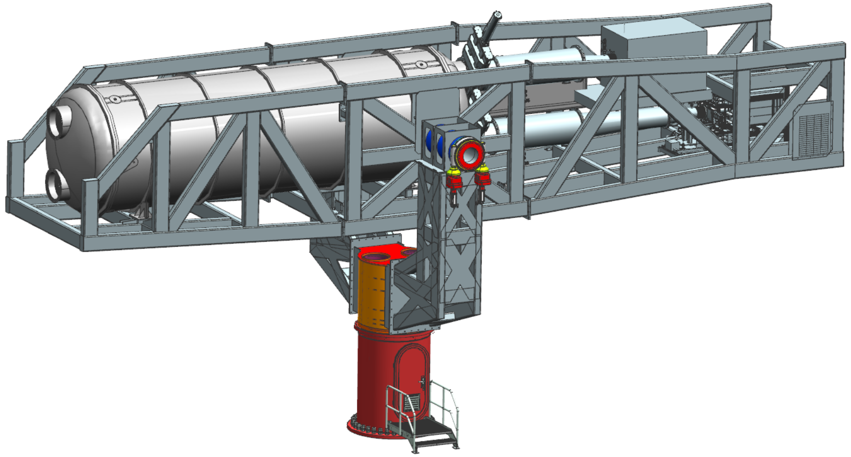
Axion searches at DESY

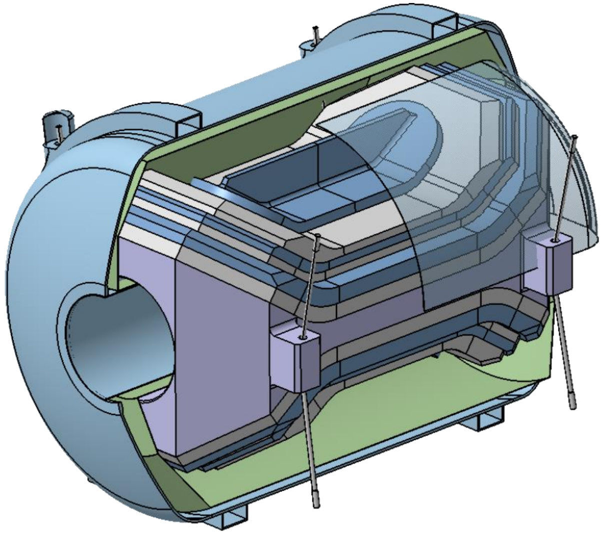
Reviving the HERA infrastructure with ALPS II, BabyIAXO, MADMAX

33rd Rencontres de Blois

24 May 2022

Axel Lindner
DESY





Outline

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

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

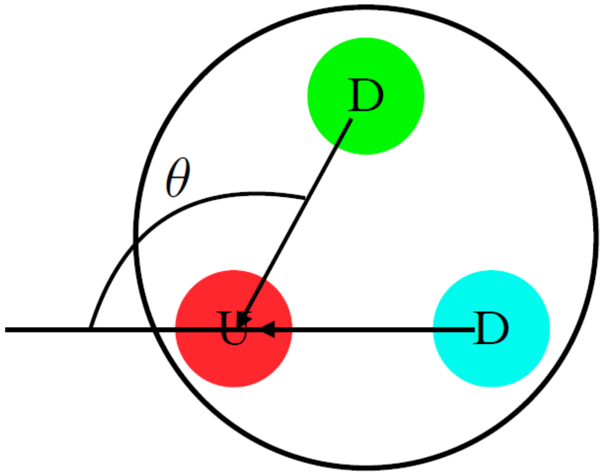
- Conclusions

Axions

A very brief motivation

CP symmetry violation in strong interactions ?

- QCD predicts an EDM of the neutron: $d_n = \theta \cdot 3{\cdot}10^{-16}$ e·cm.
  θ is a free parameter



https://arxiv.org/abs/1812.02669

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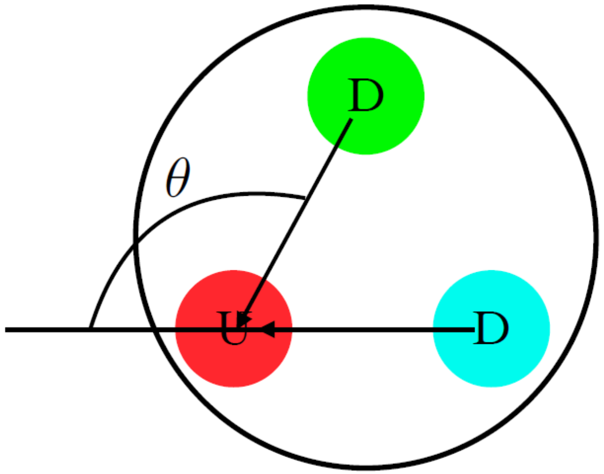

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Experiments: $d_n < 3{\cdot}10^{-26}$ e·cm; $\theta < 10^{-10}$

QCD conserves CP!

Axions

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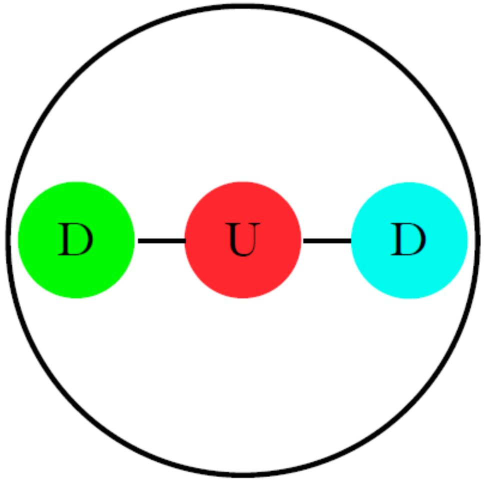
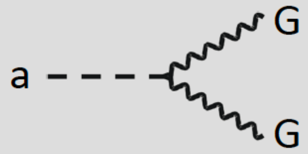


https://arxiv.org/abs/1812.02669

Axions

Saving CP symmetry in QCD

Axions are a consequence of the Peccei-Quinn symmetry to explain $\theta=0$.

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Axions

Saving CP symmetry in QCD and more

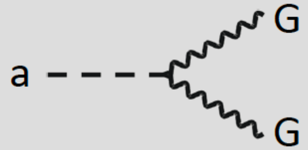
Axions are a consequence of the Peccei-Quinn symmetry to explain $\theta=0$.

There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an "invisible axion".

Traditional benchmarks:

- DFSZ (Dine, Fischler, Srednicki, Zhitniskii): axions couple to fermions. E/N = 8/3
- KSVZ (Kim, Shifman, Vainshetein, Zakharov): axions couple to BSM quarks only. E/N = 0

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
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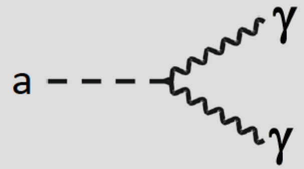
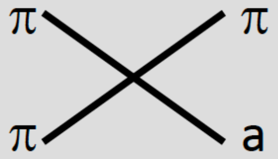
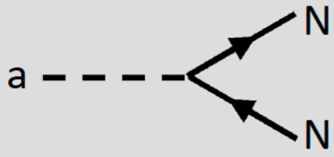
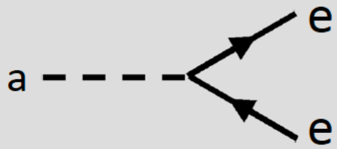
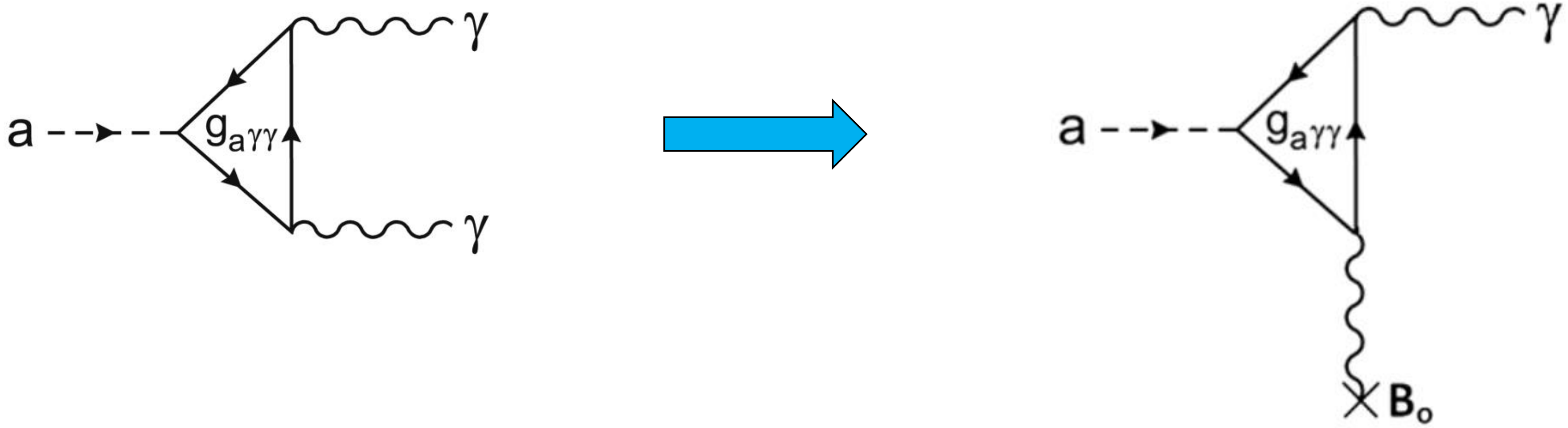
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \cdots)\partial^\mu a$	
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a}\bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\partial_\mu a$	
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a}\bar{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$	

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Axions

Photon coupling

Exploited by many experiments as relatively “simple”.

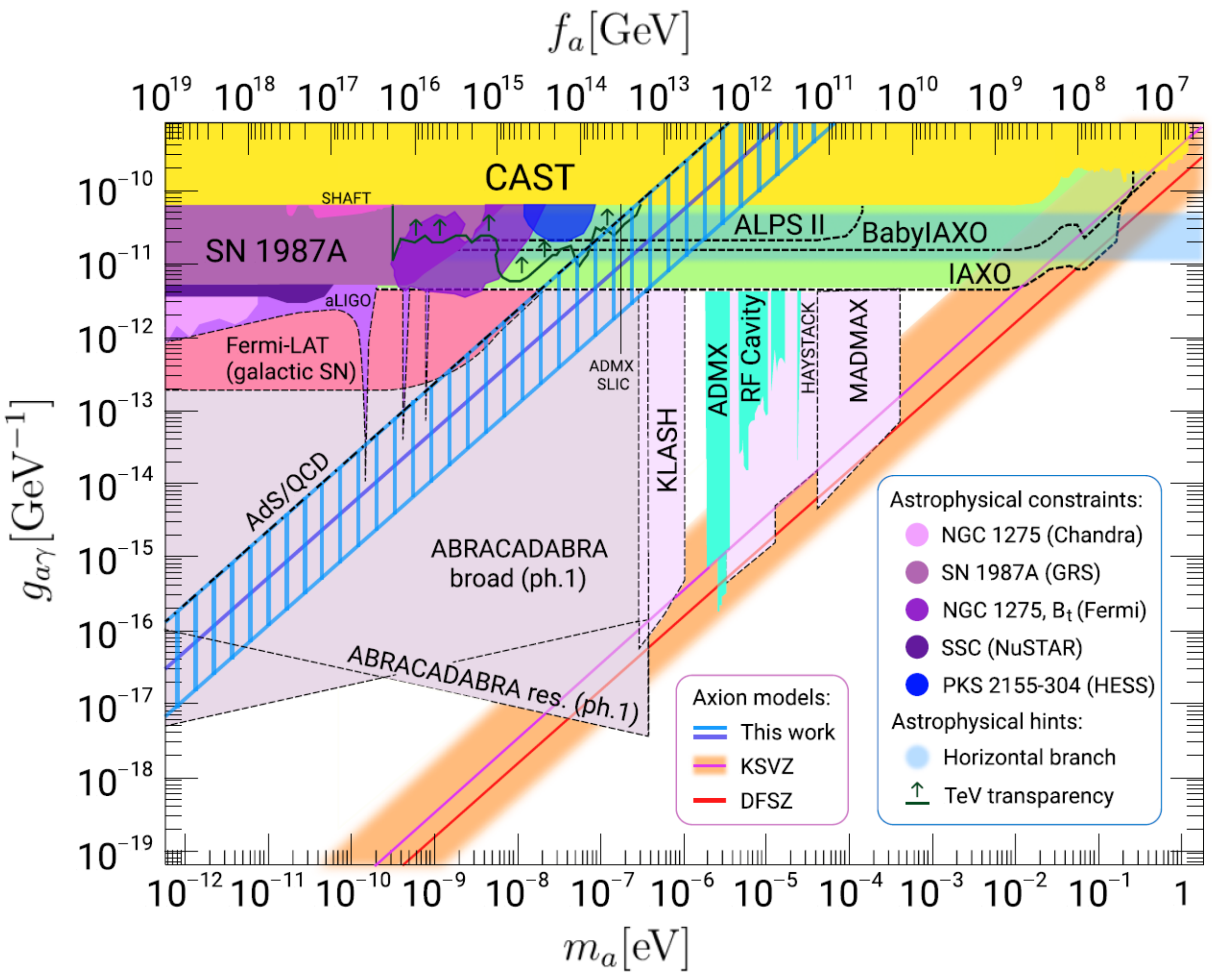


Axions

Photon coupling

Exploited by many experiments as relatively "simple".

Be aware of model dependencies.



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

Axions

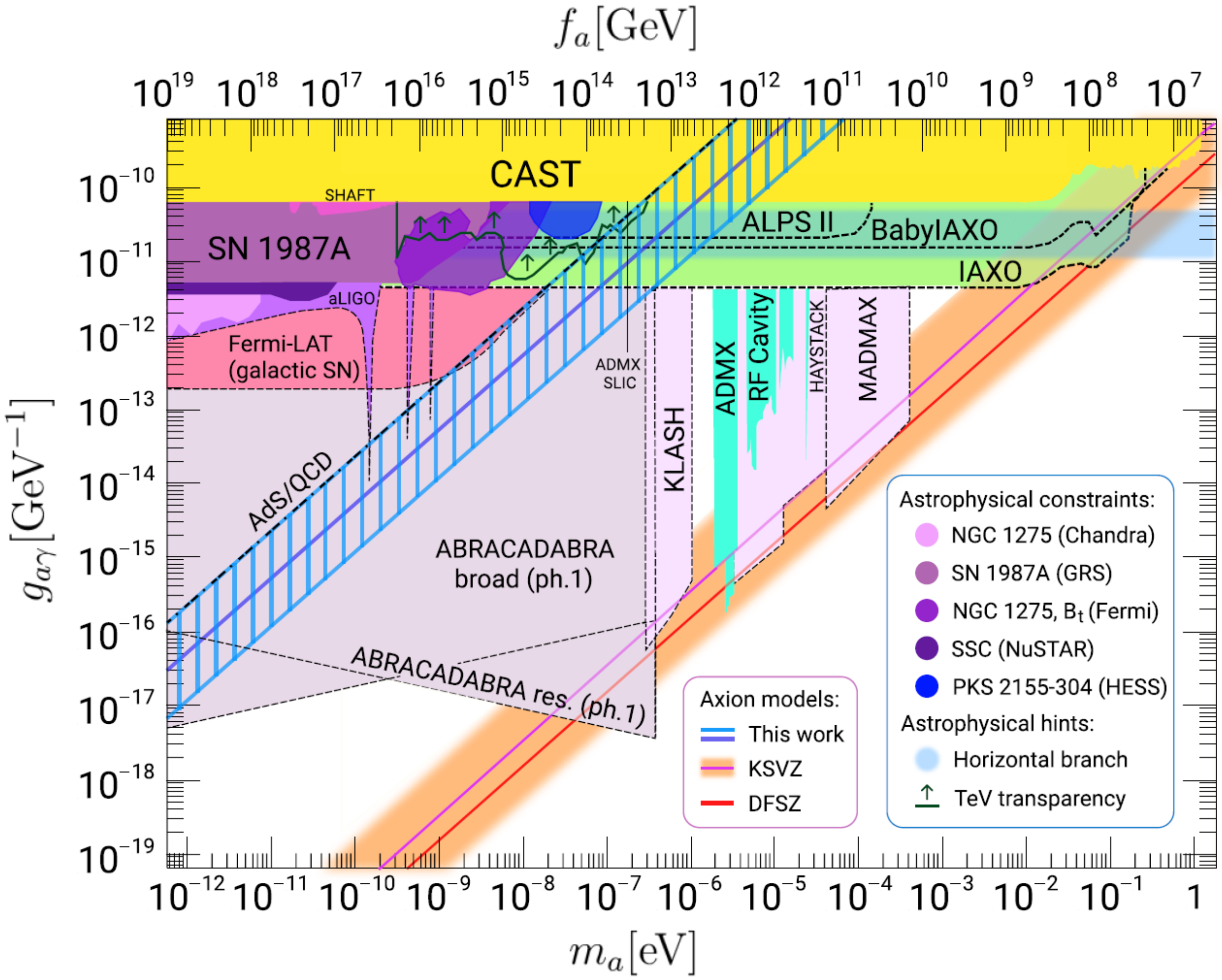
Photon coupling

Exploited by many experiments as relatively “simple”.

Be aware of model dependencies.

Be aware of model dependencies when comparing axion searches looking for different couplings.

There might be axion-like-particles (ALPs) as motivated by string theories for example.
Such particles are not related to QCD-CP.



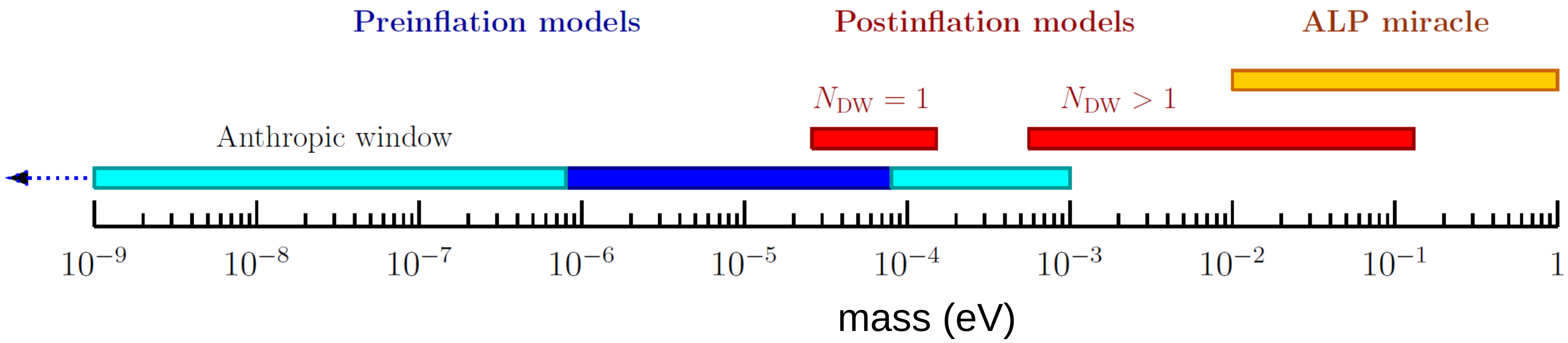
Sokolov, A.V., Ringwald, A. Photophilic hadronic axion from heavy magnetic monopoles. *J. High Energ. Phys.* **2021,** 123 (2021).

Axions

and Dark Matter

Lightweight axions are perfect dark matter candidates.

- DM axions originate from the PQ phase transition in the early universe (non-thermal generation).
- They come with a huge number density and behave like an axion field.
- Different cosmology models predict different axion mass ranges where axions could make up all of the DM.



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

DM axion searches "only" probe [(axion exists) AND (DM is made out of axions)]

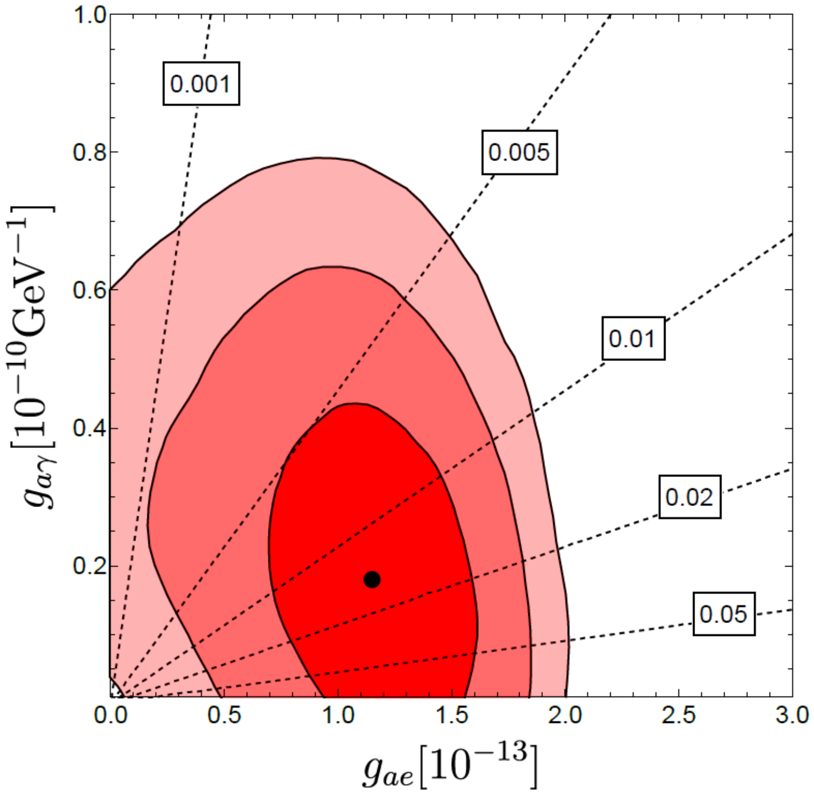
- Thus DM search limits don't tell about the existence of axions.

Axions /ALPs

Evidences from astrophysics?

Lightweight axions / ALPs might explain

- puzzles in the evolution of stars



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

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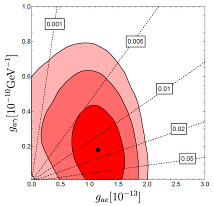
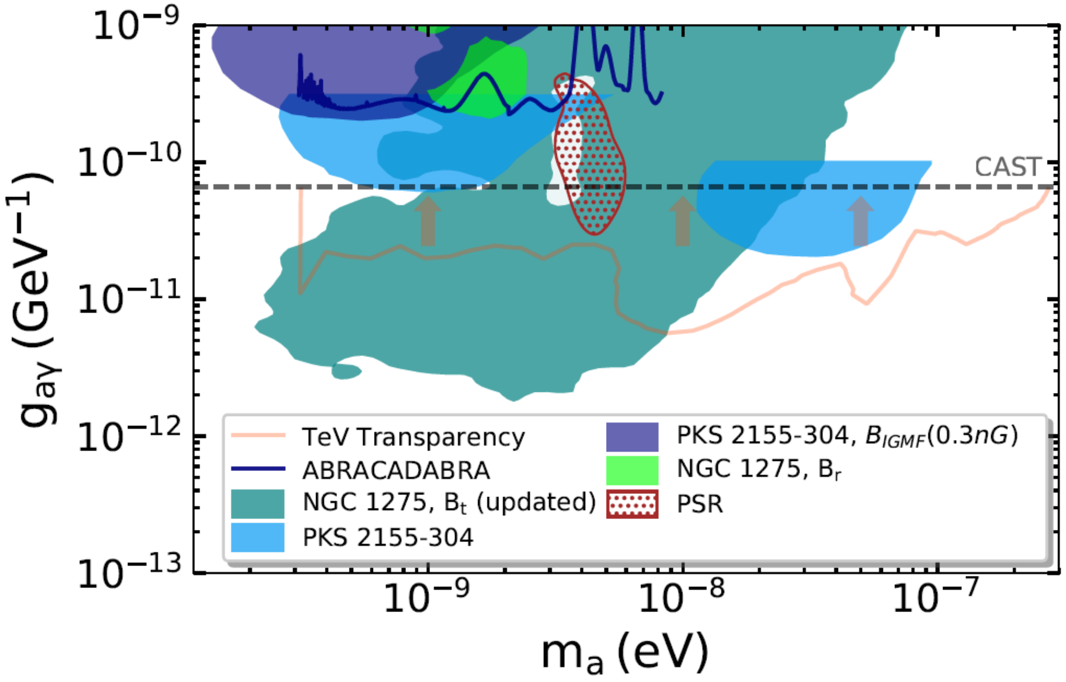


- features in high energy photon spectra



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

Axions /ALPs

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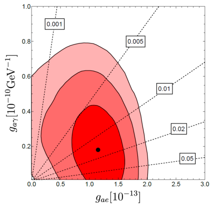
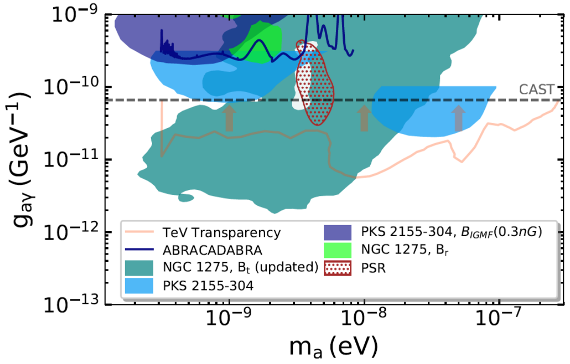


- puzzles in the evolution of stars



- 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 DM axion searches with other approaches!

Axion searches

With and without the dark matter paradigm

If axions are dark matter, their number density at earth would be extremely large:

- $n_a \approx 3 \cdot 10^{13} \cdot (10\mu eV / m_a)\ cm^{-3}$.
- Dark matter axions originate from a phase transition.
- In general, searches for dark matter axions are significantly more sensitive than other approaches and target f_a up to 10^9 TeV ($10^{-7} \cdot M_{Planck}$).
- "Two Nobel prizes or none".

Experiments relying on other axion production mechanisms:

- Axion production: couplings to SM constituents are suppressed by $1/f_a$ and hence extremely weak.
  - Flux of solar axions: $flux_{Primakoff} \approx 1.8 \cdot 10^{13} \cdot (10^5\ TeV / f_a)^2\ s^{-1} \cdot m^{-2} \approx 0.02 \cdot (10^5\ TeV / f_a)^2 \cdot$ [solar neutrino flux] corresponding roughly to $0.1 \cdot (10^5\ TeV / f_a)^2\ W \cdot m^{-2} \approx 10^{-4} \cdot (10^5\ TeV / f_a)^2 \cdot$ [solar constant]
- Target: BSM energy scales up to $f_a = 10^5$ TeV.

Disclaimer:

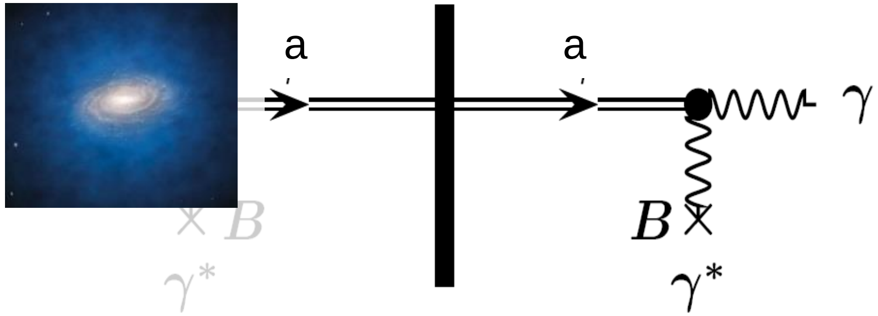
In the following I will not distinguish anymore between the QCD-axion and ALPs, but use both as synonyms.

Unless stated otherwise.

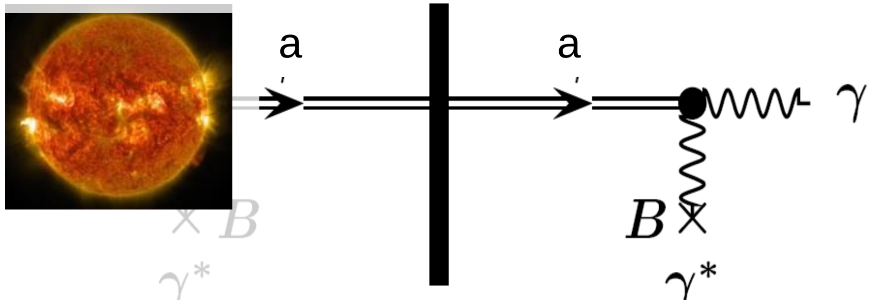
How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

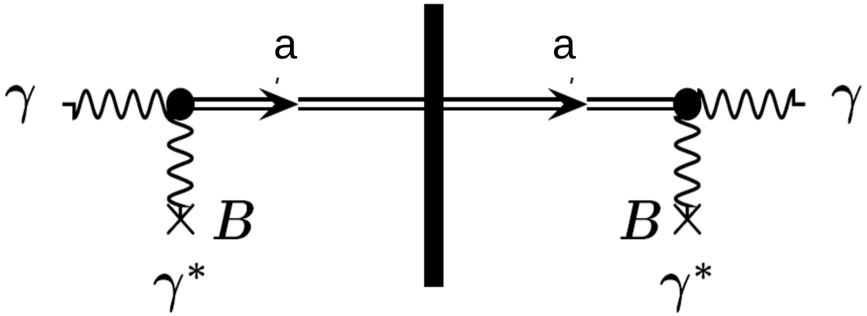
- Haloscopes
  looking for dark matter constituents,
  microwaves



- 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

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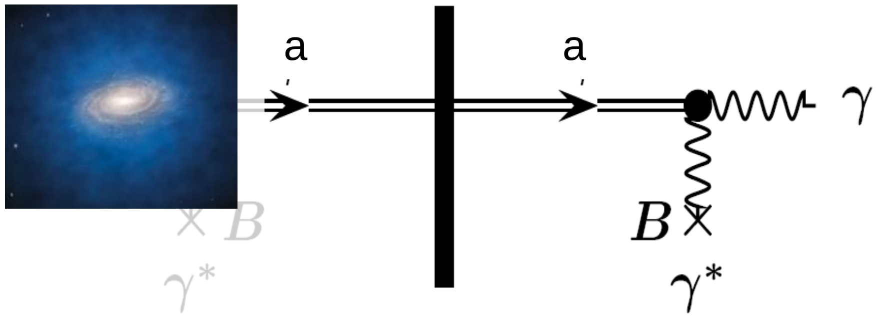
non-relativistic axions, "monochromatic" photons



- Helioscopes
  Axions emitted by the sun,
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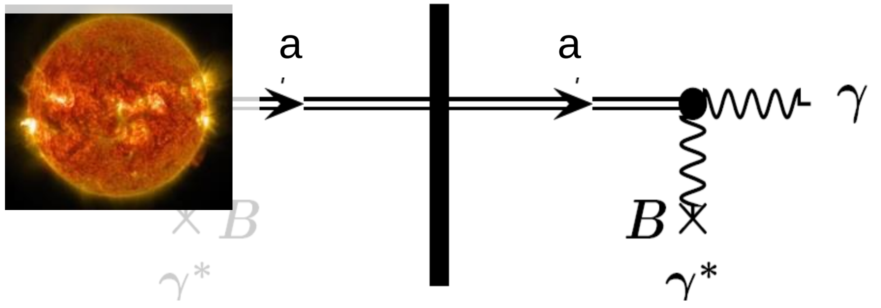
relativistic axions, thermal photon spectrum



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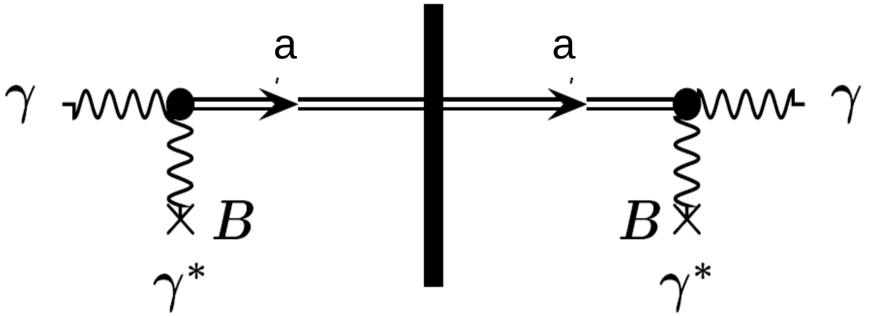
relativistic axions, monochromatic photons



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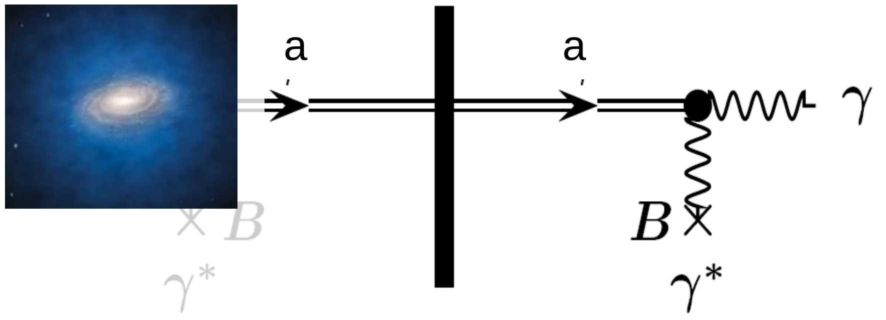
10^{-23} W
exploit resonant detection



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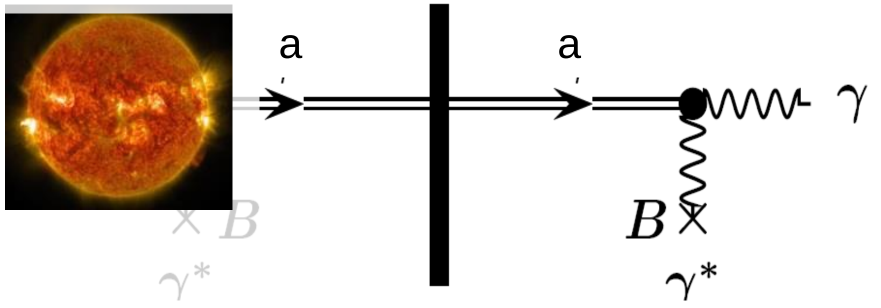
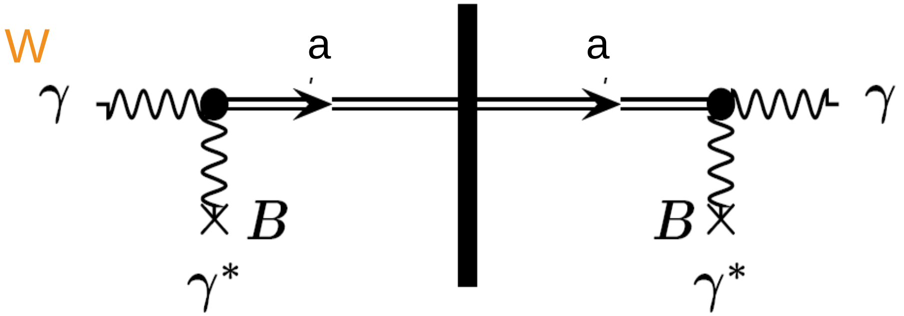
1 photon/year
(10^{-23} W)



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

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



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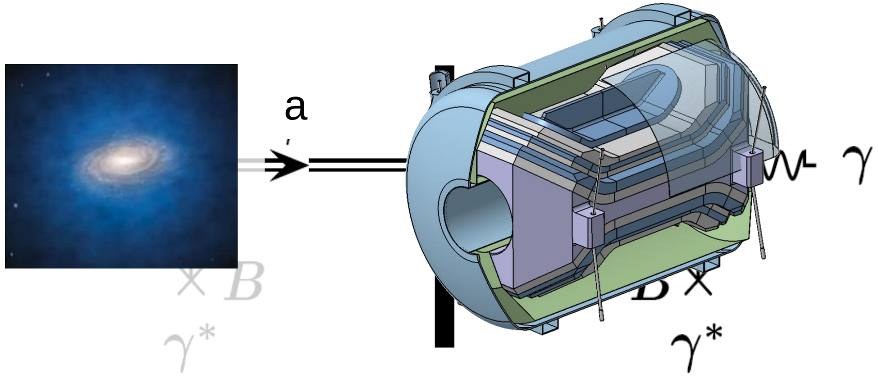
MADMAX



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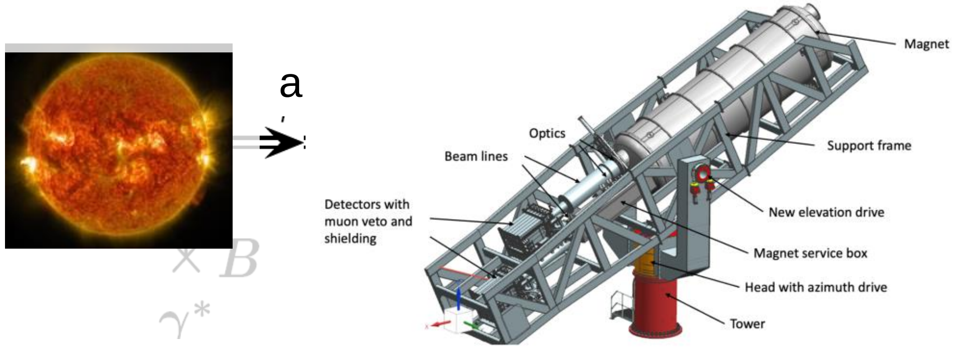
BabyIAXO



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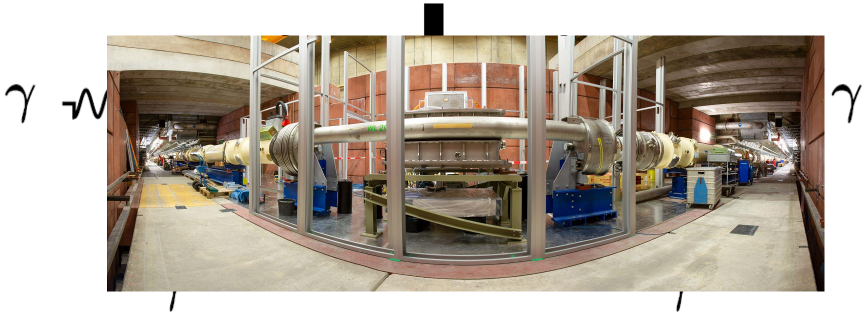
ALPS II



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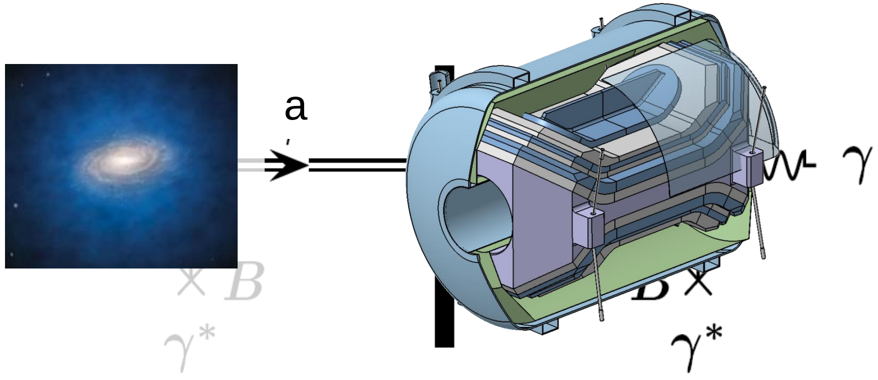

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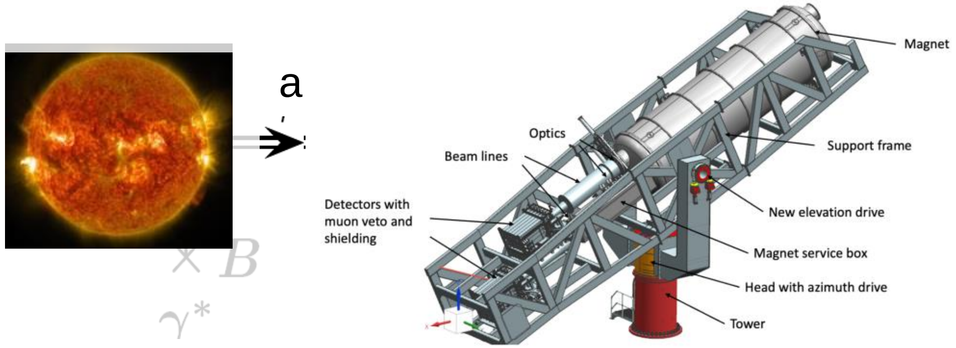

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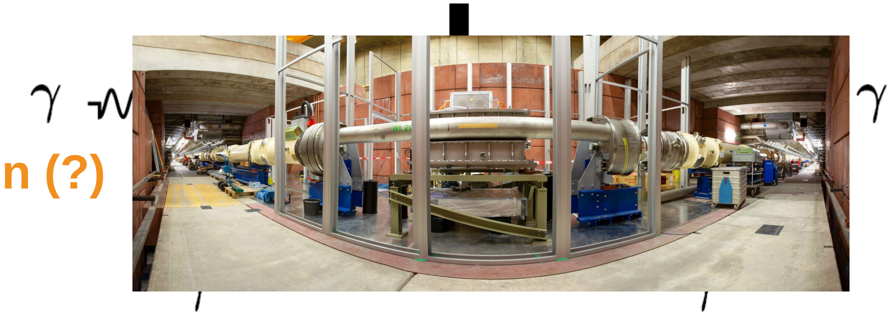
ALPS II
1st science run soon (?)



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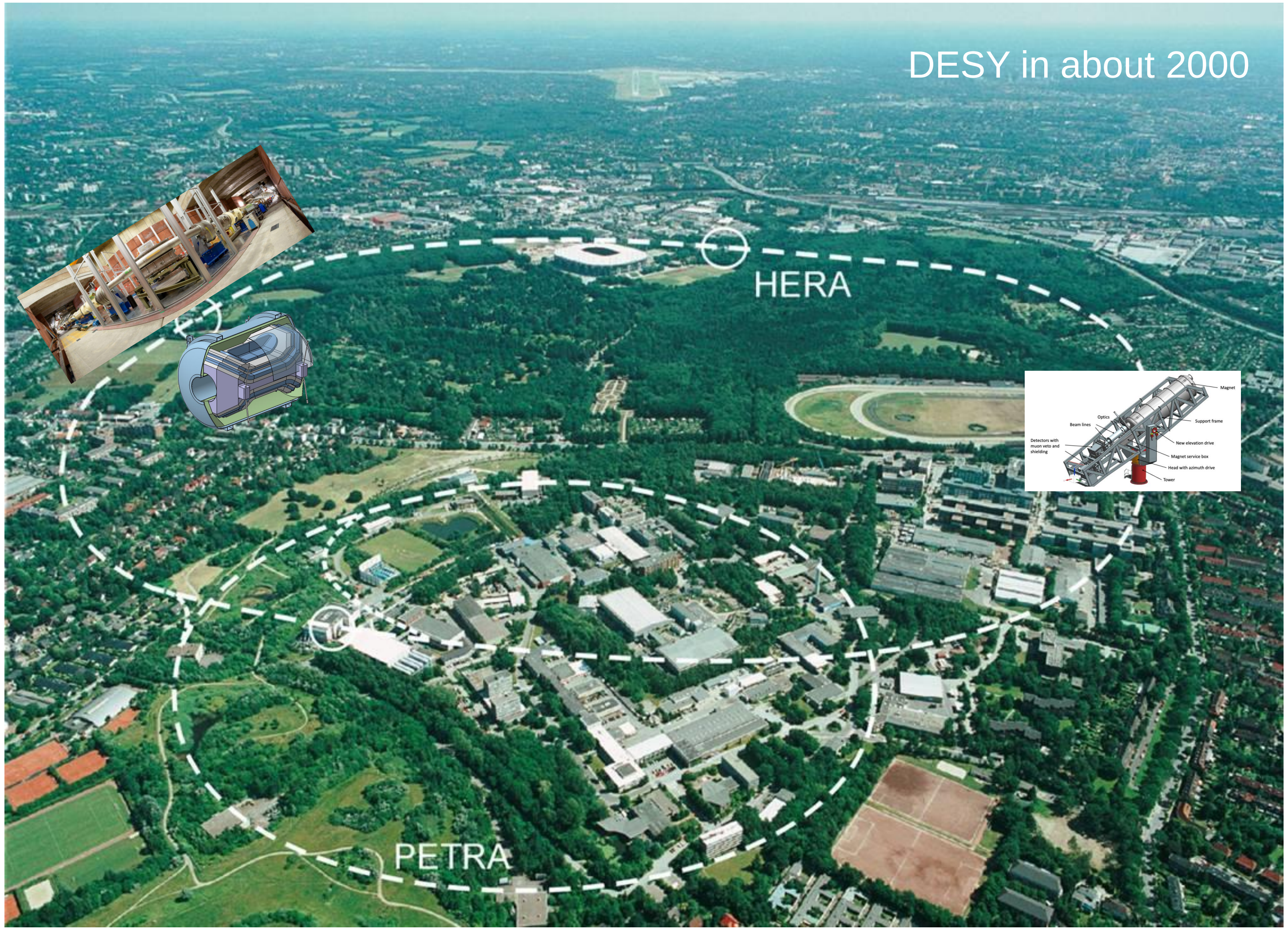
Infrastructure at DESY in Hamburg

Re-using HERA

Infrastructure at DESY in Hamburg

Re-using HERA

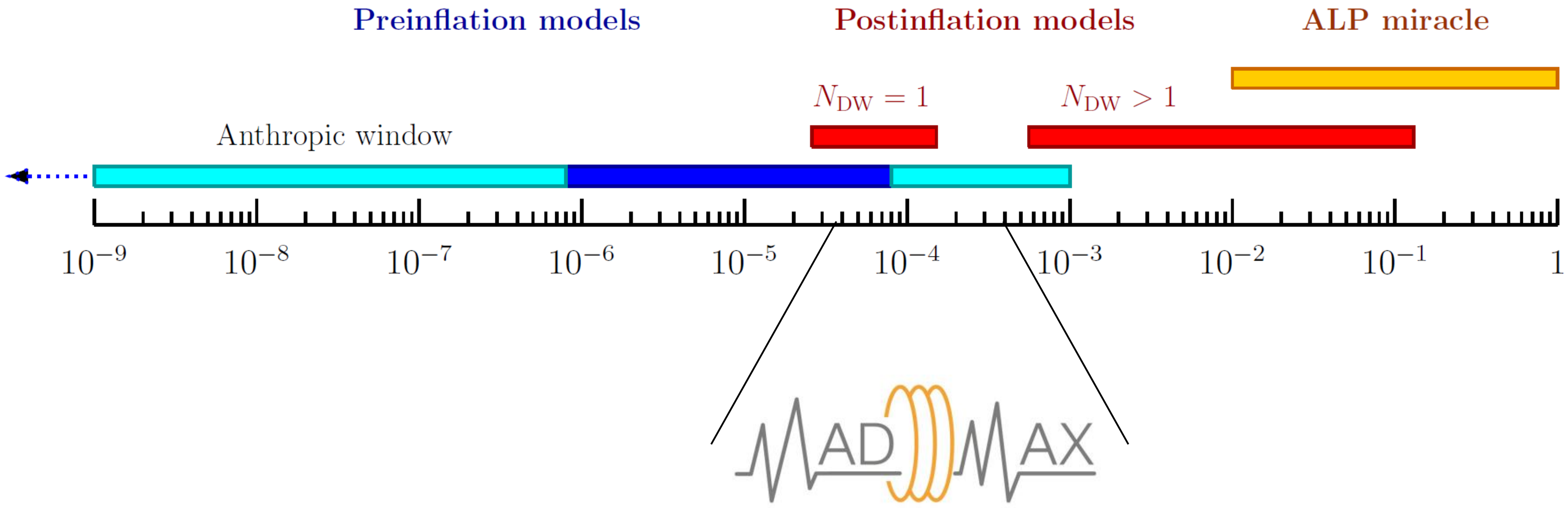


MAgnetized Disc and Mirror Axion eXperiment

Direct dark matter search

Physics goal: look for 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/

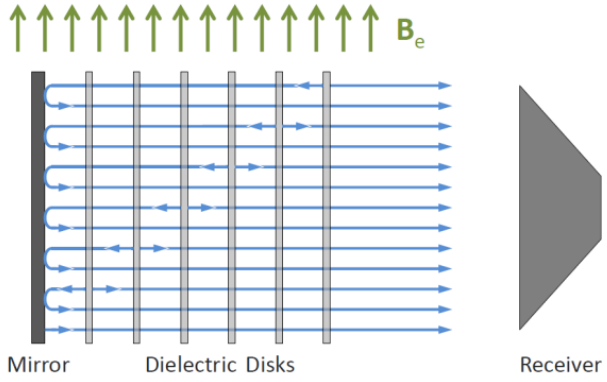
- Centre de Physique des Particules de Marseille (CPPM), France
- DESY Hamburg, Germany
- Néel Institute, Grenoble, France
- **MPI für Physik, Munich, Germany**
- MPI für Radioastronomie, Bonn, Germany
- RWTH Aachen, Germany
- University of Hamburg, Germany
- University of Tübingen, Germany
- University of Zaragoza, Spain

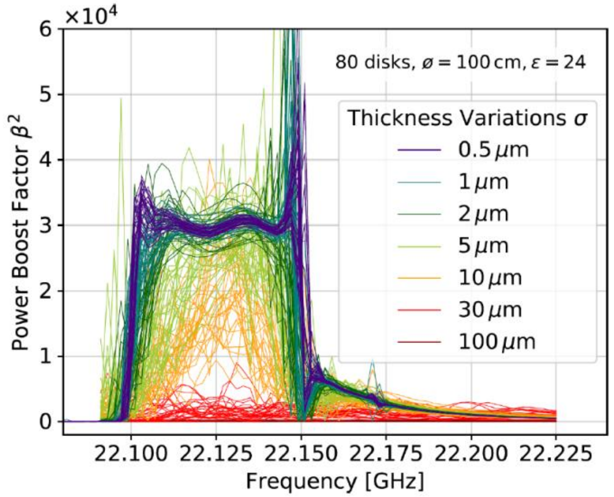
MAgnetized Disc and Mirror Axion eXperiment

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.
- A stack of dielectric plates inside a strong magnetic dipole field is tuned to the radiofrequencies corresponding to axion masses from 40 to 400 μeV.
    - The measured power can be enhanced by several 10^4.
    - Tradeoff between bandwidth and “boost factor”.





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

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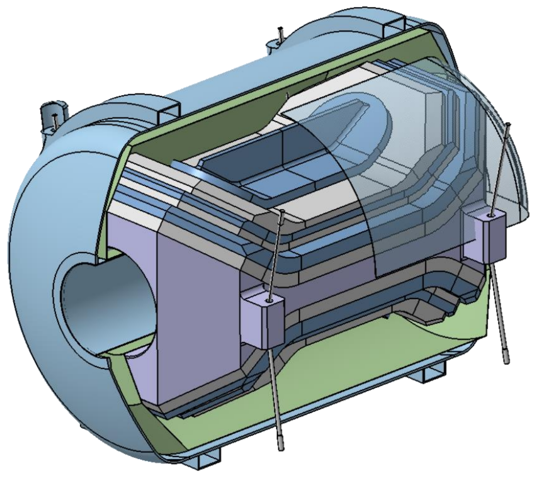
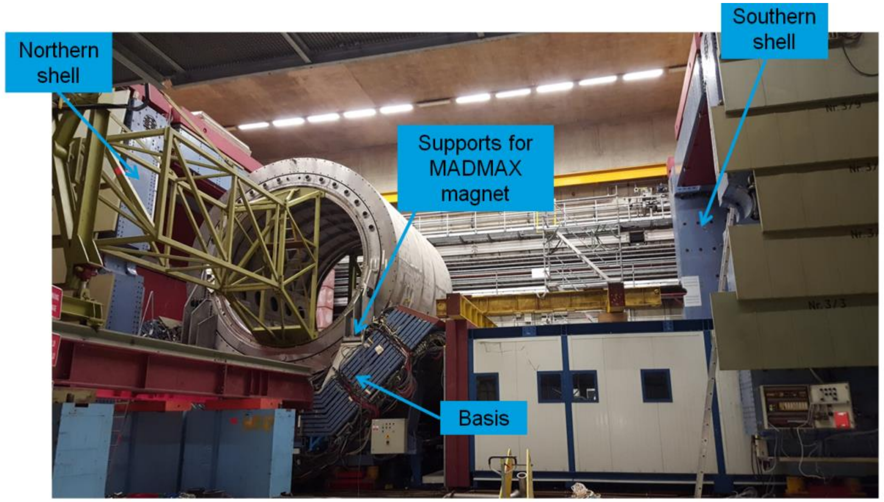
- Photons from DM axion conversion show a very narrow energy distribution (10^{-6}) as the DM axions move with non-relativistic speeds.
- A stack of dielectric plates inside a strong magnetic dipole field is tuned to the radiofrequency corresponding to axion masses from 40 to 400 µeV.
- A huge dipole magnet providing about 10 T with an aperture of 1 m is required.
  - To be installed in the iron yoke of the former HERA experiment H1.





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

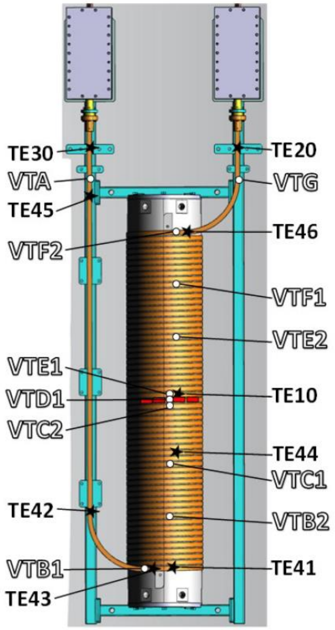
115 kg TNT

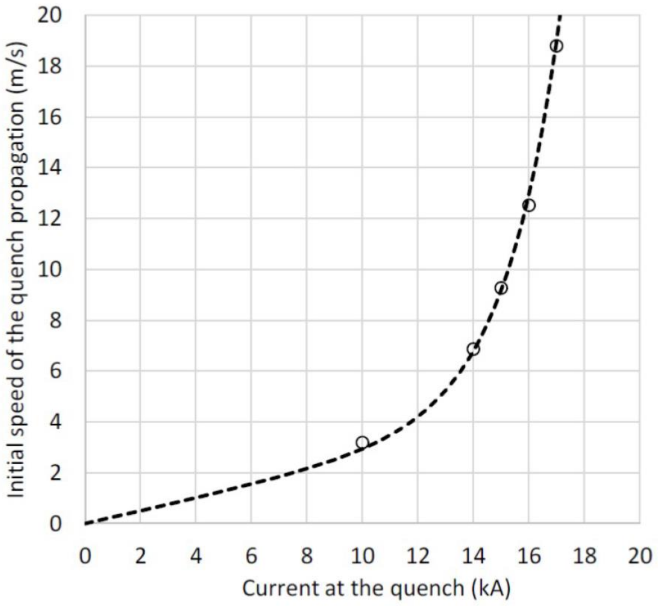
MAgnetized Disc and Mirror Axion eXperiment

Status

Nice progress in the prototyping phase:

- Magnet:
  - Conceptual design.
  - Very successful conductor test at CEA / Saclay.





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

MAgnetized Disc and Mirror Axion eXperiment

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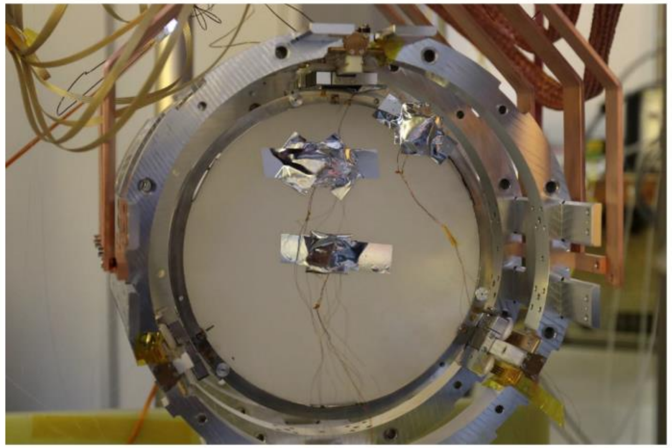
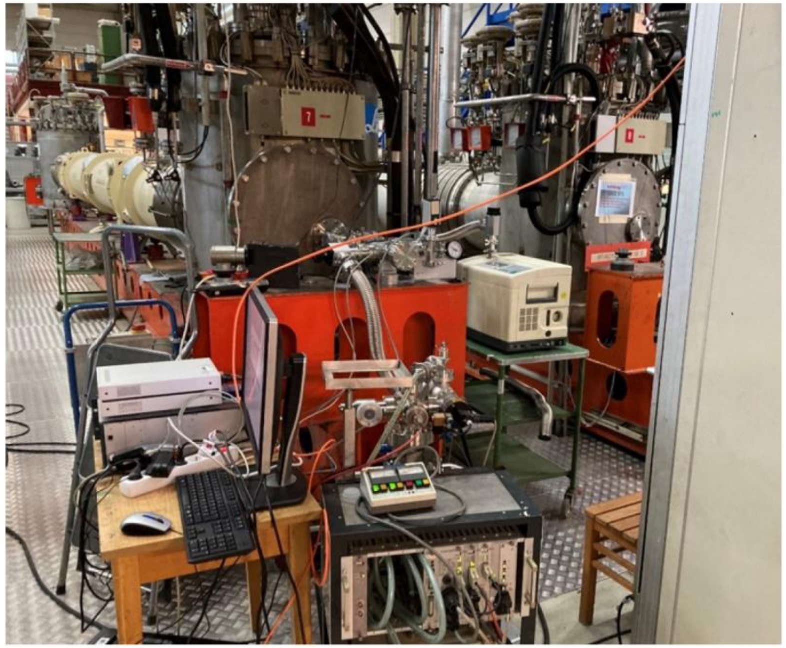
Nice progress in the prototyping phase:

- 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.



MAgnetized Disc and Mirror Axion eXperiment

Status

Nice 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)
- Booster understanding:
    - Series of prototype tests just started at CERN,
      in future also at Hamburg University.

Maybe even first physics results with a prototype?

Prototype at MORPURGO / CERN

MAgnetized Disc and Mirror Axion eXperiment

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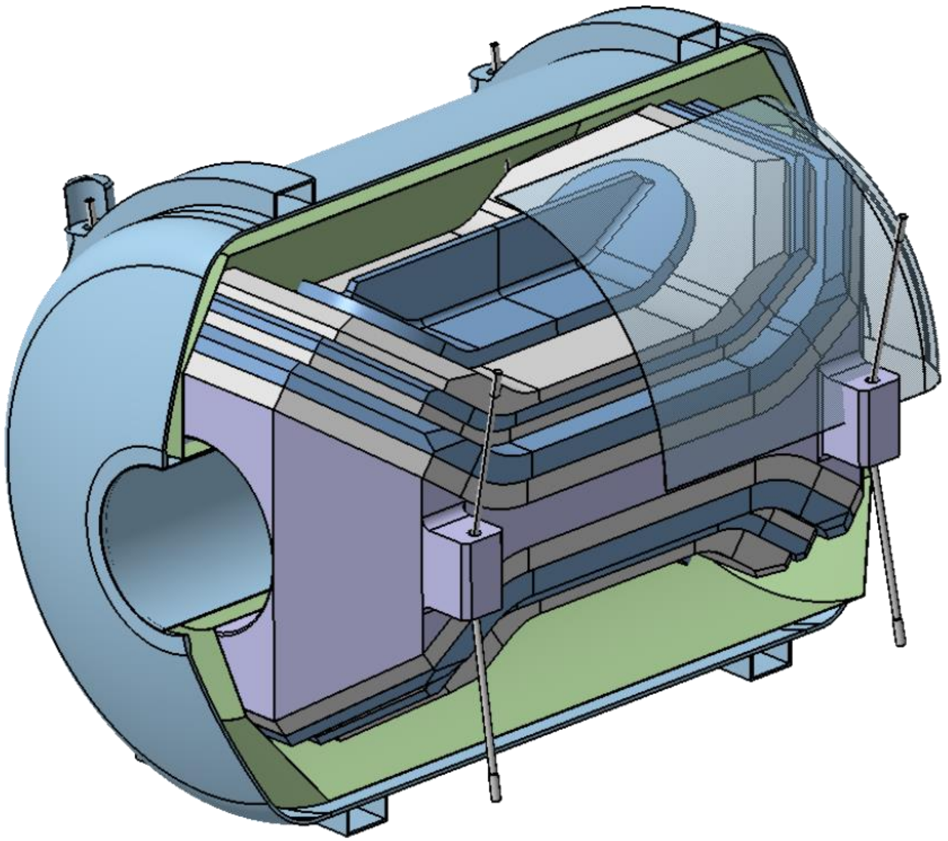
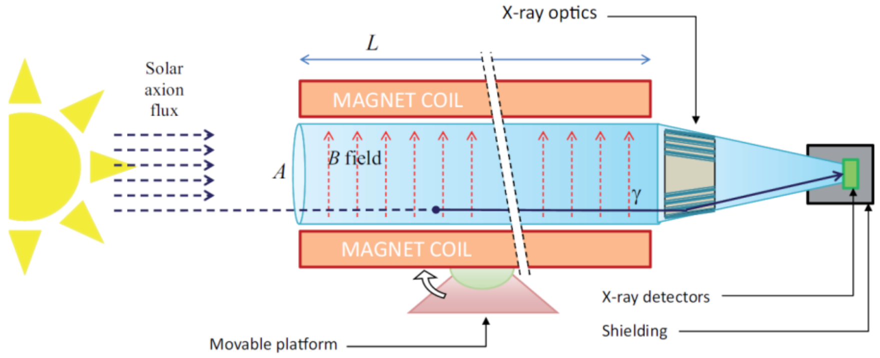


Start of data taking with MADMAX in 2028 at HERA North?

(Baby) International AXion Observatory

Looking for solar axions

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

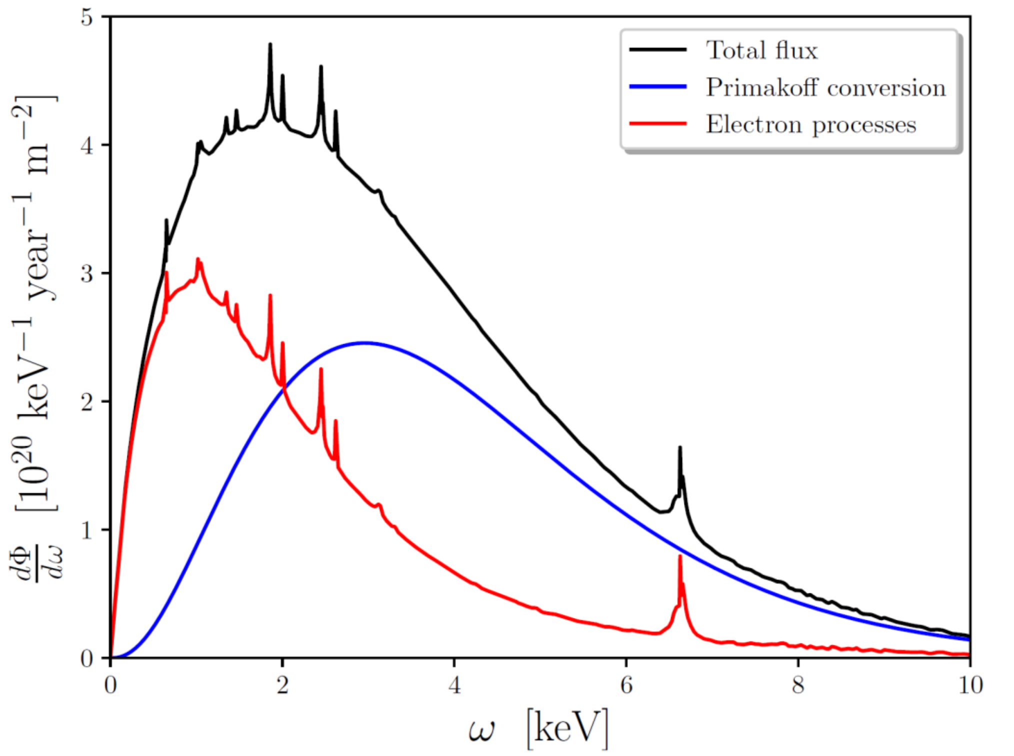


Solar axions produced via

- 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

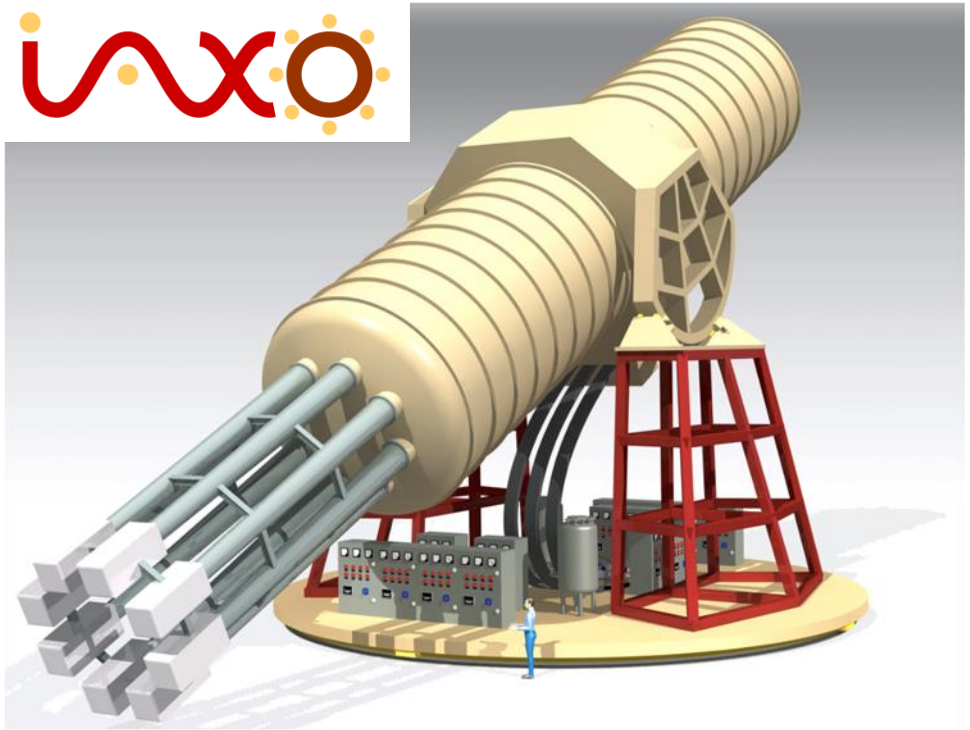
Experiments need to track the sun!



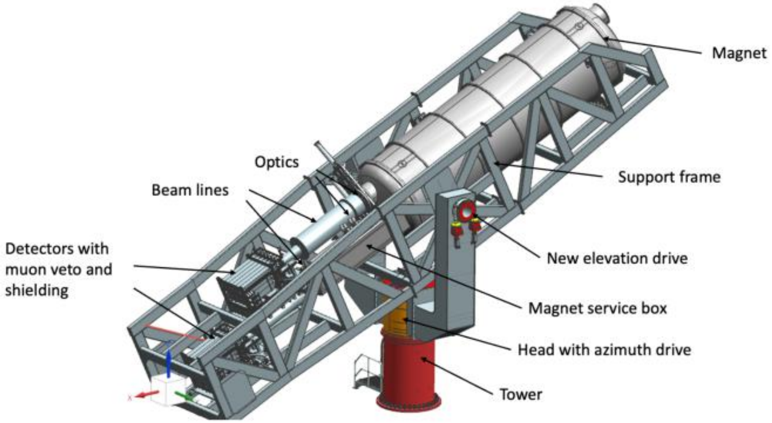
"Distinguishing Axion Models with IAXO"
J. Jaeckel, L.J. Thormaehlen, JCAP 03 (2019), 039

(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

Before 24 February: essential ready to start construction!

- Magnet providing dipole fields in the bores:
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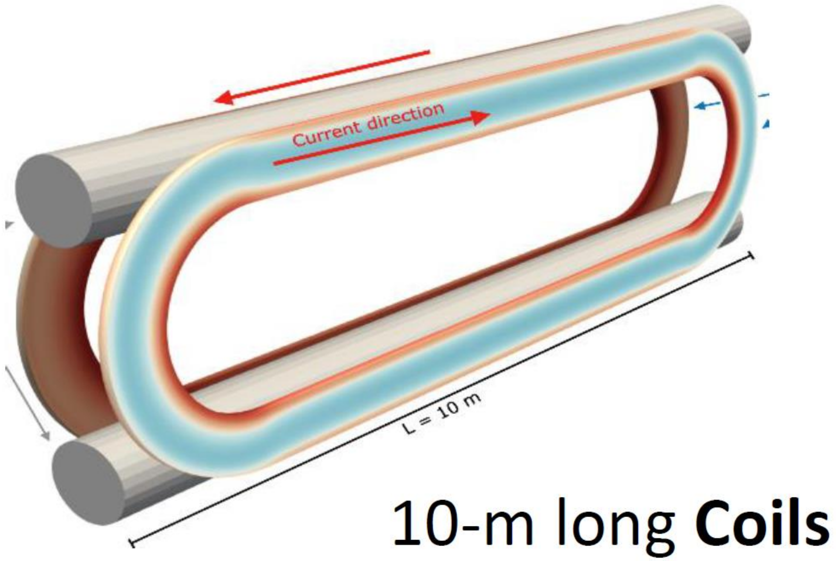

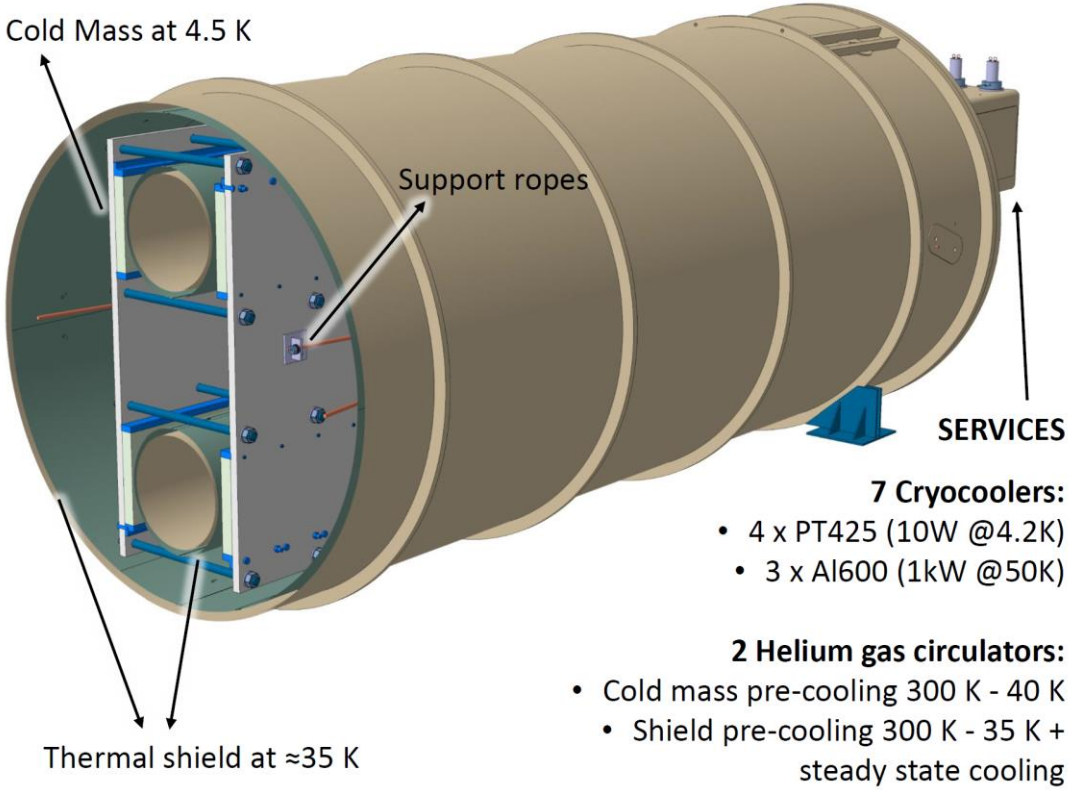

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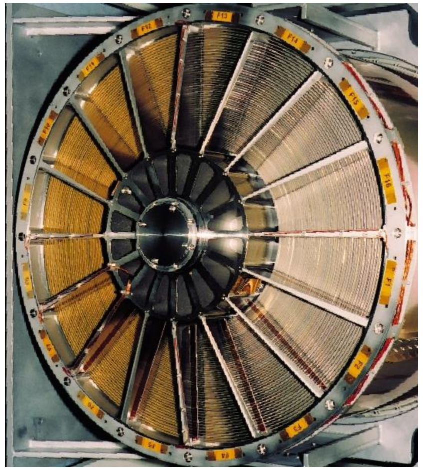

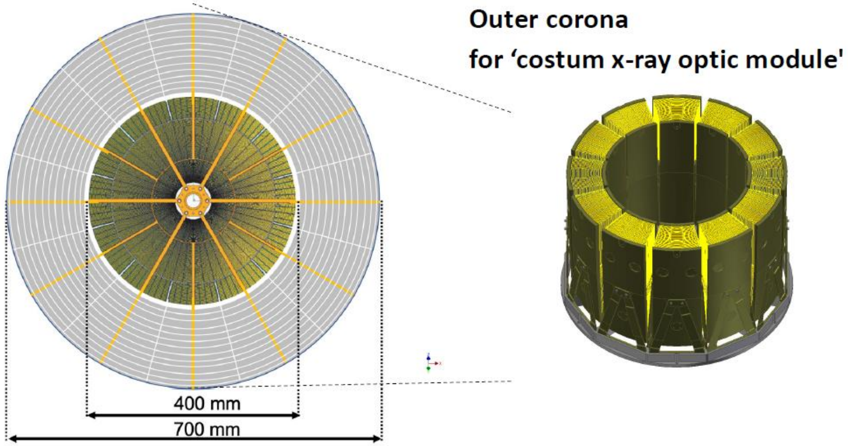

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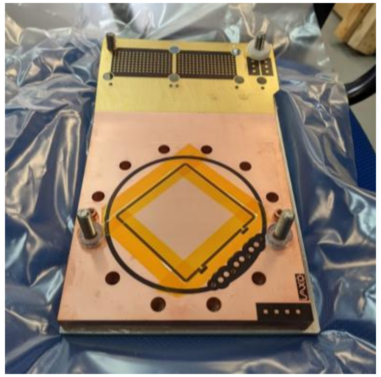
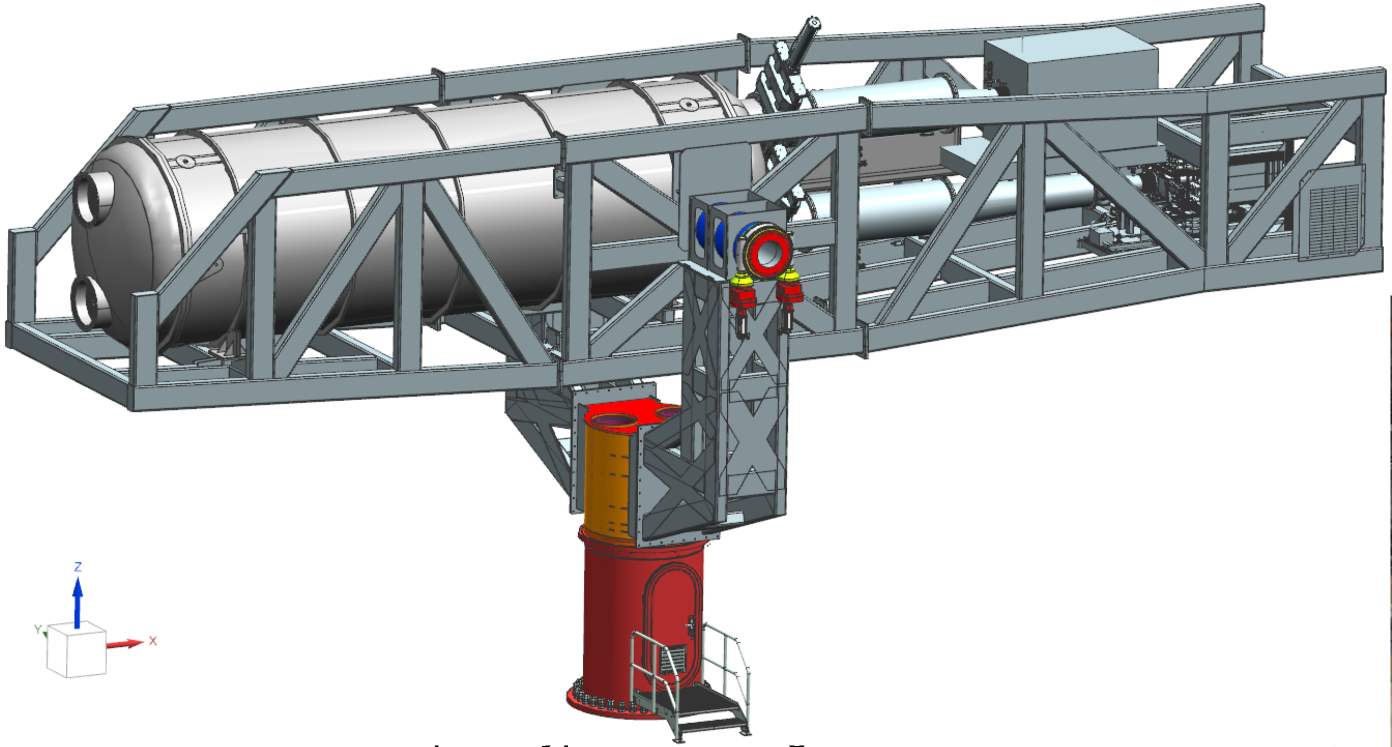
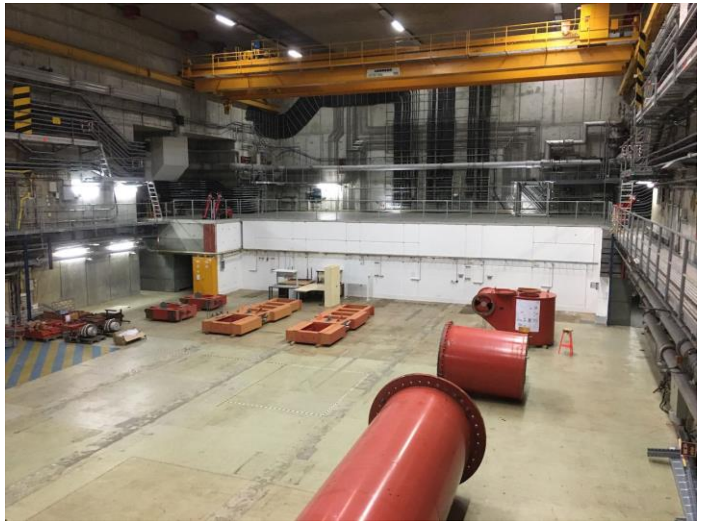
- Low-background detector:
  - Final tests of prototype micromegas this summer in Canfranc, multiple detector options (“discovery detectors”, energy resolving detectors).



BabyIAXO

Status





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

BabyIAXO

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- Structure and drive system
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Start data taking in 2026 In HERA-South?

Collaboration members

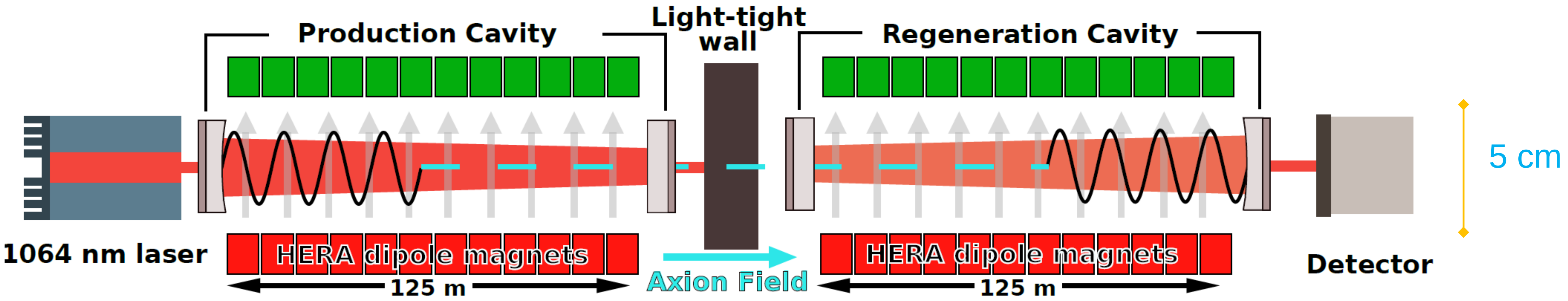
ALPS II

Supported by

Any Light Particle Search II

Light-through-a-wall

Probing axion-photon couplings model independently.



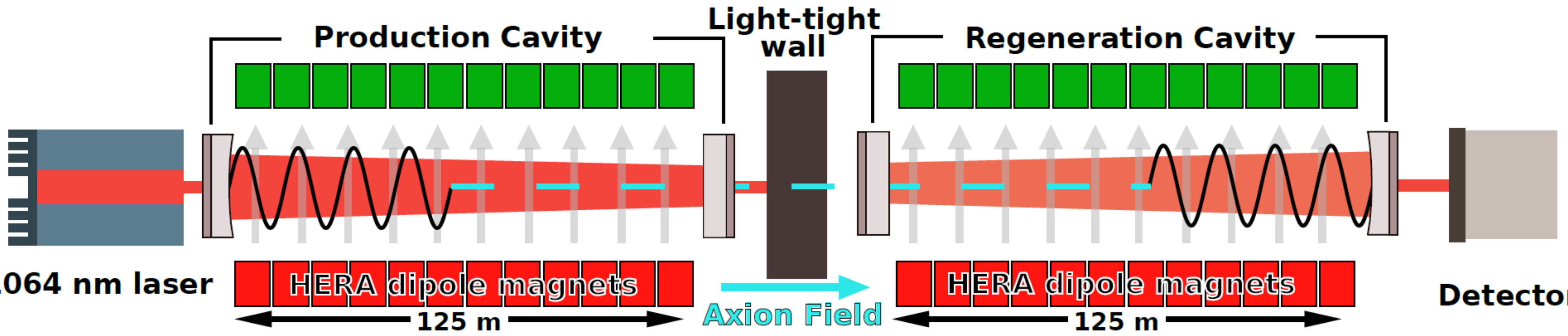
Light injection

Axion pass the wall

Light detection

Any Light Particle Search II

Exploiting mode matched optical cavities



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

5,000 — 40,000 — 0.2 — 5.3 — 10.56

$= 10^{-25}$

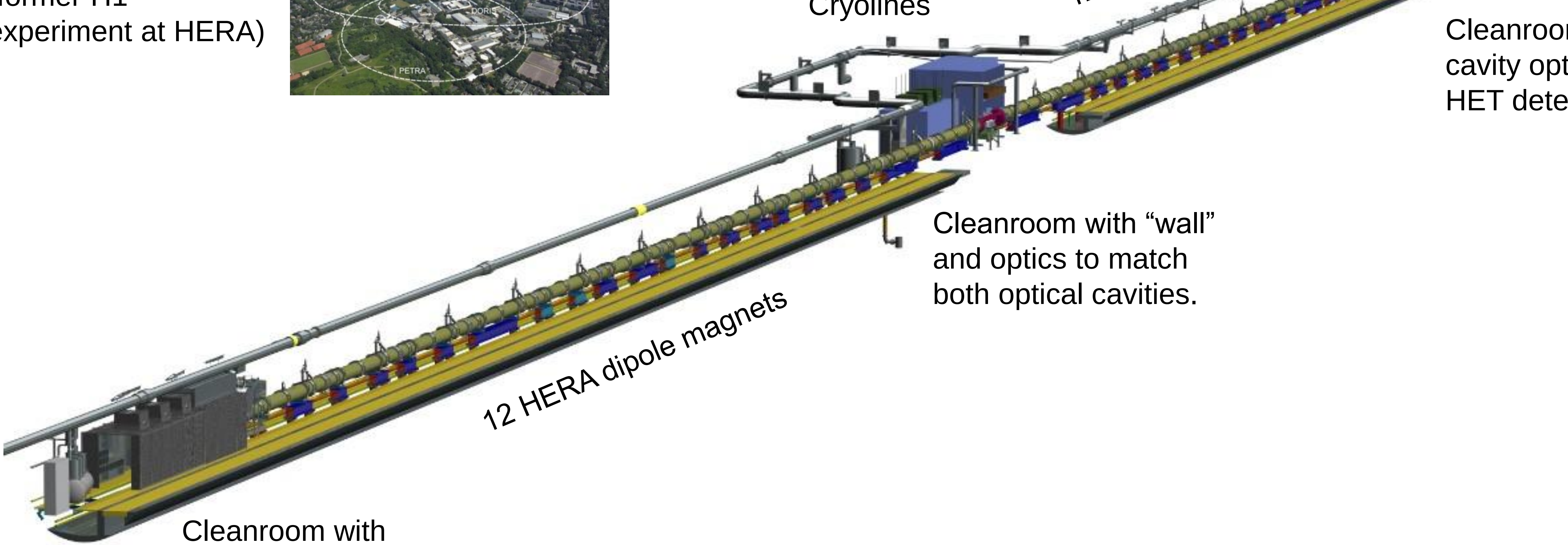
0.2 ↕ Motivated by astrophysics

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

Any Light Particle Search II

Constructed in a straight section of the HERA tunnel

HERA hall North
(former H1
experiment at HERA)



Any Light Particle Search II

Status of autumn 2020

Any Light Particle Search II

Demounting HERA: mid 2018 to mid 2019

Any Light Particle Search II

Foundations for the optics

Any Light Particle Search II

Magnets into the tunnel

First Magnet Fest 28 October 2019

Any Light Particle Search II

More magnets

Any Light Particle Search II

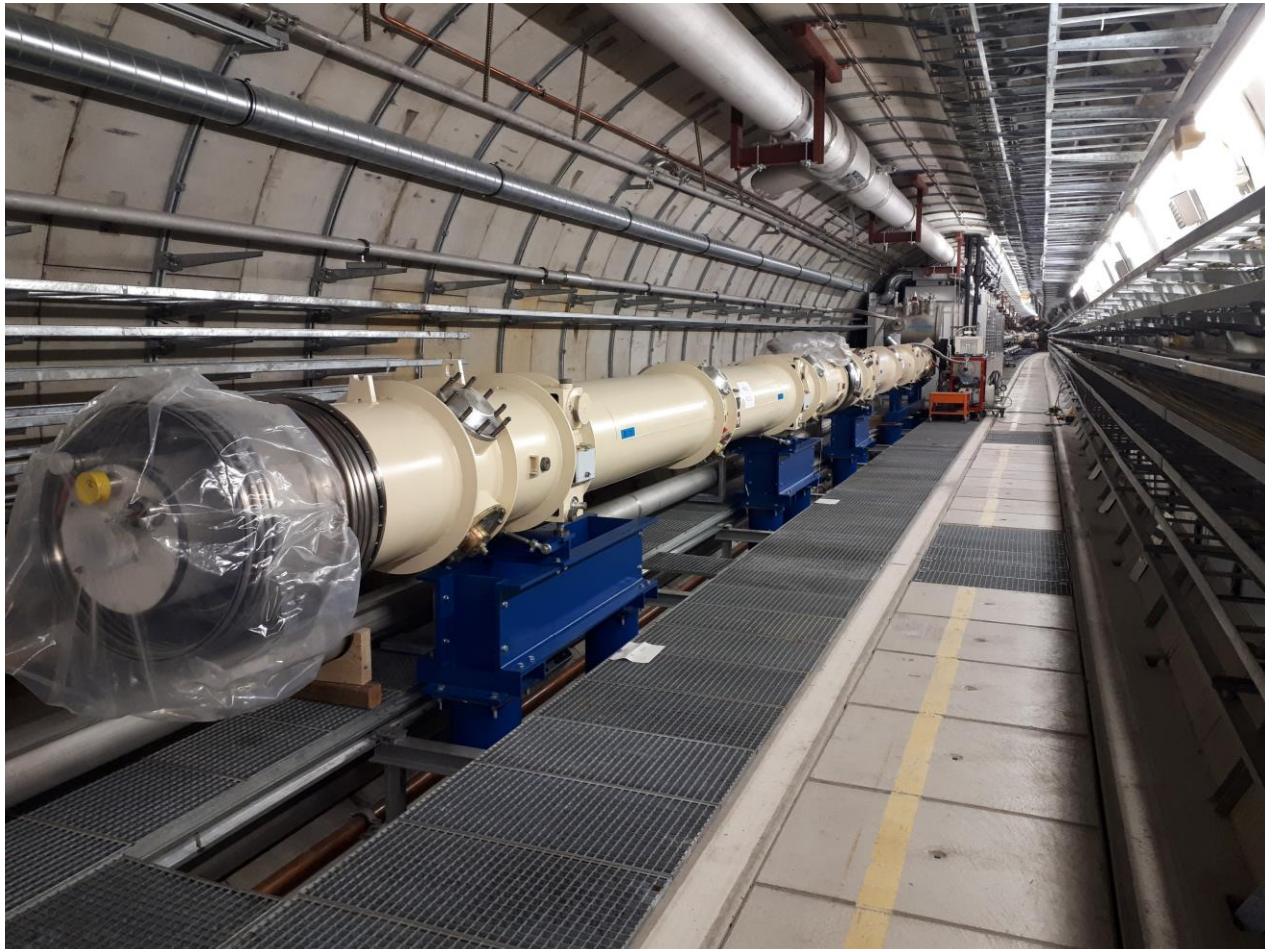
More magnets

Any Light Particle Search II

More magnets

Any Light Particle Search II

More magnets



Any Light Particle Search II

More magnets

Any Light Particle Search II

22 October 2020: last magnets installed!

Joachim Mnich, Director for particle physics (now at CERN)

Wim Leemans, Director for accelerators

Any Light Particle Search II

Technologies

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

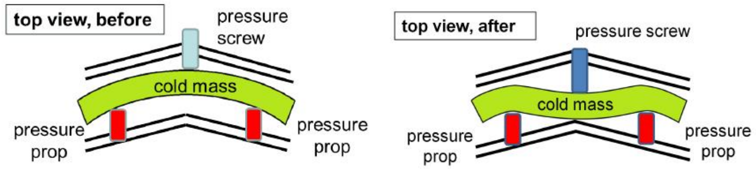
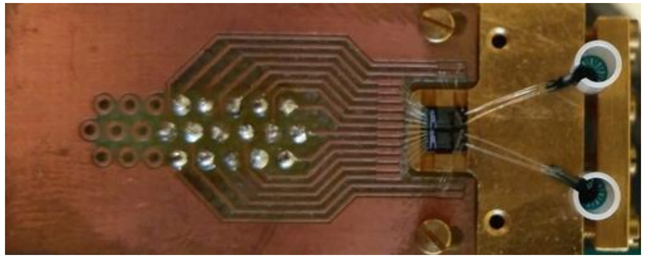


Figure 9: *Schematics of straightening. Left: Before applying the deforming force, Right: The deformation forces the pipe to develop two 'camel humps,' exaggerated in the figure for better illustration. This deformation yields the largest achievable horizontal aperture.*

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

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

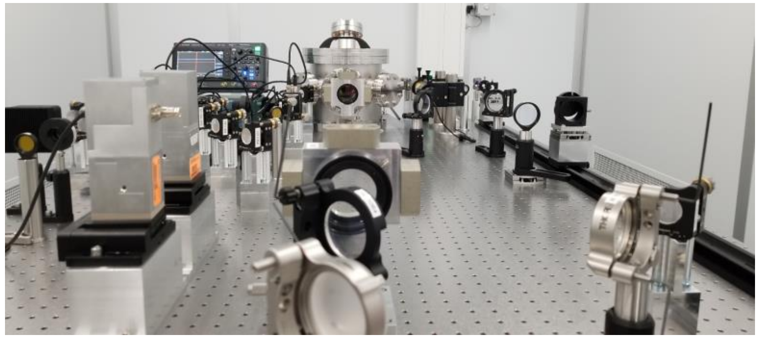
- Extremely low 1064 nm photon flux detection:
heterodyne sensing and
superconducting transition edge sensor (TES)



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 requirements for the first full science run

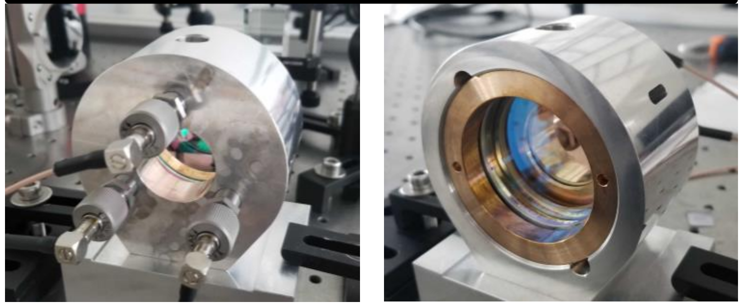
RC resonant enhancement (β_{RC})	> 10 000
RC absolute length changes (ΔL_{RC})	~ 15 µm
RC linewidth (HWHM)	15 Hz
PC circulating power	> 150 kW
PC relative power noise (RMS)	< 0.1%
Axion Coupling to RC (η)	> 90%
Coherence ($\eta_{\Delta f}$)	> 95%
Dynamic phase noise ($\Delta\varphi$)	< 0.2 rad
Static 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

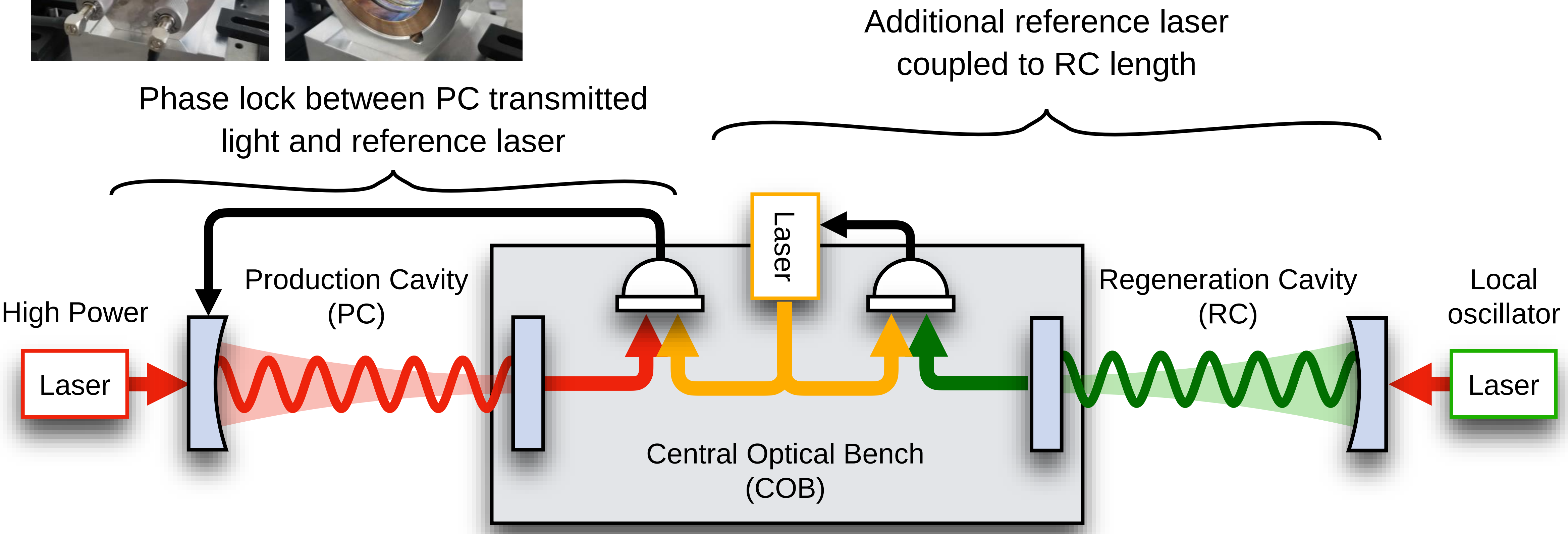
15 Hz out of $3\cdot10^{14}$ Hz

Any Light Particle Search II

Optics “locking” scheme to overcome seismic noise

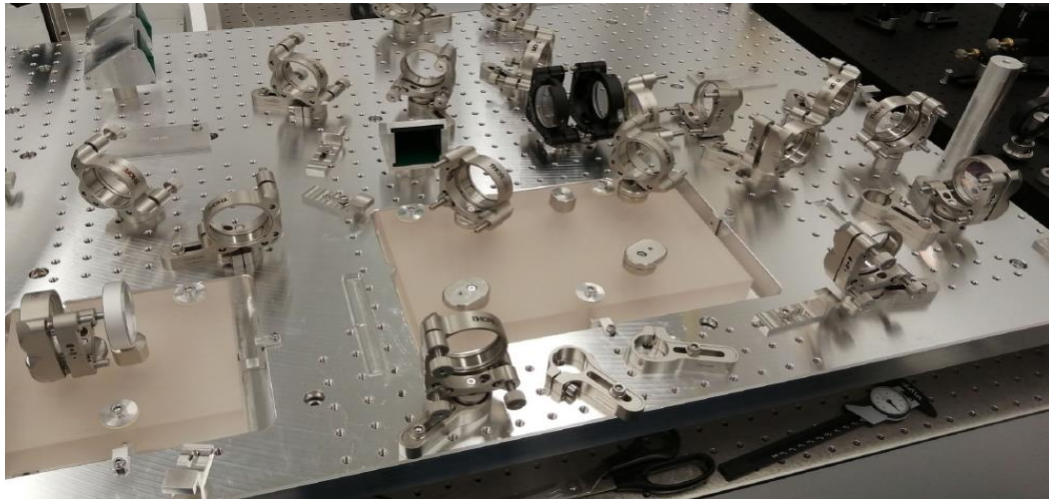
Actuators: *picometer* position accuracy required

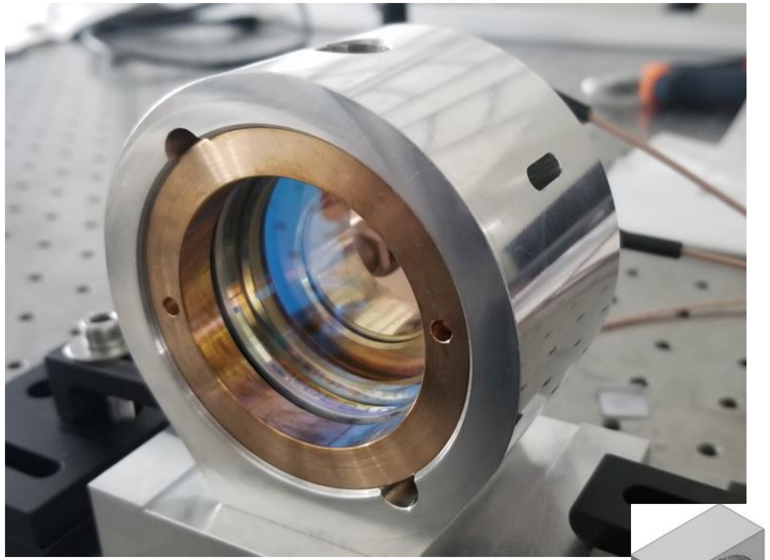


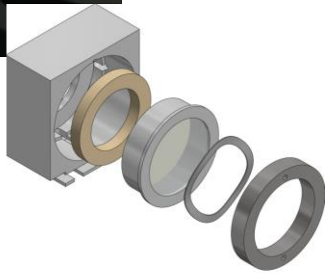


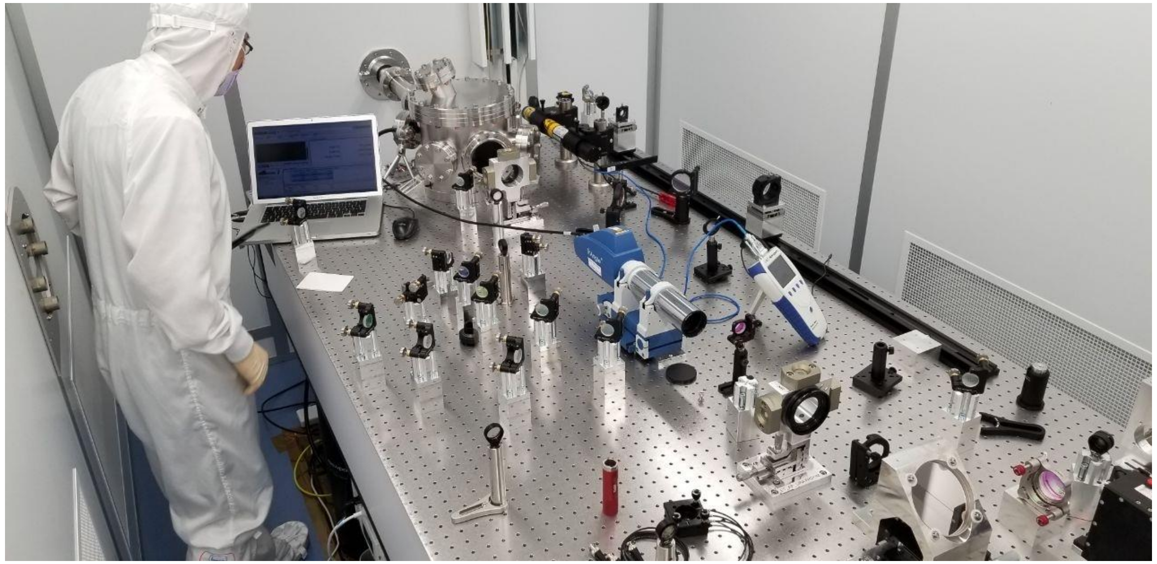
Any Light Particle Search II

Optics





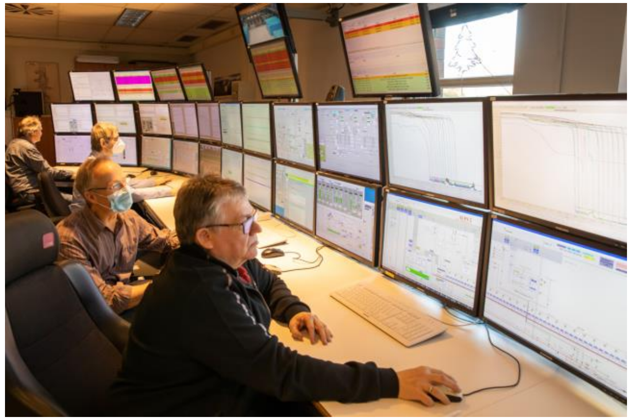


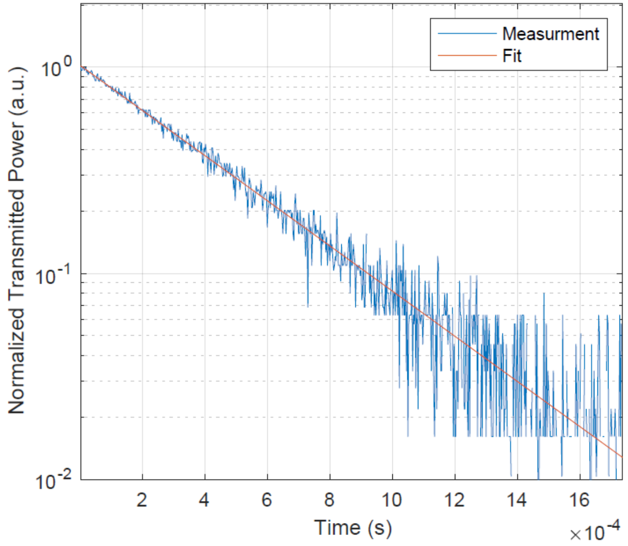


Any Light Particle Search II

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.
- Late 2022: first science run (hopefully)!





250 m cavity storage time (prel. mirrors)

Outline

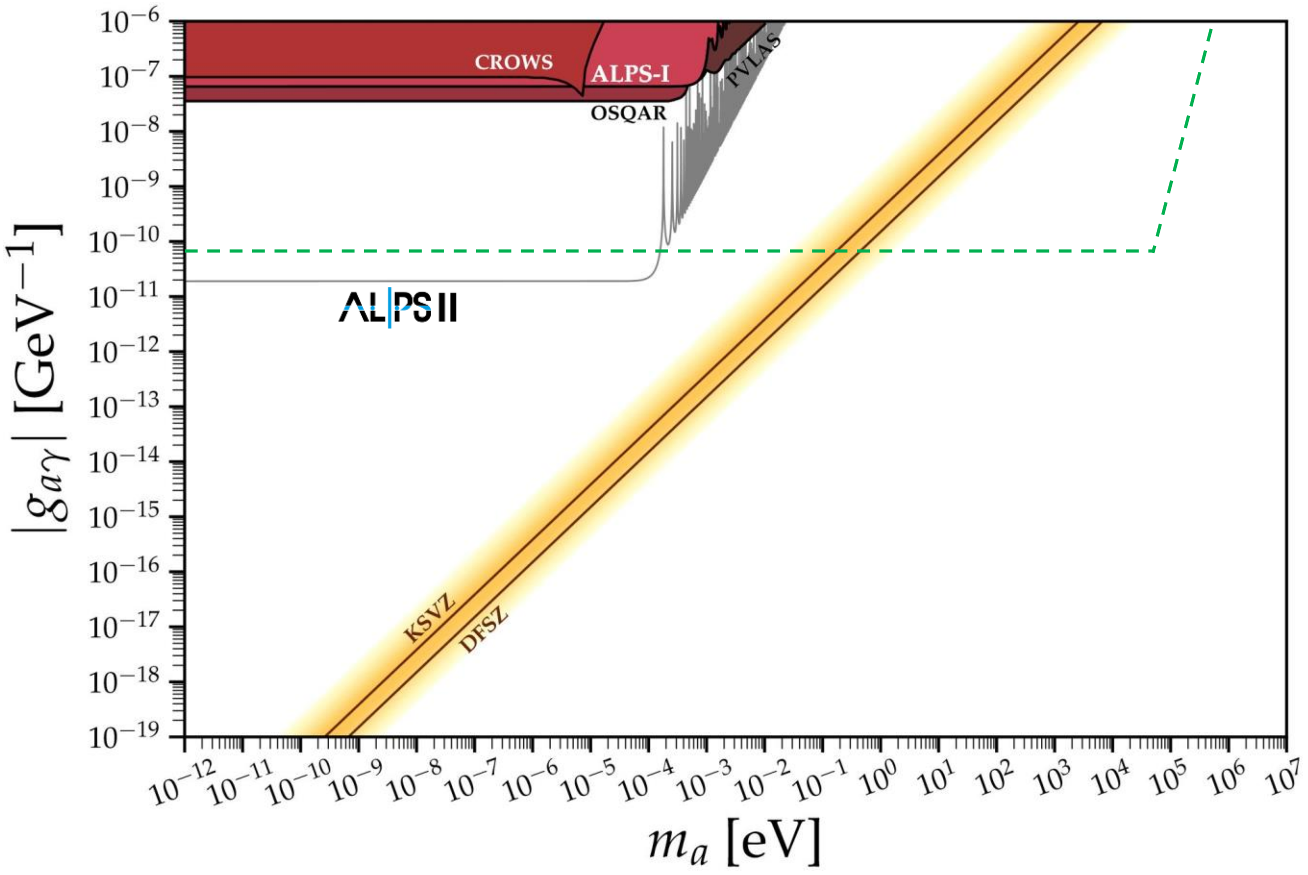
- Axions:
  - A very brief motivation.
  - Three kinds of experiments.
- Axions @ DESY:
  - MADMAX
  - (Baby)IAXO
  - ALPS II
- Conclusions

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.



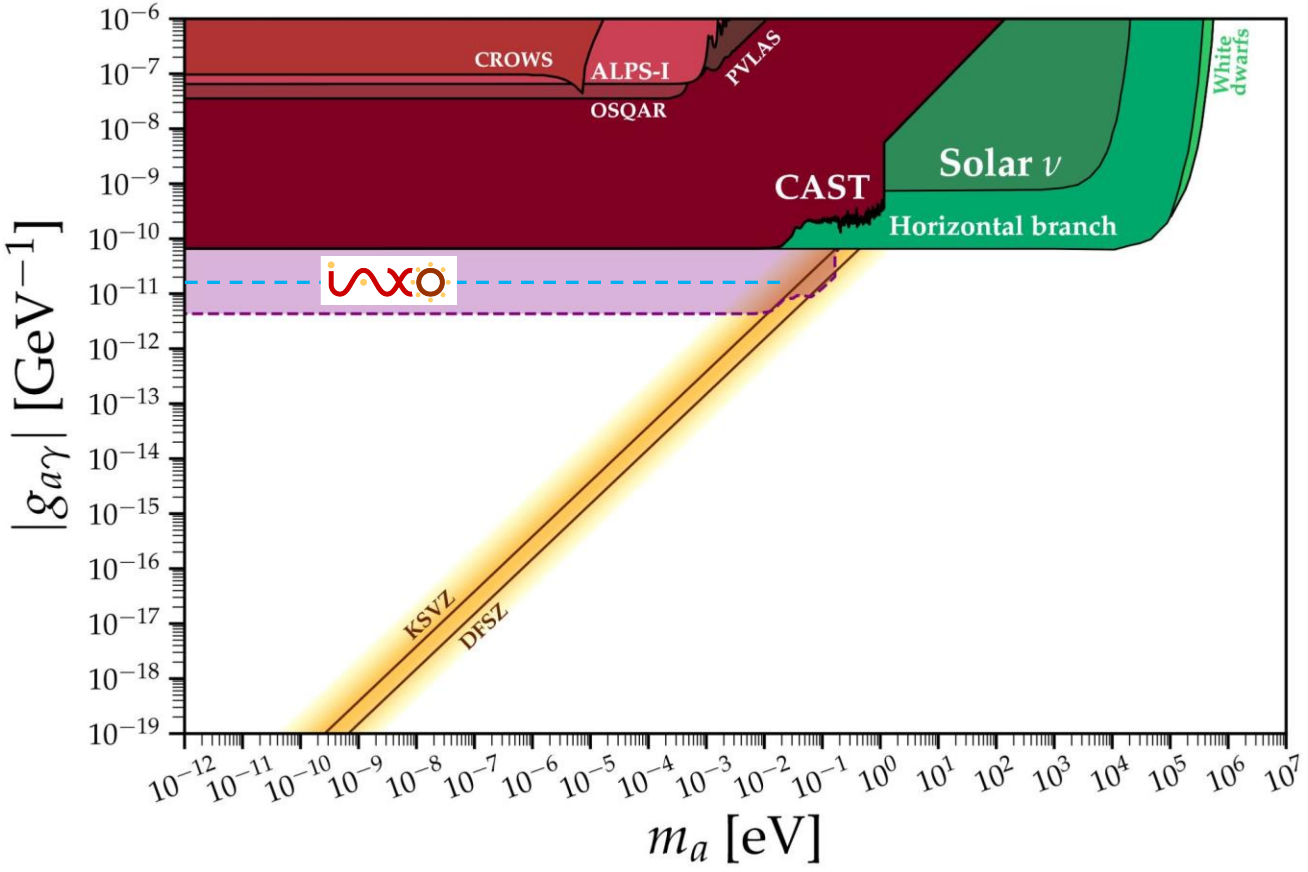
https://github.com/cajohare/AxionLimits

Axion searches at DESY

In context

IAXO, solar axion searches:

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



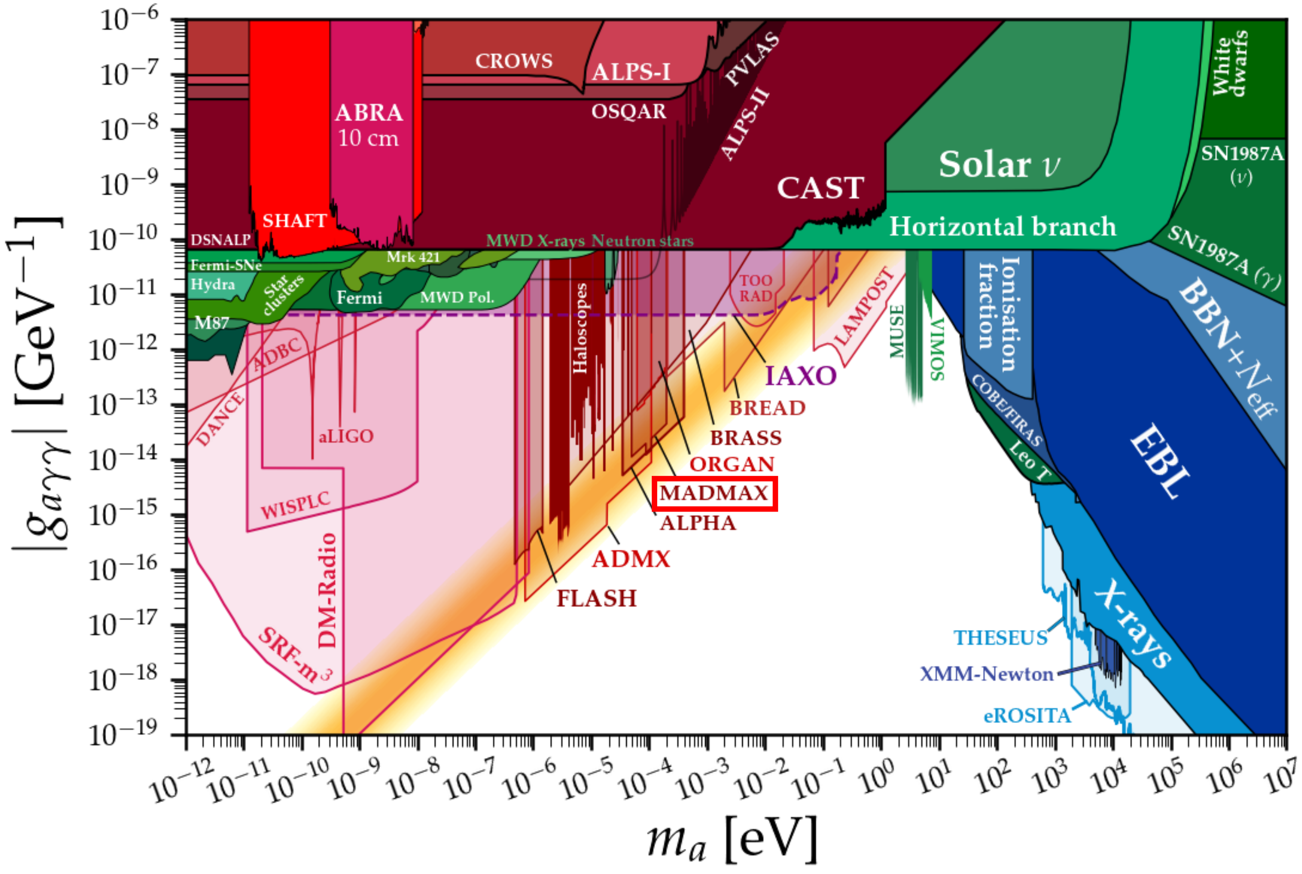
https://github.com/cajohare/AxionLimits

Axion searches at DESY

In context

MADMAX, dark matter axion searches:

- Probe the mass region between 40 and 400 µeV.



https://github.com/cajohare/AxionLimits

Instead of a summary

A dream

ALPS II, first data taking in 2022:

- Determine the axion-photon coupling model-independently.

IAXO, first data taking of BabyIAXO in 2026 ?

- 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 2028 ?

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

Thank you

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

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Axel Lindner
FH-ALPS
axel.lindner@desy.de
+49 40 8998 3525