BARYOGENESIS AND COSMIC ANTIMATTER

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Content of the lectures:

1. **Introduction.**
2. **Search for cosmic antimatter.**
3. **General features of baryogenesis.**
4. **CP-violation in cosmology.**
5. **Models of baryogenesis.**
6. **Mechanisms of creation of cosmological antimatter.**
7. **Observational manifestations of (abundant) antimatter.**
8. **Perspectives and conclusion.**

82 years ago, one of the greatest break-throughs of XX century: P.A.M. Dirac, Proc. Royal Soc. London, A117 (1928) 610, discovered "with the tip of his pen" a whole world of antimatter (not just a small planet).

Carl Anderson, discovery of positron, 1933; Nobel prize 1936.
Dirac's Nobel prize in 1933 immediately after the experiment.

Paul A.M. Dirac: "Theory of electrons and positrons", Nobel Lecture, December 12, 1933: "It is quite possible that... these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

There are ways to observe them now!
Maybe spectra are not exactly the same?
CPT?, branching ratios??

In 1898, 30 years before Dirac and one year after discovery of electron (J.J. Thomson, 1897) Arthur Schuster (another British physicist) conjectured that there might be other sign electricity, ANTIMATTER, and supposed that there might be entire solar systems, made of antimatter and indistinguishable from ours.

Schuster's wild guess: matter and antimatter are capable to annihilate and produce VAST energy.
He believed that they were gravitationally repulsive having negative mass.
Two such objects on close contact should have vanishing mass!?

A. Schuster, Nature, 58 (1898) 367.
Potential Matter. Holiday Dream.
“When the year’s work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable?”
”Astronomy, the oldest and yet most juvenile of the sciences, may still have some surprises in store. May antimatter be commended to its case”.

Older than century questions:
Whether antiworlds, antistars or similar astronomically large pieces of antimatter may exist in the universe?
What are observational bounds on existence of antimatter in the universe and in the Galaxy.
Do theory and observations allow for significant amount of antimatter in our neighborhood?

Two types of observational data:
Indirect: astronomical manifestations of antimatter: 0.5 MeV or 100 MeV gamma-rays, distortion of CMB, impact on BBN and LSS formation.
Direct: registration of antimatter which cannot be secondary produced, mainly cosmic anti-nuclei, partly antiprotons and positrons in cosmic rays.
Nowadays, burst of experimental activity for direct search of cosmic antimatter:

Existing missions for the direct search:

1. BESS: Japanese Balloon Borne Experiment with Superconducting Solenoidal Spectrometer.

2. PAMELA (Italian-Russian space mission): Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics.

3. AMS: AntiMatter Spectrometer (Alpha Magnetic Spectrometer), CERN-MIT-NASA.

Planned missions:

PEBS (Positron Electron Balloon Spectrometer, 2010?), search for cosmic positrons and antiprotons.

GAPS (Gaseous Antiparticle Spectrometer, 2014?), search for X-rays from de-excitation of exotic atoms, may reach 2 orders of magnitude better sensitivity than AMS for $\bar{H}e/He$.

Search for cosmic anti-helium, existing bounds:

BESS: $\bar{H}e/He < 3 \times 10^{-7}$.

Expected:
PAMELA: $\bar{H}e/He < 3 \times 10^{-8}$;
AMS-2: $\bar{H}e/He < 10^{-9}$.

Observed flux of cosmic helium at $E < 10$ GeV/nuclei:
$dN/dE = 10^2/m^2/str/sec/GeV$.

Expected secondary produced anti-nuclei

Anti-deuterium is produced in $\bar{p}\,p$ or $\bar{p}\,He$ collisions (Duperray et al, 2005)
The predicted flux of anti-deuterium:
$\sim 10^{-7}/m^2/s^{-1}/sr/(GeV/n)$,
i.e. 5 orders of magnitude lower than the observed flux of antiprotons.
The expected fluxes of secondary produced $^3\bar{H}e$ and $^4\bar{H}e$ are respectively 4 and 8 orders of magnitude smaller than the flux of anti-D.

Observations and bounds, summary.

$\bar{p}/p \sim 10^{-5} - 10^{-4}$, observed, can be explained by secondary production;

$He/p \sim 0.1$;

Upper limit: $\bar{H}e/He < 3 \times 10^{-7}$;

Theoretical predictions: $\bar{d} \sim 10^{-5}\bar{p}$, $^3\bar{H}e \sim 10^{-9}\bar{p}$, $^4\bar{H}e \sim 10^{-13}\bar{p}$.

From the upper limit on $\bar{H}e$: the nearest single antigalaxy should be further than 10 Mpc (very crudely).

From cosmic gamma rays:

Nearest anti-galaxy could not be closer than at $\sim$10 Mpc (Steigman, 1976), from annihilation with p in common intergalactic cloud.

Fraction of antimatter Bullet Cluster $< 3 \times 10^{-6}$ (Steigman, 2008).

CMB excludes LARGE isocurvature fluctuations at $d > 10$ Mpc.

BBN excludes large "chemistry" fluctuations at $d > 1$ Mpc.

The bounds presented above are true if antimatter makes the same type objects as the OBSERVED matter.

For example, compact objects made of antimatter may be abundant, live in the Galaxy but still escape observations (discussed below).

Prevailing point of view at the present time: all the universe is made only of matter and there is no primeval anti-matter.

Still the fact that antimatter exists created fundamental cosmological puzzle: why the observed universe is 100% dominated by matter?
Antimatter exists but not antiworlds, why? The problem deepened because of approximate symmetry between particles and antiparticles.
In fact before 1956, the common faith in exact C, P, and T symmetries looked unbreakable.

The puzzle of cosmological predominance of matter over antimatter was resolved by baryogenesis based on three conditions (Sakharov, 1967):

I. Nonconservation of baryons.

II. Violation of symmetry between particles and antiparticles, i.e. C and CP.

III. Breaking of thermal equilibrium.

(None of these conditions are obligatory.)

Despite of excellent explanation of baryonic dominance in the universe, maybe antiworlds still exist?

Plethora of baryogenesis scenarios which can explain one number:

$$\beta_{observed} = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \times 10^{-10}.$$

The usual outcome: $\beta = const$, which makes it impossible to distinguish between models and does not leave space for cosmological antimatter.

NB: all the models, but one (Affleck and Dine) give rise to a small β but AD may create $\beta \sim 1$.

Natural generalizations of the simplest models of baryogenesis allow for a lot of antimatter almost at hand.

An observation of cosmic antimatter will give a clue to baryogenesis, to the mechanism of cosmological C and CP breaking, and present an extra argument in favor of inflation.

Since generalized scenarios predict a whole function $\beta(x)$ the models are falsifiable.

Now let's discuss three Sakharov's conditions.

I. Non-conservation of baryonic number, B.

The weakest point when Sakharov proposed the mechanism. It was believed that baryons last forever, as "a diamond-and-safire bracelet" (from Anita Loos's "Gentlemen Prefer Blondes").

The motto was: "we exist ergo baryons are conserved".

Today situation is opposite: theory predicts nonconservation of B and cosmology presents an "experimental proof of that.

Now: "we exist ergo baryons are not conserved" the same fact (our existence) but opposite conclusion. Sometimes theory helps to understanding the world.

Proof of nonconservation of baryons comes from inflation. **Cosmological inflation is practically an experimental fact:**

1. Flatness, $\Omega = 1$. Without inflation the adjustment should be at 10^{-60}.

2. Homogeneity, isotropy, horizon - all solved.

3. Small primordial perturbations at astro-scales with almost FLAT spectrum, OBSERVED.

An observation of gravitational waves will eliminate all existing skepticism, but their absence will not kill inflation.

Inflation is the only known way to create the observed, suitable for life universe universe.

However, beware of danger of no-go theorems in physics, e.g. SUSY.

Sufficient inflation
($\sim$ 70 Hubble times)
could proceed only if the energy density is approximately constant.

$$H = \dot{a}/a \sim \sqrt{\rho}/m_{Pl}$$

and a $\sim \exp(\mathrm{Ht})$ if $H = const.$

If baryons are conserved, the energy density associated with baryonic charge (baryonic number) cannot be constant and inflation could last at most 4-5 Hubble times.

If baryonic charge were conserved:

$$B \sim 1/a^3, \;\; \rho_B \sim 1/a^n, \, n = 3 - 4$$

At RD-stage $\rho_B \approx 10^{-7}\rho_{tot}$ **and**

$$\rho_B/\rho_{tot} \approx const$$

till inflation, backward in time. At inflation $\rho_{tot} = const$ **(without baryons), while** $\rho_B \sim exp(-4Ht)$.
For $Ht > 4{-}5$**: sub-dominant baryons became dominant,** $\rho_{tot} \approx \rho_B$ **and**

$$\rho \neq const$$

B-nonconservation, theory.

1. B is classically conserved in the minimal standard electroweak theory, but this conservation is broken due to quantum corrections - chiral anomaly ('t Hooft, 1974).

The non-conservation is tiny at $T = 0$ but may be strongly enhanced at high temperatures:

$$\Gamma(0) \sim m_W^4 \, e^{-4\pi/\alpha_W} \sim 10^{-170} \, ,$$

$$\Gamma(T) \sim \alpha^{4-5} T^4 \, , \; T > TeV \, .$$

2. Grand unified theories (GUT): quarks and leptons are in the same multiplet, so naturally transformed into each other, $\Delta B \neq 0$:

$$\Gamma \sim M_{GUT}^{-4}.$$

3. Many extended theories, e.g. SUSY, where all operators with $\Delta B \neq 0$ are allowed.

No direct experimental confirmation of B-nonconservation, only upper bounds

Proton life-time:

$$\tau_p > 10^{30} - 10^{33} \text{ years}$$

In some theories proton is stable but neutron may transform into antineutron:

$$\tau_{n\bar{n}} > 10^8 \, s.$$

Gravitational interactions do not conserve baryonic number. Gravity breaks all global symmetries. Gravitational proton decay through virtual black hole (Zeldovich, 1976). Three quarks in proton form a BH which evaporates e.g. into $e^+\pi^0$:

$$\tau_p = m_{Pl}^4/m_p^5 \sim 10^{45}\,\text{years}\,.$$

Effect is negligible but maybe observable in TeV gravity with $m_{Pl} \sim$ TeV. Life-time diminishes by 64 orders of magnitude. See, however, below.

II. C and CP violation in cosmology.
Both are discovered and confirmed by direct experiment but the mechanism realized in cosmology may have nothing to do with that realized in particle physics.
What about Occam's razor: entities must not be multiplied beyond necessity ("entia non sunt multiplicanda praeter necessitatem").

HISTORY:

Before 1956, all conserved: P, C, T.

1956, Lee, Yang, Wu: discovery of parity non-conservation.

CP-invariance assumed, Landau(?)

1964: CP-VIOLATION, Christenson, Cronin, Fitch, Turlay. Almost discovered in JINR (Okonov).

After this discovery life in the universe became possible.

Only CPT survived destruction - the symmetry with solid theoretical justification: CPT-theorem:

1. Lorenz-invariance.

2. Canonical spin-statistics relation.

Still some models without CPT are considered, e.g. for explanation of some neutrino anomalies and just for fun.

NB: If CP is broken but CPT is not, T must be broken as well.

Why CP-breaking is necessary but C-breaking is not enough?

A formal answer:

Assume that the universe is in C eigenstate, i.e.

$$C|u\rangle = \eta|u\rangle$$

where $|\eta| = 1$.

This means, in particular, that the universe has all zero charges.

May some non-zero charge, e.g. B, be generated dynamically?

Assume first that C is conserved, i.e.

$$[C, \mathcal{H}] = 0$$

Time evolution of B:

$$B(t) = \langle u | e^{-i\mathcal{H}t} J_0^B e^{i\mathcal{H}t} | u \rangle.$$

Insert $I = C^{-1}C$:

$$B(t) = \langle u | I e^{-i\mathcal{H}t} I J_0^B I e^{i\mathcal{H}t} I | u \rangle = -B(t)$$

taken that $\mathrm{C J_0^B C^{-1} = -J_0^B}$.

Thus in C-conserving theory

$$B(t) = B_{in} = 0.$$

The same arguments with CP instead of C prove that charge asymmetry cannot be generated, if CP is conserved and the universe is an eigenstate of CP:

$$CP|u\rangle = \eta|u\rangle$$

In globally rotating universe charge asymmetry might be generated even if CP is conserved. Global rotation can be transformed into baryonic charge! New long-range interactions, possibly pathological, are needed??? Observed predominant galaxy rotations in one direction !?.

For B-generation in elementary (local) processes no assumption about the universe state is necessary:
if CP is conserved, no asymmetry is generated through particle decays or reactions.
- discuss below in concrete scenarios.

Three possibilities to break CP :

1. **Explicit**, the usual one in particle physics. Normally leads to the universe without antimatter.

2. **Spontaneous,** locally indistinguishable from explicit, but leading to globally charge symmetric universe.

3. **Stochastic or dynamical,** unobservable in particle physics. May lead to noticeable amount of antimatter and globally asymmetric universe.

I. Explicit CP- breaking. **Complex constants in Lagrangian, in particular (in MSM), complex Yukawa couplings transformed by the Higgs field $\langle \phi \rangle \neq 0$ into a non-vanishing phase in CKM-mixing matrix. However, in MSM the baryon asymmetry is too small, by 10 orders of magnitude.**

New physics beyond MSM is necessary.

CP-breaking in MSM

is absent for two quark families - can be rotated away.
Three families are necessary - an anthropic explanation of number of flavors? (does not work).
If masses of different up or down quarks are equal, CP violation can be rotated away because unit matrix is invariant.
If mass matrix is diagonal in the same representation as flavor matrix CP-violation can also be rotated away.

Thus CP-breaking is proportional to the product of the mixing angles and to the mass differences of all down and all up quarks:

$$\mathbf{A}_{-} \sim \sin\theta_{12}\sin\theta_{23}\sin\theta_{31}\sin\delta$$
$$(\mathbf{m}_t^2 - \mathbf{m}_u^2)(\mathbf{m}_t^2 - \mathbf{m}_c^2)(\mathbf{m}_c^2 - \mathbf{m}_u^2)$$
$$(\mathbf{m}_b^2 - \mathbf{m}_s^2)(\mathbf{m}_b^2 - \mathbf{m}_d^2)(\mathbf{m}_s^2 - \mathbf{m}_d^2)/\mathbf{M}^{12}$$

At high T the characteristic energy where B is not conserved
$\mathbf{M} \geq 100$ GeV and

$$\mathbf{A}_{-} \sim 10^{-19}.$$

At T = 0 the mass in the denominator is the zero-temperature quark mass and the CP-odd amplitude is not such vanishingly small.

At high T quarks acquire QCD corrections to the "mass" of order T, while in the numerator there are still "Higgs masses" or, better to say, small Yukawa coupling constants.

Attempts to modify quark dispersion relation at high T, $E = E(p, T)$, were unsuccessful.

More about the usual CP-violation.
CP-odd phases in Dirac mass matrix:

$$\mathcal{L}_m = m_{ij} \bar{q}_i q_j \, .$$

Diagonal terms m_{ii} are real because of Hermicity. Off-diagonal m_{ij} with $i \neq j$ can be complex. Phase rotation:

$$q_i \to e^{i\phi_i} q_i \, .$$

One can change the phase of m_{ij} by

$$m_{ij} \to e^{i(\phi_i - \phi_j)} m_{ij} \equiv e^{i\phi_{ij}} m_{ij} \, .$$

Evidently $\phi_{12} + \phi_{23} + \phi_{31} = 0$.
Three phases in m_{ij} and 2 conditions, one arbitrary phase remains.

Majorana mass matrix:

$$\mathcal{L}_M = M_{ij}\nu_i C\nu_j \, .$$

All M_{ij} may be complex.
One can kill three phases in M_{ii} by 3 phase rotations of ν_i. No freedom left after that and three phases of M_{12}, M_{23}, and M_{31} remain arbitrary.

A problem: How many CP-odd phases are allowed in the case of both Dirac and Majorana mass matrices?

II. Spontaneous CP-violation, (T.D. Lee, 1974). **A complex scalar field Φ acquiring different vacuum expectation values:**

$$\langle \Phi \rangle = \pm f \, .$$

Lagrangian is CP-invariant.
Locally indistinguishable from explicit but leads to globally charged symmetric universe, 50:50 matter and anti-matter.

PROBLEMS:

1. Domain wall problem, (Zel'dovich, Kobzarev, Okun): huge surface energy density of walls between domains with different signs of CP-breaking amplitude destroys isotropy of the universe. To avoid that the nearest domain of antimatter should be at $l_B \gg$ Gpc or a mechanism of wall destruction is necessary.

Mohapatra, Senjanovic 1979. Symmetry is not restored at high T, as well as at low T. No antimatter domains. Opposite to the normal situation but can be realized. Moreover, it exists in solid state physics.

2. The size of domains are too small and matter and antimatter annihilate leaving behind an empty universe. Can be solved with mild inflationary expansion after CP-breaking took place (Sato, 1980). Still many problems: domain wall extinction, suppression of powerful annihilation, etc...

If inflation is invoked, the domain size can be arbitrary large. Observational bound from gamma-ray background: $l_B >$ Gpc (Cohen, De Rujula, Glashow, 1996).

The size of empty regions between domain should be smaller than 10 Mpc to avoid noticeable density perturbations, but this is smaller than mean free path of photons which brings $p\bar{p}$ into contact. Positive feedback: annihilation creates excessive pressure far from the annihilation zone and push $p\bar{p}$ together. Some loopholes may invalidate this bound.

Kuzmin, Shaposhnikov,Tkachev, 1981. CP was spontaneously broken at high T and restored at low T. An explicit CP-violation is also necessary. Anti-matter exists but not in 50:50 share. A mixture of explicit and spontaneous CP violation may lead to too large density perturbations and distort BBN.

III. Dynamical or stochastic CP-violation (AD, 1992), realized by a complex scalar field displaced from the equilibrium point due to infrared instability of light scalars at DS (inflationary) stage, $\chi^2 \sim H^3 t$, (sign ?) and relaxed to the equilibrium point after baryogenesis.

It could operate only in the early universe and disappeared without trace today. No domain wall problem.

Why do we multiply entities against Occam? Nature is usually very economical. Such mechanism always operate in the early universe if there exists any complex scalar field with $m < H_{inf}$.

Such temporary CP-violation could give rise to an inhomogeneous baryon asymmetry, $\beta(x)$, with antimatter nearby.

III. Breaking of thermal equilibrium.

Canonical equilibrium distributions:

$$f_{eq} = \left[e^{(E-\mu)/T} \pm 1 \right]^{-1},$$

where μ is chemical potential prescribed to any conserved quantum number if number of particles is not equal to that of antiparticles.

If some quantum number is not conserved, then in equilibrium $\mu = 0$, as can be seen from kinetic equation.

If $\mu = 0$ and $m = \bar{m}$ (by CPT), then the number of particles is equal to the number antiparticles.

$$n = g_s \int \frac{d^3p}{(2\pi)^3} f_{eq}(p) = \bar{n} \, .$$

Do the equilibrium distributions have the same canonical form if T-invariance is broken?

Collision integral:

$$I_{coll} \sim |A_{fi}|^2 \Pi f_f \Pi (1 \pm f_i) - (inverse)$$

If T-invariance holds, i.e. $|A_{if}| = |A'_{fi}|$:

$$I_{coll} \sim \left[\Pi f_i (1 \pm f_f) - (i \leftrightarrow f) \right] d\tau \,.$$

$I_{coll} = 0$ **for arbitrary** T **and** μ.

If T-invariance is broken and $|A_{if}| \neq |A'_{fi}|$, :

$$I_{coll}[f_{eq}] \sim \Pi f_i (1 \pm f_f) \left[|A_{fi}|^2 - |A_{if}|^2 \right]$$

This term is surely non-vanishing!
Do equilibrium distributions remain the same in T-broken theory?

Breaking of T-invariance is unobservable if only one reaction channel is open. In this case $T_{if} = T^*_{fi}$ with time reflected momenta.

f_B^C annihilates collision integral after summation over all relevant processes, due to S-matrix unitarity or CPT and conservation of probability.

Instead of the detailed balance condition there operates "the cyclic balance" condition' (AD, 19??).

If CPT is broken and $m \neq \bar{m}$ then $n \neq \bar{n}$ in equilibrium.
However, if CPT is broken, the equilibrium distributions may be different from their canonical form! The result depends upon the concrete mechanism of CPT violation and is not yet well studied.

In cosmology thermal equilibrium is distorted due to universe expansion. **Massive particles are always (slightly) out of equilibrium.**

Kinetic equation in FRW metric:

$$\left(\partial_t - Hp\partial_p\right) f(t,p) = I_{coll}$$

can be rewritten as

$$Ha\frac{\partial f}{\partial a} = \Gamma\left(f_{eq} - f\right) \,,$$

where a is the cosmological scale factor and H is the Hubble parameter.

For small deviation from equilibrium $f = f_{eq} + \delta f$ and

$$\frac{\delta f}{f_{eq}} \approx \frac{Hm^2}{\Gamma E T} \approx \frac{10^2 m}{m_{Pl}} \approx \frac{m}{\alpha m_{Pl}},$$

if $T \sim m$, $\Gamma \sim \alpha m$, and $\alpha \sim 10^{-2}$. For large $\delta f/f$ either heavy particles are needed or low decay rate, $\alpha \ll 10^{-2}$, but smallness of α does not enter the final result.

Massless particles are almost always in equilibrium.

Exception: neutrinos after e^+e^- - annihilation due to energy-dependent heating of cool neutrinos by hotter electrons and positrons.

First order phase transition is another possible source of equilibrium breaking. Two coexisting different phases is a non-equilibrium state.

An incomplete "shopping list" of the baryogenesis (BG) scenarios includes:

I. Heavy particle decays (Sakharov)

II. Electroweak BG (Kuzmin, Rubakov, Shaposhnikov).

III. Baryo-through-leptogenesis (Fukugit Yanagita).

IV. SUSY condensate BG (Affleck, Dine).

V. Spontaneous BG (Cohen, Kaplan).

VI. BG by evaporation of primordial black holes (Zeldovich, AD).
VII. Space separation of baryons and antibaryons. (Omnés, and later, into higher dimensions) or compact (anti)quark nuggets.
VIII. BG due to CPT violation (Zeldovich, AD) .
IX. Baryogenesis and darkogenesis.
X. BG by topological defects.

I. BG through heavy particle decays.
Particles and antiparticles can have different decay rate into charge conjugated channels if C and CP are broken, while total widths are equal due to CPT invariance.
If only C is broken, but CP is OK, then partial widths, summed over spins, are the same:

$$\Gamma\left(X \to f, \sigma\right) = \Gamma\left(\bar{X} \to \bar{f}, -\sigma\right)$$

If both C and CP are broken, partial widths are different. Example:

$$X \to qq, \;\; X \to q\bar{l},$$
$$\bar{X} \to \bar{q}\bar{q}, \;\; \bar{X} \to \bar{q}l\,.$$

Width are different if re-scattering with baryonic charge non-conservation in the final state is taken into account:

$$\Gamma_{X\to qq} = (1+\Delta_q)\Gamma_q, \;\; \Gamma_{X\to q\bar{l}} = (1-\Delta_l)\Gamma_l,$$
$$\Gamma_{\bar{X}\to \bar{q}\bar{q}} = (1-\Delta_q)\Gamma_q, \;\; \Gamma_{\bar{X}\to \bar{q}l} = (1+\Delta_l)\Gamma_l.$$

Hence $B \sim (2/3)(2\Delta_q - \Delta_l)$.
$\Delta \sim g^2/4\pi \ll 1$,

Rough estimate of the asymmetry:

$$\beta \sim \frac{\delta f}{f}\frac{\Delta\Gamma}{\Gamma} \sim \frac{m}{m_{Pl}},$$

if $\delta f \sim m$ and not by 1st order p.t.
Some small numerical coefficients make the result even smaller.
Subsequent entropy dilution by about 1/100 is not included.

For successful lepto/baryo-genesis by heavy particle decays the mass of the decaying particle should be larger than 10^{10} GeV (or $m_{Pl} \ll 10^{19}$ GeV), realized e.g. in GUT or TeV gravity, see below; potential problem for leptogenesis, may be solved by resonance transformation.

Comments.

1. Necessity of re-scattering with $\Delta B \neq 0$ or $\Delta L \neq 0$.

In lowest order $A = \bar{A}^*$ because of hermicity of Lagrangian.
The same would be true for higher order contributions if they were real.
Imaginary part is generated by re-scattering in the final state.
Why re-scattering with $\Delta B \neq 0$?

S-matrix unitarity:

$$\mathbf{i}(\mathbf{T_{if}} - \mathbf{T^{\dagger}_{if}}) = -\sum_{\mathbf{n}} \mathbf{T_{in}} \mathbf{T^{\dagger}_{nf}}$$
$$= -\sum_{\mathbf{n}} \mathbf{T^{\dagger}_{in}} \mathbf{T_{nf}} \,.$$

CPT: $\mathbf{T_{fi}} = \tilde{\mathbf{T}}_{\overline{\mathbf{fi}}}$, "tilde" means change of spin signs by PT-transformation. Since $\mathbf{T^{\dagger}_{if}} = \mathbf{T^{*}_{fi}}$, total probabilities of any process with particles and antiparticles are equal in the lowest order (r.h.s. of unitarity relation is neglected).

If only two channels i and f are open, still $\Gamma = \bar{\Gamma}$. Indeed:

$$2\mathcal{I}m T_{ii}[\lambda] = \int d\tau_i |T_{if}|^2 + \int d\tau_f |T_{ff}|^2$$

By CPT:

$$T_{ii}[\lambda] = T_{\overline{ii}}[-\lambda]$$

and after summing over polarization we find $\Gamma_{\mathrm{if}} = \Gamma_{\overline{\mathrm{if}}}$.

Hence to destroy the equality of partial widths $\Gamma_{\mathrm{if}} = \bar{\Gamma}_{\overline{\mathrm{if}}}$ at least three channels must be open:

$$\mathbf{i} \leftrightarrow \mathbf{f}, \;\; \mathbf{i} \leftrightarrow \mathbf{k}, \;\; \mathbf{k} \leftrightarrow \mathbf{f}.$$

2. How charge asymmetry vanishes in equilibrium? By inverse decay? Using CPT, one finds:

$$\Gamma_{\bar{q}\bar{q}\to\bar{X}} = (1+\Delta_q)\Gamma_q,\ \Gamma_{\bar{q}l\to\bar{X}} = (1-\Delta_l)\Gamma_l,$$
$$\Gamma_{qq\to X} = (1-\Delta_q)\Gamma_q,\ \Gamma_{q\bar{l}\to X} = (1+\Delta_l)\Gamma_l.$$

Thus direct and inverse decays produce the same sign of baryon asymmetry!? - a problem to solve

GUT baryogenesis:
natural B-nonconservation, large masses to break thermal equilibrium but temperatures, $T \sim 10^{16}$ GeV, are needed, probably not reachable after inflation. Still out-of-equilibrium heavy particles might be produced.
Gravitino problem.

VI. BG through PBH evaporation.

It does not demand B-nonconservation at particle physics level but evidently baryonic number is not conserved. E.g. BH made exclusively of baryons would decay practically into equal amount of B and anti-B. Outside the only "hairs" of BHs are mass, angular momentum, and electric charge.

Some formulae:

Black hole temperature:

$$T_{BH} \sim 1/r_g \sim m_{Pl}^2/M_{BH}\,.$$

Luminosity:

$$L_{BH} \sim T^4 r_g^2 \sim m_{Pl}^4/M_{BH}^2\,.$$

Life-time:

$$\tau_{BH} \sim M_{BH}^3/m_{Pl}^4\,.$$

For $\mathrm{M_{BH}} = 10^{15}$g, $\tau_{BH} \approx t_U$.

It was believed that thermal evaporation cannot create any charge asymmetry. However the spectrum of the evaporated particles is not BLACK but GRAY due to propagation of the produced particles in gravitational field of BH. Moreover, an interaction among the produced particles is essential.

A model: A-meson is created at the horizon and decays as:

$$A \to H + \bar{L} \text{ and } A \to \bar{H} + L$$

with different branching ratios.
Back-capture of H is larger than that of L. Net baryon asymmetry could be created. If $\rho_{BH}/\rho_{tot} = \epsilon$ at the production, then at red-shift $z = 1/\epsilon$ BH would dominate. Their evaporation could provide baryon asymmetry and reheat the universe.

Example: $\mathbf{T_{BH} = 10^{10}}$ GeV,
$\mathbf{M_{BH} = 10^9 m_{Pl} = 10^4 g}$,
$\tau_{BH} \sim 10^{-16}$ sec,
which corresponds to cosmological temperature $\mathbf{T \sim 10^5}$ GeV and red-shift from the moment when horizon mass was equal to $\mathbf{M_{BH}}$, was about $\mathbf{10^{10}}$.

If mass fraction of BH at production was 10^{-10} then at the moment of their evaporation they would dominate cosmological energy density and could create observed baryon asymmetry. Planck mass remnants of PBH, if they are stable, could be cosmological DM.

During BH domination stage the universe expands in non-relativistic regime, small primordial fluctuations rose as $a(t)$. They may reach unity and above. Gravitational waves from this epoch may be observable with high frequency GW detectors (AD, D. Ejlli).

Mechanisms of PBH formation:

PBHs are formed if the density contrast at horizon scale is of the order of unity, $\delta\rho/\rho \sim 1$. Hence PBHs formed at cosmological time t_p have masses:

$$M = t_p m_{Pl}^2, \quad t_p = r_g/2$$

where $r_g = 2M/m_{Pl}^2$ and

$$m_{Pl} = 1.22 \times 10^{19} GeV \approx 2.18 \times 10^{-5} g.$$

With flat spectrum of perturbations the probability of BH formation is low, $\Omega_p \ll 1$. Large density perturbations at small scales after inflation could be created by a massive scalar field with general renormalizable coupling to the inflaton (AD, J. Silk):

$$\lambda(\Phi - \Phi_1)^2|\chi|^2 .$$

Log-normal mass spectrum of BH. Discussed below.

II. Electroweak baryogenesis in MSM:
1. CP is broken, but very weakly.
2. Baryonic charge is non-conserved because of nonabelian chiral anomaly. At $T = 0$ it is exponentially suppressed:

$$\Gamma \sim \exp\left(- 4\pi/\alpha_W \right).$$

At high T it is possible to go over the barrier, but abundant formation of classical field configuration, sphalerons is necessary. Problems with sphaleron formation in particle collisions?

3. Thermal equilibrium is broken if phase transition is first order,
but heavy Higgs makes it improbable.
Deviation from equilibrium due to non-zero mass is weak:

$$\sim m_{EW}/m_{Pl} \sim 10^{-16},$$

but it could be large in TeV-gravity!

TeV gravity (Arkani Hamed, Dimopulos, Dvali), unification of gravity with EW at TeV scale due to multidimensional nature of gravitational forces, $m_{Pl} \to TeV$ at small distances.
Strong nonconservation of all global quantum numbers B, L, L_a, etc...

Several suggestions to lift the low scale global symmetry breaking.

In classical GR, a BH with mass smaller than m_{Pl} cannot be formed if it has a non-zero electric charge or if it rotates. Conjectured (Bambi, AD, Freese) that this result remains true for virtual BHs mediating e.g. proton decay:

$$\left(\frac{M_{BH}}{M_{Pl}}\right)^2 > \frac{Q^2}{2} + \sqrt{\frac{Q^4}{4} + J^2}.$$

The calculations of the rates of processes with any flavor violation with a set of some hand-waving rules leads to the results below, but quite close to the experimental bounds.

The conjecture is favorable for BG:
Large deviation from equilibrium.
Nonconservation of baryons in heavy quark decays.
Non-negligible CP-violation because BS might proceed below the sphaleron scale, where $T \ll$ TeV.

III. Baryo-thru-lepto-genesis, a mixture of I and II.

Creation of lepton asymmetry by heavy ($m \sim 10^{10}$ GeV) Majorana ν decay, similar to GUT, and transformation of L into B by CP and $(B-L)$ conserving EW processes later.

L is naturally nonconserved.

Heavy particles, $m \sim 10^{10}$ GeV, to break thermal equilibrium are present.

Three CP-odd phases of order unity might be there.

V. Spontaneous baryogenesis.

May operate in thermal equilibrium.
Explicit CP-violation is not obligatory.
Spontaneous breaking of U(1):

$$U(\phi) = \lambda(|\phi|^2 - \eta^2)^2,$$

related e.g. to baryonic charge, leads to massless, Goldstone boson, $\theta(x)$:

$$\phi = \eta\, exp(i\theta)$$

If the potential $V(\theta) \neq 0$ the boson would be massive but usually light.
E.g. $\delta U(\phi) = m^2\left(\phi^2 + \phi^{*2}\right)$.

In the broken phase the Lagrangian can be written as:

$$\mathcal{L} = \eta^2(\partial\theta)^2 + \partial_\mu\theta j_\mu^B - V(\theta) + i\bar{Q}\gamma_\mu\partial_\mu Q + i\bar{L}\gamma_\mu\partial_\mu L + (g\eta\bar{Q}L + h.c.)$$

Red term looks like chemical potential, $\dot{\theta}n_N$ but in reality is not, because the coupling is derivative and $\mathcal{L} \neq \mathcal{H}$.

If $V(\theta) = 0$, i.e. purely Goldstone case, we can integrate equation of motion:

$$2\eta^2 \partial^2 \theta = -\partial_\mu j_\mu^B$$

and obtain:

$$\Delta n_B = -\eta^2 \Delta \dot{\theta}$$

i.e. non-zero baryon asymmetry in thermal equilibrium and without explicit CP-violation. The latter is created by initial $\dot{\theta} \neq 0$.

In realistic case $\dot{\theta}$ is small and pseudogoldstone case could be more efficient.

Equation of motion:

$$\eta^2\ddot{\theta} + 3H\dot{\theta} + V'(\theta) = \partial_\mu j^B_\mu.$$

with $V(\theta) \approx m^2\eta^2\left[-1 + (\theta - \pi)^2\right]$
and $j^B_\mu = \bar{\psi}\gamma_\mu\psi$.

Initially θ is uniform in $[0, 2\pi]$ and after inflation it started to oscillate around minimum.

Second equation for the quantum baryonic Dirac field:

$$(i\partial + m)\,\psi = -g\eta l + (\partial_\mu \theta)\gamma_\mu \psi$$

Find solution in one-loop approximation for $\psi(\theta)$ in external classical field θ and substitute $\bar{\psi}\psi = F(\theta)$ into equation of motion for θ. The solution oscillates with alternating baryonic number. Net result:

$$n_B \sim \eta^2 \Gamma_{\Delta B} (\Delta\theta)^3 .$$

IV. Supersymmetric condensate.

SUSY predicts existence of scalars with $\mathbf{B \neq 0}$.

Such bosons may condense along flat directions of the potential:

$$U_\lambda(\chi) = \lambda|\chi|^4 \left(1 - \cos 4\theta\right),$$

where $\chi = |\chi| \exp\left(i\theta\right)$.

In GUT SUSY baryonic number is naturally non-conserved.

Due to infrared instability of massless (m $\ll$ H) fields χ travels away form zero:

$$|\chi|^2 \sim H^3 t$$

Mass term, $m^2\chi^2 + m^{*\,2}\chi^{*\,2}$, leads to:

$$U_m(\chi) = m^2|\chi|^2[1 - \cos{(2\theta + 2\alpha)}],$$

where $m = |m|e^{\alpha}$.

If $\alpha \neq 0$, C and CP are explicitly broken.

"Initially" (after inflation) χ is away from origin and when inflation is over starts to evolve down to equilibrium point, $\chi = 0$, according to Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$

Baryonic charge of χ:

$$B_\chi = \dot{\theta}|\chi|^2$$

is analogous to mechanical angular momentum. When χ decays its baryonic charge is transferred to that of quarks in B-conserving process.

If $m = 0$ the B-charge of χ is in its "rotational" motion, induced by quantum fluctuations in orthogonal to valley direction. Leads to globally charge symmetric universe.
The domain size l_B is determined by the size of the region with a definite sign of $\dot{\theta}$. Usually l_B is too small if no special efforts are done.

If m $\neq$ 0, the angular momentum, B, is generated by a different direction of the valley at low χ.
If CP-odd phase α is small but non-vanishing, both baryonic and antibaryonic regions are possible with dominance of one of them.
Matter and antimatter domain may exist but globally B $\neq$ 0.

VIII. BS with broken CPT.

If $m \neq \bar{m}$ (though it is not necessarily so), BS could proceed in thermal equilibrium:

$$\frac{N_B - N_{\bar{B}}}{N_B} = \int \frac{d^3p}{(2\pi)^3}\left[f_B(p) - f_{\bar{B}}(p)\right].$$

For m > T:

$$\frac{N_B - N_{\bar{B}}}{N_B} \approx \frac{\delta m}{T}.$$

For m < T:

$$\frac{N_B - N_{\bar{B}}}{N_B} \approx \frac{\delta m}{T}\frac{m}{T}.$$

Care should be taken of electric neutrality. Electric charge asymmetry must be zero or extremely small. For a closed universe even a single excessive e is not allowed, if $m_\gamma = 0$.
Vanishing Q demands non-zero chemical potentials. In realistic MSM model:

$$\beta = -4.2 \cdot 10^{-3} \sum_f \frac{6\delta m_{u_f}^2 + 5\delta m_{d_f}^2}{T^2}.$$

To create the observed $\beta_0 = 6 \cdot 10^{-10}$, we need $\delta m_q \sim (10^{-7} - 10^{-8})T$ at $T \sim 100$ GeV. So it is necessary: $\delta m_q \sim 10^{-5} - 10^{-6}$ GeV, compare to $m_p - m_{\bar{p}} < 10^{-8}$ GeV. Natural expectation: $\delta m_p \sim \delta m_{u,d}$. Thus we need either $\delta m_q \sim T$ or $\delta m_q \sim m_q$.
If so the expected δm_p should be close to the existing upper bound.

Estimates of asymmetry are true if the equilibrium distributions do not change because of CPT breaking-
may be not so, because CPT-violating proposals demand destruction of the corner stones of the existing theory.

To break CPT we need one or all of: non-locality, breaking of Lorenz invariance, breaking of spin-statistics theorem, non-hermitian Hamiltonian... all disasters from the Pandora box.
In such theories equilibrium statistics may be much different from the canonical one, even stationary equilibrium may not exist. Some sacred principles must be respected. "If God does not exist anything is allowed", Dostoevsky, "Karamazov's brothers".

Comment:

Greenberg: breaking of CPT leads to breaking of Lorenz because $m \neq \bar{m}$. **However, it is non necessarily so. E.g. one can break CPT by non-locality, breaking only T and preserving C.** **In this case $\delta m = 0$ and Lorenz invariance is not broken.**

However, breaking of spin-statistics relation seems to break both CPT and Lorenz.

VII. Space separation of B and anti-B. **Omnés (1970), due to mutual repulsion. Separation of matter and anti-matter in multidimensional cosmologies to different branes (DGP).**
Pure QCD, no new physics (Zhitnitsky): quark-antiquark bubbles with slight predominance of anti-bubbles; background is dominated by baryons.
Scenarios are baryo-conserving and the universe is globally baryo-symmetric.

IX. Darkogenesis-baryogenesis with conserved B, normal baryons and heavier sterile ones. **BG creates simultaneously normal baryon asymmetry and DM** (Dodelson, Widrow, 1990).

Burst of activity recently:

T. Frandsen, S. Sarkar, "Asymmetric dark matter..."

H. Davoudiasl et al, "Hylogenesis..."

N. Haba, S. Matsumoto, "Baryogenesis from Dark Sector".

M. R. Buckley, L. Randall, "Xogenesis"

Probably not interesting for real antimatter.

Anti-creation scenarios.

Discussed above:
spontaneous CP-violation;
mixture of explicit and spontaneous.
Both have serious problems.

Favorable scenarios of anti-creation:

1. Spontaneous baryogenesis. Theory is symmetric with respect to spontaneously broken global $U(1)$ associated with B. In the broken phase there appears a massless or light Goldstone field θ. Its Lagrangian contains:

$$\mathcal{L} = \eta^2(\partial\theta)^2 + \partial_\mu\theta j_\mu^B - V(\theta).$$

The time derivative of θ looks as a chemical potential, would allow for baryogenesis in thermal equilibrium.
In fact, this is not exactly so.

Due to stochastic behavior of θ, this scenario is favorable for creation of cosmologically significant amount of antimatter.
However, this and similar scenarios of antimatter creation suffer from too large isocurvature density perturbations at large scales which are forbidden by CMBR.

2. Affleck-Dine mechanism, with a minor modification may work pretty well and create plenty of antimatter quite close to us.

GREAT EXPECTATIONS:

Both a simple and probably unique, generalization of the theory, and available astronomical data allow for a lot of antimatter just "next door".

Maybe Dirac and Schuster were right saying that antiworlds exist!?

NB: interesting anti-objects should be astronomically large, so inflation is necessary and not too large to avoid problems with existing observations.

OBSERVATIONS (reminder):

Up to now no astronomically significant objects consisting antimatter have been observed. A little antiprotons and positrons in cosmic rays are most probably of secondary origin.

No unexplained excess of 100 MeV gamma-rays.

Antimatter either does not live in the universe or it is very far away, if cosmic antimatter is in the same form as matter.

If the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects or PBH, plus subdominant observed baryonic background, the amount of antimatter may be much larger than that of the KNOWN baryons, but such "compact" (anti)baryonic objects could escape observations through BBN and CMB and even make DM.

THE ANTI-CREATION MECHANISM

AD, J. Silk (1993); AD, M. Kawasaki, N. Kevlishvili (2008).

Affleck-Dine baryogenesis: SUSY condensate of a scalar baryonic field χ along flat directions of the potential. Normally it predicts very high $\beta = n_B/n_\gamma \sim 1$ and theoretical efforts are needed to diminish it.

However, if the window to flat direction is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small χ.

Phase transition of 3/2 order.

Affleck-Dine field χ with CW potential coupled to inflaton Φ:

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right)$$
$$+\lambda_1\left(\chi^4 + h.c.\right) + (m^2\chi^2 + h.c.).$$

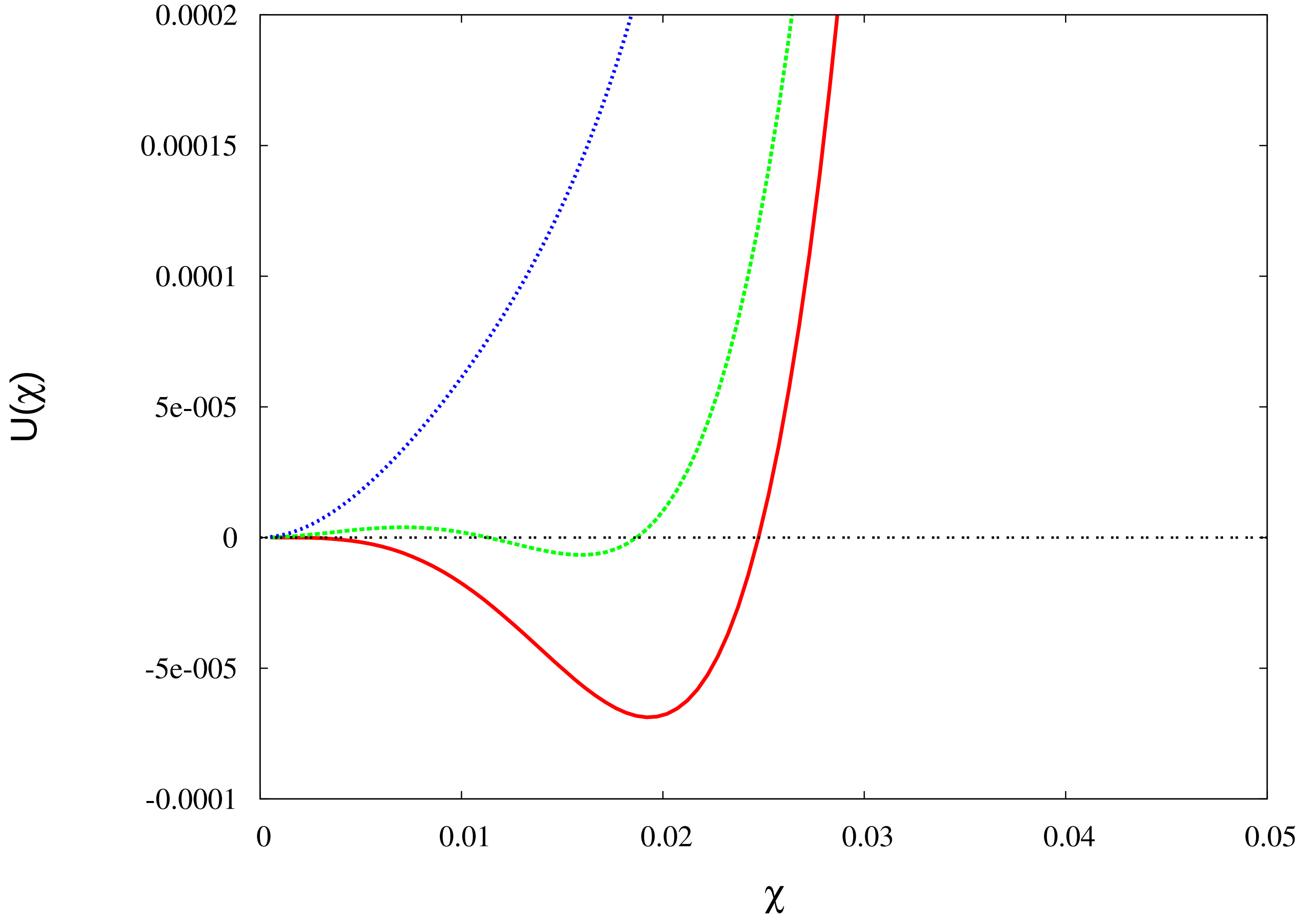
CP would be broken, if the relative phase of λ_1 and m is non-zero, otherwise one can "phase rotate" χ and come to real coefficients. Coupling to fermions may break CP.
Coupling to inflaton is general renormalizable one.

Flat directions: $\cos(4\theta) = 0$, $\chi = |\chi| e^{i\theta}$,
if mass term is negligible w.r.t. to λ_1-interaction.

Two last (red) terms are not $U(1)$ invariant and break B-conservation.

$$J_\mu^{(B)} = i\chi^\dagger \partial_\mu \chi + h.c.,$$

$B = J_t^{(B)}$ **is the angular momentum.**



Evolution of the potential of χ as a function of the inflaton field Φ.

Probability for χ to reach a high value is determined by the diffusion equation (Starobinsky):

$$\frac{\partial \mathcal{P}}{\partial t} = \frac{H^3}{8\pi^2} \sum_{k=1,2} \frac{\partial^2 \mathcal{P}}{\partial \chi_k^2} + \frac{1}{3H} \sum_{k=1,2} \frac{\partial}{\partial \chi_k} \left[\mathcal{P} \frac{\partial U}{\partial \chi_k} \right]$$

where $\chi = \chi_1 + i\chi_2$.

The effective mass behave as $m_{eff}^2 \approx m_0^2 + m_1^4(t - t_1)^2$, when Φ passes through Φ_1. Correspondingly the dispersion is:

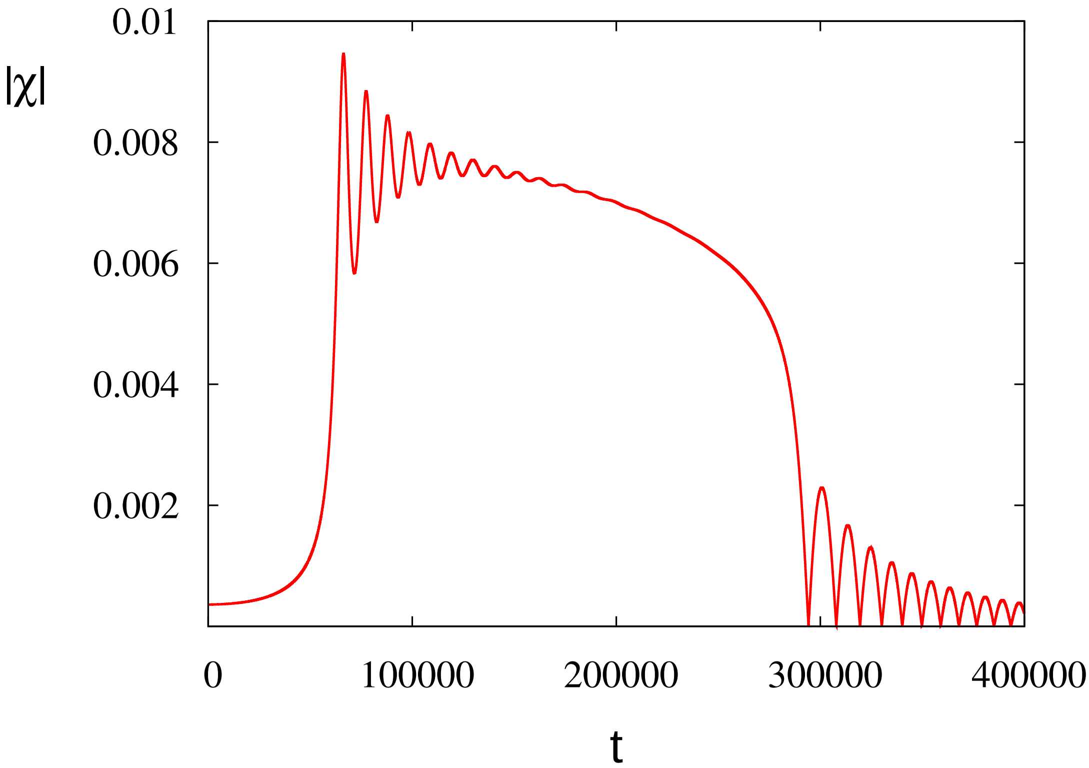
$$\langle \chi^2 \rangle \sim \left[m_0^2 + m_1^4(t - t_1)^2 \right]^{-1}$$

The distributions of high baryon density bubbles over length and mass have log-normal form:

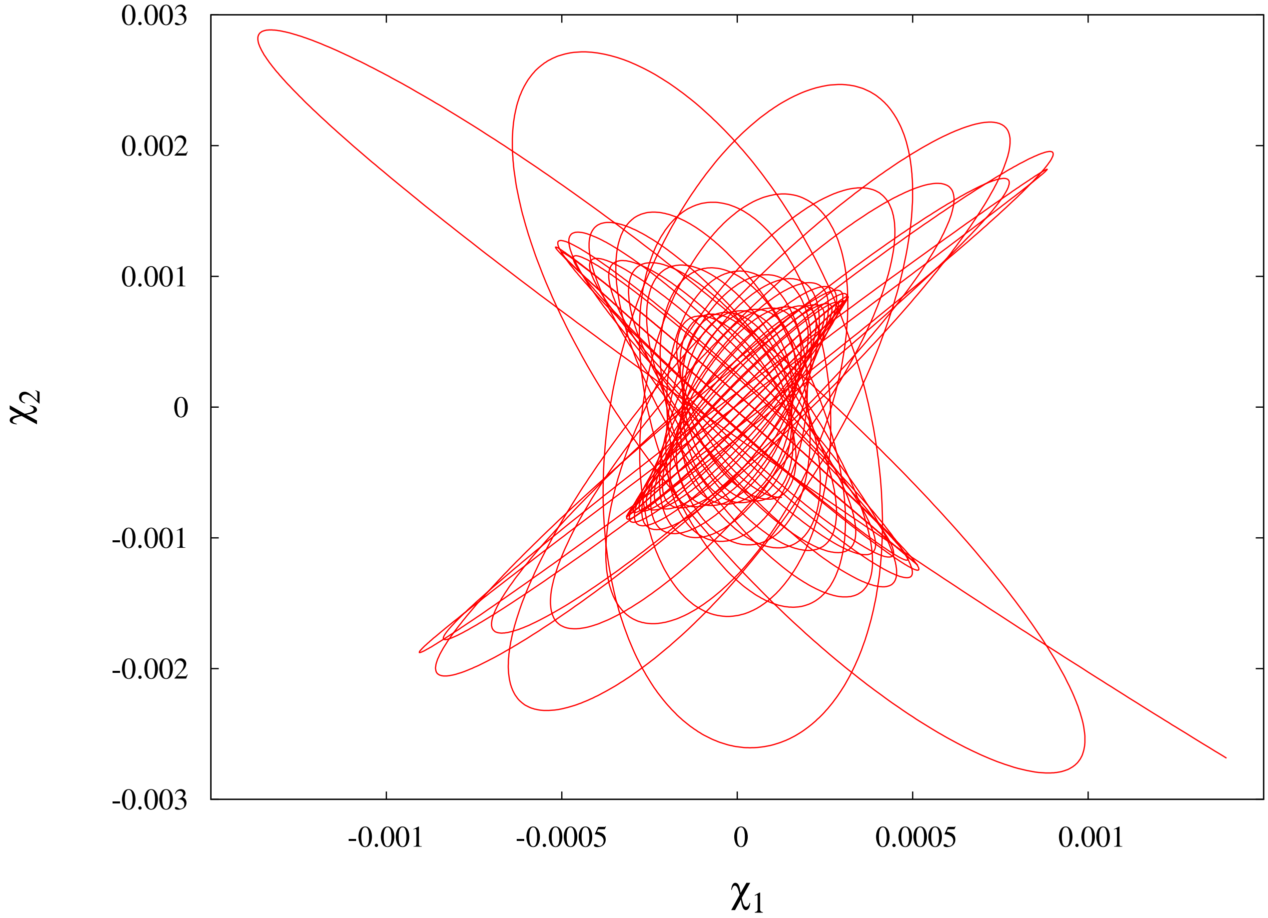
$$\frac{dN}{dM} = C_M \exp\left[-\gamma \ln^2(M/M_0)\right]$$

where C_M, γ, and M_0 are constant parameters.

Spectrum is practically model independent, it is determined by inflation.



Evolution of $|\chi|$ in the bubble. The phase is chaotic.



“Rotation” of χ due to non-sphericity of the potential and creation of $B \neq 0$.

“Rotation” of χ is transformed into baryonic number of quarks by B-conserving decays of χ, producing small homogeneous background baryon asymmetry, to this end an explicit CP-violation is necessary, and little bubbles with huge baryonic number density.

INHOMOGENEITIES.

1. After formation of domains with large χ due to different equations of state inside and outside of the domains: some nonrelativistic matter inside the bubbles and relativistic outside.

2. Second period of $\delta\rho$ generation after the QCD phase transition at T $\sim$ 100 MeV when quarks made non-relativistic protons. BH masses from a few $M_\odot$ to $10^{6-7} M_\odot$.

Compact objects (not BH) with smaller masses could be formed too.

On the tail of the distribution very heavy BH may be created, $M_{BH} \sim 10^7 M_{\odot}$.

A mechanism of early quasar formation with evolved chemistry - one of the mysteries of the standard model.

Superheavy PBH are seeds for structure formation!?

At the moment there is no satisfactory mechanism for formation of the observed superheavy BH.

Impact on BBN.

If $\beta \equiv \eta \gg 10^{-9}$, light (anti)element abundances would be anomalous: much less anti-deuterium, more anti-helium.

Look for clouds with anomalous chemistry. However, with 50% probability it may be the normal matter with anomalous n_B/n_γ.

If such a cloud or compact object is found, search for annihilation there.

The suggested mechanism leads to creation of compact stellar-like objects and equal number of compact anti-objects in the early universe at $t = 0.01 - 1$ sec.

So the universe may be full of early formed and by now dead stars.

MACHOS.

EVOLUTION IN THE EARLY UNIVERSE, C. Bambi, AD (2007).

Bubbles with $\delta\rho/\rho < 1$ but with

$$M_B > M_{Jeans}$$

at horizon would decouple from cosmological expansion and form compact stellar type objects or lower density clouds.

Could such anti-objects survive against early annihilation?

EARLY SUMMARY:

1. Compact anti-objects mostly survived in the early universe, especially if they are PBHs.
2. A kind of early dense stars might be formed with initial pressure outside larger than that inside.
3. Such "stars" may evolve quickly and, in particular, make early SNs, enrich the universe with heavy (anti)nuclei and reionize the universe.

4. Energy release from stellar like objects in the early universe is small compared to CMBR.
5. Not dangerous for BBN since the volume of B-bubbles is small.

One can always hide any undesirable objects into black holes.

ANTIMATTER TODAY

Democratic guiding principle:
forget theory,
anything not forbidden is allowed.

Possible astronomical objects:

1. **Gas clouds of antimatter.**
2. **Isolated antistars.**
3. **Anti stellar clusters.**
4. **Anti black holes.**
5. **What else?**

WHERE:

Inside galaxies or outside galaxies?
Inside galactic halos or in intergalactic space?

Consider all the options.
New part: unusual compact objects, e.g. dead or half dead (anti)stars, (anti)BH with (anti)atmosphere.

OBSERVATIONAL SIGNATURES

1. **Gamma background.**
2. **Excessive antiprotons.**
3. **Positrons.**
4. **Antinuclei.**
5. **Compact sources of γ radiation.**
6. **Catastrophic phenomena.**
7. **Rapid change of stellar luminosity.**

Two types of objects:

1. Gas clouds, mean free path of protons l_p is larger than the size of the (anti)cloud. Annihilation proceeds in whole volume.

Low density or small clouds would not survive in a galaxy. They would disappear during

$$\tau = 10^{15}\ sec\ \left(\frac{10^{-15} cm^3/s}{\sigma_{ann} v}\right)\left(\frac{cm^{-3}}{n_p}\right),$$

may survive in the halo.

The luminosity for volume annihilation:

$$L_\gamma^{(vol)} \approx 10^{35}\,\frac{\mathrm{erg}}{\mathrm{s}}\left(\frac{R_B}{0.1\,\mathrm{pc}}\right)^3 \left(\frac{n_p}{10^{-4}\,\mathrm{cm}^{-3}}\right)\left(\frac{n_{\bar p}}{10^{4}\mathrm{cm}^{-3}}\right).$$

Flux on the Earth at d=10 kpc: $10^{-7}\gamma/\mathrm{s}/\mathrm{cm}^2$ or $10^{-5}\mathrm{MeV}/\,\mathrm{s}/\mathrm{cm}^2$, to be compared with cosmic background $10^{-3}/\mathrm{MeV}/\mathrm{s}/\mathrm{cm}^2$, pointlike sources.

Compact stellar type objects, $l_s \gg l_{free}$, surface annihilation, much less efficient. Total luminosity, $L = 2m_p \cdot 4\pi \, l_s^2 \, n_p v$:

$$L_{tot} \approx 10^{27} \frac{erg}{sec} \left(\frac{n_p}{cm^3} \right) \left(\frac{l_s}{l_\odot} \right)^2$$

Fraction into gamma-rays is about 20-30%.

Unidentified EGRET sources, from clouds or compact objects?

Stellar wind:

$$\dot{M} = 10^{12} W \, g/sec$$

where $W = \dot{M}/\dot{M}_{\odot}$.

If all "windy" particles annihilate, the luminosity per star:

$$L = 10^{33} W \text{ erg/sec.}$$

Mean free path of $\bar{p}$ **in the galaxy is about** 10^{23} **cm (depending on their velocity). Gamma luminosity of the Galaxy:** $L_\gamma \approx 10^{33} \bar{N} W \, erg/s$ **.**

Number density of antinuclei is bounded by the density of "unexplained" $\bar{p}$ and the fraction of antinuclei in stellar wind with respect to antiprotons.
It may be the same as in the Sun but if antistars are old and evolved, this number must be much smaller.

Heavy antinuclei from anti-SN may be abundant but their ratio to $\bar{p}$ can hardly exceed the same for normal SN.
Explosion of anti-SN would create a large cloud of antimatter, which should quickly annihilate producing vast energy - a spectacular event.
However, most probably such stars are already dead and SN might explode only in very early galaxies or even before them.

COSMIC POSITRONS.

Gravitational proton capture by an (anti)star is more probable than capture of electrons, due to larger mobility of p. Antistar is neutralized by forced positron ejection.
It would be most efficient in galactic center where n_p is large.
0.511 MeV line (observed) must be accompanied by wide spectrum $\sim$ 100 MeV radiation.

EXOTIC EVENTS

Similar mass star-antistar collision, γ-bursters (???):

$$\Delta E \sim 10^{48}\, erg \left(\frac{M}{M_\odot}\right)\left(\frac{v}{10^{-3}}\right)^2$$

Annihilation pressure pushes the stars apart. Collision time $\sim$ 1 sec.
Radiation is emitted in the narrow disk but not jet.

Collision with RED GIANT: compact antistar travels inside creating an additional energy source. Change of color and luminosity(?).
$\Delta E_{tot} \sim 10^{38}$ erg and $\Delta t \sim$ month.

Transfer of material in binary system - hypernova explosion!?

DARK MATTER
made out of high B compact objects, black holes or dead (anti)stars.

Normal CDM with new features:

1. DM "particles" have different masses.
2. Very heavy ones with $M > 10^6 M_\odot$ should exist and may be seeds of structure formation. Lighter stellar type objects populate galactic halos as usual CDM.

No stars are observed in the halo. It means that all high B compact objects are already dead or semi-dead stars. Stellar wind is absent. However, annihilation of background protons on the surface should exist.

OBSERVATIONAL BOUNDS.

I. Stellar wind:

$$\mathrm{N}_{\bar{\mathrm{S}}}/\mathrm{N}_{\mathrm{S}} \leq 10^{-6}\mathrm{W}^{-1},$$

from the total galactic luminosity in 100 MeV photons, $L_\gamma = 10^{39} erg/s$ and from the flux of the positron annihilation line $F \sim 3 \cdot 10^{-3}/cm^2/s$.

$W \ll 1$ is natural to expect because the primordial antistars may be already evolved.

II. Antihelium-helium ratio:

$$N_{\bar{S}}/N_S = (\bar{H}e/He) \leq 10^{-7},$$

if the antistars are similar to the usual stars, though most probably not.

DARK MATTER
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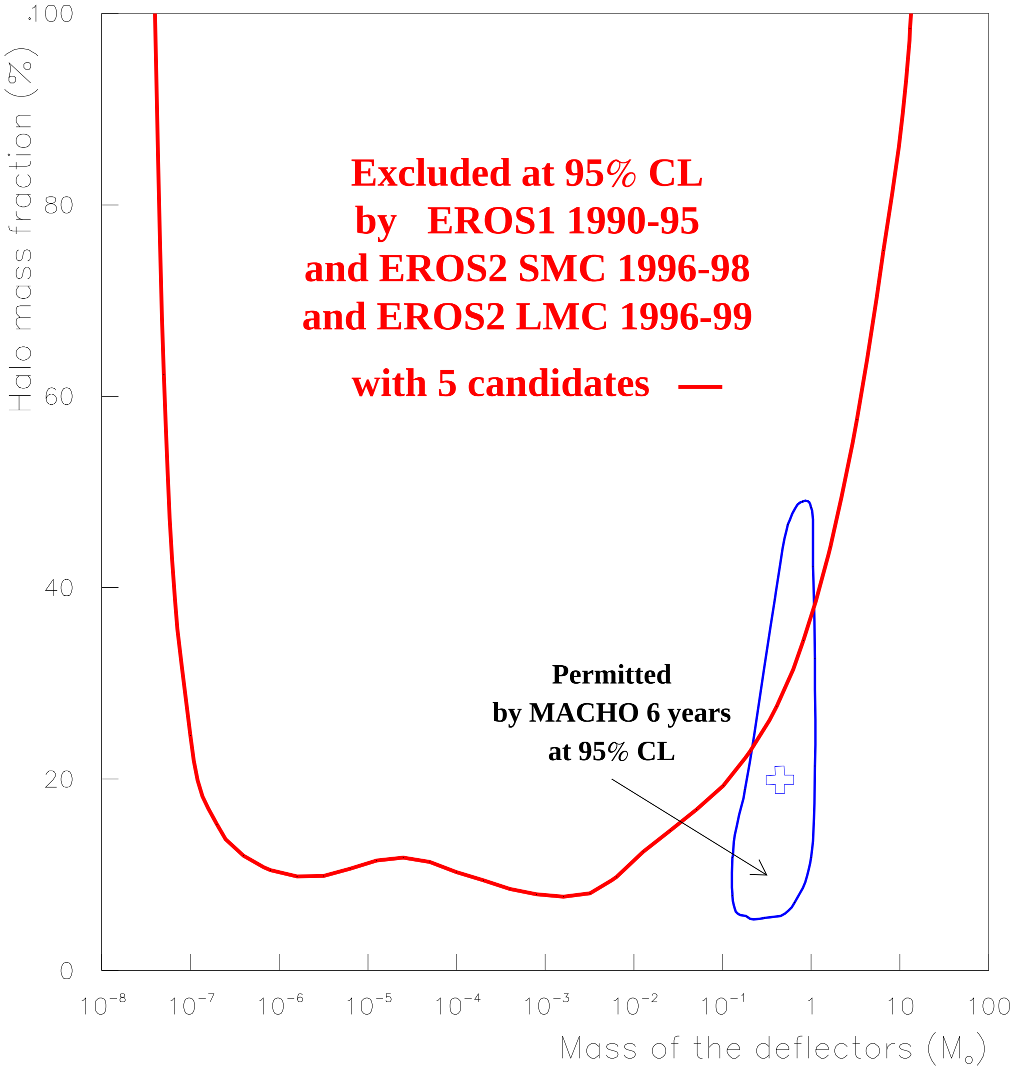

Excluded at 95% CL
by EROS1 1990-95
and EROS2 SMC 1996-98
and EROS2 LMC 1996-99
with 5 candidates
Permitted
by MACHO 6 years
at 95% CL
Halo mass fraction (%)
100
80
60
40
20
0
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
100
Mass of the deflectors (M☉)

Other bounds on PBP=DM see:

I. Reviews by Carr.

II. More recent:

1. N. Afshordi, P. McDonald, D. N. Spergel, astro-ph/0302035;

2. J. Yoo, J. Chaname, A. Gould, astro-ph/0306437;

3. N. Seto, A. Cooray, astro-ph/0702586.

Results strongly depend upon the mass spectrum.

CONCLUSION

1. The Galaxy may possess a noticeable amount of antimatter.

2. Theoretical predictions are vague and model dependent.

3. Not only $^4\bar{\mathrm{He}}$ is worth to look for but also heavier anti-elements. Their abundances should be similar to those observed in SN explosions.

4. Regions with an anomalous abundances of light elements are suspicious that there may be anti-elements.
5. A search of cosmic antimatter has nonvanishing chance to be successful.
6. Dark matter made of BH, anti-BH, and dead stars is a promising candidate. There is a chance to understand why $\Omega_{\rm B} = 0.05$ is similar to $\Omega_{\rm DM} = 0.25$.

7. Detection of $\bar{\nu}$ in the first burst from anti-SN explosion.

8. Measurement of polarization of synchrotron radiation (?).

9. Signatures in favor:

May the observed positron 0.511 MeV line from the galactic bulge and possibly from the halo be a signature of cosmic antimatter!?

Unidentified EGRET sources.

THE END