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COSMIC RAY ANTIMATTER AND BARYON SYMMETRIC COSMOLOGY

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SUMMARY

We examine the relative merits and difficulties of the primary and secondary origin hypotheses for the observed cosmic-ray antiprotons, including the new low-energy measurement of Buffington, et al. We conclude that the cosmic-ray antiproton data may be evidence for antimatter galaxies and baryon symmetric cosmology. The present $\bar{p}$ data are consistent with a primary extragalactic component having $\bar{p}/p \simeq 3.2 \pm 0.7 \times 10^{-4}$ independent of energy. We propose that primary extragalactic cosmic ray antiprotons are most likely from active galaxies and that expected disintegration of $\bar{\alpha}$'s in the source quite naturally leads to $\bar{\alpha}/\alpha < \bar{p}/p$. We further predict an estimate for $\bar{\alpha}/\alpha \sim 10^{-5}$, within range of future cosmic ray detectors.

1. INTRODUCTION

Measurements of cosmic-ray antiprotons can give us important information about cosmic ray propagation and also provide a test for primary cosmological antimatter. Gaisser and Levy (1974) pointed out that observation of a cosmic ray $\bar{p}$ flux without the low energy cutoff characteristic of secondary antiprotons would be a signal of a primary component of antiprotons in the cosmic rays. Buffington, et al. (1981), observing at energies well below the secondary cutoff, appear to see just such a signal of primary antiprotons. Data on $\bar{p}$ fluxes at higher energies (Golden et al., 1979: Bogomolov et al. 1979) give measured values a factor of 4-10 above the fluxes expected for a standard propagation model. We will consider here the question of primary versus secondary origin of these cosmic ray antiprotons.

The magnitude of the secondary $\bar{p}$ component depends critically upon how cosmic rays are stored in and propagate through the Galaxy. The simplest model describing the propagation of cosmic rays in the Galaxy is the leaky box model. The parameter describing the model is the mean amount of matter that cosmic rays pass through between production and observation, this given in g/cm^2. Gaisser and Maurer (1973) made the first reliable predictions of the $\bar{p}/p$ ratio and used this model with a mean escape length of 5 g/cm^2 of hydrogen. Their result is consistent with later predictions as reviewed by Protheroe (1982). All these predictions show a cutoff in the secondary $\bar{p}$ spectrum for kinetic energies below ~1 GeV, which is a basic feature of the kinematics of the $\bar{p}$ production process.

The closed galaxy model (Rasmussen & Peters, 1975: Peters & Westergaard, 1977) gives a higher $\bar{p}/p$ ratio than the leaky box model (Steigman 1977) as do models in which a number of cosmic ray sources are shrouded by ~50 g/cm^2 of

matter (Cowsik and Gaisser, 1981; Cesarsky and Montmerle, 1981). The spectrum of secondary antiprotons produced in these models is similar to that in the closed galaxy model, not accounting for the Buffington, et al. data. The $\bar{p}/p$ ratio expected in this model and in the leaky box model is plotted in Fig 1 for the acceptable range of the parameter K (see Protheroe, 1981, for discussion and details of the method of calculation. It should be noted that the closed galaxy model appears to be in conflict with radio (Price 1974, Brindle, et al. 1978) and γ-ray observations (Stecker and Jones 1977).

2. PRIMARY ANTIPROTONS

It is difficult to see how the high flux of antiprotons below the low energy cutoff characteristic of secondary antiprotons can be explained by a secondary galactic component unless there is significant adiabatic deceleration of the $\bar{p}$'s, in diffusing away from an accreting production region near a compact object along with expanding material (Eichler, 1982), a difficult situtation to imagine. We show in Figure 1, the prediction of Protheroe (1981) for the leaky box model using the energy dependence of the mean escape length obtained from secondary to primary ratios (Protheroe et al., 1981). If this model provides the correct description of galactic cosmic ray confinement and propagation, then the spectrum of an additional primary antiproton component making up the deficit $\bar{p}$ flux would have roughly the same shape as the galactic proton spectrum. The ratio of the extragalactic $\bar{p}$ flux to the galactic proton flux would then be $(3.2\pm0.7)\times10^{-4}$. This is plotted as the heavy dashed line in Figure 1. The reduction in the $\bar{p}/p$ ratio below this value at low energies is due to the combined effects of "galactic modulation" (ionization energy losses, nuclear interactions and $\bar{p}$ annihilation) and solar

modulation assuming a mean energy loss in the heliosphere of 600 MeV. For galactic wind models (Jokipii 1976: Jones 1979), energy losses would be greater and the reduction enhanced. The $\bar{p}/p$ ratio for the sum of this extragalactic component plus the secondary (leaky box model) component is shown by the heavy line of Figure 1.

A primary origin for the low energy $\bar{p}$'s in terms of evaporation of primordial black holes in the galaxy has been considered by Kiraly et al. (1981) and by Turner (1982) who also considered evaporation of extragalactic black holes. An alternative hypothesis wherein the observed high $\bar{p}$ flux is due to an extragalactic component of cosmic rays produced in part by antimatter galaxies has been briefly discussed by Stecker (1981,1982), Stecker et al. (1981) and Kiraly et al. (1981). We shall consider this prossibility in detail here.

2.1 BARYON SYMMETRIC COSMOLOGY

With the advent of grand unification theories, models have been suggested to generate a universal baryon asymmetry, with the consequence that no important amounts of antimatter would be left in the universe at the present time (see e.g., Langacker 1981 and references therein). These models have been motivated by observational constraints on antimatter at least in our region of the universe (Steigman 1976). However, some of these constraints have been shown to be overrestrictive (Stecker 1978, Allen 1981). Indeed there may be cosmologically significant amounts of antimatter, even whole galaxies of antimatter, elsewhere in the universe (Stecker 1981, 1982).

In grand unified theories, a scenario has been developed for the evolution of the early universe wherein the matter which eventually forms the galaxies arises as a "baryon excess" owing to baryon number non-conserving

interactions at ultrahigh energies. This scenario requires that CP symmetry be broken.

The basic physics argument regarding the question of a baryon symmetric versus an asymmetric cosmology hinges on the manner in which CP violation is incorporated into unified gauge theories (and into nature). If the CP violation is spontaneous, it will arise with random sign changes in causally independent regions and the universe will naturaly split into domains of baryon and antibaryon excesses with no preferred direction of CP symmetry nonconservation.

The basic scenario envisioned for this baryon symmetric cosmology is outlined in Fig. 2. This scenario provides a viable explanation of the cosmic γ-ray background spectrum as presently observed (Stecker 1982b). Since the γ-ray background observations indicate that matter and antimatter regions in the universe are separated on at least a galactic scale, a small extragalactic cosmic ray flux containing $\bar{p}$'s would be consistent with this cosmology. Using rough energetics arguments (Ginzburg & Syrovatskii 1964; Hayakawa 1969) one can estimate that leakage from normal galaxies would produce an extragalactic cosmic ray component with a flux $(I_{ex}/I_{gal})_{NG} = \xi_{NG} \simeq 10^{-5}$-$10^{-4}$. For active galaxies, these estimates yield $\xi_{AG} \simeq 10^{-3}$. The γ-ray data allow values for ξ ranging as high as 10^{-1} (Said et al., 1982; see also Stecker 1975, Dodds et al 1975), but the implication of galactic source dominance favors lower values. If we assume that half of the extragalactic flux is from antimatter sources, the resulting estimate for $\bar{p}/p \simeq \frac{1}{2}\xi_{AG} \simeq 5\times10^{-4}$ is interestingly quite close to the measured values (see Fig. 1).

2.2 ANTIHELIUM FLUXES

It has been argued (Steigman 1976, Buffington et al. 1981, Eichler 1982) that a primary origin for cosmic-ray $\bar{p}$'s would imply that the ratio $\bar{p}/p = \bar{\alpha}/\alpha$ and an observed value for $\bar{\alpha}/\alpha < \bar{p}/p$ would be a serious problem for the primary origin hypothesis. The best 95% confidence upper limits at present are $\bar{\alpha}/\alpha \lesssim 1.5\times10^{-4}$ at 4.33 GeV/c (Badhwar et al. 1978) barely consistent with $\bar{\alpha}/\alpha \approx \bar{p}/p$, and $\bar{\alpha}/\alpha < 2.2\times10^{-5}$ in the low energy range of 130-370 MeV/nucleon (Buffington et al., 1981) indicating that $\bar{\alpha}/\alpha < \bar{p}/p$ in this energy range. However our proposed hypothesis leads naturally to $\bar{\alpha}/\alpha < \bar{p}/p$ and furthermore leads to predicted value for $\bar{\alpha}/\alpha$.

We have postulated that the bulk of extragalactic cosmic rays are produced in active galactic nuclei (or quasars). We can make estimates of the disintegration probability for cosmic ray He escaping from these objects. Photodisintegration of He nuclei by low energy γ-rays and spallation will be the most important processes. We can estimate the importance of these effects in the context of a simple spherical accretion model of quasars and active galactic nuclei (e.g. Protheroe and Kazanas, 1982: see also the model of Berezinsky and Ginzburg 1981).

The photodisintegration timescale of non-relativistic nuclei at a distance r from an active galaxy depends on the photon density in the γ-ray region and thus depends on the γ-ray luminosity:

$$T_{photo} \approx \frac{2.3\pi\ r^2\ \varepsilon_0^2}{L(\varepsilon_0)\ \Sigma_d}$$

where $L(\varepsilon)$ is the luminosity at energy ε in (MeV s^{-1} decade^{-1}, ε_0 is the peak energy of the dipole resonance (~ 30 MeV for He) and Σ_d is the energy-

integrated dipole resonance cross section, ~ 60 MeV mb for He (Puget, et al 1976). For example, taking 3C273, $L \approx 2 \times 10^{46}$ erg s^{-1} decade and the source radius is probably in the range 10^{15} to 10^{18} cm. This results in a photodisintegration time in the range $3 \times 10^2 - 3 \times 10^8$ years. This process can thus be important for disintegration of He but its efficiency depends on the photon density.

If the radiation from active galaxies is produced when the directed infall kinetic energy of accreting matter is dissipated by some efficient mechanism at a distance r from a black hole, then the luminosity, L, is related to the accretion rate, $\dot{M}$, by,

$$L \approx \frac{r_s}{r} \dot{M} c^2$$

where r_s is the Schwartzchild radius. Matter conservation during the accretion flow constrains the matter density as a function of radius:

$$n = \frac{\dot{M}}{m_p} (4\pi r^2 v)^{-1}$$

where m_p is the proton mass and v is the flow velocity, $(\frac{r_s}{r})^{1/2} c$.

Taking a spallation cross section for He of ~100 mb (Riddiford and Williams 1960), the spallation time at radius r is then

$$T_{spall} \approx \frac{6 \times 10^{44}}{L_{Tot}} (\frac{M}{M_\odot}) (\frac{r}{r_s})^{1/2} \text{ s}$$

where M is the black hole mass and L_{Tot} is the total luminosity in erg s^{-1}. For quasars with luminosities in the range $10^{44} - 10^{46}$ erg/s, black hole masses in the range $10^8 - 10^{10}$ $M_\odot$ and (r/r_s) ranging from $10^0 - 10^3$, we obtain

T_{spall} in the range $2 \times 10^{-1} - 6 \times 10^{4}$ years (about 10^4 times the light travel time, r/c). In our galaxy, cosmic rays are trapped for $\sim 10^7$ years before escaping (Garcia-Munoz et al., 1977), i.e. $\sim 10^4$ times the crossing time of the matter disk of our galaxy. Since magnetic fields in quasars are known to be higher than in our Galaxy, it is not unreasonable to expect trapping times as large or greater than T_{spall} in active galaxies resulting in spallation of most of the He nuclei produced, before they escape as extragalactic cosmic rays. In the "cocoon" model of Berezinsky and Ginzburg (1981), spallation of He would also occur.

As we have just discussed, given the observed photon fields and matter densities, it is quite plausible that cosmic-ray α's and $\bar{\alpha}$'s can be spalled or photodisintegrated in the cores or jets of active galaxies. Thus we expect $\bar{\alpha}/\bar{p} < \alpha/p$ or $\bar{\alpha}/\alpha < \bar{p}/p$. Assuming that $\bar{\alpha}$'s are destroyed in AG sources and that those from NG sources dominate, we expect $\bar{\alpha}/\alpha = \frac{1}{2}\xi_{NG} \approx 5\times10^{-6} - 5\times10^{-5}$. In this case, future cosmic-ray experiments may soon detect $\bar{\alpha}$'s!

Antimatter active galaxies containing regions of high photon or matter density may not be detectable as γ-ray sources, however, they may be directly determined to be antimatter sources through their production of cosmic ray $\bar{\nu}_e$'s (Learned & Stecker 1980: Berezinsky & Ginzburg 1981). Other cosmic ray $\bar{\nu}_e$ tests for cosmic antimatter have also been suggested (Brown & Stecker 1982).

In a matter-antimatter symmetric domain cosmology it is possible for the helium formed in the first three minutes of the big-bang to have been partialy or totally destroyed by photodisintegration by annihilation γ-rays (Combes et al. 1975). If this is indeed the case (see also Stecker 1980; Rana 1982; Rayo, Peimbert and Torres-Peimbert 1982), active galaxies and quasars during an early "bright phase" may have had very little He to accelerate.

2.3 PROPAGATION OF EXTRAGALACTIC COSMIC RAYS

A diffusion model can be considered as a first approximation to the problem (Ginzburg & Syrovatskii 1964). The mean distance cosmic rays diffuse in time t_u is $\langle R \rangle \approx (2Dt_u)^{1/2}$ where $D = (1/3)\,\ell v$ is the diffusion coefficient and $t_u \sim 10^{10}$ years. Since $v \sim 10^{10}$ cm s^{-1}, the largest uncertainty lies with the determination of the length scale. The length ℓ is of the order of the scale of inhomogeneity of the intergalactic magnetic field, which is not less than the intergalactic particle mean free path, i.e. $\ell \gtrsim (n\sigma)^{-1}$. In an ionized gas $\sigma \approx 3\times10^{-6}T^{-2} \ln (600T/n_e^{1/3})$, which for $T \sim 10^6$-10^8K and $n_e \sim 10^{-7}$- 10^{-5} cm^{-3} gives $\ell \gtrsim 10^{21}$-10^{27}cm. (If the cosmic X-ray background is attributed to thermal emission, the corresponding temperature would then be 10^8K (Marshall et al. 1980; Boldt 1981)). The corresponding lower limits for the diffusion distance $\langle R \rangle$ is then in the range 0.5 to 500 Mpc. There is thus no intrinsic difficulty for extragalactic particles reaching our galaxy in a Hubble time from other clusters or superclusters which may consist of antimatter galaxies and contain cosmic ray sources. The estimates are admittedly quite uncertain, especially since they depend on the topology of intergalactic field lines which the cosmic rays follow.

3. CONCLUSIONS

We conclude that the primary origin hypothesis should be considered as a serious alternative explanation for the cosmic-ray $\bar{p}$ fluxes, particularly the result of Buffington *et al.* (which should be confirmed by further observation.) Such extragalactic primary origin can be considered in the context of a baryon symmetric domain cosmology. The fluxes and propagation characteristics suggested are found to be in rough agreement with the

present $\bar{p}$ data. The primary cosmic ray $\bar{p}$'s under this hypothesis would most likely be from active galaxies whereas the $\bar{\alpha}$'s may be from normal galaxies, accounting for a lower $\bar{\alpha}/\bar{p}$ ratio than the observed galactic α/p ratio. The estimates presented here suggest that present upper limits on the flux of $\bar{\alpha}$'s may be close to detection levels.

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Figure Caption

Figure 1: The predicted $\bar{p}/p$ ratio for the closed galaxy model and leaky box model compared with the observed ratio. The curve labled K=50 Mod indicates the effect of solar modulation with a mean energy loss of 600 MeV on the closed galaxy model prediction for K=50. Key to data: (■) Buffington, et al.(1981);(O) Bogomolov et al.(1979); (●) Golden et al.(1979). The heavy line shows the effect of adding an extragalactic $\bar{p}$ component to the leaky box model prediction as discussed in the text.

Figure 2: Simplest Baryon Symmetric Big Bang Scenario.

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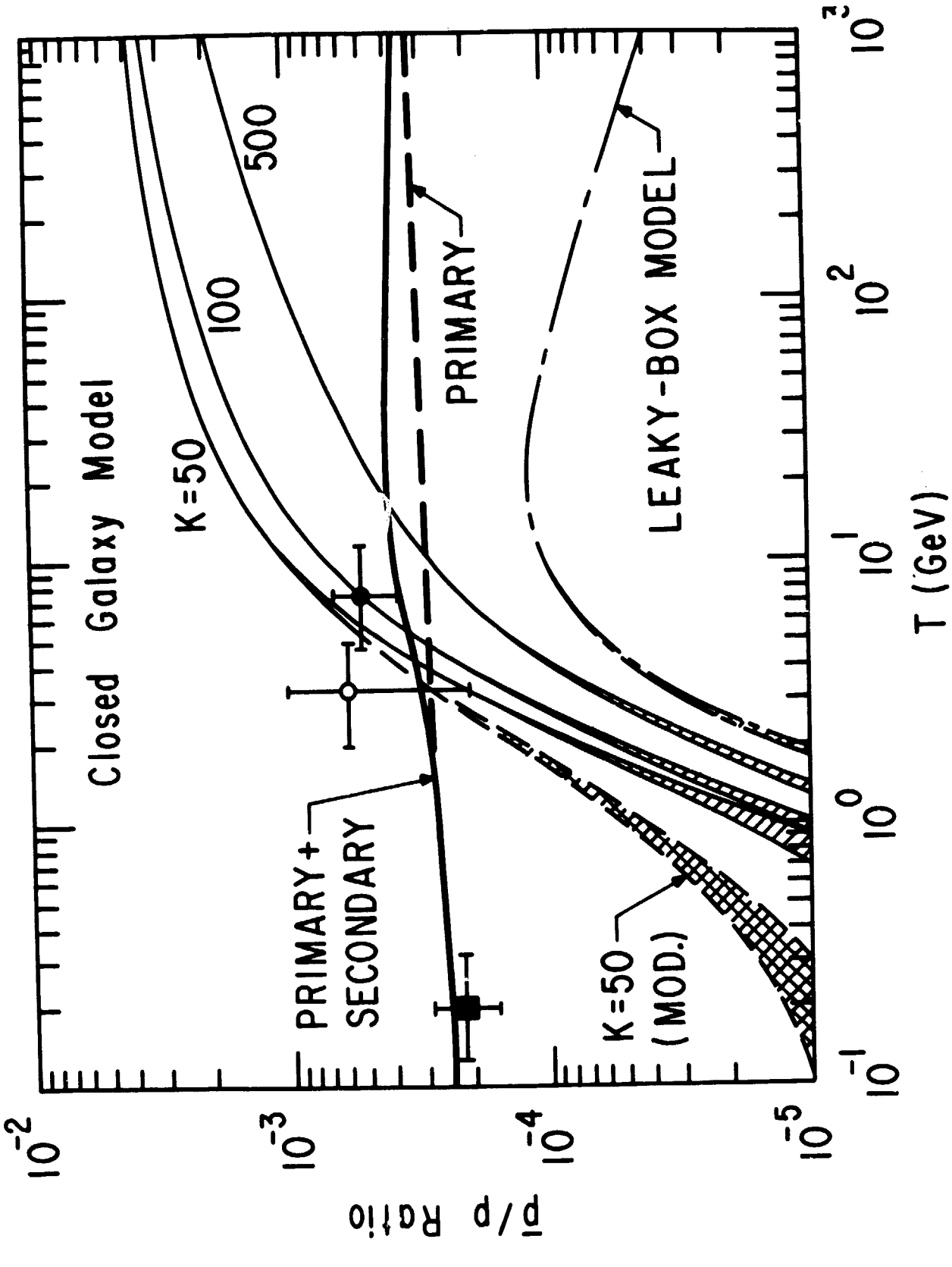
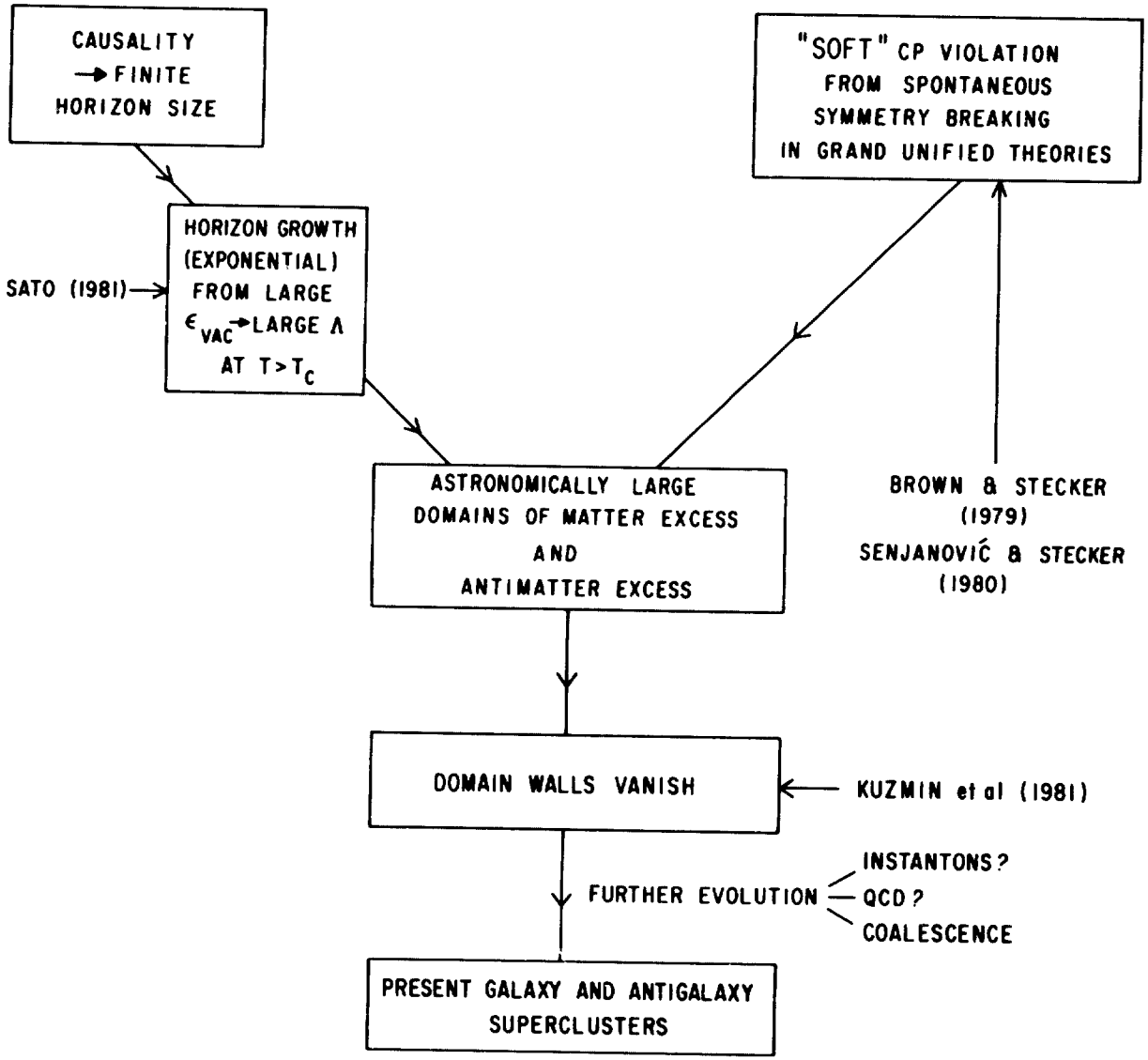


SIMPLEST BARYON SYMMETRIC BIG-BANG SCENARIO



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