Bose Einstein condensation of Dark Matter Axions?

Martin Elmer
based on:
Sacha Davidson and M.E.
arXiv:1307.8024

IPNL Lyon

October 25, 2013
New Perspectives in Dark Matter

Outline

Axions, a short reminder

Sikivie's idea

Gravitational thermalisation?
- Where to start
- Axion viscosity estimate
- Result

Summary

Outline

The idea:
Observable difference between axions and WIMPS if axions are in a Bose Einstein condensate

Different galactic halo structure

Strong CP problem

Review on axions: Raffelt, Stars as Laboratories for Fundamental Physics

- QCD contains CP violating term

$$\mathcal{L}_\Theta = \Theta \frac{\alpha_s}{8\pi} G \widetilde{G}$$

- induces neutron electric dipole moment $\Rightarrow$ not observed

$$|\Theta| < 10^{-10}$$

Strong CP problem

Review on axions: Raffelt, Stars as Laboratories for Fundamental Physics

- QCD contains CP violating term

$$\mathcal{L}_\Theta = \Theta \frac{\alpha_s}{8\pi} G \widetilde{G}$$

- induces neutron electric dipole moment ⇒ not observed

$$|\Theta| < 10^{-10}$$

strong CP problem

Strong CP problem

Review on axions: Raffelt, Stars as Laboratories for Fundamental Physics

- QCD contains CP violating term

$$\mathcal{L}_\Theta = \Theta \frac{\alpha_s}{8\pi} G \widetilde{G}$$

- induces neutron electric dipole moment $\Rightarrow$ not observed

$$|\Theta| < 10^{-10}$$

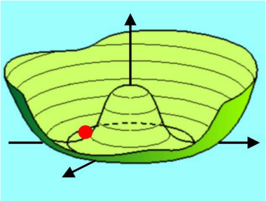
strong CP problem

Peccei Quinn solution:

make Θ dynamical variable with potential min at 0

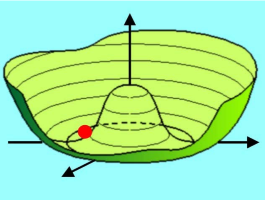
Peccei - Quinn Mechanism Peccei Quinn, Phys. Rev. D. 16 (1977)

- new $U(1)_{PQ}$ symmetry spontaneously broken at scale f_{PQ}
- axion $a(x)$ = Gloldstone boson, "phase" of new complex scalar field
- gluon coupling by construction $\Rightarrow \mathcal{L}_\Theta \to \frac{a(x)}{f_{PQ}} \frac{\alpha_s}{8\pi} G\widetilde{G}$

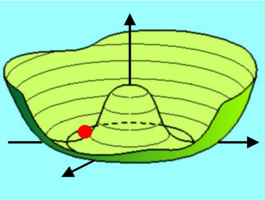


Peccei - Quinn Mechanism Peccei Quinn, Phys. Rev. D. 16 (1977)

- new $U(1)_{PQ}$ symmetry spontaneously broken at scale f_{PQ}
- axion $a(x)$ = Glodstone boson, "phase" of new complex scalar field
- gluon coupling by construction $\Rightarrow \mathcal{L}_\Theta \to \frac{a(x)}{f_{PQ}} \frac{\alpha_s}{8\pi} G \widetilde{G}$
  - mixing with pions $\Rightarrow$ mass $m_a f_{PQ} \sim m_\pi f_\pi$ (after QCD phase transition)
  - axion potential with minimum at $a = 0$
  - CP conservation



Peccei - Quinn Mechanism Peccei Quinn, Phys. Rev. D. 16 (1977)



- new $U(1)_{PQ}$ symmetry spontaneously broken at scale f_{PQ}
- axion $a(x)$ = Gloldstone boson, "phase" of new complex scalar field
- gluon coupling by construction $\Rightarrow \mathcal{L}_\Theta \rightarrow \frac{a(x)}{f_{PQ}} \frac{\alpha_s}{8\pi} G\widetilde{G}$
  - mixing with pions $\Rightarrow$ mass $m_a f_{PQ} \sim m_\pi f_\pi$ (after QCD phase transition)
  - axion potential with minimum at $a = 0$
  - CP conservation

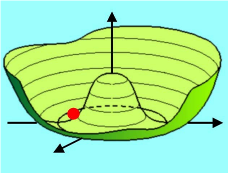
f_{PQ} is the determining parameter!

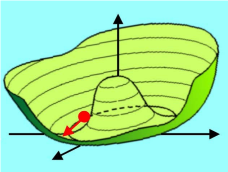
(up to $\mathcal{O}(1)$ model dependent factors)

Axion cosmology

Misalignment mechanism Dine and Fischler, Phys Lett. B 120

- for $T \sim f_{PQ}$:
  - $U(1)_{PQ}$ spontaneously broken
  - axion field sits fixed at $a_{init} = \theta_{init} f_{PQ}$
- after QCDPT ($T \sim 100 Mev$)
  - axion potential tilted $\Rightarrow$ axion mass
  - axion field oscillates (classical field oscillations)
  - $\Rightarrow$ cold dark matter





G. Raffelt © (BLV2013)

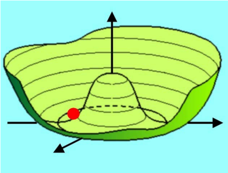
Axion cosmology

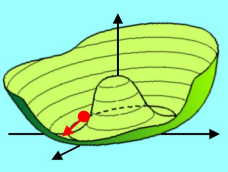
Misalignment mechanism
Dine and Fischler, Phys Lett. B 120

- for $T \sim f_{PQ}$:
  - $U(1)_{PQ}$ spontaneously broken
  - axion field sits fixed at $a_{init} = \theta_{init} f_{PQ}$
- after QCDPT ($T \sim 100 Mev$)
  - axion potential tilted $\Rightarrow$ axion mass
  - axion field oscillates (classical field oscillations)
  - $\Rightarrow$ cold dark matter
- Assuming inflation before PQ symmetry breaking

$$\Omega_a h^2 \sim 0,4 \left(\frac{10\mu eV}{m_a}\right)^{7/6}$$

- good DM candidate: $m_a \gtrsim 10\mu eV$





G. Raffelt © (BLV2013)

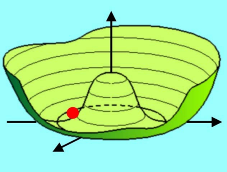
Axion cosmology

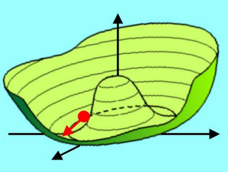
Misalignment mechanism Dine and Fischler, Phys Lett. B 120

- for $T \sim f_{PQ}$:
  - $U(1)_{PQ}$ spontaneously broken
  - axion field sits fixed at $a_{init} = \theta_{init} f_{PQ}$
- after QCDPT ($T \sim 100 Mev$)
  - axion potential tilted $\Rightarrow$ axion mass
  - axion field oscillates (classical field oscillations)
  - $\Rightarrow$ cold dark matter
- Assuming inflation before PQ symmetry breaking

$$\Omega_a h^2 \sim 0,4 \left(\frac{10\mu eV}{m_a} \right)^{7/6}$$

- good DM candidate: $m_a \gtrsim 10\mu eV$



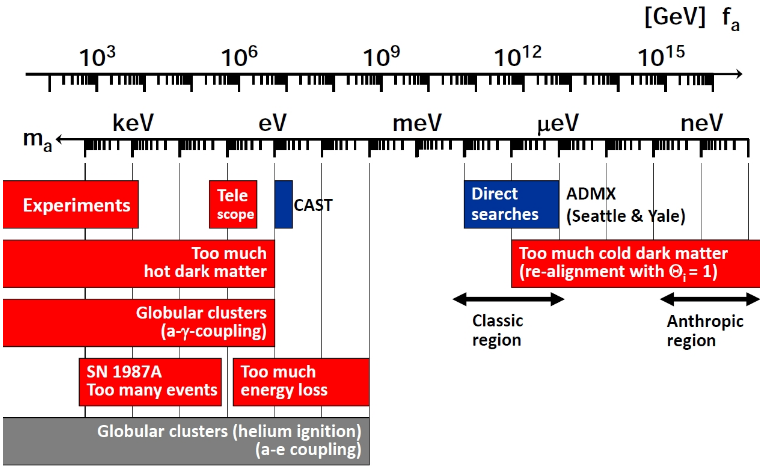


G. Raffelt © (BLV2013)

Cosmic string decays

Cold dark matter, ongoing discussion, Hiramatsu et al. arXiv:1202.5851, Sikivie astro-ph/0610440

Astrophysics and laboratory searches G. Raffelt @ (BLV2013)



Sikivie et al's idea arXiv:0901.1106

Do axions behave differently than WIMPS?

(except for successful direct detection)

- If axions are in a Bose-Einstein condensate they develop a different galactic halo structure than WIMPs. (Caustics)
- BEC formation needs dissipation
- self-interaction λa^4 is not enough
- gravitational interaction (Saikawa, Yamaguchi et al, arXiv:1210.7080, arXiv:1310.0167)

Do gravitational interactions thermalize cosmic axions?

Our starting point

S.Davidson and M.E. arXiv:1307.8024

- Axions are born as classical field oscillations ⇒ classical problem
- What we already know about gravity:
  - **expands the universe**
  - **grows density fluctuations**

  } leading order solutions to GR
- Do not contain dissipation
- Fast interaction rate is not enough for BEC formation!
- Dissipative effects must be sub leading

How to divide gravity into deterministic and dissipative part?

Our trick

Observations:

- off diagonal terms of $T_{\mu\nu}$ not used for leading order solutions
- imperfect fluid has viscosity on its off diagonal
- viscosity damps density fluctuations on short length scales $\Rightarrow$ homogenisation, BEC formation?

Idea: Estimate axion viscosity by comparing T_{ij}

axion scalar field $\Leftrightarrow$ imperfect fluid

perturbed metric $\nearrow$ $\nwarrow$ homogeneous metric

Viscosity estimate

scalar field:

$$T^i_j(\vec{x}, t) = -\frac{1 + 2\phi}{R^2(t)} \partial_i a \partial_j a$$

imperfect fluid:

$$T^i_j(\vec{x}, t) = -\eta(t)(\partial_j U^i(\vec{x}, t) + \partial^i U_j(\vec{x}, t))$$

η = viscosity, U_μ= fluid velocity, ϕ= Newtonian potential

Viscosity estimate

scalar field:

$$T^i_j(\vec{x}, t) = -\frac{1 + 2\phi}{R^2(t)} \partial_i a \partial_j a$$

imperfect fluid:

$$T^i_j(\vec{x}, t) = -\eta(t)(\partial_j U^i(\vec{x}, t) + \partial^i U_j(\vec{x}, t))$$

η = viscosity, U_μ= fluid velocity, ϕ= Newtonian potential

$\Rightarrow$ estimate viscosity

$$\frac{\eta(t)}{n_a(t)} \sim 2\pi G \sum_p \frac{\delta\widetilde{\rho}(p, t) R^2(t)}{|\vec{p}|^2}$$

Source of gravitational interactions $\delta\widetilde{\rho}(p, t)$ can be dominated by axions or photons!

Viscosity impact

Decay rate for perturbation (comoving size $1/|\vec{p}|$) due to viscosity dumping

$$\Gamma_g \sim \frac{\eta(t)|\vec{p}|^2}{R^2(t)\overline{\rho}(t)} \sim \frac{G m_a^2 n_a(t)}{H_{QCD}^2} \frac{p^2}{m_a^2} \frac{R(t)}{R_{eq}}$$

Comparing $\Gamma_g \sim H$ gives damping scale: $\ell^2_{damp}(t = 1/H)$

Results:

- Damping scale is always smaller than the Jeans length!!
- no effects on cosmological length scales
- No thermalisation on horizon scales found!

Picture of gravitational thermalisation

- Leading order solutions of GR:
  - Homogeneous part of axion energy density drives expansion
  - Density perturbations grow at leading order
- Dissipation cannot be obtained from time-reversal invariant classical field equations at leading order

Picture of gravitational thermalisation

- Leading order solutions of GR:
  - Homogeneous part of axion energy density drives expansion
  - Density perturbations grow at leading order
- Dissipation cannot be obtained from time-reversal invariant classical field equations at leading order
- Dissipative effects of gravity must be suppressed
- estimation of axion viscosity gives negligible effects on cosmological scales
- No claim that our estimate is leading order dissipative process

Summary

- axions are very interesting CDM candidates, soon news from ADMX

Do axions behave differently from WIMPS?

- Sikivie's idea: difference when axions form a BEC
- BEC formation needs dissipation
- Is thermalisation provided by gravitational interaction?
- Our thermalisation estimate
  - leading order gravitational effects do not contain dissipation
  - look for sub-leading effects
  - trick: estimate axion viscosity $\Rightarrow$ dumping of fluctuations on negligible small scales
- We cannot confirm gravitational axion thermalisation!

Backup

Linear perturbation theory

Dynamics determined by

- **Einstein equations** $G_{\mu\nu} = 8\pi G T_{\mu\nu}$
- **Energy momentum conservation** $T^{\mu\nu}_{;\nu} = 0$

Linear perturbation theory

Dynamics determined by

- **Einstein equations** $G_{\mu\nu} = 8\pi G T_{\mu\nu}$
- **Energy momentum conservation** $T^{\mu\nu}_{;\nu} = 0$

Metric

Stress energy tensor

Linear perturbation theory

Dynamics determined by

- **Einstein equations** $G_{\mu\nu} = 8\pi G T_{\mu\nu}$
- **Energy momentum conservation** $T^{\mu\nu}_{;\nu} = 0$

Metric in Newtonian gauge

$$ds^2 = (1 + 2\psi)dt^2 - R^2(t)(1 - 2\phi)\delta_{ij}dx^i dx^j$$

Stress energy tensor

- **scalar field** $T^{\mu}_{\nu} = \partial^{\mu} a \partial_{\nu} a - \frac{1}{2}(\partial_{\alpha} a \partial^{\alpha} a - m^2 a^2)\delta^{\mu}_{\nu}$
- in a homogeneous and isotropic Universe $T^{\mu}\nu = \mathrm{diag}(\bar{\rho}, \bar{P}, \bar{P}, \bar{P})$
- adding scalar perturbations:

$$\overline{\rho}(t) \to \overline{\rho}(t) + \delta\rho(\vec{k}, t) \ , \ \overline{P}(t) \to \overline{P}(t) + \delta P(\vec{k}, t)$$

$$ik_j \delta T^0_j = (\overline{\rho} + \overline{P})\theta(\vec{k}, t) \ , \ (\hat{k}_i \hat{k}_j - \frac{1}{3}\delta_{ij})\delta T^i_j = -(\overline{\rho} + \overline{P})\sigma(\vec{k}, t)$$

Linear perturbation theory

(0-0) Einstein equation (in Fourier space inside the horizon):

$$\frac{|\vec{p}|^2}{R^2(t)}\widetilde{\phi}(\vec{p},t) \simeq 4\pi G_N \delta\widetilde{\rho}(\vec{p},t)$$

Poisson equation for density perturbations!

The evolution equation leading order ($\delta \equiv \frac{\delta\widetilde{\rho}(\vec{p},t)}{\overline{\rho}(t)}$)

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\overline{\rho}\delta + c_s^2 \frac{p^2}{R^2(t)}\delta = 0$$

- describes growth of fluctuations on cosmological scales
- fluctuations oscillate below Jean length $\lambda_{Jeans} \sim 1/\sqrt{H(t)m}$
- T^i_j off diagonal terms of no importance
- no dissipation!