Seeding of cosmic structures and anti-structures by primordial black holes

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Crisis in cosmology

Conventional ΛCDM cosmology encounters serious difficulties describing astronomical observations during **all the history** of the universe, **starting from our time with the universe age about 15 billion years, and back to the past down to $\sim$ 300 million years discovered recently by HST, JWST, and ALMA at high redshifts $z \sim 10$.**

The cosmological problems that emerged earlier are reviewed in 2018: 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.

Contradiction between observations and canonical theory is neatly solved if the universe is populated by primordial black holes (PBH) that **seeded** formation of cosmic structures, as it has been suggested 30 years ago - **inverted mechanism of galaxy formation (first BH and later galaxy)**:
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 subsequent publications by our group.

Problems of the contemporary universe. Summary.

1. Supermassive BH (SMBH) in all large galaxies. Too short time (15 billion year) for their formation through the conventional accretion mechanism.
2. Huge SMBH in small galaxies and even in (almost) EMPTY space. No material for their creation. Pushed out of large galaxies? Wandering BHs?
3. Too old stars, older than the Galaxy and maybe one **older** than the universe?
4. MACHOs, non-luminous objects, $M \sim 0.5 M_\odot$, observed through microlensing.
5. The BH mass spectrum in the Galaxy with $(M = 7.8 \pm 1.2) M_\odot$.
6. Origin and properties of the sources of the observed gravitational waves.
7. Origin of intermediate mass BH (IMBH) with masses $(10^3 - 10^5) M_\odot$. Plenty of them are observed everywhere in the universe, in particular in dwarfs and globular clusters, as was predicted by AD & K. Postnov.
8. Discovery of BH with $M \approx 100 M_\odot$, that is strictly forbidden but nevertheless observed by LIGO/Virgo.
9. Strange stars in the Galaxy, too fast and with unusual chemistry.

Problems of the early universe

Serious problems, similar to those recently found by JWST, are known already for many years. 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 exists in conventional cosmology.**

"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.

Huge BHs in small galaxies discovered in the early universe (as well as in the contemporary one). Such huge BHs could not be created by the accretion of matter to galactic center, since the amount of available material is too small.

All the problems are neatly solved if the universe is populated by primordial black holes (PBH) and the astrophysical large bubbles with very high baryonic density, according to DS and DKK.

Predictions and observations

Experimental confirmation of DS/DKK mechanism:

- 1.The calculated mass spectrum of PBH very well agrees with "experiment".
- Noticeable antimatter population of the Galaxy is anticipated and confirmed by the observations of **positrons, antinuclei, and antistars.**
- 3. The early galaxy formation observed by HST and JWST is explained if galaxies are SEEDED by BHs, as it is rediscovered in several recent papers.
- 4. Prediction of IMBH, with $\boldsymbol{M} \sim (10^3 - 10^5)\boldsymbol{M}_\odot$ in dwarfs and globular clusters, by AD & K. Postnov. "Globular Cluster **Seeding** by Primordial Black Hole Population", JCAP 04 (2017) 036, e-Print: 1702.07621, confirmed:

F. Peiβker, M. Zajaček, M. Labaj, *et al*, "The Evaporating Massive Embedded Stellar Cluster IRS 13 Close to Sgr A*. II. Kinematic Structure". Discovery of IMBH with $M \approx 3 \times 10^4 M_\odot$, 2024, ApJ **970** 74.

M. Hӓberle, N. Neumayer, A. Seth, A., *et al*, 2024, Nature, 631, 285, Fast-moving stars around an intermediate-mass black hole in ω Centauri $M = 8200 M_\odot$ "great unexpected discovery, predicted in 2017".

The origin of IMBH is mysterious, if they are not primordial.

- **4. Possible observation of star-antistar collision!?**

Rediscovery of galaxy and quasar seeding by BH

A. Bogdan *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 and A.D. Goulding *et al*, "UNCOVER: The Growth of the First Massive Black Holes from JWST..." Ap.J.Lett. 955 (2023) 1, L24; 2308.02750.

It was postulated that **seeds** of the observed early galaxies and BHs 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 (???).

It is also stated that the detection of an X-ray-luminous quasar powered by SMBH with the mass $\sim 4 \times 10^7 M_{\odot}$ in the galaxy identified by JWST at $z \approx 10.3$ **indicates that such BHs originated from heavy seeds.**

The BH mass is comparable to the stellar mass of the host galaxy, while what is found in the local Universe is usually: $\sim 0.1\%$.

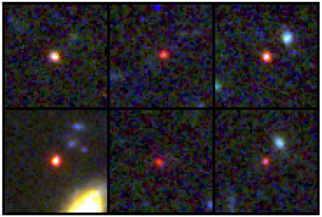
In all the cases accretion at the Edddington limit is assumed.

However, the origin of the first seeding BHs remains questionable.

Much simpler if the seeds are PBH, as suggested by DS and DKK.

Impossible galaxies

A population of red candidate massive galaxies 600 Myr after the Big Bang,
I. Labbe, *et al*, Nature 616 (2023) 7956, 266, 2207.12446 [astro-ph.GA]
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)

Strong blow to the super-Eddington accretion

A dormant, overmassive black hole in the early Universe I. Juodzbalis, R. Maiolino, W.M. Baker, *et al*, 2403.03872: **Recent observations have found a large number of SMBHs 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.**

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 black hole to stellar mass ratio is 0.4, i.e. 10^3 times above the local relation. Huge BH in small galaxies, see more examples below.

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.**

Huge black holes in tiny galaxies at high z

Black holes in high z universe are too massive w.r.t. the expectations based on observations of BHs in contemporary large galaxies - PBHs solve the problem.

F. Pacucci, B. Nguyen, S. Carniani *et al* "JWST CEERS and JADES Active Galaxies at $z = 4 - 7$ Violate the Local $M_* - M_{BH}$ Relation at $> 3\sigma$: Implications for Low-mass Black Holes and Seeding Models", The Astrophysical Journal Letters, 957:L3 (10pp), 2023 November 1.
Black holes are overmassive by factor $10 - 100$ compared to their low-z counterparts in galactic hosts of the same stellar mass.

M. Volonteri, M. Habouzit, M. Colpi. "What if young $z > 9$ JWST galaxies hosted massive black holes?" Monthly Notices of the Royal Astronomical Society, Volume 521, Issue 1, pp.241-250. Only MBHs overmassive relative to expected galaxy scaling relations, accreting at high Eddington rates, would be detectable. Their discovery would point to the presence of heavy MBH **seeds**, but care is needed to exclude the existence of lighter seeds as only overmassive MBHs.

Possible resolution: BH are primordial. The seeding by BH operated too little time to create very massive galaxies as in the contemporary universe.

Huge black holes in tiny galaxies today

Primordial IMBHs with masses of a few thousand solar mass explain formation of globular clusters (GCs) and dwarf galaxies, otherwise the formation is not well understood, even mysterious.
In the last several years several such IMBH inside GSs are observed. Similar IMBHs are observed in dwarf galaxies.

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.

JWST and HST common galaxy

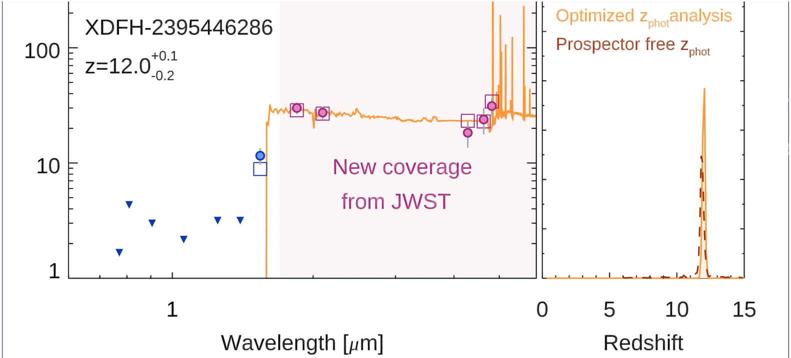
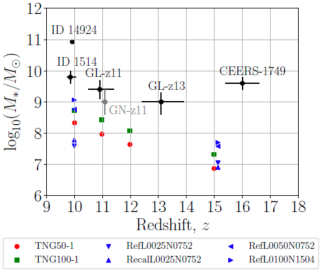


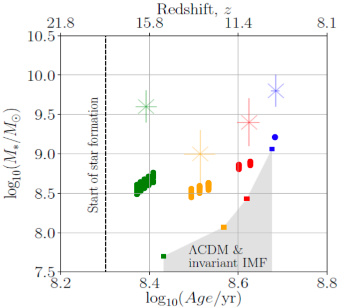
Figure 5. (*left*) Fits of a model spectral energy distribution to the observed *HST* + *JWST* photometry available for the highest redshift candidate UDFj-39546284 identified over the HUDF with *HST* (Bouwens et al. 2011a). Flux measurements blueward of 1.6μm are with *HST* (*blue filled points and 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 the conventional ΛCDM cosmology

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.



Two orders of magnitude discrepancy.

Rich chemistry

Unexpectedly high abundances of metals (elements heavier than helium).

T.J. Bakx, J.A. Zavala, I. Mitsuhashi, *et al*, "Deep ALMA redshift search of a $z \sim 12$ GLASS-JWST galaxy candidate", MNRAS, 519, Issue 4, pp.5076-5085

Age of Most Distant Galaxy is confirmed with Oxygen observation.
ALMA has measured the exact cosmic age of a distant JWST-identified galaxy, GHZ2/GLASS-z12, at 367 million years after the Big Bang. ALMA's deep spectroscopic observations revealed a spectral emission line associated with ionized Oxygen near the galaxy, This observation **heralds a leap in our ability to understand the formation of the earliest galaxies in the Universe.**

B. Peng, et al, Ap J Lett., **944**, 2, L36. "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, 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.

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 orrgin was considered **impossible.** 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 a few millions $M_\odot$ (e,g, Milky Way) up to almost hundred billions $M_\odot$. **However, the conventional accretion mechanisms are not efficient enough to create such monsters during the universe life-time, $t_U \approx 14.6$ Gyr. 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, which 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 $100M_\odot$.

The origin of most of these BHs is unclear, except maybe of the BHs with masses of a few solar masses, which may be astrophysical.
Highly unexpected was abundance of IMBH which are appearing during last few years in huge numbers.
The assumption that (almost) all black holes in the universe are primordial strongly reduce or even eliminate the tension.

Predicted mass spectrum of PBH

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 a 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 $10 M_\odot$, for $\mu = 0$ and $T_{pt} = 100$ MeV. At larger chemical potential the T_{pt} is smaller and M_{hor} is larger. Lattice QCD estimates demand $T_{pt} \approx 70$ MeV and $M_0 \approx 17 M_\odot$ (I. Arefyeva, Quarks-24).

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."

1. 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 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 created with sufficient density.

2. Formation of BH binaries from the original stellar binaries. **Recoil is usually so strong that the binaries are destroyed.**

K.B. Burdge, *et al*. "The black hole low mass X-ray binary V404 Cygni is part of a wide hierarchical triple, and **formed without a kick**", arXiv:2404.03719.

3. **Low spins of the coalescing BHs .**

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_1, M_2 are the masses of two bodies in the binary system and M_c is the so called chirp mass:

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

and

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

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.

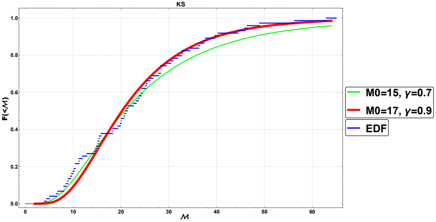
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

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.

Chirp mass distribution

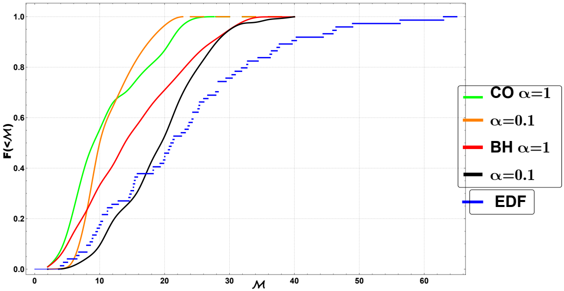
Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



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.

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.

PBH and inflation

In earlier works the predicted masses of PBH were quite low.
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 the predicted spectrum is multi-parameter one and quite complicated
The only exception is the log-normal spectrum of DS and DKK tested by observatons.

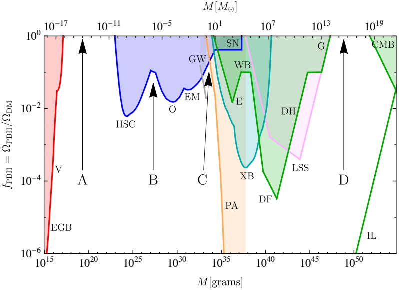
Black Dark Matter

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. R. astr. Soc. (1971) 152, 75 and repeated 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.
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).



BH clustering may strongly weaken these limits, see Y. Eroshenko, V. Stasenko, "Gravitational waves from the merger of two primordial black hole clusters", Symmetry 15 (2023) 3, 637, arXiv:2302.05167, and allows **all DM to be PBHs.**

Intermediate summary and antimatter in the Galaxy

The mechanism of AD and DKK solves the problem of the observed population of the universe at high redshifts by SMBH (QSO), galaxies, SN, and of rich chemistry (a large amount of dust).

The predicted log-normal spectrum of PBH is tested and confirmed by the observations (the only one existing in the literature).

The existence of IMBH in GCs is confirmed.

The crazy by-product of AD and DKK mechanism, namely prediction of antimatter in the Galaxy seems to come true as well:

• Observation of 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).

Antimatter int the universe:
F. W. Stecker, et al 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 polarization of radiation could be a good indicator or the type of emitted neutrinos/antineutrinos from supernovae.

Antimatter history

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

Bounds on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars, the objects with short mean free path of protons, 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 accepted explanation was that e^+ are created in the strong magnetic fields of pulsars but the recent results of AMS Alpha Magnetic Spectrometer (or AntiMatter Spectrometer) probably exclude this mechanism, since the spectrum of $\bar{p}$ and e^+ at high energies are identical. S. Ting, L'Aquila Joint Astroparticle Colloquium, 10.XI.2021.

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 $\overline{He}$, (~ 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.
Recently AMS has revealed a surprising surplus of cosmic rays made of deuterons.
"Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer", M. Aguilar, et al PRL 132, 261001 (2024) - strong contradiction with the canonical model.

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 smaller than unity, but the observed one is 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. 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 $\overline{He}$!!!

Possible discovery of anti-stars 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 $p\bar{p}$ 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, JCAP 08 (2023) 027, e-Print: 2304.04623.

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.
In particular the observed excess of deuterium could be also explained.

Gamma burster from star-antistar collision

Very powerful gamma-ray burster (GRB) was reported in M.E. Ravasio, O.S. Salafia, G. Oganesyan, *et al*, SCIENCE, 25 Jul 2024, Vol 385, Issue 6707, pp. 452-455, e-Print: 2303.16223 [astro-ph.HE].

This event got the nickname: the Brightest Of All Time or the "BOAT."

This extremely strong GRB occurred in October 2022. A bright megaelectronvolt emission line was observed, that appeared 280 seconds after the GRB began and then rapidly faded away while shifting to lower energies.

Usually the gamma-ray spectra of GRBs consist of a smooth continuum without absorption or emission lines.

The authors interpret this line as having been produced by the annihilation of electron-positron pairs within the relativistic jet produced by the GRB **possibly emerging from star-antistar annihilation !?**

Star-antistar collision, was briefly mentioned in: A.D. Dolgov arXiv:2301.01365. Plenary talk at 36th Rencontres de Physique de la Vallée d'Aoste on Results and Perspectives in Particle Physics. It may be a quasi-periodic process of a star-antistar direct contact, explosion forcing them apart, and possible, but not necessary return to each other by gravitational attraction.

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 one.
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 mechanism of massive PBH formation quite different from all others. 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, as e.g. 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 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.

Seeding of cosmic structures by PBHs rescued the conventional ΛCDM cosmology.

Antimatter observations prove validity of the model.