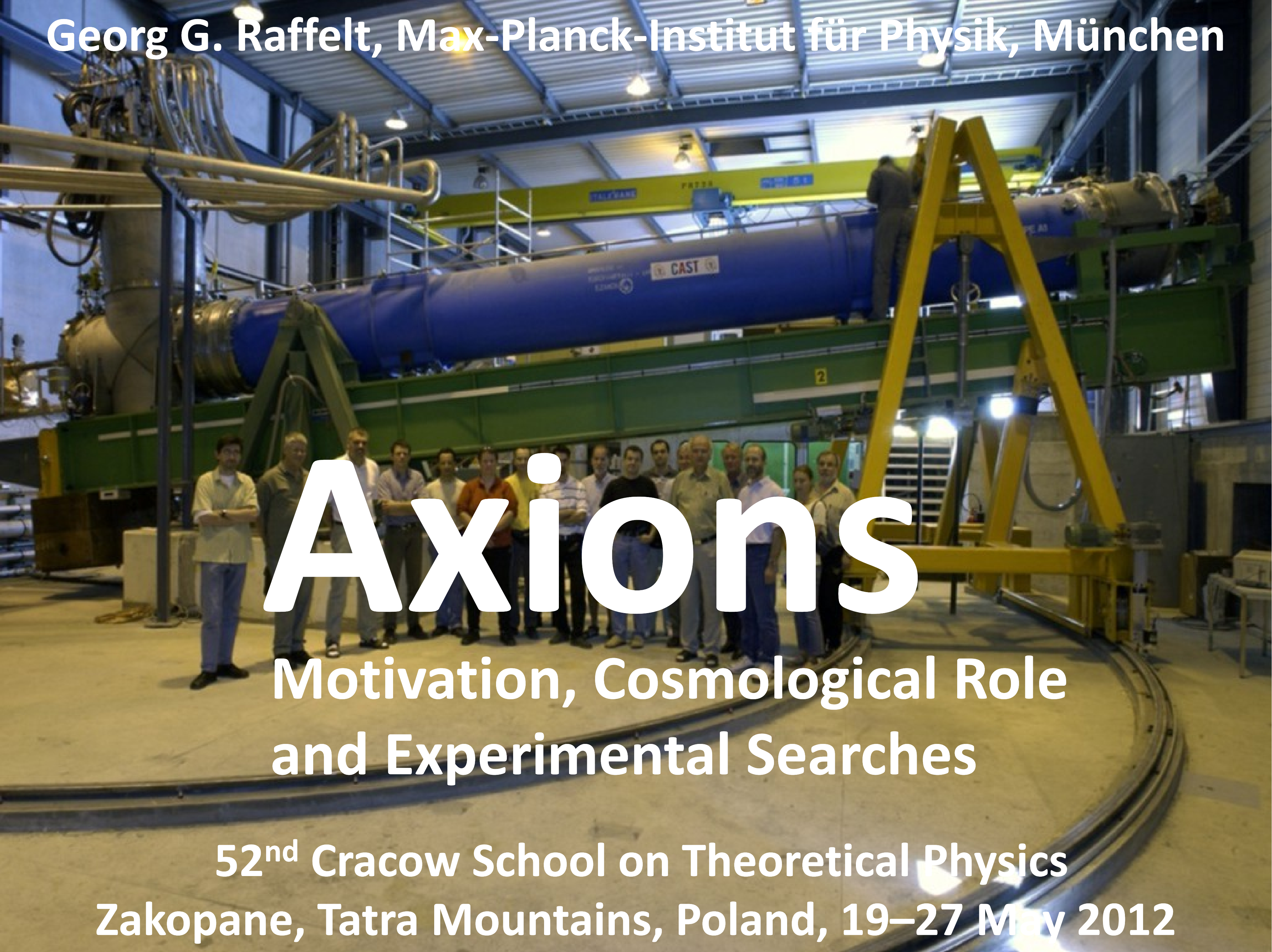


Georg G. Raffelt, Max-Planck-Institut für Physik, München

Axions

Motivation, Cosmological Role and Experimental Searches

52nd Cracow School on Theoretical Physics
Zakopane, Tatra Mountains, Poland, 19–27 May 2012

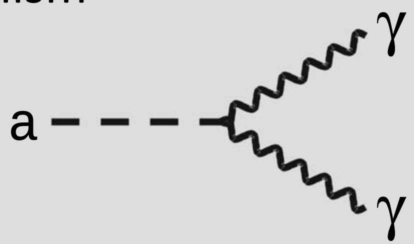
Axion Physics in a Nut Shell

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

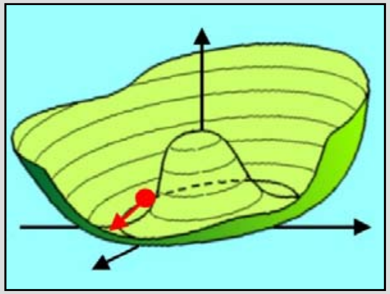
Solar and Stellar Axions

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

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

Cosmology

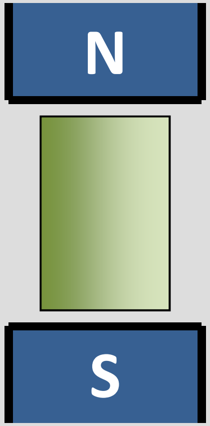
In spite of small mass, axions are born non-relativistically (non-thermal relics)



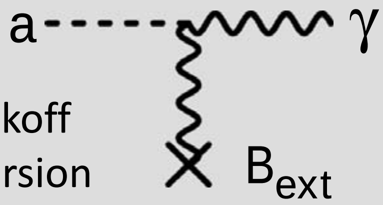
Cold dark matter candidate

$m_a \sim 10\ \mu\text{eV}$ (or much smaller or larger)

Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

ADMX-LF (UW Seattle)
ADMX-HF (Yale)

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 theory

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

Physics Nobel Prize 2008

- All measured CP-violating effects derive from a single phase in the quark mass matrix (Kobayashi-Maskawa phase),
i.e. from complex Yukawa couplings
- Cosmic matter-antimatter asymmetry requires new ingredients

The CP Problem of Strong Interactions

Real quark mass

Phase from Yukawa coupling

Angle variable

CP-odd quantity $\sim \mathbf{E}\cdot\mathbf{B}$

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q e^{\mathrm{i}\theta_q}\right)\psi_q - \tfrac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \Theta\,\frac{\alpha_{\mathrm{s}}}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

Remove phase of mass term by chiral transformation of quark fields

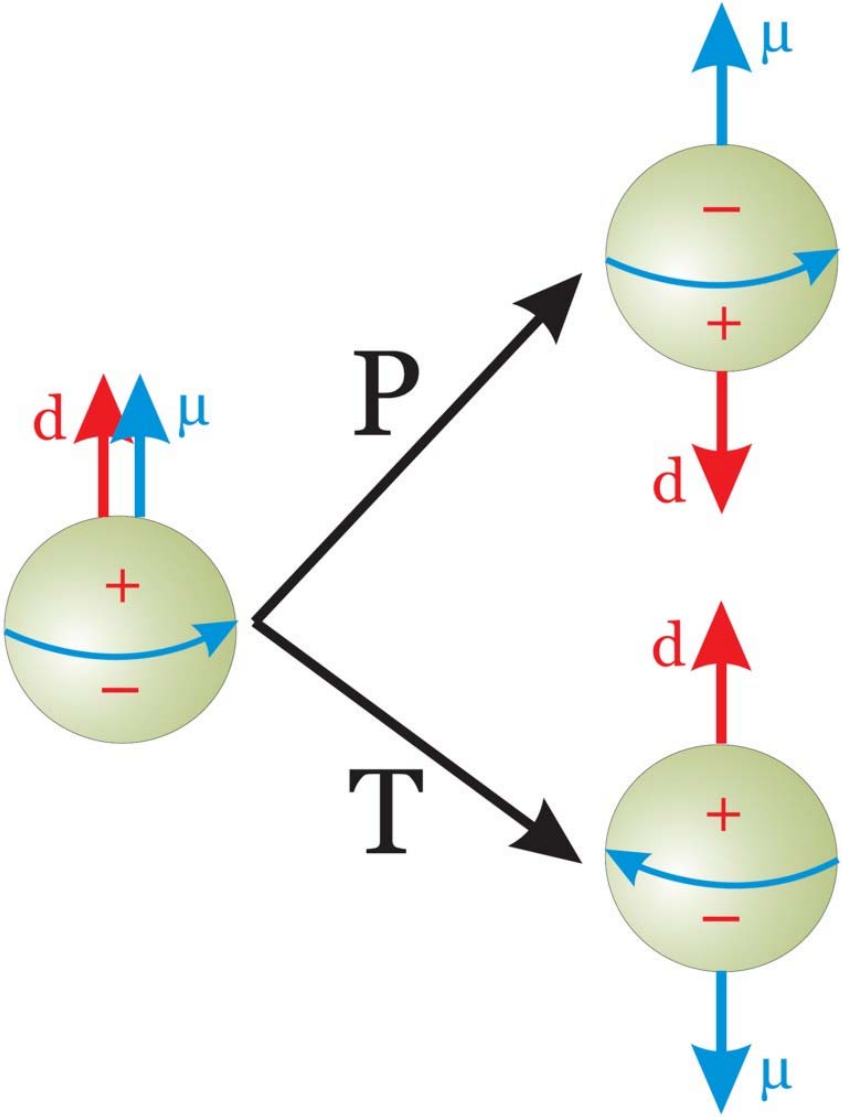
$$\psi_q \to e^{-i\gamma_5\theta_q/2}\psi_q$$

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q\right)\psi_q - \tfrac{1}{4} GG - \underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi \le \bar{\Theta} \le +\pi} \frac{\alpha_{\mathrm{s}}}{8\pi} G\tilde{G}$$

- $\bar{\Theta}$ can be traded between quark phases and $G\tilde{G}$ term
- No physical impact if at least one $m_q = 0$

Experimental limits: $|\bar{\Theta}| < 10^{-11}$ Why so small?

Neutron Electric Dipole Moment



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

Natural scale

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

Experimental limit

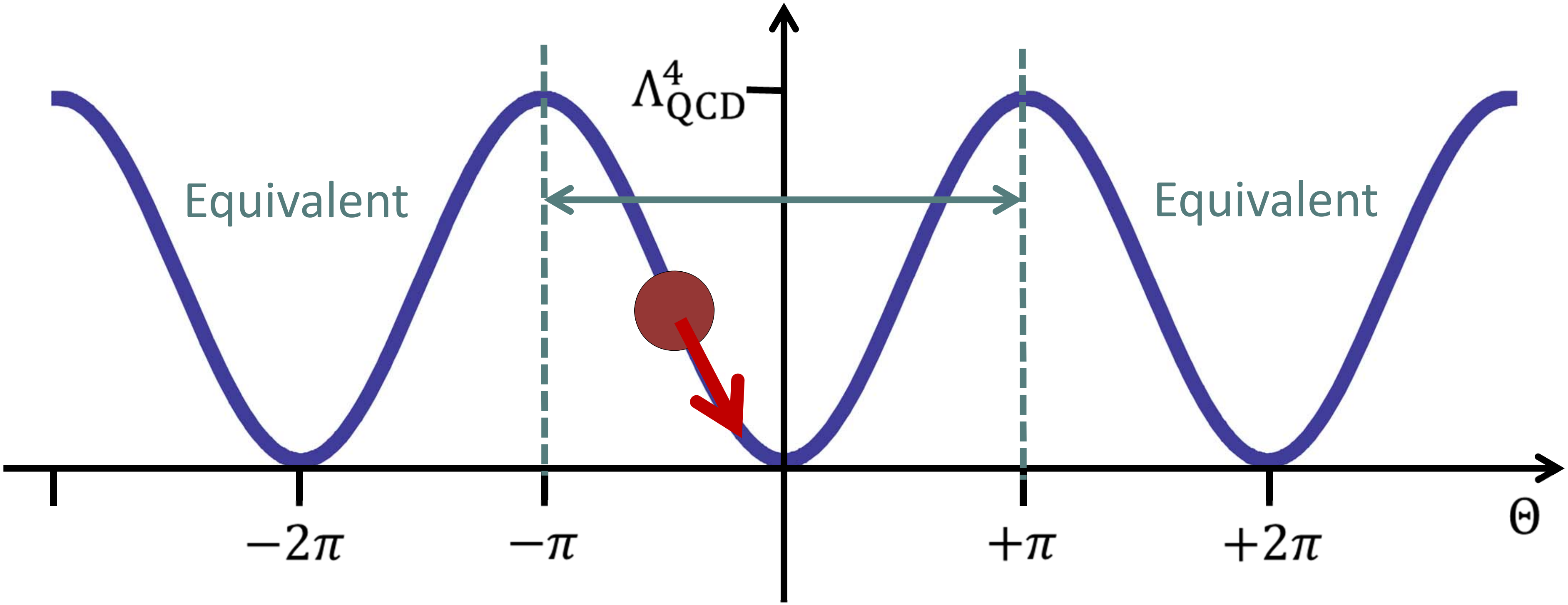
$$|d| < 0.63\ \times 10^{-25} e\ \mathrm{cm}$$

Limit on coefficient

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

Strong CP Problem

QCD vacuum energy $V(\Theta)$



- CP conserving vacuum has $\Theta = 0$ (Vafa and Witten 1984)
- QCD could have any $-\pi \leq \Theta \leq +\pi$, is "constant of nature"
- Energy can not be minimized: Θ not dynamical

Peccei-Quinn solution:

Make Θ dynamical, let system relax to lowest energy

Dynamical Solution

Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978

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

$$\mathcal{L}_{\rm CP} = -\frac{\alpha_{\rm s}}{8\pi}\,\overline{\Theta}\,{\rm Tr}\big(G\tilde{G}\big) \rightarrow -\frac{\alpha_{\rm s}}{8\pi}\,\frac{a(x)}{f_a}\,{\rm Tr}\big(G\tilde{G}\big)$$

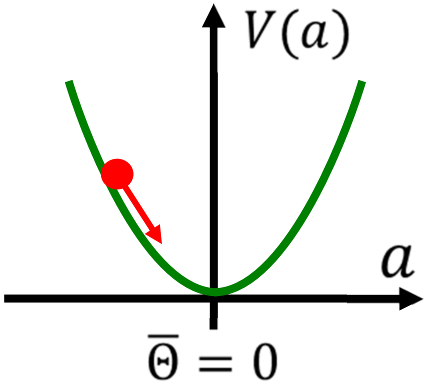
  $a(x)$ is pseudoscalar axion field, f_a axion decay constant (Peccei-Quinn scale)

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

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

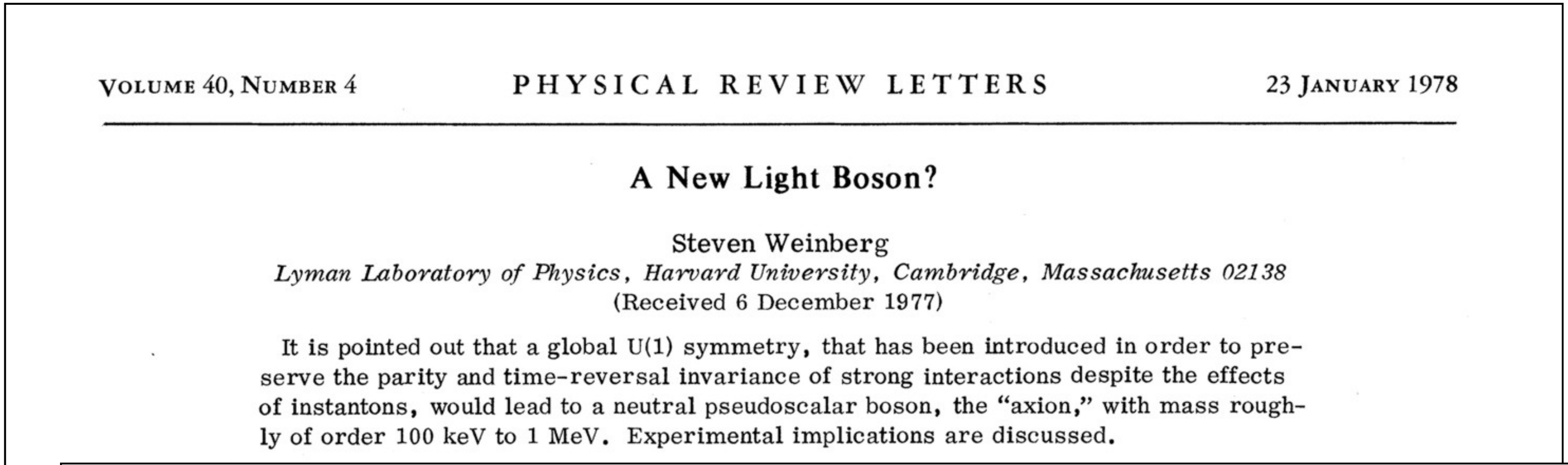
$$\begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

- Potential (mass term) induced by $\mathcal{L}_{\rm CP}$ drives $a(x)$ to CP-conserving minimum



CP-symmetry dynamically restored

35 Years of Axions

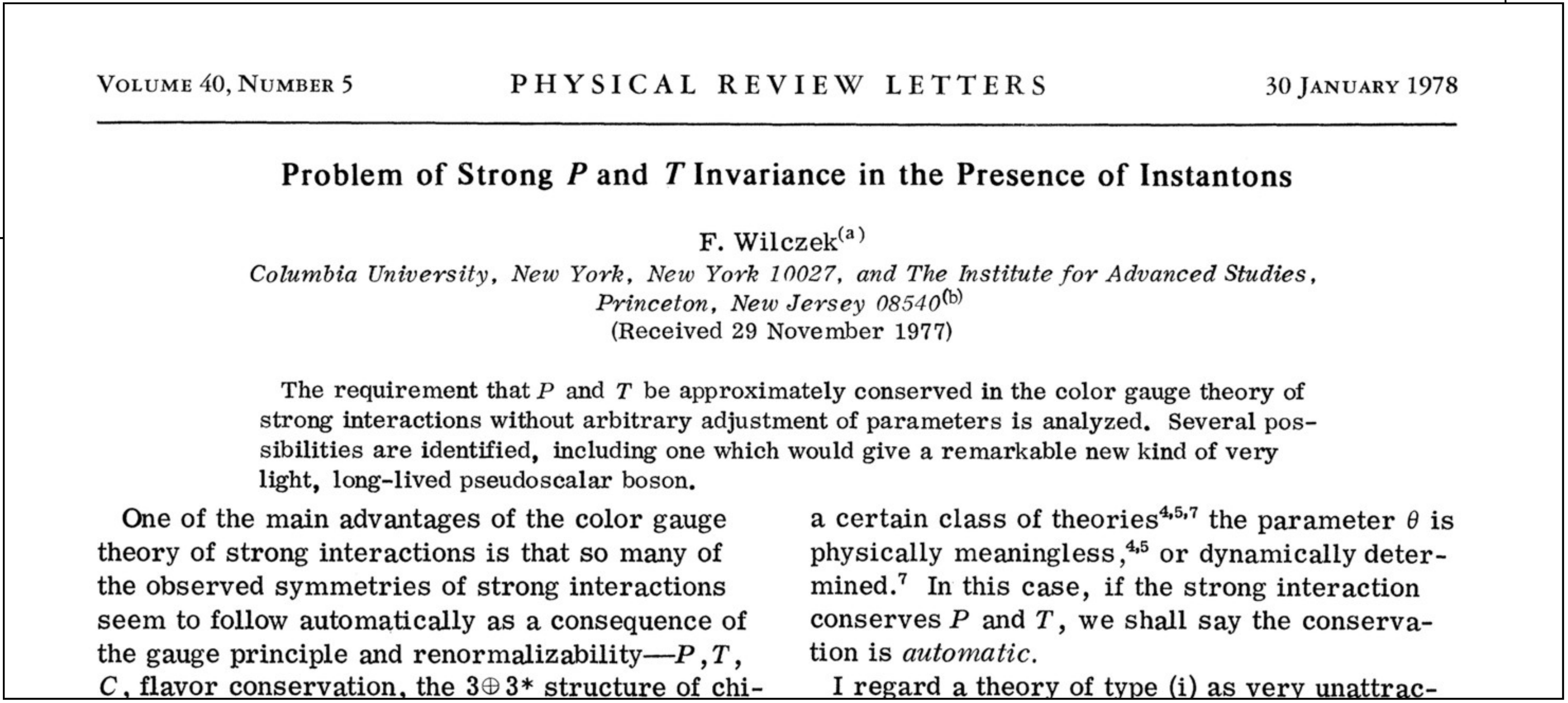


VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

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.



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)

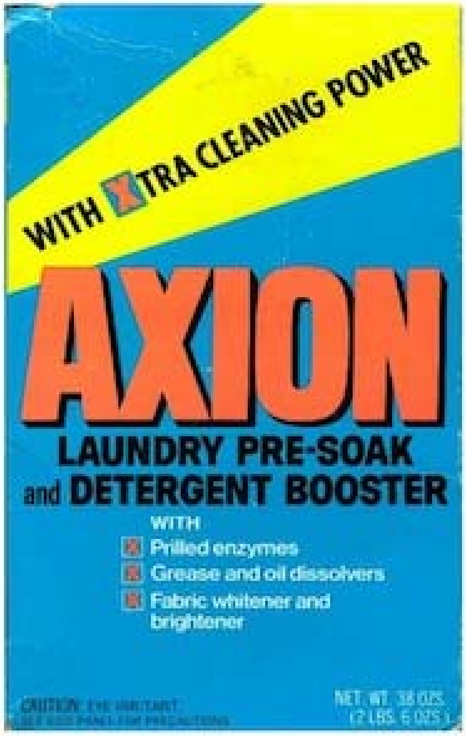
The requirement that P and T be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

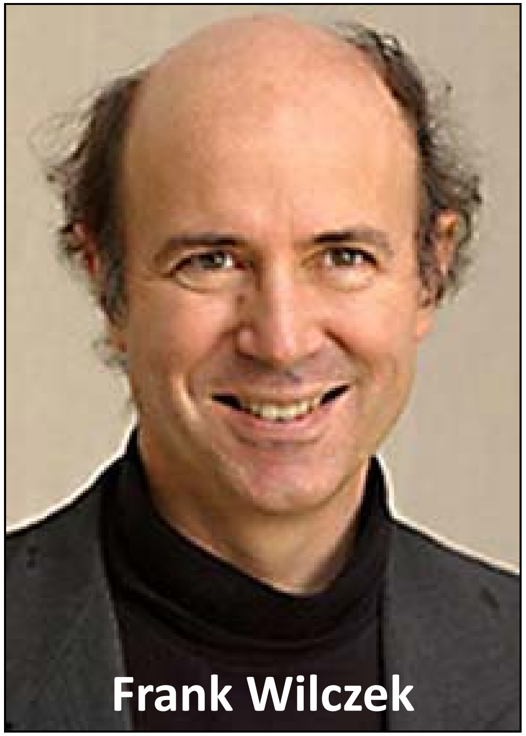
One of the main advantages of the color gauge theory of strong interactions is that so many of the observed symmetries of strong interactions seem to follow automatically as a consequence of the gauge principle and renormalizability—P, T, C, flavor conservation, the $3 \oplus 3^*$ structure of chi-

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-

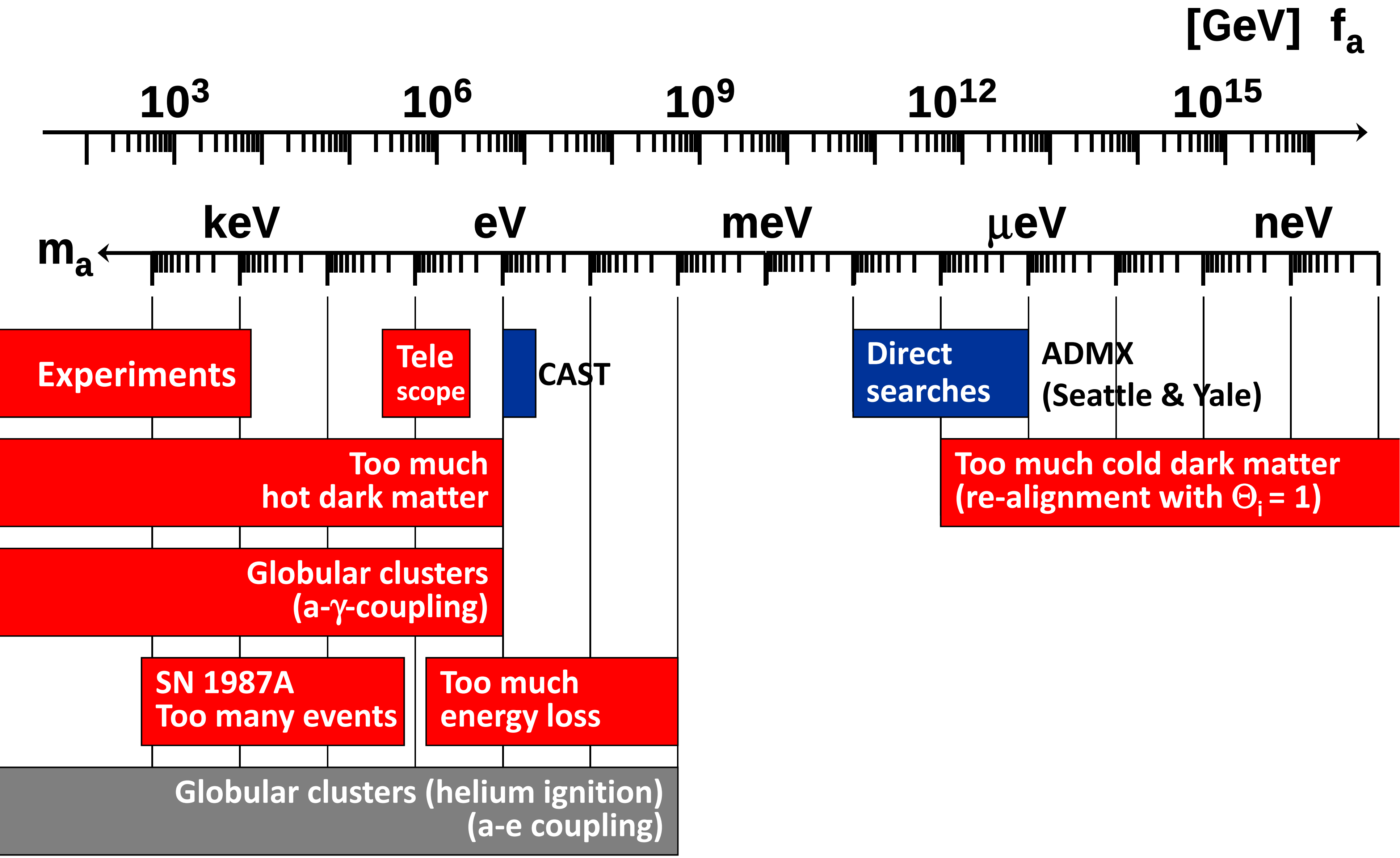
The Cleansing Axion




Frank Wilczek

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

Axion Bounds and Searches



Experiments

Tele scope

CAST

Direct searches

ADMX (Seattle & Yale)

Too much hot dark matter

Too much cold dark matter (re-alignment with $\Theta_i = 1$)

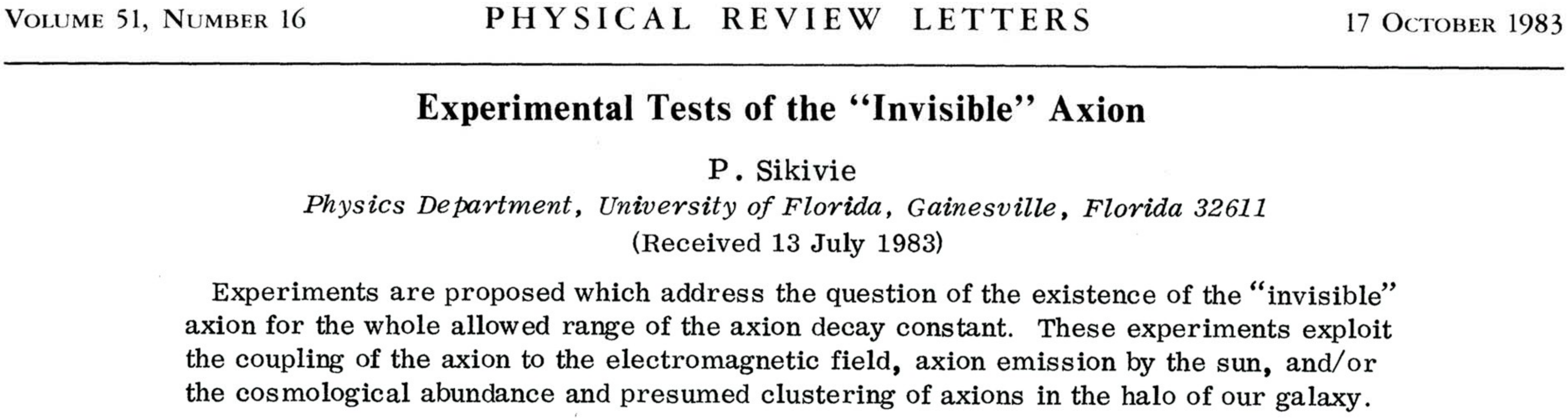
Globular clusters (a-γ-coupling)

SN 1987A
Too many events

Too much energy loss

Globular clusters (helium ignition)
(a-e coupling)

Searching for Axion-Like Particles



VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

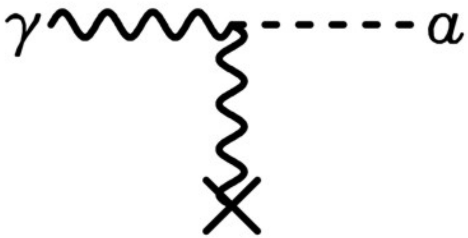
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(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)

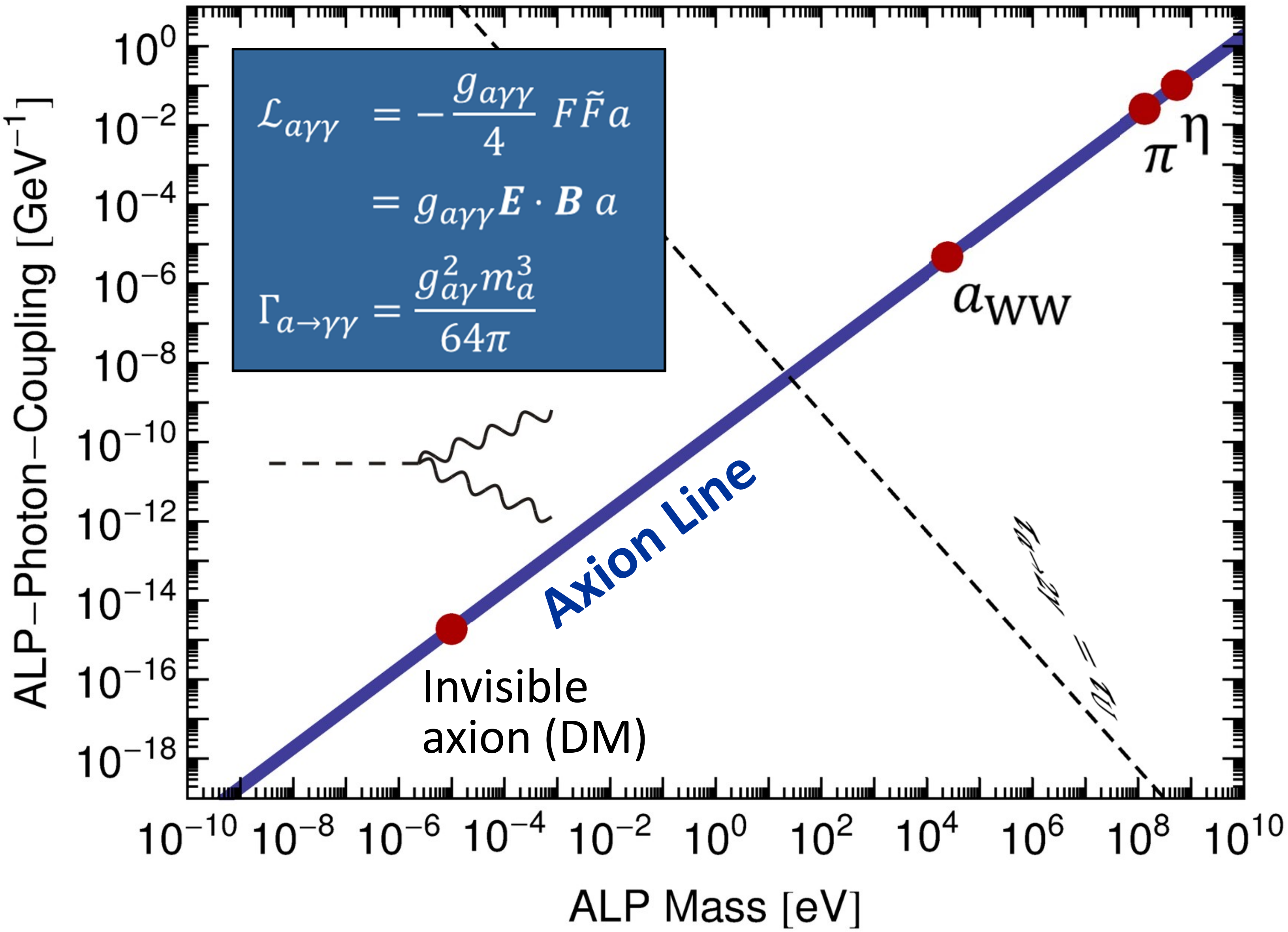


Pierre Sikivie:

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

Parameter Space for Axion-Like Particles (ALPs)

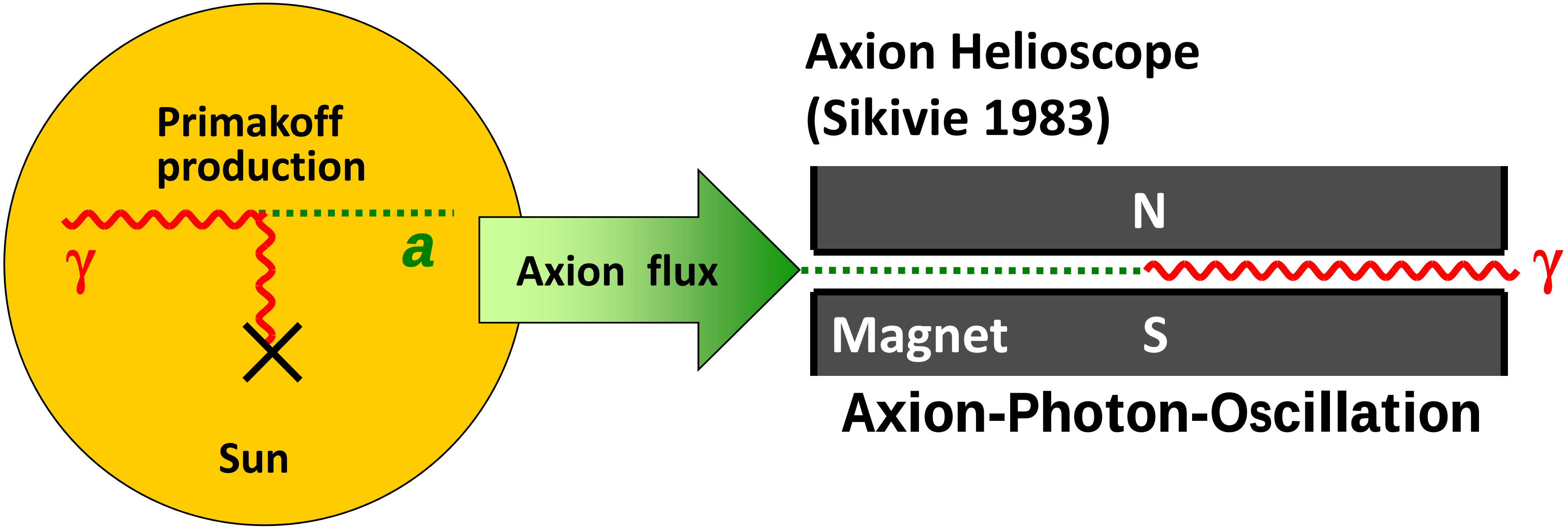


$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F\tilde{F} a$$

$$= g_{a\gamma\gamma} \boldsymbol{E}\cdot\boldsymbol{B}\, a$$

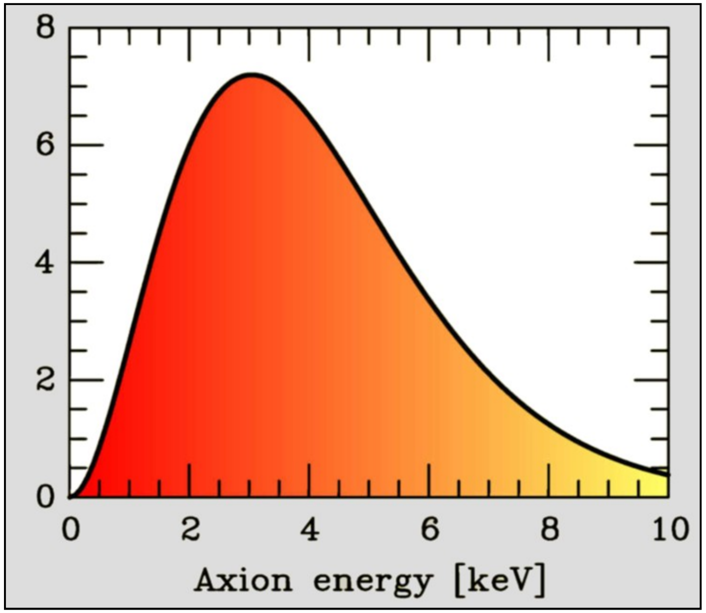
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

Search for Solar Axions



Axion Helioscope (Sikivie 1983)

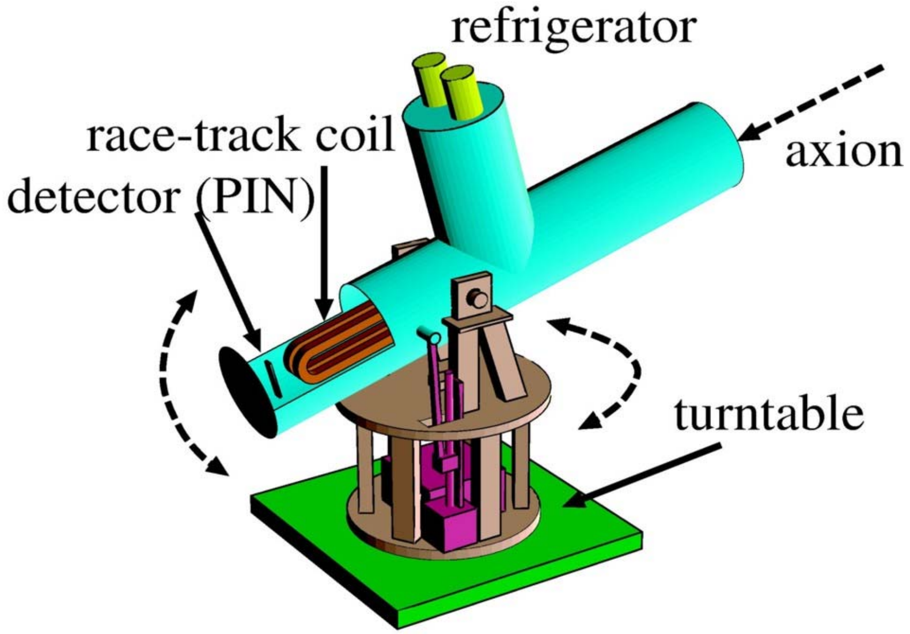
Axion-Photon-Oscillation

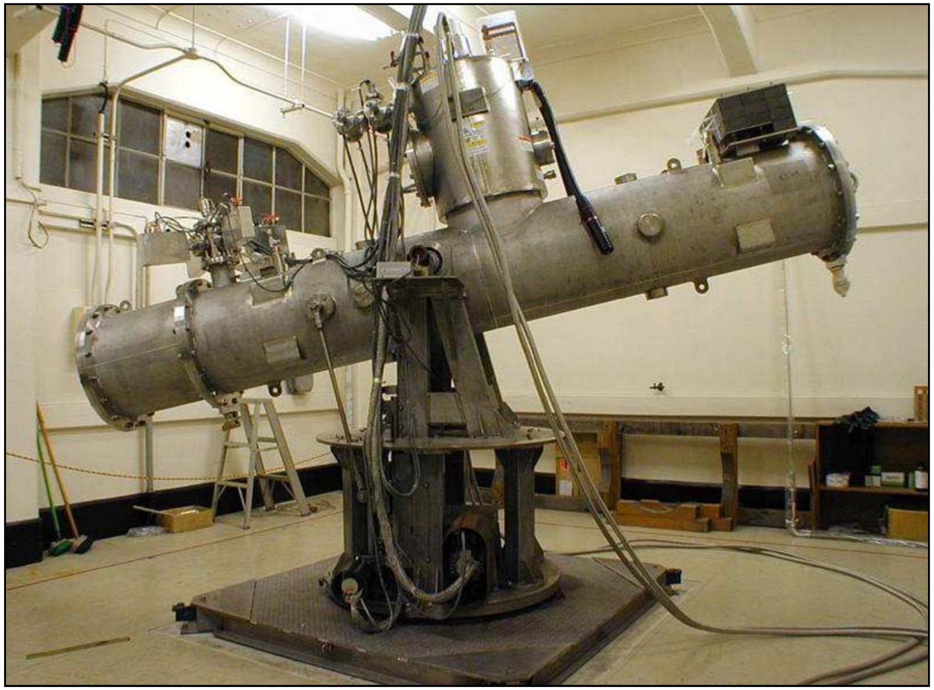


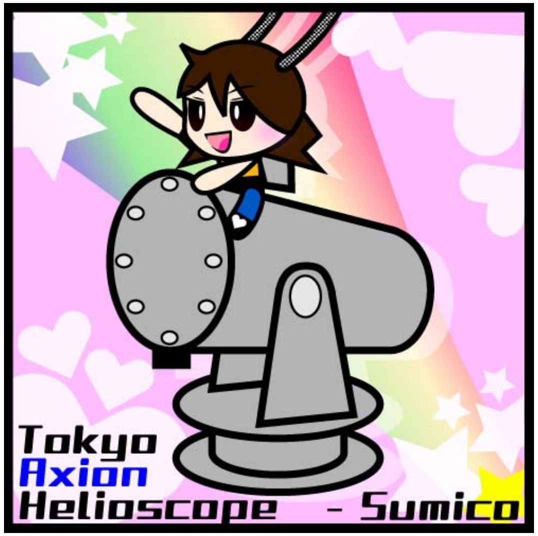
- Tokyo Axion Helioscope (“Sumico”) (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

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

Tokyo Axion Helioscope (“Sumico”)





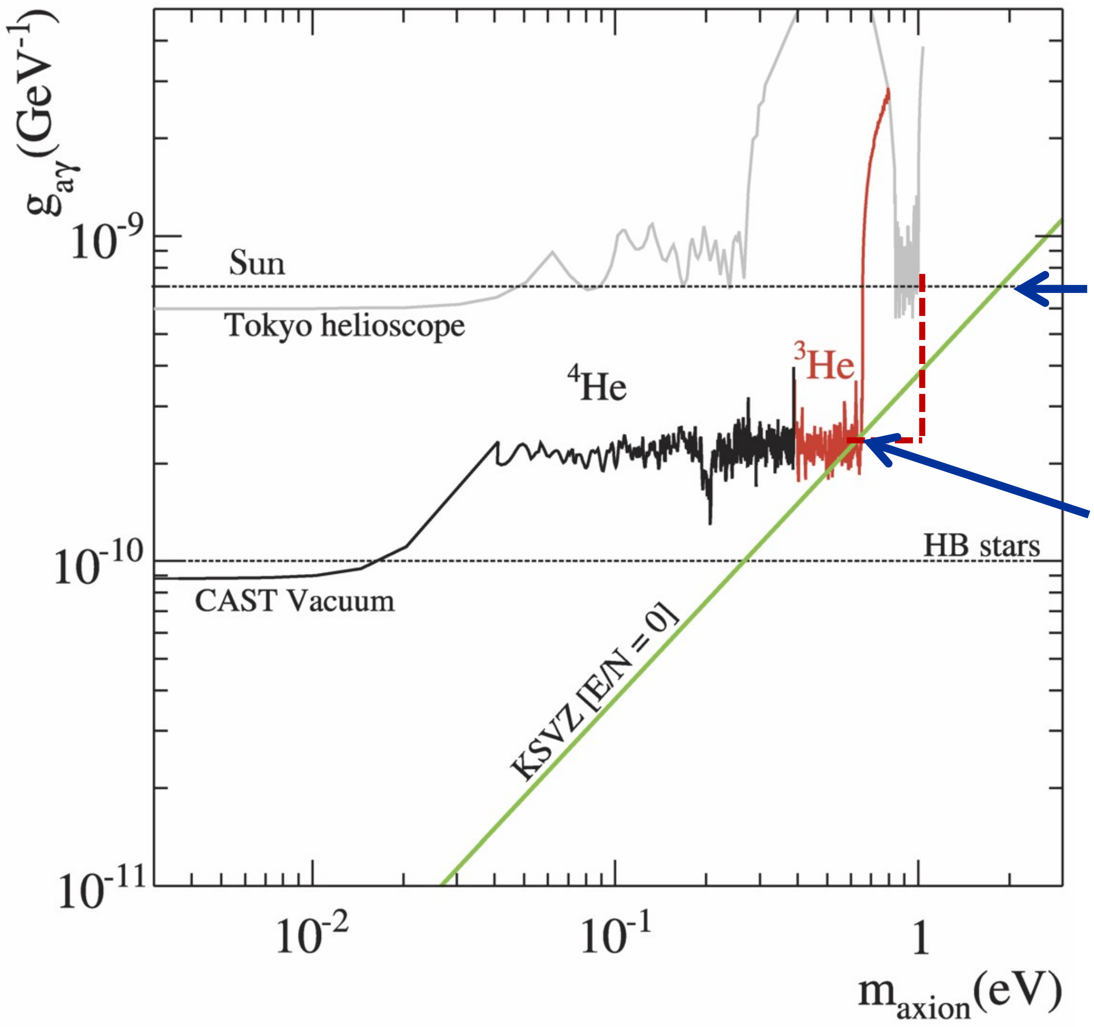


Moriyama, Minowa, Namba, Inoue, Takasu & Yamamoto
PLB 434 (1998) 147

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

CAST at CERN

Helioscope Limits



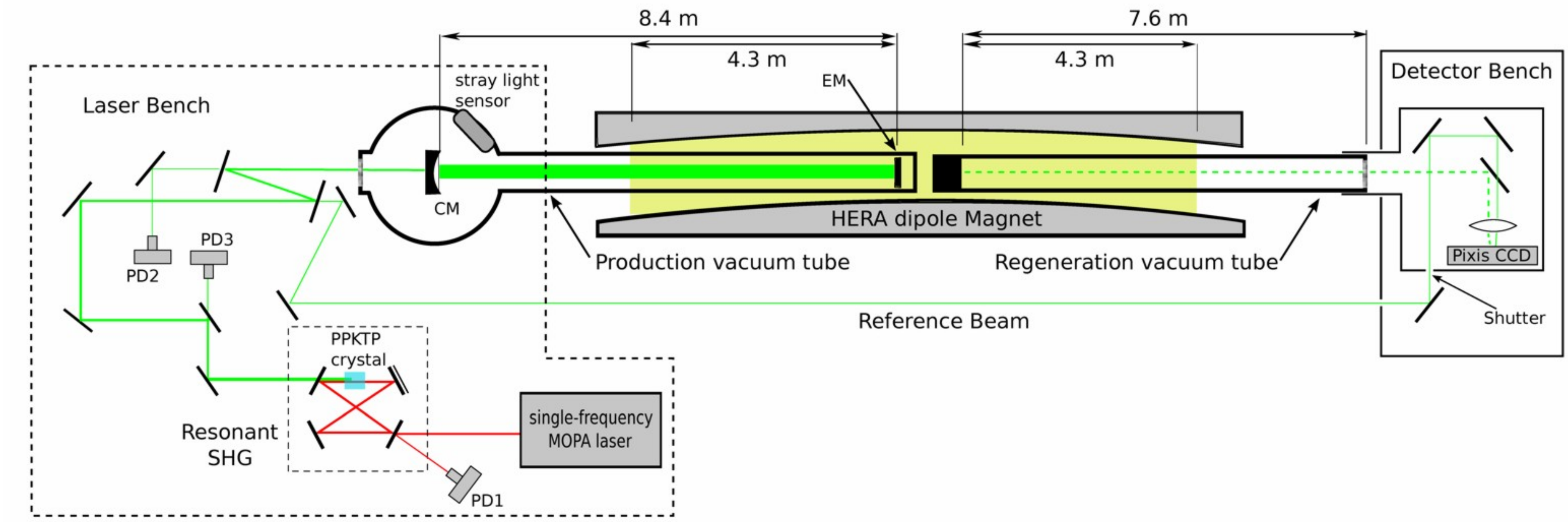
Solar neutrino limit

First experimental crossing of the KSVZ line

CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008
CAST-II results (He-3 filling, range 1): PRL 107 (2011) 261302

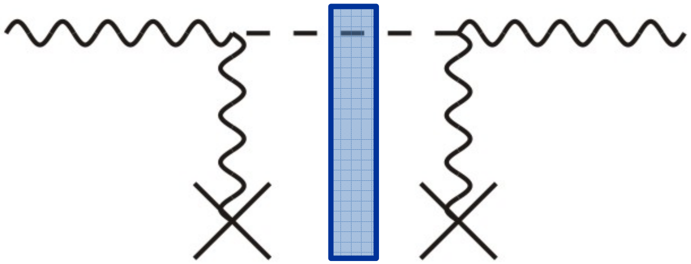
Photon Regeneration Experiments

Ehret et al. (ALPS Collaboration), arXiv:1004.1313

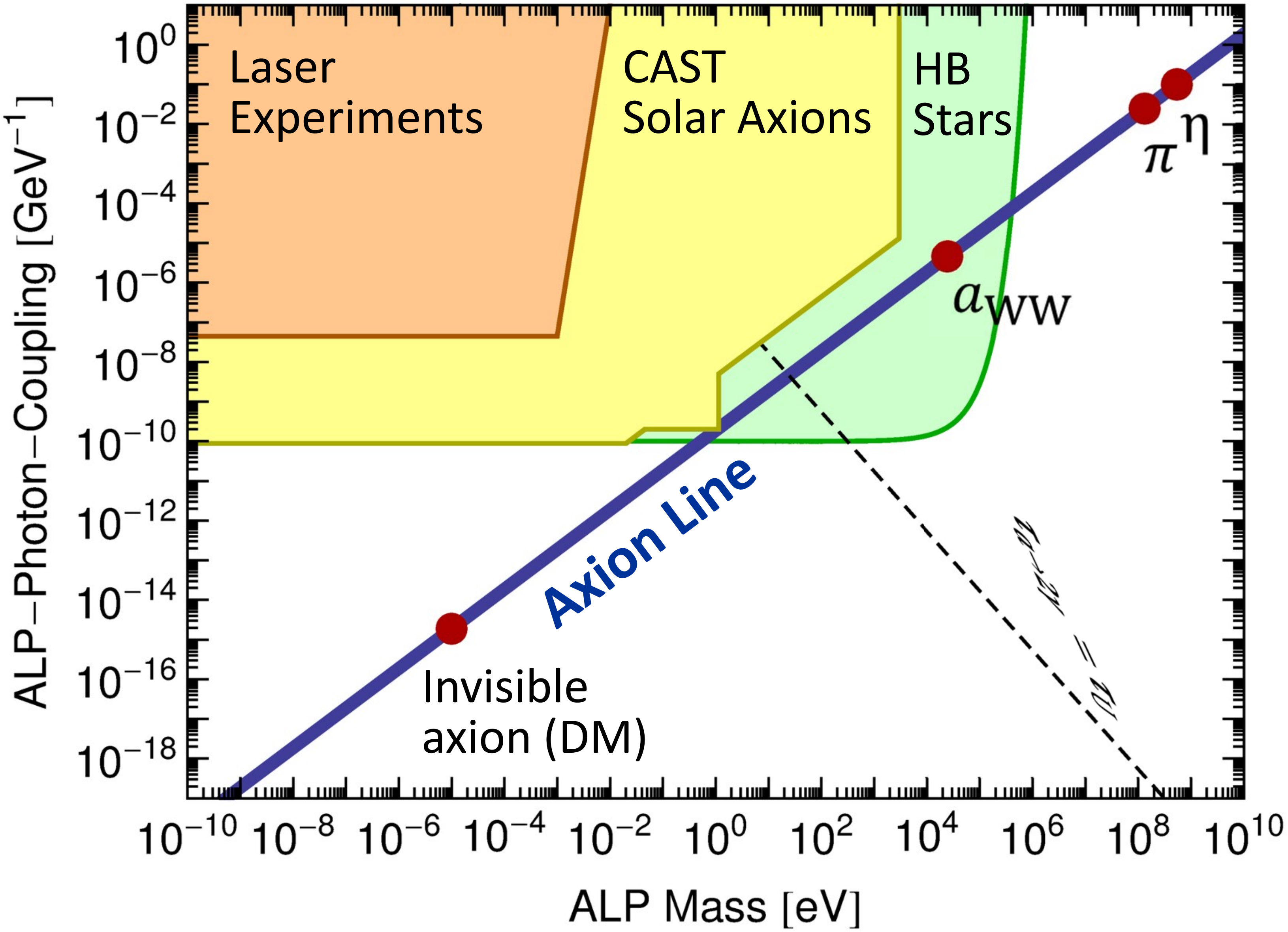


Recent “shining-light-through-a-wall” or vacuum birefringence experiments:

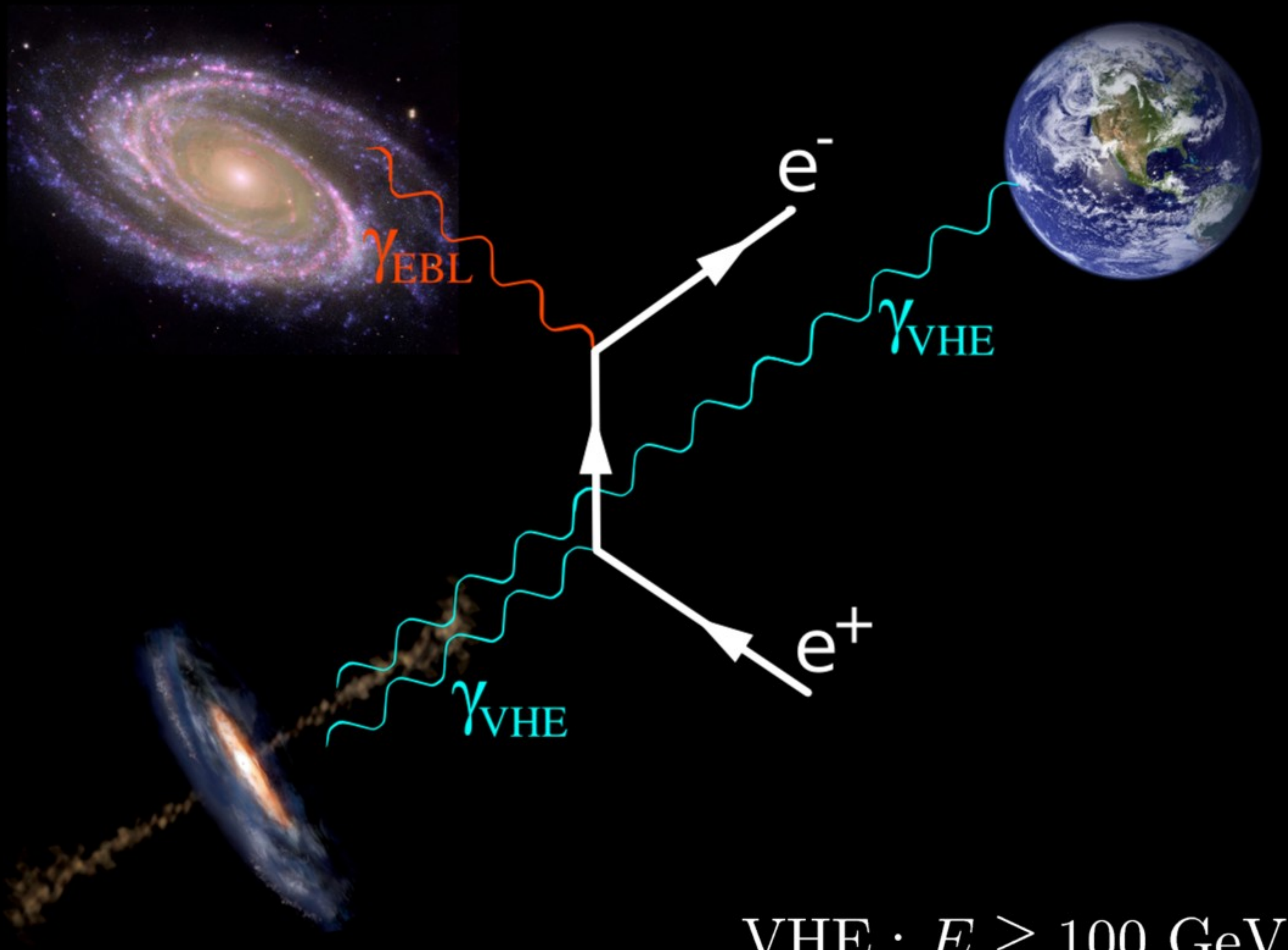
- ALPS (DESY, using HERA dipole magnet)
- BMV (Laboratoire National des Champs Magnétiques Intens, Toulouse)
- BFRT (Brookhaven, 1993)
- GammeV (Fermilab)
- LIPPS (Jefferson Lab)
- OSQAR (CERN, using LHC dipole magnets)
- PVLAS (INFN Trieste)



Parameter Space for Axion-Like Particles



Shining TeV Gamma Rays through the Universe



$$\mathrm{VHE} : E \gtrsim 100\ \mathrm{GeV}$$

Figure from a talk by Manuel Meyer (Univ. Hamburg)

Shining TeV Gamma Rays through the Universe

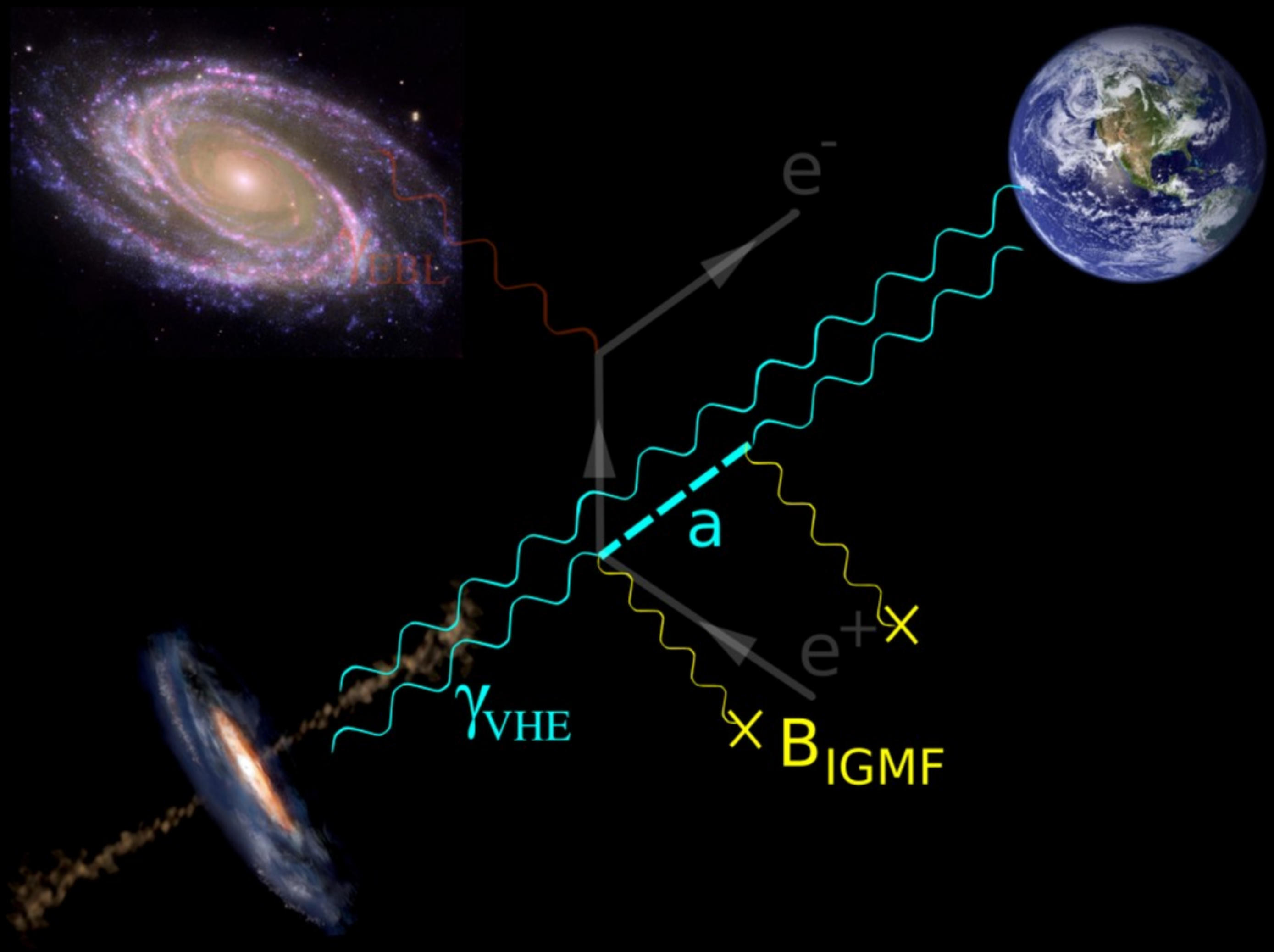
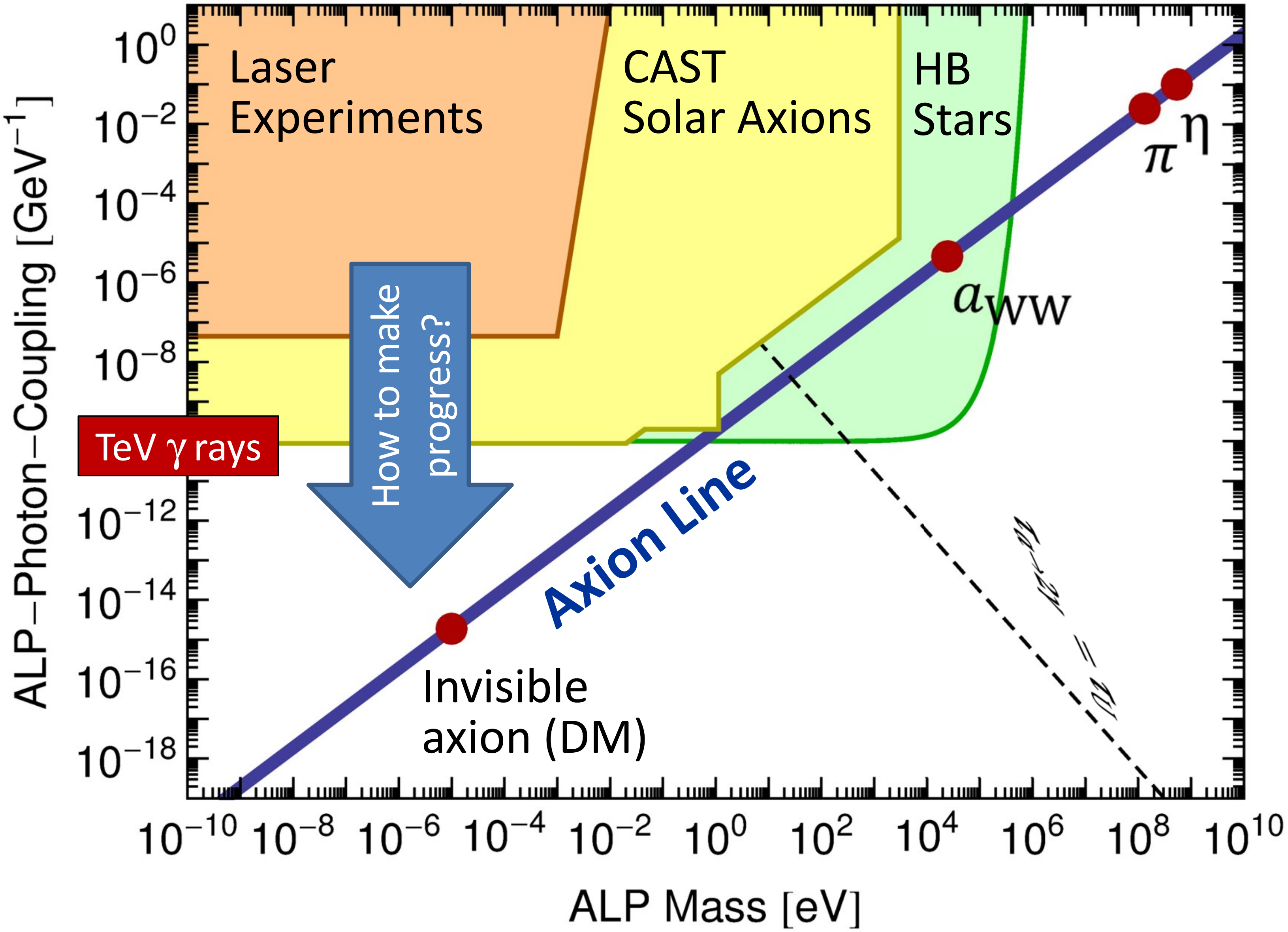
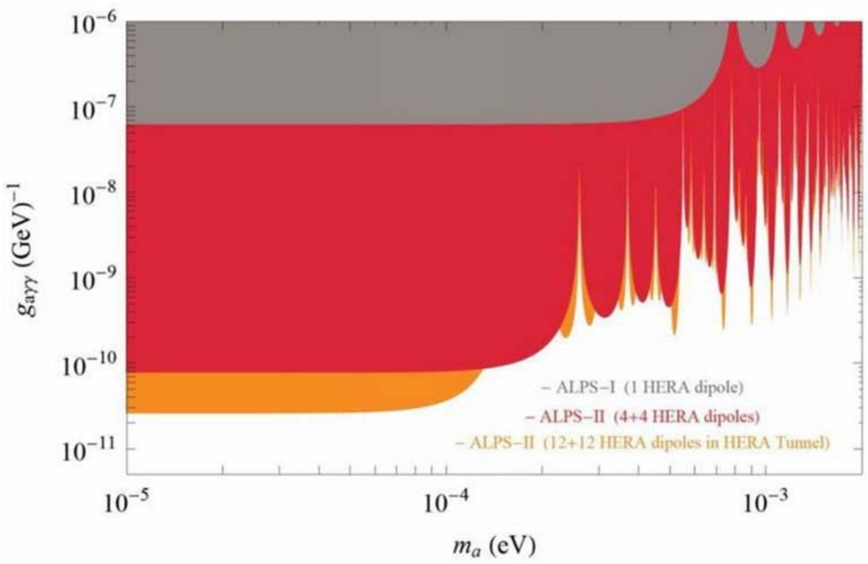


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Parameter Space for Axion-Like Particles



Perspectives for ALPS-II (DESY)



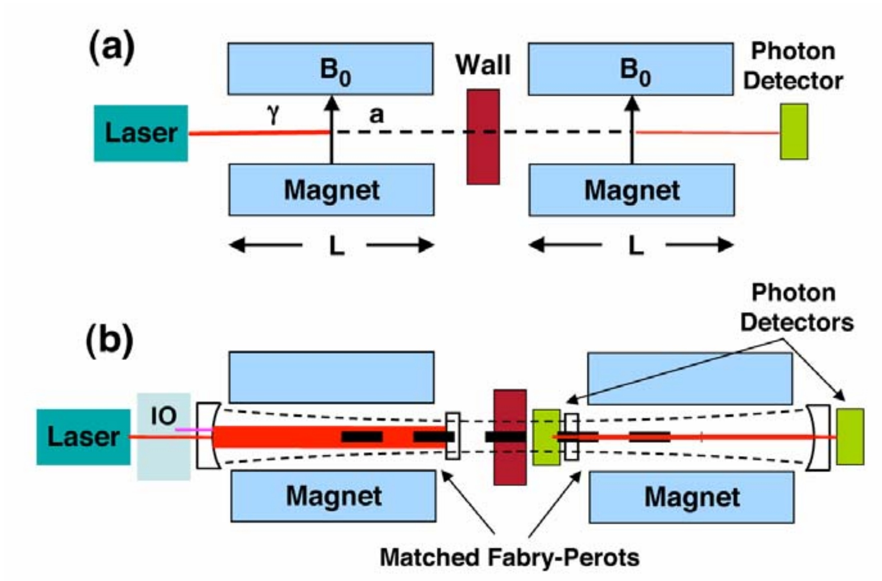
Photon regeneration experiment with 12+12 HERA dipoles

- May reach 10^{-11} GeV^{-1} level

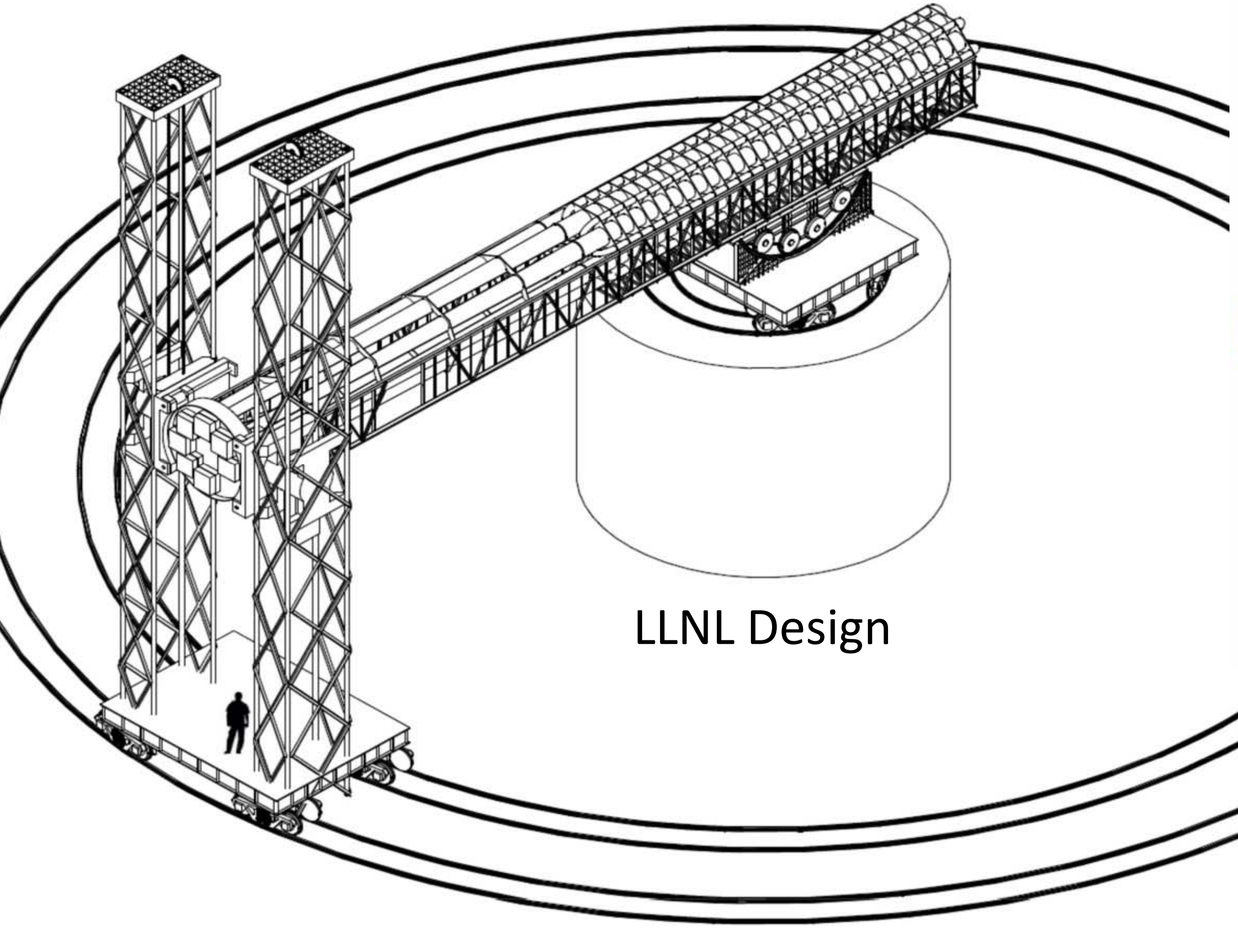
Challenges

- Optical system
- Getting dipoles straight
- Detectors
- Running a 260 m long system (decision 2015)

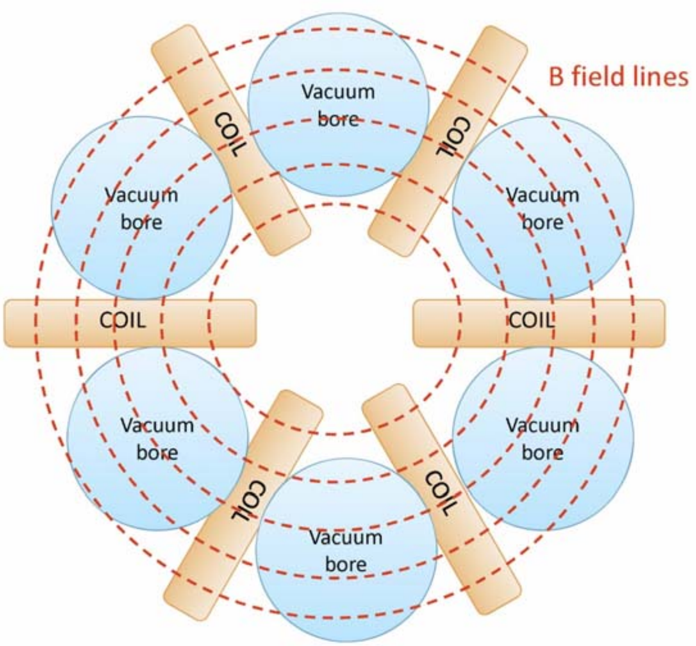
(Axel Lindner and Andreas Ringwalc PIs at DESY)



Next Generation Axion Helioscope (IAXO)



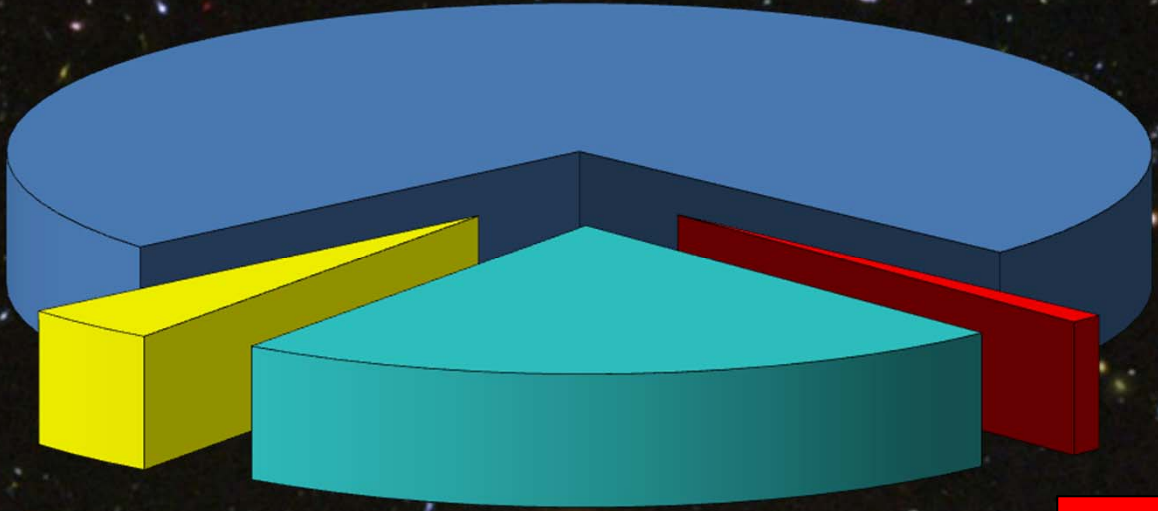
LLNL Design



Need new magnet with
- Much bigger aperture: $\sim 1\ \mathrm{m}^2$ per bore
- Lighter (no iron yoke)
- Bores at room temperature

Irastorza et al., “Towards a new generation axion helioscope”, arXiv:1103.5334

Axions as Cold Dark Matter of the Universe



Dark Energy 73%
(Cosmological Constant)

Ordinary Matter 4%
(of this only about
10% luminous)

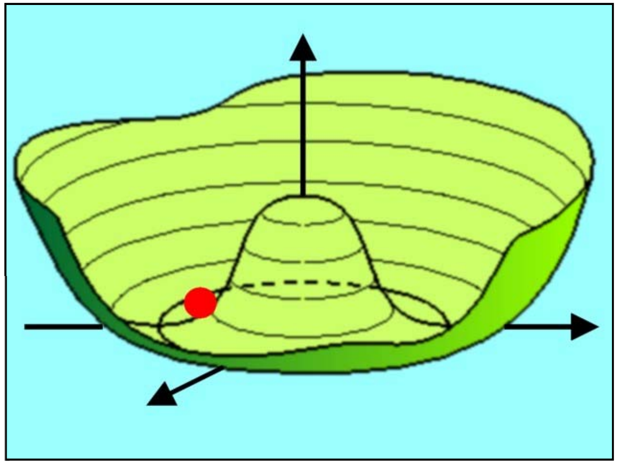
Dark Matter
23%

Neutrinos
0.1–2%

Axion as a Nambu-Goldstone Boson

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

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



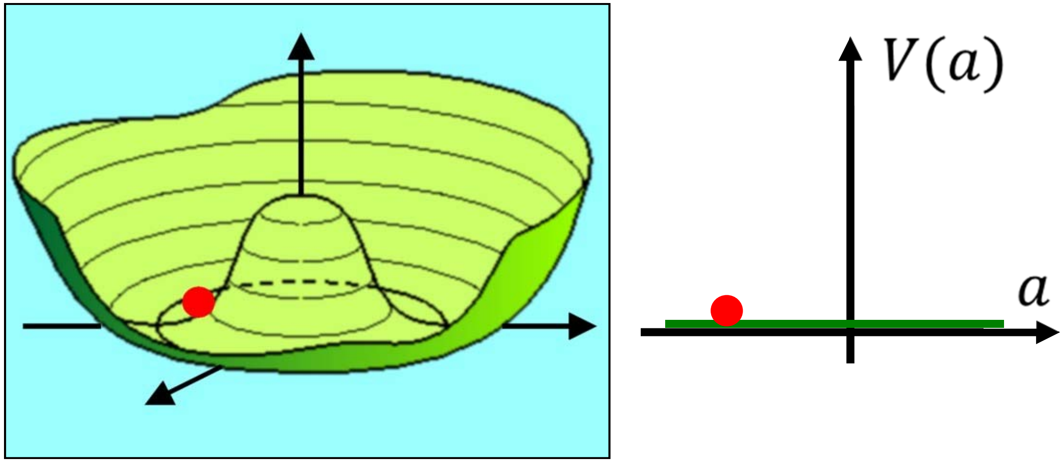
- New U(1) symmetry, spontaneously broken at a large scale f_a
- Axion is “phase” of new Higgs field: angular variable $a(x)/f_a$
- By construction couples to $G\tilde{G}$ term with strength $\alpha_s/8\pi$, e.g. triangle loop with new heavy quark (KSVZ model)
- Mixes with π^0-η-η' mesons
- Axion mass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

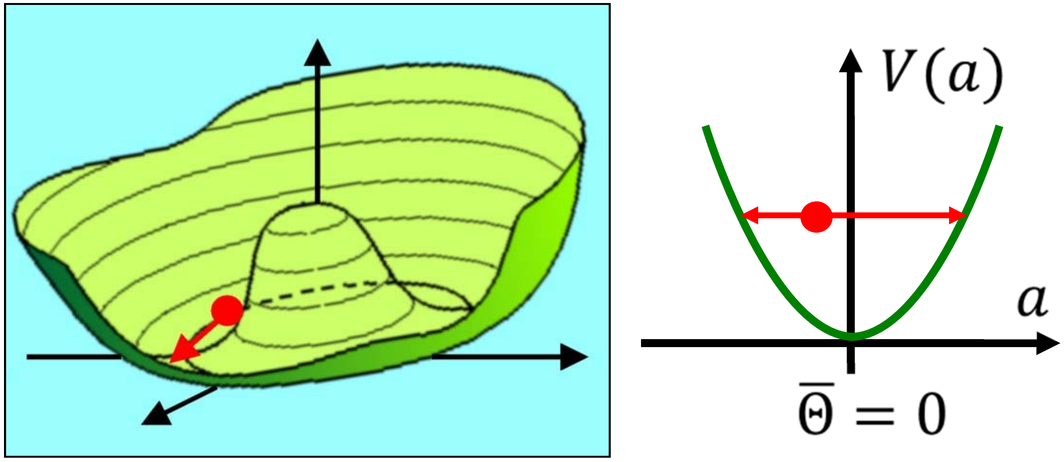
$T \sim f_a$ (very early universe)

- $\mathrm{U_{PQ}}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i\, fa$



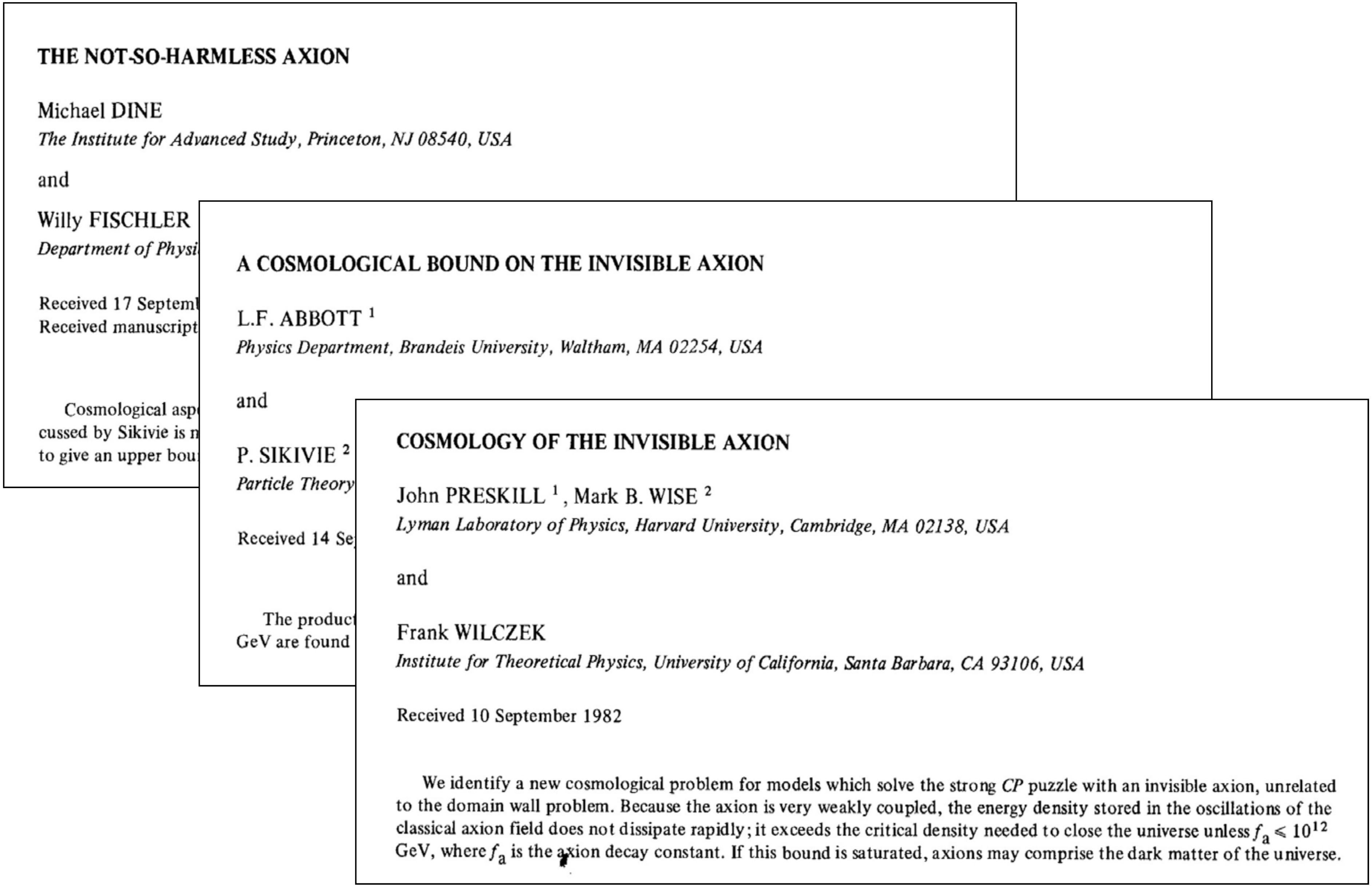
$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)



Axions are born as nonrelativistic, classical field oscillations
Very small mass, yet cold dark matter

Axion Cosmology in PLB 120 (1983)



THE NOT-SO-HARMLESS AXION

Michael DINE
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and

Willy FISCHLER
Department of Physi

Received 17 Septem
Received manuscript

Cosmological asp
cussed by Sikivie is n
to give an upper bou

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

L.F. ABBOTT [1]
Physics Department, Brandeis University, Waltham, MA 02254, USA

and

P. SIKIVIE [2]
Particle Theory

Received 14 Se

The product
GeV are found

COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL [1], Mark B. WISE [2]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

and

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

Received 10 September 1982

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

Cosmic Axion Density

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

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

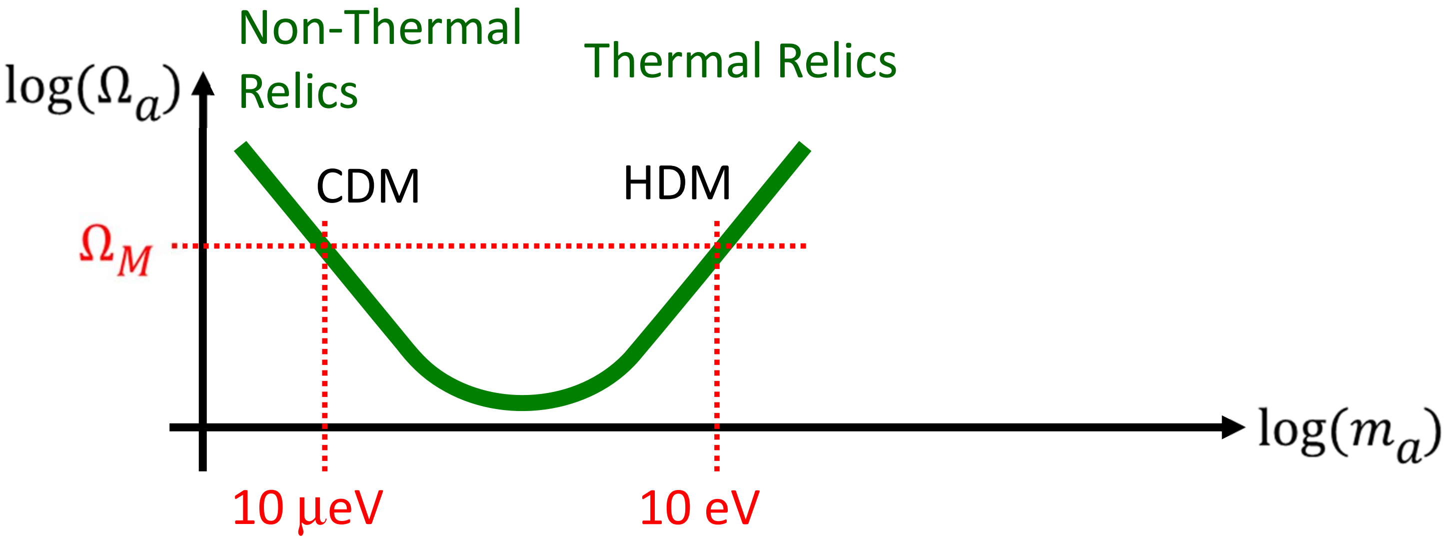
If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

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

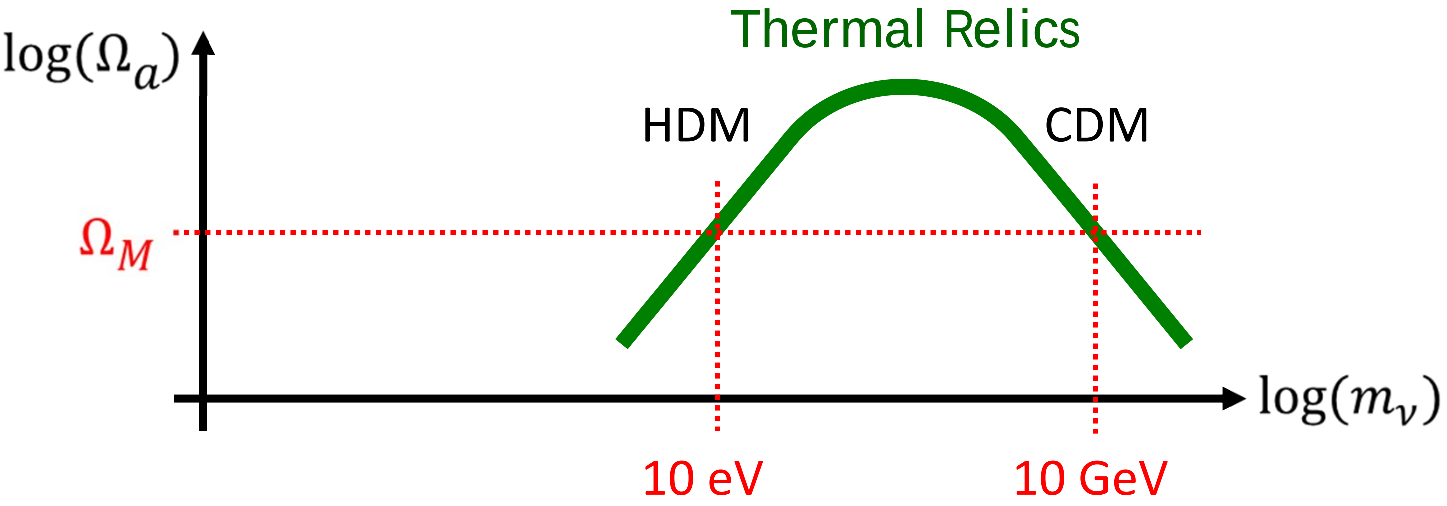
- $\Theta_\mathrm{i} \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu\mathrm{eV}$ ("classic window")
- $f_a \sim 10^{16}$ GeV (GUT scale) or larger (string inspired) requires $\Theta_\mathrm{i} \lesssim 0.003$ ("anthropic window")

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos
& WIMPs



Cold Axion Populations

Case 1
Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

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

Dependence on initial misalignment angle $\Omega_a \propto \Theta_{\rm i}^2$

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

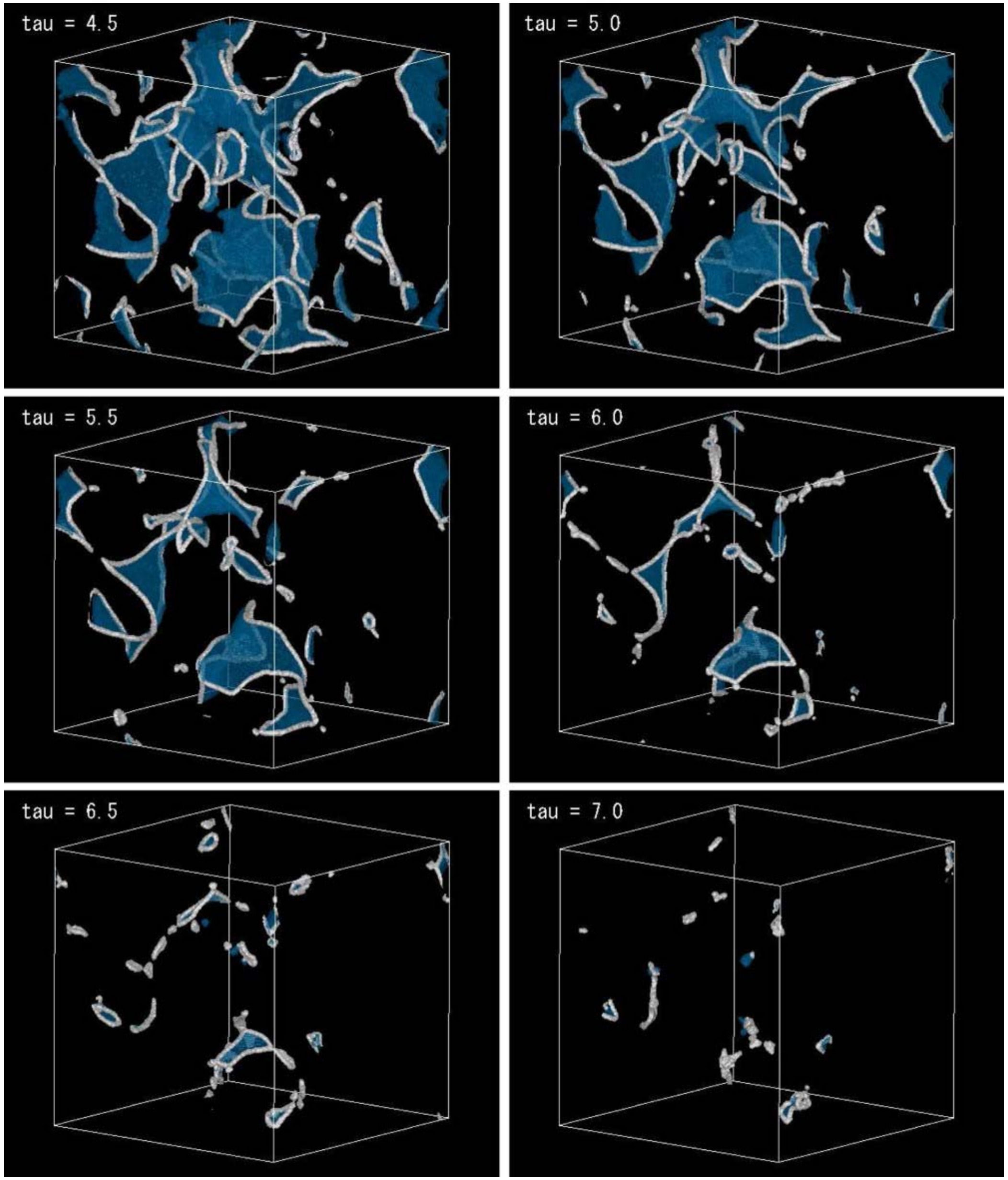
- Cosmic strings of broken $U_{\rm PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_a independent of initial conditions
- $N = 1$ or else domain wall problem

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

Typical properties

- Mass $\sim 10^{-12}\, M_{\rm sun}$
- Radius $\sim 10^{10}$ cm
- Mass fraction up to several 10%

Axion Production by Domain Wall and String Decay



Recent numerical studies of collapse of string-domain wall system

$$\Omega_a h^2 = (16 \pm 6)\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \times \left(\frac{g_{*,1}}{70}\right)^{-0.41}\left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$$

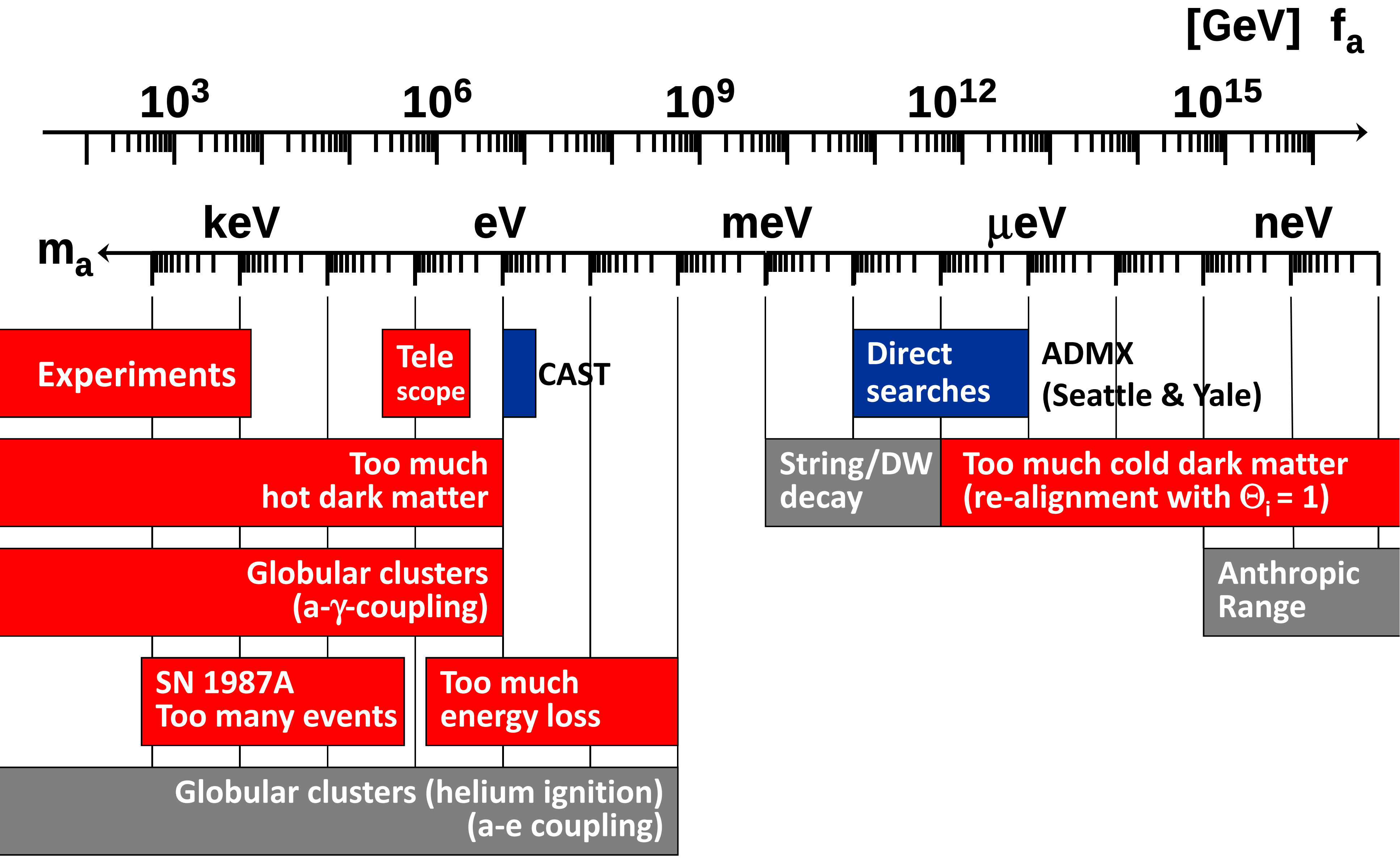
Implies a CDM axion mass of

$$m_a \sim 1\ \mathrm{meV}$$

Hiramatsu, Kawasaki, Saikawa, Sekiguchi, arXiv:1202.5851 (2012)

Remains to be confirmed, interpretation of numerical studies not entirely straightforward

Axion Bounds and Searches



Experiments

Tele scope

CAST

Direct searches

ADMX (Seattle & Yale)

Too much hot dark matter

String/DW decay

Too much cold dark matter (re-alignment with $\Theta_i = 1$)

Globular clusters (a-γ-coupling)

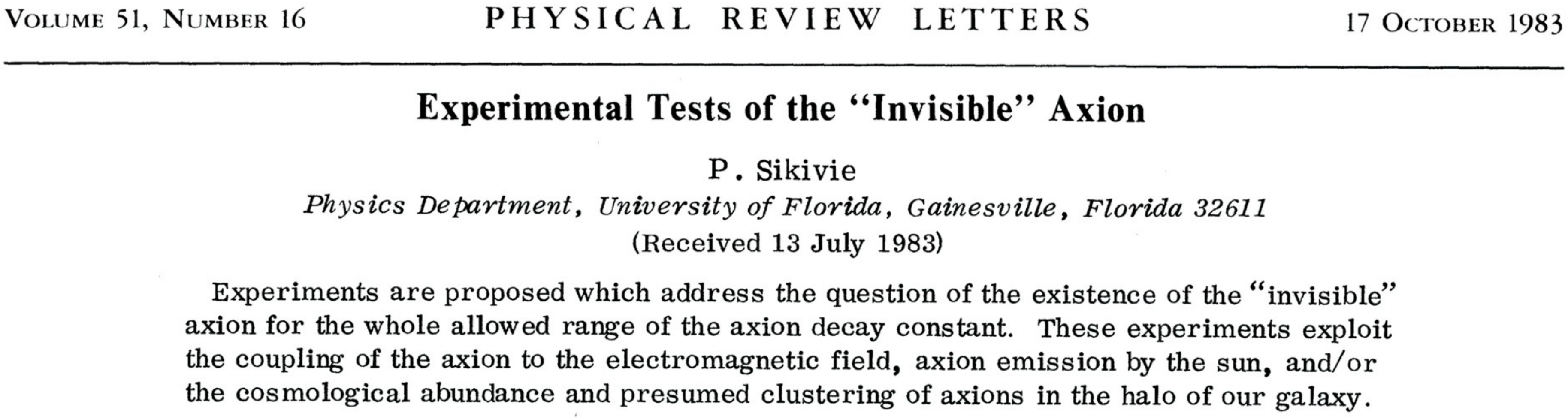
Anthropic Range

SN 1987A Too many events

Too much energy loss

Globular clusters (helium ignition) (a-e coupling)

Searching for Axion Dark Matter



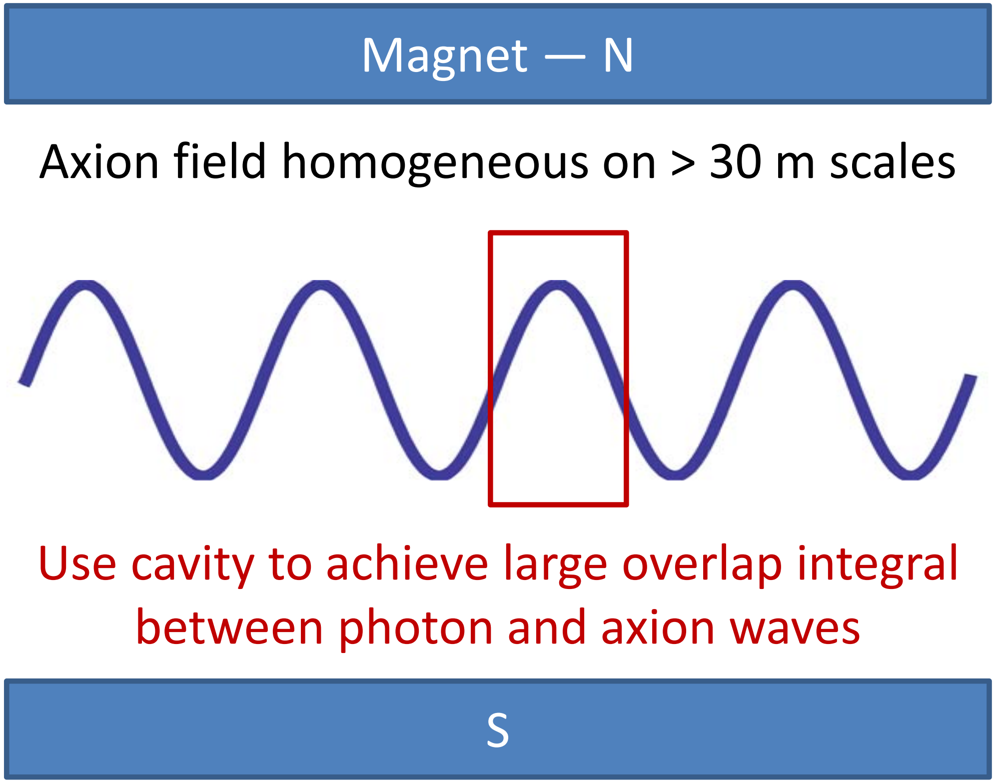
Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

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.



Magnet — N

Axion field homogeneous on > 30 m scales

Use cavity to achieve large overlap integral between photon and axion waves

S

Primakoff effect:

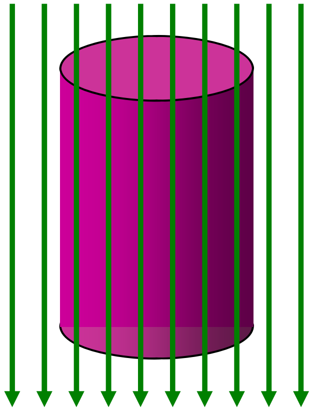
Axion-photon transition in external static E or B field

Search for Galactic Axions (Cold Dark Matter)

Dark matter axions $m_a = 1\text{–}100\ \mu\mathrm{eV}$
Velocities in galaxy $v_a \approx 10^{-3}\ c$
Energies therefore $E_a \approx (1 \pm 10^{-6})\ m_a$

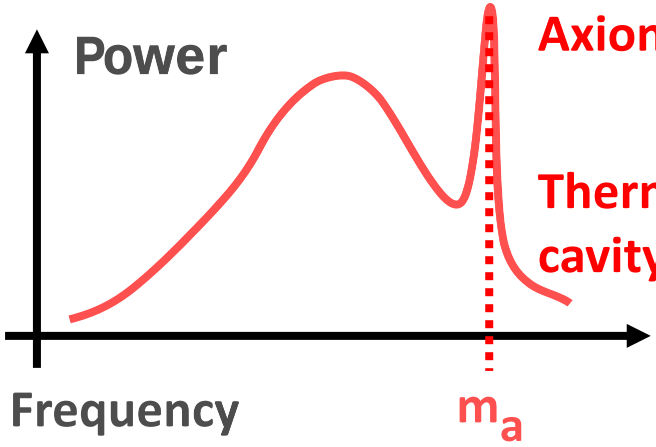
Microwave Energies
($1\ \mathrm{GHz} \approx 4\ \mu\mathrm{eV}$)

Axion Haloscope (Sikivie 1983)



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

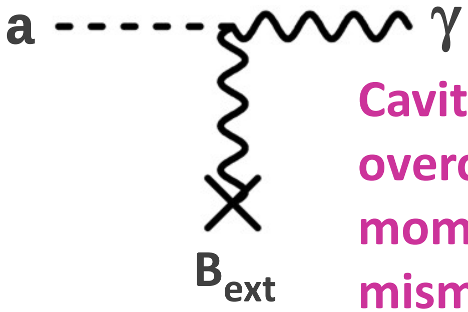
Microwave
Resonator
$Q \approx 10^5$



Axion Signal

Thermal noise of
cavity & detector

Primakoff Conversion



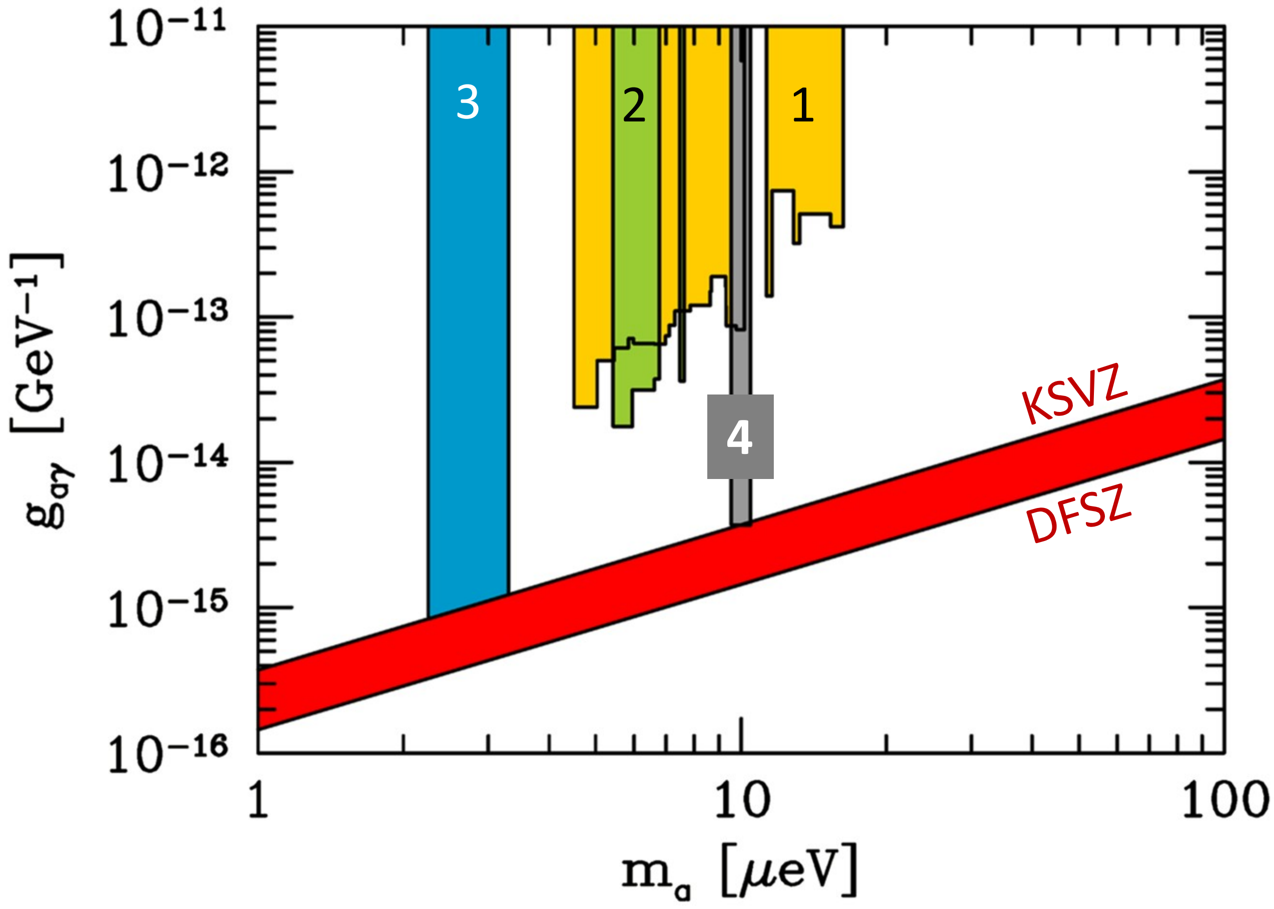
Cavity
overcomes
momentum
mismatch

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 assuming axions are the galactic dark matter with standard halo



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

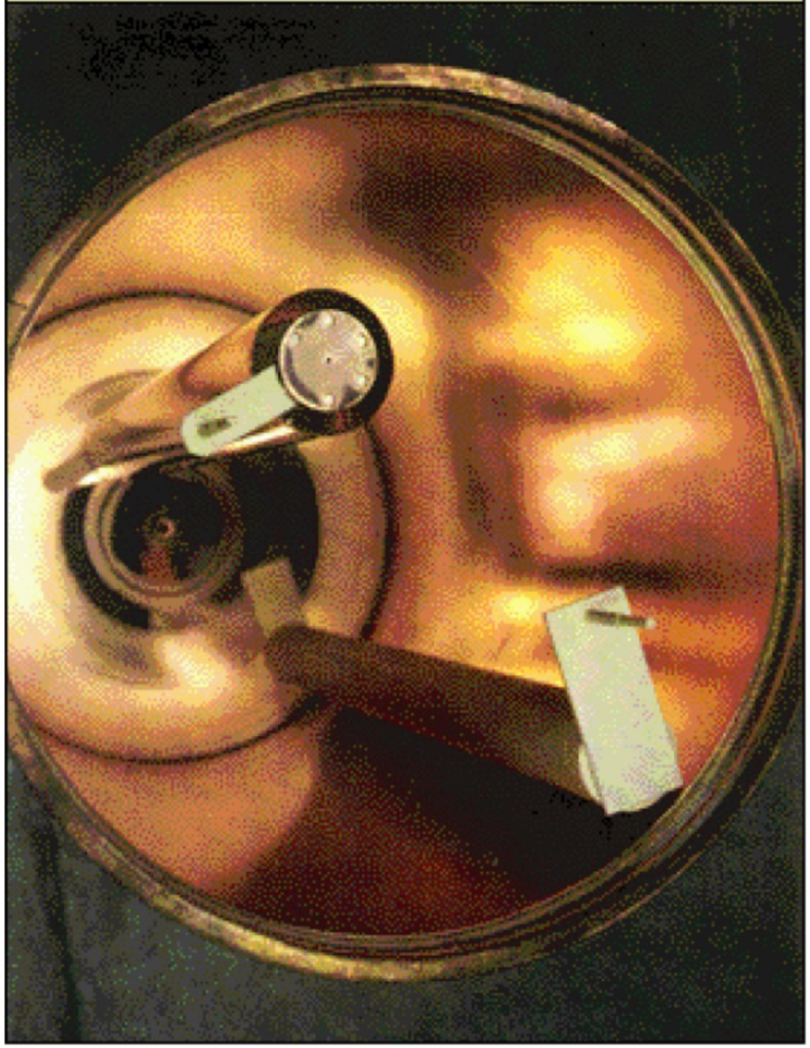
2. University of Florida PRD 42 (1990) 1297

3. US Axion Search ApJL 571 (2002) L27

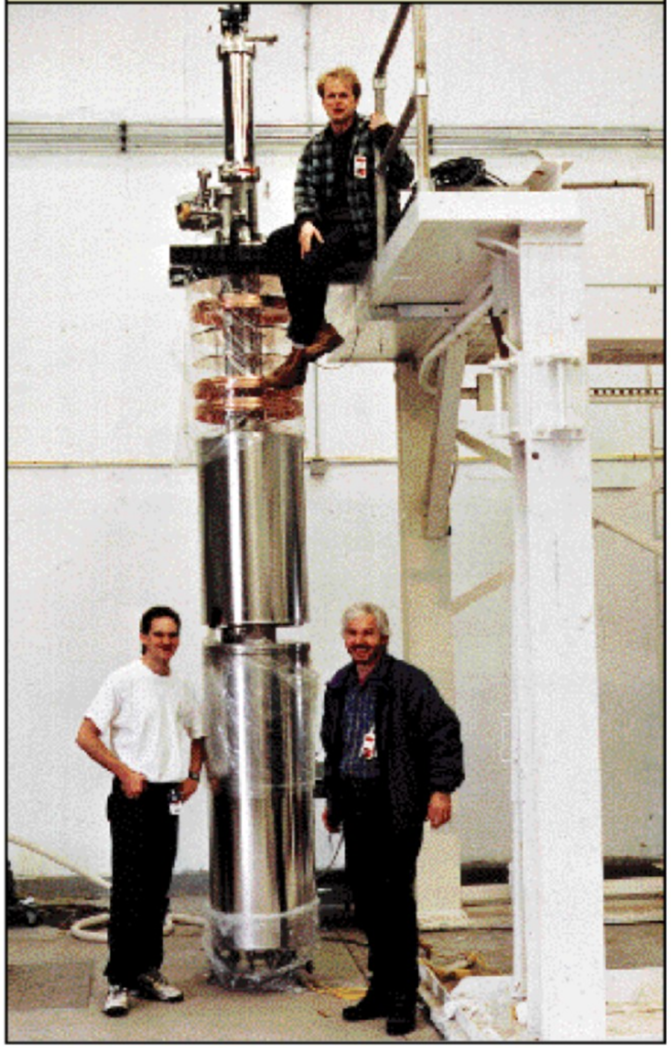
4. CARRACK I (Kyoto) hep-ph/0101200

ADMX Hardware

High-Q Cavity (~200,000)



Experimental Insert



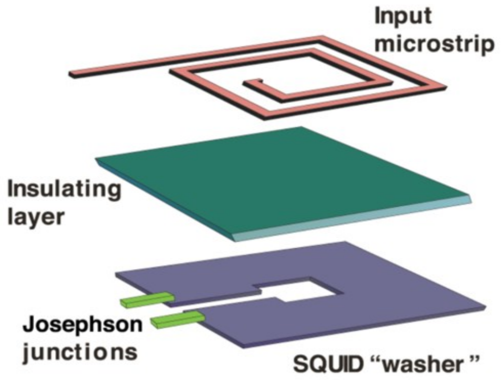
Adapted from Gianpaolo Carosi

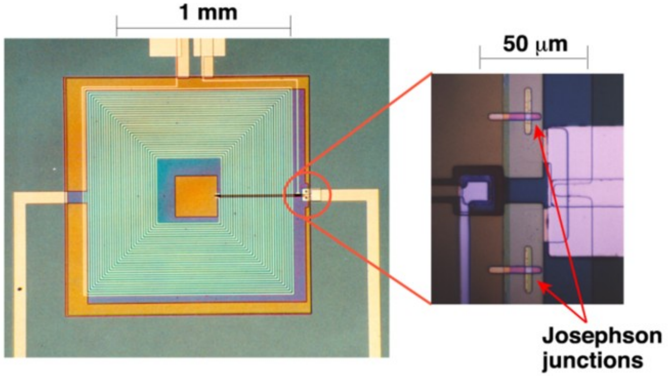
SQUID Microwave Amplifiers in ADMX

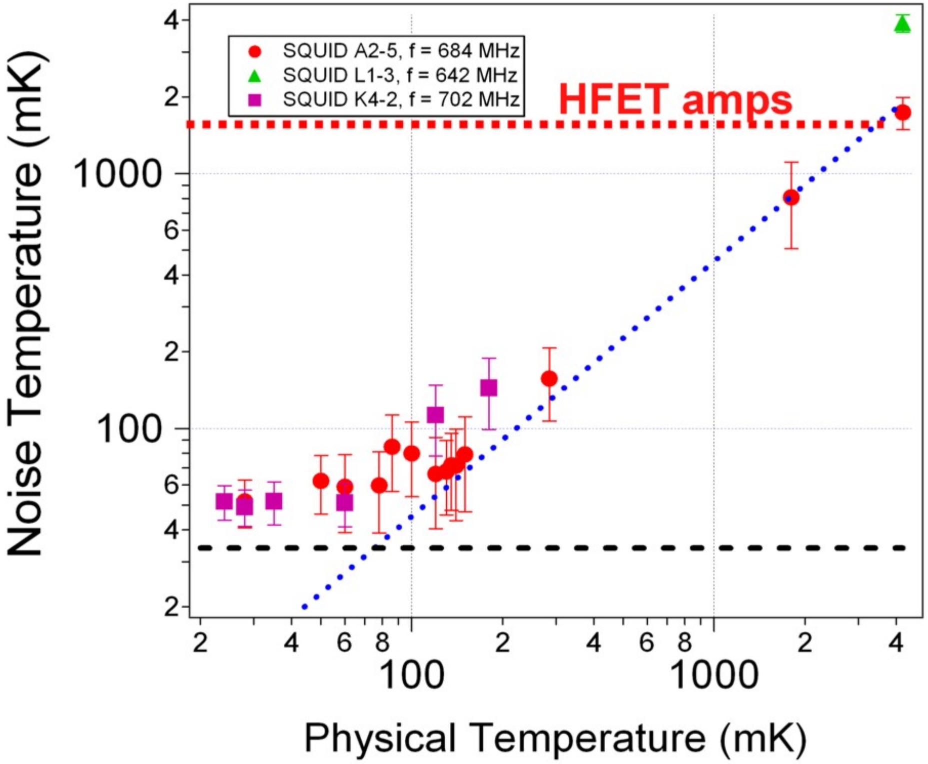
Presently the noise temperature of our HFET amps is ~ 1.5K

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

Adapted from Gianpaolo Carosi

ADMX phase I: First-year science data (2009)

PRL 104, 041301 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

SQUID-Based Microwave Cavity Search for Dark-Matter Axions

S. J. Asztalos,* G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

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

J. Hoskins, J. Hwang,† P. Sikivie, and D. B. Tanner
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R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903,

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

(Received 27 October 2009; published 28 January 2010)

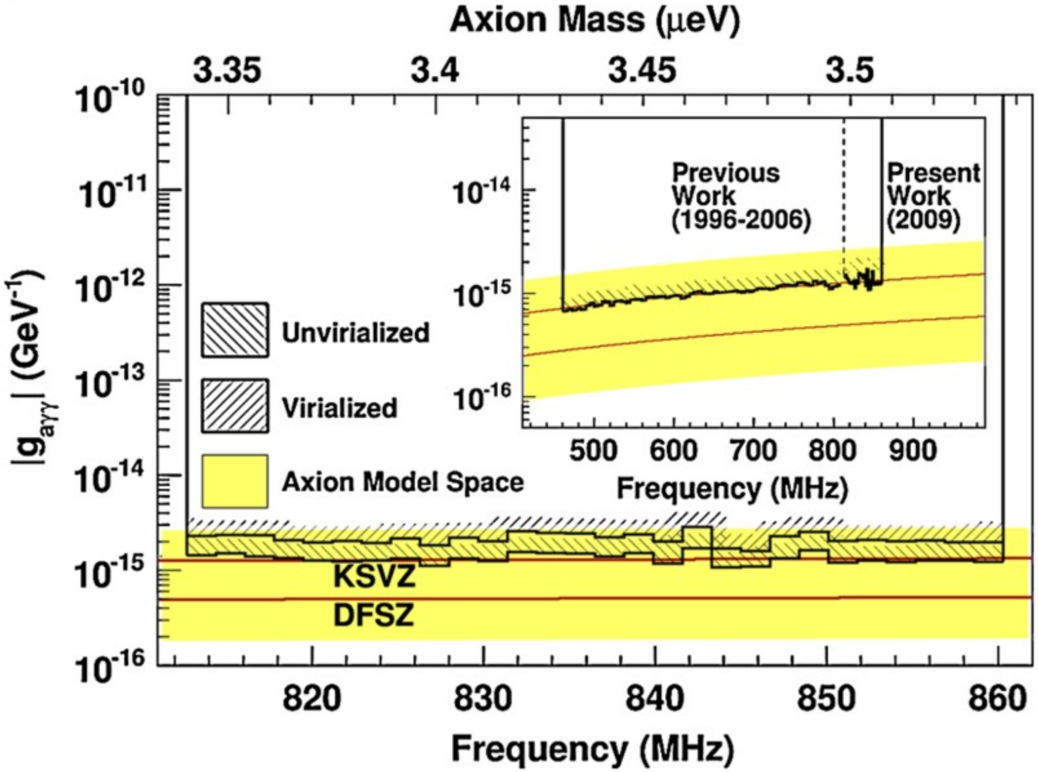
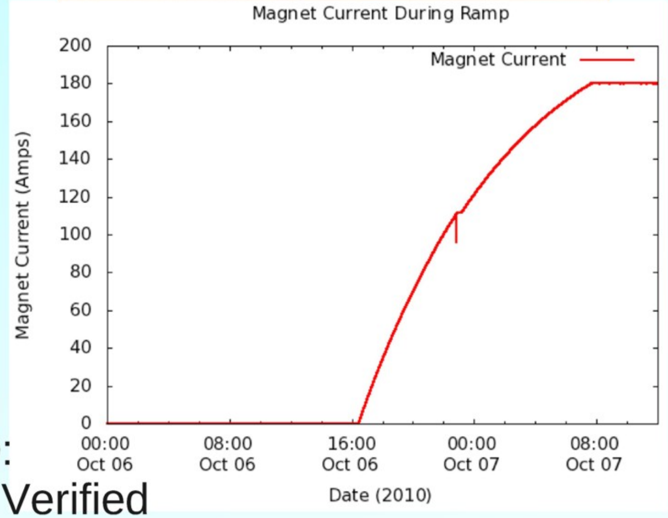


FIG. 5 (color online). Axion-photon coupling excluded at the 90% confidence level assuming a local dark-matter density of 0.45 GeV/cm^3 for two dark-matter distribution models. The shaded region corresponds to the range of the axion-photon coupling models discussed in [28].

ADMX Comes to UW

August 2010:
ADMX Moves to UW



October 2010:
Main Magnet Verified

May 2011:
Main Magnet Installed
in Experiment Area (CENPA)

Schedule

~~Summer 2010~~ ~~Winter 2010~~
~~Spring 2011~~ Summer 2011 – Funding Clears

2011-2012 Construct new insert

small axion search here

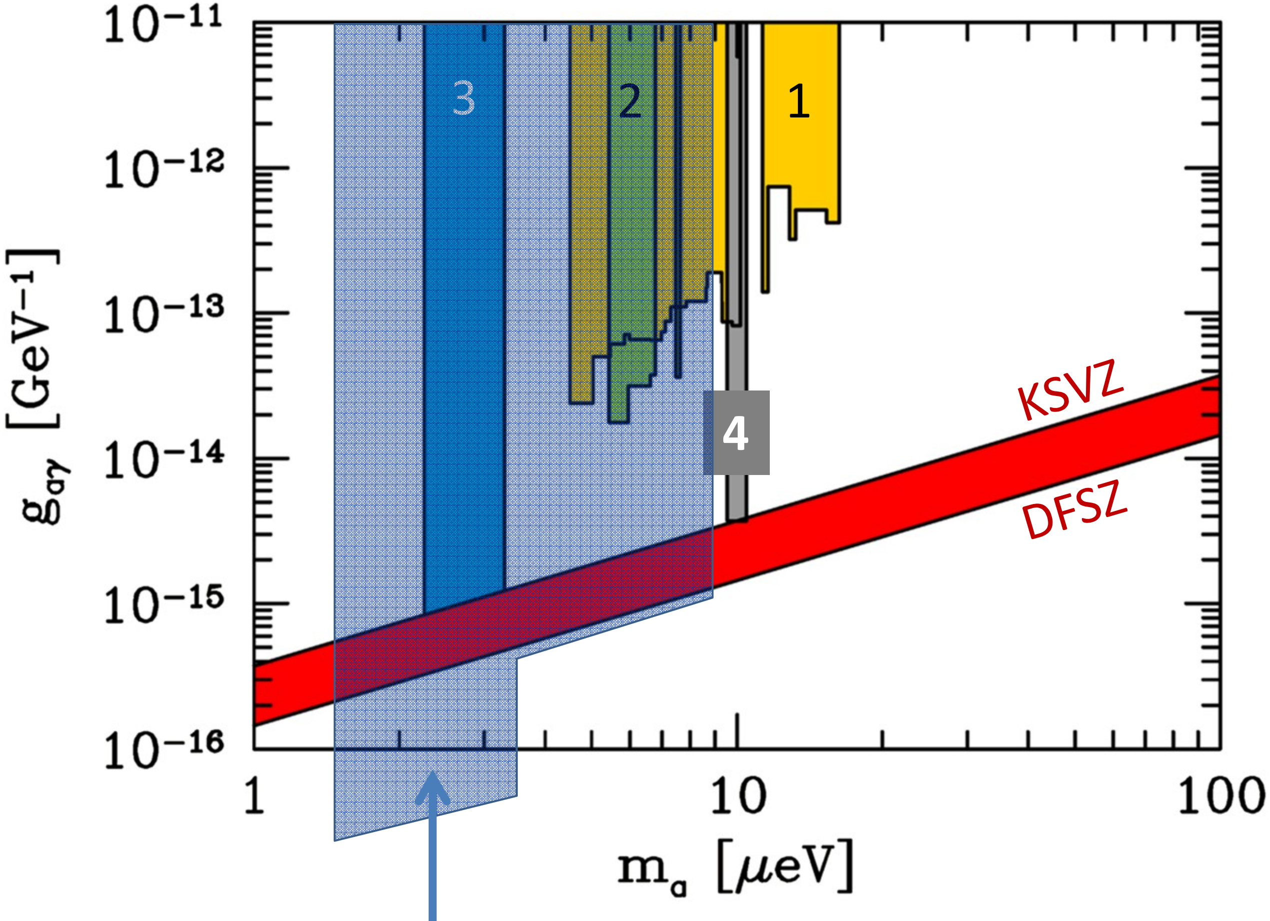
2012-2013 Commission new insert, order dilution refrigerator

2013-2014 Install dilution refrigerator, commission

2015+ Definitive Axion search

Axion Dark Matter Searches

Limits assuming axions are the galactic dark matter with standard halo



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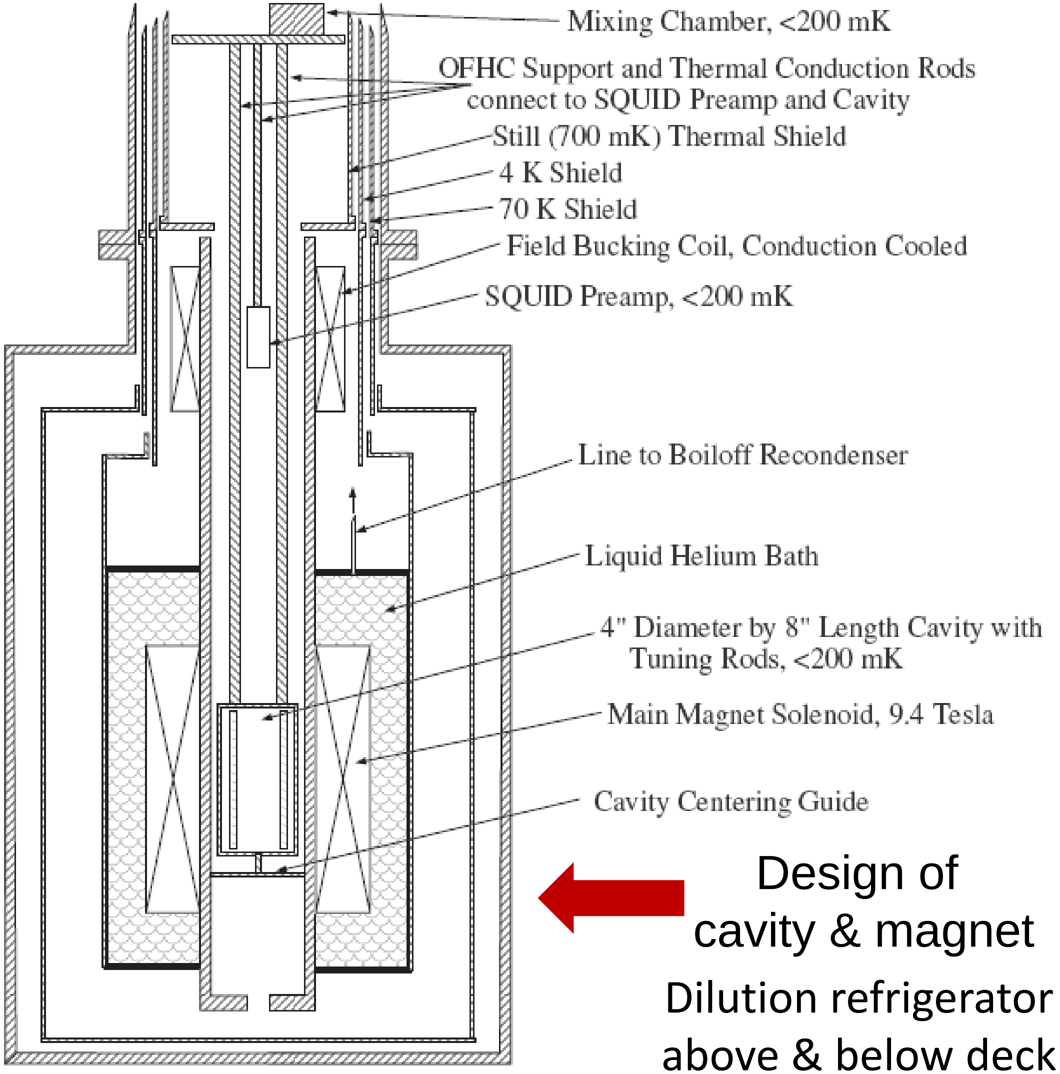
3. US Axion Search ApJL 571 (2002) L27

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

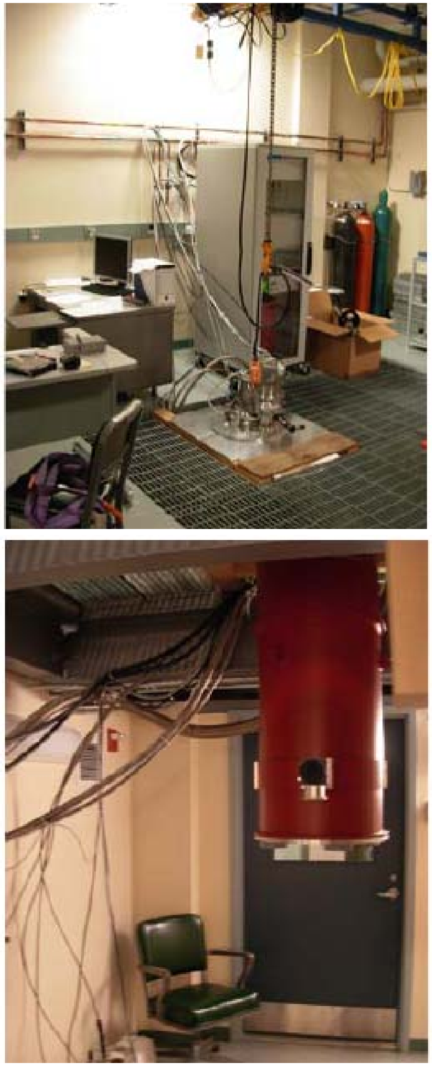
ADMX-LF (Seattle) search range (2015+)

ADMX-HF at Yale (Steve Lamoreaux Group)



Design of
cavity & magnet

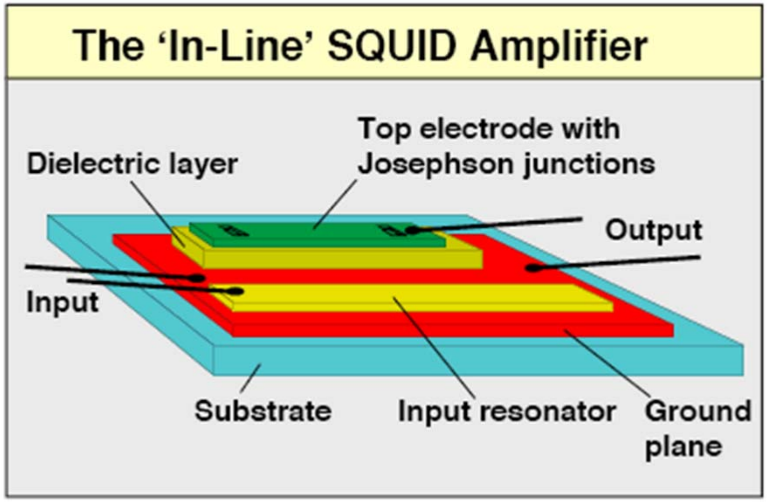
Dilution refrigerator
above & below deck



ADMX-HF will also be a test-bed for innovative concepts, e.g. thin-film superconducting cavities

Adapted from Karl van Bibber

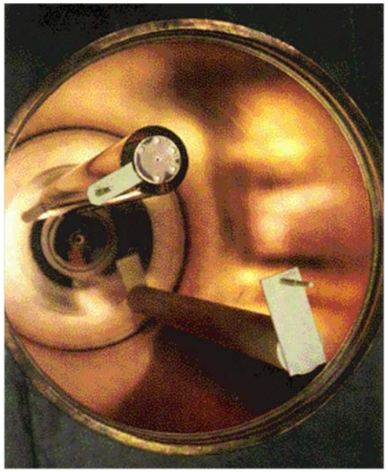
For the long term, ADMX needs concurrent R&D


The 'In-Line' SQUID Amplifier

To get to 10 GHz (40 μeV), and ultimately 100 GHz (0.4 meV), we need to:

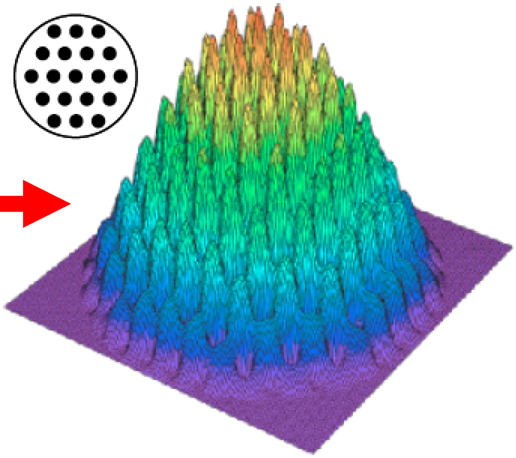
- Develop new RF cavity geometries
- Develop new SQUID geometries

1 GHz



10 GHz

100 GHz

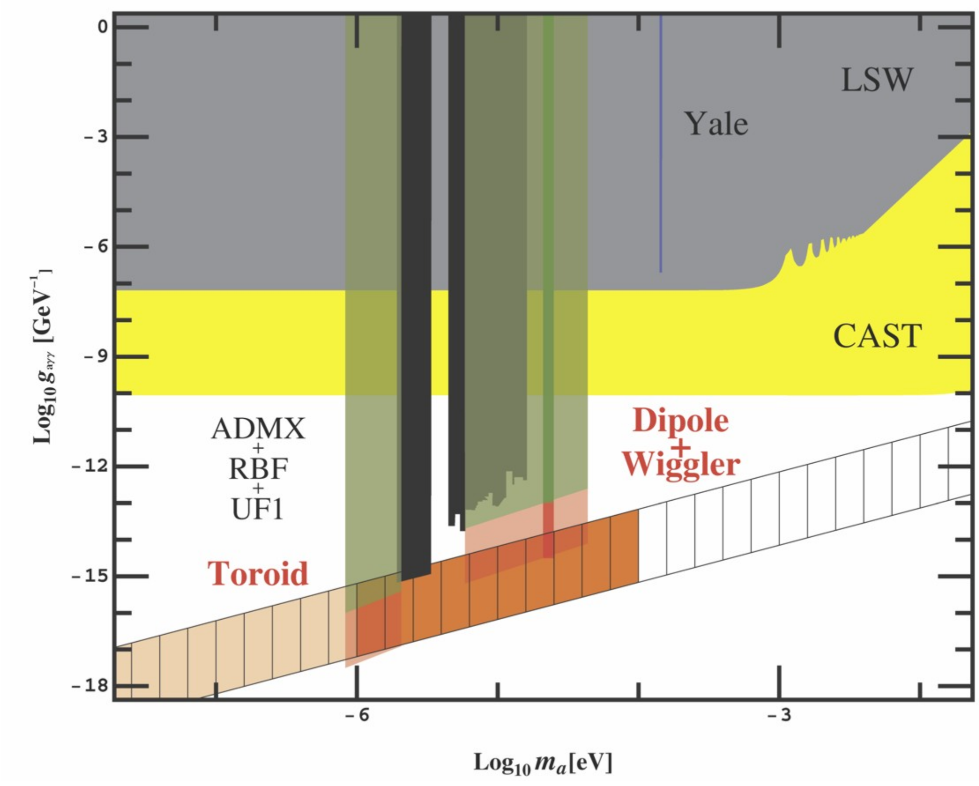


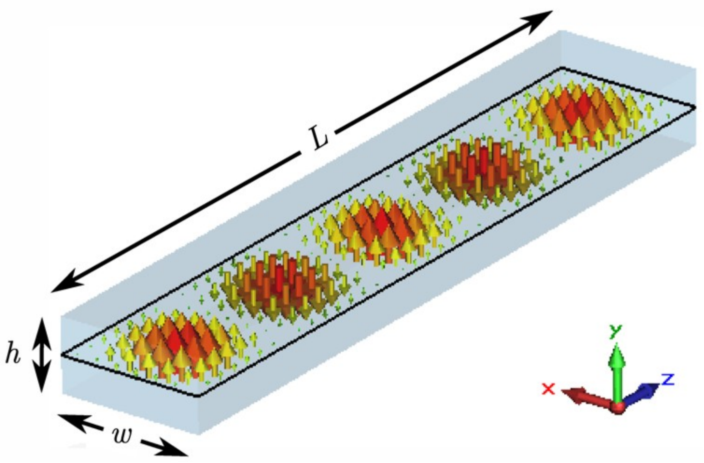
Adapted from Karl van Bibber

Prospects for Searching Axion-like Particle Dark Matter with Dipole, Toroidal and Wiggler Magnets

Oliver K. Baker[1], Michael Betz[2], Fritz Caspers[2], Joerg Jaeckel[3], Axel Lindner[4],
Andreas Ringwald[4], Yannis Semertzidis[5], Pierre Sikivie[6], Konstantin Zioutas[7].

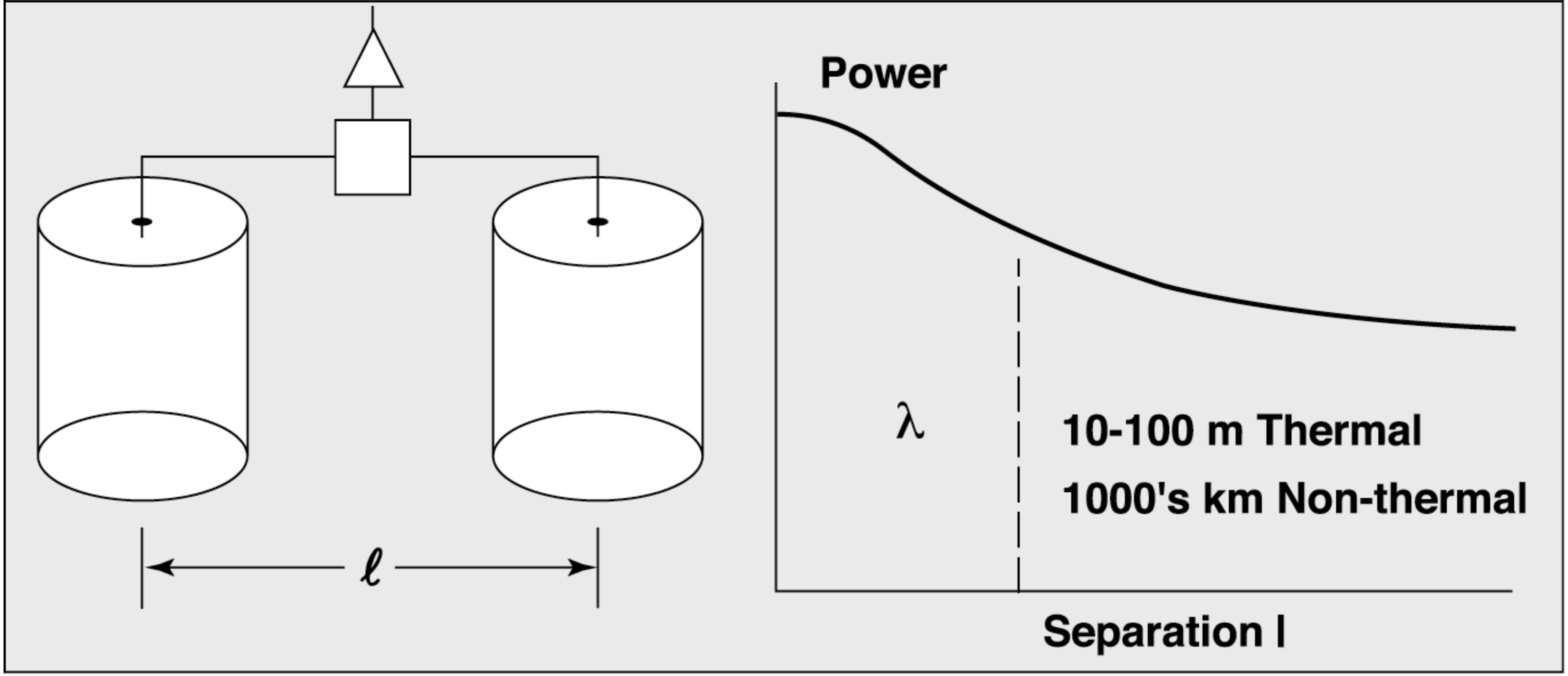
arXiv:1110.2180v1 (10 Oct 2011)





What if the axion is found?

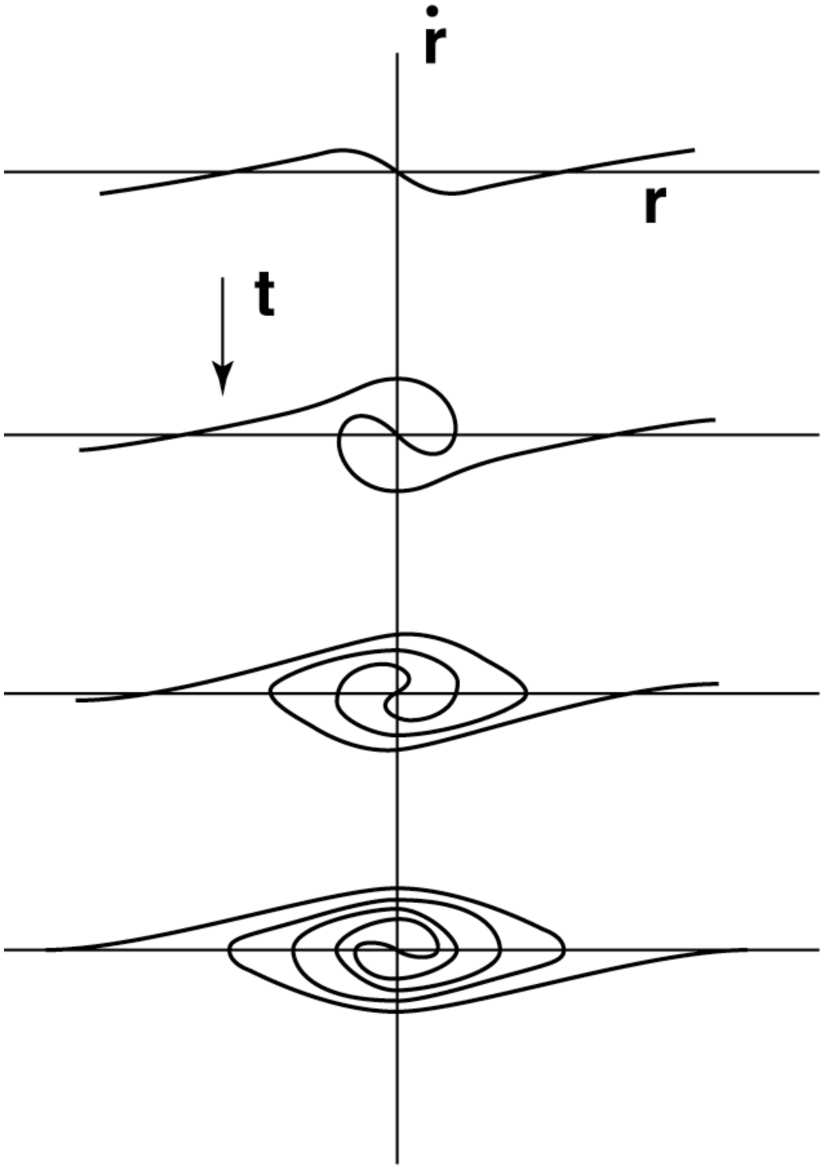
The Study of Unique Quantum System

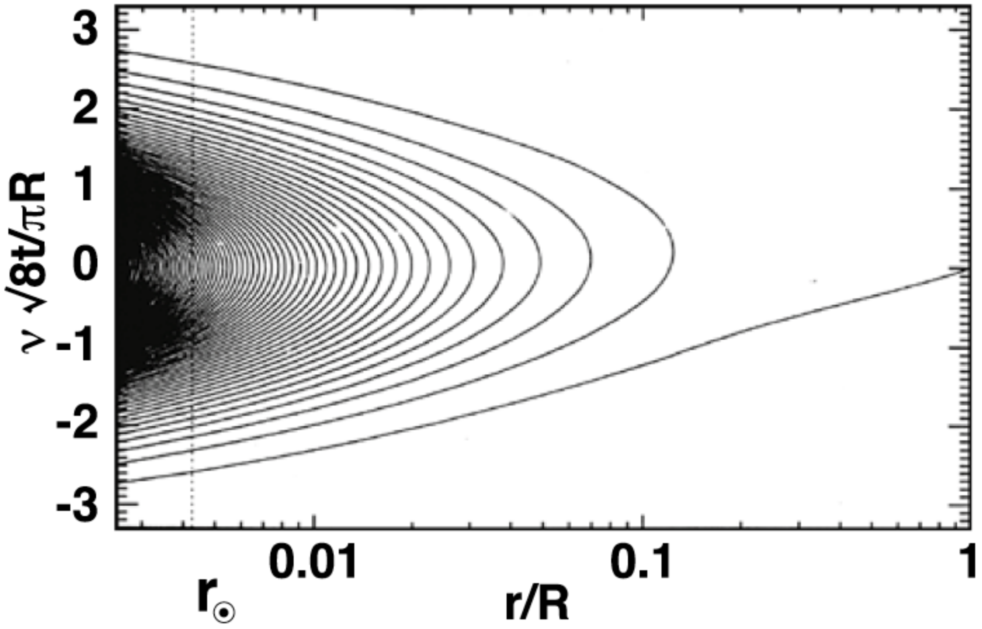


And should the axion posses fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy

Adapted from Karl van Bibber

1D Infall and the Folding of Phase Space





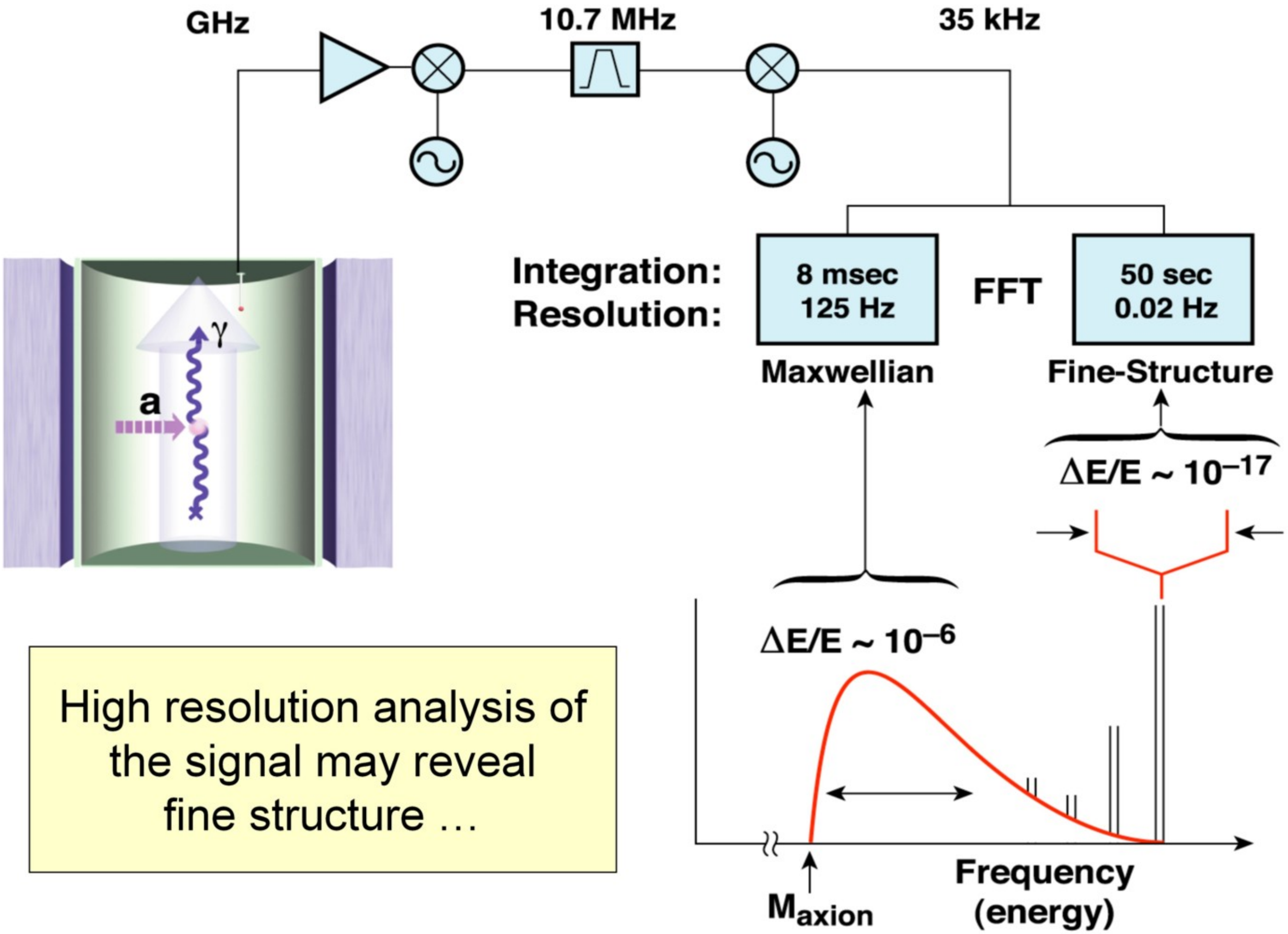
- Model begins with
  - — Zero Temperature CDM
  - — Hubble expansion
  - — Initial density perturbation r = o

- Grows self-consistent potential

Adapted from Karl van Bibber

Fine Structure in the 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

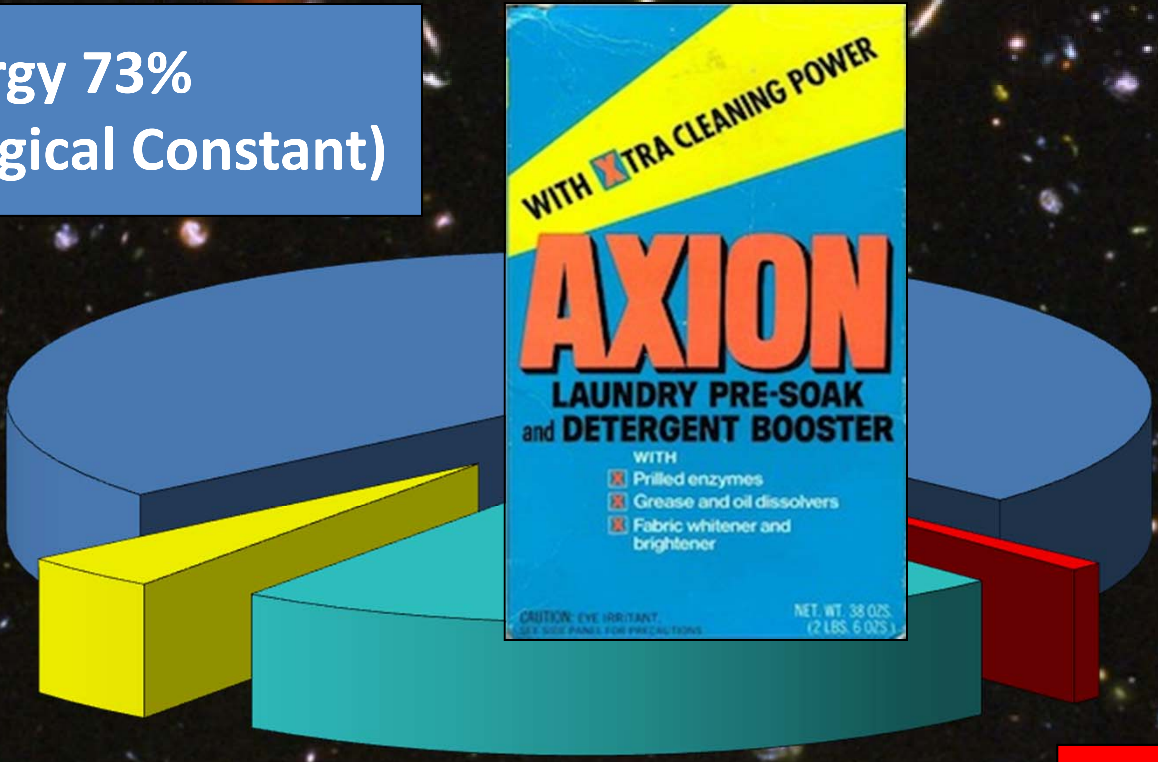


High resolution analysis of the signal may reveal fine structure …

P.Sikivie
& collaborators

Adapted from Karl van Bibber

Dark Energy 73%
(Cosmological Constant)



Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%