Supersymmetric baryogenesis and cosmological antimatter

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Antiparticles exist beyond any doubts but it remains unknown if there is antimatter in the universe.

Two quotations:

1. Paul A.M. Dirac, 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."

In fact, they are distinguishable.

2. In 1898, just after the discovery of electron (J.J. Thomson, 1897), Sir Arthur Shuster: (another British physicist) conjectured that there might be other sign electricity, ANTIMATTER, and supposed that there might be entire solar systems, made of antimatter, 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.

Sakharov did not need cosmological antimatter and astronomical data seem to support this presenting strong upper bounds on the amount of antimatter but SUSY with inflation open an exciting possibility of plenty of antimatter practically at hand's reach and still avoiding detection. Moreover, the scenario of supersymmetric baryogenesis at inflation explains some profound astronomical mysteries.

Ways to search for cosmic antimatter.

Indirect: astronomical manifestations of antimatter: 0.5 MeV or $\sim$ 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, and anomalous antiprotons and positrons in cosmic rays.

Nowadays, burst of experimental activity for direct search of cosmic antimatter.

Search for antinuclei.

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,) search for cosmic positrons and antiprotons.

GAPS (Gaseous Antiparticle Spectrometer), 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 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.

Search for antinuclei at LHC.

According to the data of ALICE detector, production of an antinucleous with an additional antinucleon is suppressed only by factor about 1/300 which is much milder than the suppression factors presented above. Probably the difference is related to much higher energies at which data of ALICE are taken. The events with such energies are quite rare in cosmic rays.

Search for antistars through circular polarization of photons in nuclei transitions. According to experiment: $P_\gamma = (4 \pm 1) \cdot 10^{-5}$ in ^{175}Lu transition with the emission of 395 keV photon, $P_\gamma = -(6 \pm 1) \cdot 10^{-6}$ for 482 keV photon emitted in ^{181}Ta transition, $P_\gamma = (1.9 \pm 0.3) \cdot 10^{-5}$ for 1290 keV photon emitted in transition of ^{41}K. An observation of the opposite sign of the polarization of such photon lines would be a discovery of antistar.
More: AD, V. Novikov, M. Vysotsky.

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.

P. von Ballmoos, arXiv:1401.7258.
Bondi accretion of interstellar gas to the surface of an antistar:

$$L_\gamma \sim 3 \cdot 10^{35} (M/M_\odot)^2 v_6^{-3}$$

put a limit $N_{\bar{*}}/N_* < 4 \cdot 10^{-5}$ inside 150 pc from the Sun.
The presented bounds are true if antimatter makes the same type objects as the OBSERVED matter.
For example, compact faster objects made of antimatter may be abundant in the Galaxy but still escape observations (discussed below).

Mysteries in the sky which may be indications to cosmic antimatter. Even if these mysteries are not related to antimatter they are quite exciting!

General trend: many objects in the universe were formed much earlier than could be explained by theory.

Observed: stars in the Milky Way, older than the Galaxy and even older than the universe (within two sigma); distant high redshift ($z \sim 10$) staff: early galaxies, QSO/supermassive BHs, supernovae, and gamma-bursters not explained by the standard mechanisms.

A novel mechanism of astrophysical objects formation in the early universe: **AD, S.Blinnikov, "Stars and Black Holes from the very Early Universe", PRD89 (2014) 021301; S. Blinnikov, AD, K. Postnov, Antimatter and antistars in the universe and in the Galaxy, PRD92 (2015) 2, 023516.**
Earlier: AD, J. Silk, PRD47 (1993) 4244; AD, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229. The model naturally explains early formation of astrophysical objects and predicts abundant cosmic antimatter in the universe and even in the Galaxy.

Universe age as a function of redshift:

$$t(z) = \frac{1}{H}\int_0^{\frac{1}{z+1}} \frac{dx}{\sqrt{1-\Omega_{tot}+\frac{\Omega_m}{x}+x^2\Omega_v}},$$

Parameters:

$\Omega_{tot} = 1,\ \Omega_m = 0.317,\ \Omega_v = 0.683;$

$H = 67.3$ **km/sec/Mpc (Planck);**

$H = 74$ **km/sec/Mpc (direct).**

Universe age (in Gyr):

$t_U \equiv t(0) = 13.8;\ \ 12.5.$

$t(12) = 0.37;\ 0.33;\quad t(10) = 0.47;\ 0.43$

$t(6) = 0.93;\ \ 0.82;\quad t(3) = 2.14;\ \ 1.94.$

Stars in the Milky Way:

Employing thorium and uranium in comparison with each other and with several stable elements the age of metal-poor, halo star BD+17^o 3248 was estimated as 13.8 ± 4 Gyr.
J.J. Cowan, C. Sneden, S. Burles, *et al* **Ap.J. 572 (2002) 861, astro-ph/0202429.**

The age of inner halo of the Galaxy 11.4 ± 0.7 Gyr, J. Kalirai, "The Age of the Milky Way Inner Halo" Nature 486 (2012) 90, arXiv:1205.6802.

The age of a star in the galactic halo, HE 1523-0901, was estimated to be about 13.2 Gyr. First time many different chronometers, such as the U/Th, U/Ir, Th/Eu and Th/Os ratios to measure the star age have been employed.

"Discovery of HE 1523-0901: A Strongly r-Process Enhanced Metal-Poor Star with Detected Uranium", A. Frebe, N. Christlieb, J.E. Norris, C. Thom Astrophys.J. 660 (2007) L117; astro-ph/0703414.

Metal deficient high velocity subgiant in the solar neighborhood HD 140283 has the age 14.46 ± 0.31 Gyr. The central value exceeds the universe age more than by two standard deviations:
if $H = 67.3$, then $t_U = 13.8$;
if $H = 74$, then $t_U = 12.5$.
H. E. Bond, E. P. Nelan, D. A. VandenBerg, G. H. Schaefer, D. Harmer, Astrophys. J. Lett. 765, L12 (2013), arXiv:1302.3180.

High redshift distant objects.

Galaxies observed at high redshifts, with natural gravitational lens "telescopes". There is a galaxy at $z \approx 9.6$ which was formed when the universe was approximately 0.5 Gyr old (W. Zheng, M. Postman, A. Zitrin, *et al*, "A highly magnified candidate for a young galaxy seen when the Universe was 500 Myrs old" arXiv:1204.2305).

Moreover a galaxy at $z \approx 11$ has been observed which was formed eariler than the universe age was 0.41 Gyr (or even shorter with larger H).

D. Coe, A. Zitrin, M. Carrasco, *et al* **"CLASH: Three Strongly Lensed Images of a Candidate $z \sim 11$ Galaxy", Astrophys. J. 762 (2013) 32; e-Print: arXiv:1211.3663.**

Another example of early formed objects are quasars observed at high z. A quasar with maximum $z = 7.085$ has been observed i.e. it was formed at $t < 0.75$ Gyr. Its luminosity is $6.3 \cdot 10^{13} L_{\odot}$ and mass $2 \cdot 10^{9} M_{\odot}$. Daniel J. Mortlock, *et al*, " A luminous quasar at a redshift of z = 7.085" Nature 474 (2011) 616, arXiv:1106.6088 The quasars are supposed to be supermassive black holes (BH) and their formation in such short time by conventional mechanisms looks problematic.

"rapid emergence of high-z galaxies may actually be in conflict with current understanding of how they came to be. This problem is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at $z \sim 6$. It is difficult to understand how $10^9 M_\odot$ black holes appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe."
F. Melia, 1403.0908.
Now they are observed at $z = 7$.

In contemporary universe: every large galaxy and some smaller ones seem to contain a central supermassive BH whose masses are $> 10^9 M_\odot$ in giant elliptical and compact lenticular galaxies and $\sim 10^6 M_\odot$ in spiral galaxies like Milky Way.

The mass of BH is typically 0.1% of the mass of the stellar bulge of galaxy but some galaxies may have huge BH: e.g. NGC 1277 has the central BH of $1.7 \times 10^{10} M_{\odot}$, or 60% of its bulge mass. This fact creates serious problems for the standard scenario of formation of central supermassive BHs by accretion of matter in the central part of a galaxy. An inverted picture looks more plausible, when first a supermassive black hole was formed and attracted matter serving as seed for subsequent galaxy formation.

Early SN are needed:

The medium around the observed early quasars contains considerable amount of "metals" (elements heavier than He). According to the standard picture, only elements up to ^{4}He and traces of Li, Be, B were formed in the early universe by BBN, while heavier elements were created by stellar nucleosynthesis and dispersed in the interstellar space by supernova explosions. If so, prior to QSO creation a rapid star formation should take place. These stars produced plenty of supernovae which enriched interstellar space by metals.

Observations of high redshift gamma ray bursters (GBR), if they are supenovae, also indicate a high abundance of supernova at large redshifts. The highest redshift of the observed GBR is 9.4 and there are a few more GBRs with smaller but still high redshifts. The necessary star formation rate for explanation of these early GBRs is at odds with the canonical star formation theory.

A recent discovery of an ultra-compact dwarf galaxy older than 10 Gyr, enriched with metals, and probably with a massive black in its center seems to be at odds with the standard model
J. Strader, *et al* **Astrophys. J. Lett. 775, L6 (2013), arXiv:1307.7707.**
The dynamical mass is $2 \times 10^8 M_\odot$ and $R \sim 24$ pc - very high density.
Chandra: variable central X-ray source with $L_X \sim 10^{38}$ erg/s, which may be an AGN associated with a massive black hole or a low-mass X-ray binary.

Model of early formation of compact stellar-like objects and heavy PBH (AD, J.Silk; AD, M.Kawasaki, N.Kevlishvili). Modified Affleck-Dine scenario of baryogenesis where the general renormalizable coupling of the scalar baryon, χ, to the inflaton field, Φ, is introduced:

$$U(\chi, \Phi) = U_\chi(\chi) + U_\Phi(\Phi) + U_{\rm int}(\chi, \Phi).$$

Here $U_\Phi(\Phi)$ is the inflaton potential, $U_\chi(\chi)$ is the quartic Affleck-Dine potential, which in SUSY theories generically has some flat directions (valleys).

Affleck-Dine scenario: field χ acquires a large expectation value along a flat direction, during inflation and evolves down, when $H < m_\chi$. The potential:

$$U_\chi(\chi) = [m_\chi^2 \chi^2 + \lambda_\chi(\chi^4 + |\chi|^4)] + h.c.$$

If flat directions in quadratic and quartic parts of the potential deviate, then approaching minimum, χ starts to "rotate". Rotation means that χ gets (a large) average baryonic number.

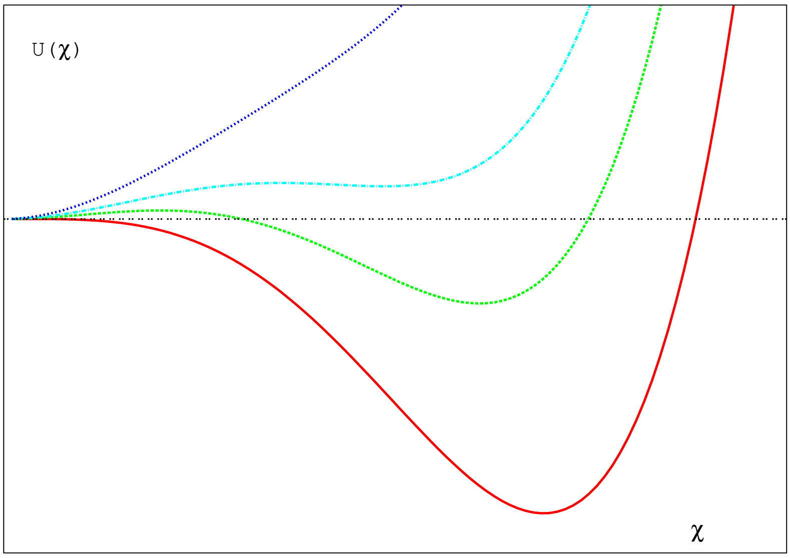
Coleman-Weinberg correction:

$$\delta U_\chi(\chi) = \lambda_2 |\chi|^4 \ln\left[|\chi|^2/\sigma^2\right].$$

We added a natural extra term - general renormalizable coupling to inflaton

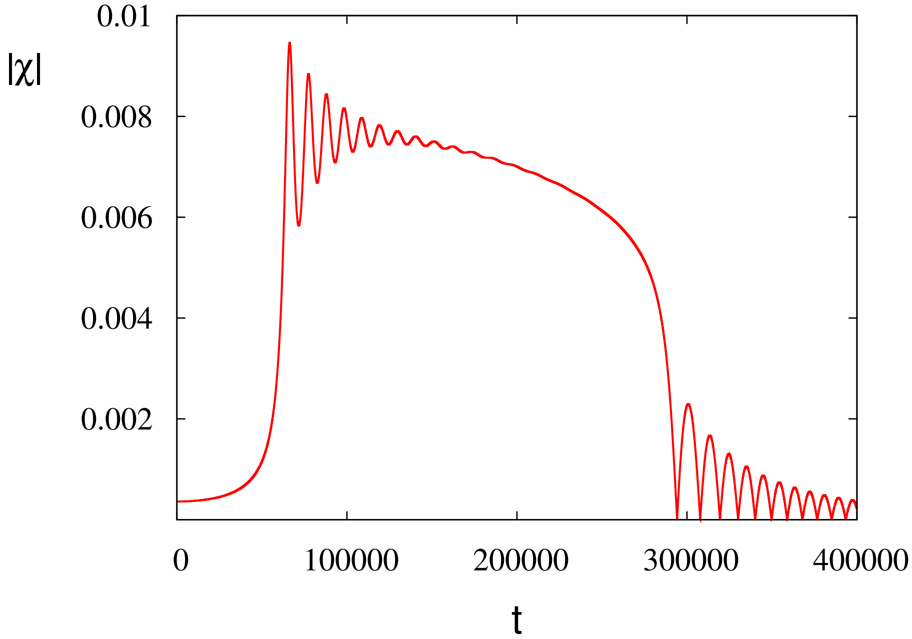
$$U_{\text{int}}(\chi, \Phi) = \lambda_1 |\chi|^2 (\Phi - \Phi_1)^2 \,,$$

where Φ_1 is some value of the inflaton field which it passes during inflation and λ_1 is a constant.
This terms acts as a positive time-dependent mass and thus gates to the valleys are open only when Φ is near Φ_1. So there is a chance for χ to reach a high value and to create a large baryon asymmetry.



Behavior of $U_\chi(\chi)$ for different values of $m^2_{eff}(t)$.

Evolution of $|\chi|$ in time.



The probability for χ to reach high value is low, so in most of space baryogenesis creates normal tiny baryon asymmetry, but in some bubbles which occupy a small fraction of the whole volume, baryon asymmetry may be huge. When χ changed the valley from quartic to either of two quadratic ones, it might rotate in clockwise or anticlockwise directions creating matter or antimatter high B bubbles. In a simple model their ratio is 50:50.

After the QCD phase transition, the contrast in baryonic charge density transformed into perturbations of the energy/mass density andthe bubbles with high B formed PBH's or compact stellar-like objects. The mass distribution of these high-B bubbles has practically model independent form:

$$\frac{dN}{dM} = C_M \exp\left[-\gamma\, \ln^2 \frac{(M - M_1)^2}{M_0^2}\right].$$

The values of the parameters can be adjusted in such a way that superheavy BHs formed at the tail of this distribution would be abundant enough to be present in every large galaxy and in some small ones.
Moreover such heavy PBHs could be seeds for the galaxy formation.

This mass distribution naturally explains some features of stellar mass black holes in the Galaxy. It was found that their masses are concentrated in narrow range $(7.8 \pm 1.2) M_\odot$ (1006.2834) This result agrees with another paper where a peak around $8 M_\odot$, a paucity of sources with masses below $5 M_\odot$, and a sharp drop-off above $10 M_\odot$ are observed, arXiv:1205.1805. These features are not explained in the standard model.

A modifications of U_{int} leads to a more interesting spectrum of the early formed stellar type objects, e.g., if:

$$\boldsymbol{U_{\text{int}} = \lambda_1 |\chi|^2 \left(\Phi - \Phi_1\right)^2 \left(\Phi - \Phi_2\right)^2 ,}$$

we come to a two-peak mass distribution of the PBHs and compact stars, which is probably observed, but not explained up to now.
ArXive: 1011.1459: "sample of black hole masses provides strong evidence of a gap between the maximum neutron star mass and the lower bound on black hole masses."

Evolved chemistry in the so early formed QSOs can be explained, at least to some extend, by more efficient production of metals during BBN due to much larger ratio $\beta = N_B/N_\gamma$. The standard BBN essentially stops at ^{4}He due to very small β. However, in the model considered here β is much larger than the canonical value, even being close or exceeding unity.

CONCLUSION.

The scenario may be speculative but not too unnatural and explains a lot:

1. Superheavy BH and early quasar formation with plenty of metals around.

2. High abundance of supenovae and gamma-bursters at $z \gg 1$.

3. Existence very old stars in the Galaxy and very old galaxies.

New types of stellar-like objects from the very early universe and probably abundant cosmic antimatter are predicted. A study of astrophysics of such new kind of stars is in order.

THE END