Encounters with the Axion

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encounters with

- jesus
- the archdruid
- angels
- god
- jesus in the bible
- unexpected animals
- jesus tim keller
- canada
- the holy spirit
- dolphins
Helen Quinn  Roberto Peccei
Chiral symmetry breaking in the two flavor quark model (u,d)

$$SU_L(2) \otimes SU_R(2) \otimes U_A(1) \otimes U_V(1)$$

$$\downarrow$$

$$SU_V(2) \otimes U_V(1)$$

4 Nambu-Goldstone bosons \(\pi^+ \pi^0 \pi^- \eta\)

\(m_\eta < \sqrt{3} \ m_\pi\)

S. Weinberg

The \(U_A(1)\) Problem
In Quantum Chromodynamics (QCD)

$U_A(1)$ has an Adler-Bell-Jackiw anomaly, and is therefore explicitly broken.

Quantum tunneling events, called instantons, produce axial charge for each flavor

\[ \mathcal{L}_{QCD} = \ldots + \bar{\theta} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \]

\[ \bar{\theta} = \theta - \text{arg} \left( m_u \ m_d \ \ldots \ m_t \right) \]
The Strong CP Problem

\[ \bar{\theta} = \theta - \arg \det (Y^u Y^d) \]

is expected to be of order one

The absence of P and CP violation in the strong interactions requires

\[ \bar{\theta} \leq 10^{-10} \]
A level pooltable on an inclined floor
$U_{PQ}(1)$

- is a symmetry of the classical action
- is spontaneously broken
- has a color anomaly

Peccei and Quinn, 1977
If a $U_{PQ}(1)$ symmetry is assumed,

$$\mathcal{L} = ... + \frac{a}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a$$

$$\bar{\theta} = \frac{a}{f_a} \quad \text{relaxes to zero},$$

and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978
Steven Weinberg            Frank Wilczek
A self adjusting pooltable

1 ton
Searching for the pooltable oscillation quantum
\[ m_a \simeq 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a} \]

\[ \mathcal{L}_{a\bar{f}f} = ig_f \frac{a}{f_a} \bar{f} \gamma_5 f \]

\[ \mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

\[ g_\gamma = 0.97 \text{ in KSVZ model} \]
\[ 0.36 \text{ in DFSZ model} \]
Axions are constrained by

- beam dump experiments
- rare particle decays \((e.g. \ K^+ \rightarrow \pi^+ \ a)\)
- radiative corrections
  \((e.g. \ the \ \mu^- \ anomalous \ magnetic \ moment)\)
- the evolution of stars
Axion constraints

Laboratory searches

Stellar evolution
A self adjusting pooltable
Effective potential $V(T, \Phi)$

$T > f_a$

$0 < f_a < T < 1 \text{GeV}$

$1 \text{GeV} > T$

- $T > f_a$: axion strings
- $0 < f_a < T < 1 \text{GeV}$: axion strings
- $1 \text{GeV} > T$: axion domain walls
Axion production by vacuum realignment

\[ T \geq 1 \text{GeV} \]

\[ T \leq 1 \text{GeV} \]

\[ n_a(t_1) \approx \frac{1}{2} m_a(t_1) a(t_1)^2 \approx \frac{1}{2t_1} f_a^2 \alpha(t_1)^2 \]

\[ \rho_a(t_1) \approx m_a n_a(t_1) \left( \frac{R_1}{R_0} \right)^3 \propto m_a^{-\frac{7}{6}} \]

Axion constraints

$\alpha_f (\text{GeV})$

$\alpha_m (\text{eV})$

laboratory searches

stellar evolution

cosmology
Axions produced by vacuum realignment are cold dark matter
The Witten Effect (1979)

When $\theta \neq 0$ magnetic monopoles acquire electric charge

$$q_e = \frac{\alpha}{\pi} \theta q_m$$

$$q_e = \frac{\alpha}{\pi} \left(\theta + \frac{a}{f_a}\right) q_m$$

with axion

$$(q_e, q_m) = (0, \frac{2\pi}{e})$$
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$$q_e = \frac{\alpha}{\pi} \left( \theta + \frac{a}{f_a} \right) q_m$$

with axion domain wall

$$(e, \frac{2\pi}{e})$$

axion domain wall
Axion Electrodynamics

\[ \nabla \cdot (\vec{E} - g a \vec{B}) = \rho_{el} \]

\[ \nabla \times (\vec{B} + g a \vec{E}) - \partial_t (\vec{E} - g a \vec{B}) = \vec{j}_{el} \]

\[ \nabla \times \vec{E} + \partial_t \vec{B} = 0 \]

\[ \nabla \cdot \vec{B} = 0 \]

\[ \partial_t^2 a - \nabla^2 a + m^2 a = -g \vec{E} \cdot \vec{B} \]
\[ \vec{\nabla} \cdot \vec{E} = g\vec{\nabla}a \cdot \vec{B} + ga\vec{\nabla} \cdot \vec{B} \]

\[ \sigma_{el} = g \Delta a B_\perp = 2\alpha B_\perp \]
Axion Electrodynamics

\[ \nabla \cdot (\vec{E} - ga \vec{B}) = \rho_{el} \]

\[ \nabla \times (\vec{B} + ga \vec{E}) - \partial_t (\vec{E} - ga \vec{B}) = \vec{j}_{el} \]

\[ \nabla \times \vec{E} + \partial_t \vec{B} = 0 \]

\[ \nabla \cdot \vec{B} = 0 \]

\[ \partial_t^2 a - \nabla^2 a + m_a^2 a = -g \vec{E} \cdot \vec{B} \]
In background electric and magnetic fields the axion field is a source of electromagnetic radiation

\[ \partial_t^2 \vec{A} - \nabla^2 \vec{A} = g(\vec{E}_0 \times \vec{\nabla}a - \vec{B}_0 \partial_t a) \]
Axions convert to photons in a magnetic field and vice-versa

\[ \partial_t^2 a - \nabla^2 a = -g\vec{B}_0 \cdot \vec{E} \]

\[ N_{\text{signal}} \sim N_\gamma \left( \frac{\alpha B_0}{\pi f_a} L \right)^2 \left( \frac{\alpha B_0}{\pi f_a} L \right)^2 \sim 10^{-48} N_\gamma \]
We may search for axions produced in the Sun or present on Earth as dark matter

- **Axion helioscope**
  \[ 10^{14} \text{ axions/cm}^2\text{sec} \]

- **Axion haloscope**
  \[ 10^{14} \text{ axions/cm}^3 \]
UF Axion Project

David Tanner

Neil Sullivan

+ Chris Hagmann (PhD student)
Rochester-Brookhaven-Fermilab Collaboration

Adrian Melissinos et al.

Yannis Semertzidis (CAPP, Korea)
Chris Hagmann and the UF axion detector
A new magnet for the cavity experiment

Karl van Bibber  
8T magnet from Wang NMR, Inc  
Michael Turner
ADMX

SQUIDs from J. Clarke’s group

Leslie Rosenberg and Gray Rybka at U. Wash.
ADMX meeting at Fermilab
HAYSTAC at Yale
Cavity haloscopes under construction

- at INFN laboratory in Legnaro
- at University of Western Australia
- at CERN
- at INFN laboratory in Frascati
Cavity haloscopes under construction

- at INFN laboratory in Legnaro  QUAX
- at University of Western Australia  ORGAN
- at CERN  RADES
Constraints on dark matter axions from cavity haloscopes

\[ \frac{1}{g \gamma} \left(\frac{\rho}{(\text{GeV/cc})}\right)^2 \]

\[ 10^{-2} \]

\[ 10^{-6} \]

\[ 10^{-5} \]

\[ 10^{-4} \]
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- **Axion haloscope**
  \[ 10^{14} \text{ axions/cm}^3 \]
Tokyo Helioscope - Sumico

Makoto Minowa et al.
CERN Axion Solar Telescope

Konstantin Zioutas et al.
International AXion Observatory

Igor Irastorza et al.
Axio-Electric and Primakoff Effects

\[ a + \text{Ge} \rightarrow e + \text{Ge}^+ \]

Dimopoulos, Starkman & Lynn, 1986

\[ a + (Z, A) \rightarrow \gamma + (Z, A) \]

constraints from SOLAX, COSME, DAMA, CDMS, EDELWEISS, XMASS, CUORE, CDEX, Xenon, LUX, PandaX
\[ g_{a\gamma\gamma} = g_{\gamma} \frac{\alpha}{\pi} \frac{1}{f_{a}} \]
Many approaches to axion detection

Dielectric haloscopes
Nuclear Magnetic Resonance
Axion to magnon conversion
LC circuit
Axion echo

Shining light through walls (SLW)

Long range forces
Stellar evolution constraints
SLW in astrophysical magnetic fields

MADMAX
CASPEr
QUAX
ABRACADABRA, SLIC, DMradio
ARIADNE

... ALPs, OSQAR

white dwarf cooling

Marco Roncadelli

Guido Mueller
Axions relate to

- particle physics
- nuclear physics
- astrophysics
- cosmology
- solid state physics (topological insulators)
- atomic physics
- statistical mechanics (Bose-Einstein condensation)
- ...

Axions produced by vacuum realignment

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$T \leq 1 \text{GeV}$

$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

$$\rho_a(t_1) \simeq m_a n_a(t_1) \left( \frac{R_1}{R_0} \right)^3 \propto m_a^{-\frac{7}{6}}$$

Axions produced by vacuum realignment are cold dark matter
Cold axion properties

• number density

\[ n(t) \simeq \frac{4 \cdot 10^{47}}{\text{cm}^3} \left( \frac{f_a}{10^{12} \text{ GeV}} \right) \left( \frac{R(t_1)}{R(t)} \right) \]

• velocity dispersion

\[ \delta v(t) \simeq \frac{1}{m_a t_1} \frac{R(t_1)}{R(t)} \]

if decoupled

• phase space density

\[ \mathcal{N} = \frac{(2\pi)^3 n(t)}{\frac{4\pi}{3}(m_a \delta v)^3} \simeq 10^{61} \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^\frac{8}{3} \]
Bose-Einstein Condensation

if identical bosonic particles are highly condensed in phase space and their total number is conserved and they thermalize

then most of them go to the lowest energy available state
why do they do that?

by yielding their energy to the non-condensed particles, the total entropy is increased.
Thermalization occurs due to gravitational interactions

\[ \Gamma_g \sim 4\pi G m^2 l^2 \quad \text{with} \quad l = (m \delta v)^{-1} \]

\[ \sim 5 \times 10^{-7} H(t_1) \left( \frac{f}{10^{12} \text{ GeV}} \right)^{2/3} \]

\[ \frac{\Gamma_g(t)}{H(t)} \propto t \, a(t)^{-1} \propto a(t) \]
Gravitational interactions thermalize the axions and cause them to form a BEC when the photon temperature

\[ T_\gamma \sim 500 \text{ eV} \left( \frac{f}{10^{12} \text{ GeV}} \right)^{\frac{1}{2}} \]

After that

\[ \delta v \sim \frac{1}{mt} \]

\[ \Gamma_g(t)/H(t) \propto t^3 \alpha(t)^{-3} \]
Tidal torque theory

neighboring protogalaxy

Stromberg 1934; Hoyle 1947; Peebles 1969, 1971
Tidal torque theory with ordinary CDM

the velocity field remains irrotational
Tidal torque theory with axion BEC

\[ \nabla \times \vec{v} \neq 0 \]

net overall rotation is obtained because, in the lowest energy state, all axions fall with the same angular momentum.
Galactic halos live in phase space

ordinary fluid

\[ d(\vec{r}; t) \quad \vec{v}(\vec{r}; t) \]

dark matter (collisionless) fluid

\[ f(\vec{r}, \vec{v}; t) \]
DM forms caustics in the non-linear regime
A shell of particles, part of a continuous flow.

The shell has net overall rotation.

As the shell falls in and out of the galaxy, it turns itself inside out.
Sphere turning inside out
simulations by Arvind Natarajan

in case of net overall rotation
The caustic ring cross-section

an elliptic umbilic catastrophe

$D_4$
IRAS

\[(1, b) = (80^\circ, 0^\circ)\]

12 \(\mu\)m

10° \(\times\) 10°
IRAS

(1, b) = (80°, 0°)

12 µm

10° × 10°
IRAS

\((1, b) = (80^\circ, 0^\circ)\)

25 \(\mu m\)

\(10^\circ \times 10^\circ\)
GAIA sky map (2016)
Conclusions

• Axions solve the strong CP problem

• A population of cold axions is naturally produced in the early universe which may be the dark matter today

• Axion dark matter is detectable