Alternative Dark Matter Candidates: Axions.

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Introduction

Many dark matter candidates

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[Fig. 4. (Color online) Several well-motivated candidates of dark matter are 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 modulo 2 (or - 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-e 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

![Graph showing various dark matter candidates](image)

- Neutrino $\nu$
- ADM
- WIMP
- Neutralino $\chi$
- Axion $a$
- Axino $\tilde{a}$
- Sterile neutrino $N$
- Gravitino $g_{3/2}$

$\log_{10}(\sigma_{int} / \text{pb})$ vs. $\log_{10}(m_{DM} / \text{GeV})$

[Baer, Choi, Kim, Roszkowski 10]
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- Many dark matter candidates
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  - Hierarchy Problem
- MSSM: Neutralino or Gravitino

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$\sigma_{\text{int}}$ 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 \cite{375,304} by including the sterile neutrino DM \cite{95,96,4}. The visible-sector particles was performed by Lee and Weinberg \cite{331}. This was followed by Goldberg \cite{209} for the case of SUSY neutralinos and has been reviewed extensively in the case of SUSY models in \cite{266}. In Fig. 4, we list several DM candidates in the cross-section vs. mass plot, which started from Ref. \cite{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 \cite{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 quantum number of $Z_2$ (or $-1$ 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 \cite{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

- Hierarchy Problem
- Neutrino Masses and Mixing
- Baryon Asymmetry

MSSM: Neutralino or Gravitino

nuMSM: Lightest sterile neutrino

Fig. 4. (Color online) Several well-motivated candidates of DM are shown.

[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
  - 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 $U(1)_{PQ}$ symmetry is added

> Symmetry is broken by vev $\langle \sigma \rangle = v_{PQ}/\sqrt{2}$

$$
\sigma(x) = \frac{1}{\sqrt{2}} (v_{PQ} + \rho(x)) e^{iA(x)/f_A}
$$

- Excitation of modulus: $m_\rho \sim v_{PQ}$
- Excitation of angle: pseudo-NGB: $m_A \ll v_{PQ}$

> PQ charges of quarks (SM or extra) are such that $U(1)_{PQ} \times SU(3)_C \times SU(3)_C$ has chiral anomaly: $A$ is called axion

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

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

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

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

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]

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

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

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

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

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

\[ m_a < 3H \]

- axion is frozen
- axion number \( N_a \) is conserved

\[ m_a \approx 3H \]
- axion starts rolling, turns into pressureless matter.

[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
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  - 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

\[\chi_{\text{t}}^{1/4} \text{[MeV]}\]

\[\chi \text{[fm}^{-4}] \text{]}\]

\[T/T_c\]

\[T\text{[MeV]}\]

[Borsanyi et al. `16]
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> QCD lattice calculations of topological susceptibility \( \chi(T) \)

- Previous estimates using dilute instanton gas approximation surprisingly accurate
- If PQ symmetry restored after inflation: \( m_A=50-1500 \mu eV \)
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,

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

[Ballesteros, Redondo, AR, Tamarit, 2016.09.nnnn]  

[Ballesteros, Redondo, AR, Tamarit, 2016.05414]
Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges

$$\mathcal{L} \supset - \left[ Y_{u ij} q_i \epsilon H u_j + Y_{d ij} q_i H^\dagger d_j + G_{i j} L_i H^\dagger E_j + F_{i j} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \right]$$

$$+ y \tilde{Q} \sigma Q + y_{Q_i} \sigma Q d_i + h.c.$$
SM*A*S*H: Solving Five Problems at One Stroke

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\]

> 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 \( \Delta N_{\nu}^{\text{eff}} \sim 0.03 \)

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

> Axion dark radiation \( N^\text{eff}_\nu \sim 0.03 \)

> Axion CDM according to post-inflationary PQ SSB

[Dias et al. `14]

[Ballesteros, Redondo, AR, Tamarit, 1608.05414]
Axion Dark Matter Direct Detection Experiments

Upcoming generation of axion dark matter experiments can probe sizeable portion of axion mass range relevant for DM:

| Axion Mass $m_A$ (eV) | $f_A$ (GeV) |
|-----------------------|-------------|
| $10^{-11}$           | $10^{17}$   |
| $10^{-10}$           | $10^{16}$   |
| $10^{-9}$            | $10^{15}$   |
| $10^{-8}$            | $10^{14}$   |
| $10^{-7}$            | $10^{13}$   |
| $10^{-6}$            | $10^{12}$   |
| $10^{-5}$            | $10^{11}$   |
| $10^{-4}$            | $10^{10}$   |
| $10^{-3}$            | $10^{9}$    |
| $10^{-2}$            | $10^{8}$    |
| $10^{-1}$            | $10^{7}$    |
| $10^{0}$             | $10^{6}$    |
| $10^{1}$             | $10^{5}$    |
| $10^{2}$             | $10^{4}$    |
| $10^{3}$             | $10^{3}$    |
| $10^{4}$             | $10^{2}$    |
| $10^{5}$             | $10^{1}$    |
| $10^{6}$             | $10^{0}$    |

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

- 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)
- NS in Cas A Hint ($g_{Ann}$ DFSZ)
- HB Stars in GCs ($g_{A_{1s}}$ DFSZ)

[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

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

[Budker et al. 14]
Magnetic Resonance Searches

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\[ M(t) \approx np \mu E^* e_s d_n \frac{\sin \left[ (2\mu B_{ext} - m_a c^2) t \right]}{2\mu B_{ext} - m_a c^2} \sin (2\mu B_{ext} t) \]

[Budker et al. 14]

|        | n     | E*    | p     | T_2   | Max B_{ext} |
|--------|-------|-------|-------|-------|-------------|
| Phase 1| 10^{22} cm^{-3} | 3 \times 10^8 V/cm | 10^{-3} | 1 ms | 10 T       |
| Phase 2| 10^{22} cm^{-3} | 3 \times 10^8 V/cm | 1 | 1 s  | 20 T       |
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

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

[13] Graham, Rajendran
Magnetic Resonance Searches

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

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

[Graham, Rajendran 13]
The axion/ALP electron coupling

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

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

- Larmor frequency and thus sensitivity extended to higher masses by factor
  \[ \mu_B/\mu_N \sim m_N/m_e \sim 10^3 \]

- **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 \( m_a = 2\pi\nu \sim 4 \, \mu eV \left( \frac{\nu}{\text{GHz}} \right) \)
Resonant Microwave Cavities

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

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

- Best sensitivity: mass = resonance frequency

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

- Under construction or design: X3 (Yale), CULTASK (South Korea), ...
Microwave cavities can probe axion dark matter for $\mu eV \lesssim m_A \lesssim 0.1$ meV

[Borsanyi et al. `16]

[Ballesteros, Redondo, AR, Tamarit, 1608.05414]
Open Fabry-Perot Resonators

ORPHEUS (Seattle):

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

[Rybka et al. 15]
Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component \([\text{Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]}\)

- A magnetised mirror in axion/ALP DM background radiates photons

- Simple broadband experiment: spherical dish antenna

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

\[\text{[Majorovits `15]}\]
Open Dielectric Resonators

> Boosting sensitivity

Many surfaces $\rightarrow$ resonator$\rightarrow$ “photon boost”

Boost factor:

- power generated in resonator/power generated on single metallic ($\varepsilon_r=\infty$) surface

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

> Experimental setup: MADMAX

[Majorovits `15]
Open Dielectric Resonators

> MADMAX prototype:

First prototype setup at MPI

[Calderwell et al. `15]
Axion Dark Matter Sensitivity

> New proposals cover mass region relevant for post-inflationary PQSB:

\[ \log_{10} m_a \, [\text{eV}] \]

\[ \log_{10} g \, [\text{GeV}^{-1}] \]

[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

- Enormous activity both in theory and experiments

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

- Stay tuned!