A New Generation Axion Helioscope

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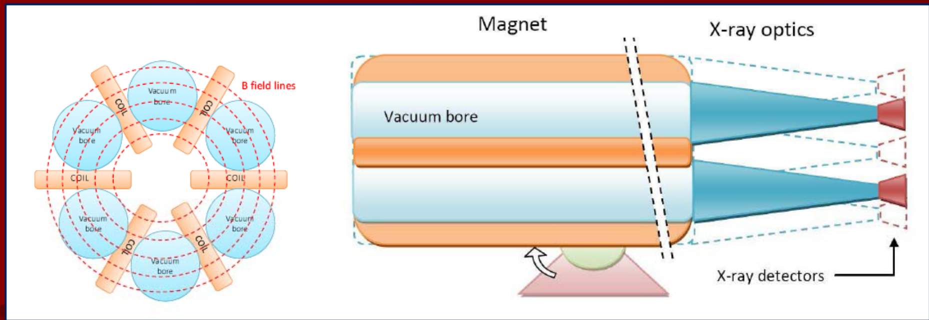

Outline

- Outline:
  - Axions: motivation, theory, cosmology.
  - Solar axions &
    the axion helioscope concept
  - Previous helioscopes & CAST
  - Technical prospects for a new helioscope
  - Sensitivity prospects
  - Conclusions

- Talk based on

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Towards a new generation axion helioscope

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AXION theory motivation

- Axion: introduced to solve the **strong CP problem**

In QCD, nothing prevents from adding a terms like that
to the lagrangian:

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

($\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}$)

In fact, two known facts may induce such kind of term:

- The structure of the QCD vacuum ($U(1)_A$ problem)
- EW quark mixing

2 contributions of
very different origin…

$$\theta = \bar{\theta} + \arg\det M\ .$$

AXION theory motivation

- Axion: introduced to solve the **strong CP problem**

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

This term is **CP violating**. But strong interactions are not observed to violate CP

In particular, this term would predict an electric dipole moment for the neutron of a magnitude:

$$|d_n| = A|\theta| \times 10^{-15} e \times cm$$ (A = 0.04 – 2.0)

AXION theory motivation

- But experiment says…

$$|d_n| < 2.9 \times 10^{-26} e\text{cm}$$

So,

$$\boxed{|\theta| < 0.7 \times 10^{-11}}$$

- **Why so small?**
- **High fine-tunning of two different contributions required**

Peccei-Quinn (1977) propose an elegant solution to this problem.
θ not anymore a constant, but a field → the axion a(x).
Fine-tunning reached naturally, dinamically.

AXION theory motivation

- **Peccei-Quinn solution** to the strong CP problem
  - New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale f_a
  - The AXION appears as the **Nambu-Goldstone boson** of the spontaneous breaking of the PQ symmetry

"Axion lagrangian"

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G \tilde{G}$$

θ absorbed in the definition of a

$\theta = \alpha/f_a$ relaxes to zero…
CP conservation is preserved "dinamically"

THE AXION

- The PQ scenario solves the strong CP-problem. But probably most interesting than this is the appearance of this new particle, the *axion*.

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

- **Basic properties:**
  - Pseudoscalar particle
  - Neutral
  - Very light (but not massless).
  - Stable (for practical purposes).
  - Phenomenology driven by the PQ scale f_a.

AXION models

- **PQ scale**
  - Original axions: f_a ~ electroweak scale

    ← too strong couplings, ruled out by experiment
  - Otherwise: f_a >> electroweak scale

- **PQ charges** of SM fermions (or additional ones)
  - KSVZ axions: only new exotic quarks carry PQ ("hadronic axions")
  - DFSZ axions: SM fermions do carry PQ charge.

Therefore, direct axion-fermion couplings are model-dependent.

Other basic axion properties are more **model-independent**

AXION phenomenology

- **Axion-gluon vertex** present in every axion model

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

axion – gluon vertex

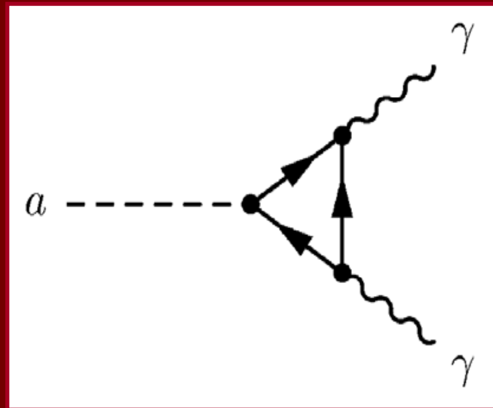
And therefore…

- **Axion-nucleon** coupling
- **Axion-pion** mixing
- **Axion gets a mass** through its mixing with the pion
  - Mass very small, but not zero.
  - Mass is related to the PQ scale

$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

AXION phenomenology

- **Axion-photon coupling** present in every model. 2 contributions:
  - Through axion-pion mixing.
  - Through fermion loops, for fermions with both a PQ charge and electric charge (therefore, model-dependent).



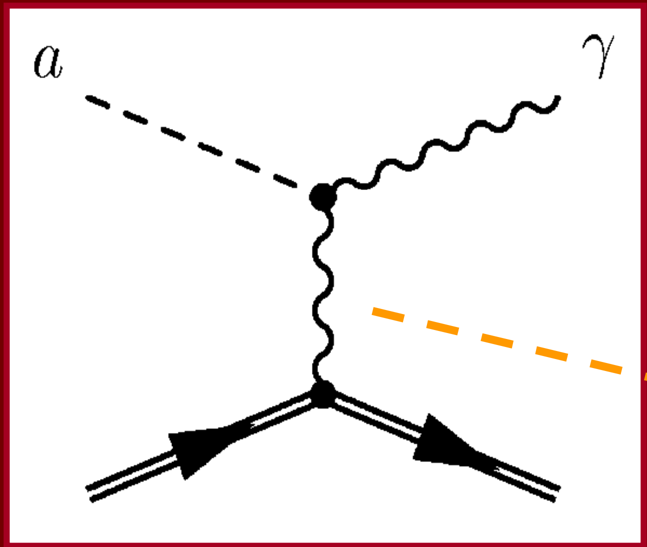
$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$$

$$g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

This is probably the most relevant of axion properties.
Most axion detection strategies are based on the axion-photon coupling

AXION phenomenology

- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)

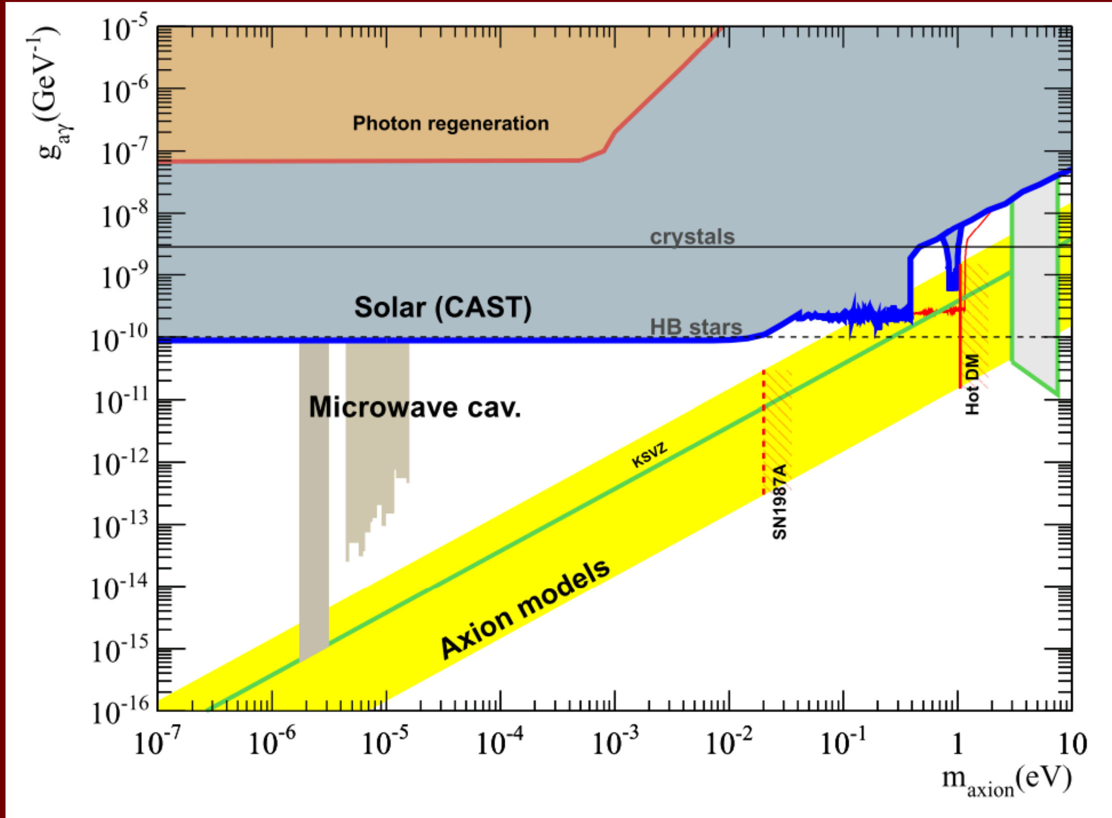


- This can be
  - an artificial magnetic field
  - The Coulomb field of the plasma in the core of a star
  - The periodic E field of a crystalline structure
  - …

Axion-like particles (ALP)

(or WISPs = Weakly Interacting Scalar Particle)

- Any pseudoscalar (or scalar) particle, neutral, light, and coupled to the photon, is considered an ALP, whatever the theory behind it.
- In this wider context, $g_{a\gamma\gamma}$ and m_a are two independent "phenomenological" parameters.
- The "proper" axion (or QCD axion) lies in a limited region of this space (yellow band)



AXION 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

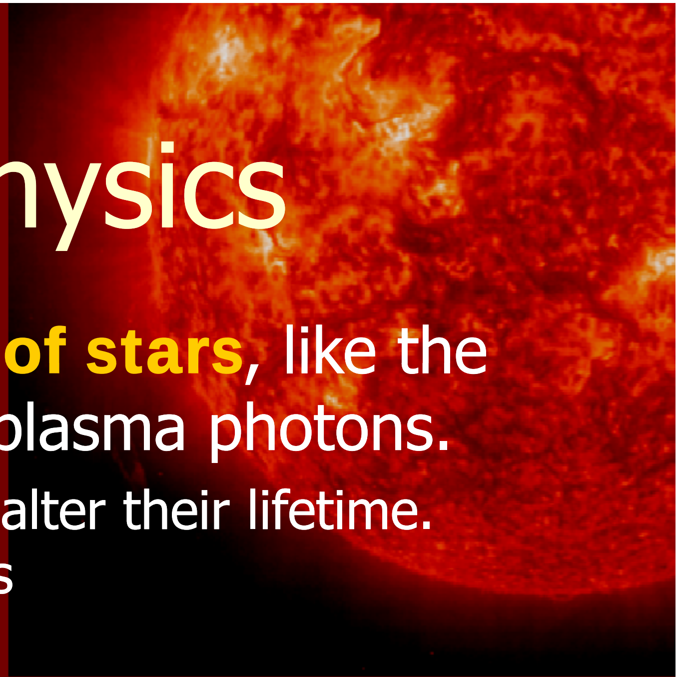
  - In general, Range of axion masses of **10^{-6} – 10^{-3} eV** are of interest for the axion to be the (main component of the) CDM.

  - Thermal production

  → RELATIVISTIC (HOT) AXIONS

- In order to have substantial relativistic axion density, the axion mass must be close to 1 eV. (**ma > ~0.9 eV** gives densities too much in excess to be compatible with latest CMB data)

Hannestad et al, JCAP 08 (2010) 001 (arXiv:1004.0695)



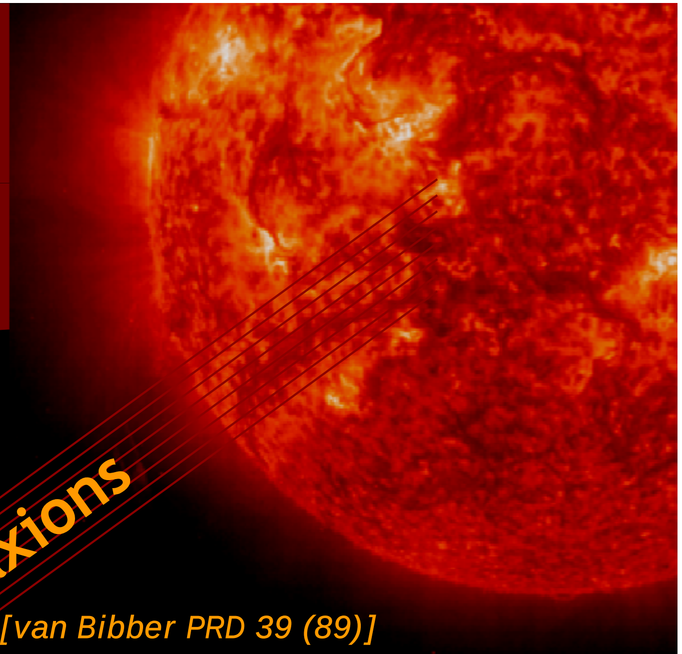
Axions in Astrophysics

- **Axions are produced at the core of stars**, like the Sun, by Primakoff conversion of the plasma photons.
  - Axions drain energy from stars and may alter their lifetime. Limits are derived to the axion properties
  - Solar Age: $g_{a\gamma} \sim< 3 \times 10^{-9}\ \mathrm{GeV}^{-1}$
  - Helioseismology: $g_{a\gamma} \sim< 10^{-9}\ \mathrm{GeV}^{-1}$
  - Neutrino flux: $g_{a\gamma} \sim< 7 \times 10^{-10}\ \mathrm{GeV}^{-1}$ [arXiV 0807.2926]
  - Helium burning lifetime: $g_{a\gamma} \sim< 10^{-10}\ \mathrm{GeV}^{-1}$
  - SN 1987A

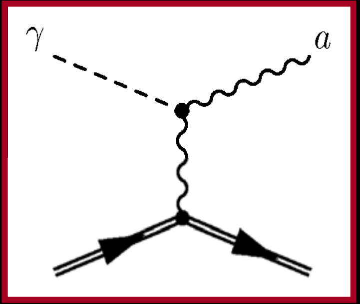
See Raffelt astro-ph/0611118 and references therein

- **Axion decay** $a \rightarrow \gamma\,\gamma$ may produce gamma lines in the emission from certain places (i.e. galactic center).
  - But axion decay constant is normally very long (>> Universe life)

Solar Axions



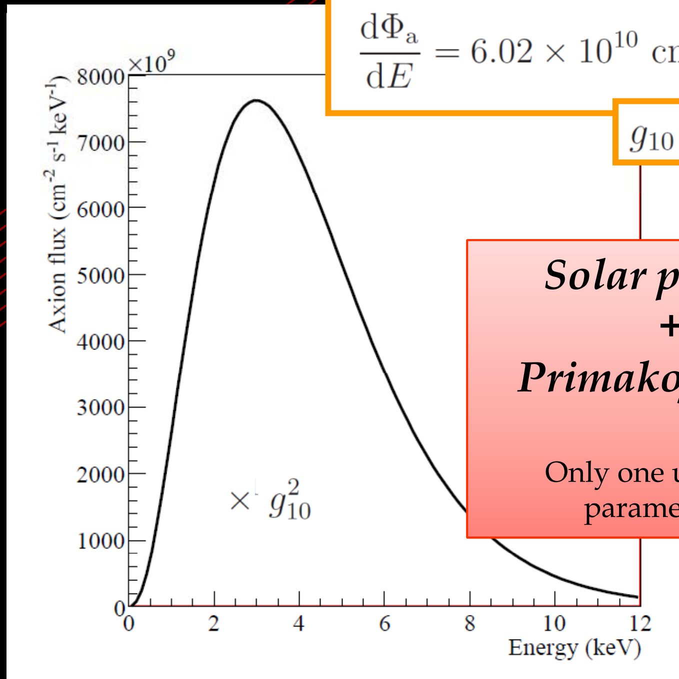
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



➢ *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 $g_{a\gamma}$

ALP astrophysical "hints"

- Observation of gamma-rays from distant sources

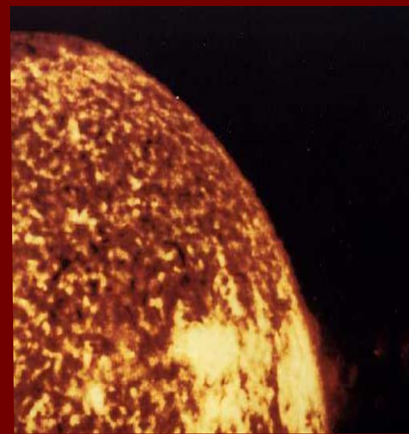
[MAGIC arXiv:0709.1475, HESS, Nature 440 (2006) 1018]

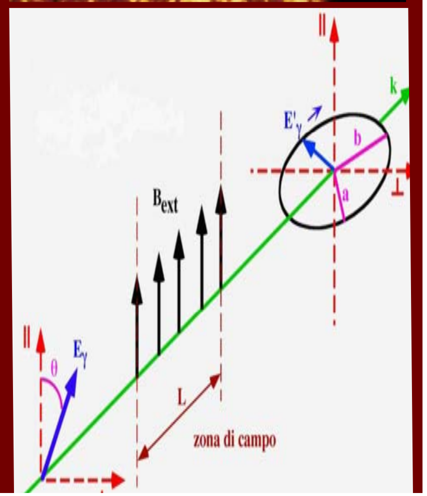
- Observation of UHE cosmic rays from distant sources
- AGN luminosity relations [Burrage et al. PRL 102 (2009)]
- Correlations in quasar polarization observed at Gpc distances. Probably local effect: axion-photon mixing in the galactic magnetic field. [Payez et al arXiv:0805.3946]

- White-dwarf luminosity function: favors axion coupled to electrons [Isern et al 2008 ApJ 682]

Axion Searches

- Axions are searched in 3 different contexts (different sources of axions):
  - Dark matter axions (as relics of Big Bang):
    - Axion Haloscopes (**ADMX**, CARRACK)
  - Axions produced in the Sun:
    - Axion Helioscopes (Kyoto, **CAST**)
    - Crystal detectors (SOLAX, COSME, DAMA)
  - Axions produced in the laboratory
    - "Light shinning through wall" experiments
    - Vacuum birrefringence experiments





Solar Axions

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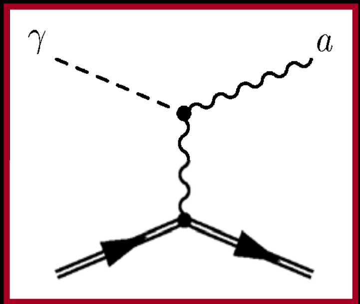

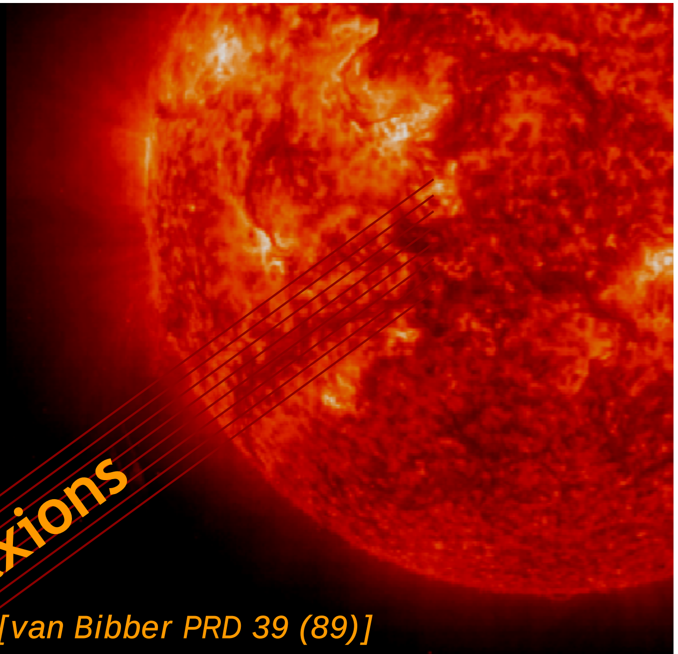

axions

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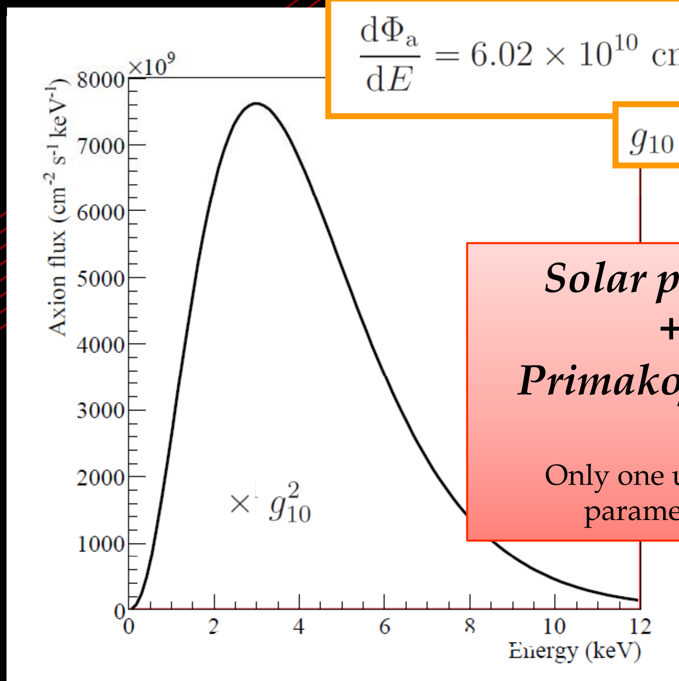


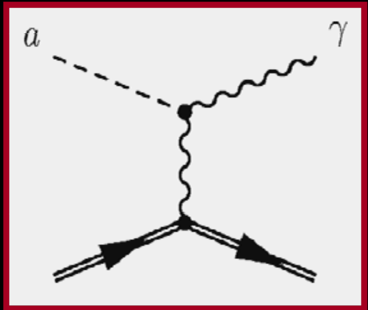
Solar physics
+
Primakoff effect

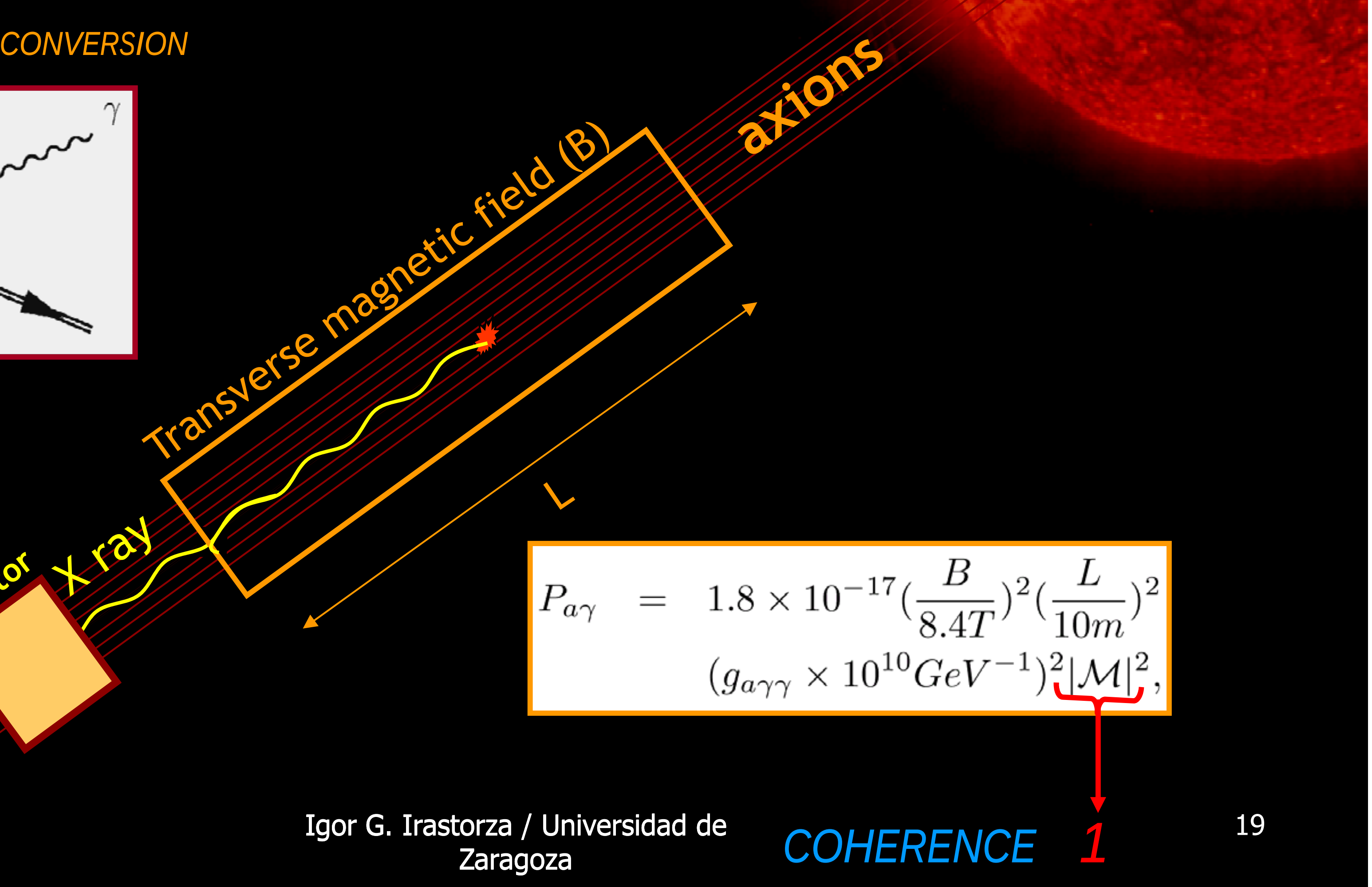
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

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

AXION PHOTON CONVERSION

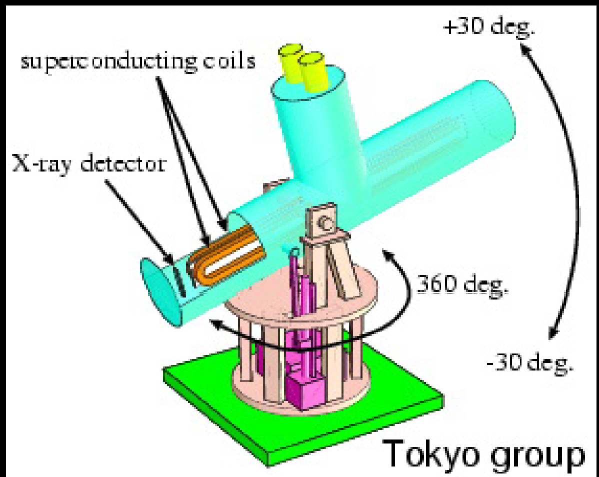


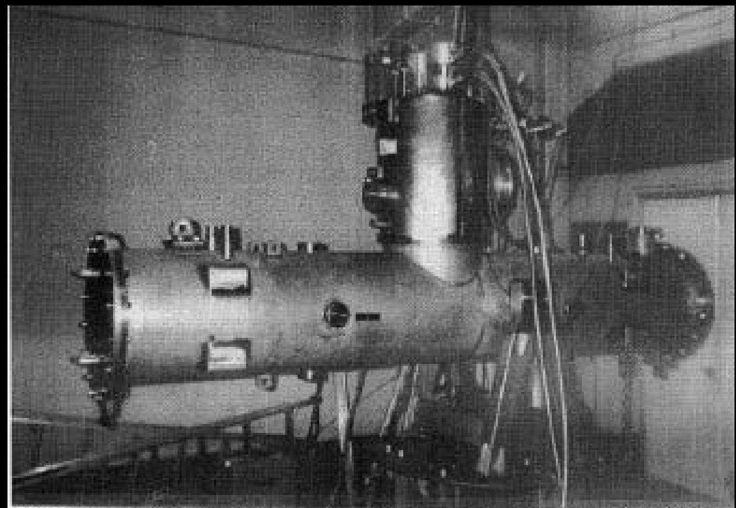


$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 \underbrace{|\mathcal{M}|^2}_{1},$$

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

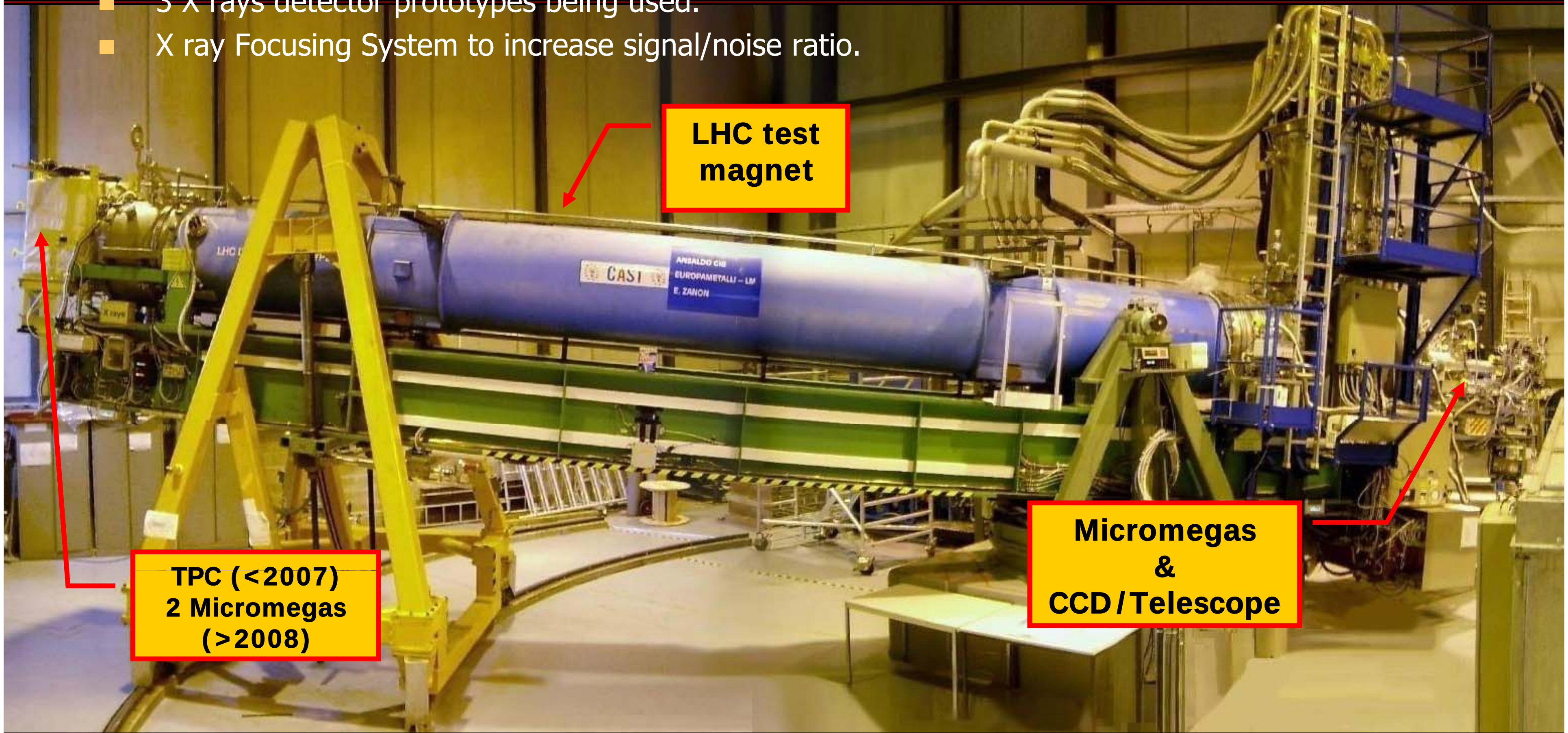




- Presently running:
  – CERN Axion Solar Telescope (**CAST**)

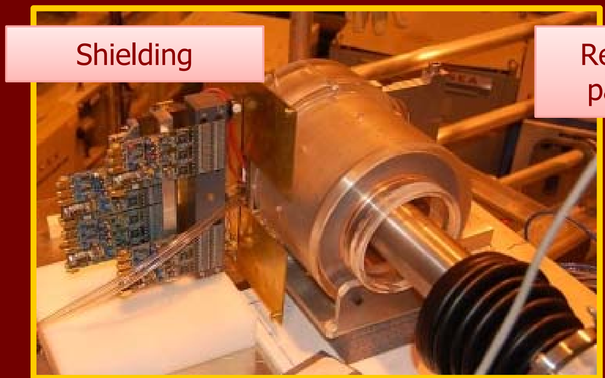
CAST experiment @ CERN

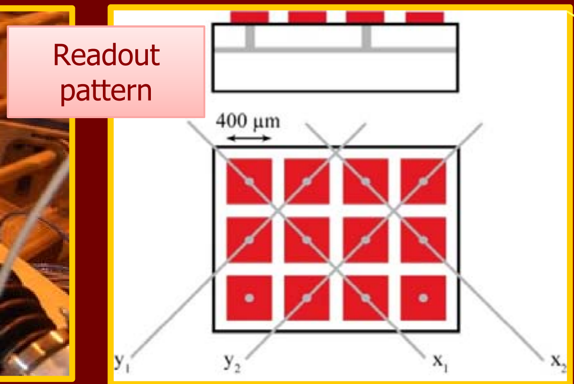
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.

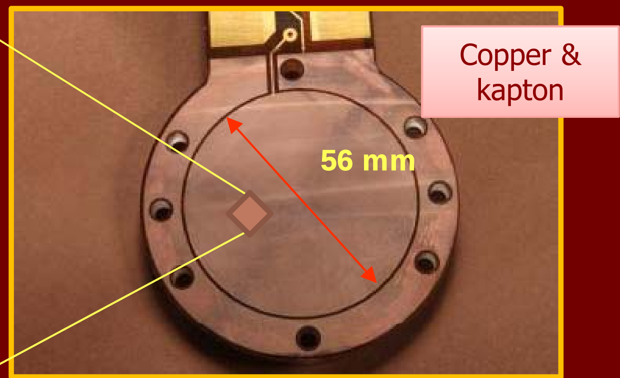


Low background x-ray detectors

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

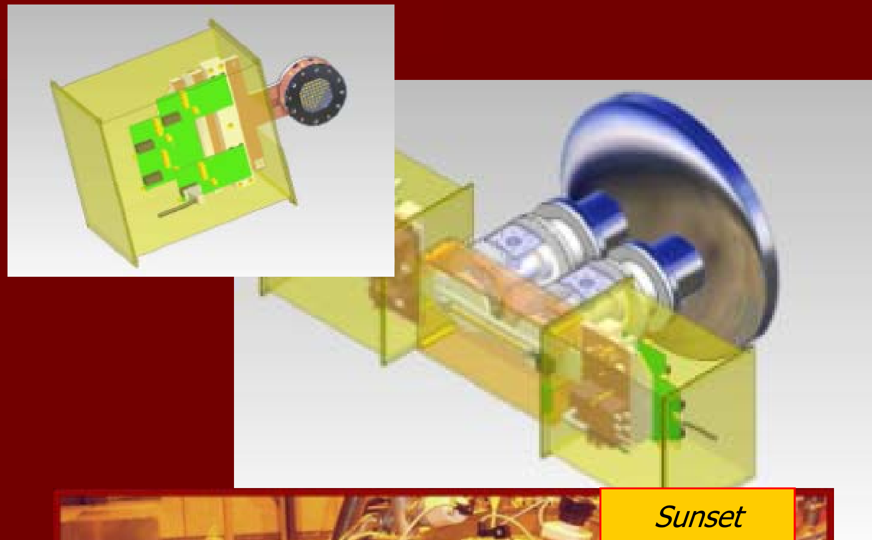


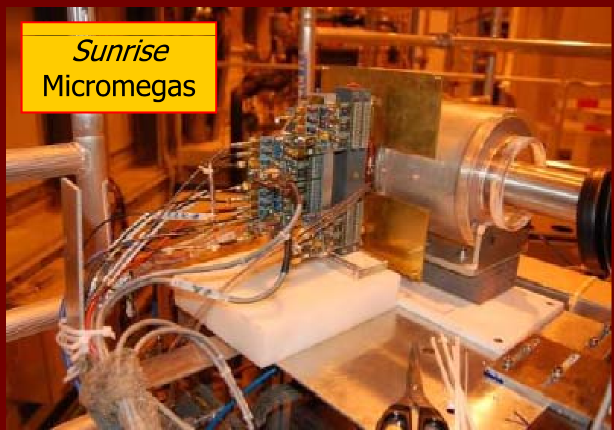


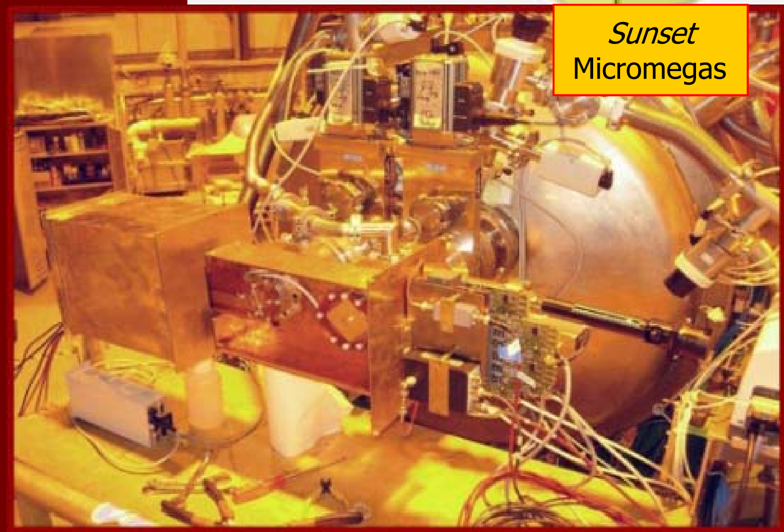


Micromegas detectors @ CAST

- Since 2008 2 new Micromegas detectors replaced the 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

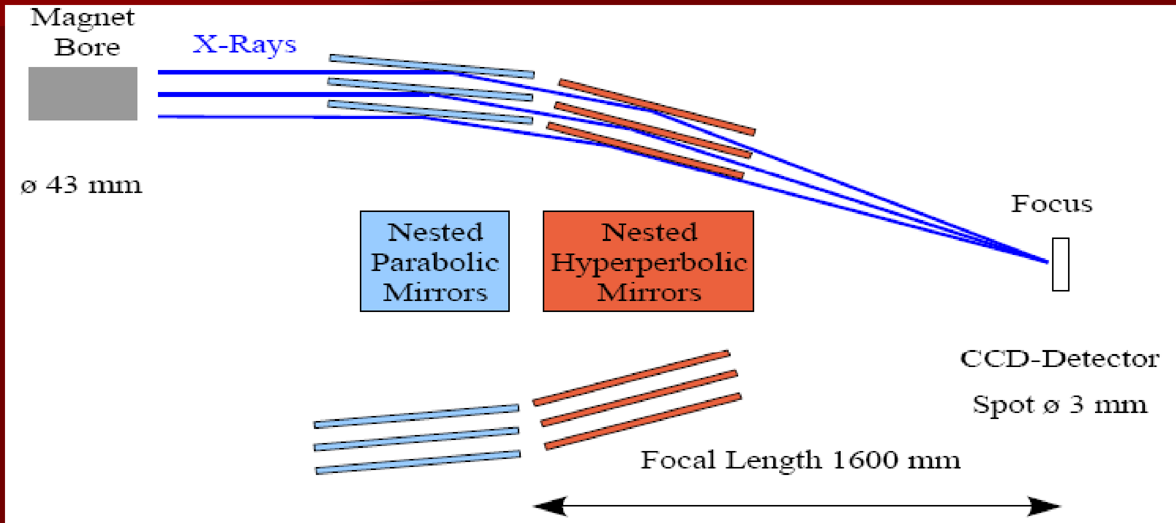


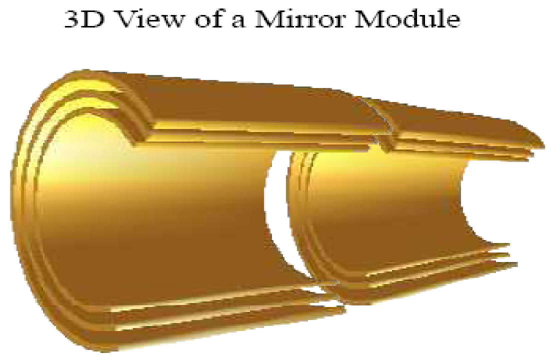




CAST X-ray telescope

- CAST innovation of the “helioscope concept”



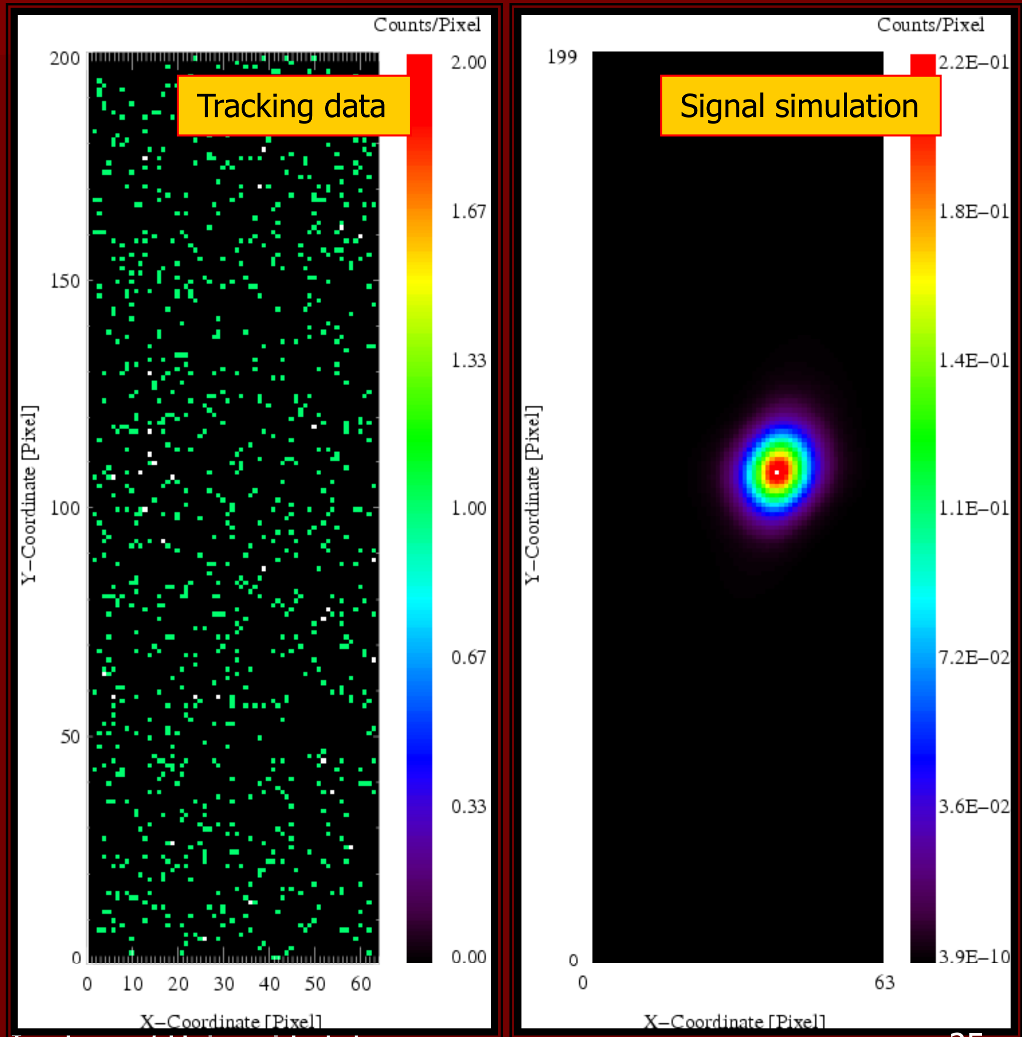


- Wolter I type grazing incident optics (prototype for ABRIXAS mission)
- From Ø43 mm (magnet bore) → Ø3 mm spot

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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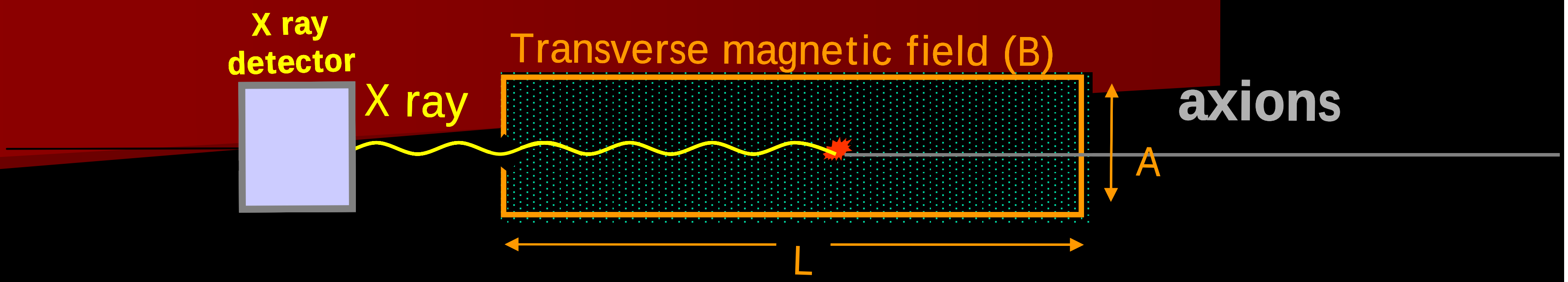
Buffer gas to go to higher masses



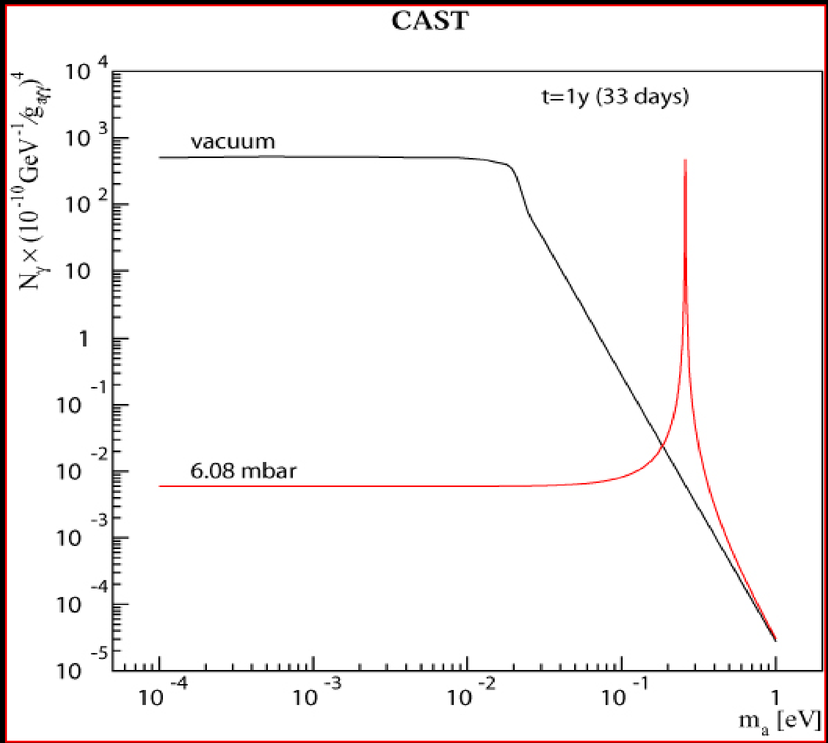
Extending the coherence to higher axion masses...

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

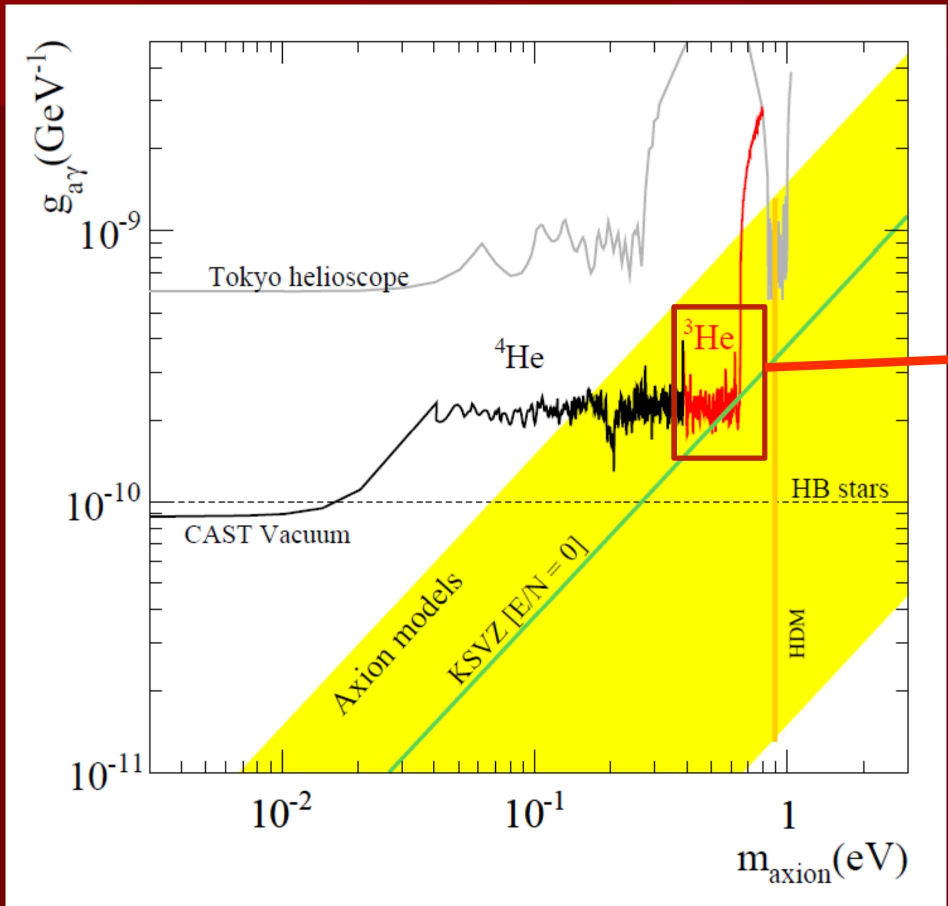
$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

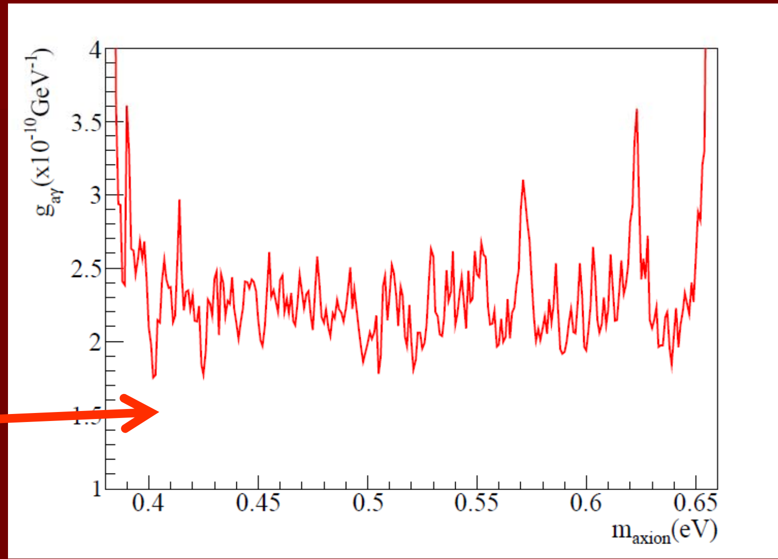
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \mathrm{eV}$$

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



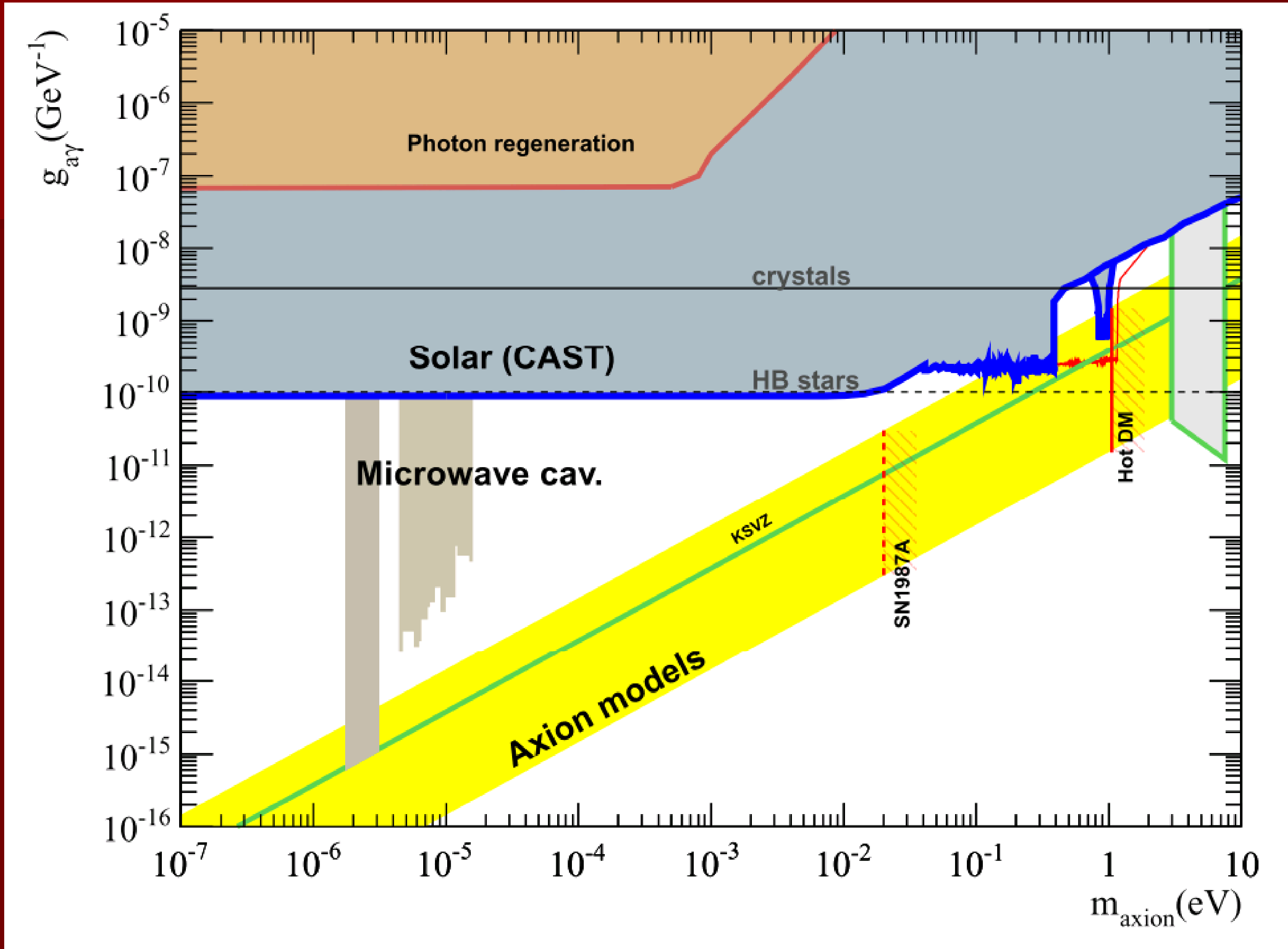
Latest CAST results





- 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.

Publicaton just accepted by PRL:
S. Aune et al. (CAST collaboration)
arXiv:1106.3919v1



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

Towards a new generation axion helioscope

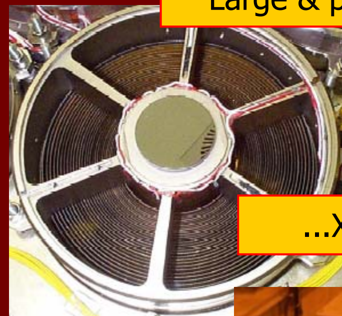
- CAST is established as a reference result in experimental axion physics CAST PRL2004 most cited experimental paper in axion physics
- No other technique can realistically improve CAST in a wide mass range.

- **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...

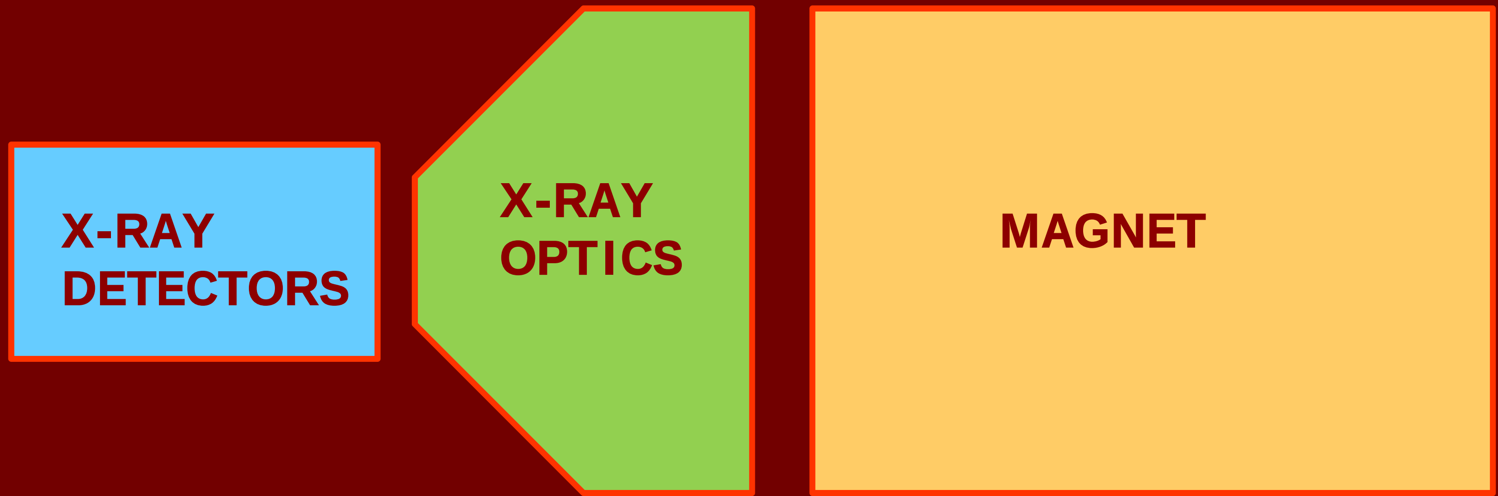


...X-ray optics,...

...and low background detectors

Axion Helioscopes FOM

- 3 elements drive the sensitivity of an axion helioscope



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

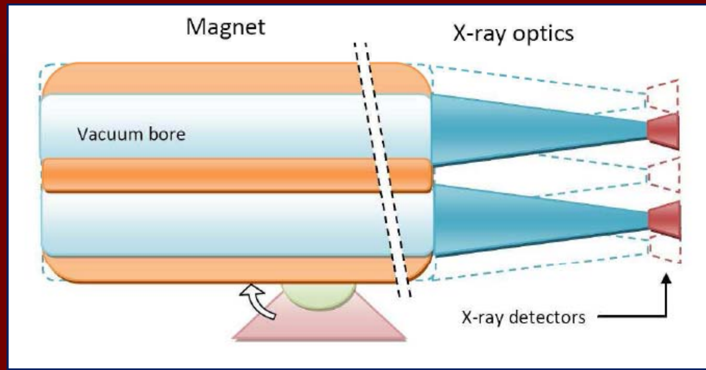
where b is the time- and area-normalized background of the detector, ϵ_d its efficiency; a is the focal spot area of the optics, ϵ_o its througput, B is the magnet field strength, L its length, and A its cross sectional area; t is the exposure time.

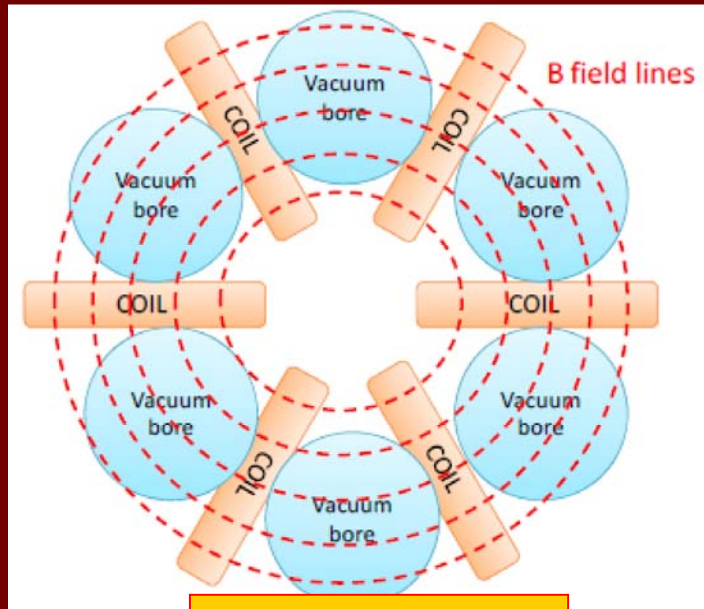
Sensitivity scenarios

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

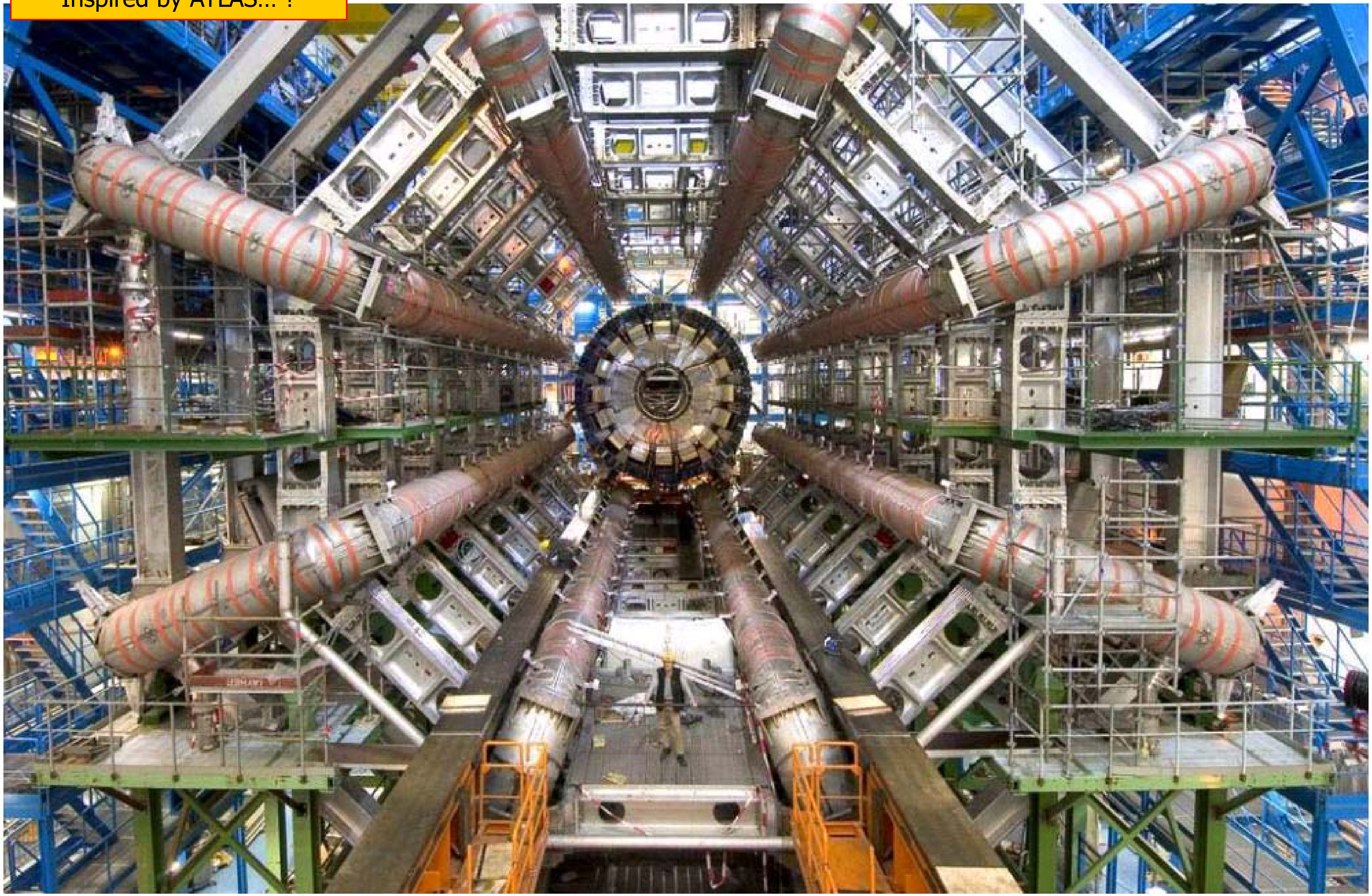
- CAST enjoys one of the best existing magnets than one can “recycle” for axion physics (LHC test magnet)
- Only way to make a step further is to built a new magnet, specially conceived for this.
- Work ongoing, but best option up to now is a **toroidal configuration:**
  - Much bigger aperture than CAST: ~0.5-1 m per bore
  - Relatively Light (no iron yoke)
  - Bores at room temperature (?)





Cross section of the magnet

Inspired by ATLAS… ?

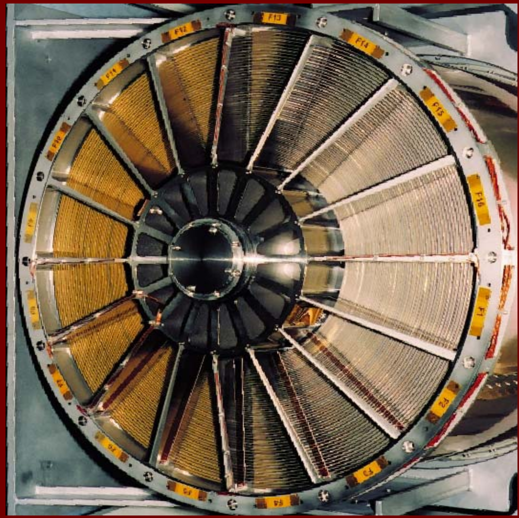


X-ray optics

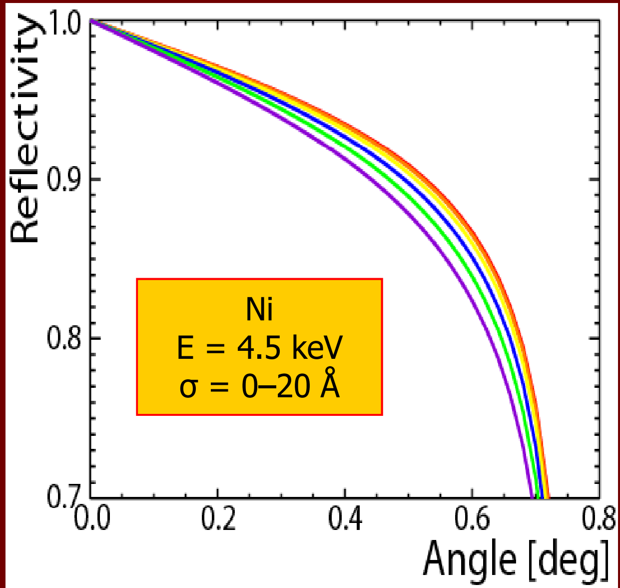
- During the last four decades, the x-ray astronomy community has devoted billions of dollars to develop reflective x-ray optics

- 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

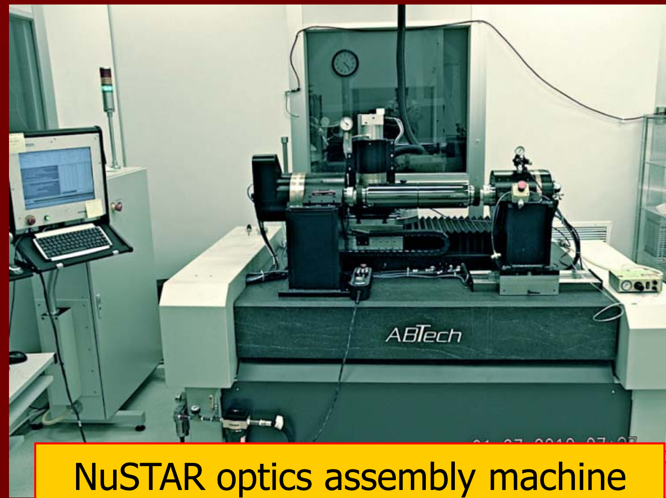


XMM-Newton telescope with 56 nested shells



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



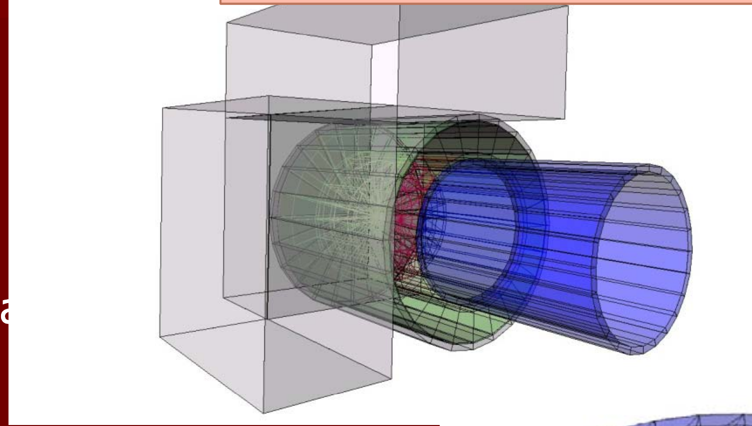
NuSTAR optics assembly machine

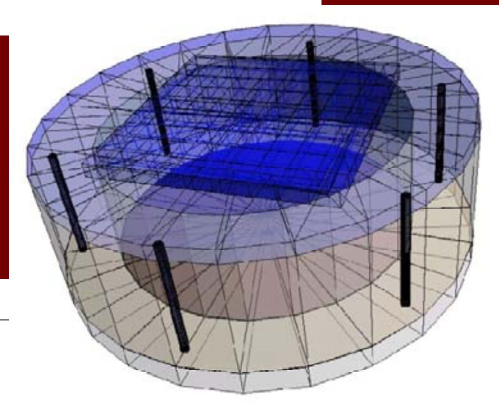

NuSTAR telescope

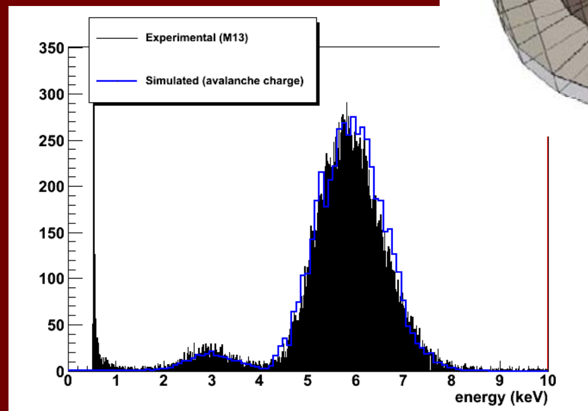
An ultralow-b MM for the NGAH

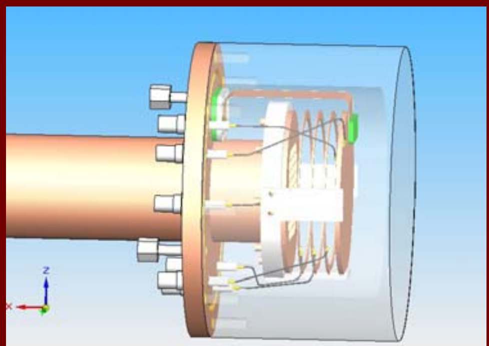
- **Goal:** at least 10^{-7} c/keV/cm^2/s, down to 10^{-8} c/keV/cm^2/s if possible.
- **Work ongoing:**
  - Experimental tests with current detectors at CERN, Saclay & Zaragoza
  - Especially: underground setup at Canfranc Lab
  - Simulation works to build up a background model
  - Design a new detector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

simulations



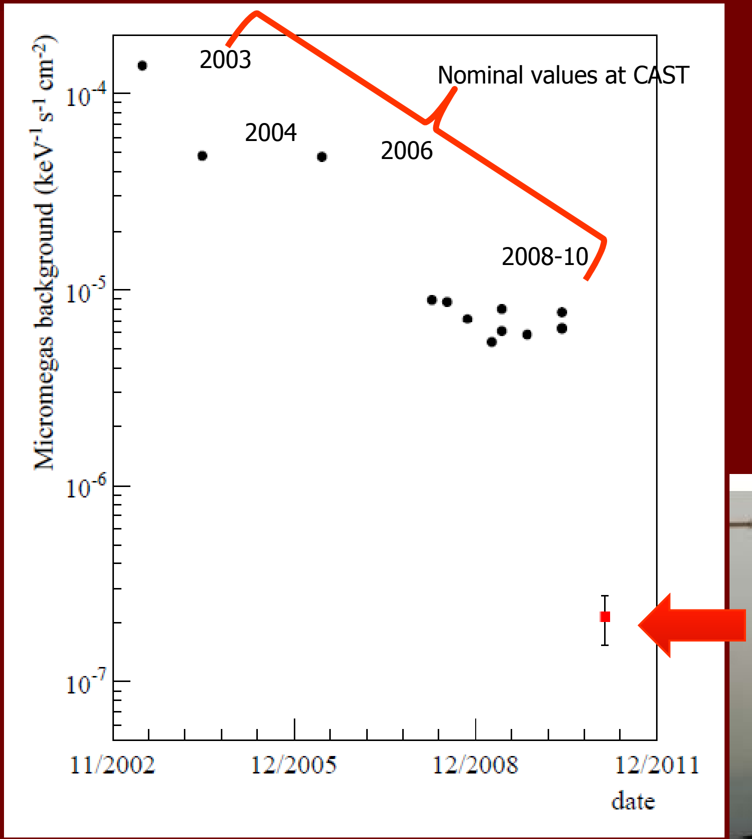




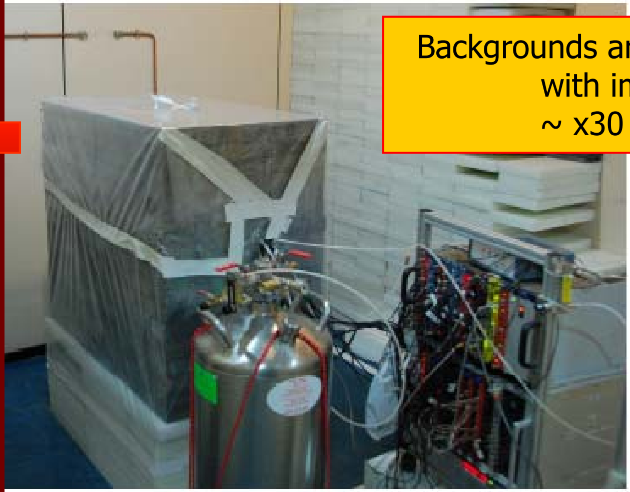


R&D low background detectors

History of background improvement of Micromegas detectors at CAST



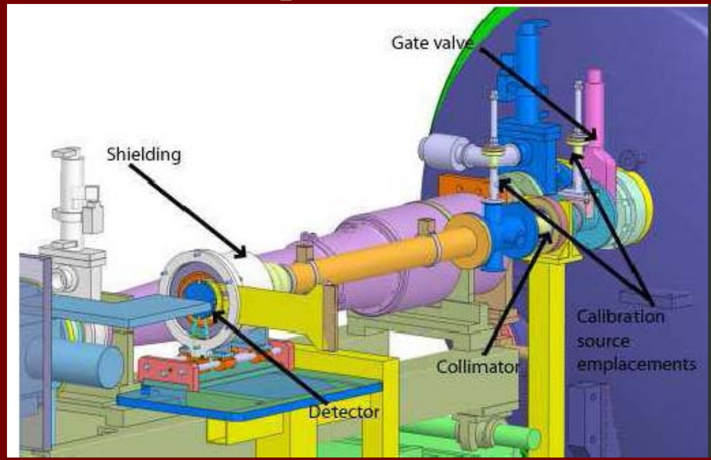
- Latest Micromegas: x20 improved background
  - Shielding
  - Radiopurity. New manufacturing technique (microbulk readouts)
  - More powerful offline cuts
- Tests in controlled conditions underground at Canfranc:
  - Better shielding coverage
  - Thicker shielding

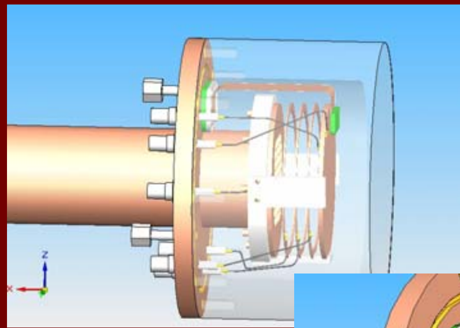


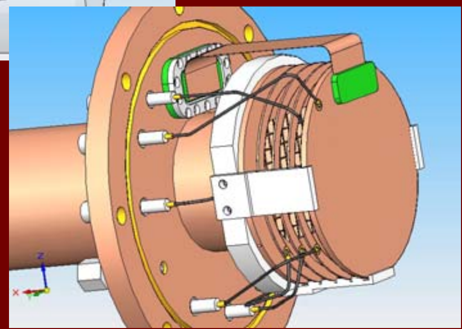
Backgrounds around 2x10-7 c/keV/s/cm2 with improved shielding ~ x30 better than CAST

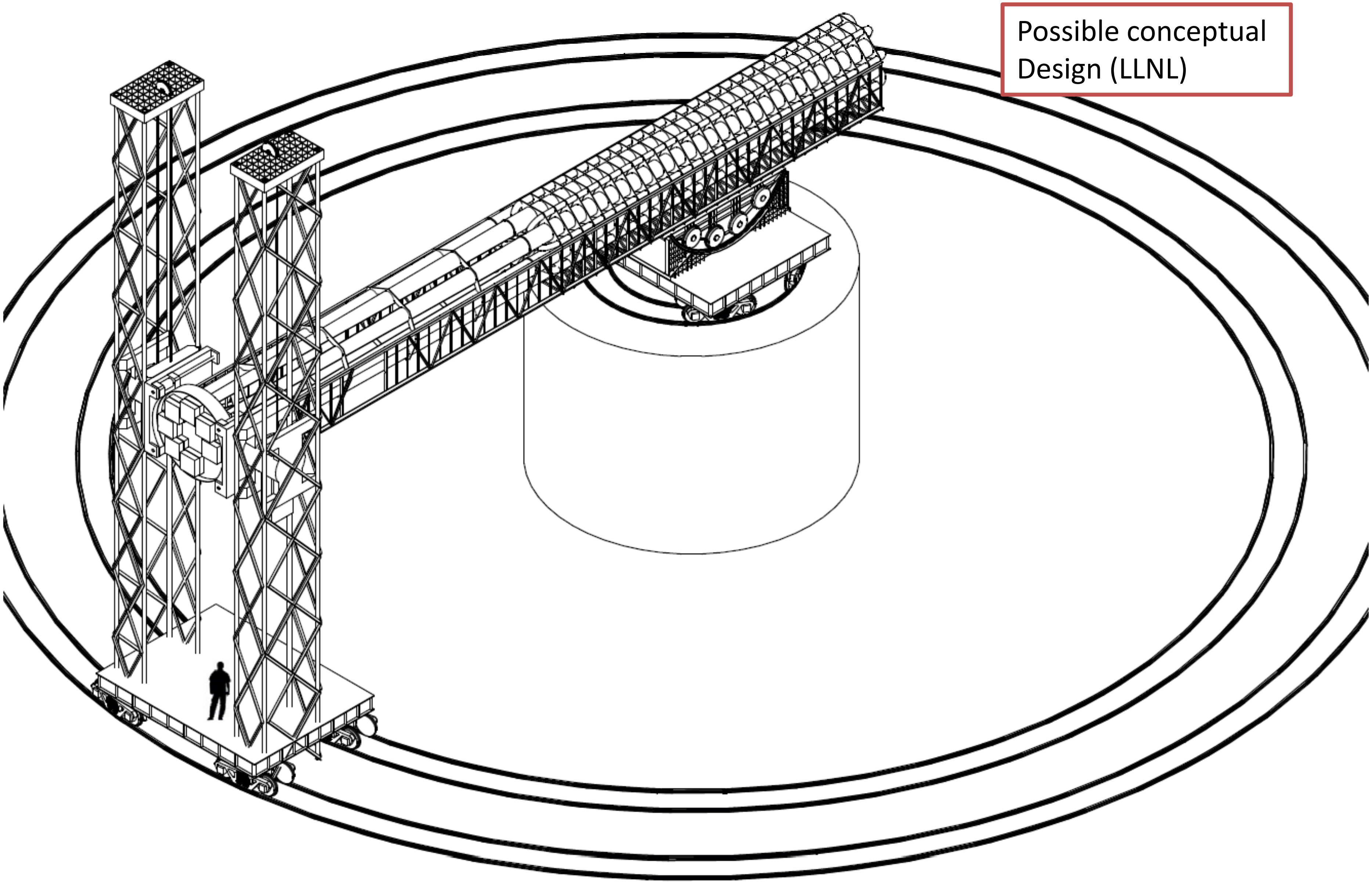
Pathfinder detector+optics

- 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 the NGAH

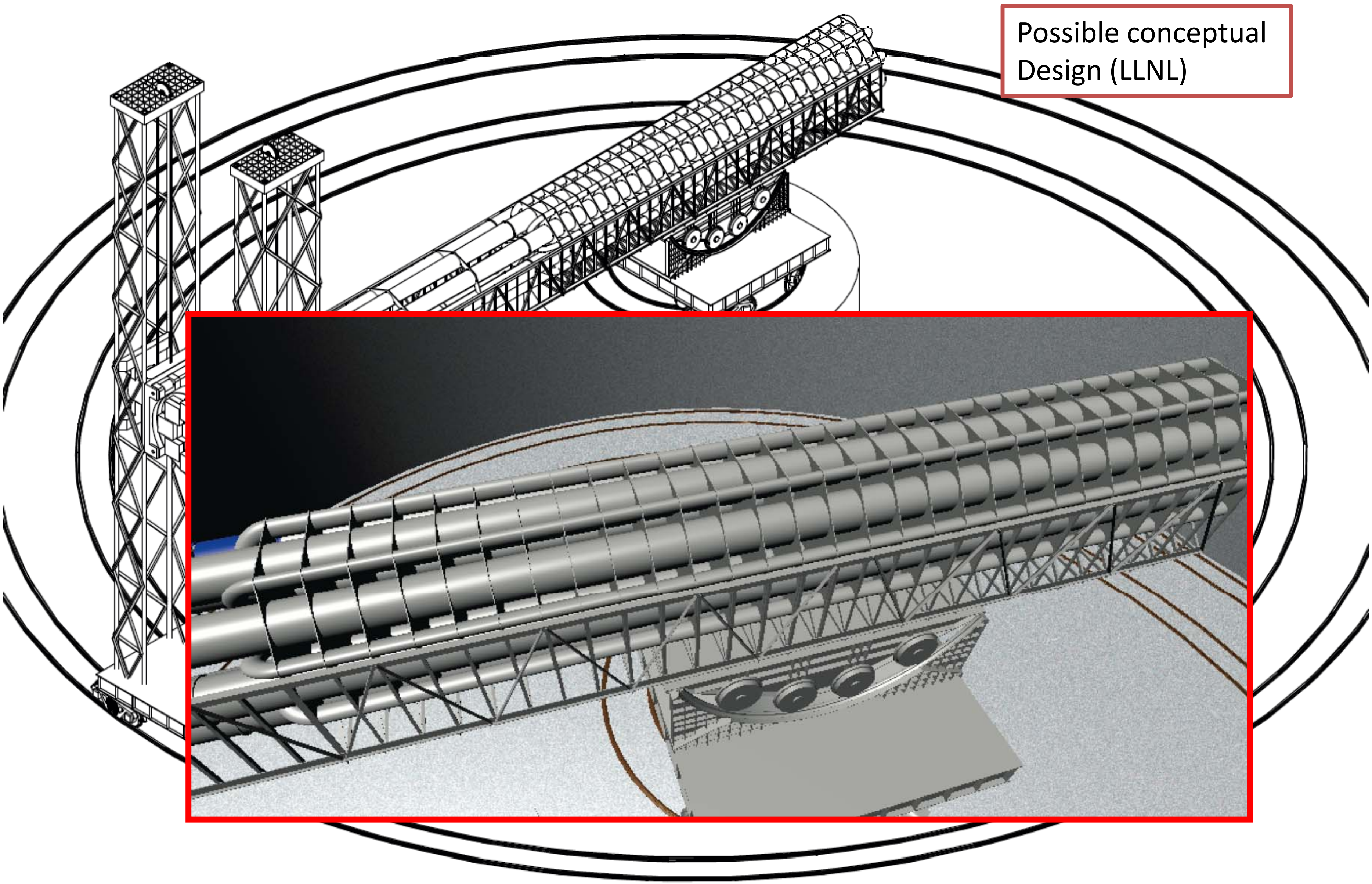


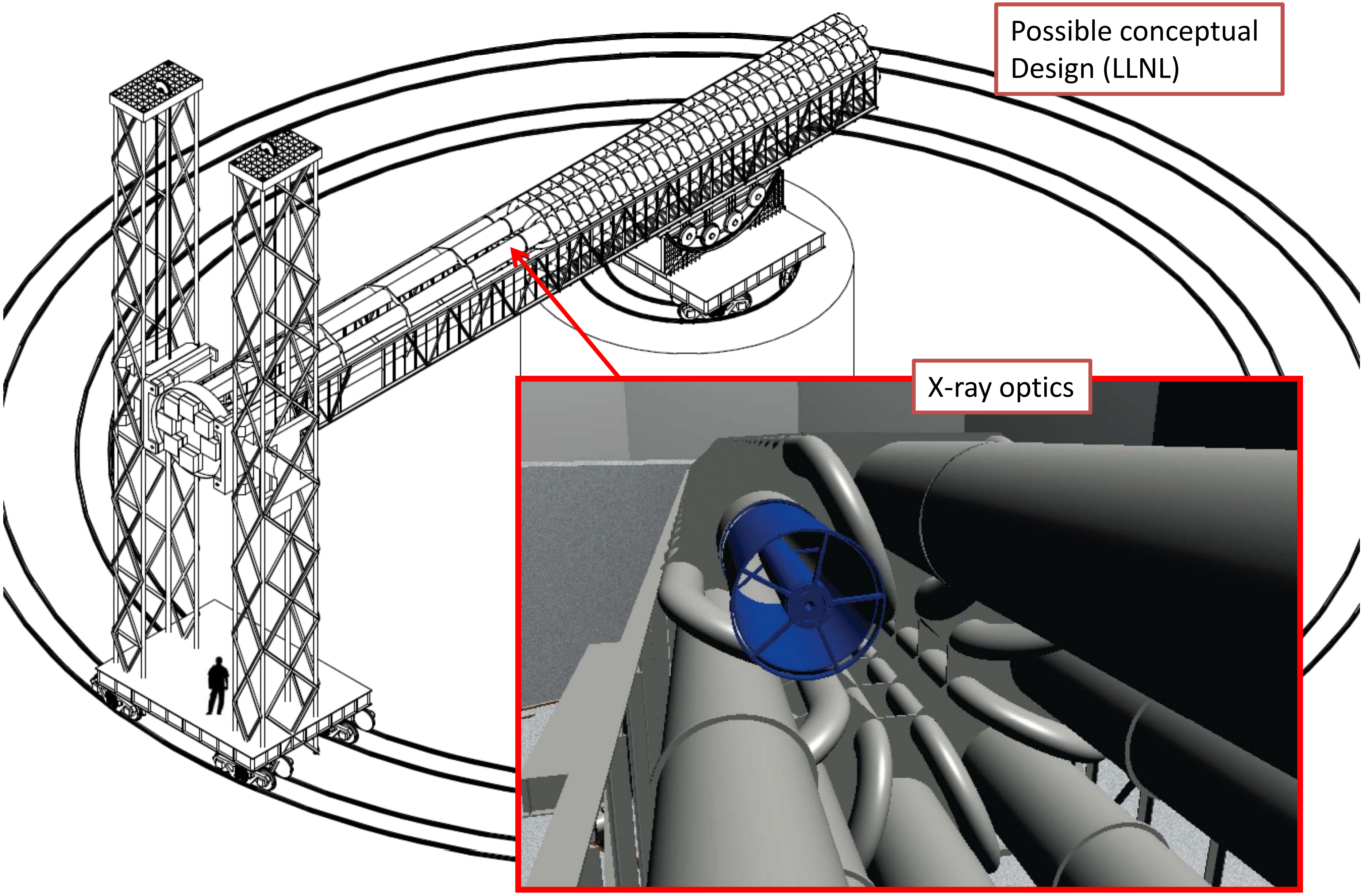


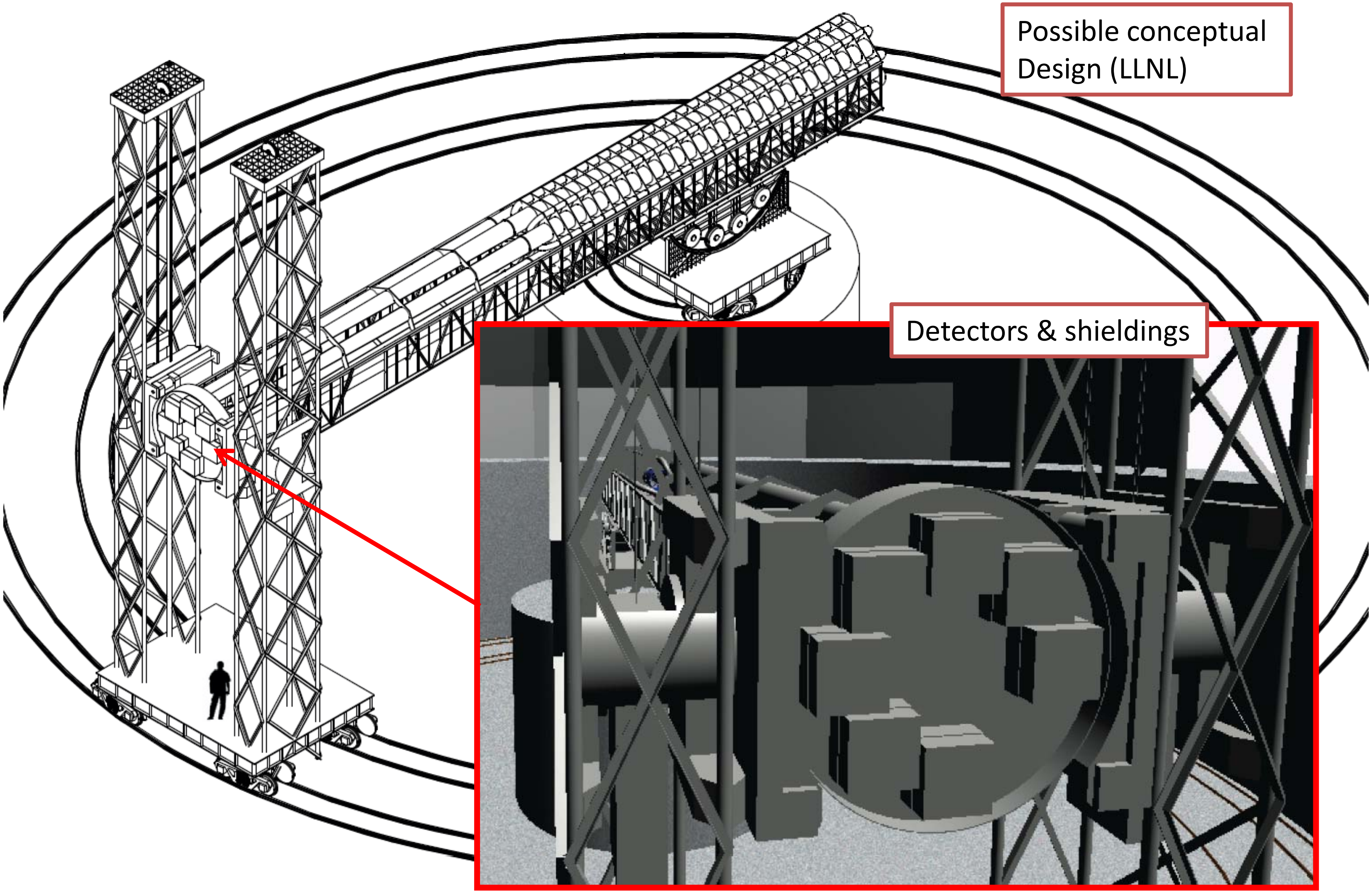




Possible conceptual Design (LLNL)


Possible conceptual
Design (LLNL)


Possible conceptual Design (LLNL)
X-ray optics


Possible conceptual Design (LLNL)
Detectors & shieldings

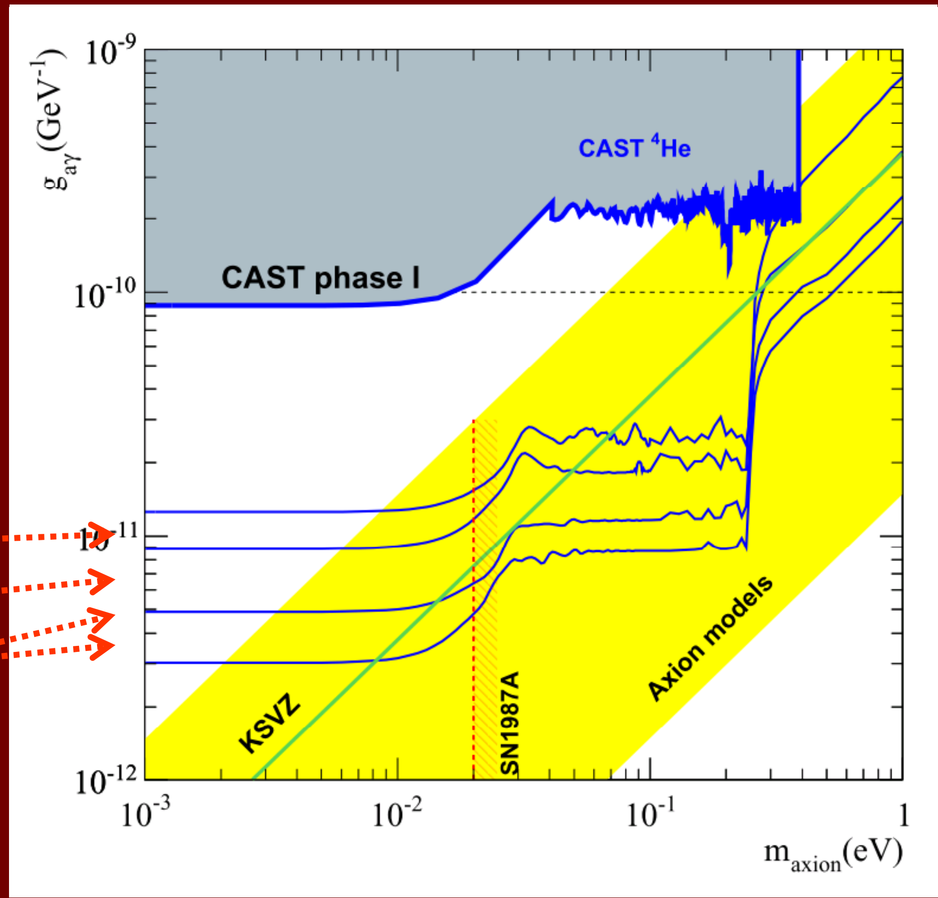
How much beyond CAST we can hope for?

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

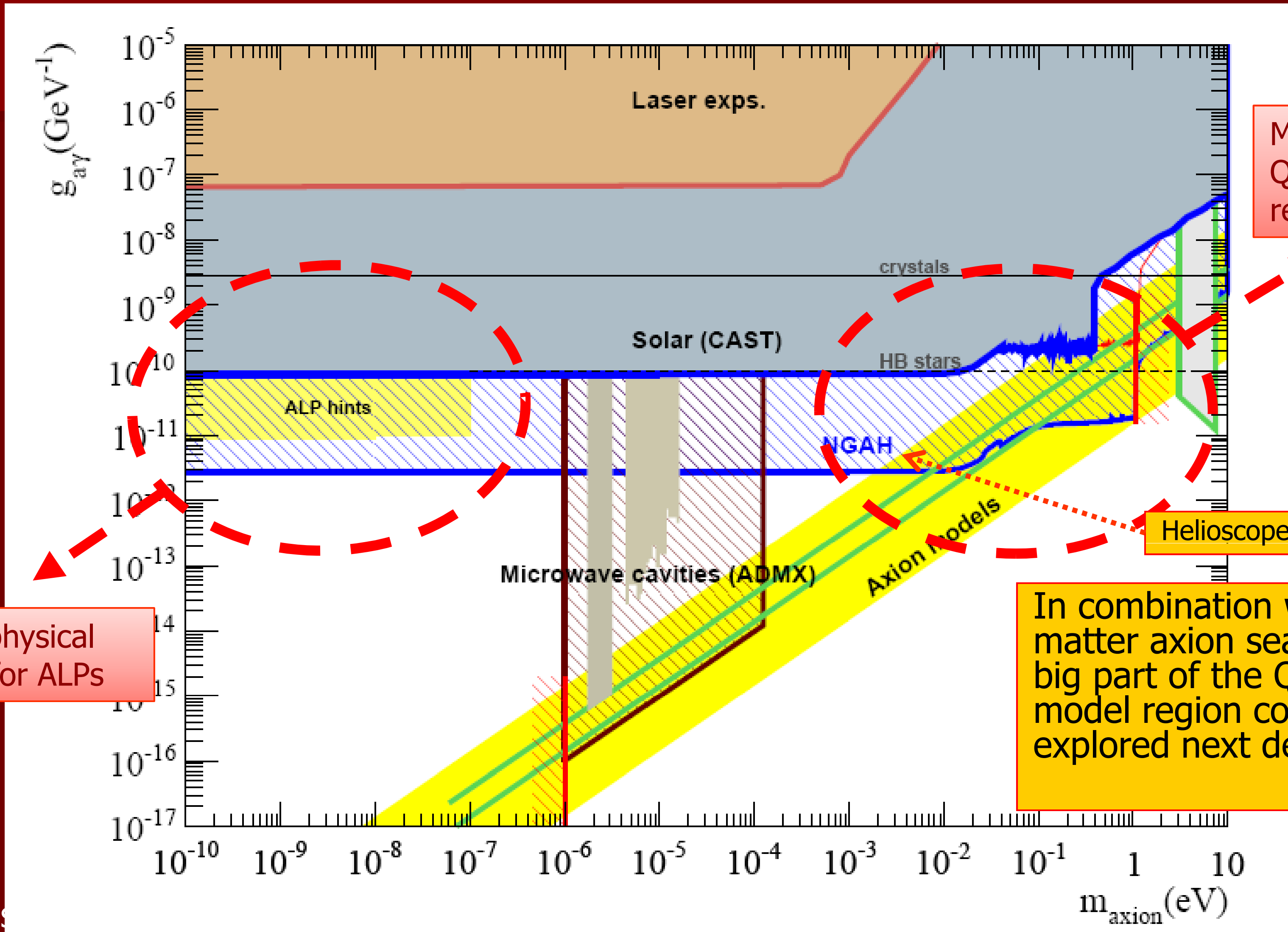
Conservative scenario

Realistic scenario

Optimistic scenarios



How much beyond CAST we can hope for?



Much larger QCD axion region explored

Astrophysical hints for ALPs

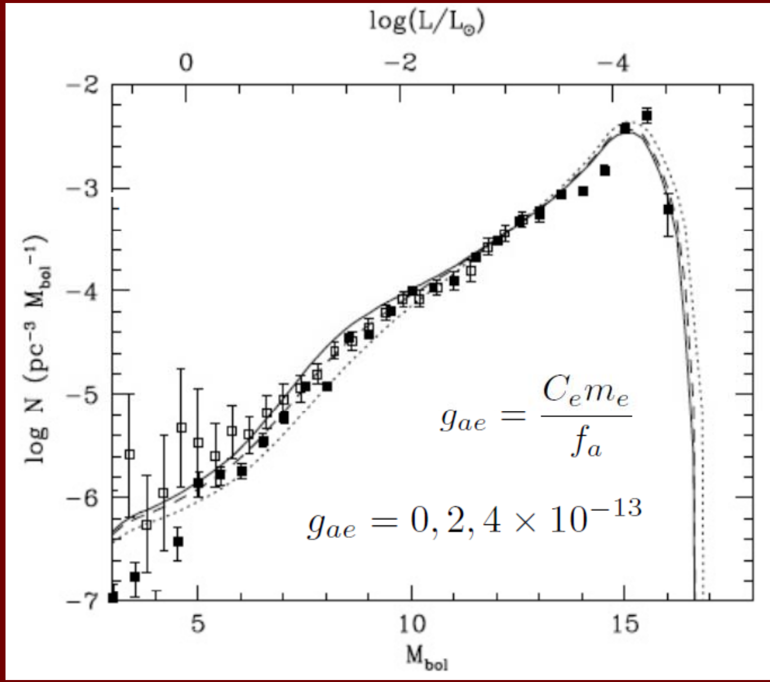
Helioscope prospects

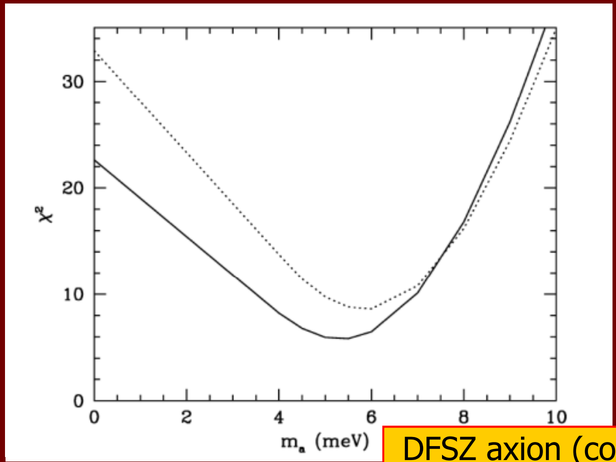
In combination with dark matter axion searches a big part of the QCD axion model region could be explored next decade.

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



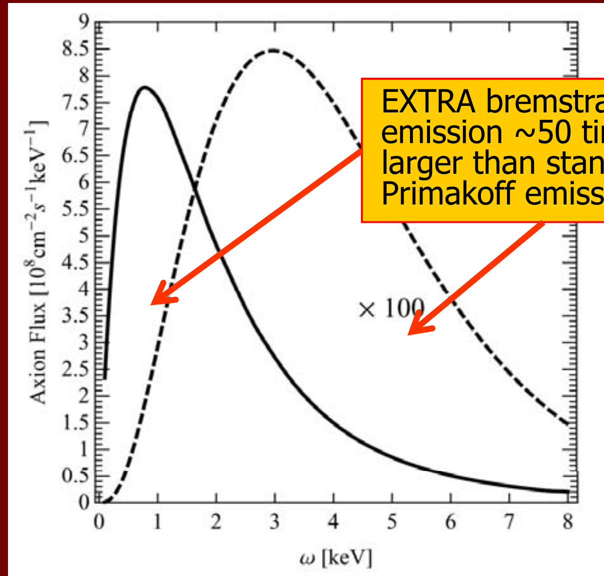


DFSZ axion (cosβ=1)

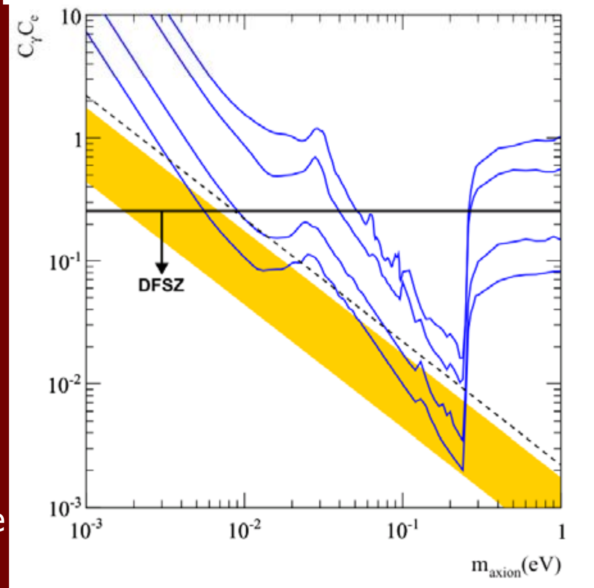
The cooling of white dwarfs

- 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 the new axion helioscope**



EXTRA bremstrahlung emission ~50 times larger than standard Primakoff emission



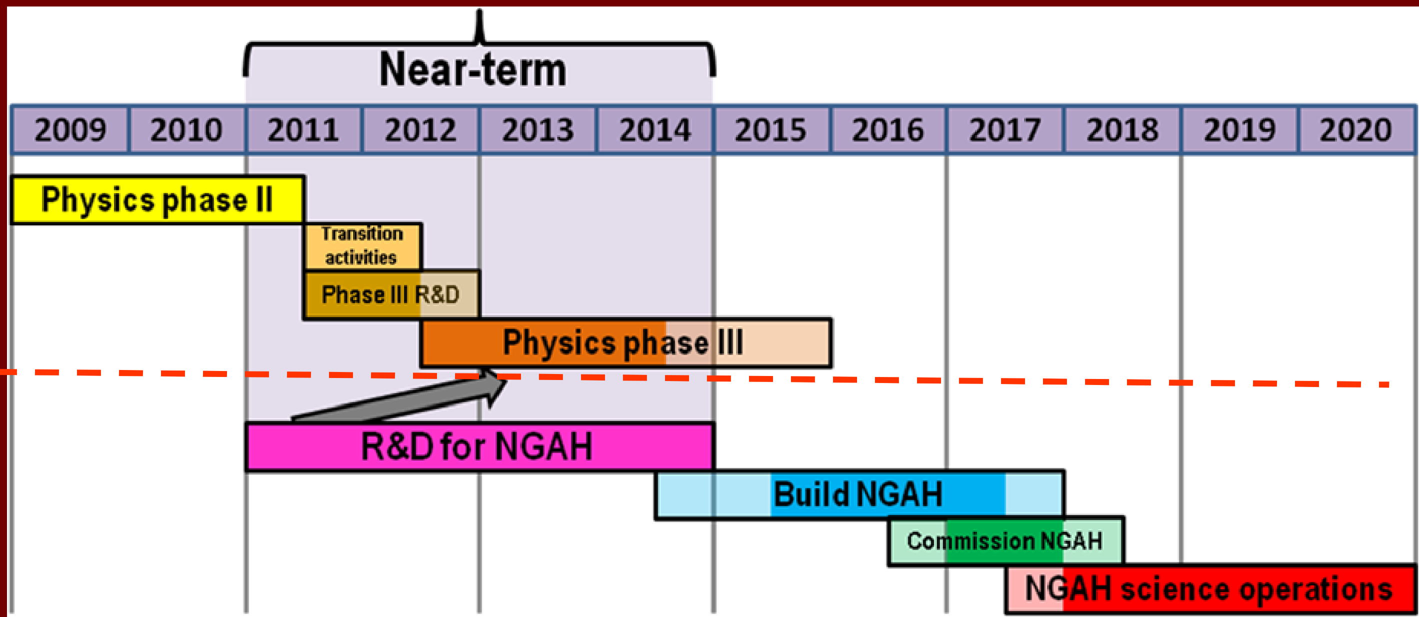
Further physics cases

- 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, extending the sensitivity to lower masses. ← under study

Project status & timetable

- Proto-collaboration being formed.
  - Most CAST groups
  - New groups + extended expertises (magnet, optics).
- Conceptual Design Report in preparation
- Letter of Intent to be submitted to CERN soon (~1 year)

- CAST
- NGAH



The new helioscope in ASPERA

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 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 axion observatory