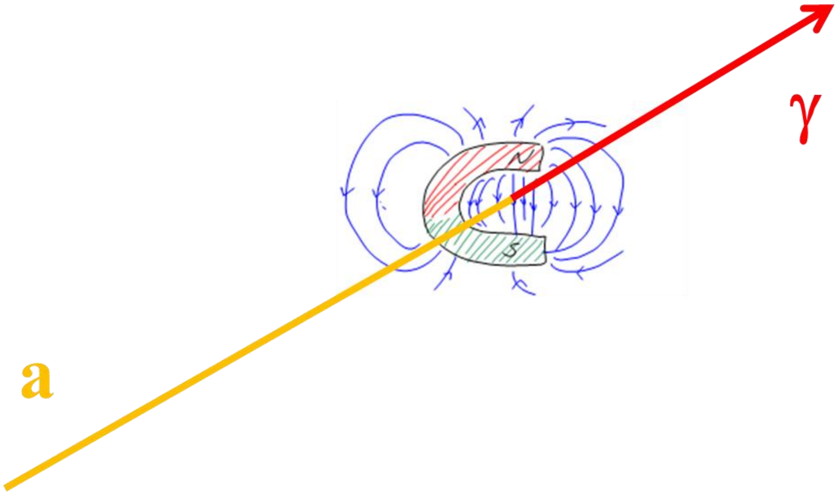
Axion Projekte (und mehr)



Axel Lindner

Strategieworkshop Teilchenphysik, Universitätsclub Bonn,
3. Mai 2018

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Frank A. Wilczek, Nobel lecture 2004

https://www.nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.pdf

The established symmetries permit a sort of interaction among gluons … that violates the invariance of the equations of QCD under a change in the direction of time. Experiments provide extremely severe limits on the strength of this interaction, much more severe than might be expected to arise accidentally.

By postulating a new symmetry, we can explain the absence of the undesired interaction. The required symmetry is called Peccei-Quinn symmetry after the physicists who first proposed it. If it is present, this symmetry has remarkable consequences. It leads us to predict the existence of new very light, very weakly interacting particles, axions. (I named them after a laundry detergent, since they clean up a problem with an axial current.) In principle axions might be observed in a variety of ways, though none is easy. They have interesting implications for cosmology, and they are a leading candidate to provide cosmological dark matter.

Frank A. Wilczek, Nobel lecture 2004

https://www.nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.pdf

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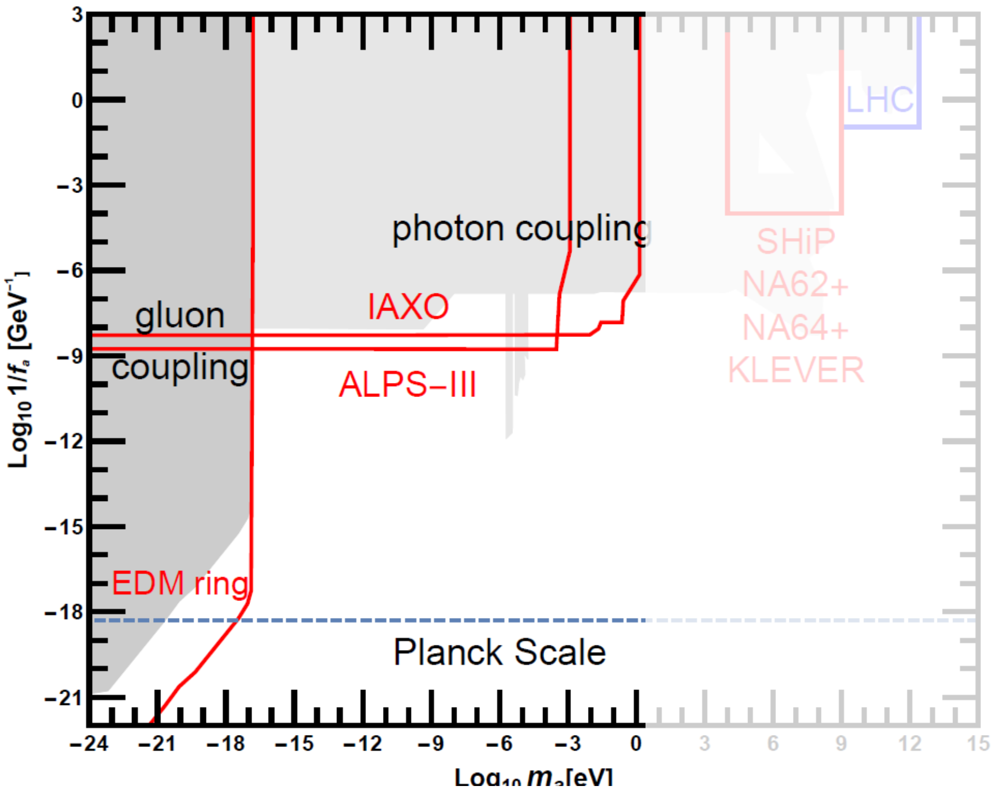
Outline

- An introduction to axions and axion-like particle searches
- Strategic aspects: a personal view
- Summary

Axions and axion-like particles (ALPs)

At low masses:

Roughly m < 1 eV

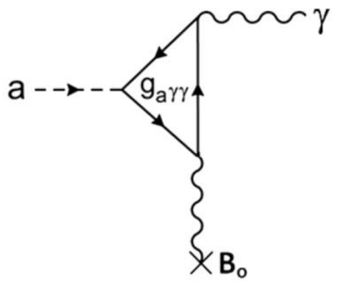


Courtesy J. Jäckel, this meeting

Axions and axion-like particles (ALPs)

How to look at low masses: exploiting photon couplings

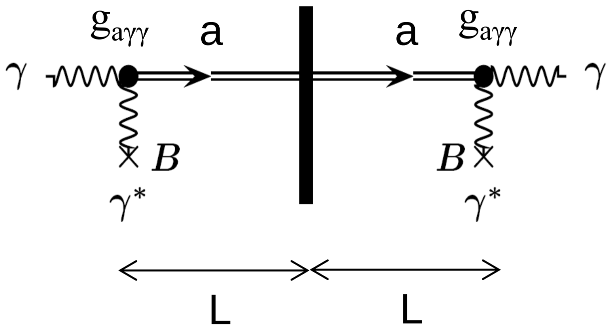
Primakoff-like axion conversion



and light-shining-through-walls.

$P(\gamma \rightarrow a \rightarrow \gamma) \sim (g_{a\gamma\gamma} \cdot B \cdot L)^4$

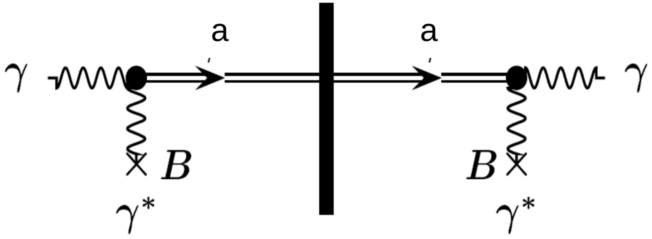
ALPS II: $P(\gamma \rightarrow a \rightarrow \gamma) \approx 10^{-36}$



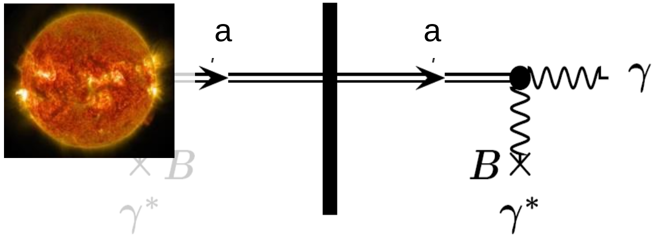
Sub-eV axions and axion-like particles (ALPs)

How to look: three kinds of light-shining-through-walls

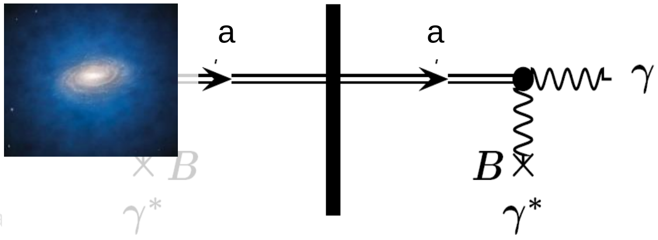
- Purely laboratory experiments
  “light-shining-through-walls”,
  optical photons



- Helioscopes
  ALPs emitted by the sun,
  X-rays,



- Haloscopes
  looking for dark matter constituents,
  microwaves.



Pros and cons for different experimental approaches

ALP parameter	LSW (laboratory)	Helioscopes	Dark matter searches
Parity and spin	yes	perhaps	yes
Coupling $g_{a\gamma\gamma}$	yes	no	no
Coupling · flux	(does not apply)	yes	yes
Mass	perhaps	perhaps	yes
Electron coupling	no	yes	no
Rely on astrophysical assumptions	no	yes	yes
QCD axion	no (?)	yes	yes

The three approaches complement each other.

Selection of experiments: laboratory

Orange: with strong German participation

Name	Type	Sens (10^{-11} GeV^{-1})	Location	Status	Reference
ALPS II	LSW	2, m < 0.1 meV	DESY	construction	https://arxiv.org/abs/1302.5647
OSQAR	LSW	5,700, m < 1 meV	CERN	finished (?)	https://arxiv.org/abs/1410.2566
NEXT/STAX	LSW	0.1, m < 0.01 meV		proposed	https://arxiv.org/abs/1510.06892
ARIADNE	5th force	Nucleon interact. NMR, axion 0.1 < m < 10 meV		proposed	https://arxiv.org/abs/1710.05413

Selection of experiments: helioscopes

Orange: with strong German participation

Name	Type	Sens (10^{-11} GeV^{-1})	Location	Status	Reference
CAST	$g_{a\gamma\gamma}$	6.6, m < 20 meV, axion around 1000 meV	CERN	finished	https://arxiv.org/abs/1705.02290
IAXO (babyIAXO)	$g_{a\gamma\gamma}$	0.5, m < 10 meV, axion 1 < m < 3000 meV	DESY	CDR	https://arxiv.org/abs/1401.3233
TASTE	$g_{a\gamma\gamma}$	2, m < 10 meV, axion 20 < m < 100 meV	INR Troitsk	proposed	https://arxiv.org/abs/1706.09378

Selection of experiments: haloscopes, photon coupling (1)

Orange: with strong German participation

Name	Type	ALP / axion mass range	Location	Status	Reference
ABRACADABRA	toroid	ALP 10^{-14} to 10^{-6} eV	MIT	prototype	https://arxiv.org/abs/1602.01086
ADMX G2	cavity	Axion, 10^{-6} to 10^{-5} eV	Seattle	running	Phys. Rev. Lett. 120, 151301
BEAST	capacitive	ALP 10^{-11} eV	Perth	tests	https://arxiv.org/abs/1803.07755
BRASS	dish	ALP (axion) 10^{-5} to 10^{-2} eV	Hamburg	proposed	http://www.iexp.uni-hamburg.de/groups/astroparticle/brass/brassweb.htm
CULTASK&more	cavity	Axion, 10^{-5} to 10^{-4} eV	Daejeon	construction	https://capp.ibs.re.kr/html/capp_en/

Selection of experiments: haloscopes, photon coupling (2)

Orange: with strong German participation

Name	Type	ALP / axion mass range	Location	Status	Reference
FUNK	dish	(hidden photon search)	KIT	running	https://arxiv.org/abs/1711.02961
HAYSTAC	cavity	ALP, $\approx 2.4 \cdot 10^{-5}$ eV	New Haven	running	https://arxiv.org/abs/1803.03690
KLASH	cavity	Axion, $2 \cdot 10^{-7}$ eV	INFN	proposed	https://arxiv.org/abs/1707.06010
LC circuit		ALP, 10^{-11} to 10^{-7} eV	LANL	prototype	https://arxiv.org/abs/1802.01721
MADMAX	dish, dielect. booster	Axion, $4 \cdot 10^{-5}$ to $4 \cdot 10^{-4}$ eV	DESY	preparation	https://arxiv.org/abs/1712.01062

Selection of experiments: haloscopes, photon coupling (3)

Orange: with strong German participation

Name	Type	ALP / axion mass range	Location	Status	Reference
Multilayer Haloscope	multi-layers	Axion, 10^{-1} to 10 eV		proposed	https://arxiv.org/abs/1803.11455
ORGAN	cavity	ALP 10^{-4} eV	Perth	prototype	https://arxiv.org/abs/1706.00209
ORPHEUS	open resona-tor	Axion, 10^{-4} to 10^{-3} eV	Seattle	prototype	https://doi.org/10.1103/PhysRevD.91.011701
RADES	cavity	Axion, $\approx 3.5 \cdot 10^{-5}$ eV	CERN / CAST	protoype	https://arxiv.org/abs/1803.01243

Selection of experiments: haloscopes, spin coupling

Orange: with strong German participation

Name	Type	ALP / axion mass range	Location	Status	Reference
CASPEr	NMR	ALP, axion, 10^{-17} to 10^{-6} eV	Mainz	proposed	https://arxiv.org/abs/1711.08999
GNOME	magnetometer	Domainwalls, 10^{-21} to 10^{-10} eV	(Mainz)	running	https://budker.uni-mainz.de/gnome/
QUAX	NMR	Axion, $\approx 2\cdot10^{-4}$ eV		proposed	https://doi.org/10.1016/j.dark.2017.01.003

An axion / ALP strategy: criteria

> Support the blooming phase:
provide resources for the development of new ideas / proposals!

> Develop a coherent strategy for experimental approaches which

- target a well defined / unique physics question,
- need substantial funding,
- need new cross-disciplinary collaborations,
- require larger scale infrastructure,
- need significant resources for operation,
- need long-term planning.

> Focus here on approaches with strong German participation.

A German axion / ALP strategy: experiments

Name	Type	Sens (10^{-11} GeV^{-1})	Location	Status	Reference
ALPS II	LSW	2, m < 0.1 meV	DESY	construction	https://arxiv.org/abs/1302.5647

Name	Type	Sens (10^{-11} GeV^{-1})	Location	Status	Reference
IAXO (babyIAXO)	$g_{a\gamma\gamma}$	0.5, m < 10 meV, axion 1 < m < 3000 meV	DESY	CDR	https://arxiv.org/abs/1401.3233

Name	Type	ALP / axion mass range	Location	Status	Reference
MADMAX	dish, dielect. booster	Axion, $4 \cdot 10^{-5}$ to $4 \cdot 10^{-4}$ eV	DESY	preparation	https://arxiv.org/abs/1712.01062

These are to be complemented with other experiments (see haloscope mass range for example)!

Axion / ALP "non strategic" experiments

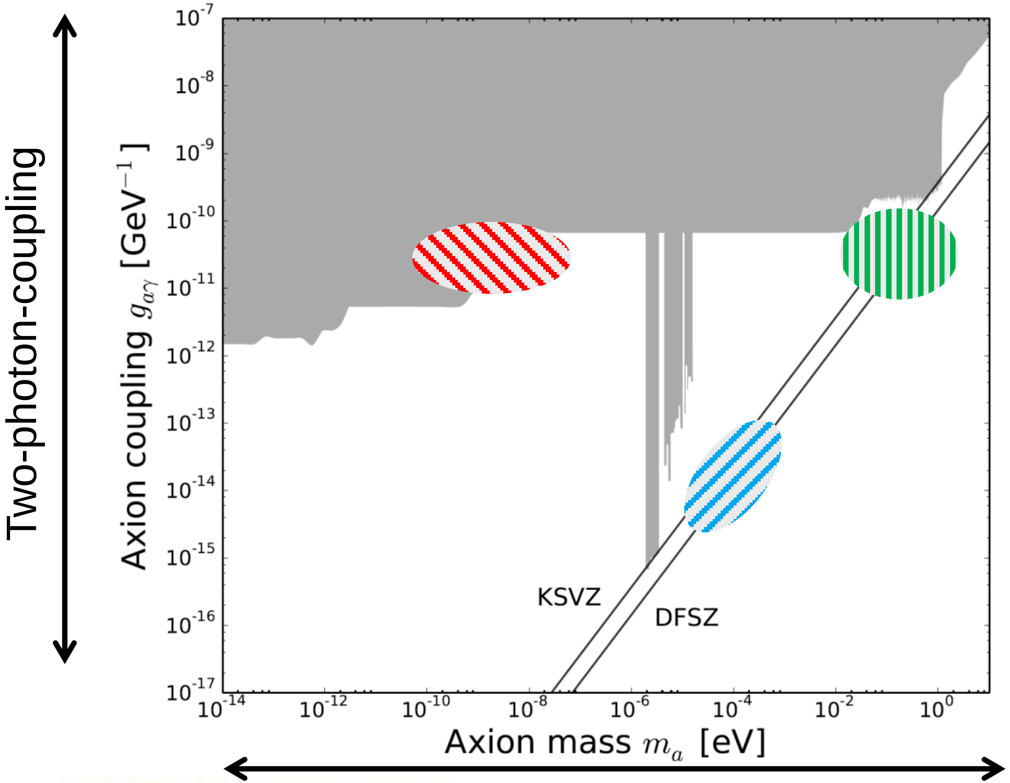
with strong German contribution

"Strategic" and "non-strategic" does not correlate with "scientific value" here!

Name	Type	ALP / axion mass range	Location	Status	Reference
BRASS	dish	ALP (axion) 10^{-5} to 10^{-2} eV	Hamburg	proposed	http://www.iexp.uni-hamburg.de/groups/astroparticle/brass/brassweb.htm
FUNK	dish	(hidden photon search)	KIT	running	https://arxiv.org/abs/1711.02961
CASPEr	NMR	ALP, axion, 10^{-17} to 10^{-6} eV	Mainz	proposed	https://arxiv.org/abs/1711.08999
GNOME	magnetometer	Domainwalls, 10^{-21} to 10^{-10} eV	(Mainz)	running	https://budker.uni-mainz.de/gnome/

Axions and axion-like particles: strategic approaches

Where to look: hot spots for strategy

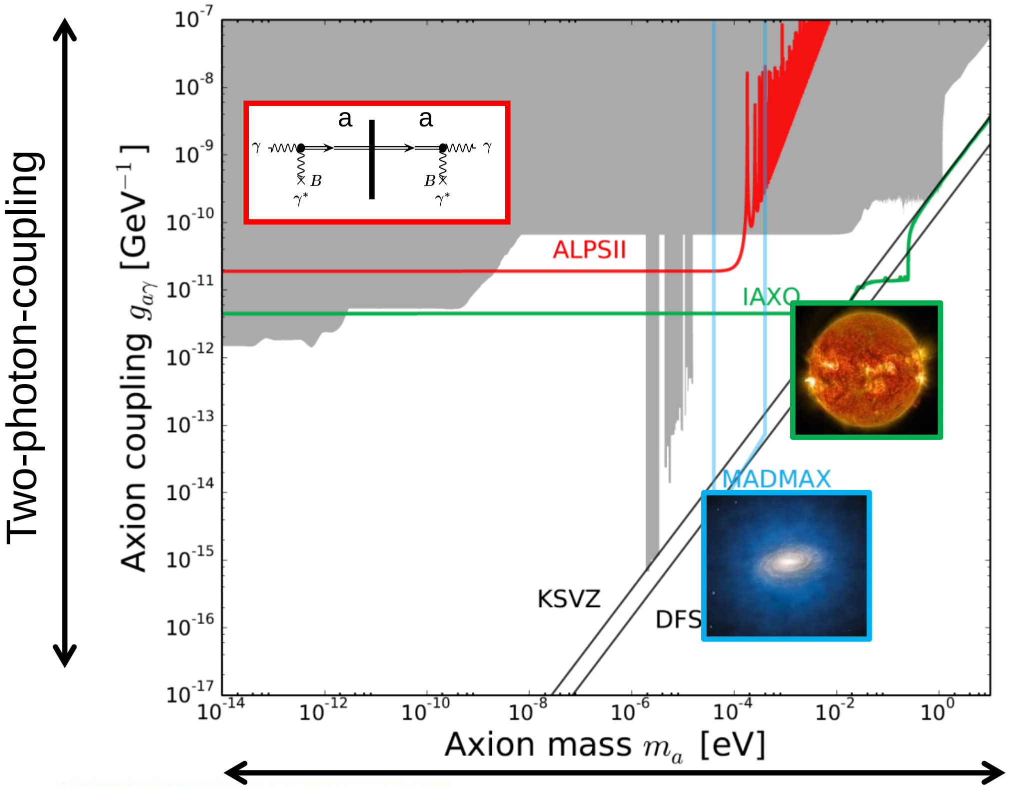


Three main regions of interest:

- Axion-like particles:
  TeV transparency, stellar evolution,
  $m_a < 10^{-7}$eV, $g_{a\gamma} = O(10^{-11}\text{GeV}^{-1})$
- QCD axions:
  CP, stellar evolution, (dark matter),
  $m_a = O(10^{-3}\text{eV})$, $g_{a\gamma} = O(10^{-11}\text{GeV}^{-1})$
- QCD axions:
  CP, dark matter,
  $m_a = O(10^{-5}\text{eV})$, $g_{a\gamma} = O(10^{-14}\text{GeV}^{-1})$

Axions and axion-like particles: strategic approaches

Where to look: hot spots for strategy



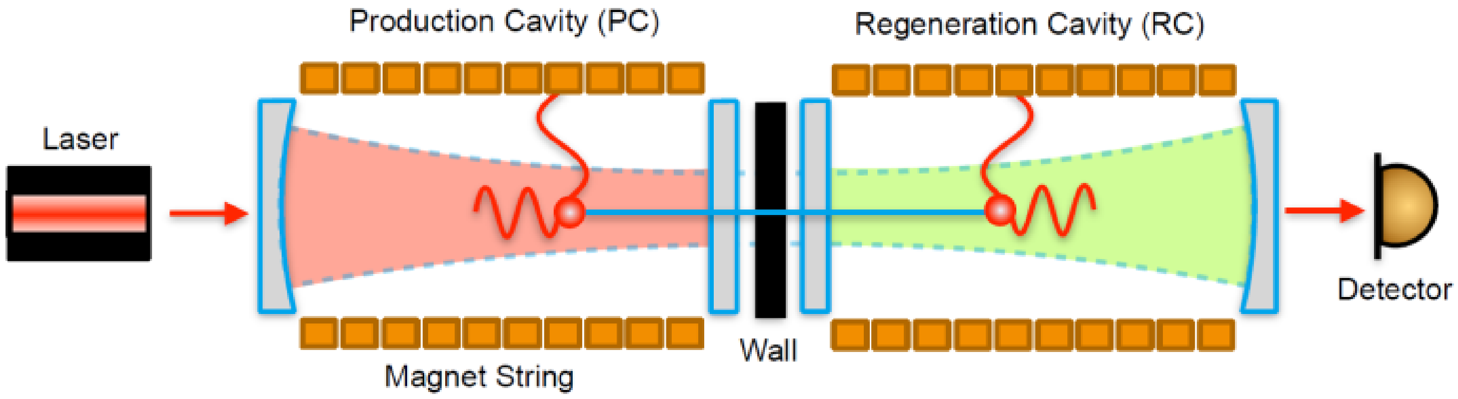
Three main regions of interest:

- Axion-like particles:
  TeV transparency, stellar evolution,
  $m_a < 10^{-7}$eV, $g_{a\gamma} = O(10^{-11}\text{GeV}^{-1})$,
  ALPS II.

- QCD axions:
  CP, stellar evolution, (dark matter),
  $m_a = O(10^{-3}$eV$)$, $g_{a\gamma} = O(10^{-11}\text{GeV}^{-1})$,
  IAXO.

- QCD axions:
  CP, dark matter,
  $m_a = O(10^{-5}$eV$)$, $g_{a\gamma} = O(10^{-14}\text{GeV}^{-1})$,
  MADMAX

ALPS II @ DESY in Hamburg: construction started!



10+10 dipole magnets from the HERA proton accelerator

Production cavity and regeneration cavity, mode matched

$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16} \cdot \mathcal{F}_{PC}\mathcal{F}_{RC} \cdot (g_{a\gamma\gamma}Bl)^4 = 6 \cdot 10^{-38} \cdot \mathcal{F}_{PC}\mathcal{F}_{RC} \cdot \left(\frac{g_{a\gamma\gamma}}{10^{-10} GeV^{-1}} \frac{B}{1\,T} \frac{l}{10m} \right)^4$$

ALPS II @ DESY in Hamburg

Strategic issues

> Target a well defined / unique physics question:

- Model independent search for ALPs motivated by astrophysics phenomena.

> Need substantial funding:

- Funded by HGF, DFG, (BMBF), NSF, Heising-Simons.

> Need new cross-disciplinary collaborations

- Particle physics and gravitational wave community.

> Require larger scale infrastructure:

- 200 m long string of superconducting dipoles.

> Need significant resources for operation:

- Cryogenics to operate the magnet string.

> Need long-term planning:

- Plans have to be aligned with DESY accelerator construction and operation.

ALPS II main components: magnets from HERA

- 10+10 dipoles from HERA, each 5.3 T on 8.8 m.
- To be straightened to achieve ≈ 50 mm aperture.
- 9 magnets modified successfully (out of 9).
- The HERA tunnel is being cleared.

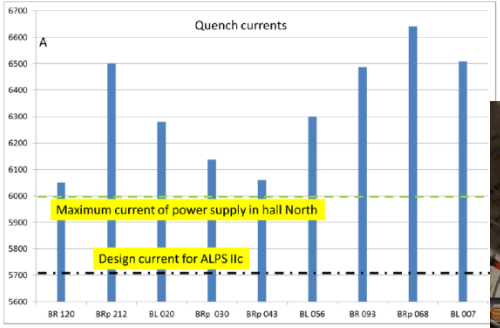


Figure 6.1: Obtained quench currents of straightened HERA dipoles

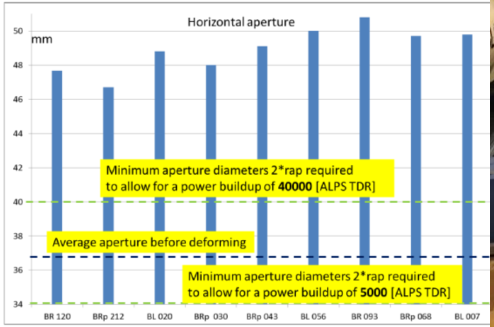
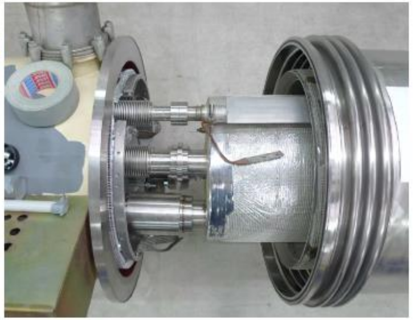
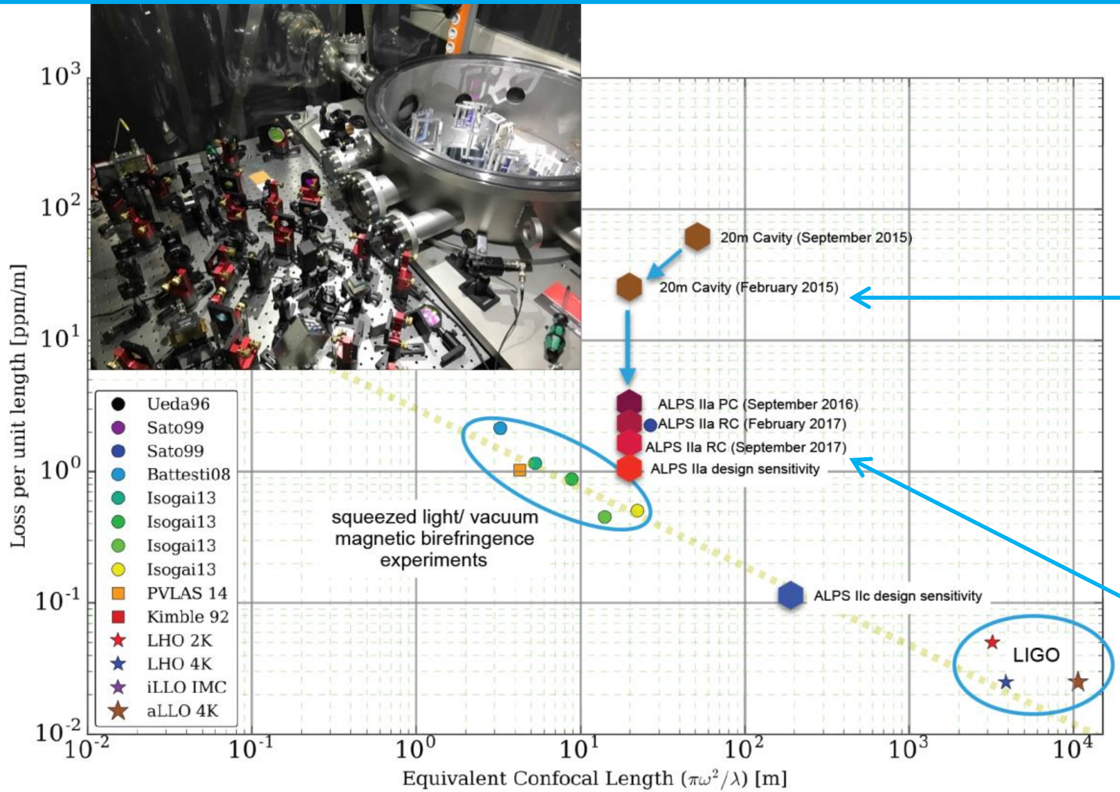


Figure 6.2: Horizontal aperture of HERA dipoles after straightening



ALPS II main components: optics status summary



plot from LIGO T-1400226-v6

Research Article Vol. 24, No. 25 | 12 Dec 2016 | OPTICS EXPRESS 29237
Optics EXPRESS

Characterization of optical systems for the ALPS II experiment

AARON D. SPECTOR,[1,*] JAN H. PÕLD,[2] ROBIN BÄHRE,[3,4] AXEL LINDNER,[2] AND BENNO WILLKE [3,4]

[1]Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
[2]Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, D-22607 Hamburg, Germany
[3]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstraße 38 D-30167 Hannover, Germany
[4]Institute for Gravitational Physics of the Leibniz Universität Hannover, Callinstraße 38, D-30167 Hannover Germany
[*]aaron.spector@desy.de

Demonstration of the length stability requirements for ALPS II with a high finesse 10 m cavity

Jan H. Põld,[1,*] and Aaron D. Spector[1]

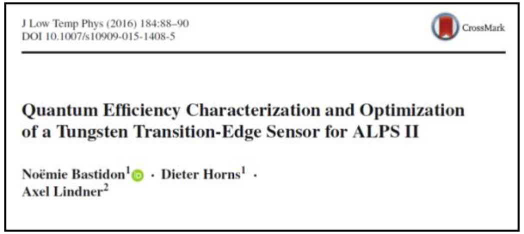
[1]Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, D-22607 Hamburg, Germany
[*]jan.pold@desy.de

https://arxiv.org/abs/1710.06634

ALPS II main components: detectors

One option (alternative heterodyne):

- Transition edge sensor (TES) operated at 80 mK.
- Single 1064 nm photon detection demonstrated:
  - 5% energy resolution,
  - 10^{-4} counts/s intrinsic background.
- R&D will resume soon with a new cryostat.

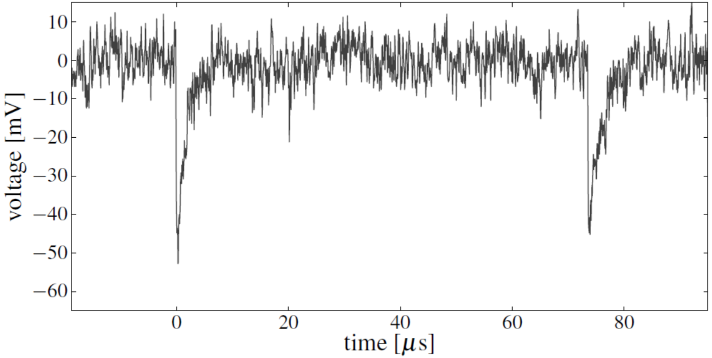


J Low Temp Phys (2016) 184:88–90
DOI 10.1007/s10909-015-1408-5

CrossMark

Quantum Efficiency Characterization and Optimization of a Tungsten Transition-Edge Sensor for ALPS II

Noëmie Bastidon[1] · Dieter Horns[1] · Axel Lindner[2]



ALPS II: aiming for data taking in 2020 @ DESY in HH

Collaboration

ALPS II main contributions				
Partner	Magnets	Optics	Detectors	Infrastructure
DESY	X	X	X	X
AEI Hannover		X		
U. Florida		X	X	X
U. Mainz			X	

Albert Einstein Institute Hannover

DESY

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UF UNIVERSITY of FLORIDA

Significant funding support also by the

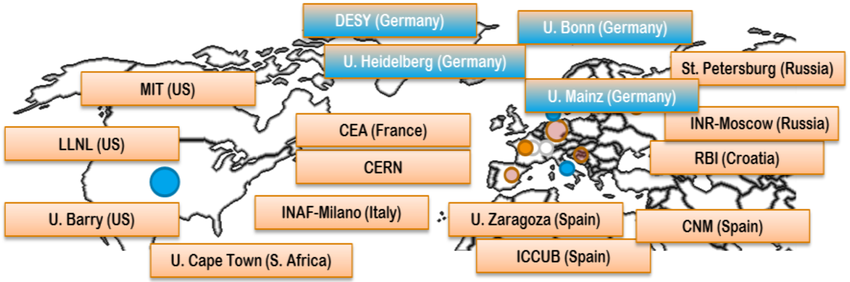
HEISING-SIMONS FOUNDATION

International Axion Observatory IAXO

Searching for solar axions from the sun

Collaboration:

- 17 Institutes from 8 countries.
- Formal collaboration founding 03 July 2017 at DESY.
- DESY has offered to host IAXO.



- German involvement:
  physics case, infrastructure, detectors.

Experiment:

- Motivation:
  explore a well motivated axion parameter region (for example stellar evolutions) not accessible by other techniques.
- Approach:
  use experience gained at CAST (CERN) to optimize solar axion searches with dedicated magnets, X-ray optics and detectors.
- Timeline:
  prototype ready in 2021.
- Location:
  several options at DESY in Hamburg.

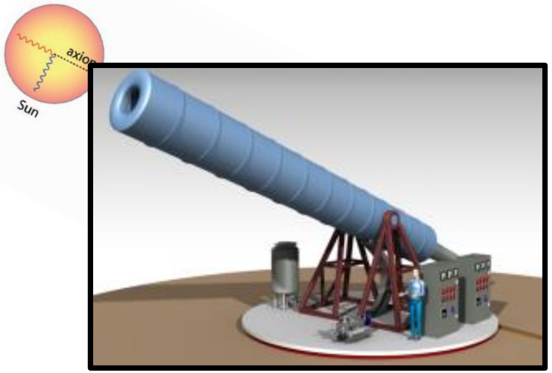
International Axion Observatory IAXO

Strategic issues

- Target a well defined / unique physics question:
  - Axions "from hell" around 0.1 meV are only accessible with helioscopes (close-to-model-independent).
- Need substantial funding:
  - Largest project within axion physics.
- Need new cross-disciplinary collaborations:
  - Particle physics and X-ray astronomy.
- Require larger scale infrastructure:
  - 25 m long apparatus with superconducting magnet.
- Need significant resources for operation:
  - Cryogenics to operate the magnet, about 10 years of operation.
- Need long-term planning:
  - Secure funds for construction and operation, ensure infrastructure availability for 10 years.

International Axion Observatory IAXO

Searching for solar axions from the sun



Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

MAgnetized Disc and Mirror Axion eXperiment

Direct dark matter search

Collaboration:

- 8 Institutes from 3 countries.
- Formal collaboration founding 20 October 2017 at DESY.

- German involvement:
  physics case, infrastructure, magnet, booster, detector.

Experiment:

- Motivation:
  look for well motivated axion dark matter (for example “SMASH”) in a mass region not accessible by present techniques.
- Approach:
  install a tunable “booster” of 80 dielectric disks inside a 2 m long dipole magnet providing $B^2 \cdot A = 100\ T^2m^2$.
- Timeline:
  prototype ready in 2021.
- Location:
  next to ALPS II in HERA North, funding proposal for infrastructure approved by Helmholtz.

MAgnetized Disc and Mirror Axion eXperiment

Strategic issues

> Target a well defined / unique physics question:

- Dark matter axions between 40 and 400 meV will only be accessible with MADMAX.

> Need substantial funding:

- Magnet development is a cost driver; magnet studies financed by MPG.

> Need new cross-disciplinary collaborations

- Particle physics and radio astronomy.

> Require larger scale infrastructure:

- 10 T superconducting dipole with a bore of A = 1m^2 and 2 m length.

> Need significant resources for operation:

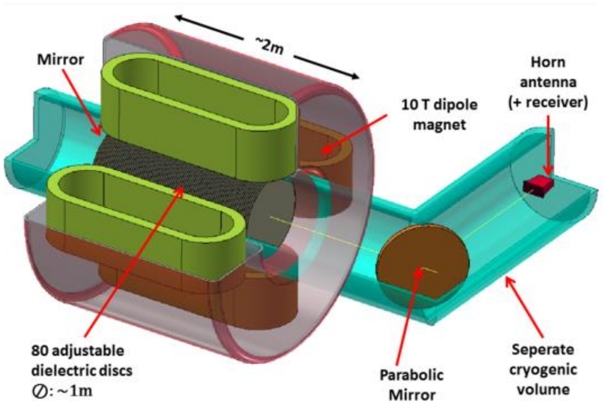
- Cryogenics to operate the magnet, about 8 years of operation.

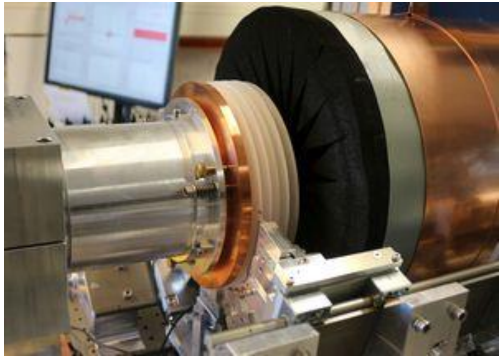
> Need long-term planning:

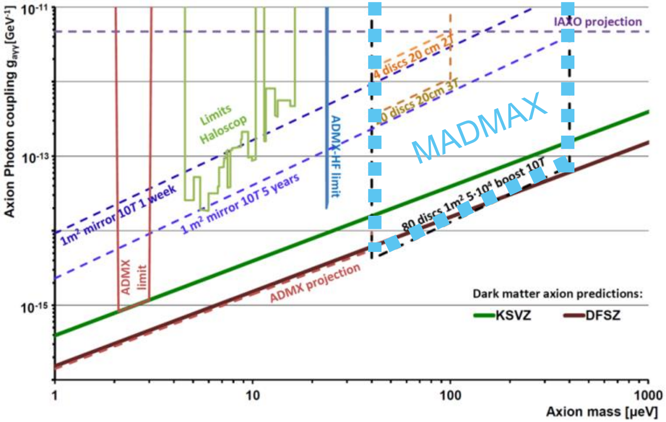
- Secure funds for construction and operation, ensure infrastructure availability for 8 years.

MAgnetized Disc and Mirror Axion eXperiment

MADMAX concept







Summary (1)

“The Future of non-Collider Physics“, April 2017, HI Mainz

https://indico.him.uni-mainz.de/event/9/

Axionen sind durch das CP Problem der starken Wechselwirkung motiviert und könnten astrophysikalische Phänomene erklären. Die in Deutschland verfolgten Ansätze ALPS II, IAXO, MADMAX, BRASS und CASPER sind international führend und decken komplementäre Bereiche der Axion-Phänomenologie ab. Sie sollten durch eine koordinierte Weiterentwicklung des Axion-Programms gestärkt werden. Für das große Helioskop IAXO sollten die Voraussetzungen für einen deutschen Standort geschaffen werden.

“The Future of non-Collider Physics“, April 2017, HI Mainz

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IAXO @ DESY in Hamburg

DESY has offered to host IAXO.

This was accepted by the collaboration as the site baseline.

“The Future of non-Collider Physics“, April 2017, HI Mainz

https://indico.him.uni-mainz.de/event/9/

Axionen sind durch das CP Problem der starken Wechselwirkung motiviert und könnten astrophysikalische Phänomene erklären. Die in Deutschland verfolgten Ansätze ALPS II, IAXO, MADMAX, BRASS und CASPER sind international führend und decken komplementäre Bereiche der Axion-Phänomenologie ab. Sie sollten durch eine koordinierte Weiterentwicklung des Axion-Programms gestärkt werden. Für das große Helioskop IAXO sollten die Voraussetzungen für einen deutschen Standort geschaffen werden.

BMBF-Antrag

R&D für künftige Experimente zur Suche nach Axionen (ALPS, IAXO, MADMAX)

Verbundantrag AXION-D

Rheinisch-Westfälische Technische Hochschule Aachen *
Rheinische Friedrich-Wilhelms-Universität Bonn
Universität Hamburg
Leibniz Universität Hannover
Ruprecht-Karls-Universität Heidelberg
Johannes Gutenberg-Universität Mainz
Universität Siegen
Eberhard Karls Universität Tübingen

in Zusammenarbeit mit

Deutsches Elektronen-Synchrotron DESY, Hamburg
Max-Planck-Institut für Radioastronomie, Bonn
Max-Planck-Institut für Physik, München

> Antrag eingereicht beim Projektträger DESY im Rahmen der Ausschreibung „Physik der kleinsten Teilchen“ (Deadline 01.11.2017).

> Positive Nachrichten!

Summary (2): aus der Einleitung des BMBF-Antrags

Viele Erweiterungen des Standard-Modells der Teilchenphysik sagen die Existenz leichter skalarer oder pseudoskalarer Bosonen vorher, die nur sehr schwach an bekannte Materie oder Strahlung koppeln. Solche Bosonen treten oft als Nambu-Goldstone spontan gebrochener globalen U(1)-Symmetrien wie beispielsweise in String-Theorie motivierten Erweiterungen des Standard-Modellsauf. …

Im Allgemeinen ist die Kopplung dieser Bosonen an die im Standard-Modell beschriebenen Teilchen um die Energieskala der Symmetriebrechung unterdrückt. Eine Entdeckung von sehr schwach wechselwirkenden Bosonen würde daher Einblick in Erweiterungen des Standardmodels geben, die weit über den an Beschleunigerexperimenten zugänglichen Parameterbereichen liegen. Im Umkehrschluss resultiert daraus die Notwendigkeit, völlig neue experimentelle Konzepte zu entwickeln.

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We have a clear program proposal here with larger and smaller scale experiments complementing nicely accelerator based particle physics!