Recent constraints on axion-photon and axion-electron coupling with the CAST experiment

Closing in on Dark Matter
January, 2013. Aspen, CO.

J. Ruz, *on behalf of the CAST and IAXO Collaboration*

LLNL-PRES-563700
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Outlook

- Axions: motivation, phenomenology and cosmology
- Solar axions: the helioscope concept
  - Axions in astrophysics
  - Detection of solar axions
  - The coherence condition
- Detection of Solar axions with CAST
  - Hadronic axions
  - Non-hadronic axions
- Helioscope's future
  - The Near term future: CAST
  - The goal: IAXO

Axions: motivation, phenomenology and cosmology

Axion cosmology

- **Axions could be produced** in the early Universe by a number of processes:

  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

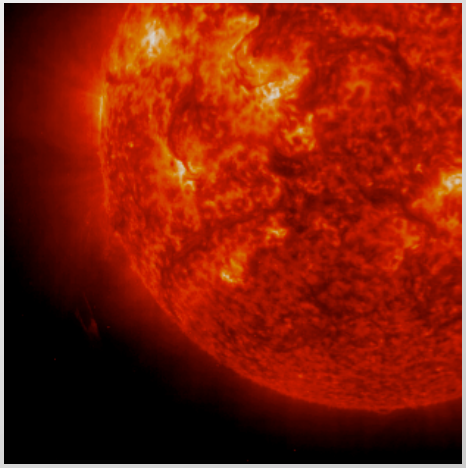
  → NON-RELATIVISTIC (COLD) AXIONS Cold Dark Matter (CDM) candidate

  - Thermal production

  → RELATIVISTIC (HOT) AXIONS Hot Dark Matter (HDM) candidate

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

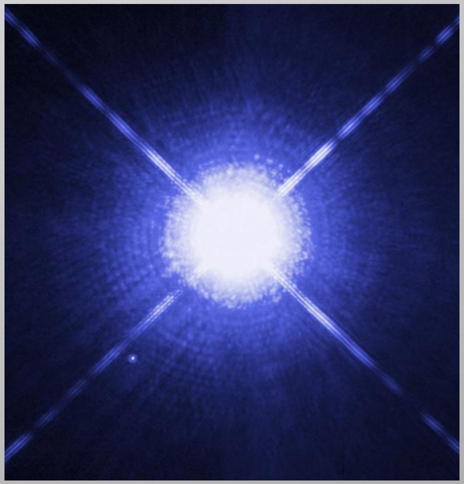
Axions in astrophysics



- **Axions can be produced in the core of stars,** like the Sun, by Primakoff conversion of plasma photons.

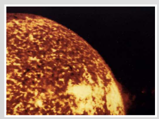
- **Axion decay** may produce γ-ray emission lines originating from certain places (e.g., galactic center).

- **Axions may have a wider impact:** The cooling of white dwarfs

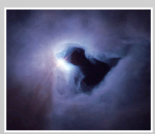


Classic axion searches

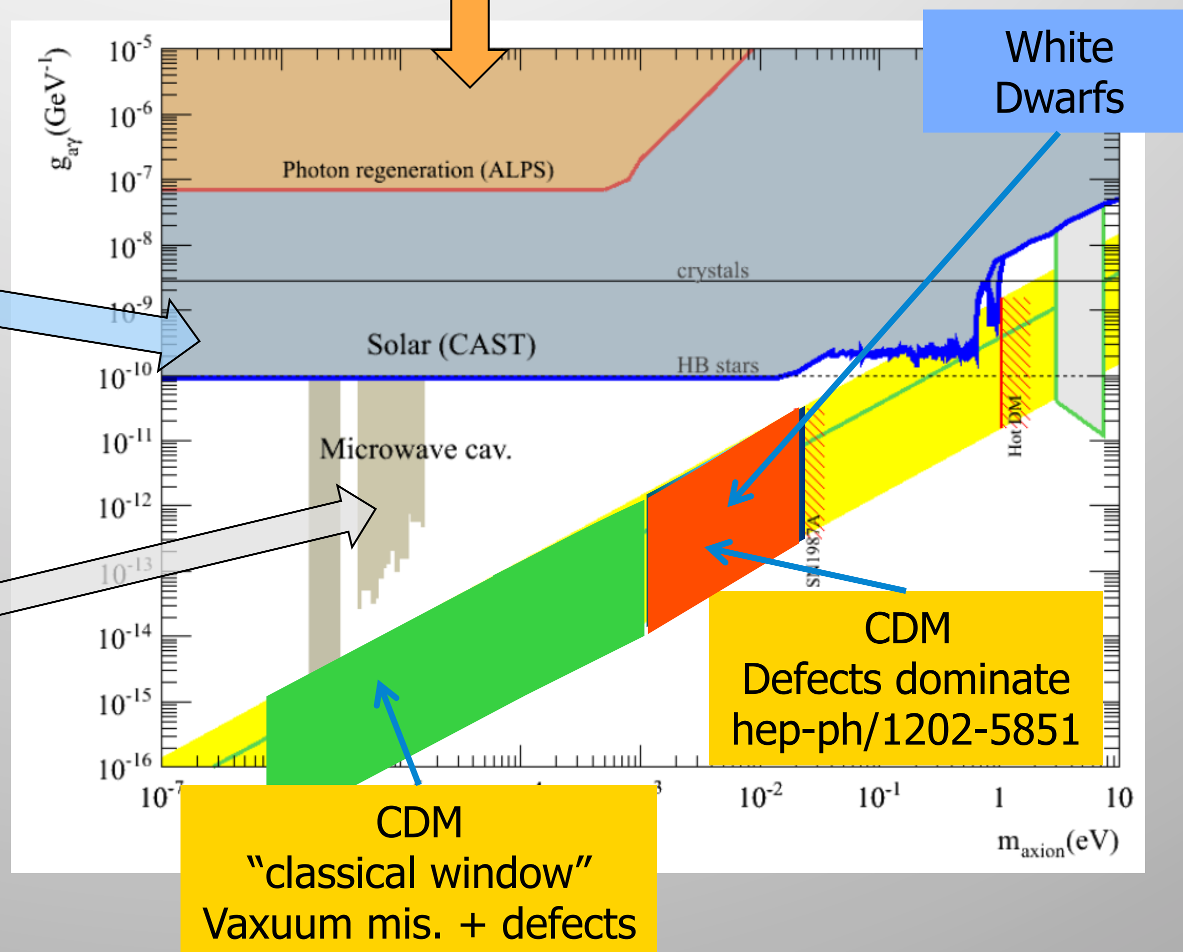
- Laboratory axions
  - → Shining-Light-through-Walls (OSQAR, LIPSS, ALPS)
  - → Polarization (PVLAS)
- Solar axions



  - → Crystals (SOLAX,COSME)
  - → Helioscopes (Tokyo, **CAST**)
- Halo axions (relics of Big Bang)



  - → Haloscopes (ADMX,Carrack)
  - → Telescopes (Haystack)

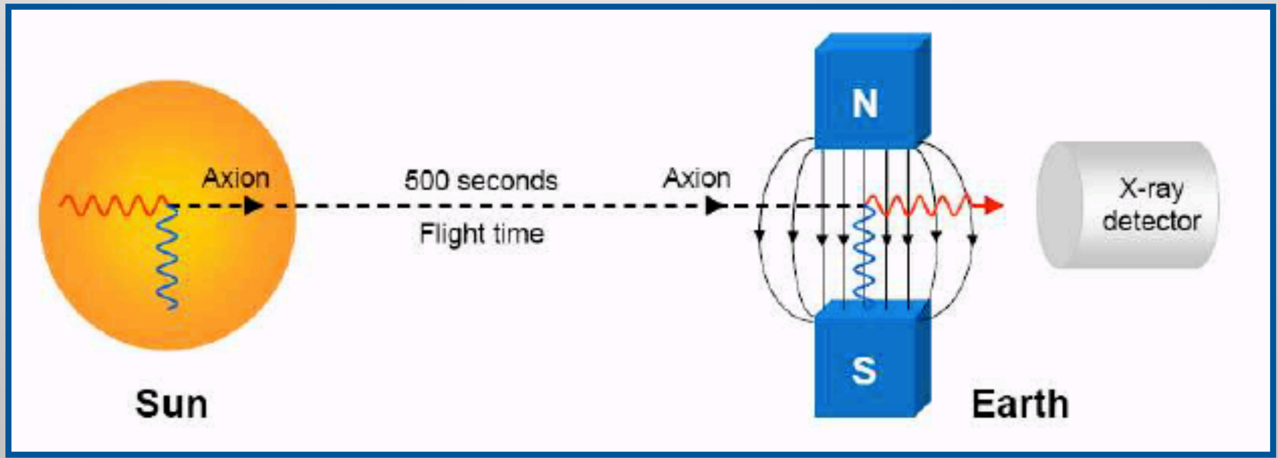


Solar axions: the helioscope concept

Detection of solar axions

- **The Helioscope concept**

Axions created in the solar core travel towards Earth where by means of an intensive electromagnetic field they can be converted to photons via Primakoff effect

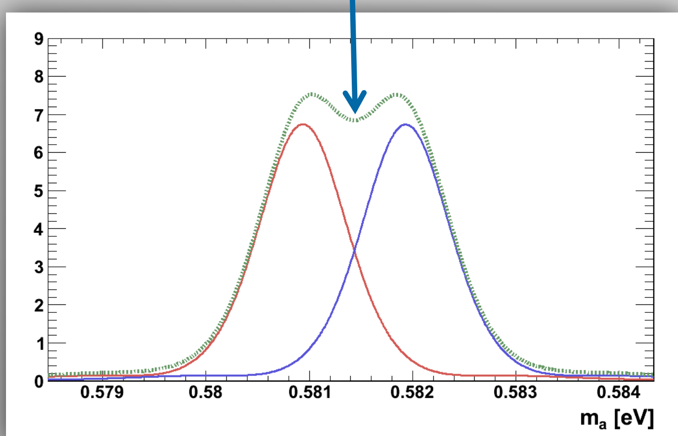


The interaction of an axion converting to a photon via Primakoff effect in the presence of magnetic fields is the proposed detection mechanism

Detection of solar axions

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

The converted photons may acquire an effective mass in the presence of gas extending the axion mass sensitivity range of an experiment that has a fixed magnet length



Conversion Probability

$$P_{a\gamma} = g_{10}^2 \times \left(\frac{B_\perp}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos qL\right]$$

↓

Coherence Condition

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

Axion-to-photon conversion in the presence of a nearly homogeneous magnetic field **B** is only effective when the polarization plane is parallel to the incident particle

CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10 m, B=9 T)
- Moving platform ±8°V, ±40°H (allows 3 hours/day of solar tracking)
- 4 magnet bores to look for x-rays from axion conversion
- X-ray focusing system to increase signal/background ratio

Axion models

- **Axion decay constant**
  - The axion mass and the scale of the interaction are closely related

$$m_a = \frac{m_u + m_d}{\sqrt{m_u m_d}} \frac{m_\pi f_\pi}{f_a} = 6\,\text{meV}\,\frac{10^9\ \text{GeV}}{f_a}$$

$$\boxed{z = 0.56} \longleftarrow z = \frac{m_u}{m_d} \subseteq [0.35, 0.6]$$

  - The nature of axion implies they must interact with hadrons and photons

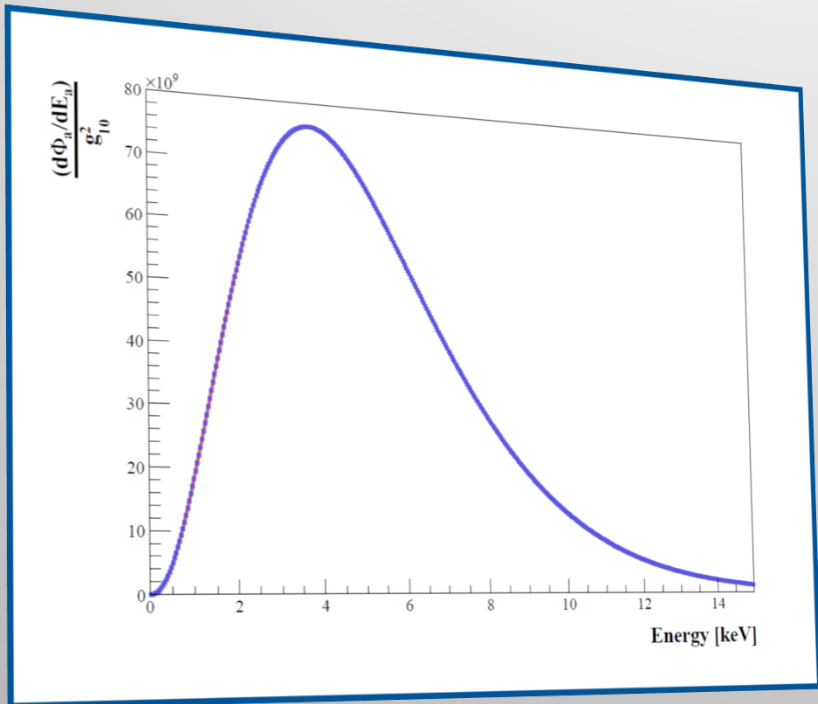
➢ Hadronic axion models

  - GUT motivated axion models suggest that axions can also significantly interact with leptons

➢ Non-hadronic axion models

Hadronic axions at CAST

- Primakoff production of axions in the Sun



Differential axion flux at the Earth surface due to Primakoff production in the solar core

$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

- No significant signal observed
- Typical upper limit
- Touching KSVZ benchmark

Hadronic axions from the Sun

- To date, interpretation of solar axion experimental results has looked at photon-axion coupling: hadronic models

❑Vacuum Phase

$$m_a \le 0.02\ eV$$

Phys.Rev.Lett.94:121301, 2005

JCAP 04 (2007) 010

❑⁴He Phase

$$0.02\ eV \le m_a \le 0.39\ eV$$

JCAP 02 (2009) 008

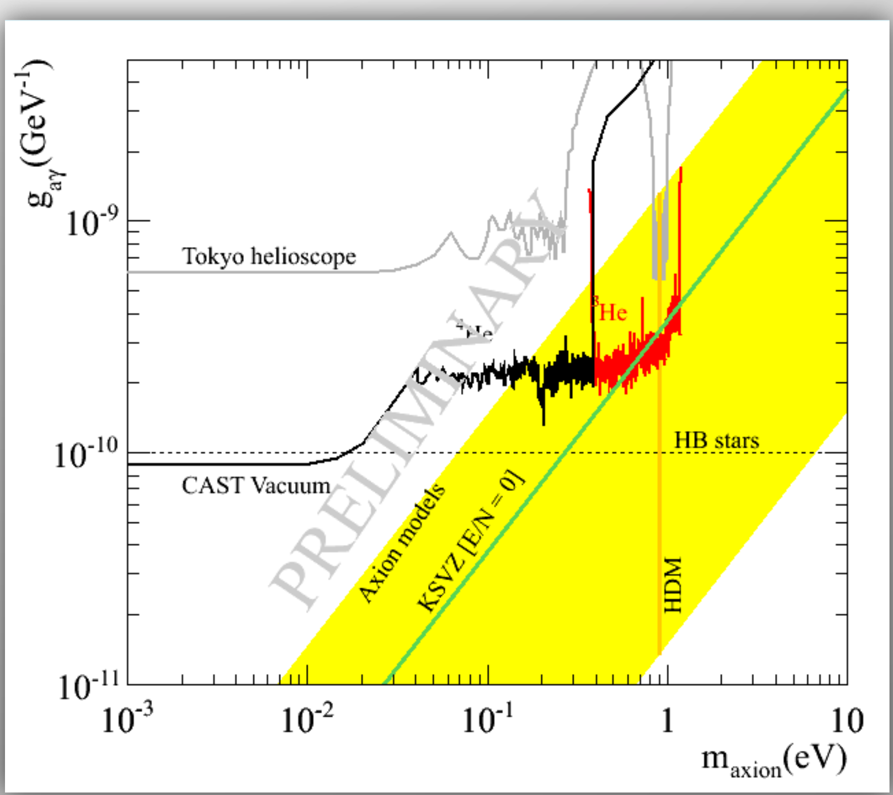
❑First Results from ³He Phase

$$0.39\ eV \le m_a \le 0.65\ eV$$

Phys.Rev.Lett. 107:261302, 2011

❑Preliminary analysis of rest ³He Phase

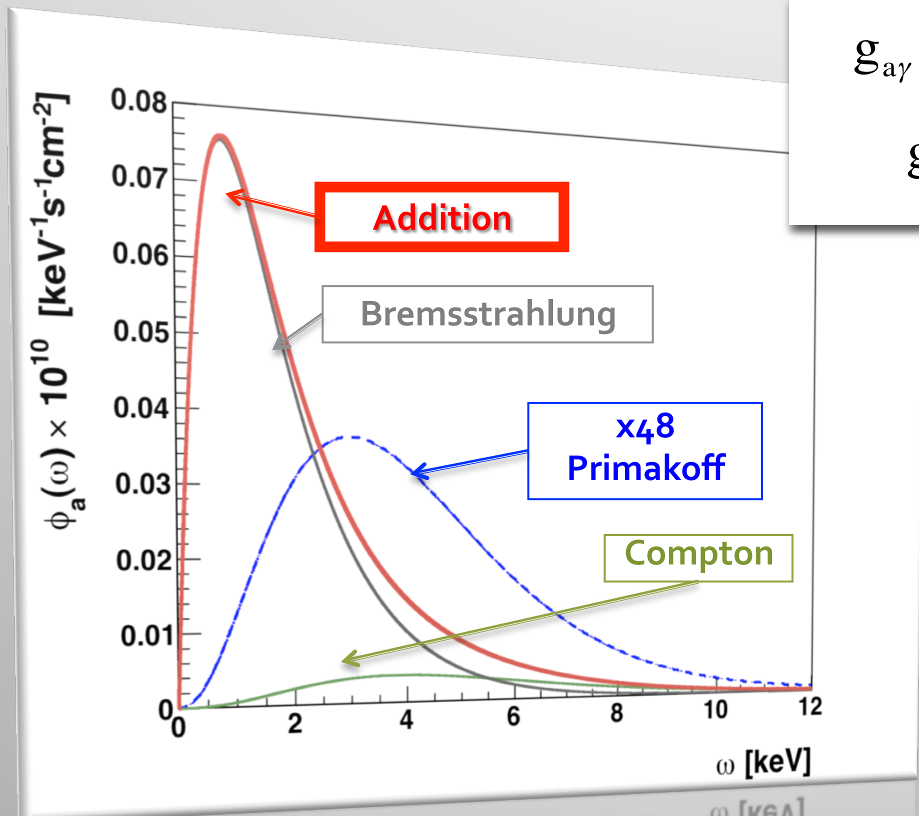
$$0.65\ eV \le m_a \le 1.18\ eV$$



But we know that other processes might be at play …

Non-hadronic axions at CAST

- Primakoff and electron production of axions in the Sun



$$g_{a\gamma} = 1 \times 10^{-12} \mathrm{GeV}^{-1}$$

$$g_{ae} = 1 \times 10^{-13}$$

- No significant signal observed
- White Dwarf compatible?

$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

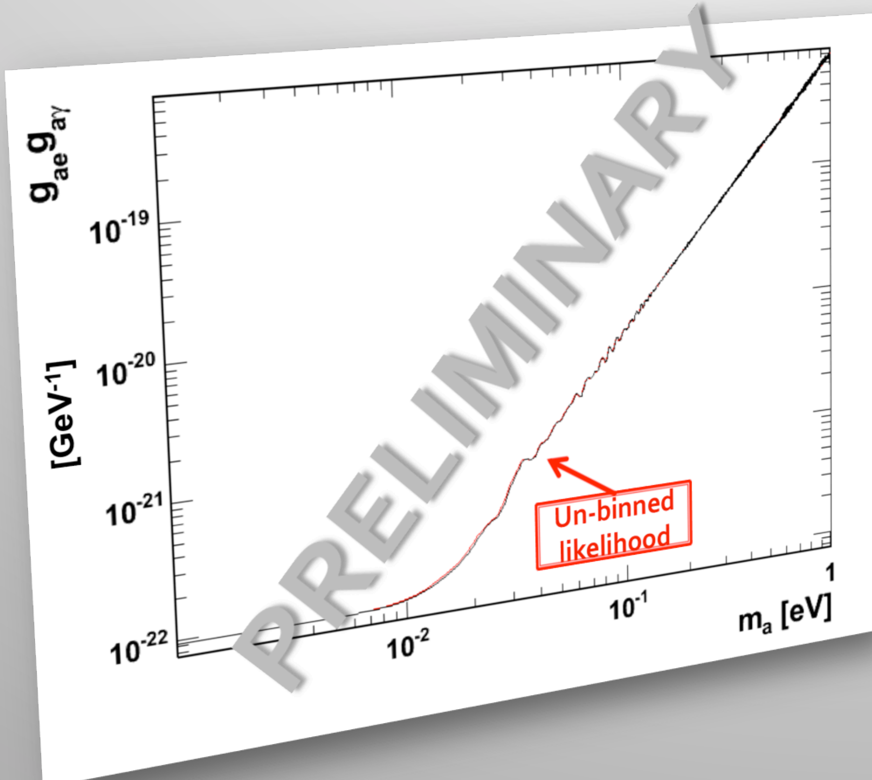
$$\mathcal{L}_{aee} = C_e \frac{\partial_\mu a}{2 f_a} \overline{\psi}_e \gamma_5 \gamma^\mu \psi_e \longleftarrow \boxed{g_{ae} = \frac{C_e m_e}{f_a}}$$

Non-hadronic axions at CAST

- **Extraction of a limit,** a generic limit can be expressed as

Axion-electron Yukawa coupling

$$C_e C_\gamma = g_{ae} g_{a\gamma} \frac{2\pi}{\alpha} \frac{1}{m_e} \left[\frac{6\,\mathrm{meV} \cdot 10^9\,\mathrm{GeV}}{m_a} \right]^2$$



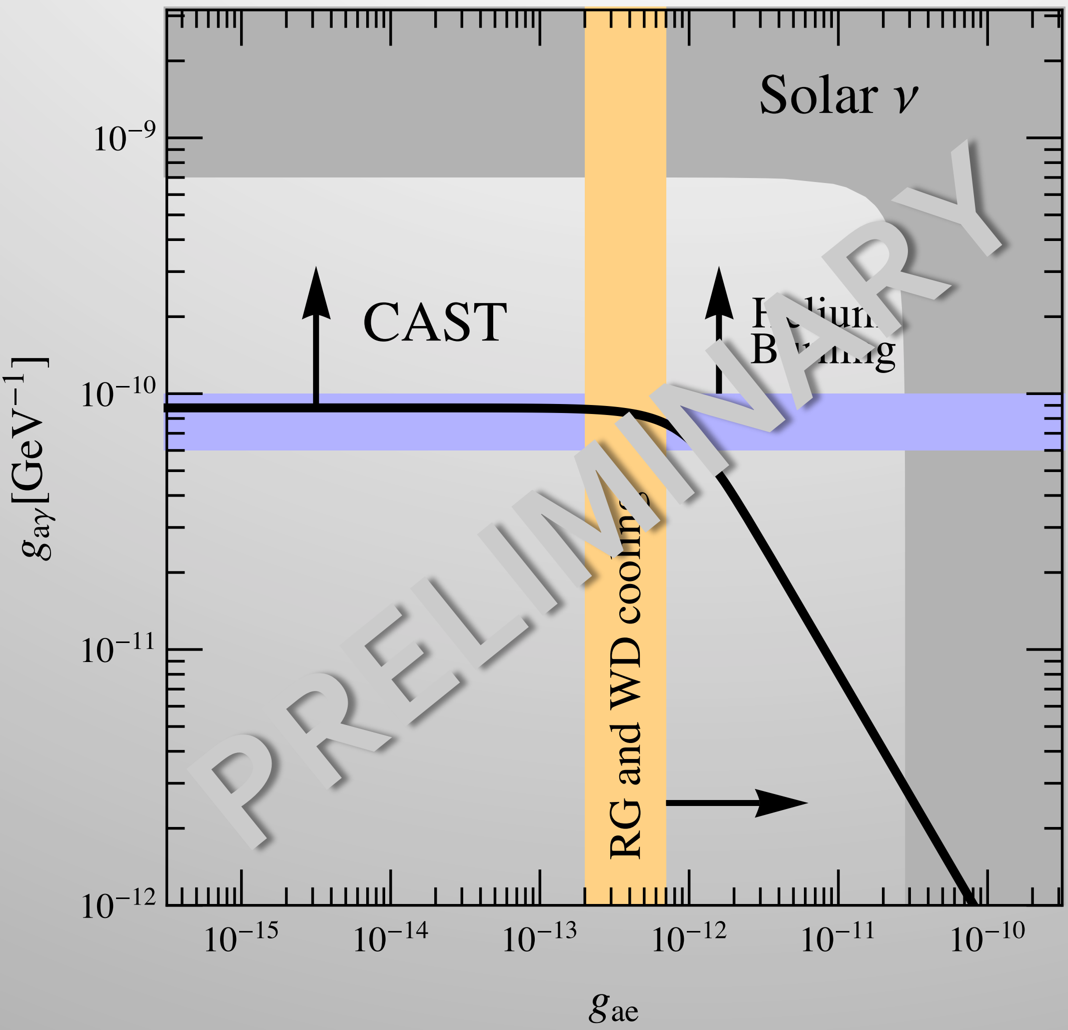
$$g_{ae} \times g_{a\gamma} \leq 8.1 \times 10^{-23}\, GeV^{-1}$$

Model dependent parameter

$$C_\gamma = \frac{E}{N} - \frac{2(4m_d + m_u)}{3(m_u + m_d)} \approx \frac{E}{N} - 1.92$$

Electromagnetic and color anomalies ratio

Axions with CAST



$C_e C_\gamma < 0.25$

⇩

DFSZ Models

$C_\gamma = 0.75$

⇩

GUT

Near term future:
CAST

Near term future at CAST

- **Current CAST science program** approved by CERN, runs through 2014
- **Schedule for the near future**
  - **Re-visit ^4He phase (2012) and vacuum phase (2013-14):**

    Better detectors → higher sensitivity

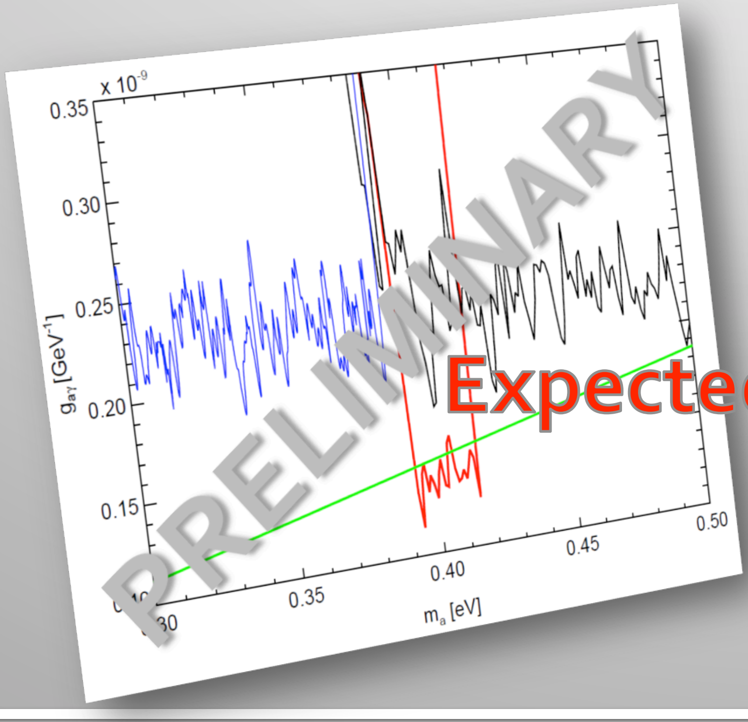
    New optics → increased discovery potential

    - Improve present limits
    - Study axion-electron coupling g_{ae}

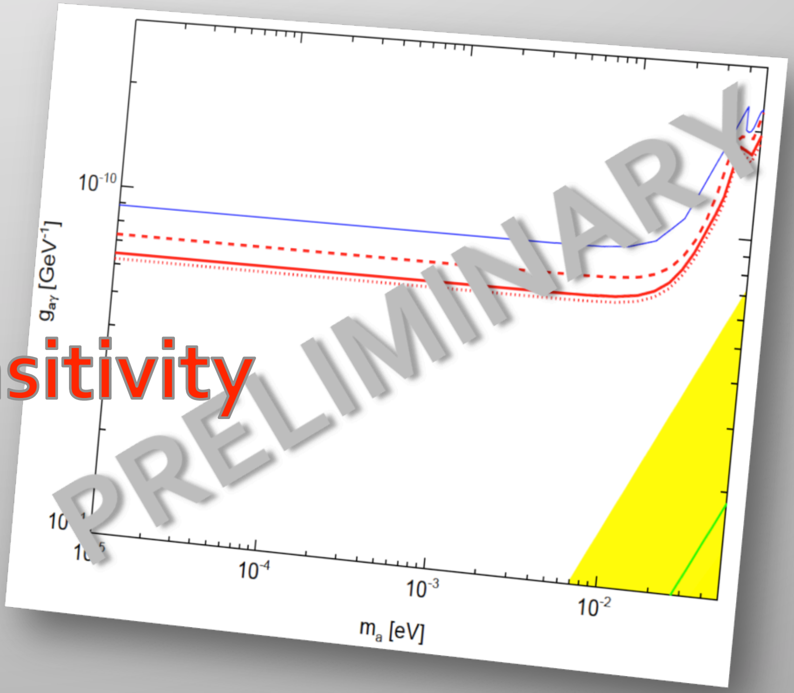
      Direct access to DFSZ models
  - **Possible access to:**
    - Exotica
      - Paraphotons, chameleons, low energy axions
    - Relic axions

Near term future at CAST

- Re-visit 4He phase (ongoing)
- Re-visit vacuum phase (2013-14)
  - Better detectors, new optics →higher sensitivity and increased discovery potential (red line)
  - Probing standard KSVZ model (green line)



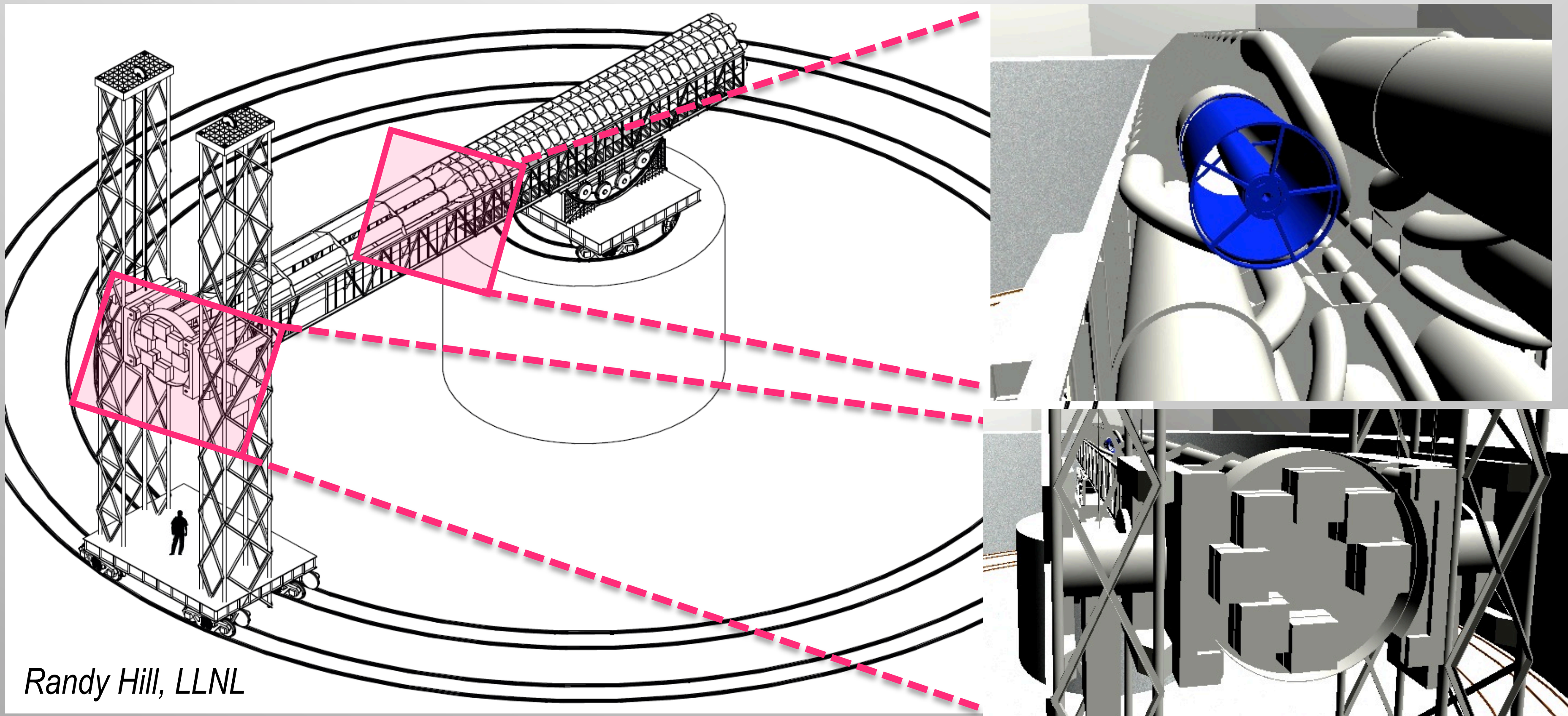
Expected sensitivity



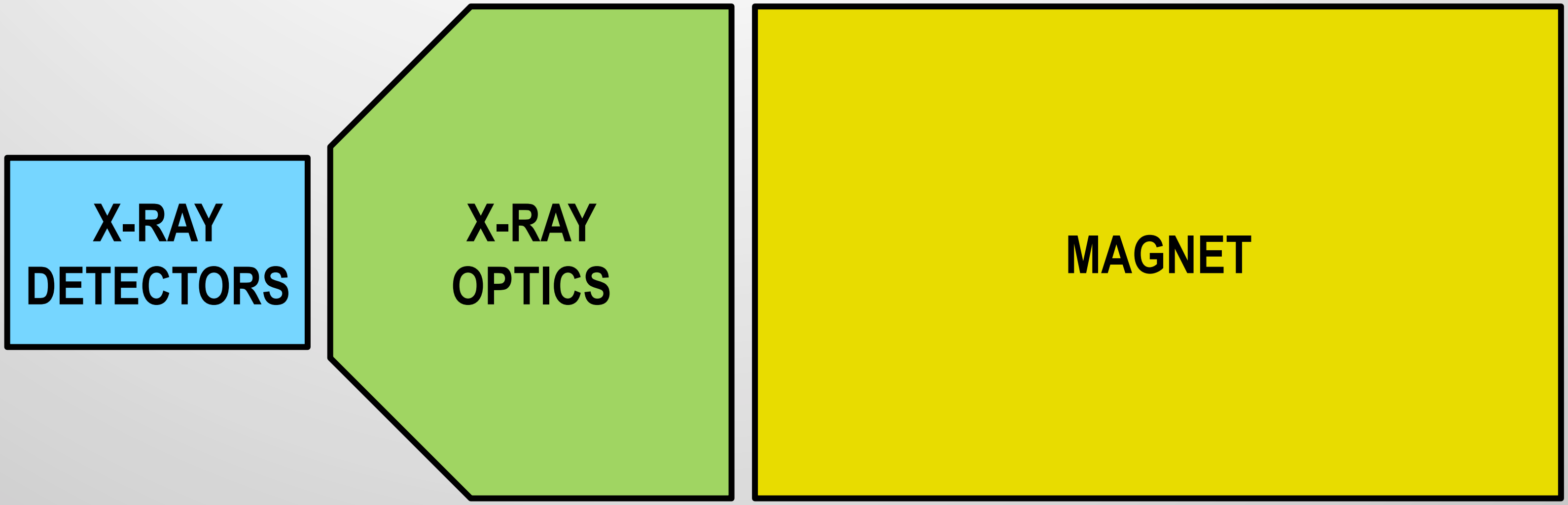
The goal: IAXO

Initial structural design by LLNL

- **Challenge:** move a 25-meter long structure (15 m for the magnet, another 10 m for the x-ray telescopes) that weighs 200 tons
- **Solution:** borrow from other heavy-industry and ground-based astronomy



Three technologies impact 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

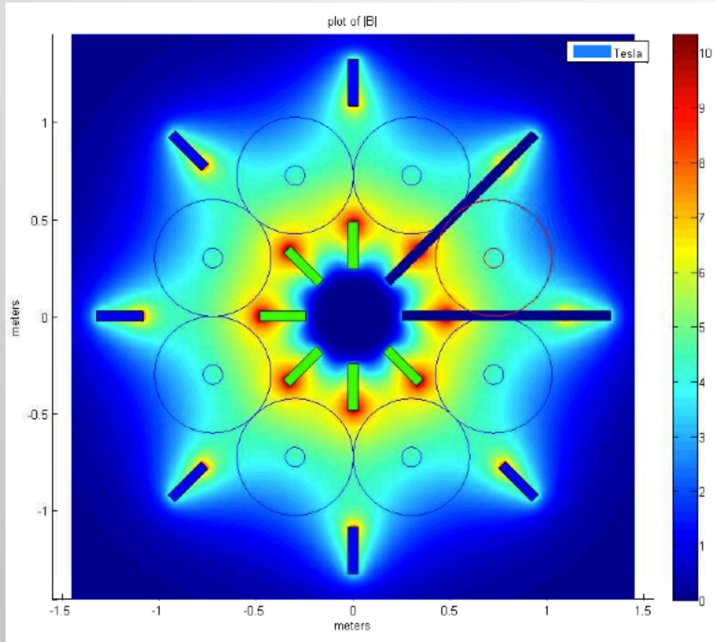
magnet

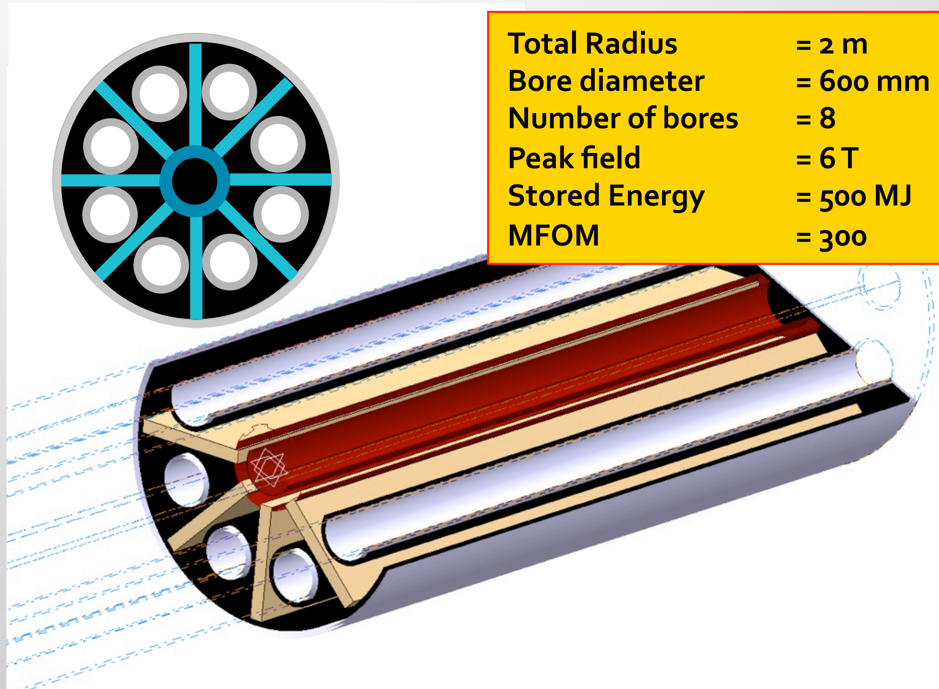
B = magnetic field
L = magnet length
A = cross-sectional area

exposure

t = time

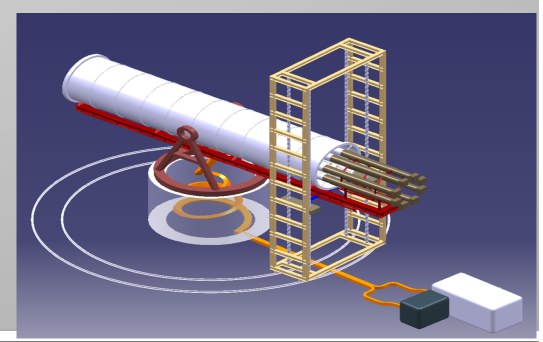
New Magnet





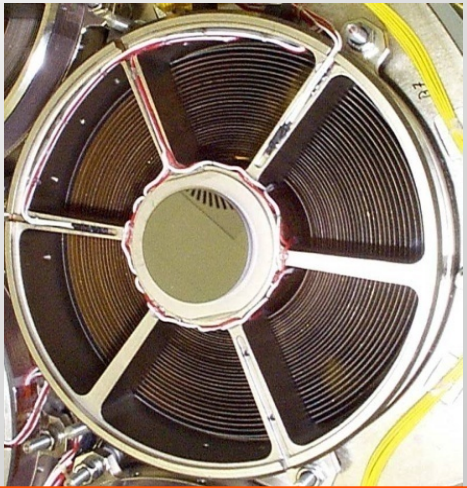
Total Radius	= 2 m
Bore diameter	= 600 mm
Number of bores	= 8
Peak field	= 6 T
Stored Energy	= 500 MJ
MFOM	= 300

- 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 conceived for axions.
- Toroidal magnet configuration (ATLAS-like magnet)

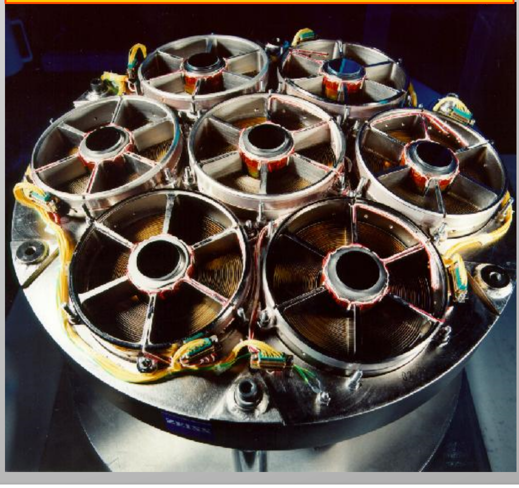


New x-ray optics

- X-ray optics are critical to high-sensitivity solar axion experiments, since they greatly reduce the size of the x-ray detector, which in turn, reduces the overall background
- Without an optic, the detector would have to be as large as the magnet bore; with an optic, it is possible to achieve a reduction in area by at least a factor of 100×
- For CAST, the size of the optic is limited by existing, unchangeable physical infrastructure (e.g., exterior walls and support structures)
- We need the ability to construct inexpensive and high-quality optics of various configurations

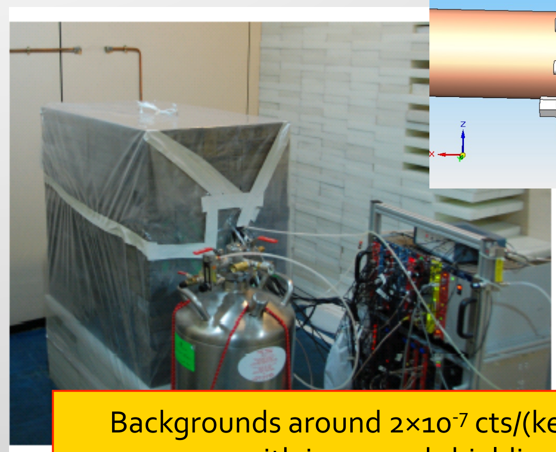


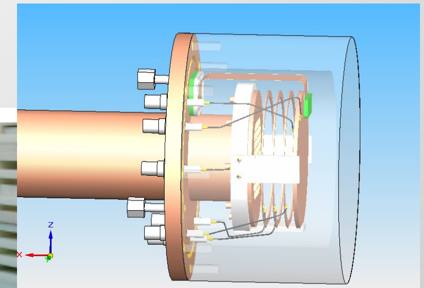
ABRIXAS flight-spare telescope



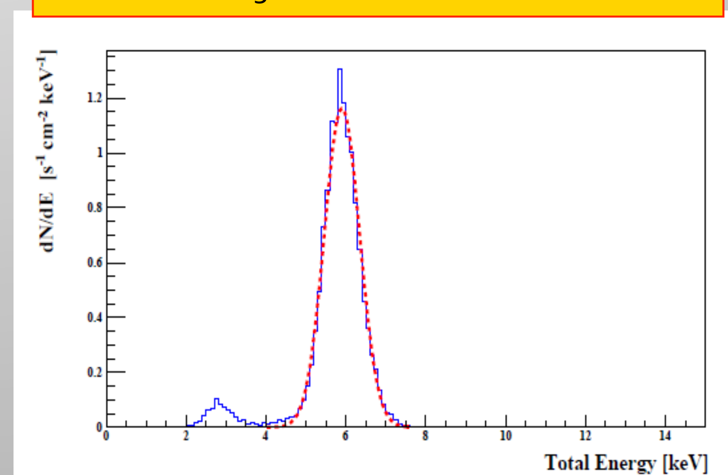
R&D low background detectors

- **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 detectors at CERN, Saclay & Zaragoza
  - Especially: underground setup at Canfranc Underground Lab
  - Simulation works to build up a background model
  - Design a new detector with improvements implemented



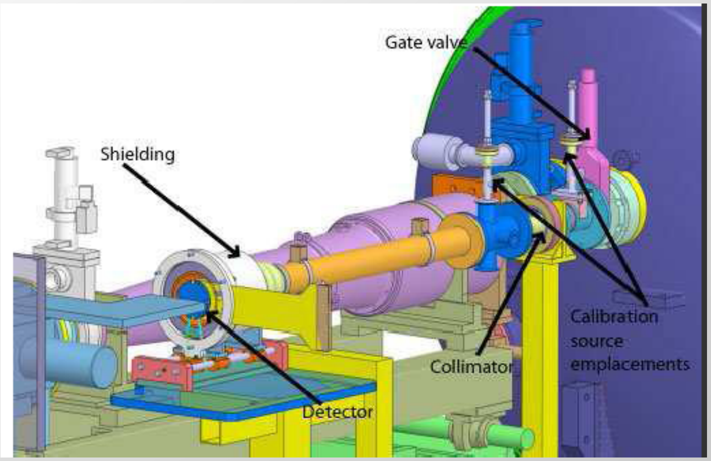


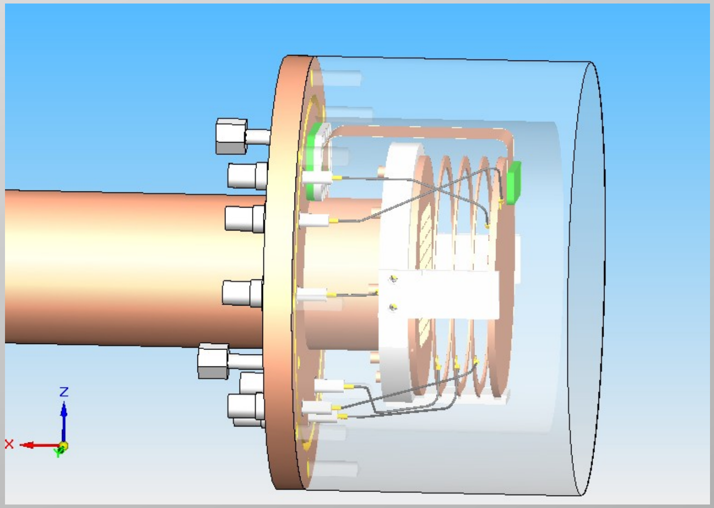
Backgrounds around 2×10^{-7} cts/(keV×cm^2×s) with improved shielding
×30 better than CAST



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 from R&D: compactness, better shielding, radiopurity,…
  - Goal: 10^{-7} cts/(keV×cm²×s) or better
- To be operated at CAST in 2014





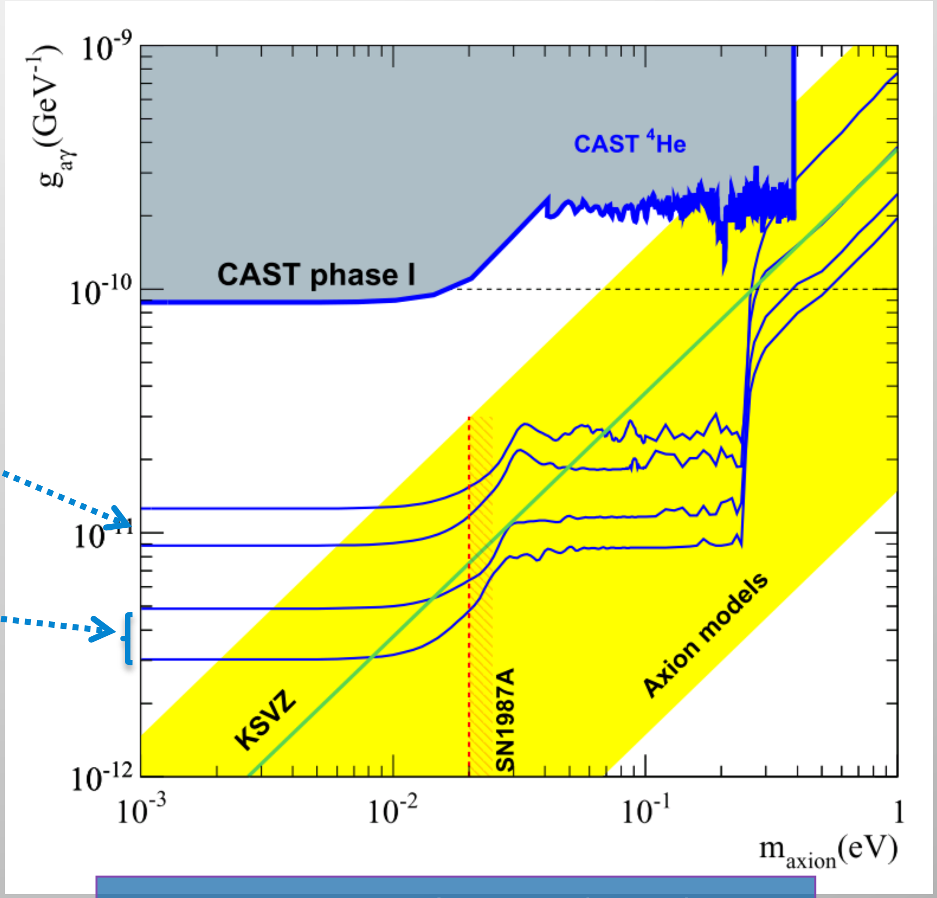
How much beyond CAST we can hope for?

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

Conservative scenario

Realistic scenario

Large parts of the QCD favored models could be explored in the coming decade with IAXO



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

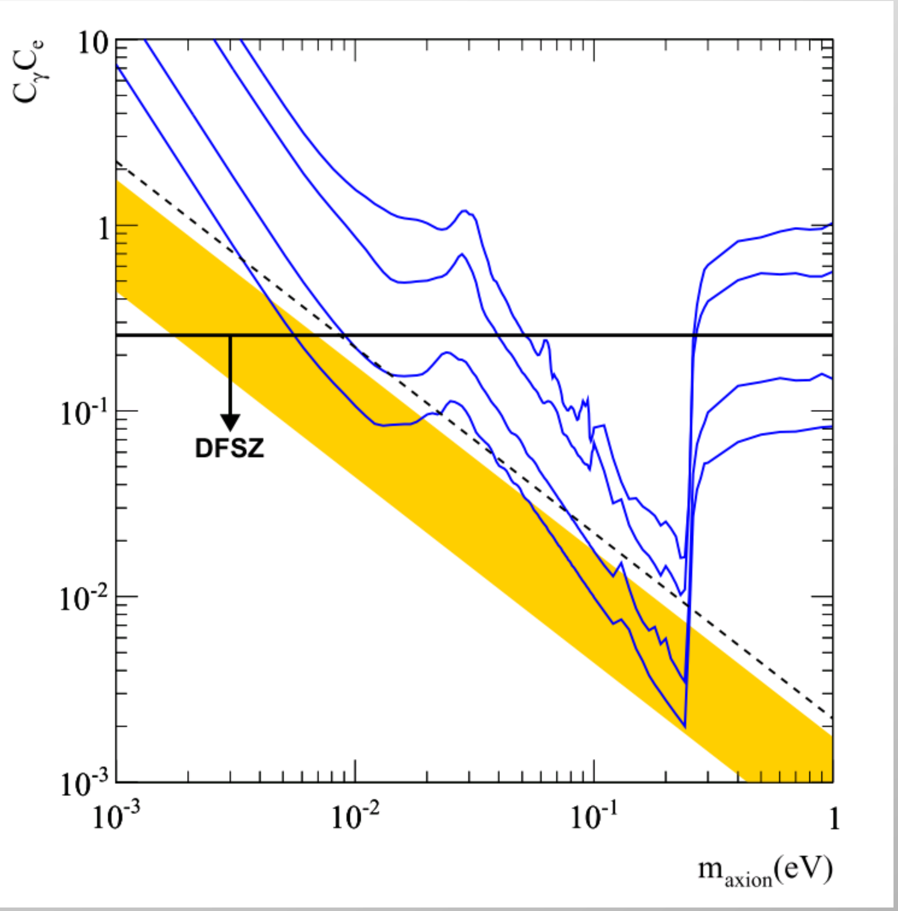
Prospects for non-hadronic models

- QCD axions at masses ~meV seem out of reach even for an improved axion helioscope…

BUT

- Non-hadronic models for axions provide extra axion emission from the Sun through axion-electron compton and bremsstrahlung processes

IAXO could improve current CAST sensitivity to non-hadronic axions by about 3 orders of magnitude



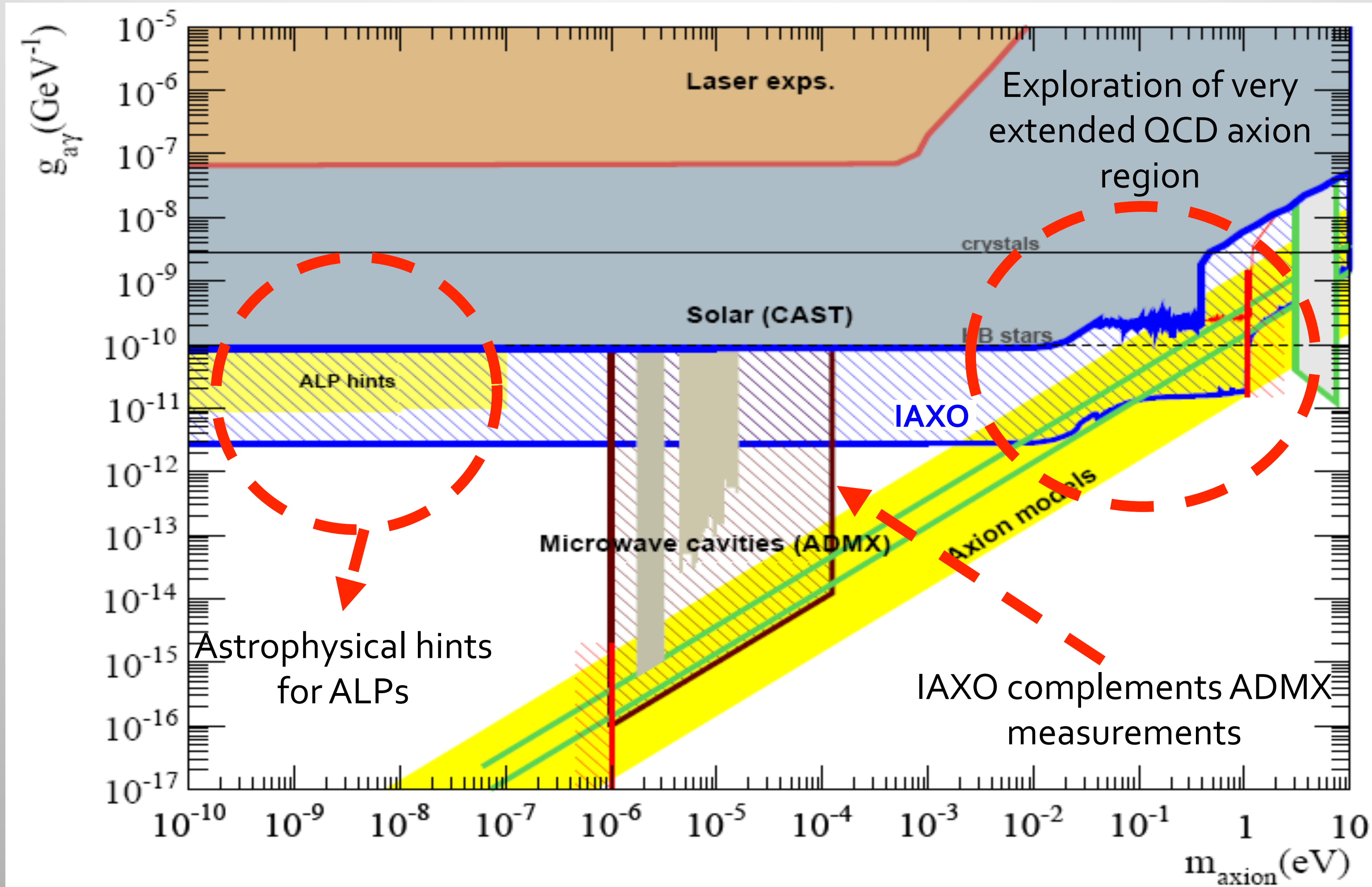
IAXO "Community"

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]

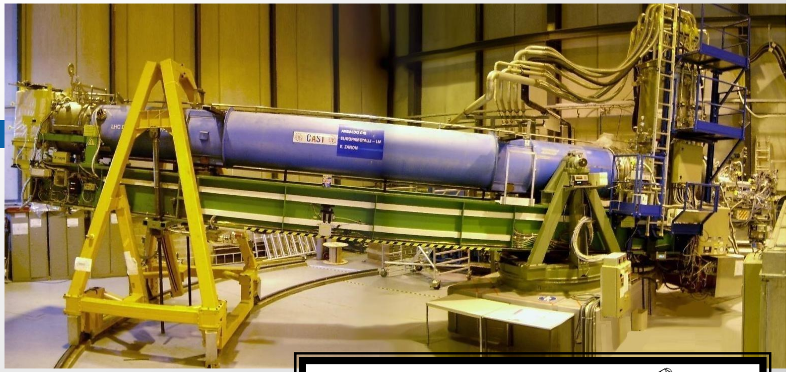
[a]Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, Zaragoza, Spain
[b]Department of Physics and Astronomy, University of South Carolina, Columbia, SC, U.S.A.
[c]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.
[d]CERN, Geneva, Switzerland
[e]National Center for Scientific Research "Demokritos", Athens, Greece
[f]IRFU, Centre d'Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France
[g]Technische Universität Darmstadt, IKP, Darmstadt, Germany
[h]Rudjer Bošković Institute, Zagreb, Croatia
[j]Lawrence Livermore National Laboratory, Livermore, CA, U.S.A.
[k]Max-Planck-Institut für Physik, Munich, Germany
[i]Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel
[l]Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia
[m]Naval Postgraduate School, Monterey, CA, U.S.A.
[n]University of Patras, Patras, Greece

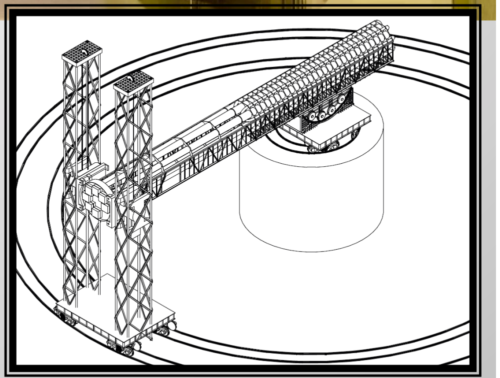
+ others

Axion search prospects



Conclusions





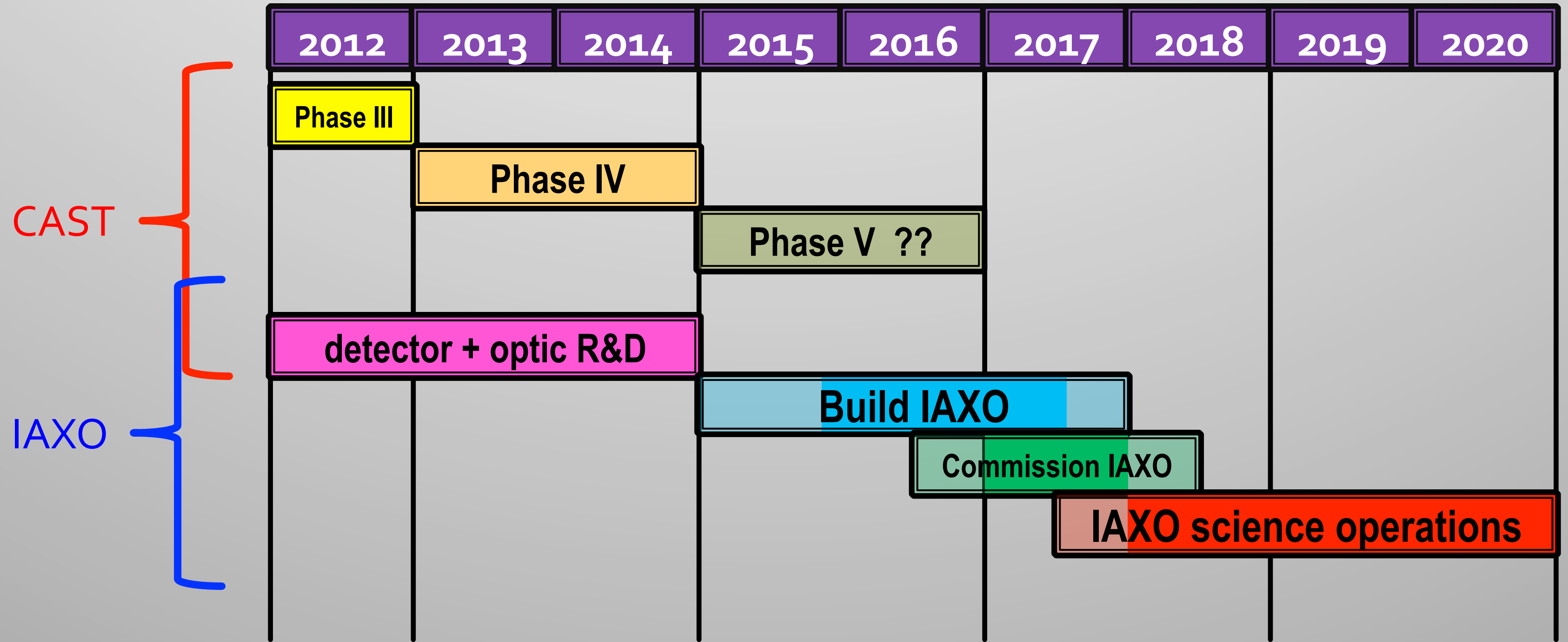
- **CAST** is established as a reference result in experimental axion physics:
  - CAST PRL2004 most cited experimental paper in axion physics
  - Expertise gathered in magnet, optics, low bgrd detectors, gas systems
  - No other technique can realistically improve CAST in such wide mass range.
- **IAXO** 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,...)

Thank you!

Backup slides

Notional plan

- 100 million dollar class project (*ROM estimate, to be refined!*)
- Socialization with CERN, European funding agencies (including ASPERA), HEP (2011 LLNL site visit and Intensity Frontier workshop)
- European CAST+IAXO team just submitted Marie Curie ITN proposal
- Working to engage burgeoning U.S. axion and ALP community (e.g., Yale, Fermilab and astronomy community)



IAXO and LLNL

- IAXO builds on CAST team and will require participation and support from Europe, US and CERN
- ATLAS magnet as starting point for design
  - CERN already supports design studies
  - Role for Fermilab or LBNL ?
- X-ray optics:
  - LLNL, Columbia U. and DTU-Space (Denmark)
- Detectors
  - CEA Saclay (France), U. Zaragoza (Spain), LLNL
- Theory
  - US and Europe

LLNL's role in IAXO:

→ **X-ray optics, detector technology, engineering, and leadership**

Other US institutions, potentially:

Theory, magnet fabrication, host institution?