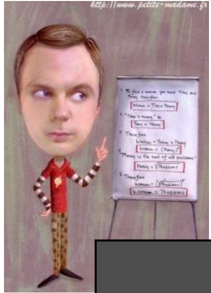
DARK SIDE OF THE UNIVERSE

ダークマター
アクシオンの探索

福井大学大学院工学研究科
小川　泉

Contents

1. Axionの簡単な紹介
   A) Strong CP problem
   B) “invisible” axions
2. Axion質量に対する制限
   A) 星の進化
   B) Cosmology
3. Axion searches
   A) Laser Experiments
   B) Axion helioscope
   C) Axion haloscope
4. Summary



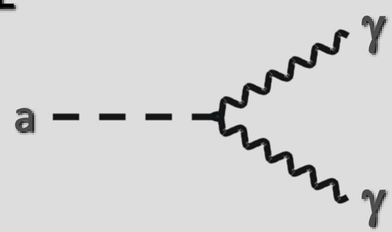
Axionとは？

素粒子物理学から

「QCDにおけるCPの破れの問題」を解決
Peccei-Quinn 対称性

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



$f_a \gg f_\pi$ axions は “見えない” かつ、非常に軽い

天体物理学から

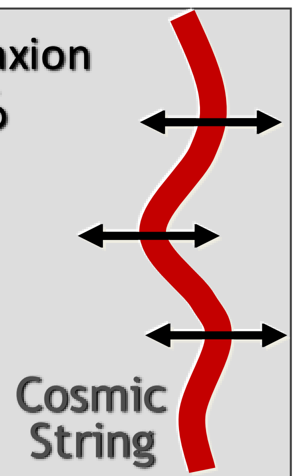
Axionは星（太陽）の中で作られる
Primakoff効果

- 星の成長からの制限
- 太陽アクシオンの探索(CAST, Sumico)

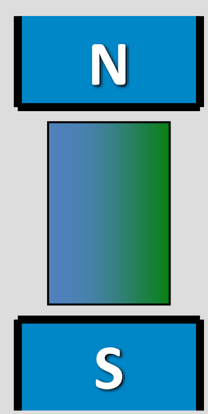
宇宙物理学から

軽い質量にもかかわらず, axion は非相対論的に生成される
(“non-thermal relics”)

→ “冷たい”ダークマターの候補
$m_a \sim$ 1-1000 μeV

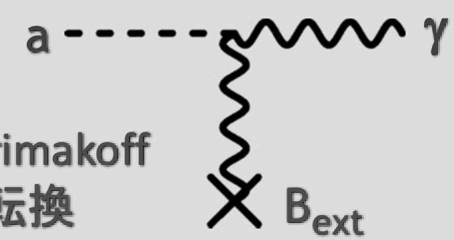


ダークマターaxionの探索



マイクロ波共振器
(1 GHz = 4 μeV)

Primakoff
転換



Strong CP problem

- 標準理論 : QCD Lagrangian は、CPを破る項を含んでいる。

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\leq\overline{\Theta}\leq 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

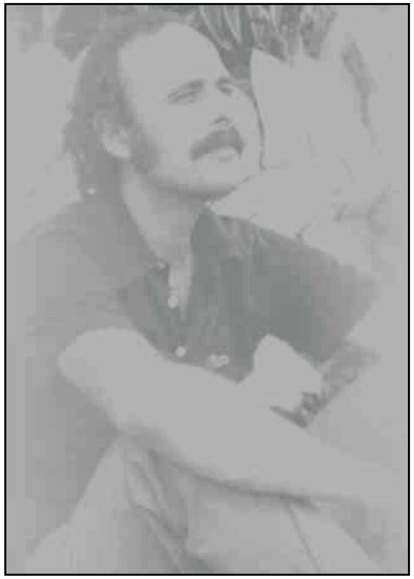
  - Θ: Characterizes degenerate QCD ground state (Θ vacuum)
  - arg det M_q : Phase of Quark Mass Matrix

- 実験: 中性子の電気双極子モーメント(nEDM)

$$d_n \approx \overline{\Theta}\,10^{-16}\,e\,cm \approx \frac{\overline{\Theta}}{10^2}\,\mu_n < 3\times 10^{-26}\,e\,cm$$

$\overline{\Theta} \lesssim 10^{-10}$ Why so small ?

Peccei–Quinn Mechanism (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*

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[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

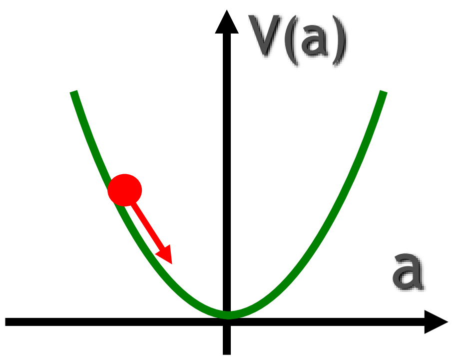
PQ symmetry

- Dynamical Solution – Peccei & Quinn (1977)
  - Re-interpret $\bar{\Theta}$ as a dynamical variable (scalar field)

$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

⇒ Pseudo-scalar axion field

⇒ Peccei-Quinn scale, axion decay constant

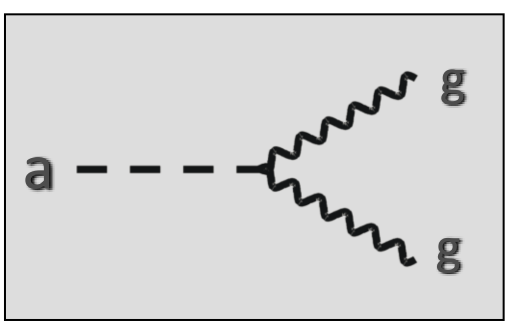


$\bar{\Theta} = 0$

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

⇩

CP symmetry dynamically restored



Axions couple to gluons and mix with π^0

$$m_a = \frac{z^{1/2}}{1+z} m_\pi \frac{f_\pi}{f_a} = 0.6\,\mathrm{meV}\,\frac{10^{10}\,\mathrm{GeV}}{f_a}$$

$$z = m_u / m_d = 0.56\,(0.35 - 0.60)$$

Axionsの提唱 (1978)

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

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 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-

$U(1)_{PQ}$], 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 $U(1)_{PQ}$ 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

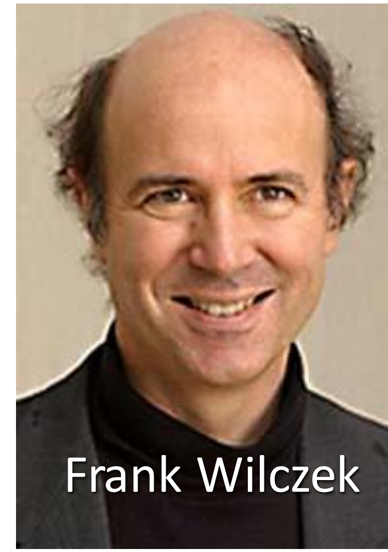
F. Wilczek[(a)]
Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[(b)]
(Received 29 November 1977)

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 $3\oplus3^*$ 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-



"I named them after a laundry detergent, since they clean up a problem with an axial current."
(2004年ノーベル賞記念講演)

“invisible” axion

- アクシオン

  (Weinberg 1978, Wilczek 1978)

  - Peccei-Quinn scale $f_a = f_{ew}$ (electroweak scale)
  - 実験等により排除される

- 「見えない」アクシオン

  (KSVZ; Kim 1979, Shifman, Vainshtein, Zakharov 1980,

  DFSZ; Dine, Fischler, Srednicki 1981, Zhitnitsky 1980)

  - $f_a \gg f_{ew}$
  - 非常に軽く、相互作用が小さい

$$L_{a\gamma\gamma} = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a$$

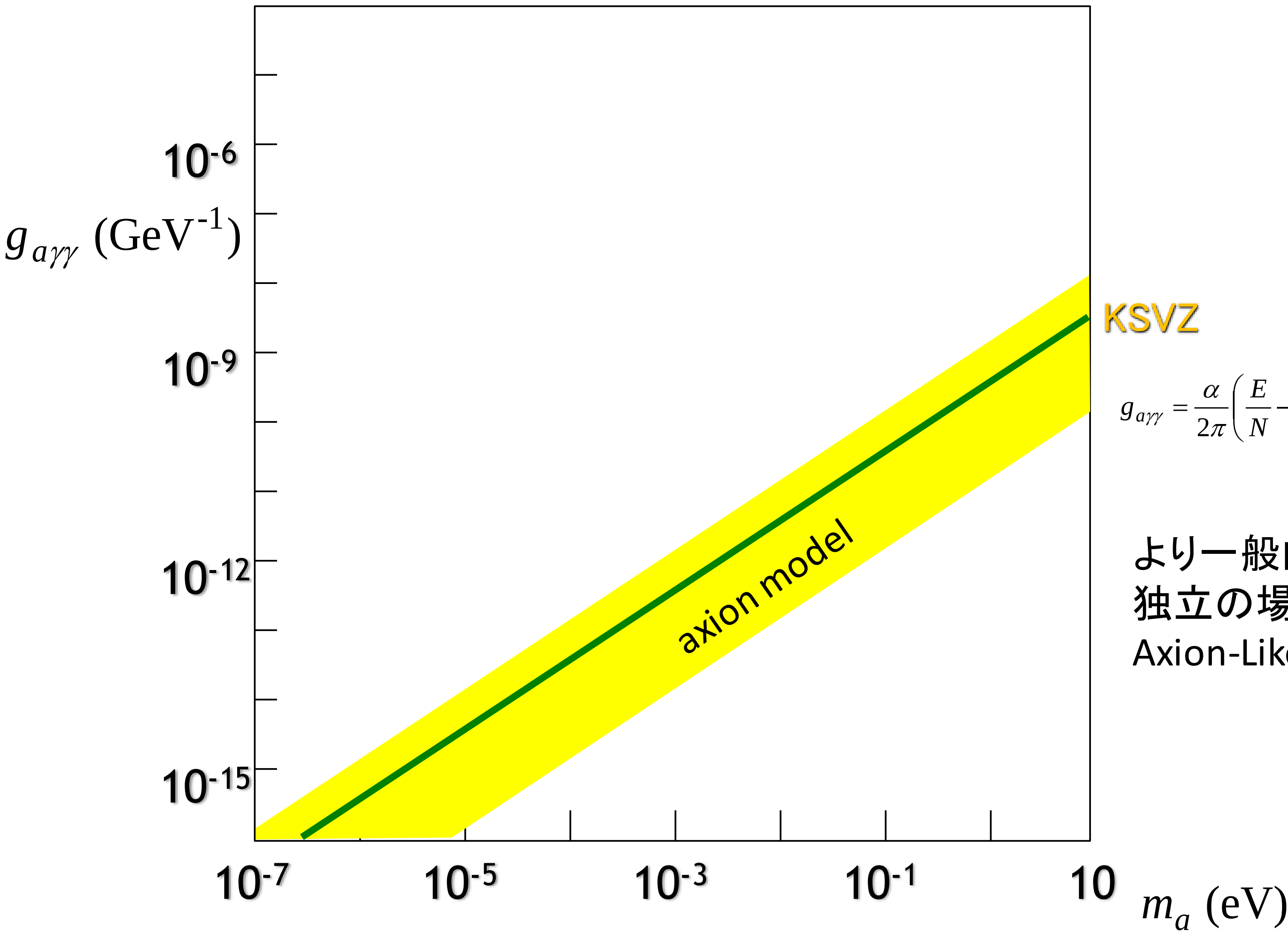
$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)\frac{1+z}{z^{1/2}}\frac{m_a}{m_\pi f_\pi}$$

$\frac{E}{N} = 0$ KSVZ (“hadronic” axion)

$= \frac{8}{3}$ DFSZ

※他にもさまざまなモデルあり

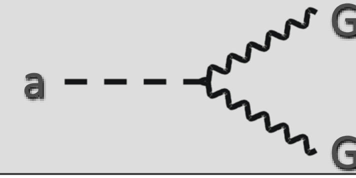
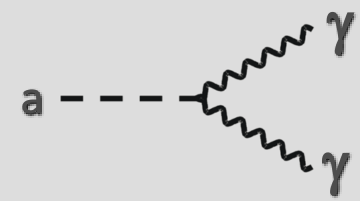
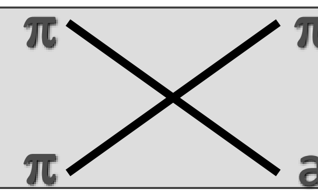
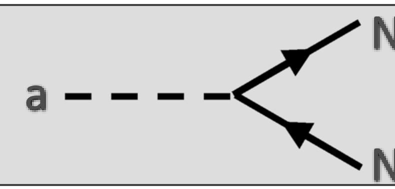
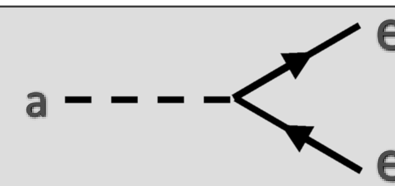
$g_{a\gamma\gamma}$ VS m_a



$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)\frac{1+z}{z^{1/2}}\frac{m_a}{m_\pi f_\pi}$$

より一般的にmとgが
独立の場合
Axion-Like Particles (ALPs)

Axion Properties

Gluon coupling (Generic property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass	$m_a = \frac{0.6\,\mathrm{eV}}{f_a / 10^7\,\mathrm{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma} \vec{E}\cdot\vec{B}a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \ldots)\partial^\mu a$	
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \, \partial_\mu a$	
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \, \partial_\mu a$	

Axion質量に対する制限

- PDG, Phys. Rev. D86 (2012) 010001

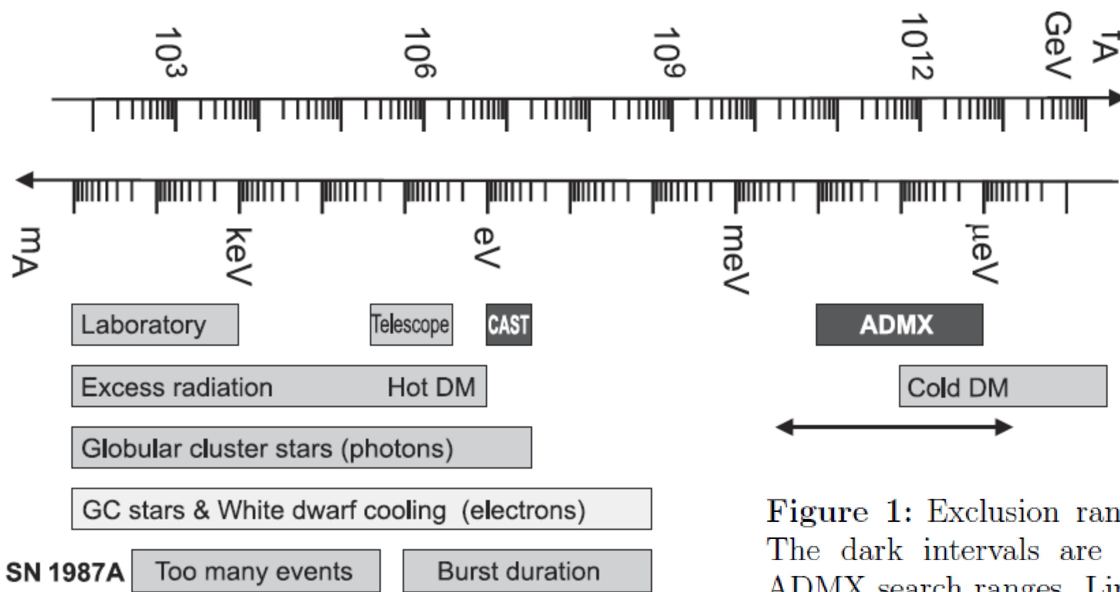
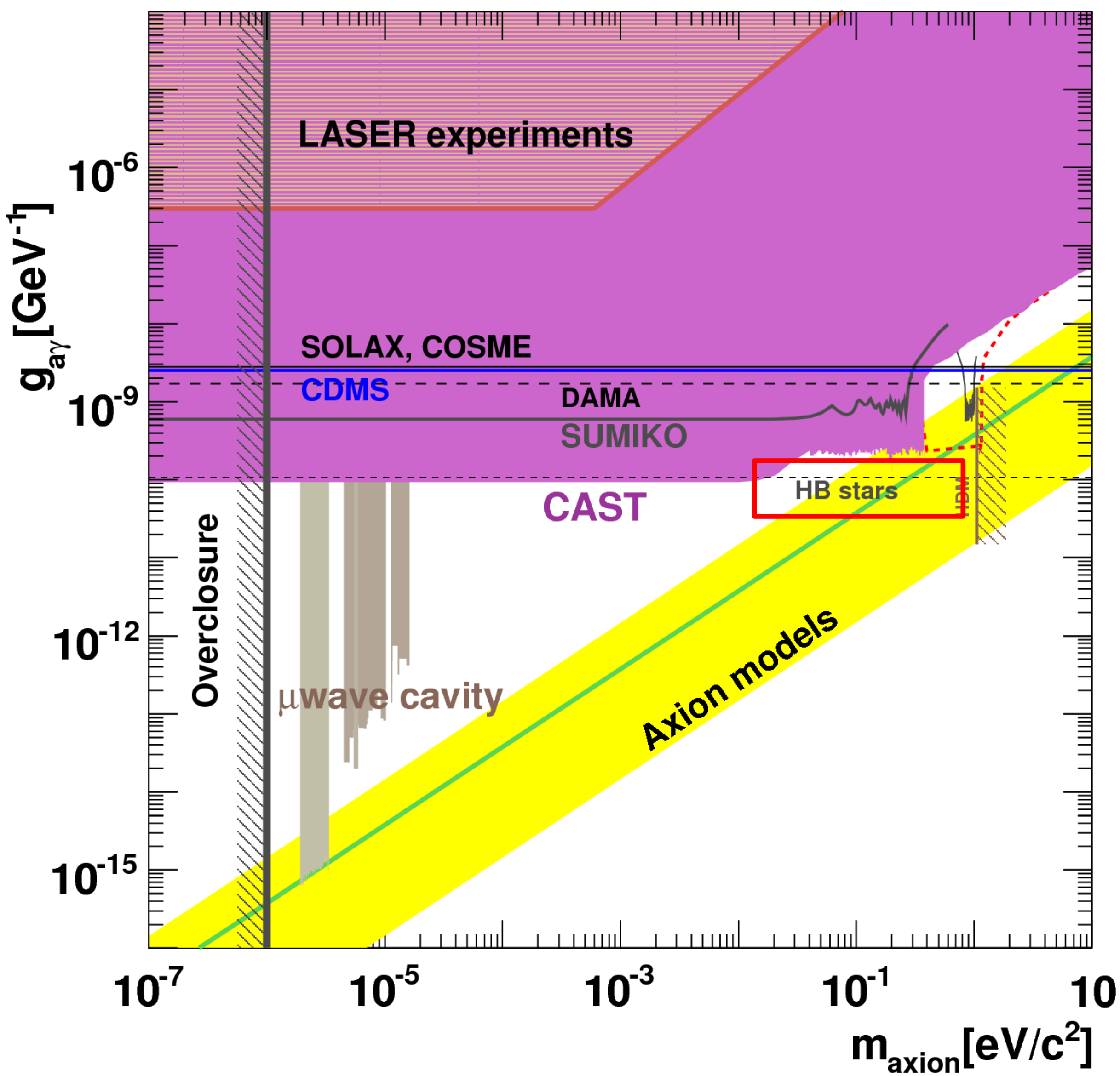


Figure 1: Exclusion ranges as described in the text. The dark intervals are the approximate CAST and ADMX search ranges. Limits on coupling strengths are translated into limits on m_A and f_A using $z = 0.56$ and the KSVZ values for the coupling strengths. The "Laboratory" bar is a rough representation of the exclusion range for standard or variant axions. The "GC stars and white-dwarf cooling" range uses the DFSZ model with an axion-electron coupling corresponding to $\cos^2\beta = 1/2$. The Cold Dark Matter exclusion range is particularly uncertain. We show the benchmark case from the misalignment mechanism.

World exclusion plot

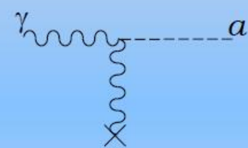


- 星の進化
- Cosmology
- Laser実験
- Solar axion search
- Halo axion search

星の進化からの制限

Light ALPs can be produced in stars through various mechanisms, e.g.

Primakoff conversion
$$\gamma + Ze \rightarrow a + Ze$$

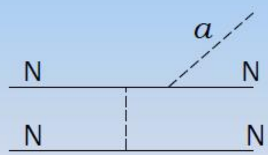


Relevant in He-burning stars

Compton scattering
$$\gamma + e \rightarrow a + e$$

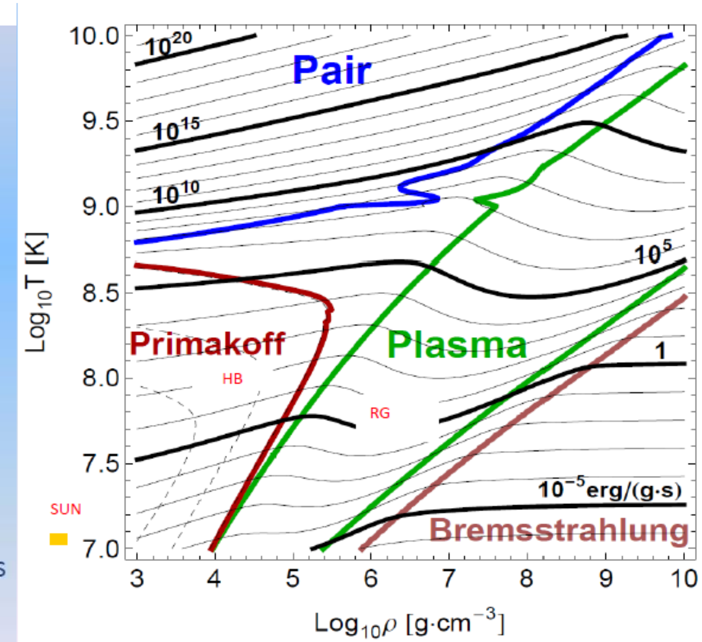
Relevant in RG and WD

Nucleon Bremsstrahlung
$$N + N \rightarrow N + N + a$$



Relevant in SN and neutron stars

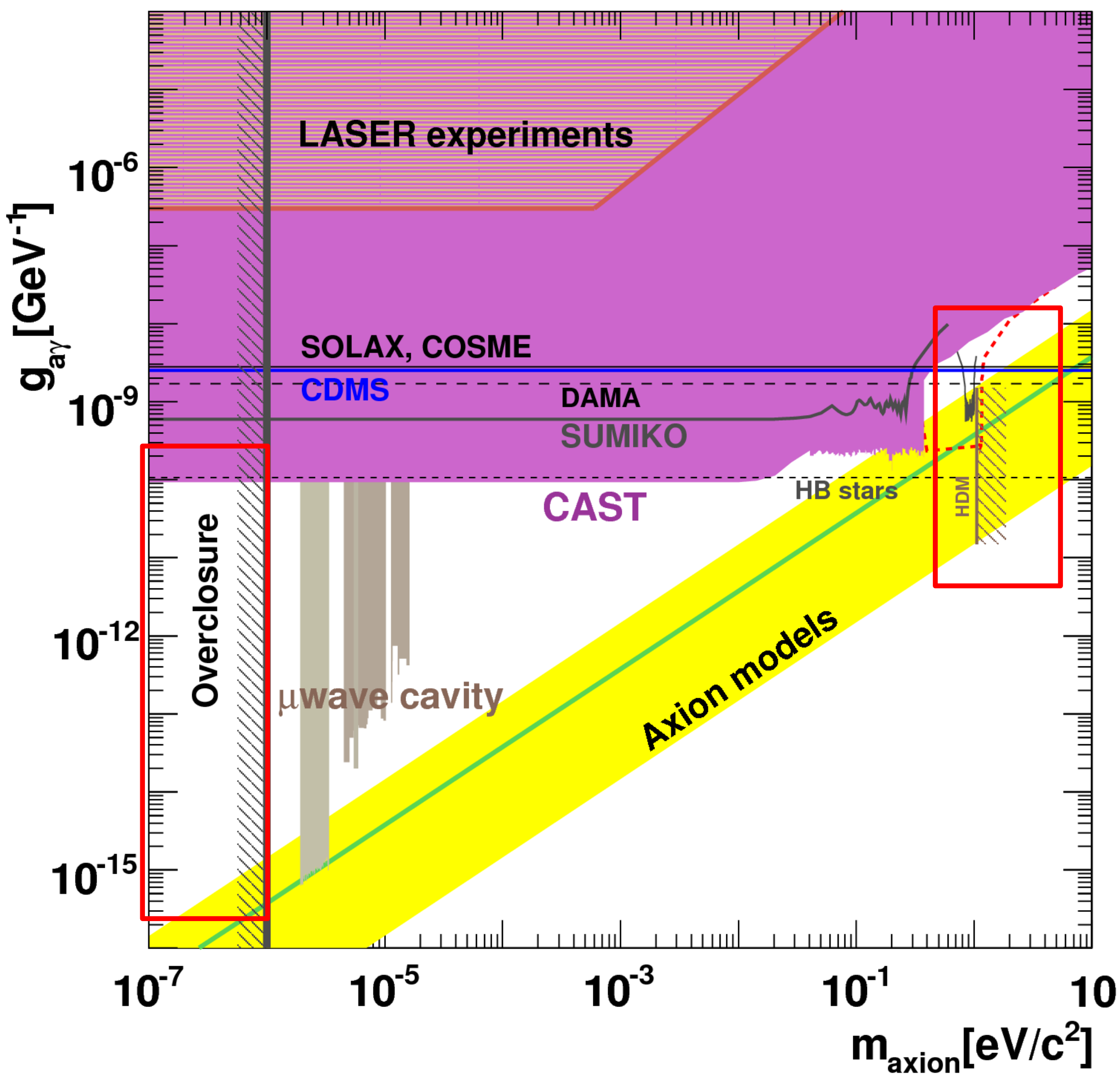
The emission of axions could lead to an *overly efficient energy drain*, inconsistent with observations. This leads to bounds on the axion couplings with photons, electrons and nuclei.



HB stars are, evidently, in the region where axion dominates over neutrino cooling

- **Maurizio Giannotti, 9th Patras Workshop**

World exclusion plot



- 星の進化
- **Cosmology**
- Laser実験
- Solar axion search
- Halo axion search

Cosmology
Axion Hot Dark Matter

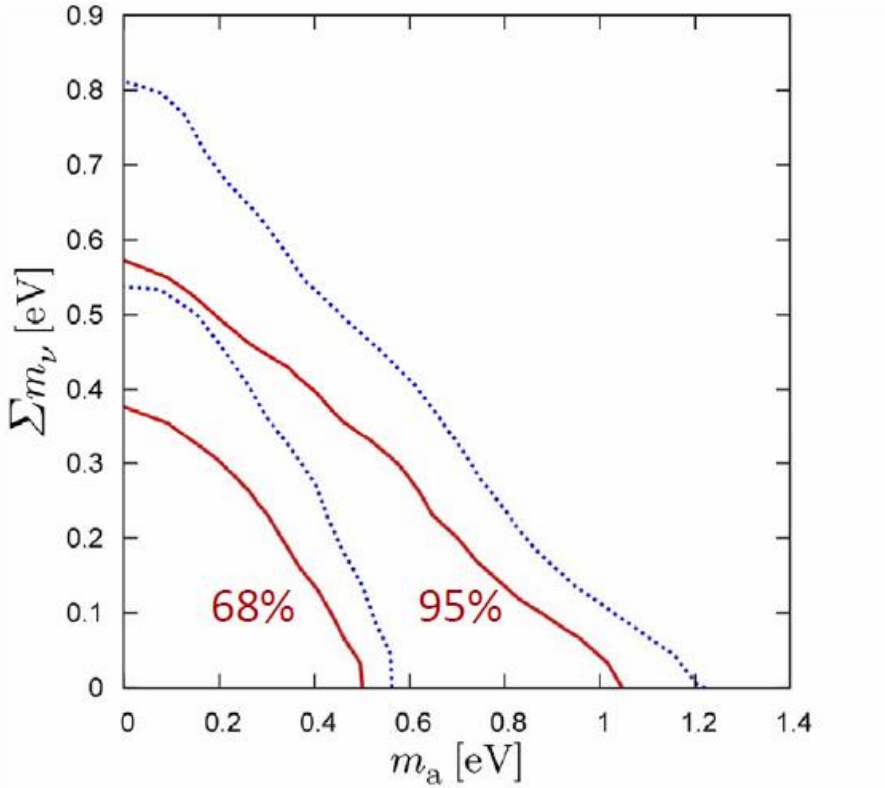


Figure 1. 2D marginal 68% and 95% contours in the $\sum m_\nu$–m_a plane. The blue lines correspond to our results using CMB+HPS, and the red lines using CMB+HPS+HST.

Credible regions for neutrino plus axion hot dark matter (WMAP-7, SDSS, HST) Hannestad, Mirizzi, Raffelt & Wong [arXiv:1004.0695]

Marginalizing over neutrino hot dark matter component

$m_a < 0.7$ eV (95% CL)

Assuming no axions

$\sum m_\nu < 0.4$ eV (95% CL)

- G. Raffelt, Vistas in Axion Physics

Cosmology
Axion Cold Dark Matter

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

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

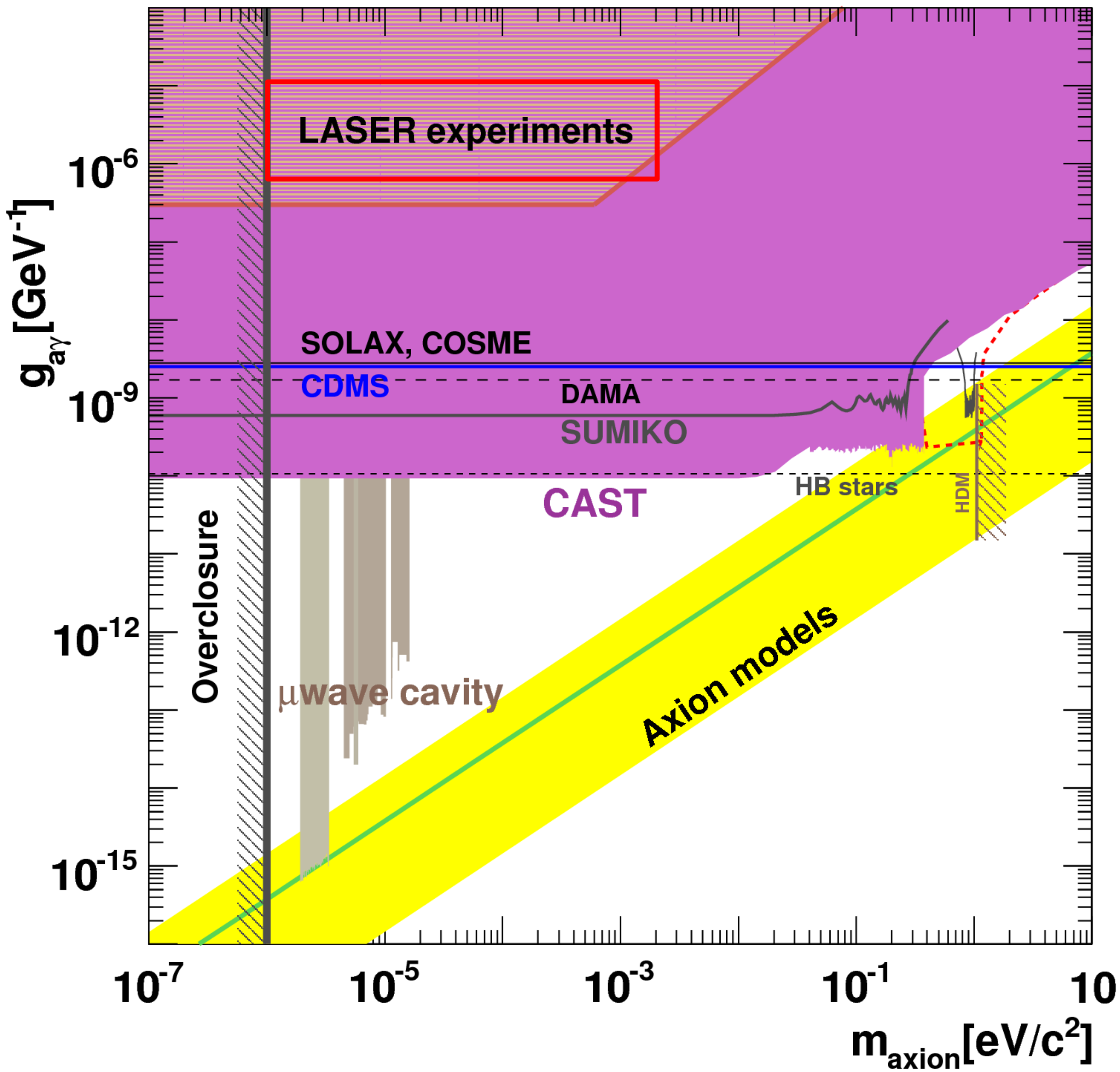
If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

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

- $\Theta_{\mathrm{i}} \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu$eV

- G. Raffelt, Vistas in Axion Physics

World exclusion plot



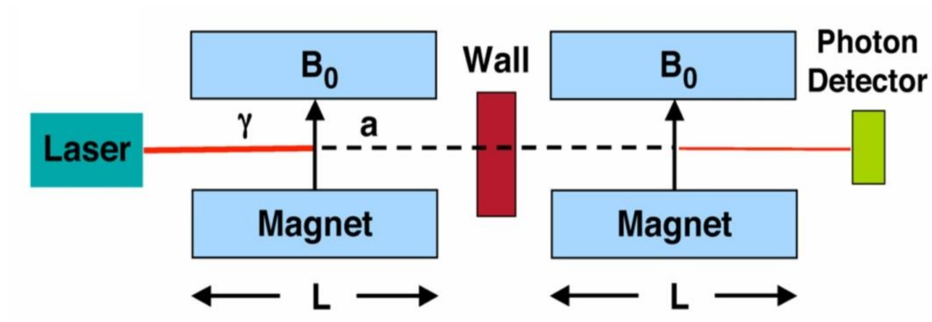
- 星の進化
- Cosmology
- **Laser実験**
- Solar axion search
- Halo axion search

Laser実験

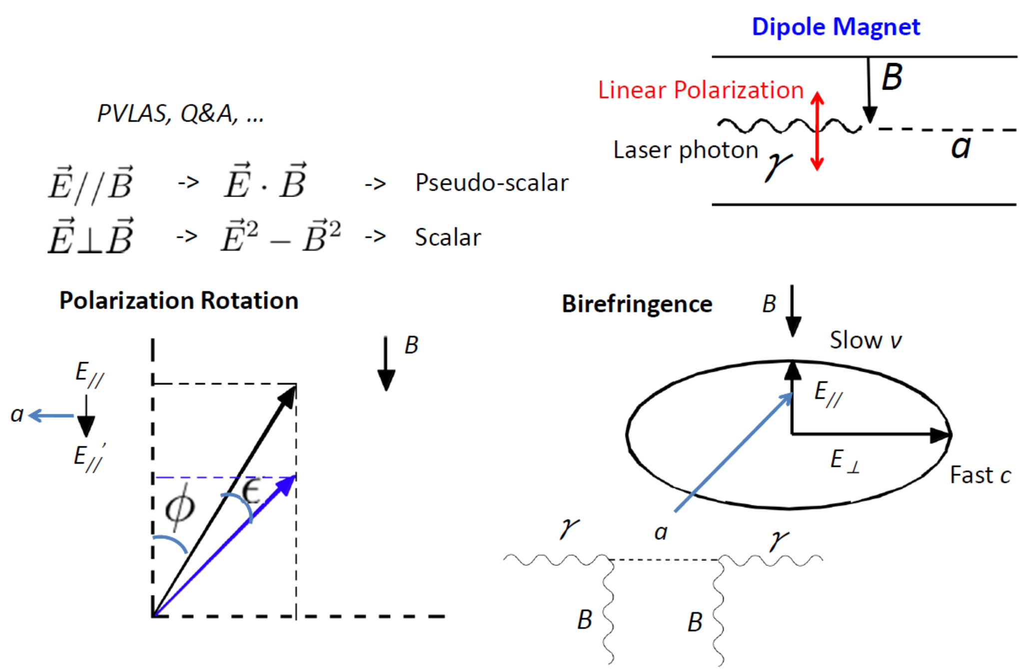
- Light Shining through Walls (LSW)実験

$$P(\gamma \to a \to \gamma) = \Pi^2$$

$$\Pi^2 \sim \frac{1}{4}\left(g_{a\gamma\gamma} B_0 L\right)^2$$



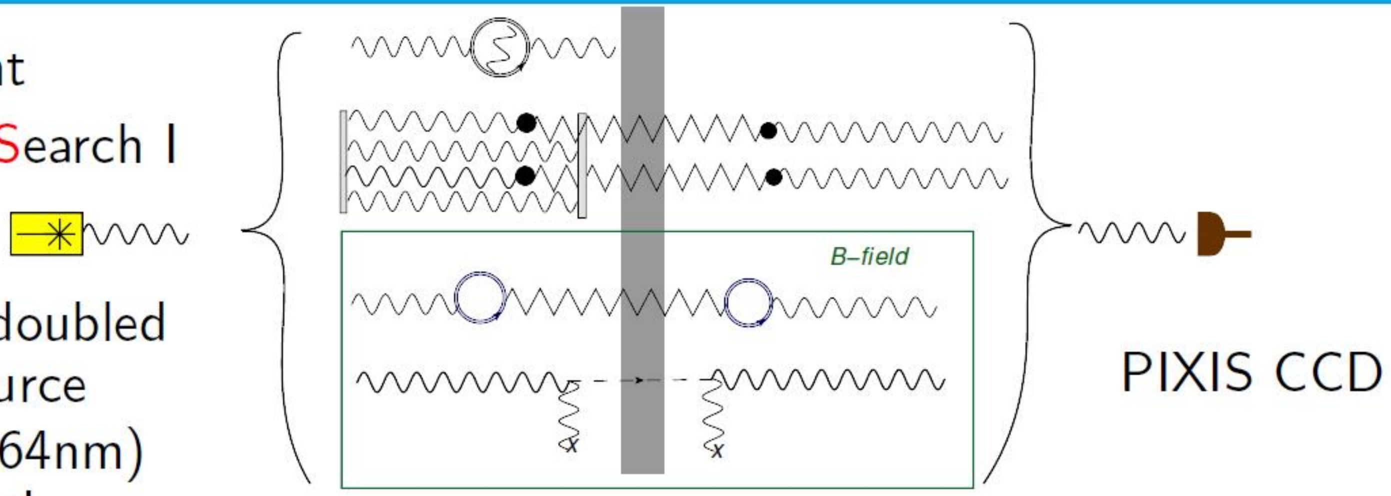
- Polarization実験

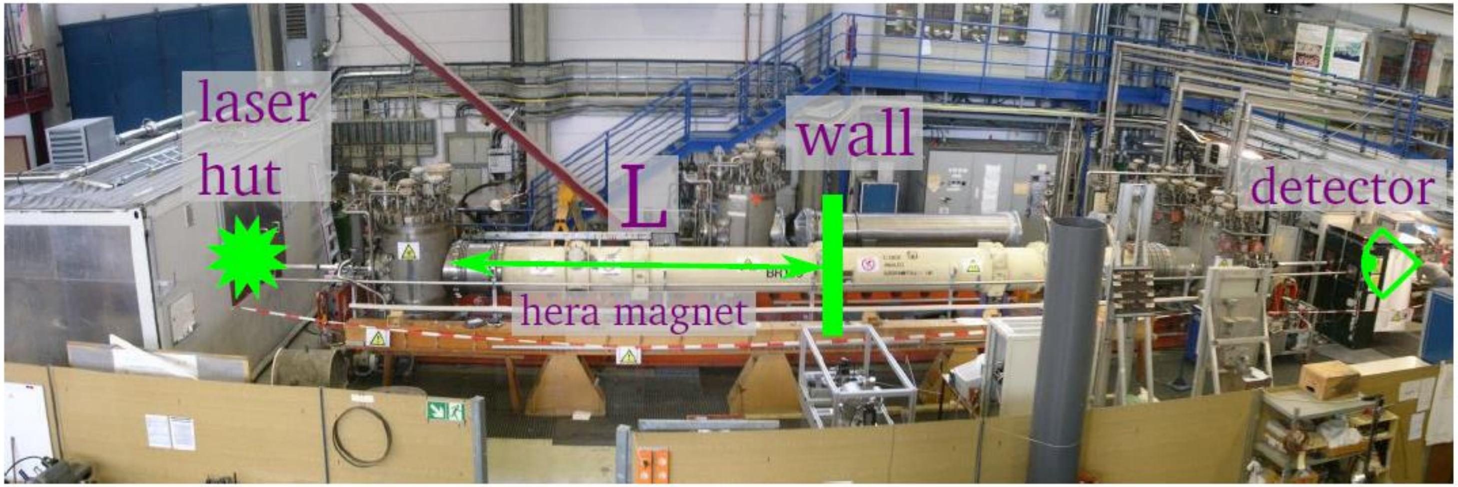


ALPS-I (2010) and upgrades towards ALPS-II

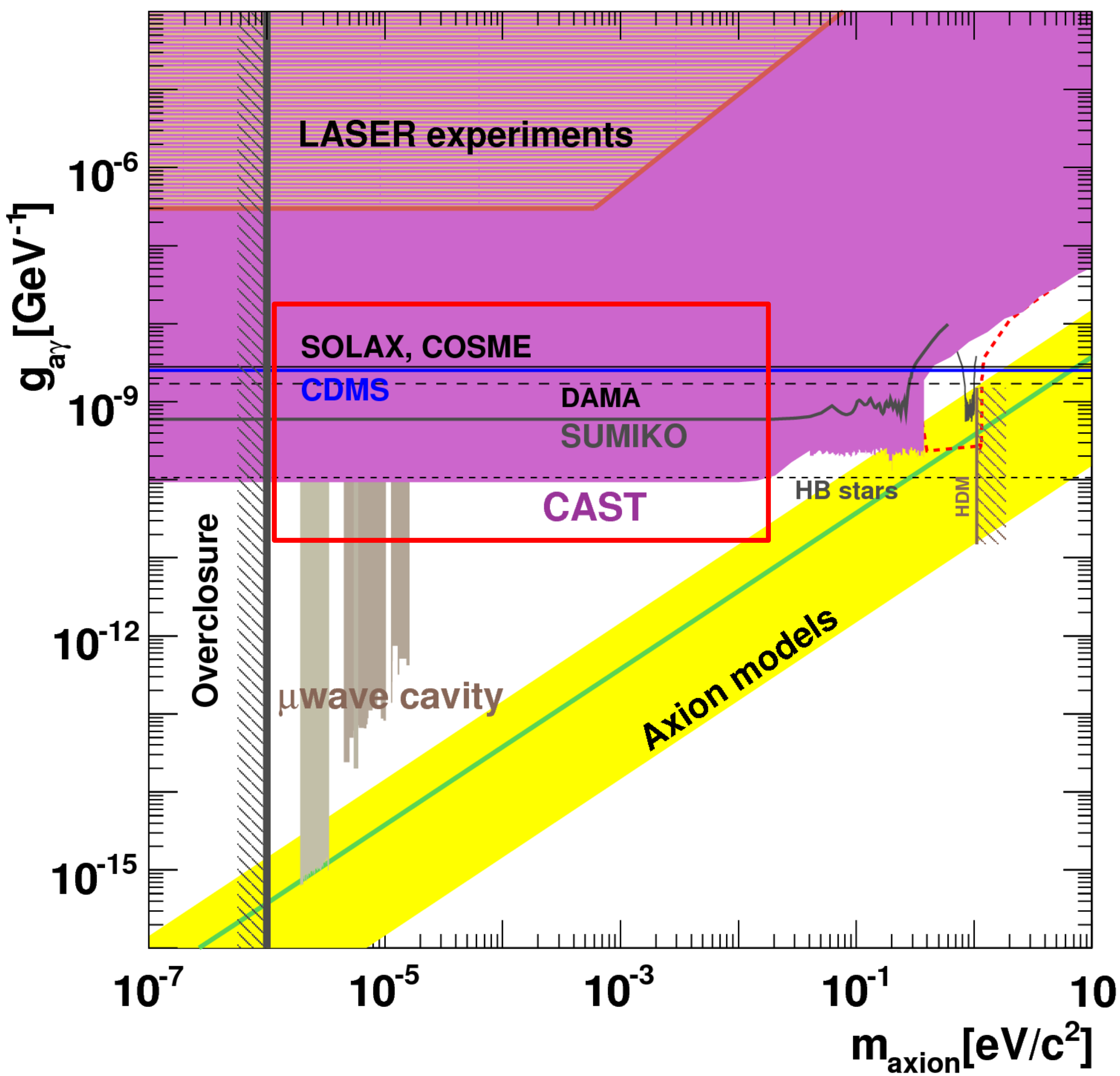
Any Light
Particle Search I

frequency doubled infrared source ('35W', 1064nm) +Resonator!



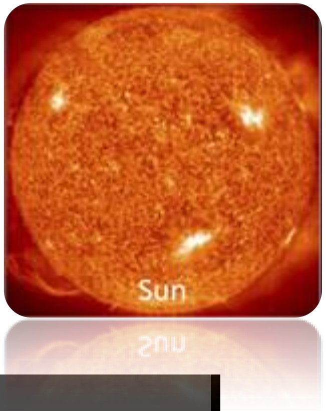


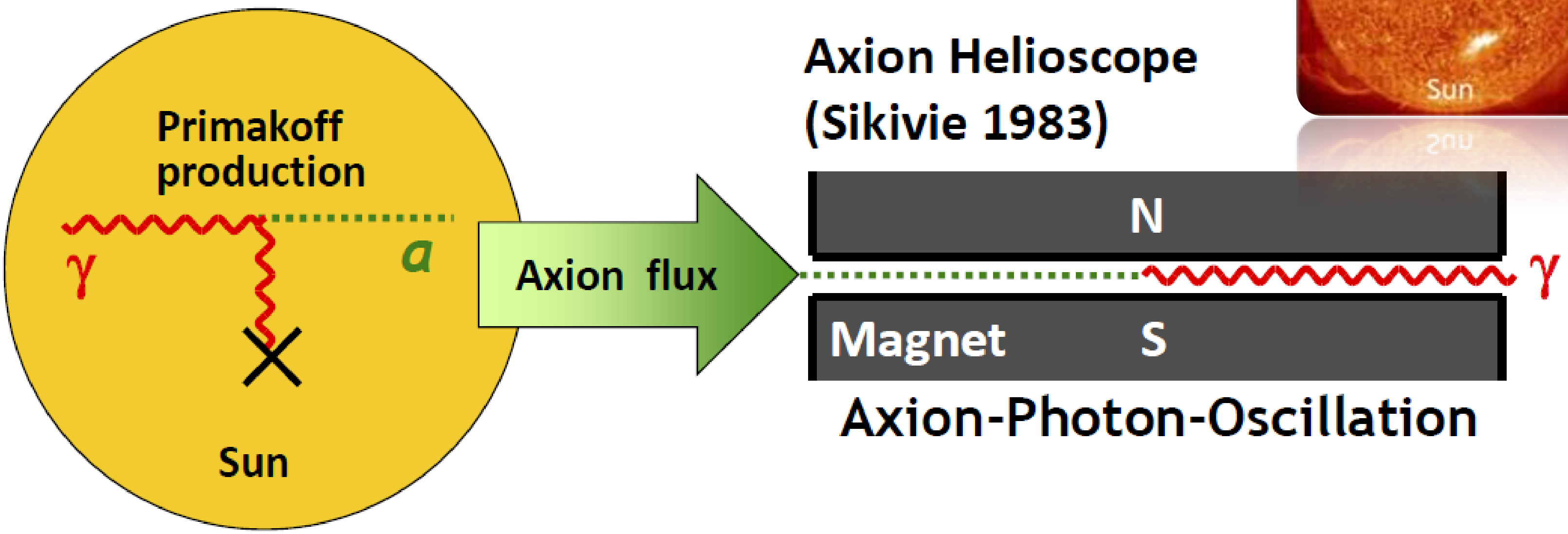
World exclusion plot

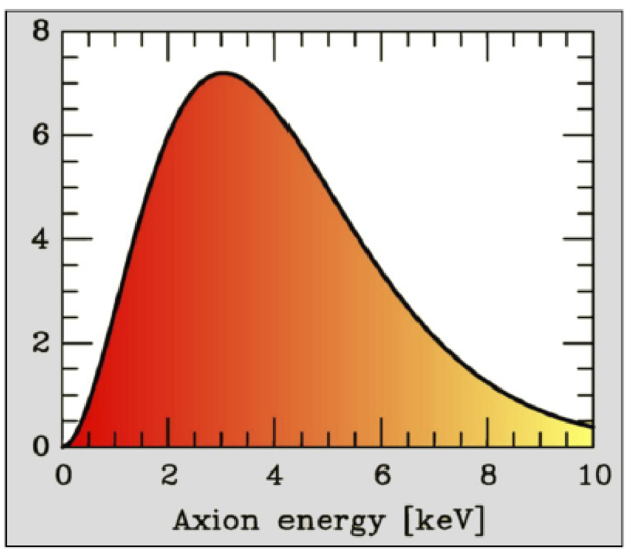


- 星の進化
- Cosmology
- Laser実験
- **Solar axion search**
- Halo axion search

太陽アクシオン



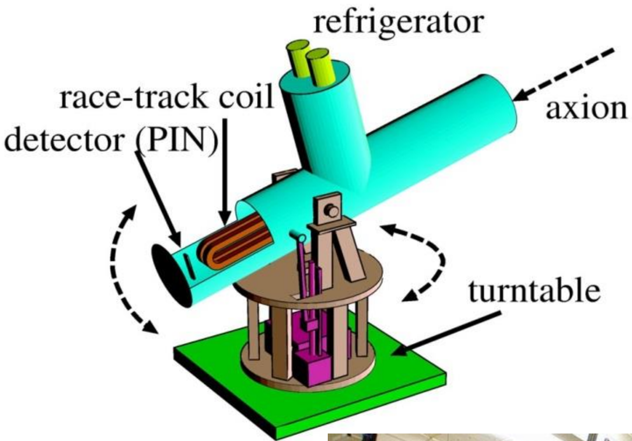


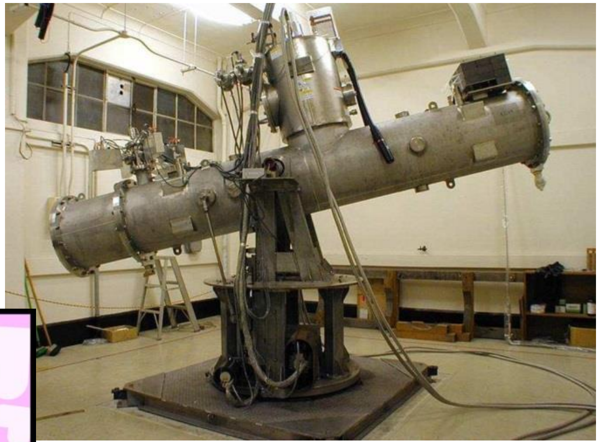


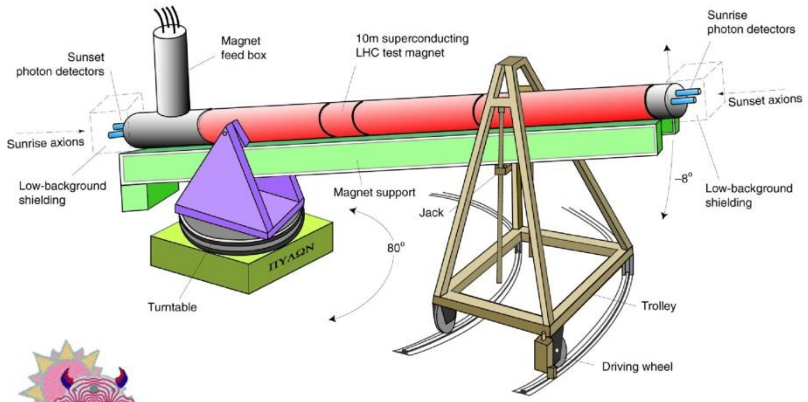
- Tokyo Axion Helioscope ("Sumico") (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

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

Axion Helioscope
Sumico & CAST

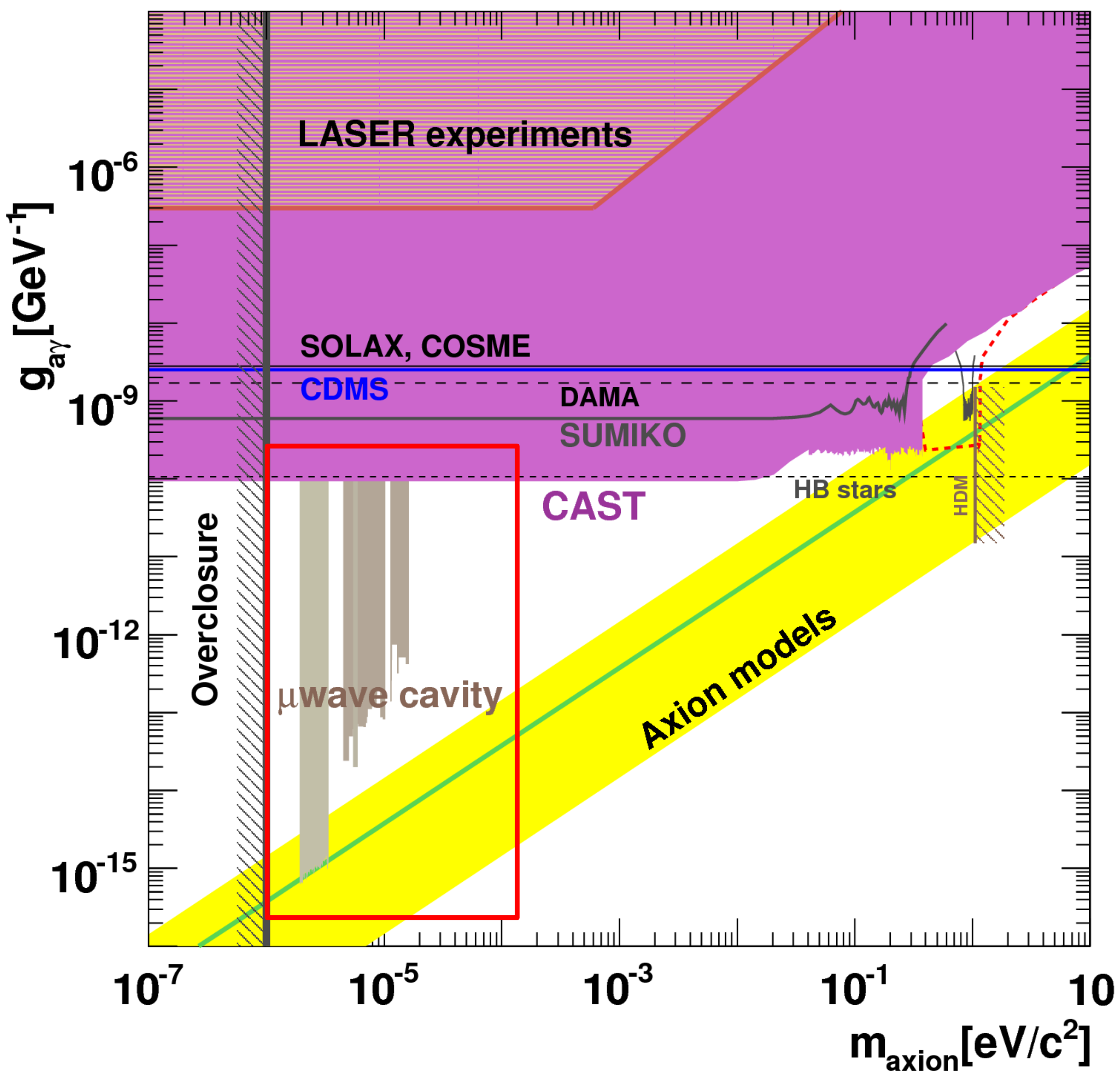






Cern Axion Solar Telescope

World exclusion plot



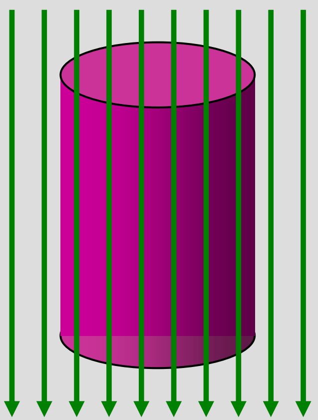
- 星の進化
- Cosmology
- Laser実験
- Solar axion search
- **Halo axion search**

Dark Matter (Halo) Axion

DM axionsの質量　m_a = 1-1000 μeV
銀河系での速度　$v_a \approx 10^{-3}\,c$
エネルギー　$E_a \approx (1 \pm 10^{-6})\,m_a$

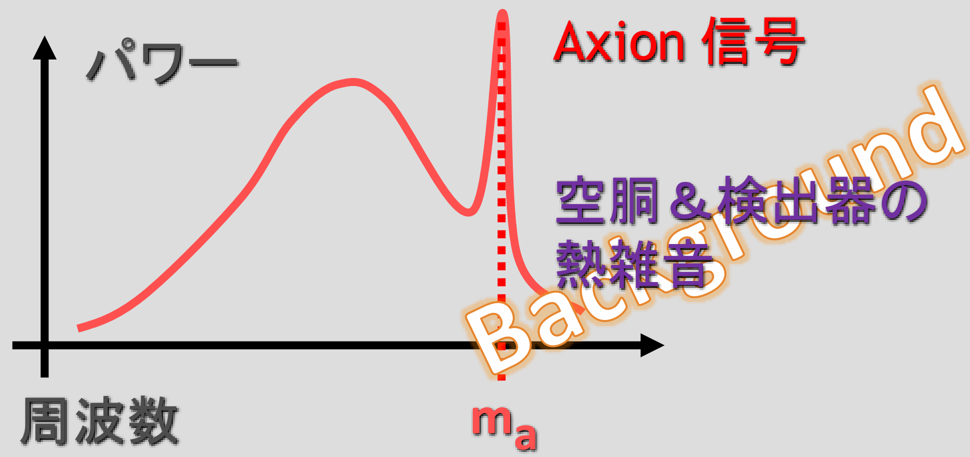
→ マイクロ波エネルギー
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

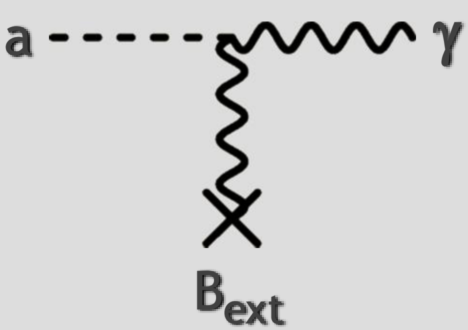


$B_{ext} \approx 8$ Tesla

マイクロ波
共振器
$Q \approx 10^5$



Primakoff 変換



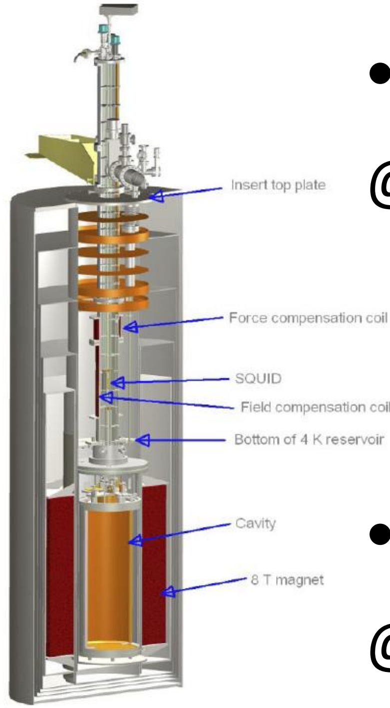
銀河中のaxionによる信号のパワー

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

Axion Haloscope

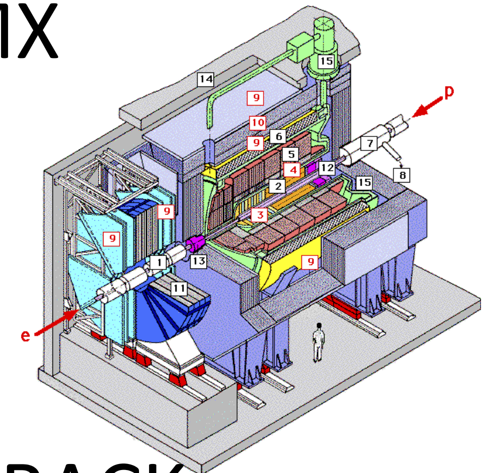
- ADMX-II

  @U. Washington



- WISPDMX

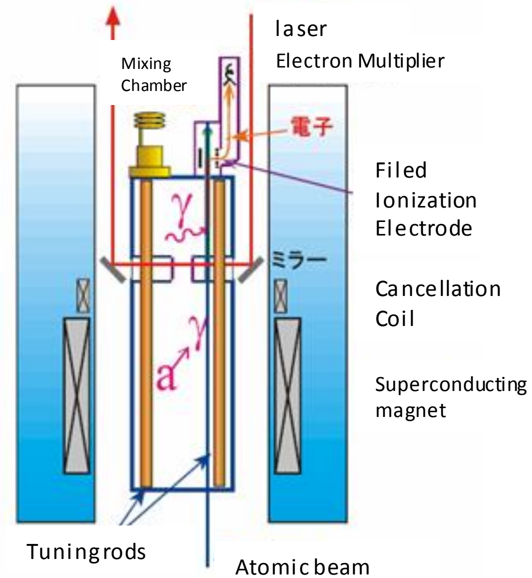
  @DESY



- Yale

- newCARRACK

  @京大



sensitivity

$$\frac{S}{N} = \frac{P_{sig}}{kT_s} \cdot \sqrt{\frac{t}{\Delta\nu}} \qquad P_{sig} \sim B^2 V Q m_a \rho_a$$

- System Noise Temperature

$$T_s = T + T_N$$

- 温度 : T=10~100 mK
  - 希釈冷凍器
- 検出器の等価雑音温度: HFET amp.
  - SQUID アンプ
    - ADMX
  - Rydberg原子による単一光子計数
    - CARRACK

Standard Quantum Limit

- 光子数と位相は同時には不確定

$$\Delta n \cdot \Delta \phi \geq \frac{1}{2}$$

  - 増幅器の使用

    振幅と位相の同時観測

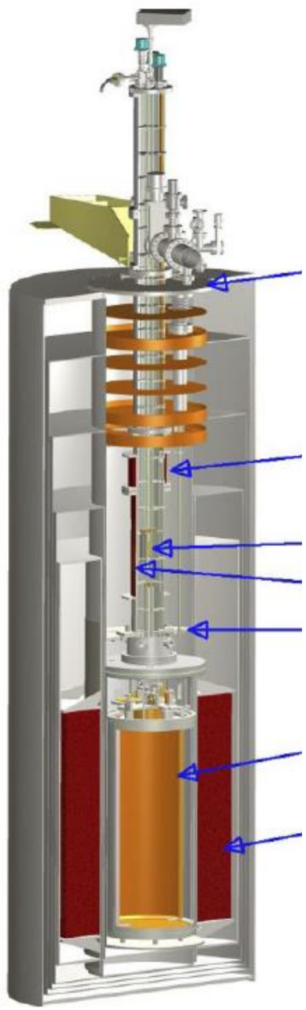
    ⇒ $\hbar\omega/k_B$程度の熱雑音に相当（$10\mu\mathrm{eV} \Leftrightarrow 0.116\ \mathrm{K}$）

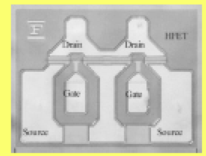
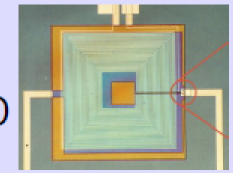
  - Rydberg原子の遷移

    マイクロ波の位相によらない

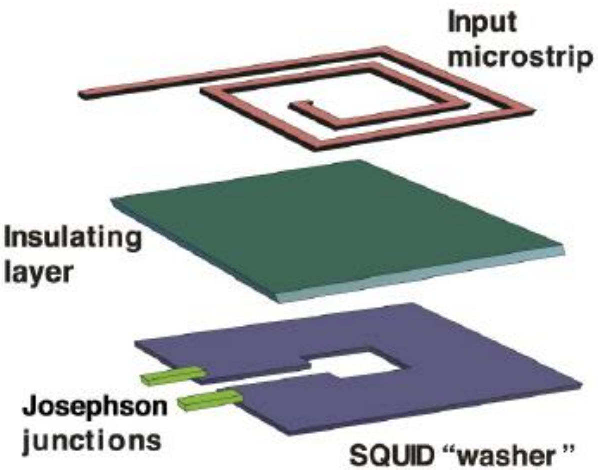
    ⇒ SQLなし

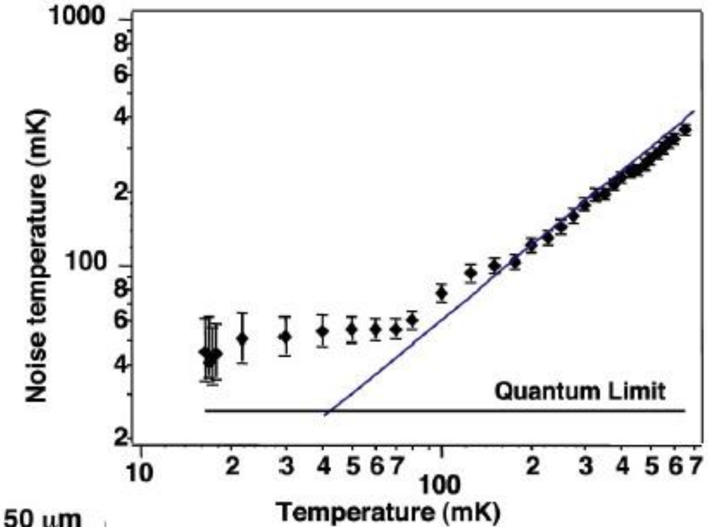
Axion Dark Matter eXperiment

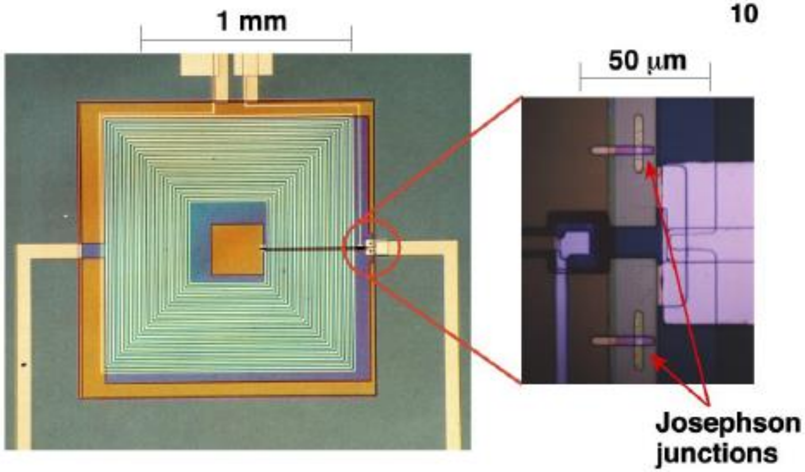


Stage	**Phase 0**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Dilution Fridge 
T_{phys}	2 K	2 K	100 mK
T_N	2 K	1 K	100 mK
$T_{sys} = T_{phys} + T_N$	4 K	3 K	200 mK
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	1.75 @ KSVZ	5 @ DFSZ
		OR	*AND !*
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	0.75 x KSVZ	DFSZ

SQUID in ADMX



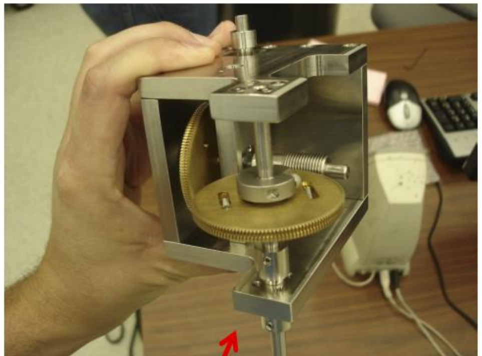


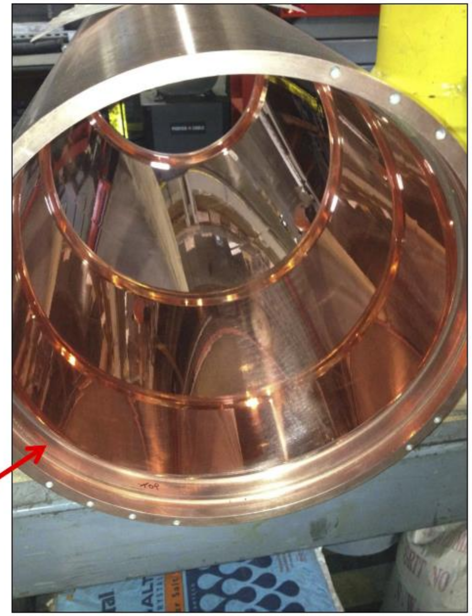


(J. Clarke *et al.*, U.C. Berkeley)

- At least to 100 mK
- Must reduce cavity physical temperature to below 100 mK also.

ADMX



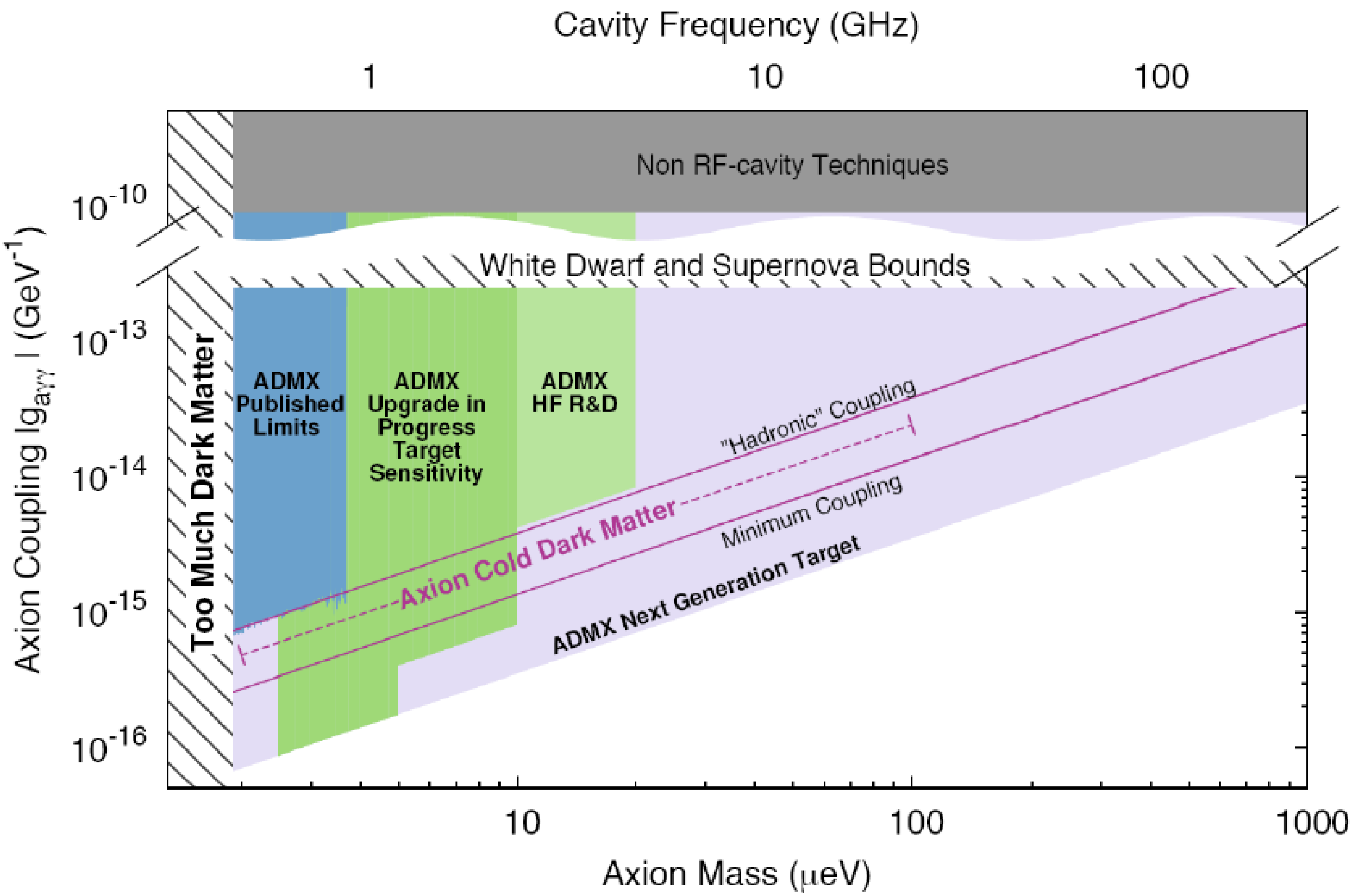


New modular gear systems
(19600:1 reduction)

Newly plated microwave cavity

Summer 2010.
Magnet has been cooled and energized.

ADMX sensitivity

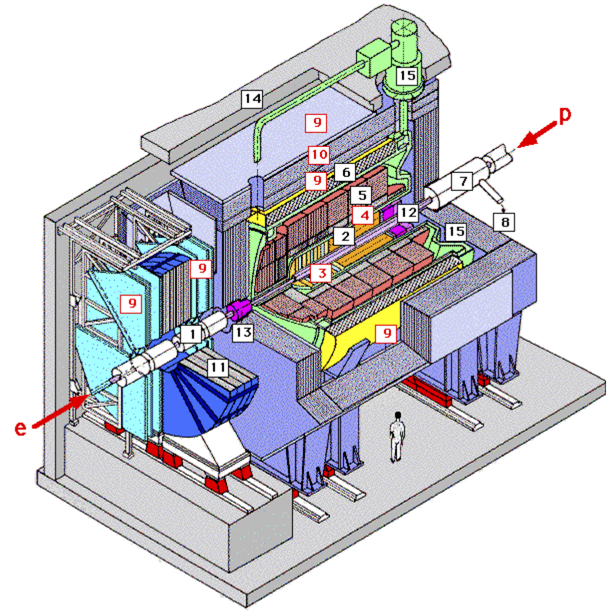


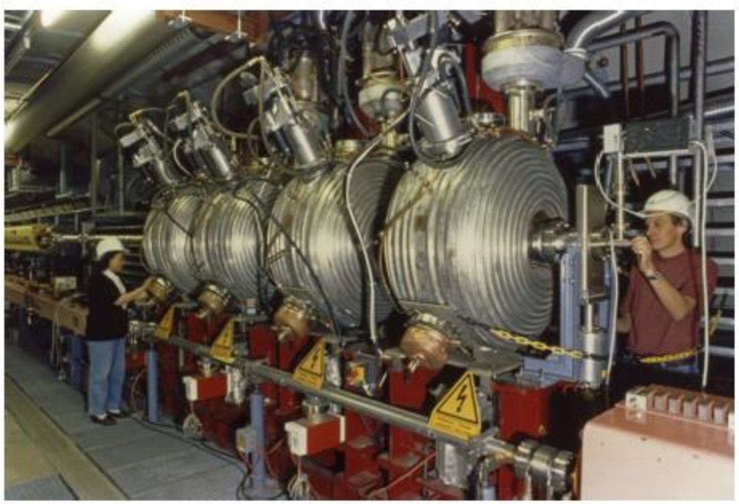
Will scan the lower-mass decade at or below DFSZ sensitivity

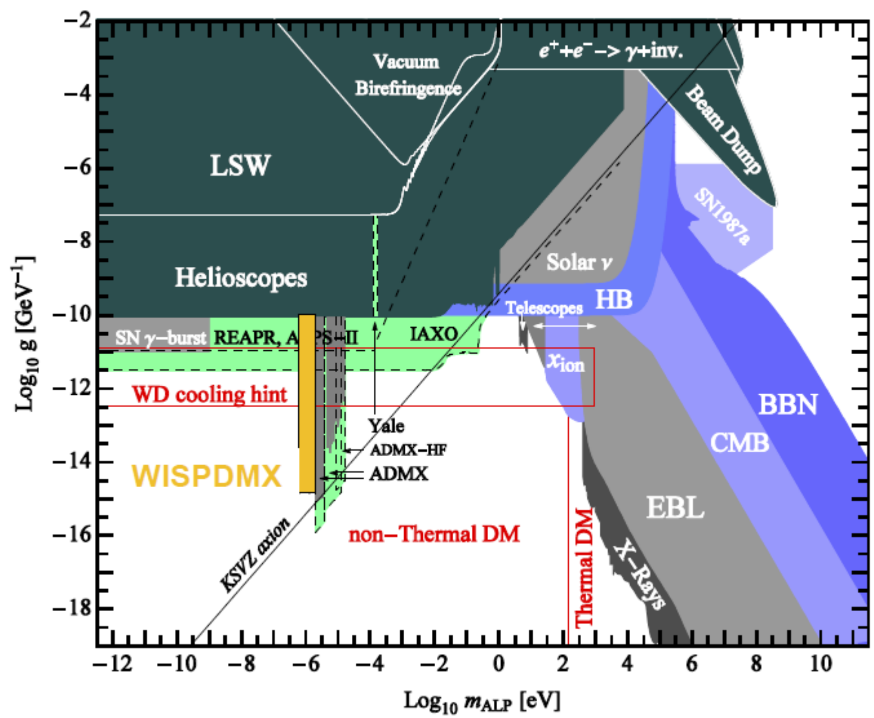
WISPDMX

> Available building blocks (DESY)
  - HERA proton ring cavities
  - H1 superconducting solenoid

> Available competence (MPIfR)
  - receiver, amplifier, FFT, …





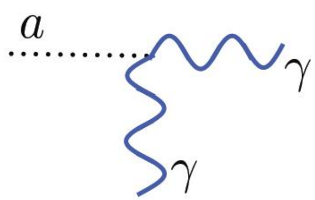


A. Ringwald

Yale

- 重い質量領域($m_a = 0.14$ meV)の探索

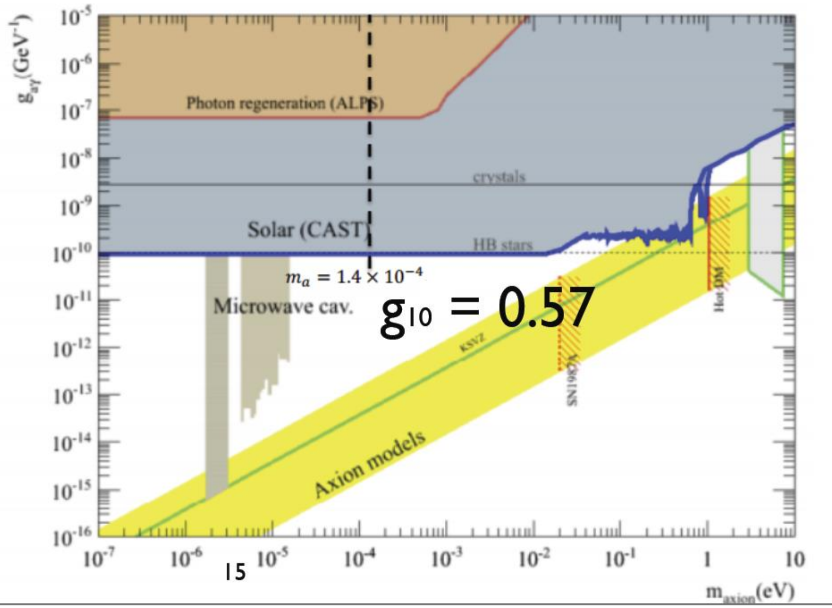
Dark Matter ALPs



$$P_{\rm sig} = g_\gamma^2 B^2 C_{020} V Q \rho_a / m_a$$

integration time
50 minutes

$$B = 7\ \mathrm{T}$$
$$C_{020} = 0.12$$
$$V = 1.6\ \mathrm{cm}^3$$
$$Q \approx 10,000$$
$$m_a = .14\ \mathrm{meV}$$
$$\rho_a = .3\ \mathrm{GeV/cm^3}$$



TM$_{020}$ Cavity

A.T. Malagon
9th Patras Workshop

CARRACK（華洛）

- Rydberg原子によるマイクロ波光子検出
  - SQLなし！
  - Rydberg原子
    - （主としてアルカリ原子で）最外殻電子が主量子数nの大きい（～100）状態に励起した原子
    - Large radius $\propto n^2$ $(R = 0.13\mu m$ for n=50)
    - Long lifetime $\tau \propto n^3$ ~ msec for n~100
    - Energy level $E_n \propto n^{-2}$
    - Energy separation $E_{np} - E_{ns} \propto n^{-3}$

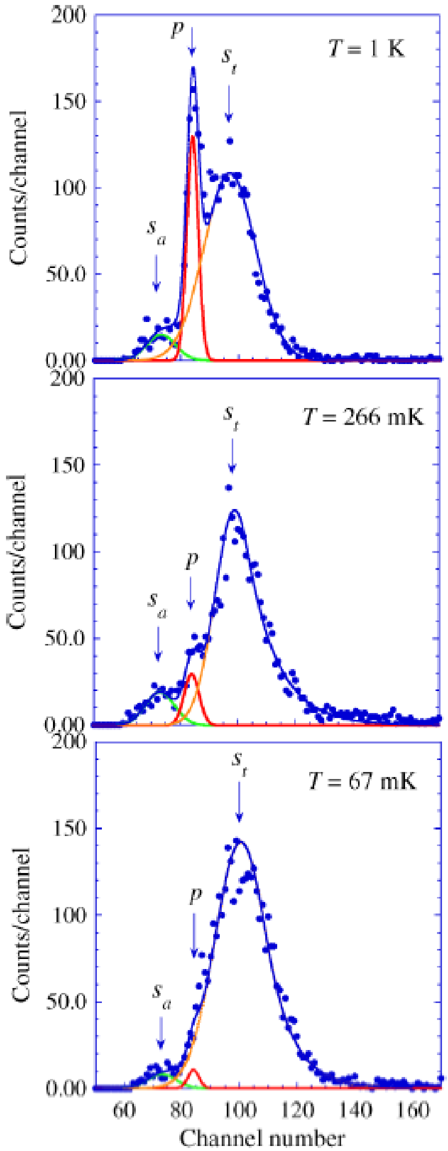
      axion as CDM ⟺

      ^{39}K: $110s_{1/2} \rightarrow 110p_{1/2}$ 10.06 μ eV
      ^{85}Rb: $112s_{1/2} \rightarrow 112p_{1/2}$ 9.98 μ eV
    - Large E1 transition probability

      $\langle np | e\mathbf{r} | ns \rangle \propto n^2$
    - Low ionization threshold $F_{\mathrm{ionize}} \propto n^{-4}$

      classical ionization threshold : 2.2 V/cm for n=110

Rydberg原子による黒体輻射光子の検出



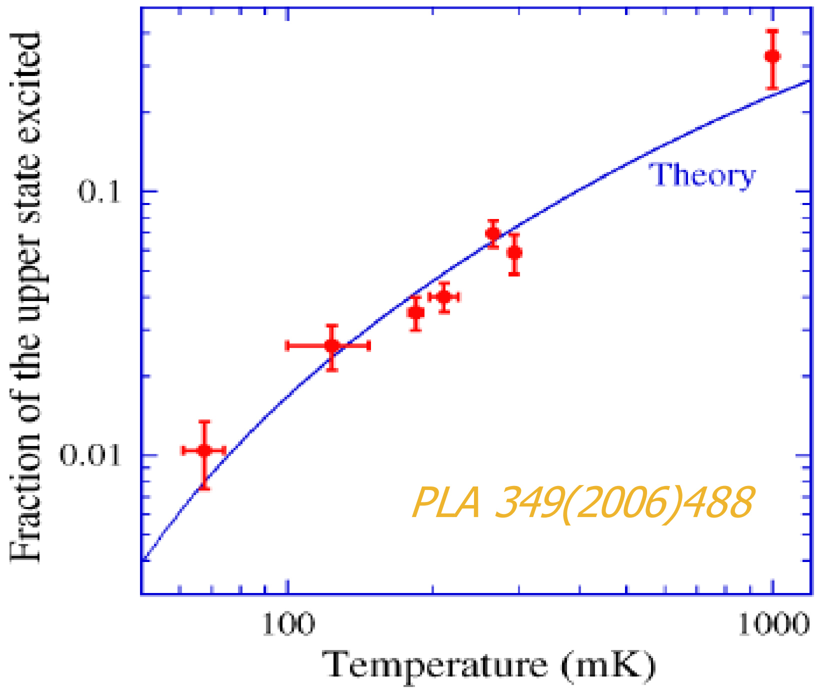


Fig. 4. Temperature dependence of the fraction of the 111 $p_{3/2}$ states excited by the blackbody-photon absorption in the cavity. The dependence was measured with the present Rydberg-atom single photon detector. Solid line is a theoretical prediction (see text in detail) in the over-damped regime.

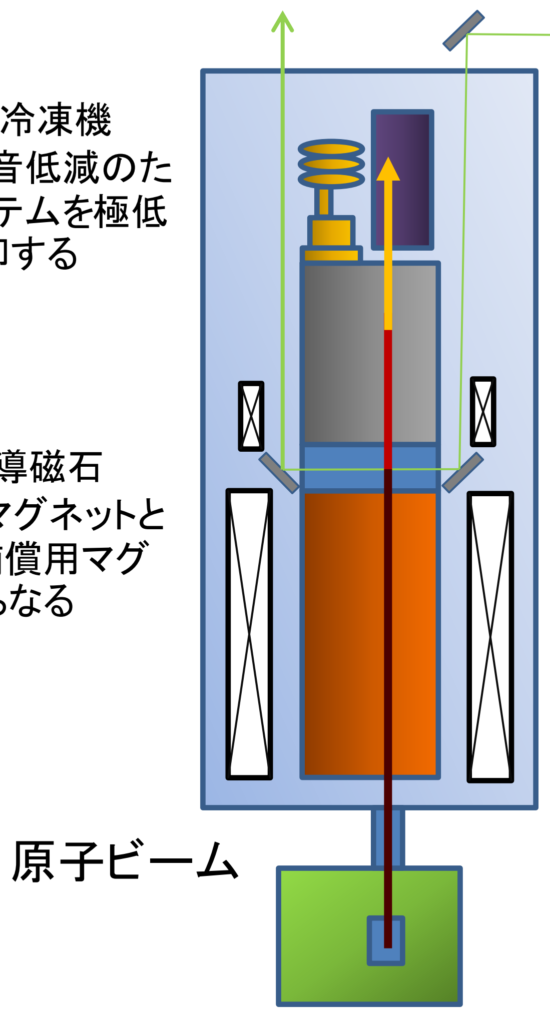
$111s_{1/2} \Rightarrow 111p_{3/2}$

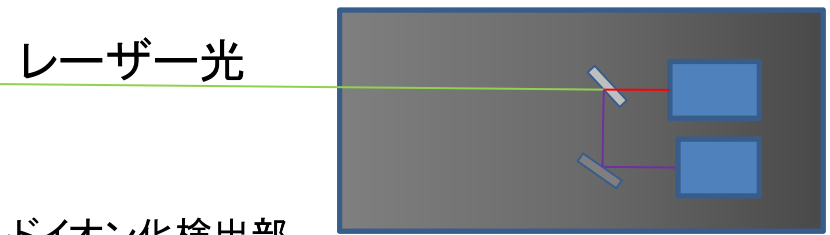
2527 MHz SQL: 121 mK

CARRACK装置の原理

⑥ 希釈冷凍機
　熱雑音低減のため、システムを極低温に冷却する

⑤ 超伝導磁石
　②用マグネットと④用の補償用マグネットからなる





⑤ フィールドイオン化検出部
　上の準位に励起したRydberg原子だけ($|np>$)を選択的にイオン化して検出する。

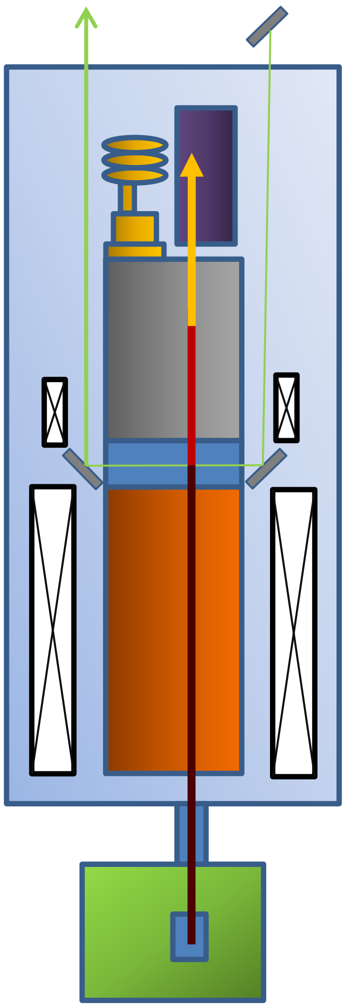
④ 検出用空胴
　Rydberg原子がアクシオン転換光子を吸収して励起する
　($|ns> \rightarrow |np>$)

③ レーザーシステム
　２本のレーザー光を用いてアルカリ原子を基底状態からRydberg状態へ励起させる($|g> \rightarrow |ns>$)

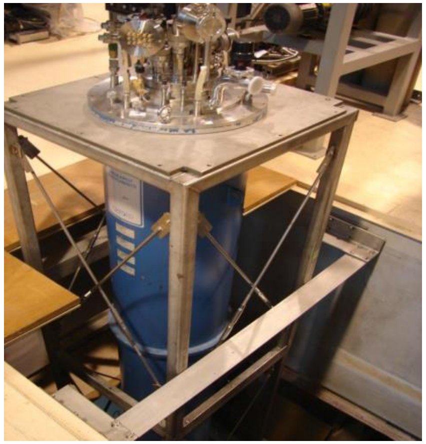
② 転換空胴
　強磁場中の共鳴空胴中でaxionをマイクロ波光子に転換する
　$a \rightarrow \gamma$

① 原子ビームオーブン部
　アルカリ原子（K）ビームを作る（ $|g>$ ）

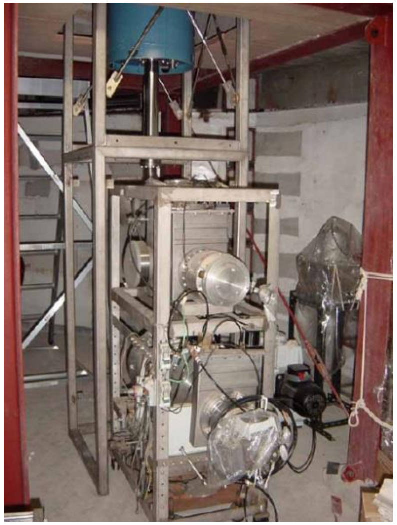
CARRACK装置

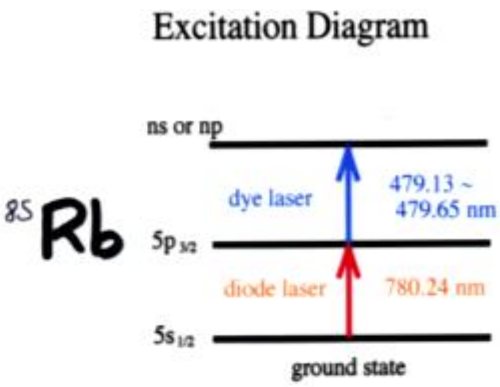


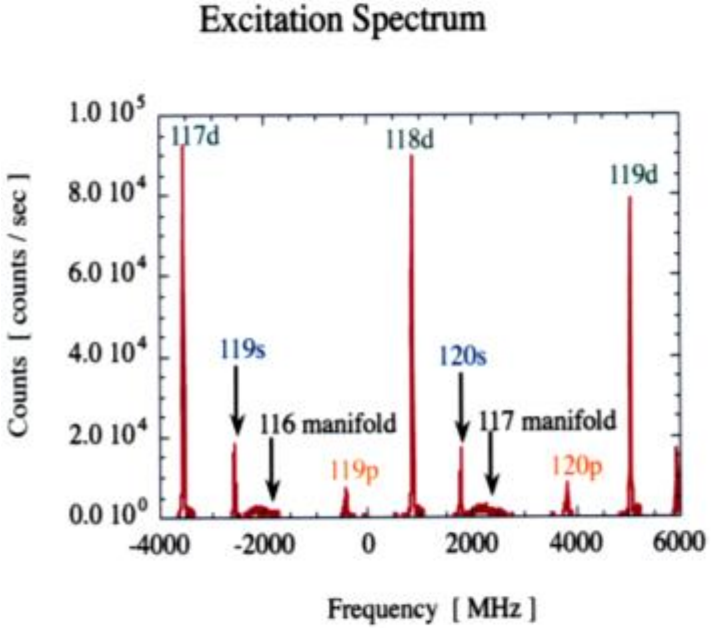
クライオスタット上部



原子ビーム発生装置

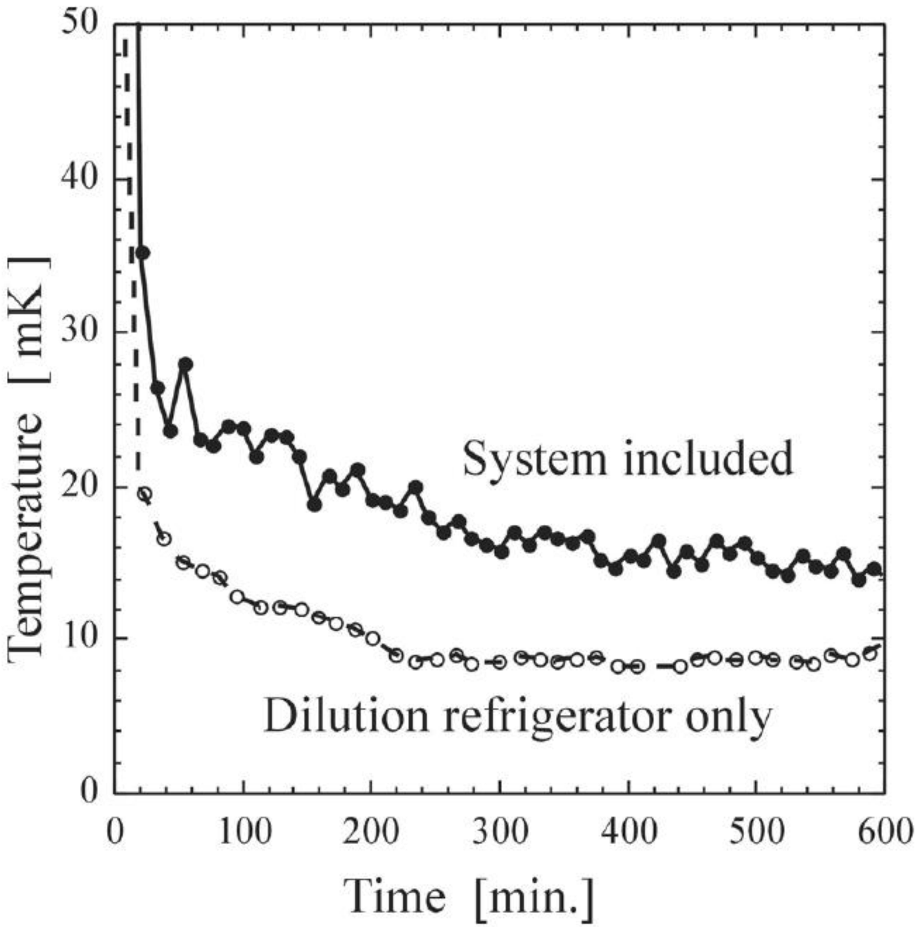






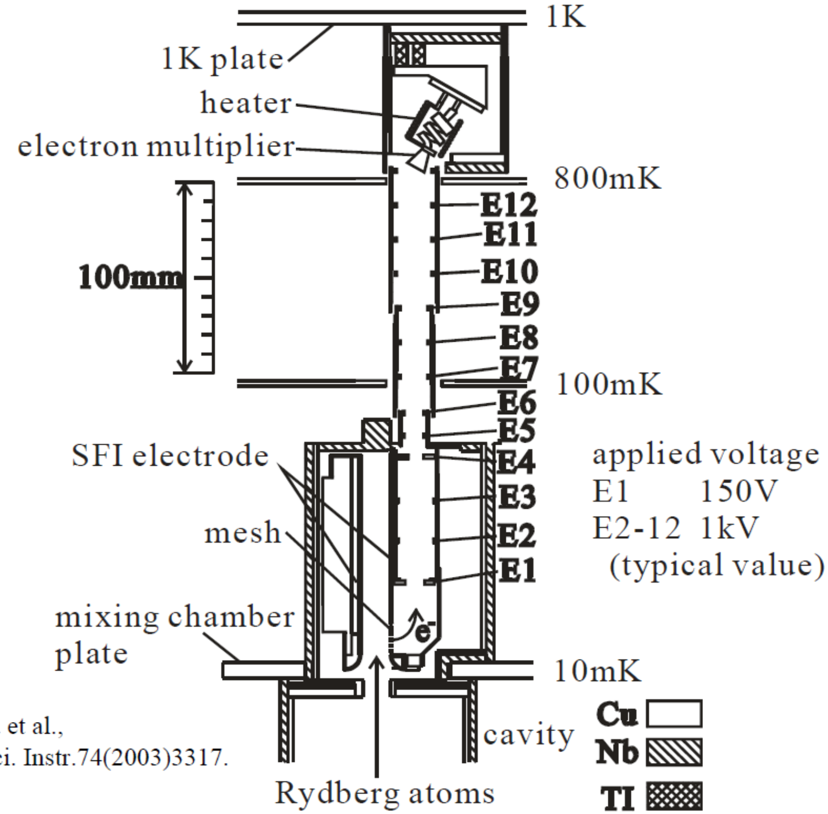
希釈冷凍機

- Cooling Power 370μW at 100 mK

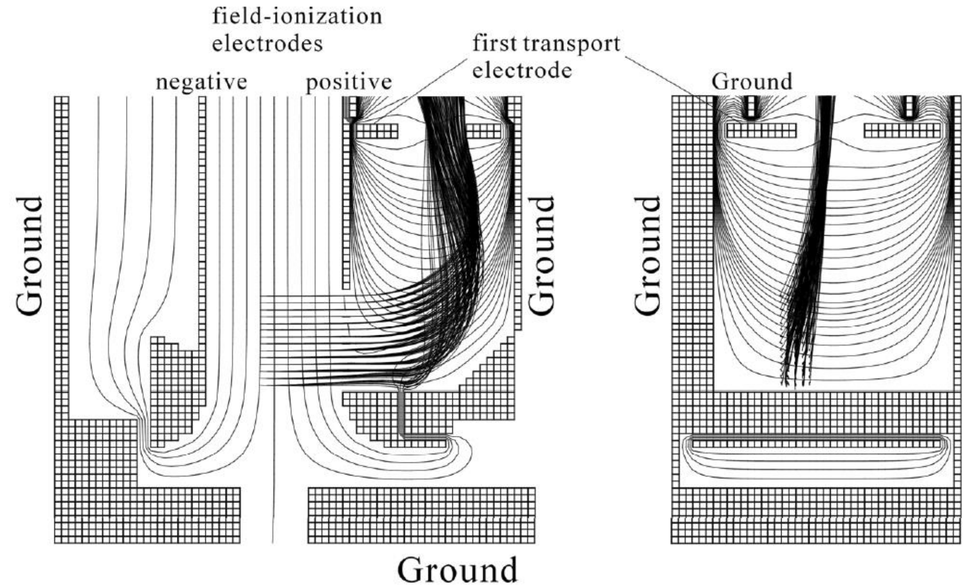


System : ~25 kg

選択的フィールドイオン化検出部



Shibata et al.,
Rev. Sci. Instr.74(2003)3317.



Transport efficiency for the ionized electrons
~ 100 %

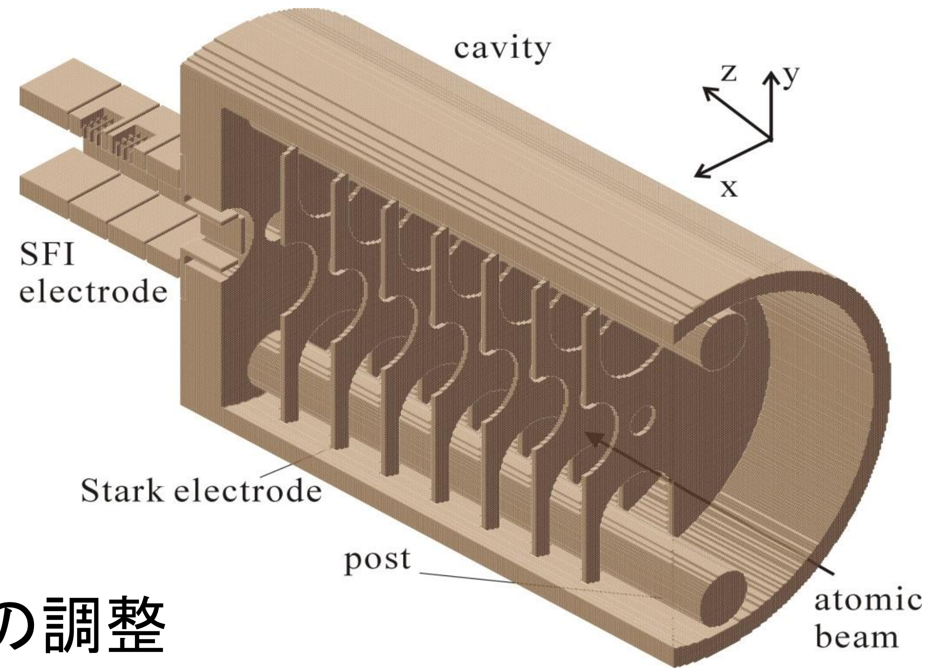
探索axion質量の掃引

- Conversion & Detection Cavity
  - 共振周波数の調整

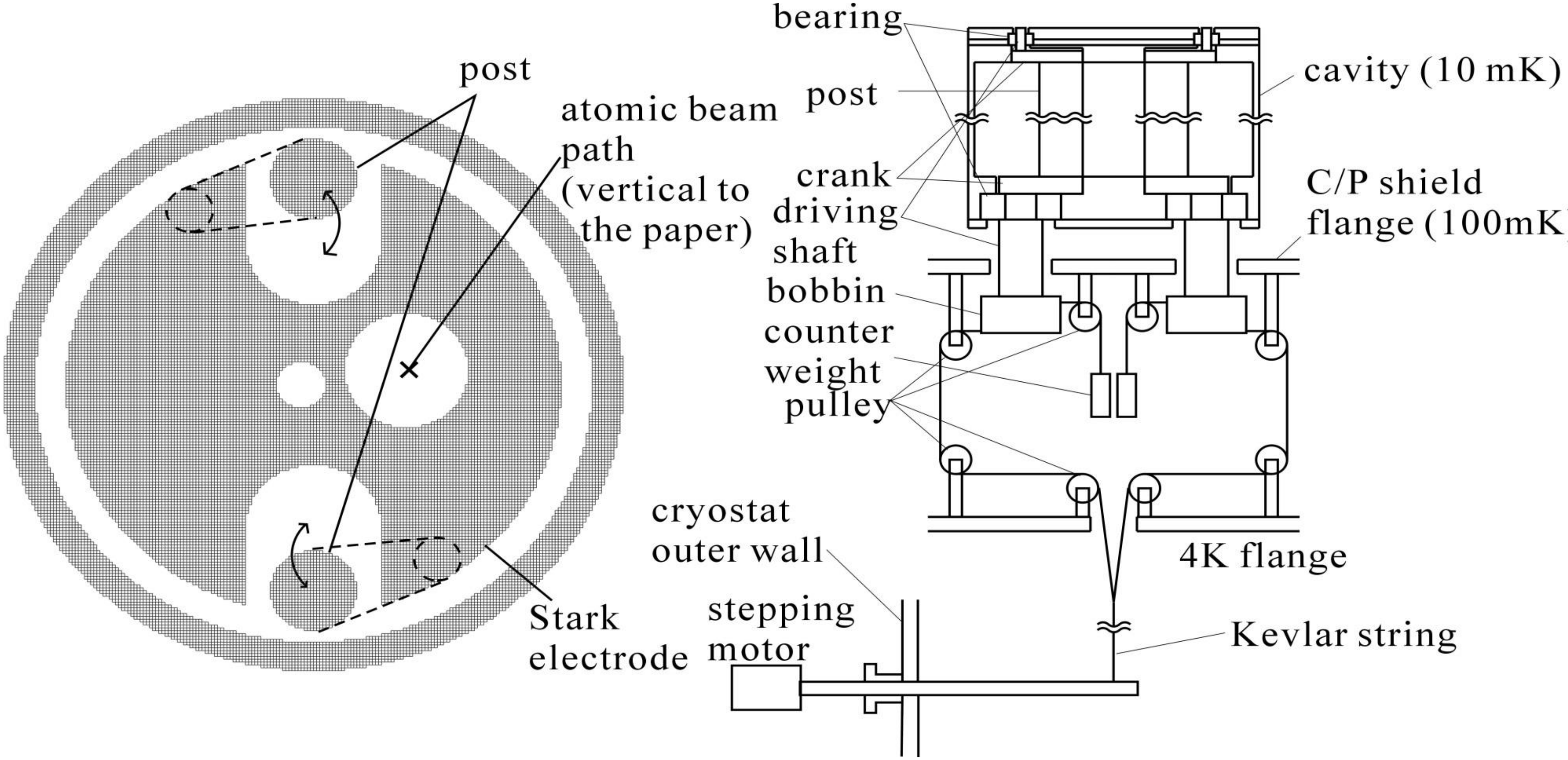
    メタルポストの移動
- Rydberg atom
  - 粗調整

    主量子数の変更
  - 微調整

    Stark effectによる準位間の調整



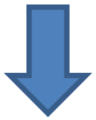
Cavity共振周波数調整システム



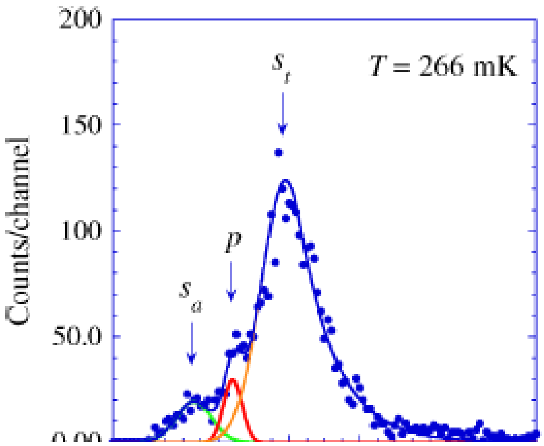
heat flow from Kevlar
<1nW

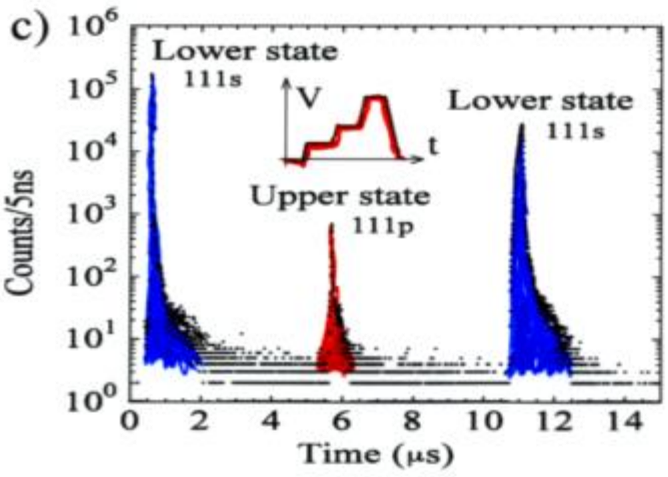
Background

- Cavity中のStray fieldによる準位の混合
  - 極低温時、電極表面に不純物が付着して、空間的に非一様な浮遊電場が生じる。O(10 mV/cm)



  - 浮遊電場が吸収線幅を広げてしまう。

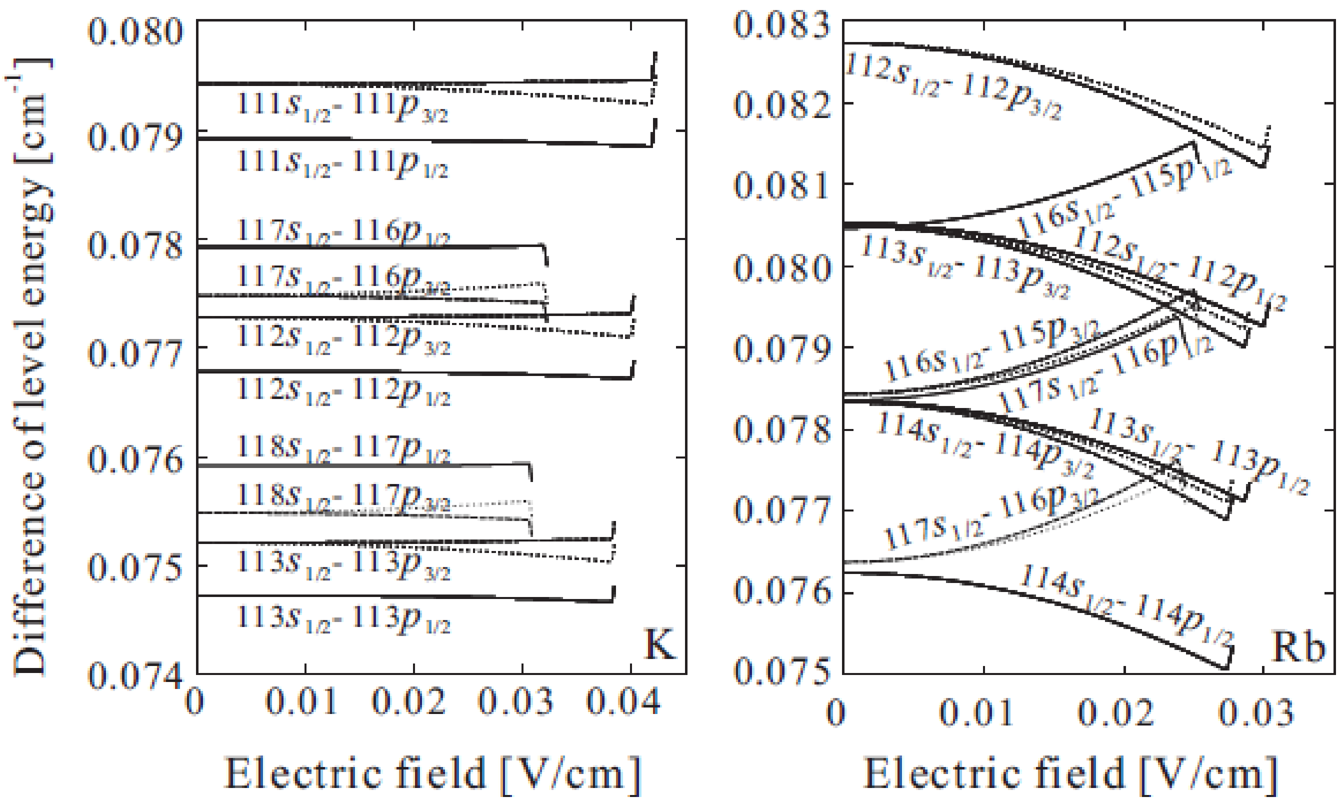




Ideal situation

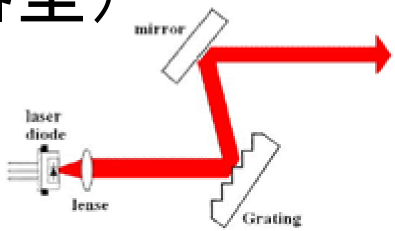
newCARRACK

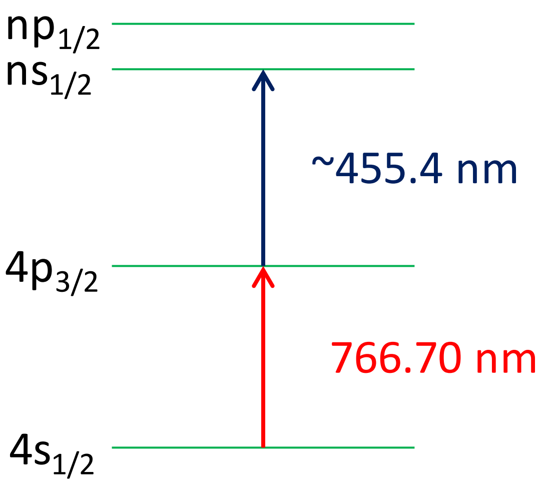
- 原子ビームとして、^{85}Rbの代わりに^{39}Kを使用
  - 外部電場に対して非常に鈍感であると予想されている



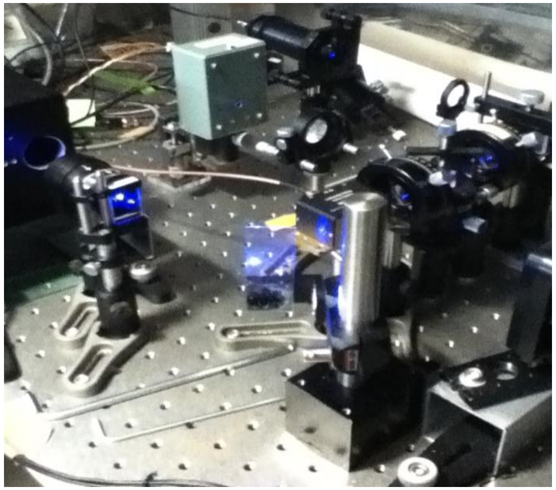
現在の準備状況

- ^{39}K励起用レーザーの整備
  - ２段階励起
  - 半導体レーザー
    ECDL（外部共振器型）



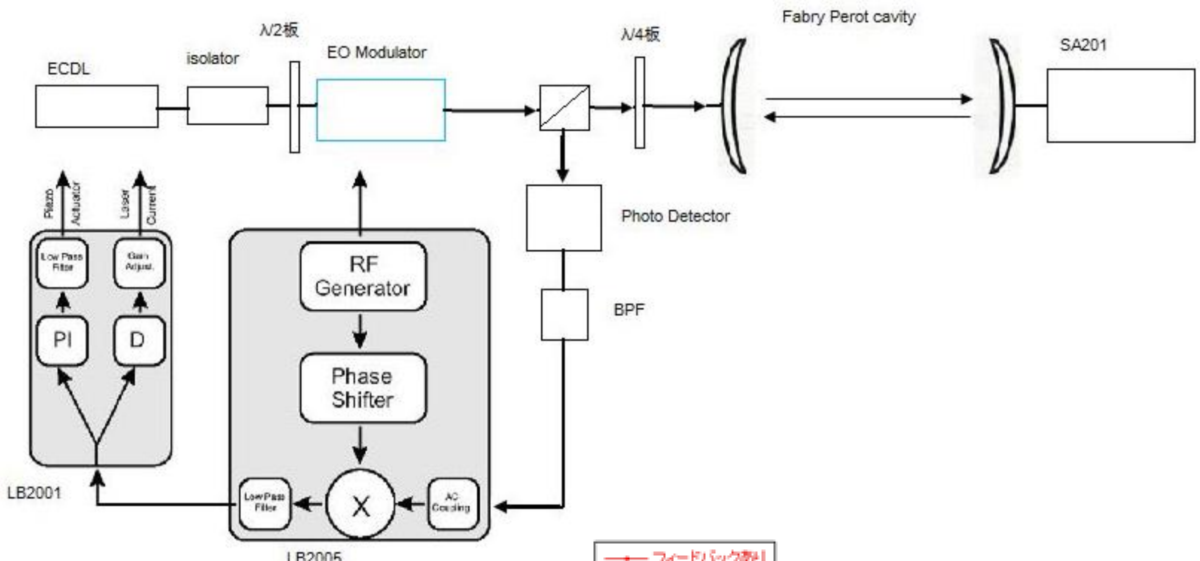


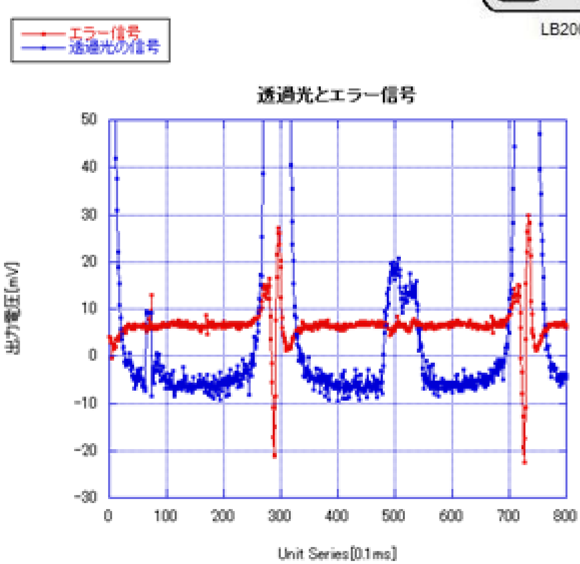
  - 周波数の安定化
    - 初段：外部の原子セルを利用して飽和吸収分光法でロック
    - ２段：外部のFabre-Perot共振器にPDH法でロック

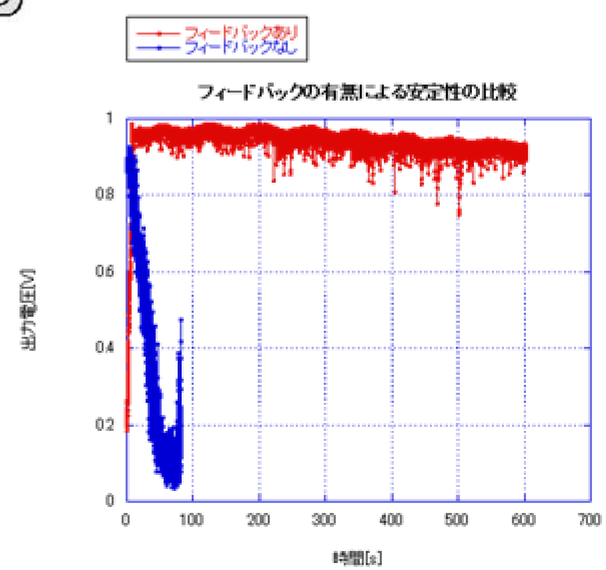


2段目レーザーの安定化

- PDH法

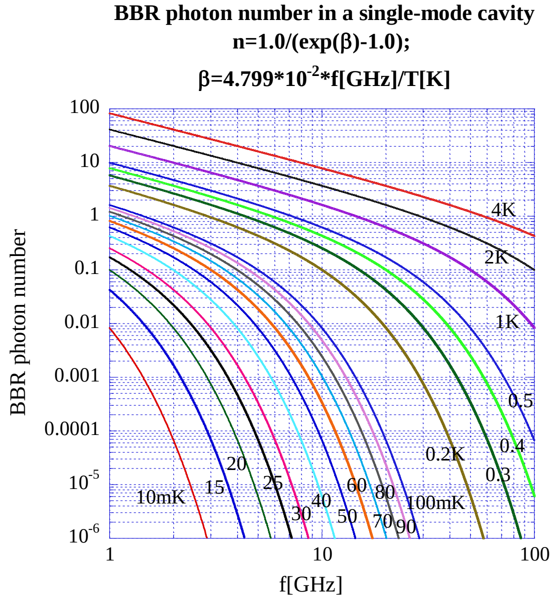


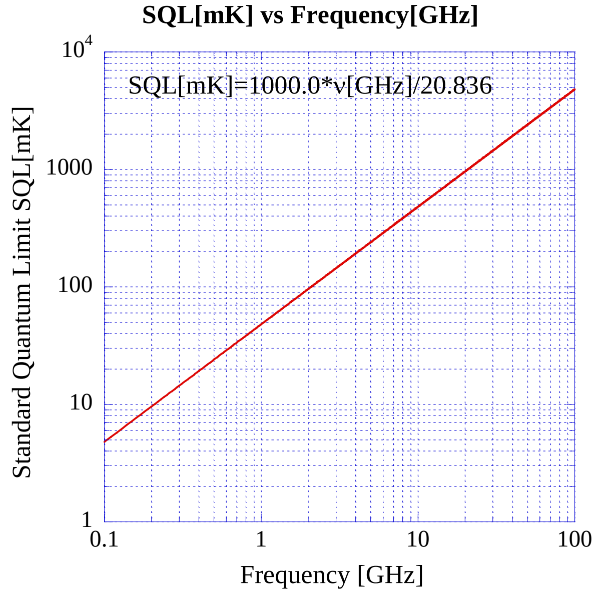




Future Prospects

- ^{39}Kビームにおいて、Rydberg状態の生成と黒体輻射光子の検出実験を行う
- Dark halo axionの探索
  - $m_a \sim 40\ \mu$eV（ADMXより重い質量領域）を狙う





まとめ

- AxionはWIMPsと並んで有力なDM候補粒子である。
- 宇宙論における議論や実験・観測などからその質量は$1-1000\mu$eVに制限されている。
- CDMとしての関心領域（a few×10μeV）で感度があるのはmicrowave cavityを用いた実験“axion haloscope” (ADMX, WISPDMX, Yale, CARRACK)である。