Cosmological Matter-Antimatter Asymmetry.

Blois, 16-22 June, 2002

Prediction (Dirac) and discovery (Anderson) of antimatter are among the greatest scientific achievements of XX century.

But:

new discoveries $\Rightarrow$ new problems

I. Why the Universe is strongly (~100%) matter dominated

at least in our neighbourhood ?

– answered by Sakharov in 1967

II. Are there astronomically large domains or objects of antimatter?

Unanswered yet. Challenge for XXI century (or III Millenium ?)

Dirac, 1934: "... quite possible ... these stars being built up mainly of positrons and negative protons. In fact there may be half of the stars of each kind.

Observations: p, e^-, nuclei in our part of the Universe

a little $\bar{p}$, e^+, in cosmic rays (of secondary origin)

Not a single antinuclei yet observed.

Theory: predicts a lot of relic antineutrinos, $\sim 55/cm^3$ of each flavor

Data analysis: γ ray background, ~ 100 MeV

nearest antigalaxy at

(Stecker, Puget, 1972) $\bar{l} > 10$ Mpc

(Steigman, 1978 - review)

Cohen, De Rujula, Glashow, 1998:

$\bar{l} >$ Gpc

if $M : \bar{M} = 50:50$ and adiabatic perturbations

Angular fluctuations of CMBR — bound depends on scale; no limits for small scales.

Despite ~~all~~ limits above:

existence of astronomically large objects of antimatter (gas clouds, antistars, ...) is <u>not excluded</u> and even <u>natural.</u> They may be as close as halo of our galaxy and rich of heavy antinuclei ($\bar{C}$, $\bar{N}$, $\bar{O}$, ... $\bar{Fe}$?)

Very interesting to search for them. Why?

1. Evident (no other motivation is necessary)

2. Understanding of C, CP - breaking in cosmology

3. Proof (or evidence) of inflation.

ElBa5 / BG

Local (?) excess of baryons over antibaryons is:

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

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

Now $N_B \gg N_{\bar{B}}$;

early, at $T \gtrsim 100\,MeV$, $N_{\bar{B}} \simeq N_B(1-\beta)$

β = baryon asymmetry of the Universe (BAU)

5* - questions for XXI century:

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

2. $\beta > 0$ or somewhere $\beta < 0$?

3. $B_{tot} = \int \beta \, d^3x \gtrless 0$ or $B = 0$?

global charge symmetry

4. If $\beta = \beta(x)$ what is the characteristic scale l_B?

5. What kind of anti-objects may exist?

Theory allows anything.

Data possibly exclude $B=0$ inside hozizon, $l_{hor} \approx 3\,Gpc$.

Scenarios of Baryogenesis

Pioneers:

A. Sakharov (67) ← nonconserved B;

R. Omnés (69,70) ← conserved B.

→ spatial dynamical separation of M and $\bar{M}$; is not known how to achieve at large scale

[crazy idea: higher dimensions, $\bar{M}$ is pushed to another brane?] energy conservation?

modified Omnés, in our world looks as a realization of Sakharov's idea of non-conserved B

3 principles of baryogenesis:

1. Non-conservation of baryons

Weakest point in 1967:
"we exist, hence Baryons are stable"

Theory: GUT, electroweak $\Rightarrow \Delta B \neq 0$

Inflationary cosmology is impossible if baryons are conserved.

Our universe is a strong experimental indication in favor of B-nonconservation

Now: we exist, hence baryons are unstable.

2. Breaking of charge symmetry (C, CP ⇓)

Experiment: $K_L \to 2\pi$, $K^0 \to \pi e^\pm \nu$ well established.

Theory: many models, do not know which is realized.

3. Deviation from thermal equilibrium

In equilibrium $f = (1+e^{E/T})^{-1}$

and $f = \bar{f}$ if $m = \bar{m}$ (CPT)

Chemical potentials $\mu = \bar{\mu} = 0$ if B is not conserved

Theory: FRW - cosmology ⇒ nonstationary universe

) ↳ particles with $m \neq 0$ are always out of equilibrium.

) First order phase transitions during hot stage ⟹ strong deviation from equilibrium

— * —

NB: none of the three above is obligatory.

Necessary conditions for creation of matter and antimatter domains

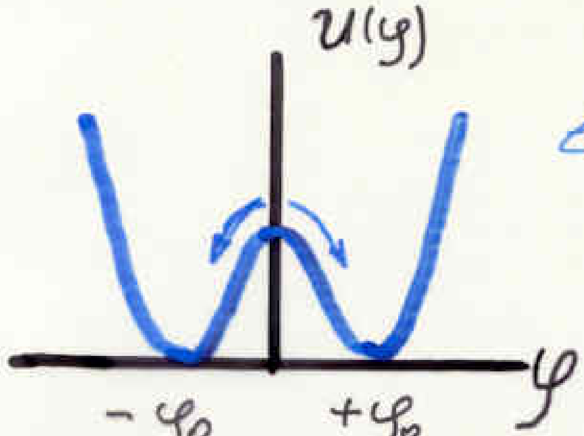
1. Different signs of C (CP) - breaking in different regions
   (Brown, Stecker, spont. CP breaking)

2. Exponential (inflationary) but moderate blow-up of regions with a definite sign of C, CP-breaking.
   (K. Sato, before inflation was proposed)

Mechanisms of C, CP - breaking in cosmology.

1. Explicit — complex constants in Lagrangian
   ↳ $\beta = const$ (space point independent)

2. Spontaneous (T.D. Lee)



← complex field $\varphi(x)$

50% of $\varphi = +\varphi_0$
50% of $\varphi = -\varphi_0$

Globally charge symmetric universe

Domain wall problem (Kobzarev, Okun, Zeldovich)

Necessary $l_B > l_{horizon}$ to solve domain wall problem or to destroy the walls

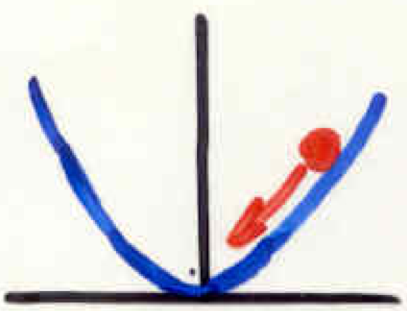
Even if walls were eliminated, B and $\bar{B}$ were in close contact and $l_B > \mathrm{Gpc}$ (CdRG)

3. Stochastic C, CP- breaking (by chaotic initial conditions); does not manifest in particle physics

E.g. $\varphi(t,x) \neq 0$ initialy
← complex field

[inflation $\langle \varphi^2 \rangle \sim H^3 t$ chaotically]

If $\varphi(t \to \infty) \to 0 \Rightarrow$ no C, CP breaking observable today,



no domain walls;

but CP-odd amplitudes $\neq 0$ during baryogenesis.

Possibly both explicit and stochastic were operative.

→ $\bar{M} : M < 1$

Models of Baryogenesis

1. GUT - baryogenesis.

gauge bosons, $m_X \sim 10^{16}$ GeV

$X \to qq, \bar{q}\ell$; B nonconserved

$$\frac{B(X \to qq)}{B(\bar{X} \to \bar{q}\bar{q})} \neq 1 \Leftarrow \text{CP nonconservation}$$

Deviation from thermal equilibrium at $T = m_X$:

H = Hubble parameter

$$\frac{H(T=m_X)}{\Gamma_X} \approx \frac{m_X}{10^{17}\,\text{GeV}} \leftarrow \text{quite large}$$

Problem: probably universe was never at $T \approx m_X$ and X-bosons never were abundant.

Naturally gives $\beta = $ const, no antimatter

2. Electro-weak baryogenesis

CERN B16
Kuzmin
Rubakov
Shaposhnikov

Characteristic temperatures:

$$T_{EW} = (\text{a few}) \times 100\ \text{GeV} - \text{TeV}$$

Normal, known, "low-energy" physics
$SU(3) \times SU(2) \times U(1)$

Baryons do no conserve due to quantum chiral anomaly.

Thermal equilibrium is broken if EW phase transition is first order.

Problem: if $m_{Higgs} > 100\ \text{GeV}$ phase transition is second order.

EW not good for creation of $\bar{n}$
(as well as GUT)

3. Baryo-through-lepto

(combination of 1 and 2).

817
Fukugita
Yanagita

Heavy Majorana neutrino ν_M
(invented for explanation of small masses of ordinary ν's)

$m_{\nu_M} \sim 10^{10}$ GeV

Decays of ν_M naturally do not conserve L, produce lepton asymmetry

EW processes convert L into B in thermally equilibrium state.

B-thru-L is also bad for TM.

Problems: deviation from equilibrium of ν_M at $T \sim m_{\nu_M}$ is small;
CP-breaking effects are probably also small and resulting baryon asymmetry may be to low (?)

People working on B-thru-L are more optimistic

4. Black hole evaporation.

(Ya.B.Z.; S.H.; $\overline{BB}$ AD)

$$BH \to M \begin{smallmatrix}\nearrow \\ \searrow\end{smallmatrix} \frac{B_h \bar{B}_e}{\bar{B}_h B_e} \neq 1 \qquad \left(\text{eg. } \begin{matrix} B_h = t \\ B_e = u \end{matrix}\right)$$

meson (↗ M)

↑ $C, CP \neq +$

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)]

Bad for antimatter.

Problems: unnaturalness,
mechanism of early BH formation?

Intermediate conclusion.

BAD NEWS

All simple models discussed above are bad for antimatter

but simultaneously they are not very good for creating the baryon asymmetry of the observed magnitude.

An introduction an additional complex scalar field $\varphi(t,x) \to$ stochastic CP-violation, may give rise to cosmic antimatter.

GOOD NEWS

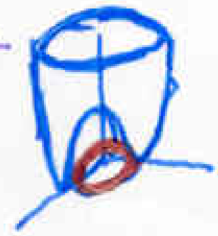
There are (at least) two known models which can explain the observed baryon asymmetry and naturally produce plenty of antimatter.

5. Spontaneous baryogenesis

(A. Cohen, D. Kaplan)

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

$$\mathcal{L} = \lambda(|\varphi|^2 - f^2)^2 + \bar{\psi}(i\partial\!\!\!/ + m)\psi + g\varphi\bar{\psi}_B\psi_e - |(\partial\varphi)|^2 \ldots$$



$\varphi = f e^{i\theta}$, $\psi_B \to \psi_B e^{i\theta}$

$$\mathcal{L} \to f^2(\partial\theta)^2 + \partial_\mu\theta \cdot \bar{\psi}_B\gamma_\mu\psi_B + \ldots$$

← baryonic current

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

$\dot{\theta} = \mu_B$ (chemical potential)

not exactly true

$B \overset{?}{\sim} \dot{\theta} T^2$ in thermal equil

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

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

Sign of $\dot{\theta}$ is arbitrary → matter / → antimatter

6. SUSY condensate (Affleck, Dine)

Necessary ingredients:

a) scalar field, χ, with $B \neq 0$;

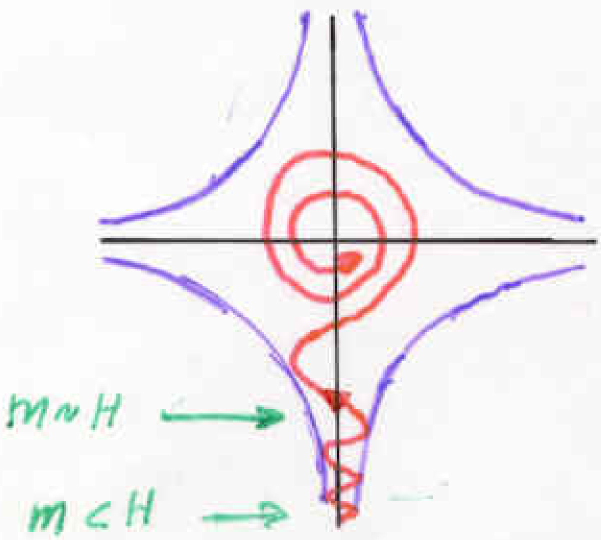
b) flat directions in $U(\chi)$;

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

Natural in SUSY models.

$x^4 + y^4$

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



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

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

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

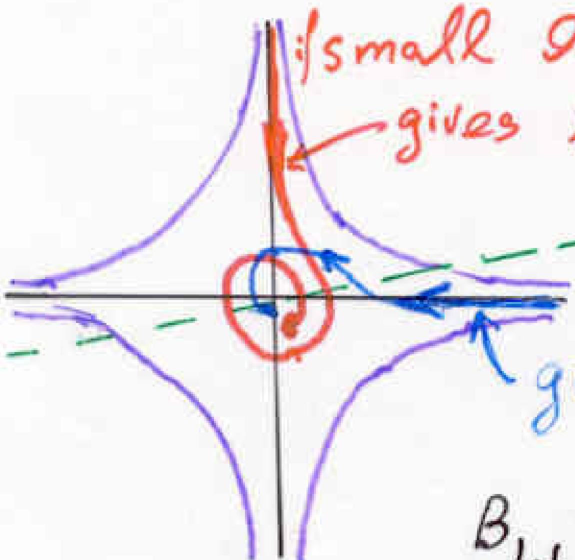
$$J^B_\mu(\chi) = \chi^* \overleftrightarrow{\partial}_\mu \chi, \quad \underline{B = \dot{\vartheta} |\chi|^2} \leftrightarrow \text{angular momentum}$$

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

Explicit CP-violation:

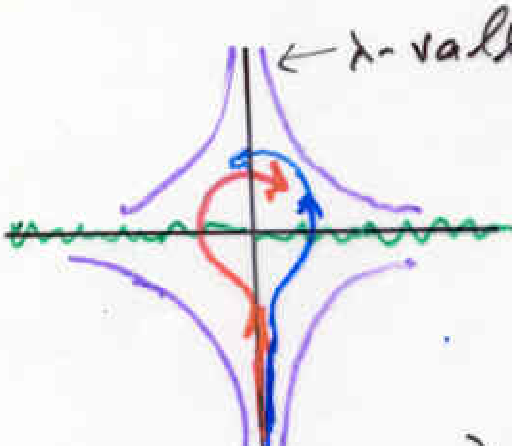
$$U(\chi) = \lambda |\chi|^4 (1 - \cos 4\vartheta) + m^2 |\chi|^2 [1 - \cos(2\vartheta + 2\alpha)]$$

↑ relative phase of m and λ



$B_{tot} = 0$ 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

Evolution of high density anti baryonic bubbles

B22

1. Form Black Holes if $\left(\frac{\delta\rho}{\rho}\right)_{horizon} \sim 1$.

$$\frac{\delta\rho}{\rho} \simeq \frac{m_B}{3T}\,\frac{n_B}{n_\gamma} = \frac{1}{3}\beta\,\frac{m}{T}$$

$$M_{horizon} = \frac{8\pi}{3}\cdot 8t^3\cdot\rho = 5\cdot 10^4 M_\odot \left(\frac{t}{sec}\right)$$

$\overline{BH}$ would possess atmosphere of antimatter

2. Before hydrogen recombination diffusion is slow and atmosphere might survive

3. Recombination in high $\bar{\beta}$ regions occures earlier $T = 1-10$ eV

Hence atmosphere would not be stripped by CMBR at the onset of structure formation.

4. Annihilation could heat the plasma and create secondary ionization

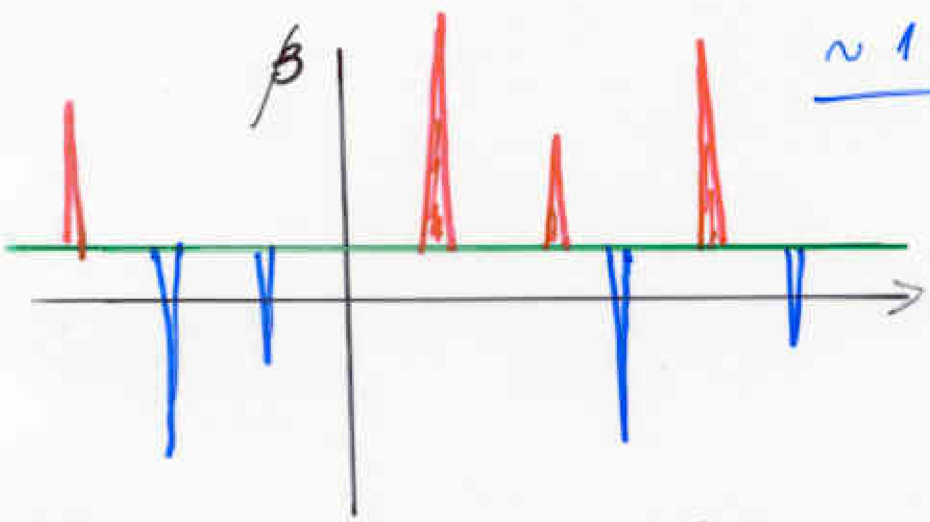
How strong?

If χ is coupled to inflaton

$\lambda(\chi^2 + \chi^{*2})(\Phi - \Phi_1)^2$ (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 $M = 1 - 10^9 M_\odot$

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

↑ Quasars?

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

Isocurvature perturbations and antimatter

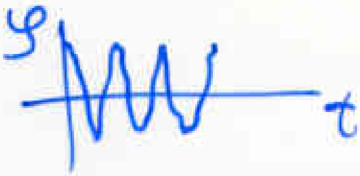
CERN 16
B24

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

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

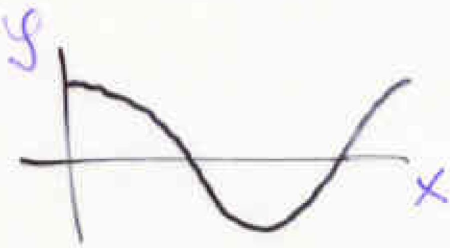
↳ spatial fluctuations of baryon asymmetry at astronomically large scale

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



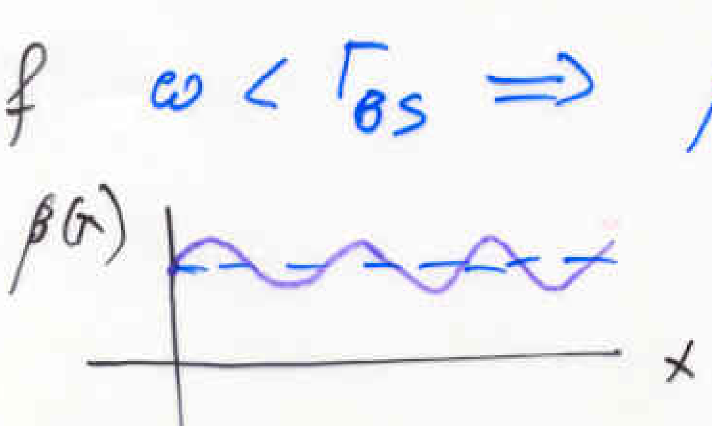
$\omega \sim \sqrt{\lambda}\,\varphi_i(x)$

↳ $\varphi(x;t_{fixed}) =$



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

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



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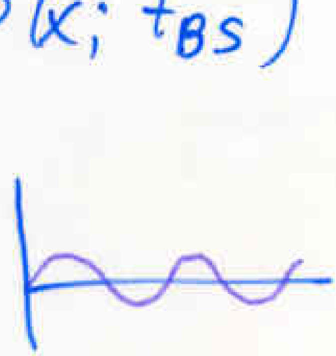

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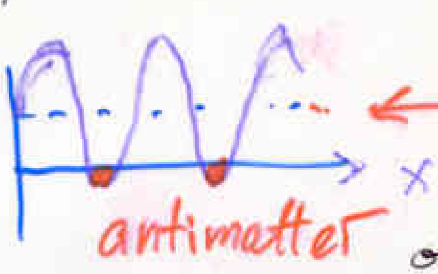


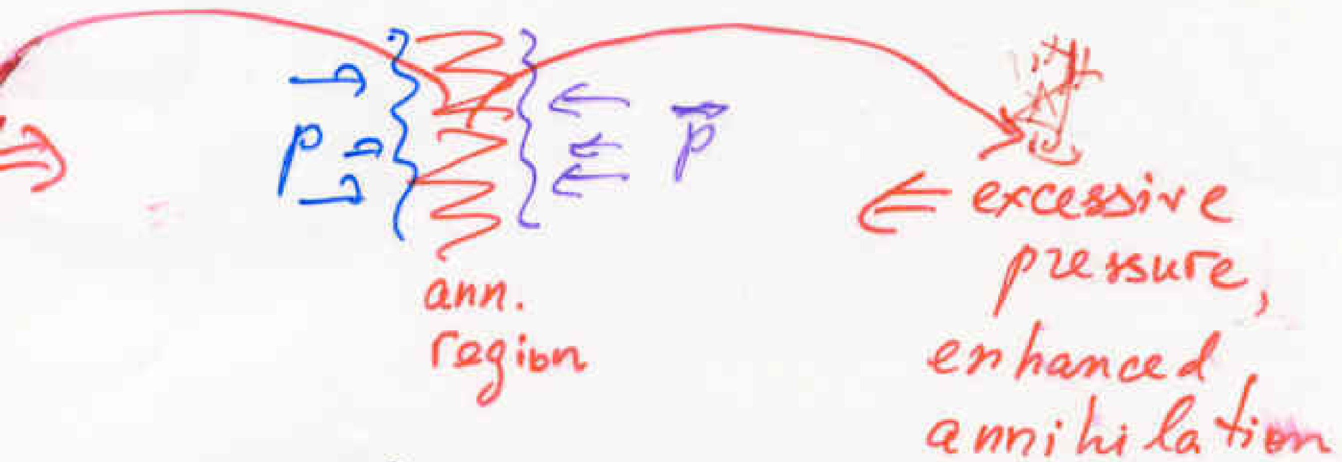
← explicit CP-breaking

Large scale excluded by CMBR
only very large $\lambda > \sim$ Gpc is allowed

B25

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



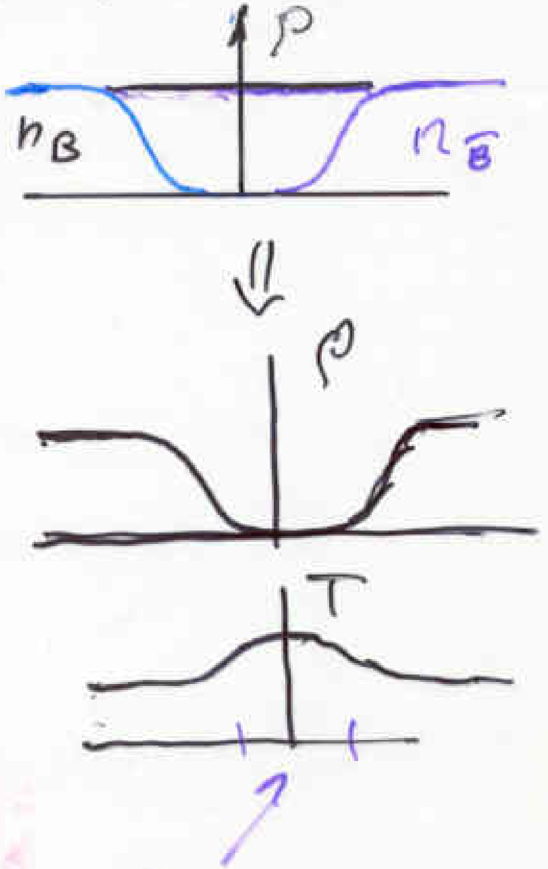
Valid for $M \simeq \bar{M}$

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



$\Delta\rho_{in} = 0$

$\Downarrow$

$\Delta\rho \neq 0$

$\Delta T \neq 0$

Non-relativistic matter cools faster

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

Role of gravity of large scale structure in DM - ??

Conclusion.

1. Simplest models of baryogenesis predict no antimatter but they are also not very good for explanation of the observed asymmetry
2. Spontaneous BG and Affleck-Dine one can explain observed asymmetry and naturally predict large fraction of antimatter.
3. In a version of AD-model with coupling to inflaton baryon rich compact objects may be in galactic halo and even make all DM from BH and anti-BH surrounded correspondingly by M or $\bar{M}$.
4. Heavy $\bar{A}$ may be even more abundant than $\overline{He^4}$.
5. In model 3 detailed predictions are possible (if $DM = BH + \overline{BH}$) but more (a lot) work is necessary.