

# Bose Einstein condensation of Dark Matter Axions?



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*based on:*  
*Sacha Davidson and M.E.*  
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# Outline

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## Axions, a reminder

- Pecci-Quinn Mechanism
- Axion cosmology
- Axion parameter space

## BEC of dark matter axions?

- Sikivie's idea
- Gravitational  
thermalisation?

## Summary

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## BEC of dark matter axions?

- Sikivie's idea
- Gravitational thermalisation?

## The idea:

Observable difference between axions and WIMPS if **axions are in a Bose Einstein condensate**

Different galactic halo structure

## Summary

# Strong CP problem

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

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- QCD contains CP violating term

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

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

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

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strong CP problem

**Peccei Quinn solution:**

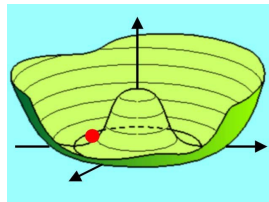
make  $\Theta$  dynamical variable with potential min at 0

# Peccei - Quinn Mechanism

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

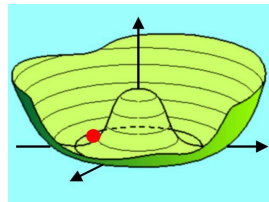
- new  $U(1)_{PQ}$  symmetry spontaneously broken at scale  $f_{PQ}$
- axion  $a(x)$  = Goldstone boson, "phase" of new complex scalar field
- gluon coupling by construction  $\Rightarrow \mathcal{L}_\Theta \rightarrow \frac{a(x)}{f_{PQ}} \frac{\alpha_s}{8\pi} G \tilde{G}$



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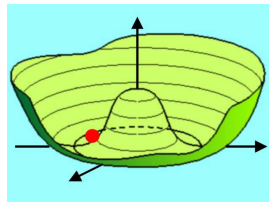
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  - mixing with pions  $\Rightarrow$  mass  $m_a f_{PQ} \sim m_\pi f_\pi$  (after QCD phase transition)
  - axion potential with minimum at  $a = 0$
  - CP conservation





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- **CP conservation**

$f_{PQ}$  is the determining parameter!

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

## Axions as CDM candidates

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### "Invisible" axions

- if  $f_{PQ} \gg f_\pi$  then axions couplings are small and  $m_a \ll m_\pi$
- typical values

$$10\mu eV \leq m_a \leq 10meV$$

- Axions are very light BSM particles!!

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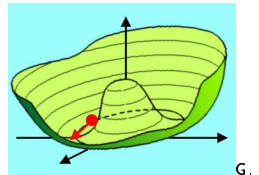
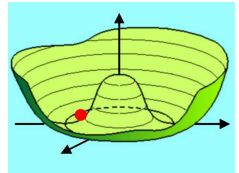
### Can this be a good DM candidate?

- thermal axion production  $\Rightarrow$  Hot dark matter!  $m_a < 0,7\text{eV}$  Hannestad et al. arXiv:1004.0695
- Non-thermal production mechanism  $\Rightarrow$  Cold dark matter
  - Misalignment angle mechanism
  - Cosmic string decay: ongoing discussion, Hiramatsu et al. arXiv:1202.5851, Sikivie astro-ph/0610440

# Misalignment angle mechanism

## 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 ( $T \sim 100 \text{ MeV}$ )
  - axion potential tilted  $\Rightarrow$  axion mass
  - axion field oscillates (classical field oscillations)
  - $\Rightarrow$  cold dark matter



Raffelt © (BLV2013)

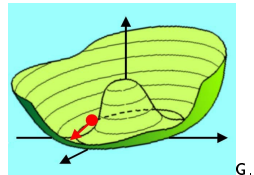
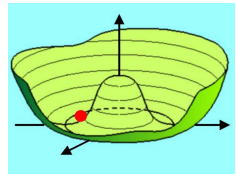
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- Assuming inflation before PQ symmetry breaking

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

- Observed DM density:  $\Omega_{DM} h^2 = 0.12$
- good DM candidate:  $m_a \gtrsim 10 \mu\text{eV}$



Raffelt © (BLV2013)

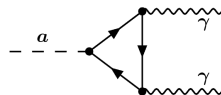
# Axion constraints

axions mix with pions  $\Rightarrow$  coupling to photons

- coupling constant  $\sim \frac{1}{f_{PQ}}$

- **Stability?**

decay is slow on cosmological time scales for  $m_a < 20\text{eV}$



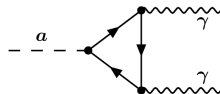
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- **Constraints from astrophysics**

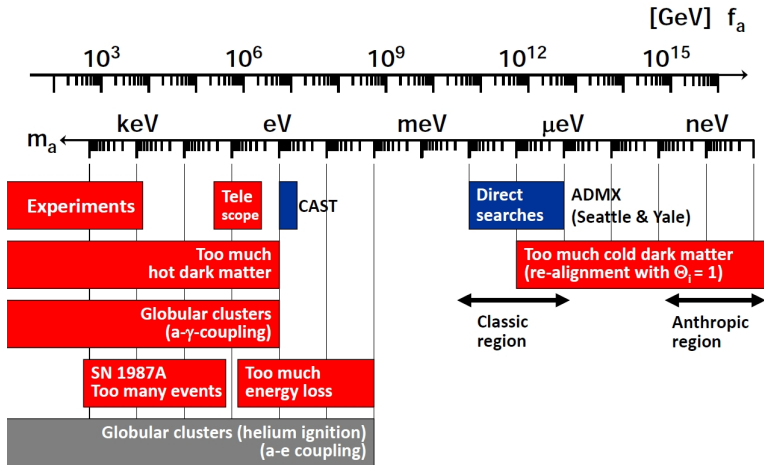
- axions produced in hot plasma  $\Rightarrow$  transport energy  $\Rightarrow$  lifetime (sensitive to different couplings)
- $m_a < 10\text{meV}$

- **Direct detection possibilities:** (probe axion photon coupling)

- Solar axion **telescope** (CAST), probing  $m_a \sim \text{eV}$
- **Microwave cavity** searching dark matter axions (ADMX), probing  $\sim \mu\text{eV}$
- **Light shining through wall** (ALPS) probing  $\sim \text{keV}$

# Astrophysics and laboratory searches

G. Raffelt @ (BLV2013)





# Sikivie et al's idea arXiv:0901.1106

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## 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 thermalisation
- self-interaction  $\lambda a^4$  is not enough
- gravitational interaction (Saikawa, Yamaguchi et al, arXiv:1210.7080, arXiv:1310.0167)

## Do gravitational interactions thermalize cosmic axions?

# Our starting point

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S.Davidson and M.E. JCAP 1312 (2013) 034; arXiv:1307.8024

- Axions are born as classical field oscillations  $\Rightarrow$  classical problem
- What we already know about gravity:
  - **expands the universe**
  - **grows density fluctuations**
- Do not contain dissipation
- Fast interaction rate is not enough for BEC formation!
- Dissipative effects must be sub leading

} leading order solutions to GR

How to divide gravity into deterministic and dissipative part?

# Axion viscosity estimate

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**Idea:** Estimate **axion viscosity**

- 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?

**Results:**

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

# Summary

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- axions can solve the **strong CP problem**
- axions could solve the **DM problem**: Misalignment angle mechanism
- **simple parameter space** constrained by astrophysics, cosmology and experiments:

$$10\mu\text{eV} \leq m_a \leq 10\text{meV}$$

axions are very interesting CDM candidates

- Sikivie's idea: difference between WIMPS and axions if BEC
  - Is thermalisation provided by gravitational interaction?
    - leading order gravitational effects do not contain dissipation
    - trick: estimate axion viscosity  $\Rightarrow$  dumping of fluctuations on negligible small scales
  - We cannot confirm gravitational axion thermalisation!

# Backup

## Linear perturbation theory

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Dynamics determined by

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

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Metric

Stress energy tensor

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Dynamics determined by

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

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

$$\bar{\rho}(t) \rightarrow \bar{\rho}(t) + \delta\rho(\vec{k}, t), \quad \bar{P}(t) \rightarrow \bar{P}(t) + \delta P(\vec{k}, t)$$

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



## Linear perturbation theory

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

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

Poisson equation for density perturbations!

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

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

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

## Viscosity estimate

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scalar field:

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

imperfect fluid:

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

$\eta$  = viscosity,  $U_\mu$  = fluid velocity,  $\phi$  = Newtonian potential

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$\Rightarrow$  estimate viscosity

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

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

## Viscosity impact

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

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

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

**Results:**

- Damping scale is always smaller than the Jeans length!!
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# Picture of gravitational thermalisation

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- 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

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- 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