Primordial Antimatter
(Possible Antistars in the Galaxy)

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Content (in arbitrary order)

• **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].**

• **Other evidence of primordial antimatter.**

• Impossible or expected? Mechanism description
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".

• **New X-ray window to antistars.** A.E. Bondar, S.I. Blinnikov, A.M. Bykov, A.D. Dolgov, K.A. Postnov, e-Print: 2109.12699.

Antimatter in cosmology

Canonical picture, (A.D. Sakharov, 1967):

1. Non-conservation of baryonic number.
2. **Explicit C and CP violation.**
3. Deviation from thermal equilibrium.

Allows to explain the observed baryon baryon asymmetry

$$\beta = \frac{N_B}{N_\gamma} = 6 \times 10^{-9}$$

where $N_\gamma = 411/\text{cm}^3$ - number density of CMB photons.
According to this model β is a universal "cosmological constant", the same over all the universe. No antimatter at all except for secondary produced antiparticles: antiprotons, positrons, antinuclei.

Antimatter in cosmology

Spontaneous C and CP breaking, induced by a nonzero vacuum value of a complex scalar field acquiring different signs in different patches of space (T.D. Lee, 1974). Double well potential:

$$U(\phi) = -m^2\phi^2 + \lambda\phi^4$$

leads to formation of domains of matter and antimatter. They should be much larger than the galactic size, otherwise diffusion and subsequent annihilations would destroy them. $l_B \gtrsim$ **Gpc** (A. Cohen, A. De Rujula, and Sh. Glashow, 1996).

Domain wall problem.

Antimatter in cosmology

Dynamical or stochastic C(CP) violation (AD, 1992, 2005) a complex scalar field pushed away from the equilibrium point by quantum instability of massless, $m_\phi \ll H$, scalar at inflationary stage.
Domain structure but no domain wall problem,

$$U(\phi) = m^2\phi^2 + \lambda\phi^4.$$

In all the cases large structures consisting either of matter or antimatter, much larger than galaxies are formed, while galaxies consist solely of one form of (anti)matter.

Observational bounds

From cosmic gamma rays:
Nearest anti-galaxy could not be closer than at $\sim$10 Mpc (Steigman, 1976), from annihilation with p in common intergalactic cloud.
Fraction of antimatter Bullet Cluster $< 3 \times 10^{-6}$ (Steigman, 2008).
CMB excludes LARGE isocurvature fluctuations at $d > 10$ Mpc.
BBN excludes large "chemistry" fluctuations at $d > 1$ Mpc.

Review: P. von Ballmoos, arXiv:1401.7258 Bondi accretion of interstellar gas to the surface of an antistar:

$$L_\gamma \sim 3 \cdot 10^{35} (M/M_\odot)^2 v_6^{-3}$$

put a limit $N_{\bar{*}}/N_* < 4 \cdot 10^{-5}$ inside 150 pc from the Sun.
The presented bounds are true if antimatter makes the same type objects as the OBSERVED matter.
For example, compact stellar-like objects made of antimatter may be abundant in the Galaxy but still escape observations (discussed below).

Antimatter in cosmology

Summary: **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 antistars might live in the Galaxy and in its halo:

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".

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.

Possible ways for search for antimatter in the Galaxy

- **Observation of excessive positrons.**
- **Observations of anti-nuclei.**
- **Observations of gamma-rays with 100-1000 MeV.**
- **Observations of keV X-rays (project, 2021)**

Anti-data: cosmic positrons

Observation of 0.511 MeV line from Galactic centre, evidence e^+e^--annihilation at rest. In the central region of the Galaxy electron–positron annihilation proceeds at a surprisingly high rate:

$$\Phi_{511\ \mathrm{keV}} = 1.07 \pm 0.03 \cdot 10^{-3}\ \mathrm{photons\ cm^{-2}\,s^{-1}}$$

with the width of about 3 keV. 511 keV line emission is significantly detected towards the galactic bulge region and, at a very low level, from the galactic disk.

G. Weidenspointner *et al.*, "The sky distribution of positronium annihilation continuum emission measured with SPI/INTEGRAL", Astron. Astrophys. **450**, 1013 (2006), astro-ph/0601673.
J. Knodlseder *et al.*, "The sky distribution of positronium annihilation continuum emission measured with SPI/INTEGRAL", Astron. Astrophys. **441**, 513 (2005) [arXiv:astro-ph/0506026].
P. Jean *et al.*, "Spectral analysis of the Galactic e+e- annihilation emission", Astron. Astrophys. **445**, 579 (2006) [arXiv:astro-ph/0509298].

Anti-data: cosmic positrons

Earlier measurements:

The first evidences of the Galactic 511 keV line date back to the '70s:
W.N. Johnson, F.R. Harnden, R.C. Haymes,
"The Spectrum of Low-Energy Gamma Radiation from the Galactic-Center Region". Astrophys. J. **172**, L1 (1972);
M. Leventhal, C.J. MacCallum and P.D. Stang,
"Detection of 511 keV positron annihilation radiation from the galactic center direction." Astrophys. J. **225**, L11 (1978).
Over the past 40 years, there have been numerous publications on the observation of this line, see e.g.
W.R. Purcell *et al.* "OSSE Mapping of Galactic 511 keV Positron Annihilation Line Emission", Astrophys. J. **491**, 725 (1997);
P.A. Milne, et al Supernovae and Positron Annihilation, New Astron. Rev. **46**, 553 (2002) [arXiv:astro-ph/0110442]. and references therein for earlier measurements.

Anti-data: cosmic anti-nuclei

Observation of antihelium: **AMS-02 reported possible registration of six anti-helium-3 and two anti-helium-4 events**

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.

The secondary production of $\bar{\mathrm{He}}^4$ has negligible probability.

Anti-deuterium is produced in $\bar{p}\,p$ or $\bar{p}\,He$ collisions (Duperray et al, 2005) The predicted flux of anti-deuterium:

$\sim 10^{-7}/m^2/s^{-1}/sr/(GeV/n)$,

i.e. 5 orders of magnitude lower than the observed flux of antiprotons.

The expected fluxes of secondary produced $^3\bar{He}$ and $^4\bar{He}$ are respectively 4 and 8 orders of magnitude smaller than the flux of anti-D.

After AMS announcement of possible observation of anti-He^4, there appeared attempts to create anti-He^4 in dark matter annihilation (?).

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

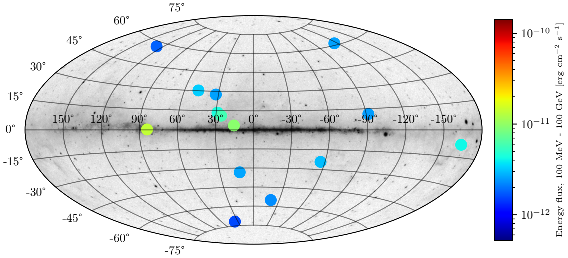


Figure: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV

Gamma ray signatures of antistars

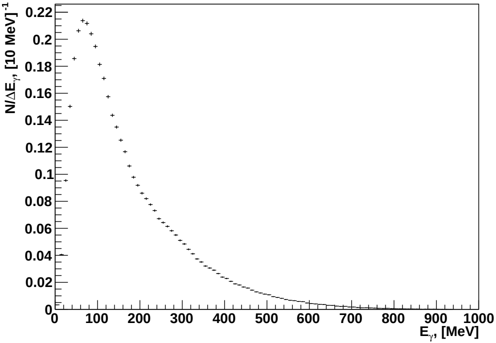


Figure: Gamma-ray spectrum from hadronic $p\bar{H}$ annihilation. The mean number of γ-quanta per event is $< N_\gamma >= 4.12$. The mean number of $\gamma-$quanta above 100 MeV is 2.63 per event. The mean energy radiated in gamma-rays per one annihilation is $\Delta E_\gamma = 617.5$ MeV. Calculations by Geant4 code.

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] 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.

Other ways to spot antistars

"How to see an antistar"
A.D. Dolgov, V. A. Novikov, M. I. Vysotsky JETP Lett. 98 (2013) 519-522 • e-Print: 1309.2746 [hep-ph]
Polarisation of photons emitted in weak decays occurring at distant star allows to determine whether this star is made from antimatter. Even more promising is the observation of neutrinos (antineutrinos) produced at neutronisation (antineutronisation) reactions at the beginning of SN (SN) explosion.

A.D. Dolgov, I.B. Khriplovich, A.S. Rudenko 'Difference between radiative transition rates in atoms and antiatoms". JETP Lett. 96 (2012) 421-423; e-Print: 1208.3565

Both are not much promising at the present state of art.

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 suggestion on galactic antimatter 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 (in fact in all the galaxies) was predicted many years ago.

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".

The mechanism predicted a large population of massive and supermassive primordial black holes (PBH) with **log-normal mass spectrum in perfect agreement with observations.**

It also allows to solve multiple problems related to the observed black holes in the universe in all mass values, in particular, **the origin of supermassive BHs and black holes with intermediate masses, from $M \sim 10^2 M_\odot$. up to $10^5 M_\odot$, otherwise mysterious.**

As a by-product compact stellar type objects, which are not massive enough to form BHs, made of matter and antimatter are predicted.

The predicted mass spectrum of PBHs

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 $10 M_\odot$". JCAP 07 (2020) 063 e-Print: 2004.11669 . In excellent agreement with observations.

The log-normal form of the mass spectrum of primordial black holes is strongly confirmed by the chirp mass distribution of the LIGO events, AD, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, I.V. Simkin, **"On mass distribution of coalescing black holes,"** JCAP 12 (2020) 017

Chirp mass distribution

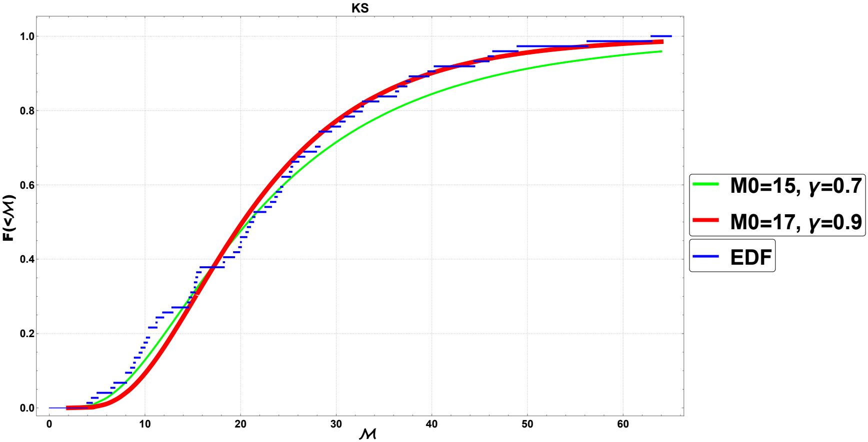
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/ runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum.

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.

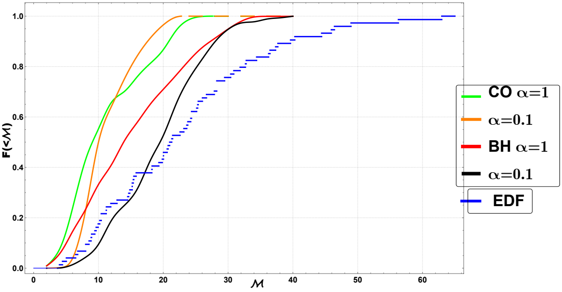
Chirp mass distribution

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.

Why can we trust the antistar creation model

How reliable is the prediction of antistars in the Galaxy?

The mechanism predicts the log-normal mass spectrum of PBH, observed by LIGO/Virgo, well confirmed by the observations: AD, K.A.Postnov et al, JCAP 07 (2020) 063, 2004.11669 and JCAP 12 (2020) 017, 2005.00892. PBHs formed according to this scenario explain the peculiar features of the sources of GWs observed by LIGO/Virgo, S. Blinnikov, AD, N. Porayko, K. Postnov, Solving puzzles of GW150914 by primordial black holes, JCAP 11 (2016) 036.

The proposed mechanism of massive PBH creation allow to cure multipie inconsistencies with the standard cosmology and astrophysics. 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.

The existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is explained.

Why can we trust the antistar creation model

The 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, $\boldsymbol{z = 5 - 10}$ universe. Are they primordial?

Log-normal mass spectrum with the predicted value $\mathbf{M_0 \sim 10M_\odot}$ (A.D. and K. Postnov) and $\boldsymbol{\gamma \sim 1}$ very well describes the data on the IMBH and SMBH.

Why can we trust the antistar creation model

The predicted features of PBH in all mass ranges well agree with the data, thus one may expect that the underlying mechanism of their creation indeed operated in the early universe.
This perfectly working model of PBH creation also predicts creation of primordial antistars, so it is quite natural to see a population of antistars in the Galaxy.
Unusual stellar type compact objects could also be created, in particular, extremely old stars, even a star formally older then the universe, are observed.
It looks too old because its initial chemistry is enriched by heavy elements.

Anti-Creation Mechanism

Creation of of rich population of BBH and antistars is based on SUSY motivated baryogenesis, Affleck and Dine (AD), which operated in the very early universe in a relatively small fraction of space.

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 was away from origin and, when inflation was over, it started to evolve down to the equilibrium point, $\chi = 0$, according to the equation of Newtonian mechanics with the Hubble friction term:

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

Baryonic charge of χ:

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

is analogous to mechanical angular momentum. χ decays transferred its 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}.
DSP

Anti-Creation Mechanism

If $m \neq 0$, the angular momentum, B, is generated by different directions of the quartic and quadratic valleys at low χ. If CP-odd phase α is 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.

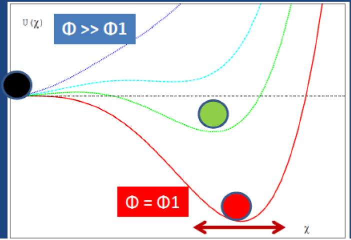
Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition.

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

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

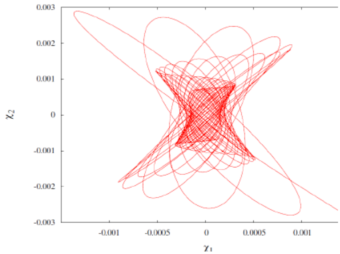


Evolution of AD-field

- $\varrho_\chi \ll \varrho_\Phi$, even inside large χ bubbles.
- Bubbles with large χ occupy a small fraction of the universe volume.
- When $\Phi < \Phi_1$ but inflation still lasts, χ is large and oscillates fast. Hence it does not feel shallow valleys of $m^2\chi^2$. At this stage baryon asymmetry is not generated.
- Inflation ends and the oscillations of Φ heats up the universe.
- Ultimately the amplitude of χ drops down, the field started to feel m^2-valley, and started to rotate, generating large baryon asymmetry.
- The picture is similar to the original AD-scenario in the universe.
- With the chosen values of couplings and masses the density contrast between the bubles and the rest of the world can be rather small, at the per-cent level.

(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 created.
- **β may be negative leading to creation of (compact?) antistars which could survive annihilation with the homogeneous baryonic background.**
- Disperse hydrogen and helium clouds with (much) higher than average n_B density. Simiilar anti-clouds already annihilated (?) in matter dominated backgound
- Strange stars with unusual chemistry and velocity.
- Extremely old stars would exist even, "older than the universe" are found; the old 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.

MORE DATA ARE BADLY NEEDED