Recurrent Axinovae and their Cosmological Constraints

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Light Dark World 2023

Our Universe and axion Universe

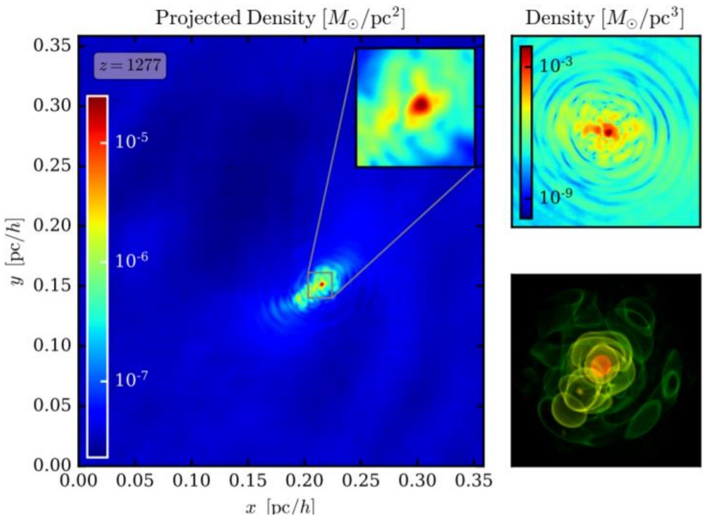
Our Universe: Standard CDM halos (z~20)------> Cold and dense gas cloud -------> Stars

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.

Our knowledge of axion minihalos 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. Therefore it is potentially very constraining by cosmological observations.

The condensation of axion stars

The timescale of axion star formation is Bose-enhanced:

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

The phase space density is

$$f_{\mathrm{BE}} = 6\pi^2 n (m_a v)^{-3}$$

The timescale is

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

Mass growth

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

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

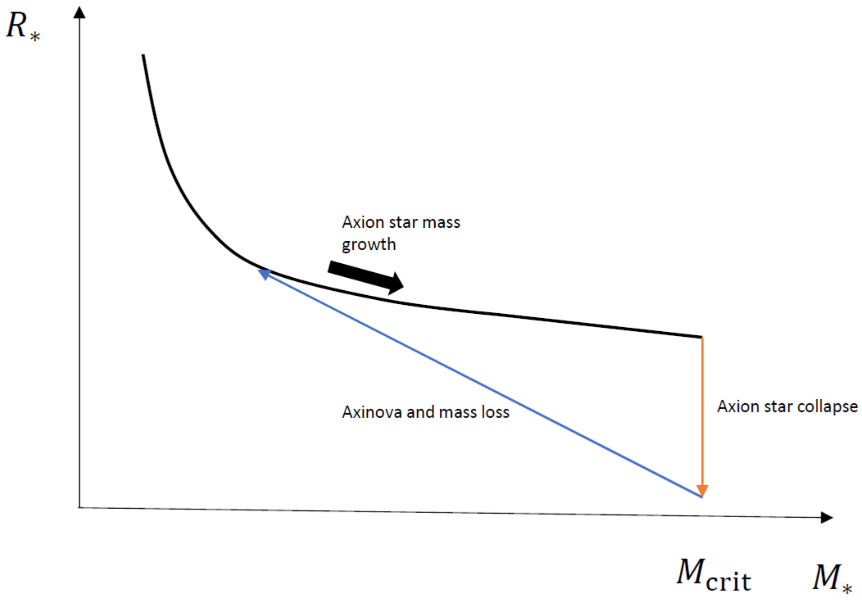
After this mass, the mass growth is a power law. Before that, it is an exponential.

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

Lifecyle of Axion Stars

In the dilute branch of axion stars, the radius of axion stars decreases as the mass grows.

At critical mass, self-interaction turns on and the kinetic pressure cannot balance the self-interaction and gravity any more. Axion stars start to collapse.



Converting matter to dark radiation

The fraction of matter converted to radiation is governed by

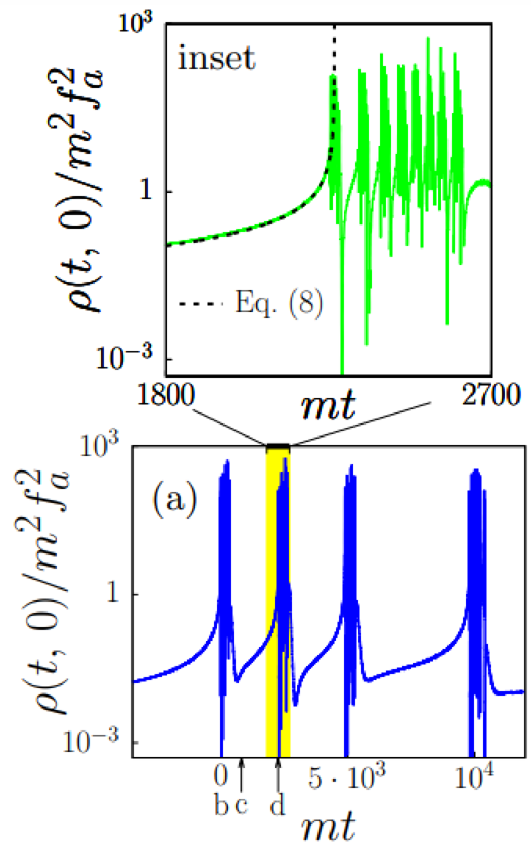
$$\frac{df_{\rm decay}}{dt} = \frac{\kappa\, M_*^{\rm max}}{M_{\rm peak}(z)\, t_{\rm crit}}$$

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

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).

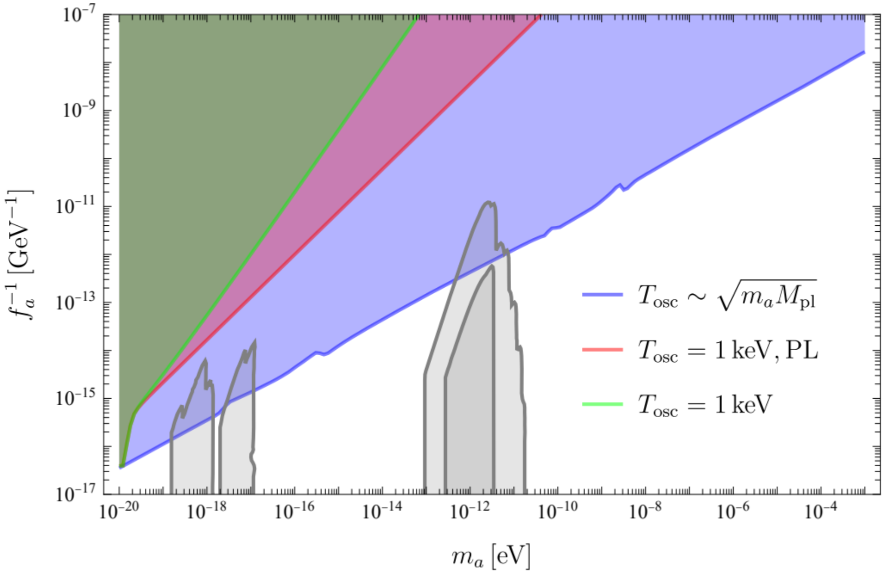


Cosmological constraints

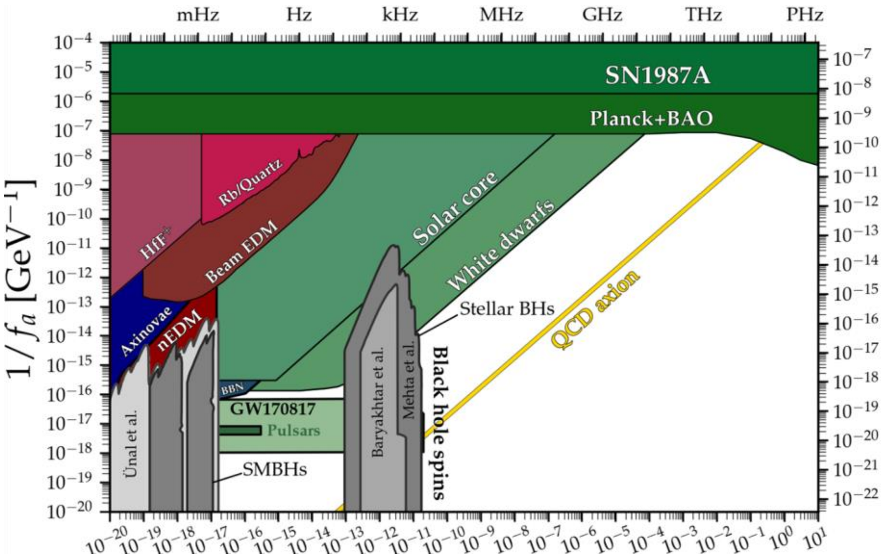
The physics of axion star formation is determined by: minihalo formation and self-interaction.

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

They are unrelated, giving constraints in axion parameters.



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.