Early Galaxies and Primordial Black Holes

A.D. Dolgov

Novosibirsk State University, Novosibirsk, Russia
Bogolyubov Laboratory of Theoretical Physics, JINR, Dubna, Russia

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Crisis in cosmology

Crisis in cosmology, is it real?

Dense population of the early universe, 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 subsequent papers by our group.

Inverted mechanism of galaxy formation

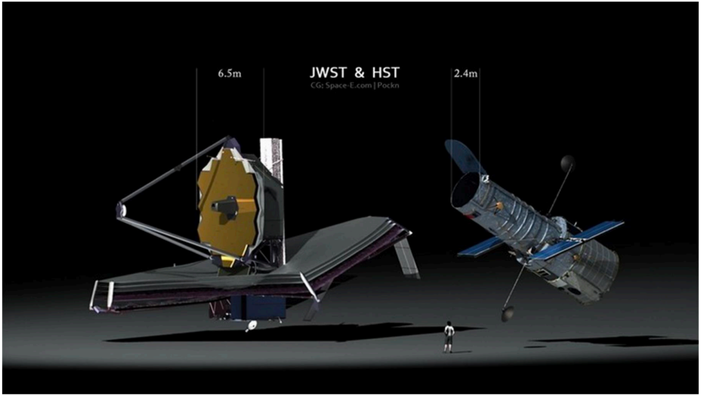
Usually it is assumed that supermassive BHs (SMBHs), observed in centers of all large galaxies, are created by natter accretion to the matter excess in the galactic center, but the necessary time is much larger than the universe age, even for the contemporary universe, with the age about 15 biliion years, 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, first a primordial SMBH was formed and later it seeded the galaxy formation. This idea was rediscovered recently under the pressure of HST and JWST observations.
The validity of AD/DKK mechanism is supported by the form of predicted mass spectrum of BHs, strongly confirmed by the data, and possible observation of antimatter in the Milky Way.

Brief content

Recent problems discovered by HST and LWST.
Cosmological problems of the contemporary universe
PBH solution of new and old problems
Antimatter in the MIky Way, including antistars
Observational tests of the predicted Log-normal mass spectrum of PBHs,
Black dark matter.
Gravitational waves and PBH.

The model is based on an unusual mechanism of BH creation, prepared at **inflation** from initially large isocurvature perturbations (baryon number density) transformed into matter density perturbations at the QCD phase transition.
The mechanism essentially differs fiom all others described in the literature.

JWST infrared telescope and HST



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

Comparison of JWST and HST

HST: Distance: 570 km
Mirror 2.4 m
Wave length: optical, e.g. blue 450 nm and UV,
some IR: 0.8-2.5 microns;

JWST: Distance 1.5×10^6 km
Mirror: 6.5 m
Wave length: 0.6 - 28,5 micron.

JWST and HST common galaxy

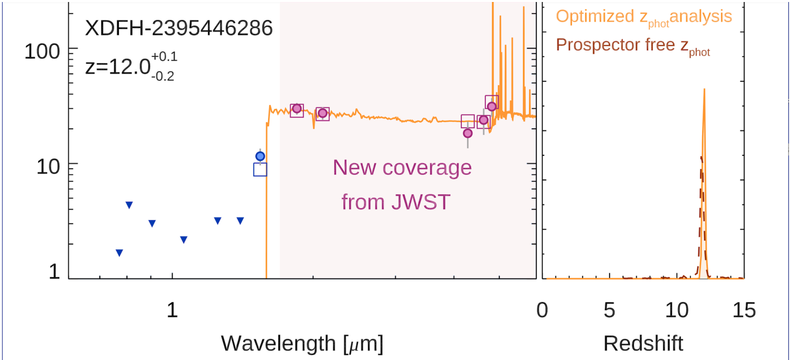
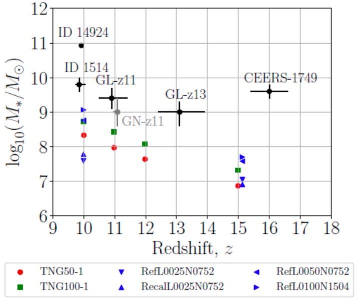


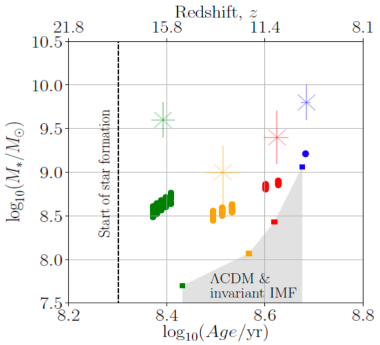
Figure 5. (*left*) Fits of a model spectral energy distribution to the observed *HST* + *JWST* photometry available for the highest redshift candidate UDFj-39546284 identified over the HUDF with *HST* (Bouwens et al. 2011a). Flux measurements blueward of 1.6μm are with *HST* (*blue filled points and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



Early galaxies, spectroscopic confirmation

Only continuum in micron range was measured till February. That raised doubts in determination of the redshifts of the observed galaxies.
Now numerous spectral observations excellently confirm the early data.

A couple examples of redshift confirmation:

S. Tacchella, et al arXiv:2302.07234 The JWST NIRCam 9-band near-infrared imaging of the luminous $z = 10.6$ galaxy GN-z11 from the JWST Advanced Deep Extragalactic Survey (JADES). **A spectral energy distribution (SED) is entirely consistent with the expected form of the high-redshift galaxy.**

A.J. Bunker, *et al* arXiv:2302.07256, JADES NIRSpec Spectroscopy of GN-z11: Lyman-α emission and possible enhanced **nitrogen** abundance in a $z = 10.60$ luminous galaxy, The spectroscopy of GN-z11, the most luminous candidate $z > 10$ Lyman break galaxy is presented. **Redshift of** $\mathrm{z} = 10.603$ **is derived (lower than previous determinations) based on multiple emission lines in low and medium resolution spectra over** $0.8 - 5.3\,\mu$**m.** The spectroscopy confirms that GN-z11 is a remarkable galaxy with extreme properties seen 430 Myr after the Big Bang.

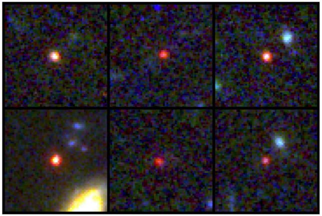
Early galaxies, spectroscopic confirmation

Another example by a diffrent instrument.

Age of Most Distant Galaxy is confirmed with Oxygen observation.
The radio telescope array ALMA (Atacama Large Millimeter Array) has pin-pointed the exact cosmic age of a distant JWST-identified galaxy, GHZ2/GLASS-z12, at 367 million years after the Big Bang. ALMA's deep spectroscopic observations revealed a spectral emission line associated with ionized Oxygen near the galaxy, which has been shifted in its observed frequency due to the expansion of the Universe since the line was emitted. This observation confirms that the JWST is able to look out to record distances, and **heralds a leap in our ability to understand the formation of the earliest galaxies in the Universe.**
NASA / ESA / CSA / T. Treu, UCLA / NAOJ / T. Bakx, Nagoya U. MNRAS, 22.02,2023.

Impossible galaxies

I. Labbé et al, A population of red candidate massive galaxies 600 Myr after the Big Bang, Nature, published online 22.02.2023, 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)

Ultra-massive early QSO observed 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, Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 3, April 2023, Pages 4609–4620, Published: 24.02.2023
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.
Nearly impossible, but PBH could seed such monster.

Rich chemistry

Unexpectedly high abundances of heavy elements (high metallicity)
(All elements heavier than helium are called metals.)
B. Peng, et al, The Astrophysical Journal Letters, Volume 944, Issue 2, id.L36, 8 pp. '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— amounts of elements heavier than helium and hydrogen, 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.

Rich chemistry

One more example of well developed chemistry, that demand long evolution with the conventional mechanism.

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:2302.10142, 20.02.2023.

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.

Suggested explanation: yields from runaway stellar collisions in a dense stellar cluster or a tidal disruption event provide promising solutions to give rise to these unusual emission lines at $z = 10.6$, and explain the resemblance between GN-z11 and a nitrogen-loud quasar.

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 primordial black holes (PBH) and the astrophysically large bubbles with very high baryonic density

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.

Problems of the contemporary universe. Summary.

1. SMBH in all large galaxies. Too short time for their formation through the usual 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: the Hobby-Eberly Telescope at Texas's McDonald Observatory suggested the presence of a black hole with a mass of about 17 billion $M_\odot$ equivalent to 14% of the total 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 that the universe?
4. MACHOs, non-luminous objects with masses $\sim 0.5\boldsymbol{M_\odot}$ obsserved through microlensing; origin unknown.
5. Problems with the BH mass spectrum in the Galaxy, masses are concentrated in the narrow interval $(7.8 \pm 1.2)\boldsymbol{M_\odot}$.
6. Origin and properties of the sources of the observed gravitational waves.
7. IMBH, with $\boldsymbol{M} \sim (10^3 - 10^5)\boldsymbol{M_\odot}$, in dwarfs and globular clusters, discovered but unexpected..
8. Strange stars in the Galaxy, too fast and with unusual chemistry. Observed during the last decade..

Solution of all the problems by PBH

To summarise, a large amount of observational data are at odds with the conventional model but nicely fits the model of creation of primordial black holes and primordial stars suggested by DS and DKK.
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 $\mu = 0$. At larger chemical potential the T_{pt} is smaller and M_{hor} is larger.

Seeding of galaxy formation by PBH

The hypothesis by DS (1993) and DKK (2006), that SMBH seeded galaxy formation allows to explain presence of SMBH in all large and several small galaxies accessible to observation This mechanism explains how the galaxies observed by JWST in the very young universe might be created. **It was rediscovered in two 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

A. Bogdan, et al Detection of an X-ray quasar in a gravitationally-lensed $z = 10.3$ galaxy suggests that early supermassive black holes originate from heavy seeds, 2305.15458 [astro-ph.GA]
Observations of high-redshift quasars reveal that many supermassive black holes were in place less than 700 Million years after the Big Bang.
However, the origin of the first BHs remains a mystery.
Seeds of the first BHs are postulated to be either light i.e., $(10 - 100)M_\odot$ remnants of the first stars or heavy i.e., $(10^4 - 10^5)M_\odot$, originating from direct collapse of gas clouds, according to the authors.
Much simpler and easier if the seeds are primordial BH, as predicted by DS and DKK.

Seeding of quasars by PBH

The same paper, A. Bogdan, et al Detection of an X-ray quasar in a gravitationally-lensed $z = 10.3$ galaxy suggests that early supermassive black holes originate from heavy seeds, 2305.15458 [astro-ph.GA]
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 $z \approx 10.3$ 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 $\sim$ 500 Myrs after the Big Bang is consistent with a picture wherein **such BHs originated from heavy seeds.**

Problems solved by PBH

The origin of IMBH is unknown in all mass ranges, though plenty of them are discovered everywhere.
Moreover, BH with $M \approx 100 M_\odot$ is strictly forbidden but nevertheless observed by LIGO/Virgo.

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

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

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.**

Primordial stars in the Galaxy

Jiaqi Martin Ying, *et al*, The Absolute Age of M92,
Astron.J. 166 (2023) 1, 18, e-Print: 2306.02180 [astro-ph.SR]
Absolute age of the globular cluster M92 is evaluated and found to be practically equal to the universe age, $t_{M92} = 13.8 \pm 0.75$ Gyr.
Possibly they came to us from JWST epoch or even from the earlier one.
The DS/DKK mechanism predicts early formation of compact stars, that do not have enough mass to turn into PBH. They could be stars as well antistars, but the latter might not survive in large numbers till the present time.

Pristine stars in the Galaxy

An international team of researchers, Pristine Inner Galaxy Survey (PIGS) team, has obtained the largest set of detailed observations yet of the oldest stars in the center of our Galaxy, the Milky Way. Some of the stars that were born in the first billion years after the Big Bang are still around today, presented by A. Arentsen from the University of Cambridge of the new work at the National Astronomy Meeting 2023 at the University of Cardiff.

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 $M \sim 100 M_\odot$. 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 $M > 100 M_\odot$. 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 easily 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_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.

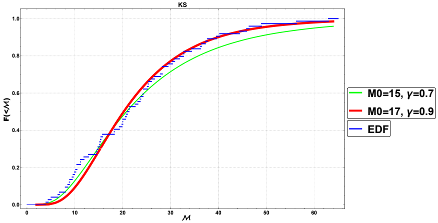
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

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

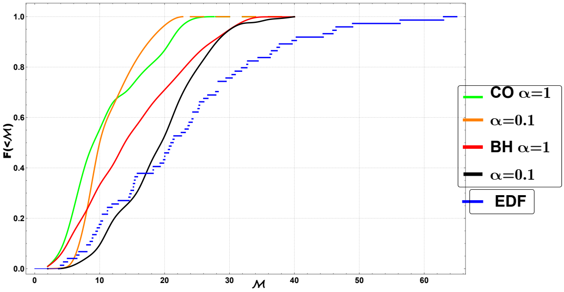
Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



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 - overlap with 2022 talk

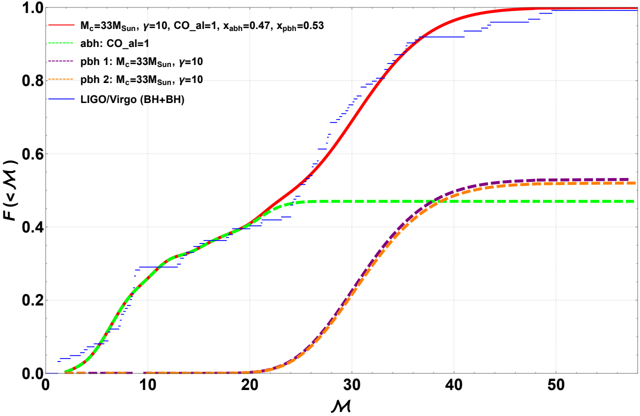
Cumulative distributions $F(< M)$ for several **astrophysical** models of binary BH coalescences.



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]. 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.



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

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 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 (caution, model-dependent).

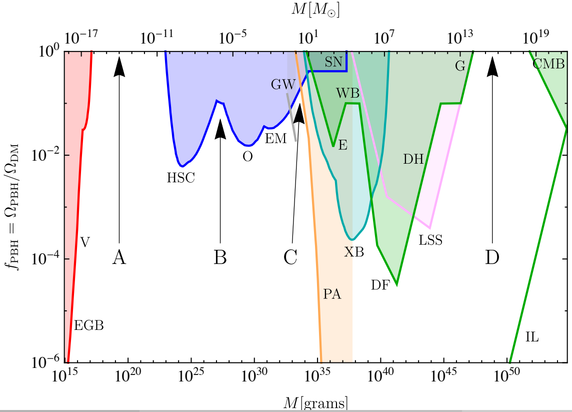


Figure caption

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.
Thanks to K. Postnov for these references.

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 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.

Astronomical data of the several recent years present strong evidence in favour of notieable antimatter population in our Galaxy including:

• 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 univerese:
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

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 positrons

However, this conclusion is questioned in astro-ph:1504.06472,
Signatures of a two million year old supernova in the spectra of cosmic ray protons, antiprotons and positrons,
M. Kachelriess, A. Neronov, D.V. Semikoz, where it is shown that
these features are consistently explained by a nearby source which was active ~ 2 Myr ago and has injected $(1-2)\times 10^{50}$ erg in cosmic rays.

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 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 $\overline{He}$!!!

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

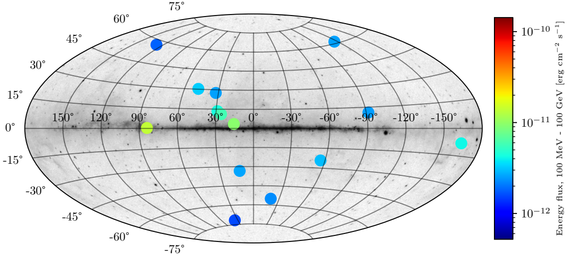


Рис.: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV

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, 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.

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 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.

ΛCDM cosmology is saved by PBH