principle that he would abandon himself within a few years. But in the new conception of cosmology he introduced, there is a precise way of treating the "universe as a whole," at least in terms of the mathematical features of cosmological models. In addition, various important features of cosmological models are best understood as global properties of the models rather than as properties attributed to local regions. We have arrived at properties of the "totality" directly, by giving a mathematical description of the universe treated as a solution to the field equations; as Munitz (1951) argued, Kant's arguments in the Antinomies do not apply since Kant assumed that totality is approached via a series of successive syntheses. But there is a lingering question about our epistemic access to such global properties; even granting that they can be well defined mathematically, we can imagine a Kantian asking what impact these global properties have on our experience. In the next section, we will see that the Kantian has good reason to be worried; although it is perfectly cogent to define and characterize the global properties of cosmological models, they generally cannot be established via observations.

## 3 Horizons

One of the leitmotifs of Munitz (1986) is the importance of horizons in cosmology — including observational horizons and "horizons of intelligibility" due to the inherent limitations of the concepts employed by any cosmological model. Part of Munitz's argument derives from general claims about the structure of scientific theories, and as a result it is sometimes difficult to differentiate "horizons" specific to cosmology from the conceptual limitations that would arise for any scientific theory. Below my main focus will be on explaining two senses of "horizons" in cosmology that are both quite closely tied to features of cosmological models: (1) limitations on observation due to the finite speed of light, and the resulting inability to establish global properties of spacetime, and (2) the "horizon" encountered in early universe cosmology, due to the need to combine quantum field theory and general relativity.

### 3.1 Observational Indistinguishability and Cosmological Principles

As with the more familiar horizons, in relativity "horizons" mark the boundary of what we can observe — although in the case of cosmology the horizon is a three-dimensional surface at a given time separating unobservable galaxies from those that we could in principle observe. There are a variety of different "horizons" discussed in cosmology, but for present purposes we only need to clarify the limits of an observer's window on the universe.[6] Due to the finite speed of light, an observer taken to be located at a point $p$ in spacetime can receive signals from the region marked out by the chronological past $J^{-}(p)$ (the set of points that connect to $p$ via trajectories that are at or below the speed of light).[7] The physical state at points outside of $J^{-}(p)$ is not fixed by observations on $J^{-}(p)$ in conjunction with the laws of physics. Even fully specifying the state on $J^{-}(p)$ places few constraints on the global properties of spacetime, in the sense that it can be embedded in a spacetime $< M', g'_{ab}, T'_{ab} >$ with different global features than the original spacetime $< M, g_{ab}, T_{ab} >$. This is the idea behind Glymour's definition of "observational indinstinguishability" (OI): if $I^{-}(p)$ can be embedded in $M'$, our observer at $p$ would have no observational grounds to claim that she is in $< M, g_{ab}, T_{ab} >$ rather than its indistinguishable counterpart $< M', g'_{ab}, T'_{ab} >$. Any global features that are not invariant under the relation of OI cannot be observationally established by our idealized observer at $p$. Thus the question of observationally establishing global features of spacetime can be translated into a more precise "topological" question: what constraints are imposed on $M, g_{ab}$ by the requirement that a collection of sets $I^{-}(p)$ can be isometrically embedded in it? Here I will focus on clarifying the scope of OI given different assumptions regarding the space of allowed counterparts. At the lowest level—only imposing this "embedding" requirement—very little can be said about the global structure of spacetime based on observations confined to $J^{-}(p)$. As we will see, adding stronger physical and symmetry constraints, and thereby narrowing down the space of allowed models, allows the observer to make stronger local to global inferences.

The modest goal of pinning down the geometry of $J^{-}(p)$ observationally can be realized, at least for "idealized" observers (as Ellis 1980 describes with remarkable clarity). The relevant evidence comes from two sources: the radiation emitted by distant objects reaching us along our null cone, and evidence, such as geophysical data, gathered from "along our world line," so to speak. Considering only the former, suppose that astronomers somehow have full access to ideal observational evidence: comprehensive data on a set of "standard objects" scattered throughout the universe, with known intrinsic size, shape, mass and luminosity. With this data in hand one could study the distortion or focusing effects of the standard objects as well as their proper motion. Suppose that observers report no distortion or focusing effects and no proper motions — could they then conclude that the observable universe is isotropic around the observer? Not without assuming some background dynamics, such as EFE with a particular equation of state. But coupled with fixed dynamics the ideal observational data are sufficient to determine the spacetime geometry of the observer's null cone, $J^-(p)$, as well as the matter distribution and its velocity.[8] Thus in principle one could observationally establish isotropy. Numerous practical limitations on astronomical observations make it extremely difficult to actually measure the various quantities included in the ideal data set. The idealization appealed to above sidesteps one of the most pressing sources of systematic error in interpreting observations: differentiating evolutionary effects on the objects used as "standard candles" (such as galaxies or supernovae) from cosmological effects. In any case, the difficulties with actually determining the geometry of $J^-(p)$ using real astronomical data differ in kind from the limitations on claims regarding global structure discussed below.

Turning now to the definition of OI, the intuitive requirement that all observers' past light cones are compatible with two different spacetimes can be formalized as follows (Malament 1977, p. 68):[9]

> *Weak Observational Indistinguishability*: Cosmological models $< M, g_{ab}, T_{ab} >$ and $< M', g'_{ab}, T'_{ab} >$ are WOI if every $p \in M$ there is a $p' \in M'$ such that: (i) there exists an isometry $\phi$ mapping $I^-(p)$ into $I^-(p')$, (ii) $\phi^* T_{ab} = T'_{ab}$.

The adjective "weak" distinguishes this formulation from Glymour (1972, 1977)'s original, which was cast in terms of inextendible timelike curves and stipulated that the relation is symmetric. I agree with Malament's argument that these features of the original definition fail to capture the epistemic situation of observers in cosmology. First, if observers are idealized as inextendible timelike curves, whether or not a given spacetime has OI counterparts depends upon the nature of future infinity. Second, surely the epistemic situation of an observer in $M$ does not depend on that of observers in $M'$—undercutting the symmetry requirement.

The epistemic limitations of an observer can then be delimited quite precisely: what global properties vary between WOI counterparts? Consider, for example, Minkowski spacetime with a closed ball $O$ surgically removed.[10] The pre-surgery version of Minkowski spacetime $\Re^4, \eta_{ab}$ is WOI from the mutilated version, since the chronological past of any observer in Minkowski spacetime can be embedded "below" the mutilation. Symmetry fails, since

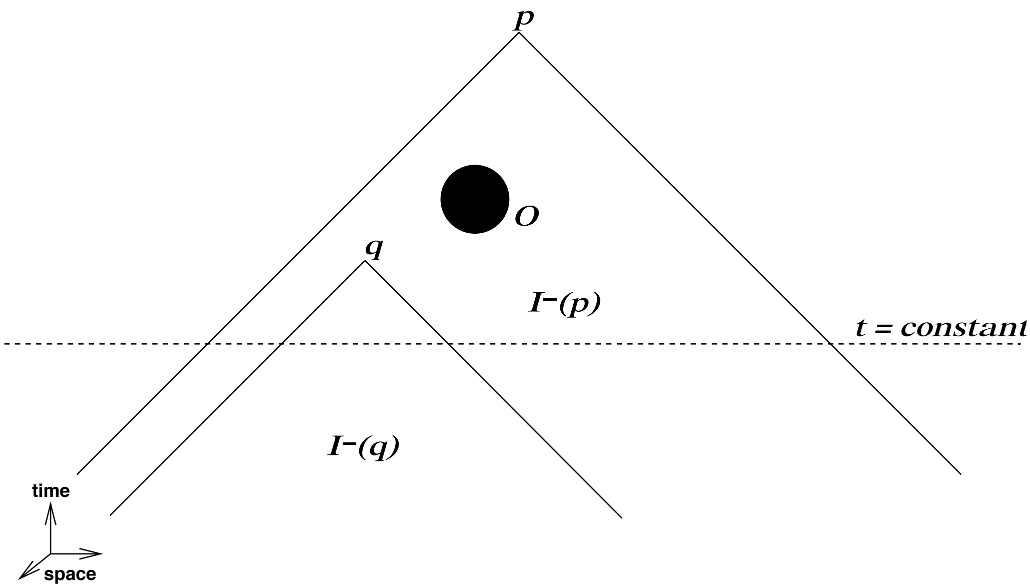


Figure 1: "Mutilated" Minkowski spacetime (the set $O$ excised), which is WOI from standard Minkowski spacetime. An observer at $p$ can detect the causality violations associated with the excised region, but an observer at $q$ cannot.

any observer in the mutilated spacetime $(\Re^4 - O, \eta_{ab})$ whose causal past included the removed set would be well aware that she was not in Minkwoski spacetime anymore. This example illustrates that the existence of a Cauchy surface is not invariant under the relation of WOI (there are Cauchy surfaces in Minkowski spacetime, but not in the mutilated counterpart). More generally, the WOI counterpart to a given spacetime can be visualized as the sets $I^-(p_i)$ hung along a "clothesline" with space-time filler in between.[11] Here we are not concerned with whether the WOI counterpart is actually a *sensible* cosmological model in its own right; the space-time filler is allowed to vary arbitrarily between the $I^-(p)$ hung on the clothesline, as long as continuity holds on the boundaries. Malament (1977) presents of series of brilliant constructions to illustrate that only the *failure* of various causality conditions necessarily holds in WOI counterparts (see, in particular, the table on p. 71).[12] As Malament emphasizes, an observer may know conclusively that one of the causality conditions is violated, but no observers will ever be able to establish conclusively that causality conditions hold.

A natural objection to this line of thought is that we *should* be concerned with whether the constructed indistinguishable counterparts are sensible cosmological models in their own right. While these indistinguishable counterparts are solutions of the EFE, they are constructed by stringing together "copies" of $J^-(p)$ sets and generally require a bizarre distribution of matter.

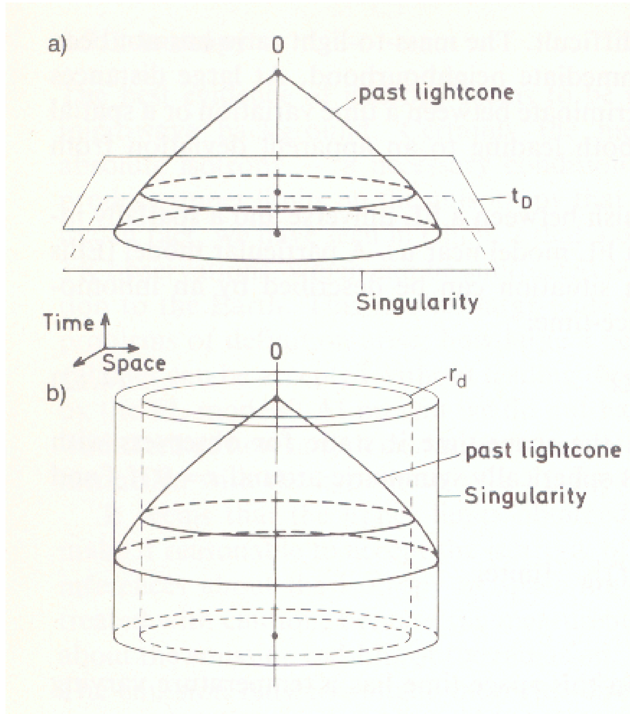


Figure 2: This figure contrasts the standard big bang model (a) and Ellis et al. (1978)'s model (b); in the latter, a cylindrical timelike singularity surrounds an observer $O$ located near the axis of symmetry, and the constant time surface $t_D$ from which the CMBR is emitted in the standard model is replaced with a surface $r_D$ at fixed distance from $O$ (figure from Börner 1993, p. 130).

This objection suggests that counterparts should be subject to a stronger constraint, namely that they correspond to solutions of the EFE that can be derived from physically motivated assumptions about the matter content.

Ellis et al. (1978)'s example of an indistinguishable counterpart to the observed universe illustrates the difficulties with satisfying such a stronger constraint. Their model incorporates isotropy for a preferred class of observers, but abandons homogeneity and the usual conception of how sources evolve. In this static, spherically symmetric model, *temporal* evolution (of, e.g., the matter density or various astronomical objects) in the standard FLRW models is replaced with *spatial* variation symmetric around a preferred axis (see 2). Unlike the timelike big bang singularity of the FLRW models, this model incorporates a singularity that "surrounds" the central region at a finite distance (all spacelike radial geodesics intersect the singularity). Ellis et al. (1978) show that such a model can accomodate several observational constraints, at least for an observer whose worldline is sufficiently close to the axis of symmetry. They counter the obvious objection that it is unreasonable to expect our location to be close to the "center of the universe" with an anthropic argument (p. 447): in such a model, only the central region is (literally) cool enough for observers. However, there is a more substantial objection: it turns out to be quite difficult to match the observational constraints on the magnitude-redshift relation given EFE with a perfect fluid source.[13] But this is precisely the point of the exercise: the model is suspect *not* because it violates spatial homogeneity, but rather because of the difficulty in satisfying both the EFE for a reasonable equation of state and observational constraints.

The major difficulty with replacing the definition of WOI given above with a physically motivated constraint along these lines also appears in other areas, such as attempts to prove Penrose's cosmic censorship conjecture: what exactly should be required of a "physically reasonable" cosmological model? Requiring that the source term $T_{ab}$ satisfies various energy conditions will not do, since a clothesline-constructed counterpart satisfies any energy conditions satisfied in the original spacetime; other more restrictive constraints on $T_{ab}$ fail for the same reason. Ignorance of the space of solutions of the EFE also makes it difficult to imagine how one could formulate a "naturalness" or "simplicity" requirement in terms of initial data specified on some Cauchy surface $\Sigma$ that would rule out WOI counterparts. The WOI counterparts certainly look like Rube Goldberg devices rigged up to be indistinguishable from a given spacetime, but we lack a clear way of limiting the space of allowed models to only the "natural" ones. Without an entirely general formulation, we have instead the piecemeal approach of Ellis et al. (1978): construct a model without spatial homogeneity and a given equation of state, then see whether it can accommodate various observational results. Failure to construct a workable model may reflect lack of imagination rather than a fundamental feature of general relativity, and so this only provides slight evidence for the claim that the FLRW models are the only physically reasonable models incorporating isotropy.

Adding information from multiple observers reduces the freedom in constructing indistinguishable counterparts. Spatial homogeneity is the strongest form of this requirement: it stipulates exact symmetry between every fundamental observer. More precisely, homogeneity holds if there are isometries of the spatial metric on each $\Sigma$—three-surfaces orthogonal to the tangent vectors of the fundamental observers' worldlines—that carry any point on the surface into any other point. Suppose that we amend the definition of WOI to include the requirement that homogeneity must hold in $< M, g_{ab}, T_{ab} >$ as well as $< M', g'_{ab}, T'_{ab} >$. Pick a point in $p \in M$ such that $p$ lies in $\Sigma$ and its image $\phi(p) \in M'$ under the isometric imbedding map $\phi$. If homogeneity holds, then $M'$ must include an isometric "copy" $\Sigma'$ of the *entire*

*Cauchy surface* $\Sigma$ along with its entire causal past. Take $\xi$ to be an isometry of the spatial metric defined on $\Sigma$, and $\xi'$ an isometry on $\Sigma'$. Since $\phi \circ \xi(p) = \xi' \circ \phi(p)$, and any point $q \in \Sigma$ can be reached via $\xi$, it follows that $\Sigma$ is isometric to $\Sigma'$. Mapping points along an inextendible timelike curve from $M$ into $M'$ eventually leads to an isometric copy of our original spacetime. If both cosmological models are inextendible, there are no indistinguishable counterparts (up to isomorphism) under this amended definition.[14]

Even a weaker requirement than the exact symmetry of spatial homogeneity reduces the scope of indistinguishable counterparts. The "Copernican Principle" is typically characterized as requiring that "our location is not distinguished"; I will take this to mean that no point $p \in M$ is distinguished from other points $q$ by any spacetime symmetries (e.g., $p$ is not near an axis of symmetry as in Ellis et al. (1978)'s model).[15] Coupled with the observed near isotropy of the microwave background radiation, the Copernican principle yields a powerful argument in favor of the approximate validity of the FLRW models. The Ehlers-Geren-Sachs theorem (Ehlers et al. 1968) shows that if all fundamental observers in an expanding model find that freely propagating background radiation is exactly isotropic, then their spacetime is an FLRW model.[16]

This line of thought leads to a clearer understanding of the "cosmological principle," which has been a subject of debate in cosmology ever since Milne introduced it. Munitz (1952, 1954) criticized Milne's treatment of the principle, and the use of the "perfect cosmological principle" by the steady state theorists following Milne's lead, as an axiom to be used in deriving cosmological theories. In Milne's formulation, the cosmological principle required the physical equivalence of different spatial locations in the universe; Bondi and Gold's "perfect cosmological principle" went one step further, requiring the physical equivalence of different temporal locations as well.[17] Bondi and Gold argued that this principle is a condition for the possibility of scientific cosmology, and proceeded to deduce the steady state theory as a consequence of this general principle. Munitz (1954, §6) identified a crucial tension in this argument: the principle is akin to a generic assumption made in all scientific theories, namely the universality and invariance of the laws of nature, and as such it is not specifically related to cosmology. But then the principle cannot be used as the basis for deducing a new cosmological theory or criticizing alternative theories.[18] Munitz is certainly correct to criticize the proposal of the steady state theorists that the laws could "vary" if not for the validity of the perfect cosmological principle (Munitz 1954, p. 44). However, the discussion above illustrates that the question of whether the cosmological principle (understood as the requirement that the cosmological model is homogeneous and isotropic) holds is independent of the local validity of EFE.[19]

The cosmological principle is the strongest of many possible "uniformity principles" that allow local-to-global inferences. As we saw above, if we require only that the $J^{-}(p)$ sets for all observers can be embedded in a cosmological model, then the global properties of spacetime are radically underdetermined. Introducing different constraints on the construction of the indistinguishable counterparts mitigates the degree of underdetermination; the cosmological principle is the strongest of these constraints — strong enough to effectively eliminate the underdetermination, and *every* observer can take their limited view on the universe as accurately reflecting its global properties.

Two further comments about the cosmological principle will bring this discussion to a close. First, how does the cosmological principle compare to other "uniformity principles" appealed to in scientific theories? It is clear that extrapolations to the global properties of cosmological models based on an appeal to the cosmological principle are much less productive than other inductive extrapolations in science. To make the contrast clear, consider the extrapolations Newton made in the *Principia*: after inferring that the force of gravitation holds between the sun and the planets, he leaps to the general conclusion that the force of gravitation holds universally. On the basis of this inductive extrapolation he gives preliminary accounts of the tides, the motion of the moon, the shape of the earth, and so on; each of these proposals led to further empirical problems and opportunities to refine and develop the theory of gravity. By way of contrast, the inferences to global properties of spacetime based on the cosmological principle (or weaker such principles) do not lead into similarly rich empirical territory. Assumptions regarding the global structure of spacetime are needed to prove the singularity theorems, but there is effectively no opportunity to further refine and develop relativistic cosmology based on extrapolations justified by the cosmological principle. However, and this is the second point, typical discussions of cosmological models implicitly rely on an extrapolation from our the observed universe to the properties of the universe as a whole. For example, the origin and eventual fate of the universe would be quite different in an approximately FLRW model and in one of its WOI counterparts. And there are reasons to consider spacetimes in which nothing like the cosmological principle holds. In some current versions of inflationary cosmology, for example, the cosmological principle only holds in the interior of a post-inflationary "bubble"; the global structure of spacetime outside this bubble is anything but uniform. This is not to say that the assumption that the cosmological principle or some weaker analog is *unreasonable*; my main point is simply that it is *necessary* to underwrite claims about the global properties of spacetime.

### 3.2 Conceptual Horizons in the Early Universe

The discussion of cosmological models above is based on a tremendous extrapolation: empirical tests of general relativity have been confined to systems of roughly the scale of the solar system, yet in describing cosmological models we are assuming that the theory applies to the entire observed universe. There is always some inductive risk associated with making such an extrapolation — it may turn out to be as misguided as the extrapolation of classical mechanics to microscopic scales and to velocities near the speed of light. However, at present there is no specific reason to doubt that general relativity can be extrapolated to length scales far greater than those used in testing the theory. By way of contrast, there *are* compelling reasons to doubt the extrapolation of general relativity to the early universe in the standard big bang models. The early universe falls within "overlapping domains" of two distinct, incompatible theories: quantum field theory and general relativity. As a result of this feature of the big bang models, the treatment of the early universe lies beyond a "horizon of intelligibility" in the sense that we lack an adequate theory describing that domain.

Often the existence of such "horizons" of general relativity are treated as a straightforward consequence of the singularity theorems: the theory "breaks down" as $t \rightarrow 0$, and the "singularity" itself is a boundary or limit of intelligibility of general relativity. I am not making this argument, which I find puzzling for two distinct reasons. The first follows on the difficulty with giving a local analysis of spacetime singularities discussed above. The idea that the theory breaks down at or near the singularity assumes that the singularity can be "localized" in some sense; if "singular" is instead treated as an adjective applied to spacetime as whole, it is not clear how to cash out the metaphor in more precise terms. Second, I take the invocation of horizons to indicate a fundamental incompleteness of the theory — it fails to provide an account of what lies "beyond the horizon," and this is a mark of inadequacy. If this were the case it would constitute a demerit for general relativity. However, it is hard to see how general relativity can be convicted of incompleteness on its own terms (cf. Earman 1995). If general relativity proved to be the correct final theory, then there is nothing more to be said regarding singularities; the laws of general relativity apply throughout the entire spacetime, and there is no obvious incompleteness. On the other hand there are good reasons to doubt that general relativity is the correct final theory, and further reasons to expect that the successor to general relativity will have novel implications for singularities. But then the argument for incompleteness is based on grounds other than the existence of singularities.

There are two more convincing reasons for taking general relativity to be incomplete: first, since it is a theory of gravity and sets aside the other fundamental forces it is not a complete theory, and second, it is incompatible with the theory describing the other fundamental forces, quantum field theory (QFT) (cf. Callender and Huggett 2001). The incompatibility of QFT and general relativity is not a pressing problem for most of the applications of each theory, due to the different length scales at which the strength of the forces is relevant. However, the world is not cleanly divided into separate domains of applicability for QFT and general relativity, and neither theory offers a complete account of phenomena even within their intended domains of applicability. The early universe and black holes are the two most important examples of overlapping domains. Although research in quantum gravity is often motivated by calls for "theoretical unification" and the like, it can also be motivated by the more prosaic demand for a consistent theory applicable to such phenomena.

Many theorists currently approach these domains using hybrid theories combining aspects of each theory (such as QFT on curved spacetime, semi-classical quantum gravity), as a stepping stone towards complete theories. However, there are several difficulties with these hybrids due to the stark differences in the conceptual structures of the two underlying theories. These problems have forced cosmologists to reconsider and reinterpret the underlying theories, in an attempt to isolate and combine their most secure parts. The most notorious problem results from treating the energy of the vacuum state in quantum field theory as a source for the gravitational field (see, e.g., Saunders 2002; Weinberg 1989). The vacuum in QFT is the state of lowest energy, but it is certainly not simply "nothing." The lowest energy state often has non-zero energy, but this "vacuum energy" cancels out of all calculations relevant to the empirical tests of QFT. Usually the vacuum energy is like a free wheel in the sense that it is not engaged in typical calculations, but the wheel squeaks loudly when gravity is included. Gravitation is the only interaction that is sensitive to the value of the vacuum energy; since all energy and matter gravitates, the vacuum energy cannot be simply "cancelled out" or ignored as it is in other calculations. A natural way of combining the two theories leads to an incredible discrepancy between the vacuum energy calculated in QFT and observational constraints. At a minimum, this astounding discrepancy rules out a straightforward combination of the two theories, but it may also indicate a more subtle flaw in the current understanding of one or both of them. In any case, foundational problems such as this have not deterred theorists from studying the early universe. Following the advent of inflationary cosmology (Guth 1981), early universe cosmology has become an incredibly active area of research based on a combination of ideas from particle physics and general relativity.

Although there are many interesting foundational problems related to these hybrid theories, my point in the present context is simply that the lack of a consistent theory covering the domain of interest provides good reason to claim that the early universe lies beyond the "horizon of intelligibility." Many of those pursuing inflation and other early universe theories would argue that the hybrid theory they employ is reliable in the domain in which they use it. However, assessing this argument, and finding precisely where this horizon lies, is a guessing game without a full theory of quantum gravity in hand, with which we could understand how classical general relativity and QFT emerge in the appropriate limits.

## 4 Logic of Cosmology

Discussions of the method or logic cosmology typically start by noting the uniqueness of the universe. If cosmology is defined as the study of the most comprehensive system of physical objects, the "whole universe," then it follows directly that the object of study is unique. But despite apparent agreement on this starting point, the lines of argument regarding the appropriate logic of cosmology diverge rapidly: there is no logic of cosmology because there can be no scientific study of a single object; cosmology must assume the "perfect cosmological principle" as an axiom; there are no "laws of nature" in cosmology; etc. Munitz (1962) reaches the conclusion that cosmology differs from other sciences in that it employs "cosmological models" of a particular kind; to avoid confusion with "cosmological model" as I have employed the term above, I will hereafter denote Munitz's sense with "model$_M$." Munitz argues that model$_M$'s offer intelligibility in a sense different than that usually provided by physical theories; cosmologists seek a description of the universe offering "the kind [of intelligibility] which involves grasping the structure of a whole of which at present only a part is given" (p. 43). Munitz (1962) further argues against the idea that the merits of model$_M$'s should be assessed in terms of an isomorphism or correspondence between the model$_M$ and "the universe" (a topic explored further in Munitz 1986).

Before turning to Munitz's argument, I should emphasize that the distinction between a model and a model$_M$ is not a minor terminological difference; it is, in a sense, the crux of our disagreement. Central to the discussion above is the conception of a cosmological model as a solution to EFE, although I would allow that the term is often used more broadly to refer to a detailed account of the universe's history, including various physical processes such as the formation of elements, galaxies, and other structures. In direct contrast to this conception, model$_M$'s are autonomous from theories: "the term 'model of the universe', as used in cosmology, does *not* represent a subsidiary or associated element *in* a theory but is itself the name to be given the principal device used for understanding of the universe" (45). I am wary of making such strong claims regarding usage in the scientific literature, as scientists often treat "model" without the respect appropriate for a term of art. In any case, Munitz's claim does not seem true of contemporary cosmology, although this may partially reflect the context in which Munitz's paper was written — at a time when the steady state vs. big bang debate was still ongoing. But the main point of interest is Munitz's case for the normative claim that the appropriate aim of research in cosmology is the construction of an autonomous model$_M$ of the universe.[20]

Munitz's argument in favor of this account of cosmology proceeds in two steps. First, as a consequence of the uniqueness of the universe it is not possible to have multiple instantiations of a "law of the universe." Munitz draws a helpful distinction here between "laws of the universe" and laws applied to constituents of the universe. A law that directly appeals to global properties of a cosmological model would qualify as a "law of the universe," contrasted with a law applicable to subsystems that has been generalized to apply universally. As a candidate for a "law of the universe," consider Penrose (1979)'s "Weyl Curvature Hypothesis," which holds (roughly) that the Weyl tensor goes to zero as one approaches the initial singularity.[21] This purported "law" applies in a single instance – the early universe – and it is formulated in terms of a global property, not as a law applying to subsystems that is then universally generalized. But does such a "law" deserve the honorific? Munitz (and many others) have argued that it does not, on the following grounds. The usefulness of physical laws derives from the fact that they cover numerous instances; for example, the laws of motion governing projectiles cover a wide variety of initial velocities and positions. As Bondi remarked, if we were given only a single trajectory what use would there be for a law of motion? The first step is meant to establish that the search for laws of the universe is not an appropriate aim for cosmology; to use slightly different terminology, cosmology is properly a descriptive, historical science rather than a science in which new laws can be discovered.

Second, Munitz gives a positive characterization of what kind of intelligibility cosmology should aim to achieve. On Munitz's view, this will not come in the form of a theory akin to the theory of gravity or electromagnetism. Since cosmology does not properly deal with laws it does not deal with theories, either; as he puts it,

> Not only is cosmology not concerned with the discovery of laws for the purpose of 'explaining' the universe, it cannot even be said to be interested in the discovery of a *theory* of the universe, in the sense in which we have been using the term 'theory,' that is to say, as a name for the conceptual means primarily employed

> for the explanation of laws. (Munitz 1962, 43)

Instead, one aim of cosmology is the aim appropriate to a historical science — namely a complete descriptive account of the historical evolution of objects within the observed universe. Where cosmology extends beyond this aim is in the attempt to understand how the observed portion of the universe can be treated as a part of the whole; quoting again,

> What the cosmologist finds insufficient about his grasp is precisely that the observable region is incomplete. What he looks for is some way of understanding it as completed, in the sense of seeing how the observable region forms a part of a whole whose complex pattern he can specify. The intelligibility cosmology looks for accordingly is of the kind which involves grasping the structure of a whole of which at present only a part is given. (Munitz 1962, 43)

Model$_M$'s come into play in giving precisely this sense of "intelligibility." The autonomy of these model$_M$s from theory apparently rests on the further claim that they are generated via analogical reasoning. On Munitz's view, statements regarding global properties of the universe cannot be treated as empirical claims – they can only be understood as analogies (45-46).

This final step of the argument is admittedly somewhat obscure, but it seems that Munitz overlooked one way of understanding global properties that requires neither model$_M$s nor analogies. We have seen above in some detail how, following Einstein's "lunge for totality," cosmologists have been forced to describe global properties of spacetime via the study of models of the theory of general relativity. These properties are not described via analogies; they are instead perfectly well-defined properties of the spacetime. Of course that is not to say that they can be directly established via observations on the limited portion of the universe accessible to us. The cosmological principle and other weaker principles regarding the "typicality" of our window on the universe make it possible to show precisely how properties of the observed universe relate to global properties of the full spacetime. The interesting question then regards the status of the cosmological principle or its variants, as they provide the step from the "part" to "grasping the whole." Such a treatment of global properties and the possibility of inferences regarding them based on observations does not accord with Munitz's claims, but I do not see how to construct an argument on his behalf against this account.

The more important problem lies with the first step of the argument and its treatment of laws. Munitz (and others who make a similar argument, such as Ellis 2007) treat the relation between laws and the relevant phenomena as that of a general claim (such as $\forall x(Fx \rightarrow Gx)$), and an instance of it ($Fa \wedge Ga$). But this logical relation does not do justice to the relation between laws of nature in physics and the phenomena used in assessing them, because it treats the laws themselves as having empirical content properly attributed only to the equations of motion derived from the laws with the help of supplementary conditions. Consider the application of Newton's gravitational theory to the solar system as an example. Newton's three laws of motion must be combined with other assumptions regarding the relevant forces and distribution of matter to derive a set of equations of motion, describing, say, the motion of Mars in response to the Sun's gravitational field. It is this equation of motion that is compared to the phenomena and used to calculate the positions of Mars given some initial conditions. The motion of Mars is not an "instance" of Newton's laws; rather, the motion of Mars is well approximated by an equation of motion derived from Newton's laws along with a number of other assumptions. Furthermore, there is no expectation that at any stage of inquiry one has completely "captured" the motion of Mars with a particular equation of motion, even as further physical effects (such as the effects of the gravitational fields of other planets) are included in the derivation. The success of Newton's theory consists in the ability to give more and more refined descriptions of the motion of Mars and the other planets, all based on the three laws of motion and the law of gravity.

The main consequence of this different conception of laws is that we can see that "multiplicity of instantiations" is a red herring. The example of the solar system illustrates the first point that "instantiation" is not the best way to think of the relation between a law and the phenomena, but it also illustrates a second point: that complexity of the phenomena and the possibility of further refinement of a theoretical description are important to empirical support. The standard arguments that it is not possible to discover laws in cosmology seem to assume that the universe is not only unique, but in effect "given" to us entirely, in a comprehensive manner — leaving cosmologists with nothing further to discover. But this is clearly not the case. One can imagine, then, a case for a new law in cosmology that is supported by its success in providing successively more refined descriptions of some aspect of the universe's history, just as Newtonian mechanics is supported in part by its success in underwriting research related to the solar system. There will be various obstacles to making such a case in cosmology: for example, the interpretation of observations in cosmology is typically closely intertwined with the theory under consideration, unlike the Newtonian case. But this obstacles have nothing to do directly with the uniqueness of the universe.

## 5 Conclusions

By way of summary, I have considered a number of issues central to Munitz's work in philosophy of cosmology. I have described a conception of cosmology due to Einstein, which takes cosmology to be in essence the study of exact solutions of the field equations of general relativity. These models have interesting global properties that can be defined precisely, allowing a treatment of the "whole universe" embedded within a particular theory that does not depend upon analogical reasoning. My account of the cosmological principle and the importance of horizons in relativity drew more heavily on the technical aspects of general relativity than Munitz's discussion of similar issues, although we arrive at positions that are in some ways quite similar. Finally, I have criticized Munitz's account of the implications of the uniqueness of the universe based on a different conception of the laws of physics and their role. Although my comments here are at best suggestive, exploring these issues further is a task for another day.

# Notes

[1]Peter Scheuer made the remark in the course of warning a student, Malcolm Longair, about the current status of cosmology in 1963; the list included (1) that the sky is dark at night, (2) that the galaxies recede, as observed by Hubble, and (2 1/2) that the universe is evolving (qualified as a half fact due to its uncertainty).

[2]The best single book chronicling the earlier development of cosmological thought is still Munitz (1957); for the twentieth century, see also Bernstein and Feinberg (1986); Longair (2006).

[3]The gravitational force for an arbitrary point in an infinite universe filled uniformly with matter diverges, and Newtonian theory also cannot consistently describe an alternative to the infinite, uniform distribution of matter, an "island universe" of stars clumped within a finite region of an otherwise empty universe. Although Einstein's presentation is compelling, his dilemma for Newtonian theory collapses on closer examination. First, it is possible to avoid the divergences and the instability of an island universe with a clever, hierarchical structure of matter, as demonstrated by Charlier (1908); more importantly, the "divergence" is an artifact of a particular formulation of Newtonian gravitational theory that can be avoided in a geometric reformulation of the theory. For further discussion of the paradoxes, see Malament (1995); Norton (1999). For a more general discussion of Eistein's role in the birth of relativistic cosmology, which I draw on here, see Smeenk (2008).

[4]The model includes the spacetime manifold $M$, the metric tensor $g_{ab}$, which represents the gravitational field and the geometric structure of the spacetime, and the stress-energy tensor $T_{ab}$, which encodes the contribution of matter; Einstein's equations specify the relationship between the last two items.

[5]See Earman (1995) for a detailed discussion of these issues (in Chapter 2).

[6]See Ellis and Rothman (1993) for a concise technical introduction; Munitz (1986)'s Chapter 5 also covers this territory, with a philosophical orientation.

[7]In Minkowski spacetime, this set is the past lobe of the light cone at $p$, including interior points and the point $p$ itself. In the discussion below I will shift to using $I^-(p)$, the chronological past (in Minkowski space, the interior of the past lobe) for convenience, since these are always open sets. Nothing is lost since $J^-(r)$ is a subset of $I^-(p)$ if $r \in I^-(p)$, except in the case of maximal timelike curves with future endpoints. The causal sets $J^\pm(p), I^\pm(p)$ are defined in terms of the following relations. A point $p$ *chronologically precedes* $q$ (symbolically, $p << q$), if there is a future-directed timelike curve of non-zero length from $p$ to $q$. Since timelike trajectories represent possible trajectories of massive particles, a signal travelling slower than light can reach $q$ from $p$. Similarly, $p$ *causally precedes* $q$ ($p < q$), if there is a future-directed curve with timelike vectors that are timelike or null at every point; a light signal $q$ can reach $p$. The causal sets are defined in terms of these relations: $I^-(p) = \{q : q << p\}$, $I^+(p) = \{q : p << q\}$, the *chronological past* and *future*, and $J^-(p) = \{q : q < p\}$, $J^+(p) = \{q : p < q\}$, the *causal past* and *future*. These definitions generalize immediately to spacetime regions: for the region $S$, $I^+(S) = \cup_{p \in S} I^+(p)$.

[8]As Ellis notes, the metric quantities that determine how the null cone is em-

bedded in the spacetime cannot be directly measured without using the dynamical equations, but the distortion and focusing effects of standard objects can be used to directly measure the intrinsic geometry of the null cone.

[9]My definition differs slightly from that given by Malament, in that I am requiring that the source fields (rather than only the $T_{ab}$) are diffeomorphic in the indistinguishable counterparts (cf. Malament 1977, pp. 74-76). Although $T_{ab}$ inherits the symmetries of the metric, the source fields $O_1, ..., O_n$ do not necessarily share the symmetries. The source fields are tensor fields defined everywhere on $M$, such as the Maxwell tensor $F_{ab}$, which satisfy the appropriate field equations.

[10]Although constructions such as this may seem glaringly artificial, they are a staple of the study of global causal structure in relativistic spacetimes for two reasons: (1) the "mutilated" spacetime still qualifies as a possible model in general relativity, and (2) these simple, artificial constructions illustrate features that arise in more realistic models.

[11]A proof due to Geroch (1968, pp. 1743-44) guarantees that one can always find a countable sequence $\{p_i\}$ such that the union of their chronological past covers $M$, i.e. $M = \bigcup_{p_i} \{I^-(p_i)\}$.

[12]I share Malament's intuition that the only spacetimes without a WOI counterpart are *totally vicious* (i.e., for $\forall p \in M, p \in I^-(p)$), although I have not been able to prove a theorem to this effect.

[13]Ellis et al. (1978) note that the for the solution to remain static the gradient in the gravitational potential as one moves out along the radius must be matched by a pressure gradient. But this implies that the present era is radiation dominated in the alternative model (rather than matter dominated, as in the standard models), since "dust" uncoupled to radiation does not satisfy the equation of hydrostatic support. Hence the alternative model uses an equation of state with $p = \rho/3$, with a non-zero $\Lambda$ thrown in for an added degree of freedom. They conclude that that if $\rho > 0$ (satisfying the strong energy condition), there is no choice of the parameters of the theory that fits the observed magnitude - redshift relation. There are a few ways to avoid this conclusion, such as considering much more complicated equations of state or alternative gravitational theories, but Ellis et al. (1978) dismiss the alternatives as not "immediately compelling."

[14]An *inextendible* spacetime cannot be imbedded as a proper subset of another spacetime. This qualification is needed to rule out spacetimes such as a "truncated" FLRW model, in which there is an end of days—a "final" time slice at an arbitrary cosmic time $t_{end}$. Such a model would be WOI (in the amended sense) from its extension, in which time continues past $t_{end}$.

[15]What is lacking here is a precise way of stating that there should be an "approximate symmetry" obtaining between different fundamental observers separated by some length scale $L$, in that they see a distribution of galaxies and fluctuations of temperature in the CMBR that differ only due to the random processes generating them. See Stoeger et al. (1987) for a proposed definition of "statistical homogeneity" along these lines, defined with respect to a given foliation.

[16]"Freely propagating" means that the radiation is decoupled from the matter; the stress energy tensor can be written as two non-interacting components, one

for the dust-like matter and another representing the background radiation. Recent work has clarified the extent to which this result depends on the various exact claims made in the antecedent. The fundamental observers do not need to measure *exact* isotropy for a version of the theorem to go through: Stoeger et al. (1995) have further shown that *almost* isotropic CMBR measurements imply that the spacetime is an *almost* FLRW model. Wainwright and Ellis (1997) introduce various dimensionless parameters defined in terms of the shear, vorticity, and Weyl tensor to measure departures from the exact FLRW models; a spacetime is *almost* FLRW if all such parameters are $<< 1$ (see, in particular, pp. 62-64). There are, however, counterexamples showing that the theorem does not generalize in other respects. Given the assumption that the matter content can be characterized as pressureless dust completely decoupled from background radiation, the fundamental observers travel along geodesics. Clarkson and Barrett (1999) show that non-geodesic observers can observe an isotropic radiation field in a class of inhomogeneous solutions. In addition, observational constraints confined to a finite time interval may not rule out more general models which approximate the FLRW models during that interval but differ at other times (Wainwright and Ellis 1997).

[17]One must specify the intended sense of physical equivalence for the principles to have some bite; one way of doing so is to take physical equivalence to be coarse-grained equivalence of the large-scale distribution of matter.

[18]Munitz (1952) makes a similar case against Milne. Munitz makes two main critical points: first, the cosmological principle combined with assumptions regarding temporal measurements are not sufficient to fully determine a cosmological model, as Milne had hoped, and, second, Milne's mathematical approach neglects the crucial question of how the resulting cosmological theory acquires empirical content.

[19]Homogeneity and isotropy together entail that the models are topologically $\Sigma \times R$, where the three-dimensional surfaces $\Sigma$ are orthogonal to the wordlines of fundamental observers. The spatial geometry induced on the surfaces $\Sigma$ is such that there is an isometry carrying any $p \in \Sigma$ to any other point lying in the same surface (homogeneity), and at any $p$ the three spatial directions are isometric (isotropy).

[20]I should note that many of the claims in Munitz (1962) are formulated as descriptive claims regarding what cosmologists do and how they approach various questions, but it seems clear that Munitz intends his arguments to have normative force.

[21]The Weyl tensor is the trace-free part of the Riemann curvature tensor, and Penrose formulates the hypothesis as a precise way of requiring that the universe at early time approaches the simple FLRW models. The hypothesis can be formulated more precisely in terms of the limiting behavior of the Weyl tensor in a conformal completion of a given spacetime.

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