CAST – Direct Search for Solar Axions

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for the CAST Collaboration

TU Darmstadt
MPE Garching

The 3rd Joint ILIAS-CERN-DESY Axion-WIMPs Training Workshop

2007 June 22

Overview

- Direct Solar Axion Searches
- The CERN Axion Solar Telescope – CAST
- Results of Phase I and II of CAST
- Conclusions and Prospects

The CAST Collaboration

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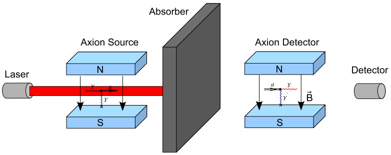
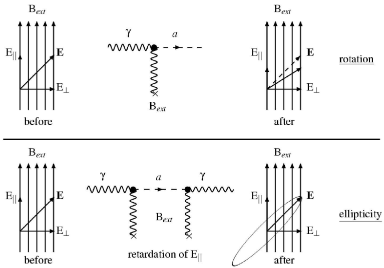
Direct Axion Detection Techniques I

Laser Induced Axions

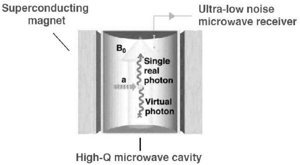
Light Shining Through Wall



Vacuum Properties



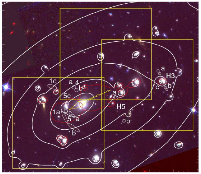
Microwave Cavity Searches



e.g. Asztalos et al., Phys. Rev. D 69, 011101 (2004)

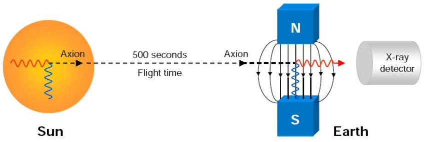
[astro-ph/0310042]

Telescope Searches



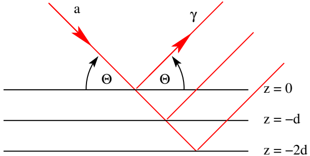
e.g. Grin et al. 2006 astro-ph/0611502v1

Helioscope Searches

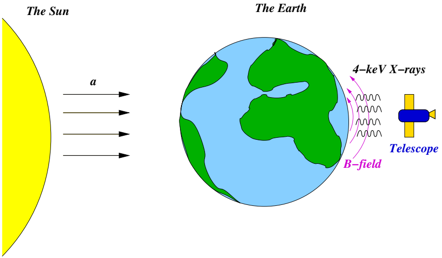


Inoue et al. 2002 astro-ph/0204388v1
Lazarus et al. Phys. Rev. Lett. 69 2333 (1992)

Bragg Diffraction



Geomagnetic Axion Conversion

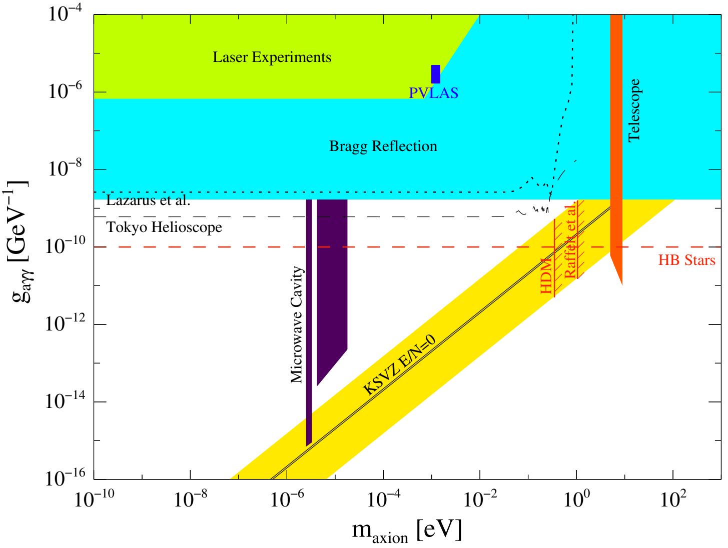


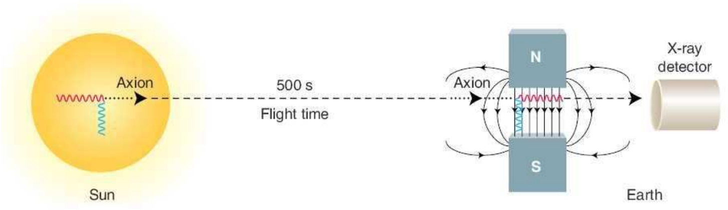
Davoudiasl & Huber, hep-ph/0509293

Idea

- Axions can convert to photons in Earth's magnetic field $\Longrightarrow$ Observe the Sun through the Earth
- Sensitivity $g_{a\gamma\gamma} \approx 10^{-11}\,\mathrm{GeV}^{-1}$

Limits on the Axion Parameter Space





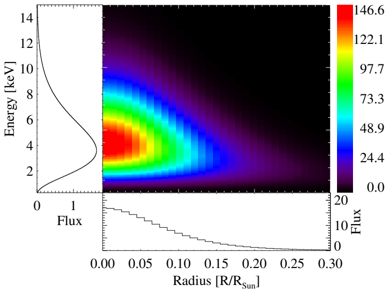
Principle of the Axion Helioscope P. Sikivie, Phys. Rev. Lett. 51 (1983)

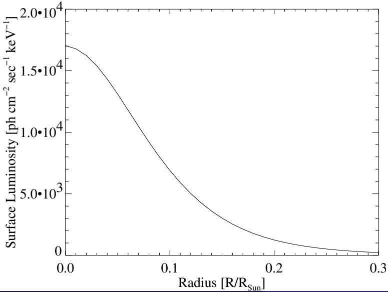
- Assumption: Axions are produced via Primakoff effect in the sun
- Point a strong magnetic field towards the sun to convert axions back to X-ray photons
- Use background optimized X-ray detectors to observe the X-rays

Advantages

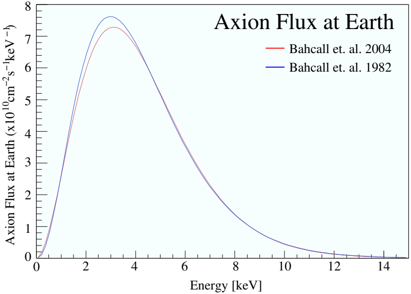
1. Axion detection essentially assumption-free and model-independent
2. Covers a broad-band mass range $m_a \approx 0\text{–}1.2\,\text{eV}$
3. Observe other celestial objects

Axion Surface Luminosity





Differential Axion Spectrum



Mean Axion Energy: $\langle E \rangle = 4.2\,\mathrm{keV}$

Axion Luminosity:

$$L_a = g_{10}^2 \cdot 1.85 \times 10^{-3} L_\odot$$

Axion Flux:

$$\Phi_a = g_{10}^2 \cdot 3.75 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Provided by P. Serpico & G. Raffelt

Based on the standard solar model BP2004 (Bahcall et al., 2004)

BNL Helioscope 1992

Experimental Parameters

- Magnet $B = 2.2\,\mathrm{T}$ $L \approx 1.8\,\mathrm{m}$
- Mounted fix, 15 min observation time during sunset
- Proportional counter

Lazarus et al. Phys. Rev. Lett. 69 2333 (1992)

Results (95% C.L.)

$m_a < 0.03\,\mathrm{eV}$

$g_{a\gamma\gamma} < 3.6 \times 10^{-9}\,\mathrm{GeV}^{-1}$

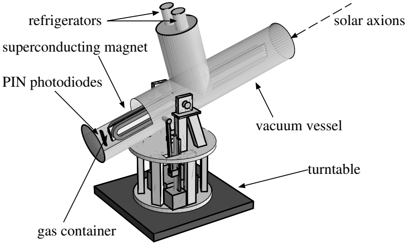
$g_{a\gamma\gamma} < 6.0 \times 10^{-10}\,\mathrm{GeV}^{-1}$

$0.03\,\mathrm{eV} < m_a < 0.11\,\mathrm{eV}$

$g_{a\gamma\gamma} < 7.7 \times 10^{-9}\,\mathrm{GeV}^{-1}$

$g_{a\gamma\gamma} < 6.8\text{–}10.9 \times 10^{-9}\,\mathrm{GeV}^{-1}$

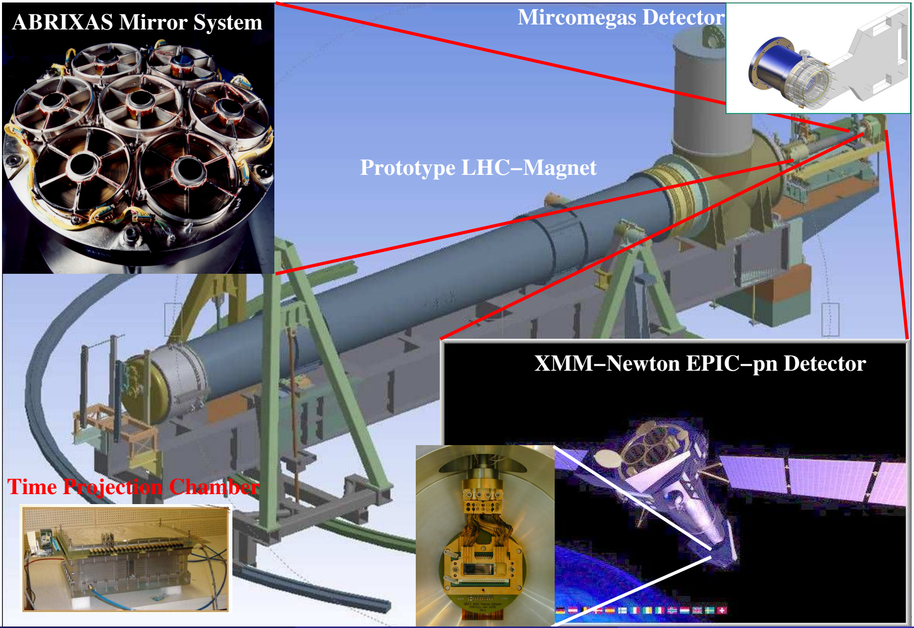
Tokyo Helioscope 1997-2000



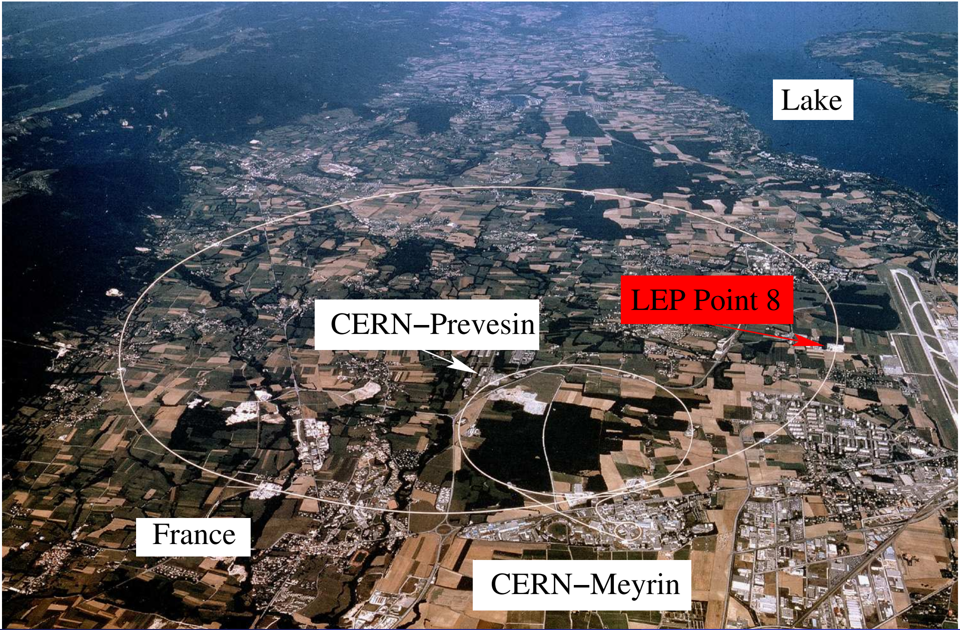
Inoue et al. 2002 astro-ph/0204388v1

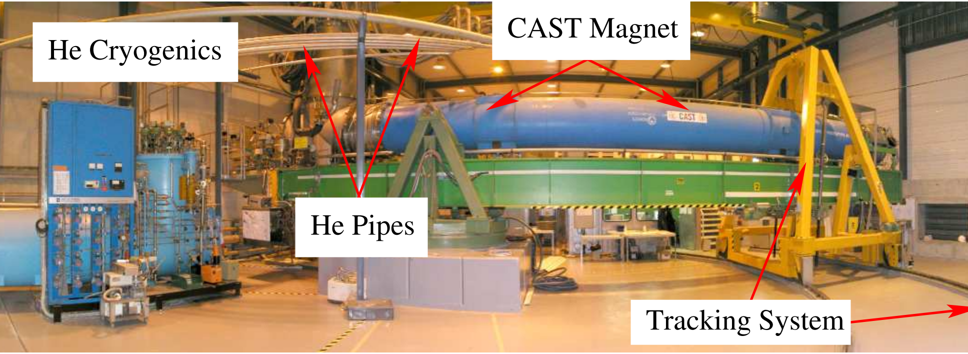
Experimental Parameters

- Magnet $B = 4\,\mathrm{T}$ $L = 2.3\,\mathrm{m}$
- Sky coverage
  Ra 360° Dec ±28°
  $\Longrightarrow$ 24h observation time
- PIN-diodes


ABRIXAS Mirror System
Mircomegas Detector
Prototype LHC–Magnet
XMM–Newton EPIC–pn Detector
Time Projection Chamber

CAST at CERN





Prototype LHC magnet

$$B = 9.0\,\text{T} \quad l = 9.26\,\text{m}$$
$$T = 1.8\,\text{K} \quad m \approx 30\,\text{t}$$

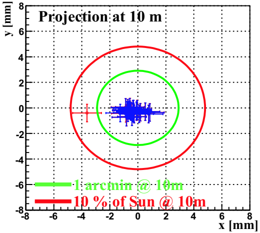
Tracking system

$$H = -8^\circ \ldots 8^\circ \; Az = 40^\circ \ldots 140^\circ$$

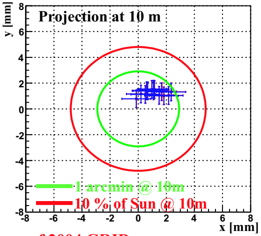
$\Longrightarrow$ 1.5 h observation time during sun rise and sun set ($\approx$ 46 days/year)

Verification 2002/04/06

Apr 2006 in comparison with 2004

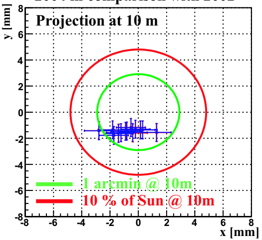


Oct 2006 in comparison with 2004

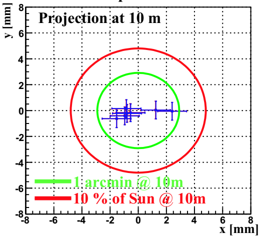


(0.0) is the reference of 2004 GRID

2004 in comparison with 2002



2006 in comparison with 2002

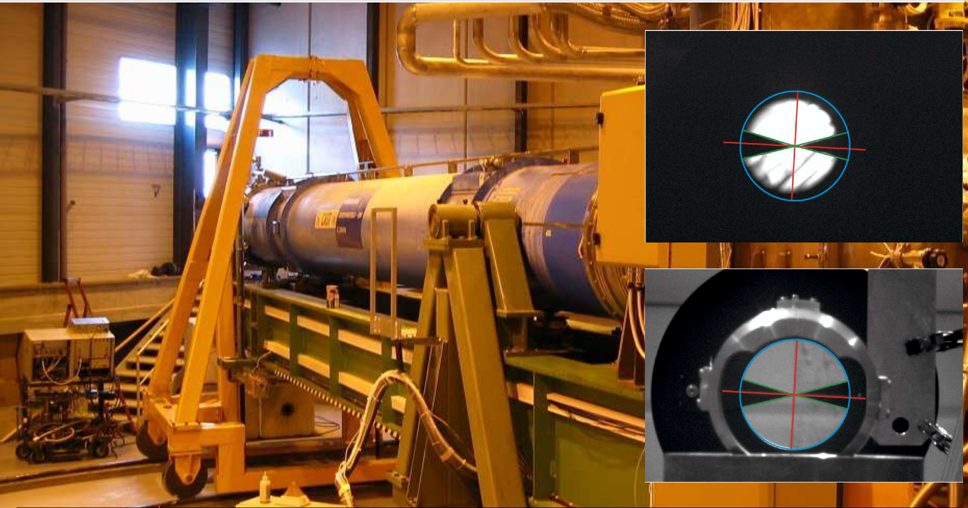


(0.0) is the reference of 2002 GRID
= Sun center according to the geometers

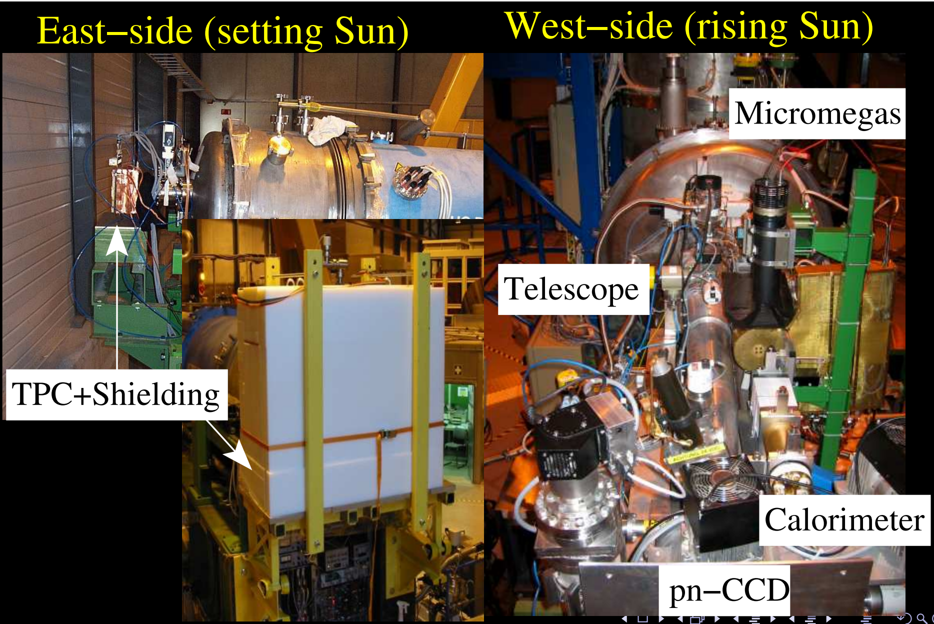
- Regular verification of the pointing precision of the tracking system
- No change observed since 2004
- Small shift with respect to 2002 grid reference $\Longrightarrow$ has been corrected

Magnet points to the Sun with required precision !

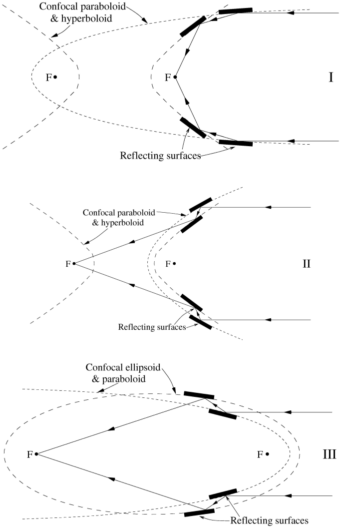
Sun Filming



In March & September we can observe the Sun with an optical telescope.
CAST tracks the Sun with the required precision !


East–side (setting Sun)
West–side (rising Sun)
Micromegas
Telescope
TPC+Shielding
Calorimeter
pn–CCD

Wolter Designs



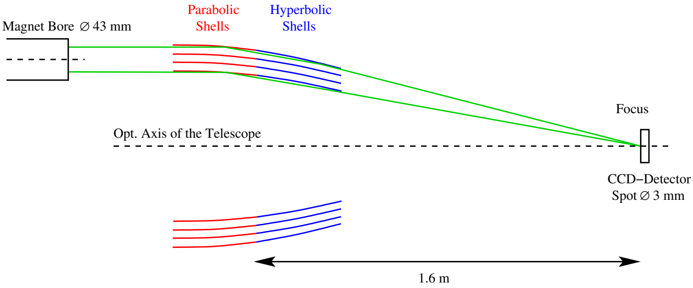
Wolter, H. Ann. Phys. 10, 1952

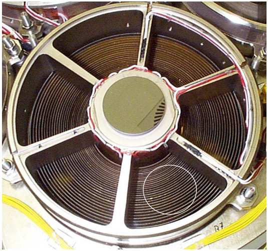
General Properties

- Basic principle
  Total reflection for $\Theta < \Theta_c$
- Snell's law for critical angle Θ_c
  $\cos(\Theta_c) = n \Longrightarrow \Theta_c = 2\delta$
  Far from absorption edges
  $$\Theta_c^2 = \pi\lambda^2 r_0 N_e$$
  r_0 electron radius, N_e electron density
- Basic relations
  $$\Theta_c \propto \lambda \propto 1/E_\gamma$$
  $$\Theta_c \propto \sqrt{N_e} \simeq A$$
  $\Longrightarrow$ High Z materials are better reflectors

  Most popular Gold

The X-ray Telescope of CAST



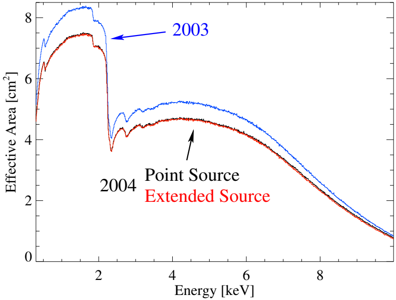


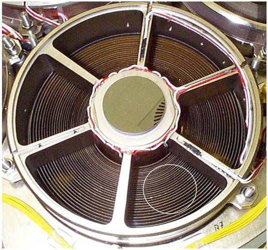
Wolter I type grazing incident optics (prototype for ABRIXAS mission):

- 27 nested gold coated nickel shells, on-axis resolution ≈ 43 arcsec
- Telescope aperture 16 cm, used for CAST 43 mm
- Only one sector of the full aperture is used for CAST

∅43 mm (LHC Magnet aperture) ⟹ ∅3 mm (spot of the sun)
Significantly improves the signal to background ratio !

The X-ray Telescope of CAST





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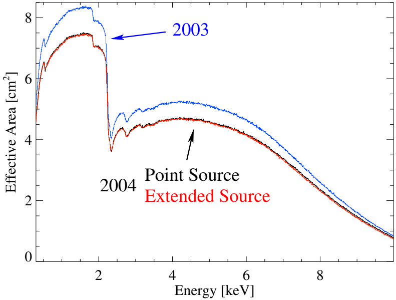
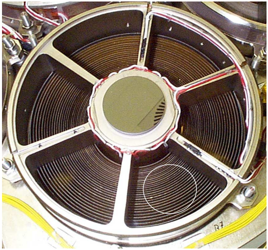
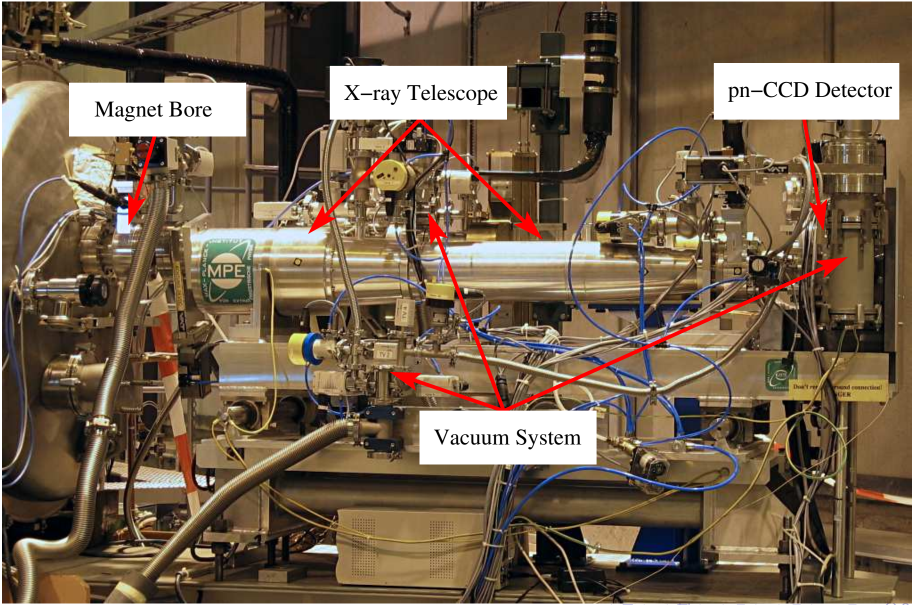




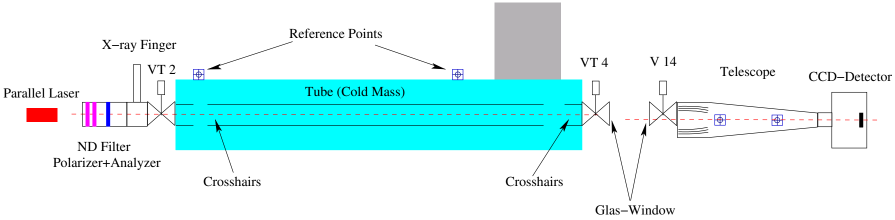
Wolter I type grazing incident optics (prototype for ABRIXAS mission):

- 27 nested gold coated nickel shells, on-axis resolution $\approx$ 43 arcsec
- Telescope aperture 16 cm, used for CAST 43 mm
- Only one sector of the full aperture is used for CAST

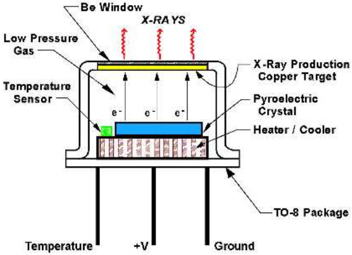
See following presentation by R. Soufli on X-ray optics !



Magnet Bore
X–ray Telescope
pn–CCD Detector
Vacuum System
MPE



X-ray Finger



Alignment Procedure

- Use parallel laser beam to align the bore to the telescope.
- Use X-ray source to check the stability of the system.
- For both cases observe the spot on the CCD under different conditions !

Phase I – Magnet bore evacuated

Conversion Probability

$$P_{a\rightarrow\gamma} \propto (BL\, g_{\mathrm{a}\gamma\gamma})^2 \cdot \frac{\sin^2(qL/2)}{(qL)^2} \text{ with } q = \frac{m_{\mathrm{a}}^2}{2E_{\mathrm{a}}}$$

For coherence: $qL \ll 1$ (axion and photon field are in phase)

$\Longrightarrow$ Sensitivity limit for CAST Phase I $m_{\mathrm{a}} \approx 0.02\,\mathrm{eV}$

Expected Count Rate (X-ray Telescope)

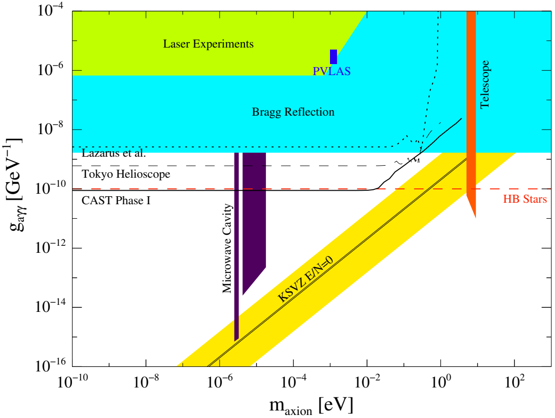
$$N_\gamma = \int \frac{\mathrm{d}\Phi_a}{\mathrm{d}E_a} P_{a\rightarrow\gamma}\, \epsilon\, t\, \mathrm{d}E$$

$$\Phi_\gamma \approx 1.81\, g_{10}^4 \,\text{counts}\,\text{day}^{-1}$$

Summary

- No signal detected
- Improved CAST 2003 limit
- CAST improves previous direct experimental limits by a factor of 7
- CAST improves best astrophysical limit from HB stars

Axion Exclusion Plot



Upper limit on $g_{a\gamma\gamma}$ for $m_a \lesssim 0.02\,\text{eV}$:

$$g_{a\gamma\gamma}(95\%) \leq 0.88 \times 10^{-10}\,\text{GeV}^{-1}$$

Andeiamonje et al., J. Cos. Astro. Phys. submitted hep-ex/0702006

Phase II – Magnet bore filled with buffer gas (^{4}He/^{3}He)

Conversion Probability

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

Absorption coefficient: Γ

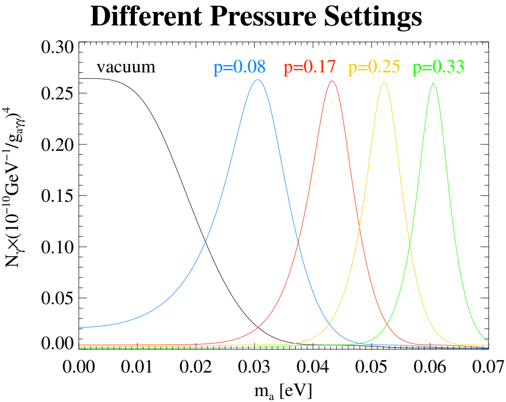
$\Longrightarrow$ photon acquires an effective mass

$$q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right| \qquad m_{\gamma,\mathrm{eff}} \approx \sqrt{\frac{4\pi\alpha n_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \approx \sqrt{0.02\frac{P[\mathrm{mbar}]}{T[\mathrm{K}]}}[\mathrm{eV}]$$

Coherence for: $\sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$

Fill magnet pipes with gas $\Longrightarrow$ coherence restored

$\Longrightarrow$ Enter axion parameter range favored by theoretical models $m_a > 0.02\,\mathrm{eV}$



Possible buffer gases

^{4}He or ^{3}He

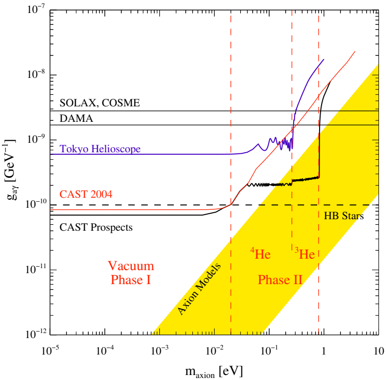
($p_{\text{vap}} = 16/140\,\text{mbar}@1.8\,\text{K}$)

Systematically change pressure $\Longrightarrow$ scan mass range $m_a > 0.02\,\text{eV}$

- ^{4}He: $\approx$ 160 pressure steps $0 \leq p \leq 13\,\text{mbar}$ $m_a \leq 0.4\,\text{eV}$
- ^{3}He: $\approx$ 660 pressure steps $13 < p \lesssim 135\,\text{mbar}$ $m_a \leq 1.2\,\text{eV}$

$\Longrightarrow$ Allows to scan axion masses $0.02\,\text{eV} \leq m_a \leq 1.12\,\text{eV}$

CAST Phase I/II



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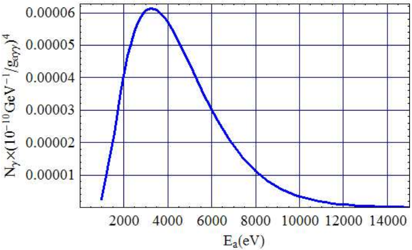
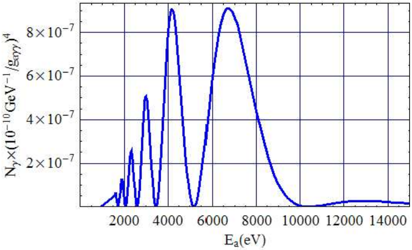
CAST Phase II – Off Resonance Spectrum

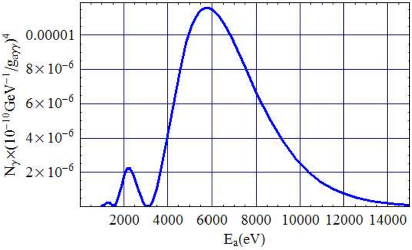
On Resonance



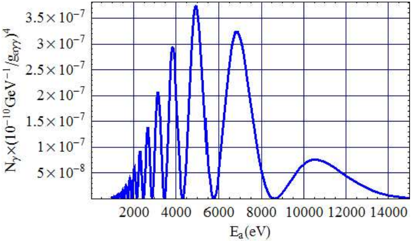
Off Resonance $\Delta m = 0.007$ eV



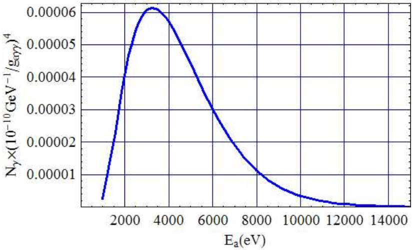
Off Resonance $\Delta m = 0.002$ eV



Off Resonance $\Delta m = 0.011$ eV



On Resonance



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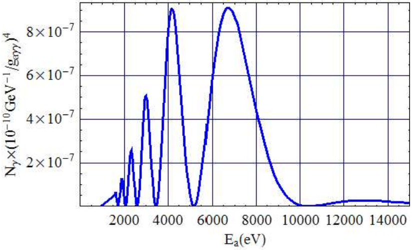
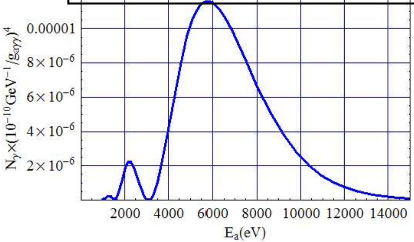
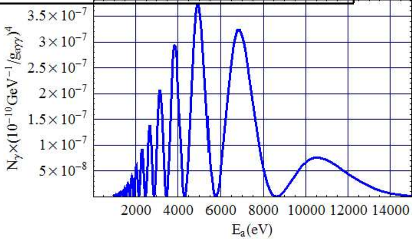


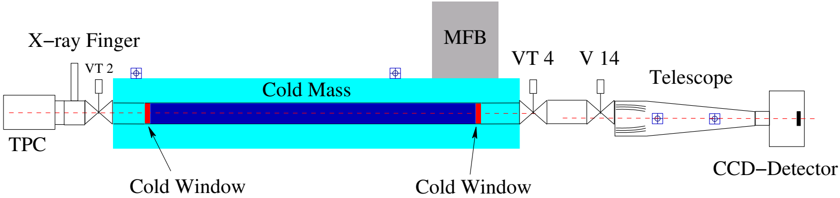
Off

Signature to identify an axion signal !

eV



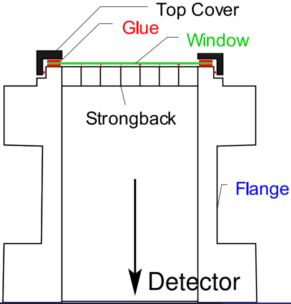




Cold Windows/He-Gas System

- Cold windows (installed)/He-Gas System
- ^{4}He gas system (in operation 2005–2006)
  max. ^{4}He pressure $\approx 13.4\,\mathrm{mbar} \Longrightarrow m_{\mathrm{a}} \approx 0.39\,\mathrm{eV}$
- ^{3}He gas system installation in progress since start of 2007
  max. ^{3}He pressure $\approx 136\,\mathrm{mbar} \Longrightarrow m_{\mathrm{a}} \approx 1.2\,\mathrm{eV}$

Prototype Cold Window 2005



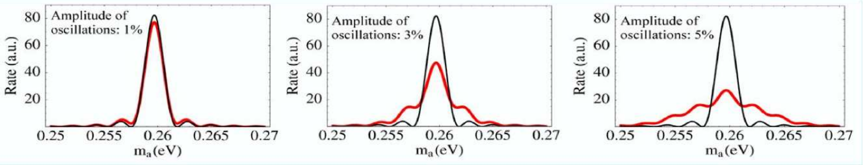
Technical Requirements

- High transmissivity at 1–7 keV
- Minimum He leak rate $q_{^4\mathrm{He}} < 10^{-8}\,\mathrm{mbar\,l/s}$ at 1.8 K
- Transparent in the optical $\Longrightarrow$ alignment of the telescope
- Survive a "Quench" ($\approx$ 1 bar)

Design

- Polypropylene 15 μm
- Electro-eroded strong-back
- Tests and Qualification: CERN Cryolab

Expected Photon Signal Depending on Oscillation Amplitude



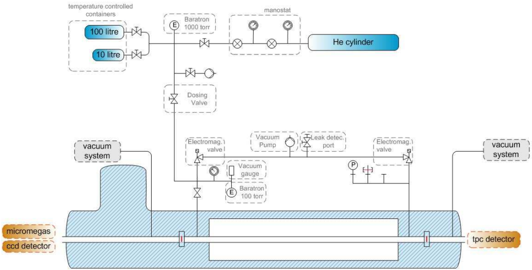
Pressure Oscillations in the Cold Bore

- Triggered by temperature gradient in the connection cold bore → outside world for $p > 2\,\text{mbar}$
- Frequency $f = 3.7\,\text{Hz}$ with 6% amplitude

  $\Longrightarrow$ 3.4% density fluctuation ($\Delta p/p$)

  $\Longrightarrow$ Significant loss in sensitivity !

Installed dampers $\Longrightarrow$ problem solved !



^{4}He **Operation**

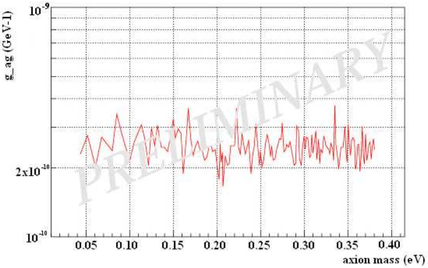
- System operated 2005 – 2006 $\Longrightarrow$ well understood
- Thermo-acoustic oscillations eliminated
- Windows regularly backed out $\Longrightarrow$ avoid contamination
- Window flanges heated to 120 K $\Longrightarrow$ avoid cryopumped gases to contaminate windows

Phase II Results ^{4}He– MM

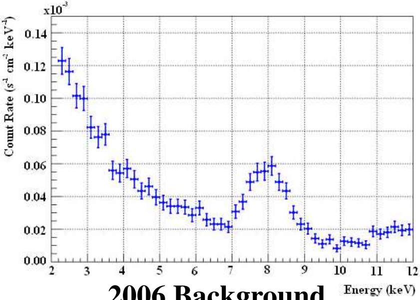
Micromegas ^{4}He Data Taking

- Completed 145 density steps (277 h tracking data, 3306 h background data)
- New improved detector installed for ^{4}He data taking

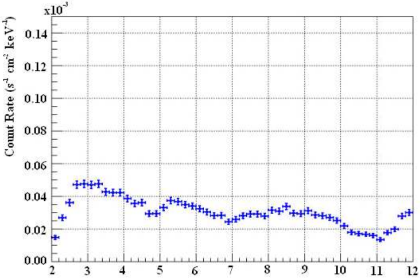
Preliminary Result ^{4}He



2005 Background



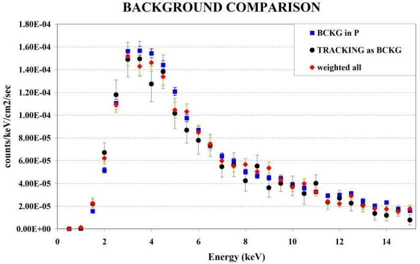
2006 Background



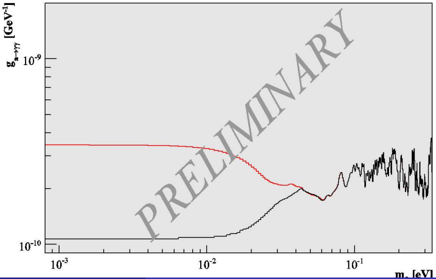
TPC ^{4}He Data Taking

- Completed 155 density steps (501 h tracking data, 3000 h background data)
- Improved shielding
- Stable performance (no background variation depending on magnet orientation)

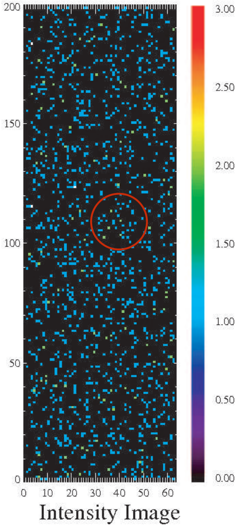
2006 Background



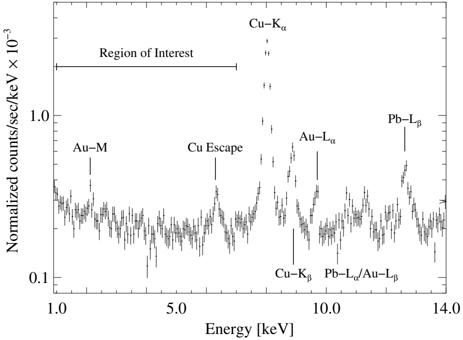
Preliminary Result ^{4}He



Background Data



Background Spectrum

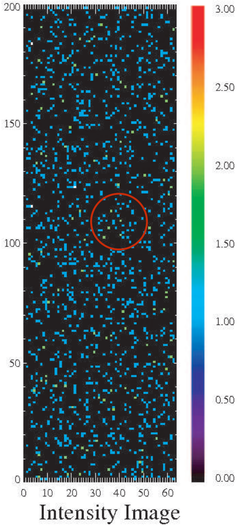


Performance

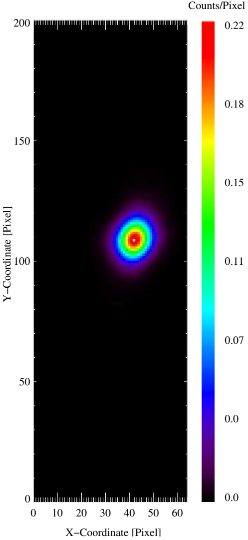
- Background $8.54 \pm 0.17 \times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}
- Single pressure/mass step 0.24 ± 0.04 counts tracking^{-1}

Phase II Results ^{4}He– X-ray Telescope

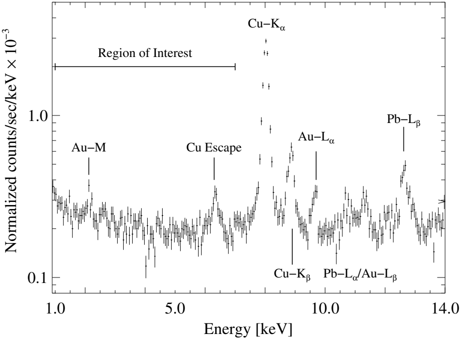
Background Data



Simulation



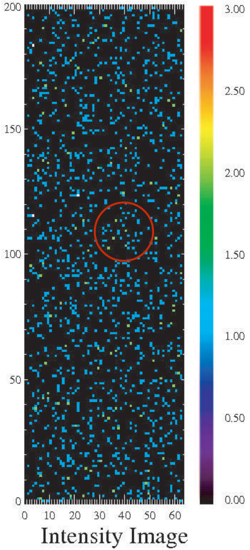
Background Spectrum



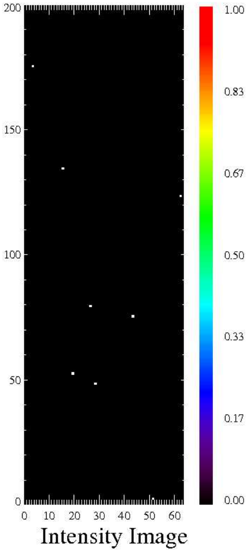
Performance

- Background $8.54 \pm 0.17 \times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}
- Single pressure/mass step 0.24 ± 0.04 counts tracking^{-1}

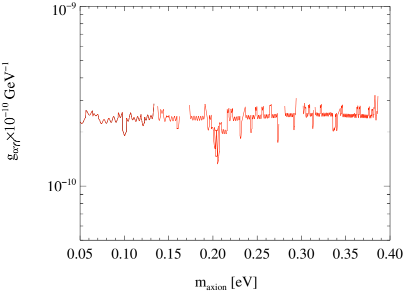
All Data



Single Step

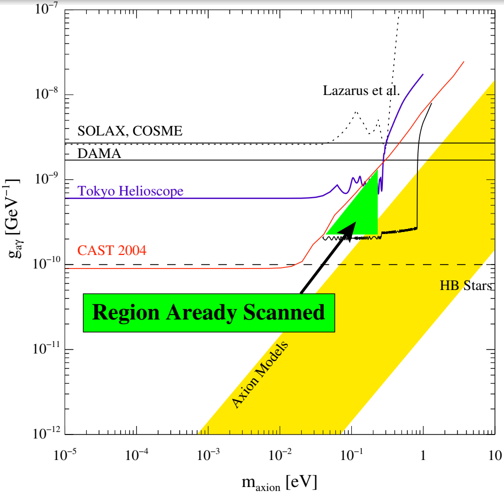


Preliminary Result ^{4}He



- 144 density steps 300 h high quality data
- Spot location continously monitored

No signal detected !



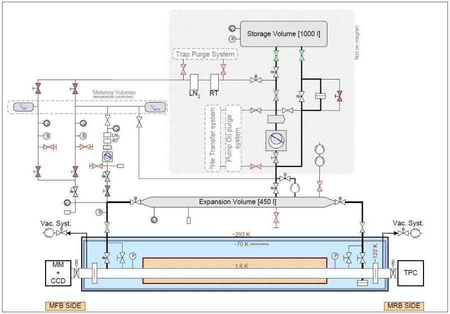
^{4}He runs of Phase II finished ! No signal detected !

^{3}He Gas System – Cryolab CERN

Requirements

- Safety against loss of ^{3}He/release only to storage vessel
- Metering of the amount of ^{3}He in the magnet bores (100 ppm) + reproducibility
- Absence of thermo-acoustic oscillations
- Protection of the thin X-ray windows during a quench
- Remote data logging of the state of the gas system
- “Stepping”/“Ramping”-Mode

^{3}He **System Layout**



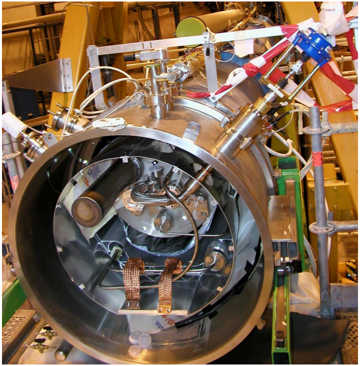
Technical Design Report (CERN-SPSC-2006-029)

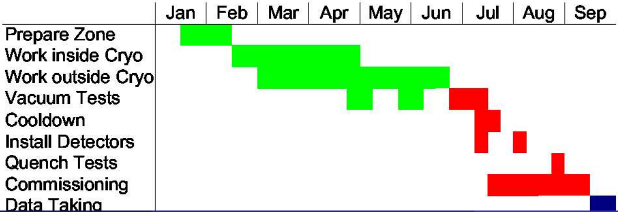
Successful review October 2006
$\Longrightarrow$ started manufacturing and integration

^{3}He Gas System – Status

- Cold window development
- 3D modeling of new components (very limited space), e.g. cryogenic valves, rupture disk, ...
- Inside cryostat: welding, cutting, installation of new components
- Design and manufacturing of large storage vessels
- PLC for gas system operation and control

Inside the Cryostat





X-ray Concentrator

- Focal length 1.3 m
- 14 Iridium coated plastic shells
- Throughput $\approx 36\%$
- 3 mm spot diameter ($100\times$ background reduction)

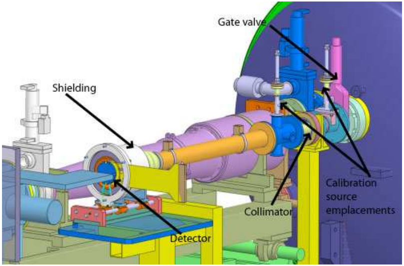
Optimized Shielding

- Copper, Lead, Cadmium and Polyethylen + N_2 flux
- Expected background reduction factor 4

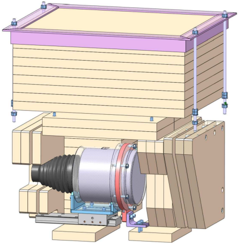
Detector Gas

- Change Argon to Xenon
  $\Longrightarrow$ 10% gain in conversion

Micromegas with X-ray Optics



PE Shield



CAST and Low Energy Axions

Potential new field beyond QCD axions

Solar magnetic fields $B \Longrightarrow$ ignored so far ($B_{\text{sunspots}} < 0.5\,\text{T}$)

- Sun as a strong source of low energy axions (visible/UV)
  $\Longrightarrow$ Opportunity: next solar maximum
- Mechanism behind outstanding problems in solar physics ?
  Solar corona problem
  B^2 dependence of X-ray flux
- CAST as complementary experiment to laboratory-based experiments

Analysis of CAST Phase I data is in progress.
See presentations of K. Zioutas/S. Solanki

Conclusions

- CAST Phase I provides best laboratory based upper limit for $m_a < 0.02\,\mathrm{eV}$
$$g_{a\gamma\gamma} < 8.8 \times 10^{-11}\,\mathrm{GeV}^{-1}$$
which is comparable to the best astrophysical limit
- Phase II ^{4}He data taking finished in December 2006
$\Longrightarrow$ no signal detected
$\Longrightarrow$ CAST will reach the predicted sensitivity for $m_a < 0.4\,\mathrm{eV}$
- Preparation for ^{3}He measurements are in progress
expect first data in September this year
- Request for extension to run in 2008–2010
Main goal: Cover mass range up to $m_a \approx 1.16\,\mathrm{eV}$

Keep fingers crossed that we will experience the opposite to PVLAS !
A signal appears ...

Thanks to All Collaboration Members !!!