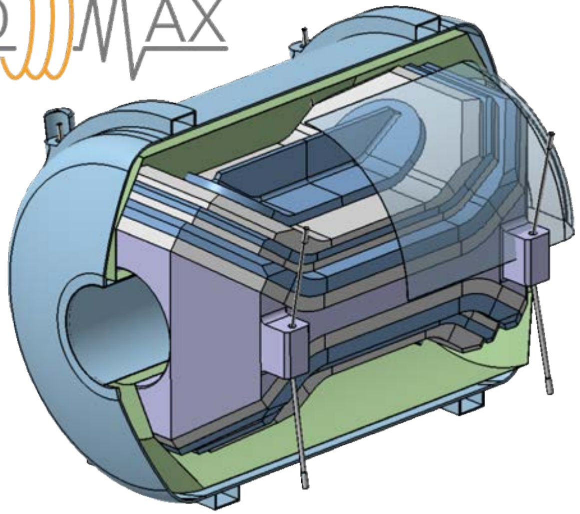
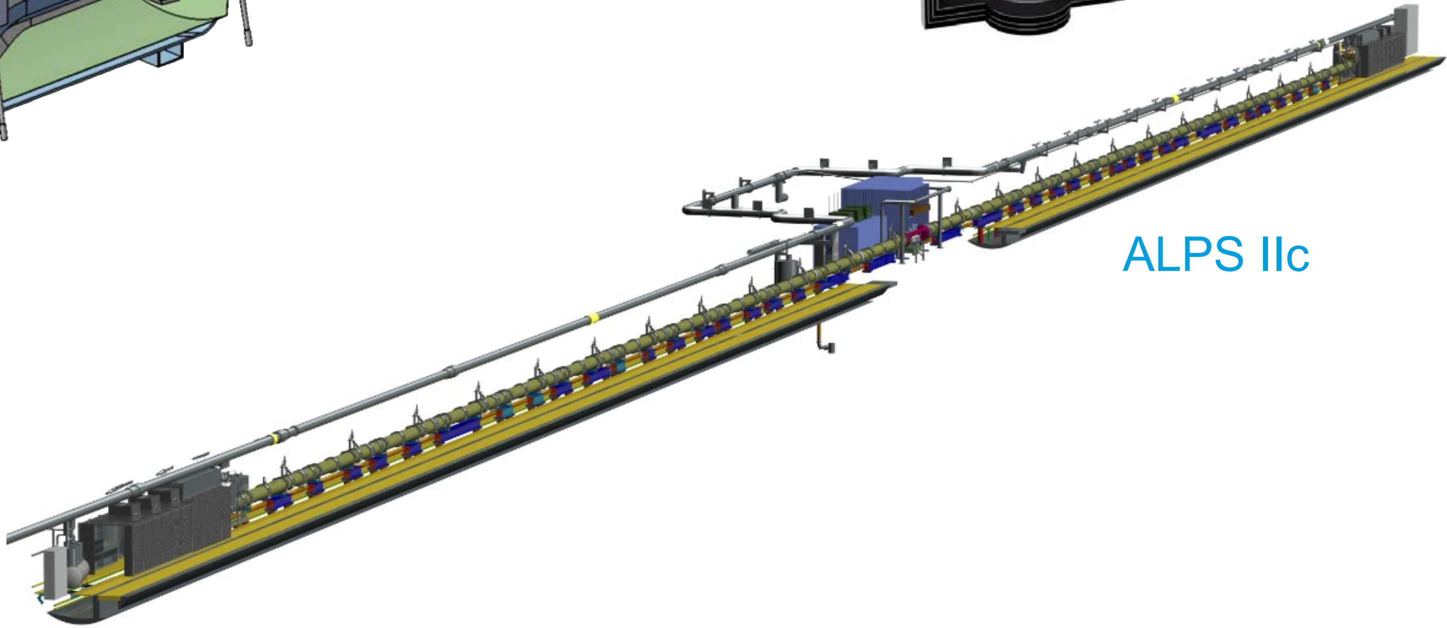
Axion search experiments
Exploring the low-energy frontier



ADMX



ALPS IIc

K. Desch
University of Bonn
Graduiertenkolleg Freiburg
22/07/2020

Three biggest questions of particle physics (arguably):

- Why are we here? (Baryon asymmetry of Universe)
- Why are we sub-dominant? (The Dark “World” gravitates, what else?)
- Is our world fine-tuned?

The (QCD) axion is possibly addressing two of them

Outline

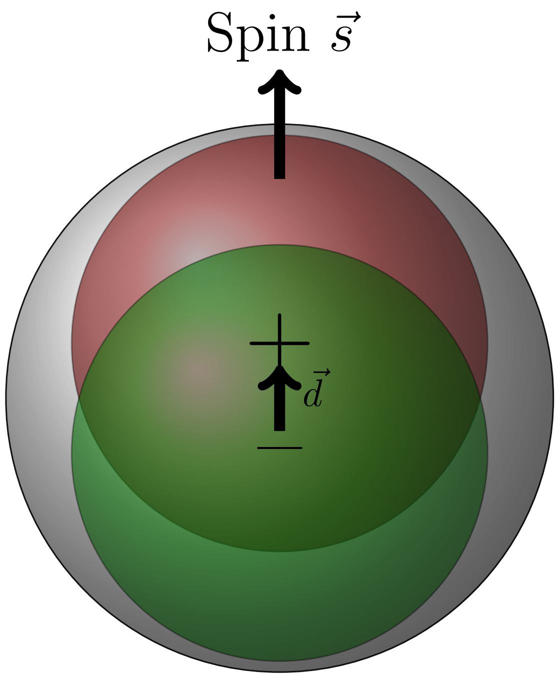
- (At least) five reasons to like Axions
- Axions and ALPS: What are they?
- Axions and ALPS: How to find them?

Before telling you what the axion actually is, should like it!

[https://www.particlezoo.net/collections/all]

Five reasons to like Axions and ALPS: Axions...

1. ... may solve the strong CP problem



QCD Lagrangian admits CP-violating term(s):

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu \psi - \bar{\psi} M \psi - \theta \frac{1}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

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

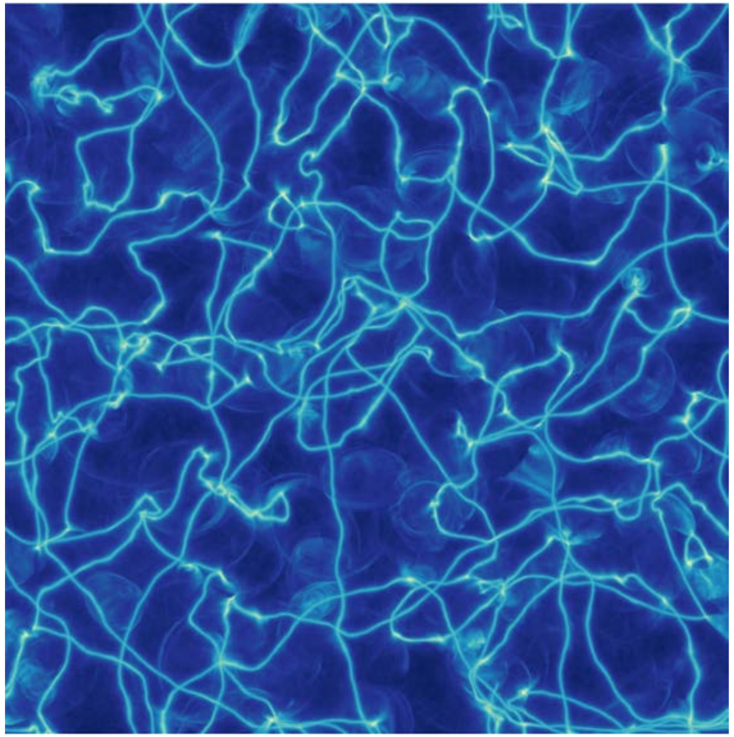
induces (e.g.) electric dipole moment of neutron: $d_n \approx \bar{\theta} \cdot 10^{-3} e \text{ fm}$

measurement: $d_n < 0.30 \times 10^{-12} e \text{ fm} \rightarrow \bar{\theta} \lesssim 10^{-10}$ → ppt fine tuning

Five reasons to like Axions and ALPS : Axions…

2. … may be the Dark Matter

Despite their small mass, axions are viable Dark Matter candidates
Abundance depends on (complicated) details of early universe physics
(which I don´t understand 😞)



[Redondo]

Five reasons to like Axions and ALPS : Axions and/or ALPS…

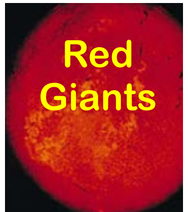
3. … may explain anomalous star cooling

Emission of Axions strongly constrained from too fast cool down of stars

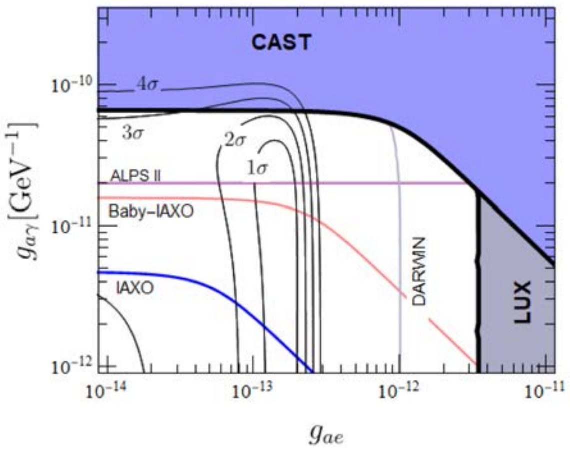
Some stars appear to cool down faster than expected (stellar cooling anomaly)!

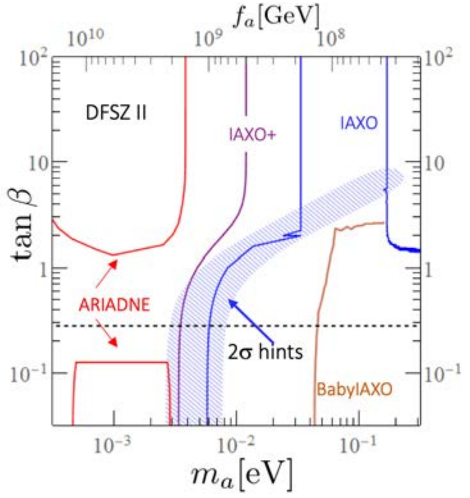
Bounds:

Stellar system	Bound
RGB stars	$g_{ae} \leq 4.3 \times 10^{-13}$
WDs	$g_{ae} \leq (3-4) \times 10^{-13}$
HB stars	$g_{a\gamma} \leq 0.65 \times 10^{-10}\ \mathrm{GeV}^{-1}$
SN 1987A	$g_{ap} \leq 6 \times 10^{-10}$
NS	Similar to SN 1987A



Anomalies:

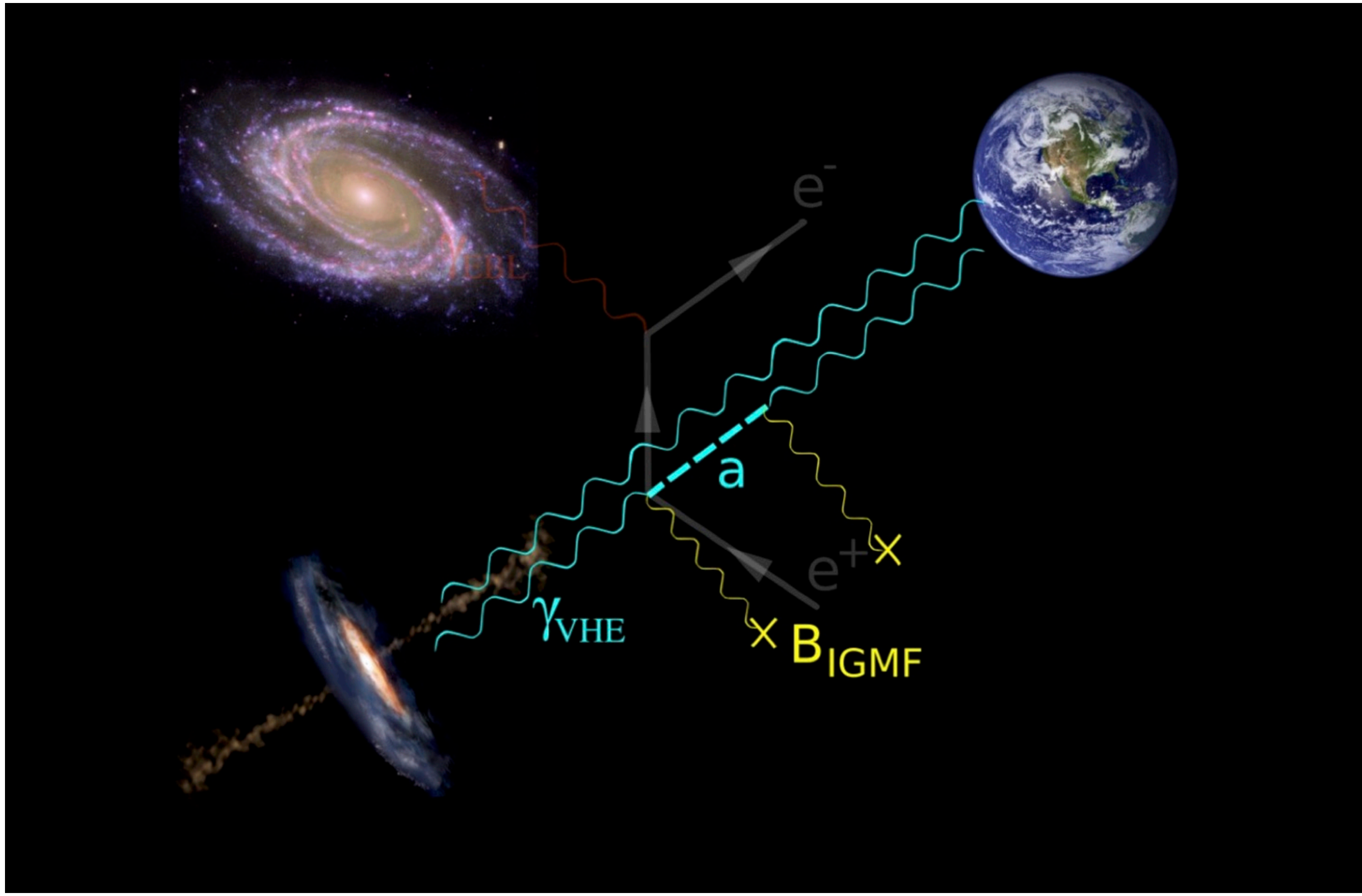




Five reasons to like Axions and ALPS: Axions…

4. … may explain anomalous

   TeV transparency of the sky

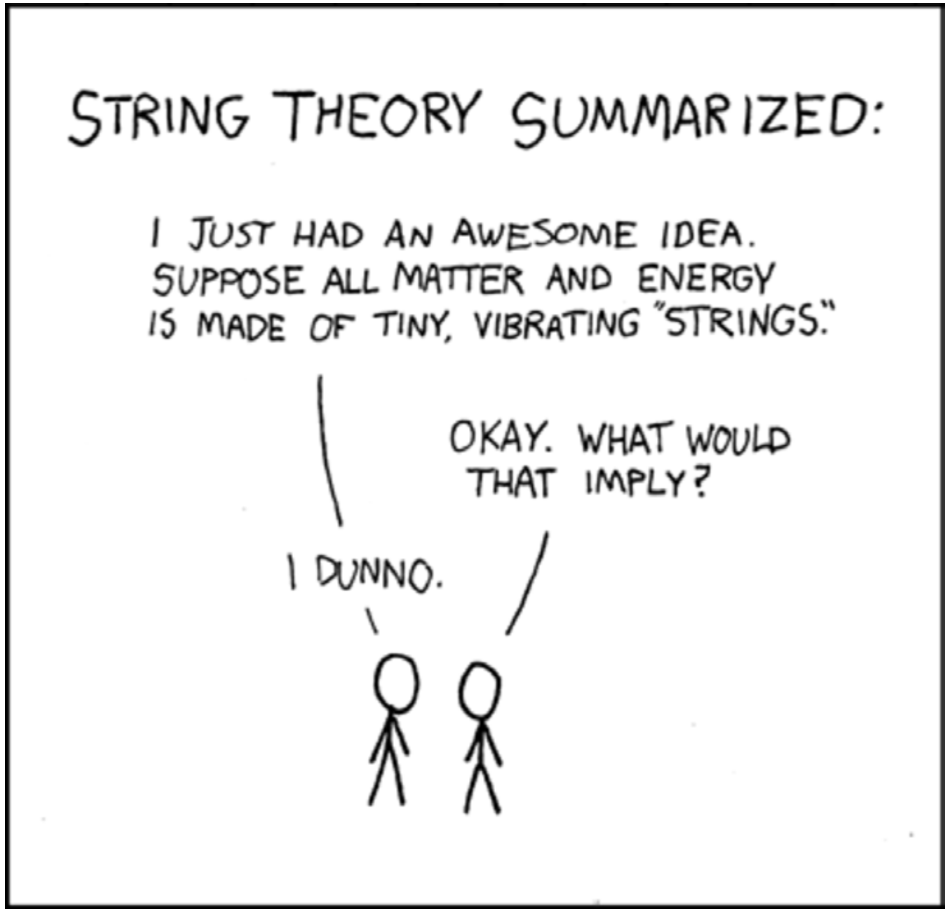


[Horns, Meyer; Troitsky; …]

Five reasons to like Axions and ALPS

Axions...

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



Outline

- (At least) five reasons to like Axions
- Axions and ALPS: What are they?
- Axions and ALPS: How to find them?

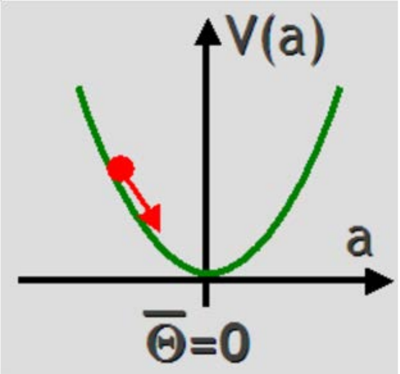
The (QCD) Axion

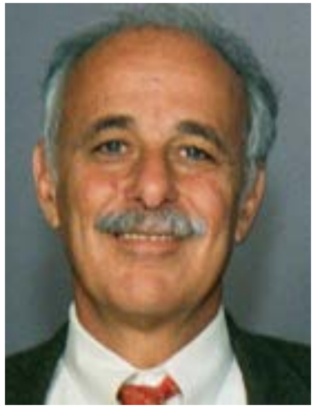
$$\mathcal{L}_{CP} = -\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu} \longrightarrow \mathcal{L}_{CP} = -\frac{\alpha_s}{8\pi}\frac{a(x)}{f_a}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

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)

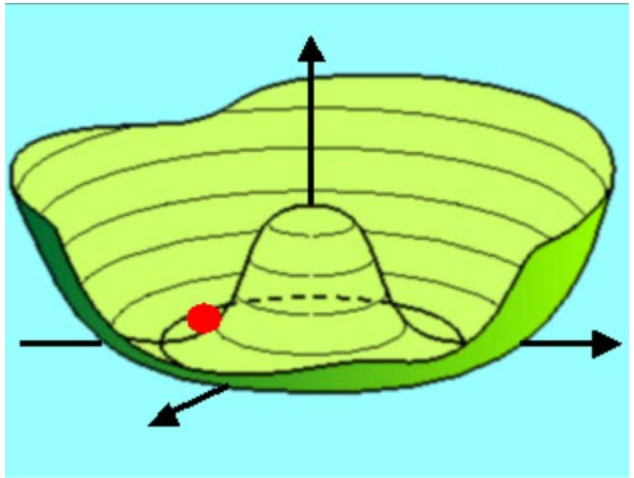
F. Wilczek (1978)

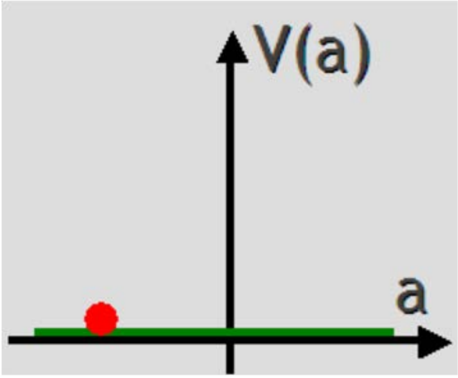
S. Weinberg (1978)

The (QCD) Axion mass

$E \sim f_a$ (large)

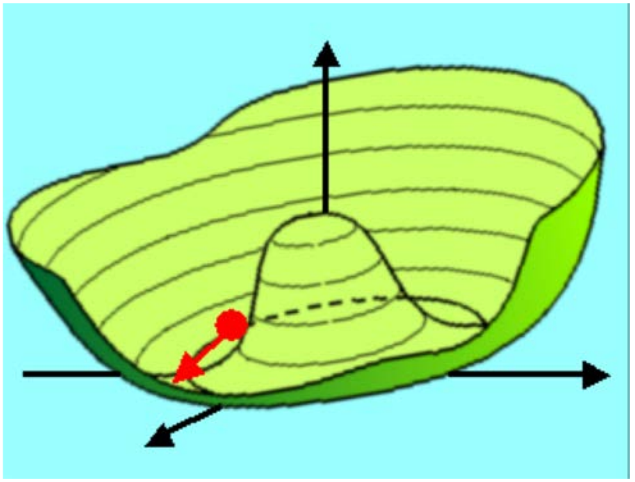
- spontaneously broken symmetry
- Axion = Nambu-Goldstone Boson (massless)

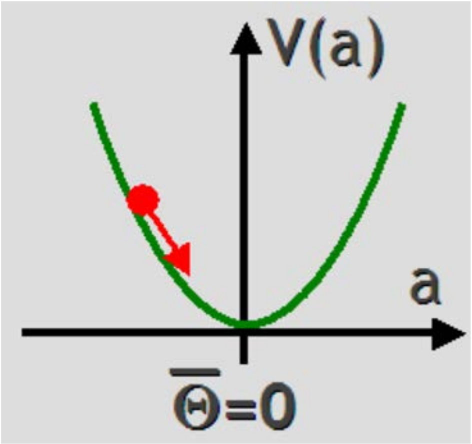




$E \sim \Lambda_{QCD}$

- 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…

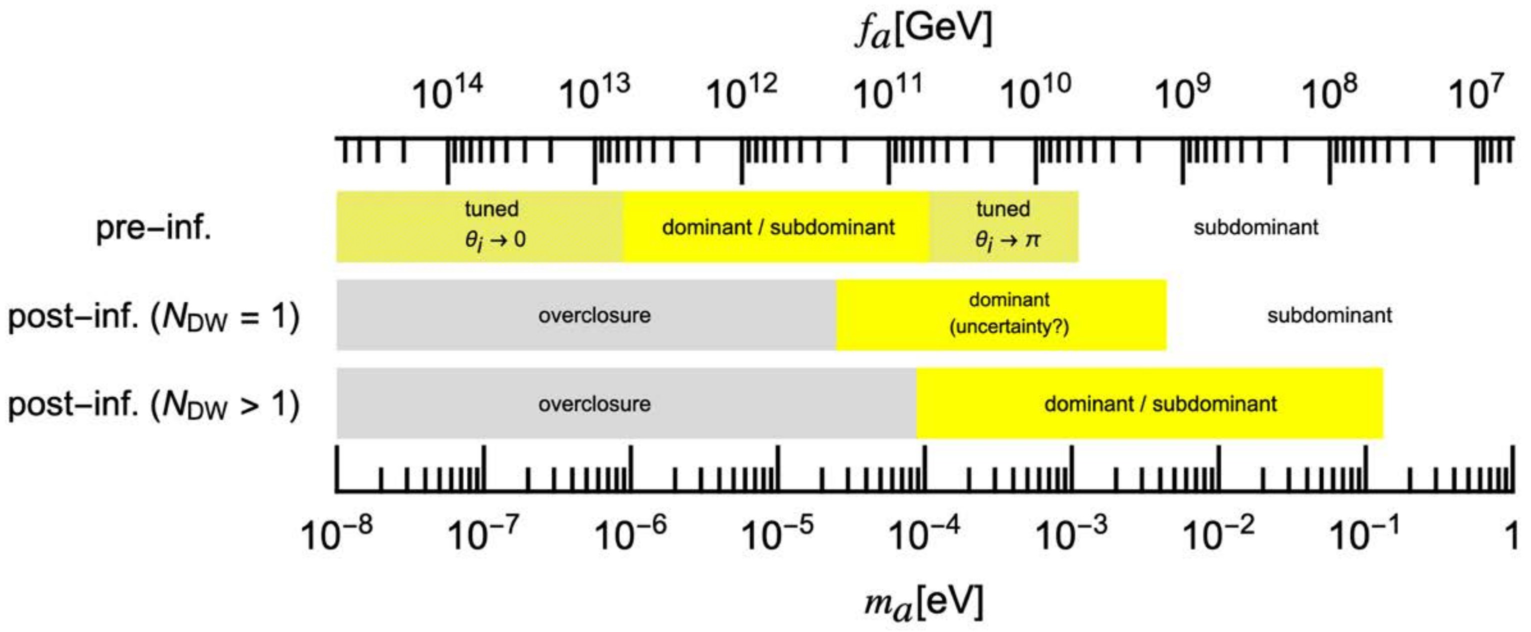
There may be more than one ALP

QCD Axion mass predictions?

- QCD axion mass is essentially unconstrained (due to unknown f_a)

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

- If QCD axion = dark matter, mass constrained by observed DM density but axion cosmology is complicated and model-dependent



DM axions can be anywhere between ~ 1 μeV and 0.1 eV

Some „standard“ models prefer m_a ~ o(10 μeV)

[Redondo]

- Stellar cooling anomalies favour ~ few meV axions/ALPs

Outline

- (At least) five reasons to like Axions
- Axions and ALPS: What are they?
- Axions and ALPS: How to find them?

Axion phenomenology

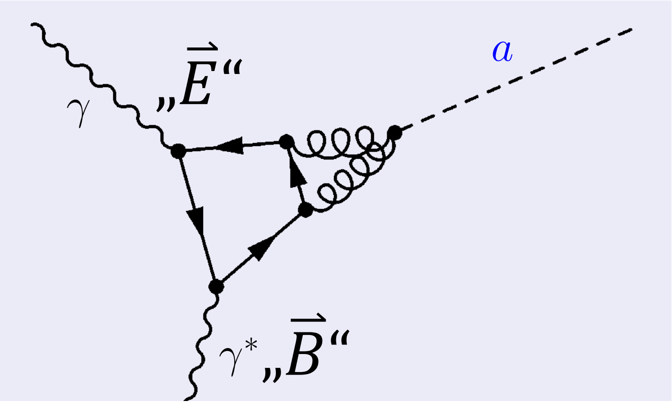
Most axion experiments exploit the (effective) axion-photon coupling

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

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

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

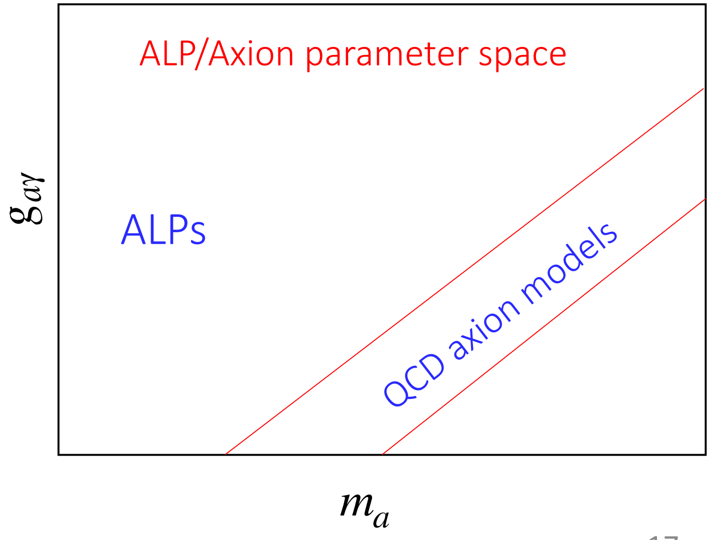
1T ≙ 300 MV/m



- QCD axion: axion mass ~ axion-photon coupling

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

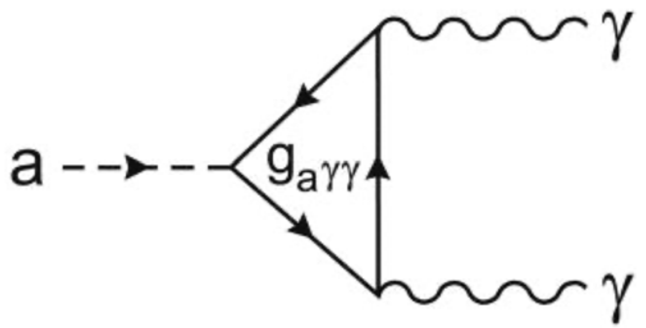
C_γ ~ 0.75 (-1.92) for DFSZ (KSVZ) (benchmark models)



- DFSZ model also predicts a significant axion-electron coupling
- ALPs: any combination of mass and photon-coupling

Axion decay?

yes, but ☺



$$\Gamma_{A\to\gamma\gamma} = \frac{G_{A\gamma\gamma}^2 m_A^3}{64\,\pi} = 1.1 \times 10^{-24}\ \mathrm{s}^{-1} \left(\frac{m_A}{\mathrm{eV}}\right)^5$$

$$m_A = \frac{z^{1/2}}{1+z}\,\frac{f_\pi m_\pi}{f_A} = \frac{0.60\ \mathrm{meV}}{f_A/10^{10}\,\mathrm{GeV}}$$

m_A [eV]	τ [$T_{universe}$]	f_A [LHC]
1	10^6	10^2
0.0001	10^{26}	10^6

[A. Lindner]

State-of-the art

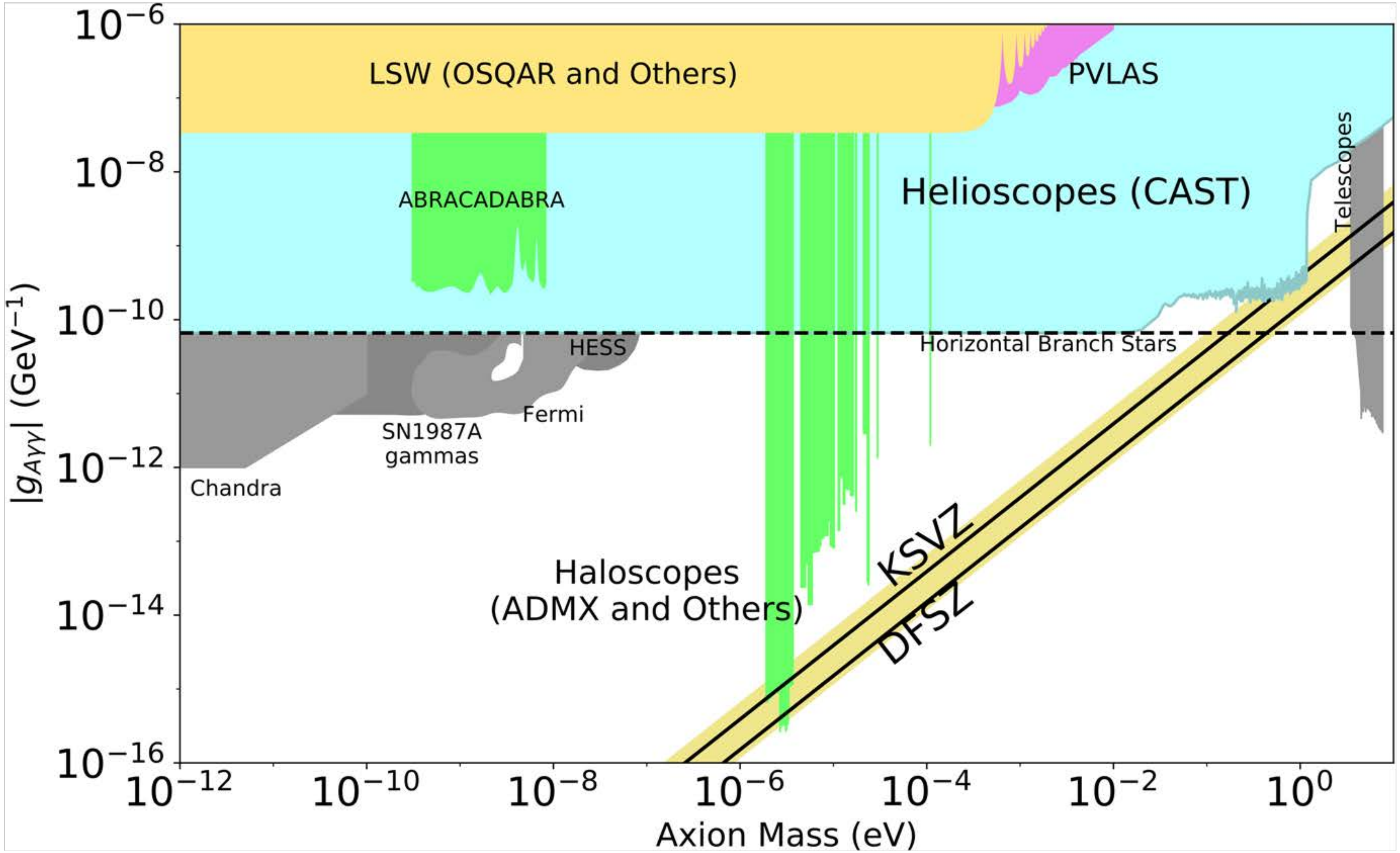


Figure 91.1: Exclusion plot for ALPs as described in the text. [PDG]

a lot to do!

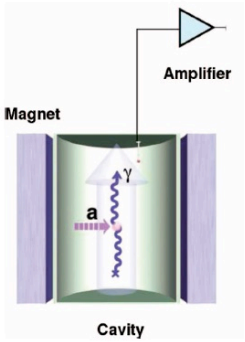
New Axion experiments

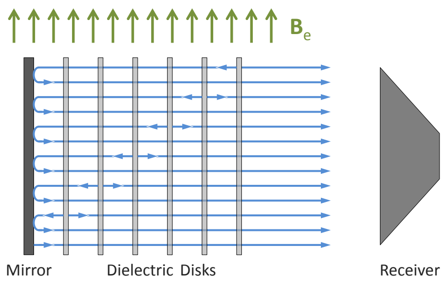
Photon energies

"Haloscopes"

Axion source: Dark Matter Halo
(if axions are the DM)

~µeV

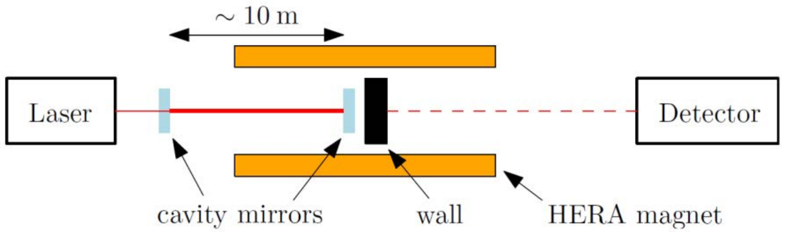




"Light shining through wall"

Axion source: laser + B-field

~eV

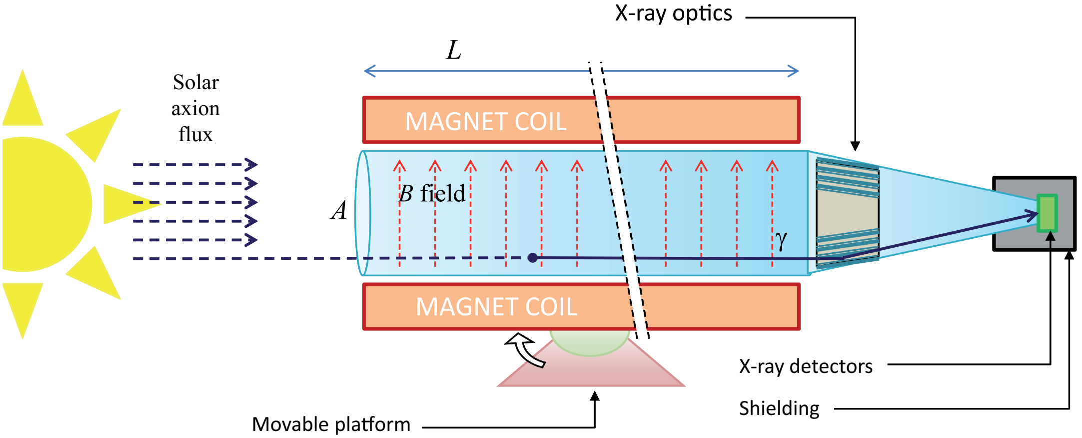


(a) ALPS-I

"Helioscopes"

Axion source: Sun
(rather unavoidable, if axions exist,
robust prediction)

~µeV

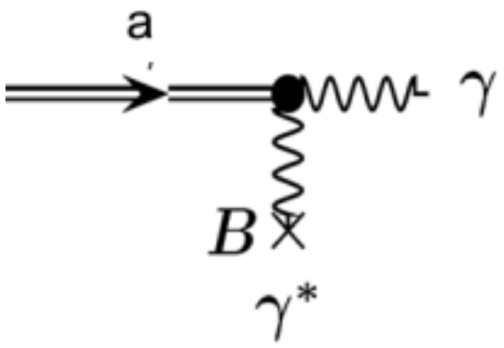


Other (not covered here)

Haloscope experiments (search for ambient DM axions)

1. Cavity haloscope:

- exploit mixing of axion field with photon field in strong B field
- additional source term in Maxwell´s equations
- if $m_a c = h\nu$ → conversion of axion field to photon field in resonant microwave cavity
- needs scanning of resonance frequency of cavity (axion mass unknown)
- tradeoff between quality factor and sensitivity
- limited to small masses (cavitiy size) f[GHz] = 0.66 m_a [μeV]

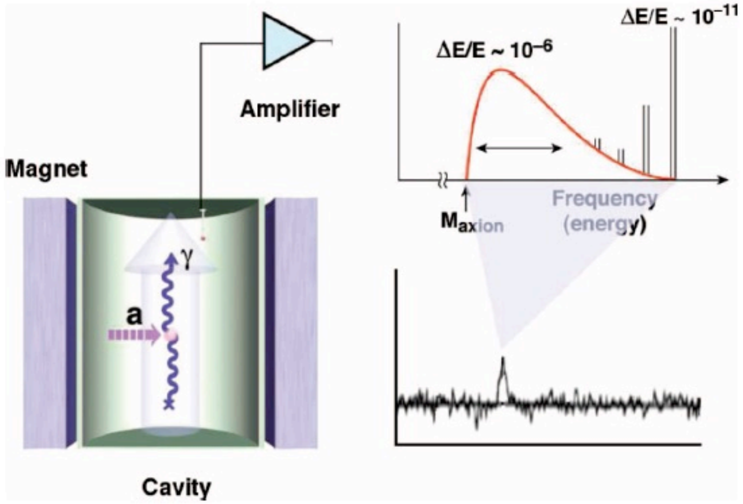


$$\vec{\nabla} \cdot \vec{D} = \rho_f + g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B} \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t} - g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\vec{B}\frac{\partial a}{\partial t} + \vec{\nabla} a \times \vec{E}\right),$$

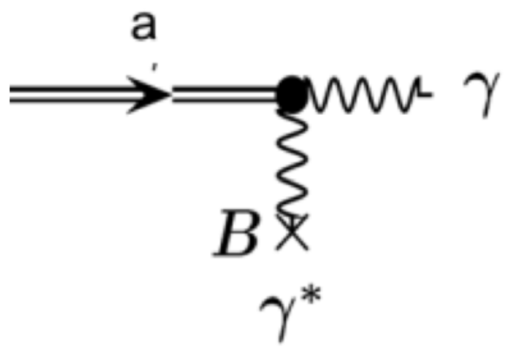
$$\vec{\nabla} \cdot \vec{B} = 0,$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t},$$



Experiments: ADMX (US), CAST/CAPP, RADES (CERN), CAPP (Korea), ...

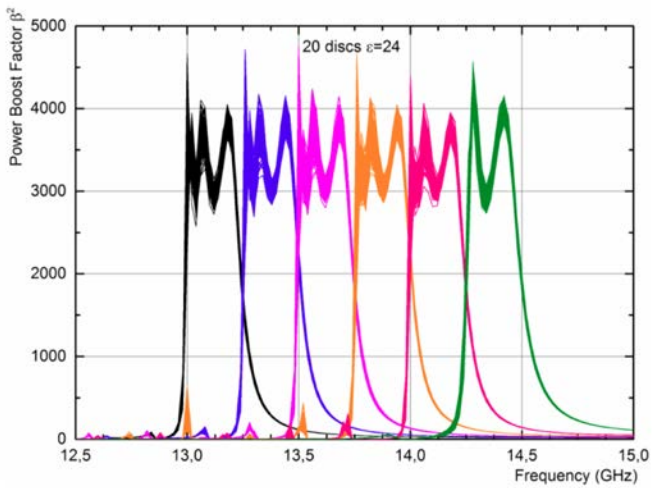
Haloscope experiments (search for ambient DM axions)

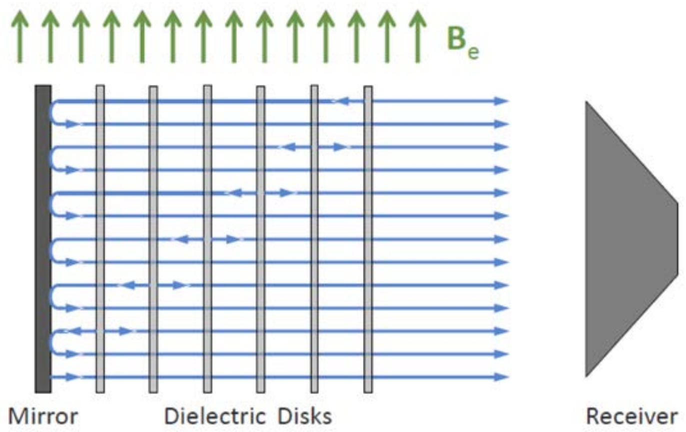


2. <u>Dielectric haloscope:</u>

- exploit mixing of axion field with photon field in strong B field
- at <u>surfaces</u> with transition of ε → (microwave) photon emission
- build layered structure with many transitions
- broadband enhancement of signal through interference
- needs scanning of resonance frequency of cavity (axion mass unknown)
- enter o(10 μeV) mass region

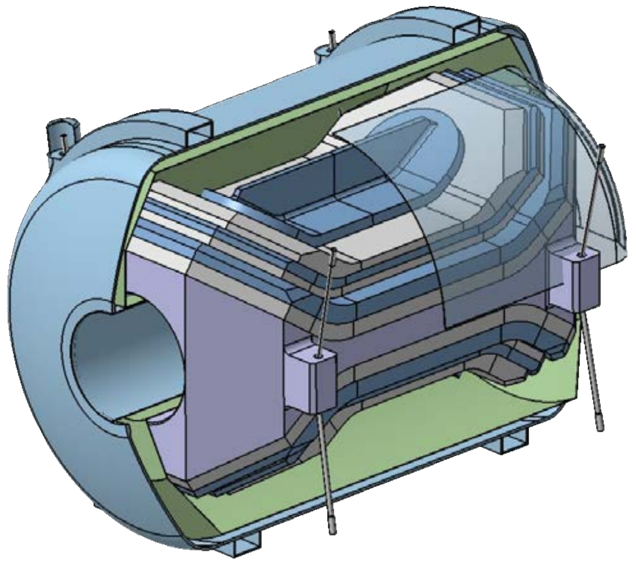
MADMAX experiment (MPP Munich, DESY, ...)



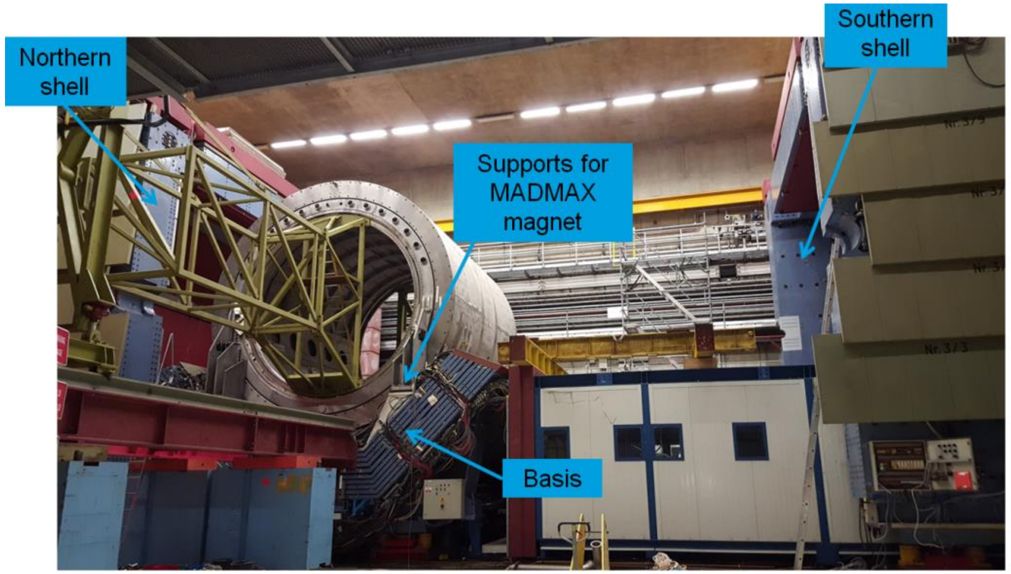


MADMAX

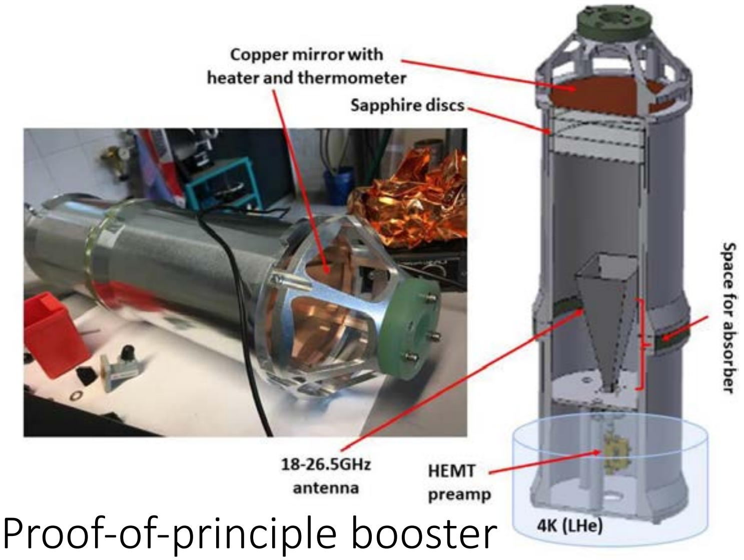
(MAgnetized Disc and Mirror Axion eXperiment)



Parameter	Results
J_E	50 A/mm²
By (0,0,0)	-8.82 T
Bpeak (x,y,0)	9.85 T
Bpeak	**9.87 T**
Overfield (B_{peak}/B_0)	11.8 %
FoM	**94.4 T²m²**
H+ / H- (Z = 0.0 m)	-0.9 % / 5.0 %
Energy	**482 MJ**
Volume	**4.435 m³**
Length	**5.0 m**



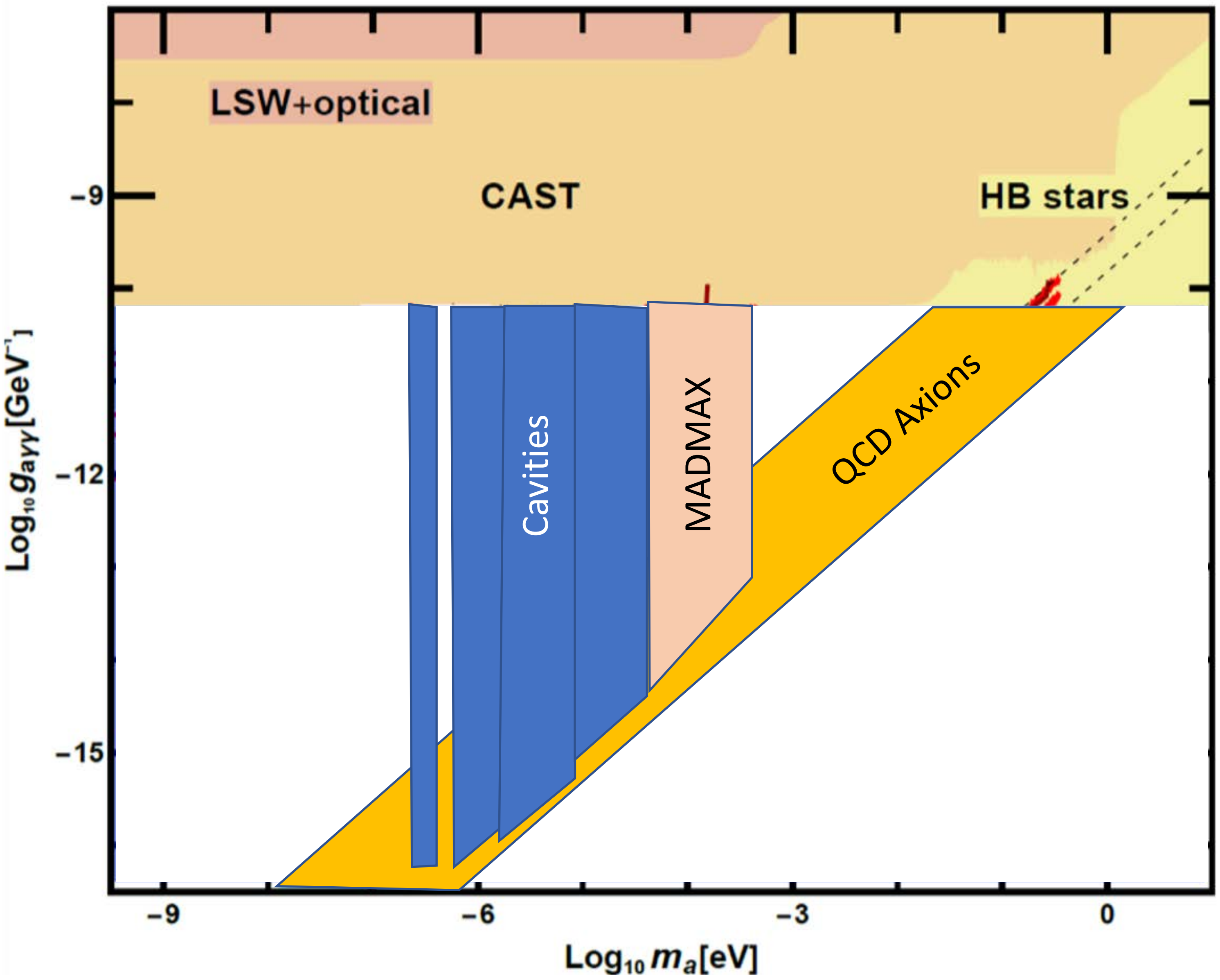
MADMAX site: HERA Halle Nord, using H1 yoke



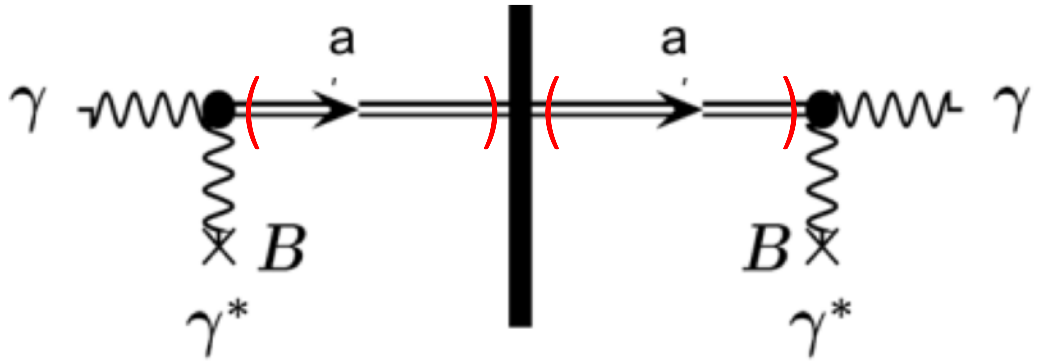
Proof-of-principle booster

- large volume + large field magnet needed (FOM ~ $B^2 * A$)
- dielectric discs (1.2 m^2 $LaAlO_3$ or Saphire)
- µm precise alignment of discs at 4K
- scan by movement of discs

Haloscope experiments: prospects



Light-Shining-Through-Wall Experiments



- exploit mixing of axion field with photon field in strong B-field
- enhance conversion through optical resonator
- FOM ~ $B^2 * L^2$
- full „theoretical control“ (no dependence on astrophysics/cosmology for axion production)
- small rate ~ $g_{a\gamma}{}^{4}$ → not sensitive to QCD-Axion (but interesting ALP parameter space)
- „broadband“ sensitivity independent of m_a (as long as $o(m_a) < o(1/L)$)

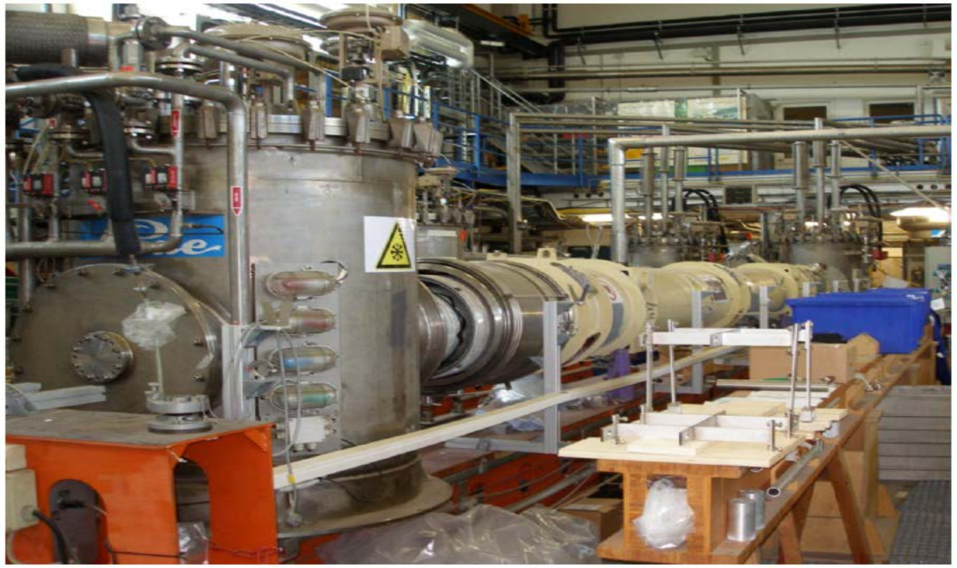
Leading experiment: ALPS (Any Light Particle Search) at DESY

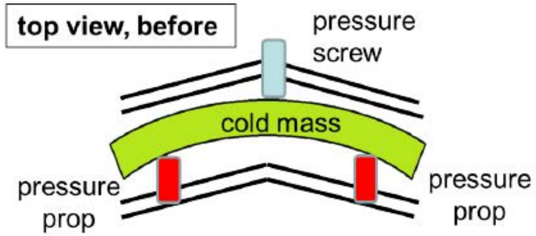
ALPS IIc experiment

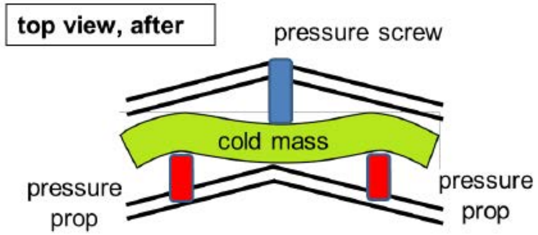
- Using 2 strings of 12 HERA SC dipoles each
- Aperture > 46 mm: straightening required

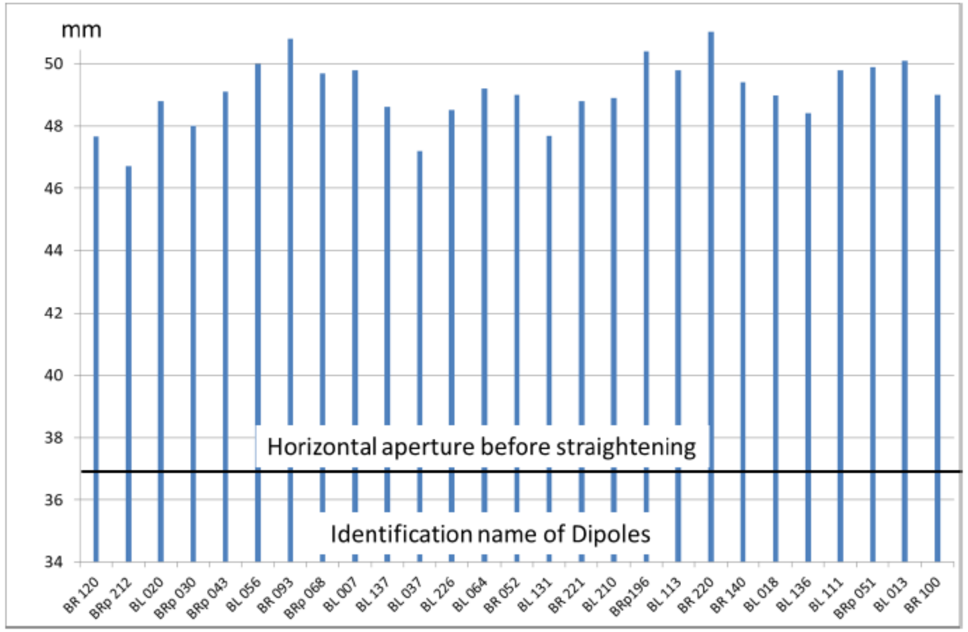
Status (April)

- All magnets including two spares successfully modified,
  tested and painted.
- First magnets installed in the tunnel.
- Critical milestone: close experimental vacuum in 2020.

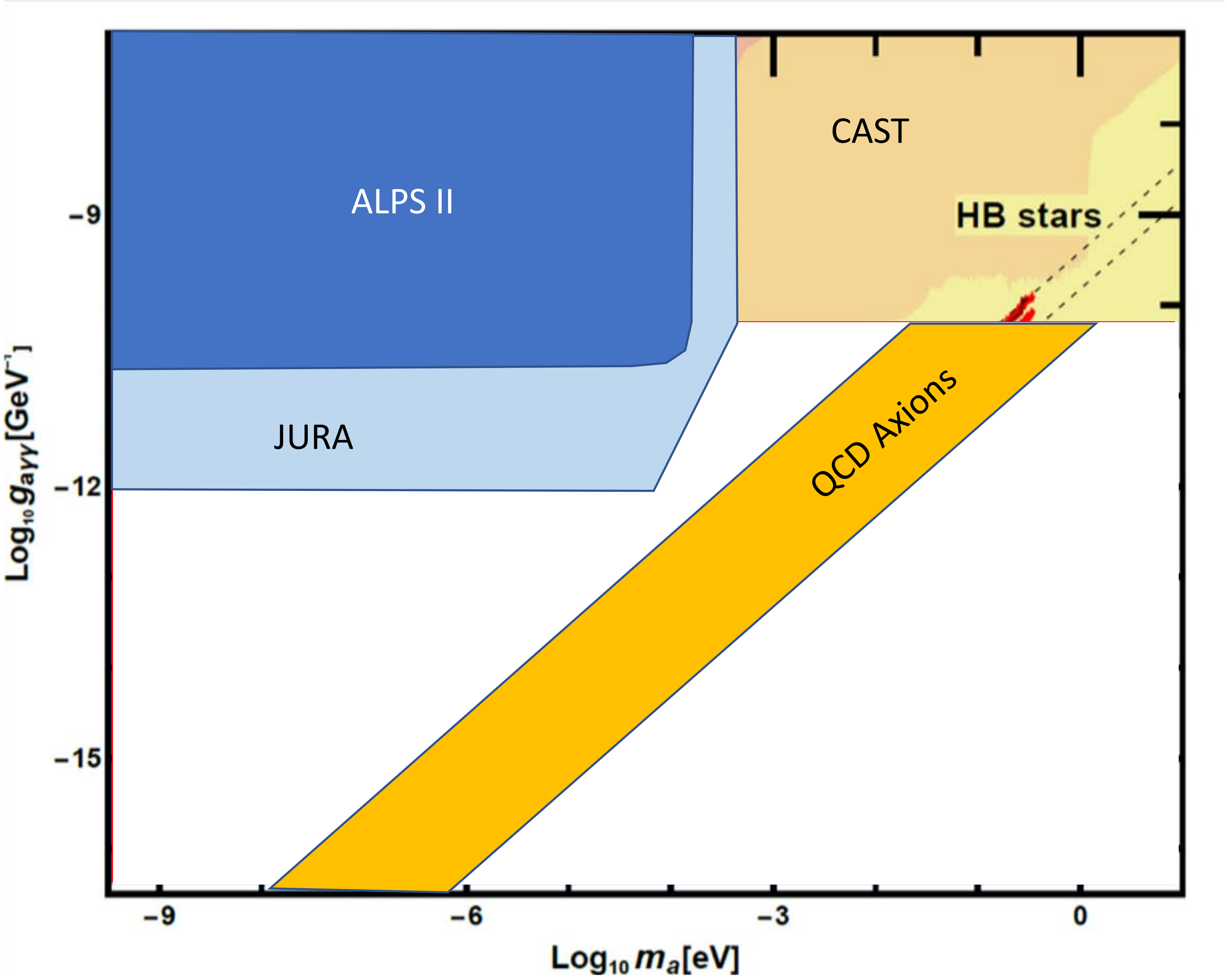




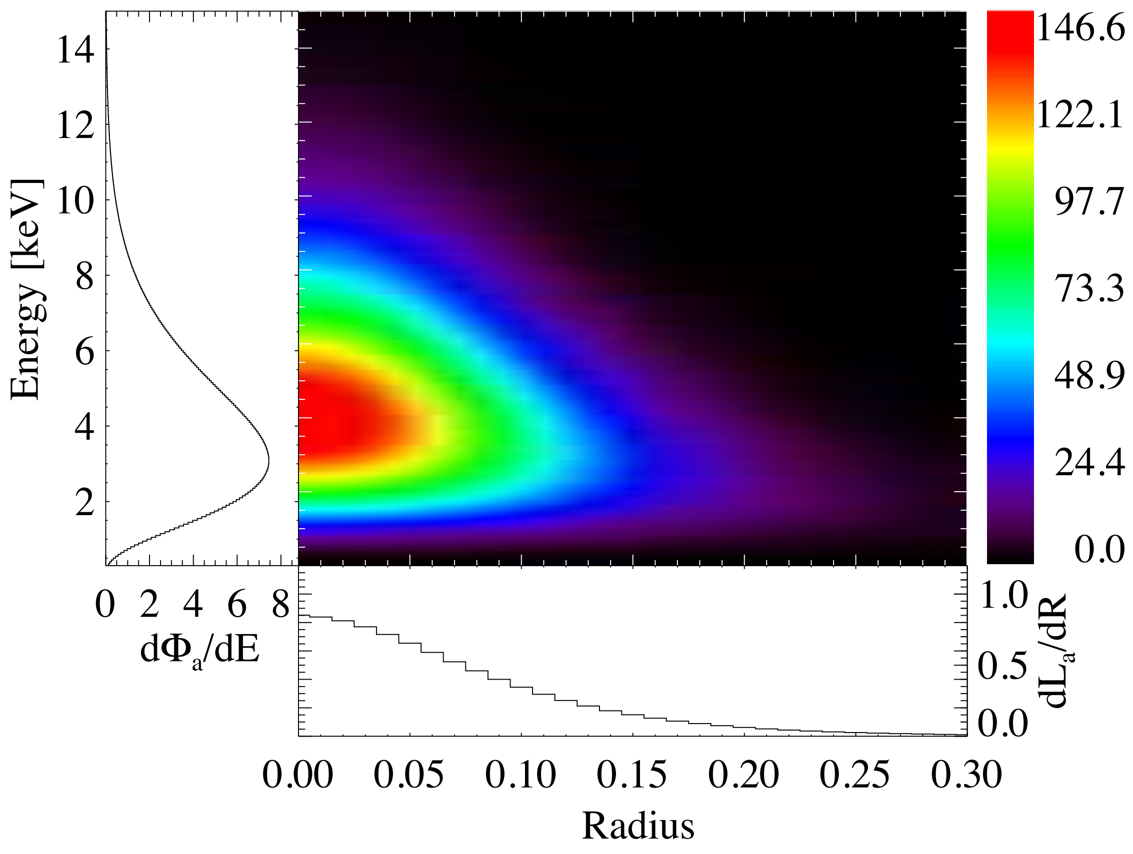


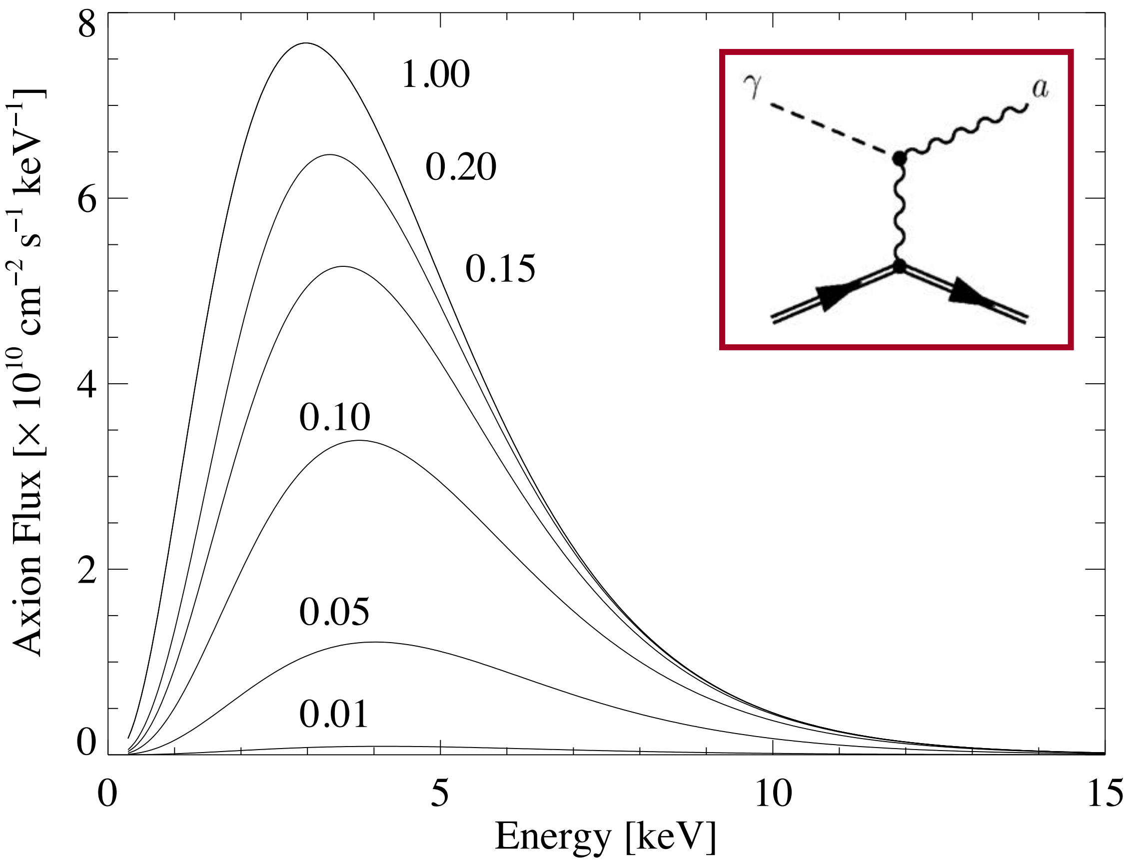


LSW experiments: prospects



Axions from the sun: Helioscope experiments

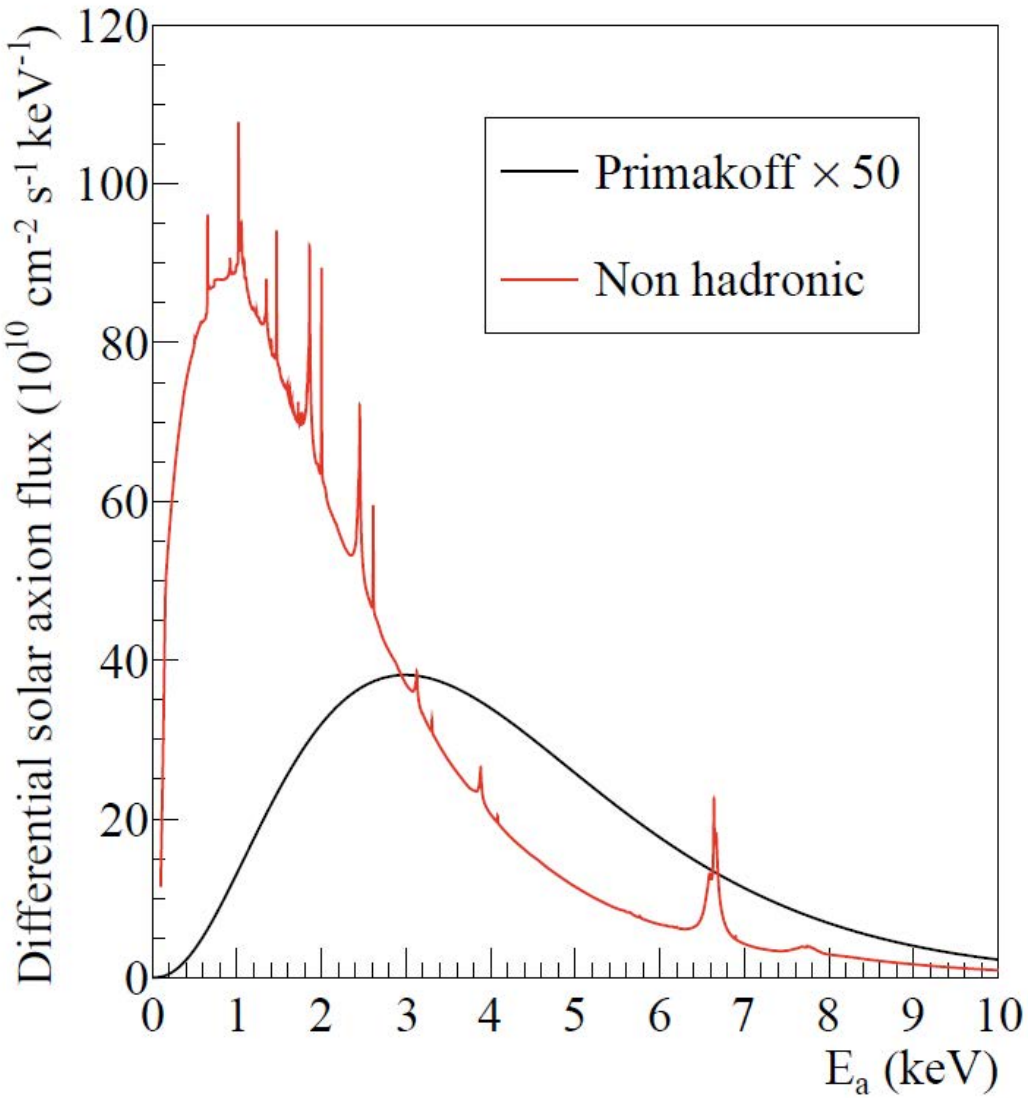




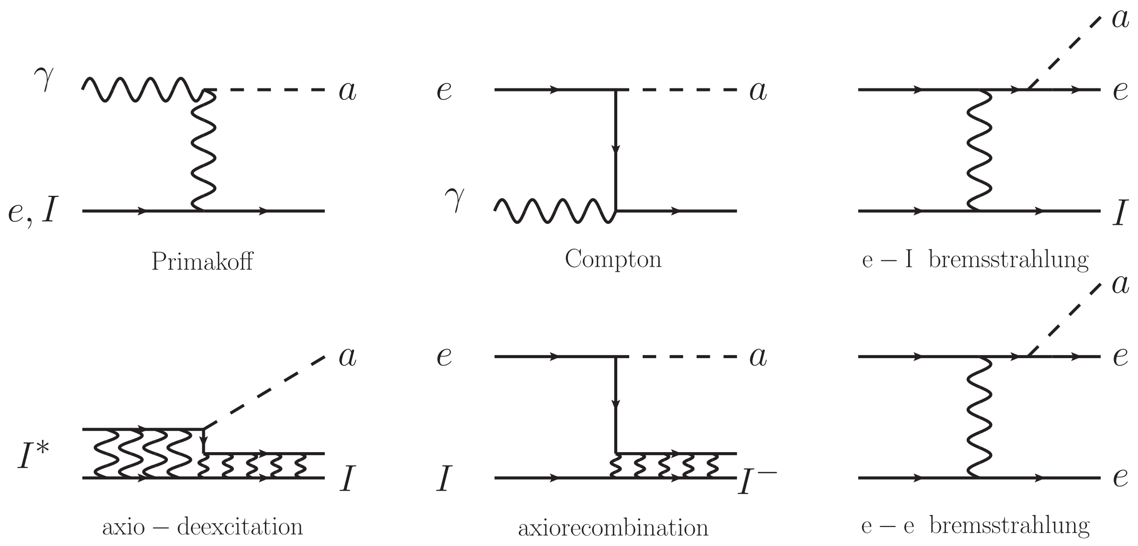
- Solar axions produced (mainly) in the core of the sun
- Energy <E> ~ 4.2 keV
- rather robust prediction

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

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



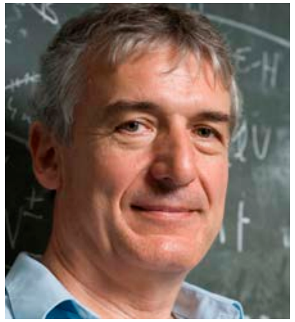
[Redondo, JCAP 1312 (2013) 008]

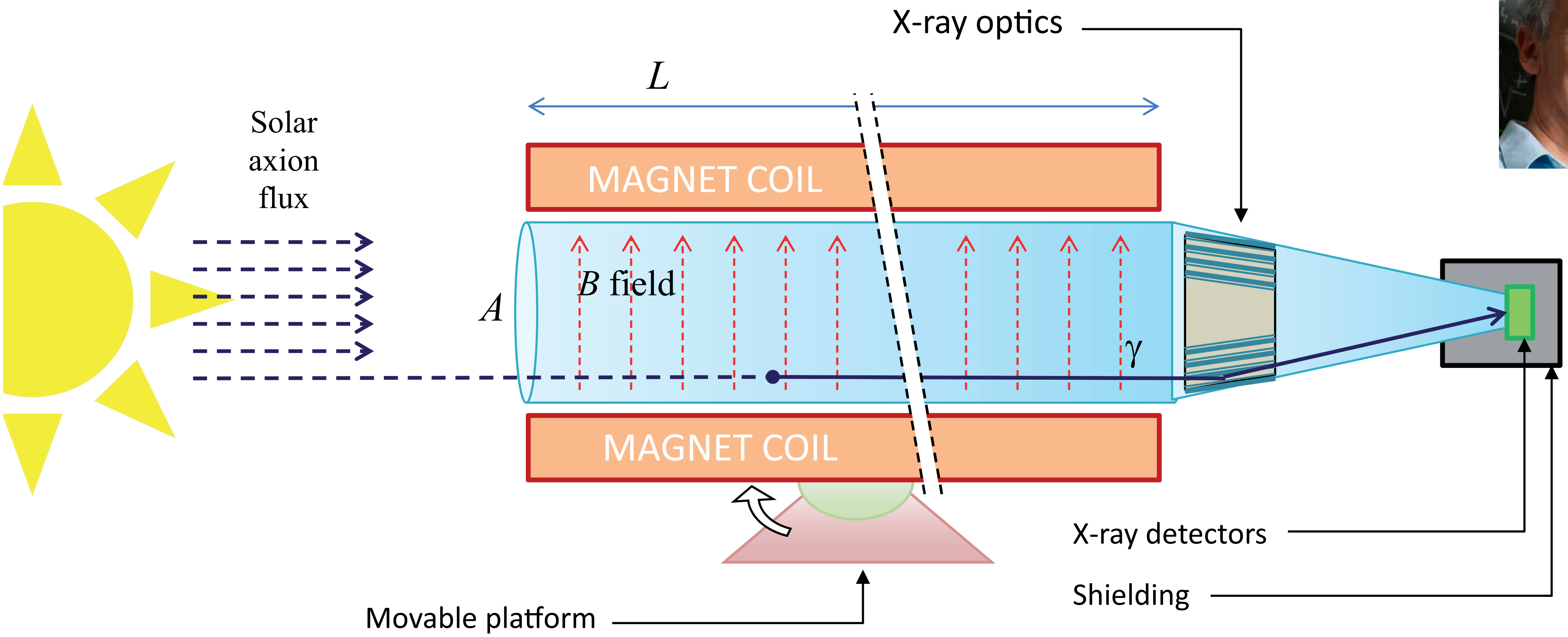


If direct axion-electron coupling exists, additional flux with characteristic features

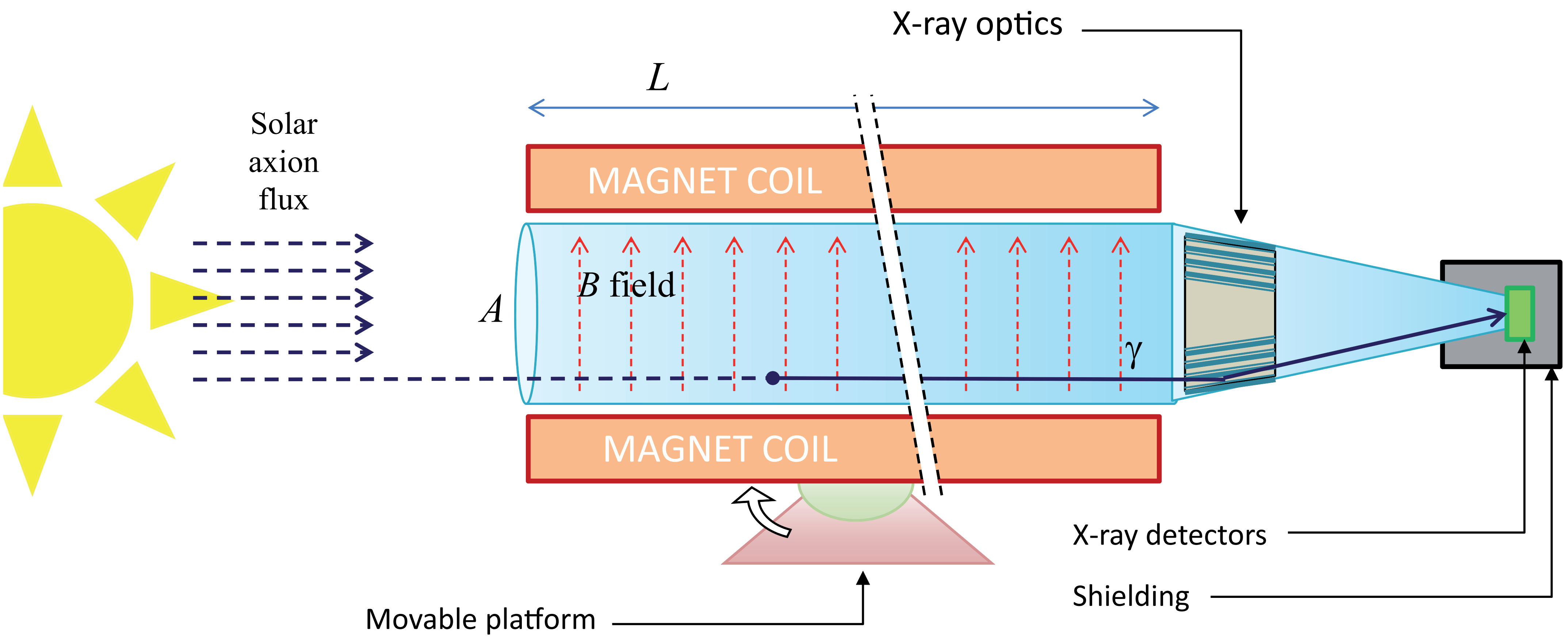
Helioscopes

[Sikivie]





Helioscopes: sensitivity

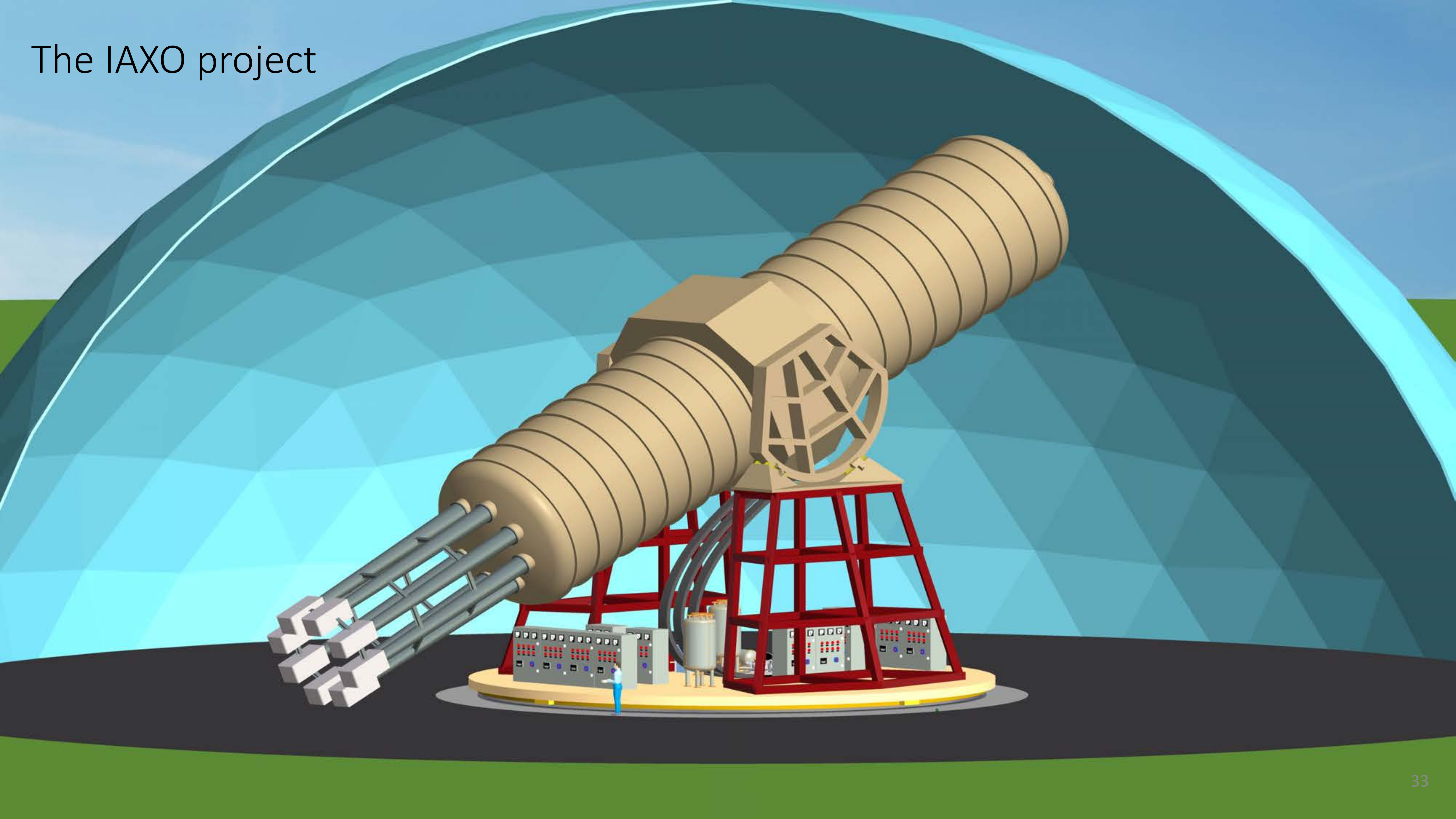


Signal: $\sim g_{a\gamma}^2$ $\sim g_{a\gamma}^2 \ B^2 \ L^2 \ A_{bore}$ $\sim \varepsilon_{optics}$ $\sim \varepsilon_{detector}$

Bkg: $\sim A_{spot}$ $\sim B / A$

CAST@CERN

The IAXO project



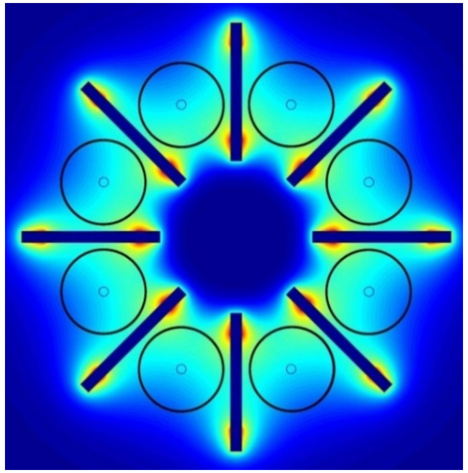
IAXO parameters

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

IAXO magnet (CDR design)

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

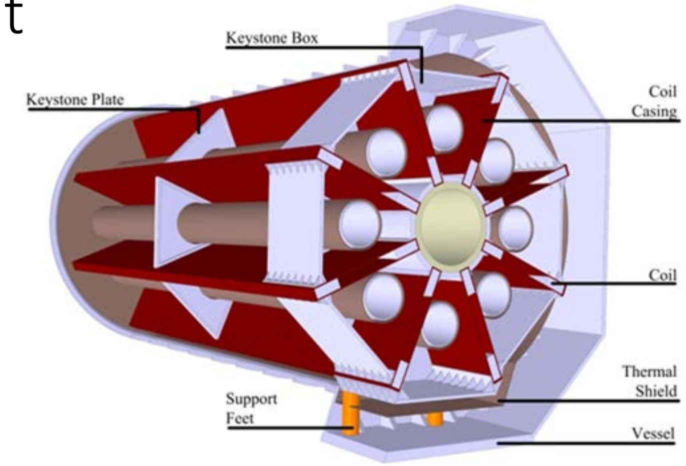
B: superconducting NbTi at 4.5K → B_{peak} 6 T , B_{user} = 2.5 T



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

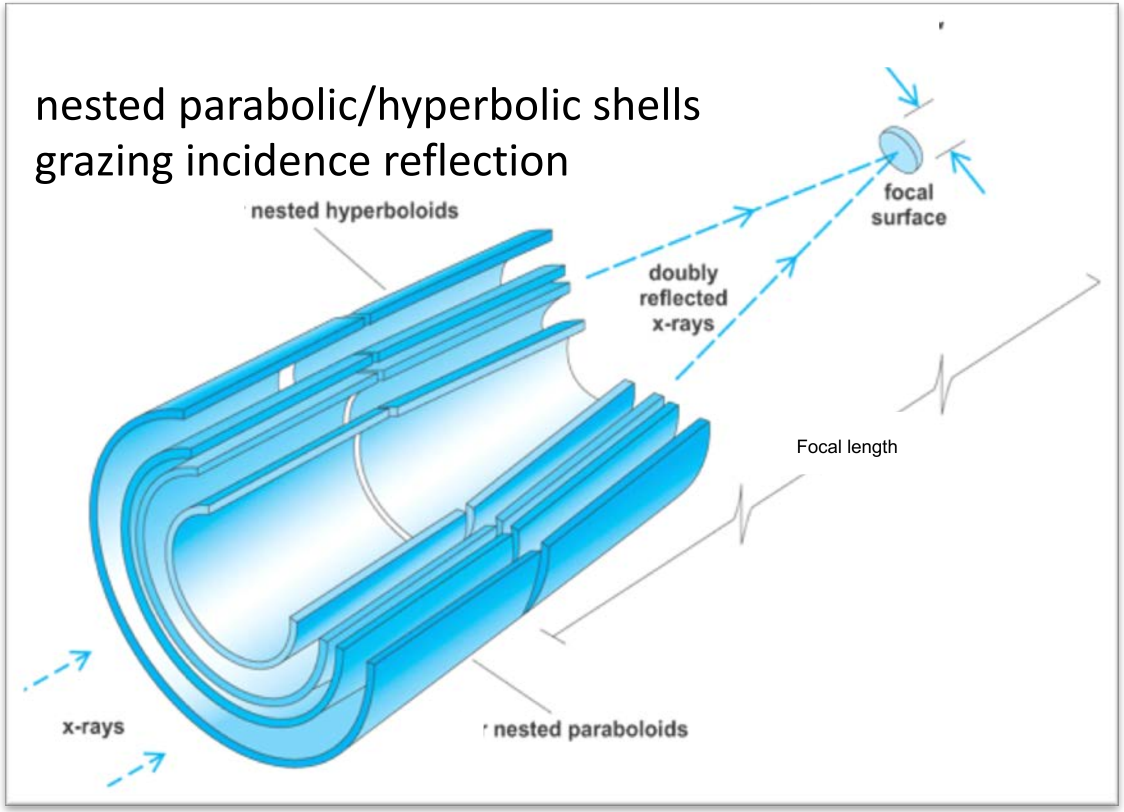
A: driven by optics, D=60/70 cm per bore, n=8

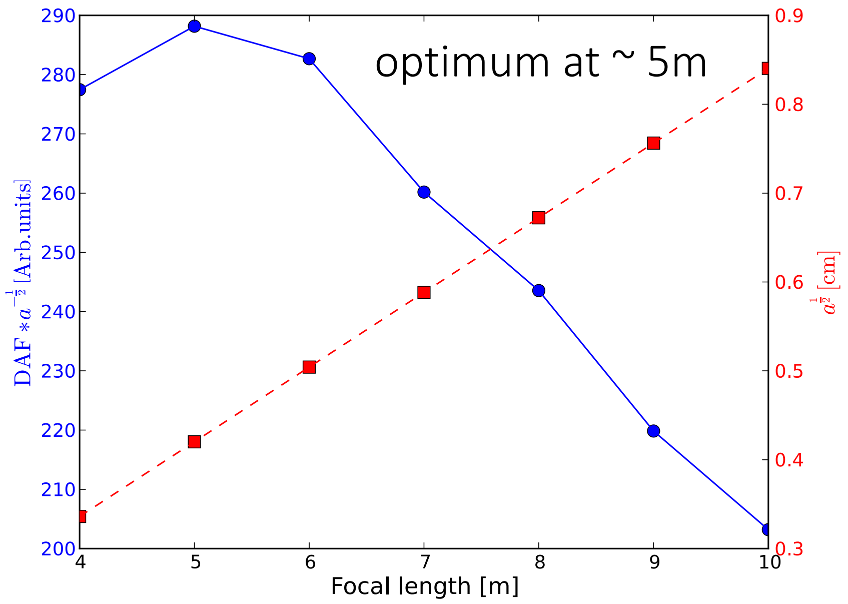
Baseline design inspired by ATLAS toroid, large "user volume" at reasonable cost



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 detectors

Name of the game:

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

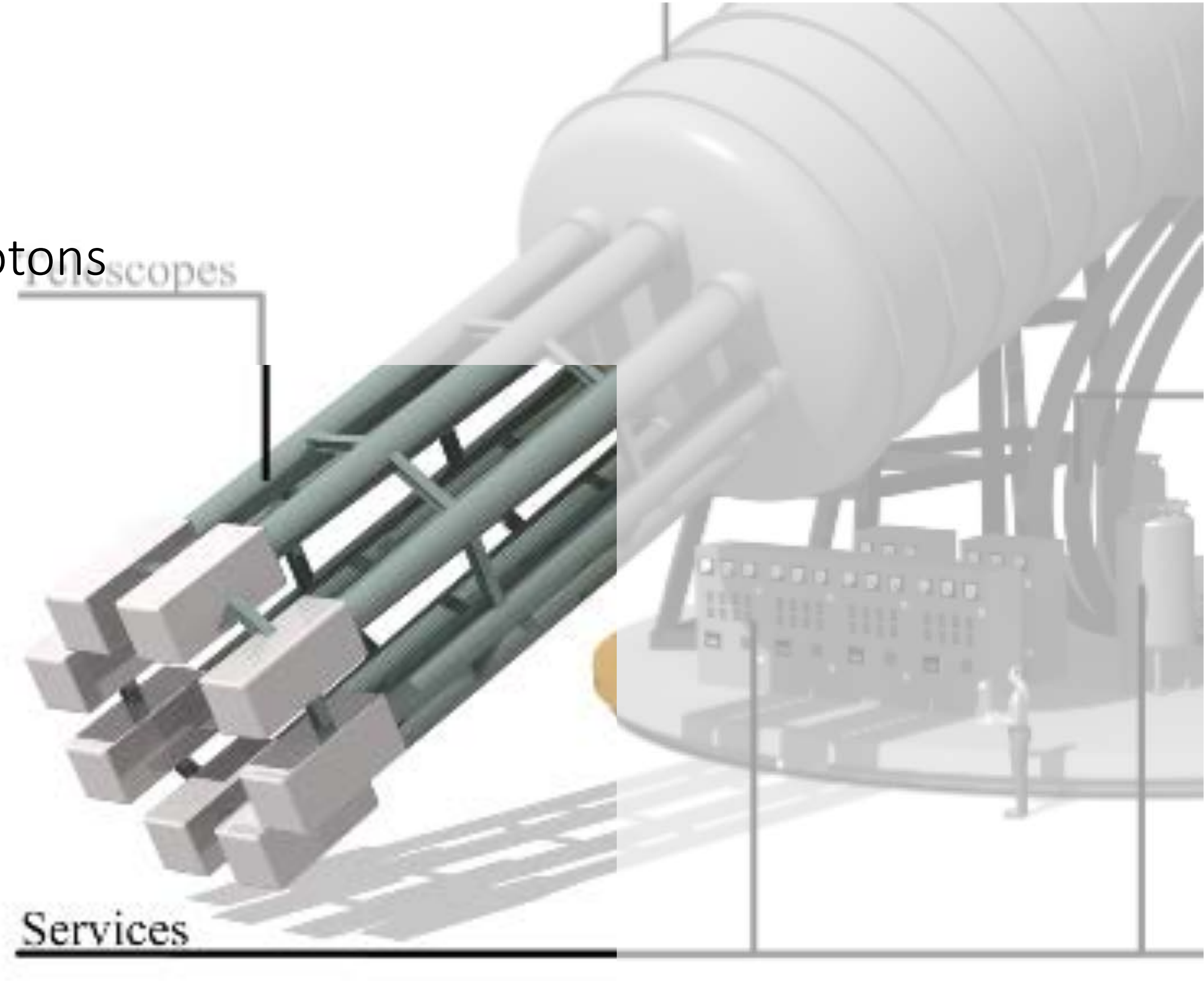
In addition:

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

Multitude of technologies

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

Several technologies already studied in CAST



IAXO detectors

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

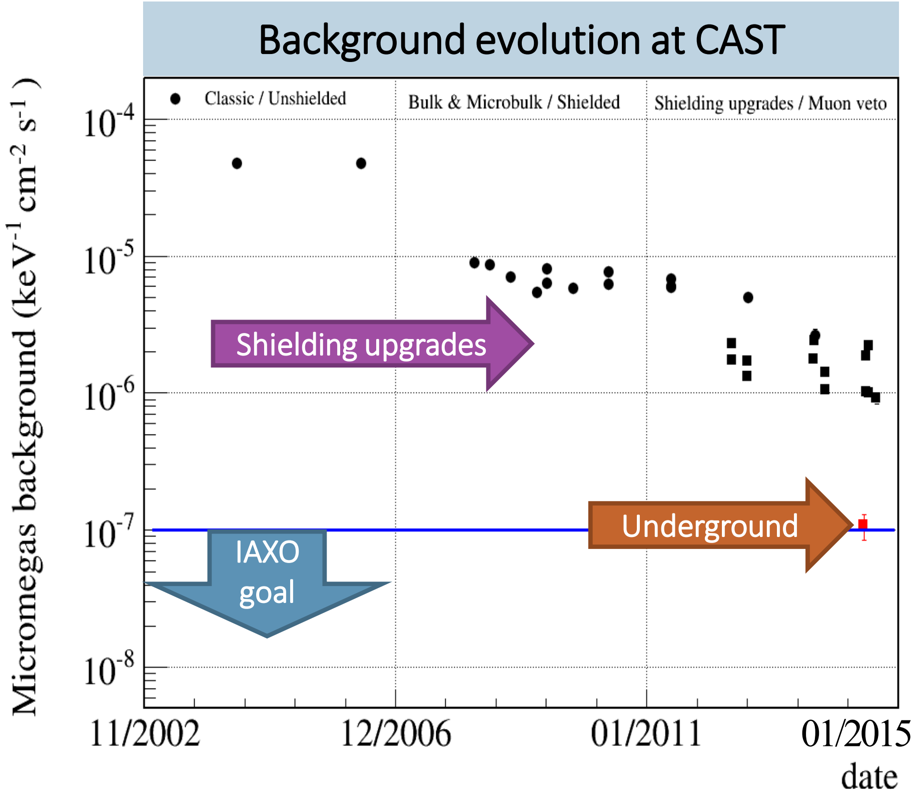
sensitive signal area o(1 cm^2), solar observation time o(10^8) seconds

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

Market leader: Microbulk Micromegas

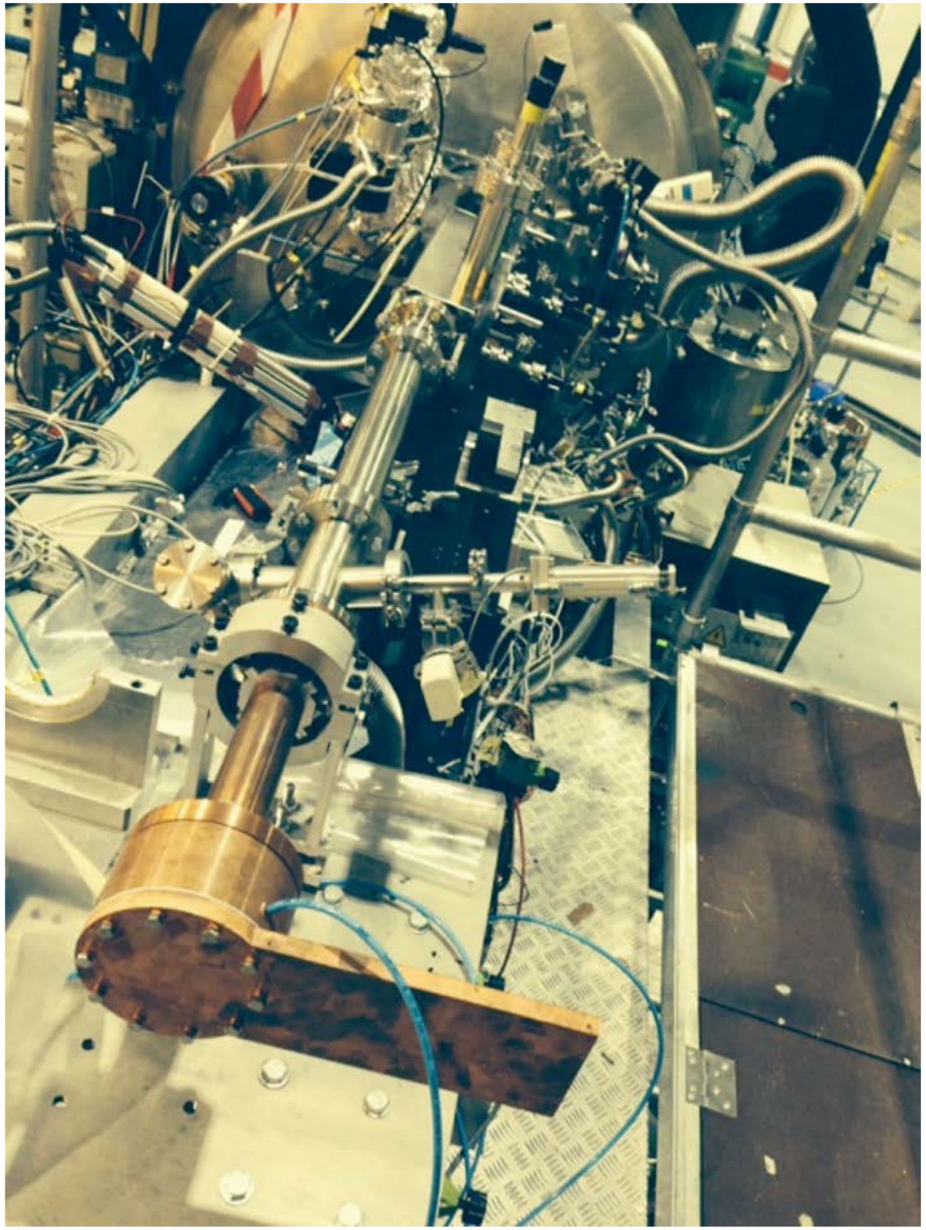
- design for radiopurity
- passive shielding
- offline discrimination

Active shielding will get us to 10^{-7} $keV^{-1}cm^{-2}s^{-1}$
Further R&D towards 10^{-8} ongoing (materials, gas)



[E.Ruiz-Chóliz]

IAXO detector baseline: small Micromegas detector



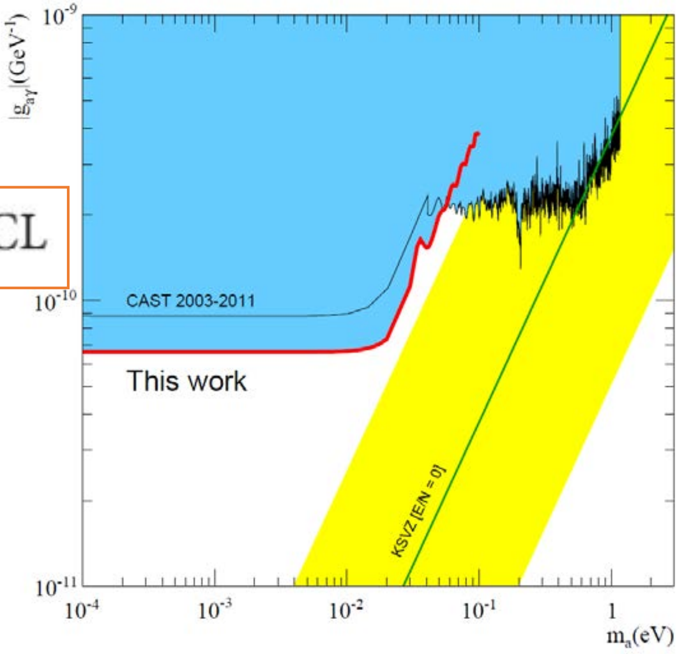
IAXO Pathfinder operated in CAST

nature physics | ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

New CAST limit on the axion–photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a
Here, we report the best limit on t
CAST, which now reaches similar le

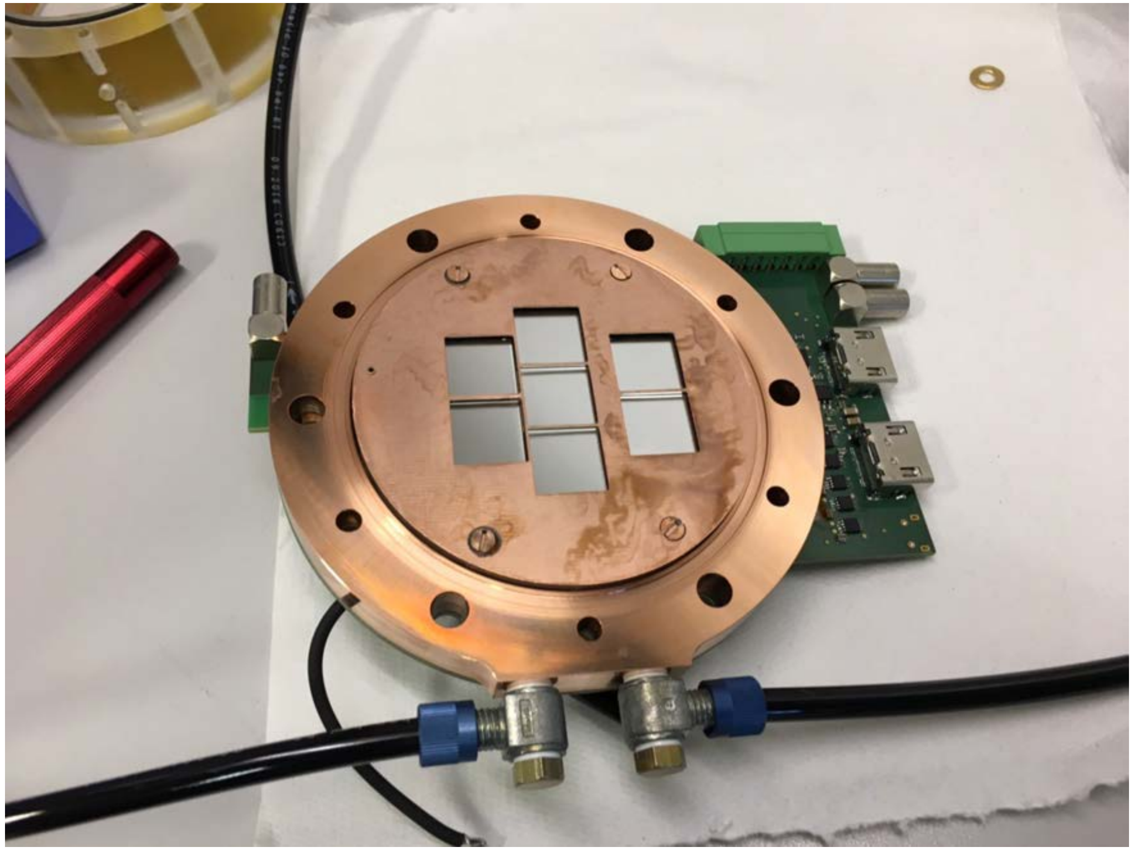


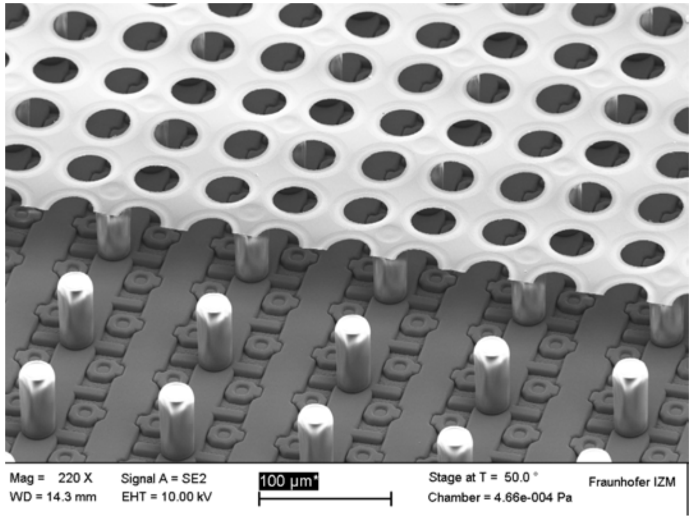
$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{at 95\% CL}$$

World best limit to date.

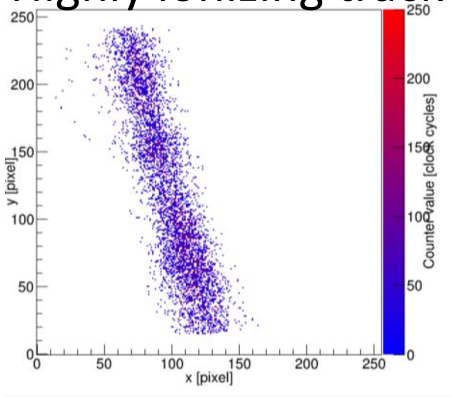
IAXO detectors: InGrid/GridPix

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

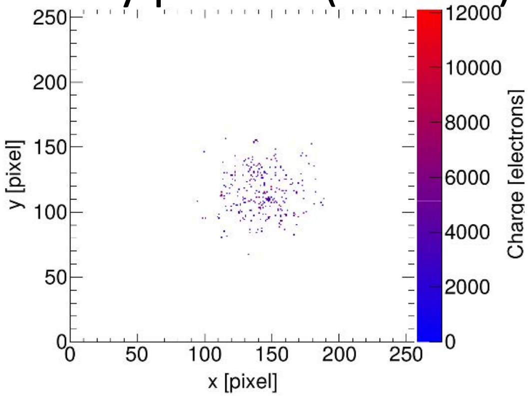


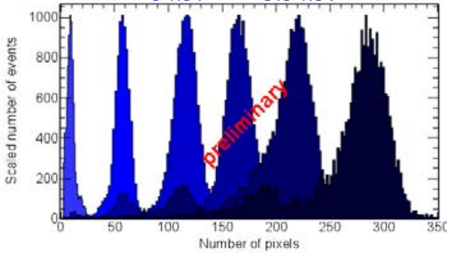


Highly ionizing track

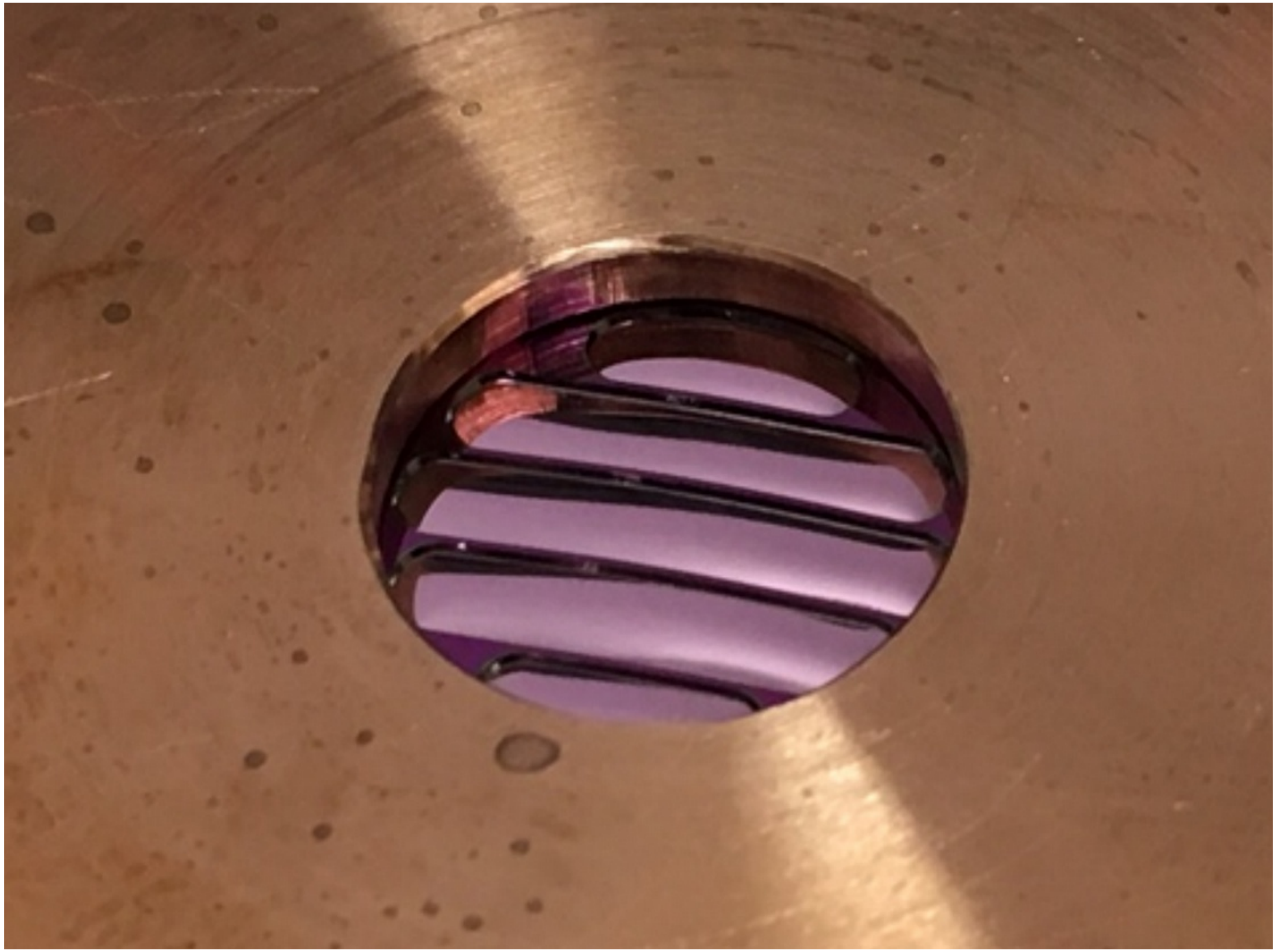


X-ray photon (5.9 keV)

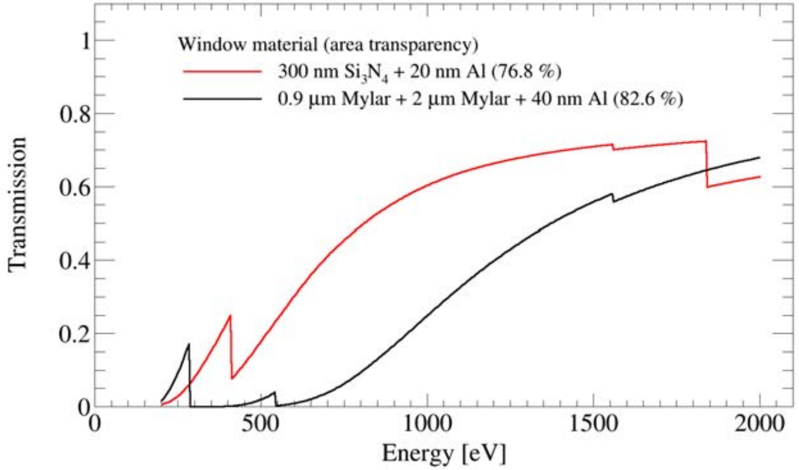




IAXO detectors: X-ray windows



300 nm Silicon-Nitride window at 1.5 bar overpressure

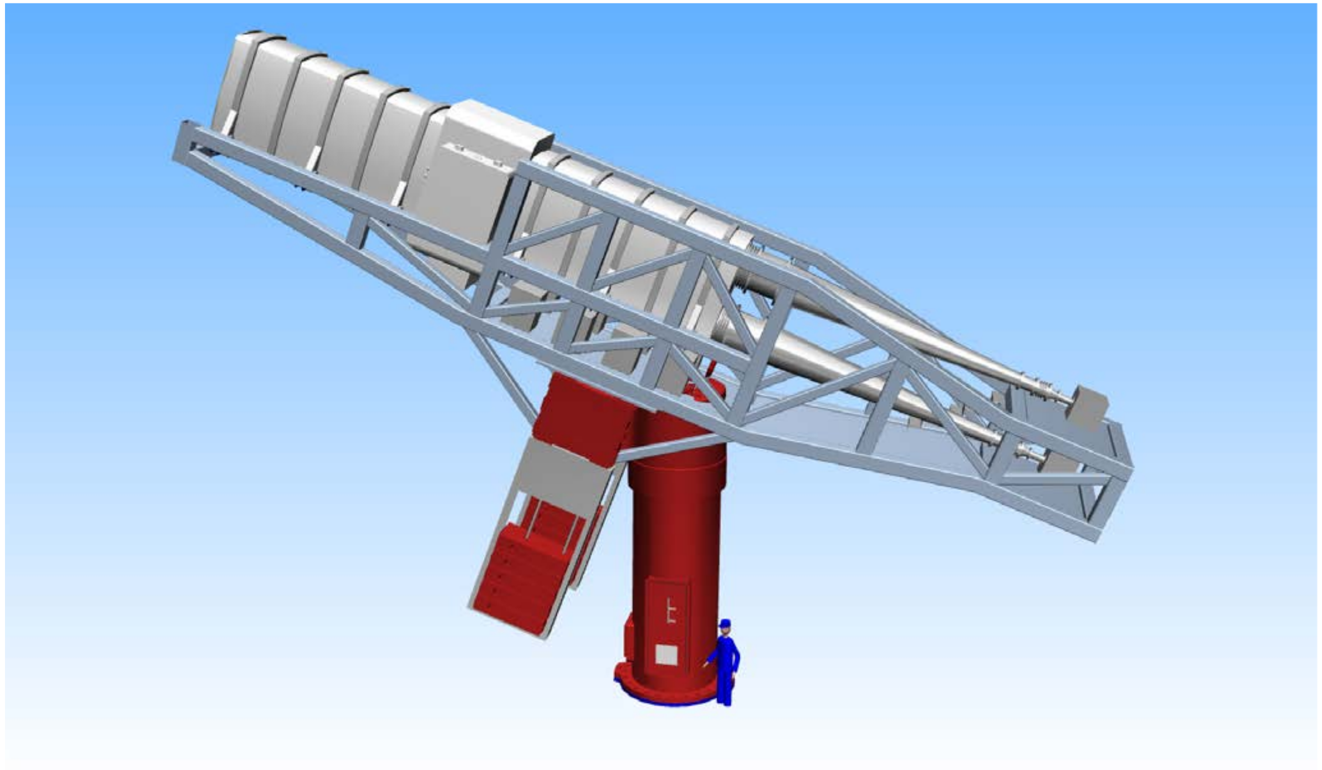


UNIVERSITÄT BONN NORCADA

BabyIAXO: paving the way for IAXO

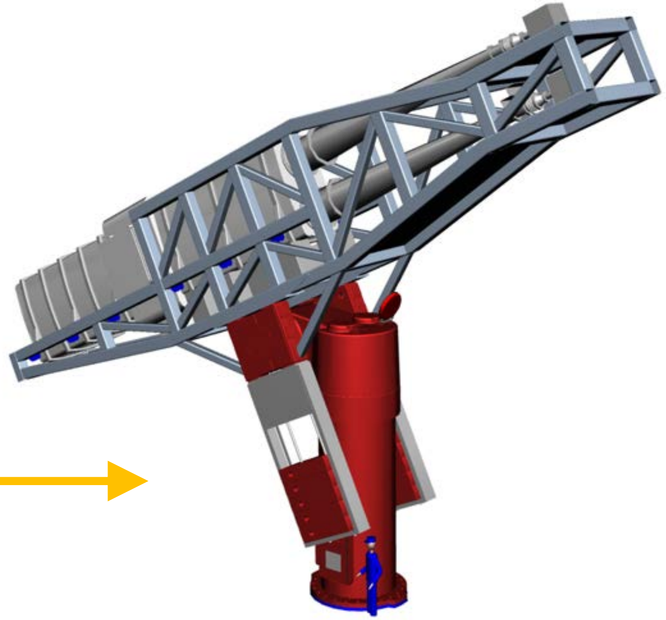
Original plan: build realistic TDR prototypes for main subsystems (magnet, optics, detectors)

Developed into a full-fledged experiment with sensitivity ~100xCAST and ~0.01xIAXO with its own physics potential.



BabyIAXO@DESY

Telescope mount: CTA MST prototype at Adlershof is well suited to hold the BabyIAXO magnet (instead of CTA mirrors)

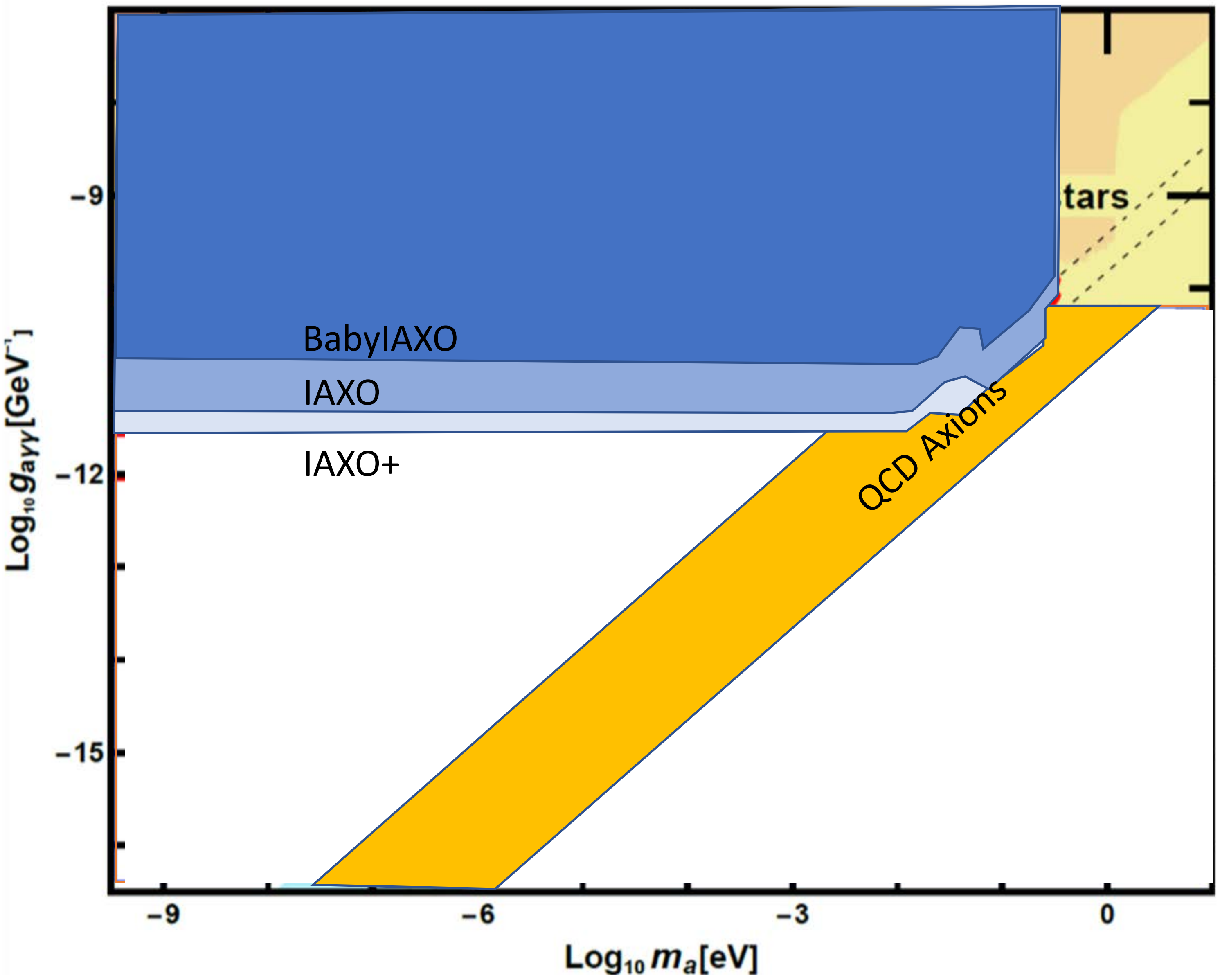


Uwe Schneekloth | BabyIAXO Drive & Support System, Oct. 2019| Page 4

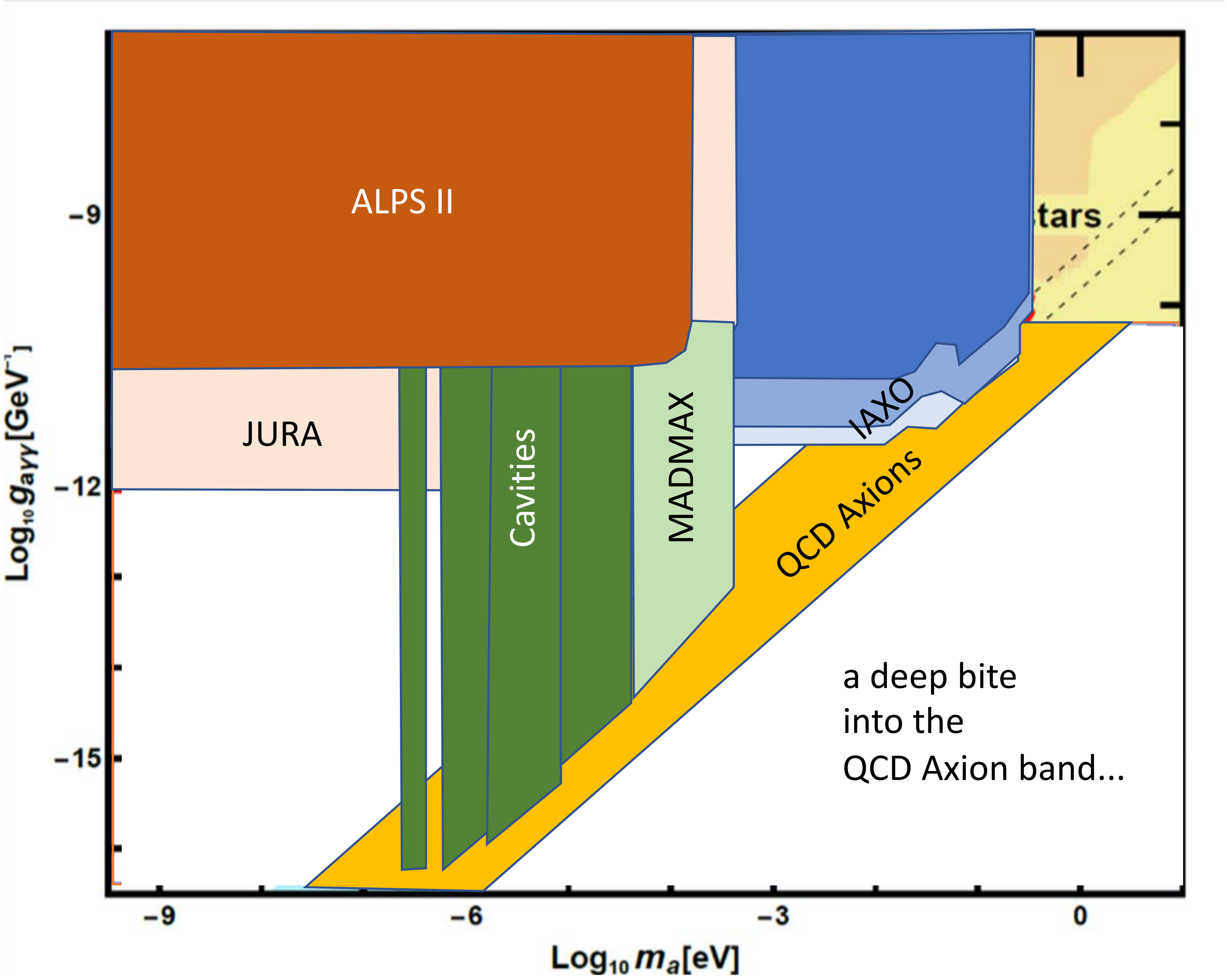
Has already been shipped to Hamburg

[First parts of BabyIAXO telecope mount in HERA hall south]

Helioscope experiments: prospects



Altogether now

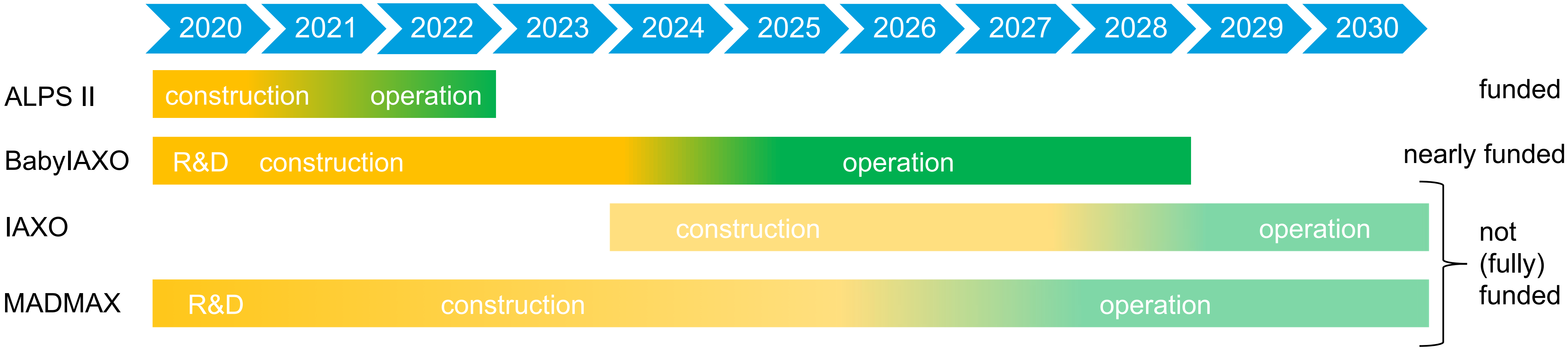


Timelines

ALPS II, BabyIAXO, IAXO, MADMAX

[A. Lindner, DESY PRC 04/20]

Some optimistic view (funding), assuming no surprises (axion discovery, Corona).

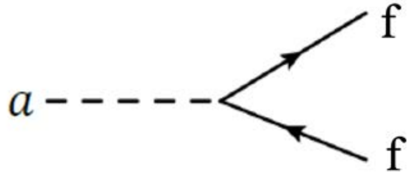


DESY: also a center for experimental axion physics in this decade?

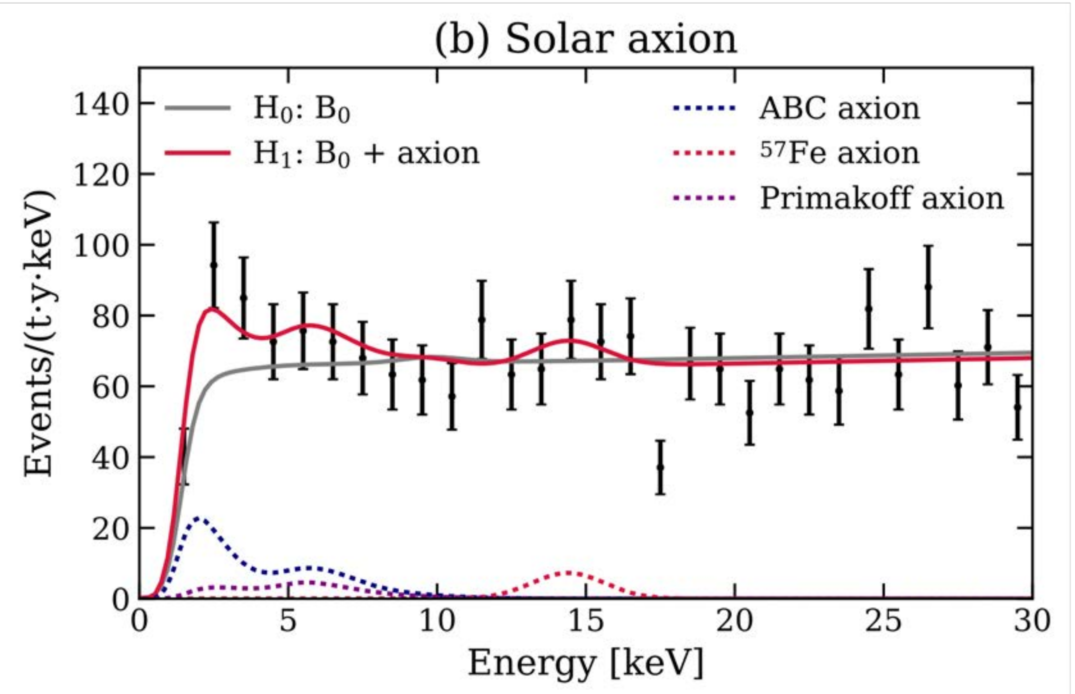
Program well aligned with other international axion searches.

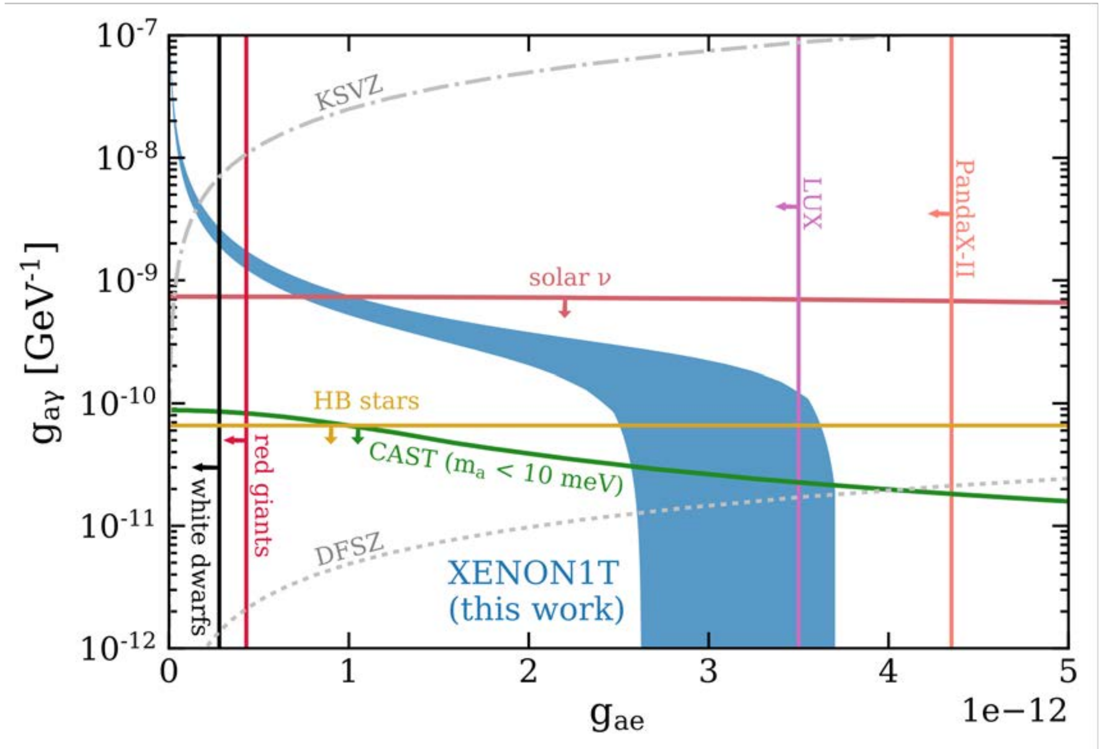
Finally... Hot: A new kid on the (helioscope) block: Xenon1t

$$\mathcal{L}_{aee} = g_{ae}\frac{\partial_\mu a}{2m_e}\bar{\psi}_e\gamma^\mu\gamma^5\psi_e = -ig_{ae}a\bar{\psi}_e\gamma^5\psi_e$$



~keV axions from sun can kick off electrons from (Xe) atoms

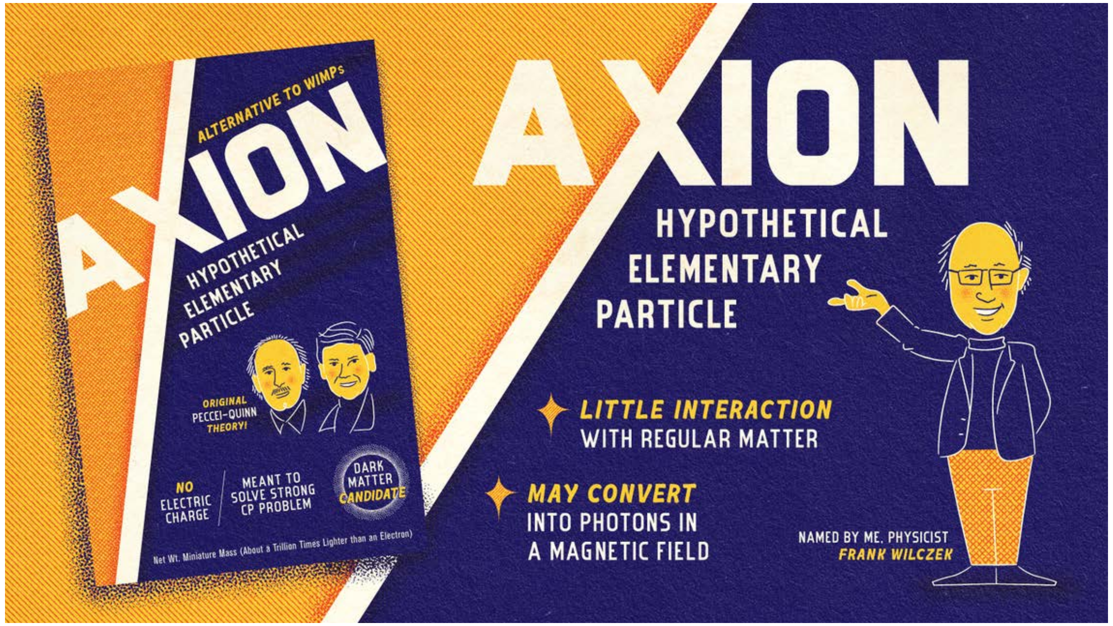




[XENON collaboration, 2006.09721 [hep-ex]]

Summary and Conclusions

- Axions (and ALPS) are a well motivated extension of the Standard Model
- Could solve more than one of the most burning problems
- Experimental exploration needs several complementary experiments
- DESY as a European centre for axions in this decade?



https://www.symmetrymagazine.org/article/the-other-dark-matter-candidate

Axions and WISPs
Bad Honnef Physics School

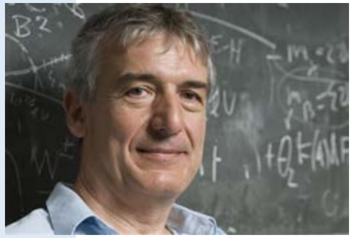
~~August 2-7, 2020~~ August 19-24 2021

Physikzentrum Bad Honnef, Germany

Organizers: Igor Irastorza (Zaragoza), Joerg Jaeckel (Heidelberg), Klaus Desch (Bonn)

5-day school for students (Master´s, PhD students, early career postdocs) working on or interested in Axions/ALPs/WISPs in experiment or theory

Confirmed lecturers/topics:
Gaia Lanfranchi (INFN, Frascati): Axions and light particles at accelerators
Axel Lindner (DESY): Axion experiments
David J. E. (Doddy) Marsh (Göttingen): Axion cosmology
Javier Redondo (Zaragoza): Axion astrophysics
Andreas Ringwald (DESY): Axion theory
Special lecture: Pierre Sikivie, Laureate of the Sakurai Prize 2020
Excursion to Effelsberg 100m Radiotelescope
Poster session, Exercises



Fee: 200 € full board and lodging (for DPG members 100 €)
Web: https://www.dpg-physik.de/veranstaltungen/2020/axions-and-wisps?set_language=en
~~Registration (open): Registration~~ (not yet…)