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Axions

Motivation, Cosmological Role and Experimental Searches

IPMU Colloquium, 10 June 2009, Tokyo

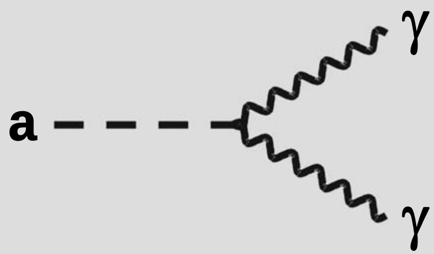
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ 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

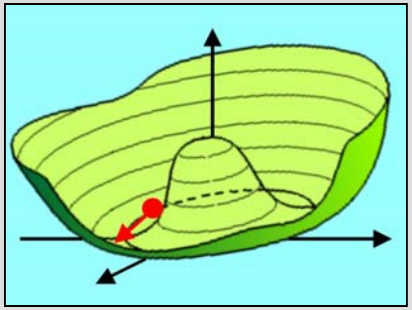
Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

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

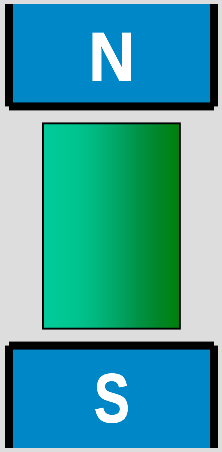
Cosmology

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

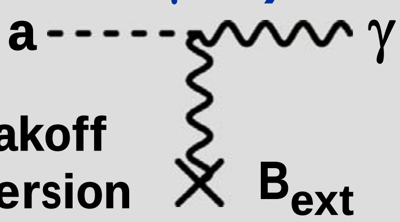


Cold dark matter candidate
$m_a \sim \mu eV$ or even smaller

Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



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

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

Cabbibo-Kobayashi-Maskawa (CKM) Matrix

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

$$\frac{g}{\sqrt{2}}\overline{\psi}_{uL}\gamma^{\mu}V_{CKM}\psi_{dL}W_{\mu}^{+}+\text{h.c.}$$

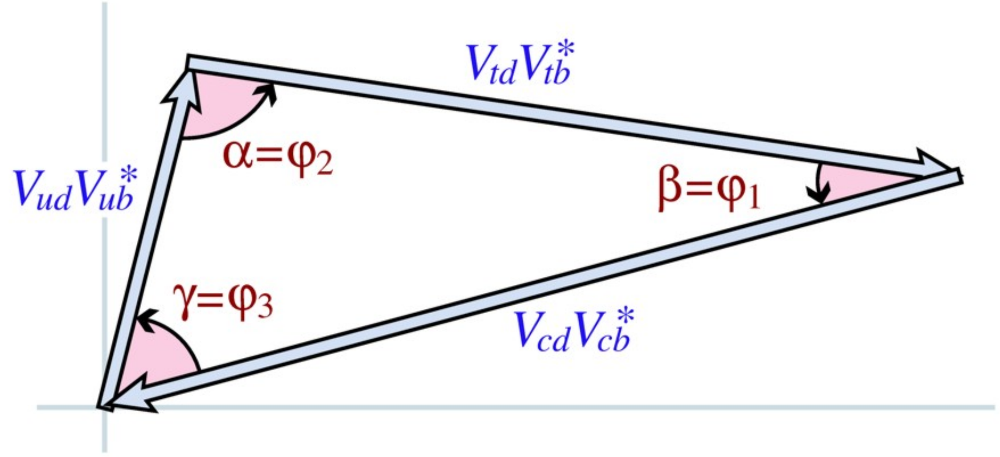
$$\psi_u=(u,c,t)\qquad \psi_d=(d,s,b)$$

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

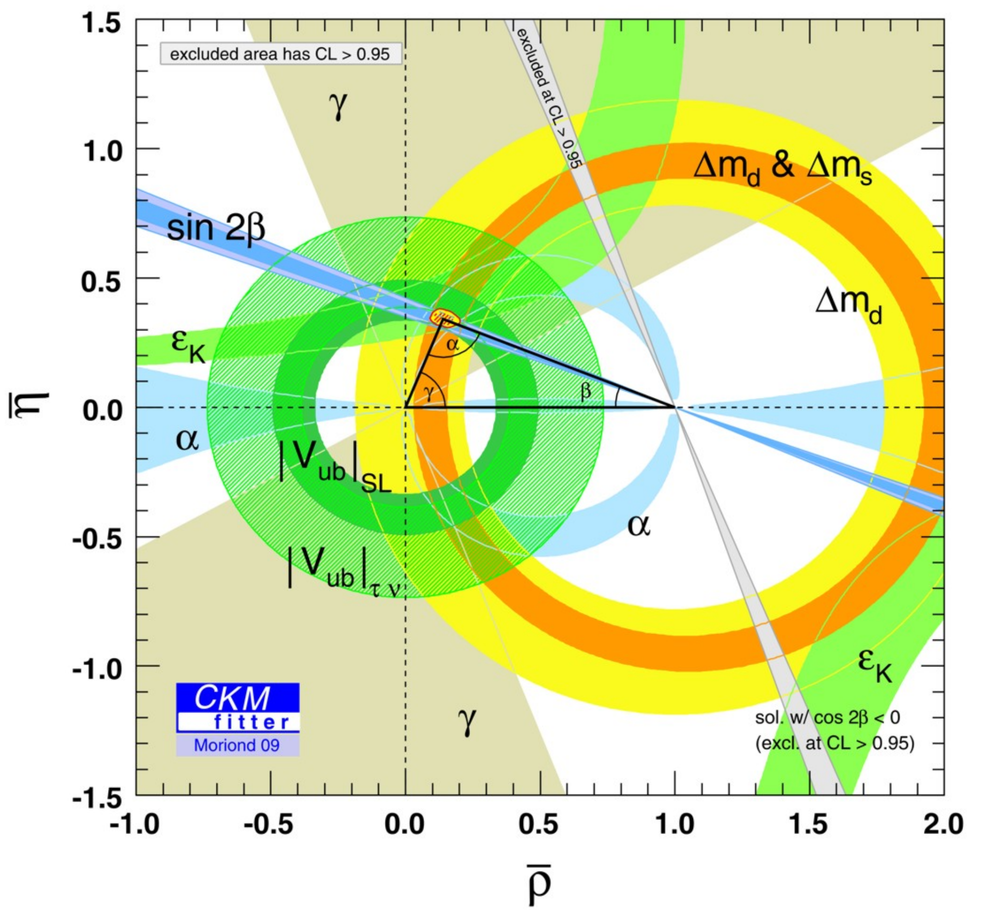
$$V_{CKM}=\begin{pmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{pmatrix}$$

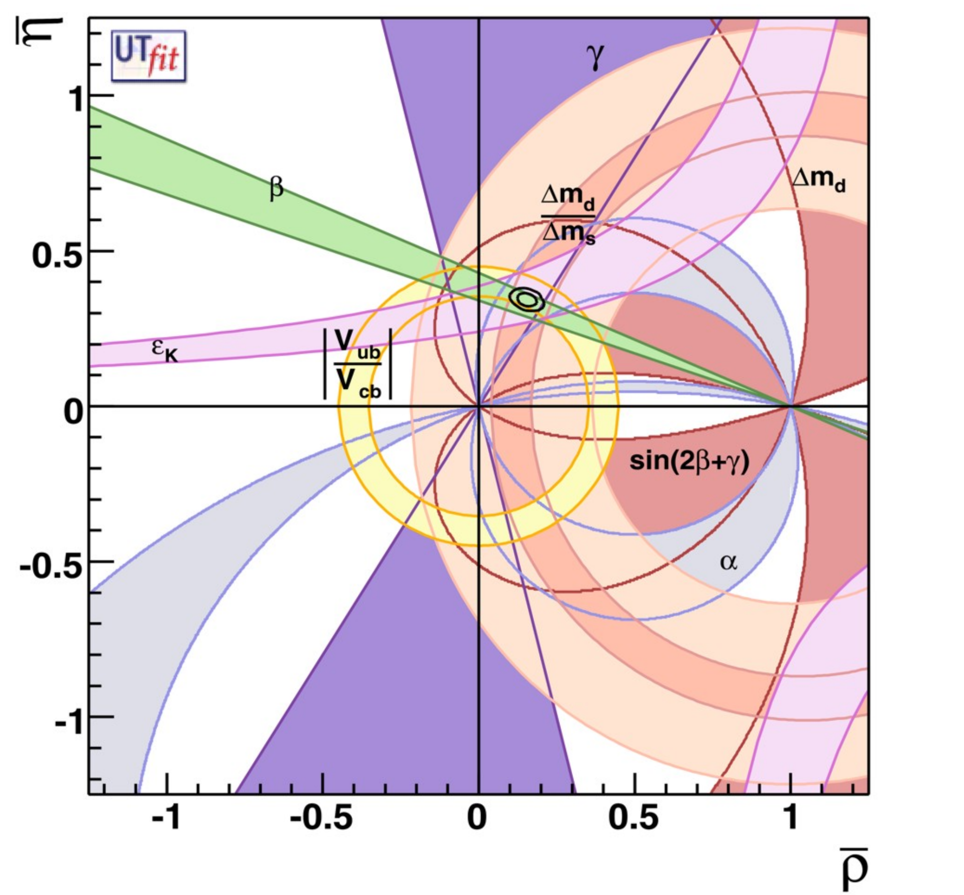
V_{CKM} depends on three mixing angles and one phase δ, explaining all observed CP-violation

Precision tests use “unitarity triangles” consisting of products of measured components of V_{CKM}, for example:



Measurements of CKM Unitarity Triangle





CKMfitter Group
http://ckmfitter.in2p3.fr

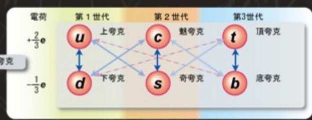
UTfit Collaboration
http://www.utfit.org

2008 年諾貝爾物理獎！小林益川理論是什麼？

Q 夸克是什麼呢？

原子核是由質子和中子所構成，而質子和中子由「更小的粒子」所組成，而這個「更小的粒子」，就是我們現在所說的「基本粒子」。如圖一，質子內部是由上夸克 (u) 和下夸克 (d) 所組成。以目前的了解，除了上夸克和下夸克之外，還有其他四種夸克存在，總共有六種夸克。而這六種夸克，依據它們所帶的電荷量和「世代」，我們將它們進行分組，如圖二。

圖一



圖二

Q 反粒子是什麼呢？

夸克和電子都是基本粒子，他們的反粒子也對應的存在著。粒子和反粒子所帶的電荷相反，質量相同。例如，電子帶負電，而電子的反粒子（正電子）帶正電。基本粒子和其反粒子是成對被生成：當兩者相遇時又會變成能量而消失。我們已知的六種夸克各自存在其反粒子。介子是由一個夸克和一個反夸克所組成。電荷宇稱對稱性破壞的研究，就是針對介子衰變的研究。K 介子和 B 介子的內部組成，如圖三。

圖三

Q 電荷宇稱對稱性破壞是什麼呢？為什麼重要呢？

電荷宇稱對稱的意思就是，在粒子的世界裏，粒子與其反粒子遵守相同的物理法則。1964 年，美國普林斯頓大學的克隆尼 (J.Cronin) 和費奇 (V. Fitch) 在其 K 介子的實驗中，發現了電荷宇稱對稱性破壞，震驚了物理界。原因是在 1930 年代，正電子未被發現之前，人類並不知道反粒子的存在。在我們身處的宇宙中，所見物質皆由粒子所組成，不見由反粒子所構成的物質。那麼，大爆炸之後的宇宙，數目相同的粒子和反粒子被同時生成。為什麼反粒子不見了？這個謎團要解開，最重要的關鍵在於粒子與其反粒子一定是不遵守相同的物理法則，也就是電荷宇稱對稱性破壞了。

Q 小林益川理論是什麼呢？

1973 年，小林和益川兩位博士提出 3 個世代以及 6 種夸克的理論。這是他們針對 K 介子的電荷宇稱對稱性破壞實驗結果，所想出的夸克跨世代衰變的想法。那個時代所提出的夸克種類只有 3 種 (u,d,s)，再加入 3 種未知夸克的想法很新穎。然而，1974 年發現魅夸克 (c)，1977 年發現底夸克 (b)，1995 年發現頂夸克 (t)，證明了 6 種類的夸克的確存在。因此兩位博士對於電荷宇稱對稱性破壞的解釋，受到重視。檢驗含有底夸克的 B 介子的衰變特性，變成這個世界必做的實驗。

Q 為什麼夸克一定是六種呢？

如果只有 3 種或是 5 種夸克，同一種夸克的電荷轉移太過頻繁，與實驗結果不符。若是只有 2 個世代 4 種夸克，變數的數目不夠多，無法解釋電荷宇稱對稱性破壞。因此，使用複數做為相位差的變數，就解決了變數不足的問題了。所以，小林與益川博士才提出至少 6 種夸克的理論。

小林益川的理論
B 工廠的實驗數據支持

等待了許久 B 工廠實驗結果終於證實了小林益川理論！

Q 為什麼我們知道小林益川理論是正確的呢？

所有的理論都得用實驗的結果來證實。隨著加速器技術不斷的進步，人類一直到 1994 年才把六種夸克全部找出來。之後，科學家們在日本和美國各建造了一座 B 工廠。直到 2001 年從 B 工廠獲得數千萬個 B 介子事件，才得以進行觀測，並且進而發現了 B 介子的電荷宇稱對稱性破壞。從小林益川理論提出開始，到做出實驗數據證實，約花了三十年的時間。

Q B 工廠是什麼呢？

B 工廠就是大量產生 B 介子的地方。換句話說，就是可以用來測量電荷宇稱對稱性是否破壞的實驗設備。1980 年，小林益川理論預言，B 介子衰變存在著不小的電荷宇稱對稱性破壞。不過，必須要比以往多出一百倍以上的 B 介子事件數，才能驗證這個預言。於是從 1994 年到 1999 年，高能加速器研究機構 (KEK) 和美國的史丹福線型加速器中心 (SLAC)，動工興建 B 工廠。

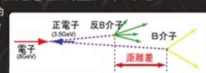
Q KEK 的 B 工廠，請更詳細具體的描述。

KEK 的 B 工廠，是一個圓周長 3 公里的加速器 (KEKB) 和一個直徑約 8 公尺、重量約 1400 公噸的 Belle 偵測器。KEKB 加速器裏面有 8GeV 的電子與 3.5GeV 的正電子進行正面的高速對撞。撞了之後，產生了 B 介子與反 B 介子，我們稱之為 B 介子對。B 介子對被生成的頻率為每秒 18 回，是美國史丹福大學的加速器 (SLAC, PEP-II) 的 1.5 倍。由此看來，KEKB 加速器可以列入世界上最優秀的加速器之一。至於研究 B 介子的性能，就是 Belle 偵測器的工作。Belle 偵測器的內部，具有可以精確的測量出粒子的位置、時間、能量等功能：精密的感測器至少有二十萬個：約 360 名的研究人員進行設計與製作，並且分析從感測器測量到的龐大數據資料。這些數據的容量大小超過 100 萬 GB。

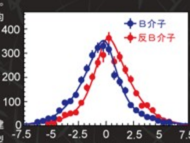
本海報是為了紀念小林老師與益川老師獲得諾貝爾獎以及解釋 B 工廠實驗在其中所扮演的角色，而由 Belle 小組所製作的。以上這些圖文解釋，都是為了說明為什麼 B 工廠實驗的報告，是小林老師與益川老師長期等待的結果。

Q 電荷宇稱破壞是怎麼測量出來的呢？

從 KEKB 產生的 B 介子與反 B 介子，會沿著電子束前進的方向飛行，此時 b 夸克若改變成 c、s、u、d 夸克，就稱為「衰變」。發生衰變所需要的平均時間為 1.5 ps（一兆分之 1.5 秒，非常短的時間，所以從被產生到衰變發生時，B 介子對所走的距離約為 0.2 mm，如圖四。我們重建某一種 B 介子衰變的型態和同時伴隨的反 B 介子衰變，測量兩者衰變的時間差，藉以推算衰變位置的距離差，做出來的分布圖，如圖五（藍色點代表 B 介子的時間差，紅色點代表反 B 介子的時間差）。如果電荷宇稱對稱性守恆的話，藍色點與紅色點會重疊：可是實驗結果顯示兩者有差異，證明了 B 介子的電荷宇稱對稱性不守恆。



圖四



圖五

Q 小林益川理論可以說明世界上一切的現象嗎？

很抱歉，不可以。基本粒子物理學裏面未知的東西還很多呢，我們還需要很努力的再接再厲做研究。現在日本不僅在傳統的理論或是現在的實驗，都可以到達世界第一的水準，例如 B 工廠和超級神岡探測器的實驗 (Super-Kamiokande)。小林益川理論所突破的，是解釋了 137 億年前宇宙創立之初，由於非常大的電荷宇稱對稱性破壞，造成了現在只有物質存在的狀況。超級 KEKB 加速器／超級 Belle 實驗計畫正在提案中，請大家一起加入我們的行列吧。

Q 在一個大的研究團隊裏，個人有機會發揮所長嗎？

大的加速器跟所有的實驗裝置一樣，都是靠人類的智慧去完成的。就算每一個人都只是擔任整個運作環節的一小部分，可是得以和大家一起思考「宇宙到底是遵守怎麼樣的法則」，不也是挺有趣嗎？在大團隊裏，其實有很多的機會讓個人展現其能力和創造力，如果每個人都不努力，實驗也不會成功，不是嗎？

參加 B 工廠實驗的研究教育機關

ブドカー研究所　チェンナイ数理科学研　千葉大学
チョンナム大学　シンシナチ大学　イーファ女子大学
ギーセン大学　ギョンサン大学　ハワイ大学
広島工業大学　北京·高能研
モスクワ·高エネルギー研　モスクワ·理論実験物理研
カールスルーエ大学　神奈川大学　コリア大学
クラコウ原子核研　京都大学　キュンポック大学
ローザンヌ大学　マックスプランク研究所
ヨセフステファン研究所　メルボルン大学

名古屋大学　奈良女子大学　台湾·中央大学
台湾·聯合大学　台湾大学　台湾·輔仁大学
日本歯科大学　新潟大学
ノバ·ゴリカ 科学技術学校　大阪大学　大阪市立大学

パンジャブ大学　北京大学　ピッツバーグ大学
プリンストン大学　理化学研究所　佐賀大学
中国科学技術大学　ソウル大学　信州大学
サンキュンカン大学　シドニー大学　首都大学東京
タタ研究所　東邦大学　東北大学　東北学院大学
東京大学　東京工業大学　東京農工大学
トリノ·核物理研　富山商船高等専門学校
ウェイン大学　ウィーン高エネルギー研
バージニア工科大学　延世大学

Belle Group http://belle.kek.jp
高能加速器研究機構 http://www.kek.jp
KEKB Group http://kekb.jp

Poster Designed by T. Iijima, Y. Iwasaki, S. Kataoka, N. Katayama, K. Miyabayashi
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The CP Problem of Strong Interactions

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

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

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

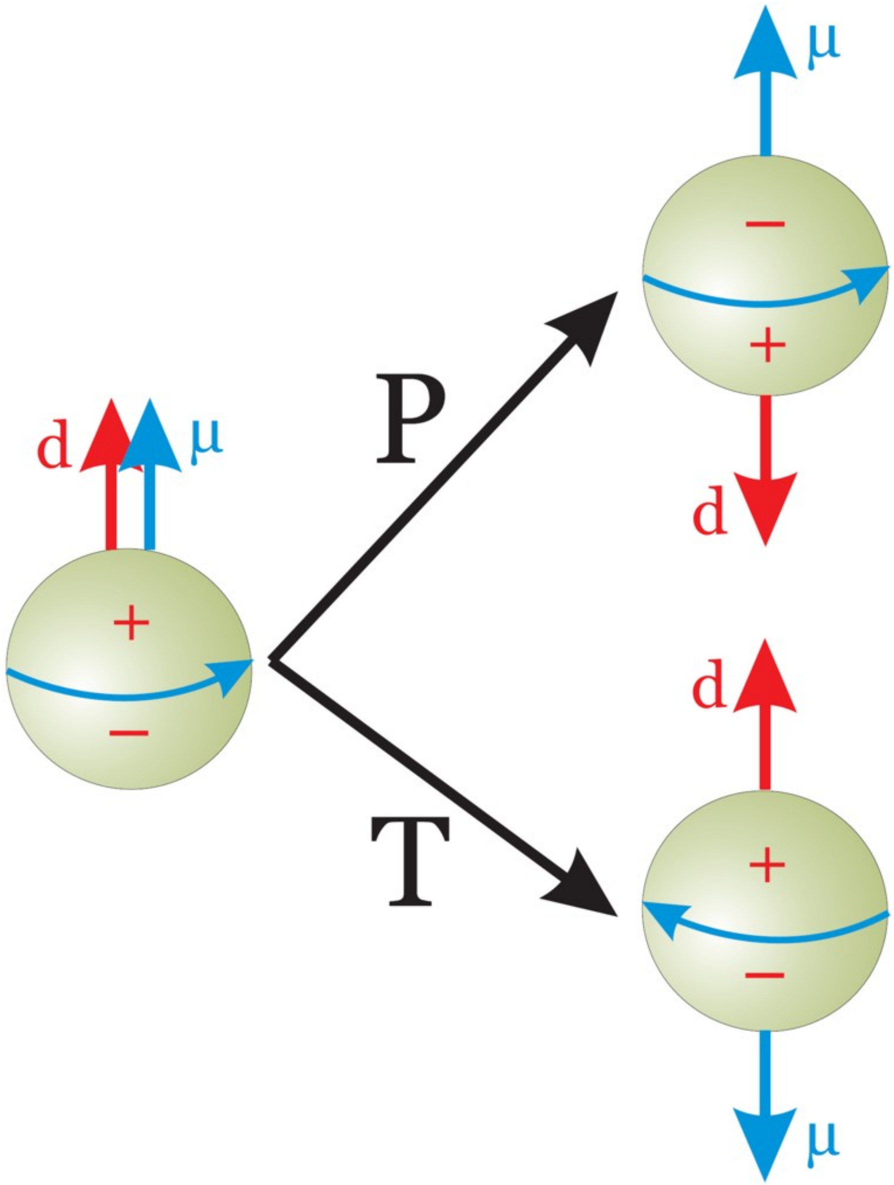
$$\psi_q \to e^{-i\gamma_5 \theta_q / 2} \psi_q$$

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

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

Experimental limits: $|\overline{\Theta}| < 10^{-10}$ **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 Solution

Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978

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

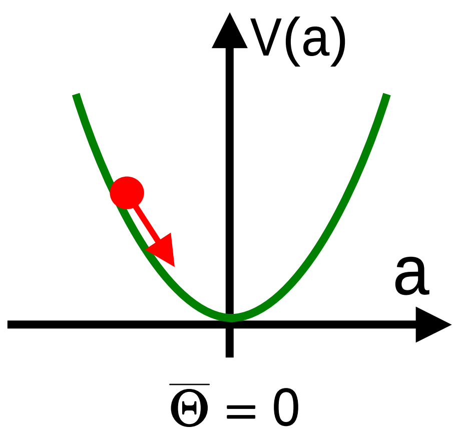
$$L_{CP} = -\frac{\alpha_s}{8\pi}\,\overline{\Theta}\,\mathrm{Tr}(G\tilde{G}) \rightarrow -\frac{\alpha_s}{8\pi}\,\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$

$a(x)$ 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 $a(x)$**

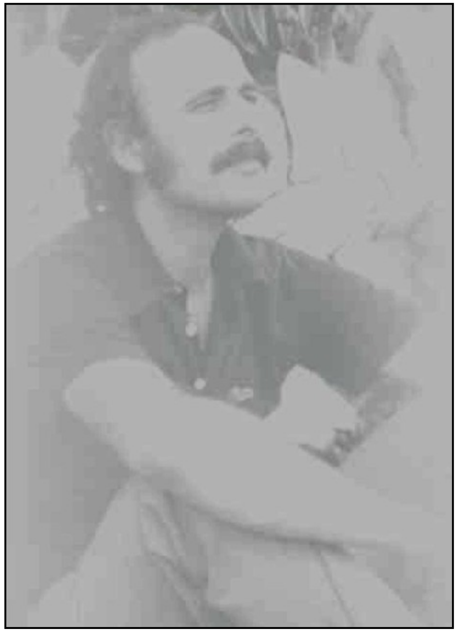
$$m_a f_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\, m_\pi f_\pi \qquad \begin{pmatrix}\text{Axion mass} \\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass} \\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

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



CP-symmetry dynamically restored

Peccei-Quinn Mechanism Proposed in 1977



VOLUME 38, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1977

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 θ choices give equivalent theories.[1,3] This is most clearly seen by remarking that a change in the

PHYSICAL REVIEW D VOLUME 16, NUMBER 6 15 SEPTEMBER 1977

Constraints imposed by *CP* conservation in the presence of pseudoparticles*

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(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.

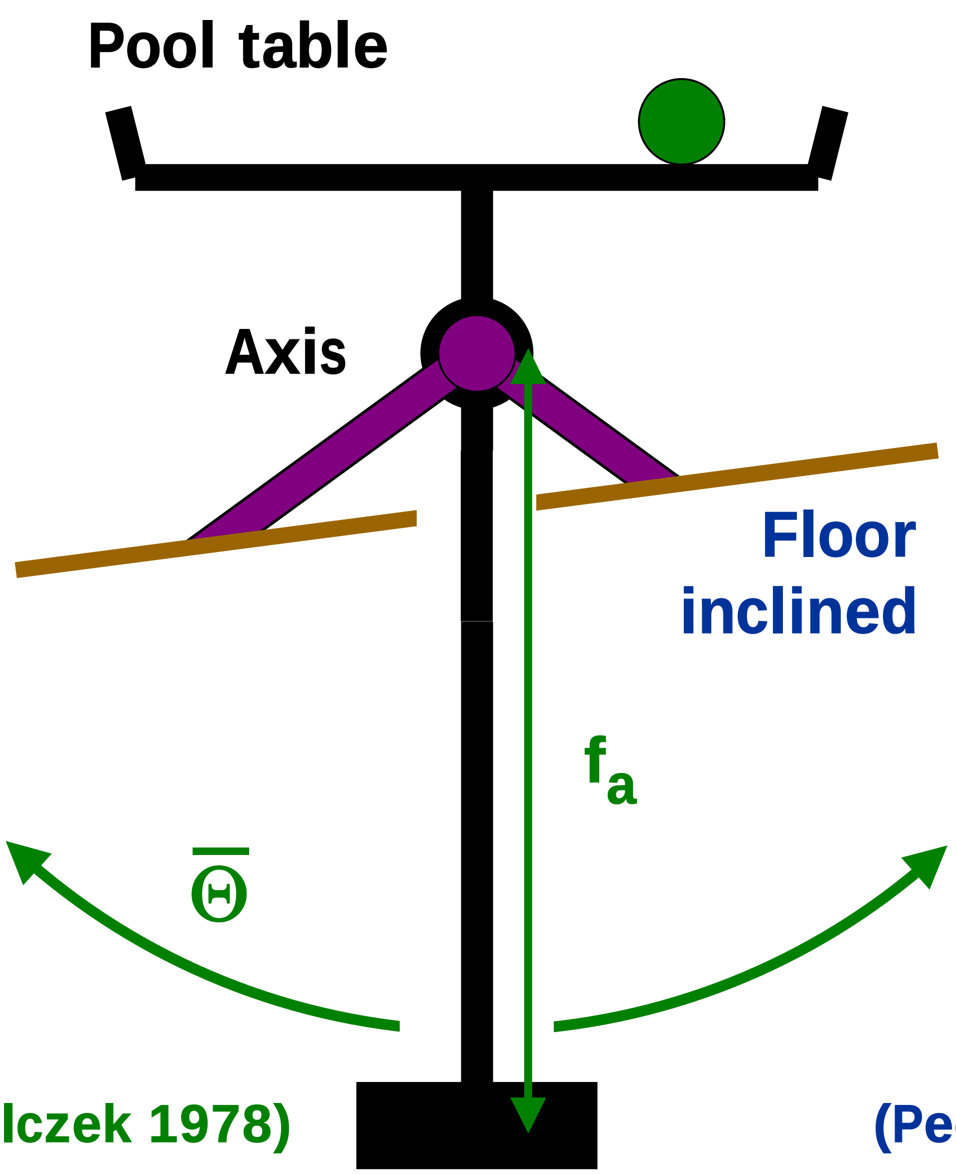
I. INTRODUCTION

In a recent letter[1] we have discussed the question of CP conservation of the strong interactions in

The appearance of this additional term shows the problem to which we address ourselves. It appears to be a P- and CP-violating term. Thus if $\mathcal{L}$ represents a non-Abelian gauge theory of the strong

The Pool Table Analogy (Pierre Sikivie 1996)

Gravity



Symmetric relative to gravity

Symmetry broken

New degree of freedom → Axion

(Weinberg 1978, Wilczek 1978)

Symmetry dynamically restored

(Peccei & Quinn 1977)

31 Years of Axions

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

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(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve 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 explanation of why C, P, T, and all quark flavors are conserved by strong interactions, and by order-α effects of weak interactions.[2] However, the discovery of quantum effects[3] associated with the "instanton" solution of QCD has raised a puz-

$\mathrm{U}(1)_{\mathrm{PQ}}$], 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 perturbation theory, and is fixed only by instanton effects which break the $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry. However, the potential will then depend on $\bar{\theta}$, but not separately on θ and $\arg\det m$, so that it is not a mir-

VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

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)

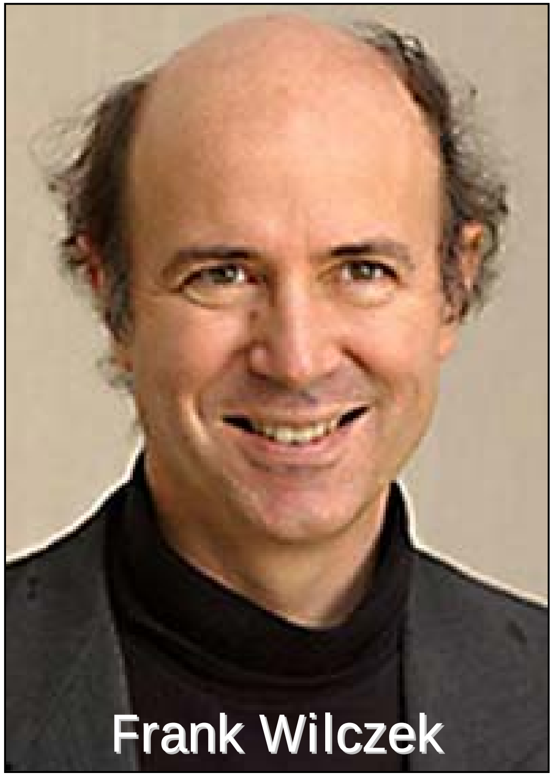
The requirement that P and T be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

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 $3 \oplus 3^*$ structure of chi-

a certain class of theories[4,5,7] the parameter θ is physically meaningless,[4,5] or dynamically determined.[7] In this case, if the strong interaction conserves P and T, we shall say the conservation is *automatic*.

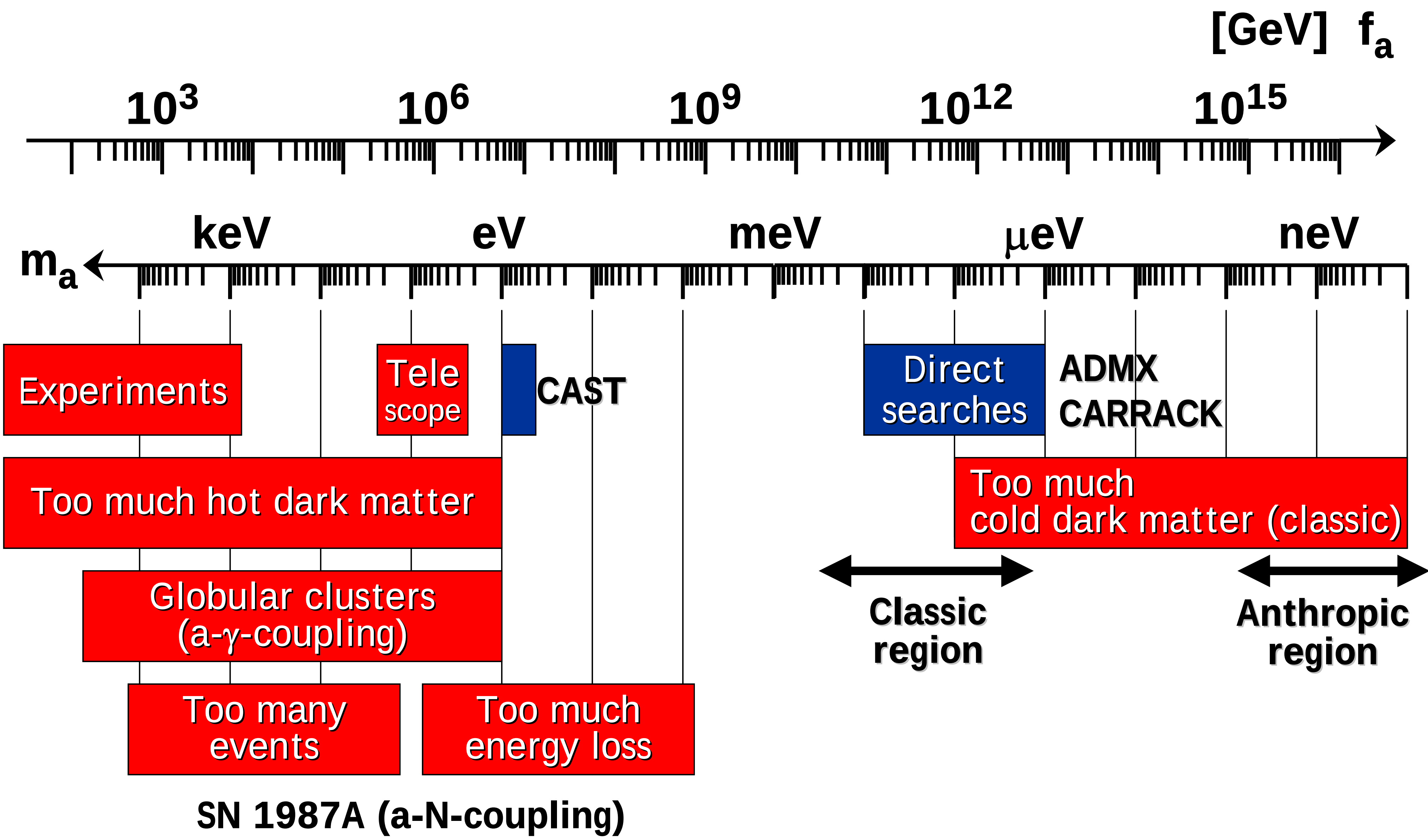
I regard a theory of type (i) as very unattrac-

The Cleansing Axion

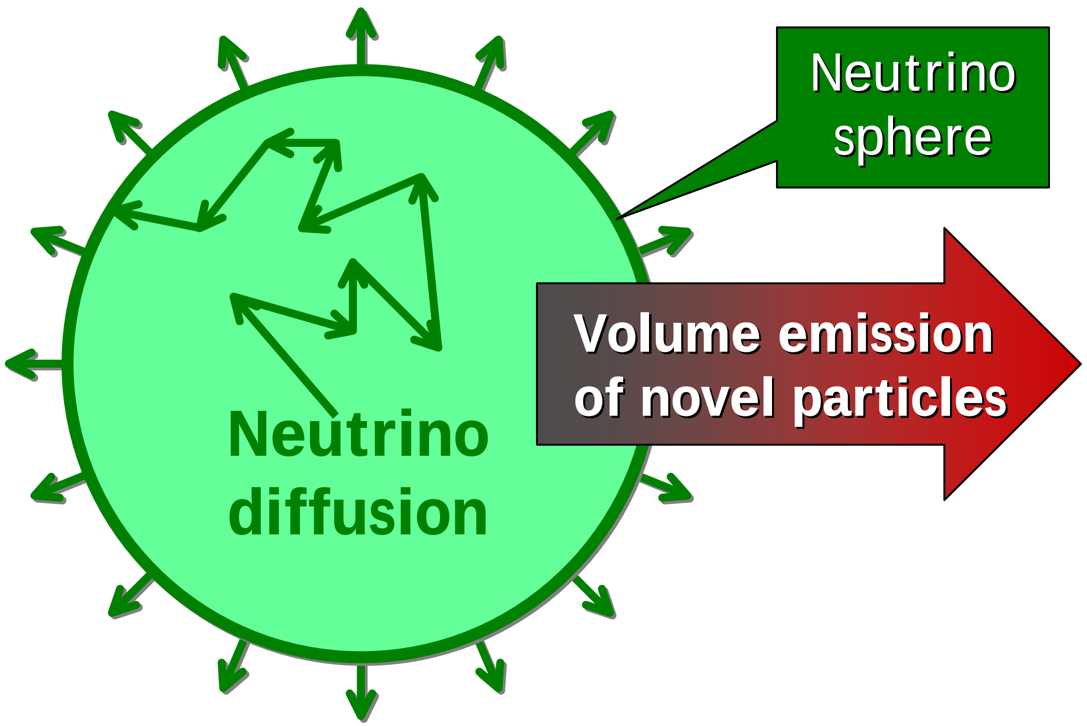


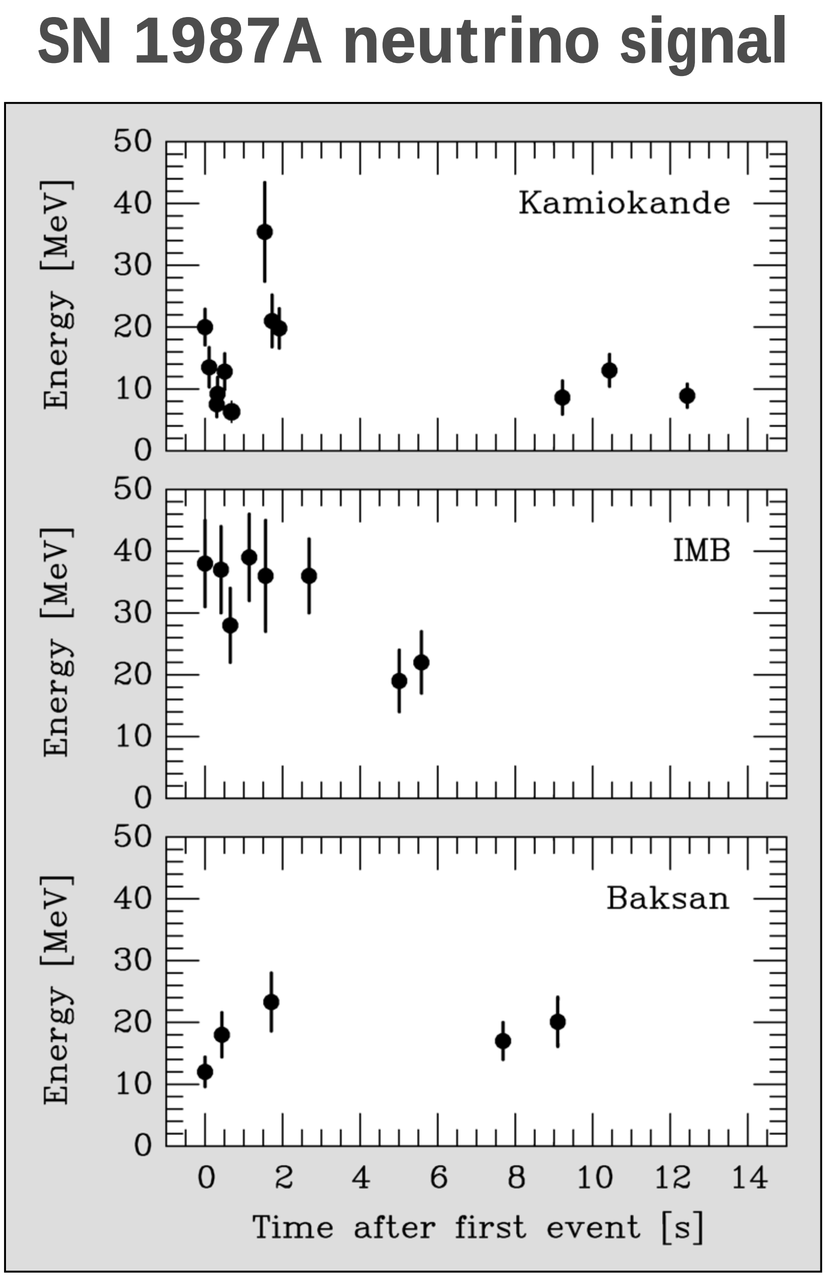
"I named them after a laundry detergent, since they clean up a problem with an axial current."
(Nobel lecture 2004 written version)

Axion Bounds



Supernova 1987A Energy-Loss Argument





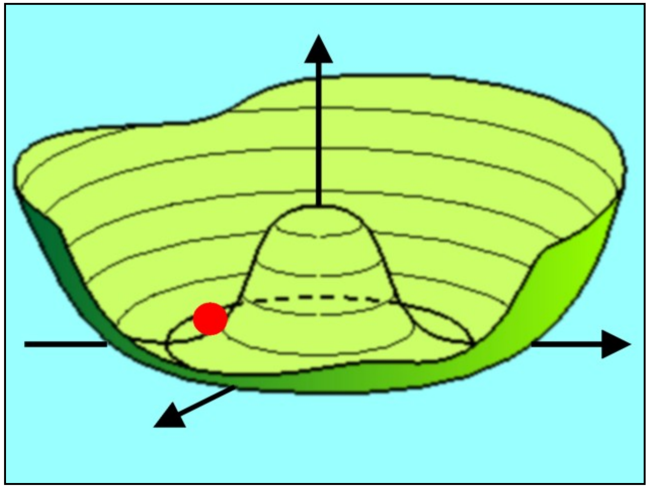
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axions as Nambu-Goldstone Bosons

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

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



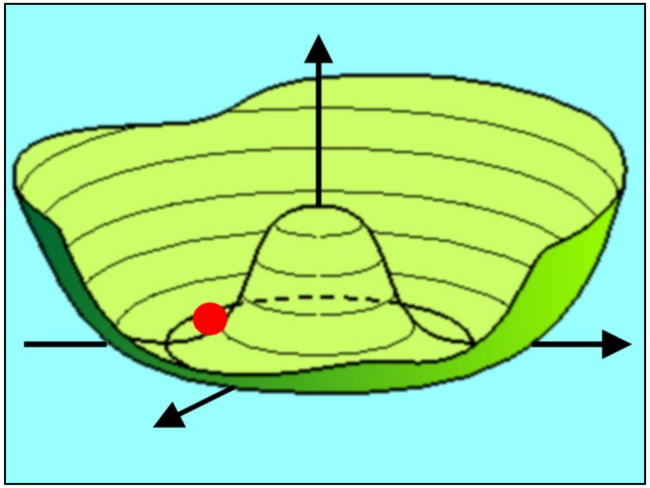
- New U(1) symmetry, spontaneously broken at a large scale f_a
- Axion is "phase" of new Higgs field: angular variable $a(x)/f_a$
- By construction couples to $G\tilde{G}$ term with strength $\alpha_s/8\pi$, e.g. triangle loop with new heavy quark (KSVZ model)
- Mixes with π^0-η-η' mesons
- Axion mass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

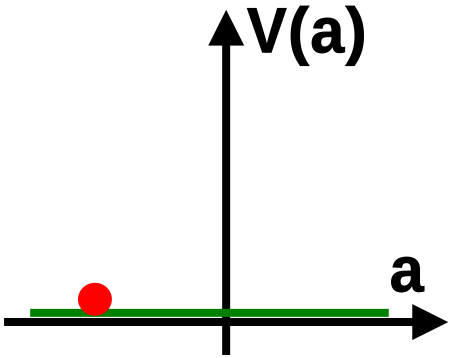
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\,\frac{m_\pi}{f_\pi f_a}$$

Creation of Cosmological Axions

$T \sim f_a$ (very early universe)

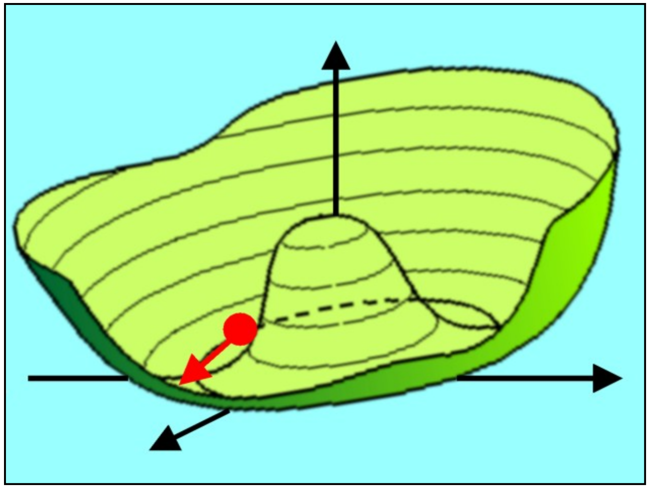
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_1 = \Theta_1 f_a$

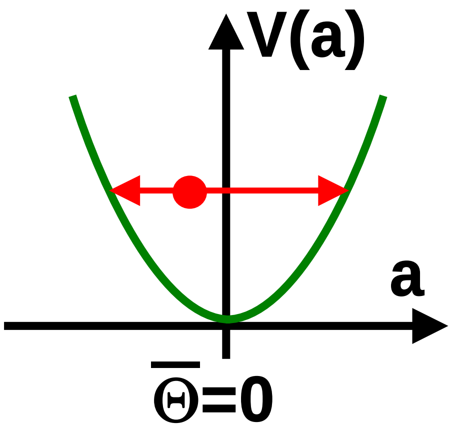




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- 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: $\rho_a = m_a n_a \propto \Theta_1^2 m_a f_a^2 \propto \Theta_1^2 \frac{m_a^2 f_a^2}{m_a} \propto \Theta_1^2 \frac{m_\pi^2 f_\pi^2}{m_a}$

Axion Cosmology in PLB 120 (1983)

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983
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COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL [1], Mark B. WISE [2]
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and

Frank WILCZEK
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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 $f_a \leqslant 10^{12}$ GeV, where f_a is the axion decay constant. If this bound is saturated, axions may comprise the dark matter of the universe.

Axion Cosmology in PLB 120 (1983)

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983
Page 133

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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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.

Axion Cosmology in PLB 120 (1983)

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983
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THE NOT-SO-HARMLESS AXION

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

and

Willy FISCHLER
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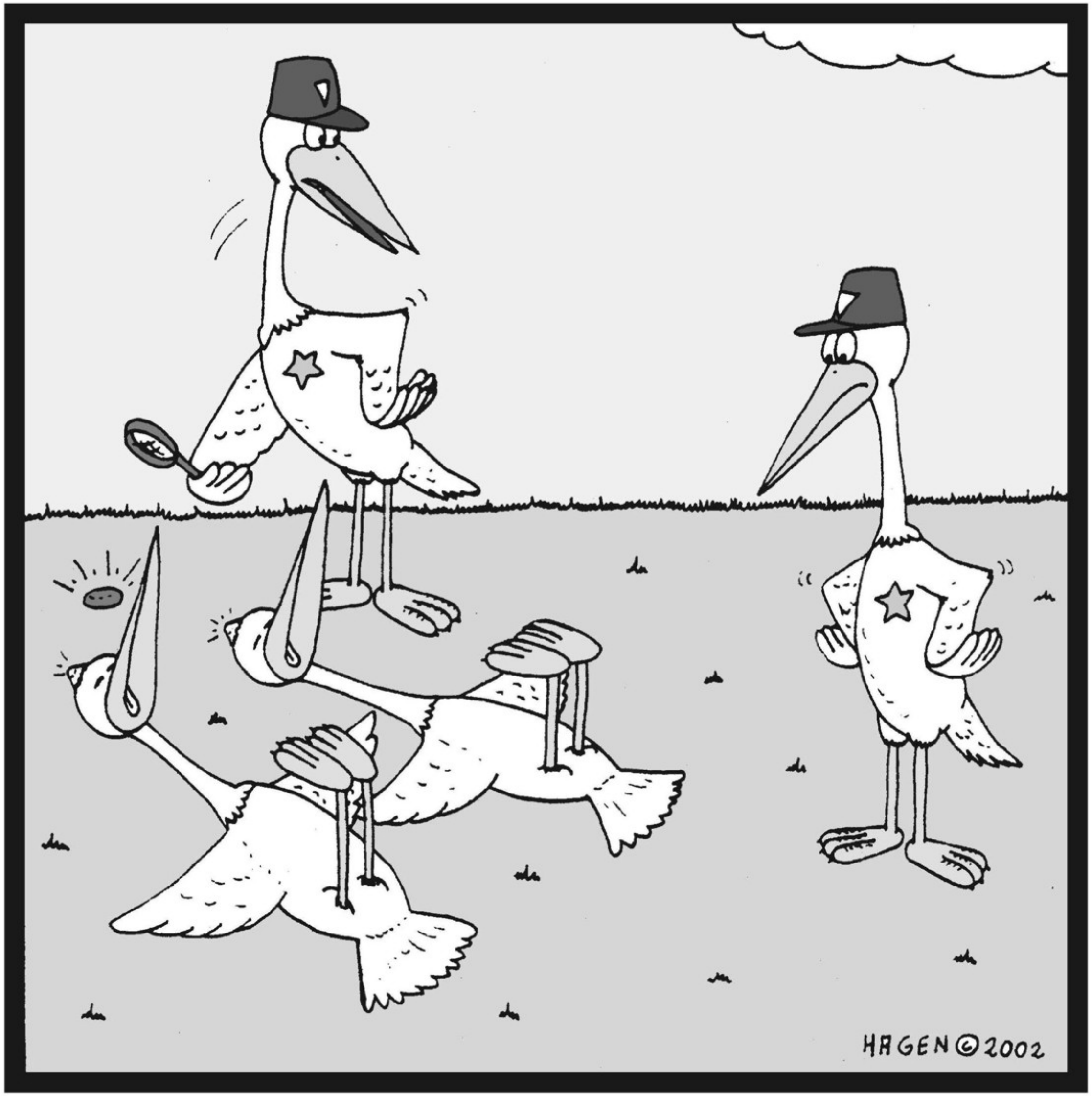
Received 17 September 1982
Received manuscript received 14 October 1982

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



Unbelievable! It looks like they've
both been killed by the same stone...

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

Cosmic Axion Density

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

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

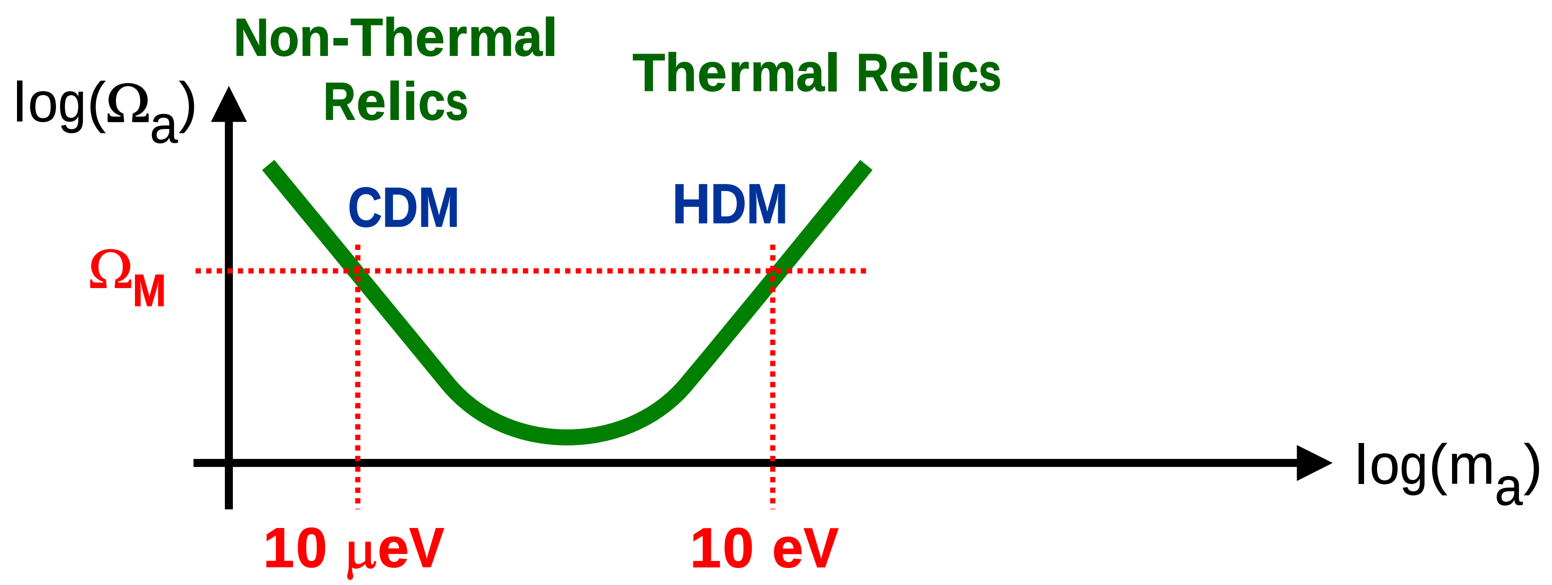
If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

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

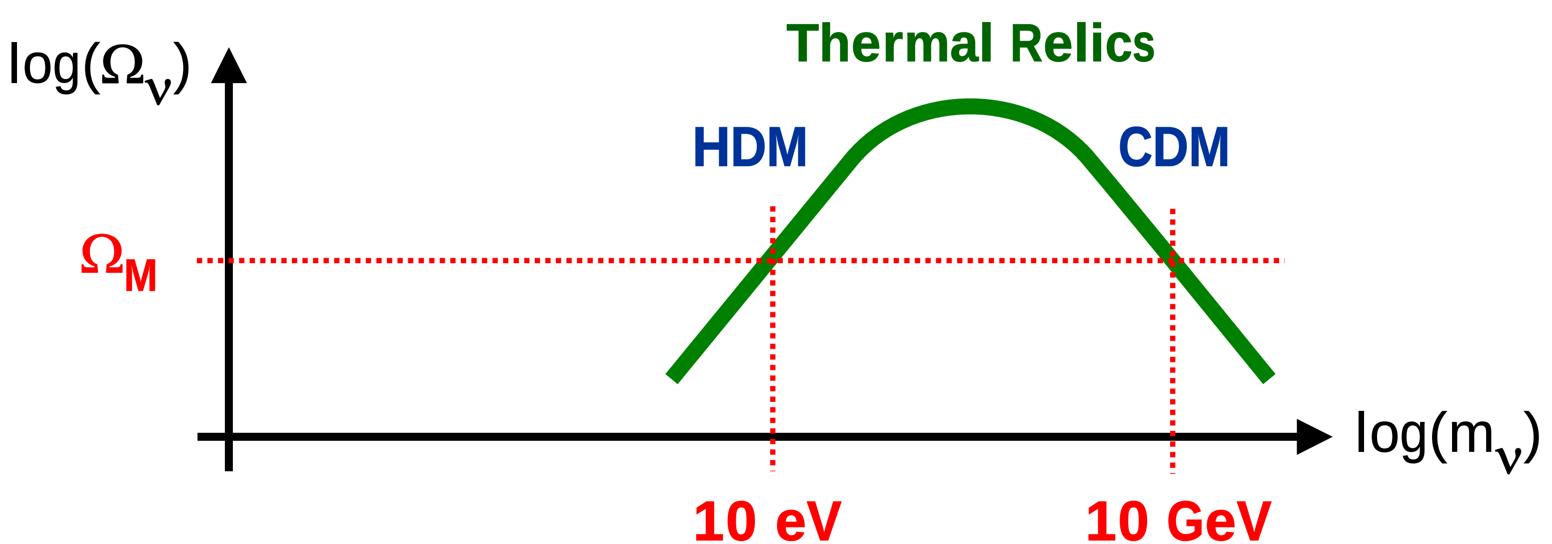
- **$\Theta_i \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu$eV ("classic window")**
- **$f_a \sim 10^{16}$ GeV (GUT scale) or larger (string inspired) requires $\Theta_i \lesssim 0.003$ ("anthropic window")**

Lee-Weinberg Curve for Neutrinos and Axions

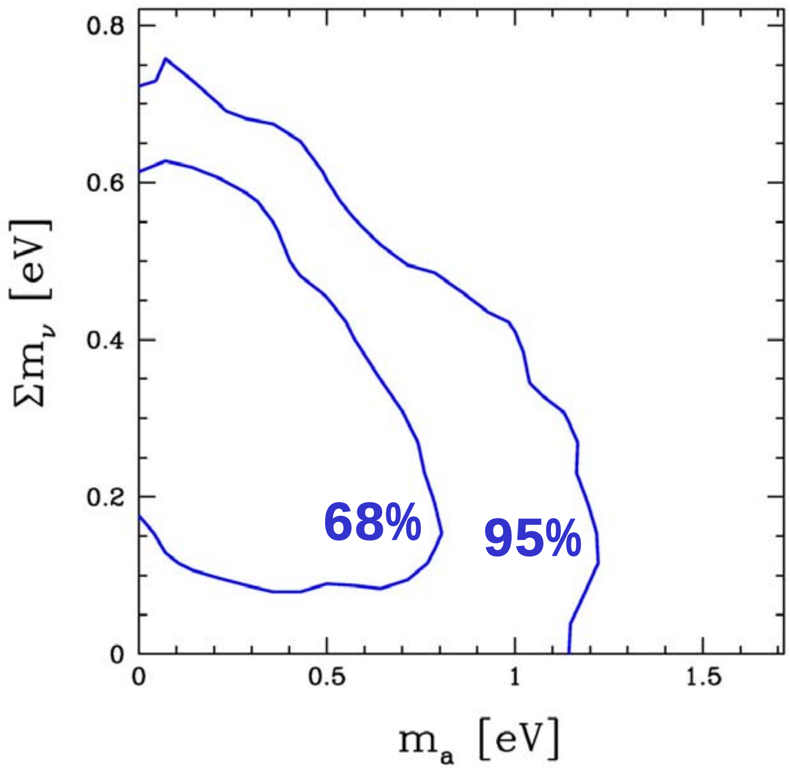
Axions



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

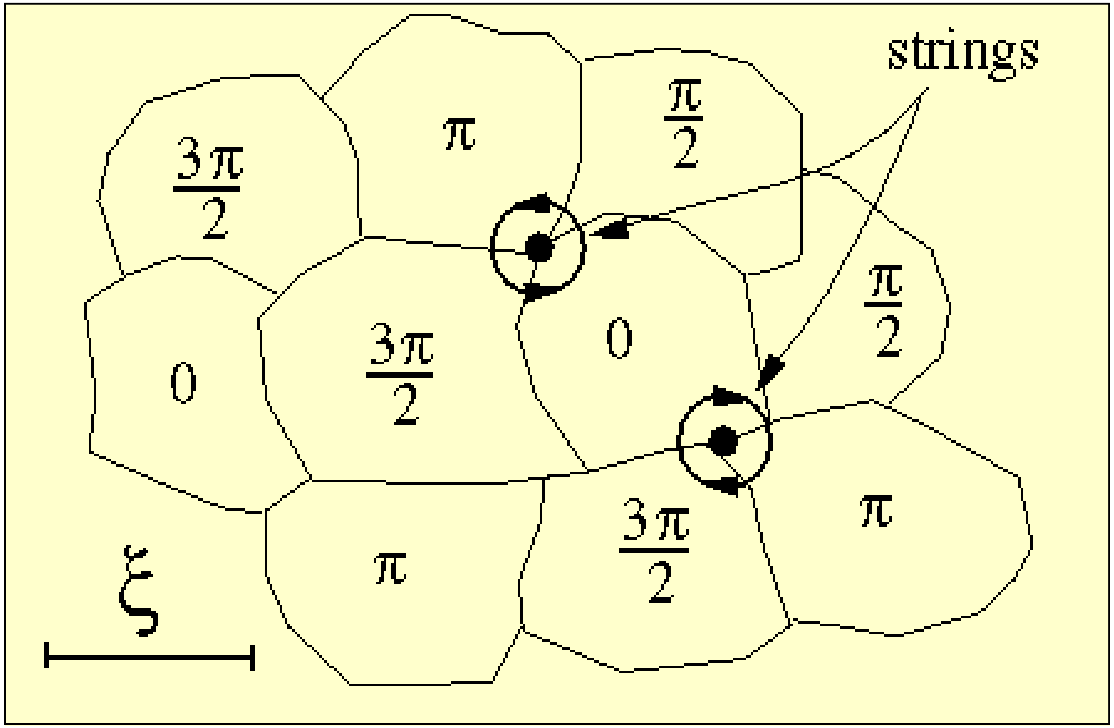
- Cosmic strings of broken $U_{PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_a independent of initial conditions
- N = 1 or else domain wall problem

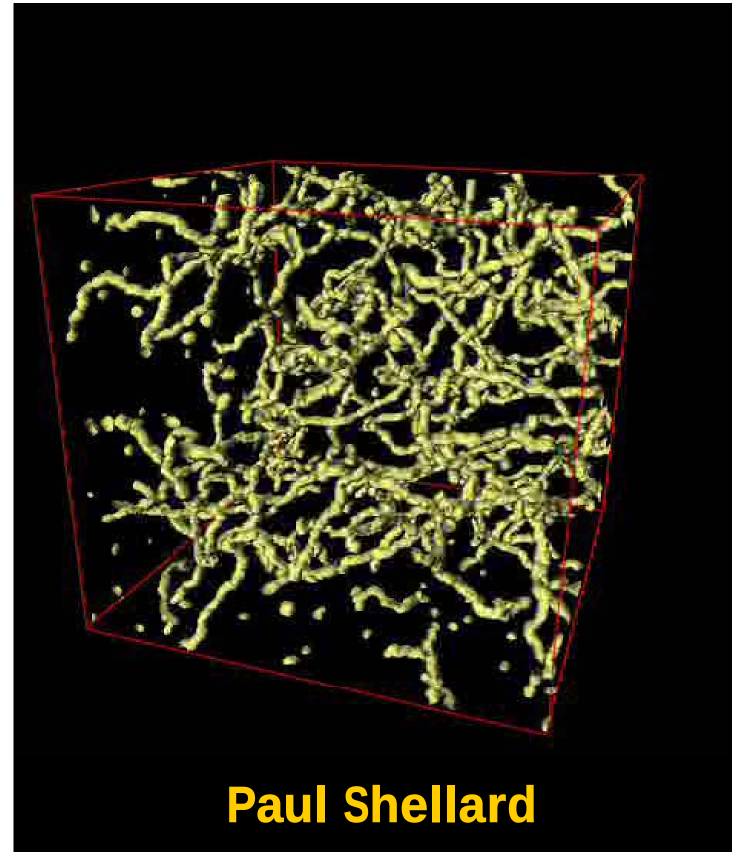
Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

Typical properties
- Mass ~ 10^{-12} M_{sun}
- Radius ~ 10^{10} cm
- Mass fraction up to several 10%

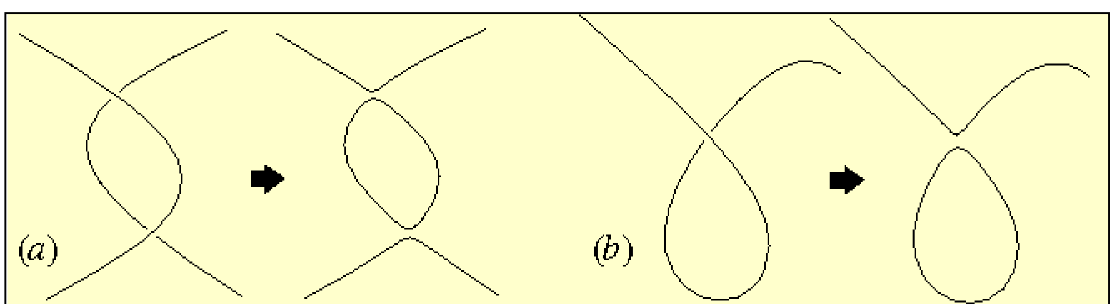
Axions from Cosmic Strings

Strings form by Kibble mechanism after break-down of $U_{PQ}(1)$





Small loops form by self-intersection



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**

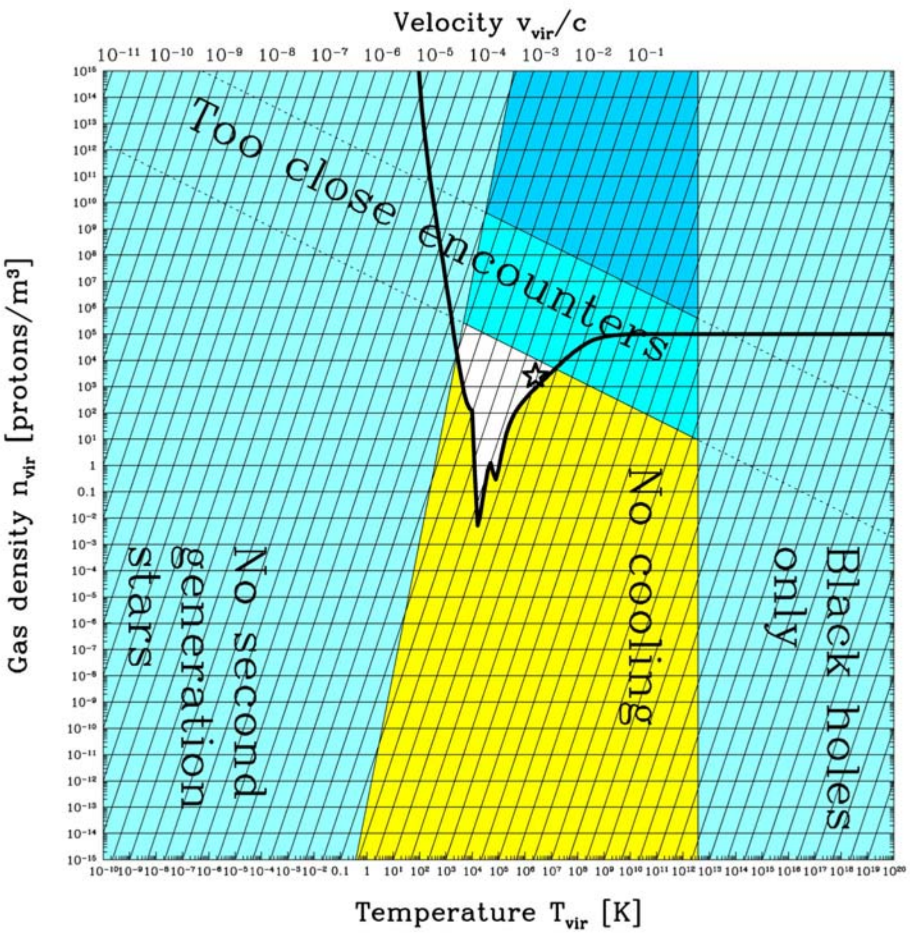
Allows for small $\Theta_i \lesssim 0.003$ and thus for f_a at GUT or string scale

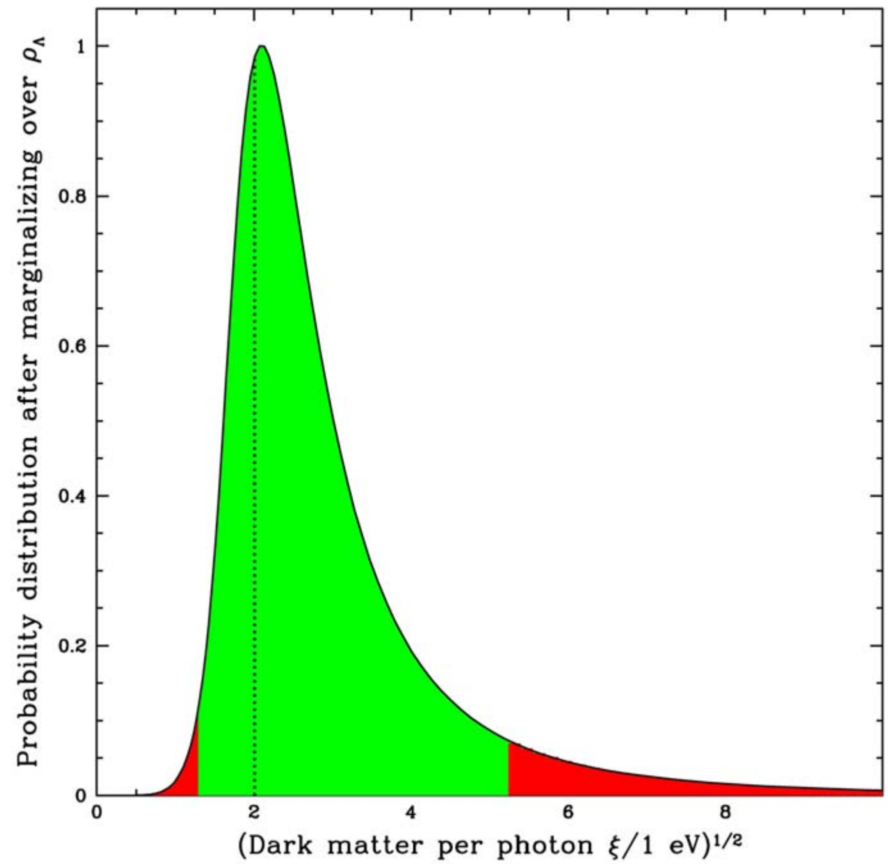
- **Is this "unlikely" or "unnatural" or "fine tuning"?**
- **Should one design experiments for very small-mass axion dark matter?**

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]

Posterior Dark Matter Probability Distribution



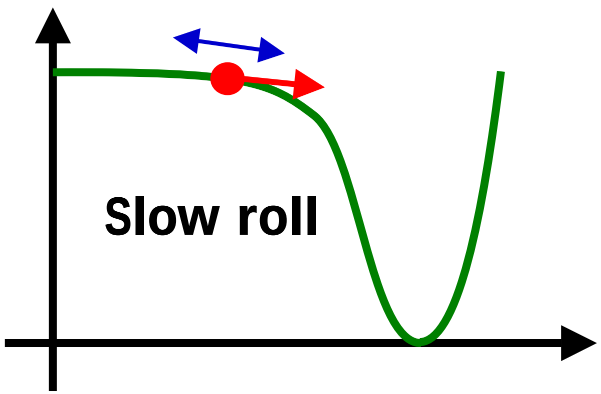


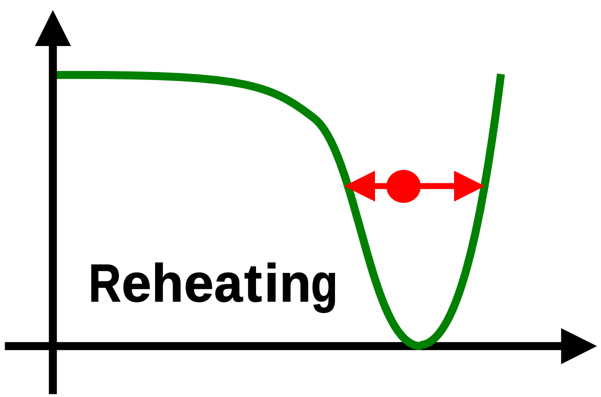
Tegmark, Aguirre, Rees & Wilczek,
“Dimensionless constants, cosmology and other dark matters,”
PRD 73:023505, 2006 [astro-ph/0511774]

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field:

De Sitter expansion imprints scale invariant fluctuations

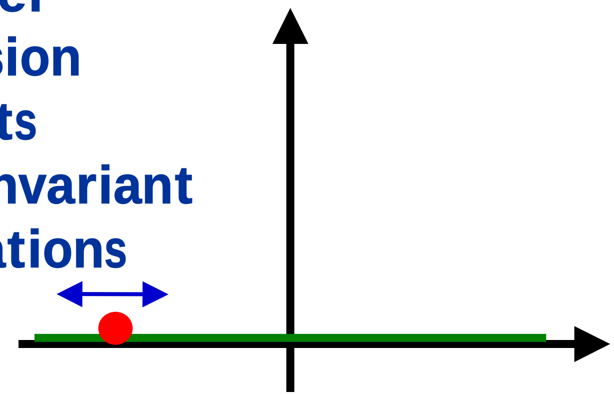


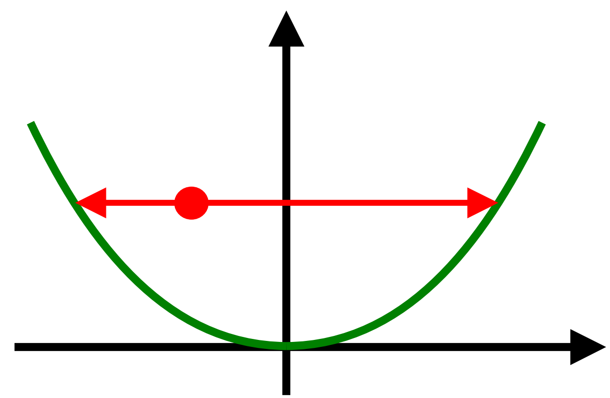


Inflaton decay → matter & radiation
Fluctuations in both (adiabatic)

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 ($n_{iso} = 1 - 2\varepsilon$, slow-roll parameter ε)

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

Usual curvature power spectrum

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

Total power spectrum uncorrelated sum

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

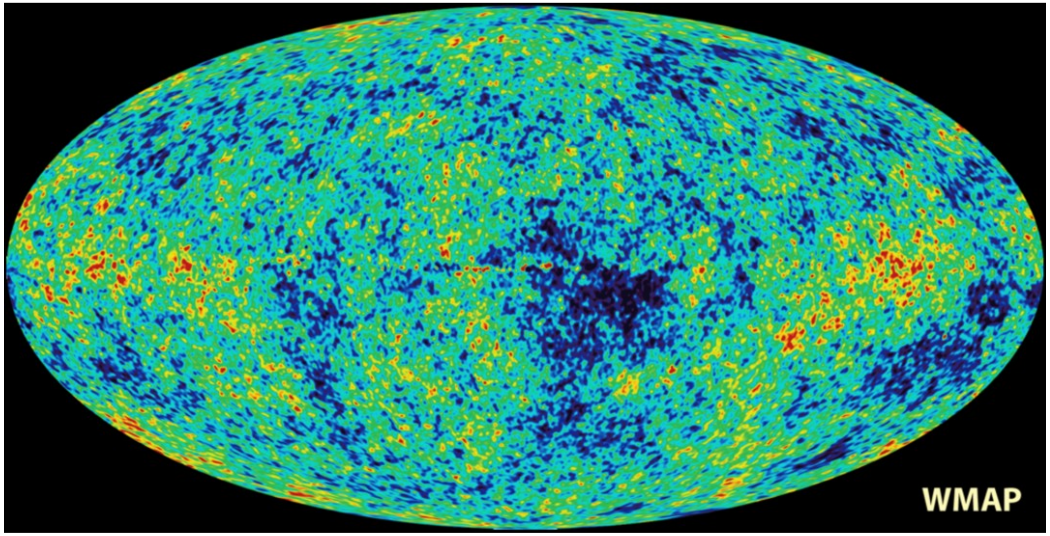
Isocurvature fraction at pivot scale $k_0 = 0.002\ \mathrm{Mpc}^{-1}$

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

Power Spectrum of CMB Temperature Fluctuations

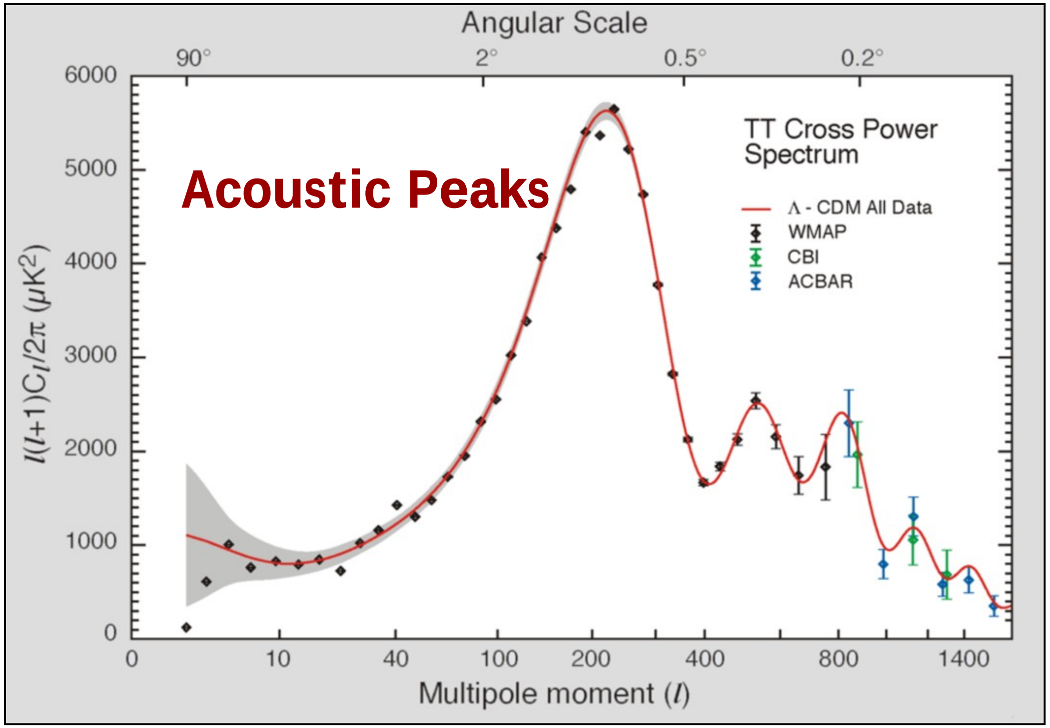
Sky map of CMBR temperature fluctuations

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



Multipole expansion

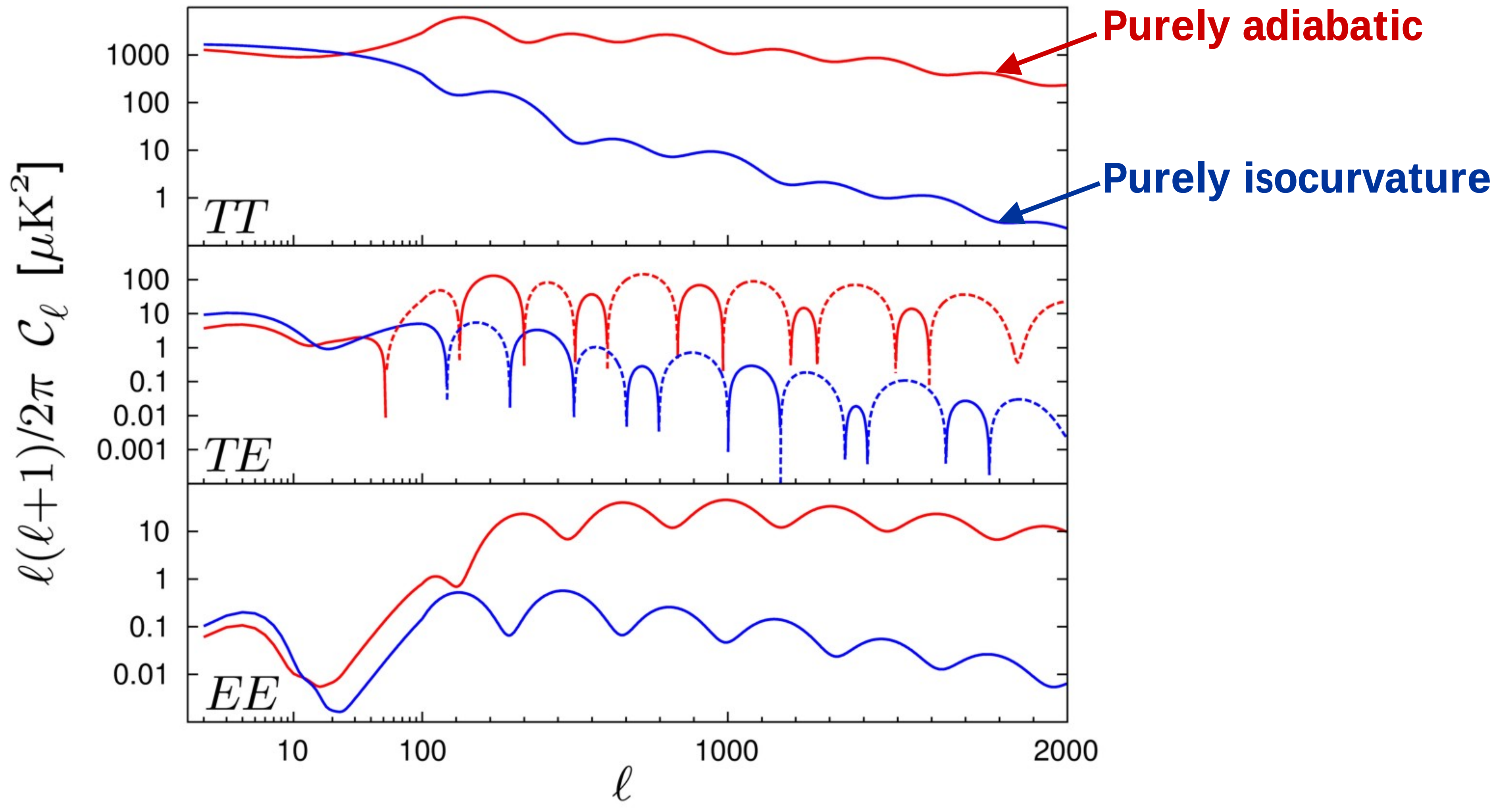
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$



Angular power spectrum

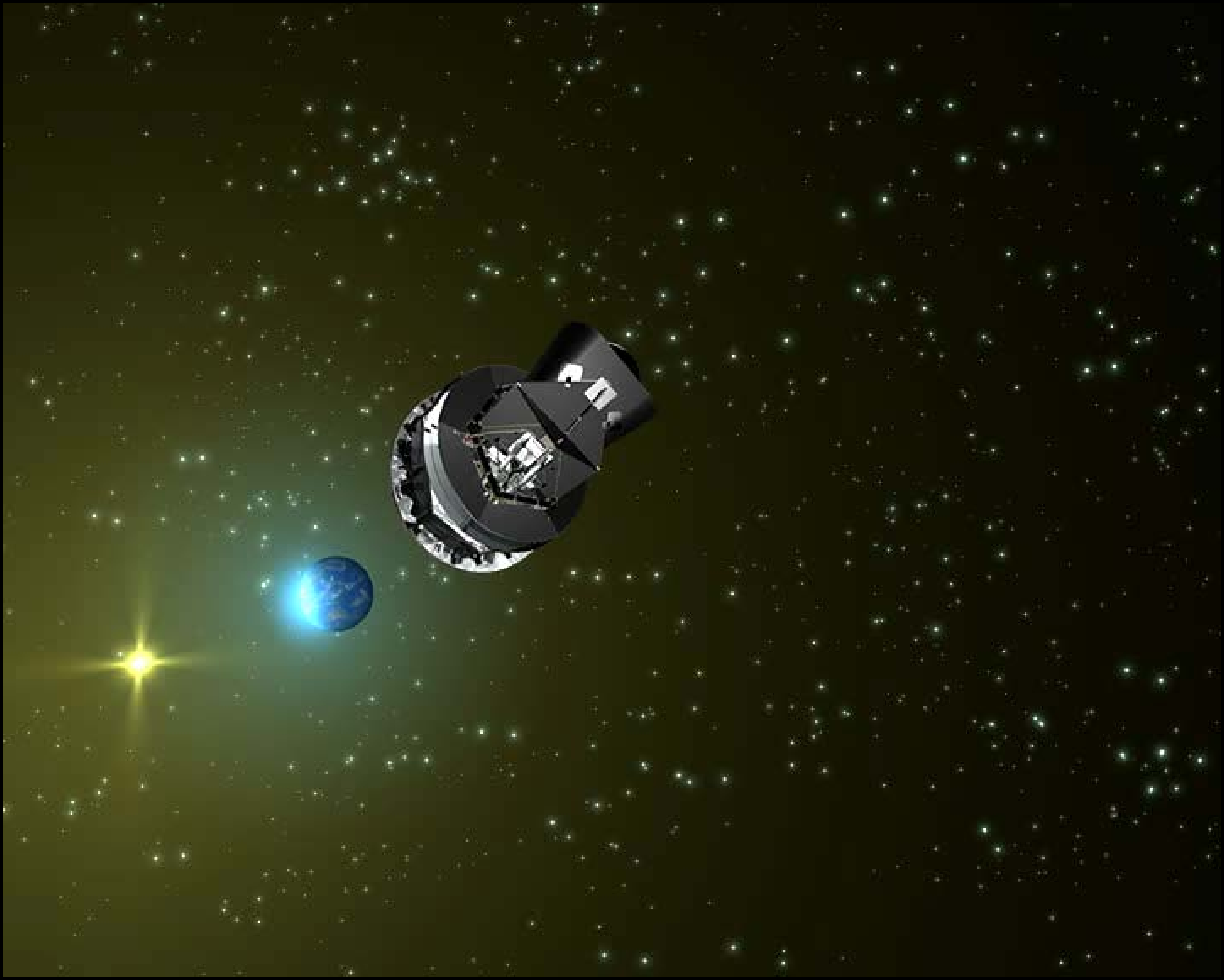
$$C_\ell = \langle a^*_{\ell m} a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^*_{\ell m} a_{\ell m}$$

CMB Angular Power Spectrum

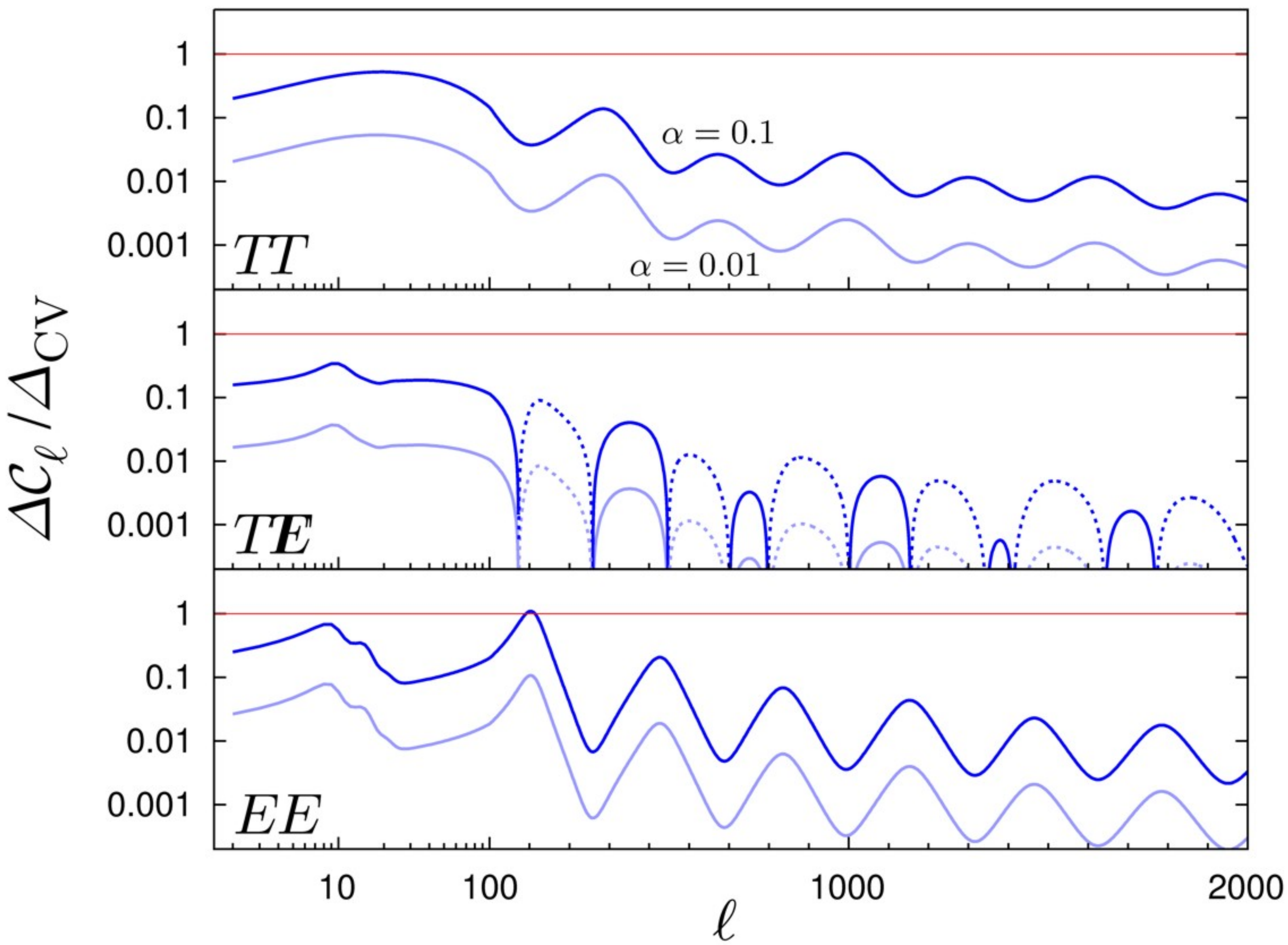


Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

PLANCK Satellite – Successful Launch on 14 May 2009

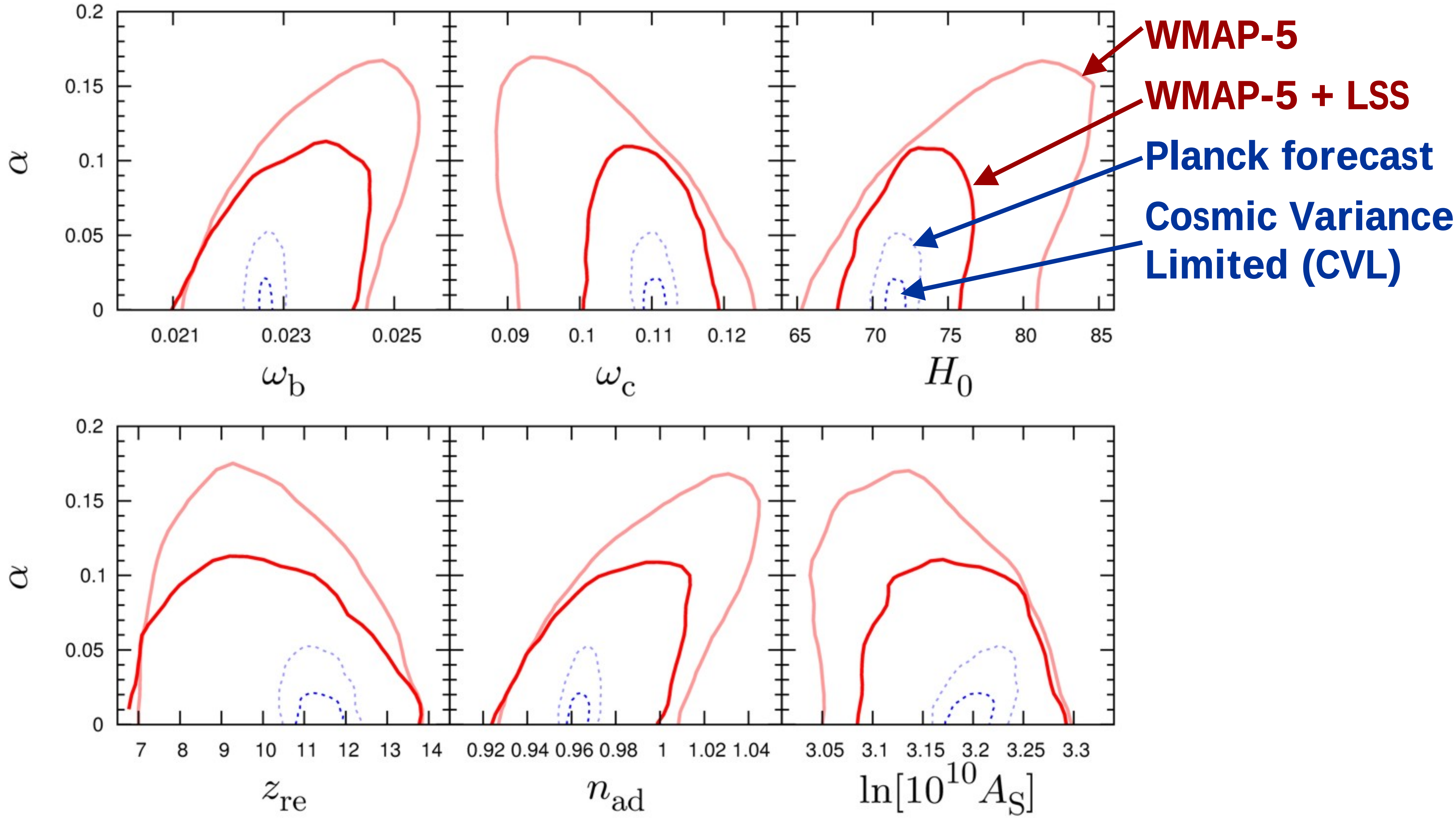


Scale-Dependent Isocurvature Fraction



Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

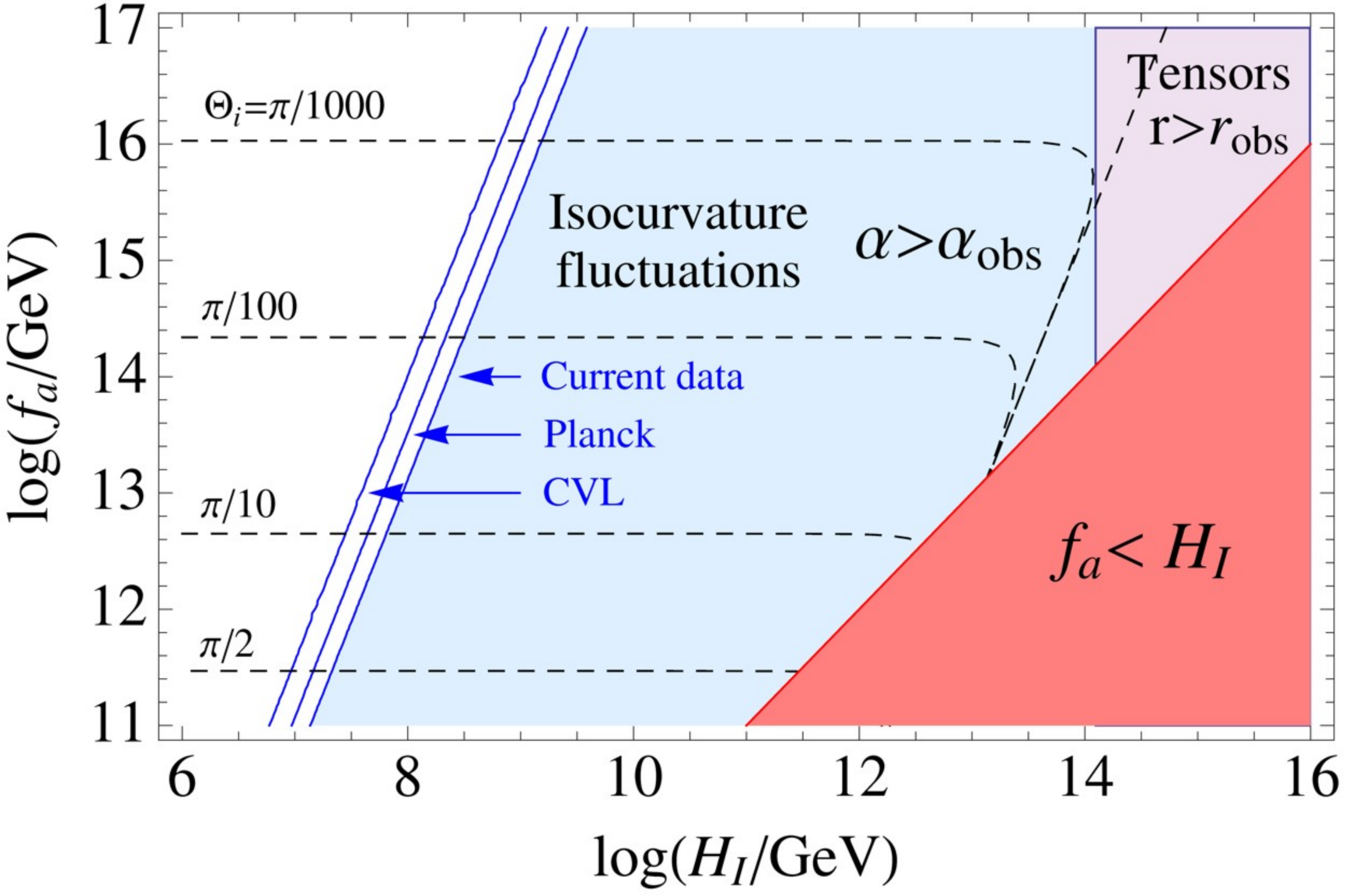
Parameter Degeneracies



Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

Isocurvature Forecast

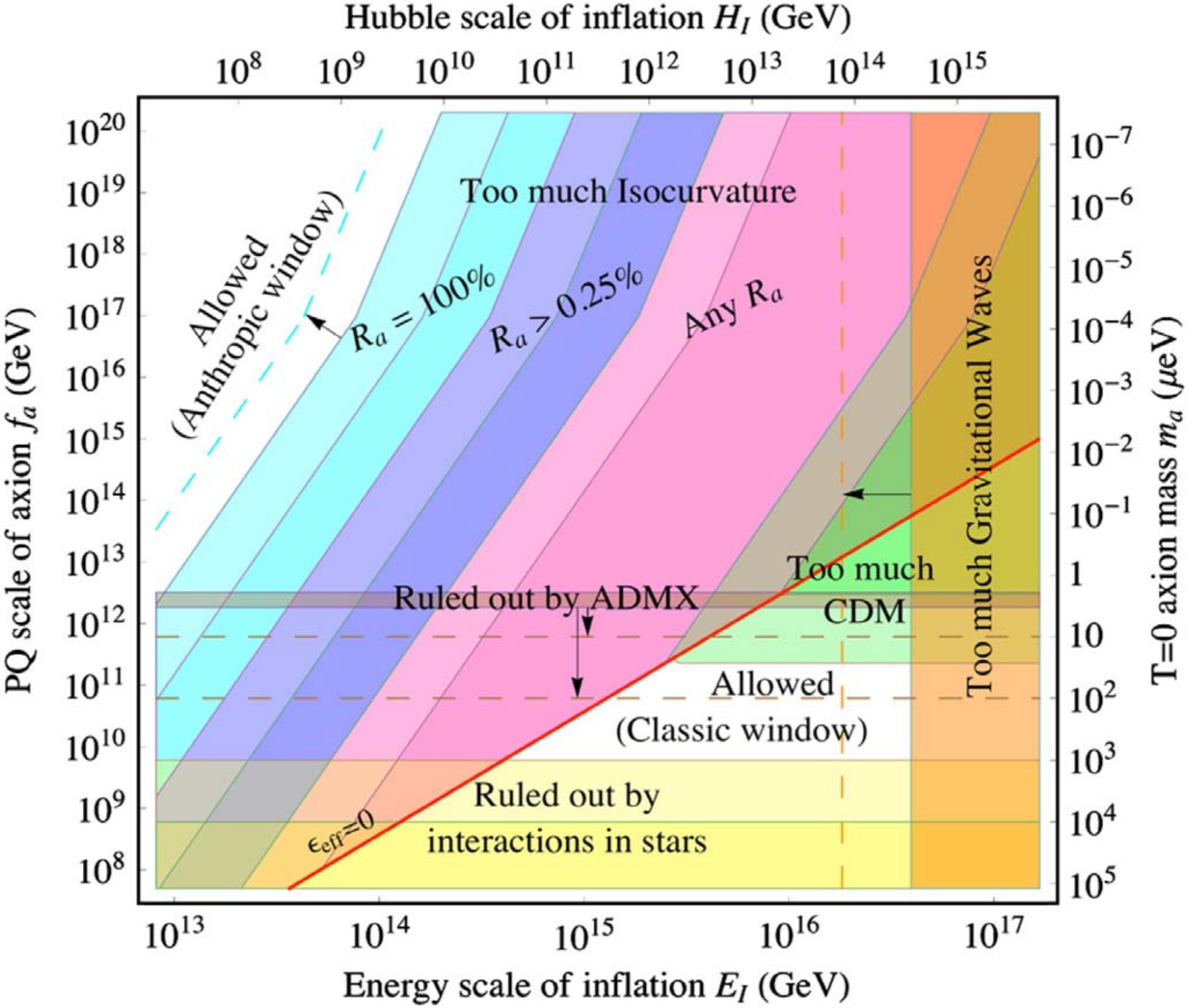
Hubble scale during inflation



Axion decay constant

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

Classic and Anthropic Axion Windows



Hertzberg, Tegmark & Wilczek, PRD 78 (2008) 083507

Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

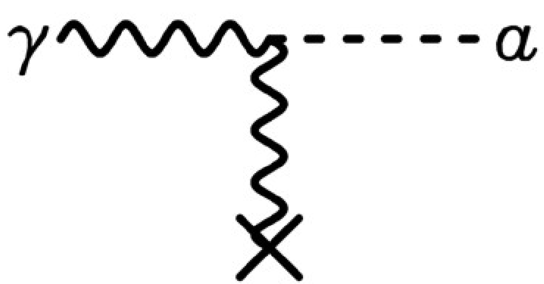
Experimental Tests of the "Invisible" Axion

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)

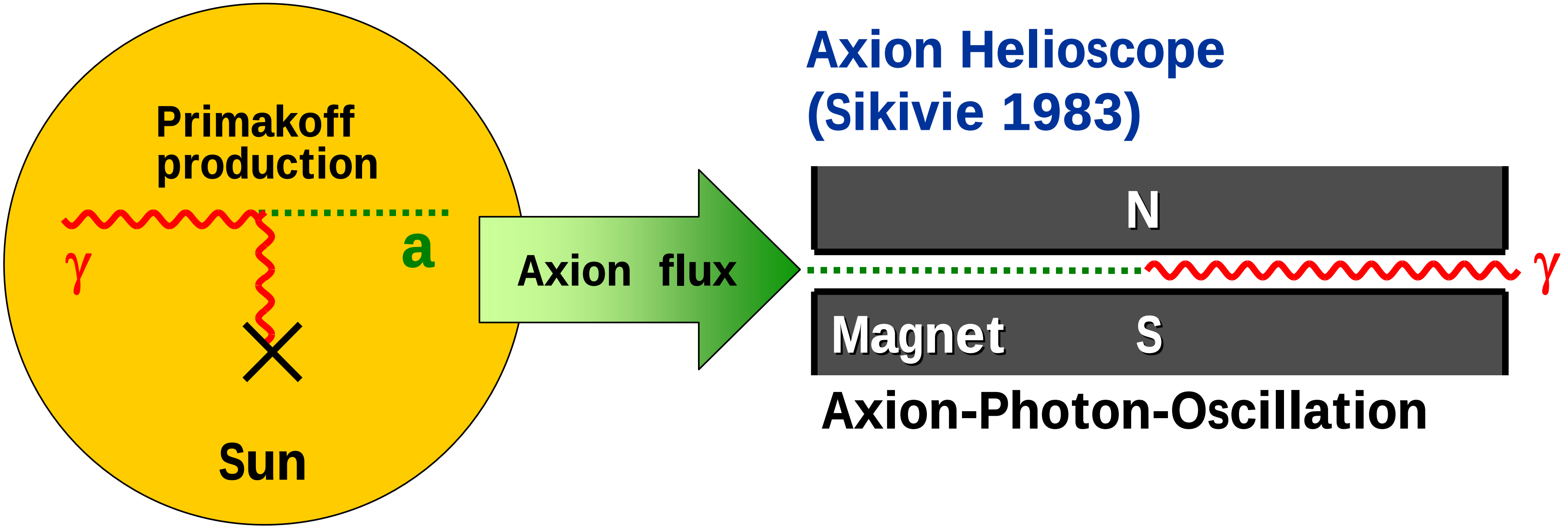


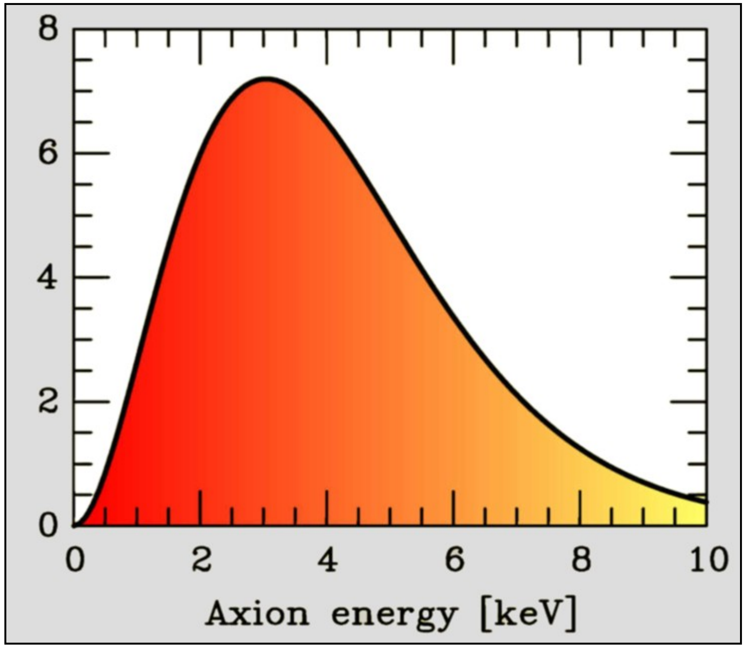
Pierre Sikivie:

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



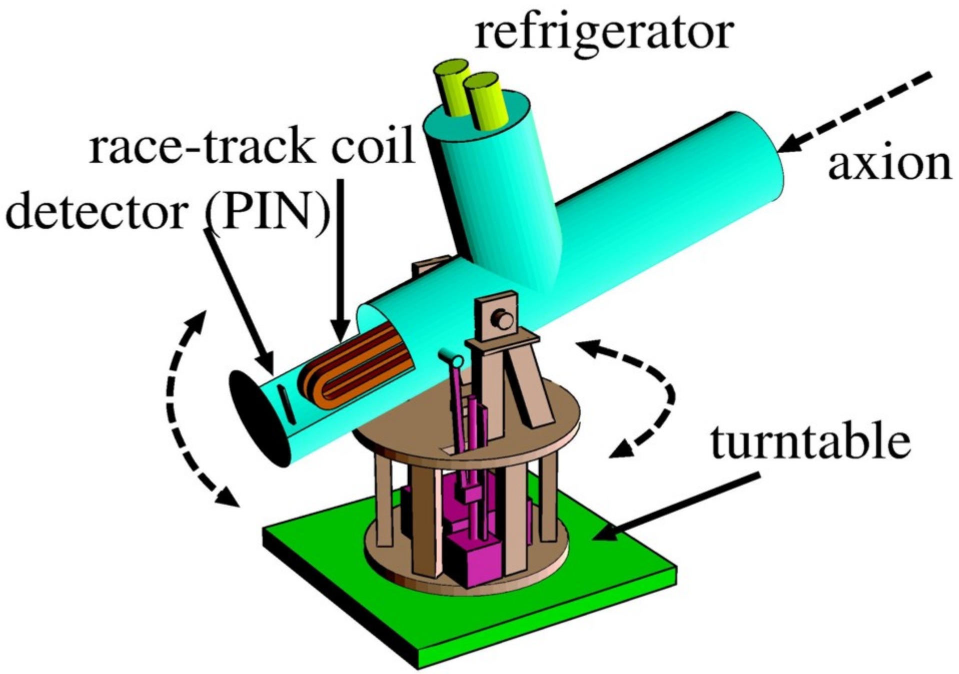


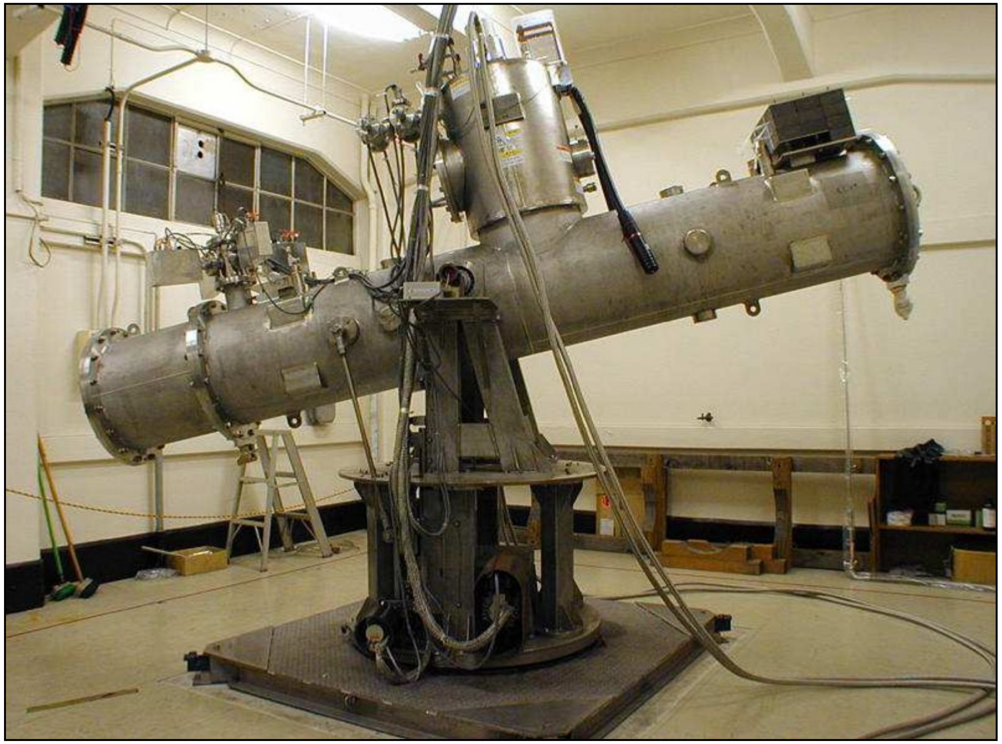
➔ Tokyo Axion Helioscope ("Sumico")
(Results since 1998, up again 2008)

➔ CERN Axion Solar Telescope (CAST)
(Data since 2003)

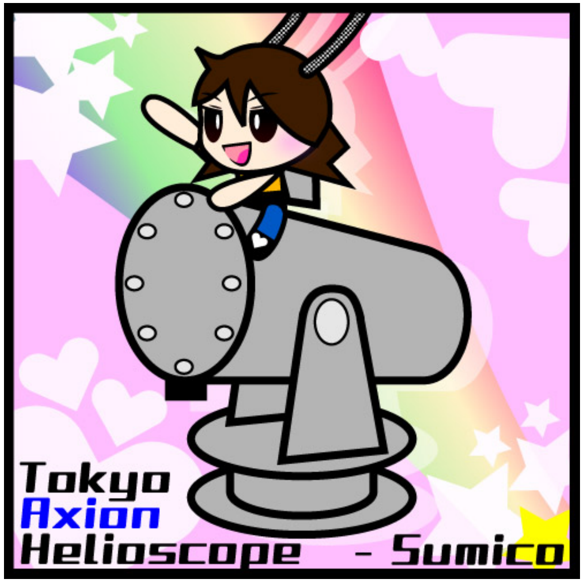
Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments
(SOLAX, COSME, DAMA, CDMS ...)

Tokyo Axion Helioscope (“Sumico”)





~ 3 m



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

Inoue, Akimoto, Ohta, Mizumoto, Yamamoto & Minowa
PLB 668 (2008) 93

CAST at CERN

Sun Spot on CCD with X-Ray Telescope

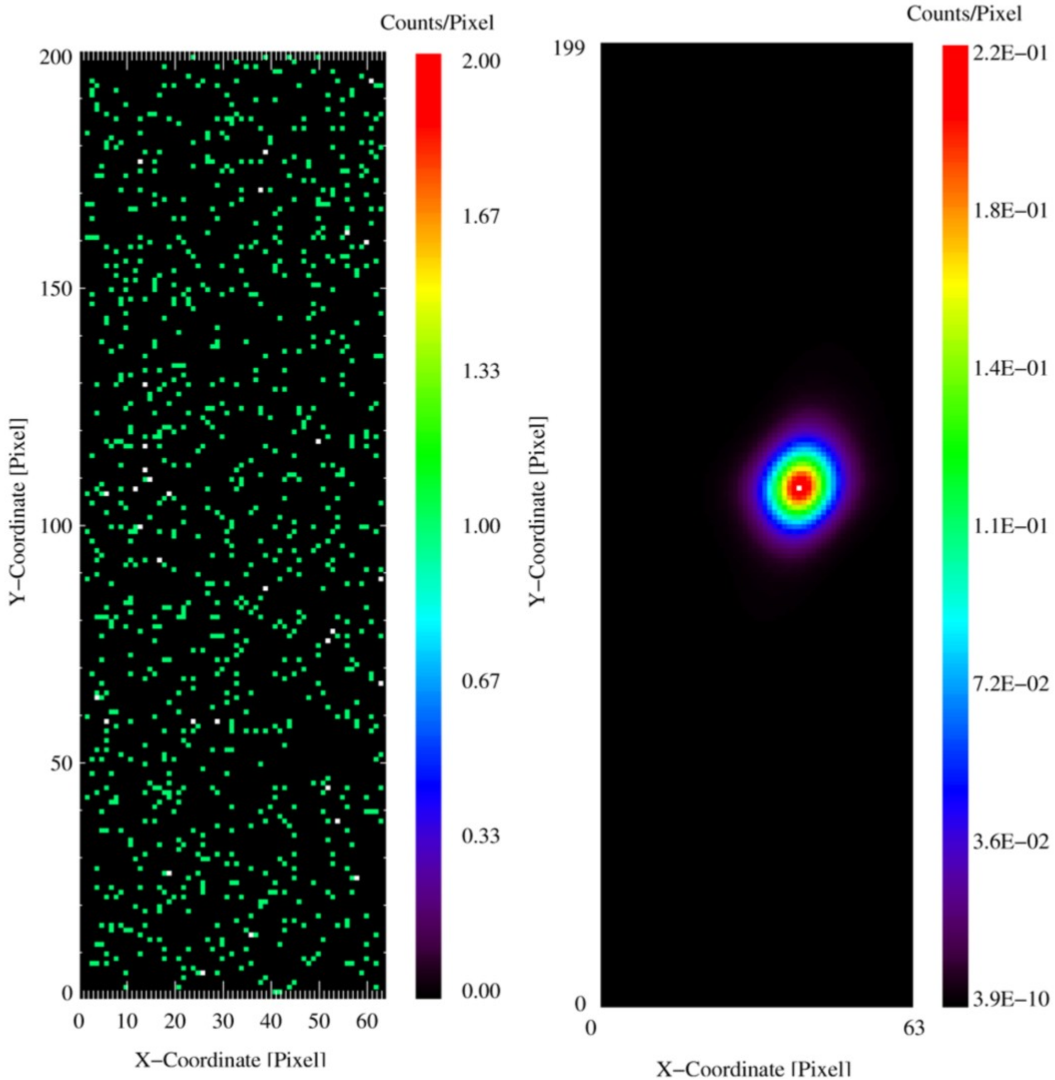


Figure 6: Left: Spatial distribution of events observed under axion sensitive conditions by the CAST X-ray telescope during the 2004 data taking period. The intensity is given in counts per pixel and is integrated over the full observation period of $t_{\rm obs} = 707\,{\rm ksec}$. Right: Expected "axion" 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.

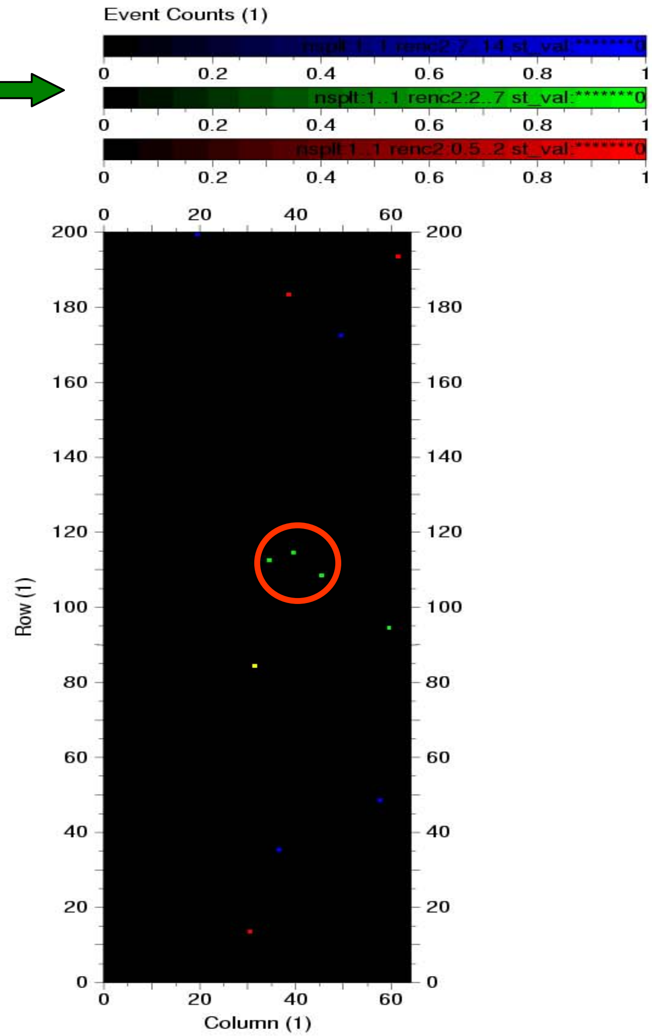
True Colour Event Image | **C09_07_10_060530_02000**

EVTMAPE03 | cast / kuster ||| FF / -130.0 degC / -

Source	-
CCD temperature (degC)	-130.0
Observation comment(s)	none
Start time	2006-05-30T02:55:48.845
End time	2006-05-30T04:26:01.776
Livetime (s)	5412.9
Cycle time (ms)	71.8
Frames (total/cal/softcal)	75420 0 0
Single Chip Info	9.?| 64|200|150|150| 0| 0| 0
Wafer Info	|111|Epi| | |300|16| |
Filter	--
Window	1 64 1 200
Observer	kuster

90 min tracking result

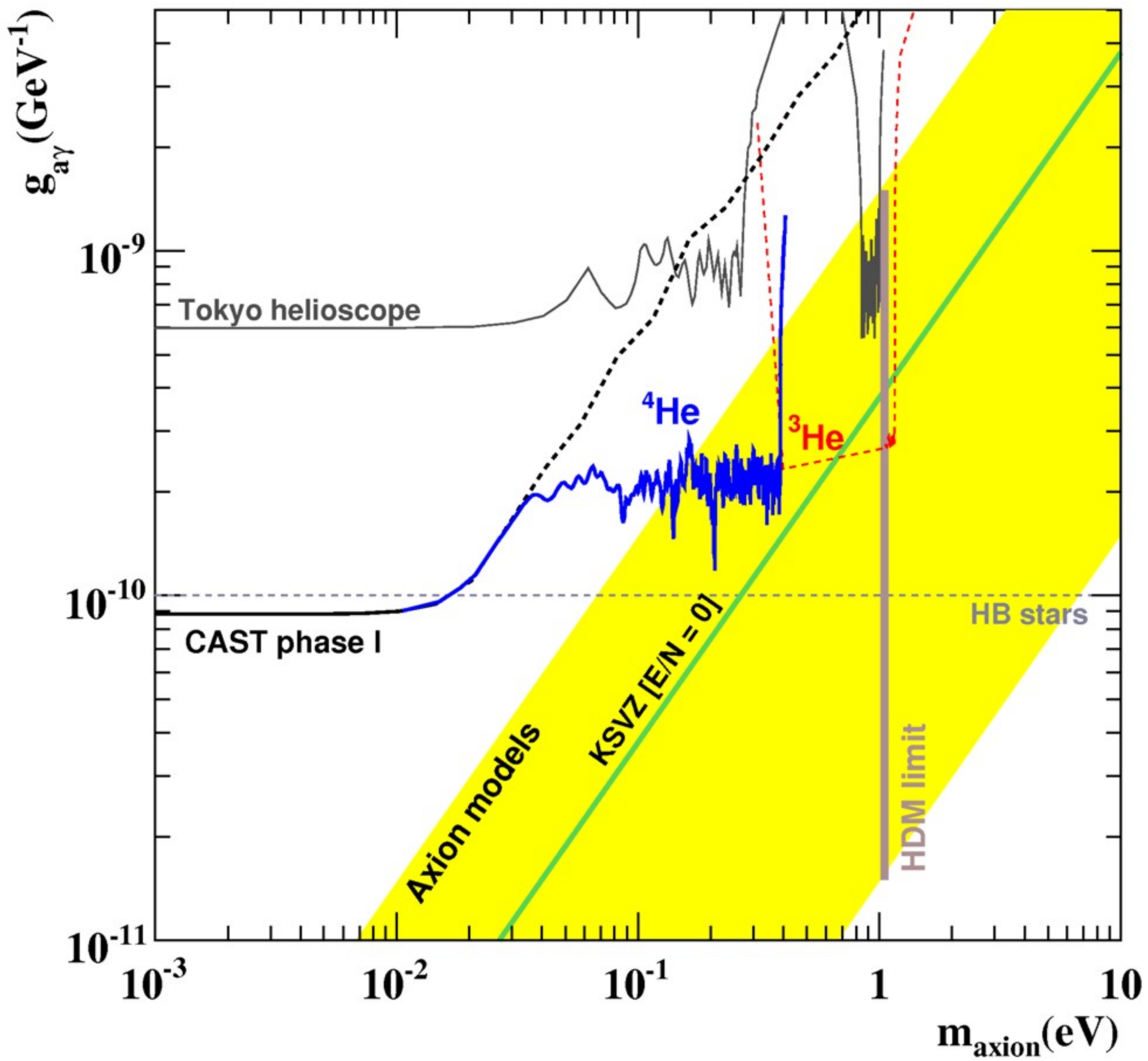
ROI →



min	max	mean	sum	hits
0.000	1.000	0.000	4.0	4
0.000	9.000	0.001	13.0	5
0.000	118.000	0.009	121.0	4

„suspicious pressure“

Helioscope Limits



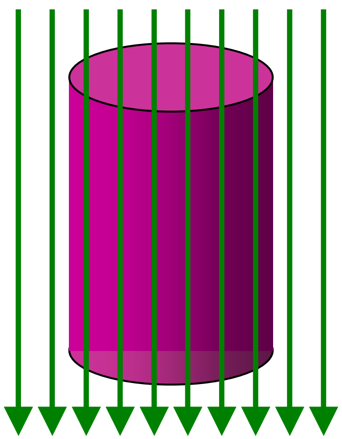
CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008

Search for Galactic Axions (Cold Dark Matter)

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

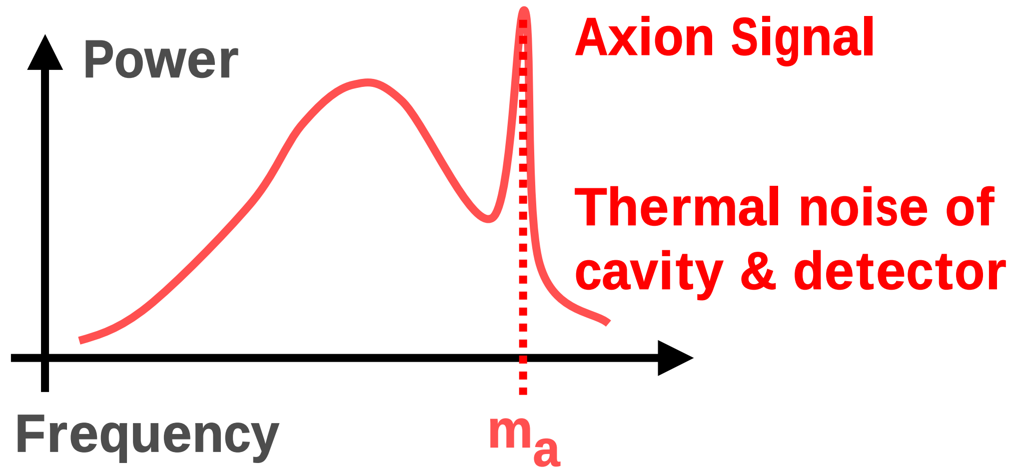
→ Microwave Energies ($1\ \text{GHz} \approx 4\ \mu\text{eV}$)

Axion Haloscope (Sikivie 1983)

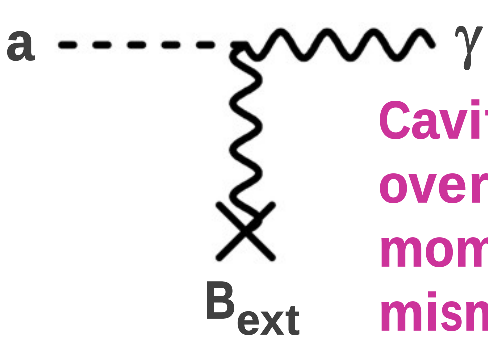


$B_{ext} \approx 8$ Tesla

Microwave Resonator $Q \approx 10^5$



Primakoff Conversion



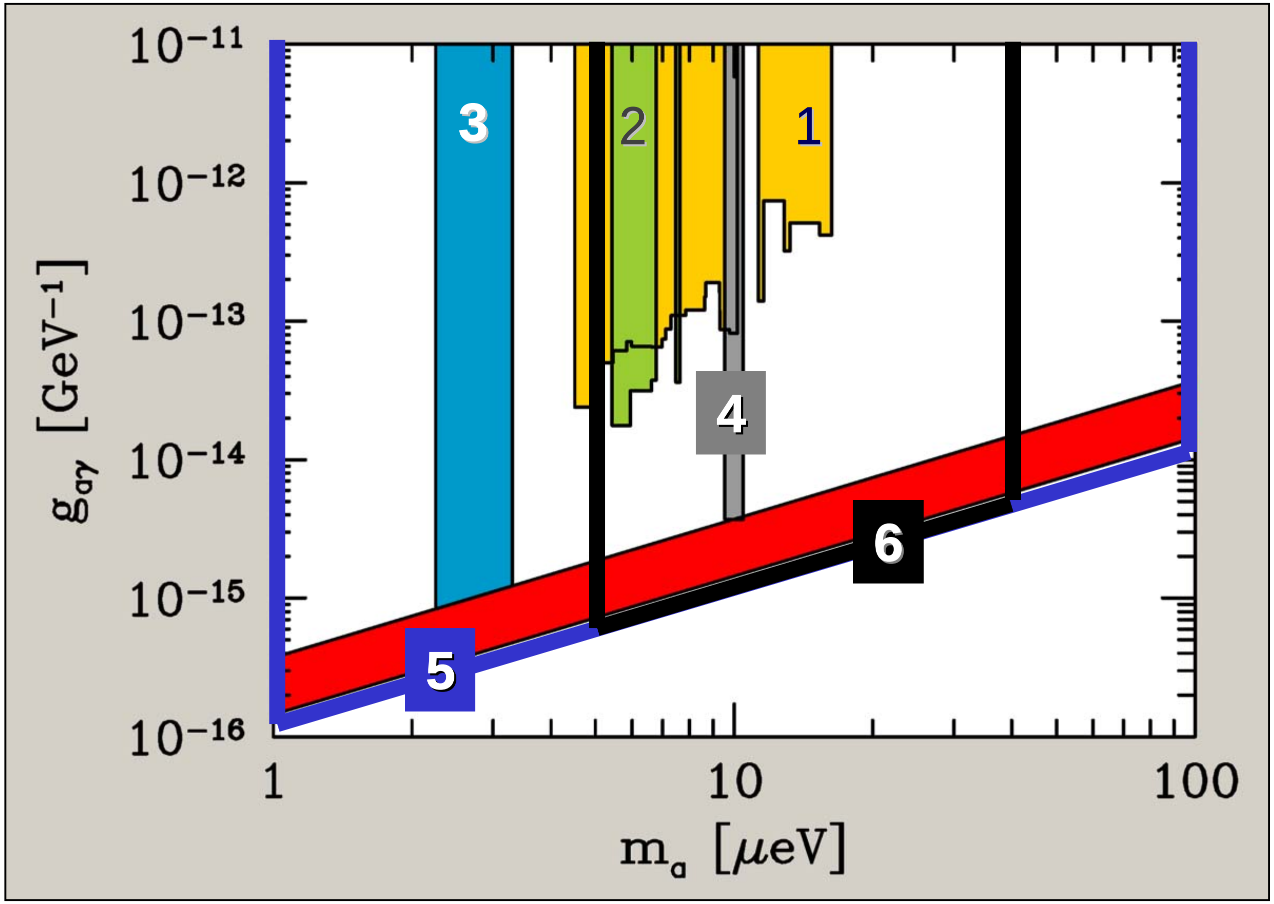
Cavity overcomes momentum mismatch

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)

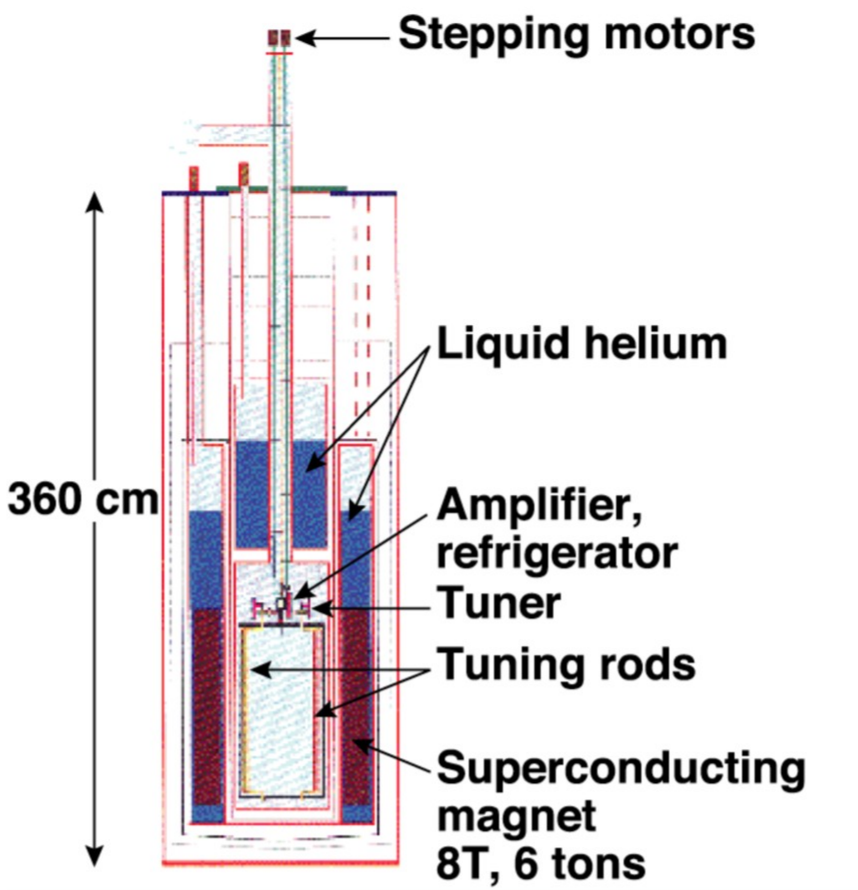
ADMX (Gianpaolo Carosi, Fermilab, May 2007)

Axion hardware

ADMX LLNL-Florida-Berkeley-NRAO

ADMX

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

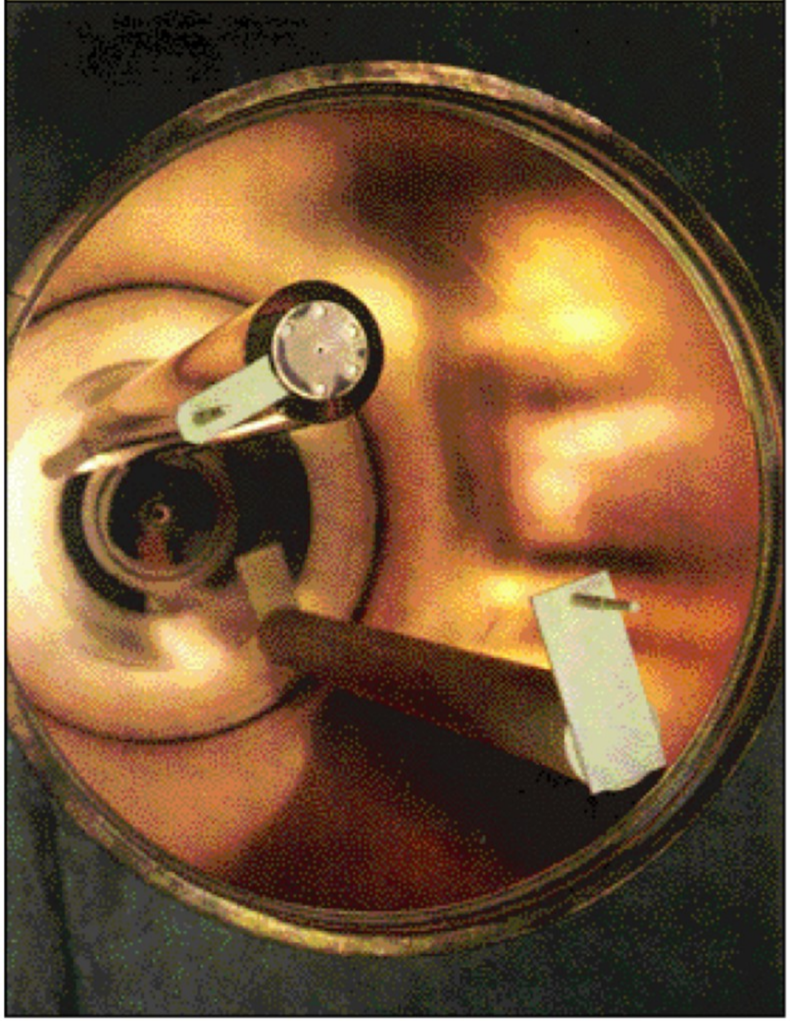
Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

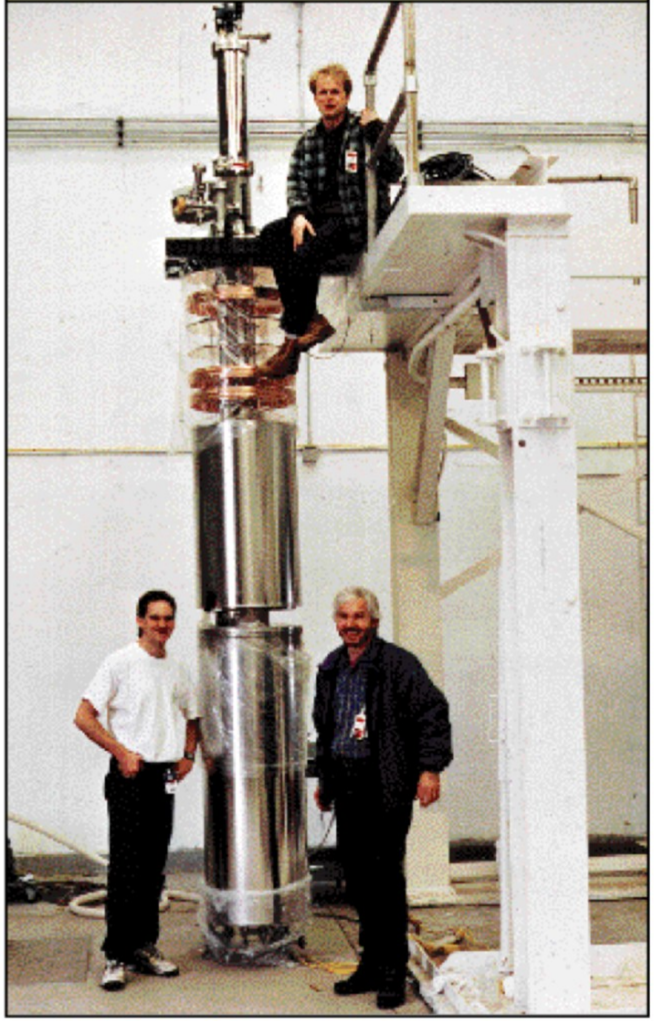
Axion hardware (cont'd)

ADMX

High-Q Cavity (~200,000)



Experimental Insert



ADMX (Gianpaolo Carosi, Fermilab, May 2007)

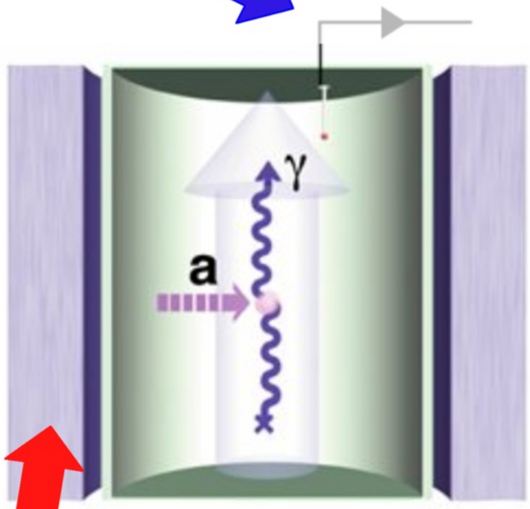
The radiometer eqn.* dictates the strategy

ADMX

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

But integration time limited to ~ 100 sec

* *Dicke, 1946*



System noise temp. now

$T_S = T + T_N \sim 1.5 + 1.5$ K

But $T_{Quant} \sim 30$ 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 ~ \$

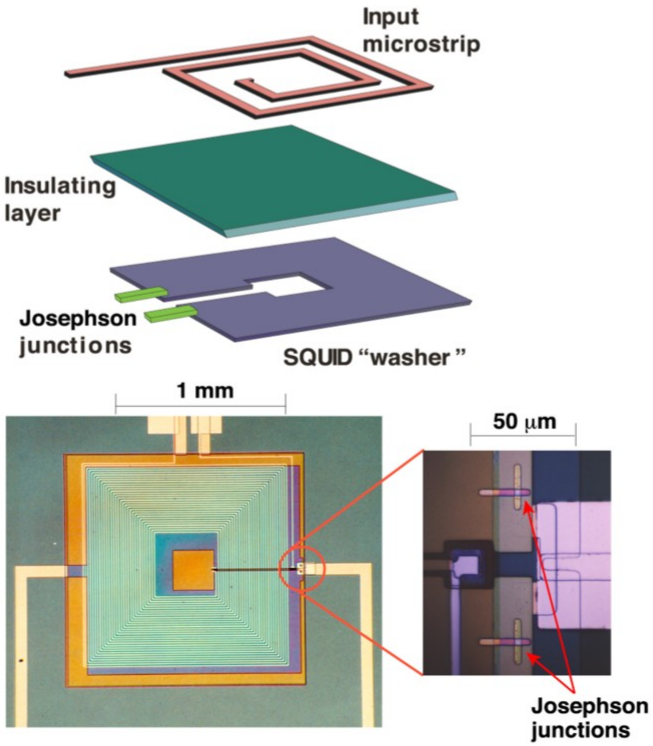
ADMX (Gianpaolo Carosi, Fermilab, May 2007)

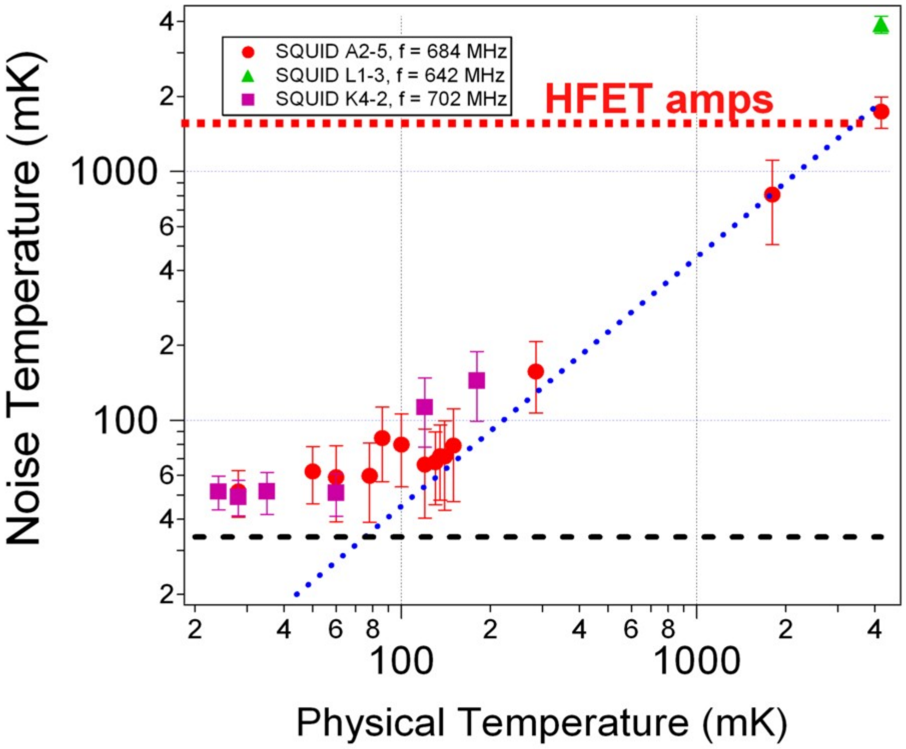
The enabling technology – GHz SQUID amplifiers* *ADMX*

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

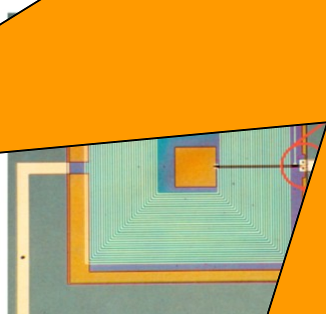
ADMX (Gianpaolo Carosi, Fermila[...] May 2007)

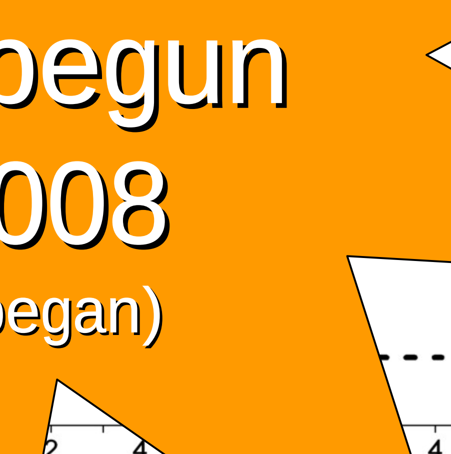
...e enabling technolo... GHz SQUI... lifiers* *ADMX*

Pr... noise te... f o... s i...

...uar...

Josep... junction





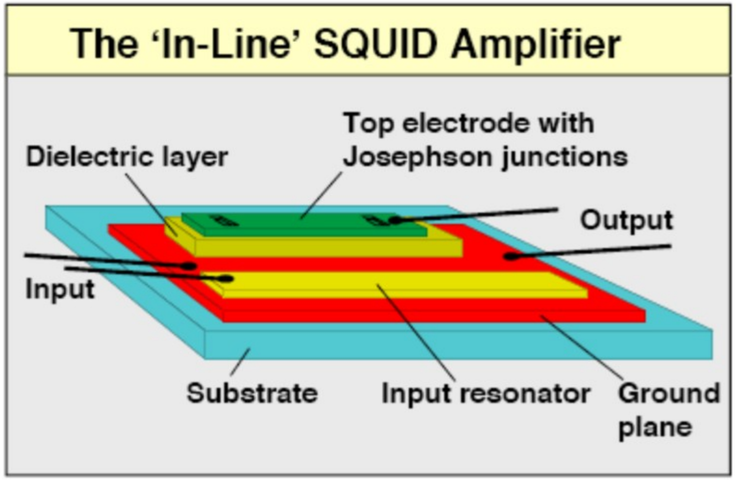
Renewed ADMX
data taking has begun
on 28 March 2008
(Same day as CAST He-3 began)

Our latest SQUIDs are now ... 15% of the ...dard Quantum Limit

ADMX (Gianpaolo Carosi, Fermilab, May 2007)

To complete the job, ADMX needs concurrent R&D

ADMX

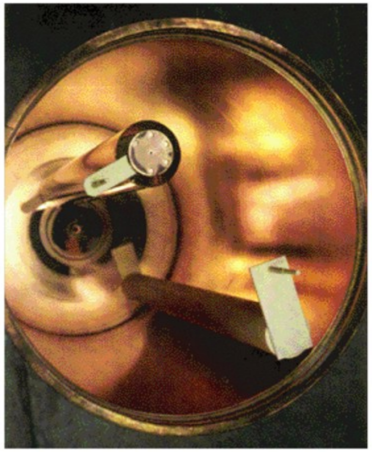


To get to 10, and then 100 GHz, we need to:
- Develop new RF cavity geometries
- Develop new SQUID geometries

We know what to do, but have bootlegged as far as we can; now it needs real attention

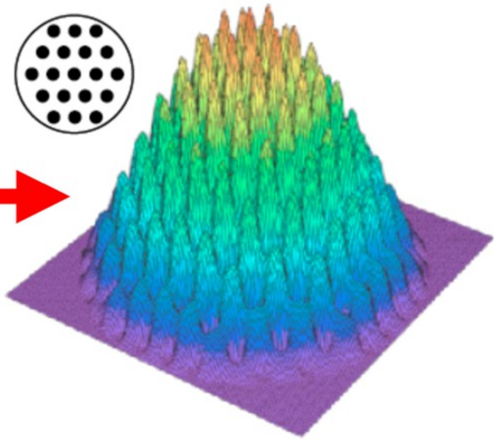
Our Road-Map includes support for R&D

1 GHz



10 GHz

100 GHz



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

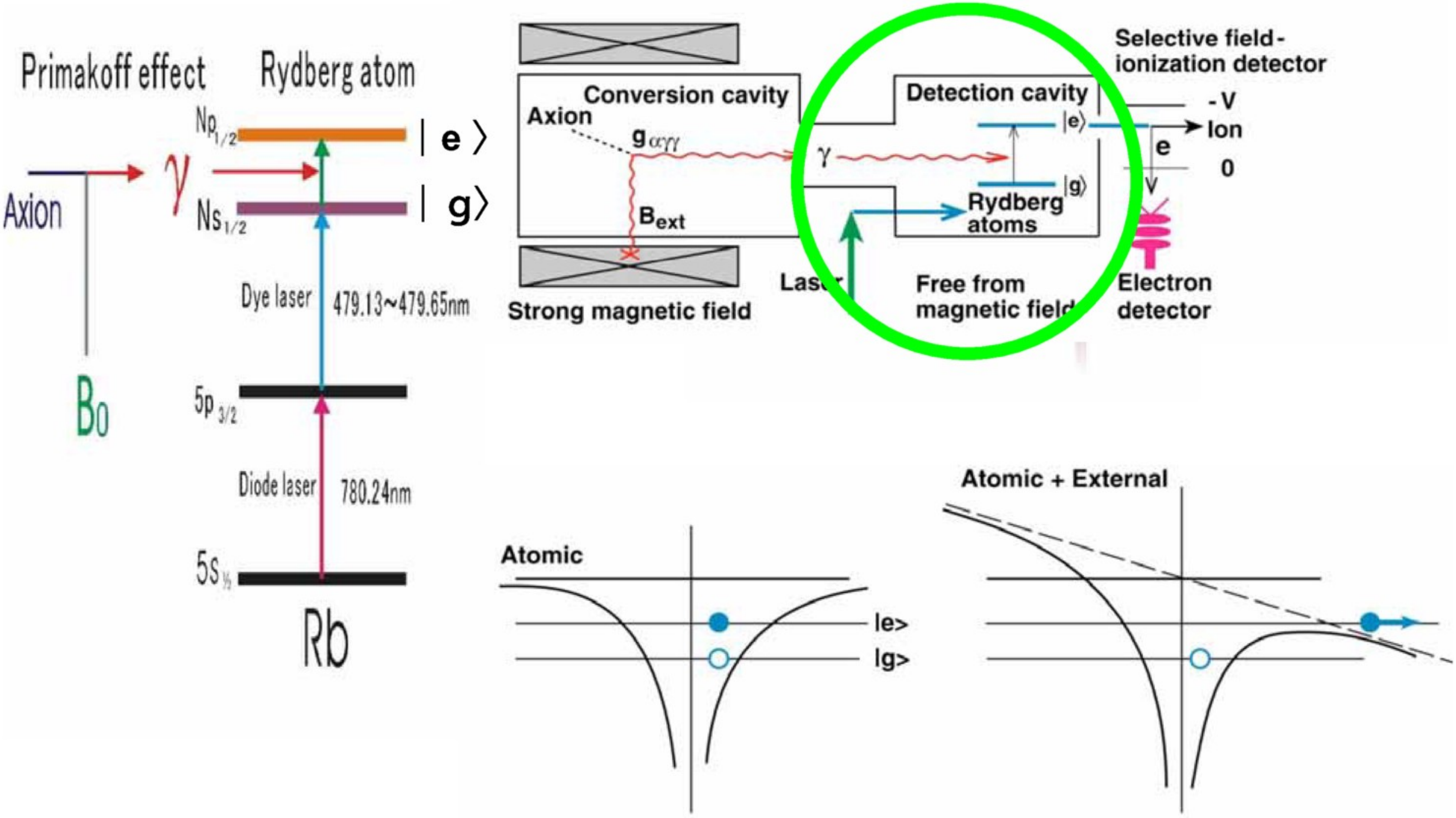
and K. Yamamoto

Kyoto Univ.

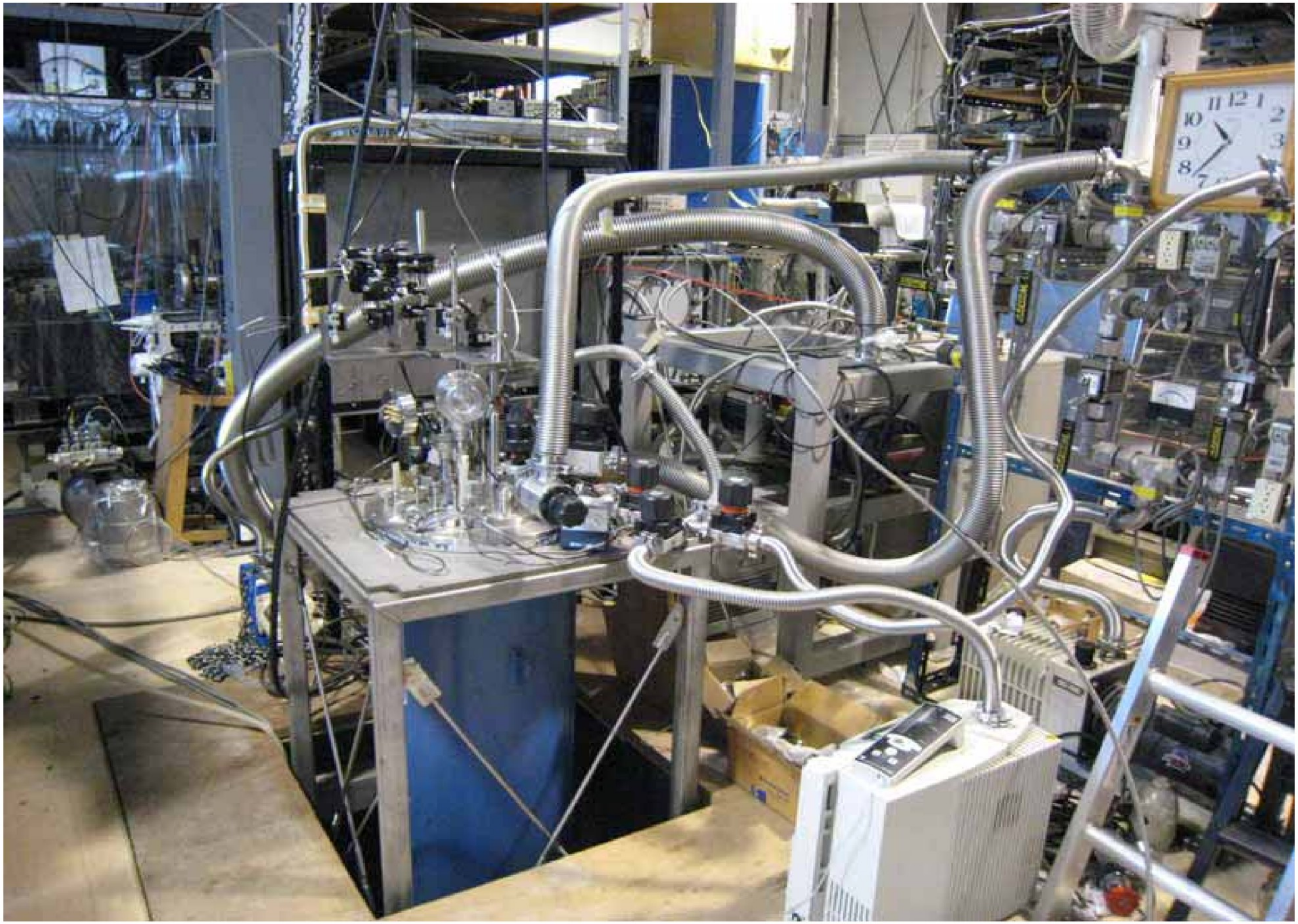
Osaka Electro-comunication Univ.

$ Ritsumeikan Univ.

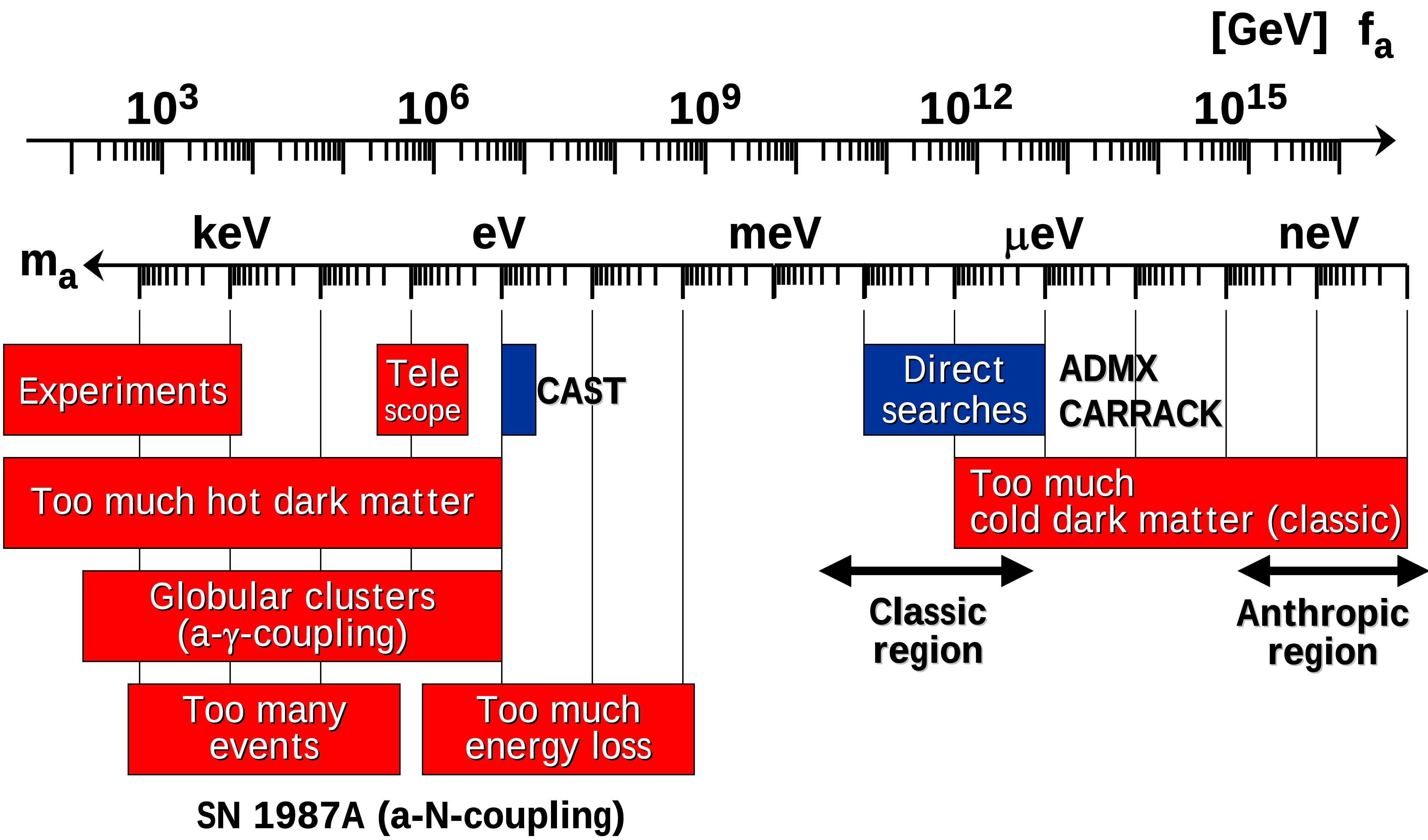
New CARRACK (Kyoto)



The search for dark matter will start early next year



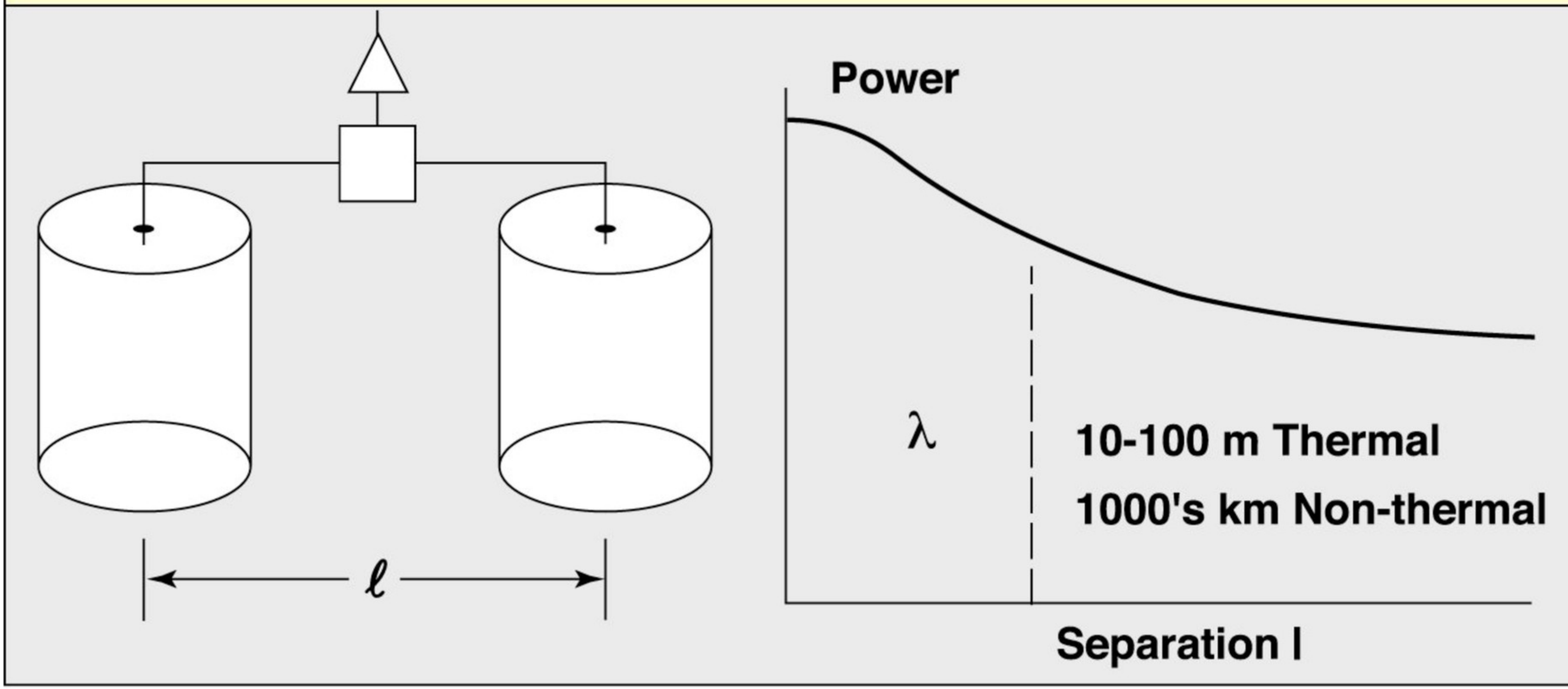
Axion Bounds



Karl van Bibber
at IDM 2008

And if the axion be found?

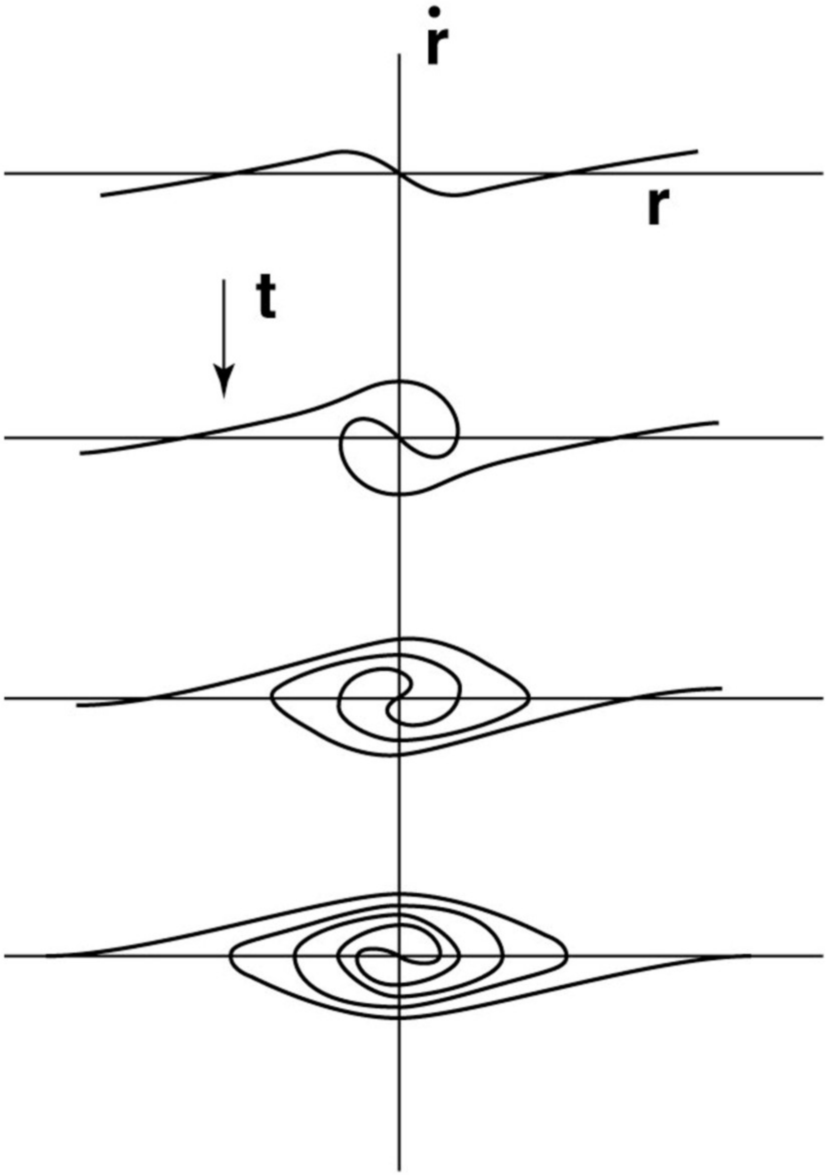
The Study of Unique Quantum System

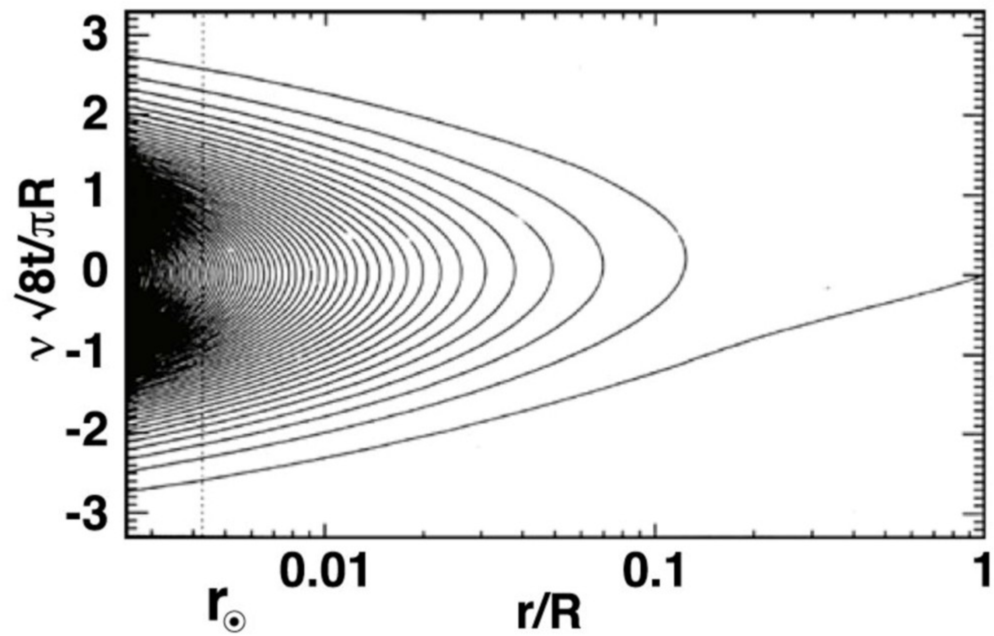


And should the axion posses fine-structure, it would constitute a "movie" of the formation of our Milky Way galaxy

Karl van Bibber
at IDM 2008

1-D infall, and the “folding” of phase space

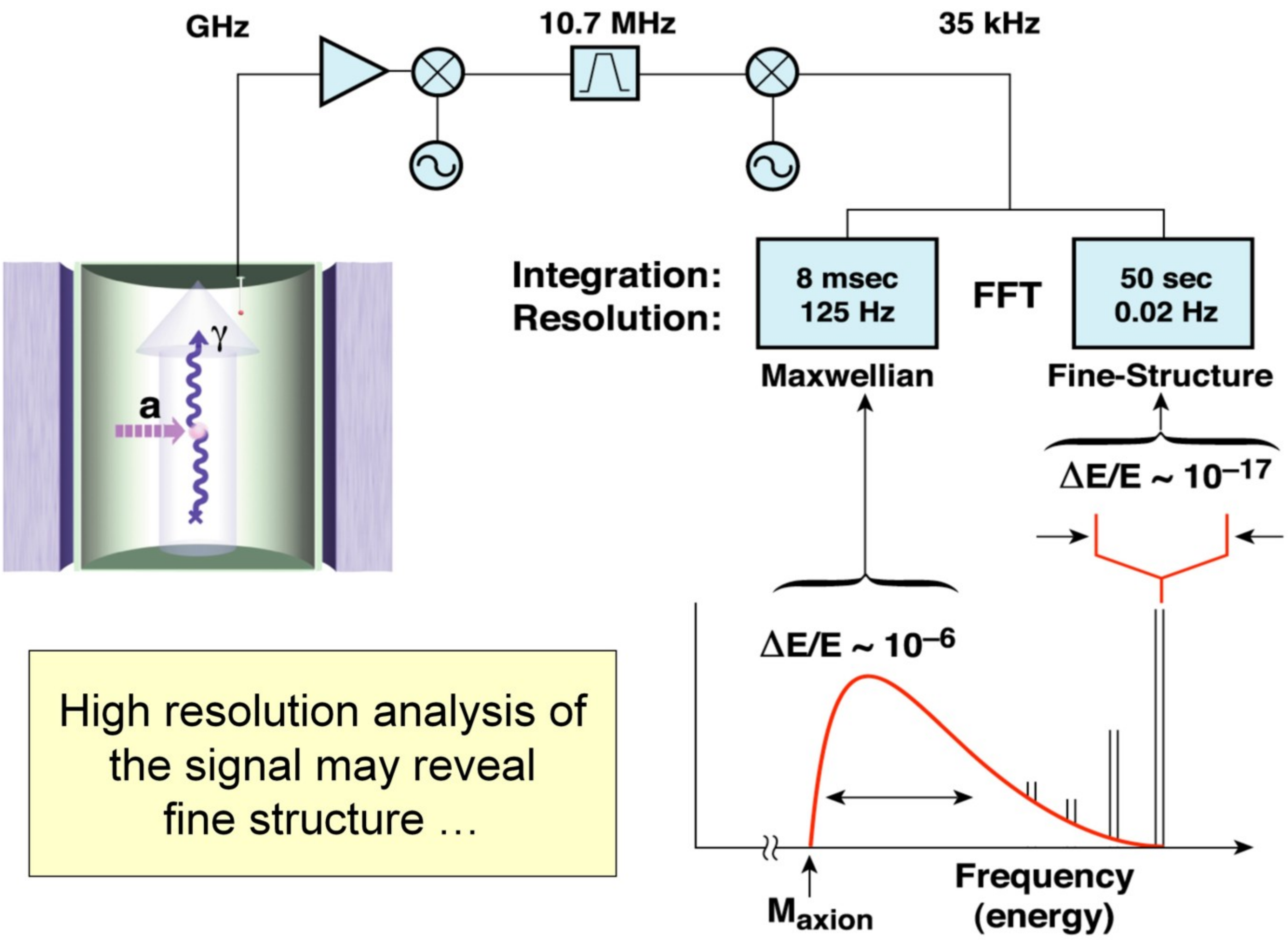




- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation r = o
- Grows self-consistent potential

Fine Structure in Axion Spectrum

- Axion distribution on a 3-dim sheet in 6-dim 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 ~ 1–100 μeV) 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