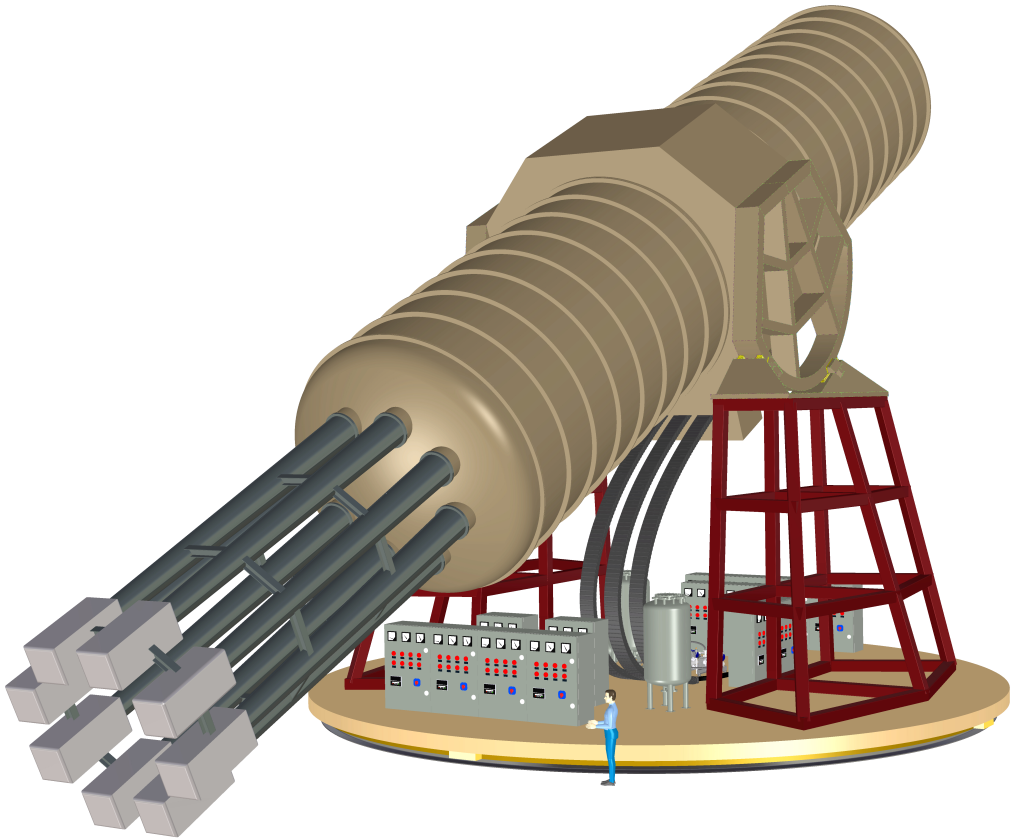
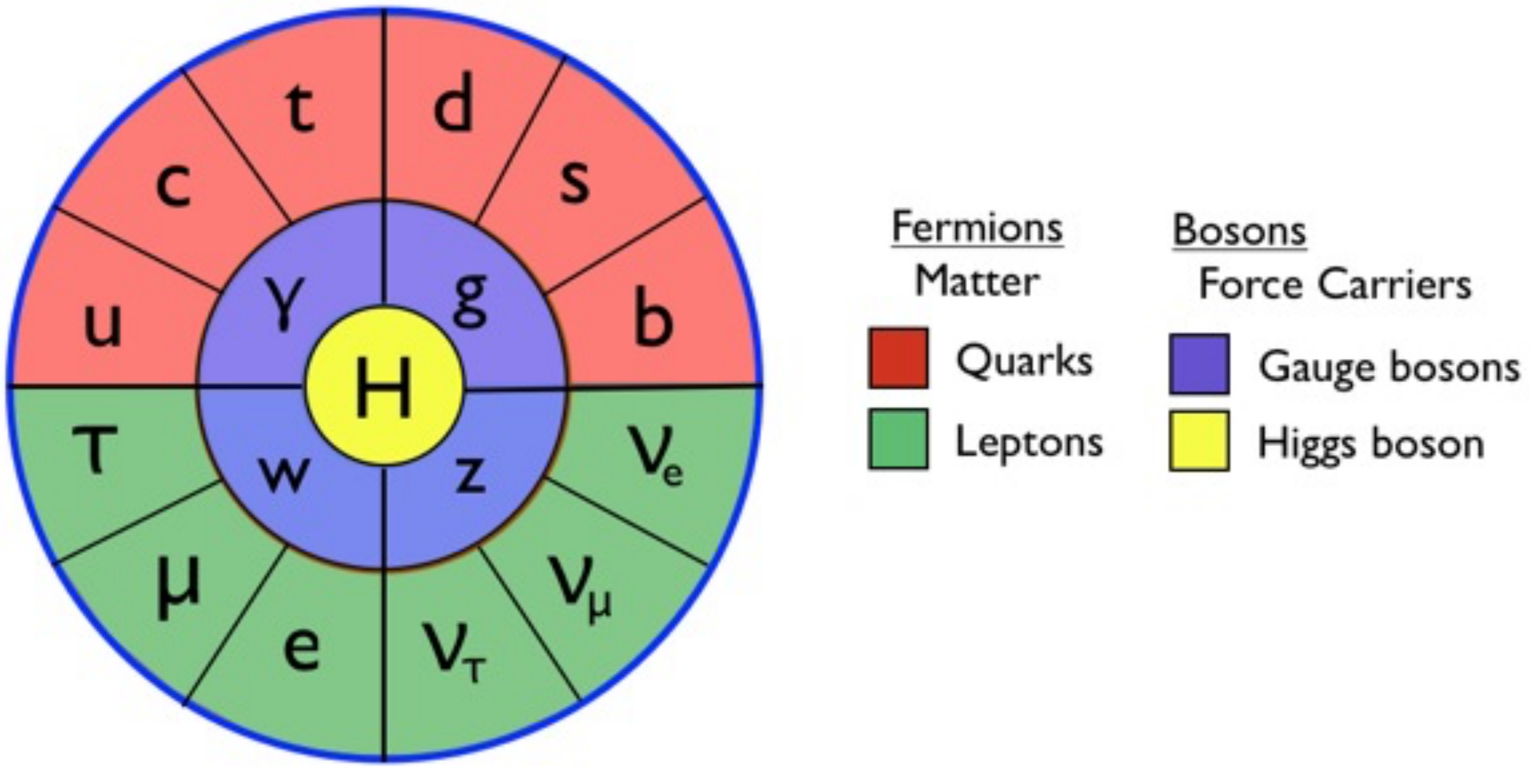
Axions from the Sun?

Exploring the low-energy frontier with the International Axion Observatory IAXO



K. Desch
University of Bonn
DESY Seminar
04/07/2017

Is the Standard Model complete?



Particles of the Standard Model

Is the Standard Model complete?

For sure: it is not!

Electro-weak scale is not stable – Why is m_H so small?

What gives mass to neut

What creates the symmetry of the Universe?

What conse n the strong interaction?

What is the Dark Matter?

What is Dark Energy?

Do we understand stars and radiation in the Universe?

Physics drives

Need multiple approaches!

Colliders at high energy

Accelerators with high y

Ultraprecision e nts in atomic + nuclear physics

Exploit stro ophysical particle/photon sources

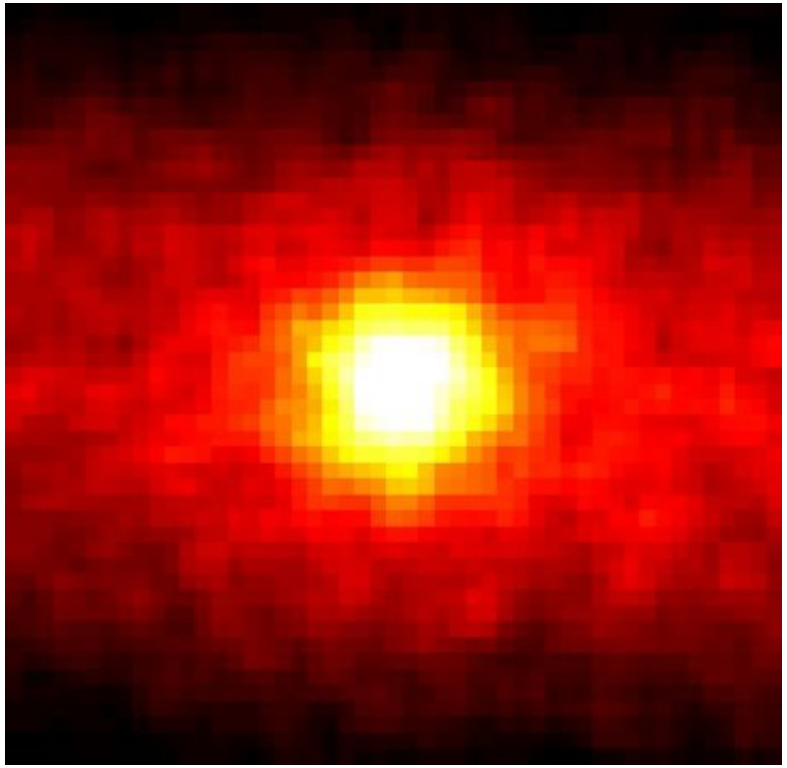
Exploit strong magnetic fields

$$|\vec{B}| = \frac{1}{c}|\vec{E}|$$

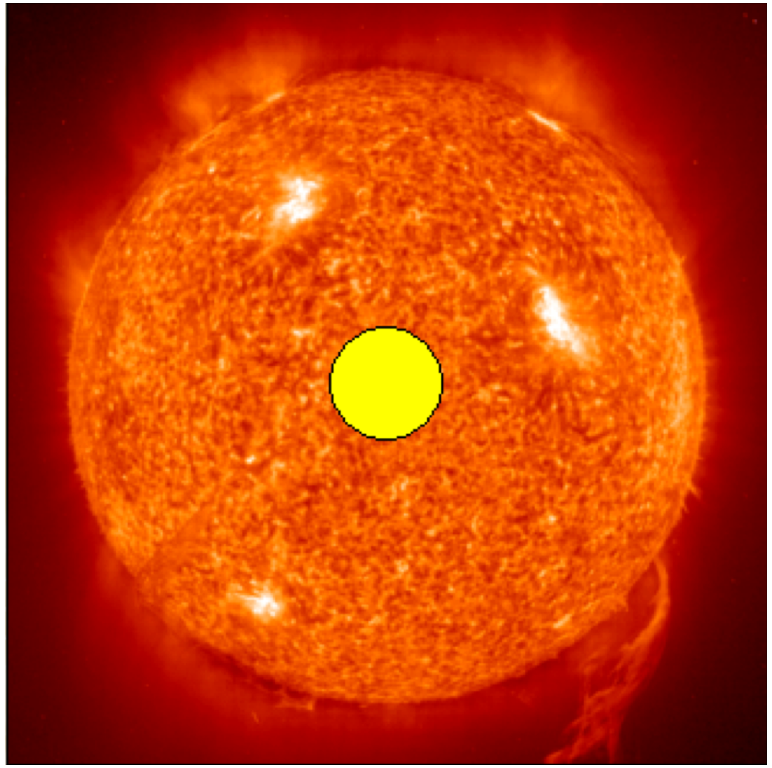
1T ≙ 300 MV/m

Technology enables

Vision: Axions from the sun?



Neutrino image of the Sun
[Superkamiokande]



2025: Axion image of the sun???

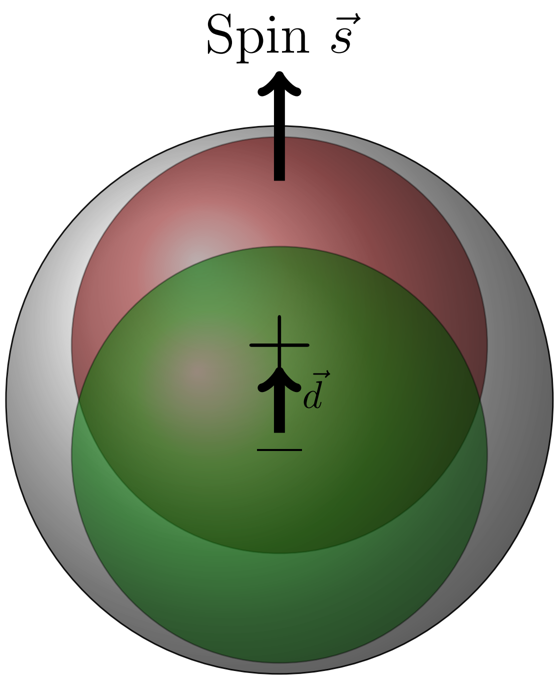
Outline

- Five reasons to like Axions
- Axions and ALPS: What are they?
- Axions and ALPS: How to find them?
- International Axion Observatory IAXO

Five reasons to like Axions and ALPS

Axions...

1. ... may solve the strong CP problem



QCD allows for: $\mathcal{L}_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\theta - \text{arg det } M_q)}_{\bar{\theta}\ \in\ (0,2\pi)}\tilde{G}_{\mu\nu}G^{\mu\nu}$

induces non-zero neutron EDM: $d_n \approx \bar{\theta}\ 10^{-16}$ e cm

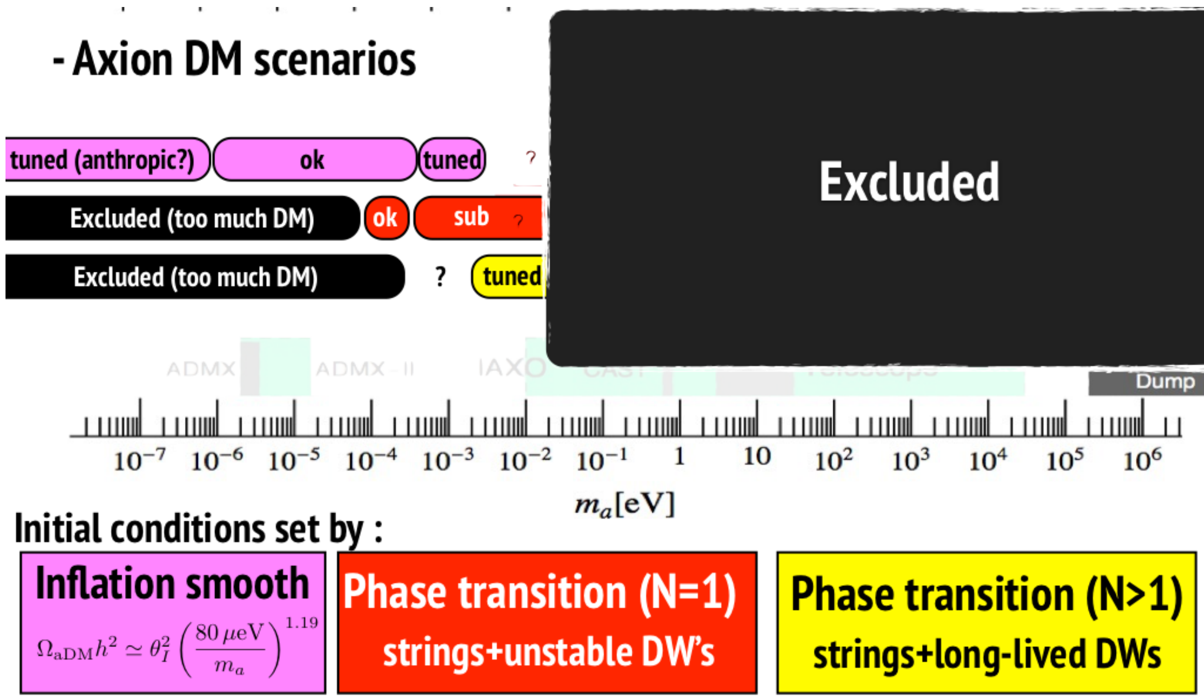
measurement $d < 0.30 \times 10^{-25}\ e\,\text{cm},\ \text{CL} = 90\%$

$\bar{\theta} \lesssim 10^{-10}$ extreme fine tuning !?!?

Five reasons to like Axions and ALPS

Axions...

1. ... may solve the strong CP problem
2. ... may be the Dark Matter



[Redondo]

Despite their small mass, axions are viabale Dark Matter candidate

Non-thermal production → non relativistic

Abundance depends on details of early universe physics 😞

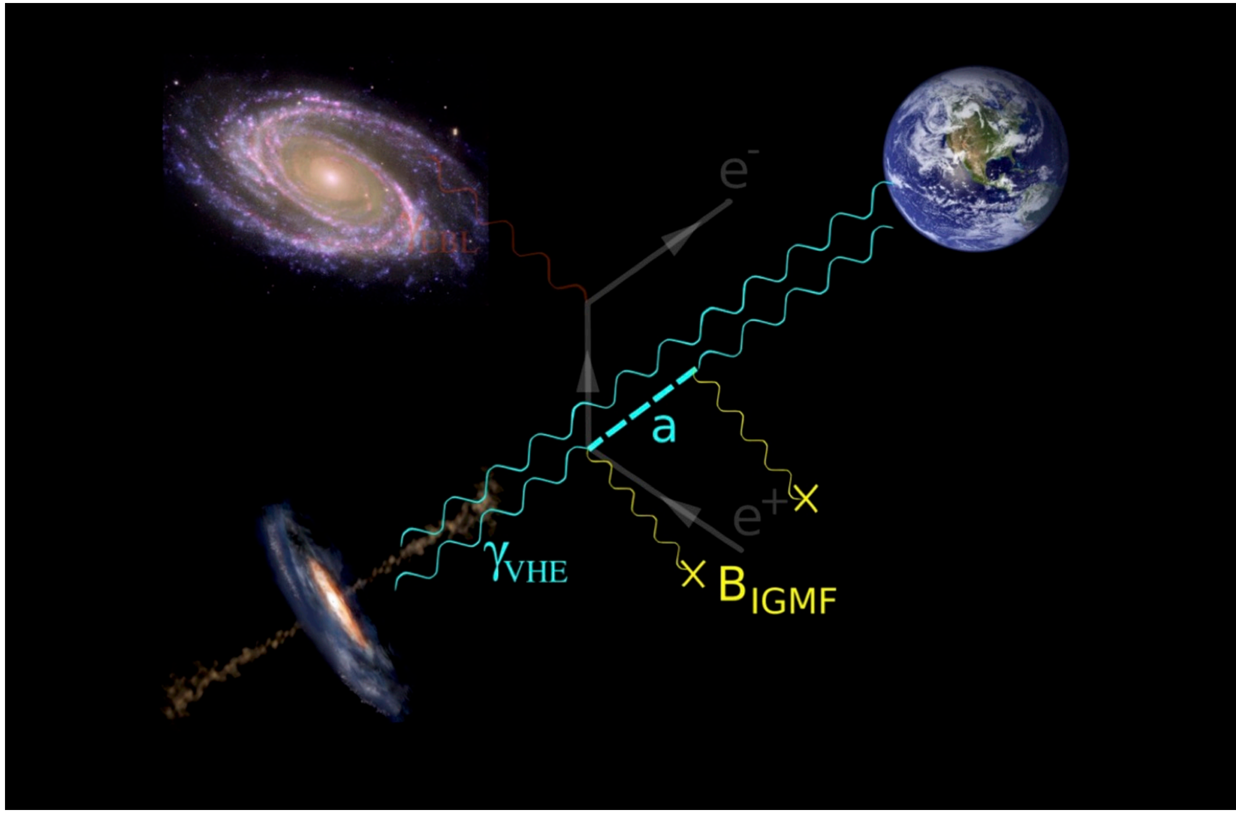
Five reasons to like Axions and ALPS

Axions...

1. ... may solve the strong CP problem

2. ... may be the Dark Matter

3. ... may explain TeV transparency

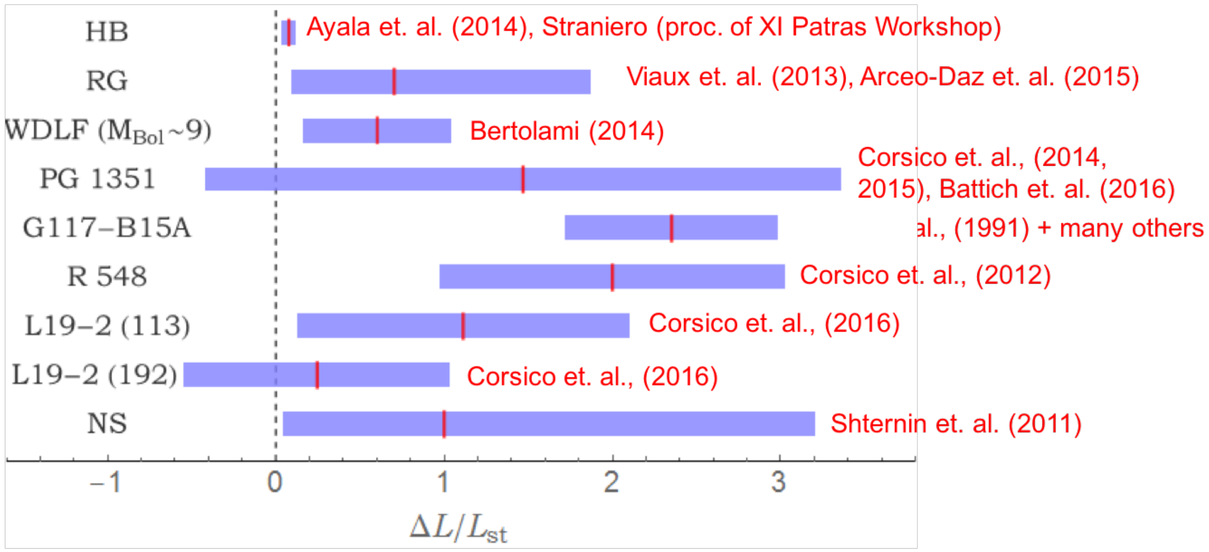


[Horns, Meyer; Troitsky; …]

Five reasons to like Axions and ALPS

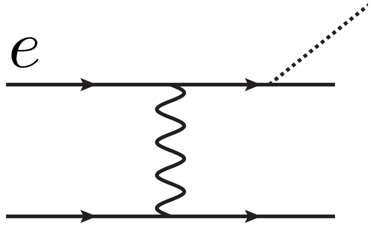
Axions and/or ALPS

1. … may solve the strong CP problem
2. … may be the Dark Matter
3. … may explain TeV transparency
4. … may explain anomalous star cooling



M.G., Irastorza, Redondo, Ringwald (2015); M.G., Irastorza, Redondo, Ringwald (in preparation)

some stars appear to cool down faster than expected from standard stellar evolution

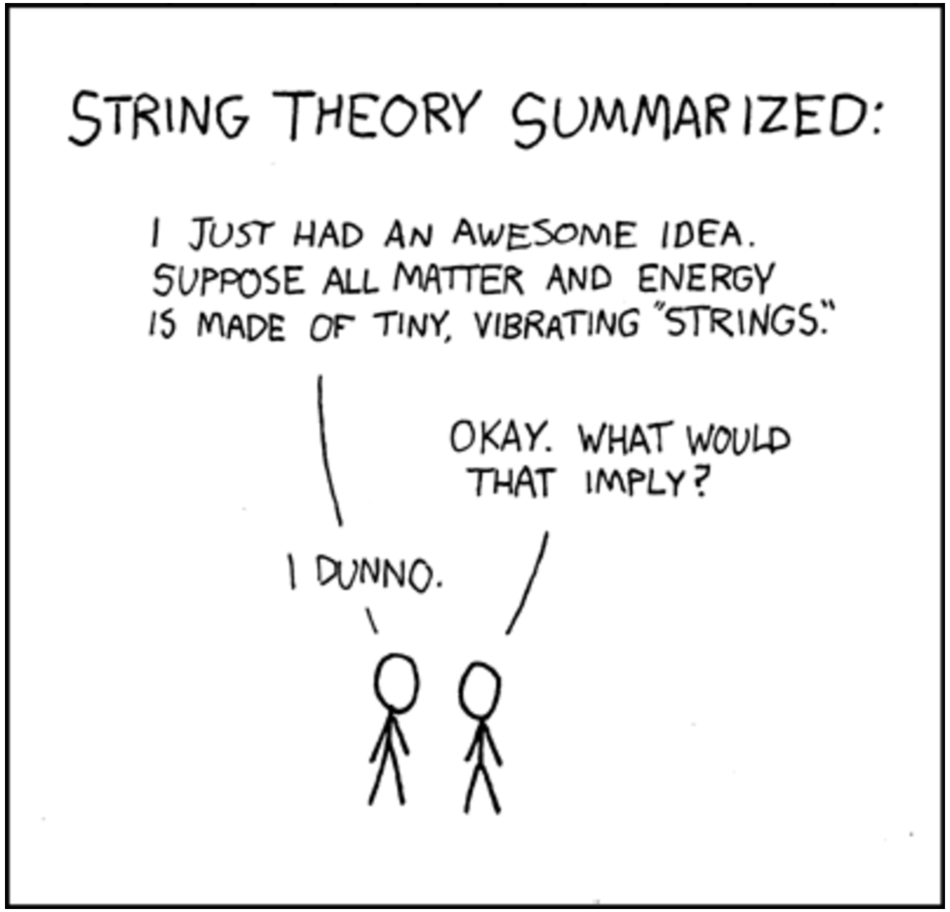


ALP bremstrahlung

Five reasons to like Axions and ALPS

Axions...

1. … may solve the strong CP problem
2. … may be the Dark Matter
3. … may explain TeV transparency
4. … may explain anomalous star cooling
5. … are well-motivated by string theory

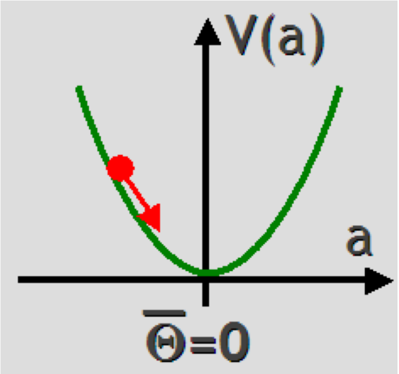


The (QCD) Axion

$$\mathcal{L}_{CP} = -\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu} \quad \longrightarrow \quad \mathcal{L}_{CP} = -\frac{\alpha_s}{8\pi}\frac{a(x)}{f_a}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

a(x): Axion field
f_a : "Peccei-Quinn scale"

- a(x) arises as from spontaneously broken U(1) at (large) scale f_a
- a(x) acquires a mass (potential) a(x) is driven to minimum (CP-conserving)
- a(x) has a generic coupling to gluons




R. Peccei & H. Quinn (1977)

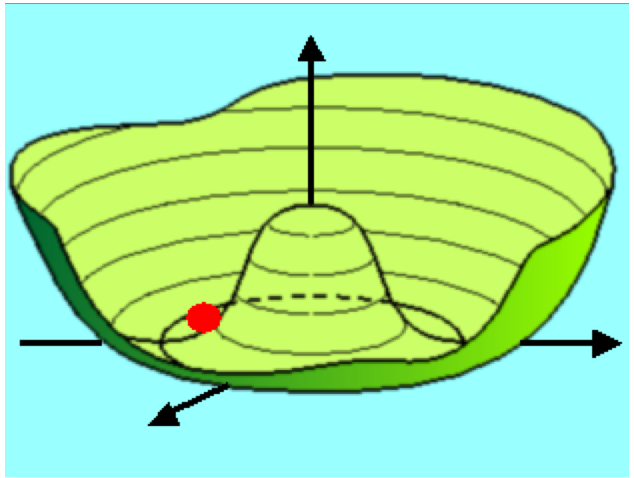
F. Wilczek (1978)

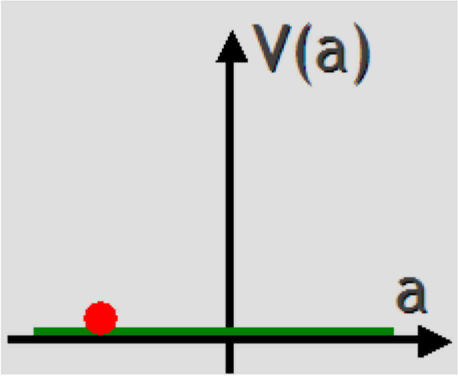
S. Weinberg (1978)

The Axion mass

E ~ f_a (large)

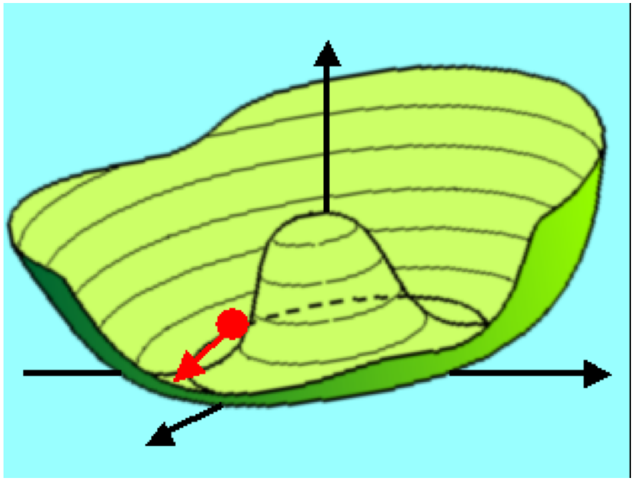
- spontaneously broken U(1)
- Axion = Nambu-Goldstone Boson (massless)

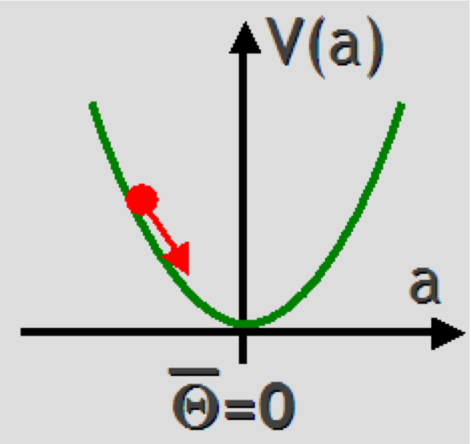




E ~ Λ_{QCD}

- QCD instanton effects break U(1) explicitely
- “tilted mexican hat”
- Axion = Pseudo-Nambu-Goldstone Boson (massive)
- drives Potential to Θ = 0
- CP symmetry restored





$$m_a \simeq 6\,\mathrm{meV}(10^9\,\mathrm{GeV}/f_a)$$

after Raffelt

The QCD-Axion

Axionlike Particles (ALPS)

AXION
energy

AXION
RISK MANAGEMENT STRATEGIES

Axion $m_a \sim 1/f_a$

ALPS m_a and f_a independent

ALPS may arise "generically" from "any" broken U(1) symmetry…

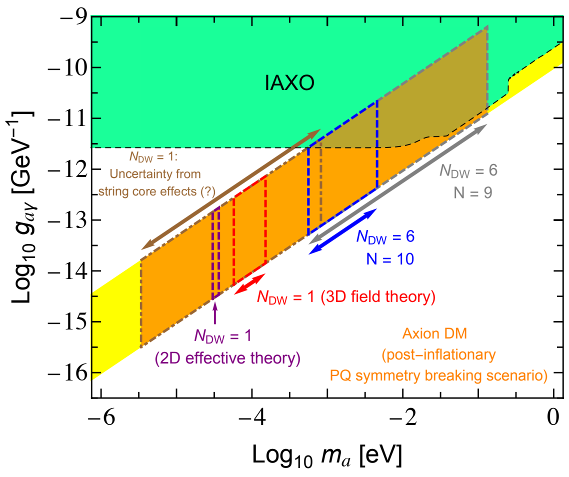
There may be more than one ALP

The Axion/ALP mass predictions

- A difficult job…
- Mass constraints depend on requirements on the considered Axion/ALP (e.g. explain QCD, DM, anomalies)
- Mass constraints depend on model assumptions (e.g. early universe conditions/assumptions pre/post inflation for DM)

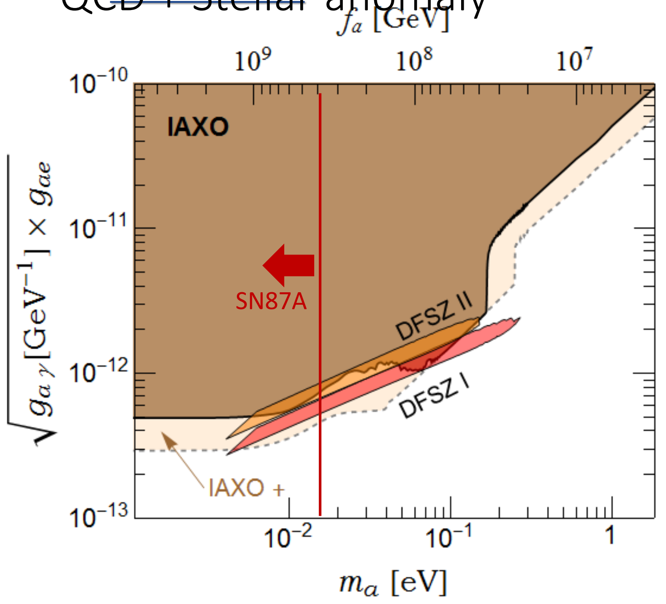
Examples:

QCD + DM



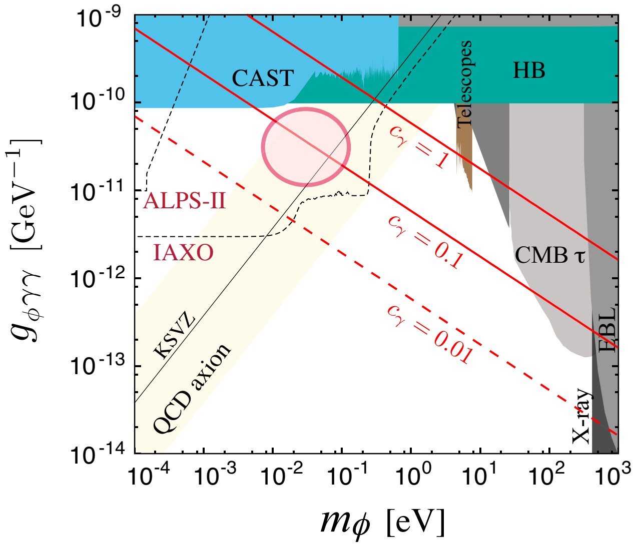
[Ringwald, Saikawa 2016]

QCD + Stellar anomaly



[Giannotti et al 2017]

DM + Inflation



[Daido,Takahashi,Yin 2017]

Axion phenomenology

Almost all axion experiments exploit the (effective) axion-photon coupling

- QCD axion via its gluon coupling and mixing with π^0
- Primakoff(-like) effect

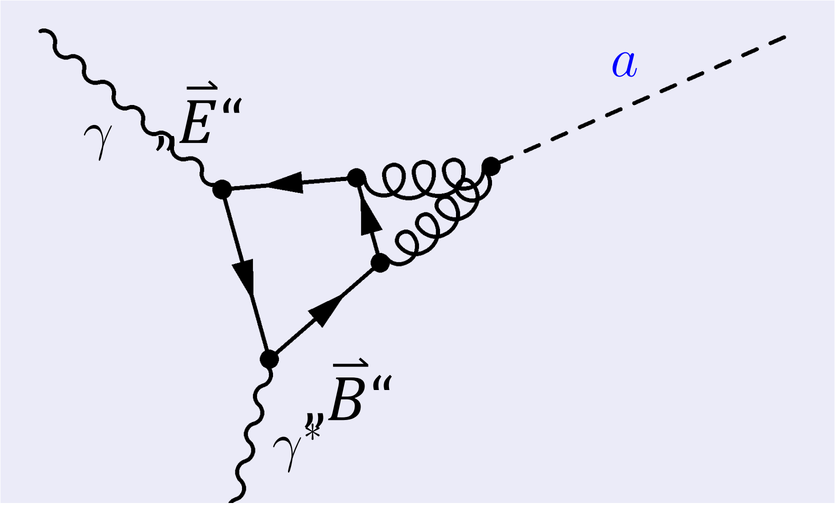
$$\mathcal{L}_{a\gamma} \equiv -\frac{g_{a\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

- QCD axion: axion mass ~ axion-photon coupling

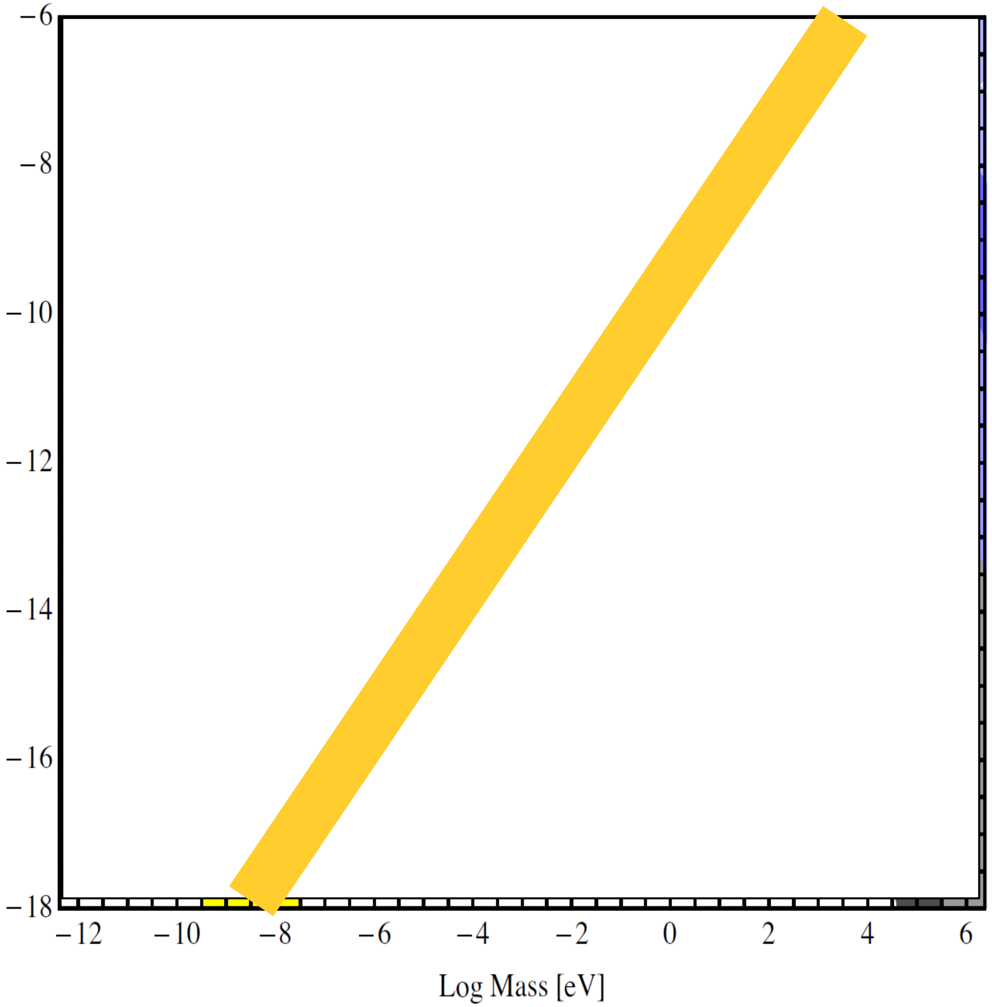
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} C_\gamma$$

C_γ ~ 0.75 (-1.92) for DFSZ (KSVZ)

- ALPS: any combination of mass and photon-coupling



Axion phenomenology: the $g_{a\gamma}$ vs. m_a plane



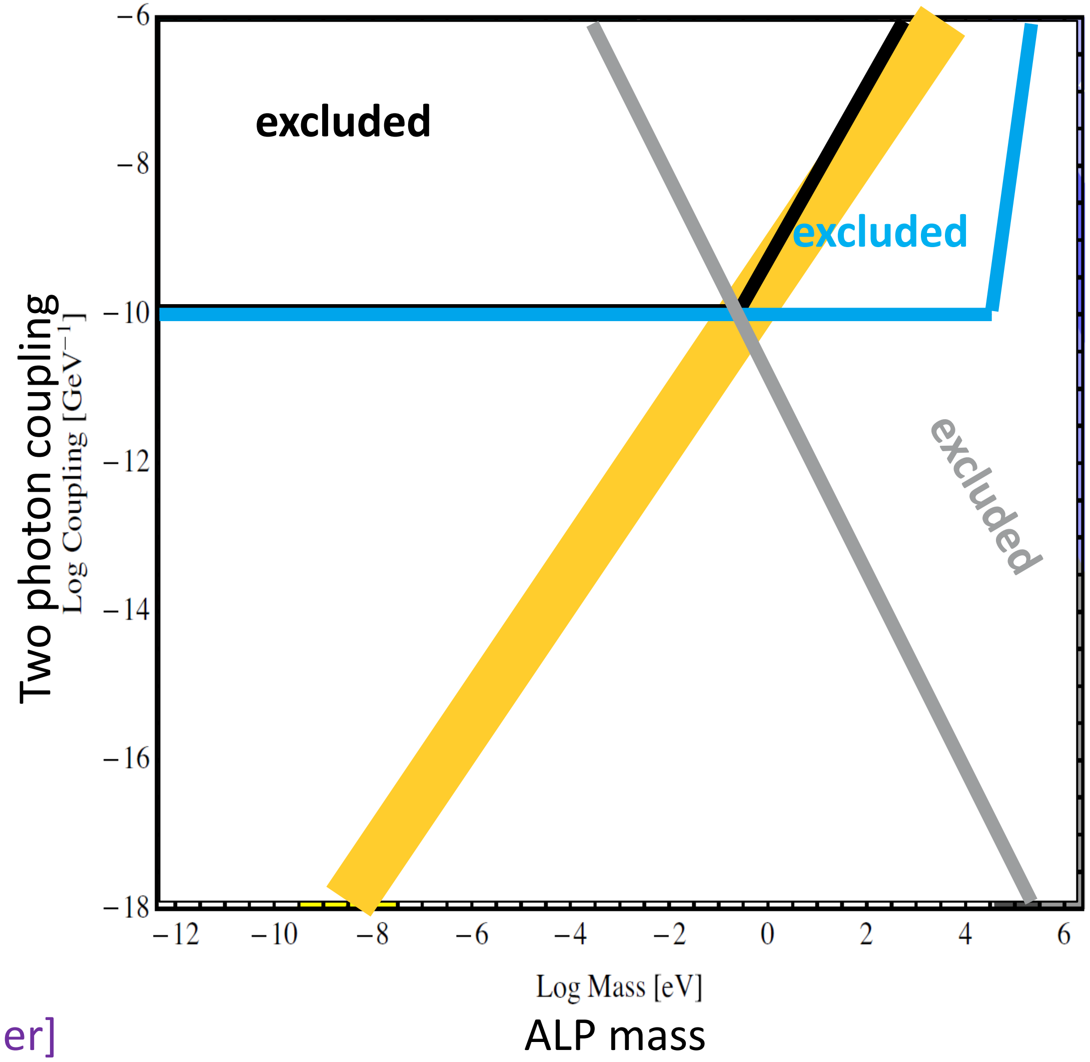
Two photon coupling

QCD axion range

ALP mass

[Lindner]

Axion phenomenology: the $g_{a\gamma}$ vs. m_a plane



QCD axion range

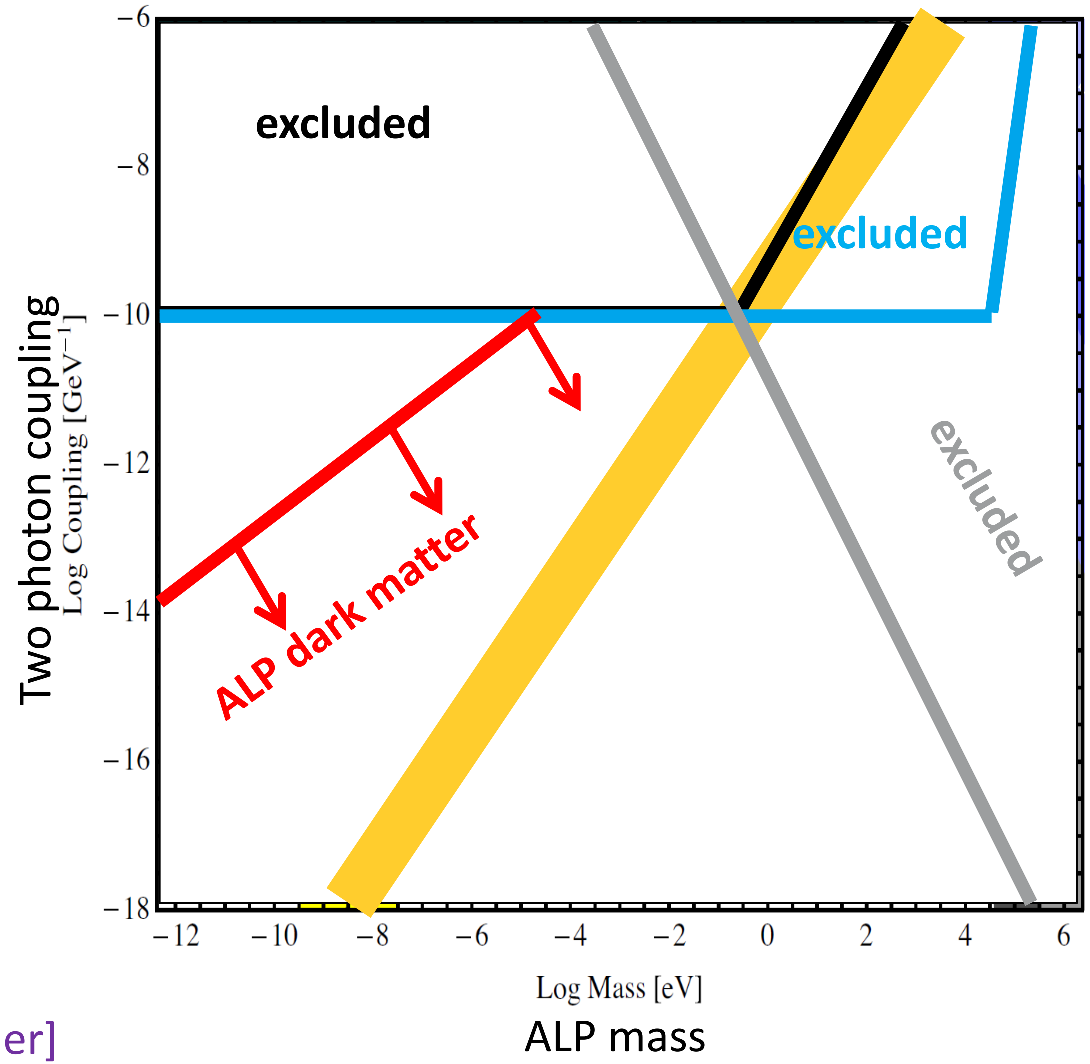
Excluded by WISP experiments

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

[Lindner]

Axion phenomenology: the $g_{a\gamma}$ vs. m_a plane



QCD axion range

Excluded by WISP experiments

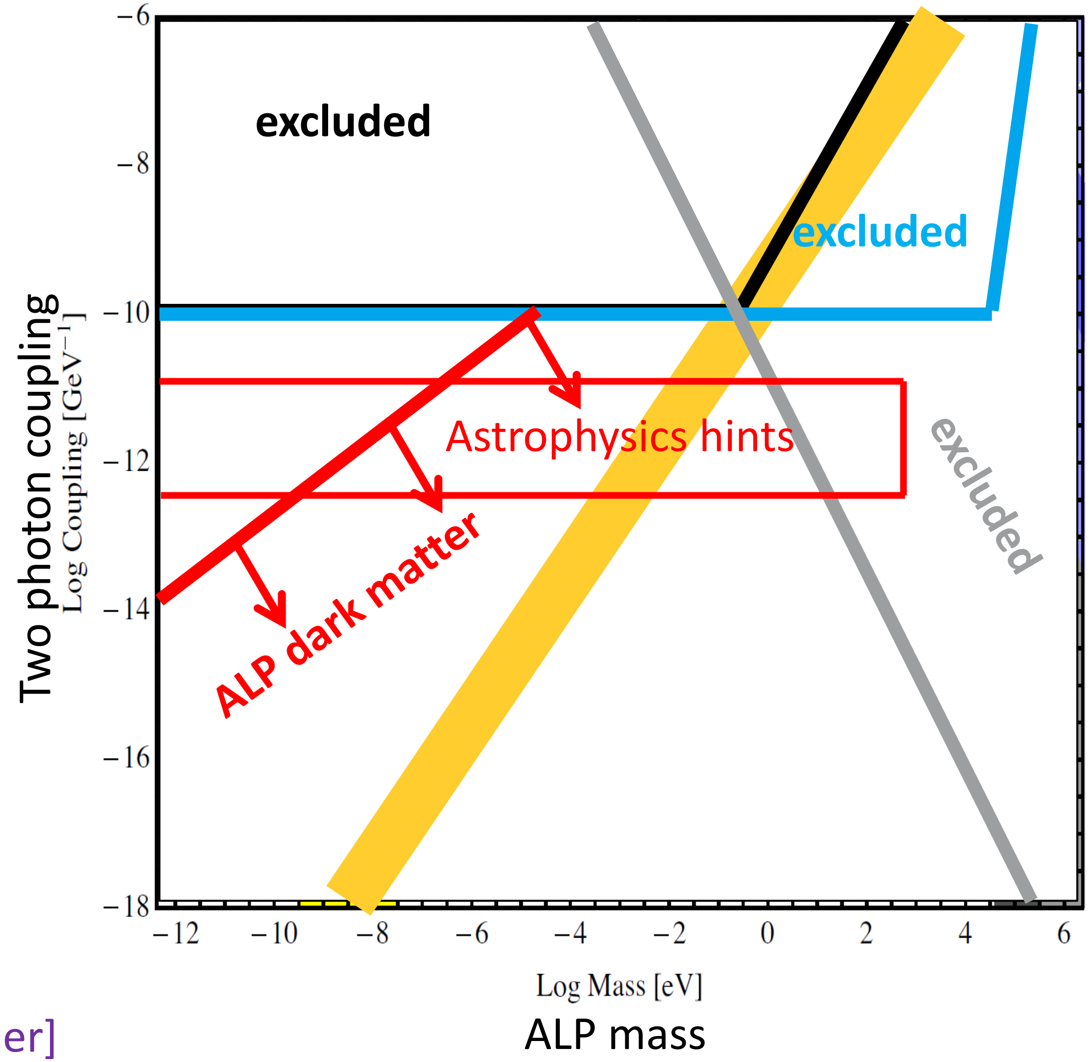
Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

[Lindner]

Axion phenomenology: the $g_{a\gamma}$ vs. m_a plane



QCD axion range

Excluded by WISP experiments

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

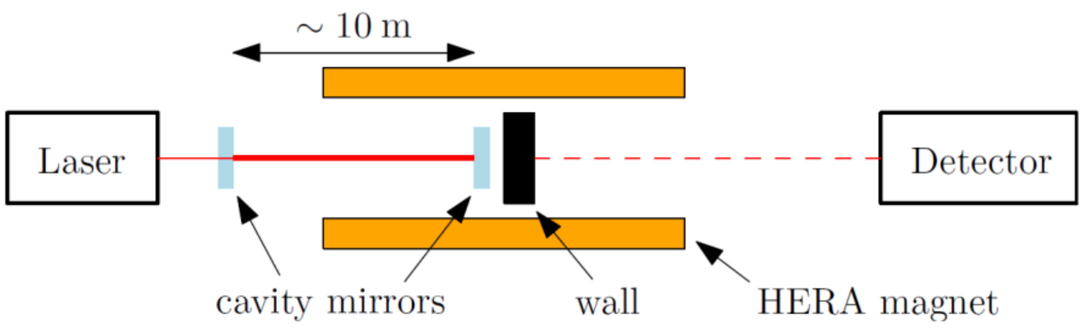
WISP hints from astrophysics

[Lindner]

Three ways to explore the axion-photon coupling

"Light shining through wall"

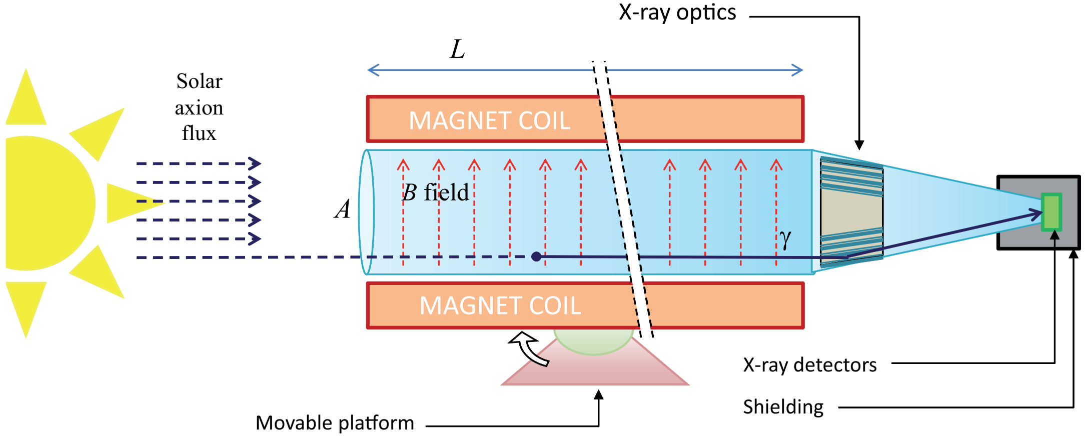
Axion source: laser + B-field



(a) ALPS-I

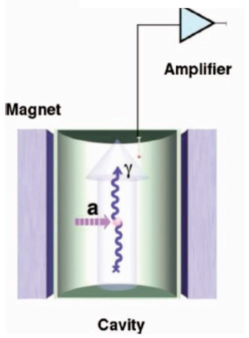
"Helioscopes"

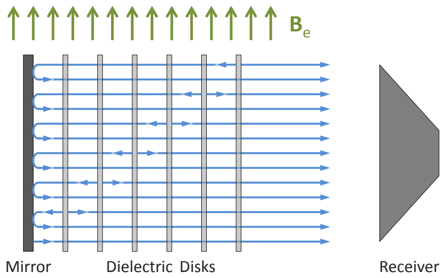
Axion source: Sun



"Haloscopes"

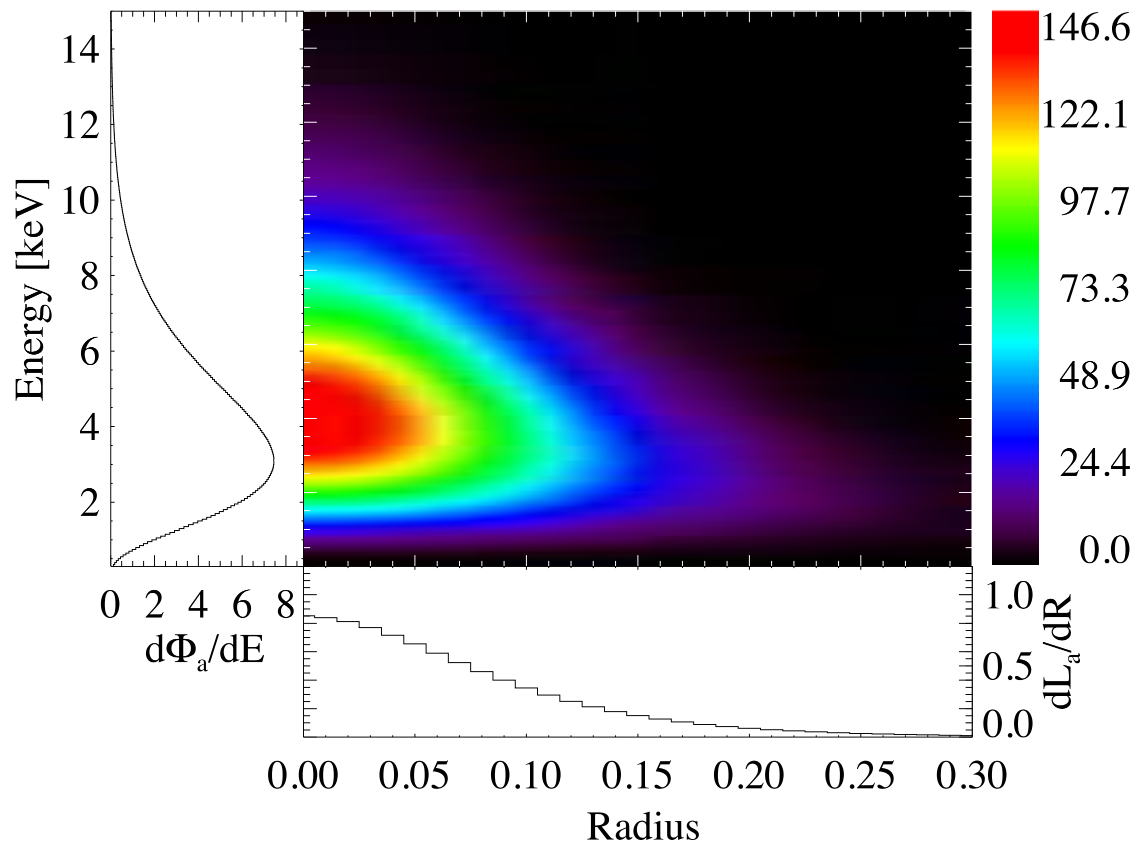
Axion source: Dark Matter Halo

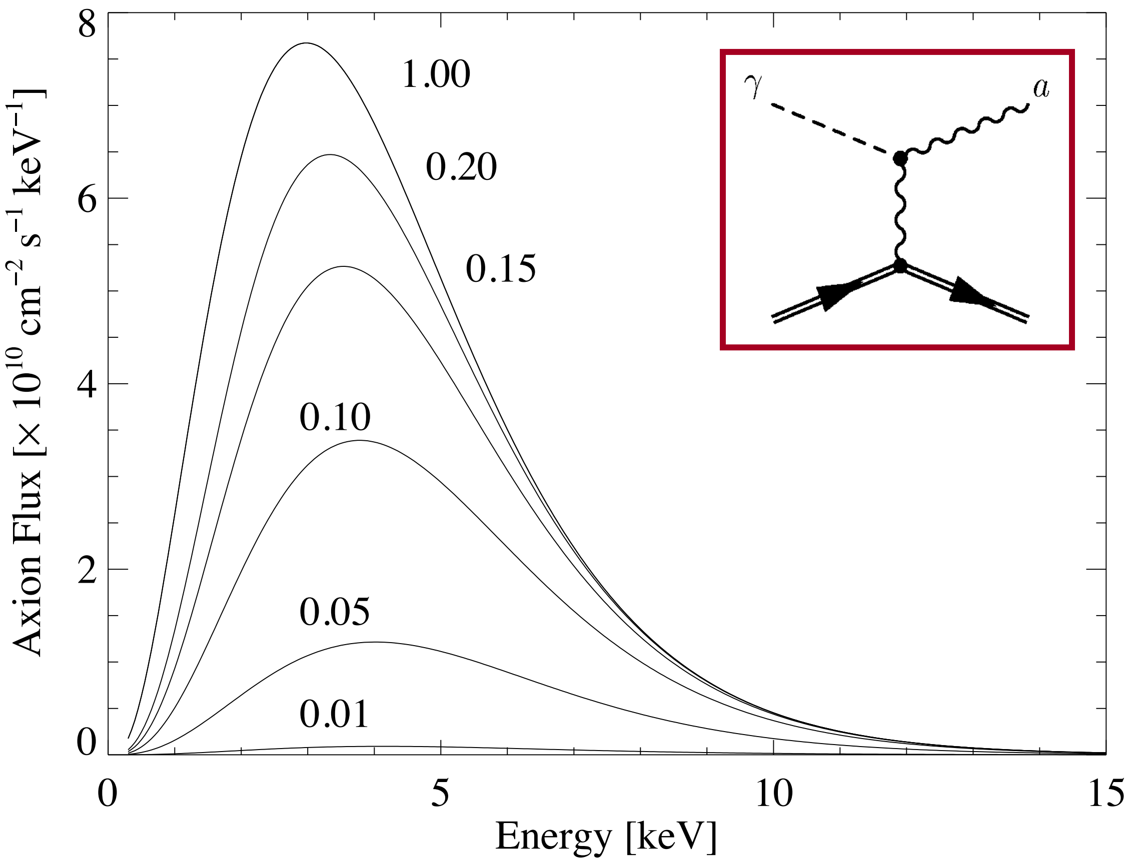




MADMAX

Axions from the sun

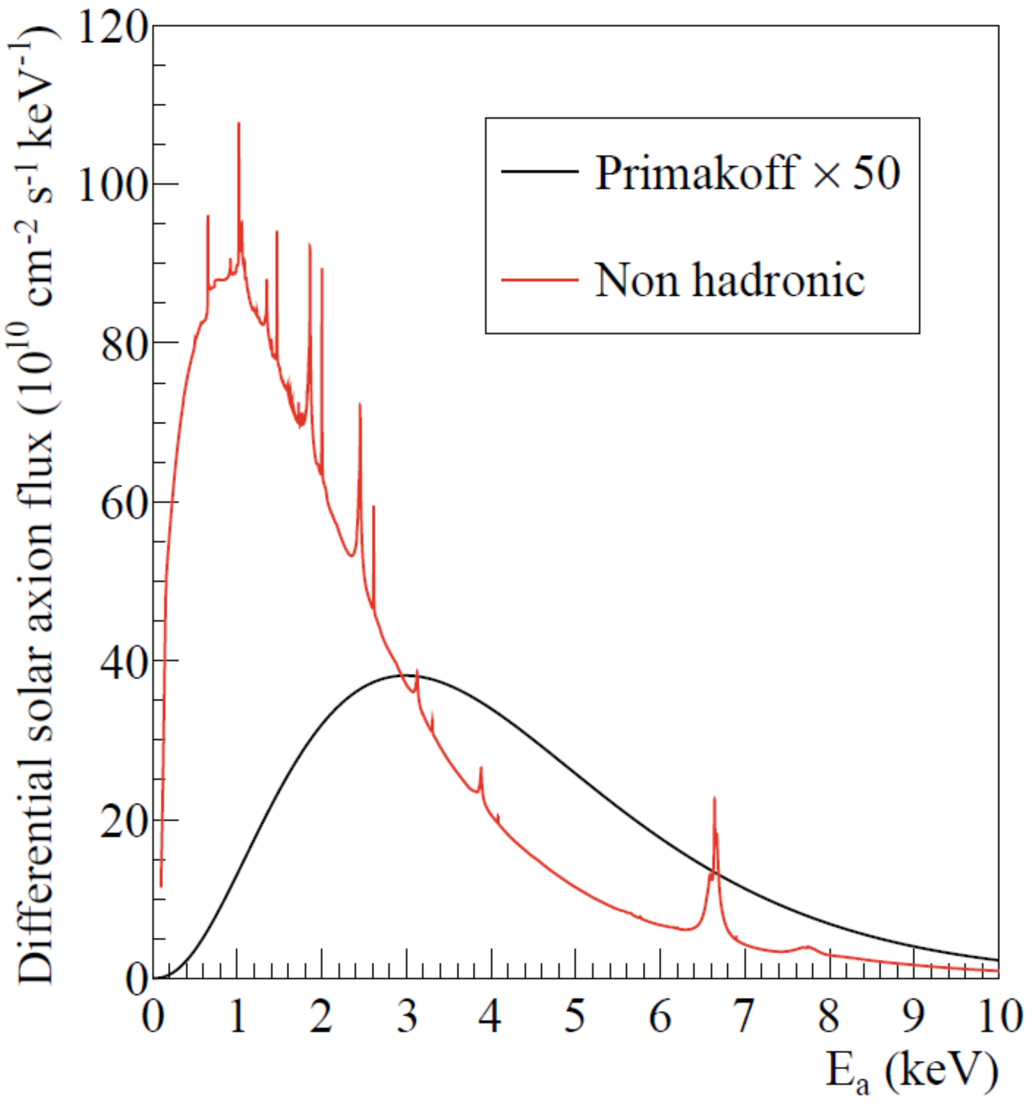




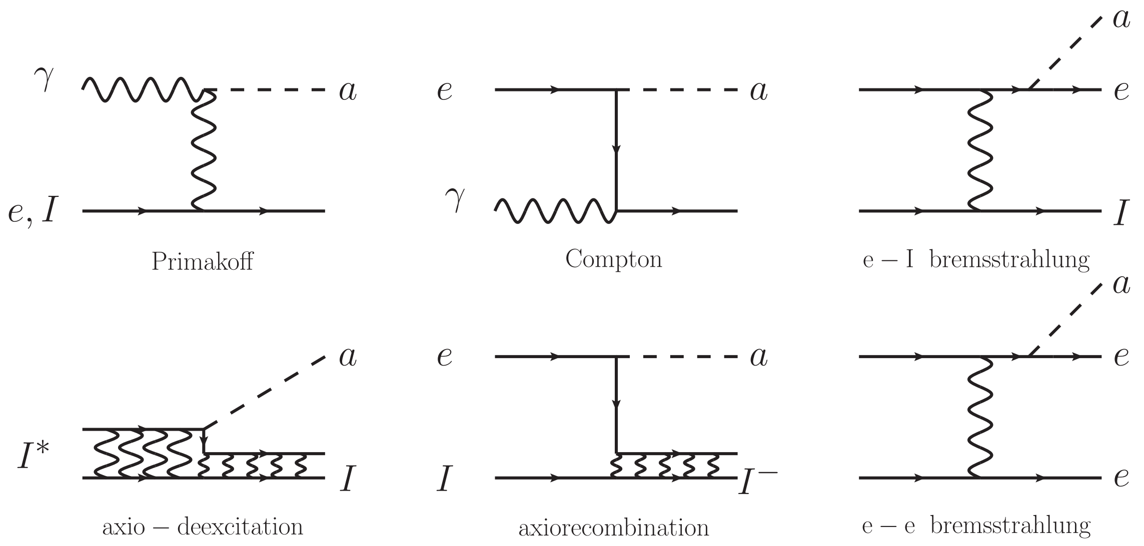
- Solar axions produced (mainly) in the core of the sun
- Energy <E> ~ 4.2 keV
- rather robust prediction

[CAST coll., JCAP 0704:010,2007]

Helioscopes – Axions from the sun – axion-electron-coupling



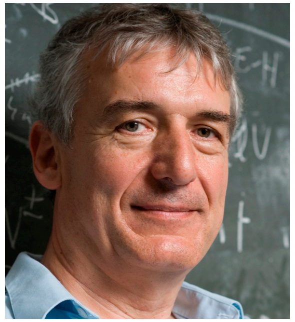
[Redondo, JCAP 1312 (2013) 008]

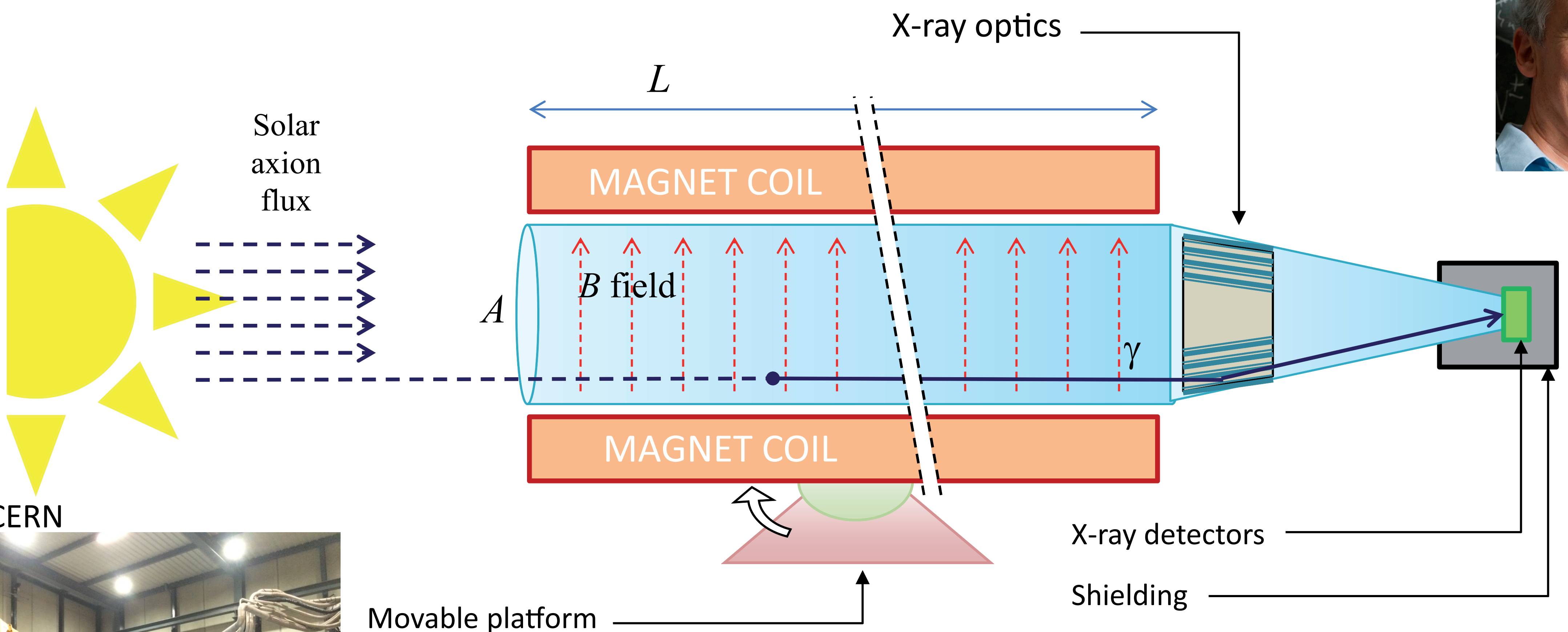


If direct axion-electron coupling exists, large flux with characteristic features

Helioscopes

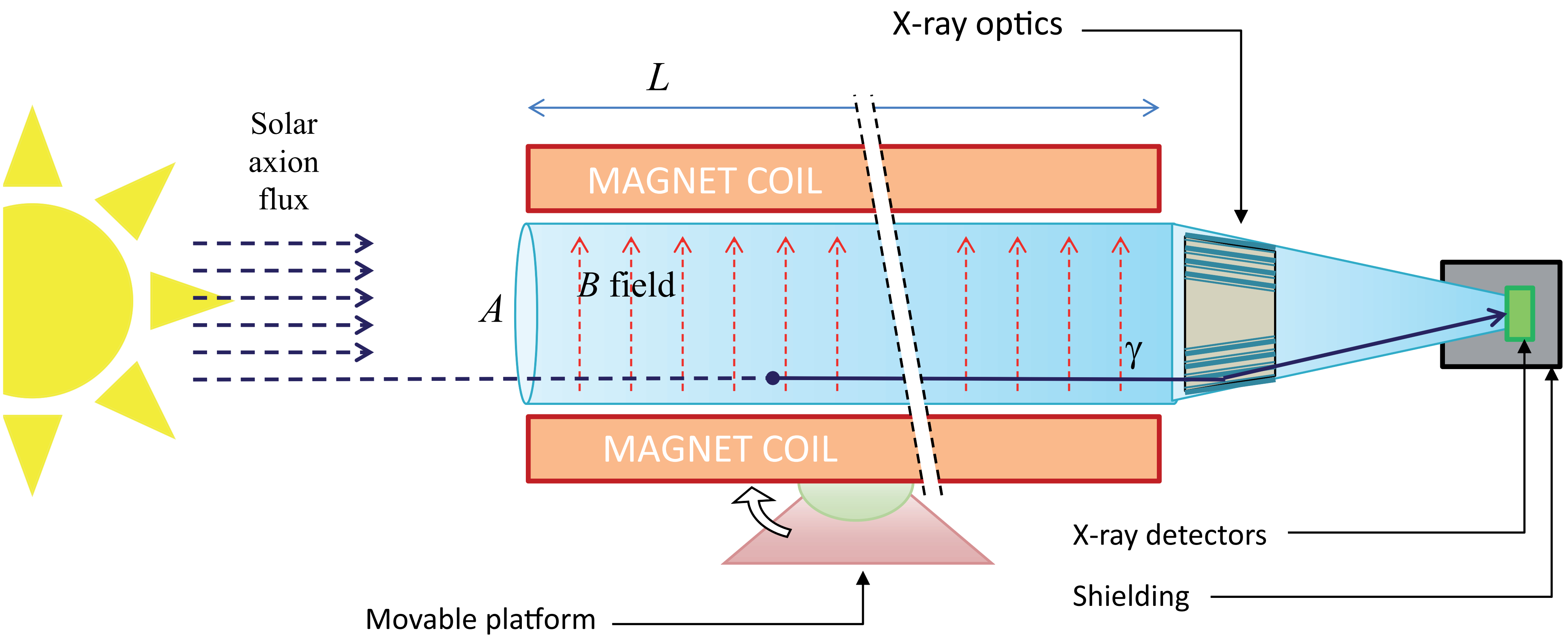
[Sikivie]





CAST@CERN

Helioscopes: sensitivity



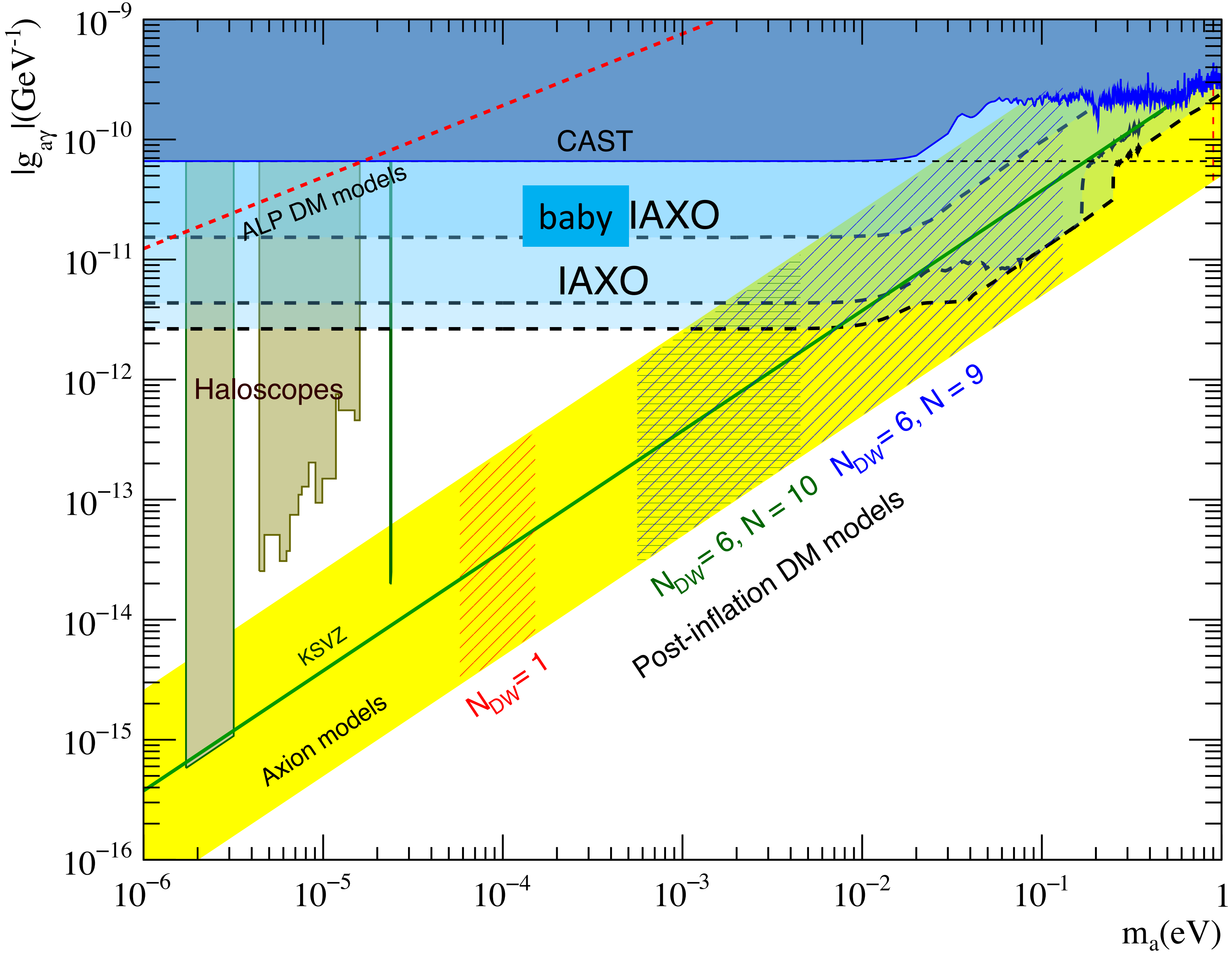
Signal: ~ $g_{a\gamma}^2$ ~ $g_{a\gamma}^2$ B^2 L^2 A_{bore} ~ ε_{optics} ~ $\varepsilon_{detector}$

Bkg: ~ A_{spot} ~ B / A

IAXO parameters

Parameter	CAST	IAXO nominal	IAXO+
B [T]	9	2,5	2,5
L [m]	9,3	20	25
A_{bore} [m^2]	0.003	2.3	4.0
$f^*_{Magnet} \sim B^2L^2A$	1	300	1200
b [keV^{-1} cm^{-2} s^{-1}]	10^{-6}	1-5 x 10^{-8}	10^{-9}
$\varepsilon_{detector}$	0,7	0,7	0,8
ε_{optics}	0,3	0,5	0,7
A_{bore} /A_{spot}	200	14500	33000
$\varepsilon_{solar\ tracking}$	0,12	0,5	0,5

IAXO sensitivity

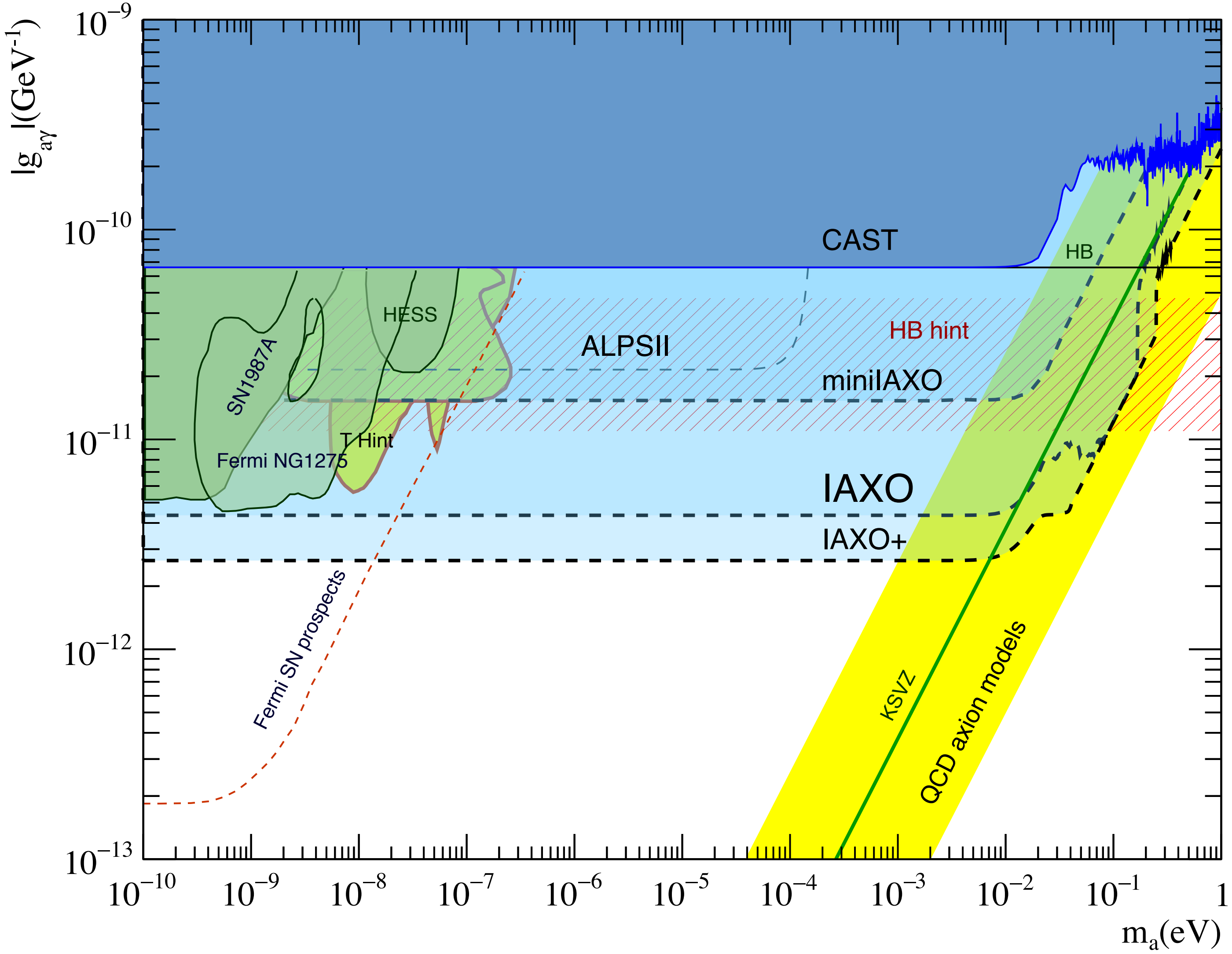


to test the QCD axion in 2 – 1000 meV region

no other approach known in this mass range

~ 20xCAST on $g_{a\gamma}$

IAXO sensitivity

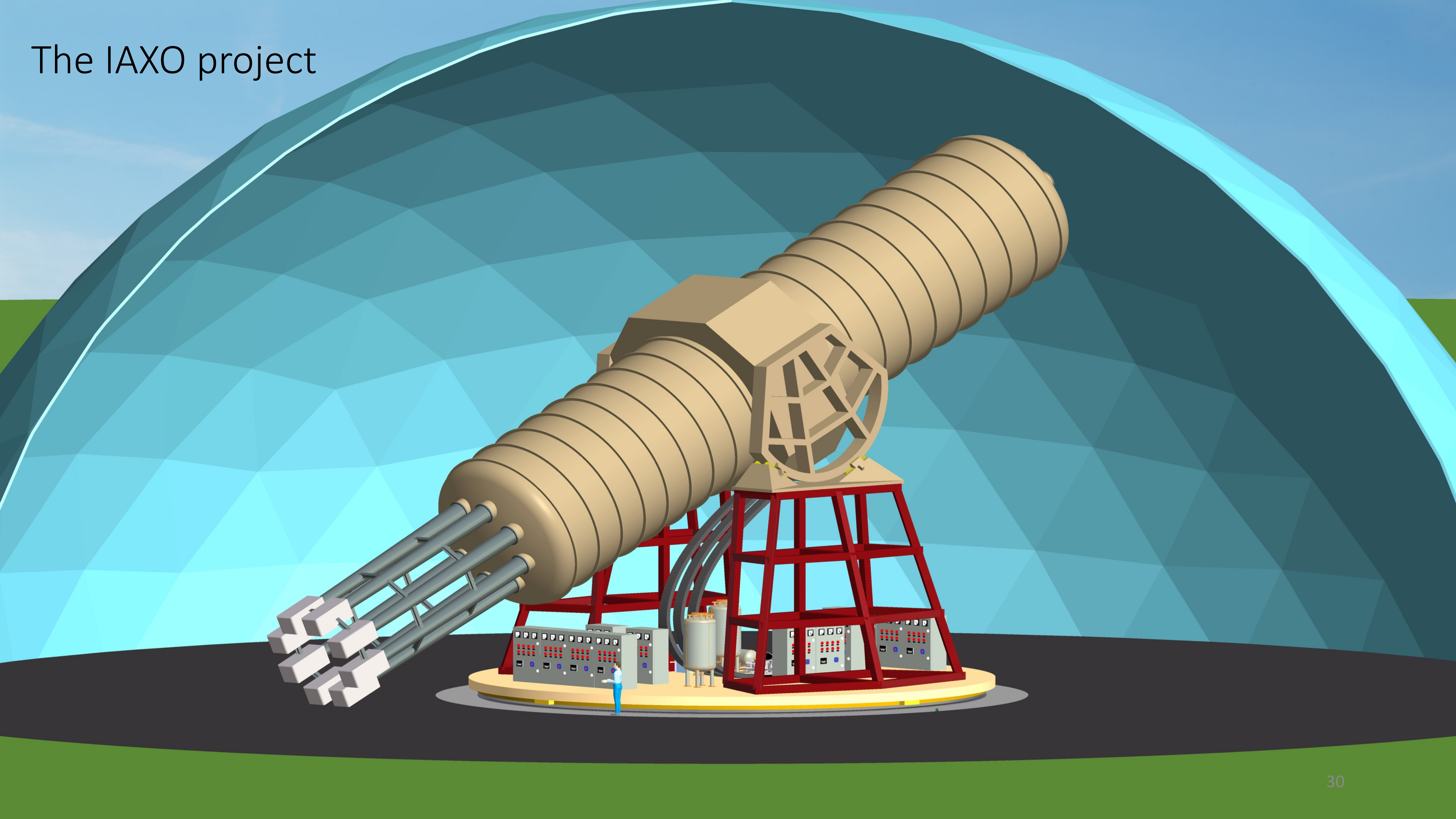


sensitive to astrophysical hints

The IAXO project

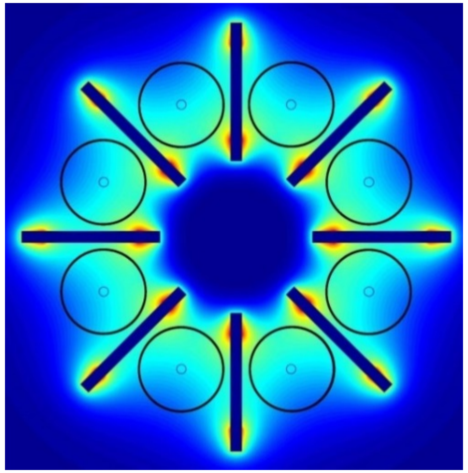
- 2011: First studies concluded (JCAP 1106:013,2011)
- 2013: Conceptual Design finished (arXiv:1401.3233).
  - Most activity carried out up to now ancillary to other group's projects (e.g. CAST)
- August 2013: Letter of Intent submitted to the CERN SPSC
  - LoI: [CERN-SPSC-2013-022]
  - Presentation in the open session in October 2013:
- January 2014: Positive recommendations from CERN SPSC.
- 2014-16: Transition phase: In order to continue with TDR & preparatory activities, formal endorsement & resources needed.
  - Some IAXO preparatory activity already going on as part of CAST near term program: IAXO pathfinder system (Micromegas + telescope) installed in CAST in 2014
  - Preparation of a MoU to carry out TDR work.
- July 2017: Formation of IAXO collaboration

The IAXO project



IAXO magnet (CDR design)

Magnet optimization figure of merit: $f_M = L^2 \int B^2(x,y)dxdy \rightarrow L^2 B^2 A$



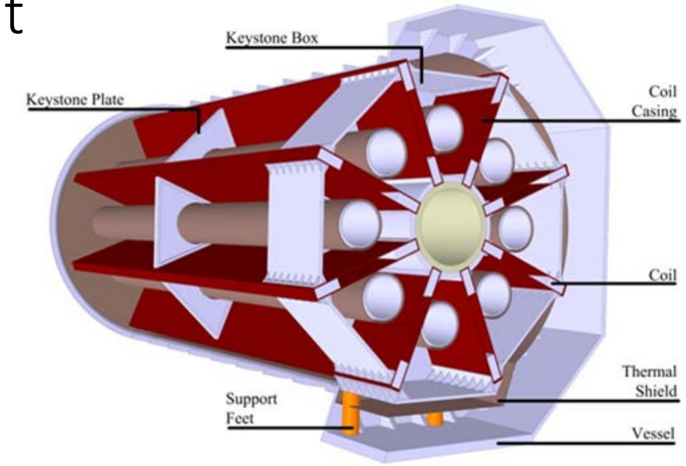
B: superconducting NbTi at 4.5K → B_{peak} 6 T , B_{user} = 2.5 T

L: as long as reasonably possible (rotatable): L = 22 m

A: driven by optics, D=60 cm per bore, n=8

Baseline design inspired by ATLAS toroid, large “user volume” at reasonable cost

Not ideal in terms of magnet cost, amount of SC cable → new alternative



IAXO magnet (CDR design)

Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	~ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	~ 250
Coils:	Number of racetrack coils	8
	Winding pack width (mm)	384
	Winding pack height (mm)	144
	Turns/coil	180
	Nominal current, I_{op} (kA)	12.0
	Stored energy, E (MJ)	500
	Inductance (H)	6.9
	Peak magnetic field, B_p (T)	5.4
	Average field in the bores (T)	2.5
Conductor:	Overall size (mm^2)	35 × 8
	Number of strands	40
	Strand diameter (mm)	1.3
	Critical current @ 5 T, I_c (kA)	58
	Operating temperature, T_{op} (K)	4.5
	Operational margin	40%
	Temperature margin @ 5.4 T (K)	1.9
Heat Load:	at 4.5 K (W)	~150
	at 60-80 K (kW)	~1.6

A Review of the Principle Design
of the Superconducting Toroidal Magnet System for the
International AXion Observatory (IAXO)

Fellowship Summary Report

Idan Shilon

Under supervision of
Herman H. J. ten Kate
and
Alexey Dudarev

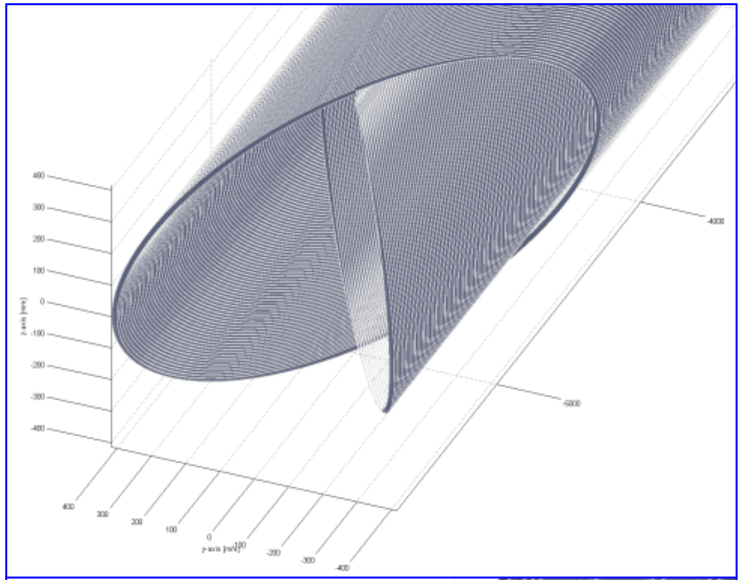
ATLAS Magnet Team
Physics Department
CERN

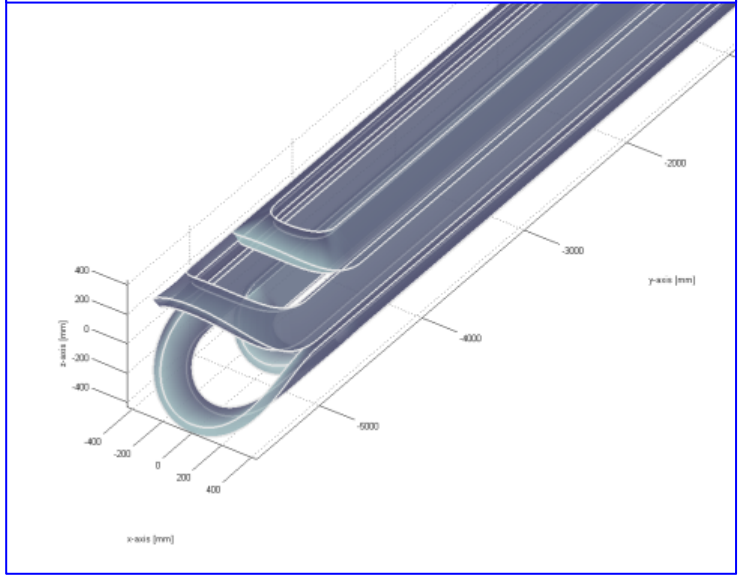
March 26, 2014

IAXO magnet (beyond baseline)

- Single bore winding yields potentially higher FOM at given amount of SC cable
- Modularity
- But: more R&D needed
- MiniIAXO as scale-up demonstrator with physics potential:
  - Test magnet design at relevant scale (only 1 bore full diameter)
  - Test bench for optics + detector
  - Able to do relevant physics (at intermediate level)

TODO: wait for Hermans/Igors talks…

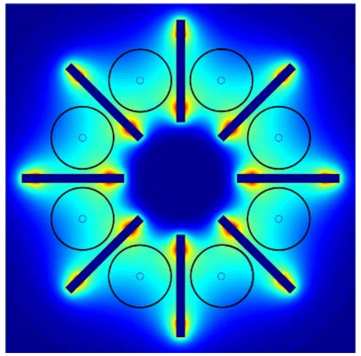




IAXO magnet (beyond baseline)

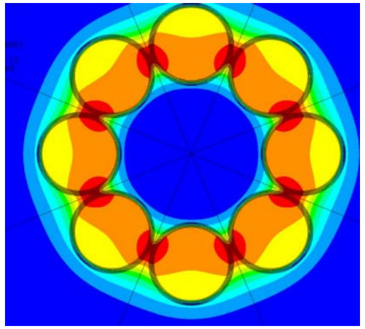
Flat Racetrack Coils - Toroid design (CDR Default)

- Straightforward coil winding and support structure
- Proven technology for his size of magnets
- But: Somewhat inefficient in terms of NbTi usage



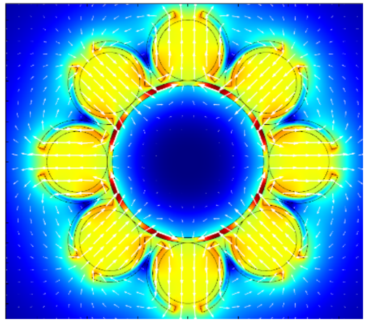
CCT Dipoles - Toroid design

- More efficient in terms of field configuration --> Reduced stored energy, amount of NbTi
- But: More complicated conductor layout



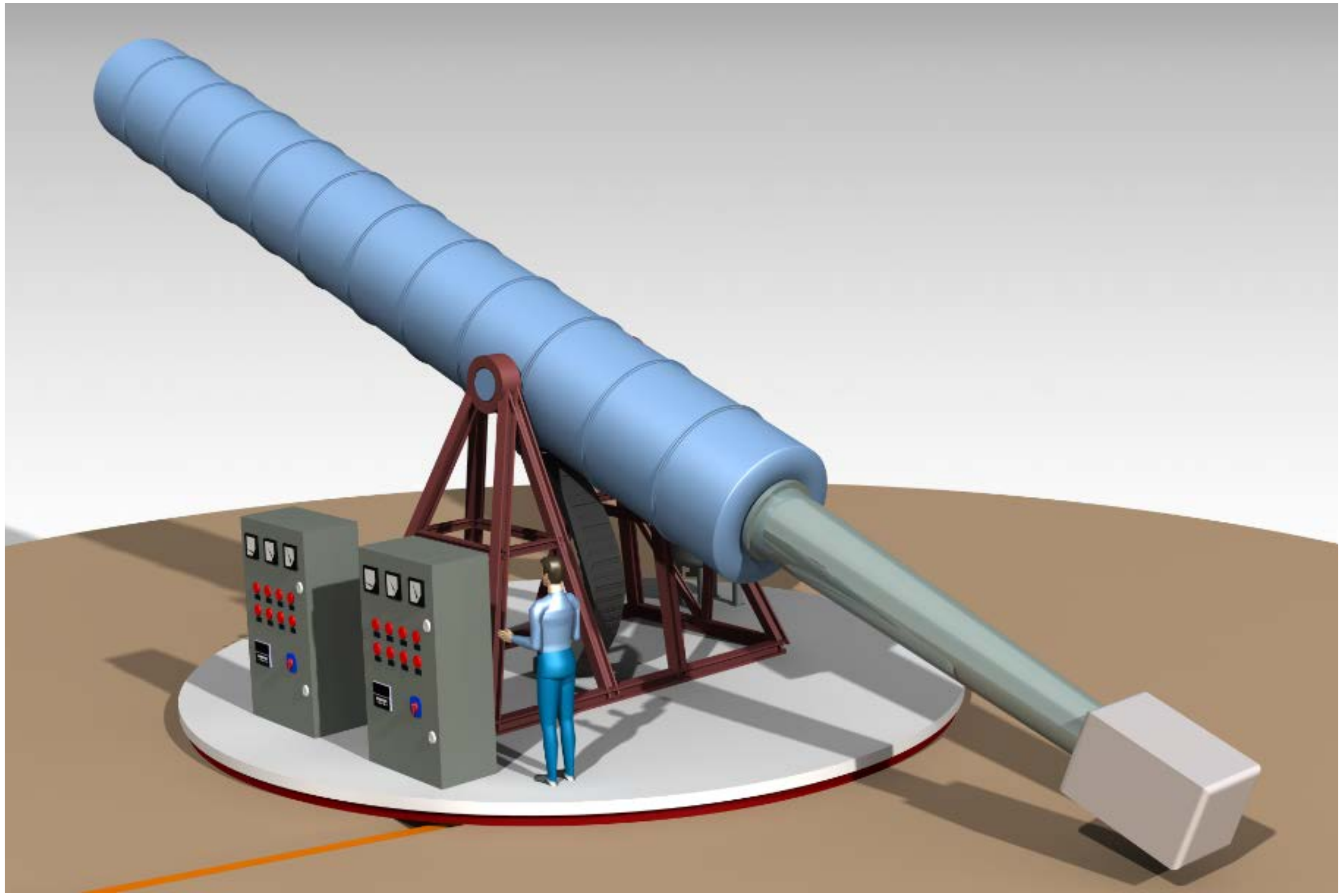
Saddle coils Octupole or Toroid design

- Field configuration efficiency similar to CCT
- Very homogeneous field inside bore
- Still more complicated conductor layout compared to conceptual toroidal design



[H. ten Kate]

BabyIAXO



Parameter	MiniIAXO
B [T]	2,5
L [m]	10
A_{bore} [m^2]	0,28 (1 bore)
f^*_{Magnet} ~ B^2L^2A	10

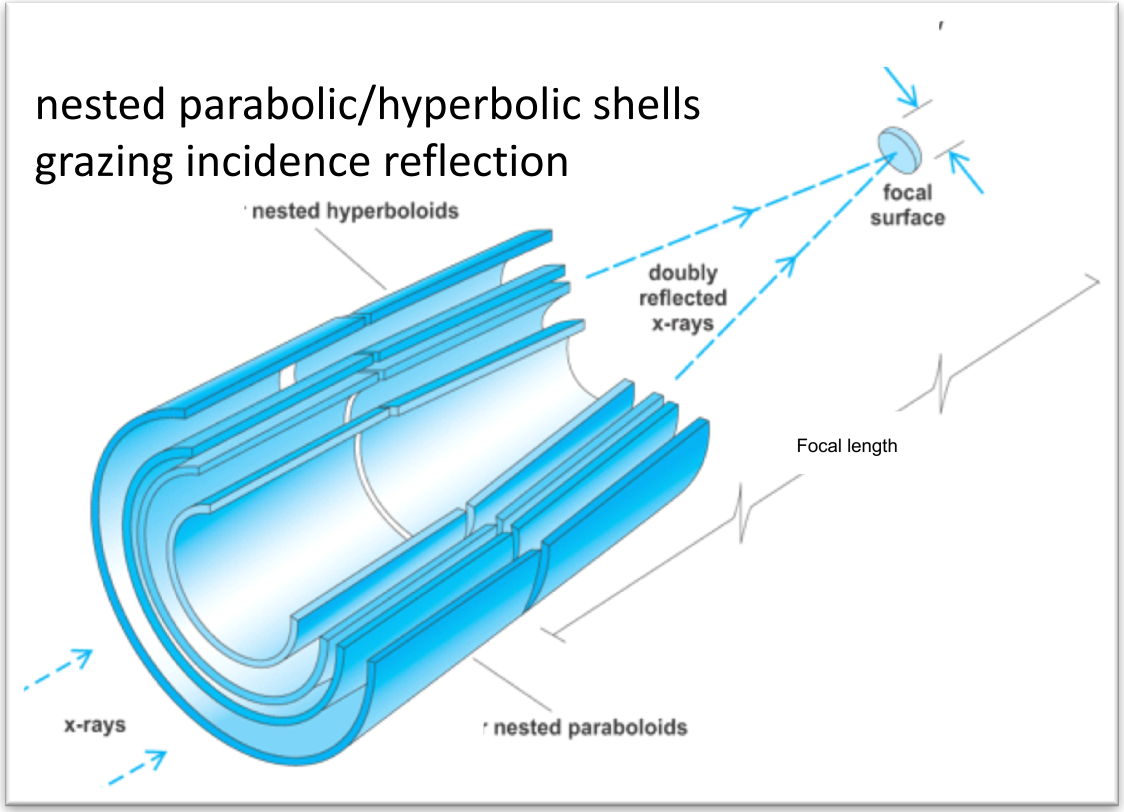
[H. ten Kate]

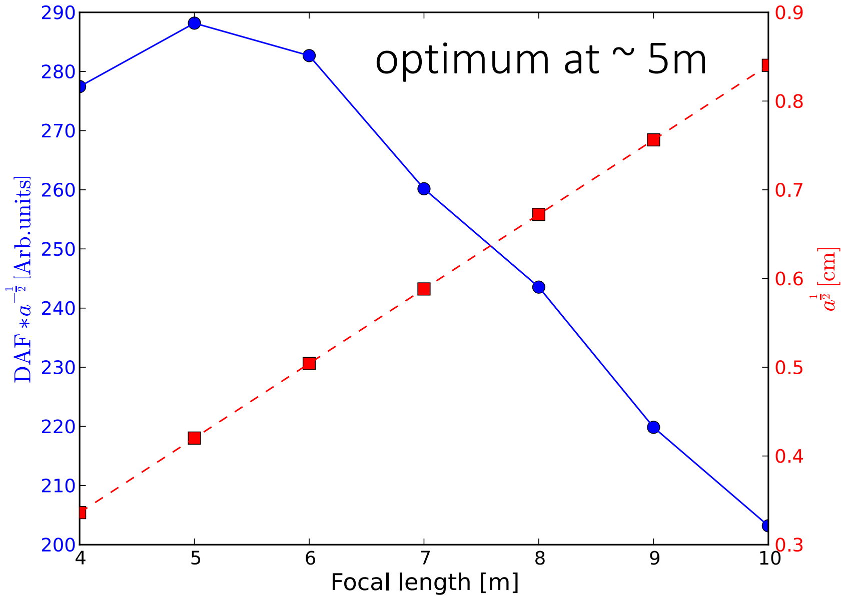
IAXO optics

Overall FOM ~ S/√B

B scales with sensitive area → focus sensitive area to smallest achievable size → small focal length

S scales with efficiency of optics → high efficiency at small angles → large focal length





Demagnification ~ 14400

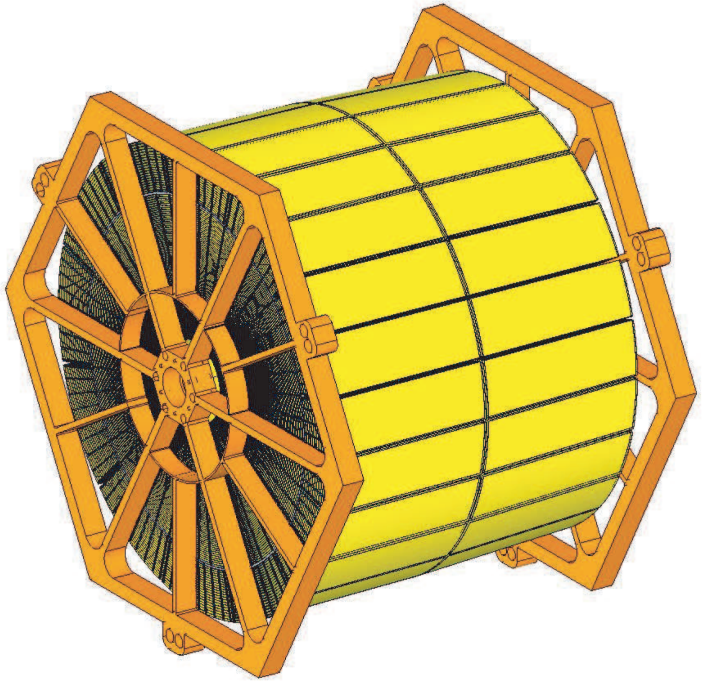
Efficiency ~ 0.7

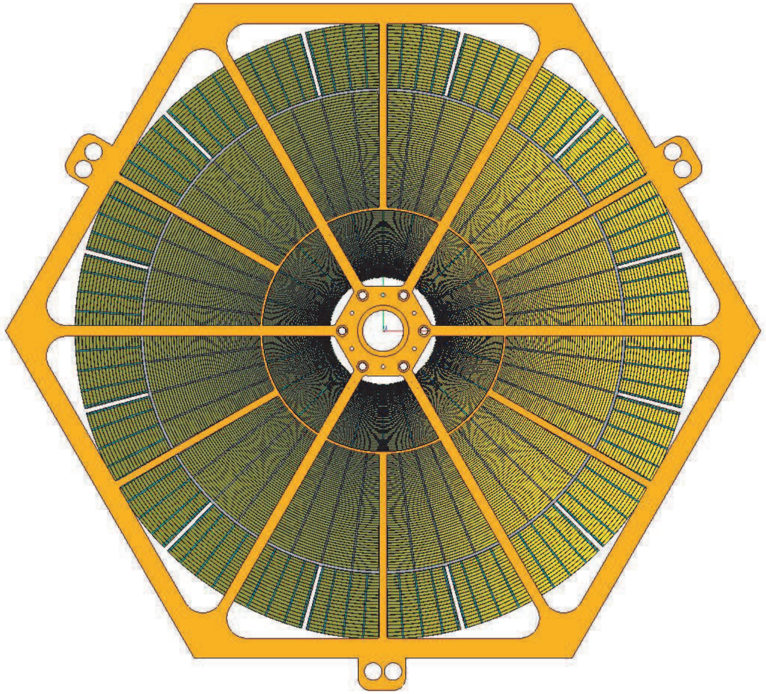
→ improves sensitivity by factor 84 w.r.t. no optics

IAXO optics

Challenges:

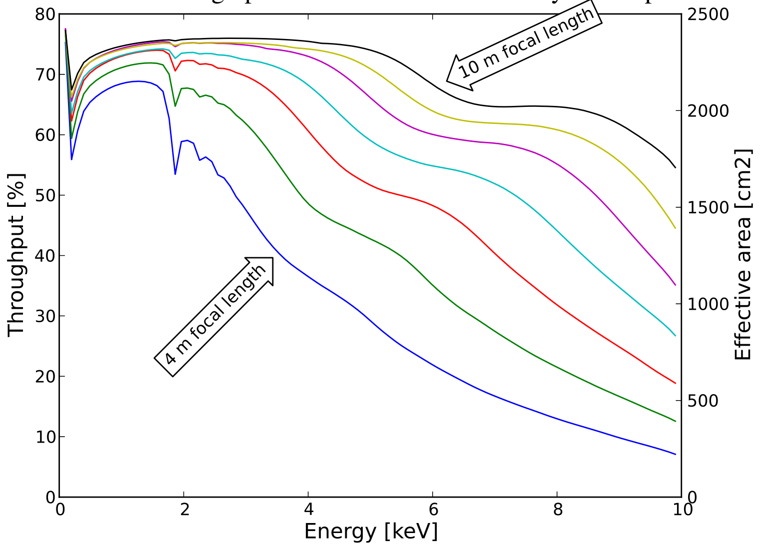
- precision vs. cost
- optimize coating → efficiency
- off axis efficiency (sun is not a point source)





Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
Focal length	5.0 m
Inner radius	50 mm
Outer Radius	300 mm
Minimum graze angle	2.63 mrad
Maximum graze angle	15.0 mrad
Coatings	W/B_4C multilayers
Pass band	1−10 keV
IAXO Nominal, 50% EEF (HPD)	0.29 mrad
IAXO Enhanced, 50% EEF (HPD)	0.23 mrad
IAXO Nominal, 80% EEF	0.58 mrad
IAXO Enhanced, 90% EEF	0.58 mrad
FOV	2.9 mrad

Table 2. Main design parameters of the IAXO x-ray telescopes.



IAXO detectors

Name of the game:

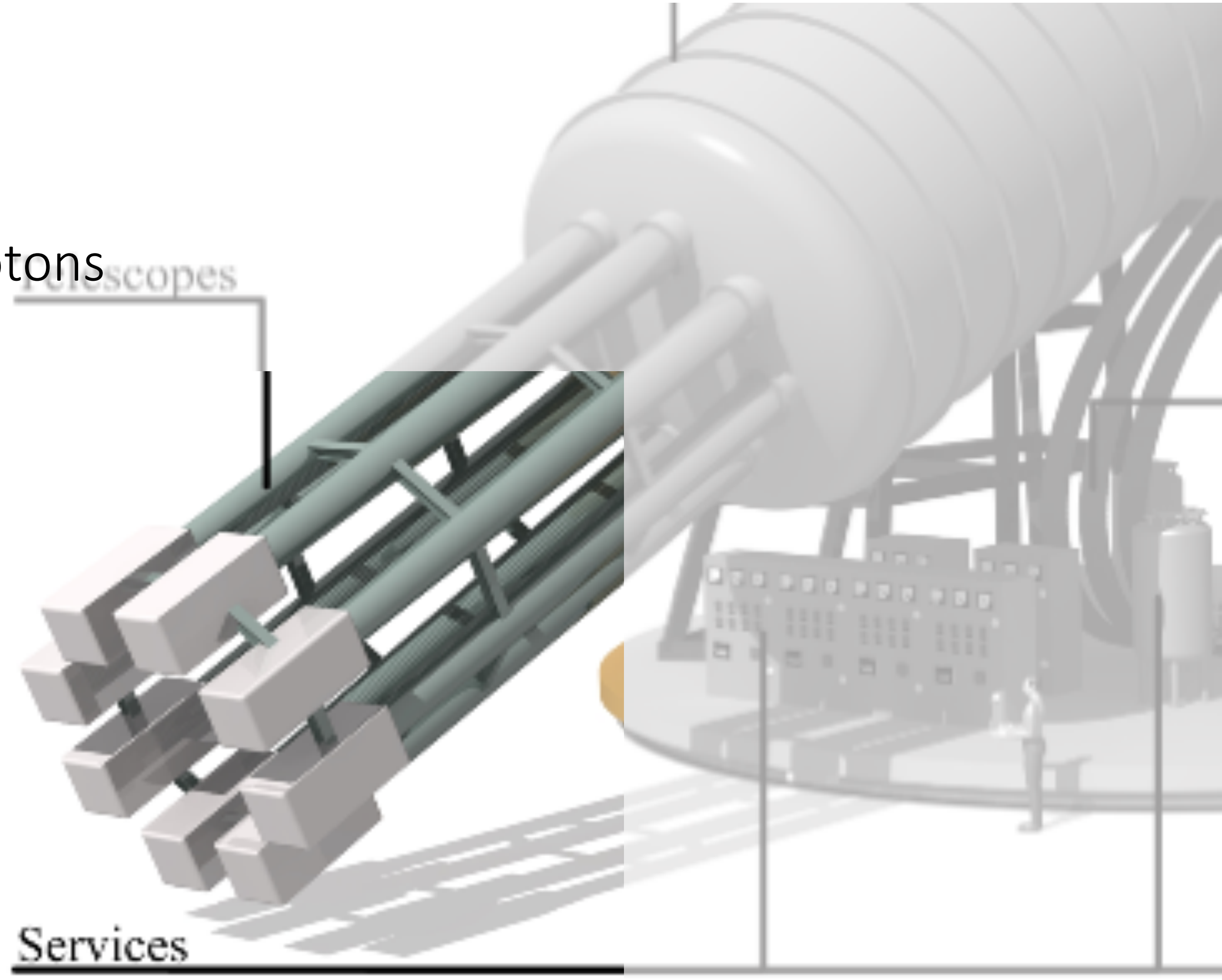
- high efficiency for single soft X-ray photons
- at lowest possible background

In addition:

- low threshold (< 1 keV)
- good energy resolution

Multitude of technologies

- gaseous (Micromegas, InGrid)
- semiconductors (SDD, ...)
- cryogenic (MMC, TES, ...)



Severeal technologies already studied in CAST

IAXO detectors

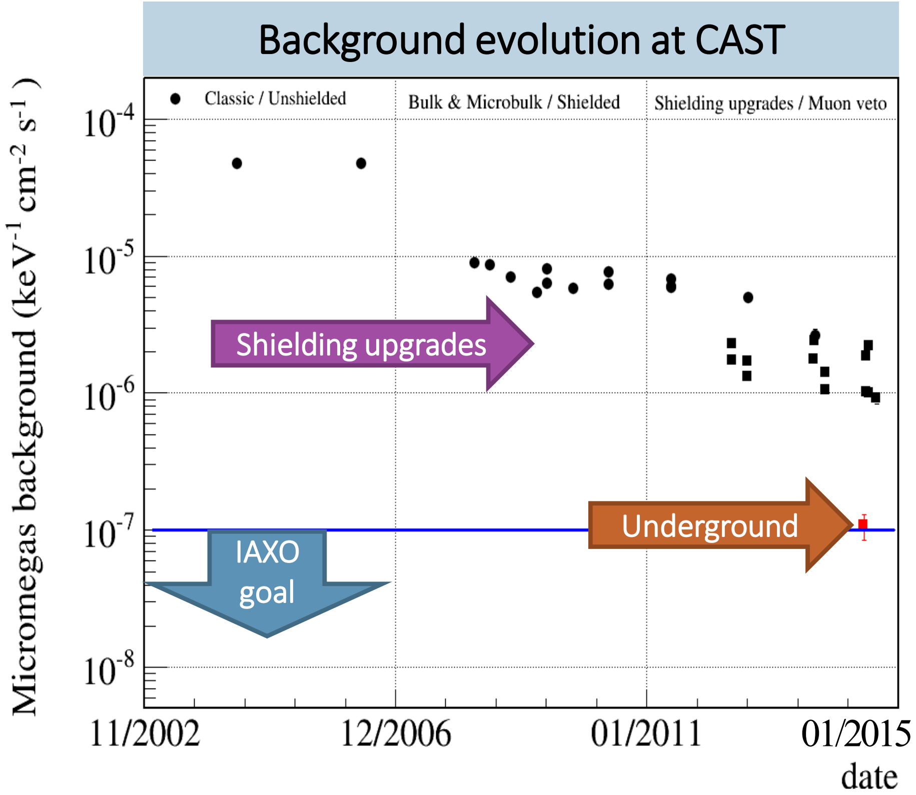
Background goal: o(1) background events/keV during 5 years of operation

sensitive signal area o(1 cm^2), solar observation time o(10^8) seconds

→ ultimate background level goal: 10^{-8} $keV^{-1}cm^{-2}s^{-1}$

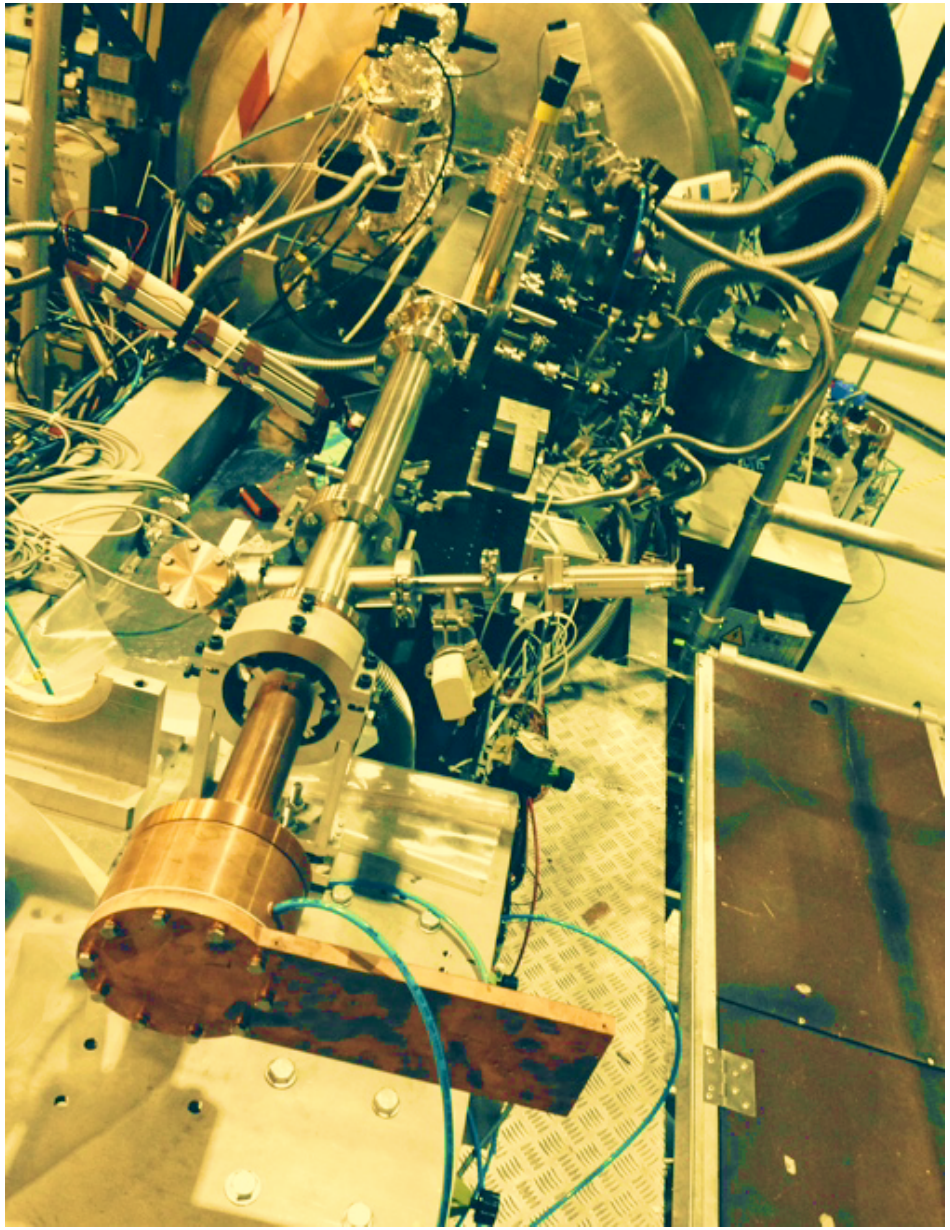
Market leader: Microbulk Micromegas

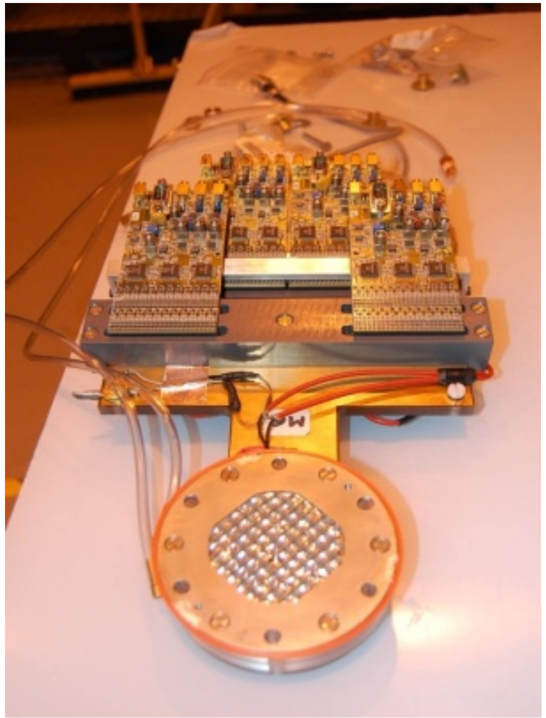
- design for radiopurity
- passive shielding
- active shielding
- offline discrimination

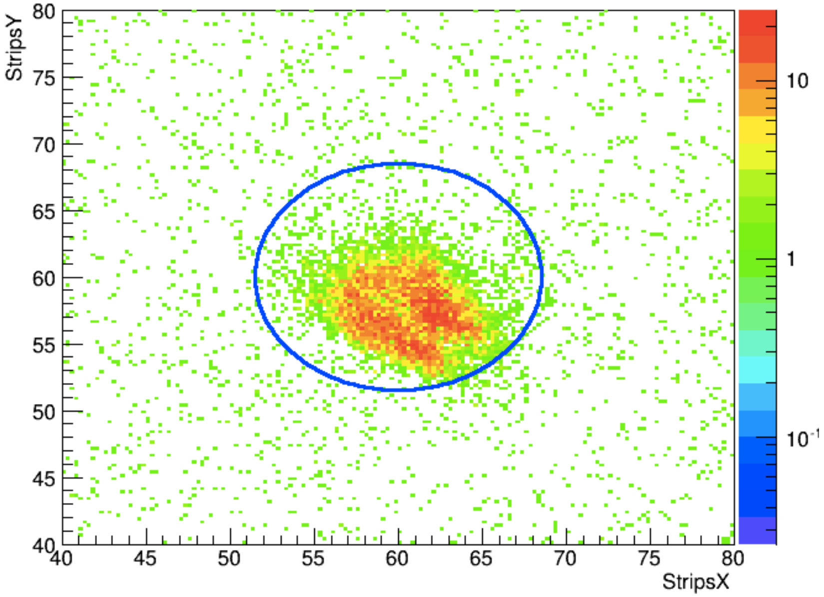


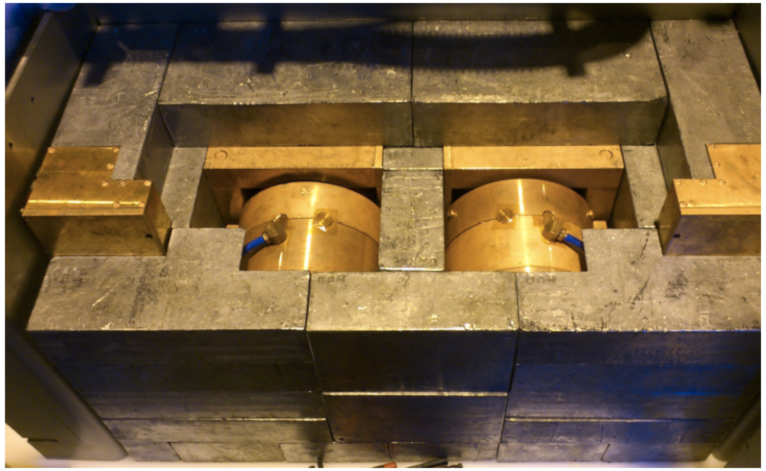
[E.Ruiz-Chóliz]

IAXO detector baseline: small Micromegas detector





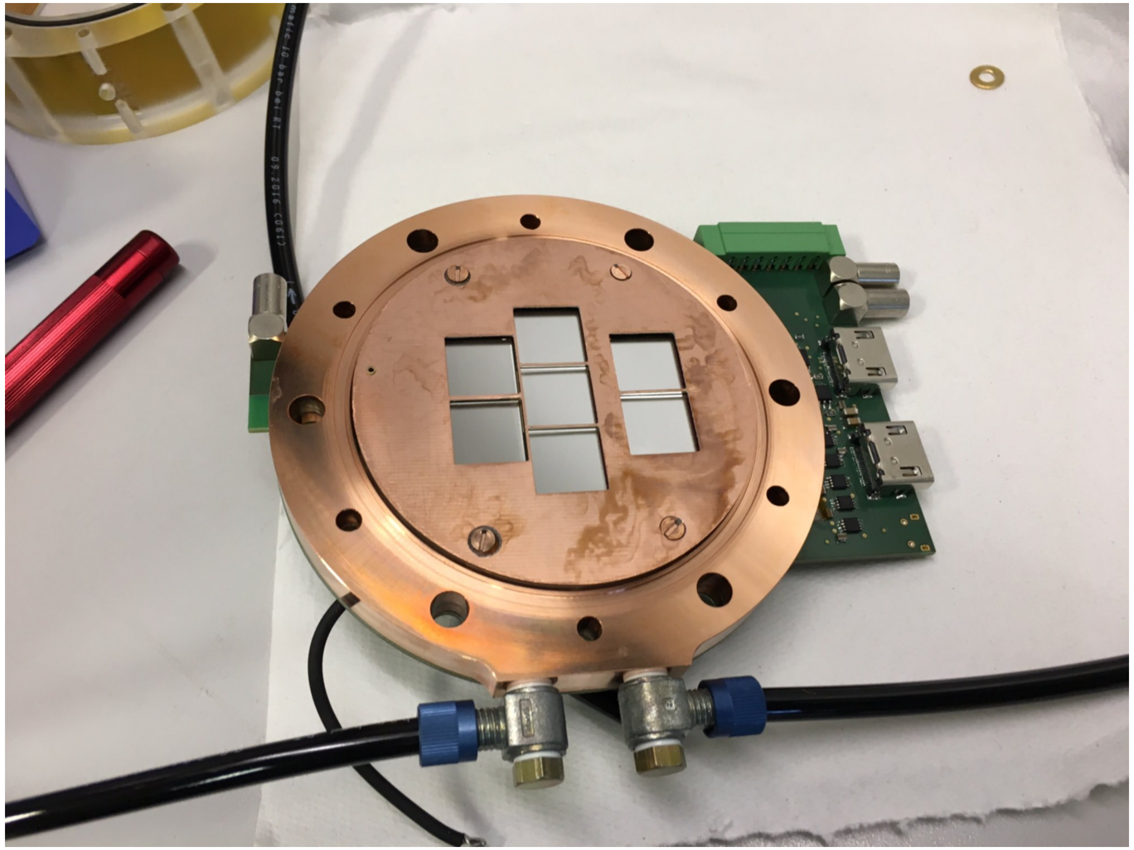


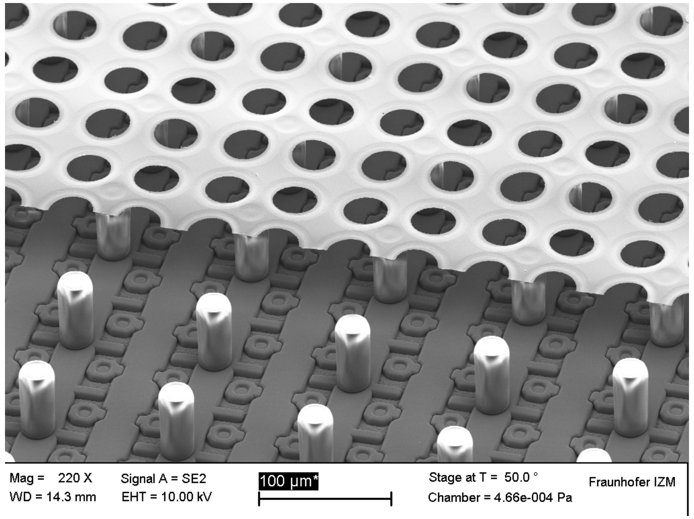


[Irastorza et al, Zaragoza
Ferrer-Ribas et al, Saclay]

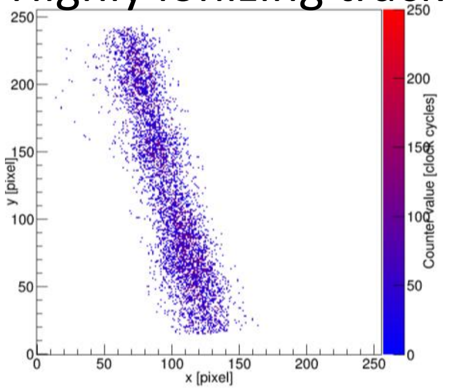
IAXO detectors: InGrid/GridPix

Micromegas on a pixel readout chip (Timepix/Timepix3)
Low energy threshold (~200 eV)
Topological (charged) background rejection
Robust energy measurement (counting)
Already being used in CAST

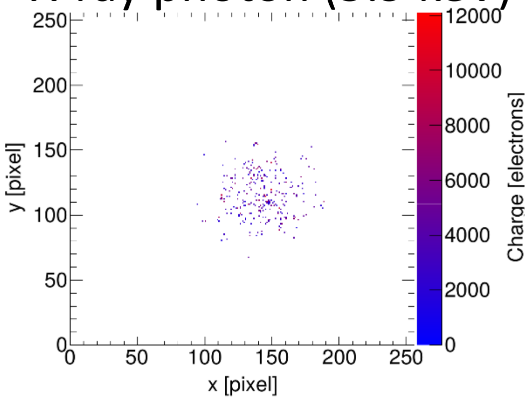


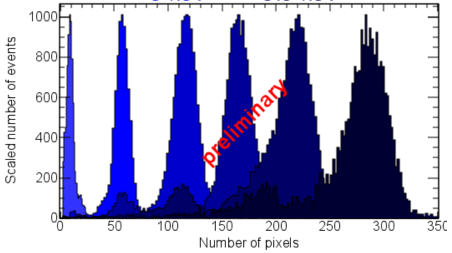


Highly ionizing track



X-ray photon (5.9 keV)

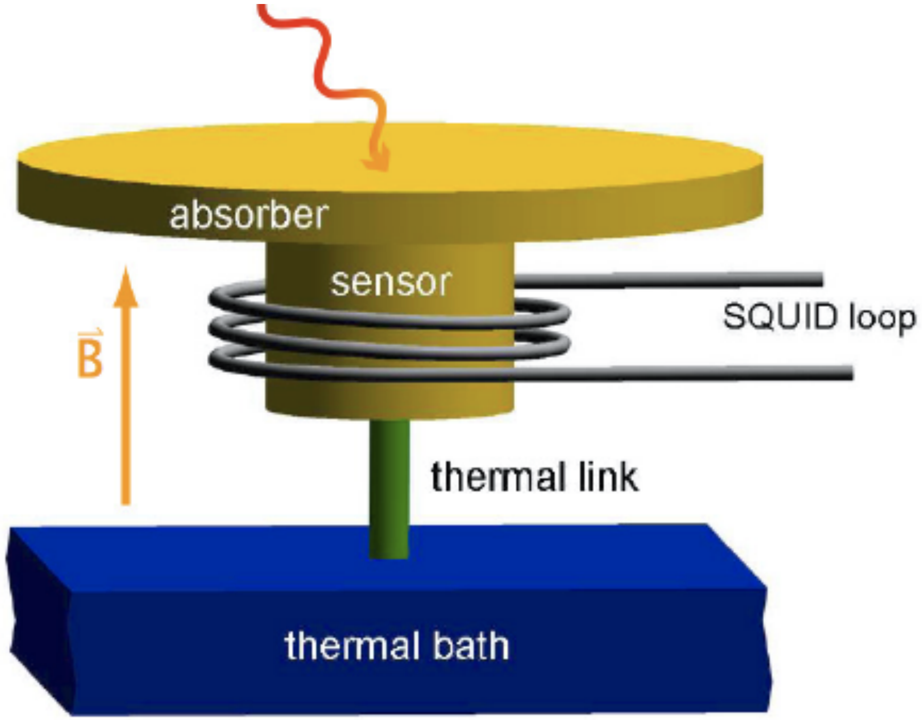


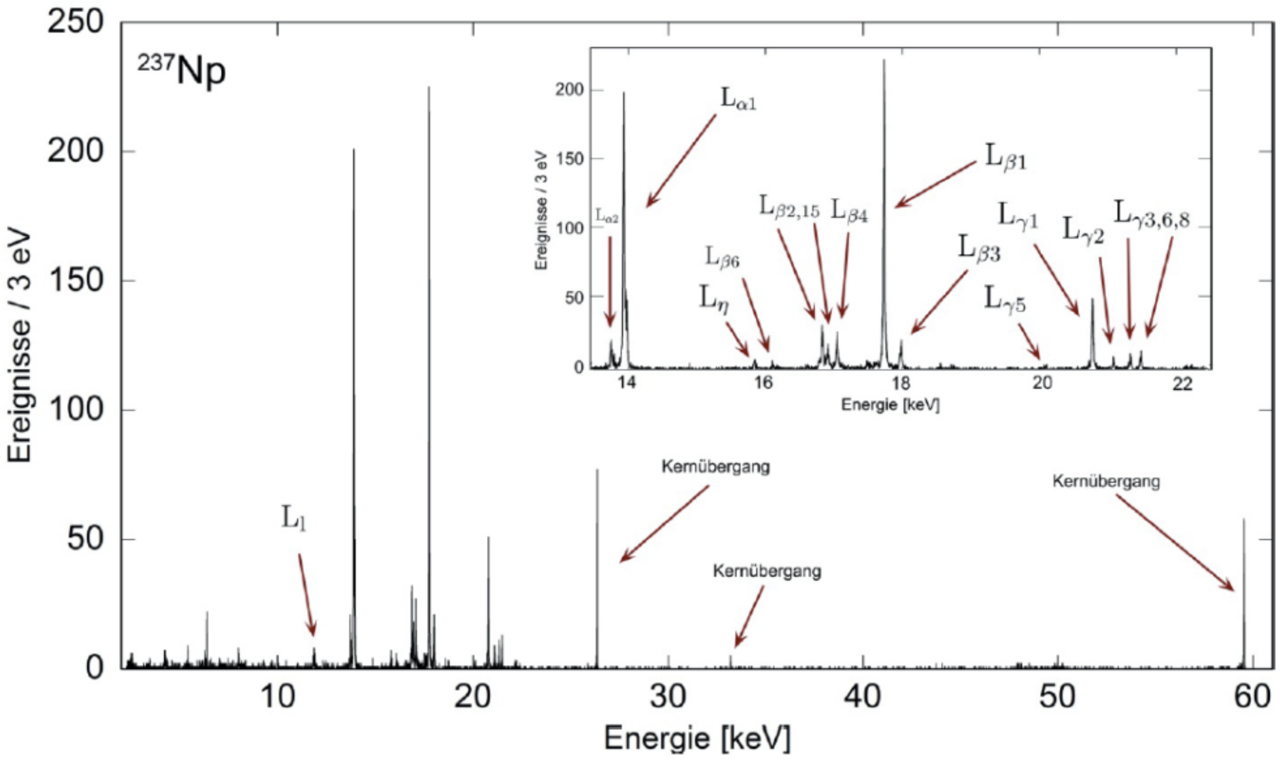


[Krieger, Schmidt et al, Bonn]

IAXO detectors: ultimate E resolution - MMCs

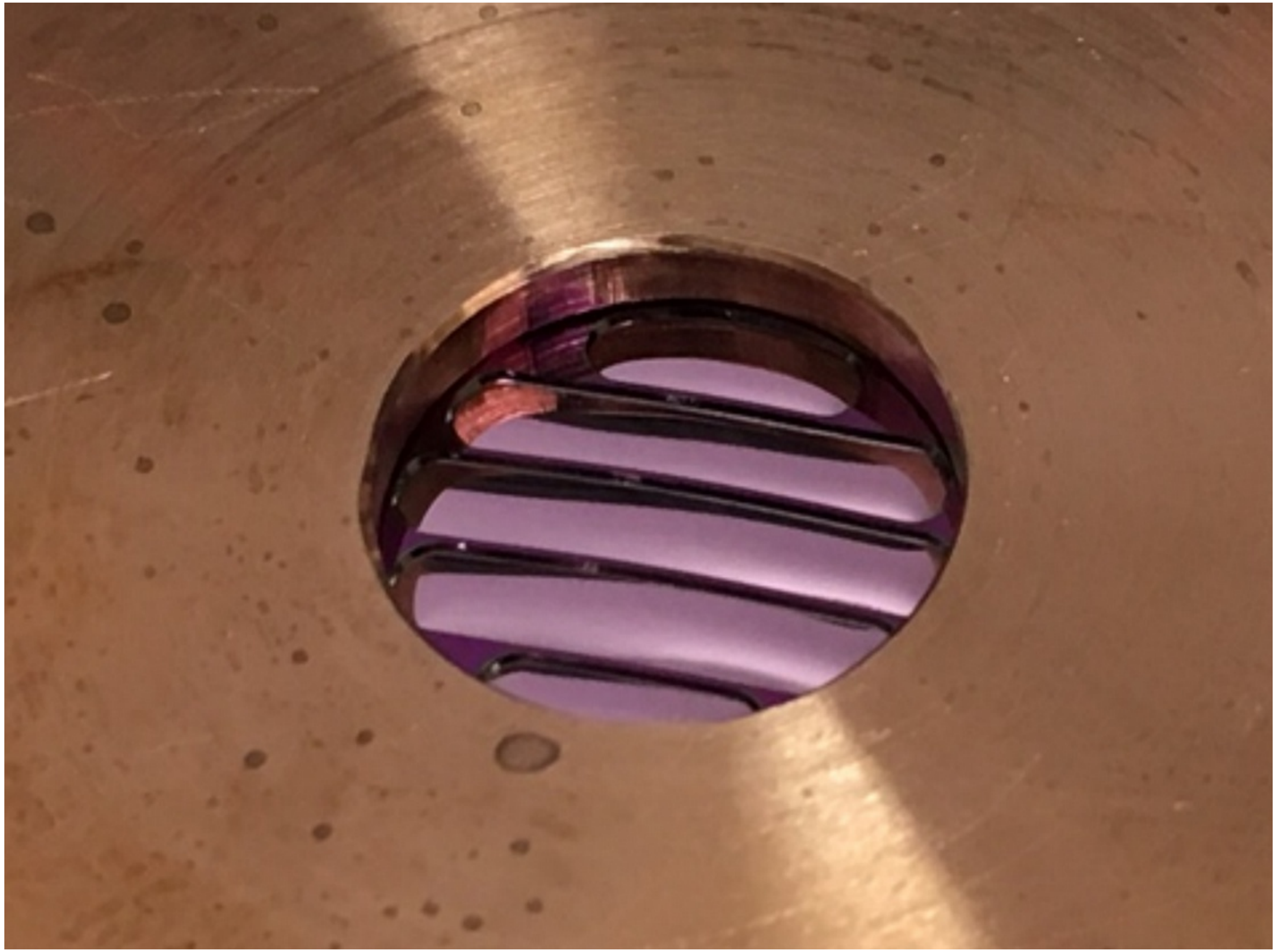
Metallic Micro Calorimeter (MMC)
Extremely low threshold & eV energy resolution!
To be operated at mK temperatures
Background to be studied



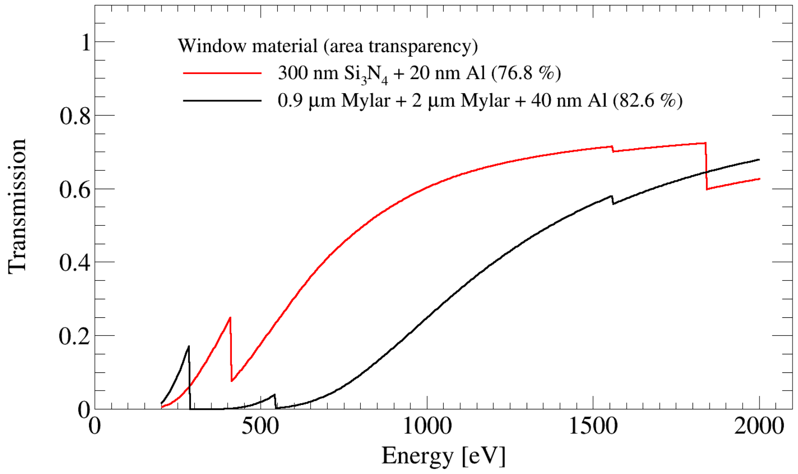


[L. Gastaldo, HD]

IAXO detectors: X-ray windows

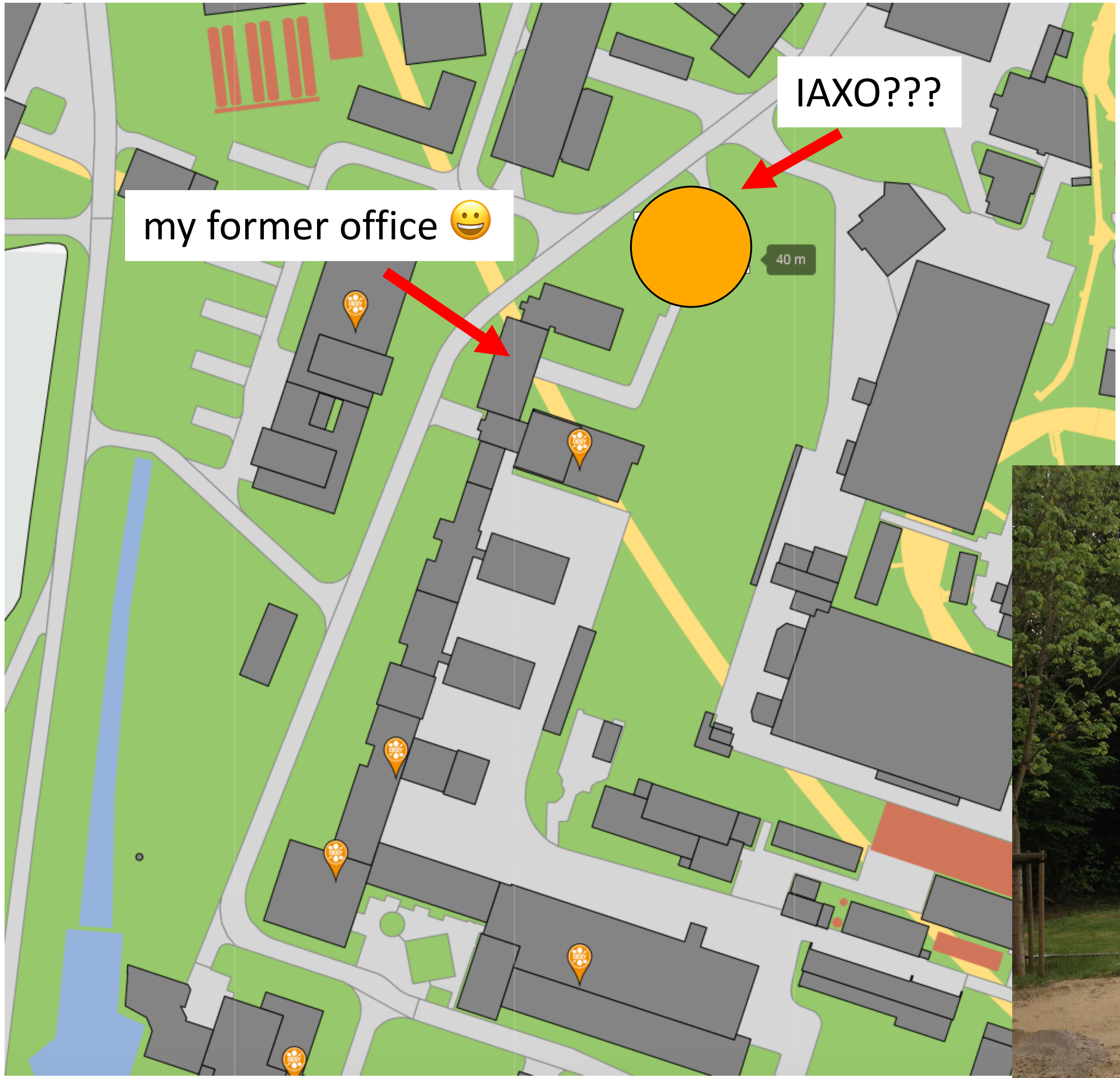


300 nm Silicon-Nitride window at 1.5 bar overpressure



[Krieger et al, Bonn & NORCADA Inc.]

IAXO site – why not here?



- Presently assembly area building 1
- DESY wall
- Nice trees
- Close to cryo lines
  - 120m to FLASH hall
  - 150m to cryo plant

IAXO site – why not here?

Hot news: IAXO collaboration founded today

Institutions ready to sign the bylaws

1. Barry University
2. Irfu/CEA Saclay
3. University of Cape Town
4. Institut de Ciències del Cosmos of the Universitat de Barcelona
5. Lawrence Livermore National Laboratory
6. Petersburg Nuclear Physics Institute named by B. P. Konstantinov of National Research Centre <Kurchatov Institute>
7. Heidelberg University
8. Universidad de Zaragoza
9. MIT's Laboratory of Nuclear Science
10. Institute for Nuclear Research of the Russian Academy of Sciences, Moscow
11. Rudjer Bošković Institute, Zagreb
12. Physikalisches Institut der Universitaet Bonn
13. Instituto de Microelectronica de Barcelona, Centro Nacional de Microelectronica, CSIC, Spain
14. JGU Mainz

Also (to be confirmed):
CERN,
DESY,
DTU Denmark,
U South Carolina,
University Columbia

19 initial member institutes
8 countries
3 regions

Summary & Conclusions

- Axions are a trending topic in particle physics, astrophysics, cosmology!
- Need several next-generation experiments to cover complete parameter space
- IAXO unique to cover the 1 … 1000 meV region for the QCD axion
- IAXO sensitive to clarify astrophysical anomalies
- Technology quite advanced, scale-up approach (BabyIAXO) enables us to start “now”! Full IAXO by 2025?
- DESY appears as a very suitable site!