Astrophysics of Axions and Axion-Like Particles

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LSST Dark Matter Workshop,
KICP, August 5-7 2019, Chicago
Axions Overview

Theory
Strong CP problem

Cosmology
Cold DM candidate

Axions
ALPs

Astrophysics
Anomalous stellar cooling + UHE $\gamma$ transparency

String theory

Dark radiation

Inflation

Dark Energy?
Axions Overview

Most compelling solution of the Strong CP problem of the SM

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + i\bar{\Psi} \gamma^\mu D_\mu \Psi - \bar{\psi} M \psi - \bar{\theta} \frac{1}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Observable consequence: neutron electric dipole moment

which, however, is not observed

Peccei and Quinn solution: $\bar{\theta}$ is dynamical:

$$\bar{\theta} \rightarrow a/f_a$$

$a$ is the axion field!

The potential of $a$ has a minimum in zero (Vafa-Witten theorem)
Axions Overview

*Rich phenomenology!!*

Axions interact with matter and photons.

Axion mass

\[
m_a = \frac{(5.70 \pm 0.07) \mu eV}{f_a / 10^{12} \text{GeV}}
\]

Grilli di Cortona et al., JHEP 1601 (2016)
Axions Overview

Most compelling solution of the **Strong CP problem** of the SM

May account for the totality or part of the **DM in the universe**

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**Misalignment production**

(non thermal)

\[
\ddot{\theta} + 3H(T)\dot{\theta} + m_a(T)^2\sin(\theta) = 0
\]

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*If axions exist and are weakly interacting, a little axion DM is inevitable.*

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Preskill, Wise and Wilczek (1983)
Abbott and Sikivie (1983)
Dine and Fischler (1983)
Axions Overview

Most compelling solution of the Strong CP problem of the SM

May account for the totality or part of the DM in the universe

Problem with initial condition (unknown)

If PQ symmetry broken after inflation: the problem with the initial conditions is removed but axion production from topological defects becomes important and has large uncertainties (Gorghetto, Hardy, Villadoro (2018))

The preferred mass region for axion DM is still not well known!
Axions Overview

Most compelling solution of the Strong CP problem of the SM

May solve the DM problem

Axions would account for the excessive energy loss in stars

...Observed in WDs, RGB and HB stars

In general, axions may affect stellar evolution in a significant way!

M.G., Irastorza, Redondo, Ringwald (2015)
M.G., Irastorza, Redondo, Ringwald, Saikawa (2017)
Axions & Stars: WD variables

<table>
<thead>
<tr>
<th>WD</th>
<th>class</th>
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<th>$\dot{P}_{\text{obs}}$ [s/s]</th>
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Notice that $\dot{P}/P$ is practically proportional to $\dot{T}/T$
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**2 \sigma hint for $g_{ae} > 0$,**

**Best fit:** $g_{ae} = 2.9 \times 10^{-13}$

**Bound (2\sigma):** $g_{ae} \leq 4.1 \times 10^{-13}$

Córsico, Althaus, Miller Bertolami (2019)

Figure from G. Raffelt, *Stars as laboratories for fundamental physics*
Axions & Stars: WD Luminosity Function

Axion analysis

\[ \chi^2 / \text{dof} = 6 \]

\[ \chi^2_{\text{min}} / \text{dof} = 0.94 \]

Best fit: \( g_{ae} = 1.4 \times 10^{-13} \)

Bound: \( g_{ae} \leq 2.1 \times 10^{-13} \)

Data from: M. Bertolami et. al. (2014)

Tremendous improvement expected with LSST!

Axions & Stars: RGB-Tip

Additional cooling increases the luminosity of the RGB tip

Best fit: $g_{ae} = 1.4 \times 10^{-13}$

Bound: $g_{ae} < 3.1 \times 10^{-13}$ (2σ)

- Viaux et al., Phys.Rev.Lett. 111 (2013);
- Arceo-Daz et al. (2015)
- O. Straniero et al. (2017)
Axions & Stars: RGB-Tip

Additional cooling raises the luminosity of the RGB tip

Best fit: $g_{ae} = 1.4 \times 10^{-13}$

Bound: $g_{ae} < 3.1 \times 10^{-13}$ (2$\sigma$)

The largest systematic error is the distance.

The final GAIA data release (2022-2023) will provide an improvement of roughly a factor of 10 on the uncertainty in the distance.

Axions & Stars: R-parameter

$$R = \frac{N_{\text{HB}}}{N_{\text{RGB}}}$$

Sensitive to both axion-electron and axion-photon coupling.

*RGB*: very dense. Sensitive to $g_{ae}$

*HB*: not very dense. Sensitive to $g_{a\gamma}$

In the case of $g_{ae} = 0$ the R-parameter bound is known as the

**HB bound**: $g_{a\gamma} \leq 0.65 \times 10^{-10} \text{GeV}^{-1} \ (2\sigma)$

- Straniero (proc. of XI Patras Workshop, 2015)
- M.G., Irastorza, Redondo, Ringwald (2015)
Axions & Stars: Global analysis

Best fit:

\[ g_{a\gamma} = 1.2 \times 10^{-11} \text{ GeV}^{-1} \]
\[ g_{ae} = 1.6 \times 10^{-13} \]

ALPs are the best candidates to explain the excessive energy loss

Cooling anomalies point to specific region of the ALP parameter space

M.G., Irastorza, Redondo, Ringwald, Saikawa (2017)
A Bright Future?

Observations from the Gaia satellite → catalog of WDs increased by an order of magnitude with respect to SDSS. However, the Gaia sample is limited to WDs within 100 pc. LSST may detect WDs 5 to 6 magnitudes fainter, bringing the census of WDs to tens of millions.

Expected a large growing sample of the WD Variable sample (LSST + TESS).

Accurate astrometry from the Gaia satellite → Precise determination of cluster distances. LSST will enable independent measurements of GC distances, providing a valuable handle on systematic uncertainties of Gaia observations.

LSST is expected to discover ~ a few $10^5$ CCSNe per year, and will be able to resolve massive progenitor stars in pre-explosion imaging in the case of nearby SNe. This may ultimately also constraint/reveal new-physics of light particles.
A Bright Future?

Our best option for the astro-region are the new generation of axion Helioscopes.

CAST (CERN Axion Solar Telescope) is the currently most powerful helioscope.

BabylAXO improves on the CAST sensitivity by a factor of $\sim 100$ (to be built in DESY).

IAXO, by a factor of $>10^4$
A bright Future?


Tremendous experimental effort!!

Many other experiments testing other couplings
Summary and conclusions

1. Growing interest in axions with many new proposals and experiments.

2. Stellar evolution constraints the axion properties and hints at well defined regions of the axion parameter space.

3. These regions are accessible to the next generation of axion-scopes

4. The next generation of astrophysical probes, particularly LSST, will provide much information to test the axion hypothesis in astrophysics

5. *Lots to be expected in the early 2020s…stay tuned!*