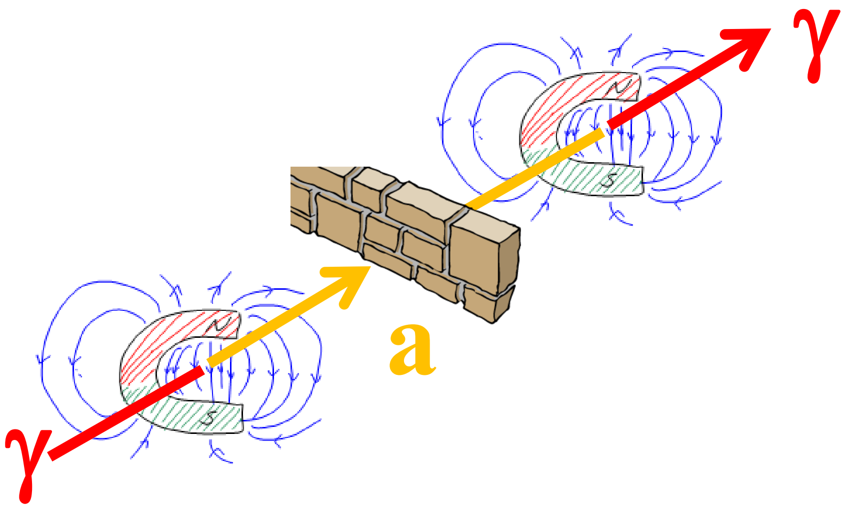
Axion Projects at DESY

Axel Lindner

Thursday Colloquium,
PSI, 17 May 2018



HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Particle physics in 1986

S. Weinberg 1986
(The cosmological constant problem, http://journals.aps.org/rmp/pdf/10.1103/RevModPhys.61.1)

- *Physics thrives on crises.*
- *Unfortunately, we have run short of crises lately. The "standard model" of electroweak and strong interactions currently faces neither internal inconsistencies nor conflicts with experiment.*
  It has plenty of loose ends; we know no reason why the quarks and leptons should have the masses they have, but then we know no reason why they should not.
- *One veritable crisis: theoretical expectations for the cosmological constant.*

Particle physics in 2018: crisis? what crisis?

- The LHC at CERN and others have confirmed our understanding of the microcosm.
- We’ve confirmed general relativity to a previously unimaginable precision.
- We’ve found a deep connection between particle physics and cosmology leading to an understanding of the universe’s history.

Beyond the Standard Model ?

The standard model (SM) of particle physics is

- extremely successful, but
- does not provide answers to crucial questions (a selection):
  - How to integrate non-zero neutrino masses?

Here the SM fails!

  - What are dark matter and dark energy?
  - How to explain the baryon-antibaryon asymmetry of the universe?

Cosmology

  - Why is the Higgs so light?
  - Why is CP conserved in QCD?
  - Why is the vacuum energy so tiny?

Fine tuning

Where to look for beyond-SM-Physics?

Wherever you can! An exemplary selection:	energy reach
> Laboratory experiments	
▪ Energy frontier	10 TeV (LHC)
▪ Precision frontier	10^2 TeV (BELLE II, model dependent)
▪ Rare decays	10^3 TeV (Mu3e, model dependent)
▪ Light-through-walls	10^5 TeV (axions, model dependent)
> Astrophysics	
▪ Stellar evolutions, light propagation	10^5 TeV (axions, model dependent)
▪ Dark matter searches	10^9 TeV (axions, model dependent)
> Cosmology	
▪ CMB, gravitational waves	10^{12} TeV (inflation, model dependent)

Outline

- An introduction to axions and axion-like particles
- Axions and ALPs in the sky?
- Experimental approaches
  - ALPS II at DESY in Hamburg
  - IAXO and MADMAX
- Summary

Introduction to axions and axion-like particles (ALPs)

Looking for an entrance to the dark sector

A dark sector beyond the Standard Model

- is strongly motivated by cosmology,
- might be complex with several constituents.

Axions and axion-like particles

- are (pseudo)scalars strongly motivated
  by theory and cosmology
  (CP conservation in QCD ↔ neutron EDM),
- offer new experimental approaches towards the dark sector,
- might be showing up
  in astro (particle)physics already.

http://www.symmetrymagazine.org/sites/default/files/images/standard/Feature_DarkMatter3.jpg

The QCD axion

CP conservation of QCD and the neutron's EDM

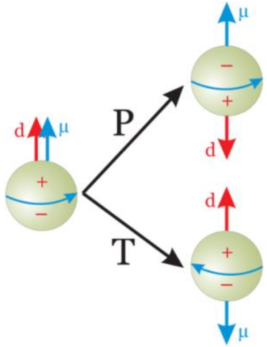
CP conservation in QCD:

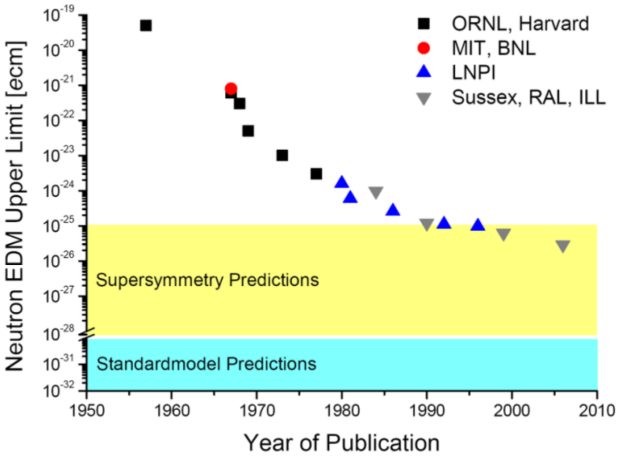
- The QCD Lagrangian includes a CP violating term:

$$L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$$

This would impose an electric dipole moment to the neutron for $\theta \neq 0$.

Any EDM of the neutron would violate CP:





The QCD axion

CP conservation of QCD and the neutron's EDM

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- The QCD Lagrangian includes a CP violating term:

$$L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$$

  This would impose an electric dipole moment to the neutron for θ ≠ 0.

- The observable CP-violation is given by

$$\theta + \arg(\det \mathcal{M})$$

- To our understanding,
  θ (QCD parameter) and
  $\arg(\det \mathcal{M})$ (weak interaction) are not related,

- but experimentally, | $\theta + \arg(\det \mathcal{M})$ | < 10^{-9}.

A fine tuning issue?

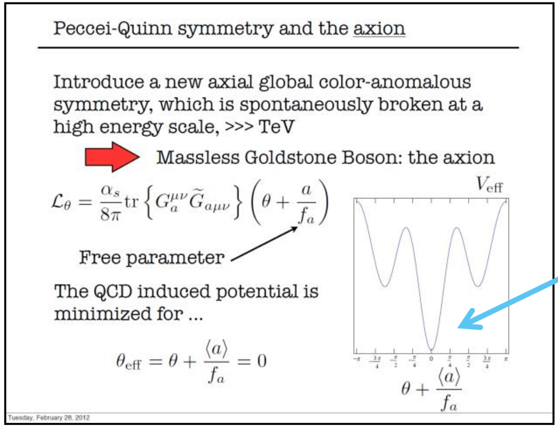
The QCD axion

Caring for CP conservation

Instead of fine-tuning:

- Introduce a new symmetry (Peccei-Quinn 1977) so that $\theta + \arg(\det \mathcal{M})$ evolves to zero.

Courtesy J. Redondo



Peccei-Quinn symmetry and the axion

Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a high energy scale, >>> TeV

Massless Goldstone Boson: the axion

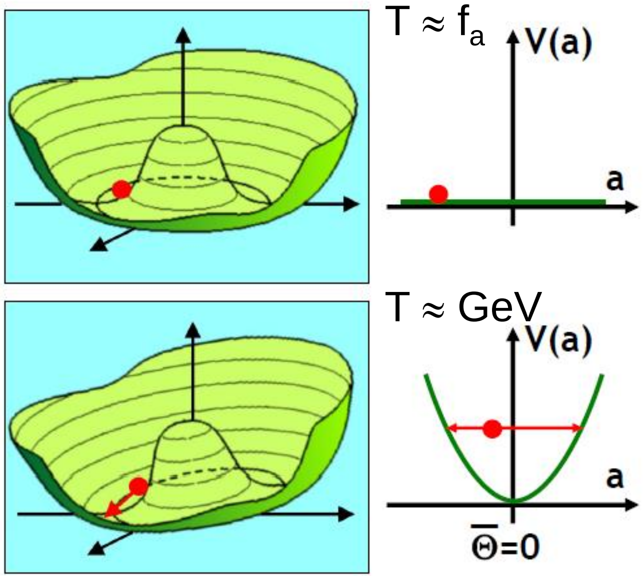
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{a}{f_a}\right)$$

Free parameter

The QCD induced potential is minimized for ...

$$\theta_{\rm eff} = \theta + \frac{\langle a\rangle}{f_a} = 0$$

The axion adjusts its v.e.v. to cancel the effects of any theta from QCD



S. Hannestad, presentation at 5th Patras Workshop 2009

- As the PQ-symmetry is broken: a pseudo Goldstone boson should exist. This axion was predicted in 1978 by Weinberg and Wilczek.

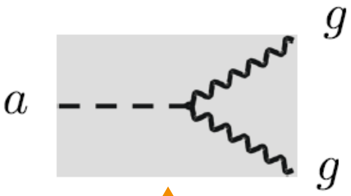
The QCD axion

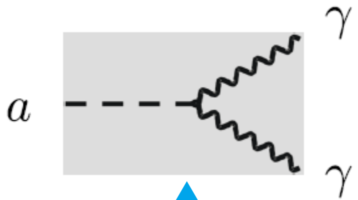
Mass and coupling determined by one energy scale

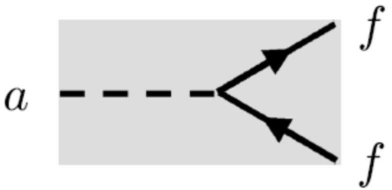
With the PQ symmetry breaking scale f_a:

- Mass: $m_a = 0.6\text{eV} \cdot (10^7\text{GeV} / f_a)$
- Couplings ~ $1/ f_a$ (hence ~ m_a)

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$







Courtesy A. Ringwald

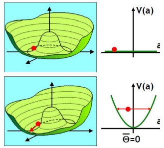
CP conservation in QCD

Exploited in most experiments

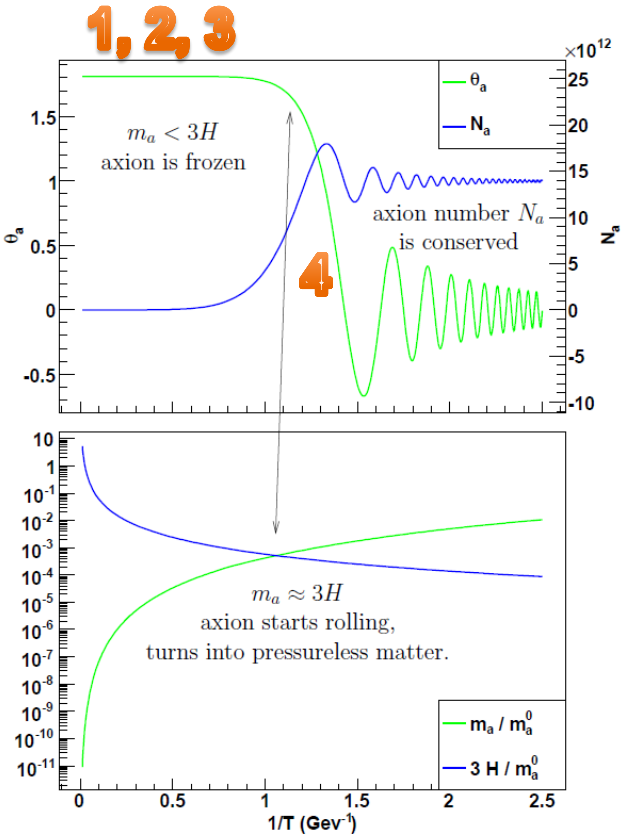
The axion and dark matter: a brief history of the universe

Ultracold dark matter from phase transition

1. Very high temperatures $T > f_a$:
   Nature picks a random initial θ_i.
2. For $T < f_a$,
   the “Mexican hat” potential appears.



3. As long as the size of the universe is smaller than the axion Compton wavelength ($H > m_a$), the axion field is frozen. At this stage, the axion acts like dark energy and might drive inflation.
4. When $H < 3m_a$, the axion field starts to oscillate around $\theta = 0$. The quanta of this oscillating field constitute dark matter.



https://arxiv.org/abs/0910.1066

The axion and dark matter

Ultracold dark matter from phase transition

- Axions would constitute very cold dark matter in spite of their very low mass.
- Very roughly the abundancy of axion cold dark matter is given by:

  $\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6} = (6\ \mu\text{eV} / m_a)^{7/6}$

  For m_a around 10 µeV the axion could make up all of the dark matter!

- Axion dark matter could even be similar to a Bose-Einstein condensate.

  See for example:
  https://arxiv.org/abs/1501.05913,
  Cosmic Axion Bose-Einstein Condensation (Nilanjan Banik, Pierre Sikivie)

The axion and dark matter

Different cosmological scenarios

1. Inflation after PQ symmetry breaking (and no PQ restauration due to reheating):
   The observable universe originates from on PQ “patch”,
   the amount of dark matter is given by f_a and the initial alignment angle θ_i.

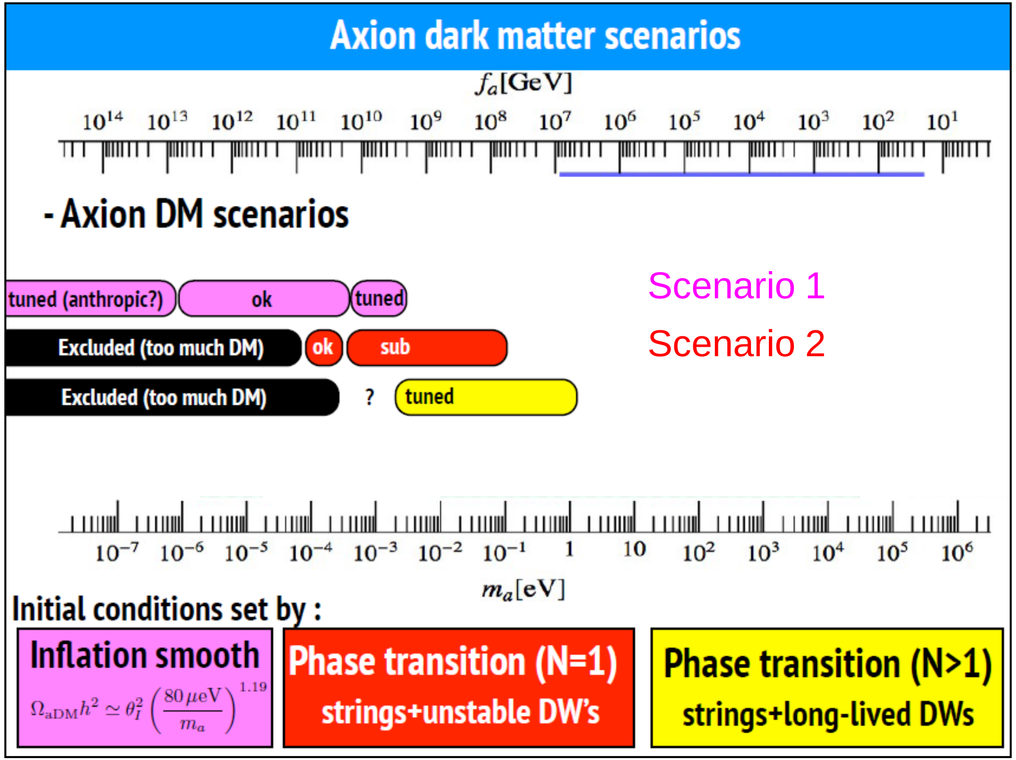
   The QCD axion could make up all of the Dark Matter in the universe
   in the 10^{-6} to 10^{-4} eV mass range (depending on the amount of fine tuning …)

2. PQ symmetry breaking after inflation:
   The observable universe consists of many “patches” with different θ_i.
   The patches mix (easy), but one gets additional axion DM contributions from string and domain wall decays (hard).

   Most favored region: a few 10^{-4} eV.

The axion and dark matter

Different cosmological scenarios



J. Redondo at http://bctp.uni-bonn.de/bethe-forum/2016/axions/

N: color anomalies of the axial current associated with the axion.

Axion and axion-like particles (ALPs)

More than one QCD axion

PHYSICAL REVIEW D **81**, 123530 (2010)

String axiverse

Asimina Arvanitaki,[1,2] Savas Dimopoulos,[3] Sergei Dubovsky,[3,4] Nemanja Kaloper,[5] and John March-Russell[6]

[1]Berkeley Center for Theoretical Physics, University of California, Berkeley, California, 94720, USA
[2]Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California, 94720, USA
[3]Department of Physics, Stanford University, Stanford, California 94305, USA
[4]Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia
[5]Department of Physics, University of California, Davis, California 95616, USA
[6]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, England

(Received 22 October 2009; published 28 June 2010)

- *String theory suggests the simultaneous presence of many ultralight axions possibly populating each decade of mass down to the Hubble scale 10^{-33} eV. Conversely the presence of such a plenitude of axions (an "axiverse") would be evidence for string theory.*

JHEP — Published for SISSA by Springer

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Accepted: September 17, 2012
Published: October 22, 2012

The type IIB string axiverse and its low-energy phenomenology

Michele Cicoli,[a,b] Mark D. Goodsell[c] and Andreas Ringwald[d]

[a]Abdus Salam ICTP, Strada Costiera 11, Trieste 34014, Italy
[b]INFN — Sezione di Trieste, Trieste, Italy
[c]CERN, Theory Division, CH-1211 Geneva 23, Switzerland
[d]Deutsches Elektronen-Synchrotron, DESY, Notkestraße 85, 22607 Hamburg, Germany
E-mail: mcicoli@ictp.it, mark.goodsell@cern.ch, andreas.ringwald@desy.de

- *Moreover, we show how models can be constructed with additional light axion-like particles that could explain some intriguing astrophysical anomalies, and could be searched for in the next generation of axion helioscopes and light-shining-through-a-wall experiments.*

ALPs

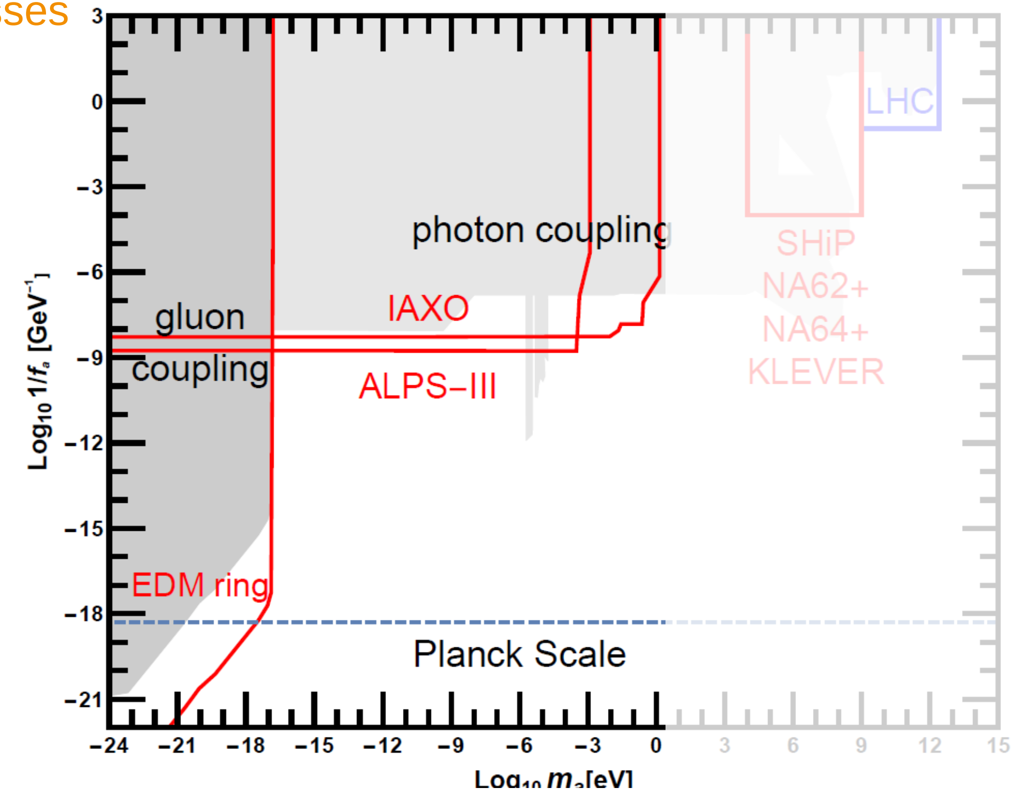
> don’t solve the problem of CP conservation of QCD,

> have couplings ~ $1/f_{alp}$, but m_{alp} and f_{alp} are not related.

Axion and axion-like particles (ALPs)

Here: only low masses

Roughly m < 1 eV

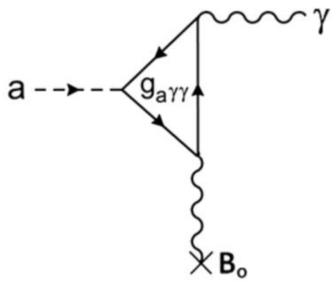


Courtesy J. Jäckel

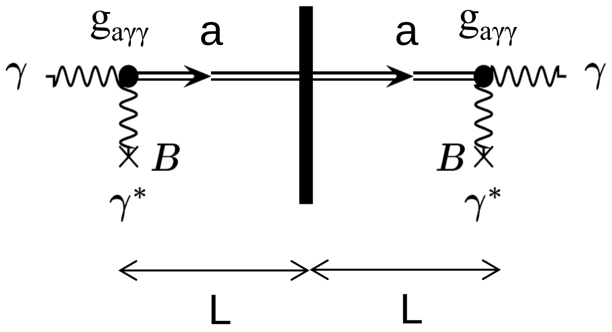
Axions and axion-like particles (ALPs)

How to look at low masses: exploiting photon couplings

Primakoff-like axion conversion



and light-shining-through-walls.



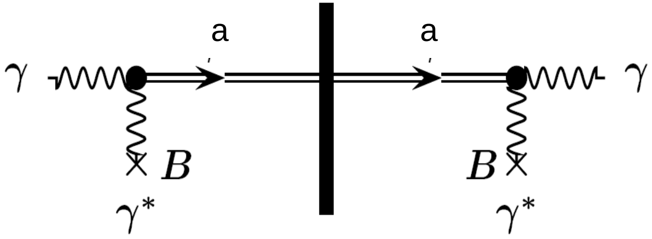
$P(\gamma\to a\to\gamma) \sim (g_{a\gamma\gamma}\cdot B\cdot L)^4$

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

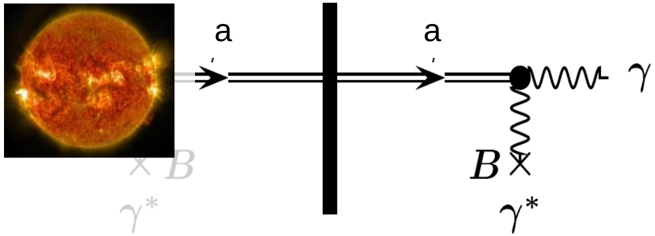
Sub-eV axions and axion-like particles (ALPs)

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

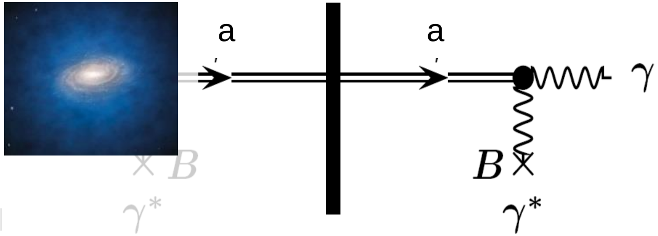
- **Purely laboratory experiments**
  “light-shining-through-walls”,
  optical photons



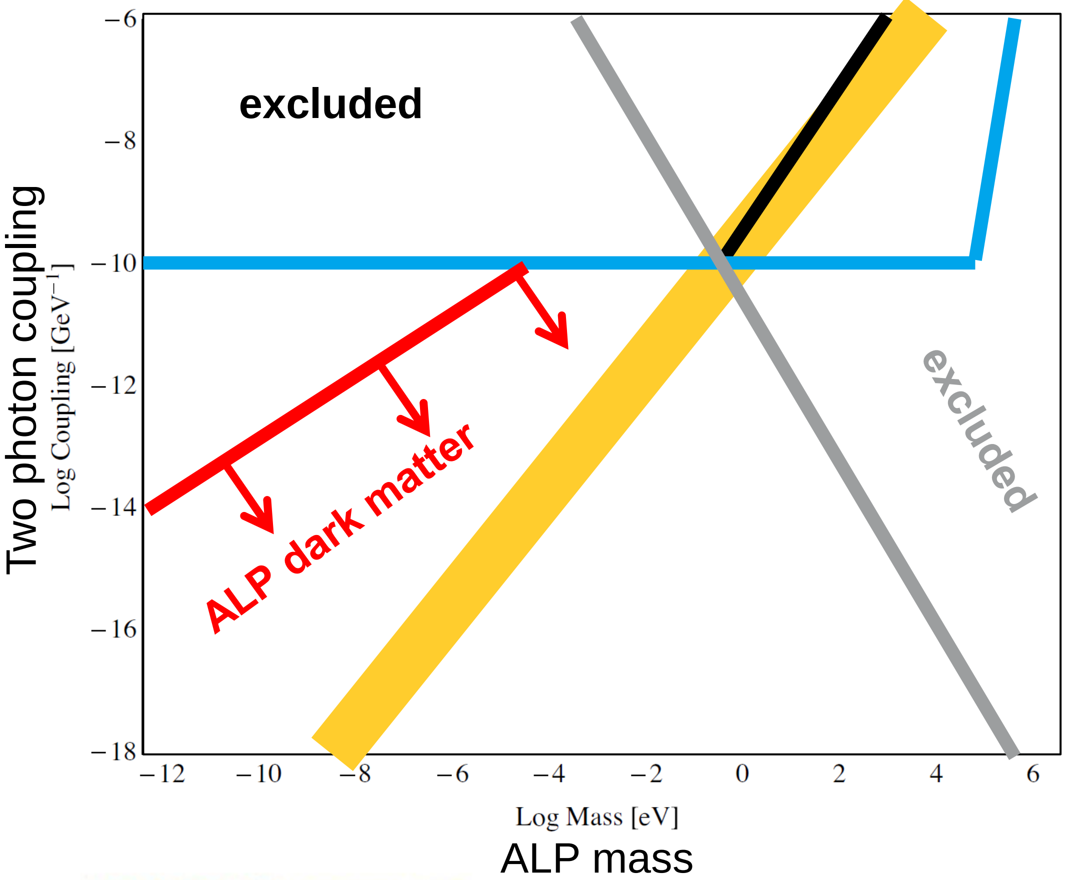
- **Helioscopes**
  ALPs emitted by the sun,
  X-rays,



- **Haloscopes**
  looking for dark matter constituents,
  microwaves.



The big picture: ALPs



QCD axion range

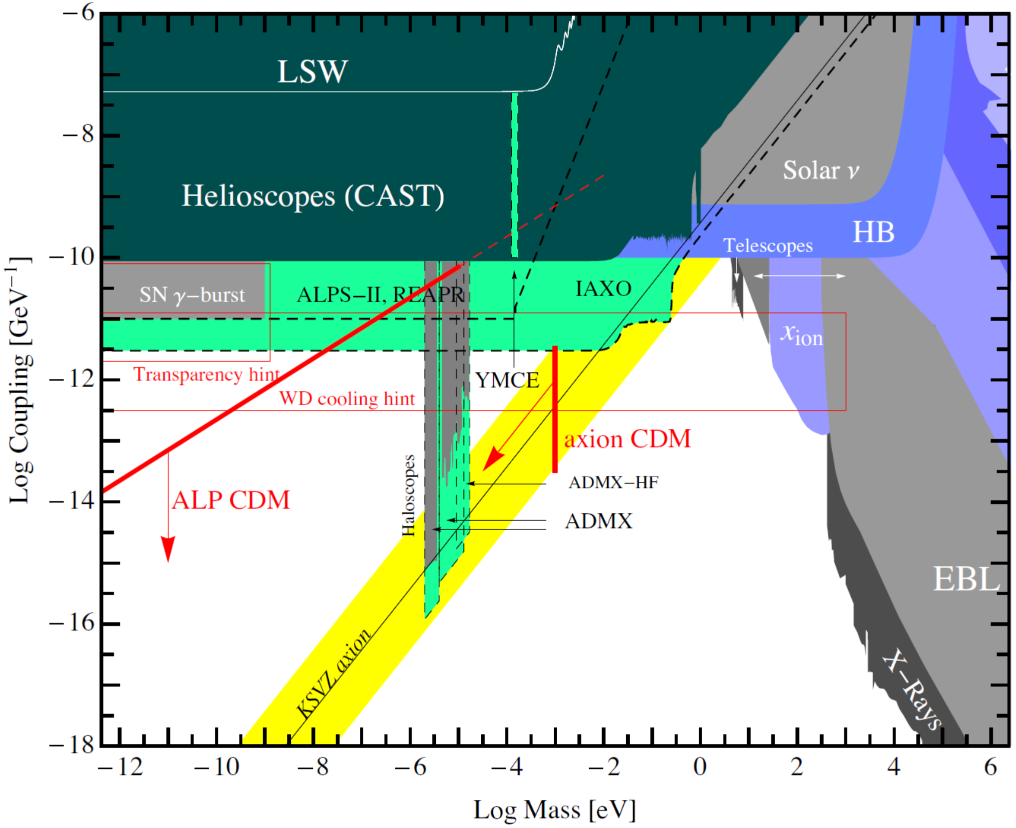
Excluded by WISP experiments

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

The big picture: ALPs



ALP mass

QCD axion range

Excluded by WISP experiments

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

Outline

- An introduction to axions and axion-like particles
- Axions and ALPs in the sky?
- Experimental approaches
  - ALPS II at DESY in Hamburg
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Axions and ALPs in the sky

Hints from astrophysics?

> Stellar evolutions

> Propagation of TeV photons

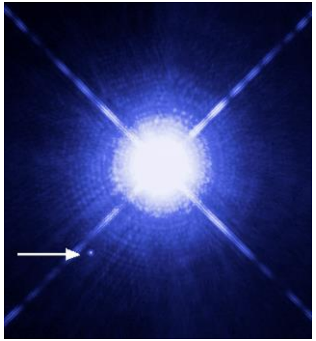
> Photon propagation in magnetic fields

Axions and ALPs in the sky

Stellar evolutions

- Extra energy loss beyond SM expectations
  is indicated by stellar developments.

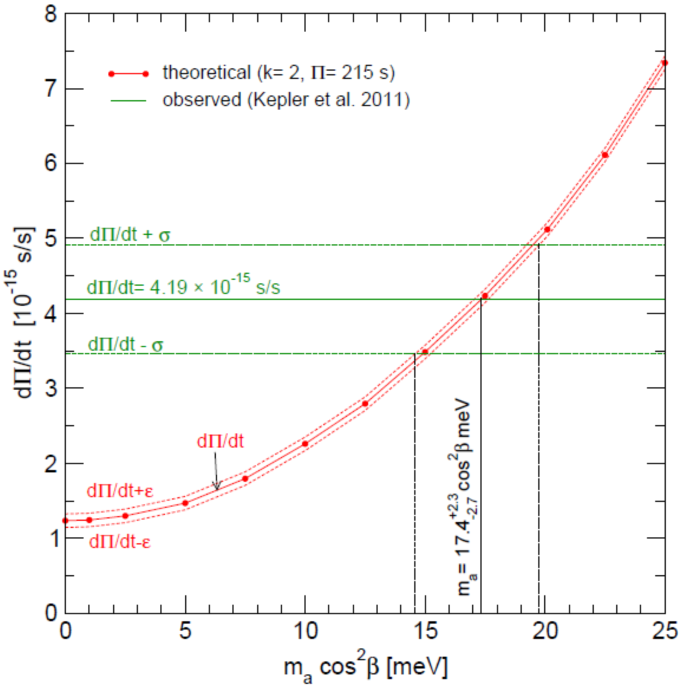
- Example:
  white dwarf stars.



The change of frequency of a pulsating DA white dwarf measures its cooling rate.

Data indicate that the white dwarf cools "too fast".

G117−B15A

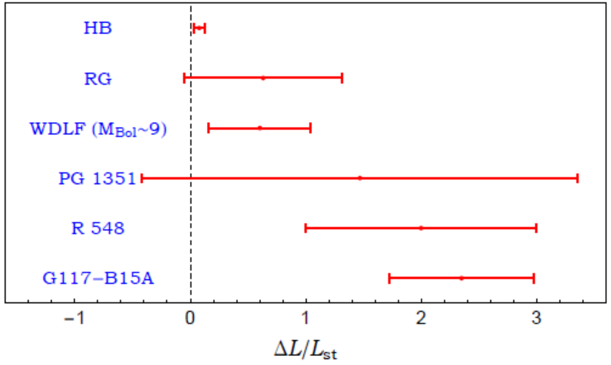


https://arxiv.org/abs/1205.6180

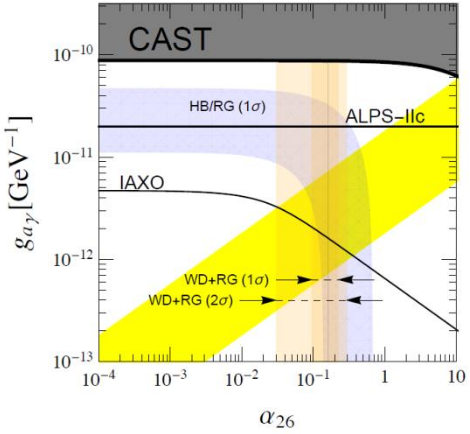
Axions and ALPs in the sky

Stellar evolutions

- Extra energy loss beyond SM expectations
  is indicated by stellar developments.
- Such losses can be explained consistently
  by the emission of axions coupling to photons and electrons.
  Light ALPs would also work.



M. Giannotti, I. Irastorza,
J. Redondo, A. Ringwald,
http://arxiv.org/abs/1512.08108



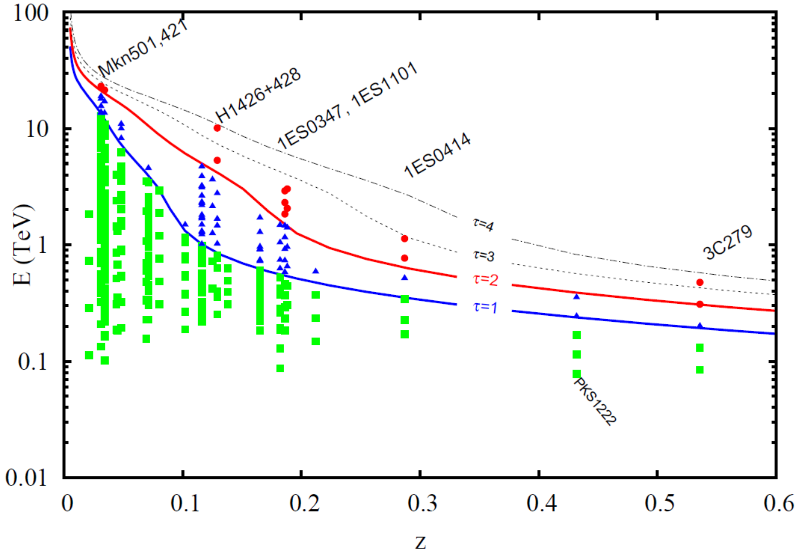
M. Giannotti, I. Irastorza,
J. Redondo, A. Ringwald, K. Saikawa
https://arxiv.org/abs/1708.02111

Axions and ALPs in the sky

Propagation of TeV photons

Anomalous transparency of the universe to TeV photons:

- TeV photons might not be absorbed in the intergalactic space due to $\gamma+\gamma \rightarrow e^+e^-$ scattering as predicted by QED.



D. Horns, M. Meyer, JCAP 1202 (2012) 033

Axions and ALPs in the sky

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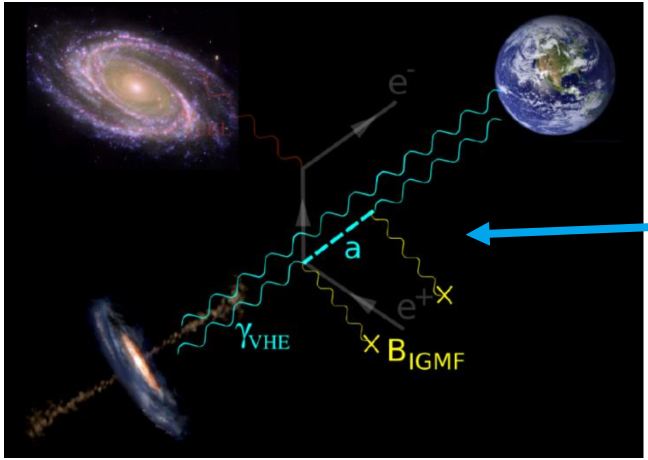
- This could be explained by axion-like particles.



TeV photons in the universe

might convert in magnetic fields to ALPs via their two-photon coupling.

Such ALPs might convert back to photons in the vicinity of earth.

Axions and ALPs in the sky

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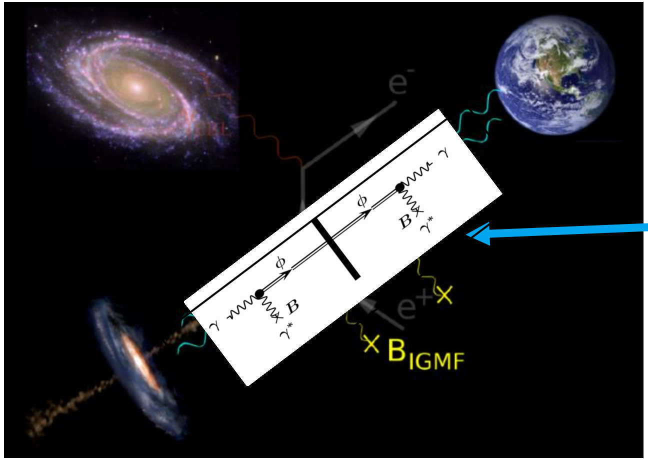

TeV photons in the universe:

“Light-shining-through-the-wall” of extragalactic background light?

Axions and ALPs in the sky

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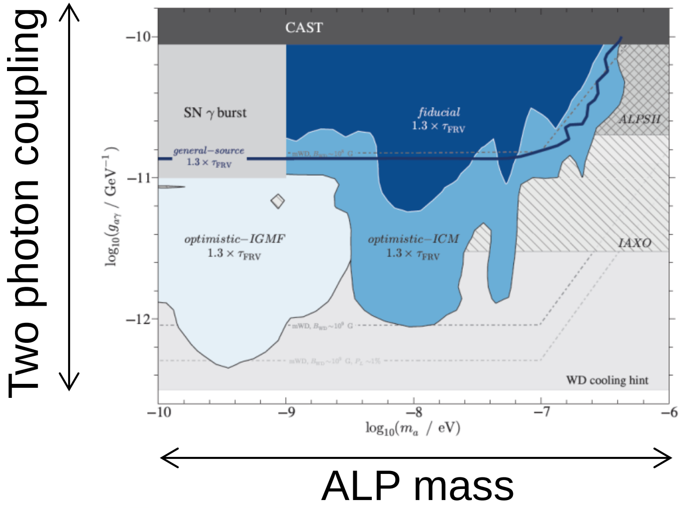


A very similar axion-photon coupling as derived from stellar developments is required!

M. Meyer, D. Horns, M. Raue,
arXiv:1302.1208 [astro-ph.HE], Phys. Rev. D 87, 035027 (2013)

S. V. Troitsky,
arXiv:1612.01864 [astro-ph.HE], JETP Lett. 105 (2017) no.1, 55

Axions and ALPs in the sky

Propagation of TeV photons

ALPs to explain an unexpected high transparency of the universe for TeV photons:

PROCEEDINGS OF SCIENCE

Hints for an axion-like particle from PKS 1222+216?

https://arxiv.org/abs/1409.4401

Advantages of axion-like particles for the description of very-high-energy blazar spectra

https://arxiv.org/abs/1503.04436

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Sensitivity of the Cherenkov Telescope Array to the detection of axion-like particles at high gamma-ray opacities

https://arxiv.org/abs/1410.1556

PHYSICAL REVIEW D **86,** 075024 (2012)

Hardening of TeV gamma spectrum of active galactic nuclei in galaxy clusters by conversions of photons into axionlike particles

https://arxiv.org/abs/1207.0776

PHYSICAL REVIEW D **93,** 045014 (2016)

Towards discrimination between galactic and intergalactic axion-photon mixing

https://arxiv.org/abs/1507.08640

Axion-like particles and the propagation of gamma rays over astronomical distances

https://arxiv.org/abs/1612.01864

Axions and ALPs in the sky

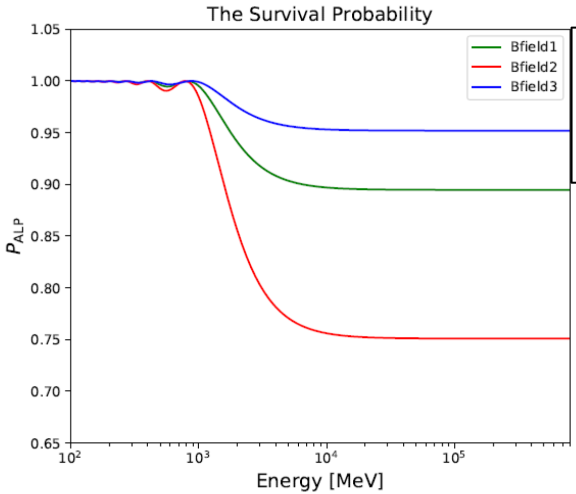
Photon propagation in magnetic fields

Photon spectra might be changed due to photon-ALP conversion in magnetic fields (10.1103/PhysRevD.97.063003, Zi-Qing Xia et al.):

$$
\begin{aligned}
P_{\mathrm{ALP}} &= 1 - P_{\gamma\to a} \\
&= 1 - \frac{1}{1 + E_c^2/E_\gamma^2} \sin^2\left[\frac{g_{a\gamma} B_{\mathrm{T}} l}{2}\sqrt{1 + \frac{E_c^2}{E_\gamma^2}}\right]
\end{aligned}
$$

where the characteristic energy E_c is defined as

$$
E_c = \frac{\left|m_a^2 - w_{\mathrm{pl}}^2\right|}{2 g_{a\gamma} B_{\mathrm{T}}},
$$



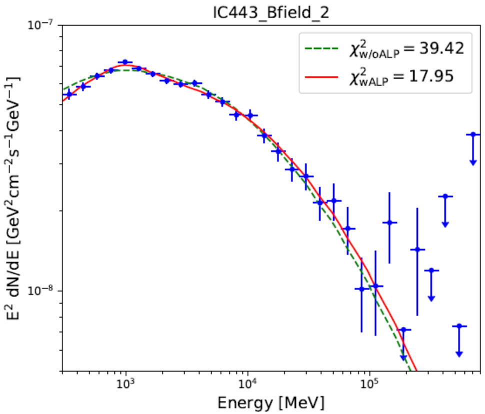
SNR IC443, 1.5 kpc
$m_a = 6.6\cdot10^{-9}$eV
$g_{a\gamma\gamma} = 1.3\cdot10^{-10}$GeV^{-1}

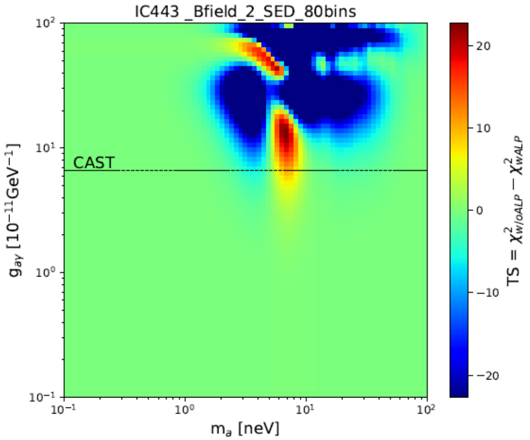
Spectral modulations might hint at the existence of ALPs!

Axions and ALPs in the sky

Photon propagation in magnetic fields: conflicting results!

Galactic SNR (10.1103/PhysRevD.97.063003, Zi-Qing Xia et al.):





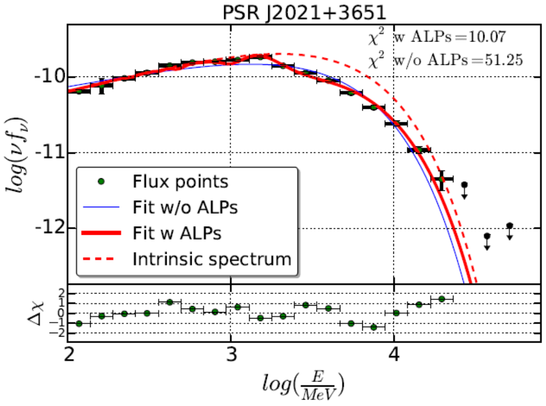
Evidence for ALPs from IC443?

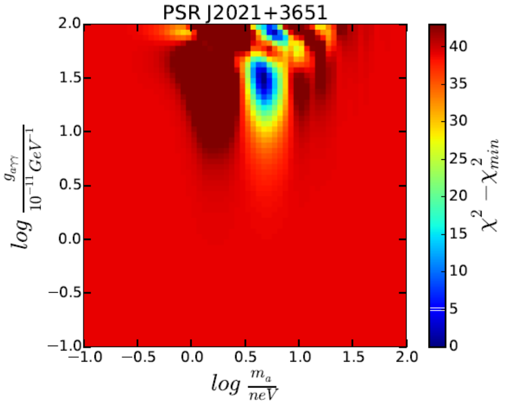
No ALPs indications from W44 and W51C, method checked with close SNRs.

Axions and ALPs in the sky

Photon propagation in magnetic fields: conflicting results!

Galactic pulsars (J. Majumdar *et al* JCAP04(2018)048):





Pulsar name	N_0 [10^{-9}MeV^{-1} cm^{-2} s^{-1}]	Γ_1	E_{cut} [GeV]	$g_{a\gamma\gamma}$ [10^{-10} GeV^{-1}]	m_a [neV]
J1420-6048	0.0016(2)	1.74(4)	5.4(6)	1.7(3)	3.6(1)
J1648-4611	0.0028(2)	0.88(3)	3.4(2)	5.3(9)	4.3(1)
J1702-4128	0.13(3)	0.9(1)	1.0(2)	4.4(2)	8.1(5)
J1718-3825	0.024(2)	1.48(4)	2.1(1)	2.4(3)	8.9(2)
J2021+3651	0.18(1)	1.45(3)	3.5(1)	3.5(3)	4.4(1)
J2240+5832	0.005(1)	1.5(1)	2.4(6)	2.1(4)	3.7(3)

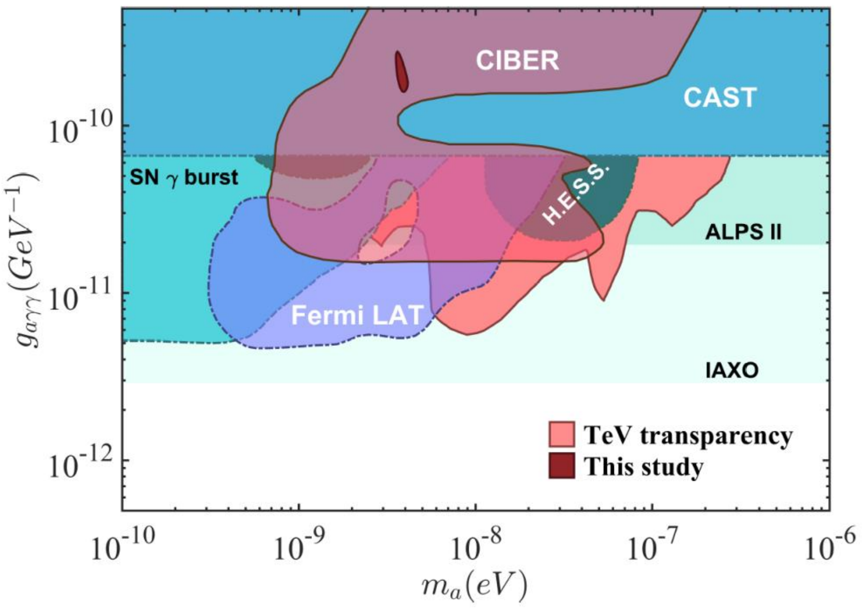
Pulsars selected according to the magnetic field strength along the line of sight.

Method checked with close pulsar.

Axions and ALPs in the sky

Photon propagation in magnetic fields: conflicting results!

Galactic pulsars (J. Majumdar *et al* JCAP04(2018)048):



Surprising agreement with SNR analyses!

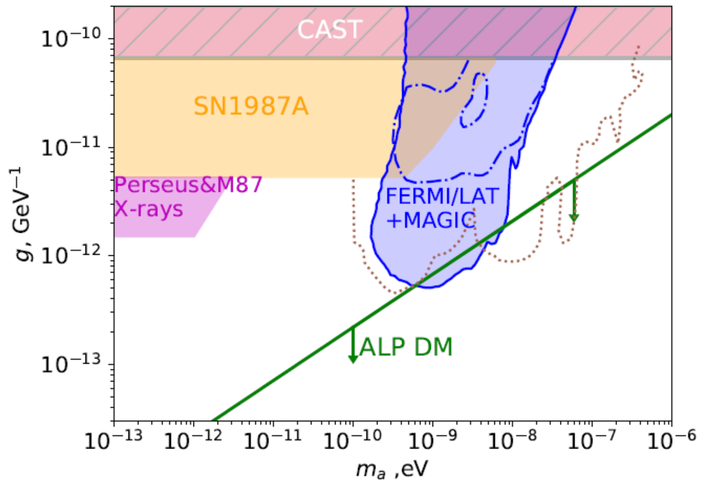
Conflict to other exclusions!

Do we understand astrophysics?

Axions and ALPs in the sky

Photon propagation in magnetic fields: conflicting results!

NGC 1275, Perseus cluster (D. Malyshev et al, arXiv:1805.04388 [astro-ph.HE]):



No evidence for ALPs! "Galactic hints" are excluded!

Do we understand astrophysics?

Axions and ALPs in the sky

Hints from astrophysics?

- Stellar evolutions
- Propagation of TeV photons
- Photon propagation in magnetic fields

Nothing conclusive yet, but lot's of interesting data.

Strive for model independent measurements: ALPS II at DESY!

Outline

- An introduction to axions and axion-like particles
- Axions and ALPs in the sky?
- Experimental approaches
  - ALPS II at DESY in Hamburg
  - IAXO and MADMAX
- Summary

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: some details later

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: some details later

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: some details later

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: some details later

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, $\approx 2.4\cdot10^{-5}$ eV	New Haven	running	https://arxiv.org/abs/1803.03690
KLASH	cavity	Axion, $2\cdot10^{-7}$ 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, $4\cdot10^{-5}$ to $4\cdot10^{-4}$ eV	DESY	preparation	https://arxiv.org/abs/1712.01062

Selection of experiments: haloscopes, photon coupling (3)

Orange: some details later

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: some details later

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, $\approx 2 \cdot 10^{-4}$ eV		proposed	https://doi.org/10.1016/j.dark.2017.01.003

Experiments (possibly) located at DESY in Hamburg

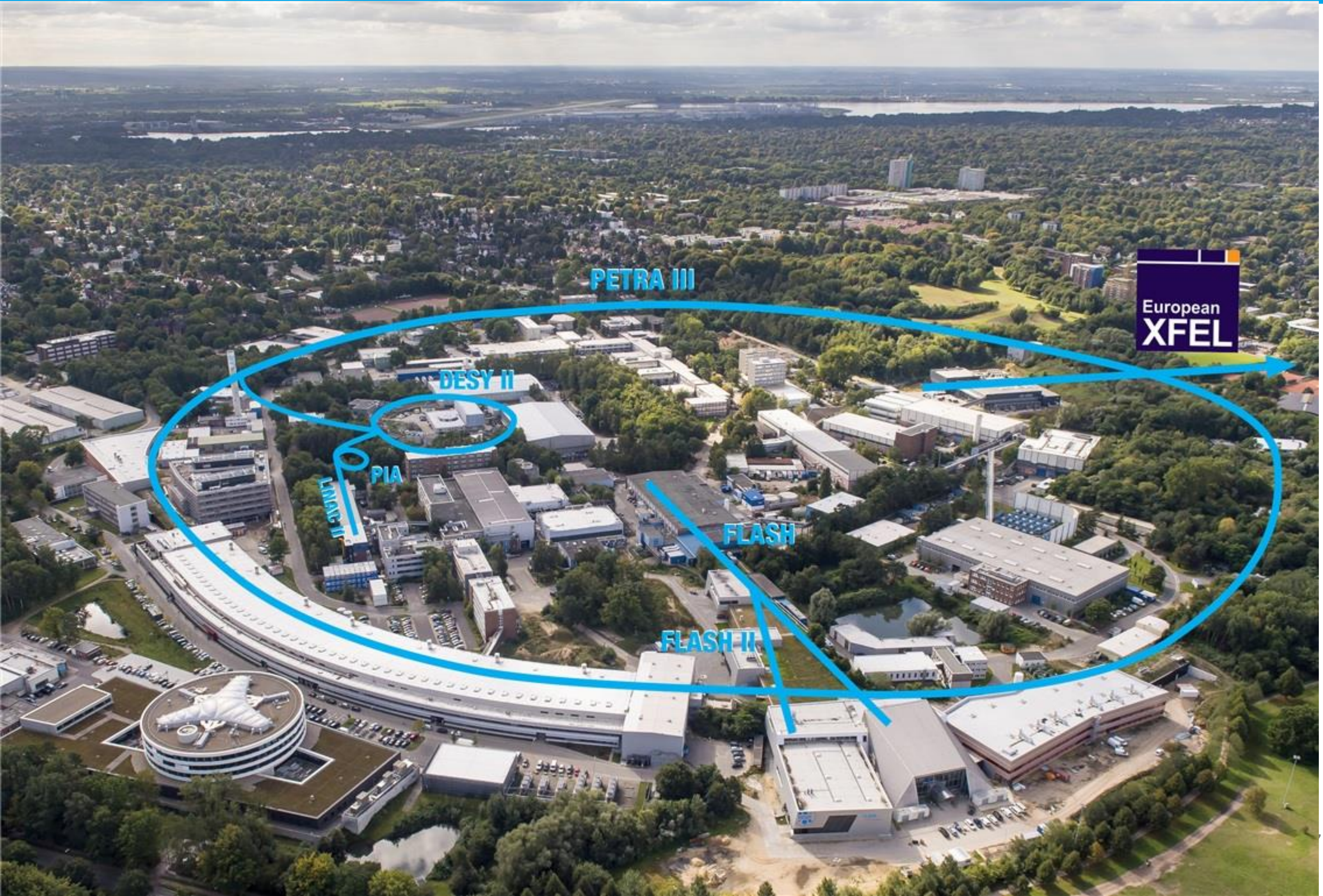
Name	Type	Sens (10^{-11} GeV^{-1})	Location	Status	Reference
ALPS II	LSW	2, m < 0.1 meV	DESY	construction	https://arxiv.org/abs/1302.5647

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)!

DESY in Hamburg

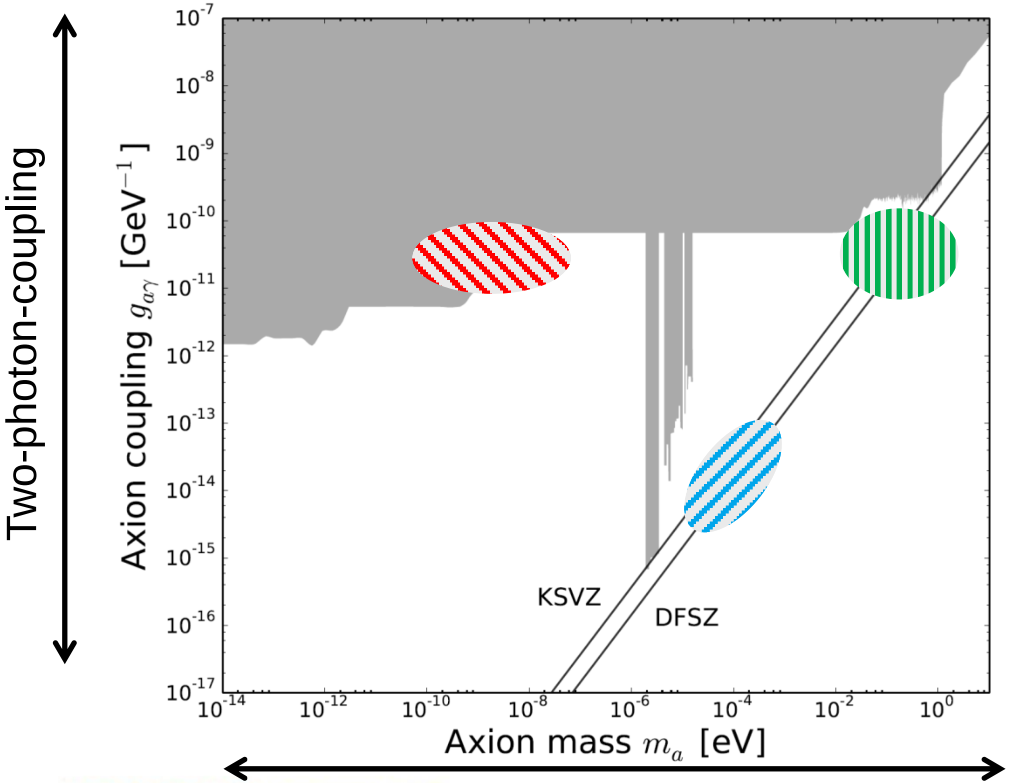


Axion physics:

Opportunity to have particle physics experiments on-site complementing participation in remote experiments (ATLAS, CMS, BELLE II).

Axions and axion-like particles: approaches at DESY

Where to look: hot spots

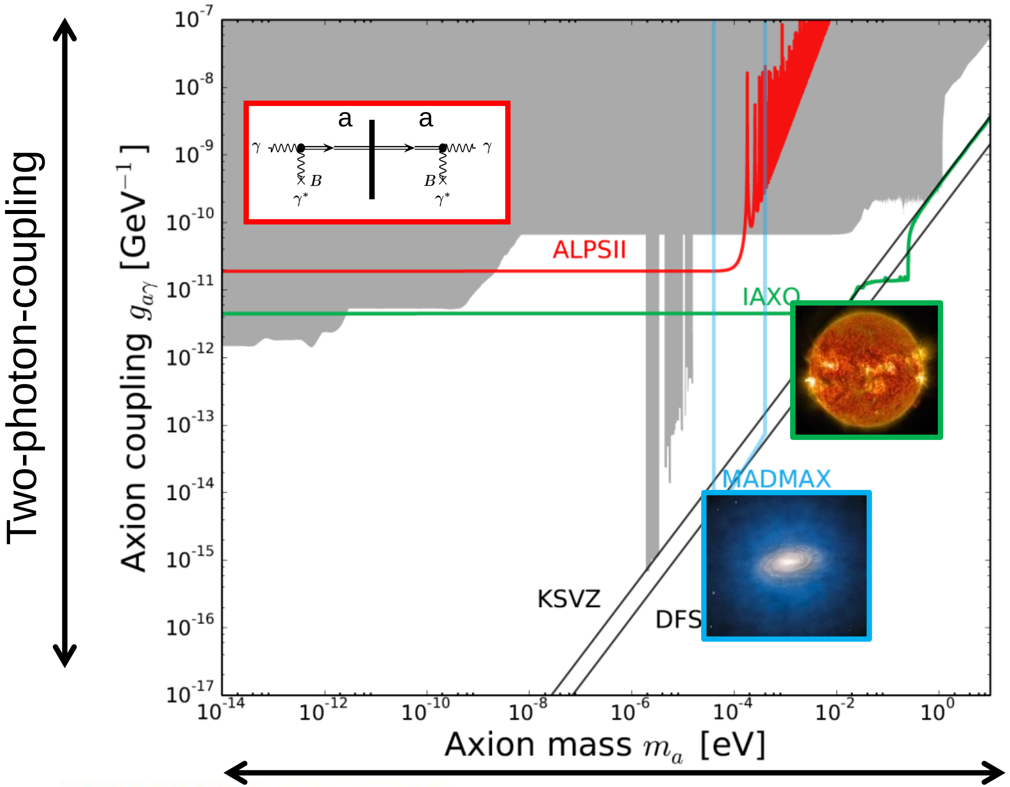


Three main regions of interest:

- Axion-like particles:
  photon propagation, stellar evolution,
  $m_a < 10^{-7}$eV, $g_{a\gamma} = O(10^{-10} - 10^{-11}\text{GeV}^{-1})$
- 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: approaches at DESY

Where to look: hot spots



Three main regions of interest:

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

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

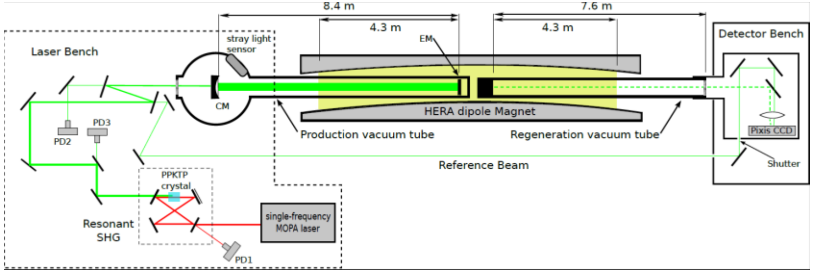
- QCD axions:
  CP, dark matter,
  $m_a = O(10^{-5}\text{eV})$, $g_{a\gamma} = O(10^{-14}\text{GeV}^{-1})$,
  MADMAX

Any Light Particle Searches @ DESY in Hamburg

From ALPS I to ALPS II

ALPS I

- based on one HERA proton accelerator dipole magnet,
- initiated 2006 by theory, exp. particle physics and administration,
- approved 2007 and concluded 2010,
- most sensitive ALP search experiment in the lab up to 2014 (surpassed by OSQAR @ CERN using two LHC dipoles).



Basis of success:
combine forces with LIGO community
to implement an optical resonator in the magnet bore.

Any Light Particle Searches @ DESY in Hamburg

From ALPS I to ALPS II

ALPS I

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TECHNICAL REPORT

Any light particle search II — Technical Design Report

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R Bähre *et al* 2013 *JINST* **8** T09001

ALPS II

- proposed 2011,
  TDR evaluated in 2012,
  directorate decided to continue
  with the preparatory phase,
- construction phase started in 2017.
- Main goal:
  increase sensitivity on $g_{a\gamma}$ by > 10^3
  to probe for axion-like particles
  motivated by
  astrophysics phenomena.

NATURE|Vol 465|20 May 2010

RESEARCH HIGHLIGHTS

CELL BIOLOGY

Viral vote

Cell **141**, 682-691 (2010)

Why do identical cells often respond differently to the same stimulus? Researchers generally blame noise inherent in biological systems, but there may, in fact, be specific processes at play, according to Ido Golding, now at Baylor College of Medicine in Houston, Texas, and his co-workers.

They watched individual particles of a bacterial virus infect single *Escherichia coli* cells (pictured, top panel, green dots indicate virus particles) — in theory subjecting the cells to the same stimulus. Each virus particle, they found, makes an individual 'decision': to kill the host cell or to become dormant by integrating into the host's DNA. Those decisions are then summed to determine the cell's ultimate fate. Only a unanimous decision by all virus particles to integrate into the DNA of a particular cell keeps that cell alive (red). If even one particle 'votes' for death, the cell bursts (bottom panel, in green). A.K.

NEUROSCIENCE

Bright eyed

PHYSICS

Not a WISP of evidence

Phys. Lett. B doi:10.1016/j.physletb.2010.04.066 (2010)

In extensions to the standard model, which describes the fundamental particles and forces of physics, some theorists have proposed the existence of very light subatomic particles called WISPs. These could be dark matter, which keeps a spinning galaxy from flying apart.

One way to detect WISPs would be to look for the rare conversion of light particles to WISPs, and later back to photons. In between these conversions, a WISP could zip through any barrier. So Axel Lindner at DESY, the German electron synchrotron in Hamburg, and his colleagues shone green laser light at a 'wall', a thick piece of light-absorbing material, hoping that a few photons might pop out the other side. They increased the chances of a WISP conversion by using optical resonators to boost the power of the laser light and by applying a strong magnetic field. But the researchers did not detect any emerging photons, limiting the chance of a WISP conversion to nearly 1 in 10^{25} — the most sensitive limit yet. E.H.

ELSEVIER

JOURNAL CLUB

Marc Vrakking
Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin

A physicist discusses how to visualize a molecule changing shape.

It is the dream of many a chemist to watch a movie of a molecule undergoing structural change. So how can we achieve this? One way is to use the relationship between a molecule's absorption spectrum and its structure to deduce how the structure changes over time. However, a drawback of this technique is its reliance on prior knowledge of the molecular absorption spectrum.

Faton Krasniqi at the Max Planck Advanced Study Group in Hamburg, Germany, and his co-workers present an alternative idea: using photoelectrons ejected from molecules excited by X-ray free-electron lasers to determine molecular structures that change over time (F. Krasniqi *et al. Phys. Rev. A* **81**, 033411; 2010).

They explain how electrons that are ejected and directly detected without any further interaction with the molecule interfere with electrons that scatter off the surrounding atoms in the molecule, thereby creating

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

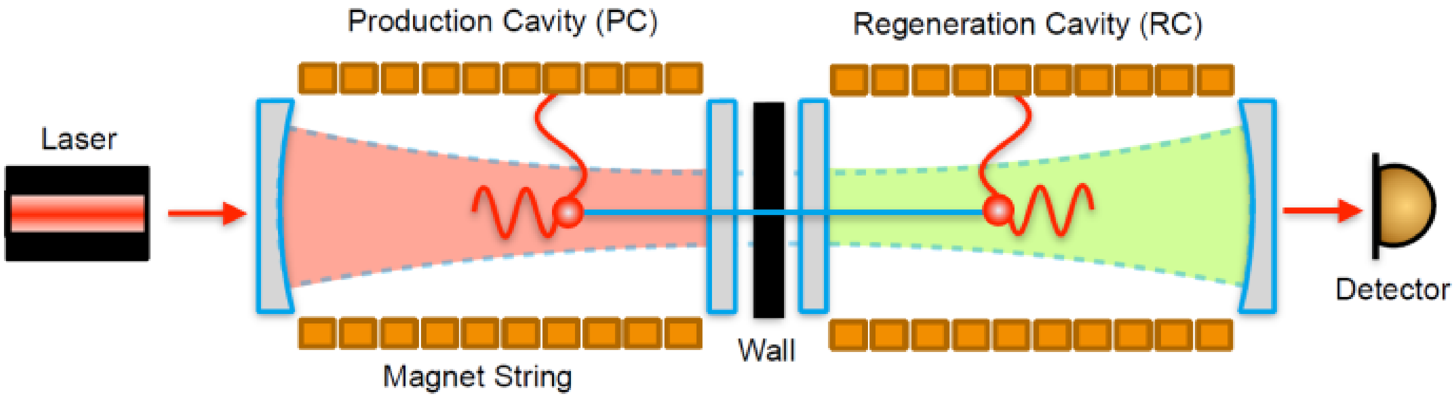
Collaboration

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	

Significant funding support also by the

HEISING-SIMONS FOUNDATION

ALPS II @ DESY in Hamburg: construction started!



10+10 dipole magnets from the HERA proton accelerator

Production cavity and regeneration cavity, mode matched

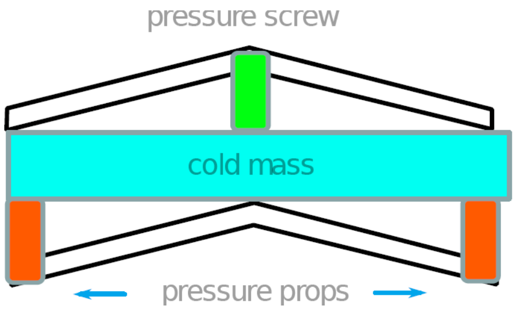
$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot 10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

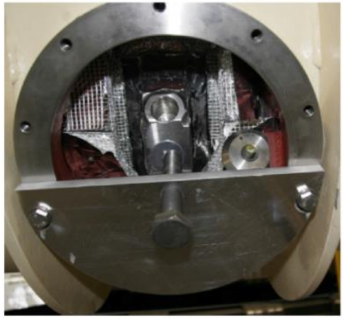
ALPS II main components: magnets from HERA

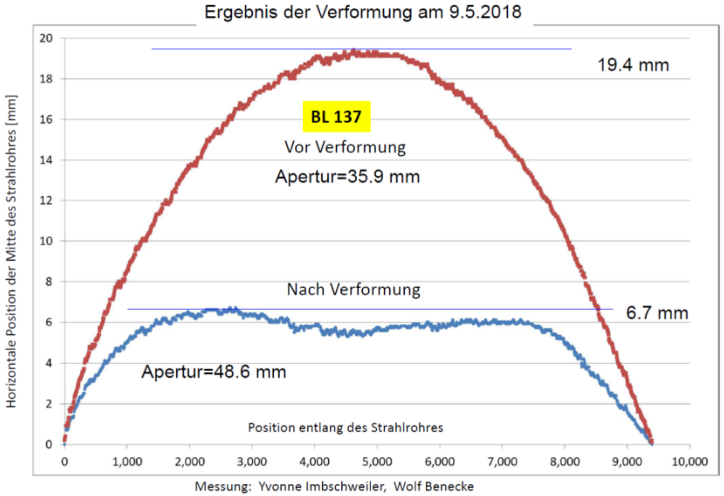
- 10+10 dipoles from HERA,
  each 5.3 T on 8.8 m.
- To be straightened to achieve
  ≈ 50 mm aperture
  from 35 mm (600 m bending radius)

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 from 35 mm (600 m bending radius)







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.
- 10 magnets modified successfully (out of 10).
- The HERA tunnel is being cleared.

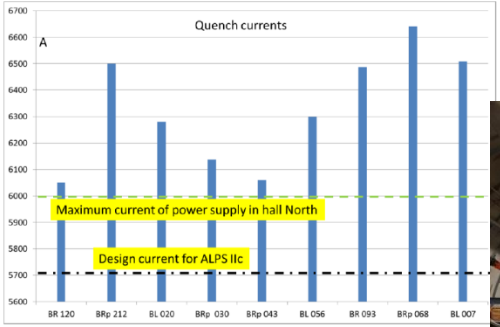


Figure 6.1: Obtained quench currents of straightened HERA dipoles

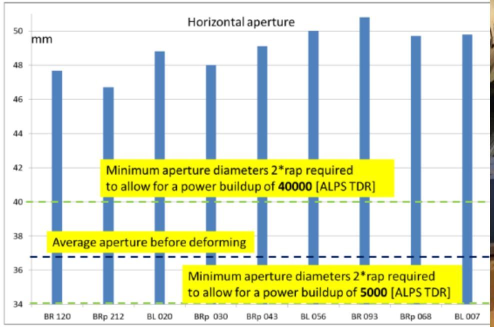
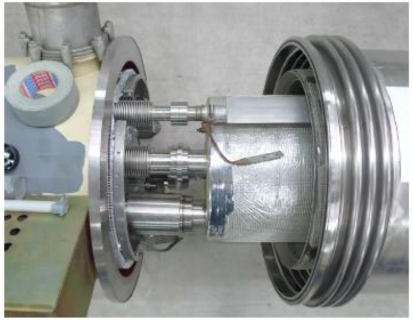
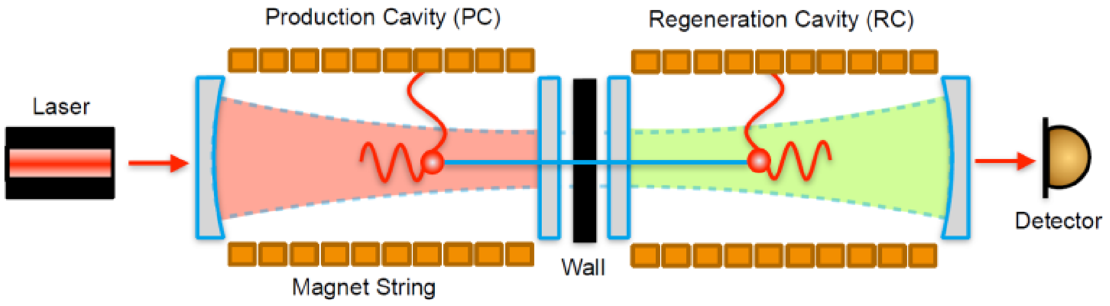


Figure 6.2: Horizontal aperture of HERA dipoles after straightening



ALPS II main components: optics adapted from LIGO

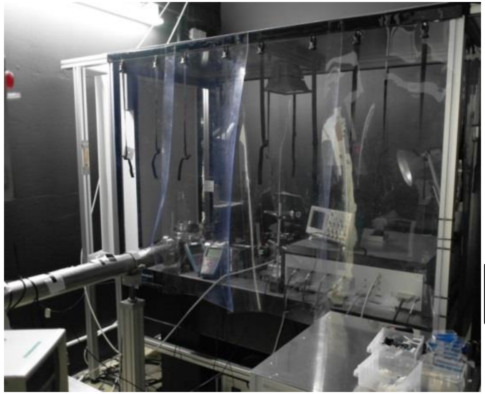


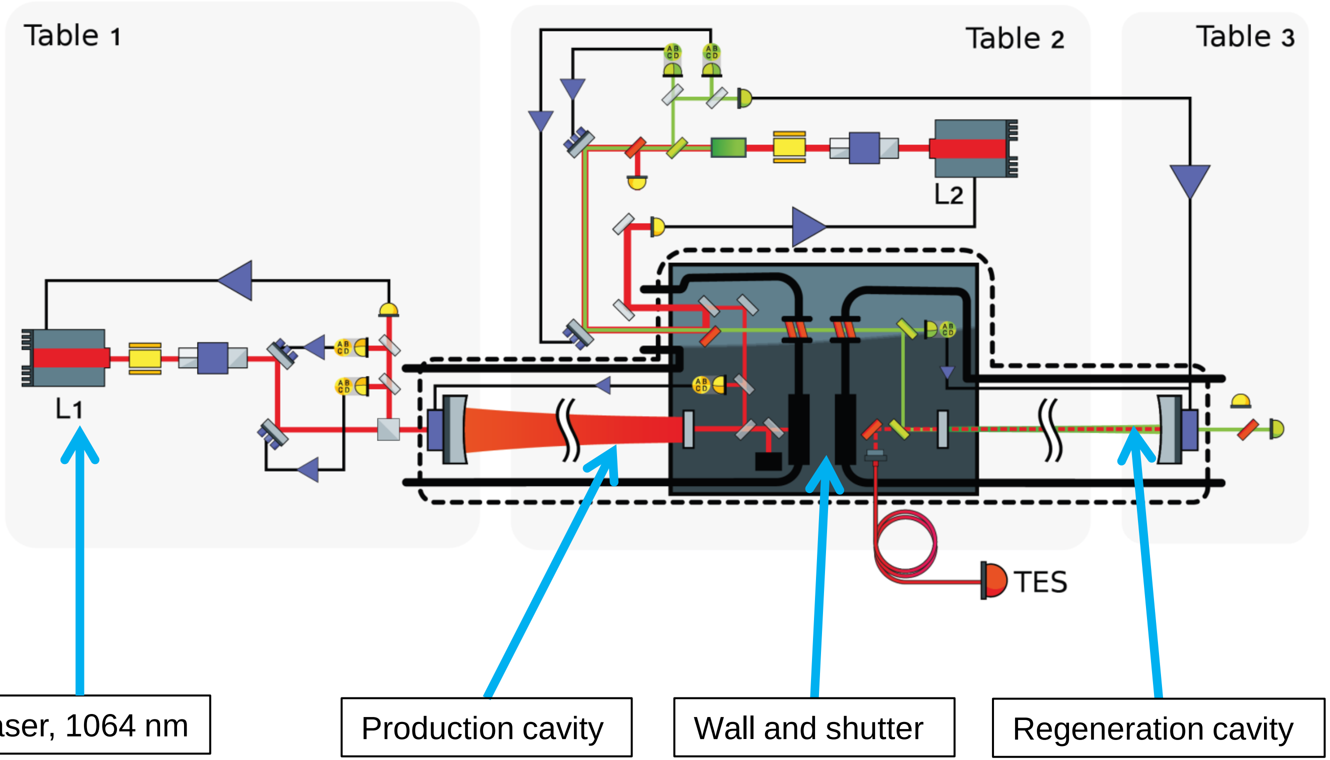
- Mode-matched optical resonators before (“PC”) and behind (“RC”) the wall.
- Relative angle between PC and RC less than 0.5 µrad.
- Each about 100 m long, need to compensate seismic noise.
- Power built-up PC: 5,000: 150 kW circulating power.
- Power built-up RC: 40,000: length relative to light wavelength stabilized to 0.5 pm.

ALPS II main components: optics adapted from LIGO

Laser:

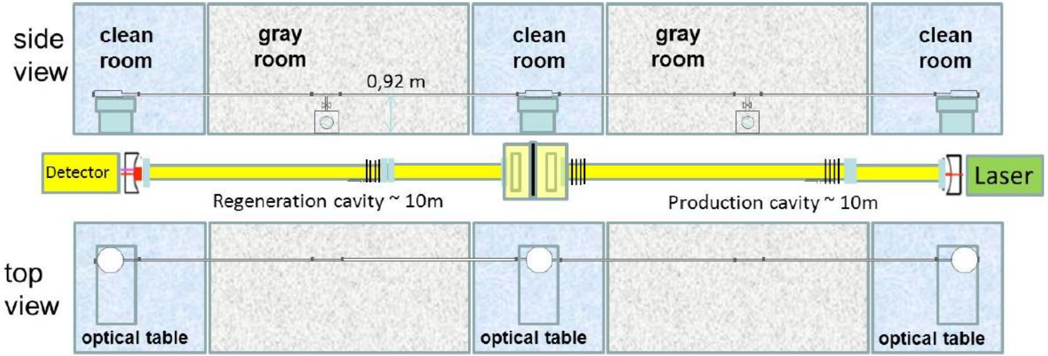
- developed for LIGO,
- based on 2 W NPRO by Innolight/Mephisto (Nd:YAG, neodymium-doped yttrium aluminium garnet),
- 1064 nm, 35 W, $M^2<1.1$

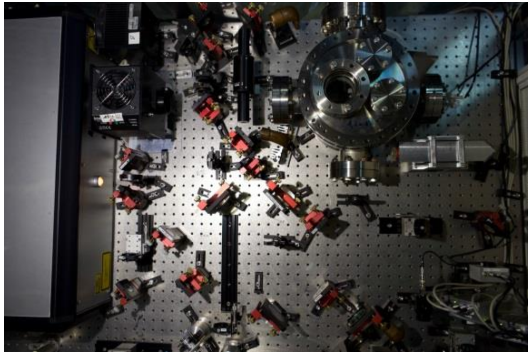


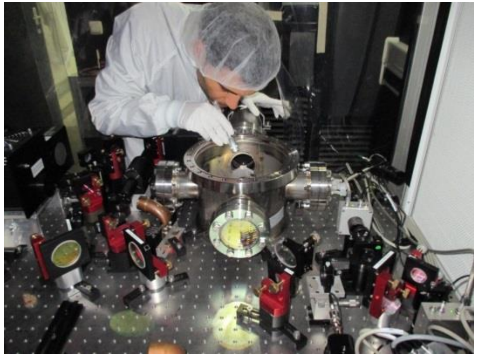


ALPS II main components: optics

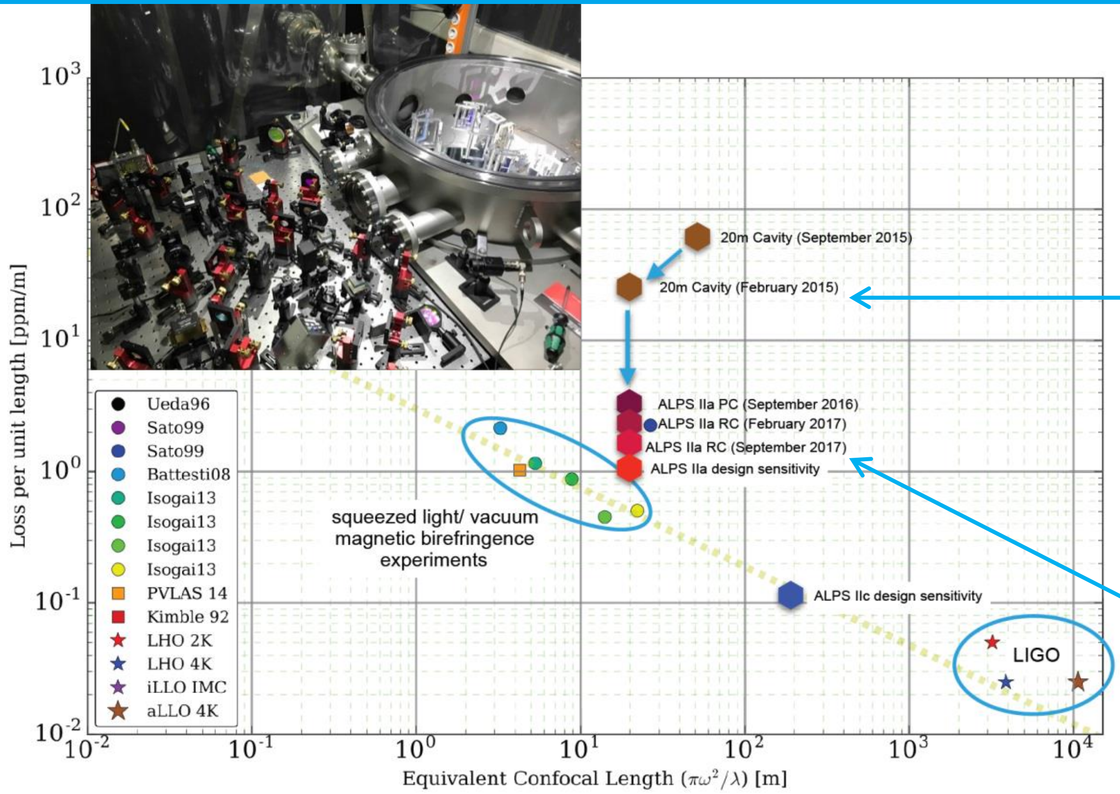
The optics is developed in a 20 m long dedicated lab “ALPS IIa“.







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]

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[*] *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: optics status summary

	Requirement	Status
PC circulating power	150 kW	50 kW
RC power buildup factor	40,000	23,000
CBB mirror alignement	< 5 µrad	< 1 µrad
Spatial overlap	> 95%	work ongoing
RC length stabilization	< 0.5 pm	< 0.3 pm

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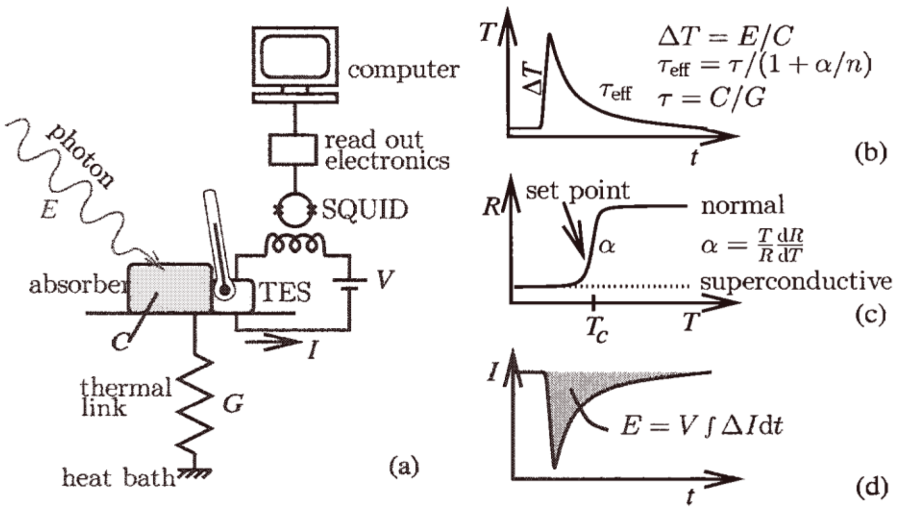
https://arxiv.org/abs/1710.06634

ALPS II main components: detectors

DESY:

- Transition edge sensor (TES) operated at 80 mK.



$\Delta T \approx 100\ \mu K$

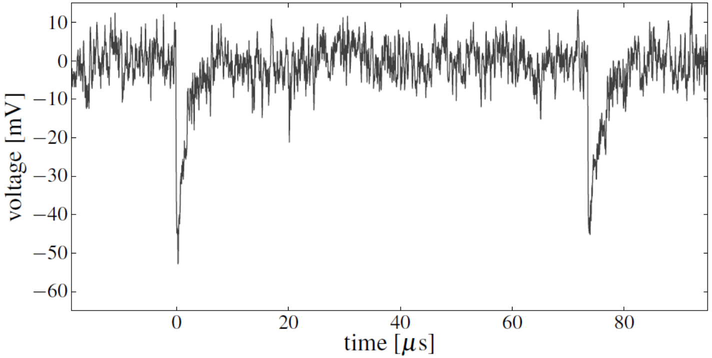
$\Delta R \approx 1\ \Omega$

$\Delta I \approx 70\ nA$

ALPS II main components: detectors

DESY:

- 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 with a new cryostat in summer 2018.



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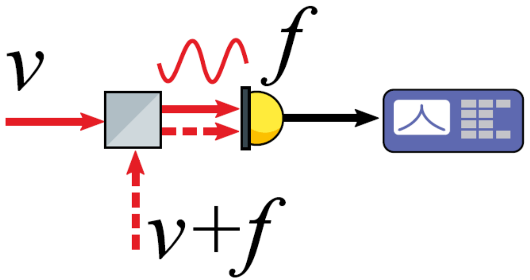
University of Florida:

- Heterodyne detection scheme.



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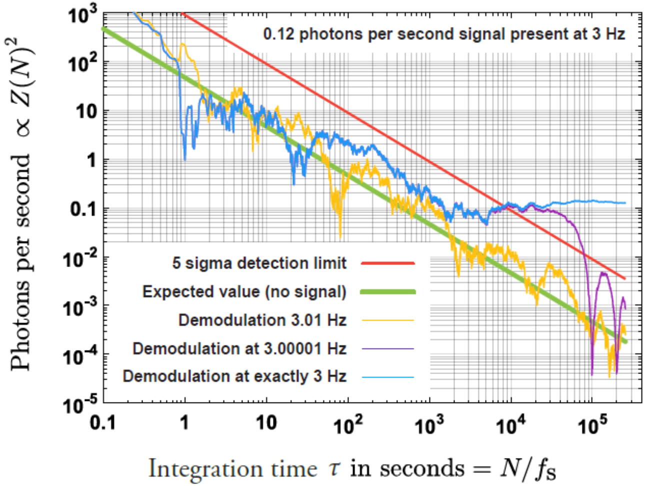


ALPS II main components: detectors

DESY:

- Transition edge sensor (TES) operated at 80 mK.
- Single 1064 nm photon detection demonstrated.

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]

University of Florida:

- Heterodyne detection scheme.
- 0.1 photons/s detected.

Single Photon Detection Using Optical Heterodyne Interferometry

Zachary Bush[1], Simon Barke[1], Harold Hollis[1], Guido Mueller[1], and David Tanner[1]

[1] Department of Physics, University of Florida, PO Box 118440, Gainesville, Florida, 32611, USA

Compiled October 13, 2017

We detail and explore the application of heterodyne interferometry for a weak field coherent detection scheme. Planned use in a current dark matter search experiment sets specification goals to accurately measure fields on the order of 1 photon per week. While such weak signals are buried under orders of magnitude of noise, by knowing its exact frequency, coherent detection can be made. Initial results of successful generation and measurement of a signal with a field strength on the order of 10^{-1} photons per second are presented.

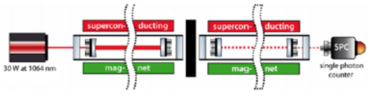


Fig. 1. Simplified model of the ALPS experiment. Axions generated in the left-hand side cavity traverse the wall and regenerate back into detectable photons in the right-hand side cavity. [3]

https://arxiv.org/abs/1710.04209

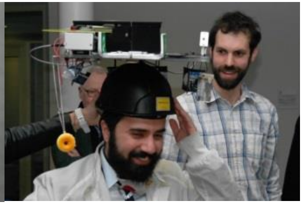
ALPS II @ DESY in Hamburg

Results and schedule

Results:

- Axions and ALPs:
  none (no data run yet …)
- Publications:
  5 on optics and detector developments;
  several conference contributions.
- People (since 2012):
  6 Ph.D. theses completed,
  about 8 to come,
  4 postdocs left for a next career step.

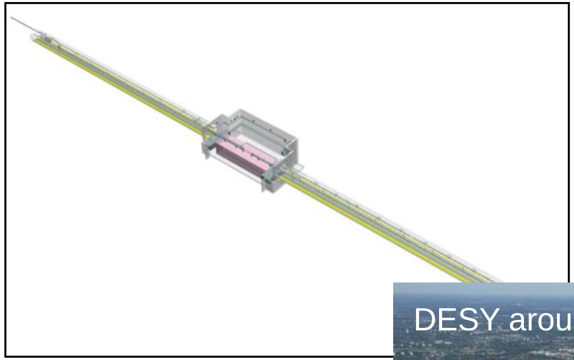
Jan Dreyling-Eschweiler

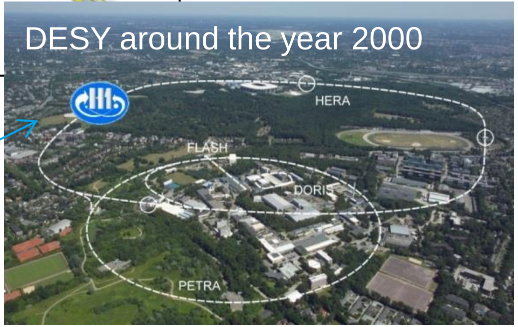


Reza Hodajerdi

Schedule and site:

- Start data taking in the HERA tunnel in 2020.

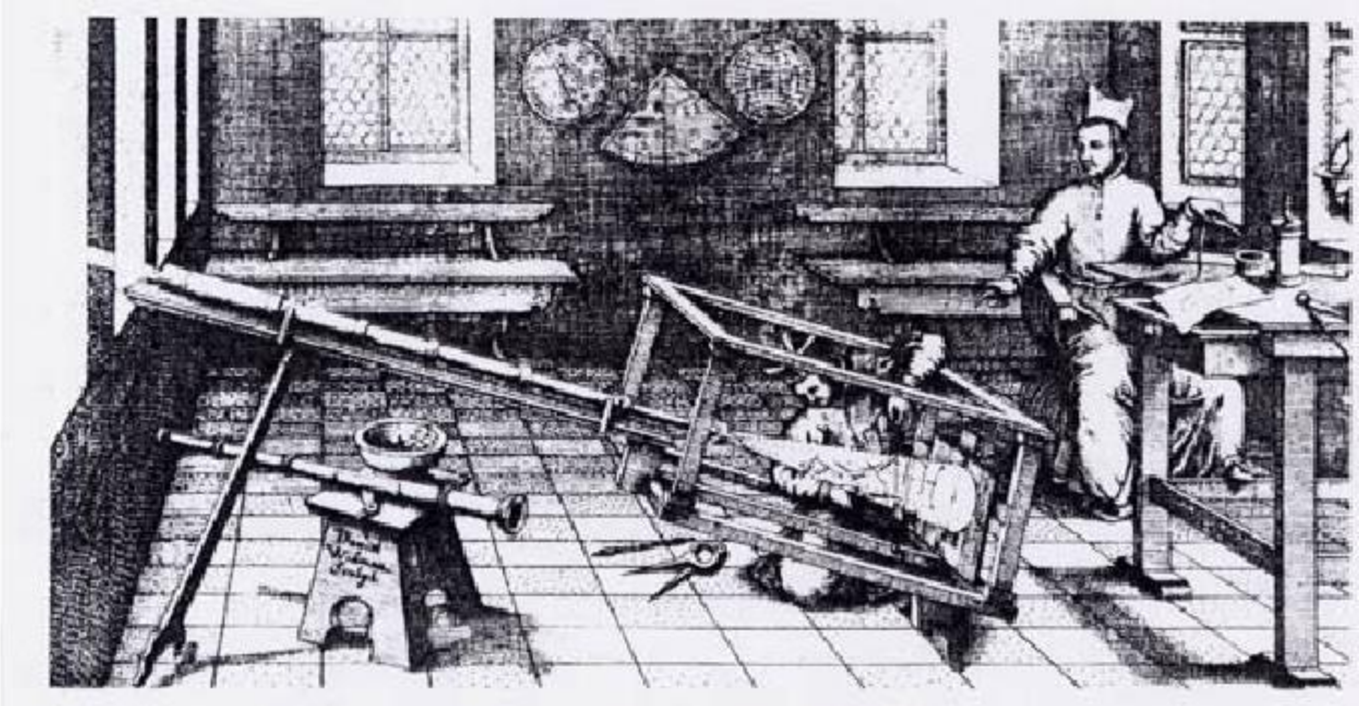




HERA hall North
(former H1 experiment at HERA)

Axions from the sun

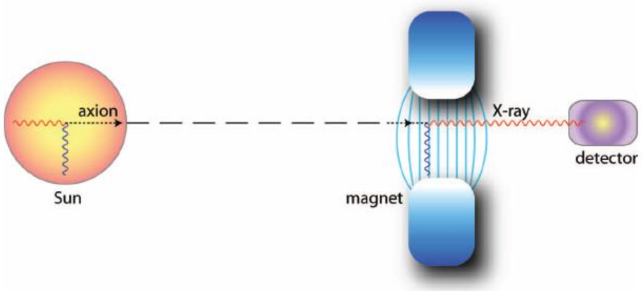
Helioscopes

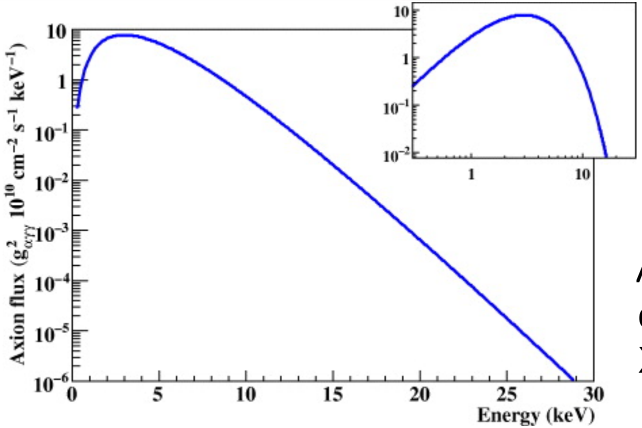


Father Christoph Scheiner
(1575 – 1650)

Axions from the sun: CAST at CERN

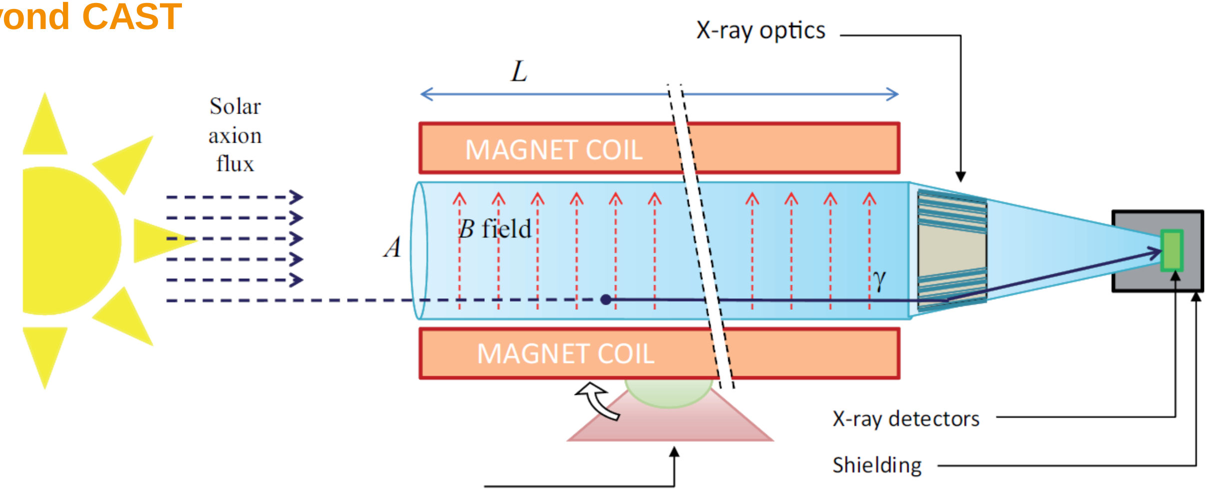
LHC prototype magnet pointing to the sun.





Axions or ALPs from the center of the sun would come with X-ray energies, thermal spectrum.

A factor of 10 beyond CAST



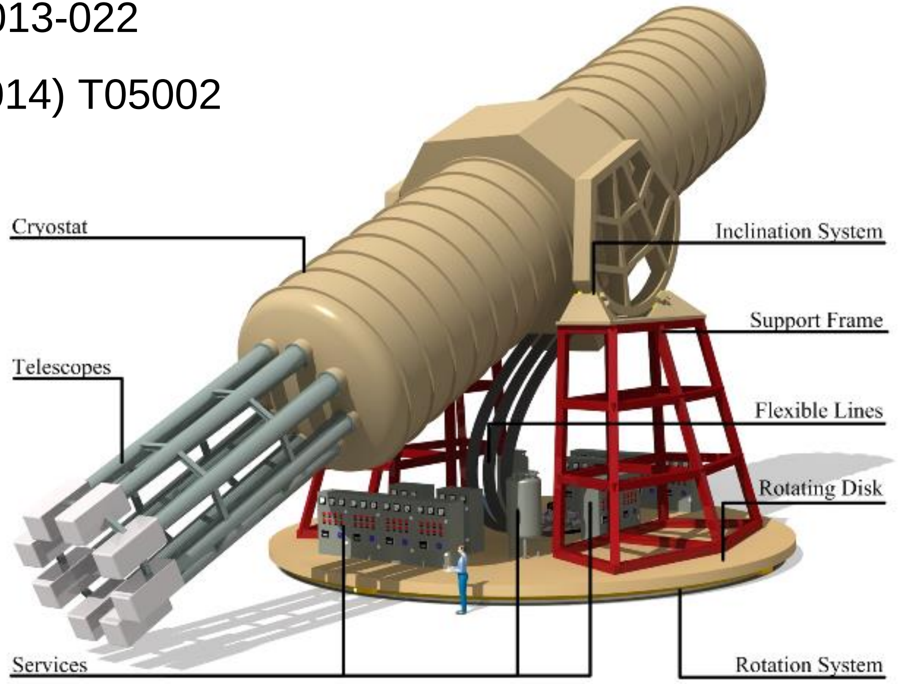
$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

Compared to CAST:	1/17	1/300	1/3.5

International Axion Observatory IAXO

Baseline

- IAXO Letter of Intent: CERN-SPSC-2013-022
- IAXO Conceptual Design: JINST 9 (2014) T05002



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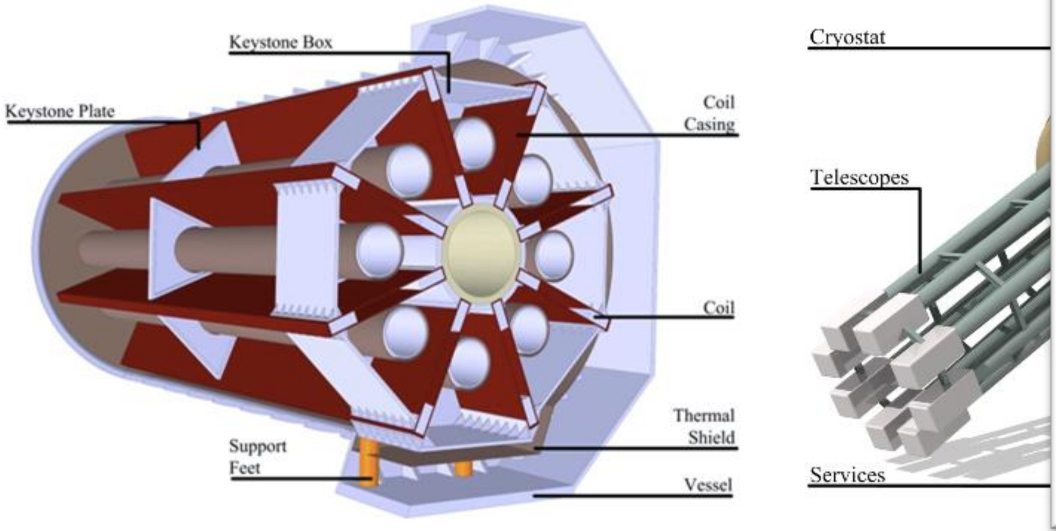


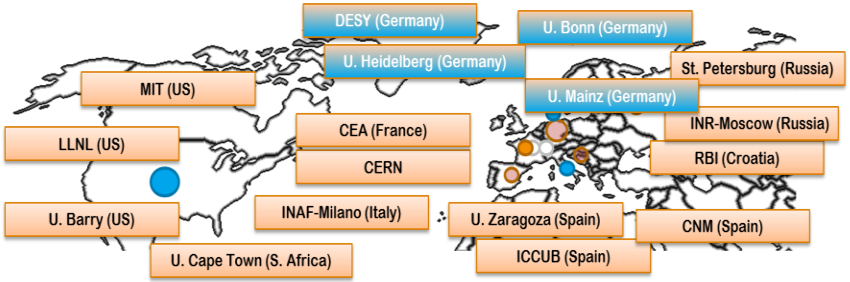
Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	$\sim$ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	$\sim$ 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

International Axion Observatory IAXO

Summary

Collaboration:

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

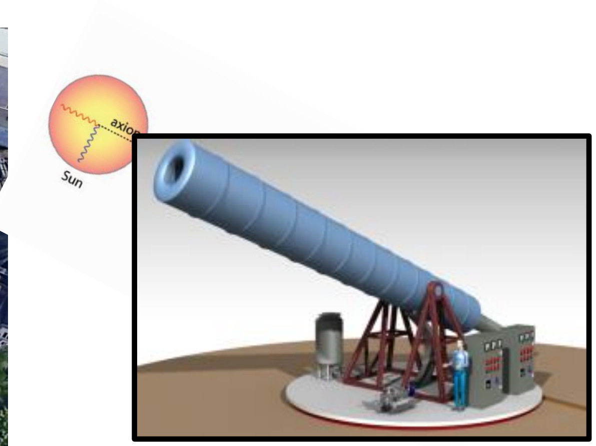


Experiment:

- 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

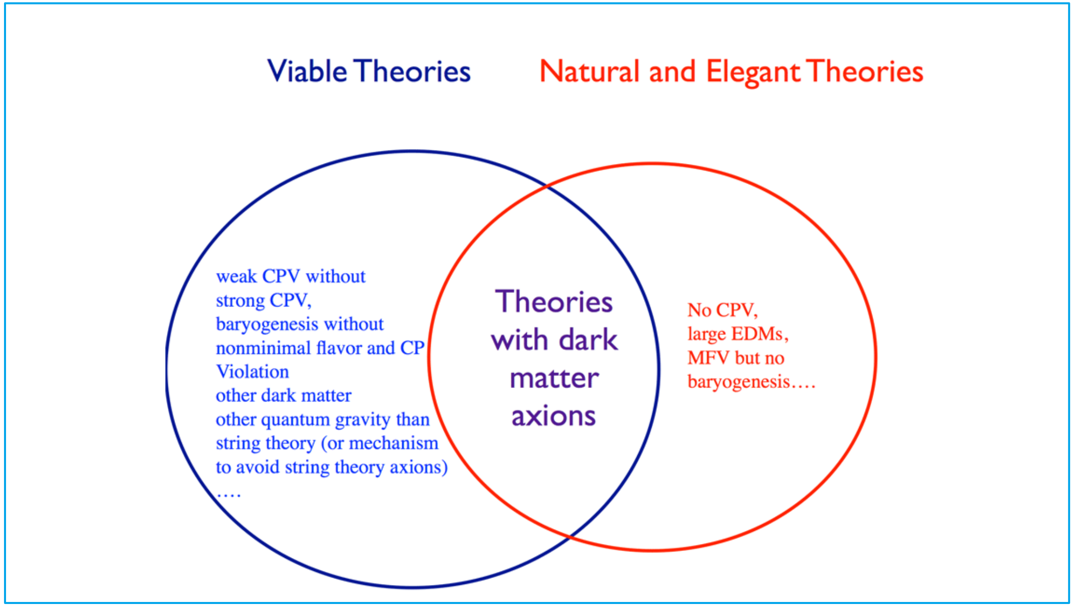
From babyIAXO to the full experiment



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

Dark matter axions

Haloscopes



Ann Nelson, University of Washington

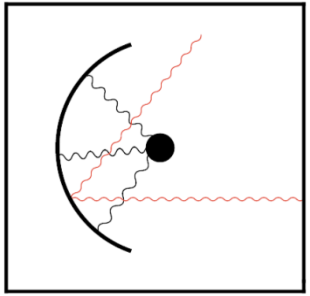
MAgnetized Disc and Mirror Axion eXperiment

Principle

Dish antenna: dark matter axions might convert to photons at the surface of a magnetic mirror.

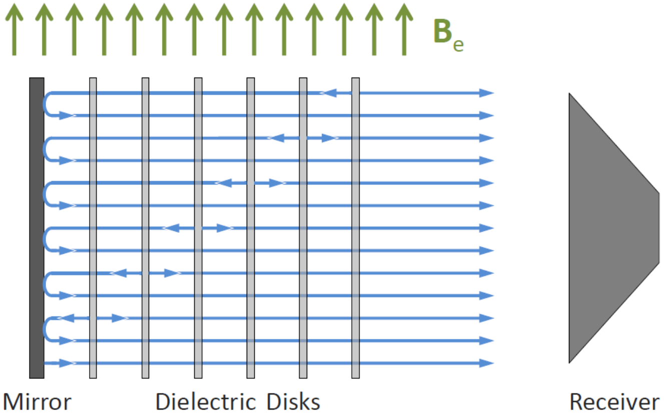
- The discontinuity of ε causes reflection.
- Such photons are emitted perpendicular to the surface.

D. Horns et al, JCAP04(2013)016



MADMAX: combines the dish antenna with a tunable resonating structure out of dielectric disks to boost the axion-photon conversion probability.

- Balance bandwidth and boost factor.
- Access dark matter mass range not reachable with techniques (microwave cavities).



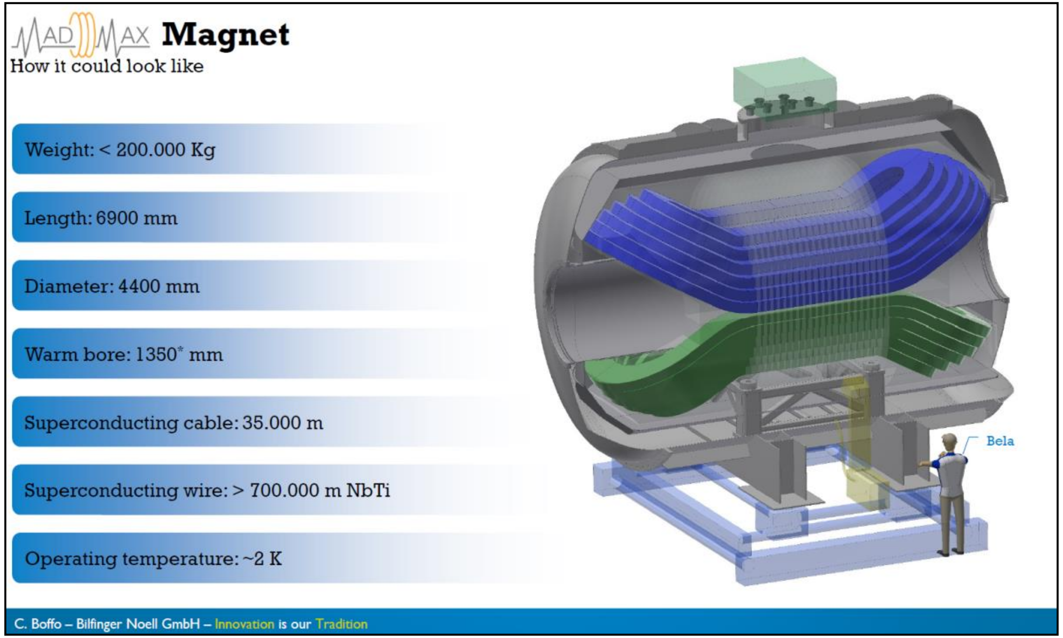
A. J. Millar et al., JCAP 061 (2017)

MAgnetized Disc and Mirror Axion eXperiment

R&D

Critical items:

- provide a large aperture strong dipole magnet to host the “booster” (dielectric disks).

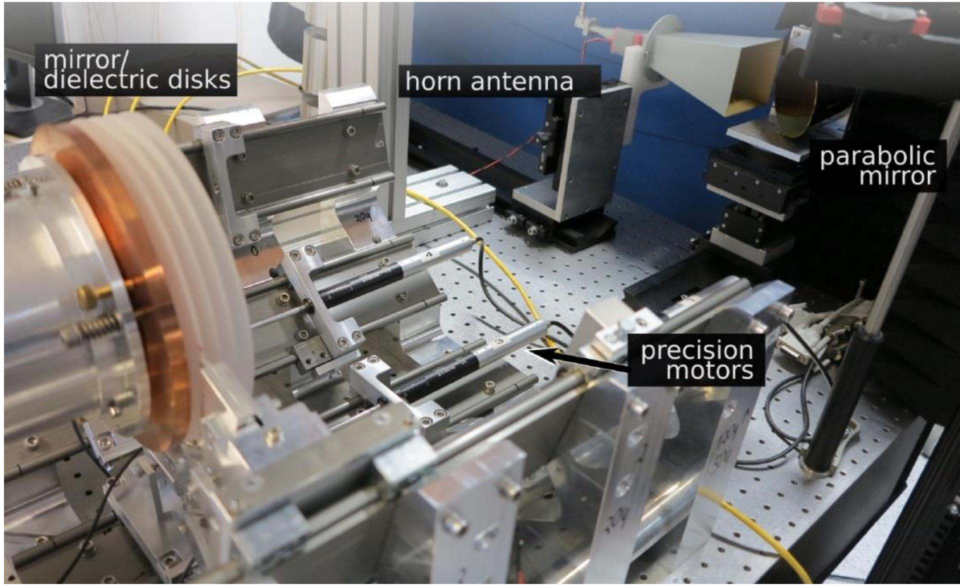


Studies ongoing by Bilfinger-Noell and CEA Saclay.

R&D

Critical items:

- provide a large aperture strong dipole magnet to host the "booster" (dielectric disks).
- Understand and construct the "booster".
  - Up to 80 Sapphire or $LaAlO_3$ discs with $A=1m^2$ to be positioned with µm accuracy on 2 m.



Test setup at MPI Munich

MAgnetized Disc and Mirror Axion eXperiment

R&D

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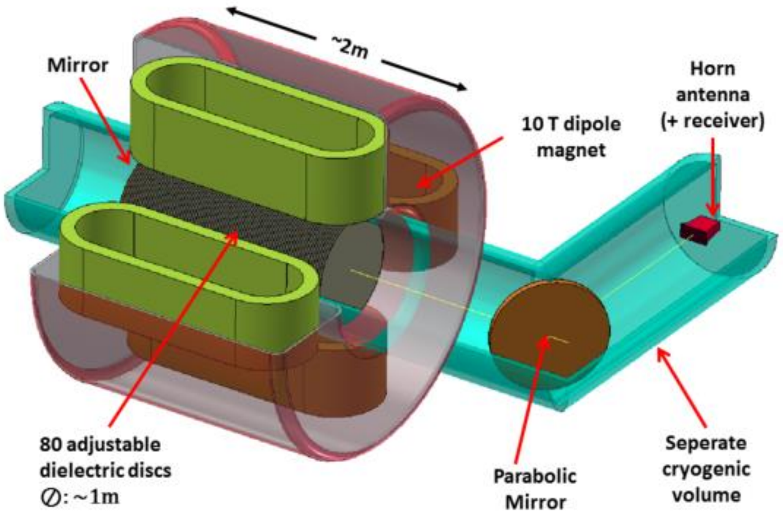


MAgnetized Disc and Mirror Axion eXperiment

Status

Collaboration:

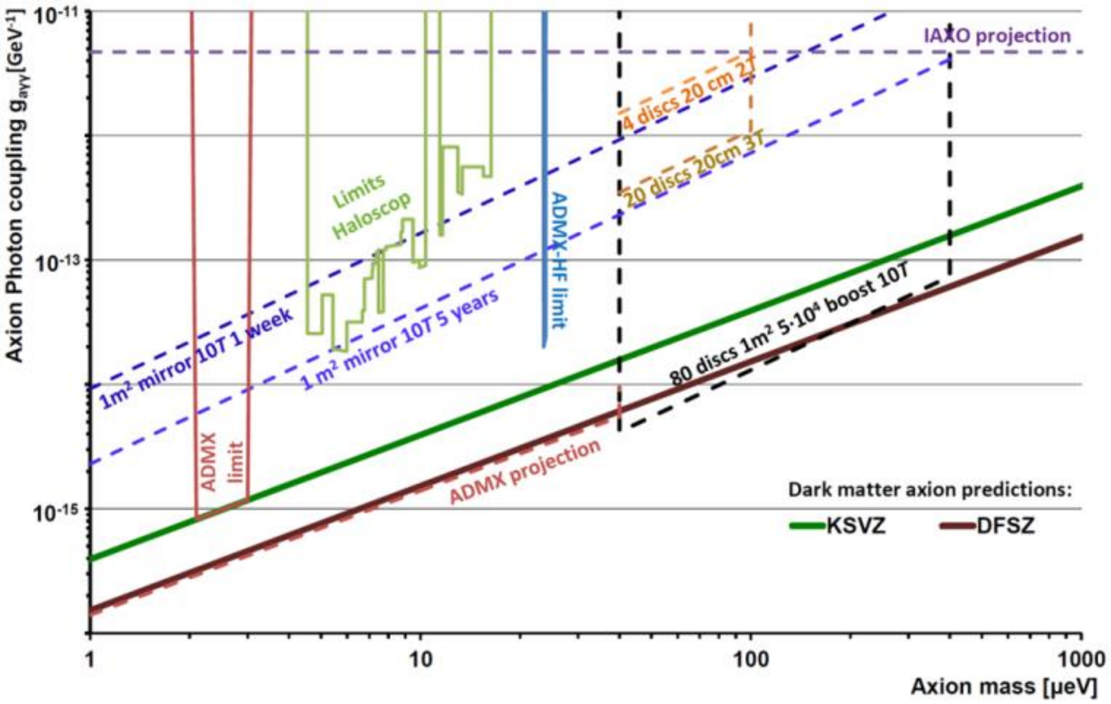
- 8 Institutes from 3 countries.
- Formal collaboration founding 20 October 2017 at DESY.

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

MADMAX reach



Community building

http://axion-wimp.desy.de

The "Patras" workshop series started 2008 at DESY… and will be back in 2018!

Summary

Axion and axion-like particle physics

- is very well motivated by theory, cosmology and astro(particle)physics,
- ALPS II will be the first experiment probing the astrophysics hints on ALPs.

ALPS II

- is close to finishing the R&D phase with very good perspectives to reach (most of) the specifications of the 2012 TDR.

With IAXO and MADMAX in addition

- DESY might become (also) a center for experimental axion physics with
- some risks, but potentially high rewards!