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GLOBALLY BARYON SYMMETRIC COSMOLOGY, GUT SPONTANEOUS SYMMETRY BREAKING
AND THE STRUCTURE OF THE UNIVERSE

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Abstract

Grand unified theories (GUT) such as SU(5), with spontaneous
symmetry breaking, can lead more naturally to a globally baryon symmetric
big bang cosmology with a domain structure than to a totally asymmetric
cosmology. The symmetry is broken at random in causally independent
domains, favoring neither a baryon nor an antibaryon excess on a universal
scale. Because of the additional freedom in the high-energy physics
allowed by such GUT gauge theories, new observational tests may be
possible. Arguments in favor of this cosmology and various observational
tests are discussed.

1. Introduction

Two basic schemes for baryon-symmetric big-bang cosmologies have
been suggested. In one scheme regions containing excess baryons existed
apart from regions containing excess antibaryons as an initial condition
of the big-bang.[1] The other, more ambitious picture is that of an ini-
tially globally (universally) symmetric big-bang where a small scale
dynamical separation of matter and antimatter follows. Like regions then
coalesce into astronomically large domains.[2] A review of these symmetric
cosmologies and their consequences together with a large list of references
may be found in Ref. 3, but we should mention that one of the long-standing
attractive features of such theories is the explanation of the origin and
spectrum of the observed cosmic background γ-radiation.

In spite of the pleasing initial and overall symmetry of the above
schemes, the case against antimatter existing anywhere on a large scale
in the universe has been made and has a pervasive influence in present
thinking about cosmology.[4] If this alternative view is correct, we seem
to be up against the baryon excess as an initial condition, ex nihilo.
However, advocates of this alternative can, on the face of it, be heart-
ened by recent developments in elementary particle theory involving
baryon-non-conserving forces in grand unified field theories. Perhaps
an initial, aesthetic baryon symmetry is broken in an early stage of the
universe by leptoquark interactions.[5-10] (Even if there was an initial
baryon excess, leptoquark interactions would first restore and then break
the overall baryon symmetry as the universe cools). Such interactions
will also provide for proton decay with a lifetime $\leqslant 10^{33}$ years or so,[11]
a prediction which is the basis of some new experimental proposals[12,13]
and may soon be tested. It is even said that the matter-antimatter
asymmetry is the first good thing about proton instability, the latter
being hard to avoid in grand unified theories.[14]

Thus a popular scenario is that the universe has the observed baryon number to photon number ratio of about 10^{-9} throughout as the result of baryon nonconservation. A universal symmetry has evolved to a universal asymmetry. We believe, on the other hand, that the assumption of a universal asymmetry may not be justified. We argue in this paper that, in fact, the microscopic physics may very well maintain an overall, universal symmetry in the present epoch through a network of random domains of varying degrees of baryon excess, positive and negative.

2. Causal Domain Structure

There are three important considerations in models where the baryon symmetry is broken spontaneously in the early big-bang:

(1) Owing to the finite age of the universe, t_u, regions separated by distances greater than the event horizon ct_u are not and never were in causal contact.[15]

(2) The symmetries of the particle interactions involved in obtaining theoretical estimates of the baryon excess change as the universe cools. In those theories where at least part of the CP (charge conjugation X parity) violation arises from spontaneous symmetry breaking, we need thermal disequilibrium, baryon non-conservation, C and CP violation for a net effect. We start with CP symmetry at high temperatures (energies) and achieve a "soft" CP asymmetry at low temperatures. (There may be additional "hard" CP violation throughout the temperature range.)

(3) There is no way of determining a priori which way such CP breaking will occur. From the continuous set of vacuum states admitted by the Lagrangian with which we begin, the resulting degree of CP violation from spontaneous symmetry breaking may be fixed at random. Indeed, the choice of sign in the existing calculations has never been questioned. (Never mind the fact that one could change the definition of which field represents the quark or the antiquark.)

Thus, if there is additional CP symmetry breaking at time t^*, it should be broken in such a way that regions separated by distances greater than ct^* will have independent phases in the symmetry breaking parameters. Whatever the possible subsequent evolution of these domains[16-17] and coalescence processes occurring in the quark or baryon interactions which follow[16-21], it appears that causality does not permit the generation of a universal asymmetry from the spontaneous symmetry breaking process. Rather, one might expect a domain structure not unlike the domain structure generated when a piece of ferromagnetic material cools without the presence of an external magnetic field. In that case, spin-spin interactions produce a phase transition to a state where the directional symmetry of the Lagrangian becomes hidden on a small scale owing to a spontaneous symmetry breaking into a mosaic of independent domains, each of which contains atoms having their magnetic moments aligned in a given direction. On the average, there will be no preferred direction on a global scale. Analogously, one may expect that spontaneous symmetry breaking processes in the early big-bang will most likely break baryon symmetry in localized regions of the universe, but will preserve the overall global matter-antimatter symmetry of the initial state. Thus,

present ideas of unified gauge theories with spontaneous symmetry breaking can lead more naturally to a baryon-symmetric cosmology[3], as opposed to the totally asymmetric cosmology implicit in the work of previous authors.[5-10]

3. CP Violation in Grand Unified Theories

We now focus on the relationship between fundamental parameters in the symmetry breaking and the astrophysical baryon asymmetry. As an illustration of a simple spontaneous symmetry breaking, we remind the reader of the toy instructional model for two scalar fields ϕ_i with Lagrangian

$$L = \frac{1}{2}(\partial_\mu \phi_i)(\partial^\mu \phi_i) - V(\phi_i)$$

where (1)

$$V(\phi_i) = \frac{1}{2}m^2\phi_i\phi_i + \frac{1}{4}\lambda(\phi_i\phi_i)^2$$

for which the vacuum expectation value (VEV) satisfies

$$\langle\phi_1^2 + \phi_2^2\rangle_0 = -\frac{m^2}{\lambda}$$ (2)

in the case $m^2 < 0$ (See Figure 1).

Thus there is an infinitely degenerate number of possible vacuum states, all having the same ground state energy and all of which are equally possible. The overall symmetry of the universe is then implied by the symmetry of the VEV solution set, which in the example of equation (1) is a U(1) symmetry which can be characterized by a phase angle α.

The above analysis is dangerously simplified. We must, of course, consider a rather rich Higgs sector in a grand unified model. In general the phases α involved in the VEVs in such a model could not all be simply
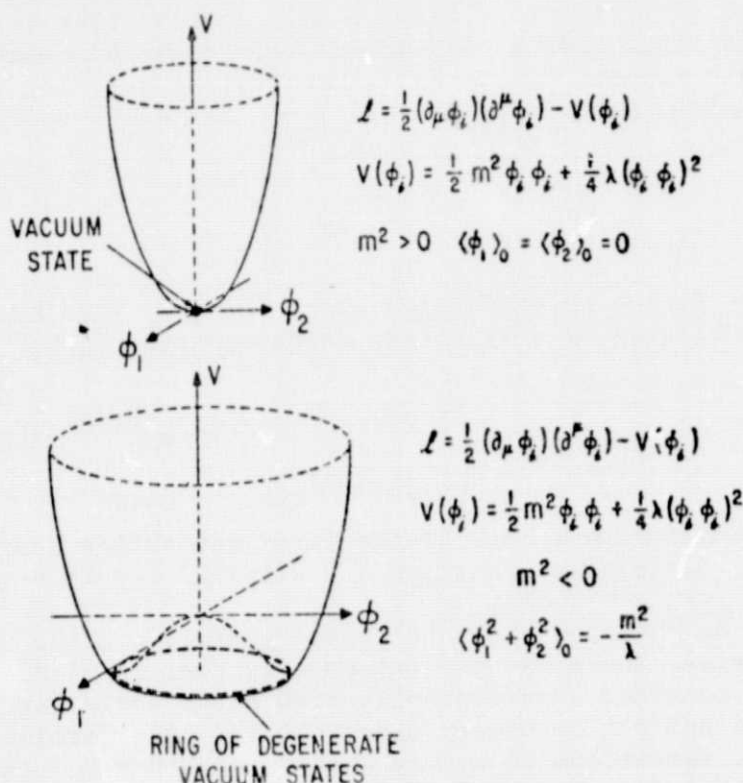

Fig. 1 - The potential for the simple two-field ϕ^4 model described in the test. The case $m^2>0$ has a unique vacuum state with $\langle\phi\rangle_0=0$. The case $m^2<0$ has an S^1 solution set where the fields in general have a non-zero VEV.

redefined into the fermion fields, as is the case with the toy model above.

In general the baryon asymmetry is proportional to a parameter ξ which characterizes CP violation.[8-10] Let us introduce the CP phase parameter δ where

$$\xi \propto \sin \delta \tag{3}$$

If δ takes on random values in different domains, we cannot achieve a uniform baryon excess throughout the universe. That δ _is_ randomized follows if it is an appropriate linear combination of vacuum-expectation-value phases α_i, e.g.,

$$\delta = \sum_i N_i \alpha_i \tag{4}$$

where N_i is an integer. More complicated, and perhaps more realistic, relations $\delta(\alpha_i)$ may have the same effect.

Although there has been a good deal of interest in understanding CP non-invariance through spontaneous symmetry breaking[22], the specific gauge model relationships giving $\delta(\alpha_i)$ have received little attention. Thus, an example may be helpful. The general idea is that the Yukawa terms give rise to a fermion mass matrix after the scalar fields are translated. For a four-quark left-right symmetric model with two Higgs doublets, patterned after that of Ref. 23, a mass matrix of the form

$$M = \begin{pmatrix} ae^{i\alpha_1} & ce^{-i\alpha_2} \\ ce^{-i\alpha_2} & be^{i\alpha_1} \end{pmatrix} \tag{5}$$

holds for quark pairs of a given charge. This symmetric matrix can be diagonalized by a biunitary transformation $U_L M U_R^{-1}$ where

$$U_L = U_R^* = \begin{pmatrix} \cos\theta & e^{i(\delta/2)}\sin\theta \\ -e^{i(\delta/2)}\sin\theta & \cos\theta \end{pmatrix} e^{i\varphi} \tag{6}$$

Neglecting the masses of the first generation quarks, i.e. $m_u, m_d \ll m_s$, m_c, we obtain the relation $\delta = 2(\alpha_1 + \alpha_2)$ for this model.

As one goes about calculating $\delta(\alpha_i)$ for the various grand unified theories, there are two extremes to keep in mind. On the one hand, we must consider a sufficiently rich Higgs sector such that the phases α_i could not all be simply redefined into the fermion fields. On the other hand, variations in α_i may change more than δ. In general, different breaking directions may lead to quite different physics for a given model. However, the breakdown of SU(5) to SU(3)⊗SU(2)⊗U(1) _can_ be independent of the phases if the Higgs potential parameters are so restricted.[24,25]

4. Domain Growth and Galaxy Formation

In the light of the above discussion, we suggest that the initial

domains formed at a time when the temperature of the universe was comparable to the masses of the superheavy gauge or Higgs bosons involved in the symmetry breaking. The initial domains could then have acted as nuclei for triggering growth to much larger sized regions. Although an examination of possible growth mechanisms is beyond the scope of this paper, several possibilities come to mind. One is domain growth through CP-violating instanton transitions.[26] Another relevant scheme involves not the Higgs fields, but the quarks. In this regard, possible mechanisms involving quark-gluon Leidenfrost effects and quark clustering remain to be explored.

At low temperatures, nuclear effects and Leidenfrost effects have been suggested[2] and studied up to the stage of galaxy formation as mechansims for increasing the size of domains to encompass masses on the scale of galaxy clusters.[3] Such explorations have shown that globally baryon symmetric cosmology can lead more readily to galaxy formation than can the standard totally asymmetric cosmology.[18,20] It is important to note in this context that among cosmological models involving spontaneous symmetry breaking in grand unified theories, the standard asymmetric model requires an even stronger domain growth so that the whole universe becomes the final domain! The only other alternative is to put in an ad hoc hard CP violation without knowing over what size scale it applies. However, it is not clear that such a gauge theory with an external CP-violating piece in the Lagrangian would preserve the attractive aspects of the spontaneous-symmetry-breaking models for CP violation, such as renormalizability.

Various workers have tried to trace the growth of the domains of matter and antimatter from an era of phase transition to the era marking the decoupling of the matter and antimatter from the blackbody radiation field.[2] This takes us to a time of the order of 10^5-10^7 years after the big-bang when the cosmic plasma was almost cool enough to combine into neutral atoms. Starting at this point in the evolution of the universe, the question of structure and galaxy formation arises. Models of galaxy formation from "primordial turbulence" have always been attractive as a way of accounting for galaxy formation as well as for observed parameters such as the angular momenta and spatial distribution of galaxies. However, in this work, turbulence was introduced in ad hoc manner and, furthermore, such turbulence is strongly damped out in the cosmic plasma because of the very high viscosity of the blackbody radiation field which remains coupled to the cosmic plasma until the neutralization ("recombination") epoch. Several years ago, a model was proposed[18] for galaxy formation within the context of baryon symmetric big-bang cosmology. In this model, dissipation is constantly fought by continuing radiation pressure from annihilation on the boundaries of domains, which regenerates the turbulence. Radiation pressure from the annihilation, being directed generally away from the boundary regions, can drive mass fluid motions of the domains as well as causing further coalescence until the domains reach the size of galaxy clusters.

At the recombination epoch, two important changes were caused in the cosmic fluid motions. The viscosity dropped drastically and the turbulent fluid motions became supersonic. This occurred because the sound speed dropped sharply from its value in the cosmic plasma of $3^{-1/2}c$ (because the momentum was transferred by radiation) to the thermal velocity of the

neutral gas. Thus, whereas the cosmic plasma behaved as a viscous incompressible fluid, both "small-scale" turbulence and density fluctuations could start to build up in the decoupled atomic fluid and later contract to form galaxies. In this scenario annihilation pressure can provide a continuous source of generating turbulence. Figures 2 and 3 show that this model for galaxy formation gives reasonable values for rotational velocities of galaxies and domain sizes (of galaxy cluster or supercluster size) for the present epoch ($Z = 0$).
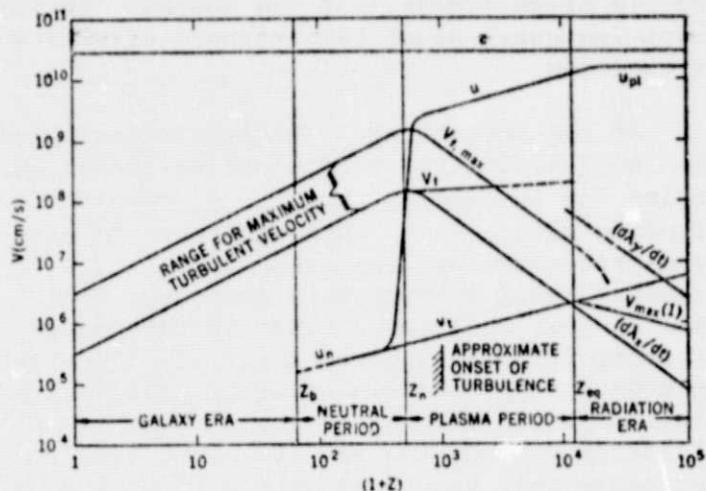

Fig. 2 - Various velocities discussed in the galaxy formation model of Ref. 18 given as a function of redshift: c, speed of light; u_{pl}, speed of sound in the cosmic plasma; u_n, speed of sound in the neutralized gas; V_f gives the lower limit on the fluid velocity at neutralization redshift Z_n; V_t is the thermal velocity. The turbulent velocities predicted for $Z = 0$ are comparable to those observed for spiral galaxy rotation.

Fig. 3 - Range of domain size d as a function of redshift from Ref. 18. Domain sizes of the order of 1-10 Mpc are predicted for the present era ($Z = 0$).
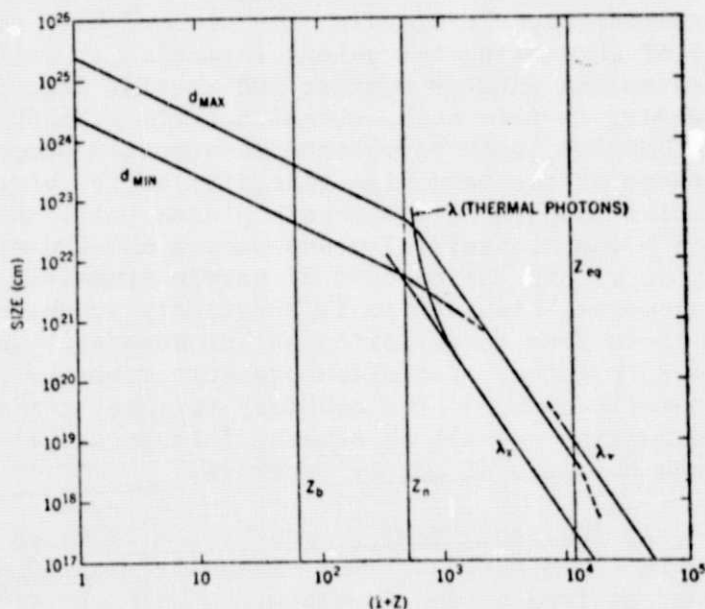
5. Observational Consequences

While we cannot claim that the arguments presented above constitute a proof for the baryon-symmetric domain-type cosmology, there are recent astrophysical data which tend to support this point-of-view.

5.1 The Cosmic γ-Ray Background Radiation

One of the most significant consequences of globally baryon symmetric big-bang cosmology lies in the production of an observable cosmic background of γ-radiation from the decay of π^0-mesons produced in nucleon-antinucleon annihilations throughout the history of the universe. This is also perhaps at present the most encouraging aspect of this cosmology, since it satisfactorily explains the observed energy spectrum of the cosmic background γ-radiation as no other proposed mechanism does (with the possible exception of hypothetical point sources).

At high redshifts Z, when pair production and Compton scattering become important, it becomes necessary to solve a cosmological-photon-transport equation in order to determine the γ-ray background spectrum. For a differential photon energy spectrum, we find this equation to be of the form

$$y\frac{\partial I}{\partial y} + \epsilon\frac{\partial I}{\partial \epsilon} = 2I + \frac{y^2\Omega\nu}{[1+\Omega(y-1)]^{1/2}}\left[A(\epsilon)I - \int_\epsilon^{b(\epsilon)} d\epsilon' B(\epsilon|\epsilon')I(\epsilon',y)\right.$$

$$\left. -\xi^2\Omega n_c y^3 v(R(y))\frac{\sigma_A(T(y))}{\pi r_e^2}G_A(\epsilon)\right], \tag{7}$$

where $I=I(\epsilon,y)$ is the annihilation γ-ray flux,

$$y = 1 + Z, \quad \epsilon = E_\gamma/m_e c^2, \tag{8}$$

and

$$\nu = (n_c c/H_0)(\pi r_e^2), \quad (H_0 = \text{Hubble constant})$$

r_e being the classical electron radius and σ_A is the annihilation cross section, and $G_A(\epsilon)$ is the source annihilation γ-ray function. The function A(ε) is proportional to the total cross section for absorption and scattering of γ rays by pair production and Compton interactions. The scattering function $B(\epsilon|\epsilon')$ is proportional to the probability that a γ ray of energy ϵ' will Compton scatter to energy ϵ. The upper limit is

$$b(\epsilon) = \begin{cases} \epsilon/(1-2\epsilon), & \epsilon<\frac{1}{2} \\ \infty, & \epsilon\geq\frac{1}{2}. \end{cases} \tag{9}$$

The function $I_A(E_\gamma, y=1)$ obtained by numerical solution of equation (7) corresponds to the present-day (Z=0) γ-ray-background spectrum predicted from these calculations to arise from matter-antimatter annihilations in the universe. The peak in the calculated annihilation spectrum near 1 MeV is caused by absorption and scattering of the γ rays by interactions with an intergalactic medium. This is because the γ-ray "window" of the universe closes below 1 MeV (see Figure 4).

Figure 5 shows the observational data on the γ-ray background spectrum as compiled in Ref. 3. The dashed line marked X is an extrapolation of the data from the x-ray range. The theoretical curve marked "annihilation" is the calculated annihilation spectrum with a mean present universal gas density of $3 \times 10^{-7} cm^{-3}$ and a Hubble constant $H_o = 50 km/s/Mpc$ according to present observational evidence regarding these parameters. This corresponds to a value of $\Omega \approx 0.1$, where Ω is the ratio of the mass of the universe to that needed to gravitationally close the universe.
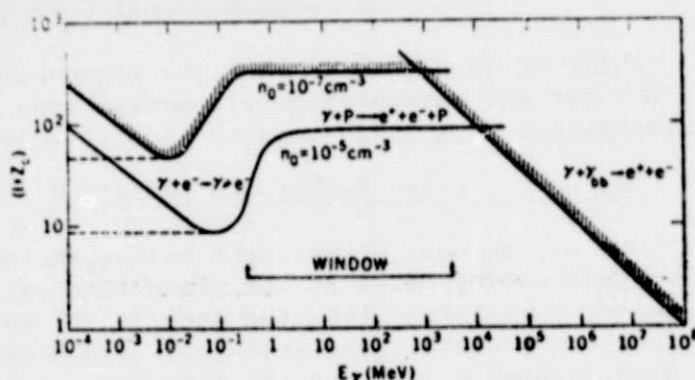

Fig. 4 – The redshift at which the universe becomes opaque to photons given as a function of observed gamma-ray energy. Gamma-rays originating at all redshifts below the curve can reach us unattenuated with the energy indicated. The two curves on the left side of the figure are for attenuation by Compton scattering with intergalactic electrons having the densities indicated and for pair production. The right-hand curve results from attenuation of gamma-rays by interactions with the microwave blackbody radiation.

Other recent attempts to account for the diffuse γ-ray background radiation above 100 MeV energy give spectra which are in one way or another inconsistent with the observations, generally by being too flat.

5.2 "Cell" Structure of the Universe

In addition to the data on the cosmic γ ray background, there is other evidence for matter and antimatter domains.

The first additional piece of evidence comes from new and striking results on the distribution of galaxies in the universe. Not only do galaxies form clusters, but also these clusters of galaxies are not uniformly distributed; they cluster into superclusters. Between the superclusters are large voids - regions with a very low (possibly zero) space density of galaxies.[27-29] The existence of these holes, which is difficult to understand in the context of standard big-bang cosmology, is the kind of structure which can arise from a domain-type universally symmetric cosmology. The cosmic background γ-radiation originating from supercluster boundary annihilations[3] should exhibit angular fluctuations which can best be studied with a high-resolution detector[30] such as the 100 MeV spark chamber detector proposed for a future satellite "Gamma Ray Observatory".

The astronomical observations of the non-uniform "cell structure" distribution of galaxies also gains credence with the third piece of

Fig. 5 – Cosmic γ-Ray Background Spectrum from Matter-Antimatter Annihilation and Observational Data.
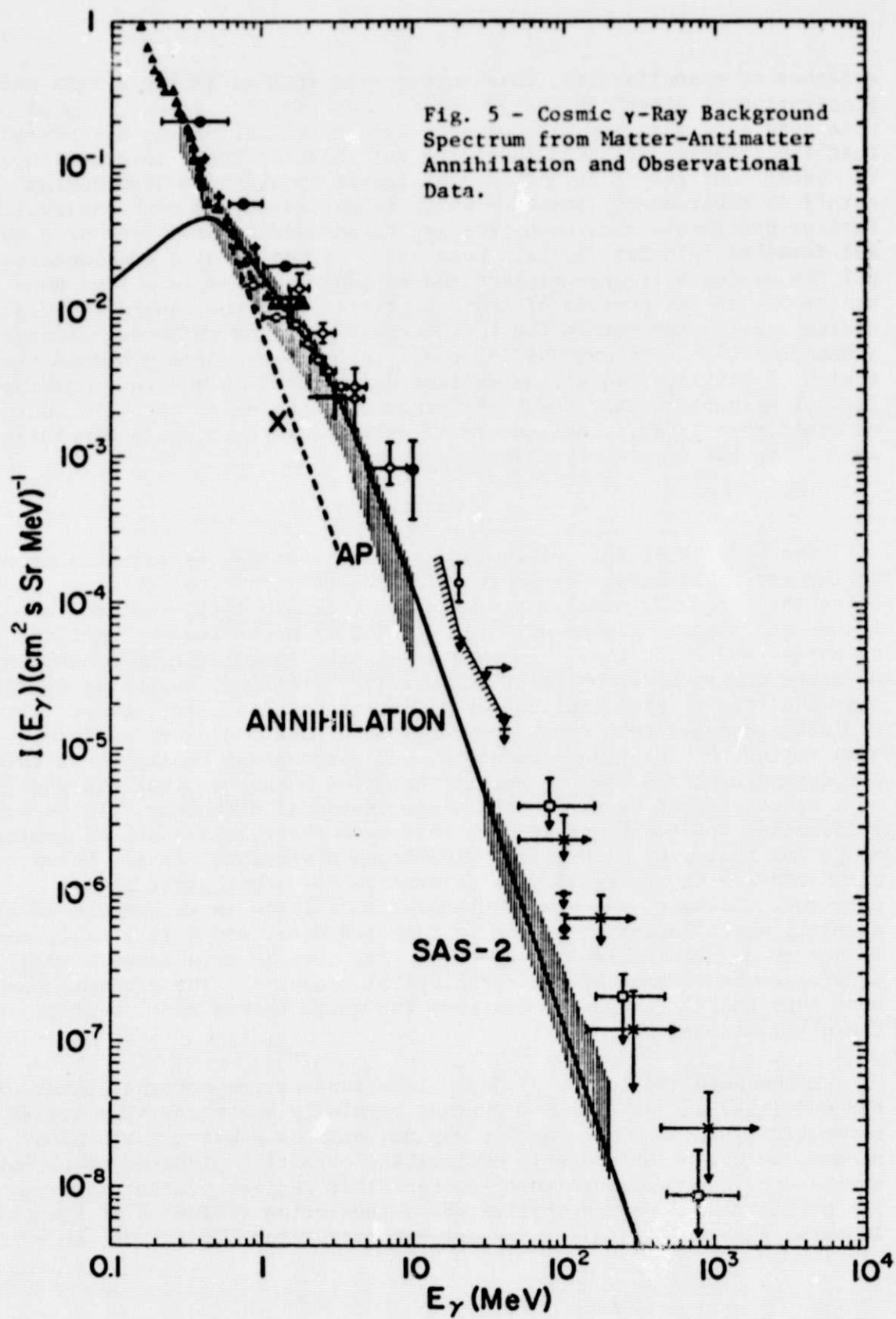
evidence of nonuniformity, which comes from studies of the origin and propagation of ultrahigh energy cosmic rays (UHCR). It was pointed out some time ago, when the microwave background radiation was discovered, that the lifetime of UHCRs should be cut short by their interaction with the background radiation.[31,32] The result should be a high-energy cutoff in their energy spectrum which is not in accord with observation. Various hypothesis have been proposed to account for the lack of a cutoff and detailed calculations have been made. After careful consideration of all the evidence it appears that the explanation lies in a true non-uniformity of the sources of these particles with the observed UHCRs coming mainly from within the local supercluster of which our galaxy is a member.[33,34] The obvious inference is that immediately beyond the region of the local supercluster is a dearth of UHCR sources. Making the logical assumption that UHCRs are produced in galaxies or radio sources, we would then infer a real dearth of galaxies between the superclusters, supporting the domain structure viewpoint.

6. Conclusion

The bedrock of this viewpoint has been spontaneous symmetry breaking in the early big-bang. Accounting for the CP violations this way may solve the strong CP problem and keep renormalizability. We are thus led to the seeds whose growth may give cluster or supercluster domains – cells of matter and antimatter. In this framework, there must be constraints on gauge theory model building and symmetry breaking, depending on the nature of the physics implied for different domains. (Of course, CP violation changes from domain to domain.) Quantities such as fermion mass ratios, P violation parameters, and gauge group breakdown patterns can depend upon the vacuum-expectation-value phases so that the models must be considered by the tests of observational cosmology. It is both interesting and important to note that such observations are of limited scope and that many high-energy laboratory observables (e.g., heavy quark masses) cannot readily be determined for other parts of the universe. However, the proton-electron mass ratio is an example of a quantity which cannot be violently tampered with, since it affects the frequency of observable line spectra. But even in this case, a small effect can be blurred by the cosmological redshift. The scenario presented here thus poses a challenge for both the gauge theory model builder and the observational astronomer.

If we heed the lesson of Copernicus that we are not the center of the universe, and we also realize that seemingly arbitrary high energy parameters such as mixing angles may not only be arbitrary but also random, we allow ourselves to explore the potential richness of phenomena admitted by the new gauge theories for other regions of the universe. The subtleties of cosmic physics which then arise remind us of Einstein's immortal phrase *"Raffiniert ist der Herrgott, aber boshaft ist er nicht"*.

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