Physics Case for Axion or ALP DM.

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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
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- nuMSM: Lightest sterile neutrino

[M. Shaposhnikov, Phil. Trans. R. Soc. A 373 (2014) 0038]
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> PQSM: Axion

Axion $A$ \[ \text{Axion} \leq 10 \text{ meV} \] [wikipedia]
A global (or accidental) $U(1)_{\text{PQ}}$ symmetry featuring a $U(1)_{\text{PQ}} \times SU(3)_C \times SU(3)_C$ chiral anomaly is added to the SM

- Symmetry is broken by the vev of a new hidden (SM singlet) scalar field
  $$\sigma(x) = \frac{1}{\sqrt{2}} (v_{\text{PQ}} + \rho(x)) e^{iA(x)/f_A}$$
  - Radial excitation: $m_\rho \sim v_{\text{PQ}}$
  - Nambu-Goldstone boson: the axion
    $$m_A \ll v_{\text{PQ}}$$

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

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{A}{f_A} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} - \frac{\alpha}{8\pi} C_A \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_A}{f_A^2} \partial_\mu A \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

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

[Pecei, Quin 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]

\[
\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{C'_{ig}}{f_{a'_i}} a'_i G_{\mu\nu}^b \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} \frac{C'_{i\gamma}}{f_{a'_i}} a'_i F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C'_{a'_i f}}{f_{a'_i}} \partial_\mu a'_i \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f
\]

> 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-Like Particles (ALPs)

4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs

- KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string

\[\text{[Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli, Goodsell, AR 12]}\]

- NGBs from accidental PQ symmetries appearing as low energy remnants of discrete symmetries from compactification

\[\text{[Lazarides, Shafi 86; Choi et al. 09; Dias et al. 14]}\]
Axion/ALP Dark Matter

>- DM from vacuum realignment:

  - In early universe, axion/ALP frozen at random initial value
  - Later, field feels pull of mass towards zero and oscillates around it
  - Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM

>- Key quantity: Topological susceptibility, $\chi(T) = m_A^2(T) f_A^2$

$\theta_a < 3H$
axion is frozen

$\text{axion number } N_a$
is conserved

$m_a \approx 3H$
axion starts rolling, turns into pressureless matter.

[Wantz,Shellard 09]
Axion/ALP Dark Matter

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

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> DM from topological defects

- Important contribution if PQ symmetry restored after inflation
- Inflated away if SSB happens before inflation and not restored after
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[Borsanyi et al. `16]
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\[
g_{a\gamma} = C'_{a\gamma} \alpha / (2\pi f_a)
\]

[Arias et al. `12]
\[ | \sigma | = \rho / \sqrt{2} \] may play the role of the inflaton field, if it has a non-minimal coupling to gravity, [Fairbairn et al. `14; Ballesteros et al. `16]

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

[Ballesteros, Redondo, AR, Tamarit, 1607.nnnn]
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\[ S \supset - \int d^4x \sqrt{-g} \left[ \frac{M^2}{2} + \xi_\sigma \sigma^* \sigma \right] \]

Augmenting PQSM with three SM singlet neutrinos, getting their Majorana masses also through the vev \( \nu_\sigma \)

- No strong CP problem
- Axion dark matter
- Inflation
- Neutrino masses and mixing
- Thermal leptogenesis

[Ballesteros, Redondo, AR, Tamarit, 1607.nnnn]

[Dias et al. `14; Ballesteros et al. `16 ]
Astro-Hints on Axion/ALPs?

- Modest hints for
  - excessive energy losses of stars in various evolutionary stages,
  - photon-ALP conversion in astrophysical magnetic fields
Hints of Axion/ALP Energy Losses of Stars?

- Excessive energy losses of Red Giants (RGs), Helium Burning stars (HBs) and White Dwarfs (WDs):

\[ \Delta L / L_{\text{st}} \]

Hints of Axion/ALP Energy Losses of Stars?

Excessive energy losses of RGs, HBs and WDs can all be explained at one stroke by production and emission of axion/ALP with coupling both to electrons and photons: [Giannotti,Irastorza,Redondo,AR, arXiv:1512.08108]
Gamma ray spectra from distant AGNs should show an energy and redshift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL).
Photon – ALP Conversion in Cosmic Magnetic Fields?

- Gamma ray spectra from distant AGNs should show an energy and redshift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL)

- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis, Roncadelli et al. 07;...; Horns, Meyer 12;...; Rubtsov, Troitsky 14]
Photon – ALP Conversion in Cosmic Magnetic Fields?

> Possible explanation: photon <-> ALP conversions in magnetic fields
[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]
Photons – ALP Conversion in Cosmic Magnetic Fields?

Possible explanation: photon $\leftrightarrow$ ALP conversions in magnetic fields
[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer, Horns, Raue 13]

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<th>$k_{EIMF}$ (Mpc)</th>
<th>$\sigma_{\alpha,\gamma,\tau}^0$ ($\times 10^{-7}$ cm$^{-3}$)</th>
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<th>$r_{\gamma\gamma}$ (Mpc)</th>
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[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer]
Photon – ALP Conversion in Cosmic Magnetic Fields?

> Part of parameter space of interest ruled out by non-observation of spectral irregularities by Fermi-LAT in gamma-ray spectrum of NGC 1275, the central galaxy of the Perseus cluster, due to photon-ALP oscillations, at significant level.

[Fermi-LAT PRL 116 (2016) 161101]
Photon – ALP Conversion in Cosmic Magnetic Fields?

> Part of parameter space of interest ruled out by non-observation of spectral irregularities by Chandra in X-ray spectrum of NGC 1275, the central galaxy of the Perseus cluster, at O(30%) level  

[adapted from Carvajal et al. 15]

> O(10%) irregularities at 2.2 and 3.5 keV may be explained by ALP with

\[ g_{a\gamma} \sim 1 - 5 \times 10^{-12} \text{ GeV}^{-1}, \quad m_a \lesssim 10^{-12} \text{ eV} \]
Conclusions

> Strong physics case for axion and ALPs:
  - Axion and ALPs occur naturally as NG bosons from breaking of well motivated symm.
  - Solution of strong CP problem
  - Candidates for dark matter
  - Explanation of astrophysical hints (energy losses of stars; photon-ALP conversions in astrophysical magnetic fields)

> Need terrestrial experiments which can probe the parameter space suggested by astro and cosmo hints