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Black Dark Matter and Antimatter

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Abstract—It is shown that the dense population of the early universe with well developed galaxies and supermassive black holes (quasars), observed by HST and JWST, nicely fits the conjecture that the galaxies and quasars are seeded by primordial black holes (PBHs), proposed in our work more than 30 years ago. This idea of galaxy seeding by massive black holes is rediscovered in recent publications by several groups. The predicted log-normal mass spectrum of PBHs very well agrees with the observations. Our other prediction of noticeable amount of antimatter in the Galaxy is also confirmed by the data.

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1. INTRODUCTION

Cosmological dark matter (DM) can be divided into two large sub-classes: WIMPs and MACHOs. WIMPs are weakly interacting massive particles. i.e. elementary particles, different interaction strength with visible matter (e.g. heavy leptons or sterile neutrinos) self-interacting DM, mirror DM, etc. Their masses could vary from $\sim 10^{-22}$ eV (axion-like particles) up to 10^{13} GeV (see the talk by E. Arbuzova presented at the same day at this conference). MACHOs are massive astrophysical compact halo objects, most probably primordial black holes (PBHs), topological or non-topological solitons, or any other macroscopically large objects. The public opinion pool is definitely in favour of WIMPS but PBHs are steadily becoming more and more popular.

The present talk is dedicated the primordial black holes and that's why it may be called "black dark matter." An eclectic point of view that there are comparable contribution to DM density from WIMPs and MACHOs is not excluded, and even more there could be several kinds of WIMPs and MACHOs, but this surely would be grossly excessive.

2. BLACK DARK MATTER

The first suggestion PBH might be dark matter "particles" was made by S. Hawking in 1971 [1]. A concrete model leading to black dark matter, tested by "experiment", is suggested in [2, 3] with more realistic masses. The work [2] is the first paper where inflation was applied to PBH formation, so PBH masses as high as $10^6 M_\odot$, and even higher can be created. The log-normal mass spectrum of PBH was predicted, that very well agrees with observational data. It is the only known mass spectrum of PBH that is tested by observations without adjustment of theoretically predicted parameters (see below).

The constraints on the cosmological fraction of Black Dark Matter are summarised in [4, 5] by B. Carr and F. Kuhnel. The bounds are obtained for monochromatic mass spectrum of PBHs and according to the authors they are model-dependent and should be taken with caution.

Possible ways to eliminate or weaken the upper limits on PBH density are suggested in several works. In [6] possible loopholes in LIGO bounds are discussed in the case that the mass of LIGO black holes changed with time. If this is so, then dark matter in the form of LIGO-mass PBHs becomes possible.

It is argued in [7] that the most questionable step in the chain of arguments leading to the presented limits is the use of overly simplified accretion models. The study of the accretion models applied to X-ray observations from supermassive black holes SMBHs, M87 and Sgr A*. suggests that the latter could provide a significant constituent of all the dark matter.

As conjectured in [8], PBHs ccould be formed in clusters and it would lead to substantial weakening of the restrictions on their density.

Dynamical interactions in PBH clusters offers additional channel for the orbital energy dissipation thus increasing the merging rate of PBH binaries, and the constraints on the fraction of PBH, $f_{\rm PBH}$, obtained by assuming a homogeneous PBH space distribution can be weaker. A recent analysis [9] based on the PBH formation model of [10, 11] shows that even $f_{\rm PBH} = 0.1$–1 is not excluded.

3. TYPES OF BLACK HOLES

(1) Astrophysical black holes. They are created by the collapse of a star which exhausted its nuclear fuel. The expected masses should start immediately above the neutron star mass, i.e. about $3M_\odot$, but noticeably below $100M_\odot$. Instead we observe that the BH mass spectrum in the galaxy has maximum at $M \approx 8M_\odot$ with the width ~(1–2)$M_\odot$. The result is somewhat unexpected but an explanations in the conventional astrophysical frameworks is possible.

Recently LIGO/Virgo discovered BHs with masses close to $100M_\odot$. Their astrophysical origin was considered impossible due to huge mass loss in the process of collapse. To save their astrophysical origin some clever but exotic formation mechanisms are specially invented.

(2) Black holes formed by the accretion on the mass excess in the galactic centers.

In any large galaxy there exists a supermassive BH (SMBH) at the center, with masses varying from a few millions $M_\odot$ (e.g., Milky Way) up to almost hundred billions $M_\odot$. However, the conventional accretion mechanisms are not efficient enough to create such monsters during the universe life-time, $t_U \approx 14.6$ Gyr. To make them with the standard accretion mechanism at least an order of magnitude longer time is necessary, to say nothing about SMBH observed by HST and JWST in the universe that was about 20 times younger.

(3) Primordial black holes (PBH) created during pre-stellar epoch in very early universe.

The idea of the primordial black hole (PBH) i.e. of black holes that could be formed the early universe prior to star formation was first put forward by Zeldovich and Novikov [12]. According to their idea, the density contrast in the early universe inside the bubble with radius equal to the cosmological horizon might accidentally happen to be large, $\delta\rho/\rho \approx 1$, then that piece of volume would be inside its gravitational radius i.e., it became a PBH, decoupled from the cosmological expansion. Elaborated later by S. Hawking and B. Carr [13, 14].

4. GRAVITATIONAL WAVES (GW) FROM BH BINARIES, PROBLEMS

GW discovery by LIGO presents strongl evidence that the sources of GW are indeed PBHs. This is the first direct observation of the Schwarzschild metric that according to GR describes non-charged, mostly (almost) non-rotating BH. The observations permit to determine the masses of two coalescing BHs, the mass of the final one and their spins.

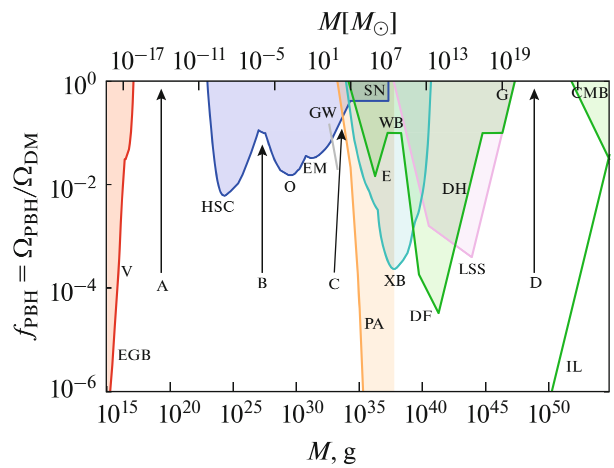

Fig. 1. Constraints on $f(M)$ for a monochromatic mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple). Evaporation limits from the extragalactic gamma-ray background (EGB), the Voyager positron flux (V) and annihilation-line radiation from the Galactic centre (GC). Lensing limits from microlensing of supernovae (SN) and of stars in M31 by Subaru (HSC), the Magellanic Clouds by EROS and MACHO (EM) and the Galactic bulge by OGLE (O). Dynamical limits from wide binaries (WB), star clusters in Eridanus II (E), halo dynamical friction (DF), galaxy tidal distortions (G), heating of stars in the Galactic disk (DH) and the CMB dipole (CMB). Large scale structure constraints(LSS). Accretion limits from X-ray binaries (XB) and Planck measurements of CMB distortions (PA). The incredulity limits (IL) correspond to one PBH per relevant environment (galaxy, cluster, Universe). There are four mass windows (A, B, C, D) in which PBHs could have an appreciable density.

As argued in [16], as well as in several other independent papers, the assumption that the LIGO (or LIGO/Virgo/Kagra) sources are astrophysical black holes encounters several problems serious problems:

(1) Origin of heavy BHs (~$30M_\odot$).

(2) Formation of BH binaries from stellar binaries.

(3) Low spins of the coalescing BHs.

Recently there appeared much more striking problem of BH pair with $M \sim 100M_\odot$ that is impossible to form in the standard astrophysical way.

5. GRAVITATIONAL WAVES FROM BH BINARIES, CHIRP MASS DISTRIBUTION

The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1–O3 LIGO/Virgo runs are analysed [17] and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

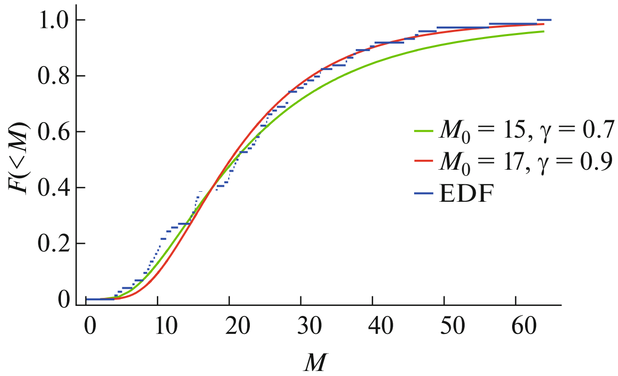

Fig. 2. Model distribution $F_{PBH}(<M)$ with parameters $M_0 \approx 17M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov–Smirnov tests. EDF = empirical distribution function.

The inferred best-fit mass spectrum parameters, $M_0 = 17M_\odot$ and $\gamma = 0.9$, fall within the theoretically expected range and shows excellent agreement with observations. On the opposite, binary black hole formation based on massive binary star evolution require additional adjustments to reproduce the observed chirp mass distribution.

The data allow to conclude that PBHs with log-normal mass spectrum perfectly fit the data, while astrophysical BHs seem to be disfavoured.

6. SEEDING OF COSMIC STRUCTURES DURING WHOLE LIFE-TIME OF THE UNIVERSE

6.1. Seeding in the Young Universe

Dense population of the early universe, noticeably younger than one billion years at redshifts $z \gtrsim 10$, pin-pointed by Hubble Space Telescope (HST) and later by James Webb Space Telescope (JWST), was taken as a strong blow to the conventional ΛCDM cosmology. The Hubble space telescope (HST) discovered that the early universe, at $z = 6$–7 is too densely populated with quasars, alias SMBH, supernovae, gamma-bursters and it is very dusty. No understanding how all these creature were given birth in such a short time is found in conventional cosmology. Moreover great lots of phenomena in the present day universe are also in strong tension with canonical cosmological expectations, as reviewed in [19]. “Hubble” sees the universe up to $z = 6$–7, but accidentally a galaxy at $z \approx 12$ has been discovered for which both Hubble and later Webb happened to be in good agreement.

The crisis became much more pronounced when JWST has looked deeper into the universe past to $z > 10$ and even up to $z \gtrsim 15$, when the universe age was as short as 200–300 Ma. To common surprise, that young universe looks not so young containing very well developed galaxies, quasars, and supermassive black holes.

Usually it is assumed that supermassive BHs (SMBHs), observed in 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 larger than the universe age, even for the contemporary universe, with the age about 15 billion yr, to say nothing of the 20 times younger universe at $z \sim 10$. In [2, 3] the inverted formation mechanism of galaxies and their central black holes is proposed. Namely, primordial SMBHs in prestellar cosmological epoch was formed first and later they *seeded* galaxy formation. Basic features of the proposed mechanism of PBH creation are the following: first bubbles with very large baryon number density were created. At this stage density perturbations were quite low. Later at QCD phase transition they either make PBHs or compact stellar-like objects made of matter or antimatter.

The validity of the suggested in [2, 3] mechanism is strongly supported by very good agreement with observations of the predicted log-normal mass spectrum of PBH and observations of also predicted antimatter in our Galaxy. The hypothesis of seeding cosmic structures by PBHs [2, 3] allows to understand the presence of SMBH in all large and several small galaxies accessible to observation. In particular, this mechanism explains how the galaxies observed by JWST in the very young universe might be created.

Under the pressure of JWST data the hypothesis of seeding was rediscovered in several recent works. The first rediscovery is made in [20]. The authors noted that the recent observations with JWST have identified several bright galaxy candidates at $z \sim 10$, some of which appear unusually massive (up to $\sim 10^{11} M_\odot$. Such early formation of massive galaxies is difficult to reconcile with standard ΛCDM predictions. The observed massive galaxy candidates can be explained, if structure formation is accelerated by massive $\sin 10^9 M_\odot$) PBHs that enhance primordial density fluctuations. Up to the value of the PBH mass this is exactly our hypothesis [2, 3].

Another paper, where authors resicovered the idea of seeding [21], appears practically at the time of this conference. As is stated by the authors the James Webb Space Telescope is now detecting early black holes (BHs) at their transition from seeds to supermassive BHs. Similar statement is contained in a different paper of the same group [22]. It is reported there the detection of an X-ray luminous supermassive black hole, UHZ-1, with a photometric redshift at $z > 10$. Such an extreme source at this very high redshift provides new insights on seeding and growth models for BHs given the short time available for formation and growth. The resulting ratio of M_{BH}/M_* remains two to three orders of magnitude higher than local values, thus lending support to the heavy seeding channel for the formation of supermassive BHs within the first billion years of cosmic evolution.

The hypothesis that was proposed in [2, 3] that supermassive primordial black holes (SMBH) seeded galaxy formation allows to explain presence of SMBH in all large and several small galaxies accessible to observation. This mechanism explains how the galaxies observed by JWST in the very young universe might be created. The idea of seeding was rediscovered in several recent works.

6.2. Seeding of Globular Clusters and Dwarfs

The described above model of PBH formation excellently solves all the inconsistencies if the inverted picture of galaxy formation is assumed, namely initially supermassive PBH are created and later they seed galaxy formation. It is worth noting that seeding by primordial IMBHs with masses of a few thousand solar mass explains formation of globular clusters (GCs), that is mysterious otherwise, as it was envisaged in [23]. In the last several years several such IMBH seeds inside GSs are observed in accordance with our prediction. Similar BH seeds are predicted and observed in dwarf galaxies.

In particular, in [24] a discovery of two active galactic nuclei (AGN) in two merging dwarf galaxies is reported, that are presumably supermassive black holes. According to our hypothesis these SMBP were seeds of the observed two dwarf galaxies. For the first time, astronomers have spotted evidence of a pair of dwarf galaxies featuring giant black holes on a collision course with each other. In fact, they haven't just found just one pair, they've found two.

The discovery of a dwarf galaxy hosting an intermediate mass black hole with $M_{\rm BH} = 3.6^{+5.9}_{-2.3} \times 10^5 M_\odot$. is reported in [25]. Such an INBH that surely cannot be created by accretion inside this tiny galaxy, but might seed its formation.

Already after this Conference was over, a new IMBH discovery was reported in [26]. Analysis of the observations of the Galactic globular cluster 47 Tucanae with the Australia Telescope Compact Array indicates a black hole mass of $M = (54\text{–}6000)M_\odot$, that may be an intermediate-mass black hole or a heavy stellar-mass black hole.

As is summarised in [27] primordial black holes created in the early Universe can constitute a substantial fraction of dark matter and seed the early galaxy formation. PBHs with log-normal mass spectrum centred at $M_0 = (15\text{–}17)M_\odot$ simultaneously explain both the chirp mass distribution of the detected LIGO/Virgo binary black holes and the differential chirp mass distribution of merging binaries as inferred from the LIGO/Virgo observations. The obtained parameters of log-normal mass spectrum of PBHs also give the fraction of seeds with $M \approx 10^4 M_\odot$

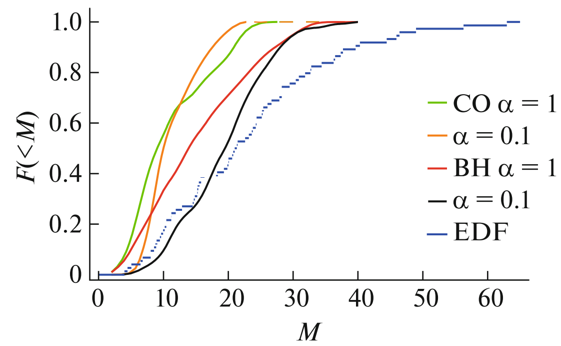

Fig. 3. Cumulative distributions $F(<M)$ for several astrophysical models of binary BH coalescences.

required to explain the observed population of supermassive black holes at $z = 6\text{–}7$.

7. ANTIMATTER IN COSMOLOGY

7.1. Antimatter, Prehistory

The godfather of antimatter (not only just of antiparticles) is rightfully considered Paul Dirac. In his Nobel lecture he mentioned that there might exist stars made of antimatter: "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."

This is not exactly true, there may be some ways to distantly spot an antistar, as it was suggested for example in [28]. The position and intensity of different spectral lines may not be exactly the same, even if CPT is unbroken. Also the polarisation of radiation from weak decays could be a good indicator or the type of emitted neutrinos/antineutrinos from supernovae or anti-supenova. Though it is not realistic at the present time but in principle such a possibility exists.

7.2. Antimatter, Modern History

One should distinguish between galactic and cosmological antimatter. Antimatter at cosmological scales could be created without breaking any sacred principles, simply by changfing sign of C and CP violation at the process of baryogenesis, such as e.g. is the case of spontaneous of CP violation or some other mechanisms leading to sigh variation of C(CP) odd amplitude. The mechanisms of C(CP) violation that could lead to cosmologically significant domains of antimatter are reviewed in [29].

On the other hand, antimatter in the Galaxy was taken with gross reluctance. The reason is simple, since no reasonable mechanism of creation of galactic antimatter in small but significant amount was known. In fact such mechanism has been proposed ages ago in

1993 [2] and now it opens the only known way to create antimatter in the Galaxy that is seemingly confirmed by quite a few pieces of observational data of the last several years.

The search of antimatter in the galaxy was initiated by B.P. Konstantinov, as early as in 1968 [30, 31].

Somewhat later the idea of antimatter in the universe was discussed by F. Stecker and collaborators [32, 33]. Summary of the situation with cosmological antimatter at year 2002 was presented in two keynote lectures at the 14th Rencontres de Blois [34, 35].

8. ANTIMATTER IN THE GALAXY

8.1. Anti-Evidence: Cosmic Positrons

Observation of intense 0.511 MeV e^+e^--annihilation line presents a strong proof of abundant positron population in the Galaxy. In the central region of the Galaxy electron–positron annihilation proceeds at a surprisingly high rate, creating the flux:

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

The width of the line is about 3 keV, see [36–38] and references therein. Emission mostly goes from the Galactic bulge and at much lower level from the disk

8.2. Anti-Evidence: Cosmic Antinuclei

In 2018 AMS-02 announced possible observation of six $\overline{\mathrm{He}}^3$ and two $\overline{\mathrm{He}}^4$ [39]. Later, in 2022 [40] the following antinuclej have been registered 7 $\bar{D}$ ($E \lesssim 15$ GeV) and 9 $\overline{\mathrm{He}}$, ($E \sim 50$ GeV).

The fraction $\overline{\mathrm{He}}/\mathrm{He} \sim 10^{-9}$, too high to be explained by their secondary production in cosmic rays that is negligibly weak. Indeed, according to the theoretical estimates by [41] of the secondary production anti-nuclei in cosmic ray collisions the dominant channels of anti-deuterium creation are $\bar{p}p$ or $\bar{p}\mathrm{He}$ that would produce the flux of $\bar{D}$ approximately equal to $\sim 10^{-7}/\mathrm{m}^2/\mathrm{s}^{-1}$/steradian/GeV/neutron), i.e., 5 orders of magnitude below the observed flux of antiprotons. The fluxes of $\overline{\mathrm{He}}^3$ and $\overline{\mathrm{He}}^4$, that could be created in cosmic rays are respectively 4 and 8 orders of magnitude smaller than the flux of anti-D. It is not excluded that the flux of anti-helium is even much higher because low energy $\overline{\mathrm{He}}$ may escape registration in AMS.

After AMS announcement of observations of anti-He^4 there appeared theoretical attempts to create anti-He^4 through dark matter (DM) annihilation. It looks quite unnatural and might be at odds with the fluxes of other products of the DM annihilation.

Possible source of high rate of antinuclej production could be antimatter domains with high baryon-to-photon ratio η and/or antistars in the Galaxy, as predicted in [2, 3]. At first sight this suggestion contradicts to the observed high ratio of antideuterium to antihelium. Indeed, the canonical big bang nucleosynthesis with large η predicts negligibly low fraction of (anti)deuterium, see e.g. [42] and references therein. There is noticeable discrepancy between the observed large fraction of anti-D with respect to anti-He. In the case of the standard BBN this ratio should be much smaller than unity, but the observed ratio is practically unity.

However, 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 (anti)BBN may stop before abundant He formation with almost equal abundances of D and He. One can see that looking at abundances of light elements at a function of temperature. In particular, if it is so, antistars would have approximately equal amounts of $\bar{D}$ and $\overline{\mathrm{He}}$, see also the next subsection.

8.3. Anti-Evidence: Antistars in the Galaxy

Bounds on the density of galactic antistars are rather mild, as it has been analysed in several papers [43–45]. The reason for that is that the annihilation proceeds only on the surface of antistars, the objects with very short mean free path of protons. Hence the total energy release is would be quite low and one has to look at a possible antistar with very great attention.

Possibly such an observation is already performed [46]. The authors identified in the catalog 14 antistar candidates not associated with any objects belonging to established gamma-ray source classes and with a spectrum compatible with baryon-antibaryon annihilation.

In [47] a different method to search for antistars is proposed. In astrophysically plausible cases 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 $\mathrm{He}\bar{p}$ 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 L ($3p$–$2p$) 1.73 keV line (yield more than 90%) from $p\bar{p}$ atoms, and M (4–3) 4.86 keV (yield ~60%) and L (3–2) 11.13 keV (yield about 25%) lines from $\mathrm{He}^4\bar{p}$ 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 SRG/eROSITA all-sky survey.

Possible sources of antinuclei in cosmic rays from antistars are discussed in [48]. The expected fluxes and isotopic content of antinuclei in the GeV cosmic rays produced in scenarios involving antistars are estimated. 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.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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