Recurrent Axinovae and their Cosmological Constraints

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Outline

1. Introduction — why axions?
2. Axion miniclusters
3. Axion stars and axinovae

Why axions?


Date of paper
1977
2023
Number of authors
Single author
3,246
10 authors or less
9,537
10,200 results |
cite all
Citation Summary
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Citation Summary
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Citeable
Published
Papers 8,765 6,392
Citations 417,629 389,284
h-index 239 234
Citations/paper (avg) 47.6 60.9
Papers
3.5K
Citeable
Published
2918
3046

Why axions

1. QCD axion. The most popular solution to the strong CP problem.
2. Axion like particle, a natural candinate for ultralight dark matter, can be motivated from string theory. (String axiverse)
3. As light particles produced nonthermally, axions have rich phenomenlogy that can be tested in upcoming astrophysical and cosmological observations. (In analogy to WIMP indirect detection)

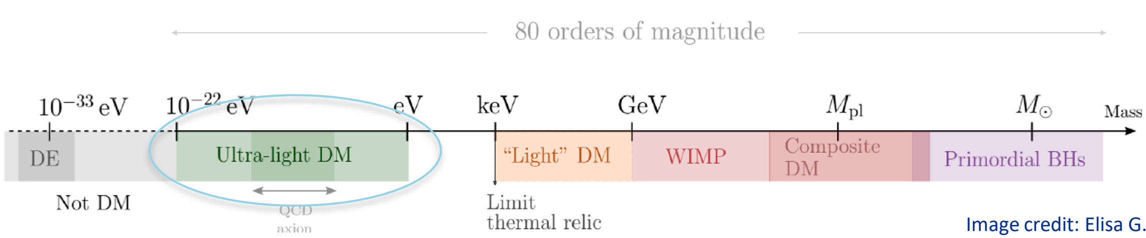
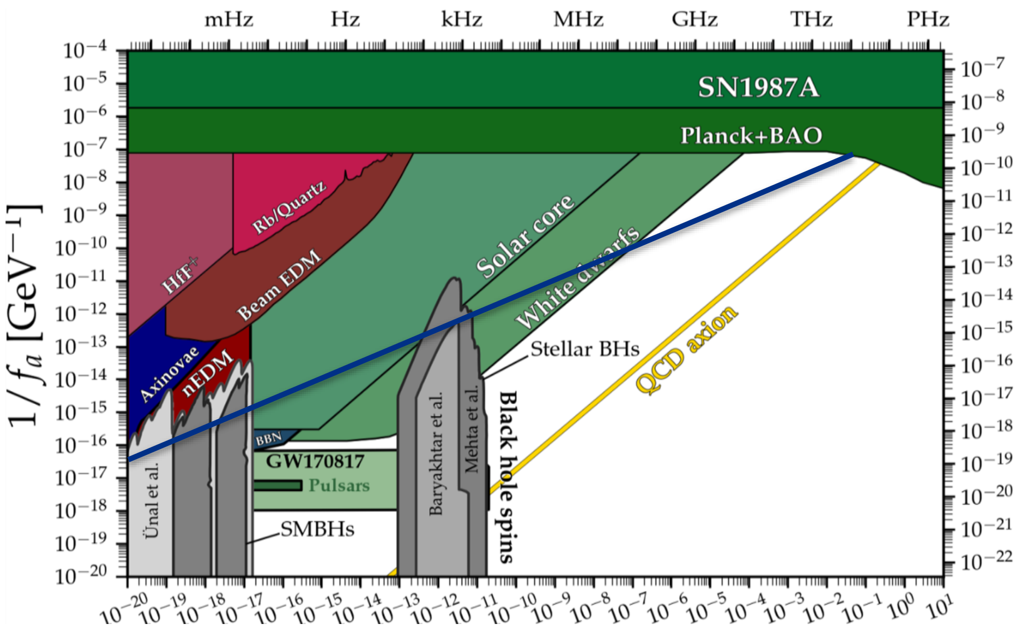


Image credit: Elisa G. M. Ferreira, Astron.Astrophys.Rev. 29 (2021)

Current axion limits (with spoilers!!!)



The goal of this work is to show parameter space can be ruled out by theory considerations without running any experiments.

The theory calculation is to reveal the fate of **axion stars.**

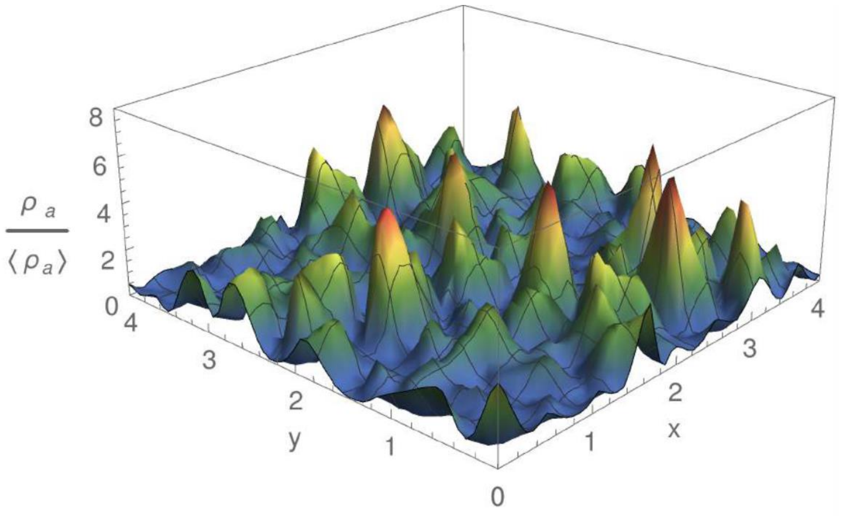
Initial Density Perturbations

Uncorrelated field values

⇩

Order one white-noise matter density fluctuations

Forming miniclusters at matter-radiation equality! (C.J.Hogan, M.J.Rees, 1988)

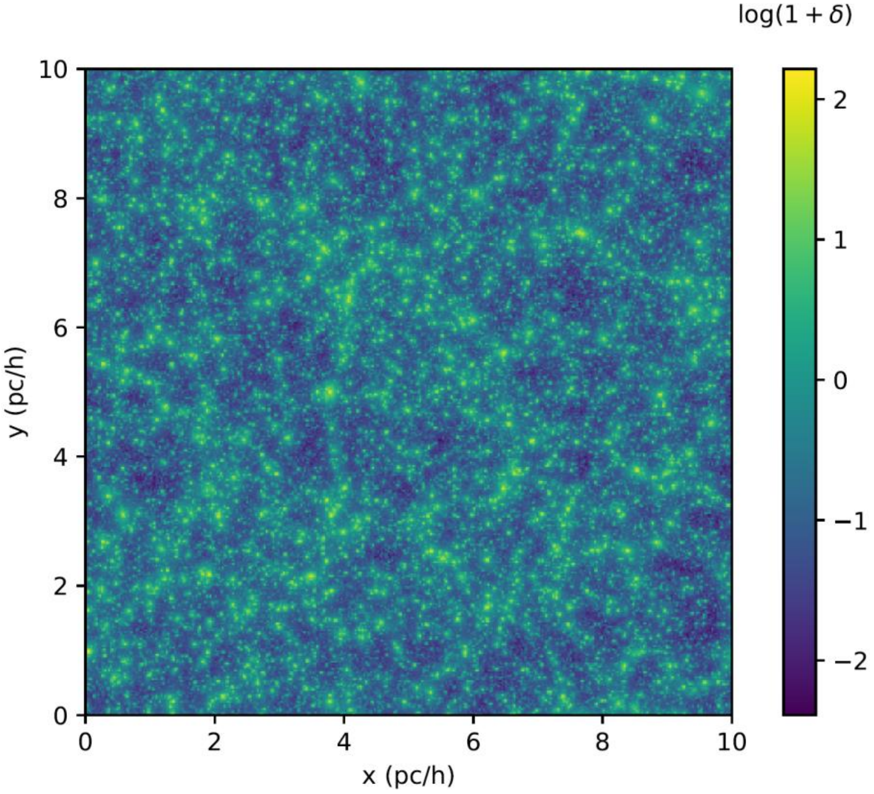


E. Hardy, 2017

Axion minihalos

Axion miniclusters formed at matter radiation equality will merge and grow into slightly larger structures called axion minihalos.

The population of those objects has been studied numerically.



H. Xiao, I. Williams, M. McQuinn, 2021

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Our Universe and axion Universe

Our Universe: Standard CDM halos (z~20)------> Cold and dense gas cloud -------> Stars

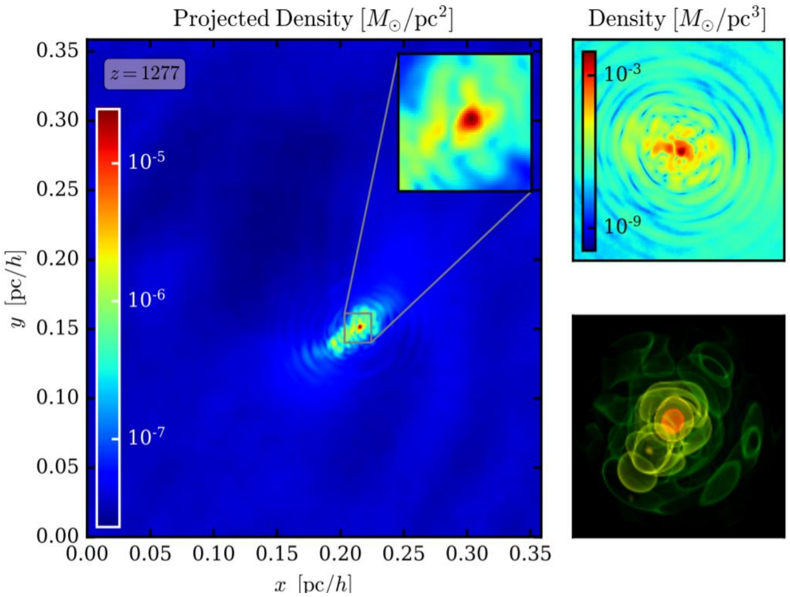
Axion Universe: Axion miniclusters (matter-radiation equality)----> already **cold** (light! Small virial velocity) and **dense** (form early)!-----> Axion stars

Axion star formation in axion minihalos

Axions are bosons. Go through **Bose-Einstein condensation** and form coherent objects in minihalos, known as axion stars. The formation of condensate is unavoidable due to the high occupancy number of axion dark matter.

Dilute axion stars are balanced by **kinetic pressure** and gravity. Dense axion stars, are unstable, and **self-interaction** starts to become relevant. We call the explosions of dense axion stars **axinovae.**

Our knowledge of axion minihalos and axion miniclusters can help us determine the **formation rate** of axion stars.



Eggemeier and Niemeyer, 2019

Axion star explosions are "dangerous"

Our visible star explosions will not change cosmology. It can only convert matter to radiation up to the nuclear binding energy. The baryon number is **conserved** in this case.

However, the axion number is **not conserved** due to the **quartic** self-interaction. **Axinovae,** namely the collapse and explosion of axion stars, involve violent processes that emitt relativistic axions (or potentially photons), consuming $\mathcal{O}(1)$ of the rest energy in axion stars.

Therefore axinovae are potentially very constraining by cosmological observations.

The condensation of axion stars

The timescale of axion star formation is Bose-enhanced:

$$\tau \sim (f_{\rm BE} n \sigma v)^{-1}$$

The phase space density is $f_{\rm BE} = 6\pi^2 n (m_a v)^{-3}$

The timescale is

$$\tau_{\rm gr} = \frac{b}{48\pi^3} \frac{m_a v^6}{G_N^2 n^2 \log(m_a v R)} \qquad \tau_{\rm self} = \frac{64 d m_a^5 v^2}{3\pi n^2 \lambda^2}$$

Converting matter to dark radiation

As the axion star grows, the kinetic pressure can no longer balance the gravity and the axion star starts to collapse, triggering axinovae. The rate given as

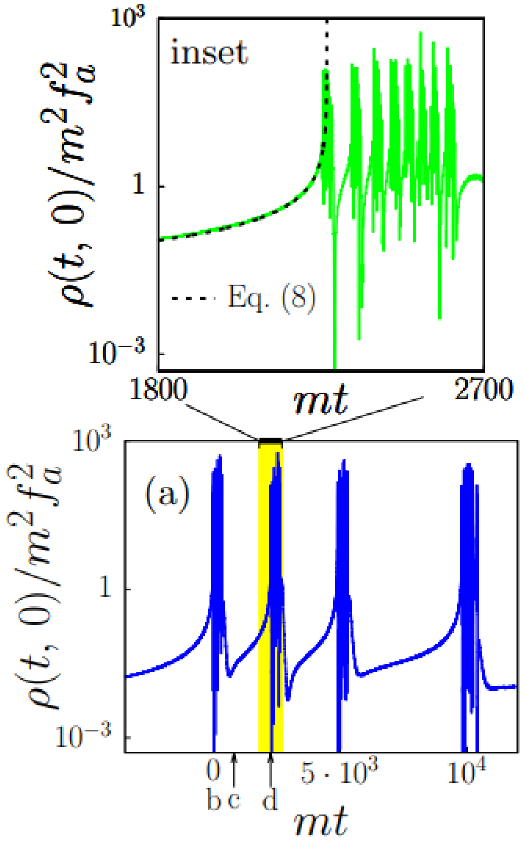
$$\frac{df_{\rm decay}}{dt} = \frac{\kappa\, M_*^{\rm max}}{M_{\rm peak}(z)\, t_{\rm crit}}$$

$$\frac{df_{\rm decay}}{dz} \sim 76500\pi^{2/3}\kappa \frac{M_{pl}^3 \overline{\rho}_{\rm col}^{-2}}{M_0 f_a^5 m_a^4} \left(\frac{1+z}{1+z_c}\right)^8 \frac{1}{(1+z)^{5/2} H_0} \times \left[1 + 75\pi^{4/3}\left(\frac{f_a}{M_0^{1/3}\overline{\rho}_{\rm col}^{1/6}}\right)^4 \left(\frac{1+z}{1+z_c}\right)^{2/3}\right] \times \left(\frac{\overline{M}_*}{M_*^{\rm max}}\right)^{\alpha-2} \Theta\left(M_{peak}(z) - M_*^{\rm max}\right) \;,$$

Key observation: Recurrent axinovae

If axion stars are not taking away a significant fraction of energy in axion minihalos, they should form again if the timescale is short enough.

This assumption has been confirmed by numerical studies (Levkov et al., 2016).



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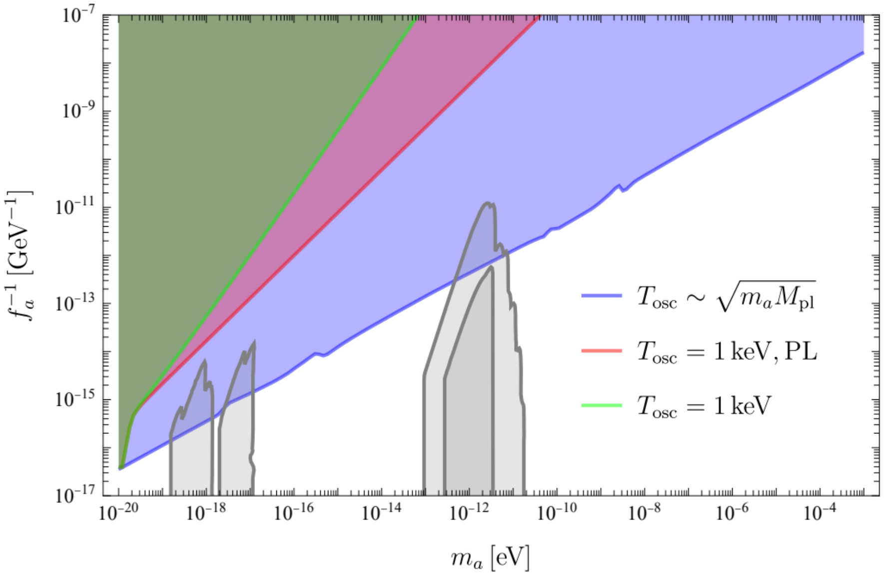
Cosmological constraints

The physics of axion star formation is determined by: **axion minicluster formation** and self-interaction.

The physics of instability of axion stars is governed by **self-interaction.**

They are unrelated, giving constraints in axion parameters.

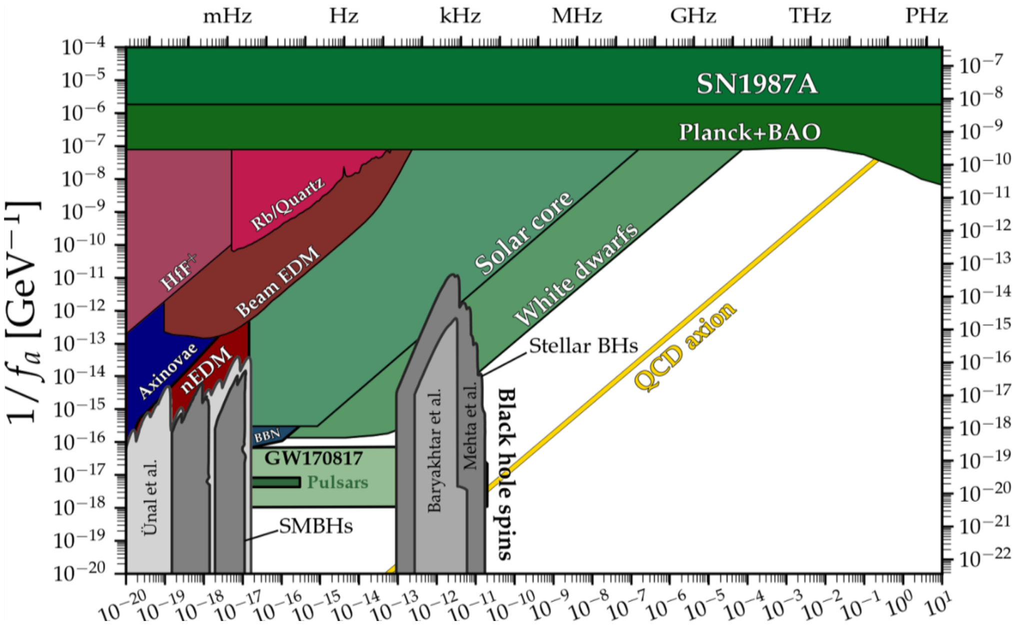


P. Fox, N. Weiner, **H. Xiao**, 2023

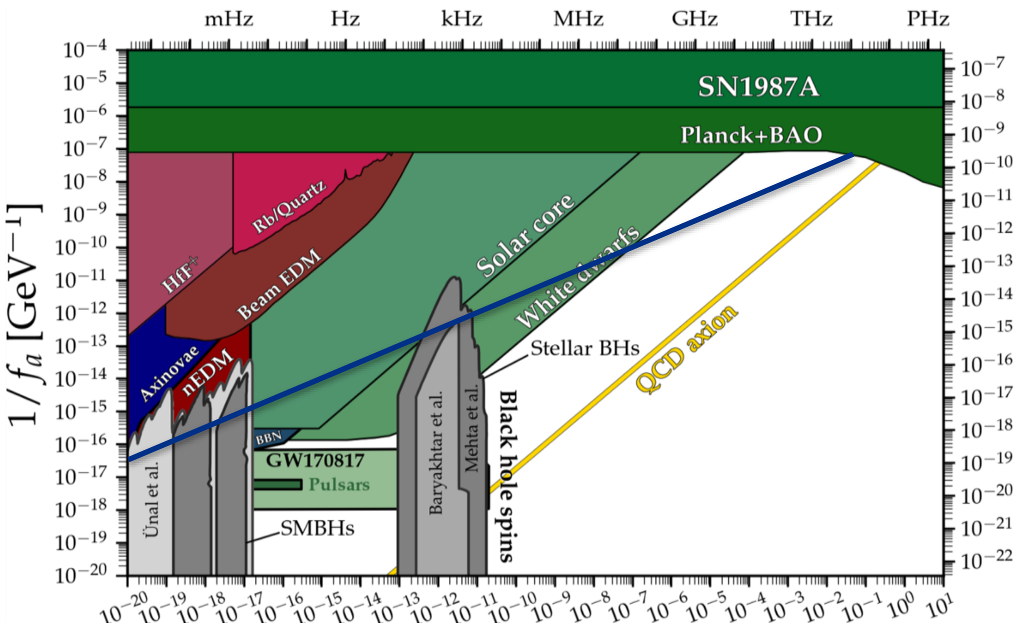
Current axion limits

Taking the conservative assumptions about the axion substructures, we obtain competitive bounds at the ultralight mass range.

Our bounds apply to self-interaction instead of gluon coupling.



Current axion limits



Conclusion

1. Axion stars will form efficiently in the post-inflationary scenario when axion miniclusters formed at matter radiation equality. The axion Universe is very colorful with only one particle!
2. Axionovae place strong constraints in axion parameters, which will be interesting implications for experimental searches.

Radio axinovae

Do we expect the product of axion star explosion to contain any radio photons at all?

Maybe… When there is a parametric resonance.

Axion decay to two photons with energy $m_a/2$ while those photons can further stimulate the decay of axions due to Bose enhancements.

Ongoing work with Paddy Fox and Neal Weiner. To appear soon.

Axion electrodymanics

The axion-photon coupling will modify Maxwell's equations

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \\
\nabla \times \mathbf{B} &= \dot{\mathbf{E}} + \mathbf{J} + g_{a\gamma\gamma} (\dot{a} \mathbf{B} + \nabla a \times \mathbf{E}) \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\dot{\mathbf{B}} \ .
\end{aligned}
$$

The equation of motion of B field becomes

$$\ddot{B}_{\pm} + k^2 B_{\pm} = \mp g_{a\gamma\gamma} m_a f_a k \, \Theta(z) \sin(m_a t + \delta) \, B_{\pm}$$

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Solving the B field

Define $\eta = (m_a t + \delta)/2$, a mathematician who died long ago solved this for us

$$B''_{\pm} + \left[\left(\frac{2k}{m_a} \right)^2 \pm \frac{4 g_{a\gamma\gamma} f_a k}{m_a} \Theta(z) \sin 2\eta \right] B_{\pm} = 0$$

$$B_{\pm}(t) \sim \frac{1}{\sqrt{2}} \left(e^{ikz} + e^{-ikz} \right) e^{\mu t}$$

The solution of Mathieu equ

$$\mu = \frac{1}{2} \sqrt{ \left(g_{a\gamma\gamma} f_a \Theta(z) k \right)^2 - \frac{m_a^2}{4} \left(1 - \left(\frac{2k}{m_a} \right)^2 \right)^2 }$$

Does this happen in axion stars?

Write with axion star parameters

$$\overline{\mu} = \frac{g_{a\gamma\gamma} m_a f_a \Theta \, \pi}{8} \equiv \mu_0 \Theta \sim \frac{\pi^{1/4}}{8} g_{a\gamma\gamma} \sqrt{\frac{M}{R}},$$

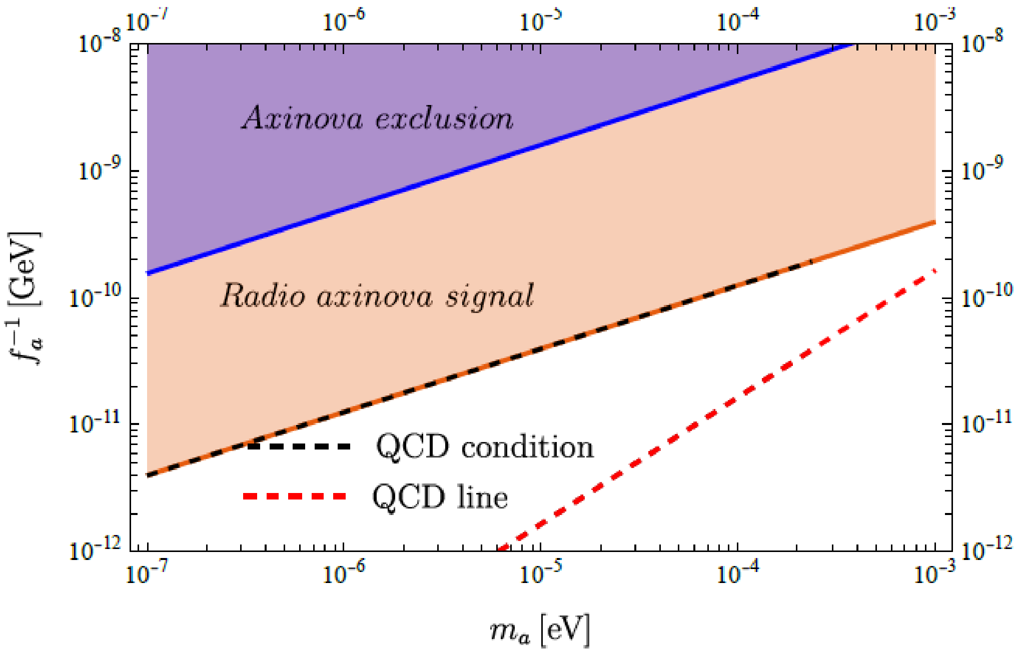
For dense axion stars, the parametric resonance when $g_{a\gamma\gamma} \gtrsim \frac{10}{M_{\rm pl}^{1/3} f_a^{2/3}}$.

For ordinary axion models, we expect $g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi f_a}$

More constraints

The radio axinovae bounds greatly enhance the parameter space.

However, it still cannot reach the QCD line..



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New Ideas of Detecting Small Structures

The Square Kilometre Array

- Pulsar timing arrays (sensitive to masses, $10^{-12}M_{\odot} - 100M_{\odot}$, *J. A. Dror, H. Ramani, T. Trickle, and K. M. Zurek,* 2019)

- Lensing in Highly Magnified Stars (*L. Dai and J. Miralda-Escudé,* 2019)

Those small substructures are **detectable!** Time to study their formation and evolution from interesting physics.

James Webb Space Telescope

Partition function argument

$$\mathcal{Z} = \int \mathcal{D}A \exp i \int d^4x \mathrm{Tr}\left(-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{g^2\theta}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu}\right)$$

After wick rotation

$$\mathcal{Z} = \int \mathcal{D}A \exp \int d^4x \mathrm{Tr}\left(-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\frac{g^2\theta}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu}\right)$$

Partition function tells us something about the ground state energy at the zero temperature limit

$$\mathcal{Z} \propto \mathrm{Exp}(-E_0/T)$$

A non-zero CP-violating term —> a smaller partition function —> a larger ground state energy

Mass growth

Numerical studies suggest that there is a characteristic mass of axion stars in axion minihalo

$$\overline{M_*} \approx 3\rho_a^{1/6} G_N^{-1/2} m_a^{-1} M_h^{1/3}$$

After this mass, the mass growth is a power law. Before that, it is an exponential.

$$t_{\rm crit} = \tau \times \begin{cases} \log\left(\overline{M_*}/M_*^{\rm max}\right) + 1, & M_*^{\rm max} \leq \overline{M_*} \\ \left(M_*^{\rm max}/\overline{M_*}\right)^{\alpha}, & M_*^{\rm max} > \overline{M_*} \end{cases}$$

Critical Mass

At some point the axion cannot support themselves. The critical radius is (See L. Visinelli, S. Baum, J. Redondo, K. Freese, F. Wilczek 2017)

$$R_*^+ = 9.9 \frac{M_{\rm pl}^2}{m_a^2 M_*}$$

The corresponding critical mass is

$$M_*^{max} = \frac{10.7}{\sqrt{\lambda}} M_{\rm pl}$$

However, the evolution history has not been studied yet. We do not know if axion stars will reach the critical mass.

Dense axion stars

After critical mass, dilute stars (given by the solution we provided before) will collapse to dense axion stars, which will decay after ~1000/m.

They are cosmologically unstable.