Antimatter in the universe and in Galaxy

A.D. Dolgov

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Earliest searches for antimatter in Milky Way

According to the **unconditional faith** each galaxy consists only of matter and any amount of antimatter should be of secondary origin, created via cosmic ray interactions, and hence negligibly tiny.
The first person who doubted this commonly accepted "fact" was Boris Pavlovich Konstantinov with collaborators, who had initiated the search of galactic antimatter looking for meteors consisting of antimatter:

- B.P. Konstantinov, M.M. Bredov, Belyaevskii, A. I. *et al* "The Possible Antimatter Nature of **Micrometeorites**", Cosmic Research, Vol. 4, p.58, 1966.
- B.P. Konstantinov, R.L. Aptekar', M.M. Bredov, "Investigation of gamma-radiation on Cosmos 135 in connection with possible antimatter composition of **meteors**." Izv. Akad. Nauk SSSR, Ser. Fiz., **33**, p. 1820 1969.
- S.V. Golenetskii, B.P. Konstantinov, E. P. Mazets, et al *et al* "Investigation of Variations of Annihilation γ-Radiation by the Artificial Earth Satellite "Cosmos-135" in Connection with the Possible Antimatter Nature of **Meteor** Streams" Cosmic Research, Vol. 8, p.849, 1970.

[B.P. Konstantinov was a directer of the Leningrad (now Petersburg) Nuclear Physics Institute named in his honor.]

Search for antimatter in the Milky Way

Konstantinov was strongly criticized by Ya.B. Zeldovich, despite warm personal relationship between them, but Zeldovich was probably acting according to the famous credo: "Amicus Plato, sed magis amica veritas" - "Platon is my friend but the truth is dearer to me".
However, a very strong evidence is now obtained, confirming existence of different type and noticeable population of Milky Way with antimatter thus supporting Konstantinov's "heresy".

Antimatter in the Milky Way. Predictions.

Antimatter population of the Milky Way was predicted in our long-ago papers:
A.Dolgov, J.Silk, "Baryon isocurvature fluctuations at small scale and baryonic dark matter" PRD 47 (1993) 4244. (DS)
A.Dolgov, M.Kawasaki, N.Kevlishvili, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter", Nucl. Phys. B807 (2009) 229 (DKK),
where a model of consisting of baryonic or antibaryonic bubbles of high density in practically empty space was worked out.
Bubble with sufficiently high mass made primordial black holes,
while those, not massive enough, remained in the form of interstellar gas of star-like objects made of matter and antimatter.

Antimatter early history

Antimatter is justly associated with Paul Dirac, but still he was not the first person to guess about antimatter. In 1898, 30 years prior to Dirac and one year after discovery of electron (J.J. Thomson, 1897) Arthur Schuster (another British physicist) publishes a paper
A. Schuster, Nature, 58 (1898) 367. "Potential Matter. Holiday Dream"
where he conjectured that there could 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, though $\boldsymbol{E = mc^2}$ was not yet known.
Schuster believed that antimatter particles had negative mass and gravitationally repel from the matter ones.
Two such objects on close contact should have vanishing mass!?
Quoting the Schuster paper: "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, rediscovery

The real scientific father of antimatter is definitely Paul Dirac.
According to Werner Heisenberg: "his discovery of **antimatter** was perhaps the biggest jump of all big jumps in physics in our century" W. Heisenberg, in "The Physicist's Conception of Nature" (Kluwer Academic,1972), p.264.

Dirac anticipated that there could be antistars and possibly **antiworlds** in his Nobel Lecture "Theory of electrons and positrons", at December 12, 1933 dedicated to his prediction of positrons: "... 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."**
Strictly speaking the last statement is not correct. There are some, though difficult, may be even unrealistic, ways to distinguish a star from an antistar even at very large distances.

Stars and antistars possible distant identification

It seems that now we know some ways to distinguish stars from an antistars by observations from the Earth. As is discussed in 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 of the emitted radiation from weak decays and its polarization are not exactly the same and they could be good indicators. Also the spectrum of emitted neutrinos versus antineutrinos from supernovae or anti-supernovae would be different.

In the exotic case of CPT violation, when masses of particles and antiparticles and the total decay widths are not the same, more interesting possibilities could be open.

Antimatter in the universe

A review of "anti-situation" at the state of art in 2002 is presented in two keynote lectures at 14th Rencontres de Blois

F. W. Stecker, "The Matter-Antimatter Asymmetry of the Universe (keynote address for XIVth Rencontres de Blois)", 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, hep- ph/0211260.

Antimatter in the universe

Antimatter in the universe at large scales was thoroughly studied by Floyd Stecker:
• 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).
In this work a revolutionary statement has been made: that according to calculation of the cosmological γ-ray spectrum from matter-antimatter annihilation in the universe, the similarity of the calculated spectrum with the observations of the γ-ray background spectrum above 1 MeV suggests that such observations may be evidence of the existence of antimatter on a large scale in the universe.

Antimatter in the universe

This idea of anti-matter galaxies was later developed in:

• F.W. Stecker "A new view of Baryon symmetric cosmology based on grand unified theories", Presented at Oxford Intern. Symp. on Progress in Cosmology, England, Sep. 1981 Pub Date: September 1981.

• F. W. Stecker, "Grand Unification and possible matter-antimatter domain structure in the universe". Tenth Texas Symposium on Relativistic Astrophysics, p. 69 (1981). New York Academy of Sciences, Annals, vol. 375, Dec. 29, 1981, p. 69-89. Pub Date: December 1981.

Stecker argued that in the framework of grand unified theories, **spontaneous CP violation** leads to a domain structure in the universe with the domains evolving into separate regions of matter and antimatter excesses. This can result in population oi the universe of matter and antimatter galaxies.

Essentially the same ideas were replicated a year later in V.M. Chechetkin, M.Yu. Khlopov, M.G. Sapozhnikov, and Ya.B. Zeldovich, "Astrophysical aspects of antiproton interaction with 4He (antimatter in the universe)" Phys. Lett. B, 118, Issue 4-6, p. 329-332. Pub Date: December 1982

Anti-galaxies

If anti-galaxies exist, they could not be close to us. Some room is allowed for them but it is considerably restricted. It is argued by G. Steigman "Observational tests of antimatter cosmologies", Ann. Rev. Astron. Astrophys. 14, 339 (1976), that the nearest anti-galaxy should be out of our galaxy cluster and thus could not be closer than at ~ 10 Mpc.
In a subsequent paper by the same author: G. Steigman, "When Clusters Collide: Constraints On Antimatter On The Largest Scales", JCAP 10, 001 (2008); e-Print: 0808.1122 [astro-ph]. it is argued that the fraction of antimatter in Bullet Cluster **should be below** 3×10^{-6}**.**

The analysis, performed by A.G. Cohen, A. De Rujula, S.L. Glashow, "A Matter - antimatter universe?" Astrophys.J. 495 (1998) 539, e-Print: astro-ph/9707087 permits to conclude that the nearest anti-galaxy should be at least at 200 Mpc based on on the bounds to the observations of the the annihilation products. Future searches for antimatter via cosmic rays might increase this lower bound by an order of magnitude.

PBH Creation Mechanism and antimatter in the Galaxy

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. Randomly χ might rotate clock-wise or anti-clock-wise, creating either matter or antimatter.
Finally χ decays would transfer baryonic charge to that of quarks/antiquarks 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 the χ mass is non-zero, 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.

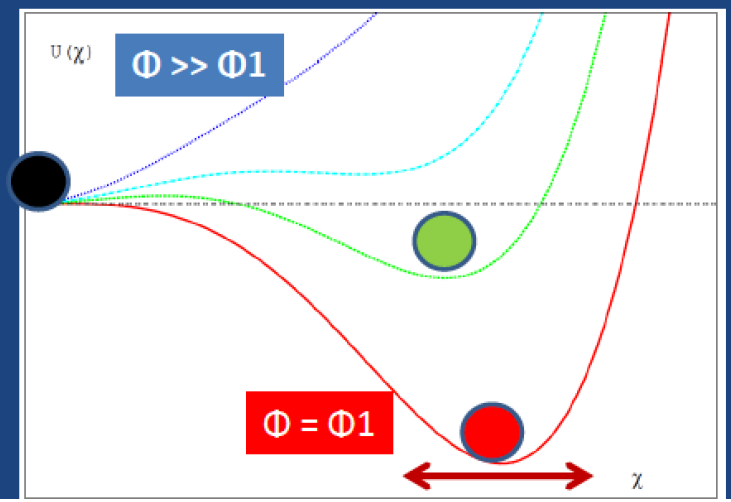
Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition. **The mechanism is very much different from other conventionl ones.**

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

Evolution of AD-field potential

Effective potential of χ for different values of the inflaton field Φ. The upper blue curve corresponds to a large value Φ >> Φ1 which gradually decreases down to Φ = Φ1, red curve. Then the potential returns back to the almost initial shape, as Φ drops down to zero. The evolution of χ in such a potential is similar to a motion of a point-like particle (shown as a black ball in the figure) in Newtonian mechanics. First, due to quantum initial fluctuations χ left the unstable extremum of the potential at χ = 0 and "tried" to keep pace with the moving potential minimum and later started to oscillate around it with decreasing amplitude. The decrease of the oscillation amplitude was induced by the cosmological expansion. In mechanical analogy the effect of the expansion is equivalent to the liquid friction term, $3H\dot{\chi}$. When Φ dropped below Φ1, the potential recovered its original form with the minimum at χ = 0 and χ ultimately returned to zero but before that it could give rise to a large baryon asymmetry

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



Log-normal mass spectrum

The log-normal mass spectrum of PBHs was predicted by Dolgov-Silk (DS) and further worked out in A.Dolgov, M. Kawasaki, N. Kevlishvili (DKK), NPB807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter":

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

According to DS and DKK scenario initial large perturbations of baryonic number (isocurvature perturbations, since quarks are massless) are generated at inflationary stage, transformed into density perturbations when massless quarks turned into heavy protons and neutrons. Hence M_0 is equal to horizon mass at the QCD phase transition: $M_0 \sim 10 M_\odot$: AD, K.Postnov, "Why the mean mass of primordial black hole distribution is close to $10 M_\odot$". JCAP 07 (2020) 063. The horizon mass at QCD p.t. is close to $10 M_\odot$, for $\mu = 0$. At larger chemical potential T_{pt} is smaller and M_{hor} is larger, namely, $\approx 17 M_\odot$, according to lattice calculations: I. Ya. Aref'eva, A.Hajilou K. Rannu, P Slepov "Magnetic catalysis in holographic model with two types of anisotropy for heavy quarks", Eur. Phys. J. C 83 (2023) 12, 1143, e-Print: 2305.06345 [hep-th].

Exactly what is observed.

Antimatter in the Milky Way

Antimatter is observed in our Galaxy, which was believed earlier to be absolutely impossible.

The data include observations of:

- positrons,
- antinuclei, observed by the AMS space spectrometer;
- strong indications to existence of antistars.

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,
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).
There is no commonly accepted point of view on the origin of the positrons. **Until recently a possiblle 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 and $\bar{p}$ cannot be created by such mechanism** L'Aquila Joint Astroparticle Colloquium, 10th November, 2021 by S. Ting.
Reviewed in: M. Aguilar et al. (AMS Collaboration), "Towards Understanding the Origin of Cosmic-Ray Positrons", Phys. Rev. Lett. **122** (2019) 041102.

Possible sources of positrons

A competing option is that positrons are created by the Schwinger process at the horizon of small black holes with masses 10^{20}g namely by positron production via proton to positron transformation at PBH horizon, as is suggested in

• C. Bambi, A.D. Dolgov, A.A. Petrov, Black holes as antimatter factories, JCAP 09 (2009) 013, arXiv:0806.3440 [astro-ph].

and discussed in more details in

• A.D. Dolgov, A.S. Rudenko, "Conversion of protons to positrons by a black hole", Phys. Part. Nucl. Lett. 21 (2024) 4, 865-872 • e-Print: 2308.01689.

One more possibility that is closer to the spirit of this talk is that positrons are primordial, produced in the early universe in relatively small antimatter domains.

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.

Deuterium/Helium problem

The observed ratio of (anti)deuterium to (anti)helium abundances at high energies is of the order of unity, whereas in standard primordial nucleosynthesis it is less than 10^{-4}.
There is noticeable discrepancy between the large fraction of D with respect to He. In the case of the standard BBN this ratio should be much smaller than unity, but the observed 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

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.

Possible discovery of anti-stars in the Galaxy

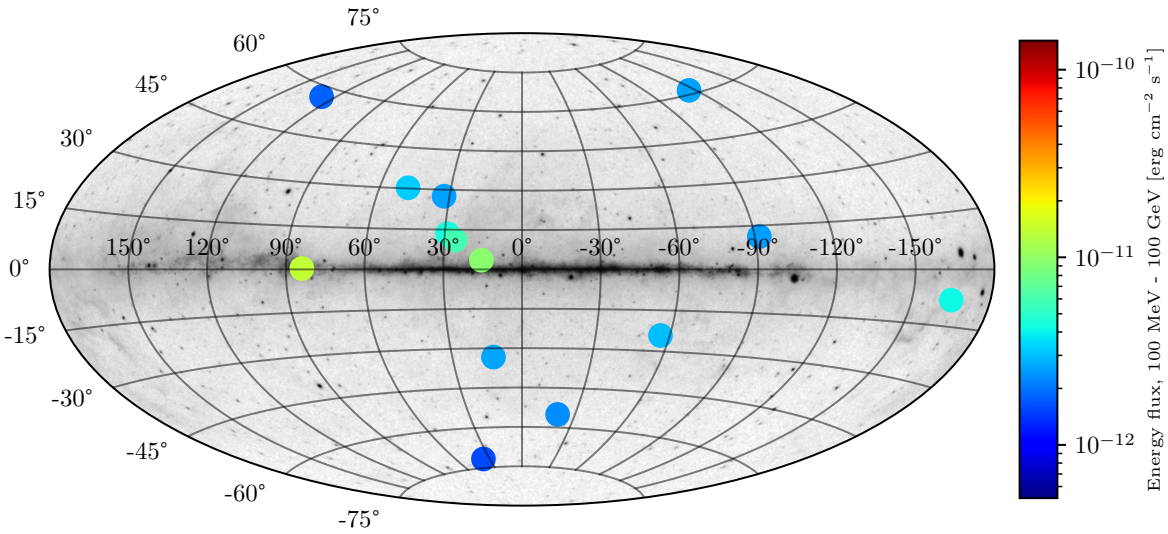


Figure: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV

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", JCAP 08 (2023) 027 • e-Print: 2304.04623 [astro-ph.HE].

Abstract: 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.

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, **385**, Issue 6707, p. 452; 2303.16223 [astro-ph.HE].
This event got the nickname: the Brightest Of All Time or the bf 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 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.
The only gamma-ray burst showing lines from e^+e^- annihilation.

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. A possible way out was proposed in J. Ziegler, K. Freese, "Mechanism for nonnuclear energy to fill in the black hole mass gap", Phys.Rev.D 109 (2024) 10, 103042 • e-Print: 2212.13903 based on assumption of dark matter annihilation inside heavy stars.
2. Formation of BH binaries from the original stellar binaries. Recoil momentum?
3. Low spins of the coalescing BHs .

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.

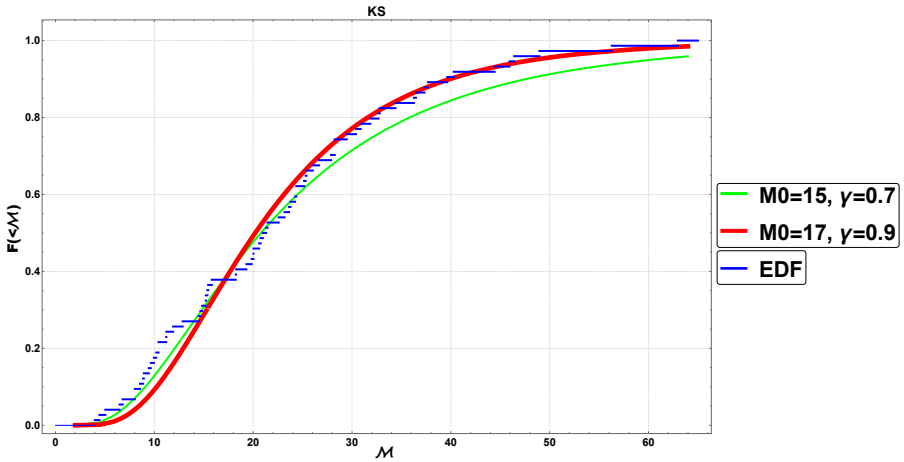
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

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.



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

The value $M_0 \approx 17 M_\odot$ perfectly well agrees with calculations of I.Ya. Aref'eva, A.Hajilou K. Rannu, P Slepov "Magnetic catalysis in holographic model with two types of anisotropy for heavy quarks", Eur. Phys. J. C 83 (2023) 12, 1143, e-Print: 2305.06345 [hep-th].

"Experimental" proof of the model

- PBHs with log-normal mass spectrum - **confirmed by astronomical data!**
- **Predicted abundant population in antimatter of our Galaxy is observed.**