THE BARYON ASYMMERY OF THE UNIVERSE

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OBSERVATIONS AND THEORETICAL CONSIDERATIONS

THE BARYON ASYMMETRY OF THE UNIVERSE

Big-bang nucleosynthesis calculations compared with cosmic H, He, d and L measurements and cosmic background radiation anisotropy measurements imply:

$$\Omega_B \simeq 0.04,$$

i.e., baryonic matter makes up 4% of the closure density of the universe (*e.g.*, review of Olive 2002; Sievers, *et al.* 2002).

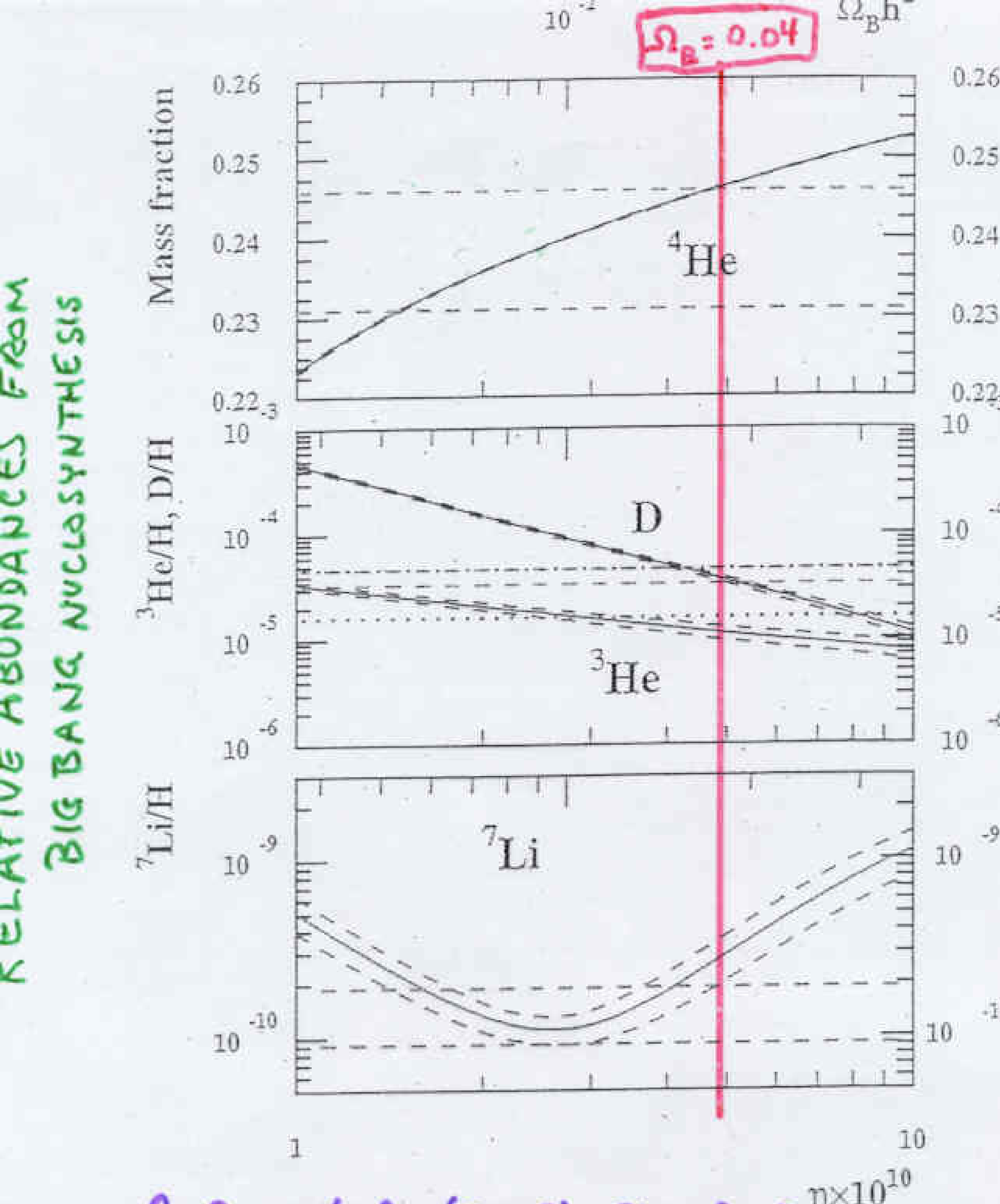
But – if N and N were in thermal equilibrium in the early hot big-bang and dropped out of equilibrium owing to the expansion of the universe, *i.e.*, when the interaction rate,

$$\Gamma = n_N v \sigma \sim n_N v m_\pi^{-2}$$

dropped below the expansion rate, H, which would have occurred at $m/T \sim 40$ ($T \simeq 20$ MeV), then we would expect

$$\Omega_B \sim 4 \times 10^{-11},$$

i.e., nine orders of magnitude less than the value implied by cosmological observations (Chiu 1966).



A. Coc et al. (2002) Phys. Rev. D.

FIG. 4. Abundances of ^4He (mass fraction), D, ^3He and ^7Li (by number relative to H) as a function of the baryon over photon ratio η. Mean values (solid curves) and 2σ limits (dashed curves) are obtained from Monte Carlo calculations. Horizontal lines represent primordial ^4He, D and ^7Li abundances deduced from observations (see text). For D the dotted lines represents the range of observed values (see Fig. 1) while the dashed lines corresponds to the adopted value of Ref. [20].

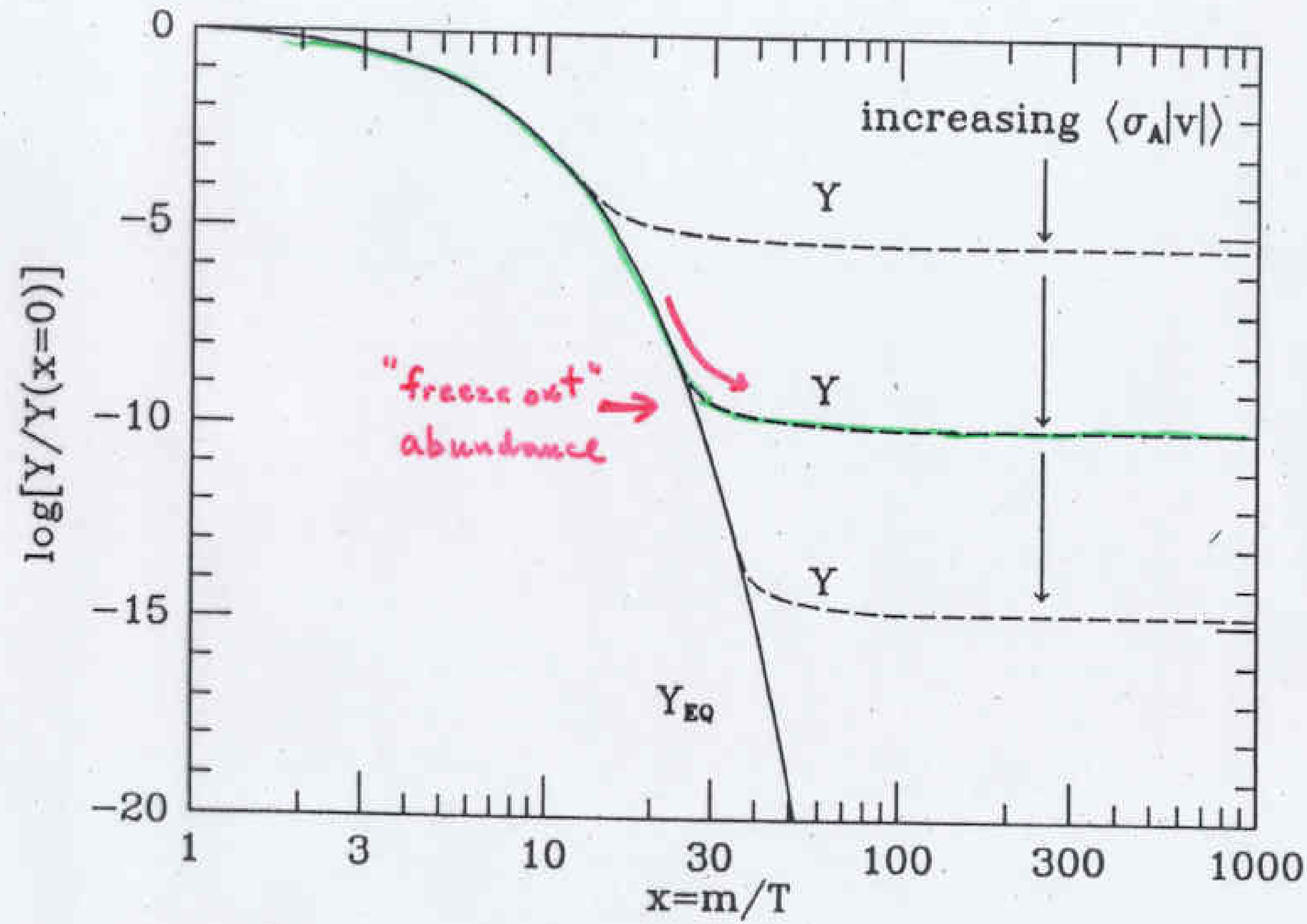


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance. (Kolb + Turner)

You can't make an omelet without breaking some eggs.

You can't make the Universe without breaking some symmetries.

Sakharov (1967) Conditions for Matter-Antimatter Asymmetry

B Violation (Grand Unified Theories)

CP Violation

Non-equilibrium (expansion)

Baryon Nonconservation in Early Universe

(Weinberg Scenario)

In Big-Bang $T \propto t^{-1/2}$

When T high enough ($T \gg M_X c^2/k$), lots of $X, \bar{X}$ pairs of gauge (or Higgs) bosons in thermal equilibrium

Consider 2 decay modes

Particle		Mode	Branching Ratio
X	→	QL	R
X	→	$\overline{QQ}$	$1-R$
$\bar{X}$	→	$\overline{QL}$	$\bar{R}$
$\bar{X}$	→	QQ	$1-\bar{R}$

If CP is violated $R \neq \bar{R}$

If $X, \bar{X}$'s fall out of thermal equilibrium owing to expansion of universe and they can decay freely, net baryon no. produced will be

$$\Delta B = \frac{1}{2}\left[\frac{1}{3}R - \frac{2}{3}(1-R) - \frac{1}{3}\bar{R} + \frac{2}{3}(1-\bar{R})\right] = \frac{1}{2}(R-\bar{R})$$

If CP not violated, $R=\bar{R} \rightarrow \Delta B = 0$! Also sign of ΔB determined by sign of CP violations.

I) EXPANSION RATE OF UNIVERSE $\dot{R}/R \equiv H \propto T^2$

FOR WEAK AND SUPERWEAK INTERACTIONS WITH FERMI CONST.'S OF FORM

$$G_X \sim \frac{\alpha_X}{M_X^2}$$

GET COLLISIONAL INTERACTION RATES

II) $$\Gamma_C^* \sim G_X^2 (kT)^5 \sim \frac{\alpha_X^2}{M_X^4} (kT)^5$$

GET DECAY RATES

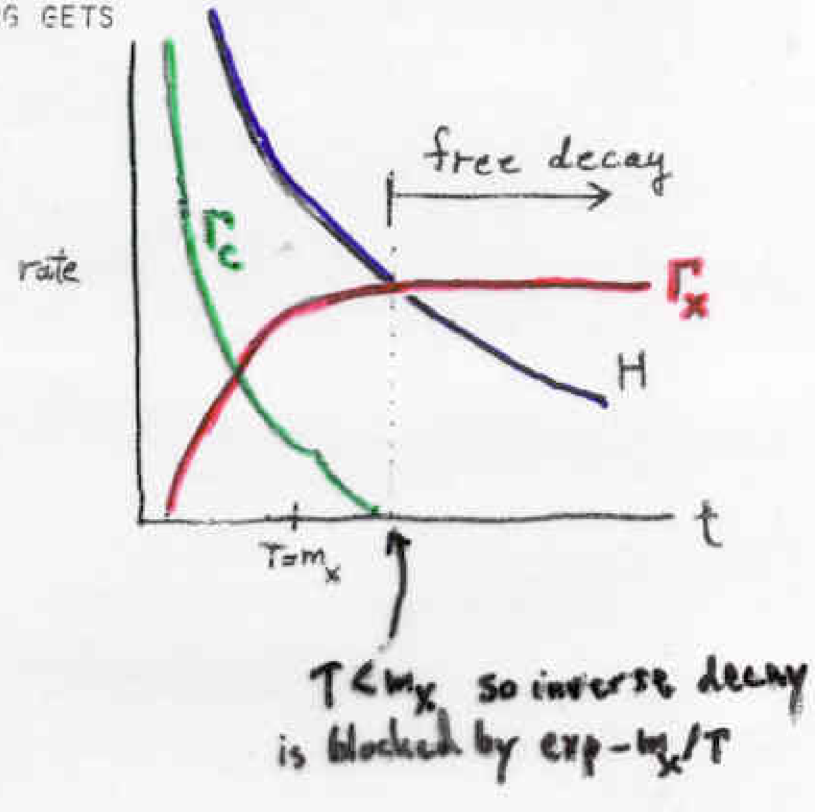
$$\Gamma_{X,0} \sim \frac{\alpha_X}{M_X^2} M_X^3 N$$

PUTTING IN TIME DILATION

III) $$\Gamma_X \sim \frac{\alpha_X M_X N}{\gamma} \sim \frac{\alpha_X M_X^2 N}{\sqrt{M_X^2 + (kT)^2}}$$

*MORE EXACTLY, TAKING ACCOUNT OF VIRTUAL BOSON PROPAGATION, ETC., WEINBERG GETS

IV) $$\Gamma_C \sim \frac{\alpha_X^2 (kT)^5 N}{(M_X^2 + (kT)^2)^2}$$



X DECAY SCENARIO:

At $T > M_X$, $n_X \sim n_\gamma$.

If there is a CP asymmetry δ, then

$$n_B \sim \delta n_X \sim \delta n_\gamma$$

But $s \sim g_* n_\gamma$, so that $n_B/n_\gamma \sim \delta/g_*$.

At GUT temperatures $g_* \sim 10^2 - 10^3$.

Therefore the CP asymmetry at the GUT temperature required to explain the present value of n_B/n_γ is

$$\delta \sim 10^{-8}$$

$\sim 5\times10^{-10}$

At low temperatures, the CP asymmetry observed for the decay modes

$$K_L^0 \to \pi^{\mp} e^{\pm} \nu(\overline{\nu})$$

is $\sim 3 \times 10^{-3}$.

Cosmic Antimatter

To be or not to be; that is the question!

Baryon Symmetric Domain Cosmology (BSDC)

- R.W. Brown & F.W. Stecker, Phys. Rev. Letters 43, 315 (1979)
- K. Sato, Phys. Lett. 99B, 66 (1981)
- F.W. Stecker, Nucl. Phys. B252, 25 (1985)

4th Condition needed for Local, Instead of Global, Asymmetry:

- Spontaneous CP breaking at GUT level followed by moderate inflation.

SPONTANEOUS SYMMETRY BREAKING

⇕

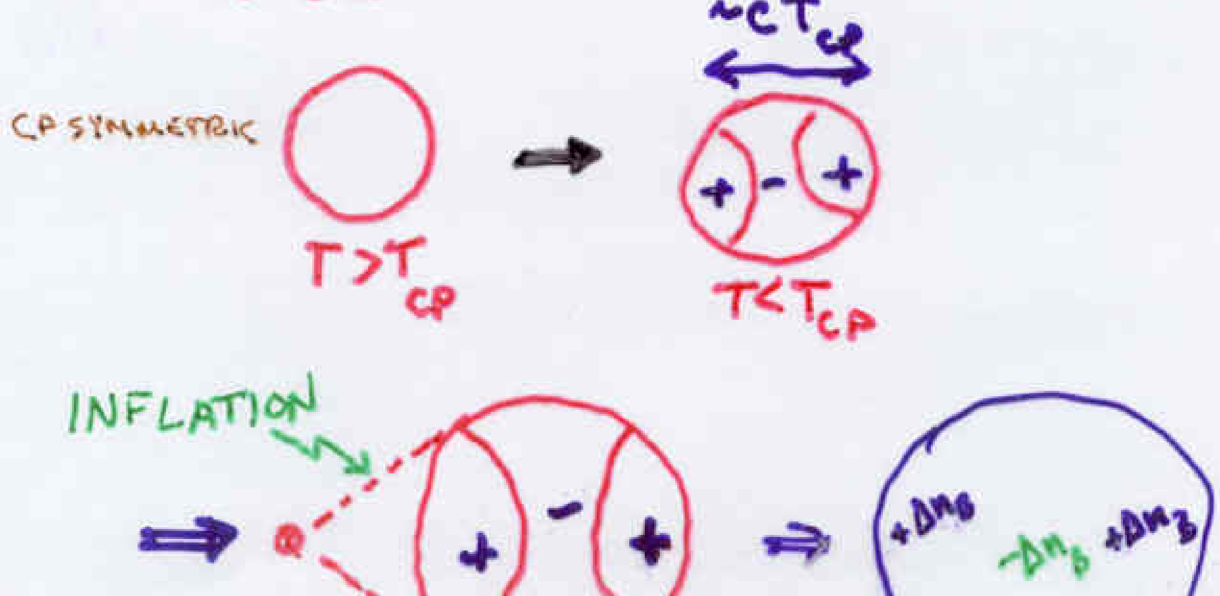
HIDDEN SYMMETRY

⇓

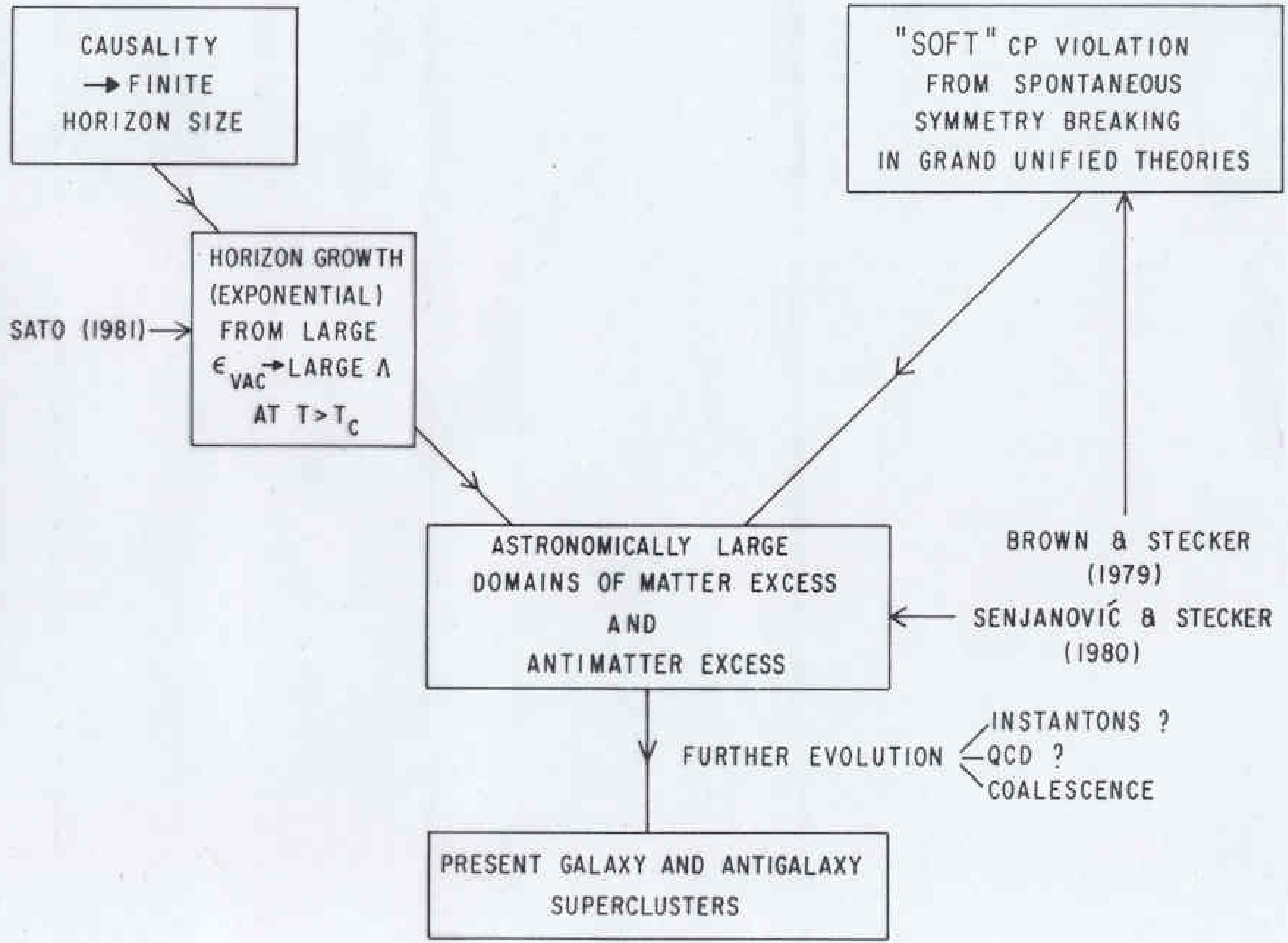
DOMAINS

cf. FERROMAGNETISM

CP CASE



SIMPLEST BARYON SYMMETRIC BIG-BANG SCENARIO



Technical Problems with BSDC

- Fine tuning of inflation
- Domain Walls

POSSIBLE SOLUTION TO THE CP DOMAIN WALL PROBLEM

(Mohanty & Stecker, Phys. Lett. 143B (1984) 351)

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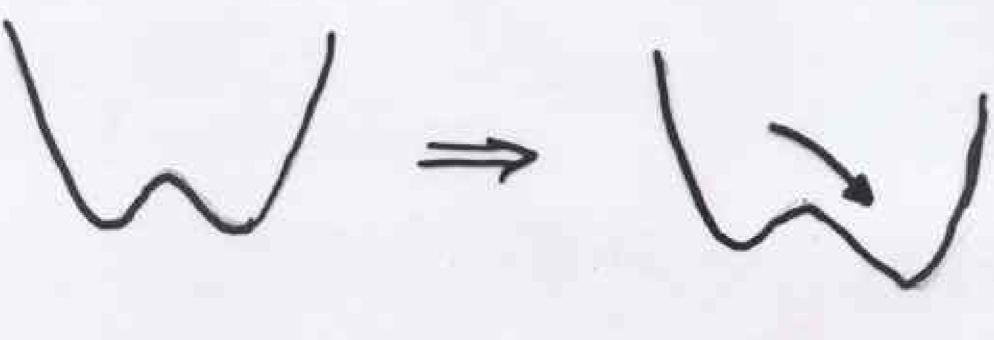
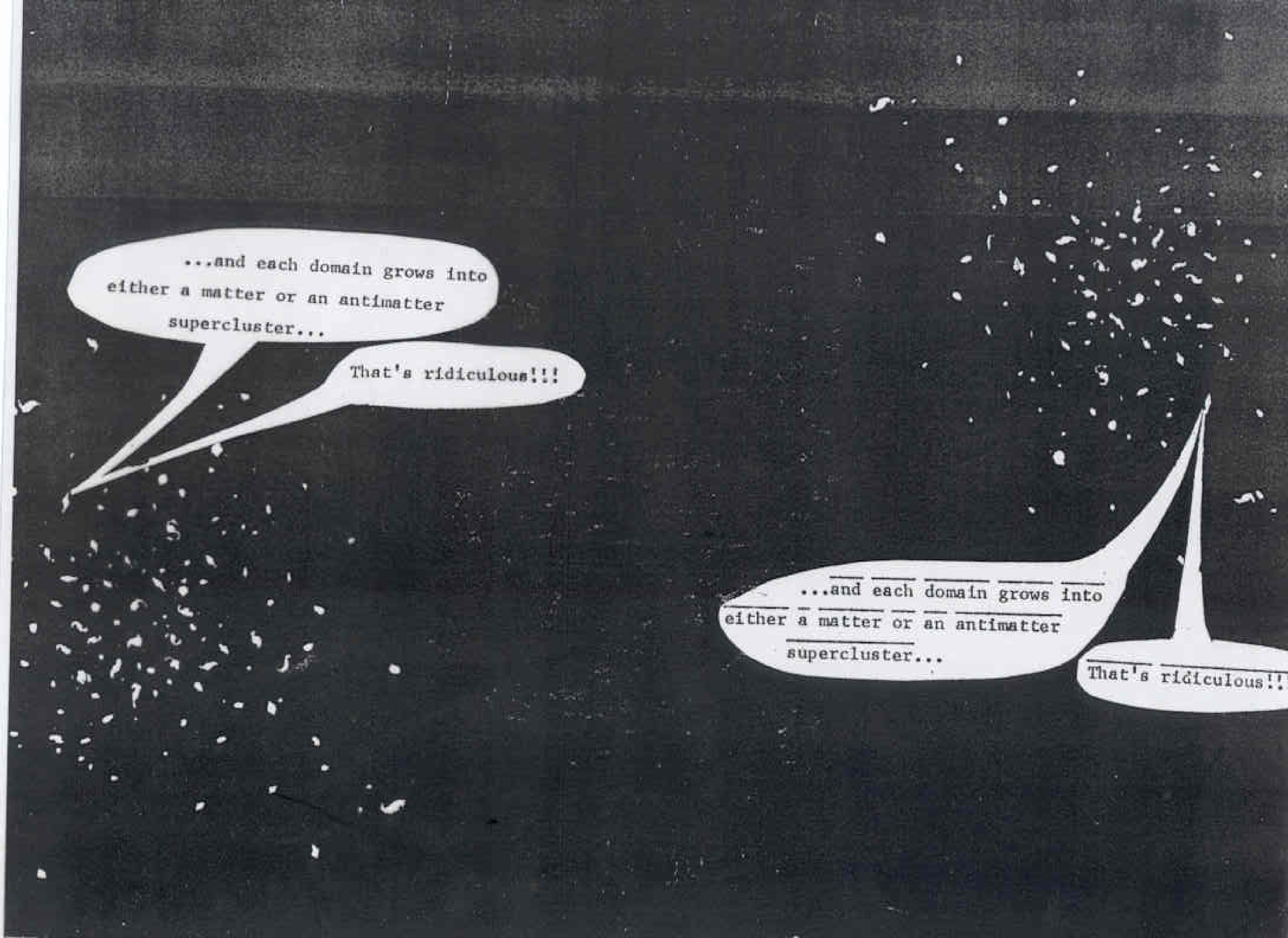
1. Assume that there is a heavy fermion sector, ψ_i

2. In analogy with QCD, form $< \bar{\psi}_i \psi_i >$ condensates in a supercooled, strongly interacting phase. Get terms like

$$Tr\Phi^3 m(T) e^{3i\beta} + h.c. \propto cos(3\theta + \beta)$$

where β is a nontrivial phase which breaks the CP degeneracy and drives the universe to a "true vacuum" *after* the baryon (and antibaryon) assymetries are created.




...and each domain grows into either a matter or an antimatter supercluster...
That's ridiculous!!!
...and each domain grows into either a matter or an antimatter supercluster...
That's ridiculous!!

J. Fabergé, *CERN Courier*, **6**, No. 10, 193 (October 1966). (Courtesy of Madame Fabergé.)

PRODUCTION OF BARYON AND ANTIBARYON EXCESSES

NECESSARY CONDITIONS:

I. NON-EQUILIBRIUM (SUPPLIED BY EXPANSION OF THE UNIVERSE)

II. PROCESSES WHICH DO NOT CONSERVE BARYON NUMBER (GUTS)

III. BREAKING OF CP SYMMETRY

CRUCIAL QUESTION: HOW IS CP SYMMETRY BROKEN ?

POSSIBILITIES:

A) CP BROKEN AT ALL TIMES AND TEMPERATURES BY EXPLICITLY PUTTING "HARD" CP VIOLATION INTO THE LAGRANGIAN OF THEORY IN THE FORM OF COMPLEX YUKAWA COUPLINGS F

$$L_Y = F \, \phi \bar{\psi} \psi$$

OR COMPLEX HIGGS SELF-COUPLINGS λ

$$L_H = \lambda \, \phi^4$$

B) CP VIOLATION "SOFT" :

1. START WITH REAL COUPLINGS IN THE LAGRANGIAN SO THAT IT IS CP - INVARIANT
2. BREAK CP SPONTANEOUSLY THROUGH COMPLEX VEV's IN THE HIGGS FIELDS

ADVANTAGES:

1. CAN USE PERTURBATION THEORY TO CALCULATE CP VIOLATION
2. SOLVES THE "STRONG CP PROBLEM" IN QCD
3. IS HARD TO AVOID IN ANY CASE IN A "REALISTIC" GUT

"*I don't know—it just doesn't* look *like antimatter.*"

COSMIC RAY $\overline{He}$ LIMITS

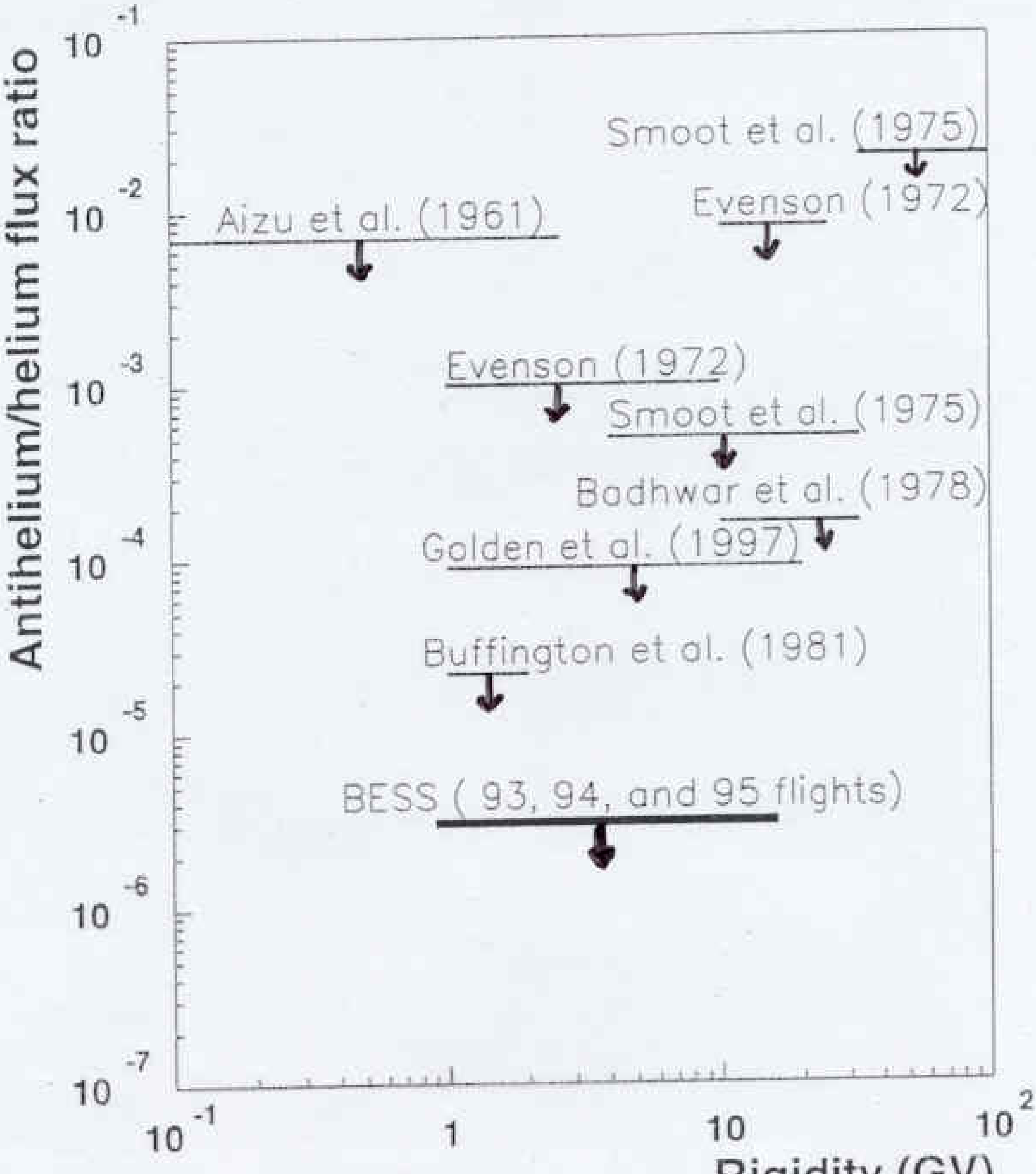


FIG. 5. The resultant upper limit of $\overline{He}/He$ flux ratio of the present paper together with previous limits.

Saeki, etal.
astro-ph/9710228

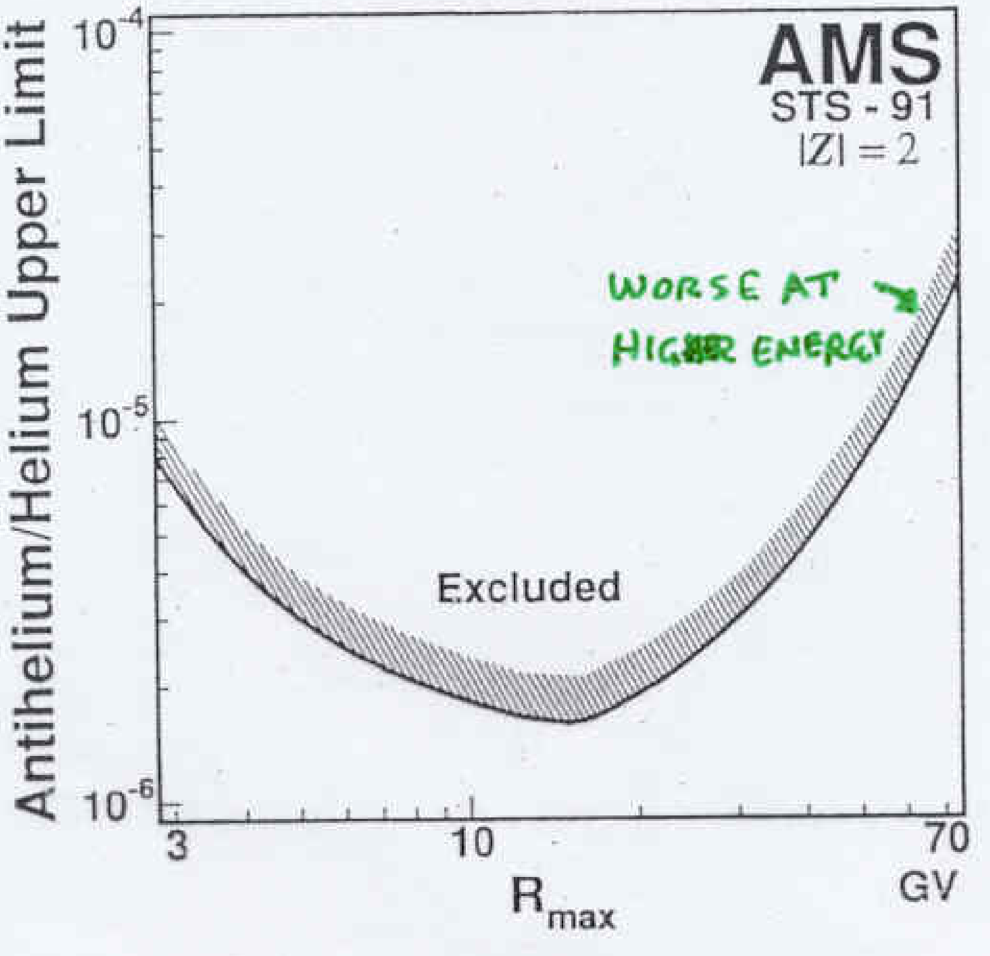


Fig. 9. Upper limits on the relative flux of antihelium to helium, at the 95% confidence level, as a function of the rigidity interval $R = 1.6\,GV$ to R_{max}. These results are independent of the incident antihelium spectra.

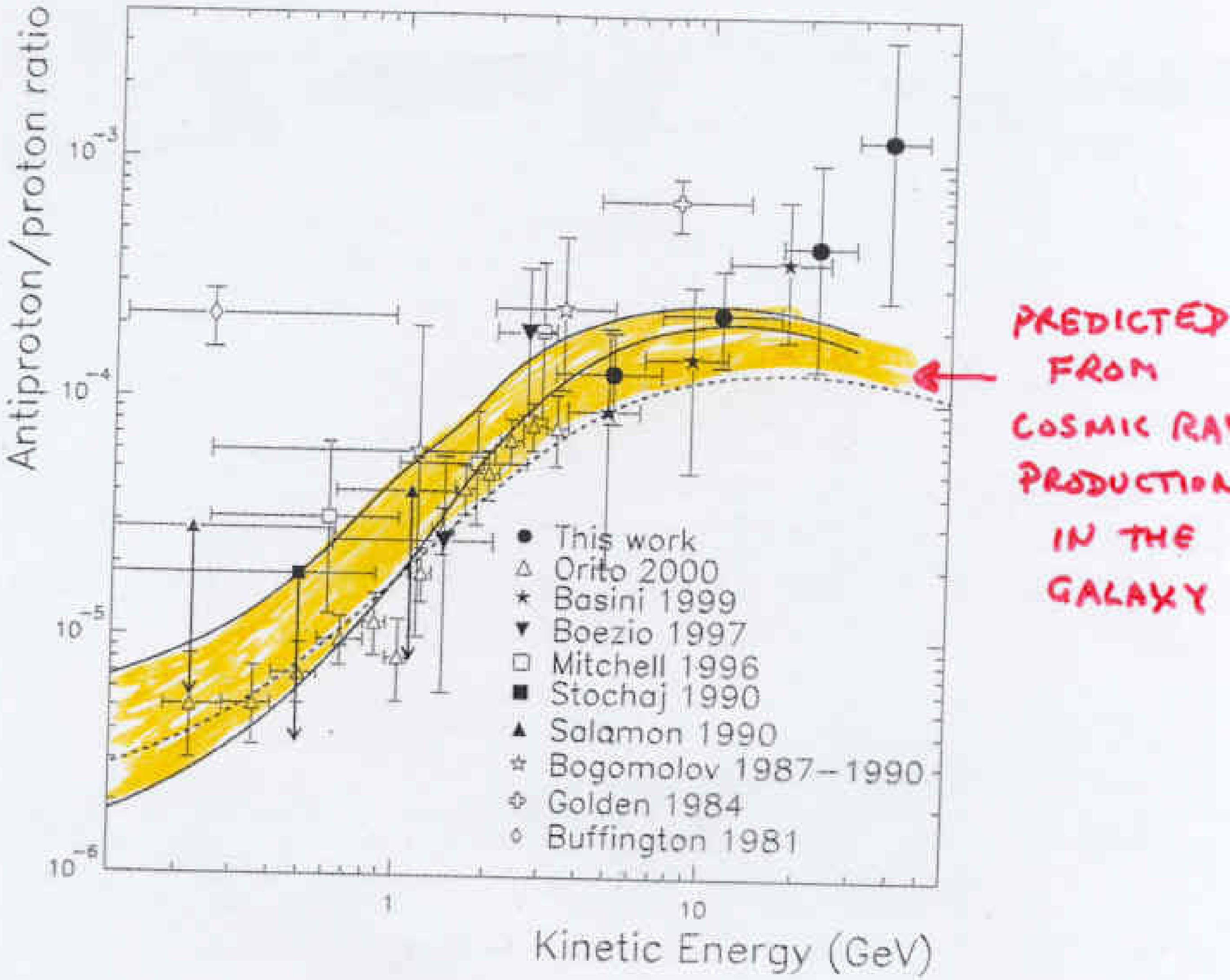
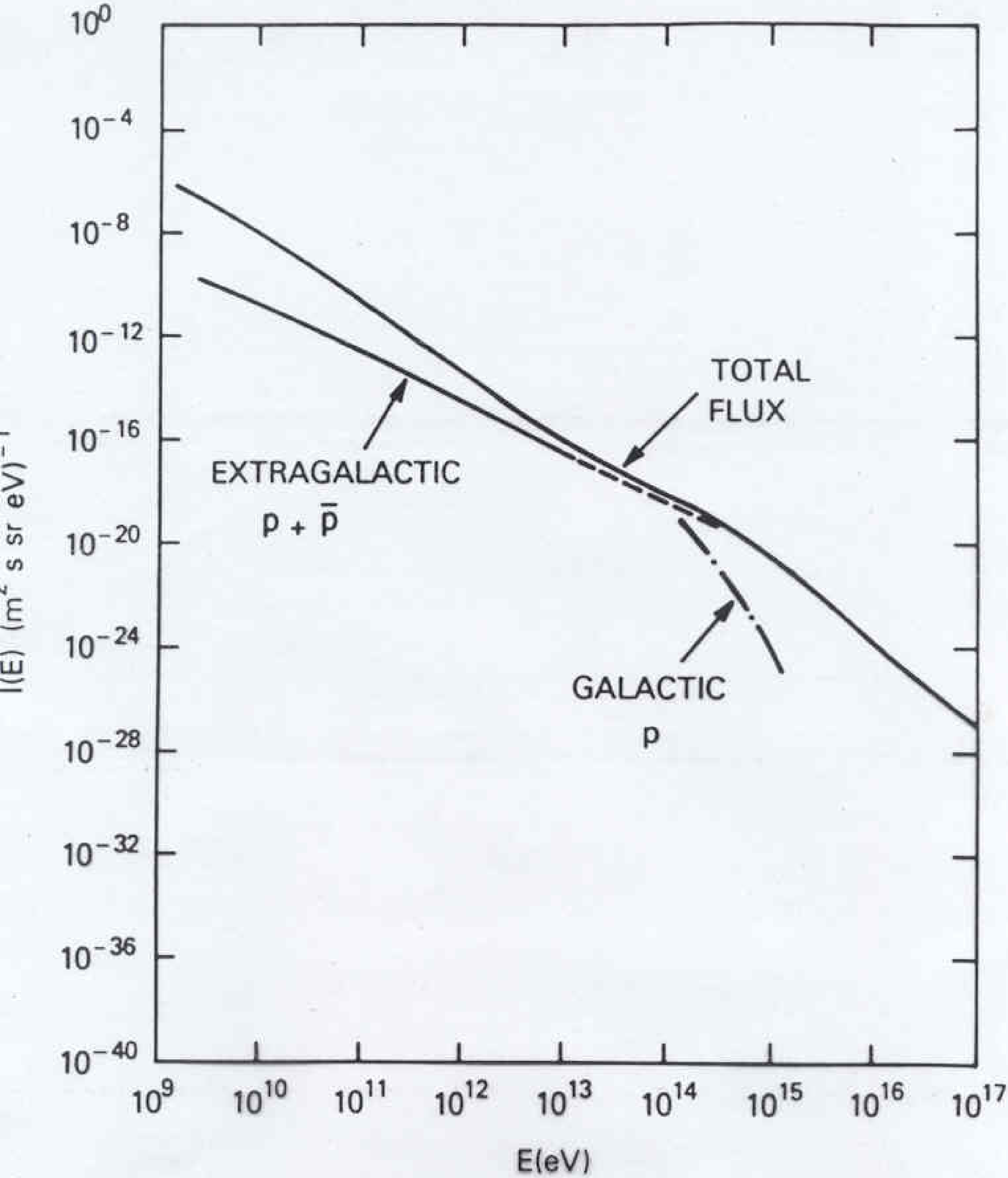


Fig. 10.— The $\overline{p}$ /p ratio at the top of the atmosphere obtained in this work compared with previous measurements (Buffington, Schindler, & Pennypacker 1981; Golden et al. 1984; Bogomolov et al. 1987, 1990; Salamon et al. 1990; Stochaj et al. 1990; Mitchell et al. 1996; Boezio et al. 1997; Basini et al. 1999; Orito et al. 2000). The lines are the calculations of interstellar antiprotons assuming a pure secondary production during the propagation of cosmic rays in the Galaxy by Simon, Molnar, & Roesler (1998) (solid lines, upper and lower limits of the calculation) and by L. Bergström and P. Ullio 1999 (private communication) (dashed line).

Boezio et al.
astro-ph/0103513



I(E) (m² s sr eV)⁻¹
10^0
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
10^-32
10^-36
10^-40
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
E(eV)
TOTAL
FLUX
EXTRAGALACTIC
p + p̄
GALACTIC
p

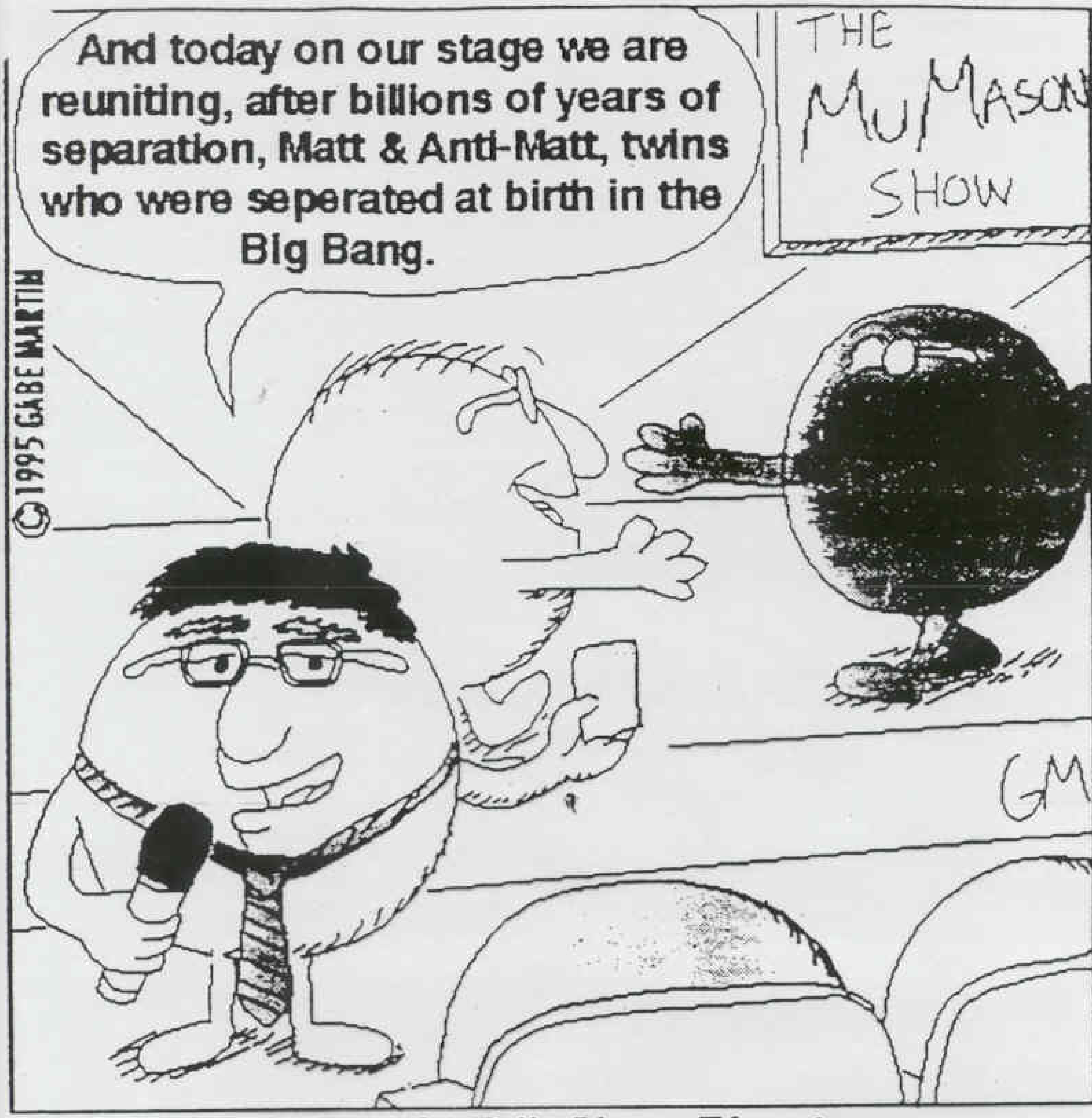
Constraints on Large-Scale Baryon-Antibaryon Domains

CBR Distortion

Gamma-Ray Background Radiation

Cosmic Ray Antihelium*

*If it can reach us.



Sub-Atomic Talk-Show Disasters

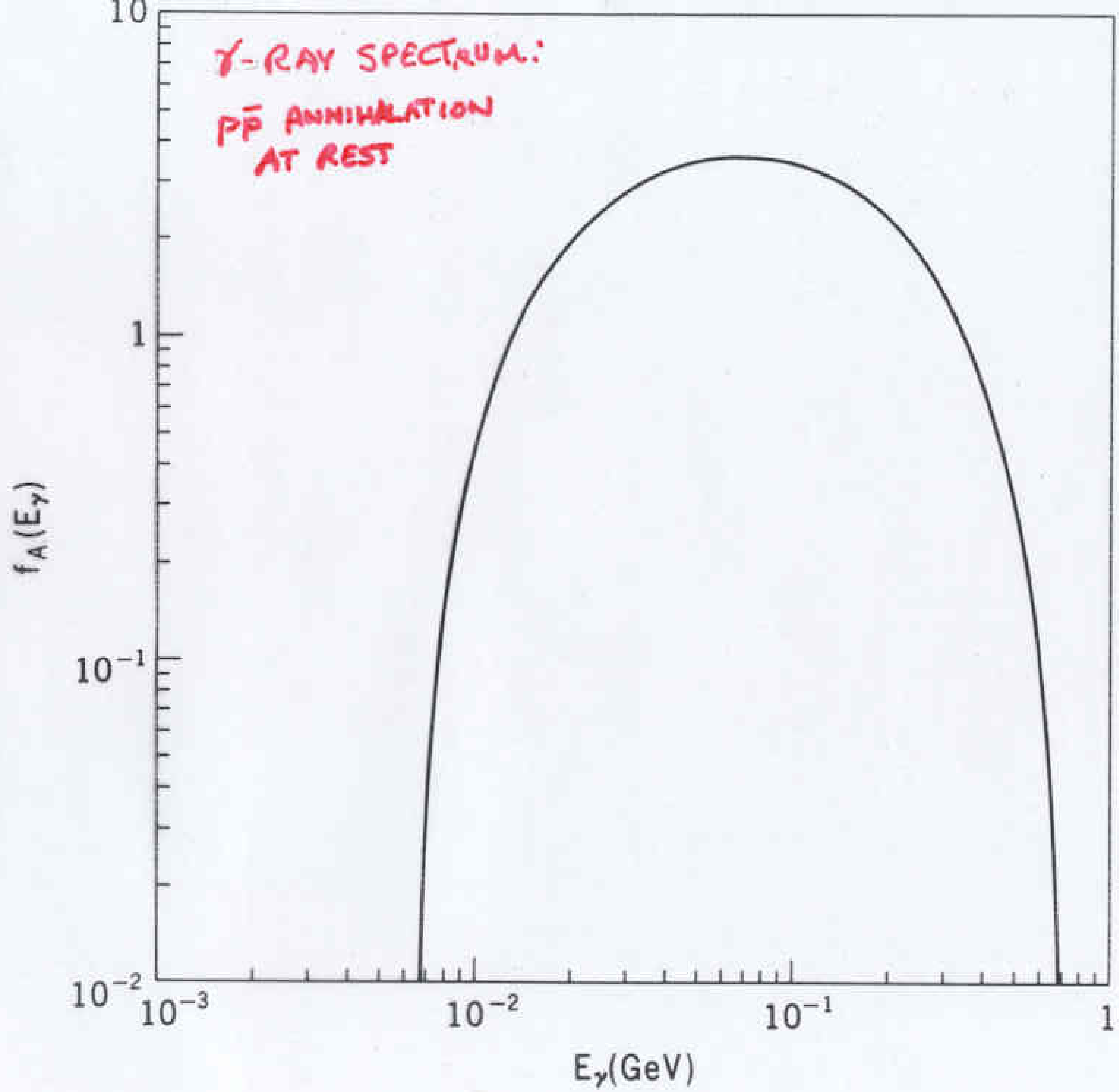
Distortion of CBR by Annihilation Energy Input in High Energy Particles

Parameter y = (fractional energy input)/4:

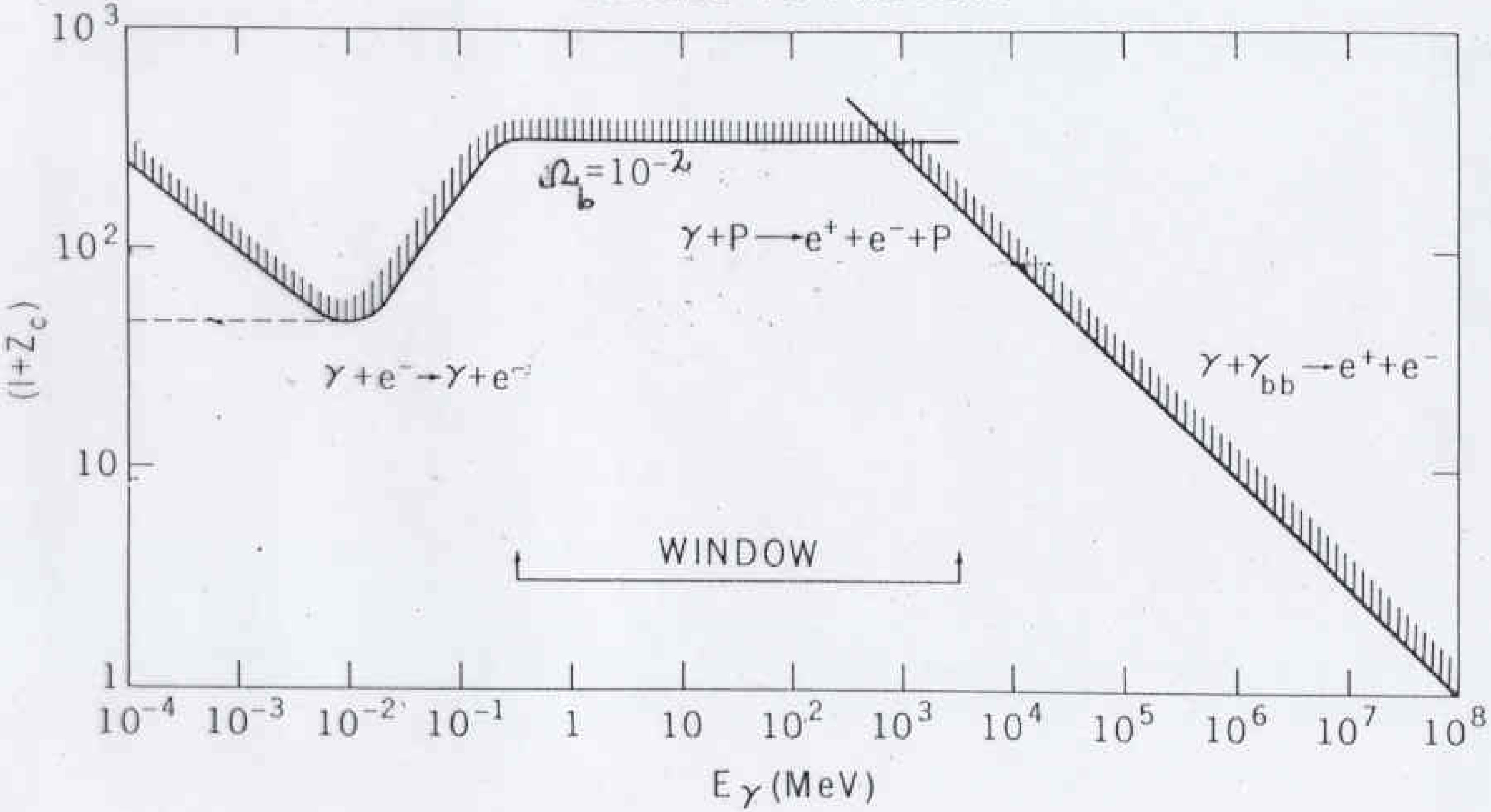
From COBE measurements, y is less than 2.5×10^{-5} (Wright et al. 1994)

Predicted y less than 9×10^{-9} (Cohen et al. 1998)

No Conflict!


γ-RAY SPECTRUM:
$p\bar{p}$ ANNIHILATION AT REST
$f_A(E_\gamma)$
E_γ(GeV)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1

REDSHIFT AT WHICH THE UNIVERSE BECOMES OPAQUE TO PHOTONS



This integro-differential equation takes account of γ-ray production, absorption, scattering, and redshiftin and is of the form

$$\frac{\partial \mathcal{I}}{\partial t} + \frac{\partial}{\partial E}\left[-E\dot{H}(z)\mathcal{I}\right] = \mathcal{Q}(E,z) - \kappa_{AB}(E,z) + \int_{E}^{\varepsilon(E)} dE'\, \kappa_{sc}(E,z)\, \mathcal{I}(E;\, E')\, dE' \qquad (1)$$

Cosmological Photon Transport (CPT) Equation

– Stecker, Morgan & Bredekamp, Phys. Rev. Letters 27, 1469 (1971)

where

$$\mathcal{I}(E,z) \equiv (1+z)^{-3}\, I(E,z)$$

$$\mathcal{Q}(E,z) \equiv (1+z)^{-3}\, Q(E,z)$$

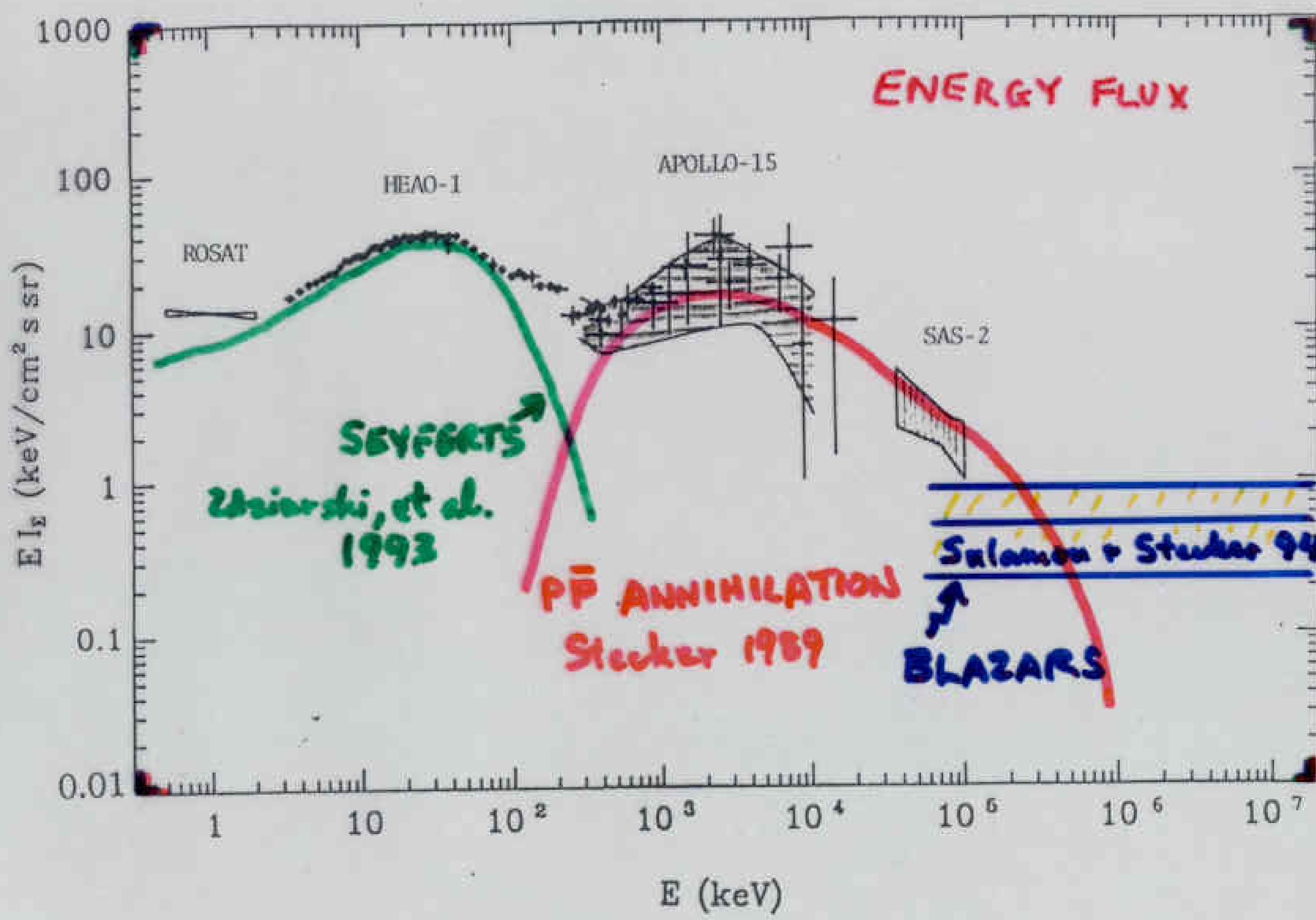
and

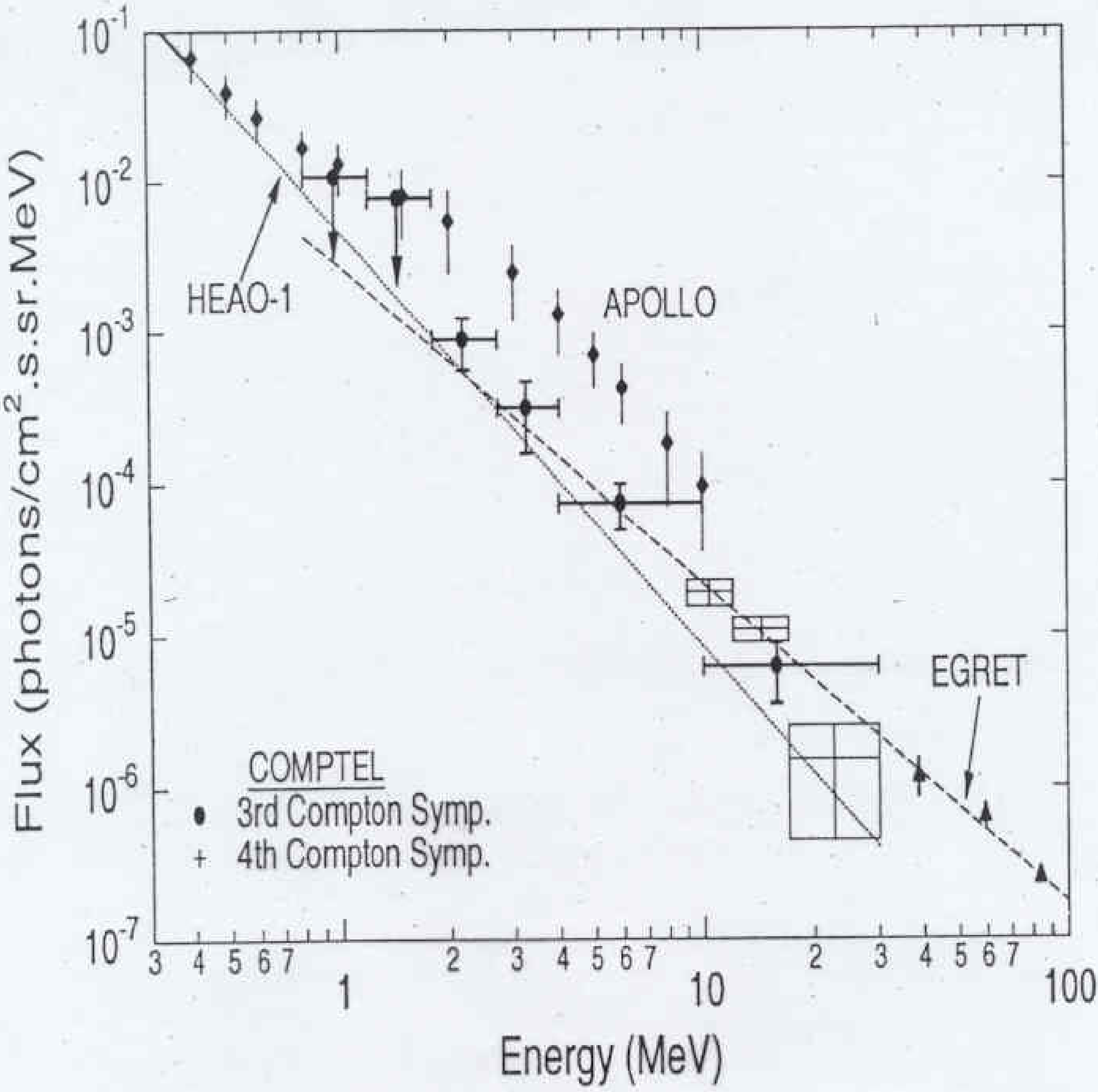
$$\frac{\partial \mathcal{I}}{\partial t} = -\,(1+z)\, H(z)\, \frac{\partial \mathcal{I}}{\partial z},$$

$$H(z) = H_o(1+z)\,(1+\Omega z)^{1/2}$$

The second term in eq. (1) expresses energy loss from the redshift effect. The third term is the γ-ray source term from $p\bar{p}$ annihilati primarily into π^os. The absorption term is from pion production an Compton interactions with electrons at high z and the scattering integral puts back Compton scattered γ-rays at lower energies $E<E'$.

EXTRAGALACTIC X- AND γ-RAY BACKGROUND





PHOTON FLUX*

*LARGE INTRINSIC BACKGROUND SUBTRACTIONS!

Minimum Domain Size

- From Gamma-Ray Background* Constraints:

  A) 10 Mpc (Stecker & Puget 1972 – based on data of Trombka et al. (1972)

  B) 1 Gpc (Cohen et al. 1998 – based on data of Kappadath et al. 1995)

*all data in the critical MeV range are questionable – need dedicated experiment!

Summary of Astrophysical Information:

Completely mixed antimatter ruled out by thermodynamics (Chiu 1966).

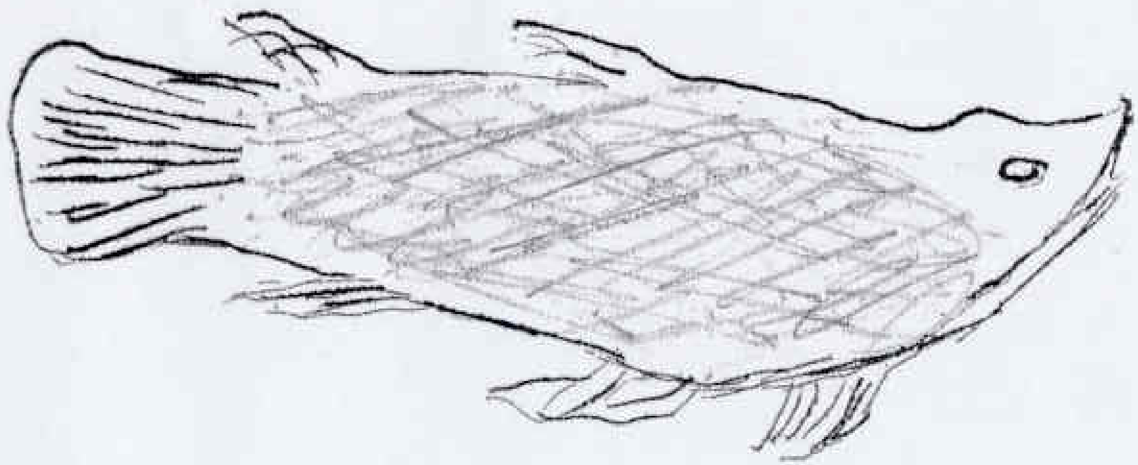
Sub-galaxy size antimatter domains ruled out by big-bang nucleosynthesis (Kurki-Suonio & Sihvola 2000; Rehm & Jedamzik 2002).

Large-scale antimatter in our galaxy ruled out by low-energy cosmic ray measurements.

Gamma-ray background data indicate that matter-antimatter domains must be at least galaxy supercluster size.

"HELICANTH"

$\bar{\alpha}$



Conclusions:

There is no evidence for cosmologically significant amounts of antimatter in the universe.

With inflation and spontaneous CP breaking one can get a either a locally or globally baryon asymmetric universe.

Astrophysical data are not conclusive. It is still possible that there are domains of antimatter galaxies in the universe; absence of evidence is not evidence of absence. We need reliable gamma-ray background measurements as a conclusive test.