Axions in cosmology and astrophysics

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Based on:

LV, Baum, Redondo, Freese, Wilczek, PLB 777, 64 (2018)
LV, PRD 96, 023 (2017)
LV & P. Gondolo, PRL 113, 011802 (2014)
LV & P. Gondolo, PRD 81, 063508 (2010)
LV & P. Gondolo, PRD 80, 035024 (2009)
Sources of CP violation in the SM

\[ \mathcal{L}_{\text{CP}} = \theta \frac{\alpha_s}{2\pi} \text{Tr} \left( E^\mu B_\mu \right) \]

\(\theta\) controls matter-antimatter differences in QCD

\[ |\theta| \lesssim 10^{-10} \]
Axion coherent oscillations

\[ \Phi_{PQ} = \rho e^{i\theta} \]
\[ \langle \rho \rangle \approx f_a \]

~ One parameter theory
\[ \theta(t, x) = a(t, x)/f_a \]
axion mass
\[ m_a = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a} \]

\[ m_a f_a \propto \Lambda_{QCD}^2 \]

PQ “Mexican hat” potential, tilted by QCD effects
Axion searches

- Effective axion-photon coupling

\[ g_{a\gamma\gamma} \propto m_a \]
Axion parameter space

Black hole super-radiance

ADMX

ADMX Forecast

MadMAX Forecast

IAXO Forecast & WDCT Hint

Red giants brightness

Log$_{10} r$

Log$_{10} f_a$ / GeV

Log$_{10} H_I$ / GeV

Log$_{10} m_a$ / eV

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LV & P. Gondolo, PRL 113, 011802 (2014); PRD 80, 035024 (2009)
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Log$_{10} r$

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2

Log$_{10} f_a / \text{GeV}$

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2

Log$_{10} m_a / \text{eV}$

-12 -9 -6 -3 0 3 6 9 12

Log$_{10} H_I / \text{GeV}$

LV & P. Gondolo, PRL 113, 011802 (2014); PRD 80, 035024 (2009)
Axion parameter space

\[
\theta_i = 0.01 \\
\theta_i = 0.1 \\
\theta_i = 0.001
\]

\[
f_a = H_I/2\pi
\]

Ade et al (PLANCK) AA 571 A16 (2014)

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LV&P. Gondolo, PRL 113, 011802 (2014); PRD 80, 035024 (2009)
Axion parameter space

\[ \log_{10} r \]

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2

\[ \log_{10} f_a / \text{GeV} \]

18
16
14
12
10
8

\[ \theta_i = 0.001 \]
\[ \theta_i = 0.01 \]
\[ \theta_i = 0.1 \]
\[ \theta_i = 1 \]

\[ \log_{10} H_I / \text{GeV} \]

4 6 8 10 12 14

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

-12 -9 -6 -3 0

-2 -4 -6 -8 -10 -12

Black hole super–radiance
Axion Isocurvature Fluctuations

ADMX

ADMX Forecast

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Red giants brightness

\[ f_a = H_I / 2\pi \]

\[ \Omega_{ad} > \Omega_{CDM} \]

\[ \Omega_{ad} \]

LV&P. Gondolo, PRL 113, 011802 (2014); PRD 80, 035024 (2009)
Ultra-light axions?

• We address the “Missing Satellite” problem, i.e. overabundance of small satellites in numerical simulations compared to observations.

Moore et al. (1999); Klypin et al. (1999)
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• Alleviated by cutoff of $P_{\text{CDM}}(k)$ at $k \sim 4.5 \, h \, \text{Mpc}^{-1}$

  Kamionkowski&Liddle (1999)
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• Alleviated by cutoff of $P_{\text{CDM}}(k)$ at $k \sim 4.5 \, h \, \text{Mpc}^{-1}$ Kamionkowski&Liddle (1999)

• An axion with $m \sim 10^{-22} \, \text{eV}$ leads to the desired cutoff Hu, Barkana, Gruzinov, PRL 85 (2000)
Is the Ultra-light Axion viable?

\[ m = 10^{-22} \text{eV} \]

During inflation

After inflation

\[ f = H_I/2\pi \]
Is the Ultra-light Axion viable?

Log$_{10} r$

\( m = 10^{-22} \text{eV} \)

\( f = \frac{H_I}{2\pi} \)

ALP CDM (Arias 2012)

LV, PRD 96 023013 (2017)
Is the Ultra-light Axion viable?

\[ m = 10^{-22} \text{eV} \]

\[ f \sim \text{GUT scale} \]

Hui et al, PRD 95 043541 (2017)

\[ m(T) \propto T^{-n} \]

LV, PRD 96 023013 (2017)
Is the Ultra-light Axion viable?

Ade et al (BICEP2)  
*PRL* **116** 031302 (2016)

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Is the Ultra-light Axion viable?

\[ m = 10^{-22} \text{eV} \]

\[ \log_{10} H_I / \text{GeV} \]

\[ \log_{10} f_a / \text{GeV} \]

\[ \Omega_a > \Omega_{\text{CDM}} \]

\[ \Omega_a < \Omega_{\text{CDM}} \]

ALP CDM

Tensor modes

LV, PRD 96 023013 (2017)
Axion Stars

Axions that oscillate in the lowest energy state coherently

\[ v \sim \frac{\hbar}{m R} \]

\[ M = N m \]

LV, Baum, Redondo, Freese, Wilczek, PLB 777, 64 (2018)

Schiappacasse and Hertzberg, JCAP 1801, 037 (2018)

See talk by E. Schiappacasse!
Axion Stars

Axion star radius vs mass

\( f = 10^{11} \text{GeV} \)

\( f = 10^{13} \text{GeV} \)

\( f = 10^{15} \text{GeV} \)

LV, Baum, Redondo, Freese, Wilczek, PLB 777, 64 (2018)

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Conclusions

• Axions are well-motivated, viable CDM candidates;

• Details (coupling, temperature-dependence, defects) require much further efforts. Work in progress...

• The parameter space is being tackled;

• Miniclusters and axion stars are formed, work is needed!

• Ultra-light axions models are difficult to motivate given PLANCK-BICEP2 data
Scenario A: PQ breaks after inflation

Courtesy of J. Redondo
Scenario A: PQ breaks after inflation

Axion strings!

CDM axions also from defects...
Scenario B: PQ breaks during inflation

One initial configuration is singed out.