

BLACK HOLES AND COSMIC ANTIMATTER

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The possible existence of antimatter at astrophysical and cosmological scales is considered. The case of spontaneous breaking of charge symmetry in elementary particle interactions, which leads to a matter-antimatter symmetric universe equally populated by galaxies and by anti-galaxies, is discussed in detail. The mechanisms of baryogenesis based on the evaporation of black holes are also reviewed. It is shown that the primordial black hole model of 1993 may lead to a noticeable population of our Galaxy with different forms of antimatter, and observational manifestations of the latter are presented.

Keywords: antimatter, antistars, primordial black holes, baryogenesis, CP violation, antinuclei

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1. INTRODUCTION

According to the canonical faith, each galaxy consists only of matter and any amount of antimatter should be of secondary origin, created via cosmic ray interactions, and hence negligibly tiny. The first person who doubted this seemingly evident «fact» was B.P. Konstantinov with coauthors [1–3]. They searched for meteors consisting of antimatter, despite being very strongly criticized by Ya. B. Zeldovich, who was in very good personal relations with Konstantinov. But «Amicus Plato, sed magis amica veritas» — «Plato is my friend, but the truth is dearer to me.» Still, nowadays very strong evidence confirming the existence of a different type and quite noticeable population of the Milky Way with antimatter has been found, and it became clear that Konstantinov was right.

The notion of antimatter appeared at the end of the XIX century in the publication of the British physicist Arthur Schuster. In 1898, one year after the discovery of the electron (J.J. Thomson, 1897), he published a paper [4] with the conjecture that there might be elec-

tricity of the opposite sign, antimatter, and supposed that there might be entire solar systems, made of antimatter, indistinguishable from ours. Schuster made the fantastic wild guess that matter and antimatter are capable of annihilating and producing vast energy. However, he believed that they were gravitationally repulsive, having negative mass. Schuster concluded that two such objects in close contact should have vanishing mass!? Quoting his paper [4]: «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.»

Except for the incorrect assumption of negative mass of antimatter particles, the rest of Schuster's work was an ingenious guess ahead of the scientific development for almost half a century. Still, the notion of negative mass is revived even nowadays by some illiterate authors.

The real scientific father of antimatter is definitely Paul Dirac. According to Werner Heisenberg, «his discovery of antimatter was perhaps the biggest jump of all big jumps in physics in our century» [5].

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In his Nobel Lecture of December 12, 1933, «Theory of electrons and positrons», dedicated to his prediction of positrons, Dirac anticipated that there could be antistars and possibly antiworlds: «... 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.»

Strictly speaking, the last statement is not correct. There are some, though difficult, maybe unrealistic, ways to distinguish a star from an antistar even at very large distances, as is found in ref. [6]. The spectra of the emitted radiation are not exactly the same, the polarization of radiation from weak decays could be a good indicator, and lastly the spectrum of emitted neutrinos versus antineutrinos from supernovae or anti-supernovae would be different. In the exotic case of CPT violation, when the masses of particles and antiparticles and the decay probabilities are not the same, more interesting possibilities would be open.

2. GALAXIES AND ANTI-GALAXIES

2.1. Pioneering papers

The choice between formation of a galaxy or an anti-galaxy is determined by details of Sakharov's mechanism of baryogenesis [7], which is based on three known principles:

- a) non-conservation of the baryonic number B ;
- b) deviation from thermal equilibrium;
- c) breaking of the symmetry between particles and antiparticles, i.e. breaking of C and/or CP invariance.

Depending on the sign of the charge symmetry breaking, either a galaxy or an antigalaxy would be created. There are several mechanisms of breaking the conservation of baryons. In particular, the one related to black hole evaporation has been suggested by Zeldovich [8]. In this work he examined a possibility for the origin of an excess of baryons through predominant emission of baryons by black holes. The idea of this mechanism comes from a remark of Hawking [9] about non-conservation of the baryon number in the evaporation of black holes. According to Zeldovich [8] the specific process is the following. The black hole can emit hypothetical heavy mesons A . It is further assumed that these mesons can decay via the channels $A \rightarrow L + \bar{R}$ and $A \rightarrow R + \bar{L}$, where L and R are light and heavy (anti)baryons. Because of non-conservation of C/CP the partial widths of these two

channels must in general be different. Detailed calculations of the probabilities of these processes have been done in refs. [10, 11], where it was shown that the observed cosmological baryon asymmetry may indeed be generated.

The mechanism of generation of matter-antimatter asymmetry which could operate even if the baryonic number is conserved was proposed in ref. [12]. It is related to different mobilities of particles and antiparticles in the very early universe, which could lead to different probabilities of their capture by primordial black holes.

However, all these mechanisms create either a galaxy or an antigalaxy, but not both. To make the universe (approximately) charge symmetric, cosmological inflation should be invoked. Such a mechanism, not related to black hole evaporation, which leads to an (approximately) matter-antimatter symmetric universe and moreover to a noticeable antimatter population of the Galaxy, was proposed in refs. [13, 14]. It is discussed below in Sec. 4.2.

The possible existence of anti-galaxies, i.e. of galaxies consisting solely of antimatter, was foreseen by Floyd Stecker with collaborators in 1971 [15], and later this was further developed in his works of 1981 [16, 17]. The authors of ref. [15] argued that, according to the results of their calculation of the cosmological γ -ray spectrum from matter-antimatter annihilation in the universe, the similarity of the calculated spectrum with the present observations of the γ -ray background spectrum above 1 MeV suggests that such observations may be evidence of the existence of antimatter on a large scale in the universe.

It is shown in refs. [16, 17] that in the framework of grand unified theories spontaneous CP violation leads to a domain structure in the universe, with the domains evolving into separate regions of matter and antimatter excesses. Subsequent to exponential horizon growth, this can result in a universe of matter galaxies and antimatter galaxies. Various astrophysical data appear to favor this form of big bang cosmology. Essentially the same ideas were replicated a year later in ref. [18].

A review of the «anti-situation» in the state of the art at 2002 is presented in two keynote lectures at the 14th Rencontres de Blois on Matter–Anti-matter Asymmetry [19, 20].

2.2. CP violation in cosmology

There are two possible ways to break $C(CP)$ symmetry in particle physics:

- explicit, by complex coupling constants in the Lagrangian;
- spontaneous, suggested by T. D. Lee [2], realized by a non-zero vacuum expectation value of a complex scalar field.

The latter mechanism is locally indistinguishable from the explicit one, but globally it would create a charge symmetric universe, with the same fractions of matter and antimatter, in particular, a universe equally populated by galaxies and anti-galaxies.

Indeed, spontaneous breaking of charge symmetry implies the existence of domains with different signs of the symmetry violating interactions and, as a result, leads to a different sign but equal magnitude of the emerging matter-antimatter asymmetry (i.e. of the cosmological baryon asymmetry).

The idea is beautiful but encounters serious problems. Domain walls between matter and antimatter regions should have extremely large energy and destroy the observed homogeneity and isotropy of the universe [22]. So a mechanism of wall destruction is necessary.

Moreover, if the domain size happened to be too small, the domains would mutually annihilate due to particle-antiparticle diffusion. As argued in ref. [23], to save their lives, exponential (inflationary) expansion after spontaneous CP breaking is needed, which allows the domains to be stretched exponentially. Hence the radius of the domains could be much greater than that of the horizon of the standard big bang model.

All the above mentioned problems can be solved by the mechanism worked out in paper [24], where a model of spontaneous (or dynamical) C and CP violation was formulated, permitting to generate domains of matter and antimatter separated by cosmologically large distances. It was assumed that such C(CP) violation existed only in the early universe and later it disappeared, leaving the trace of the generated baryonic and/or anti-baryonic domains. So the problem of domain walls in this model does not exist. These features are achieved through a postulated form of interaction between the inflaton and a new scalar field, realizing short time C(CP) violation.

2.3. Matter and antimatter in the Universe

To summarize, it is quite plausible that the universe could be globally symmetric, consisting of matter and antimatter domains. If the domain size is sufficiently large, they could survive in the process of matter-antimatter annihilation at the domain boundaries. The domains should be sufficiently far away to

escape observational constraints on the cosmic gamma-ray radiation. All that would be realized if the domain formation was followed by the exponential (inflationary) period [23].

To the best of my knowledge, the first papers on cosmological antimatter were published by F. Stecker in 1971 [15], independently of the three year earlier papers by Konstantinov et al. [1–3] on the search of antimatter in the Galaxy, see below Sec. 3. Further development of the idea of a matter-antimatter domain structure of the universe was presented in ref. [16].

The analysis performed in ref. [25] permits to conclude that a matter-antimatter symmetric universe, or a state close to the symmetric one, is excluded by the observed cosmic diffuse gamma-ray background and a distortion of the cosmic microwave background, if the domains are not sufficiently far away.

However, there still remains some space for the fraction of cosmological antimatter, but considerably restricted. It is argued by G. Steigman in ref. [26] that the nearest anti-galaxy should be out of our galaxy cluster and thus could not be closer than at ~ 10 Mpc. In a subsequent paper by the same author [27] it is argued that the fraction of antimatter in the Bullet Cluster should be below $3 \cdot 10^{-6}$.

3. BOUNDS ON ANTIMATTER IN THE MILKY WAY

As mentioned above, the search of antimatter in the Milky Way was initiated by Konstantinov with coworkers in 1968 [1–3]. Until recently there was no reason to suspect that any noticeable amount of antimatter might be in the Galaxy. The predictions of papers [13, 14] were not taken seriously. Now there are plenty of data indicating that the Milky Way contains a significant amount of antimatter of different kinds: positrons, antinuclei, and possibly antistars. The observations do not violate the existing bounds on galactic antimatter. According to the results of refs. [13, 14], antimatter objects could be not only in the Galaxy but in its halo as well.

According to ref. [28], the analysis of the intensity of gamma rays created by the Bondi accretion of interstellar gas to the surface of an antistar allows one to put a limit on the relative density of antistars in the Solar neighbourhood: $N_*/N_* < 4 \cdot 10^{-5}$ inside 150 pc from the Sun.

The bounds on galactic antimatter are analysed in refs. [29–31]. The limits on the density of galactic antistars are rather loose, because the annihilation pro-

ceeds only on the surface of antistars, i.e. on objects with a short mean free path of protons, so the extra luminosity created by matter-antimatter annihilation is relatively low.

4. GALACTIC ANTIMATTER PREDICTION

4.1. Supporting data

In papers [13, 14] a new mechanism of PBH creation was proposed, the first ones where inflation was invoked for PBH creation. This allowed one to create PBHs with masses well above those predicted in the canonical approach, up to $10^5 M_\odot$ or even larger than that.

A great achievement of these works was the prediction of the very simple log-normal mass spectrum of PBHs:

$$\frac{dN}{dM} = \mu^2 \exp[-\gamma \ln^2(M/M_0)], \quad (1)$$

where M_0 should be equal to the mass in the cosmological horizon at the QCD phase transition. A simple order of magnitude estimate gives $M_0 = M_{\text{hor}} \approx 10 M_\odot$, as estimated in our paper [32] for a negligibly small baryonic chemical potential, i.e. for the chemical potential of quarks. At larger chemical potential the temperature of the phase transition T_{pt} is smaller and M_{hor} is larger. As shown by the lattice calculations [33], for quark chemical potential $\mu/T \approx 0.3$ one has $M_0 = 17 M_\odot$. This is exactly the value obtained by the best fit to the data on gravitational waves registered by LIGO–Virgo–KAGRA, performed in the work [34], where more references on the subject can be found.

On the other hand, the alternative analysis performed in ref. [35], based on the LIGO–Virgo–KAGRA (LVK) collaboration data (GWTC-3 catalogue), indicates that the chirp mass distribution of the LVK BH binaries can be fitted with two distinct and almost equal populations: (1) astrophysical mergings from BH+BH formed in the modern Universe from the evolution of massive binaries and (2) mergings of binary PBHs with an initial log-normal mass distribution. It is found that for the PBH central mass $M_0 \approx 30 M_\odot$, $\gamma \approx 10$, the observed LVK chirp masses are almost insensitive to the assumed double PBH formation model. To comply with the observed LVK BH+BH merging rate, the CDM PBH mass fraction should be $f_{\text{PBH}} \sim 10^{-3}$, but can be higher if PBH clustering is taken into account. It is shown that almost equal populations of astrophysical binary BHs from massive binary evolution and binary PBHs with a log-normal mass spectrum can describe both the ob-

served chirp mass distribution and the effective spin-mass ratio anti-correlation of the LVK binary BHs.

Anyhow, the fact that the mechanism proposed in refs. [13, 14] successfully described the observed features of PBHs hints that the other prediction of these works, namely the prediction of galactic antimatter, could also be valid.

4.2. Mechanism of antimatter creation in the Galaxy

In papers [13, 14] a rather unusual way of PBH formation in comparison to other approaches has been worked out. Firstly, it was assumed that the basis of PBH formation was created at the cosmological inflationary stage. This was the first paper where such an assumption has been made. Now this is commonly used. Inflation allows one to create PBHs with very high masses, impossible with previously considered mechanisms.

Another assumption is the highly essential role of a scalar field χ with non-zero baryonic number. Such a field naturally appears in the supersymmetric (SUSY) baryogenesis scenario proposed by Affleck and Dine [36]. In contrast to other mechanisms, the cosmological baryon to photon ratio generated by the Affleck–Dine mechanism, $\beta = N_B/N_\gamma$, is huge, of order unity, much larger than the observed $\beta_{\text{obs}} = 6 \cdot 10^{-10}$. Special efforts should be made to suppress it down to the observed value, diminishing the initial value of χ .

Another prediction of high energy SUSY models is the existence of flat directions in the χ -potential, either quartic (self-interaction):

$$U_\lambda(\chi) = \lambda |\chi|^4 [1 - \cos(4\theta)], \quad (2)$$

or quadratic, i.e. the mass term, $U_m = m^2 \chi^2 + m^{*2} \chi^{*2}$ with $m = |m| e^{i\alpha}$:

$$U_m = m_\chi^2 |\chi|^2 [1 - \cos(2\theta + \alpha)], \quad (3)$$

where $\chi = |\chi| \exp(i\theta)$. Here θ is the phase angle of the χ field in the complex plane $[\text{Re } \chi, \text{Im } \chi]$. If $\alpha \neq 0$, the charge symmetry C/CP is broken.

As shown in several papers [37–40], at the inflationary stage the average value of a real field χ rises with time as $\langle \chi^2 \rangle \sim 8\rho t/(3H)$, where ρ is the cosmological energy density and H is the Hubble parameter, which is assumed to be larger than the mass of χ . In our case of a complex field χ the average value of χ^2 rises along the flat directions of the potential. For larger values of χ it rises along the flat directions of the self-interaction potential at $\cos(4\theta) = 1$, and for smaller χ the rise

goes along the mass term at $\cos(2\theta + \alpha) = 1$. Generally these flat directions do not coincide for non-zero α . In other words, bosons χ condense via rising quantum fluctuations along the flat directions of their potential. For large values of χ the quartic potential (2) dominates and χ^2 could reach large values along one of the directions with $\cos(4\theta) = 1$.

Note that there is a sign difference between the papers [37–39] and the later one [40], though the absolute values are the same. In paper [40] the calculations of the average value of $\langle\chi^2\rangle$ have been done by solution of the corresponding equation of motion, while in the three previous ones by a regularization of the infrared divergent quantity $\langle\chi^2\rangle$. Solution of the equation of motion is surely more reliable.

In GUT SUSY theories the baryonic number is naturally non-conserved, because of the generic non-invariance of $U(\chi)$ with respect to the phase rotation, which is indeed demonstrated by the behavior of U_λ (2) or U_m (3).

When inflation was over or slowed down to $H < m$, the field χ was far away from the origin $\chi = 0$, and when inflation ended it started to evolve down to the equilibrium point according to the equation of motion that formally coincides with the equation of motion of a point-like particle in Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0. \quad (4)$$

The baryonic charge of χ ,

$$B_\chi = \dot{\theta}|\chi|^2, \quad (5)$$

is analogous to the mechanical angular momentum.

If λ and m are both non-zero, the angular momentum, or what is the same, the baryonic charge density, could be generated by a different direction of the quartic and quadratic valleys at low χ . CP would be broken if the relative phase of λ and m is non-zero; otherwise one can «phase rotate» χ and arrive at real coefficients. The CP-odd phase α could be small but non-vanishing, and both baryonic and antibaryonic domains might be formed, with possible dominance of one of them. The decay of χ would transfer its baryonic charge to that of quarks in a B-conserving process. Coupling to fermions may break CP, though not necessarily. Matter and antimatter objects may exist, but globally it is natural to expect that the baryonic number density $B \neq 0$.

In refs. [13,14] the following coupling of the Affleck–Dine field χ to the inflaton Φ is proposed:

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right) + \lambda(\chi^4 + \text{h.c.}) + (m^2\chi^2 + \text{H.c.}). \quad (6)$$

The last terms in this expression are the above mentioned quartic and quadratic potentials, and the log-term is the Coleman–Weinberg effective potential [41], induced by one-loop corrections to the χ self-interactions.

The first term, describing the coupling of χ to the inflaton Φ , is «invented» in our works [13,14] for creation of bubbles with a large baryonic number density during the inflationary stage. It is the general renormalizable coupling of two scalar fields. The only fine tuning is that the value Φ_1 is reached by the inflaton during inflation when still considerable inflation proceeds, about 30–40 e-foldings.

When $\Phi = \Phi_1$, the effective mass of χ along the flat direction is zero. When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large values according to the quantum diffusion equation derived by Starobinsky [42], generalized to a complex field χ . A large χ could generate a cosmological baryon asymmetry of order unity.

If the window to the flat direction, when $\Phi \approx \Phi_1$, is open only during a sufficiently 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 $\beta = 6 \cdot 10^{-10}$, created by small χ . The mechanism of massive PBH formation is quite different from all others. The fundament of PBH creation is built at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations. The initial isocurvature perturbations are in the chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition. The emerging universe looks like a piece of Swiss cheese, «upside down», where the holes are high baryonic density objects occupying a minor fraction of the universe volume.

It is interesting that sufficiently long inflation demands non-conservation of the baryon number, as was noticed by Ya. B. Zeldovich [43]. The point is the following: inflation could be realized if the total cosmological energy density was (approximately) constant. However, if the baryonic number is conserved, the energy density of baryons scales as the inverse cosmological expansion factor cubed, or to the power minus four, depending upon whether baryons are relativistic or not. Anyhow, even if baryons make about 10^{-6} (or even smaller) of the total cosmological energy density, this energy density would rise with respect to the constant energy density which governs inflation. So it would kill inflation going backward in time in less than 7 Hubble times, while sufficient inflation demands about 65–70

Hubble times. As Zeldovich concluded, «the idea of inflation unambiguously leads also to the necessity of baryon nonconservation after the end of inflation».

5. OBSERVATIONS OF GALACTIC ANTIMATTER

The prediction of a possible antimatter population in our Galaxy was met by the community with a «grain of salt», to say it mildly. But recent observations strongly indicate that there is indeed some antimatter in the Galaxy that definitely is not of secondary creation through cosmic ray interactions with the interstellar matter.

5.1. Anti-evidence: cosmic positrons

The existence of rich populations of positrons in the Galaxy was noticed long ago through the observations of the 511 keV gamma ray line (see refs. [44–46] and references therein) with the flux

$$\Phi_{511 \text{ keV}} = (1.07 \pm 0.03) \cdot 10^{-3} \text{ photons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}. \quad (7)$$

The width of the line is about 3 keV. The emission mostly goes from the Galactic bulge and at a much lower level from the disk. This unambiguously indicates frequent annihilation of nonrelativistic e^+e^- pairs in the Galactic bulge with the rate [44]

$$\dot{N}_{ee}^{\text{bulge}} \sim 10^{43} \text{ s}^{-1}. \quad (8)$$

Note that one of the brightest X-ray sources in the region around the Galactic Center got the name Great Annihilator [47]. Possibly it is a microquasar, first detected in soft X-rays by the Einstein Observatory [48] and later detected in hard X-rays by the space observatory «Granat» [49].

There is no commonly accepted point of view on the origin of the cosmic positrons. The conventional hypothesis that positrons are created in strong magnetic fields of pulsars is at odds with the AMS data [50]. However, this conclusion is questioned in ref. [51], where it is shown that these features could be consistently explained by a nearby source which was active ~ 2 Myr ago and has injected $(1-2) \cdot 10^{50}$ erg in cosmic rays.

A competing option is that positrons are created by the Schwinger process at the horizon of small black holes with masses $\gtrsim 10^{20}$ g, as suggested in ref. [52] and discussed in more detail in ref. [53].

One more possibility, that is closer to the spirit of this paper, is that positrons are primordial, produced

in the early universe in relatively small antimatter domains [13, 14].

5.2. Anti-evidence: cosmic antinuclei

In 2018 AMS-02 announced the possible observation of six $\overline{\text{He}}^3$ and two $\overline{\text{He}}^4$ [54, 55]. The data accumulated by 2022 [56, 57] contain some more events: 7 $\overline{\text{D}}$ (at energies $\lesssim 15$ GeV) and 9 $\overline{\text{He}}^4$ (at $E \sim 50$ GeV). These numbers correspond, roughly speaking, to $\overline{\text{He}}/\text{He} \sim 10^{-9}$. This number is much larger than the expected number of $\overline{\text{He}}^4$ if it were created in cosmic ray collisions. It is possible that the total flux of anti-helium is even much higher, because low energy $\overline{\text{He}}$ may escape registration in AMS.

The probability of the secondary creation of different antinuclei was estimated in ref. [58]. According to this work, anti-deuterium could be most efficiently produced in the collisions $\bar{p}p$ or $\bar{p}\text{He}$, that can create the flux $\sim 10^{-7} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1} \text{ nucleon}^{-1}$, i.e. 5 orders of magnitude below the observed flux of antiprotons. Antihelium could be created in similar reactions, and the fluxes of $\overline{\text{He}}^3$ and $\overline{\text{He}}^4$ that could be created in cosmic rays would respectively be 4 and 8 orders of magnitude smaller than the flux of the secondary created anti-D.

According to the works [13, 14], antinuclei should be primordial, i.e. created in the very early universe during big bang nucleosynthesis (BBN) inside antimatter bubbles with high baryon density. However, the standard anti-BBN surely does not help, since normally BBN gives 75% of hydrogen, 25% of helium-4, and a minor fraction of deuterium, at the level of a few times 10^{-5} , in a huge contrast to the observed ratio of anti-deuterium to anti-helium which is of order unity. The same problem exists for the ratio of $\overline{\text{He}}^3$ to $\overline{\text{He}}^4$, that is also of order unity instead of the standard $\sim 3 \cdot 10^{-5}$.

If we assume that in the model of refs. [13, 14] the abundances of anti-D and anti-He are determined by normal BBN with a large baryon-to-photon ratio $\beta \sim 1$, the problem would be even more pronounced, because the amount of deuterium and helium-3 would be negligibly small, even much less than 10^{-5} . On the other hand, in our scenario the formation of primordial elements takes place inside non-expanding compact stellar-like objects with practically fixed temperature. If the temperature is sufficiently high, this so-called BBN may stop with almost equal abundances of D and He. One can see that looking at the abundances of light elements as a function of temperature. If it is so, antistars may have equal amounts of $\overline{\text{D}}$ and $\overline{\text{He}}$.

5.3. Anti-evidence: antistars in the Galaxy

A striking announcement of the possible discovery of antistars in the Galaxy was made in ref. [59]. A catalog of 14 antistar candidates was identified, not associated with any objects belonging to established gamma-ray source classes and with a spectrum compatible with baryon-antibaryon annihilation.

In ref. [60] a supplementary method of antistar identification was proposed. Namely, in the process of the interaction of neutral atmospheres or winds from antistars with ionised interstellar gas, the hadronic annihilation will be preceded by the formation of excited $p\bar{p}$ and $\text{He}^4\bar{p}$ atoms. These atoms rapidly cascade down to low levels prior to annihilation, giving rise to a series of narrow lines which can be associated with the hadronic annihilation gamma-ray emission. The most significant are the L (3p–2p) 1.73 keV line (yield more than 90%) from $p\bar{p}$ atoms, and the M (4–3) 4.86 keV (yield $\sim 60\%$) and L (3–2) 11.13 keV (yield about 25%) lines from $\text{He}^4\bar{p}$ atoms. These lines can be probed in dedicated observations by forthcoming sensitive X-ray spectroscopic missions XRISM and Athena and in wide-field X-ray surveys like the SRG/eROSITA all-sky survey.

The unexpectedly high flux of antinuclei [56,57] and the observation of antistars in the Galaxy [59] strongly support the hypothesis of ref. [61] that antihelium cosmic rays are created by antistars. It is shown that the flux of antihelium cosmic rays reported by the AMS-02 experiment can be explained by Galactic anti-nova outbursts, thermonuclear anti-SN Ia explosions, a collection of flaring antistars, or an extragalactic source, with abundances not violating existing gamma-ray and microlensing constraints on the antistar population.

A minor population of antistars in galaxies has been predicted by some non-standard models of baryogenesis and nucleosynthesis in the early Universe, and their presence is not yet excluded by the currently available observations. Detection of an unusually high abundance of antinuclei in cosmic rays can probe the modified baryogenesis scenarios in the early Universe.

A very powerful gamma-ray burst (GRB) was reported in ref. [62]. This event got the nickname the Brightest Of All Time, or the BOAT. This extremely strong GRB occurred in October 2022. A bright mega-electronvolt emission line was observed that appeared 280 s after the GRB began and then rapidly faded away while shifting to lower energies. Usually the gamma-ray spectra of GRBs consist of a smooth continuum without absorption or emission lines. The authors interpret this MeV line as having been produced by the annihilation of electron-positron pairs within the relativis-

tic jet produced by the GRB, possibly emerging from star-antistar annihilation!? Star-antistar collision was discussed in the talk [63]. It may be a quasi-periodic process of star-antistar direct contact, with explosion pushing them apart and possible, but not necessary, return to each other by gravitational attraction.

6. PBH AND GALAXY FORMATION

The above presented arguments on the existence of antimatter both in the universe and in the Galaxy (galaxies) are strongly based on the assumption of an inverted mechanism of galaxy formation.

There are two conflicting options of galaxy and supermassive black hole formation: either galaxies are formed first and SMBHs were created later by matter accretion to the center, or the other way around (the inverted one), first SMBHs, which later seeded galaxy formation. According to our model [13, 14], black holes with masses up to $(10^5 - 10^6)M_\odot$ are primordial, created at the pre-stellar epoch in the early universe. Later on these PBHs seeded the formation of BHs with masses up to a billion solar masses, and they in turn seeded galaxy formation.

An essential input of the DS and DKK papers is the suggestion of an inverted formation mechanism of galaxies and their central black holes. Usually it is assumed that supermassive BHs (SMBHs), that are observed in the centres of all large galaxies, are created by matter accretion to the density excess in the galactic centre, but the estimated necessary time is much longer than the universe age, even for the contemporary universe, with the age about 15 billion years, to say nothing about the 20 times younger universe at $z \sim 10$. On the contrary, as was conjectured in refs. [13, 14], supermassive black holes were created first in the early universe at the prestellar epoch — that is why they are called primordial — and later they have seeded galaxy formation.

There are several observational facts in favor of this picture; let us mention a few of them.

1. The existence of SMBHs in the early universe in practically empty space [64].

2. The small ratio of the stellar mass of a young galaxy to the mass of the central black hole, see e.g. ref. [65], which is much smaller than the same ratio in contemporary galaxies. This fact proves that the early galaxies are still in the process of formation seeded by a central PBH.

3. The impossibility of direct collapse is proven in ref. [66]. For realization of direct collapse several quite

unnatural assumptions are to be made, which contradict well established particle physics and the canonical cosmological scenario. It is suggested that the universe is dominated by new massive sterile particles, whose origin is unclear. At redshift of order ten, the cosmological expansion is dominated by normal matter consisting of photons, neutrinos, electrons and baryons. The latter have relatively small number density but considerably larger energy density than light particles. The baryon to photon ratio, measured by big bang nucleosynthesis and angular fluctuations of the microwave background, is $N_B/N_\gamma \approx 6 \cdot 10^{-10}$. There could also be particles of dark matter contributing about 5 times more than the baryon energy density. The latter could be either massive particles of dark matter or primordial black holes. Anyhow, interactions with background photons and baryons would prevent matter from free falling and creating a supermassive black hole.

4. Super-Eddington accretion. To explain the early and efficient formation of supermassive black holes, the authors of ref. [67] claimed that they discovered super-Eddington accretion, despite the fact that this assumption is at odds with known physics.

All these mysterious phenomena can be simply explained by the existence of massive primordial black holes. We may conclude that the model of papers [13, 14] is verified by a very good agreement of the calculated log-normal mass spectrum of PBHs with observations and by the discovery of an abundant antimatter population in the Galaxy. The model also predicts an early formation of galaxies, seeded by PBHs, quasars (alias SMBHs), rich chemistry (heavy elements), and dust in the early universe.

7. CONCLUSION

The outcome of the DS/DKK mechanism is the following.

- PBHs with log-normal mass spectrum — confirmed by the observations!
- Compact stellar-like objects, similar to cores of red giants.
- Disperse hydrogen and helium clouds with (much) higher than average baryon number density n_B .
- Strange stars with unusual chemistry and velocity.
- β may be negative, leading to creation of (compact?) antistars which could survive annihilation despite being submerged into the homogeneous baryonic background.
- Extremely old stars could exist, and indeed they are observed; even an «older than the universe star»

is found, its prehistoric age being mimicked by the unusual initial chemistry.

The mechanism of PBH creation is pretty well verified by the data on the BH mass spectrum and on the existence of antimatter in the Galaxy, especially of antistars. So we may expect that it indeed solves the problems created by the HST and JWST data. So the canonical Λ CDM cosmology is saved by PBHs. Antimatter in our backyard is predicted and found.

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