Ultralight dark matter

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- ultralight dark matter?

1 - candidates: QCD axion, ALPs, HPs ...

2 - Non-thermal production mechanisms

3 - BEC?

4 - Detection ...
Ultralight dark matter? *

- Low mass ... stabilised by symmetry?
  - Nambu-Goldstone Bosons,
  - U(1) vector-boson
  - ... 

- Tremaine-Gunn, mass < eV -> Bosons

- Secluded from SM interactions... Weakly-Interacting-SLIM-Particless
  - Production mechanism?
  - Isocurvature constraints?
  - BEC?
  - Experimental Detection?
The strong CP problem

Flavor conserving CP-violation in the SM, one phase

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

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

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 \( \theta = 0 \)

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

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

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

new energy scale!

\[
\theta(x) = \frac{a(x)}{f_a}
\]
Simple model KSVZ

- **Peccei-Quinn symmetry, color anomalous, spontaneously broken at** \( f_a \)

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

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

- **At energies below** \( f_a \) (SSB)

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

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

**Axion mass**

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

**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 ...

**Elastic scattering**

\[
N_a \sim \frac{1}{2f_a} \frac{m_\pi}{m_a} a
\]

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- nucleons ...
- photons ...
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**Elastic scattering**

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Landscape, what do we know?

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!
Vacuum realignment, strings, walls...

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

Domains=horizon

Cosmic strings

QCD

D. Walls

Damped oscillations=CDM

SSB

\[ \theta = 0 \]

time, \( I/T \)
Axions: small mass, small interactions, thermal DM, non-thermal DM, Initial conditions

SCENARIO-I
realignment + CS + DWs

O(1) inhomogeneous DM, QCD-horizon scale, miniclusters

Vacuum realignment, strings, walls...

SSB

time, $1/T$

Damped oscillations = CDM

Domains = horizon, Cosmic strings, θ, QCD, D. Walls
Vacuum realignment, strings, walls...

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

SCENARIO-II
realignment only

INFLATION!!

SSB

QCD D.Walls

Damped oscillations=CDM

time, 1/T
Axion DM, how much

\[ \ddot{a}_k + 3H \dot{a}_k + (k^2 + m_a^2) a_k \approx 0 \]

\[ \frac{a(t)}{a_0} \]

\[ \rho \sim \frac{\rho_0}{R^{3(4)}} \]

\[ t \sim \frac{1}{\sqrt{k^2 + m_a^2}} \sim \min\{\lambda, \frac{1}{m_a}\} \]
why decreases with the mass?

- 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

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

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

- with T-dependence

\[ \rho_a(t_0) \propto \theta_I^2 m_a^{-7/6} \]
Axion DM, how much

Axion density today

\[ \rho_{a}[\text{keV/cm}^3] \]

- \[ \theta_I = 0.1 \]
- \[ \theta_I = 0.1 \]
- \[ \theta_I = 1 \]

\[ \rho_{\text{obs, DM}} \]

Cosmic strings + domain walls

Realignment

Thermal

Axion decay

Axion DM decay

\[ \gamma \rightarrow \text{axion} + \text{gamma} \]
If axions exist, they are very light and VERY weakly interacting!
Axion fluctuates during inflation

\[
P_{\text{iso}} = \frac{\langle a^2 \rangle}{a_I^2} = \frac{\langle n_a \rangle}{n_a} \sim \frac{H_I^2}{\pi^2 a_I^2} < 0.039 P_s = 0.88 \times 10^{-10}
\]

insisting on axion DM

Constraint \( \theta_I = \theta_I(f_a) \)

\[
\langle \delta a^2 \rangle \sim \frac{H_I^2}{\pi^2}
\]

so then ...

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

- of course, there are plenty of ways out ...

- note that inflation cannot generate the initial amplitude required for DM
ultralight DM forms a BEC?

- Condensed... they are

phase-space density
\[ \mathcal{N} = \frac{\rho_{\text{DM}}/m_a}{4\pi (\delta p \sim H)^3} \sim 10^{61} \]

Evolution of ~ coherent state with huge number of non-relativistic quanta, subhorizon correlation scale

- thermalisation rates

Self-interactions : marginally relevant for a few H-times (axitons,...)

\[ V(a) = \Lambda_{\text{QCD}}^4(T)(1 - \cos(a/f_a)) \approx \frac{1}{2} \frac{\Lambda_{\text{QCD}}^4}{f_a^2} a^2 - \frac{1}{24} \frac{\Lambda_{\text{QCD}}^4}{f_a^4} a^4 \]

\[ \Gamma \lambda \sim \frac{1}{4} \frac{\lambda n}{m^2} \propto a^3 \quad \text{(condensed regime, Sikivie 1111.1157)} \]

Gravity : increasingly relevant

\[ \Gamma_g \sim 4\pi G n m^2 l_{\text{corr}}^2 \propto a \quad \text{(condensed regime, Sikivie 1111.1157)} \]
ultralight DM forms a BEC?

- gravitational thermalisation -> BEC?

<table>
<thead>
<tr>
<th>thermalisation, maximal entropy configuration</th>
</tr>
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<tbody>
<tr>
<td>Intuition of BEC from atomic physics -&gt; highly occupied k=0 state due to REPULSIVE interactions</td>
</tr>
<tr>
<td>ATTRACTIVE interactions (gravity) led to different configurations: BOSE STARS!</td>
</tr>
</tbody>
</table>

solutions of the Schoedinger-Newton equation

\[ i \frac{\partial \psi}{\partial t} = -\frac{1}{2m} \nabla^2 \psi + m \phi_N \psi \]

Wave-function \hspace{1cm} Heisenberg-pressure \hspace{1cm} Newton’s potential

Jean’s instability

\[ k < k_J = (16\pi G m^3 n_0)^{1/4} \]

Looks like axion-modes evolve just like a q-mechanical version of density fluctuations

\[ n = |\psi|^2 \]

thermalisation = virialisation?

Controversy is served: Guth’s bottleneck (1412.5930) vs Sikivie’s big vortex (1307.3547)

Numerical simulations under way (Guth, Davidson)
Detecting Axion (Dark Matter) in the lab

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

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

Roughly ...

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

\begin{align*}
\text{Fourier-transform} \quad & a(x) \\
\omega & \approx m_a (1 + v^2/2 + \ldots) \\
\delta \omega & = \frac{m_a v^2}{2} \\
\delta \omega/\omega & \sim 10^{-6} \\
\delta t & \sim \frac{1}{\delta \omega} \sim 0.13 \text{ms} \left( \frac{10^{-5}\text{eV}}{m_a} \right) \\
\delta L & \sim \frac{1}{\delta p} \sim 20 \text{m} \left( \frac{10^{-5}\text{eV}}{m_a} \right)
\end{align*}
Detecting Axion (Dark Matter) in the lab

**Spin precession**
- CASPER (Mainz-Berkely)

**Cavity experiments**
- ADMX, ADMX-HF, Yale, WISPDMX
- CARRACK, IAXO, RADES...

**Oscillating EDM**
- $d_n \sim \mathcal{O}(10^{-34}) \cos(m_a t)[e\, cm]$
- Graham, Rajendran 2011

**Axion-photon conversion**

**Axion-electron absorption**
- Sikivie 2014

<table>
<thead>
<tr>
<th>Mass</th>
<th>neV</th>
<th>µeV</th>
<th>0.1 meV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spin precession</strong></td>
<td>[Diagram]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
</tbody>
</table>
Axion DM in a B-field

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

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

- 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  
  \[ \frac{1}{m_a} \frac{d \Delta m_a}{dt} \propto \frac{c_\gamma^4}{m_a^9} \]

Very easy, but needs large magnet volume!
Very complicated, needs new ideas...
Axion DM searches with IAXO?

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

A=10m^2, T=5K, B=5T, t=1 year,

A=10m^2, T=QL, B=10T, t=1 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

\( \frac{\delta \omega}{\omega} \sim O(1) \)
Enhance the emissivity by multilayers of dielectric

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

Increases sensitivity but losses bandwidth

4 layers tuned lambda/2

possible boost
- Typical Dish antenna experiments fall a bit short, if the DM density is just $\rho_{\text{CDM}} = 0.3$ 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...)
Detecting Axions

**Solar Axions**

IAXO CDR 2014

**5th forces**

Arvanitaki Geraci PRL 2014

**Photon regeneration**

ALPS-II TDR 2013
Detecting Axions

Solar Axions

IAXO CDR 2014

5th forces

Arvanitaki Geraci PRL 2014

Photon regeneration

ALPS-II TDR 2013
Detecting Axions

Solar Axions

CAST
CAST phase I
IAXO?

IAXO CDR 2014

5th forces

PQ Axion $f_{\alpha}$ in GeV

Arvanitaki Geraci PRL 2014

Photon regeneration

CAST
ALPS-I
ALPS-II
ALPS-IIeC

ALPS-II TDR 2013

SN $\gamma$-burst
TeV transparency
WD cooling

ALPs as cold dark matter
QCD Axion

SN $\gamma$-burst
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IAXO CDR 2014

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ALPS-II TDR 2013
A developing picture

osc. EDM

Atomic transitions?

5th forces?

Dish Antenna?

IAXO DM

IAXO DM

ADMX ADMX-HF

White Dwarfs ($g_{ae}$)

Solar Neutrino

Hot-DM / CMB

Burst Duration

Globular Clusters

$\frac{m_a}{eV}$

$\frac{f_a}{GeV}$
Conclusions

- 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?)
  - other ultralight DM candidates...
Thank you!!!
want more? ... come to Zaragoza!

11th Patras Workshop on Axions, WIMPs and WISPs

22 - 26 June 2015
University of Zaragoza, Spain

AXION-WIMP 2015

Organizing committee:
Igor G Irastorza (Chair, University of Zaragoza)
Vassilis Anastassopoulos (University of Patras)
Laura Baudis (University of Zurich)
Joerg Jaeckel (University of Heidelberg)
Axel Lindner (DESY)
Andreas Ringwald (DESY)
Marc Schumann (University of Bern)
Konstantin Zioutas (University of Patras & CERN)

http://axion-wimp2015.desy.de/