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(NON-INFLATIONARY) HOT BIG BANG MODEL PROBLEMS OF THE CONVENTIONAL

☆ If infinities are cut off at the Planck scale (quantum gravity scale), then infinities become finite, but

★ For lack of a better explanation, many cosmologists (including Steve maybe there are many types of vacuum (as predicted by string theory). fly apart (if positive) or implode (if negative), so life could not form. reside. A large vacuum energy density would cause the universe to rapidly roughly 120 orders of magnitude larger than ours. Maybe we live in a very energy density is determined by "anthropic" selection effects: that is, low energy density vacuum because that is where almost all living beings with different vacuum energy densities, with most vacuum energy densities Weinberg and yours truly) seriously discuss the possibility that the vacuum

Alan Guth, Problems of the Conventional (Non-Inflationary) Hot Big Bang Model, 8.286 Class 22, November 23, 2022, p. 1.

Particle Physics of a Cosmological Constant

$$u_{\text{vac}} = \rho_{\text{vac}} c^2 = \frac{\Lambda c^4}{8\pi G}$$

- A Contributions to vacuum energy density:
- 1) Quantum fluctuations of the photon and other bosonic fields: positive and divergent.
- 2) Quantum fluctuations of the electron and other fermionic fields: negative and divergent.
- 3) Fields with nonzero values in the vacuum, like the Higgs field

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and the String Theory Landscape Anthropic Selection Effects

- ☆ Since the inception of string theory, theorists have sought to find the vacuum of string theory — with no success.
- 🖈 Since about 2000, most string theorists have come to believe that there is no unique vacuum.
- Instead, there are perhaps 10⁵⁰⁰ or more long-lived metastable states, any one of which could serve as a substrate for a pocket universe.
- ★ Eternal inflation, which we will talk about later, can lead to an infinite number of "pocket universes," of which one would be the universe in which we live. The pocket universes are filled with different types of vacuum, very likely providing examples of every type of vacuum in the string theory
- ☆ Although string theory would govern everywhere, each type of vacuum would have its own low-energy physics its own "standard model," its own "constants" of nature, and its own vacuum energy density.

 $"> \frac{1}{2} \] If the landscape has <math>10^{500}$ vacua, and a fraction 10^{-120} have small vacuum energy densities like our universe, then we expect about

$$10^{-120} \times 10^{500} = 10^{380}$$

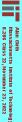
vacua with low energy densities like ours

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vacua with low energy densities like ours

🖈 But how could we explain why we are living in such a fantastically unusual type of vacuum?



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☆ As early as 1987, Steve Weinberg pointed out that the vacuum energy density might be explained as a selection effect.

☆ Maybe the vacuum energy density IS huge in most pocket universes density is very near zero. sion of the universe to accelerate. If large and negative, the universe quickly implodes. If large and positive, the universe flies apart before galaxies can form. It is plausible, therefore, that life can arise only if the vacuum energy Nonetheless, we need to remember that vacuum energy causes the expan-

☆ In 1998 Martel, Shapiro, and Weinberg made a serious calculation of the density is as small as what we measure. effect of the vacuum energy density on galaxy formation. They found that to within a factor of order 5, they could "explain" why the vacuum energy

🖈 Possible answer: maybe it is a selection effect. I.e., maybe life only forms

where the vacuum energy density is unusually small.

🖈 But how could we explain why we are living in such a fantastically unusual

vacua with low energy densities like ours

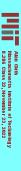
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Does the Selection Effect Explanation Anthropic Selection Effects: Amount to Giving Up?

🖈 A number of physicists regard an "anthropic" explanation as simply giving

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Does the Selection Effect Explanation Anthropic Selection Effects: Amount to Giving ∪p?

- 🖈 A number of physicists regard an "anthropic" explanation as simply giving цþ.
- ☆ In my opinion, the selection effect explanation is both logical and scientific. I think we all accept anthropic explanations for some facts

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Alan Guth, Problems of the Conventional (Non-Inflationary) Hot Big Bang Model, 8.286 Class 22, November 23, 2022, p. 3.

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- ☆ But I would advocate that anthropic explanations be thought of as the is the absence of any other. explanation of last resort — the best evidence for an anthropic explanation

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The Horizon/Homogeneity Problem

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The Horizon/Homogeneity Problem

☆ General question: how can we explain the large-scale uniformity of the universe?

The Horizon/Homogeneity Problem

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- 🖈 Possible answer: maybe the universe just started out uniform.

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The Horizon/Homogeneity Problem

- ☆ General question: how can we explain the large-scale uniformity of the universe?
- 🖈 Possible answer: maybe the universe just started out uniform.
- There is no argument that excludes this possibility, since we don't know how the universe came into being.

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The Horizon/Homogeneity Problem

- ☆ General question: how can we explain the large-scale uniformity of the
- 🖈 Possible answer: maybe the universe just started out uniform.
- There is no argument that excludes this possibility, since we don't know how the universe came into being.
- However, if possible, it seems better to explain the properties of the attribute them to things that we don't understand. universe in terms of things that we can understand, rather than to

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The Horizon in Cosmology

- ☆ The concept of a horizon was first introduced into cosmology by Wolfgang Rindler in 1956.
- ☆ The "horizon problem" was discussed (not by that name) in at least two early textbooks in general relativity and cosmology: Weinberg's (MTW's) Gravitation (1973). Gravitation and Cosmology (1972), and Misner, Thorne, and Wheeler's

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The Cosmic Microwave Background

☆ The strongest evidence for the uniformity of the universe comes from the CMB, since it has been measured so precisely.

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The Cosmic Microwave Background

- ☆ The strongest evidence for the uniformity of the universe comes from the CMB, since it has been measured so precisely.
- 🖈 The radiation appears slightly hotter in one direction than in the opposite direction, by about one part in a thousand — but this nonuniformity can be attributed to our motion through the background radiation.
- ☆ Once this effect is subtracted out, using best-fit parameters for the velocity, it is found that the residual temperature pattern is uniform to a few parts



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- 🖈 Could this be simply the phenomenon of thermal equilibrium? If you put an ice cube on the sidewalk on a hot summer day, it melts and comes to the same temperature as the sidewalk.

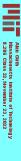


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- 🖈 Could this be simply the phenomenon of thermal equilibrium? If you put an ice cube on the sidewalk on a hot summer day, it melts and comes to the same temperature as the sidewalk.
- ☆ BUT: in the conventional model of the universe, it did not have or information can travel faster than light, then it is simply not enough time for thermal equilibrium to explain the uniformity, if we assume that it did not start out uniform. If no matter, energy,
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Basic History of the CMB

- 🖈 In conventional cosmological model, the universe at the earliest times was radiation-dominated. It started to be matter-dominated at $t_{\rm eq} \approx 50,000$ years, the time of matter-radiation equality.
- * At the time of decoupling $t_d \approx 380,000$ years, the universe cooled to thoroughly that free electrons were very rare. At earlier times, the universe the CMB was released at about 380,000 years. were essentially frozen with the matter. At later times, the universe was was in a mainly plasma phase, with many free electrons, and photons about 3000 K, by which time the hydrogen (and some helium) combined so transparent, so photons have traveled on straight lines. We can say that
- \Rightarrow Since the photons have been mainly traveling on straight lines since $t = t_d$, which they were released form a sphere centered on us. This sphere is called the surface of last scattering, since the photons that we receive now they have all traveled the same distance. Therefore the locations from surface. in the CMB was mostly scattered for the last time on or very near this



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- ☆ As we learned in Lecture Notes 4, the horizon distance is defined as the present distance of the furthest particles from which light has had time to reach us, since the beginning of the universe.
- \Rightarrow For a matter-dominated flat universe, the horizon distance at time t is 3ct, while for a radiation-dominated universe, it is 2ct.
- $ightharpoonup At t = t_d$ the universe was well into the matter-dominated phase, so we can approximate the horizon distance as

 $\ell_h(t_d) \approx 3ct_d \approx 1,100,000 \text{ light-years.}$

surface of last scattering, at time t, as $\ell_p(t)$. scattering at time t_d , since this region is the origin of the photons that we are now receiving in the CMB. I will denote the physical radius of the For comparison, we would like to calculate the radius of the surface of last

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$\ell_p(t_0) = 2cH_0^{-1} \left[1 - \frac{1}{\sqrt{1+z}} \right] .$

☆ The redshift of the surface of last scattering is about

$$1 + z = \frac{a(t_0)}{a(t_d)} = \frac{3000 \text{ K}}{2.7 \text{ K}} \approx 1100 .$$

- ★ If we take $H_0 = 67.7 \text{ km-s}^{-1}\text{-Mpc}^{-1}$, one finds that $H_0^{-1} \approx 14.4 \times 10^9 \text{ yr}$ and $\ell_p(t_0) \approx 28.0 \times 10^9 \text{ light-yr}$. (Note that $\ell_p(t_0)$ is equal to 0.970 times the current horizon distance — very close.)
- $ightharpoonup^{*}$ To find $\ell_{p}(t_{d})$, just use the fact that the redshift is related to the scale factor:

$$\begin{split} \ell_p(t_d) &= \frac{a(t_d)}{a(t_0)} \ell_p(t_0) \\ &\approx \frac{1}{1100} \times 28.0 \times 10^9 \text{ lt-yr} \approx 2.55 \times 10^7 \text{ lt-yr} \ . \end{split}$$

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$\ell_h(t_d) \approx 3ct_d \approx 1,100,000 \text{ light-years.}$

scattering at time t_d , since this region is the origin of the photons that we are now receiving in the CMB. I will denote the physical radius of the surface of last scattering, at time t, as $\ell_p(t)$. For comparison, we would like to calculate the radius of the surface of last

To calculate $\ell_p(t_d)$, I will make the crude approximation that the universe it won't matter.) has been matter-dominated at all times. (We will find that this horizon problem is very severe, so even if our calculation is wrong by a factor of 2,

*

X Strategy: find $\ell_p(t_0)$, and scale to find $\ell_p(t_d)$. Under the assumption of today to an object at redshift z is a flat matter-dominated universe, we learned that the physical distance

$$\ell_p(t_0) = 2cH_0^{-1} \left[1 - \frac{1}{\sqrt{1+z}} \right] .$$

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 $\ell_h(t_d) \approx 3ct_d \approx 1,100,000 \text{ light-years.}$

$$\begin{split} \ell_p \left(t_d \right) &= \frac{a(t_d)}{a(t_0)} \ell_p (t_0) \\ &\approx \frac{1}{1100} \times 28.0 \times 10^9 \; \text{lt-yr} \approx 2.55 \times 10^7 \; \text{lt-yr} \;\; . \end{split}$$

☆ Comparison: At the time of decoupling, the ratio of the radius of the surface of last scattering to the horizon distance was

$$\frac{\ell_p(t_d)}{\ell_h(t_d)} \approx \frac{2.55 \times 10^7 \, \text{lt-yr}}{1.1 \times 10^6 \, \text{lt-yr}} \approx 23 \ .$$

Summary of the Horizon Problem

Suppose that one detects the cosmic microwave background in a certain model, for these two sources to have come into thermal equilibrium by distances. Thus it is absolutely impossible, within the context of this direction in the sky, and suppose that one also detects the radiation from any physical process. these two signals were separated from each other by about 46 horizon precisely the opposite direction. At the time of emission, the sources of

Although our calculation ignored the dark energy phase, we have found in accurate calculation could cause this problem to go away. previous examples that such calculations are wrong by some tens of a been about 50,000 years.) Since $46 \gg 1$, there is no way that a more percent. (For example we found $t_{\rm eq} \approx 75,000$ years, when it should have

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 \Rightarrow The underlying fact is that the value $\Omega = 1$ is a point of unstable in the early universe must have been extraordinarily close to one. one, it will rapidly fall toward zero. For Ω to be anywhere near 1 today, Ω one, it will rapidly grow toward infinity; if Ω is ever slightly smaller than equilibrium, something like a pencil balancing on its point. If Ω is ever (k=0) universe remains flat. However, if Ω is ever slightly larger than exactly equal to one, it will remain equal to one forever — that is, a flat

- 🖈 Like the horizon problem, the flatness problem could in principle be solved $\Omega \equiv 1.$ by the initial conditions of the universe: maybe the universe began with
- But, like the horizon problem, it seems better to explain the properties of the universe, if we can, in terms of things that we can understand, rather than to attribute them to things that we don't understand.

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The Flatness Problem

- A second problem of the conventional cosmological model is the flatness close to 1? problem: why was the value of Ω in the early universe so extraordinarily
- ☆ Today we know, according to the Planck satellite team analysis (2018),

$$\Omega_0 = 0.9993 \pm 0.0037$$

at 95% confidence. I.e., $\Omega = 1$ to better than 1/2 of 1%.

 \Rightarrow As we will see, this implies that Ω in the early universe was extaordinarily close to 1. For example, at t = 1 second.

$$|\Omega - 1|_{t=1 \text{ sec}} < 10^{-18}$$

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History of the Flatness Problem

The mathematics behind the flatness problem was undoubtedly known to almost here were Robert Dicke and P.J.E. Peebles, who published a discussion in apparently the first people to consider it a problem in the sense described anyone who has worked on the big bang theory from the 1920's onward, but

*R.H. Dicke and P.J.E. Peebles, "The big bang cosmology — enigmas and nostrums," in **General Relativity: An Einstein Centenary Survey**, eds. S.W. Hawking and W. Israel, Cambridge University Press (1979).

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The Mathematics of the Flatness Problem

Start with the first-order Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{a^2} \ . \label{eq:H2}$$

Remembering that $\Omega=\rho/\rho_c$ and that $\rho_c=3H^2/(8\pi G)$, one can divide both sides of the equation by H^2 to find

$$1 = \frac{\rho}{\rho_c} - \frac{kc^2}{a^2H^2} \implies \Omega - 1 = \frac{kc^2}{a^2H^2} .$$

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$$\Omega - 1 = \frac{kc^2}{a^2H^2} \ .$$

the Matter-Dominated Phase Evolution of $\Omega-1$ During

For a (nearly) flat matter-dominated universe, $a(t) \propto t^{2/3}$, so $H = \dot{a}/a = 2/(3t)$.

$$\Omega - 1 \propto \left(\frac{1}{t^{2/3}}\right)^2 \left(\frac{1}{t^{-1}}\right)^2 \propto t^{2/3}$$
 (matter-dominated).

the Radiation-Dominated Phase Evolution of $\Omega-1$ During

$$\Omega - 1 = \frac{kc^2}{a^2H^2} \; .$$

For a (nearly) flat radiation-dominated universe, $a(t) \propto t^{1/2}, \text{ so } H = \dot{a}/a = 1/(2t).$ So

$$\Omega - 1 \propto \left(\frac{1}{t^{1/2}}\right)^2 \left(\frac{1}{t^{-1}}\right)^2 \propto t \quad \text{(radiation dominated)}.$$

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Tracing $\Omega-1$ from Now to 1 Second

Today,

$$|\Omega_0 - 1| < .01.$$

I will do a crude calculation, treating the universe as matter dominated from $50,\!000~\mathrm{years}$ to the present, and as radiation-dominated from 1 second to 50,000 years.

During the matter-dominated phase

$$(\Omega - 1)_{t=50,000 \text{ yr}} \approx \left(\frac{50,000}{13.8 \times 10^9}\right)^{2/3} (\Omega_0 - 1) \approx 2.36 \times 10^{-4} (\Omega_0 - 1) .$$

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$$\approx \left(\frac{50,000}{2}\right)^{2/3} (O_0 - 1) \approx 9.36 \times 10^{-3}$$

During the radiation-dominated phase,

 $(\Omega - 1)_{t=50,000 \, \mathrm{yr}} \approx$

 13.8×10^9

 $(\Omega_0 - 1) \approx 2.36 \times 10^{-4} (\Omega_0 - 1)$.

$$(\Omega - 1)_{t=1 \text{ sec}} \approx \left(\frac{1 \text{ sec}}{50,000 \text{ yr}}\right) (\Omega - 1)_{t=50,000 \text{ yr}}$$

 $\approx 1.49 \times 10^{-16} (\Omega_0 - 1)$.

The conclusion is therefore

$$|\Omega - 1|_{t=1 \text{ sec}} < 10^{-18}$$
.

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The conclusion is therefore

$$|\Omega - 1|_{t=1 \text{ sec}} < 10^{-18}$$
.

Even if we put ourselves mentally back into 1979, we would have said that $0.1 < \Omega_0 < 2$, so $|\Omega_0 - 1| < 1$, and would have concluded that

$$|\Omega - 1|_{t=1 \text{ sec}} < 10^{-16}$$
.

The Dicke & Peebles paper, that first pointed out this problem, also considered t=1 second, but concluded (without showing the details) that

$$|\Omega - 1|_{t=1 \text{ sec}} < 10^{-14}$$
.

They were perhaps more conservative, but concluded nonetheless that this extreme fine-tuning cried out for an explanation.

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