Axions as Dark matter candidates

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**The strong CP problem**

**Flavor conserving CP-violation in the SM, one phase**

\[ \theta = \theta_{QCD} + N_q \delta \]

\[ \mathcal{L}_{SM} \in - ( \bar{u} \quad \bar{d} \quad \ldots )_L \left( \begin{array}{ccc} m_u e^{i \delta} & 0 & \ldots \\ 0 & m_d e^{i \delta} & \ldots \\ \ldots & \ldots & \ldots \end{array} \right) ( \begin{array}{c} u \\ d \\ \ldots \end{array} ) - \frac{\alpha_s}{8\pi} G \tilde{G} \theta_{QCD} \]

This CP violation is not observed (Neutron electric dipole moment,..)

\[ d_n \sim \theta \times \mathcal{O}(10^{-15}) [e \text{ cm}] \]

predictions

\[ d_n^{\text{exp}} < 3 \times 10^{-26} [e \text{ cm}] \]

\[ \theta < 10^{-10} !! \]
The strong CP problem and axions

In pure SM the vacuum energy has a minimum at $\theta = 0$

$$\exp\left(-\int_x V(\theta)\right) = \int DA^i_\mu \exp(-S_{\text{eff}}[\phi, A^i_\mu]) \exp\left(-i\theta \frac{\alpha_s}{8\pi} G\tilde{G}\right) < \exp\left(-\int_x V(0)\right)$$

$V(\theta)$

... but theta is a constant of nature...

If $\theta$ is a dynamical field (axion!), will roll down to zero, problem solved!

$$\frac{\alpha_s}{8\pi} G\tilde{G}\theta \rightarrow \frac{\alpha_s}{8\pi} G\tilde{G}\theta(x) + \frac{1}{2} (\partial_\mu \theta)(\partial^\mu \theta) f_a^2$$

$$\theta(x) = \frac{a(x)}{f_a}$$

new energy scale!
**Simple model KSVZ**

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at $f_a$

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{Q}DQ - (y\bar{Q}_L Q_R \Phi + \text{h.c}) - \lambda |\Phi|^4 + \mu^2 |\Phi|^2$$

$$\Phi(x) = \rho(x)e^{i\frac{a(x)}{f_a}}$$

- At energies below $f_a$ (SSB)

$$\mathcal{L} \in \frac{1}{2} (\partial a)^2 + \frac{\alpha_s}{8\pi} G\tilde{G} \frac{a}{f_a}$$

- At energies below $\Lambda_{QCD}$, $a - \eta' - \pi^0 - \eta - ...$ mixing

axion mass

$$m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6\text{meV} \frac{10^9\text{GeV}}{f_a}$$

couplings

$$\mathcal{L}_{a,I} = \sum_N c_{N,a} \bar{N} \gamma^\mu \gamma_5 N \frac{a}{f_a} + c_{a\gamma} \frac{\alpha}{2\pi} F_{\mu\nu} \tilde{F}^{\mu\nu} \frac{a}{f_a} + ...$$

nucleons ...

photons ...

mesons ...
If axions exist, they are very light and VERY weakly interacting!
Landscape, what do we know?

If axions exist, they are very light and VERY weakly interacting!
- Axions: small mass, small interactions, thermal DM

- non-thermal DM, Initial conditions

Domains=horizon Cosmic strings

\[ \theta = 0 \]

Damped oscillations=CDM

SSB

QCD D. Walls

Vacuum realignment, strings, walls...
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Domains=horizon
Cosmic strings
SSB

D. Walls
✓
QCD
D. Walls

Damped oscillations=CDM

SCENARIO-I
realignment+CS+DWs

0(1) inhomogeneous DM
QCD-horizon scale
miniclusters

time, T

SSB
Vacuum realignment, strings, walls...

- Axions: small mass, small interactions, thermal DM
- non-thermal DM, Initial conditions

SCENARIO-II
realignment only

INFLATION!!

SSB

Damped oscillations=CDM

QCD D.Walls

time, 1/T

QCD

Vacuum realignment, strings, walls...

Vacuum realignment, strings, walls...
Axion DM, how much

\[
\rho_{\text{obs,DM}} \quad \rho_a \left[ \text{keV/cm}^3 \right]
\]

\[
\theta_1 = 0.01 \quad \theta_1 = 0.1 \quad \theta_1 = 1
\]

\[
\mu \text{eV} \quad \text{meV} \quad \text{eV}
\]

\[
\rho_a \times c_{a\gamma\gamma}
\]

Axion decay

DM density today

realignment

cosmic strings + domain walls

thermal
- Energy density redshifts as matter, from the onset of oscillations

\[ \rho_a(t) \sim \theta_I^2 \Lambda_{QCD}^4 \left( \frac{R_1}{R(t)} \right)^3 \propto \theta_I^2 \Lambda_{QCD}^4 m_a^{-3/2} \]

**Dilution factor**

\[ \left( \frac{R_1}{R_0} \right)^3 \sim \left( \frac{T_0}{T_1} \right)^3 \sim \left( \frac{T_0}{\sqrt{H_1 m_{Pl}}} \right)^3 \sim \left( \frac{T_0}{\sqrt{m_a m_{Pl}}} \right)^3 \propto m_a^{-3/2} \]

Small mass axions, start oscillating later, and get less diluted ...

- with T-dependence

\[ \rho_a(t_0) \propto \theta_I^2 m_a^{-7/6} \]
If axions exist, they are very light and VERY weakly interacting!
- Axion fluctuates during inflation (entropy perturbations)

$$P_{iso} = \frac{d\langle n_a \rangle}{n_a} \sim \frac{d\langle a^2 \rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2}$$

insisting on axion DM $$\theta_I = \theta_I(f_a)$$

Constraint $$f_a(H_I)$$

BICEP2 would exclude SC-II in the simplest models...

of course, there are plenty of ways out...
Detecting Axions
Detecting Axion (Dark Matter) in the lab

\[ \rho_{\text{CDM}} \simeq 0.3 \frac{\text{GeV}}{\text{cm}^3} = m_a n_a \simeq \frac{1}{2} m_a^2 f_a^2 \theta^2 \rightarrow \theta \sim O(10^{-19}) \]

velocities in the galaxy \[ v \lesssim 300 \text{ km/s} \sim 10^{-3} c \]

phase space density \[ \frac{n_a}{4 \pi p^3} \sim 10^{29} \left( \frac{\mu \text{eV}}{m_a} \right)^4 \]

occupation number is HUGE! \[ \rightarrow \text{treat it like a classical coherent (NR) field} \]

Roughly ... \[ a(t) = a_0 \cos(m_a t) \]

Fourier-transform \[ a(x) \]
\[ \omega \simeq m_a (1 + v^2/2 + ...) \]

\[ \delta \omega = \frac{m_a v^2}{2} \]
\[ \frac{\delta \omega}{\omega} \sim 10^{-6} \]
Detecting Axion (Dark Matter) in the lab

Spin precession

CASPER (Mainz-Berkely)

Cavity experiments

ADMX, ADMX-HF,Yale,WISPDMX
CARRACK, IAXO, RADES...

Oscillating EDM

d_n \sim \mathcal{O}(10^{-34}) \cos(m_a t) [e \text{ cm}]

Graham, Rajendran 2011

Axion-photon conversion

Axion-electron absorption

B \rightarrow B^* Sikivie 2014

Atomic transitions?

mass

neV

\mu eV

0.1 meV
- In a static magnetic field, the oscillating axion field generates EM-fields

\[ \mathcal{L}_I = -c_{a\gamma\gamma} \frac{\alpha}{2\pi f_a} \mathbf{B} \cdot \mathbf{E} \]

- Electric fields of order

\[ |\mathbf{E}| \sim \mathcal{O}(10^{-12} \text{V/m}) |\mathbf{B}_{\text{ext}}| c_{a\gamma} \cos(m_a t) \]

- Oscillating at a frequency given by the axion mass

Do not depend on mass or coupling strength!
Cavity experiments

- Haloscope (Sikivie 83)
  “Amplify resonantly the EM field in a cavity”

\[ P \sim Q |E_a|^2 (V m_a) G \kappa \] (on resonance)

- Past experiments Florida U., RBF, ADMX, CARRACK
- Future endeavors: ADMX, ADMX-HF, YMCE, CAPP
- Parameters unexplored at low and high masses: WHY?

Cylindrical cavity \((h/r=b)\) like ADMX but scaled

- Signal \((V \propto m_a^{-3})\) \(P_{\text{out}} \propto V m_a \sim \frac{1}{m_a^2}\)
- Noise \(P_{\text{noise}} = T_{\text{sys}} \Delta \nu_a \propto m_a^2\)
- Signal/noise in \(\Delta \nu_a\) of time, \(t\), \(\frac{S}{N} = \frac{P_{\text{out}}}{P_{\text{noise}}} \sqrt{\Delta \nu_a t}\)
- Scanning rate \(\frac{1}{m_a} \frac{d \Delta m_a}{dt} \propto \frac{c^4}{m_a^9}\)

Very easy, but needs large magnet volume!

Very complicated, needs new ideas...
- Length = 20 m
- Magnetised radius ~ 1 m
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)

- Sensitivity
  
  Big cavity (realistic)
  Many flat (exploit the huge volume)
  (very speculative, R&D needed!)
Dish antenna experiment?

\[ P \sim |E|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{c_\gamma}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{ Watt} \]
\( A=10 \text{m}^2, T=5 \text{K}, B=5 \text{T}, t=1 \text{year}, \)

\( A=10 \text{m}^2, T=QL, B=10 \text{T}, t=1 \text{year}, \)

\( \rho_{\text{CDM}} \sim \frac{0.3 \text{GeV}}{\text{cm}^3} \)

\( m_a[\text{eV}] \)

\( \delta \omega \sim O(1) \)

measure 1/octave of a decade with the same detector at the same time
Enhance the emissivity by multilayers of dielectric

\[ |E_a| \rightarrow |E_a| \times N \]

+ back production and all reflexions ...

Increases sensitivity but losses bandwidth
- Typical Dish antenna experiments fall a bit short, if the DM density is just $\rho_{CDM} = 0.3 \text{GeV/cm}^3$.

- 0.1-1 meV range is most interesting in **Scenario-II**.

- S-II predicts miniclusters of axion CDM:

  $$M_{mc} \sim 10^{-12} M_\odot$$

  $$\Omega_{mc}/\Omega_{aCDM} \sim O(1)$$

- Encounter with the Earth (every $10^4$ years)

  $$\rho_{CDM} \times 10^6, Q_a \sim 10^9, t \sim 3\text{days}$$

- Even with a modest realistic experiment one can get a huge signal! (if lucky...)

Zurek et al 07, See also Kolb & Tkachev 94
Detecting Axions

Solar Axions

5th forces

Photon regeneration

Saturday, 29, November, 2014
Detecting Axions

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Photon regeneration

IAXO CDR 2014

Arvanitaki Geraci PRL 2014

ALPS-II TDR 2013

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A developing picture

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- Axion DM - well motivated and testable
  - but underrepresented
  - key targets still not covered
  - plenty of new ideas

- Cavity experiments on the run
  - micro-eV range by ADMX, ADMX-HF, CAPP?
  - lower masses, IAXO?
  - Dish antenna?

- Millions of things not covered here
  - Axions in BSM physics
  - Axion DM astrophysics (BEC?, miniclusters?, BHs?)
Thank you!!!