Primordial Black Holes, Seeding of Cosmic Structures, and Dark Matter and Antimatter

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Predictions and observations

30 year old idea, A.Dolgov & J.Silk, 1993 (DS) that the galaxy formation is SEEDED by supermassive primordial black holes (PBH) is gaining increasingly stronger support. 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"

Supporting data:
• Predicted mass spectrum of PBH very well agrees with "experiment".
• Noticeable antimatter population of the Galaxy is predicted and confirmed by the observations of **positrons, antinuclei, and antistars.**
• The early galaxy formation observed by HST and JWST can be explained if galaxies are SEEDED by BHs, as is also rediscovered in a few papers of last years.

Inverted mechanism 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 an order of magnitude 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 AD and DKK an inverted formation mechanism of galaxies and their central black holes is proposed. Namely, primordial SMBHs was formed first in prestellar cosmological epoch and later they **SEEDED** galaxy formation.

The idea of seeding, but of different kind, was rediscovered recently under the pressure of HST and JWST observations.

Main features of the model

The model is based on the mechanism of BH creation at **inflation** from initially large isocurvature perturbations (baryon number density) transformed into matter density perturbations at the QCD phase transition.
The mechanism essentially differs from all others described in the literature.
It is assumed that at inflationary stage astrophysically large but cosmoloically small bubbles with with high baryonic number density were created in the process of Affleck and Dine baryogenesis. We call them HBB (High Baryon Bubbles).
Such bubbles could be created due to postulated coupling of the inflaton field Φ to scalar field χ with non-zero baryon number:

$$L_{int} = \lambda|\chi|^2 \left(\Phi - \Phi_1\right)^2 ,$$

where Φ_1 is a value of the inflaton field that it passed in the process of inflation.
The density contrast of HBBs with respect to background were initially small since quarks in the early universe were massless. Hence the so called isocurvature perturbations were created.
Only at QCD phase transition (p.t.) at $T \sim 100$ MeV when quarks turned into heavy protons and neutrons with masses about 1 GeV the density contrast became large and HBB turned mostly into PBHs or stellar kind objects.

Primordial Black Holes (PBH)

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).

Mass spectrum of PBHs

The proposed mechanism is the first where inflation and Affleck-Dine baryogenesis are applied to PBH formation, repeated now in many works. The striking feature of it is the **log-normal** mass spectrum which is the only known spectrum **tested by "experiment", in very good agreement:**

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

Log-normal spectrum is a generic feature of many chaotic processes.
The central mass M_0 should be equal to the mass inside cosmological horizon at the QCD p.t. $\boldsymbol{M_0 \sim 10 M_\odot}$, 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 $\sim 10 M_\odot$, for $\mu = 0$. At $\mu \sim 1$ the T_{pt} could be smaller and M_{hor} would be larger.

JWST and HST common galaxy

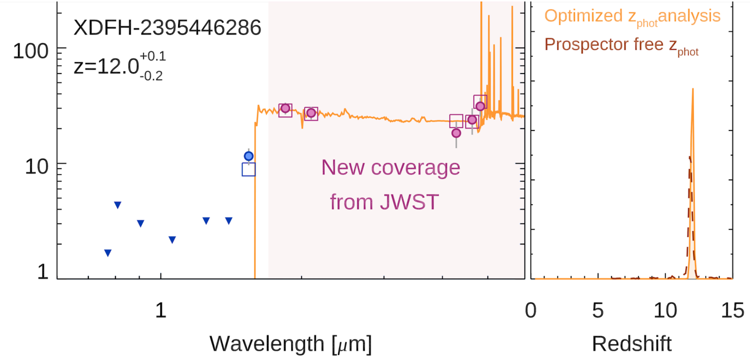
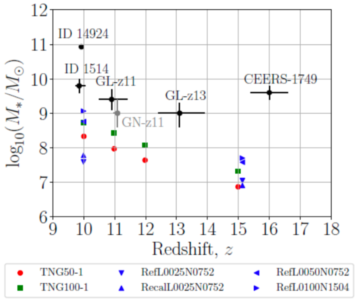


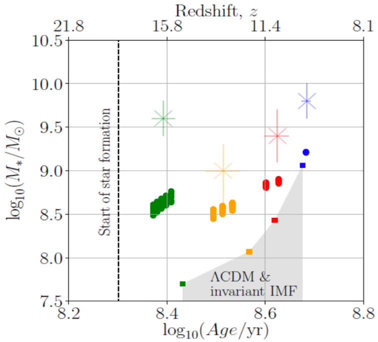
Figure 5. (*left*) Fits of a model spectral energy distribution to the observed *HST* + *JWST* photometry available for the highest redshift candidate UDFj-39546284 identified over the HUDF with *HST* (Bouwens et al. 2011a). Flux measurements blueward of 1.6μm are with *HST* (*blue filled points and downward triangles*) and those redward of this limit are with *JWST* (*magenta filled points*). The blue downward triangles correspond to 2σ upper limits on the fluxes. The open squares indicate the expected fluxes from the best-fitting SED model. (*right*) Redshift likelihood distribution derived for UDFj-39546284 from the EAzY photometric redshift code (Brammer et al. 2008) on our photometric measurements, and UDFj-39546284 seems to almost certainly have a redshift of $z = 12.0^{+0.1}_{-0.2}$, as the JADES team has confirmed with spectroscopy (Curtis-Lake et al. 2022) and similar to what Ellis et al. (2013), McLure et al. (2013), Oesch et al. (2013), and Bouwens et al. (2013) inferred using the available *HST+Spitzer* data in 2013. As such, UDFj-39546284 appears to be the most distant galaxy discovered by *HST* in its more than 30 years of operation. Figure 7 shows postage stamp images of this source.

JWST and ΛCDM, 2 orders of magnitude mismatch

Moritz Haslbauer et al, Has JWST already falsified dark-matter-driven galaxy formation? arXiv:2210.14915



Comparison of the size of the most massive galaxies, obtained in models of formation and growth of galaxies based on LCDM (colored dots) with JWST observations (black dots with errors) depending on the redshift of the observed galaxies.



HIgh metallicity in not so young universe

Unexpectedly high abundances of heavy elements (high metallicity)
(All elements heavier than helium are called metals.)
B. Peng, et al, Ap.J.L., 944, 2, L36, 8 p. ''Discovery of a Dusty, Chemically Mature Companion to $z \sim 4$ Starburst Galaxy in JWST Early Release Science Data''.
Most surprising about the companion galaxy, considering its age and mass, was its mature metallicity— such as carbon, oxygen and nitrogen.
The amount is comparable to 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.
High abundances of heavy elements may be a result of BBN with large baryon-to-gamma ratio, as predicted in DS and DKK.

Early galaxies, high metallicity, several examples

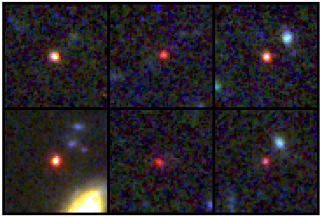
• A.J. Bunker, A, Saxena, A.J. Cameron, *et al,* "JADES NIRSpec Spectroscopy of $GN-z11$: Lyman-α emission and possible enhanced **nitrogen** abundance in a $z = 10.60$ luminous galaxy", Astron.Astrophys. 677 (2023) A88.

• T. Bakh, J.A. Zavala, I. Mitsuhashi, *et al*, "Deep ALMA redshift search of a $z \sim 12$ GLASS-JWST galaxy candidate", MNRAS, **519**, 4, p.5076.
Age of Most Distant Galaxy is confirmed with Oxygen observation at 367 million years after the Big Bang. This observation **heralds a leap in our ability to understand the formation of the earliest galaxies in the Universe.**

• "Nitrogen enhancements 440 Myr after the Big Bang: super-solar N/O, a tidal disruption event or a dense stellar cluster in GN-z11?" A.J. Cameron, et al, arXiv:2302.
Observations of GN-z11 with JWST/NIRSpec revealed numerous oxygen, carbon, nitrogen, and helium emission lines at $z = 10.6$.
The data prefers (N/O), greater than 4 times solar. The derived $C/O \approx 30$ solar.
Nitrogen enhancement in GN-z11 cannot be explained by enrichment from metal-free Population III stars.

Impossible galaxies

I. Labbé, P. van Dokkum, E. Nelson, *et al*, A population of red candidate massive galaxies 600 Myr after the Big Bang", Nature, 616, Issue 7956, 266 (2022), arXiv:2207.12446. Six 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. According to the 'science' it is impossible to create so well developed galaxies. **NB: "May be they are supermassive black holes of the kind NEVER SEEN BEFORE. That might mean a revision of usual understanding of black holes." Well agrees with our predictions of PBHs.**



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

Seeding of ultra-massive early QSO claimed by ALMA

ALMA confirmation of an obscured hyper-luminous radio-loud AGN at z = 6.853 associated with a dusty starburst in the 1.5 deg2 COSMOS field,
R. Endsley et al, MNRAS 520, 3, , p 4609, (2023)
VIRCam and IRAC photometry perhaps suggests that COS-87259 is an extremely massive reionization-era galaxy with $M_* = 1.7 \times 10^{11} M_\odot$
Such a very high AGN luminosity suggests that this object is powered by $\sim 1.6 \times 10^9 M_\odot$ black hole if accreting near the Eddington limit.
BH mass is about 1% of the stellar mass, 100 times larger than usually.

Nearly impossible, but PBH could seed such monster.
Summarising: recent observations have found a large number of supermassive black holes already in place in the first few hundred million years after Big Bang.

The channels of formation and growth of these early, massive black holes are not clear, with scenarios ranging from heavy seeds to light seeds experiencing bursts of high accretion rate.

Rediscovery of seeding by black holes

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 in the **contemporary** and early universe. **It was rediscovered in several recent works.** According to B. Liu, V. Bromm, "Accelerating early galaxy formation with primordial black holes", Astrophys.J.Lett. 937 (2022) 2, L30 • e-Print: 2208.13178 [astro-ph.CO] early galaxies could be created if their production was accelerated by BH with huge masses $\gtrsim 10^9\ \mathrm{M}_\odot$. The origin of this SMBH was not explained.

More about rediscovery of seeding by BH

Seeding was advocated also in A. Bogdan, A. Goulding, P. Natarajan, *et al*, "Evidence for heavy-seed origin of early supermassive black holes from a $z \approx 10$ X-ray quasar", Nature Astron. 8 (2024) 1, 126, 2305.15458 [astro-ph.GA] and A.D. Goulding, J.E. Greene, D. J. Setton, *et al*, "UNCOVER: The Growth of the First Massive Black Holes from JWST/NIRSpec—Spectroscopic Redshift 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].

It was postulated that seeds of the observed early galaxies and SMBHs could be either light BH with masses $(10 - 100)M_\odot$, or heavy ones, $M = (10^4 - 10^5)M_\odot$. According to the authors the light BHs could be remnants of the first stars and the heavy ones might be created by direct collapse of gas clouds, **assuming accretion at the Edddington limit.**

Strong blow to the conventional seeding picture

A dormant, overmassive black hole in the early Universe I. Juodzbalis, R. Maiolino, W.M. Baker, *et al*, 2403.03872v1.

The detection, from the JADES survey, of broad Halpha emission in a galaxy at $z = 6.68$, which traces a black hole with mass of $\sim 4 \times 10^8 M_\odot$ and accreting at a rate of **only 0.02 times the Eddington limit.** The host galaxy has low star formation rate $\sim 1 m_\odot$/yr a factor of 3 below the star forming main sequence).

The black hole to stellar mass ratio is 0.4, i.e. 10^3 times above the local relation. This object is most likely the tip of the iceberg of a much larger population of dormant black holes around the epoch of reionization. Its properties are consistent with scenarios in which short bursts of **super-Eddington accretion have resulted in black hole overgrowth and massive gas expulsion from the accretion disk; in between bursts, black holes spend most of their life in a dormant state.**

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 the problems are neatly solved if the universe is populated by seeds created by primordial black holes (PBH) and the astrophysically large bubbles with very high baryonic density

Gravitational waves from BH binaries

GW discovery by LIGO strongly indicate that the sources of GW are PBHs, see e.g. S.Blinnkov, A.Dolgov, N.Porayko, K.Postnov, JCAP 1611 (2016), 036 "Solving puzzles of GW150914 by primordial black holes":

- 1. Formation of BH binaries from the original stellar binaries.
- 2. Low spins of the coalescing BHs .
- 3. Origin of heavy BHs ($\sim 30 M_\odot$). There appeared much more striking problem of BH with $M \sim 100 M_\odot$. 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 collapce. 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 could be created with sufficient density.

Chirp mass

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:

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

where M_c is the so called chirp mass:

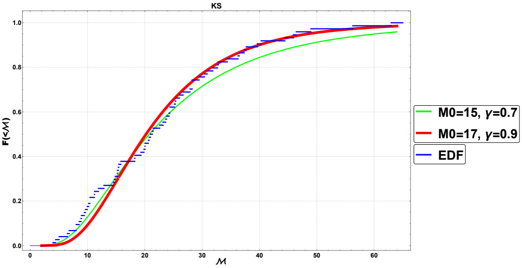
$$M_c = \frac{(M_1\, M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

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.

Chirp mass distribution

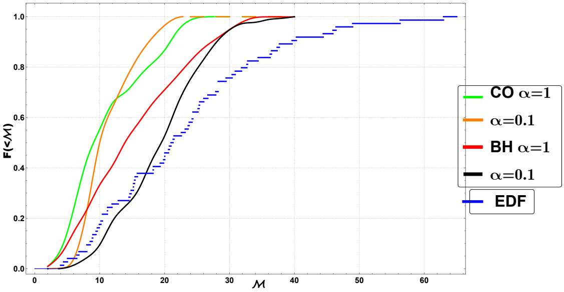
Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



See also K. Postnov and N. Mitichkin, e-Print: 2302.06981.
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.

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.

Problems of the contemporary universe. Summary.

1. SMBH in all large galaxies. Too short time for their formation.
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. IMBH, with $\boldsymbol{M} \sim (10^3 - 10^5)\boldsymbol{M_\odot}$, in dwarfs and globular clusters, unexpectedly discovered, despite being predicted by AD & K. Postnov. "Globular Cluster **Seeding** by Primordial Black Hole Population JCAP 04 (2017) 036, e-Print: 1702.07621 [astro-ph.CO].
5. Strange stars in the Galaxy and her halo, too fast and with unusual chemistry.
6. BH with $\mathrm{M} \approx 100\mathrm{M}_\odot$ is strictly forbidden, but recently LIGO/Virgo discovered BHs with masses close to $100M_\odot$. Their astrophysical origin is forbidden due to huge mass loss in the process of collapse. but nevertheless observed by LIGO/Virgo.

BHs in dwarf galaxies

Masses of dwarfs: $(10^7 - 10^9)M_\odot$.

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, O.J. Holmes, B.N. Wells, J.A. Irwin, Two Candidates for Dual AGN in Dwarf-Dwarf Galaxy Mergers, Astrophys.J. 944 (2023) 2, 160 • e-Print: 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.

J. Yang, Z. Paragi, S. Frey, *et al* "Intermediate-mass black holes: finding of episodic, large-scale, and powerful jet activity in a dwarf galaxy", Mon.Not.Roy.Astron.Soc. 520 (2023) 4, 5964-5973 • e-Print: 2302.06214 [astro-ph.GA]. 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.**

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 MNRAS (1971) 152, 75 and repeated later by G. Chapline, Nature, 253, 251 (1975). 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.

The next one: DS (Mar 13, 1992), Baryon isocurvature fluctuations at small scales and **baryonic 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.**

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 (model-dependent and have caveats).

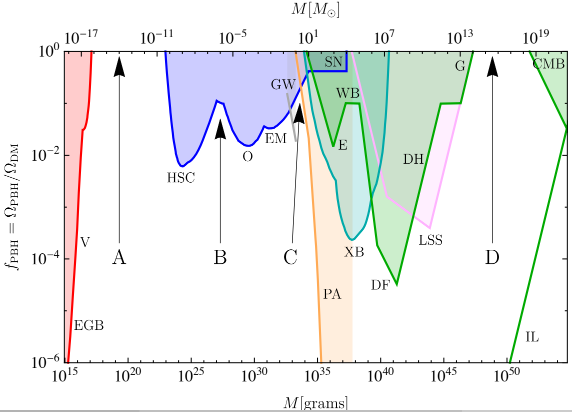


Figure caption

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.

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, PRL, 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 form weak decays could be a good indicator or the type of emitted neutrinos/antineutrinos from supernovae.

Bounds on the density of galactic antistars are rather loose, 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 $\overline{He}$ 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 $\overline{D}$ and $\overline{He^3}$ with respect to $\overline{He^4}$. In the case of the standard BBN this ratio should be much smaller than unity, but the observed ratios are practically 1.

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 and He^3.

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, 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 as 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".

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 $p\bar{p}$ or $He\bar{p}$ atoms and similar.**

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 $He^4\bar{p}$, or $\overline{He}^4 p$ 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:

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

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

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

where $\chi = |\chi| \exp(i\theta)$ 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.

ΛCDM cosmology is rescued by PBHs

Predicted antimatter in Milky Way is observed