COSMIC ANTIMATTER: MODELS AND PHENOMENOLOGY

A.D. Dolgov

ITEP, 117218, Moscow, Russia
INFN, Ferrara 40100, Italy
University of Ferrara, Ferrara 40100, Italy

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81 years ago, one of the greatest breakthroughs 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 experimen.

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 OF 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.

Now there are ways to observe them!

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”.

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

Later C and CP violation have been discovered by direct experiment.

1956: PARITY NON-CONSERVATION, Lee, Yang, and Wu. Breaking of C and assumption of CP-invariance. CP-invariance prevented from local generation of cosmic charge asymmetry.

1964: Discovery of CP-VIOLATION: Christenson, Cronin, Fitch, and Turley.

After this discovery life in the universe became possible.

Okonov (1962) 600 decays, experiment stopped.

BARYOGENESIS

Stimulated by discovery of CP-violation, Sakharov, 1967, proposed an explanation of antimatter absence assuming:

I. Nonconservation of baryons.

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

III. Breaking of thermal equilibrium.

Instead of almost empty baryo-symmetric world there appeared 100% asymmetric one, with life possible.

Possible existence of anti-worlds depends upon the mechanism of breaking of symmetry between particles and antiparticles, i.e. of C and CP.

Three kinds of theoretical models:

1. Explicit, by complex parameters in Lagrangian, e.g. by a non-zero phase in CKM mass matrix, usual way in particle physics.

2. Spontaneous, by v.e.v. of a complex scalar field (T.D. Lee, 1974). Locally indistinguishable from the explicit one but globally leads to charge symmetric universe, 50:50 matter and antimatter.

Domain wall problem, Zel'dovich, Kobzarev, Okun killed the model.

3. Dynamical or stochastic (AD, 1992), by complex scalar field shifted from the equilibrium position due to infrared instability of light scalars at DS (inflationary) stage and not yet relaxed to equilibrium point at baryogenensis.

It could operate only in the early universe and disappeared without trace today; at odds with Occam razor, but nevertheless it must operate in the early universe if there exists any complex scalar field with $m < H_{inf}$.

Shopping list of BG scenarios.

1. Heavy particle decays (Sakharov).

2. Electroweak BG (Kuzmin, Rubakov, Shaposhnikov). **Too weak in MSM but may work with TeV gravity.**

3. Baryo-thru-leptogenesis (Fukugita, Yanagita).

4. SUSY condensate BG (Affleck, Dine).

5. Spontaneous BG (Cohen, Kaplan).

6. BG by PBH evaporation (Zeldovich, A.D.)

7. Space separation of B and $\bar{\mathrm{B}}$ (Omnés, and later, into higher dimensions) or compact (anti)quark nuggets.

7. BG due to CPT violation.

New physics beyond standard model is necessary.

With proper choice of parameters all scenarios 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!?

Intermediate summary: It is established that antimatter EXISTS but it is commonly believed that there are very FEW antiparticles in the universe (except for $\bar{\nu}$) and thus no antiworlds. Nevertheless, an active search for galactic antimatter started in recent years. Existing: PAMELA, BESS, AMS. Future: AMS-02 (2010), PEBS (2010), GAPS (2013) (according to P. Picozza, TAUP 2007)

Looking for antimatter in the Galaxy is like searching under a lamp-post but at least one needs to switch-on the light, i.e. to find a mechanism for creation of sufficiently abundant galactic antimatter avoiding an immediate contradiction with observations.

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, but not too large to avoid problems with existing observations.

OBSERVATIONS:

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.

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

Observational bounds:

Charge symmetric universe: $l_B >$ Gpc (Cohen, De Rujula, Glashow, 1996).
Nearest anti-galaxy could not be closer than at ∼10 Mpc (Steigman, 1976).
Fraction of antimatter Bullet Cluster $< 3 \times 10^{-6}$ (Steigman, 2008).
Fraction of $\bar{p}$ in cosmic rays $< 10^{-4}$.
Fraction of antihelium: $< 10^{-7}$.
CMB excludes 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.

Picture of antiworlds: the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects or PBH, plus sub-dominant observed baryonic background, all created by the same baryogenesis mechanism.
The amount of antimatter may be much larger than that of the KNOWN baryons, but such "compact" (anti)baryons could escape observations through BBN and CMB and even make all DM.

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 during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe volume, 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:

$$U(\chi,\Phi) = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln(\frac{|\chi|^2}{\sigma^2}$$

$$+\lambda_1\left(\chi^4 + h.c.\right) + (m^2\chi^2 + h.c.).$$

m may be complex but CP would be still conserved - "phase rotate" χ.
Flat directions: $\cos(4\theta) = 0$, $\chi = |\chi|e^{i\theta}$.
Red terms are not $U(1)$ invariant.
Coupling to inflaton is general renormalizable one.

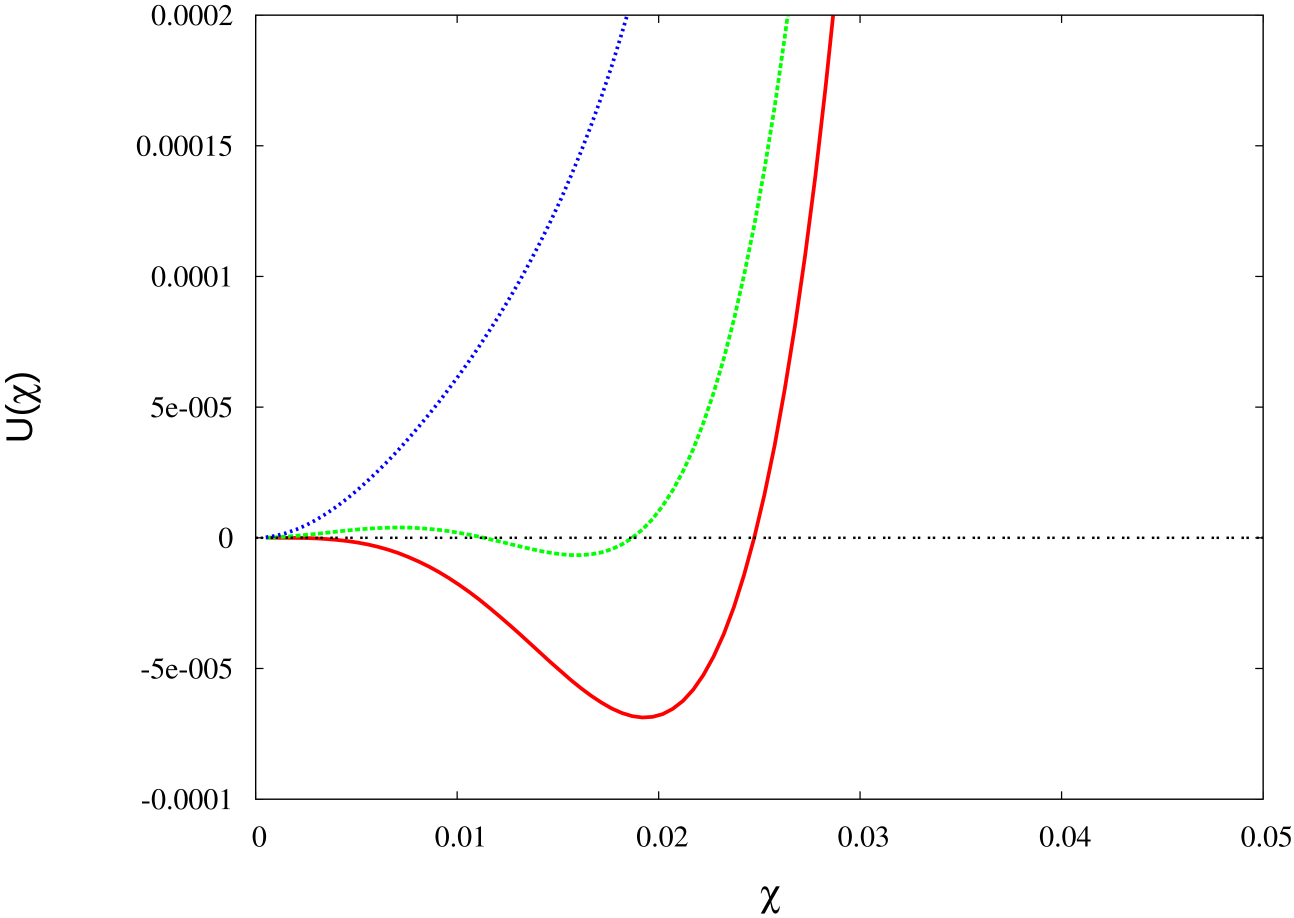
Equation of motion for homogeneous χ is the same as in Newtonian mechanics:

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

Baryonic number

$$B = i\chi^\dagger \partial_t \chi + h.c.$$

is the angular momentum. If $U(\chi)$ is spherically symmetric, i.e. depends upon $|\chi|$ baryonic number is conserved. The last two terms break B-conservation.



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

Probability for χ to fluctuate away from zero is determined by the diffusion equation (Starobinsky):

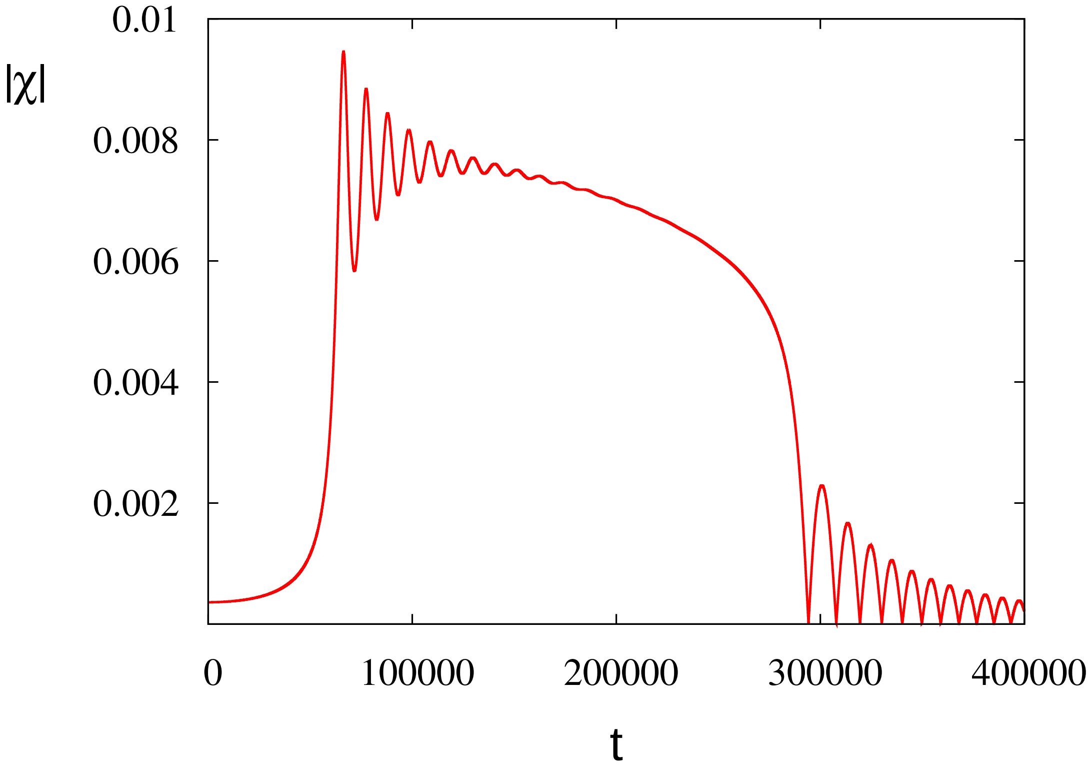
$$\frac{\partial \mathcal{P}}{\partial t} = \frac{H^3}{8\pi^2} \sum_{k=1,2} \frac{\partial^2 \mathcal{P}}{\partial \chi_k^2} + \frac{1}{3H} \sum_{k=1,2} \frac{\partial}{\partial \chi_k} \left[\mathcal{P} \frac{\partial U}{\partial \chi_k} \right]$$

where $\chi = \chi_1 + i\chi_2$.
Infared instability of massless scalars at DS stage.

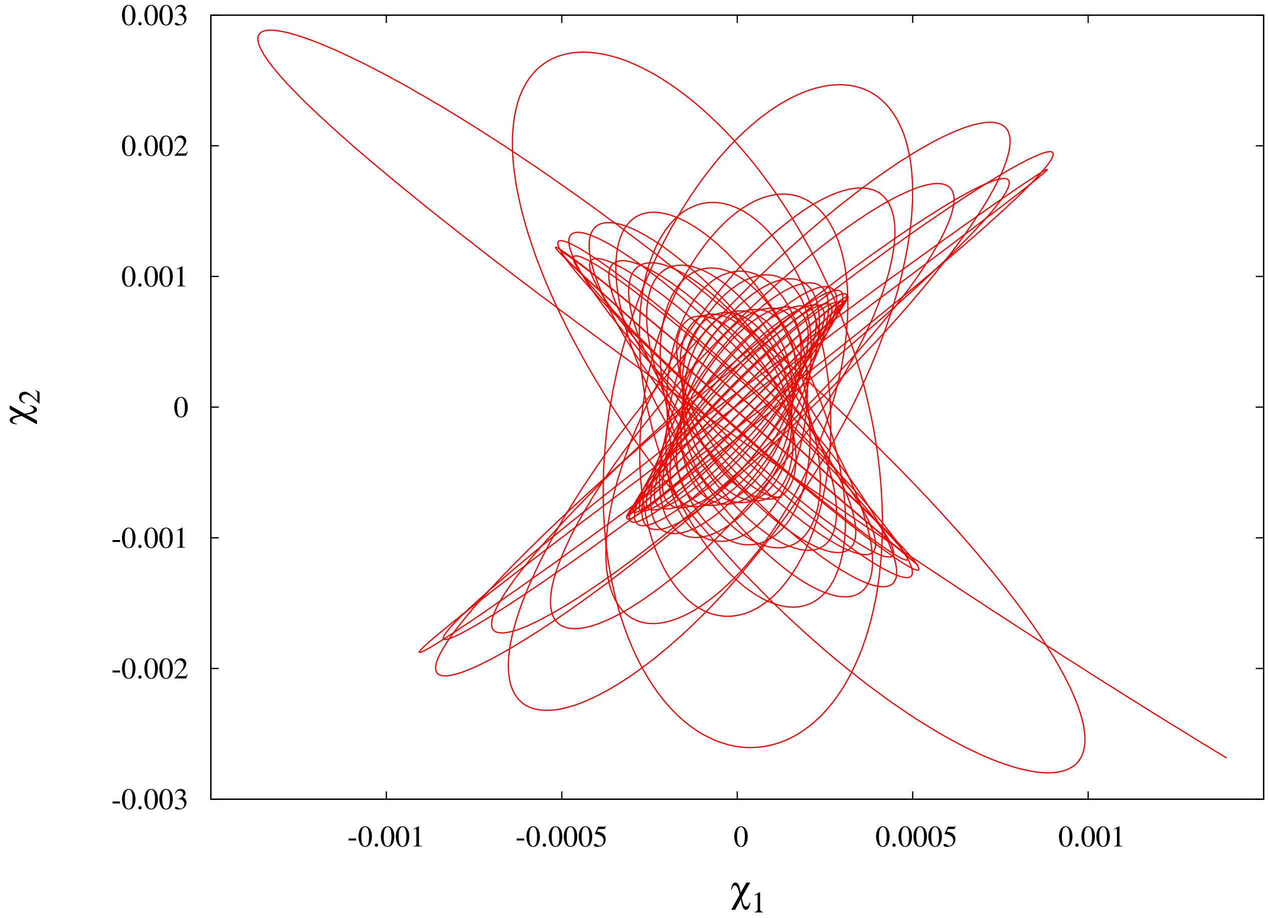
The bubble distributions over length and mass have log-normal form:

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

where C_M, γ, and M_0 are constant parameters. Spectrum is 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.

INHOMOGENEITIES.

Two kinds of density perturbations:

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.**

If $\delta\rho/\rho = 1$ at horizon crossing, PBHs would be formed.
Horizon mass: $M_{hor} = 10^{38}g\,(t/sec)$.
For $T = 10^8$ GeV the PBH mass would be 10^{16} g.
Perturbations with $\delta\rho/\rho < 1$ might still make PBH due to subsequent matter accretion.

2. Second period of $\delta\rho$ generation after the QCD phase transition at T $\sim$ 100 MeV when quarks made non-relativistic protons.

Stellar like objects with masses from solar up to to $10^{6-7} M_{\odot}$. with high baryonic density could be formed. They might be BH or dense primeval stars. Anti-BH may be surrounded by anti-atmosphere if β slowly decreases.

These stars might be either evolved low luminocity ones or dead by now, and together with BH they could make (all?) cosmological DM, i.e. cold DM with dispersed mass.

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.

Nonrelativistic baryonic matter starts to dominate inside the bubble at

$$T = T_{in} \approx 65\,\beta\,\mathrm{MeV}$$

Mass inside a baryon-rich bubble at the radiation dominated stage is

$$M_B \approx 2 \cdot 10^5\, M_{\odot}(1 + r_B) \left(\frac{R_B}{2t}\right)^3 \left(\frac{t}{\mathrm{sec}}\right)$$

Mass density at onset of MD stage:

$$\rho_B \approx 10^{13} \beta^4 \ \mathrm{g/cm^3}\,.$$

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.

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?

For example, if $M_B \sim M_\odot$:

$$\rho_B = \rho_B^{(in)} (a_{in}/a)^3 \approx 6 \cdot 10^5 \text{ g/cm}^3$$

and $R_B \approx 10^9$ cm;
temperature when $M_J = M_\odot$:

$$T \approx T_{in} (a_{in}/a)^2 \approx 0.025 \text{ MeV}.$$

Similar to RED GIANT core.
Initially the external pressure could be larger than the internal one.

Three processes of energy release:

1. Cooling down because of high internal temperature, $T \sim 25$ keV.

2. Nuclear reactions inside.

3. Annihilation of surrounding matter on the surface.

1. Cooling time is determined by photon diffusion:

$$t_{diff} \approx 2 \cdot 10^{11}\,\mathrm{sec} \left(\frac{M_B}{M_\odot}\right) \left(\frac{\mathrm{sec}}{R_B}\right) \left(\frac{\sigma_{e\gamma}}{\sigma_{Th}}\right)$$

Thermal energy stored inside B-ball

$$E^{(tot)}_{therm} = 3TM_B/m_N \approx 1.5 \cdot 10^{50}\mathrm{erg}$$

Luminosity: $L \approx 10^{39}$ erg/sec.
If $\Omega_{BB} = 0.25$, then thermal keV photons would make 10^{-4}–10^{-5} of CMBR, red-shifted today to background light.

2. Nuclear helium burning, (similar to red giant): $3He^4 \to C^{12}$, however with larger T by factor ~ 2.5. Since $L \sim T^{40}$, life-time would be very short. Total energy influx would be below 10^{-4} of CMBR if $\tau < 10^9$ s.

Could it lead to B-ball explosion and creation of solar mass anti-cloud?

Astrophysics of such early formed objects is not yet studied.

3. Annihilation on the surface.

(Anti)proton mean free path before recombination is small:

$$l_p = \frac{1}{(\sigma n)} \sim \frac{m_p^2}{\alpha^2 T^3} = 0.1\, cm \left(\frac{MeV}{T}\right)^3$$

After recombination the number of annihilation on one B-ball per unit time:

$$\dot{\mathrm{N}} = 10^{31} \mathrm{V_p} \left(\frac{\mathrm{T}}{0.1\ \mathrm{eV}}\right)^3 \left(\frac{\mathrm{R_B}}{10^9\ \mathrm{cm}}\right)^2,$$

gives about 10^{-15} of CMBR.

Distortion of CMBR energy spectrum.
Annihilation before recombination, when the produced photons are not completely thermalized but degraded down to CMBR energies. Chemical potential may be induced.
Mean free path of energetic photons at $T \ll \mathrm{MeV}$:

$$l_\gamma \approx 10^{25}\,\mathrm{cm}\left(\frac{E}{100\,\mathrm{MeV}}\right)^2\left(\frac{\mathrm{eV}}{T}\right)^3$$

The effect is weak (preliminary estimates).

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 re-ionize 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.
More detailed calculations are necessary.

ANTIMATTER TODAY

Democratic guiding principle:
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)B 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.**
2. **Compact stellar-like objects.**

Gas of antimatter: mean free path of protons l_p is larger than the size of the (anti)cloud, $l_c \equiv l_B$.

$$l_p = \frac{1}{\sigma_{tot} n_{\bar{p}}} = 10^{24}\, cm \left(\frac{cm^{-3}}{n_{\bar{p}}}\right) \left(\frac{barn}{\sigma_{tot}}\right)$$

for $v \sim 10^{-3}$; Zommerfeld-Sakharov correction would increase cross-section by an order of magnitude.

Annihilation proceeds in whole volume.

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

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

if supply of protons from galactic gas is sufficient.

They could survive in the halo.

The luminosity for volume annihilation:

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

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

Compact stellar type objects, $l_s \gg l_{free}$, surface annihilation - all that hits the surface annihilate.

Gamma-radiation from $\bar{\mathrm{p}}\mathrm{p} \to$ pions and $\pi^0 \longrightarrow 2\gamma$ ($E_\pi \sim 300$ MeV) and from e^+e^--annihilation originating from $\pi^\pm$-decays and from the "original" positrons in the B-ball.

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 25%.
UNIDENTIFIED EGRET SOURCES!?

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 luminocity 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 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 must be accompanied by dispersed, ~ 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.

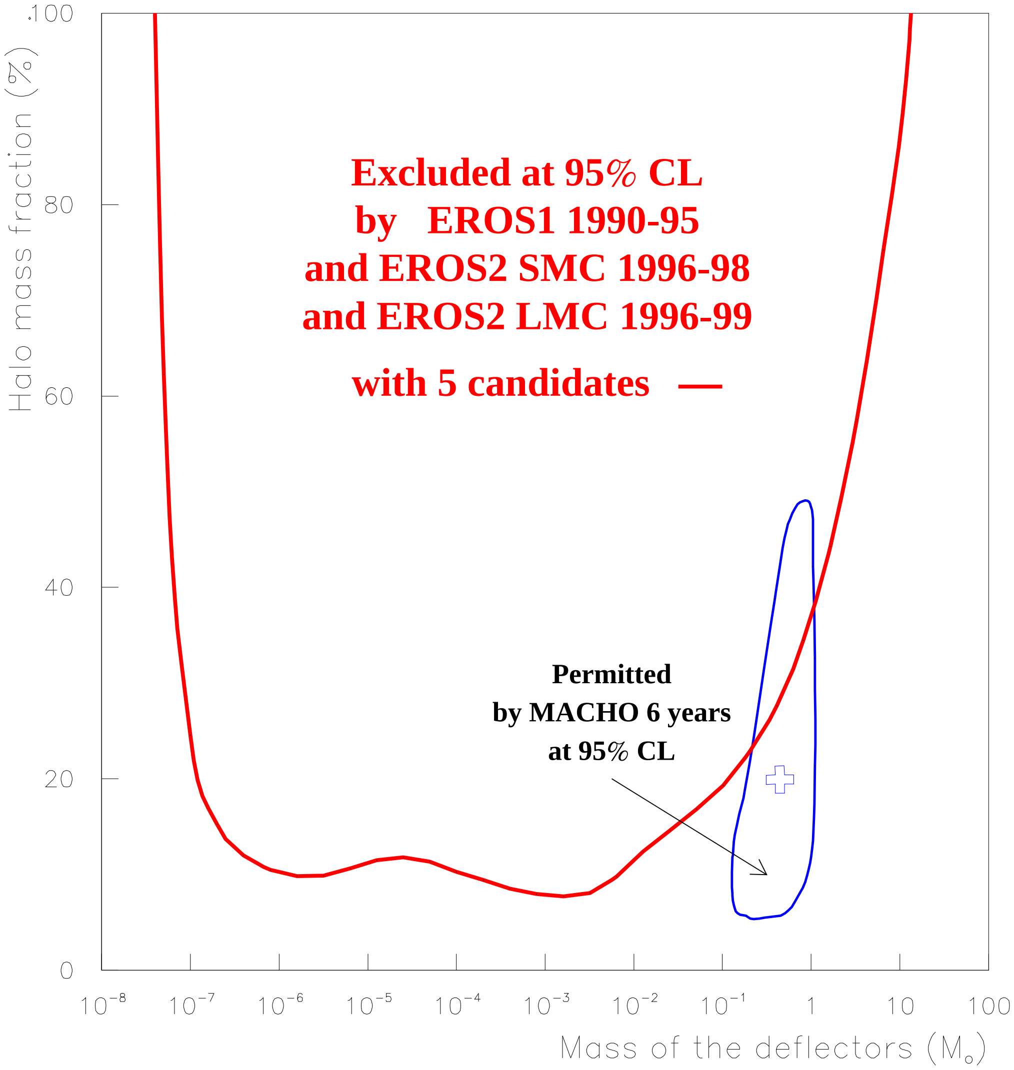
Collision with red giant: compact antistar travels inside creating an additional energy source. Change of color and luminosity(?).
$\Delta E_{tot} \sim 10^{38}$ erg and $\Delta t \sim$ month.

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.


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.

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:

$$\mathbf{N_{\bar{S}}/N_S \leq 10^{-6} W^{-1}},$$

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.

The best up to date bound from PAMELA is a little better.

Signatures in favor:

0.511 MeV photon line from galactic center and from galactic halo!?

CONCLUSION

1. The Galaxy may possess a noticeable amount of antimatter predominantly in the form of compact objects.
2. An observable $\sim$ 100 MeV gamma ray background may exist.
3. Not only $^4\bar{He}$ 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 $\Omega_B = 0.05$ is similar to $\Omega_{DM} = 0.25$.

7. Unidentified EGRET sources may be (dead) antistars.

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

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

THE END