Visible Axinovae: Axion Star Explosions with Photon Emissions

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Our Universe and axion Universe

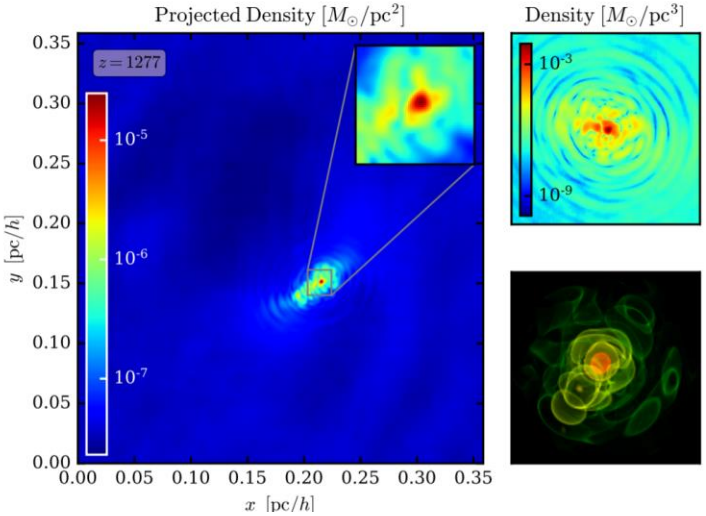
Our Universe: Standard CDM halos (z~20)------> Cold and dense gas cloud -------> Stars

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.

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



Eggemeier and Niemeyer, 2019

Axion star explosions are “dangerous”

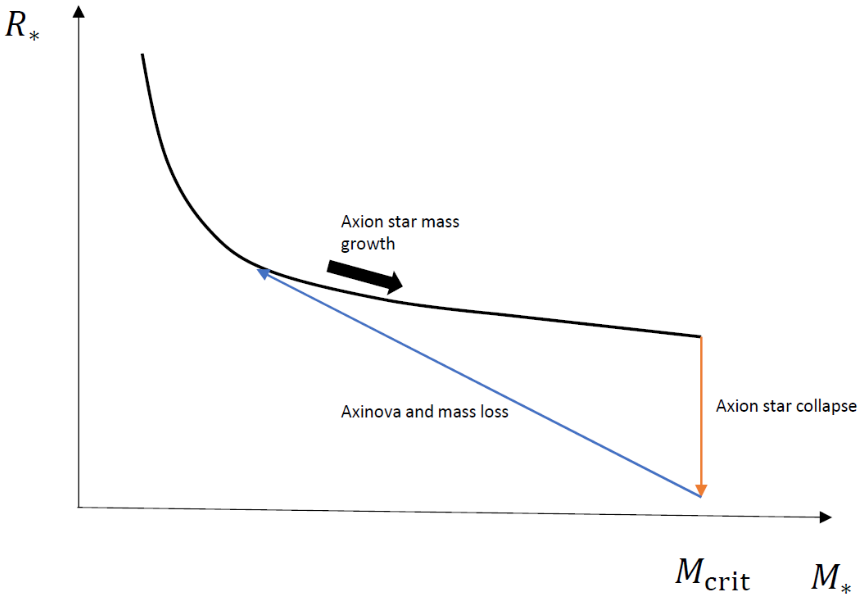
Our visible star explosions will not change cosmology. It can only convert matter to radiation up to the nuclear binding energy. The baryon number is conserved in this case.

However, the axion number is not conserved due to the quartic self-interaction. Therefore axion star explosions are potentially very constraining by cosmological observations. Furthermore, if they emit electromagnetic radiation, this will lead to striking signal.

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:

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

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

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

Mass growth

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

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

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

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

Converting matter to dark radiation

The fraction of matter converted to radiation is determined by the axion star formation rate:

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

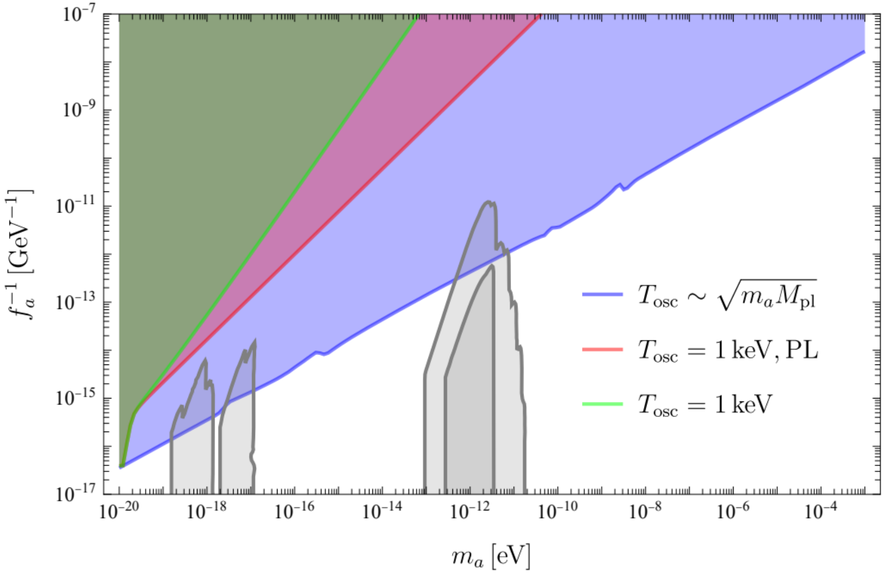
$$\begin{aligned}\frac{df_{\rm decay}}{dz} \sim\ & 76500\pi^{2/3}\kappa \frac{M_{pl}^3\bar{\rho}_{\rm col}^2}{M_0 f_a^5 m_a^4}\left(\frac{1+z}{1+z_c}\right)^8 \frac{1}{(1+z)^{5/2}H_0} \\ & \times \left[1+75\pi^{4/3}\left(\frac{f_a}{M_0^{1/3}\bar{\rho}_{\rm col}^{1/6}}\right)^4\left(\frac{1+z}{1+z_c}\right)^{2/3}\right]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

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.



Visible 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.

Axion electrodynamics

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

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

Solving the B field

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

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

The solution of Mathieu equation is

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

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

Does this happen in axion stars?

Write with axion star parameters

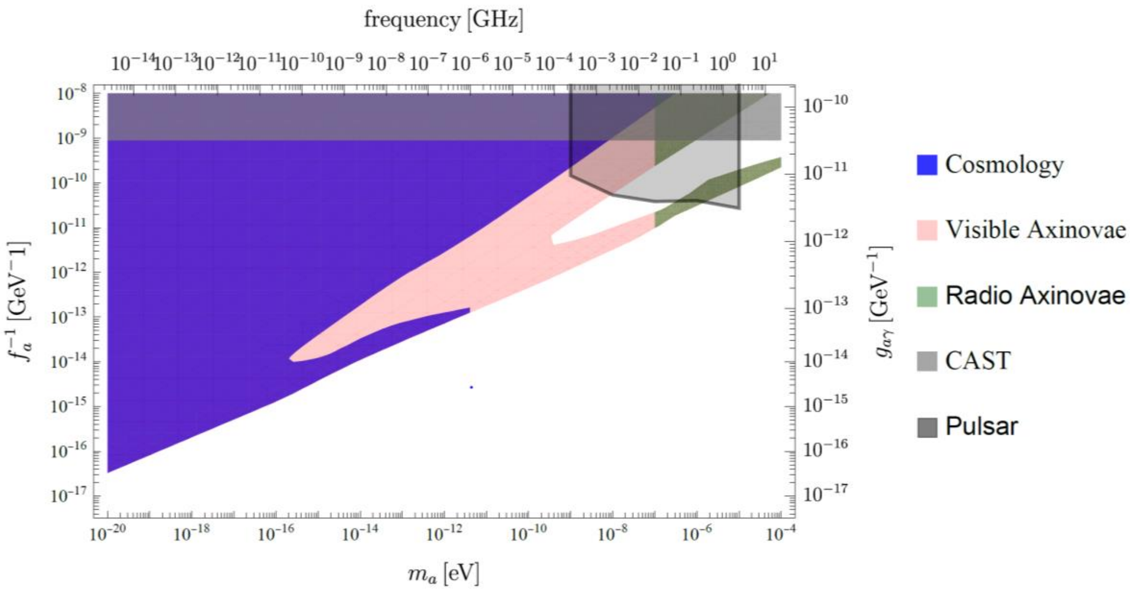
$$\bar{\mu} = \frac{\pi}{8} g_{a\gamma\gamma} m_a f_a \Theta \sim \frac{1}{8} g_{a\gamma\gamma} \sqrt{\frac{M_*}{R_*}}$$

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

For ordinary axion models, we expect $g_{a\gamma\gamma} = \kappa \frac{\alpha}{2\pi f_a}$, with $\kappa \sim 1$. For sufficient photon emissions, we found κ has to satisfy $\kappa > 64 \left(\frac{f_a}{10^{10}\mathrm{GeV}}\right)^{1/3}$. Therefore we need slightly axion-photon couplings to trigger visible axinovae.

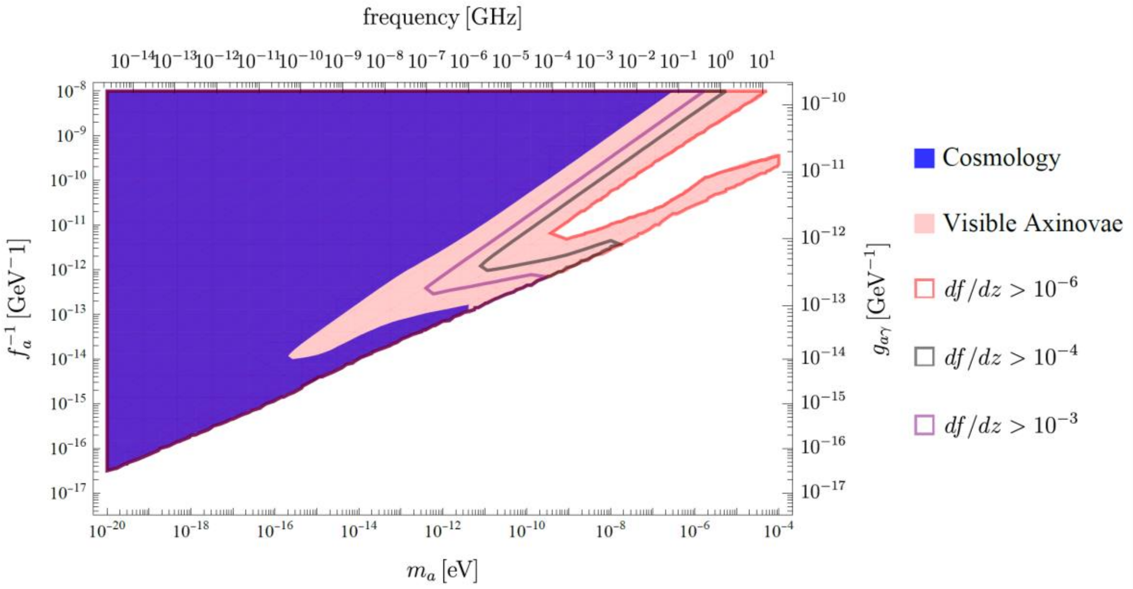
Axion parameter of visible axinovae

The blue region is excluded by cosmological observations. The orange region can have a striking signal with low energy photon emissions. The green is excluded because it predict too many bright radio axinovae in the sky.



Mass fraction of dark matter converted to radiation

The contours showing different decay fraction of dark matter from axion star explosions in the current time. Note that we at least get 10^{-6} of them converted to electromagnetic radiation.



Brightness of radio axinovae

We can estimate the nearest axinova event:

$$D \sim \left(\frac{df}{dz} H_0 \Delta t \frac{\rho_a}{M_0}\right) \sim \left(\frac{M}{10^{-10} M_\odot}\right)^{\frac{1}{3}} 200 \text{ pc}$$

This corresponds to a flux density:

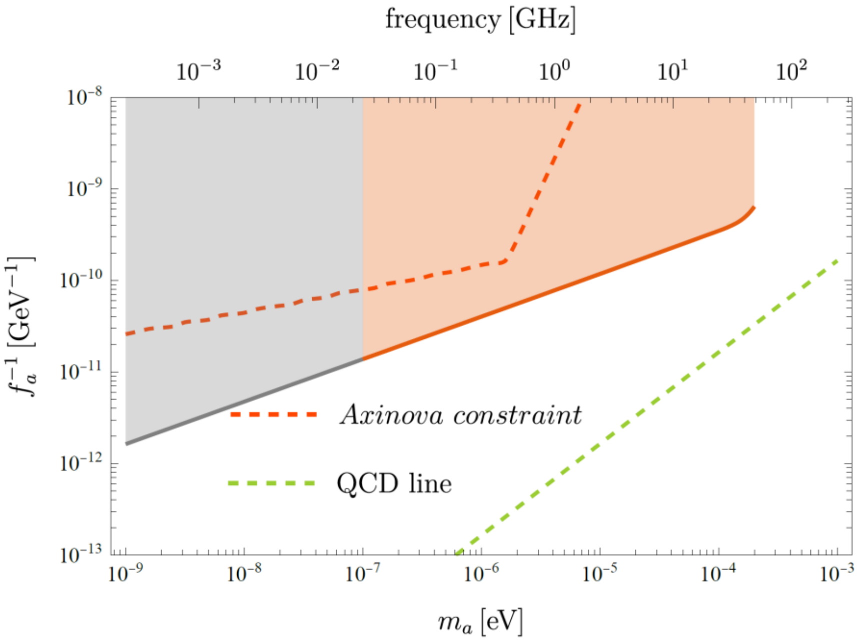
$$S \sim \frac{M}{4\pi D^2 \tau_{life} m_a} 10^{20} \left(5 \frac{\text{GHz}}{m_a}\right)\left(\frac{M}{10^{-10} M_\odot}\right)^{\frac{1}{3}} \text{Jy}$$

This is simply something you would not miss if they are at radio frequencies.

Do QCD axion stars explode?

No.

The critical mass of QCD axion stars is too high. Those stars are stabilized compact objects. Ongoing work with Jae Hyeok Chang and Paddy Fox.



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. Visible axinovae will further expand the model parameters one can probe, and provide new signals we can look for.

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).