Towards a new generation axion helioscope

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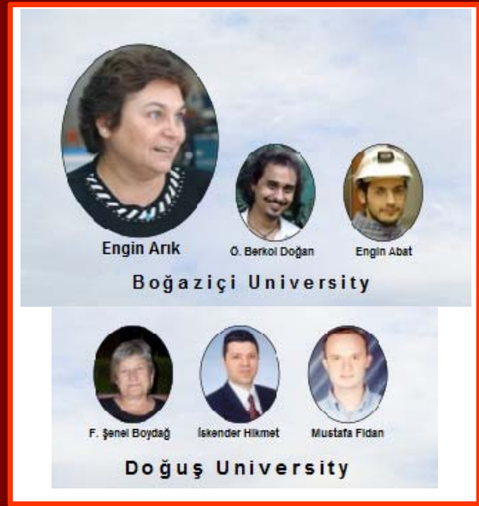

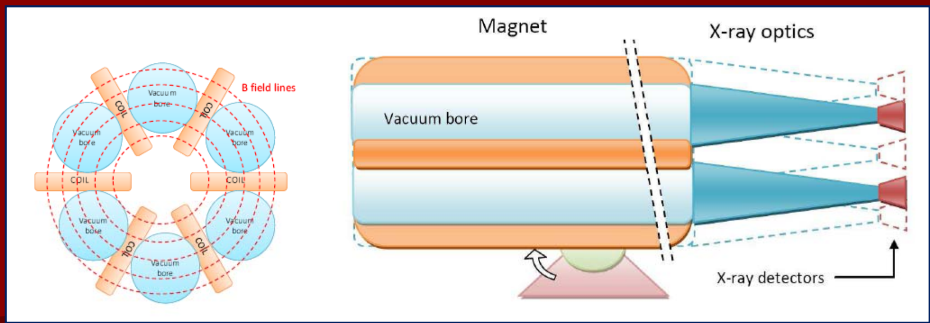

Outline

- Talk based on

  JCAP 06 (2011) 013

- Outline:
  - Axions: motivation, theory, cosmology.
  - Solar axions &

    the axion helioscope concept
  - Previous helioscopes & CAST
  - Technical prospects for a new helioscope
  - Sensitivity prospects
  - Conclusions

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Towards a new generation axion helioscope

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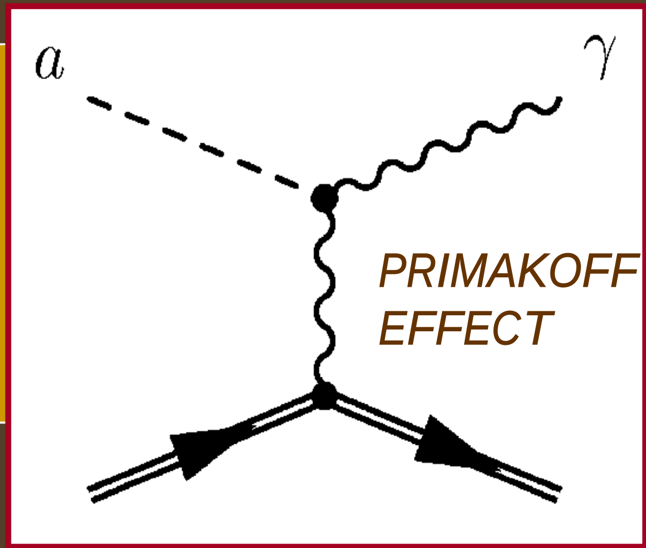
AXION motivation

- **Strong CP problem:** why strong interactions seem not to violate CP?
  - CP violating term in QCD is not forbidden. But neutron electric dipole moment not observed.
- Natural answer if Peccei-Quinn mechanism exist.
  - New U(1) global symmetry → spontaneously broken.

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

- As a result, new pseudoscalar, neutral and very light particle is predicted, **the axion.**
- It couples to the photon in every model.



AXION motivation: Cosmology

- **Axions are produced** in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

  → NON-RELATIVISTIC (COLD) AXIONS

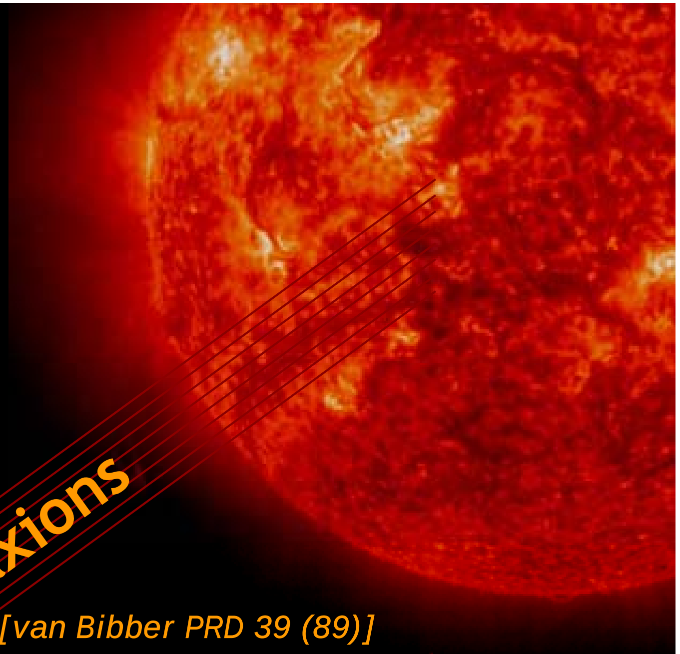
  - In general, Range of axion masses of **10^{-6} – 10^{-3} eV** are of interest for the axion to be the (main component of the) CDM.

  - Thermal production → RELATIVISTIC (HOT) AXIONS

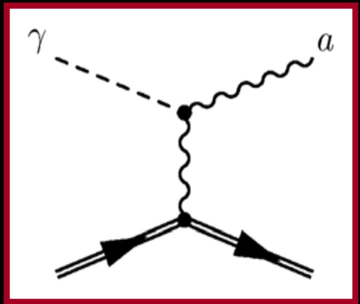
- In order to have substantial relativistic axion density, the axion mass must be close to 1 eV. (**ma >1.02 eV** gives densities too much in excess to be compatible with latest CMB data)

Hannestad et al, JCAP 0804 (2008) 019 [0803.1585 (astro-ph)]

Solar Axions



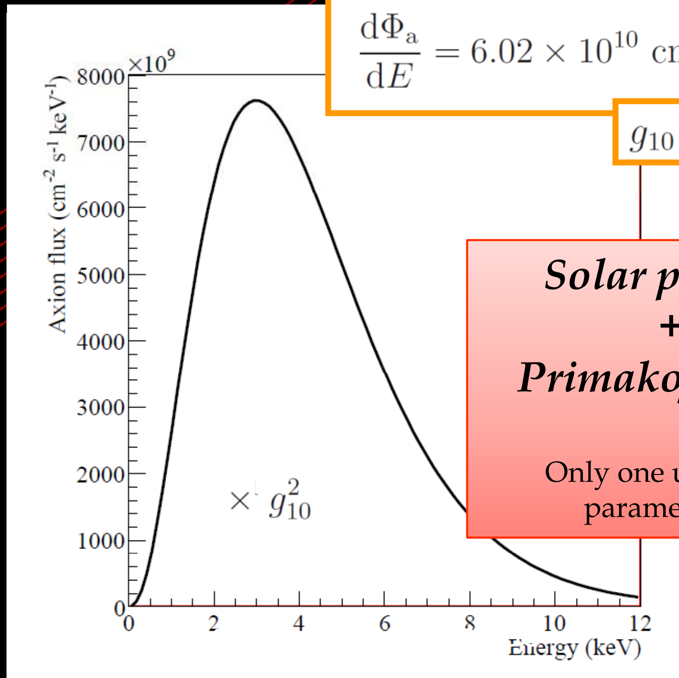
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



- ➢ *Solar axion flux* *[van Bibber PRD 39 (89)]* *[CAST JCAP 04(2007)010]*

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

$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV}^{-1}$$



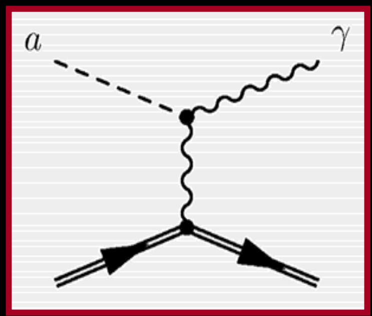
Solar physics
+
Primakoff effect

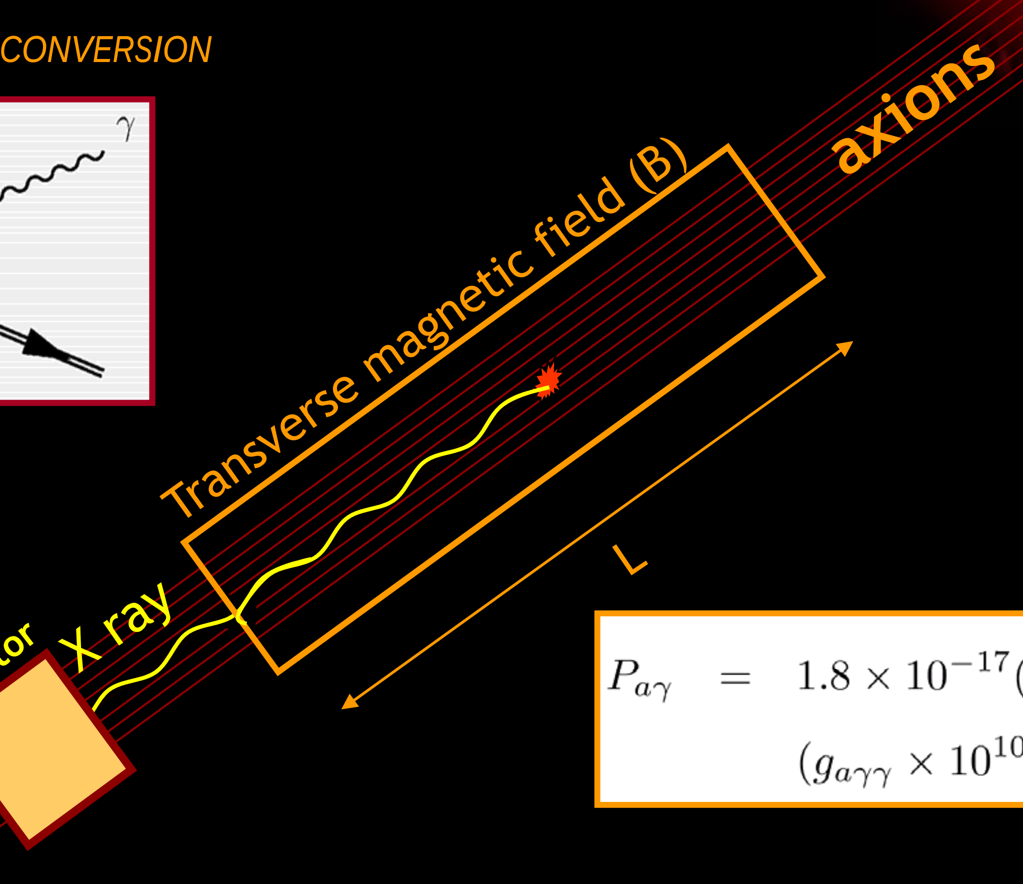
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

- Axion helioscope [Sikivie, PRL 51 (87)]

AXION PHOTON CONVERSION



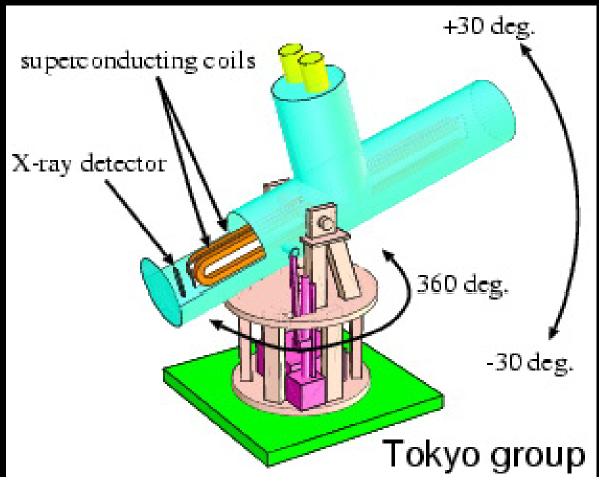


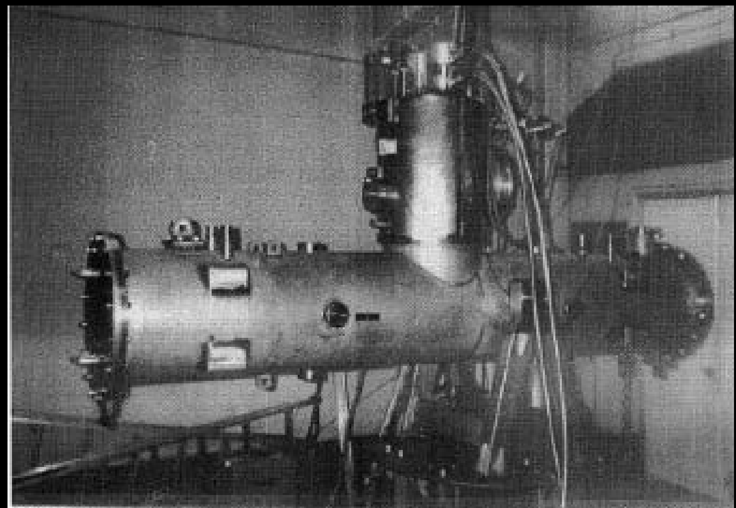
$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 \underbrace{|\mathcal{M}|^2}_{1},$$

COHERENCE 1

Helioscopes

- Previous helioscopes:
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

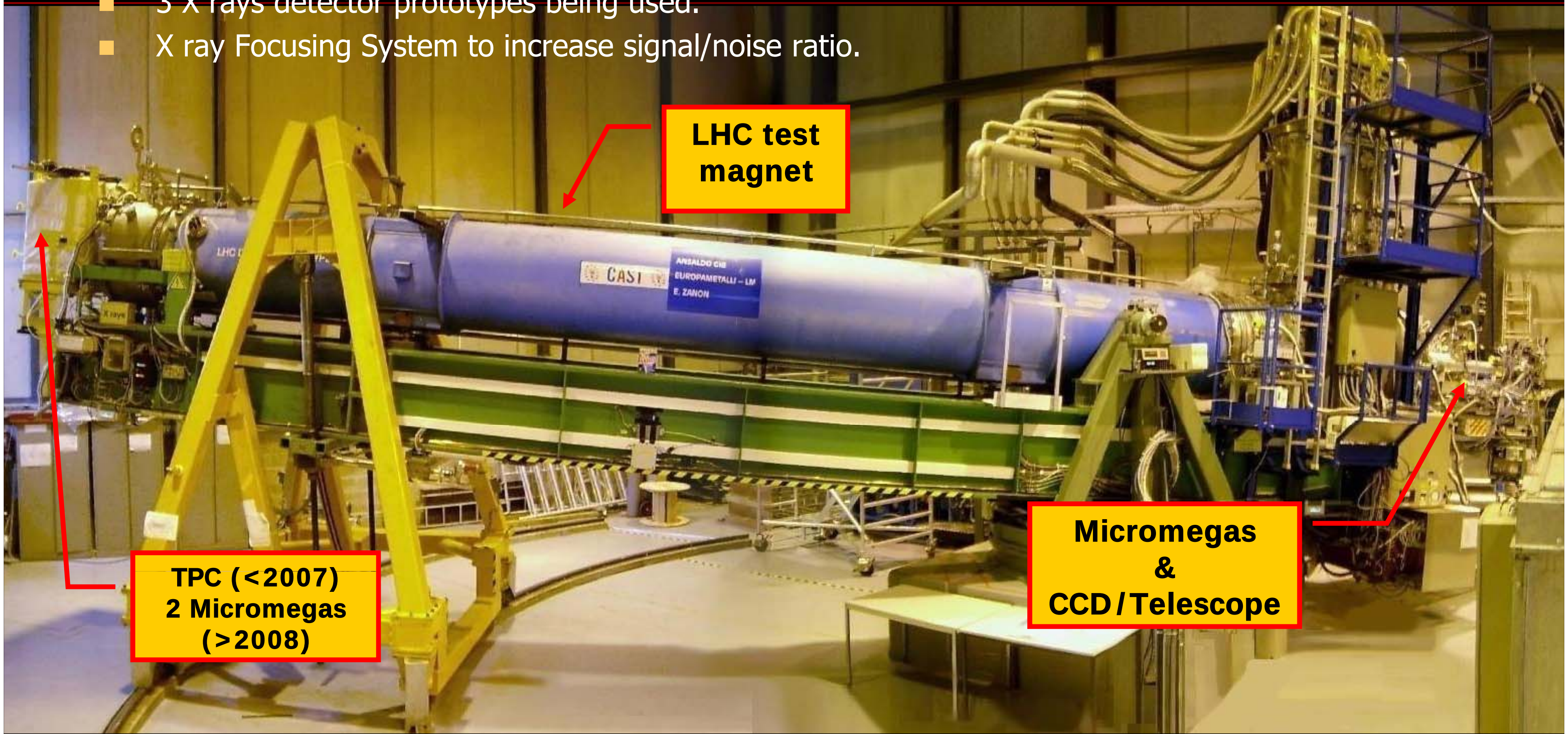




- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

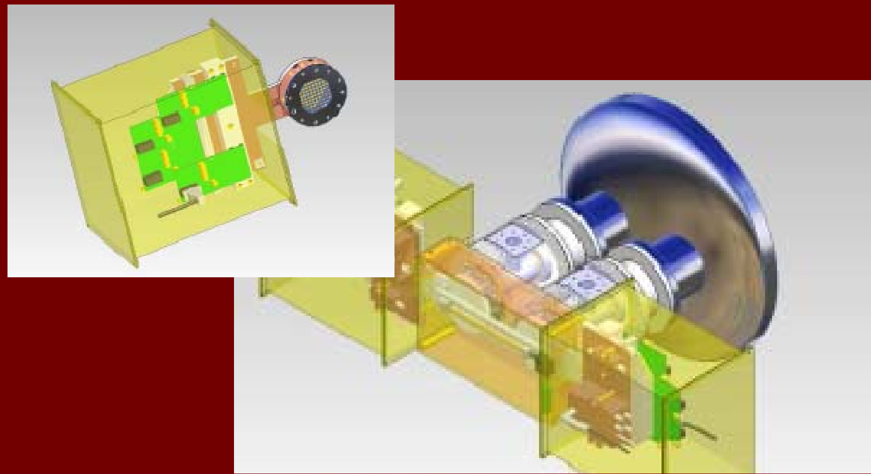
CAST experiment @ CERN

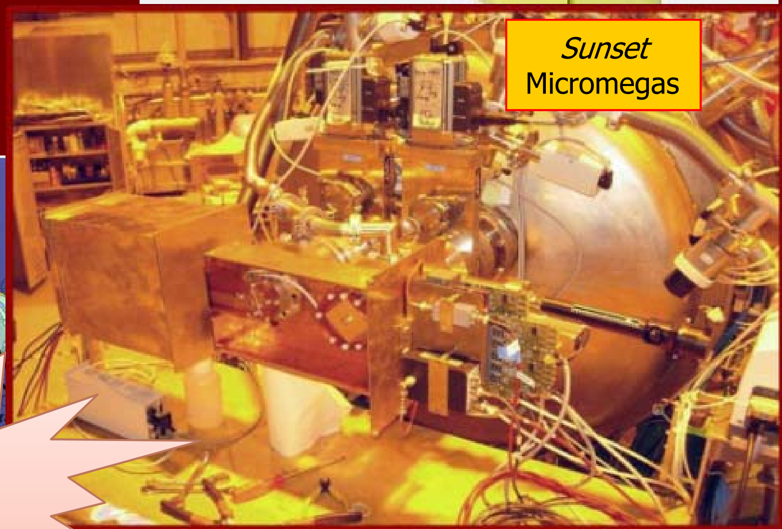
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.

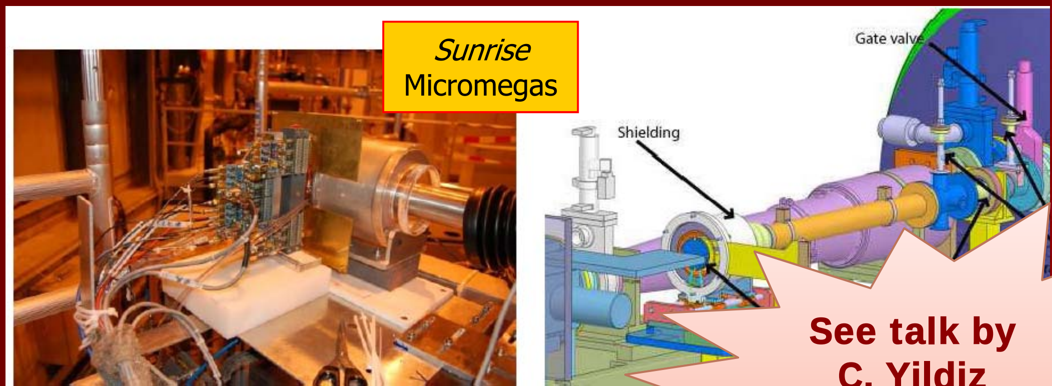


New Micromegas detectors for CAST

- Since 2008 2 new Micromegas detectors replaced the TPC in the *sunset* side.
  - Better shielding
- At sunrise side. The Micromegas detector substantially upgraded:
  - microbulk, shielding, monitoring, frontal calibration, flow controller,
- In overall → increasingly better backgrounds & sensitivity



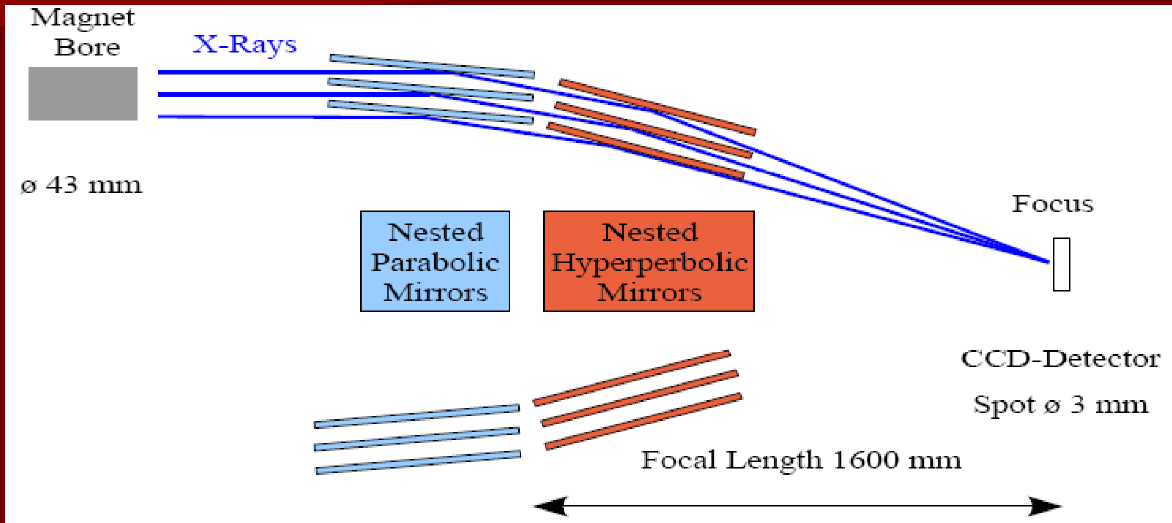


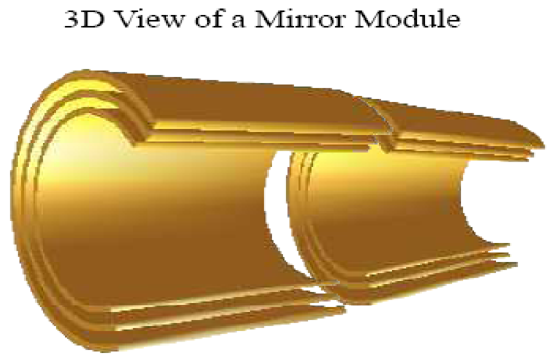


See talk by C. Yildiz

CAST X-ray telescope

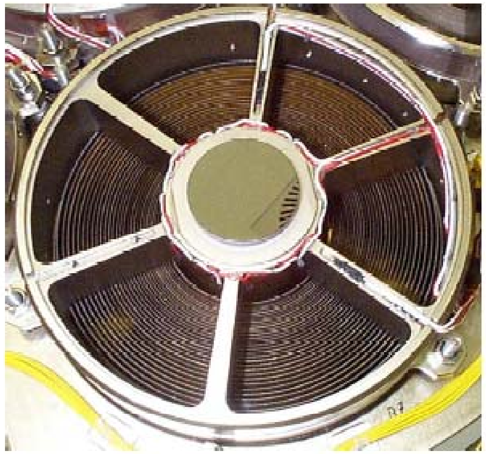
- CAST innovation of the “helioscope concept”





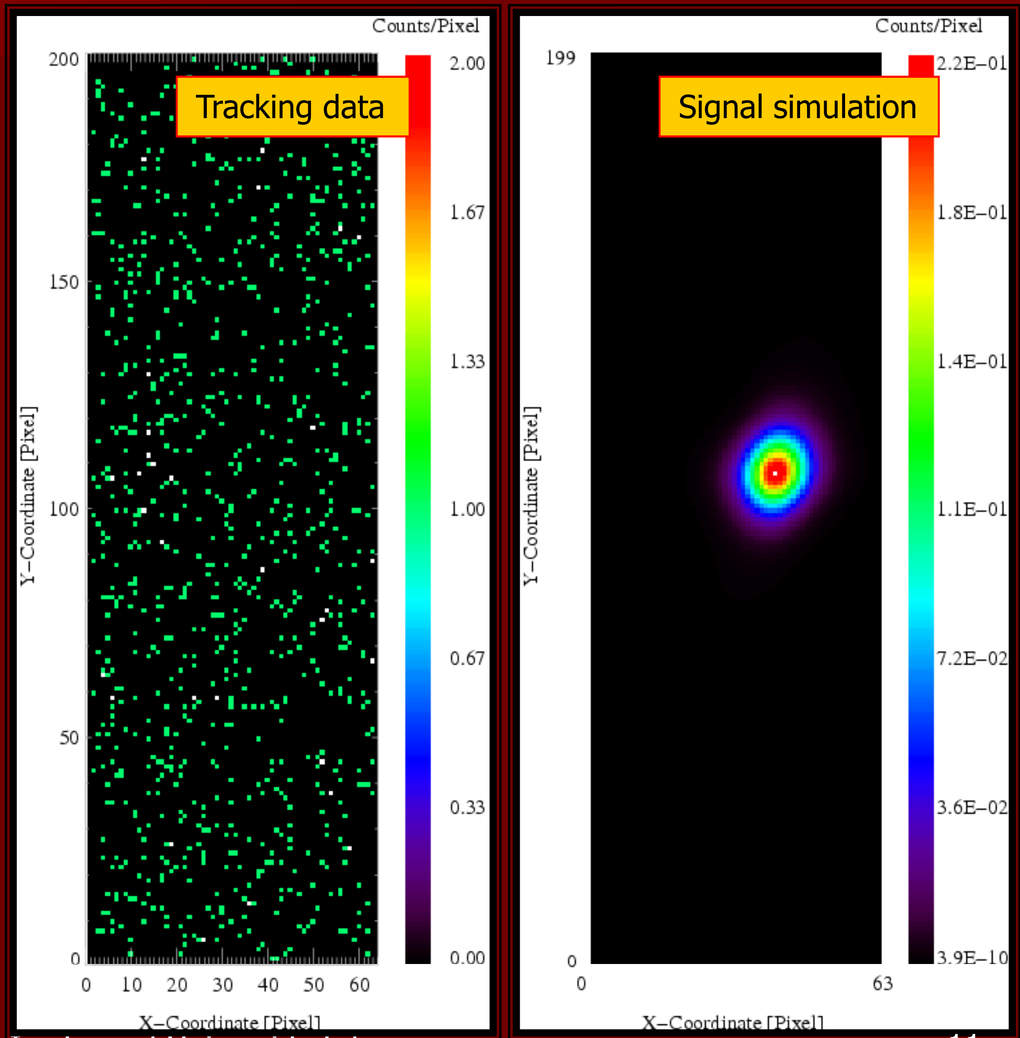
- Wolter I type grazing incident optics (prototype for ABRIXAS mission)
- From Ø43 mm (magnet bore) → Ø3 mm spot

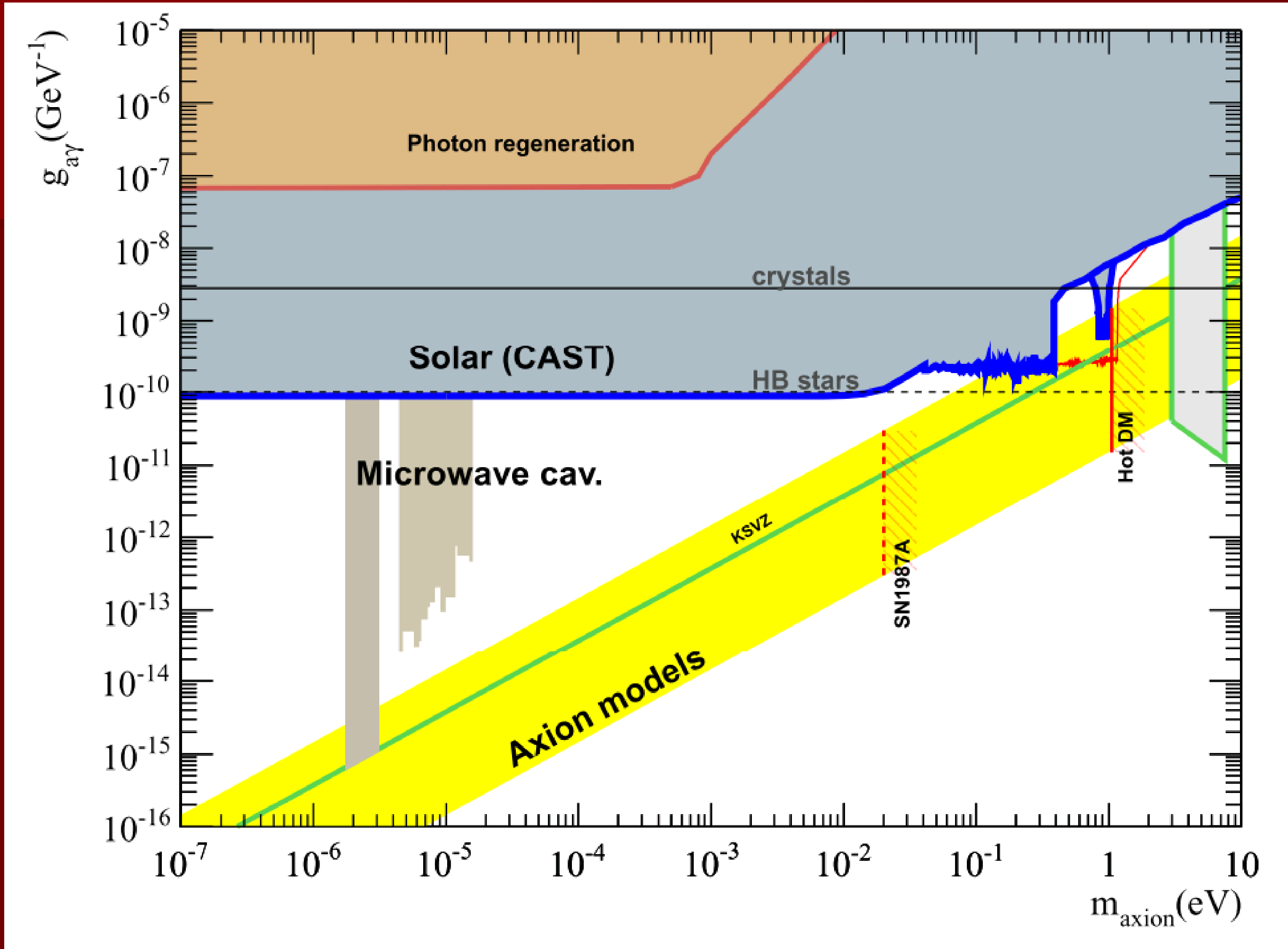
  improves signal to background ratio



CAST X-ray telescope

- Spot from the telescope on the CCD detector
- Determination of the spot position by calibrations and precise alignment of telescope.
- Counts inside the spot compatible with background level





$g_{a\gamma}(\mathrm{GeV}^{-1})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Photon regeneration
crystals
Solar (CAST)
HB stars
Microwave cav.
KSVZ
SN1987A
Hot DM
Axion models
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
$m_{axion}(\mathrm{eV})$

Towards a new generation axion helioscope

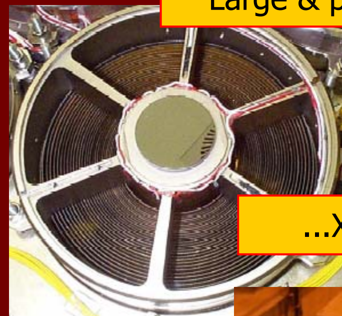
- CAST is established as a reference result in experimental axion physics (*)
- CAST PRL2004 most cited experimental paper in axion physics
- No other technique can realistically improve CAST in a wide mass range.

- **Next step in the field → new generation axion helioscope**

- CAST has shown the way to improve the helioscope technique…

Ingredients of a successful helioscope

Large & powerful magnet...

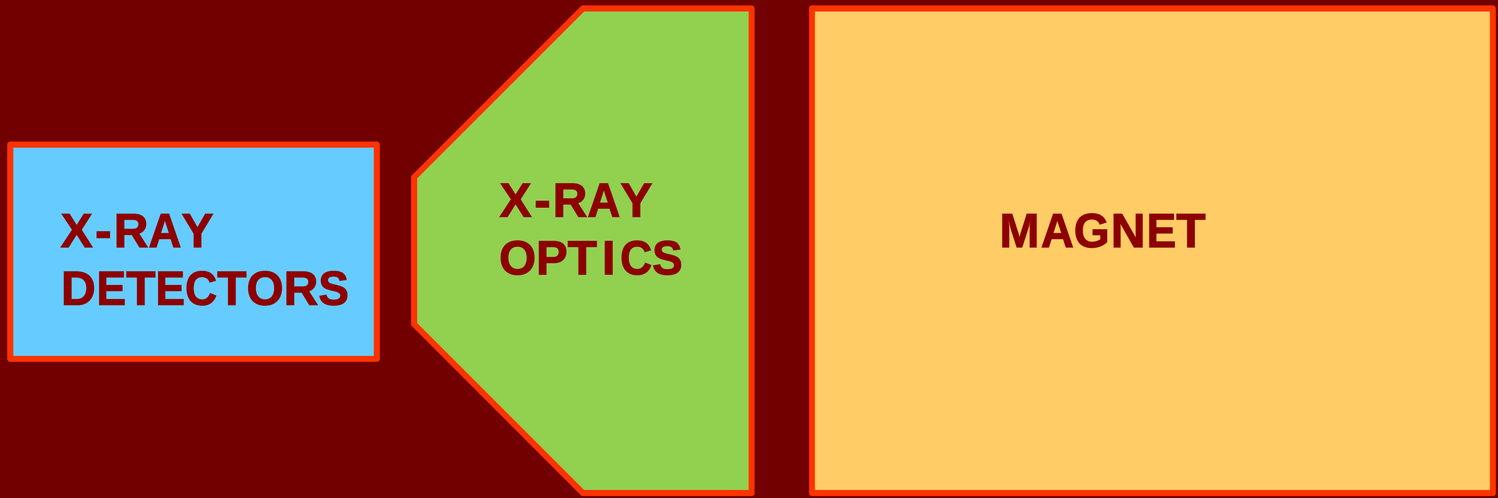


...X-ray optics,...

...and low background detectors

Axion Helioscopes FOM

- 3 elements drive the sensitivity of an axion helioscope



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

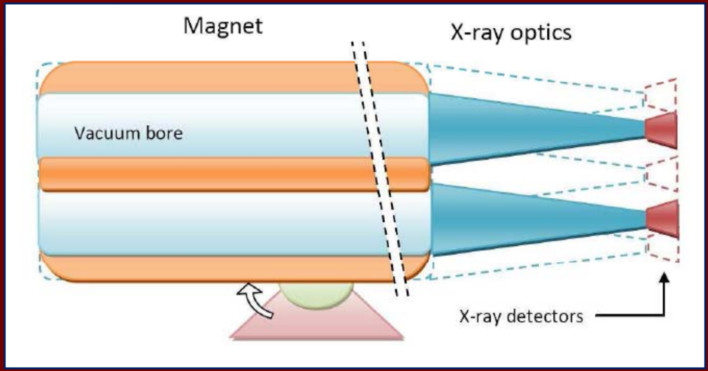
where b is the time- and area-normalized background of the detector, ϵ_d its efficiency; a is the focal spot area of the optics, ϵ_o its througput, B is the magnet field strength, L its length, and A its cross sectional area; t is the exposure time.

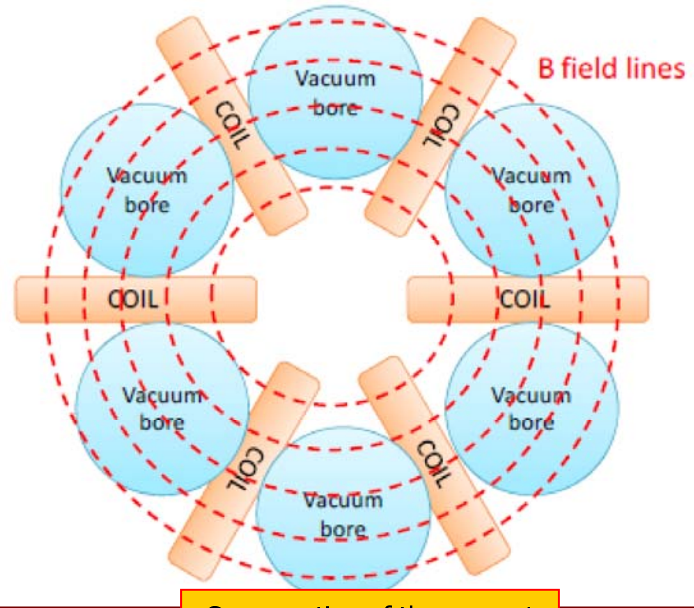
Sensitivity scenarios

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

New magnet

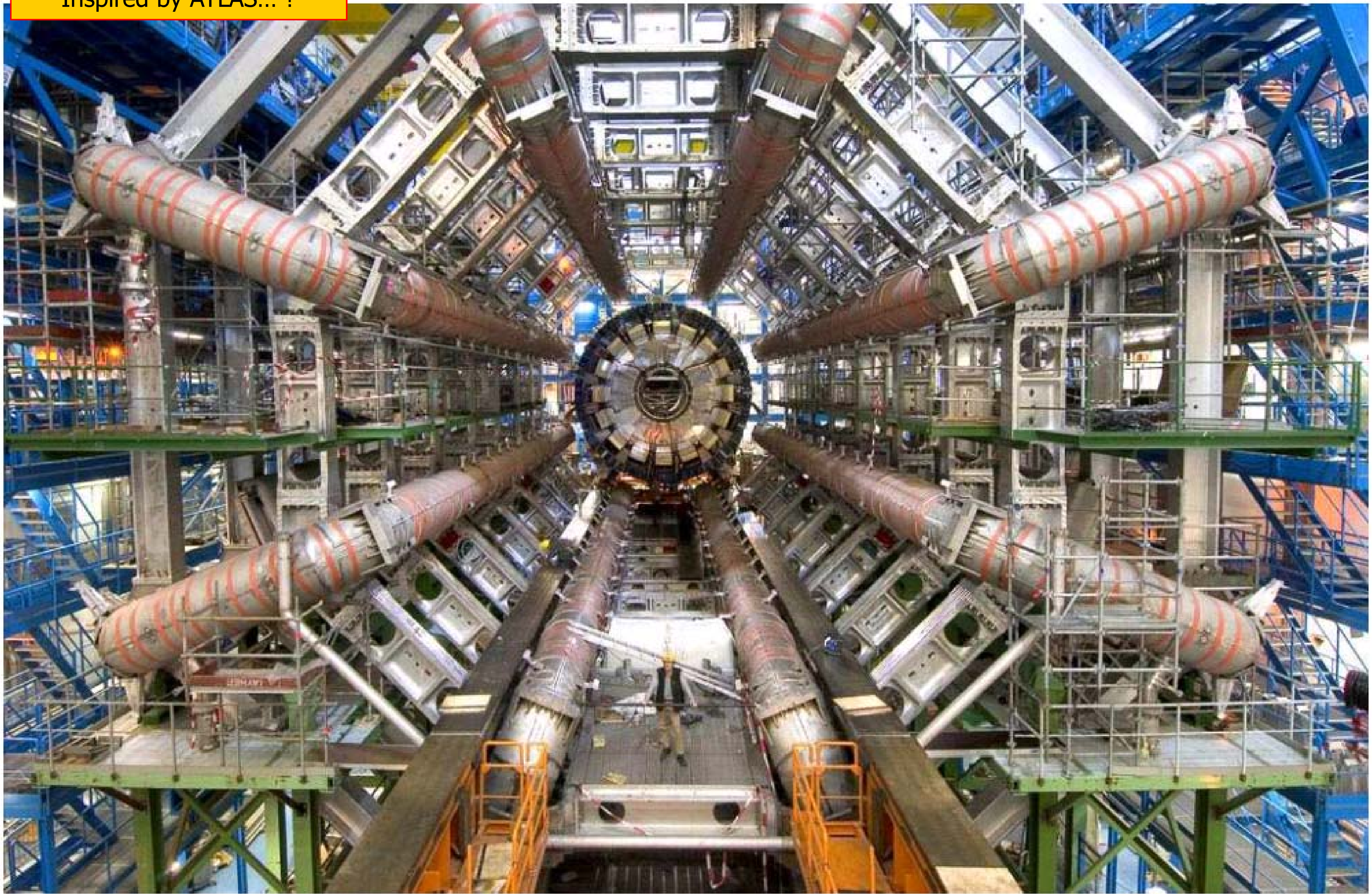
- CAST enjoys one of the best existing magnets than one can “recycle” for axion physics (LHC test magnet)
- Only way to make a step further is to built a new magnet, specially conceived for this.
- Work ongoing, but best option up to know is a **toroidal configuration:**
  - Much bigger aperture than CAST: ~1 m per bore
  - Relatively Light (no iron yoke)
  - Bores at room temperature (?)





Cross section of the magnet

Inspired by ATLAS… ?

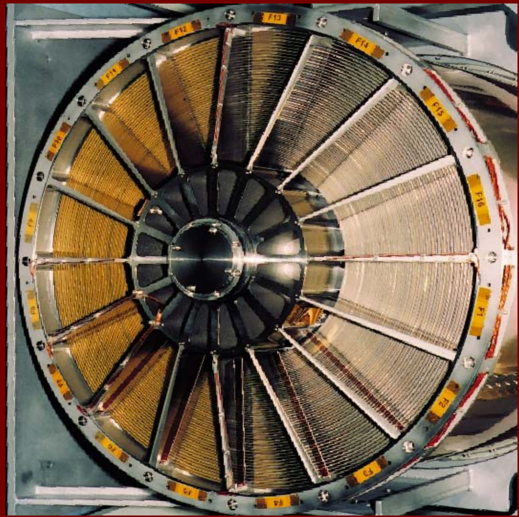


X-ray optics

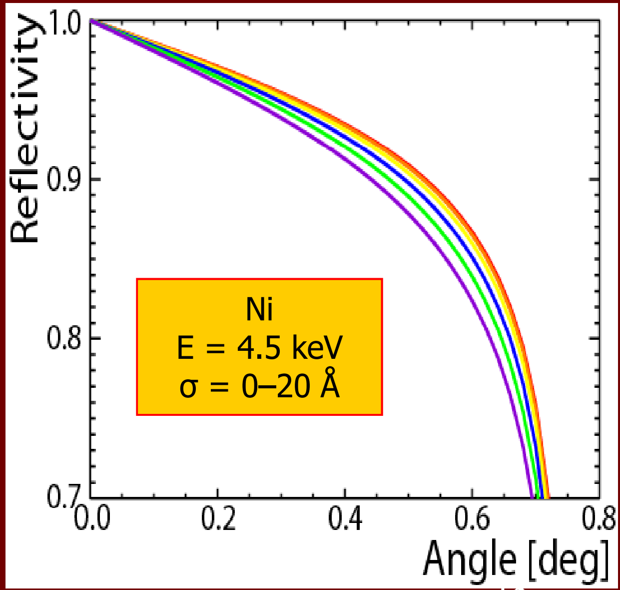
- During the last four decades, the x-ray astronomy community has devoted billions of dollars to develop reflective x-ray optics

- 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

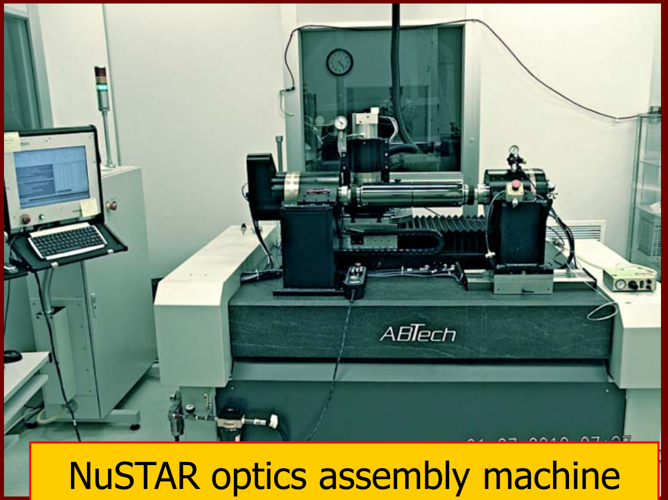


XMM-Newton telescope with 56 nested shells



One possibility: thermally-formed glass substrates

- NASA is currently building NuSTAR, a hard x-ray telescope
- NuSTAR uses thin glass substrates coated with multilayers to enhance reflectivity up to 80 keV
- The specialized tooling to shape the substrates and assemble the optics will be available after NuSTAR is launched in 2012
- Hardware can be easily configured to make optics with a variety of designs and sizes



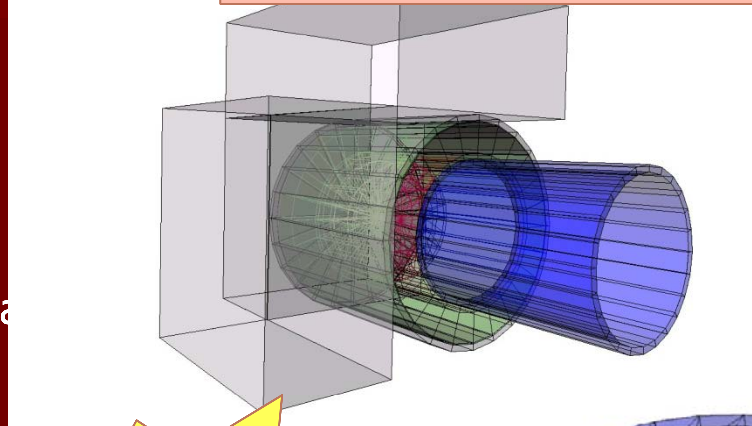
NuSTAR optics assembly machine

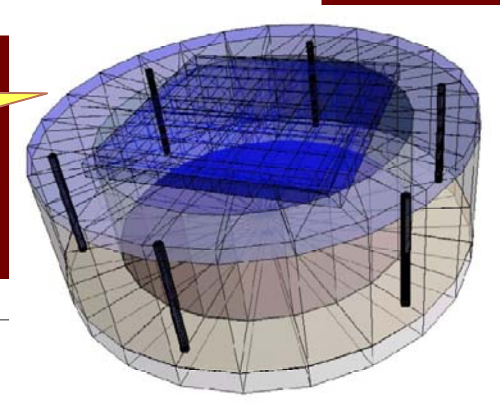
NuSTAR telescope

An ultralow-b MM for the NGAH

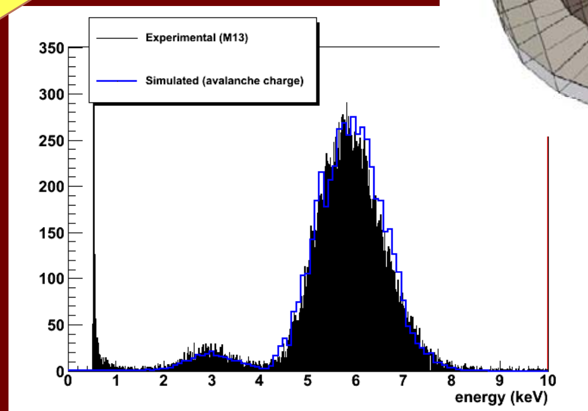
- **Goal:** at least 10^{-7} c/keV/cm^2/s, down to 10^{-8} c/keV/cm^2/s if possible.
- **Work ongoing:**
  - Experimental tests with current detectors at CERN, Saclay & Zaragoza
  - Especially: underground setup at Canfranc Lab
  - Simulation works to build up a background model
  - Design a new detector with improvements implemented

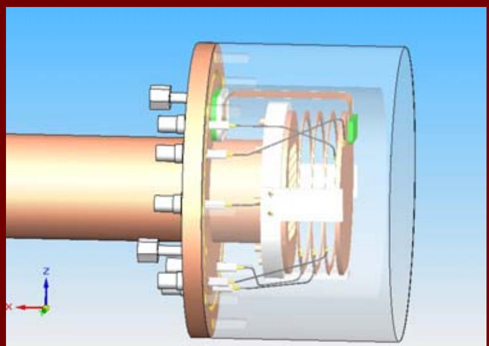
simulations





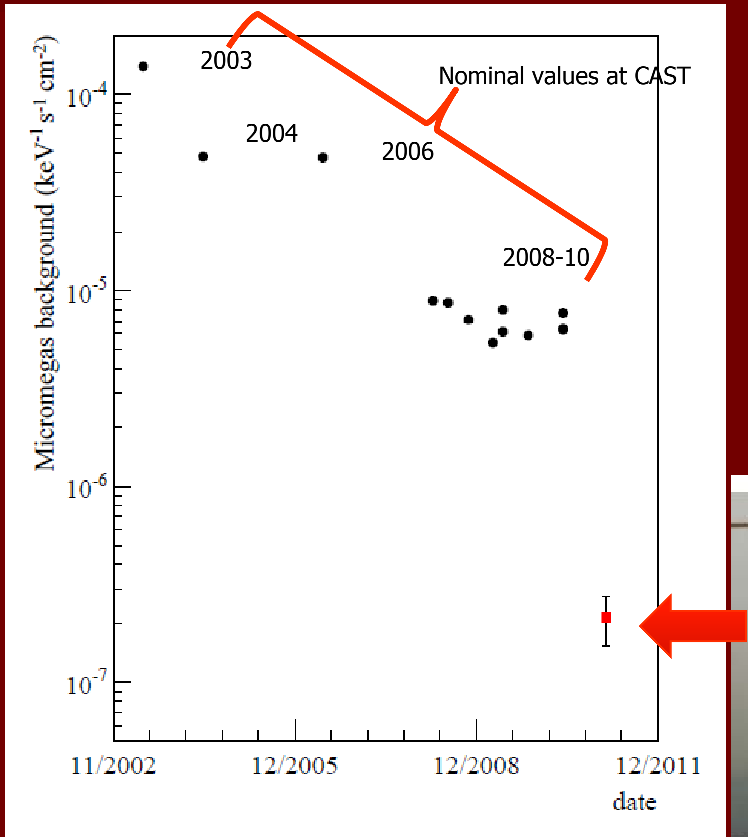
See talks by C. Yildiz & T. Dafni



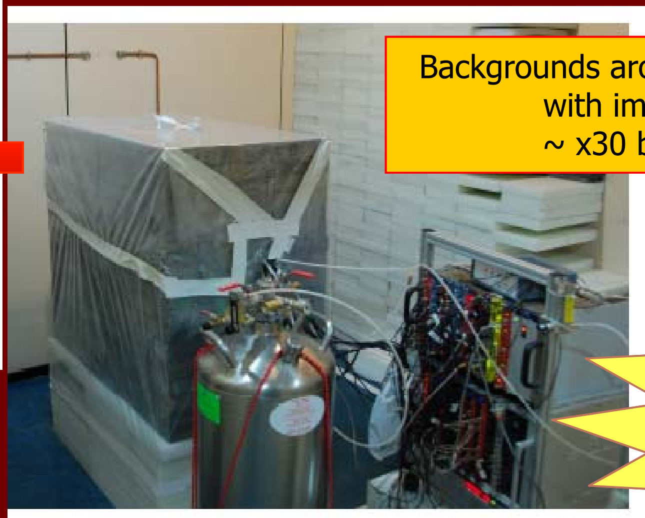


R&D low background detectors

History of background improvement of Micromegas detectors at CAST



- Latest Micromegas: x20 improved background
  - Shielding
  - Radiopurity. New manufacturing technique (microbulk readouts)
  - More powerful offline cuts
- Tests in controlled conditions underground at Canfranc:
  - Better shielding coverage
  - Thicker shielding



Backgrounds around 2x10-7 c/keV/s/cm2
with improved shielding
~ x30 better than CAST

See talks by C. Yildiz & T. Dafni

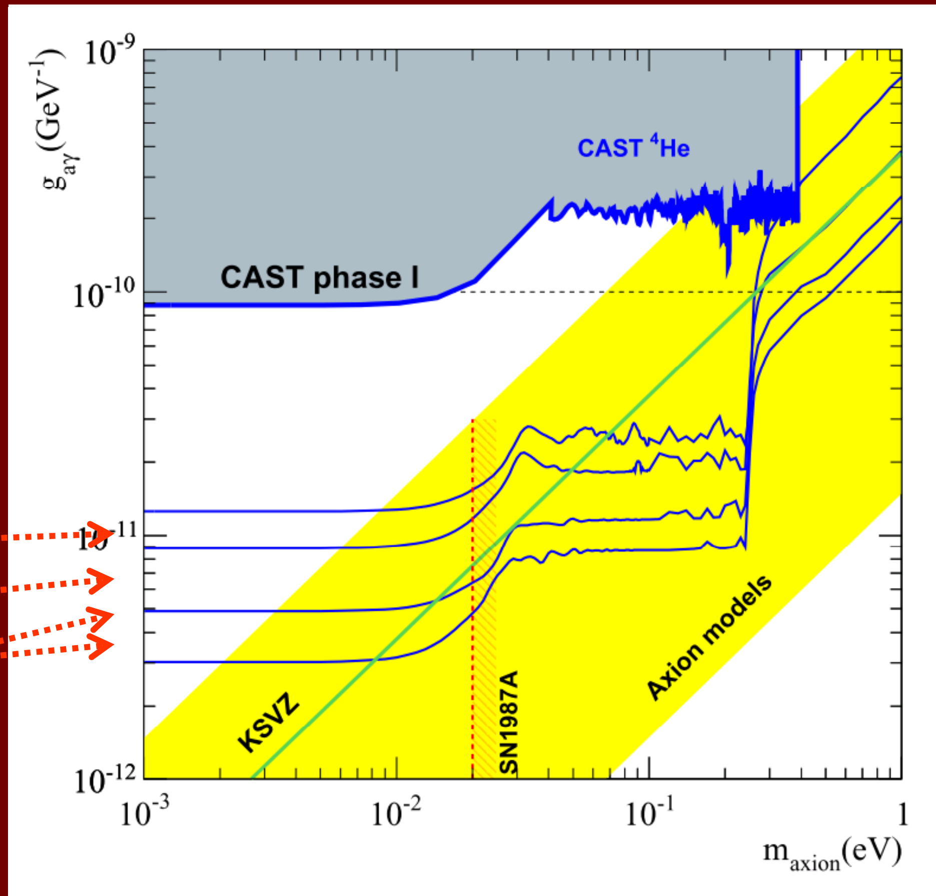
How much beyond CAST we can hope for?

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

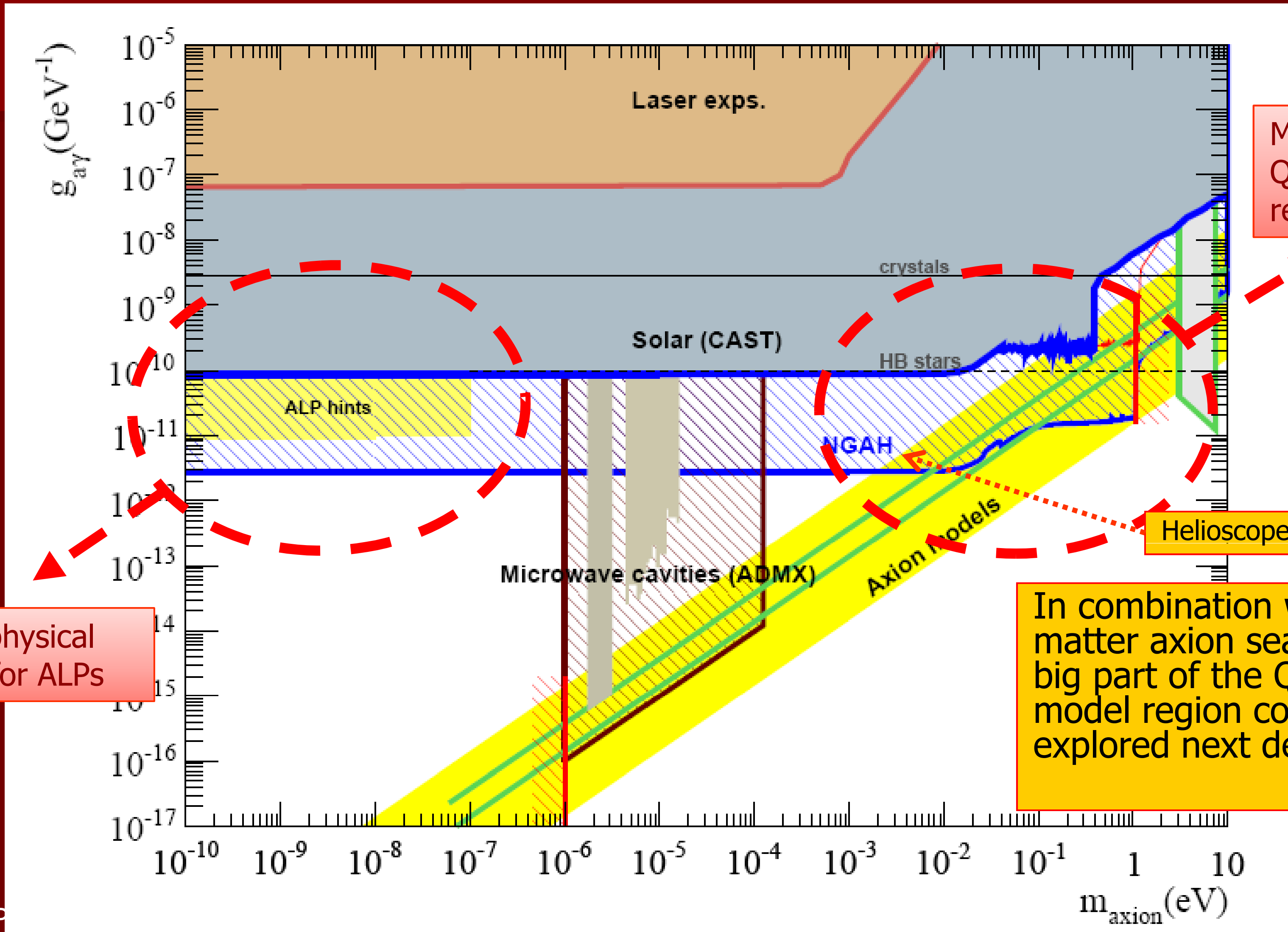
Conservative scenario

Realistic scenario

Optimistic scenarios



How much beyond CAST we can hope for?



Much larger QCD axion region explored

Astrophysical hints for ALPs

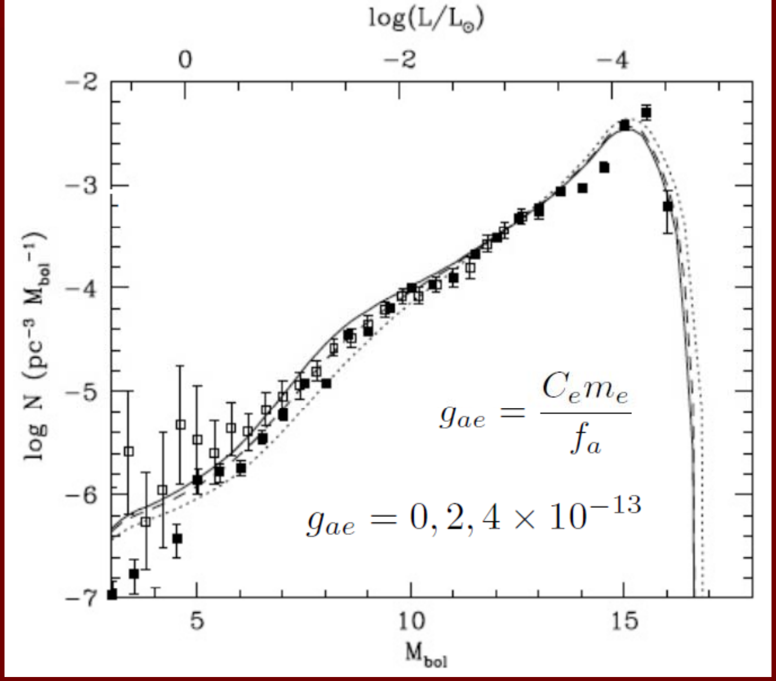
Helioscope prospects

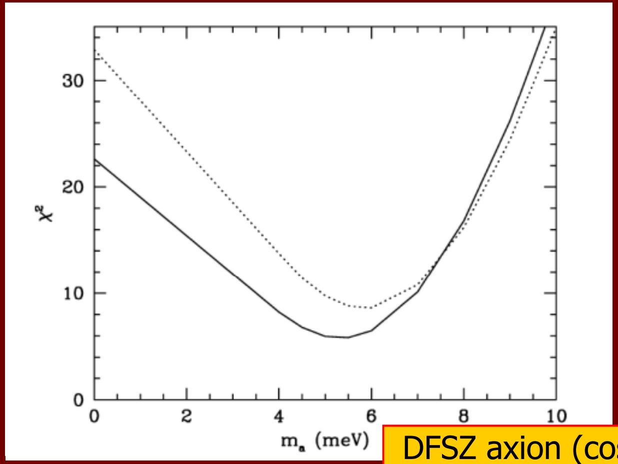
In combination with dark matter axion searches a big part of the QCD axion model region could be explored next decade.

The cooling of white dwarfs

(Isern et al. 2008,2010)

- Luminosity function (WD’s per unit magnitude) altered by axion cooling
- Claim of detection of new cooling mechanism (Isern 2008)
- Axion-electron coupling of ~$1\text{x}10^{-13}$ (→ axion masses of 2-5 meV or larger) **fits data.**



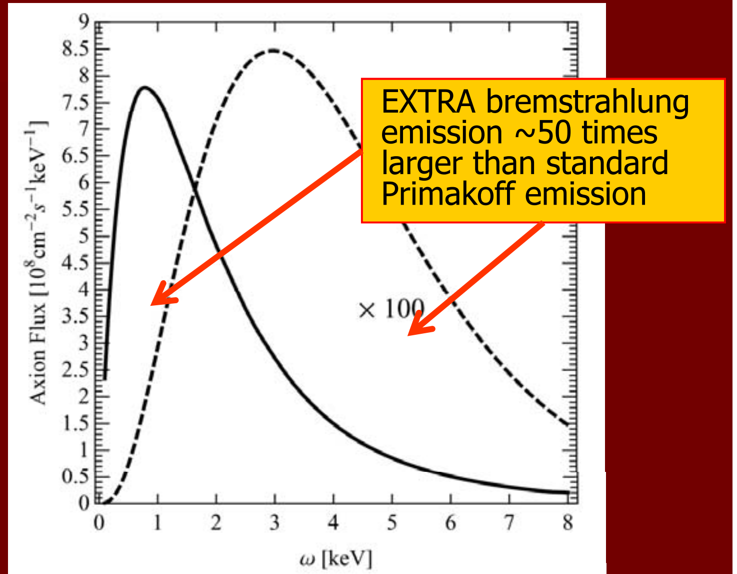


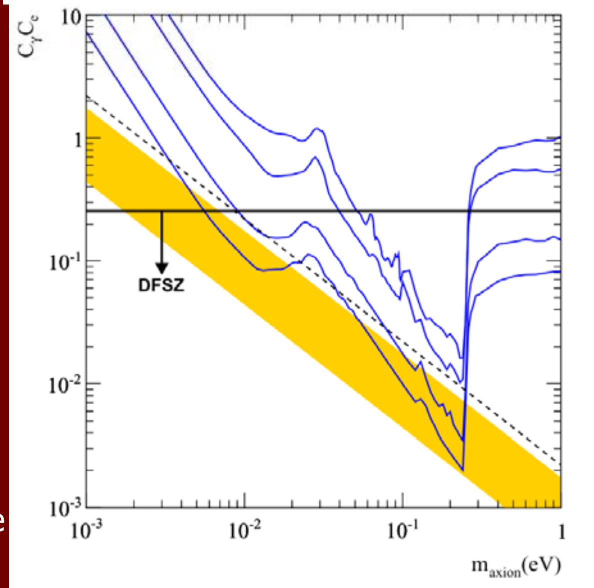
DFSZ axion (cosβ=1)

The cooling of white dwarfts

- meV masses seem out of reach of even an improved axion helioscope… BUT
- 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 most powerful axion helioscope to-date. Established as a reference result in axion physics.
- Expertise gathered in magnet, optics, low back detectors

- Towards a **new generation axion helioscope**: feasibility study in progress.
- First results (JCAP 016) show good prospects to improve CAST 1-1.5 orders of magnitude in $g_{a\gamma\gamma}$.
- In combination with dark matter axion searches (ADMX) a big part of the QCD axion model region could be explored next decade.
- White dwarfts e-coupled axions?, relic axions?, ALPs?… towards an **International Axion Observatory**
- Looking for more interested groups…