Update on the CAST experiment

Theodoros Vafeiadis

On behalf of the CAST collaboration

HEP 2019

17 April 2019, Athens

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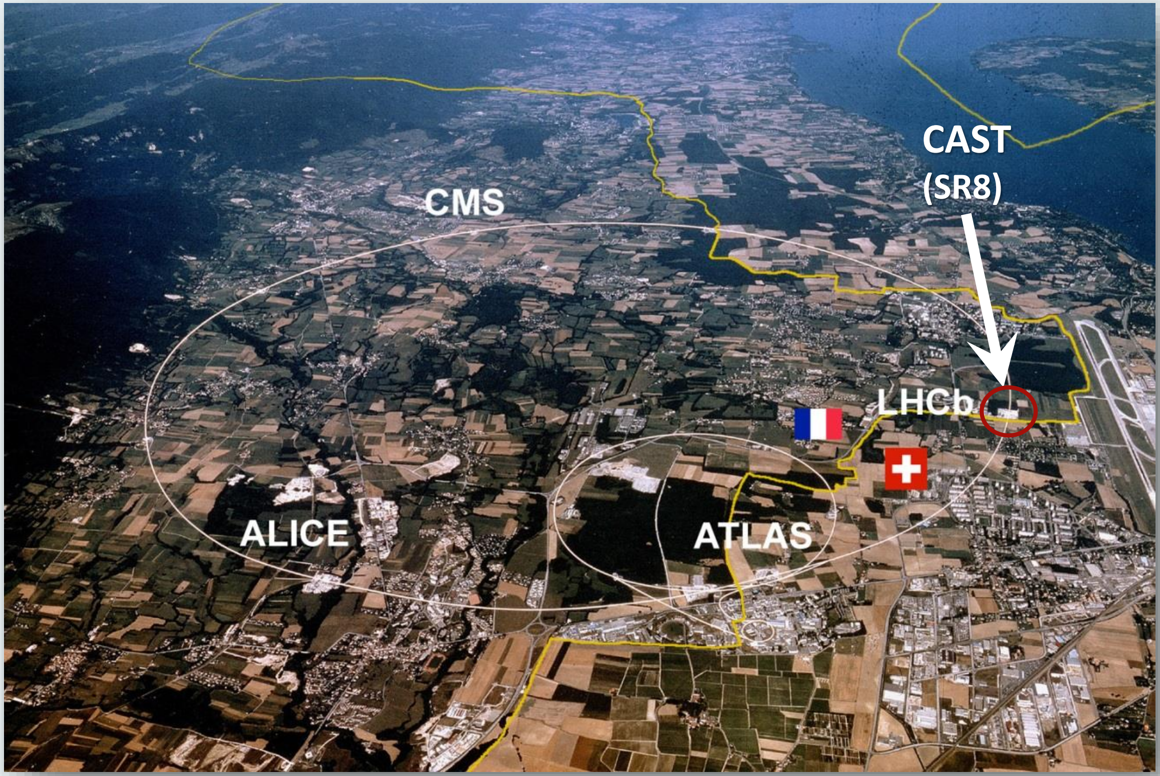


Axions

"I named them after a laundry detergent, since they clean up a long standing problem in theoretical physics." Wilczek

Strong CP problem

- Strong interactions do NOT violate CP symmetry

Elegant solution: Peccei & Quinn mechanism (Peccei & Quinn, 1977)
AXION : pseudo Nambu-Goldstone boson of spontaneous breaking of PQ symmetry (Weinberg and Wilczek , 1978)

axion properties

- $m_a \propto 1/f_a$
- Couples to photons
- Weakly interacting
- **Dark matter candidate**

Techniques

Axion : WANTED

Search strategy by Sikivie (axion couplings)

Most common : axion to photon coupling (Primakoff effect – exists in all models)

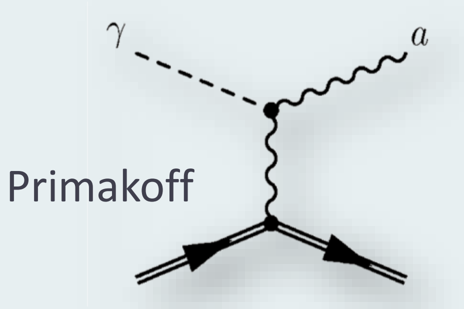
Helioscopes

- Solar axions
- Powerful magnet $\rightarrow$ transverse magnetic field
- Primakoff effect (Tokyo, **CAST**)

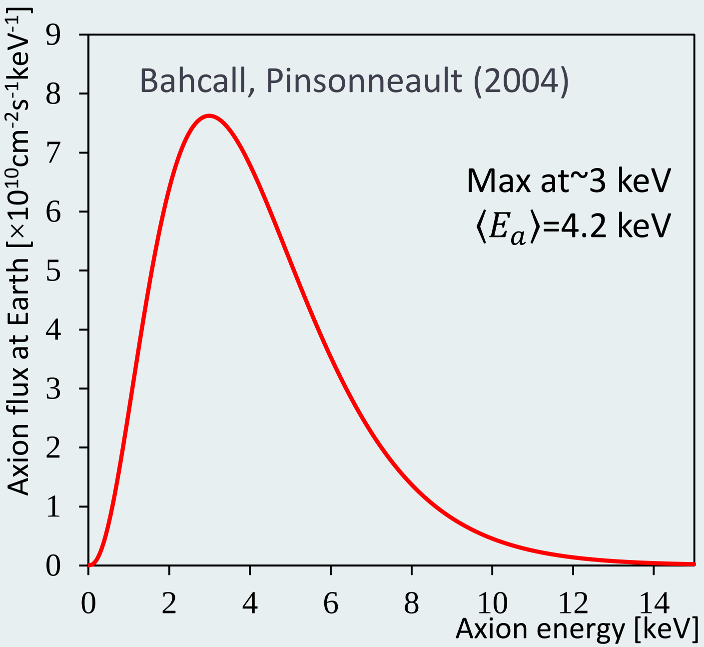
Haloscopes

- Relic axions produced in early universe.
- Electromagnetic cavities in strong magnetic fields (ADMX, CARRACK, **CAST**)

Helioscope technique

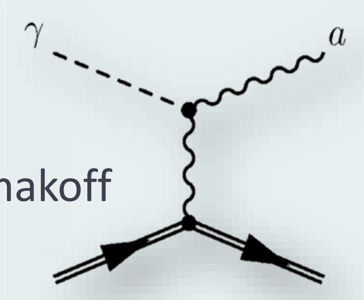


Axions are produced in the Sun via the Primakoff effect

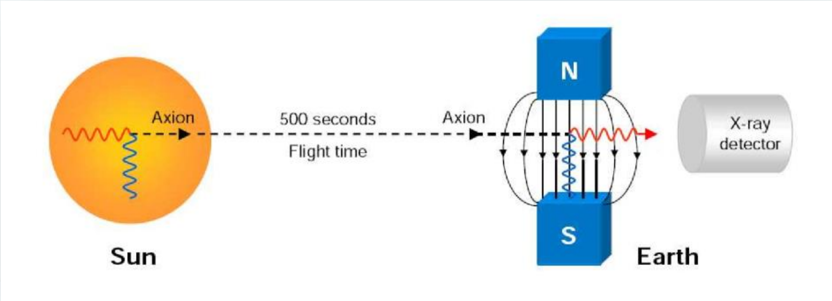


Helioscope technique

Re-convert to photons in the presence of a strong magnetic field
P. Sikivie, Phys. Rev. Lett. 51, 1415–1417 (1983)



Primakoff



Signal: Excess of X-rays in detectors while the magnet is pointing to the Sun

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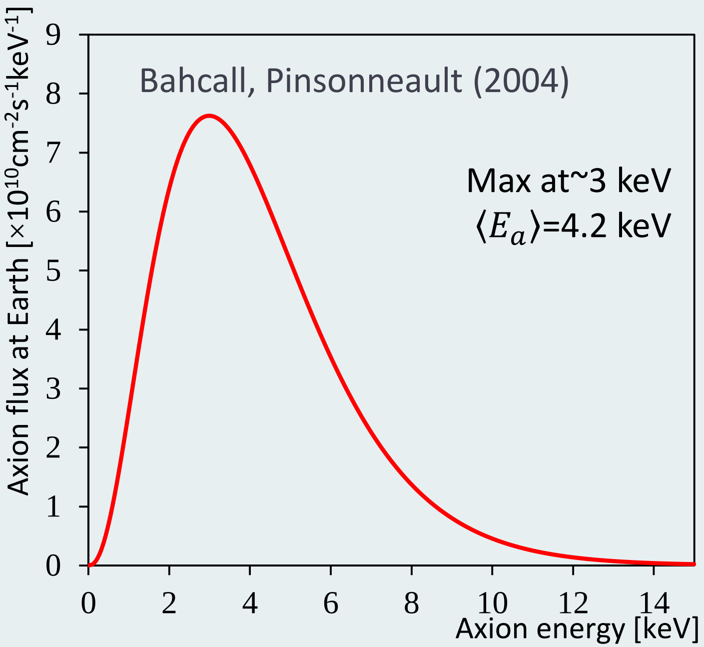

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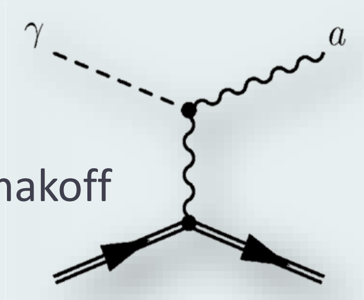

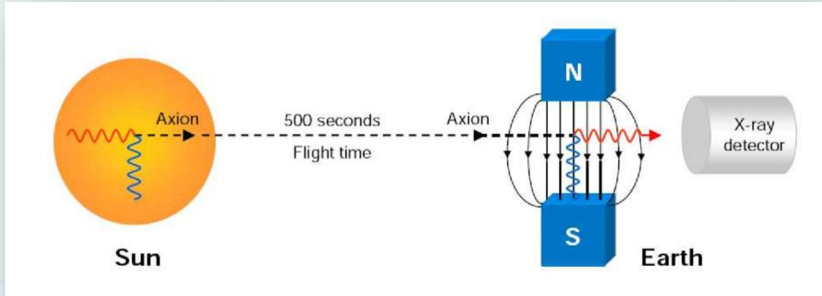

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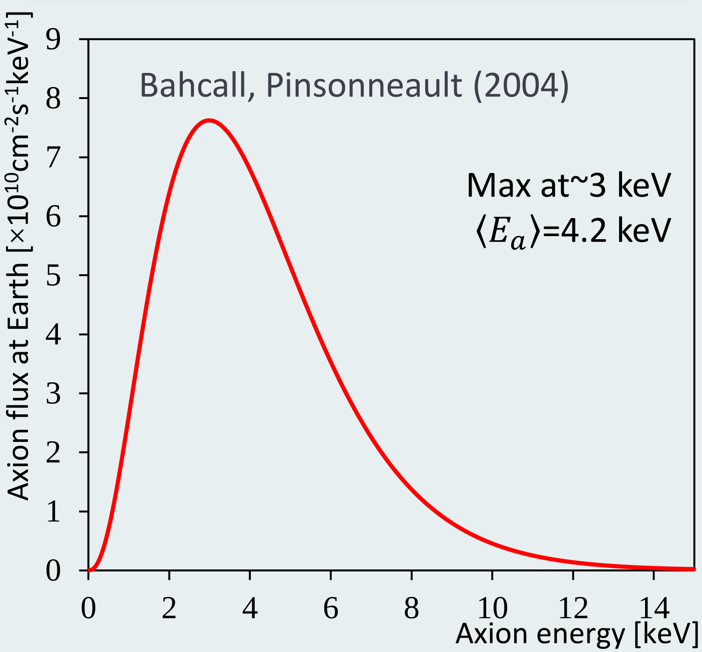
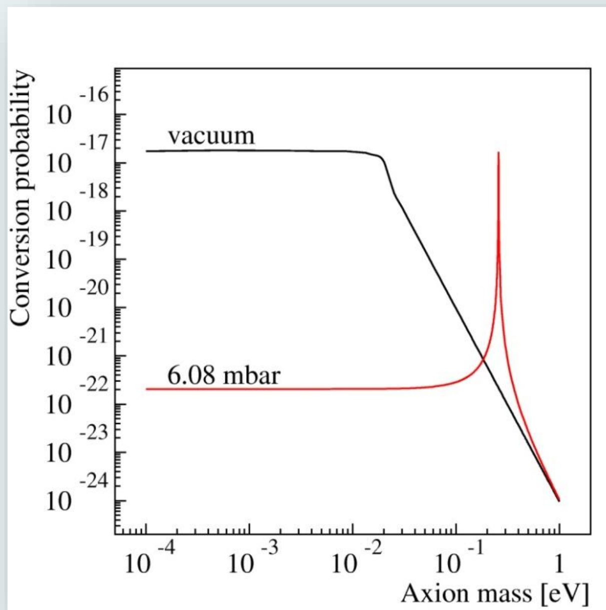




Conversion probability:

Magnet $(BL)^2$

Buffer medium

Coherence

Vacuum $m_a < 0.02$ eV

Buffer medium:

Higher ρ restoration of coherence for higher m_a

Haloscope technique

- Axions are natural cold dark matter (DM) candidates if their mass lies within the range 1–100 μeV.

- The haloscope technique consists of a high-Q microwave cavity properly aligned in a magnetic field.
- The magnetic field triggers the conversion of axions to photons.
- If the resonant frequency of the cavity corresponds to the frequency of the photon the probability of conversion ***can be significantly enhanced***.

- The probability of conversion is enhanced by the Q-factor, the volume, and the geometrical form factor G of the cavity.

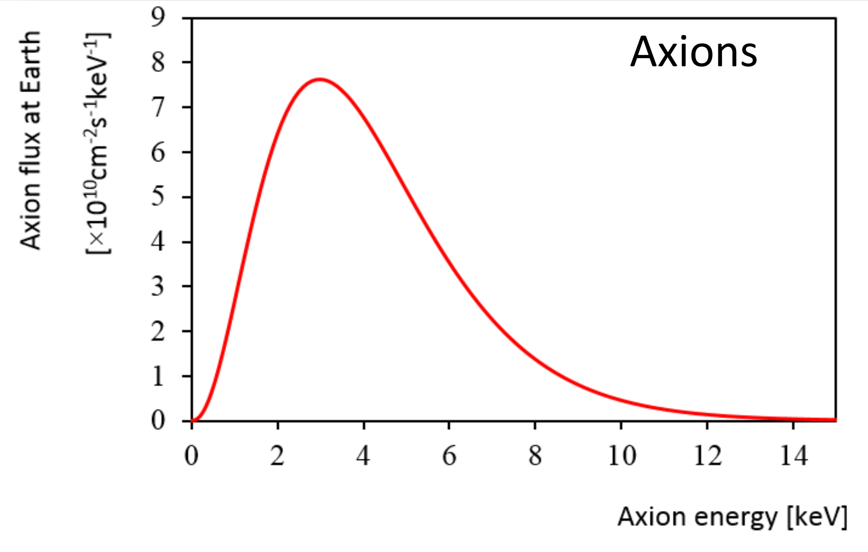
Chameleons

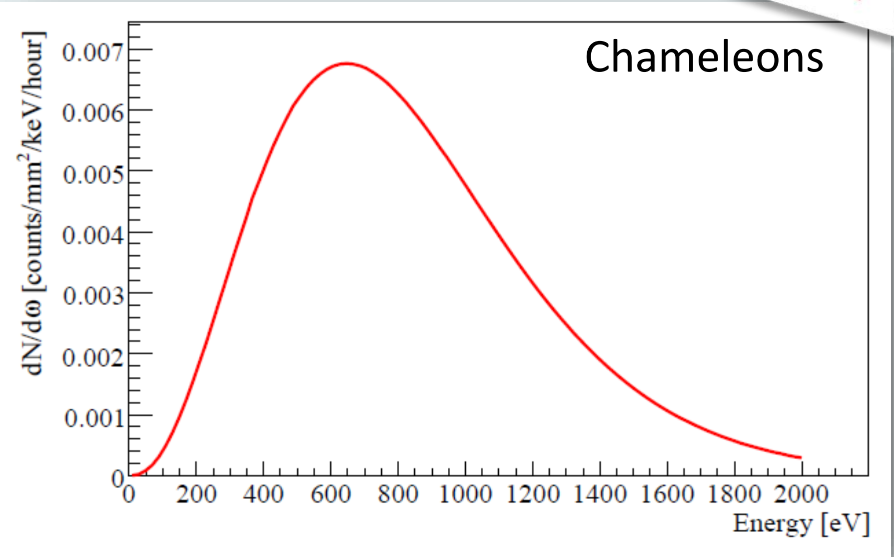
Brax, Lindner and Zioutas - Phys. Rev. D 85(2012), 043014

New searches in vacuum : **Chameleons**

- Dark Energy candidates
- Their mass depends on the energy density of the environment
- Can be created by the Primakoff effect in the tachocline region of the Sun ($R \sim 0.7 R_{\odot}$) They can be converted to X-ray photons in CAST via the inverse Primakoff effect (like axions)

Detector requirements:
Low energy threshold
Low background
Good energy resolution





CAST – research program

CAST Phase I: vacuum operation (2003 - 2004)

m_a <0.02 eV

PRL 94 (2005) 121301

JCAP04(2007)020

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^{4}He run, (2005–2006)

0.02 eV < m_a < 0.39 eV

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^{3}He run (2008-2011)

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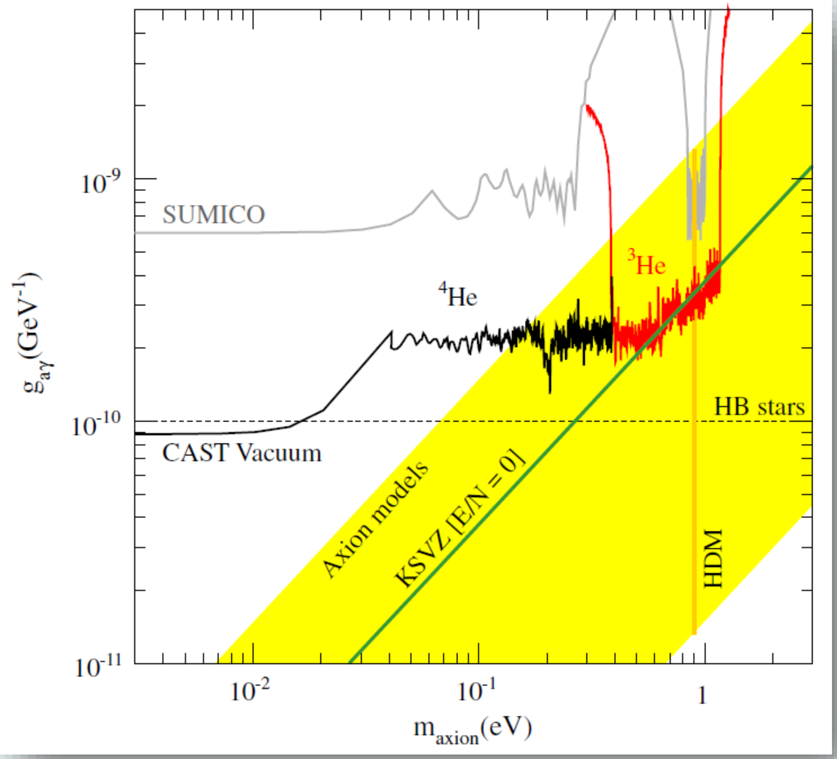

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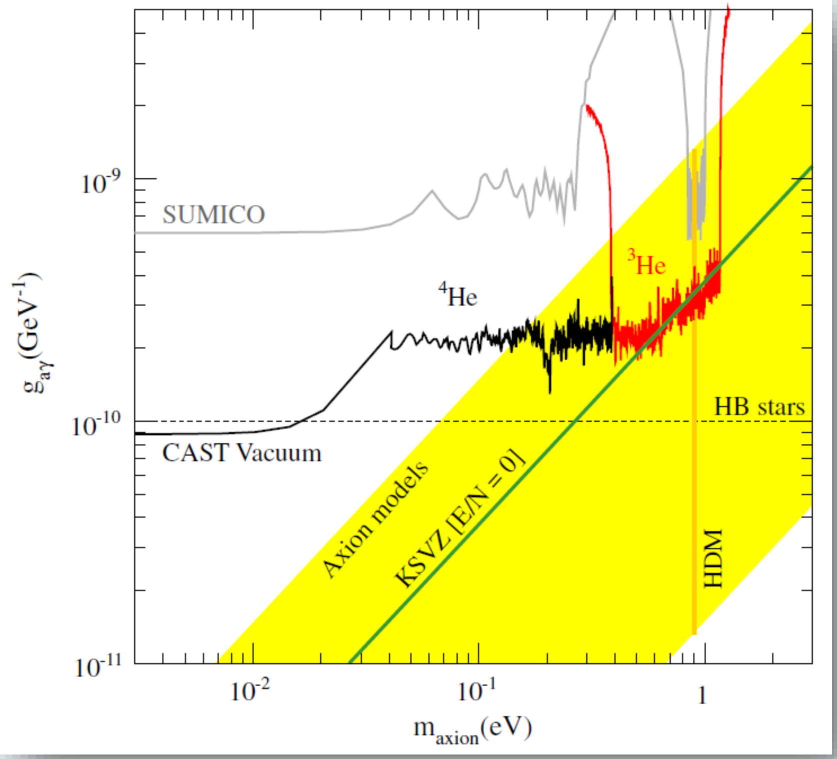
PRL 112 (2014) 091302

^{4}He run (2012)

0.39 eV < m_a < 0.42 eV



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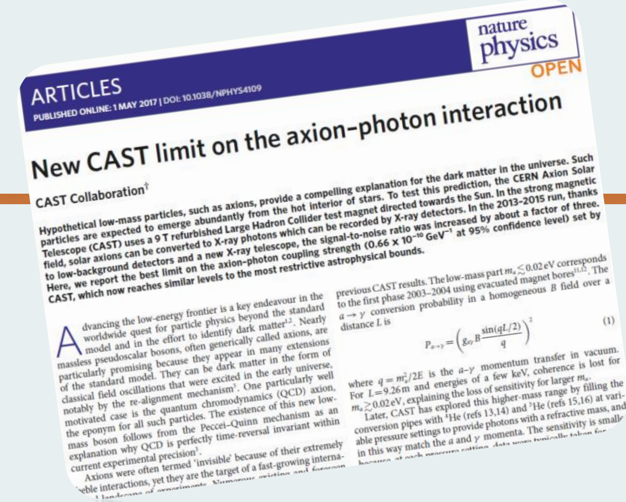

ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
nature physics OPEN

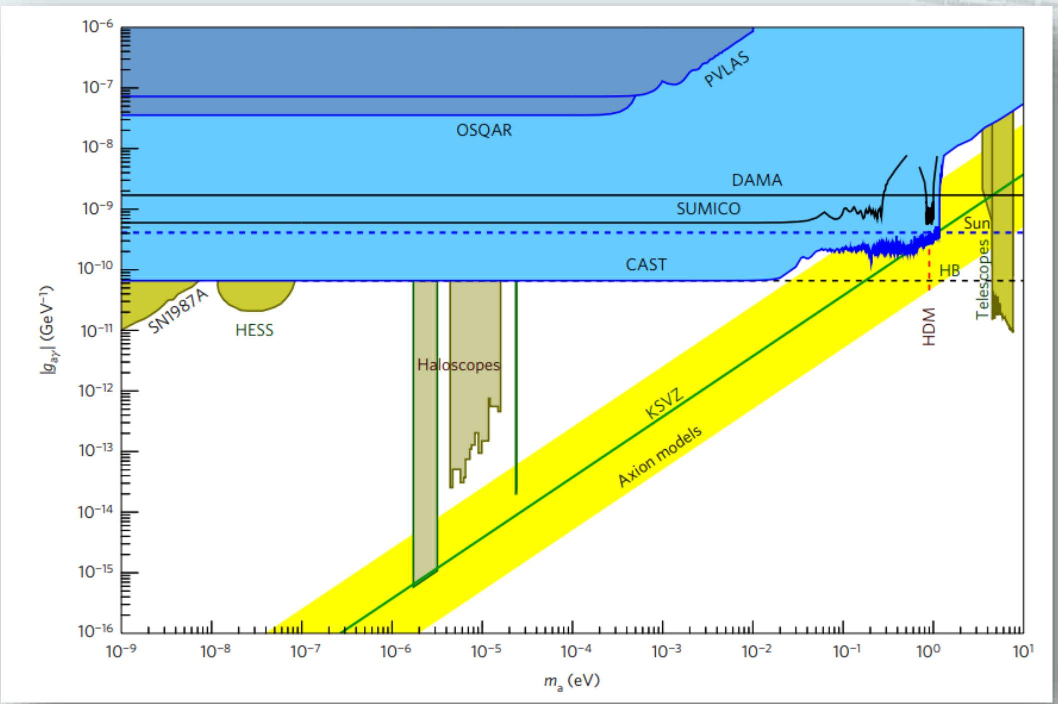
New CAST limit on the axion-photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion-photon coupling strength (0.66×10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.

Vacuum run (2013-2015) – factor 3 improved sensitivity

$g_{\alpha\gamma}$= 0.66 × 10^{-10} /GeV at 95% C.L.



Nature Physics, Volume 13, pages 584–590 (2017)

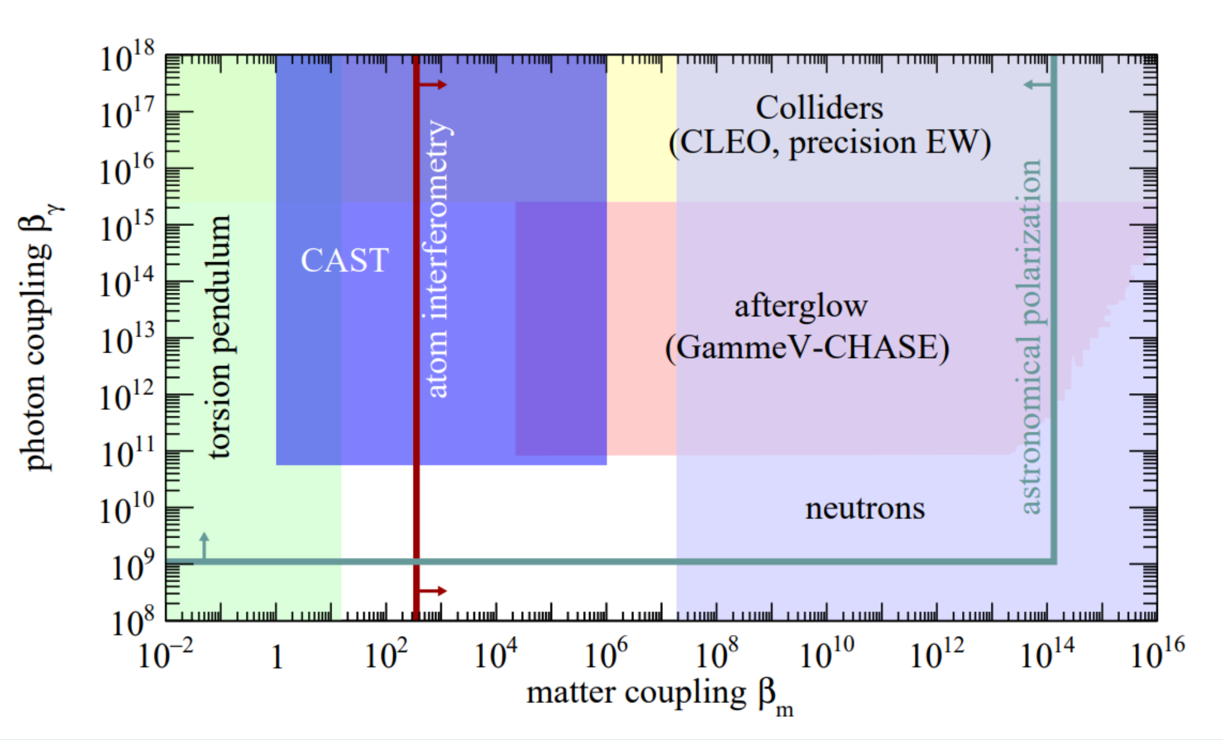
CAST – research program

Phys.Lett. B749 (2015) 172-180
&
JCAP 1901 (2019) no.01, 032

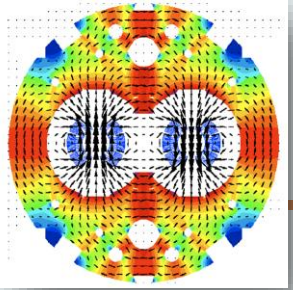
Vacuum run (2013-2015) – Chameleons

Limit to $\beta_\gamma \leq 5.7\times10^{10}$ at 95% C.L.

Valid for $1 \leq \beta_m \leq 10^6$



CAST – experimental layout



- 10 m decommissioned LHC prototype magnet (B ≈ 9 T, T≈ 1.8K)
- Two cold bores of 43 mm aperture.
- 4 x low-background X-ray detectors - 2 focusing devices
- Rotating platform : H= ±40°, V ±8°.
- 2 × 1.5 hours of tracking / day.

CAST

CAST Detectors

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

Requirements for high sensitivity:

- Detectors
  - -Constructed with radiopure materials
  - -Signal topology and 2D reconstruction for offline background rejection
  - -Good efficiency in the energy range of interest
- Optics: Improve signal / background ratio

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Micromegas, InGRID

- Solar axions

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- Solar axions — **Micromegas, InGRID**
- Chameleons — **SDD, InGRID, KWISP**

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- Solar axions
- Chameleons
- Relic axions

Micromegas, InGRID

SDD, InGRID, KWISP

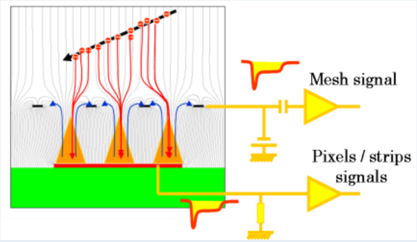
RADES, CAPP

Y. Giomataris *et al.*, NIM A 376 (1996) 29
MICRO MEsh GASeous Structure

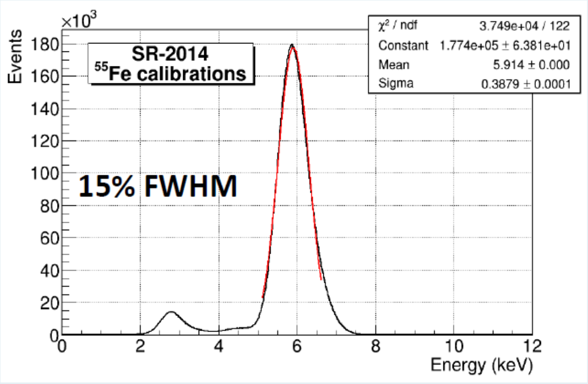
Micromegas

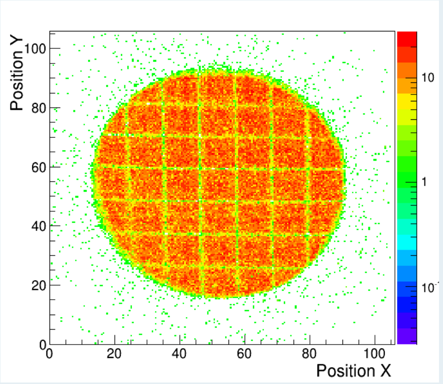
- High gain
- Long term stability
- Good energy resolution (~15% @ 6 keV)

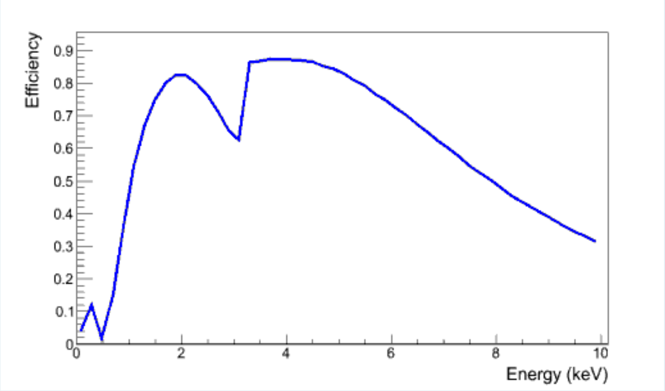
- Mesh pulse: Pulse shape analysis
- Strips signal: Topological analysis



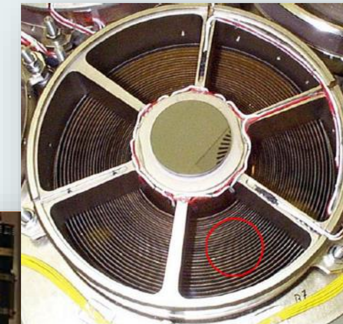
CAST Micromegas (Ar, 2.3% iC_4H_{10})

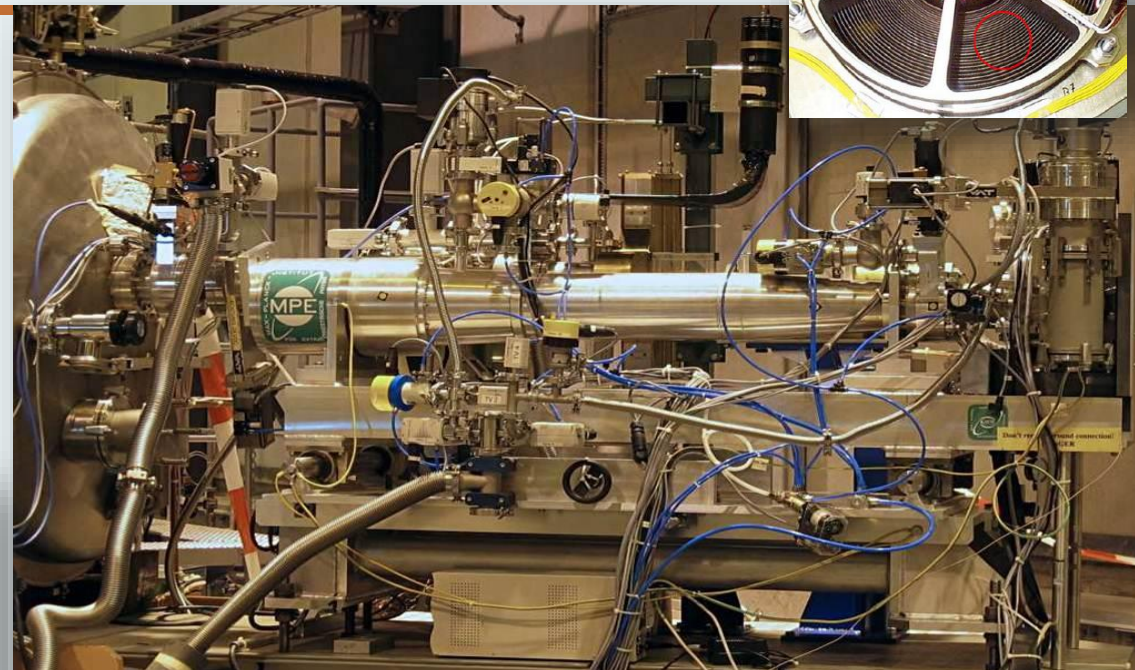






CCD (removed in 2012)



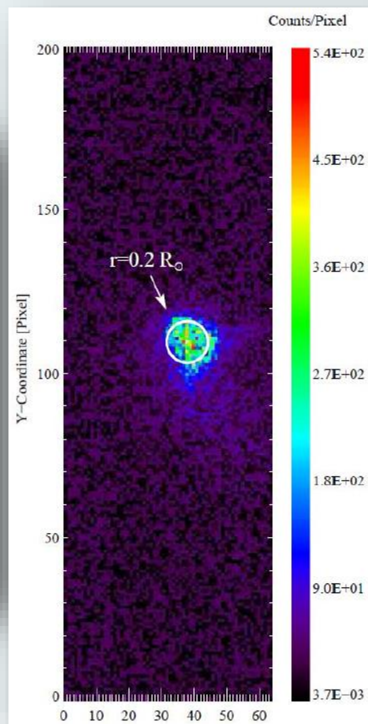


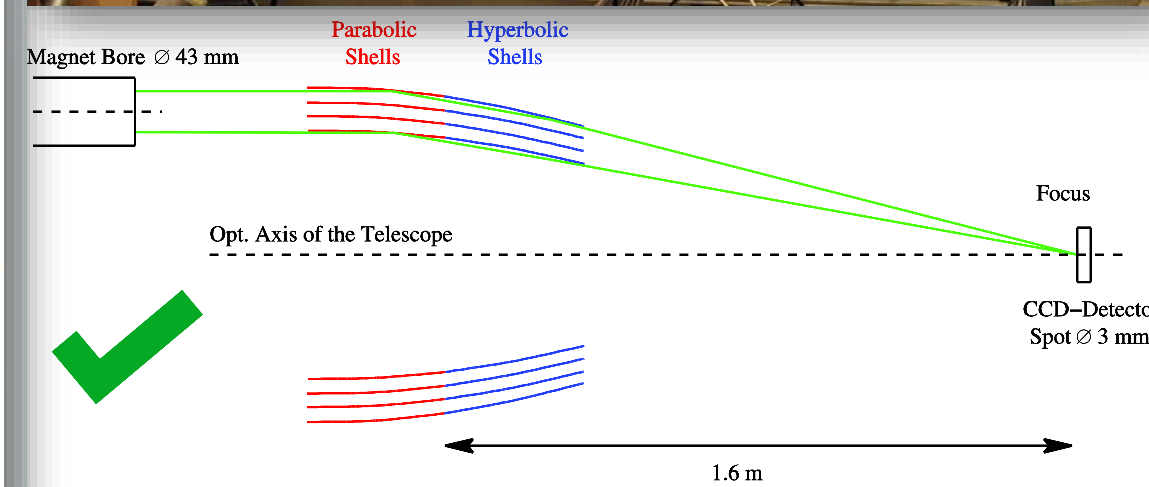
X-ray telescope

- Focal length 1600 mm
- 14.5 cm^2 focused to ~9 mm^2

pn-CCD

- 0.2 counts/h (1-7 keV)



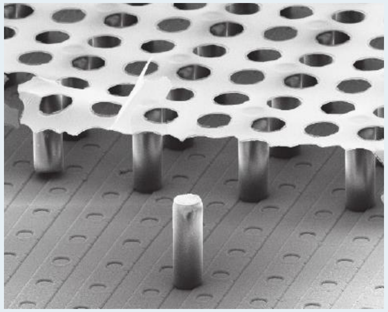


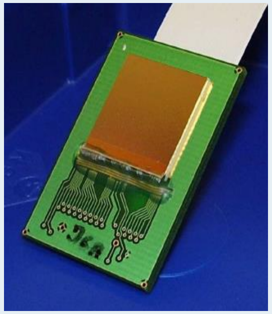
InGRID

Chefdeville et al - Nucl. Inst. Meth. A 556(2006), p 490
Integrated Micromegas – InGrid

Micromegas mounted on a pixel chip via photolithographic post-processing

- **7 x Timepix chip**

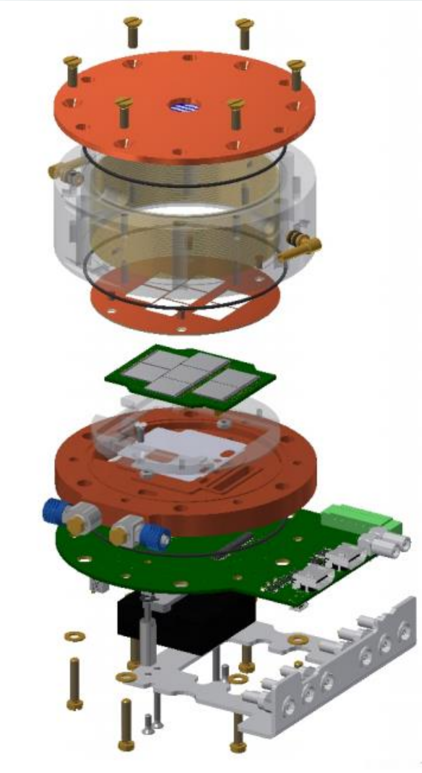


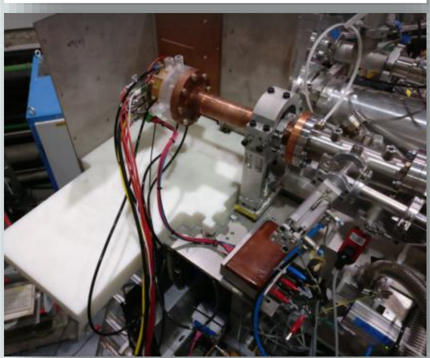


Threshold well below 1 keV
- X-ray Window made of 2 µm Mylar with copper strongback

New for 2017 : 300 nm SiN window

Simultaneous search for solar axions and chameleons



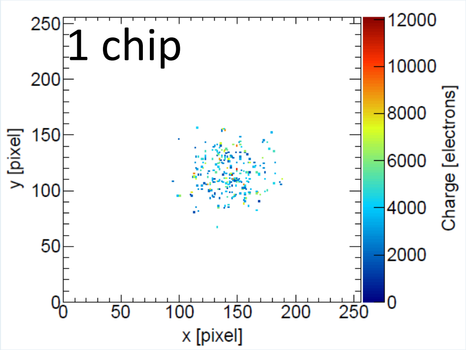


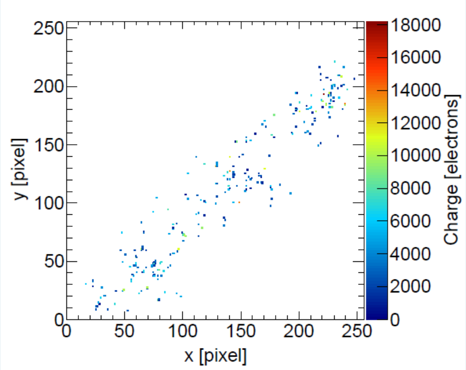
InGRID

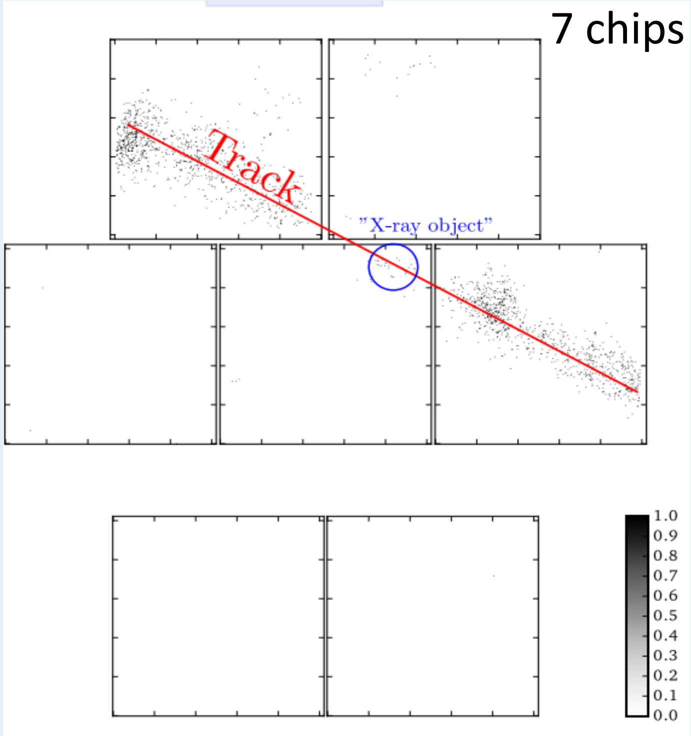
- Each avalanche is collected in one pixel
- Detection of single electrons possible

Background rejection:

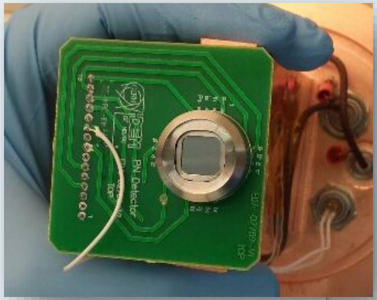
- Shape of pixel hit pattern. X-rays (left), background (right)





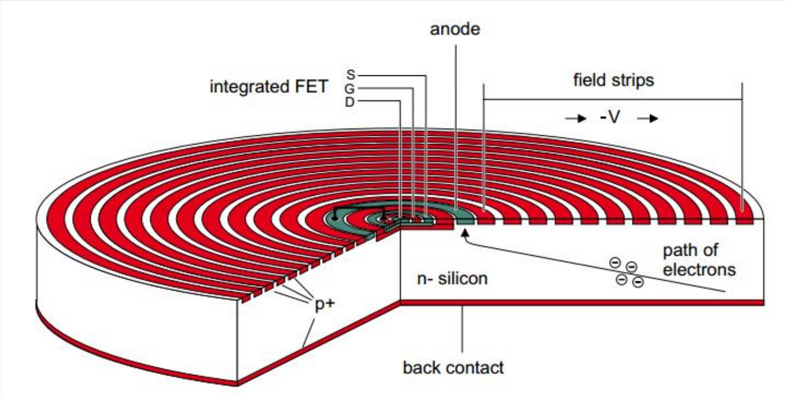


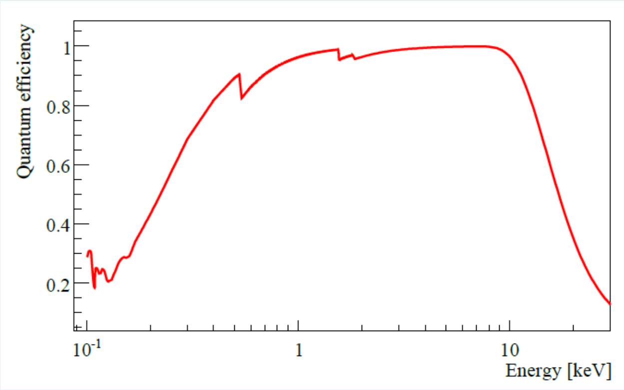
SDD



For the 1st attempt on chameleon searches

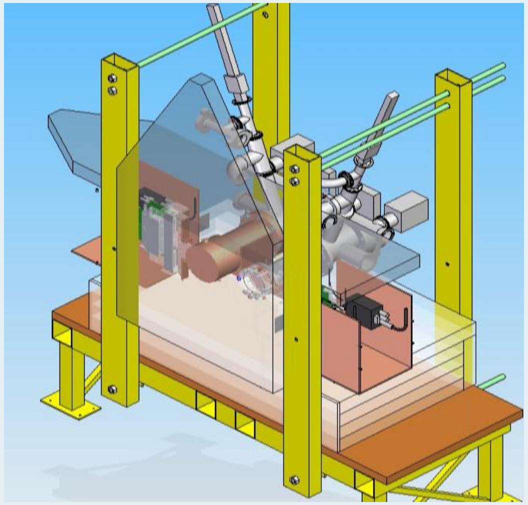
- Took advantage of the available port due to MPE-XRT recalibration at the end of 2013
- SDD (from PN-Detector) ~100 mm^2 surface without vacuum window
- Detector system R&D at CERN

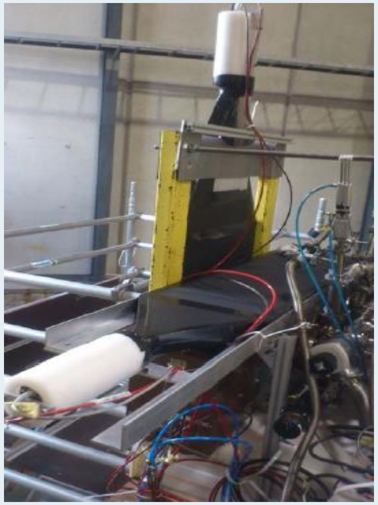




Sunset 2013

2 x Microbulk Micromegas
Installation of Muon veto (2013)





Sunrise 2013

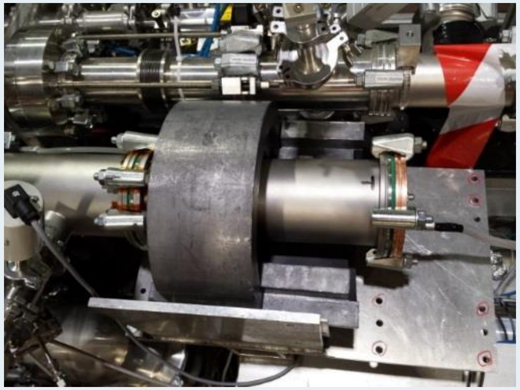
1 x new Microbulk Micromegas

New detector design

- Field shaper
- Cu body & support (serves as inner shielding)
- Teflon layer to minimize 8 keV fluorescence Cu-peak
- Hermetic lead shielding

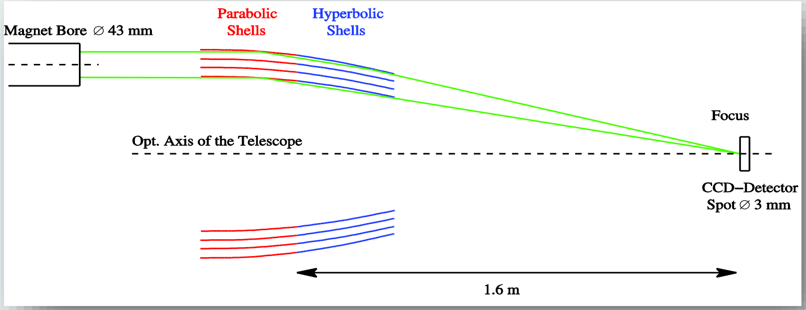
Sunrise 2013

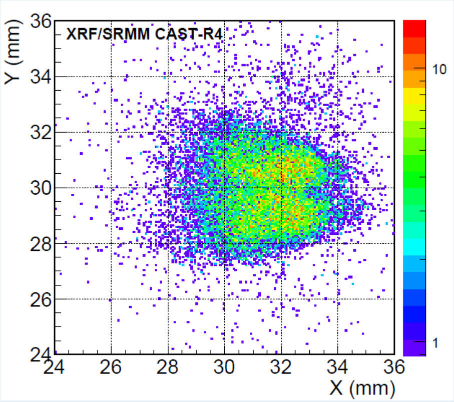
SDD (Chameleon searches)

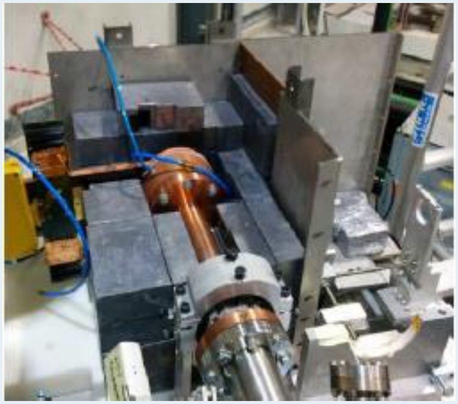


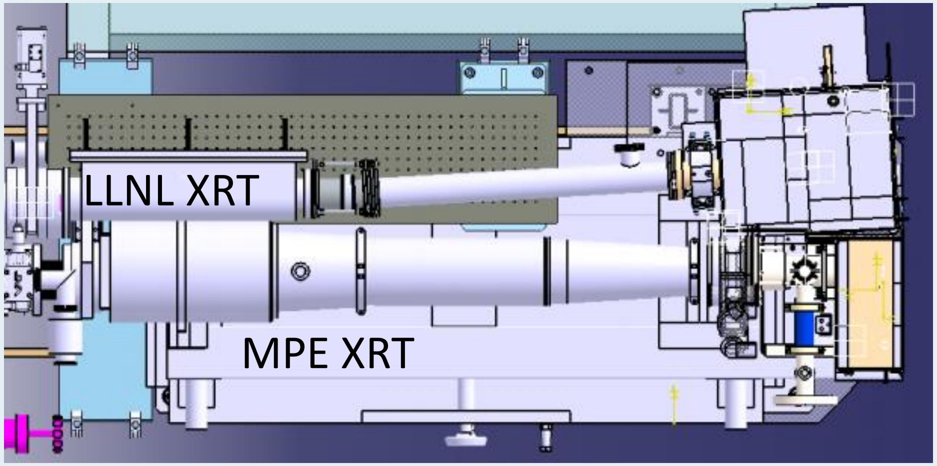
Sunrise 2014-2015

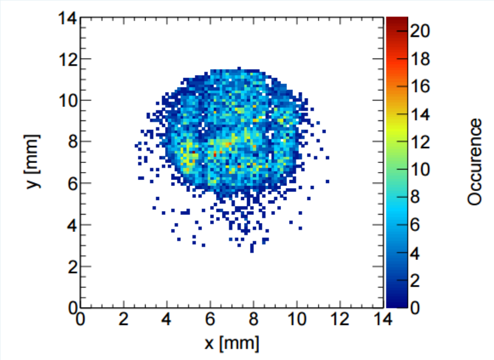
- 2 x X-ray telescopes
- New Micromegas + muon veto
- Background ~0.003 counts/h
- InGRID

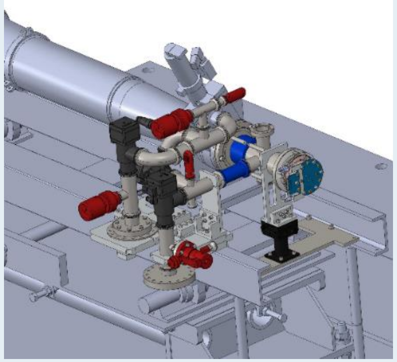












Relic axion detectors 2016 - today

- Being non-relativistic, the axions convert to monochromatic photons with energy equal to m_a.
- For a cavity resonant frequency matching m_a, the conversion is enhanced by a factor proportional to the quality factor of the cavity Q

$$\mathcal{F} \sim g_{A\gamma}^4 m_a^2 B^4 V^2 T_{sys}^{-2} \mathcal{G}^4 Q$$

- Replicate a cavity many times and combine their output: CAPP/IBS Detector

- The high-frequency resonant structure is an array of N small rectangular cavities connected with irises: Relic Axion Detector Exploratory Setup (RADES)

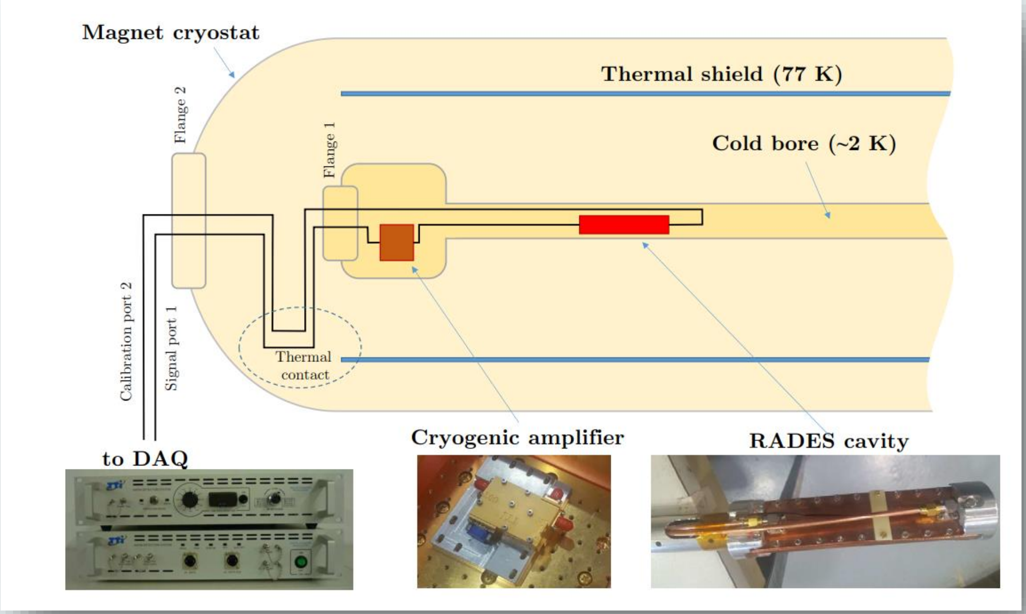
RADES 2017 onwards

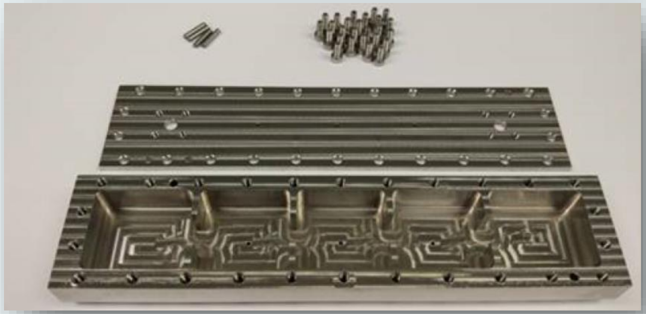
arXiv:1803.01243v1 (prepared for JCOP)

Axion Searches with Microwave Filters: the RADES project

As a first step, a small-scale RADES cavity with 5 elements and no tuning has been built and installed inside the CAST magnet.

New for 2019: 1 m long cavity will be installed beginning of summer.





RADES 2017 onwards

arXiv:1803.01243v1 (prepared for JCOP)

Axion Searches with Microwave Filters: the RADES project

As a first step, a small-scale RADES cavity with 5 elements and no tuning has been built and installed inside the CAST magnet.
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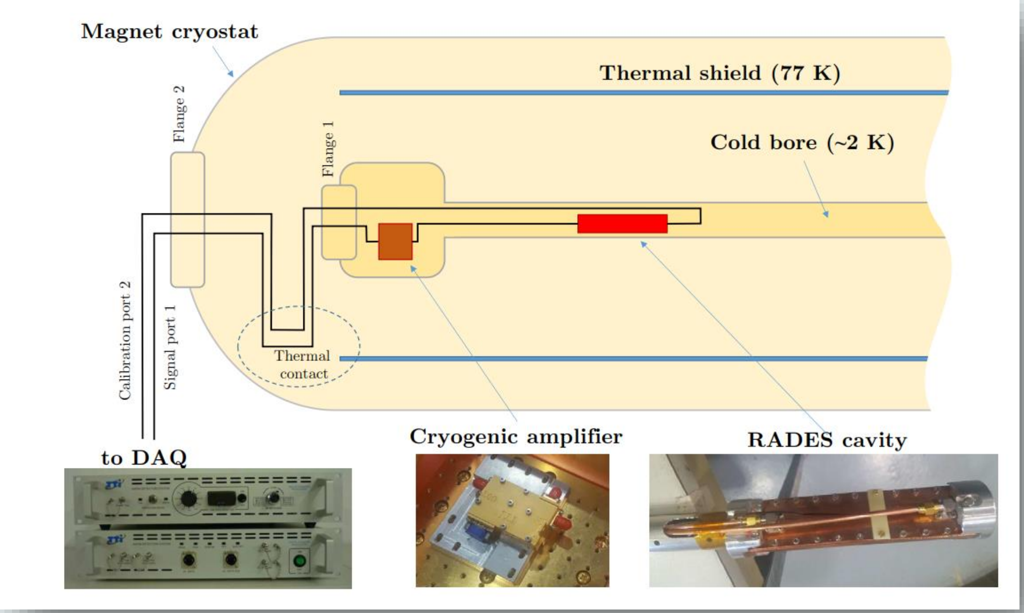
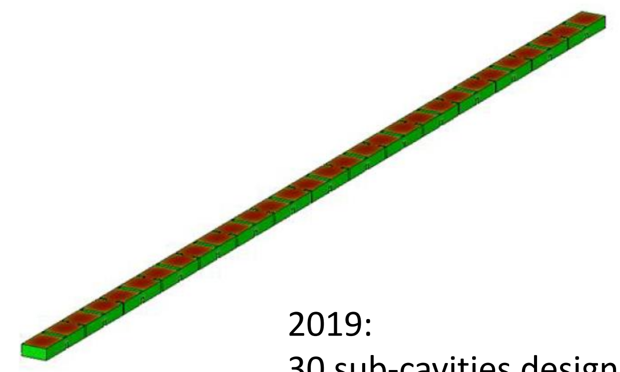


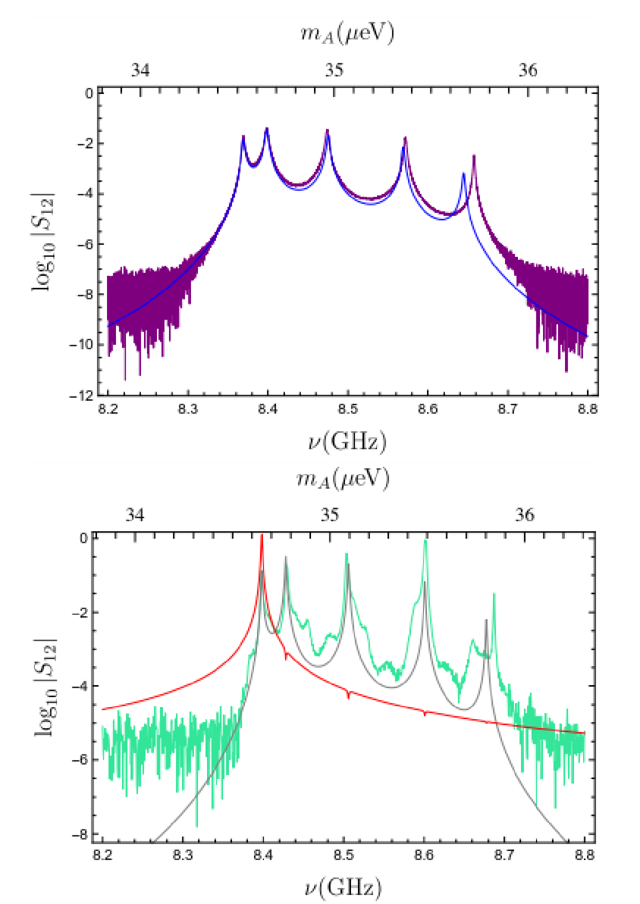


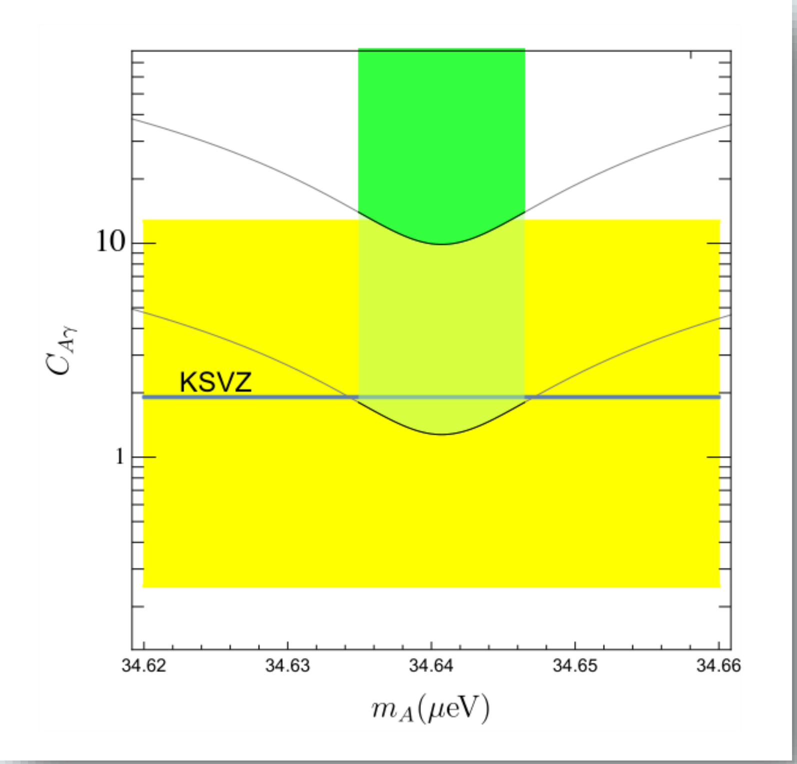
2019:
30 sub-cavities design

RADES 2017 onwards

arXiv:1803.01243v1 (prepared for JCOP)

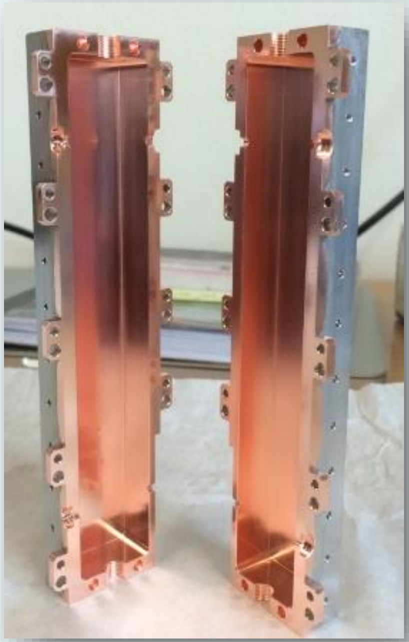
Axion Searches with Microwave Filters: the RADES project



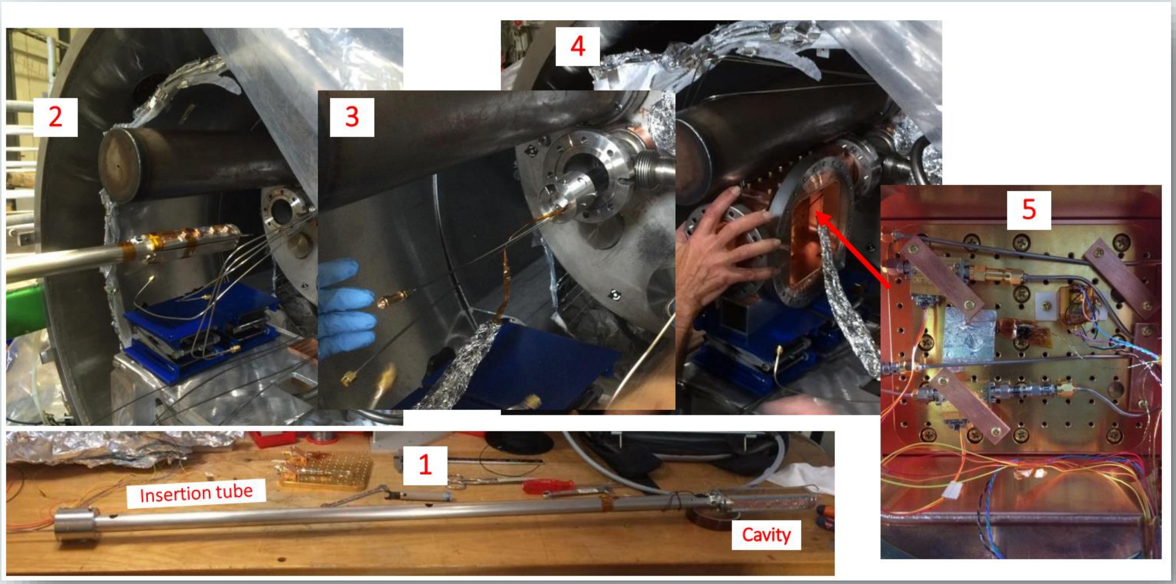


CAPP 2016 - 2017

DOI: 10.3204/DESY-PROC-2015-02/miceli_lino
Conference: C15-06-22.2, p.164-168
Haloscope axion searches with the cast dipole magnet: the CAST-CAPP/IBS detector

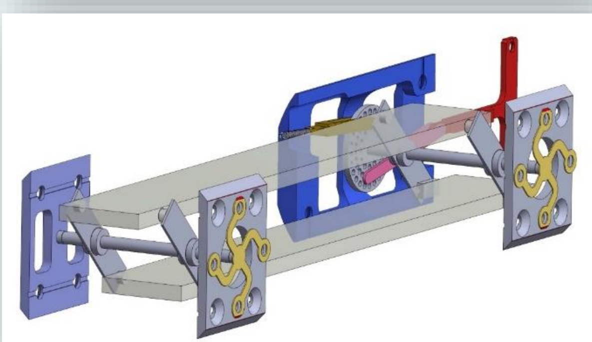


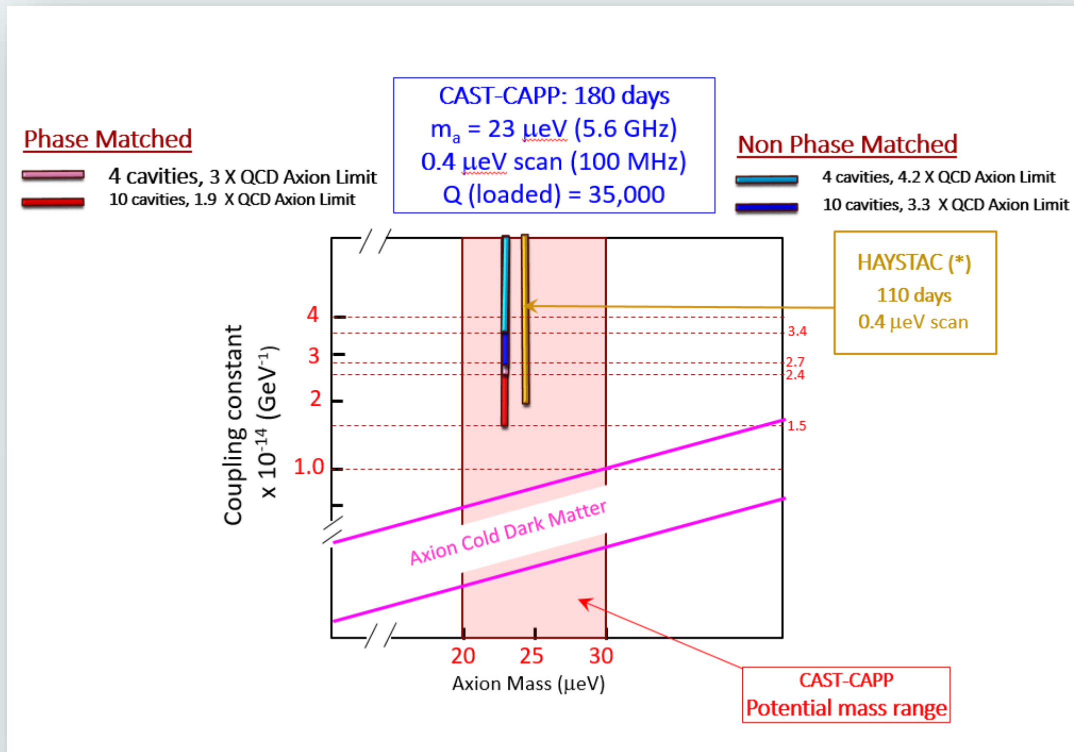
Test installation in 2016



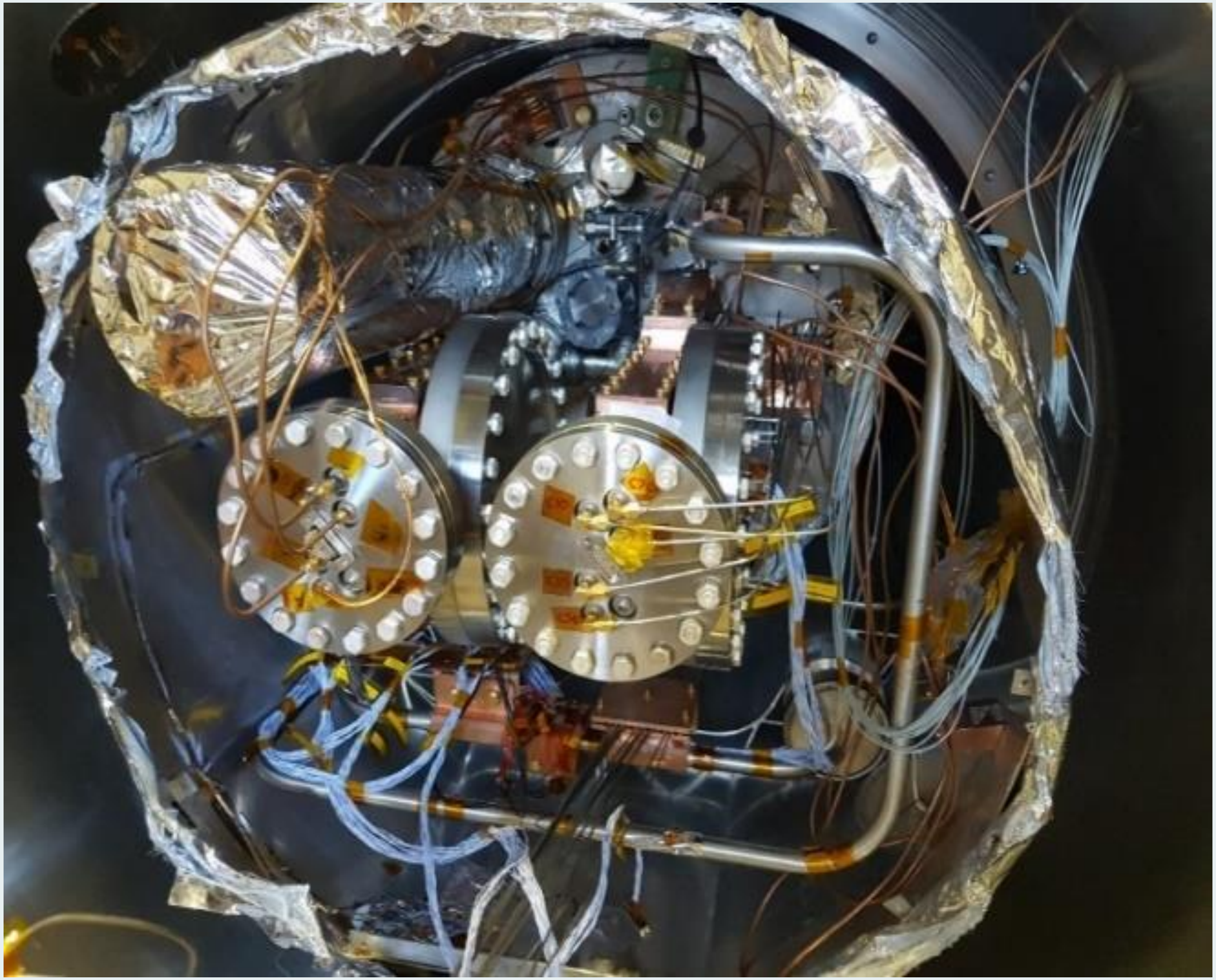
CAPP 2018 onwards

4 tunable, phase matched cavities where installed in 2018.
1st Technical run completed, 2nd underway.
Physics run to start in July 2019.





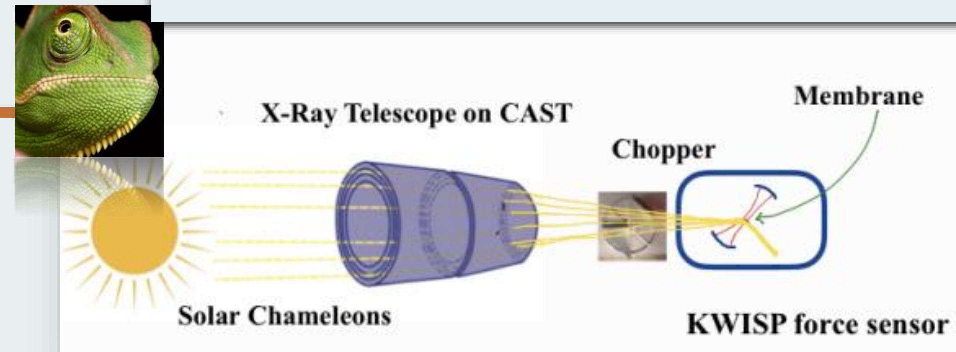
CAPP & RADES @ CAST



KWISP 2016 onwards

Physics of the Dark Universe 12 (2016) 100–104

KWISP: An ultra-sensitive force sensor for the Dark Energy sector



100 nm Si_3N_4 membrane

KWISP 2016 onwards

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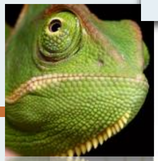
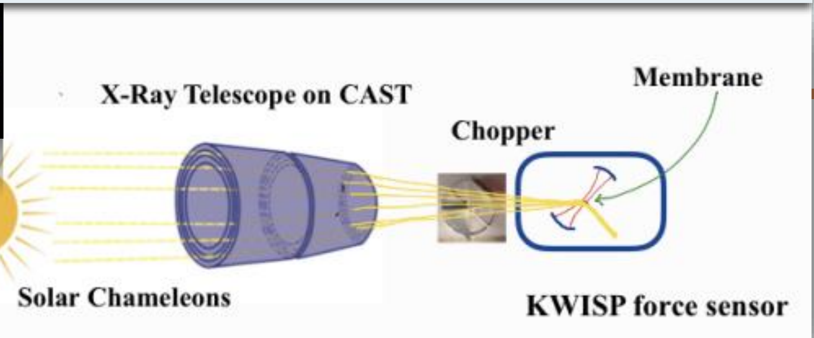
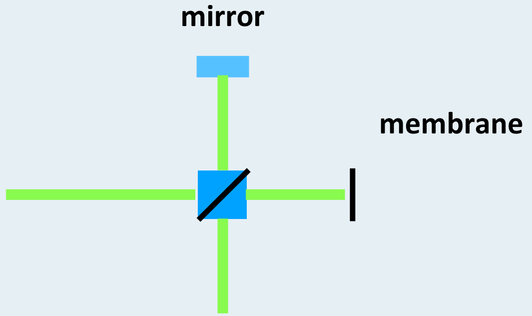




Different methods to measure the membrane displacement
(displacement ~ force)

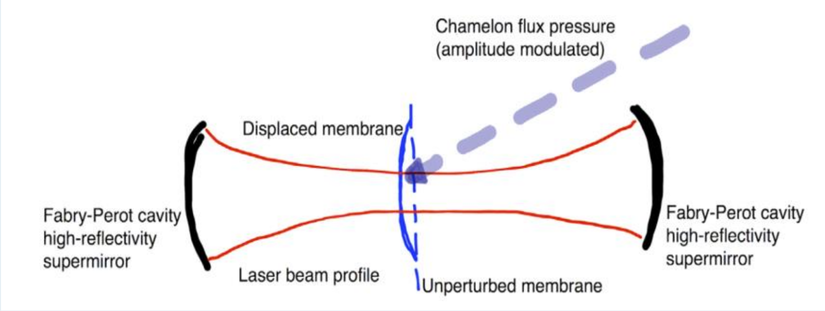
Michelson interferometer



KWISP 1.5

- ✓ green laser
- ✓ "low" sensitivity
- ✓ high stability
- ✓ "easy" to setup

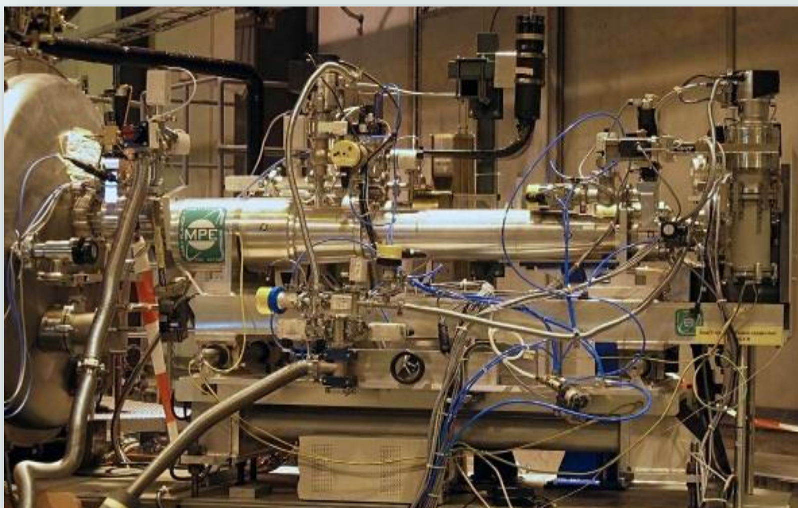
100 nm Si_3N_4 membrane

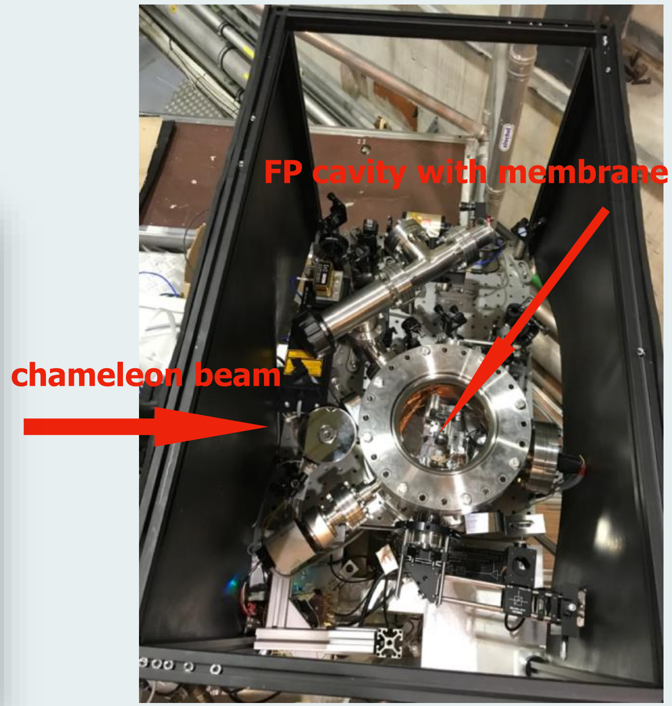


KWISP 2.0

- ✓ IR laser
- ✓ high sensitivity (multiplied by finesse)
- ✓ complicated to setup
  (cavity mode matching and locking)
- ✓ sensitive to environmental noise

KWISP 2016 onwards





- Monolithic breadboard housing the membrane chamber
- Optics vibration isolated
- Fully enclosed in a heavy rubber shielding for acoustic noise damping

Conclusions & future outlook

- CAST has provided the best experimental limit on axion-photon coupling constant over a broad range of axion masses.

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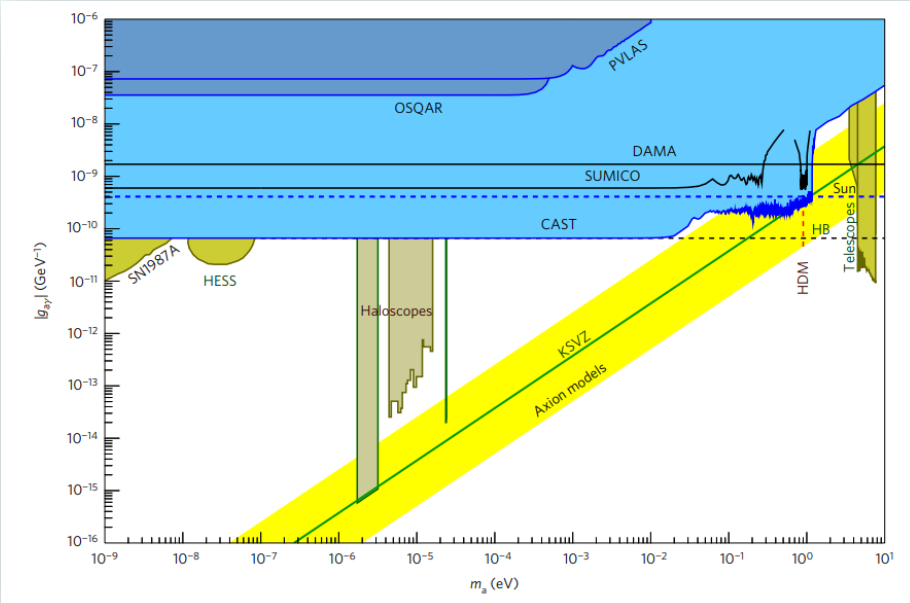
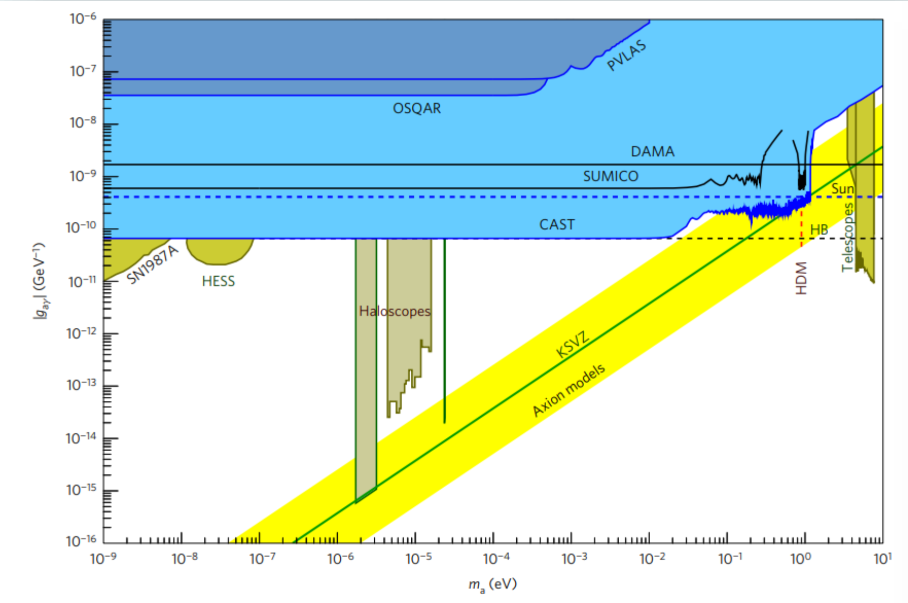
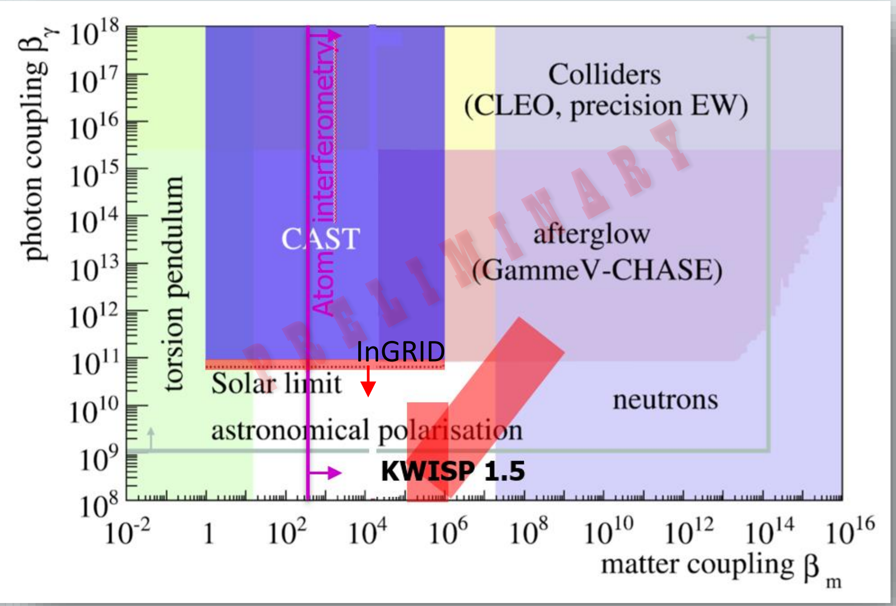


Conclusions & future outlook

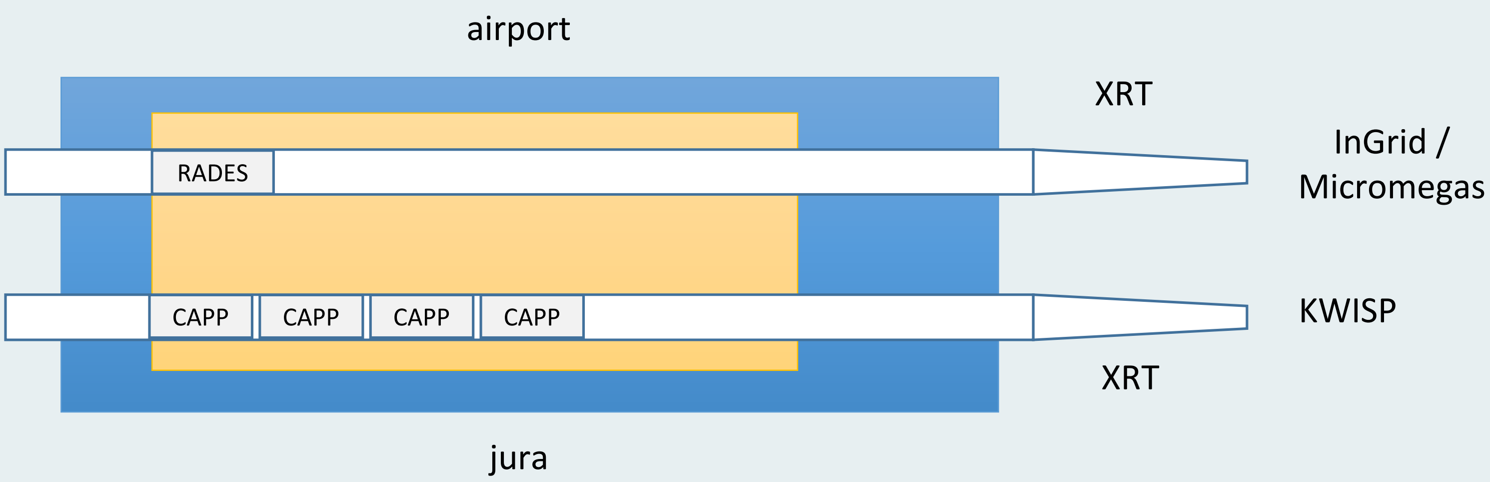
- CAST has provided the best experimental limit on axion-photon coupling constant over a broad range of axion masses.
- In 2013 CAST has provided the first limit for the chameleon-to-photon coupling constant with a helioscope and has continued the dark energy searches with the InGRID and KWISP detectors.





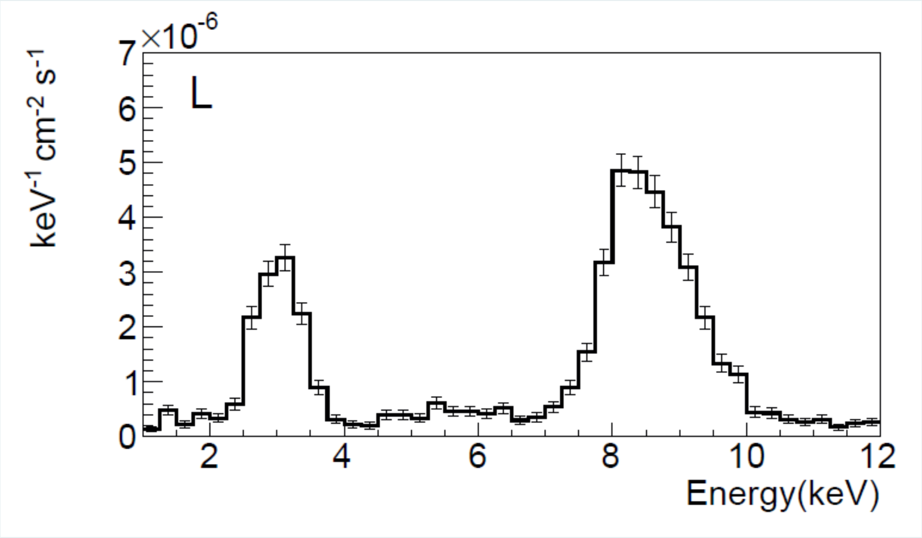
Conclusions & future outlook

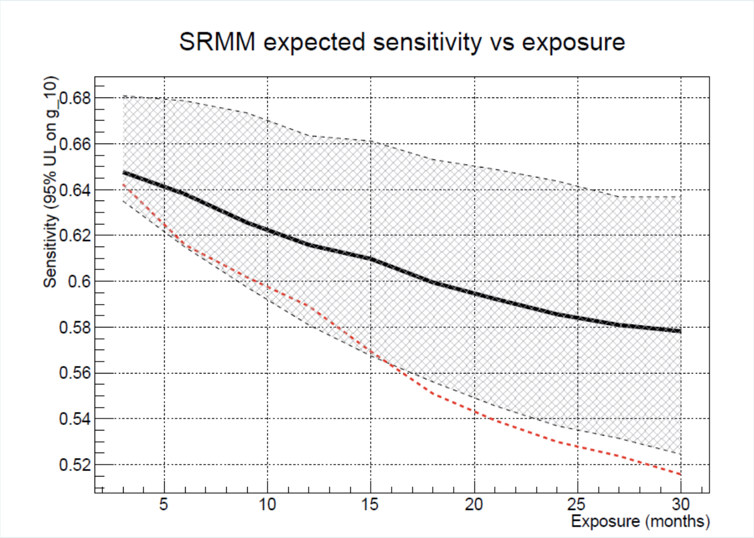
- Recently CAST became a haloscope expanding its range of searches even further.
- In 2018 we have already collected data with RADES and InGRID and currently CAST is working with the following setup:



- We are preparing a proposal for a 3-year run which will include the above projects and a roadmap for improvements.
- **RADES**: Longer cavity (30 subcavities design)
- **CAPP**: More cavities (up to 10)
- **KWISP**: Cryogenic operation

Conclusions & future outlook





Micromegas run (20 months)

- Reduce background by using Xe as gas & push for low threshold advances (thin windows).
- Improve the result obtained in the 2013-15 phase & set a hard limit on $g_{\alpha\gamma}$.
- Determine statistical/systematic origin of some tensions.
- Provide additional technical and operational experience for IAXO/babyIAXO.

Thank you

Baby IAXO: A full experimental stage

- ➢ Two bores of dimensions similar to final IAXO bores
- ▪ detection lines representative of final ones.
- ➢ Test & improve all systems.
- ➢ Risk mitigation for full IAXO
- ▪ Will produce relevant physics
- ▪ Move earlier to "experiment mode"
- ▪ Magnet Technical Design ongoing at CERN

$t \cong 12h/day$

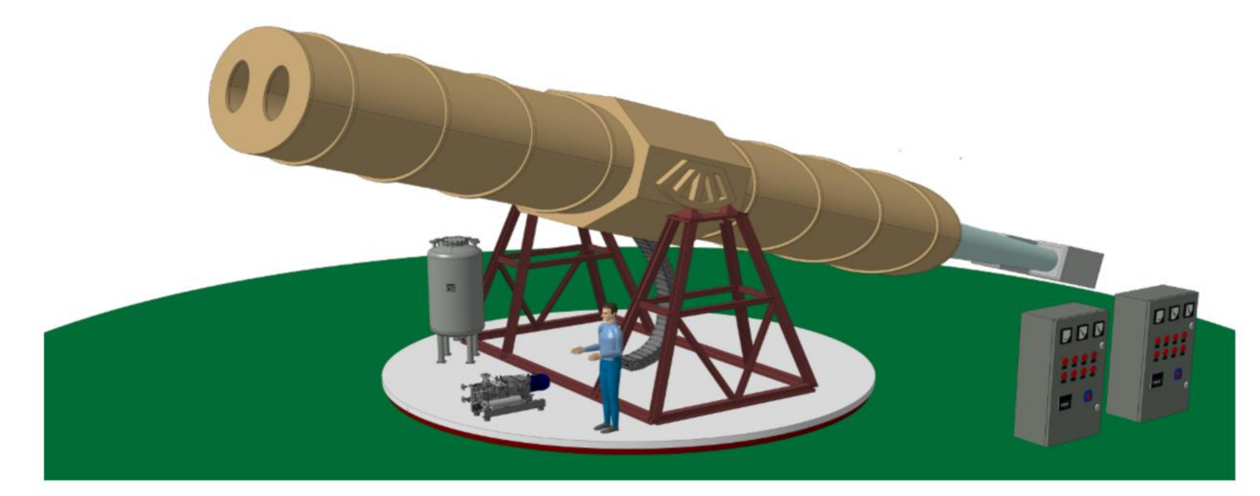
$\alpha \cong 2 \times 0.2\ cm^2$

$b \sim 10^{-7} c\ keV^{-1} cm^{-2} s^{-1}$

$B \cong 2.5T$

$L = 10m$

$A \cong 2 \times 0.4 m^2$



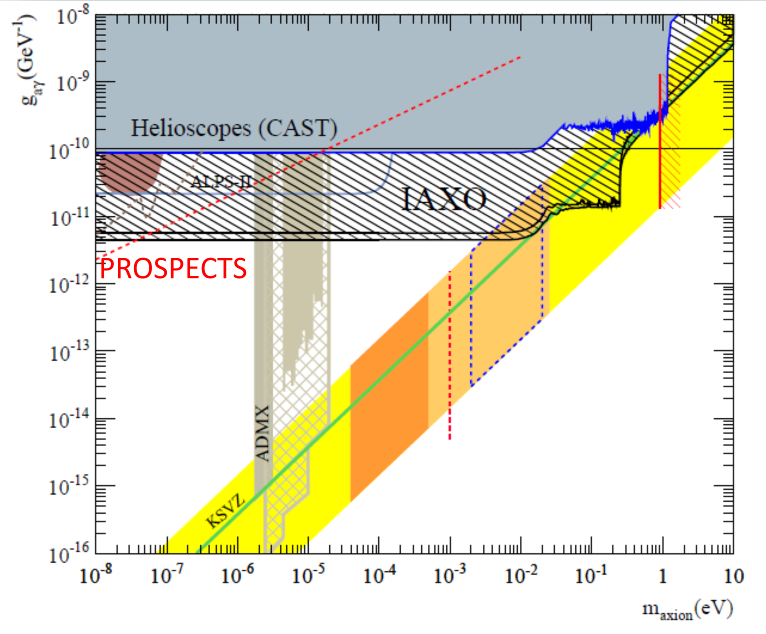
View to the future: IAXO

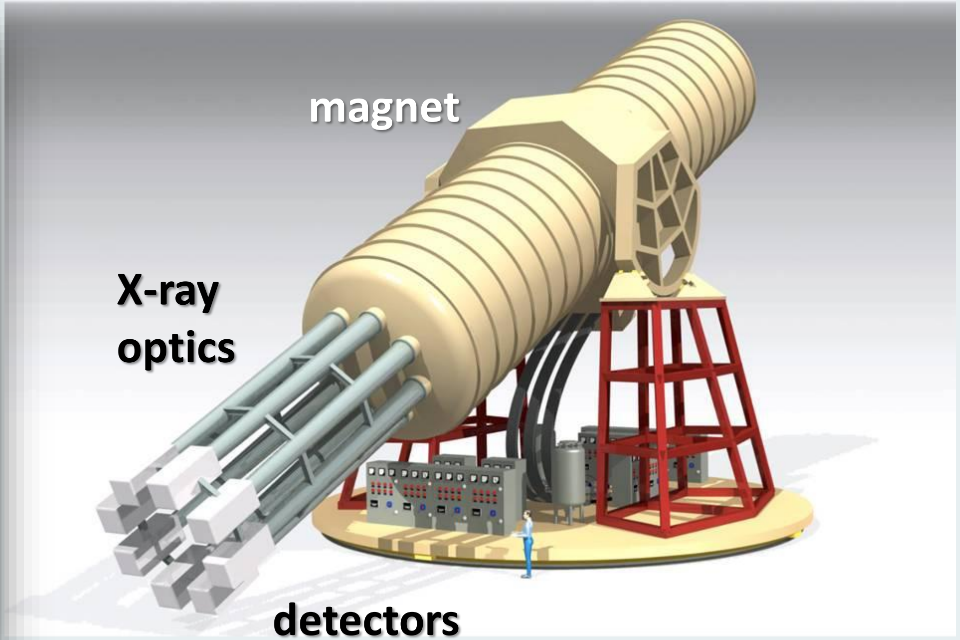
International AXion Observatory

JCAP 1106 (2011) 013

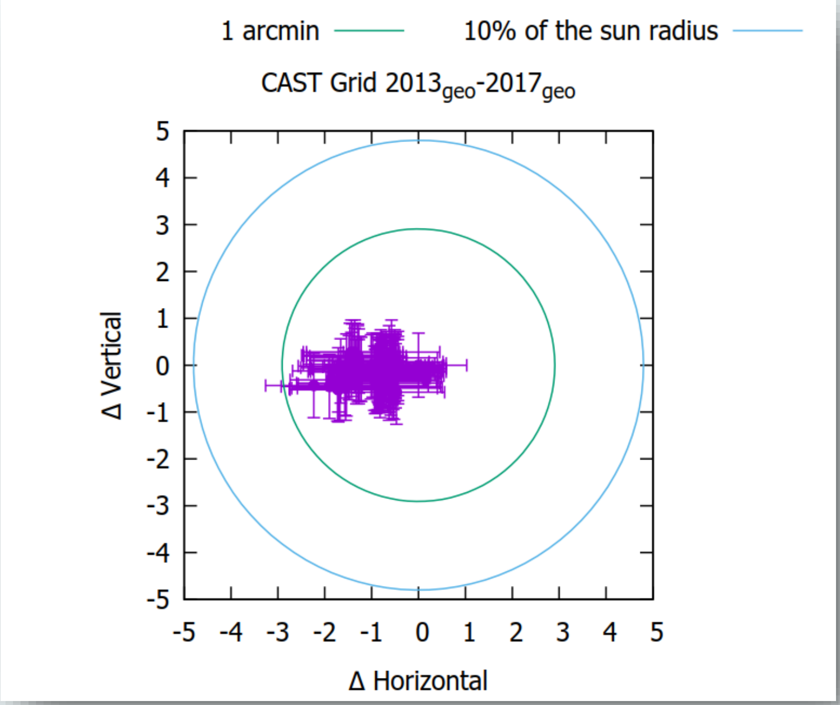
The accumulated experience from CAST put into practice

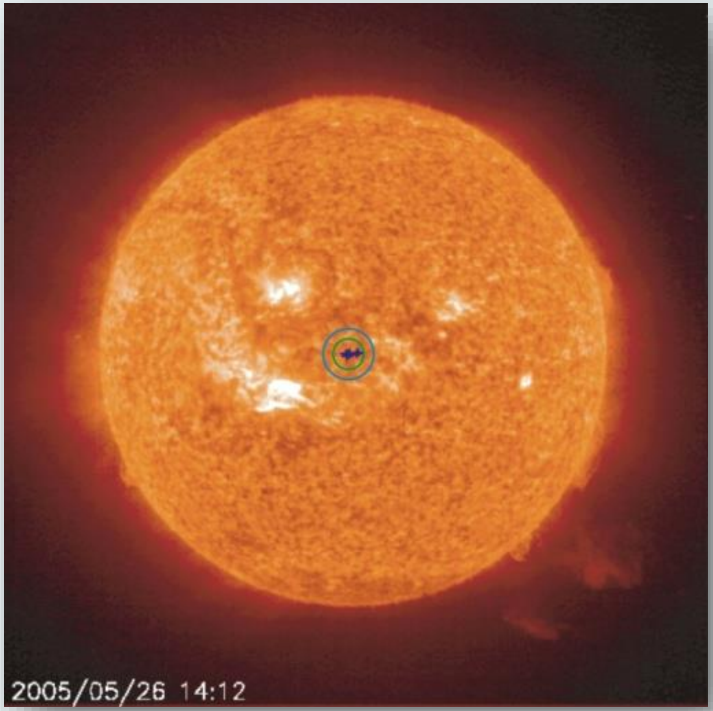
- All bores equipped with X-ray focusing devices and low background detectors. Will improve the CAST limits by 1 order of magnitude
- LoI submitted to CERN (CERN-SPSC-2013-022)
- SPSC recommended that IAXO proceeds to a TDR





Controls & Operation –Pointing precision





Controls & Operation – Pointing precision

Sun filming

- March & September
- Sun visible through window in the east-facing wall
- SLR camera + optics aligned (Survey team)
- Precision (R_{sun} = 1139±2 pixels, alignment ±25 pixels)

Not always easy…

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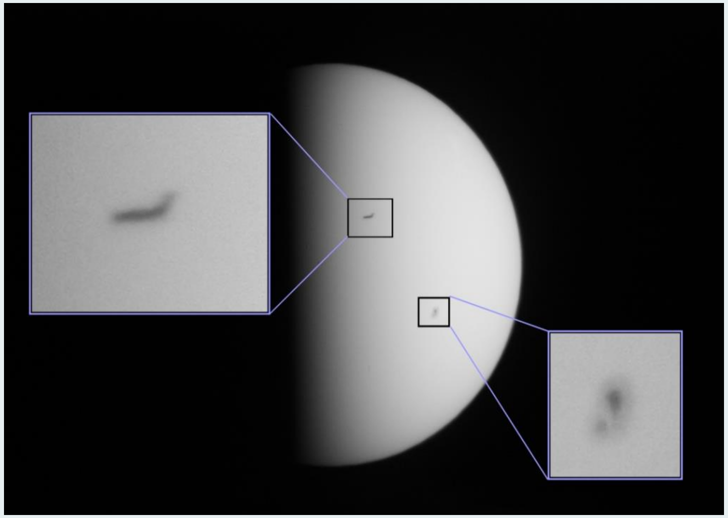
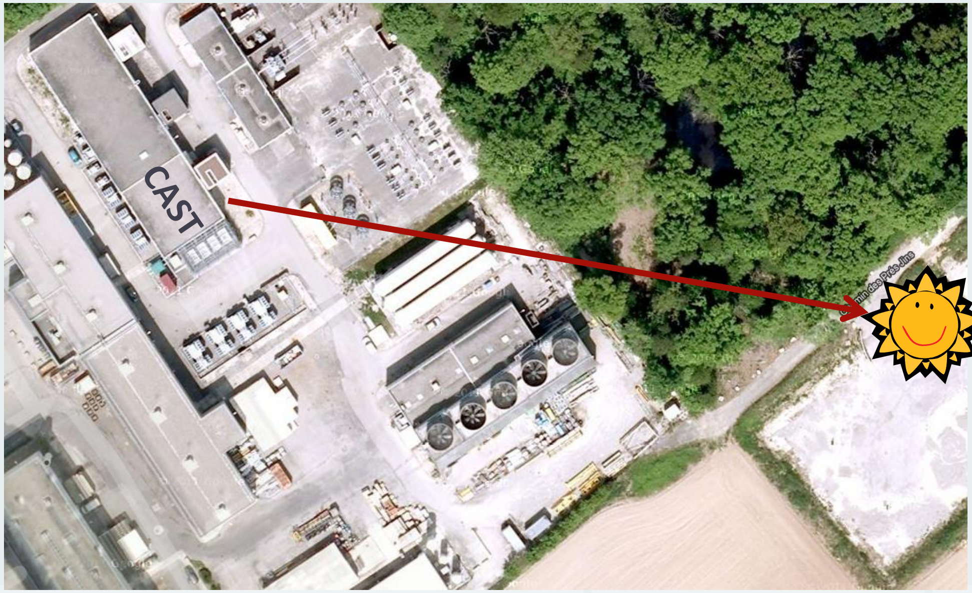
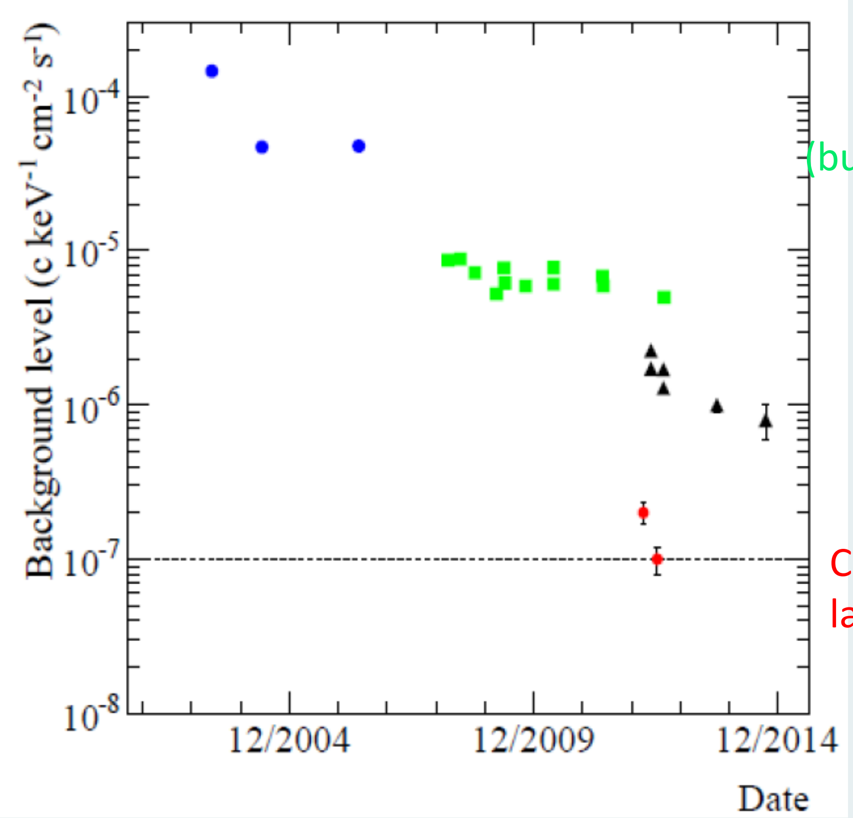




Micromegas background evolution

Unshielded Micromegas (classic technology)

Improvement of two orders of magnitude in background over the years



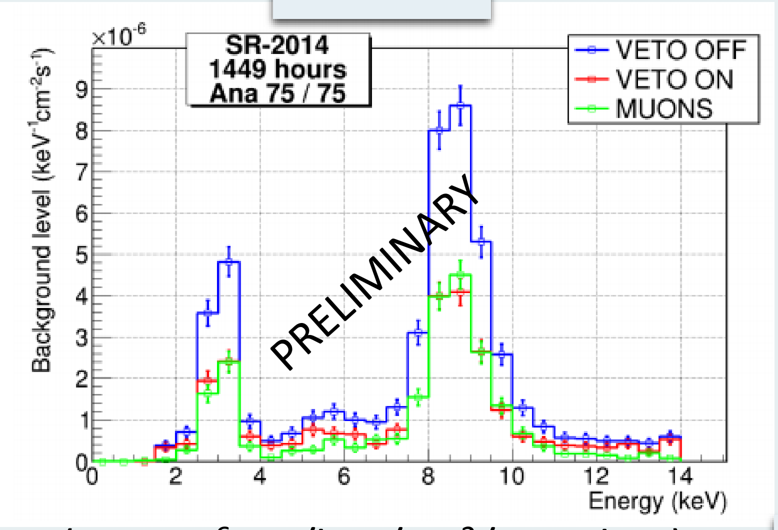
Shielded Micromegas (bulk and microbulk technology)

Shielding upgrade
Electronics upgrade

Canfranc, underground laboratory

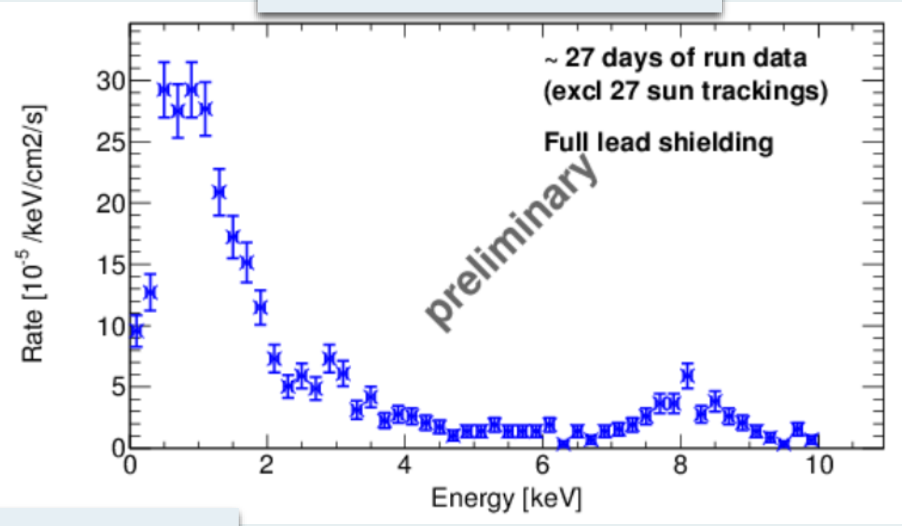
Background spectra

SR 2014

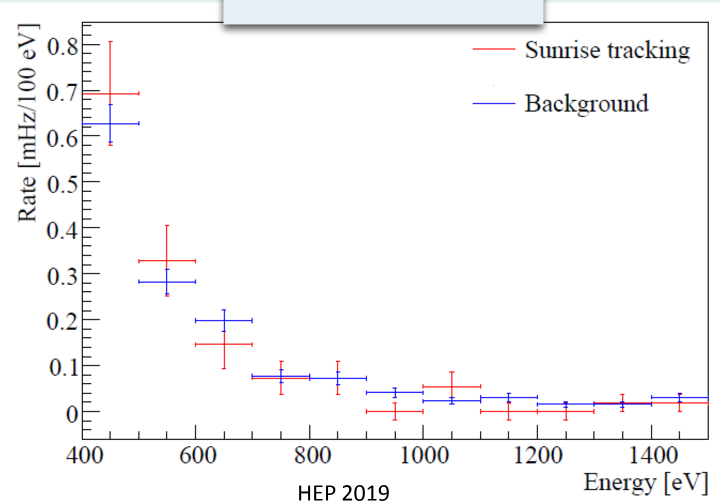


(0.8x10^{-6} cts/keV/cm^2/s 2-7 keV)

InGRID Oct/Nov 2014



SDD Nov 2013



(10^{-3} cts/keV/cm^2/s
or 1.4 mHz
from 400-1500 eV)

Fabrication of detectors

Bulk Micromegas

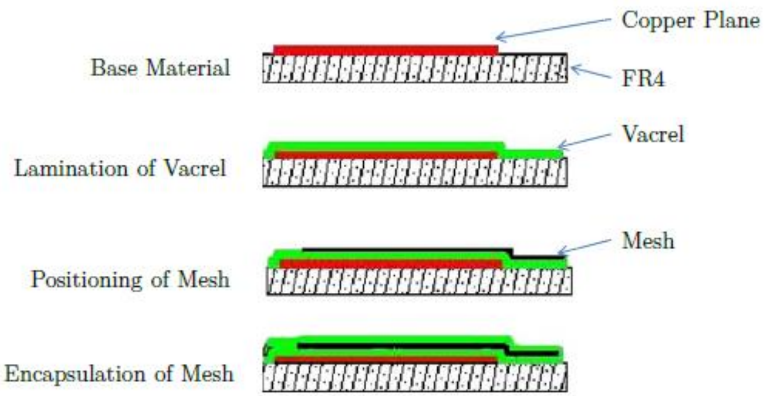
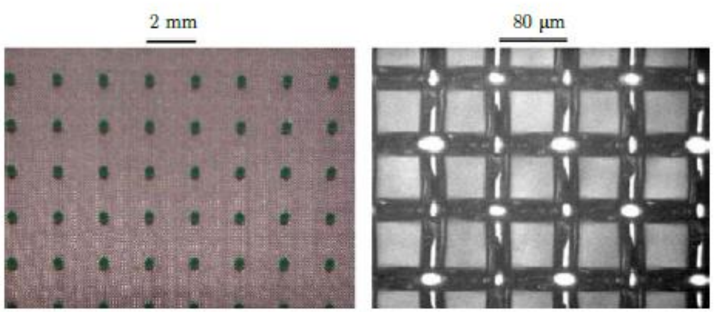
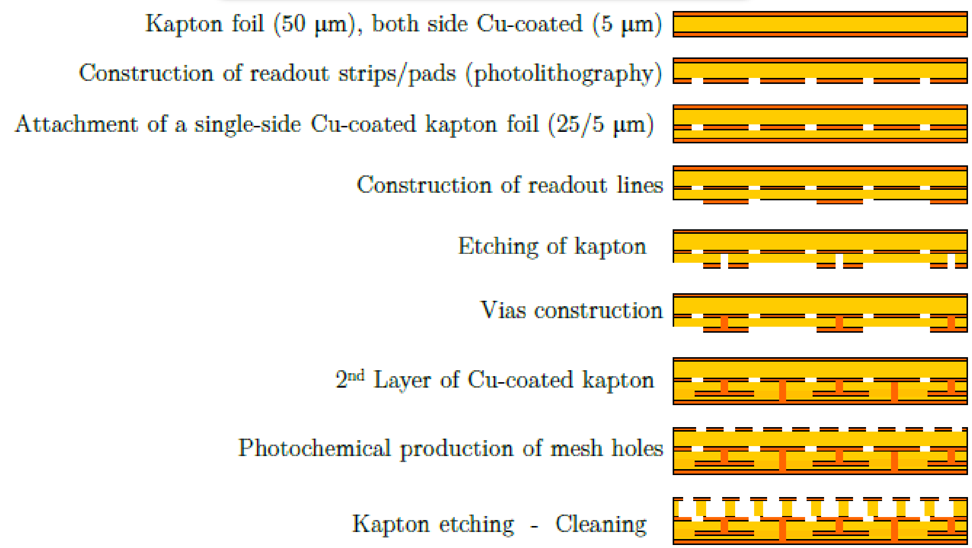


Figure 3.10 : The fabrication process of a bulk Micromegas detector.



Microbulk Micromegas

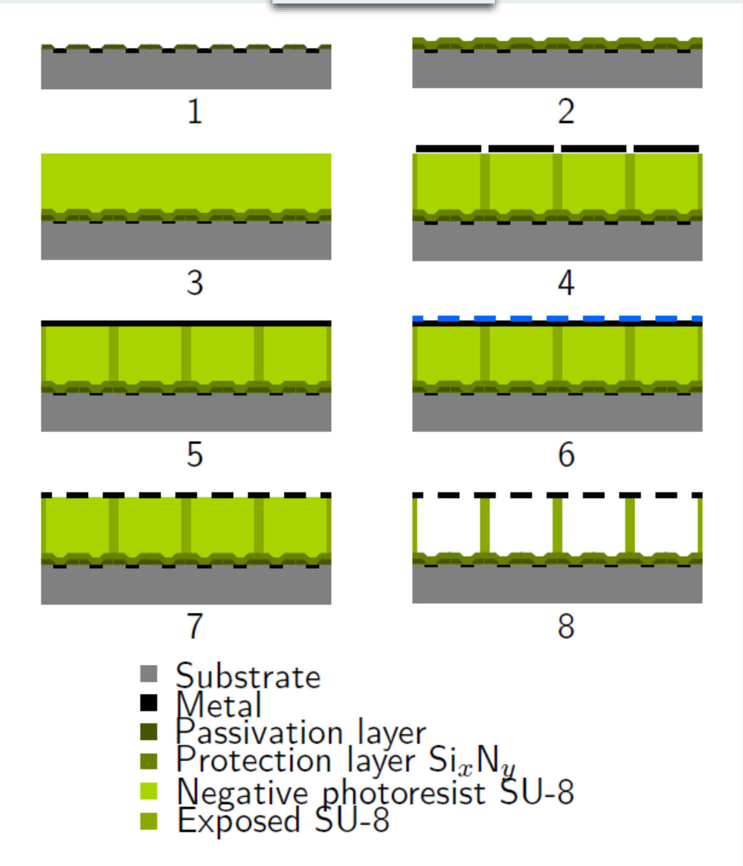


Fabrication of detectors

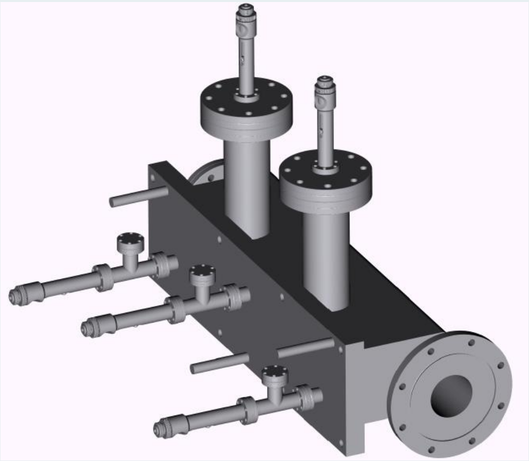
INGRID

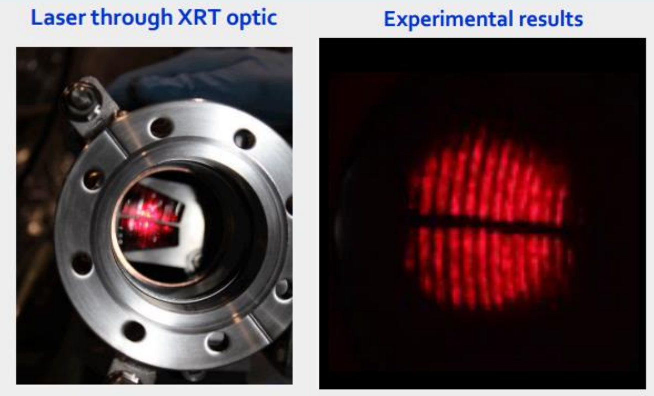
Timepix

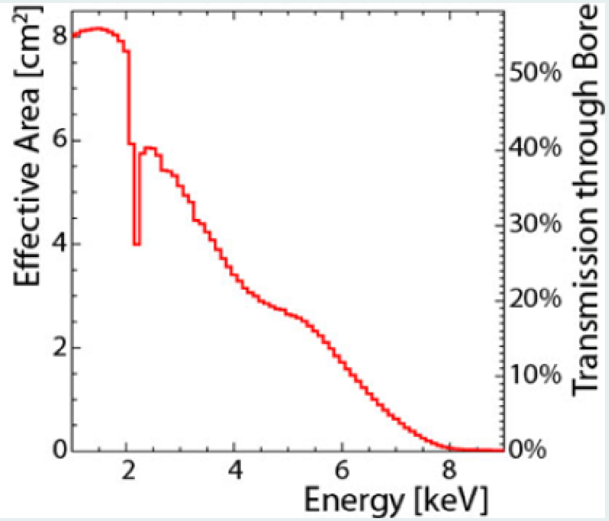
1. Starting with bare Timepix
2. Deposition of protection layer (4 or 8 µm Si_xN_y)
3. Deposition of negative photoresist SU-8 (50 µm)
4. Exposure of SU-8
5. Sputtering aluminium (1 µm)
6. Putting mask on aluminium layer (photoresist)
7. Structuring aluminium layer by etching the holes
8. Development of SU-8, cleaning of interstitials

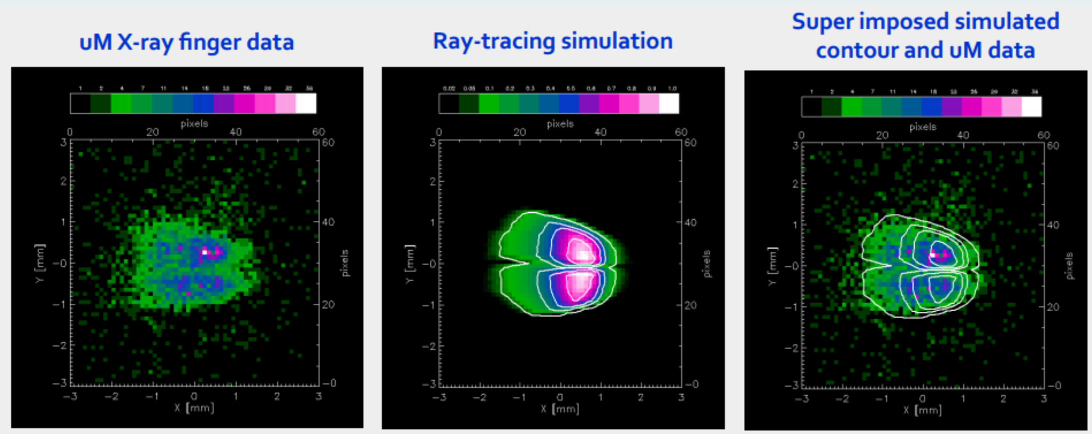


XRT – LLNL

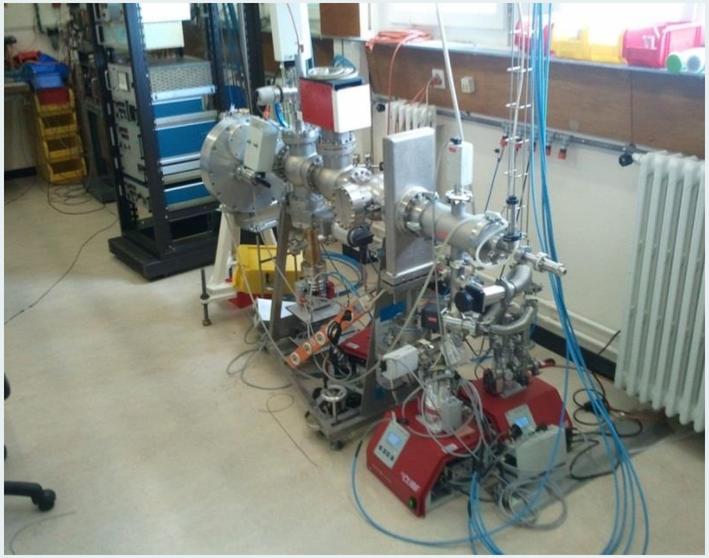



Laser through XRT optic
Experimental results

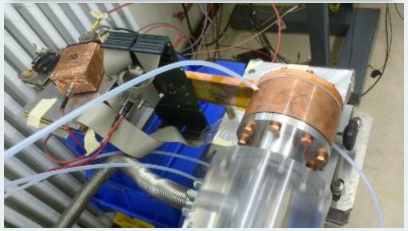

Effective Area [cm²]
Transmission through Bore
Energy [keV]
0
2
4
6
8
0%
10%
20%
30%
40%
50%


uM X-ray finger data
Ray-tracing simulation
Super imposed simulated contour and uM data

CAST Detector Lab

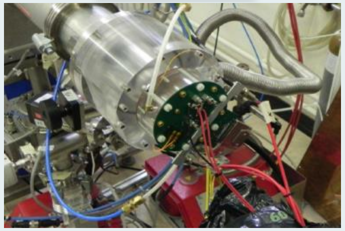


New Micromegas



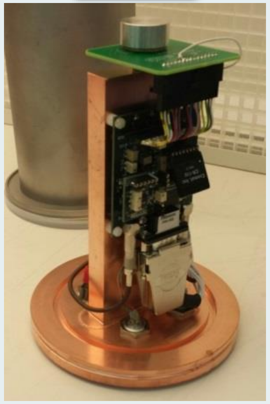
-Calibration
-Selection criteria
-Weakness in design

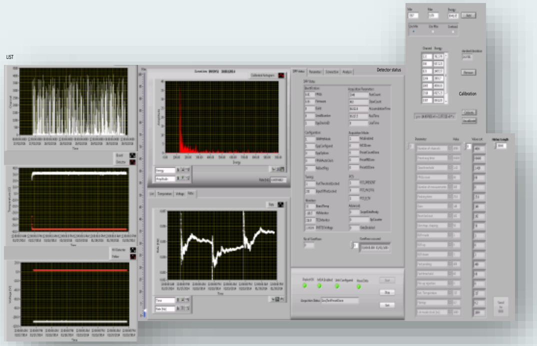
InGrid



-Vacuum interface
-Light tightness
-Definition of voltages

SDD





-DAQ Software development
-Detector performance simulation/analysis
-**New generation under study**

Backup - The trigger for axions

"I named them after a laundry detergent, since they clean up a long standing problem in theoretical physics." Wilczek

Standard Model

- Strong interactions do NOT violate CP symmetry

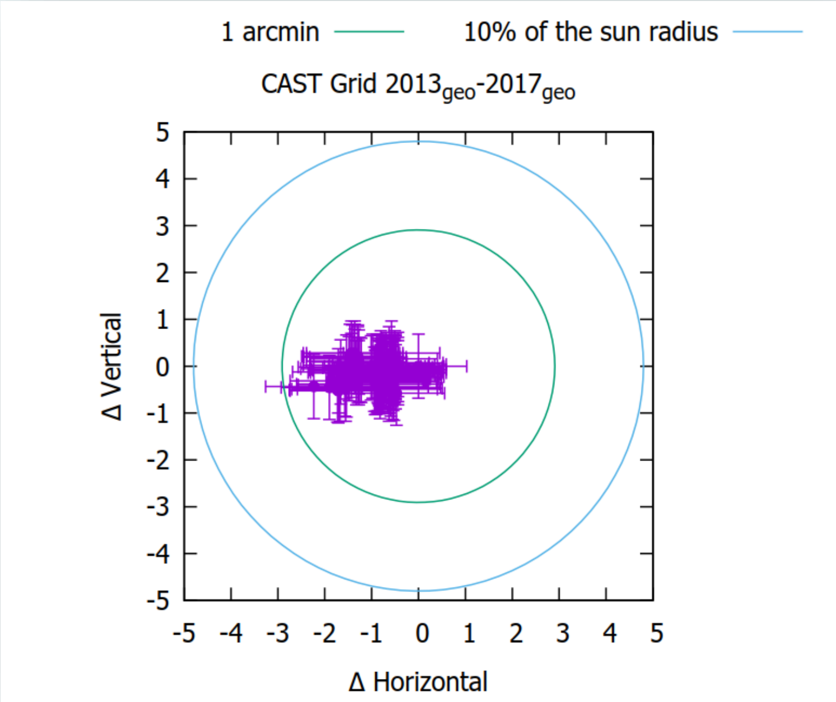
Experimental limit to neutron electric dipole moment $|d_n| \leq 2.9 \times 10^{-26}\, e \times cm$ (90% CL)

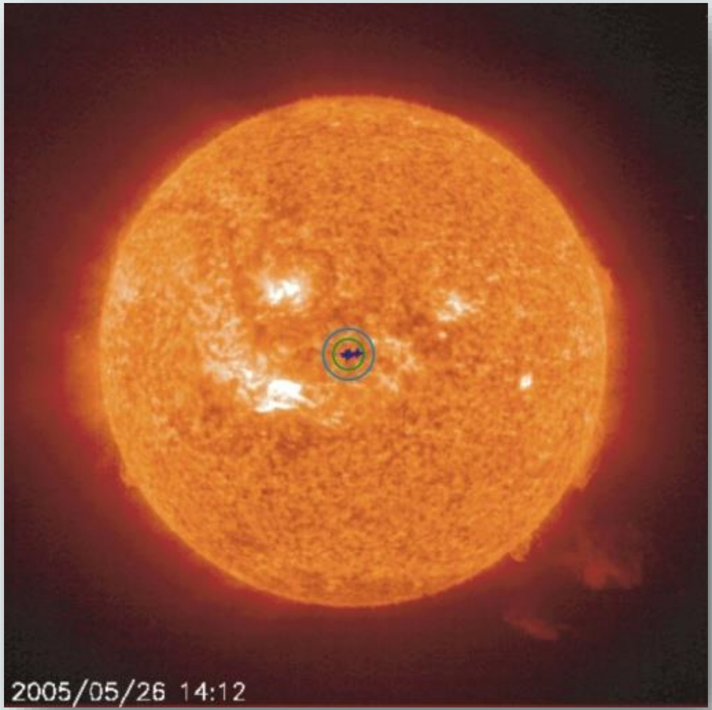
Elegant solution:

Peccei & Quinn (1977) proposed a spontaneously broken global symmetry (PQ)

AXION : pseudo Nambu-Goldstone boson of spontaneous breaking of PQ symmetry (Weinberg and Wilczek , 1978)

Controls & Operation –Pointing precision





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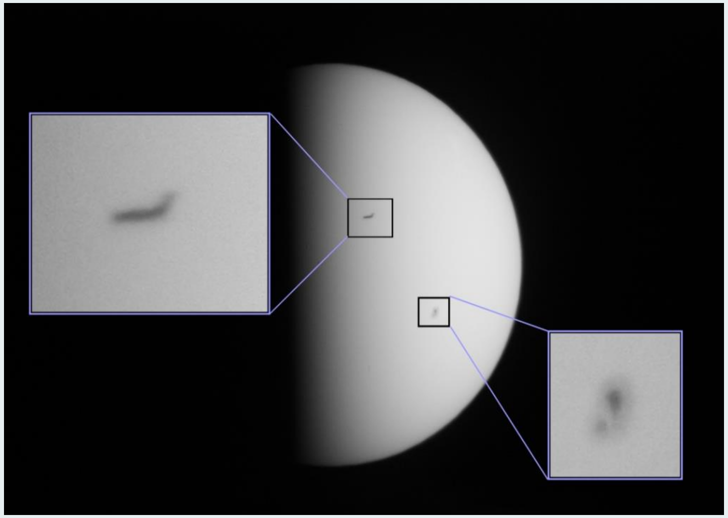
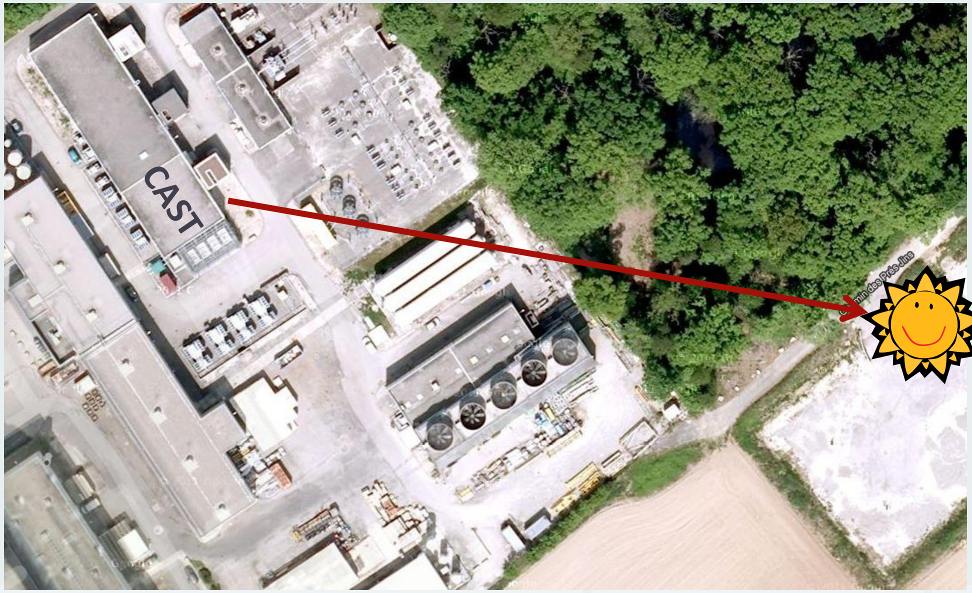


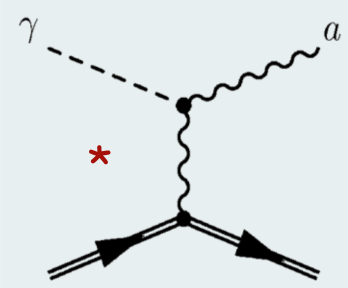


Backup - Axion properties

Axion properties

- Pseudoscalar boson
- Color and charge neutral
- Light
- Long lived
- Couples to photons
- Weakly interacting
- Dark matter candidate

Primakoff



* magnetic field
from the plasma of the center of the sun