Solar Axion Search Workgroup

Vistas in Axion Physics:
A Roadmap for Theoretical and Experimental Axion Physics through 2025

23-26 April 2012

J. Vogel on behalf of the Solar Axion WG

Lawrence Livermore National Laboratory

Many thanks to WG participants for their contributions!!!

LLNL-PRES-554792

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Outline

- Helioscopes: Where are we at?
- What are we aiming for?
- How do we get there?

    → WG presentations

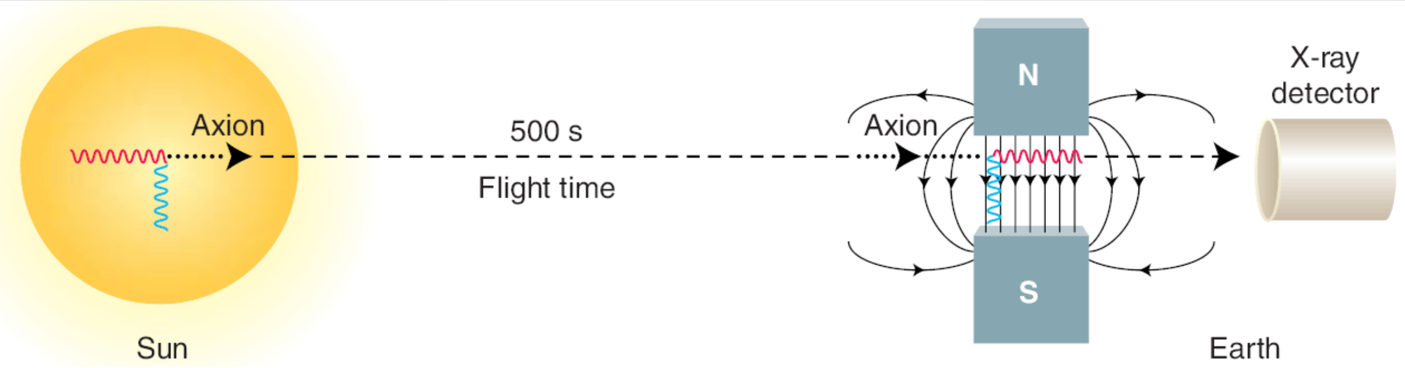
- Challenges?

Production and detection of axions

- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

  - Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagentic fields in the plasma
  - Reconversion of axions into x-ray photons is possible in strong laboratory magnetic fields

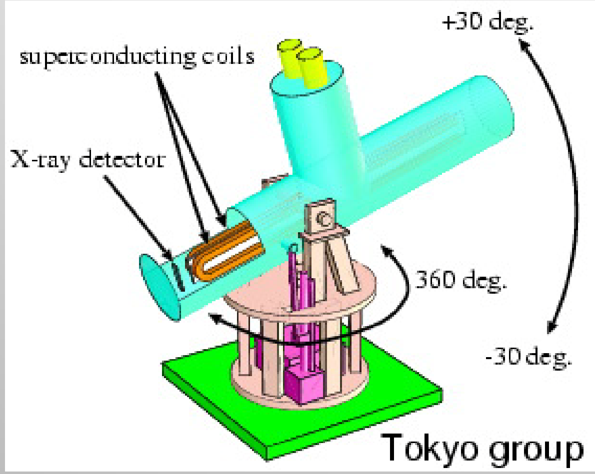


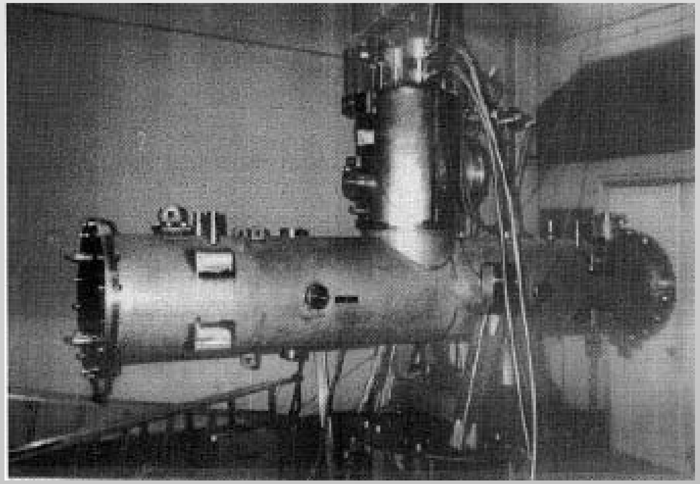
- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *PhysRevD* 39:2089 (1989)

Helioscope searches

- **Helioscope timeline:**
  - 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

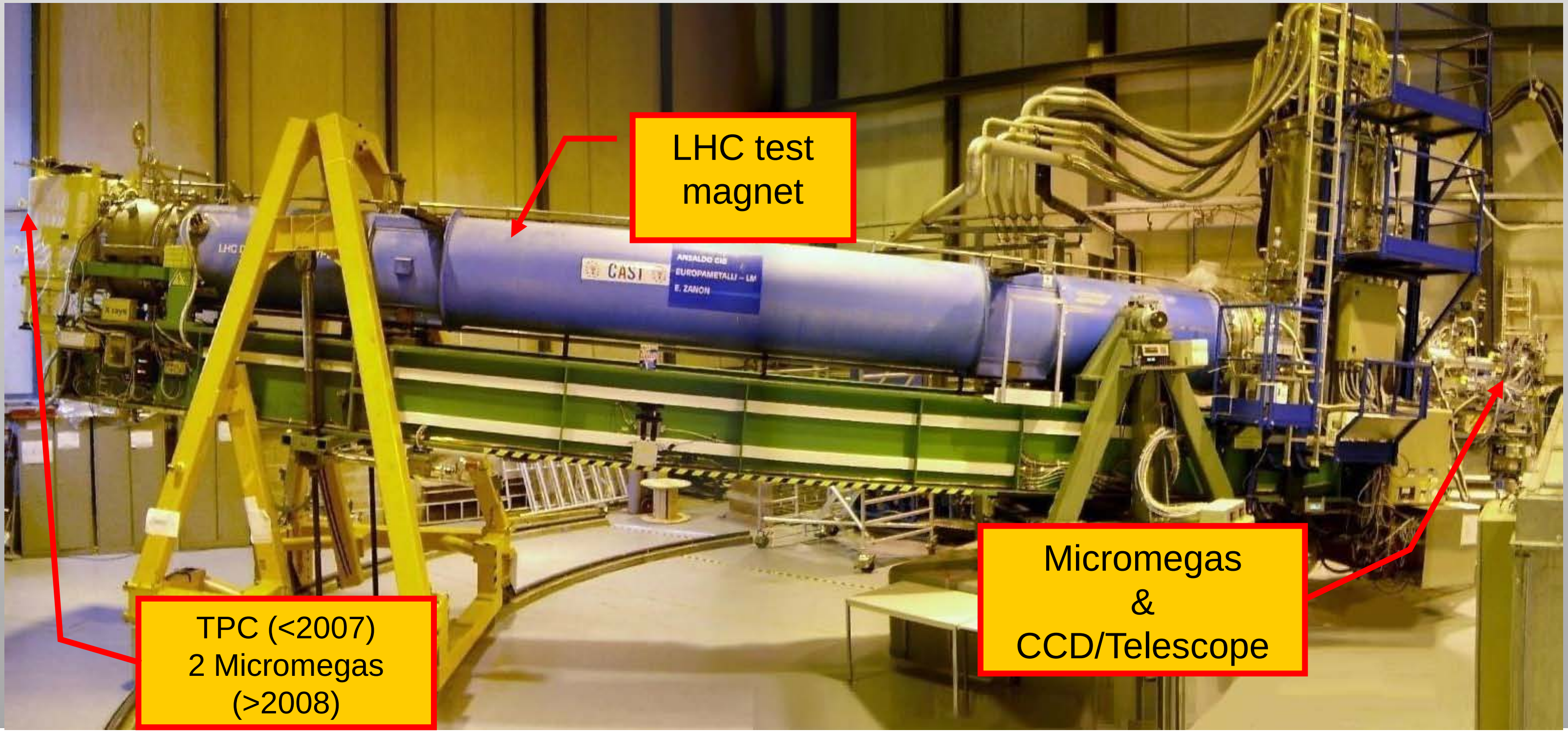




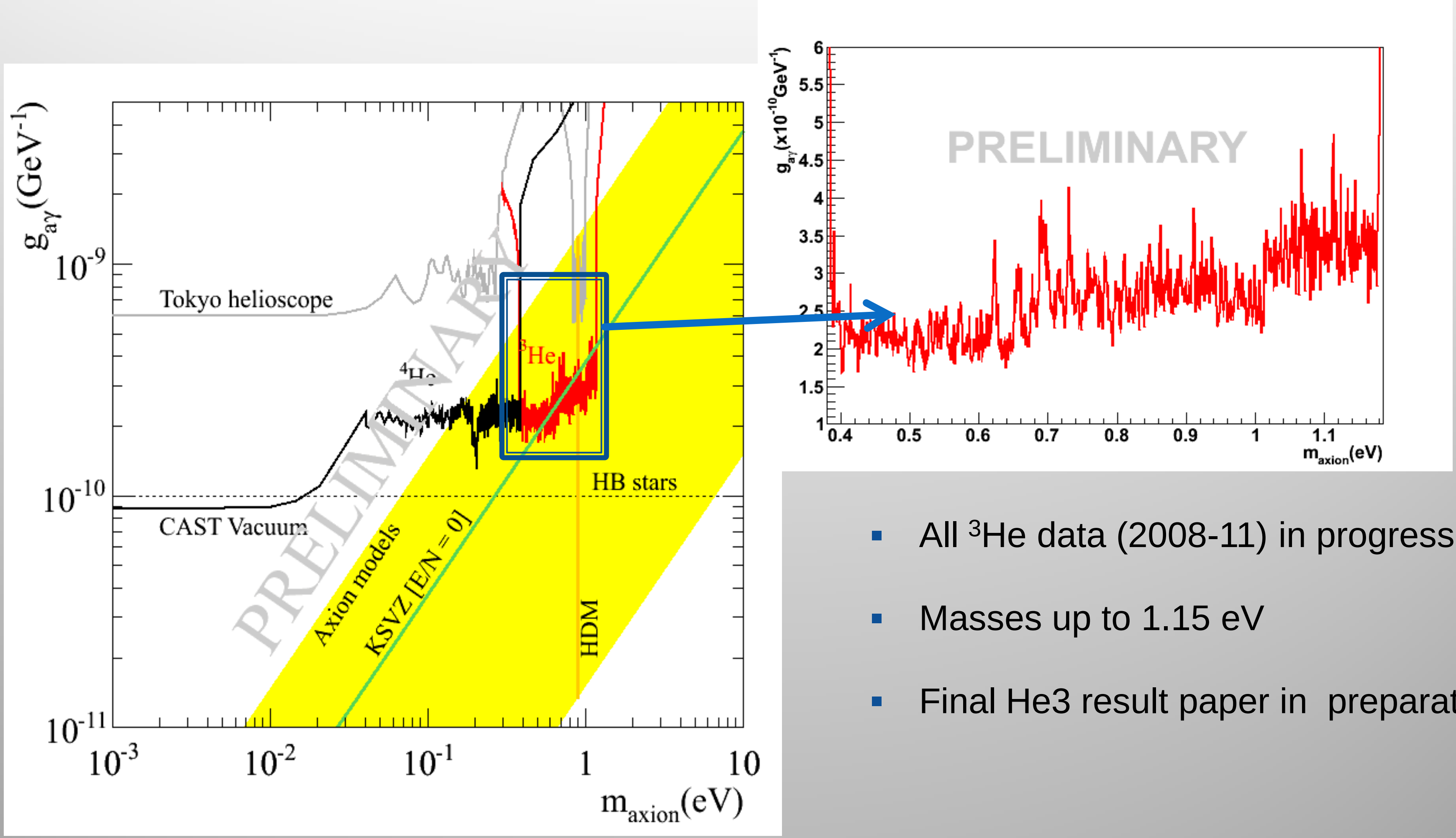
- **Most sensitive running helioscope:**
  - CERN Axion Solar Telescope (**CAST**)

CAST experiment @ CERN

- International collaboration started in 1999
- Almost continuously acquired data since 2003
- 20 institutions from 11 countries, approximately 70 PhD scientists
- Thesis project for 10 PhD students, 6 more pending
- **Very mature technology → CAST is 3rd generation helioscope**



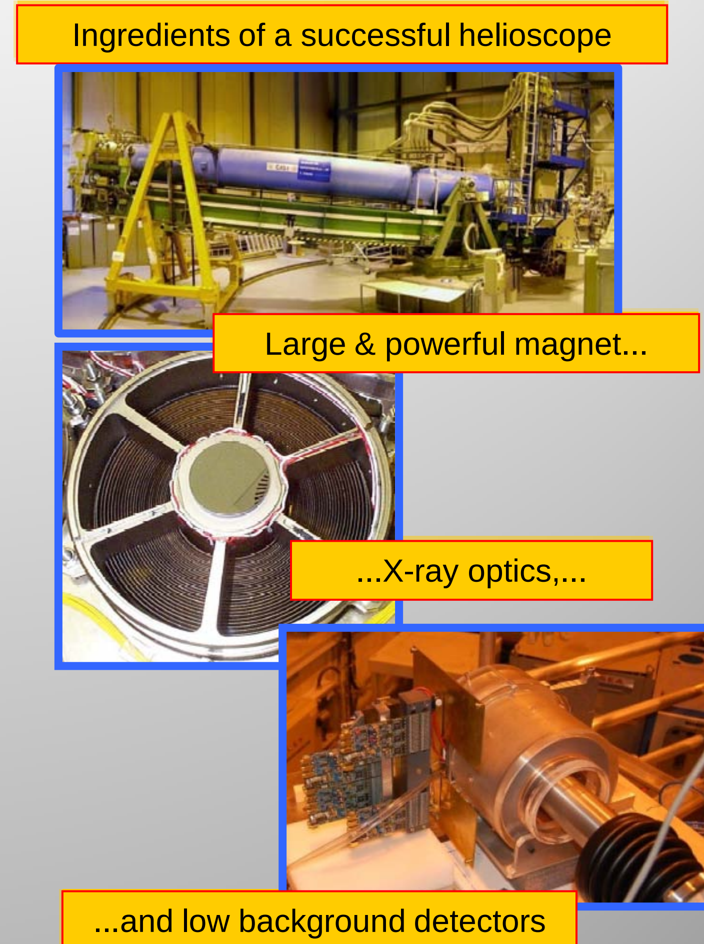
CAST results



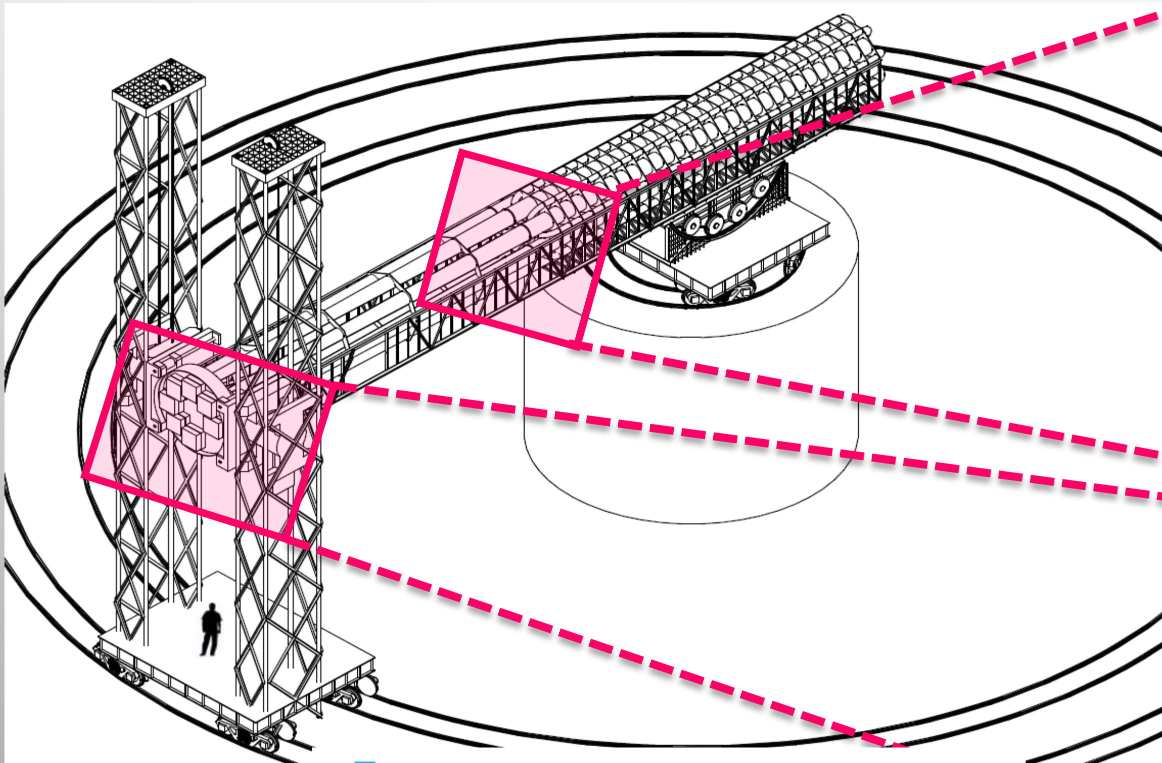
- All ^{3}He data (2008-11) in progress.
- Masses up to 1.15 eV
- Final He3 result paper in preparation

IAXO – The new generation helioscope

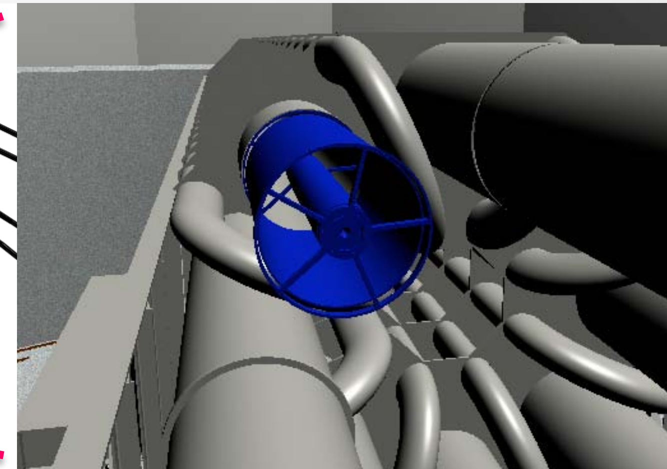
- **4th generation axion helioscope**
  - **Based on the more than a decade CAST experience!!**
  - CAST is established as a reference result in experimental axion physics CAST PRL2004 most cited experimental paper in axion physics
  - No other technique can realistically improve CAST in such wide mass range.
  - **No miracle needed!** IAXO builds on CAST innovations to improve the helioscope technique…

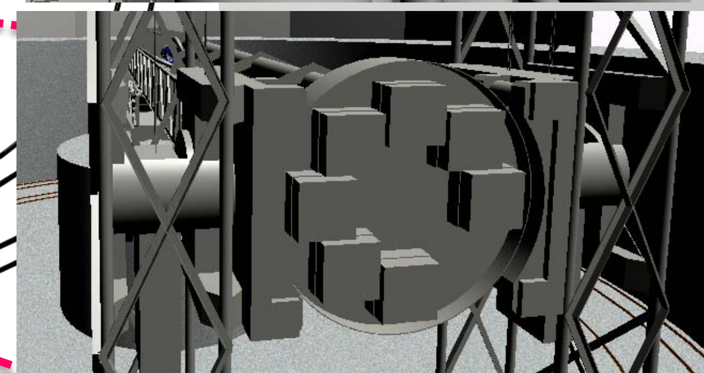


IAXO – The new generation helioscope



Randy Hill, LLNL





Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Towards a new generation axion helioscope

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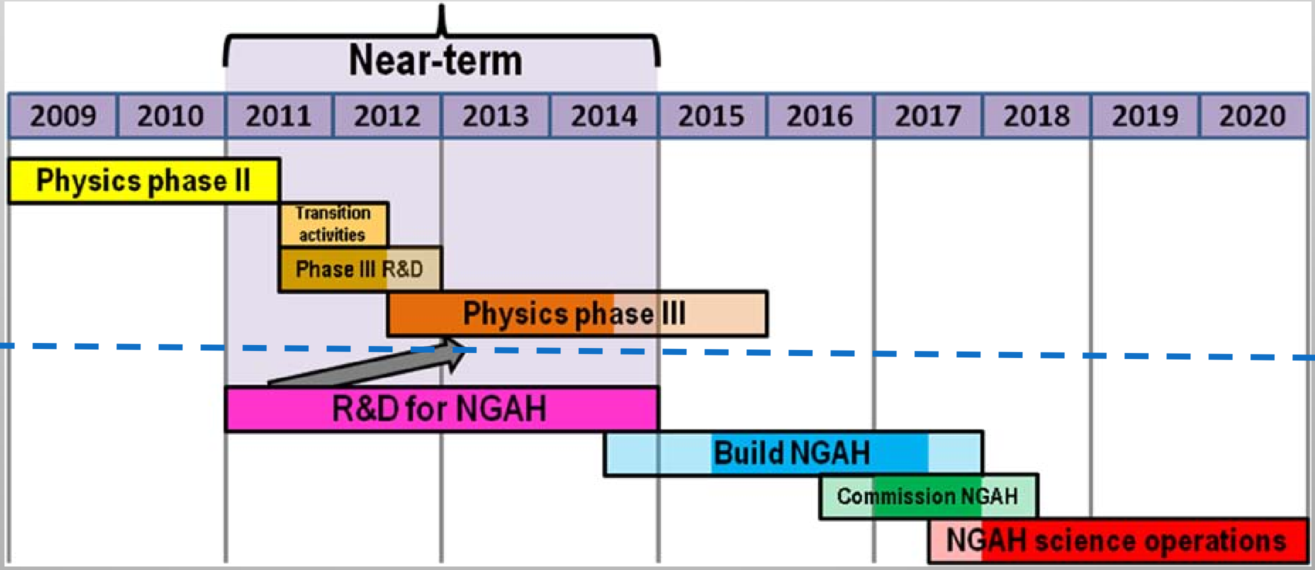
JCAP 06 (2011) 013

IAXO – Timeline

- 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

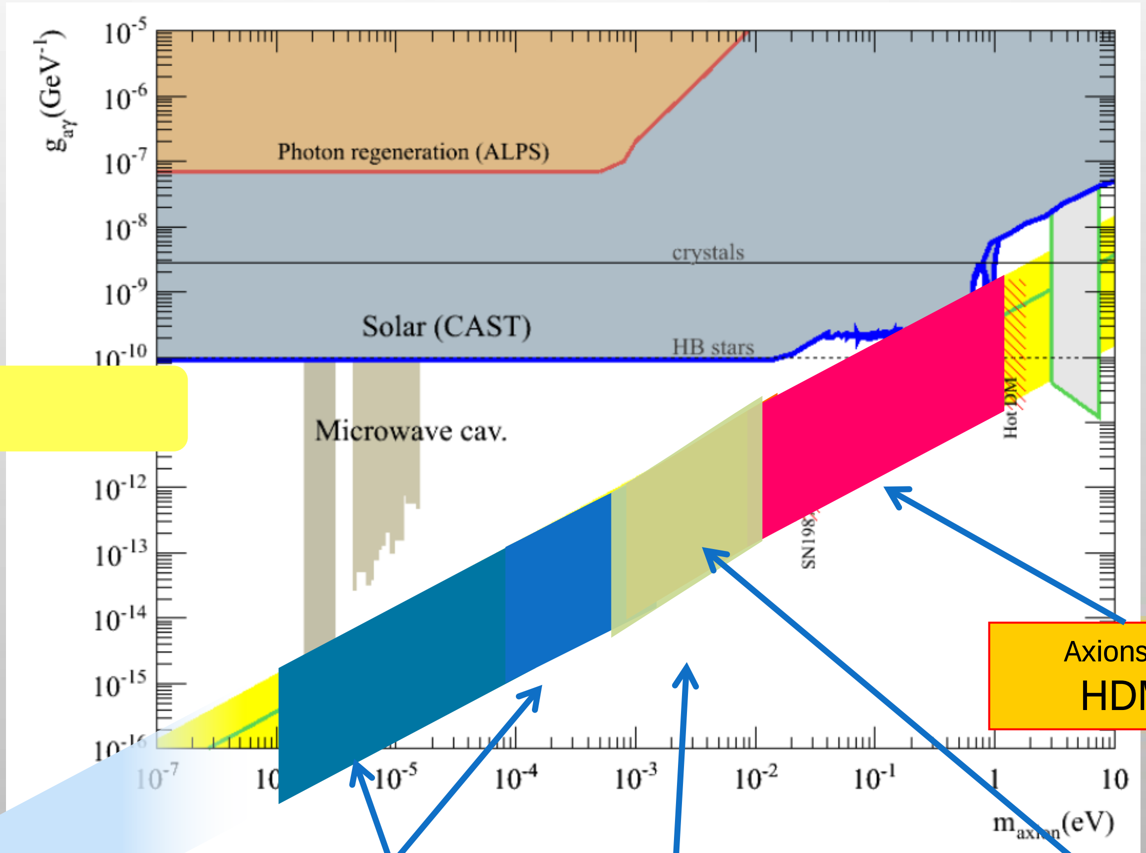
Axions (without an imperative connection to dark matter) can be produced in the Sun's core when X-rays turn to axions in the presence of strong electric fields. On Earth, these axions can be converted back in a strong magnetic field. Arriving as axions they tunnel a wall in a large magnet and appear 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

Axion parameter space

Astrophysical hints for ALPs



CDM
"anthropic window"

CDM
"classical window"
Vaxuum mis. + defects

CDM
Defects dominate
hep-ph/1202-5851

Axions as
HDM

White
Dwarfs

See talk
I. Irastorza

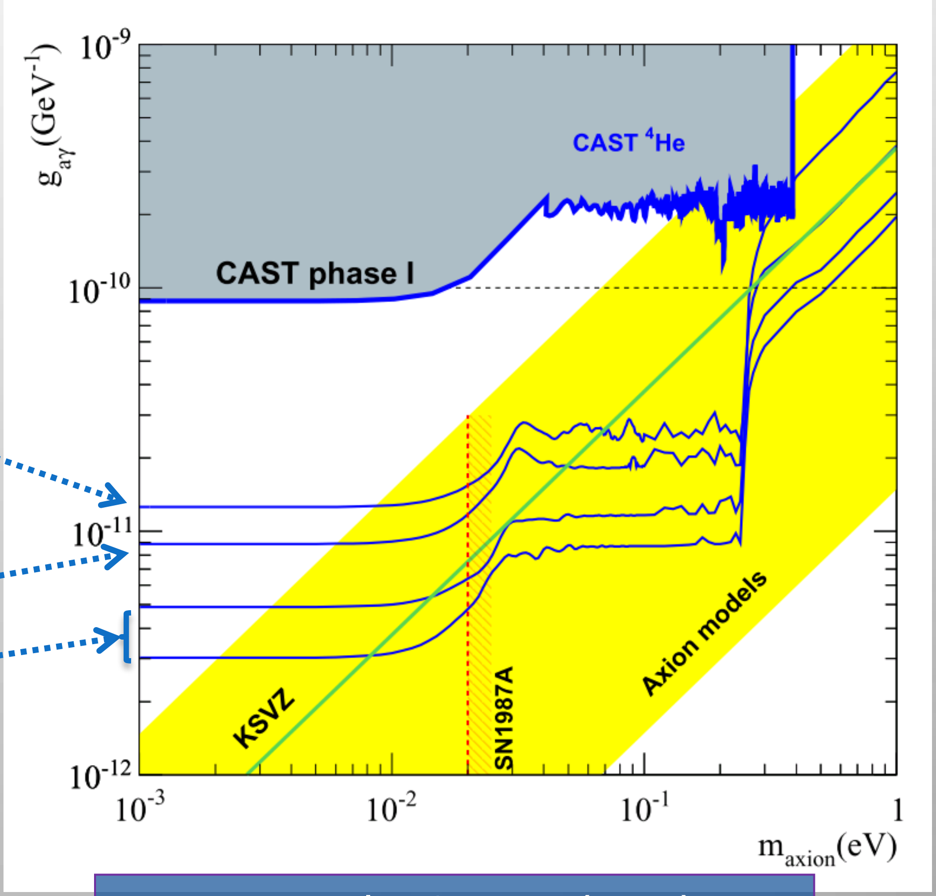
How much beyond CAST can we hope for?

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

Conservative scenario

Realistic scenario

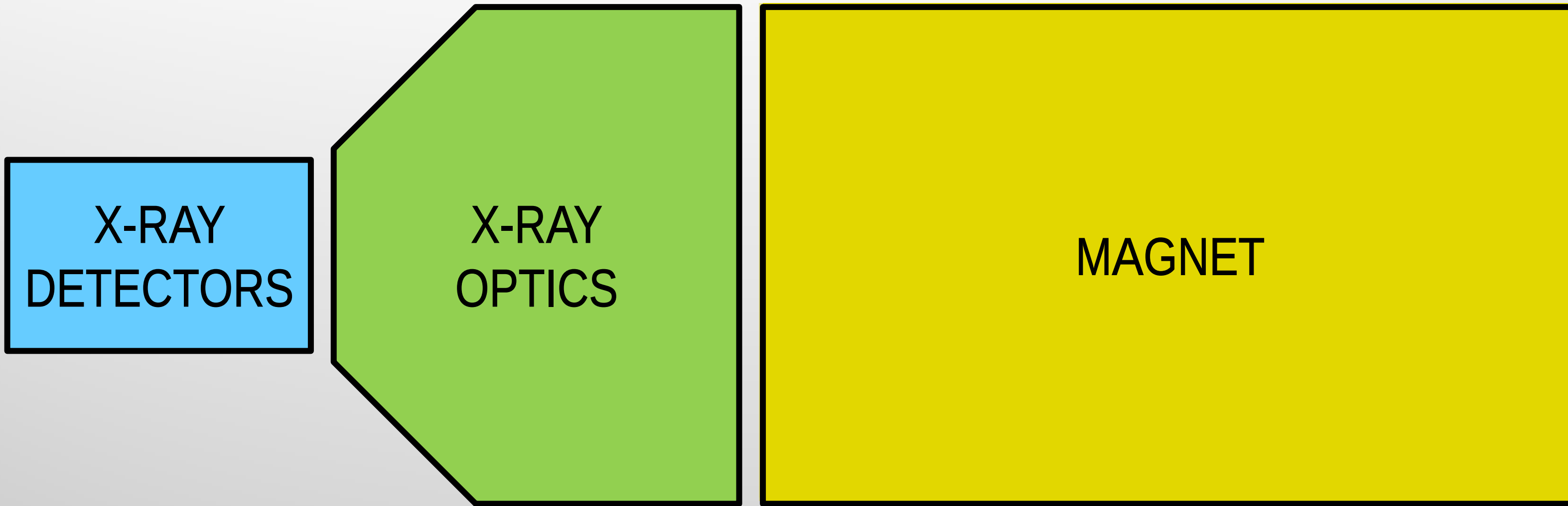
Optimistic scenarios



Irastorza et al. *JCAP* 06 (2011) 013

See talk
I. Irastorza

IAXO – How to improve sensitivity



$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\varepsilon^{-1}}_{\textit{detectors}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\textit{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\textit{magnet}} \times \underbrace{t^{-1/2}}_{\textit{exposure}}$$

detectors

b = background
ε = efficiency

optics

s = spot size
ε_0 = efficiency

magnet

B = magnetic field
L = magnet length
A = cross-sectional area

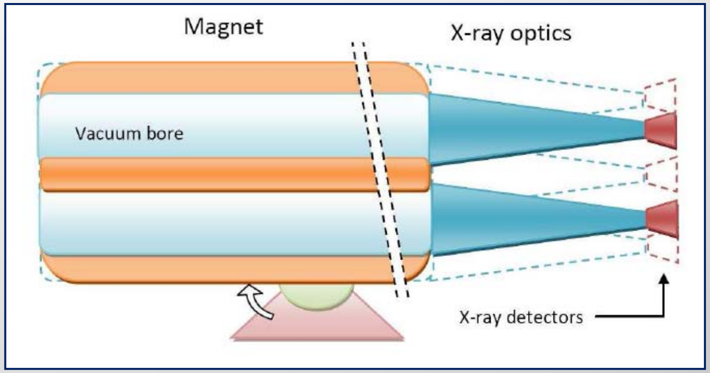
exposure

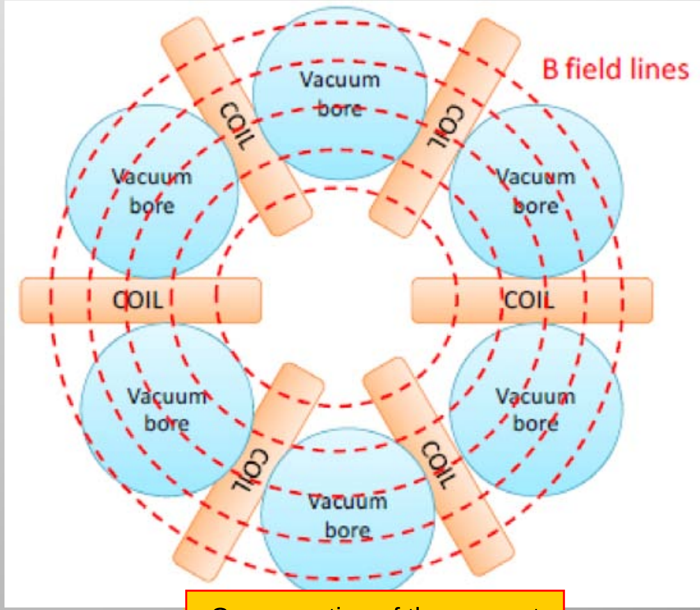
t = time

Magnet technology for IAXO

- CAST has 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 build a new magnet, specifically for axions.
- 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 (?)

  → A magnet that looks like a detector magnet with the behavior of an accelerator magnet (little stress, strong field,…)

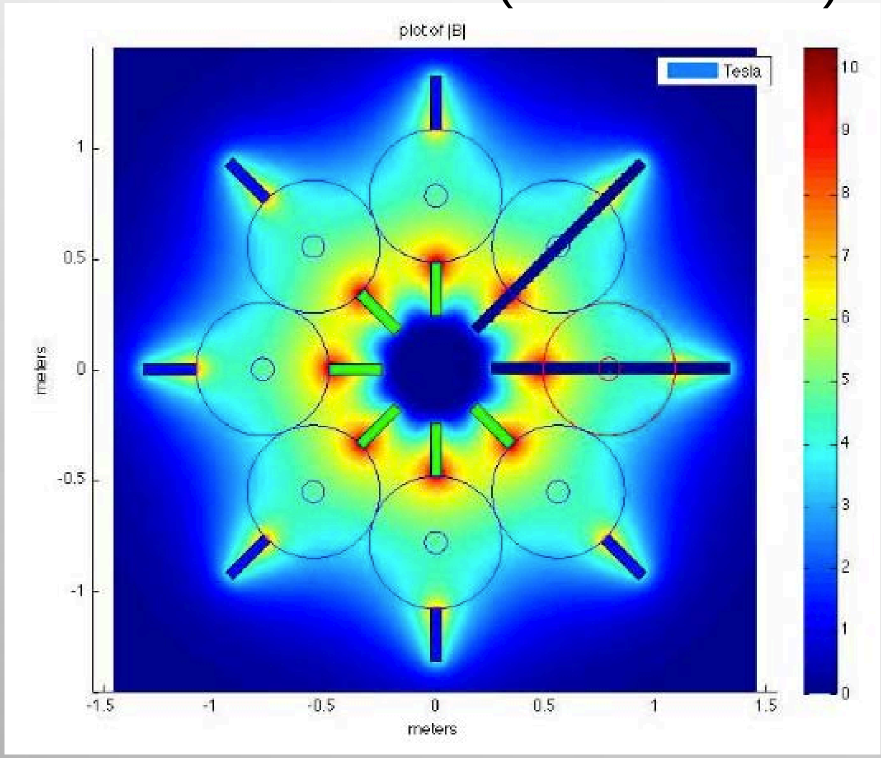




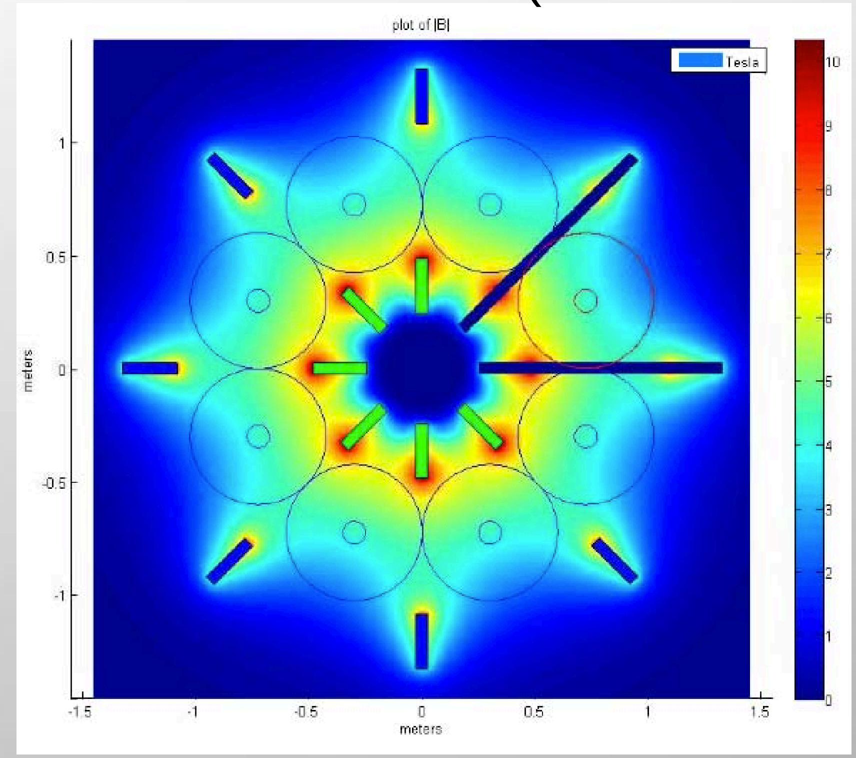
Cross section of the magnet

IAXO magnet: Design studies

"**Behind**" scenario (field-oriented)



"**Between**" scenario (area-oriented)

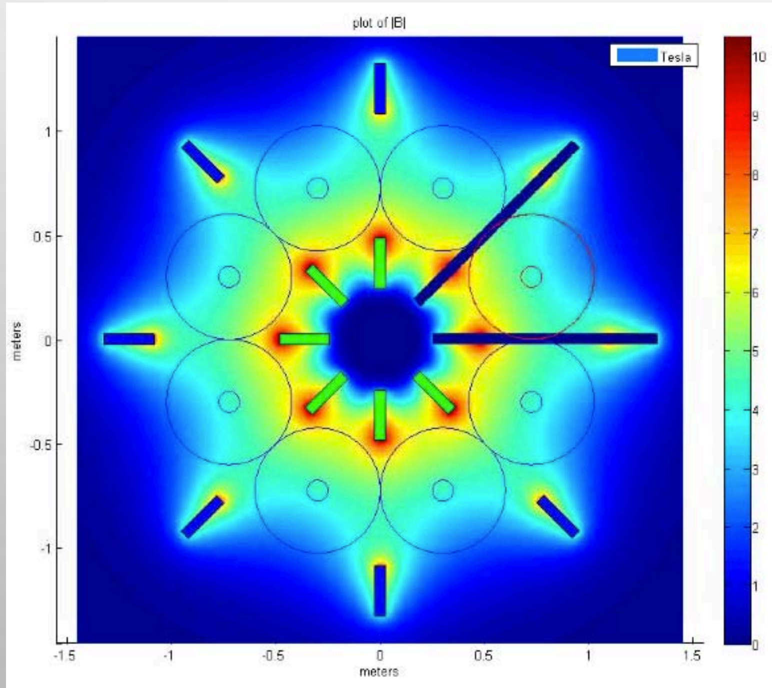


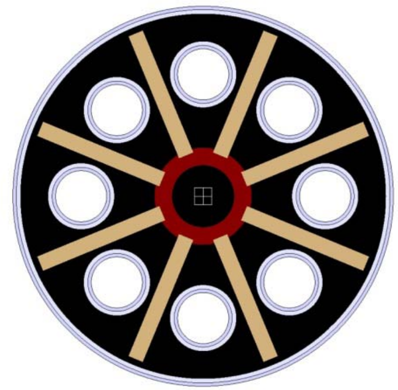
- Comparison FOM on "critical surface"
- Vary set of parameters (radii,width coils…) for configuration of 8 bores

→ "Between" scenario more flexible but lower realistic FOM

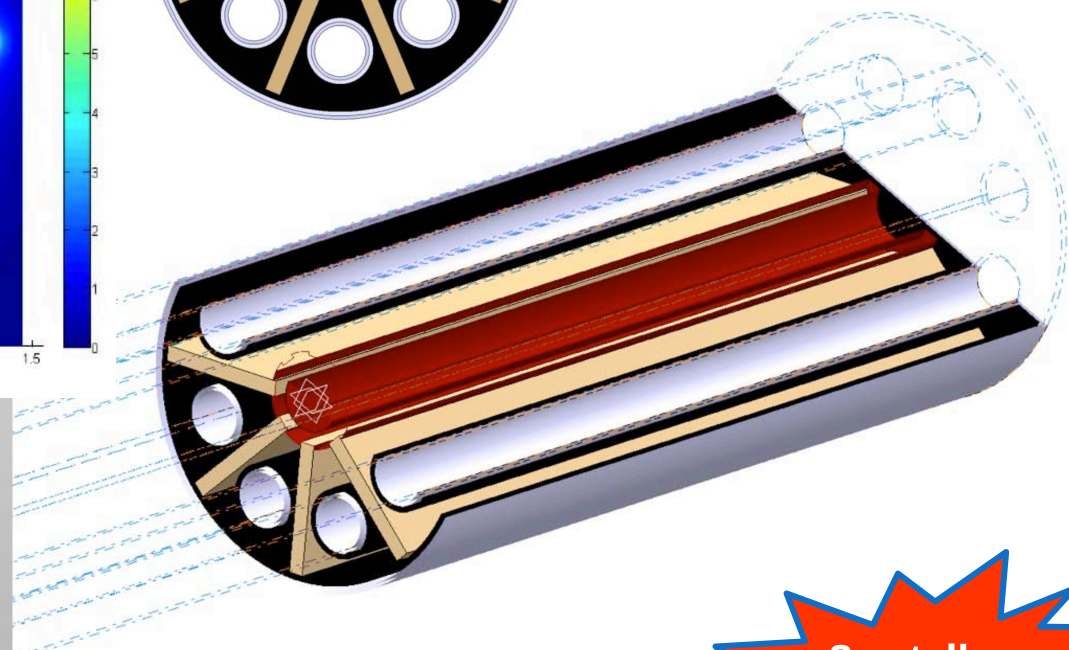
See talk I. Shilon

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

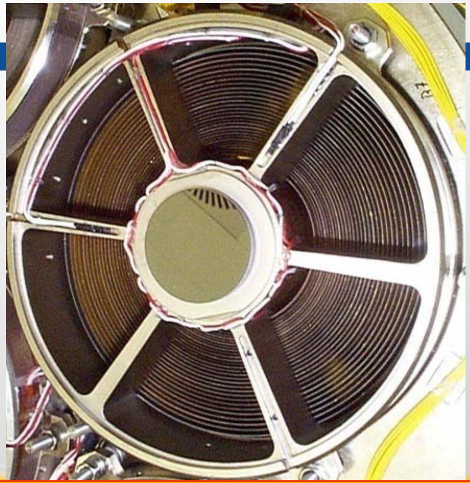
IAXO magnet: 1st concept

R_{in}	1.05 m
R_{out}	2.05 m
R_{cen}	1.43 m
Length	20 m
B_c	9.8 T
J_c	116 A/mm^2
Average Field in Bores	4 T
Relative MFOM	770
Stored Energy (B_p = 0.5*B_c)	350 MJ
Mass	330 Tons

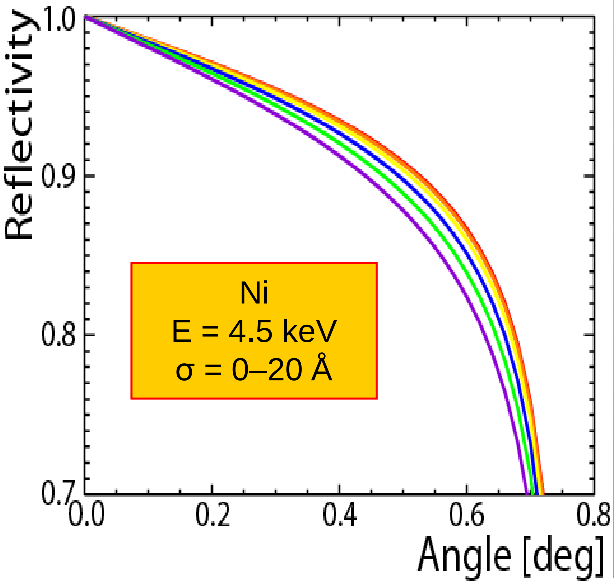
See talk I. Shilon

X-ray optics for IAXO

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



ABRIXAS flight-spare telescope



See talk M. Pivovaroff

X-ray optics for IAXO

- The fabrication technique developed for NuSTAR is ideal for solar axion experiments:
  - Significantly lower costs compared to using substrates produced from replication (ABRIXAS, XMM-Newton), or Zerodur (Chandra)
  - Better performance than Al foils (ASCA, Suzaku)
- Using thermally formed glass substrates allows:
  - Optimization of the reflective coating (multilayers or thin metal films) of each layer
- Hardware can be easily configured to make optics with a variety of designs and sizes

NuSTAR optics assembly machine

NuSTAR telescope

X-ray optics studies for IAXO

$$g_{a\gamma}^{4} \propto \underbrace{b^{1/2}\varepsilon^{-1}}_{\text{detectors}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

- Optics are needed, primarily, because detectors have non-zero backgrounds (***s*** above)
- Spectral response and effective area are also important (ε_0 above)
- Practical constrains
  - Size (*e.g.*, focal length or size of assembly machine), cost, temperature

Specific Considerations for IAXO:

- Required HPD can be done
- # of optics: 8
- Large radius: 300mm
- Notional focal length ($\alpha_{max} \approx 0.8°$, $f \approx 5.4$ m)

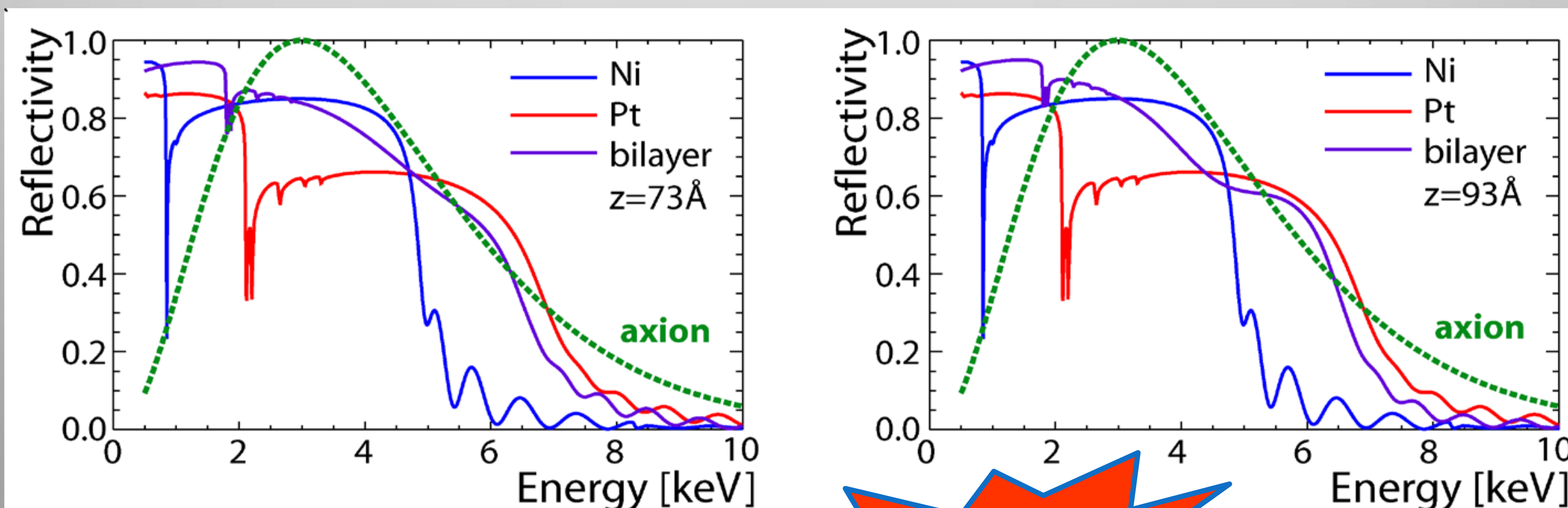
See talk M. Pivovaroff

X-ray optics studies for IAXO

Which mirror coatings optimal depends on several factors

- Must worry about total system throughput:
  - $d\Phi(E) \otimes QE(E) \otimes EffArea(E)$ (axion spectrum, detector efficiency and telescope area)
- Compare pure Ni and Pt coatings with a simple bi-layer, B_4C on W

(a) 2-5 keV   (b) 1-10 keV



See talk M. Pivovaroff

X-ray optics studies for IAXO

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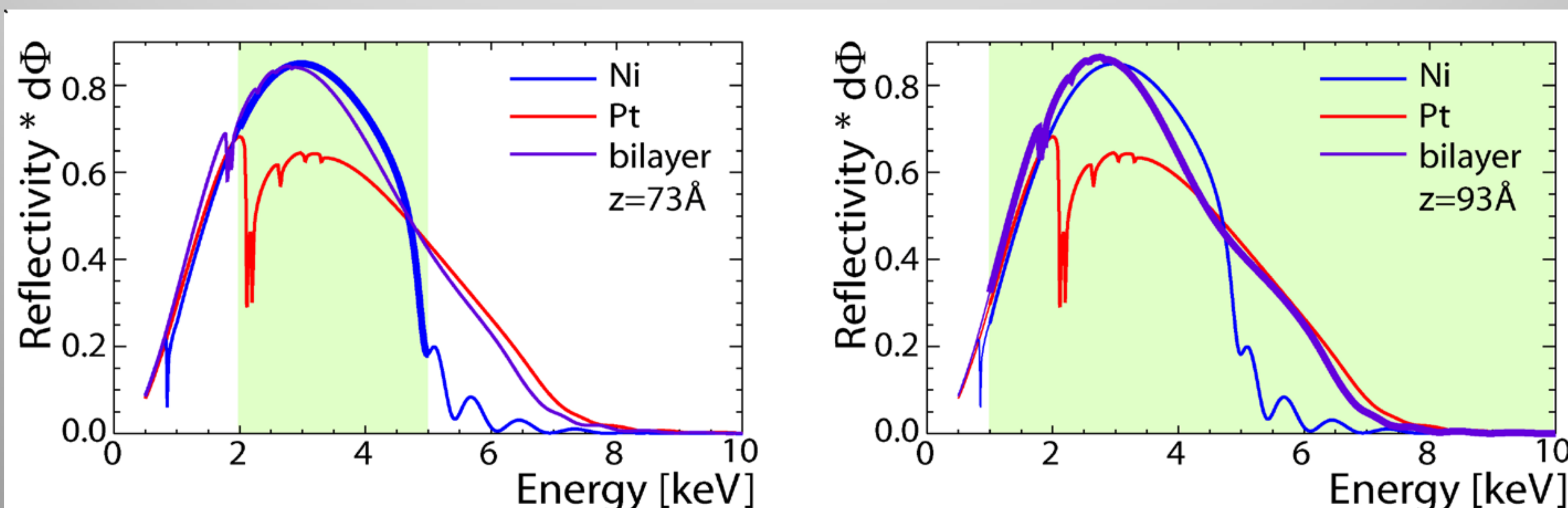
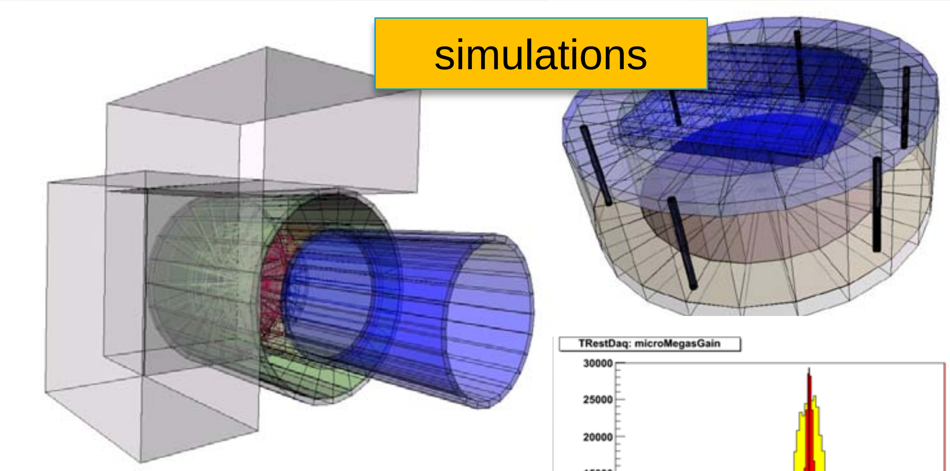


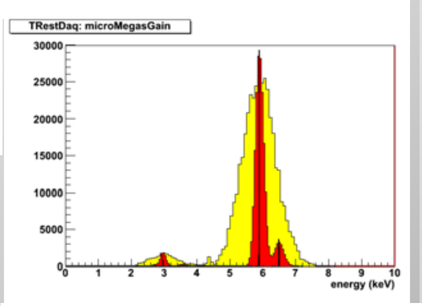
Ni best, Pt: 80%, bilayer: 99%

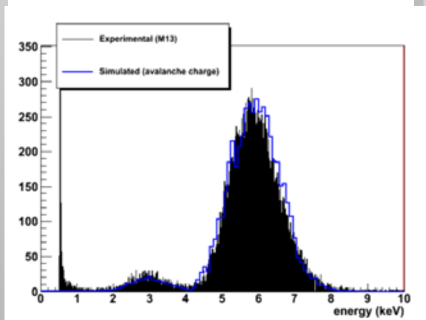
bilayer best, Pt: 88%, Ni: 87%

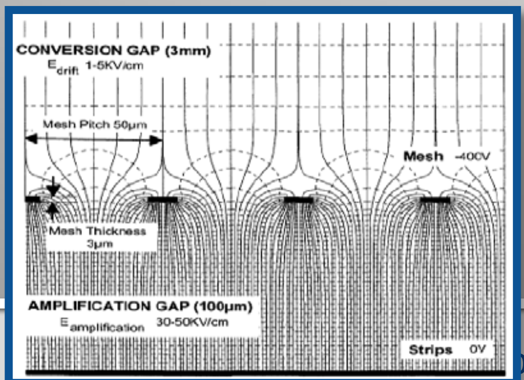
Low background detectors for IAXO

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



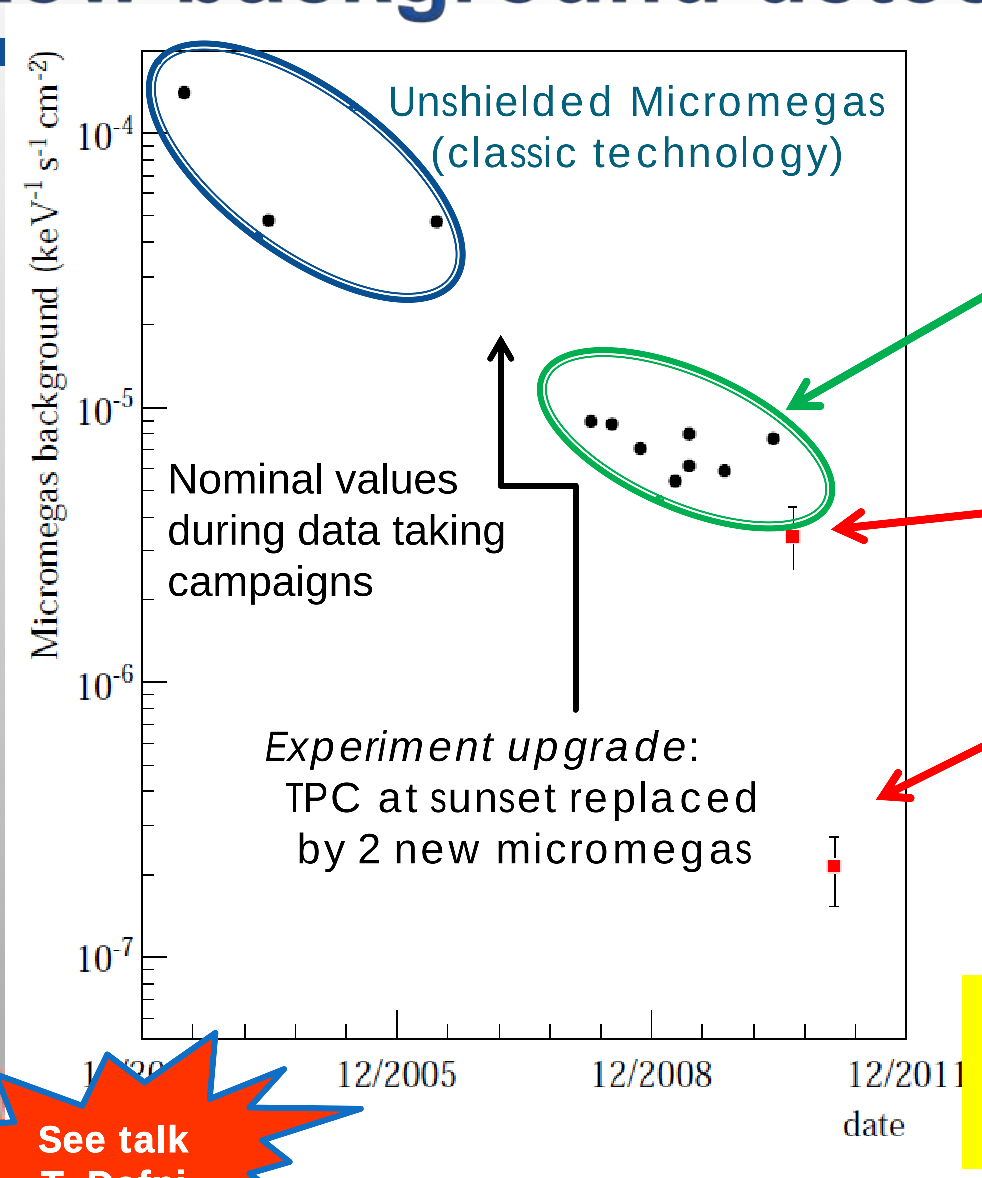






radiopurity	^{232}Th	^{235}U	^{238}U	^{40}K	^{60}Co
Microbulk mM	<9.3	<13.9	26.3±13.9	57.3±24.8	<3.1*
Kapton-Cu foil	<4.6*	<3.1*	<10.8	<7.7*	<1.6*
Cu-Kapton-Cu foil	<4.6*	<3.1*	<10.8	<7.7*	<1.6*

Low background detectors for IAXO



Shielded Micromegas
(bulk and microbulk technology)

~5x10^{-6} c/keV/s/cm^{2}

2,5cm Pb shielding
in **Canfranc**

≥ 10cm Pb shielding
in **Canfranc**

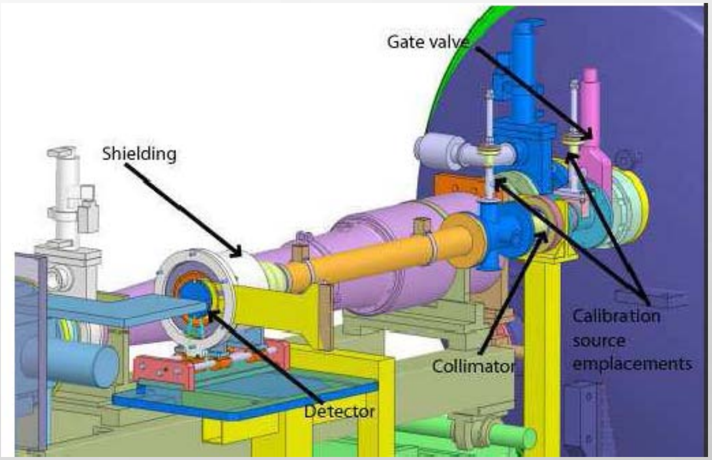
Reduction of a factor ~20
wrt CAST results
2x10^{-7}c/keV/s/cm^{2}

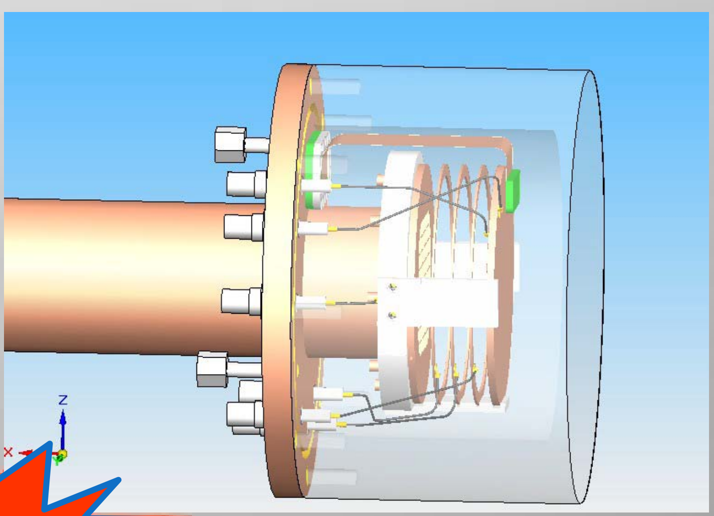
Good possibilities to reach the IAXO requirements of ~10^{-7}-10^{-8} c/s/keV/cm^{2}

See talk T. Dafni

Pathfinder detector+optics for IAXO

- 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 from R&D: compactness, better shielding, radiopurity,…
  - Goal: 10^{-7} cts/(keV cm^2 s) or better
- To be operated at CAST in 2013
- Tests of techniques and know-how for IAXO





See talk T. Dafni

Large gas systems: Extending mass range

The axion mass band for which a Primakoff based experiment is sensitive can be extracted from the coherence condition

Vacuum

The converted photons are mass less

$$\left(m_a^2 / keV^2 \right) << 2 \left(\frac{E_a / keV}{L \cdot keV} \right)$$

The magnet length sets the range of the axion mass coherence

Gas

The converted photons acquire an effective mass

$$\left(m_a^2 / keV^2 \right) << \left(m_\gamma^2 / keV^2 \right) + 2 \left(\frac{E_a / keV}{L \cdot keV} \right)$$

Able to extend the axion mass sensitivity range of an experiment that has a fixed magnet length

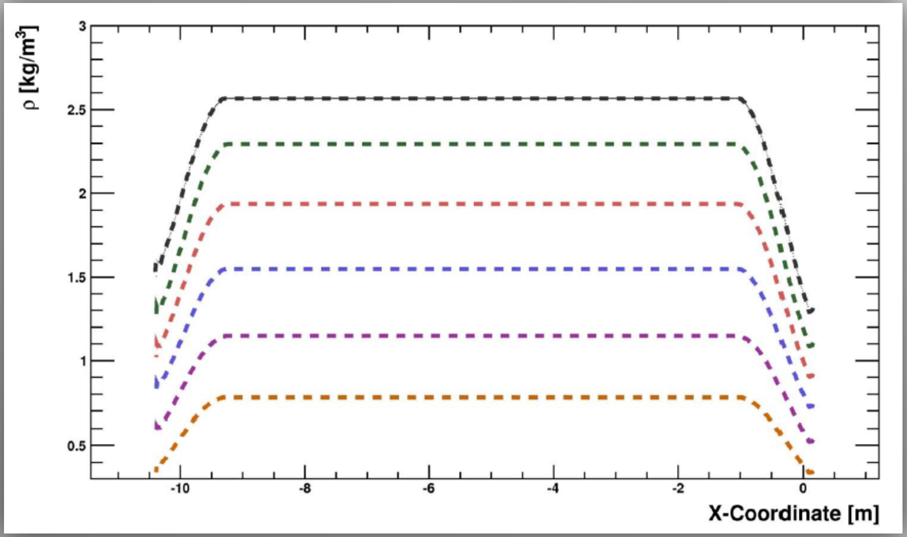
Model of a large gas system

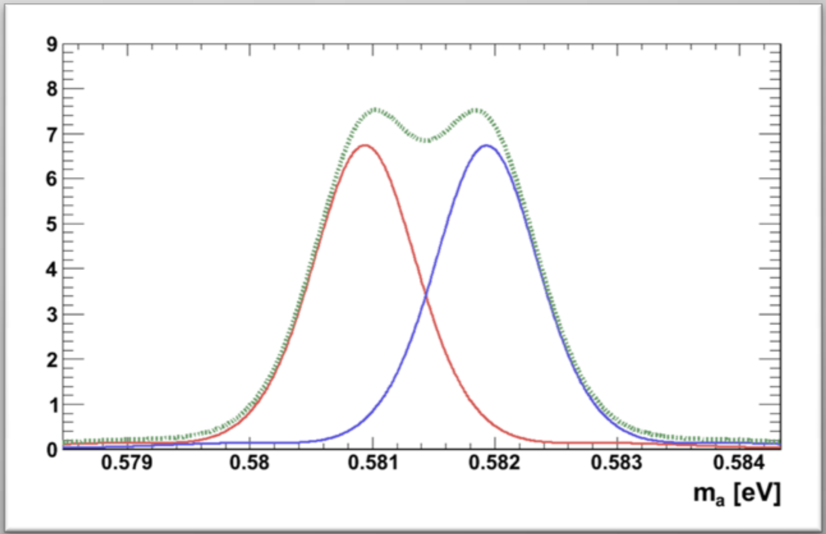
Computational fluid dynamics

- Density profile

- Stable conditions
- Include all the physics
- Fine tune models
- Compatibility with experimental data

See talk J.Ruz



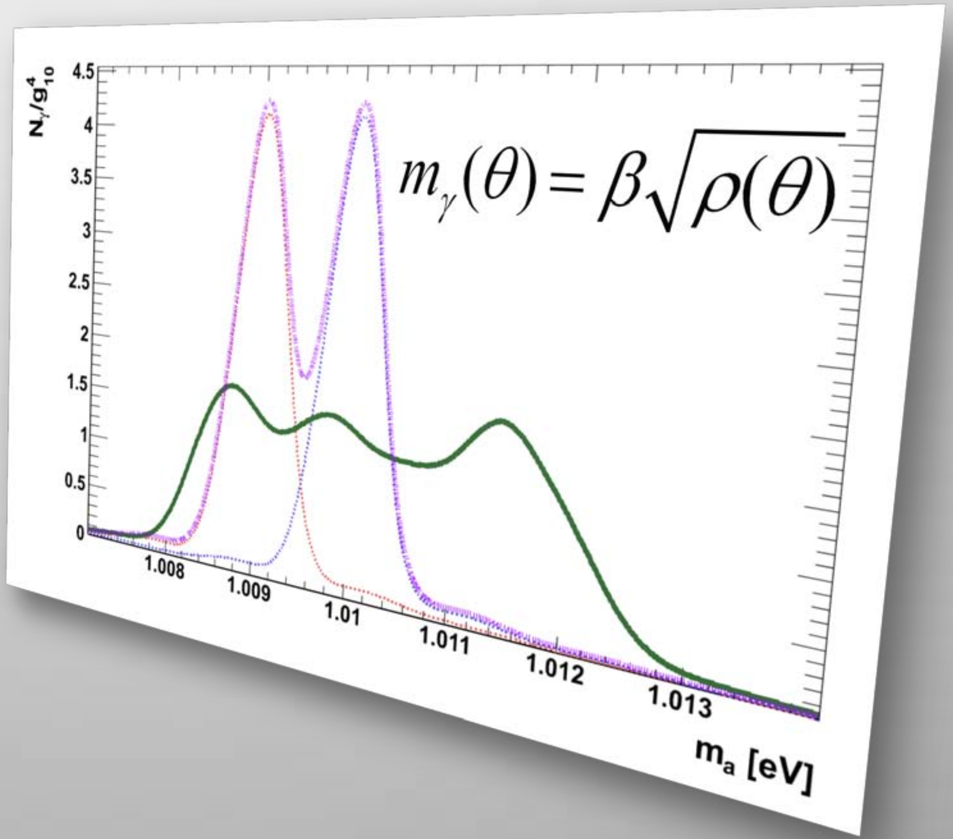


Challenges of a moving gas system

Such effect can be corrected by applying an effective density to the whole gas column

Considering $\alpha(\theta)$ the factor that accounts for the density in the center of the magnet bore relative to the density at $\theta = 0^o$.

$$\rho(\theta) = [1 + \alpha(\theta)] \times \rho_{center,0}$$



See talk J.Ruz

Layout for the new IAXO

- **Extending the axion mass sensitivity is possible**
  - o The use of 3,4-Helium has become a standard technique for helioscope experiments
- **Model system**
  - o Obtain the gas density profile in the magnet region
  - o Crosscheck with experimental data to validate the evolution of the system
- **Monitor evolution**
  - o Allows to find systematics in the analysis, such as leaks and strange behavior
- **Apply models**
  - o Fight systematic
  - o Impact to the sensitivity of the experiment
- **Towards a new generation of Axion Helioscopes**

See talk J.Ruz

ANTI CRYOSTAT?

Ongoing work/Challenges

- Magnet design:
  - Decisions on final design have to be taken
  - Study if cavities can be included → Work together with cavity groups
- Detectors:
  - Improve bgrd levels, lower thresholds
- Optics:
  - Optimizations of design, coatings etc.

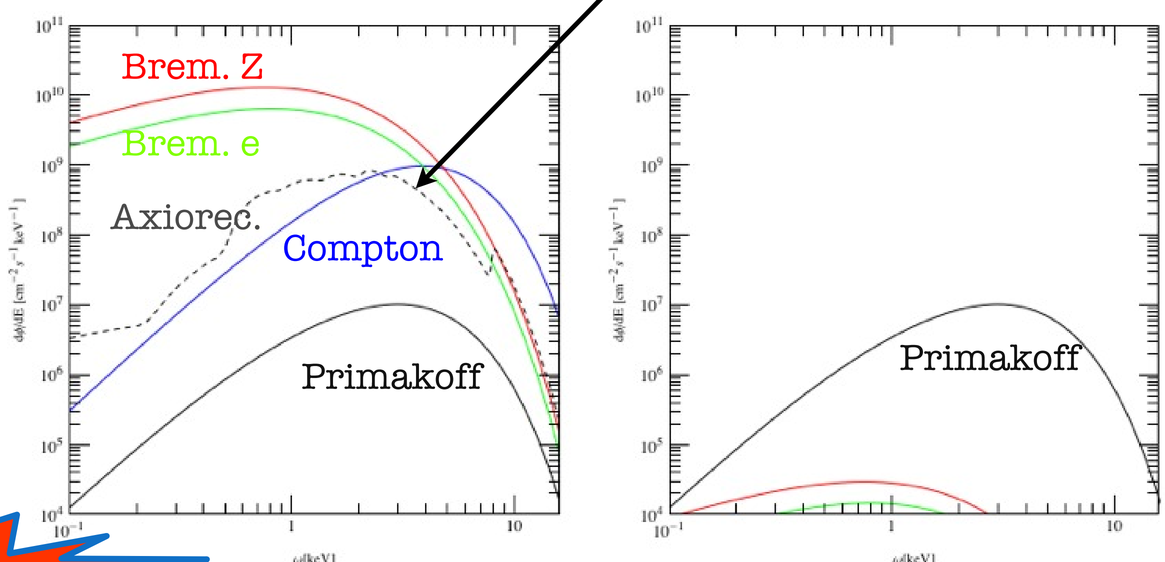
Theoretical considerations

Solar Axions: what's left to do?

- Emission is VERY well understood

Some subdominant processes have not been cross/checked
- Axio-recombination effect (Dimopoulos et al)

adronic



J. Redondo

$$f_a = 10^9\,\mathrm{GeV}; C_\gamma = 1; C_e = 1, \alpha^2 \log \frac{f_a}{m_e}$$

Theoretical considerations

Solar Axions: testing WD cooling in non-had. models

- Recently, the WD preferred parameters have been revisited upwards

White dwarfs as physics laboratories: the case of axions

J. Isern[1,2], L. Althaus[3,4], S. Catalán[5], A. Córsico[3,4], E. García-Berro[6,2], M. Salaris[7], S. Torres[7,2]

$$g_{ae} \simeq 2 - 7 \times 10^{-13}$$

felt and Weiss, 1994

Raffelt, Redondo and Viaux, in prep.

J. Redondo

Theoretical considerations

Solar Axions: testing WD cooling in non-had. models

- So far we always used E/N = 8/3, as motivated by unification but ...

Unificaxion

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heavy fermions	α_{GUT}	M_{GUT}	M_Ψ	E/N	E/N-1.92
Q	1/38	2×10^{15} GeV	1×10^{6} GeV	5/3	0.75
$2Q$	1/38	2×10^{15} GeV	5×10^{10} GeV	5/3	-0.25
$3Q$	1/38	2×10^{15} GeV	2×10^{12} GeV	5/3	-0.25
$2Q\oplus D$	1/36	8×10^{15} GeV	6×10^{9} GeV	22/15	-0.25
$2Q\oplus U$	1/34	5×10^{15} GeV	2×10^{8} GeV	28/15	-0.45
$G\oplus 2V$	1/38	5×10^{15} GeV	2×10^{8} GeV	4/3	-0.05
$Q\oplus G\oplus V$	1/35	9×10^{16} GeV	8×10^{7} GeV	16/15	-0.59
$Q\oplus D\oplus L$	1/36	2×10^{15} GeV	1×10^{6} GeV	2	-0.85
					0.08

Table 2: *Models of unificaxion with up to 3 fermion multiplets, intermediate mass between* 10^3 *and* 10^{14} GeV *and unification mass satisfying eq. (5). Their predictions for* α_{GUT},

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Theoretical considerations

The case of IAXO

- **Finding new particles**
  arise very often in extensions of the SM
  Some could be already been hinted:

  - strong CP problem hints an axion
  - Dark matter

  and VERY weak hints

  - WD cooling hints an ALP (could be the axion)
  - Transparency hints an ALP (not the axion)

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IAXO is not a direct axion/ALP/HP dark matter search

However, it is almost guaranteed that:

- Any particle IAXO finds (this includes the QCD axion) IS a subdominant component of DM

- In some models can be ALL the DM

- Can guide the detection of DM (after all is broadband) pinpointing the mass and coupling

- Cavity experiments cannot measure the coupling and the DM abundance independently (need for complementary experiments)

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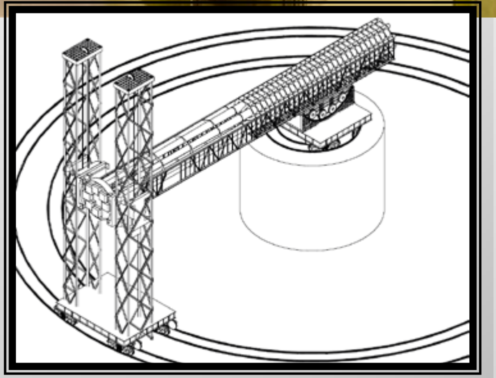
Conclusions



- **CAST** is established as a reference result in experimental axion physics:
  - CAST PRL2004 most cited experimental paper in axion physics
  - Expertise gathered in magnet, optics, low bgrd detectors, gas systems
  - No other technique can realistically improve CAST in such wide mass range.
- **IAXO** is a new generation helioscope (4th generation):
  - 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 (WG presentations)
  - 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 (White Dwarf, ALPs,…)