LAUNCH09: Neutrinos and Beyond, 9–12 Nov 09, MPIK, Heidelberg

Axion Dark Matter

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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

Physics Nobel Prize 2008

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

The CP Problem of Strong Interactions

Real quark mass **Phase from Yukawa coupling** **Angular variable** **CP-odd quantity ~E·B**

$$L_{QCD} = \sum_q \bar{\psi}_q \left(i\not{D} - m_q e^{i\theta_q} \right) \psi_q - \frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

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

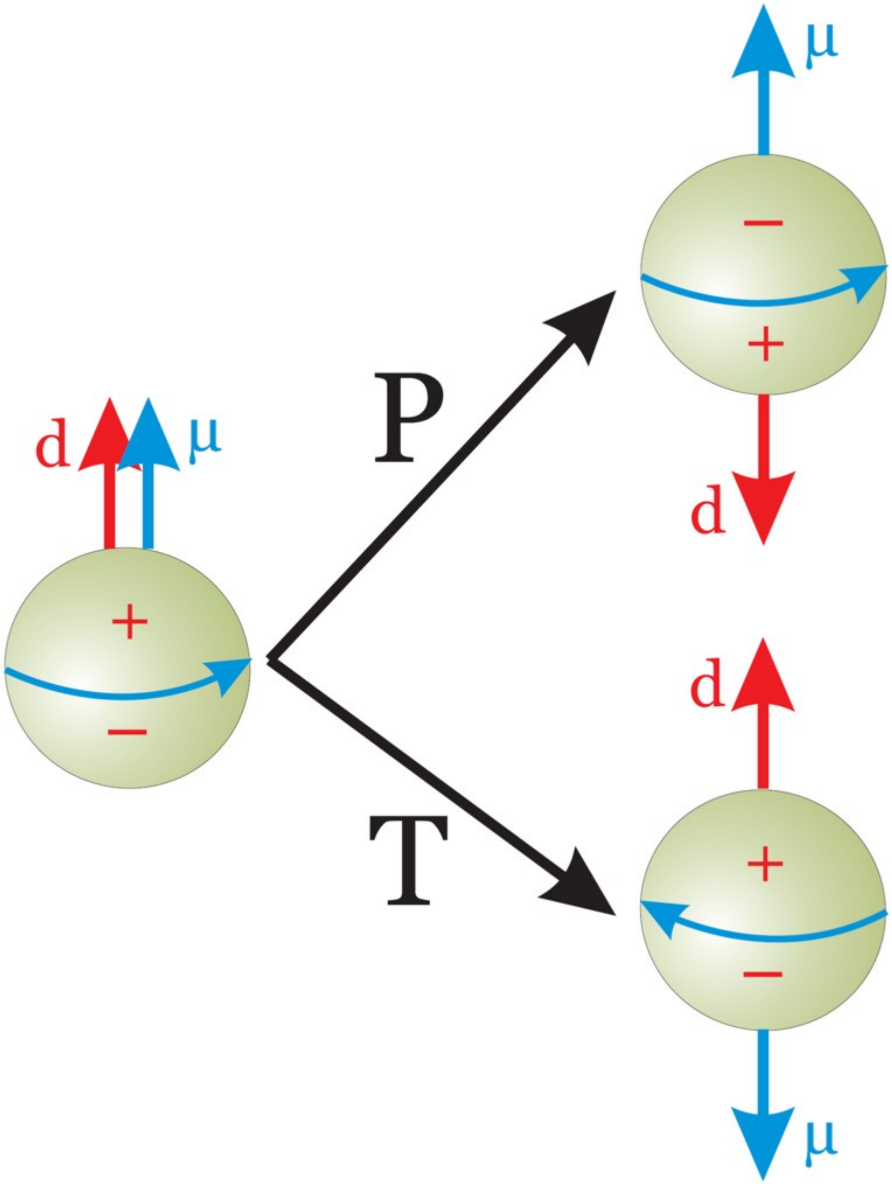
$$\psi_q \to e^{-i\gamma_5 \theta_q / 2} \psi_q$$

$$L_{QCD} = \sum_q \bar{\psi}_q (i\not{D} - m_q) \psi_q - \frac{1}{4} GG - \underbrace{(\Theta - \arg\det M_q)}_{-\pi < \bar{\Theta} < +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

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

Experimental limits: $|\bar{\Theta}| < 10^{-10}$ **Why so small?**

Neutron Electric Dipole Moment



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

Natural scale

$e/2m_N = 1.06 \times 10^{-14}$ e cm

Experimental limit

$|d| < 0.63 \times 10^{-25}$ e cm

Limit on coefficient

$$\bar{\Theta}\,\frac{m_q}{m_N} \lesssim 10^{-11}$$

Dynamical Symmetry Restoration

Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978

- Re-interpret $\bar{\Theta}$ as a dynamical variable (scalar field)

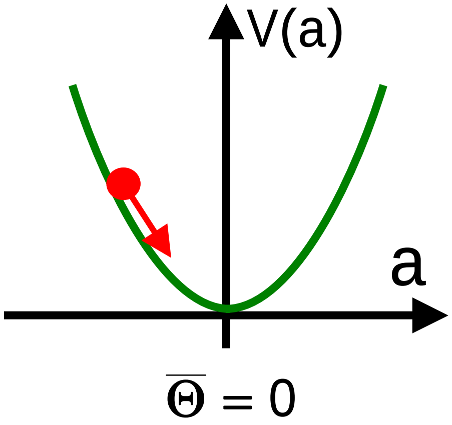
$$L_{CP} = -\frac{\alpha_s}{8\pi}\,\bar{\Theta}\,\mathrm{Tr}(G\tilde{G}) \to -\frac{\alpha_s}{8\pi}\,\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$

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

- Axions generically couple to two gluons and mix with π^0, η, η' mesons, inducing a mass (potential) for a(x)

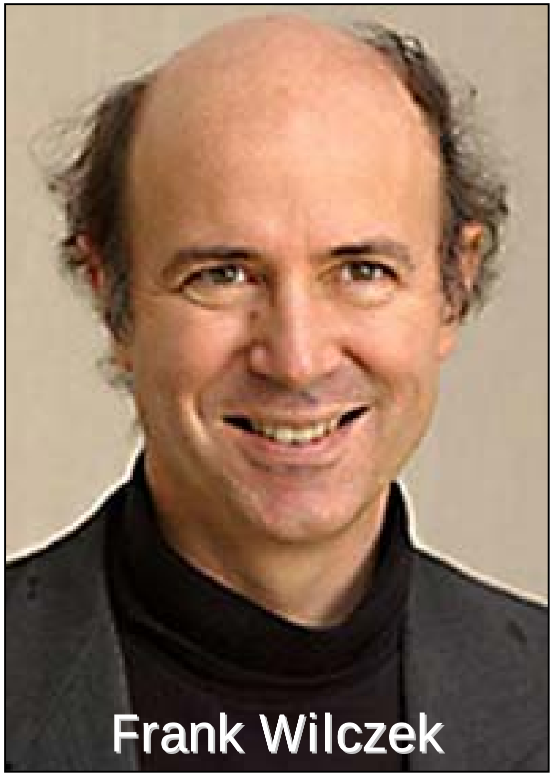
$$m_a f_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\, m_\pi f_\pi \qquad \begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

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



CP-symmetry dynamically restored

The Cleansing Axion

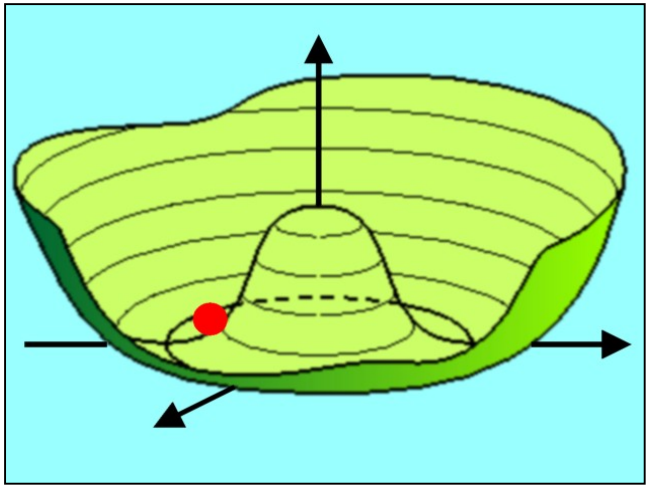

Frank Wilczek

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

Axions as Nambu-Goldstone Bosons

$$L_{CP} = \frac{\alpha_s}{8\pi}\,\overline{\Theta}\,G_a\tilde{G}_a \rightarrow \frac{\alpha_s}{8\pi}\underbrace{\left(\overline{\Theta} - \frac{a(x)}{f_a}\right)}_{\text{Periodic variable (angle)}} G_a\tilde{G}_a$$

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



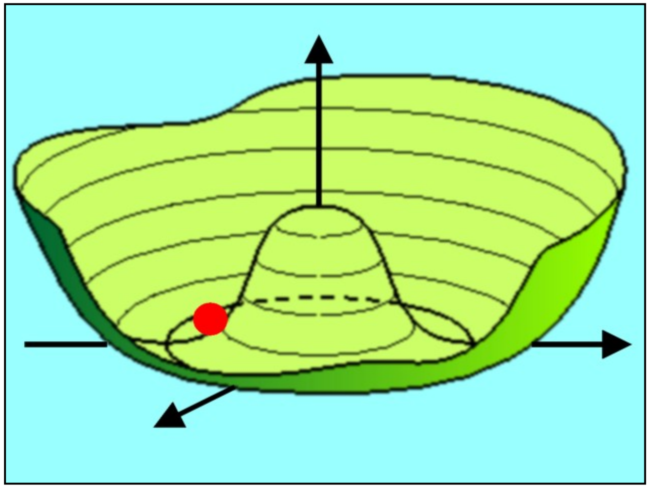
- New U(1) symmetry, spontaneously broken at a large scale f_a
- Axion is “phase” of new Higgs field: angular variable $a(x)/f_a$
- By construction couples to $G\tilde{G}$ term with strength $\alpha_s/8\pi$, e.g. triangle loop with new heavy quark (KSVZ model)
- Mixes with π^0-η-η’ mesons
- Axion mass (vanishes if m_u or $m_d = 0$)

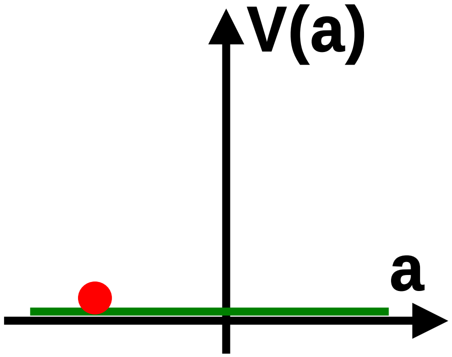
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\,\frac{m_\pi}{f_\pi f_a}$$

Creation of Cosmological Axions

$T \sim f_a$ (very early universe)

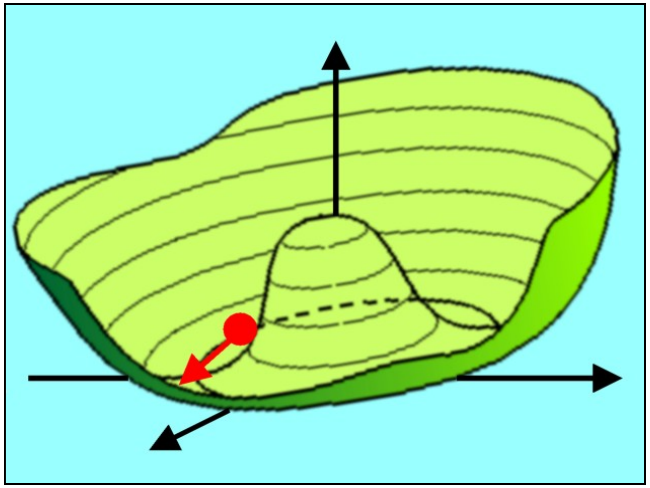
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_1 = \Theta_1 f_a$

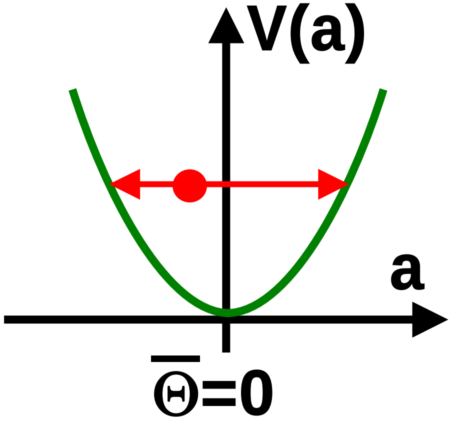




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- 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

$$n_a R^3 = m_a(T_1)\, a_1^2 R_1^3 \sim 3H_1 R_1^3 \Theta_1^2 f_a^2$$

- Axion mass density today: $\rho_a = m_a n_a \propto \Theta_1^2 m_a f_a^2 \propto \Theta_1^2 \dfrac{m_a^2 f_a^2}{m_a} \propto \Theta_1^2 \dfrac{m_\pi^2 f_\pi^2}{m_a}$

Cosmic Axion Density

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

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

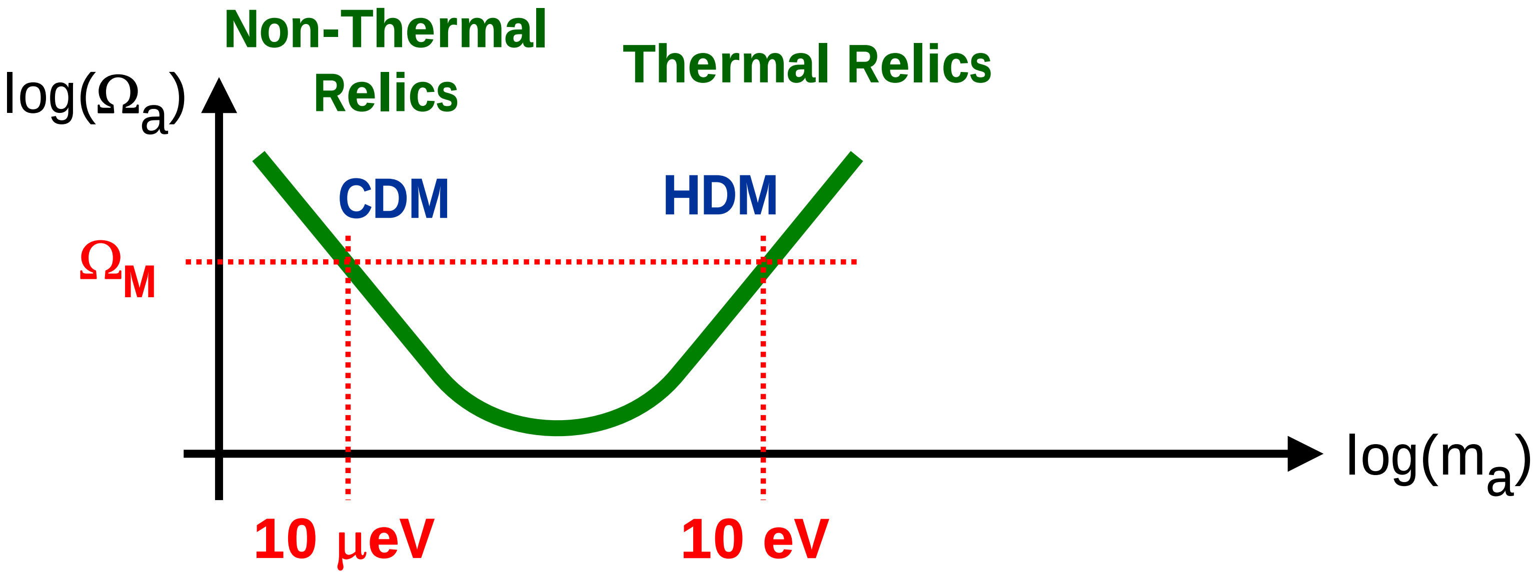
If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

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

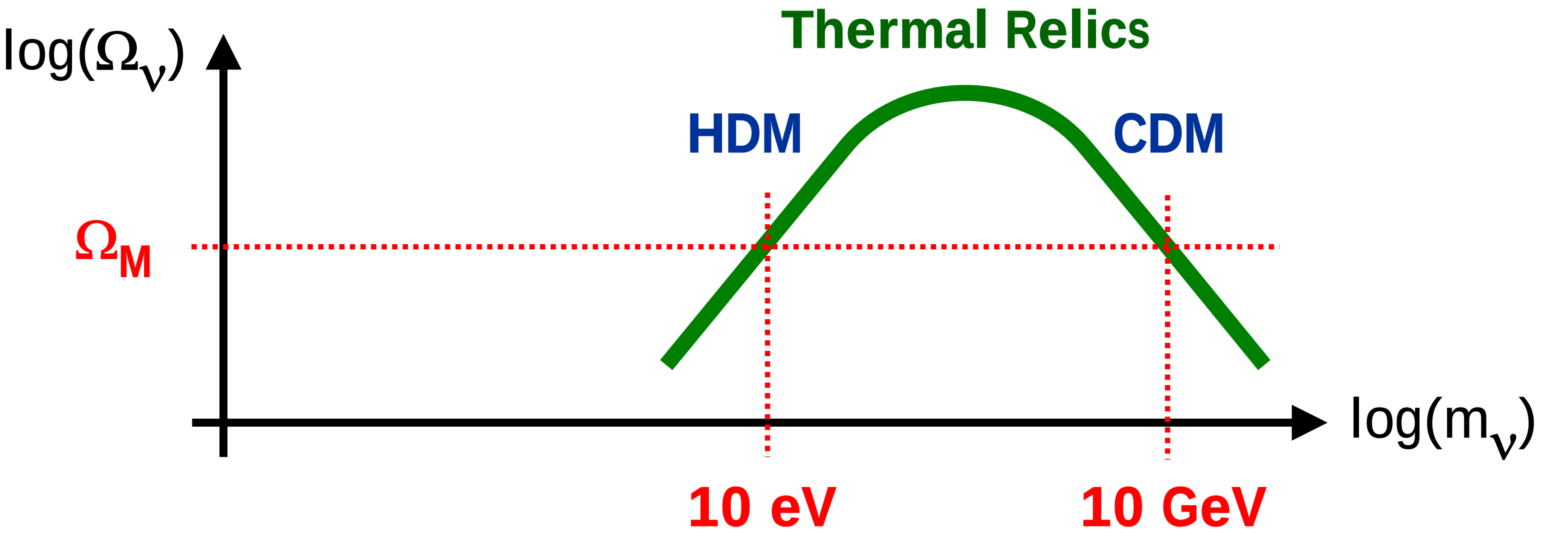
- **$\Theta_i \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu$eV ("classic window")**
- **$f_a \sim 10^{16}$ GeV (GUT scale) or larger (string inspired) requires $\Theta_i \lesssim 0.003$ ("anthropic window")**

Lee-Weinberg Curve for Neutrinos and Axions

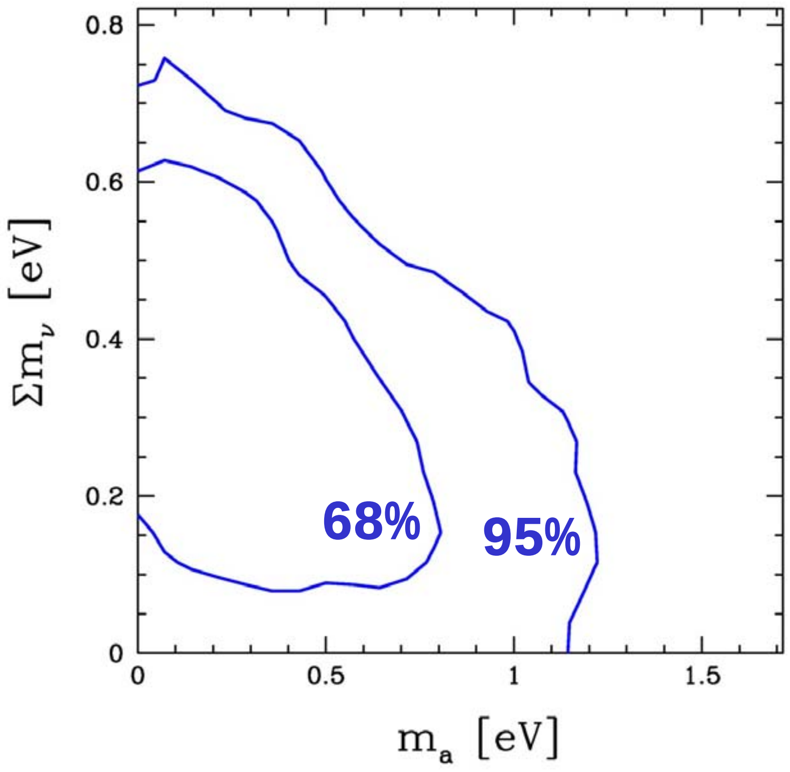
Axions



Neutrinos & WIMPs



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

$m_a < 1.0$ eV (95% CL)	**WMAP-5, LSS, BAO, SNIa**	**Hannestad, Mirizzi, Raffelt & Wong [arXiv:0803.1585]**
$m_a < 0.4$ eV (95% CL)	**WMAP-3, small-scale CMB, HST, BBN, LSS, Ly-α**	**Melchiorri, Mena & Slosar [arXiv:0705.2695]**

Cold Axion Populations

Case 1: Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

$$T \lesssim \Lambda_{QCD}$$

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 $U_{PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_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 ~ 10^{-12} M_{sun}
- Radius ~ 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 tuning"?
- Should one design experiments for very small-mass axion dark matter?

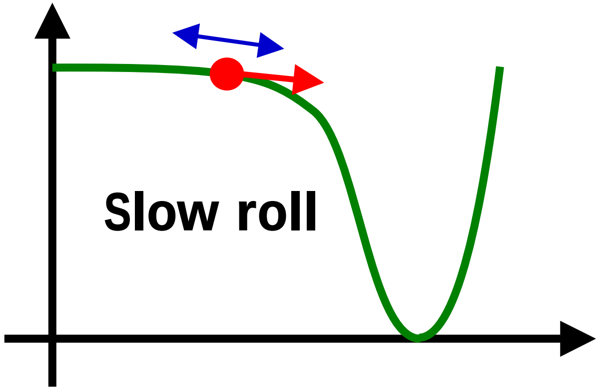
Difficult to form baryonic structures if baryon/dark matter density too low, posterior probability for small Θ_i not necessarily small

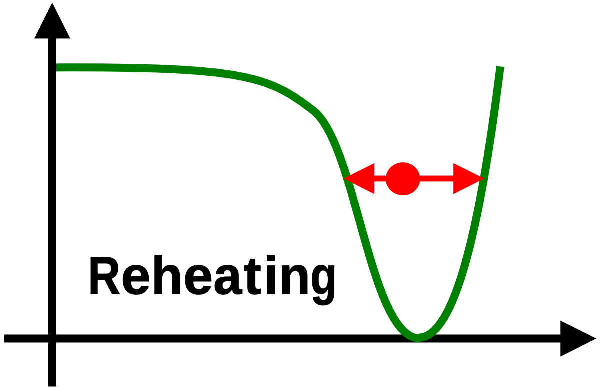
- Linde, "Inflation and axion cosmology," PLB 201:437, 1988
- Tegmark, Aguirre, Rees & Wilczek, "Dimensionless constants, cosmology and other dark matters," PRD 73:023505, 2006 [astro-ph/0511774]

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field:

De Sitter expansion imprints scale invariant fluctuations

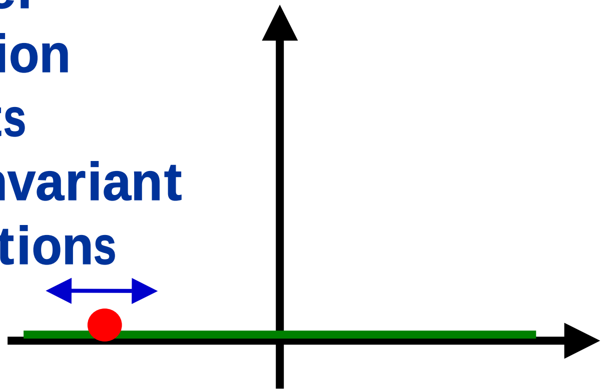


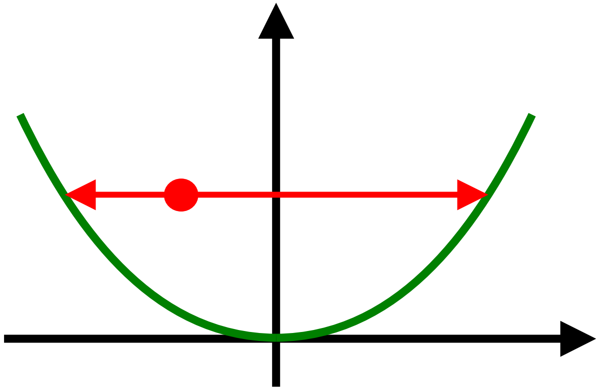


Inflaton decay → matter & radiation
Fluctuations in both (adiabatic)

Axion field:

De Sitter expansion imprints scale invariant fluctuations





Inflaton decay → radiation
Axion field oscillates late → matter
Fluctuations of matter relative to radiation: Entropy fluctuations

Amplitudes of Adiabatic and Isocurvature Perturbations

Entropy fluctuations induced by de Sitter expansion on axion field

$$S(k)=\frac{\Theta^2-\langle\Theta^2\rangle}{\langle\Theta^2\rangle}$$

Isocurvature power spectrum, assuming Gaussian fluctuations ($n_{\rm iso}=1-2\varepsilon$, slow-roll parameter ε)

$$\langle|S(k)|^2\rangle\sim\sigma_\Theta^2\sim\frac{H_I^2}{\pi^2 f_a^2\Theta_i^2}\propto\left(\frac{k}{k_0}\right)^{n_{\rm iso}-1}$$

Usual curvature power spectrum

$$\langle|R(k)^2|\rangle\sim\frac{H_I^2}{\pi M_{\rm Pl}^2\,\varepsilon}\propto\left(\frac{k}{k_0}\right)^{n_{\rm ad}-1}$$

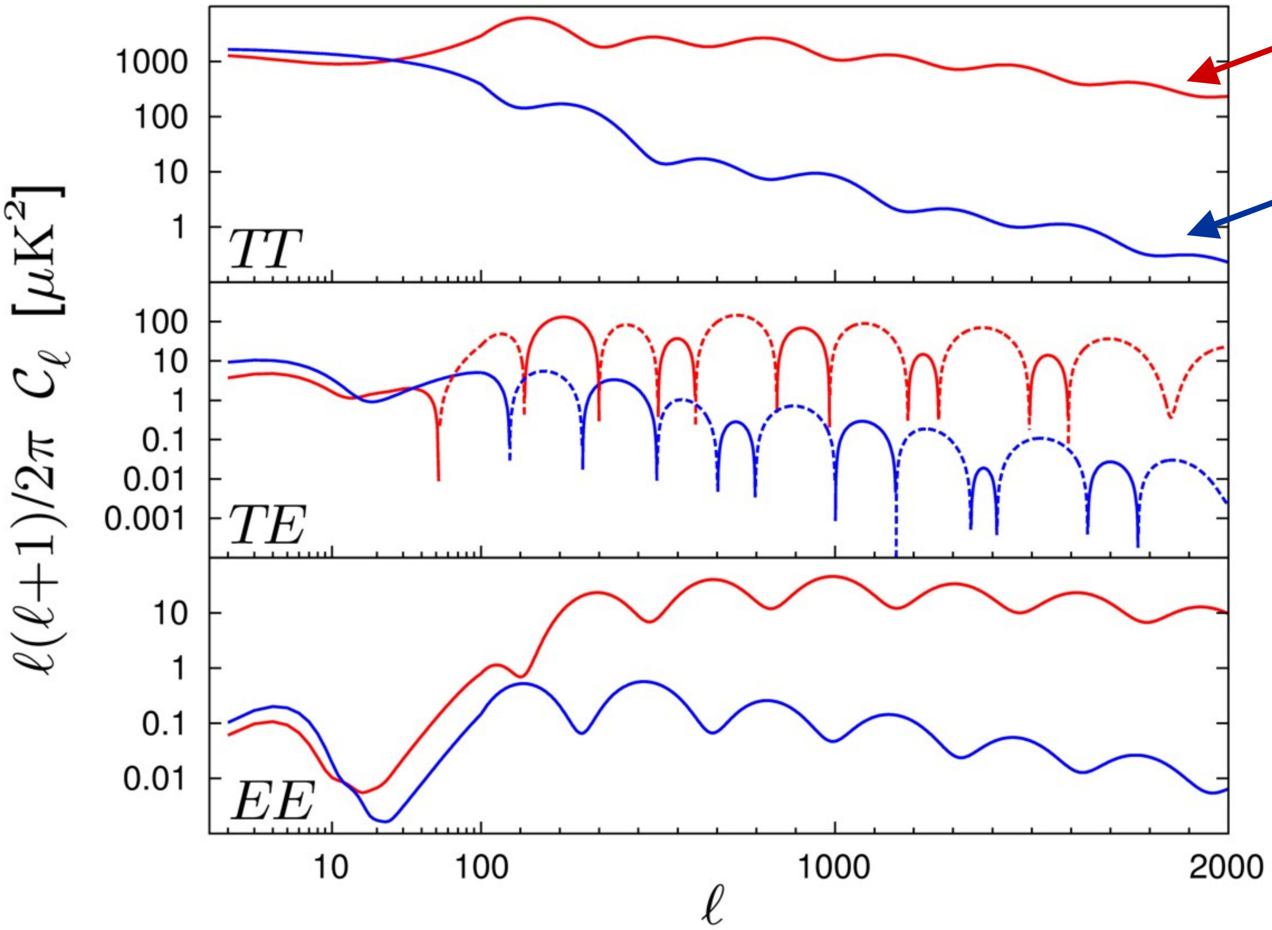
Total power spectrum uncorrelated sum

$$P(k)=\langle|R(k)^2|\rangle+\langle|S(k)^2|\rangle$$

Isocurvature fraction at pivot scale $k_0=0.002~\mathrm{Mpc}^{-1}$

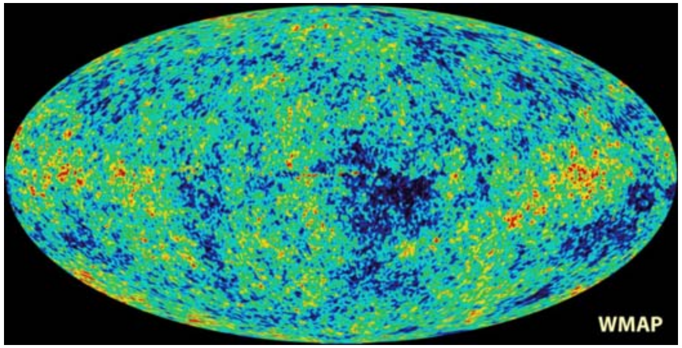
$$\alpha=\left.\frac{\langle|S(k)^2|\rangle}{\langle|R(k)^2|\rangle+\langle|S(k)^2|\rangle}\right|_{k=k_0}\sim\frac{H_I^2}{A_S\pi^2 f_a^2\Theta_i^2}$$

CMB Angular Power Spectrum



Purely adiabatic

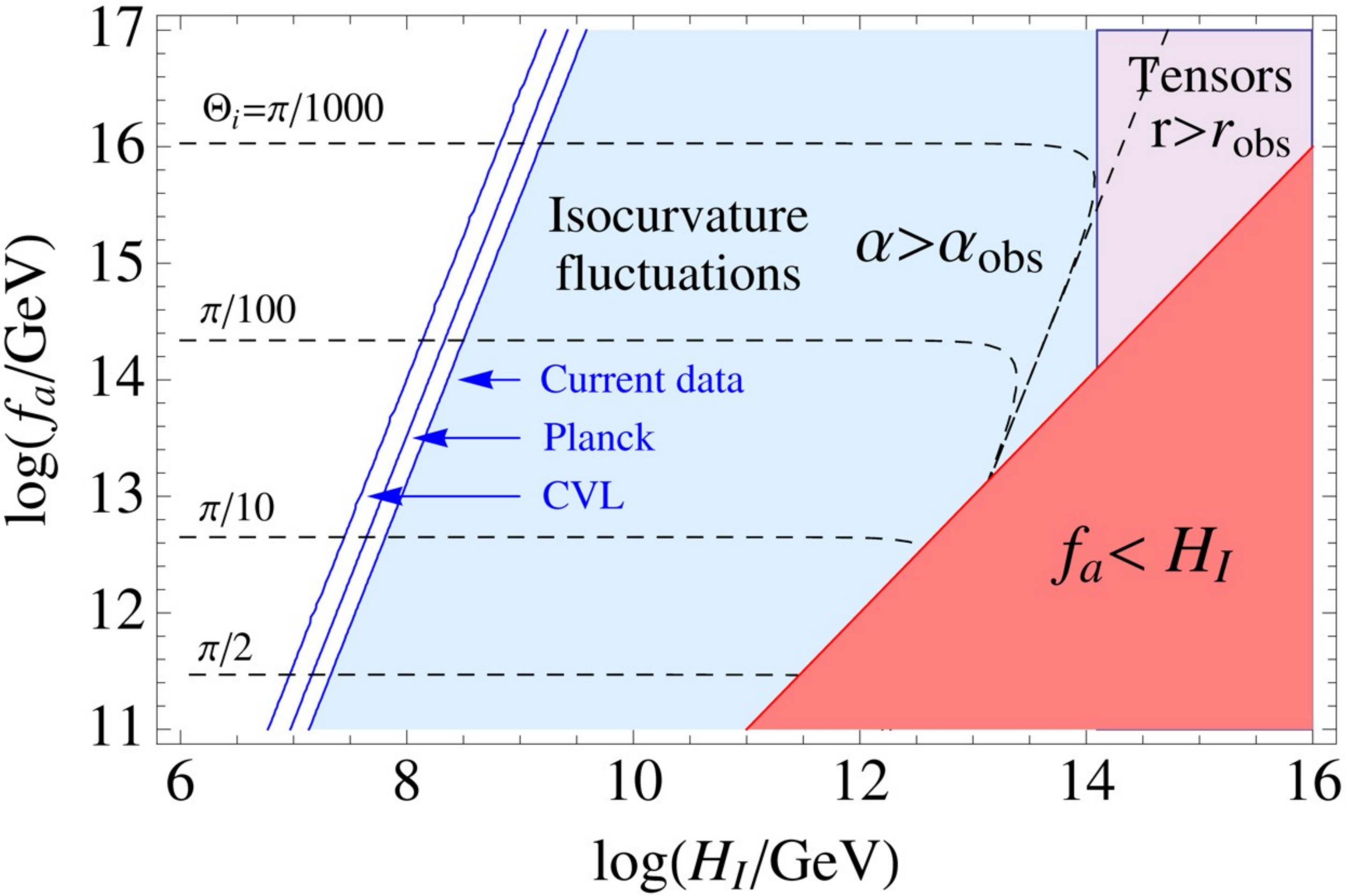
Purely isocurvature



Hamann, Hannestad, Raffelt & Wong
arXiv:0904.0647

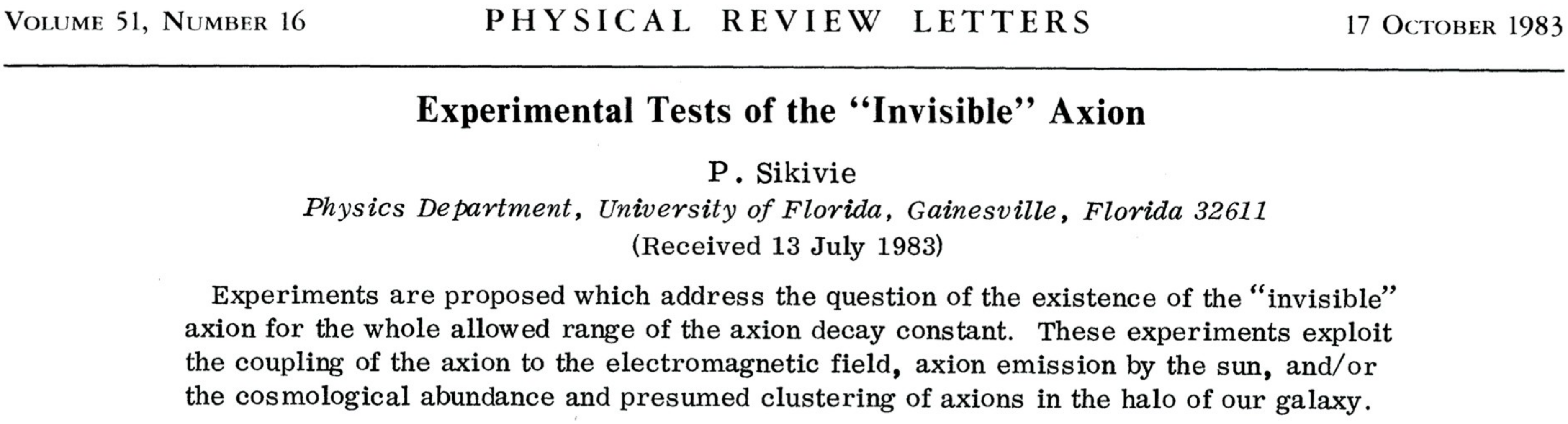
Isocurvature Forecast

Hubble scale during inflation



Axion decay constant

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647



Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

Experimental Tests of the "Invisible" Axion

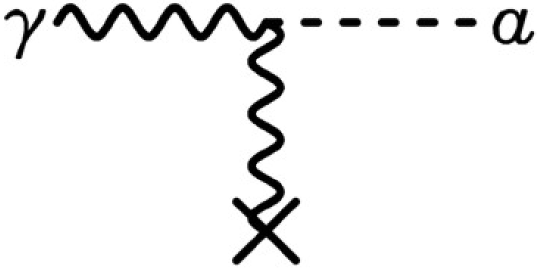
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(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 π^0 by Henri Primakoff 1951)

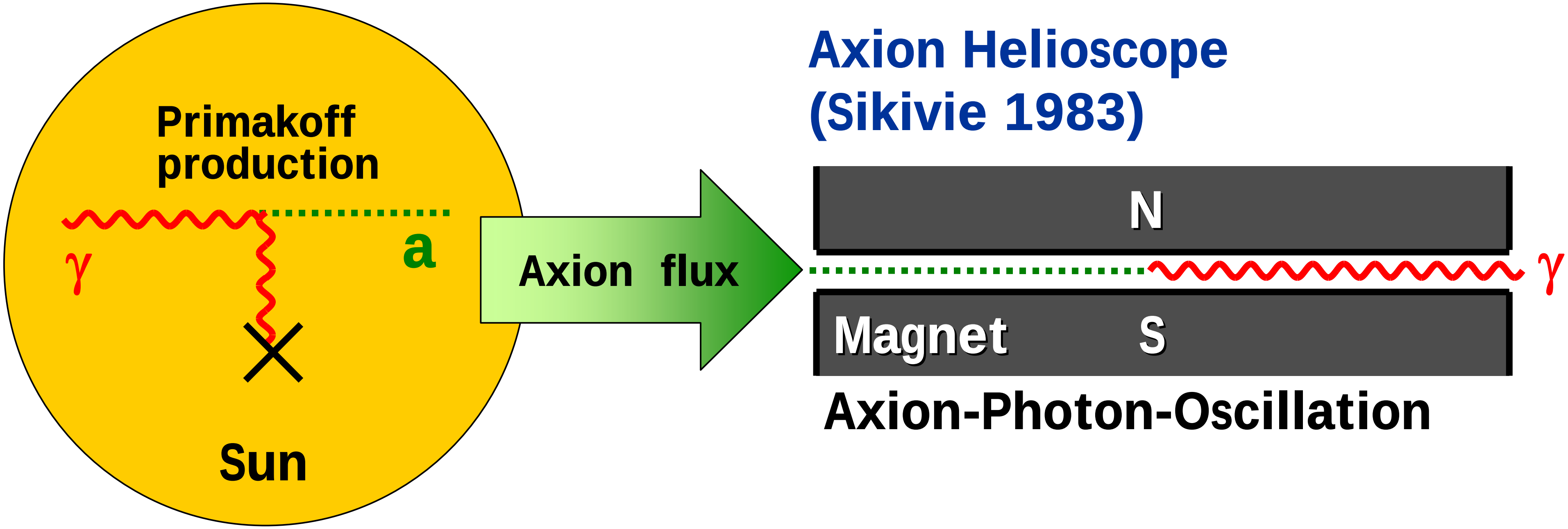


Pierre Sikivie:

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

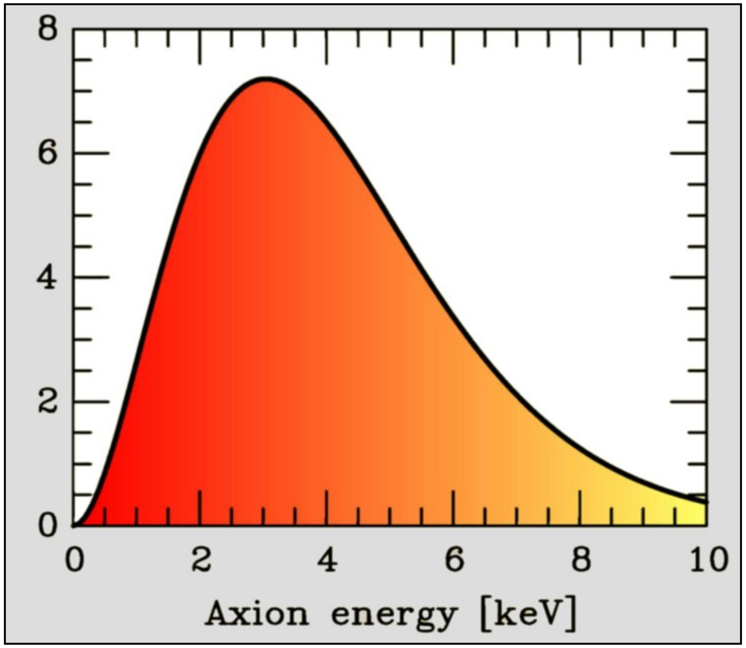
- **Axion helioscope:**
  Look at the Sun through a dipole magnet
- **Axion haloscope:**
  Look for dark-matter axions with A microwave resonant cavity

Search for Solar Axions



Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation

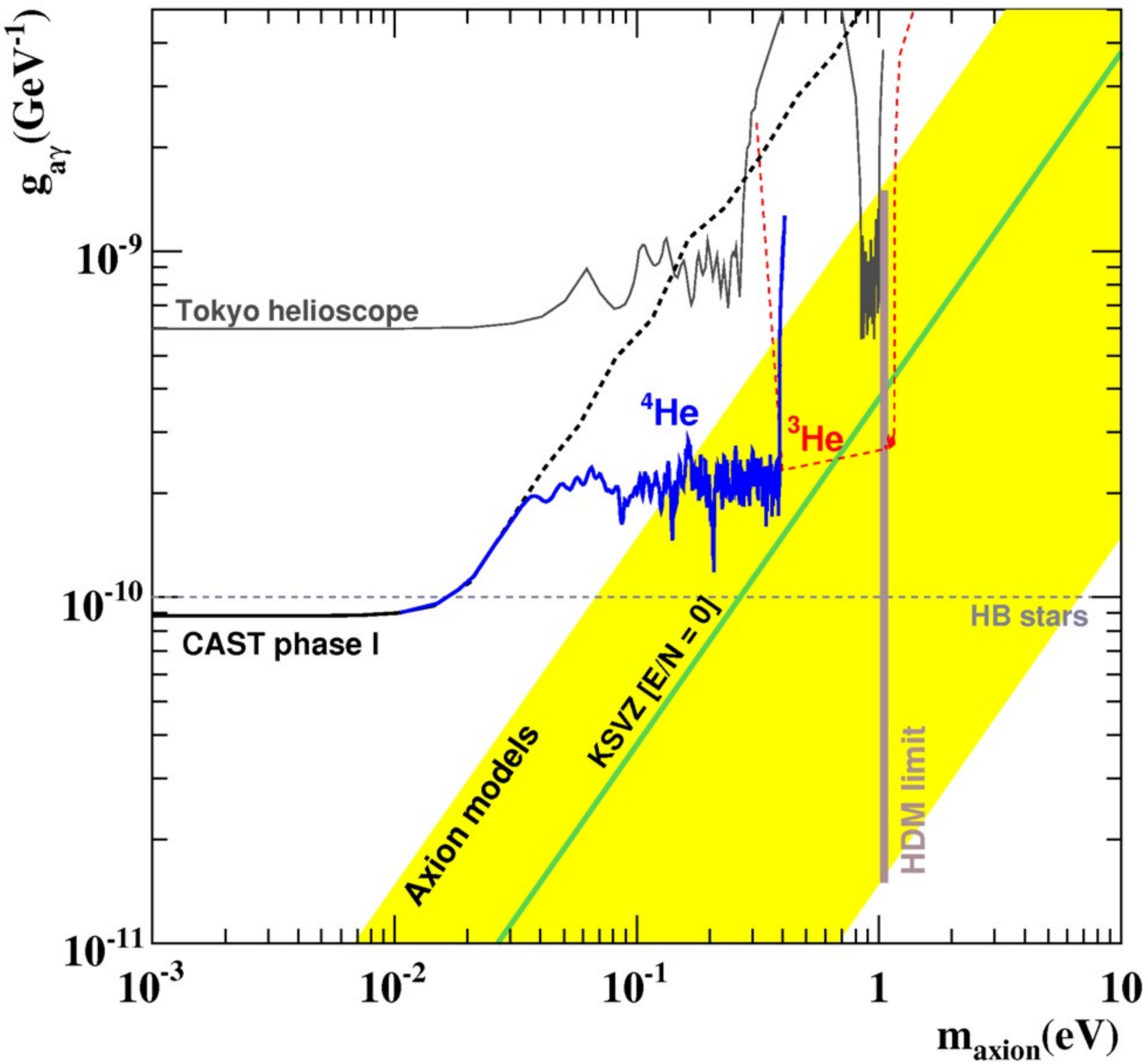


- ➔ Tokyo Axion Helioscope ("Sumico")
  (Results since 1998, up again 2008)
- ➔ CERN Axion Solar Telescope (CAST)
  (Data since 2003)

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

CAST at CERN

Helioscope Limits



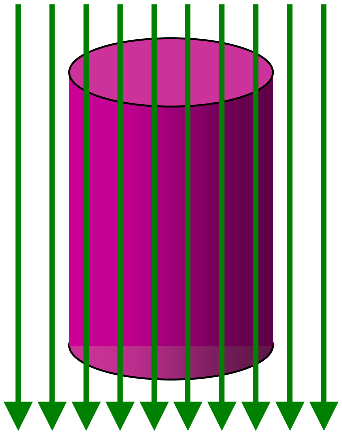
CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008

Search for Galactic Axions (Cold Dark Matter)

Dark matter axions	$m_a = 1\text{–}1000\ \mu\mathrm{eV}$
Velocities in galaxy	$v_a \approx 10^{-3}\ c$
Energies therefore	$E_a \approx (1 \pm 10^{-6})\ m_a$

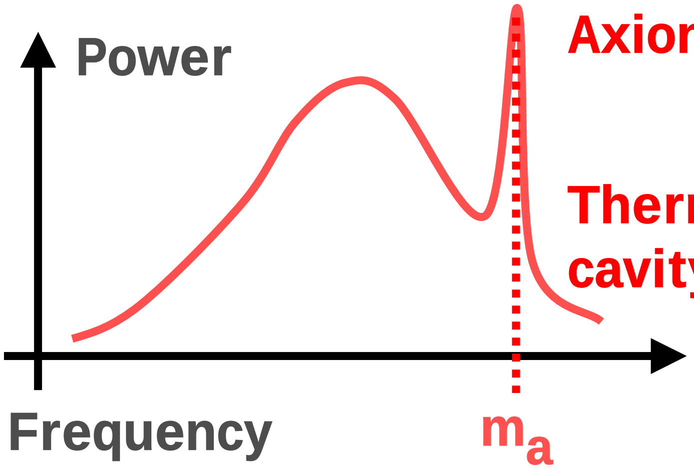
Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)



$B_{\mathrm{ext}} \approx 8$ Tesla

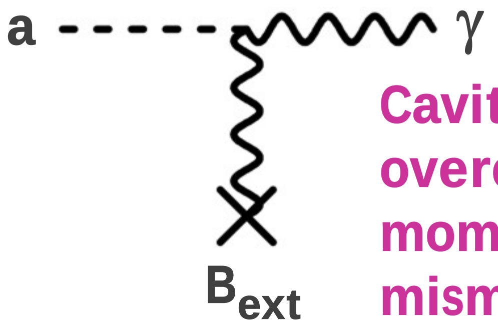
Microwave Resonator $Q \approx 10^5$



Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion



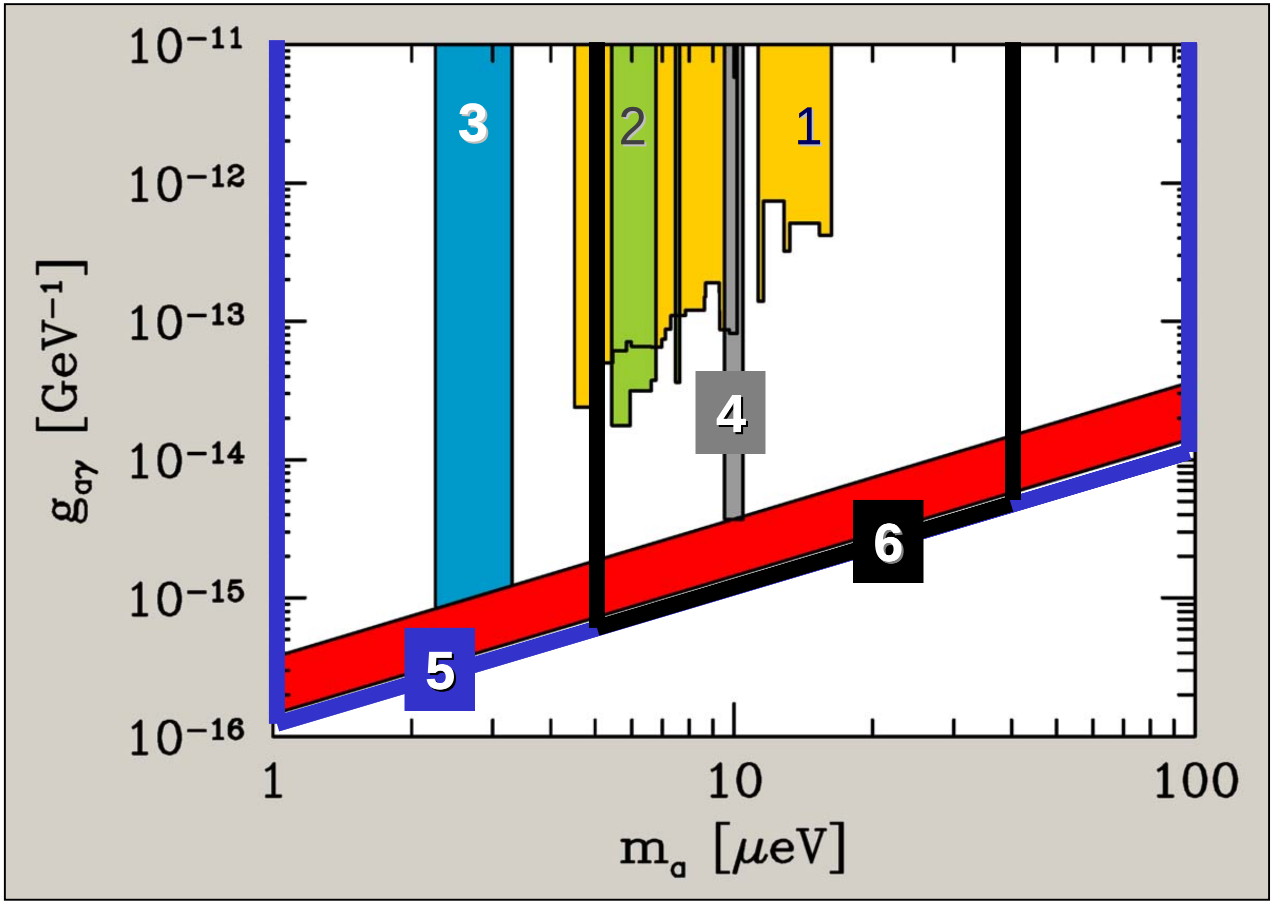
Cavity overcomes momentum mismatch

Power of galactic axion signal

$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm^3}}\right)$$

Axion Dark Matter Searches

Limits/sensitivities, assuming axions are the galactic dark matter



1. Rochester-Brookhaven-Fermilab,
   PRD 40 (1989) 3153

2. University of Florida
   PRD 42 (1990) 1297

3. US Axion Search
   ApJL 571 (2002) L27

4. CARRACK I (Kyoto)
   hep-ph/0101200

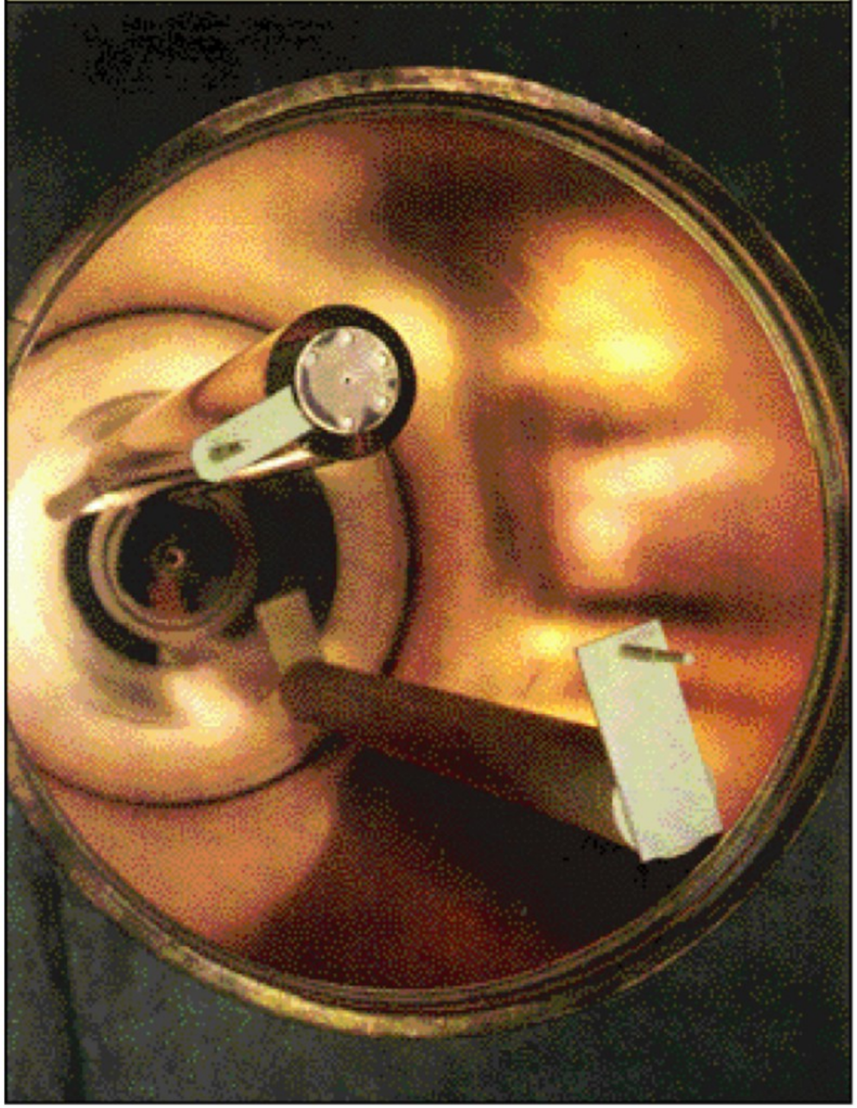
5. ADMX (US) foreseen
   RMP 75 (2003) 777

6. New CARRACK (Kyoto)
   K.Imai (Panic 2008)

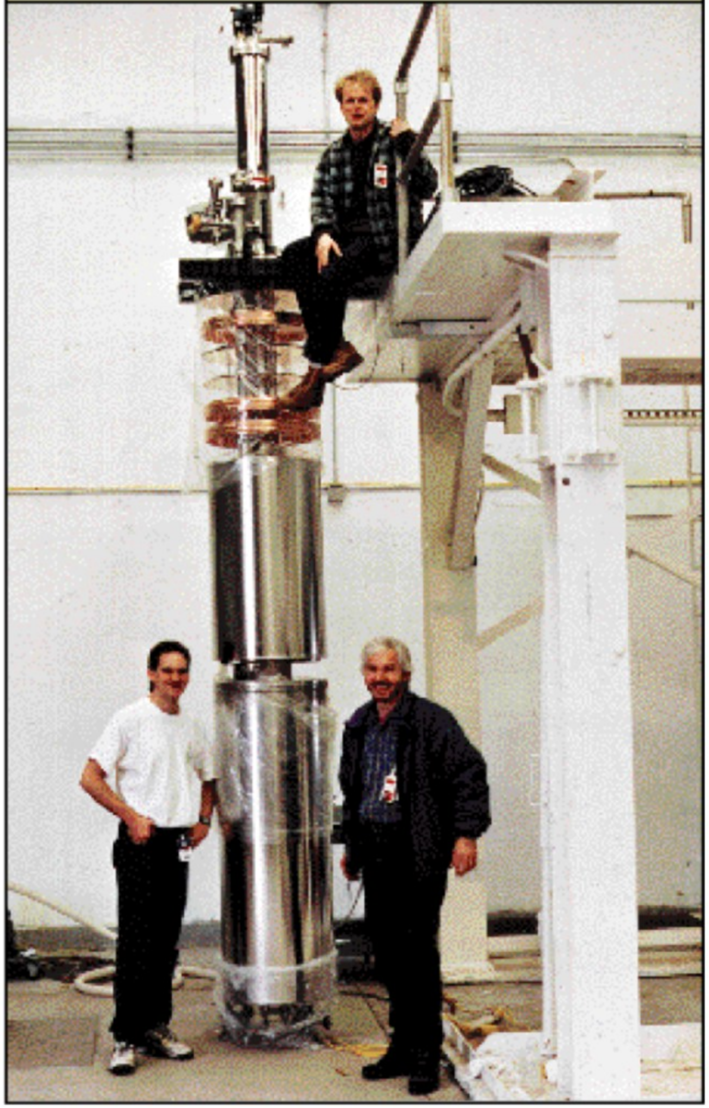
Axion hardware (cont'd)

ADMX

High-Q Cavity (~200,000)



Experimental Insert

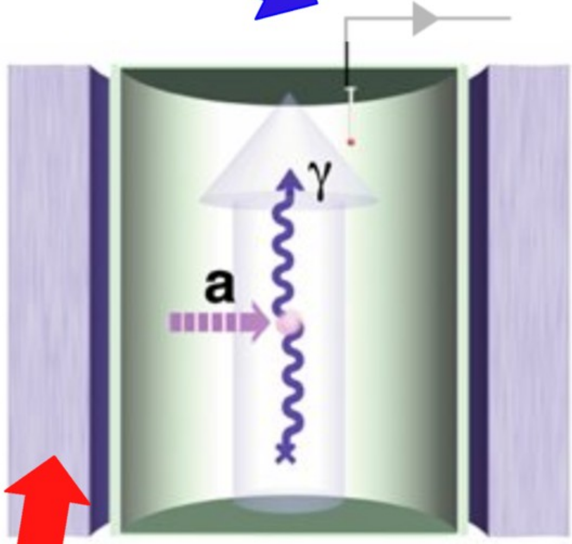


The radiometer eqn.* dictates the strategy

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

But integration time limited to ~ 100 sec

* *Dicke, 1946*



System noise temp. now

$T_S = T + T_N$ ~ 1.5 + 1.5 K

But T_{Quant} ~ 30 mK

INVEST HERE!

$$P_{sig} \sim (B^2V\ Q_{cav})(g^2 m_a \rho_a)$$

$$\sim 10^{-22} \text{ watts}$$

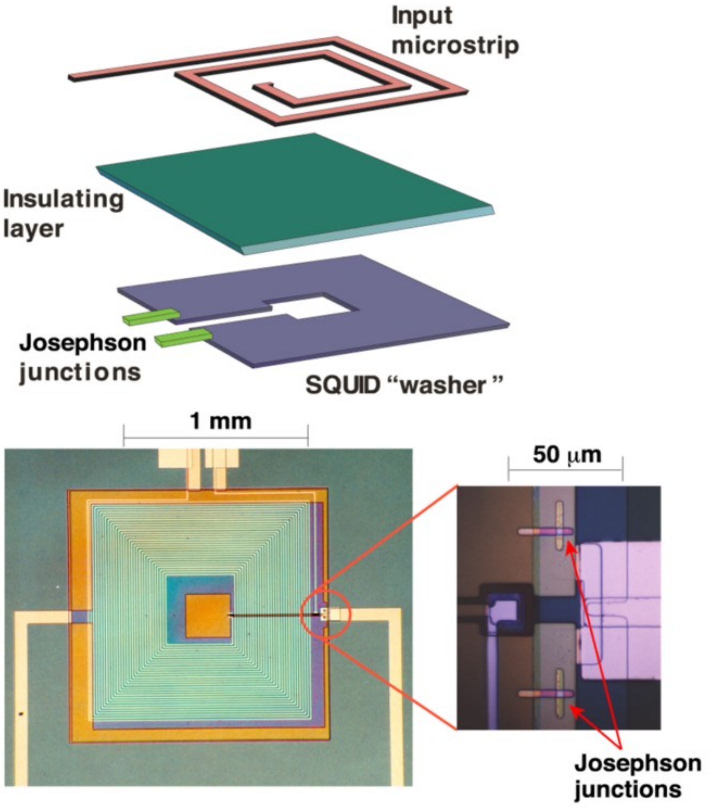
But magnet size, strength B^2V ~ $

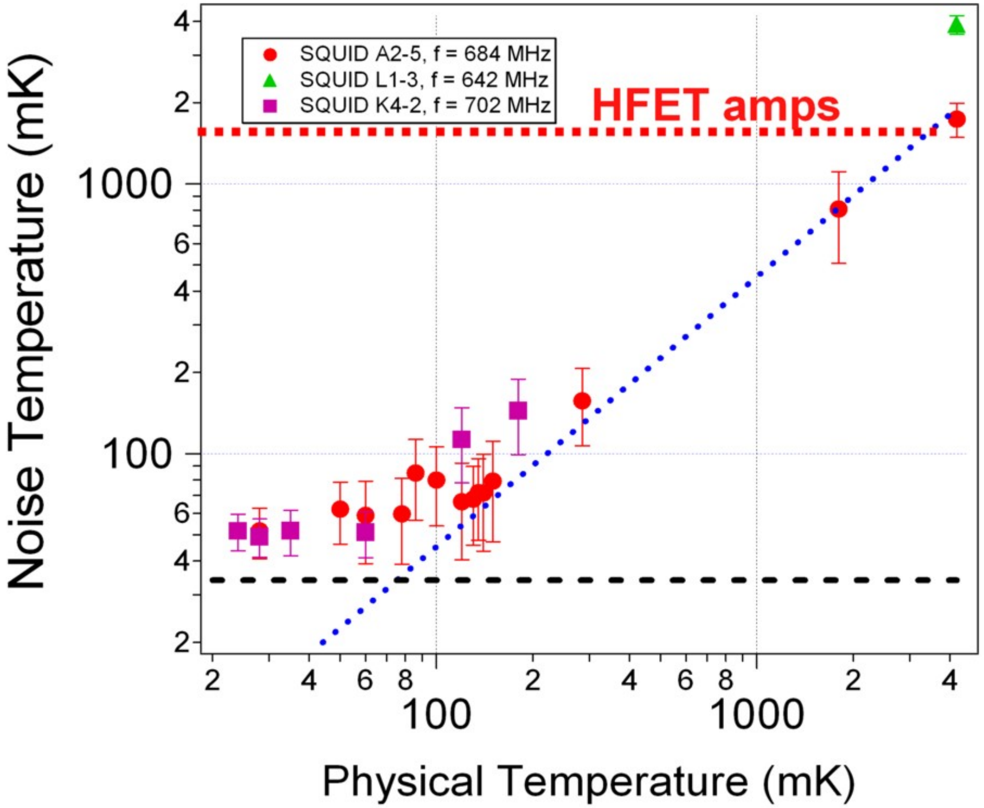
The enabling technology – GHz SQUID amplifiers*

Presently the noise temperature of our HFET amps is ~ 1.5K

But the quantum limit at 1 GHz is ~ 50 mK

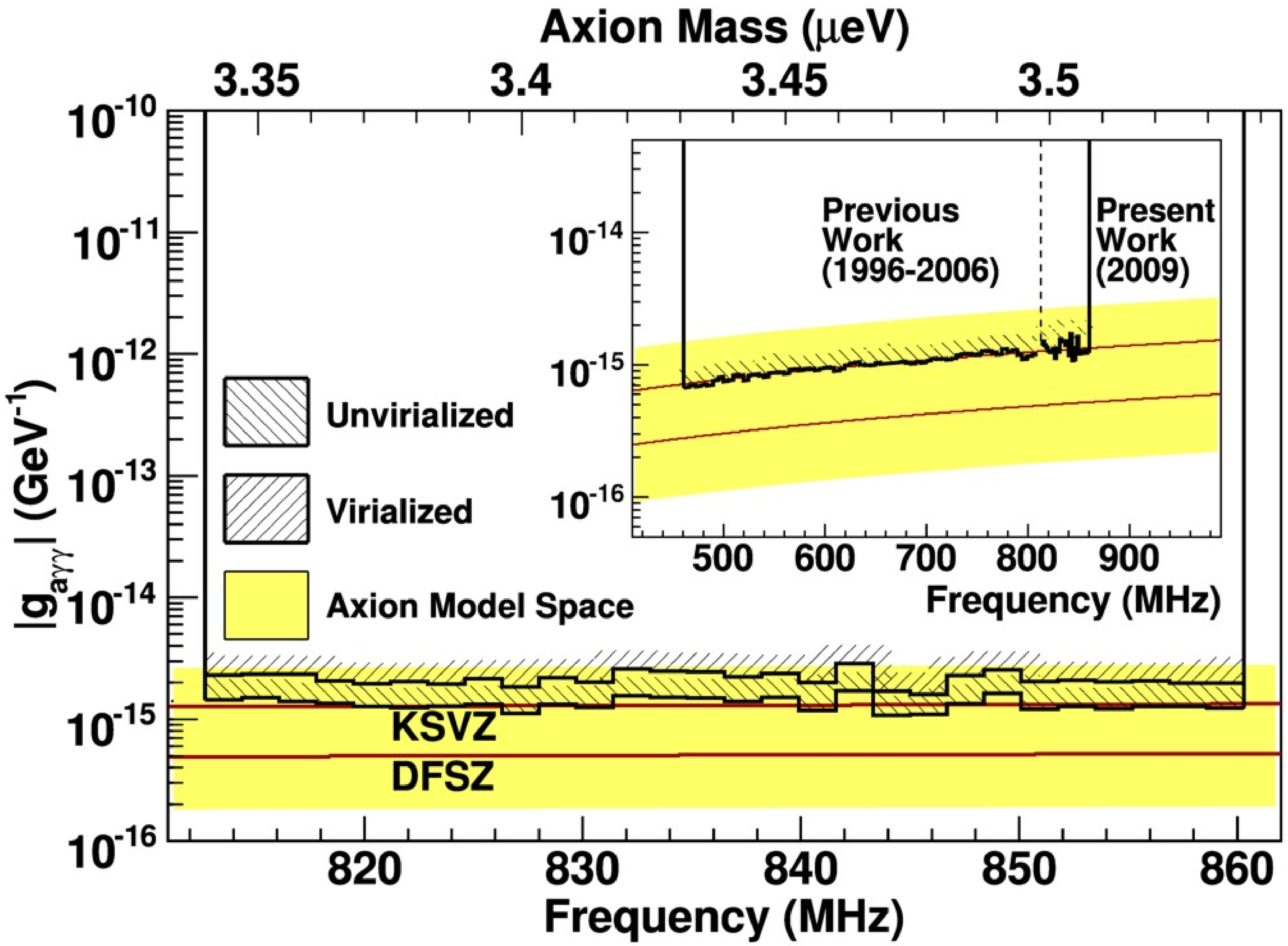
*Prof. John Clark and Dr. Darin Kinion (UC Berkeley)





Our latest SQUIDs are now within 15% of the Standard Quantum Limit

First ADMX Results using SQUID Amplifiers



Asztalos et al. (ADMX Collaboration), 30 Oct 2009, arXiv:0910.5914

CARRACK 華洛

- Cosmic Axion Research with Rydberg Atoms in Cavities in Kyoto

T. Arai, A. Fukuda, H. Funahashi#, T. Haseyama, S.Ikeda, K. Imai, Y. Isozumi, T. Kato, Y. Kido$,

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

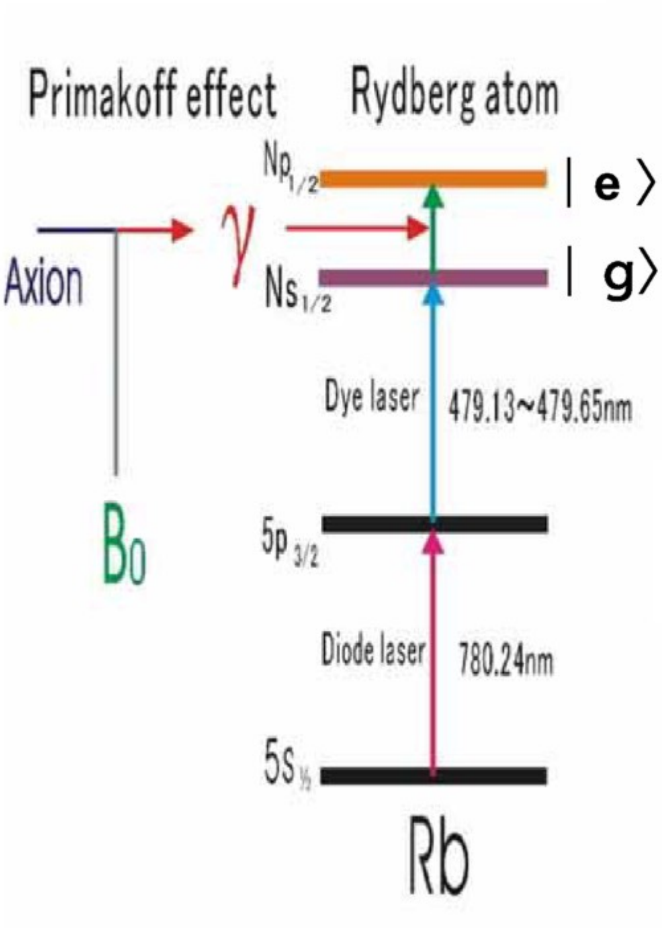
and K. Yamamoto

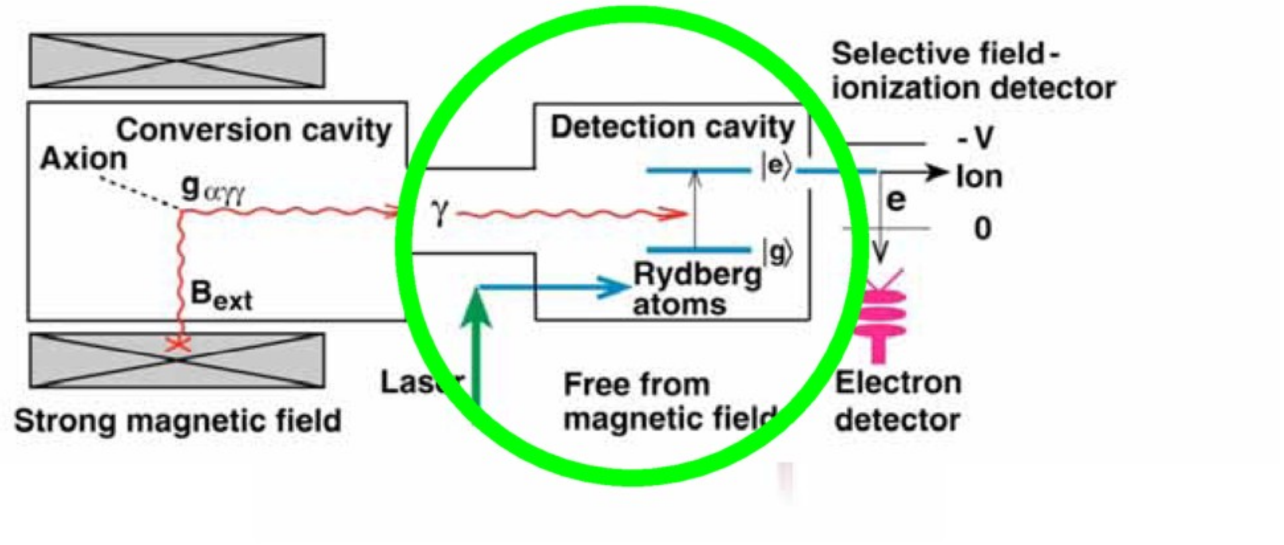
Kyoto Univ.

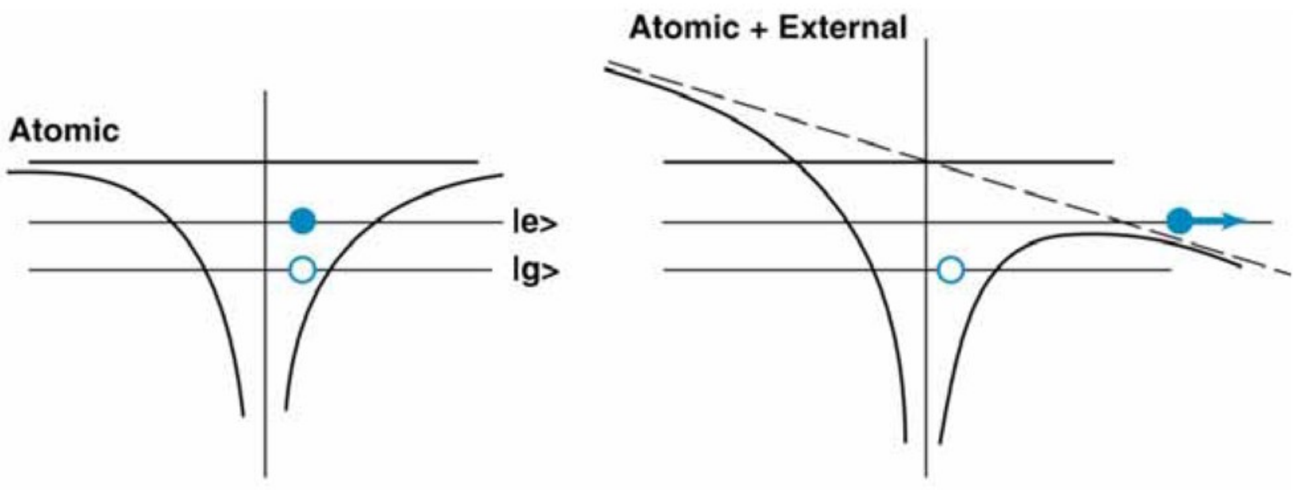
Osaka Electro-comunication Univ.

$ Ritsumeikan Univ.

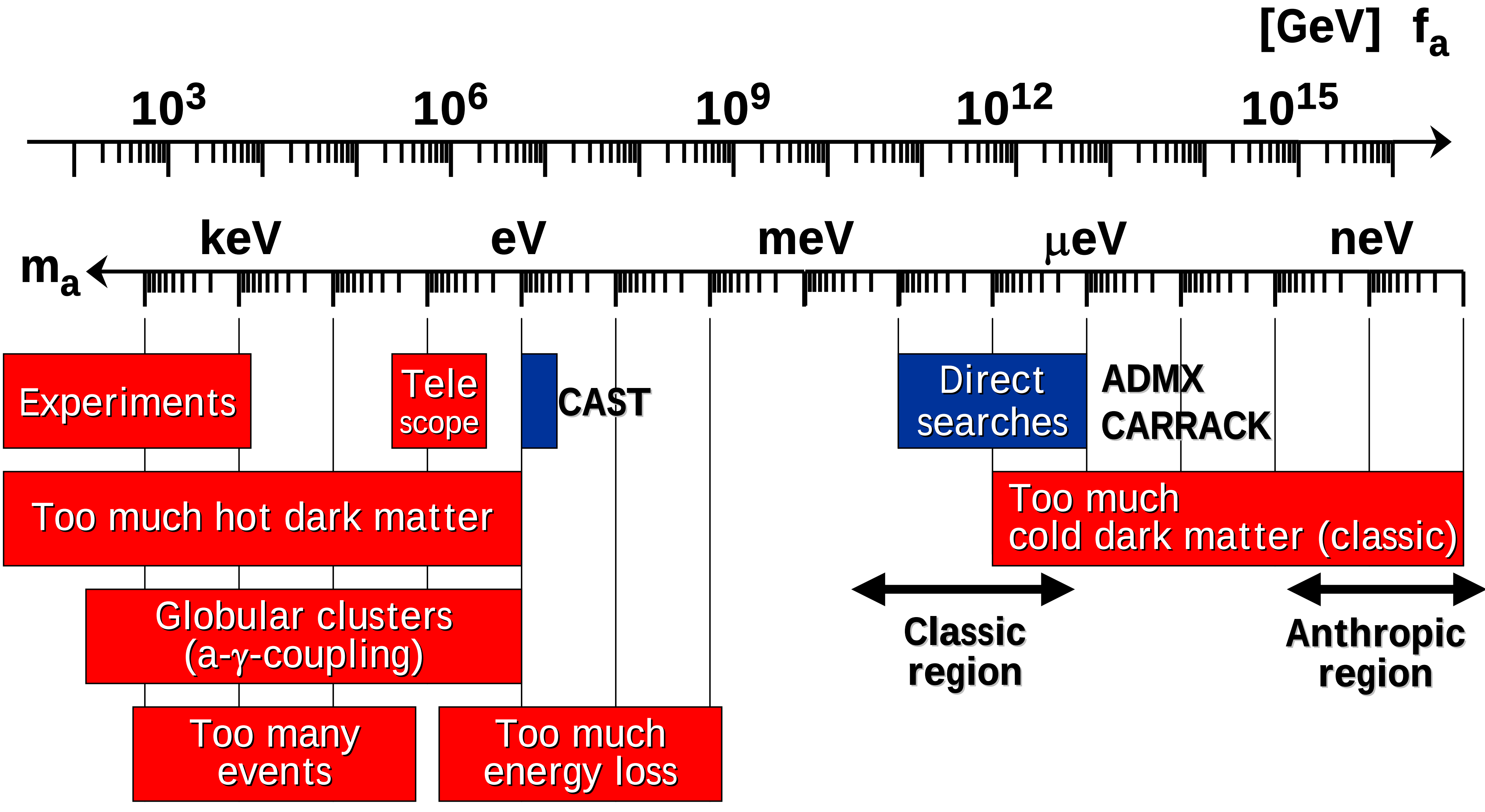
New CARRACK (Kyoto)







Axion Bounds and Searches



Experiments

Tele scope

CAST

Direct searches

ADMX

CARRACK

Too much hot dark matter

Too much cold dark matter (classic)

Globular clusters (a-γ-coupling)

Classic region

Anthropic region

Too many events

Too much energy loss

SN 1987A (a-N-coupling)

Summary

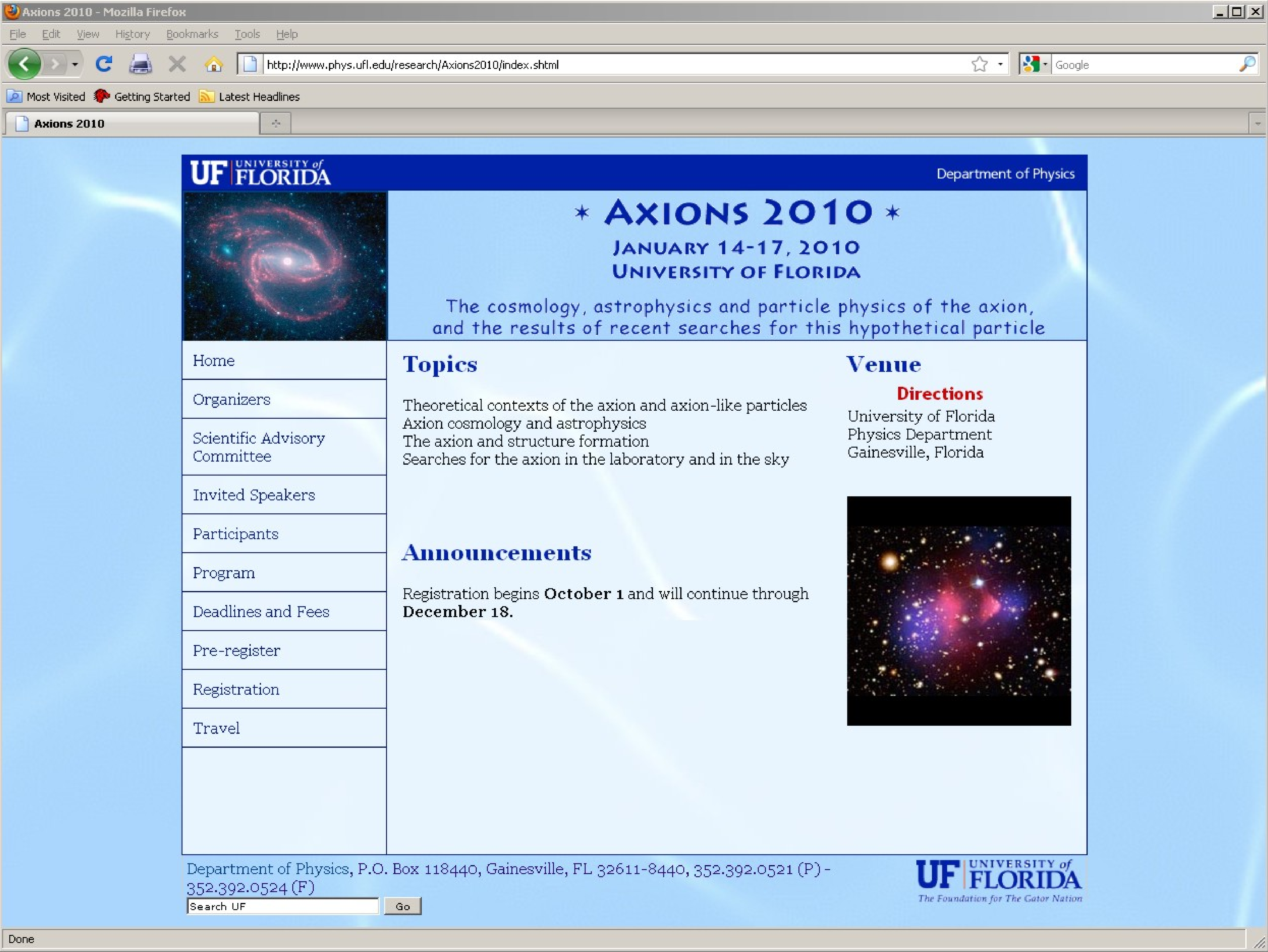
Peccei-Quinn dynamical CP symmetry restoration is better motivated than ever

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

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

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

Experimental approach in “anthropic window” ($m_a \lesssim$ neV) is missing



✶ AXIONS 2010 ✶

JANUARY 14-17, 2010
UNIVERSITY OF FLORIDA

The cosmology, astrophysics and particle physics of the axion, and the results of recent searches for this hypothetical particle

Topics

Theoretical contexts of the axion and axion-like particles
Axion cosmology and astrophysics
The axion and structure formation
Searches for the axion in the laboratory and in the sky

Announcements

Registration begins **October 1** and will continue through **December 18.**

Venue

Directions

University of Florida
Physics Department
Gainesville, Florida

Department of Physics, P.O. Box 118440, Gainesville, FL 32611-8440, 352.392.0521 (P) - 352.392.0524 (F)