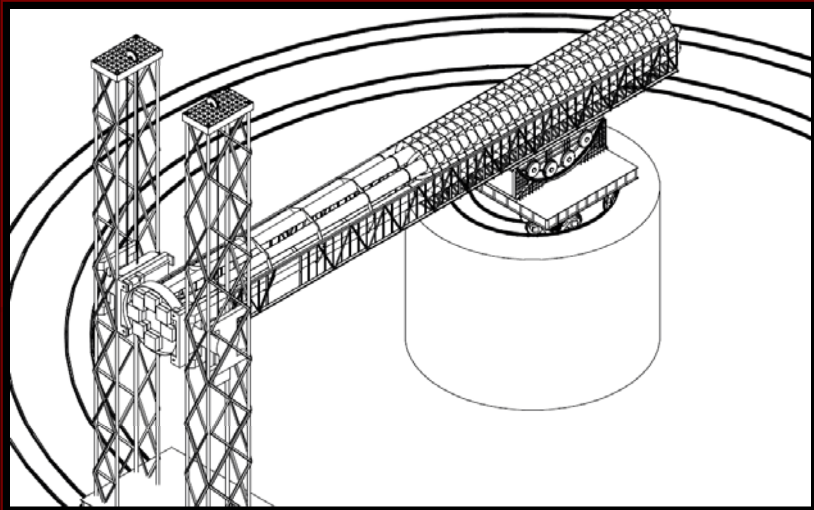
Status and physics prospects for the International AXion Observatory **IAXO**

Igor G Irastorza
Universidad de Zaragoza

Workshop "Vistas in Axion Physics" April 2012
Institute for Nuclear Theory, Seattle, University of Washington



Outline

- Outline:
  - Axions: motivation, theory, cosmology.
  - Solar axions &
    the axion helioscope concept
  - Previous helioscopes & CAST
  - IAXO project: technical prospects for a new helioscope
    - Magnet
    - X-ray optics
    - Low background detectors
  - Sensitivity prospects
  - Status of project
  - Conclusions

Talk partially based on
JCAP 06 (2011) 013

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Towards a new generation axion helioscope

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

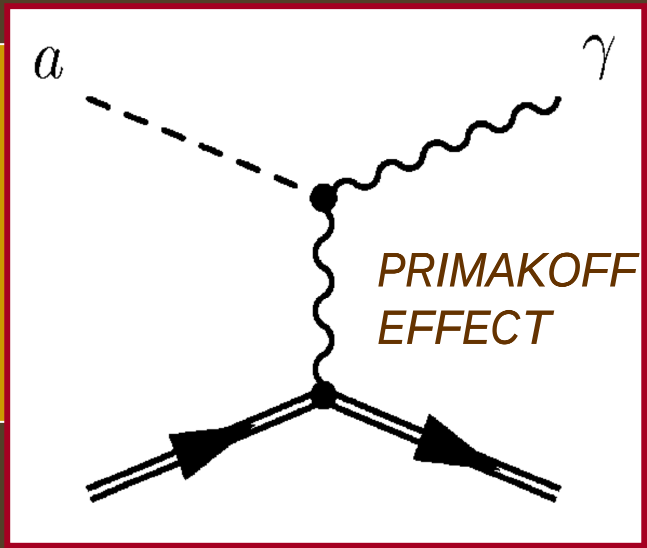
AXION motivation

- **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.

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

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

- 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.

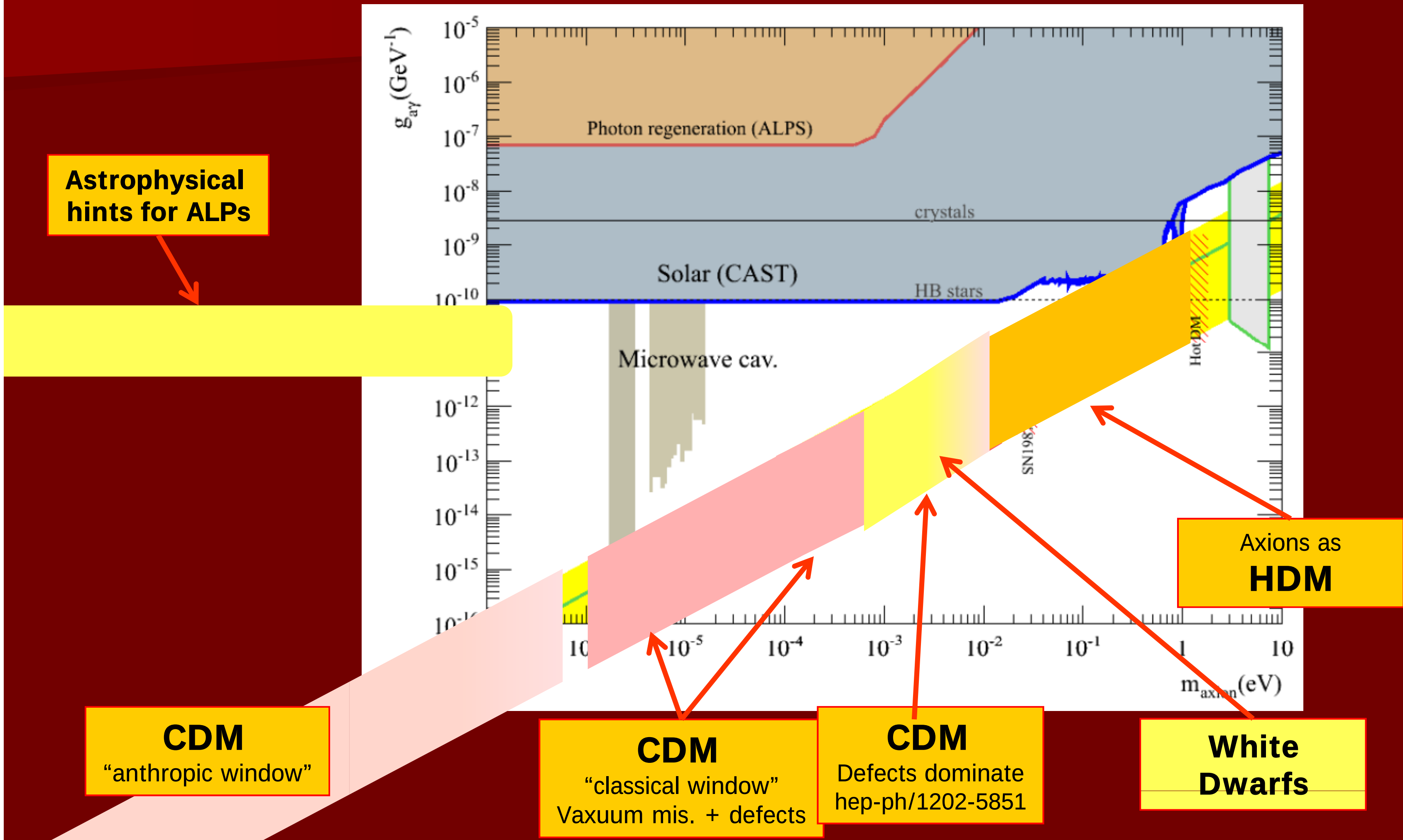
  - Thermal production

  → 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)]

Axion parameter space



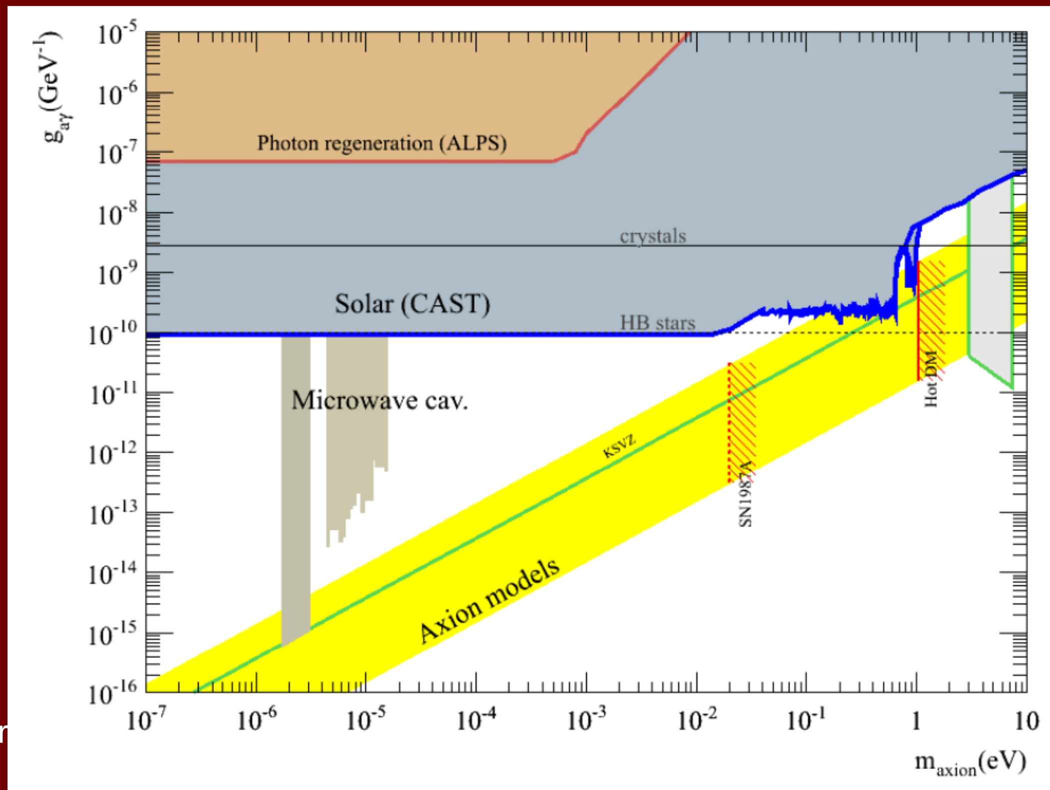
Beyond axions

Hidden photons / paraphotons — ALPS — **AXIONS** — Chamaleons — Minicharged particles

WISPs (Weakly interacting Slim Particle)

- Diverse theory motivation
  - Higher scale symm. breaking
  - String theory
  - DM / DE candidates
  - Astrophysical hints

- Generic Axion-like particles (ALPs) parameter space →

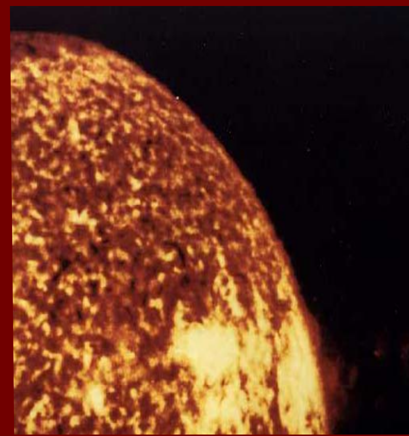


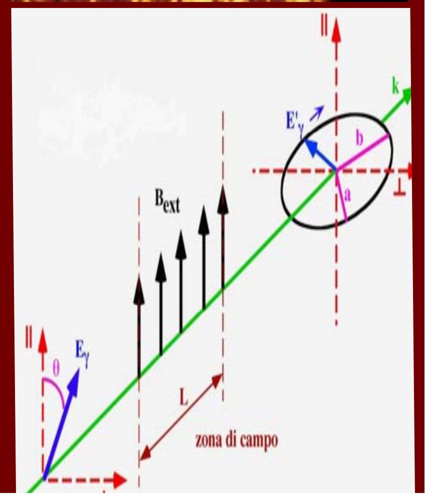
Detecting axions

- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes

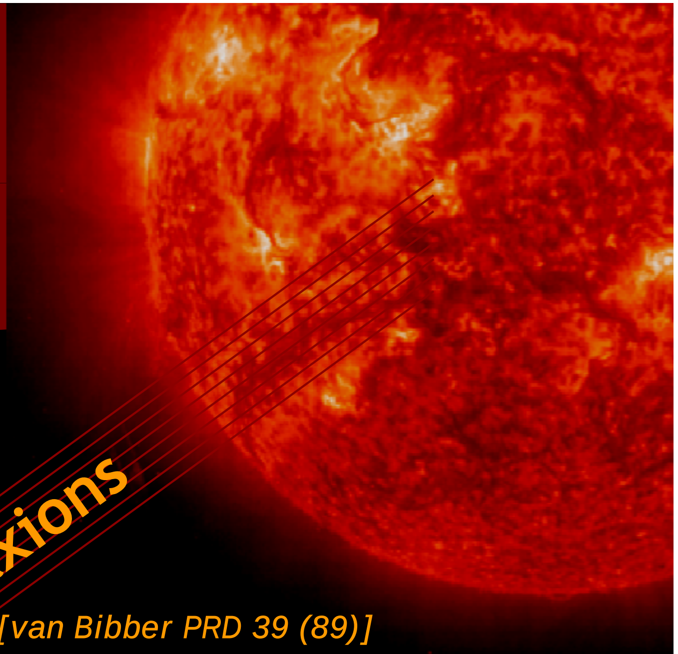
- Solar Axions
  - Emitted by the solar core.
    - Crystal detectors
    - Axion Helioscopes (**CAST → IAXO**)

- Axions in the lab
    - “Light shinning through wall” experiments
    - Vacuum birrefringence experiments

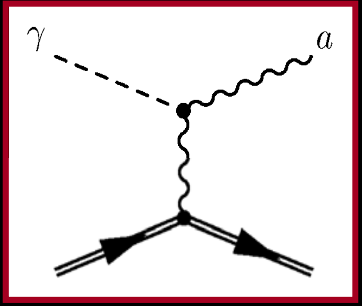




Solar Axions



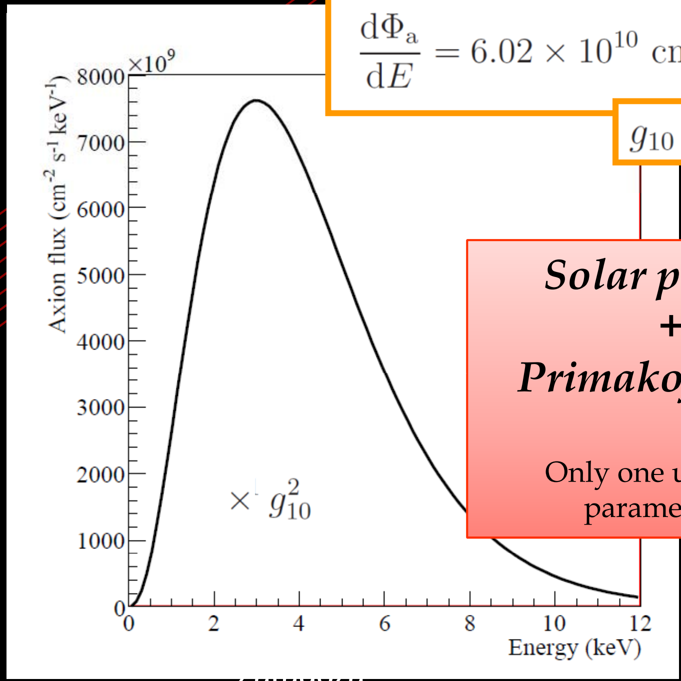
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



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

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

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



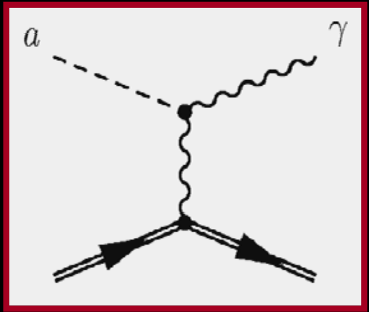
Solar physics
+
Primakoff effect

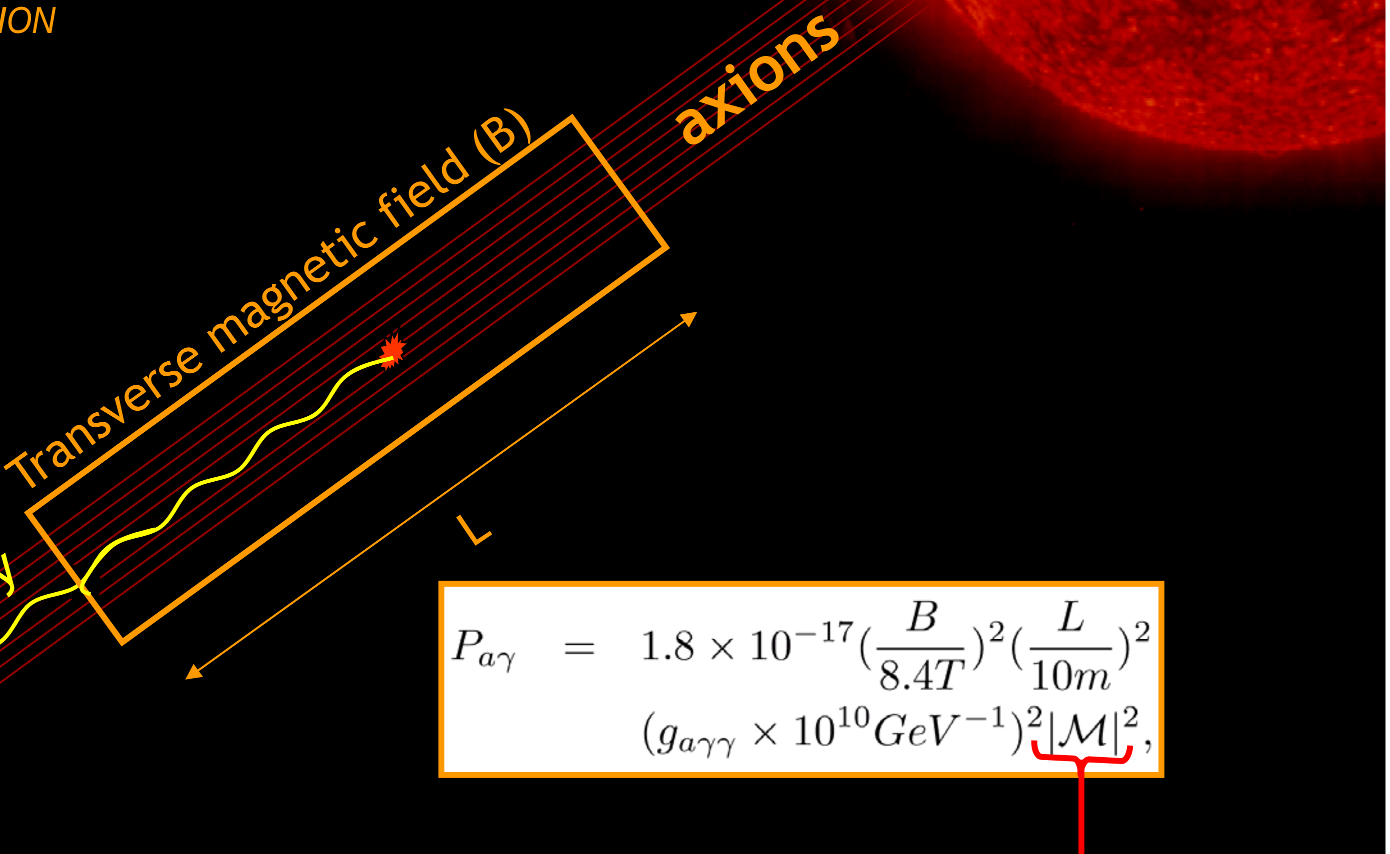
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

- Axion helioscope [Sikivie, PRL 51 (83)]

AXION PHOTON CONVERSION



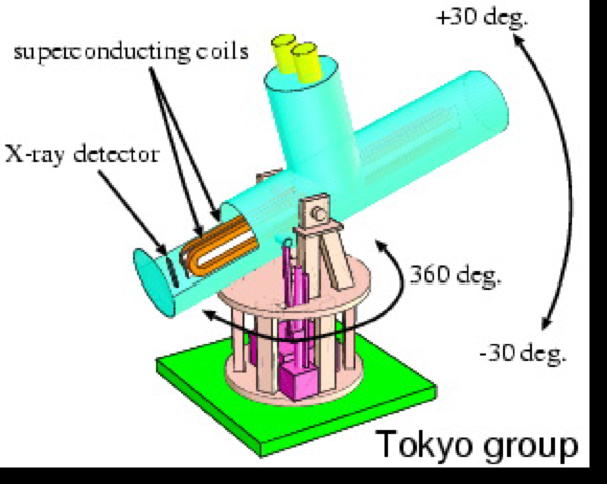


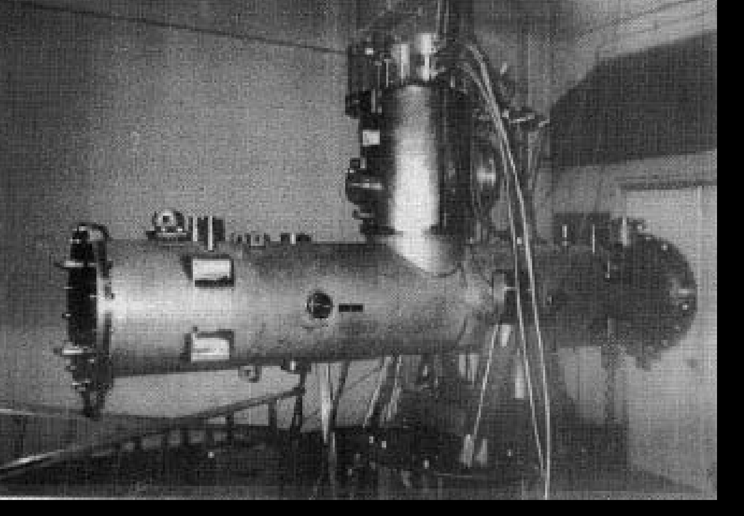
$$P_{a\gamma} = 1.8 \times 10^{-17} (\frac{B}{8.4T})^2 (\frac{L}{10m})^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$

COHERENCE 1

Axion 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

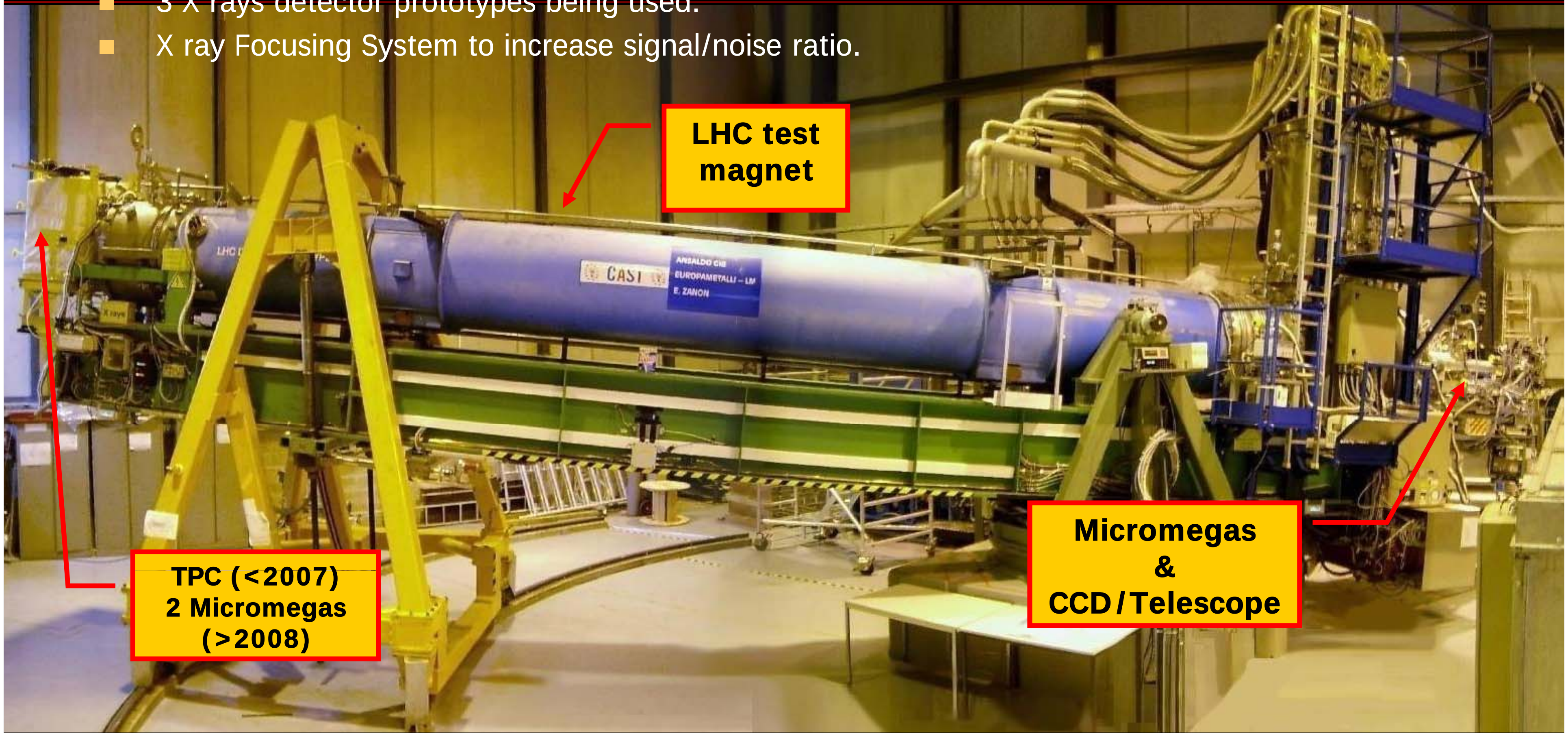




- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

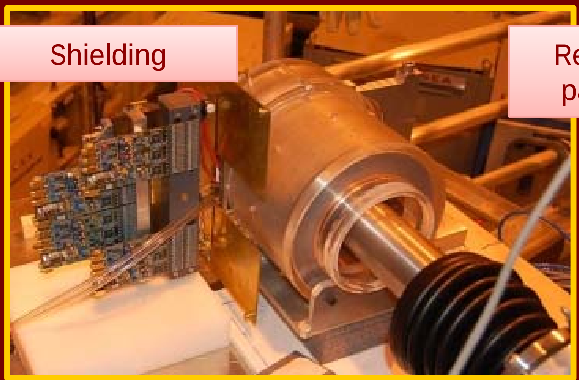
CAST experiment @ CERN

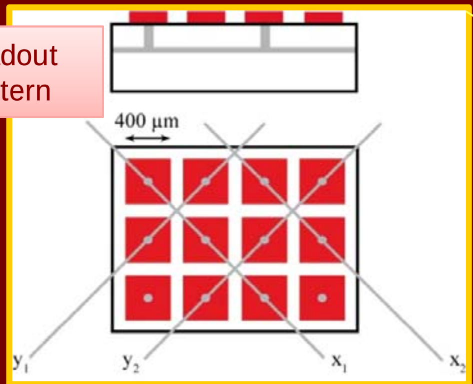
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.

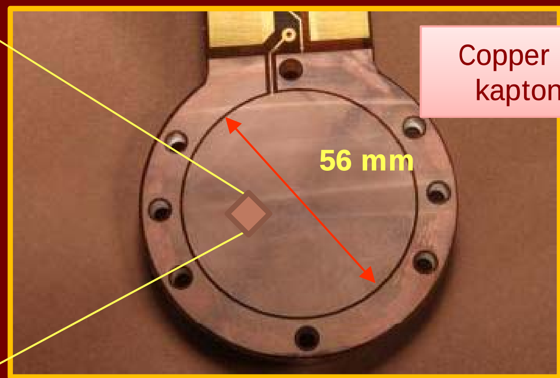


Low background x-ray detectors

- *Microbulk* Micromegas
  - Low radioactivity materials
    [Astropart.Ph. 2011,34,354]
  - High granularity readout → powerful offline discrimination of events in gas
  - Shielding techniques

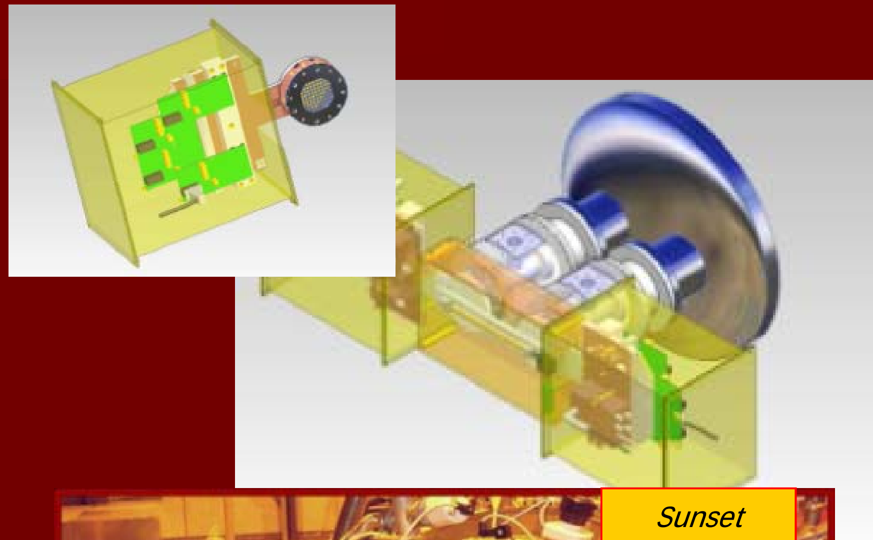


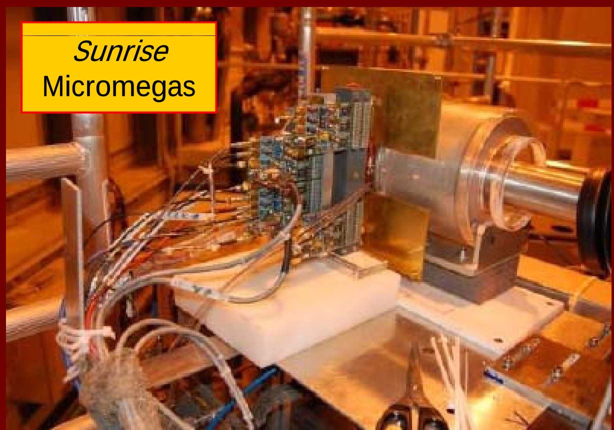


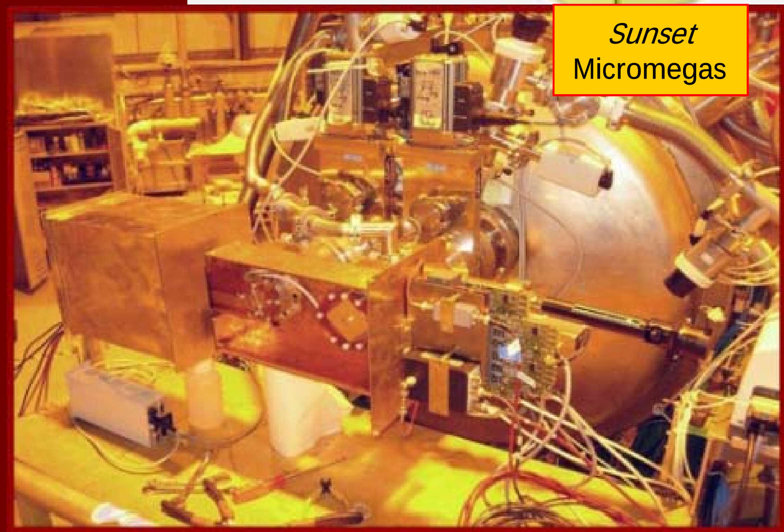


Micromegas detectors @ CAST

- Since 2008 2 new Micromegas detectors replaced the multiwire 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

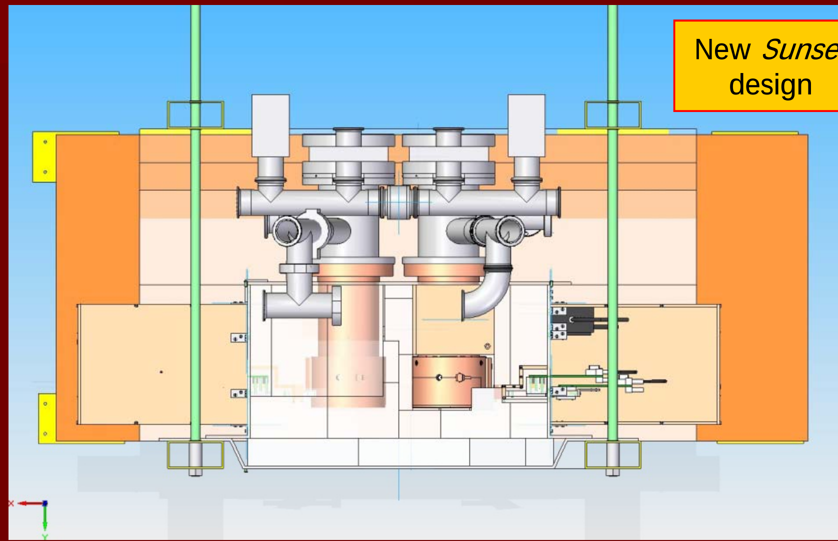






Micromegas detectors @ CAST

- New detectors for 2012
  - New microbulk Micromegas for sunset side
  - Improved shielding
    - Thickness
    - Coverage
  - Some components replaced (radiopurity)
  - Possible muon veto
- Tests of low background strategies developed
- Setup to be mounted at CAST next week !



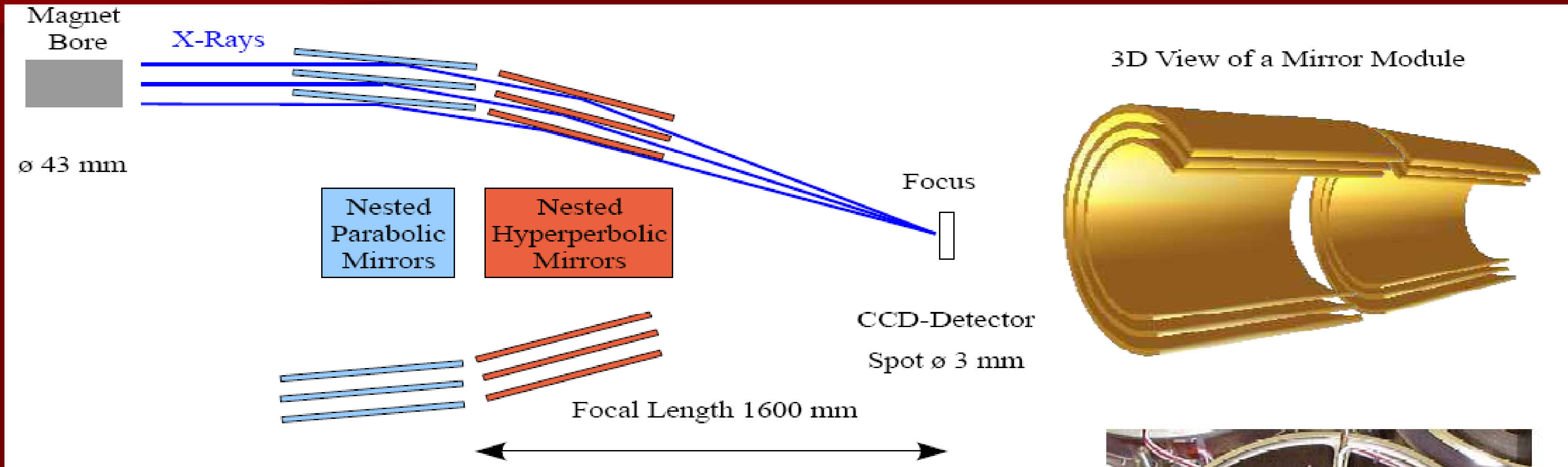
New *Sunset* design

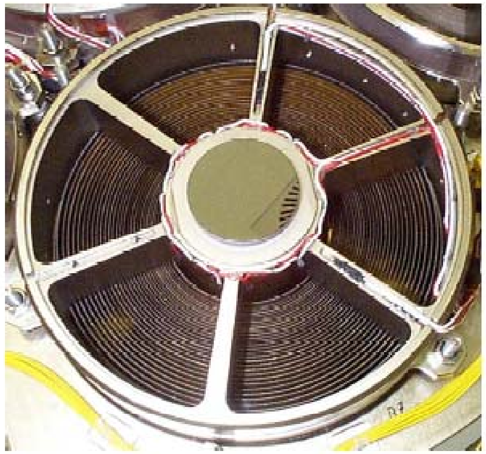
Test mounting (Zaragoza)

See talk
T. Dafni

CAST X-ray telescope

- CAST innovation of the “helioscope concept”



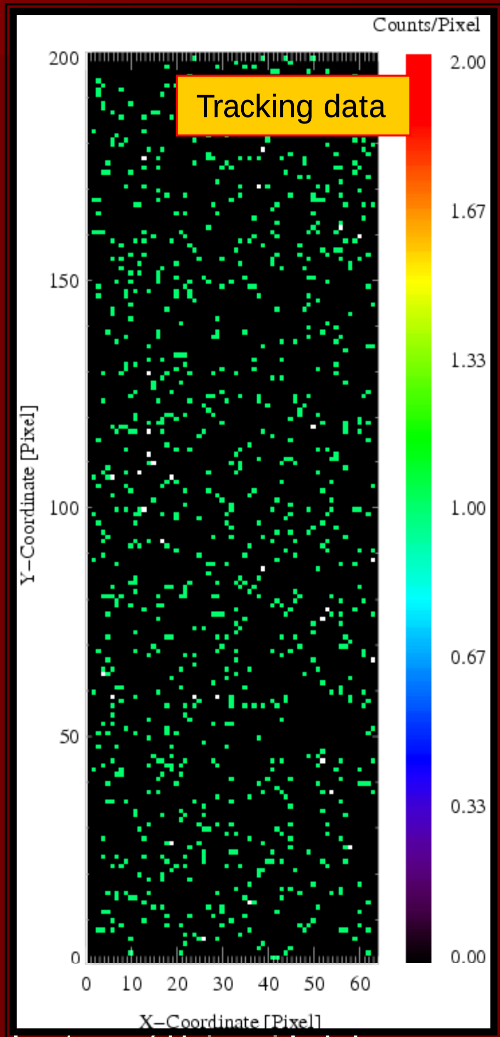


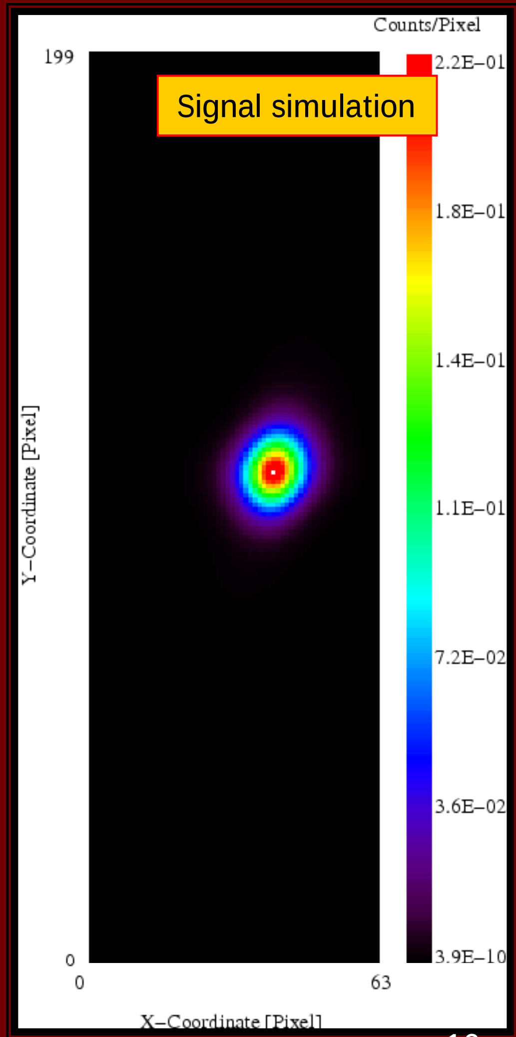
- Wolter I type grazing incident optics (prototype for ABRIXAS mission)
- From Ø43 mm (magnet bore) → Ø3 mm spot

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





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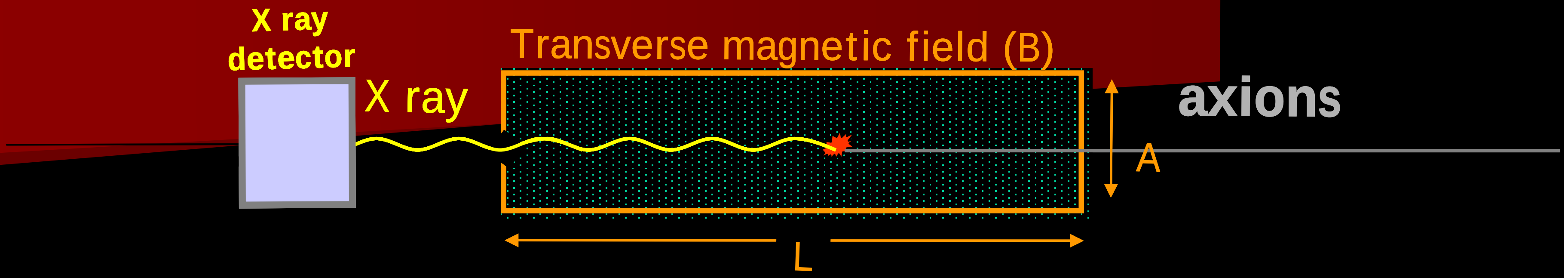
Buffer gas to go to higher masses



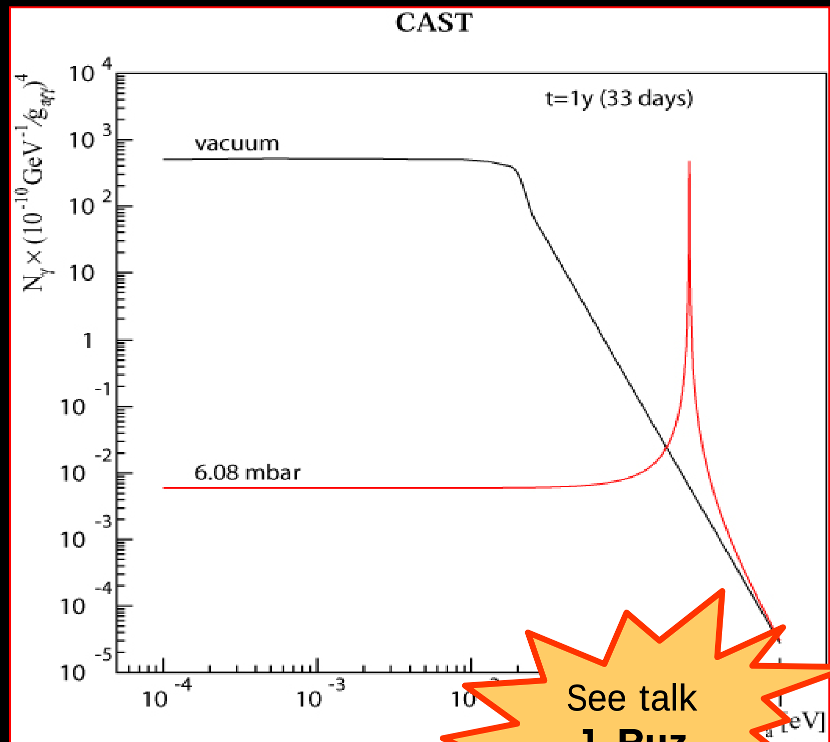
Extending the coherence to higher axion masses...

•Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

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

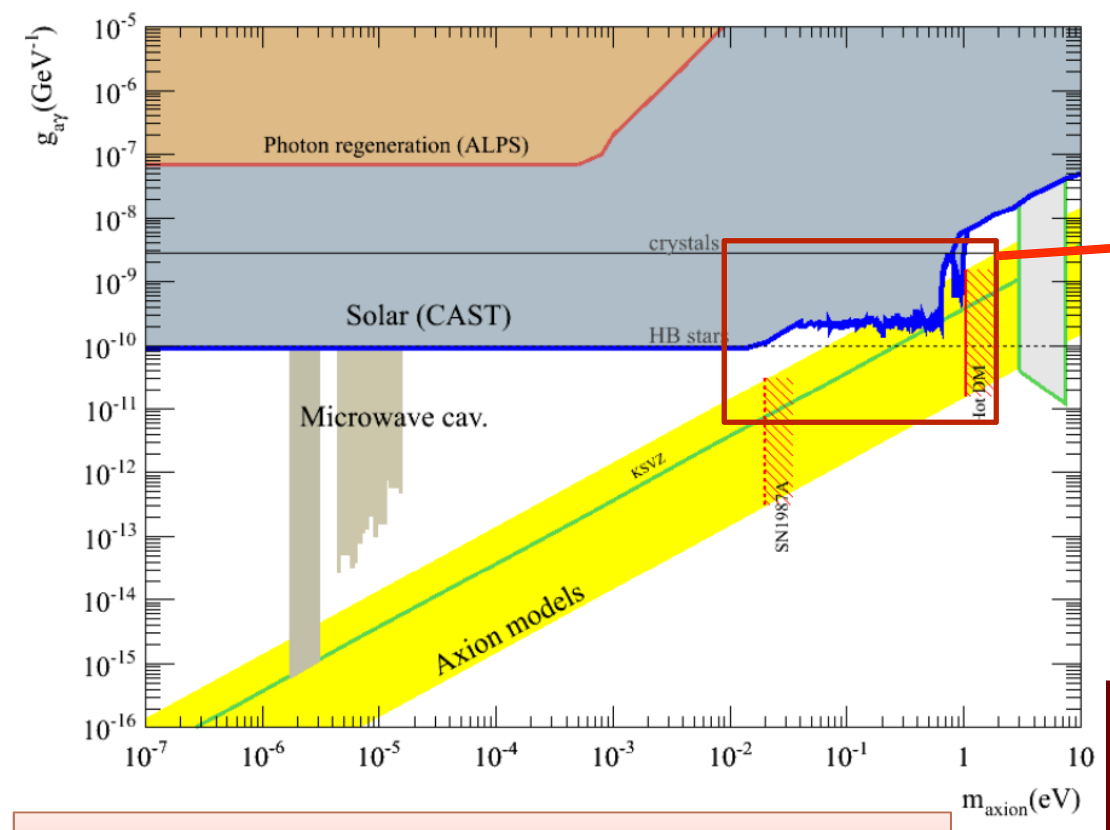
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

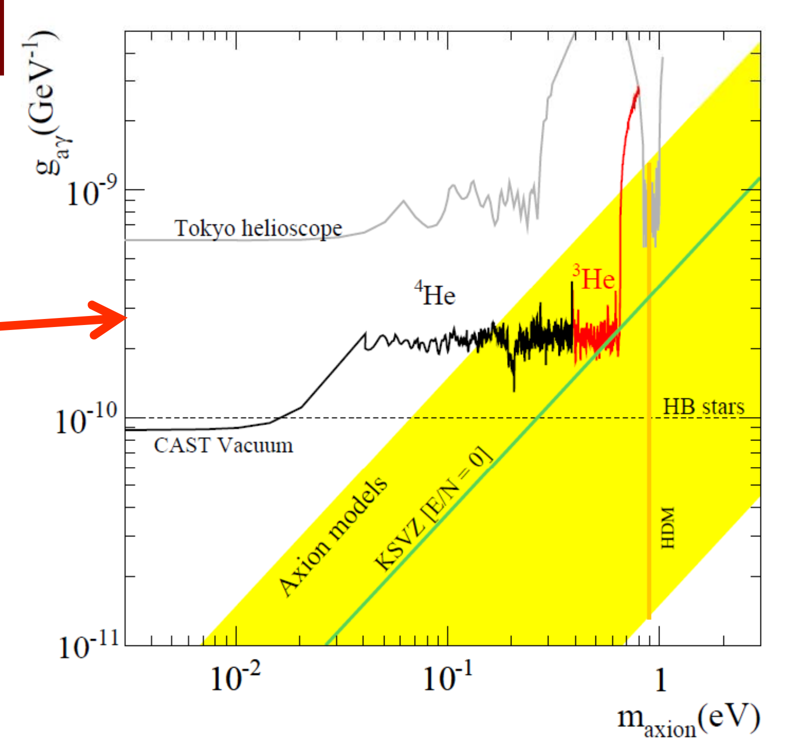
N_e: number of electrons/cm^3
ρ: gas density (g/cm^3)



See talk
J. Ruz

Latest CAST results

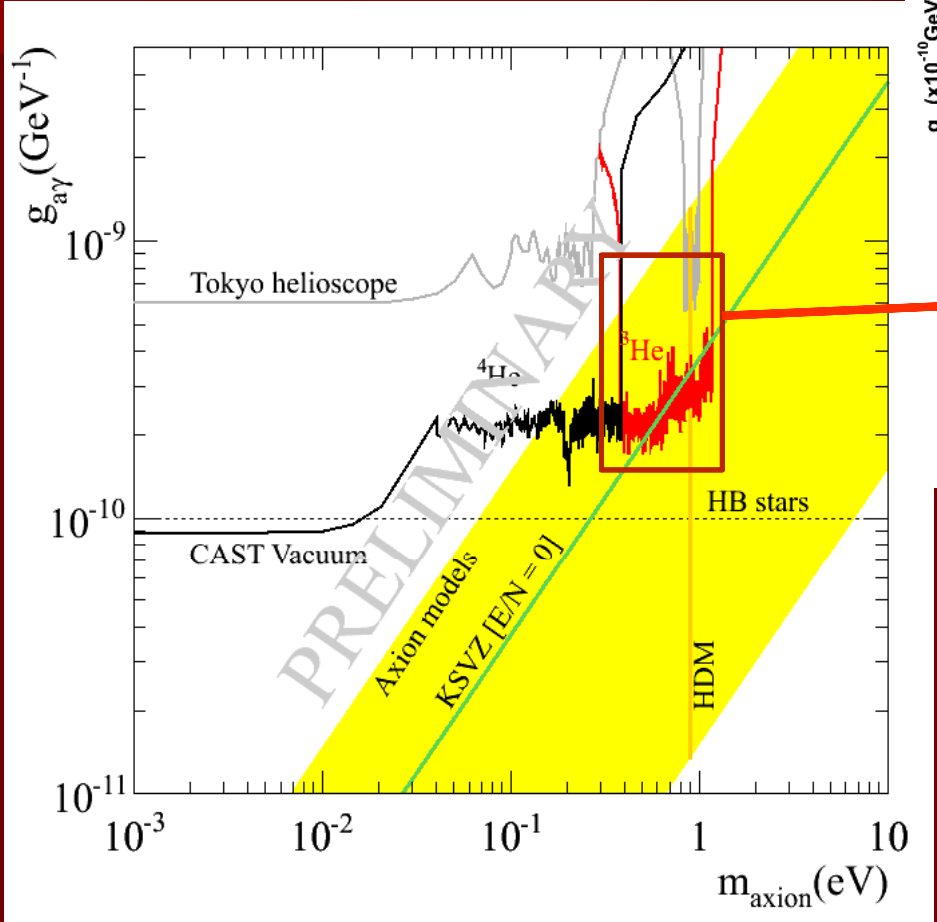


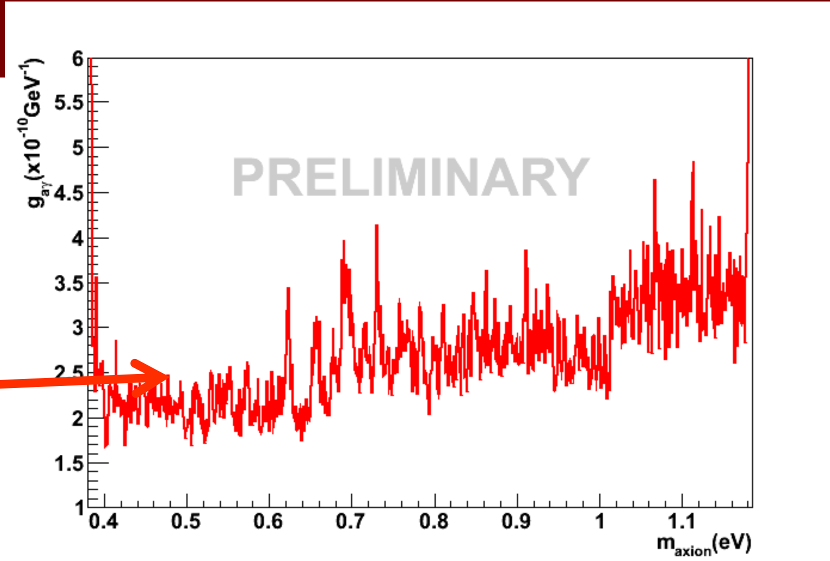


S. Aune et al. (CAST collaboration)
PRL 107 (2011) 261302 (arXiv:1106.3919v1)

- Results from first ^{3}He (2008) data (red line).
- Masses 0.39 – 0.65 eV excluded down to 2-2.5 x 10^{-10} GeV^{-1}
- Touching KSVZ benchmark models for the first time
- He3 data up to 1.15 eV taken, being analyzed.

Latest CAST results: preliminary





- All ^{3}He data (2008-11) in progress.
- Masses up to 1.15 eV
- Final He3 result paper in preparation

Future prospects

- CAST Near term future:
  - CAST will revisit phase II He4 in 2012 and again the vacuum phase I in 2013-14 with better detectors → better sensitivity.
  - Search in parallel for exotica: chamaleons, paraphotons, non standard axions (visible wavelenghts)

- Longer term future:
  - Studies for a new generation axion helioscope (>1 order of magnitude more sensitive than CAST):

The International Axion Observatory IAXO

The International Axion Observatory IAXO:
towards a new generation axion helioscope

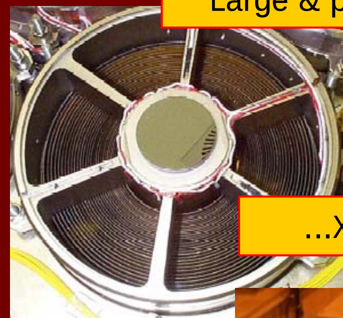
- CAST is established as a reference result in experimental axion physics CAST PRL2004 most cited experimental paper in axion physics
- No other technique can realistically improve CAST in such wide mass range.

- **Next step → IAXO, a new generation axion helioscope**

- Build up on CAST innovations to improve the helioscope technique...

Ingredients of a successful helioscope

Large & powerful magnet...

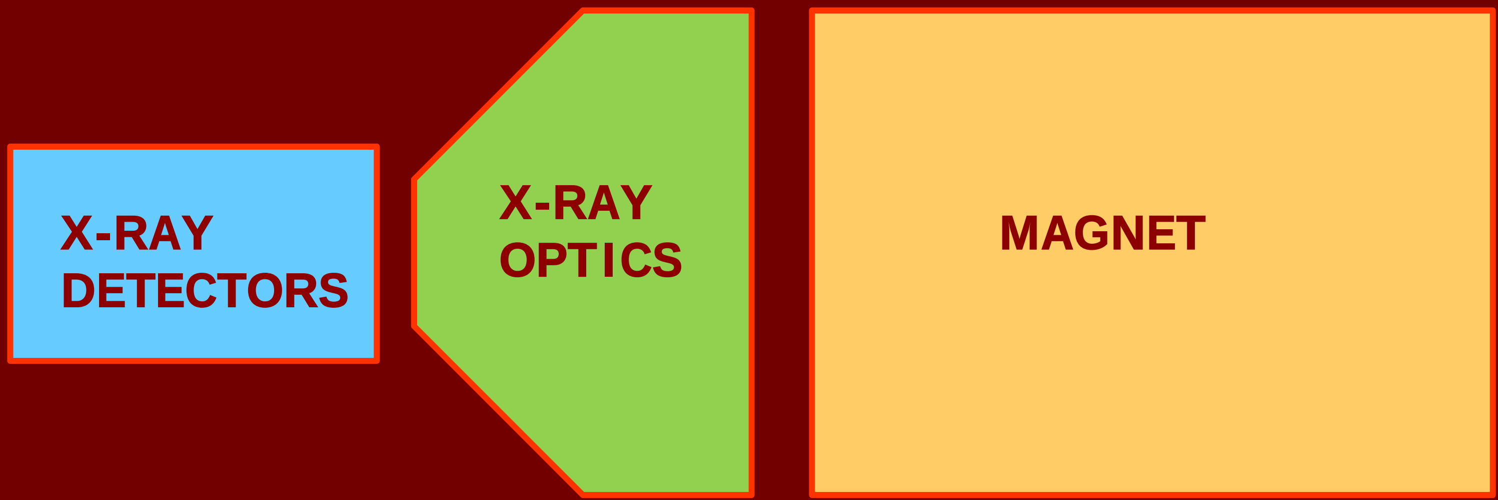


...X-ray optics,...

...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.

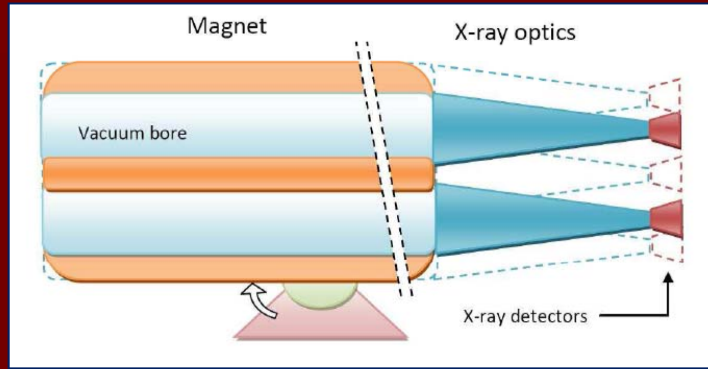
IAXO sensitivity scenarios

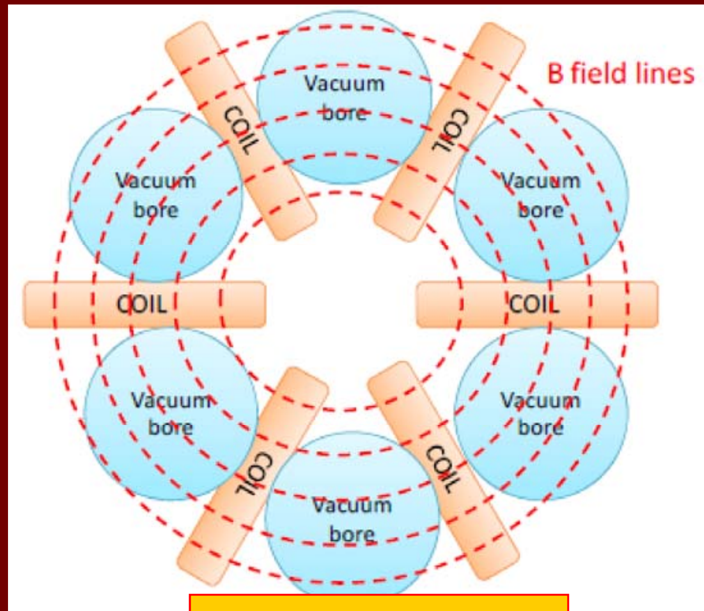
Parameter	Unit	CAST-I	Scenario 1	Scenario 2	Scenario 3	Scenario 4
B	T	9	3	3	4	5
L	m	9.26	12	15	15	20
A	m^2	2×0.0015	1.7	2.6	2.6	4.0
f_M^*		1	100	260	450	1900
b	$\frac{10^{-5}\,c}{keV\,cm^2\,s}$	~ 4	3×10^{-2}	10^{-2}	3×10^{-3}	10^{-3}
ϵ_d		0.5–0.9	0.7	0.7	0.7	0.7
ϵ_o		0.3	0.3	0.3	0.6	0.6
a	cm^2	0.15	3	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

IGI et al.
JCAP 016 (2011)

New magnet for IAXO

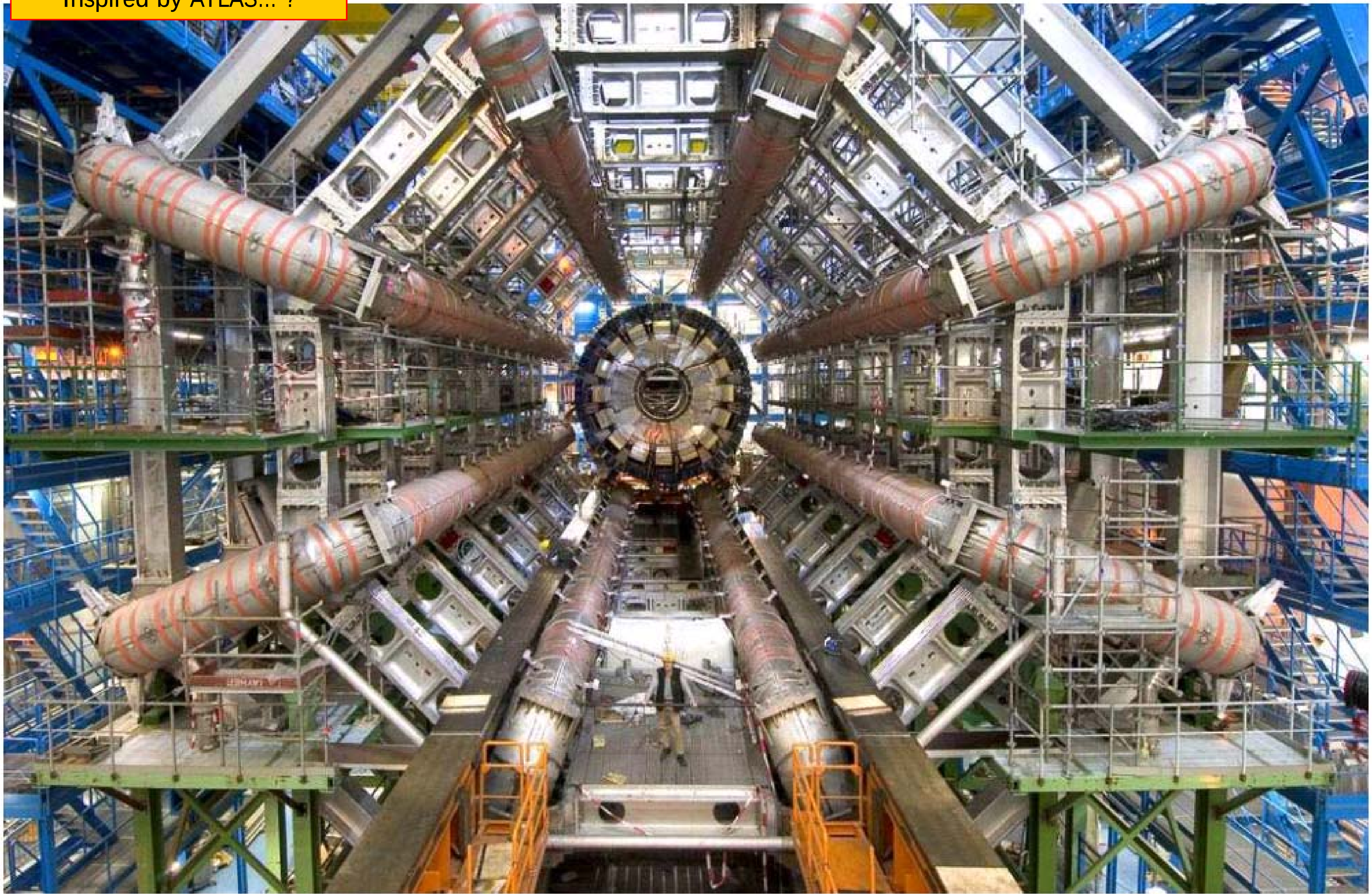
- CAST enjoys one of the best existing magnets than one can "recycle" for axion physics (LHC test magnet)
- Only way to make a step further is to built a new magnet, specially conceived for IAXO.
- After prel. study best option seems to be a **toroidal configuration:**
  - Much bigger aperture than CAST: ~0.5-1 m per bore
  - Relatively Light (no iron yoke)
  - Bores at room temperature (?)



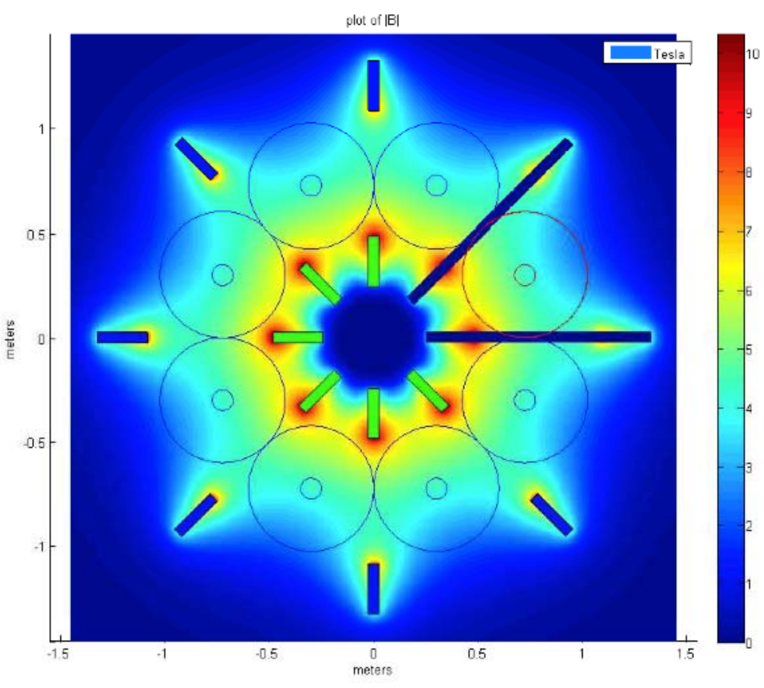


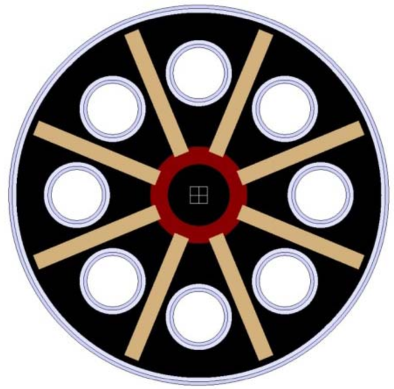
Cross section of the magnet

Inspired by ATLAS... ?

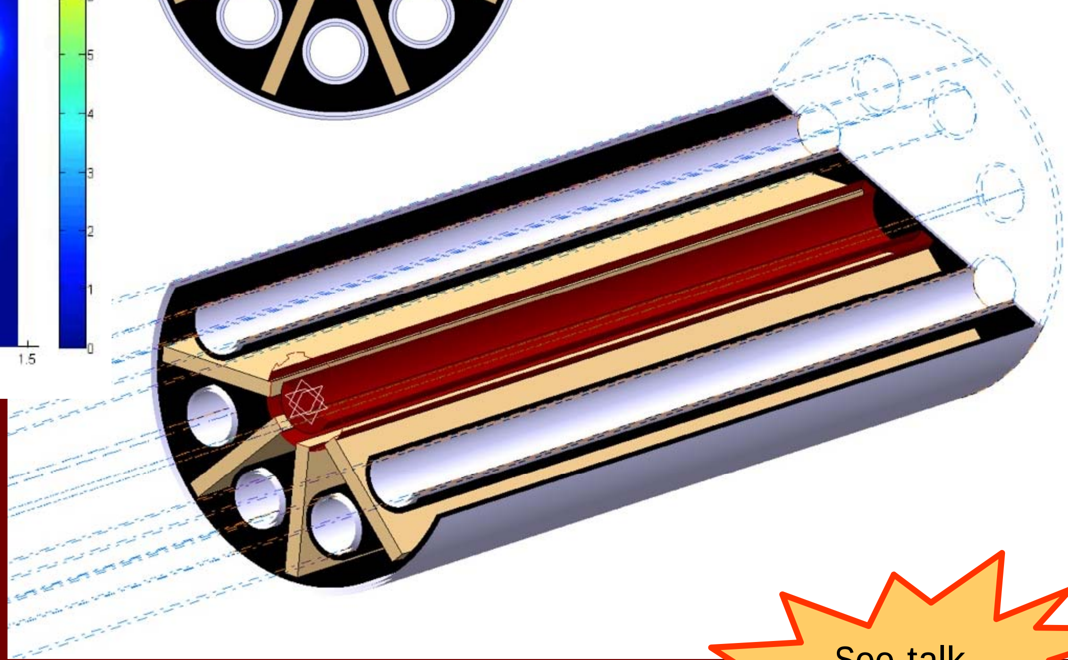


IAXO magnet: 1st concept





Total R = 2 m
Bore diameter = 600 mm
N bores = 8
Average B in bore = 4 T
(in critical surface)
MFOM = 770

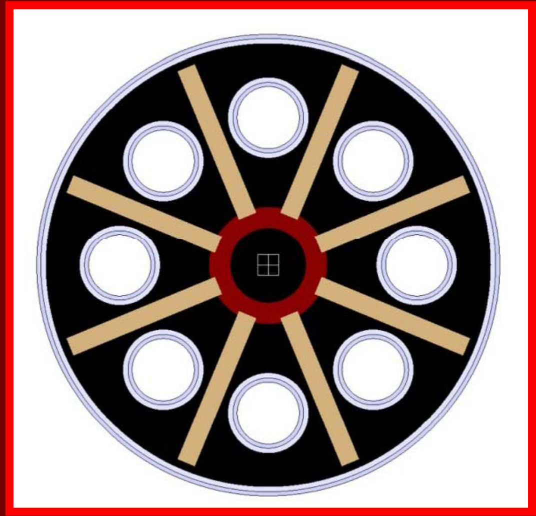


- IAXO scenario 2 conservative
- Surpass IAXO scenario 3 is possible
- Further optimization ongoing

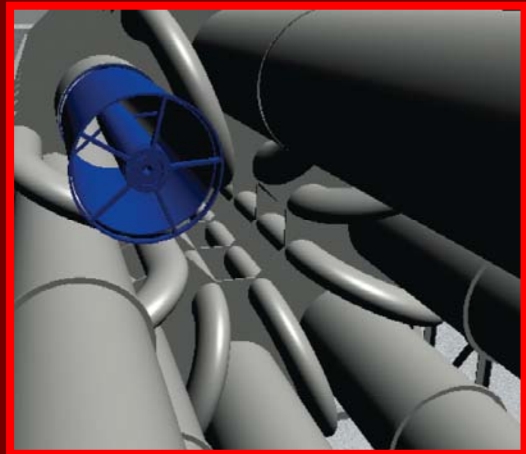
See talk **I. Shilon**

X-ray optics for IAXO

- CAST x-ray optics "recycled" from x-ray astronomy
  - High technology, expensive, "unique" objects, due to exquisite imaging properties required for x-ray astronomy.



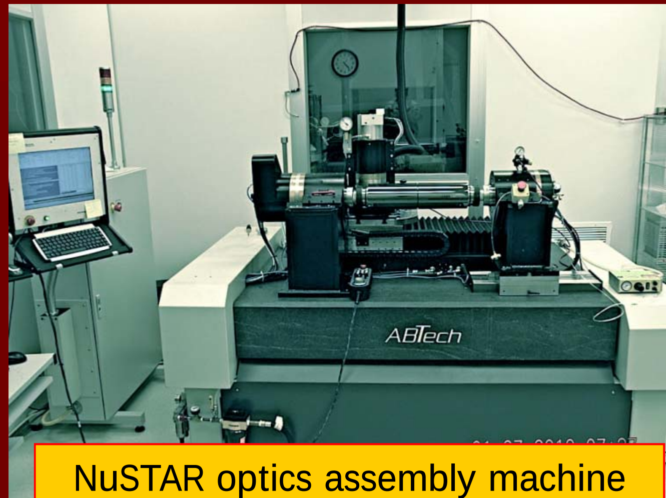
- IAXO optics:
  - Exquisite imaging not required
  - BUT, large area (~ 2 m^2) to be covered. Require fabrication of dedicated optics → cost effective solution.
  - Good throughput (0.3 – 0.5)
  - Small focal point (~1 cm2)



- **Pursued solution:** thermally-formed glass substrates optics
  - Successfully used in NUSTAR
  - Leverage existing infrastructure. Minimize costs & risks

Thermally-formed glass substrates

- NASA has recently built 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 is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !



NuSTAR optics assembly machine

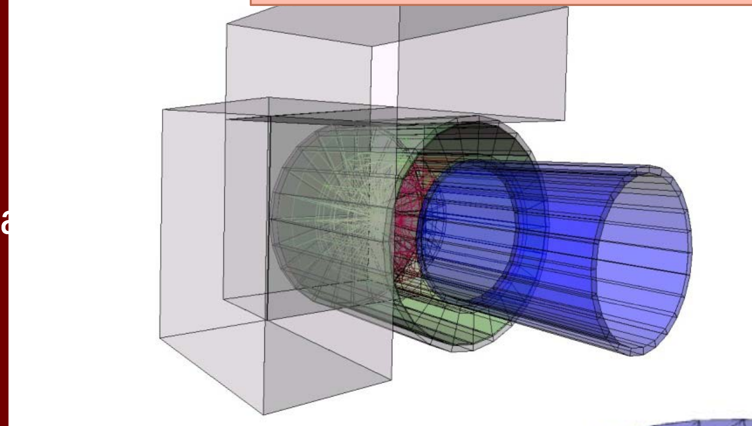
NuSTAR telescope

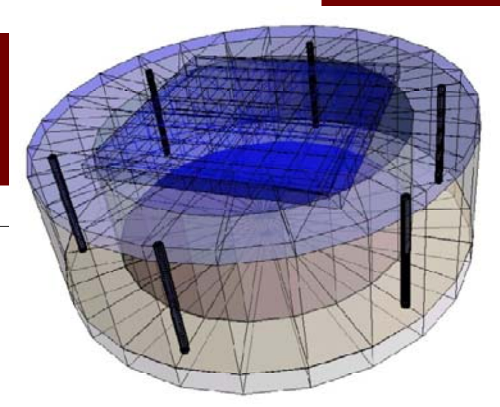
See talk
M. Pivovaroff

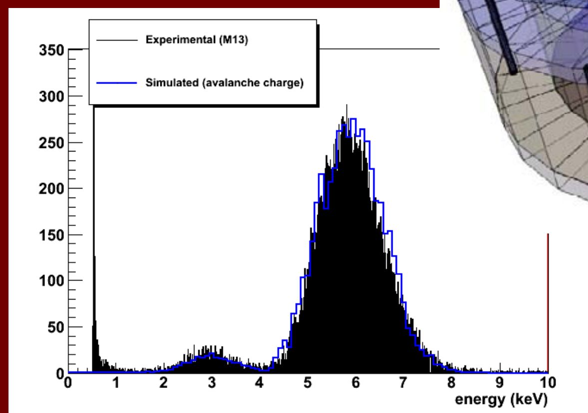
Ultralow-b detectors for IAXO

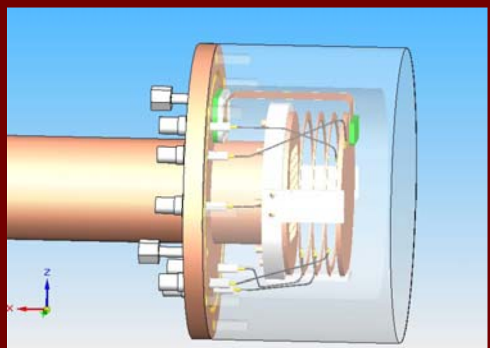
- **Goal:** at least 10^{-7} c/keV/cm^2/s, down to 10^{-8} c/keV/cm^2/s if possible.
- **Work ongoing:**
  - Experimental tests with current detectors at CERN, Saclay & Zaragoza
  - Especially: underground setup at Canfranc Lab
  - Simulation works to build up a background model
  - Design a new detector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

simulations



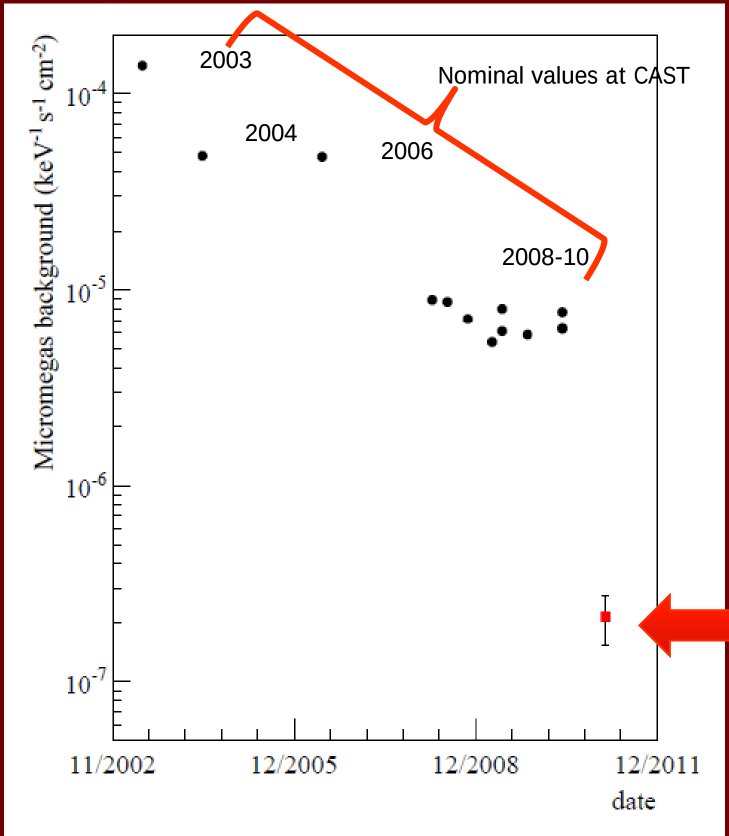




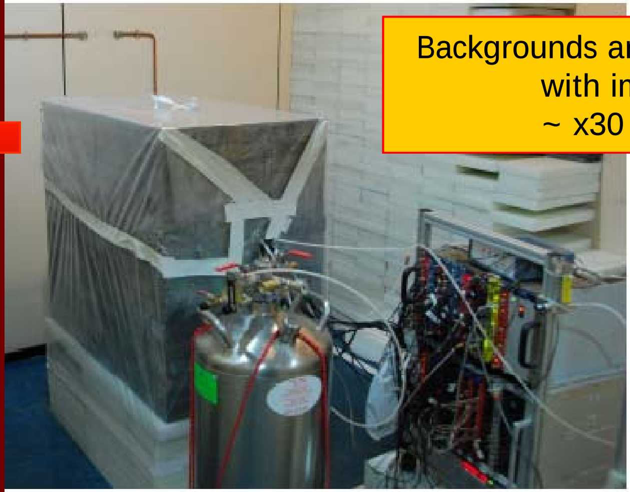


R&D low background Micromegas

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

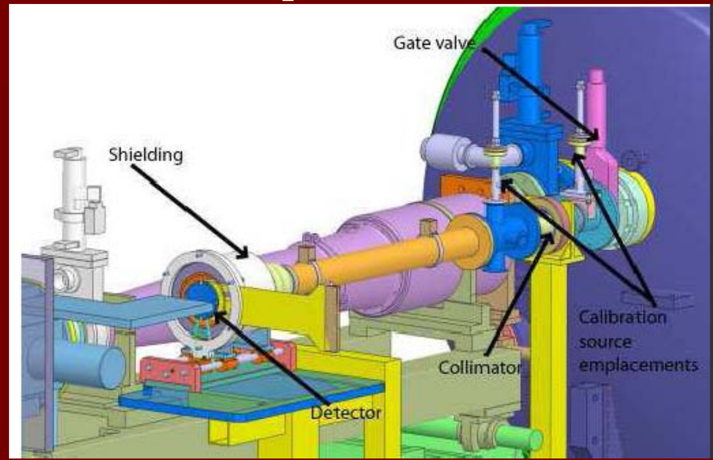


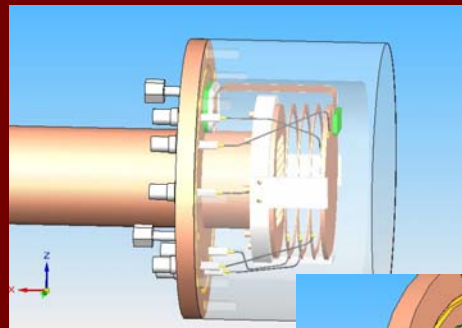
Backgrounds around 2x10-7 c/keV/s/cm2 with improved shielding ~ x30 better than CAST

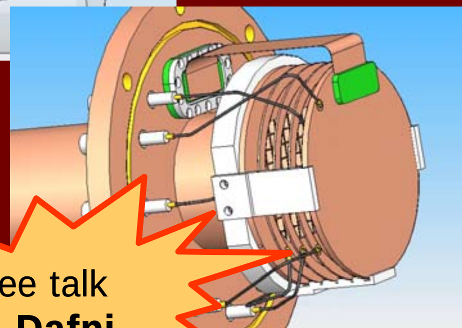
Pathfinder detector+optics

- Collaboration Saclay, Zaragoza, LLNL, DTU, U. Columbia
- Small x-ray optics (~5 cm aperture)
  - Fabricated purposely using thermally formed glass substrates
- Micromegas low background detector:
  - Apply lessons learned in R&D: compactness, better shielding, radiopurity,...
  - Goal: 10^{-7} c/keV/s/cm2 or better

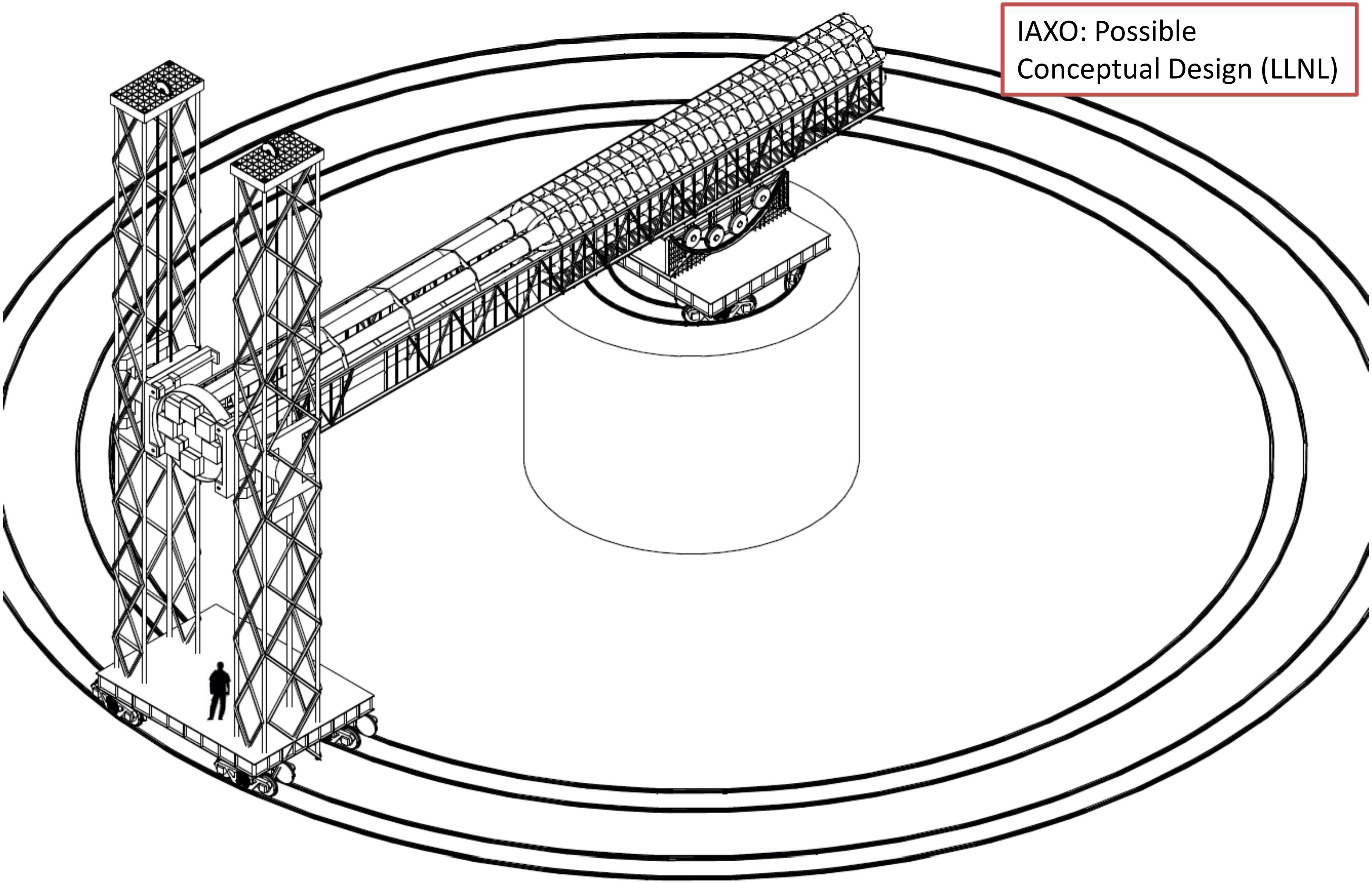
- To be operated in CAST in 2013
- Tests of techniques and know-how for IAXO



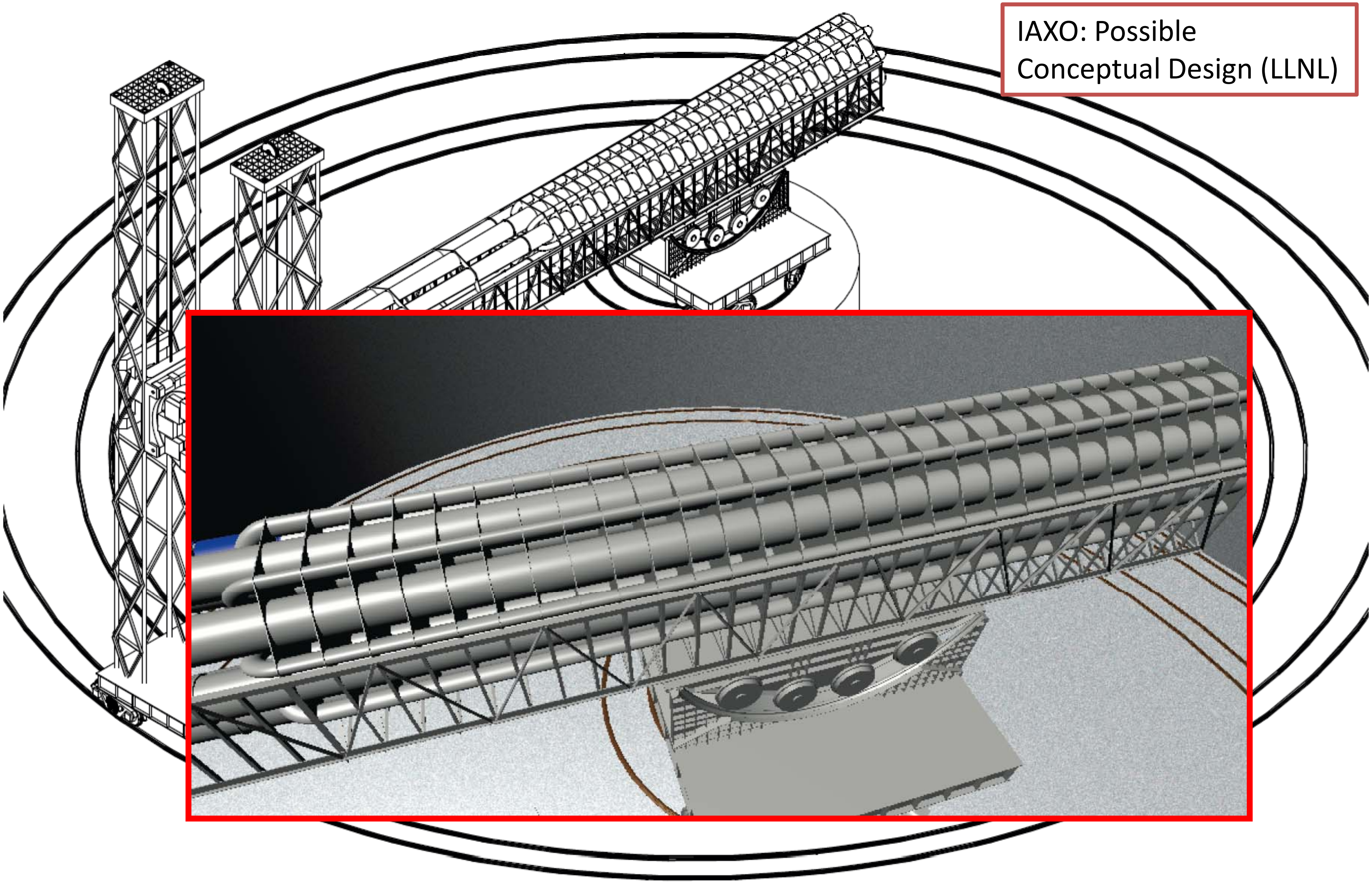




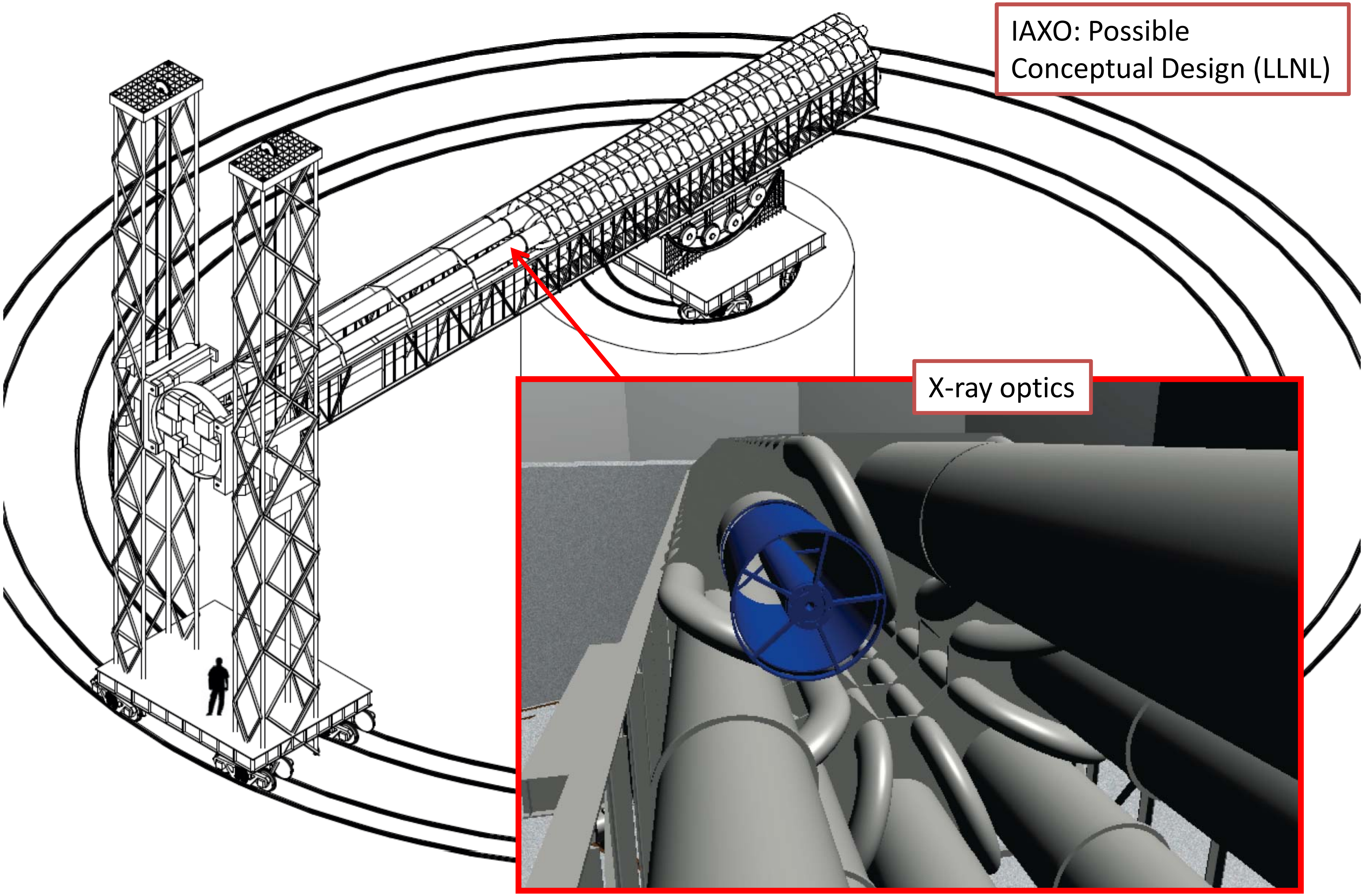
See talk **T. Dafni**

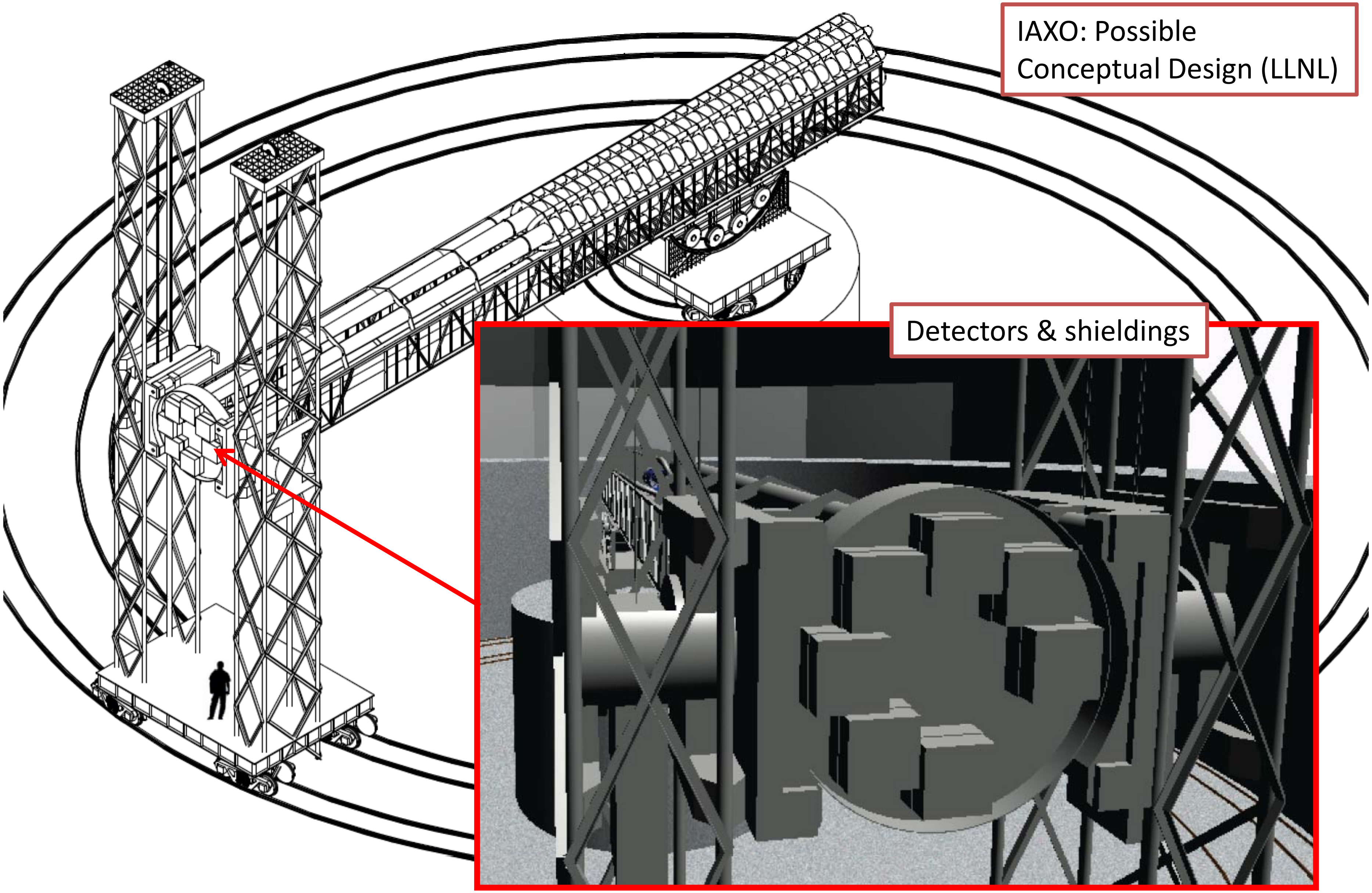


IAXO: Possible
Conceptual Design (LLNL)



IAXO: Possible Conceptual Design (LLNL)


IAXO: Possible Conceptual Design (LLNL)
X-ray optics


IAXO: Possible Conceptual Design (LLNL)
Detectors & shieldings

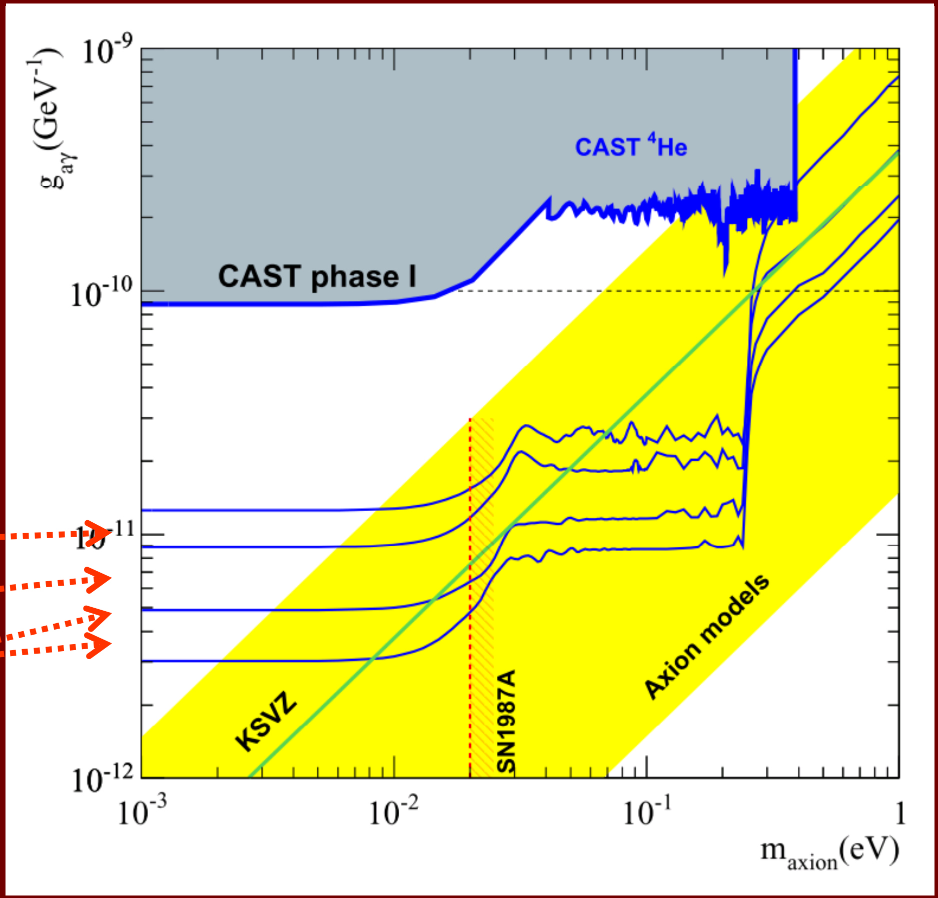
IAXO sensitivity prospects

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

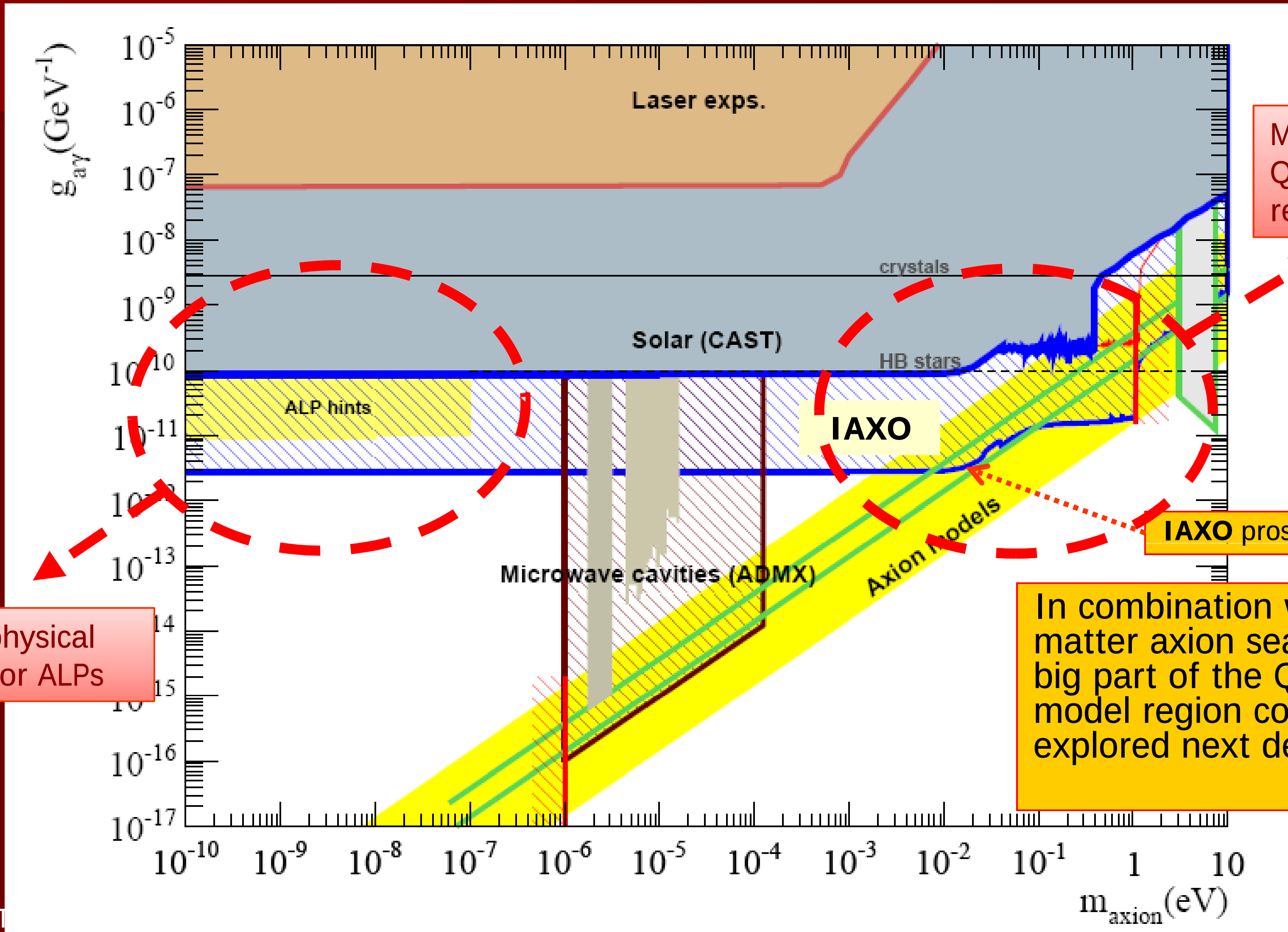
Conservative scenario

Realistic scenario

Optimistic scenarios



IAXO sensitivity prospects



Much larger QCD axion region explored

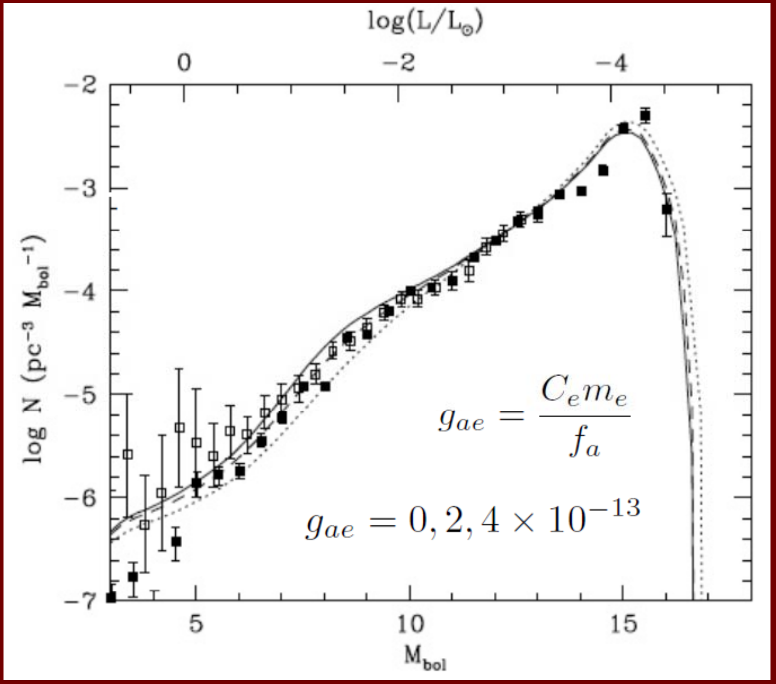
Astrophysical hints for ALPs

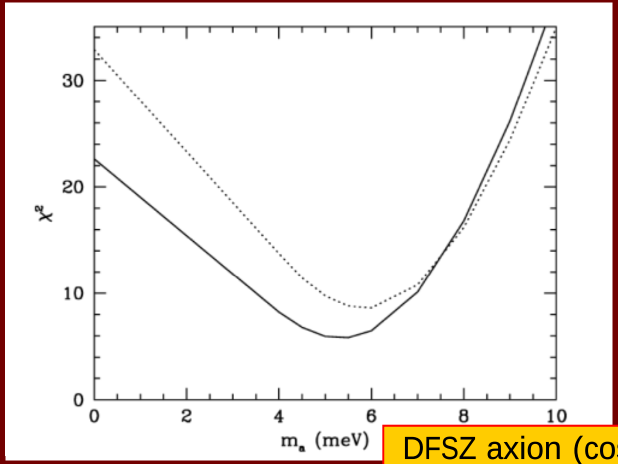
In combination with dark matter axion searches a big part of the QCD axion model region could be explored next decade.

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 ~1x10^{-13} (→ axion masses of 2-5 meV or larger) **fits data**.



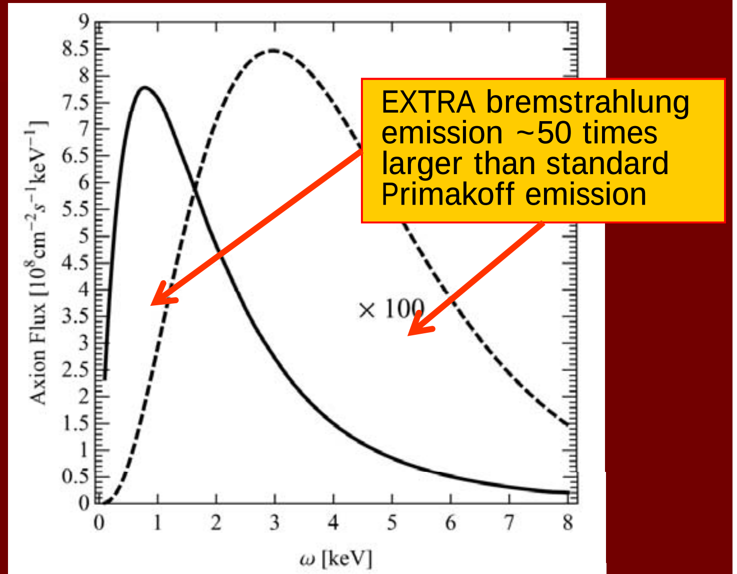


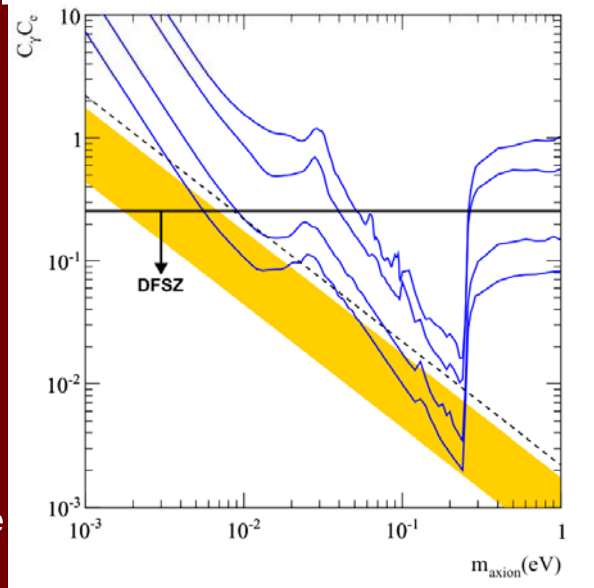
DFSZ axion (cosβ=1)

The cooling of white dwarfs

- 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 IAXO**





Further physics cases

- More specific ALP or WISP (weakly interacting slim particle) models could be searched for at the low energy frontier of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production

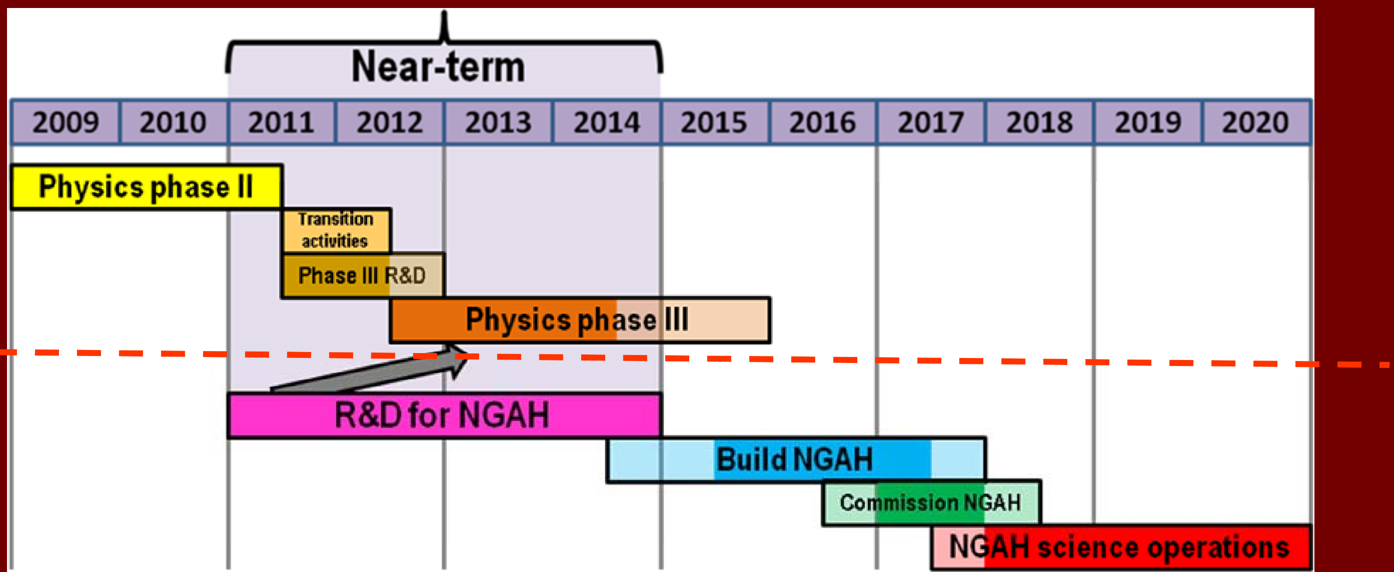
- If equipped with microwave cavities, **dark matter** halo axions could be searched for. ← under study [Baker et al. PRD 85]

- IAXO as a true "axion facility" open to the community:
- Groups invited to contribute and enrich the science programme of IAXO.

IAXO: project status & timetable

- Proto-collaboration being formed.
  - Most CAST groups
  - New groups + extended expertises (magnet, optics).
  - Open for new interested groups
- Conceptual Design Report in preparation
- Letter of Intent to be submitted to CERN soon

- CAST
- IAXO



IAXO in ASPERA

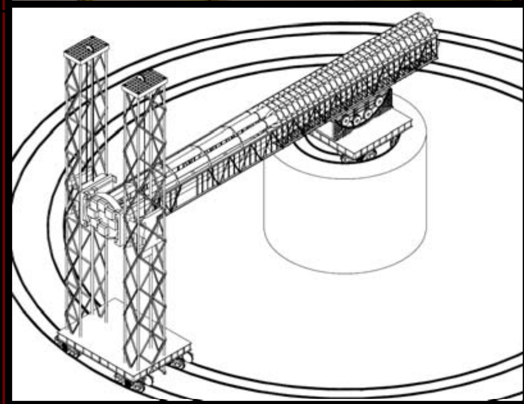
European Astroparticle Roadmap

Axions (without an imperative connection to dark matter) can be produced in the Sun's core when X-rays turn to axions in the presence of strong electric fields. On Earth, these axions can be converted back in a strong magnetic field. Arriving as axions they tunnel a wall in a large magnet and appear again as keV X-rays. This is the approach of the Axion Solar Telescope (CAST) at CERN and of the Tokyo Axion Helioscope, with CAST in a clear lead position. With $g_{a\gamma\gamma} < 10^{-10}$, the present CAST limit cannot compete with microwave cavities in the mass region below 100 μeV which is preferred for the dark matter hypothesis. Actually CAST sets a similar limit as that derived from the cooling rate of horizontal branch stars. The CAST experiment, however, plans a new experiment with the goal to reach as sensitivity of $g_{a\gamma\gamma} \sim 0.5\times10^{-11}$, and there are even ideas towards extending sensitivity to $g_{a\gamma\gamma}$ by another order of magnitude. This would, at least, cover a non-negligible part of the $g_{a\gamma\gamma}$-m_a parameter space predicted by QCD axion models for axion masses larger a few meV.

A CAST follow-up is discussed as part of CERN's physics landscape. It requires new magnets with increased field and aperture, as well as improved cryogenic and X-ray detection devices. Even if not all approaches in this field are strictly related to dark matter, there is a potential for revealing new physics. **Therefore we support the continuation of the corresponding programs.**

→ Latest draft of the ASPERA roadmap 2011

Conclusions



- **CAST** is the most powerful axion helioscope to-date.
  - Established as a reference result in axion physics.
  - First CAST PRL most cited axion experimental result ever.
  - Expertise gathered in magnet, optics, low back detectors
- **IAXO:** International Axion Observatory.
  - A new generation axion helioscope
  - First results (JCAP 016) show good prospects to improve CAST 1-1.5 orders of magnitude in $g_{a\gamma\gamma}$.
  - First solid steps towards conceptual design
- In combination with dark matter axion searches (ADMX) a big part of the QCD axion model region could be explored next decade.
- Potential for other physics cases: white dwarfts e-coupled axions?, relic axions?, ALPs?...
- IAXO as a "axion/ALP research facility".
- New groups to enlarge and enrich IAXO.