Axion Dark matter and detection

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- Axions and strong CP
- Axion CDM
- Isocurvature problems
- Detecting Axion CDM
- Cavities
- Dish antenna
The strong CP “hint” and axions

- $U(1)_A$ is color anomalous, CP-violating phase $\theta = \theta_{QCD} + \delta$ is physical

$$\mathcal{L}_{SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \ldots \\ 0 & m_d e^{i\delta} & \ldots \\ 0 & 0 & \ldots \end{pmatrix} \begin{pmatrix} u \\ d \\ \ldots \end{pmatrix} - \frac{\alpha_s}{8\pi} G G \theta_{QCD}$$

Neutron EDM

$$d_n \sim \theta \times \mathcal{O}(10^{-2})[e\text{ fm}]$$
$$d_n^{\exp} < 3 \times 10^{-13}[e\text{ fm}]$$

$$\theta < 10^{-10}!!$$

- why is soooo small? is there any fundamental reason?

Axion $\alpha$

- New axial $U(1)$ c.a. symmetry
- spontaneously broken (PGB!)
- $\theta$ promoted to field $\theta \to \alpha / f_a$
- QCD potential

$$\theta \to 0$$
Axion mass and couplings (and model dependencies)

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

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

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

- At energies below $f_a$  
  \[ \mathcal{L} \in \frac{1}{2} (\partial a)^2 + \frac{\alpha_s}{8\pi} G\tilde{G} \frac{a}{f_a} \]

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

**Axion mass**  
\[ m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 6\text{meV} \frac{10^9\text{GeV}}{f_a} \]

**Axion couplings**

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

nucleons ...
photons ...
mesons ...
- Axions (if existing) are very light and very weakly interacting! -> WISP!
Axion cold dark matter: vacuum alignment

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

Domains=horizon
Cosmic strings

QCD
D. Walls
θ = 0
Damped oscillations=CDM

SSB
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SCENARIO-I
realignment+CS+DWs

O(1) inhomogeneous DM
QCD-horizon scale miniclusters

time, I/T

SSB

Damped oscillations=CDM
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SSB

Damped oscillations = CDM

INFLATION!!

time, 1/T

QCD DW, SSB
Axion cold dark matter: vacuum alignment

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SCENARIO-II
realignment only

INFLATION!!

SSB

QCD D.Walls

Damped oscillations=CDM

time, I/T
Rough relic abundance of axion Dark matter

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

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

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

- today...

\[ \rho_a(t_0) \propto \theta_I^2 m_a^{-3/2} \]

- doing it properly... (thermal axion mass)

\[ \rho_a(t_0) \propto \theta_I^2 m_a^{-7/6} \]
Axion DM abundance fitting the observations

\[ f_a [\text{GeV}] \]

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

SCENARIO-II

SCENARIO-I

- ADMX
- ADMX-II
- IAXO
- CAST
- Telescope

Hot-DM / CMB / BBN

Burst Duration

SK

SN1987A

Globular Clusters \( (g_{ae}) \)

White Dwarfs \( (g_{ae}) \)

Solar Neutrino flux \( (g_{a\gamma}) \)

Beam Dump

Excluded (too much DM)

\( m_a \sim 0.5 \text{meV} \)
The isocurvature problem after BICEP2

- Axion fluctuates during inflation (entropy perturbations)

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

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

Constraint \( f_a(H_I) \)

\[ f_a \gg H_I \]

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

of course, there are plenty of ways out ...
Laboratory
Experiments to detect axion DM

- Dish antenna

- Cavity experiments

- Light propagation

- Oscillating EDM
DM around us

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

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!

\[ \text{still can treat it like a classical (NR) field} \]

Roughly ...

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

Fourier-transform \( a(x) \)

\[ \omega \sim m_a(1 + v^2/2 + ...) \]

\[ \delta \omega = \frac{m_a v^2}{2} \quad \frac{\delta \omega}{\omega} \sim 10^{-6} \]
E-fields from axion CDM in a B-field

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

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

\[ \mathcal{L}_I = -c a \gamma \gamma \frac{\alpha}{2\pi} \theta(t) \mathbf{B}_{\text{ext}} \cdot \mathbf{E} \]

- Electric fields of order

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

- oscillating at a frequency given by the axion mass

Do not depend on mass or coupling strength!
Detecting EM fields from Axion Dark Matter

- Haloscope (Sikivie 83)
  “Amplify resonantly the EM fields created by axionDM in a B-field in a cavity”

\[ P \sim Q |E_a|^2 (V m_a) \mathcal{G}_\kappa \]  
(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 \(\frac{1}{m_a} \frac{d\Delta m_a}{dt} \propto \frac{c_\gamma^4}{m_a^9}\)

\(\nu \left[ \text{GHz} \right]\)

\(m_a \left[ \mu eV \right]\)

Very easy, but needs large magnet volume!
Very complicated, needs new ideas...
DM searches with future IAXO (International Axion Observatory)

- 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!)
Simplest experiment: Dish antenna

\[ P \sim |E|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{c_\gamma}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{Watt} \]
Simplest experiment: Dish antenna

\[ A = 10 \text{m}^2, T = 5 \text{K}, B = 5 \text{T}, t = 1 \text{year}, \]

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

\[ \rho_{\text{CDM}} \sim \frac{0.3 \text{GeV}}{\text{cm}^3} \]

measure 1/octet of a decade with the same detector at the same time
Possible improvement

Enhance the emissivity by multilayers of dielectric

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

Increases sensitivity but losses bandwidth
Dish antenna and miniclusters

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

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

- S-II predicts miniclusters of axion CDM

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

$$\Omega_{mc}/\Omega_{a\text{CDM}} \sim O(1)$$

Zurek et al 07, See also Kolb & Tkachev 94

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

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

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

\[ m_a [\text{eV}] \]
\[ \gamma \]
\[ C_\gamma \]

8-Dish IAXOQL

8-Dish IAXOSYS

Scenario II
Conclusions

- Axion DM - well motivated and testable
  - but underrepresented (gets better)
  - key targets not covered
  - plenty of new ideas uncovered here

- Cavity experiments on the run
  - micro-eV range by ADMX, ADMX-HF
  - lower masses, IAXO?
  - higher masses, new ideas!

- Dish antenna
  - a little short for axions
  - broadband/miniclusters!
  - boost with dielectric layers!
  - good for ALPs, hidden photons!
Getting better

- New IBS (Institute of Basic Science) Center for Axion and Precision Physics (CAPP) KAIST campus, Daejeon/Korea

- + in US
  - Yale developing ADMX-HF
  - CASPER

- Europe getting involved
  - CASPER, Budker@Mainz
  - DESY, CERN, Unizar

- International AXion Observatory

main goal:
  solar axions
  but also DM