Recurrent Axinovae and their Cosmological Constraints

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Our Universe and axion Universe

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

Axion Universe (post-inflationary scenario): small scale structures such as axion miniclusters form at matter-radiation equality----> already **cold** (light! Small virial velocity) and **dense** (form early)!-----> formation of axion stars

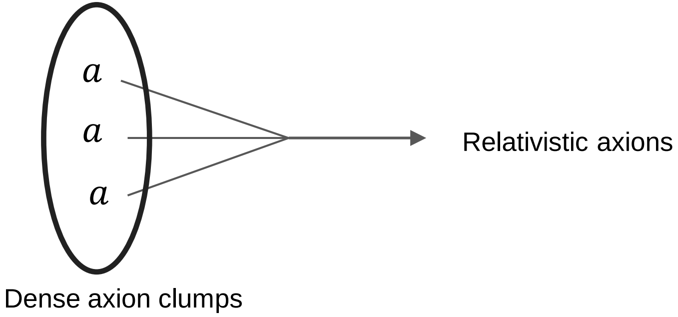
Axion stars can collapse and explode after a certain mass due to the attractive self-couplings. The explosions will cause a change on Ω_m.

Therefore, **cosmological observables** can be related to the dynamics of **axion dark matter**!

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 (~1% of its rest mass). The baryon number is conserved at these low energies.

However, the axion number is not conserved due to the quartic self-interaction. Therefore it is potentially constrained by cosmological observations.



Therefore, axions reverse neutrino effects. Axions will convert nonrelativistic clumpy axion dark matter to free-streaming relativistic axions.

Axion stars, precisely

- They mostly do not emit lights… In that sense they are not stars.
- They are the ground state of axion field configurations, and thus energetically favorable.
- Balanced by gravity and kinetic pressure.

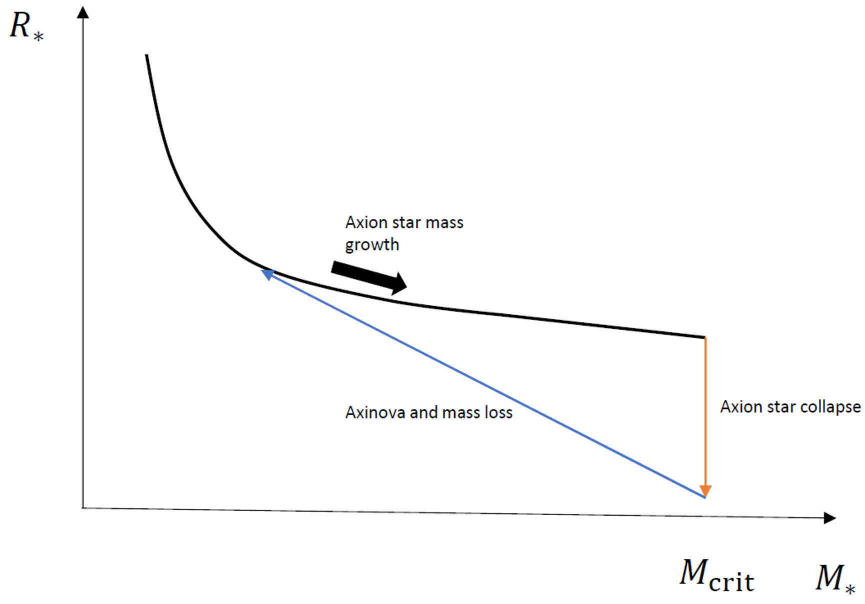
$$E_* \sim -\frac{GM_*^2}{R_*} + \frac{M_*}{2m_a^2 R_*^2} - \frac{\lambda M_*^2}{12 m_a^4 R_*^3}$$

The last term, corresponding to the attractive self-interaction, will cause instabilities.

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.



The condensation of axion stars

The timescale of axion star formation is Bose-enhanced and well described by the scattering timescale between axion waves. This can be understood as, axions always tend to form condensates, and the only barrier is the thermalization timescale:

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

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

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

Mass growth

Numerical studies suggest that there is a characteristic mass of axion stars in axion minihalos (This is determined by equating the halo virial velocity to star virial velocity)

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

The mass growth is well described by a power low model:

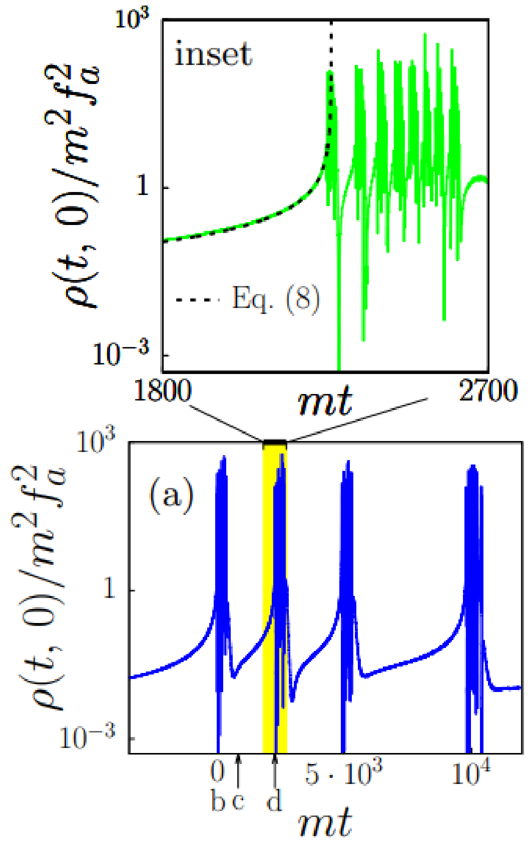
$$M_* = \overline{M_*}\left(\frac{t-\tau}{\tau}\right)^{1/2}$$

The growth at $t \gg \tau$ is still under debate and an active area of research. The initial growth is more well-understood, which is needed to determine the critical collapse behavior of axion stars.

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).



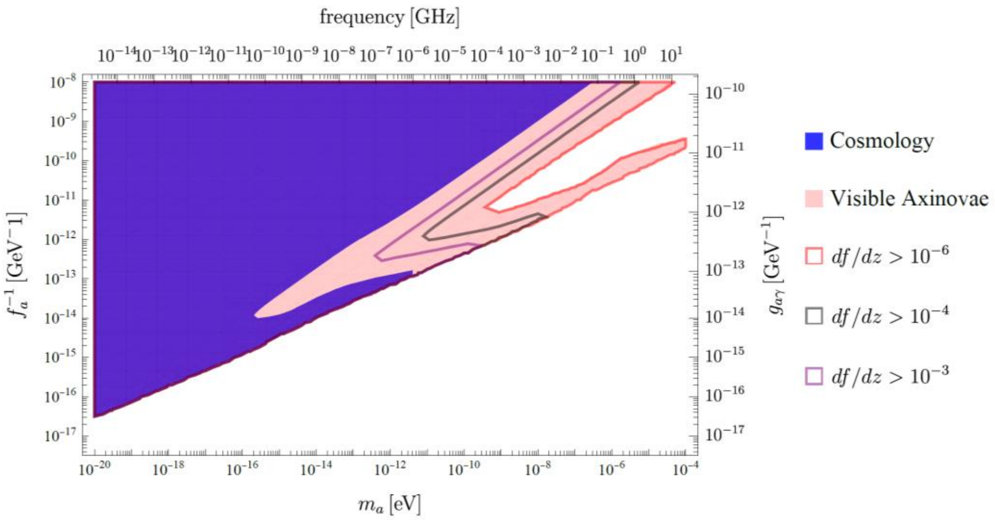
Cosmological constraints

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

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

They are unrelated, giving constraints in axion parameters.

$$\frac{d\Omega_m}{dz} \sim 0.1 \left(\frac{10^{13}\mathrm{GeV}}{f_a}\right)^3 \left(\frac{10^{-14}\mathrm{eV}}{m_a}\right)^2 \frac{1}{(1+z)^{5/2}}$$



Conclusion

1. Axion stars will form efficiently in the post-inflationary scenario. 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.

Numerical evidences of axion star collapse

It was found that the axion stars slightly above the critical mass will cause collapse, which has been confirmed by numerical simulations. (Levkov, 2016)

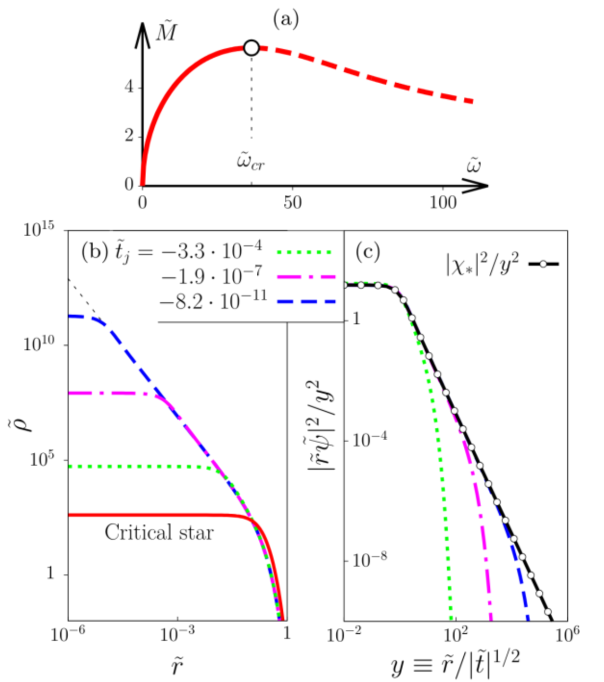


FIG. 1. (a) Star mass as a function of the binding energy $\tilde{\omega}$. (b) Numerical solution $\tilde{\rho} \equiv |\tilde{\psi}(\tilde{t}_j, x)|^2$ at fixed time moments $\tilde{t}_j$ approaching $\tilde{t}_* \equiv 0$. (c) The same solution in the self-similar coordinates versus the asymptotic profile $\chi_*(y)$.