Experimental Search for Physics beyond the SM:

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

Lecture 2

K. Zioutas

University of Patras / Greece

➔ **exercises?**

➔ **Ongoing research!**

Spring Blockcourse 2011
Dresden

8th- 10th March 2011

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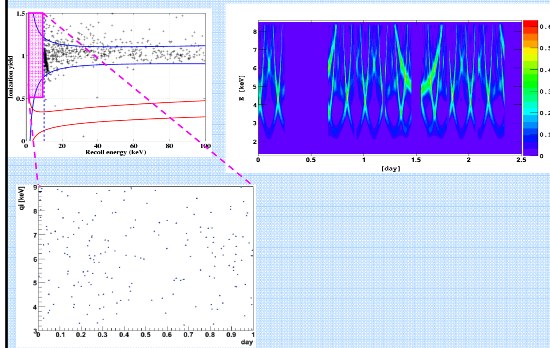
aBragg CDMS Low Energy Gammas



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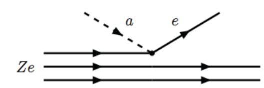
aBragg feedback: solids with large periodicities!?

a-e coupling: axioelectric effect ➔

Relic axion-like particles in the local halo

As dark matter candidates axions may be distributed in the local halo.

May materialize in the detectors via an axio-electric coupling:

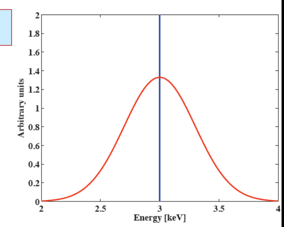


➔ Axio-electric effect

http://prl.aps.org/abstract/PRD/v82/i6/e065006
2010

Energy of the electron is given by the mass of the axion.

Conversion results in a gaussian distribution with width given by the detector's energy resolution.

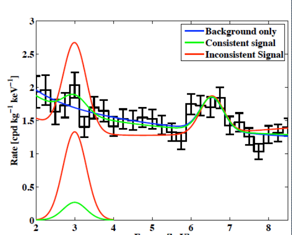


Likelihood analysis II

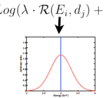
Take possible contribution from Fe decays into account when modeling the background.

Do not subtract this contribution while approaching this energy range.

Maximise the unbinned log likelihood function for each energy/axion mass.



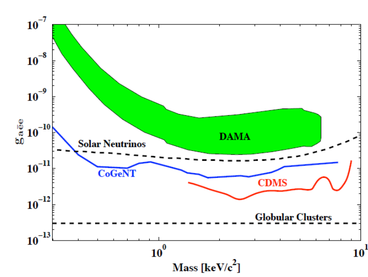
$$Log(\mathcal{L}) = -R_T + \sum_{i,j} Log(\lambda \cdot \mathcal{R}(E_i, d_j) + B(E_i, d_j))$$



Determine total rate λ for which a signal contribution is rejected at a 90% C.L.

Relic axion result

Excludes the relic axion interpretation of the DAMA signal claim.
World-leading experimental upper limit on the axio-electric coupling.



➔ WDs

Z. Ahmed et al., CDMS, PRL 103, 141802 (2009)
http://prl.aps.org/pdf/PRL/v103/i14/e141802

a-axion-electron coupling

Q:

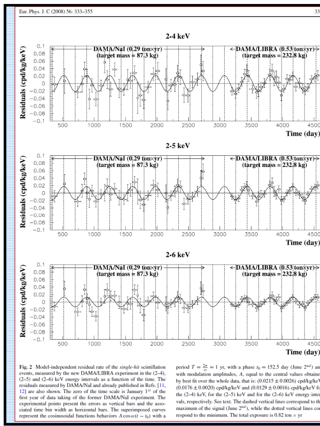
***a*Bragg via**
coherent Compton scattering?

Similarly to Primakoff scattering off the nucleus
→ off the atomic electrons too?

$\sigma_c \sim (E_a/511\text{keV})^2$

excersize!

DAMA → annual modulation



Signal:
higher rate in June,
lower in Decemeber

Background:
constant in time?

http://www.springerlink.com/content/gw517728p3386645/fulltext.pdf

A testable conventional hypothesis for the DAMA-LIBRA annual modulation

February 2011

Abstract: The annual modulation signal observed by the DAMA-LIBRA Collaboration (D-L) may plausibly be explained as a consequence of energy deposited in the NaI(Tl) crystals by cosmic ray muons penetrating the detector. Delayed pulses in the approximate energy range of interest have been observed as a sequel to energy deposited by UV irradiation. The same behavior may be reasonably expected to occur for energy deposited by any source of ionization or excitation. D-L can test this hypothesis by searching for time correlations between muon events and pulses in modulation energy range in current data, and by renewed operation of the array at a sufficiently low temperature that would freeze out the phenomenon.

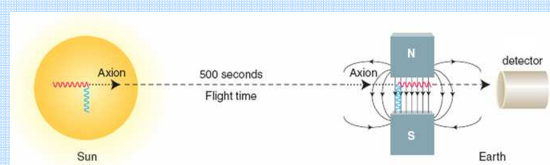
D. Nygren, astro-ph/1102.0815 http://xxx.lanl.gov/abs/1102.0815

✚ **S. Gninenko,** private communication.

Axion production and detection

- Use the sun as an active source of both **plasma** fields and **nuclear processes** to produce axions
- Convert solar axions into detectable photons via **coherent** Primakoff effect in a laboratory magnetic field

→ **always!**



...elsewhere too! → **stars!**

Sun:

A perfectly shielded (radioactive) source of:

neutrinos,
axions,
chameleons,
paraphotons( ),
....

*a*Mößbauer effect

... with "wall" between source and absorber!

Volume 217, number 3 PHYSICS LETTERS B 26 January 1989

SEARCH FOR LIGHT BOSONS VIA THE MÖSSBAUER EFFECT

A. DE RÚJULA
CERN, CH-1211 Geneva 23, Switzerland

and

K. ZIOUTAS
University of Thessaloniki, GR-54006 Thessaloniki, Greece

:10.1016/0370-2693(89)90880-0

→

Thermal nuclear excitations inside stars

VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

Red-Giant Evolution, Metallicity, and New Bounds on Hadronic Axions

W. C. Haxton and K. Y. Lee

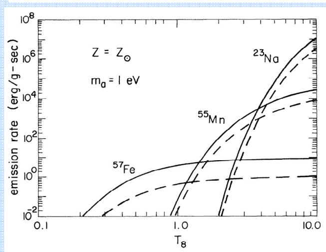


FIG. 1. Hadronic axion emission rates as a function of temperature for $m_a = 1$ eV and $Z = Z_\odot$. The solid (dashed) lines correspond to $S = 0.68$ (-0.09), the NQM (EMC) value.

→ Axion emission from nuclear M1-transitions

http://prl.aps.org/pdf/PRL/v66/i20/p2557_1

Axion emission from ^{57}Fe 14.4keV M1-transitions

VOLUME 75, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1995

Proposal to Search for a Monochromatic Component of Solar Axions Using ^{57}Fe

Shigetaka Moriyama*

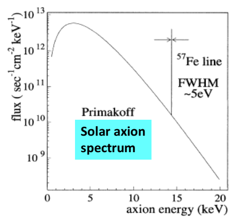
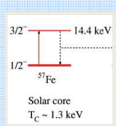


FIG. 1. Differential flux of the axion from the Sun. The sharp peak corresponds to the axion emission from the ^{57}Fe deexcitation. The broad part of the differential flux corresponds to the axion generated through the Primakoff effect.

http://prl.aps.org/pdf/PRL/v75/i18/p3222_1

Axion emission from nuclear transitions

- **nuclear de-excitation via axion emission** $(J^\pi_{axion}=0^-,1^+,2^-,...)$
  - → axion emission from magnetic nuclear transitions
  - → monoenergetic solar axions ($E_a \approx E_{transition}$)
- excitation of nuclei in the Sun (kT ~ 1.3 keV) :
  - thermal excitations : ^{57}Fe (14.4 keV) , ^{83}Kr (9.4keV)

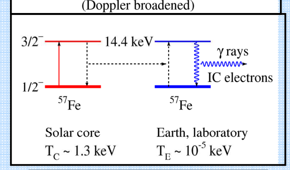


Search for solar axions using ^{57}Fe – RBI /Zagreb

M. Krčmar, Z. Krečak, M. Stipčević, A. Ljubičić, D.A. Bradley, PLB 442 (1998) 38

Due to Doppler broadening, axions could be detected via resonant absorption

AXION LINE: E_a ~ 14.4 keV, FWHM ~ 5 eV (Doppler broadened)



$$P = \int \frac{d\Phi(E)}{dE}\sigma_D(E)\,dE,$$

$\Gamma = 4.7 \times 10^{-9}$ eV, $E_{recoil} = 1.9 \times 10^{-3}$ eV

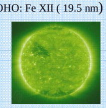
$E_{reds} = 0.15$ eV

$$\sigma_D(E) = \sigma_0 \frac{\Gamma_a}{\Gamma_\gamma}\frac{\sqrt{\pi}\,\Gamma}{\sqrt{2}\,\sigma(T_E)} e^{-\frac{(E^*-E)^2}{2\sigma(T_E)^2}}; \quad \sigma_0 = 2\pi g \left(\frac{\hbar c}{E^*}\right)^2 \frac{\Gamma_\gamma}{\Gamma}$$

Search for solar axions using ^{57}Fe – RBI /Zagreb

W.C. Haxton & K.Y. Lee, PRL 66 (1991) 2557; S. Moriyama, PRL 75 (1995) 3222

SOHO: Fe XII (19.5 nm)



- Axion source: thermally excited ^{57}Fe nuclei
  - 2.2% abundance in natural Fe (solar abundance 2.7 x 10^{-5})
  - 14.4 keV axion spectrum :

Gaussian

$$\frac{d\Phi(E)}{dE} = \frac{1}{4\pi R_{SE}^2} N \frac{1}{\tau_\gamma}\frac{\Gamma_a}{\Gamma_\gamma} M_S \int \frac{2e^{-E^*/kT}}{1+2e^{-E^*/kT}} \frac{1}{\sqrt{2\pi}\sigma(T)} e^{-\frac{(E^*-E)^2}{2\sigma(T)^2}} dM_r$$

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k}\right)^3 \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2} \times \left[\frac{g_0\beta + g_3}{(\mu_0 - \frac{1}{2})\beta + \mu_3 - \eta}\right]^2$$

$$\sigma(T) = E^*\left(\frac{kT}{m}\right)^{\frac{1}{2}}$$

$N = 2.9 \times 10^{17}$ g^{-1}, $\tau_\gamma = 1.3 \times 10^{-6}$ s

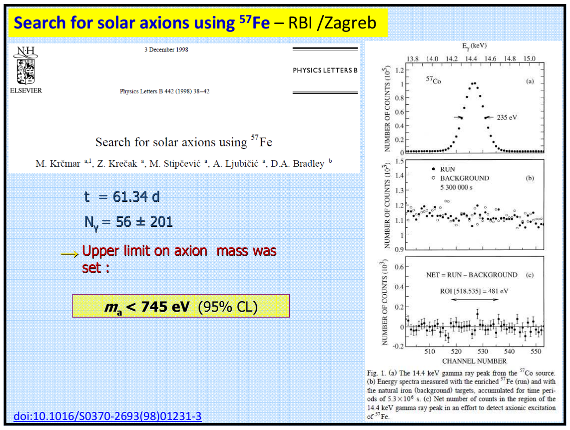
Doppler broadening

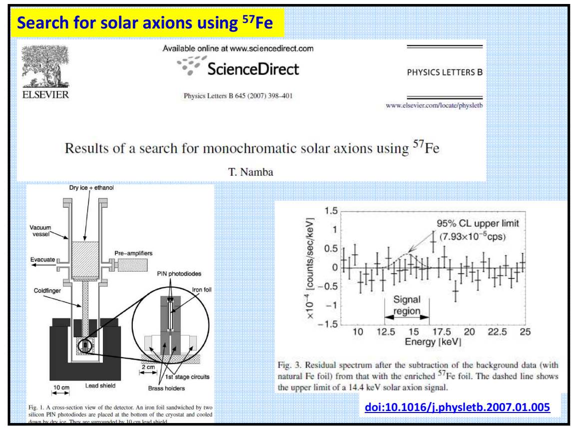
μ_0, μ_3 = isoscalar and isovector nuclear magnetic moments β = -1.19, η = 0.80

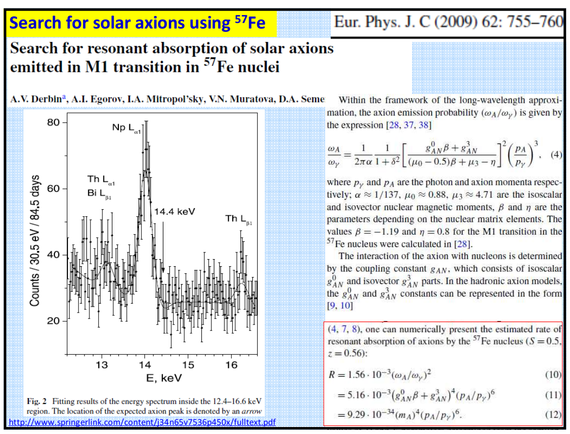
Search for solar axions using ^{57}Fe – RBI /Zagreb

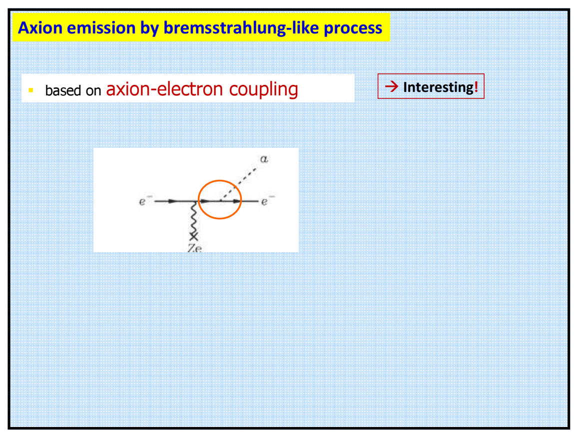
Experimental setup:

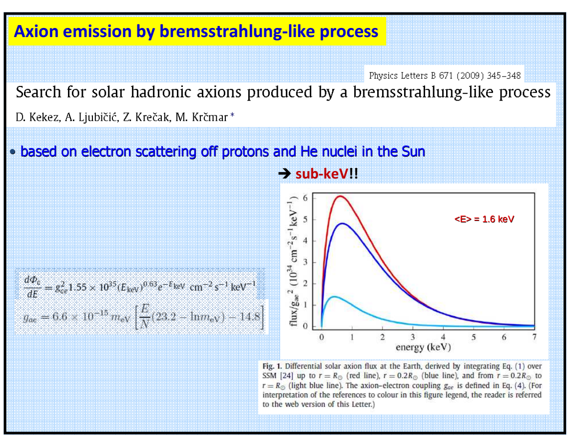
- **Si(Li) detector**
- resolution @ 14.4 keV: 235 eV
- **target** made of **enriched ^{57}Fe** (m= 31.53 mg, Φ=10 mm, d=53μm)
- efficiency @ 14.4 keV: 1.6%

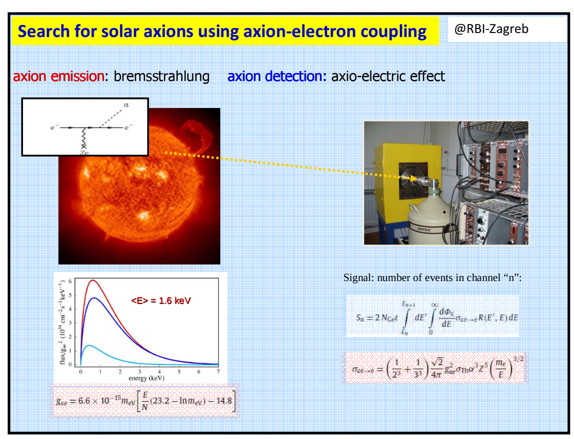

Search for solar axions using 57Fe – RBI /Zagreb
3 December 1998
PHYSICS LETTERS B
Physics Letters B 442 (1998) 38–42
Search for solar axions using 57Fe
M. Krčmar, Z. Krečak, M. Stipčević, A. Ljubičić, D.A. Bradley
t = 61.34 d
Nγ = 56 ± 201
Upper limit on axion mass was set :
ma < 745 eV (95% CL)
doi:10.1016/S0370-2693(98)01231-3
CHANNEL NUMBER
NET = RUN – BACKGROUND
RUN
BACKGROUND
Fig. 1. (a) The 14.4 keV gamma ray peak from the 57Co source. (b) Energy spectra measured with the enriched 57Fe (run) and with the natural iron (background) targets, accumulated for time periods of 5.3×10^6 s. (c) Net number of counts in the region of the 14.4 keV gamma ray peak in an effort to detect axionic excitation of 57Fe.


Search for solar axions using 57Fe
Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
PHYSICS LETTERS B
Physics Letters B 645 (2007) 398–401
Results of a search for monochromatic solar axions using 57Fe
T. Namba
95% CL upper limit
(7.93×10^-6 cps)
Signal region
Energy [keV]
×10^-4 [counts/sec/keV]
Fig. 3. Residual spectrum after the subtraction of the background data (with natural Fe foil) from that with the enriched 57Fe foil. The dashed line shows the upper limit of a 14.4 keV solar axion signal.
doi:10.1016/j.physletb.2007.01.005


Search for solar axions using 57Fe
Eur. Phys. J. C (2009) 62: 755–760
Search for resonant absorption of solar axions emitted in M1 transition in 57Fe nuclei
A.V. Derbin, A.I. Egorov, I.A. Mitropol'sky, V.N. Muratova, D.A. Seme
Counts / 30.5 eV / 84.5 days
E, keV
14.4 keV
Fig. 2 Fitting results of the energy spectrum inside the 12.4–16.6 keV region. The location of the expected axion peak is denoted by an arrow
http://www.springerlink.com/content/j34n65v7536p450x/fulltext.pdf
Within the framework of the long-wavelength approximation, the axion emission probability (ωA/ωγ) is given by the expression [28, 37, 38]
where pγ and pA are the photon and axion momenta respectively; α ≈ 1/137, μ0 ≈ 0.88, μ3 ≈ 4.71 are the isoscalar and isovector nuclear magnetic moments, β and η are the parameters depending on the nuclear matrix elements. The values β = −1.19 and η = 0.8 for the M1 transition in the 57Fe nucleus were calculated in [28].
The interaction of the axion with nucleons is determined by the coupling constant gAN, which consists of isoscalar g0AN and isovector g3AN parts. In the hadronic axion models, the g0AN and g3AN constants can be represented in the form [9, 10]
(4, 7, 8), one can numerically present the estimated rate of resonant absorption of axions by the 57Fe nucleus (S = 0.5, z = 0.56):


Axion emission by bremsstrahlung-like process
based on axion-electron coupling
→ Interesting!

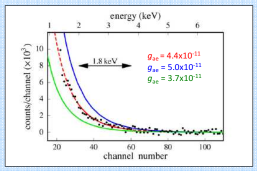

Axion emission by bremsstrahlung-like process
Physics Letters B 671 (2009) 345–348
Search for solar hadronic axions produced by a bremsstrahlung-like process
D. Kekez, A. Ljubičić, Z. Krečak, M. Krčmar
based on electron scattering off protons and He nuclei in the Sun
→ sub-keV!!
<E> = 1.6 keV
energy (keV)
Fig. 1. Differential solar axion flux at the Earth, derived by integrating Eq. (1) over SSM [24] up to r = R⊙ (red line), r = 0.2R⊙ (blue line), and from r = 0.2R⊙ to r = R⊙ (light blue line). The axion–electron coupling gae is defined in Eq. (4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)


Search for solar axions using axion-electron coupling
@RBI-Zagreb
axion emission: bremsstrahlung
axion detection: axio-electric effect
<E> = 1.6 keV
Signal: number of events in channel "n":

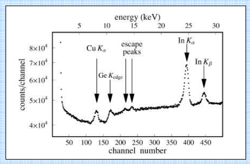
Search for solar axions using axion-electron coupling

Experimental setup:

- HPGe detector
- resolution @ 2.0-3.8 keV: 660eV
- target HP**Ge** detector
  m=**1.5 kg**, Φ=67 mm, d=80mm
- efficiency @ 2.0-3.8 keV: 100%



Results:



conservative limit:

$g_{ae} \leq 4.4x10^{-11}$

$m_a \leq 334$ eV (95% CL)

Search for solar axions using axion-electron coupling: 8.41keV, ^{169}Tm

PHYSICAL REVIEW D 83, 023505 (2011)

Constraints on the axion-electron coupling for solar axions produced by a Compton process and bremsstrahlung

A. V. Derbin,* A. S. Kayunov, V. V. Muratova, D. A. Semenov, and E. V. Unzhakov

Source excitation?

DERBIN et al.

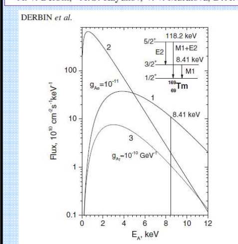


FIG. 1. 1,2—the spectra of the axions produced by the Compton process and the bremsstrahlung, correspondingly ($g_{Ae} = 10^{-11}$). 3—spectrum of the axions produced by the Primakoff effect ($g_{A\gamma} = 10^{-10}$ GeV^{-1}). The level scheme of the ^{169}Tm nucleus is shown in the inset.

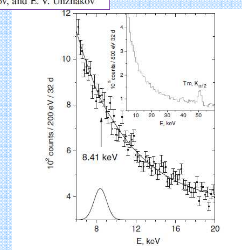
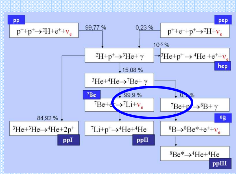


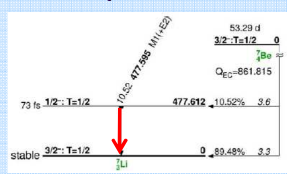
FIG. 2. The Si(Li)-detector energy spectra measured in the anticoincidence with the veto signal. The solid line shows the fitting result in the 6–20 keV range corresponding to the minimum χ^2. The spectrum in the (4–60) keV region is shown in the inset.

http://prd.aps.org/pdf/PRD/v83/i2/e023505

Axion emission from nuclear transitions: 477keV, ^{7}Li

- **nuclear de-excitation via axion emission** (J^π_{axion}=0$^-$,1$^+$,2$^-$,...)
  - → axion emission from magnetic nuclear transitions
  - → monoenergetic axions ($E_a \approx E_{transition}$)
  - Excitation of nuclei in the Sun (kT ~ 1.3 keV) :
    - thermal excitation : ^{57}Fe (14.4 keV) , ^{83}Kr (9.4keV)
    - nuclear reaction : ^{7}Be + e$^-$ → ^{7}Li* (478 keV) + ν_e (384 keV)





"aMößbauer" effect: M1, 477keV ^{7}Li

PHYSICAL REVIEW D, VOLUME 64, 115016

Search for solar axions using ^{7}Li

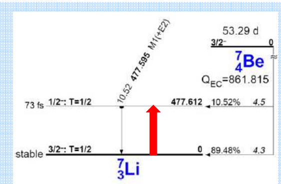
M. Krčmar,[1,*] Z. Krečak,[1] A. Ljubičić,[1] M. Stipčević,[1] and D. A. Bradley[2]

[1]Rudjer Bošković Institute, POB 180, 10002 Zagreb, Croatia

[2]School of Physics, University of Exeter, Stocker Road, Exeter EX4 4Q1, United Kingdom

(Received 20 April 2001; published 13 November 2001)

We describe a novel approach to the search for solar, near-monochromatic hadronic axions, the latter being suggested to be created in the solar core during $M1$ transitions between the first excited level of ^{7}Li, at 478 keV, and the ground state. As a result of Doppler broadening, in principle these axions can be detected via resonant absorption by the same nuclide on the Earth. Excited nuclei of ^{7}Li are produced in the solar interior by ^{7}Be electron capture and thus the axions are accompanied by emission of ^{7}Be solar neutrinos of energy 384 keV. An experiment was made which has yielded an upper limit on hadronic axion mass of 32 keV at the 95% confidence level.



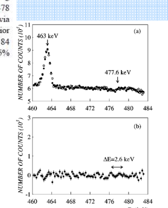


FIG. 2. (a) The energy spectra accumulated for 9.6×10^6 s. Filled and open circles denote the run and background data, respectively. The peak at 463 keV arises from environmental radioactivity and corresponds to the γ transition in ^{228}Th. (b) Net number of counts (run–background) in the region of the 478 keV gamma ray peak determined in an effort to detect axionic excitation of ^{7}Li.

http://prd.aps.org/pdf/PRD/v64/i11/e115016

Search for solar axions from M1, 477keV transition ^{7}Li with Borexino CTF

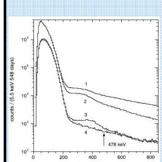


Fig. 5. CTF3 spectrum measured during 548 days. The sequence of the applied cuts is shown from *upper plot* to the *lower one*: 1 – total data; 2 – data without events tagged by muon veto and time correlated events; 3 – radial cut $r < 83$ cm; 4 – all previous cuts plus α/β discrimination

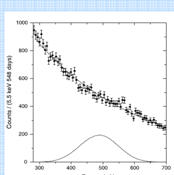
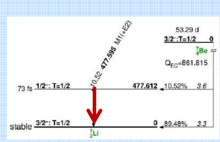


Fig. 7. The exponential fit in the region 290–700 keV. The response function S_{AE} for axio-electric effect corresponds to 5×10^3 events



CTF is a simplified scaled version of the Borexino detector. Its active volume, □ 4 tons of liquid scintillator, is contained in a transparent spherical nylon vessel, 2m diameter and 0.5mm thick. The active detector is surrounded by 100 PMTs mounted on an open support structure. The PMTs are fitted with light concentrators which provide a 21% optical coverage. The construction is immersed in 1000m^3 of high purity shielding water, contained in an external cylindrical tank 10m diameter and 11m high. Water shields the scintillator against γ radiation emitted by radioactive contaminants in the PMTs and their support structure as well as against γ's following the capture of neutrons generated within the walls of the experimental hall. Another 16 upward-looking PMTs mounted on the bottom of the tank form an active muon veto system (MVS).

The BOREXINO Coll., Eur. Phys. J. C 54, 61–72 (2008)

http://www.springerlink.com/content/194176060l870p86/fulltext.pdf

Search for solar axions from the M1-transition of ^{7}Li w/ Borexino CTF

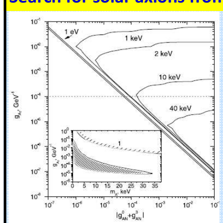


Fig. 12. Primakoff conversion process on ^{12}C. Parameters $g_{a\gamma}$ and g_{AN} are excluded inside outlined regions. In *inset* the excluded region of $g_{A\gamma}$ and m_A is shown (1 – limits from [33])

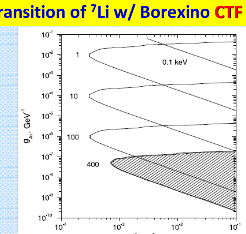


Fig. 11. $A \to 2\gamma$ decay. The excluded regions of $g_{A\gamma}$ and g_{AN} values obtained for different axion masses

Search for solar axions emitted in the 478 keV M1-transition of 7Li performed with the CTF prototype of Borexino detector. **The Compton conversion of axion to a photon, axio-electric effect, decay axion in two photons and Primakoff conversion on nuclei were searched.** The signature of all above reactions is the appearance of 478 keV peak in the energy spectra of CTF. No statistical significant indications on axion interactions were found. The new, model independent, upper limits on constants of interaction of axion with electrons, photons and nucleons – gAegAN ≤ (1.0–2.4)×10−10 at mA ≤ 450 keV and gAγgAN ≤ 5×10^{-9}GeV^{-1} at mA ≤ 0 keV were obtained (90%c.l.). For heavy axions the limits gAe < (0.7–2.0)×10^{-8} and gAγ < 10^{-9}–10^{-8} at 100<mA < 400 keV are obtained in assumption that gAN depends on mA as for KSVZ axion model. These limits are (2–100) times stronger than obtained by laboratory-based experiments using nuclear reactors and artificial radioactive sources and put some restrictions for heavy axion models.

The BOREXINO Coll., Eur. Phys. J. C 54, 61–72 (2008) http://www.springerlink.com/content/194176060l870p86/fulltext.pdf

*"a*Mößbauer" effect: M1, 477keV ^{7}Li

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 806 (2008) 388–397

^{7}Li solar axions: Preliminary results and feasibility studies

P. Belli, R. Bernabei, R. Cerulli, F.A. Danevich, A. d'Angelo, V.I. Gorlitetsky, B.V. Grinyov, A. Incicchitti, V.V. Kobychev, M. Laubenstein, V.M. Mokina, S.S. Nagorny, S. Nisi, D. Prosperi, O.G. Shkulkova, V.I. Tretyak

A sample with N_7 ^{7}Li nuclei + the Solar Standard Model:

$$R = N_7 \times t \times 1.74 \times 10^{-45} \times \left(\frac{m_a}{1\ \mathrm{eV}}\right)^4$$

→ m_{axion}<13.9keV/c²

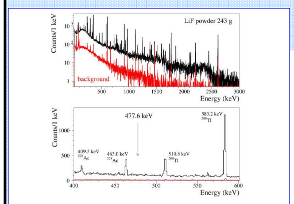


Fig. 2. Energy distribution measured with the LiF sample (243 g) by the LNGS HP Ge GSOR detector (408 cm³) during 722 h in comparison with the background measured during 1571 h (normalized here to 722 h).

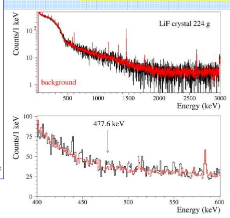


Fig. 3. Energy distribution measured with the LiF(W) crystal (224 g) by the LNGS HP Ge GEBER detector (244 cm³) during 633 h in comparison with the background measured during 3047 h (normalized here to 633 h).

doi:10.1016/j.nuclphysa.2008.02.306

Laboratory experiment

2x Primakoff effect

PRL 105, 250405 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Photon Regeneration Experiment for Axion Search Using X-Rays

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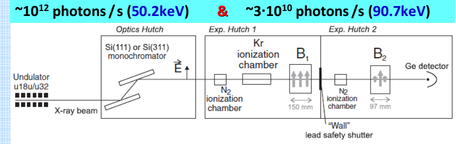
European Synchrotron Radiation Facility, F-38043 Grenoble, France, EU
(Received 16 August 2010; published 16 December 2010)

In this Letter we describe our novel photon regeneration experiment for the axionlike particle search using an x-ray beam with a photon energy of 50.2 and 90.7 keV, two superconducting magnets of 3 T, and a Ge detector with a high quantum efficiency. A counting rate of regenerated photons compatible with zero has been measured. The corresponding limits on the pseudoscalar axionlike particle–two-photon coupling constant is obtained as a function of the particle mass. Our setup widens the energy window of purely terrestrial experiments devoted to the axionlike particle search by coupling to two photons. It also

~10^{12} photons / s (50.2keV) & ~$3\cdot10^{10}$ photons / s (90.7keV)



Experimental Setup. The double crystal monochromator is adjusted to select the desired photon energy. The first experimental hutch corresponds to the ALP generation area with the transverse magnetic field B1. The second experimental hutch contains the second magnetic field B2 which allows us to reconvert ALPs to photons. Photon detector: a liquid N_2 cooled Ge with a high quantum efficiency.

http://prl.aps.org/abstract/PRL/v105/i25/e250405

Laboratory experiment

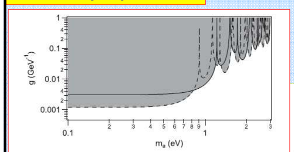


FIG. 2. Confidence level limits of 95% on the ALP-two photon coupling constant g as a function of the particle mass m_a. The grey area is excluded. The dashed line represents limits obtained with a photon energy of 50.2 keV while the solid line corresponds to 90.7 keV.

Our experimental setup is shown in Fig. 1. We use two different photon energies, $\omega = 50.2$ keV and 90.7 keV, corresponding to slightly different settings of the x-ray beam line. For 50.2 keV (resp. 90.7 keV), a Si(111) [resp. Si(311)] double crystal monochromator is adjusted to select x rays emitted by the 5th (resp. 9th) harmonic of the cryogenic permanent magnet multipole undulator source U18, closed to a gap of 6.0 mm [27,28]. The energy bandwidth is 7.3 eV (resp. 6.8 eV). For both energies, the size of the beam is 2×2 mm² and the synchrotron x rays are horizontally polarized. The beam direction is stabilized

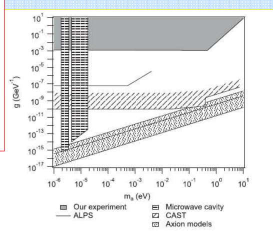
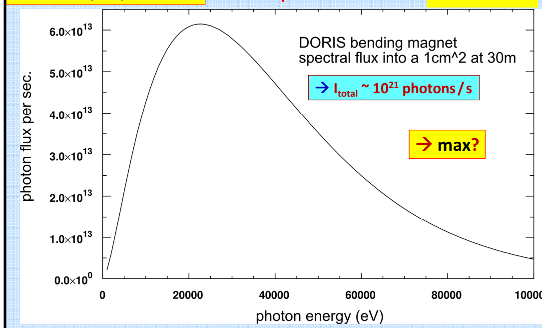


FIG. 3. Limits on the ALP–two-photon coupling constant g as a function of the particle mass m_a obtained by experimental searches. Our exclusion region is presented as the grey area. See text for more details.

http://prl.aps.org/abstract/PRL/v105/i25/e250405

Laboratory experiments

Improvement? → excersize!!

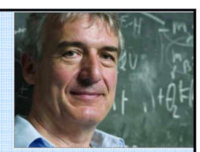


→ from / with Axel Lindner / DESY

a-helioscopes →

Idea #1

...the principle



P. Sikivie 1983

Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

Experimental Tests of the "Invisible" Axion

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(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

http://prl.aps.org/pdf/PRL/v51/i16/p1415_1

Idea #2 … **the detector design**

PHYSICAL REVIEW D

THIRD SERIES, VOLUME 39, NUMBER 8 — 15 APRIL 1989

http://prd.aps.org/pdf/PRD/v39/i8/p2089_1

Design for a practical laboratory detector for solar axions

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Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, University of California, Livermore, California 94550
and Astronomy Department, University of California, Berkeley, California 94720

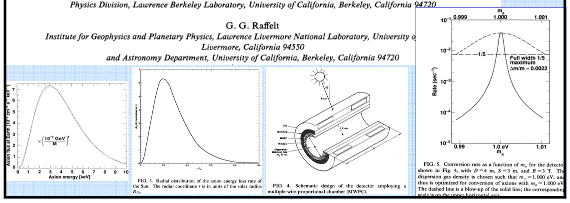
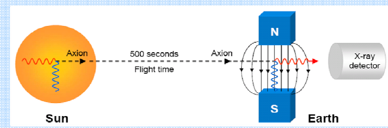


FIG. 5. Conversion rate as a function of m_a for the detector ...

CERN Axion Solar Telescope:
QCD Axions or other similar exotica → WISPs



Signal: excess of X-rays during alignment over background

Production: Primakoff effect
Thermal photons interacting with solar nuclei produce Axions.

Detection Inverse Primakoff:
axion interacting with a very strong magnetic field converts to a photon

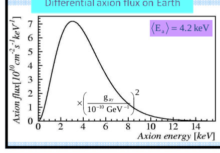
Expected number of Photons:

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} \cdot P_{a\to\gamma} \cdot S \cdot t \cdot dE_a$$

$P_{a\to\gamma} \approx 1.7\times10^{-17}$

$$\Phi_\gamma = 0.51 \text{ cm}^{-2}\text{ d}^{-1}\, g_{10}^4 \left(\frac{L}{9.26\text{ m}}\right)^2 \left(\frac{B}{9.0\text{ T}}\right)^2$$

Differential axion flux on Earth



Photon-axion mixing

In an external transverse magnetic field photons and axion mix, leading to photon-axion oscillations. The probability in a constant field is given by

$$p_\gamma = \frac{1}{2} g_{a\gamma}^2 B^2 \frac{1-\cos qL}{q^2}$$

where

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

In the limit $q \to 0$ we obtain

$$p_\gamma = \frac{1}{4} g_{a\gamma}^2 B^2 L^2$$

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

Axion-photon conversion probability:

$$p_\gamma(L) = \left(\frac{B}{2M}\right)^2 \left[\frac{1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)}{q^2 + (\Gamma^2/4)}\right]$$

Raffelt, Stodolsky (1988)
van Bibber, McIntyre, Morris, Raffelt (1989)

- L: path length.
- $\Gamma = \lambda_x^{-1}$.
- λ_x: absorption length.
- $\ell = 2\pi/q$: oscillation length.

$$q = \left|m_\gamma^2 - m_a^2\right| / (2\omega_a).$$

- m_γ: photon plasma mass.

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

Birth of solar axion astrophysics in BNL 1990

69, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1992

Search for Solar Axions

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Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

F. A. Nezrick
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

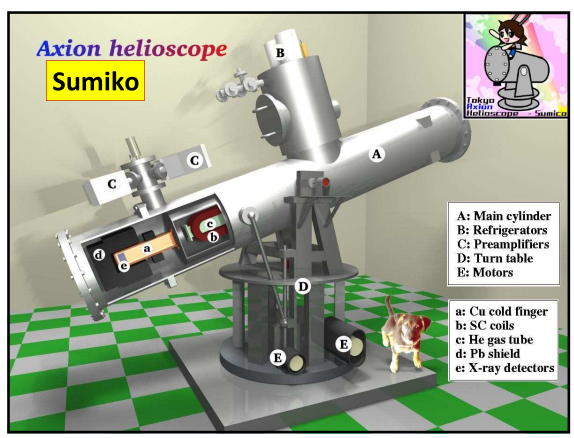
(Received 22 May 1992)

We have searched for a flux of axions produced in the Sun by exploiting their conversion to x rays in a static magnetic field. The signature of a solar axion flux would be an increase in the rate of x rays detected in a magnetic telescope when the Sun passes within its acceptance. From the absence of such a signal we set a 3σ limit on the axion coupling to two photons $g_{a\gamma\gamma} \equiv 1/M < 3.6\times10^{-9}$ GeV^{-1}, provided the axion mass $m_a < 0.03$ eV, and $< 7.7\times10^{-9}$ GeV^{-1} for $0.03 < m_a < 0.11$ eV.

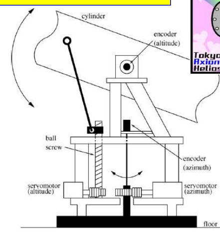
PACS numbers: 14.80.Gt, 95.85.Qx, 96.60.Vg

nt theories of elementary particles predict the ex- of low mass scalar or pseudoscalar particles. rise naturally when a global symmetry is spon-

Axions that couple directly to electrons through an eea vertex provide a very efficient energy-loss mechanism and their relative coupling is excluded by many orders of



The Tokyo axion helioscope Sumico

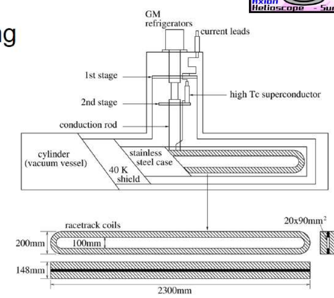


- Azimuth: 360°
- Altitude: ±28°
- Driving system with AC servomotors
- NOVAS-C for calculating position of celestial object
- Case of tracking the Sun: 12 hours/day on average

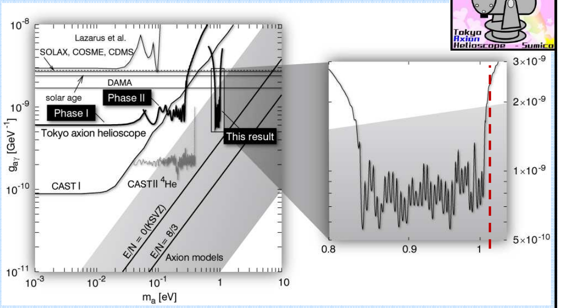
The Tokyo axion helioscope Sumico

Magnet

- Superconducting magnet (4T 2.3m)
- Two GM refrigerators
  - No liquid He



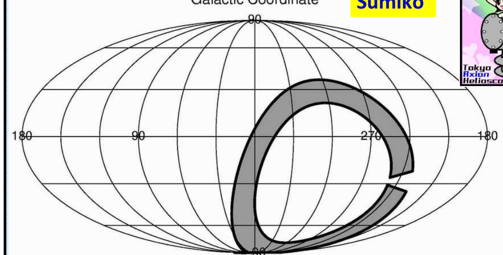
The Tokyo axion helioscope Sumico



http://www.icepp.s.u-tokyo.ac.jp/~minowa/Minowa_Group.files/sumico.htm

See about Sumico http://xxx.lanl.gov/PS_cache/arxiv/pdf/1002/1002.0468v1.pdf
http://xxx.lanl.gov/PS_cache/arxiv/pdf/1004/1004.1308v1.pdf

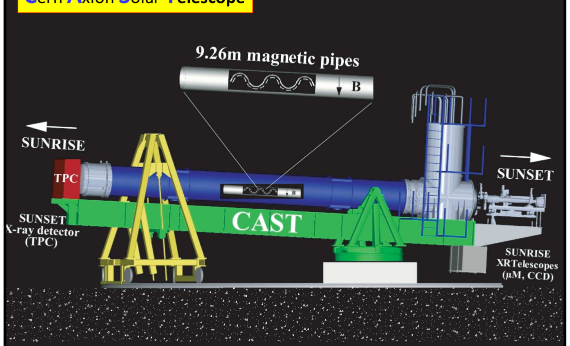
Galactic Coordinate Sumiko



Search for possible axions emitted by other celestial objects. We scanned about 10% of the celestial sphere as shown in the following figure and searched for point axion sources. We also searched for axions from four compact objects, the galactic center, Sco X-1, Vela X-1, and Crab nebula. The AXION HELIOSCOPE is further directed toward the soft gamma ray repeater SGR 1900+14 to search for axions produced in it with its very strong magnetic field. No positive signal is found so far, and we put limits on the axion flux coming from them for the first time.

http://www.icepp.s.u-tokyo.ac.jp/~minowa/Minowa_Group.files/sumico.htm

Cern Axion Solar Telescope



CAST

Decommissioned prototype LHC dipole magnet.
Magnetic field: B=9 T
Length: L=9.26 m

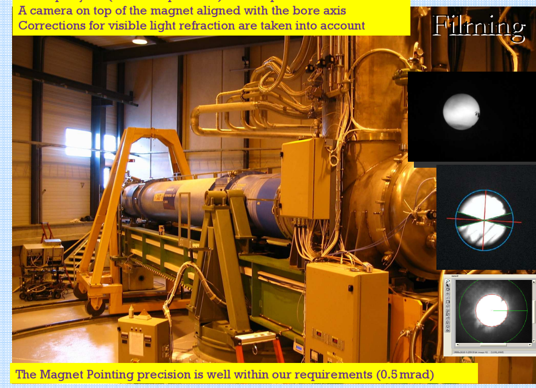
Rotating platform
(Vertical: ±8°, Horizontal: ±40°)
2x90 min solar tracking/day
Sunrise: X-ray Focusing Device coupled to CCD + 1 Micromegas
Sunset: 2 Micromegas

CAST is a difficult experiment:

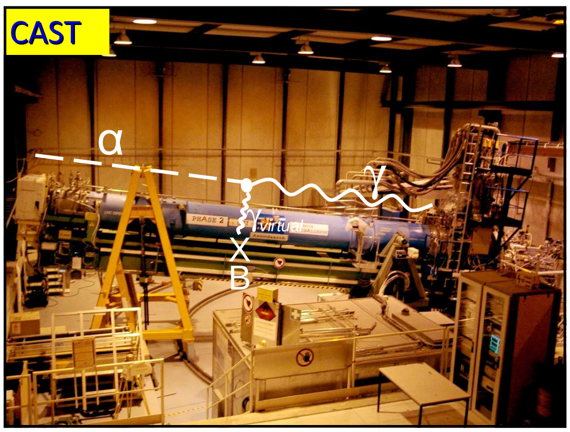
- 1.8K
- superconducting (→ quenches!)
- moving / alignment
- Cryo Fluid Dynamics of buffer gas
  → tracking
- low background X-ray detectors

→ **the only(!?) telescope at 1.8K**

Twice per year (March/September) direct optical check
A camera on top of the magnet aligned with the bore axis
Corrections for visible light refraction are taken into account

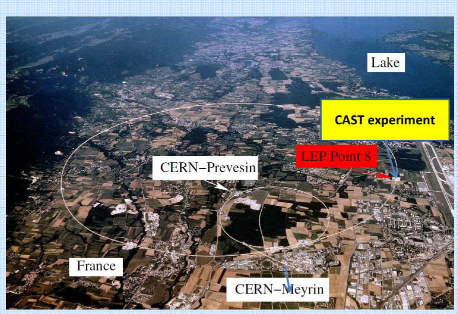


The Magnet Pointing precision is well within our requirements (0.5 mrad)



The CAST experiment

Location



PRL 94, 121301 (2005) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2005

First Results from the CERN Axion Solar Telescope

K. Zioutas,[8] S. Andriamonje,[2] V. Arsov,[13,4] S. Aune,[2] D. Autiero,[1,*] F. T. Avignone,[3] K. Barth,[1] A. Belov,[11] B. Beltrán,[6] H. Bräuninger,[5] J. M. Carmona,[6] S. Cebrián,[6] E. Chesi,[1] J. I. Collar,[7] R. Creswick,[3] T. Dafni,[4] M. Davenport,[1] L. Di Lella,[1,†] C. Eleftheriadis,[8] J. Englhauser,[5] G. Fanourakis,[9] H. Farach,[3] E. Ferrer,[2] H. Fischer,[10] J. Franz,[10] P. Friedrich,[5] T. Geralis,[9] I. Giomataris,[2] S. Gninenko,[11] N. Goloubev,[11] M. D. Hasinoff,[12] F. H. Heinsius,[10] D. H. H. Hoffmann,[4] I. G. Irastorza,[2] J. Jacoby,[13] D. Kang,[10] K. Königsmann,[10] R. Kotthaus,[14] M. Krčmar,[15] K. Kousouris,[9] M. Kuster,[5] B. Lakić,[15] C. Lasseur,[1] A. Liolios,[8] A. Ljubičić,[15] G. Lutz,[14] G. Luzón,[6] D. W. Miller,[7] A. Morales,[6,‡] J. Morales,[6] M. Mutterer,[4] A. Nikolaidis,[8] A. Ortiz,[6] T. Papaevangelou,[1] A. Placci,[1] G. Raffelt,[14] J. Ruz,[6] H. Riege,[4] M. L. Sarsa,[6] I. Savvidis,[8] W. Serber,[14] P. Serpico,[14] Y. Semertzidis,[4,§] L. Stewart,[1] J. D. Vieira,[7] J. Villar,[6] L. Walckiers,[1] and K. Zachariadou[9]

The CAST Collaboration

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PARTICLE PHYSICS

Magnetic Scope Angles for Axions

After 2 years of staring at the sun, an unconventional "telescope" made from a leftover magnet has returned its first results. Although it hasn't yet found the quarry it was designed to spot—a particle that might or might not exist—physicists say the CERN Axion Solar Telescope (CAST) is beginning to glimpse uncharted territory. "This is a beautiful experiment," says Karl van Bibber, a physicist at Lawrence Livermore National Laboratory in California. "It is a very exciting result."

CAST is essentially a decommissioned, 10-meter-long magnet that had been used to design the Large Hadron Collider, the big atom smasher due to come on line in 2007 at CERN, the European high-energy physics lab near Geneva. When CERN scientists turn on the magnet, it creates a whopping 9-tesla magnetic field—about five times higher than the field in a typical magnetic resonance imaging machine. From a particle physicist's point of view, magnetic fields are carried by undetectable "virtual" photons flitting from particle to particle. The flurry of virtual photons seething around CAST should act as a trap for particles known as axions.

Axions, which were hypothesized in the 1970s to plug a gap in the Standard Model of particle physics, are possible candidates for the exotic dark matter that makes up most of the mass in the cosmos. Decades of experiments have failed to detect axions from the depths of space, and many physicists doubt the particles exist (*Science*, 11 April 1997, p. 200). If axions do exist, however, oodles of them must be born every second in the core of the sun and fly away in every direction.

That's where CAST comes in. "When an axion comes into your magnet, it couples with a virtual photon, which is then transformed into a real photon" if the axion has the correct mass and interaction properties, says Konstantin Zioutas, a spokesperson for the project. "The magnetic field works as a catalyst, and a real photon comes out in the same direction and with the same energy of the incoming axion." An x-ray detector at the bottom of the telescope is poised to count those photons.

X-files. CAST "telescope" hopes to detect hypothesized particles from the sun by counting the x-rays they should produce on passing through an intense magnetic field.

The first half-year's worth of data, analyzed in the 1 April *Physical Review Letters*, showed no signs of axions. But CAST scientists say the experiment is narrowing the possible properties of the particle in a way that only astronomical observations could do before. "It's comparable to the best limits inferred from the stellar evolution of red giants," van Bibber says, and he notes that plans to improve the sensitivity of the telescope will push the limits further. Even an improved CAST would be lucky to spot axions, van Bibber acknowledges, because most of the theoretically possible combinations of the particle's properties would slip through the telescope's magnetic net. Still, he's hoping for the best. "Maybe Nature will deal a pleasant surprise," he says.

–CHARLES SEIFE

head Los Alamos if they beat out the lab's current contractor, the University of California. Final competition details are expected soon, with bids in the summer. Meanwhile, former weapons chief Thomas Hunter has been promoted to director of Sandia, which has facilities in California and New Mexico.

–ELI KINTISCH

Pig Flu Scare—Case Closed?

The World Health Organization (WHO) hopes that the results of a new study will put to rest suspicions that pigs in South Korea have become infected with a potentially dangerous flu strain.

Last fall, Sang Heui Seo of Chungnam National University in Daejeon, Korea, deposited flu sequences in GenBank that suggested that Korean pigs carried WSN/33, a flu strain widely used in labs but not known to occur in nature. Several experts and WHO dismissed the findings as the result of lab contamination (*Science*, 4 March, p. 1392); now, Yoshi Kawaoka of the University of Wisconsin, Madison, and his colleagues have tested 400 samples from two Korean pig farms, WHO says, and found no trace of WSN/33.

Seo declined to comment. Henry Niman, a business owner in Philadelphia who backs Seo's claim, says Kawaoka's study wasn't broad enough to refute the theory. But, says WHO flu expert Klaus Stöhr, "we've spent too much time on these speculations already."

–MARTIN ENSERINK

Plant Center to Cut Jobs

The John Innes Centre in Norwich, U.K., one of Europe's top plant science institutions, plans to cut up to 35 researchers from its 800-person staff. Director Christopher Lamb announced on the center's Web site last week that the center began losing money 18 months ago when two funders—the European Union and private industry—became "less reliable sources." Income to the center, which has a $40 million annual budget, has dropped by $5.7 million.

This is "a big blow," says plant geneticist Michael Wilkinson of the University of Read-

SCIENCE 308 15 APRIL 2005

Tracking system precision

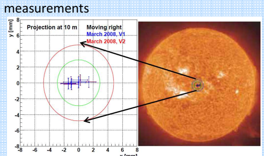
Several yearly checks cross-check that the magnet is following the Sun with the required precision

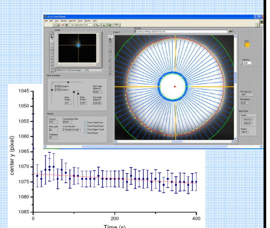
GRID Measurements

- Horizontal and Vertical encoders define the magnet orientation
- Correlation between H/V encoders has been established for a number of points (GRID points)
- Periodically checked with geometer measurements

Sun Filming

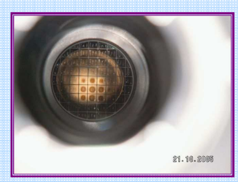
- Twice a year (March – September) Direct optical check. Corrected for optical refraction
- Verify that the dynamic Magnet Pointing precision (~ 1 arcmin) is within our aceptance





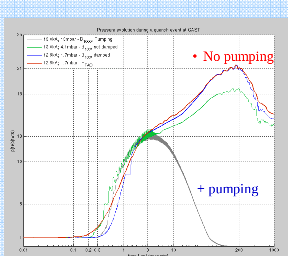
Cold thin Windows

- Observation: "Dark spots" on the windows
  - Condensation of water from residual vacuum (outgasing) of the "warm" side
  - Vacuum better controlled (pumped)
  - Periodic bake out of windows



CONSTRAINTS

TAOs



- **Fast Increase - ~13x, in about 3 seconds,**
- **Maximum increase < 20x, in about 200 seconds.**

The CAST experiment

X-ray detectors

CAST is a dipole magnet so it can host up to four detection lines (two at each side)

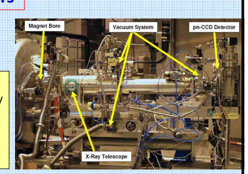
Sunrise side

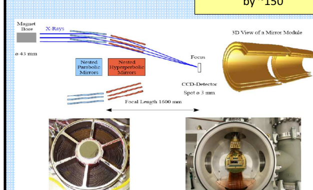
Unshielded Micromegas Detector
Background about 12 cts/h

+

The X-Ray Telescope is focusing a ø43 mm x-ray beam to ø3mm

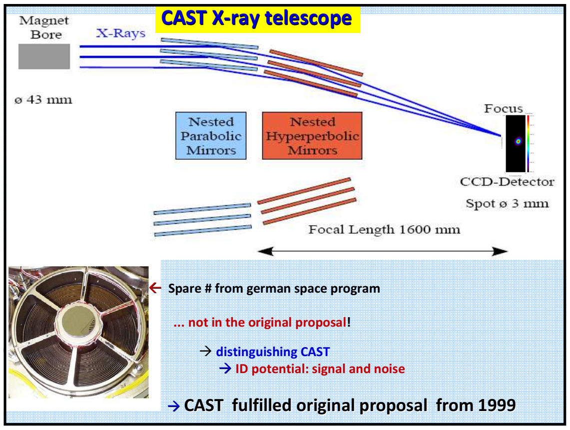
S/B improvement by ~150

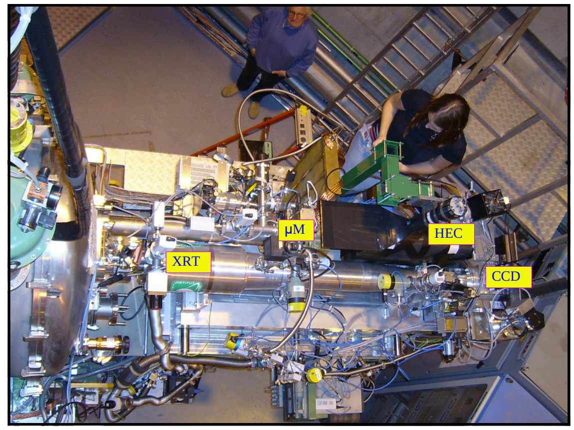


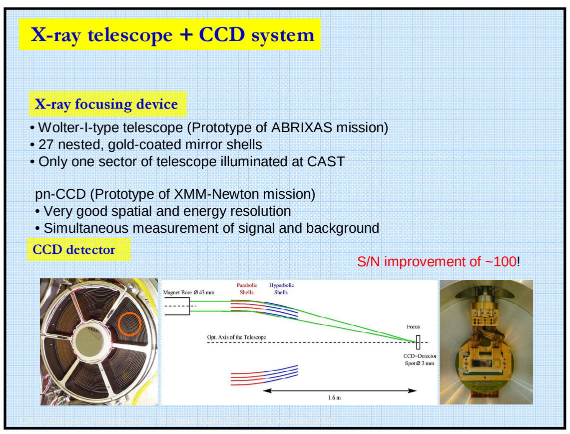


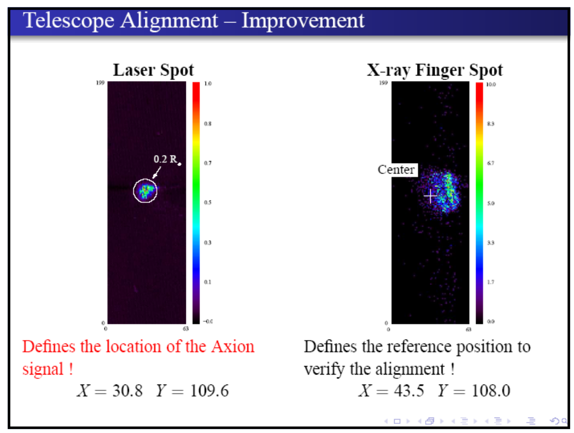
Sunset side

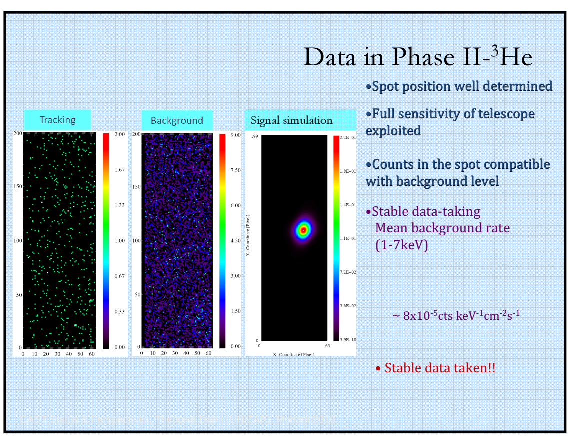
TPC chamber operated by the group at U. Zaragoza and covered two magnet bores.
Backgr. level about 50 cts/hour

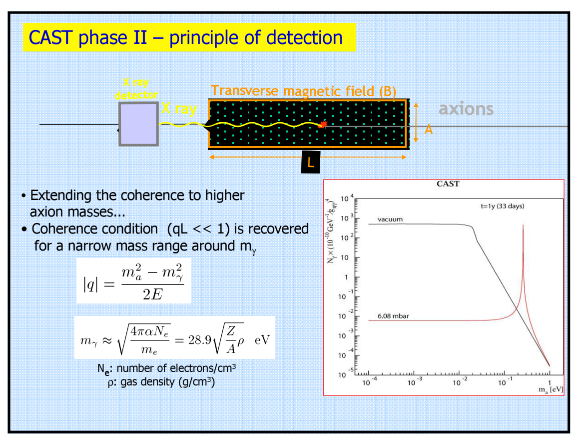

CAST X-ray telescope
Magnet Bore
X-Rays
ø 43 mm
Nested Parabolic Mirrors
Nested Hyperperbolic Mirrors
Focus
CCD-Detector
Spot ø 3 mm
Focal Length 1600 mm
Spare # from german space program
... not in the original proposal!
→ distinguishing CAST
→ ID potential: signal and noise
→ CAST fulfilled original proposal from 1999


XRT
μM
HEC
CCD


X-ray telescope + CCD system
X-ray focusing device
• Wolter-I-type telescope (Prototype of ABRIXAS mission)
• 27 nested, gold-coated mirror shells
• Only one sector of telescope illuminated at CAST
pn-CCD (Prototype of XMM-Newton mission)
• Very good spatial and energy resolution
• Simultaneous measurement of signal and background
CCD detector
S/N improvement of ~100!


Telescope Alignment – Improvement
Laser Spot
X-ray Finger Spot
0.2 R
Center
Defines the location of the Axion signal !
X = 30.8 Y = 109.6
Defines the reference position to verify the alignment !
X = 43.5 Y = 108.0


Data in Phase II-3He
Tracking
Background
Signal simulation
•Spot position well determined
•Full sensitivity of telescope exploited
•Counts in the spot compatible with background level
•Stable data-taking
Mean background rate (1-7keV)
~ 8x10-5cts keV-1cm-2s-1
• Stable data taken!!


CAST phase II – principle of detection
X ray detector
X ray
Transverse magnetic field (B)
axions
A
L
• Extending the coherence to higher axion masses...
• Coherence condition (qL << 1) is recovered for a narrow mass range around mγ
$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$
$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho}$ eV
Ne: number of electrons/cm3
ρ: gas density (g/cm3)
CAST
t=1y (33 days)
vacuum
6.08 mbar

The CAST experiment

Axion-photon probability conversion in a magnetic field.

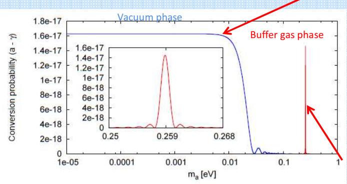
Probability to convert an axion to photon in amagnetic field ~B^2 and ~L^2.

$$P_{a\to\gamma} = \frac{(g_{a\gamma}BL/2)^2}{L^2(q^2+\Gamma^2/4)}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right]$$

The probability conversion is maximum when the momentum transferred is zero → $q = \left|\frac{m_a^2-m_\gamma^2}{2E_a}\right|$

Magnet field in vacuum conditions ($m_\gamma = 0$) enhances conversion probability for low axion masses → $m_a < 0.02$ eV

Conversion probability

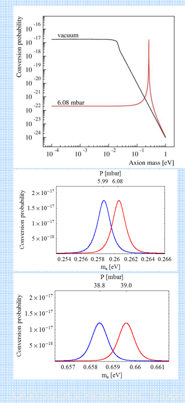


Buffer gas is required for recovering coherence with higher axion masses.

$$m_\gamma \simeq 28.77\sqrt{\frac{Z}{W_A}\rho\left[\frac{g}{cm^3}\right]}\ \mathrm{eV}$$

THIN axion mass resonance, many overlapping densities required for covering a wide axion mass region

CAST Physics



Conversion Probability in gas

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma}}{2}\right)^2\frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L/2}-2e^{-\Gamma L/2}\cos(qL)\right]$$

(In vacuum $m_\gamma = 0, \Gamma=0$)

L= magnet length, Γ =absorption coefficient

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

$$m_\gamma(eV) = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9\sqrt{\frac{Z}{A}\rho} \approx \sqrt{0.02\cdot\frac{P(mbar)}{T(K)}}$$

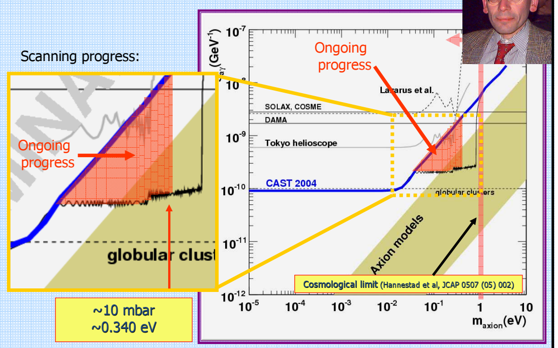
Coherence condition

$$qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

CAST Phase II → ^{4,3}He

1989 →

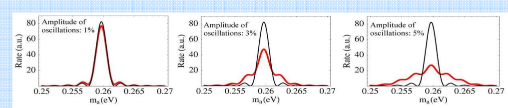
Scanning progress:



~10 mbar
~0.340 eV

THERMO ACOUSTIC OSCILLATIONS

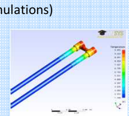
Not foreseen!

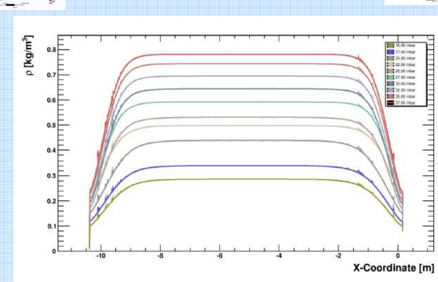


- Thermoacoustic oscillations were observed with ^{4}He gas filling for p > 2mbar with f=3.7Hz and ~6% amplitude (δp/p); Isentropic model gives 3.5% density fluctuation (δρ/ρ).
- Phenomenon was studied and solutions designed; Damping plugs installed on the linking pipes

Coherence length?

Gas behaviour simulation (CFD Simulations)

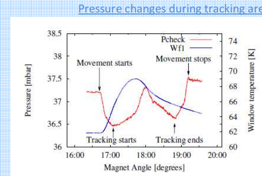




The leak problem during 2008

Towards a description of the axion mass coverage

Pressure changes during tracking are related with density changes



The density at the magnetic region does not remain constant during tracking.

A new analysis method is required to be able to obtain a limit.

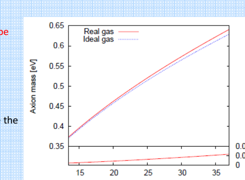
Ideal gas approach of the pressure in the system starts to do not be accurate enough in this new phase.

A more accurate equation of state is used

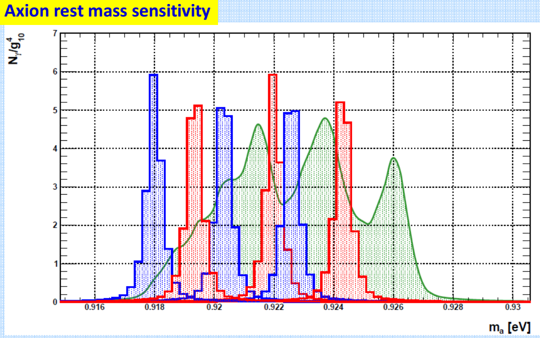
$$\frac{p}{\rho RT} = 1 + B(T)\rho + C(T)\rho^2 + ...$$

The best approach to the density inside the cold bore is to translate the measured pressure directly into density

$$P_{check} = \rho RT_o + B(1.8\,K)\rho^2 RT_o$$



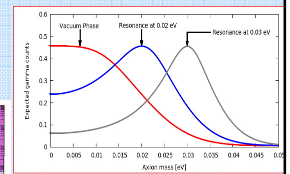
Axion rest mass sensitivity



Jaime Ruz

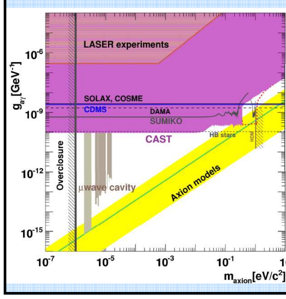
The CAST experiment

The CAST Physics program



CAST requires a data taking period to cover axion masses up to ~1.2 eV.

The idea is to cover a conteneous axion mass region by overlapping thin axion mass resonances.



CAST Phase I (Vacuum), Completed (2003-04)

$g_{a\gamma\gamma} < 0.88 \times 10^{-10}$ GeV^{-1} $m_a < 0.02$eV

JCAP04(2007)010, CAST Collaboration

PRL (2005) 94, 121301, CAST Collaboration

CAST Phase II (4He), Completed (2005-06)

$g_{a\gamma\gamma} < 2.2 \times 10^{-10}$ GeV^{-1}

0.02 eV $< m_a < 0.39$ eV

JCAP 0902:008,2009, CAST Collaboration

160 density steps

CAST Phase II (^{3}He), Running (2008-11)

$0.39 < m_a < 1.15$ eV

X-ray telescope + future CCD system:

A back-up CCD system :

Electronics

New CCD chip:

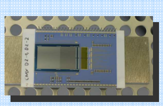
- Lower background (better selection of materials)
- Lower threshold (~200 eV)
- Better energy resolution (<160 eV (FWHM) @ 6 keV)
- Mechanical design, cooling system (CERN: engineers, Cryolab)
- Decoupling of telescope and detector: Simplification of alignment

Imaging area

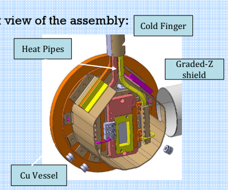
256 x 256 Pixels

75 x 75 μm^2

1.92 x 1.92 cm^2

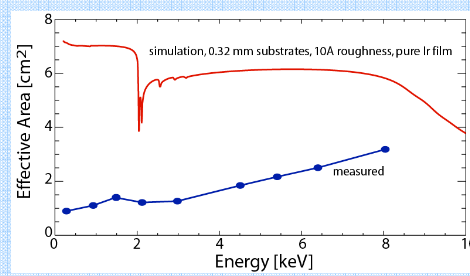


Front view of the assembly:



2nd X-ray optic

- **Measured effective area (throughput) very different than simulations**
- **Several factors at play**



Micromegas detectors for the CAST experiment

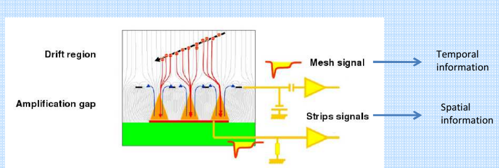
Micromegas detector concept

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 Status

✓CAST Phase I, Vacuum

- ma<0.02eV
- Completed, (2003-2004)
- PRL94(2005)121301
- JCAP04(2007)020

✓CAST Phase II, ^{4}He

- P< 13.4mbar, 160steps
- 0.02<ma<0.39eV
- Completed(2005-2006)
- JCAP02(2009)008

✓CAST Phase II, ^{3}He

- P< 120 mbar
- 0.39<ma<1.16eV
- Started in Nov 2007
- Will continue to July 2011

Parallel searches

- **High Energy Axions**: Data taking with a HE calorimeter arXiv:0904.2103
- **14.4 keV Axions**: TPC data (arXiv:0906.4488)
- **Low Energy (visible) Axions**: Data taking with a PMT/APD. (arXiv:0809.4581)

.... ???

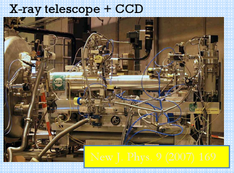
CAST detectors, Phase I & Phase II-^{4}He

Sunrise_detectors

unshielded MICROMEGAS

New J. Phys. 9 (2007) 170

X-ray telescope + CCD



New J. Phys. 9 (2007) 169

	Typical Rates
TPC	85 counts/h (2-12 keV)
MM	25 counts/h (2-10 keV)
CCD	0.18 counts/h (1-7 keV)

Sunset detector
(covering two bores)

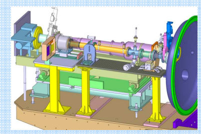
TPC

New J. Phys. 9 (2007) 171

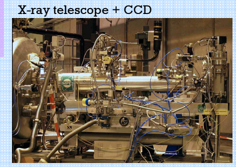
CAST detectors, Phase II-^{3}He

Sunrise detectors

New generation Micromegas

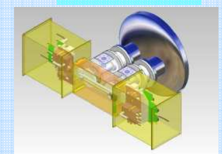


X-ray telescope + CCD



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

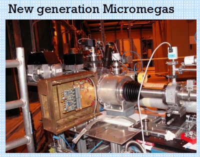
Sunset detectors
(2 new Micromegas)



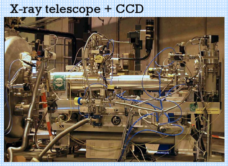
CAST detectors, Phase II-^{3}He

Sunrise detectors

New generation Micromegas

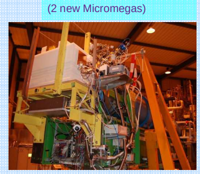


X-ray telescope + CCD



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

Sunset detectors
(2 new Micromegas)

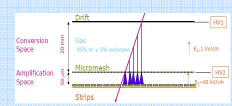


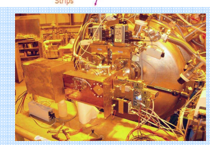
New generation Micromegas

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

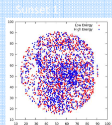




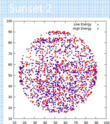
See also
2010 JINST 5 P01009
2010 JINST 5 P02001

Data in Phase II-^{3}He

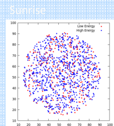
Sunset 1



Sunset 2

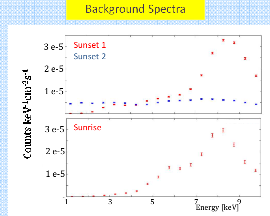


Sunrise



2d Hitmaps:
Uniform response of the detectors

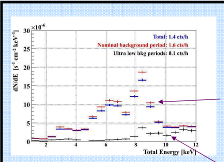
Background Spectra



Mean background rate (1-7keV)

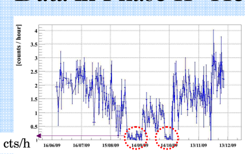
$< 1x10^{-5}$cts keV^{-1}cm^{-2}s^{-1}

Data in Phase II-^{3}He

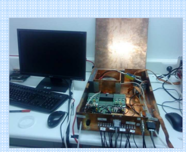


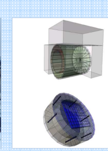
1.6 cts/h

0.1 cts/h



Very low background:
Without loss of efficiency
Not really understood yet



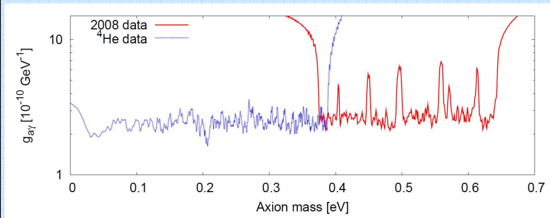


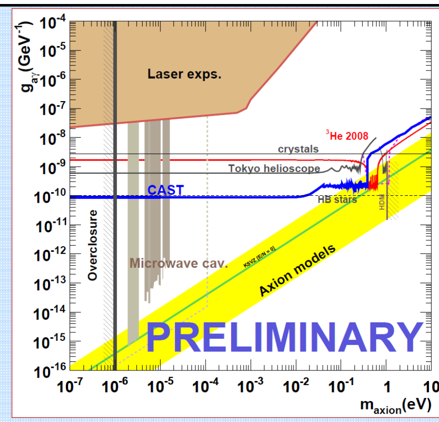
Studies underway:

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

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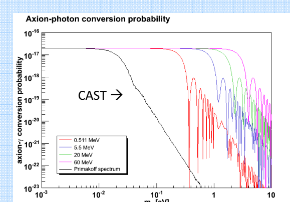
Abstract. Axions with mass $m_a \gtrsim 0.7$ eV are excluded by cosmological precision data because they provide too much hot dark matter. While for $m_a \gtrsim 20$ eV the $a \to 2\gamma$ lifetime drops below the age of the universe, we show that the cosmological exclusion range can be extended to 0.7 eV $\lesssim m_a \lesssim$ 300 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.

JCAP02(2011)003

...byproduct ➔ **New solar axion-ID**

→ exercise!

Remember:

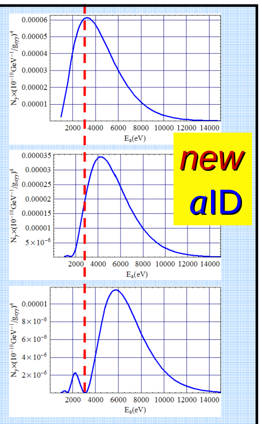
- $$|q| = \frac{m_a^2 - m_\gamma^2}{2E} = \pi/L_{coh}$$
- 

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

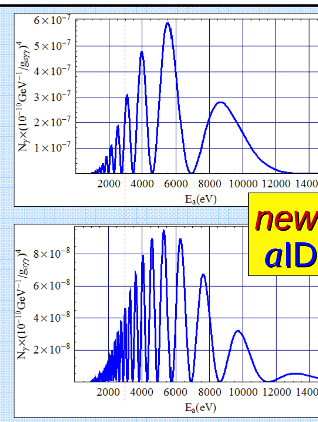


converted axion spectrum

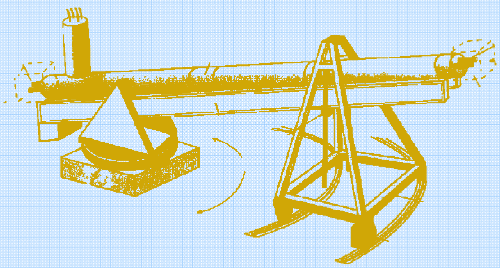
Δm=0.0088, ΔP=0.332 (*4 steps*)
⟨E⟩=6.48 keV ➔ off-resonance

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

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



Search for HE/LE solar axions with CAST



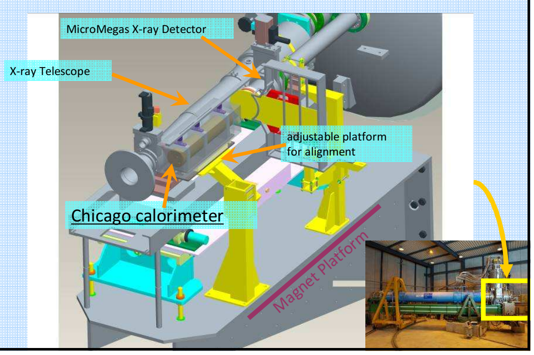
The CAST gamma-ray calorimeter

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

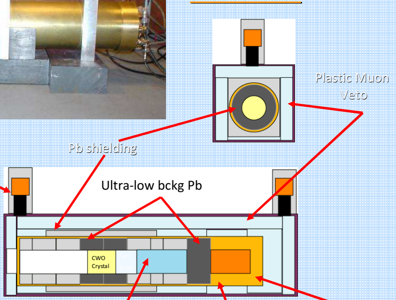
Search for solar axion emission from ^{7}Li and D(p,γ) ^{3}He nuclear decays
JCAP, arXiv:0904.2103

Calorimeter installation on CAST magnet platform

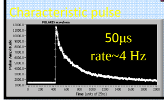


Calorimeter Design and Properties

- 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**

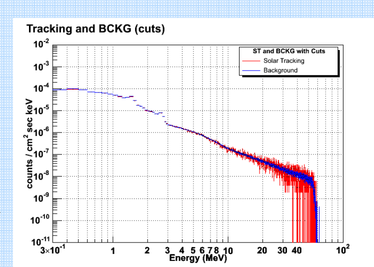


Characteristic pulse

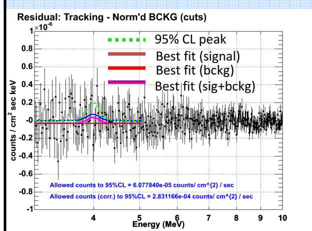


Compare solar tracking spectrum with background

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



Look for excess signal buried in data

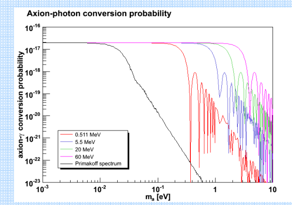


- Signal:
  - *mono-energetic peaks* at low energies
  - structured energy deposition at high energies
- Obtain 95% CL (2σ) allowed *counts* at each energy

David W. Miller, APS Apker Award, 8 September, 2005

From "photons" to "axions"

- Combine:
  - 95% CL allowed **photon flux:** Φ_γ
  - **conversion probability:** $P_{a\to\gamma}$ (a constant dep. on mass, after sep. $g_{a\gamma\gamma}$)
  - helioseismology upper limit on **axion flux:** Φ_a
- Obtain limit on **axion-photon coupling:** $g_{a\gamma\gamma}$

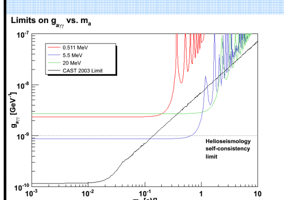


$$\Phi_\gamma \geq P_{a\to\gamma}(m_a)\Phi_a g^2_{a\gamma\gamma}$$

$$g_{a\gamma\gamma} \leq \sqrt{\frac{\Phi_\gamma}{P_{a\to\gamma}(m_a)\Phi_a}}$$

Can fix either quantity to obtain limits on the other

Final results from the CAST calorimeter



- 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
- Use the helioseismology limit on Φ_a (0.2$L_\odot$) to set upper limit on the axion-photon coupling $g_{a\gamma\gamma}$

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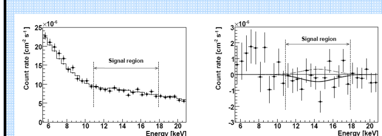
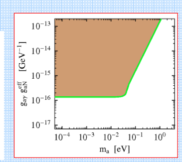
14.4 keV solar axions byproduct:

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





JCAP12(2009)002 arXiv:0906.4488

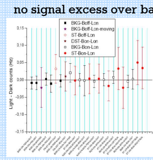
BaRBE: Low Energy Axions

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



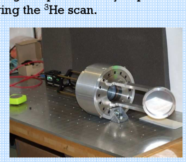
arXiv:0809.4581

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.



bridge to other exotica too

➔ **demanding + inspiring new experiments**