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Axions

Motivation, Limits and Searches

Seminar CEA Saclay 4 Feb 2009 Gif-sur-Yvette France

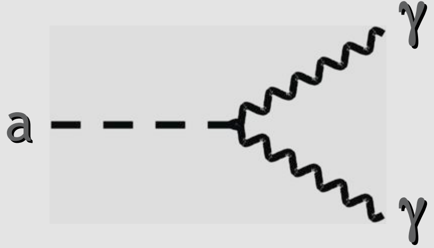
Axion Physics in a Nut Shell

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

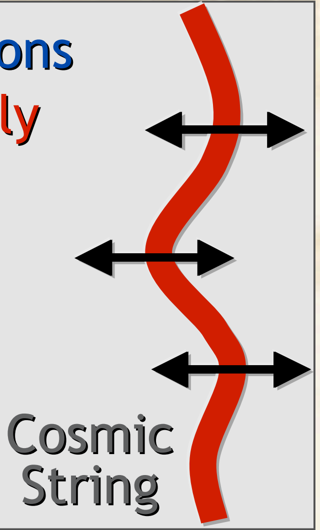
Axions thermally produced in stars, e.g. by Primakoff production

- Limits from avoiding excessive energy drain
- Search for solar axions (CAST, Sumico)

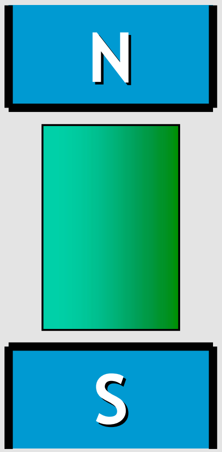
Cosmology

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

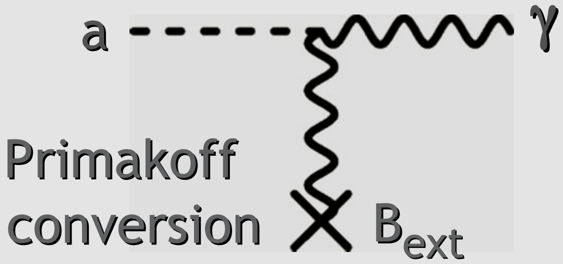
→ "Cold dark matter" candidate
$m_a \sim 1\text{-}1000\ \mu\text{eV}$



Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



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 (Cabbibo-Kobayashi-Maskawa)


M. Kobayashi


T. Maskawa

Physics Nobel Prize 2008

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

The CP Problem of Strong Interactions

Real quark mass

Phase from Yukawa coupling

Angular variable

CP-odd quantity ~E·B

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

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 CP-violating quantity)

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

Dynamical Solution

Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

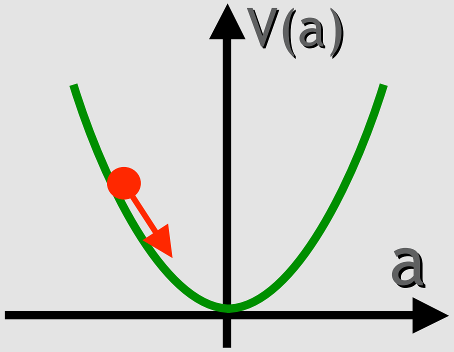
Re-interpret $\bar{\Theta}$ as
a dynamical variable
(scalar field)

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

Pseudo-scalar axion field

Peccei-Quinn scale,
Axion decay constant

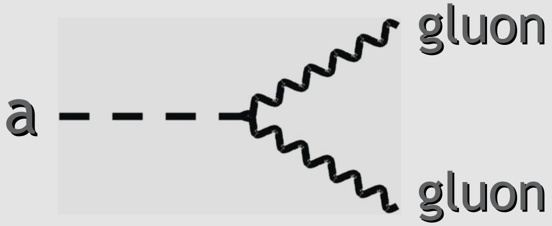
$$L_{CP} = -\frac{\alpha_s}{8\pi}\,\bar{\Theta}\,\mathrm{Tr}(G\tilde{G}) \Rightarrow L_{CP} = -\frac{\alpha_s}{8\pi}\,\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$



$\bar{\Theta} = 0$

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

CP-symmetry
dynamically restored

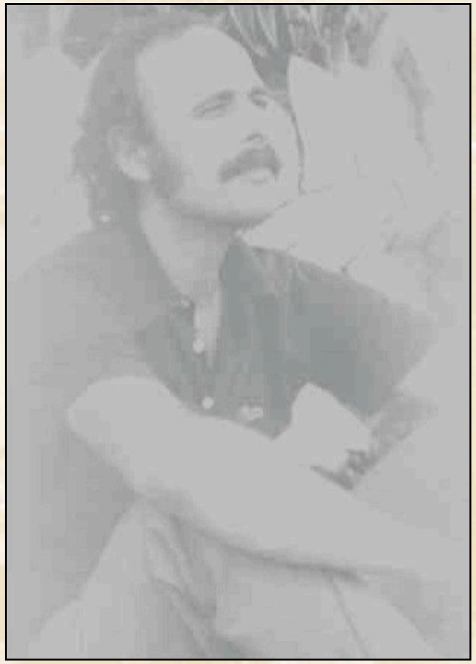


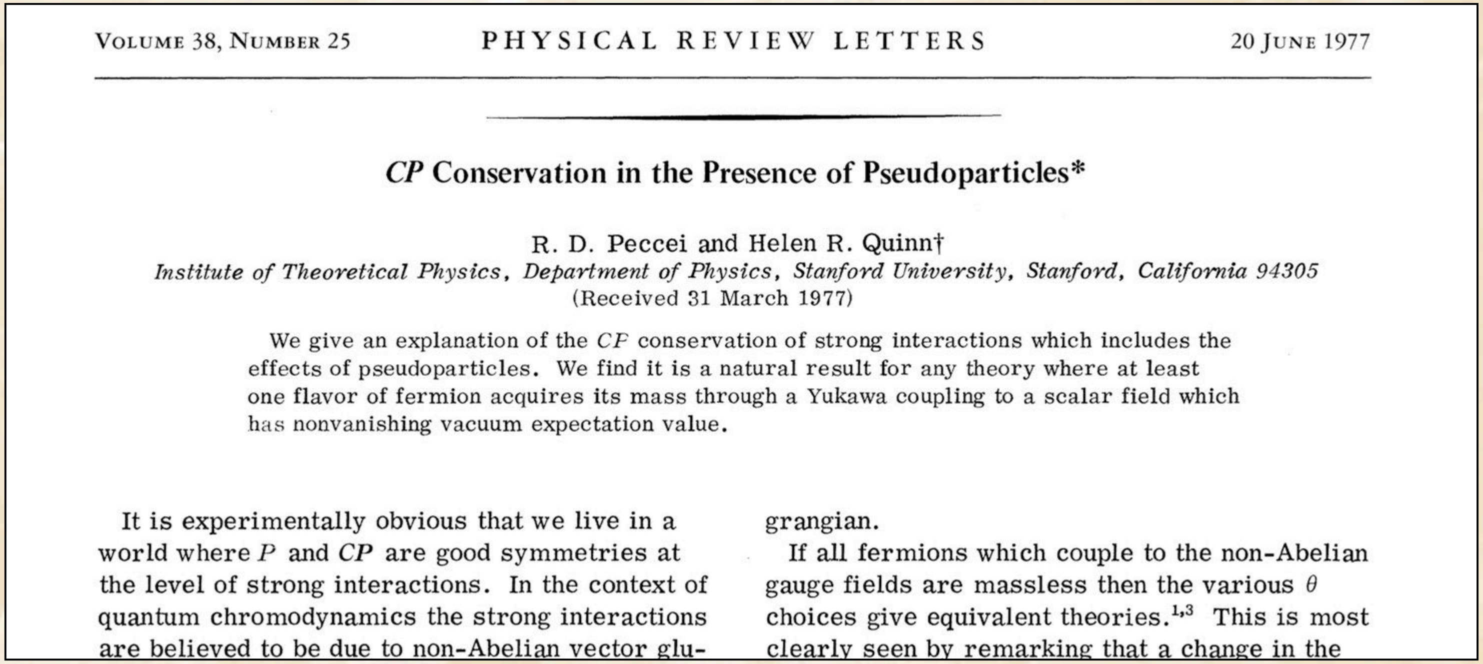
Axions generically couple to gluons and mix with π^0

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

$f_\pi \approx 93$ MeV
Pion decay constant

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†
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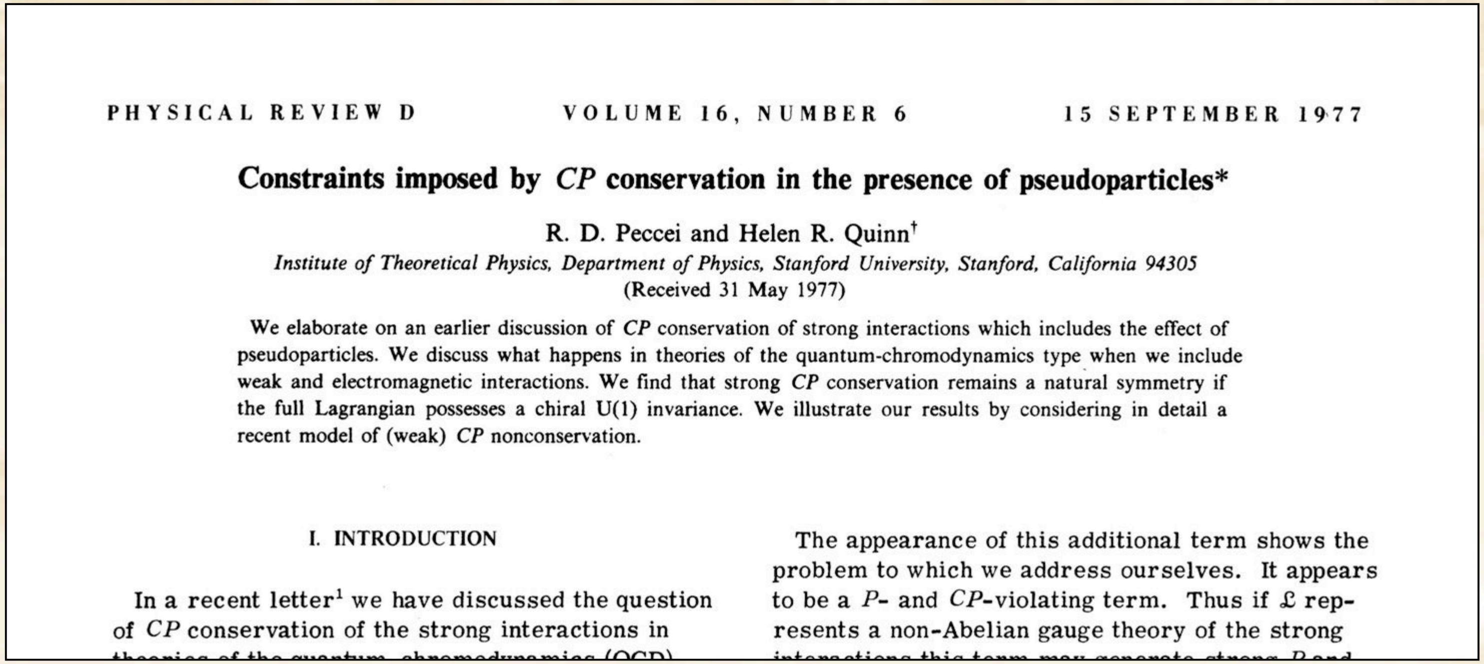
(Received 31 March 1977)

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.

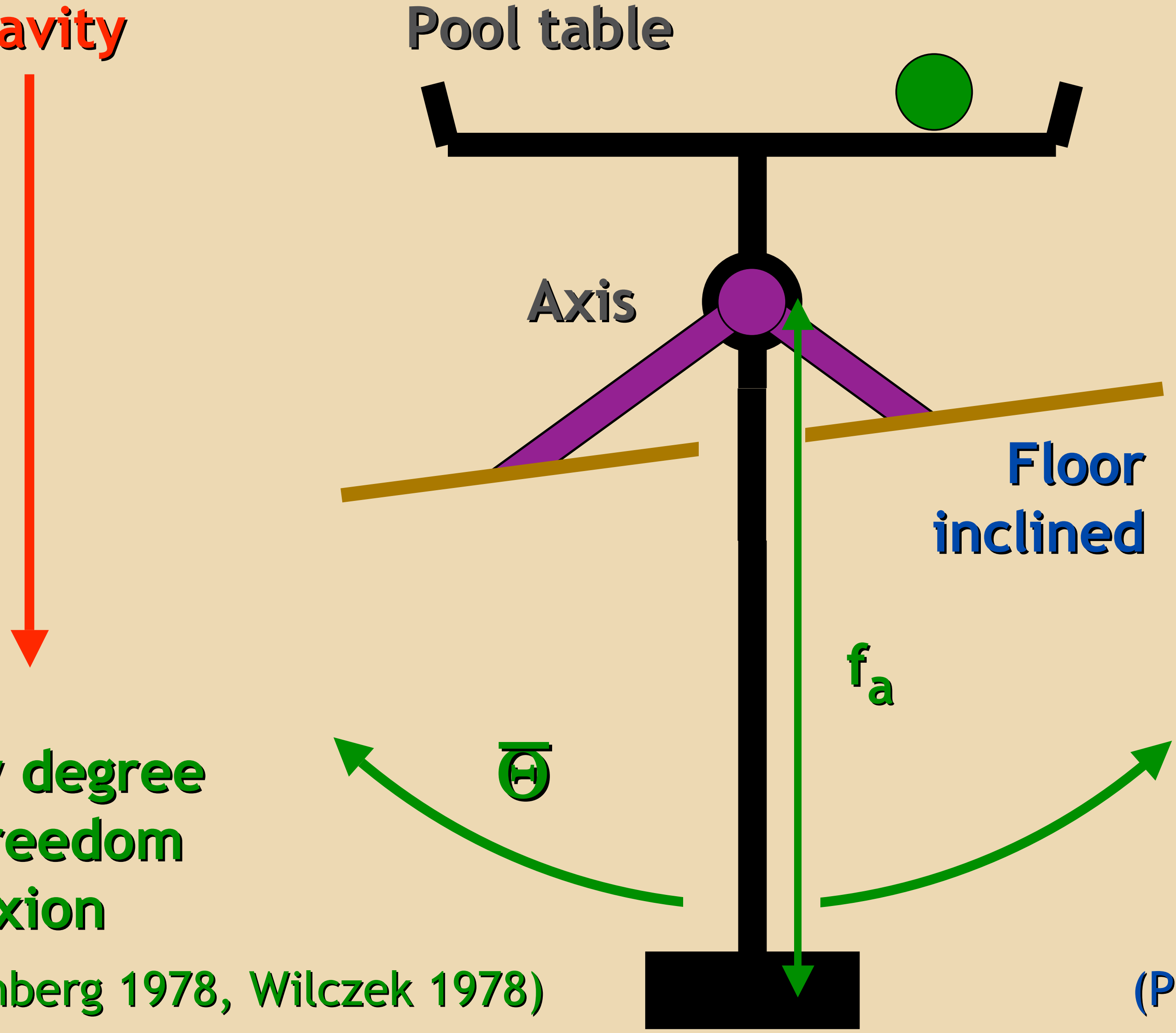
I. INTRODUCTION

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

P.Sikivie, Physics Today, Dec. 1996, pg. 22



Gravity

Pool table

Axis

Floor inclined

f_a

$\overline{\Theta}$

Symmetric relative to gravity

Symmetry broken

Symmetry dynamically restored

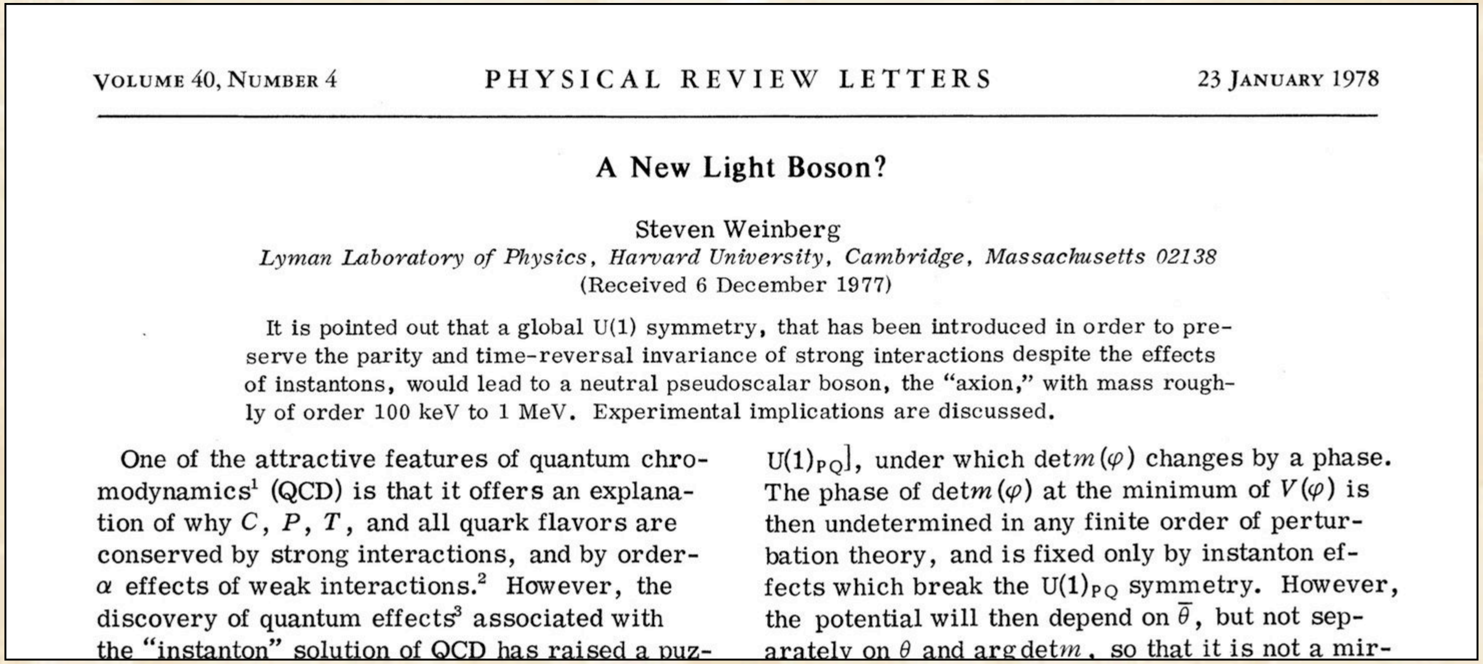
(Peccei & Quinn 1977)

New degree of freedom

➡ Axion

(Weinberg 1978, Wilczek 1978)

30 Years of Axions



VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

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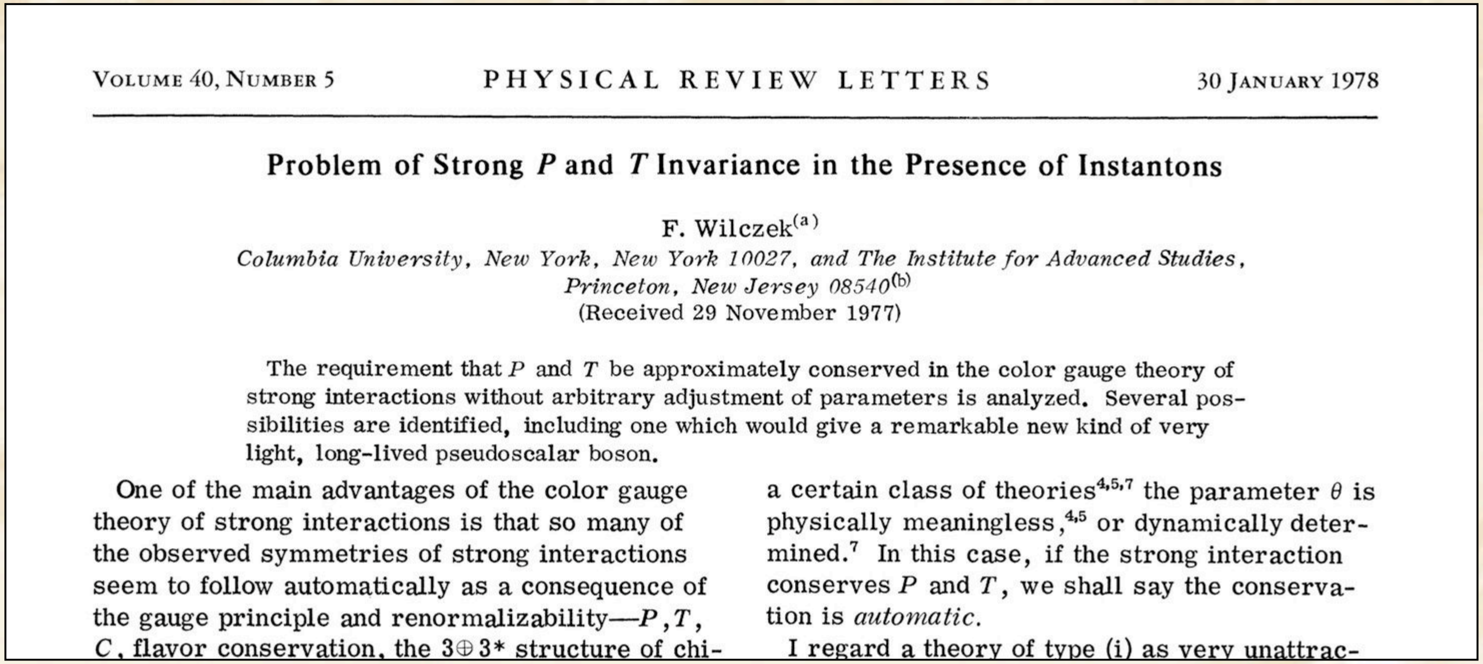
(Received 6 December 1977)

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

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(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-

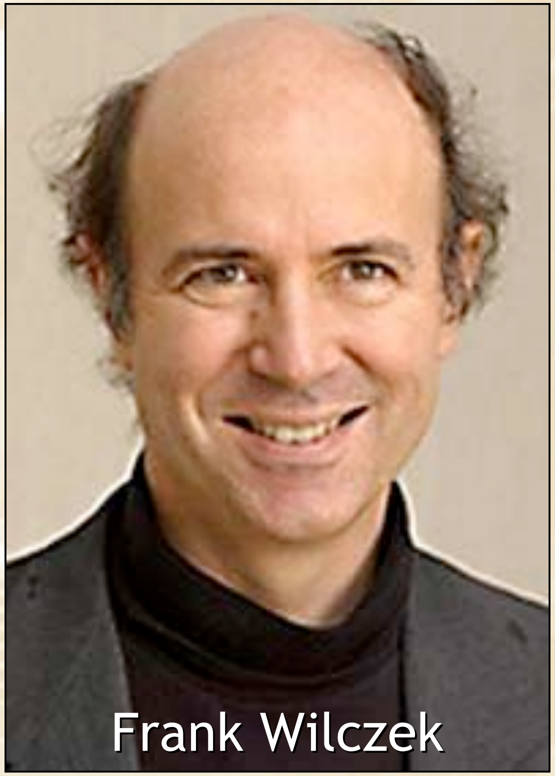
Properties of the $G\,\tilde{}$ term

$L_{CP} = \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$	CP-violating term in QCD Lagrangian
$\exp(i\int d^4x\, L)$	Physically relevant quantity in path integral
$G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a} = \partial_\mu K^\mu$	$G\,\tilde{}$ term is total divergence of the Bardeen current K, constructed from color gauge fields
$\int d\sigma_\mu K^\mu$	• Only surface integral at infinity contributes to action • Naively vanishes if gauge fields fall off fast enough
$\int d\sigma_\mu K^\mu \neq 0$	Non-zero because of topologically nontrivial gauge-field configurations (instantons) with winding number n
$\lvert\Theta\rangle = \sum_{n=-\infty}^{+\infty} e^{in\Theta}\lvert n\rangle$	Θ-vacuum is gauge invariant and stable against tunneling
$\int d^4x \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$	• Integer quantity related to winding numbers of n-vacua • Θ an angle variable in the interval [−π, +π]

Relation of the $\tilde{G}$ Term to the Quark Sector

$L_{CP} = \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$	CP-violating term in QCD Lagrangian
$L_q = \bar{\psi}_q(i\not{D} - m)\psi_q$	For massless quarks seemingly invariant against chiral transformations
$\partial_\mu \bar{\psi}_q \frac{\gamma_5}{2}\gamma^\mu\psi_q = \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$	• Adler-Bell-Jackiw anomaly of axial vector current • Same structure as L_{CP}
$\psi_q \to e^{i\alpha\gamma_5/2}\psi_q$ $\Theta \to \Theta + \alpha$	• Chiral transformation of quark field shifts Θ • Θ can be absorbed in phase of quark fields
$m \to e^{i\alpha}m$	For massive quarks shows up in phase of mass
$\bar{\Theta} = \Theta_{QCD} - \arg\det M_q$	• Physically relevant parameter is $\bar{\Theta}$ • Θ_{QCD} can be “rotated away” into phase of M_q
$d_n \sim \bar{\Theta}\frac{\sqrt{m_u m_d}}{m_N}\frac{e}{2m_N}$	Neutron EDM vanishes if m_u or m_d = 0

The Cleansing Axion

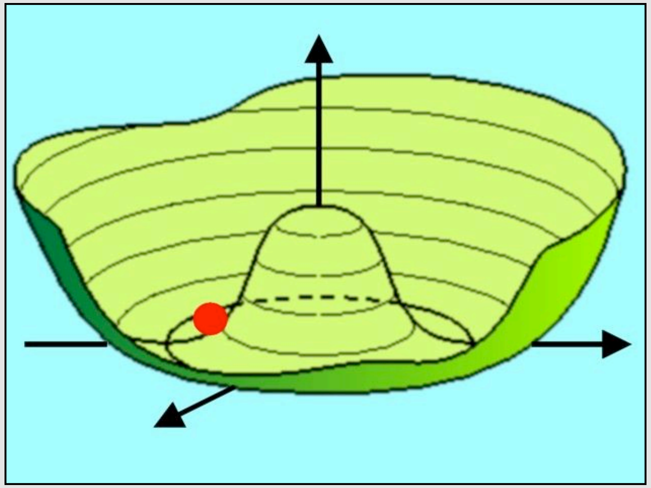

Frank Wilczek

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

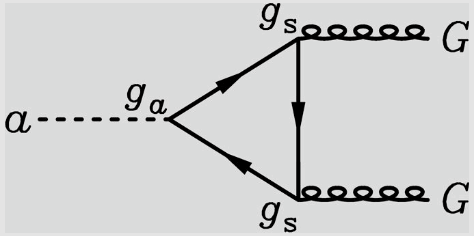
Axions as Nambu-Goldstone Bosons

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

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



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



- Mixes with π^0-η-η' mesons
- Axion mass (vanishes if m_u or $m_d = 0$)

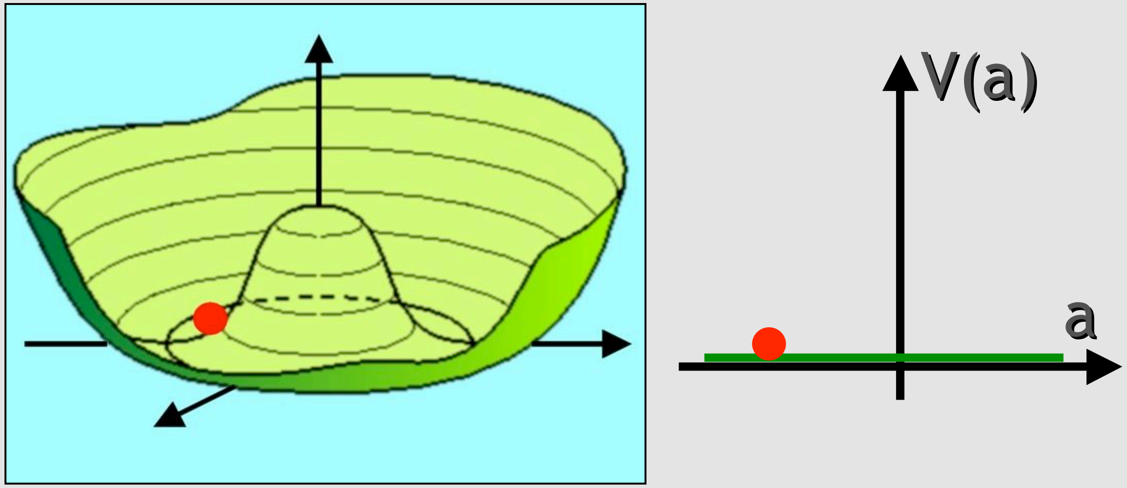
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\,\frac{m_\pi}{f_\pi f_a}$$

Spontaneous and Explicit Breaking of PQ Symmetry

- The realization of the Peccei-Quinn mechanism involves a new chiral U(1) symmetry, spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode

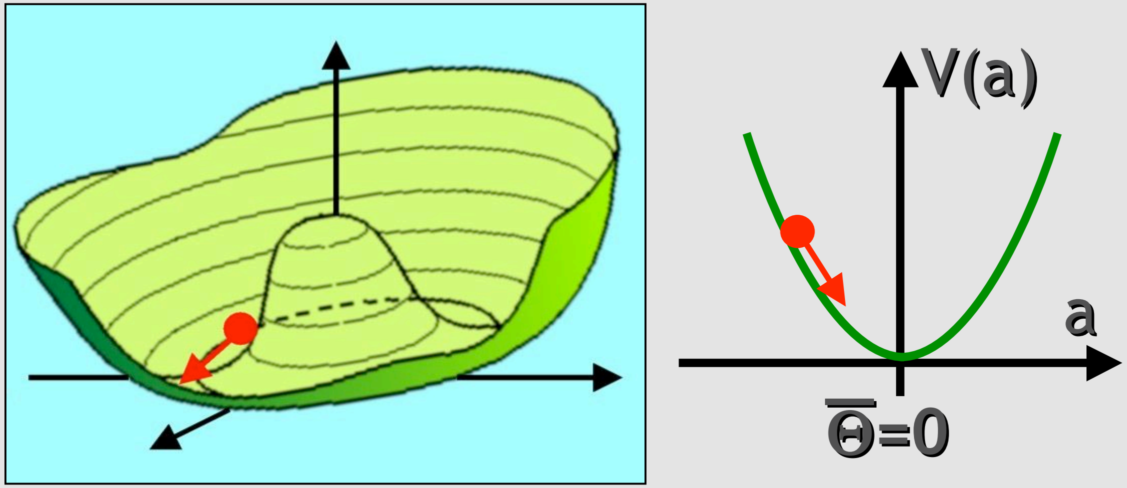
$E \sim f_a$

- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"

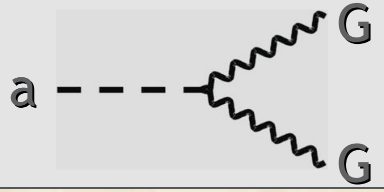
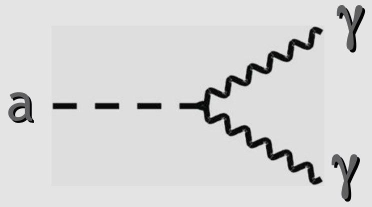
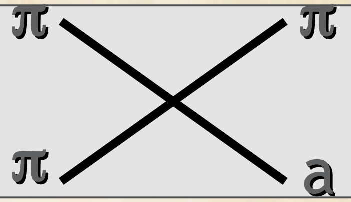
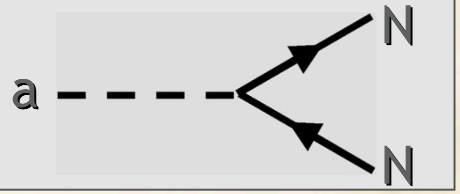
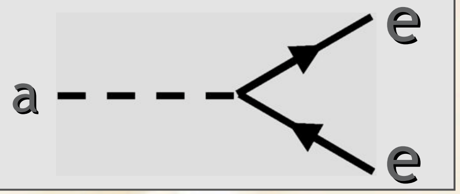


$E \sim \Lambda_{QCD} \ll f_a$

- $U_{PQ}(1)$ explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass



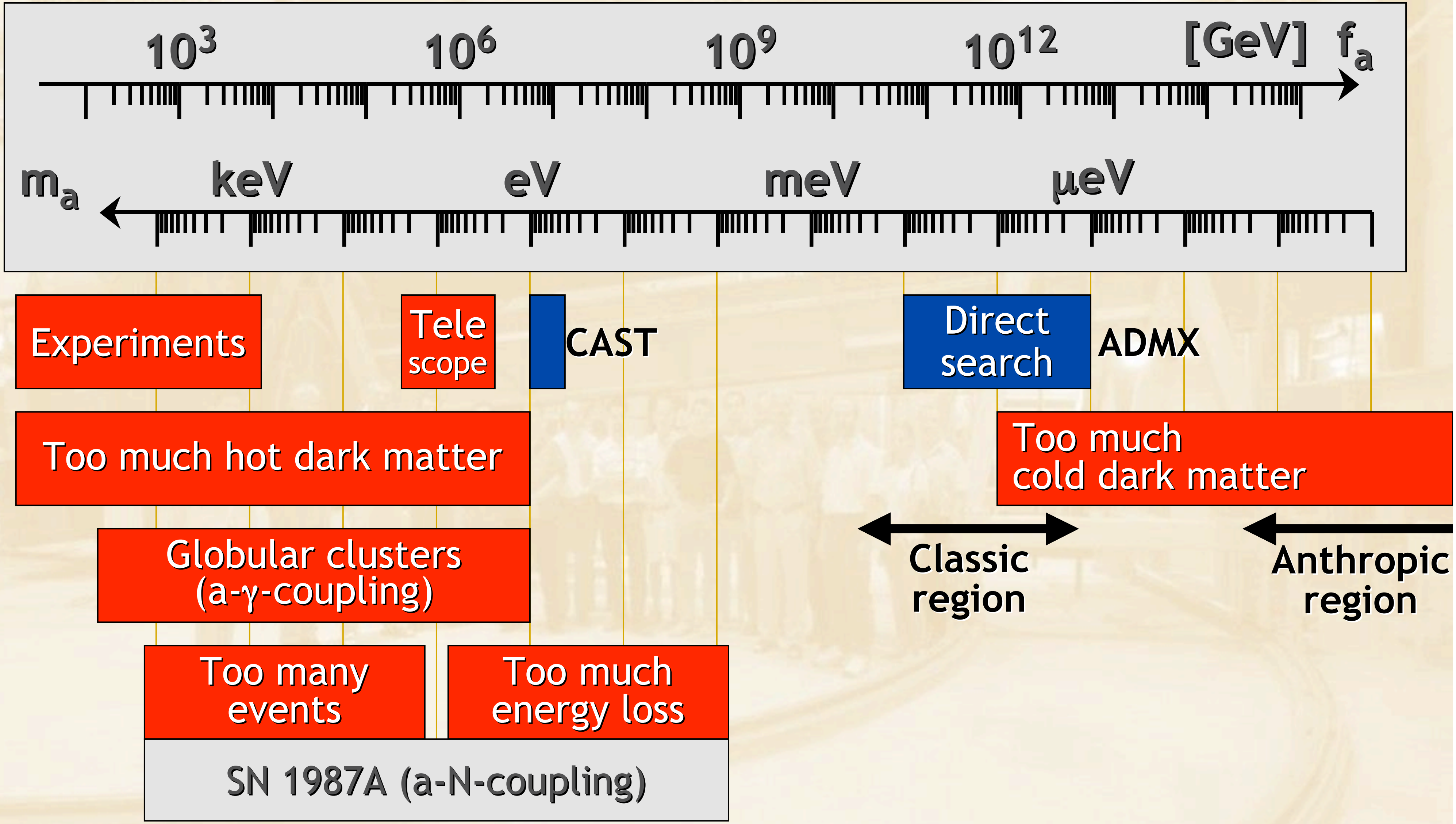
Axion Properties

Gluon coupling (generic)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\,\mu\mathrm{eV}}{f_a / 10^{12}\,\mathrm{GeV}}$
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma} \vec{E}\cdot\vec{B}\,a$ $g_{a\gamma} = \frac{\alpha}{\pi f_a}\left(\frac{E}{2N} - 0.96\right)$ 
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)	$L_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e\, \partial_\mu a$ 

From Standard to Invisible Axions

Standard Model	Standard Axion Weinberg 1978, Wilczek 1978	Invisible Axion Kim 1979, Shifman, Vainshtein, Zakharov 1980, Dine, Fischler, Srednicki 1981 Zhitnitsky 1980
All Higgs degrees of freedom are used up	• Peccei-Quinn scale $f_a = f_{ew}$ (electroweak scale) • Two Higgs fields, separately giving mass to up-type quarks and down-type quarks	• Additional Higgs with $f_a \gg f_{ew}$ • Axions very light and and very weakly interacting
No room for Peccei-Quinn symmetry and axions	Standard axions quickly ruled out experimentally	• New scale required • Axions can be cold dark matter • Can be detected

Axion Bounds



Experiments

Tele scope

CAST

Direct search

ADMX

Too much hot dark matter

Too much cold dark matter

Classic region

Anthropic region

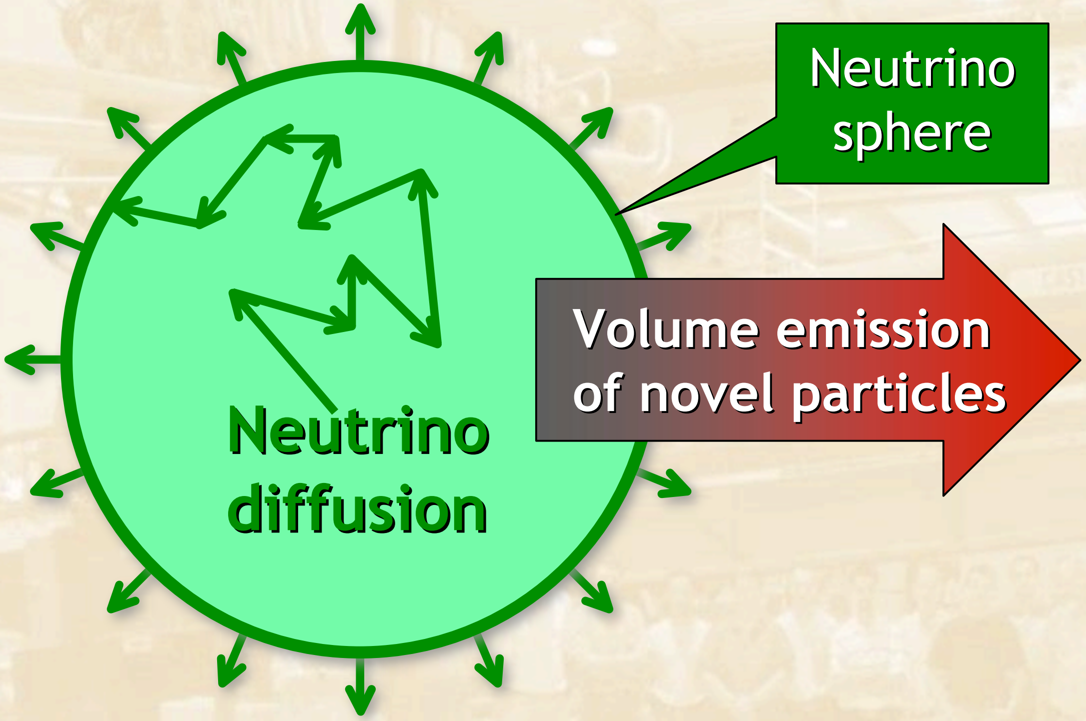
Globular clusters (a-γ-coupling)

Too many events

Too much energy loss

SN 1987A (a-N-coupling)

Supernova 1987A Energy-Loss Argument



Neutrino sphere

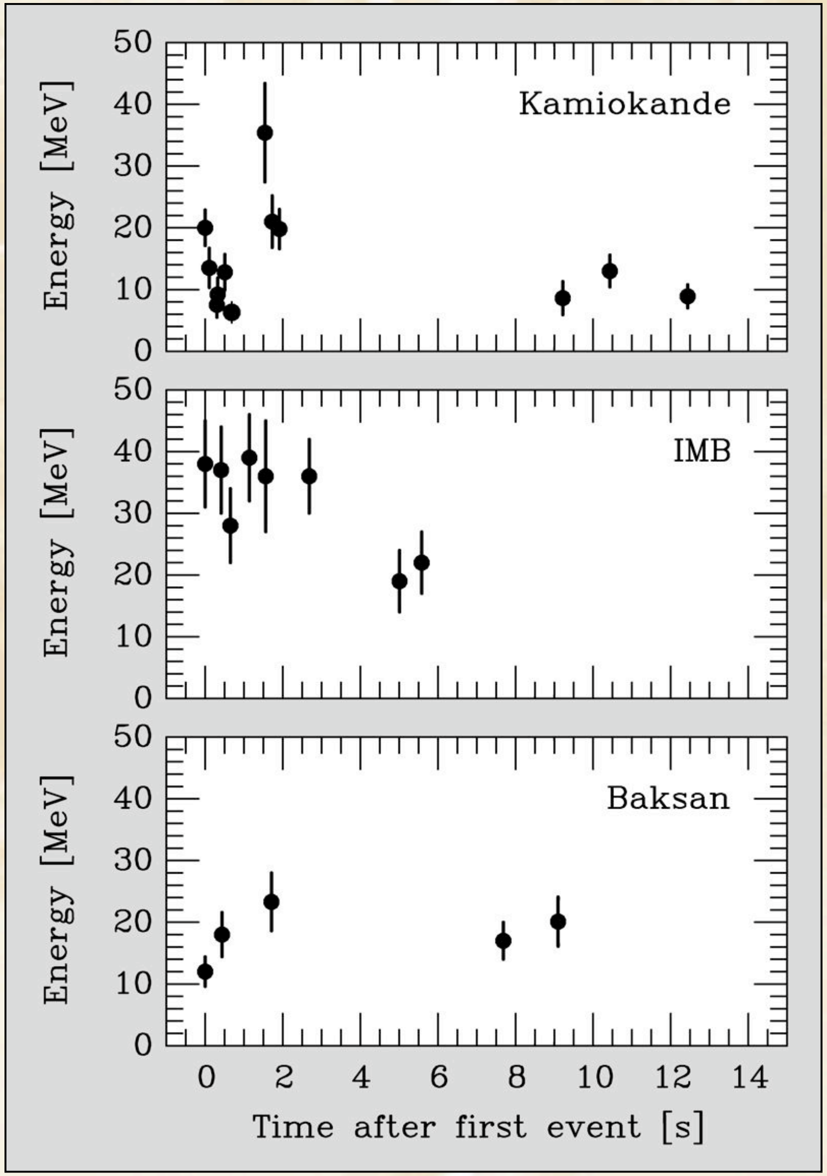
Neutrino diffusion

Volume emission of novel particles

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

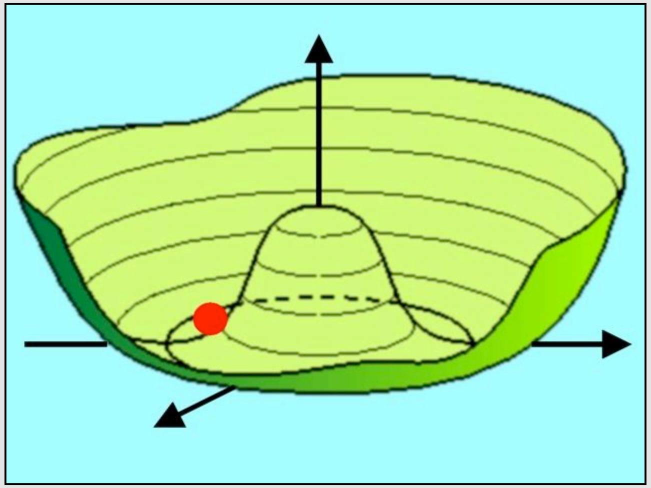
SN 1987A neutrino signal

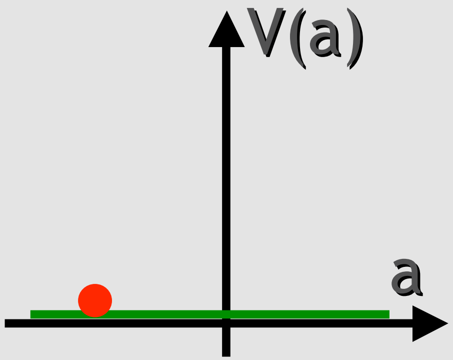


Creation of Cosmological Axions

$T \sim f_a$ (very early universe)

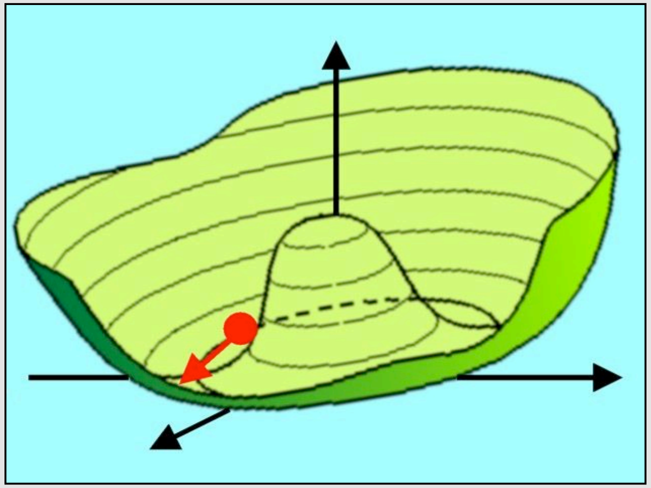
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_1 = \Theta_1 f_a$

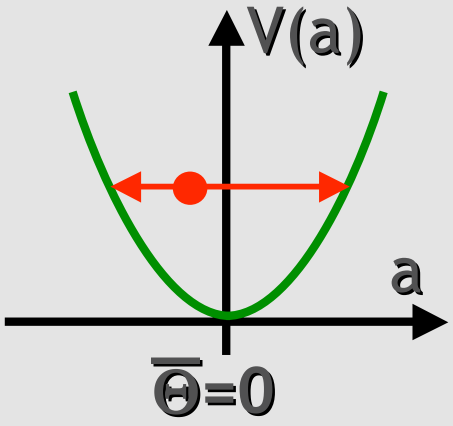




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

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



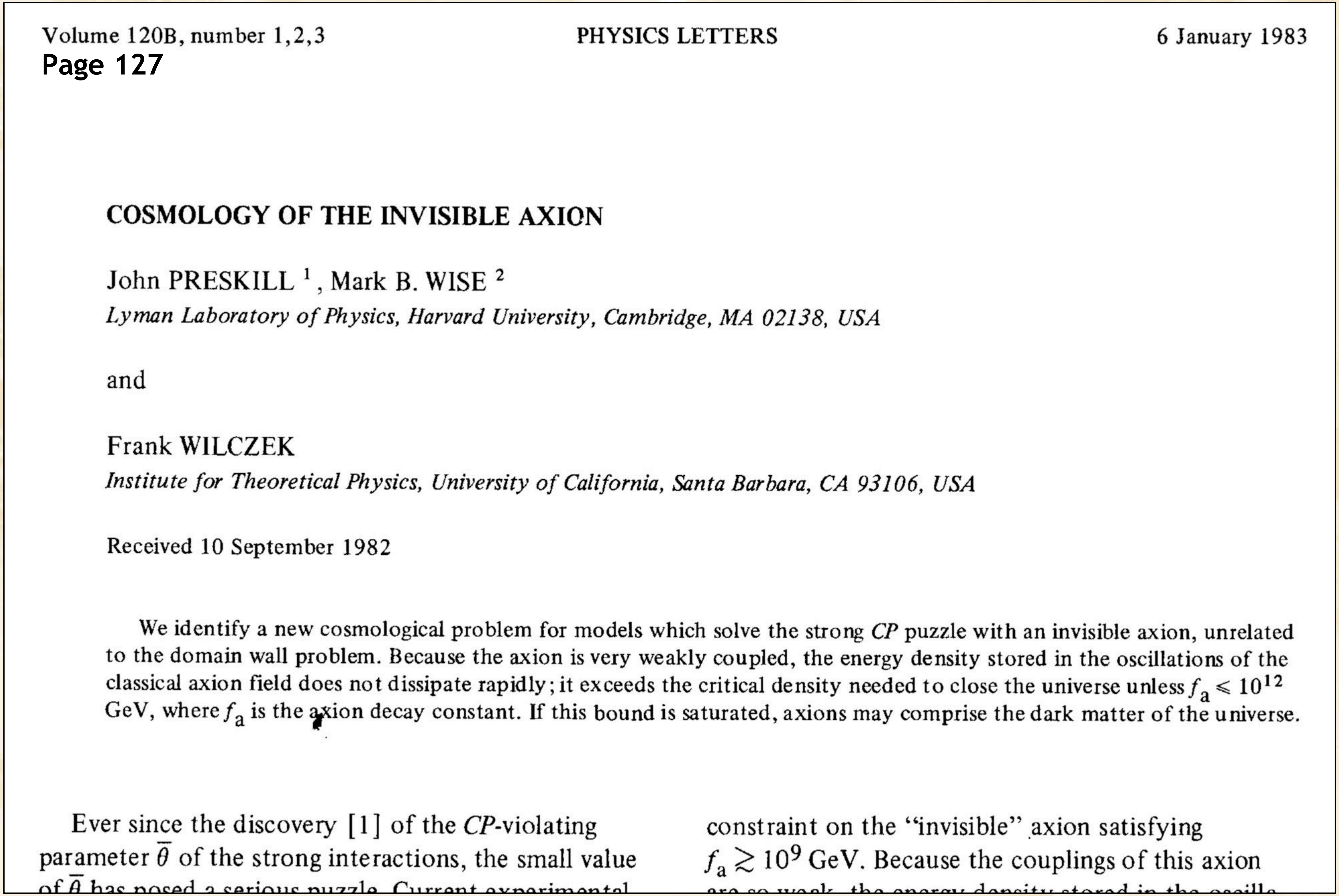


- Axion number density in comoving volume conserved

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

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

Series of Papers on Axion Cosmology in PLB 120 (1983)



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COSMOLOGY OF THE INVISIBLE AXION

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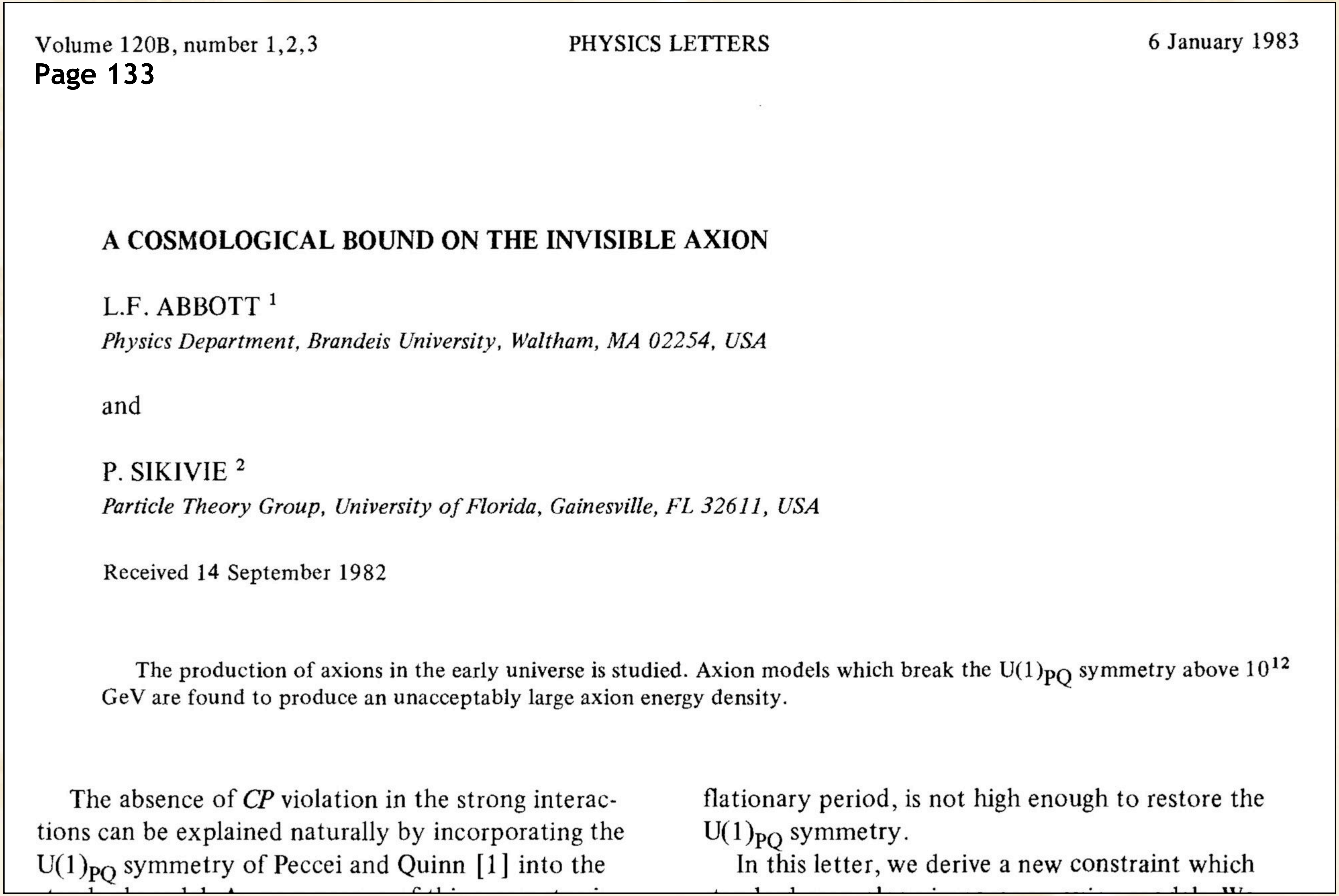
Received 10 September 1982

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.

Ever since the discovery [1] of the *CP*-violating parameter $\bar{\theta}$ of the strong interactions, the small value of $\bar{\theta}$ has posed a serious puzzle. Current experimental

constraint on the “invisible” axion satisfying $f_a \gtrsim 10^9$ GeV. Because the couplings of this axion are so weak, the energy density stored in the oscilla

Series of Papers on Axion Cosmology in PLB 120 (1983)



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A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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and

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Received 14 September 1982

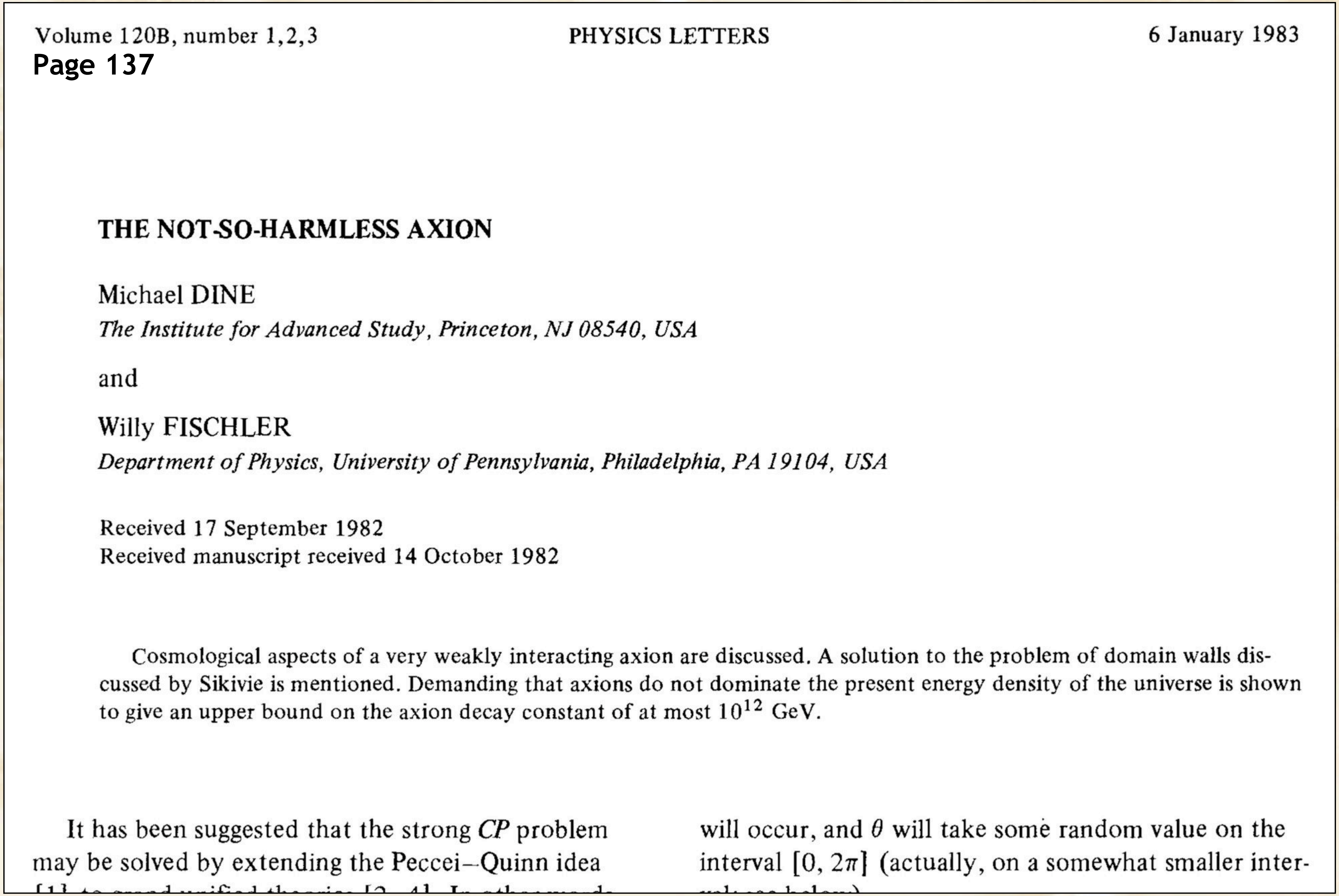
The production of axions in the early universe is studied. Axion models which break the $U(1)_{PQ}$ symmetry above 10^{12} GeV are found to produce an unacceptably large axion energy density.

The absence of *CP* violation in the strong interactions can be explained naturally by incorporating the $U(1)_{PQ}$ symmetry of Peccei and Quinn [1] into the

flationary period, is not high enough to restore the $U(1)_{PQ}$ symmetry.

In this letter, we derive a new constraint which

Series of Papers on Axion Cosmology in PLB 120 (1983)



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

Page 137

THE NOT-SO-HARMLESS AXION

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and

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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.

It has been suggested that the strong *CP* problem may be solved by extending the Peccei–Quinn idea

will occur, and θ will take some random value on the interval $[0, 2\pi]$ (actually, on a somewhat smaller inter-

Killing Two Birds with One Stone

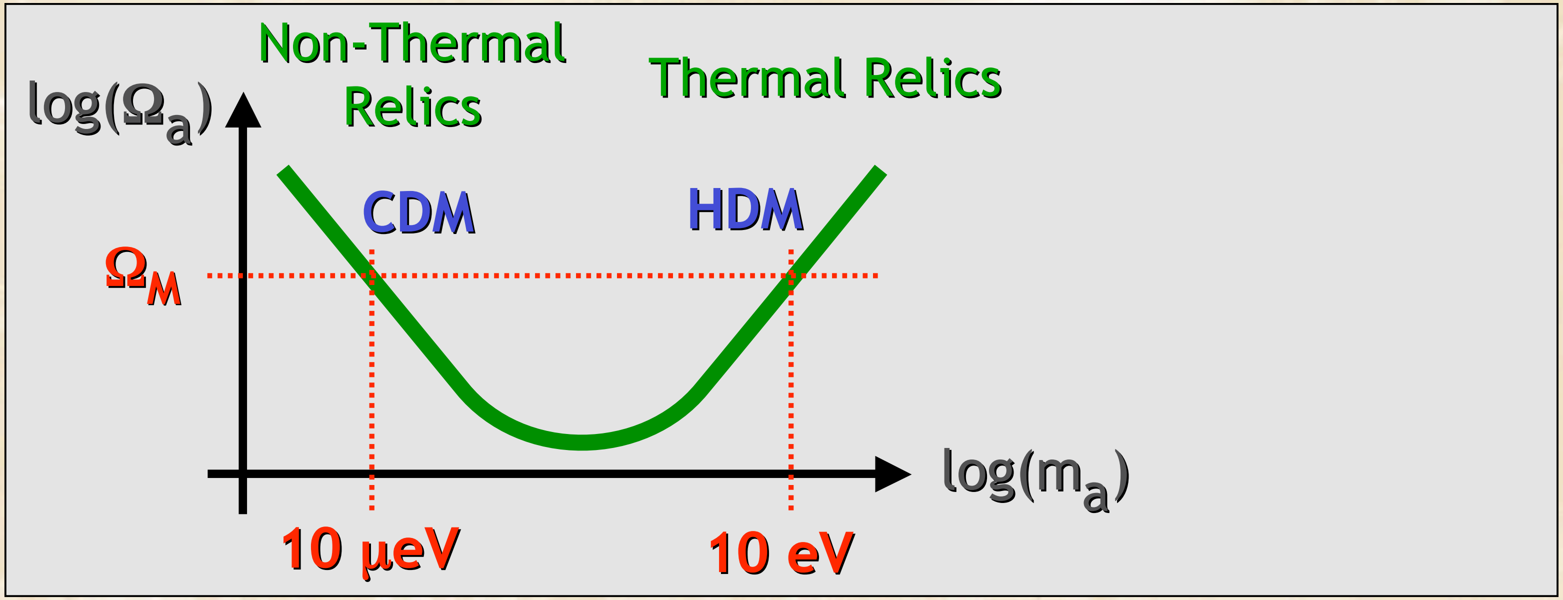
Unbelievable! It looks like they've both been killed by the same stone...

Peccei-Quinn mechanism

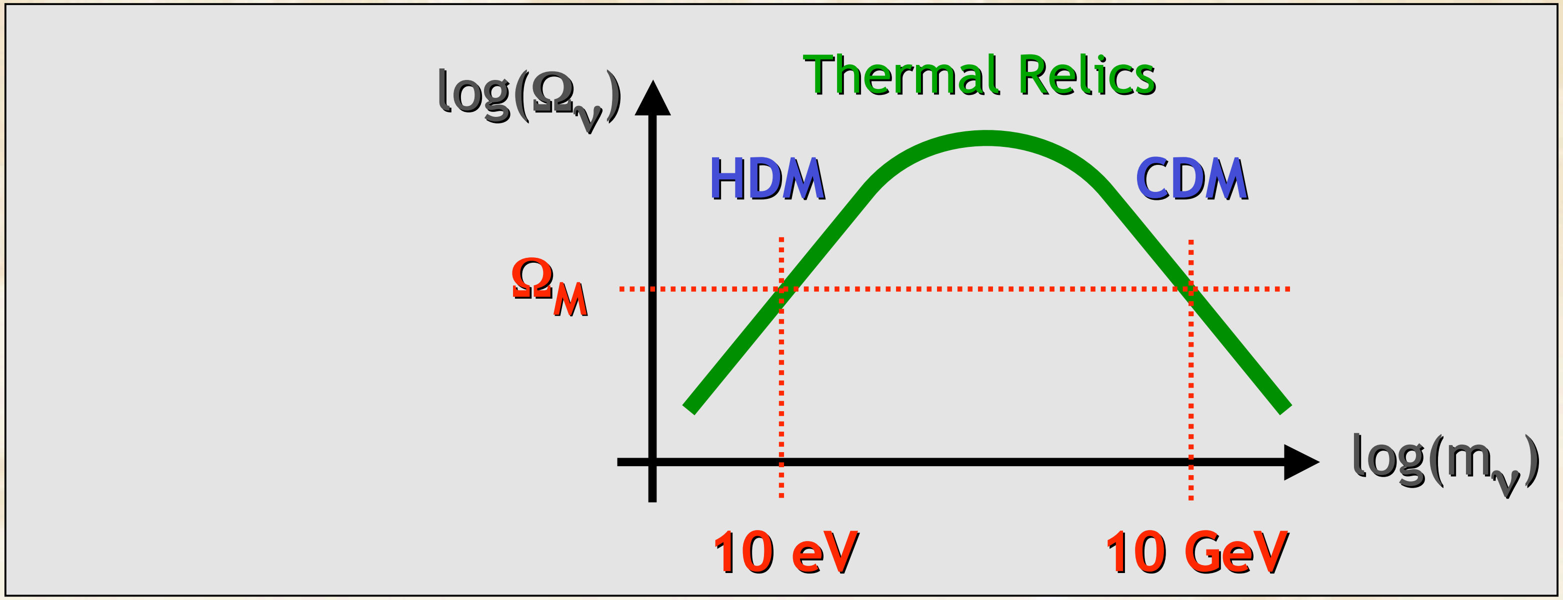
- Solves strong CP problem
- May provide dark matter in the form of axions

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos & WIMPs



Cold Axion Production

Approximate axion
cold dark matter density

$$\Omega_a \approx 0.5 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \approx 4 \left(\frac{1\,\mu\mathrm{eV}}{m_a}\right)^{7/6}$$

Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

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

Dependence on initial misalignment angle

$$\Omega_a \propto \overline{\Theta}_i$$

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMBR bounds on isocurvature fluctuations
- Scale of inflation required to be very small $\Lambda_I \lesssim 10^{13}$ GeV

[e.g. Beltrán et al. hep-ph/0606107
Hertzberg et al., arXiv:0807.1726]

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

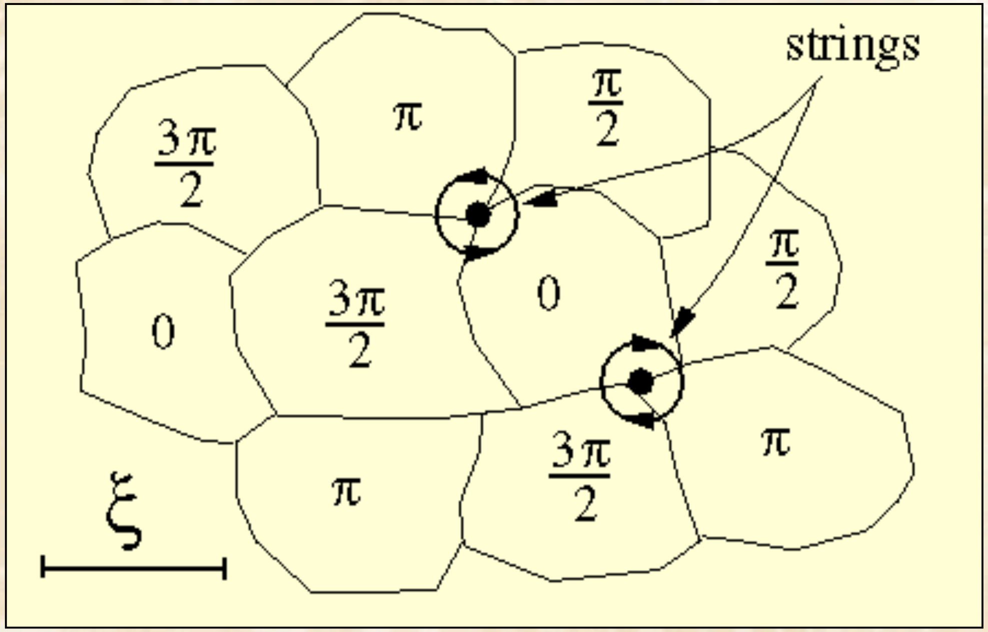
Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

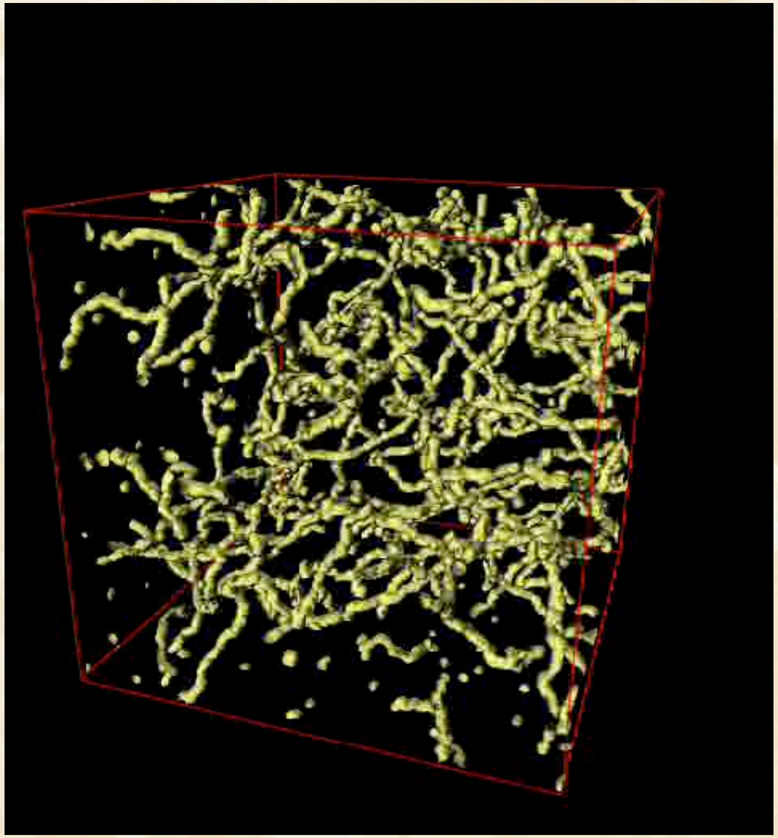
Typical properties

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

Axions from Cosmic Strings

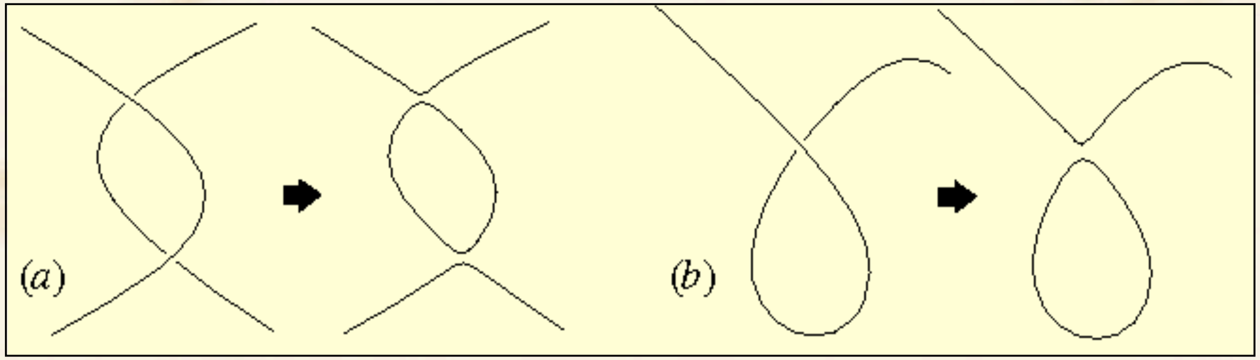
Strings form by Kibble mechanism after break-down of $U_{PQ}(1)$





Paul Shellard

Small loops form by self-intersection



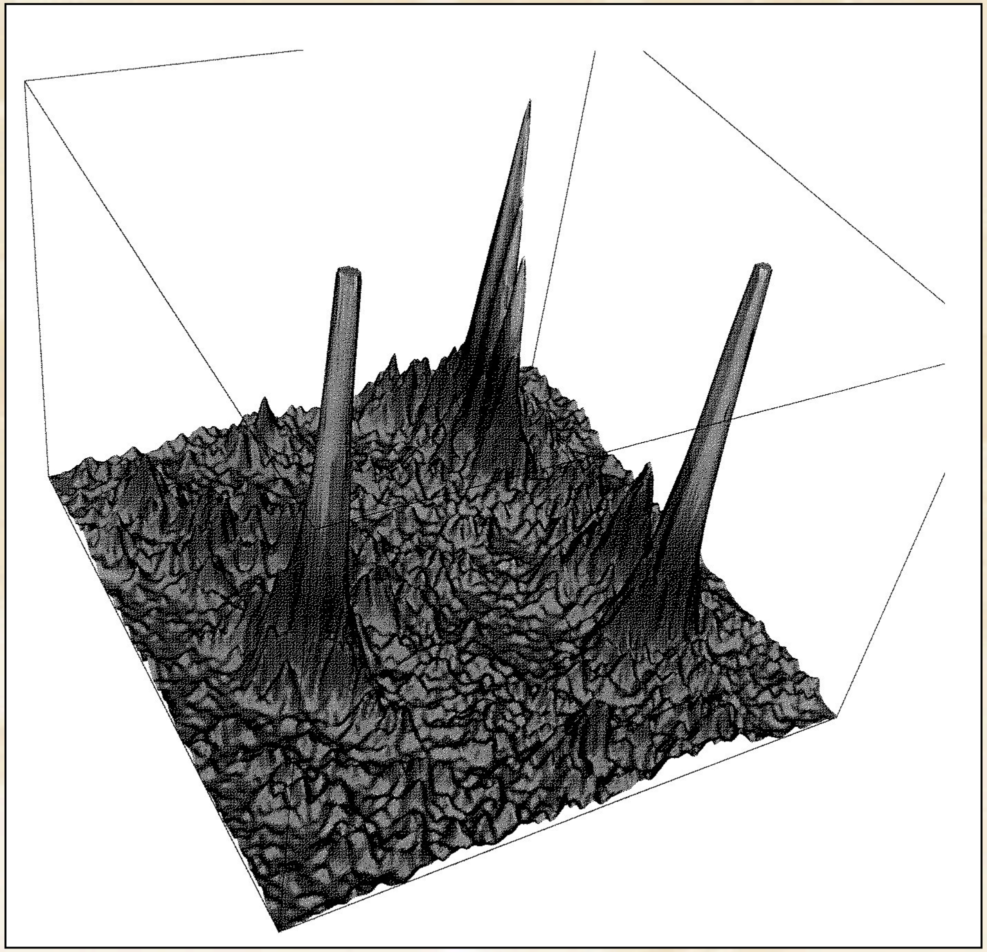
Axion Mini Clusters

The inhomogeneities of the axion field are large, leading to bound objects, "axion mini clusters". [Hogan & Rees, PLB 205 (1988) 228.]
Self-coupling of axion field crucial for dynamics.

Typical mini cluster properties:

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

Potentially detectable with gravitational femtolensing



Distribution of axion energy density.
2-dim slice of comoving length 0.25 pc
[Kolb & Tkachev, ApJ 460 (1996) L25]

Inflation, Axions, and the Anthropic Principle

Late inflation scenario of axion cosmology

- Axion dark matter density determined by the initial random number Θ_i
- Is different in different patches of the universe
- Our universe, after inflation, from a single patch

Axion dark matter fraction is a random number, chosen by spontaneous symmetry breaking process

Natural case for anthropic selection effects concerning the observed dark matter density relative to baryons

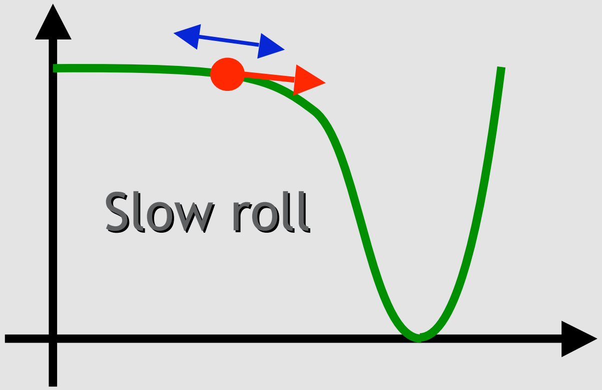
- Linde, "Inflation and Axion Cosmology," PLB 201:437, 1988
- Tegmark, Aguirre, Rees & Wilczek,
  "Dimensionless constants, cosmology and other dark matters,"
  PRD 73, 023505 (2006) [arXiv:astro-ph/0511774]

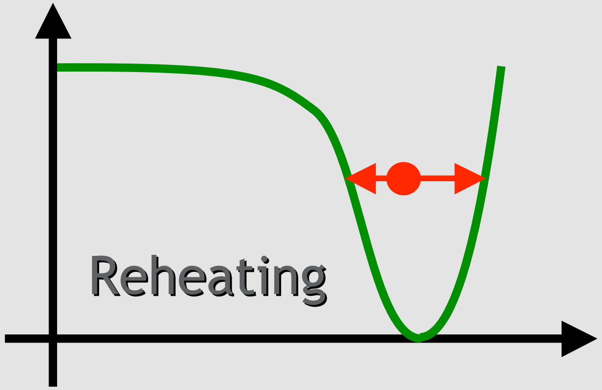
A small initial Θ not unnatural
$f_a \gg 10^{12}$ GeV (e.g. GUT scale or string-inspired) not excluded

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field

De Sitter expansion imprints
scale invariant fluctuations

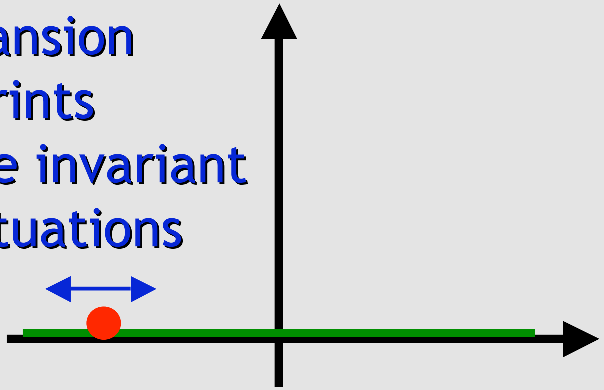


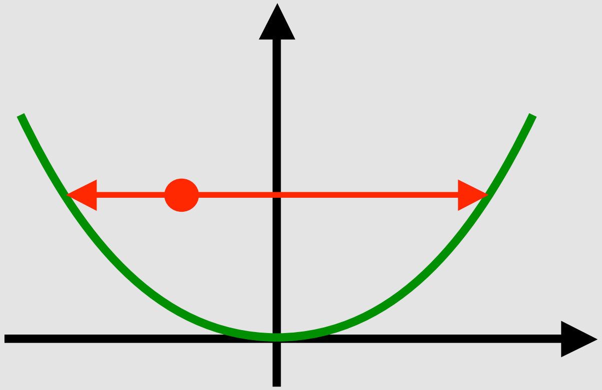


Inflaton decay → matter & radiation
Fluctuations in both (adiabatic)

Axion field

De Sitter
expansion
imprints
scale invariant
fluctuations



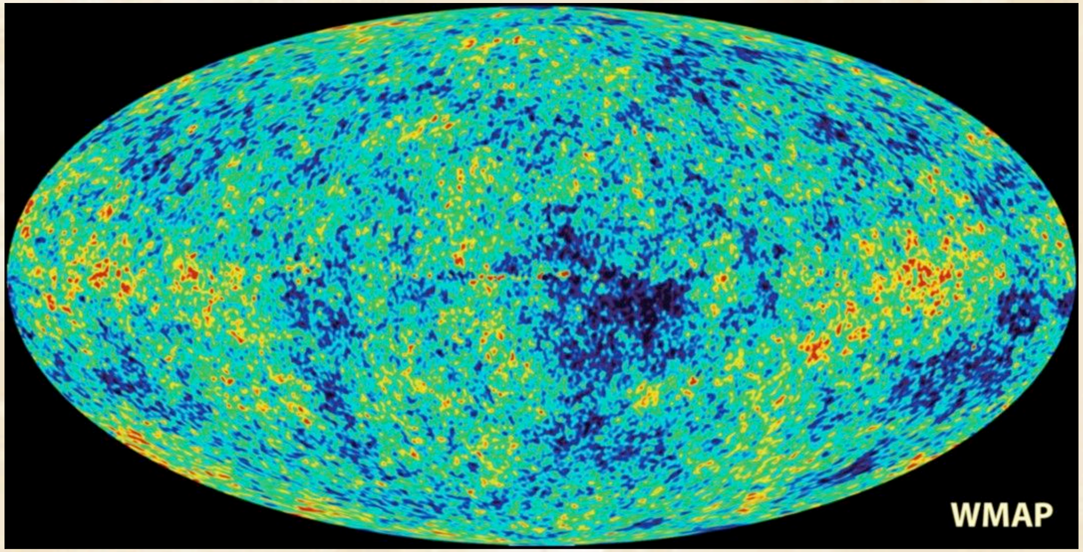


Inflaton decay → radiation
Axion field oscillates late → matter
Fluctuations of matter relative to
radiation: Entropy fluctuations

Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

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

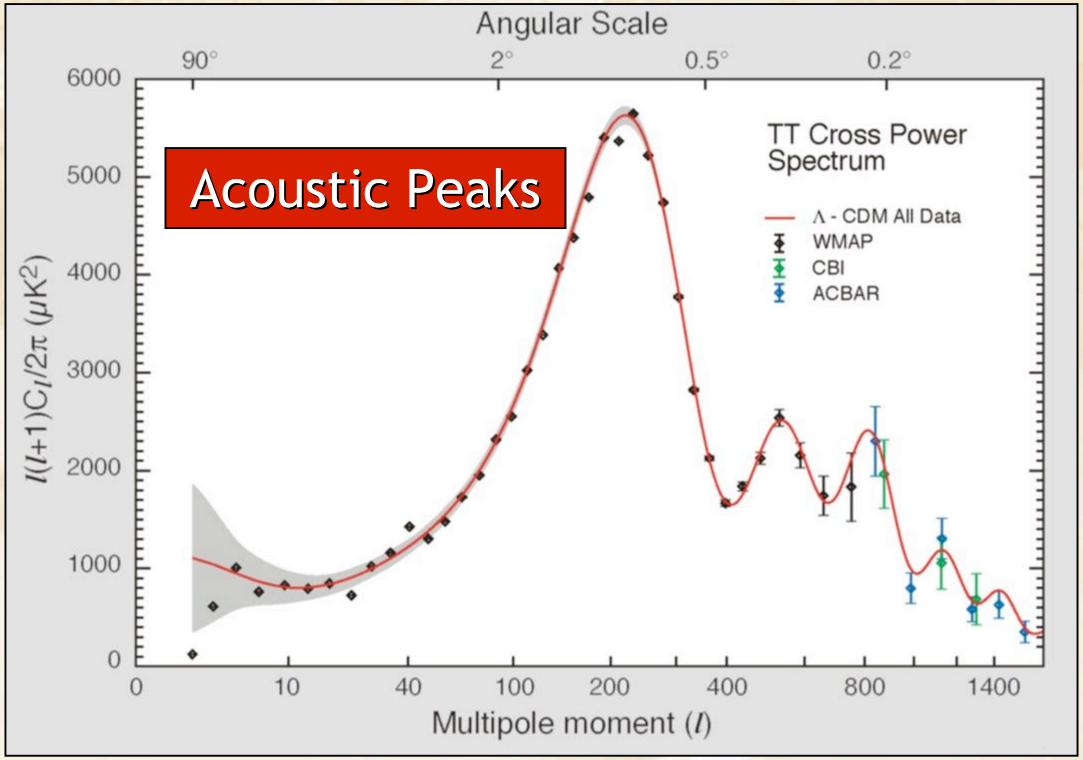


Multipole expansion

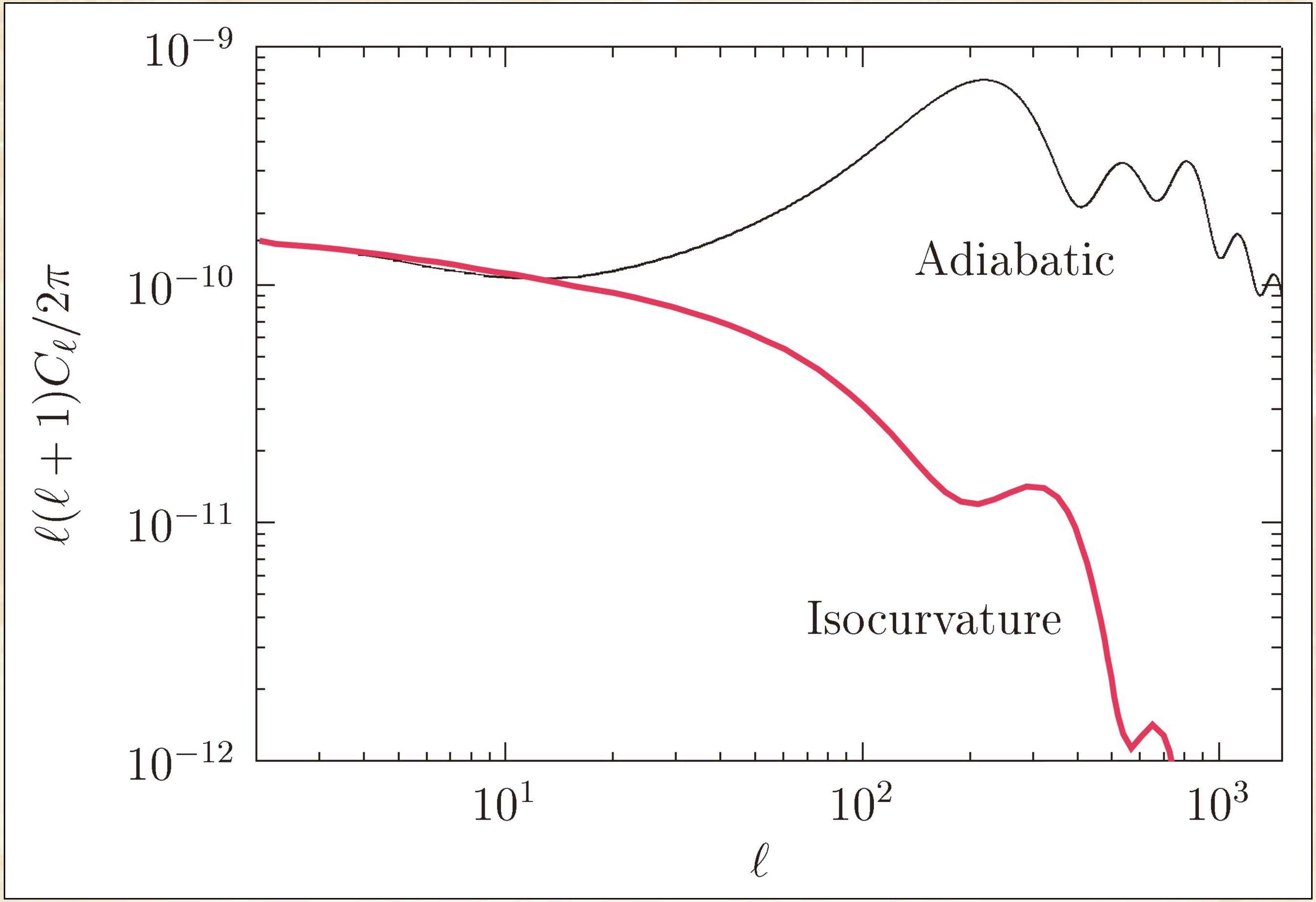
$$\Delta(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell}a_{\ell m}Y_{\ell m}(\theta,\varphi)$$

Angular power spectrum

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

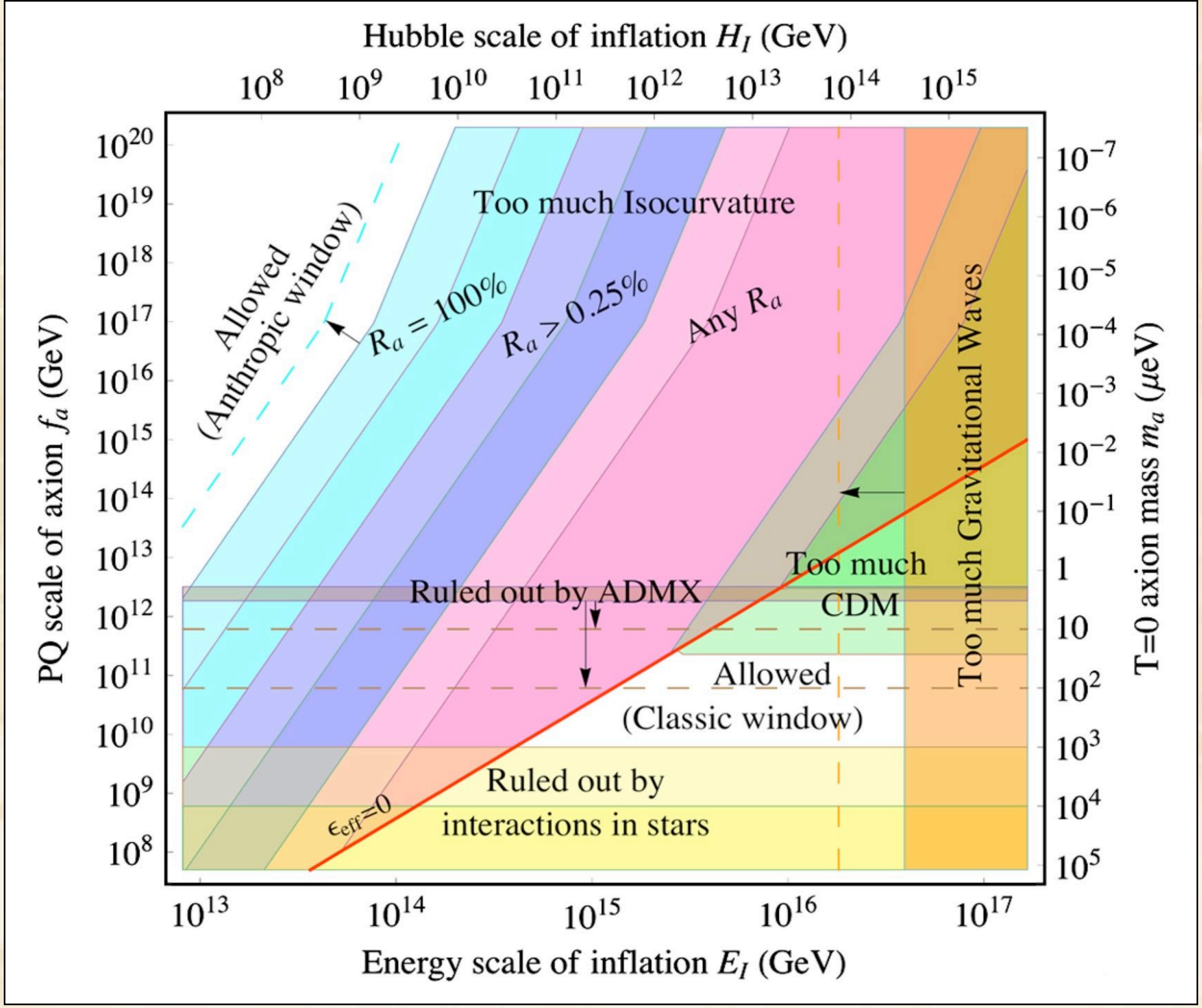

Acoustic Peaks

Adiabatic vs. Isocurvature Temperature Fluctuations



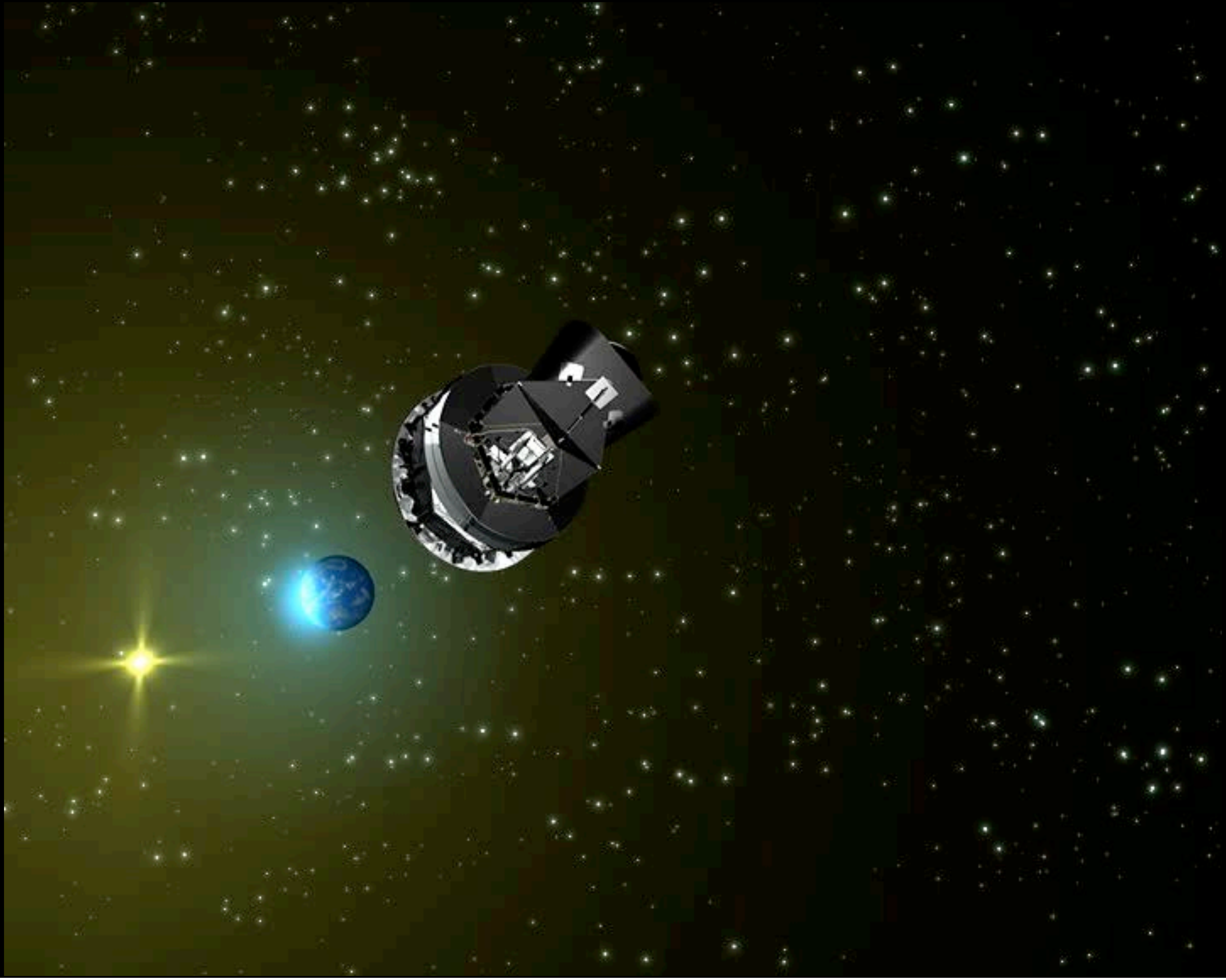
Adapted from Fox, Pierce & Thomas, hep-th/0409059

Axion Limits from Isocurvature Fluctuations

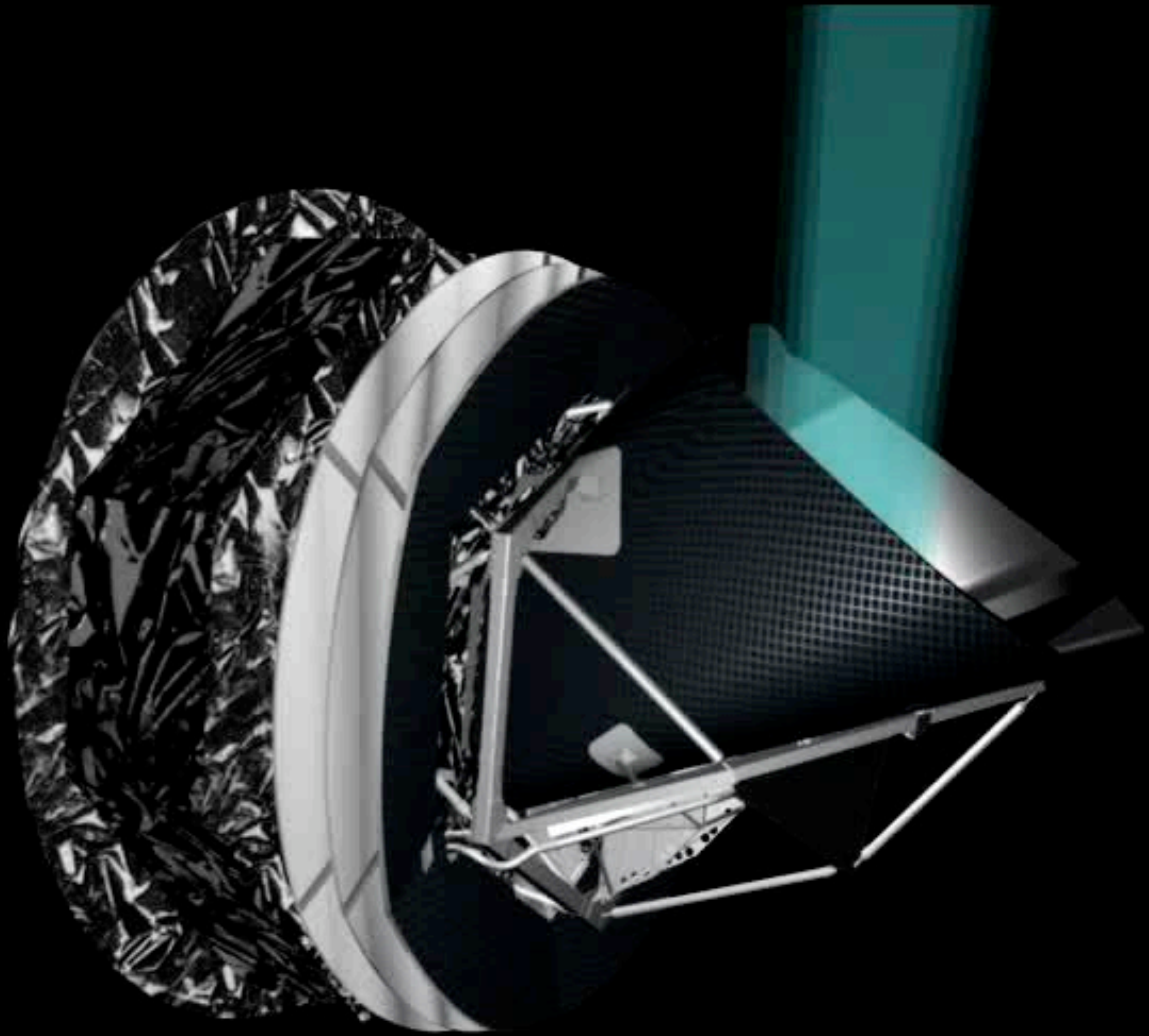


Hertzberg, Tegmark & Wilczek, PRD 78 (2008) 083507

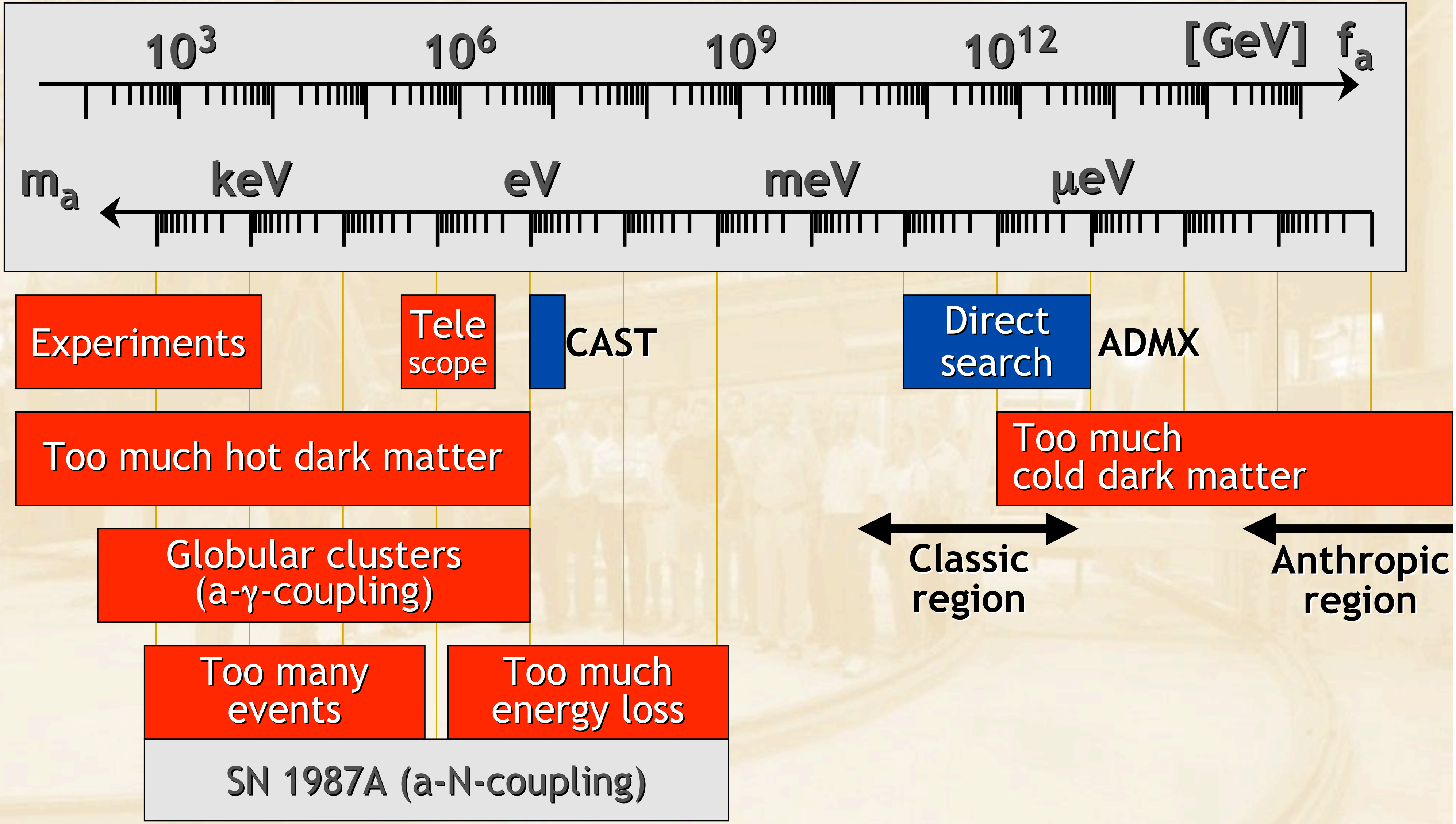
PLANCK Satellite – Launch in Early April 2009



PLANCK Satellite



Axion Bounds



Experiments

Tele scope

CAST

Direct search

ADMX

Too much hot dark matter

Too much cold dark matter

Classic region

Anthropic region

Globular clusters (a-γ-coupling)

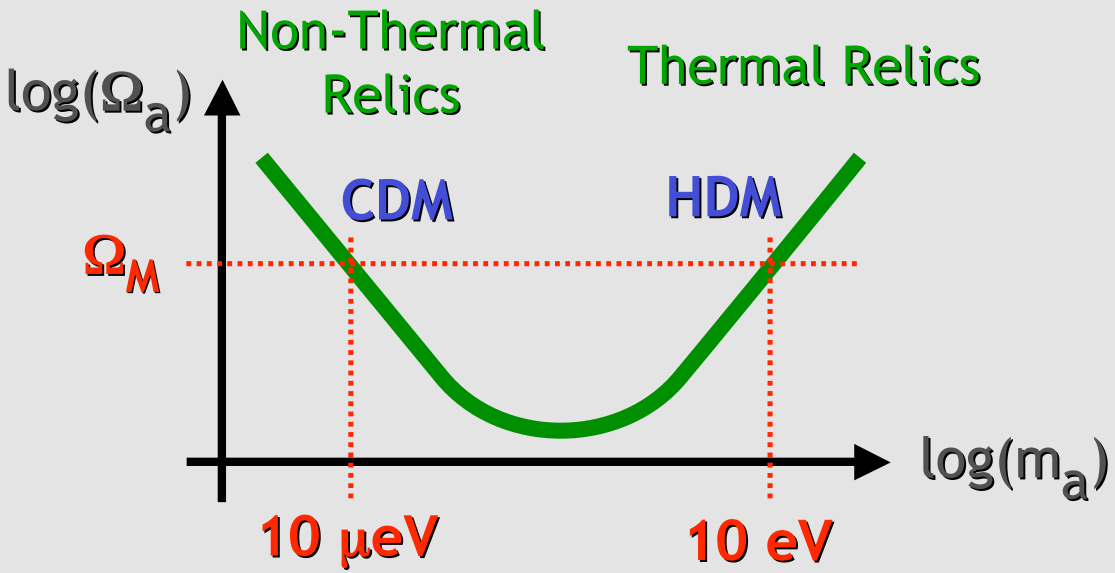
Too many events

Too much energy loss

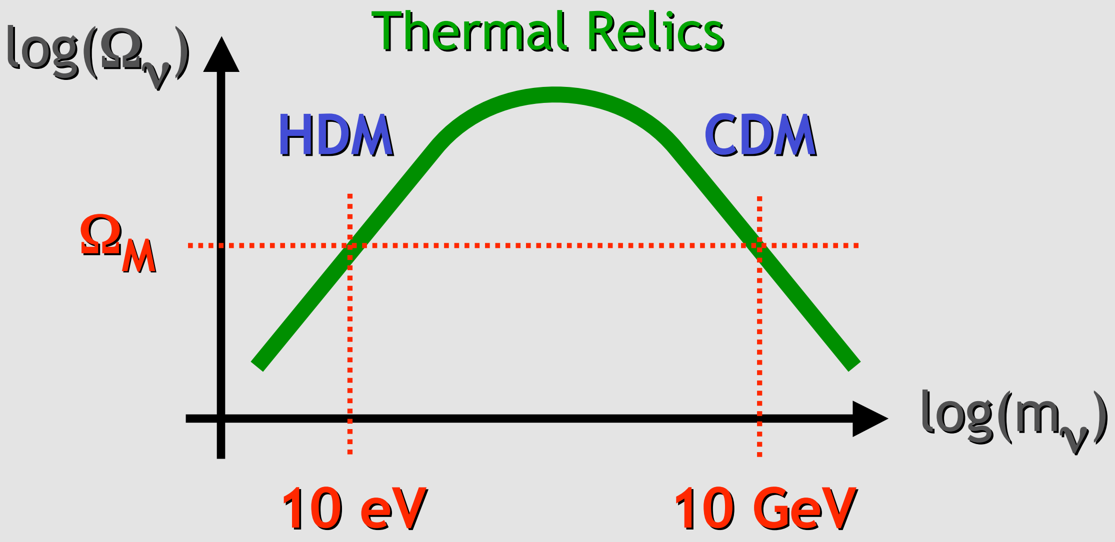
SN 1987A (a-N-coupling)

Lee-Weinberg Curve for Neutrinos and Axions

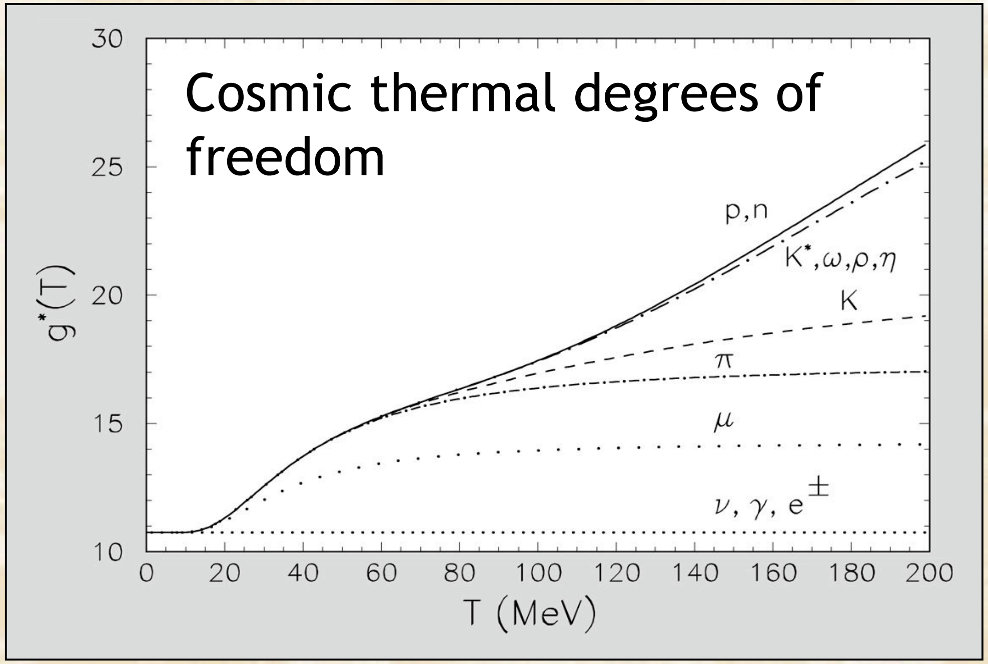
Axions

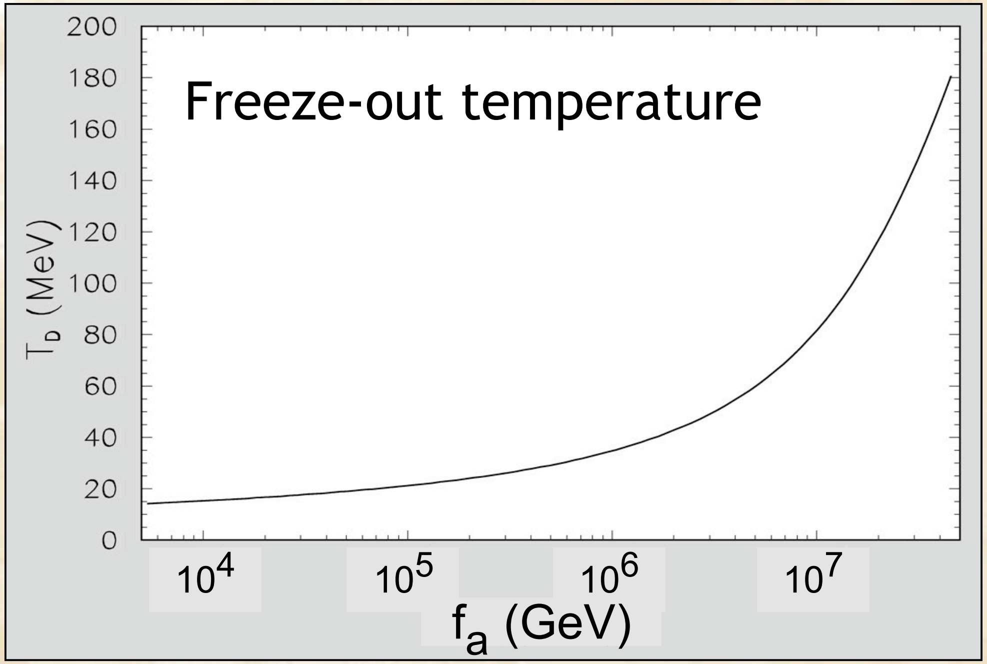


Neutrinos & WIMPs

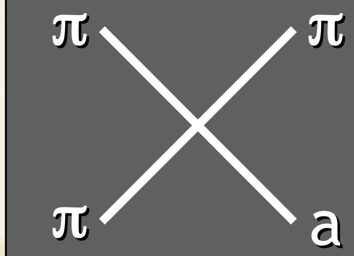


Axion Hot Dark Matter from Thermalization after Λ_{QCD}


Cosmic thermal degrees of freedom

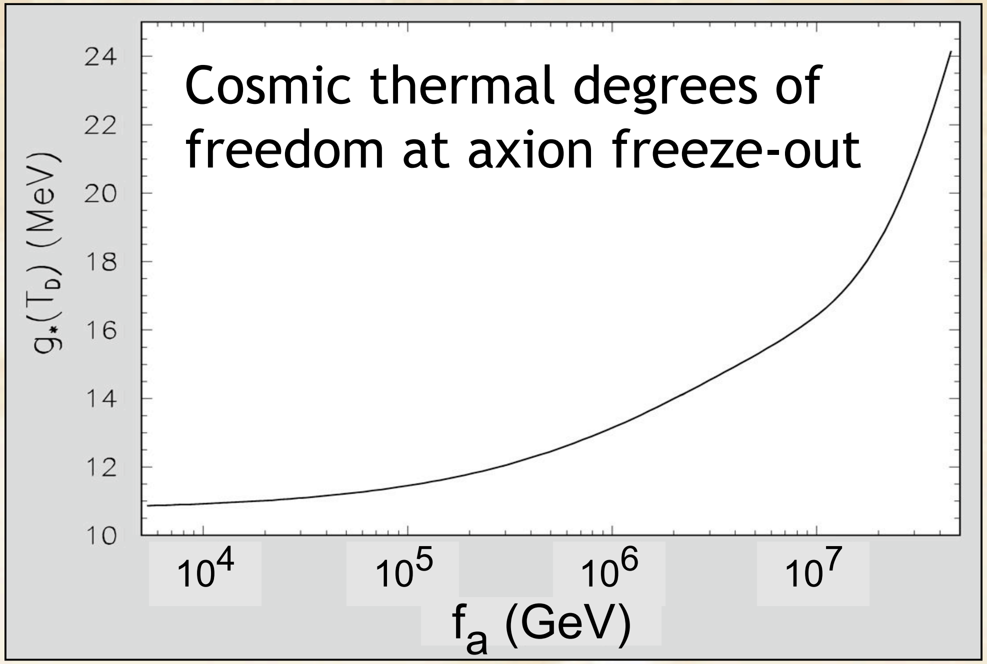

Freeze-out temperature

$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$

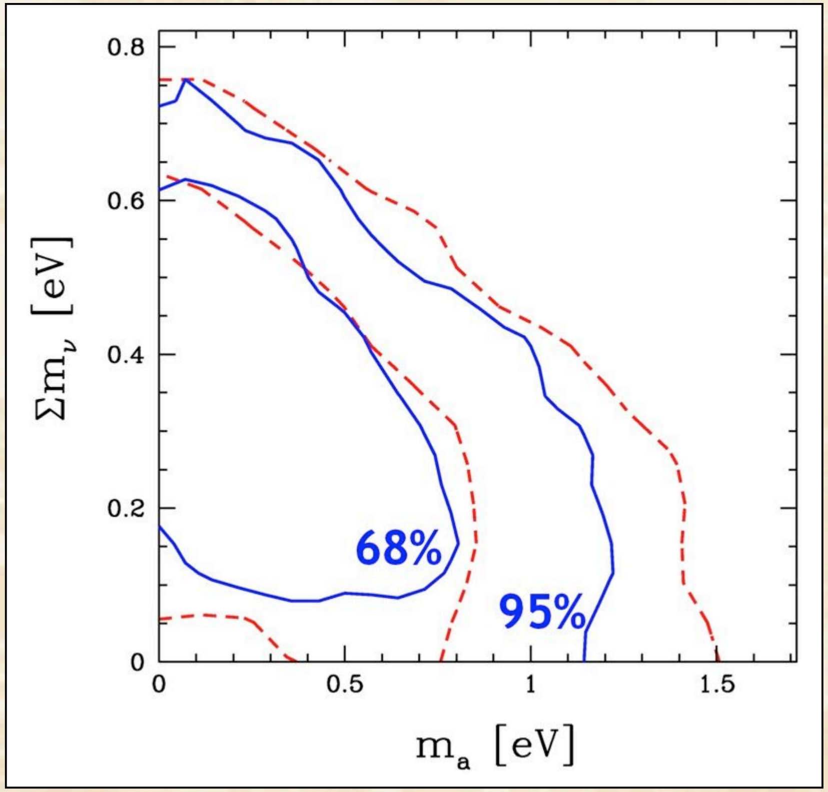


$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51


Cosmic thermal degrees of freedom at axion freeze-out

Axion Hot Dark Matter Limits from Precision Data

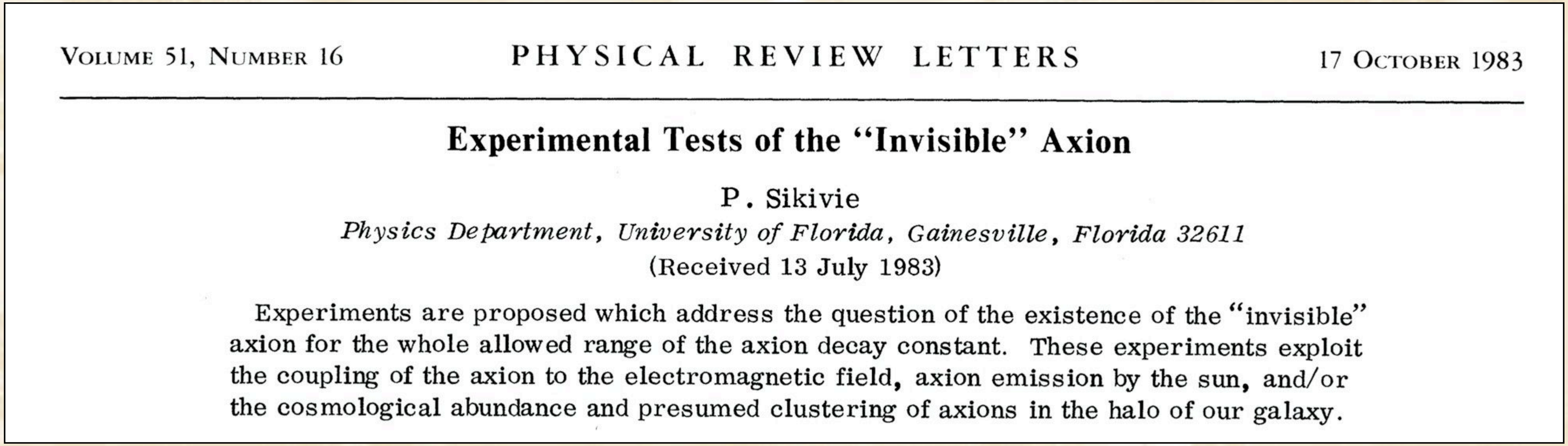


Credible regions for neutrino plus axion hot dark matter (WMAP-5, LSS, BAO, SNIa)
Hannestad, Mirizzi, Raffelt & Wong
[arXiv:0803.1585]

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]

Experimental Tests of the Invisible Axion



VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

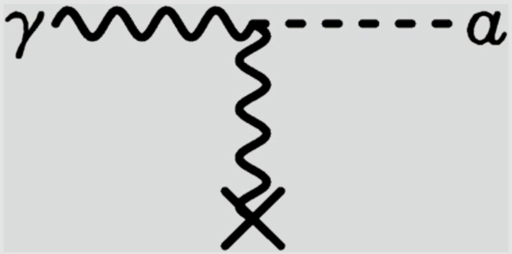
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(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:

Axions-photon transitions in external static E or B field
(Originally discussed for π^0
by Henri Primakoff 1951)

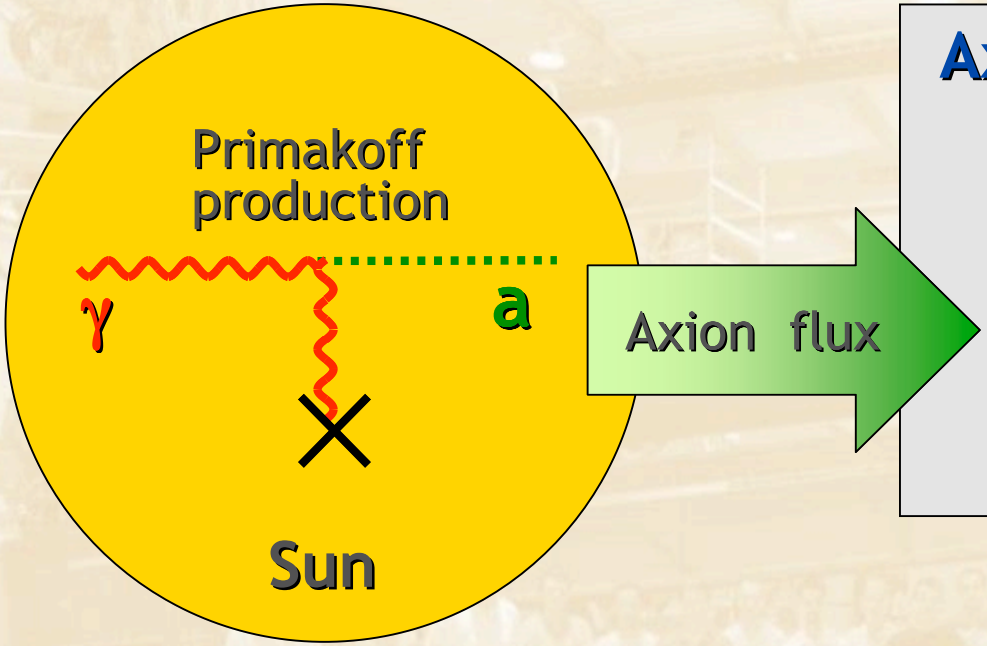


Pierre Sikivie:

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

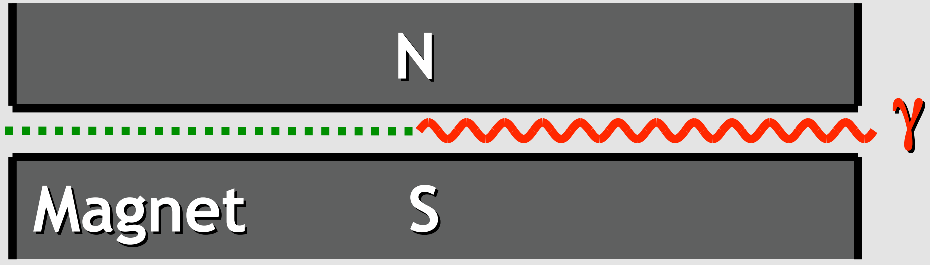
- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with A microwave resonant cavity

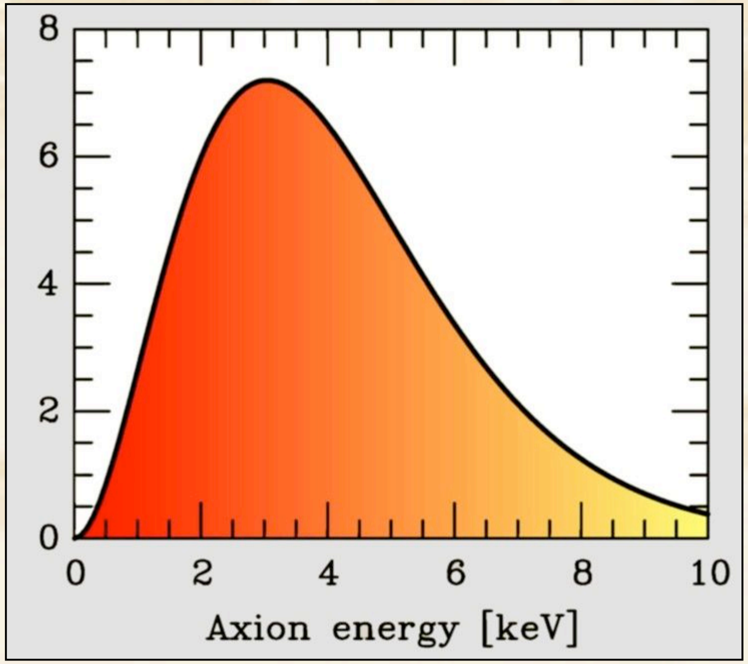
Search for Solar Axions



Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation

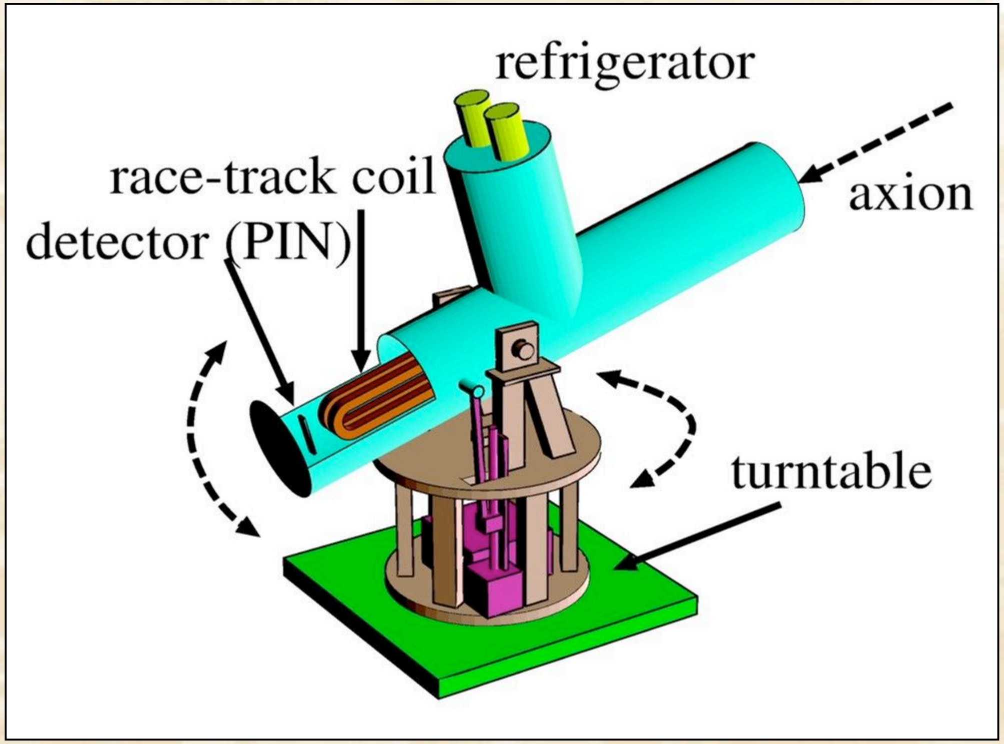


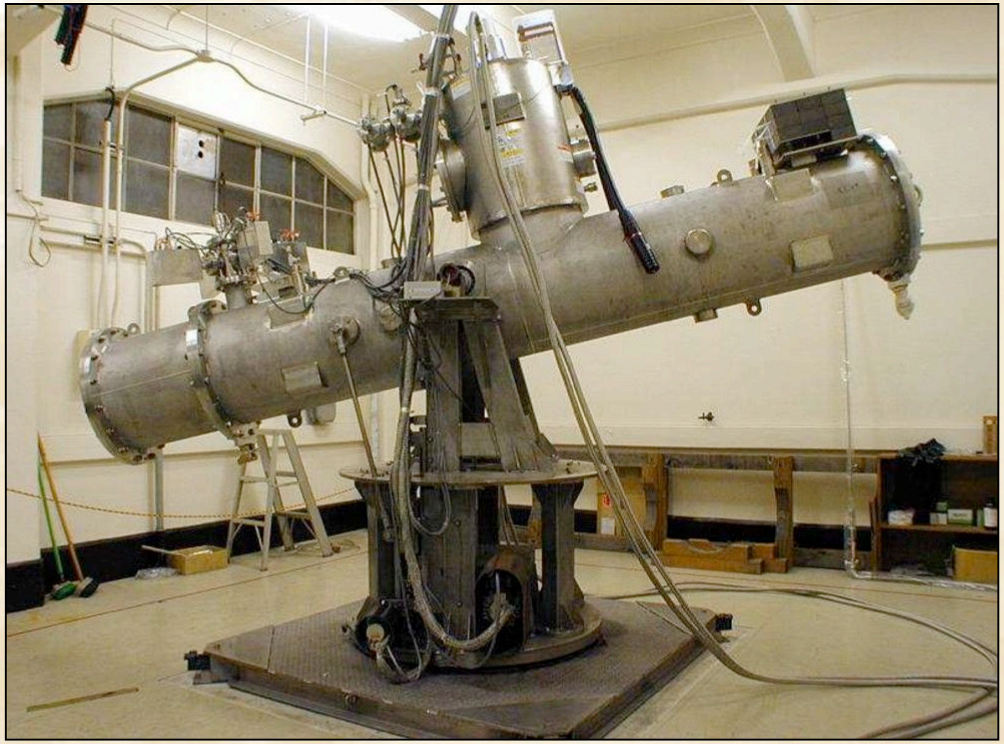


- ➡ Tokyo Axion Helioscope (“Sumico”) (Results since 1998, up again 2008)
- ➡ CERN Axion Solar Telescope (CAST) (Data since 2003)

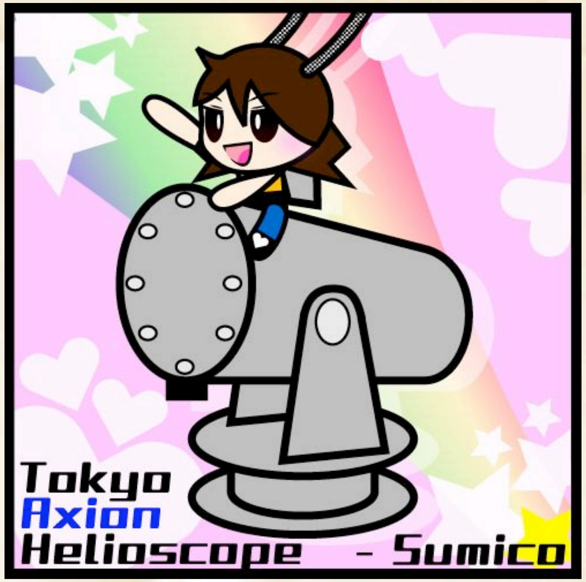
Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

Tokyo Axion Helioscope ("Sumico")



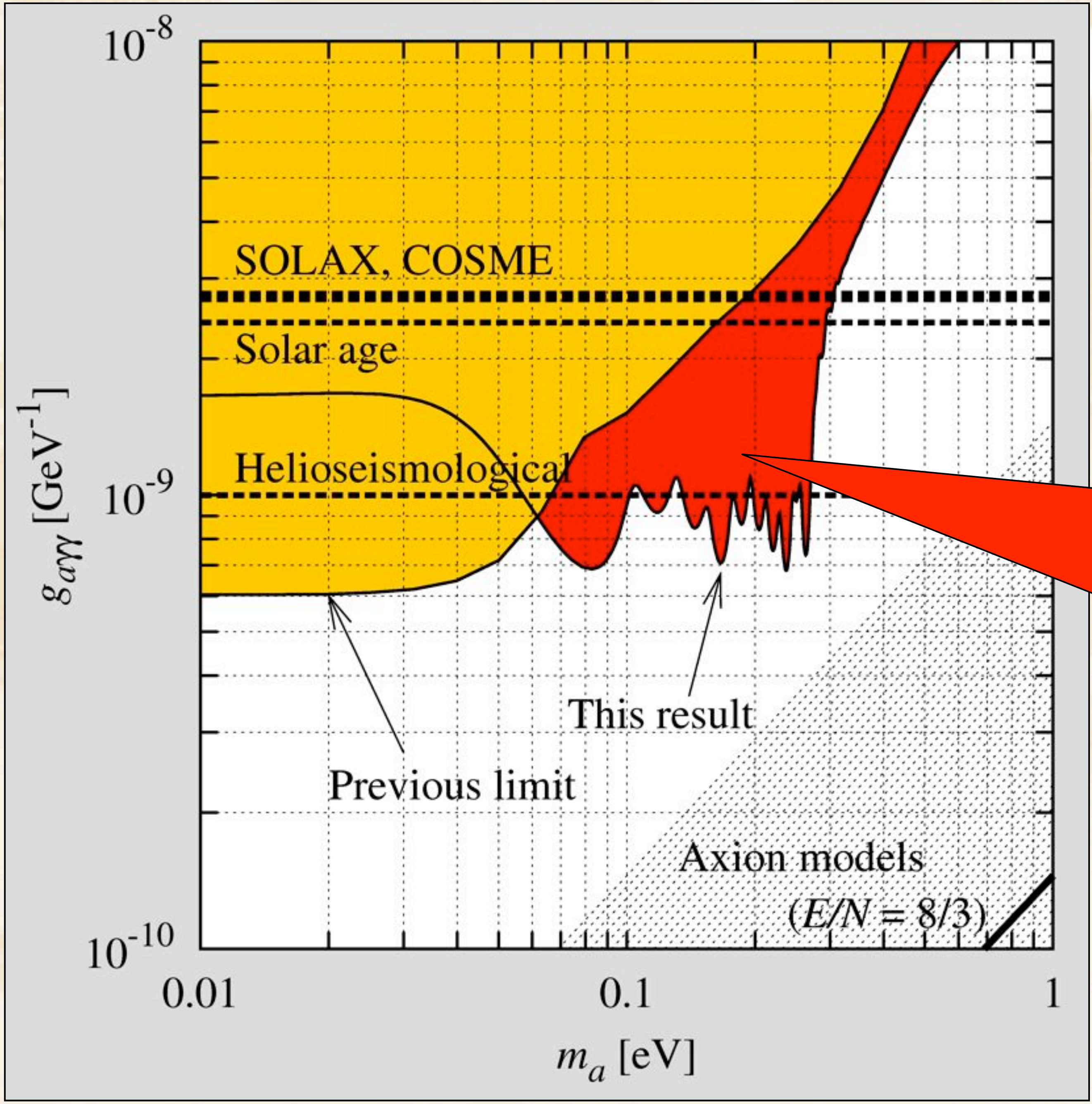


~ 3 m



S.Moriyama, M.Minowa, T.Namba, Y.Inoue, Y.Takasu
& A.Yamamoto, PLB 434 (1998) 147

Limits from Tokyo Axion Helioscope



Y. Inoue et al.,
PLB 536 (2002) 18
[astro-ph/0204388]

Axion-photon transition region filled with pressurized gas to give photons an effective mass (avoid momentum mismatch)

Extending to higher mass values with gas filling

Axion-photon transition probability

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

Axion-photon momentum transfer

$$q = \left|\frac{m_a^2 - m_\gamma^2}{2E}\right|$$

Transition suppressed for $qL \gtrsim 1$

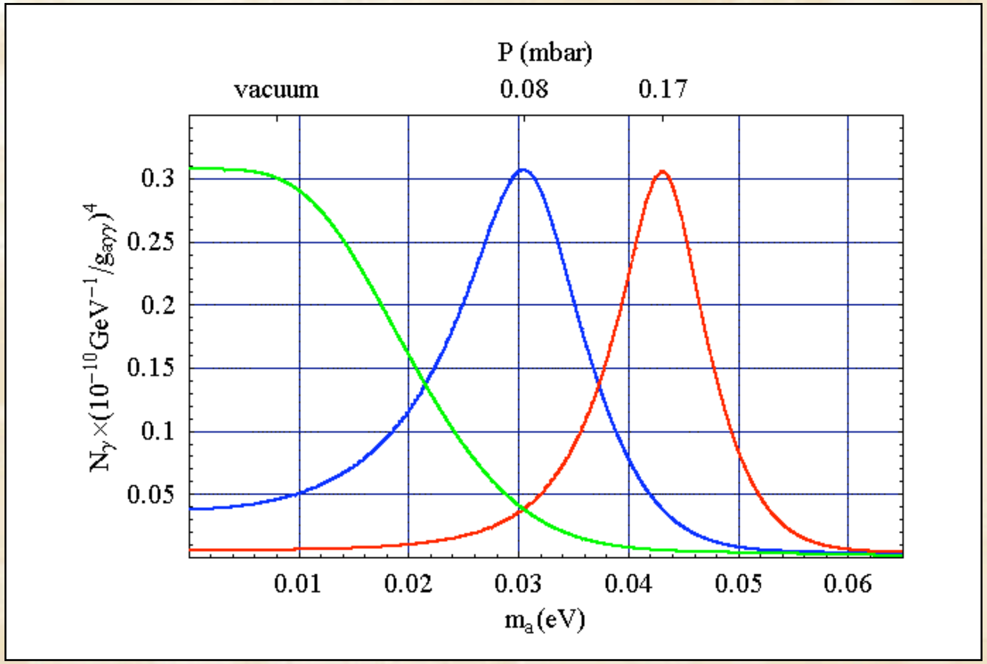
Gas filling: Give photons a refractive mass to restore full transition strength (~ MSW effect)

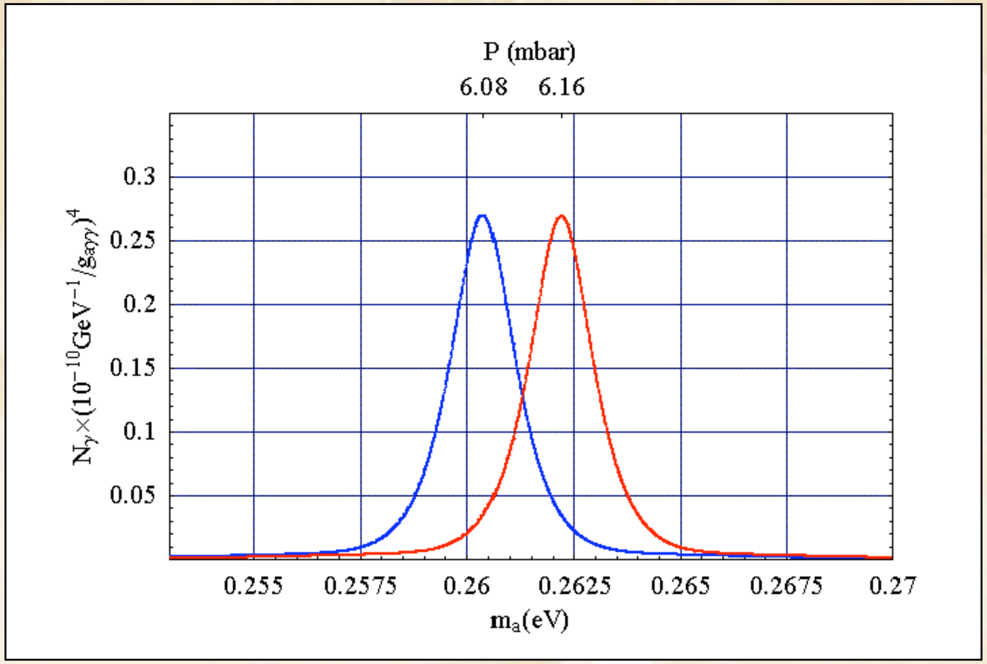
$$m_\gamma^2 = \frac{4\pi\alpha}{m_e} n_e \qquad (n_e \text{ electron density})$$

$$m_\gamma = 28.9\ \text{eV}\sqrt{\frac{Z}{A}\rho_{\text{Gas}}}$$

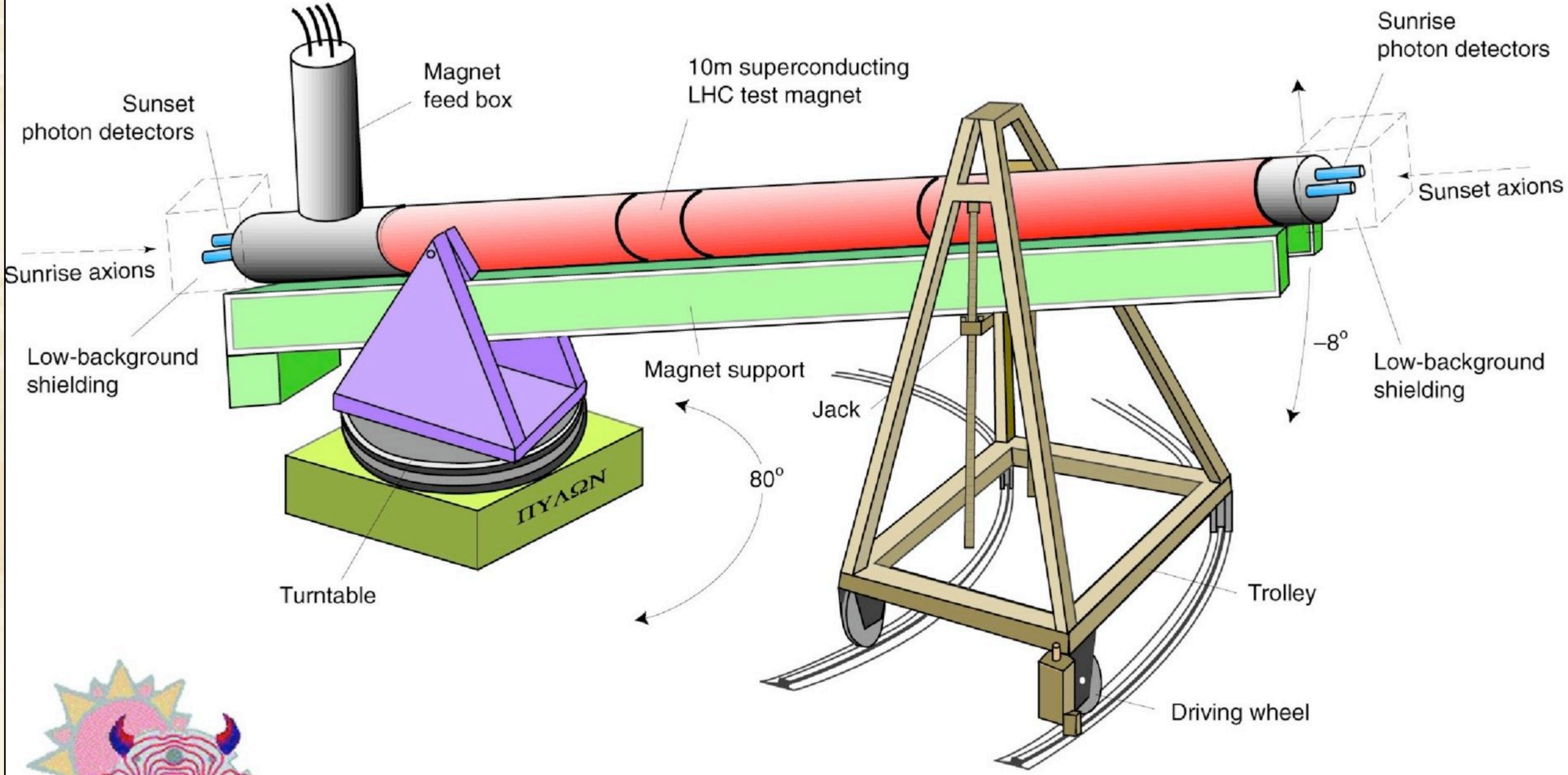
He^4 vapour pressure at 1.8 K

$$\rho \approx 0.2\times10^{-3}\ \text{g cm}^{-3} \qquad m_\gamma = 0.26\ \text{eV}$$





LHC Magnet Mounted as a Telescope to Follow the Sun



Cern Axion Solar Telescope

CAST at CERN

Sun Spot on CCD with X-Ray Telescope

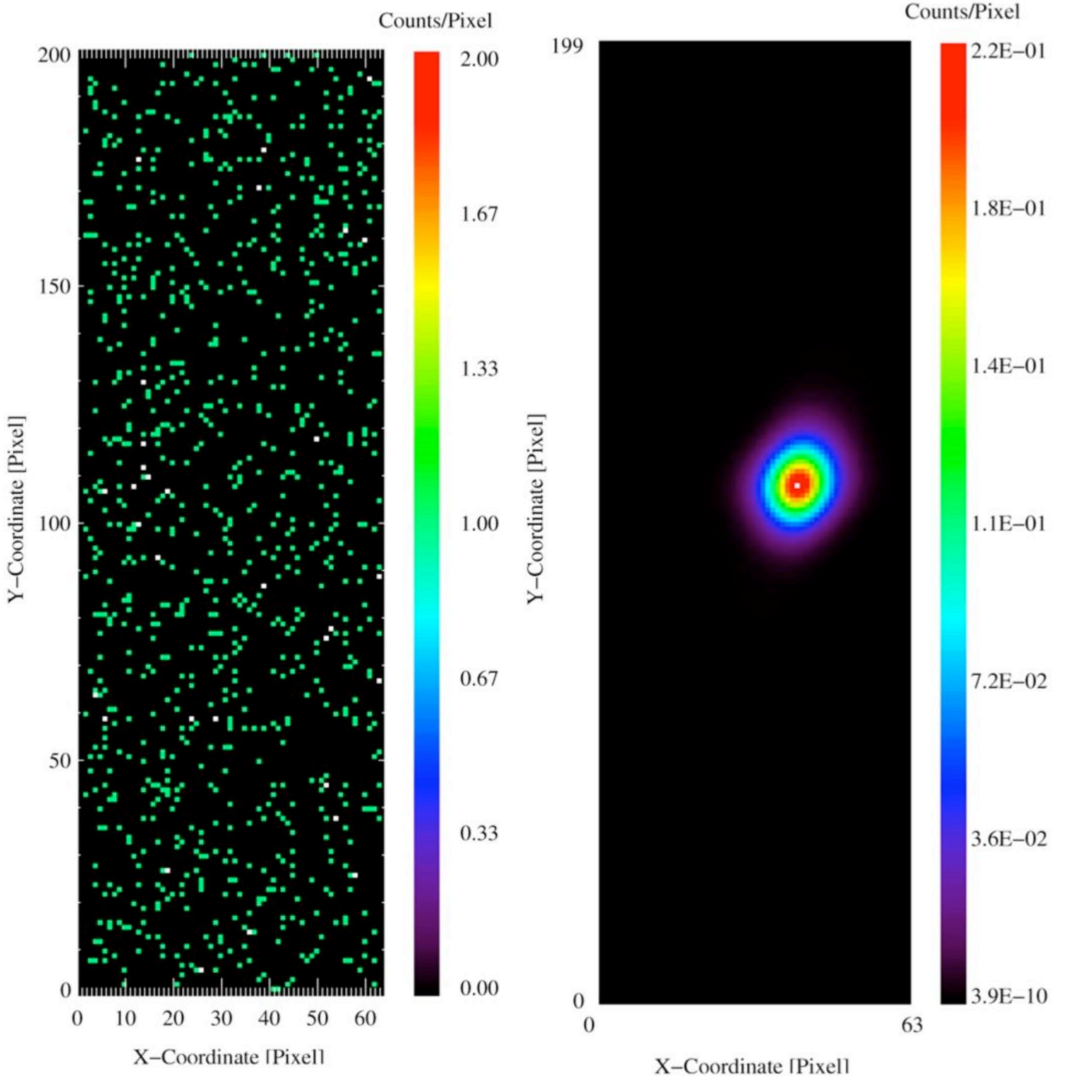
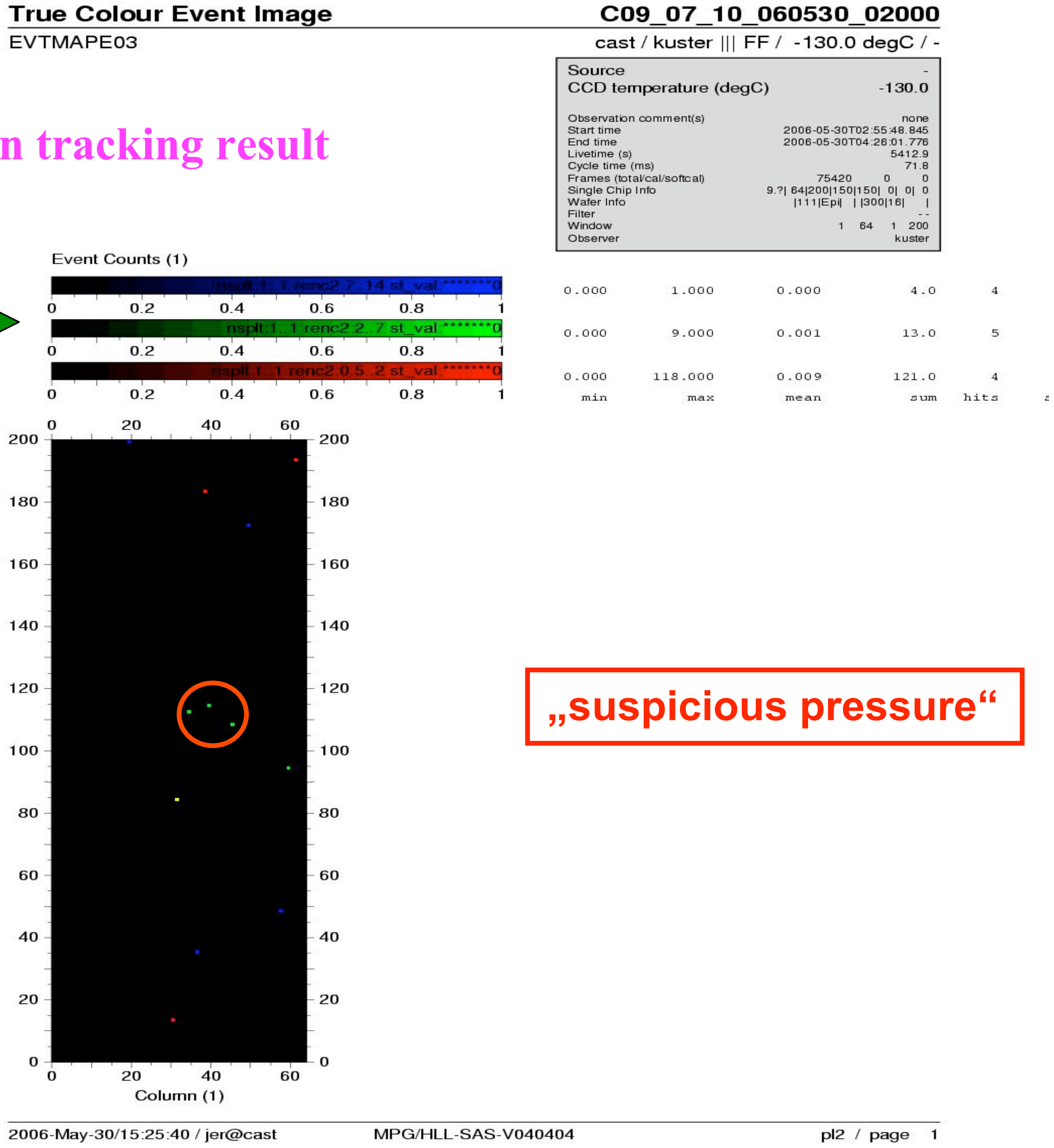


Figure 6: Left: Spatial distribution of events observed under axion sensitive conditions by the CAST X-ray telescope during the 2004 data taking period. The intensity is given in counts per pixel and is integrated over the full observation period of $t_{\mathrm{obs}} = 707\,\mathrm{ksec}$. Right: Expected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

90 min tracking result



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

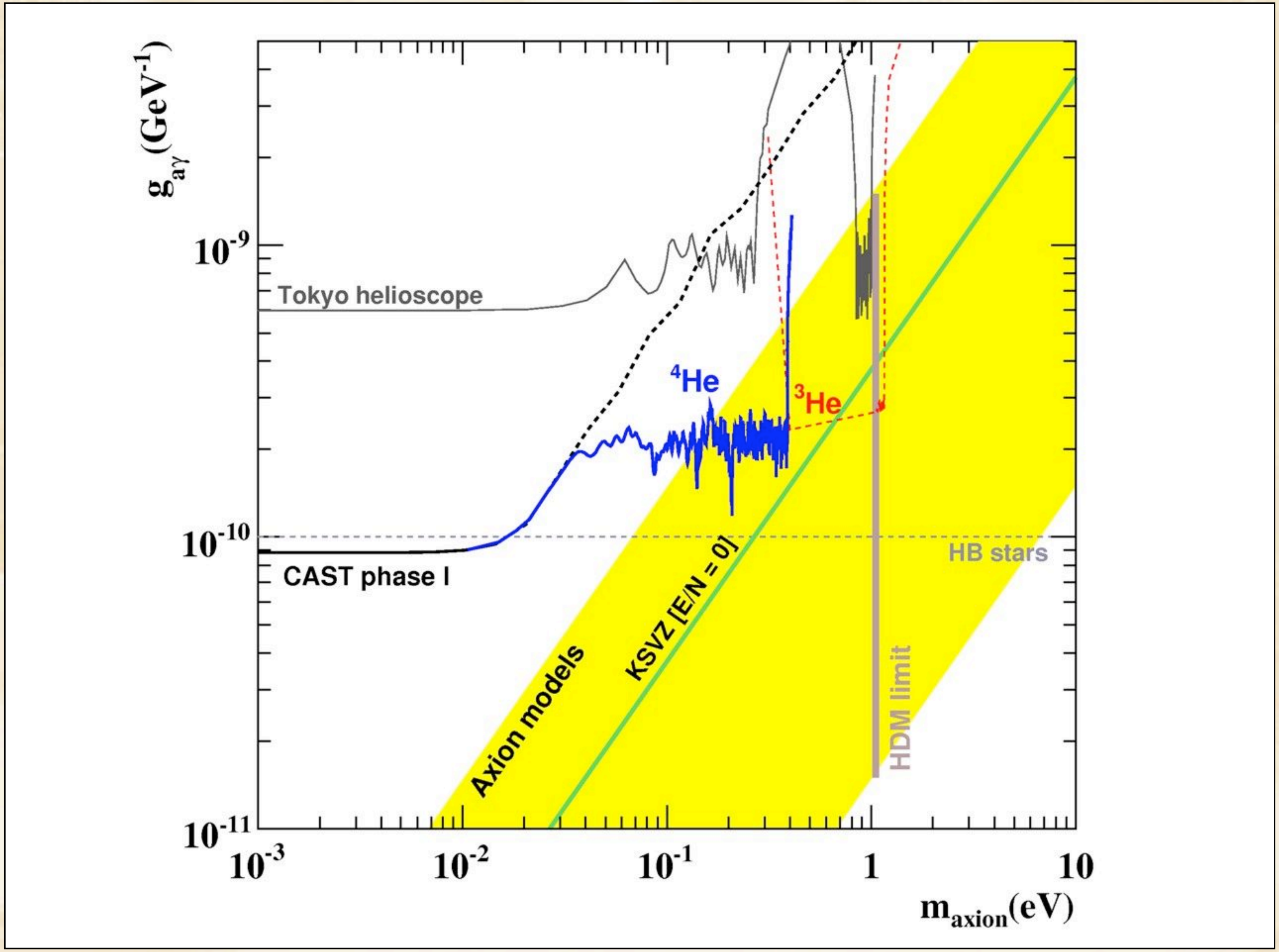
min	max	mean	sum	hits
0.000	1.000	0.000	4.0	4
0.000	9.000	0.001	13.0	5
0.000	118.000	0.009	121.0	4

2006-May-30/15:25:40 / jer@cast MPG/HLL-SAS-V040404 pl2 / page 1

ROI

„suspicious pressure“

Limits from CAST-I and CAST-II



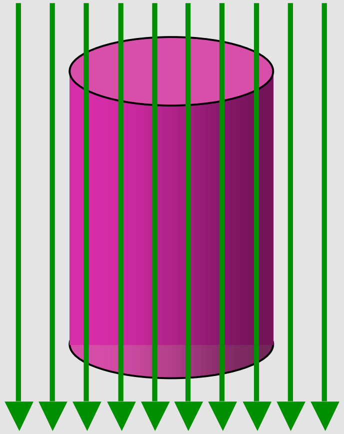
CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): arXiv:0810.4482

Search for Galactic Axions (Cold Dark Matter)

DM axions	m_a = 1-1000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$

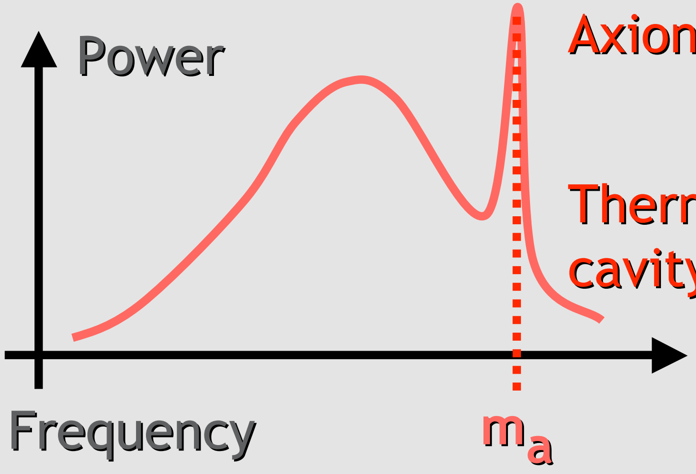
Microwave Energies
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

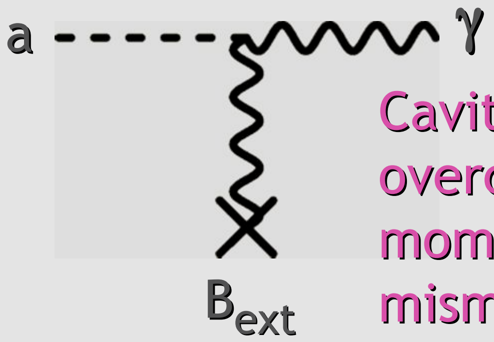


$B_{ext} \approx$ 8 Tesla

Microwave
Resonator
$Q \approx 10^5$



Primakoff Conversion



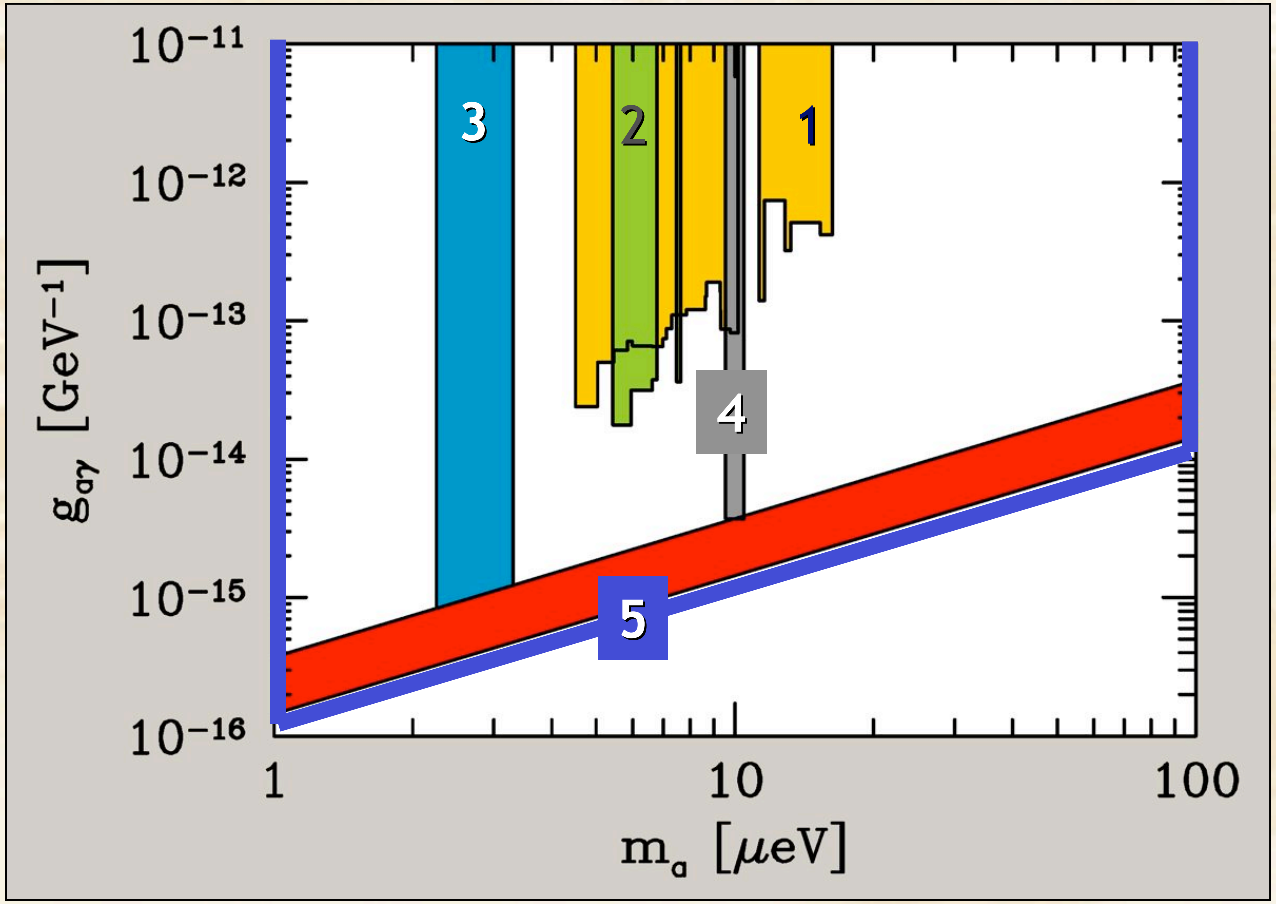
Cavity
overcomes
momentum
mismatch

Power of galactic axion signal

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

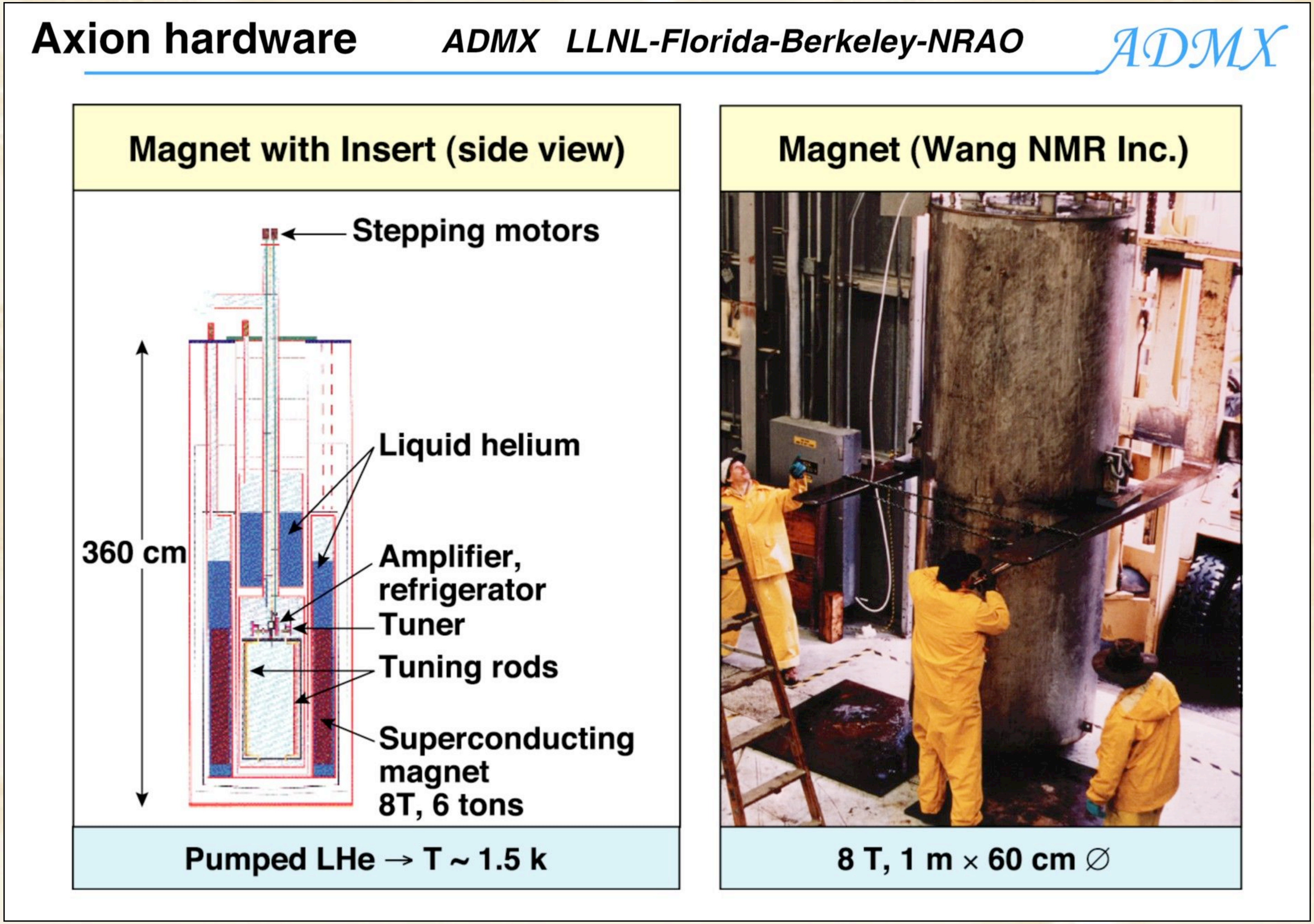
Axion Dark Matter Searches

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
   (Livermore)
   ApJL 571 (2002) L27
4. CARRACK I (Kyoto)
   preliminary
   hep-ph/0101200
5. ADMX (Livermore)
   foreseen
   e.g. Rev. Mod. Phys.
   75 (2003) 777

ADMX (G.Carosi, Fermilab, May 2007)



Axion hardware

ADMX LLNL-Florida-Berkeley-NRAO

ADMX

Magnet with Insert (side view)

Stepping motors

360 cm

Liquid helium

Amplifier, refrigerator

Tuner

Tuning rods

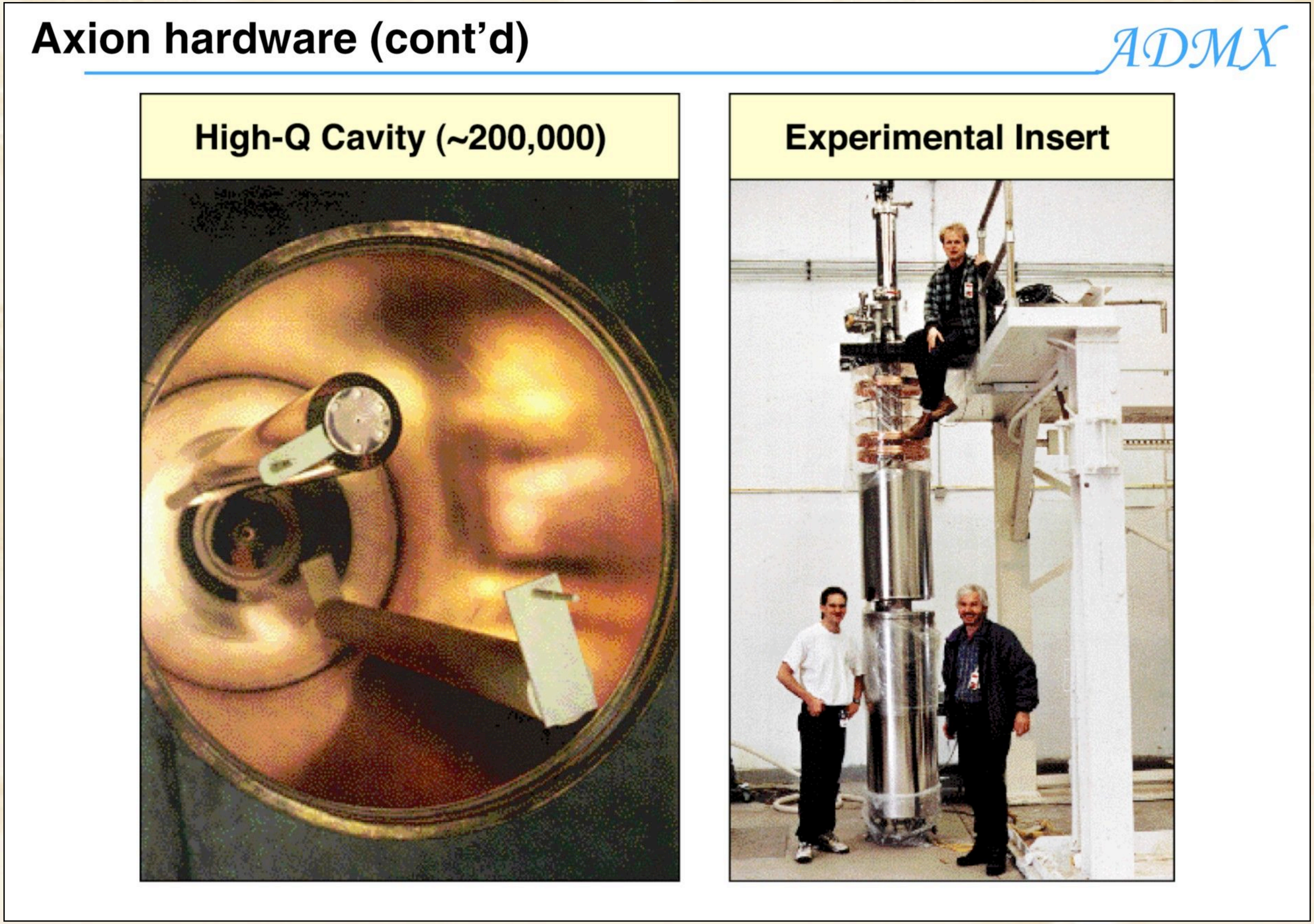
Superconducting magnet
8T, 6 tons

Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

ADMX (G.Carosi, Fermilab, May 2007)



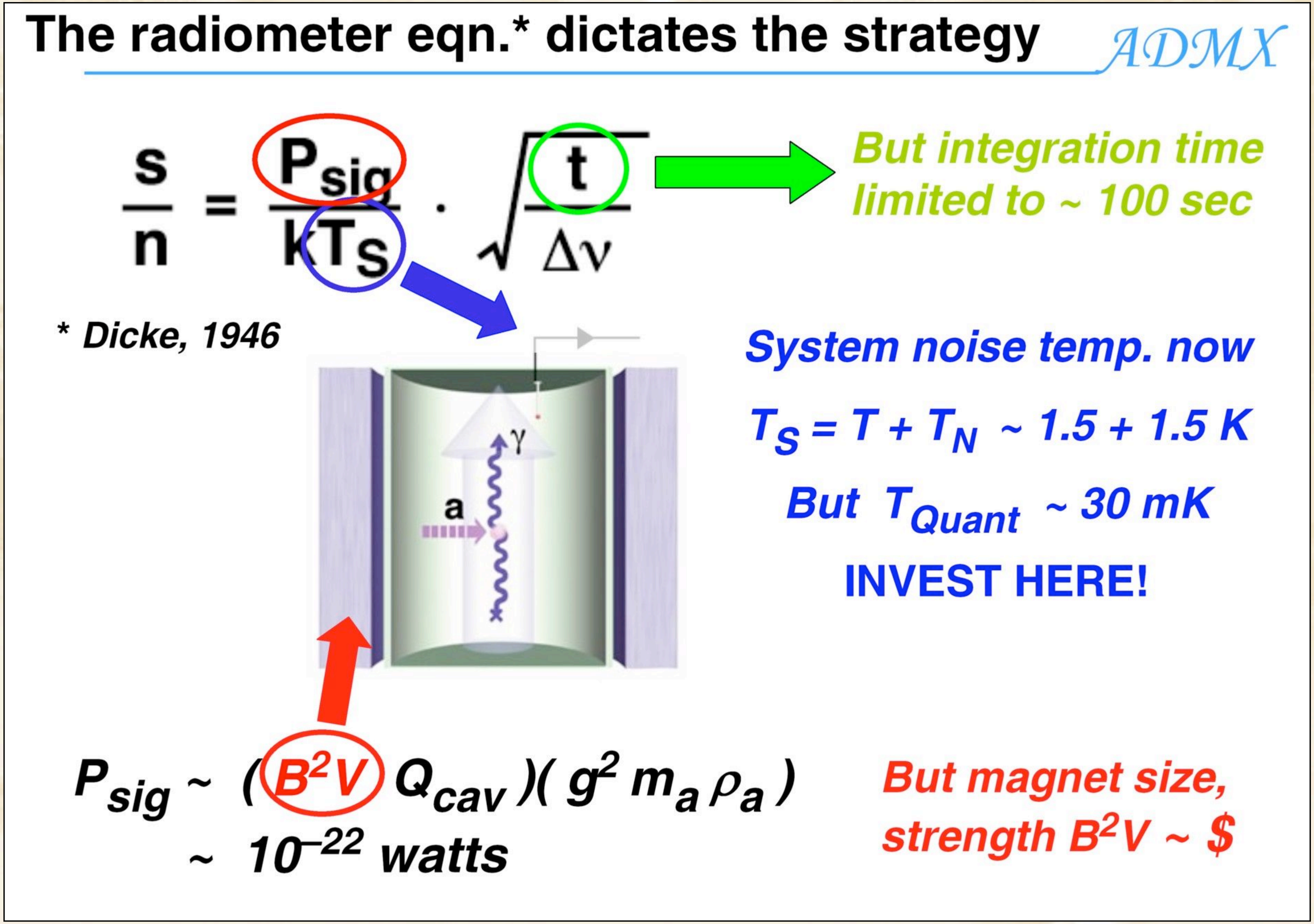
Axion hardware (cont'd)

ADMX

High-Q Cavity (~200,000)

Experimental Insert

ADMX (G.Carosi, Fermilab, May 2007)



The radiometer eqn.* dictates the strategy

ADMX

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

But integration time limited to ~ 100 sec

* *Dicke, 1946*

System noise temp. now

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

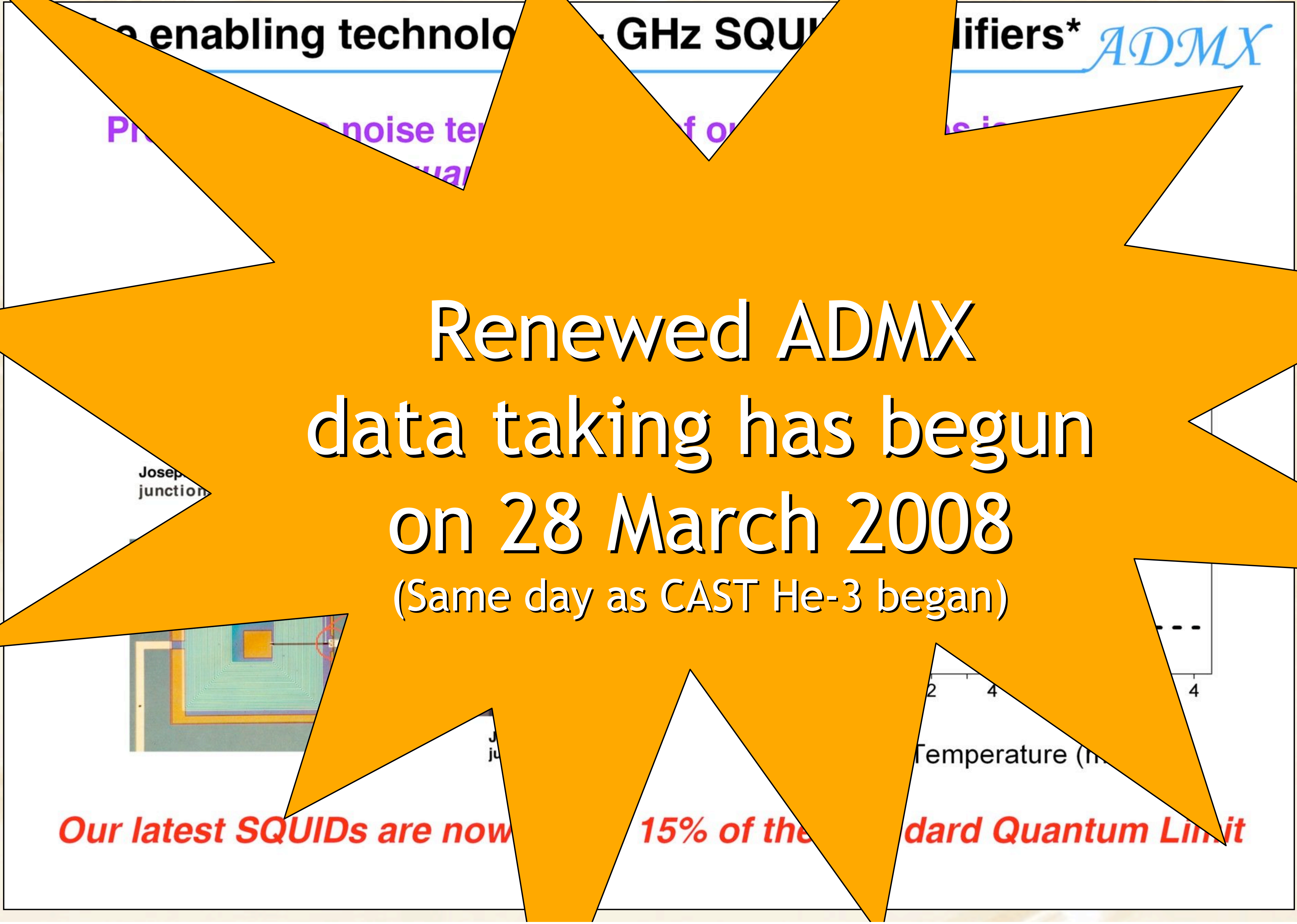
But $T_{Quant} \sim 30$ mK

INVEST HERE!

$$P_{sig} \sim (\boxed{B^2V}\, Q_{cav})(g^2 m_a \rho_a) \sim 10^{-22} \text{ watts}$$

But magnet size, strength $B^2V \sim \$$

ADMX (G.Carosi, Fermilab, M 2007)



e enabling technolo GHz SQU lifiers*

ADMX

Pr noise te f o s i

uar

Josep
junction

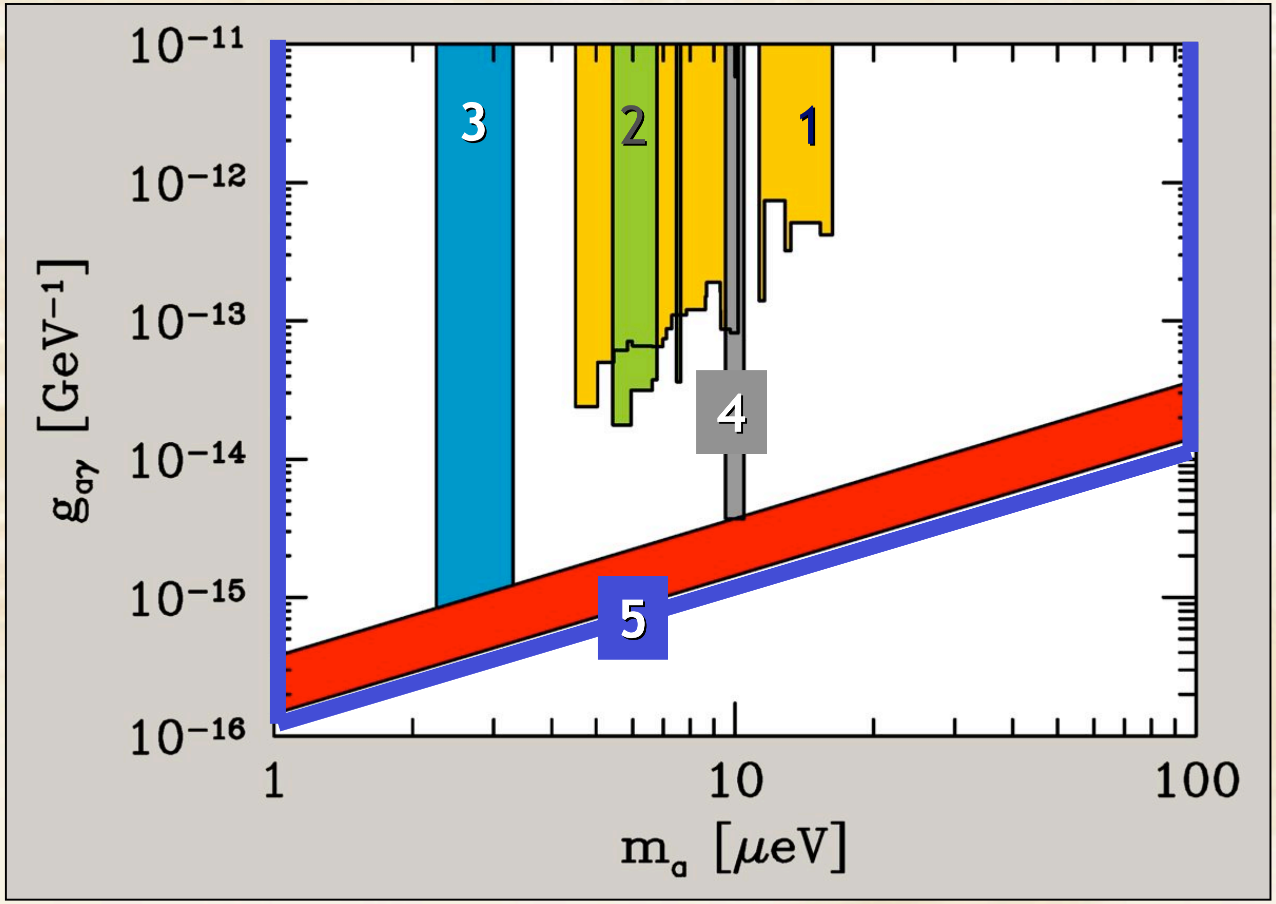
J
ju

Our latest SQUIDs are now 15% of the dard Quantum Li it

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

Axion Dark Matter Searches

Limits/sensitivities, assuming axions are the galactic dark matter



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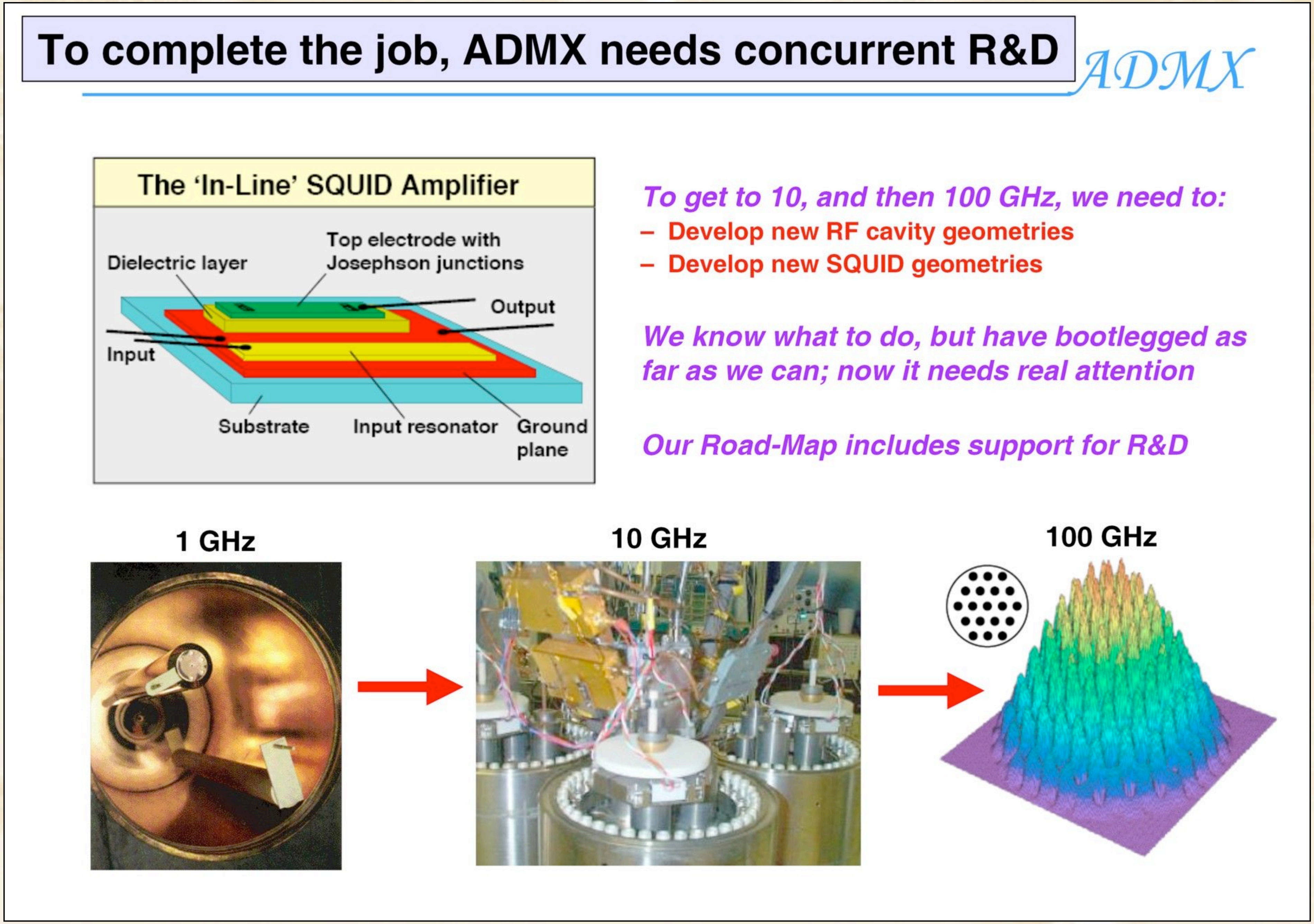
ADMX (G.Carosi, Fermilab, May 2007)



To complete the job, ADMX needs concurrent R&D

ADMX

The 'In-Line' SQUID Amplifier

To get to 10, and then 100 GHz, we need to:

- Develop new RF cavity geometries
- Develop new SQUID geometries

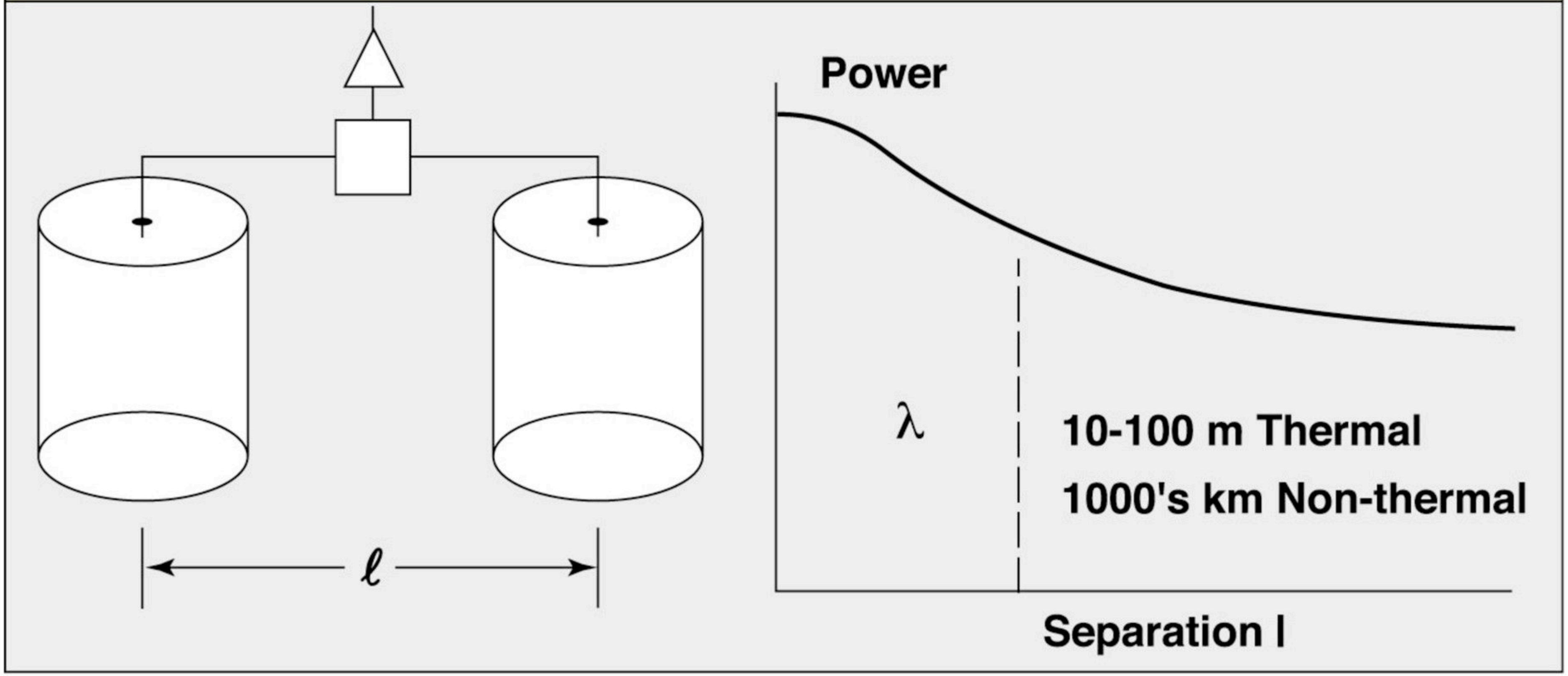
We know what to do, but have bootlegged as far as we can; now it needs real attention

Our Road-Map includes support for R&D

Karl van Bibber
at IDM 2008

And if the axion be found?

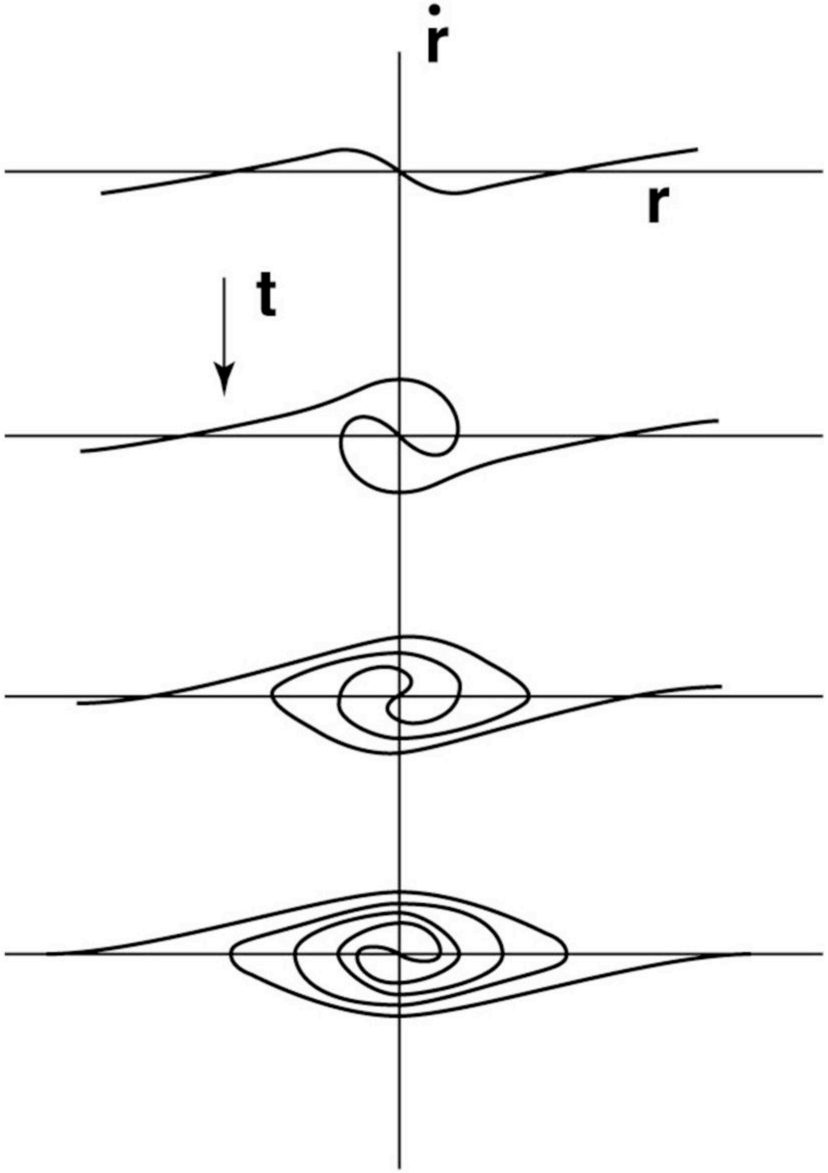
The Study of Unique Quantum System

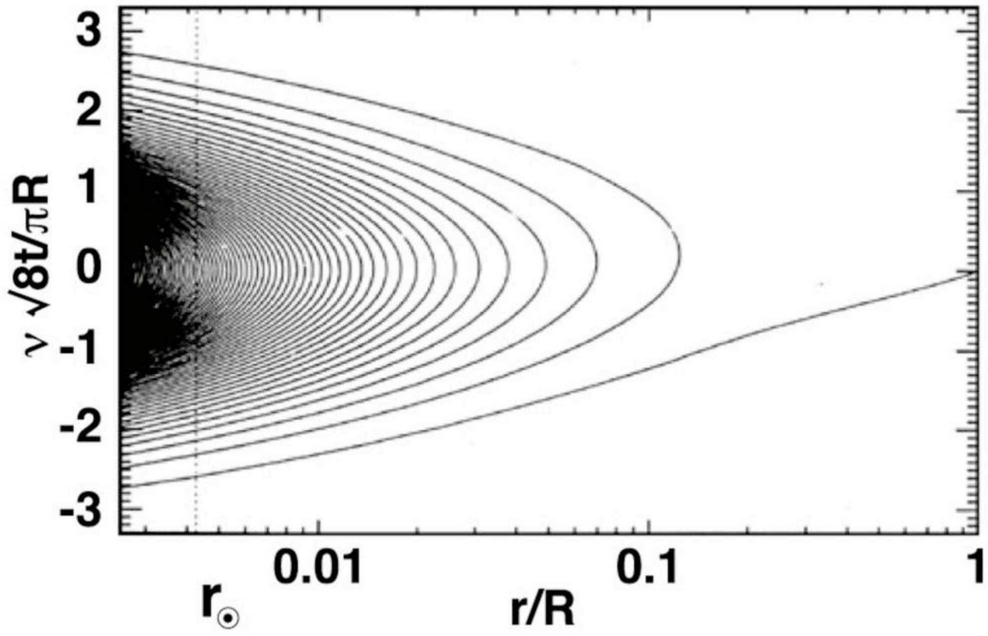


And should the axion posses fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy

Karl van Bibber
at IDM 2008

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

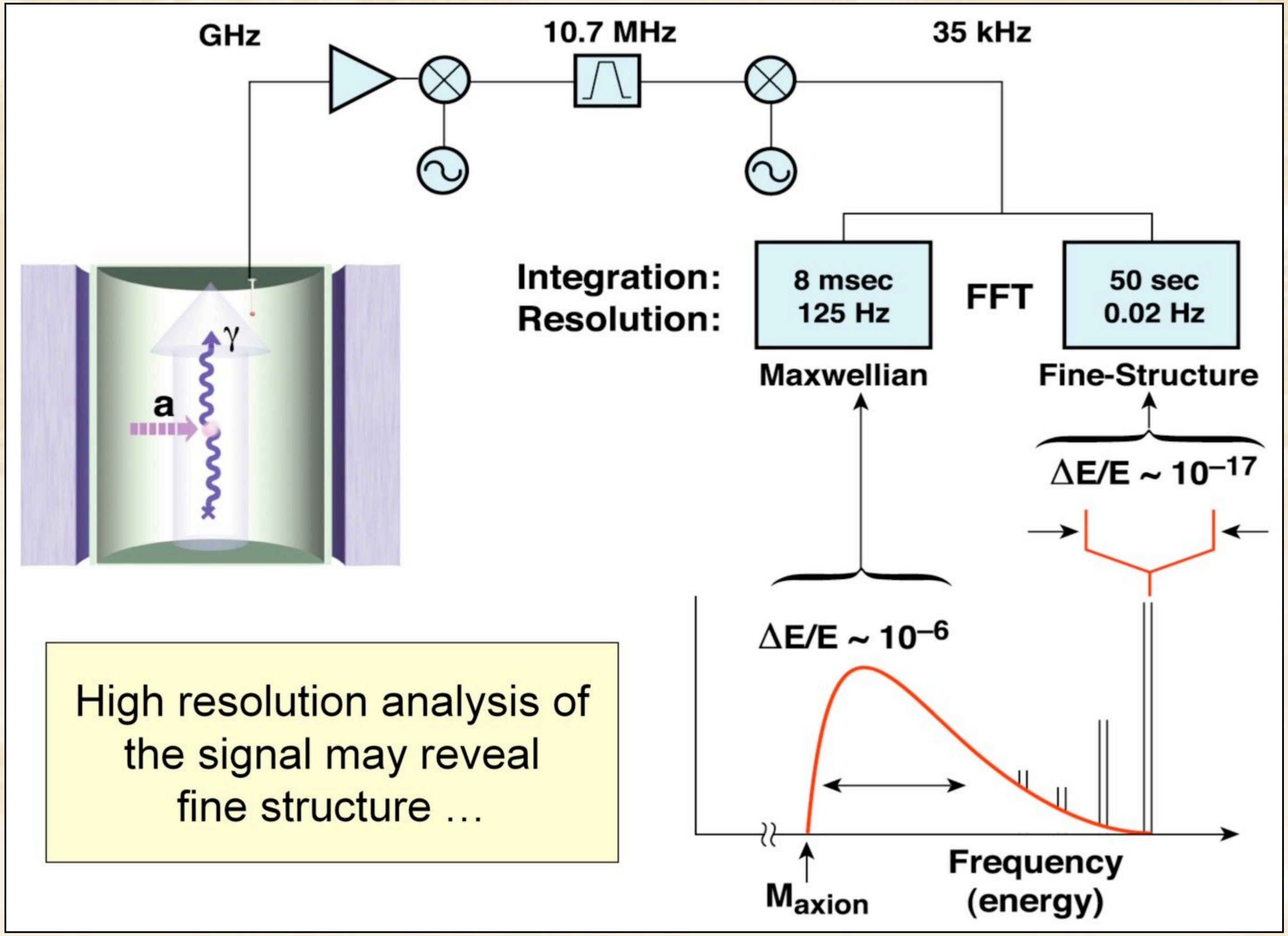




- Model begins with
  - — Zero Temperature CDM
  - — Hubble expansion
  - — Initial density perturbation r = o
- Grows self-consistent potential

Fine Structure in Axion Spectrum

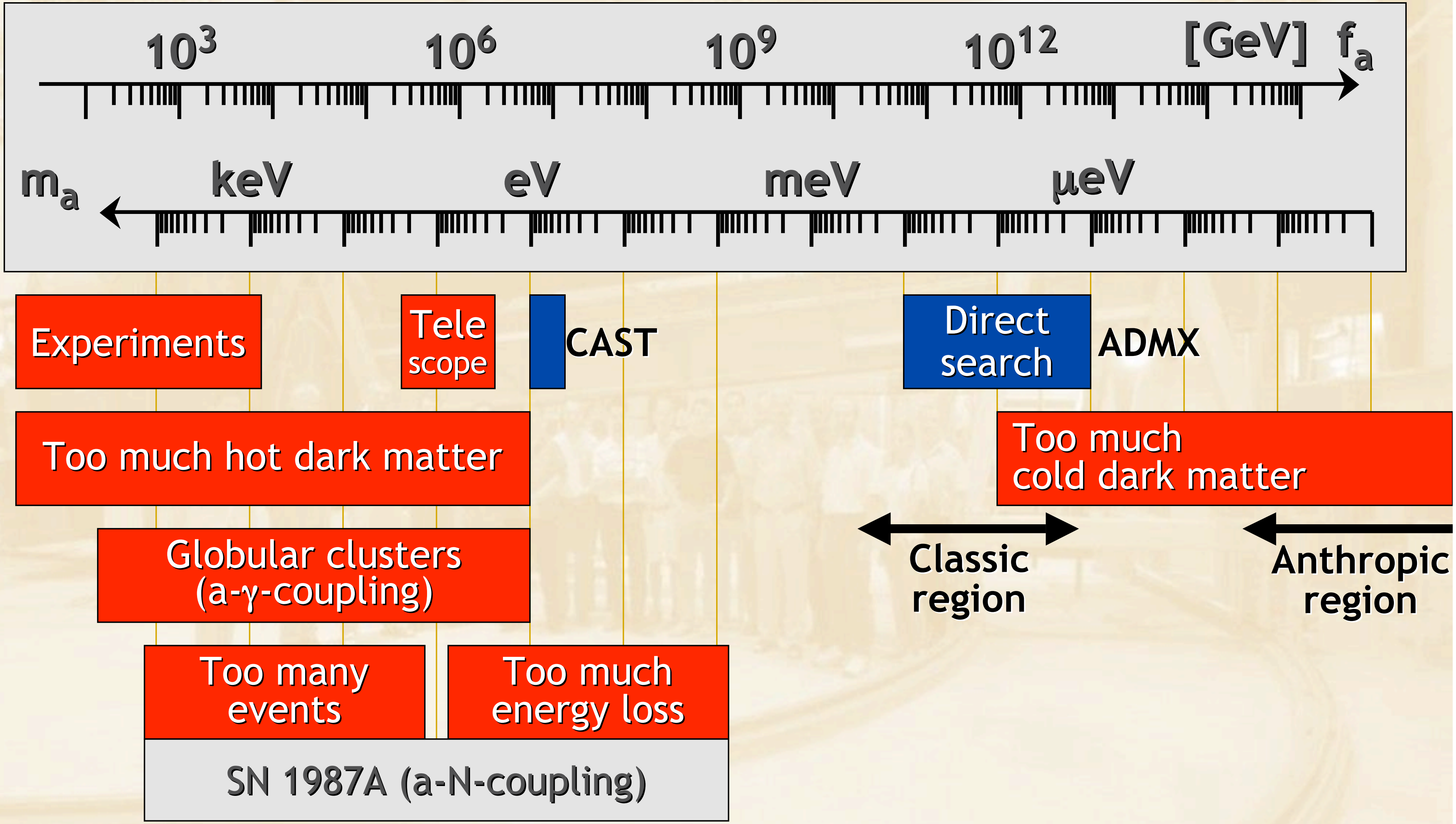
- Axion distribution on a 3-dim sheet in 6-dim phase space
- Is “folded up” by galaxy formation
- Velocity distribution shows narrow peaks that can be resolved
- More detectable information than local dark matter density



High resolution analysis of
the signal may reveal
fine structure …

P.Sikivie
& collaborators

Axion Bounds



Experiments

Telescope

CAST

Direct search

ADMX

Too much hot dark matter

Too much cold dark matter

Globular clusters (a-γ-coupling)

Classic region

Anthropic region

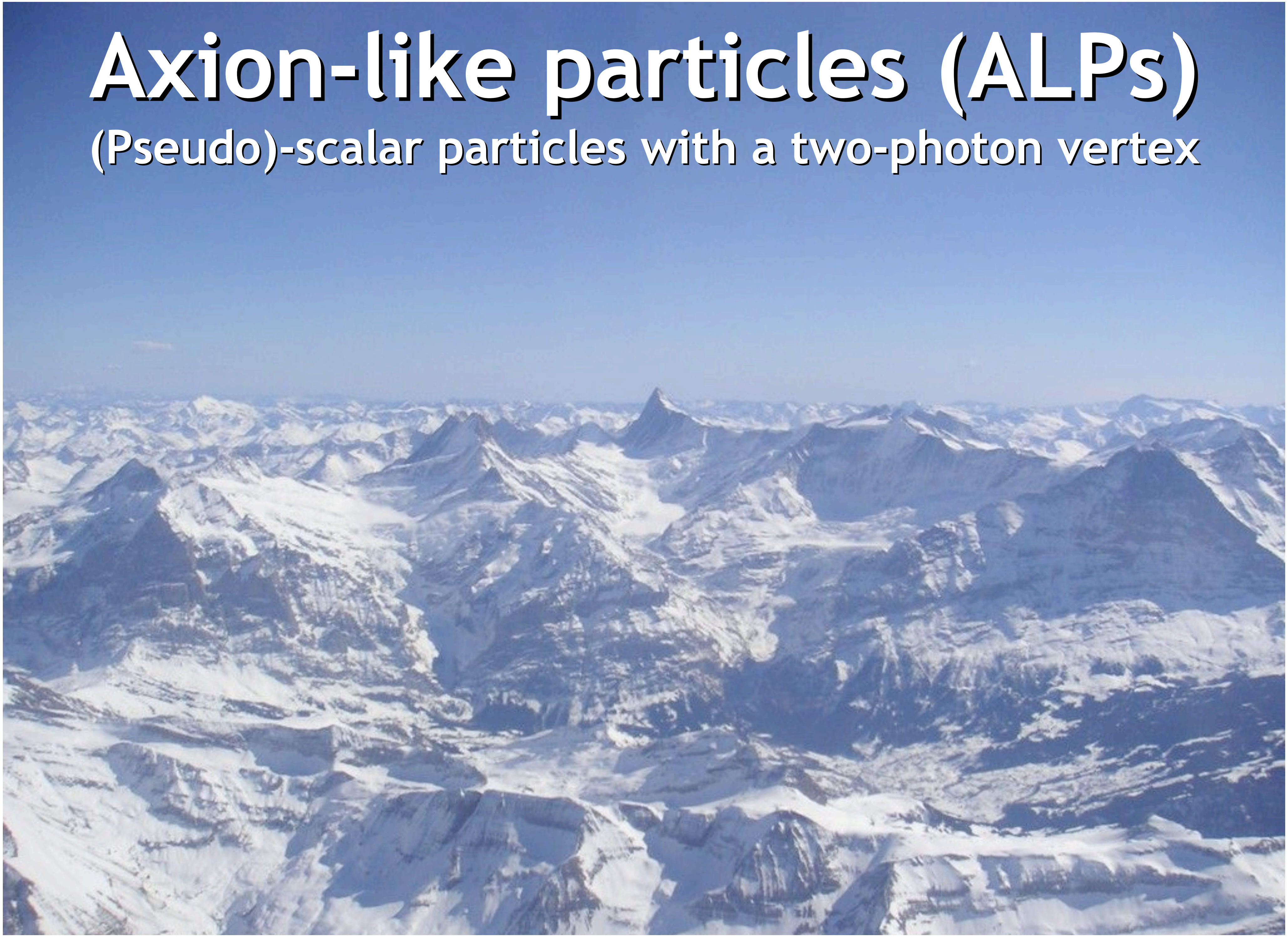
Too many events

Too much energy loss

SN 1987A (a-N-coupling)

Axion-like particles (ALPs)

(Pseudo)-scalar particles with a two-photon vertex

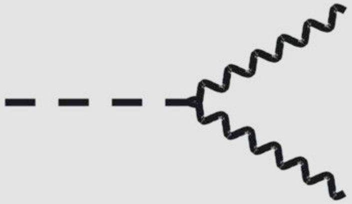


Particles with Two-Photon Coupling

Particles with two-photon vertex:

- Neutral pions (π^0), Gravitons
- Axions (a) and similar hypothetical particles

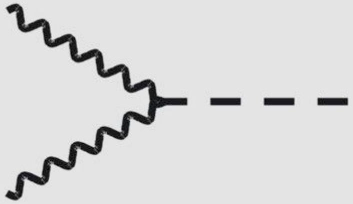
$$L_{a\gamma} = g_{a\gamma}\vec{E}\cdot\vec{B}\,a$$



Two-photon decay

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

Photon Coalescence

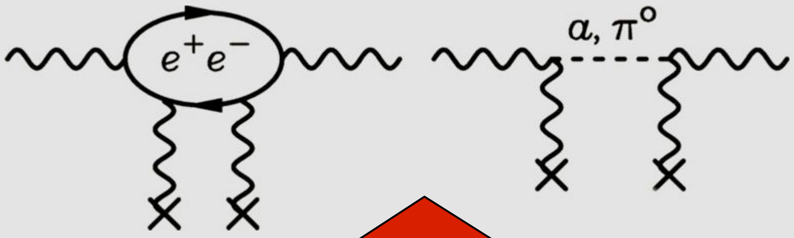


Primakoff Effect

Conversion of photons into pions, gravitons or axions, or the reverse

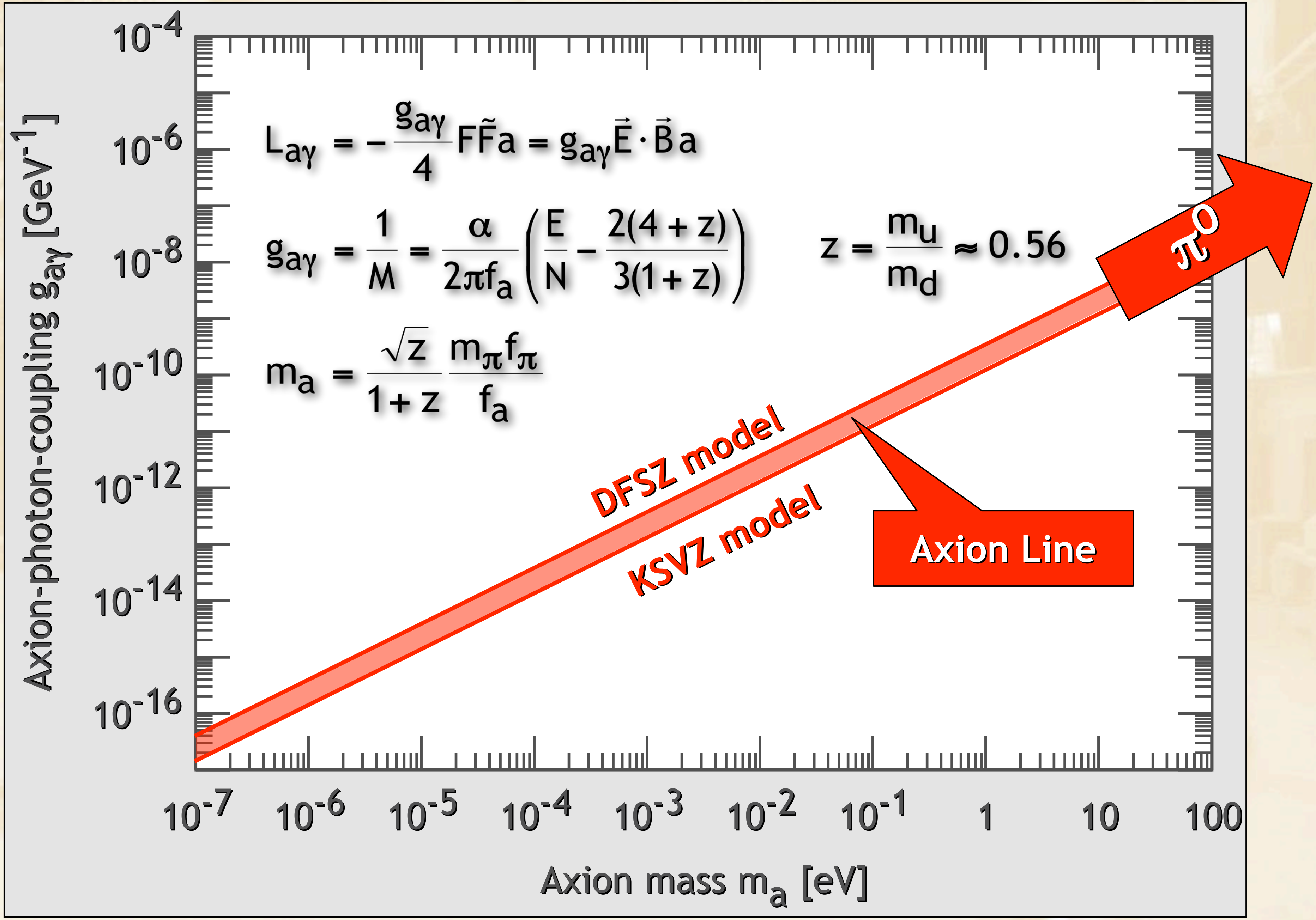
Magnetically induced vacuum birefringence

In addition to QED Cotton-Mouton-effect



PVLAS experiment recently measured an effect ~ 10^4 larger than QED expectation (Signal now disproved)

Axion-Photon-Coupling vs. Mass



$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}\,a$$

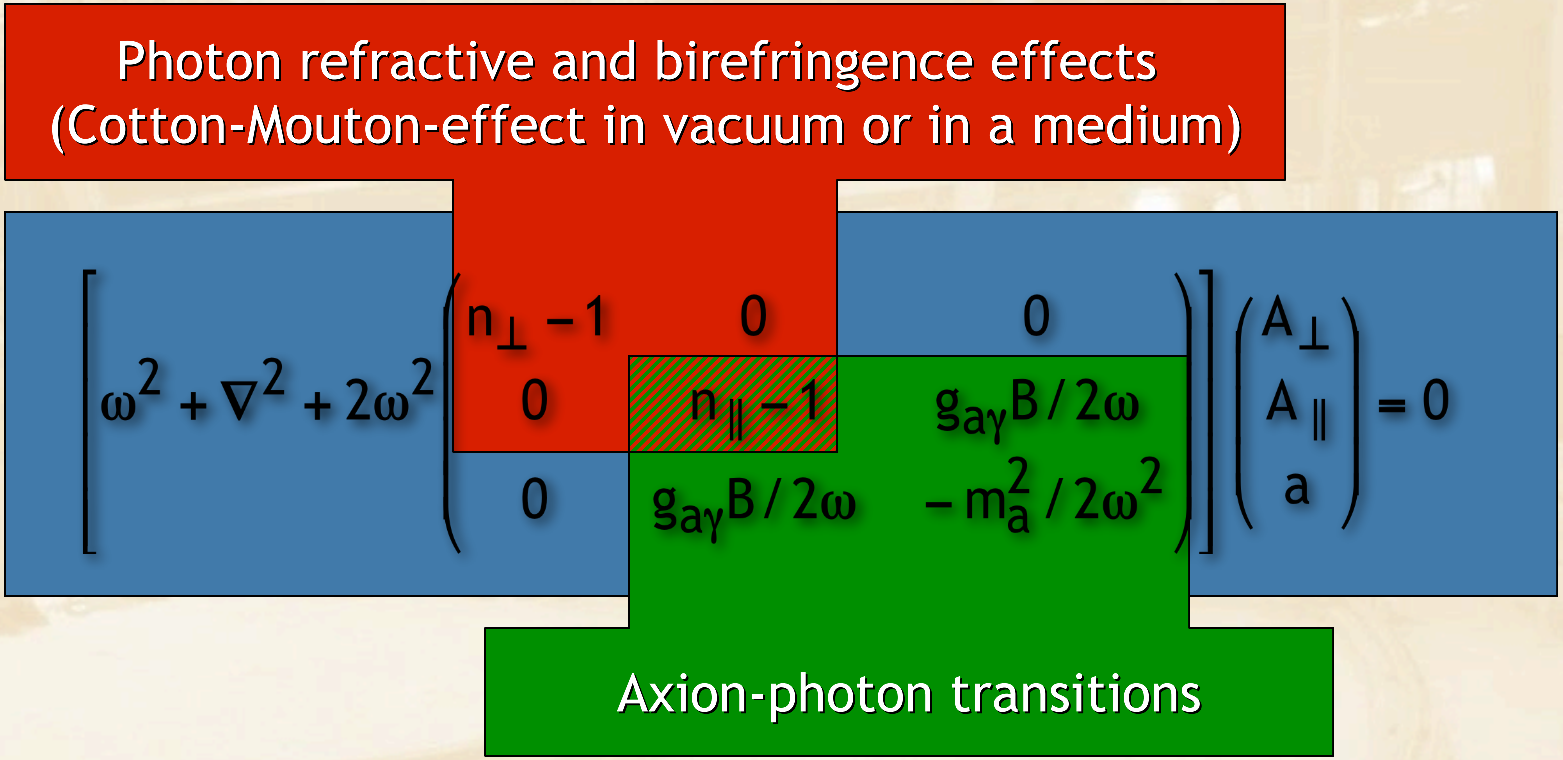
$$g_{a\gamma} = \frac{1}{M} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2(4+z)}{3(1+z)}\right) \qquad z = \frac{m_u}{m_d} \approx 0.56$$

$$m_a = \frac{\sqrt{z}}{1+z}\,\frac{m_\pi f_\pi}{f_a}$$

Axion-Photon-Transitions as Particle Oscillations

- In an external B-field, axions roughly like another photon polarization state
- In a homogeneous or slowly varying B-field, a photon beam develops a coherent axion component and the other way round

Stationary Klein-Gordon equation for coupled a-γ-system



Photon refractive and birefringence effects (Cotton-Mouton-effect in vacuum or in a medium)

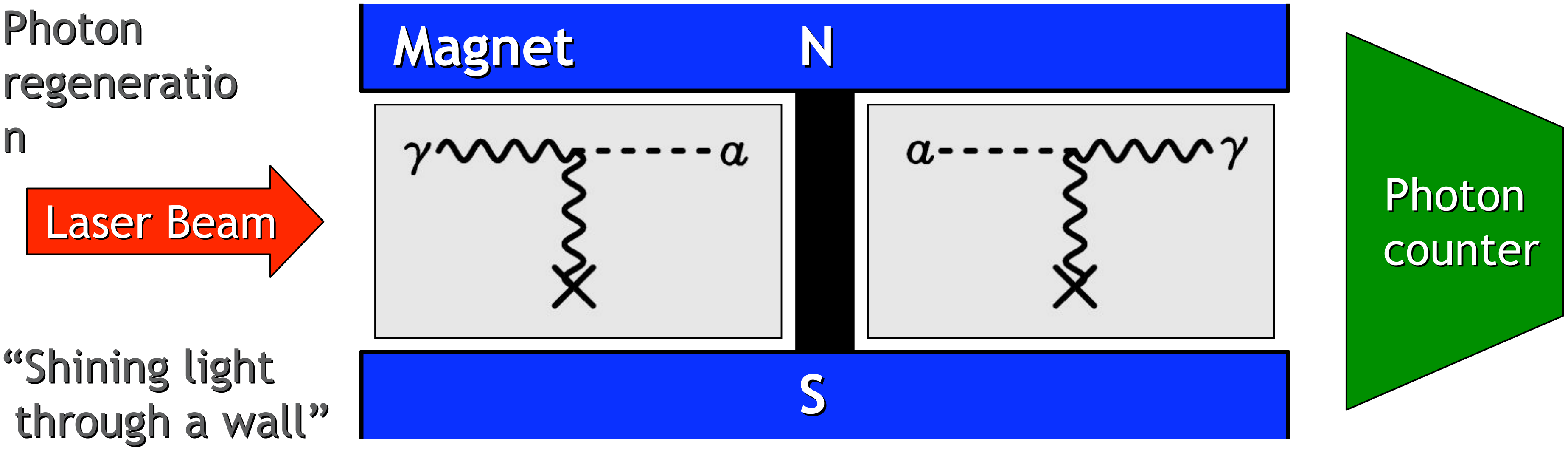
$$\left[\omega^2 + \nabla^2 + 2\omega^2 \begin{pmatrix} n_\perp - 1 & 0 & 0 \\ 0 & n_\parallel - 1 & g_{a\gamma}B/2\omega \\ 0 & g_{a\gamma}B/2\omega & -m_a^2/2\omega^2 \end{pmatrix}\right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

Axion-photon transitions

Raffelt & Stodolsky, PRD 37 (1988) 1237

Laser Search Experiments

Photon regeneration



Laser Beam

Magnet N

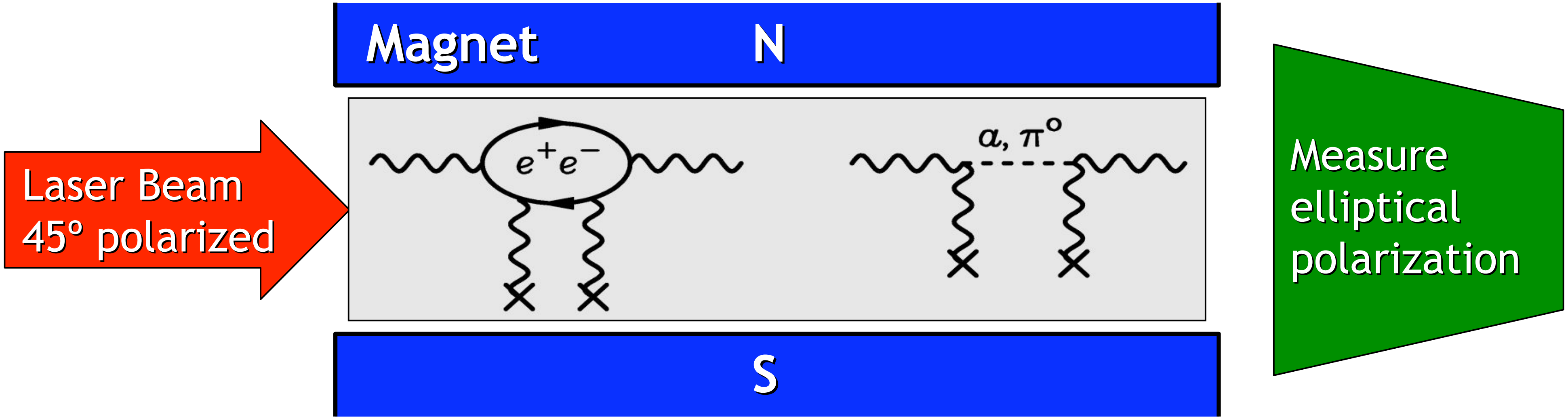
S

Photon counter

"Shining light through a wall"

Vacuum Cotton-Mouton-Effect

45° polarized light beam develops small elliptical polarization



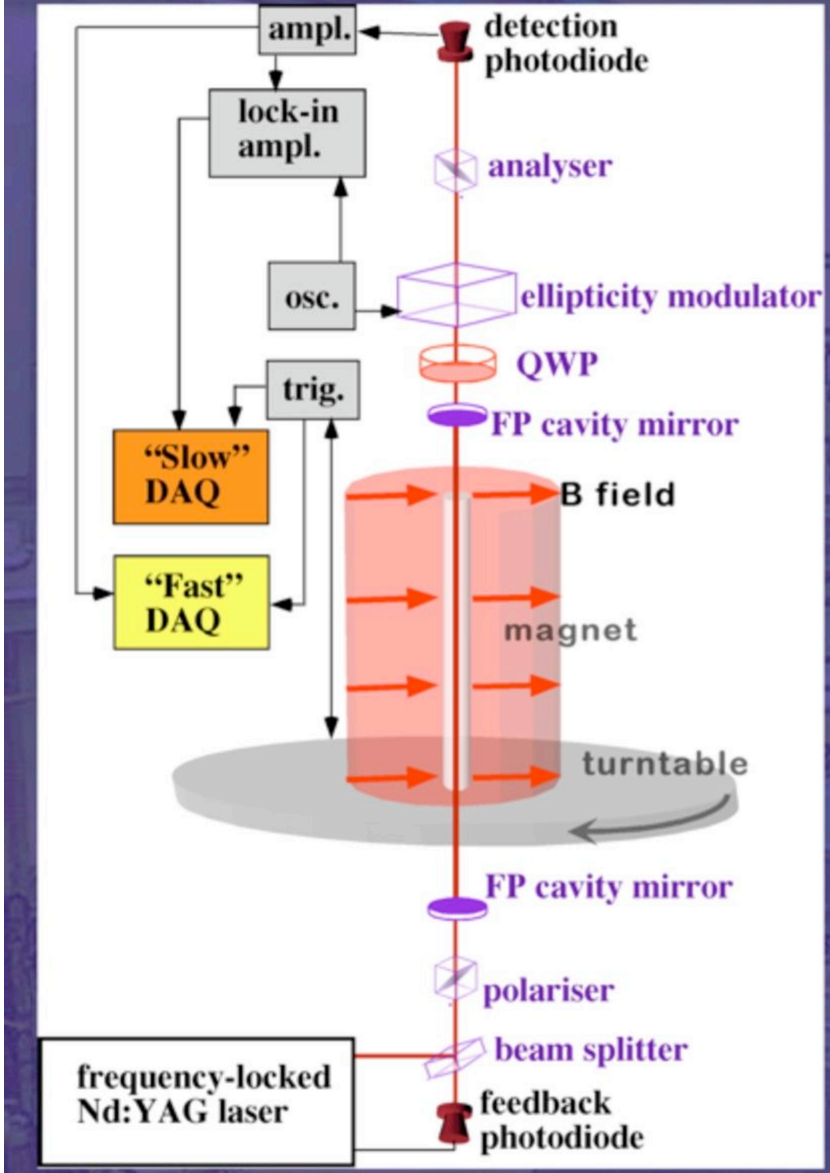
Laser Beam 45° polarized

Magnet N

S

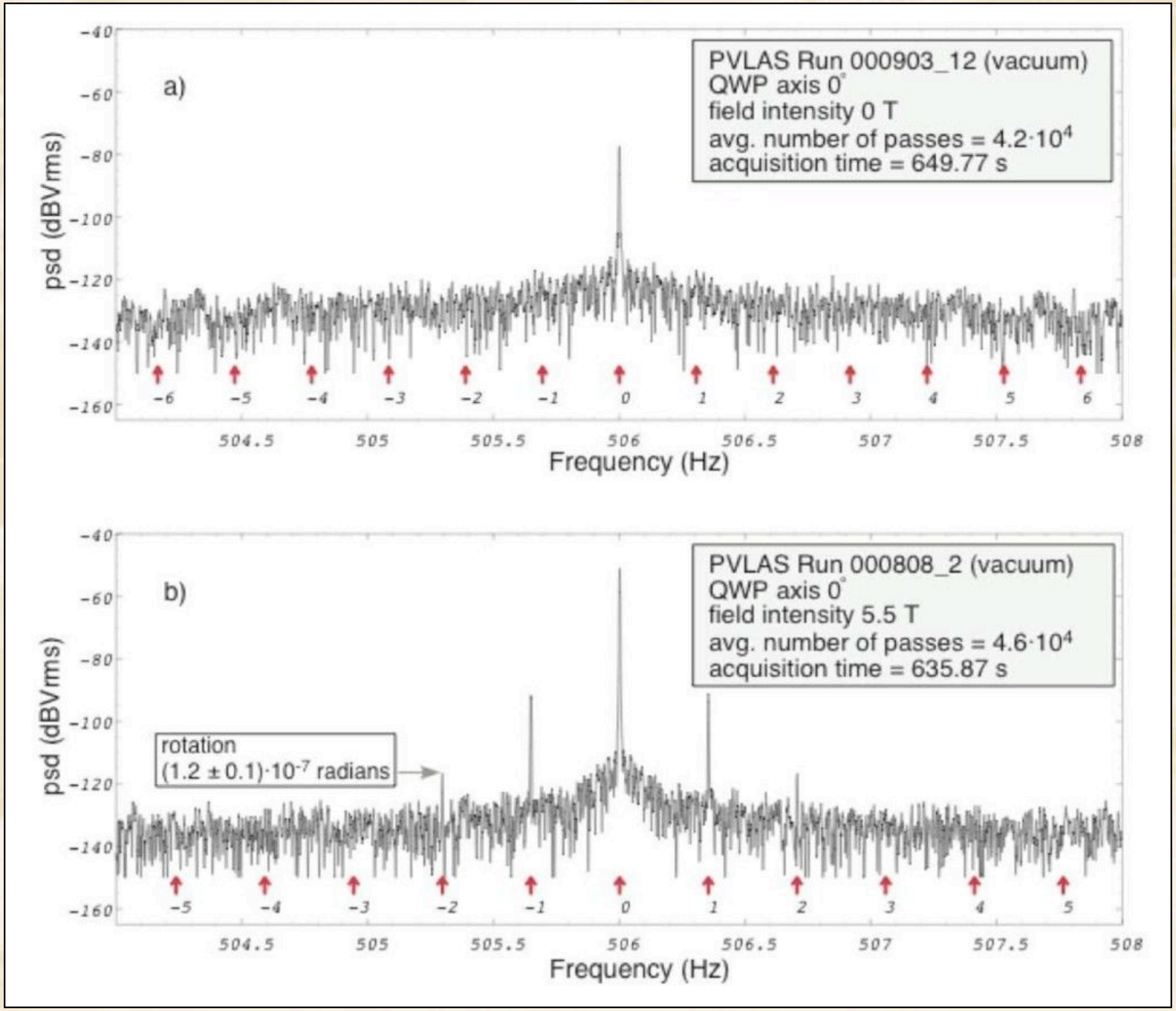
Measure elliptical polarization

PVLAS - Schematic



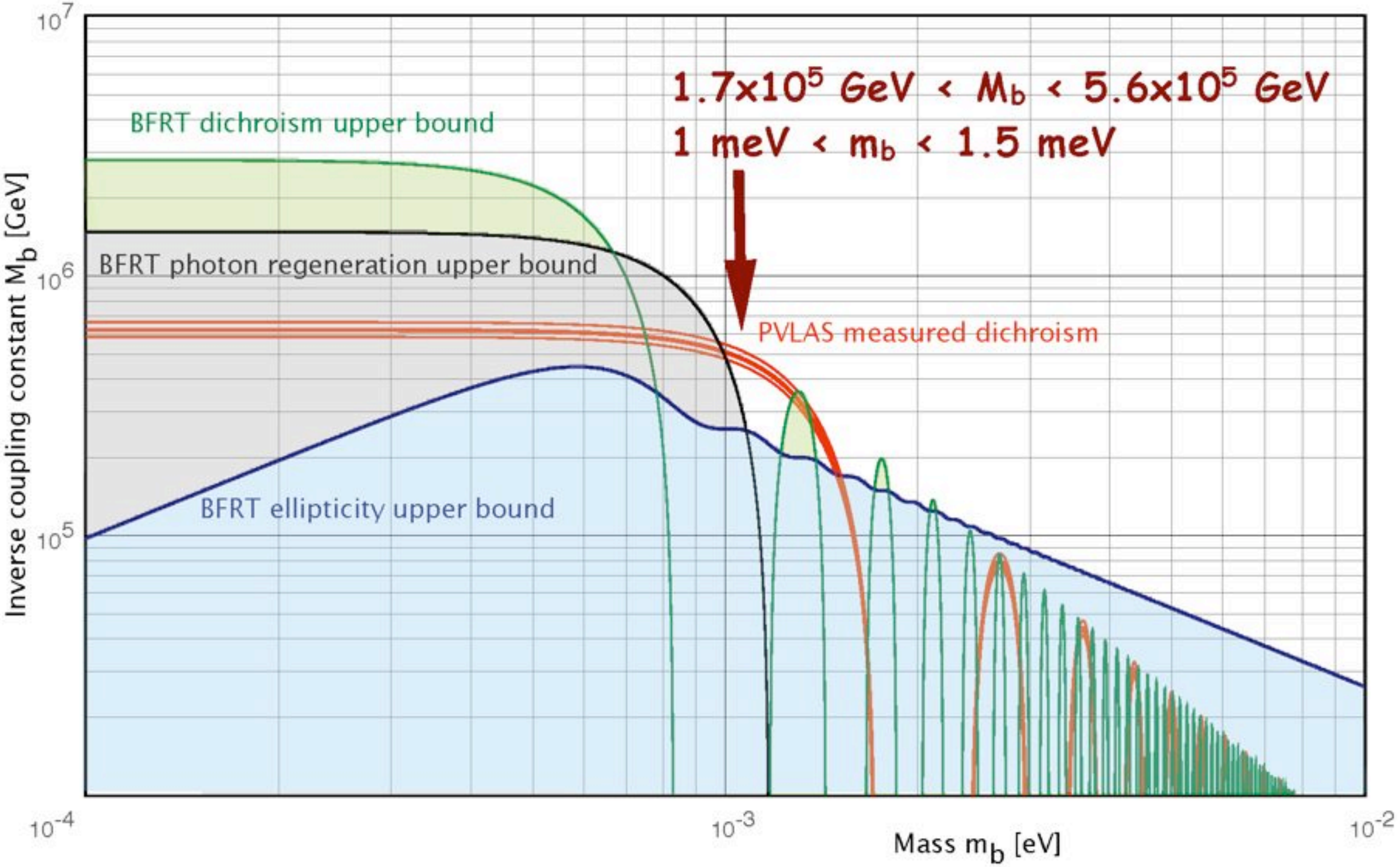
- Main parameters of the apparatus
  - magnet
    - dipole, 6 T, temp. 4.2 K, 1 m field zone
  - cryostat
    - rotation frequency ~300 mHz, sliding contacts, warm bore to allow light propagation in the interaction zone
  - laser
    - 1064 nm, 100 mW, frequency-locked to the F.-P. cavity
  - Fabry-Perot optical cavity
    - 6.4 m length, finesse ~100000, optical path in the interaction region ~ 60 km
  - heterodyne ellipsometer
    - ellipticity modulator (SOM) and high extinction (~10^{-7}) crossed polarisers + Quarter Wave Plate (QWP)
    - time-modulation of the effect
  - detection chain
    - photodiode with low-noise amplifier
  - DAQ
    - Slow: demodulated at low frequency and phase-locked to the magnetic field instantaneous direction
    - Fast: high sampling frequency direct acquisition

The PVLAS Dichroism Signal

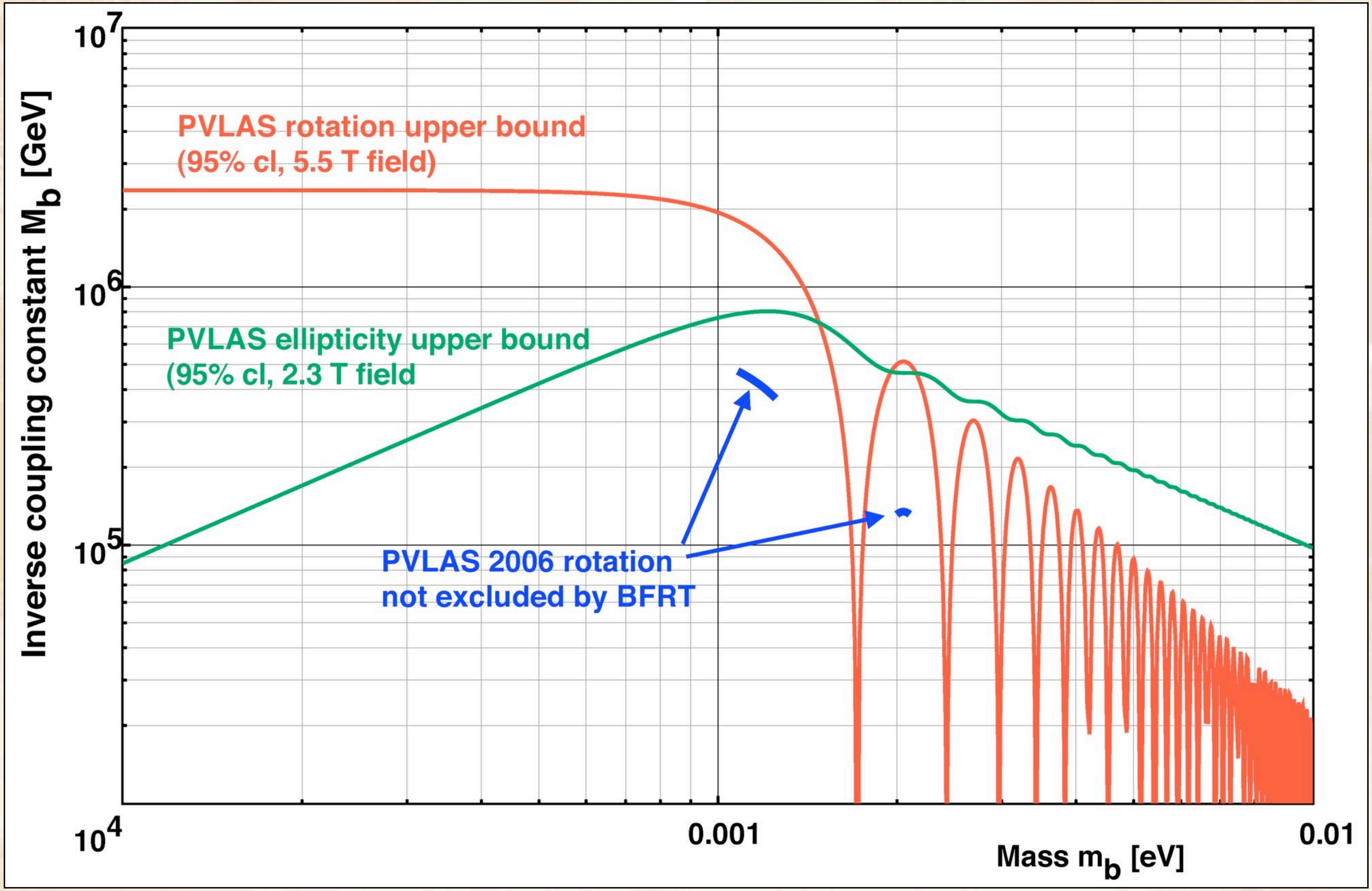


PVLAS, PRL 96:110406 (2006), hep-ex/0507107

BFRT and PVLAS results on the m_b-M_b plane



Latest PVLAS Results



Zavattini et al., PRD 77:032006, 2008 [arXiv:0706.3419]

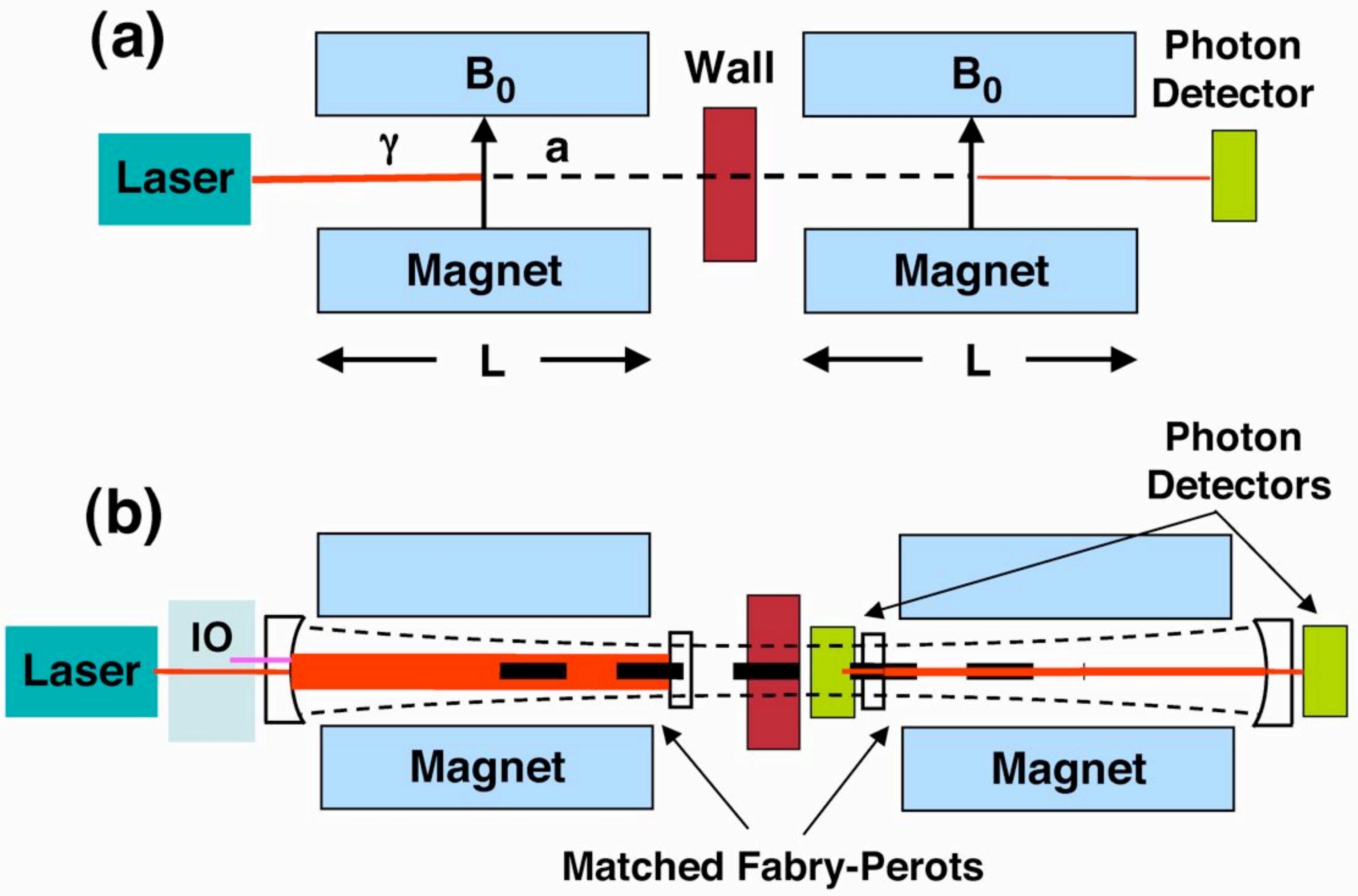
Photon Regeneration Experiments

"Shining light through a wall"

Single pass

Resonant cavities on generation & regeneration side

hep-ph/0701198



No Light Shining Through a Wall

BMV Experiment, using a pulsed laser and pulsed magnetic field (Toulouse)

Robilliard et al., arXiv:0707.1296

GammeV Experiment with a variable baseline (Fermilab)

Chou et al., arXiv:0710.3783

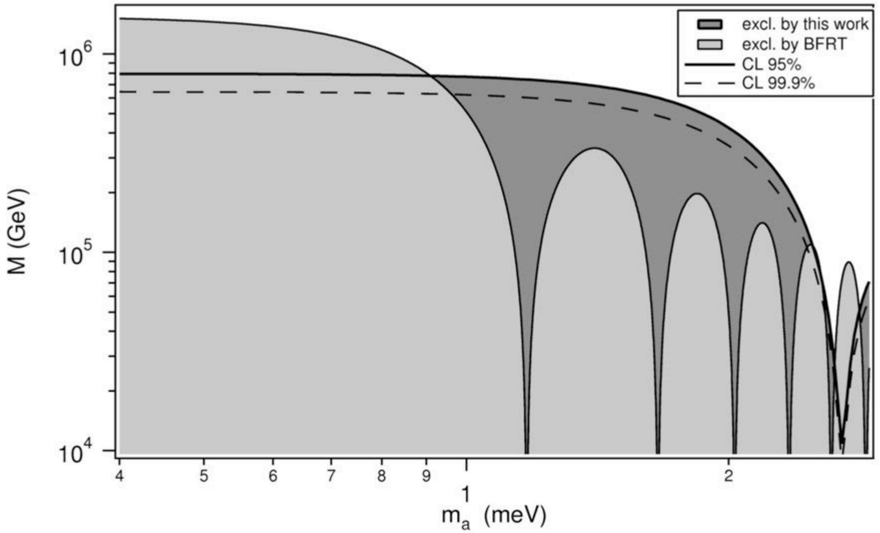


FIG. 4: 95% confidence level limits on the axion-like particle two photons inverse coupling constant M as a function of the axion-like particle mass $m_{\rm a}$ obtained thanks to our null result (dotted line). The area below our curve is excluded. Our limits are compared to the 95 % confidence level exclusion region obtained by the BFRT photon regeneration experiment [10].

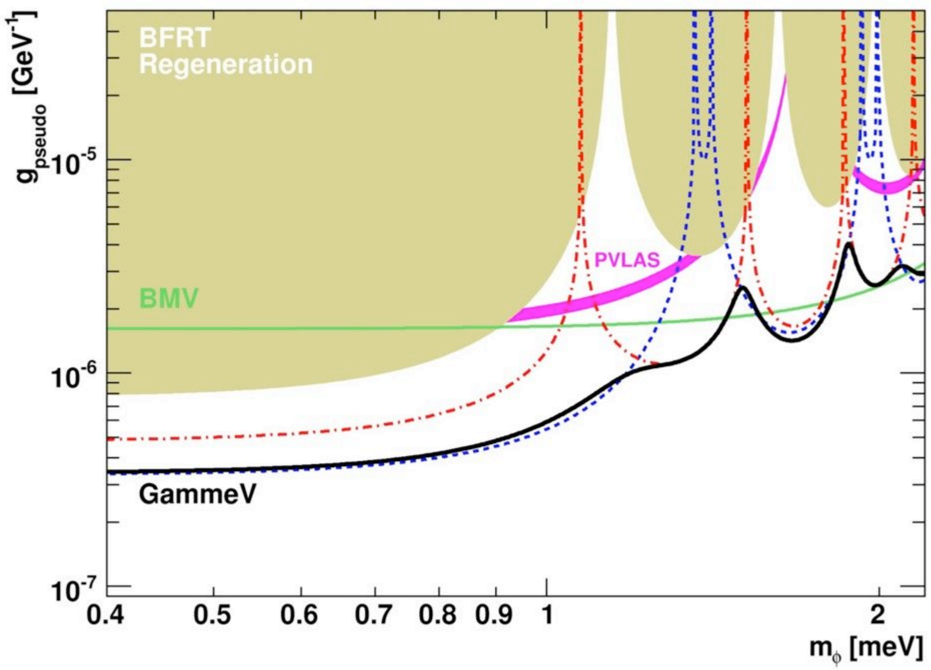
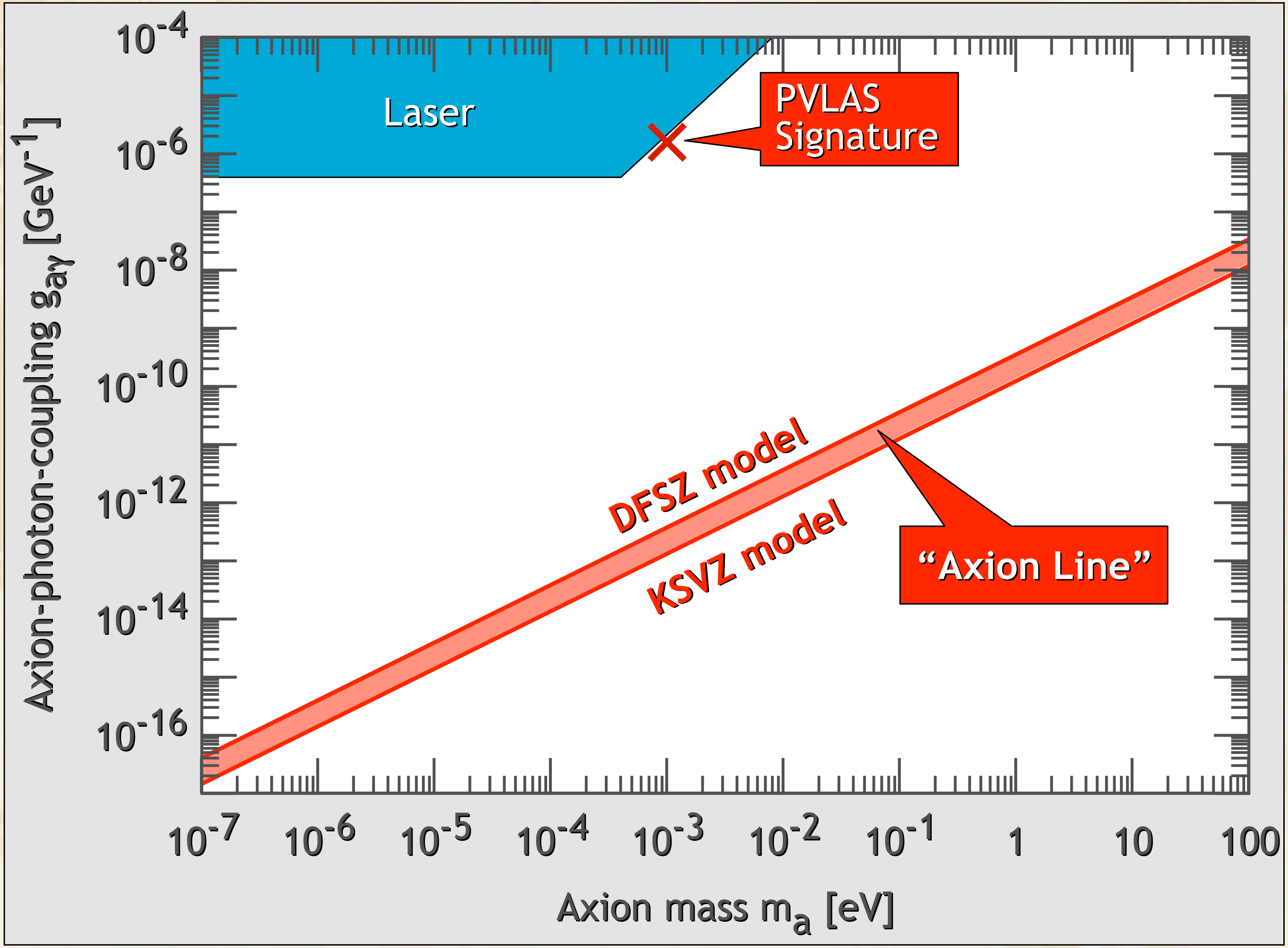
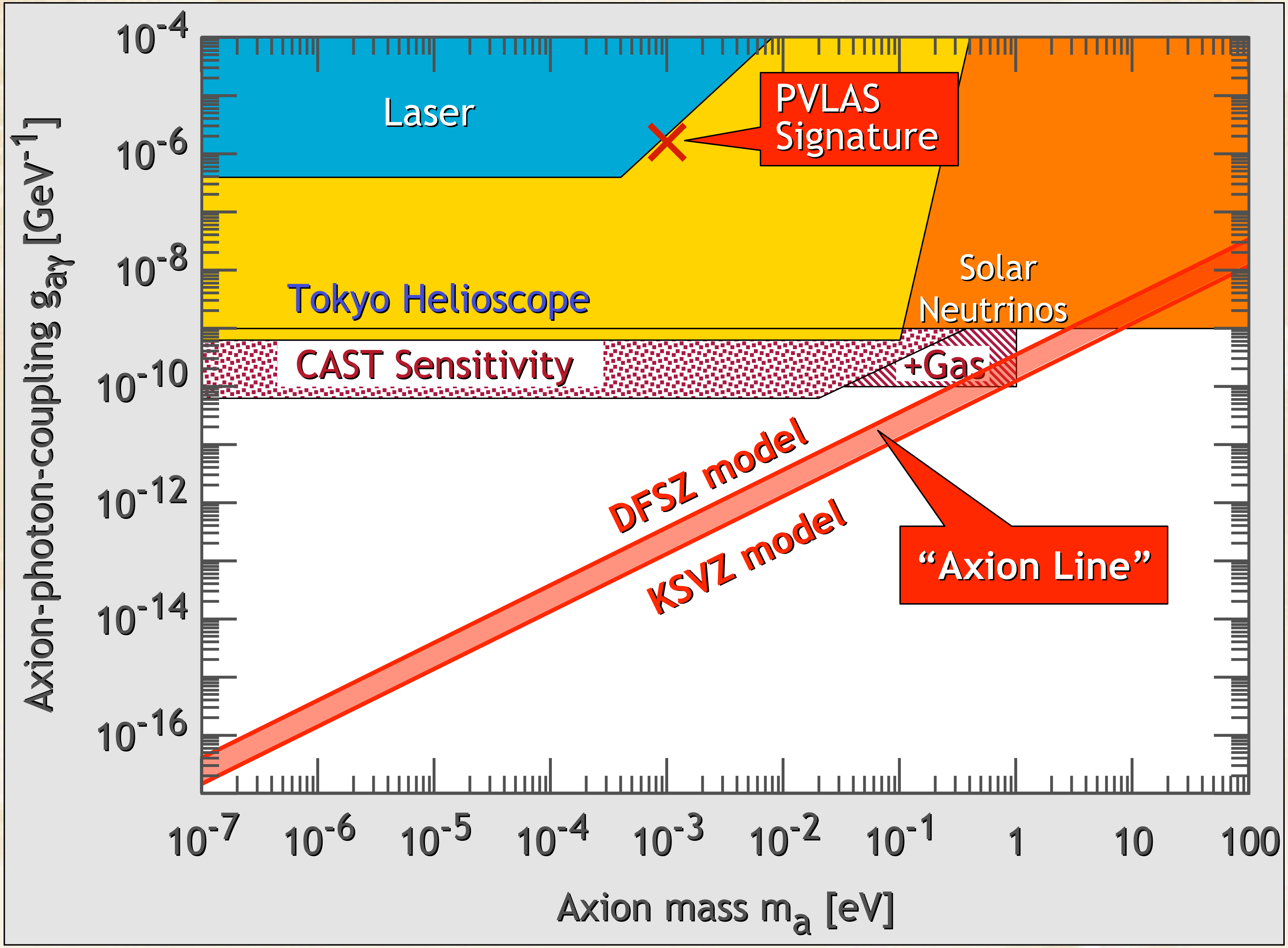


FIG. 4: 3σ limit contours for pseudoscalar particles.

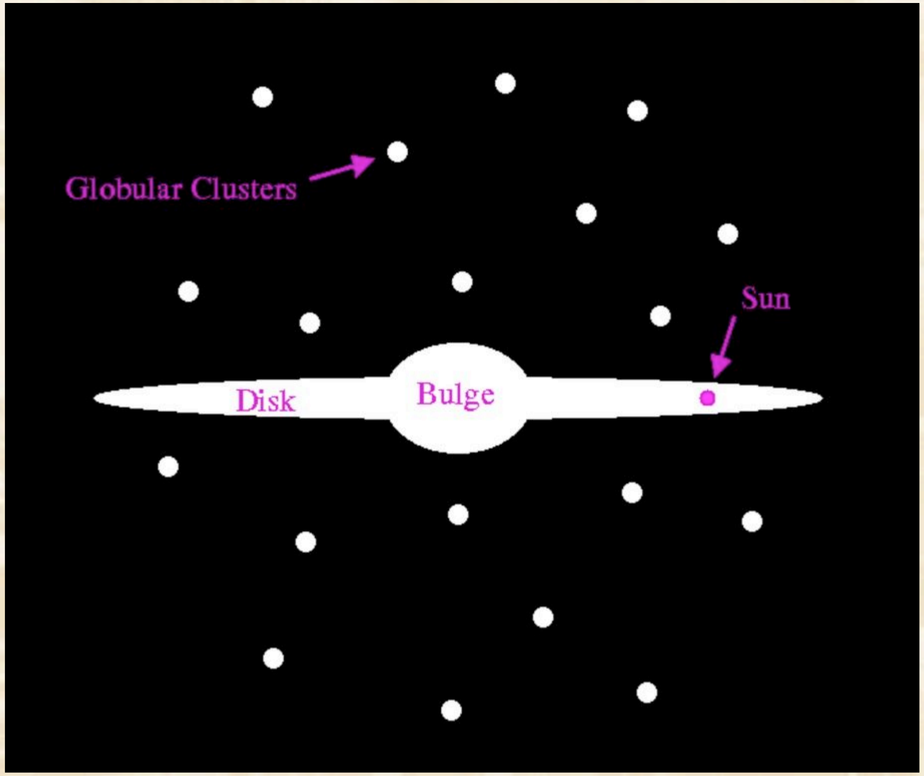
Limits on Axion-Photon-Coupling

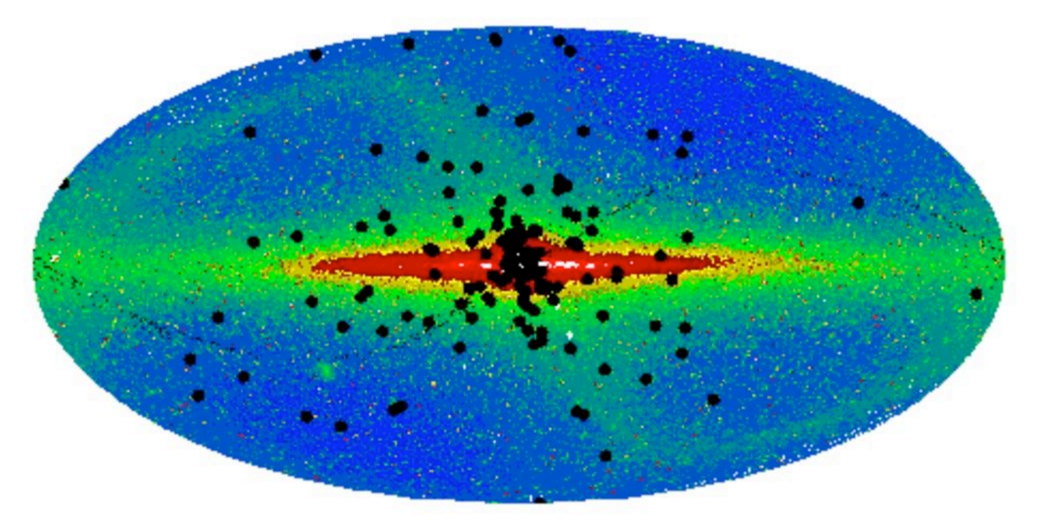


Limits on Axion-Photon-Coupling



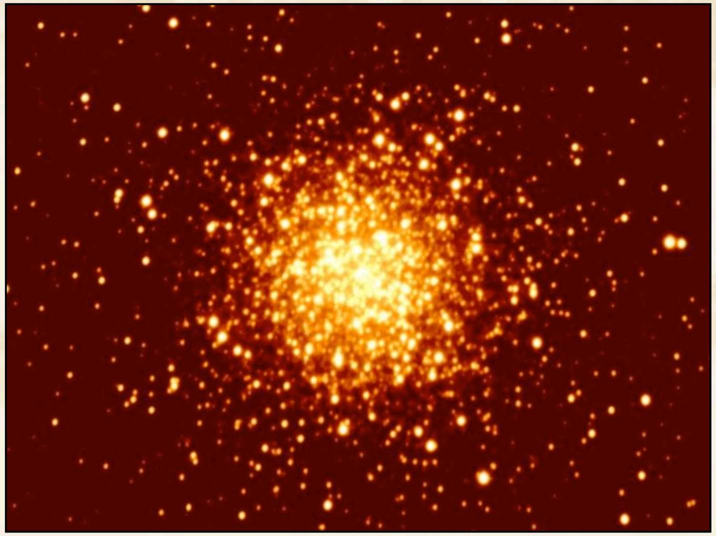
Globular Clusters of the Milky Way





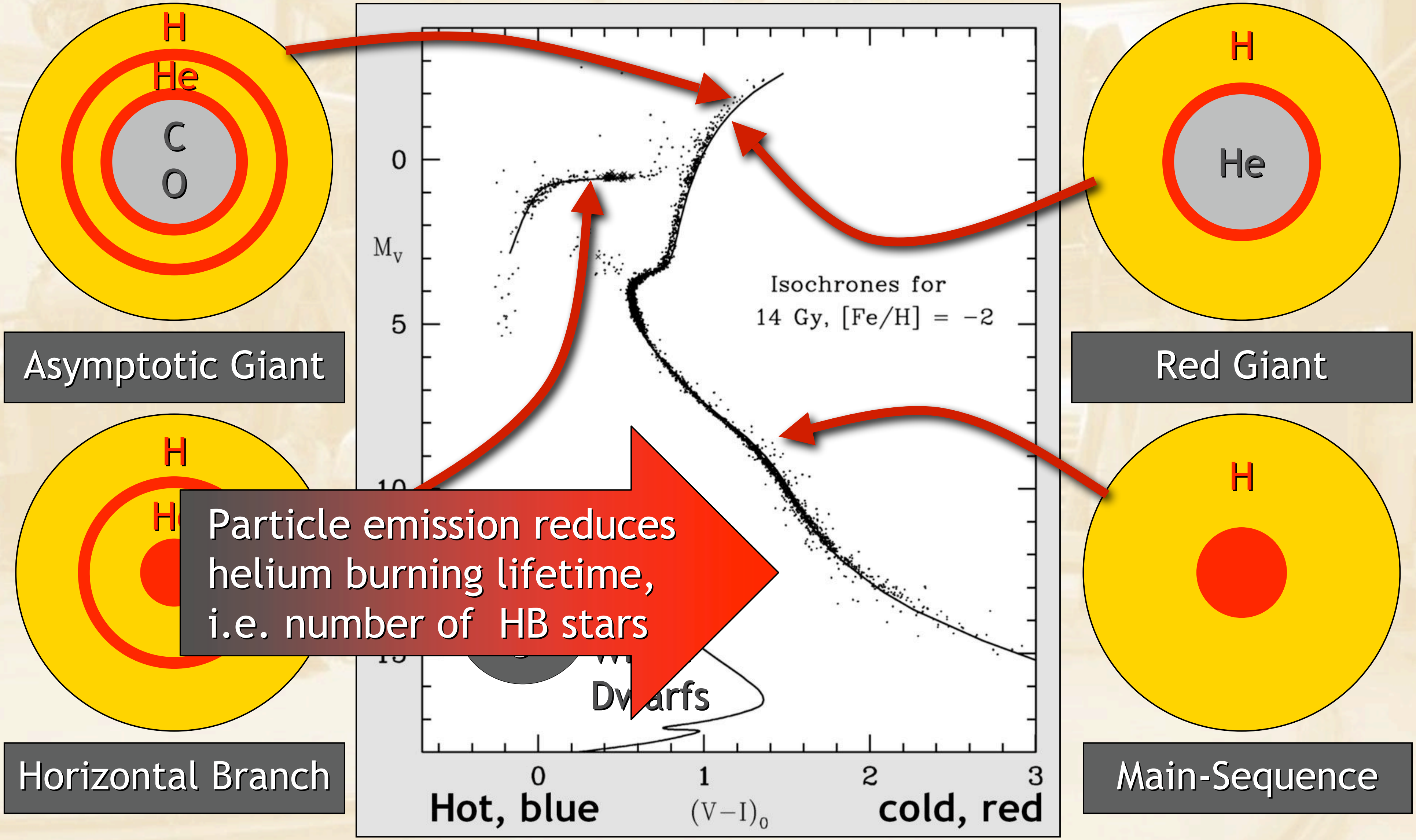
http://www.dartmouth.edu/~chaboyer/mwgc.html

Globular clusters on top of the
FIRAS 2.2 micron map of the Galaxy



The galactic globular cluster M3

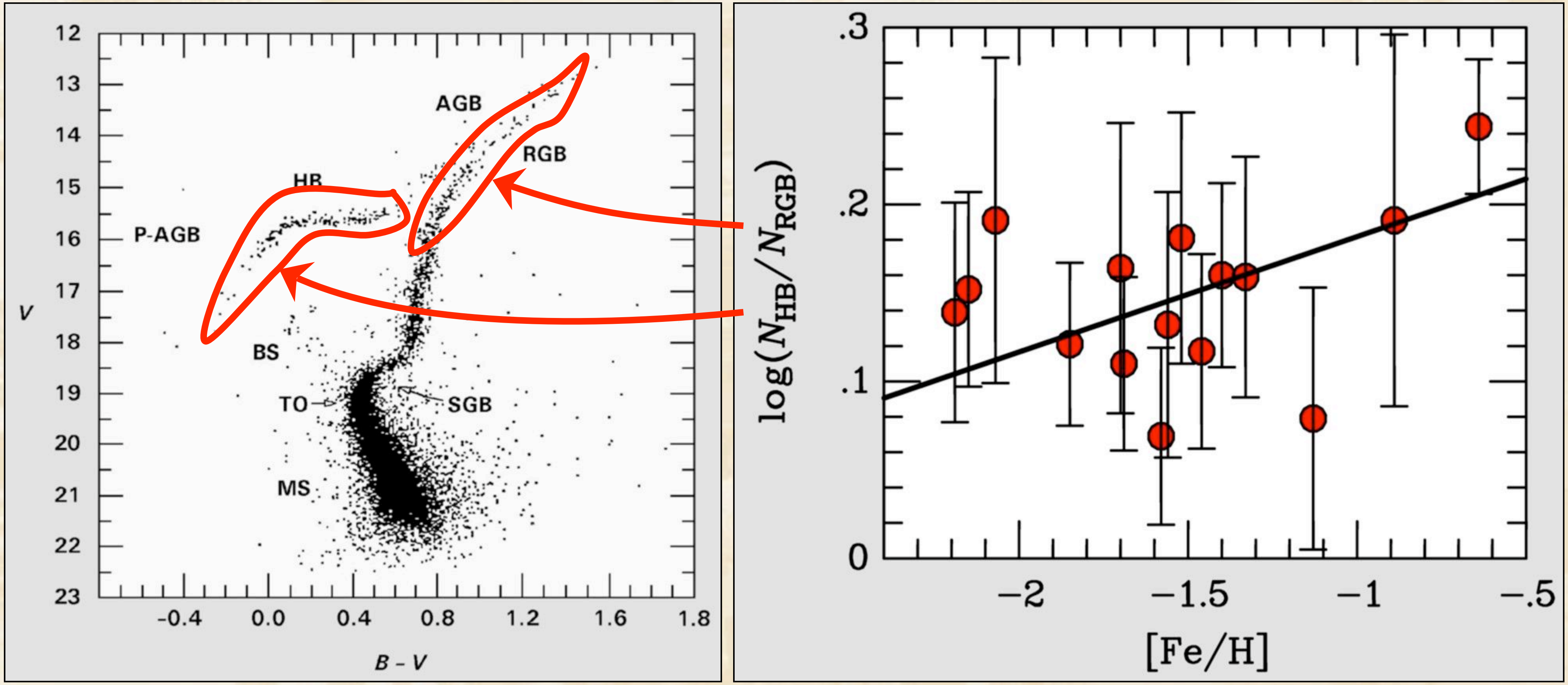
Color-Magnitude Diagram for Globular Clusters



Particle emission reduces helium burning lifetime, i.e. number of HB stars

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Helium-Burning Lifetime of Horizontal-Branch Stars



Number ratio of HB-Stars/Red Giants in 15 galactic globular clusters
(Buzzoni et al. 1983)

Helium-burning lifetime established within ±10%

Limits on Axion-Photon-Coupling