Alternative Dark Matter Candidates: Axions.

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Introduction

Many dark matter candidates

![Diagram showing various dark matter candidates with their mass and interaction cross-section.](image)

Fig. 4. (Color online) Several well-motivated candidates of dark matter shown. $\sigma_{\text{int}}$ is the typical strength of the interaction with ordinary matter. The red, pink and blue colors represent HDM, WDM and CDM, respectively. We updated the previous figures [375,304] by including the sterile neutrino DM [95,96,4]. The introduction of a $Z_2$ symmetry was needed, which is usually taken to be $R$-parity. Other unbroken discrete symmetries are also possible for an absolutely stable particle in SUSY models [252]. The simplest example of a discrete symmetry is $Z_2$ or parity $P$ because then all the visible-sector particles are simply assigned with 0 (or +) modulo 2 quantum number of $Z_2$ (or parity $P$). Because most of the visible-sector particles are assumed to be lighter than the WIMP, the WIMP is assigned with 1 modulo 2 (or − of parity $P$). The WIMP which is responsible for CDM is the lightest $Z_2=1$ modulo 2 particle, or the lightest $P=−1$ particle. This case is very elementary because the non-em may classify particles into two sectors: the visible sector with $Z_2$=even and the other sector with $Z_2$=odd. For a SUSY WIMP, an exact $Z_2$R has been used such that the lightest $Z_2$-odd particle can be the WIMP [222,220]. With a bigger discrete symmetry, classification of particles according to quantum numbers of the discrete symmetry is more complex, but may also result in a stable WIMP.

[Baer, Choi, Kim, Roszkowski 10]
Introduction

Many dark matter candidates

Strongest physics case based on UV completions of the Standard Model which solve also other problems
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- Many dark matter candidates
- Strongest physics case based on UV completions of the Standard Model which solve also other problems
  - Hierarchy Problem
- MSSM: Neutralino or Gravitino

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[Baer, Choi, Kim, Roszkowski 10]
Many dark matter candidates

Strongest physics case based on UV completions of the Standard Model which solve also other problems

- Hierarchy Problem
- Neutrino Masses and Mixing
- Baryon Asymmetry

MSSM: Neutralino or Gravitino

nuMSM: Lightest sterile neutrino

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The visible-sector particles was performed by Lee and Weinberg [331]. This was followed by Goldberg [209] for the case of SUSY neutralinos and has been reviewed extensively in the case of SUSY models in [266]. In Fig. 4, we list several DM candidates in the cross-section vs. mass plot, which started from Ref. [331]. In the case of SUSY WIMPs, the introduction of a $Z_2$ symmetry was needed, which is usually taken to be $R$-parity. Other unbroken discrete symmetries are also possible for an absolutely stable particle in SUSY models [252]. The simplest example of a discrete symmetry is $Z_2$ or parity $P$ because then all the visible-sector particles are simply assigned with 0 (or +) modulo 2 quantum number of $Z_2$ (or parity $P$). Because most of the visible-sector particles are assumed to be lighter than the WIMP, the WIMP is assigned with 1 modulo2 quantum number of $Z_2$ (or $-1$ of parity $P$). The WIMP which is responsible for CDM is the lightest $Z_2=1$ (modulo2) particle, or the lightest $P=-1$ particle. This case is very elementary because the non may classify particles into two sectors: the visible sector with $Z_2$=even and the other sector with $Z_2$=odd. For a SUSY WIMP, an exact $Z_2 R$ has been used such that the lightest $Z_2$-odd particle can be the WIMP [222,220]. With a bigger discrete symmetry, classification of particles according to quantum numbers of the discrete symmetry is more complex, but may also result in a stable WIMP.
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- Many dark matter candidates
- Strongest physics case based on UV completions of the Standard Model which solve also other problems
  - Hierarchy Problem
  - Neutrino Masses and Mixing
  - Baryon Asymmetry
  - Strong CP Problem
- MSSM: Neutralino or Gravitino
- nuMSM: Lightest sterile neutrino
- PQSM: Axion
PQSM: Peccei-Quinn Extensions of the Standard Model

- A singlet complex scalar field $\sigma$ featuring a global $U(1)_{\text{PQ}}$ symmetry is added

- Symmetry is broken by vev $\langle \sigma \rangle = v_{\text{PQ}}/\sqrt{2}$
  
  $\sigma(x) = \frac{1}{\sqrt{2}} \left( v_{\text{PQ}} + \rho(x) \right) e^{iA(x)/f_A}$
  
  - Excitation of modulus: $m_\rho \sim v_{\text{PQ}}$
  - Excitation of angle: pseudo-NGB: $m_A \ll v_{\text{PQ}}$

- PQ charges of quarks (SM or extra) are such that $U(1)_{\text{PQ}} \times SU(3)_C \times SU(3)_C$ features a chiral anomaly: A is called axion
  
  [Peccei, Quinn 77; Weinberg 78; Wilczek 78]

- Couplings of axion to SM suppressed by powers of $f_A = N v_{\text{PQ}} \gg v = 246$ GeV

\[ \mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{A}{f_A} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} - \frac{\alpha}{8\pi} C_A \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_A f}{f_A} \partial_\mu A \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f \]
PQSM: Peccei-Quinn Extensions of the Standard Model

\[ \mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{A}{f_A} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} - \frac{\alpha}{8\pi} C_A \gamma \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_A f}{f_A} \partial_\mu A \bar{\psi} f \gamma^\mu \gamma^5 \psi_f \]

> The field \( \theta_A = A/f_A \) acts as space-time dependent theta parameter and thus solves strong CP problem since QCD dynamics dictates \( \langle \theta_A \rangle = 0 \)

[Peccei, Quinn 77; Weinberg 78; Wilczek 78]

> Axion acquires a small mass from mixing with the pion

\[ m_A \sim \frac{m_\pi f_\pi}{f_A} \sim \text{meV} \left( \frac{10^9 \text{GeV}}{f_A} \right) \]
Axion-Like Particles (ALPs)

> Often, there is more than one global symmetry and therefore more than one Nambu-Goldstone boson

- Global lepton number symmetry: Majoron [Chikashige et al. 78; Gelmini,Roncadelli 80]
- Global family symmetry: Familon [Wilczek 82; Berezhiani,Khlopov 90]

\[ \mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{C_{i g}'}{f_{a_i'}} a_i' G_{\mu\nu}^b \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} \frac{C_{i\gamma}'}{f_{a_i'}} a_i' F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_{a_i'f}'}{f_{a_i'}} \partial_{\mu} a_i' \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f \]

> Then the particle corresponding to the excitation of the field combination

\[ \frac{A(x)}{f_A} \equiv \frac{C_{i g}'}{f_{a_i'}} a_i'(x) \]

is the **axion**

> Particle excitations of the fields orthogonal to this field combination are called **Axion-Like-Particles (ALPs)**

> String theory suggests a plenitude of ALPs [Witten 84; Conlon 06; Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10; Cicoli,Goodsell,AR 12]
Axion Dark Matter

> DM from vacuum realignment

\[ m_a < 3H \]
axion is frozen

\[ m_a \approx 3H \]
axion number \( N_a \) is conserved

axion starts rolling, turns into pressureless matter.

[Preskill et al 83; Abbott, Sikivie 83; Dine, Fischler 83, ...]

[Wantz, Shellard `10]
Axion Dark Matter

> DM from vacuum realignment

[Preskill et al 83; Abbott, Sikivie 83; Dine, Fischler 83,...]

> DM from topological defects

- Inflated away if SSB happens before inflation and not restored after
- Important contribution if PQ symmetry restored after inflation

[Hiramatsu et al. 12]
Axion Dark Matter

> DM from vacuum realignment

[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

> DM from topological defects

- Inflated away if SSB happens before inflation and not restored after
- Important contribution if PQ symmetry restored after inflation

> DM prediction depends critically on temperature dependence of axion mass, \( m_A(T) f_A = \sqrt{\chi(T)} \)

> QCD lattice calculations of topological susceptibility \( \chi(T) \)

- Previous estimates using dilute instanton gas approximation surprisingly accurate

[Petrecky et al. `16]
Axion Dark Matter

- **DM from vacuum realignment**
  [Preskill et al 83; Abbott, Sikivie 83; Dine, Fischler 83,...]

- **DM from topological defects**
  - Inflated away if SSB happens before inflation and not restored after
  - Important contribution if PQ symmetry restored after inflation

- **DM prediction depends critically on temperature dependence of axion mass**
  \[ m_A(T) f_A = \sqrt{\chi(T)} \]

- **QCD lattice calculations of topological susceptibility** \( \chi(T) \)
  - Previous estimates using dilute instanton gas approximation surprisingly accurate
  - If PQ symmetry restored after inflation: \( m_A = 50-1500 \mu eV \)

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[Andreas Ringwald | Alternative Dark Matter Candidates: Axions and ALPs, NOW 2]
Modulus of PQ field $|\sigma| = \rho/\sqrt{2}$, may play the role of the inflaton field, if it has a non-minimal coupling to gravity,

$$S \supset - \int d^4 x \sqrt{-g} \left[ \frac{M^2}{2} + \xi_\sigma \sigma^* \sigma \right] R$$

[Ballesteros, Redondo, AR, Tamarit, 1609.nnnn]  [Ballesteros, Redondo, AR, Tamarit, 1608.05414]
Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges [Dias et al. '14]

\[ L = - \left[ Y_{u ij} q_i \epsilon H u_j + Y_{d ij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j 
+ y \tilde{Q} \sigma Q + y Q_d \sigma Q d + h.c. \right] \]

<table>
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<th>N</th>
<th>E</th>
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SM*A*S*H: Solving Five Problems at One Stroke

> Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges

\[
\mathcal{L} \supset - \left[ Y_{uij} q_i e H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i e H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \right] + y \tilde{Q} \sigma Q + y_{Q di} \sigma Q d_i + h.c. \]

> VEV \( v_\sigma \sim 10^{11} \text{ GeV} \):

- Determines Majorana masses
- Explains smallness of active neutrino masses by see-saw relation

\[
m_\nu = 0.04 \text{ eV} \left( \frac{10^{11} \text{ GeV}}{v_\sigma} \right) \left( \frac{-F Y^{-1} F^T}{10^{-4}} \right) \]

SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414]
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> Thermal leptogenesis (out of equilibrium decay of RHN)

> Axion dark radiation \( \Delta N_{\nu}^{\text{eff}} \approx 0.03 \)

[Ballesteros, Redondo, AR, Tamarit, 1609.nnnnn]
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> Thermal leptogenesis (out of equilibrium decay of RHN)

> Axion dark radiation \( \Delta N_{\nu}^{\text{eff}} \approx 0.03 \)

> Axion CDM according to post-inflationary PQ SSB

[Dias et al. `14]

[Ballesteros, Redondo, AR, Tamarit, 1608.05414]
Upcoming generation of axion dark matter experiments can probe sizeable portion of axion mass range relevant for DM:

Axion Mass $m_A$ (eV)

- Dark Matter (pre-inflation PQ phase transition)
- Dark Matter (post-inflation PQ phase transition)
- NS in Cas A (g$_{Ann}$ DFSZ)
- SN1987A (g$_{App}$ KSVZ)
- Black Holes

Axion Mass $f_A$ (GeV)

- XENON100 (g$_{Aee}$ DFSZ)
- Hot-DM / CMB / BBN
- Telescope/EBL
- Beam Dump
- Burst Duration
- Counts in SuperK
- RGs in GCs (g$_{Aee}$ DFSZ)
- WDLF (g$_{Aee}$ DFSZ)
- WDLF Hint
- HB Stars in GCs (g$_{A_{17}}$ DFSZ)
- RB Hint

[AR,Rybka,Rosenberg RPP `16]
Magnetic Resonance Searches

> Galactic axion DM field induces oscillating nuclear EDMs:

\[ d_N(t) = g_d \sqrt{\rho_{DM}} \cos(m_a t)/m_a \]

> **CASPER (Mainz):**

MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in presence of electric field

\[ M(t) \approx n \mu \mu^* e S d n \frac{\sin[(2\mu B_{ext} - m_a c^2) t]}{2\mu B_{ext} - m_a c^2} \sin(2\mu B_{ext} t) \]

[Budker et al. 14]
Galactic axion DM field induces oscillating nuclear EDMs:

\[ d_N(t) = g_d \sqrt{\rho_{DM}} \cos(m_a t) / m_a \]

**CASPEr (Mainz):**

MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in presence of electric field

\[ M(t) \approx n \rho \mu E^* \varepsilon_s d_n \frac{\sin\left(\frac{2 \mu B_{ext} - m_a c^2}{\hbar} t\right)}{2 \mu B_{ext} - m_a c^2 / \hbar} \sin(2 \mu B_{ext} t) \]

---

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>( n )</th>
<th>( E^* )</th>
<th>( p )</th>
<th>( T_2 )</th>
<th>Max ( B_{ext} )</th>
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<tbody>
<tr>
<td>Phase 1</td>
<td>( 10^{22} ) cm(^{-3} )</td>
<td>( 3 \times 10^8 ) V/cm</td>
<td>( 10^{-3} )</td>
<td>1 ms</td>
<td>10 T</td>
</tr>
<tr>
<td>Phase 2</td>
<td>( 10^{22} ) cm(^{-3} )</td>
<td>( 3 \times 10^8 ) V/cm</td>
<td>1</td>
<td>1 s</td>
<td>20 T</td>
</tr>
</tbody>
</table>

**Budker et al. 14**
Magnetic Resonance Searches

- Axion/ALP nucleon/electron coupling leads to nucleon/electron spin precession about galactic axion/ALP DM wind

- **CASPEr** (Mainz):
  MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in DM wind

\[
M(t) \approx np\mu \left(g_{aNN} \sqrt{2\rho_{DM}}\right) \frac{\sin \left((2\mu B_{ext} - m_a)t\right)}{2\mu B_{ext} - m_a} \sin (2\mu B_{ext}t)
\]

[Graham,Rajendran 13]
> Axion/ALP nucleon/electron coupling leads to nucleon/electron spin precession about galactic axion/ALP DM wind

> CASPER (Mainz):

MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in DM wind

\[ M(t) \approx n\mu \left( g_{aNN} \sqrt{2\rho_{DM}v} \right) \frac{\sin \left( \left( 2\mu B_{\text{ext}} - m_a \right) t \right)}{2\mu B_{\text{ext}} - m_a} \sin \left( 2\mu B_{\text{ext}}t \right) \]

<table>
<thead>
<tr>
<th>Element</th>
<th>Density ((n))</th>
<th>Magnetic Moment ((\mu))</th>
<th>(T_2)</th>
<th>Max. B</th>
<th>Magnetometer Sensitivity</th>
</tr>
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<tbody>
<tr>
<td>1. Xe</td>
<td>(1.3 \times 10^{22} \frac{\text{cm}^3}{\text{cm}^3})</td>
<td>(0.35 \mu_N)</td>
<td>100 s</td>
<td>10 T</td>
<td>(10^{-16} \frac{T}{\sqrt{\text{Hz}}})</td>
</tr>
<tr>
<td>2. (^3\text{He})</td>
<td>(2.8 \times 10^{22} \frac{\text{cm}^3}{\text{cm}^3})</td>
<td>(2.12 \mu_N)</td>
<td>100 s</td>
<td>20 T</td>
<td>(10^{-17} \frac{T}{\sqrt{\text{Hz}}})</td>
</tr>
</tbody>
</table>
Magnetic Resonance Searches

- The axion/ALP electron coupling

\[
\mathcal{L} \supset g_{aee} \partial_\mu a (\bar{e} \gamma_5 \gamma^\mu e)
\]

will also lead to a spin precession about the axion/ALP DM wind

- Larmor frequency and thus sensitivity extended to higher masses by factor

\[
\frac{\mu_B}{\mu_N} \sim \frac{m_N}{m_e} \sim 10^3
\]

- **QUAX** (QUaerere AXions) in preparation by INFN (Legnaro, Padua, Torino), Birmingham, Moscow aims to exploit magnetic resonance (MR) inside a magnetized material (Electron Spin Resonance (ESR))

[Carugno, Ruoso et al.]
Resonant Microwave Cavities

- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

$$ P_{\text{out}} \sim g^2 \left| B_0 \right|^2 \rho_{\text{DM}} V Q / m_a $$

- Best sensitivity: mass = resonance frequency  
  $$ m_a = 2\pi \nu \sim 4 \ \mu\text{eV} \left( \frac{\nu}{\text{GHz}} \right) $$
Resonant Microwave Cavities

- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

\[ m_a = 2\pi\nu \sim 4 \mu eV \left( \frac{\nu}{\text{GHz}} \right) \]

- Best sensitivity: mass = resonance frequency

- Ongoing: ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid

- Construction: X3 (Yale), CULTASK (South Korea), ...
Resonant Microwave Cavities

Microwave cavities can probe axion dark matter for $\mu eV \lesssim m_A \lesssim 0.1$ meV

[Diagram showing resonance microwave cavities and axion dark matter sensitivity]

$\nu_A$ (GHz)

$m_A$ (eV)

$C_{AY}$

$[\text{Borsanyi et al. } ^\prime 16]\n
[f_A \text{[GeV]}$

$C_{AY}$

$[\text{Ballesteros, Redondo, AR, Tamarit, 1608.05414}]$
Open Fabry-Perot Resonators

> ORPHEUS (Seattle):

- exploit open Fabry-Perot resonator and series of current wire-planes

[Bybka et al. 15]
Dish Antennas

> Oscillating axion/ALP DM in a background magnetic field carries a small electric field component [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

\[
\text{Axion field mixes with photon field in a static B-field}
\]

At surfaces (reflecting or change in refractive index): emission of photons in both directions

\[
\begin{align*}
X_0 & \quad \longrightarrow \quad X_T \\
X_R & \quad \longrightarrow \quad X_T \\
A_R & \quad \longrightarrow \quad A_T
\end{align*}
\]


\[
(P/A)_{\text{single surface}} \sim 2 \cdot 10^{-27} \text{ W/m}^2 \cdot (B/5T)^2 \cdot (c/2)^2
\]

A magnetised mirror in axion/ALP DM background radiates photons [Majorovits `15]

> Simple broadband experiment: spherical dish antenna
Open Dielectric Resonators

> Boosting sensitivity

Many surfaces → resonator→ “photon boost”


Boost factor:
power generated in resonator/power generated on single metallic ($\epsilon_r=\infty$) surface

$$(P/A)_{\text{resonant cavity}} \sim 2 \cdot 10^{-27} \text{ W/m}^2 \cdot (B/5\text{T})^2 \cdot (c/2)^2 \cdot (\text{Boost factor})$$

> Experimental setup: MADMAX

[Majorovits `15]
Open Dielectric Resonators

> **MADMAX** prototype:

First prototype setup at MPI

[Caldwell et al. `15]
New proposals cover mass region relevant for post-inflationary PQSB:

[Horns, Lindner, Lobanov, AR in preparation]
Conclusions

➢ Strong physics case for axion:
  ▪ Axion occurs naturally as NG boson from breaking of well motivated symmetry
  ▪ Solution of strong CP problem
  ▪ Candidate for dark matter

➢ Great experimental activity recently in the field

➢ In the upcoming decade a sizeable fraction of the parameter space of interest for axion dark matter will be probed

➢ Stay tuned!