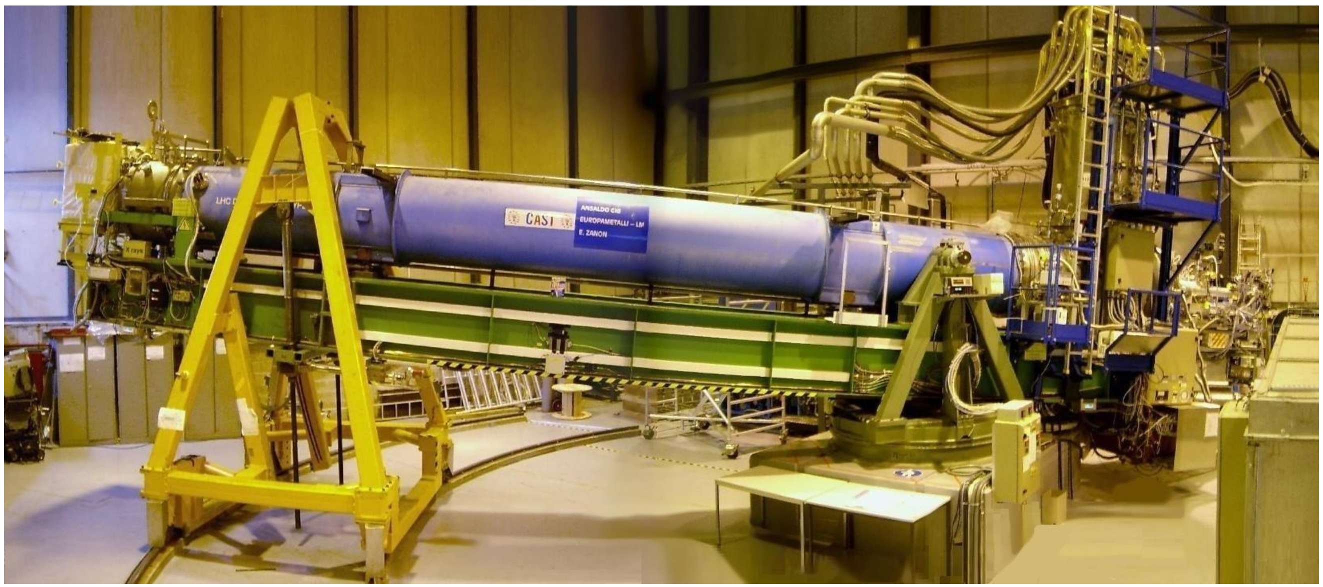
SOLAR AXION SEARCH AND RESEARCH IN THE CAST EXPERIMENT



Juan Antonio García Pascual
Institute of High Energy Physics, Beijing
3rd February 2016

e-mail: juan.antonio.garcia.pascual@cern.ch

Institute of High Energy Physics
Chinese Academy of Sciences

OUTLINE

- Axions and Axion Like Particles
- The CAST experiment
- Low background techniques
- The future IAXO
- Summary and conclusions

AXIONS

Axion arises as a solution of the strong CP problem

$$\mathcal{L}_{\bar{\theta}} = \bar{\theta}\frac{g^2}{8\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \qquad \bar{\theta} = \theta + \theta_{weak} \qquad |d_n| < 2.9 \times 10^{-26} \Rightarrow \bar{\theta} \leq 10^{-10}$$!?

But, why is $\bar{\theta}$ so small???

Solution:

R. Peccei and *H. Quinn*

Phys. Rev. D 33, 897

Phys. Rev. D 16, 1791

Introduction of new global, chiral symmetry that is spontaneously broken at the energy scale of the symmetry f_a

$$\mathcal{L}_a = -\frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int} + C_a \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

It implies the existence of a new field *a* which appears as the pseudo Nambu-Goldstone boson of the new symmetry → **The axion**

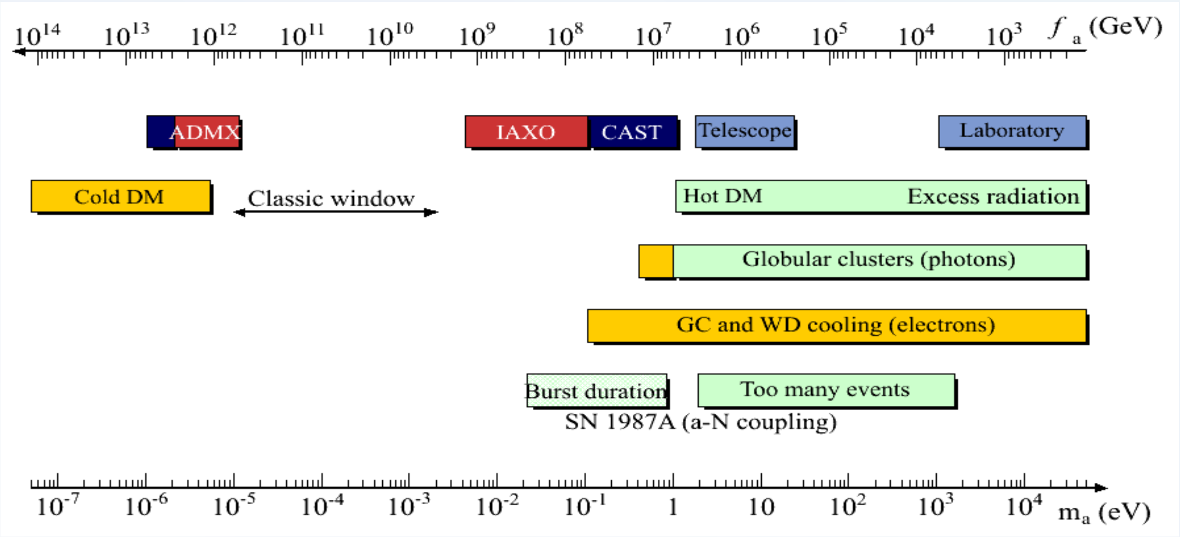
AXIONS

Axion properties: $m_a \propto \frac{1}{f_a}$, $g_{ai} \propto \frac{1}{f_a}$

Axion generically couples to photons and gluons. It could also interact with fermions.

Axions are non-massive and electrically neutral particles that interact weakly with matter. Moreover, a big amount of relic axions could have been generated in the early Universe. Axions are attractive Dark Matter candidates.

Axion masses are constrained by astrophysical and cosmological considerations.



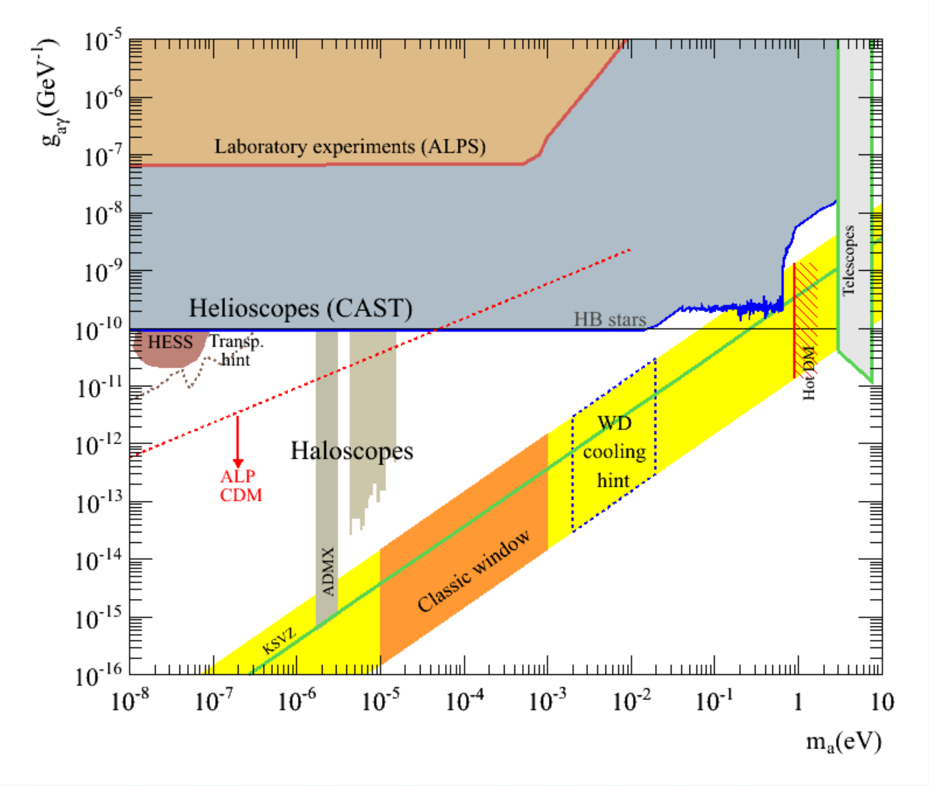
AXIONS AND ALPS

Axion Like Particles (ALPs) or more generically WISPs, share the same phenomenology as the axions. But in this case m_a and $g_{a\gamma}$ are not correlated.

ALPs arise from extensions of the SM as pseudo NG bosons of new symmetries that are broken at a high energy scale. Also, they appear in string theory.

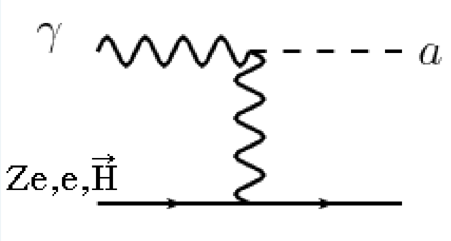
ALPs could also provide the right amount of Dark Matter, in a wide range of the parameter space.

Axions and ALPs hints:
-VHE transparency
-WD cooling rate

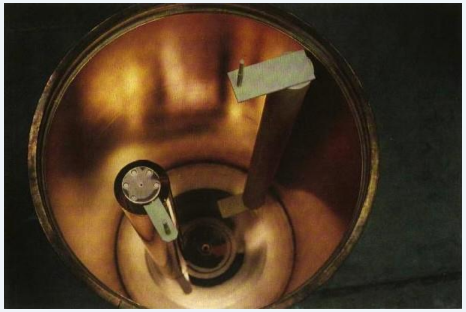


AXIONS AND ALPS

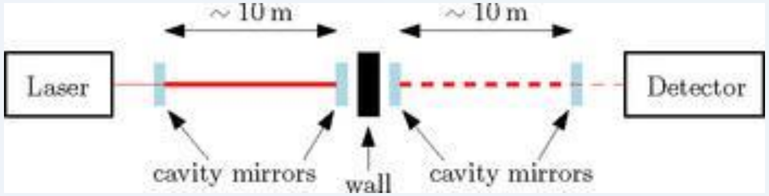
Axion and ALPs searches are based on the Primakoff effect. There are 3 main strategies:



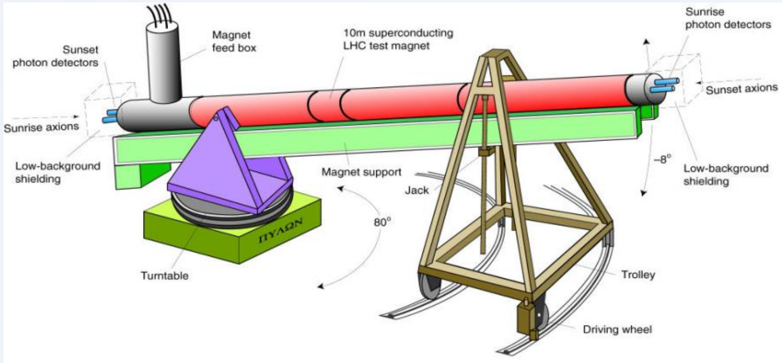
Haloscopes: Looking for relic axions in the galactic halo, which can be detected in resonant cavities inside strong magnetic fields.
Leading exp.→ ADMX



Laboratory experiments: Axions are produced and detected in the lab.
Leading exp.→ ALPS

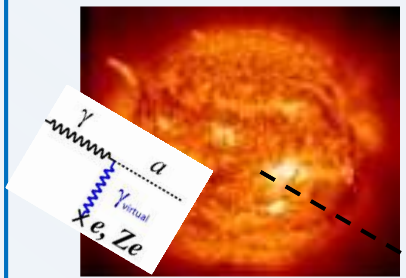


Helioscopes: Using the Sun as an axion source. Solar axions could be converted into photons inside strong magnetic fields.
Leading exp.→ CAST

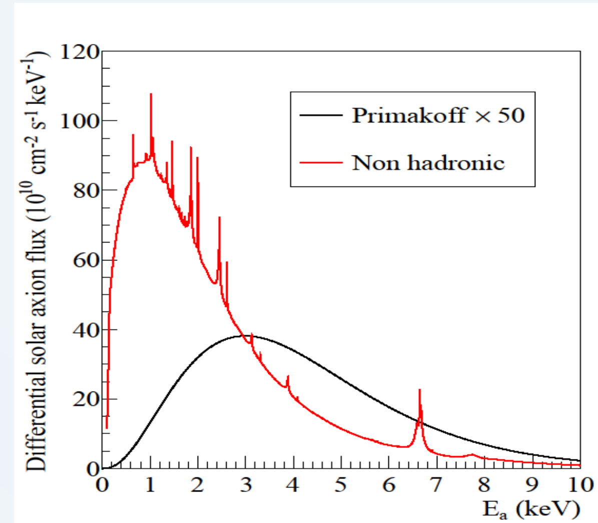


AXIONS AND ALPS

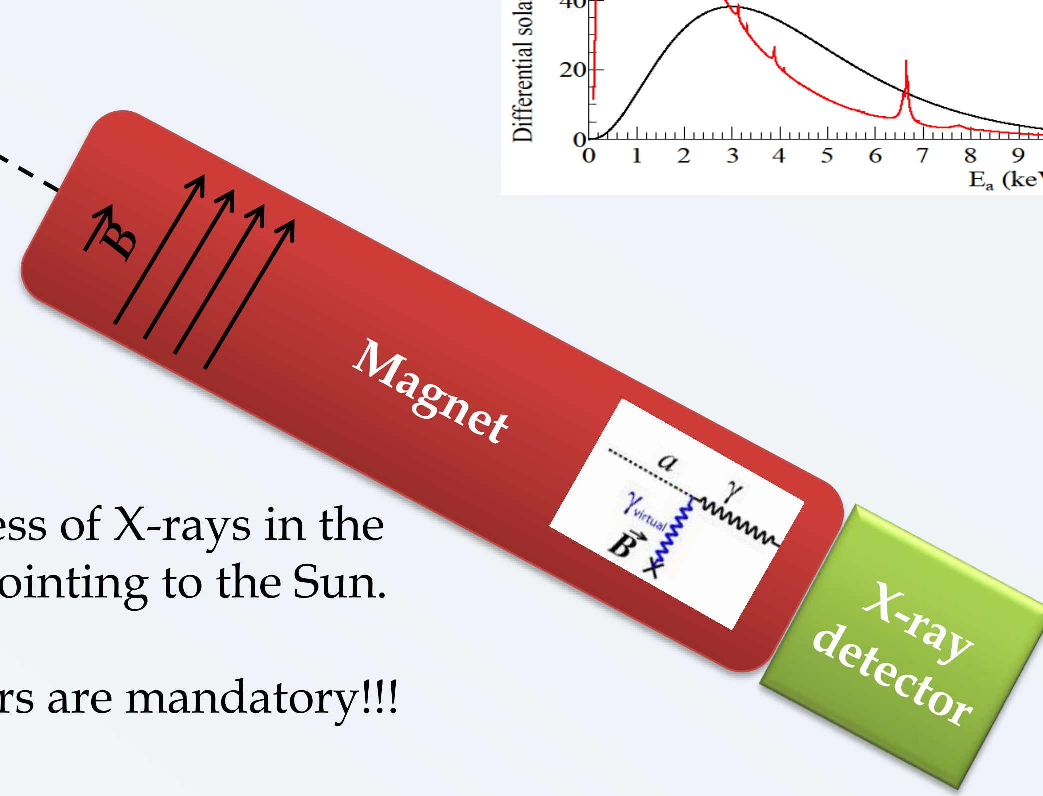
Proposed by *P. Sikivie* in 1983 **PRL 51, 1415**



Thermal photons inside the strong electric fields of the charged particles in the solar plasma could be converted into axions.



Solar axions could be reconverted into photons inside strong magnetic fields via "inverse Primakoff" effect.



The axion signal will be an excess of X-rays in the detectors while the magnet is pointing to the Sun.

Low background X-ray detectors are mandatory!!!

AXIONS AND ALPS

Probability of the axion-photon conversion:

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

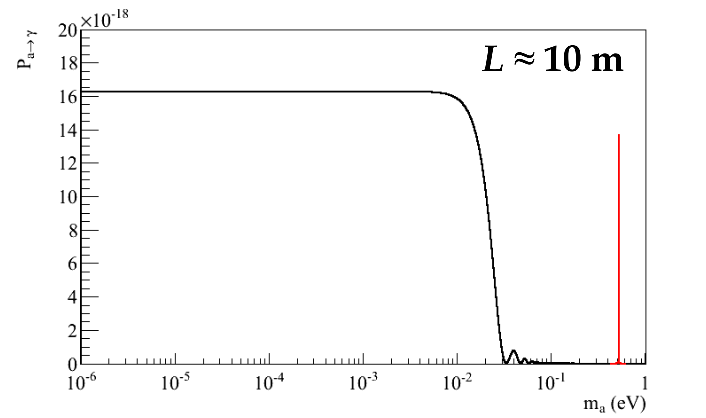
Vacuum case:

$$q = \frac{m_a^2}{2E_a}$$

$$\Gamma \simeq 0$$

$$\Rightarrow \quad P_{a\to\gamma} = \left(\frac{g_{a\gamma}BL}{2}\right)^2 \left(\frac{\sin\left(\frac{qL}{2}\right)}{\frac{qL}{2}}\right)^2$$

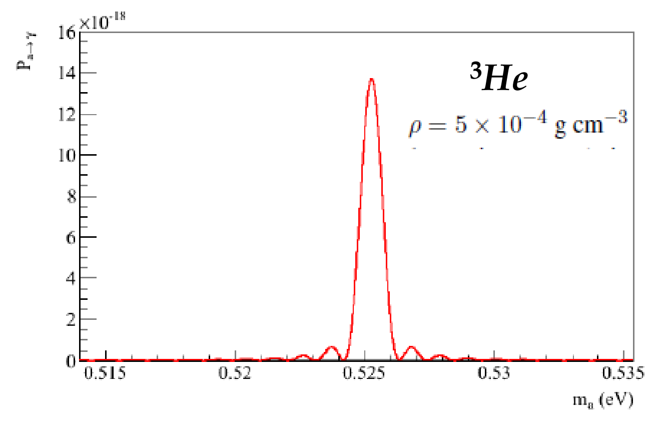
Coherence condition → $m_a < \sqrt{\frac{4\pi E_a}{L}}$



Buffer gas case:

$$m_\gamma = \omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$$

$$n_e = N_A \frac{Z}{W}\rho$$



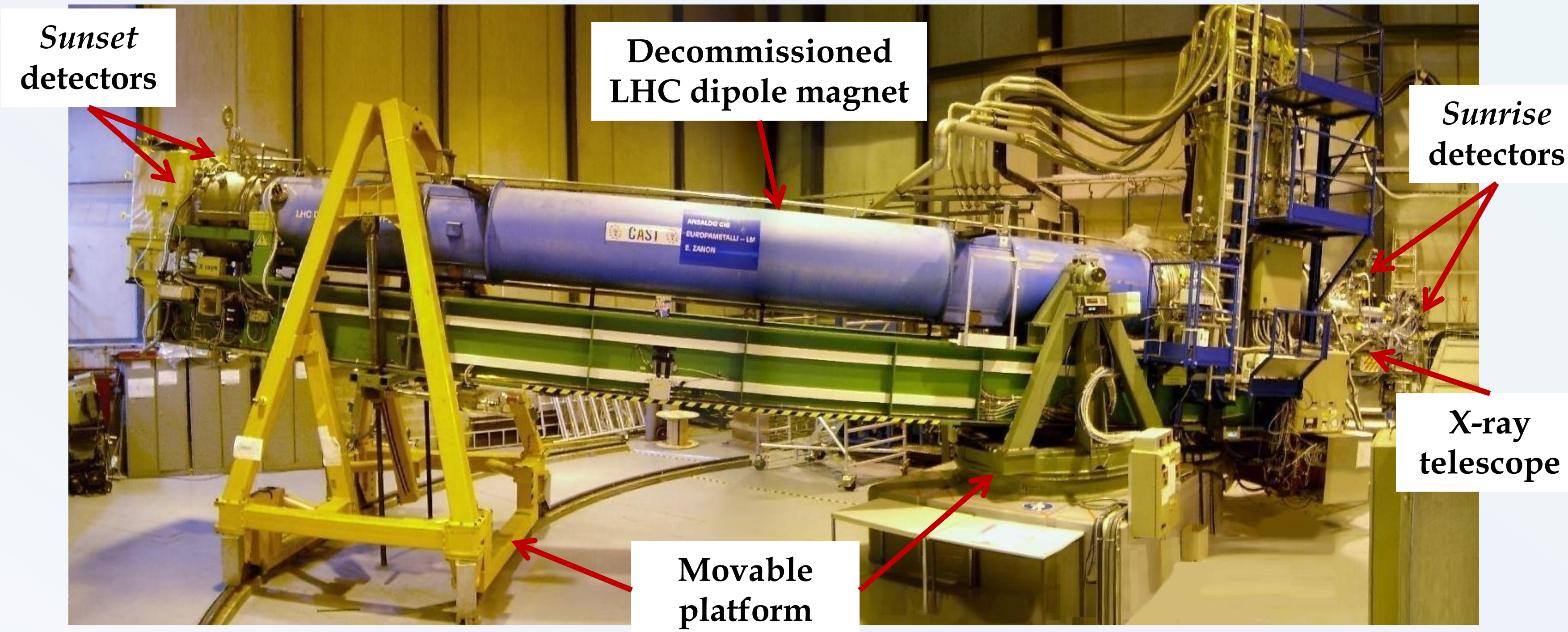
The coherence can be restored for higher axion masses.

THE CAST EXPERIMENT

The CERN Axion Solar Telescope

http://cast.web.cern.ch/CAST/

Operating at CERN since 2003, being the most sensitive helioscope, so far…



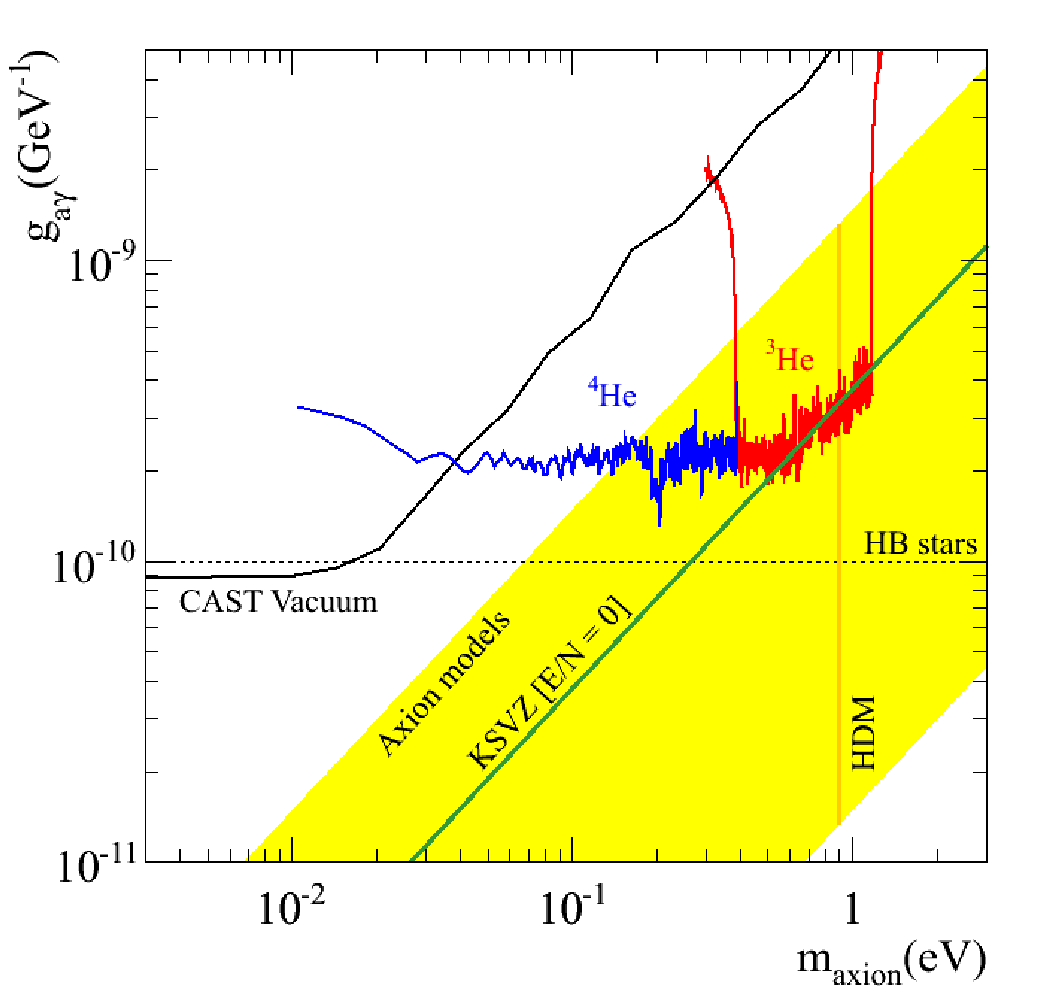
Magnet length: 9.26 m
Magnet aperture: 2 x 14.5 cm^2
Magnetic field: 8.8 T

Solar trackings:
~1.5 h during Sunset
~1.5 h during Sunrise

X-ray detectors:
- 3 Micromegas
- 1 Ingrid

THE CAST EXPERIMENT

CAST research program:



Phase I: JCAP 2007(04):010
Vacuum 2003-2004
$m_a < 0.02$ eV
$g_{a\gamma} < 8.8 \cdot 10^{-11}$ GeV^{-1}

Phase II: Buffer gas
^{4}He 2005-2006 JCAP 2009(02):008
$0.02 < m_a < 0.39$ eV
$g_{a\gamma} < 2.17 \cdot 10^{-10}$ GeV^{-1}

^{3}He 2008-2011 PRL 107, 261302
$0.39 < m_a < 0.64$ eV
$g_{a\gamma} < 2.30 \cdot 10^{-10}$ GeV^{-1}

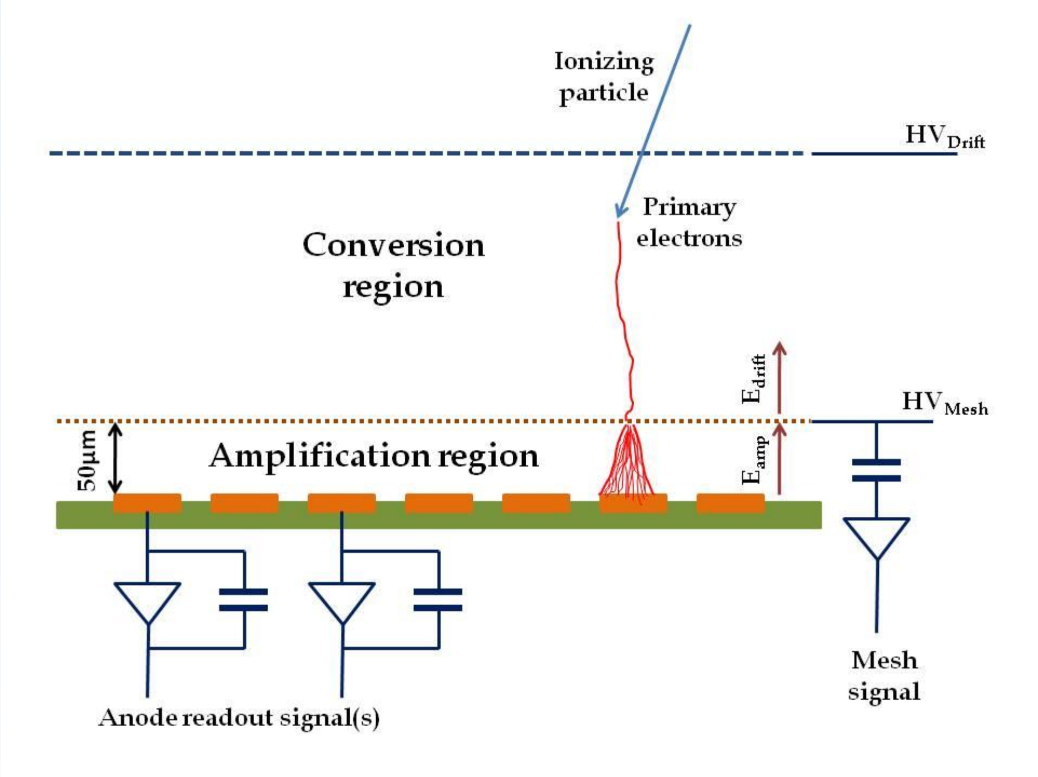
PRL 112, 091302
$0.64 < m_a < 1.17$ eV
$g_{a\gamma} < 3.30 \cdot 10^{-10}$ GeV^{-1}

THE CAST EXPERIMENT

MICRO Mesh Gaseous Structure, developed by *I. Giomataris*

NIM A 376, 29

MICROMEGAS are gaseous ionization detectors in the frame of the novel MPGD technology.



Conversion region:

- Generation of primary ion-electron pairs.
- Drift and diffusion of the primary electrons.

Amplification region:

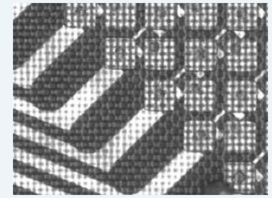
- Avalanche of electrons.
- Two readable signals: mesh and anode readout.

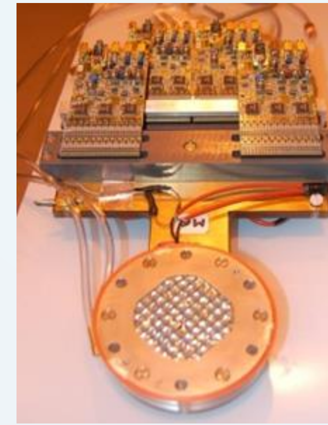
Different manufacturing techniques: *classical*, *bulk* and *microbulk*.

THE CAST EXPERIMENT

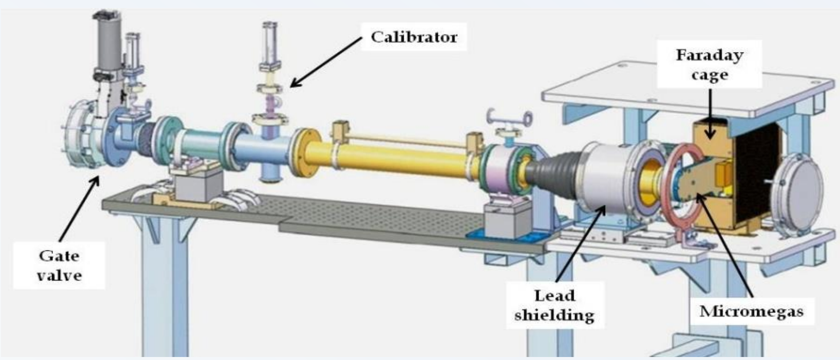
Microbulk Micromegas at CAST:

- 2D interconnected square pads.
- 106 x 106 strips → 60 x 60 mm^2
- Aluminized mylar cathode 5 μm thick.
- Body and chamber made of plexiglass.
- Ar+iC_4H_{10} gas at 1.4 bar

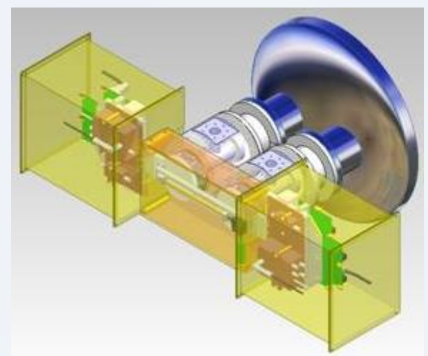




Sunrise Micromegas



Sunset Micromegas



Differential pumping, gas sytem and automatic calibrators.

Shielding: 5 mm inner Cu, 25 mm ancient Pb, 2 mm Cd sheet.

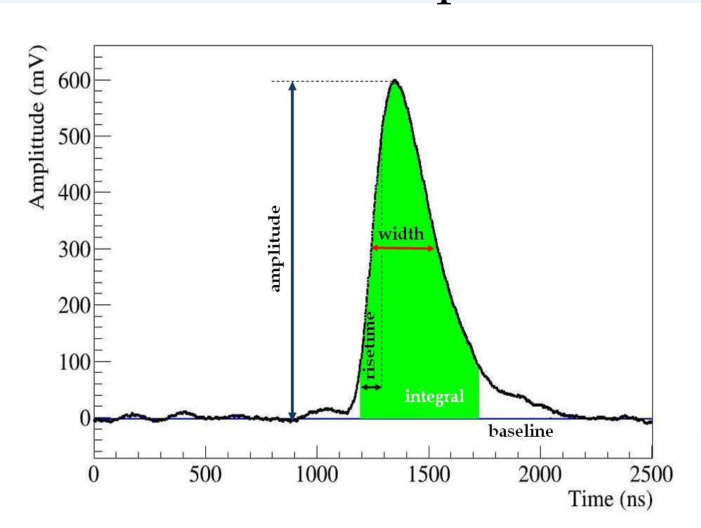
THE CAST EXPERIMENT

Data analysis:

Mesh pulse:

FFT and pulse shape analysis.

VME Matacq board



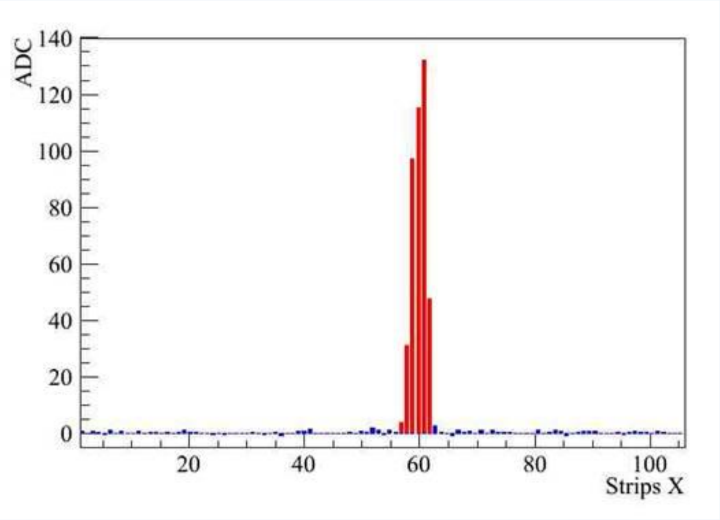
Mesh observables:

-Amplitude
- Integral
- Risetime
- Width

Strips signals:

Pedestal subtraction and cluster analysis.

Gassiplex electronics



Strips observables:

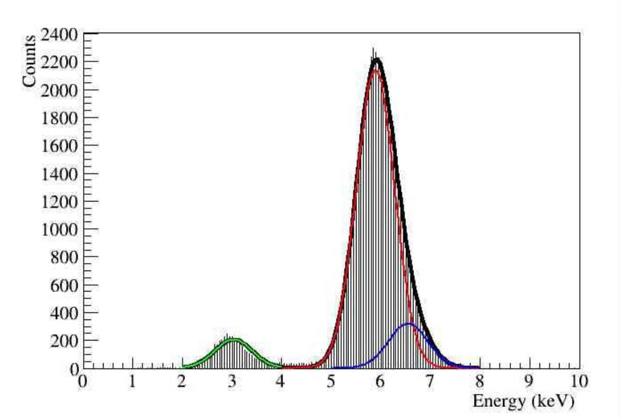
- Cluster charge
- Cluster position
- Cluster size
- Multiplicity
- Cluster balance

THE CAST EXPERIMENT

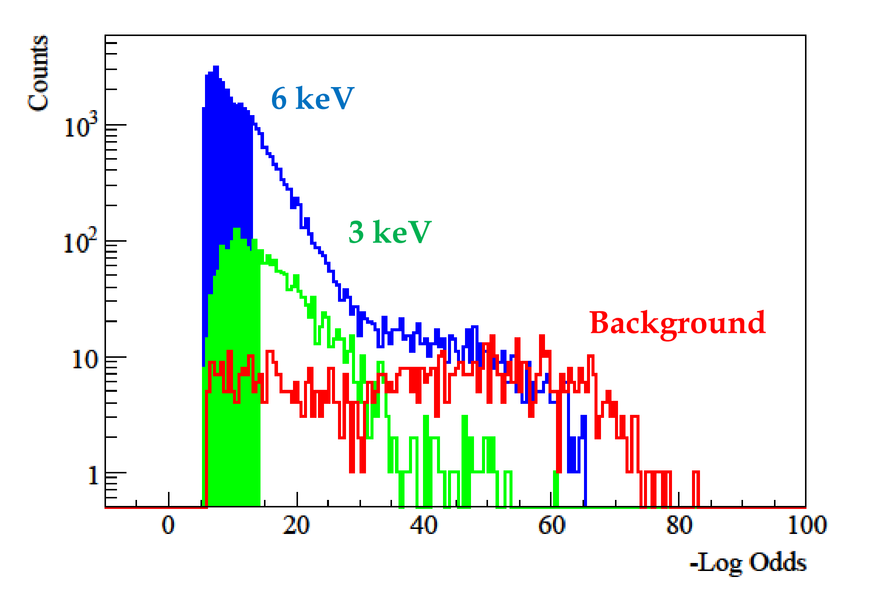
Event discrimination:

Axion signature → X-ray event [1-10] keV →Point-like events.

Daily ^{55}Fe calibrations define the characteristic parameters of X-ray like events.



Discrimination method:



The *log-odds* distribution is computed for a set of given observables for calibration and background events:

$$-\log Odds = -\sum_i \log(P_i(x_i)) + \sum_i \log(1 - P_i(x_i))$$

It allows to define a cut-value below which a certain number of calibration events are accepted.

The cut-values are determined by requiring a *software efficiency*.

THE CAST EXPERIMENT

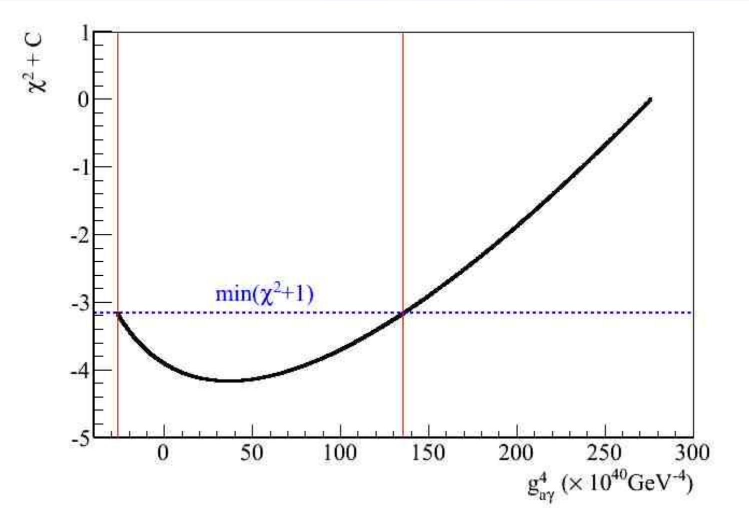
High level analysis: Likelihood: $\ln L = \sum_{i=1}^{n} n_i - \mu_i + n_i \log \frac{\mu_i}{n_i}$ where $\mu_i = b_i + s_i$

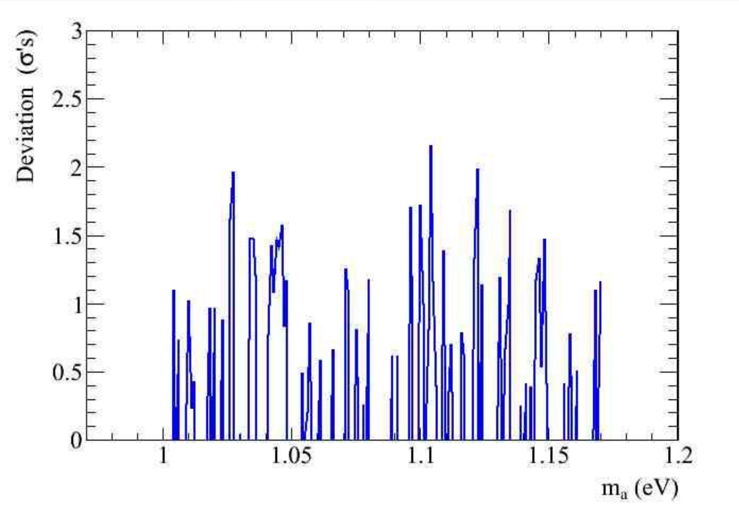
Unbinned likelihood method (infinitesimal time bins):

$$\ln \mathcal{L} = \underbrace{\sum_k L_k(n_i = 0)}_{\text{Zero counts cont.}} + \underbrace{\sum_k L_k(n_i = 1)}_{\text{One count cont.}}$$

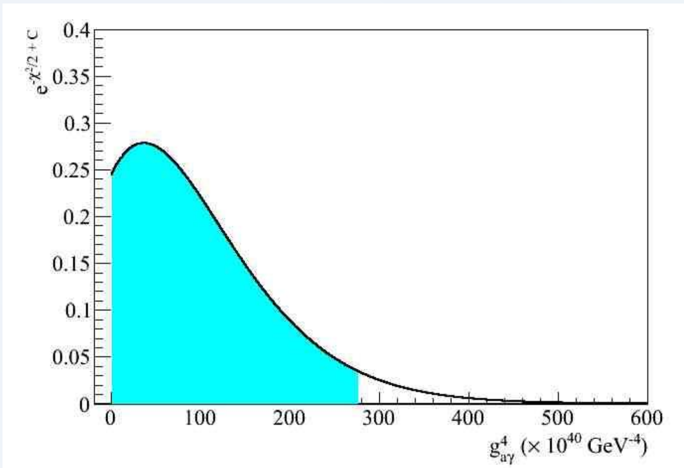
$$\ln \mathcal{L} = \underbrace{-g_{a\gamma}^4 \int_{E_i}^{E_f} \frac{dn_{a\gamma}}{dE} \Delta t dE}_{\text{Expected axion events}} + \underbrace{\sum_{i=0}^{n_c} \ln \left(\frac{db_i}{dt} + g_{a\gamma}^4 \int_{E_i}^{E_i+\Delta E} \frac{dn_{a\gamma}}{dE} dE \right)}_{\text{Counts over the background}}$$

The presence of an axion signal has been studied by computing the most probable value of $g_{a\gamma}^4$ and its standard deviation.





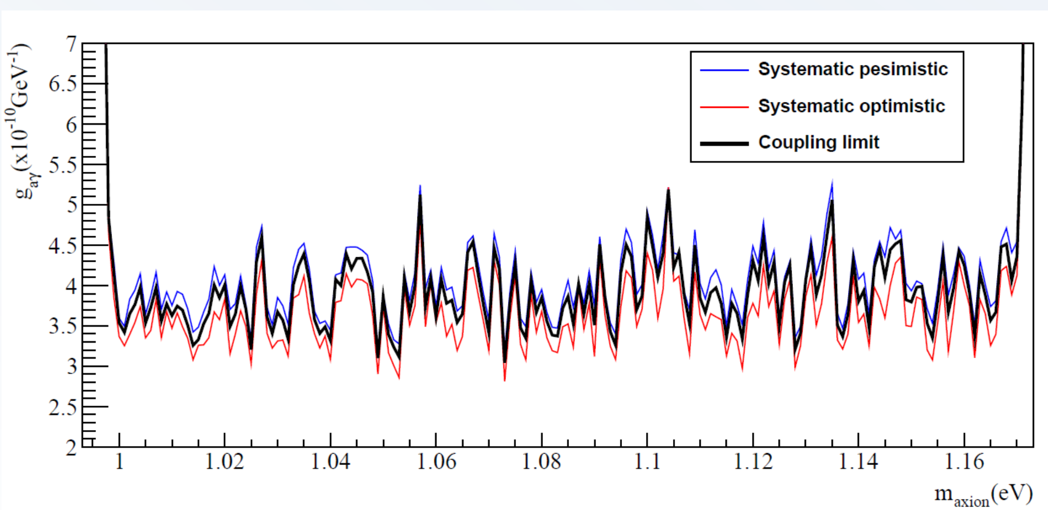
After discarding an axion signal, a limit on $g_{a\gamma}$ has been extracted:



Using the Bayesian probability from zero up to a 95%:

$$\frac{\int_0^{g^4_{a\gamma}} e^{-\frac{\chi^2}{2}} dg_{a\gamma}}{\int_0^{\infty} e^{-\frac{\chi^2}{2}} dg_{a\gamma}} = 0.95$$

2011 systematics:

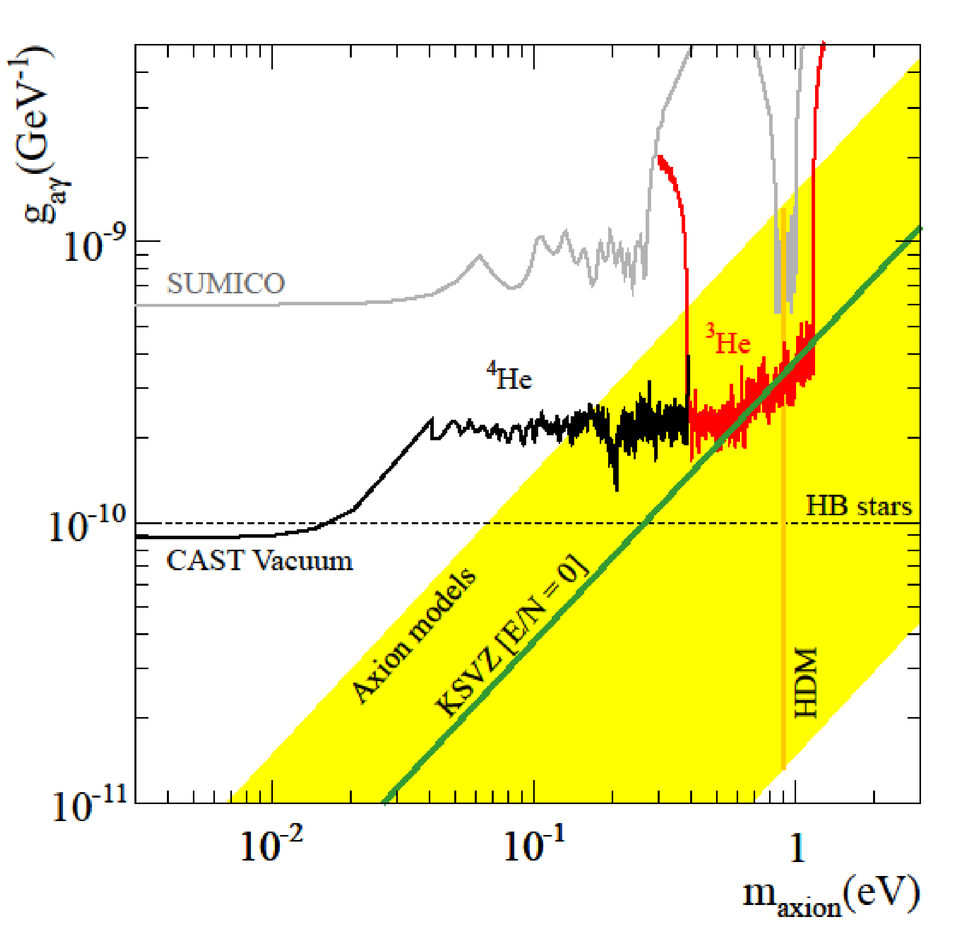


$$g_{a\gamma} \leq 4.04 \times 10^{-10}\mathrm{GeV}^{-1} \quad \text{Pessimistic}$$
$$g_{a\gamma} \leq 3.90 \times 10^{-10}\mathrm{GeV}^{-1} \quad \text{Nominal}$$
$$g_{a\gamma} \leq 3.65 \times 10^{-10}\mathrm{GeV}^{-1} \quad \text{Optimistic}$$

$$1 \leq m_a \leq 1.17 \text{ eV}$$

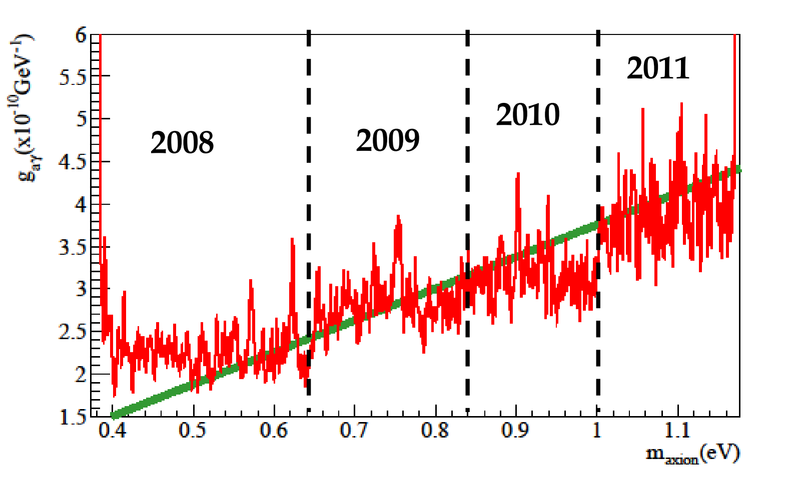
THE CAST EXPERIMENT

A coupling limit for all the ^{3}He phase data has been derived.



PRL 107, 261302

PRL 112, 091302



CAST extended its previous limit, obtaining an average value of:

$$g_{a\gamma} \leq 2.94 \times 10^{-10} \mathrm{GeV}^{-1}$$

$$0.37 \leq m_a \leq 1.17 \mathrm{eV}$$

LOW BACKGROUND TECHNIQUES

CAST microbulk Micromegas exploit different low background strategies, developed under the T-REX project:

JINST 9 P01001

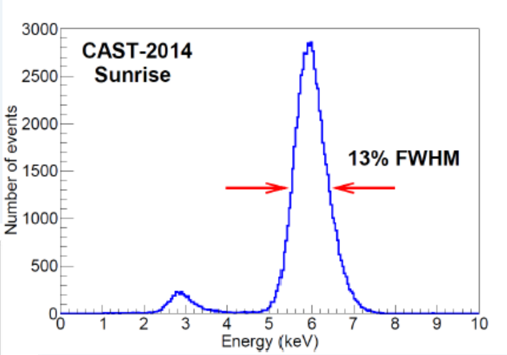
"Radiopurity of Micromegas readout planes"
Astroparticle Physics 354 (2011)

Radiopurity:

Low mass
Clean materials (copper, plexiglass, kapton,..)

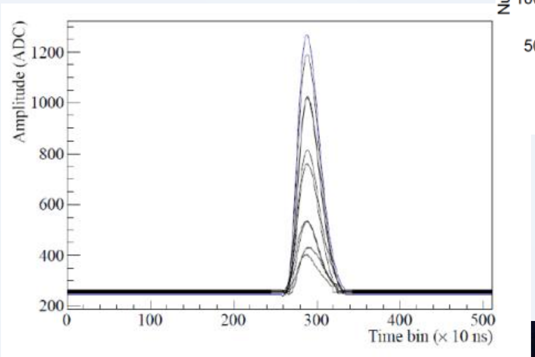
Manufacturing technology:

Improvements on the detectors performance
Better discrimination capabilities



Event discrimination:

2D readout pattern via strips
Time information from mesh pulse
New AFTER front-end electronics



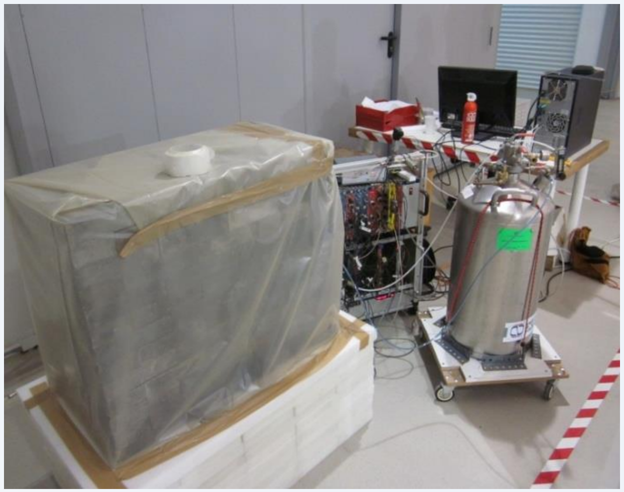
Shielding

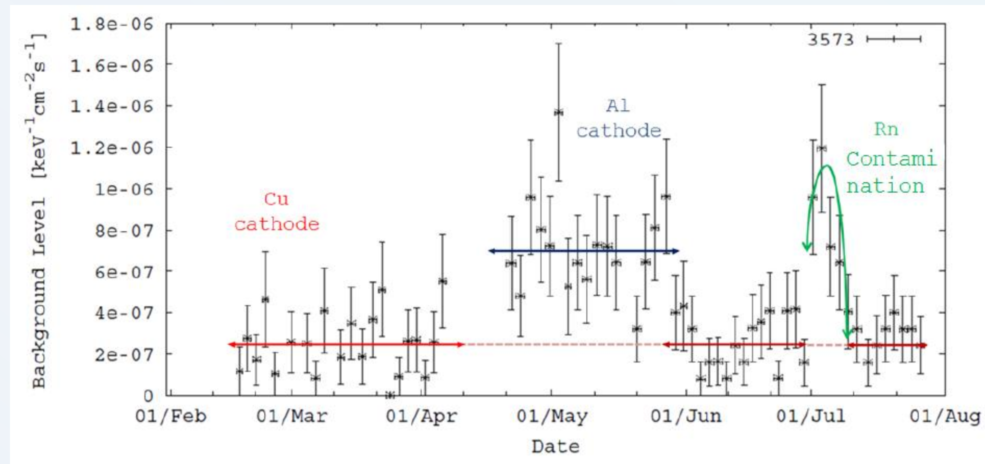
Inner Cu shielding
External lead shielding
Active muon veto

LOW BACKGROUND TECHNIQUES

Canfranc Underground Laboratory (LSC) measurements:

LSC situated at Canfranc (Huesca) in the Spanish Pyrenees under Tobazo mountain, with a depth of 2500 m.w.e. → muon flux reduced by a factor 10^4





Shielding: 10 cm Pb + 2.5 cm inner Cu

N_2 flux to avoid ^{222}Rn

Internal components are radiopure

Al cathode contribution:
~5 x 10^{-7} c keV^{-1}cm^{-2}s^{-1}

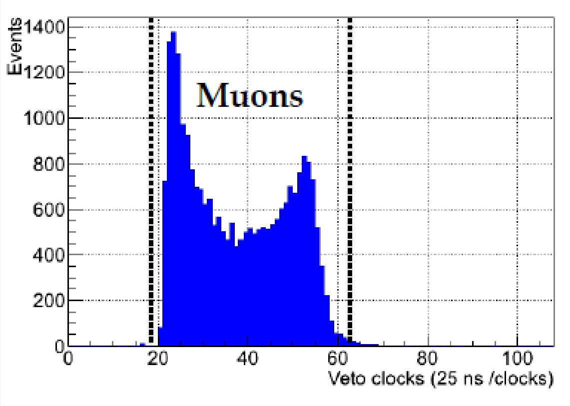
^{222}Rn contribution:
~3 x 10^{-8} c keV^{-1}cm^{-2}s^{-1} per Bq m^{-3} of ^{222}Rn

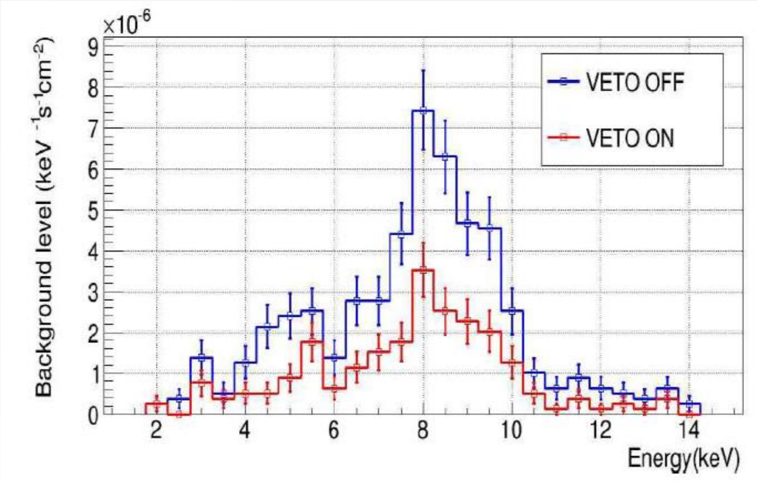
Final background level ~10^{-7} c keV^{-1}cm^{-2}s^{-1}

LOW BACKGROUND TECHNIQUES

Measurements at surface level:

The contribution of the cosmic muons to the background has been measured.





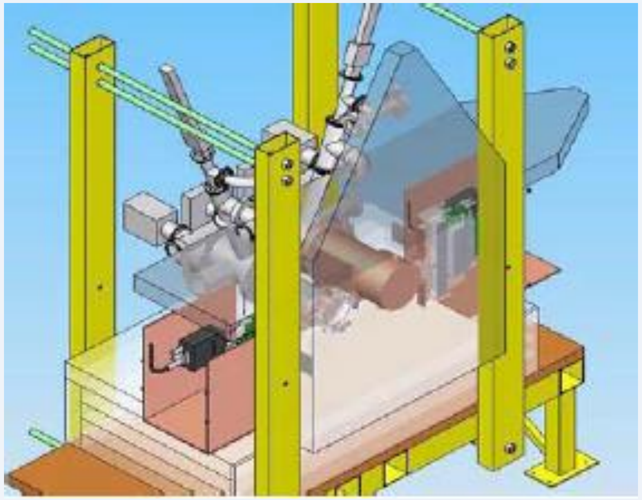
Two plastic scintillators have been installed and the time difference between the Micromegas and the veto triggers is stored.

Background level after veto cut:

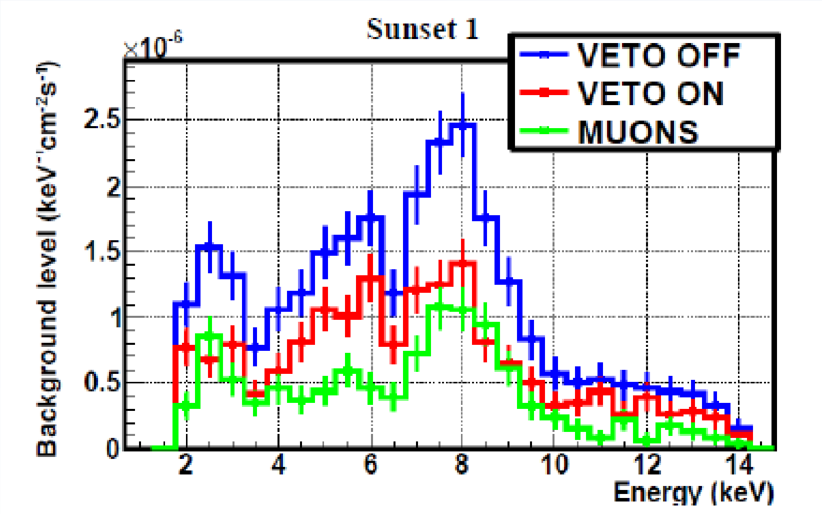
~10^{-6} c keV^{-1}cm^{-2}s^{-1} →50% of reduction

LOW BACKGROUND TECHNIQUES

Sunset Micromegas upgrade:



- New Micromegas detectors have been manufactured.
- New shielding design, extending the lead shielding along the pipes to the magnet bores.
- 10 mm of Cu shielding.
- 100 mm external Pb.
- Cu strongback.
- Plastic scintillators for muon rejection.
- AFTER front-end electronics.



After the upgrade the background level diminished to:

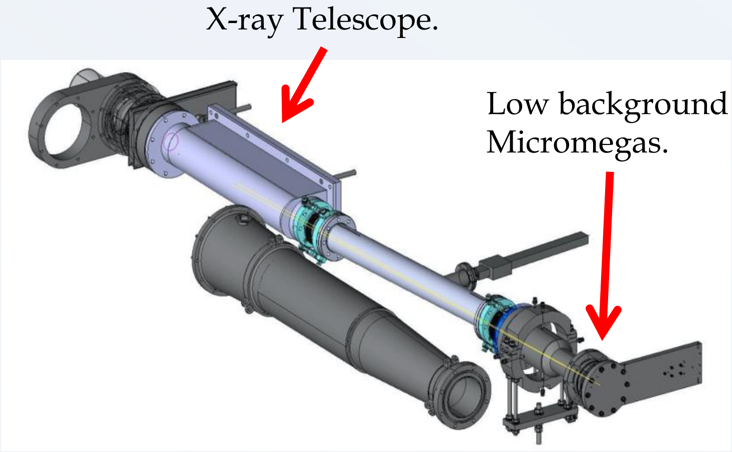
~10^{-6} c $keV^{-1}cm^{-2}s^{-1}$ → A factor ~6 of reduction.

The scintillators account for ~50% of the background events.

LOW BACKGROUND TECHNIQUES

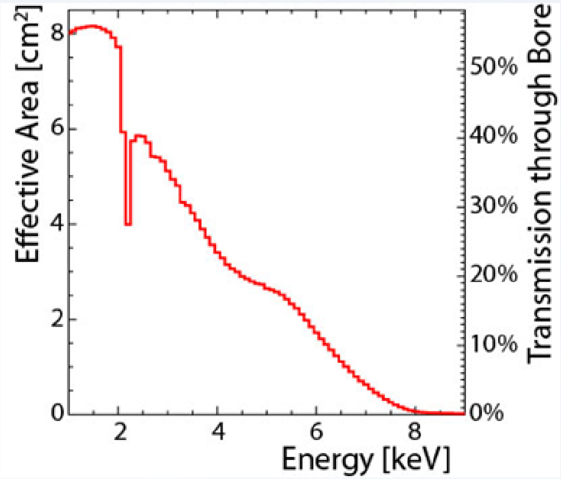
New Sunrise Micromegas + X-ray telescope

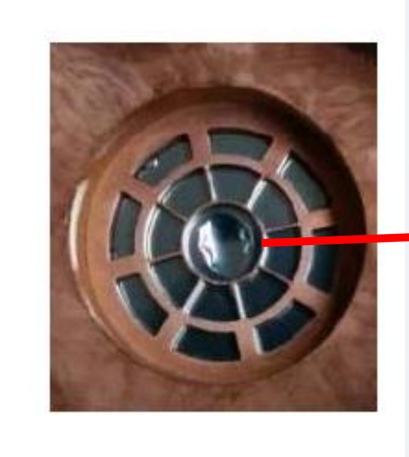
JCAP 2015(12):008

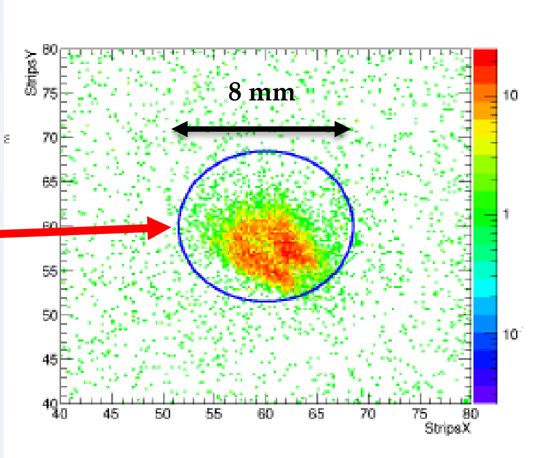


- The expected signal is focused from 14.5 cm^2 to 1-5 mm^2
- Big milestone for CAST → ~100 improve in S/B

XRT efficiency

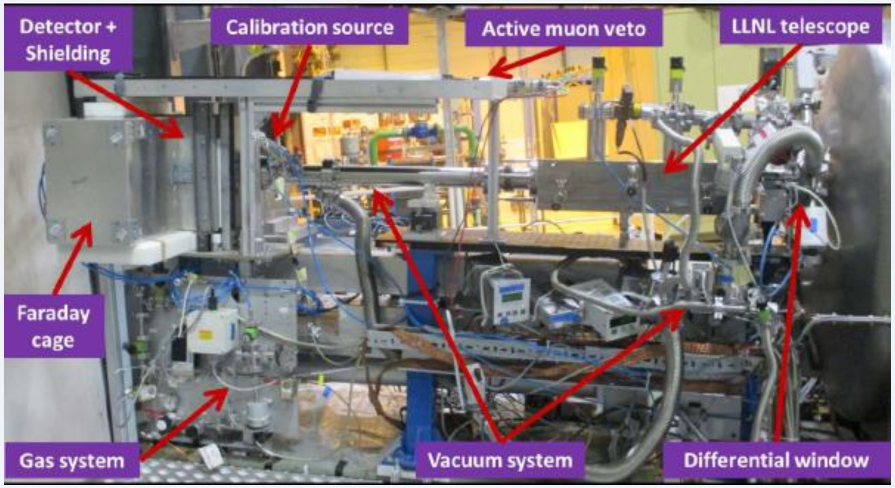


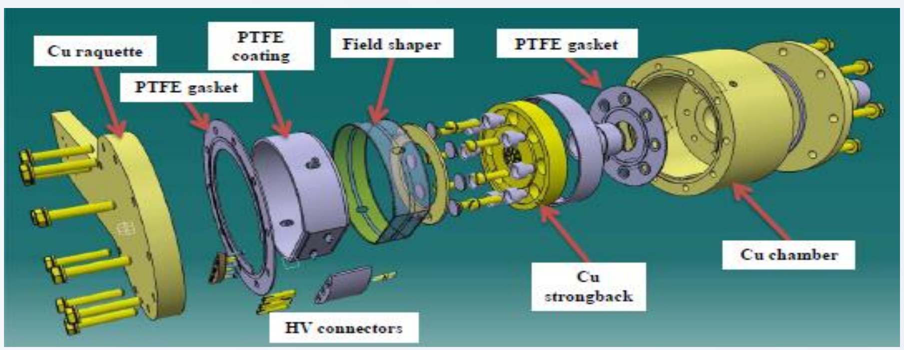




LOW BACKGROUND TECHNIQUES

New Sunrise Micromegas + XRT line

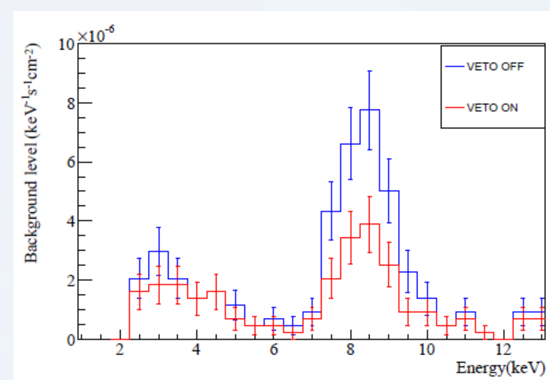




-New X-ray telescope with a Micromegas in its focal plane.
- New detector design: Cu raquette and Cu chamber.
- New Micromegas detector with excellent spatial and energy resolution.
- Radiopure materials: Cu and PTFE.
- Field shaper.
- New cathode design → Increase of the quantum efficiency.
- New shielding design: 20 mm Cu and 100 mm Pb.
- Plastic scintillator.
- AFTER front-end electronics.

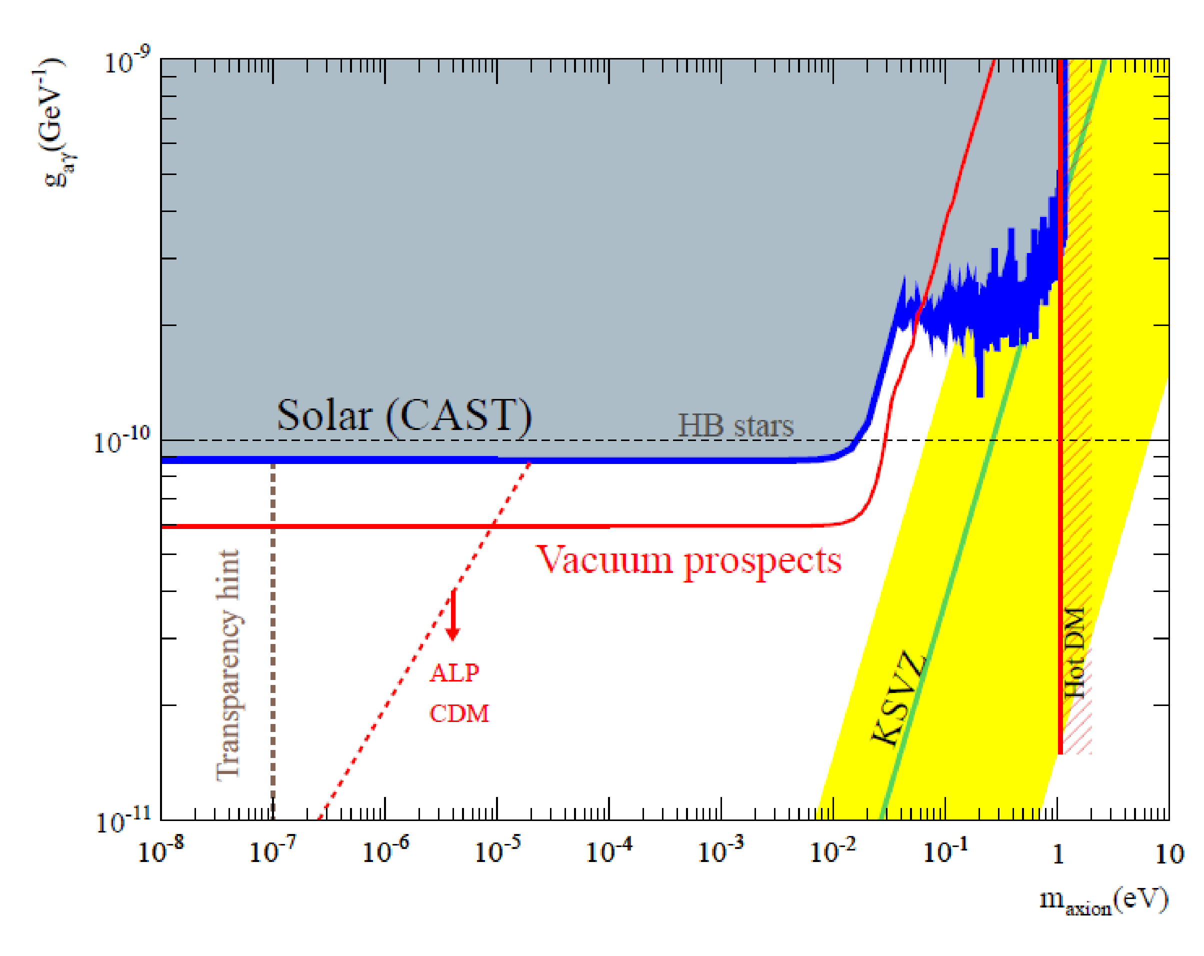
Lowest background level at surface operation

~8 x 10^{-7} c $keV^{-1}cm^{-2}s^{-1}$



LOW BACKGROUND TECHNIQUES

A revisited vacuum phase started in 2013.

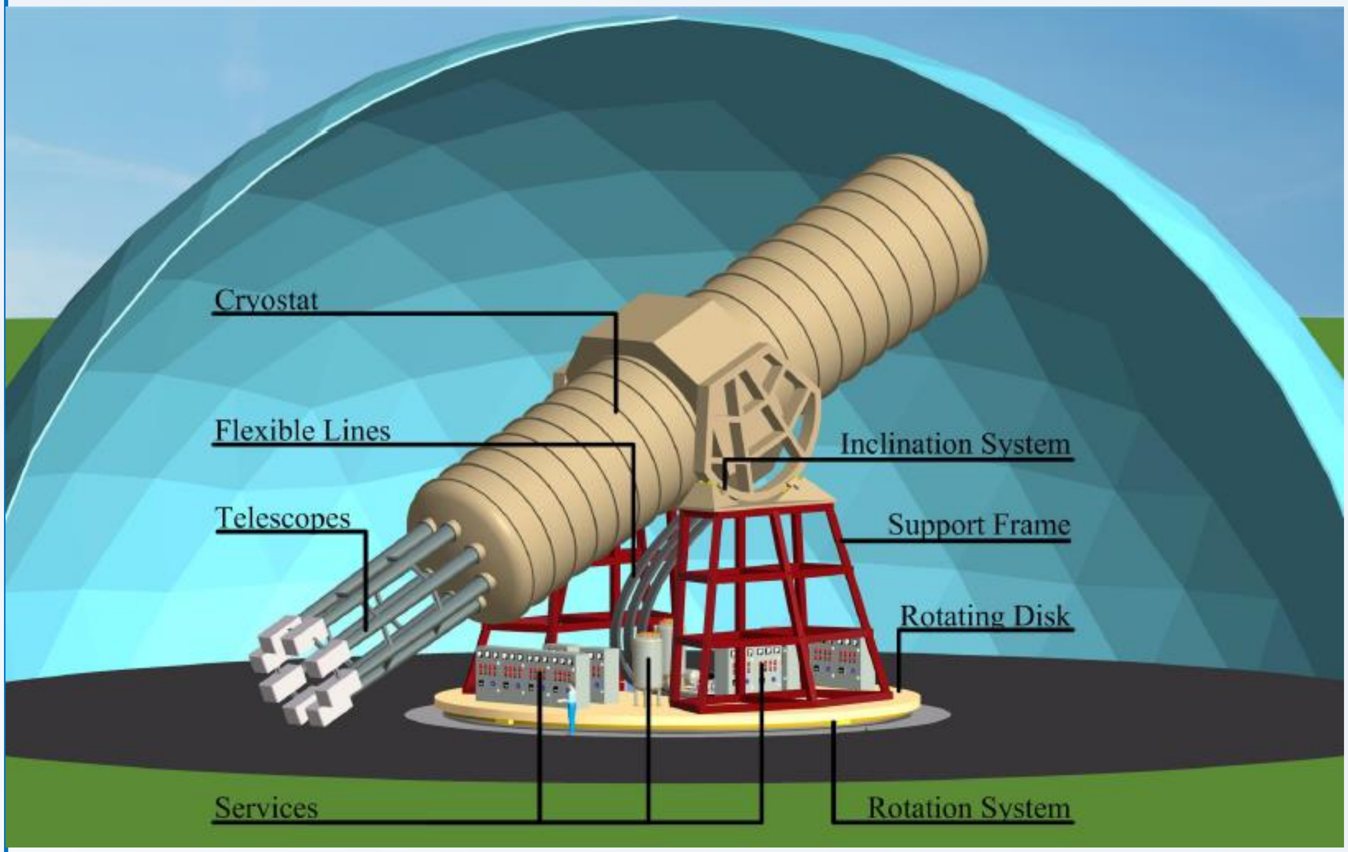


Due to the new XRT and the reduction of the background level in the Micromegas detectors, CAST will improve its previous limit down to:

$$g_{a\gamma} < \sim 6 \cdot 10^{-11}\ \mathrm{GeV}^{-1}$$
$$\text{for } m_a < 0.02\ \mathrm{eV}$$

IAXO PROSPECTS

The International AXion Observatory http://iaxo.web.cern.ch/iaxo/



Letter of Intent submitted to CERN received positive recommendation

SPSC-2013-0022

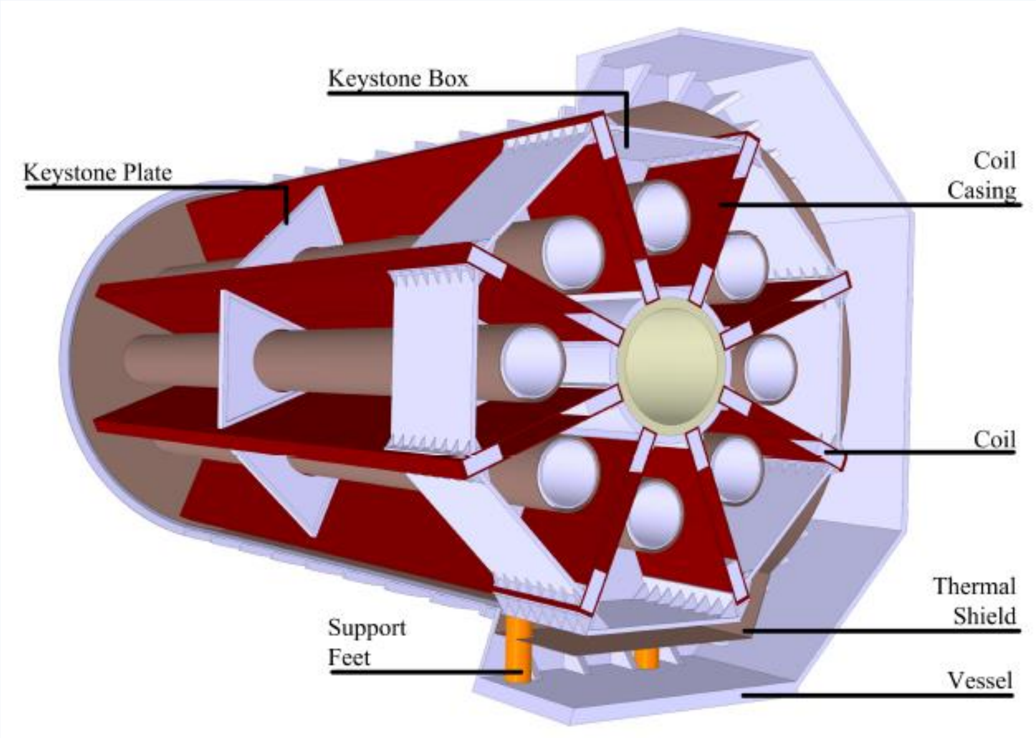
Conceptual Design Review already published

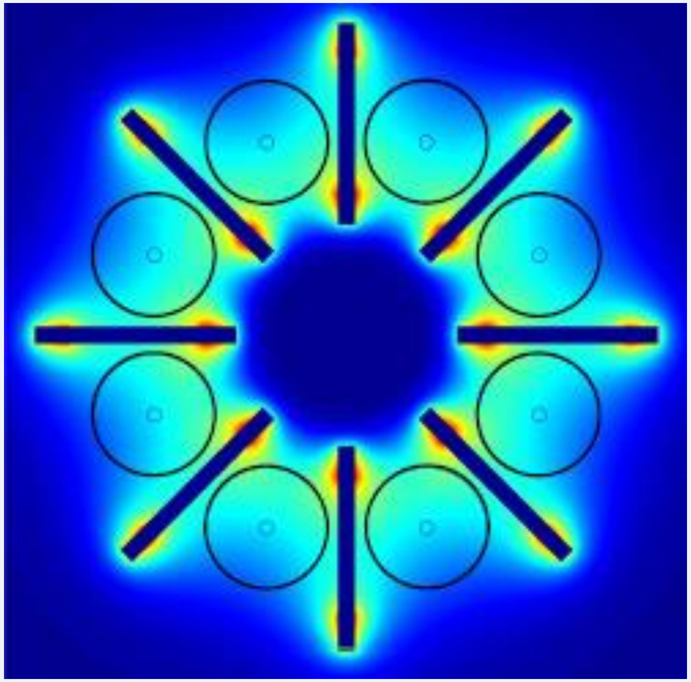
JINST 9 T05002

IAXO will enhance the helioscope technique by exploiting all the singularities of CAST.

IAXO PROSPECTS

A dedicated toroidal magnet is planned for IAXO:



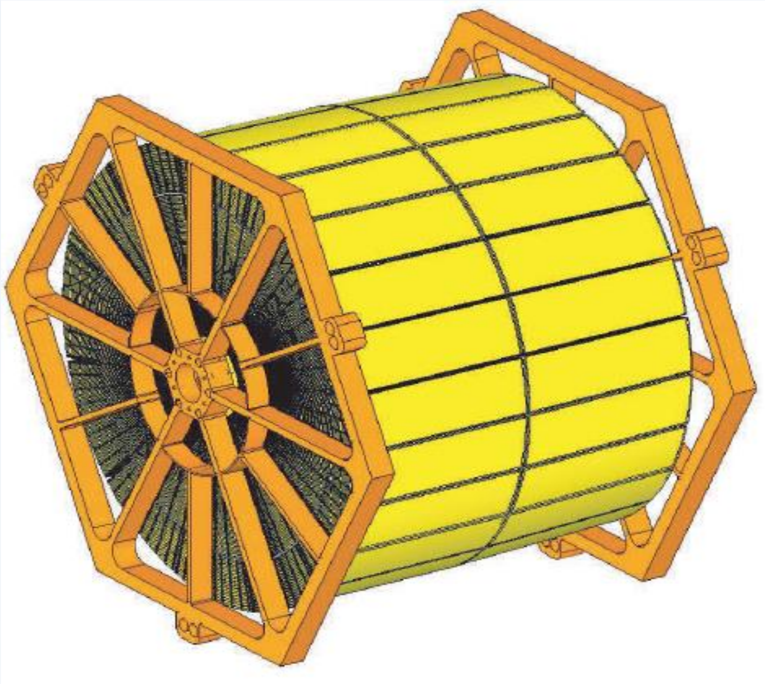


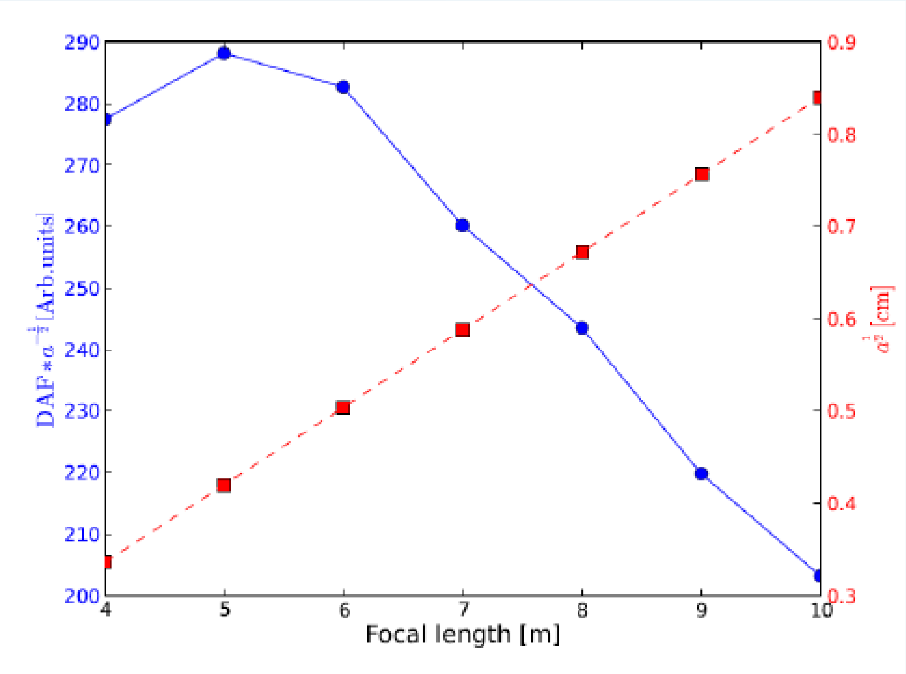
Magnet length: 21 m
Magnet aperture: 2.3 m^2
Magnetic field peak: 5.4 T

The support structure of the magnet allows solar trackings of ~12 h/day

IAXO PROSPECTS

8 X-rays telescopes will be installed



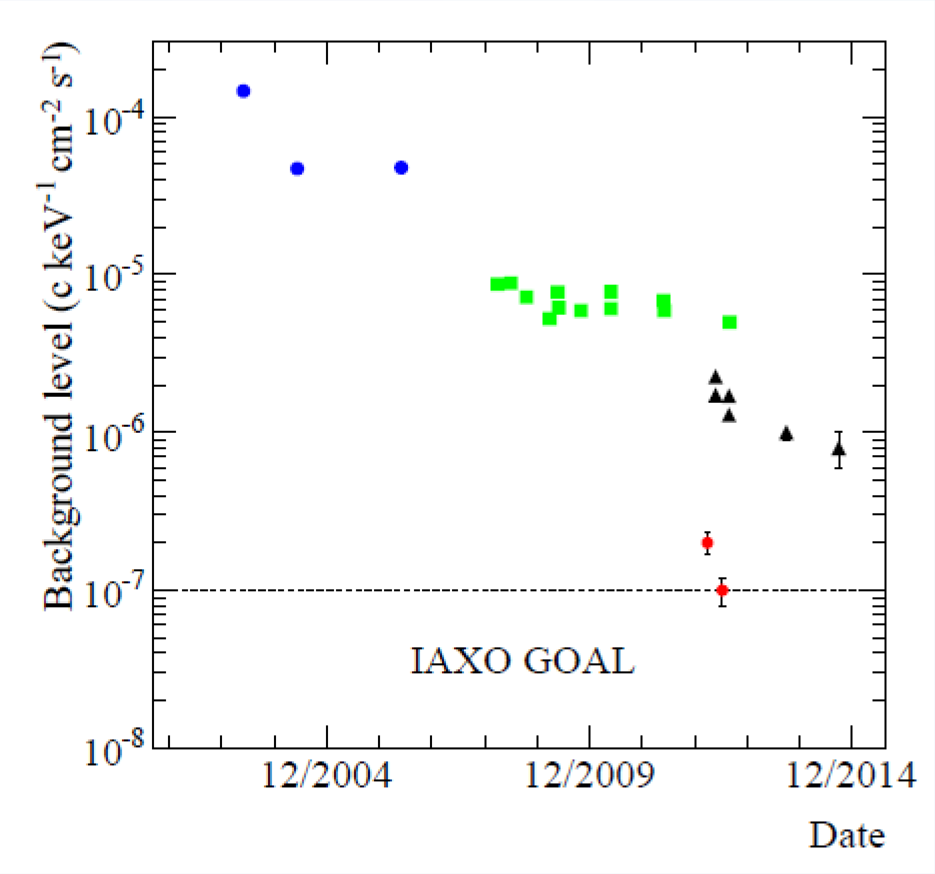


Signal to background ratio increased by a factor 10^4 !!!

Focal length: ~5 m
Focusing spot: ~0.2 cm^2

IAXO PROSPECTS

Ultra-low background detectors:



Baseline technology → Micromegas

New R&D lines:

-Veto coverage: Extend the surface area as much as possible.

- New gas mixtures: Remove the ^{39}Ar isotope. New base gas (Xe, depleted Ar).

-AGET front-end electronics: Reduce the low energy threshold.

- New thin windows: Increase the efficiency at low energies.

Goal: 10^{-8} - 10^{-7} c keV^{-1}cm^{-2}s^{-1}

IAXO PROSPECTS

In order to avoid the ^{39}Ar isotope currently present in our gas, two base gases have been proposed: depleted Ar and Xe mixtures

First studies at a working pressure of 500 mbar

Advantages:

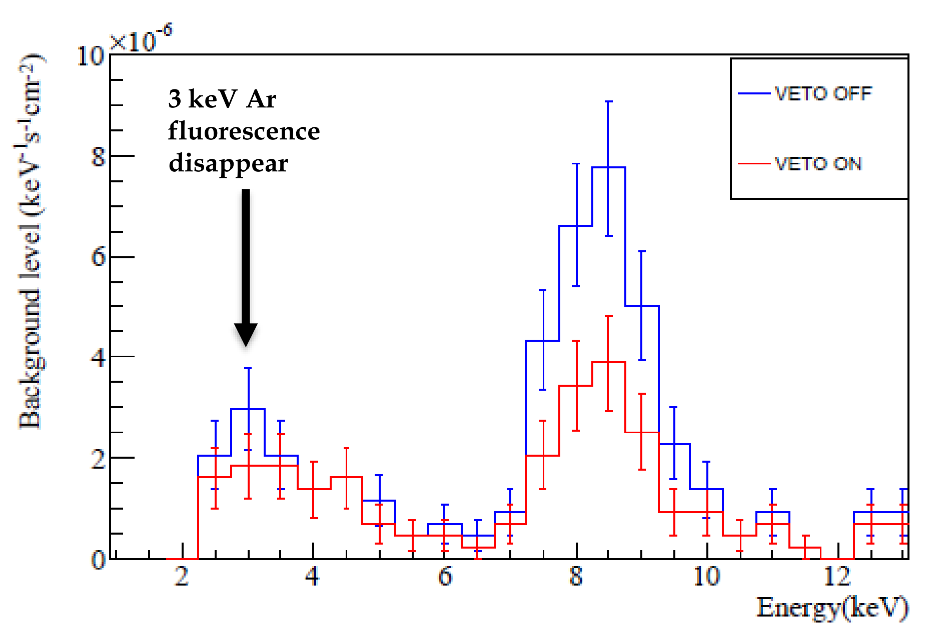
• Reduction of the escape peak (50% of the current background)

• Working at lower pressure allow the use of thinner and more transparent windows.

Disadvantages:

• Lower intrinsic gain

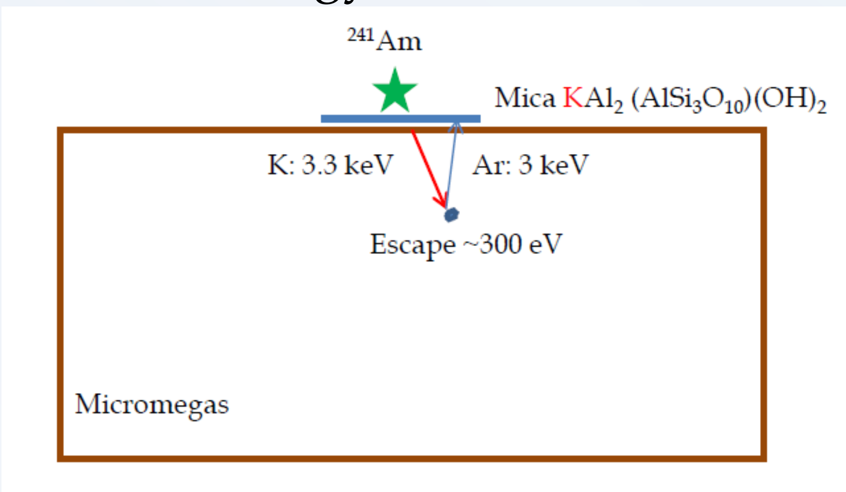
• Complex gas system



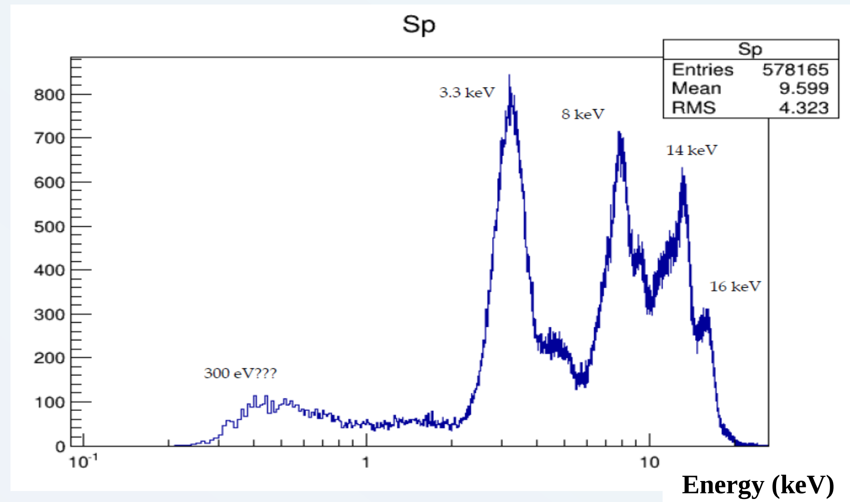
IAXO PROSPECTS

The new AGET front end electronics:

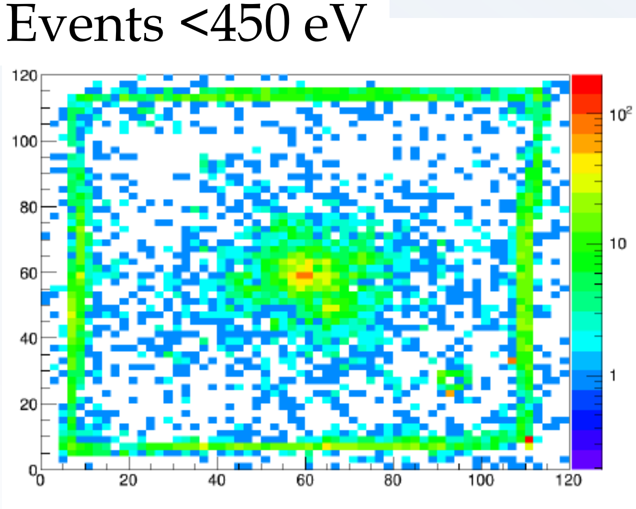
Low energy threshold studies:



Autotrigger → reduction of the low energy threshold.



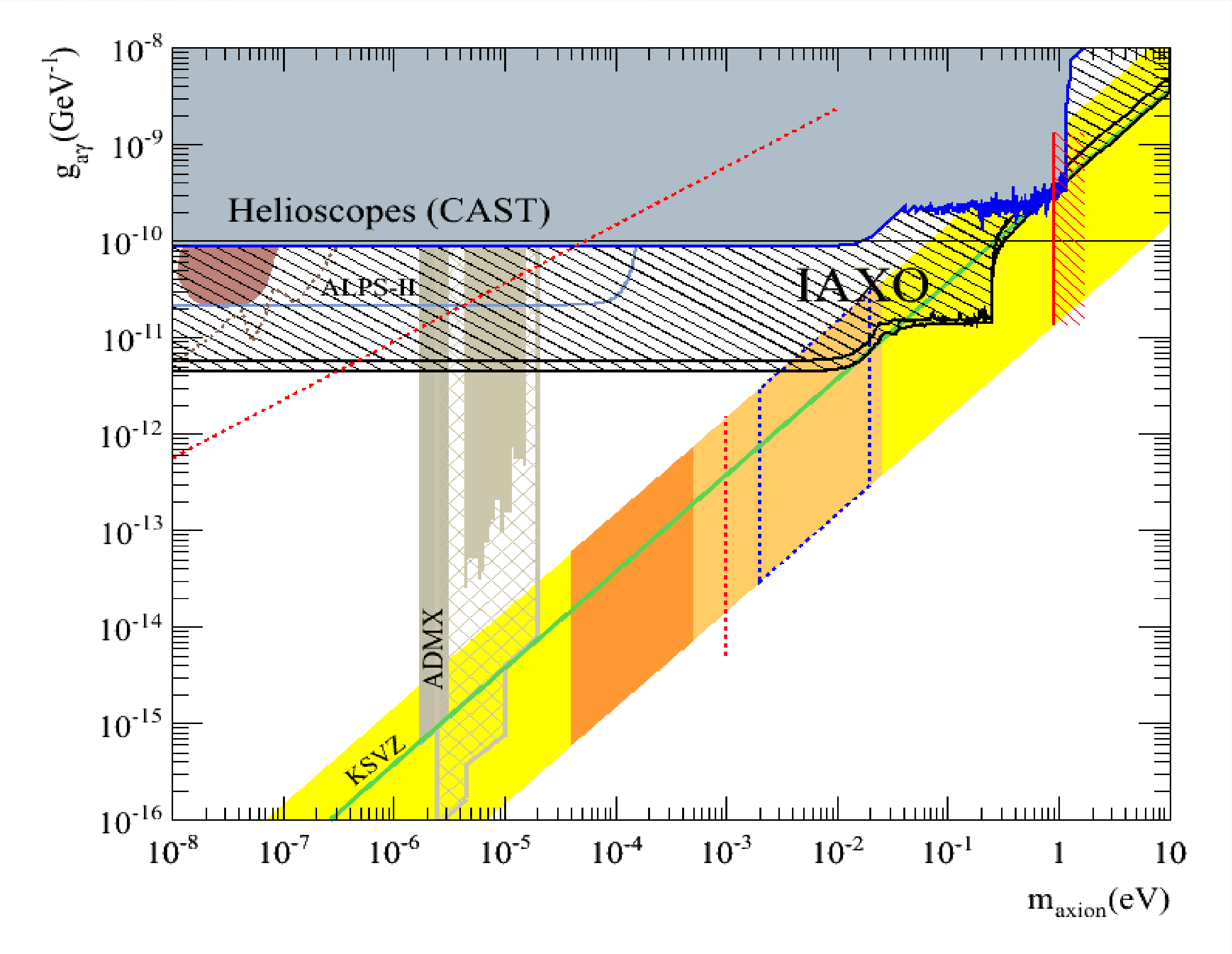
Events <450 eV



These measurements are limited by the noise in the experimental set-up, low energy thresholds of ~100 eV are feasible.

IAXO PROSPECTS

A big part of the parameter space could be explored next decade, entering in the most favored regions for axions and ALPs.

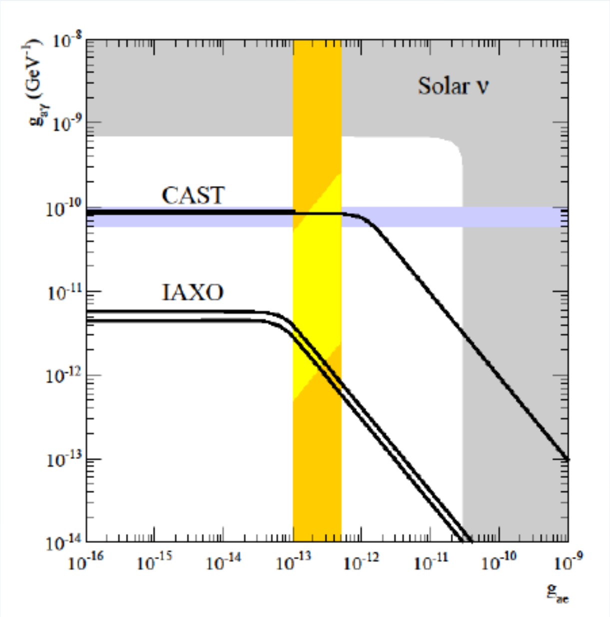


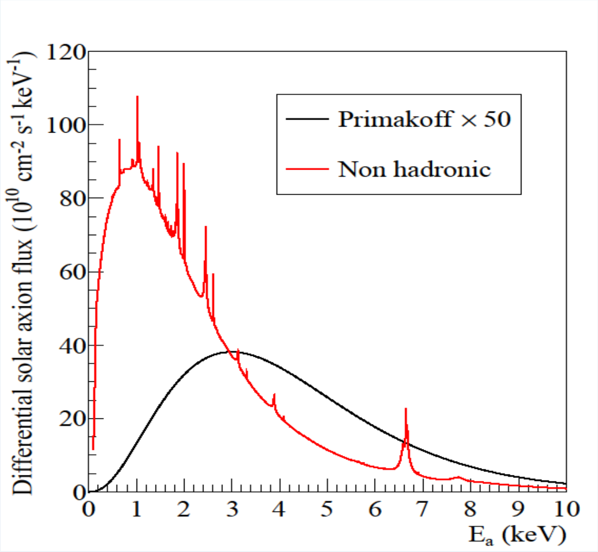
Run I with vacuum
$g_{a\gamma} < \sim 5 \cdot 10^{-12}$ GeV^{-1}
$m_a < 0.01$ eV

Run II with ^{4}He
$g_{a\gamma} < 10^{-11}$ GeV^{-1}
$0.02 < m_a < 0.25$ eV

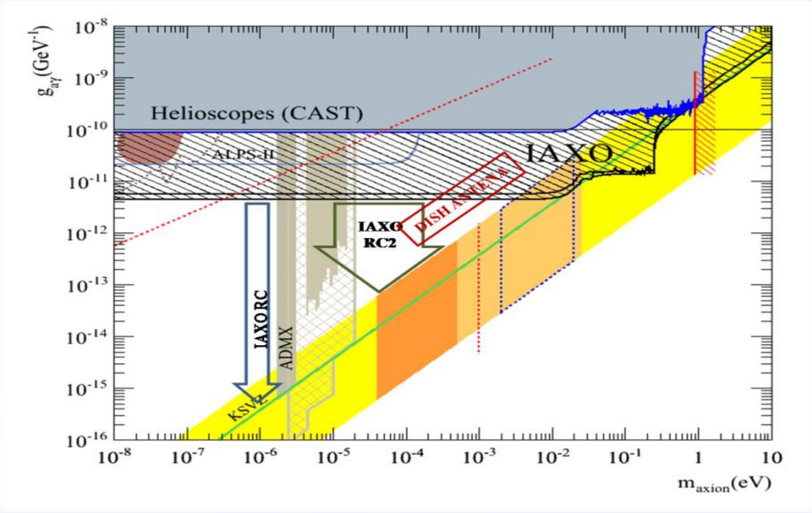
IAXO PROSPECTS

IAXO could also be sensitive to non-hadronic solar axions.





Moreover, the use of microwave cavities (haloscope) and a dish antenna for relic DM axion searches is under study.



SUMMARY AND CONCLUSIONS

- ❑Axions and ALPs are well motivated particles that could solve the DM problem.
- ❑ The CAST experiment has been looking for axions since 2003 being the most sensitive helioscope so far.
- ❑ Micromegas is a demanded technology that has been used at CAST since the beginning of the experiment.
- ❑ The data of the detectors at CAST has been analyzed. Although the axion has not be discovered so far, an upper limit on $g_{a\gamma}$ has been extracted.
- ❑ The low background techniques developed in order to reduce the background of the Micromegas have led to a reduction of the background level by a factor ~6, increasing the sensitivity of CAST to Solar axions in a factor ~2.
- ❑ IAXO, a proposed new generation helioscope will surpass CAST sensitivity in more than one order of magnitude. New strategies in order to reduce the background level of the detectors for IAXO are under development.

The End

BACK UP

The $U(1)_A$ problem:

$$\mathcal{L}_{QCD} = \sum_n \bar{\Psi}_n \left(i\gamma^\mu D_\mu - m_n\right)\Psi_n - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

The QCD Lagrangian is invariant under global axial and vector transformations. However, the corresponding axial symmetries has not been observed and by spontaneously breaking we get the NG bosons (the pions), but there is no pseudoscalar state corresponding to the NG bosons of the $U(1)_A$ symmetry.

Solution by *t'Hooft* →The problem was bypassed introducing an anomalous breaking of the $U(1)_A$ symmetry.

$$\mathcal{L}_\theta = \theta\frac{g^2}{8\pi^2}G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \qquad |\theta\rangle = \sum_{n=-\infty}^{\infty} e^{-in\theta}|n\rangle$$

$$\bar{\theta} = \theta + \theta_{weak} = \theta + arg(detM) \qquad \mathcal{L}_{\bar{\theta}} = \bar{\theta}\frac{g^2}{8\pi^2}G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$

BACK UP

Axion coupling:

Gluons:

$$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} a G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a$$

$$m_a \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

Photons:

$$\mathcal{L}_{a\gamma} = g_{a\gamma} \vec{E}\vec{B} a$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right)$$

Fermions:

$$\mathcal{L}_{af} = \frac{g_{af}}{2\, m_f}\left(\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f\right) \partial_\mu a \qquad g_{af} = \frac{C_f m_f}{f_a}$$

Electrons:

$$g_{ae}^{tree} = \frac{C_e m_e}{f_a} = 0.85 \times 10^{-10} m_a C_e \text{ eV}^{-1}$$

Nucleons:

$$g_{aN} = \frac{C_N m_N}{f_a} = 1.57 \times 10^{-7} m_a C_N \text{ eV}^{-1}$$

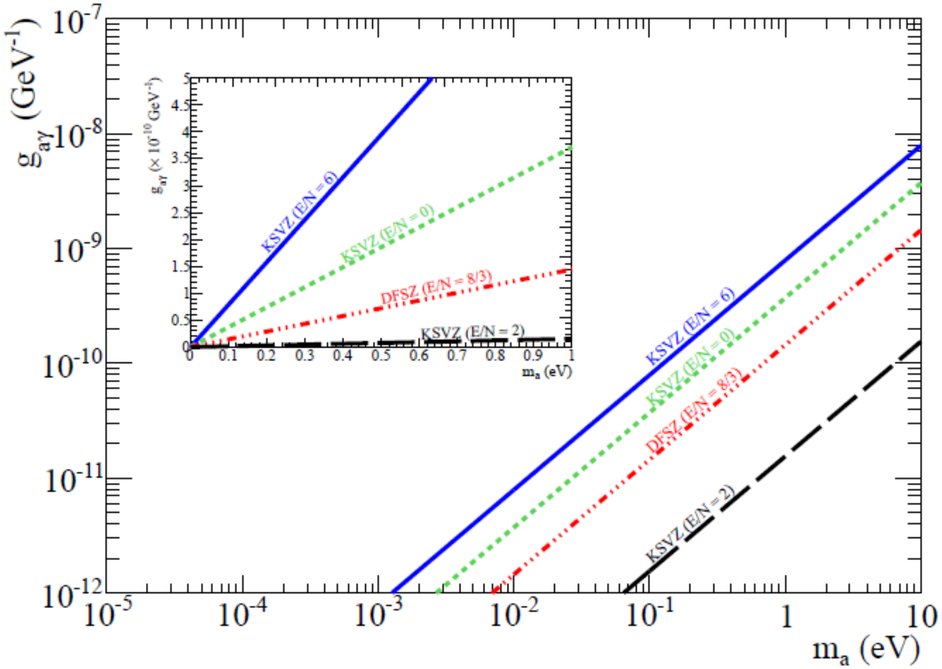
BACK UP

Axion models:

KSVZ

$$\frac{E}{N} = 6Q^2_{heavy}$$

$$Q_{heavy} = 2/3, -1/3, 1, 0$$



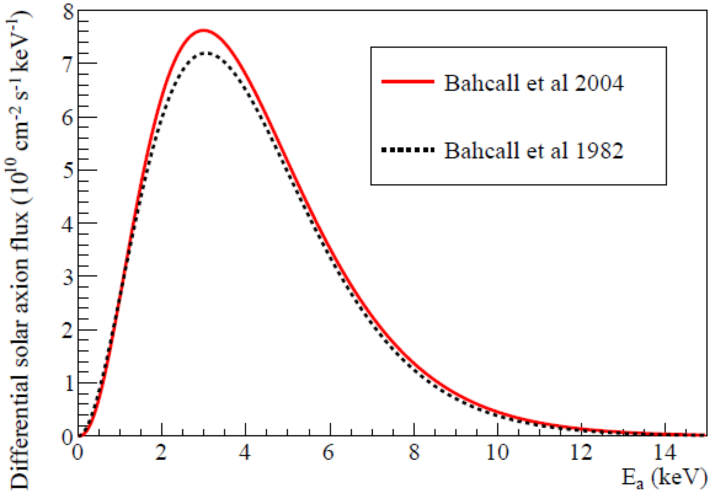
DSFZ

$$E/N = 8/3$$

BACK UP

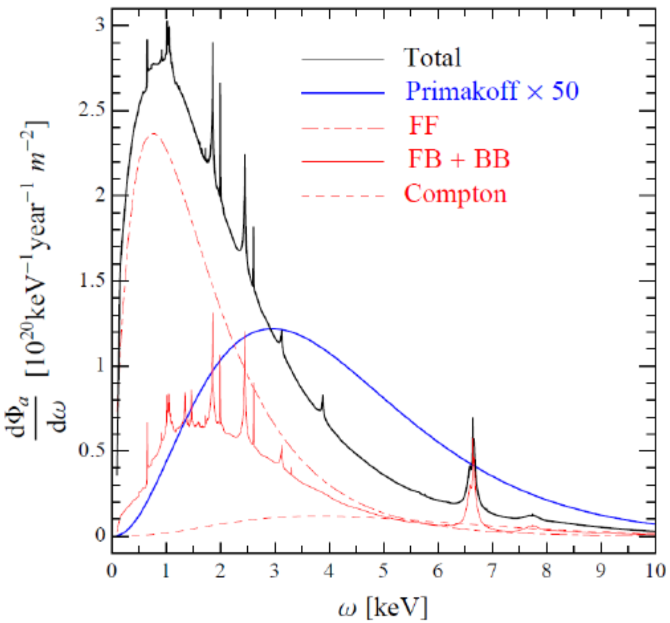
Solar axion emission:

Hadronic (Primakoff):



$$\frac{d\Phi_a}{dE_a} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 (E_a/\mathrm{keV})^{2.481}\, e^{-E_a/1.205\mathrm{keV}}$$

Non-hadronic:

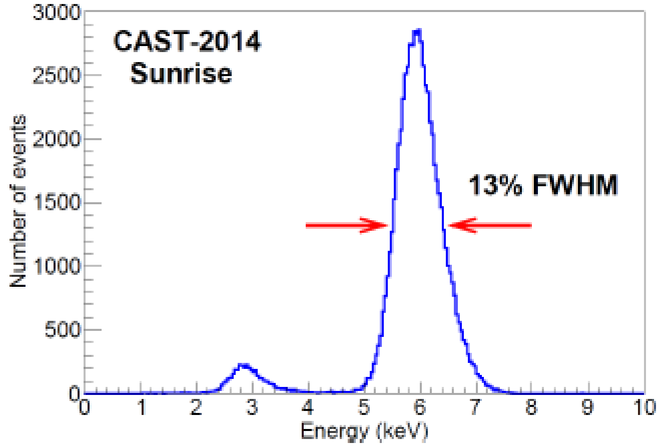


- Bremsstrahlung
- Axio-recombination
- Axio-desexcitation
- Compton

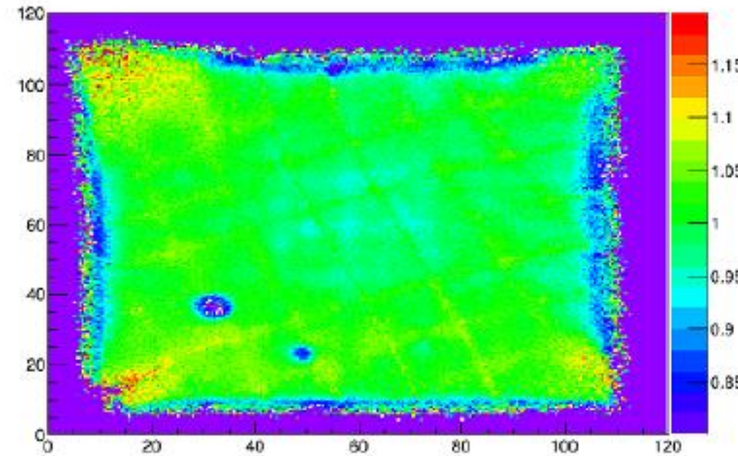
BACK UP

Sunrise Micromegas (2014) performance:

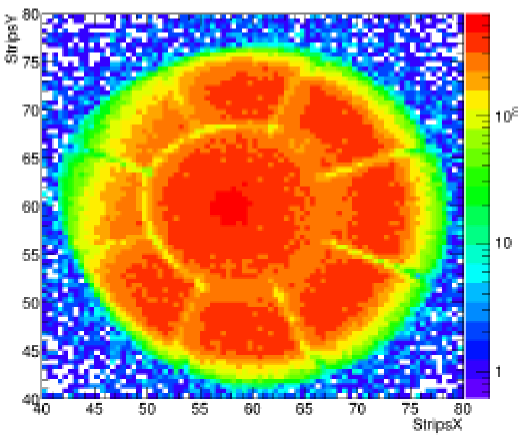
13% FWHM!!!



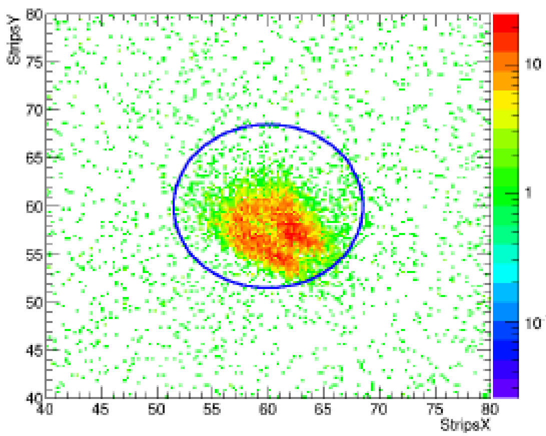
Gain homogeneity



"Spider web" cathode

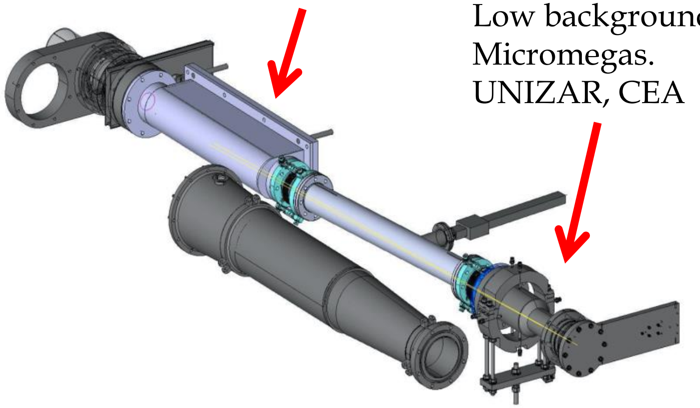


X-ray finger run



BACK UP

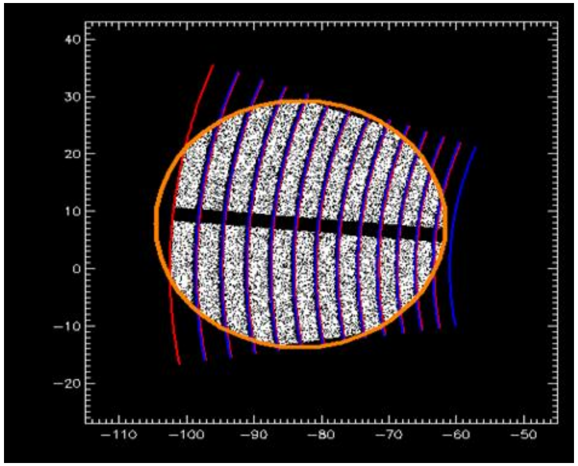
New Sunrise XRT + Micromegas line



arXiv:1509.06190

- X-ray optics specifically designed and built for CAST.
- Focal length 1.5 m
- Focusing spot 1-5 mm^2
-Big milestone for CAST → ~100 improve in S/B .
- Pathfinder system for IAXO.

13 multilayers W/B_4C



XRT efficiency