From primordial black holes to primordial antistars

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Introduction or extended abstract

Announcement of observation of 14 antistars in the Galaxy. S. Dupourqué, L. Tibaldo, P. Von Ballmoos, Phys.Rev.D 103 (2021) 8, 083016 • e-Print: 2103.10073 [astro-ph.HE].
Impossible or expected?

Predicted in 1993 and elaborated in 2009:
A. Dolgov and 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".

Introduction or extended abstract

Observational bounds are rather loose because the annihilation proceeds only on the surface of the compact 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

How reliable is the prediction of antistars in the Galaxy? The mechanism predicts the log-normal mass spectrum of PBH, well confirmed by the observations AD, K.A.Postnov et al, JCAP 07 (2020) 063 • 2004.11669 and JCAP 12 (2020) 017, 2005.00892.

This model of PBH creation also predicts antistars.

Since the predicted features of PBH well agree with the data one may expect that antistars in the Galaxy quite possibly exist.

Content

1. Possible discovery of antistars in the Galaxy.
2. Antistar dark matter.
3. Basic features of PBH creation; mass spectrum and parameters
4. A model of abundant antistar creation in galaxies.
5. Conclusion

Discovery of antistars?

Possible discovery of several **antistars in the Galaxy** was recently reported: "Constraints on the antistar fraction in the Solar System neighborhood from the 10-year Fermi Large Area Telescope gamma-ray source catalog." S. Dupourqué, L. Tibaldo, P. Von Ballmoos, Phys.Rev.D 103 (2021) 8, 083016 • e-Print: 2103.10073 [astro-ph.HE] "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."

Dark antimatter

In a recent publication a striking idea was put forward that dark matter may consist of compact anti-stars: J. S. Sidhu, R.J. Scherrer, G. Starkman, "Antimatter as Macroscopic Dark Matter", arXiv:2006.01200, astro-ph.CO. Such anti-DM may be easier to spot than other forms of macroscopic DM.

If anti-stars make dark matter, they should populate the galactic halo, as any other form of dark matter, i.e. they must be primordial, or at least pregalactic, anti-stars.

Antimatter creation by mirror matter

A competing idea was proposed in:

Antistars or antimatter cores in mirror neutron stars? Zurab Berezhiani (Jun 21, 2021) e-Print: 2106.11203 [astro-ph.HE]

The oscillation of the neutron n into mirror neutron n', its partner from dark mirror sector, can gradually transform an ordinary neutron star into a mixed star consisting in part of mirror dark matter. The implications of the reverse process taking place in the mirror neutron stars depend on the sign of baryon asymmetry in mirror sector. Namely, if it is negative, as predicted by certain baryogenesis scenarios, then $\bar{n}' - \bar{n}$ transitions create a core of our antimatter gravitationally trapped in the mirror star interior. The annihilation of accreted gas on such antimatter cores could explain the origin γ-source candidates, with unusual spectrum compatible to baryon-antibaryon annihilation, recently identified in the Fermi LAT catalog, In addition, some part of this antimatter escaping after the mergers of mirror neutron stars can produce the flux of cosmic antihelium and also heavier antinuclei which are hunted in the AMS-02 experiment.

Antistar prediction

Existence of antistars in the Galaxy was predicted many years ago.
Mechanism of massive PBH formation with log-normal mass spectrum:
A. Dolgov and J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scale and baryonic dark matter."
Log-normal mass spectrum is predicted.

A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter".
The suggested mechanism allows to solve multiple problems related to the observed BH population in the universe:

- PBHs formed according to this scenario explain the peculiar features of the sources of GWs observed by LIGO/Virgo.
- The existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is explained.

Conventional models are short by two orders of magnitude.

SMBH and IMBH in contemporary and $z \sim \mathbf{10}$ universe

Universe is full of supermassive black holes (SMBH), $M = (10^6 - 10^{10}) M_\odot$ and intermediate mass black holes (IMBH), $M = (10^2 - 10^5) M_\odot$.
Unexpectedly high amount in the present day and the early, $z = \mathbf{5} - \mathbf{10}$ universe. Are they primordial?

Review of astrophysical problems in A.D. "Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics," Usp. Fiz. Nauk 188 (2018) 2, 121; Phys. Usp. 61 (2018) 2, 115.
Log-normal mass spectrum with the predicted value $M_0 \sim 10 M_\odot$ (A.D. and K. Postnov) very well describes the data

Antistar prediction

The proposed mechanism of massive PBH creation allow to cure multipie inconsistencies with the standard cosmology and astrophysics. **Unusual stellar type compact objects are also created, including abundant antistars in the Galaxy.**

The chirp mass distribution of LIGO events very well agrees with theoretical predictions, AD, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, et al JCAP 12 (2020) 017 - **a strong support of the scenario.**

Chirp mass distribution

A.D. Dolgov, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, and I.V. Simkine On mass distribution of coalescing black holes, e-Print: 2005.00892 [astro-ph.CO], May, 2020.

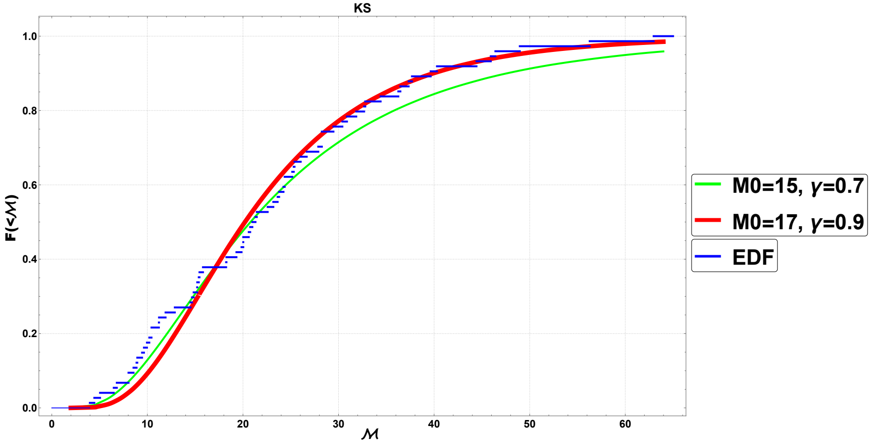
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

The inferred best-fit mass spectrum parameters, $M_0 = 17 M_\odot$ and $\gamma = \mathbf{0.9}$, fall within the theoretically expected range and shows excellent agreement with observations.

On the opposite, binary black hole models based on massive binary star evolution require additional adjustments to reproduce the observed chirp mass distribution.

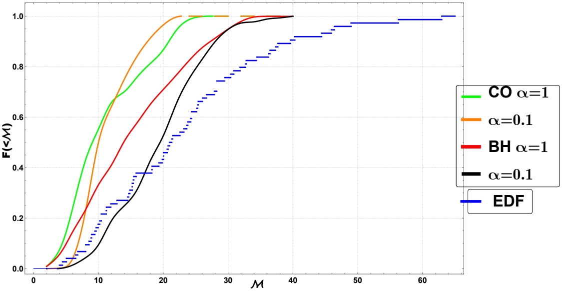
Chirp mass distribution

Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



Chirp mass distribution, astrophysical BHs

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 disfavored.

Bounds on antistars in the Galaxy

As argued in:
C. Bambi, A.D. Dolgov, **"Antimatter in the Milky Way",** Nucl.Phys.B 784 (2007) 132-150 • e-Print: 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 • e-Print: 1309.3395,
S.I. Blinnikov, A.D. Dolgov, K.A. Postnov, **"Antimatter and antistars in the universe and in the Galaxy",** Phys.Rev.D 92 (2015) 2, 023516 • e-print: 1409.5736
an abundant density of compact anti-stars in the universe and even in the Galaxy does not violate existing observational limits. Such anti-DM may be easier to spot than other forms of macroscopic DM.
Surface annihilation on a compact object is much less efficient than volume annihilation, e.g. inside gas cloud of antimatter.

Anti-Creation Mechanism

The mechanism of massive PBH and antistar formation:
A. Dolgov and 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".
Massive PBHs allow to cure multpie inconsistencies with the standard cosmology and astrophysics.
Unusual stellar type compact objects could also be created.
The model predicts the log-normal mass spectrum of PBH:

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

and predicts $M_0 \approx 10 M_\odot$. A.Dolgov, K.Postnov, Why the mean mass of primordial black hole distribution is close to $10M_\odot$. JCAP 07 (2020) 063 • e-Print: 2004.11669 . Very well agrees with observations.

Anti-Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD).
SUSY predicts existence of scalars with $\mathbf{B \neq 0}$. 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.

Anti-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}.

Anti-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.

Anti-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.

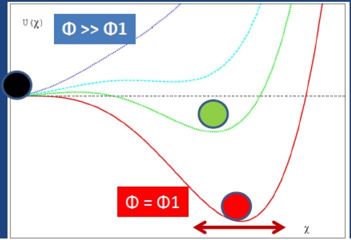
Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition.

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

Evolution of AD-field potential

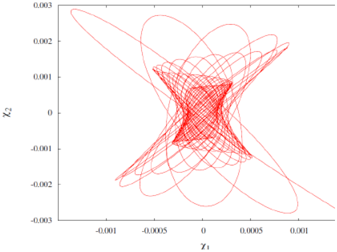
Effective potential of χ for different values of the inflaton field Φ. The upper blue curve corresponds to a large value Φ >> Φ1 which gradually decreases down to Φ = Φ1, red curve. Then the potential returns back to the almost initial shape, as Φ drops down to zero. The evolution of χ in such a potential 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

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



(Dolgov -Kawasaki-Kevlishvili)
Field χ ”rotates” in this plane with quite large angular momentum, which exactly corresponds to the baryonic number density of χ. Later χ decayed into quarks and other particles creating a large cosmological baryon asymmetry.

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



Results of (Anti-)Creation

The outcome, depending on $\beta = n_B / n_\gamma$.

- 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 formation is strongly supported by astronomical observation and thus the chances another prediction of this mechanism of abundant population of the Galaxy by antistars has high chance to be true.

THE END or BEGINNING?