Black Dark Matter and Antimatter

A.D. Dolgov

Novosibirsk State University
Novosibirsk, Russia
BLTP, JINR, Dubna. Russia

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Content/outline

Black Dark Matter, what's that?
Observations of black holes
Black hole types
Primordial black holes (PBH) and inflation
Log-normal mass spectrum of PBHs.
Gravitational waves and PBH.
Crisis in cosmology and PBH **seeding** of cosmic structures
Cosmological problems of the contemporary universe.
PBH solution of new and old problems
Antimatter in the Milky Way: positrons, antinuclei, and antistars

Two striking predictions confirmed by the recent discoveries:
Log-normal spectrum of PBH.
Abundant antimatter in our Galaxy.

Types of Dark Matter

The nature of dark matter (DM) is not yet known.
Two large classes: WIMPs and MACHOs.

WIMPS = Weakly Interactive Massive Particles:
Elementary particles, different interaction strength with visible matter (e.g. heavy leptons or sterile neutrinos) self-interacting DM, mirror DM, etc
with masses from $\sim 10^{-22}$ eV (axion-like particles)
up to 10^{13} GeV (see today's talk by E. Arbuzova).

MACHOs = Massive Astrophysical Compact Halo Objects, most probably primordial **black** holes (PBHs), topological or non-topological solitons, ...?
Public opinion pool: overwhelming majority for WIMPs.
Mildly heretic point of view: DM = primordial black holes (PBHs)
Eclectic: **all forms of DM with comparable densities: WIMPS (maybe several kinds), MACHOc, etc...**
In this talk: DM consisting fully of black holes, **Black Dark Matter**.

Black Dark Matter

The first suggestion PBH might be dark matter "particles" was made by S. Hawking in 1971 "Gravitationally collapsed objects of very low mass Mon. Not. Roy. Astr. Soc. (1971) 152, 75

and later by G. Chapline in 1975 who noticed that low mass PBHs might be abundant in the present-day universe with the density comparable to the density of dark matter. G.F. Chapline, Nature, 253, 251 (1975) "Cosmological effects of primordial black holes". Assumed flat mass spectrum in log interval:

$$dN = N_0 (dM/M)$$

with maximum mass $M_{max} \lesssim 10^{22}$ g, which hits the allowed mass range.

Black Dark Matter

More realistic model leading to black dark matter, tested by ”experiment”:

A. Dolgov, J.Silk (DS), PRD 47 (1993) 4244, "Baryon isocurvature fluctuations at small scale and baryonic dark matter.

A. Dolgov, M. Kawasaki, N. Kevlishvili (DKK), Nucl. Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter". with more realistic masses, **first paper with inflation applied to PBH formation, so PBH masses as high as $10^6 M_\odot$, and even higher can be created.** **Log-normal mass spectrum was predicted that very well agrees with observational data.** The only known mass spectrum of PBH tested by observations without adjustment of theoretically predicted parameters (see below).

Black Dark Matter, constraints

Constraints on PBHs - B.Carr, F. Kuhnel "Primordial Black Holes as Dark Matter: Recent Developments", arXiv:2006.02838, June 2020
"Primordial black holes as dark matter candidates", B. Carr, F. Kuhnel SciPost Phys.Lect.Notes 48 (2022), e-Print: 2110.02821 [astro-ph.CO]
For monochromatic mass spectrum of PBHs (caution, model-dependent).

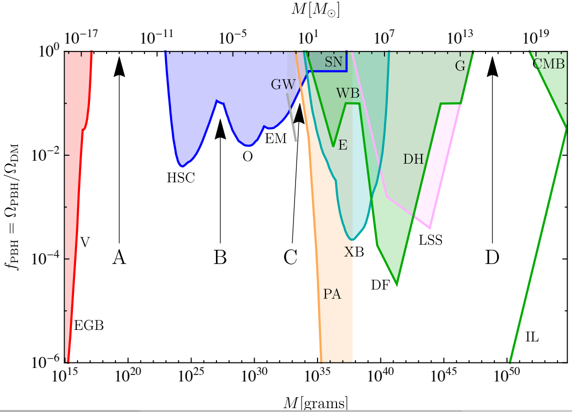


Figure caption

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.

Black Dark Matter

Carr, 2019: all limits are model dependent and have caveats.

Eliminating the LIGO bounds on primordial black hole dark matter,
C. Boehm, et al arXiv:2008.10743 .... reopens the possibility for dark matter in the form of LIGO-mass PBHs.
C. Corianò, P.H. Frampton, arXiv:2012.13821 [astro-ph.GA]
Does CMB Distortion Disfavour Intermediate Mass Dark Matter?
The most questionable step in this chain of arguments is the use of overly simplified accretion models. We compare how the same accretion models apply to X-ray observations from supermassive black holes SMBHs, M87 and Sgr A^*. The comparison of these two SMBHs with **intermediate mass MACHOs suggests that the latter could, after all, provide a significant constituent of all the dark matter.**

BH clustering and DM

As is argued by S.G. Rubin, at al in "The Formation of Primary Galactic Nuclei during Phase Transitions in the Early Universe", Soviet Journal of Experimental and Theoretical Physics. 2001, V. 92, no. 6. 921. arXiv:hep-ph/0106187 PBHs can be formed in 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 f_{PBH} obtained by assuming a homogeneous PBH space distribution can be weaker.

A recent analysis by Y. Eroshenko, V. Stasenko, "Gravitational waves from the merger of two primordial black hole clusters" arXiv:2302.05167 based on the PBH formation model M. Sasaki et al "Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914", PRL. 2016. V. 117, no. 6. P. 061101, arXiv:1603.08338 and T. Nakamura, et al "Gravitational Waves from Coalescing Black Hole MACHO Binaries", ApJL 1997, V. 487, no. 2, P. L139, arXiv:astro-ph/9708060 shows that even $f_{PBH} = 0.1 - 1$ is not excluded.

Observations of black holes

A prediction of black hole existence was done 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 days.

Observations of black holes

Nowadays many other methods are invented to observe possible black holes.

BHs evaporate and shine (Hawking radiation), though nobody yet saw it.
Near-solar mass BHs are observed by X-rays from the accreting matter.
Gravitational lensing by BH, e.g. that's how MACHOs are spotted.
Mass estimates from the stellar motion around supposed BH as e.g. in our Galaxy.
The most powerful sources of radiation, quasars (QSO), are supermassive black holes, that radiate as thousands galaxies, $\boldsymbol{L_{QSO}} = 10^{46} - 10^{47}$ erg/sec, i.e. $10^{13} L_\odot$, though they are practically point-like, their size is about $10^9 - 10^{10}$ km, smaller than the Solar System. The only known mechanism of QSO radiation is the process of ultrarelativistic particle collision in the process of matter accretion. QSOs shine until they consume all "food"around and remains almost in desert. After that the shining fades out e.g. BH in the center of our Galaxy.
All these methods only allow to determine the mass inside central volume.
According to General Ralativity there must be a BH inside.
However, strictly speaking BH existence is not proven.

Rigorous proof of BH existence.

Registration of gravitational waves (GWs) from a pair of coalescing BHs by LIGO/Virgo/Kagra.

The data directly shows that indeed colliding **black holes** emit GWs.
This is the first direct observation of the Schwarzschild metric that according to GR describes non-charged, (almost) non-rotating BH.
The observations permit to determine the masses of two coalescing BHs, the mass of the final one and their spins.

General relativity and BHs

After creation of GR (Einstein, 1915) almost immediately exact solutions of GR equations describing all possible types of BHs have been found.
BHs may have only three types of "hairs" that may be observed in external space:
gravitational created by mass, M,
electric created by charge Q,
rotational, created by spin J.

Schwarzschild (1916), BH with $Q = J = 0$.
Reissner-Nordström (1916, 1918) $J = 0,\ Q \neq 0$.
Kerr, (1963), $Q = 0, J \neq 0$,
Kerr–Newman (1965) $J \neq 0$, $Q \neq 0$.

If photon mass is non-zero, no matter how tiny, electric field of BH would completely vanish. No continuous limit to $m_\gamma = 0$.
An observation of a charged BH would present the absolute upper bound on m_γ.

BH types by formation mechanisms

1. Astrophysical black holes,
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 $3\boldsymbol{M_\odot}$, but noticeably below $100M_\odot$. Instead we observe that the BH mass spectrum in the galaxy has maximum at $\boldsymbol{M} \approx 8\boldsymbol{M_\odot}$ with the width $\sim (1-2)\boldsymbol{M_\odot}$. 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 collapce.** Now some, quite exotic, formation mechanisms are specially invented.

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 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, $\boldsymbol{t_U} \approx 14.6$ Gyr. At least 10-fold longer time is necessary,** to say nothing about SMBH in 10 times younger universe.

BH types by formation mechanisms

3. Primordial black holes (PBH) created during pre-stellar epoch

The idea of the primordial black hole (PBH) i.e. of black holes which could be formed the early universe prior to star formation was first put forward by Zeldovich and Novikov: "The Hypothesis of Cores Retarded During Expansion and the Hot Cosmological Model Astronomicheskij Zhurnal, 43 (1966) 758, Soviet Astronomy, AJ.10(4):602–603;(1967).

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, $\delta\varrho/\varrho \approx 1$, then that piece of volume would be inside its gravitational radius i.e. it became a PBH, decoupled from the cosmological expansion.

Elaborated later in S. Hawking, "Gravitationally collapsed objects of **very low mass",** Mon. Not. Roy. Astron. Soc. **152**, 75 (1971).

B. J. Carr and S. W. Hawking, "Black holes in the early Universe," Mon. Not. Roy. Astron. Soc. **168**, 399 (1974).

BH types by masses

There is the following conventional division of black holes by their masses:
1. Supermassive black holes (SMBH): $M = (10^6 - 10^{10}) M_\odot$.
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 conventional approach, except maybe of the BHs with masses of a few solar masses, that might be astrophysical.
Highly unexpected was great abundance of IMBH which are appearing in observations during last few years in huge numbers.
The suggestion that (almost) all black holes in the universe are primordial strongly reduce or even eliminate the tension.
However, in earlier works the predicted masses of PBH were quite low.

PBH and inflation

Inflation allows for formation of PBH with very large masses.
It was first applied to PBH production in DS paper, a year later in: B.J. Carr, J.H. Hilbert, J.E. Lidsey, "Black hole relics and inflation: Limits on blue perturbation spectra'', Phys.Rev.D 50 (1994) 4853, astro-ph/9405027;
and soon after in P. Ivanov, P. Naselsky, I. Novikov (May 10, 1994), ''Inflation and primordial black holes as dark matter'', PRD 50 (1994) 7173.
Presently inflationary mechanism of PBH production is commonly used. It allows to create PBH with very high masses, but almost always the calculated mass spectrum is multi-parameter one and quite complicated.
The only exception is the log-normal mass spectrum predicted by DS and DKK tested by LiGO/Virgo/Kagra with very good agreement:

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

$M_0 \sim 10 M_\odot$, is predicted, A.Dolgov, K.Postnov, "Why the mean mass of primordial black hole distribution is close to $10 M_\odot$". JCAP 07 (2020) 063.
The horizon mass at QCD p.t. is close to $10 M_\odot$, for $\mu = 0$. At larger chemical potential the T_{pt} is smaller and M_{hor} is somewhat larger.

Gravitational waves from BH binaries

• GW discovery by LIGO strongly indicate that the sources of GW are PBHs, see e.g. S.Blinnkov, A.D., N.Porayko, K.Postnov, JCAP 1611 (2016), 036 "Solving puzzles of GW150914 by primordial black holes," as well as several other papers.
1. Origin of heavy BHs ($\sim 30M_\odot$); there appeared much more striking problem of BH with $M \sim 100M_\odot$. See however, J. Ziegler, K. Freese, arXiv:2010.00254: DM annihilation inside stars
2. Formation of BH binaries from the original stellar binaries.
3. Low spins of the coalescing BHs .

To form so heavy BHs, the progenitors should have $M \gtrsim 100M_\odot$. 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. PBHs with the observed by LIGO masses may be easily created with sufficient density.

GWs from BH binaries, chirp mass distribution

Two rotating gravitationally bound massive bodies are known to emit gravitational waves. In quasi-stationary inspiral regime, the radius of the orbit and the rotation frequency are approximately constant and the GW frequency is twice the rotation frequency. The luminosity of the GW radiation is:

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

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

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

and

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

GWs from BH binaries, chirp mass distribution

A.D. Dolgov, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, I.V. Simkine On mass distribution of coalescing black holes, JCAP 12 (2020) 017, e-Print: 2005.00892.

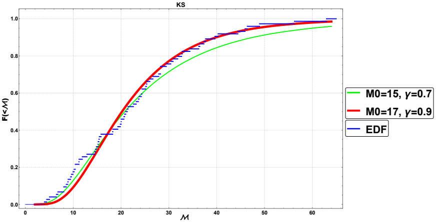
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

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.

GWs from BH binaries, chirp mass distribution

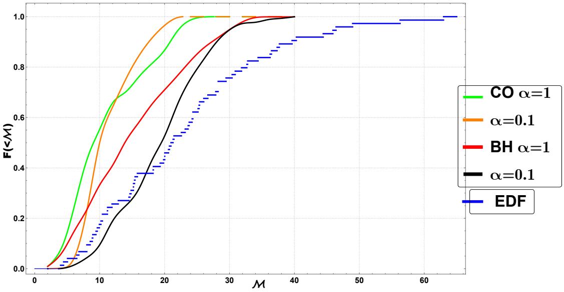
Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



Similar value of the parameters are obtained in M. Raidal et al, JCAP.,2019. Feb. V. 2019, no. 2. P. 018. arXiv:1812.01930 and L. Liu, et al arXiv:2210.16094.
See also K. Postnov and N. Mitichkin, e-Print: 2302.06981. Eto drugoe???

GWs from BH binaries, chirp mass distribution

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



Conclusion: PBHs with log-normal mass spectrum perfectly fit the data. Astrophysical BHs seem to be disfavoured.

Analysis of recent Ligo-Virgo-Kagra (LVK) data

A new analysis of the Ligo-Virgo-Kagra data was performed recently by K. Postnov and N. Mitichkin, "'On the primordial binary black hole mergings in LVK data', e-Print: 2302.06981 [astro-ph.CO]. Phys.Part.Nucl. 54 (2023) 5, 884.
They 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 QCD p.t.

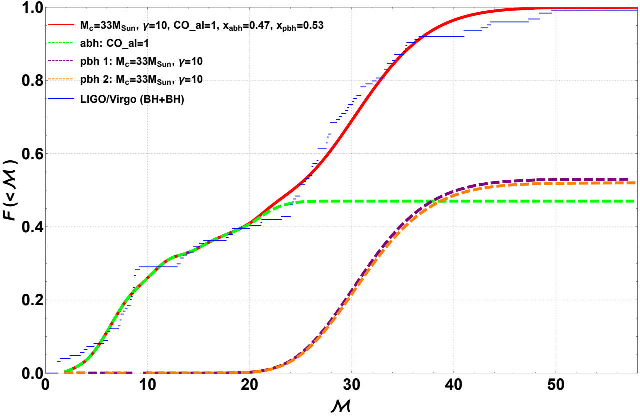
Analysis of recent Ligo-Virgo-Kagra (LVK) data

K. Postnov, A. Kuranov, N. Mitichkin, "Astrophysical appearances of primordial black holes", Contribution to: MESON 2023 • e-Print: 2309.16246 [astro-ph.HE].

Interest to astrophysical proof for PBH existence significantly increased after discovery of coalescing binary black holes with masses $\sim 10 M_\odot$ by gravitational-wave observatories.

There is increasing evidence that PBHs can provide some fraction of detected merging binary BHs and can be related to an isotropic stochastic GW background discovered by pulsar timing arrays (discussed below).

The analysis shows that almost equal populations of astrophysical binary BHs from massive binary evolution and binary PBHs with log-normal mass spectrum well describes both the observed chirp mass distribution and effective spin – mass ratio anti-correlation of the LIGO-Virgo-Kagra binary BHs.



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 $M_0 = 33 M_\odot$, $\gamma = 10$ - with such γ heavier PBH practically are not created.

Crisis in cosmology

Crisis in cosmology, is it real?

Dense population of the early universe, noticeably younger than one billion years at redshifts $z \gtrsim 10$, discovered by Hubble Space Telescope (HST) and James Webb Space Telescope (JWST), was taken as a strong blow to the conventional ΛCDM cosmology.
However, the resolution of the problems by primordial black holes (PBH) was suggested **long before these problems emerged:**
A.Dolgov, J.Silk, PRD 47 (1993) 4244 (DS) "Baryon isocurvature fluctuations at small scale and baryonic **dark matter**".
A.Dolgov, M. Kawasaki, N. Kevlishvili (DKK), NPB807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter"
and several subsequent papers by our group.

Seeding of galaxy formation

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 years, to say nothing of the 20 times younger universe at $z \sim 10$.
In DS and DKK an **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 DS mechanism of PBH creation: first bubbles with very large baryon number density were created (HBB).
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.**

Seeding of galaxy formation by PBH

K. Postnov, A. Dolgov, N. Mitichkin, I. Simkin, Coalescing primordial binary black holes with log-normal mass spectrum, arXiv:2101.02475.
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 $M_0 = (15 - 17) M_\odot$ 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 $M \approx 10^4 M_\odot$ required to explain the observed population of supermassive black holes at $z = 6 - 7$.
This idea of seeding was rediscovered/accepted recently in several publications under the pressure of HST and JWST observations.

Seeding of galaxy formation by PBH

The hypothesis by DS (1993) and DKK (2006), that SMBH seeded galaxy formation 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.
It was rediscovered in several recent works.

B. Liu, V. Bromm, "Accelerating early galaxy formation with primordial black holes", arXiv:2208.13178, 28 Aug 2022: Recent observations with JWST have identified several bright galaxy candidates at $z \gtrsim 10$, some of which appear unusually massive (up to $\sim 10^{11}\ \mathrm{M}_\odot$). Such early formation of massive galaxies is difficult to reconcile with standard $\Lambda\mathrm{CDM}$ predictions.
The observed massive galaxy candidates can be explained, if structure formation is accelerated by massive ($\gtrsim 10^9\ \mathrm{M}_\odot$) PBHs that enhance primordial density fluctuations.

Seeding of galaxy formation by PBH

Observations of high-redshift quasars reveal that many supermassive black holes were in place less than 700 Million years after the Big Bang.
In particular, A. Bogdan, *et al*, 2305.15458 [astro-ph.GA].
The detection of an X-ray-luminous quasar in a gravitationally-lensed galaxy, identified by JWST at $z \approx 10.3$, powered by SMBH with the mass $\sim 4 \times 10^7 M_\odot$ in the galaxy is reported.
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 $\sim 0.1\%$ 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.**
However, the origin of the first BHs remains a mystery.
Seeds of the first BHs are postulated that could 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, according to the authors. Questionable!
Much simpler and easier if the seeds are primordial BH, as predicted by DS and DKK.

Seeding of galaxy and QSO formation by PBH

A.D. Goulding, J.E. Greene, D.J. Setton, *et al*, UNCOVER: The growth of the first massive black holes from JWST/NIRSpec – spectroscopic confirmation of an X-ray luminous AGN at z=10.1, Astrophys.J.Lett. 955 (2023) 1, L24, e-Print: 2308.02750 [astro-ph.GA]
The James Webb Space Telescope is now detecting early black holes (BHs) as they transition from **seeds** to supermassive BHs. Recently Bogdan et al. (2023) 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.

Seeding of globular clusters and dwarfs

The described above model of PBH formation excellently solves all the inconsistencies. **The inverted picture of galaxy formation is assumed: first SM-PBH are created and later they seed galaxy formation.**

Primordial IMBHs with masses of a few thousand solar mass explain formation of globular clusters (GCs), otherwise mysterious.

In the last several years several such IMBH inside GSs are observed. Similar features are predicted for dwarf galaxies.

A. Dolgov, K. Postnov, "Globular Cluster **Seeding** by Primordial Black Hole Population JCAP 04 (**2017**) 036, e-Print: 1702.07621 [astro-ph.CO].

Observations of BHs in dwarf galaxies

The seeding of dwarfs by intermediate mass BHs is confirmed by the recent data, e.g. in the dwarf galaxy SDSS J1521+1404 the BH is discovered with the mass $M \sim 10^5 M_\odot$.

Two Candidates for Dual AGN in Dwarf-Dwarf Galaxy Mergers, M. Mićić, et al, arXiv:2211.04609 [astro-ph.GA]. 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.

Intermediate-mass black holes: finding of episodic, large-scale and powerful jet activity in a dwarf galaxy SDSS J090613.77+561015.2. Jun Yang et al, e-Print: 2302.06214 [astro-ph.GA,astro-ph.HE]. Discovery of an intermediate-mass black hole (IMBH) with a mass of $M_{BH} = 3.6^{+5.9}_{-2.3} \times 10^5 M_\odot$, **that surely cannot be created by accretion but might seed the dwarf formation.**

Pulsar humming, modulation of pure tone

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

Unexpectedly high number of SMBH binaries are presumably observed through distortion of the pulsar timing by the background of gravitational waves.
The NANOGrav 15 yr data set shows evidence for the presence of a low-frequency gravitational-wave background. The most natural possibility seems to be that the signal as coming from a population of supermassive black hole (SMBH) binaries distributed throughout the Universe, G. Agazie et al, The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background, The Astrophysical Journal Letters (2023). DOI: 10.3847/2041-8213/ace18b.
It is difficult to explain such huge number of SMBH binaries. However, this can be naturally expected if these SMBHs are primordial.

Problems prior to JWSP data

Similar serious problems are known already for many years. 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.
A.D. "Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics Phys. Usp. 61 (2018) 2, 115.
"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 Webb are in good agreement.
All these problems, existed during all life time of the universe, are neatly solved if the universe is populated by primordial black holes (PBH) and by astrophysically large bubbles with very high baryonic density.

Problems of the contemporary universe. Summary.

1. SMBH in all large galaxies. Too short time (15 billion year) for their formation through the conventional accretion mechanism.
2. SMBH in small galaxies and even in (almost) EMPTY space. No material for their creation. Pushed out of large galaxies? Wandering BHs?
A striking example: discovery by the Hobby-Eberly Telescope at Texas's McDonald Observatory of a SMBH with $M_{BH} \approx 1.7 \cdot 10^{10} M_\odot$ i.e. 14% of the stellar mass of the galaxy. Usually the mass of the central BH is about 0.1 % of the galaxy mass.
3. Too old stars, older than the Galaxy and maybe **older** than the universe?
4. MACHOs, non-luminous objects, $\boldsymbol{M} \sim 0.5 \boldsymbol{M}_\odot$, observed through microlensing; origin unknown.
5. Problems with the BH mass spectrum in the Galaxy with $(\boldsymbol{M} = 7.8 \pm 1.2) \boldsymbol{M}_\odot$.
6. Origin and properties of the sources of the observed gravitational waves.
7. The origin of IMBH in all mass ranges, plenty of them discovered everywhere in the universe. **Moreover, BH with $\mathrm{M} \approx 100 \mathrm{M}_\odot$ is strictly forbidden but nevertheless observed by LIGO/Virgo.**
IMBH, with $\boldsymbol{M} \sim (10^3 - 10^5) \boldsymbol{M}_\odot$, in dwarfs and globular clusters, discovered unexpectedly, despite being predicted by AD & K. Postnov.
8. Strange stars in the Galaxy, too fast and with unusual chemistry.

Intermediate summary and antimatter in the Galaxy

The mechanism of DS and DKK solves the problem of the observed population of the universe at high redshifts by SMBH (QSO), galaxies, SN, and of a large amount of dust. **Very well agrees with "experiment".**
The predicted log-normal spectrum of PBH is tested and confirmed by the observations (the only one existing in the literature).
The **predicted** existence of IMBH in GCs is confirmed.
The crazy by-product of DS and DKK mechanism, namely prediction of antimatter in the Galaxy seems to come true as well, indeed, astronomical data of the several recent years present strong evidence in favour of noticeable antimatter population in our Galaxy including:

- Gamma-rays with energy 0.511 MeV, which surely originate from electron-positron annihilation at rest.
- Very large flux of anti-helium nuclei, observed at AMS.
- **Several stars are found which produce excessive gamma-rays with energies of several hundred MeV which may be interpreted as indication that these stars consist of antimatter.**

Antimatter history

Search for galactic antimatter

B.P. Konstantinov, et al Cosmic Research, 4, 66 (1968);

B.P. Konstantinov, et al Bulletin of the Academy of Sciences of the USSR. Physical series, 33, No,11, 1820 (1969).

Strongly criticised by Ya.B. Zeldovich, despite very friendly relations.

Antimatter in the universe:

F. W. Stecker, D. L. Morgan, Jr., J. Bredekamp, Possible Evidence for the Existence of Antimatter on a Cosmological Scale in the Universe, Phys. Rev. Letters 27, 1469 (1971);

F. W. Stecker, Grand Unification and possible matter-antimatter domain structure in the the universe. Tenth Texas Symposium on Relativistic Astrophysics, p. 69 (1981),

Summary of the situation presented at 2002:

F. W. Stecker, "The Matter-Antimatter Asymmetry of the Universe (keynote address for XIVth Rencontres de Blois)" arXiv:hep-ph/0207323.

A.D. Dolgov, "Cosmological matter antimatter asymmetry and antimatter in the universe", keynote lecture at 14th Rencontres de Blois on Matter - Anti-matter Asymmetry • e-Print: hep- ph/0211260.

Antimatter history

Paul A.M. Dirac: "Theory of electrons and positrons", Nobel Lecture, December 12, 1933: "It is quite possible that... these stars being built up mainly of positrons and negative protons. In fact, there may be half 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."

It seems that now we know ways to distinguish stars from an antistars by observations from the Earth. A.D. Dolgov, V.A. Novikov, M.I. Vysotsky, "How to see an antistar" JETP Lett. 98 (2013) 519, e-Print: 1309.2746.

The spectra are not exactly the same, even if CPT is unbroken and the polarisation of radiation from weak decays could be a good indicator or the type of emitted neutrinos/antineutrinos from supernovae.

Not realistic at present time.

Antimatter history

In fact Dirac was the second 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's wild guess: matter and antimatter are capable to annihilate and produce VAST energy.
He believed that they were gravitationally repulsive having negative mass. Two such objects on close contact should have vanishing mass!?
A. Schuster, Nature, 58 (1898) 367. Potential Matter. Holiday Dream.
"When the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable?"
"Astronomy, the oldest and yet most juvenile of the sciences, may still have some surprises in store. May antimatter be commended to its case".

Antimatter in the Galaxy

Based on the conventional approach no antimatter object is expected to be in the Galaxy.

However, it was predicted in 1993 and elaborated in 2009 that noticeable amount of antimatter, even antistars might be in the Galaxy and in its halo:

A. Dolgov, J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scale and baryonic dark matter.

A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter".

Bounds on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars as analyzed in:

C.Bambi, A.D. Dolgov, **"Antimatter in the Milky Way** Nucl.Phys.B 784 (2007) 132-150 • astro-ph/0702350,

A.D. Dolgov, S.I. Blinnikov, **"Stars and Black Holes from the very Early Universe** Phys.Rev.D 89 (2014) 2, 021301 • 1309.3395,

S.I.Blinnikov, A.D., K.A.Postnov, **"Antimatter and antistars in the universe and in the Galaxy** Phys.Rev.D 92 (2015) 023516 • 1409.5736.

Anti-evidence: cosmic positrons

Observation of intense 0.511 line, a 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:

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

The width of the line is about 3 keV. Emission mostly goes from the Galactic bulge and at much lower level from the disk,

"Great Annihihilator"in the Galactic bulge.

G. Weidenspointner *et al.*, Astron. Astrophys. **450**, 1013 (2006);

J. Knodlseder *et al.*, Astron. Astrophys. **441**, 513 (2005);

P. Jean *et al.*, Astron. Astrophys. **445**, 579 (2006).

Until recently the commonly accepted explanation was that e^+ are created in the strong magnetic fields of pulsars but the recent results of AMS probably exclude this mechanism, since the spectrum of $\bar{p}$ and e^+ at high energies are identical. L'Aquila Joint Astroparticle Colloquium, 10th November, 2021 by S. Ting.

Anti-evidence: cosmic antinuclei

Registration of anti-helium: **In 2018 AMS-02 announced possible observation of six $\overline{He}^3$ and two $\overline{He}^4$.**
A. Choutko, AMS-02 Collaboration, "AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018).
S. Ting, Latest Results from the AMS Experiment on the International Space Station. Colloquium at CERN, May, 2018.
Recent registration of more events L'Aquila Joint Astroparticle Colloquium, 10th November by S. Ting; and COSPAR 2022, 16-24 July:
7 $\overline{D}$ ($\lesssim$ 15 GeV) and 9 $\overline{He}$, ($\sim$ 50 GeV). **fraction $\overline{He}/He \sim 10^{-9}$, too high. Secondary creation of $\overline{He}^4$ is negligibly weak.**
Nevertheless S. Ting expressed hope to observe $\overline{Si}$!!!
It is not excluded that the flux of anti-helium is even much higher because low energy $\overline{He}$ may escape registration in AMS.

Deuterium/Helium problem

There is noticeable discrepancy between the large fraction of D with respect to He. In the case of the standard BBN this ratio should be much smaller than unity, but the observed ratio is practically 1.
If it is assumed that the abundances of D and He are determined by BBN with large β (or η). However **if $\beta \sim 1$ there is no primordial D.** On the other hand in our scenario formation of primordial elements takes place inside non-expanding compact stellar-like objects with fixed temperature. If the temperature is sufficiently high, this so called 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. Is it is so, antistars may have equal amount of $\overline{D}$ and $\overline{He}$!!!

Anti-evidence: antistars in the Galaxy

S. Dupourqué, L. Tibaldo and P. von Ballmoos, Constraints on the antistar fraction in the Solar System neighborhood from the 10-year Fermi Large Area Telescope gamma-ray source catalog,
Phys Rev D.103.083016 103 (2021) 083016

We identify 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.

Possible discovery of anti-stars in the Galaxy

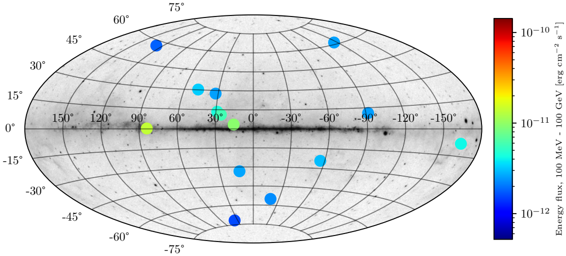


Рис.: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV

X-ray signatures of antistars

X-ray signature of antistars in the Galaxy A.E. Bondar, S.I. Blinnikov, A.M. Bykov, A.D. Dolgov, K.A. Postnov e-Print: 2109.12699 [astro-ph.HE], JCAP, Sep 26, 2021,

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 $\sim$ 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.

Antihelium and antistars

A.M. Bykov, K.A. Postnov, A.E. Bondar, S.I. Blinnikov, A.D. Dolgov, Antistars as possible sources of antihelium cosmic rays, JCAP08(2023), 2304.04623 [astro-ph.HE]

Possible sources of antinuclei in cosmic rays from antistars which are predicted in a modified Affleck-Dine baryogenesis scenario by DS (1993) are discussed. 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.

PBH Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD).
SUSY predicts existence of scalars with $B \neq 0$. Such bosons may condense along flat directions of the quartic potential:

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

and of the mass term, $U_m = m^2\chi^2 + m^{*\,2}\chi^{*\,2}$:

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

where $\chi = |\chi| \exp\left(i\theta\right)$ and $m = |m|e^\alpha$. If $\alpha \neq 0$, C and CP are broken.
In GUT SUSY baryonic number is naturally non-conserved - non-invariance of $U(\chi)$ w.r.t. phase rotation.

Creation Mechanism

Initially (after inflation) χ is away from origin and, when inflation is over, starts to evolve down to equilibrium point, $\chi = 0$, according to Newtonian mechanics:

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

Baryonic charge of χ:

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

is analogous to mechanical angular momentum. χ decays transferred baryonic charge to that of quarks in B-conserving process.

AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed 10^{-9}.

Creation Mechanism

If $m \neq 0$, the angular momentum, B, is generated by a different direction of the quartic and quadratic valleys at low χ. If CP-odd phase α is small but non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them.
Matter and antimatter objects may exist but globally $B \neq 0$.

Affleck-Dine field χ with CW potential coupled to inflaton Φ (AD and Silk; AD, Kawasaki, Kevlishvili):

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

Coupling to inflaton is the general renormalizable interaction of two scalars. When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large value, according to quantum diffusion equation derived by Starobinsky, generalized to a complex field χ.

Creation Mechanism

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 β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small χ. The fundament of PBH creation is build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations.

Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition. **The mechanism is very much different from other conventionl ones.**

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.

Results

- PBHs with log-normal mass spectrum - confirmed by the data!
- 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 with the homogeneous baryonic background.**
- Extremely old stars would exist even, "older than universe star'' is found; the older age is mimicked by the unusual initial chemistry. Several such stars are observed.

The mechanism of PBH creation pretty well agrees with 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.

Dark matter may be 100% made of PBH.

PBH seeds rescued ΛCDM cosmology.

The prediction of antimatter population of Milky Way is confirmed.