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JWST data and possible interpretation

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Recent data released by James Webb Space Telescope (JWST) and, somewhat earlier, the data presented by Hubble Space Telescope (HST) are commonly understood as a strong indication for breaking of the canonical ΛCDM cosmology. It is argued in the presented work that massive primordial black holes (PBH) could seed galaxy and quasar formation in the very young universe as it has been conjectured in our paper of 1993 and resolve the tension induced by the JWST and the HST data with the standard cosmology. This point of view is presently supported by several recent works. The proposed mechanism of PBH formation leads to the log-normal mass spectrum of PBHs and predicts abundant antimatter population of our Galaxy, Milky Way. Both these predictions are in excellent agreement with astronomical observations.

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1. Introduction

During last decade observations made by Hubble Space Telescope (HST), see e.g. [1–3] and very recently by James Webb Space Telescope (JWST) [4–7] have led to the surprising conclusion that the early universe, younger than one billion years, is densely populated by well developed galaxies, quasars (supermassive black holes), gamma-bursters, and heavy elements (heavier than helium). These striking results were taken by the community as absolutely incompatible with the canonical ΛCDM cosmology, especially after release of the JWST data. In fact already observations of HST could be a sufficient cause for anxiety, not only with respect to the early universe but also to the contemporary very old universe almost 15 billion years old. The troubling situation in the present day universe as well as in the universe with redshifts $z = 6 - 10$ are summarised in review [8]. The state of art is emphatically characterised as crisis in cosmology that is believed to hit strong blow to the conventional ΛCDM picture.

However, the resolution of the above mentioned problems was suggested in our papers [9] (DS) and [10] (DKK). long before these problems arose. In these works a new mechanism of massive primordial black hole (PBH) formation was worked out that could lead to their efficient creation with the masses in the range from a fraction of the solar mass up to billion solar masses.

An essential input of 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 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 $z \sim 10$.

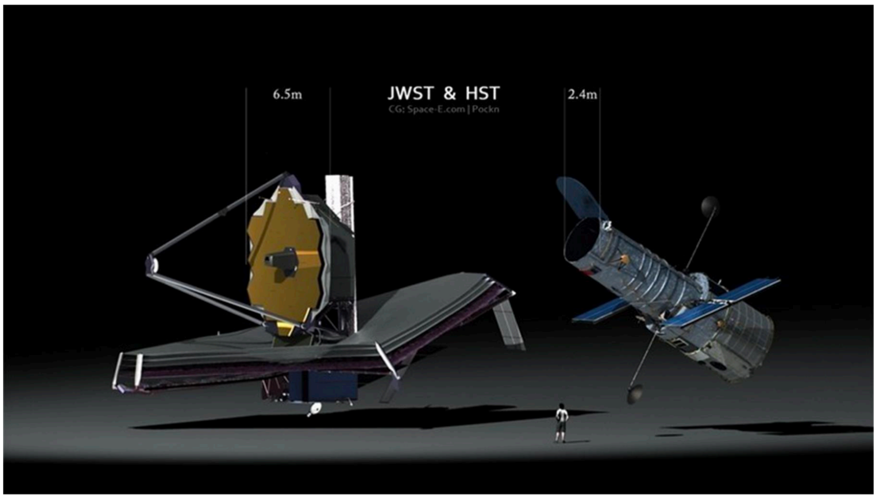
On the opposite, as it was conjectured in refs. [9, 10], supermassive black holes were created first in the early universe at prestellar epoch, that's why they are caller primordial, and later they have SEEDED galaxy formation.

Model DS/DKK is verified by a very good agreement of the calculated log-normal mass spectrum of PBH with observations and by discovery of abundant antimatter population in the Galaxy envisaged according to DS and DKK. The model also predicts an early formation of galaxies, seeded by PBH, quasars (alias SMBH), rich chemistry (heavy elements), and dust in the early universe.

2. A few words about HST and JWST observations

The orbit of HST is at the distance of 570 km from the Earth. The orbit of JWST is much larger, it is about 1.5×10^6 km. The mirror of HST has diameter equal to 2.4 m, while JWST has 2.7 time larger one and correspondingly the area of JWST mirror is approximately 7.4 times larger. In fig. 1 the images of HST and JWST are presented.

HST operates in optical wave length range, for example 450 nm, corresponding to blue light. It has also a possibility to catch the signal in the infrared range with the wave length 0.8-2.5 microns. JWST has high sensitivity to infrared radiation with the wave length 0.6 - 28,5 micron. It allows to penetrate deep into the early universe, up to redshifts $z \sim 15$.



Placing a telescope in space makes it possible to register electromagnetic radiation in the ranges in which the earth's atmosphere is opaque; primarily in the infrared range. Due to the absence of the influence of the atmosphere, the resolution of the telescope is 7-10 times greater than that of a similar telescope located on Earth.

Figure 1

Accidentally HST and JWST observed the same galaxy at $z = 12$, see fig. 2. This coincidence is a strong argument in favour of the reliable operation of these two very different instruments.

Comparison of the JWST data and theoretical expectation of the ΛCDM cosmology is depicted in fig. 3. Theoretical expectations (colored dots at $z = 15$) are noticeably below observations.

3. Spectral measurements and puzzles of the early universe

Only continuum in micron range was measured by JWST till February. That raised justified doubts on accuracy of the redshifts determination of the observed galaxies. Now numerous observations of spectra of different elements excellently confirm the early data. For example according to ref. [11] the JWST NIRCam 9-band near-infrared imaging of the luminous $z = 10.6$ galaxy GN-z11 from the JWST Advanced Deep Extragalactic Survey (JADES) proved that the spectral energy distribution (SED) is entirely consistent with the expected form of the high-redshift galaxy.

In a simultaneous work [12] the spectroscopy of GN-z11, the most luminous candidate $z > 10$ Lyman break galaxy is presented. The nitrogen lines are clearly observed. Quoting the authors: "The spectroscopy confirms that GN-z11 is a remarkable galaxy with extreme properties seen 430 Myr after the Big Bang."

Another example of spectral measurements by a different instrument: age of most distant galaxy is confirmed with Oxygen observation. The radio telescope array ALMA (Atacama Large Millimeter

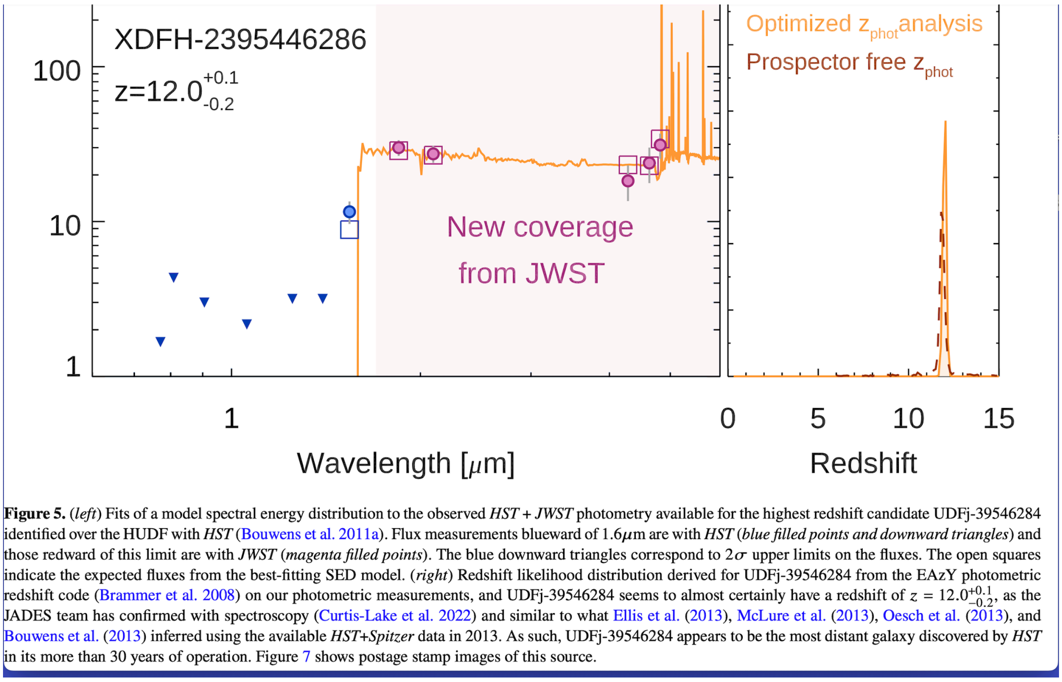


Figure 2: Observation of the same galaxy by HST and JWST

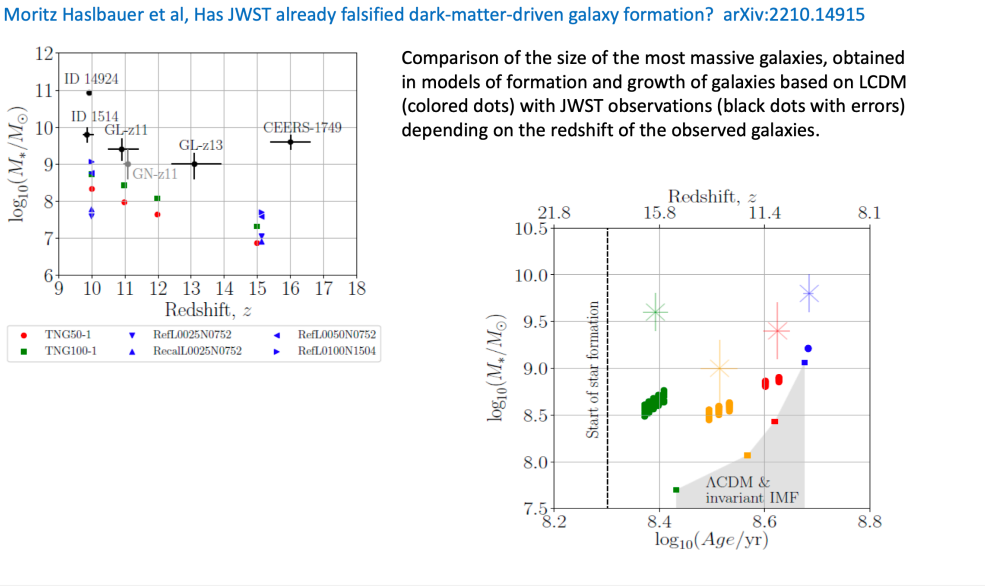
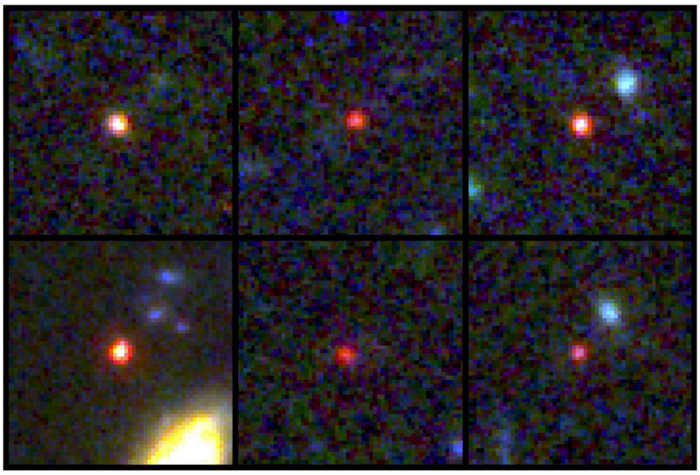


Figure 3: Comparison of JWST data with expectations of ΛCDM cosmology

Array) has pin-pointed the exact cosmic age of a distant JWST-identified galaxy, GHZ2/GLASS-z12, at 367 million years after the Big Bang [13]. The observations of the a spectral emission line emitted by ionized Oxygen near the galaxy, red-shifted according to its age in the early universe, confirms the JWST data. This data show that the JWST is able to look out to record distances and, quoting the authors, **heralds a leap in our ability to understand the formation of the earliest galaxies in the Universe.**

A population of red candidate massive galaxies (stellar mass > 10^{10} solar masses) at $7.4 \lesssim z \lesssim 9.1$, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of $\sim 10^{11} M_\odot$, too massive to be created in so early universe, is observed in [14]. Authors conclude that according to the 'science' it is impossible to create so well developed galaxies. "May be they are supermassive **black holes of the kind never seen before.** That might mean a revision of usual understanding of black holes."



The six candidate galaxies identified in the JWST data. (NASA, ESA, CSA, I. Labbe/Swinburne University of Technology)

Figure 4: Photos of 6 well developed galaxies that could also be black holes of the type never seen before.

Clearly these "black holes of the kind never seen before" nicely fit the assertion that they are primordial, as suggested in refs. [9, 10].

Recent observation by ALMA [15] of an extremely massive reionization-era galaxy with $M_* = 1.7\times10^{11} M_\odot$ at z = 6.853 with active galactic nuclei (AGN) that have huge luminosity suggests that this object is powered by $\sim 1.6 \times 10^9 M_\odot$ black hole if accreting closely to the Eddington limit. It is nearly impossible to create so massive BH in the early universe. But supermassive primordial black hole could easily feed such monster

4. Rich chemistry in the early universe

According to the standard lore, light elements, deuterium, helium, and tiny traces of lithium are created from the primordial protons and neutrons in the early universe roughly during the first 100 seconds. This process is called big bang nucleosynthesis (BBN). Heavier elements, the so called metals (everything heavier than helium-4 are called metals in astrophysics) are created through stellar nucleosynthesis. Next, supernova explosions populate interstellar medium with metals.

Unexpectedly high abundances of heavy elements (high metallicity) are observed in the very early universe by HST and JWST. For example, as reported in ref. [16], a study of a strongly lensed galaxy SPT0418-47, (where the abbreviation SPT means South Pole Telescope and number define the observed galaxy; and the same below) revealed its mature metallicity, amounts of elements heavier than helium and hydrogen, such as carbon, oxygen and nitrogen. According to the estimate of the team the amount is comparable to that of the sun, which is more than 4 billion years old and inherited most of its metals from previous generations of stars that had 8 billion years to build them up. Analysis using optical strong line diagnostics suggests that galaxy SPT0418-SE has near-solar elemental abundance, while the ring appears to have supersolar metallicity O/H and N/O.

One more example of well developed chemistry, that demands too long evolution if produced by the conventional mechanism is presented in ref. [17]. Observations of GN-z11 with JWST/NIRSpec disclosed numerous oxygen, carbon, nitrogen, and helium emission lines at $z = 10.6$. The data prefers (N/O), greater than 4 times solar and the derived $C/O \approx 30$ solar. Nitrogen enhancement in GN-z11 cannot be explained by enrichment from metal-free Population III stars. The suggested explanation is that yields from runaway stellar collisions in a dense stellar cluster or a tidal disruption event provide promising solutions to give rise to these unusual emission lines at $z = 10.6$, and explain the resemblance between GN-z11 and a nitrogen-loud quasar.

High abundances of heavy elements may be a result of BBN with baryon-to-gamma ratio close to unity, as it takes place in the DS [9] and DKK [10] model, see below.

5. Seeding of galaxy formation by PBH

5.1 Seeding of early galaxies

The hypothesis pioneered by DS [9] and DKK [10], that galaxy formation is seeded by SMBH allows to understand the 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. Presently it is rediscovered in several recent works.

As is stated in ref. [18], the recent observations with JWST have identified several bright galaxy candidates at $z \gtrsim 10$, 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 demanding very high star formation efficiency (SFE), possibly even in excess of the cosmic baryon mass budget in collapsed structures. With an idealized analysis based on linear perturbation theory and the Press-Schechter formalism, the observed massive galaxy candidates can be explained, with lower SFE than required in ΛCDM, if structure formation is accelerated by massive ($\gtrsim 10^9$ $M_\odot$) PBHs that enhance primordial density fluctuations.

Observations made by JWST (and HST) of high-redshift quasars reveal that many supermassive black holes were in place less than 700 Million years after the Big Bang. In particular, in ref. [19] the detection of an X-ray-luminous quasar powered by SMBH with the mass $\sim 4 \times 10^7 M_\odot$ in a gravitationally-lensed galaxy, identified by JWST at $z \approx 10.3$, is reported. As is stated by the authors, this mass is comparable to the inferred stellar mass of its host galaxy, in contrast to the usual examples from the local universe where mostly the BH mass is ∼ 0.1% of the host galaxy's stellar mass. The combination of such a high BH mass and large BH-to-galaxy stellar mass ratio ∼ 500 Myrs after the Big Bang is consistent with a picture wherein such BHs originated from heavy seeds. Let stress again, that this detection suggests that early supermassive black holes originate from **heavy seeds.**

However, the origin of the first BHs, that started the seeding, remains a mystery. According to the authors the seeds of the first BHs are postulated to be either light i.e., $(10-100)M_\odot$ remnants of the first stars or heavy i.e., $(10^4-10^5)M_\odot$, originating from direct collapse of gas clouds. The latter hypothesis is questionable, but a supermassive primordial black hole would perfectly work.

In a subsequent paper [20] a support to the heavy seeding channel for the formation of supermassive BHs within the first billion years of cosmic evolution is also proposed. As is mentioned in this work, "the James Webb Space Telescope is now detecting early black holes (BHs) as they originate from seeds to supermassive BHs. Recently Bogdan et al [19] reported 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.

5.2 Seeding of globular clusters and dwarf galaxies

The idea of seeding of globular clusters and dwarf galaxies by primordial black holes was worked out in ref. [21]. Primordial IMBHs with masses of a few thousand solar mass can explain their formation, poorly understood otherwise. In the last several years such IMBHs inside globular clusters are observed. Similar features are true for dwarfs. In particular the seeding of dwarfs by intermediate mass BHs is confirmed by the recent data. For instance in the dwarf galaxy SDSS J1521+1404 the BH is discovered with the mass $M \sim 10^5 M_\odot$ [22]. 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.

Another recent example [23] of intermediate-mass black holes is the finding of episodic, large-scale and powerful jet activity in a dwarf galaxy SDSS J090613.77+561015.2. This can be explained by an intermediate-mass black hole (IMBH) with a mass of $M_{BH} = 3.6^{+5.9}_{-2.3} \times 10^5 M_\odot$, Such huge black hole surely could not be created by accretion but vice versa might seed the formation of the dwarf.

6. Peculiar stars in the Galaxy

6.1 Ancient stars

A discovery of primordial stars in globular cluster M92 [24] was recently announced. The absolute age of the globular cluster M92 was evaluated and found to be practically equal to the universe age, $t_{M92} = 13.8 \pm 0.75$ Gyr. As it is stated in the paper, possibly these stars came to us from JWST epoch or even from the earlier one.

Similar declaration of pristine stars in the Galaxy was made almost at the same time [25]. An international team of researchers, Pristine Inner Galaxy Survey (PIGS) team, has obtained the largest set of detailed observations yet of the oldest stars in the center of our Galaxy, the Milky Way. Some of the stars that were born in the first billion years after the Big Bang are still around today.

In fact, extremely old stars in the Galaxy were discovered considerably earlier. As it is asserted in ref. [26], new more accurate methods of determination of stellar ages led to discovery of surprisingly old stars. Employing thorium and uranium abundances 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. For comparison the age of inner halo of the Galaxy is 11.4 ± 0.7 Gyr [27].

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 [28].

And now, the most surprising star which is older than the Universe. Metal deficient high velocity subgiant in the solar neighborhood HD 140283 has the age 14.46 ± 0.31 Gyr [29]. The determined central value of the age exceeds the universe age by two standard deviations if the Hubble parameter is low, H = 67.3 km/sec/Mpc (according to the CMB analysis) and t_U = 13.8 Gyr, if H = 74 km/sec/Mpc (according to the traditional methods), and t_U = 12.5 Gyr. The age of this star exceeds the universe age more than by 10 σ.

In our model [9, 10] not only primordial black holes could be formed but, if the bubbles with high baryon-to-photon ratio are not sufficiently massive, compact stellar kind objects could be created. Such "stars" might look older than they are because they would be enriched with heavy elements mimicking larger age.

6.2 Fast moving stars

Several stars are discovered in the Galaxy with unusually high velocity much larger than the galactic virial velocity, that is about 200 km/sec (the references to observations of such fast stars are presented just below). There are several very fast pulsars in the Galaxy, but their origin is evident. Pulsars are supposed to be rapidly rotating neutron stars are the results of supenova explosions and a small angular asymmetry in the emitted radiation could create a strong kick, which would accelerate a pulsar up to the velocity of the order of 10^3 km/sec [30, 31]. The observed fast stars look normal, except of very high velocity, about 500 km/sec.

In ref. [32] a a discovery of a low mass white dwarf, LP 40-365, was reported, that travels at a velocity greater than the Galactic escape velocity and whose peculiar atmosphere is dominated by intermediate mass elements. According to the authors these properties suggest that it could be the predicted leftover remains from a type Iax supernova. On the other hand, it can naturally be a primordial star with high initial abundances of heavy elements.

Let us mention several more discoveries of other high velocity stars in the Galaxy [33, 34]. The authors argue that these stars could be accelerated by a population of Iintermediate mass black holes (IMBHs) in Globular clusters, if there is sufficient number of IMBHs. So many IMBHs were not expected but the recent data reveal more and more of them in contrast to conventional expectations and in agreement with refs. [9, 10].

As it is noted in ref. [35] observations of stellar remnants linked to Type Ia and Type Iax supernovae are necessary to fully understand their progenitors and explain the origin of their high speed. Multiple progenitor scenarios predict a population of kicked donor remnants and partially-burnt primary remnants, both moving with relatively high velocity. But only a handful of examples consistent with these two predicted populations have been observed. It is reported in ref. [35] that the likely first known example of an unbound white dwarf that is consistent with being the fully-cooled primary remnant to a Type Iax supernova is LP 93-21. The candidate, LP 93-21, is travelling with a galactocentric velocity of $v_{gal} \approx 605$ km/sec, and is gravitationally unbound to the Milky Way. The authors claim ruling out its extragalactic origin. The Type Iax supernova ejection scenario is consistent with its peculiar unbound trajectory, given the observed anomalous elemental abundances. This discovery reflects recent models that suggest stellar ejections likely occur often.

Let us repeat here that extragalactic primordial star presumably populating the galactic halo, according to assertion of papers [9, 10], very well fits the observations made in ref. [35]

6.3 Stars with unusual chemistry

An unusually red star was observed in planetary system through microlensing event MOA-2011-BLG-291 [36]. The host star and planet masses are estimated as $M_{host} = 0.15^{+027}_{-0.10} M_\odot$ and $m_{planet} = 18^{+34}_{-12} M_\oplus$. The source star that is redder (or brighter) than the bulge main sequence. The favoured interpretation by the authors is that the source star is a lower main sequence star at a distance of 4.9 ± 1.3 kpc in the Galactic disk. According to the authors, the life-time of main sequence star with the solar chemical content is larger than the universe age already for $M < 0.8 M_\odot$. It implies the primordial origin of the registered star with already evolved chemistry.

May it be a primordial helium star? There could be stars dominated by helium, even purely helium stars, in our scenario [9, 10].

7. Pulsar humming

If a pulsar moves in any way, orbiting around a star, the relative motion of the pulsar causes the pulses to shift slightly. These shifts can be measured with extreme accuracy. The observations are so precise, pulsars were used to measure the orbital decay of binary systems as indirect evidence of gravitational waves long before they are observed directly.

Unexpectedly high number of SMBH binaries are presumably observed through distortion of the pulsar timing by emission of gravitational waves [37]. The NANOGrav 15 yr data set shows evidence for the presence of a low-frequency gravitational-wave background. While many physical processes can source such low-frequency gravitational waves, but most natural possibility seems to be that the signal as coming from a population of supermassive black hole (SMBH) binaries distributed throughout the Universe [37].

It is difficult to explain such huge number of SMBH binaries. However, this can be naturally expected if these SMBHs are primordial.

8. Possible types of black holes

8.1 BH classification by mass

There is the following conventional division of black holes by their masses:

1. Supermassive black holes (SMBH): $M = (10^6 - 10^{10}) M_\odot$ (the maximum record mass may

possibly reach $10^{11} M_\odot$ [38]).
2. Intermediate mass black holes (IMBH): $M = (10^2 - 10^5) M_\odot$.
3. Solar mass black holes: masses from a fraction of $M_\odot$ up to $100 M_\odot$.
The origin of most of these BHs is unclear in the traditional approach, except maybe of the BHs with masses of a few solar masses, that might be astrophysical. Highly unexpected was a great abundance of IMBH which are copiously appearing in observations during last few years.

The assumption that (almost) all black holes in the universe are primordial strongly reduce or even eliminate the tension between the data and expected numbers of black holes.

8.2 BH classification by formation mechanism

1. Astrophysical black holes, created by the collapse of a star that 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 $\sim (1-2)M_\odot$ [39, 40] The result is somewhat unexpected but an explanations in the conventional astrophysical frameworks might be possible. Recently LIGO/Virgo/Kagra discovered black holes with masses of several tens solar mass [41, 42] and even one BH with mass close to $100M_\odot$. The astrophysical origin of the latter was considered unfeasible due to huge mass loss in the process of collapse. Now some, quite exotic, formation mechanisms are suggested.

2. BH formed by accretion on the mass excess in the galactic center. In any large galaxy there exists a supermassive BH (SMBH) at the center, with masses varying from several millions of $M_\odot$ (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. At least 10-fold longer time is necessary, to say nothing about SMBH in 10 times younger universe.

3. Primordial black holes (PBHs) created during pre-stellar epoch. The idea of the primordial black hole (PBH) i.e. of black hole which have been formed in the early universe prior to star formation, was first put forward by Ya.B. Zeldovich and I.D. Novikov [43]. According to their arguments, if 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, that decoupled from the cosmological expansion. Subsequently this mechanism was elaborated by S. Hawking [44] and B.Carr and S.Hawking [45]

9. PBH and inflation

In earlier works the predicted masses of PBH were quite low, more or less equal to the mass of the matter inside cosmological horizon at the moment ob PBH formation. Inflation allowed for formation of PBH with very large masses. It was first applied to PBH creation by Dolgov and Silk [9], and a year later by Carr, Hilbert, and Lidsey [46], and soon after that by Ivanov, Naselsky, and Novikov [47].

Presently inflationary mechanism of PBH production is commonly used. It allows to create PBH with very high masses, but the predicted spectrum is multi-parameter one and quite complicated.

The only exception is the log-normal spectrum of refs. [9, 10] which is verified by observations in excellent agreement see below Figs. 6 and 7.

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

where μ is normalisation parameter with dimension of mass. Its value is model dependent and cannot be reliably predicted theoretically. Parameter γ is also theoretically unknown but the observed abundances of black holes in all mass ranges demand it to be of order unity. The central mass value of the distribution, $M_0 \approx 10 M_\odot$, is predicted in our paper [48] and very well agrees with the data.

10. Black Dark Matter

The first suggestion PBH might be dark matter "particles" was made by S. Hawking in 1971 [49] and later by G. Chapline in 1975 [50], who noticed that low mass PBHs might be abundant in the present-day universe and their energy density could be comparable to the energy density of dark matter. In the latter paper the scale independent spectrum of cosmological perturbations was assumed, thus leading to the flat PBH mass spectrum in log interval:

$$dN = N_0(dM/M) \tag{2}$$

with maximum mass $M_{max} \lesssim 10^{22}$ g, which hits the allowed mass range. The next proposal of BH-dominated dark matter was made in ref. [9] that even was contained in the title "Baryon isocurvature fluctuations at small scales and **baryonic dark matter,**" with much larger and more realistic black hole masses, close to $10 M_\odot$.

10.1 Bounds on BH energy density

The constraints on the density of black holes were reviewed by Carr and Kuhnel [51] and the results are presented in Fig. 5 for monochromatic mass spectrum of PBHs.

10.2 Lifting the bounds on the black hole fraction in dark matter

At the beginning of this section it would be proper to quote Bernard Carr's words at 2019 : "all limits are model dependent and have caveats."

There are several papers, where authors looking and finding ways to eliminate or weaken the limits on the number density of black holes.

In ref. [52] it is argued that primordial black holes in the mass range $(30 - 100) M_\odot$ could be the dark matter carriers since they might escape microlensing and cosmic microwave background constraints. They are however subject to the constraints from the binary merger rate observed by the LIGO and Virgo experiments. The authors argue that in realistic situation the masses of black holes in expanding universe depend upon time and this leads to a suppression of binary formation. Hence they conclude that this effect reopens the possibility for dark matter in the form of LIGO-mass PBHs.

In ref. [53] the authors have opened the window for PBH with masses in the range $(10^2 - 10^5) M_\odot$ to make full or significant contribution to cosmological dark matter. They claim that the derivation

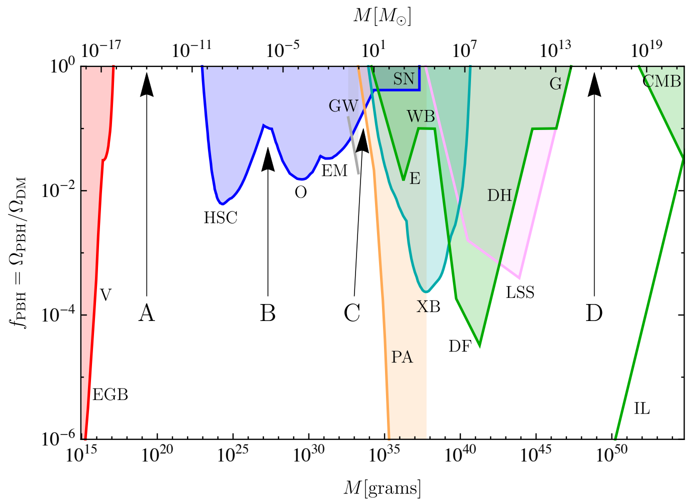


Figure 5: Constraints on $f(M)$ for a monochromatic mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple). Evaporation limits from the extragalactic gamma-ray 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.

of the accepted bound that excluded considerable contribution of PBH in this mass range is based on oversimplified accretion model.

As is argued in ref. [54], PBHs can form clusters. 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 in dark matter can be weaker than that obtained by assuming a homogeneous PBH space distribution.

A recent analysis performed in paper [55] permits to conclude that a possible clustering of PBH could significantly reduce efficiency of the merger process and the final rate of gravitational wave bursts in some parameter range. As a result the fraction of PBH in dark matter could be as large as unity without distortion of LIGO/Virgo observational data.

11. Observations of black holes

A possibility of black hole existence was ingeniously discovered in 1783 by John Michell, an English country parson, famous for many other discoveries in physics. He noticed that there could be stellar bodies having the second cosmic velocity larger than the speed of light. Since such objects neither shine nor reflect light, it would be impossible to observe them directly. Michell called such, not emitting light stars as "dark stars". According to his understanding a single dark star would be invisible, but if a double system of a dark and a usual star is formed, one may identify dark star observing the other one rotating around "nothing". This is one of possible ways to observe black holes at the present time.

However, all that happened to be not absolutely true, or possibly even entirely wrong. BHs evaporate and shine (Hawking radiation [56, 57]), though nobody yet saw it. The most powerful sources of radiation (quasars) are supermassive black holes, point-like objects radiate as thousands galaxies through ultrarelativistic particle collision in the process of matter accretion. Near-solar mass BHs are observed through X-rays from accreting surrounding matter. Black holes may act as gravitational lenses, that's how MACHOs (Massive Astrophysical Compact Halo Objects) and some other BHs are discovered. Observation of the stellar motion around supposed black hole permits to identify the latter as e.g. supermassive black hole in our Galaxy [58] with the mass $M = 4.3 \times 10^6 M_\odot$ was discovered. All these methods only allow to determine the mass inside central volume. According to theory of General Relativity, a huge mass in a small volume must form a black hole. However, strictly speaking BH existence is not proven by all these methods.

The first direct proof of black hole existence was the registration of gravitational waves from a pair of coalescing massive bodies by LIGO/Virgo/Kagra. The data explicitly shows that the the coalescence is indeed between two black holes, because the best fit to the form of the signal is achieved under assumption of the Schwarzschild metric that according to GR describes non-charged and (almost) non-rotating black hole. The observations permit to determine the masses of two coalescing BHs, their spins, and the mass of the final black hole.

12. Gravitational waves from BH binaries

12.1 Are the GW sources primordial BHs?

As it is argued e.g. in paper [59], discovery of gravitational waves (GW) by LIGO interferometer strongly indicates that the sources of GW are primordial black holes. In fact here is general agreement between several groups of theorists, that the gravitational waves discovered by LIGO/Virgo interferometers originated from PBH binaries. We discuss this issue here following our paper [59]. There are three features that indicate that the sources of GWs should most naturally be primordial black holes:

1. Origin of heavy BHs (with masses $\sim 30 M_\odot$). To form so heavy BHs, the progenitors should have $M > 100 M_\odot$ and a low metal abundance to avoid too much mass loss during the evolution. Such heavy stars might be present in young star-forming galaxies but they are not observed in the necessary amount. In fact the fraction of very heavy stars is not well known but there are strong indications that it is indeed very small. According to the classical paper by Salpeter [60] the "original" mass function behave as:

$$\xi(M) = 0.03 \left(\frac{M}{M_\odot}\right)^{-1.35}. \tag{3}$$

But this law remains true only till $M \approx 10 M_\odot$. As shown in Fig. 2 of this paper $\xi(M)$ started to drop much faster at $M > 10 M_\odot$. This statement is confirmed by the analysis performed in ref. [61]. One can see in Fig. 14 of ref. [61] that the Initial Mass Function (IMF) sharply drops down, practically to zero at $M > 30 M_\odot$.

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Recently there emerged much more striking problem because of the observation of BH with $M \sim 100 M_\odot$. Formation of such black holes in the process of stellar collapse was considered to be strictly forbidden according to the standard model of the stellar evolution. The problem is that the progenitor stars with masses from $\sim 150 M_\odot$ up to $\sim 250 M_\odot$ undergo the so called pair-instability [62, 63], i.e. efficient production of e^+e^- pairs that reduces internal pressure so the gravity would overcome it. As a result no black holes could be formed directly from stellar evolution in the range of masses $50 M_\odot$ to $150 M_\odot$. For a review see [64]. The bounds presented here are not strict but anyhow formation very heavy black holes in the course of the stellar evolution is noticeably suppressed.

On the other hand, primordial black holes with the observed by LIGO masses may be easily created with sufficient density.

2. Formation of BH binaries from the original stellar binaries. Stellar binaries are formed from common interstellar gas clouds and are quite frequent in galaxies. If BH is created through stellar collapse, a small non-sphericity would result in a huge velocity of the BH and the binary would be destroyed. BH formation from PopIII stars and subsequent formation of BH binaries with tens of $M_\odot$ is estimated to be small. The problem of the binary formation is simply solved if the observed sources of GWs are the binaries of primordial black holes. They were at rest in the comoving volume, and when inside the cosmological horizon they were gravitationally attracted and might loose energy due to dynamical friction or interaction with third body in the early universe. The probability for them to become gravitationally bound is probably high enough, see e.g. [65] The conventional astrophysical scenario is not excluded but less natural.

3. Low spins of the coalescing BHs. The low values of the BH spins has been observed in GW150914 [66] and in almost all (except for three) other events. It strongly constrains astrophysical BH formation from close binary systems. Astrophysical BHs are expected to have considerable angular momentum, nevertheless the dynamical formation of double massive low-spin BHs in dense stellar clusters is not excluded, though difficult. On the other hand, PBH practically do not rotate, because vorticity perturbations in the early universe are vanishingly small. Still, individual PBH forming a binary initially rotating on elliptic orbit could gain collinear spins about 0.1 - 0.3, rising with the PBH masses and eccentricity [67, 68]. This result is in agreement with the GW170729 LIGO [66] event produced by the binary with masses $50 M_\odot$ and $30 M_\odot$ and GW190521 [69] where the merger of two black holes with masses of $85^{+21}_{-14} M_\odot$ and $66^{+17}_{-19} M_\odot$ was registered, creating black hole with the mass $142^{+28}_{-16} M_\odot$.

To summarise: each of the mentioned problems might be solved in the conventional frameworks but it looks much simpler to assume that the LIGO/Virgo/Kagra sources are primordial black holes.

12.2 Chirp mass distribution

It is well known that two rotating gravitationally bound massive bodies emit gravitational waves. In quasi-stationary inspiral regime, the radius of the orbit and the rotation frequency are approximately constant, to be more exact, slowly decreasing, and the GW frequency is twice the rotation frequency. The luminosity of the GW radiation in inspiral regime is:

$$L = \frac{32}{5}\, m_{Pl}^2 \left(\frac{M_c\, \omega_{orb}}{m_{Pl}^2} \right)^{10/3}, \tag{4}$$

where M_1, M_2 are the masses of two bodies in the binary system and M_c is the so called chirp mass:

$$M_c = \frac{(M_1\, M_2)^{3/5}}{(M_1 + M_2)^{1/5}}\,, \tag{5}$$

and

$$\omega_{orb}^2 = \frac{M_1 + M_2}{m_{Pl}^2 R^3}\,. \tag{6}$$

In ref. [70] the available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum (1). The results are presented in Fig. 6. The inferred best-fit mass spectrum parameters, $M_0 = 17 M_\odot$ 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, see Fig. 7. Similar value of the parameters are obtained in refs. [71, 72], see also [73].

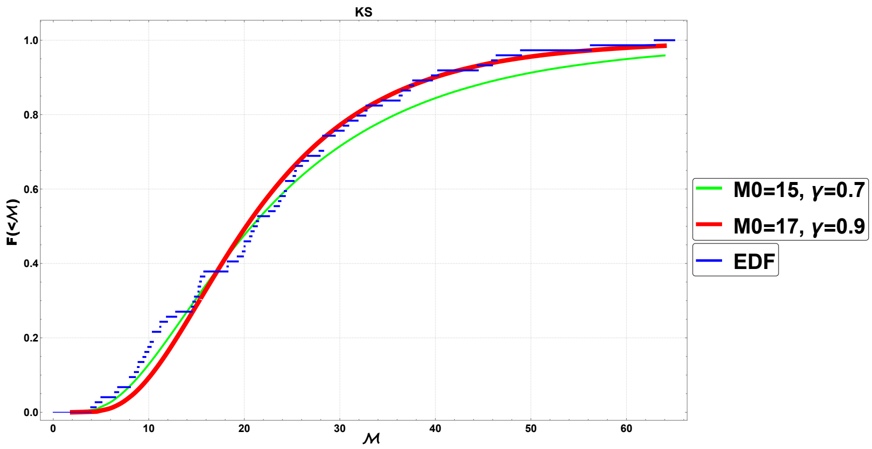

Figure 6: Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.

So looking at the figure we may conclude that PBHs with log-normal mass spectrum perfectly fit the data. At this stage rigorous statistical analysis does not make much sense. Anyhow astrophysical black holes seem to be disfavoured.

A new analysis of the Ligo-Virgo-Kagra data was performed recently in ref. [73]. The authors concluded that the chirp-mass distribution of LVK GWTC-3 BH+BH binaries with distinct two bumps can be explained by two different populations of BH+BH binaries:
1) the low-mass bump at $M_0 \sim 10 M_\odot$ due to the astrophysical BH+BH formed in the local Universe from the evolution of massive binaries
2) the PBH binaries with log-normal mass spectrum with $M_0 \simeq 10 M_\odot$ and $\gamma \simeq 10$. The central mass of the PBH distribution is larger than the expected PBH mass at the QCD phase transition ($\sim 8 M_\odot$) but still can be accommodated with the mass of the cosmological horizon provided that the temperature $T_{QCD} \sim 70$ MeV, possible for non-zero chemical potential at the QCD phase transition from the quark-gluon phase to the hadron phase in the early universe.

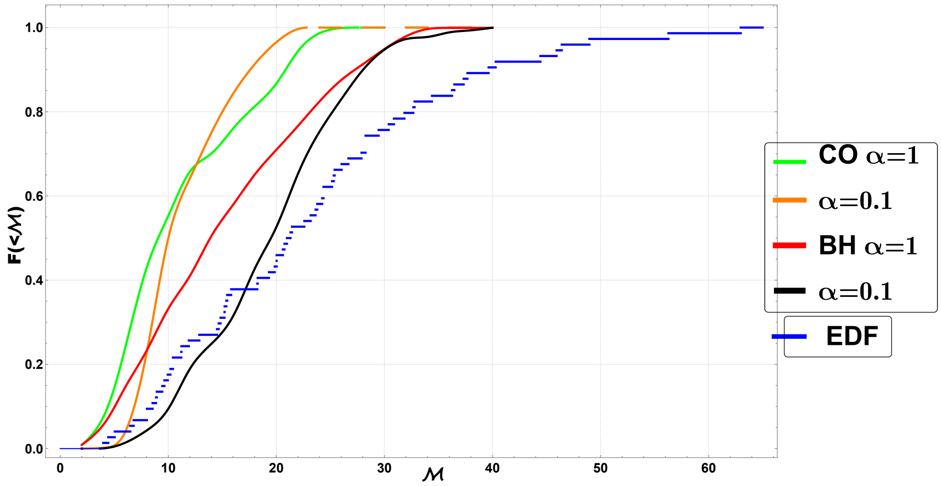

Figure 7: Cumulative distributions $F(< M)$ for several astrophysical models of binary BH coalescences.

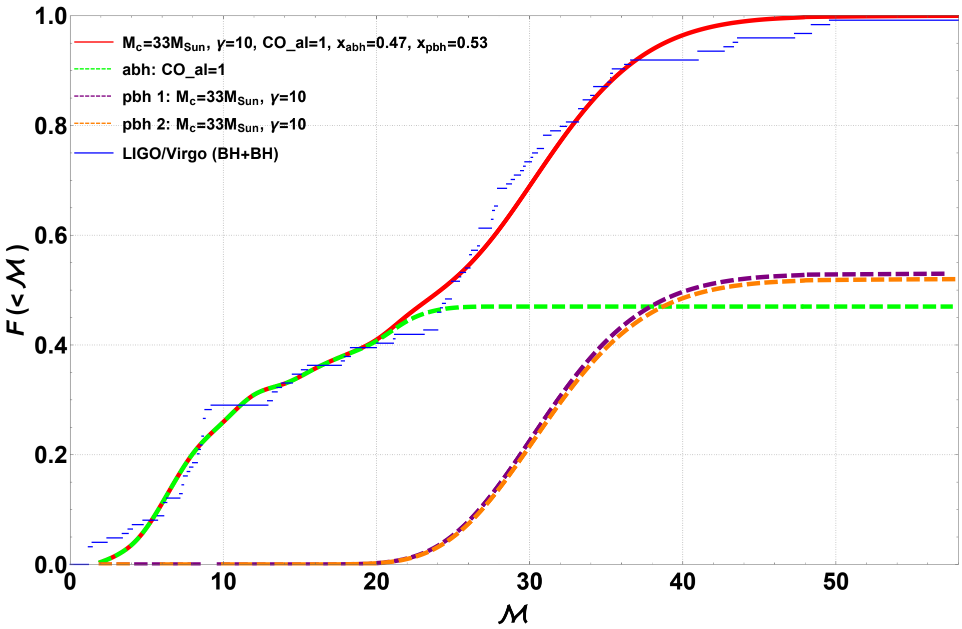

Figure 8: The observed (blue step-like curve) and model (red solid curve) distribution function of the chirp-masses of coalescing binary BHs from the LVK GWTC-3 catalogue. The model includes almost equal contributions from coalescences of astrophysical binary BHs (green dashed curve) and primordial BHs with the initial log-normal mass spectrum with parameters $M_0 = 33M_\odot$, $\gamma = 10$, with such γ heavier PBH practically are not created.

13. Cosmic antimatter

13.1 Anti-history

The father of antimatter is justly admitted to be Paul Dirac. In his Nobel Lecture at December 12, 1933 “Theory of electrons and positrons”, dedicated to his prediction of positrons, he foresaw 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.”

Now we expect that there may be some presumably small fraction of antistars in the Galaxy. Since they are immersed into interstellar gas consisting of matter, they can be detected due to excess of gamma radiation with energy of a several hundred MeV, originating from annihilation of the interstellar gas on the surface of antistar.

Situation is different if an antistar "lives" in a distant antigalaxy. Still it is possible in principle to distinguish a star from an antistar through rather subtle effects considered in ref. [74]. First of all the spectra of the emitted radiation are not exactly the same, even if CPT is unbroken and the polarisation of radiation from weak decays could be a good indicator and lastly the types of emitted neutrinos versus antineutrinos from supernovae or antisupernovae.

It is in fact surprising that Dirac was not the first person to talk about antimatter. 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, indistinguishable from ours. Schuster made fantastic wild guess that matter and antimatter are capable to annihilate and produce vast energy.

Schuster believed that they were gravitationally repulsive having negative mass. Two such objects on close contact should have vanishing mass!?

Quoting his paper [75]: “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".

According to the classical scenario of the generation of the cosmological baryon asymmetry, proposed by A.D. Sakharov [76] , the baryon excess in the universe is on the average homogeneous, having the same sign determined by the sign of symmetry breaking between particles and antiparticles. However, there are plenty of mechanisms leading to space varying amplitude of C and CP violations with possible sigh changing. If this is the case, the sign of baryon asymmetry could also be different leading to formation of matter and antimatter domains in the universe. Possible models of C and CP violation in cosmology that possess this property are reviewed in [77].

13.2 Matter and antimatter in the Universe

To the best of my knowledge the first papers on cosmological antimatter were published by F. Stecker in 1971 [78], independently on the three year earlier papers by Konstantinov et al [79, 80] on search of antimatter in the Galaxy, see below subsection 13.3. Further development of the idea of matter-antimatter domain structure of the universe was presented in ref. [81].

The analysis, performed in ref. [82], permits to conclude that matter–antimatter symmetric universe or close to that, is excluded by the observed cosmic diffuse gamma-ray background and a distortion of the cosmic microwave background.

However, there still remains some space for the fraction of cosmological antimatter, but considerably restricted. It is argued by G. Steigman in ref. [83] that the nearest anti-galaxy should be out of our galaxy cluster and thus could not be closer than at $\sim$ 10 Mpc. In a subsequent paper by the same author [84] it is argued that the fraction of antimatter in Bullet Cluster should be below 3×10^{-6}.

Summary of the situation of the year 2002 was presented in two keynote lectures at 14th Rencontres de Blois on Matter - Anti-matter Asymmetry [85, 86].

13.3 Antimatter in Milky Way

The search of antimatter in the Milky Way was intiated by Konstantinov with coworkers in 1968 [79, 80]. This activity was strongly criticised by Ya.B. Zeldovich despite very friendly relations between the two. In agreement with canonic faith no antimatter may exist in our Galaxy and that explains negative attitude of Zeldovich to Konstantinov activity. Until recently there was no reason to suspect that any noticeable amount of antimatter might be in the Galaxy. The predictions of refs. [9, 10] were not taken seriously. Now there are a lot of data indicating that Milky Way contains siginificant 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 predictions of papers [9, 10] antimatter objects could be not only in the Galaxy but in its halo as well.

According to ref. [87], the analysis of the intensity of gamma rays created by the Bondi accretion of interstellar gas to the surface of an antistar would allows to put a limit on the relative density of antistars in the Solar neighbourhood: $N_{\bar{*}}/N_* < 4 \cdot 10^{-5}$ inside 150 pc from the Sun.

The bounds on galactic antimatter are analysed in refs. [88–90]. The limits on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars, i.e on the objects with short mean free path of protons, so the extra luminosity created by matter-antimatter annihilation is relatively low.

Anti-evidence: cosmic positrons.
Existence of rich populations of positrons in the Galaxy was noticed long ago through the observations of 511 keV gamma ray line (see [91–93] and references therein) with the flux

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

According to refs. [92, 93] the width of the line is about 3 keV. The emission mostly goes from the Galactic bulge and at much lower level from the disk.This unambiguously indicates the frequent annihilation of nonrelativistic e^+e^- pairs in the Galactic bulge with the rate [91]

$$\dot{N}_{ee}^{\mathrm{bulge}} \sim 10^{43}\ \mathrm{s}^{-1}. \tag{8}$$

Note that one of the brightest X-ray sources in the region around the Galactic Center got the name Great Annihilator [94]. Possibly it is a microquasar first detected in soft X-rays by the Einstein Observatory [95] and later detected in hard X-rays by the space observatory “Granat” [96].

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 [97]. However, this conclusion is questioned in ref. [98] where it is shown that these features could be consistently explained by a nearby source which was active ~ 2 Myr ago and has injected $(1-2)\times 10^{50}$ 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 . This mechanism was suggested in ref. [99] and discussed in more detail in ref. [100].

One more possibility that is closer to the spirit of this talk is that positrons are primordial, produced in the early universe in relatively small antimatter domains [9, 10]. Possible observation of the unexpectedly high flux of antinuclei [101, 102] and antistars in the Galaxy [103] strongly supports this hypothesis, in particular, by ref. [104], where it is advocated that antihelium cosmic rays are created by antistars.

Anti-evidence: cosmic antinuclei.

In 2018 AMS-02 announced possible observation of six $\overline{He}^3$ and two $\overline{He}^4$ [105, 106]. Accumulated by 2022 data contains some more events: 7 $\overline{D}$ (at energies $\lesssim 15$ GeV) and 9 $\overline{He}^4$ at ($E\sim 50$ GeV). These numbers correspond roughly speaking to $\overline{He}/He \sim 10^{-9}$. This number is much larger than the expected number of $\overline{He}^4$, 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 $\overline{He}$ may escape registration in AMS.

The probability of the secondary creation of different antinuclei was estimated in ref. [107]. According to this work, anti-deuterium could be most efficiently produced in the collisions $\bar p\, p$ or $\bar p\, He$ that can create the flux $\sim 10^{-7}/m^2/s^{-1}$/steradian/GeV/neutron), i.e. 5 orders of magnitude below the observed flux of antiprotons. Antihelium could be created in the similar reactions and the fluxes of $\overline{He}^3$ and $\overline{He}^4$, 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 [9, 10], 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 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 $\overline{He}^3$ to $\overline{He}^4$, that is also of order unity instead of the standard $\sim 3\times 10^{-5}$.

If we assume that in the model of [9, 10] the abundances of anti-D and anti-He are determined by normal BBN with large baryon-to-photon ratio $\beta \sim 1$, the problem would be even more pronounced, because amount of deuterium and helium-3 would be negligibly small, even much less than 10^{-5}. The primordial elements production in the process of big bang nucleosynthesis with large β has been studied in refs. [108–110]. It is shown there that elements much heavier than lithium might be produced up to iron, but it is impossible to create antideuterium in comparable amount to antihelium-4, as is observed by AMS. The same problem is even more pronounced for the high ratio of antihelium-3 to antihelium-4.

On the other hand in our scenario 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 abundances of light elements at a function of temperature. If it is so, antistars may have equal amount of $\overline{D}$ and $\overline{He}$

Anti-evidence: antistars in the Galaxy.

A striking announcement of the possible discovery of anti-stars in the Galaxy was made in ref. [111] The catalog 14 antistar candidates was identifyed, not associated with any objects belonging to established gamma-ray source classes and with a spectrum compatible with baryon-antibaryon annihilation. Their results are illustrated in Fig. 9.

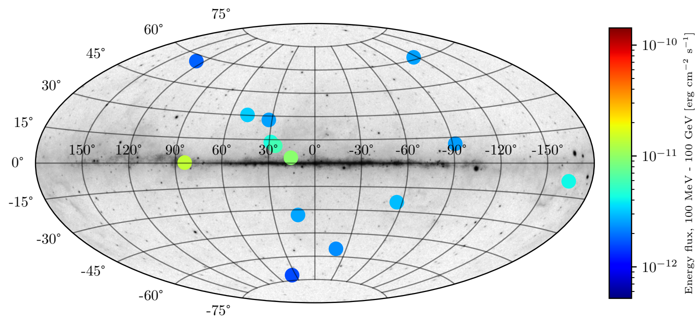

Figure 9: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV. Taken from ref. [111].

In ref. [112] a supplimentary method of antistar identification was 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 $He\bar{p}$ 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 $He^4\bar{p}$ 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.

Connection between antistars and the observed fluxes of antinuclei was studied in recent paper [104]. A minor population of antistars in galaxies has been predicted by some of 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 baryogenesis scenarios in the early Universe.

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.

14. Mechanism of creation of PBH and antimatter

The mechanism of PBH and galactic antimatter creation [9, 10] is essentially based on the scenario of supersymmetry (SUSY) motivated baryogenesis, proposed by Affleck and Dine (AD) [113]. SUSY generically predicts existence of scalars, χ, with non-zero baryonic number, $B \neq 0$. Another prediction of high energy SUSY models is an existence of flat directions in the χ-potential, either quartic (self-interaction):

$$U_\lambda(\chi) = \lambda|\chi|^4 \left(1 - \cos 4\theta\right) \tag{9}$$

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

$$U_m(\chi) = m^2|\chi|^2| \left(1 - \cos(2\theta + 2\alpha)\right] , \tag{10}$$

where $\chi = |\chi| \exp(i\theta)$ and $m = |m|e^{\alpha}$. If $\alpha \neq 0$, C and CP are broken. Potential energy does not rise along these flat directions.

At the inflationary epoch the average value of χ^2 linearly rises with time [114–116] see also [117]. In other words, χ bosons may condense along flat directions of the quartic potential, when and if its mass was smaller than the inflationary Hubble parameter.

In GUT SUSY baryonic number is naturally non-conserved, because of generic non-invariance of $U(\chi)$ w.r.t. phase rotation $\chi \to \chi \exp(i\theta)$.

After inflation χ was far away from origin due to rising quantum fluctuations and, when inflation ends, it started to evolve down to the equilibrium point, $\chi = 0$, according to equation of motion that formally coincides with the equation of motion of a point-like particle in Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0. \tag{11}$$

The baryonic number of χ:

$$B_\chi = \dot{\theta}|\chi|^2 \tag{12}$$

is analogous to mechanical angular momentum in complex plane $[Re\chi, Im\chi]$. After χ decays, the accumulated baryonic number of χ is transferred into baryonic number of quarks in B-conserving process. AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed asymmetry $\sim 10^{-9}$.

If $m \neq 0$ and the flat direction of quadratic and quartic valleys are different, the angular momentum, B, would be generated by the "rotation" induced by the motion of χ from quartic flat direction to the quadratic one. In other words, the field χ would acquire non-zero baryonic number, generically very large .

If CP-odd phase α is non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of either of them. Matter and antimatter objects may exist but possibly global $B \neq 0$.

An essential development proposed in works [9, 10] was an introduction of the new interaction between the Affleck-Dine field and the inflaton Φ, the first term in the equation below:

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right) + \lambda_1(\chi^4 + h.c.) + (m^2\chi^2 + h.c.). \tag{13}$$

This coupling between χ and the inflaton is the general renormalizable interaction of two scalar field. The only tuning is the assumption that Φ reaches the value Φ_1 during inflation significantly before it ends, with the remaining number of e-foldings about 30-40.

The window to the flat directions is open, near $\Phi = \Phi_1$. At that period the field χ could rise to large values, according to the quantum diffusion equation derived by Starobinsky, generalised to a complex field χ.

If the window to flat direction, when $\Phi \approx \Phi_1$ is open only during a short period, cosmologically small but possibly astronomically large bubbles with high baryon-to-photon ratio β could be created, occupying a tiny fraction of the total universe volume, while the rest of the universe has the observed $\beta \approx 6 \cdot 10^{-10}$, created by the normal small χ. The fundament of PBH creation has been build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations.

The initial isocurvature perturbations are contained in large baryonic number of massless quarks in rather small bubbles. We call them high baryonic bubbles, HBBs. Density perturbations were generated rather late after QCD phase transition, at temperatures around 100 MeV, when massless quarks turned into massive baryons. The resulting high density contrast could lead to creation of PBHs. The mechanism is very much different from any other described in the literature models of PBH formation.

The emerging universe looks like a piece of Swiss cheese, where holes are high baryonic density objects occupying a minor fraction of the universe volume.

Outcome of the DS/DKK mechanism:

- 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 n_B density.
- 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, "older than universe star" is found; its prehistoric age is mimicked by the unusual initial chemistry.

The mechanism of PBH creation pretty well verified by the data on the BH mass spectrum and on existence of antimatter in the Galaxy, especially of antistars. So we may expect that it indeed solves the problems created by HST and JWST.

Thus we may conclude that canonical ΛCDM cosmology is saved by PBHs. Antimatter in our backyard is found according to thirty year old prediction.

Acknowledgement

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