Axions

Motivation, Cosmological Role and Experimental Searches

Physics Theory Colloquium, 16 Feb 2010, TIFR, Mumbai
# Axion Physics in a Nut Shell

## Particle-Physics Motivation

- **CP conservation in QCD by Peccei-Quinn mechanism**
  
  \[ \text{Axions } a \sim \pi^0 \]
  
  \[ m_\pi f_\pi \approx m_a f_a \]

  For \( f_a \gg f_\pi \) axions are “invisible” and very light

## Solar and Stellar Axions

- Axions thermally produced in stars, e.g. by Primakoff production
  
  \[ \gamma \rightarrow a \]

  - Limits from avoiding excessive energy drain
  - Solar axion searches (CAST, Sumico)

## Cosmology

- In spite of small mass, axions are born non-relativistically (non-thermal relics)

  Cold dark matter candidate

  \( m_a \sim 10 \mu\text{eV} \) or even smaller

## Search for Axion Dark Matter

- Microwave resonator (1 GHz = 4 \( \mu\text{eV} \))

  - Primakoff conversion

  - ADMX (Livermore)
  - New CARRACK (Kyoto)
CP Violation in Particle Physics

Discrete symmetries in particle physics

C - Charge conjugation, transforms particles to antiparticles violated by weak interactions

P - Parity, changes left-handedness to right-handedness violated by weak interactions

T - Time reversal, changes direction of motion (forward to backward)

CPT - exactly conserved in quantum field theories

CP - conserved by all gauge interactions violated by three-flavor quark mixing matrix

All known CP-violating effects derive from a single phase in the quark mass matrix (Kobayashi-Maskawa phase), i.e. from complex Yukawa couplings
Cabbibo-Kobayashi-Maskawa (CKM) Matrix

Quark interaction with W boson (charged-current electroweak interaction)

\[ \frac{g}{\sqrt{2}} \bar{\psi}_u \gamma^\mu V_{\text{CKM}} \psi_d W_\mu^+ + \text{h.c.} \]

\[ \psi_u = (u, c, t) \quad \psi_d = (d, s, b) \]

Unitary Cabbibo-Kobayashi-Maskawa matrix relates mass eigenstates to weak interaction eigenstates

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\( V_{\text{CKM}} \) depends on three mixing angles and one phase \( \delta \), explaining all observed CP-violation

Precision tests use “unitarity triangles” consisting of products of measured components of \( V_{\text{CKM}} \), for example:
Measurements of CKM Unitarity Triangle

CKMfitter Group

UTfit Collaboration
http://www.utfit.org
The CP Problem of Strong Interactions

\[
L_{QCD} = \sum_q \overline{\psi}_q \left( i \slashed{D} - m_q e^{i \theta_q} \right) \psi_q - \frac{1}{4} G_{\mu \nu} G^\mu_\nu - \Theta \frac{\alpha_s}{8 \pi} G_{\mu \nu} \tilde{G}^{\mu \nu}
\]

Remove phase of mass term by chiral phase transformation of quark fields

\[
\psi_q \rightarrow e^{-i \gamma_5 \theta_q / 2} \psi_q
\]

\[
L_{QCD} = \sum_q \overline{\psi}_q \left( i \slashed{D} - m_q \right) \psi_q - \frac{1}{4} G G - \left( \Theta - \arg \det M_q \right) \frac{\alpha_s}{8 \pi} G \tilde{G}
\]

- \( \Theta \) can be traded between quark phases and \( G \tilde{G} \) term
- Induces a large neutron electric dipole moment (a T-violating quantity)

Experimental limits: \( \Theta < 10^{-10} \)  Why so small?
Neutron Electric Dipole Moment

Violates time reversal (T) and space reflection (P) symmetries

Natural scale
\[ \frac{e}{2m_N} = 1.06 \times 10^{-14} \text{ e cm} \]

Experimental limit
\[ |d| < 0.63 \times 10^{-25} \text{ e cm} \]

Limit on coefficient
\[ \Theta \frac{m_q}{m_N} \lesssim 10^{-11} \]
Dynamical Solution


• Re-interpret $\Theta$ as a dynamical variable (scalar field)

$$L_{CP} = -\frac{\alpha_s}{8\pi} \Theta \text{Tr}(G\tilde{G}) \rightarrow -\frac{\alpha_s}{8\pi} \frac{a(x)}{f_a} \text{Tr}(G\tilde{G})$$

$a(x)$ pseudoscalar axion field, $f_a$ axion decay constant (Peccei-Quinn scale)

• Axions generically couple to two gluons and mix with $\pi^0$, $\eta$, $\eta'$ mesons, inducing a mass (potential) for $a(x)$

$$m_a f_a = \sqrt{m_u m_d} m_{\pi} f_{\pi} \left( \begin{array}{c} \text{Axion mass} \\ \text{& couplings} \end{array} \right) \sim \left( \begin{array}{c} \text{Pion mass} \\ \text{& couplings} \end{array} \right) \times \frac{f_{\pi}}{f_a}$$

• Potential (mass term) induced by $L_{CP}$ drives $a(x)$ to CP-conserving minimum

CP-symmetry dynamically restored
CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the CP conservation of strong interactions which includes the
effects of pseudoparticles. We find it is a natural result for any theory where at least
one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which
has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a
world where $P$ and $CP$ are good symmetries at
the level of strong interactions. In the context of
quantum chromodynamics the strong interactions
are believed to be due to non-Abelian vector glu-
grangian.

If all fermions which couple to the non-Abelian
gauge fields are massless then the various $\theta$
choices give equivalent theories. This is most
clearly seen by remarking that a change in the

Constraints imposed by CP conservation in the presence of pseudoparticles*

R. D. Peccei and Helen R. Quinn†

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 May 1977)

We elaborate on an earlier discussion of $CP$ conservation of strong interactions which includes the effect of
pseudoparticles. We discuss what happens in theories of the quantum-chromodynamics type when we include
weak and electromagnetic interactions. We find that strong $CP$ conservation remains a natural symmetry if
the full Lagrangian possesses a chiral $U(1)$ invariance. We illustrate our results by considering in detail a
recent model of (weak) $CP$ nonconservation.

I. INTRODUCTION

In a recent letter we have discussed the question
of $CP$ conservation of the strong interactions in
the presence of a non-chiral pseudoscalar (OCB).

The appearance of this additional term shows the
problem to which we address ourselves. It appears
to be a $P^S$ and $CP$-violating term. Thus if $\mathcal{L}$ rep-
resents a non-Abelian gauge theory of the strong
interactions, this term could be written as $\mathcal{L} = \mathcal{L}_0 + \bar{\phi} \mathcal{K} \phi$, where $\mathcal{L}_0$ is

---

*Permanent address: Theoretical Physics Colloquium, 16 Feb 2010, TIFR, Mumbai, India

†Present address: Max-Planck-Institut für Physik, München, Germany

Georg Raffelt, Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
The Pool Table Analogy (Pierre Sikivie 1996)

Gravity

Pool table

Symmetric relative to gravity
The Pool Table Analogy  (Pierre Sikivie 1996)

Gravity

Pool table

Symmetric relative to gravity

Floor inclined

Symmetry broken
The Pool Table Analogy  (Pierre Sikivie 1996)

Gravity

Pool table

Axis

Floor inclined

Symmetric relative to gravity

Symmetry broken

Symmetry dynamically restored (Peccei & Quinn 1977)
The Pool Table Analogy  (Pierre Sikivie 1996)

Gravity

Pool table

Axis

Floor inclined

Symmetric relative to gravity

Symmetry broken

New degree of freedom → Axion
(Weinberg 1978, Wilczek 1978)

Symmetry dynamically restored
(Peccei & Quinn 1977)
A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to pre-
serve the parity and time-reversal invariance of strong interactions despite the effects
of instantons, would lead to a neutral pseudoscalar boson, the “axion,” with mass roughly
of order 100 keV to 1 MeV. Experimental implications are discussed.

One of the attractive features of quantum chromodynamics\(^1\) (QCD) is that it offers an explana-
tion of why C, P, T, and all quark flavors are conserved by strong interactions, and by order-
\(\alpha\) effects of weak interactions.\(^2\) However, the discovery of quantum effects\(^3\) associated with
the “instanton” solution of QCD has raised a puzz-
U(1)_P\(\times\)O\(\), under which \(\det m(\varphi)\) changes by a phase. The phase of \(\det m(\varphi)\) at the minimum of \(V(\varphi)\) is
then undetermined in any finite order of pertur-
bation theory, and is fixed only by instanton ef-
\(\alpha\)fects which break the U(1)_P\(\times\)O\(\) symmetry. However, the potential will then depend on \(\theta\), but not se-
parately on \(\theta\) and \(\text{arg} \det m\), so that it is not a mir-

Problem of Strong P and T Invariance in the Presence of Instantons

F. Wilczek\(^{(a)}\)
Columbia University, New York, New York 10027, and The Institute for Advanced Studies,
Princeton, New Jersey 08540\(^{(b)}\)
(Received 29 November 1977)

The requirement that \(P\) and \(T\) be approximately conserved in the color gauge theory of
strong interactions without arbitrary adjustment of parameters is analyzed. Several pos-
sibilities are identified, including one which would give a remarkable new kind of very
light, long-lived pseudoscalar boson.

One of the main advantages of the color gauge theory of strong interactions is that so many of
the observed symmetries of strong interactions seem to follow automatically as a consequence of
the gauge principle and renormalizability—\(P, T, C\), flavor conservation, the \(3 \otimes 3^*\) structure of chi-
a certain class of theories\(^4\)\(^5\)\(^6\) the parameter \(\theta\) is
physically meaningless,\(^4\)\(^6\) or dynamically deter-
m\(n\)ed.\(^7\) In this case, if the strong interaction
conserves \(P\) and \(T\), we shall say the conserva-
tion is automatic.

I regard a theory of type (i) as very unattrac-
The Cleansing Axion

I named them after a laundry detergent, since they clean up a problem with an axial current. (Nobel lecture 2004 written version)
Axion Bounds

Experiments
Telescopes
CAST
Direct searches
ADMX
CARRACK

Too much hot dark matter
Globular clusters (a-\gamma-coupling)
Too many events
Too much energy loss
SN 1987A (a-N-coupling)

Classic region
Anthropic region

[GeV] \ f_a

10^3 10^6 10^9 10^{12} 10^{15}

m_a
keV eV meV \mu eV neV

10^3 10^6 10^9 10^{12} 10^{15}

\[\text{GeV}\] \ f_a

\[\text{eV} \quad \text{meV} \quad \text{\mu eV} \quad \text{neV}\]
Supernova 1987A Energy-Loss Argument

Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it. (Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable
Axions as Nambu-Goldstone Bosons

\[ L_{\text{CP}} = \frac{\alpha_s}{8\pi} G_{a\tilde{G}_a} \rightarrow \frac{\alpha_s}{8\pi} \left( \Theta - \frac{a(x)}{f_a} \right) G_{a\tilde{G}_a} \]

Periodic variable (angle)

\[ \Phi = \frac{f_a + \rho(x)}{\sqrt{2}} e^{ia(x)/f_a} \]

- New U(1) symmetry, spontaneously broken at a large scale \( f_a \)
- Axion is “phase” of new Higgs field: angular variable \( a(x)/f_a \)
- By construction couples to \( G\tilde{G} \) term with strength \( \alpha_s/8\pi \), e.g. triangle loop with new heavy quark (KSVZ model)
- Mixes with \( \pi^0-\eta-\eta' \) mesons
- Axion mass (vanishes if \( m_u \) or \( m_d = 0 \))
  \[ m_a = \frac{\sqrt{m_um_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \]
Creation of Cosmological Axions

$T \sim f_a$ (very early universe)
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in “Mexican hat”
- Axion field sits fixed at $a_1 = \Theta_1 f_a$

$T \sim 1 \text{ GeV} \ (H \sim 10^{-9} \text{ eV})$
- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)
- Axion number density in comoving volume conserved
  $$n_a R^3 = m_a (T_1) a_1^2 R_1^3 \sim 3 H_1 R_1^3 \Theta_1^2 f_a^2$$
- Axion mass density today:
  $$\rho_a = m_a n_a \propto \Theta_1^2 m_a f_a^2 \propto \Theta_1^2 \frac{m_a^2 f_a^2}{m_a} \propto \Theta_1^2 \frac{m_{\pi}^2 f_{\pi}^2}{m_a}$$
COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL ¹, Mark B. WISE ²

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

and

Frank WILCZEK

Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

Received 10 September 1982

We identify a new cosmological problem for models which solve the strong CP puzzle with an invisible axion, unrelated to the domain wall problem. Because the axion is very weakly coupled, the energy density stored in the oscillations of the classical axion field does not dissipate rapidly; it exceeds the critical density needed to close the universe unless \( f_a < 10^{12} \text{ GeV} \), where \( f_a \) is the axion decay constant. If this bound is saturated, axions may comprise the dark matter of the universe.
A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

L.F. ABBOTT 1

Physics Department, Brandeis University, Waltham, MA 02254, USA

and

P. SIKIVIE 2

Particle Theory Group, University of Florida, Gainesville, FL 32611, USA

Received 14 September 1982

The production of axions in the early universe is studied. Axion models which break the $U(1)_{PQ}$ symmetry above $10^{12}$ GeV are found to produce an unacceptably large axion energy density.
THE NOT-SO-HARMLESS AXION

Michael DINE
The Institute for Advanced Study, Princeton, NJ 08540, USA

and

Willy FISCHLER
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

Received 17 September 1982
Received manuscript received 14 October 1982

Cosmological aspects of a very weakly interacting axion are discussed. A solution to the problem of domain walls discussed by Sikivie is mentioned. Demanding that axions do not dominate the present energy density of the universe is shown to give an upper bound on the axion decay constant of at most $10^{12}$ GeV.
Killing Two Birds with One Stone

Peccei-Quinn mechanism
• Solves strong CP problem
• May provide dark matter in the form of axions

Unbelievable! It looks like they’ve both been killed by the same stone...
Cosmic Axion Density

Modern values for QCD parameters and temperature-dependent axion mass imply (Bae, Huh & Kim, arXiv:0806.0497)

\[ \Omega_a h^2 = 0.195 \Theta_i^2 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{1.184} = 0.105 \Theta_i^2 \left( \frac{10 \text{ \mu eV}}{m_a} \right)^{1.184} \]

If axions provide the cold dark matter: \( \Omega_a h^2 = 0.11 \)

\[ \Theta_i = 0.75 \left( \frac{10^{12} \text{ GeV}}{f_a} \right)^{0.592} = 1.0 \left( \frac{m_a}{10 \text{ \mu eV}} \right)^{0.592} \]

• \( \Theta_i \sim 1 \) implies \( f_a \sim 10^{12} \text{ GeV} \) and \( m_a \sim 10 \text{ \mu eV} \) ("classic window")

• \( f_a \sim 10^{16} \text{ GeV} \) (GUT scale) or larger (string inspired) requires \( \Theta_i \lesssim 0.003 \) ("anthropic window")
Lee-Weinberg Curve for Neutrinos and Axions

Axions

\[ \log(\Omega_a) \]
\[ \log(m_a) \]
\[ \Omega_M \]

CDM | HDM

10 \( \mu \)eV | 10 eV

Non-Thermal Relics | Thermal Relics

Neutrinos & WIMPs

\[ \log(\Omega_\nu) \]
\[ \log(m_\nu) \]
\[ \Omega_M \]

HDM | CDM

10 eV | 10 GeV

Thermal Relics
Axion Hot Dark Matter Limits from Precision Data

Credible regions for neutrino plus axion hot dark matter (WMAP-5, LSS, BAO, SNIa)
Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]

Marginalizing over unknown neutrino hot dark matter component

\[ m_a < 1.0 \text{ eV (95\% CL)} \quad \text{WMAP-5, LSS, BAO, SNIa} \]
Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]

\[ m_a < 0.4 \text{ eV (95\% CL)} \quad \text{WMAP-3, small-scale CMB, HST, BBN, LSS, Ly-\(\alpha\)} \]
Melchiorri, Mena & Slosar [arXiv:0705.2695]
Cold Axion Populations

Case 1: Inflation after PQ symmetry breaking

Homogeneous mode oscillates after
\[ T \lesssim \Lambda_{\text{QCD}} \]

Dependence on initial misalignment angle
\[ \Omega_a \propto \Theta_i^2 \]

Dark matter density a cosmic random number (“environmental parameter”)

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMB bounds on isocurvature fluctuations
- Scale of inflation required to be small

Case 2: Reheating restores PQ symmetry

- Cosmic strings of broken $U_{\text{PQ}}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- $\Omega_a$ independent of initial conditions
- $N = 1$ or else domain wall problem

Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

Typical properties
- Mass $\sim 10^{-12} M_{\text{sun}}$
- Radius $\sim 10^{10}$ cm
- Mass fraction up to several 10%
Inflation, Axions and Anthropic Selection

If PQ symmetry is not restored after inflation

- Axion density determined by initial random number $-\pi < \Theta_i < +\pi$
- Different in different patches of the universe
- Our visible universe, after inflation, from a single patch
- Axion/photon ratio a cosmic random number, chosen by spontaneous symmetry breaking process

Allows for small $\Theta_i \lesssim 0.003$ and thus for $f_a$ at GUT or string scale

- Is this “unlikely” or “unnatural” or “fine tuned”?
- Should one design experiments for very small-mass axion dark matter?

Difficult to form baryonic structures if baryon/dark matter density too low, posterior probability for small $\Theta_i$ not necessarily small

Posterior Dark Matter Probability Distribution

Tegmark, Aguirre, Rees & Wilczek,
“Dimensionless constants, cosmology and other dark matters,”
Creation of Adiabatic vs. Isocurvature Perturbations

**Inflaton field:**

- De Sitter expansion imprints scale invariant fluctuations

  - Slow roll

  - Reheating

  - Inflaton decay → matter & radiation

  - Both fluctuate the same: Adiabatic fluctuations

**Axion field:**

- De Sitter expansion imprints scale invariant fluctuations

  - Inflaton decay → radiation

  - Axion field oscillates late → matter

  - Matter fluctuates relative to radiation: Entropy fluctuations
Power Spectrum of CMB Temperature Fluctuations

Sky map of CMBR temperature fluctuations

$$\Delta(\theta, \varphi) = \frac{T(\theta, \varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole expansion

$$\Delta(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \varphi)$$

Angular power spectrum

$$C_\ell = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$
CMB Angular Power Spectrum

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647
Parameter Degeneracies

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647
Isocurvature Forecast

Hubble scale during inflation

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647
Experimental Tests of the “Invisible” Axion

P. Sikivie

Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the “invisible” axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:
Axion-photon transition in external static E or B field
(Originally discussed for $\pi^0$ by Henri Primakoff 1951)

\[ \gamma \rightarrow \alpha \]

Pierre Sikivie:
Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion helioscope:
  Look at the Sun through a dipole magnet

- Axion haloscope:
  Look for dark-matter axions with A microwave resonant cavity
Search for Solar Axions

Axion Helioscope (Sikivie 1983)

- Tokyo Axion Helioscope ("Sumico")
  (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST)
  (Data since 2003)

Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments
(SOLAX, COSME, DAMA, CDMS ...)

Primakoff production

Axion flux

Magnet

Axion-Photon-Oscillation

Sun

\[ \gamma \rightarrow a \rightarrow \gamma \]
Tokyo Axion Helioscope ("Sumico")

Moriyama, Minowa, Namba, Inoue, Takasu & Yamamoto
PLB 434 (1998) 147

Inoue, Akimoto, Ohta, Mizumoto, Yamamoto & Minowa
PLB 668 (2008) 93
Figure 6: Left: Spatial distribution of events observed under axion sensitive conditions by the CAST X-ray telescope during the 2004 data taking period. The intensity is given in counts per pixel and is integrated over the full observation period of $t_{\text{obs}} = 707$ ksec. Right: Expected “axion” image of the sun as it would be observed by the pn-CCD detector. To determine the axion spot on the pn-CCD, the PSF of the mirror system and the total effective area of the X-ray telescope was taken into account. The count rate integrated over the region of the spot is normalized to unity.
90 min tracking result

ROI

„suspicious pressure“
Helioscope Limits

CAST-II results (He-4 filling): JCAP 0902 (2009) 008
Search for Galactic Axions (Cold Dark Matter)

Dark matter axions: $m_a = 1$–$1000$ $\mu$eV

Velocities in galaxy: $v_a \approx 10^{-3}$ c

Energies therefore: $E_a \approx (1 \pm 10^{-6}) m_a$

Microwave Energies: (1 GHz $\approx$ 4 $\mu$eV)

Axion Haloscope (Sikivie 1983)

$B_{ext} \approx 8$ Tesla

Microwave Resonator: $Q \approx 10^5$

Power of galactic axion signal:

$$P = 4 \times 10^{-21} W \times \frac{V}{0.22 m^3} \times \left( \frac{B}{8.5 T} \right)^2 \times \frac{Q}{10^5} \times \left( \frac{m_a}{2\pi \text{GHz}} \right) \left( \frac{\rho_a}{5 \times 10^{-25} g/cm^3} \right)$$

Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion

Cavity overcomes momentum mismatch
Axion Dark Matter Searches

Limits/sensitivities, assuming axions are the galactic dark matter

- 2. University of Florida PRD 42 (1990) 1297
- 4. CARRACK I (Kyoto) hep-ph/0101200
- 5. ADMX (US) foreseen RMP 75 (2003) 777
- 6. New CARRACK (Kyoto) K.Imai (Panic 2008)
AdMX (Gianpaolo Carosi, Fermilab, May 2007)

Axion hardware

Magnet with Insert (side view)

- Stepping motors
- Liquid helium
- Amplifier, refrigerator, Tuner, Tuning rods
- Superconducting magnet 8T, 6 tons

Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm Φ
ADMX (Gianpaolo Carosi, Fermilab, May 2007)

Axion hardware (cont’d)

High-Q Cavity (~200,000)

Experimental Insert
Presently the noise temperature of our HFET amps is \( \sim 1.5K \)

But the quantum limit at 1 GHz is \( \sim 50 \text{ mK} \)

*Prof. John Clark and Dr. Darin Kinion (UC Berkeley)

Our latest SQUIDs are now within 15% of the Standard Quantum Limit
SQUID-Based Microwave Cavity Search for Dark-Matter Axions

S. I. Asztalos, T. G. Carosi, C. Hagemann, D. Kinion, and K. van Bibber
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

M. Hotz, L. J. Rosenberg, and G. Rybka
University of Washington, Seattle, Washington 98195, USA

J. Hoskins, J. Hwang, J. P. Sikivie, and D. B. Tanner
University of Florida, Gainesville, Florida 32611, USA

R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903,

J. Clarke
University of California and Lawrence Berkeley National Laboratory, Berkeley, Calif.

(Received 27 October 2009; published 28 January 2010)

FIG. 5 (color online). Axion-photon coupling excluded at the 90% confidence level assuming a local dark-matter density of 0.45 GeV/cm$^3$ for two dark-matter distribution models. The shaded region corresponds to the range of the axion-photon coupling models discussed in [28].
CARRACK 華洛

- Cosmic Axion Research with Rydberg Atoms in Cavities in Kyoto

A. Matsubara, S. Matsuki$, T. Mizusaki, T. Nishimura$,
D. Ohsawa, A. Sawada, Y. Takahashi, T. Tosaki
and K. Yamamoto

Kyoto Univ.
# Osaka Electro-comunication Univ.
$ Ritsumeikan Univ.
New CARRACK (Kyoto)
Axion Bounds

Experiments

Too much hot dark matter

Globular clusters (a-γ-coupling)

Too many events

SN 1987A (a-N-coupling)

Telescopes

CAST

Direct searches

ADMX

CARRACK

Too much cold dark matter (classic)

Classical region

Anthropic region

[GeV] $f_a$

$10^3 \quad m_a \quad \text{keV}$

$10^6 \quad \text{eV}$

$10^9 \quad \text{meV}$

$10^{12} \quad \mu\text{eV}$

$10^{15} \quad \text{neV}$

$10^3 \quad 10^6 \quad 10^9 \quad 10^{12} \quad 10^{15}$
And if the axion be found?

The Study of Unique Quantum System

And should the axion possess fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy
Fine Structure in Axion Spectrum

- Axion distribution on a 3-D sheet in 6-D phase space
- Is “folded up” by galaxy formation
- Velocity distribution shows narrow peaks that can be resolved
- More detectable information than local dark matter density

High resolution analysis of the signal may reveal fine structure ...

P. Sikivie & collaborators
Summary

Peccei-Quinn dynamical CP symmetry restoration is better motivated than ever

Provides well-motivated cold dark matter candidate in the form of axions

Realistic full-scale search in “classic window” \((m_a \sim 1\text{--}100 \mu\text{eV})\) is finally beginning (ADMX and New CARRACK)

Isocurvature fluctuations could still show up (Planck, future CVL probe)

Experimental approach in “anthropic window” \((m_a \lesssim \text{neV})\) is missing