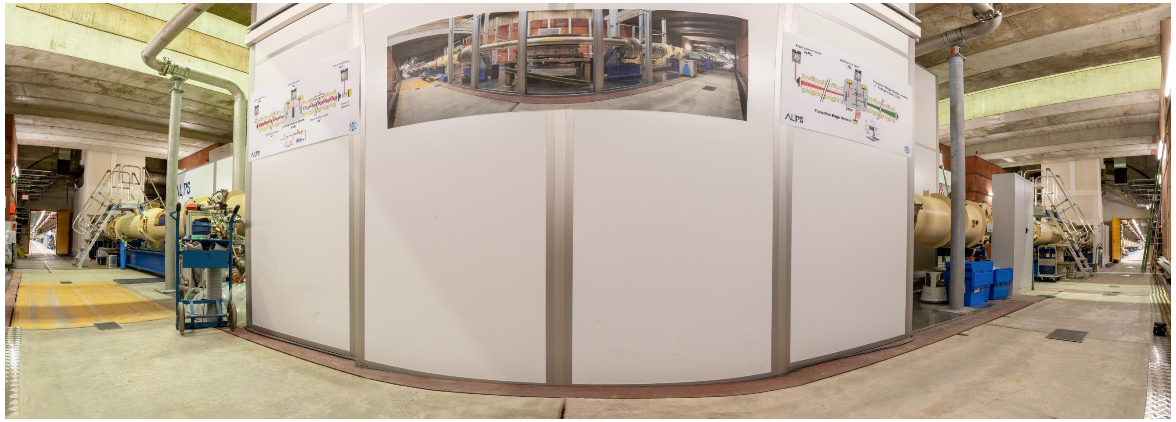
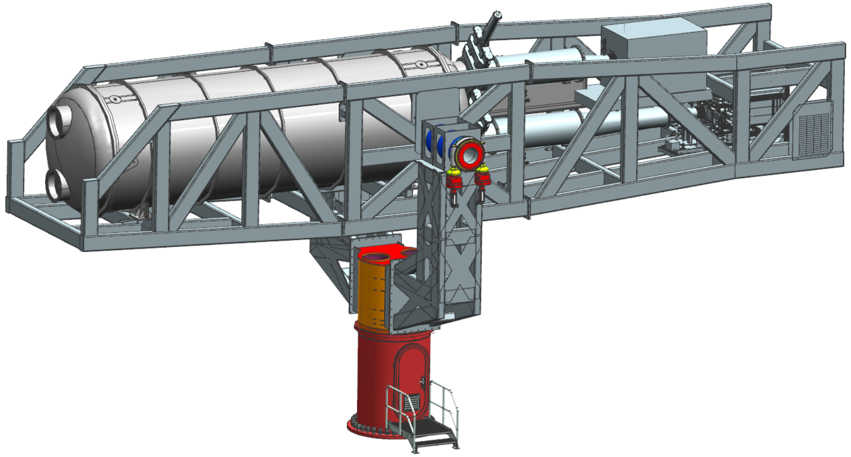
The DESY axion search program

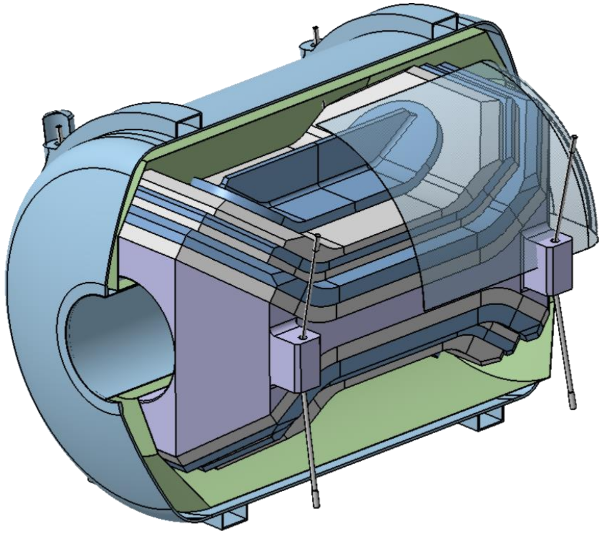
New scientific life in the HERA infrastructure with ALPS II, BabyIAXO, MADMAX



FIPs 2022 Workshop
CERN, 17 October 2022

Axel Lindner
DESY





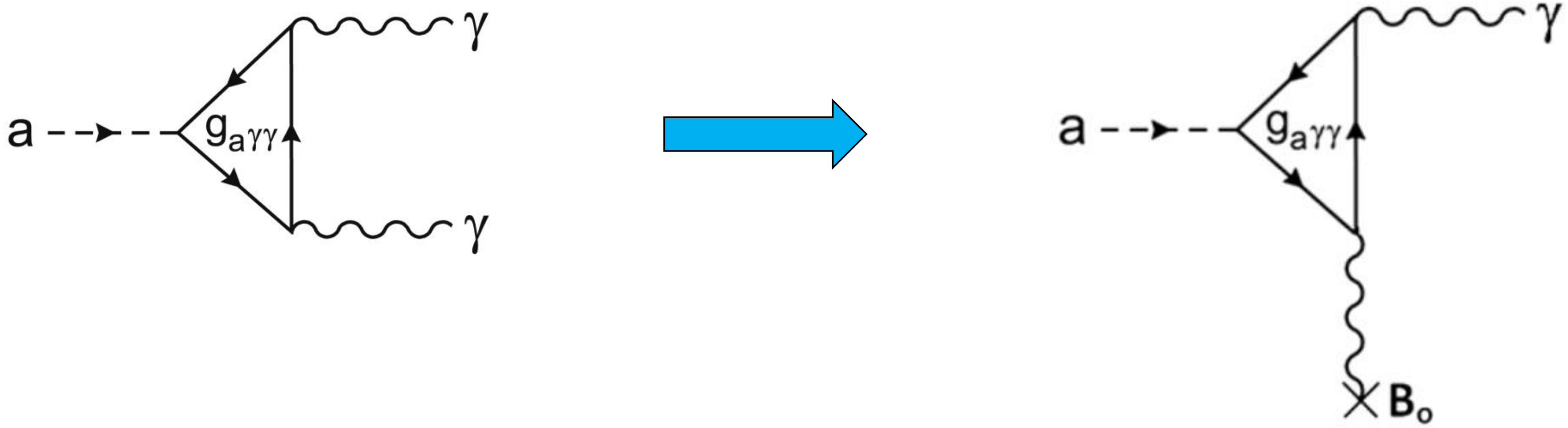
Outline

- Axions:
  - A very brief motivation.
  - Three kinds of experiments.
- Axions @ DESY:
  - MADMAX
  - (Baby)IAXO
  - ALPS II
- Conclusions

Axions

Photon coupling

Exploited by many experiments as relatively “simple”.



Axions

Photon coupling

Exploited by many experiments as relatively “simple”.

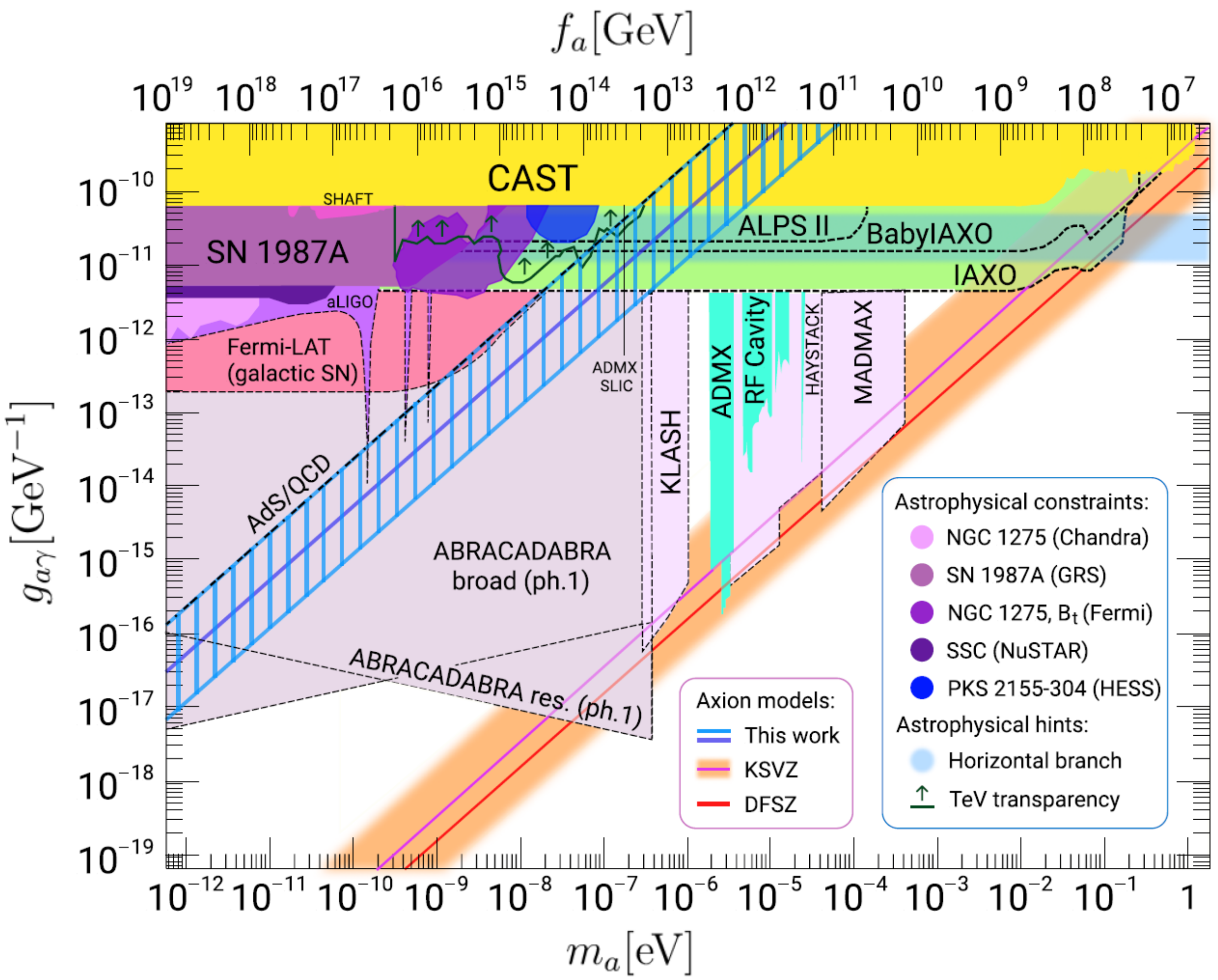
Be aware of model dependencies of $g_{a\gamma}$.

Traditional benchmarks:

- DFSZ (Dine, Fischler, Srednicki, Zhitniskii): axions couple to fermions.
- KSVZ (Kim, Shifman, Vainshetein, Zakharov): axions couple to BSM quarks only.

Recent benchmark (example):

Sokolov, A.V., Ringwald,
A. Photophilic hadronic axion from
heavy magnetic monopoles.
J. High Energ. Phys. **2021,** 123 (2021).

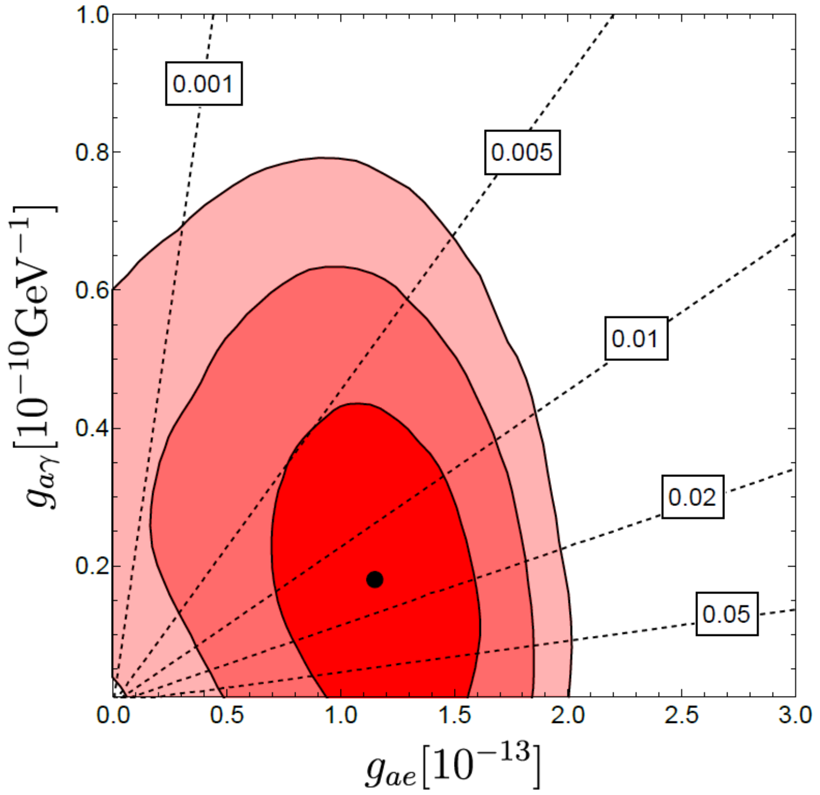


Axions /ALPs

Evidences from astrophysics?

Lightweight axions / ALPs might explain

- puzzles in the evolution of stars



Luca Di Luzio *et al* JCAP02(2022)035

Axions /ALPs

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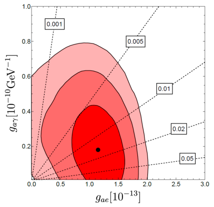
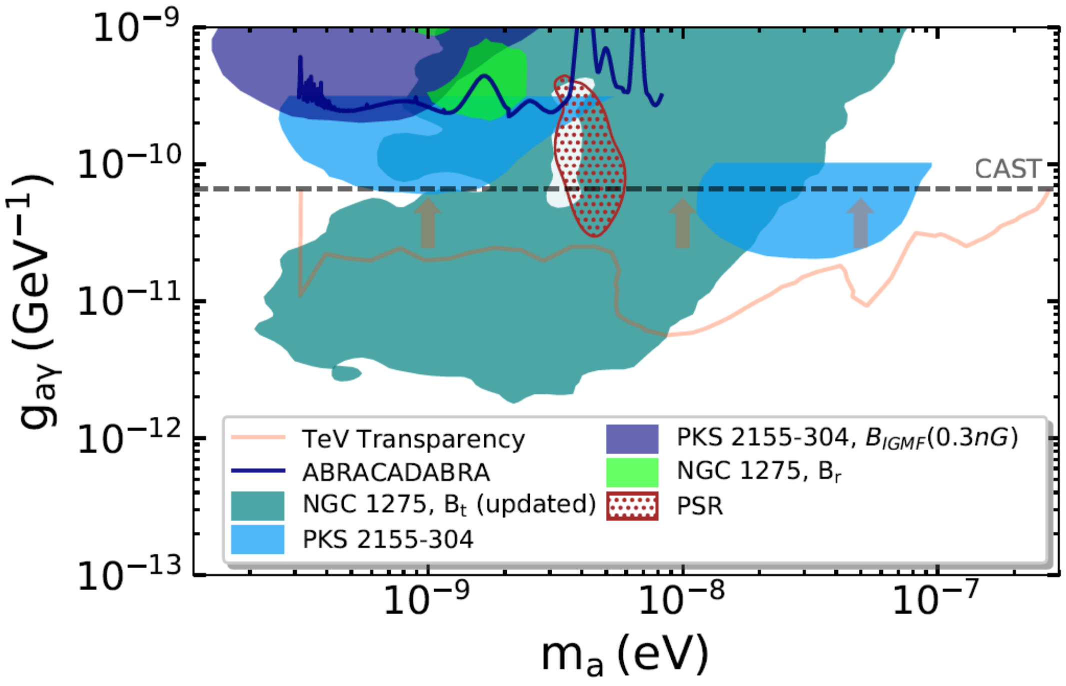


- features in high energy photon spectra



A.P. Gautham *et al* JCAP11(2021)036

Axions /ALPs

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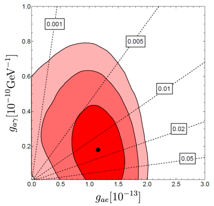
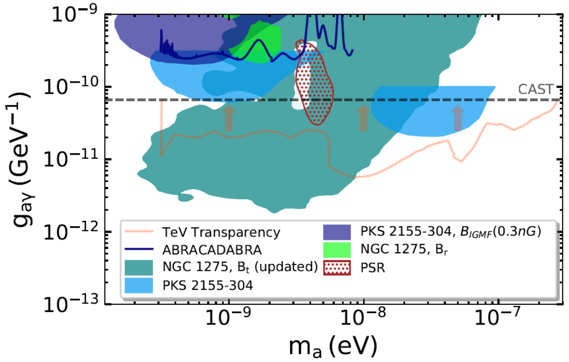


- features in high energy photon spectra



- hints for a too large TeV photon transparency.

All these effects hint at photon couplings $g_{a\gamma\gamma} = 10^{-12}$ to 10^{-10} 1/GeV.

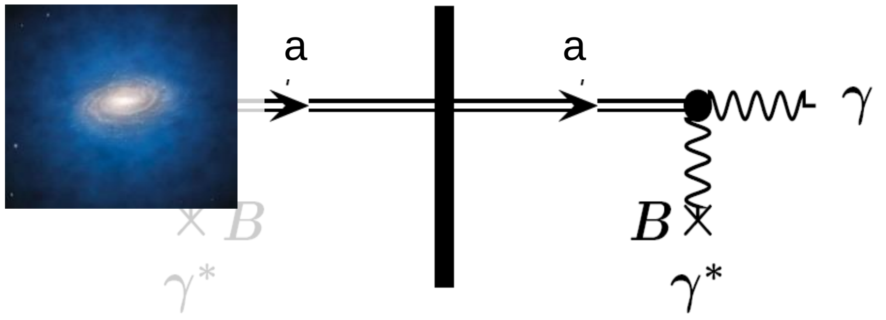
Complement Dark Matter axion searches with other approaches!

- DM search limits don't tell anything about the existence of axions.

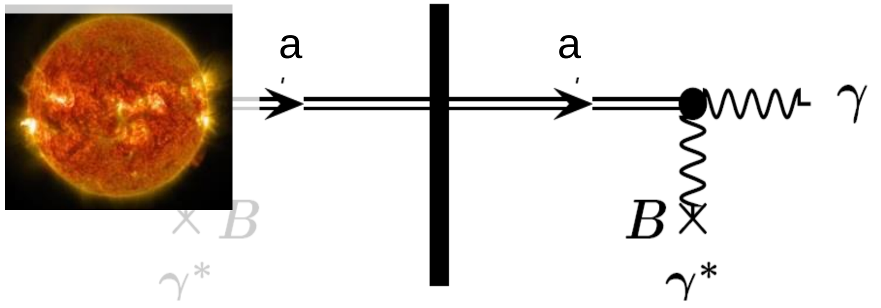
How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

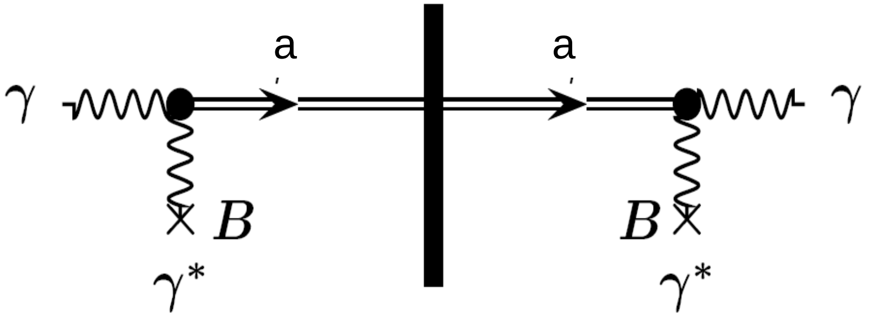
- Haloscopes
  looking for dark matter constituents,
  microwaves



- Helioscopes
  Axions emitted by the sun,
  X-rays



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



How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

- Haloscopes
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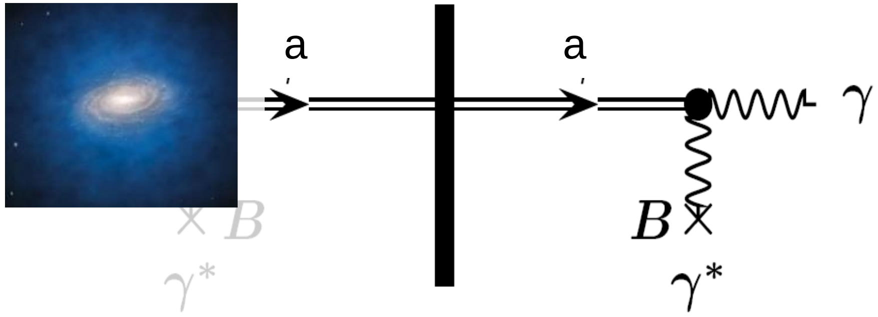
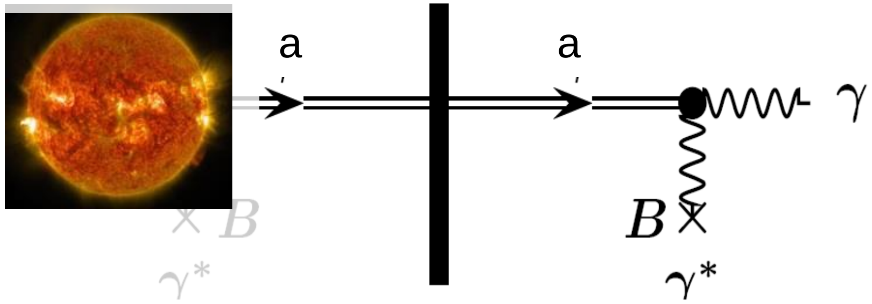
non-relativistic
axions,
“monochromatic”
photons



- Helioscopes
  Axions emitted by the sun,
  X-rays

relativistic axions,
thermal photon
spectrum



- Purely laboratory experiments
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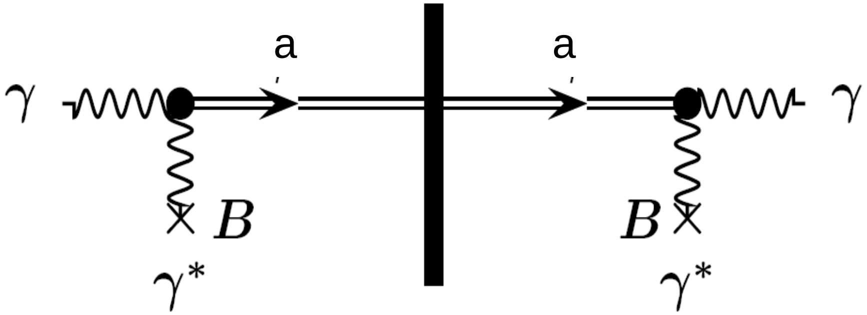
relativistic axions,
monochromatic
photons

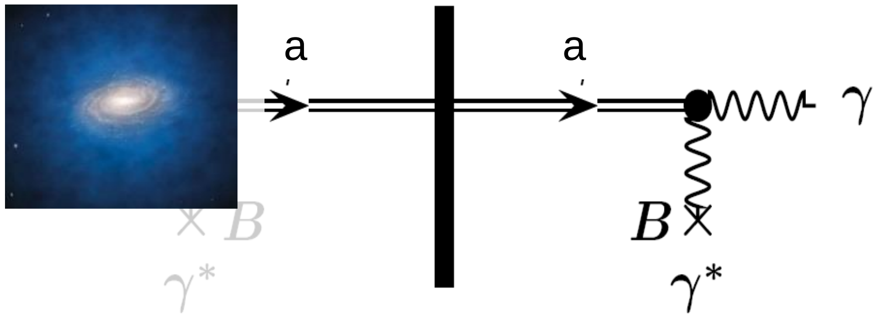


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields, targeted sensitivity

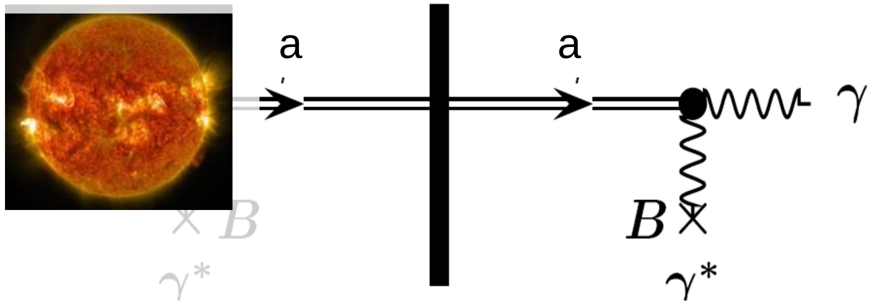
- Haloscopes
  looking for dark matter constituents,
  microwaves.

  10^{-23} W
  exploit resonant
  detection



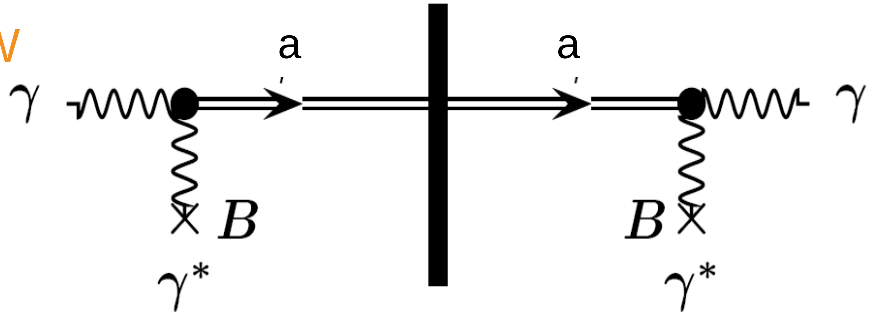
- Helioscopes
  Axions emitted by the sun,
  X-rays

  1 photon/year
  (10^{-23} W)



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

  1 photon/day, $5 \cdot 10^{-24}$ W
  exploit resonant
  detection / generation



How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

- Haloscopes
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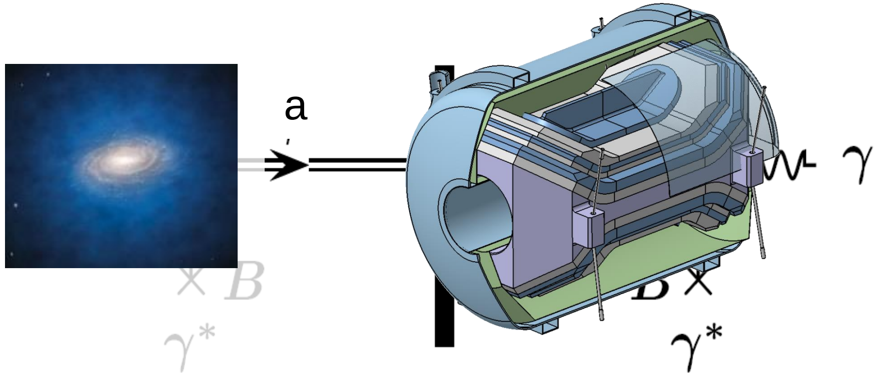
MADMAX



- Helioscopes
  Axions emitted by the sun,
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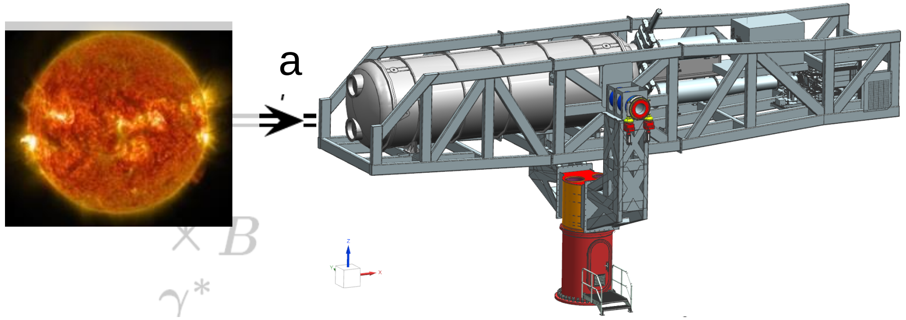
BabyIAXO



- Purely laboratory experiments
  “light-shining-through-walls”,
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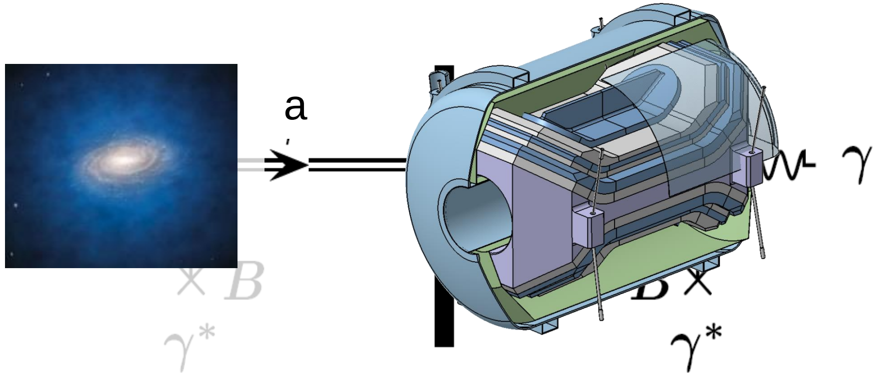
ALPS II

How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

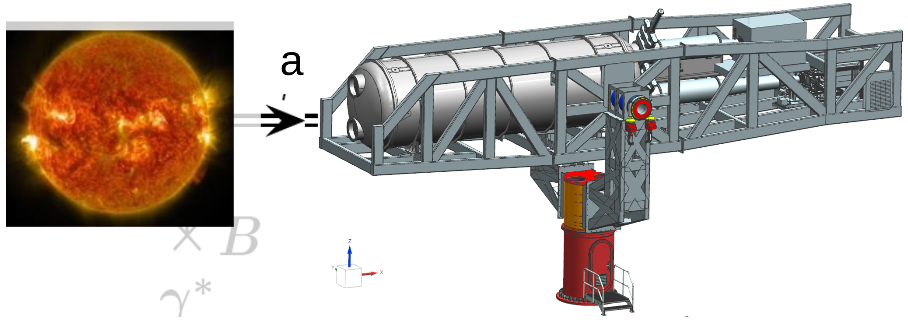
- Haloscopes
  looking for dark matter constituents, microwaves.

MADMAX



- Helioscopes
  Axions emitted by the sun, X-rays

BabyIAXO



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

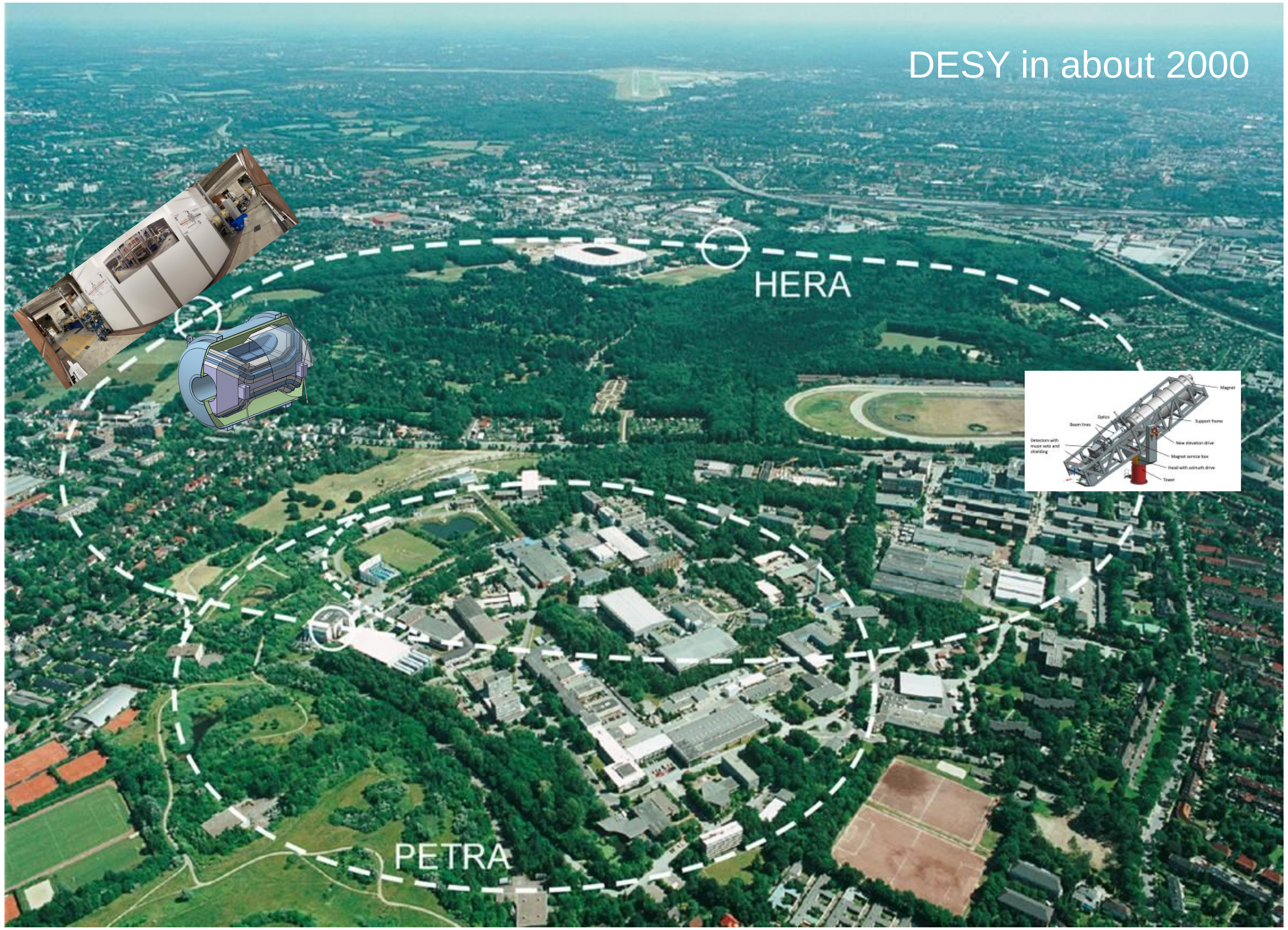
ALPS II
1st science run soon!

Infrastructure at DESY in Hamburg

Re-using HERA

Infrastructure at DESY in Hamburg

Re-using HERA



Outline

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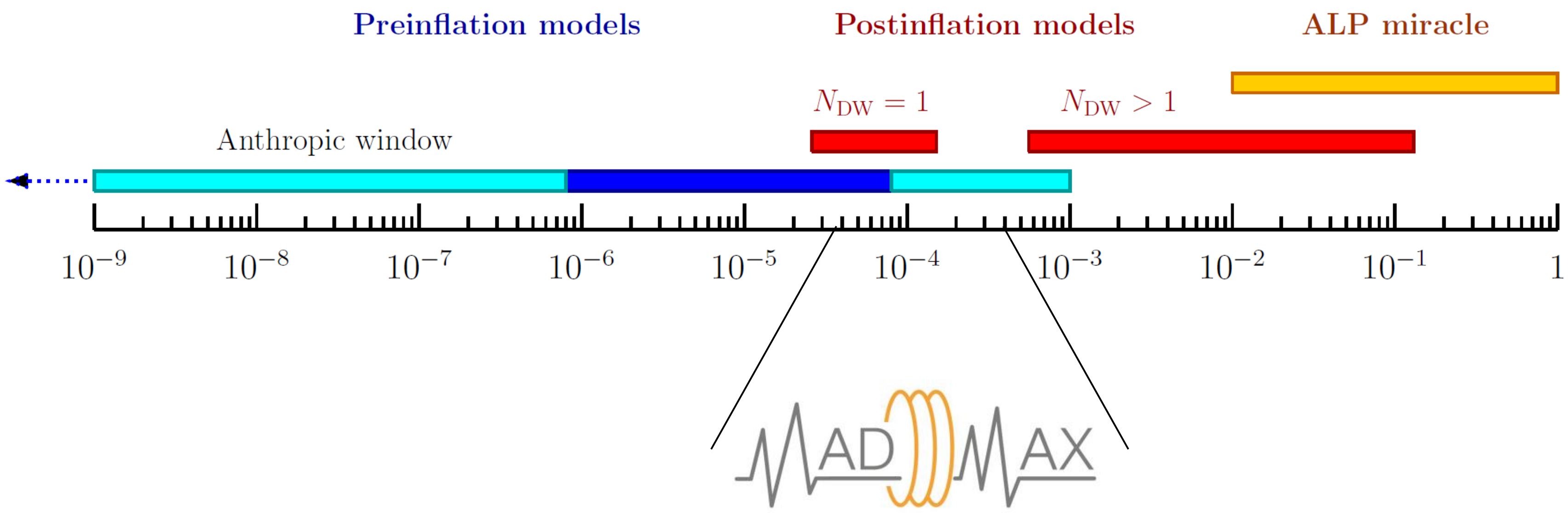
MAgnetized Disc and Mirror Axion eXperiment

Direct dark matter search

Physics goal: find axion dark matter in the mass range predicted by

- postinflation models (PQ symmetry breaking after inflation),
- high mass region of preinflation models.



Igor G. Irastorza, Javier Redondo, Progress in Particle and Nuclear Physics,
Volume 102, 2018,

MAgnetized Disc and Mirror Axion eXperiment

https://madmax.mpp.mpg.de/

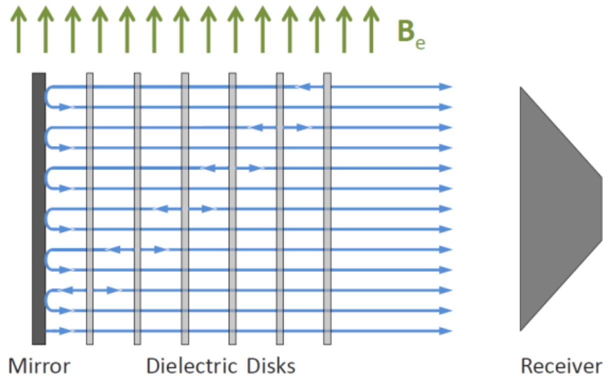
- CPPM) France
- DESY Hamburg, Germany
- Néel Institute, Grenoble, France
- **MPI für Physik, Munich, Germany**
- MPI für Radioastronomie, Bonn, Germany
- RWTH Aachen, Germany
- University of Hamburg, Germany
- University of Tübingen, Germany
- University of Zaragoza, Spain

MAgnetized Disc and Mirror Axion eXperiment

How

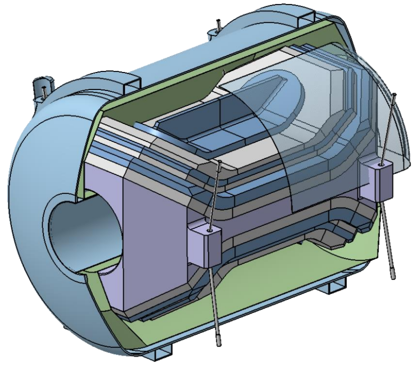
Approach: resonantly enhance axion-photon conversion

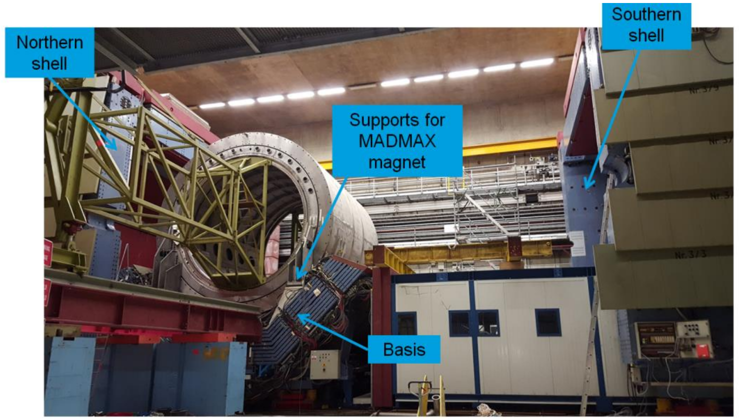
- Photons from DM axion conversion show a very narrow energy distribution (10^{-6}) as the DM axions move with non-relativistic speeds.
- Booster: a stack of dielectric plates inside a strong magnetic dipole field is tuned to the radiofrequencies corresponding to axion in the 100 µeV mass range.
  - The measured power can be enhanced by several 10^4.
  - Tradeoff between bandwidth and “boost factor”.
- Place the booster inside a huge dipole magnet of 10 T with an aperture of 1m.



For details see:

- JCAP 10 (2021) 034
- Eur.Phys.J.C 79 (2019) 3, 186



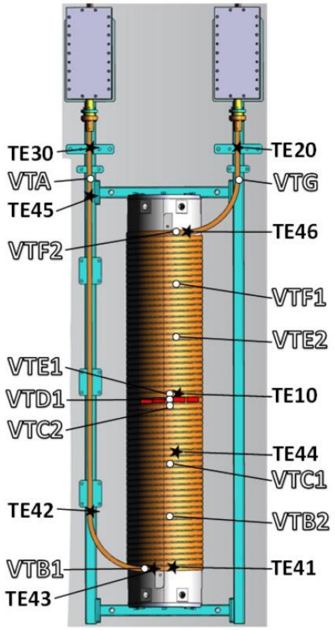


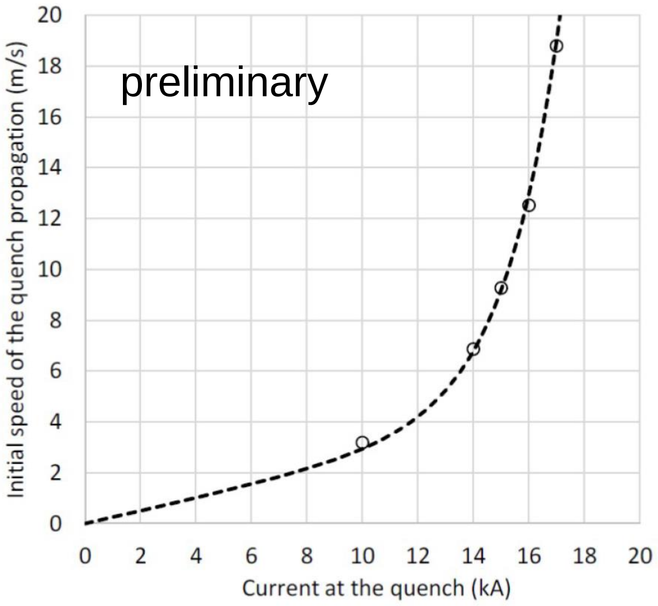
MAgnetized Disc and Mirror Axion eXperiment

Status

Very substantial progress in the prototyping phase:

- Magnet:
    - Conceptual design.
    - Very successful conductor test at CEA / Saclay on quench propagation velocity.





Quench can be detected in 0.1 to 1 s.
Main risk of the magnet project fully mitigated!

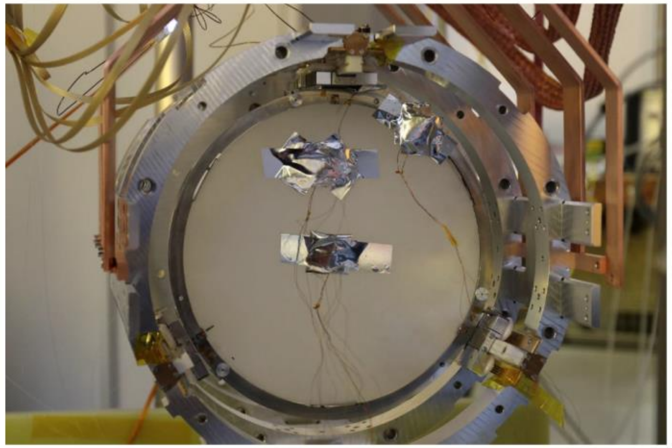
MAgnetized Disc and Mirror Axion eXperiment

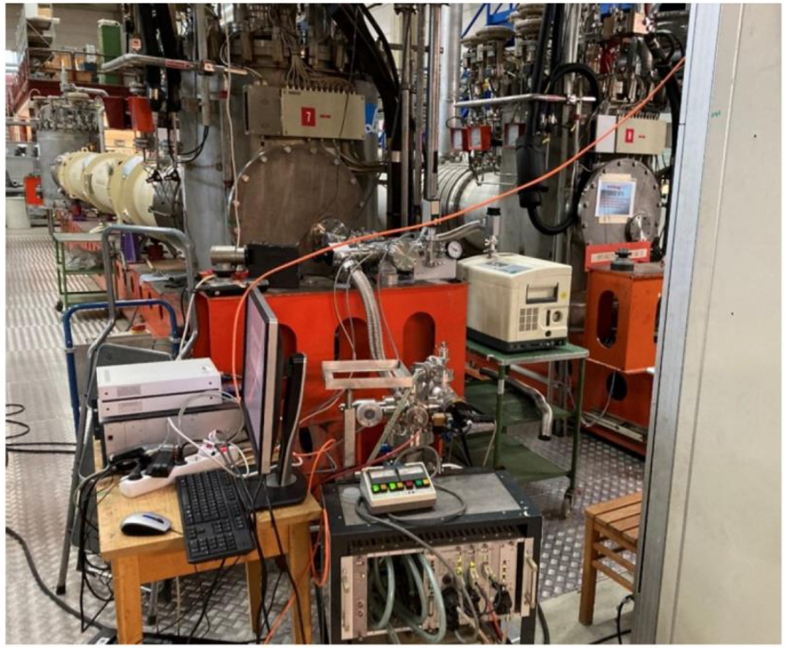
Status

Very substantial progress in the prototyping phase:

- Magnet:
  - Conceptual design.
  - Very successful conductor test at CEA / Saclay.
- Enabling technologies:
  - Dielectric disk handling and mounting.
  - Piezo motor tests (vacuum, cryogenics, magnetic field)

Successful tests at CERN
and an ALPS II magnet at DESY.





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- Booster understanding:

News › News › Topic: Experiments

Voir en français

MADMAX and CERN’s Morpurgo magnet

A new collaboration, MADMAX, will seize the chance to use a CERN magnet named Morpurgo to test their dark-matter prototype

10 NOVEMBER, 2020 | By Thomas Hortala

The Morpurgo magnet, located in the North Area on the Prévessin site, will provide a magnetic field of up to 1,6 Tesla for the MADMAX prototype (Image: CERN)

MADMAX is preparing for a stopover at CERN from 2022. Mel Gibson, his artillery and quest for revenge will not be there, but instead a handful of physicists armed with an aged magnet will be searching for dark matter in CERN’s North Area (not to be confused with a post-apocalyptic wasteland).

Indeed, the MADMAX collaboration (MAgnetized Disks and Mirror Axion eXperiment, external to CERN), humbly proposes to identify the nature of dark matter and to solve the enigma of the absence of so-called charge-parity (CP) symmetry violation in the strong sector, while detecting a particle that has eluded physicists for decades: axions.

MAgnetized Disc and Mirror Axion eXperiment

Status

Very substantial progress in the prototyping phase:

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  - Conceptual design.
  - Very successful conductor test at CEA / Saclay.
- Enabling technologies:
  - Dielectric disk handling and mounting.
  - Piezo motor tests (vacuum, cryogenics, magnetic field)
- Booster understanding:
  - Series of prototype tests started at CERN, in future also at Hamburg University.
  - **Complex booster calibration method developed at MPP Munich!**

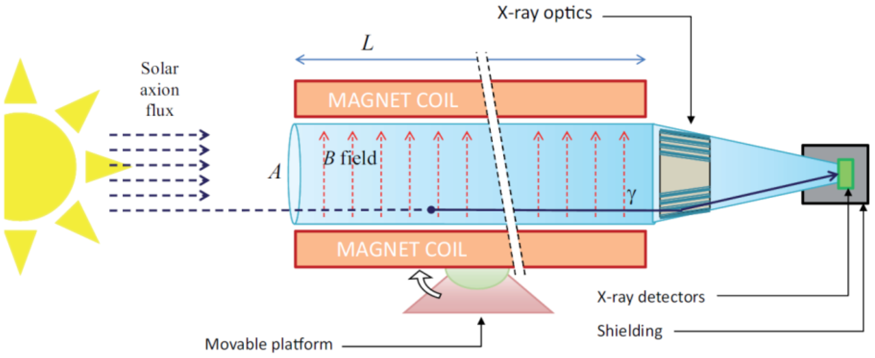
Further schedule beyond using MORPURGO depends on availability of funds.

Prototype at MORPURGO / CERN

(Baby) International AXion Observatory

Looking for solar axions

Annual Review of Nuclear and Particle Science, Vol. 65: 485-514 (2015)

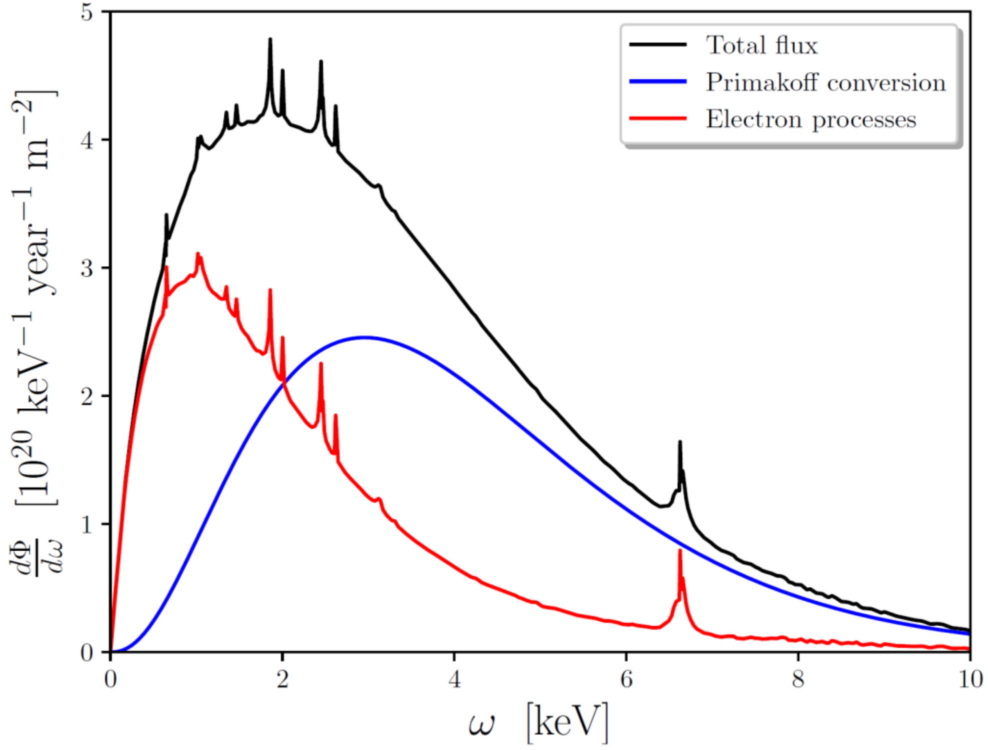


Solar axions produced via

- the Primakoff effect (axion-photon coupling),
- axion-electron coupling,
- axion-nucleon coupling
  (14.4 keV from ^{57}Fe).

Eur.Phys.J.C 82 (2022) 2, 120

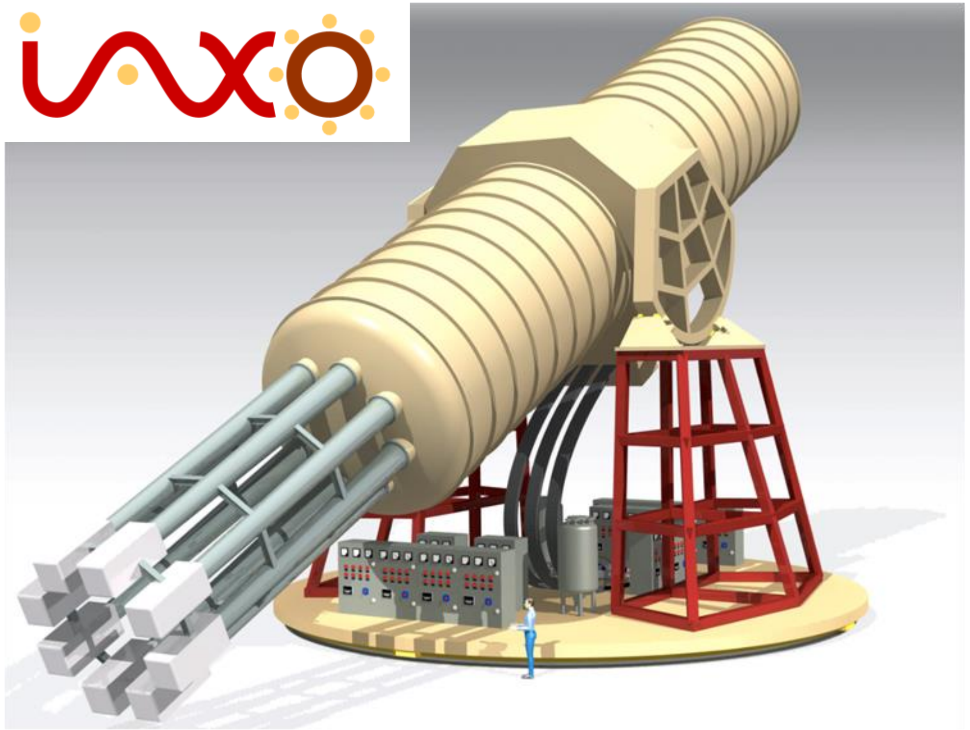
Successor of the CERN Axion Solar Telescope.



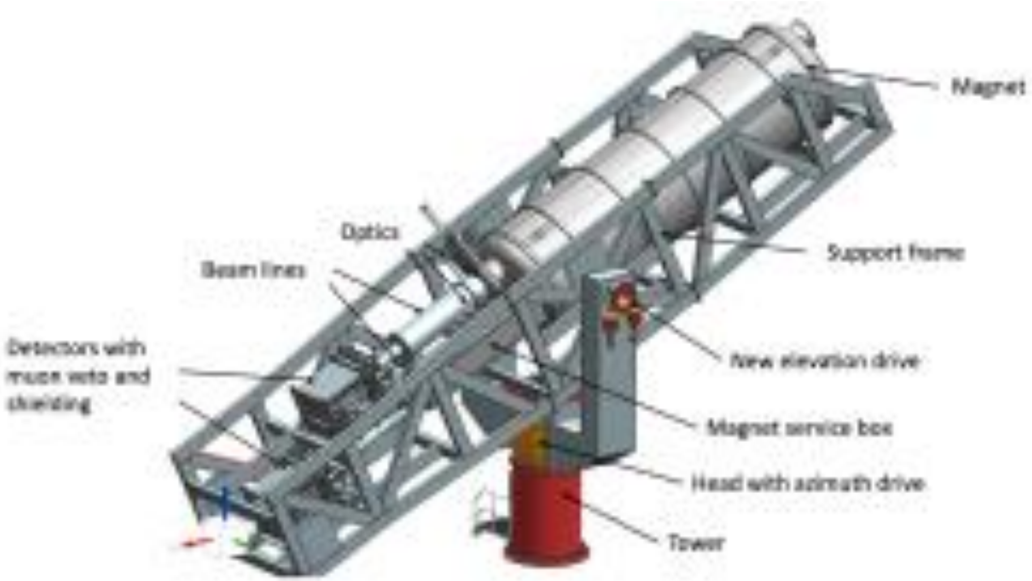
"Distinguishing Axion Models with IAXO"
J. Jaeckel, L.J. Thormaehlen, JCAP 03 (2019), 039

(Baby) International AXion Observatory

https://iaxo.desy.de



Baby: the prototype IAXO



For details see:
- JHEP 05 (2021) 137
- JCAP 06 (2019) 047

(Baby) International AXion Observatory

Collaboration

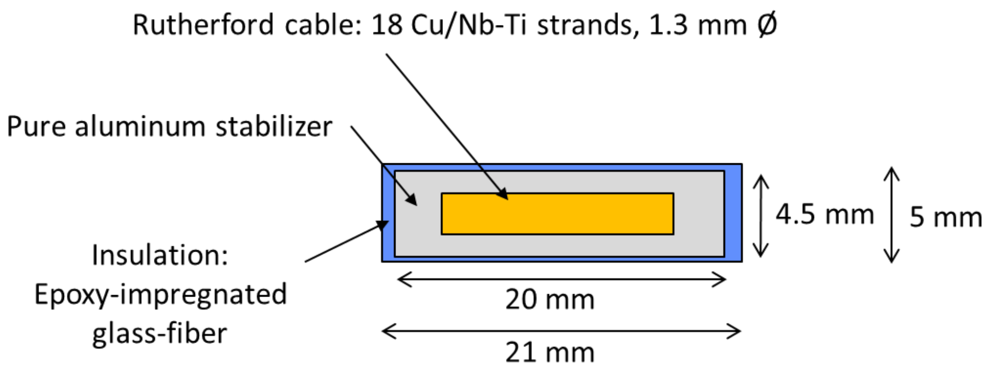
UHEI	WG Gastaldo, Kirchhoff Institute for Physics, Heidelberg University	Germany
CEA	Institut de recherche sur les lois fondamentales de l'Univers, Direction de la recherche fondamentale, CEA	France
UNIZAR	Centre for Astroparticle and High Energy Physics, Universidad de Zaragoza	Spain
CERN		Switzerland
INAF	Istituto Nazionale Astrofisica	Italy
ICCUB	Institut de Ci`encies del Cosmos, Universitat de Barcelona	Spain
PNPI	Petersburg Nuclear Physics Institute, NRC Kurchatov Institute	Russia
USIEGEN	Center for Particle Physics Siegen, Siegen University	Germany
BARRY	Barry University	USA
INR	Institute of Nuclear Research, Russian Academy of Sciences	Russia
CEFCA	Centro de Estudios de Física del Cosmos de Aragón	Spain
UBONN	University of Bonn, Physikalisches Institut	Germany
DESY	Deutsches Elektronen-Synchrotron	Germany
MAINZ	WG Schott, Institute of Physics, University of Mainz	Germany
MIT	Massachusetts Institute of Technology	USA
LLNL	Lawrence Livermore National Laboratory	USA
UCT	University of Cape Town	South Africa
MIPT	Moscow Institute of Physics and Technology	Russia
MPP	Max Planck Institute for Physics	Germany
UPCT	Universidad Politécnica de Cartagena	Spain
UHH	University of Hamburg	Germany

BabyIAXO

Status

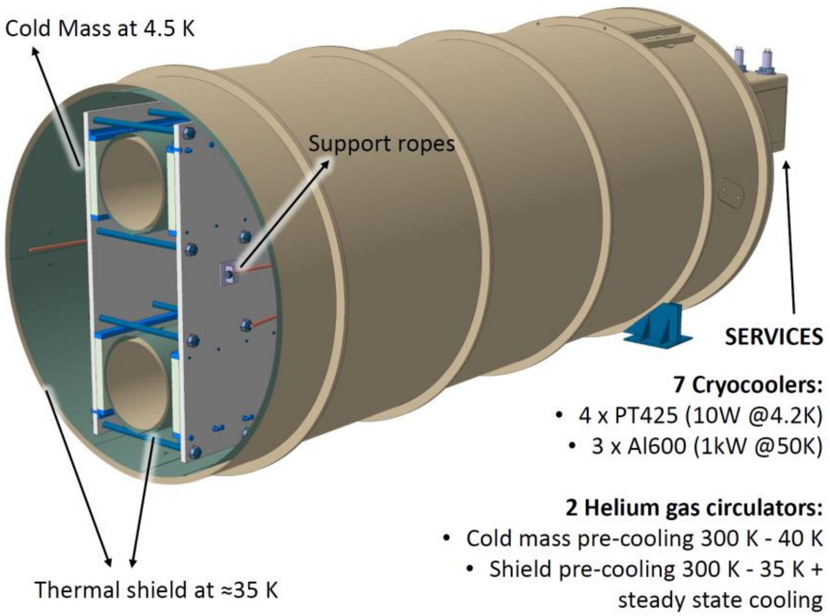
Magnet providing dipole fields in two bores:

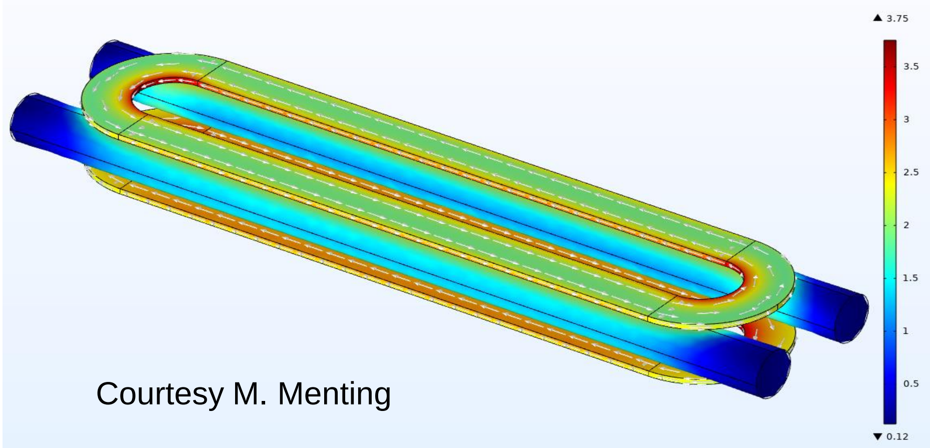
- Challenging concept, “dry” detector magnet.
- Unfortunately, since 24 February 2022
  there is no vendor for an Al-stabilized superconducting cable.
  Time and costs?



Schematic representation

Courtesy M. Menting





Common-coil dipole, with counter-flowing current in two superconducting race-track coils

BabyIAXO

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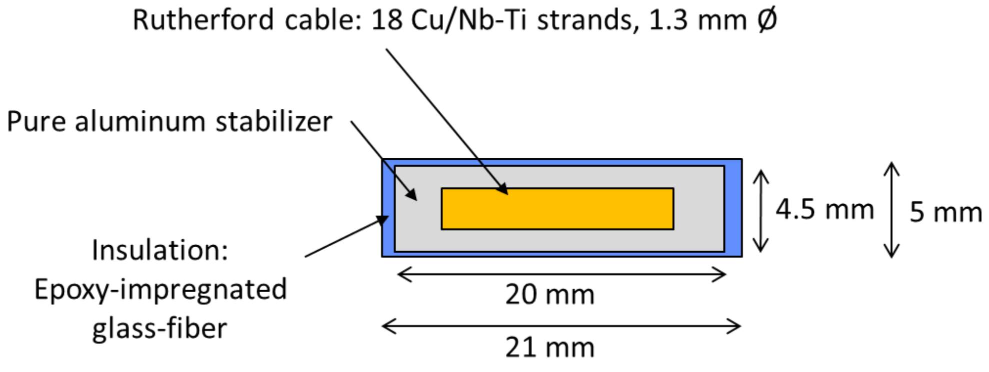

Schematic representation

Dedicated CERN workshop In September 2022 (https://indico.cern.ch/event/1162992/):

- General problem for detector magnets,
- main problem co-extrusion technology,
  not anymore available in western industry,
- no obvious solution where and when to get
  Al-stabilized superconducting cables.

BabyIAXO

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Magnet providing dipole fields in the bores:

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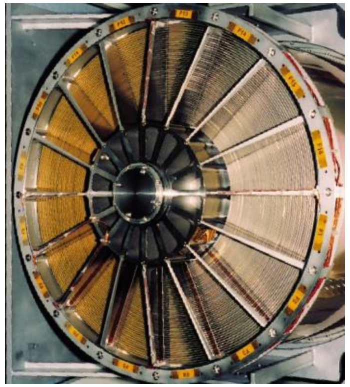
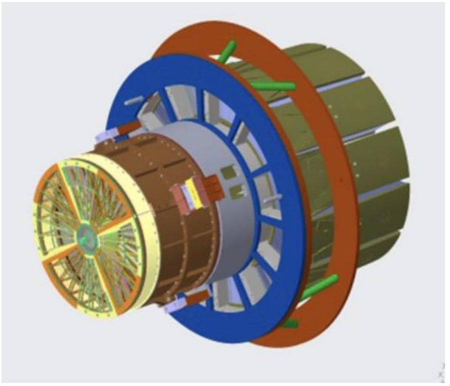


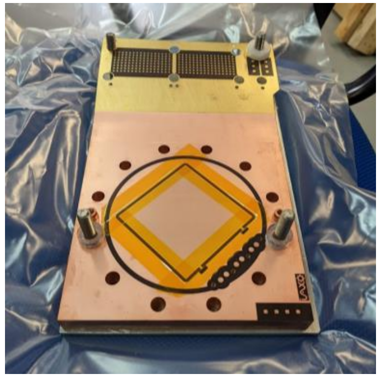


X-ray optics:

- One bore with XMM-Newton flight spare, one custom-made..

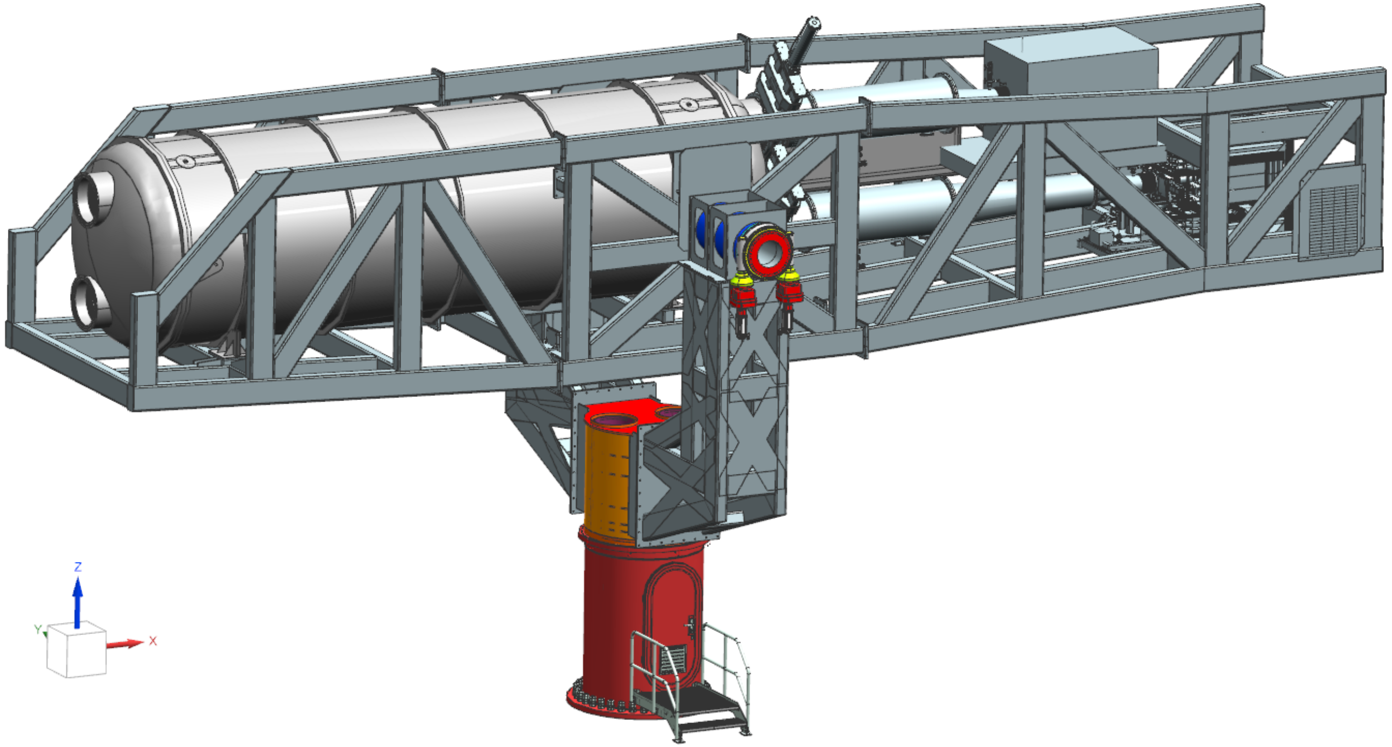
Low-background detector:

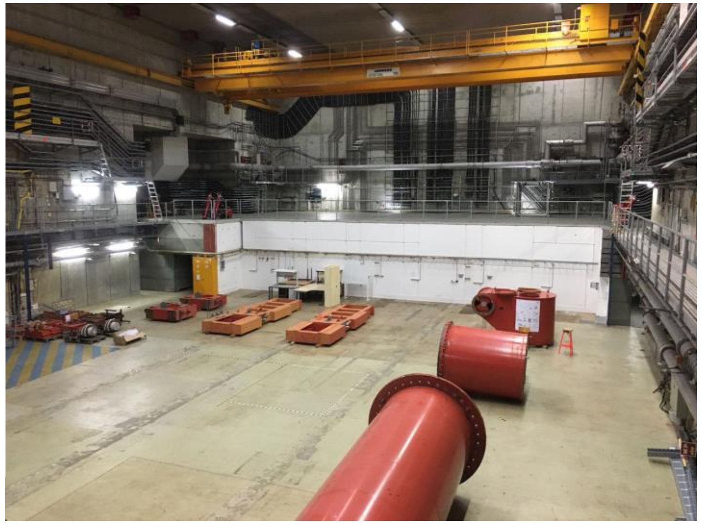
- Final tests of prototype micromegas in Canfranc, multiple detector options (“discovery detectors”, energy resolving detectors).



BabyIAXO

Status





Structure and drive system

- Main design close to be finished, re-use positioner of CTA prototype telescope.

BabyIAXO

Status

Magnet providing dipole fields in the bores:

- Challenging concept, “dry” detector magnet.
- Unfortunately, since 24 February 2022
  there is no vendor for an Al-stabilized superconducting cable.
  Time and costs?

X-ray optics:

- One bore with XMM-Newton flight spare, one custom-made..

Low-background detector:

- Final tests of prototype micromegas in Canfranc, multiple detector options (“discovery detectors”, energy resolving detectors).

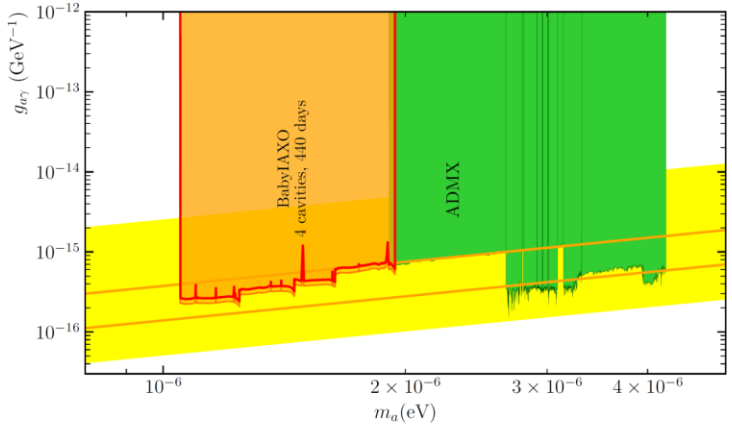
Structure and drive system

- Main design close to be finished, re-use positioner of CTA prototype telescope.

Start data taking in 2028 In HERA-South?

More physics with BabyIAXO:

- Search for halo axions (1-2 μeV) by including RADES.




ALPS II collaboration meeting 06/22

UHH
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
JG|U
DESY.
UF UNIVERSITY of FLORIDA

Collaboration members

ALPS II

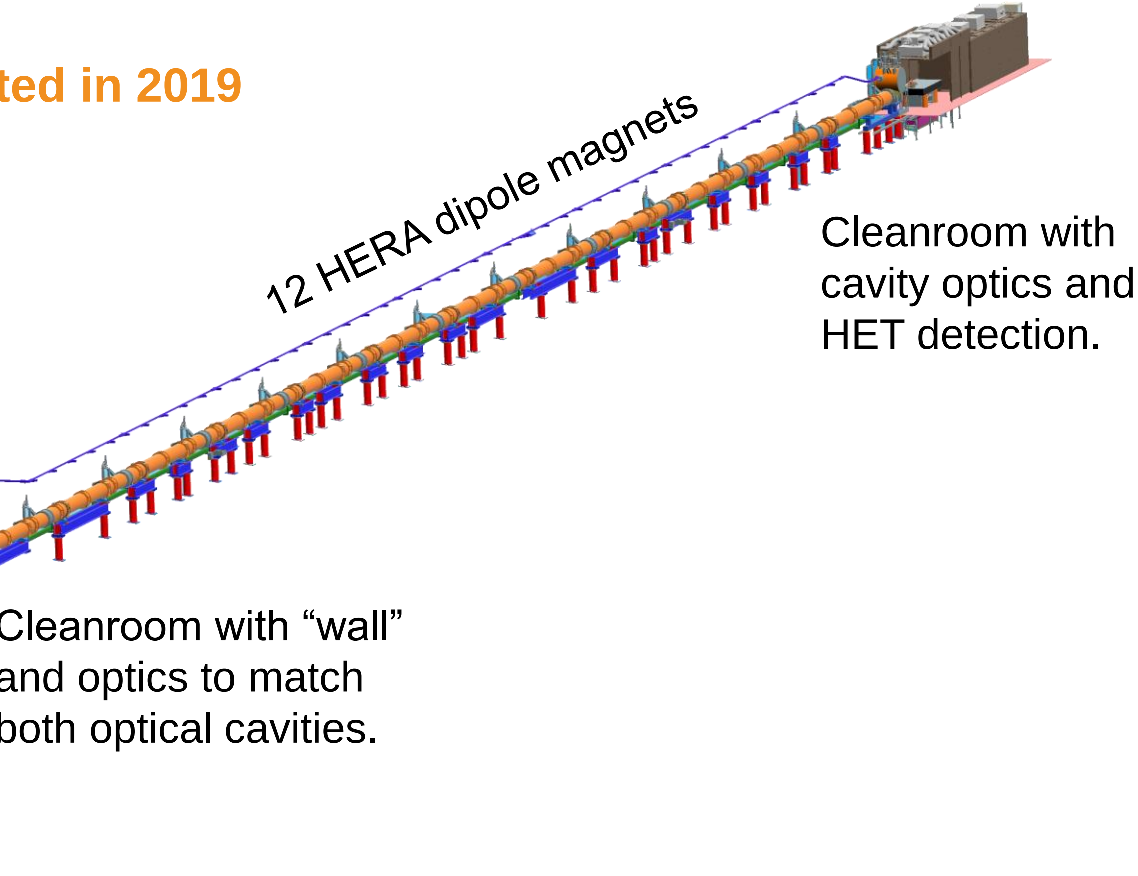
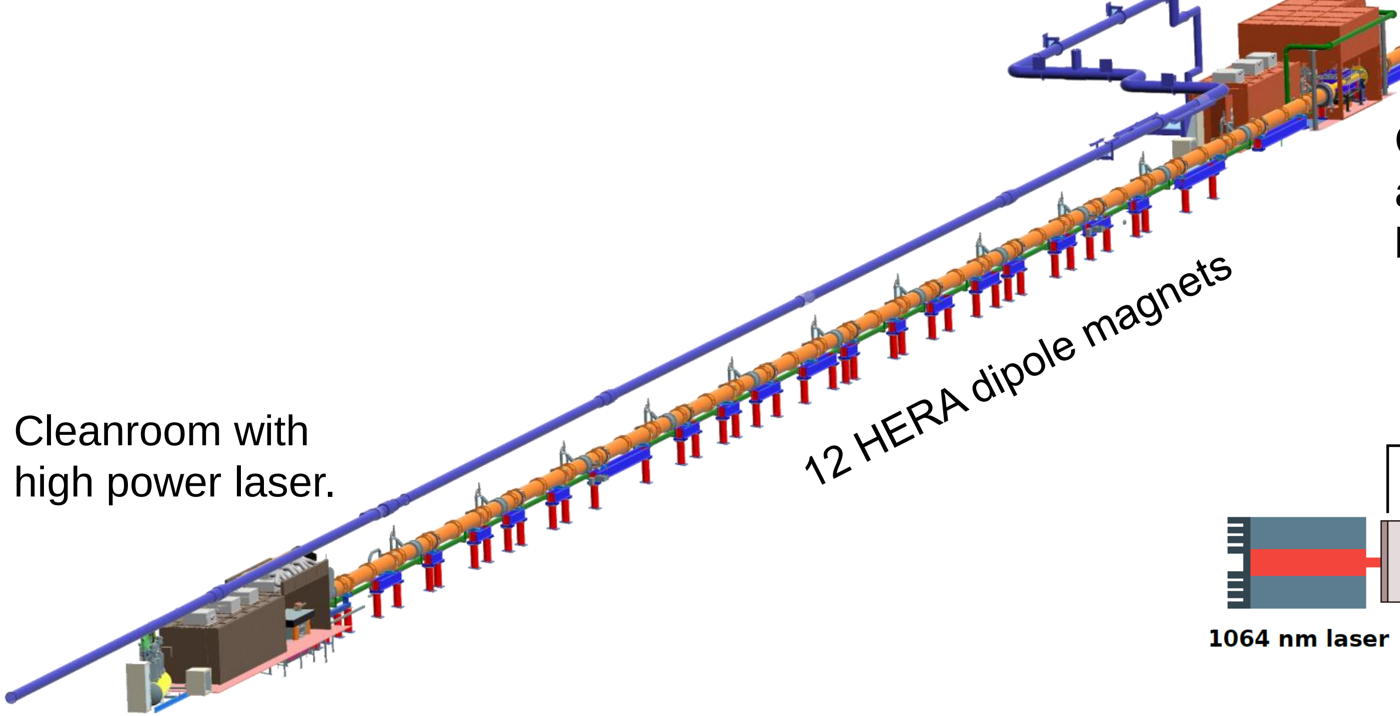
Supported by

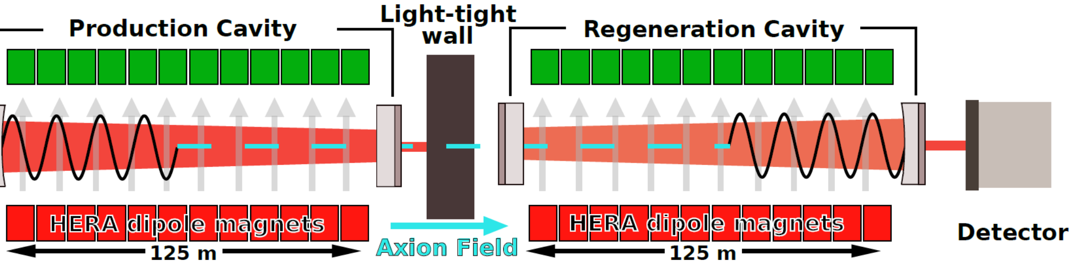
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DFG
HEISING-SIMONS FOUNDATION
NSF
UKRI Science and Technology Facilities Council
PRISMA+

Any Light Particle Search II

Constructed in a straight section of the HERA tunnel: started in 2019

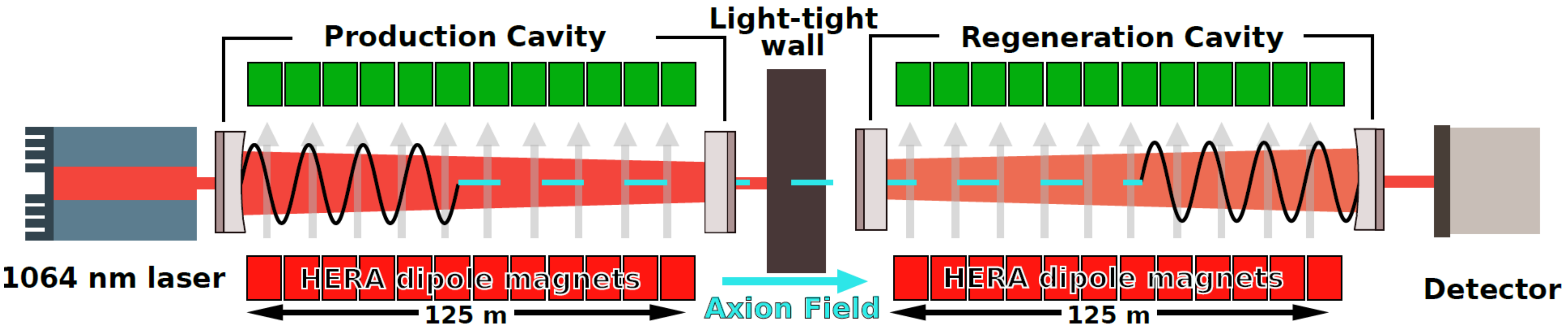
HERA hall North (former H1 experiment at HERA)



Any Light Particle Search II

Exploiting mode matched optical cavities



$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

$= 10^{-25}$

5,000 40,000 0.2 5.3 10.56

Motivated by astrophysics

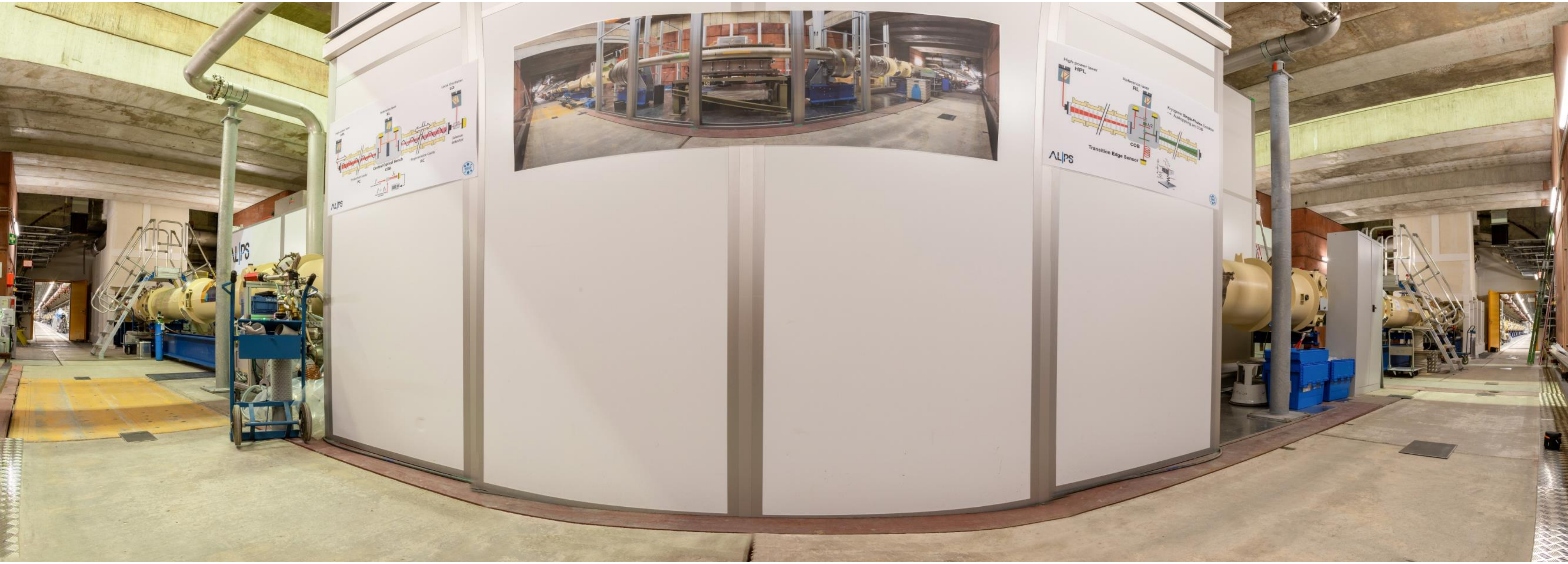
30 W cw Laser 1064 nm: $3\cdot10^{-5}$ Photonen / s ($5\cdot10^{-24}$ W).

Any Light Particle Search II

Status of autumn 2020 (no fire protection walls installed)

Any Light Particle Search II

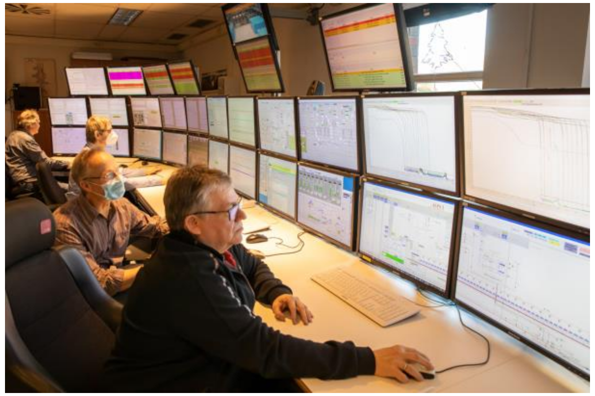
Status of September 2022 (installation completed, all components operational)

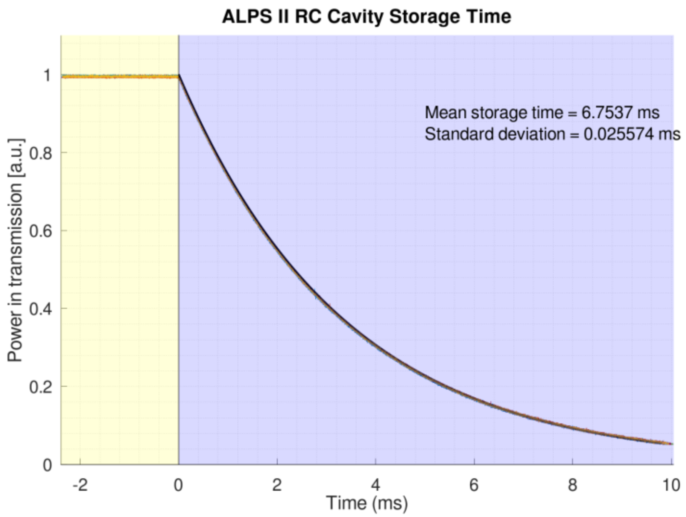


Any Light Particle Search II

Recent milestones

- Spring 2021: start of optics installation.
- June 2021: lock of 250 m long optical resonator, characterization of optics and seismic noise studies.
- September 2021: all magnets aligned and connected.
- December 2021: magnet string reaches operation temperature of 4 K.
- March 2022: magnet string reaches full operation current of 5.7 kA.
- May 2022: regeneration cavity test-installation and -lock.
- June 2022: world-record cavity storage time.
- September 2022:
  installation of central optical bench for first science run.
- Late 2022 / early 2023: start first science run (hopefully)!





125 m regeneration cavity storage time: 6 ms! (world record)

Any Light Particle Search II

Technologies

- 12+12 superconducting dipole magnets built for the former HERA proton accelerator, needed to straighten the cold mass.

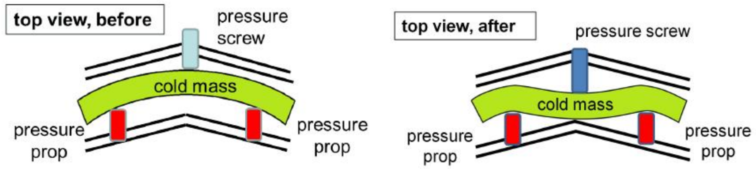
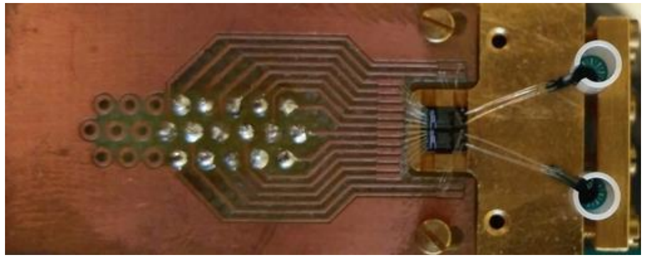


Figure 9: *Schematics of straightening. Left: Before applying the deforming force, Right: The deformation forces the pipe to develop two 'camel humps,' exaggerated in the figure for better illustration. This deformation yields the largest achievable horizontal aperture.*

Figure 10: *Outer pressure prop parts (left) and prop inserted into the cryostat (right).*

Physics Letters B
Volume 689, Issues 4–5, 31 May 2010

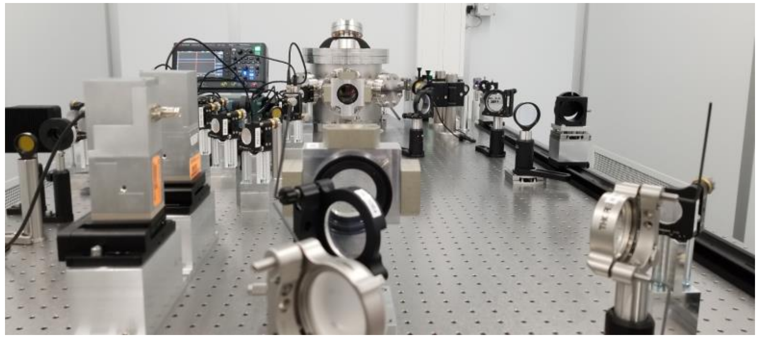
- Extremely low 1064 nm photon flux detection: heterodyne sensing and superconducting transition edge sensor (TES)



Phys.Dark Univ. 35 (2022), 100914

PoS EPS-HEP2021 (2022), 801

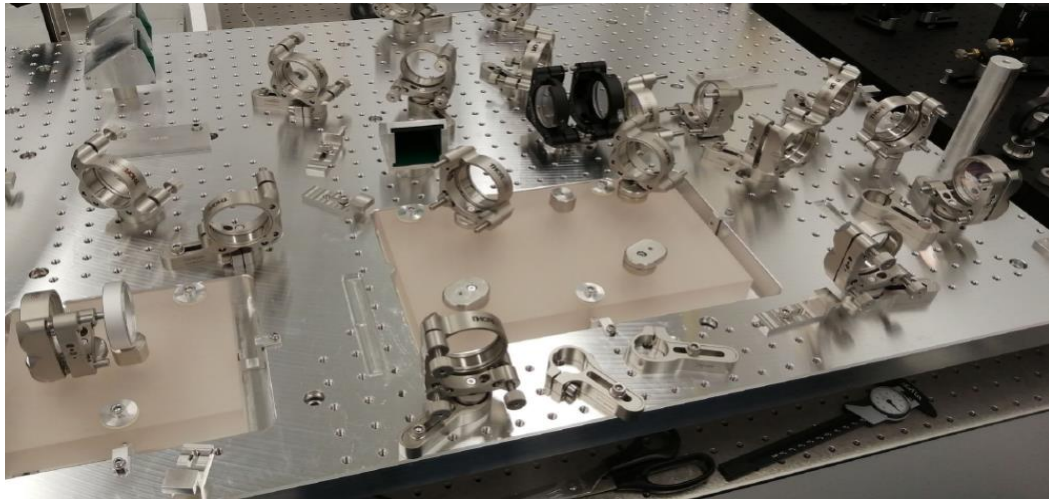
- Optics: long baseline precisions interferometry based on GEO600 and aLIGO experience.

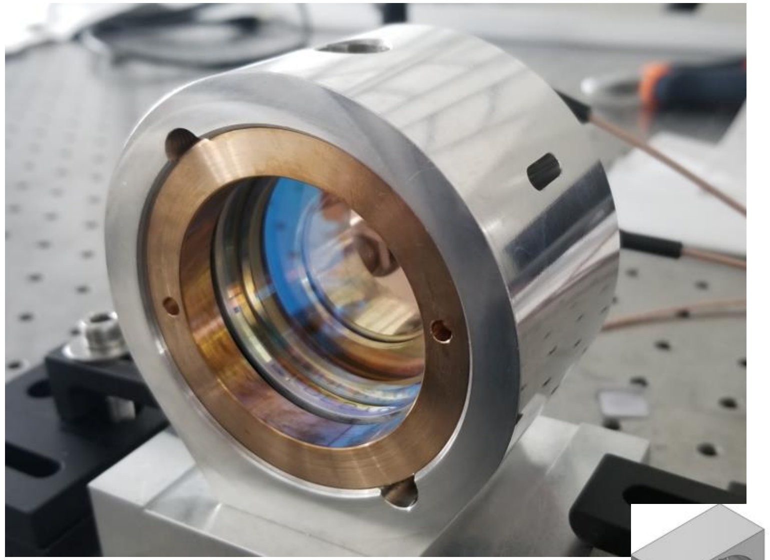


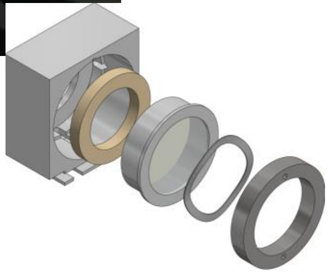
Design of the ALPS II optical system, Phys.Dark Univ. 35 (2022), 100968

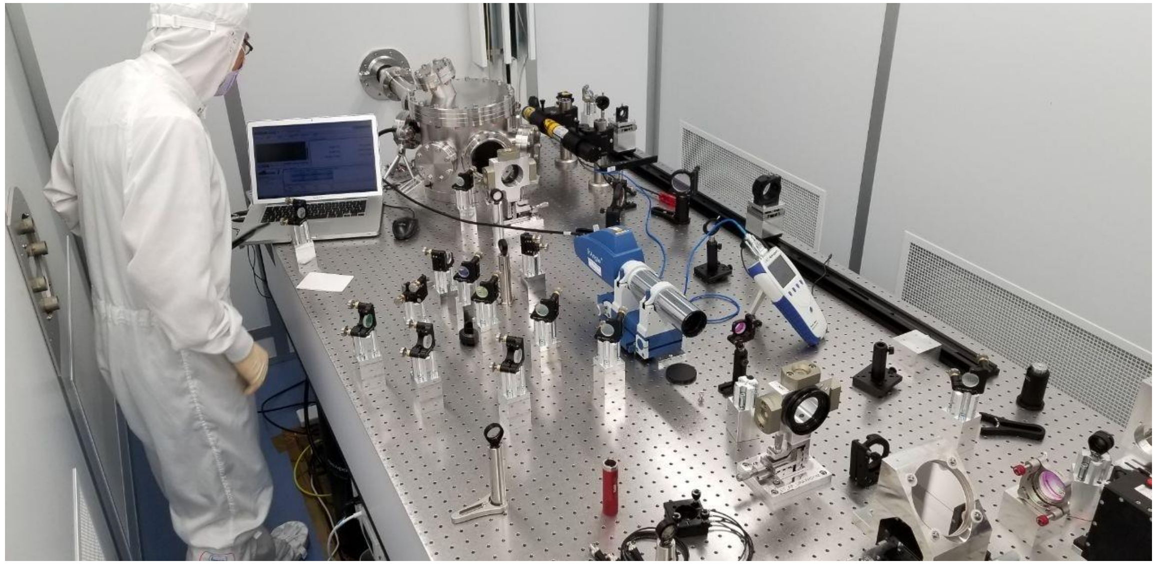
Any Light Particle Search II

Optics









The ALPS II program

A very tentative schedule

- 2023, Q1+2: initial HET science run without the production cavity (optimized for stray light search)
- 2023, Q3+4: HET science run with full optical system
- 2024, Q1+2: HET science run with upgraded optics

The further scheduling depends on the outcome of the HET science run, results of ongoing R&D, resources and world-wide science advancements.
The future program will include (from today's perspective):

- TES based science run
- Vacuum magnetic birefringence measurement
- WISP searches with optimized optics and/or extension of the ALP mass reach
- Dedicated search for high frequency gravitational waves

ALPS II might turn into a multi-purpose research infrastructure.

Outline

- Axions:
  - A very brief motivation.
  - Three kinds of experiments.

- Axions @ DESY:
  - MADMAX
  - (Baby)IAXO
  - ALPS II

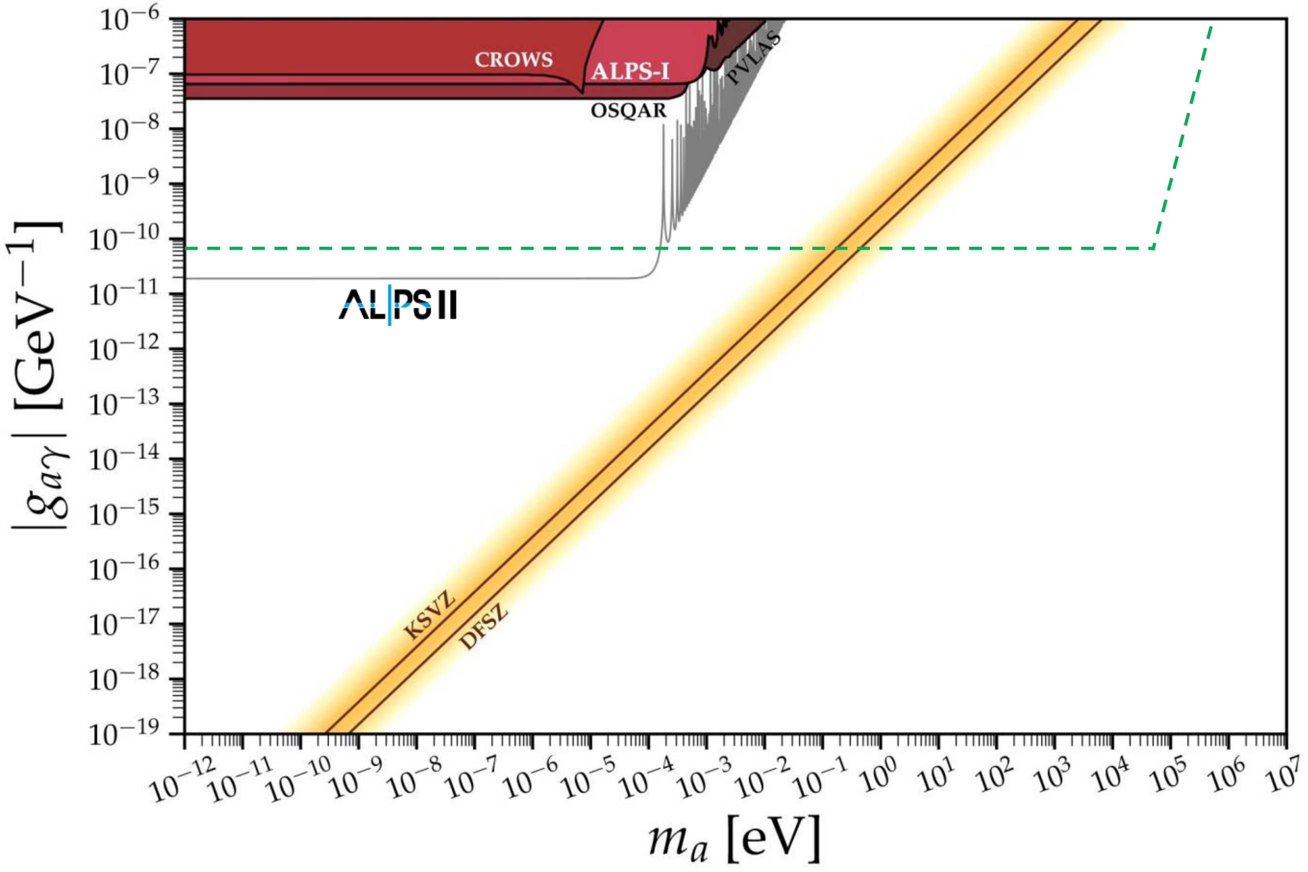
- Conclusions

Axion searches at DESY

In context

ALPS II, model independent searches:

- Improve sensitivity on axion-photon coupling by a factor of ≈ 1,000, going beyond astrophysics limits.



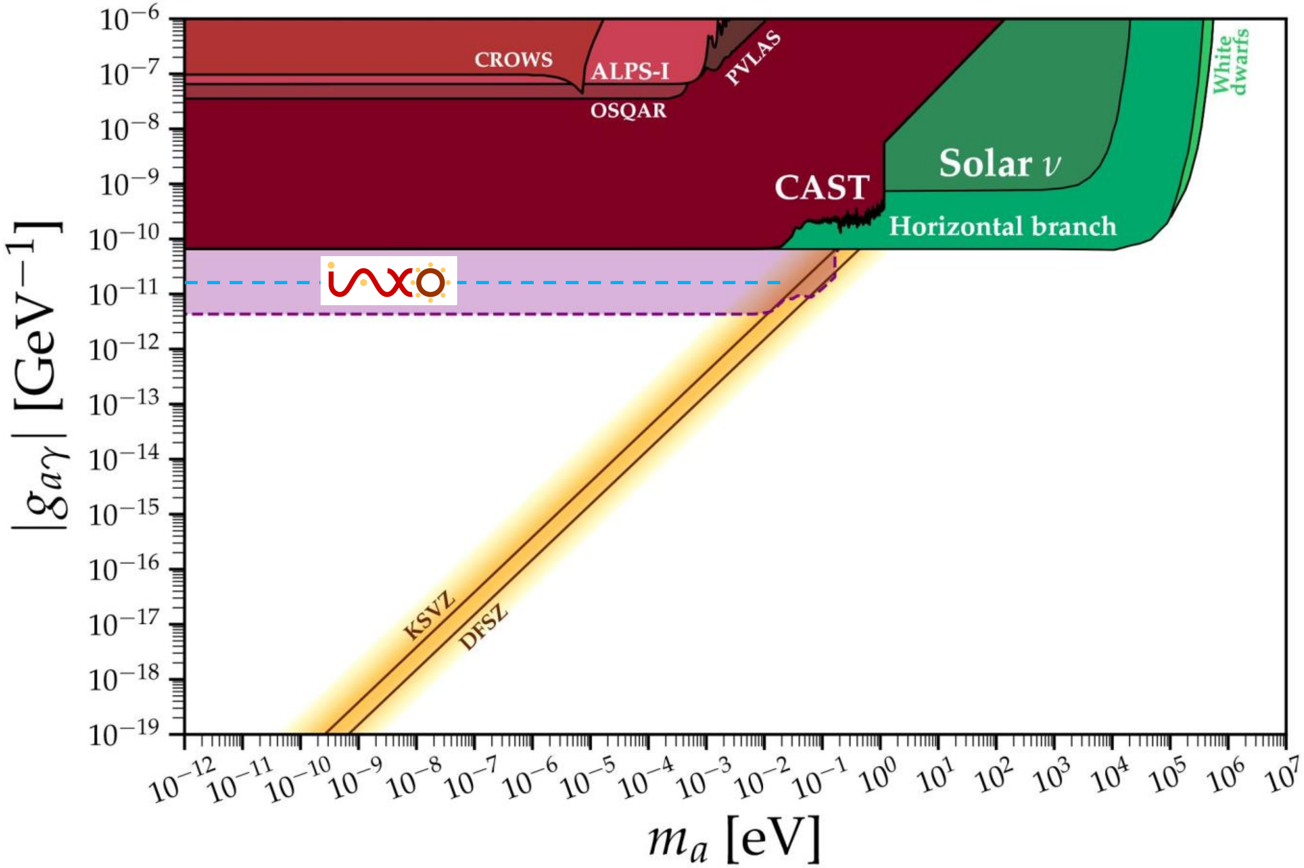
https://github.com/cajohare/AxionLimits

Axion searches at DESY

In context

IAXO, solar axion searches:

- Improve sensitivity on axion-photon coupling by a factor of ≈ 15 (BabyIAXO ≈ 4).



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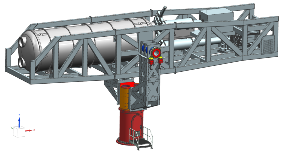
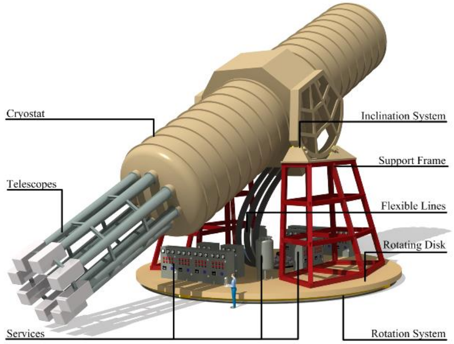


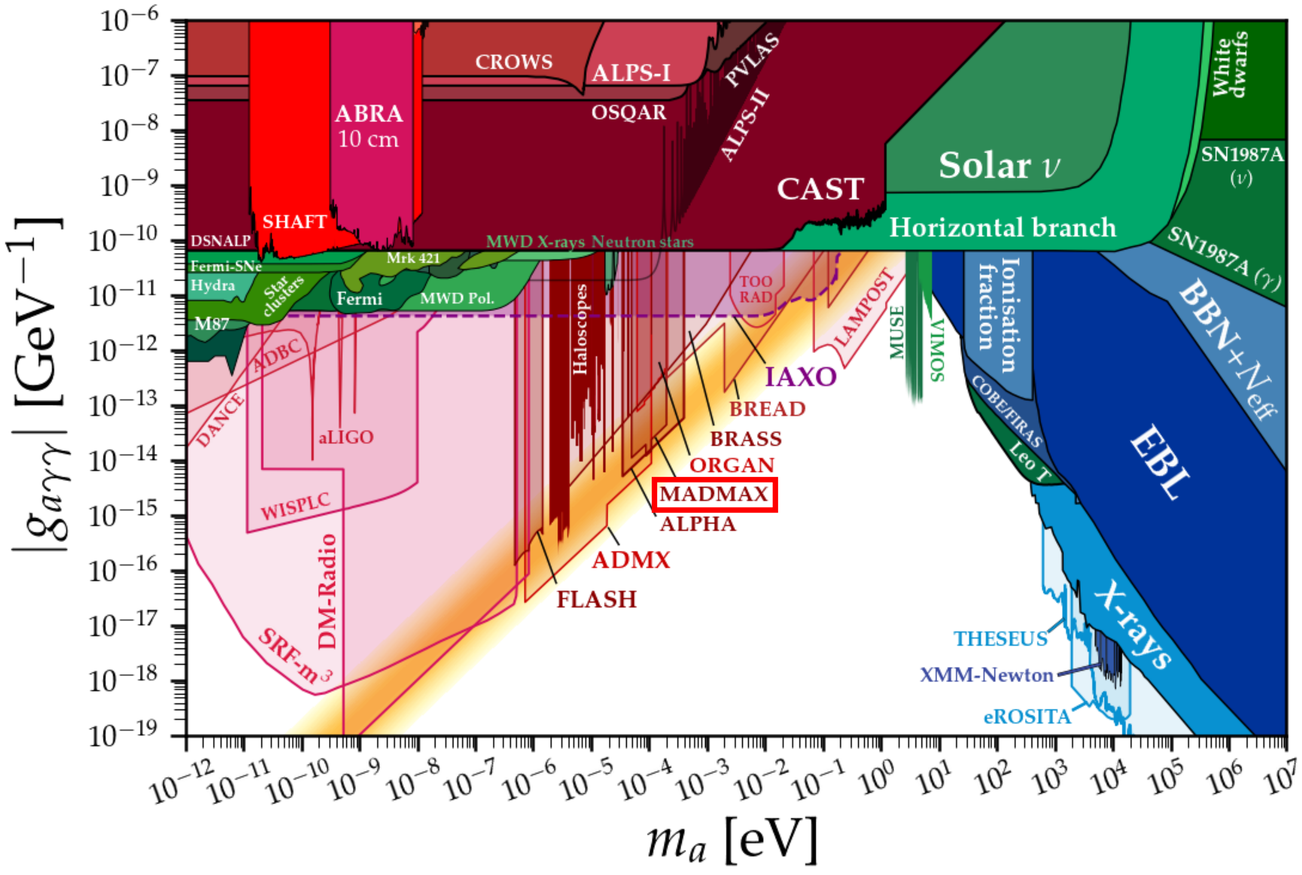


Axion searches at DESY

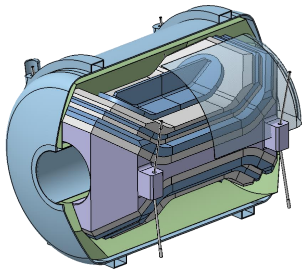
In context

MADMAX, dark matter axion searches:

- Probe the 100 µeV mass region.



https://github.com/cajohare/AxionLimits



Instead of a summary

A dream

ALPS II, data taking starting in 2023:

- Determine the axion-photon coupling model-independently.

IAXO, first data taking of BabyIAXO in 2028 ?

- Determine the absolute solar axion flux using the ALPS II result.
  - Does axion-photon couplings differ in vacuum and dense plasmas?
- Measure the axion-electron and axion-nucleon couplings.

MADMAX, first data taking in 2030 ?

- Axions make up the dark matter in our universe.
- Precisely measure the axion mass and the dark matter velocity distribution.

An unexpected correlation …

Newspaper “Bild”, 5 October 2022

SEIT BEI DESY WIEDER LASERLICHT DURCH RÖHREN SCHIESST, LÄUFT'S IM VOLKSPARK

Ist dieser Tunnel Grund für den HSV-Aufschwung?

Blick in den DESY-Tunnel unterm Volkspark: Rechts die auf - 269 Grad gekühlte Röhre mit Magneten, durch die Laserlicht schießen wird
Foto: Andreas Costanzo

Von: JÖRG KÖHNEMANN
05.10.2022 - 07:37 Uhr

Hamburg – **20 Meter unterm Volkspark brennt wieder Licht im alten DESY-Tunnel.**

30 Physiker sind dort mit 24 Mega-Magneten (jeder 9 m lang, wiegt 10 Tonnen), durch vier Spiegel 10 000-fach verstärktem Laserlicht und Helium-Kühlung in einer schnurgeraden 250-Meter-Röhre geheimnisvoller „Dunkler Materie“, einem Axion Elementarteilchen, auf der Spur. Und schon ganz nah dran.

Und was hat Teilchen-Power mit Fußball zu tun?

Die Wissenschaftler haben es nachgerechnet.

Als der Tunnel, genauer der „HERA-Ring“, 2007 stillgelegt wurde, ging es auch mit dem HSV bergab – von Platz 4 bis zum Abstieg in die 2. Liga. Jetzt ist er wieder in Betrieb – und der HSV siegt!

Das Beste: Pünktlich vorm möglichen Liga-Aufstieg 2023 läuft das Experiment auf Hochtouren!

Thank you

… any my many colleagues for their pictures and slides ….

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

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+49 40 8998 3525

Axions /ALPs

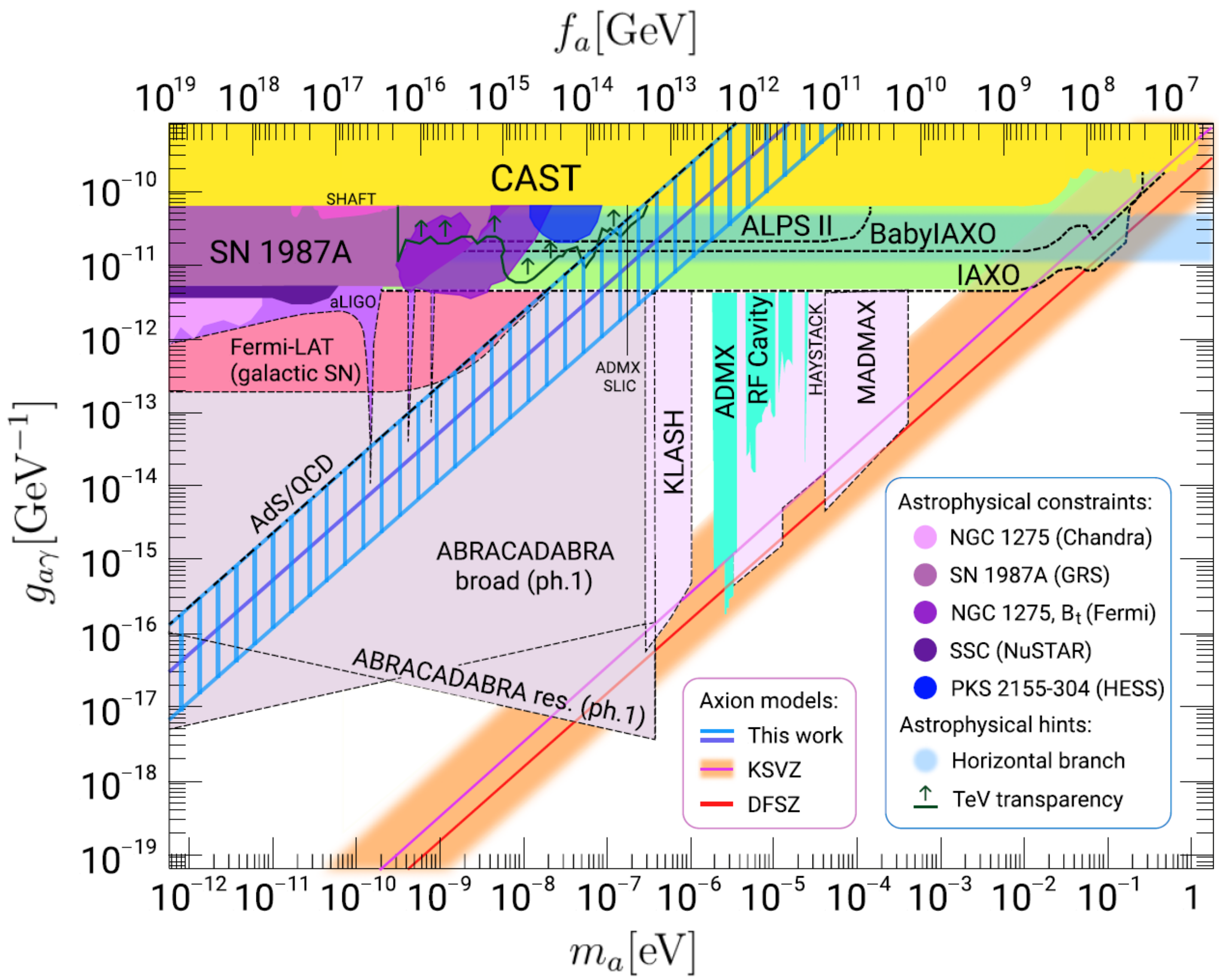
One fits all?

Photophilic hadronic axion from heavy magnetic monopoles:

- Mass about 0.01 to 1.0 µeV,
- $g_{a\gamma\gamma} = 10^{-11}$ to 10^{-10} 1/GeV.

Dark matter axions could show up at much stronger photon couplings than in traditional benchmarks.

We need experiments!



Sokolov, A.V., Ringwald, A. Photophilic hadronic axion from heavy magnetic monopoles. *J. High Energ. Phys.* **2021,** 123 (2021).

Any Light Particle Search II

Optics requirements for the first full science run

RC resonant enhancement (β_{RC})	> 10 000
RC absolute length changes (ΔL_{RC})	~ 15 µm
RC linewidth (HWHM)	15 Hz
PC circulating power	> 150 kW
PC relative power noise (RMS)	< 0.1%
Axion Coupling to RC (η)	> 90%
Coherence ($\eta_{\Delta f}$)	> 95%
Dynamic phase noise ($\Delta\varphi$)	< 0.2 rad
Static frequency offset (Δf)	< 1.5 Hz
Spatial overlap (η_T)	> 95%
Angular alignment ($\Delta\theta$)	< 5.7 µrad
Transversal shift (Δx)	< 1.2 mm
Detector sensitivity	> 2×10^{-24} W for 20 days
Environmental temperature conditions	< 0.1 K
Stray light mitigation	< 1 photon / 10 days

15 Hz out of $3\cdot10^{14}$ Hz

Any Light Particle Search II

Optics “locking” scheme to overcome seismic noise

Actuators: *picometer* position accuracy required