Axion search with the CAST experiment

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Rencontres IPhT/SPP

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Motivation for Axions

- CP violation is necessary in the SM➔matter-antimatter asymmetry
- CP violation observed in the weak interactions
- QCD predicts violation in the strong interactions

$$\mathcal{L}_\theta = \frac{g^2\bar{\theta}}{32\pi^2} G^{\alpha}_{\mu\nu}\tilde{G}^{\alpha\mu\nu} \quad with \quad \bar{\theta} = \theta + Arg(\det M)$$

- However no experiment has observed this violation of CP in QCD!

•A possible solution to the strong CP-problem

•Elimination of CP-violating term in QCD Lagrangian by introduction of new additional global U(1) symmetry

$$\mathcal{L}_a = \left(\bar{\theta} - \frac{a(x)}{f_a}\right)\frac{1}{f_a}\frac{g}{8\pi} G^{\mu\nu}_a \tilde{G}_{a\mu\nu}$$

- New pseudo-scalar field : **AXION**
- First proposed by Peccei & Quinn (1977)
- Particle interpretation by Weinberg, Wilczek (1978)

2013 SAKURAI PRIZE

Roberto Peccei

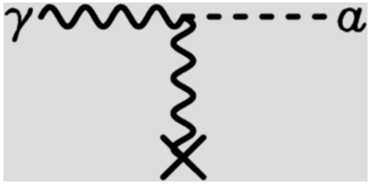
Helen Quinn

"*For their proposal of the elegant mechanism to resolve the famous problem of strong-CP violation which, in turn, led to the invention of axions, a subject of intense experimental and theoretical investigation for more than three decades.*"

2013 J.J. Sakurai Prize for Theoretical Particle Physics Recipient

Axion properties

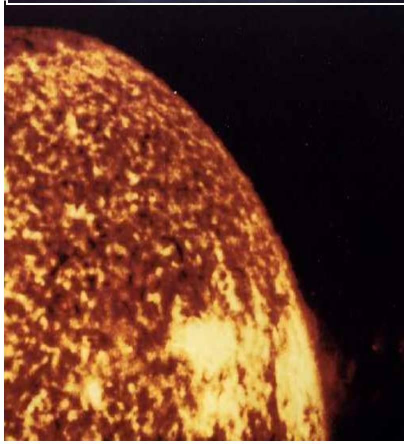
- Neutral Pseudoscalar
- Pratically stable
- Very low mass $$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$
- Very low cross-section
- Coupling to photons



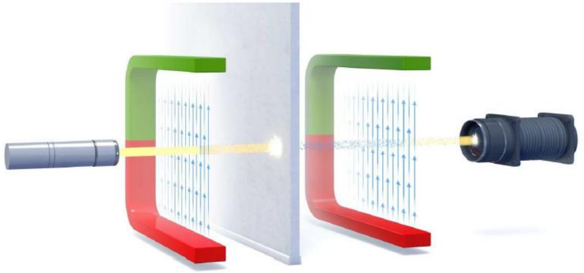
$$L_{a\gamma\gamma} = g_{a\gamma\gamma}(\vec{E} \cdot \vec{B})a$$

- Possible dark matter candidates

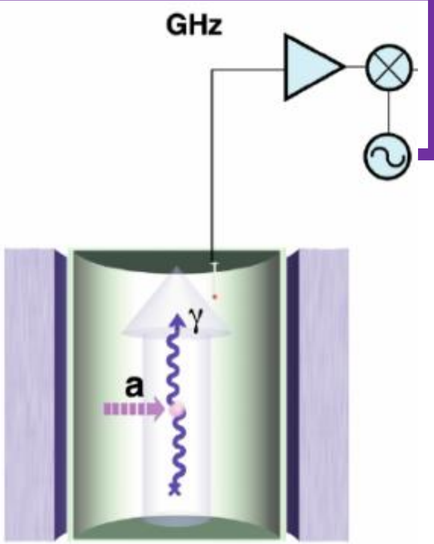
Search strategies



- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes (ADMX)
- Solar Axions
  - Emitted by the solar core.
    - Axion Helioscopes **(CAST → IAXO)**
    - Crystals (Edelweiss Thibault's talk)
- Axions in the laboratory
    - "Light shinning through wall" experiments
    - Vacuum birefringence experiments

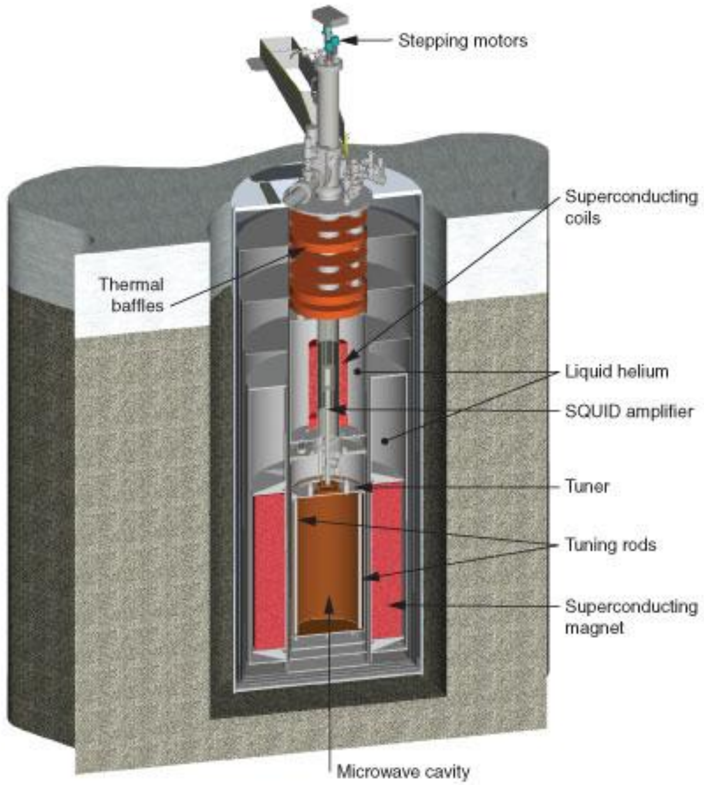


Haloscope : ADMX



•Due to their small mass cold dark matter axions/ALPS can not be detected by recoil techniques

•The mass of the dark matter particle determines the energy to be detected. For axions is in the microwave range



Tunable resonant cavity in magnetic field coupled to an ultra low noise microwave receiver

Signal: microwave photons

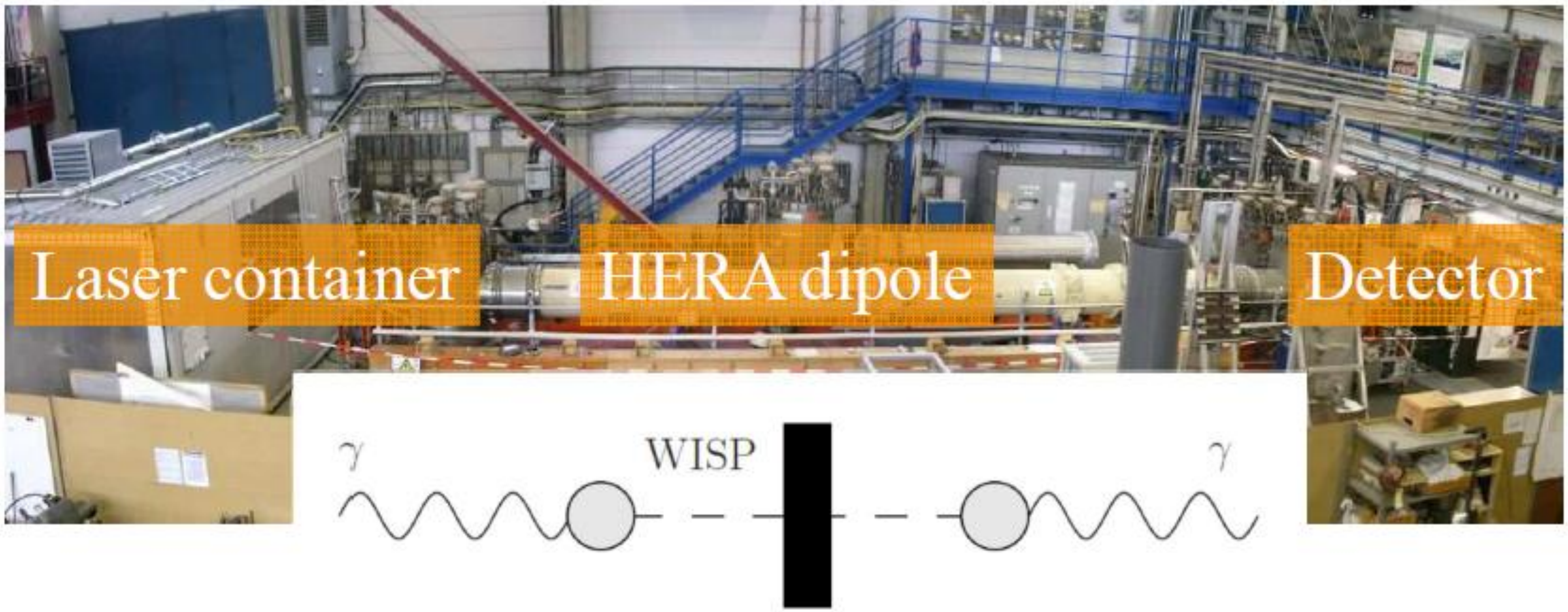
With a frequency proportional to m_a

Microwaves picked up by an antenna, amplified, and seen as an excess of power at a frequency corresponding to the mass of the Axion.

Sensitive to low mass axions: m_a~1-1000 μeV,

Light shining through a wall: ALPS

Any Light Particle Search @ DESY: ALPS-I concluded in 2010



"Light-shining-through-a-wall" (LSW)

Upgrades for ALPS-II:

- 12+12 magnets HERA dipoles (instead of ½ + ½ used for ALPS-1
- Increase power of the laser
- Regeneration cavity to increase photon conversions

Helioscopes

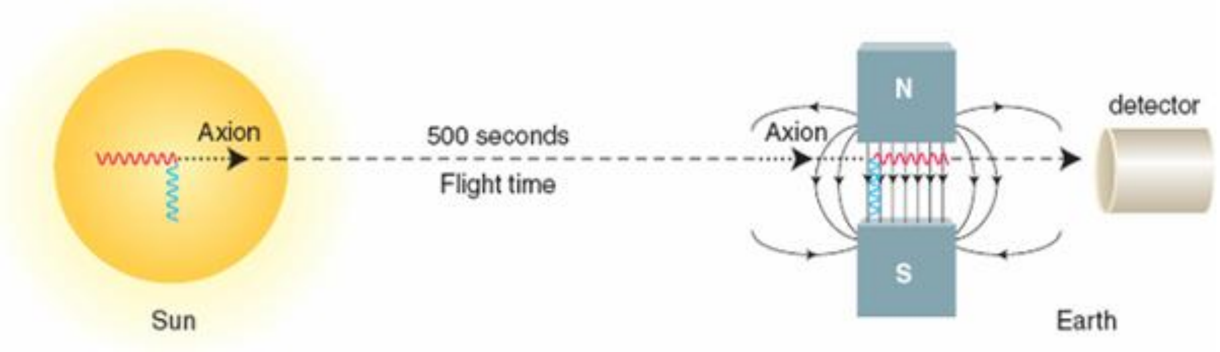
- Brookhaven (a few hours of data): Lazarus et al. PRL 69 (92)
- Tokyo Helioscope (SUMICO): 2.3 m long 4 T magnet

No Liq. He
B=4T, L=2.3m
268A persistent current
16 PIN photodiodes
Altazimuth:Horiz. 360°,
vert.±28°

Inoue et al. **Phys.Lett.B668:93-97,2008**.

Presently running: CERN Axion Solar Telescope (CAST)

CAST Physics

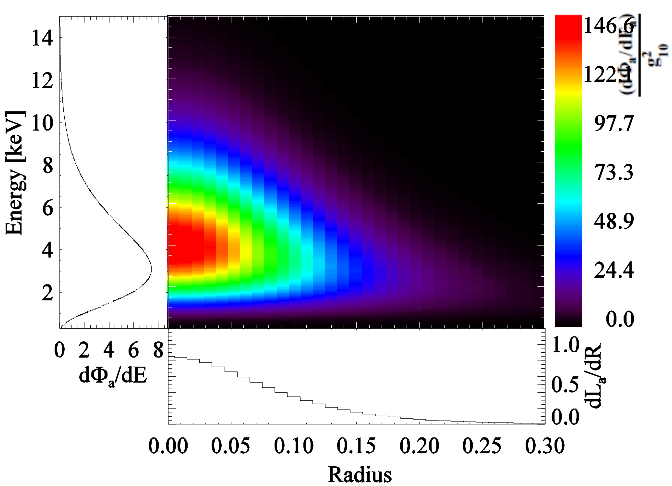


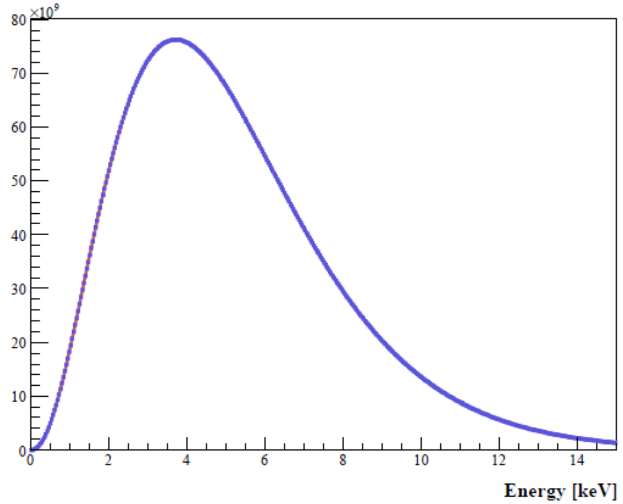
Production in the Sun

Conversion of thermal photons into axions via Primakoff effect in the solar core

Detection in CAST

Conversion of axions into photons via the inverse Primakoff effect in a strong magnetic field





Expected number of photons:

$$N_\gamma = \Phi_a \cdot A \cdot P_{a\to\gamma}$$

$$P_{a\to\gamma} = 1.7\times10^{-17}\left(\frac{B\cdot L}{9.0T\cdot 9.3m}\right)^2\left(\frac{g_{a\gamma}}{10^{-10}GeV^{-1}}\right)$$

$\approx$ 0.3 evts/hour

with $g_{a\gamma} = 10^{-10}$ GeV^{-1} and A = 14 cm^2

CAST: CERN Axion Solar Telescope

Sunset Detectors:
1 TPC (<2007)
2 Micromegas (>2008)

Sunrise Detectors:
1 CCD+telescope
1 Micromegas

Signal: excess of x-rays while pointing at the Sun

LHC dipole : L = 9.3 m, B = 9 T

Rotating platform : vertical movement 16°
horizontal movement 100°

Solar « Tracking » ~3 h/day, background data rest of the day

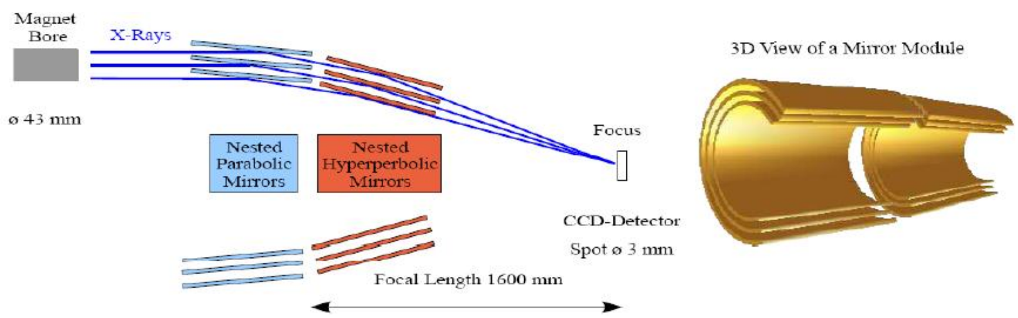
4 X-rays detectors

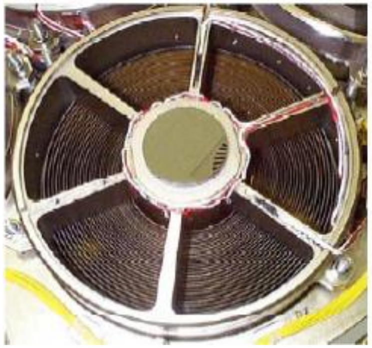
Collaboration CAST

21 Institutes
~70 authors (3 IRFU)

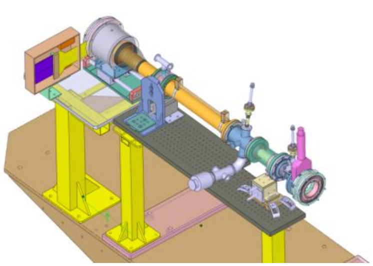
Originalities of CAST

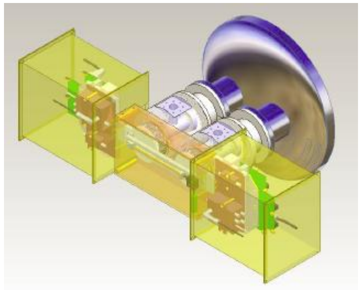
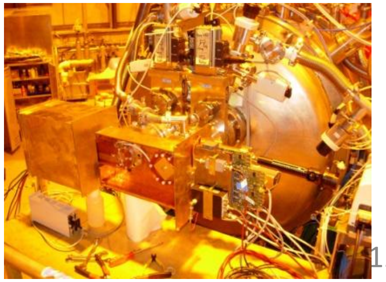
- Use of X-ray telescope ➔ increase S/B noise➔ sensitivity improved by a factor 150 by focusing a ø43 mm x-ray beam to ø3mm





- Low background techniques➔ shieldings, low radioactive materials, simulation and modeling of backgrounds….



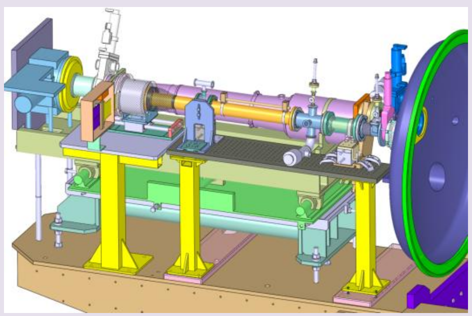



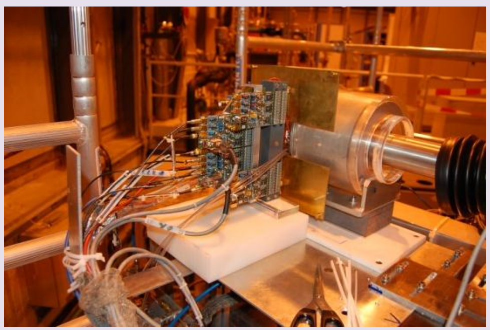
Detectors

Before 2007	Typical rates
TPC	17×10^{-4}c KeV^{-1} cm^{-2} s^{-1} (2-10 keV)
MM	5×10^{-4}c KeV^{-1} cm^{-2} s^{-1} (2-10 keV)
CCD+telescope	8×10^{-5}c KeV^{-1} cm^{-2} s^{-1} (1-7 keV)

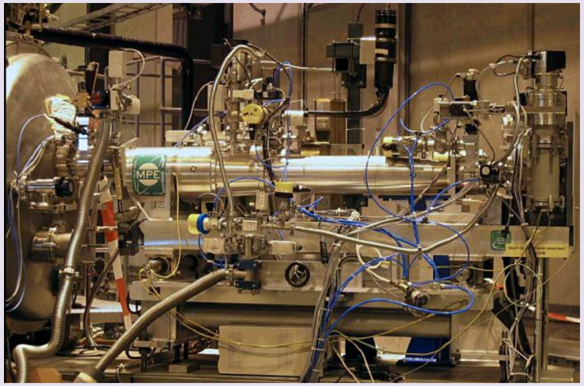
After 2007	Typical rates
2 MM	6×10^{-5}c KeV^{-1} cm^{-2} s^{-1} (2-10 keV)
CCD+telescope	8×10^{-5}c KeV^{-1} cm^{-2} s^{-1} (1-7 keV)

SUNRISE SIDE
Shielded Micromegas last generation-Microbulk type

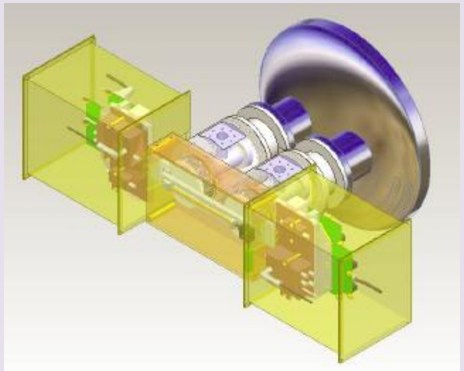


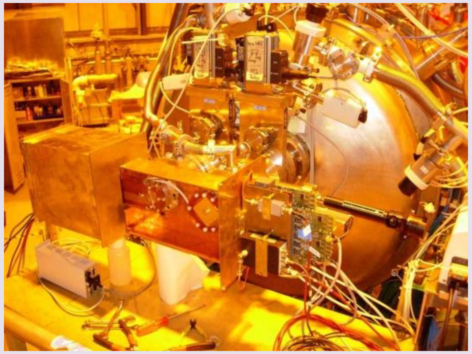


CCD +telescope

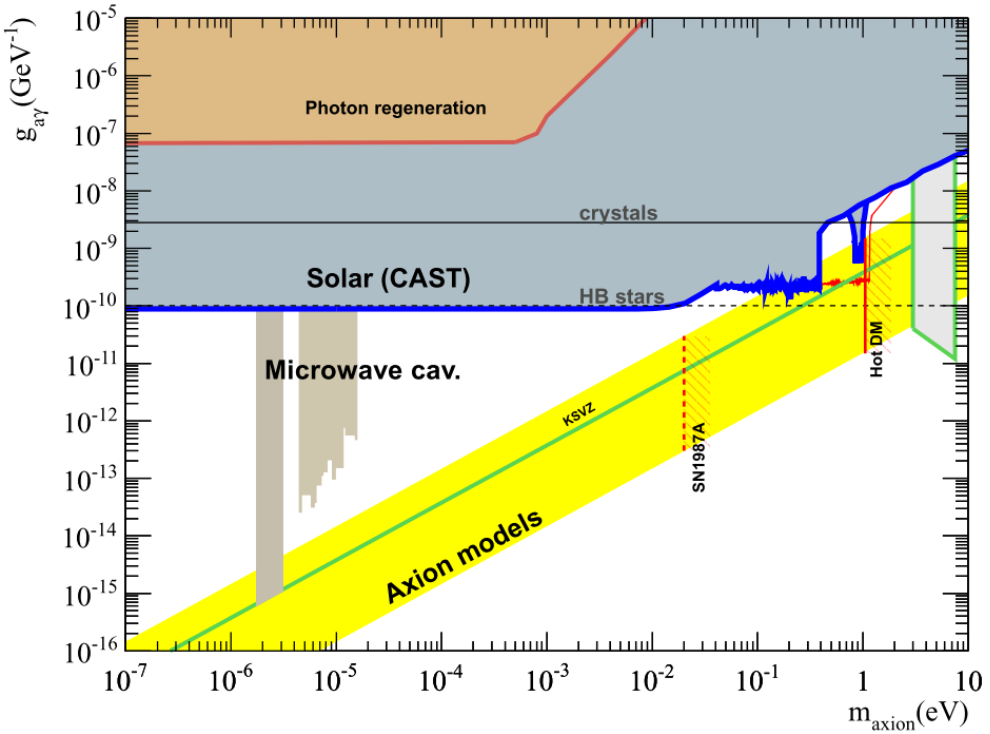


SUNSET SIDE: two shielded Micromegas last generation-Microbulk type





CAST PROGRAM AND SENSITIVITY



CAST Phase I: (vacuum operation 2003-2004)

completed (2003 - 2004), $m_a < 0.02$ eV

JCAP 0704(2007) 010, CAST Coll.

PRL (2005) 94, 121301, CAST Coll.

CAST Phase II: (buffer gas operation 2005-2011)

^{4}He completed (2005 -2006) , 0.02 eV < m_a < 0.39 eV

JCAP 0902 (2009) 008, CAST Coll.

^{3}He run completed (2007-2011),0.39 eV < m_a < 1.18 eV

First part ^{3}He run analysis PRL (2011) 107 261302.

Original aims of CAST reached!

CAST Phase III: (buffer gas ^{4}He 2012)

CAST Phase IV: (vacuum operation 2013-2014)

CAST byproducts:

High Energy Axions: Data taking with a HE calorimeter JCAP 1003:032,2010

14.4 keV Axions: TPC data (before 2006) JCAP 0912:002,2009

Low Energy (visible) Axions: Data taking with a PMT/APD arXiv:0809.4581

Extending sensitivity to higher masses

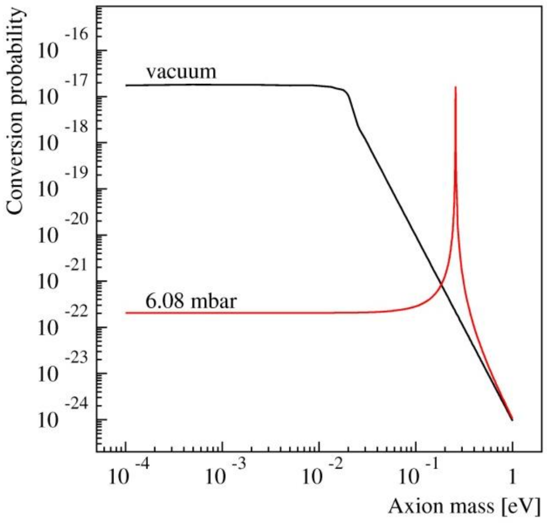
Axion to photon conversion probability:

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

Vacuum:
$\Gamma=0$, $m_\gamma=0$

with $$q = \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right| \qquad m_\gamma(\mathrm{eV}) = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9\sqrt{\frac{Z}{A}\rho\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)}$$

Coherence condition: $qL < \pi$

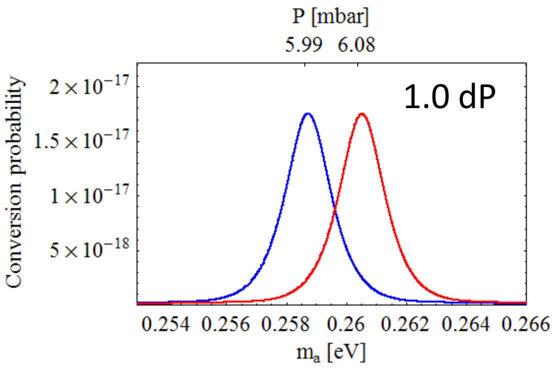


For CAST phase I conditions (vacuum), **coherence is lost for m_a > 0.02 eV**

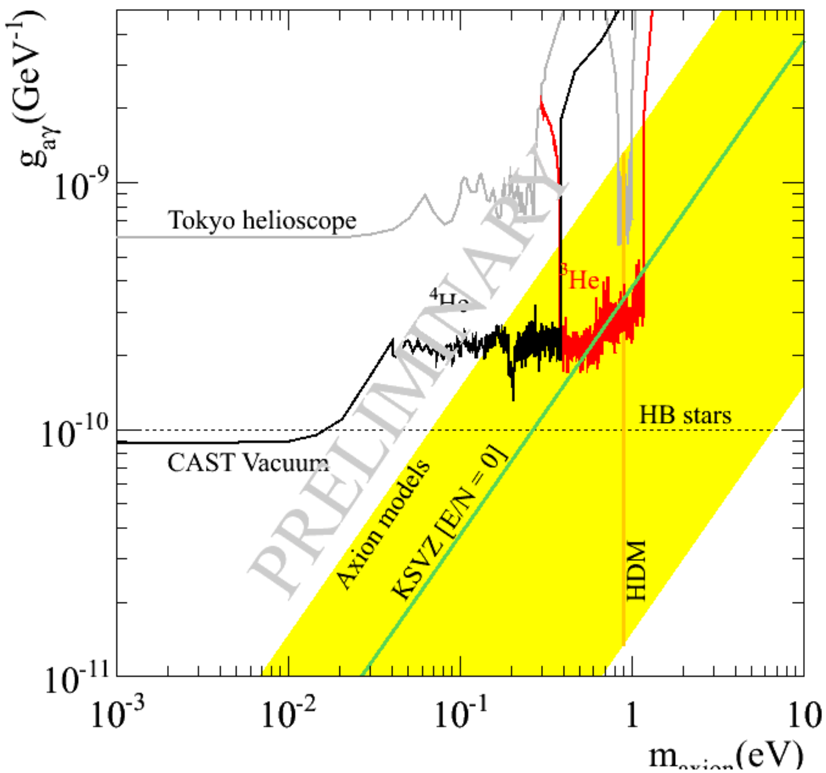
With the presence of a **buffer gas** it can be **restored** for a narrow mass range:

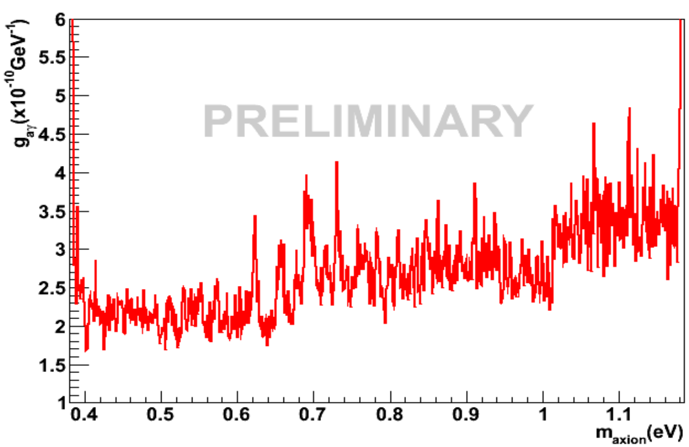
$$qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

e.g. for 50 mbar $\Delta m_a \sim 10^{-3}$ eV



Recent results





Data taken in 2008 (published) covered axion mass interval:

$0.39 \leq m_a \leq 0.64$ eV

M. Arik et al. (CAST collaboration) PRL 107 (2011) 261302 arXiv:1106.3919.

Data taken during 2009 – 2011 covered axion mass interval:

$0.64 \leq m_a \leq 1.18$ eV

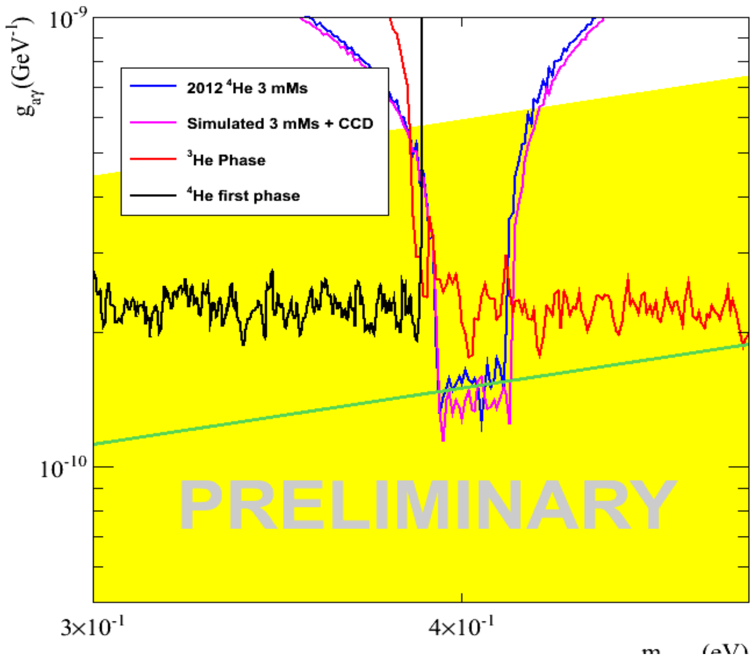
➔ Lower detector backgrounds

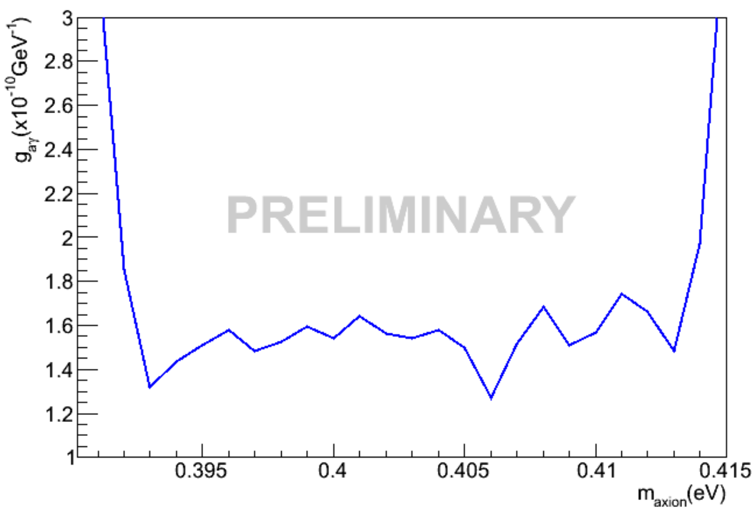
➔ Lower exposure times per m_a

Preliminary exclusion plot. Analysis to be completed

CAST is the first helioscope to have crossed the KSVZ line

2012 phase III ^{4}He





- Data taking period: 22nd June - 7th October 2012
  (axion masses: 0.39 – 0.42 eV)

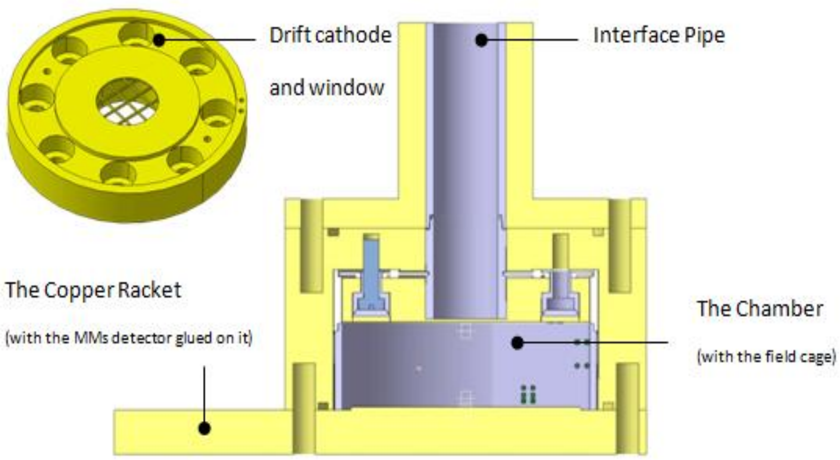
- ~ 5 solar trackings per detector & per pressure setting
  (17 settings covered)

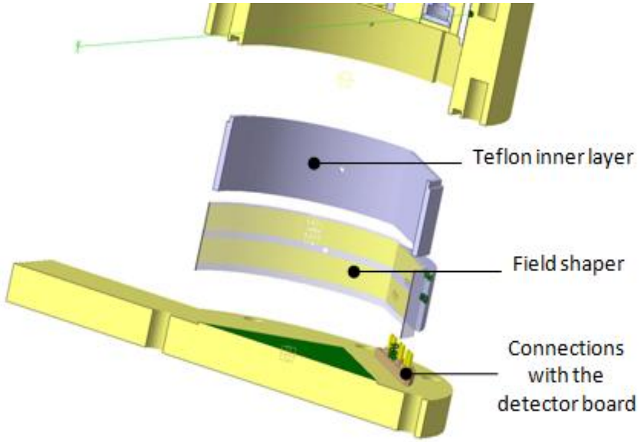
→ Improved Sunset Micromegas background

- Analysis in a similar manner like 3He data

- Preliminary results from 3 out of 4 detectors

The close future 2013-2104 phase IV vacuum



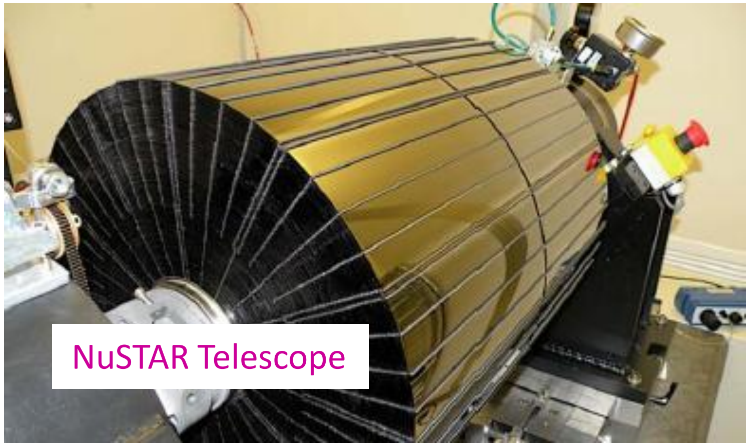


New design for the Micromegas detectors

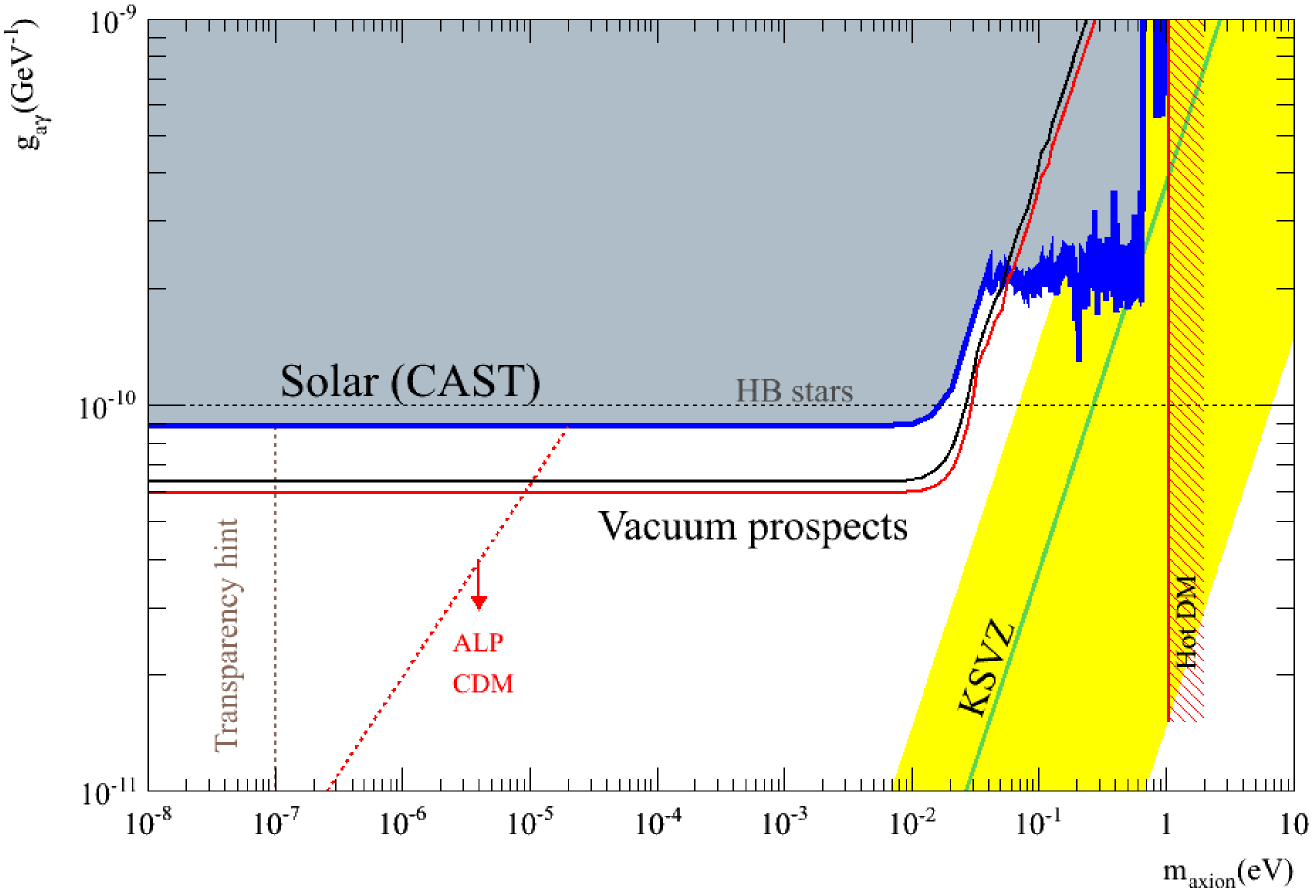
- o Upgraded shielding
- o Improvement on the radiopurity of the construction materials
- o New readout electronics
- o Improve the E threshold ➔ chameleons

New telescope for the Micromegas Sunrise line

- o Construction of new optics using the tooling of the NuSTAR telescope (thermally formed glass substrates) (LLNL, U. Columbia, DTU)
- o Operational mid 2013



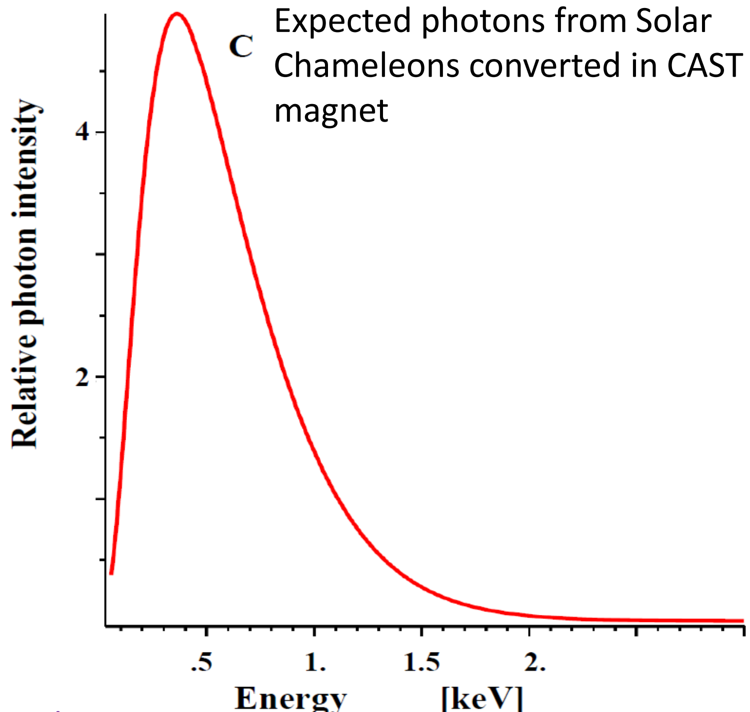
Expected sensitivity phase IV vacuum



Expected sensitivity with the setup proposed in vacuum conditions 9 calendar months assuming 75% data taking efficiency. Two assumptions for the Micromegas background: 1.5×10^{-6} (black line) and 8×10^{-7} counts keV^{-1} cm^{-2} s^{-1} (red line)

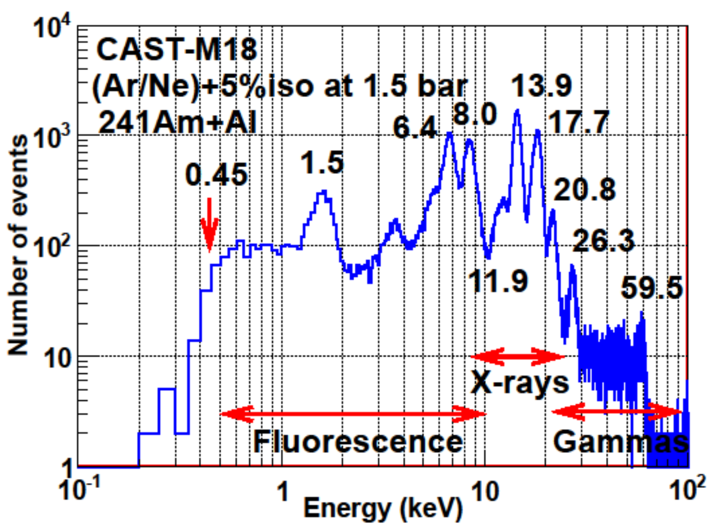
Physics motivation for the sub KeV range: chameleons

- Chameleons are **Dark Energy** candidates to explain the accelerated expansion of the Universe
- Chameleon **mass depends on the ambient energy density**
- Chameleon particles can be created by the **Primakoff effect** in a strong magnetic field. For example in the Sun.
- Like axions, in CAST they can be back – converted to X-ray photons and be detected. Similar phenomenology. Energy threshold needs to be improved.



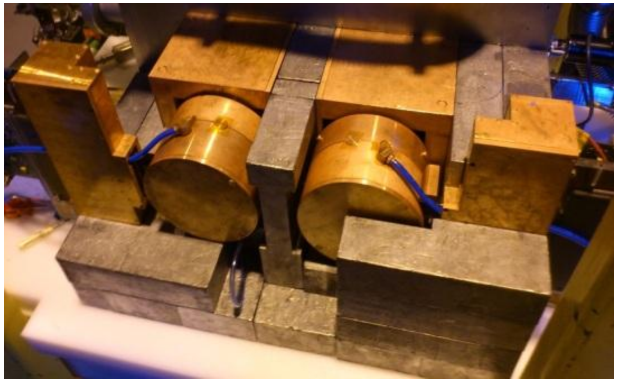
Expected photons from Solar Chameleons converted in CAST magnet

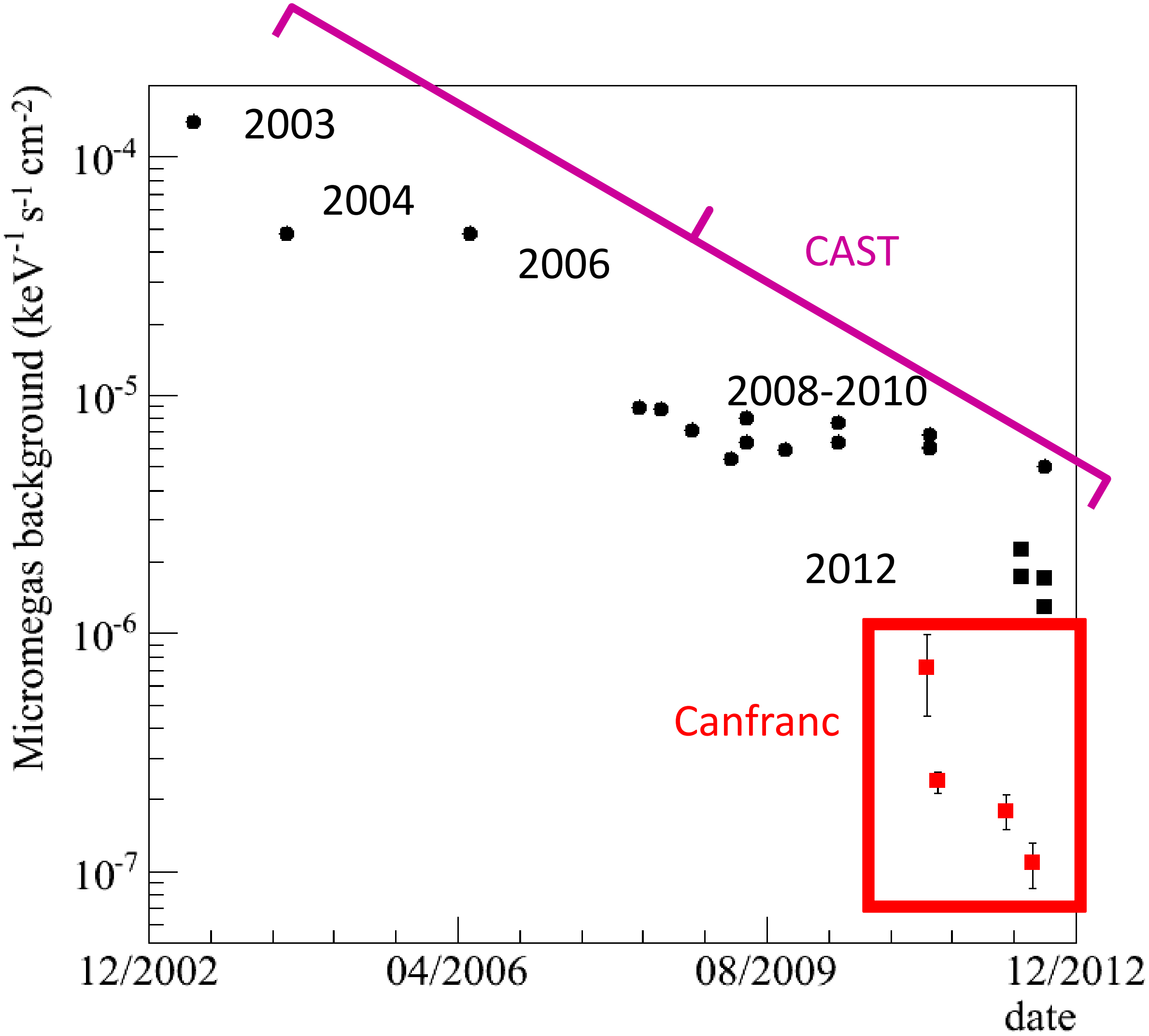
Brax et al.,
Detection prospects for solar and terrestrial chameleons
Phys. Rev. D 85, 043014 (2012)



➔Test in laboratory shows that with appropiate electronics and detector operation conditions the E threshold can be decreased easily to ~500 eV

Background evolution of Micromegas detectors in CAST





AFTER CAST: IAXO (International Axion Observatory)

CAST is established as a reference result in experimental axion physics CAST PRL2004 most cited experimental paper in axion physics

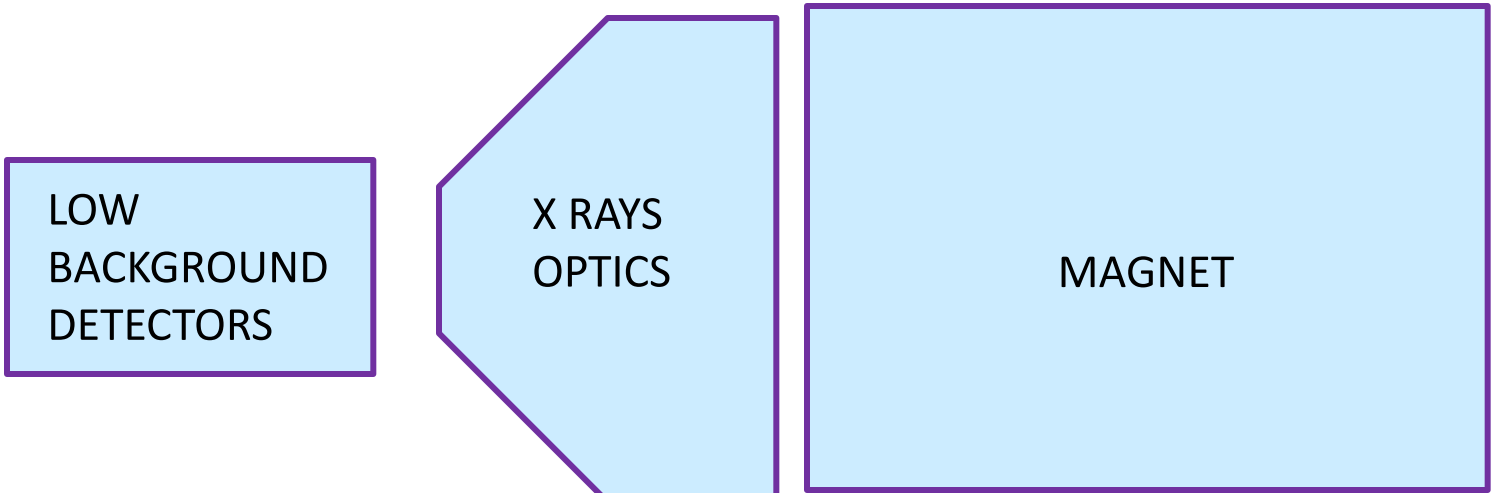
No other technique can realistically improve CAST in such wide mass range.

Future helioscope generation: improve the sensibility by 1 order of magnitude

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal
JCAP 06 (2011) 013

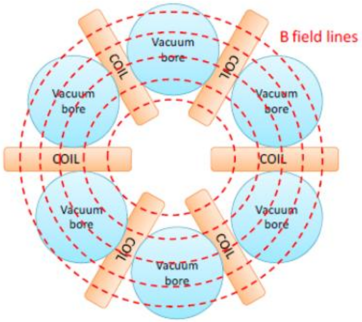
Towards a new generation axion helioscope

I.G. Irastorza,[a] F.T. Avignone,[b] S. Caspi,[c] J.M. Carmona,[a] T. Dafni,[a] M. Davenport,[d] A. Dudarev,[d] G. Fanourakis,[e] E. Ferrer-Ribas,[f] J. Galán,[a,f] J.A. García,[a] T. Geralis,[e] I. Giomataris,[f] H. Gómez,[a] D.H.H. Hoffmann,[g] F.J. Iguaz,[f] K. Jakovčić,[h] M. Krčmar,[h] B. Lakić,[h] G. Luzón,[a] M. Pivovaroff,[j] T. Papaevangelou,[f] G. Raffelt,[k] J. Redondo,[k] A. Rodríguez,[a] S. Russenschuck,[d] J. Ruz,[d] I. Shilon,[d,i] H. Ten Kate,[d] A. Tomás,[a] S. Troitsky,[l] K. van Bibber,[m] J.A. Villar,[a] J. Vogel,[j] L. Walckiers[d] and K. Zioutas[n]



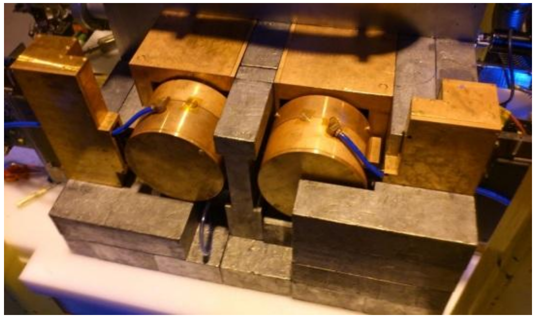
$$g_{\alpha\gamma\gamma} \propto \underbrace{(BL)^{1/2} \times A^{1/4}}_{magnet} \times \underbrace{b^{1/8}}_{Detector} \times \underbrace{t^{1/8}}_{tracking\ system}$$

IAXO (International Axion Observatory)



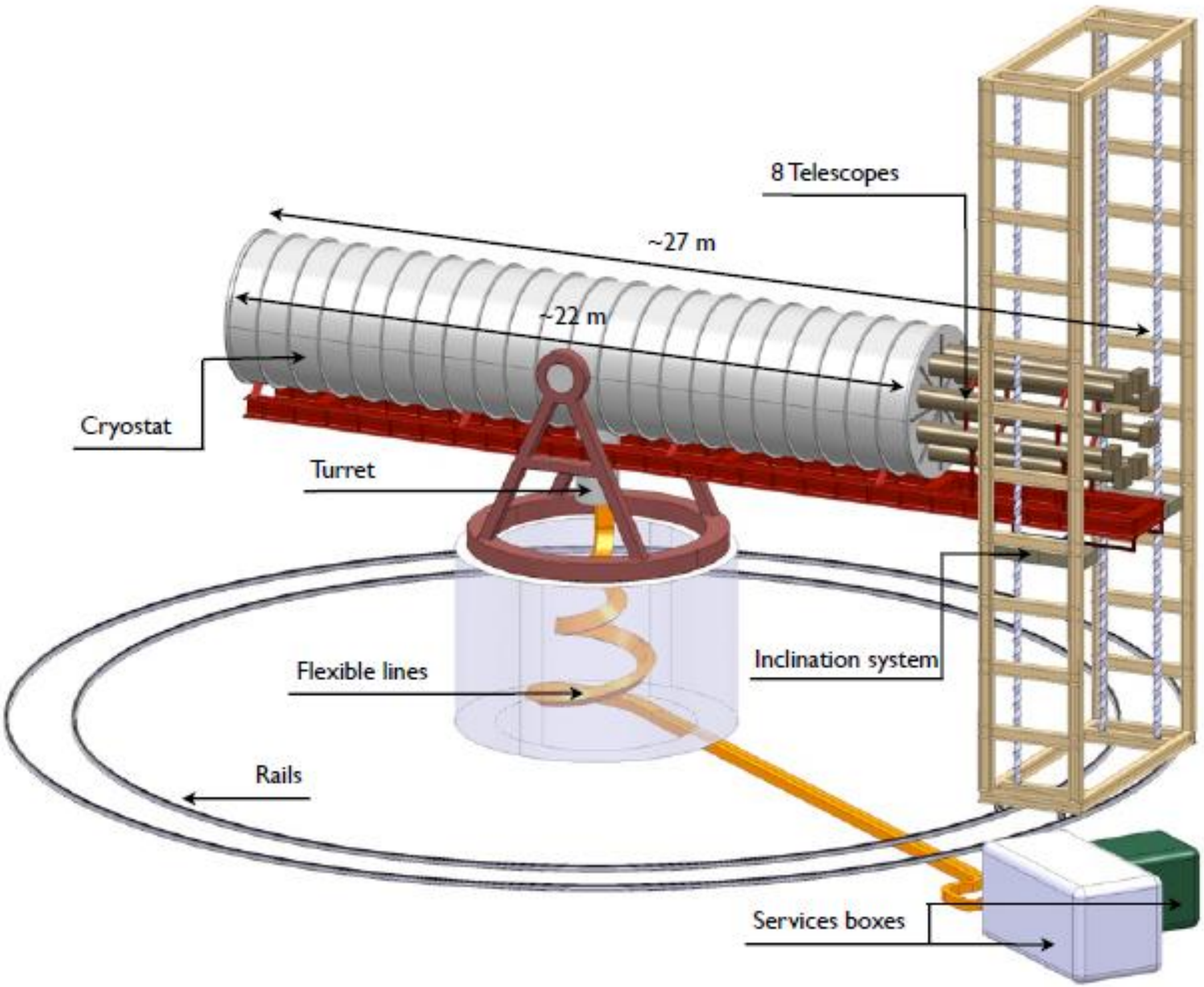
DEDICATED MAGNET
Best option **toroidal configuration:**
○ Much bigger aperture than CAST: ~0.5-1 m per bore
○ Relatively Light (no iron yoke)

X-RAY OPTICS
Thermally-formed glass substrates optics Successfully used in NUSTAR, Leverage existing infrastructure. Minimize costs & risks



ULTRA LOW BACKGROUND DETECTORS
Goal: 10^{-7} c/keV/s/cm2 or better
Apply what have been learned in CAST: compactness, radiopurity, better shielding

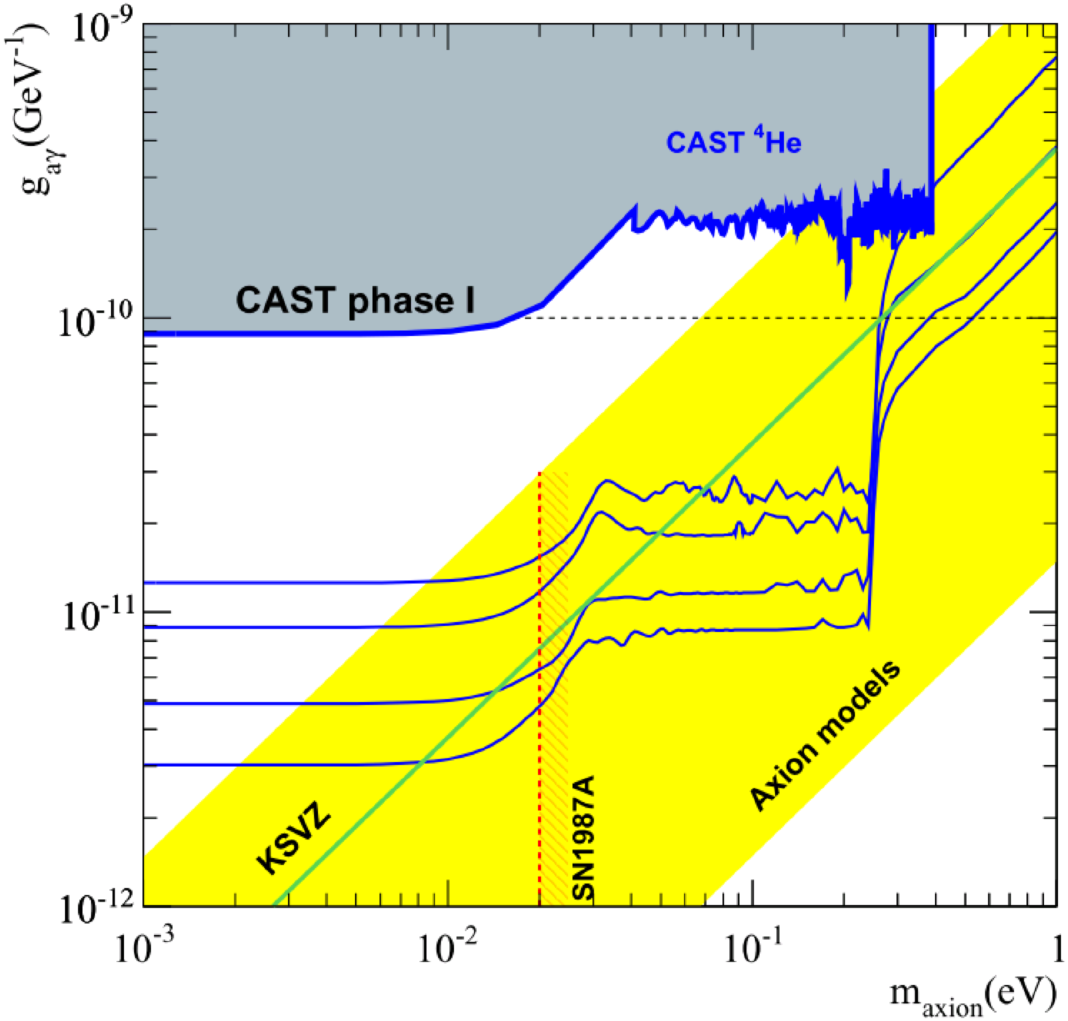
IAXO (International Axion Observatory)



Possible Conceptual Design (LLNL)

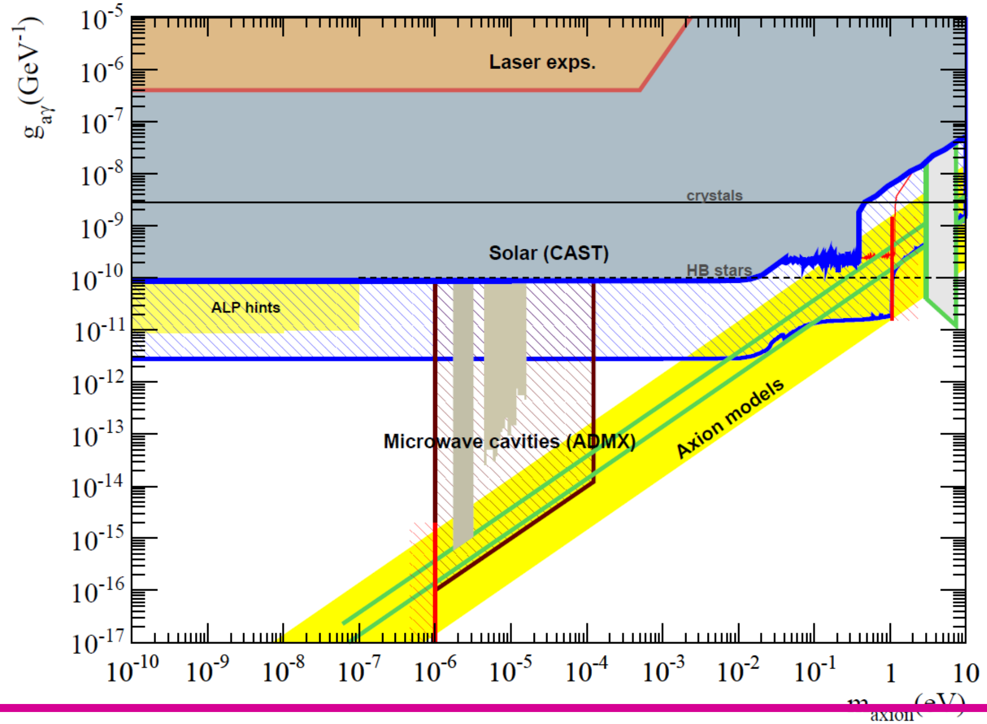
IAXO SENSITIVTY PROSPECTS

Factor 8 to 30 better in $g_{a\gamma}$ (4000 to 10^6 in signal strength!!)



LoI to CERN in preparation

CONCLUSIONS & PERSPECTIVES



CAST provides the Strictest experimental limit on axion searches for a wide m_a range entering the region most favoured by QCD models

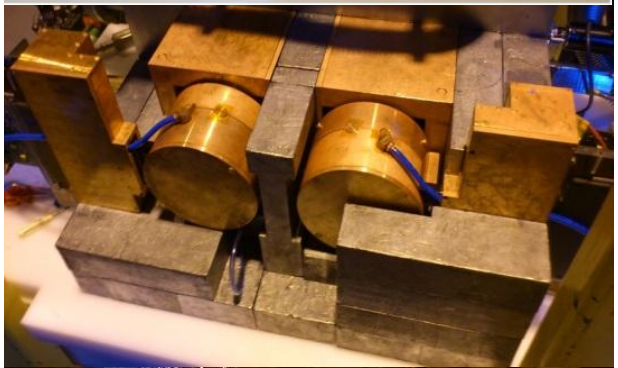
First studies show that IAXO should improve CAST sensibility $g_{a\gamma}$ by 1-1.5 orders of magnitude

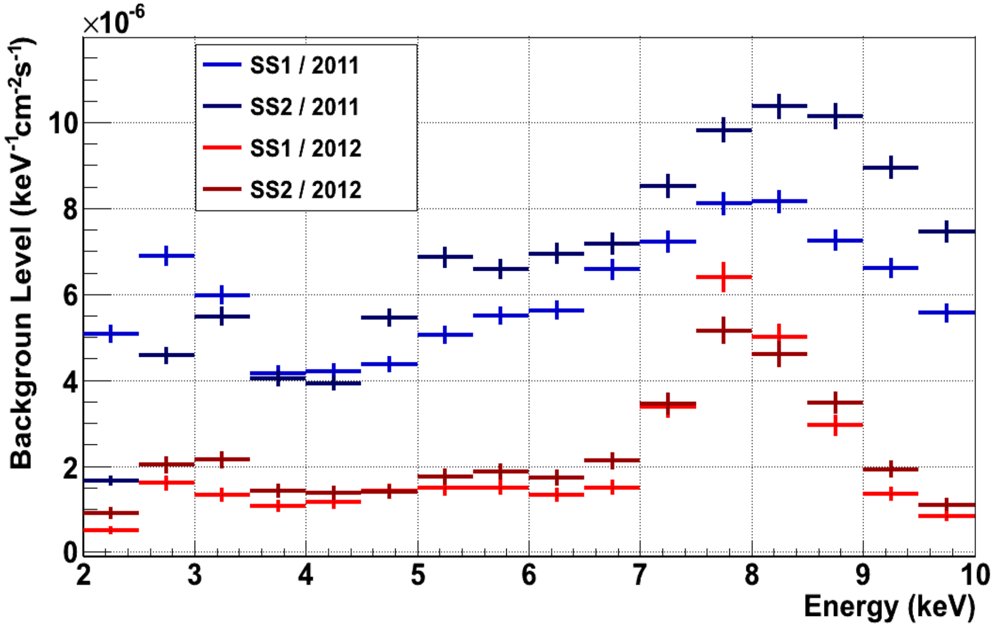
IAXO together with ADMX will be able to explore in a complementary manner a very fair part of the parameter space

- CAST extension 2012-2014 is preparing the new generation of helioscopes. The new Micromegas design+ optics for 2013-2014 data taking is a pathfinder for IAXO as it uses the same technological choices chosen for IAXO
- The CERN SPSC approved end of October the 2013-2014 extension of CAST and congratulated the detector achievements
- The last version of ASPERA roadmap includes IAXO and CAST
- Axion physics (in particular CAST and IAXO) present in Europe and USA roadmaps : European Strategy for Paritcles Physics (Krakow) and Vistas in Axion Physics (Seattle) and Intensity Frontier (Rockville)

BACK UP

PERFORMANCE OF NEW SUNSET MICROMEGAS





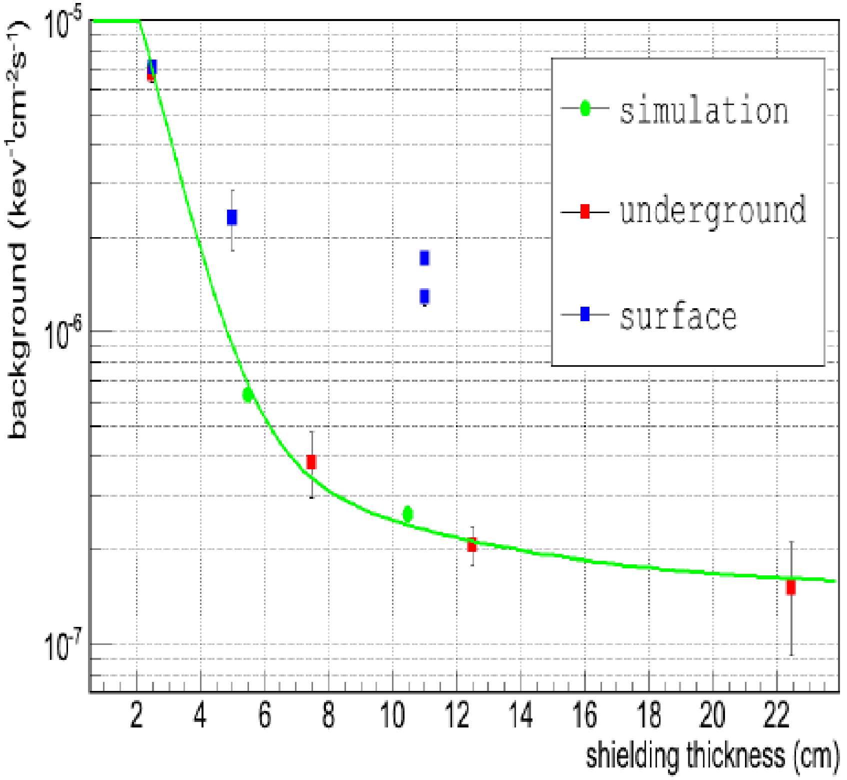
2012 Upgrade: new Microbulk detectors and new radiopure shielding (thicker and better solid angle closure)

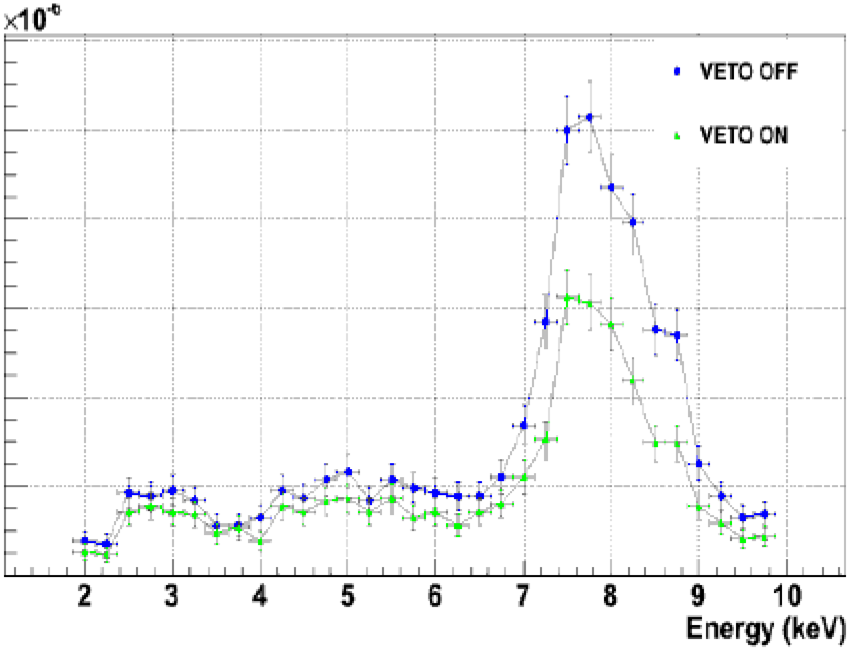
All stainless steel pieces were replaced by copper to prevent [5-7] keV fluorescences.

Background level around 4.5 times lower than previous SSMM

EFFECT OF MUON VETO

Simulated effect of the shielding thickness





Underground vs surface tests: the dominant contribution to background is cosmic rays

Confirmed by simulation: simulation of gamma radiation reproduces well the drop in background level as a function of shielding thickness

CAST constraint on axion-electron coupling

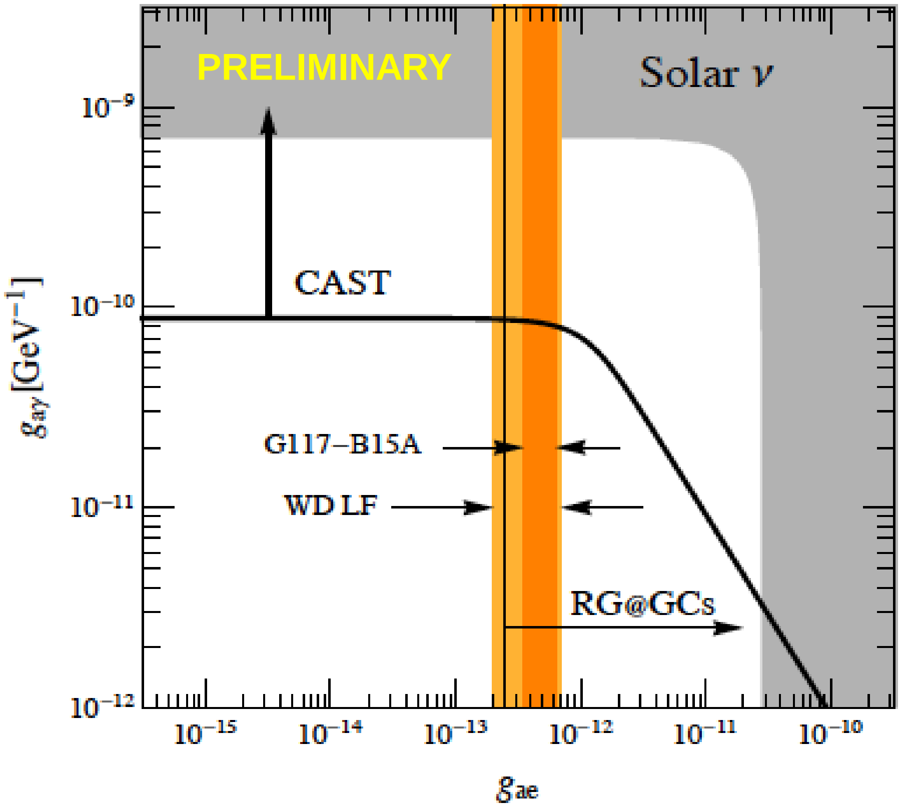
CAST has mainly focused on hadronic (KSVZ) axions:

- **no** coupling of axions to electrons at tree level
- dominant production process in the Sun is the Primakoff process
  $\gamma + Z \rightarrow a + Z$ (two-photon coupling)

Non-hadronic (DFSZ) axions:

- coupling of axions to electrons at tree level
- additional axion-production channels in stars (BCA reactions):
  - ✓ electron – nucleus and electron – electron bremsstrahlung
    ($e + Z \rightarrow e + Z + a$, $e + e \rightarrow e + e + a$)
  - ✓ Compton process ($\gamma + e \rightarrow e + a$)
  - ✓ axio – recombination ($e + I \rightarrow I^- + a$)
- astrophysical constraint (evolution of red giants): $g_{ae} \leq 2.5 \times 10^{-13}$
- couplings of $g_{ae} \leq$ few 10^{-13} might explain the anomaly in the cooling of white dwarfs (WD)
- corresponding axion mass is $m_a \sim$ meV $\Rightarrow$ other interesting phenomenological implications in the context of astrophysics and cosmology

CAST constraint on axion-electron coupling



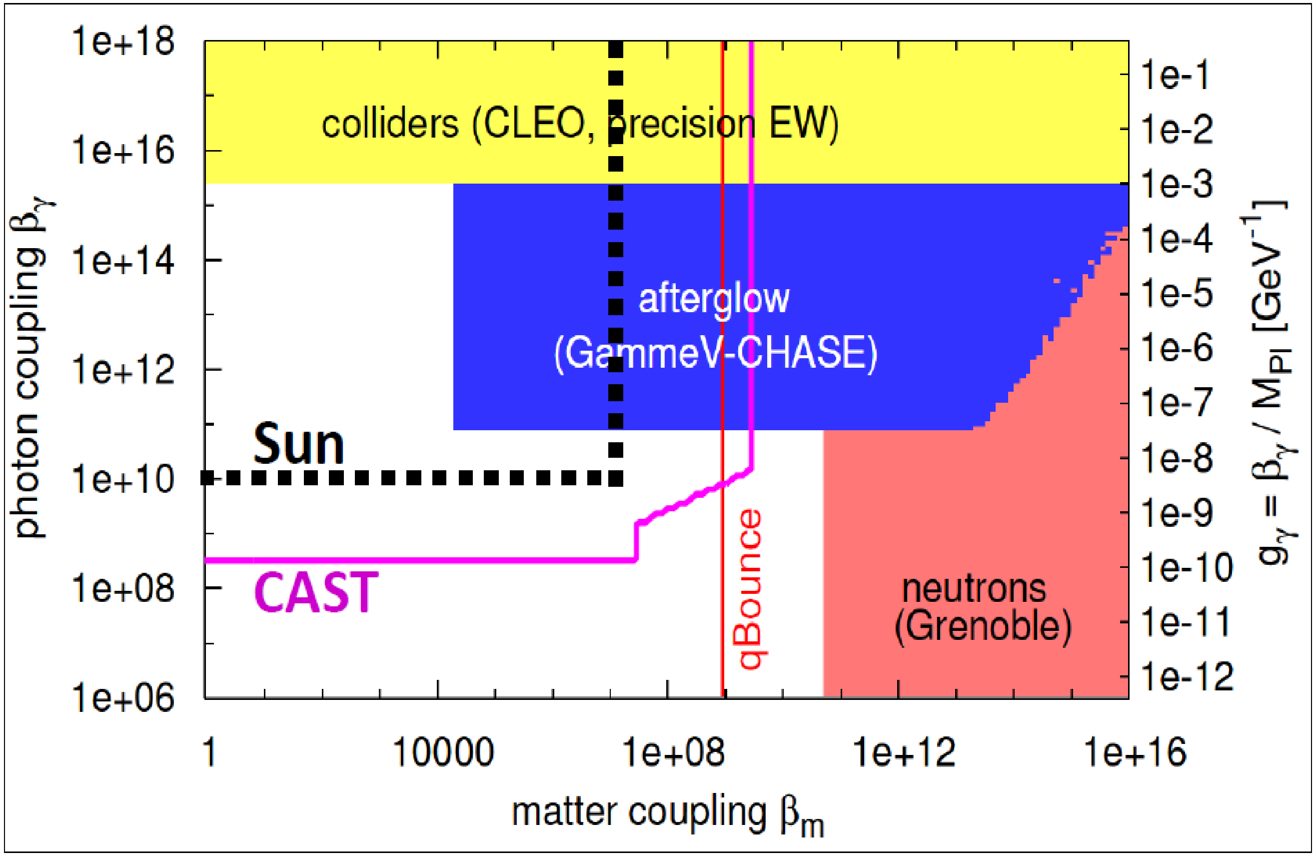
Preliminary limits on the product of the

axion – electron & axion – photon coupling constants for

$m_a \leq 0.02$ eV using CAST phase I data (vacuum phase):

$g_{ae} \times g_{a\gamma} \leq 0.9 \times 10^{-22}$ GeV^{-1} at 95% CL

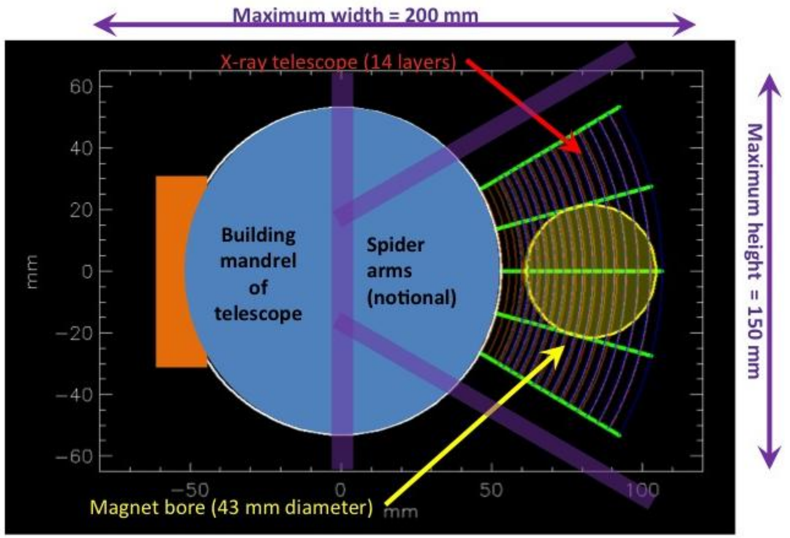
PROSPECTS FOR CHAMELEONS SENSITIVITY

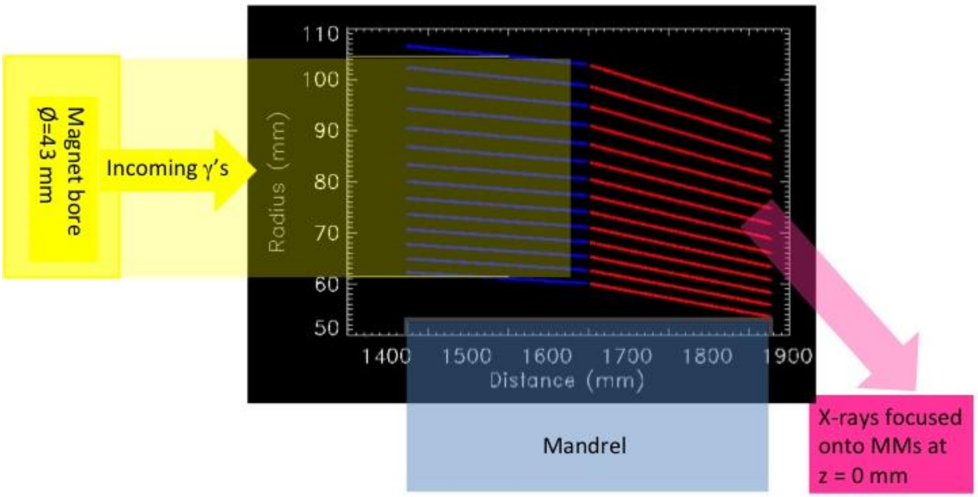


1 hour run and zero background
Detector efficiency not taken into account

Upgrades: new X-Ray optics

- Build a single optic to be coupled to a Micromegas detector on the existing Sunrise Micromegas line
  (Columbia University, the Danish Technical University-Space & LLNL)
- Similar properties similar to the ABRIXAS X-ray telescope
- “easy to build”
  - 15 nested shells
  - build 1/6th of a normal X-ray telescope, (1 of 6 mirror sectors)
- Focal length ~1.5 m
- Efficiency estimation according to NuSTAR data: 4-arcmin radius extraction region would contain ~80% of the encircled energy





Schedule

- ✓ Construct the optic in quarter 1 (Q1) 2013
- ✓ Calibration at the PANTER X-ray facility Q2
- ✓ implementation and alignment in CAST in Q3
- ✓ Ready for science at CAST in Q4 of 2013

IAXO SENSITIVITY SCENARIOS

Parameter	Unit	CAST-I	Scenario 1	Scenario 2	Scenario 3	Scenario 4
B	T	9	3	3	4	5
L	m	9.26	12	15	15	20
A	m^2	2×0.0015	1.7	2.6	2.6	4.0
f_M^*		1	100	260	450	1900
b	$\frac{10^{-5}\,\mathrm{c}}{\mathrm{keV\,cm^2\,s}}$	~ 4	3×10^{-2}	10^{-2}	3×10^{-3}	10^{-3}
ϵ_d		0.5–0.9	0.7	0.7	0.7	0.7
ϵ_o		0.3	0.3	0.3	0.6	0.6
a	cm^2	0.15	3	2	1	1
f_{DO}^*		1	6	14	40	40
ϵ_t		0.12	0.3	0.3	0.5	0.5
t	year	~ 1	3	3	3	3
f_T^*		1	2.7	2.7	3.5	3.5
f^*		1	1.6×10^3	9.8×10^3	6.3×10^4	2.7×10^5

Irastorza et al.
JCAP 016 (2011)

CCD + X-ray telesc

- No major changes to the system compared to 2011
- Reliable operation of CCD during 2012 (84 trackings - efficiency 92%)
- 3 additional noisy pixels on the CCD: removed by analysis
- Alignment of telescope and detector has been checked before the current run
- Long term stability of the detector is good (checked with ^{55}Fe calibration source)
- 123.2 hours of axion sensitive time (first 82 trackings)
- Rates:
  - $8.2\times10^{-5}\ s^{-1}\,keV^{-1}\,cm^{-2}$ (whole chip)
  - $8.9\times10^{-5}\ s^{-1}\,keV^{-1}\,cm^{-2}$ (signal region)
  - 22 events in the signal region
- **~ 0.3 counts / tracking**