The CAST Experiment and Future Prospects

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Universidad de Zaragoza
Red Nacional de Astropartículas, Barcelona, November of 2011

Outline

Motivation → CAST Physics

How to → CAST Experiment

Latest results

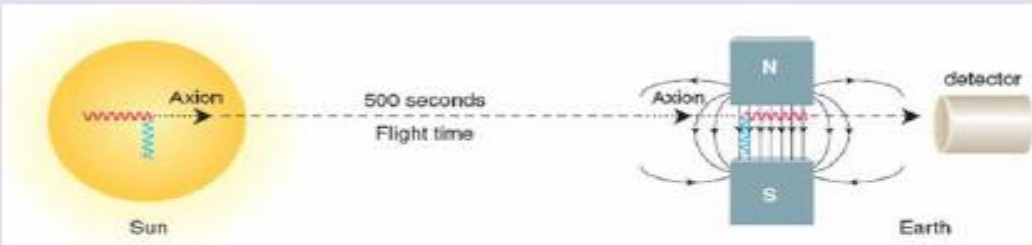
Short-term prospects

Long term prospects → NGAH

Conclusions

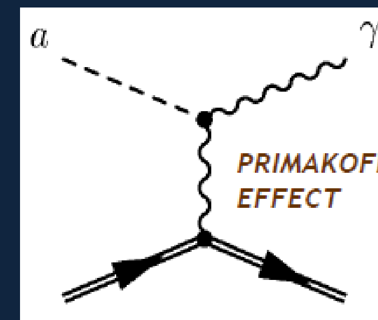
CAST PHYSICS

CERN Solar Axion Telescope
Looking for QCD Axions or Axions Like Particles (ALPs)



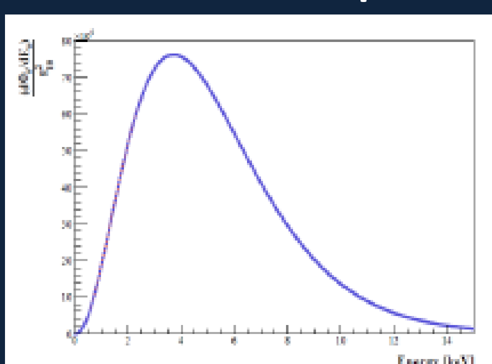
Production in the Sun
Conversion of thermal photons into axions via Primakoff effect in the solar plasma

Detection @ CAST
Conversion of axions into photons via the Inverse Primakoff in a strong magnetic field



Axions are dark matter candidates

Differential solar spectra



Expected counts

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

Conversion probability

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

CAST PHYSICS

Axion-photon conversion probability:

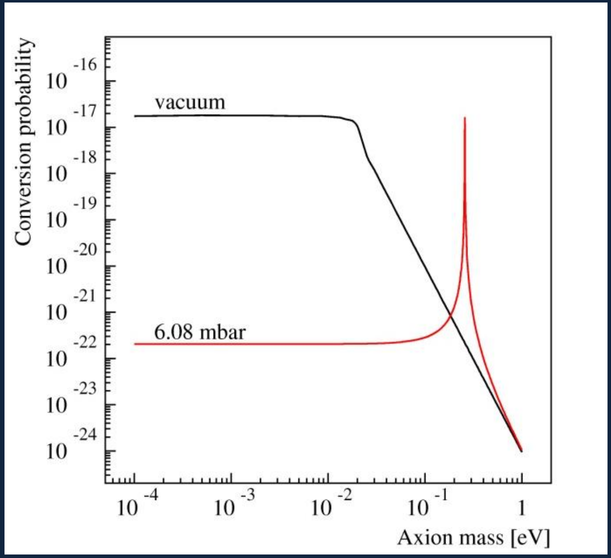
$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right]$$

L = magnet length Γ = absorption coefficient

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

Vacuum
Γ=0,m_γ=0

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



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

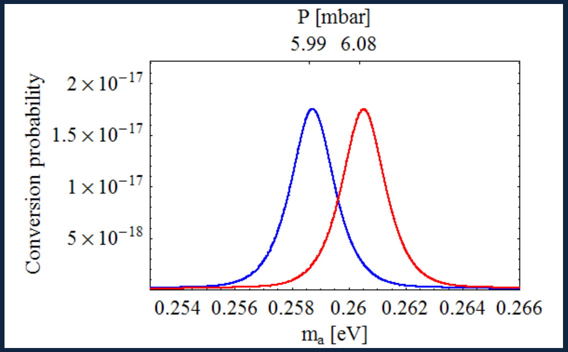
With the presence of a buffer gas it can be restored for a narrow mass range:

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

where

$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9\sqrt{\frac{Z}{A}\rho} \quad eV$$

Two gas injections



CAST EXPERIMENT

LHC prototype dipole magnet.

Magnetic field: **B=9 T**

Length: **L=9.26 m**

Rotating platform and rails

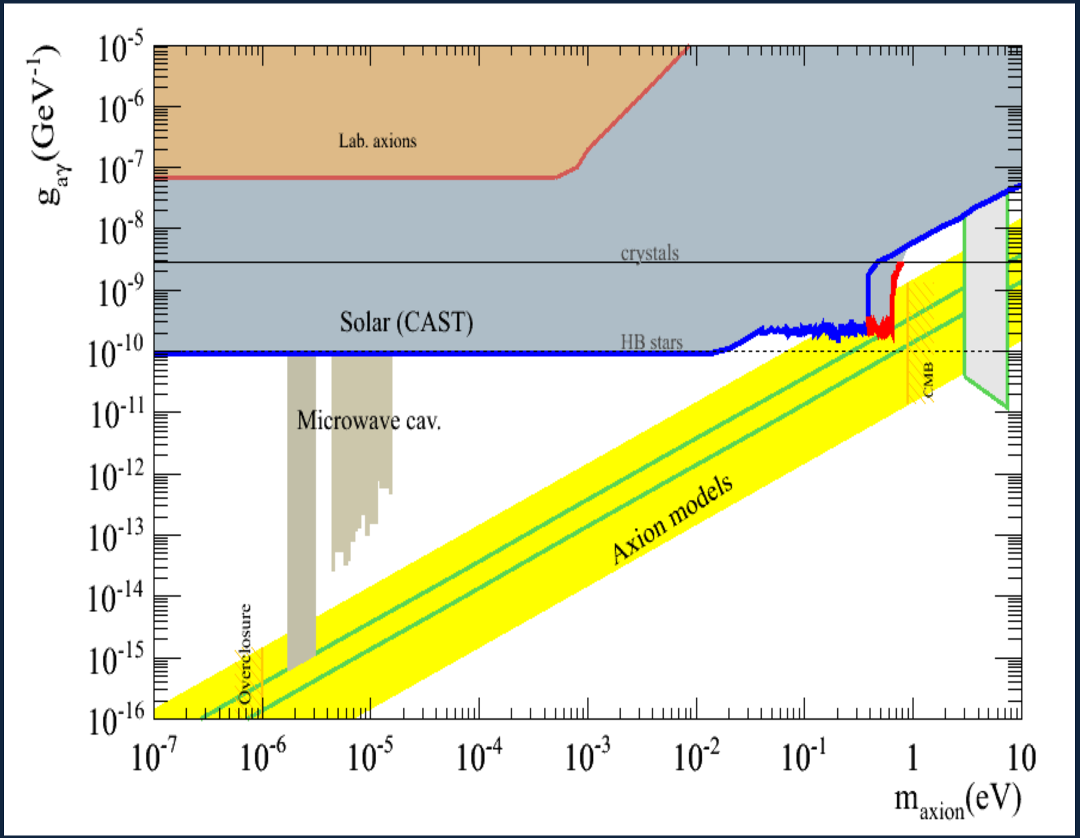
(Vertical: ±8º, Horizontal: ±40º)

2x90 min solar tracking/day

Originalities of CAST:

Use of X-ray telescope → Increase signal/background
Low background techniques → shielding, low radioactive material, …

CAST EXPERIMENT



CAST phase I (vacuum)

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

CAST phase II (buffer gas)

^{4}He completed (2005-2006)
0.02<ma<0.39 eV
JCAP02(2009)008

^{3}He completed (2007-2011)
0.39<ma<1.18 eV
Accepted in PRL, Preprint: 1106.39119

Parallel searches:

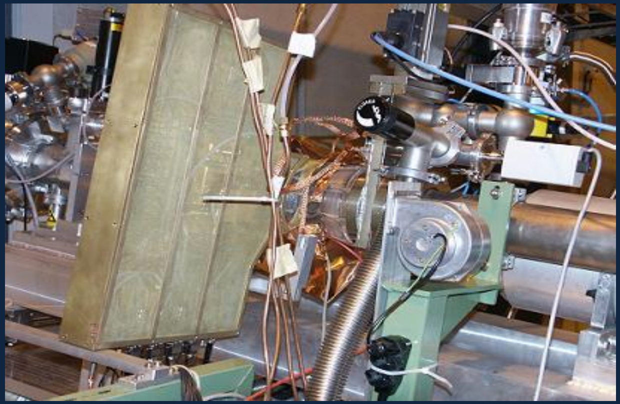
High Energy Axions: **Data taking with a HE calorimeter** JCAP 1003:032,2010
14.4 keV Axions: **TPC data (before 2006)** JCAP 0912:002,2009
Low Energy (visible) Axions: **Data taking with a PMT/APD** arXiv:0809.4581

CAST EXPERIMENT

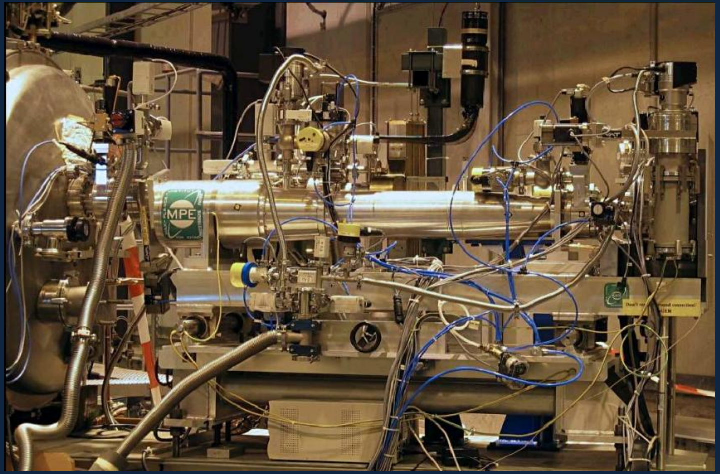
CAST detectors, Phase I and Phase II-^{4}He

Sunrise detectors

unshielded MICROMEGAS



X-Ray telescope + CCD



Sunset detectors

TPC

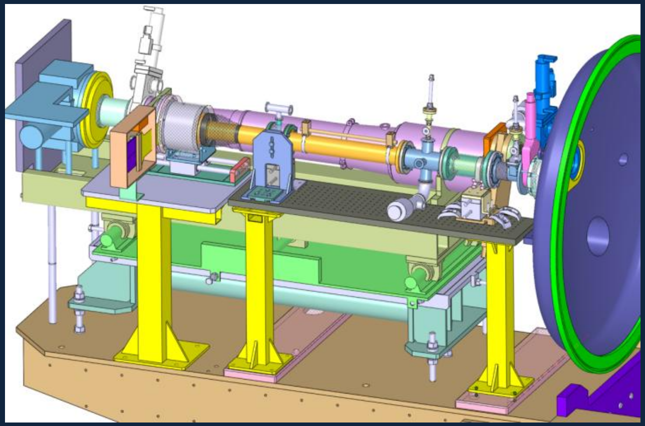
Detector	Typical rate
TPC	85 c/h (2-12 keV)
Micromegas	25 c/h (2-10 keV)
CCD	0.18 c/h (1-7 keV)

CAST EXPERIMENT

CAST detectors, Phase II-^{3}He

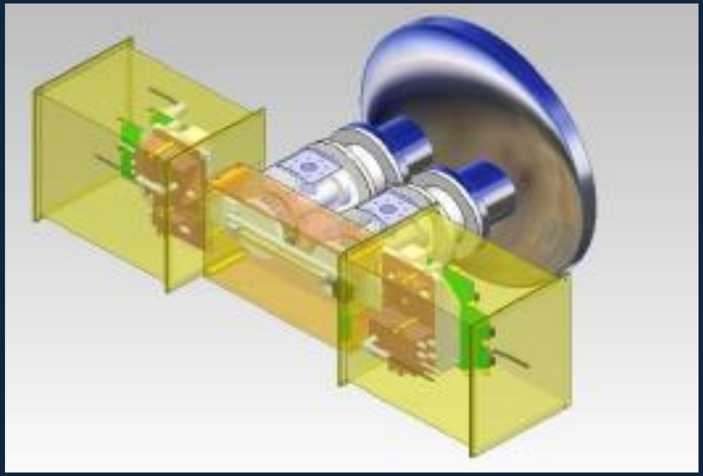
Sunrise detectors

New generation MICROMEGAS



Sunset detectors

2 new MICROMEGAS



New Micromegas technology (microbulk) with low radioactive materials.

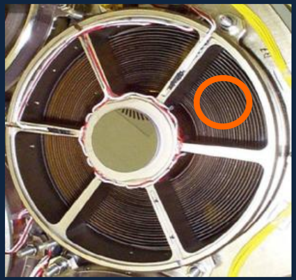
Adding shielding to Micromegas detectors

Background decrease a factor ~7

Detector	Typical rate
Micromegas	3 c/h (2-10 keV)
CCD	0.18 c/h (1-7 keV)

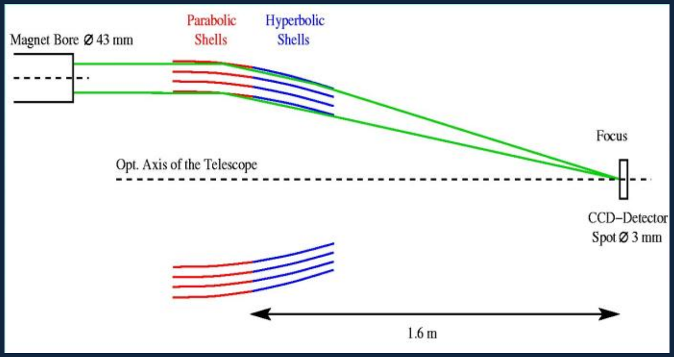
CAST EXPERIMENT

X-ray telescope + CCD system



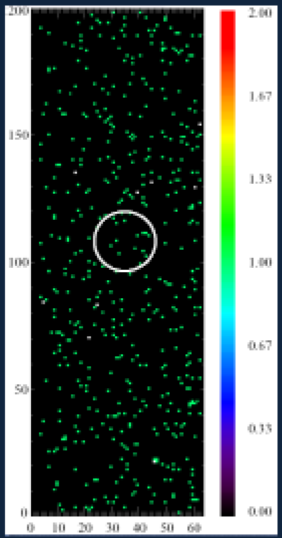
X-ray focusing device

Wolter-I-type telescope (Prototype of ABRIXAS mission)
27 nested, gold-coated mirror shells
Only one sector of telescope illuminated at CAST



CCD detector

pn-CCD (Prototype of XMM-Newton mission)
Very good spatial and energy resolution
Simultaneous measurement of signal and background
Spot position well determined
Full sensitivity of telescope exploited
Low Energy threshold (no window)



S/B improvement of ~150!

Mean background rate (1-7keV) ~ $8x10^{-5}$cts $keV^{-1}cm^{-2}s^{-1}$

CAST EXPERIMENT

Microbulk MICROMEGAS

Low intrinsic radioactivity

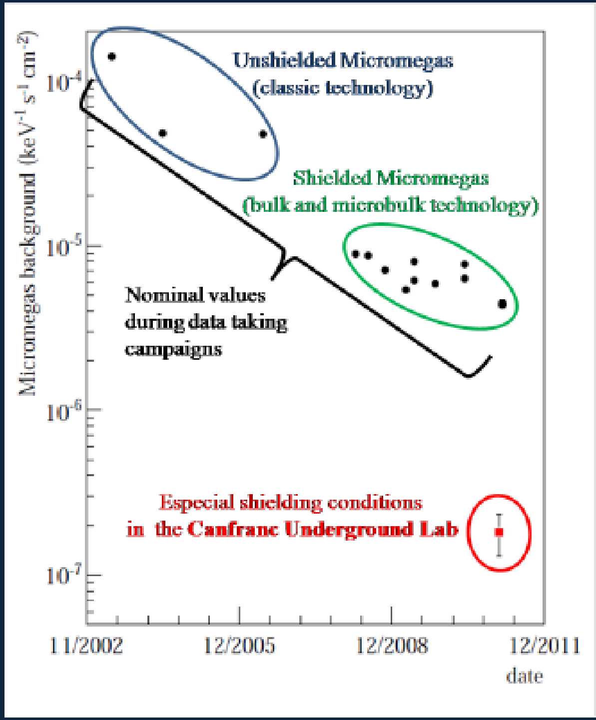
Light mass, clean materials

Signal topology, offline analysis

2D readout pattern, Time information

Shielding

Archeological lead, inner Cu, N_2 flushing.



Typical new rate: <2 c/h

Test at LSC (Canfranc Undergound Laboratory)

2500 m.w.e.

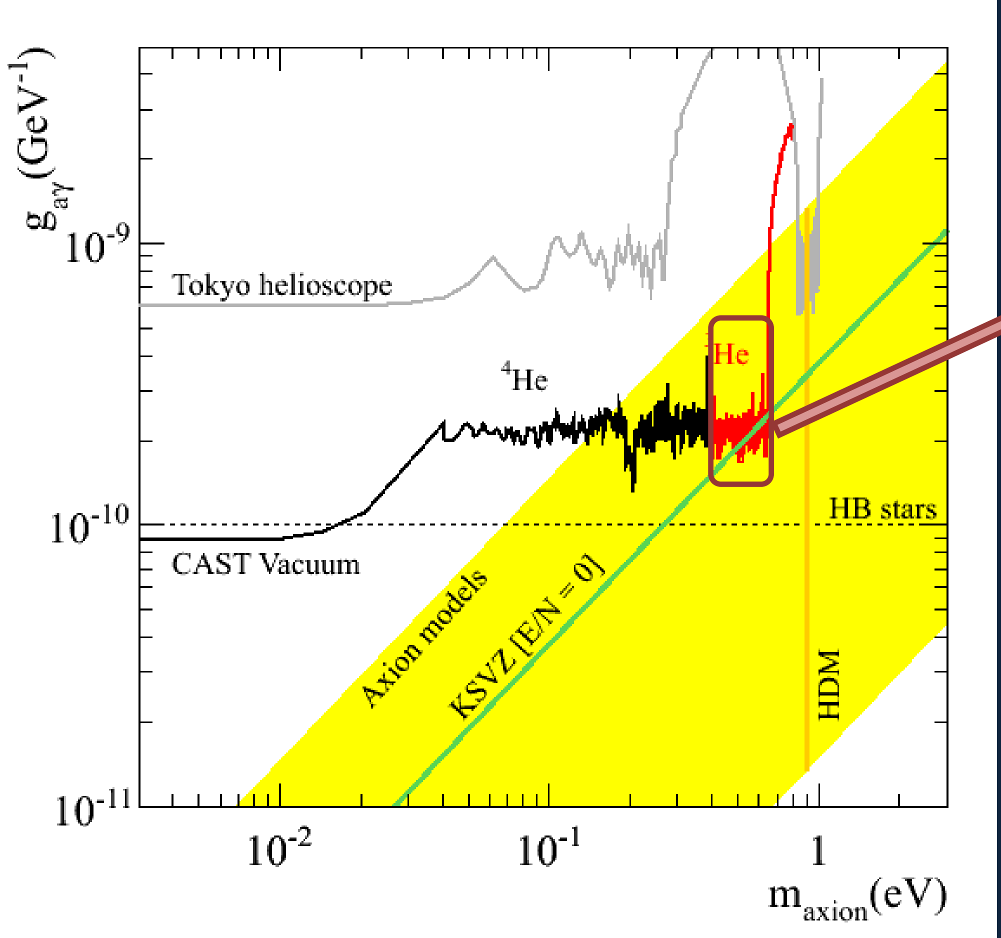
Reduction a factor 10.000 of muons flux

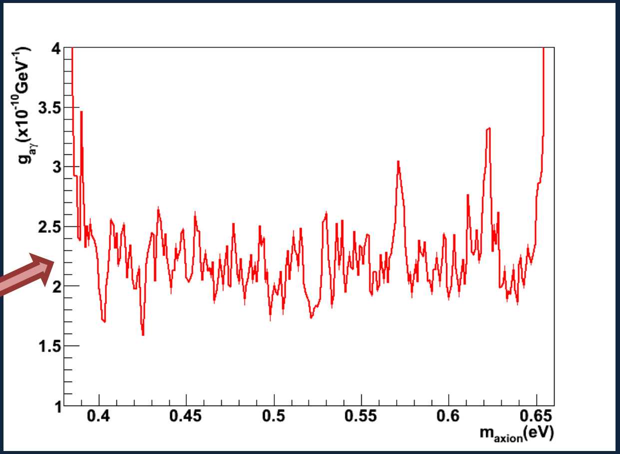
20 cm lead shielding, inner Cu, N_2 flux

Canfranc rate: <0.1 c/h

LATEST RESULTS

First ^{3}He results (2008 data taking)





Axion mass 0.39 – 0.65 eV excluded down to ~2-2.5 x 10^{-10} GeV^{-1}

Touching KSVZ benchmark models for the fisrt time

New unbinned likelihood analysis implemented.

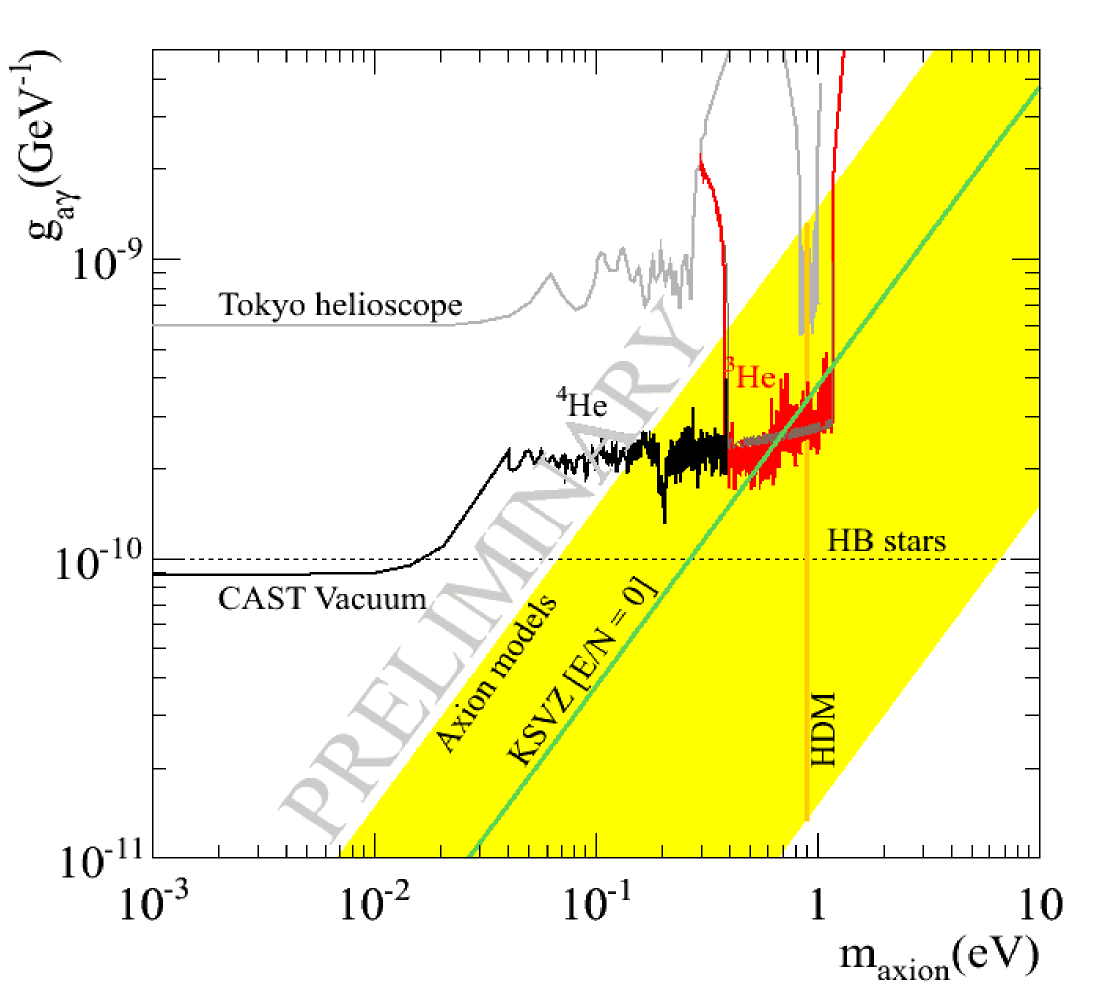
For each axion mass analysis a likelihood fit is made testing an axion positive signal

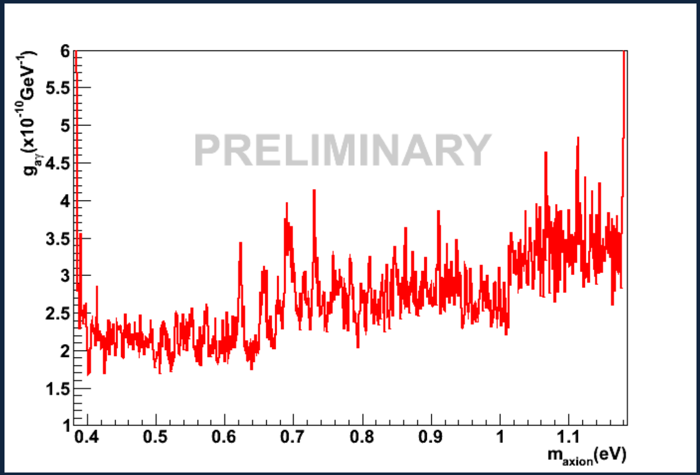
Accepted for publication in PRL

S. Aune et al. (CAST Collaboration) Preprint:1106.39119

LATEST RESULTS

Preliminary ³He results (2008-2011)





Not all detectors have been combined

Working on the analysis…

SHORT-TERM PROSPECTS

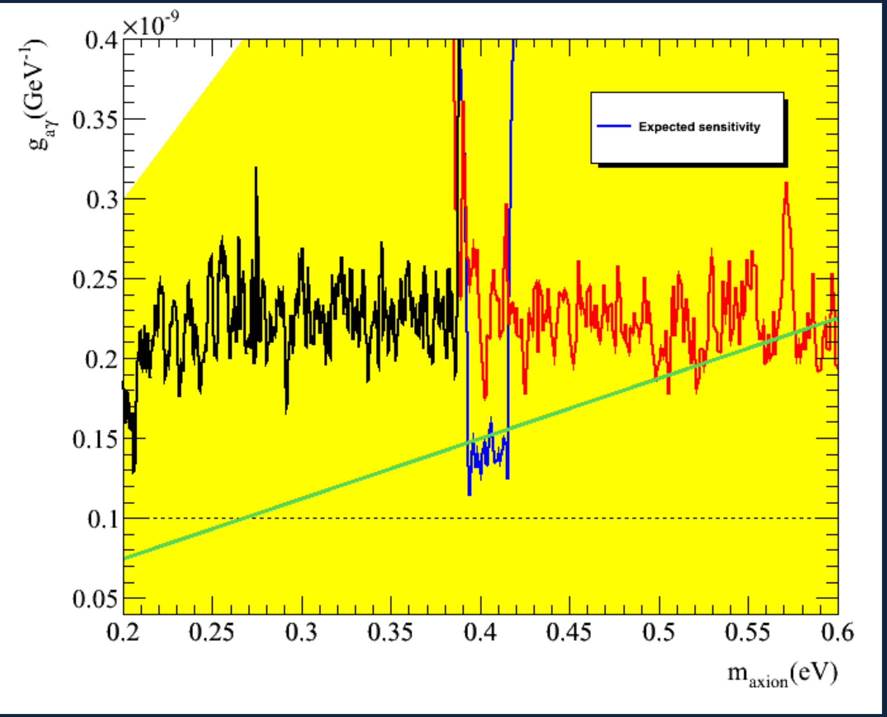
2012 prospects:

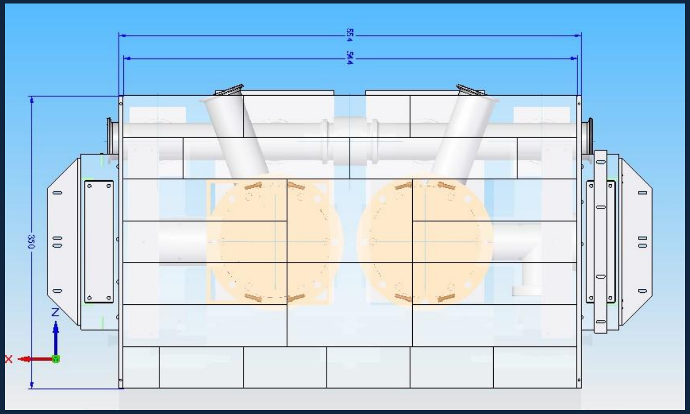
Revisit ^{4}He phase in view of the 3 high performance microbulk detectors

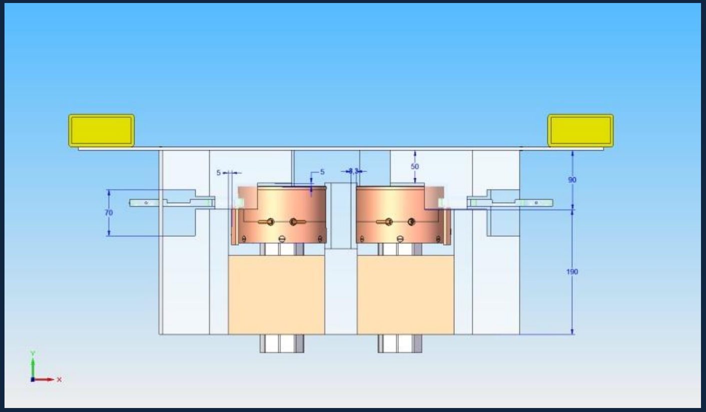
Possibility to probe the KSVZ line and below

Replacement of Sunset Micromegas detectors

Try to improve background of Sunset with a new shielding design motivated by the low background obtained at Canfranc and simulations results.







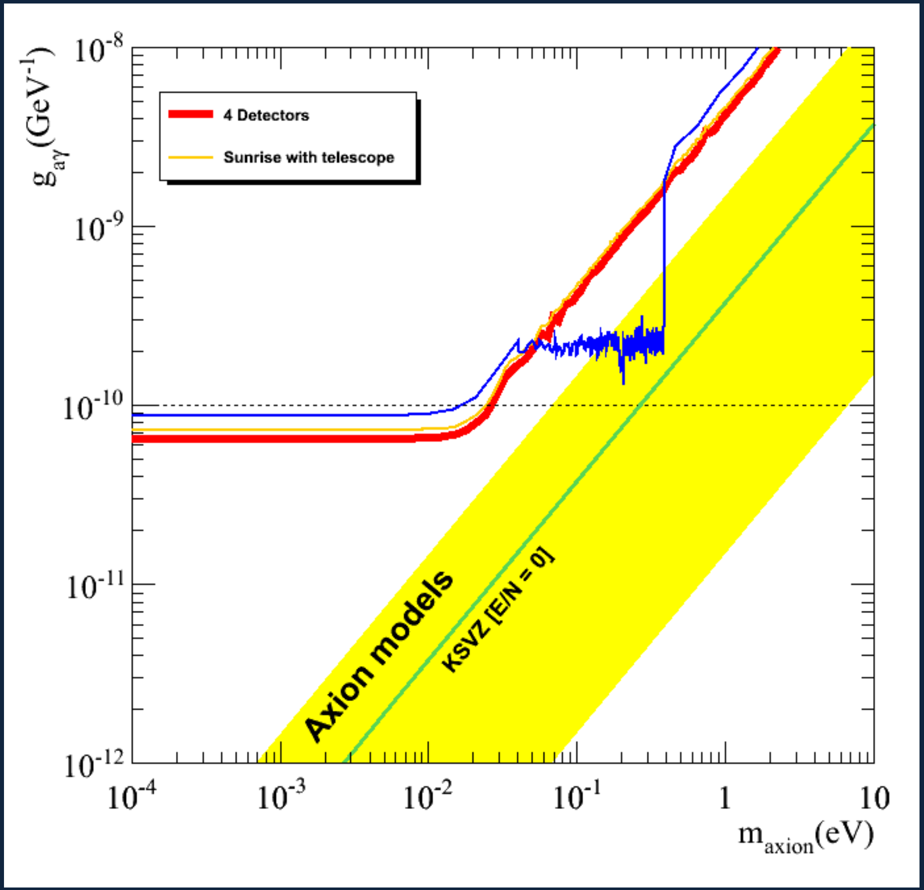
SHORT-TERM PROSPECTS

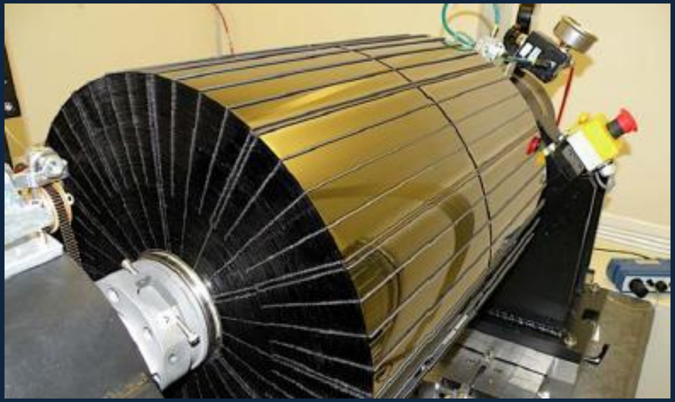
2013-2014 prospects:

Revisit vacuum phase → CAST phase I limit determined by X-Ray telescope

New optics (telescope) to be coupled to the Sunrise Micromegas detector

The new telescope and Sunrise Micromegas detector will be the most sensitive detector.





SHORT-TERM PROSPECTS

More options:

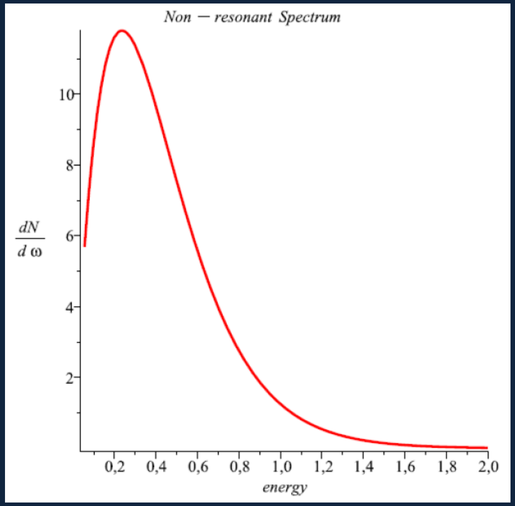
Paraphotons:

'Hidden sector' photons are thought to be massive, although very light in the sub-eV range, and able to kinetically mix with the standard photon:

oscillations between photon - hidden sector photon

Hidden photons produced in the Sun could be detected by the inverse conversion in a Helioscope like CAST

Solar Chameleons:



Chameleons are DE candidates:

could explain the acceleration of the Universe.

Created in a strong magnetic field via the Primakoff effect, e.g. in the Sun

Reconverted into x-rays inside the CAST magnet.

Spectrum peaks at much lower energies than axions.

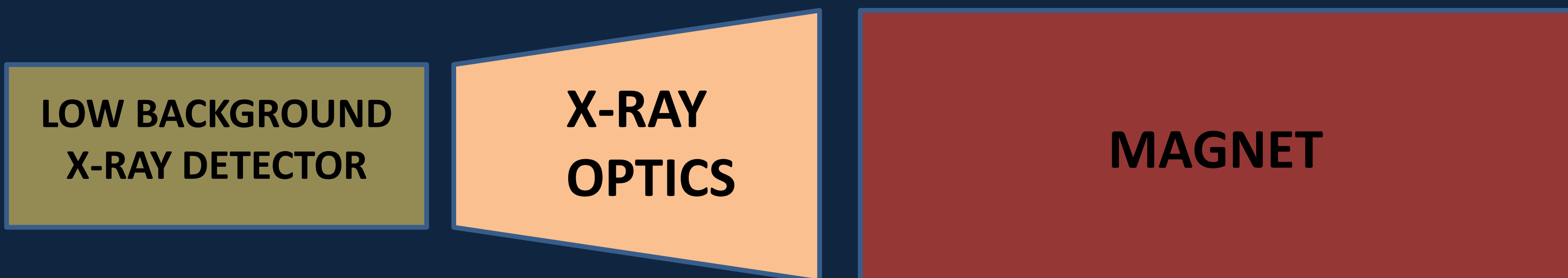
Both require detectors with low background and low Energy Threshold

LONG-TERM PROSPECTS: NGAH

Towards a New Generation Axion Helioscope:

CAST PRL2004 most cited experimental paper in axion physics
No other technique can realistically improve CAST in a wide mass range

Ingredients of CAST:



Sensitivity:

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

b = normalized background; ε = detector efficiency, a = focusing spot of the optics, ε_o = optics efficiency, B= magnetic field, L = magnet length, A = cross area and t = time exposure

LONG-TERM PROSPECTS: NGAH

Sensitivity scenarios:

Parameter	Unit	CAST-I	NGAH 1	NGAH 2	NGAH 3	NGAH 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

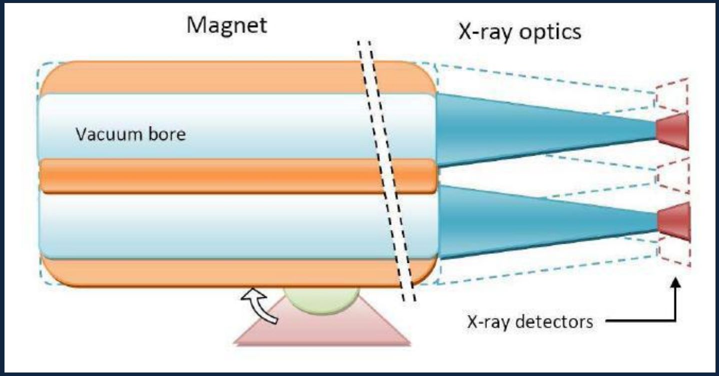
LONG-TERM PROSPECTS: NGAH

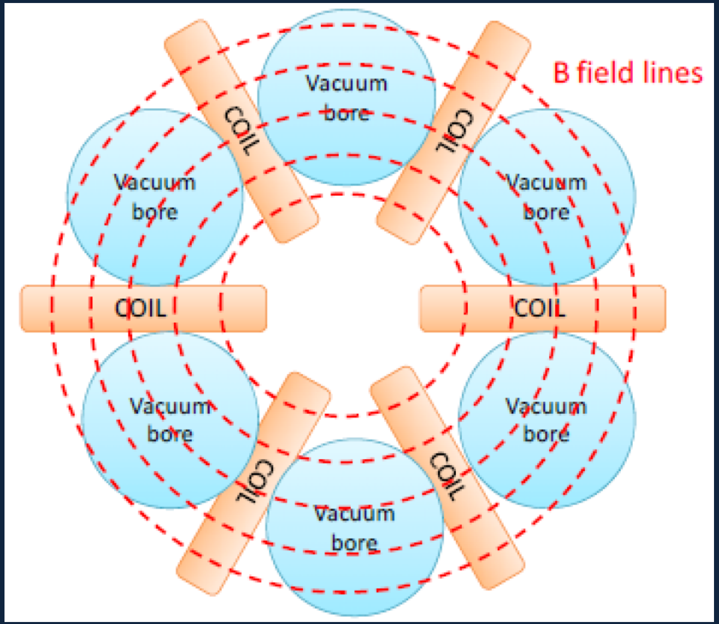
New magnet:

CAST enjoys one of the best existing magnets than one can “recycle” for axion physics (LHC test magnet)

Only way to make a step further is to built a new magnet, specially conceived for this.

Work ongoing, but best option up to know is a toroidal configuration:
– Much bigger aperture than CAST: ~1 m per bore
– Relatively Light (no iron yoke)
– Bores at room temperature (?)

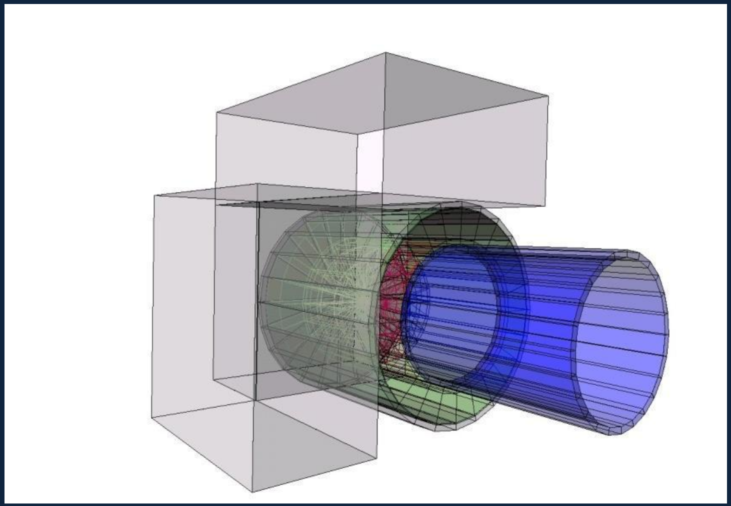




LONG-TERM PROSPECTS: NGAH

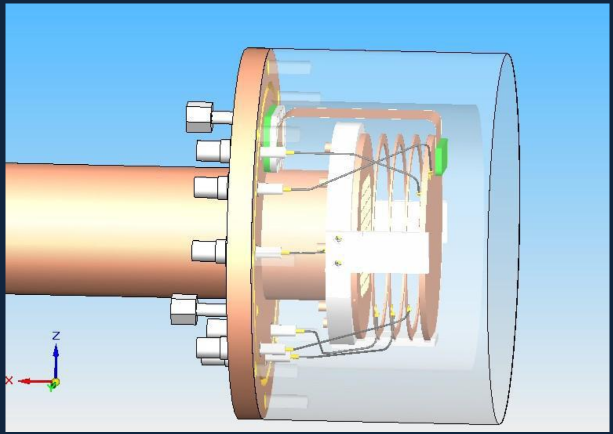
An ultralow-background Micromegas for the NGAH:

Goal: at least 10^{-7} c/keV/cm^2/s, down to 10^{-8} c/keV/cm^2/s if possible.



Work on-going:

- Experimental tests with current detectors at CERN, Saclay & Zaragoza
- Specially: underground setup at Canfranc Lab
- Simulation works to build up a background model
- Design a new detector with improvements implemented
- New T2K electronics for Micromegas detectors.



LONG-TERM PROSPECTS: NGAH

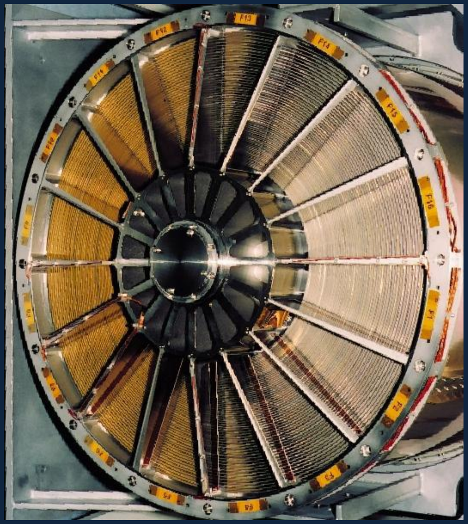
X-ray optics:

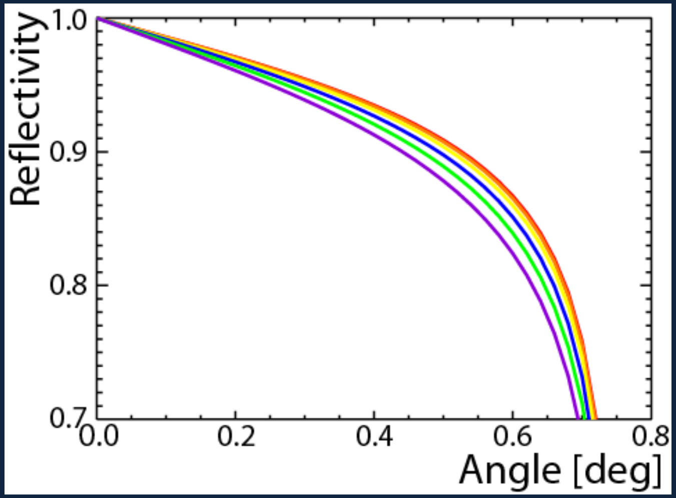
During the last four decades, the x-ray astronomy community has devoted billions of dollars to develop reflective x-ray optics

Innovations include:
–Nested designs (so called Wolter telescopes)
–Low-cost substrates
–Highly reflective coatings

Although NGAH will require fabrication of dedicated optics, it will be crucial to leverage as much infrastructure as possible to minimize cost and risks

XMM-Newton telescope





LONG-TERM PROSPECTS: NGAH

Sensitivity scenarios prospects:

Parameter	Unit	CAST-I	NGAH 1	NGAH 2	NGAH 3	NGAH 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

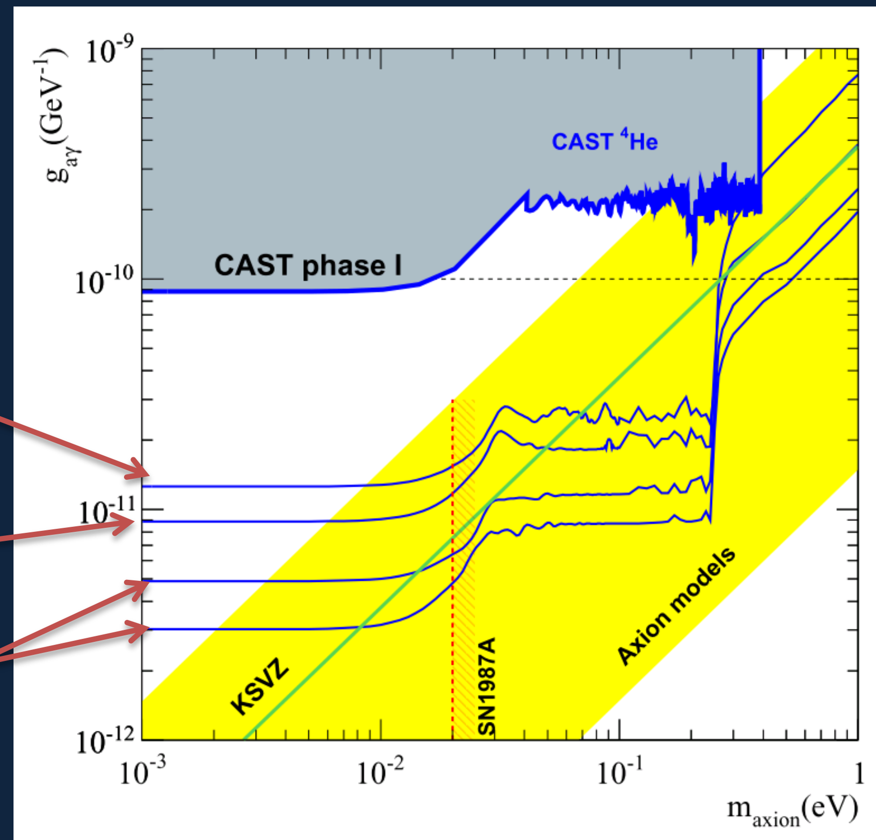
Factor 8 to 30 better in $g_{a\gamma}$
(4000 to 10^6 in signal strength!!)
JCAP06(2011)013

A big part of the QCD axion model region could be explored next decade

Pessimistic

Realistic

Optimistic



LONG-TERM PROSPECTS: NGAH

The cooling of white dwarfs:

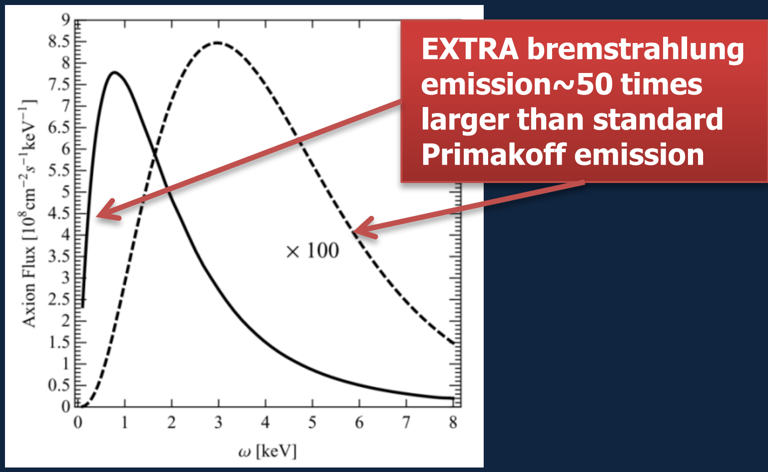
Luminosity function (WD's per unit magnitude) altered by axion cooling

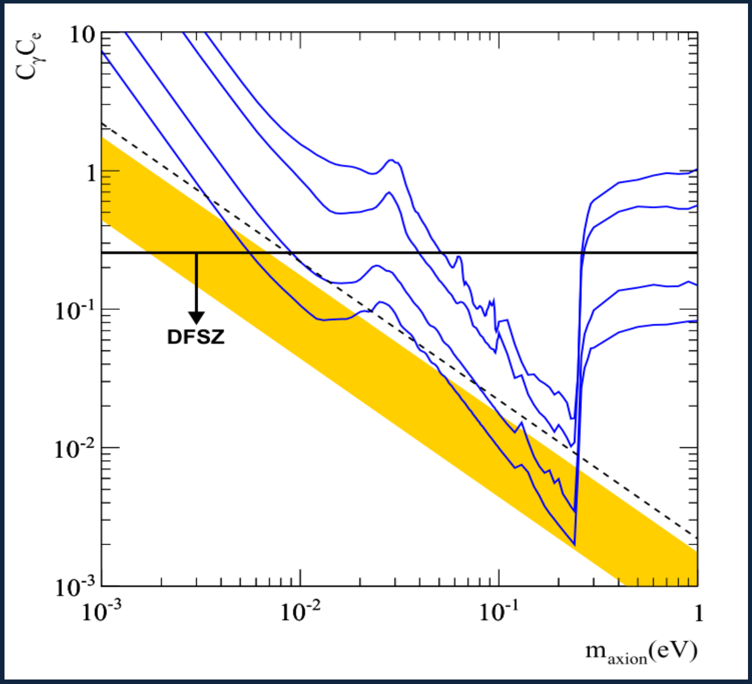
Axion-electron coupling of ~1x10^{-13}(axion masses of 2-5 meV or larger) fits data

Axion-electron coupling provides extra axion emission from the Sun…

Extra emission concentrated at lower energies(~1 keV)

Such axion could produce a detectable signal in the new axion helioscope





CONCLUSIONS

CAST past:

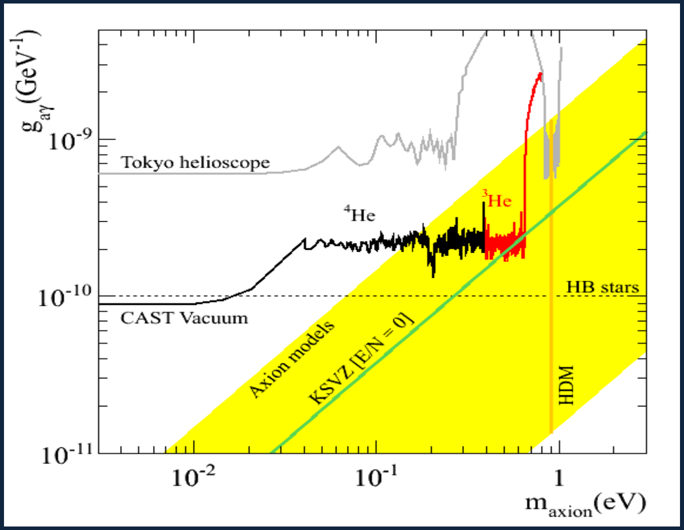
- Has put the strictest limit on axion searches for a wide m_a range

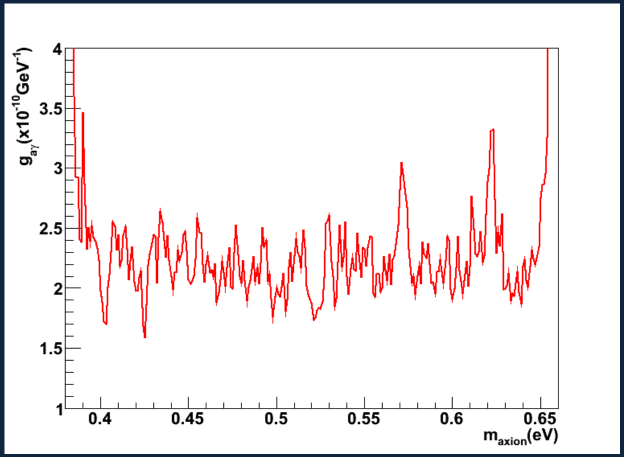
- Has scanned the region most favored by QCD models.

- Has studied by-products in parallel to the main physics: HE axions, 14.4 keV axions from nuclear transitions, LE axions(visible)

- Has gained much experience on Helioscope Axion Searches

- Is established as a reference result in axion physics.





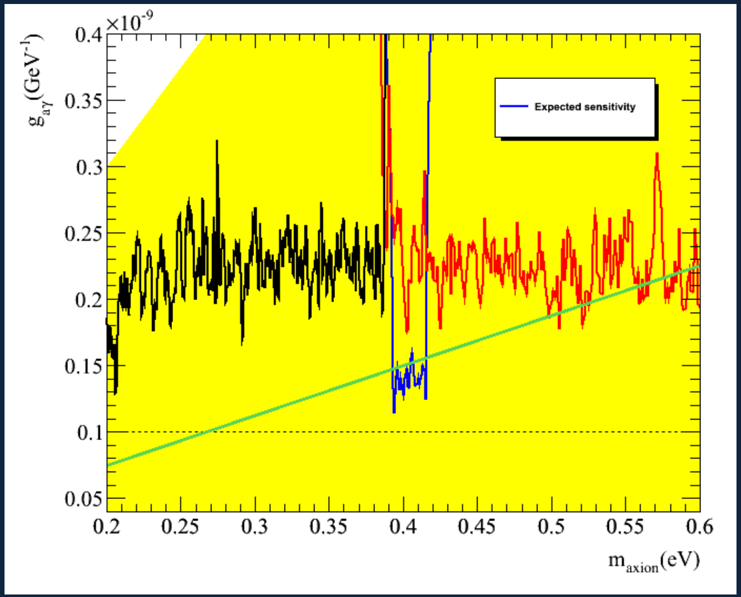
CONCLUSIONS

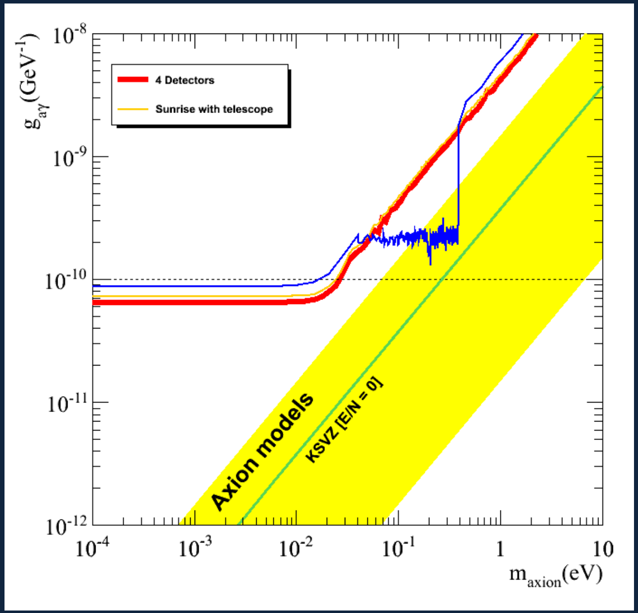
CAST present:

- Improve the ^4He and vacuum results of the experiment

- Explore the possibilities to study other exotica: paraphotons, solar chameleons and improve the LE setup.

- Working on the development of detectors that would increase the sensitivity





CONCLUSIONS

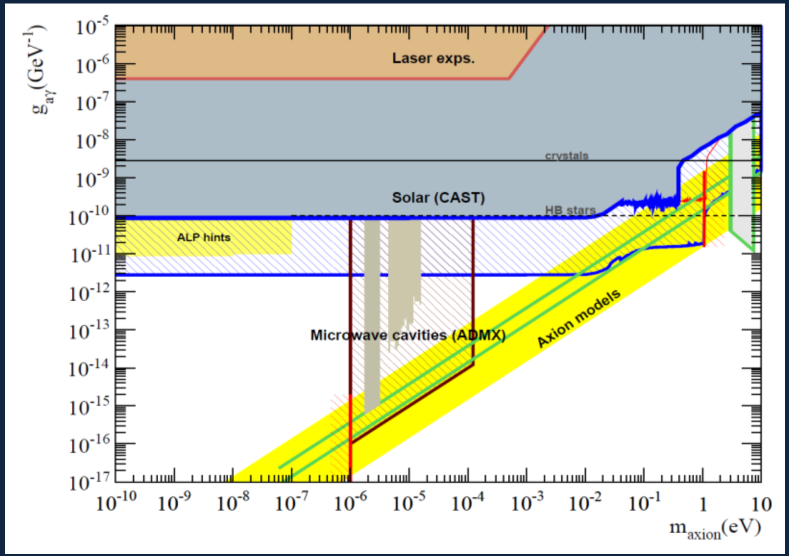
CAST future → NGAH

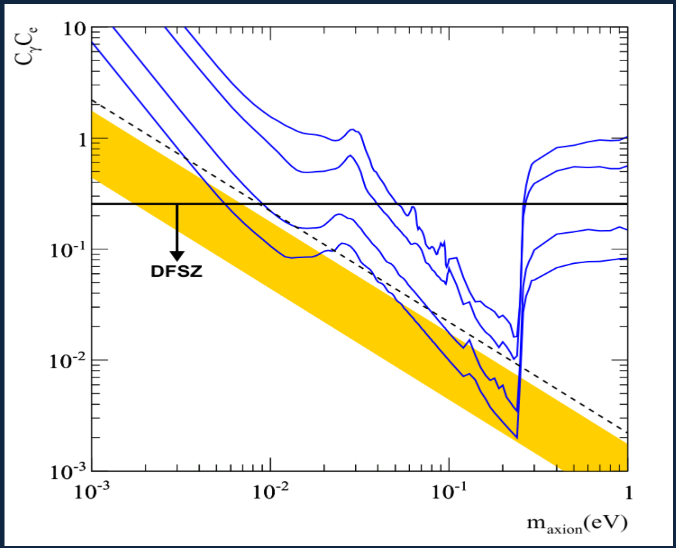
- Towards a new generation axion helioscope: feasibility study in progress.

- First results (JCAP06(2011)013) show good prospects to improve CAST 1-1.5 orders of magnitude in $g_{a\gamma}$

- In combination with dark matter axion searches (ADMX) a big part of the QCD axion model region could be explored next decade.

- White dwarfs electons-coupled axions?, ALPs?... towards an axion observatory





THANKS!!!

BACK-UP SLIDES

- Conversion probability (axion-photon coupling):

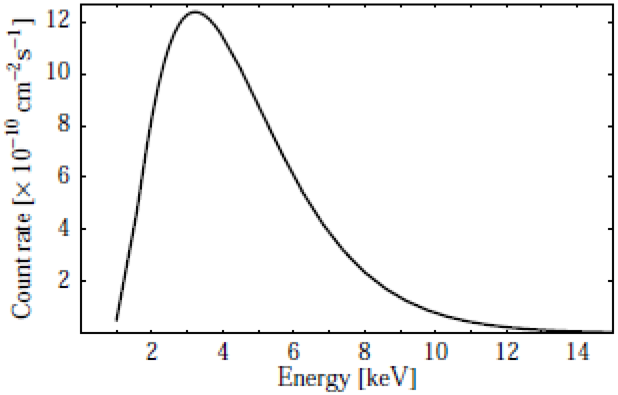
$$P_{a\to\gamma} = \left(\frac{g_{a\gamma} B}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)\right]$$

$$\downarrow \quad \Gamma \to 0$$

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma} B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

- Solar axion flux:

$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\, g_{10}^2\, E^{2.481}\, e^{-E/1.205}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$$



BACK-UP SLIDES

Unbinned likelihood method.

$$L_{m_a}(g_{a\gamma}) = \prod_k L_k(n_i = 0) \prod_k L_k(n_i = 1)$$

$$-\frac{1}{2}\chi^2_{m_a} = log\left(L_{m_a}(g_{a\gamma})\right) = \sum_{k_{n_i=1}} \left[-(\mu_{ik} + 1) + log(\mu_{ik})\right] - \sum_{k_{n_i=0}} \mu_{ik}$$

$$-\frac{1}{2}\chi^2_{m_a} = \underbrace{-g^4_{a\gamma}\int_E\int_{t_k}\frac{d^2 n_\gamma}{dE \cdot dt_k}dE \cdot dt_k}_{Zero\ counts\ detected\ contribution} + \sum_{k_{n_i}=1}\underbrace{log\int_{E_i}^{E_i+\Delta E}\left(\frac{db_{ik}}{dt_k} + g^4_{a\gamma}\frac{dn_\gamma}{dt_k \cdot dE}\right)dE}_{One\ count\ detected\ contribution}$$

BACK-UP SLIDES

Figure of merit (FOM) :

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

$$\boldsymbol{FOM} \propto \frac{(\epsilon \cdot \epsilon_o) \cdot t^{1/2}}{\left(b^{1/2} \cdot a^{1/2}\right)}$$

BACK-UP SLIDES

Axion-electron coupling

$$\mathcal{L}_{\rm int} = \frac{C_e}{2f_a}(\partial_\mu a)\,\bar{e}\gamma^\mu\gamma_5 e + \frac{C_\gamma \alpha}{8\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{ae} = \frac{C_e m_e}{f_a} \quad ; \quad g_{a\gamma} = \frac{C_\gamma \alpha}{2\pi f_a} \quad ; \quad C_\gamma = \frac{E}{N} - 1.9 \qquad C_e = \frac{1}{3}\cos^2\beta$$

$$\left.\frac{dn}{dA\,dt\,d\omega}\right|_{\rm Compton} = \left(\frac{C_e}{f_9}\right)^2 3.509\times 10^8\, w^{2.987}\, e^{-0.776w}$$

$$\left.\frac{dn}{dA\,dt\,d\omega}\right|_{\rm Brems} = \left(\frac{C_e}{f_9}\right)^2 6.857\times 10^{10}\,\frac{w}{1+0.667\,w^{1.278}}\, e^{-0.77w}$$