Antimatter in the Universe

Data: no antimatter around, except a little in cosmic rays, $\bar{p}$, e^+.
(secondary origin)

$$\beta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \cdot 10^{-10},$$

(Now $N_B - N_{\bar{B}} = N_B$, early $N_B \approx N_{\bar{B}}$)

($N_\gamma \approx 400/cm^3$)

Big questions:

1. $\beta = const$ or $\beta = \beta(x)$?

2. If $\beta = \beta(x)$ what is characteristic scale L_B ? $L < L_{horizon} \approx 3\,Gpc$
   $L > L_{horizon}$??

3. $B_{tot} = \int \beta(x)\, d^3x = 0$ (globally charge symmetric Universe)

$B_{tot} \neq 0 \leftarrow$ global charge asymmetry ?

Standard model $B_{tot} \neq 0$, $\beta = const.$

However, not excluded and <u>natural</u>

$\beta = \beta(x)$, $L_B < L_{horizon}$

Not excluded both $B=0$ and $B \neq 0$

though $B=0$ is stronger restricted (depends upon scale)

Known limits:

<u>$L_B > 15$ Mpc</u> (G. Steigman, 197?) from γ background

<u>$L_B > \sim$ Gpc</u> (Cohen, De Rujula, Glashow, 199?, 7?) from γ-background ⊕ CMBR anisotropies

assumed $B=0$ and adiabatic perturbations

some loopholes, and some (a lot?) antimatter nearby is not excluded

Good news for Pamela and AMS

<u>Need to see one $^4\overline{He}$ nuclei!</u>

Astro-ph /9907152
R. Battiston

acceptance made possible to set these stringent limits using only 4 days of exposition to deep space.

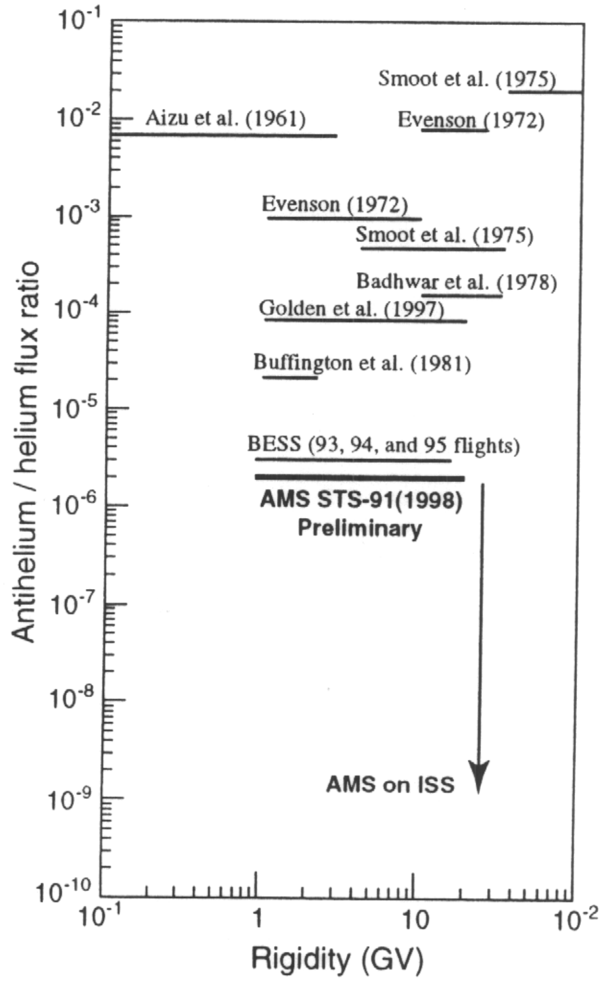


Figure 11: Limits on $\frac{\Phi_{\bar{He}}}{\Phi_{He}}$.

5 Conclusion

The AMS experiment has successfully completed the first precursor flight in June 1998 with an excellent performance of all subsystems, collecting about 100 millions primary CR during 152 orbits around the earth. AMS upper limits on the existence of antimatter improve the results of nearly 40 years of similar searches using stratospheric ballons.

There has never been a sensitive magnetic spectrometer in space covering the energy range up to hundreds of GeV. After its installation on the ISS in 2004, AMS will measure the CR rays composition with an accuracy orders of magnitude

Mechanism of generation of cosmological charge asymmetry (Sakharov, 1969?):

1. Non-conservation of baryons
2. Breaking of C and CP
3. ~~Breaking~~ Deviations from thermal equilibrium.

(none is obligatory)

2 – established in experiment

3 – always (sometimes, even often, small) exists in standard cosmology

1 → cosmology is strongest "experimental" evidence proving that baryons are not for ever

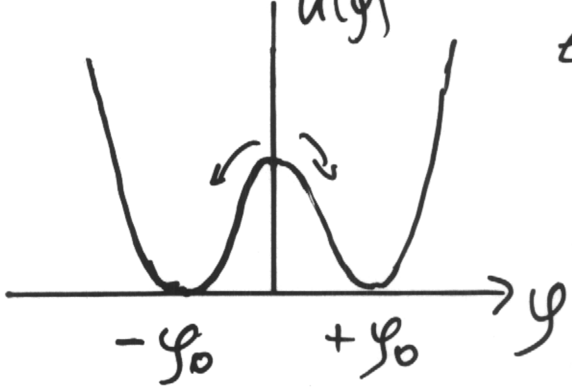
>40 years ago: "we exist ergo protons are stable"

Now: we exist ergo protons are unstable.

Mechanisms of C, CP-violation.

1. Explicit → complex constant in Lagrangian
   ↳ Usually $\beta = const$ (another cosmological constant)

2. Spontaneous (T.D. Lee)



← complex field φ

a) Problems of domain walls (KOZ)
b) $B : \bar{B} = 1$ and close contact
   ↳ $L_B \gtrsim$ Gpc (CDeRG)

3. Stochastic (by initial conditions)
   ↳ $B : \bar{B} = 1$, but no domain walls

(1+3 / 2) could give $B \gg \bar{B}$

Example: complex $\varphi(t) \neq 0$ initially
but $\varphi_{final} = 0$; inflation generated $\langle \varphi^2 \rangle \sim H^3 t$

Models of Baryogenesis

1. **Heavy particle decays** $\frac{X \to q + Y}{\bar{X} \to \bar{q} + \bar{Y}} \neq 1$ (A.S.)

Naturally gives $\beta \sim \beta_{obs}$ at GUT scale $m_{GUT} \sim 10^{16}$ GeV; too low

$\hookrightarrow \Gamma_{\Delta B} \sim H$ at $T \sim m_X \sim m_{GUT}$ at $\sim 10^{14}$ GeV

2. **Electro-weak**, $T \sim$ (a few) $\times$ 100 GeV (KRS)

In principle operates in MSM but $\beta \ll \beta_{obs}$.

To break equilibrium needs I order p.t. but now Higgs is too heavy.

Conserves $(B-L)$ but is able to destroy preexisting $(B+L)$ at $T > T_{EW}$

3. **Baryo-thru-lepto**. (Combination of 1, 2)

Heavy Majorana-ν decays at $T \sim 10^{10}$ GeV create $L \neq 0$; EW make B from L

$\hookrightarrow$ needs to be weakly interacting to break equil at $T \sim m_{..}$

Fukugita, Yanagita

4. Black hole evaporation.

(Ya.B.Z.; S.H.; A.Y.)

$$BH \to M \begin{matrix} \nearrow \\ \searrow \end{matrix} \frac{B_h \bar{B}_e}{\bar{B}_h B_e} \neq 1$$

M: meson; $\neq 1$: $C, CP \neq +$

B_h and $\bar{B}_h$ are more efficiently back captured.

Baryons outside, antibaryons inside BH

BH may possibly completely disappear.

Could give $\beta \sim \beta_{obs}$ if $\rho_{BH}(t = t_{decay}) \approx \rho_{tot}$

[similar model in particle physics

p + (heavy stable antibaryons)]

5. Spontaneous Baryogenesis (A. Cohen, D. Kaplan)

SSB of $U(1)_{B \text{ or } Y}$:

$$\mathcal{L} = \lambda(|\varphi|^2 - f^2)^2 + \bar{\Psi}(i\not{\partial} + m)\Psi +$$
$$+ g\varphi\bar{\Psi}_B\Psi_e - |(\partial\varphi)|^2 \ldots$$

$$\varphi = f e^{i\vartheta}, \quad \Psi_B \to \Psi_B e^{i\vartheta}$$

$$\mathcal{L} \to f^2(\partial\vartheta)^2 + \underline{\partial_\mu\vartheta \cdot \bar{\Psi}_B\gamma_\mu\Psi_B} + \ldots$$

Homogeneous $\vartheta = \vartheta(t) \Rightarrow \dot{\vartheta} n_B$, i.e.

$\dot{\vartheta} = \mu_B$ (chemical potential) ← not exactly true

$\underline{B \sim \dot{\vartheta} T^2}$? in thermal equil.

Still $B \sim \dot{\vartheta}$ in thermal equilibrium and without C, CP-violation

determined by initial conditions possibly by stochastic quantum fluctuations during inflation.

6. SUSY condensate (Affleck, Dine)

Necessary ingredients:

a) scalar field, χ, with $B \neq 0$;

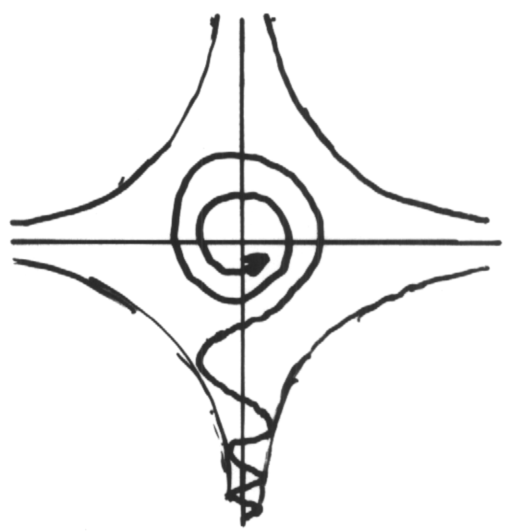
b) flat directions in $U(\chi)$;

c) non-conservation of baryonic charge of χ, i.e. $U = U(\chi)$ but not $U(|\chi|)$.

All Natural in SUSY models.

$\chi^4 + \chi^{*4}$

$$U(\chi) = \lambda |\chi|^4 (1 - \cos 4\vartheta), \quad \chi = |\chi| e^{i\vartheta}$$



$$\vartheta_{valley} = \frac{\pi}{2} \cdot n$$

$$\langle \chi^2 \rangle \sim \frac{H^3 t}{2\pi} \text{ at inflation}$$

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0 \leftarrow \text{II Newton law}$$

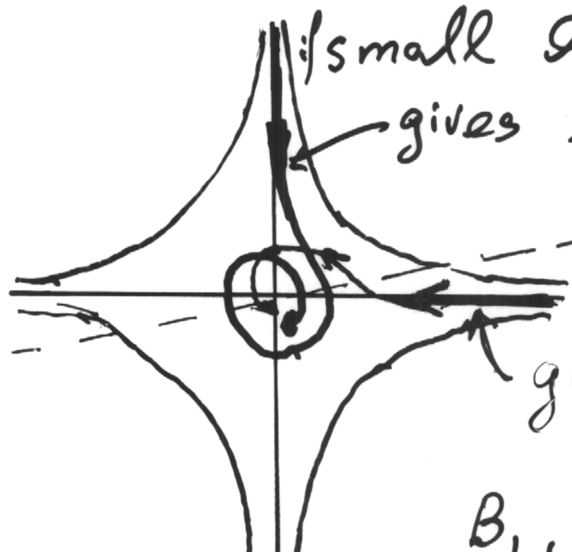
$$J^B_\mu(\chi) = \chi^* \overleftrightarrow{\partial_\mu} \chi, \quad B = \dot{\vartheta} |\chi|^2 \leftrightarrow \text{angular momentum}$$

β is determined by chaotic initial conditions (at inflation); no CP ⇓ is necessary; however the effect may be small

Explicit CP- violation:

$$U(\chi) = \lambda |\chi|^4 (1 - \cos 4\vartheta) +$$
$$+ m^2 |\chi|^2 [1 - \cos(2\vartheta + 2\alpha)]$$

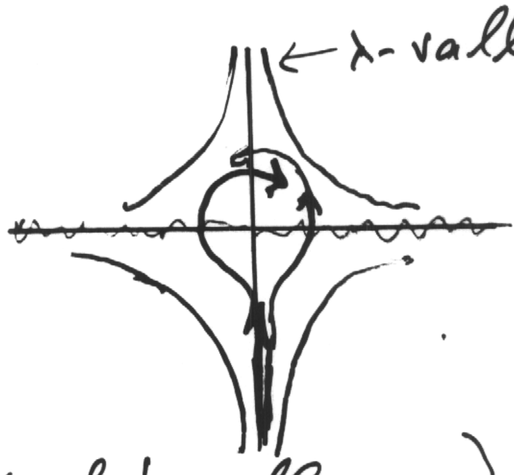
↑ relative phase of m and λ



gives baryons ⟹ could give $\beta \sim 1$

$B_{tot} = 0$ but $L_B > L_{horizon}$ (by inflation)

CP_ conserved model:



$\alpha = 0$

m and λ - valleys

50% and 50% ← as in the case of spontaneous CP- violation but no domain wall problem

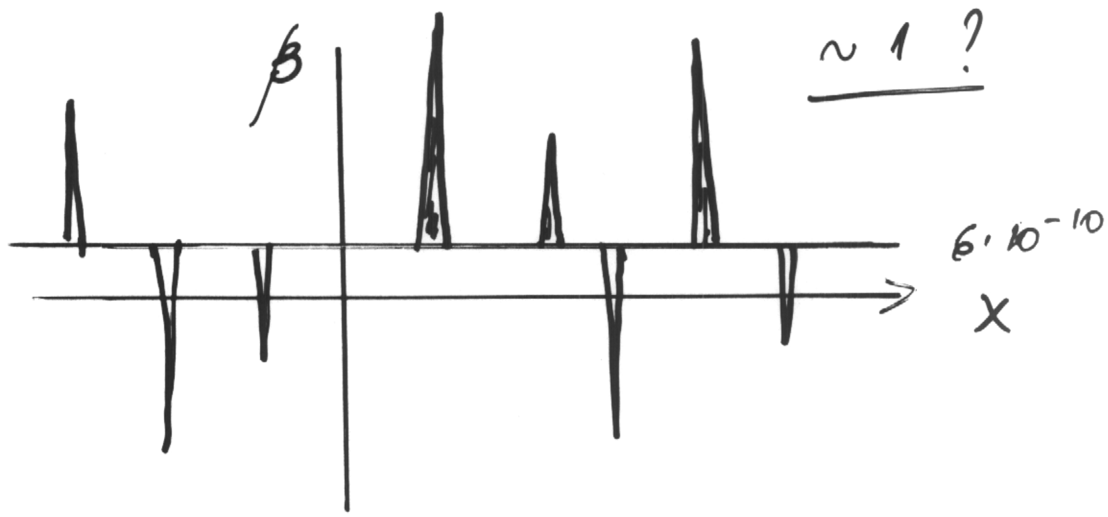
$\alpha \neq 0$, but small ⟹ 90% B and 10% $\bar{B}$ or anything one wants

If χ is coupled to inflaton

$\lambda |\chi|^2 (\phi - \phi_1)^2$ (most general renormalizable coupling)

then:

AD + J. Silk



$$\frac{dN}{dM} \sim \exp\left\{ - c \ln^2 \frac{M}{M_0} \right\}$$

↑ primordial BH with $M = 10 - 10^9 M_\odot$

plus uncollapsed clouds of antimatter, antistars, etc ...

For large β BBN efficiently produces heavier elements (does not stop on Li^7) and $\bar{O}$, $\bar{C}$, $\bar{N}$ may be observed!

Isocurvature perturbations and antimatter

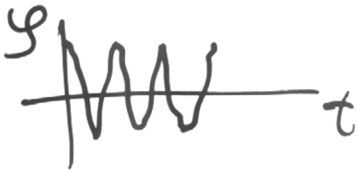
1. Complex scalar field φ
2. Inflation created condensate of φ: $\langle\varphi\rangle = \varphi(x)$
   or bubble from I order p.t.

slow variation

3. $U(\varphi) = \lambda |\varphi|^4$

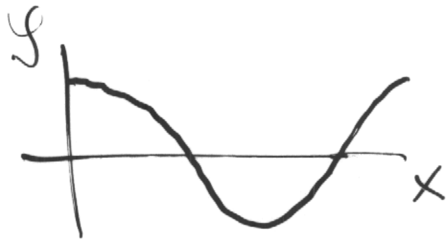
↳ spatial fluctuations of baryon asymmetry at astronomically large scale

End of inflation: $\varphi = \varphi(t; x)$



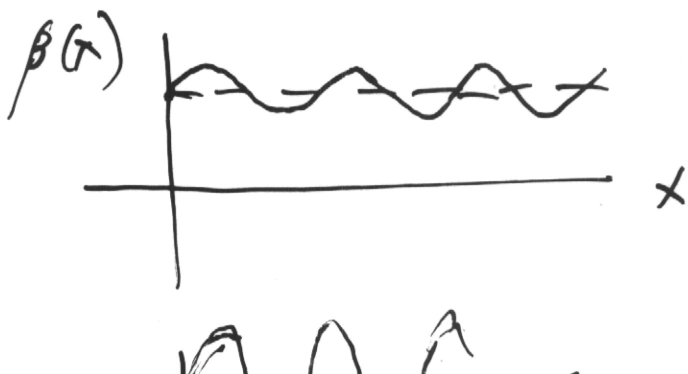
$\omega \sim \sqrt{\lambda}\, \varphi_i(x)$

↳ $\varphi(x; t_{fixed}) =$



$\lambda \sim 100$ Mpc (could be)

If $\omega < \Gamma_{BS} \Rightarrow \beta \sim \varphi(x; t_{BS})$



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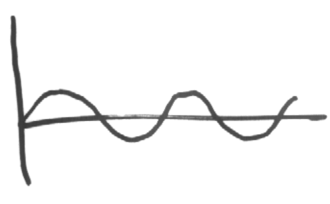


or

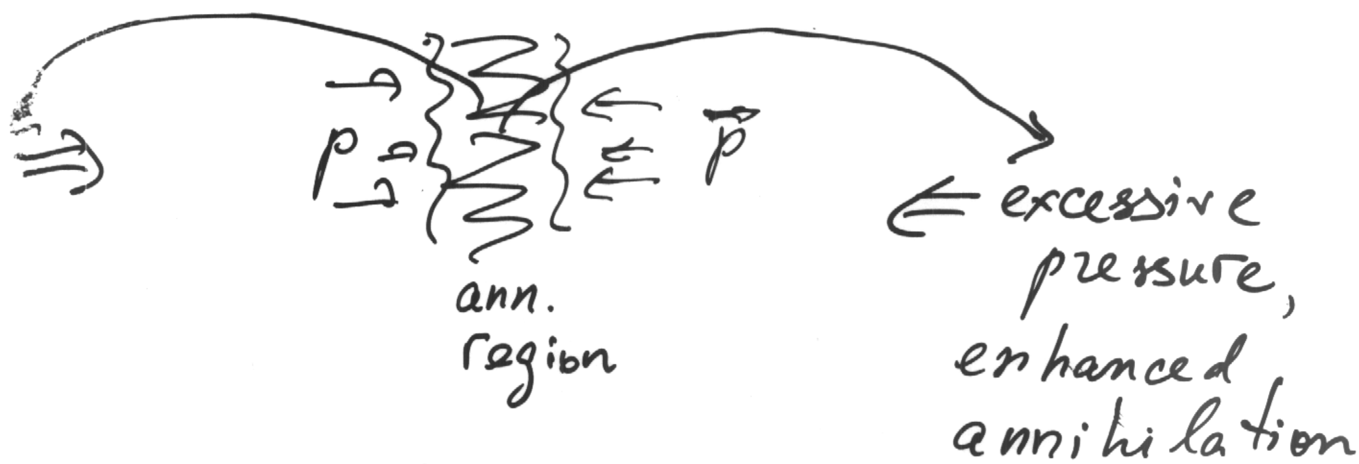
← explicit CP-breaking

CGR - bound: $L_B \gtrsim$ Gpc

1. If B and $\bar{B}$ are separated by $\Delta L > 20$ Mpc $\Rightarrow$ too large $\delta T/T$

   ↑ this small scale is already accessible to measurements.

2. $\Delta L < 20$ Mpc $\Rightarrow$ $p, \bar{p}$ diffusion brings them into contact



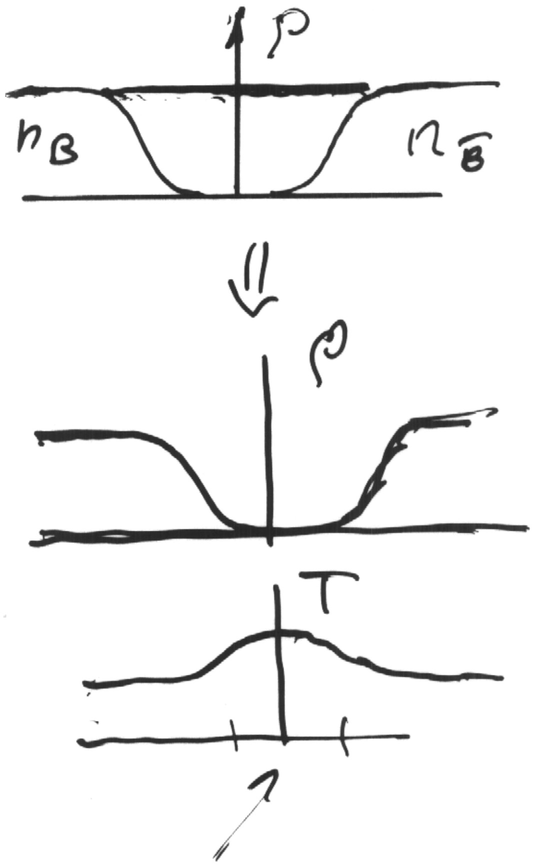
Valid for $M \simeq \bar{M}$

and adiabatic perturbations.

Small (how small?) amount of $\bar{M}$ nearby is not excluded.

Isocurvature perturbations:

1) $\delta\rho_{in} = 0$, but different chemical content



$\Delta\rho_{in} = 0$

$\Delta\rho \neq 0$

$\Delta T \neq 0$

Non-relativistic matter cools faster

excessive pressure and $M/\bar{M}$ separation

Conclusion

1. Most natural (and extremely dull) option: $\beta = const$ (or small isocurvature perturbations)

   no antimatter and $B_{tot} = \int \beta d^3x \neq 0$

2. However, not excluded and not too unnatural **$\beta < 0$** in astronomically large domains

   Significant amount of cosmic antimatter may exist and not too far away

   Look for cosmic antinuclei: **$^4\overline{He}$ or heavier**.

3. Fraction of cosmic antimatter inside horizon: $\bar{m}/m = \varepsilon$.

   Upper bound on ε?

   Accurate calculations are necessary (but results would be model dependent)