Phenomenology of Axion Miniclusters

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I review possible observational phenomena appearing in models leading to dense small-scale substructures in the axionic dark matter. Also, I discuss their imaginable implications for the direct dark matter searches in the laboratory.

1 Introduction

In a wide variety of axion models, the Dark Matter (DM) on smallest scales, $M \sim 10^{-12}\, M_\odot$, is confined in very dense axionic clumps, called miniclusters. Moreover, in every model the DM is clustered on all scales, starting from miniclusters and up to galaxies and clusters of galaxies. In the mass range $10^{-12}\, M_\odot \lesssim M \lesssim 10^{7}\, M_\odot$ the corresponding clusters are called minihalos. Over the lifetime of the Galaxy, these structures may be tidally destroyed forming tidal streams. In this talk I review and discuss possible phenomenological consequences of these structures, both for indirect and direct DM searches.

2 Axion Miniclusters

Let us specify the density of a dark-matter fluctuation prior to matter-radiation equality as $\delta\rho_a/\rho_a \equiv \Phi$. In situation when $\Phi \sim 1$ (which would correspond to non-interacting axion field $a \equiv f_a\theta$ with random initial conditions), these clumps separate from cosmological expansion and form gravitationally bound objects already at $T = T_{\rm eq}$, where $T_{\rm eq}$ is the temperature of equal matter and radiation energy densities. However, at the time when axion oscillations commence, in many regions $\theta \sim 1$, and self-interaction is important, $V(\theta) = m_a^2 f_a^2[1 - \cos(\theta)]$. Numerical investigation of the dynamics of the axion field around the QCD epoch [1, 2, 3, 4] had shown that the non-linear effects lead to "fluctuations" with Φ much larger than unity, possibly as large as several hundred. In such situation a clump separates from cosmological expansion at $T \simeq (1 + \Phi)T_{\rm eq}$ resulting in a final minicluster density today given by

$$\rho_{\rm mc} \simeq 7 \times 10^6\, \Phi^3(1 + \Phi)\, {\rm GeV/cm}^3. \tag{1}$$

This should be compared to mean DM density in the Solar neighborhood in the Galaxy, $\bar\rho \approx 0.3$ GeV/cm^3.

The scale of minicluster masses is set by the total mass in axions within the Hubble radius at a temperature around $T \approx 1$ GeV when axion oscillations commence, which is about

$$M_{\rm mc} \sim 10^{-12} M_\odot. \tag{2}$$

Masses of miniclusters are relatively insensitive to the particular value of Φ associated with the minicluster. The corresponding minicluster radius as a function of M and Φ is:

$$R_{\rm mc} \approx \frac{3 \times 10^7}{\Phi\,(1+\Phi)^{1/3}} \left(\frac{M}{10^{-12} M_\odot}\right)^{1/3} \text{km}\,. \tag{3}$$

According to Ref. [4], more than 13% of all axionic dark matter are in miniclusters with $\Phi \gtrsim 10$, more than about 20% are in miniclusters with $\Phi \gtrsim 5$ and 70% are in miniclusters $(\Phi > 1)$. Roughly half of all axions reside in miniclusters.

2.1 Bose-condensation

It is remarkable that in spite of the apparent smallness of axion quartic self-coupling, $|\lambda_a| \approx (f_\pi/f_a)^4 \sim 10^{-53}(10^{12}\ \mathrm{GeV/f_a})^{-4}$, the subsequent relaxation in an axion minicluster due to $2a \to 2a$ scattering can be significant as a consequence of the huge mean phase-space density of axions [5]. Then, instead of the classical expression, $t_R^{-1} \sim \sigma \rho_a v_e m_a^{-1}$, where σ is the corresponding cross section and v_e typical velocity in the gravitational well, one gets [5] for the relaxation time $t_R^{-1} \sim \lambda_a^2 \rho_a^2 v_e^{-2} m_a^{-7}$. The relaxation time is smaller than the present age of the Universe for miniclusters with $\Phi \gtrsim 30$ [1] which leads to a possibility of Bose-star formation inside such miniclusters. Characteristic sizes and limiting masses of resulting objects can be estimated as follows (if self coupling is negligible, otherwise see [6])

$$R \approx \frac{1}{m_a v_e} \approx 300\, \frac{10^{-12} M_\odot}{M_{BS}} \left(\frac{10\,\mu\text{eV}}{m_a}\right)^2 \text{km}. \tag{4}$$

The maximum possible mass of a stable Bose-star corresponds to $v_e \sim 1$ or $M_{\rm max}(\lambda = 0) \approx M_{\rm Pl}^2/m_a$. For non-interacting axions this would be in the range of $\sim 10^{-5} M_\odot$.

However, regardless of its smallness, the axion self-coupling cannot be neglected in the discussion of Bose-star stability as well [7]. The self-coupling of axions is negative and their interaction is attractive. Consequently, instability develops when $M_{\rm max}(\lambda < 0) = f_a\, M_{\rm Pl}/m_a \sim 10^{-12} M_\odot\,(10\,\mu\text{eV}/m_a)^2$. Overall, with time the mass of the Bose-condensed core, M_{BS}, in the minicluster grows, while its radius shrinks. When the mass of M_{BS} approaches $M_{\rm max}(\lambda < 0)$, the core collapses. At this moment its radius is equal to [7]

$$R_{\rm min} \sim M_{\rm Pl}/f_a m_a \approx 200\ \text{km}, \tag{5}$$

regardless of m_a. Note that the maximum mass for a stable axion Bose-star at $m_a = 10\,\mu$eV is of the order of the typical mass of the axion minicluster.

2.2 Fast Radio Bursts and Axion Bose-stars

The existence of axion Bose-stars and their explosions into electromagnetic radiation may explain recently discovered phenomena of Fast radio bursts (FRB). Potentially, there are two processes of explosive axion conversion into photons in astrophysical environment. The first process is coherent (parametric resonance) conversion, $a \to 2\gamma$, in a sufficiently dense axionic medium [6]. Second is $a \to \gamma$ in a strong magnetic field of a neutron star (magnetar) [8, 7]. The feasibility and relevance of both processes has to be studied yet in detail. Here we just stress the similarity of observed characteristics of FRBs to the explosions of axion Bose stars, if the latter do occur.

FRBs exhibit a frequency-dependent time delay, which obeys a quadratic form so strictly, that the only remaining explanation is signal dispersion in cosmic plasma during propagation, for the review see Ref. [9]. The magnitude of this delay is so large that the cosmological distances are inferred for the FRB sources, $z \sim 1$.

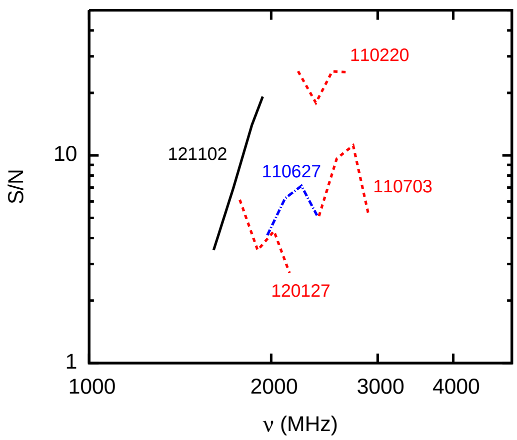

Figure 1: Fast Radio Burst (FRB) spectra shifted to their rest frame [7].

Now, we can compare parameters of FRBs and axion Bose-star explosions.

• Observed fluxes imply that the total energy radiated in the band of observation was in the range $10^{38} - 10^{40}$ ergs, assuming isotropy and quoted redshifts. Now, the typical axion minicuster mass is $10^{-12} M_\odot = 2 \times 10^{42}$ ergs, see Eq.(2). Therefore, the overall energy budget is appropriate and less then 1% conversion efficiency of a minicluster mass into γ radiation is sufficient to explain FRBs.

• Fast radio bursts occur on a very short time scale of millisecond. This implies that the size of the emitting region is small, less then 300 km. This should be compared to the radius of axion Bose-star, Eqs (4) and (5).

• Bursts are frequent, they occur at a high rate, $\sim 10^4$ events/day for the whole sky. This can also be matched (though the issue requires further study), given that the total number of miniclusters in the Galaxy is large, $N \sim 10^{24}$.

• If sources of FRBs are at Gpc distances, their brightness temperature would be $T_B \sim 10^{36}$ K, leading to the conclusion that the radiation from FRB sources should be coherent. Now, both processes of axion to photon conversion mentioned above would lead to a coherent radiation. Moreover, the spectrum will be strongly peaked at the (half) axion mass. This should be compared to FRB spectra shifted to their rest frame, see Fig. 1, which is consistent with spectra being peaked at one and the same frequency, taking into account uncertainties in FRBs redshifts. Such spectra would be unusual for pure astrophysical phenomena.

3 Miniclusters, minihalos and direct DM searches

Axion miniclusters originate from specific density perturbations with $\Phi \gtrsim 1$ which are consequence of non-linear axion dynamics around QCD epoch. Most abundant are miniclusters with $\Phi \approx 1$. There are 10^{24} of such miniclusters in the Galaxy and their density in the Solar neighborhood is 10^{10} pc^{-3}. Today minicluster with $\Phi \approx 1$ will have radius $\sim 10^7$ km. Therefore, during direct encounter of the laboratory with minicluster the local DM density increases by a factor 10^8 for about a day. That would create terrific signal in the detectors. However direct encounter with the Earth would occur less than once in 10^5 years [3].

In any axion model, as in any other cold dark matter model, structures form also on all scales, from galaxies to scales which are much smaller then a dwarf satellite galaxy. This is one and the same mechanism which leads to a galaxy formation from primordial density perturbations, i.e. corresponds to $\Phi \ll 1$. For WIMPs this process continues down to clumps with $M \sim 10^{-6} M_\odot$, which corresponds to the cut-off scale due to free streaming in a typical WIMP model. For axion DM such minihalos will form down to even smaller scales, down to $M \sim 10^{-12} M_\odot$, which is typical minicluster mass and it corresponds to the mass of all axions in the horizon volume at the epoch when axion oscillations commence. This process has been numerically modeled both for WIMPs and axions in Ref. [10] in the mass range $10^{-6}\, M_\odot \lesssim M \lesssim 10^{-4}\, M_\odot$. For a minihalo with $M \sim 10^{-6} M_\odot$ (which corresponds in our notations to $\Phi = 0.016$) one concludes that the density of such DM haloes in the Solar neighborhood is ~ 500 pc^{-3}, direct encounter with the Earth occurs once in 10^4 years, and during encounter DM density increases by a factor of 100 for about 50 years. That would also create very interesting signal in the detectors, but all those minihalos are tidally destroyed actually, producing an uninteresting density field. The situation is different for axion miniclusters though.

4 Axion streams

4.1 Tidal disruption of miniclusters

The problem of tidal stripping of satellites has a long history. With time they are tidally disrupted and form streams. A collection of these streams would resemble spaghetti of large length L and cross-section radius comparable to the initial clump radius. Recently this process was modeled for minihalos with $M \sim 10^{-6} M_\odot$, see e.g. Ref. [11]. It was found that narrow long streams are formed out of them, with a length which increases in time. For example, in 5 Gyr the length of a stream will be 10^4 of the initial minihalo radius. Therefore, we may conclude that such a stream contributes 10^{-2} of the local DM density and streams originating from tidal disruption of minihalos are not interesting phenomenologically from the point of view of direct DM detection. The situation may be different for miniclusters with $\Phi \gtrsim 1$, let us consider it now.

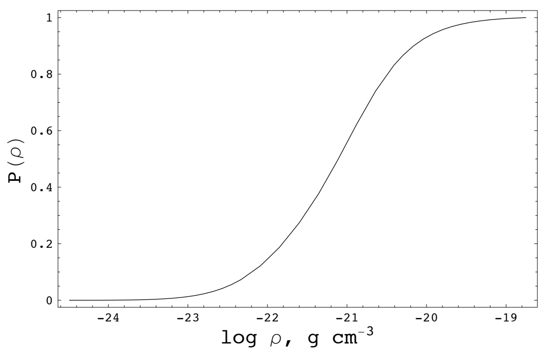

Figure 2: Survival probability for a clump in the Galaxy as a function of its density, from Ref. [13].

For a review of tidal disruption of dense DM clumps in a vide variety of models see Ref. [12]. The averaged survival probability for clumps (with trajectories such that they cross Solar neighborhood in the Galaxy) as a function of a clump density is shown in Fig. 2, see Ref. [13]. In our notations $\rho = 10^{-20}$ g/cm^{-3} corresponds to clumps with $\Phi \approx 0.1$. We see that 5% of clumps with such density is destroyed and their debris form tidal streams with potentially important phenomenological implications since the initial density in minicluster is much larger comparing to mini halo.

4.2 Implications for direct DM searches

An object with relative velocity $v \approx 10^{-3}$ crosses a stream during a time interval $\tau = 2R_{\rm mc}/v \approx 55\,\mathrm{hr}/\Phi\,(1+\Phi)^{1/3}$. This time interval corresponds to a period of high signal in the detector. The mean time between stream crossings can be found in the following way. The probability for a randomly chosen star to be found inside a stream is given by $P_{in} = \bar{\rho}/\rho_s$, where $\bar{\rho}$ and ρ_s are the mean density and the typical density of DM inside a stream correspondingly. Therefore, the time interval between successive stream crossings is $T = \tau/P_{in}$. This would be correct, however, if all miniclusters would be destroyed. If only a fraction of them is destroyed, T should be multiplied by $F \equiv (1-P_s)^{-1}$, where P_s the survival probability shown in Fig. 2.

Making the simplifying assumption that the resulting tidal stream increases in length with a rate equal to the escape velocity from the clump, and that its width does not change significantly, we find the resulting density inside a stream as well as other parameters relevant for direct DM detection. These parameters are listed in Table 1. We see, that the local DM density increase which occurs when we cross tidal streams from most abundant miniclusters with Φ from 0.1 to 1 might be interesting for the direct DM searches. To specify the situation precisely, one needs to know F as a distribution (indeed, the fate of a minicluster depends on many parameters, so it is not a unique function of Φ) and better knowledge of density evolution inside a stream is required. This study is in progress [14].

	$\Phi \approx 0.1$	$\Phi \approx 1$
Linear increase in 5 Gyr	2×10^4	10^6
Local $\rho/\bar{\rho}_{DM}$	3	100
Signal duration τ	20 days	1 day
Repeats in T	2 years	1 day $\times$ 100 $\times$ F

Table 1: Parameters of tidal streams from miniclusters.

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References

[1] E. W. Kolb and I. I. Tkachev, Phys. Rev. Lett. **71** 3051 (1993) [hep-ph/9303313].

[2] E. W. Kolb and I. I. Tkachev, Phys. Rev. D **49** 5040 (1994) [astro-ph/9311037].

[3] E. W. Kolb and I. I. Tkachev, Phys. Rev. D **50** 769 (1994) [astro-ph/9403011].

[4] E. W. Kolb and I. I. Tkachev, Astrophys. J. **460** L25 (1996) [astro-ph/9510043].

[5] I. I. Tkachev, Phys. Lett. B **261** 289 (1991).

[6] I. I. Tkachev, Sov. Astron. Lett. **12** 305 (1986) [Pisma Astron. Zh. **12** 726 (1986)].

[7] I. I. Tkachev, JETP Lett. **101** 1, 1 (2015) [arXiv:1411.3900 [astro-ph.HE]].

[8] A. Iwazaki, Phys. Rev. D **91** 2, 023008 (2015) [arXiv:1410.4323 [hep-ph]].

[9] S. R. Kulkarni, E. O. Ofek, J. D. Neill, Z. Zheng and M. Juric, arXiv:1402.4766 [astro-ph.HE].

[10] J. Diemand, B. Moore and J. Stadel, Nature **433** 389 (2005) [astro-ph/0501589].

[11] G. W. Angus and H. Zhao, Mon. Not. Roy. Astron. Soc. **375** 1146 (2007) [astro-ph/0608580].

[12] V. S. Berezinsky, V. I. Dokuchaev and Y. N. Eroshenko, Phys. Usp. **57** 1 (2014) [Usp. Fiz. Nauk **184** 3 (2014)] [arXiv:1405.2204 [astro-ph.HE]].

[13] V. Berezinsky, V. Dokuchaev, Y. Eroshenko, M. Kachelriess and M. A. Solberg, Phys. Rev. D **81** 103529 (2010) [arXiv:1002.3444 [astro-ph.CO]].

[14] P. Tinyakov, I. Tkachev, K. Zioutas, in preparation.