Experimental Search for Physics beyond the SM:
Strong CP (non-)Violation, EDMs, Axions / hidden Photons, and other beyond the SM particles from the Sun.

Lectures 3&4

K. Zioutas

University of Patras / Greece

➔ exercises?

➔ Ongoing research!

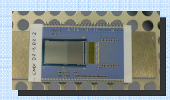
Spring Blockcourse 2011
Dresden

8th- 10th March 2011

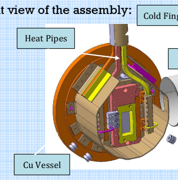
X-ray telescope + future CCD system:

A back-up CCD system :
- Electronics
- New CCD chip:
  - Lower background (better selection of materials)
  - Lower threshold (~200 eV)
  - Better energy resolution (<160 eV (FWHM) @ 6 keV)
  - Mechanical design, cooling system (CERN: engineers, Cryolab)
  - Decoupling of telescope and detector: Simplification of alignment

Imaging area
256 x 256 Pixels
75 x 75 µm^2
1.92 x 1.92 cm^2



Front view of the assembly:



Micromegas detectors for the CAST experiment

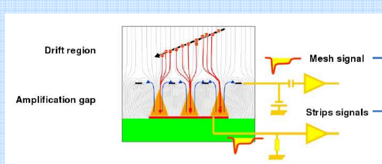
Micromegas detector concept

The Micromegas detector is a gaseous detector which consists of a readout that allows to obtain temporal and spatial information from any ionizing process that has been taken place in the detector chamber.

The detector is split into the: a) drift or conversion region, b) amplification region.

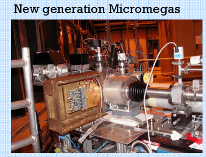
In the drift region the initial ionization occurs, where each kind of event produces a particular electron cloud pattern (defined by volume, shape, etc) which is proportional to the energy of the event.

The amplification region allows to increase the signal intensity at the readout planes.

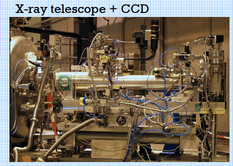


CAST detectors, Phase II-^{3}He

New generation Micromegas



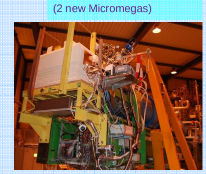
X-ray telescope + CCD



Sunrise detectors

	Typical Rates
MM	3 cts/h (2-10 keV)
CCD	0.18 cts/h (1-7 keV)

Sunset detectors
(2 new Micromegas)

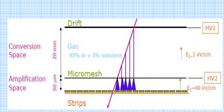


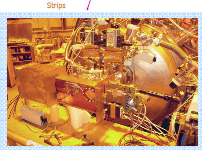
New generation Micromegas

2nd generation Micromegas:

- Novel manufacturing technique (*microbulk* technology)
- Materials selected based on low intrinsic radioactivity
- Improved shielding (modified TPC shielding)

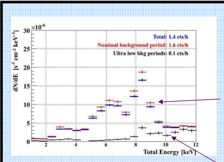
Good potential for very-low background rates



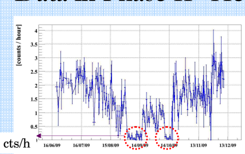


See also
2010 JINST 5 P01009
2010 JINST 5 P02001

Data in Phase II-^{3}He

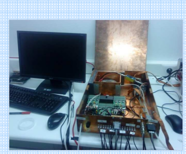


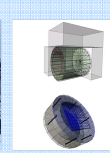
1.6 cts/h



Very low background:

0.1 cts/h



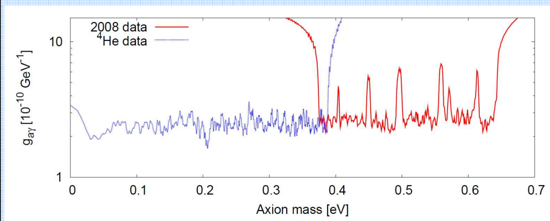


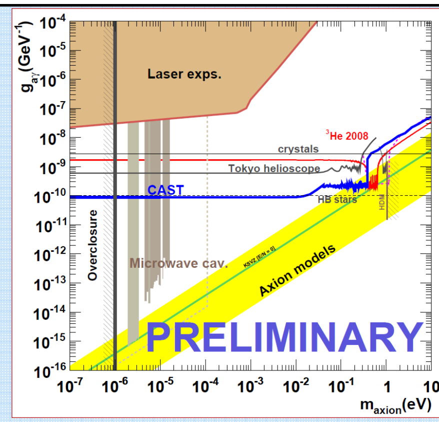
Studies underway:

complete simulation of the whole chain:
Geometry, physics processes, readout

Identical setup to be put in Canfranc Underground Laboratory to further study the effects in a very low background environment.

4He + 3He coverage with Sunrise Micromegas detector





Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmological bounds on sub-MeV mass axions

JCAP02(2011)003

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Abstract. Axions with mass $m_a \gtrsim 0.7\,\mathrm{eV}$ are excluded by cosmological precision data because they provide too much hot dark matter. While for $m_a \gtrsim 20\,\mathrm{eV}$ the $a \to 2\gamma$ lifetime drops below the age of the universe, we show that the cosmological exclusion range can be extended to $0.7\,\mathrm{eV} \lesssim m_a \lesssim 300\,\mathrm{keV}$, primarily by the cosmic deuterium abundance: axion decays would strongly modify the baryon-to-photon ratio at BBN relative to the one at CMB decoupling. Additional arguments include neutrino dilution relative to photons by axion decays and spectral CMB distortions. Our new cosmological constraints complement stellar-evolution and laboratory bounds.

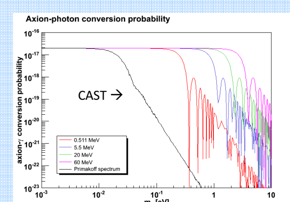
...byproduct →

New solar axion-ID

→ exercise!

Remember:

- $$|q| = \frac{m_a^2 - m_\gamma^2}{2E} = \pi/L_{coh}$$

- 

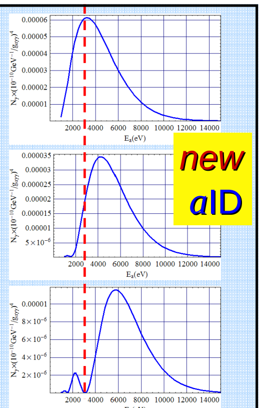
converted axion spectrum

- Δm=0, ΔP=0 → @ *resonance*
  ⟨E⟩=4.48 keV

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

- Δm=0.001, ΔP=0.037;
  ⟨E⟩=5.36 keV → off-resonance

- Δm=0.002, ΔP=0.074;
  ⟨E⟩=6.69 keV → off-resonance

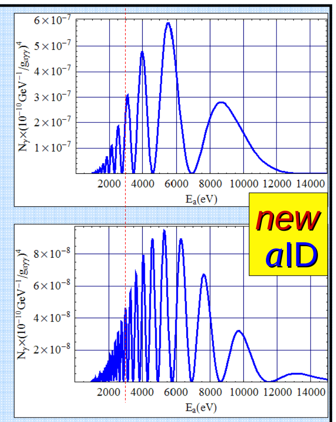


converted axion spectrum

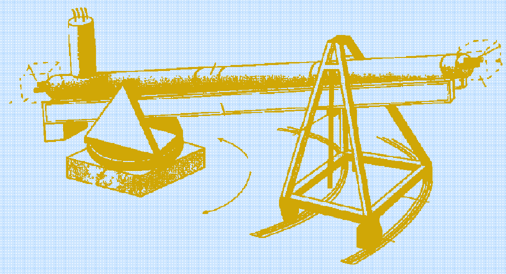
Δm=0.0088, ΔP=0.332 (*4 steps*)
⟨E⟩=6.48 keV → off-resonance

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

Δm=0.0214, ΔP=0.83 (*10 steps*)
⟨E⟩=6.46 keV → off-resonance



Search for HE/LE solar axions with CAST



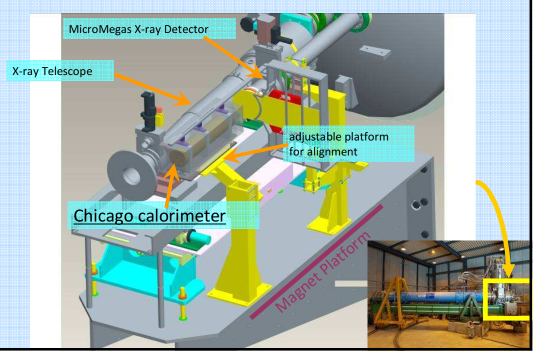
The CAST gamma-ray calorimeter

Motivation

- Axions or other exotica might be emitted in nuclear reactions within the sun (M1)
- Maximize sensitivity to high energy (MeV) axion signal via axion-γ conversions in laboratory magnetic field
- Set limits on axion couplings and mass through solar model constraints

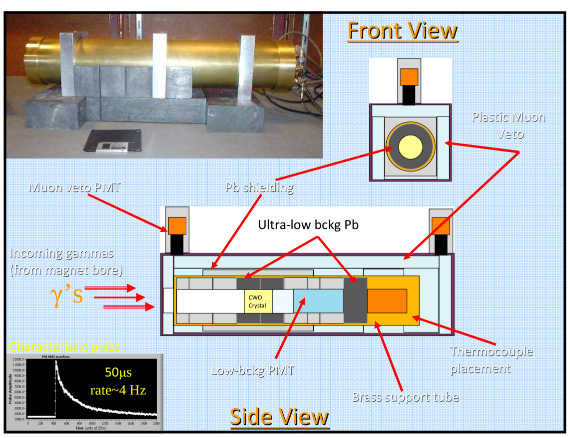
Search for solar axion emission from ^{7}Li and D(p,γ) ^{3}He nuclear decays
JCAP, arXiv:0904.2103

Calorimeter installation on CAST magnet platform



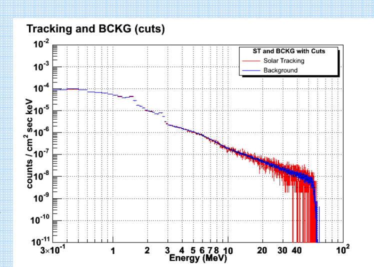
Calorimeter Design and Properties

- Large inorganic scintillating crystal (**$CdWO_4$**)
- Low intrinsic background, high γ efficiency
- Low-background photomultiplier tube (PMT)
- Pulse shape discrimination
- Env. radon displacement
- Plastic scintillator as a 4π active muon veto
- Borated thermal neutron absorber
- **Sub-200 keV threshold**
- **200 MeV dynamic range**

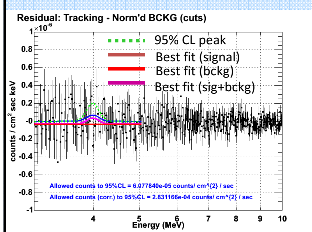


Compare solar tracking spectrum with background

- Solar tracking and background energy spectra for the CAST calorimeter
- Search for axion signal → *look at residual!*

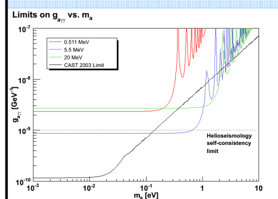


Look for excess signal buried in data



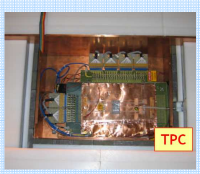
- Signal:
  - *mono-energetic peaks* at low energies
  - structured energy deposition at high energies
- Obtain 95% CL (2σ) allowed *counts* at each energy

Final results from the CAST calorimeter

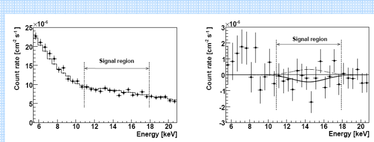


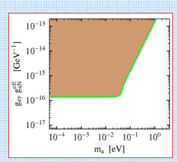
- Use the helioseismology limit on Φ_a ($0.2L_\odot$) to set upper limit on the axion-photon coupling $g_{a\gamma\gamma}$
- Alternatively, can use CAST X-ray limit on $g_{a\gamma\gamma}$ (e.g., PRL **94**, 121301, 2005) to set upper limit on solar-axion flux Φ_a

14.4 keV solar axions byproduct:



Search for 14.4 keV solar axions emitted in the M1-transition of ^{57}Fe nuclei with CAST.





JCAP12(2009)002 arXiv:0906.4488

BaRBE: Low Energy Axions

Motivation

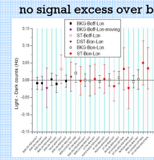
- Is there a non-standard flux of low energy axions emitted by the sun? a CAST 'first'

Visible photons would convert into axions in the strong B fields of the Sun's surface.

An optical device (PMT + APD) was coupled to a magnet end.

First measurements in the visible (2-4 eV energy range) in two periods in 2007 and 2008:

no signal excess over background

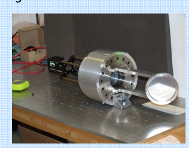


arXiv:0809.4581

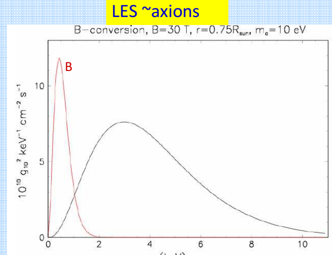
Next steps:

- Long-term: explore the whole sub-keV region
- Short-term: possibly extend up to 100 eV

- Improved detector (noise/100)
- Integrate permanently in parasitic mode during the ^{3}He scan.



LES ~axions



$$L_B \approx 6\times10^{-5} g_{10}^2 L_\odot$$

→ ~5% $L_{tot\text{-}axion}$
m=10 eV & 100 Tesla

$$\frac{L_{a,B}}{L_{a,P}} = 5\times10^{-4} B_4^2 \left(\frac{m_a}{451\ \text{eV}}\right)^{4/3} \log_{10}^2\left(\frac{m_a}{451\ \text{eV}}\right)$$

G. Raffelt

Conclusions

- CAST progressing with the Phase-II according to schedule:
  - ^{4}He results published (JCAP02(2009)008).
  - ^{3}He data taking ongoing.
- No axion found by CAST so far. Relevant parameter space excluded.
  - Compatible with best astrophysical limits
  - Entering realistic QCD axion model band for the first time.
- **Solar axion byproducts:** HE, LE ("visible"), 14.4 keV from nuclear transitions,…
- **Outlook:** In combination with **relic axion searches** (ADMX, "CAST") a big part of the QCD axion model region could be explored within the next decade.

Other physics with CAST

- **Relic axions** - Extrapolate recent ideas for CAST?

  ➔ **$\lambda_{\text{de Broglie}}$ ~1-10[m] ~ L_{magnet}**

- **Paraphotons**
- **Chameleons**
- **(RE)evaluation** *...never ends*

  ➔ **exciting perspectives .... TBC!!**

  ➔ proposal to CERN-SPSC **5th April 2011**

Towards a new generation axion helioscope

➔ in ~10 years

➔

Motivation, physics case

- Improve CAST results substantially. It is worth? How much we need to improve?
- Physics case:
  - Large region of allowed QCD axions at 0.01-1 eV scale
  - But also: ALPs at low mass. Hints from astrophysics.
- **No other axion detection technique can realistically improve CAST in the midterm.**
- ➔ To push for a NGAH as the next large infrastructure for axion physics is justified scientifically, feasible(?), fundable.

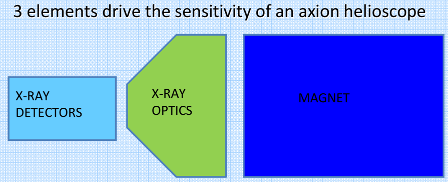
Astrophysics hints for WISPs @

$m_a \sim 10^{-10} - 10^{-7}$ eV & $g_{a\gamma\gamma} \sim 10^{-11}$ GeV^{-1}

- Observation of VHE γ from distant sources (intergalactic medium more transparent to γ than expected) by Cerenkov telescopes
- Spectra from distant sources (HESS sources)
- UHECRs from HiRes, correlated with blazars. (Also correlated with local galactic field?)
- Scatter of x-ray and g-ray luminosity relations of AGN.
  - ➔ all these point to similar ALP parameters
- Many more hints but pointing to other ALP parameters, or just stating unexplained observations that could generically fit an ALP-photon scenario.
- Caveat: papers answering some for this "hints" claiming other solutions based on known physics.

Axion Helioscopes FOM

- 3 elements drive the sensitivity of an axion helioscope



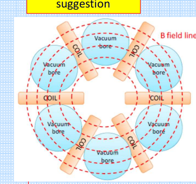
$$\frac{1}{\text{FOM}} \propto g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

where b is the time- and area-normalized background of the detector, ϵ_d its efficiency; a is the focal spot area of the optics, ϵ_o its througput, B is the magnet field strength, L its length, and A its cross sectional area; t is the exposure time.

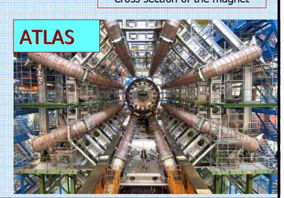
New "magnet" à la ATLAS

L. Walckiers'/CERN suggestion

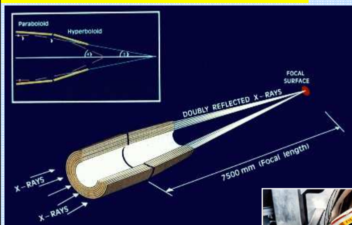
- CAST enjoys one of the best existing magnets than one can "recycle" for axion physics (LHC test magnet)
- Only way to make a step further is to built a new magnet, specially conceived for this.
- Work ongoing, but best option up to know is a **toroidal configuration:**
  - Much bigger aperture than CAST: ~0.5-1 m / bore
  - Lighter than a dipole (no iron yoke)
  - Bores at room temperature

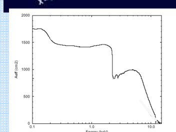


Cross section of the magnet

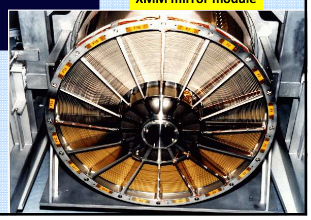


Light Path in XMM-Newton Telescope





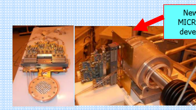
XMM mirror module

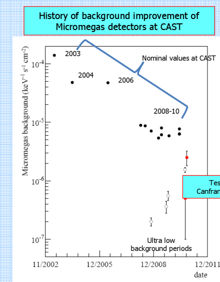


Collecting area:
~1900cm² (<150 eV), ~1500cm² (@ 2 keV), ~900cm² (@ 7keV), ~350 cm² (@ 10 keV).

New generation of helioscopes

- CAST has shown the way to improve the helioscope technique:
  - Coupling X-ray focusing devices
  - Low background detectors
  - Shielding techniques
  - Wider sun tracking range
- Most importantly, **larger magnet**





Igor G. Irastorza / Universidad de Zaragoza

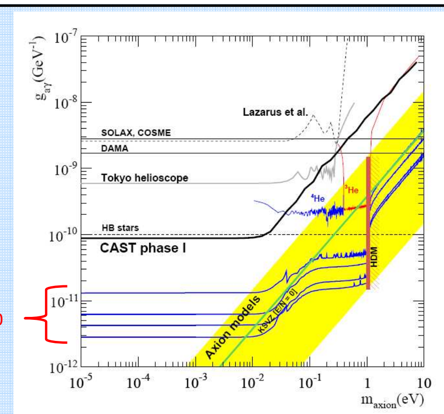
Main experimental challenges

seem reasonable, but need to be demonstrated

- **Goals for the next 1-2 years:**
  - **Magnet**
    - Built a new magnet, taylored to our needs
    - **Main goal: B^2L^2A ~ x1000 better than CAST (desirable), x100 (minimum)**
    - Other construction technical issues → feasibility study, design study.
    - Work already going on. Next steps?
  - **Optics**
    - **Cost-effective large optics (all magnet instrumented).** 0.5-1 m², several bores
    - Optimization: number of optics, dead space, focal length…
    - prospects with Nustar tooling.
  - **Detectors**
    - **Main goal: background ~ 10^{-7} c/keV/cm²/s**
  - **Platform**, general assembly engineering
    - 40-50% Sun coverage?

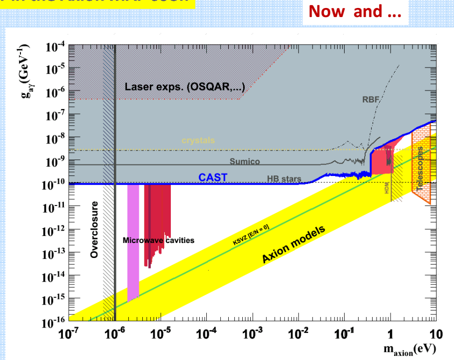
Prospects

~2020



CAST in the Axion MAP soon

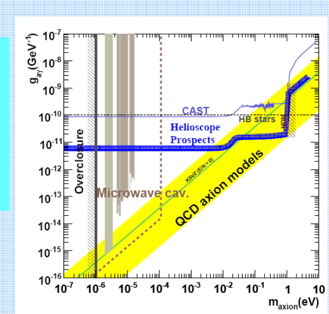
Now and …



Towards a new generation of helioscopes

Large parts of the model region for QCD axions could be explored in the coming decade

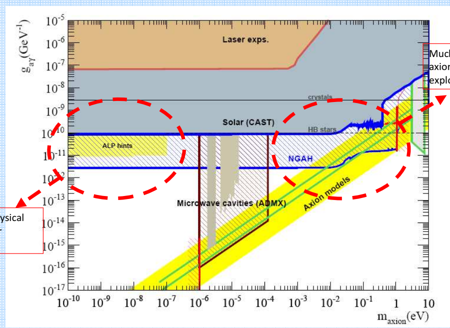
Combination of Helioscope experiments and Dark matter axion searches (ADMX)



Th. Papaevangelou talk in New Opportunities in the Physics Landscape at CERN Workshop.

How much beyond CAST?

...in ~10 Years



Politics – some useful concepts to be faced

- **NGAH fundable project?**
  - New generation of WIMP dark matter experiments (1+ ton of detector mass): EURECA, XENON1T, DARWIN, in Europe, SuperCDMS, LUX, MAX, etc… in US, are 10-100 Meur projects. A few of them will be surely funded. NGAH physics case is not inferior to theirs. Rather the opposite, being NGAH unique in its genre.
- **WIMPs vs. Axions**
  - WIMP lobby if far larger. Need to bring the discussion into scientific grounds: there is no reason to disregard the "axion option"
  - NGAH is the next step after CAST. Not to fund it represents to kill 90% of axion physics (at least in Europe).
- **Helioscope vs. microwave**
  - Microwave cavities (ADMX) are sensitive **only** to QCD axions, not ALPs. Because, they need to assume them to be the dark matter.
  - In the search for QCD axions, NGAH and ADMX (or CAST?) are **complementary**.

From Axions to ALPs and to WISPs

There might be much more than a QCD axion only:

- **ALP**s: "**a**xion-**l**ike **p**articles"

  String Axiverse A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, arXiv:0905.4720 [hep-th], **String theory** suggests the simultaneous presence of many ultralight axions, possibly populating each decade of mass down to the Hubble scale 10^{-33}eV. Conversely the presence of such a plenitude of axions (an "axiverse") would be evidence for string theory, …
- **WISP**s, **W**eakly **I**nteracting **S**light **P**articles, (axions and ALPs, hidden sector photons, mini-charged particles) occur naturally in string-theory motivated extensions of the Standard Model

  Naturally Light **Hidden Photons** in LARGE Volume String Compactifications; M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, arXiv:0909.0515 [hep-ph], JHEP 0911:027,2009; Extra "hidden" U(1) gauge factors are a generic feature of string theory that is of particular phenomenological interest. They can kinetically mix with the Standard Model photon and are thereby accessible to a wide variety of astrophysical and cosmological observations and laboratory exp's.
- **Solar Chameleons**

  P. Brax, K. Zioutas, Phys. Rev. D 82, 043007 (2010)

From Axel Lindner / DESY, PIF2010

Summary on Motivation

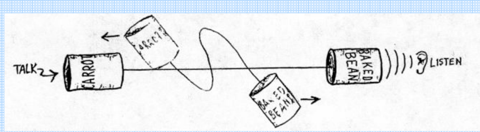
- There might be a "low energy particle physics frontier" hiding unknown particles with sub-eV masses (**WISP**s).
- The **axion** remains particular interesting as a
  - solution to the CP conservation of QCD,
  - candidate for Dark Matter.
- The might be a plenitude of **W**eakly **I**nteracting **S**light **P**articles
  - occurring naturally in string-theory inspired extensions of the Standard Model,
  - opening a window to physics beyond the TeV scale.
- Theory starts to develop detailed scenarios and predictions for WISPs to be probed by experiments.
  - Not only detections, but also upper-limits on WISP productions might become important ingredients for theory.

From Axel Lindner / DESY, PIF2010

How to search for WISPs in the lab?

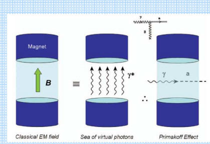
→ Light shining through a wall exp.

→ **Purely laboratory experiments!**

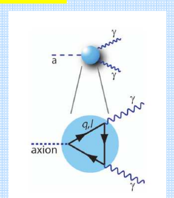


How to search for "invisible" WISPs: exemplary Basics

- **Neutral scalar or pseudoscalar WISPs couple to two photons:**
- **One of these photons can be provided by an electric or magnetic field: exploit the Primakoff effect**



The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008



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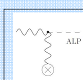


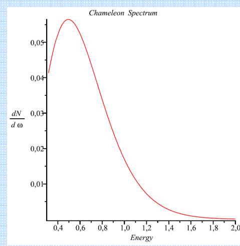
➢ **WISPs can be produced by light shining into a magnetic field.**

➢ **WISPs entering a magnetic field can convert into a photon.**

From Axel Lindner / DESY, PIF2010

How to search for "invisible" WISPs: exemplary Basics

- Neutral scalar or pseudoscalar **WISP**s: exploit the **Primakoff effect**
- Neutral vector bosons ("hidden sector photons" HP): exploit mixing with "ordinary" photons → **paraphotons**
- Minicharged particles (**MCP**, about 10^{-6} e): "loop effects".
- **Chameleons** (via Primakoff effect)
  … solar chameleons @ CAST →
  rest mass = f(environment)
  → **dark energy candidates**



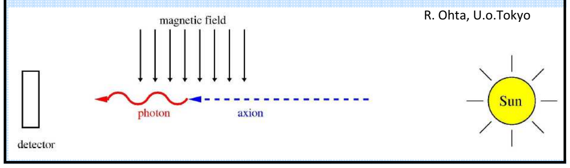
http://prd.aps.org/abstract/PRD/v82/i4/e043007

P. Brax, K. Zioutas, Phys. Rev. D82, 043007 (2010)

Search for invisible particles from the Sun

Axions / chameleons → DM / DE → coupling to 2 photons

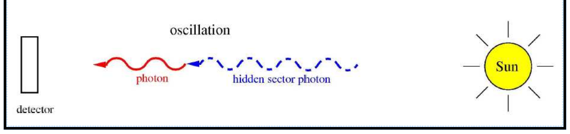
R. Ohta, U.o.Tokyo



Search for invisible particles from the Sun

Paraphotons → hidden sector → mixing with a photon

R. Ohta, U.o.Tokyo



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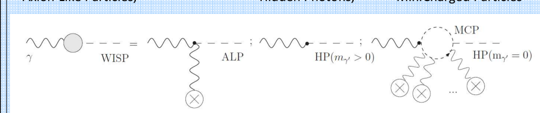
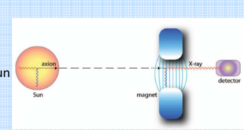
Axion-Like Particles, Hidden Photons, MiniCharged Particles

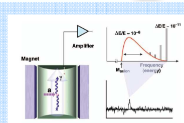


How to search for "invisible" WISPs: Astrophysics

- **Indirect:**
  WISPs would open up **new energy loss** channels for hot dense plasmas
  - stringent limits on WISP characteristics from the lifetime of stars, length of neutrino pulse from SN and cosmic microwave background radiation for example.
- **Direct:**
  - Search for axions , HP, chameleons from the sun (e.g., CAST)



  - Search for halo **dark matter axions** (ADMX, .. ?CAST?..)



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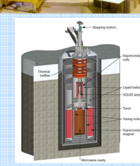
- **Direct:**
  - Search for axions, HP, Chameleons, from the sun , e.g., CAST
    → more?

http://cast.web.cern.ch

  - Search for halo dark matter axions (ADMX, …?CAST?..)

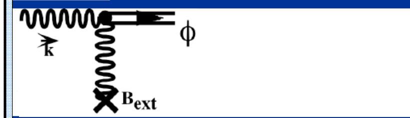


http://www.phys.washington.edu/groups/admx/home.html

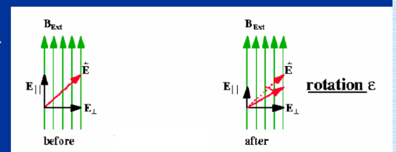
Laser exp's → LSW

...working principle ➔

QED: Vacuum Magnetic Dichroism

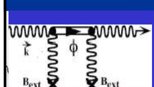


different absorption of light polarized ∥ and ⊥ to the magnetic field → rotation



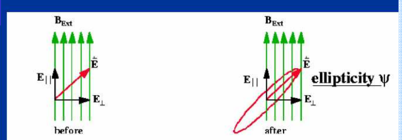
From Axel Lindner / DESY, PIF2010

QED: Vacuum Magnetic Birefringence



Different coupling of polarization component parallel and perpendicular to the magnetic field
→ different indices of refraction / velocities

Linear polarization turns into elliptical polarization



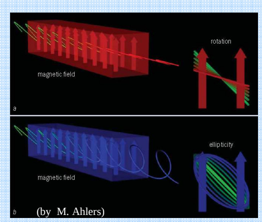
Talk by A. Ringwald

[Brandi *et al.* '01]

From Axel Lindner / DESY, PIF2010

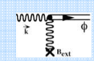
How to search for "invisible" WISPs: Lab Experiments

- (Some) WISPs could manifest themselves in fifth force experiments.
- Experiments with intense laser beams providing very high photon number fluxes or extremely good control of beam properties.
  - Indirect: search for polarization effects



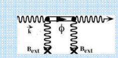
(by M. Ahlers)

Rotation:
dichroism (selective absorption) due to real WISP production



different conversion of light polarized ∥ and ⊥ to the magnetic field into WISPs.

Ellipticity:
birefringence (different light velocities) due to virtual WISP production



QED: Δn (⊥ - ∥) = $3.6 \cdot 10^{-22}$ (9.5 T @ LHC dipole)

G. Cantatore, 5th PATRAS workshop 2009,
See http://axion-wimp.desy.de/e30/e52240/e54433/GiovanniCantatore.pdf

From Axel Lindner / DESY, PIF2010

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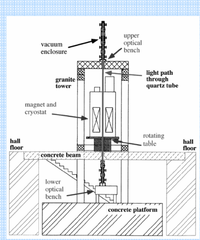

http://w3.lnl.infn.it/experiments/pvlas/physics.html

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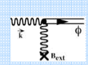

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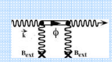

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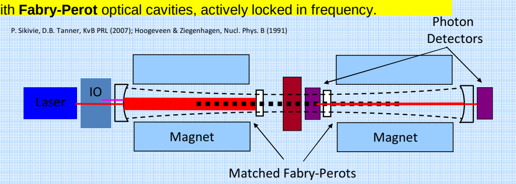
From Axel Lindner / DESY, PIF2010

Resonantly-Enhanced Photon Regeneration Basic concept

– encompass the production and regeneration magnet regions with **Fabry-Perot** optical cavities, actively locked in frequency.

P. Sikivie, D.B. Tanner, KvB PRL (2007); Hoogeveen & Ziegenhagen, Nucl. Phys. B (1991)



$$P^{Resonant}(\gamma \to a \to \gamma) = \frac{2}{\eta\eta'} \cdot P^{Simple}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} FF' \cdot P^{Simple}(\gamma \to a \to \gamma)$$

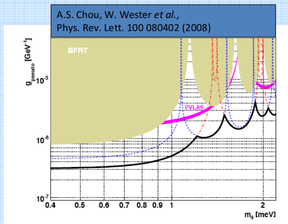
where η, η' are the mirror transmissivities & F, F' are the finesses of the cavities

For η ~ $10^{(5\text{-}6)}$, the gain in rate is of order $10^{(10\text{-}12)}$ and the limit in $g_{a\gamma\gamma}$ improves by $10^{(2.5-3)}$

AXION

Several new photon regeneration experiments:
ALPS, BMV, GammeV, LIPSS, OSQAR, ..?.

A.S. Chou, W. Wester *et al.*,
Phys. Rev. Lett. 100 080402 (2008)



FNAL Tevatron dipole, used as two halves (3m+3m, 5T); Nd:YAG 2w (532 nm) with PMT

These limits however are still orders of magnitude weaker than the limits established by astrophysics (Horizontal Branch Stars) and CAST

Outlook

The world-wide laboratory experiments in this research field are strengthening, but there is still a way to go!

Light shining through walls 17

Experiment	ω	P_g	β_g	Magnets
ALPS (DESY) [61, 62]	2.33 eV	4 W	300	$B_g = B_r = 5$ T $L_g = L_r = 4.21$ m
BFRT (Brookhaven) [64, 65]	2.47 eV	3 W	100	$B_g = B_r = 3.7$ T $L_g = L_r = 4.4$ m
BMV (LULI) [66, 67]	1.17 eV	$8 \times 10^{21} \frac{\gamma}{\text{pulse}}$ (14 pulses)	1	$B_g = B_r = 12.3$ T $L_g = L_r = 0.4$ m
GammeV (Fermilab) [68]	2.33 eV	$4 \times 10^{17} \frac{\gamma}{\text{pulse}}$ (3600 pulses)	1	$B_g = B_r = 5$ T $L_g = L_r = 3$ m
LIPSS (JLab) [69, 70]	1.03 eV	180 W	1	$B_g = B_r = 1.7$ T $L_g = L_r = 1$ m
OSQAR (CERN) [71, 72]	2.5 eV	15 W	1	$B_g = B_r = 9$ T $L_g = L_r = 7$ m
BMV (ESRF) [73]	50/90 keV	10/0.5 mW	1	$B_g = B_r = 3$ T $L_g = 1.5, L_r \sim 1$ m

Table 1. Some experimental parameters of the past and current generation of LSW experiments.

From Axel Lindner / DESY, PIF2010

Light shining through walls, J. Redondo, A. Ringwald, arXiv:1011.3741v1 [hep-ph]

~6 LSW experiments

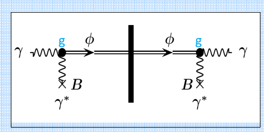
E.g., the … german exper' at DESY: ALPS

➔ Thanks to Axel Lindner / DESY

How to search for "invisible" WISPs: Lab Experiments

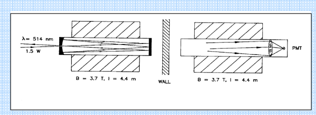
Experiments with intense laser beams providing very high photon number fluxes or extremely good control of beam properties.

– More direct: **"light-shining-through-a-wall" (LSW)**



Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Note:
$P_{\gamma\rightarrow\Phi\rightarrow\gamma} \sim g^4$



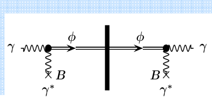
G. Ruoso et al.
(BFRT Experiment),
Z. Phys. C 56 (1992) 505

From Axel Lindner / DESY, PIF2010

Axion Production in a magnetic Field

- The production (and re-conversion) of WISPs takes place in a coherent fashion.

For ALPs (Φ):



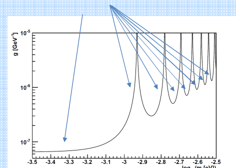
$$P_{\gamma\rightarrow\phi}(B,\ell,q) = \frac{1}{4}(g\,B\,\ell)^2\,F(q\ell) \qquad F(q\ell) = \left[\frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}\right]^2$$

q = $p_\gamma - p_\Phi$
l: length of B field

With $P_{\gamma\rightarrow\Phi} = P_{\Phi\rightarrow\gamma} = P$: $g = (P)^{1/4} \cdot 2 \cdot / (L \cdot B) / F^{1/2}$

Take note:
P(B field) / P(beam dump) =
$10^6 \cdot (\text{mm}/\lambda_{abs}) \cdot (B/T)^2 \cdot (L/m)^2$

(A. Ringwald, J. Redondo, arXiv:1011.3741v1 [hep-ph])

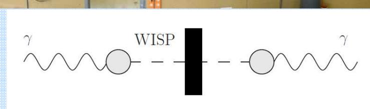


From Axel Lindner / DESY, PIF2010

Any Light Particle Search @ DESY

From Axel Lindner / DESY, PIF2010

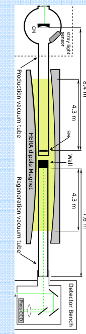
Any Light Particle Search @ DESY



A "light-shining-through-a-wall" experiment

The main components of a LSW exp.

- **Powerful laser**: optical cavity to recycle laser power (high quality laser beam)
- **Strong magnet**: HERA dipole: 5 T, superconducting (unfortunately just one)
- **Sensitive detector**: CCD (determines wavelength of laser light!)

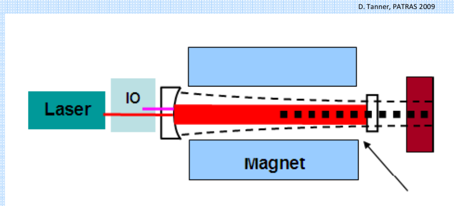


Tubes:
- diameter: 34 mm
- clear aperture: 14 mm

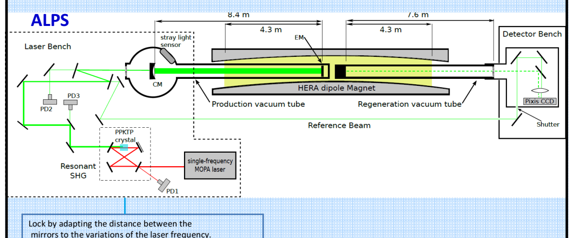
A powerful Laser System

- Trick:
  the light of a relatively low power laser with excellent beam characteristics is reflected back and forth inside the magnet,
  the light is stored inside an optical resonator (cavity)
  thus enhancing the effective laser power.

D. Tanner, PATRAS 2009



The Laser System



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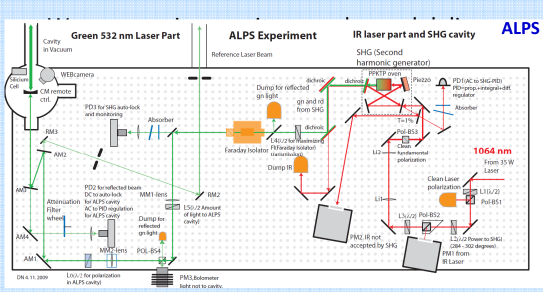
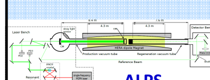
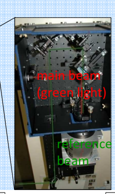
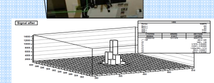


The Detector

- Conventional low noise CCD, where the light is focused onto very few pixels to minimize dark current and read-out noise.

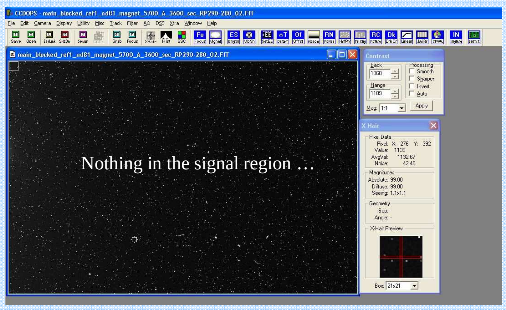






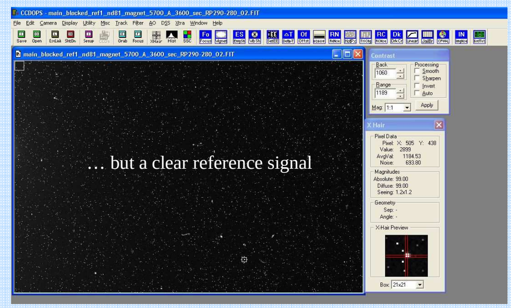
Beam spot on the CCD (pixel size 13 μm).

One Data Frame



From Axel Lindner / DESY, PIF2010

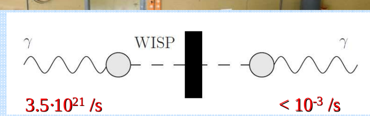
One Data Frame



From Axel Lindner / DESY, PIF2010

ALPS Results

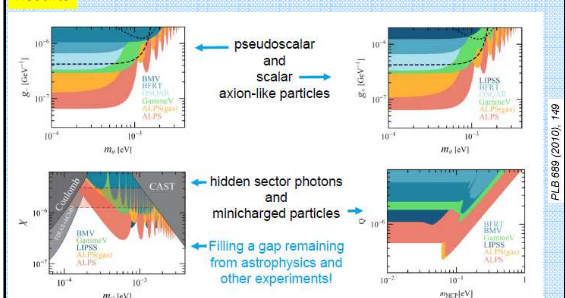
- Unfortunately, no light is shining through the wall!



PLB Vol. 689 (2010), 149, http://arxiv.org/abs/1004.1313

From Axel Lindner / DESY, PIF2010

Results

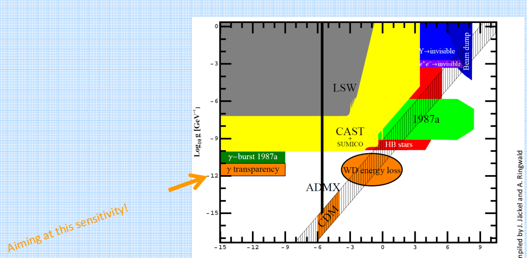


ALPS → the most sensitive lab-experiment for WISP searches

See http://arxiv.org/abs/1004.1313

From Axel Lindner / DESY, PIF2010

ALPS Summary LSW



From Axel Lindner / DESY, PIF2010

Hints for WISP Physics?

Theory:

- A QCD axion in the mass region of 10^{-5} to 10^{-4} eV would be a "perfect" cold Dark Matter candidate.
- A zoo of WISPs is expected from string theory inspired extensions of the Standard Model
  A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, arXiv:0905.4720 [hep-th]
  M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, arXiv:0909.0515 [hep-ph], JHEP 0911:027,2009

Astrophysics:

- Axions and the cooling of white dwarf stars.
  J. Isern et al., arXiv:0806.2807v2 [astro-ph], Astrophys.J.L. 682 (2008) L109
- Evidence for a New Light Boson from Cosmological Gamma-Ray Propagation? M. Roncadelli et al., arXiv:0902.0895v1 [astro-ph.CO]
- Does the X-ray spectrum of the sun points at a 10 meV axion?
  K. Zioutas et al., arXiv:0903.1807v4 [astro-ph.SR]
- Large-Scale Alignments of Quasar Polarization Vectors: Evidence at Cosmological Scales for Very Light Pseudoscalar Particles Mixing with Photons? D. Hutsemekers et al., arXiv:0809.3088v1 [astro-ph]
- Signatures of a hidden cosmic microwave background
  J.Jaeckel, J. Redondo, A. Ringwald, Phys.Rev.Lett.101:131801,2008

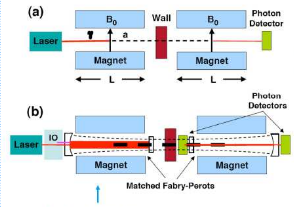
From Axel Lindner / DESY, PIF2010

... improvements ?

Double resonantly enhanced WISP regeneration experiment

Essential:

> Implementation of a second cavity in the regeneration part of the experiment to enhance the conversion probability WISP→ photon.



"Resonantly enhanced Axion-Photon Regeneration"
P. Sikivie, D.B. Tanner, Karl van Bibber, Phys.Rev.Lett.98:172002,2007.

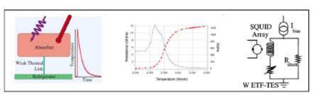
(also F. Hoogeveen, T. Ziegenhagen, DESY-90-165, Nucl.Phys.B358)

Realized at ALPS

Axel Lindner | PIF2010 – A new Particle Physics Frontier | 24 November 2010 | Page 62

Detectors

> Strive for a "background-free" single photon counter: Transition Edge Sensor @ 100 mK?



This will be investigated in collaboration with Italian partners (Camerino, Genoa and Trieste).

➔ **Also for CAST**

> Heterodyne detection: mix two signals and search for a Fourier component?

$$S = |E_{SO}e^{i(\omega_1 t+\phi)} + E_{LO}e^{i\omega_2 t}|^2 = E_{LO}^2 + 2E_{LO}E_{SO}\cos(\Omega t + \phi)$$

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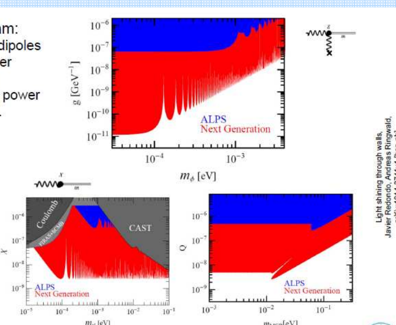
From Axel Lindner / DESY, PIF2010

Dreamed LSW experiment

An ALPS II dream:
- 20+20 HERA dipoles
- 300 kW IR laser
- TES detector
- 2^{nd} cavity with power built-up of 10^5.



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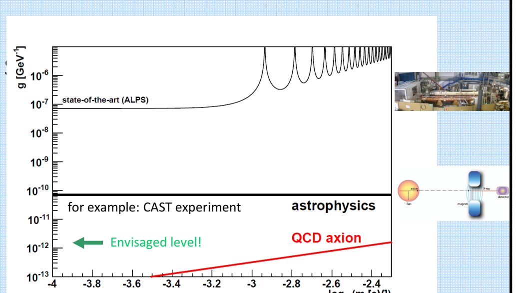
From Axel Lindner / DESY, PIF2010

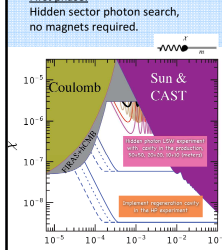
A possible Scenario for LSW experiments



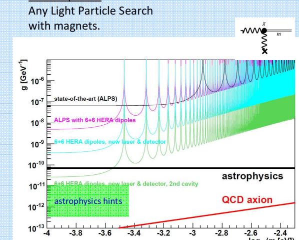
From Axel Lindner / DESY, PIF2010

Physics Prospects of ALPS II

First phase:
Hidden sector photon search, no magnets required.



Second phase:
Any Light Particle Search with magnets.



(compiled by J. Redondo)

From Axel Lindner / DESY, PIF2010

mimic CAST

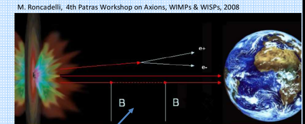
⇓

(in)direct axion-signals ?

Hints for ALP Physics: Cosmological TeV γ-propagation

TeV photons should be absorbed by e^+e^- pair production due to interaction with the extragalactic background light (EBL):
$\gamma_{TeV} + \gamma_{eV} \rightarrow e^+ + e^-$

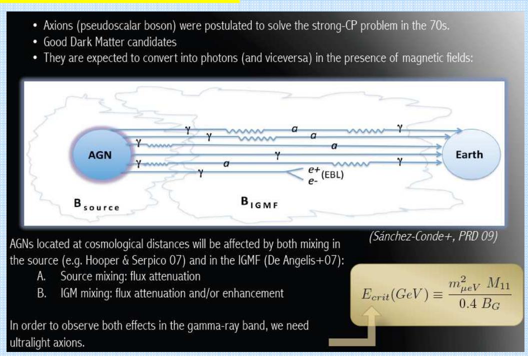
M. Roncadelli, 4th Patras Workshop on Axions, WIMPs & WISPs, 2008



However, the TeV spectra of distant galaxies do hardly show any absorption.

TeV photons may "hide" as ALPs!

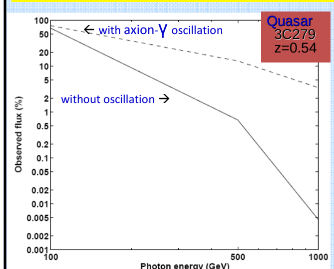
Photon axion conversion at HE



Miguel A. Sánchez Conde, http://www.iac.es/galeria/masc/Extras_files/TeVPA10_sanchezconde_200710.pdf

Large transparency to extragalactic light

➔ "New Physics"



- EBL: difficult to observe VHE
- The arrival of photons >220 GeV + z=0.54 is unexpected.

De Angelis, private communication

MAGIC Telescope:
Obs'd VHE γ's >220 GeV 5.1σ
30th ICRC'07, Merida, Mexico
astro-ph/0709.1475, 10/9/2007

Photons survive (dashed line) with an enhancement factor ~20 as expected in the absence of an a-γ oscillation: $m_a \ll 10^{-10}$ eV, $g_{a\gamma\gamma} < 2.5 \cdot 10^{-12}$ GeV^{-1}
➔ ~axion

De Angelis, Mansutti, Roncadelli, astro-ph/0707.4312, subm. PRL (2007)

Evidence for a New Light Boson from Cosmological Gamma-Ray Propagation?

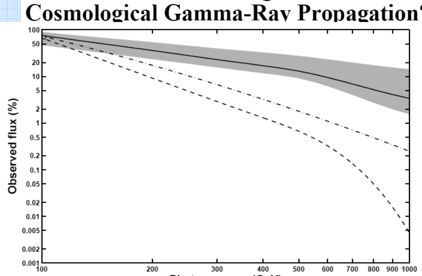


FIGURE 2. The two lowest lines give the fraction of photons surviving from a source at the same distance of 3C 279 without the oscillation mechanism, for the "best-fit model" of EBL (dashed line) and for the minimum EBL density compatible with cosmology [2]. The solid line represents the prediction of the oscillation mechanism for $B \simeq 10^{-9}$ G and $L_{dom} \simeq 1$ Mpc within the "best-fit model" of EBL. The gray band is the envelope of the results obtained by independently changing **B** and L_{dom} within a factor of 10 about their preferred values. M. Roncadelli, A. De Angelis, O. Mansutti, astro-ph/200902.0895

Galactic Center

➔ **Origin of diffuse X-rays?**

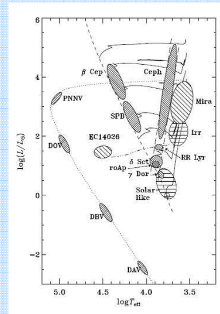
too hot (~ 90MK) to be a gravitationally bound plasma!

→ **how to produce it?**

e.g., spontaneous radiative decay of KK-axions?

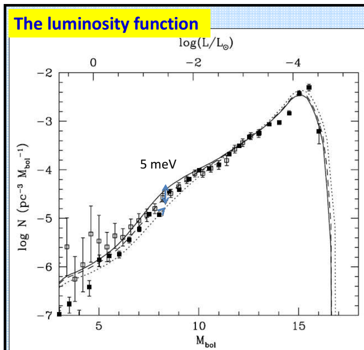
The white dwarf population: one of the best studied!

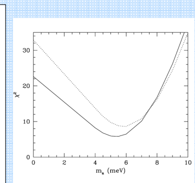
- They are the end stage of low and intermediate-mass stars
- **Their evolution is just a cooling process**
- The basic physical ingredients of their evolution are well identified (not all has been satisfactorily solved yet)
- Impressively solid observational background for testing theory.



Courtesy of Christensen-Dalgaard

The luminosity function





Axion emission dominated by bremsstrahlung (~T^4)
Best fit obtained introducing axions with a mass ~5 meV

From 3 independent results:

- WDs (g_{ae})
- SN1987A (g_{aN}) ← limit
- Solar X-rays ($g_{a\gamma\gamma}$)

m_{axion}≈10-20 [meV/c^2]

➔ CAST!?

… focus on the Sun.

NH ELSEVIER

10 December 1998

PHYSICS LETTERS B

Physics Letters B 443 (1998) 201–208

Search for energetic cosmic axions utilizing terrestrial / celestial magnetic fields

K. Zioutas [a,*], D.J. Thompson [b,1], E.A. Paschos [c,2]

doi:10.1016/S0370-2693(98)01346-X

Detecting solar axions with x-ray satellites

http://theory.tifr.res.in/~jigsaw/talks/huber.pdf

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

PRL **97**, 141302 (2006) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2006

Detecting Solar Axions Using Earth's Magnetic Field

Hooman Davoudiasl and Patrick Huber

Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

(Received 20 October 2005; published 4 October 2006)

We show that solar axion conversion to photons in the Earth's magnetosphere can produce an x-ray flux, with average energy $\langle\omega\rangle \simeq 4$ keV, which is measurable on the dark side of the Earth. The smallness of the Earth's magnetic field is compensated by a large magnetized volume. For axion masses $m_a \lesssim 10^{-4}$ eV, a low-Earth-orbit x-ray detector with an effective area of 10^4 cm^2, pointed at the solar core, can probe the photon-axion coupling down to 10^{-11} GeV^{-1}, in 1 yr. Thus, the sensitivity of this new approach will be an order of magnitude beyond current laboratory limits.

.... + orbiting X-ray detector

→ "dark earth"

➔ worked out...

http://prl.aps.org/pdf/PRL/v97/i14/e141302

Journal of Cosmology and Astroparticle Physics

An IOP and SISSA journal

JCAP08(2008)026

A feasibility study for measuring geomagnetic conversion of solar axions to x-rays in low Earth orbits

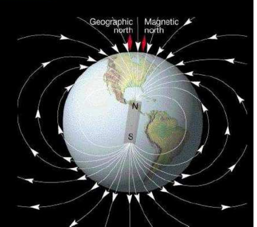
Hooman Davoudiasl[1] and Patrick Huber[2,3]

http://iopscience.iop.org/1475-7516/2008/08/026/pdf/1475-7516_2008_08_026.pdf

(in)direct axion-signals?

Key Observation

- Earth's magnetic field: $B_\oplus \simeq 0.3$ G.
- $B_\oplus \propto 1/r^3$
- $L \ll R_\oplus \approx 6400$ km $\Rightarrow B_\oplus \simeq$ Constant.
- We will use $L_\oplus \simeq 1000$ km.



Earth as the conversion region:

$\Rightarrow \mathcal{F}_\oplus \simeq 30$ T m.

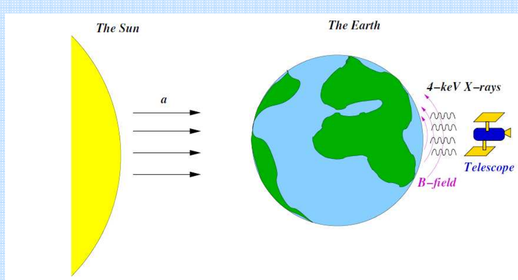
$\mathcal{F}(\text{CAST}) \simeq 83$ T m.

$\mathcal{F}_\oplus$ and $\mathcal{F}(\text{CAST})$ are comparable!

Conversion of high energy cosmic axions in $B_\oplus$: Zioutas, Thompson, Paschos (1998).

$\therefore$ A low-earth-orbit X-ray detector with $A \gg A_{\text{CAST}}$ can outperform CAST.

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf



- Using the Earth to shield solar X-rays.
- Collect data on the night side.

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

Geomagnetic field map

A feasibility study for measuring geomagnetic conversion of solar axions to x-rays in low Earth orbits

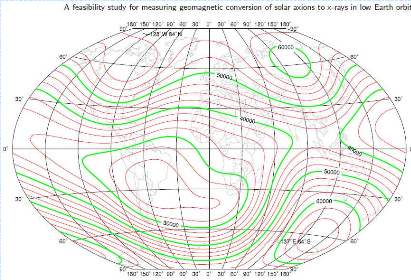


Figure 2. Map of the total magnetic field strength at sea level for 2 July 2008 [22]. Green, thick contours are in steps of 10 000 nT, thin red ones are in steps of 2500 nT. The numbers on top of the green, thick contours are the magnetic field strength in nT. The black dots denote the positions of the magnetic dip pole for each year from 2005 to 2010. The coordinates give the position of the magnetic pole on 2 July 2008. The map is a Winkel triple projection.

JCAP08(2008)026

http://iopscience.iop.org/1475-7516/2008/08/026/pdf/1475-7516_2008_08_026.pdf

Observation strategy

- enter earth shadow
- turn towards the sun
- observe
  - non-imaging – point on target for signal, point off target for background
  - imaging – use on-target pixels for signal, off-target pixels for background
- turn away from the sun
- exit earth shadow

http://theory.tifr.res.in/~jigsaw/talks/huber.pdf

Axion-Photon Conversion:

$$p_\gamma(L) = 2\left(\frac{B}{2M}\right)^2\left[\frac{1-\cos(qL)}{q^2}\right]$$

Numerical inputs:

$m_a \leq 10^{-4}$ eV, $M = 10^{10}$ GeV,

$B = b_\oplus = 3 \times 10^{-5}$ T,

$\omega = 4$ keV,

$L = L_\oplus = \pi/q_{\max} \simeq 600\,\mathrm{km}$

$\Rightarrow\ p_\gamma(L_\oplus) \approx 10^{-18}$.

$q_{\max}$ corresponds to $m_a = 10^{-4}$ eV.

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

Flux estimate

$m_a = 10^{-4}$ and $E_a = 4\,\mathrm{keV}$ the oscillation length $L = \pi/q$ is 600 km.

Using $g_{a\gamma} = g_{10}$ we get $p_\gamma \simeq 10^{-18}$.

If we integrate the axions flux from the sun over an energy range from $1 - 10\,\mathrm{keV}$ we obtain $\simeq 4 \times 10^{11}\mathrm{axions\,cm^{-2}\,s^{-1}}$

This yields a x-ray fluence of

$$4 \times 10^{-7}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$$

Taking an observation time of $t = 10^7$ s and collecting area of $A = 10^4\,\mathrm{cm}^2$ we get 10^4 x-ray photons. The signal is proportional to g_{10}^4.

http://theory.tifr.res.in/~jigsaw/talks/huber.pdf

X-ray satellites

- Collecting areas range from a few cm^2 up to a few $1000\,\mathrm{cm}^2$
- Altitudes range from several 100 km up to several 10 000 km
- Imaging vs non-imaging detectors
- Slew rate – how fast can they turn

A sensitive x-ray detector must not be pointed towards the sun since this would lead to severe damage. They can start turning towards the sun only once they are in the earth shadow and have to turn away before the leave the earth shadow, the time in the shadow is determined by the orbit.

http://theory.tifr.res.in/~jigsaw/talks/huber.pdf

Solar-axion flux at Earth:

$$\Phi_a = 3.67 \times 10^{11}(10^{10}\,\mathrm{GeV}/M)^2\,\mathrm{axions\,cm^{-2}\,s^{-1}}$$

X-ray flux at $L_\oplus \simeq 600\,\mathrm{km}$, $M = 10^{10}$ GeV:

$$\Phi_\gamma(L_\oplus) \approx 4 \times 10^{-7}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$$

- $\delta t \sim 10^7$ s and $A \sim 10^4$ cm^2 $\Rightarrow N_{\mathrm{signal}} \sim 10^4$.
- Sensitivity to $M = 10^{11}$ GeV.

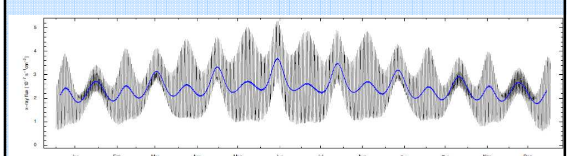
Q: Can we observe this flux?

A: Yes.

Let us look at some typical X-ray telescopes.

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

Fluxes throughout the year



Clear signal, once measured

http://theory.tifr.res.in/~jigsaw/talks/huber.pdf

X-ray missions

RXTE

- $A_{\rm eff} \sim 7000$ cm^2 ; $E_\gamma \in [1, 50]$ keV.
- Angular resolution: $0.5°$ (Sun: $0.5°$).
- Orbit: 600 km.
- 1996-1999 calibration: $\delta t \simeq 2.5 \times 10^4$ s of dark earth data.
- Background: 3 counts s^{-1}, $E_\gamma \in [2, 10]$ keV.

$\Rightarrow N_B \simeq 7.5 \times 10^4$

RXTE Sensitivity: $\sqrt{N_B}/(\delta t\, A_{\rm eff}) \sim 1.5 \times 10^{-6}$ cm^{-2} s^{-1}.

http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

X-ray missions

LOBSTER

- $A_{\rm eff} \sim 10^4$ cm^2 ; $E_\gamma \in [0.5, 3.5]$ keV.
- Angular resolution: $3'$

Core of the sun: $3'$, one pixel.

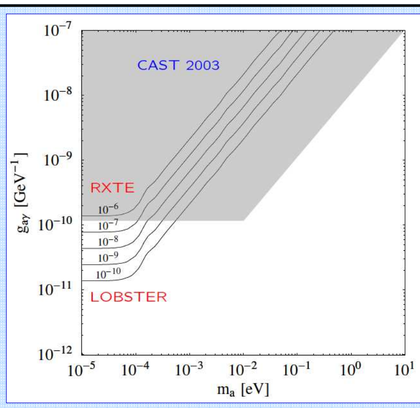
- Orbit: 350 km; to fly on ISS.
- Background per pixel: 10^{-5} counts s^{-1}

$\Rightarrow N_B \sim 100$ for $\delta t \sim 10^7$ s

Lobster Sensitivity: $\sqrt{N_B}/(\delta t\, A_{\rm eff}) \sim 10^{-10}$ cm^{-2} s^{-1}.

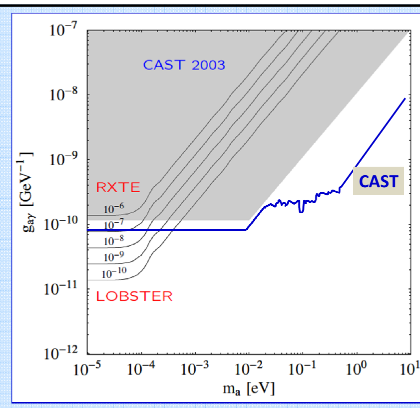
http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

prospects



http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

prospects



http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

Comparison with CAST for $m_a \lesssim 10^{-4}$ eV:

$$\frac{N_\oplus}{N_{\rm CAST}} = \frac{\mathcal{F}_\oplus^2}{\mathcal{F}_{\rm CAST}^2} \times \frac{A_\oplus}{A_{\rm CAST}} = (30/83)^2 \times (10^4/29) \simeq 45.$$

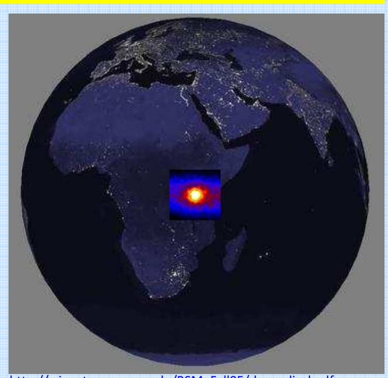
The orbiting telescope has a performance equal to 45 CAST experiments!

★ X-ray signatures are distinct:

- Direction of the solar core.
- Black-body distributed with $T \simeq 1.1$ keV.
- Flux variations: annual (Earth-Sun distance) and orbital ($B_\oplus$).

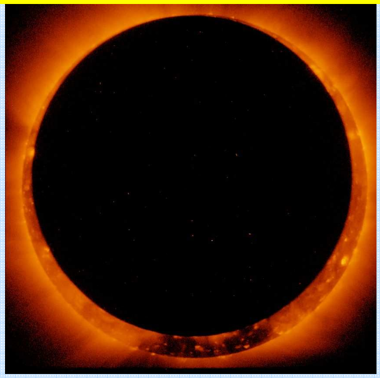
http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

.... midnight Sun image in X-rays through the Earth!



http://wingate.uoregon.edu/BSM_Fall05/davoudiasl.pdf

Solar eclipse as seen by Hinode satellite on Jan. 4, 2011



What is it?

http://www.physorg.com/news/2011-01-annular-solar-eclipse-hinode-video.html

---

BUT ...

... mimic CAST @ Sun's surface B ?

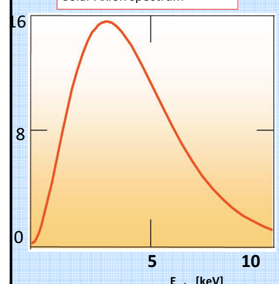
Searching for ~axions with space missions!

e.g., Yohkoh, RHESSI, HINODE, ...

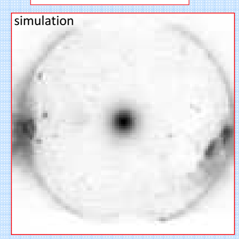
---

expected 1996-

Solar Axion spectrum



Spatial distribution



RHESSI science nugget, H. Hudson (2007)

→ $m_a \ll 10^{-4}\,eV/c^2$

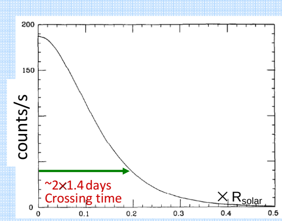
K. van Bibber, http://www-astro-theory.fnal.gov/events/080201presentation.pdf

---

CAST in Sunspots?

" Unfortunately, the signal is dominated by background →
X-ray emission from sunspots as they cross the DC of the Sun
→ a brightening ~2.5 days!

Carlson & Tseng, Phys. Lett. B365 (1996) 193



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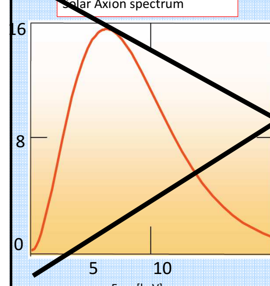
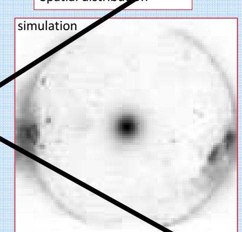
observation

Solar Axion spectrum



Spatial distribution



RHESSI science nugget, H. Hudson (2007)

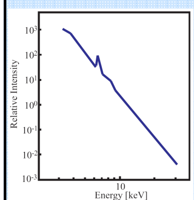
→ $m_a \ll 10^{-4}\,eV/c^2$

K. van Bibber, http://www-astro-theory.fnal.gov/events/080201presentation.pdf

Instead ....

observed

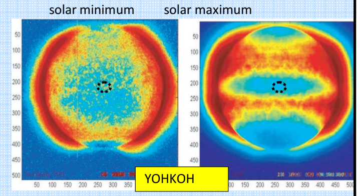
Typical spectral shape



Spatial distribution

$E_\gamma \approx 0.3 - 4\,keV$

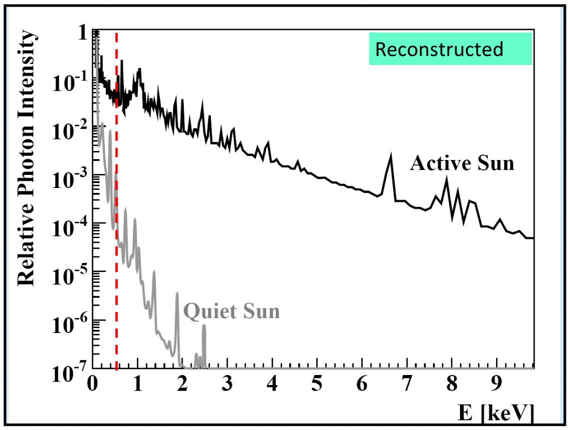
solar minimum — solar maximum

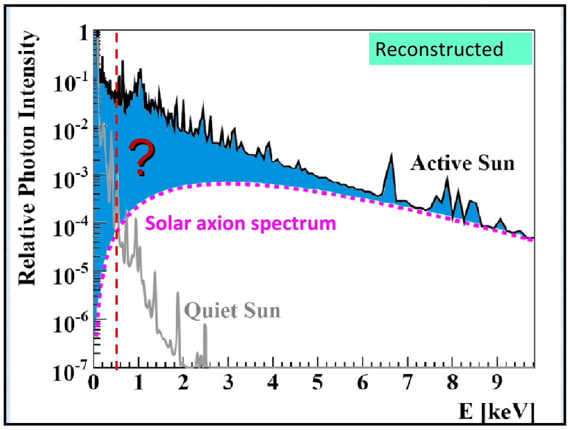


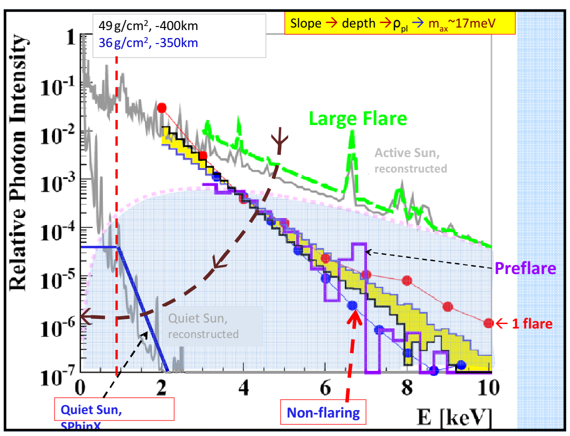
➔ Can be reconciled for $m_a \gtrsim 2\cdot10^{-2} eV/c^2$

➔ multiple Compton scattering

Axion searches with helioscopes and astrophysical signatures for axion(-like) particles
K Zioutas, M Tsagri, Y Semertzidis, T Papaevangelou, T Dafni, V Anastassopoulos
2009 New J. Phys. 11 105020 doi: 10.1088/1367-2630/11/10/105020





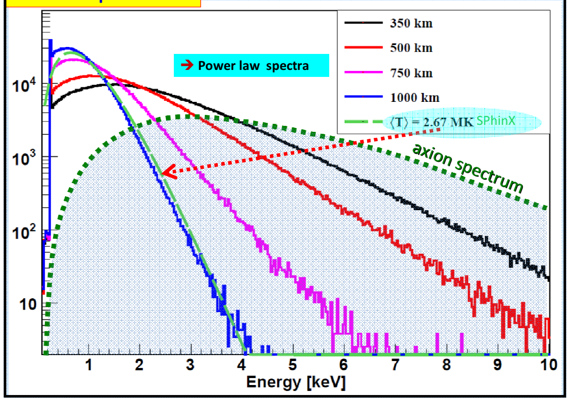


Axion-photon conversion

... if it occurs below surface due to plasma resonance?

➔ Geant4 ...

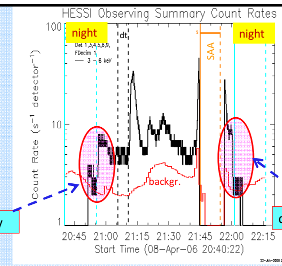
down -comptonization



NON-FLARING SUN

2002–2006

RHESSI
3-6keV



night → day

day → night

The count rate during spacecraft daytime is always higher than that immediately before + after, independent of any flaring activity, this excess is clearly solar emission.
... there exists 5–10 MK emission from the Sun, in the absence of solar flares ...

J.M. McTiernan, ApJ. 697 (2009) 94

http://www.iop.org/EJ/article/0004-637X/697/1/94/apj_697_1_94.pdf?request-id=3d4e2922-b50e-44ea-a70f-8e8aa6d73f3d

---

The X-ray excess of ~unknown origin ...

- Quiet Sun
  - → soft X-rays ← coronal heating problem
  - → hard X-rays ← power law spectrum
- Non-flaring ARs (& preflares?)
  - → hard X-rays / ~flaring "temperatures" !
  - / power law spectrum

...fits an $m_{axion} \approx 0.017\,eV/c^2$ scenario initiated near the magnetic photosphere.

It is remarkable + fascinating that the Sun emits intense X-rays ...
it still remains a mystery .

S.Tsuneta, AAPPS Bulletin, 19(#3) (2009) 11
http://www.cospa.ntu.edu.tw/aappsbulletin/data/19-3/11Hinode.pdf

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FLARES: unpredictable magnetic "explosions"

- **Where does solar flare energy come from?**
- ... at least the magnetic field serves as a conduit for the energy flux supplying the flare. 2010
- The solar "reconnection flare" concept is deceptive, ... many unknowns. (HS Hudson, SPD, May 2008)

http://xxx.lanl.gov/PS_cache/arxiv/pdf/1004/1004.5318v1.pdf

Die Flare-Häufigkeit in Fleckengruppen unterschiedlicher Klasse + magnetischer Struktur

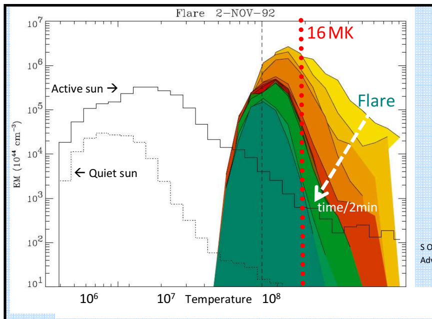
(Mitteilungen des Astrophysikalischen Observatoriums Potsdam Nr. 87)

H. Künzel **"pointed out the first clear connection between flare productivity + magnetic structure"**
Sammis, Tang, Zirin, ApJ. 540 (2000) 583

Abstract

Zur Untersuchung der Flare-Häufigkeit in Fleckengruppen unterschiedlicher Klasse und magnetischer Struktur werden von 2406 im Zeitraum 1956 bis 1958 entstandenen Fleckengruppen 886 mit Flare-Erscheinungen verbundene und für die statistische Betrachtung geeignete Fleckengruppen der Klassen A bis F verwendet. Der Anteil der zusammen mit Flares aufgetretenen Fleckengruppen an der Zahl aller beobachteten Fleckengruppen wird angegeben. Aus der Zahl aller beobachteten Flares jeder Fleckengruppenklasse werden die mittleren täglichen Flare-Zahlen getrennt für Flare- und Sichtbarkeitstage der Fleckengruppen und die mittleren Flare-Zahlen bezogen auf die Anzahl der Fleckengruppen ermittelt. An diesen Ergebnissen sind die Flares der Importance 1 (1-; 1; 1+) mit 93% beteiligt. Die Anteile der Flares mit der Importance 2 (2-; 2;2+) bzw. 3 (3-; 3;3+) betragen dagegen nur 6.5% bzw. 0.5%. Die Flare-Häufigkeit nimmt zu höheren Fleckengruppenklassen hin zu. Innerhalb der Klassen D, E und F sind nach Unterteilung der Fleckengruppen in , , und Gruppen, bei denen in einem Fleckenhof mehrere Kerne mit entgegengesetzter Polarität beobachtet wurden, deutliche Unterschiede in der Flare-Häufigkeit festzustellen. Es zeigt sich, daß die Flare-Zahlen magnetisch komplexer Fleckengruppen (und) merklich größer sind, als die normaler -Gruppen. **Die größten Flare-Zahlen innerhalb der Klassen treten jedoch bei Fleckengruppen mit entgegengesetzter Polarität mehrerer Kerne in einem Fleckenhof auf.**

Astronomische Nachrichten, 285 (1960) 271, http://www3.interscience.wiley.com/journal/112554591/abstract?CRETRY=1&SRETRY=0



S Orlando, G Peres, F Reale, Adv.SpaceRes. 32 (2003) 955

P. Chamberlin – Solar Flares - REU June 12, 2007

- Biggest mystery: the flare 'trigger'
- The luminosity of a flare originates predominantly in the chromosphere.

H. Hudson, http://sprg.ssl.berkeley.edu/~hhudson/presentations/fairbanks.070320/

Past:

Modelling the internal structure of stars → mid-1800's
→ Understanding the Sun.

→ A paradox: no known energy source capable of sustaining the Sun for the period of time it was believed to have existed on the basis of geological evidence.

→ A mystery until the 1930's

→ **Theory of stellar evolution had foreshadowed the discoveries of nuclear fusion / fission.**

Much of the physics which we use in our models has been calculated theoretically but not verified experimentally, since the temperatures and densities cannot be reached in terrestrial laboratories.

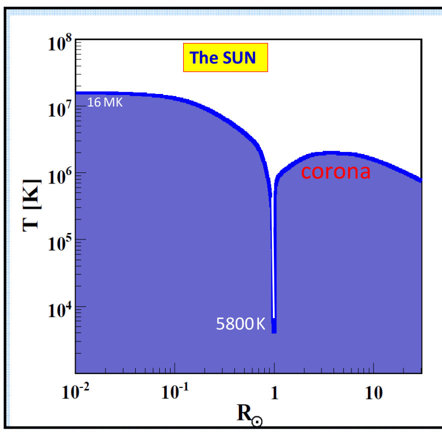
→ Solar X-rays, similarly??

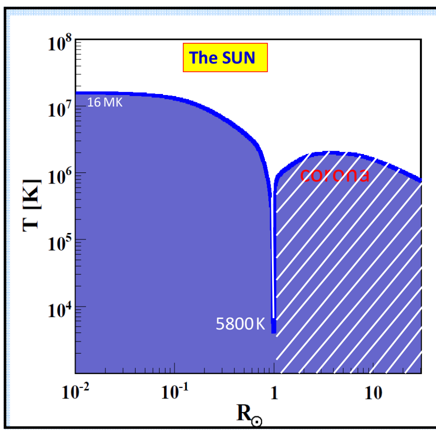
http://rocky.as.utexas.edu/~mikemon/mike_diss.pdf

Focus on paradoxes ...

Frank Wilczek

41





Solar atmosphere:

➔ **Solar coronal heating mystery**

The microscopic heating mechanism is unknown!

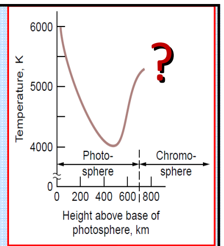
E. Marsch, http://www.mps.mpg.de/solar-system-school/lectures/sonnensystem_2008/Corona.pdf

Suggestion:

- whole Sun external irradiation by trapped KK-type axions , or other WISPs, or ..??..

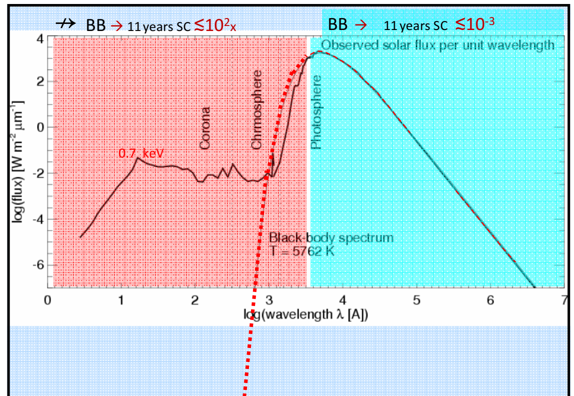
+

- B-converted axions / WISPs (occasionally)

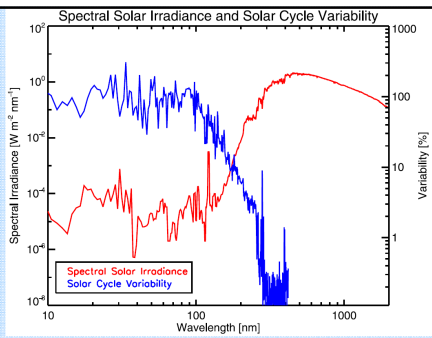


Sun ≠ bb

Coronal heating: **a buzzword!!**



M. Aschwanden, private communication



- Enhanced variability ≤400nm ➔ ~3eV **??** threshold**??**

V. Domingo ,..., S Solanki, ..., Space Sci Rev (2009) 145: 337–380
http://www.springerlink.com/content/415k421502275131/fulltext.pdf

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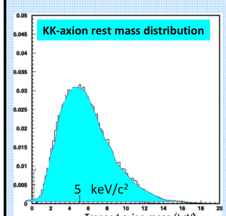
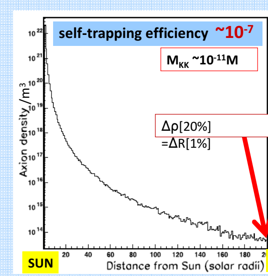
Gravitationally self-trapped solar exotica

e.g., ~KK-axions around the Sun.

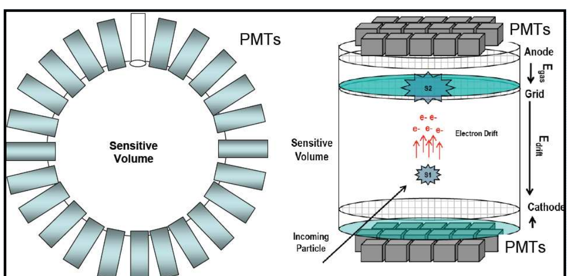




E.g., 10^{-4}M explains $a=10^{-7}$cm/s²
> Pioneer anomaly

➔ **exercise!!**

L. Di Lella, K. Zioutas, Astroparticle Phys. 19 (2003) 145



Left: Sketch of a typical modern single-phase detector geometry. A spherical volume of noble liquid is surrounded by an array of close-packed photomultiplier tubes (PMTs) to maximize light collection and simplify position reconstruction. A \neck" leads up from the top of the detector to allow insertion of calibration sources. Right: Sketch of a typical dual-phase detector geometry. Noble gas lies above the liquid with transition from liquid to gas occurring at the grid. PMTs on top or bottom of the cylinder allow mm reconstruction accuracy in the x-y plane of the detector. Interaction in the sensitive volume between the cathode and the grid produces primary scintillation (\S1") light and ionization electrons. These electrons drift upwards in the strong electric field produced by the anode and cathode, producing secondary (\S2") light proportional to the amount of ionization, due to electroluminescence in the gas. As depicted, the S2 signal is much larger than the S1 signal. The drift time of the electrons causes a delay between the S1 and S2 signals that allows mm reconstruction of the position in the vertical axis of the detector. Interactions occurring in liquid below the cathode produce S1 signals but no S2 signal, since the direction of the electric field drifts electrons from these interactions to the bottom of the detector. ➔ **KK axion -> 2γ**

Introduction to Dark Matter Experiments, R.W. Schnee, http://xxx.lanl.gov/PS_cache/arxiv/pdf/1101/1101.5205v1.pdf

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*) Grotrian (1939)

⬇

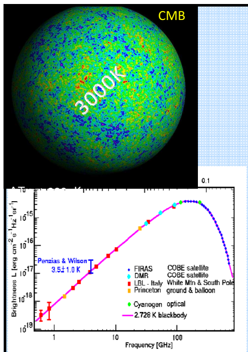
2010

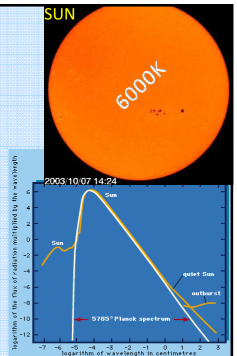
The **coronal heating problem** *), i.e., the heating of the solar corona up to a few hundred times the average temperature of the underlying photosphere, **is one of the most perplexing and unresolved problems in astrophysics to date.**

.....

how magnetic energy is converted to thermal energy of the corona remains unknown.

Antolin, P ; Shibata, K ; Kudoh, T ; Shiota, D ; Brooks, D, Proc. 2010, http://www.springerlink.com/content/x2017120x66mj042/
HP Warren, AR Winebarger, DH Brooks, ApJ. 711 (1.3.2010) 228, http://iopscience.iop.org/0004-637X/711/1/228





ΔT/T □a few×10^{-5} → ΔT/T □ 10^3

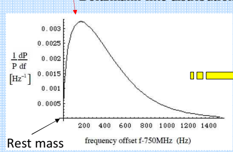
New physics! → » new physics?!

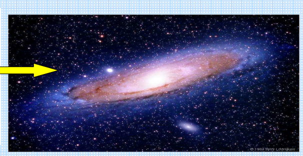
Relic axions

→ axionic dark matter →

The cold dark matter axion

- Pseudoscalar boson (μeV - meV)
- Velocity distribution:
  - DM axions pick up kinetic energy from random gravitational kicks as they fall into the galactic gravitational well.
  - Boltzmann-like distribution: mean velocity = virial velocity = 10^{-3} c

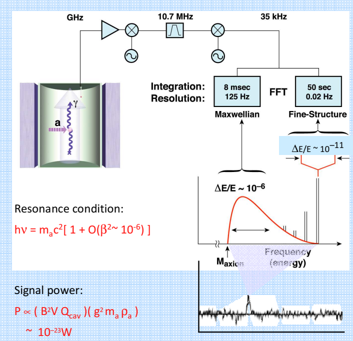




- Non-Thermal distribution
  - Coherent axion flows

ADMX experiment

P. Sikivie, PRL 51, 1415 (1983)



Resonance condition:

$h\nu = m_a c^2 [\, 1 + O(\beta^2 \sim 10^{-6})\,]$

Signal power:

$P \propto (B^2 V Q_{cav})(g^2 m_a \rho_a)$

$\sim 10^{-23}$W

Local Milky Way density:

$\rho_{halo} \sim 450$ MeV/cm³

Thus for $m_a \sim 10$ μeV:

$\rho_{halo} \sim 10^{14}$ cm^{-3}

$\beta_{virial} \sim 10^{-3}$:

$\lambda_{De\ Broglie} \sim 100$ m

$\Delta\beta_{flow} \sim 10^{-7}$:

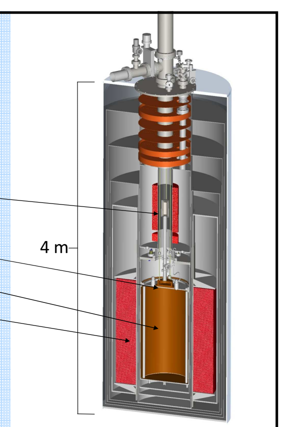
$\lambda_{Coherence} \sim 1000$ km

Key point !
The signal is the Total Energy (= Mass + Kinetic) of the axion

---

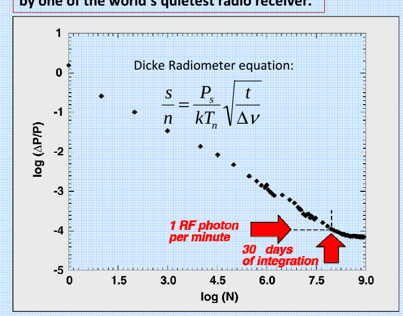
ADMX

- SQUID
- "1K" Pot
- Microwave Cavity
- Main Magnet
  13 Ton,8 Tesla in center bore



ADMX

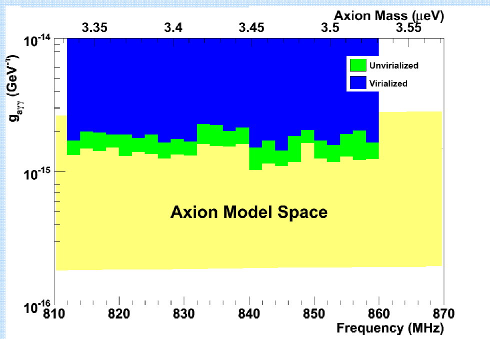
Conversion microwave photons are detected by one of the world's quietest radio receiver.



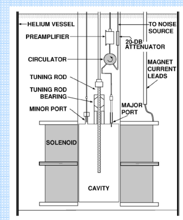
Systematics-limited for signals of 10^{-26} W → 10^{-3} of axion power.
Last signal received from Pioneer 10 (6 billion miles away) ~ 10^{-21} W.

From K. van Bibber

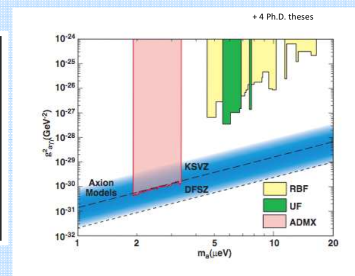
ADMX scan



ADMX scanning results



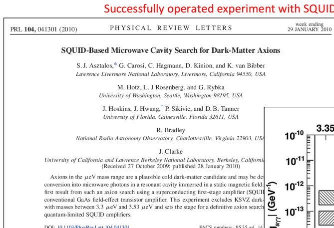
From W. Wuensch *et al.*, Phys. Rev. D40 (1989) 3153



PRL 80 (1998) 2043
PRD 64 (2001) 092003
ApJ Lett 571 (2002) 27
PRD 69 (2004) 011101(R)
PRL 95 (9) 091304 (2005)
PRD 74 (2006) 012006

ADMX results

Successfully operated experiment with SQUID amp near 7 Tesla field


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

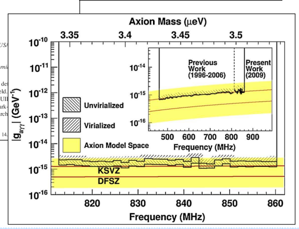
SQUID-Based Microwave Cavity Search for Dark-Matter Axions

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
University of Florida, Gainesville, Florida 32611, USA
R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA
J. Clarke
University of California and Lawrence Berkeley National Laboratory, Berkeley, Californi
(Received 27 October 2009; published 28 January 2010)

Axions in the μeV mass range are a plausible cold dark-matter candidate and may be de conversion into microwave photons in a resonant cavity immersed in a static magnetic field. first result from such an axion search using a superconducting first-stage amplifier (SQUI conventional GaAs field-effect transistor amplifier. This experiment excludes KSVZ dark- with masses between 3.3 μeV and 3.53 μeV and sets the stage for a definitive axion search quantum-limited SQUID amplifiers.

DOI: 10.1103/PhysRevLett.104.041301 PACS numbers: 95.35.+d, 14.

DOI: 10.1103/PhysRevLett.104.041301



Covered 812 – 860 MHz = 48 MHz

Total Run Time: 19 months

Continuous Data Collecting: 8 months

Rydberg-atom single-quantum detectors

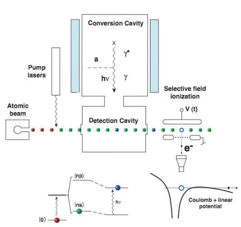
Atoms with a single electron promoted to a large principal quantum number, n >> 1. Superposition of Rydberg states yields "classical atoms" with macroscopic dimensions (e.g. ~ 1 mm).

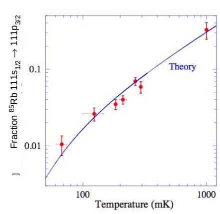
Potential for highly sensitive microwave photon detectors ("RF photo-multiplier tubes") realized by Kleppner and others in the 1970's. The axion experiment is an ideal application for Rydberg atoms:

- Large transition dipole moments → $\langle n\pm1|er|n\rangle \propto n^2 a_0$
- Long liftetimes → $\tau_n \propto n^3 \quad (l << n); \quad \tau_{100} \approx 1\,m\sec$
- Transitions span microwave range → $\Delta E_n = E_{n+1} - E_n \approx 2R/n^2 ; \quad \Delta E_{100} \approx 7\,GHz$

Most importantly, being a phaseless detector (photons-as-particles), the Rydberg-atom detector can evade the standard quantum limit: hν = kT

Rydberg single-quantum detection (S. Matsuki et al., Kyoto)





M. Tada et al., Phys. Lett. A (accepted)

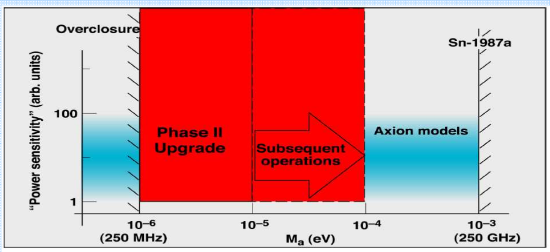
The blackbody spectrum has been measured at 2527 MHz
a factor of ~2 below the standard quantum limit (~120mK)

Future?

→ Karl van Bibber, private communication, 2011

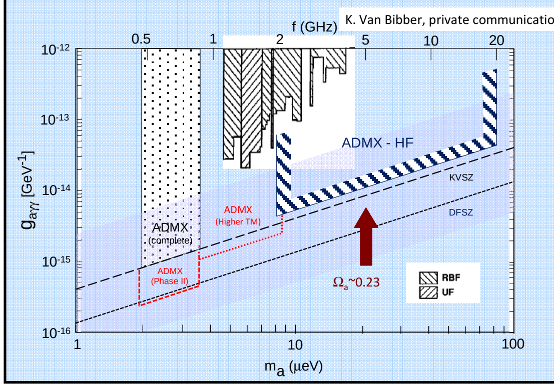
ADMX

➔ CAST too?



http://www.physics.ucla.edu/hep/dm10/talks/carosi.pdf

ADMX Phase II & ADMX-HF Coverage



Relic ~axions also with CAST?

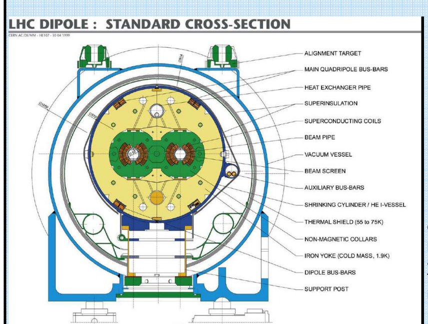
Collaboration between CAST, CERN, DESY, Yale U.

Engineering aspects of microwave axion generation and detection experiments using RF cavities

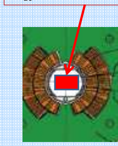
Fritz CASPERS CERN-BE-RF-BR

- **Outline**
- A microwave (axion) transmitter and receiver cavity set-up with high electromagnetic isolation
  - The "**box in a box**" concept with permanent control of RF leakage
  - Signal detection methods with very narrow observation bandwidth
- **Rectangular waveguide TE_{10n} resonator in a LHC magnet**
  - The transmitter cavity
  - The receiver cavity
- **Axion radiation patterns** (antenna diagram)-approximative figures
- The microwave radiometer – a short introduction
- Chromium Sesquioxide - an interesting axion conversion material
- A recent ultra sensitive microwave single photon receiver concept
- Conclusion and outlook

Rectangular waveguide TE_{10n} resonator in a LHC magnet → CAST ?



TE_{10} waveguide

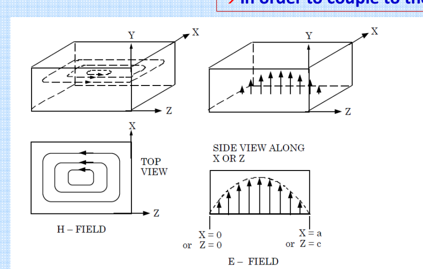


LHC dipole magnet Cross-sections and proposed position and orientation of a TE_{10} waveguide in the "beampipe"

Rectangular waveguide TE_{10n} resonator in a LHC magnet

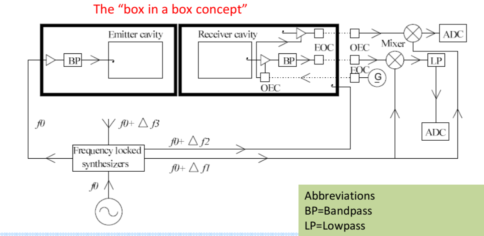
Just as a reminder : the TE_{101} mode pattern in a rectangular waveguide
For the waveguide in the LHC magnet, z would be along the beam axis and y in the direction of the static magnetic field (up to 8 Tesla)

→ In order to couple to the axion: ~E·B



Two Cavity setup with very high isolation

The “box in a box concept”



Feasibility, engineering aspects and physics reach of microwave cavity experiments searching for hidden photons and axions

Published in JINST, Nov 16, 2009

F. Caspers, J. Jaeckel and A. Ringwald

Abbreviations
BP=Bandpass
LP=Lowpass
ADC=Analog digital converter
OEC=Optical/electric converter
EOC=Electric optical converter
G=Generator (DC power source)
Δf_1 ,Δf_2 ,Δf_3 < 20 Khz

Rectangular waveguide TE_{10n} resonator in a LHC magnet

A WARM BORE ANTICRYOSTAT FOR SERIES MAGNETIC MEASUREMENTS OF LHC SUPERCONDUCTING DIPOLE AND SHORT-STRAIGHT-SECTION MAGNETS.

Presented at the 2003 Cryogenic Engineering Conference and International Cryogenic Materials Conference
CEC/ICMC 2003
22-26 September 2003, Anchorage, Alaska

O. Dunkel, P. Legrand and P. Sievers

CERN, AT Division,
CH-1211 Geneva 23, Switzerland

All LHC twin aperture magnets will be tested under operating conditions to verify their performance. The field measurement equipment works at ambient temperature and pressure. Each magnet is therefore equipped with two warm bore anticryostats. As a consequence a total of nearly 80 anticryostats of different lengths have to be assembled, handled and serviced during the test period. Two main constraints determine the frame for the design of these anticryostats: inside a given beam pipe aperture of 50 mm kept at 1.9 K, a warm bore aperture of 40 mm must provide the highest possible mechanical stability and robustness for numerous mounting cycles as well as the lowest possible heat losses towards the cryogenic system. In addition, compatibility with high magnetic fields and an insulation vacuum of about 10^{-7} mbar have to be maintained. This paper describes how a satisfactory mechanical stability as well as heat losses in the order of 0.8 W/m are achieved with a design based on very careful space and material optimization. Other aspects like assembly, installation, thermal behavior and temperature control during the operation are described.

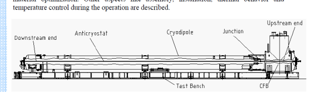
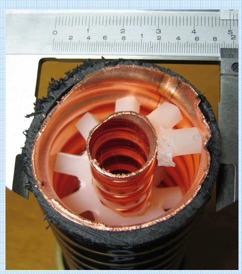


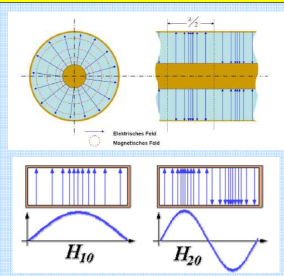
FIGURE 2. Layout of a cold test bench for dipole magnets equipped with anticryostats.

The ANTI-CRYOSTAT
We may consider using the anti-cryostat for the axion transmitter part.
Then we are no longer restricted by the cryo power dissipation limit of 2 Watt per meter of the LHC main dipole beam screen, but we could apply water cooling along the 15 meter long waveguide and possibly dissipate 10 KW maybe even 100 KW CW.
Of course this does not make sense for the receiver cavity (low noise temperature required)
Of course for patients (medical diagnostics) also
large “anti-cryostats” are in use.

A coaxial line setup in an LHC magnet – transv. el. field distributions



Coax cable with small amount of dielectric
one can reduce the dielectric content even much further just using just very few plastic or ceramic splines.



Transverse electric field distribution on coax line (upper) and for the TE_{10} and TE_{20} mode in a waveguide (lower)
A TEM_{00} type Gaussian beam has a rather similar transverse electric field distribution as the TE_{10} mode waveguide; the DC B-Field would be vertical for both pictures.

A coaxial line setup in an LHC magnet

- As already mentioned in one of the previous slides we might have the possibility to **install a coax line with about 40 mm diameter of the outer conductor in the second bore e.g. of the CAST LHC magnet.**
- Why?
- This configuration should have the same **directional characteristic** as the laser beam in vacuo.
- But in contrast to the laser beam we would be sensitive in micro eV range.
- Now there are two possibilities:
  - Operating in the resonant mode with the first possible coax resonance around 10 MHz since the length of the LHC magnet is about 15 meter and the first resonance is lamla/2. All other resonances would be spaced by 10 MHz..(usable up to about 4 GHz when waveguide cutoff of the coax line comes in.
  - OR: operating in the travelling wave mode i.e. observing all the noise from a few MHz to about 4 GHz using a microwave radiometer
- But the key question: What should could/should we measure then (Axions, chameleons anything else) if targeting at the sun….
- BUT ! There is a basic difference between the field in a coax line and a Gaussian (laser) beam; the laser beam has a well defined polarisation (hor.,vert. circ.) and the electric field in a coax line has circular symmetry..can we expect an interaction at all, if there is some transverse but not azimuthal B-Field ? The TE- mode in a rectangular waveguide is in this respect much closer to the Gaussian beam , but the phase velocity is way off..

Cromium Sesquioxide – a candidate for axion conversion materials

PHYSICAL REVIEW A **77**, 022106 (2008)

Relativistic nature of a magnetoelectric modulus of Cr_2O_3 crystals: A four-dimensional pseudoscalar and its measurement

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(Received 30 July 2007; revised manuscript received 28 October 2007; published 14 February 2008)

The magnetoelectric effect of chromium sesquioxide Cr_2O_3 has been determined experimentally as a function of temperature. One measures the electric field-induced magnetization on Cr_2O_3 crystals or the magnetic field-induced polarization. From the magnetoelectric moduli of Cr_2O_3 we extract a four-dimensional relativistic invariant pseudoscalar $\tilde{\alpha}$. It is temperature dependent and of the order of $\sim 10^{-4}/Z_0$, with Z_0 as vacuum impedance. We show that the new pseudoscalar is odd under parity transformation and odd under time inversion. Moreover, $\tilde{\alpha}$ is for Cr_2O_3 what Tellegen's *gyrator* is for two port theory, the *axion* field for axion electrodynamics, and the PEMC (perfect electromagnetic conductor) for electrical engineering.

DOI: 10.1103/PhysRevA.77.022106 PACS number(s): 11.30.Er, 75.50.Ee, 03.50.De, 14.80.Mz

Chromium Sesquioxide – a candidate for axion conversion materials

VII. OTHER SUBSTANCES AND SYMMETRIES PERMITTING MAGNETOELECTRICITY WITH THE AXION PIECE

In the present article the relativistic analysis is based on data of the antiferromagnet Cr_2O_3, because it represents so far probably the best studied magnetoelectric material and has diagonal components of the linear magnetoelectric effect tensor α; see Eq. (47). However, other materials and symmetries could have served the same purpose, in principle. Among the 122 Heesch-Shubnikov point groups 58 ones are permitting the linear magnetoelectric effect [76], and therefrom 32 ones possess diagonal components of the magnetoelectric tensor α [27,37,77]. Strictly speaking, our magnetoelectric tensor ${}^{\mathrm{rel}}\alpha$ in Eq. (47) belongs to the *EB* scheme, see Eqs. (32) and (33), whereas the corresponding tensor in the literature [78] is the one of the *EH* scheme. However, as we can see in Eq. (47), because of $\mu \approx 1$ the differences are marginal and do not touch our arguments.

One can distinguish three types of diagonals (for the complete set of magnetoelectric tensors see, e.g., Refs. [37,77,27], Table1.5.8.1, for the examples cited, see Ref. [27], Table 1.5.8.2, except for [60,78]):

(i) 19 point groups with $\alpha_{11} \neq \alpha_{22} \neq \alpha_{33}$.

Examples:
Point group $m'm'm'$: $DyAlO_3$, $GdAlO_3$, $TbAlO_3$,
Point group m': $Ni_3B_7O_{13}I$,
Point group $m'm'2$: $Cu_3B_7O_{13}Cl$.

(ii) 8 point groups with $\alpha_{11} = \alpha_{22} \neq \alpha_{33}$ ($\alpha_{11} = \alpha_{22} = \alpha_{\perp}$, $\alpha_{33} = \alpha_{\parallel}$).

Examples:
Point group $\bar{3}'m'$: [Cr_2O_3] [62], $Nb_2Mn_4O_9$, $Nb_2Co_4O_9$, $Ta_2Mn_4O_9$, $Ta_2Co_4O_9$,
Point group $\bar{3}'$: Cr_2O_3 [60,62],
Point group $4/m'm'm'$: Fe_2TeO_6.

(iii) 5 point groups with $\alpha_{11} = \alpha_{22} = \alpha_{33}$.

Examples:
Point group $\bar{4}'3m'$ (expected): $Cr_3B_7O_{13}Br$, $Cr_3B_7O_{13}I$ [78], $Cu_3B_7O_{13}I$ [79].

Thus it is clear that the pseudoscalar $\tilde{\alpha}$ occurs in quite a number of different substances. Its existence can no longer be denied.

On

- **Paraphotons** → Hidden sector
- **Chameleons** → Dark energy

Solar paraphoton spectrum

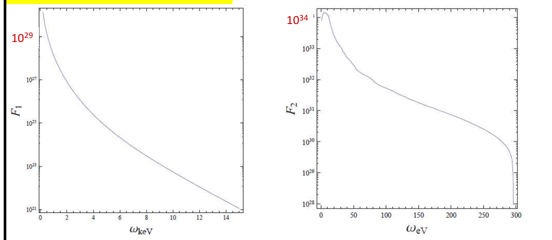
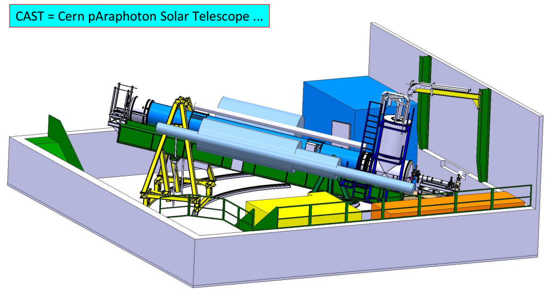


Figure 2: The F_1 and F_2 functions give the flux of solar transverse and longitudinal B's at the Earth for $m_{\gamma'} \ll 1$ eV. Notice the different energy scales, only eV L-hidden photons are emitted while the spectrum of T-modes extends to X-ray energies, although considerably suppressed. See the text for details.

... final spectra?

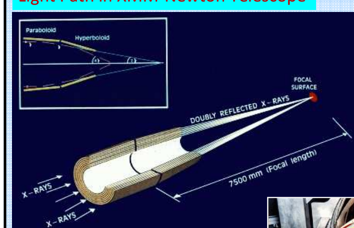
Javier Redondo, Helioscope Bounds on Hidden Sector Photons,
http://xxx.lanl.gov/PS_cache/arxiv/pdf/0801/0801.1527v2.pdf

CAST = Cern pAraphoton Solar Telescope ...



Mirror(s)
XRT present → low threshold
XMM/Newton → after axion run finishes without magnet

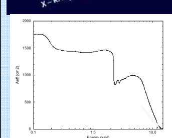
Light Path in XMM-Newton Telescope

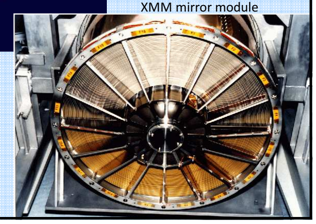


CAST' XRT without magnet:

→ after CAST !

XMM mirror module





Collecting area:
~1900cm^2 (<150 eV), ~1500cm^2 (@ 2 keV), ~900cm^2 (@ 7keV), ~350 cm^2 (@ 10 keV).

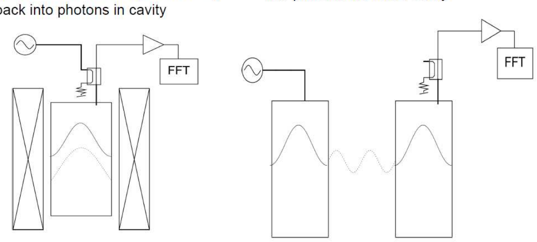
ADMX: chameleon & HSP search

Chameleons

Scalars/pseudoscalars that mix with photons, and are trapped by cavity walls. Arise in some dark energy theories. Detectable by slow decay back into photons in cavity

Hidden-sector photons

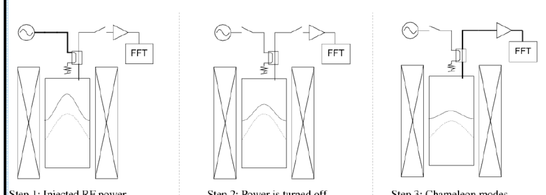
Vector bosons with photon quantum numbers and very weak interactions. Detectable by reconverting HSPs back into photons in ADMX cavity



http://www.physics.ucla.edu/hep/dm10/talks/carosi.pdf

ADMX: chameleon search

Chameleons: Particles whose mass depends on local matter density.
(possible dark energy particle)
Can mix with photons but have trouble moving through walls.



Step 1: Injected RF power excites E&M and chameleon modes

Step 2: Power is turned off, E&M modes decay

Step 3: Chameleon modes slowly decay into E&M modes which are detected through antenna

http://www.physics.ucla.edu/hep/dm10/talks/carosi.pdf

GammeV Laboratory Constraints on Chameleon Dark Energy

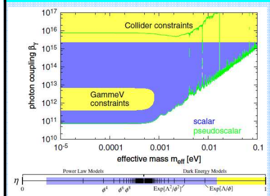


FIG. 4 (color online). Top: Scalar (solid) and pseudoscalar (outline) constraints, at 95% confidence, in the (m_{eff}, β_γ) plane for $\xi_{ref} = 0$. Bottom: CP models probed by GammeV [light gray (yellow)] and CHASE [dark gray (blue)] as parametrized by η.

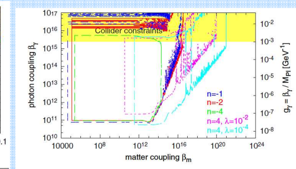


FIG. 5 (color online). 95% confidence-level limits on CPs with power-law potentials (3), where we use $\kappa = 1$ for $N < 0$ and the standard $\kappa = \lambda/4!$ for ϕ^4 theory ($N = 4$).

JH Steffen, A Upadhye, A Baumbaugh, AS Chou, PO Mazur, R Tomlin, A Weltman, W Wester, PRL 105, 261803 (2010) http://prl.aps.org/abstract/PRL/v105/i26/e261803

Solar Chameleons with CAST

...coming soon!

?

DANKE!

Excercise!!

➔ Sun as DM converter?

→ B + ρ_e

Magnetised plasmas @ Sun's atmosphere

→ (relic) ~axion-to-photon conversion?

Flare (kernels)

- ρ_e~10^{14}/cm^3 → ω_{pl} ~ $3\cdot10^{-4}$eV ~ 100GHz -> 3mm

Spicules (~1% surface)

- ρ_e~10^{12}/cm^3 → ω_{pl} ~ $3\cdot10^{-5}$eV ~ 10GHz -> 30mm

(>10x ρ_e-environment)

...?more places?...

→ a rest mass region not easily accessible yet!

Excercise!!

Spectrum?

Light Deficit in sunspots ✓

Photon ⇔ axion

⇩ ⇩

many tries (multiple scatterings) 1 try

Disappearance of photons into ~axions :

- I_{mising} ~B^2
- ⇝ 100% ↛ ½ , 1/3 , ¼
- Dynamic Sun -> disk / limb

→ source of LES ~axions!?