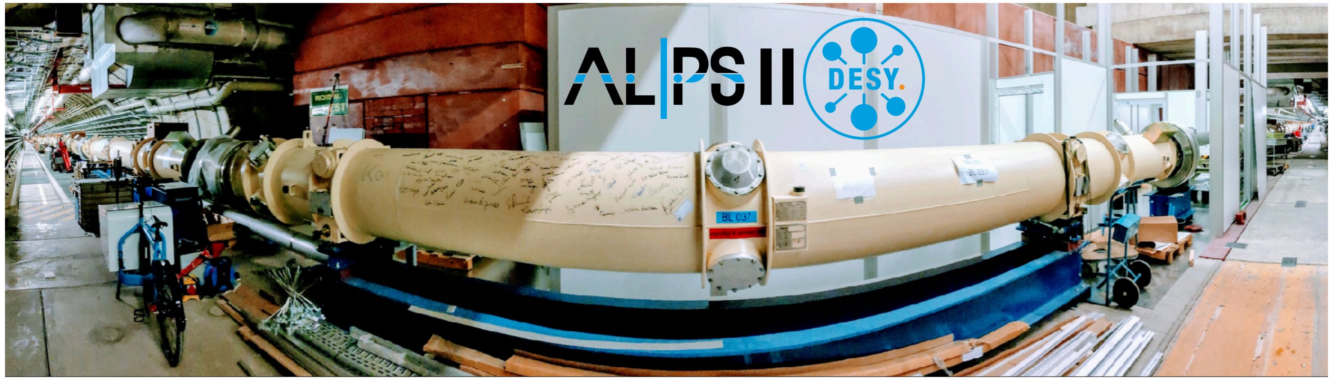
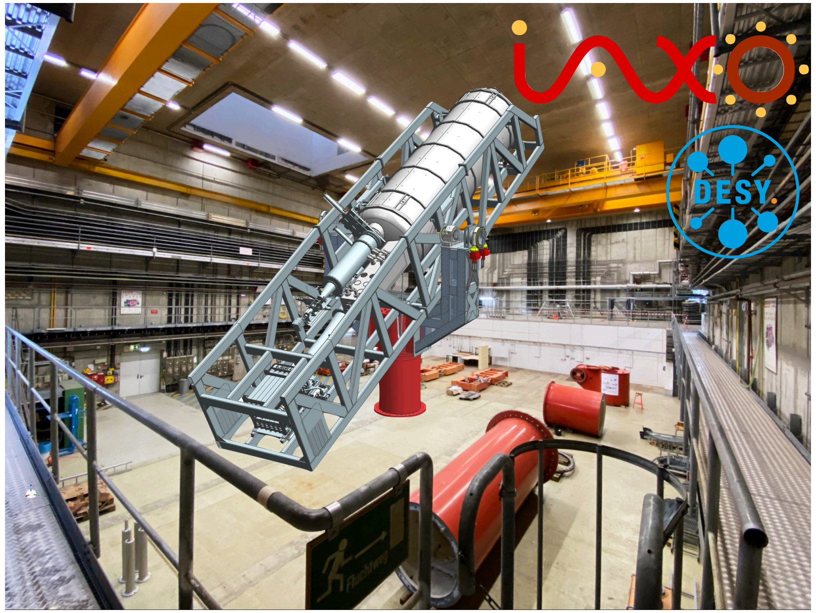
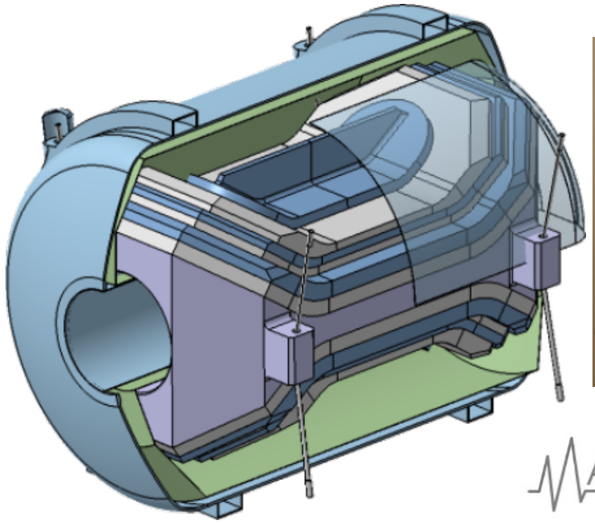
Axions & ALPs Searches at DESY

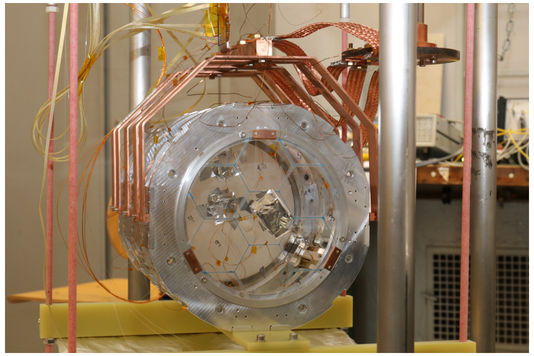
Why, How and How to Go Beyond Discovery?

Daniel Heuchel (DESY)
daniel.heuchel@desy.de
MU Days 2023
KIT, Karlsruhe, 14th September 2023









MADMAX

HELMHOLTZ

DESY.

Outline

For this Talk

- Motivation for axions/ALPs
- Status & physics prospects of:
  - ➡ ALPS II
  - ➡ BabyIAXO
  - ➡ MADMAX and the current experimental landscape
- Summary and outlook

Axions/ALPs

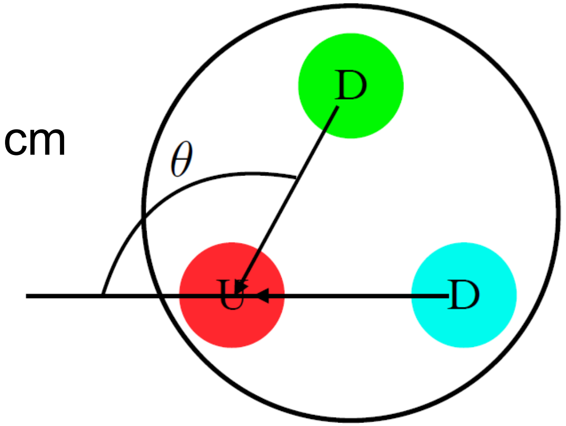
and how to detect them.

Why Axions/ALPs?

Physics Motivation

Exp: $EDM_{neutron} < 3 \times 10^{-26}$ e cm

$\rightarrow \theta < 10^{-10}$



Most compelling solution to the strong CP problem

Why Axions/ALPs?

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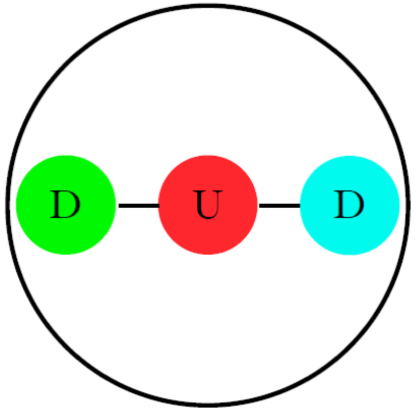

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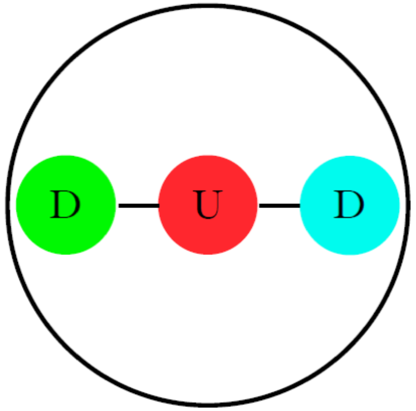

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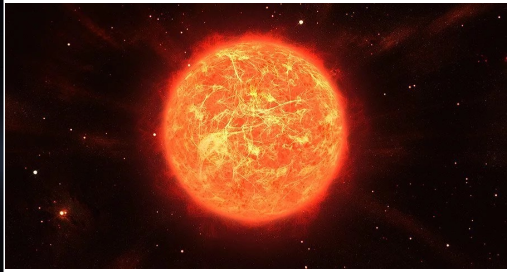

Astrophysical hints:
UHE γ transparency,
anomalous stellar cooling,
solar evolution …

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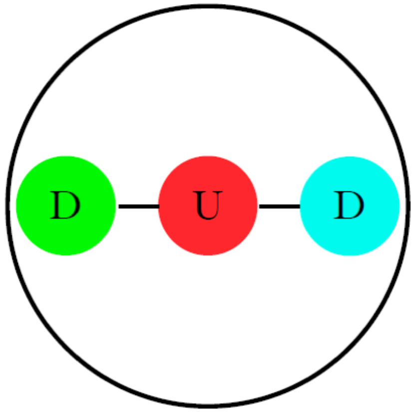

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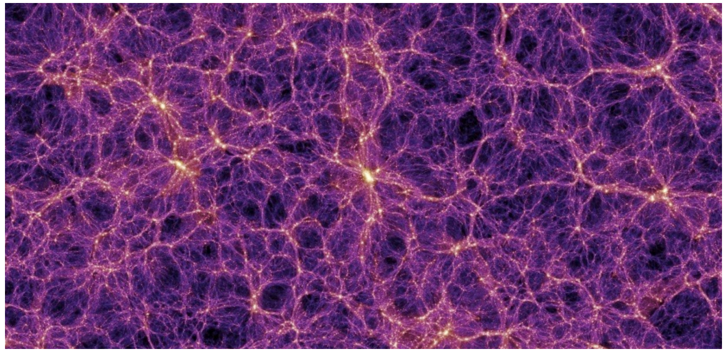

Cosmology:
Excellent cold dark matter candidate
(Not ad hoc solution to DM)

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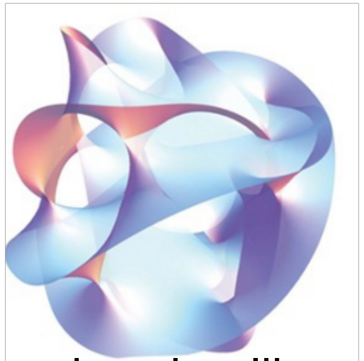
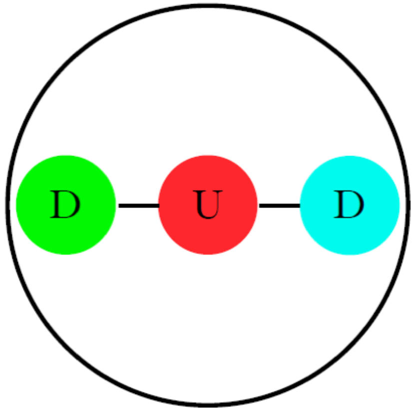


Theory:
More generic axion-like particles (ALPs) predicted by many extensions of SM (e.g. string theory)



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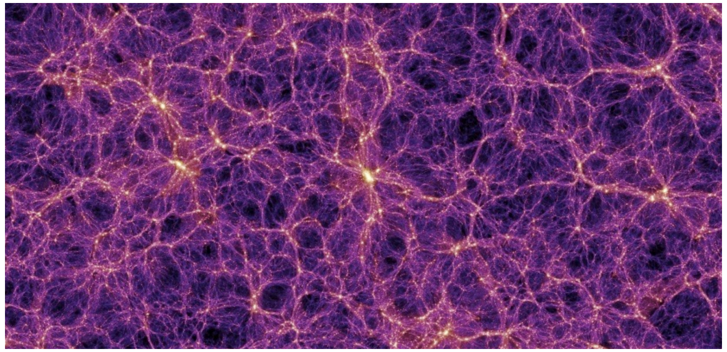

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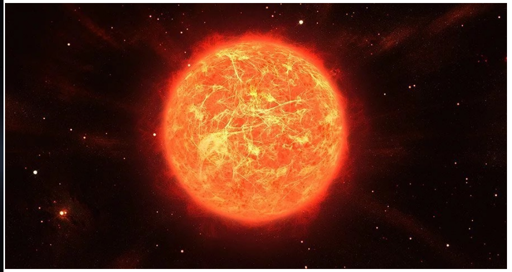

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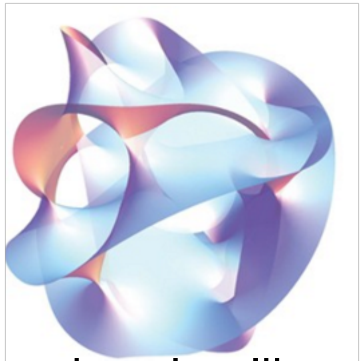

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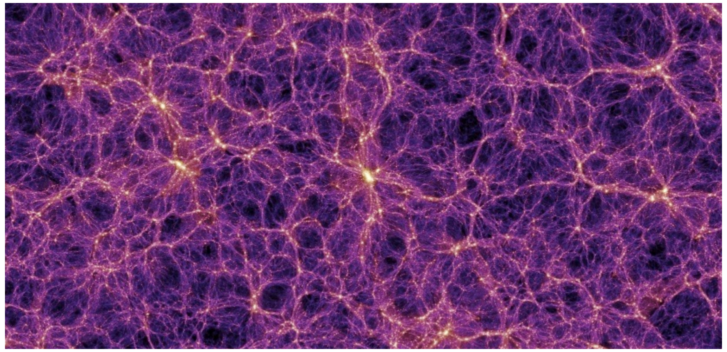

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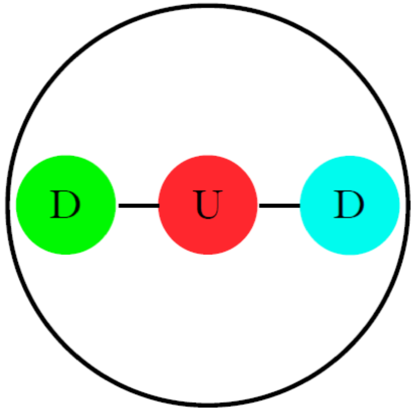

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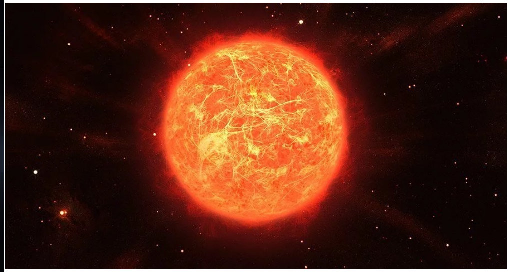

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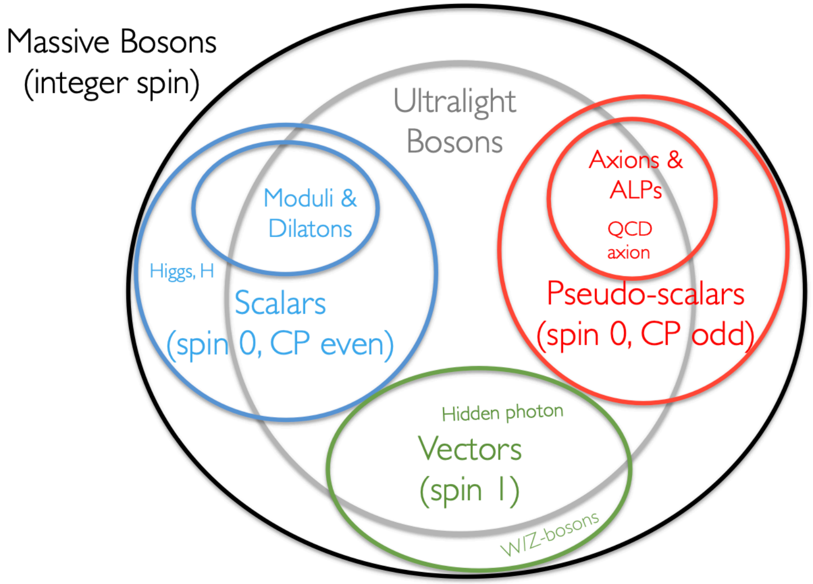
Detection of Axion/ALPs

Coupling to Photons

- Properties of axions/ALPs:
  - ➡ WISP (Weakly interacting sub-eV particles), typical: m_a < 1eV
  - ➡ Pseudo-scalar
  - ➡ Z = 0
  - ➡ Minimal interaction with SM constituents
  - ➡ **Axion/ALP photon mixing in magnetic fields**



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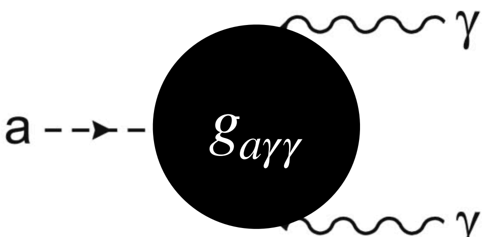

Axion decay to photons

Detection of Axion/ALPs

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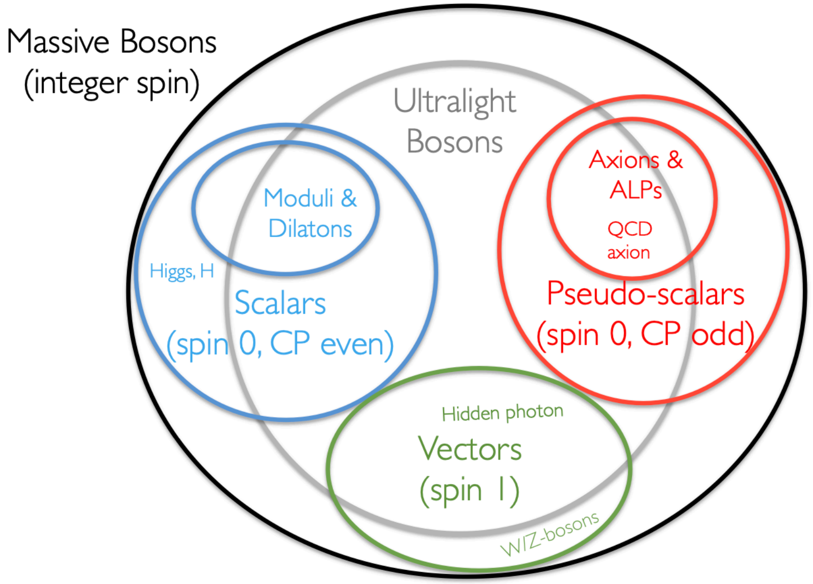

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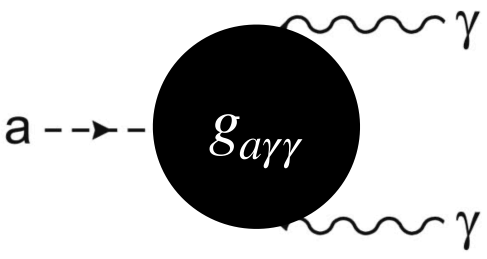
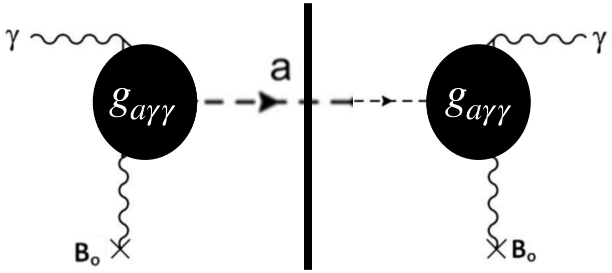


Axion decay to photons

Experimental Approaches

Complementarity & Model Dependencies

Concept	Source	Detection	Model & Cosmology Dependency	Photon Energy Experiments
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	Microwave-Optical OSQAR, CROWS, ALPS, **ALPS II,** STAX

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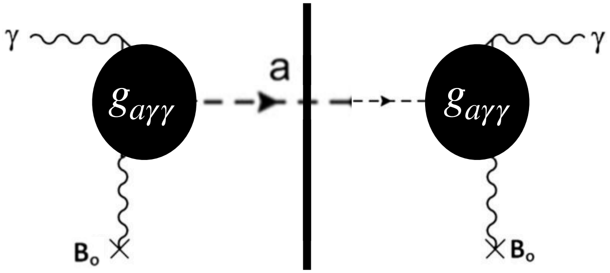
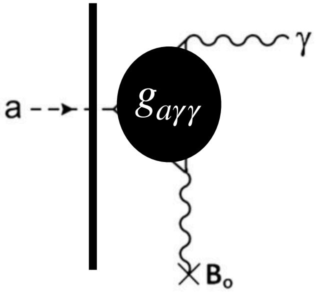
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	Microwave-Optical OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	X-Ray SUMICO, CAST, **(Baby)IAXO**

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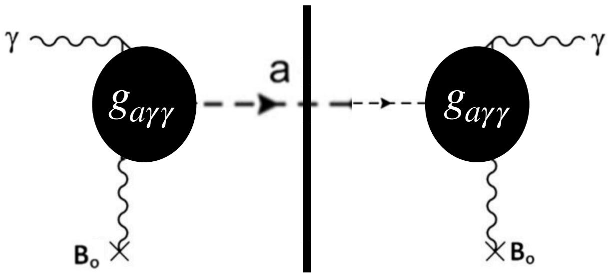
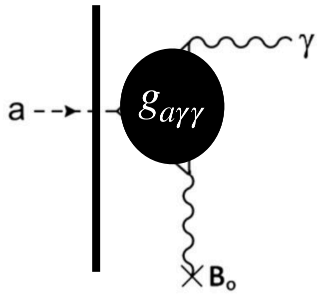
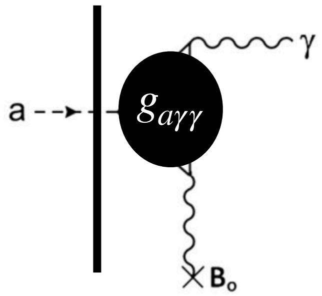
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	Microwave-Optical OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	X-Ray SUMICO, CAST, **(Baby)IAXO**
Haloscopes	 Relic axions		**High** Axions = cold dark matter constituents	Microwave ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…

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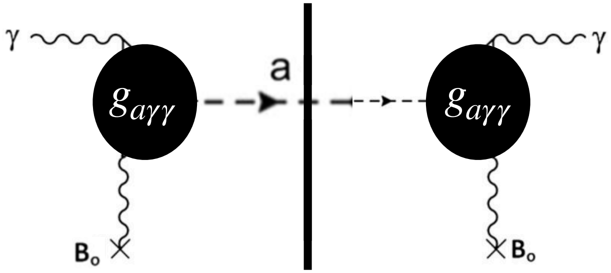
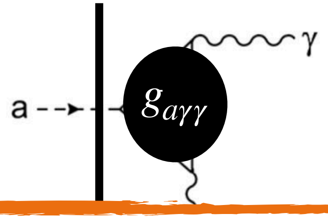
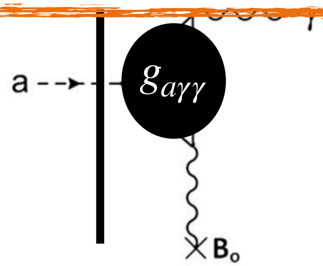
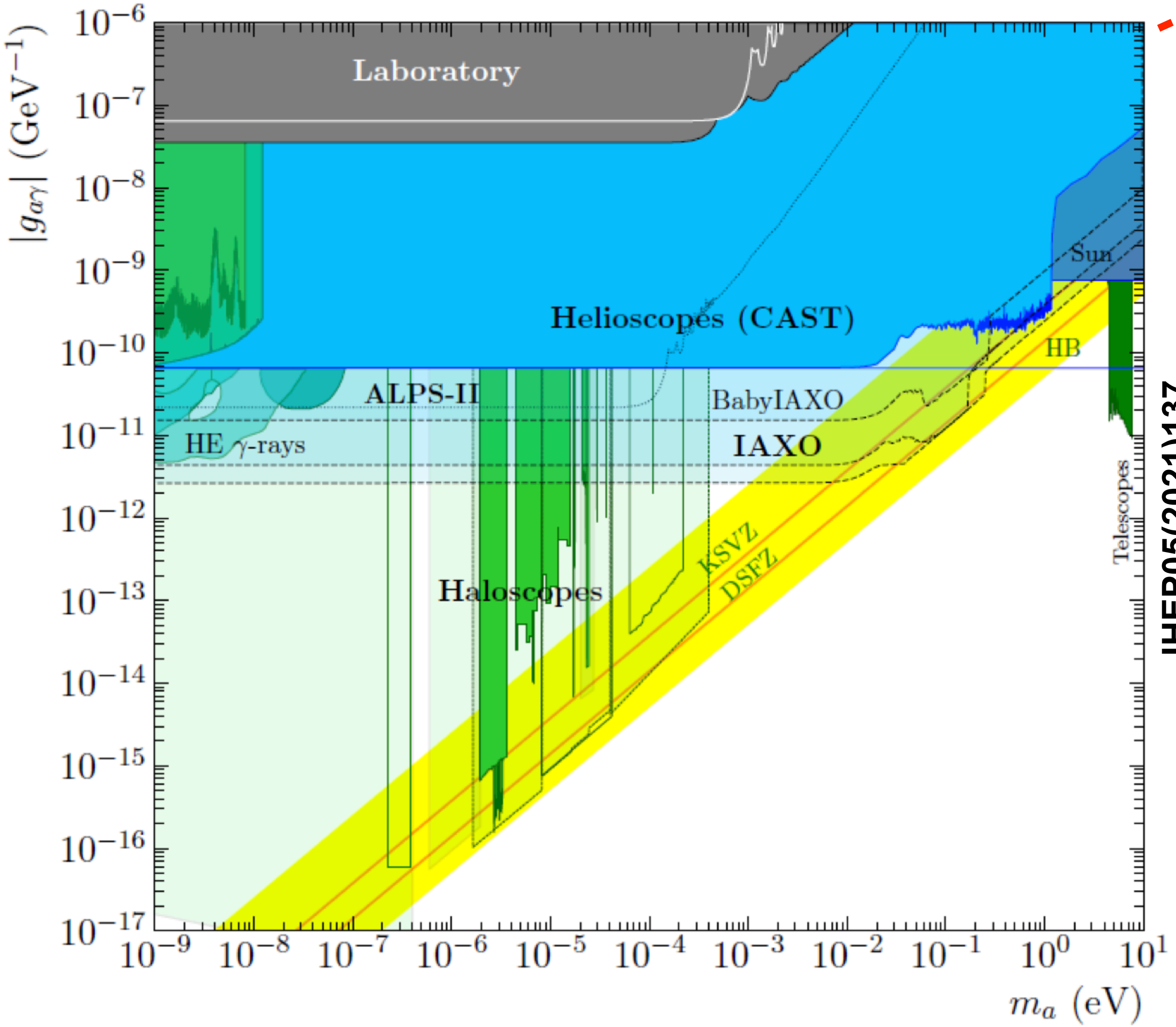
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	Microwave-Optical OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Sol		**Low - medium** Depending on solar production channel	X-Ray SUMICO, CAST, **(Baby)IAXO**
Haloscopes			**High** Axions = cold dark matter constituents	Microwave ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…

Light-shining-through-wall and helioscope experiments search for WISPs independent of the Dark Matter paradigm!

Illustration: Parameter Landscape

Axion-Photon Coupling, Experiments & Theories

Collider

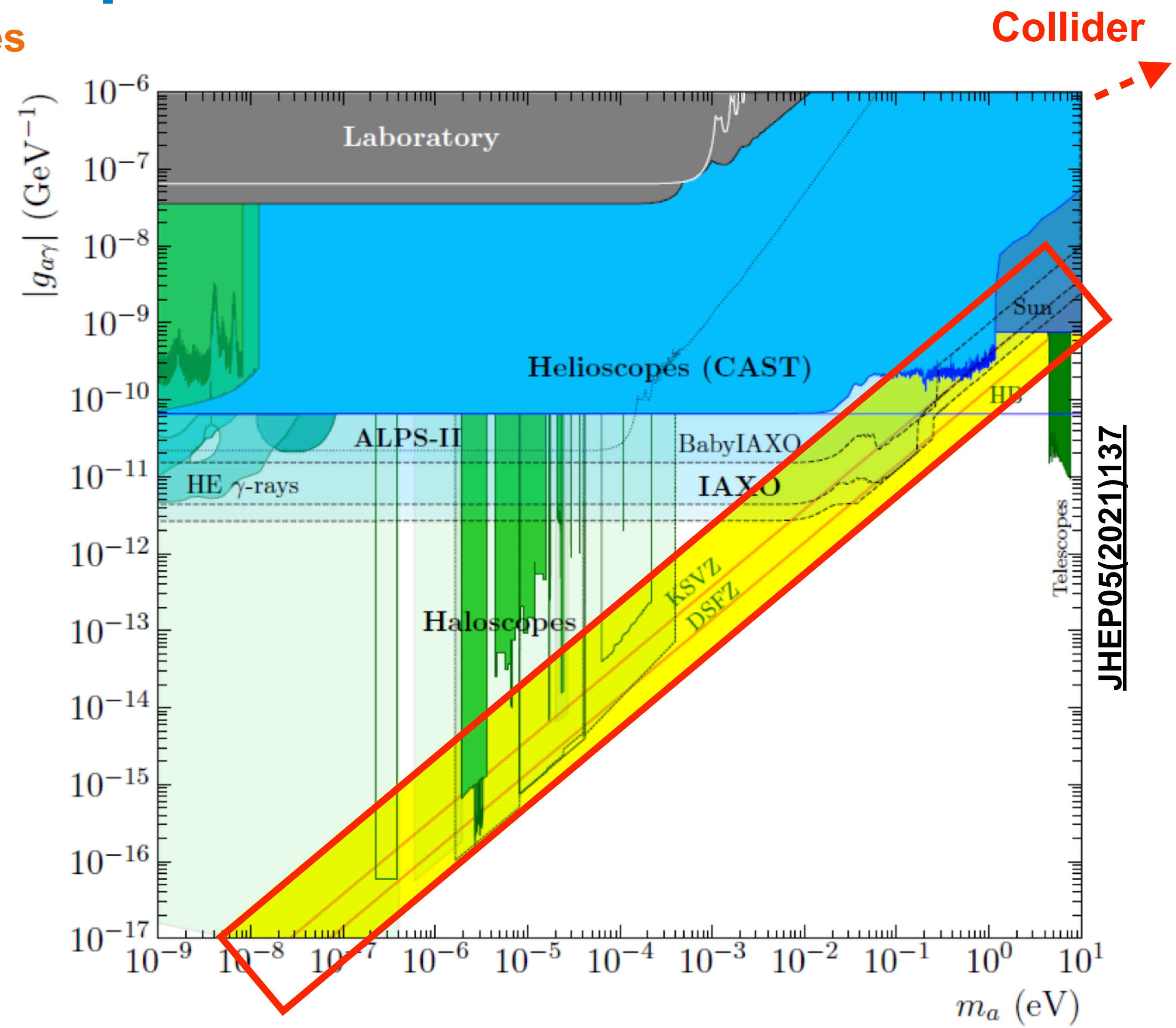


JHEP05(2021)137

Illustration: Parameter Landscape

Axion-Photon Coupling, Experiments & Theories

- Yellow band: traditional QCD axion benchmarks
  - ➡ DFSZ: axions couple to fermions
  - ➡ KSVZ: axions couple to BSM quarks only



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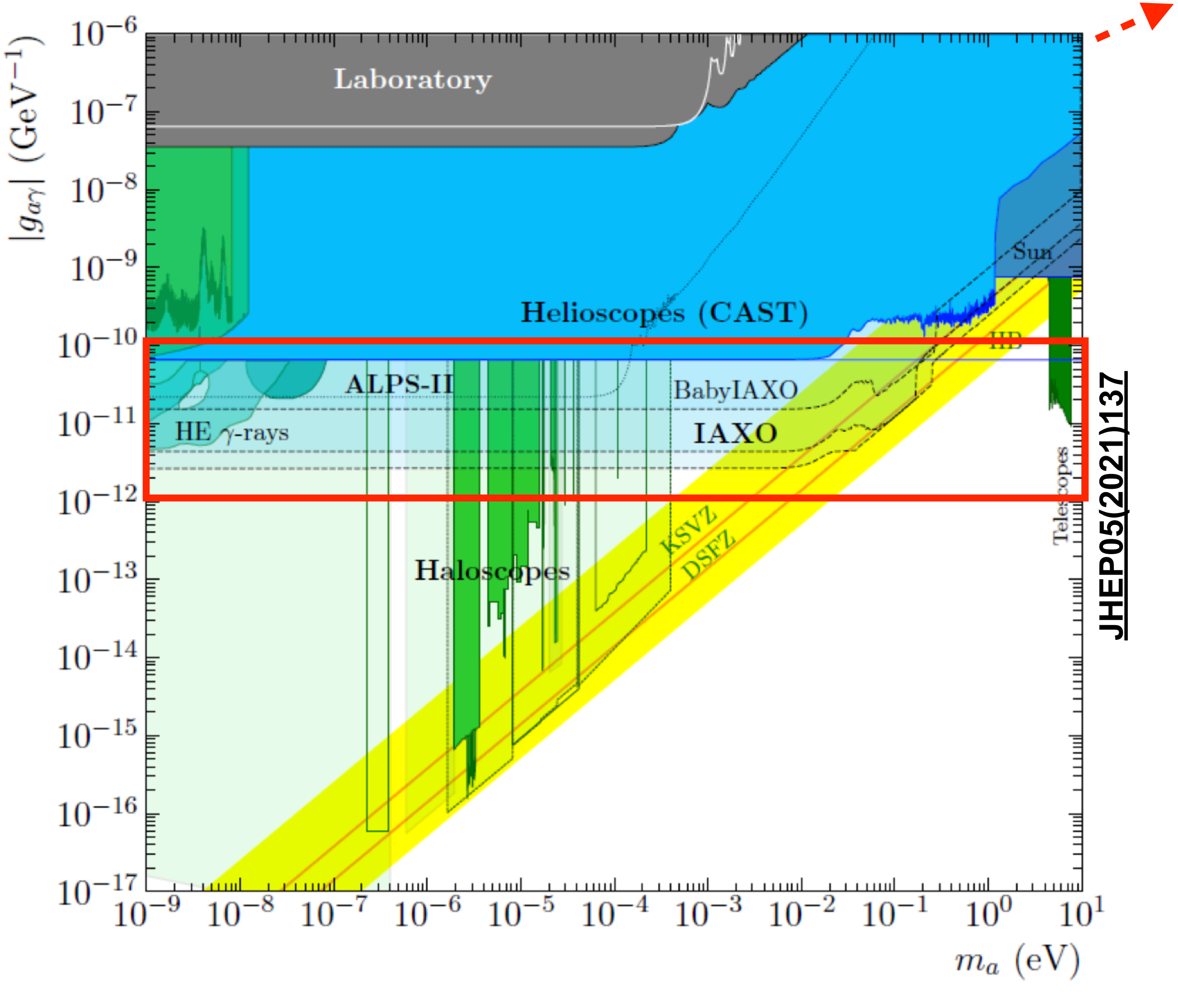

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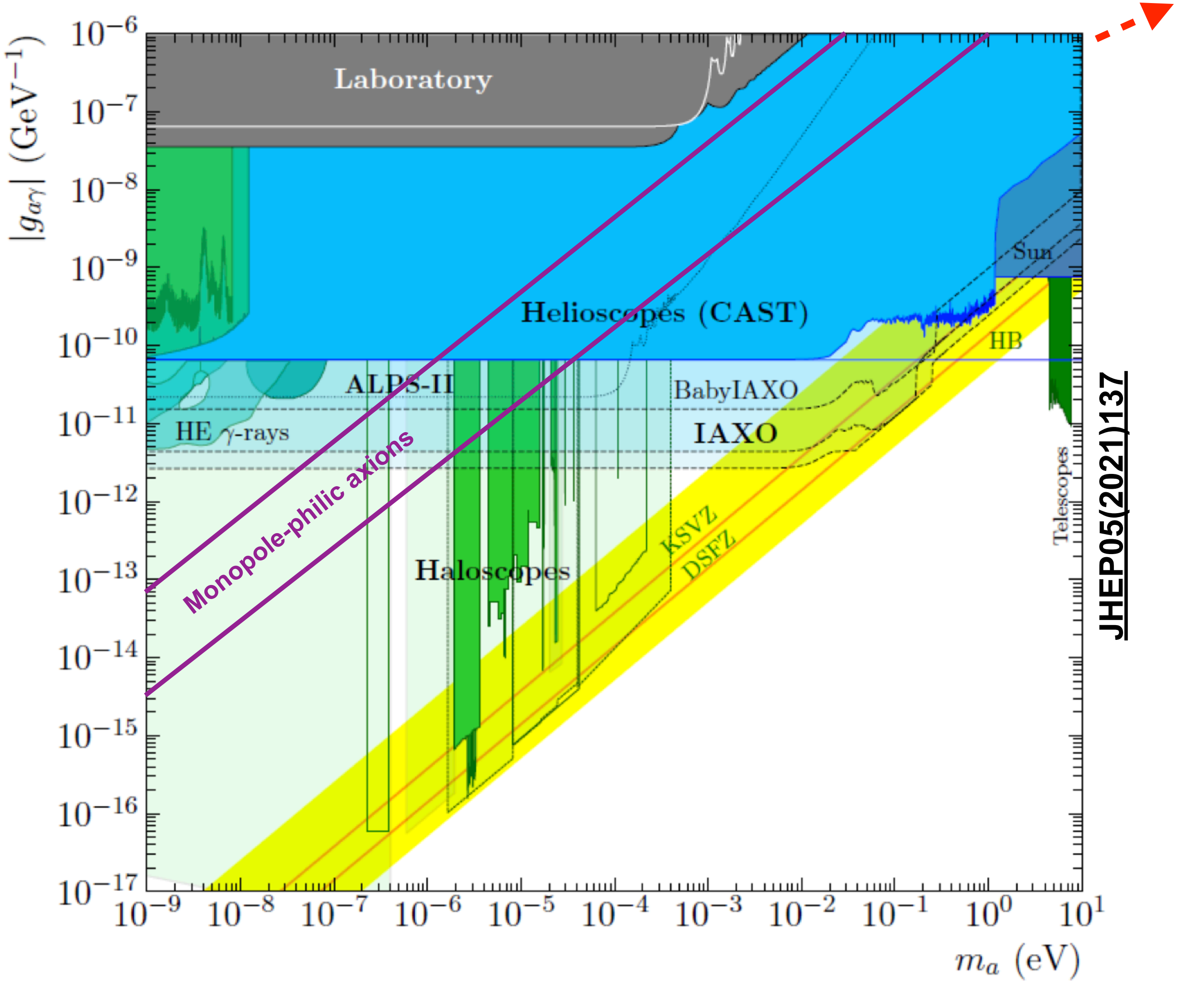

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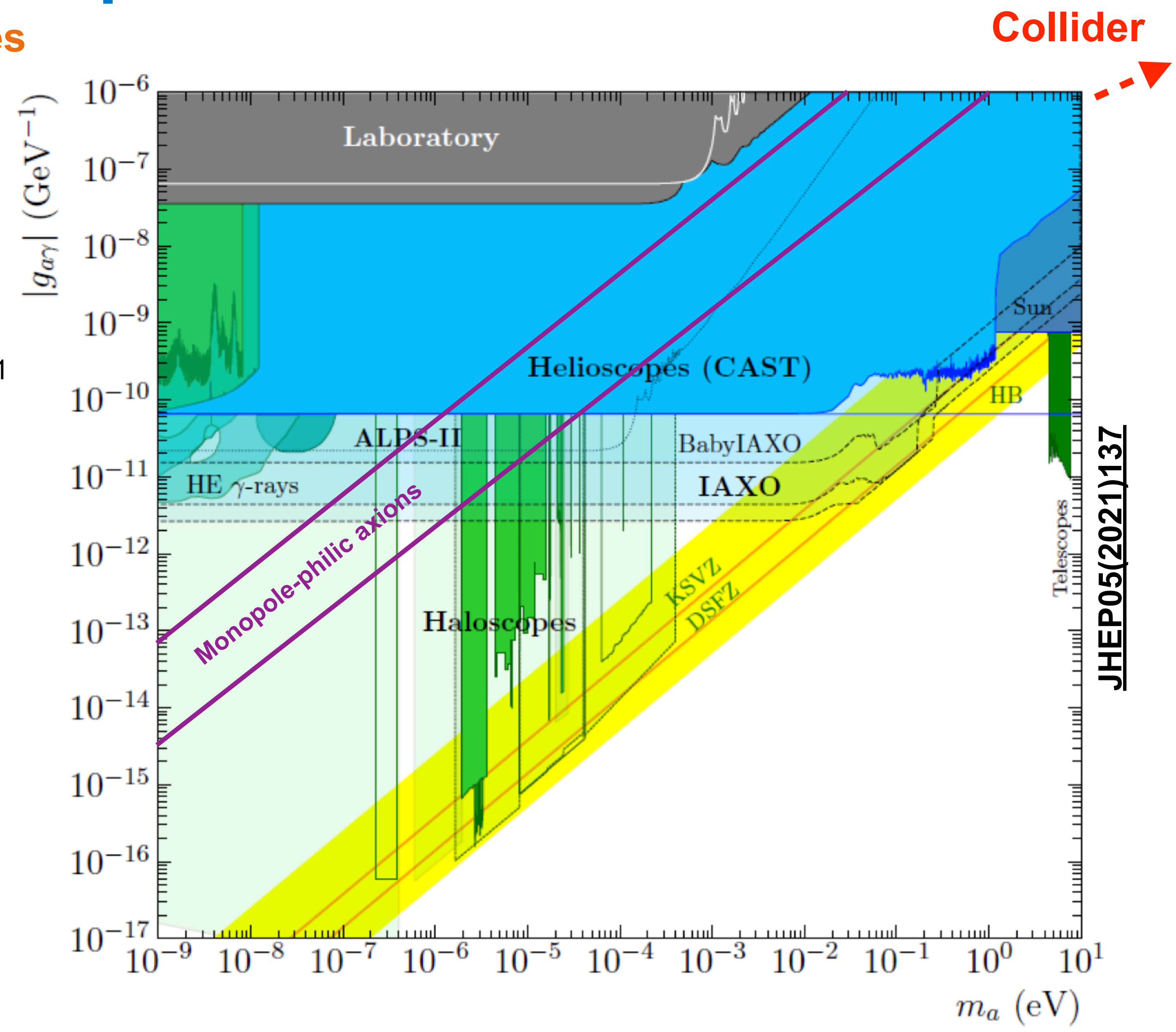
➡ **Reachable parameter space! Very interesting times for different types of axion experiments!**



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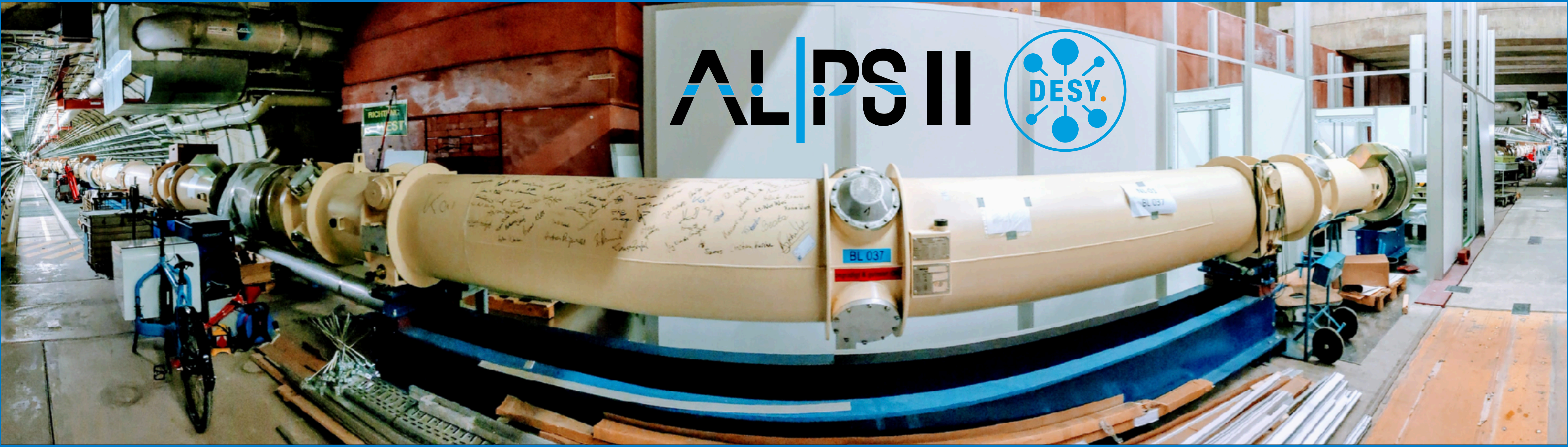
Shining light through a wall with ALPS II



The ALPS II Collaboration

Overview

ALPS II collaboration meeting 06/22

Collaboration members

Supported by

Recipe for Any Light Particle Search II (ALPS II)

Pushing Sensitivity with High Precision Interferometry

- DESY HERA infrastructure: 2x12 HERA dipole magnets, cryogenic lines, tunnel & 3 clean-rooms

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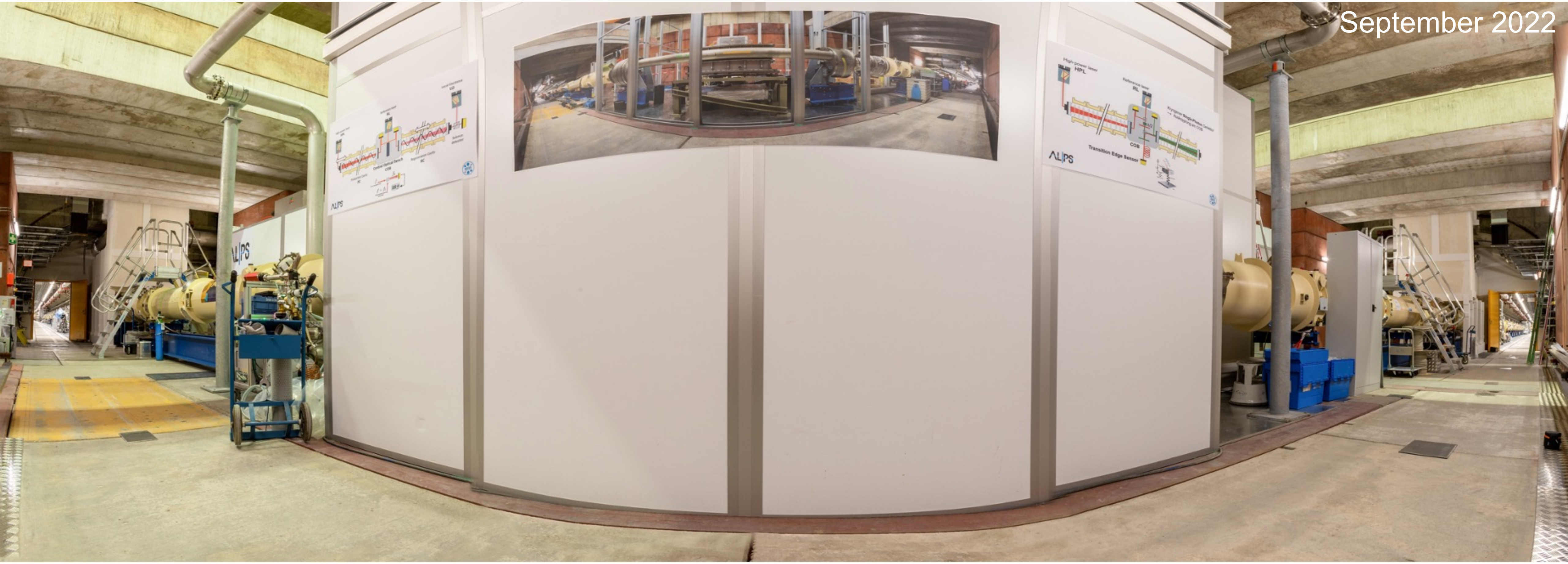

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Pushing Sensitivity with High Precision Interferometry

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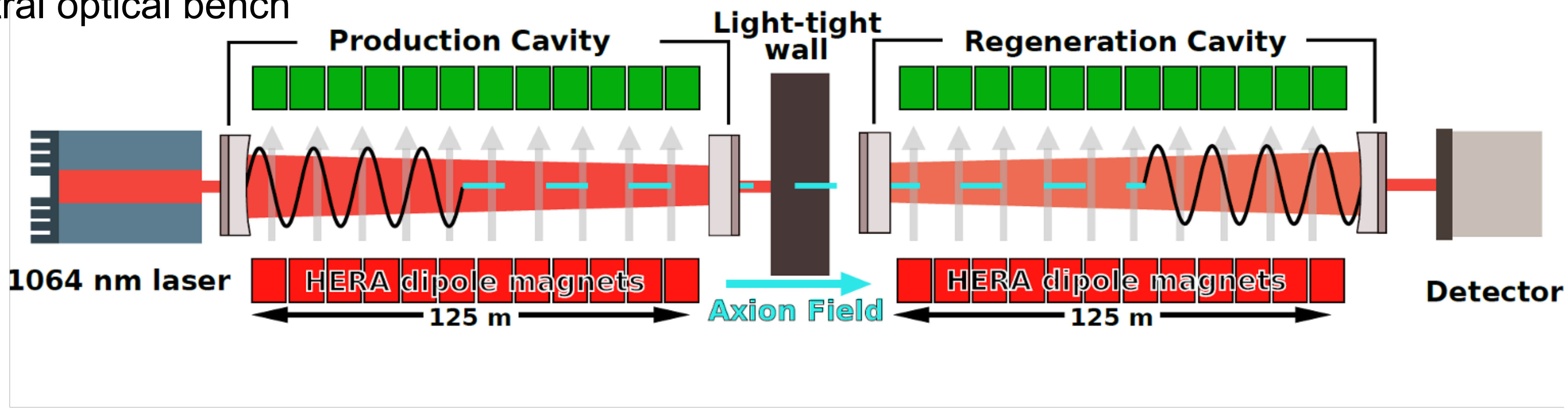
- Optical cavities both before and after wall (key: dual resonance and phase stability)
- Central optical bench



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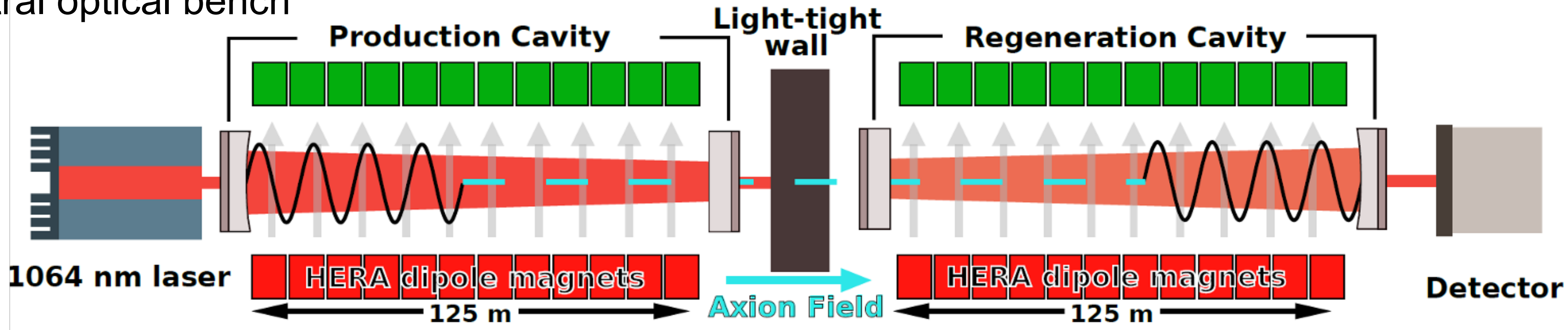

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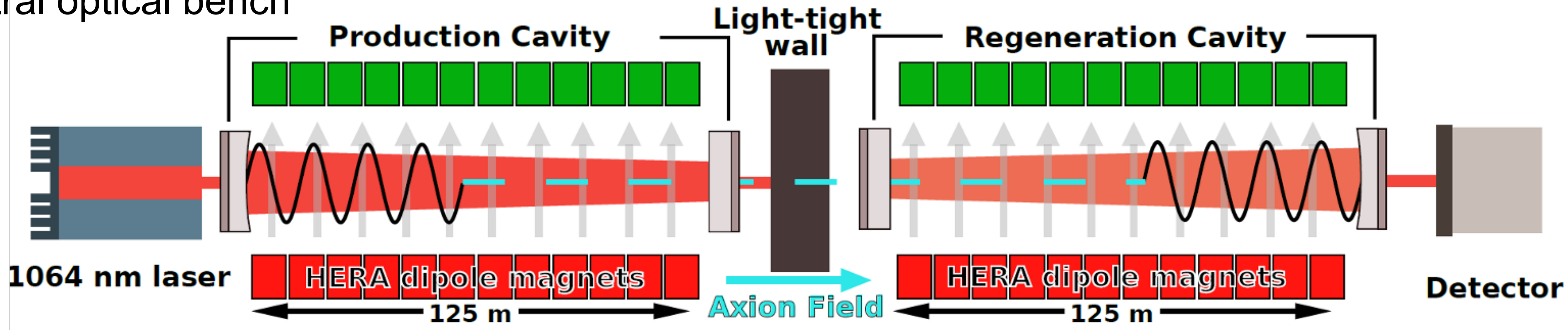

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Talk with technical details and status by Henry Frädrich in Cosmology/DM/Axion parallel session: "First data taking with ALPS II"

ALPS II - End of May 2023: Start of First Science Run

We are Taking Data!

Forschung - Hamburg

Mit Licht durch die Wand: Desy forscht zu Dunkler Materie

23. Mai 2023, 12:10 Uhr | Lesezeit: 1 min

Ein Mitarbeiter des Deutschen Elektronen-Synchrotrons (DESY) fährt am Instrument ALPS II entlang. Foto: Ulrich Perrey/dpa/Archivbild (Foto: dpa)

Link to ALPS II video

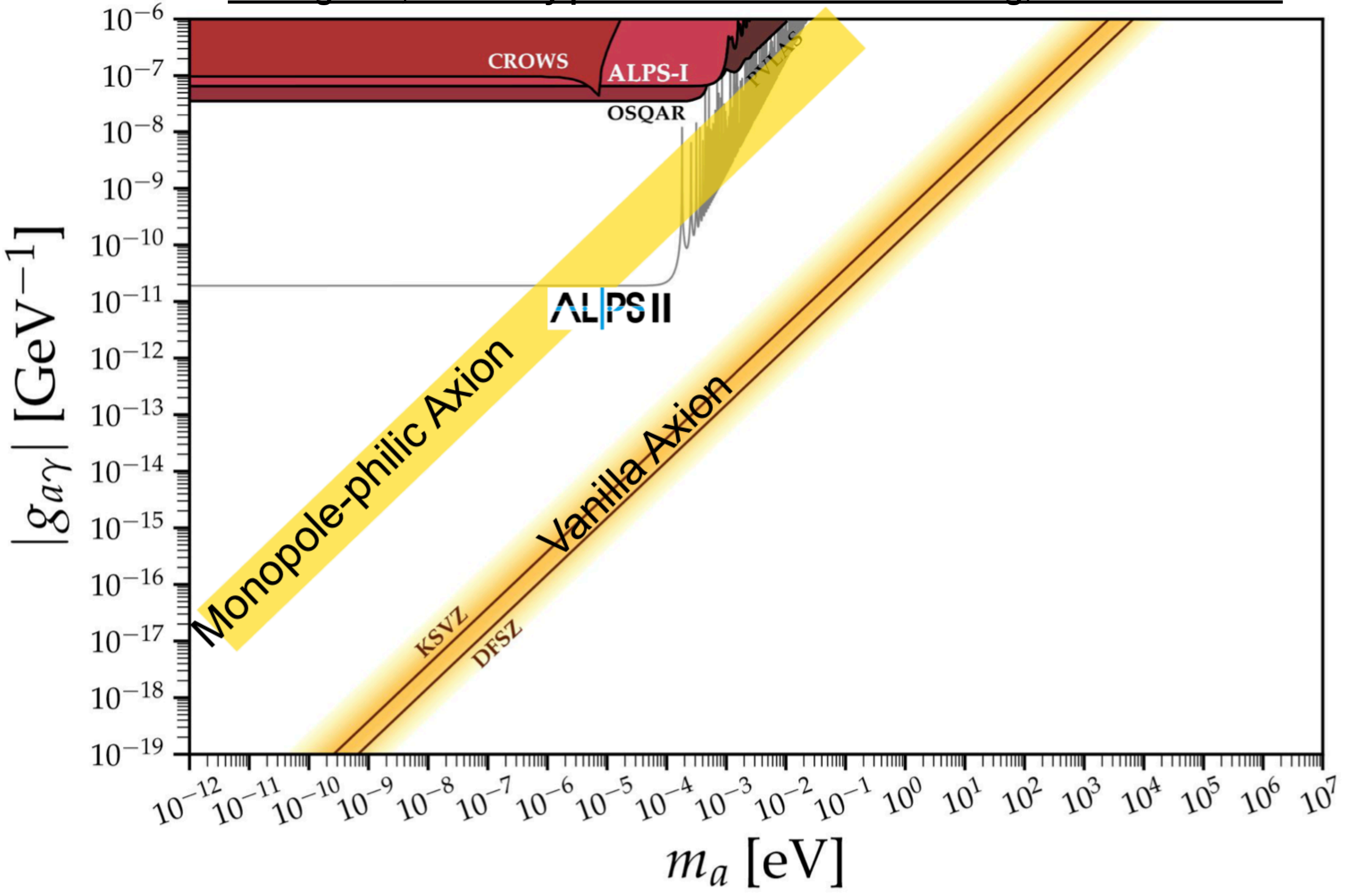
Link to drone flight video

What is ALPS II Aiming for?

Physics Prospects

- Improve sensitivity compared to ALPS I by factor ~3000

A. Ringwald, Discovery potential for axions in Hamburg, arXiv:2306.08978



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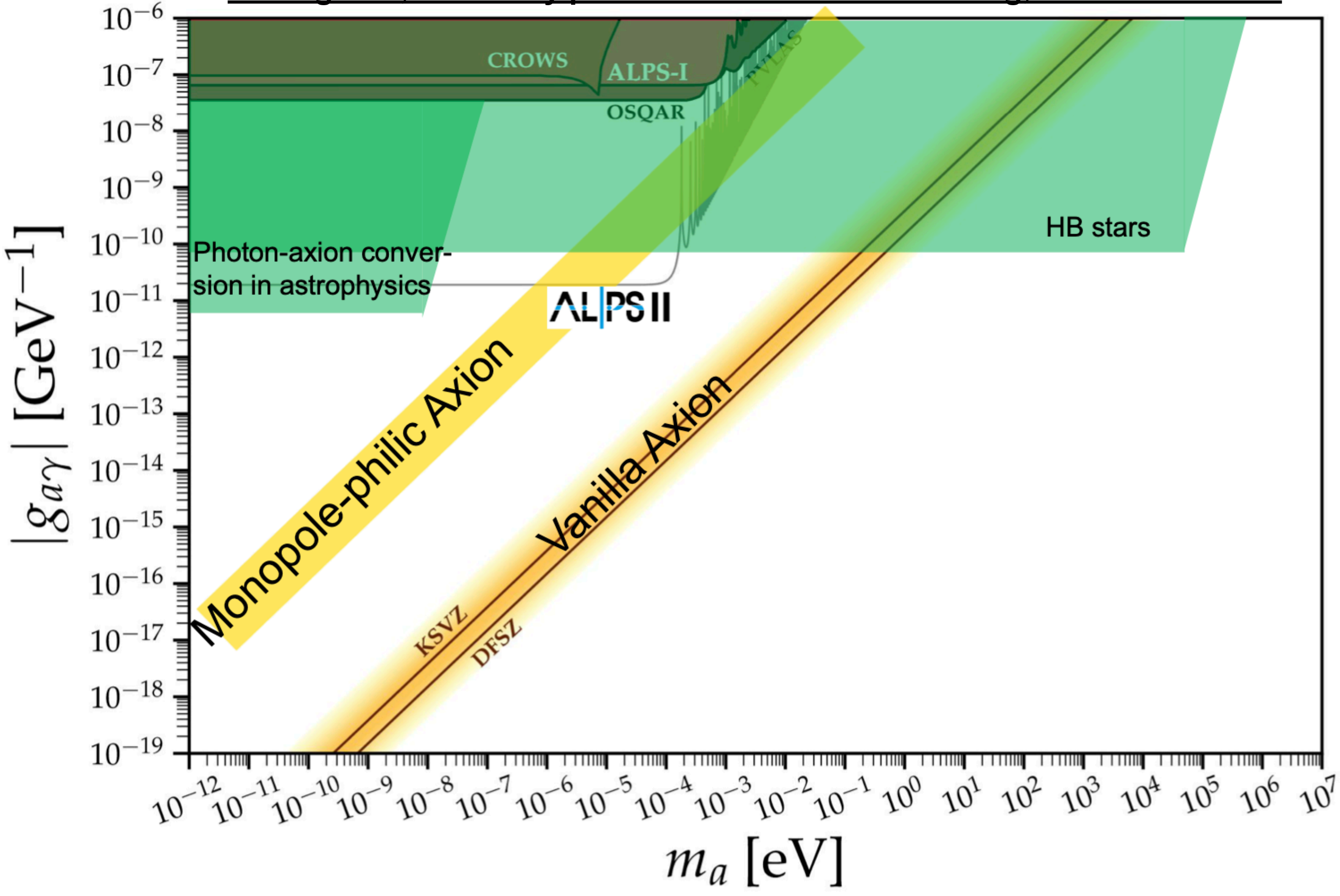

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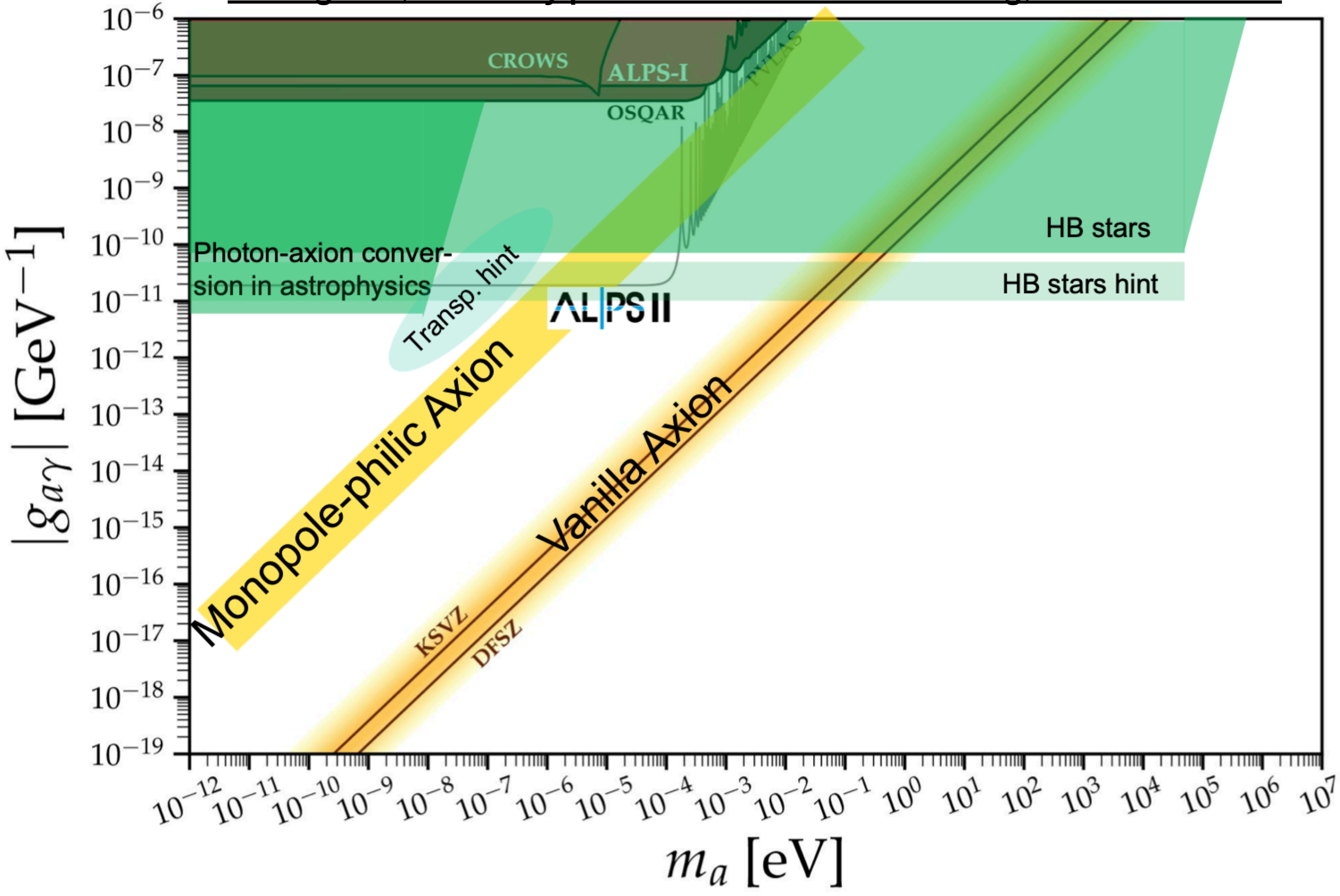

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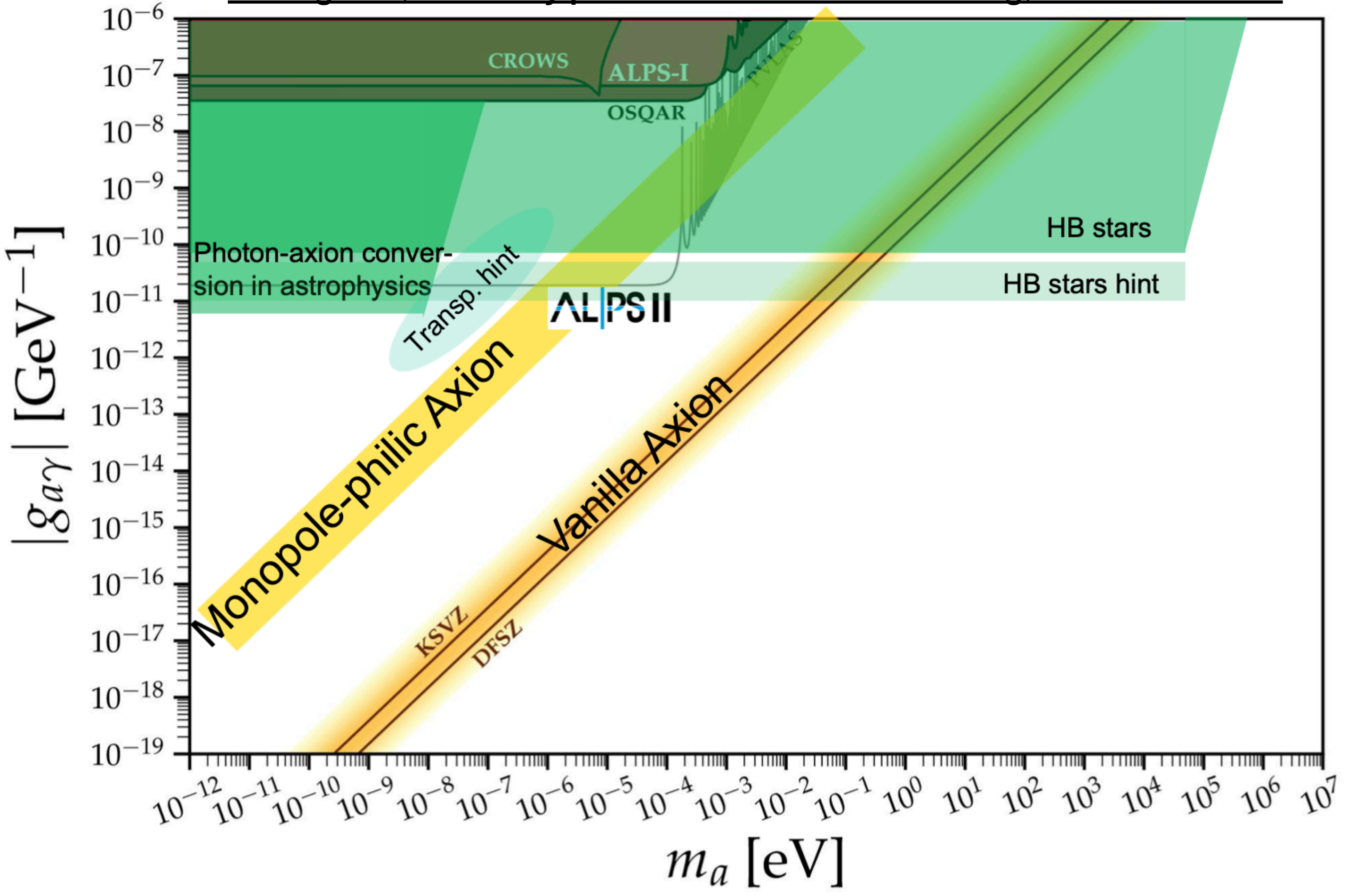

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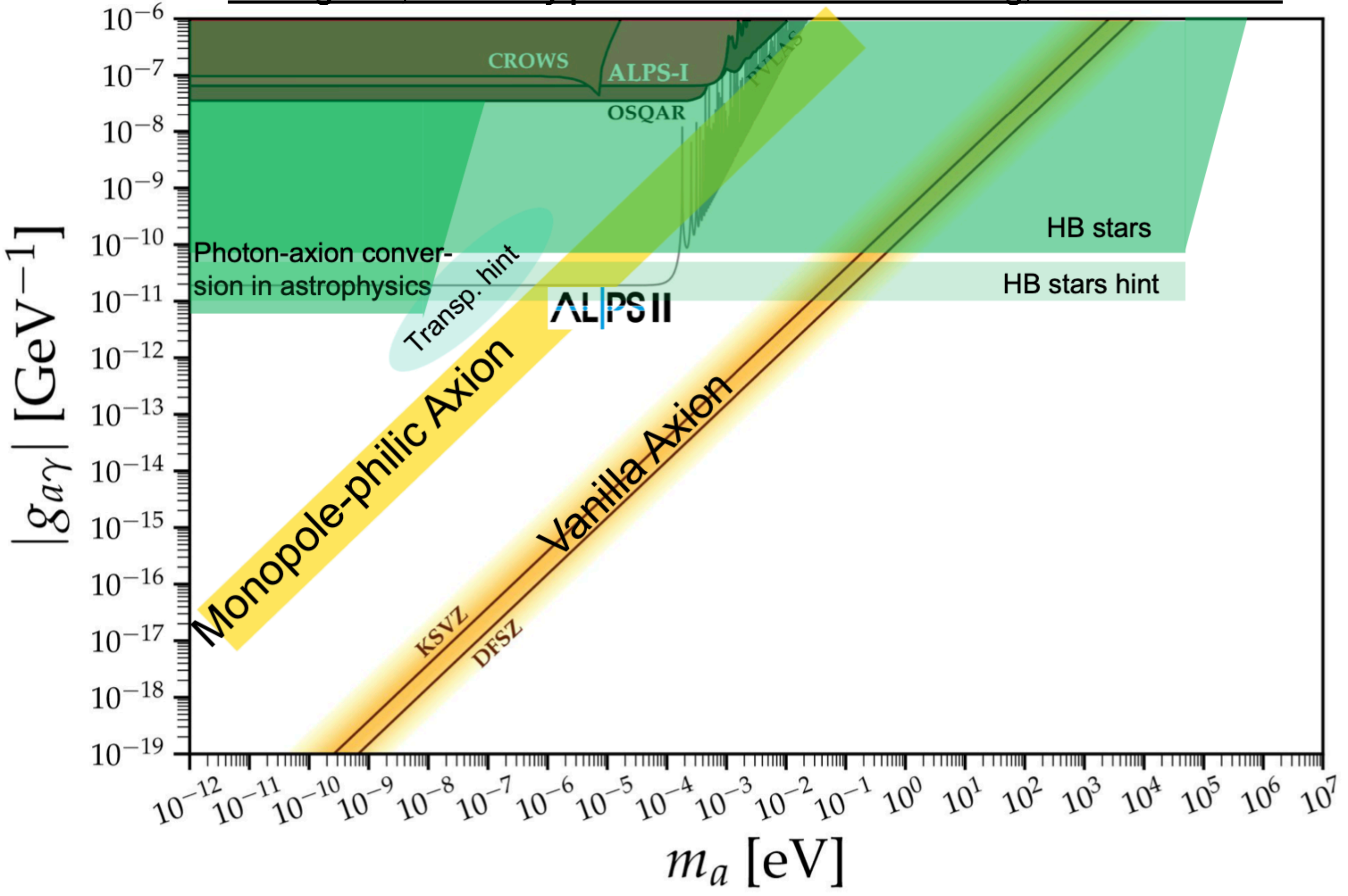
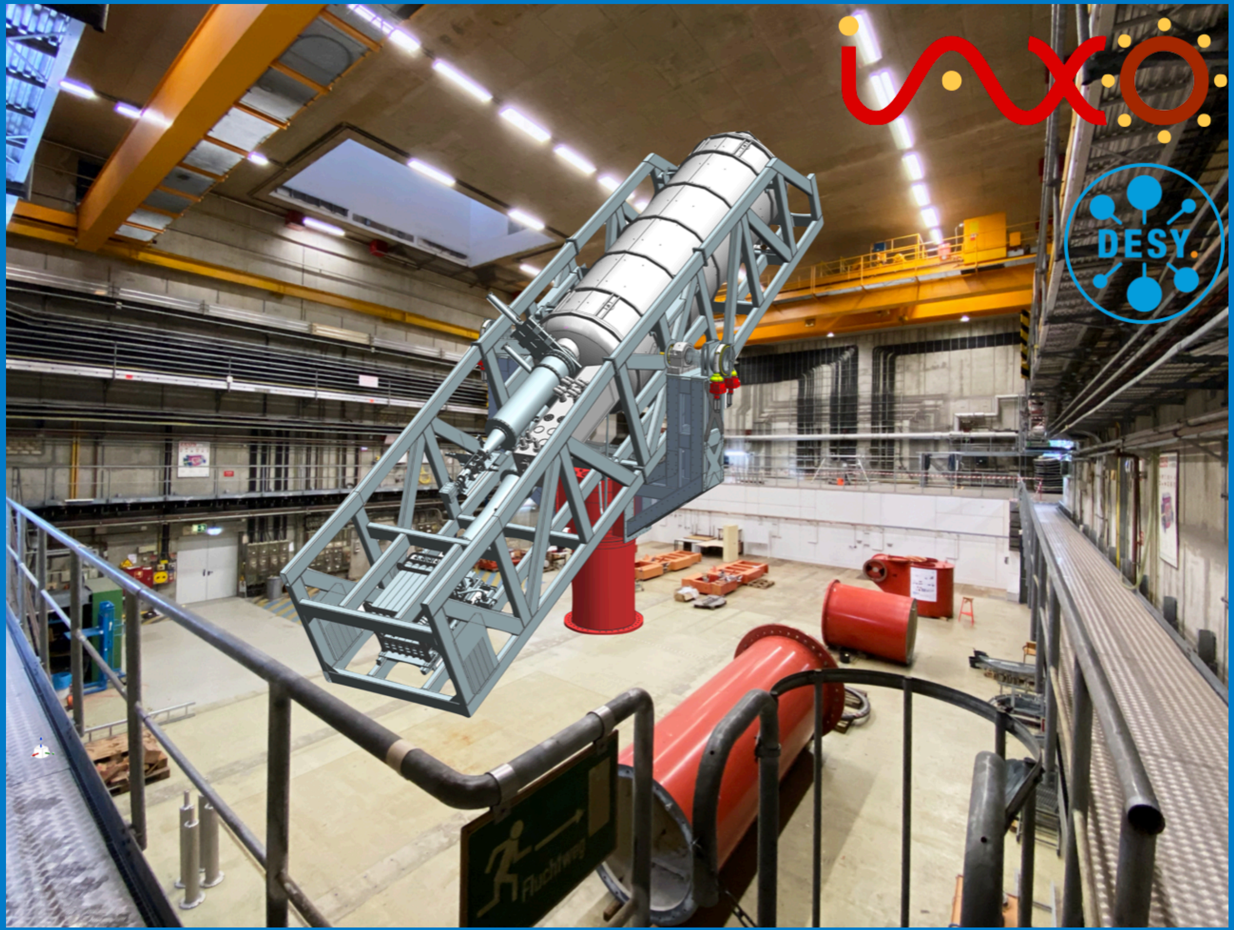
  - ➡ Covers parameter space of monopole-philic QCD axions outside of benchmark vanilla QCD axion band
- Goal: axion/ALP discovery and model-independent measurement of $g_{a\gamma\gamma}$
- And then?
  - ➡ Probe nature of the underlying BSM model with dedicated experiments!

A. Ringwald, Discovery potential for axions in Hamburg, arXiv:2306.08978



The sunny side of life with (Baby)IAXO.

https://www.stern.de/kultur/tv/-teletubbies---so-sieht-das-baby-auf-der-sonne-heute-aus-32610940.html



The IAXO Collaboration

World's Largest Axion Collaboration

IAXO Collaboration Meeting @ Teruel, Spain, 11-14.09.23
~125 scientists from 22 full member institutions + 5 associate institutions.

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | Siegen University (Germany) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Barry University (USA) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain)

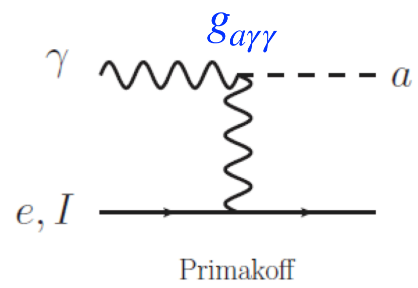
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

Solar Axions

Production Mechanisms

Solar Axions

Production Mechanisms



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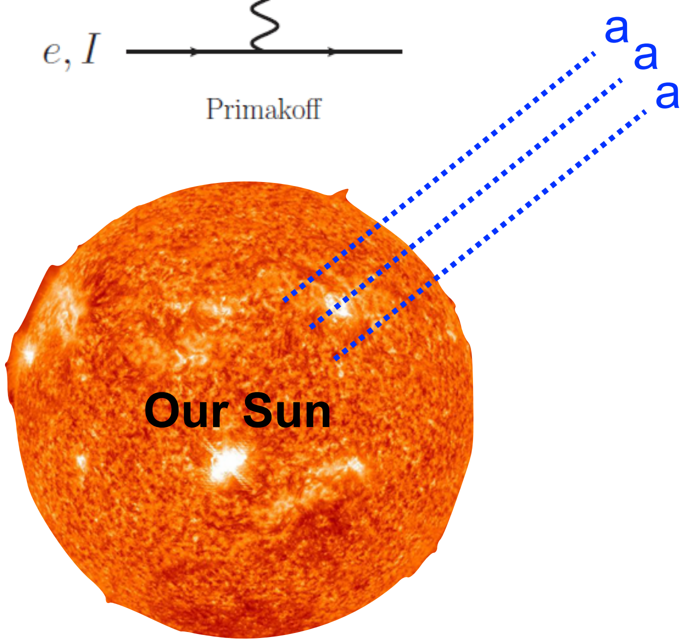
   ➡ Generic prediction of most axion models
   ➡ Axion energy: thermal spectrum of sun



Solar Axions

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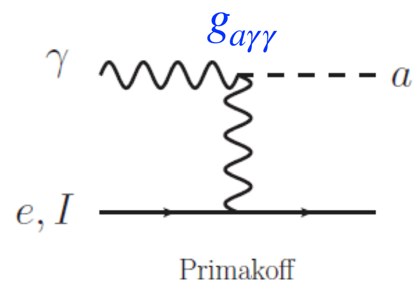

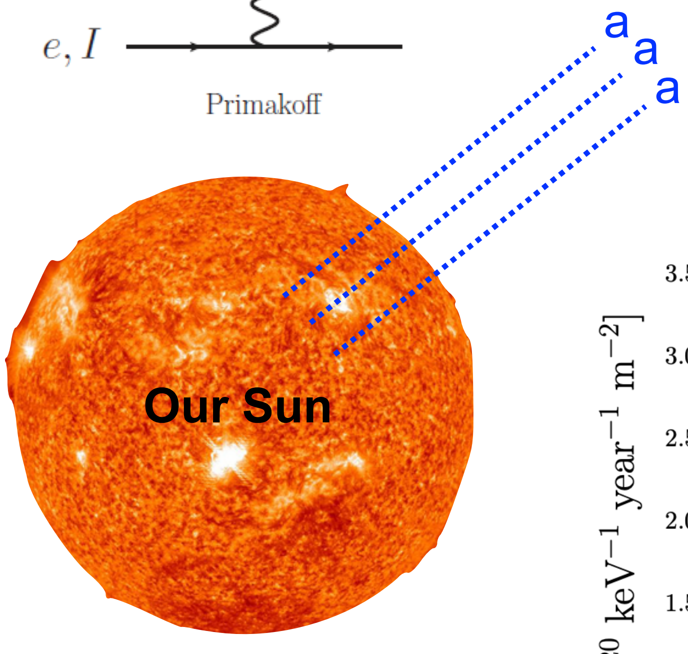

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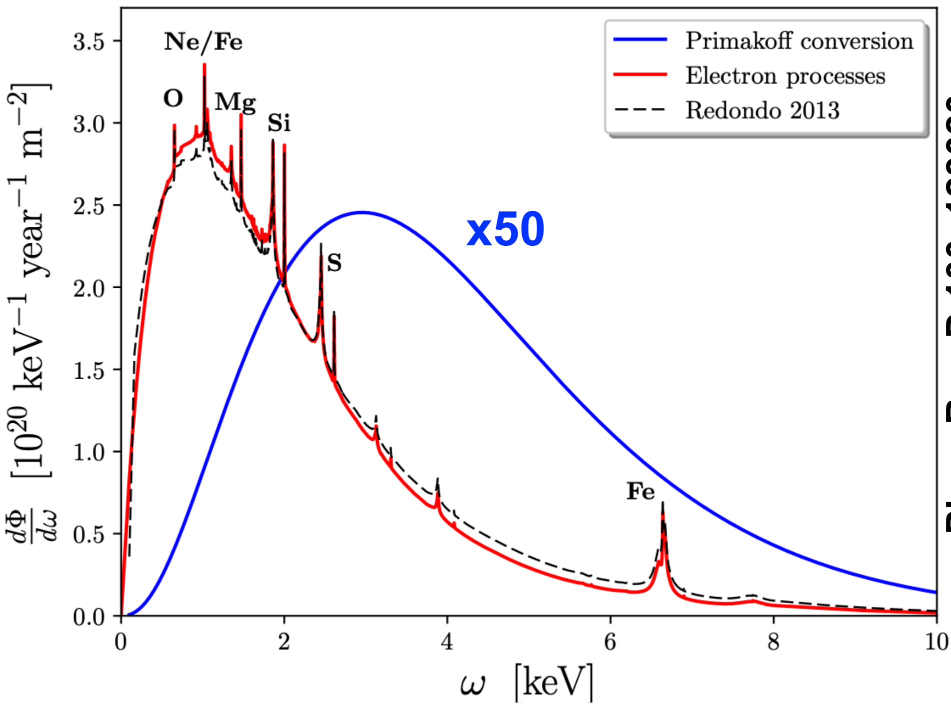

Phys. Rev. D 100, 123020

Solar Axions

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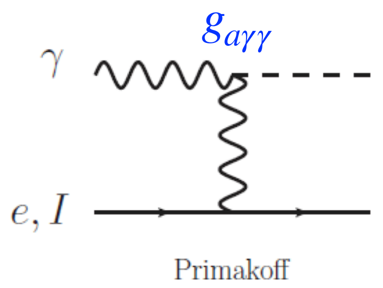

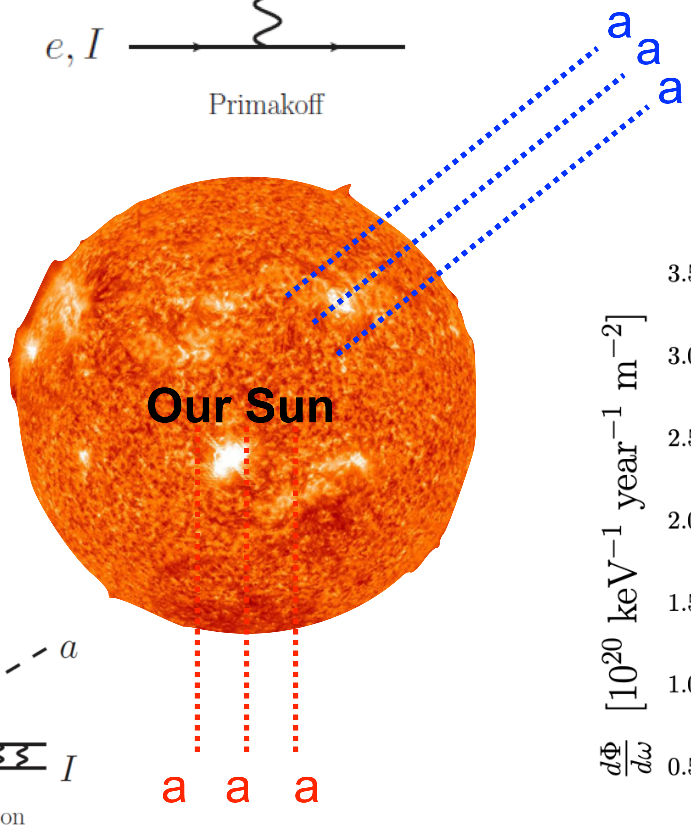

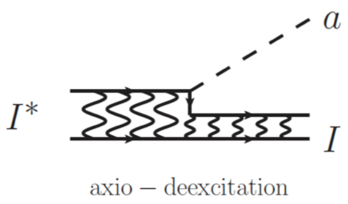

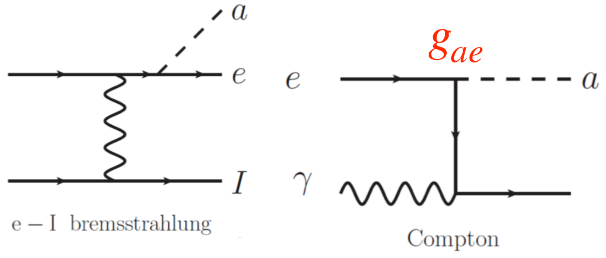

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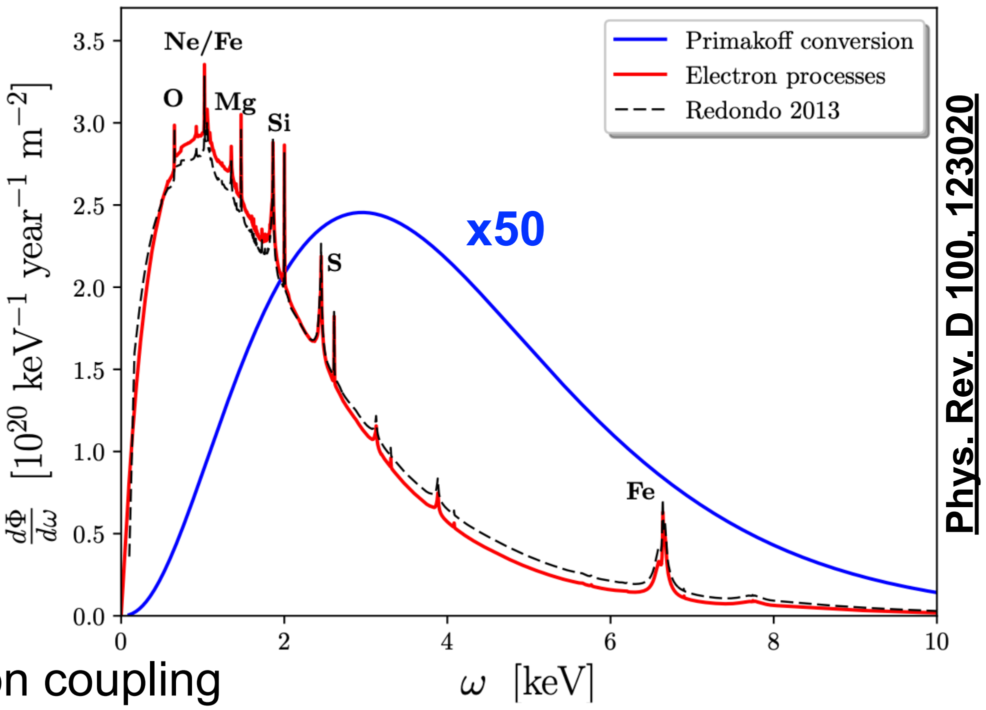

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   ➡ **Model dependent**
   ➡ Axion energy: continuous spectrum + elemental peaks

Solar Axions

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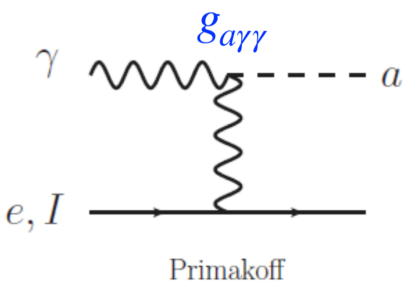
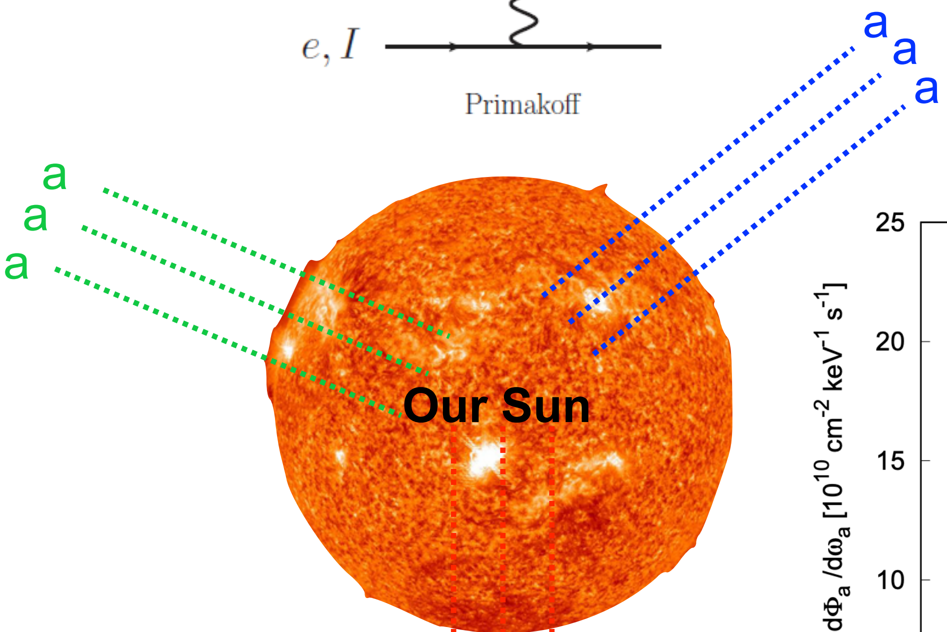
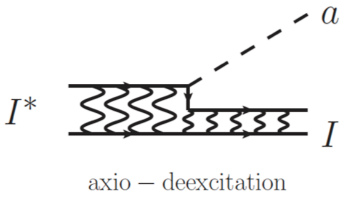
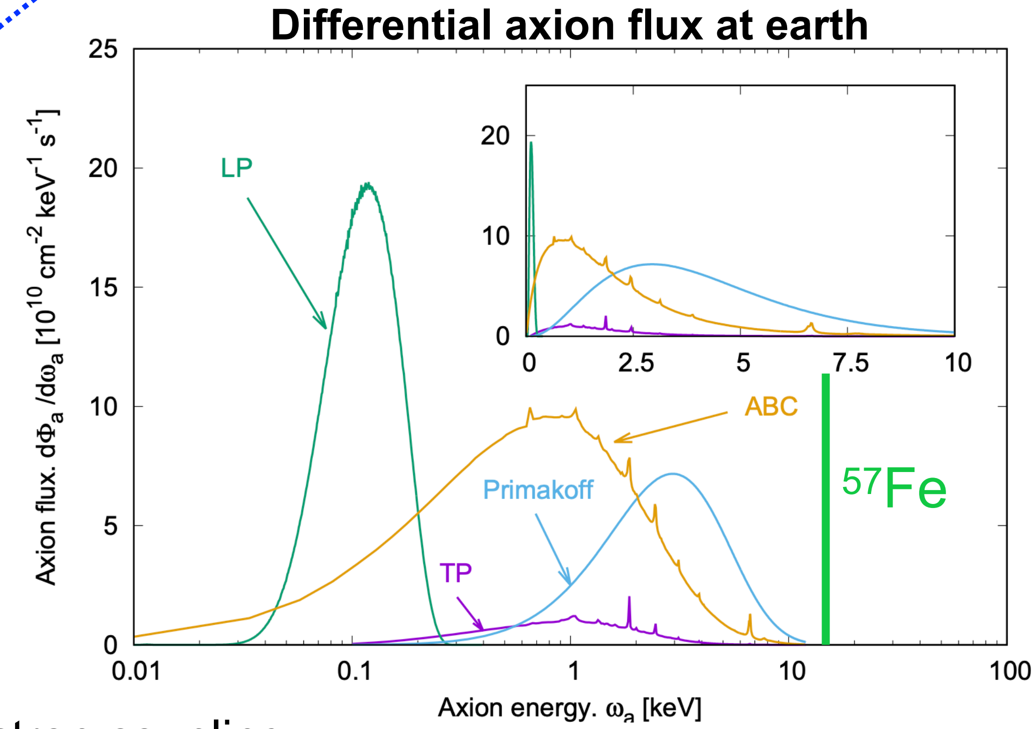
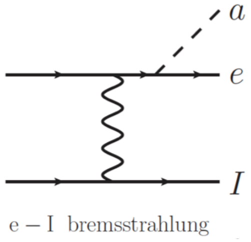


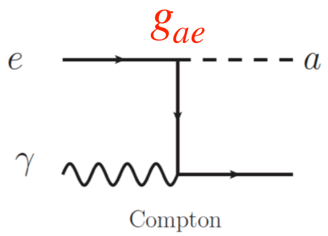
3. Solar axions from axion-nucleon coupling g_{an}
   - ➡ **Model dependent**
   - ➡ Fusion processes and nuclear transitions, e.g. most promising: ^{57}Fe
   - ➡ Monochromatic lines: e.g. 14.4 keV (^{57}Fe)











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Solar Axions

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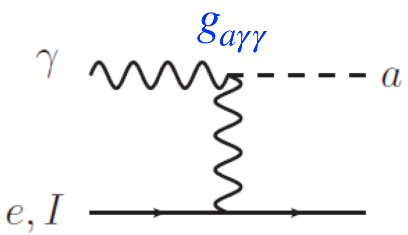

Primakoff

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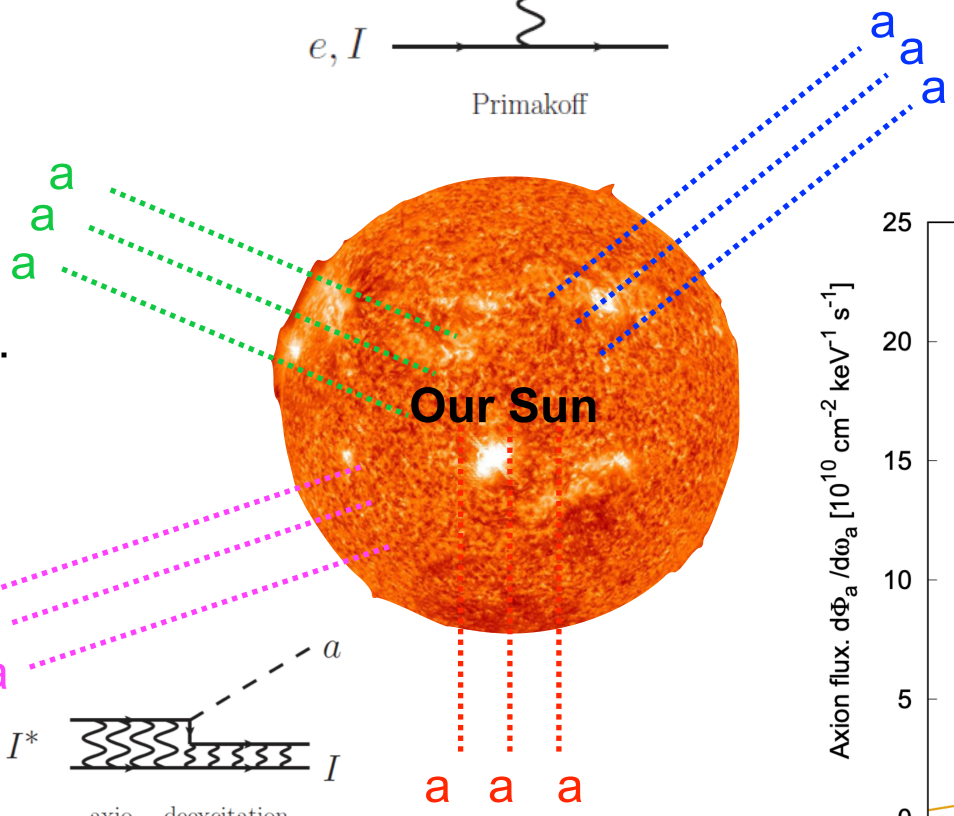
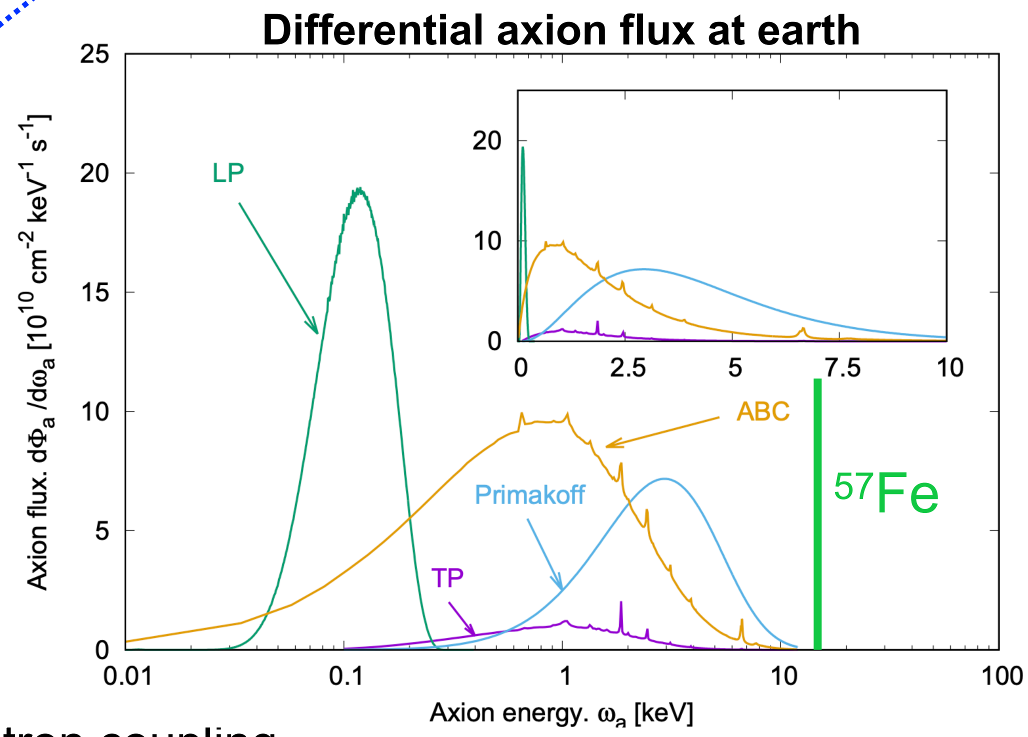


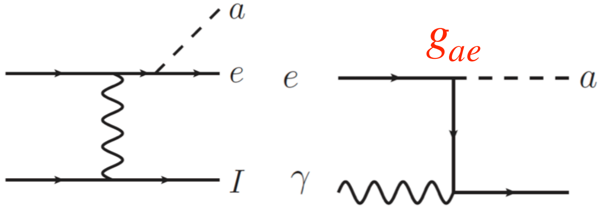


4. Other mechanisms:
   - ➡ Plasmon-axion conversion in macroscopic B-field

Phys. Rev. D 102, 123024

Phys. Rev. D 101, 123004

axio – deexcitation



e – I bremsstrahlung

Compton

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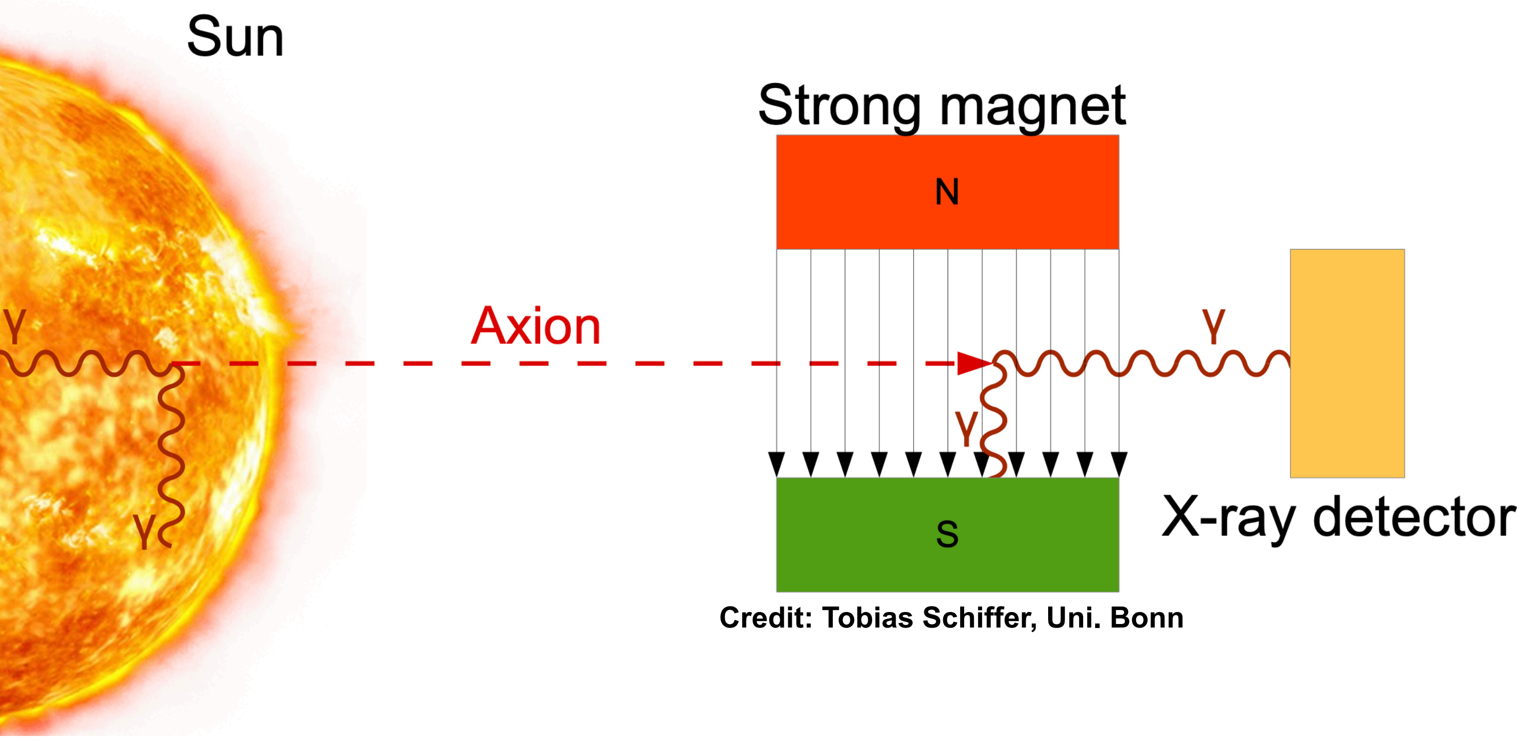
Helioscopes

Basic Components, Detection Principle and Figure of Merit



Credit: Tobias Schiffer, Uni. Bonn

Helioscopes

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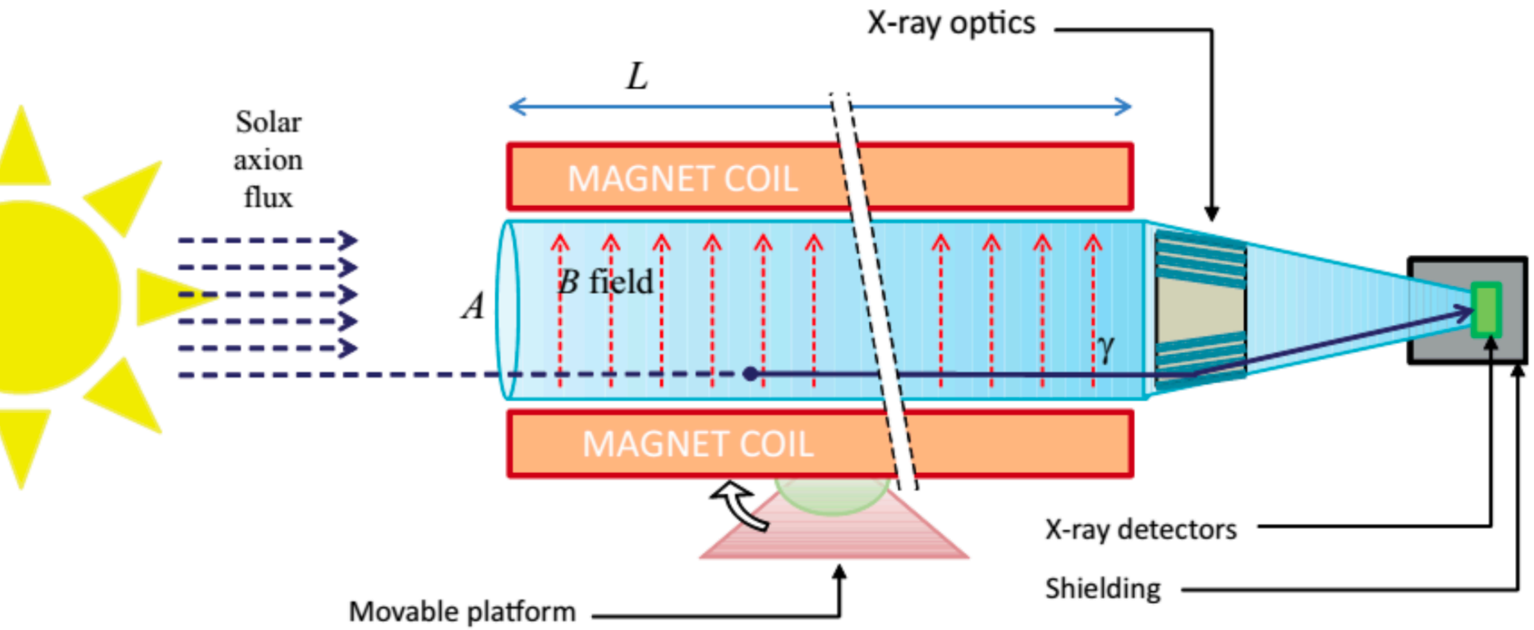

- **Structure & drive system**: precise and long sun tracking capability
- **Magnet**: large volume and high field strength
- **X-ray optics**: small focal spot and high throughput
- **X-ray detectors**: high efficiency and low background

Helioscopes

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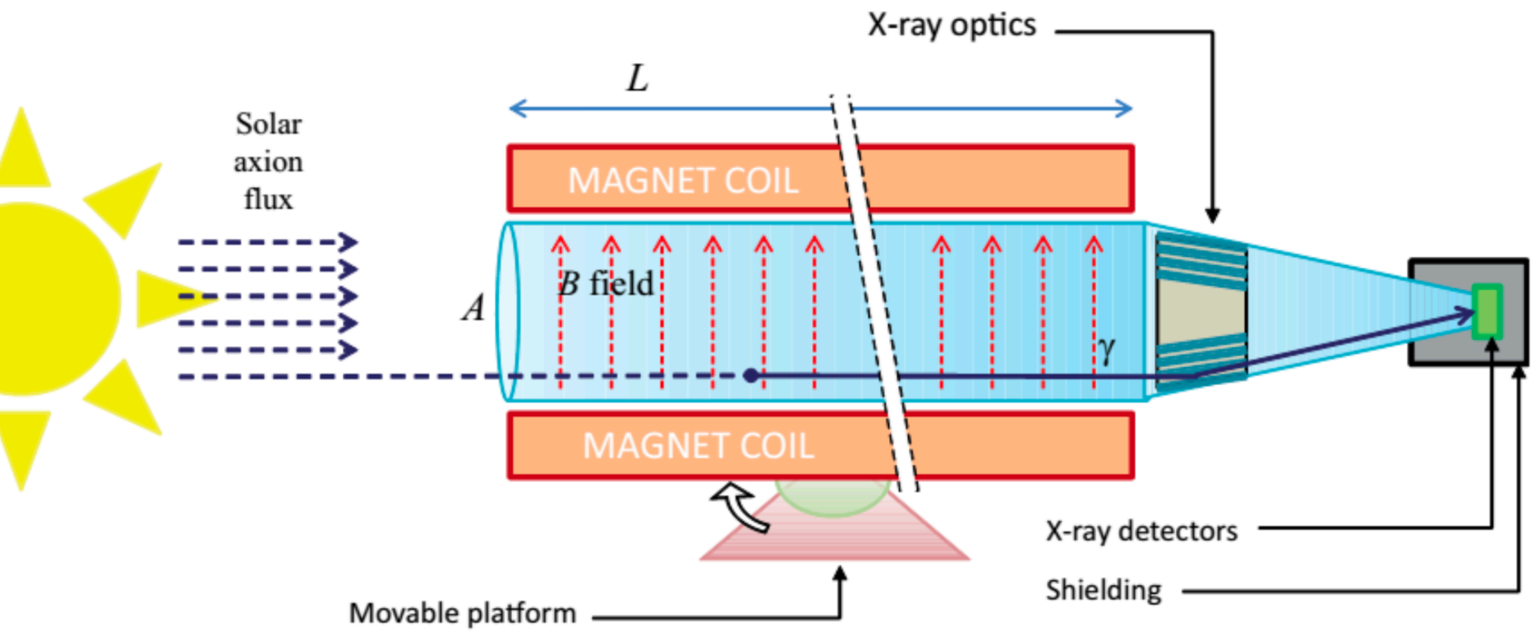

- **Structure & drive system**: precise and long sun tracking capability
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Sensitivity figure of merit: $$g^4_{a\gamma} \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

International AXion Observatory (IAXO)

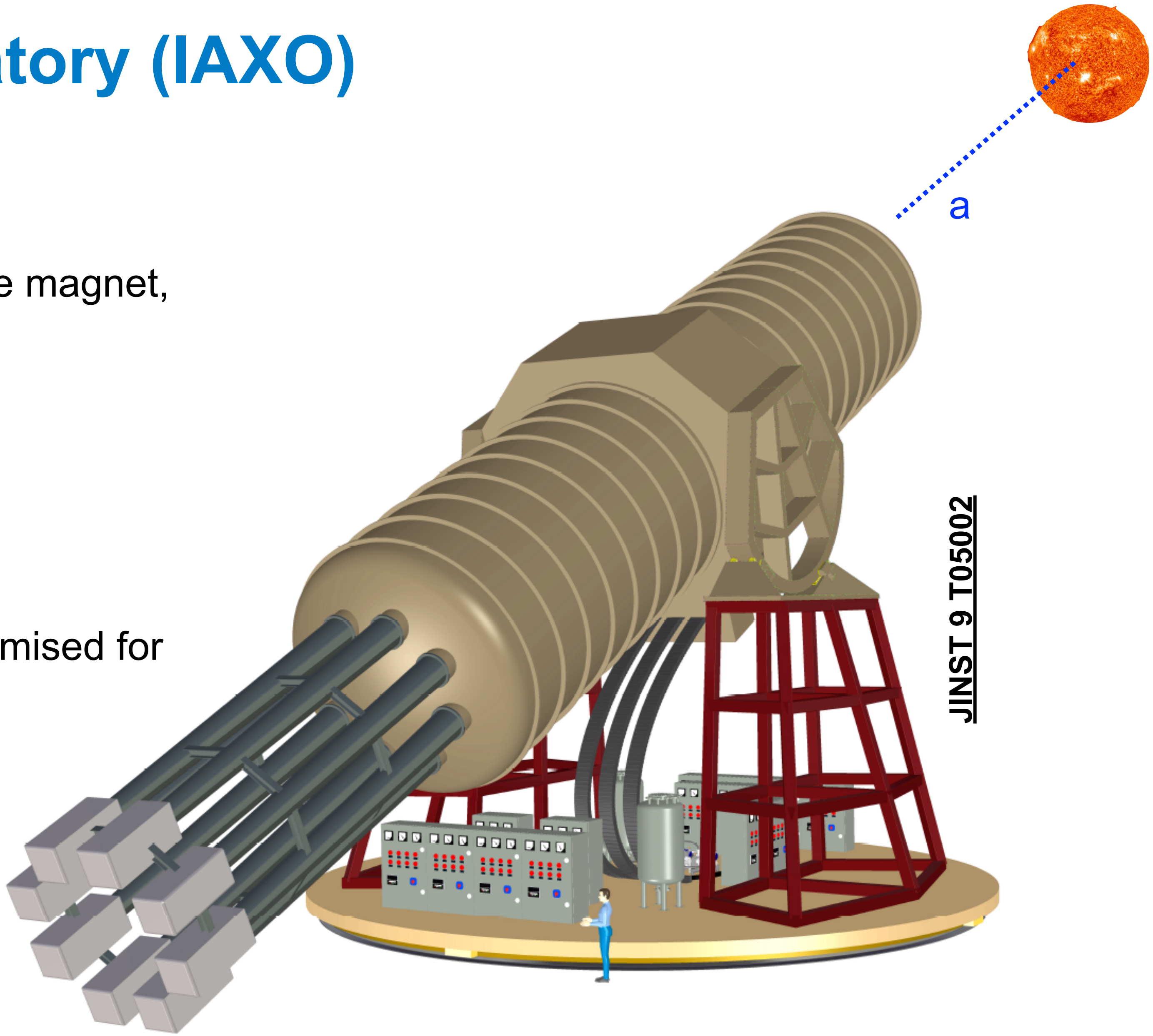
The Next Generation Axion Helioscope

- 12 hours solar tracking per day
- 20 m superconducting purpose built large scale magnet, 2-3 T, 8 bores (d = 60 cm each)

  ➡ $B^2 L^2 A$ = ~6200 $T^2 m^4$ (**300x CAST**)

- X-ray optics with ~0.2 cm^2 focal planes
- 8 detection lines

  ➡ Complementary detector technologies optimised for different measurements



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  - ➡ Complementary detector technologies optimised for different measurements
  - ➡ 4+ orders of magnitude better SNR than CAST

BabyIAXO - The Intermediate Step

But indeed not a Baby…

New life arises in HERA hall south!

BabyIAXO - The Intermediate Step

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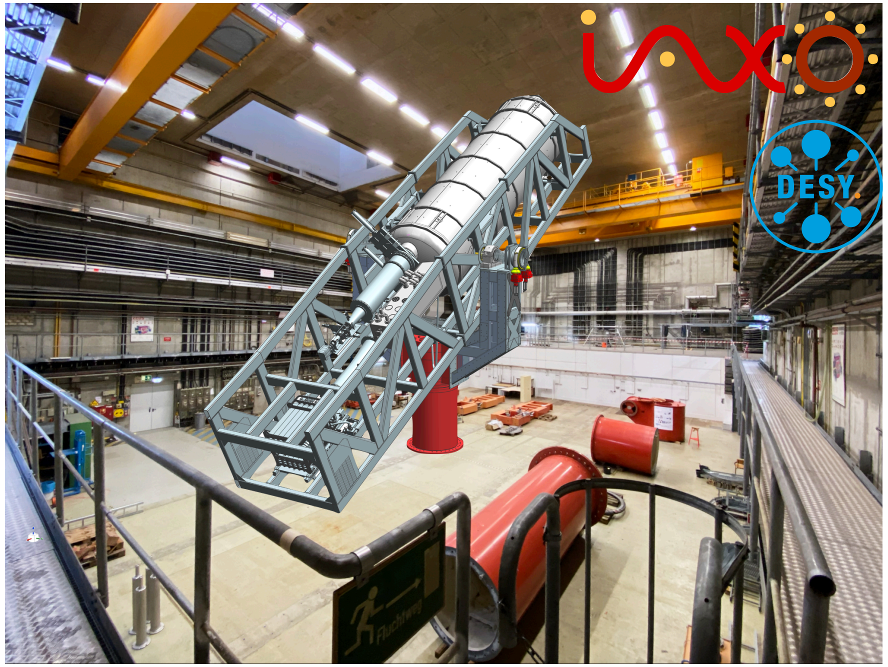


New life arises in HERA hall south!

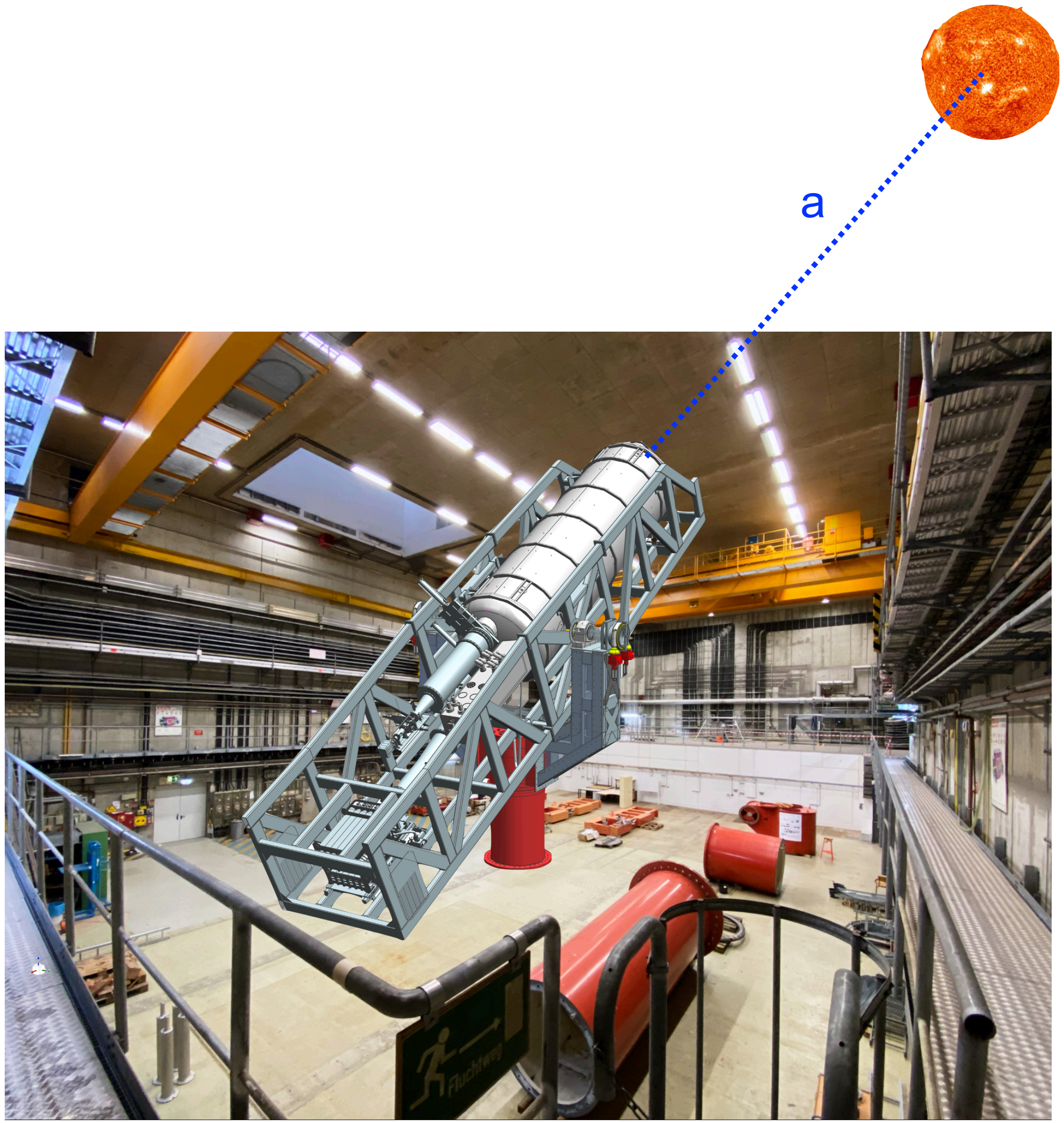
BabyIAXO - The Intermediate Step

But indeed not a Baby…

- Prototype for all IAXO sub-systems with comparable specs except:
  - 10 m superconducting purpose built large scale magnet, 2-3 T, 2 bores (d = 70 cm each)

    ➡ $B^2 L^2 A = \sim 300\ T^2 m^4$ (**>10x CAST**)
  - 2 detection lines
- Expected start of data taking: end of decade

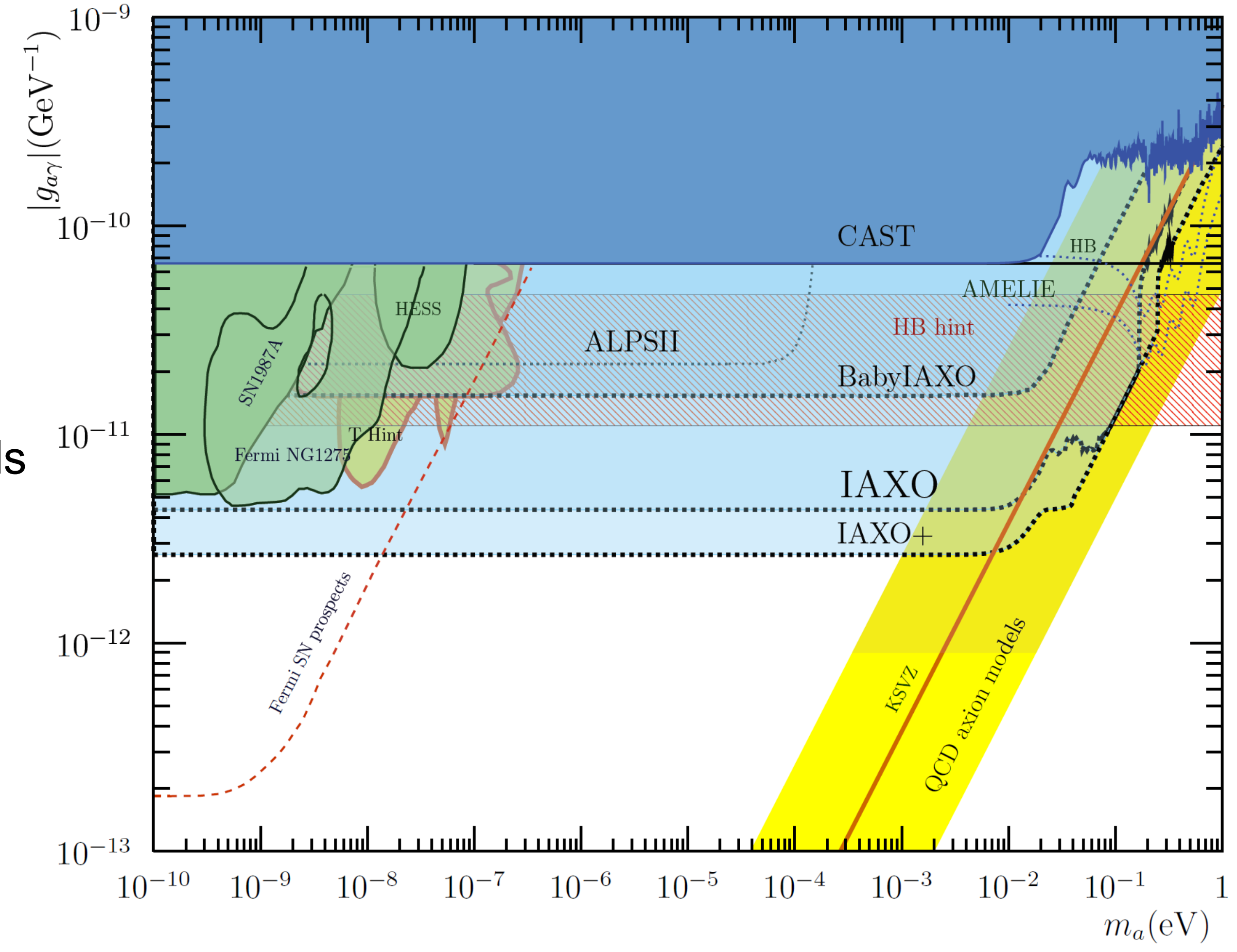
- **Fully-fledged helioscope that will study uncharted parameter spaces = potential for discovery**



What is BabyIAXO Aiming for?

Baseline (Primakoff-)Axion-Photon Coupling

- Improve $g_{a\gamma\gamma}$ sensitivity by factor 4 over CAST:
  - ➡ For low masses comparable to ALPS II: validate potential ALPS II discovery and $g_{a\gamma\gamma}$ measure
    - ➡ Is the photon-axion conversion the same in vacuum and hot solar plasma?
  - ➡ meV - eV masses: test vanilla QCD axion models
- IAXO will dig even deeper in parameter space



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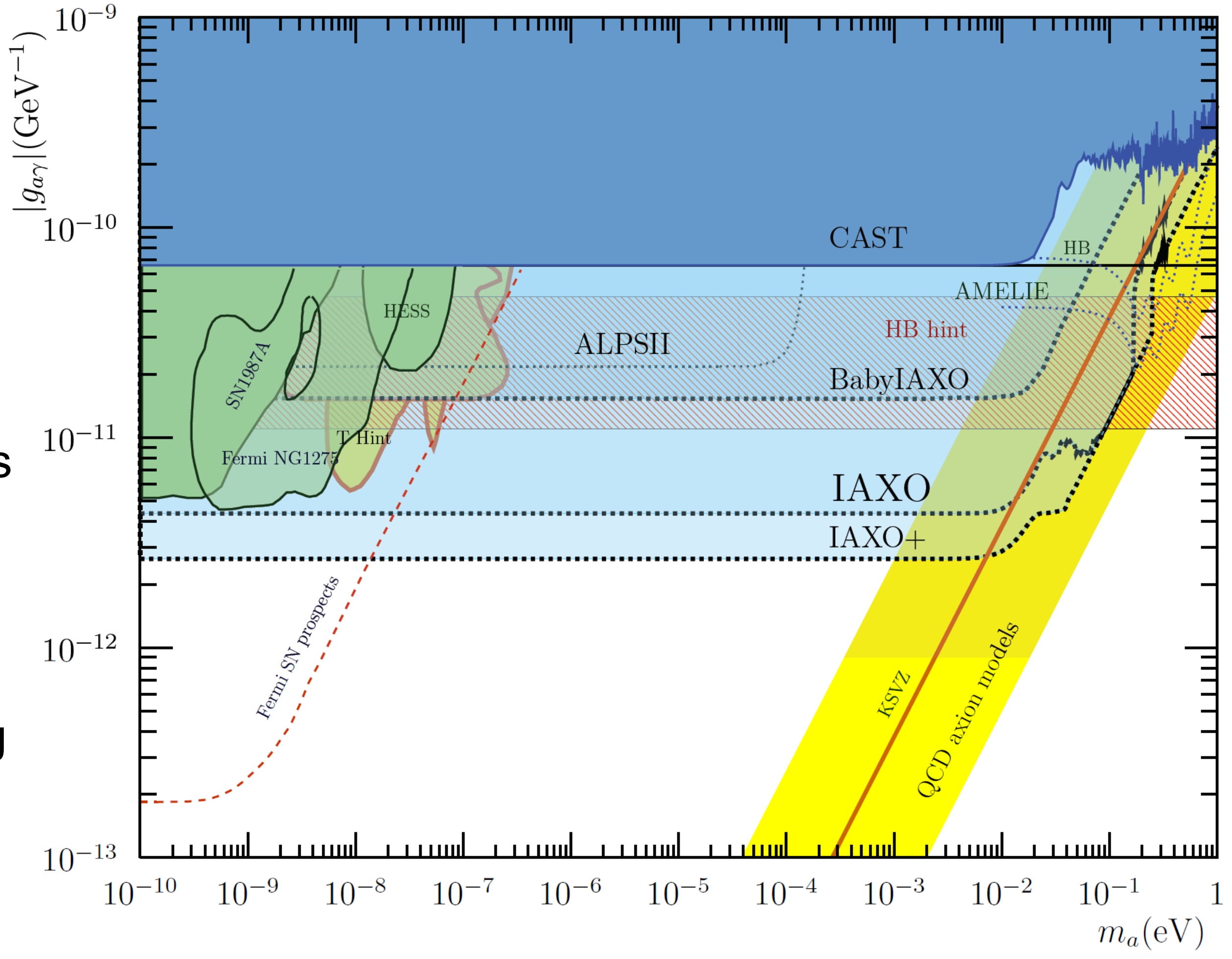
- In addition post discovery: model dependent coupling measurements to probe underlying BSM model **(unique at helioscopes!)**



Distinguishing Axion Models with $g_{a\gamma\gamma}$, g_{ae}, g_{aN} and m_a

Basic Idea and Strategies

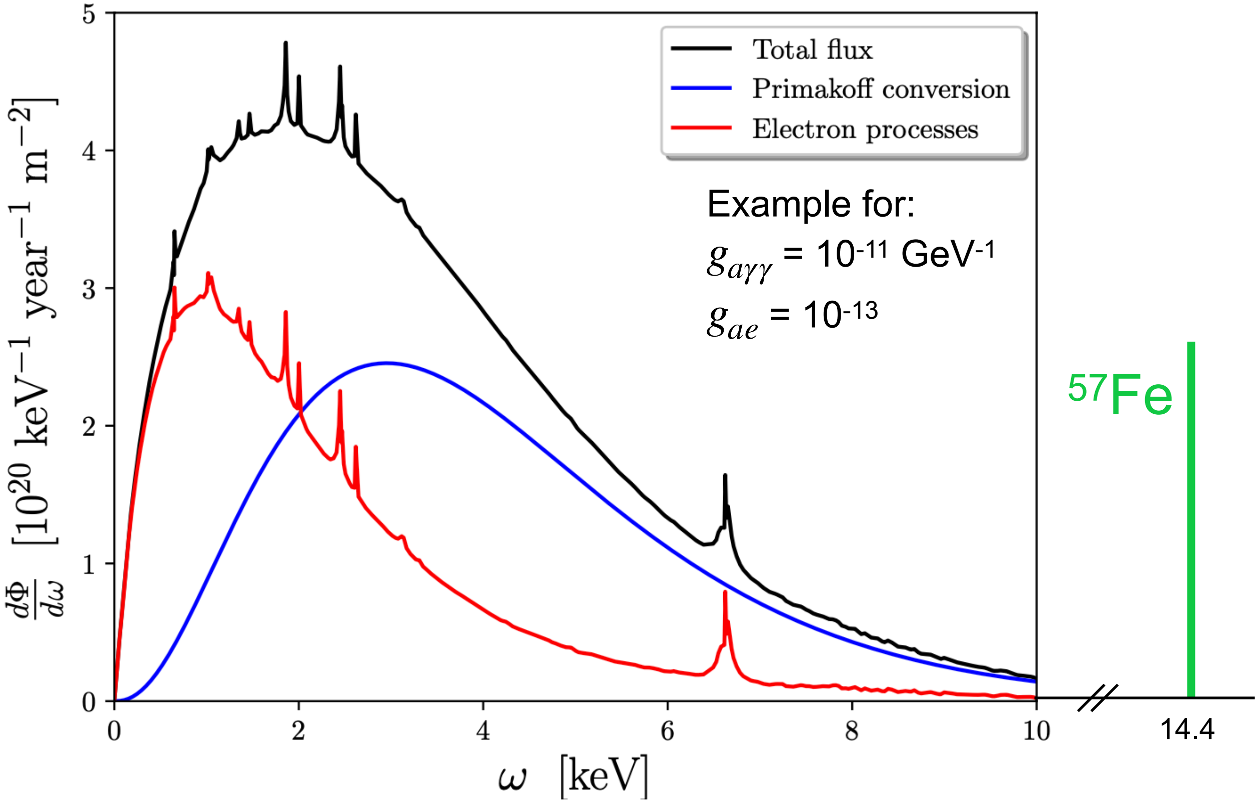
- Main idea: measured axion spectrum contains axions from different couplings

- Example: depending on spectrum shape individual determination of $g_{a\gamma\gamma}$ and g_{ae}
  - ➡ Higher g_{ae} softens the spectrum
  - ➡ Higher g_{ae} pronounces atomic trans. peaks

JCAP03(2019)039

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

Differential axion flux at earth



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  - ➡ Higher g_{ae} softens the spectrum
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- Helioscope-specific techniques (e.g. buffer gas) allow m_a measurement in large range in addition
- Detailed studies conducted to investigate sensitivities with different optics, detectors, etc.

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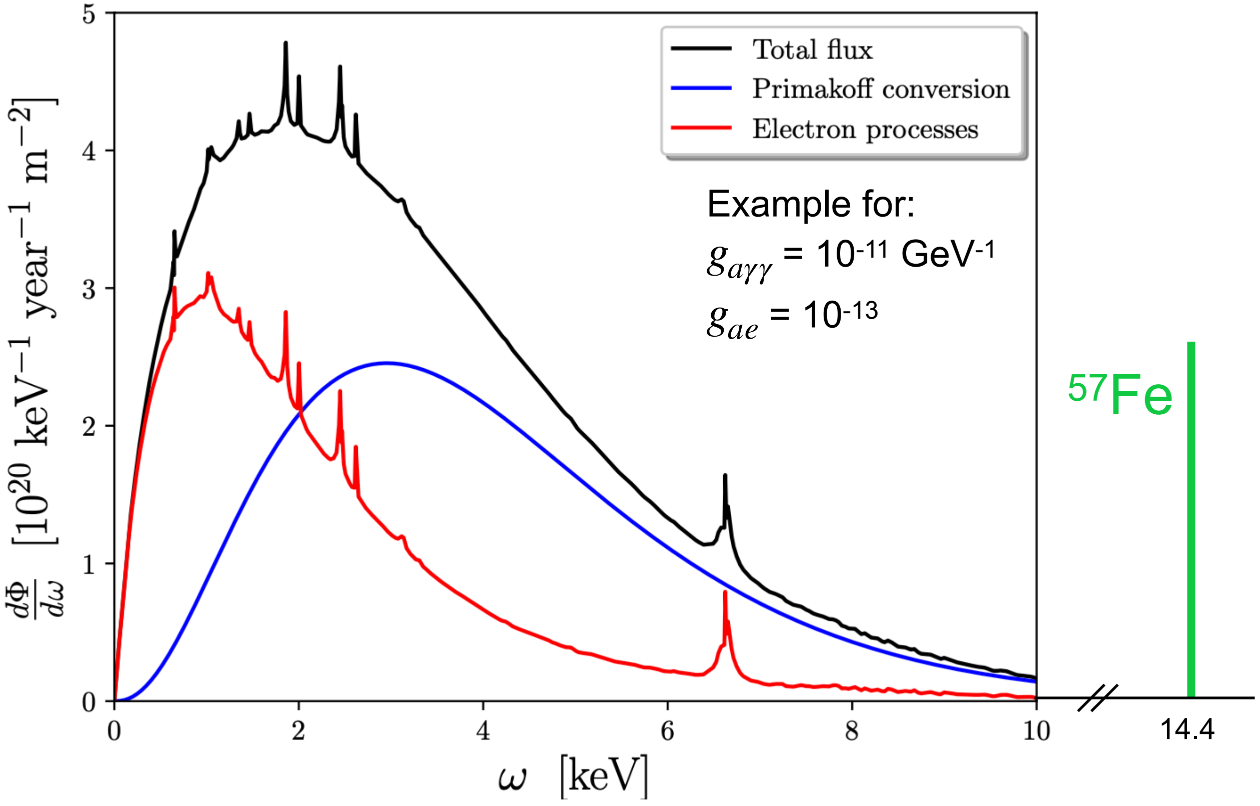
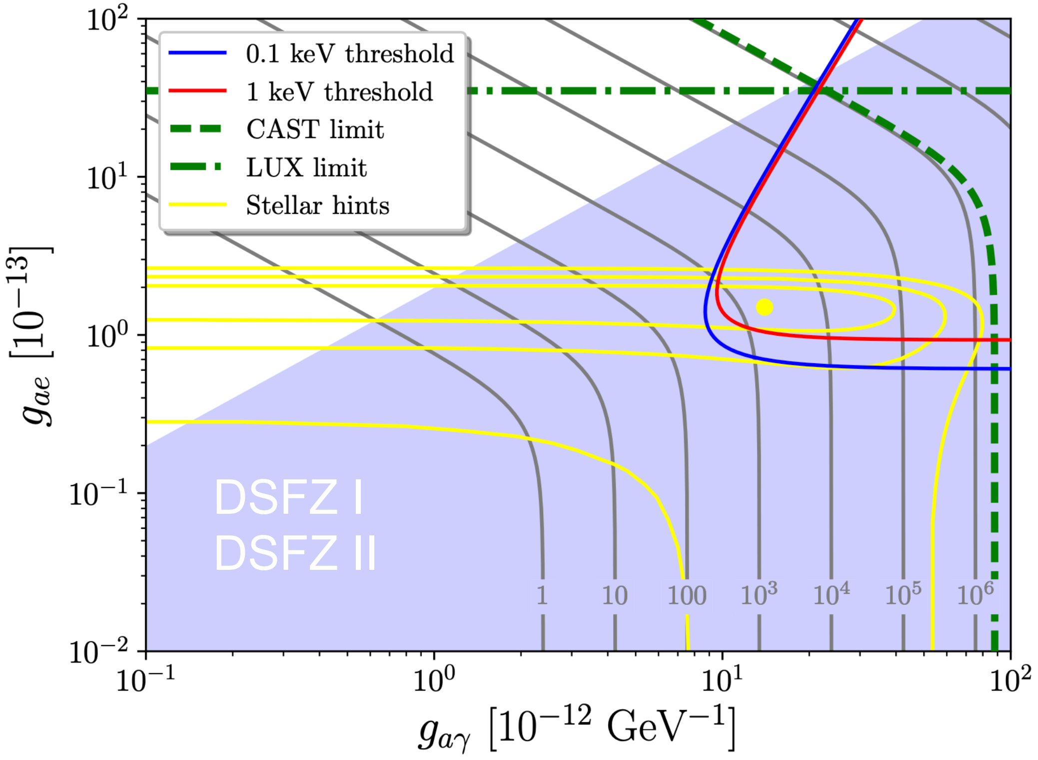


Testing Axion Models with (Baby)IAXO

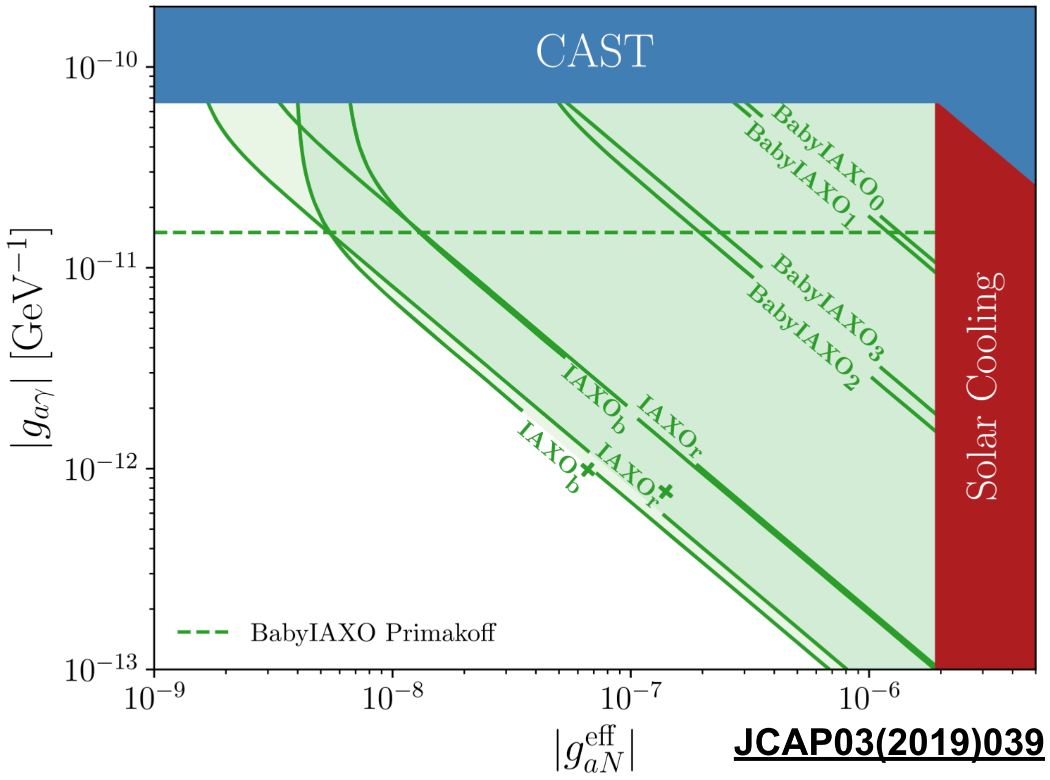
Studied Sensitivity Examples

[Eur. Phys. J. C 82, 120 (2022)]



- Studies help guide optimisation of optics+detection systems for specific channels
  - ➡ IAXO & IAXO+ will deliver higher statistics

- (Baby)IAXO will probe large unexplored parameter space beyond solar and CAST bounds
  - ➡ (Independent) coupling measurements will allow to **confront different axion models**!



[JCAP03(2019)039]

And What About Dark Matter?

Model Dependencies

Everything shown so far: independent of the Dark Matter paradigm!

Let’s assume, ALPS II discovers an axion/ALP
+
(Baby)IAXO confirms and pinpoints a specific axion model

Another important question: does the discovered particle is/contributes to Dark Matter?

Detecting Dark Matter with Haloscopes

MAgnetized Disc and Mirror Axion eXperiment

Direct Dark Matter Searches at DESY & Collaboration

- Assumed construction place: HERA hall north to re-use parts of H1 infrastructure + new cryo-platform

MAgnetized Disc and Mirror Axion eXperiment

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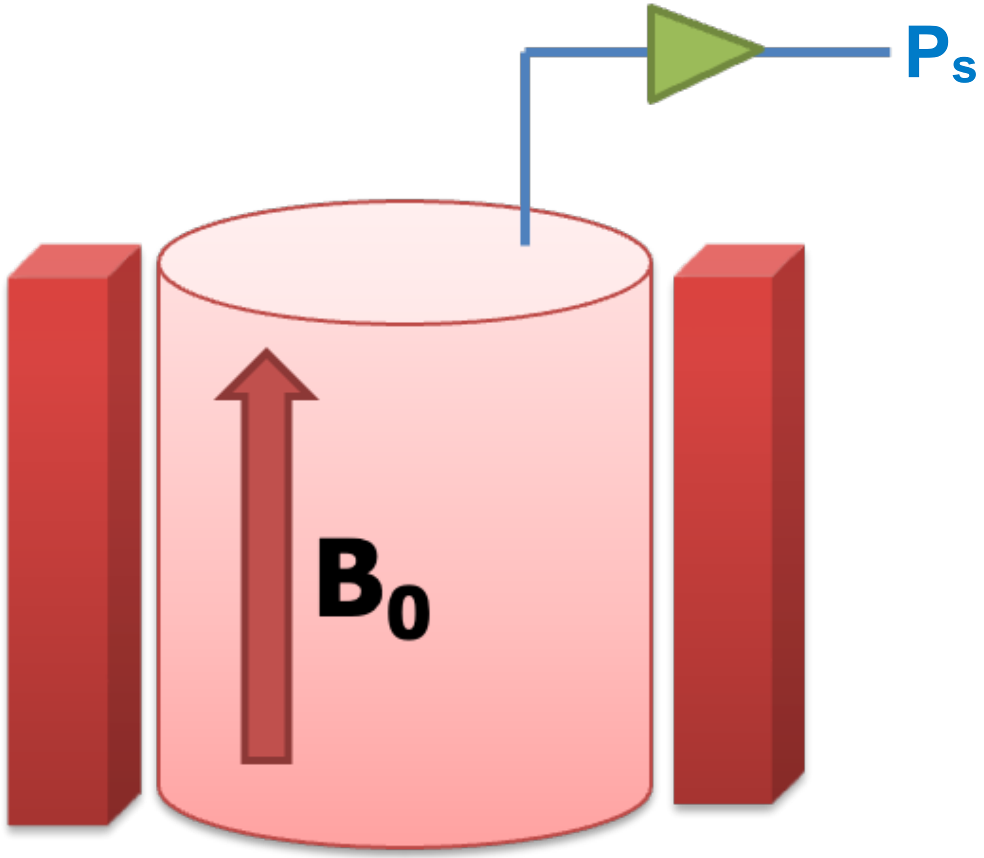
Collaboration Meeting September 2022 @ DESY

- 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

Haloscopes

Detecting Dark Matter Axions - In a Nutshell

- Assumption for haloscope: DM is mostly made of axions
  - ➡ Axions non-relativistic: $m_a \rightarrow f_{a,\gamma}$
- Resonant "Sikivie" cavities
  - ➡ Axion-photon conversion in tunable resonant cavity
  - ➡ Typically in microwave ranges
- If cavity is tuned to axion frequency: Boost of conversion by resonant factor
  - ➡ Detection: excess in measured output power P_s

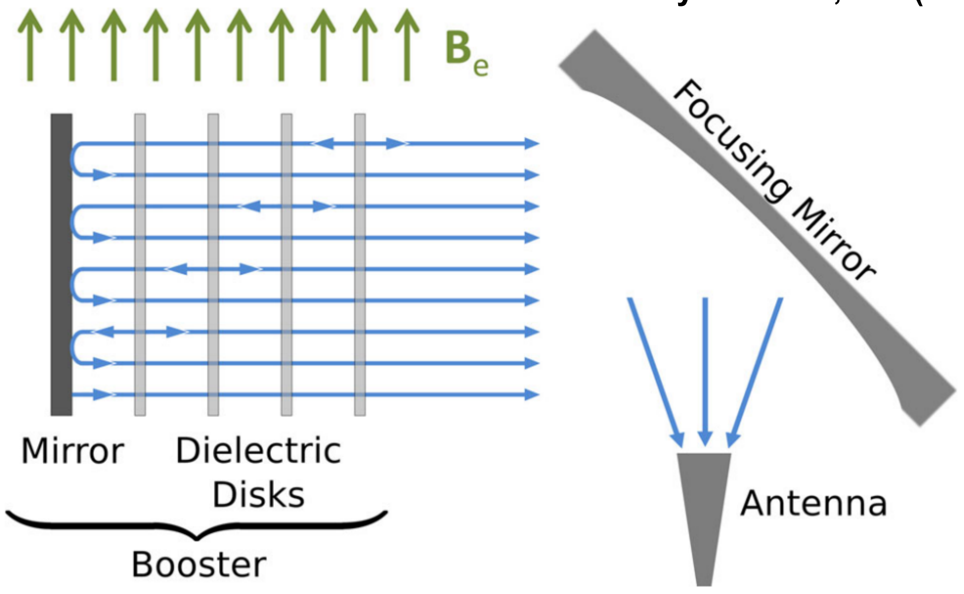


MAgnetized Disc and Mirror Axion eXperiment

A Dielectric Haloscope

- Principle: boosted dish antenna, open dielectric resonator
  - ➡ Axion-induced EM wave from the E-field discontinuity at dielectric boundary in B-field
  - ➡ Multiple dielectric disks lead to "boost" factor: emissions sum constructively
  - ➡ Precise disk separation: boost factor tunable for specific mass ranges

Eur. Phys. J. C 80, 392 (2020)



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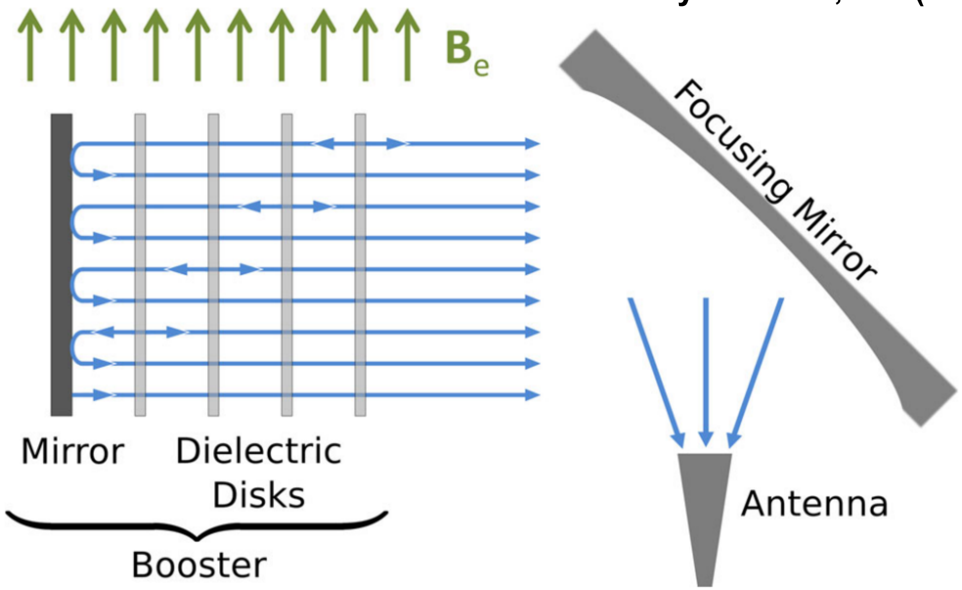
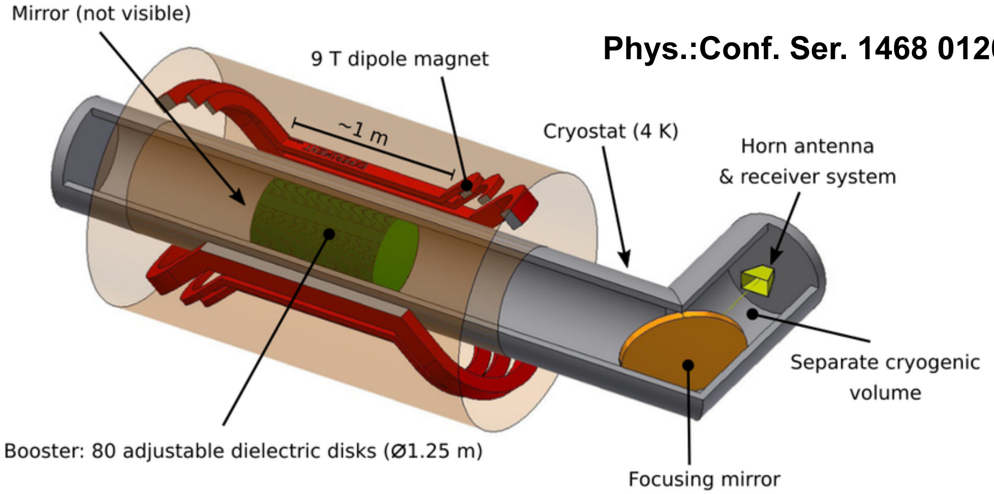
- Design considerations:
  - ➡ Many 1.25 m disks in purpose-built 9 T magnet
  - ➡ Each disk (~6 kg) to be positioned with 10 μm accuracy
  - ➡ Cryogenic cooling to reduce BKG and improve sensitivity

Eur. Phys. J. C 80, 392 (2020)



Phys.:Conf. Ser. 1468 012062



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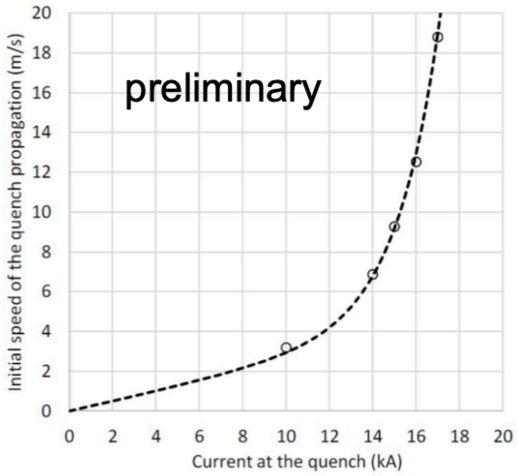
R&D and Status

- Magnet: conceptual design + successful conductor tests (quench velocity) @ CEA / Saclay



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    - ➡ **Successfully tested** in UHV / 5.3 T / 5 K @ DESY/UHH

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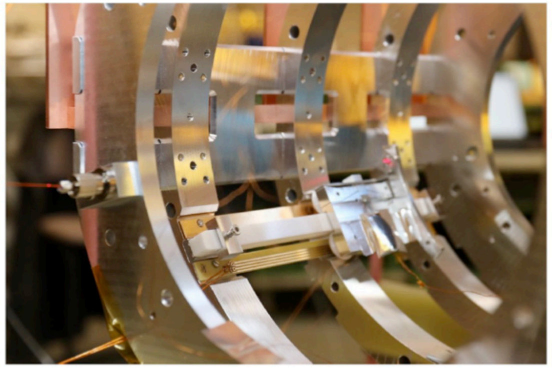

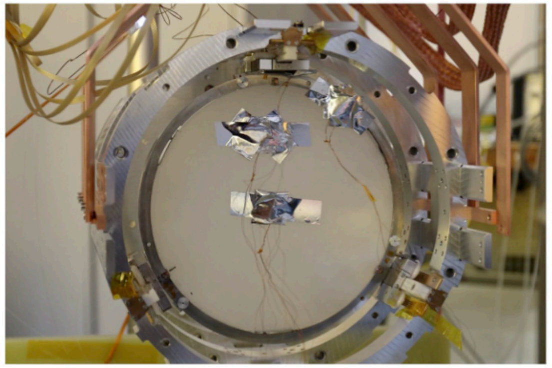

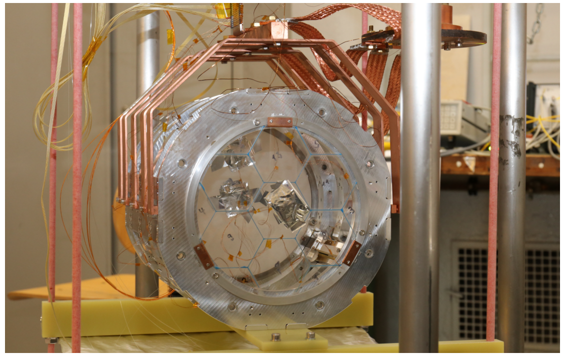

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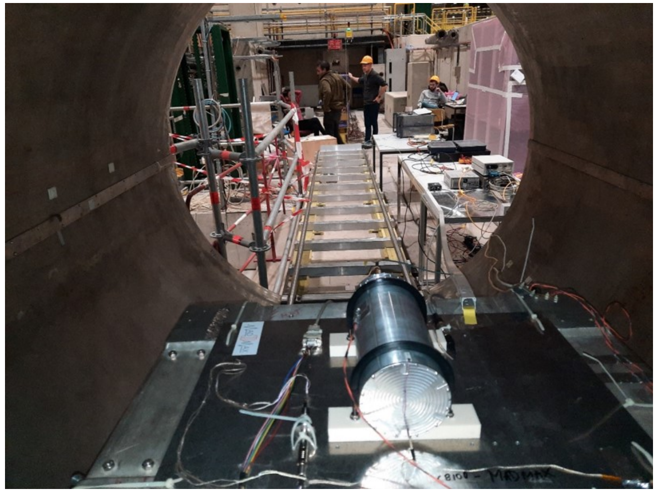
- Booster understanding:
  - ➡ Series of prototype (open & closed) tests e.g. exploiting MORPUGO magnet at CERN, future tests: UHH
  - ➡ Complex calibration method by MPP Munich



Prototype at MORPURGO / CERN

MAgnetized **D**isc and **M**irror **A**xion e**X**periment

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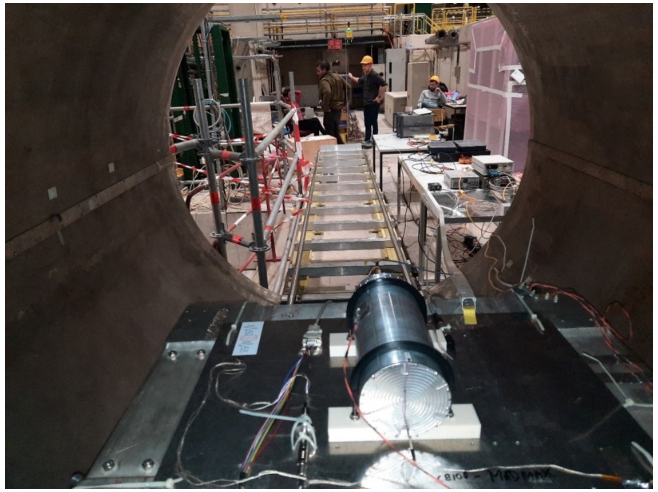
  - ➡ Complex calibration method by MPP Munich

➡ MADMAX potential ~2030 @ DESY?

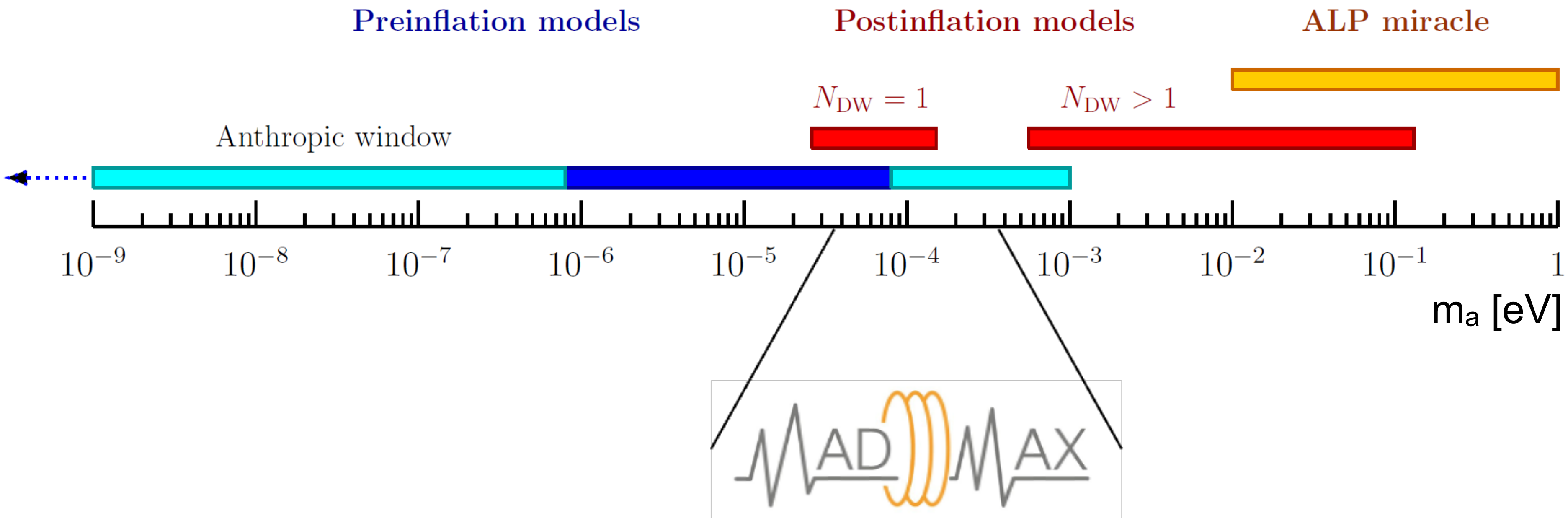


Prototype at MORPURGO / CERN

Sensitivity Range of MADMAX

Direct Dark Matter Searches

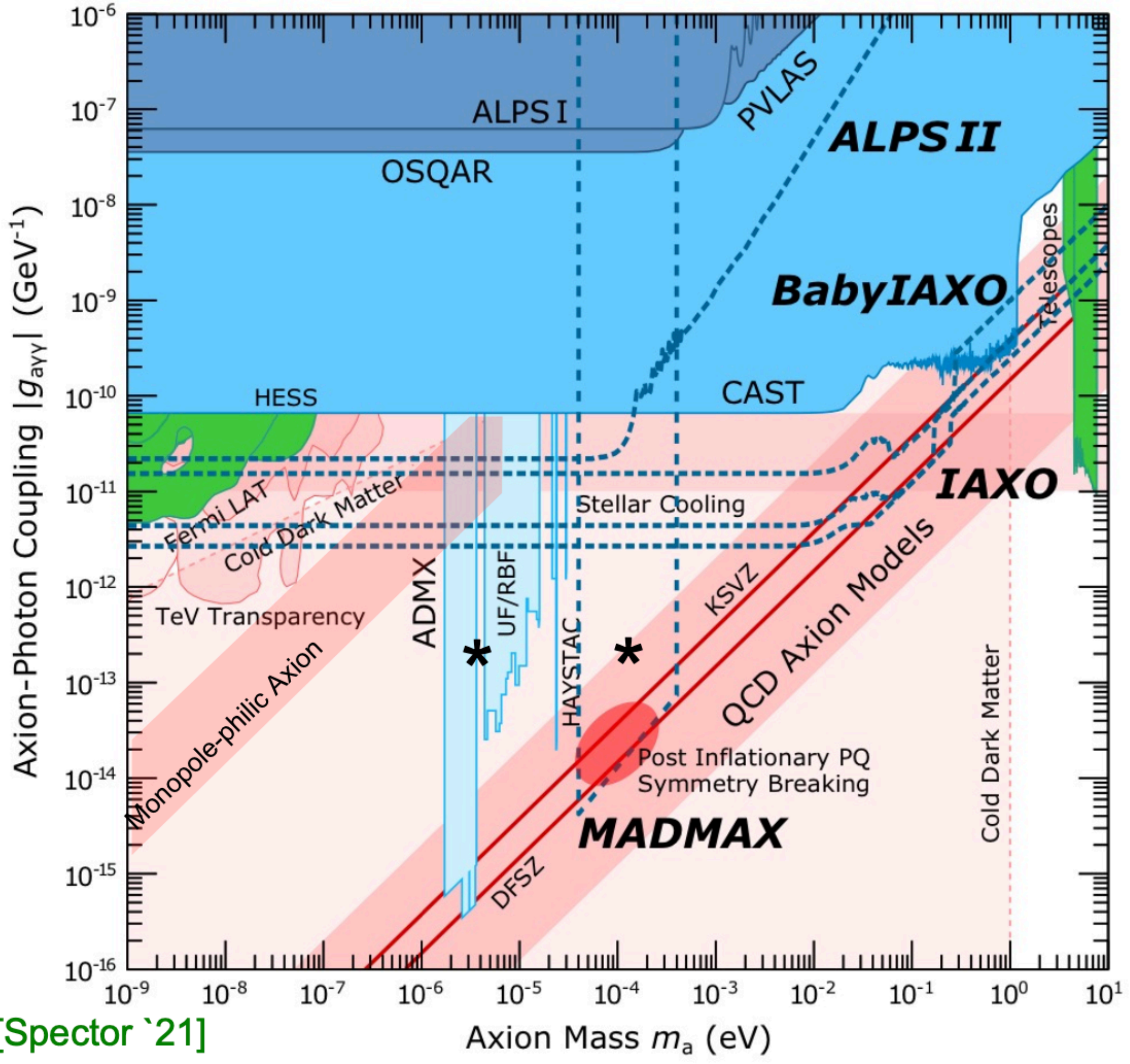
- Find axion dark matter in the mass range predicted by:
  - ➡ Post-inflation models (PQ symmetry breaking after inflation)
  - ➡ High mass region of pre-inflation models



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

Sensitivity Range of MADMAX

Direct Dark Matter Searches

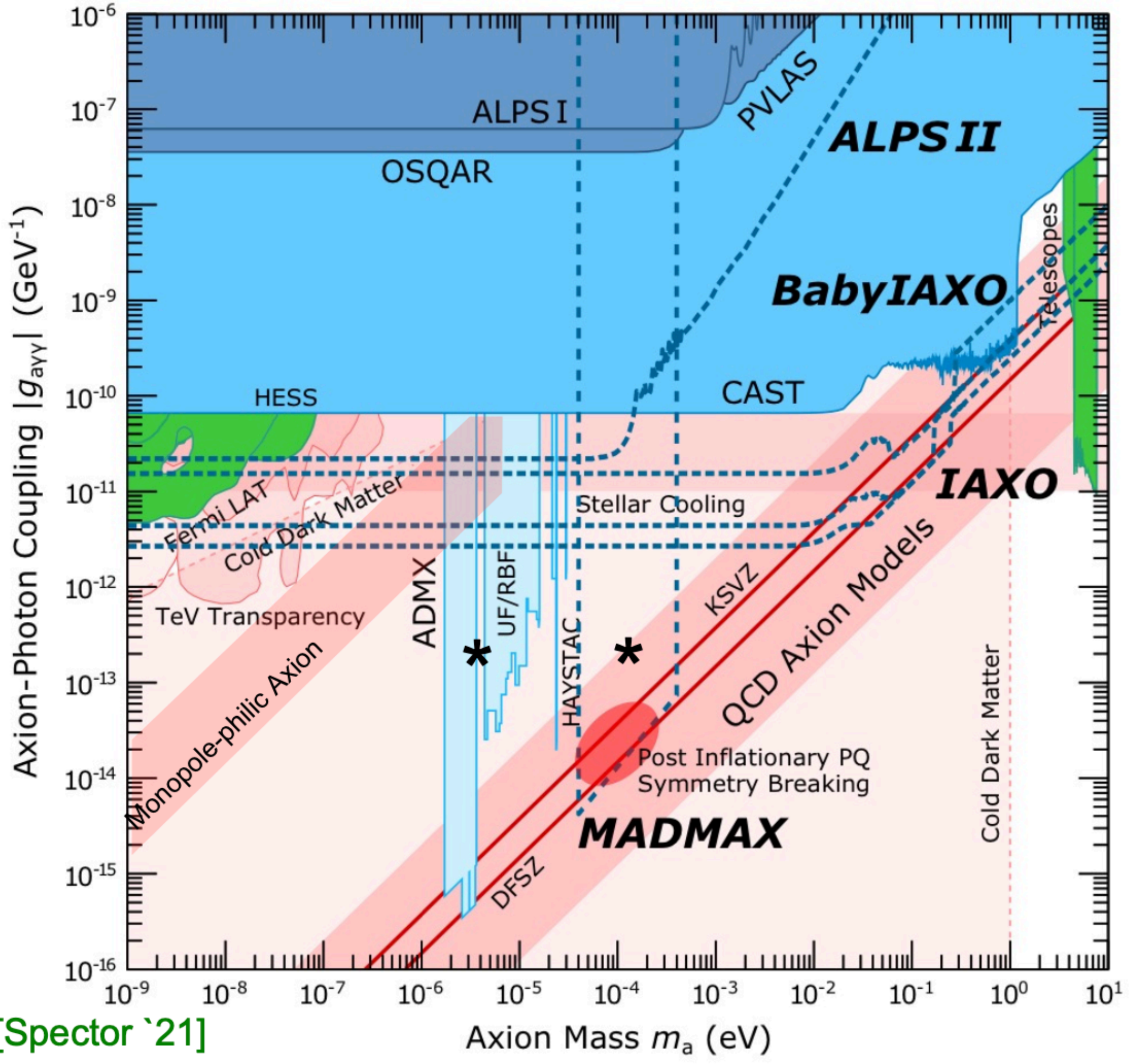


[Spector `21]

*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\mathrm{DM}}/\rho_a}$

Sensitivity Range of MADMAX

Direct Dark Matter Searches



[Spector `21]

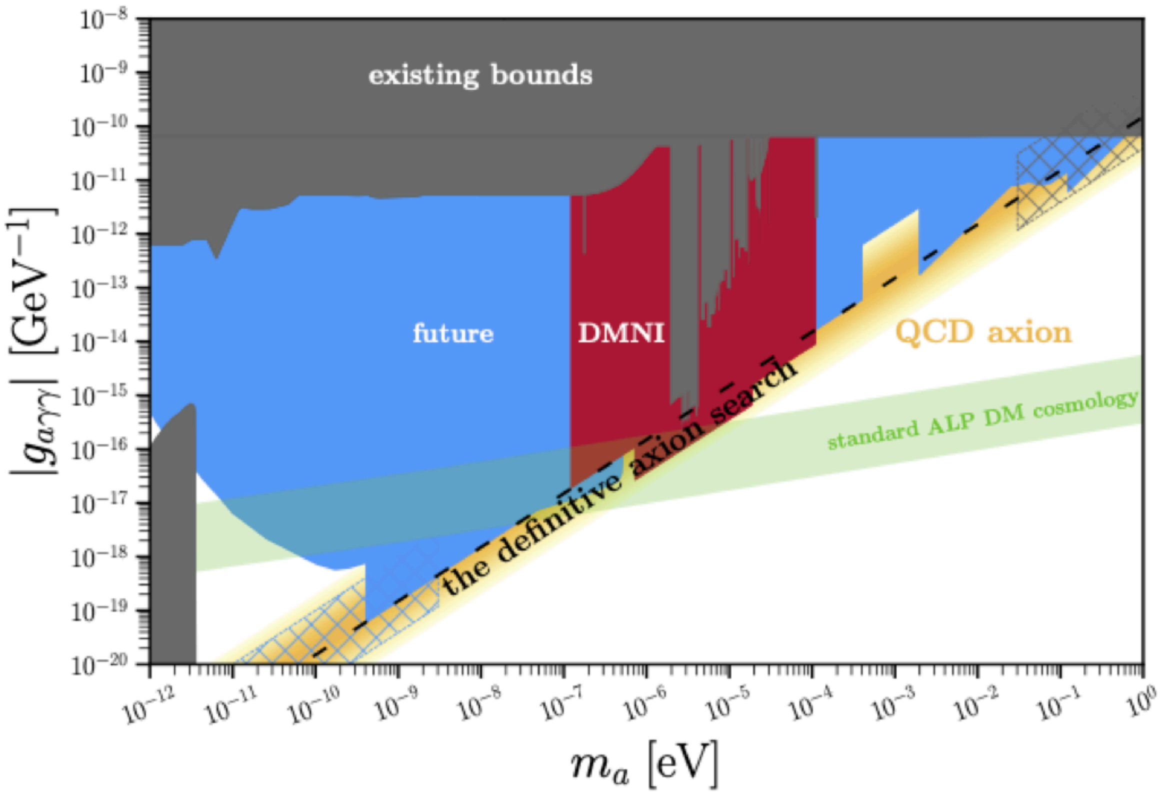
- How is MADMAX situated in the international context of Dark Matter searches (and beyond)?

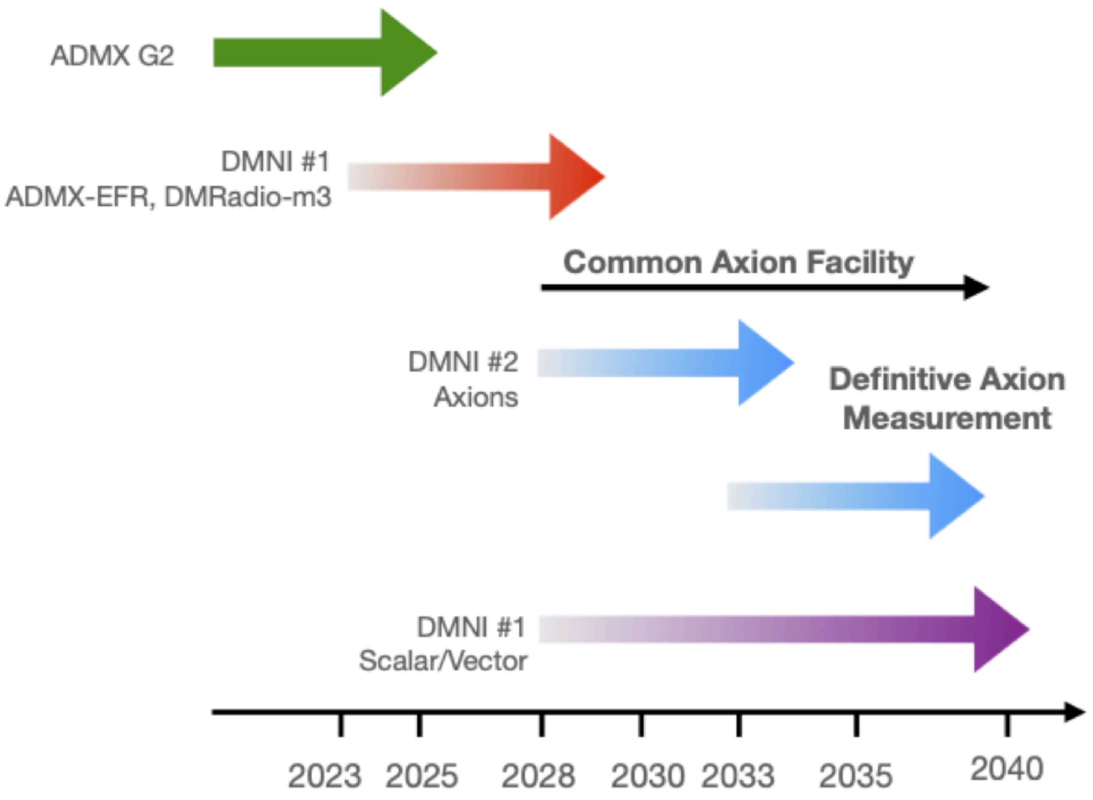
*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\mathrm{DM}}/\rho_a}$

The (Future) Landscape I

Direct Dark Matter Searches

Report of the Topical Group on Wave Dark Matter for Snowmass 2021, arXiv:2209.08125





- Until ~2030: DMNI #1 aims to reach the QCD axion benchmark band for m_a: 10^{-7} - 10^{-4} eV
- Afterwards: DMNI #2, the definitive axion search, aims for basically full bandwidth

The (Future) Landscape I

Direct Dark Matter Searches

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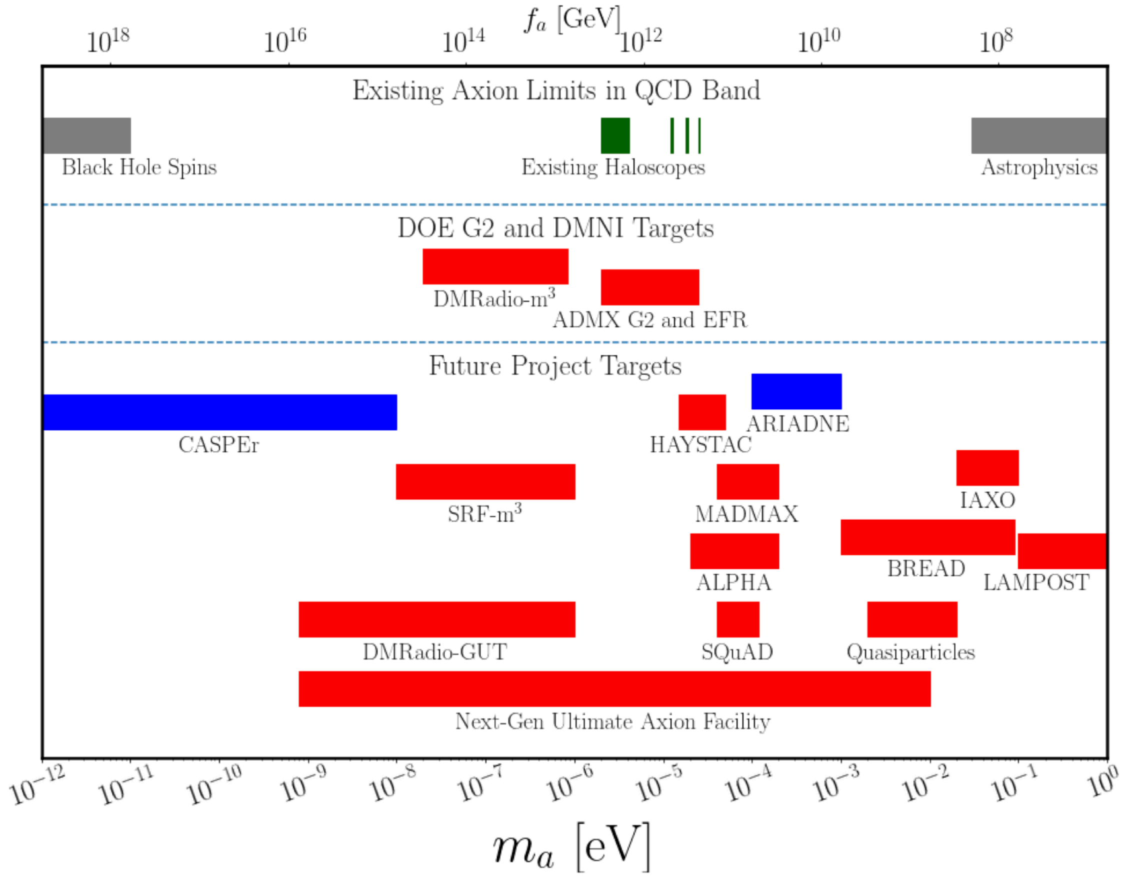
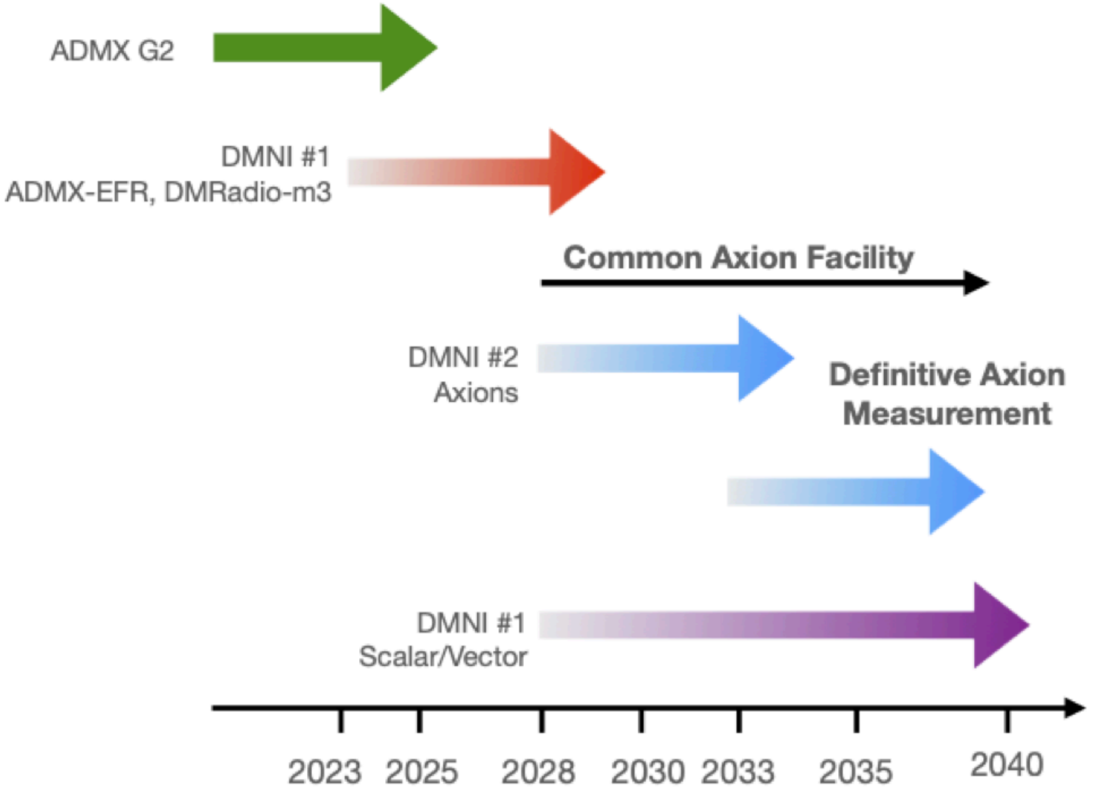


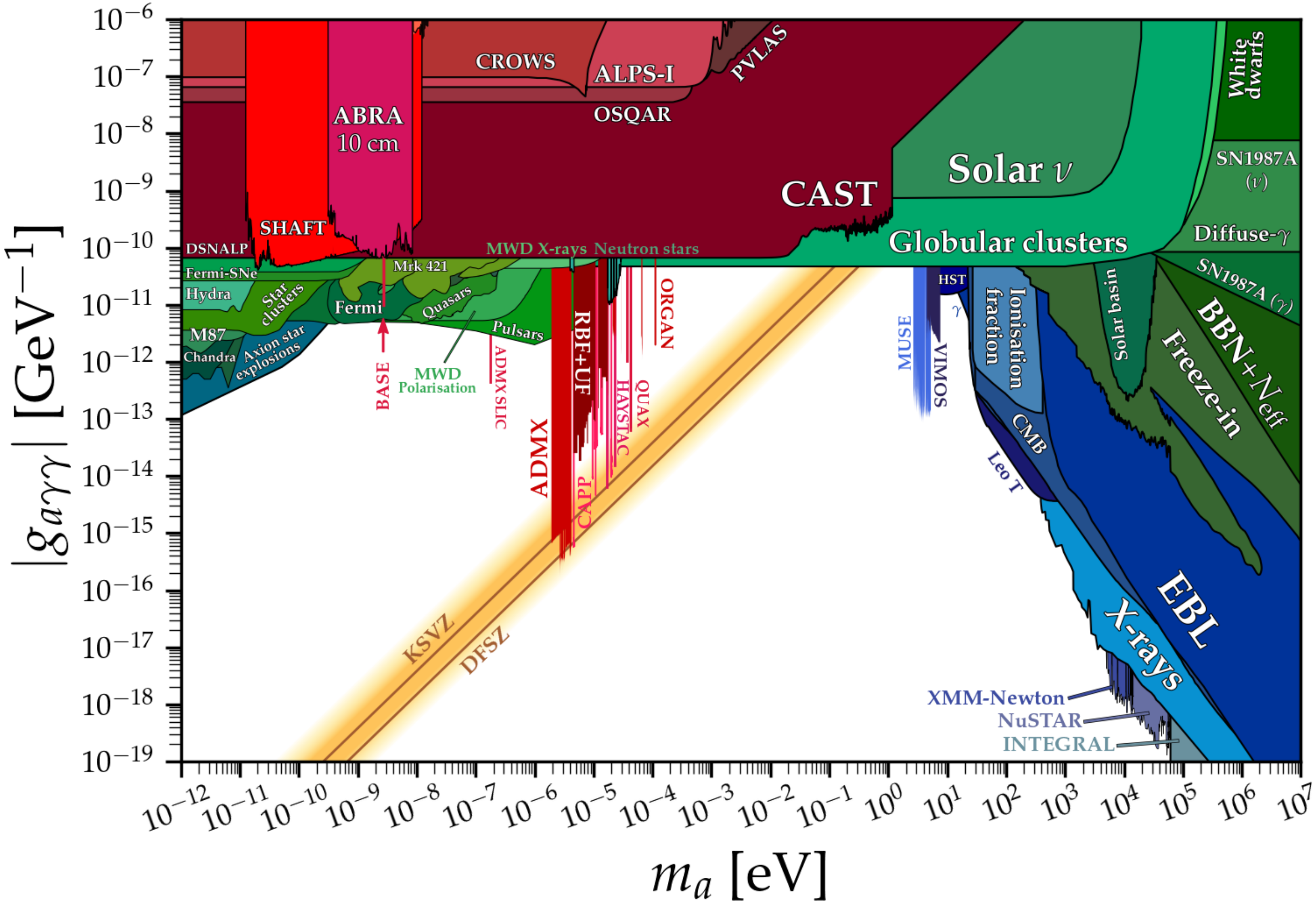


- Until ~2030: DMNI #1 aims to reach the QCD axion benchmark band for m_a: 10^{-7} - 10^{-4} eV
- Afterwards: DMNI #2, the definitive axion search, aims for basically full bandwidth
  - ➡ Various experiments up to a next-gen ultimate axion facility

The (Future) Landscape II

Other Direct Dark Matter Searches & Beyond

https://cajohare.github.io/AxionLimits/docs/ap.html



- Current experimental exclusion limits for DM experiments and beyond

*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{DM}/\rho_a}$

The (Future) Landscape II

Other Direct Dark Matter Searches & Beyond

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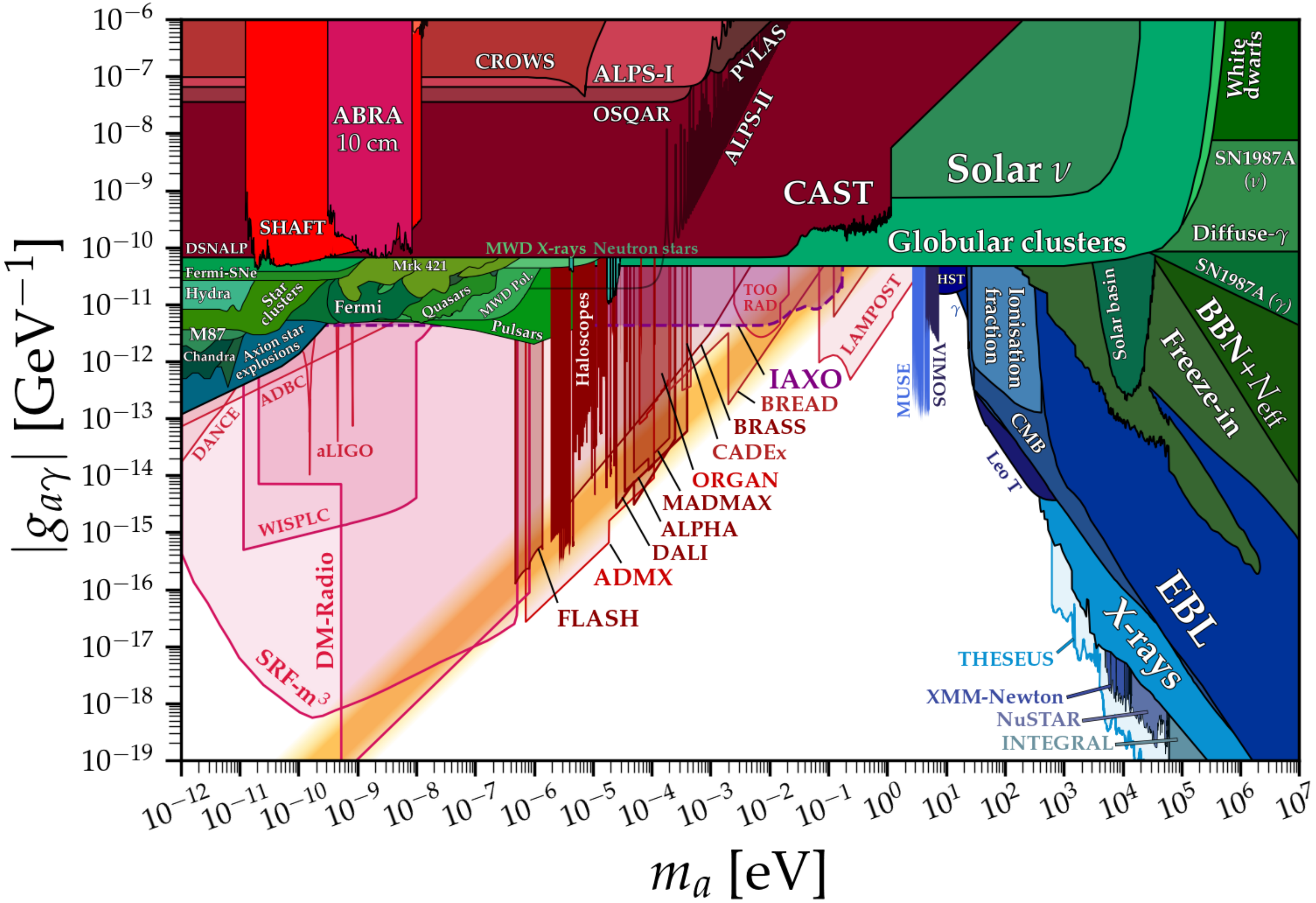


- Current experimental exclusion limits for DM experiments and beyond + projections
  - ➡ Huge efforts ongoing to reach the benchmark QCD axion band with different types of experiments
  - ➡ Exciting times ahead!

*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

Summary & Outlook

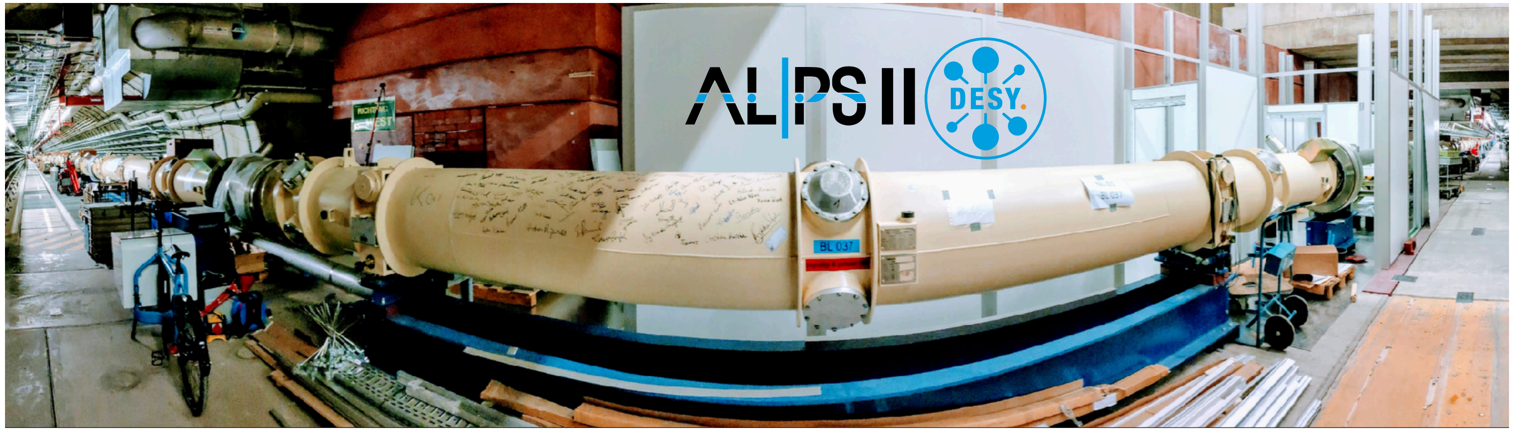
… and a Dream

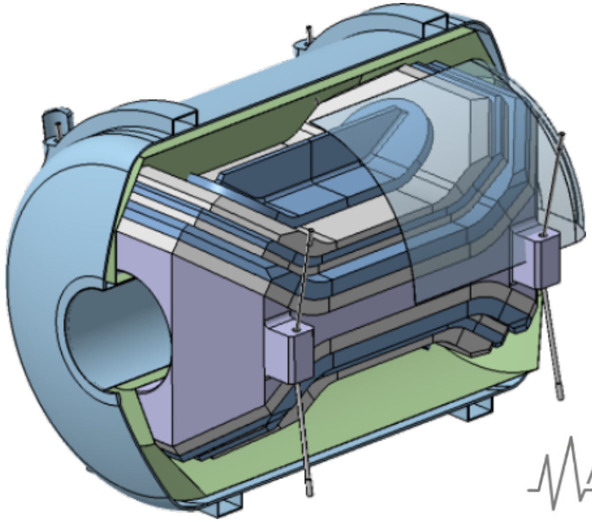
- DESY hosts a rich and complementary axion/ALP program over the next two decades
- ALPS II started data taking in May 2023
  - ➡ Determine the ALP-photon coupling model-independently
- BabyIAXO will start data taking by the end of the decade
  - ➡ Confirm ALPS II discovery and compare $g_{a\gamma\gamma}$ measurement
  - ➡ Constrain the nature of the underlying BSM model by probing $g_{a\gamma\gamma}$, g_{ae} , g_{aN} and m_a
- MADMAX (start 2030?) and other DM experiments
  - ➡ Check if discovered axion (partly) contributes do DM content
  - ➡ Precisely measure m_a and DM velocity distribution

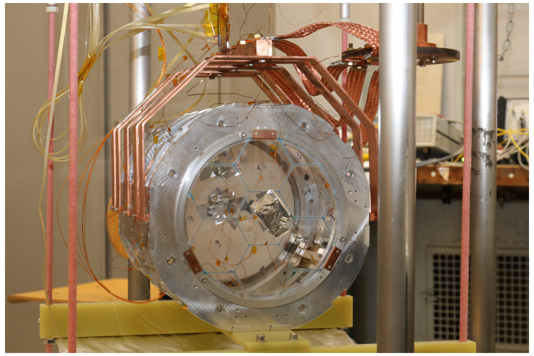
Henry Frädrich in Cosmology/DM/Axion parallel session: “First data taking with ALPS II”

Daniel Heuchel in poster session: Details of ALPS II & BabyIAXO physics prospects + further searches

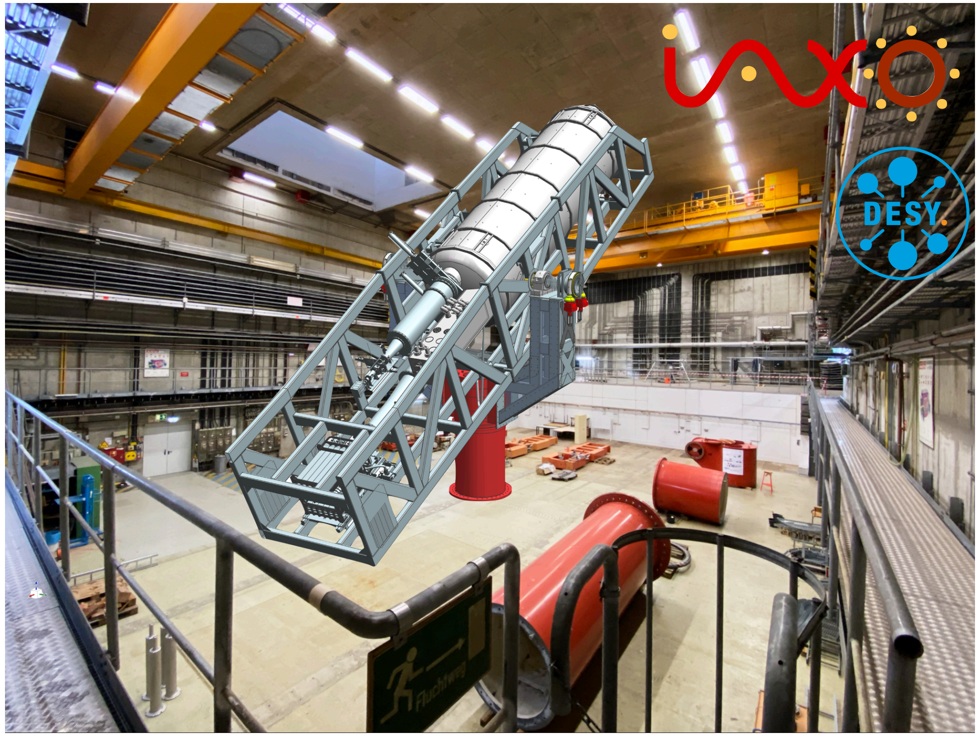
Stay tuned for the broad axion/ALP (and related) physics program at DESY and beyond!







MADMAX DESY.



Thank you for your attention!

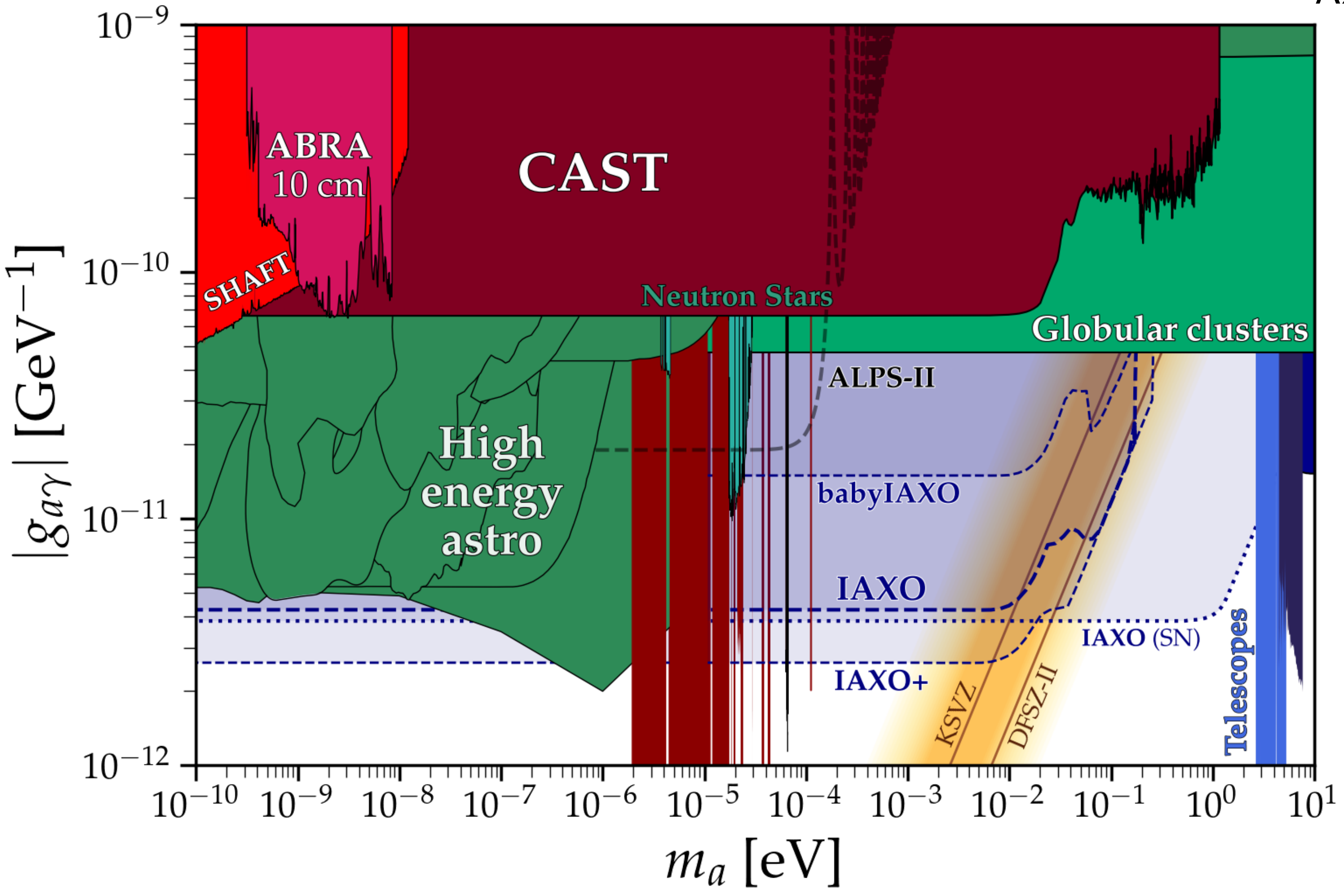
Backup

Landscape

Current Parameter Space - Axion-Photon Coupling

Experimental Limits + Projections Helioscopes

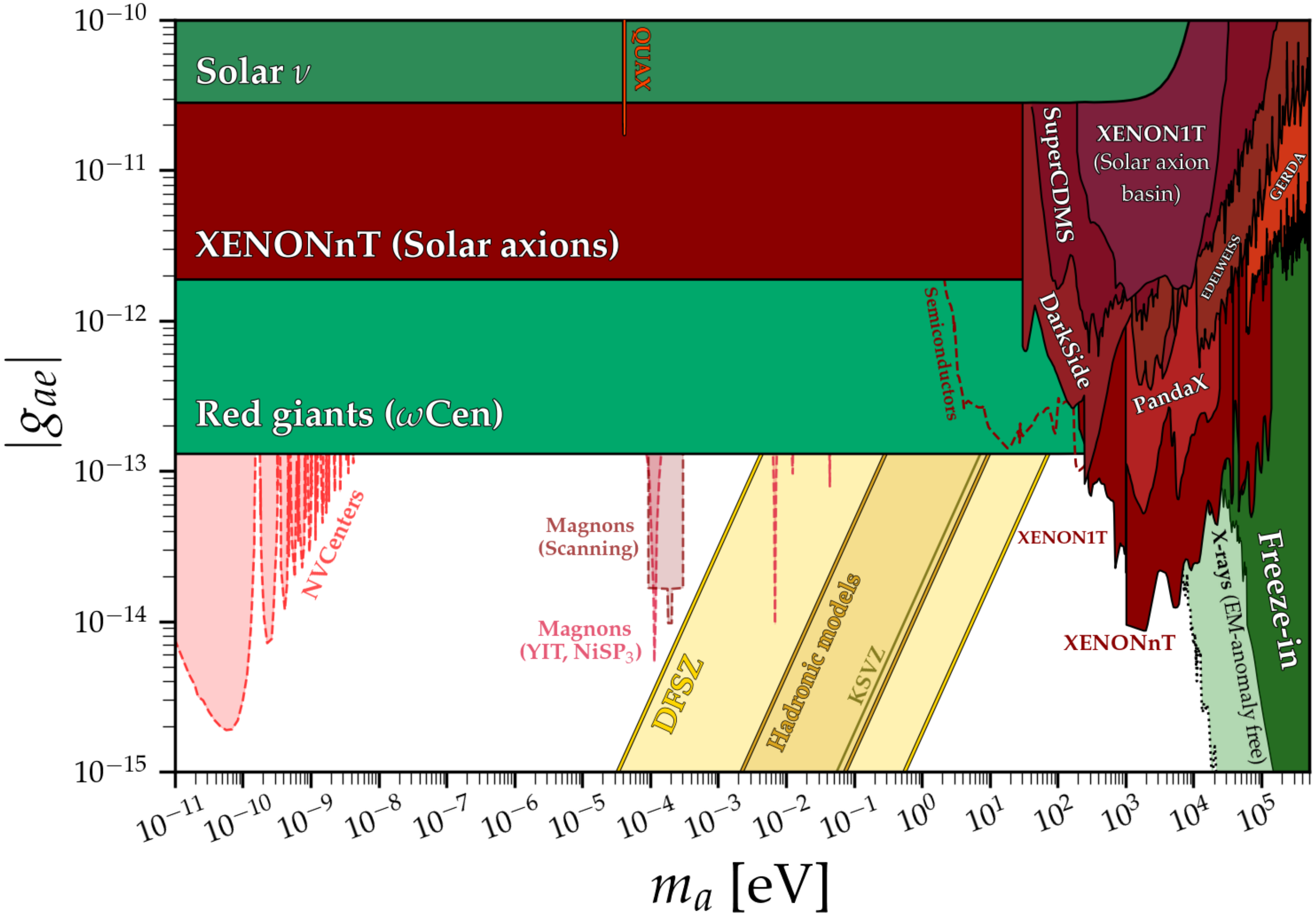
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Axion-Electron Coupling

Experimental Limits + Projections

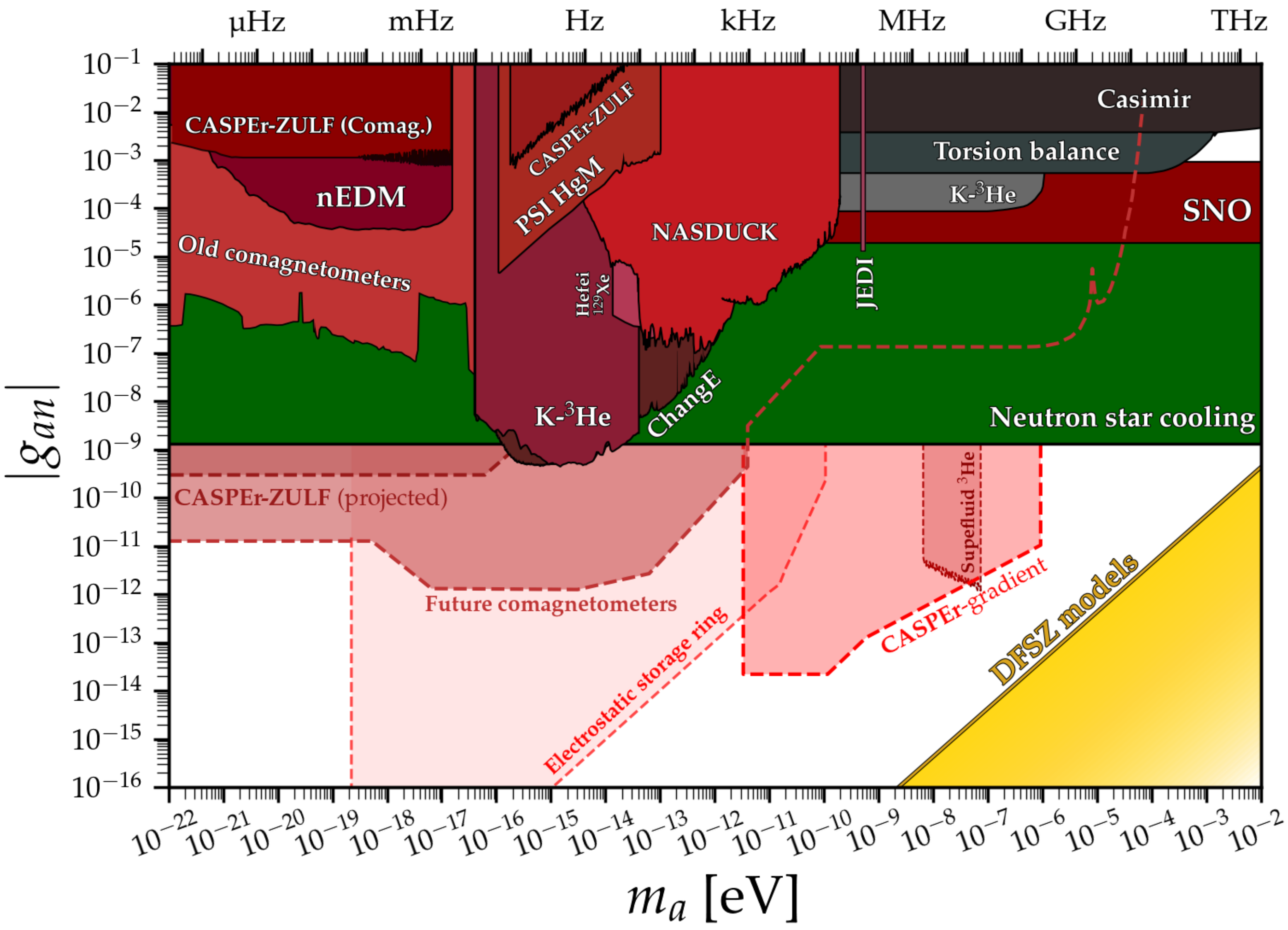
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Axion-Neutron Coupling

Experimental Limits + Projections

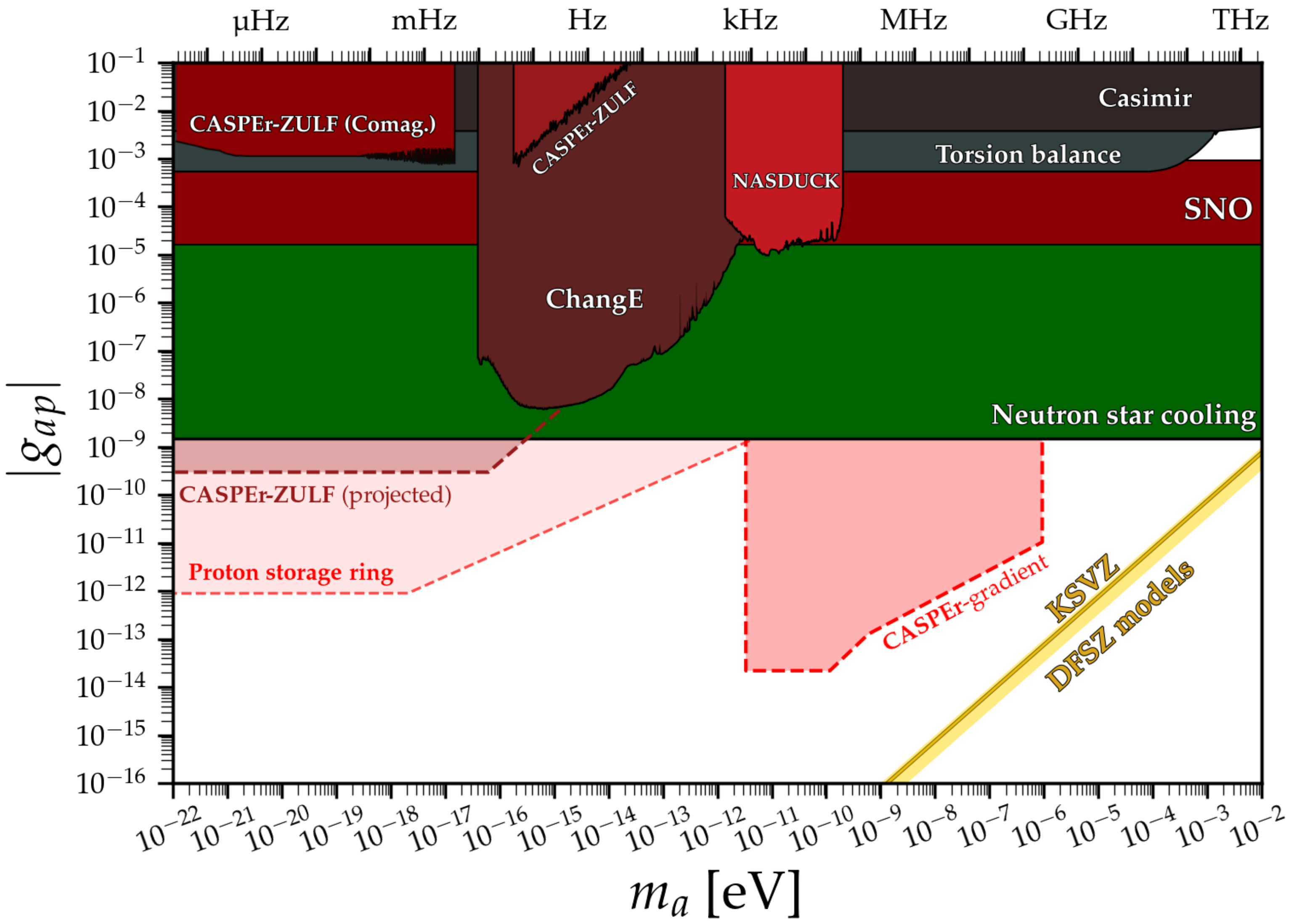
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Axion-Proton Coupling

Experimental Limits + Projections

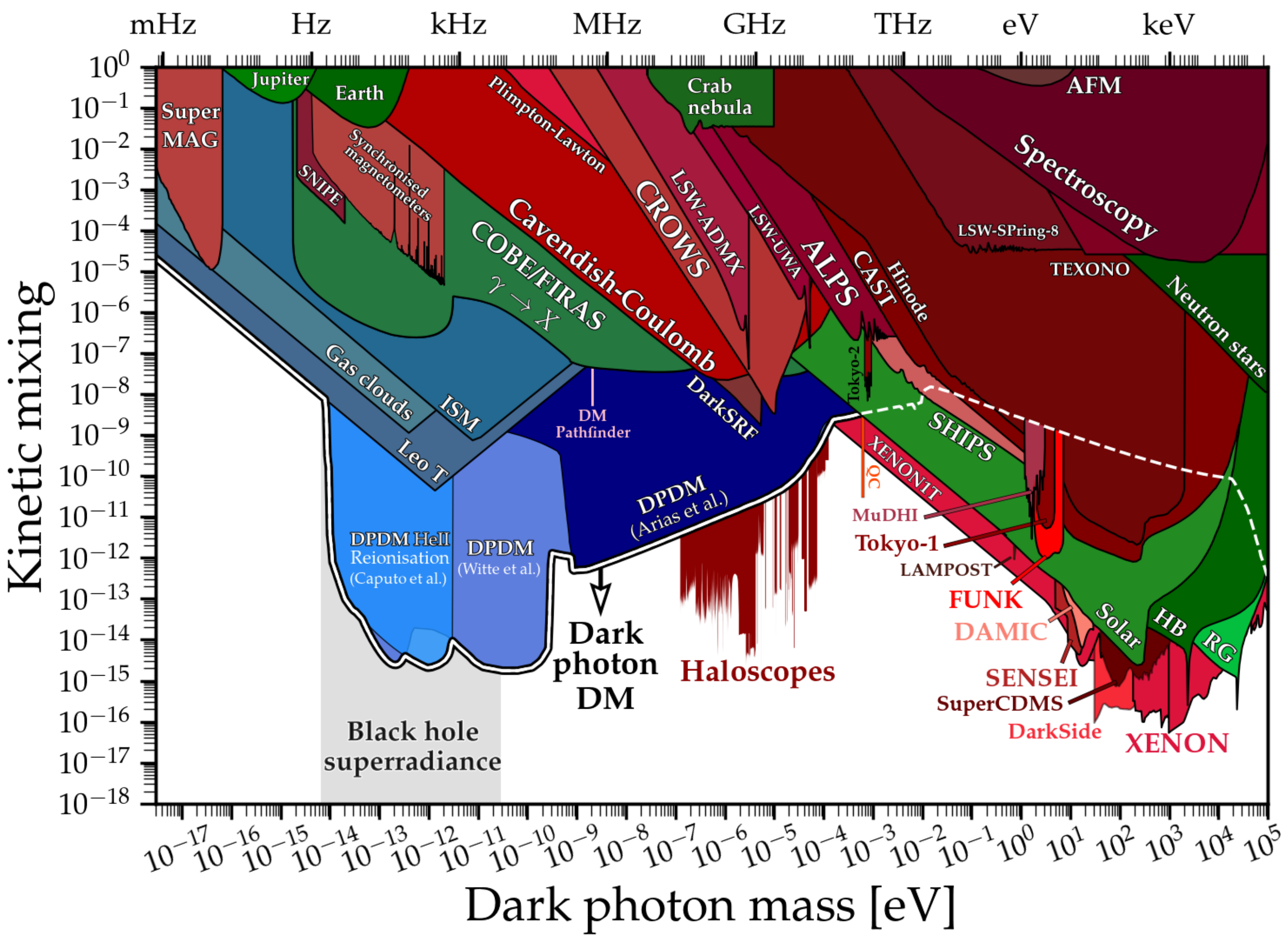
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Dark Photons

Experimental Limits + Projections

https://cajohare.github.io/AxionLimits/docs/ap.html

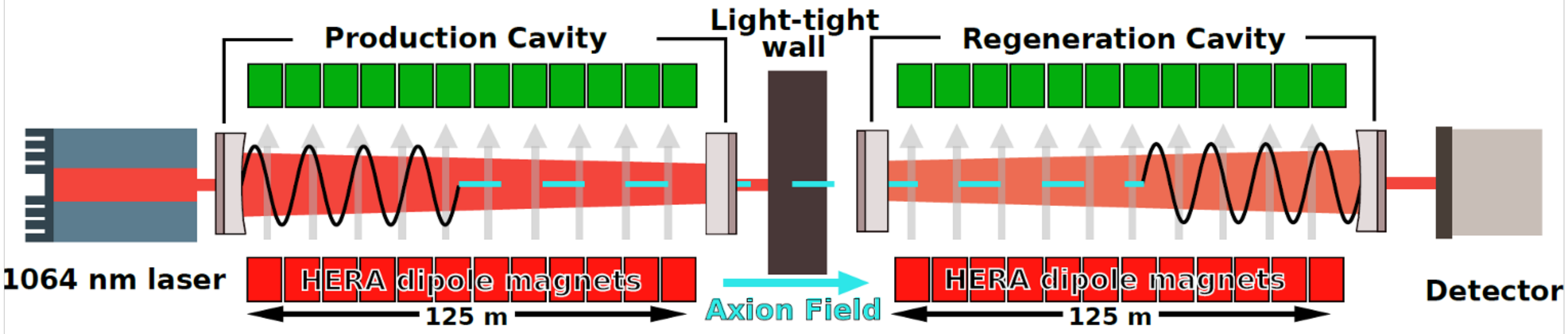


Backup

ALPS II

ALPS 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).

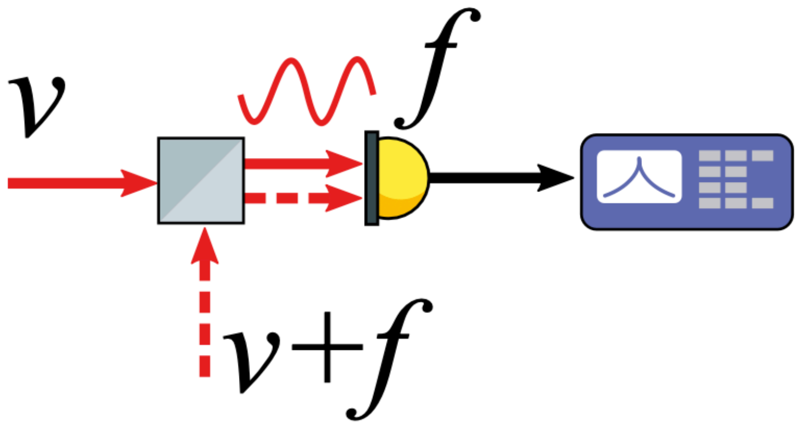
Heterodyne detection system

Measuring single photon power levels over days

Thanks to A. Spector!

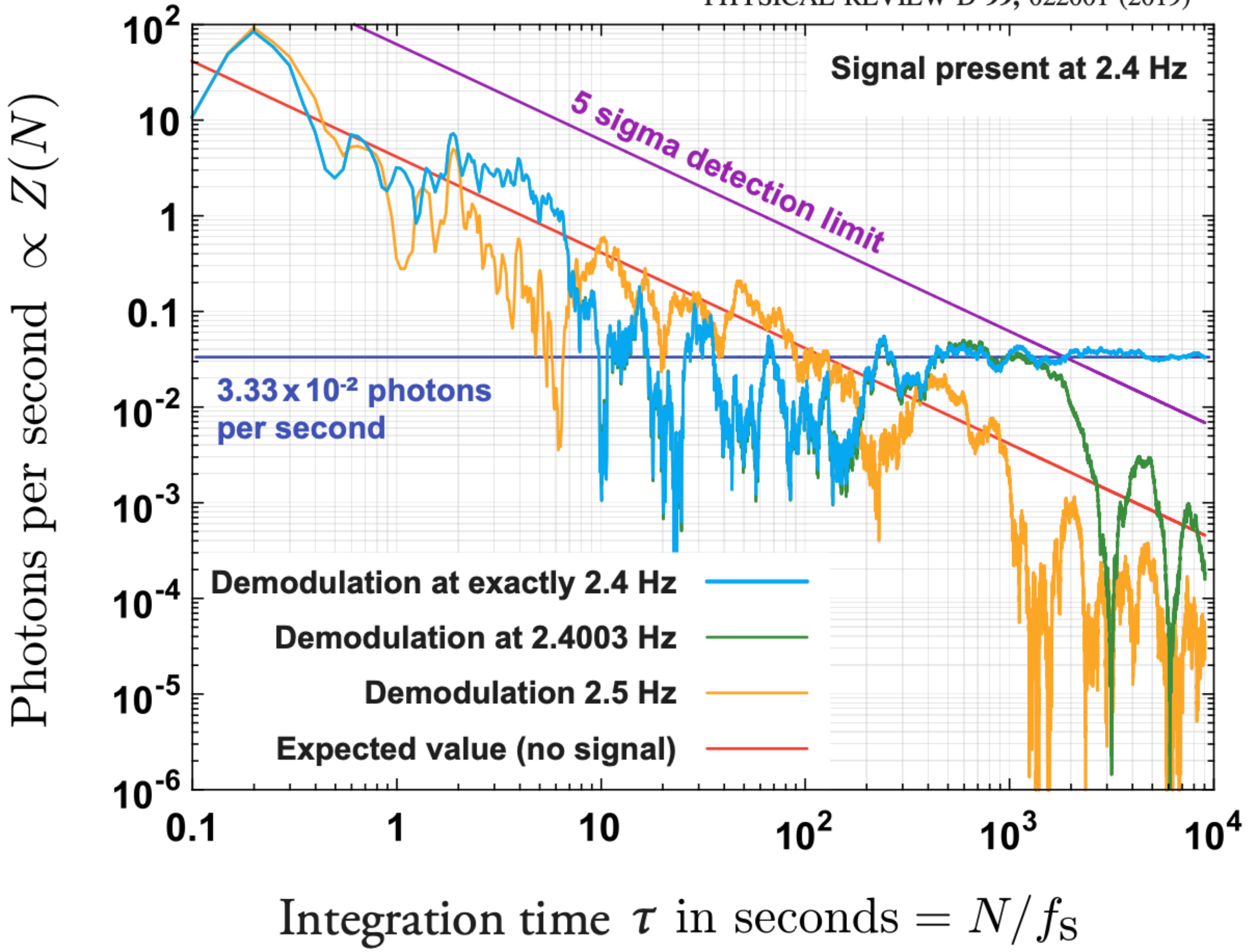
Measuring the power at a single frequency

- Interfere regenerated field (ν) with laser ($\nu + f$)
- Demodulate signal at defined frequency
- Integrate over time to shrink frequency bin



$$P(t) = P_\nu + P_{\nu+f} + 2\sqrt{P_\nu P_{\nu+f}}\cos(2\pi f t - \phi)$$

PHYSICAL REVIEW D 99, 022001 (2019)



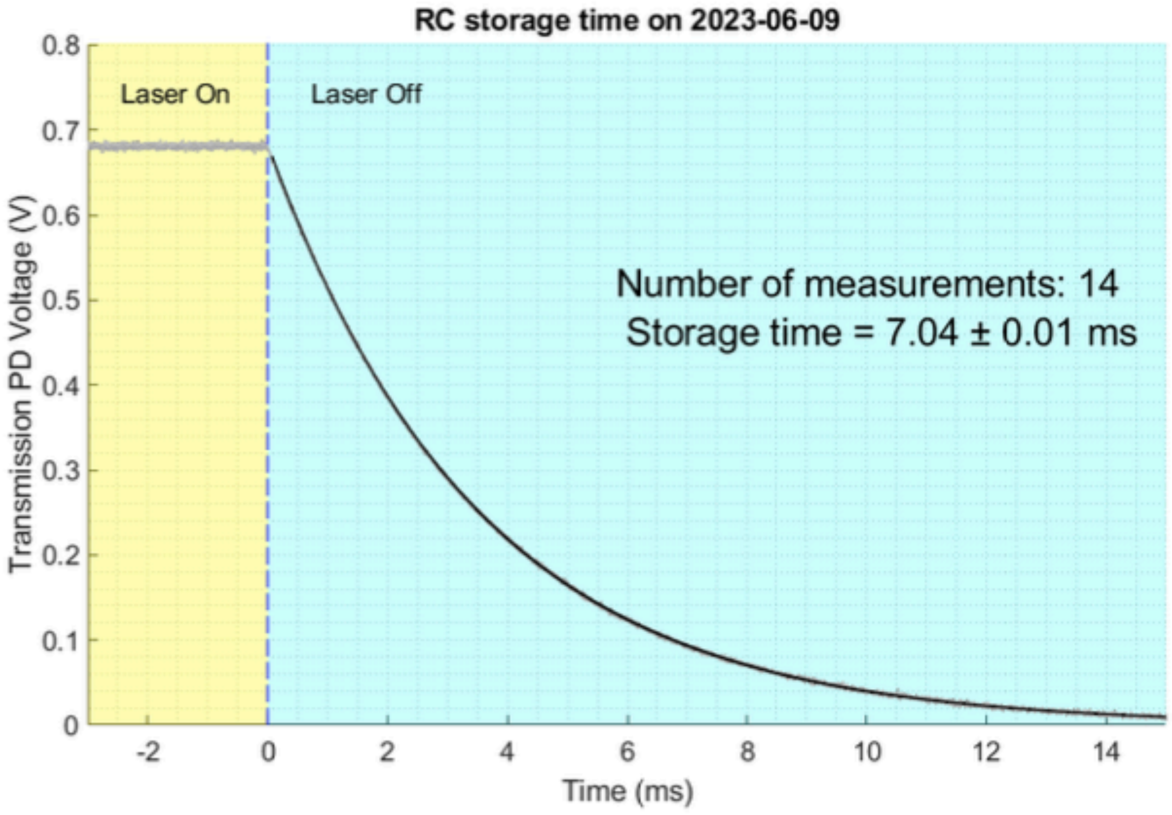
Regeneration Cavity

Reconverting axion-like particles back to photons

Thanks to A. Spector!

Longest storage time Fabry Perot cavity ever!

- Power build up factor: β = 7700
- PDH frequency stabilization, alignment control
- Multiple week locks demonstrated

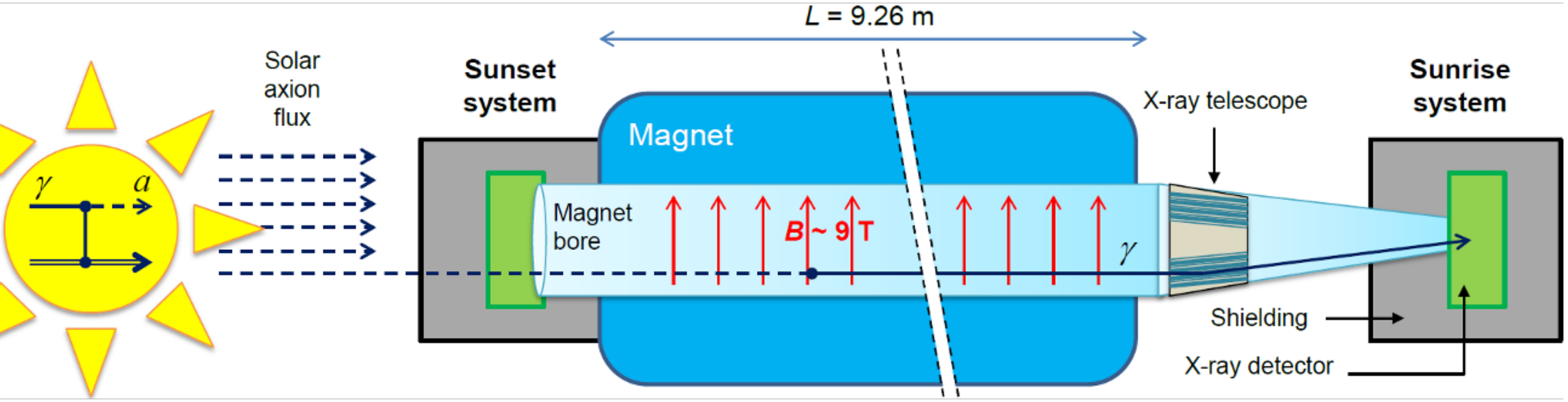


Backup

Helioscopes & IAXO

CERN Solar Axion Telescope (CAST)

State-of-the-art Helioscope



- Sunrise & sunset system: sun tracking for 2 x 1.5 hours / day
- LHC magnet: ~9 T, ~10 m long and two 4.2 cm diameter bores: $B^2 L^2 A = \sim 21\ T^2 m^4$
- First helioscope using X-ray focusing and low background techniques
- Data taking ended 2021 after 20 years of fruitful operation

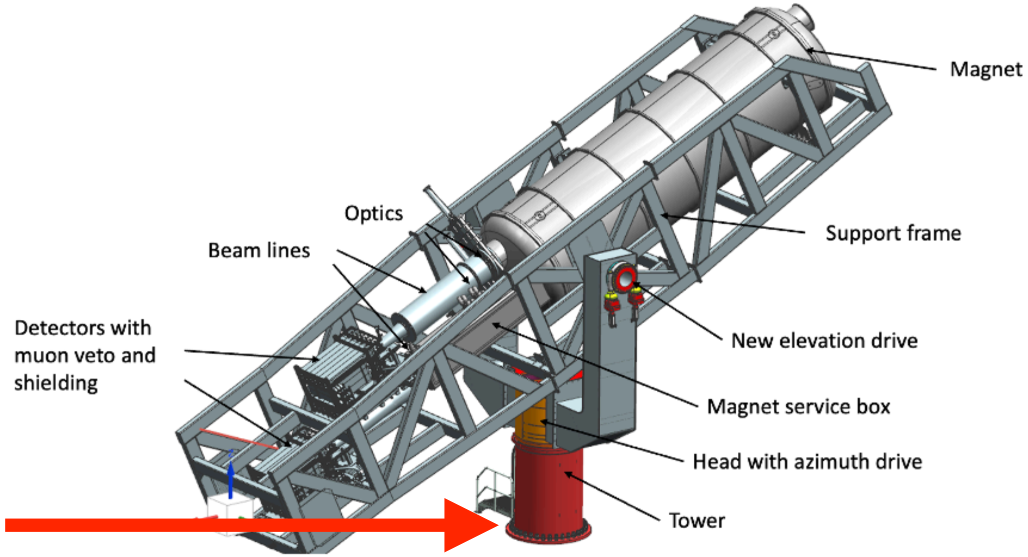
➡ Still state-of-the-art limits on $g_{a\gamma\gamma}$ vs. m_a and other parameter space

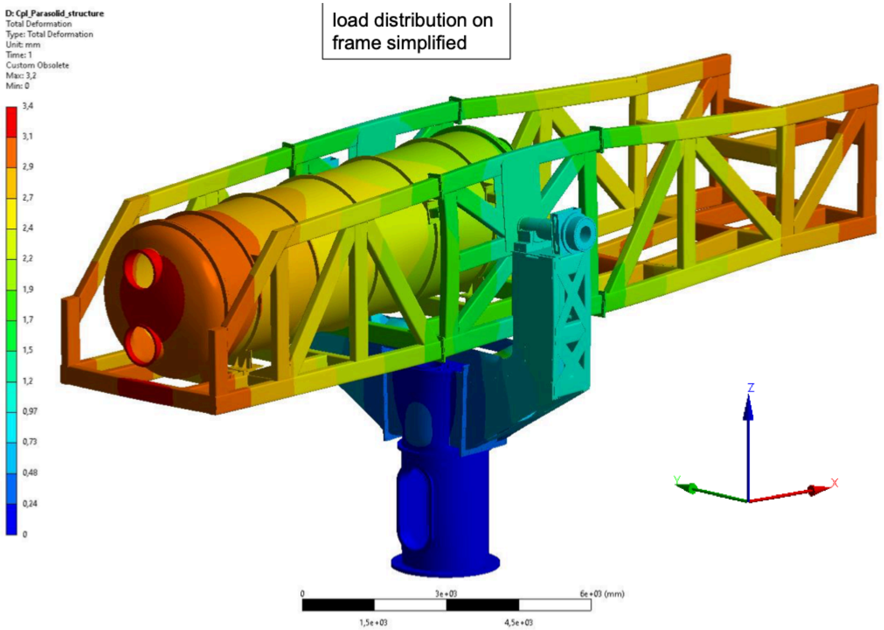
➡ **Last years of experiment: IAXO pathfinder phase**

Structure & Drive System

And Alignment to the Sun

- Reusing parts of CTA/MST prototype from DESY Zeuthen
- Technical studies progressing well
  - ➡ Design almost finished
  - ➡ Rotation: 360°, Tilt: ±25°
  - ➡ Pointing precision < 0.01°
  - ➡ Extensive simulations of load distributions and deformations
  - ➡ Internal and external alignment studies





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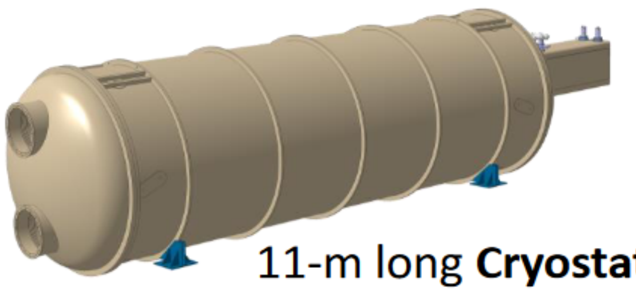
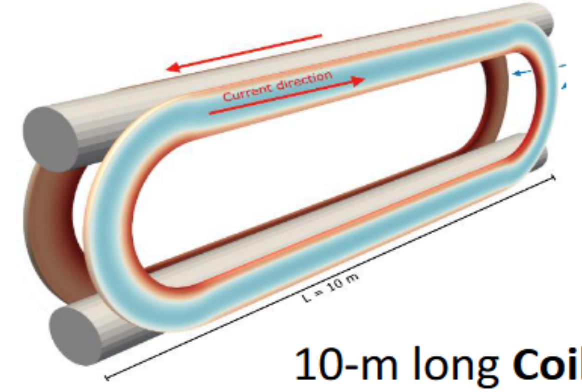
- Expertise for alignment/pointing models within IAXO: CEFCA, operating multiple large scale optical telescopes close to Teruel, Spain

Magnet (Design by CERN)

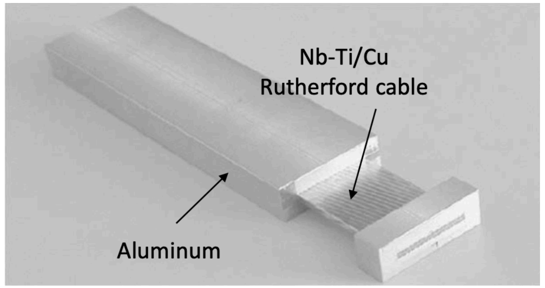
Prospects and Challenges



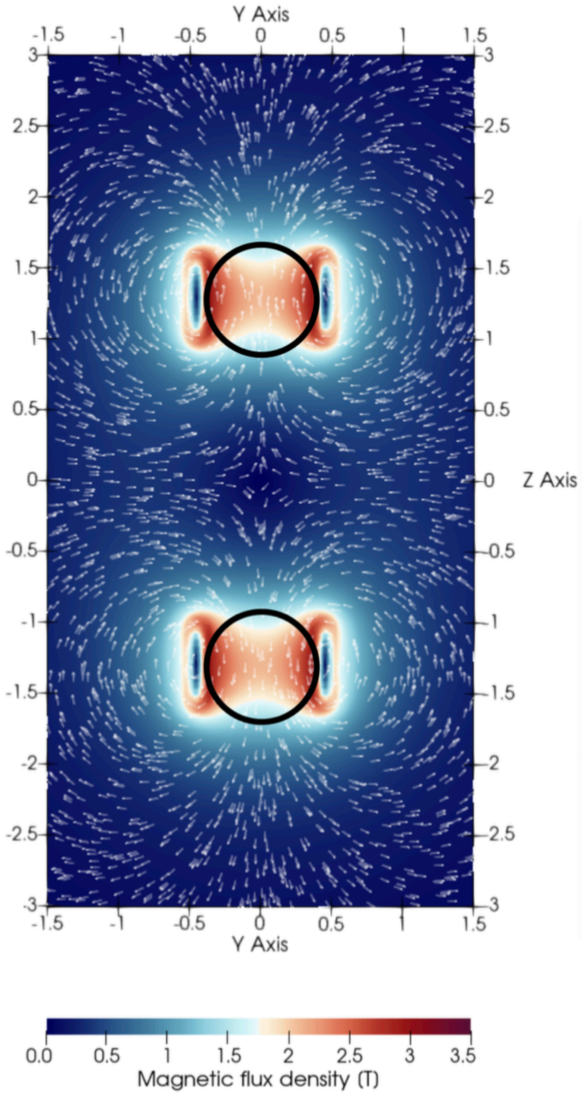
11-m long **Cryostat**



10-m long **Coils**



20-km long **Conductor**



- Two 10 m long bores with common coil racetrack design, cryocooler concept

- Ongoing discussion mainly due to difficulties in manufacturing Al-stabilised superconducting cables, **critical item**
  - ➡ Potential Russian companies not available
  - ➡ Causing additional costs and delays

- Collaboration of magnet experts (DESY+CERN)
  - ➡ Build up competence to build cable at CERN or by industrial partner
  - ➡ Constantly improving cryogenic system
  - ➡ Adapted conceptual design under preparation, new magnet review upcoming

Optics

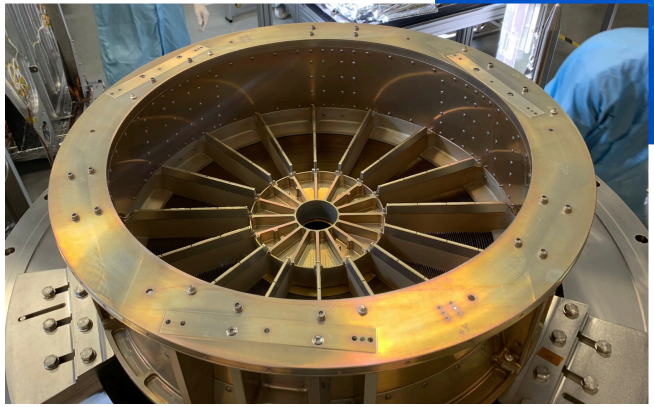
Focusing X-Rays

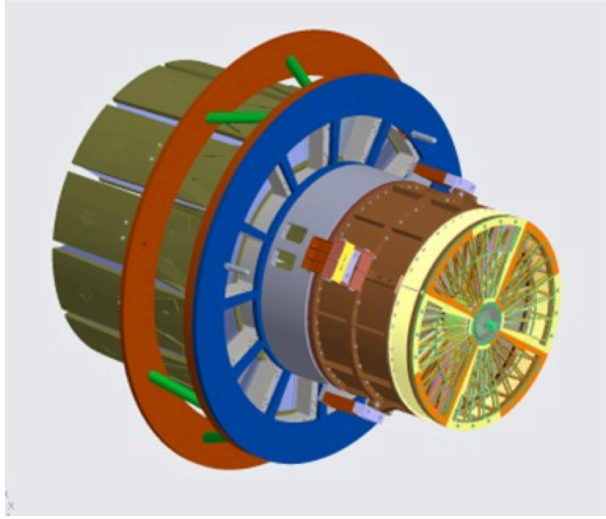
- Two different X-ray focusing optics to be used

1. XMM Newton flight spare XRT from ESA
   - ➡ Focal length: 7.5 m
   - ➡ To be re-calibrated at MPE/PANTER

2. Custom optics (hybrid approach)
   - ➡ Focal length: 5 m
   - ➡ Significant progress in test for different mirror coating, design and calibration

- Challenges: Throughput efficiency (40-60%) and focal area (0.2 cm²)





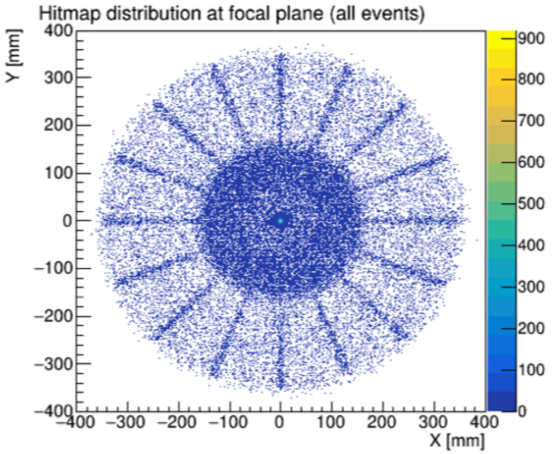
Optics

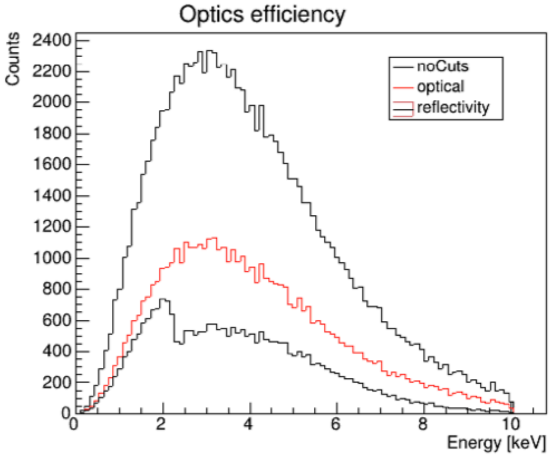
Focal Plane with Spot Events

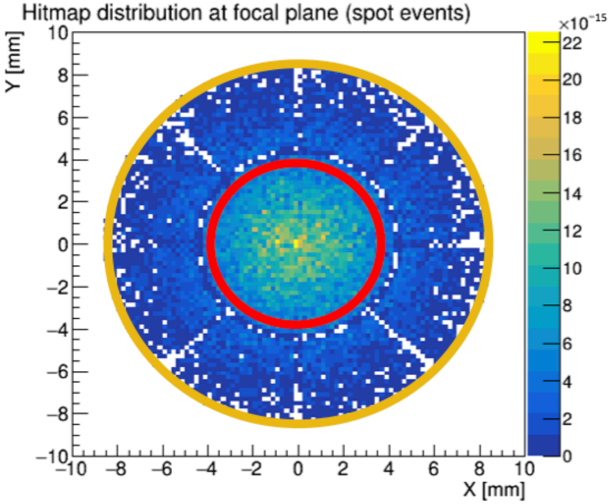
Run number : 17

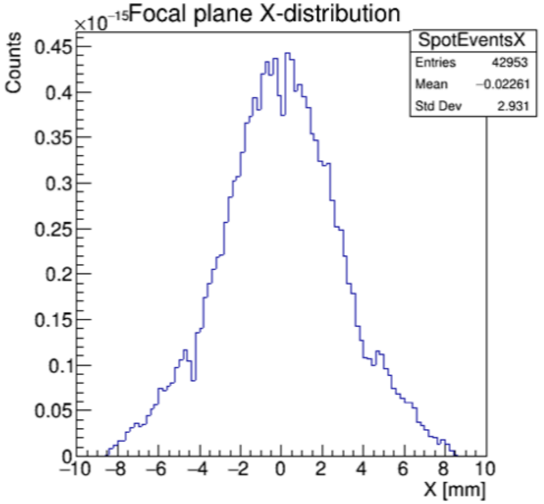
Run tag : Primakoff_XMM_Micromegas_Vacuum

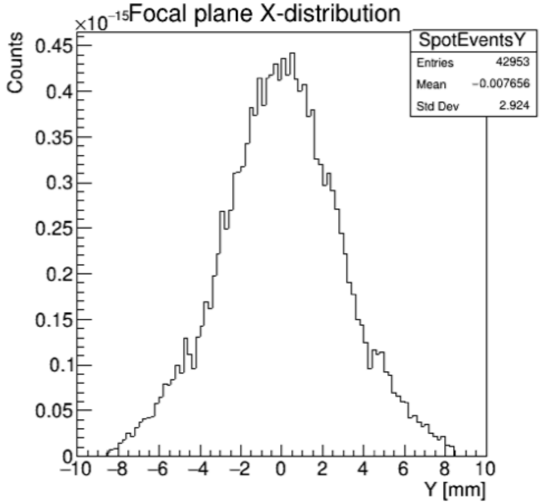
Entries : 100000









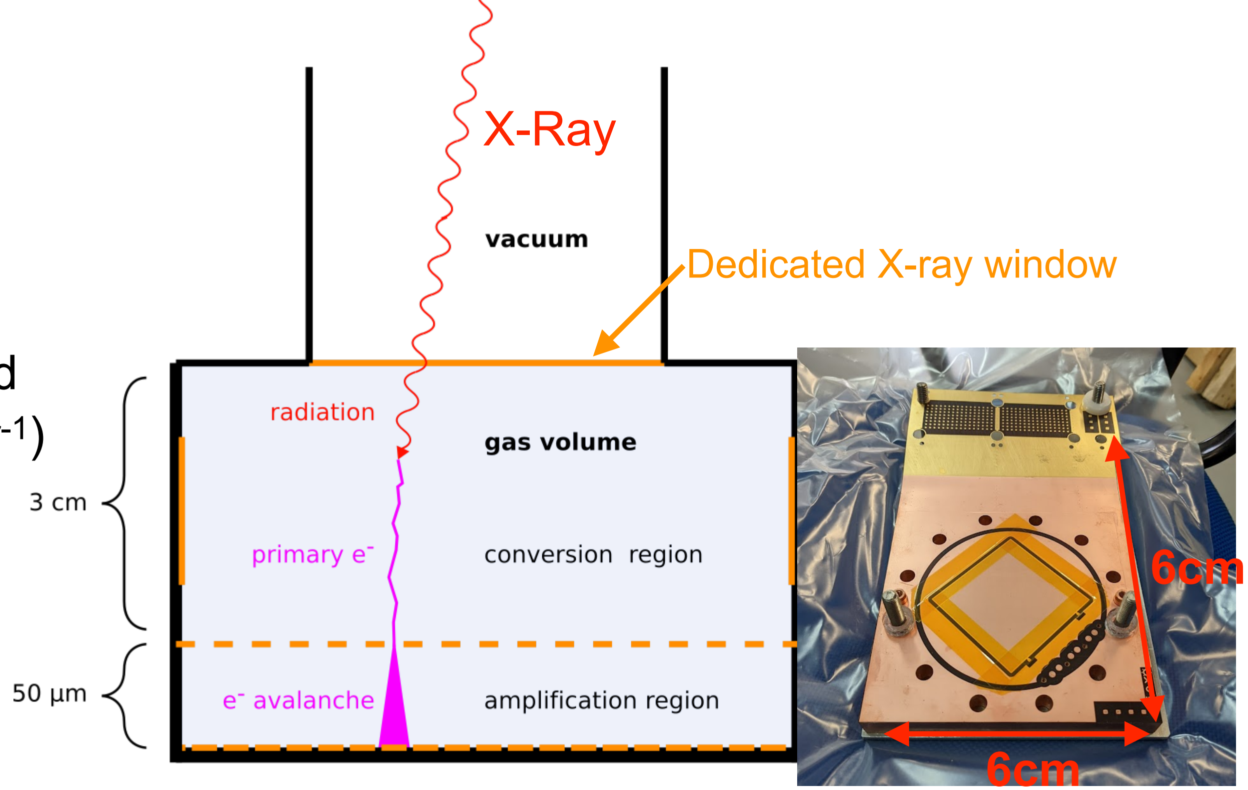


X-Ray Detectors

Complementary Technologies

Discovery:

- Requirements: High detection efficiency (1-10 keV) and ultra-low background levels (~1 photon keV^{-1} cm^{-2} $year^{-1}$)
- Baseline option: Micromegas (Micro-Mesh) TPC + shielding + veto systems



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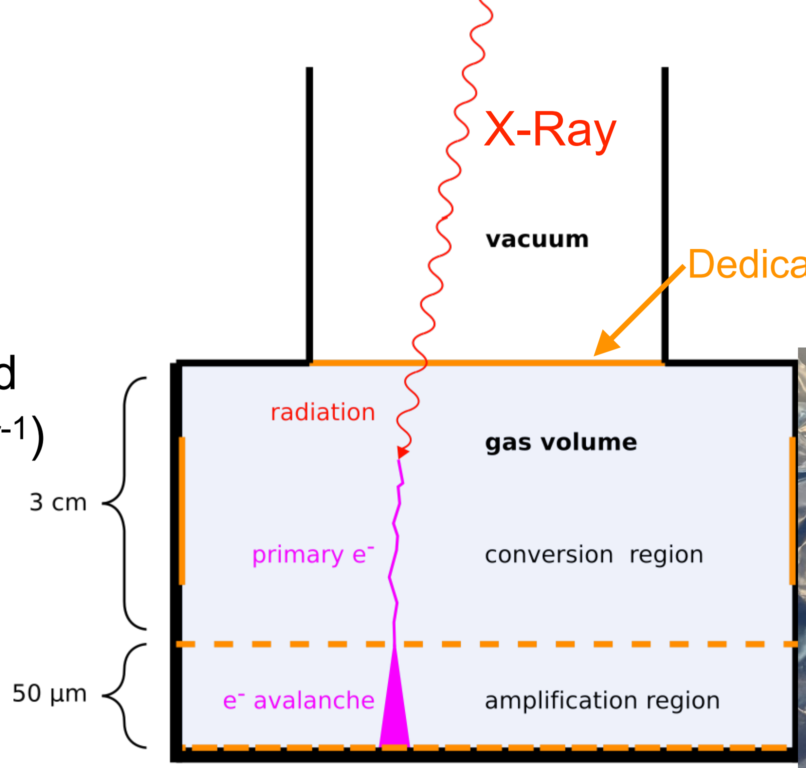

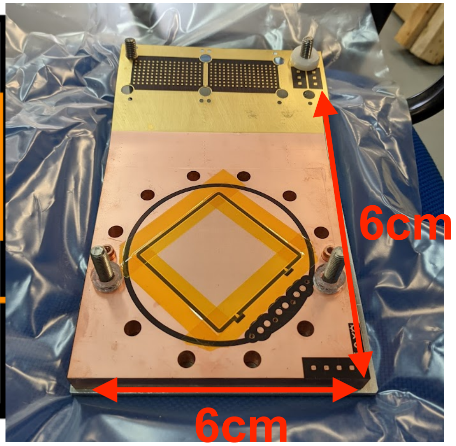

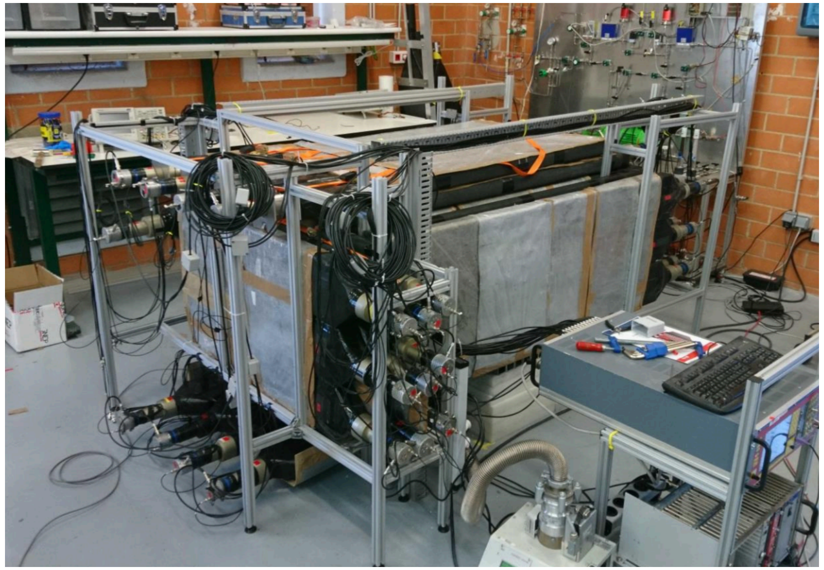

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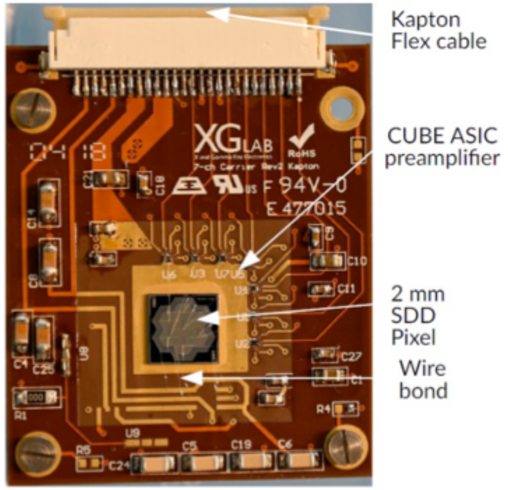
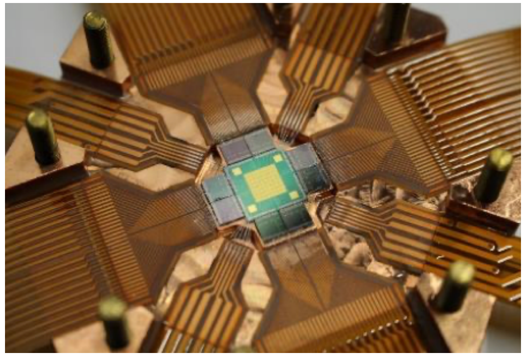
Precision / post-discovery:

- Better energy resolution: few eV - 100 eV
- Lower energy threshold: ~ 0.1 keV
  - ➡ Gridpix-TPC, SDD, MMC, TES
- Very active R&D ongoing: designs, materials, readout

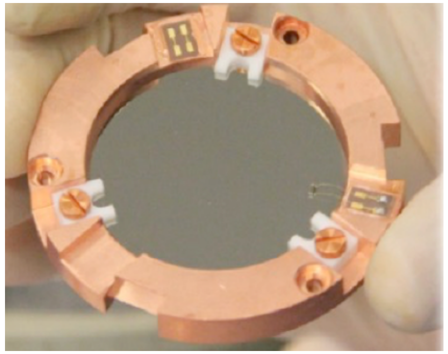


SDD: Silicon Drift Detectors (TUM)

GridPix (U. Bonn)



MMC: Metallic Magnetic Calorimeters (U. Heidelberg)

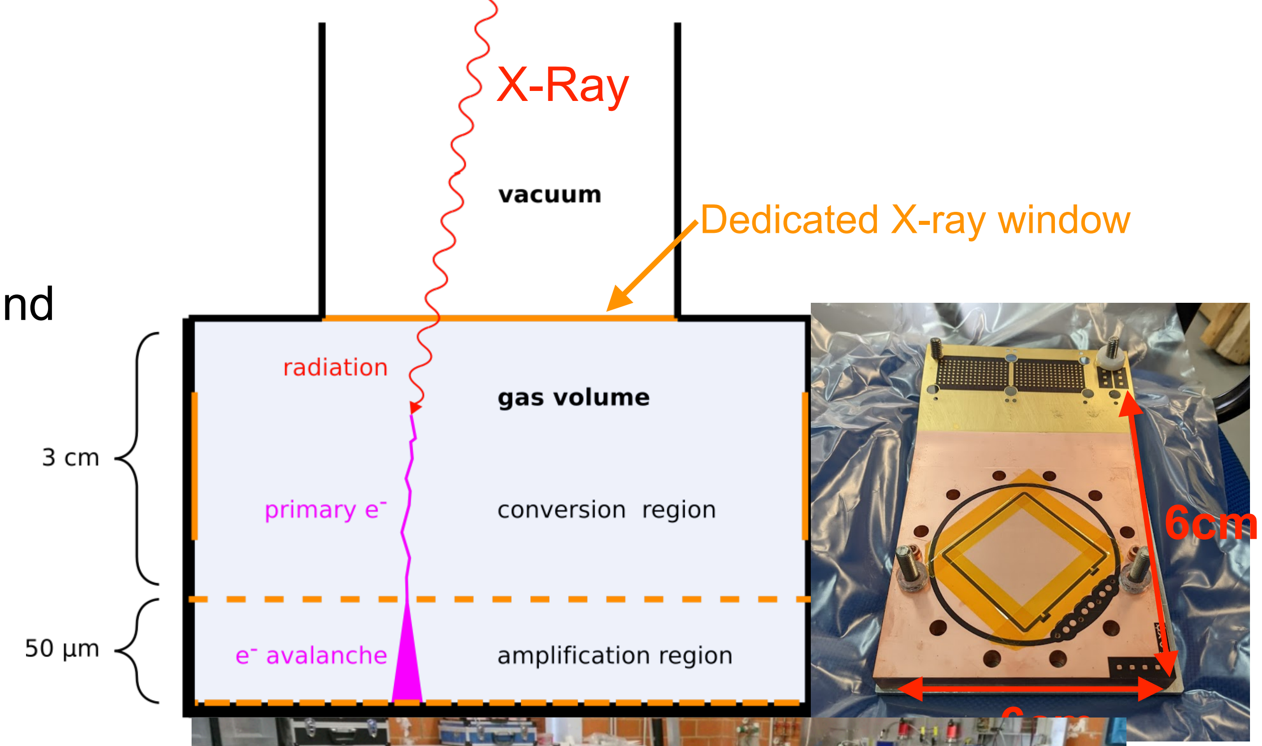


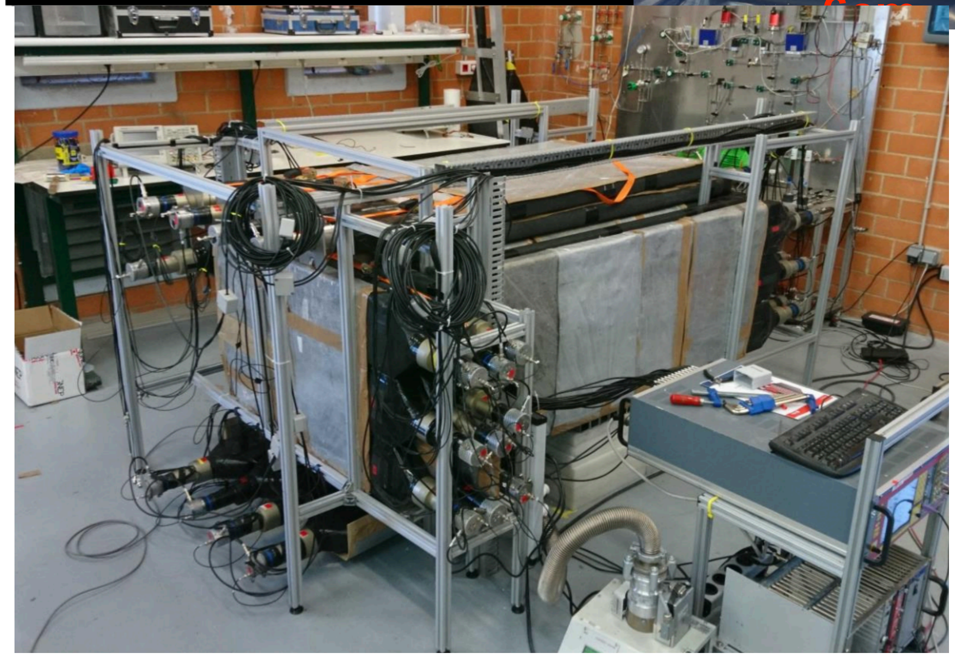
TES: Transition Edge Sensors (DESY/UHH + INMA-ICMAB CSIC)

X-Ray Detectors

Discovery Technologies

- Requirements: High detection efficiency (1-10 keV) and ultra-low background levels
- Baseline option: Micromegas (Micro-Mesh) TPC + shielding + veto systems
- Proven design (CAST) & extensive R&D:
  - ➡ 60-70% detection efficiency
  - ➡ Demonstrated BKG-level of $< 10^{-6}$ counts keV^{-1} cm^{-2} s^{-1} (32 photons per year)
    Goal: ~1 photon keV^{-1} cm^{-2} $year^{-1}$
  - ➡ Spatial resolution: ~100µm
  - ➡ Energy resolution: ~10% (FWHM, 5.9 keV ^{57}Fe)

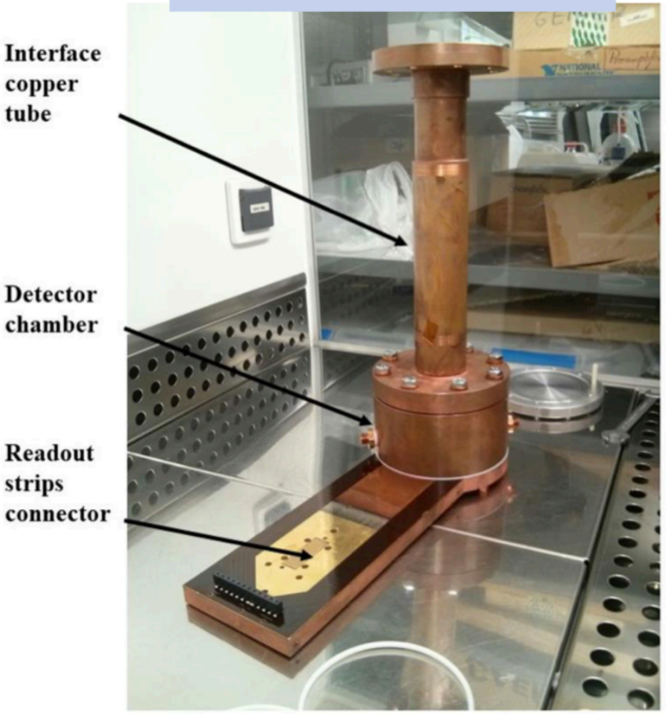




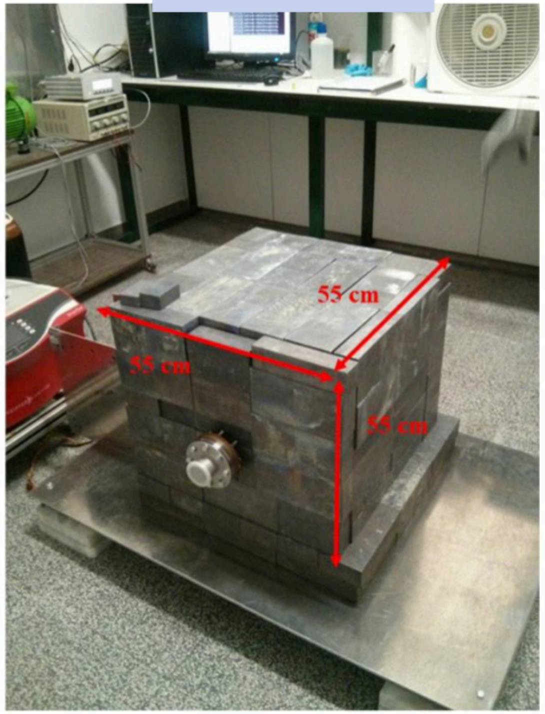
IAXO-D0: the Micromegas prototype at Unizar

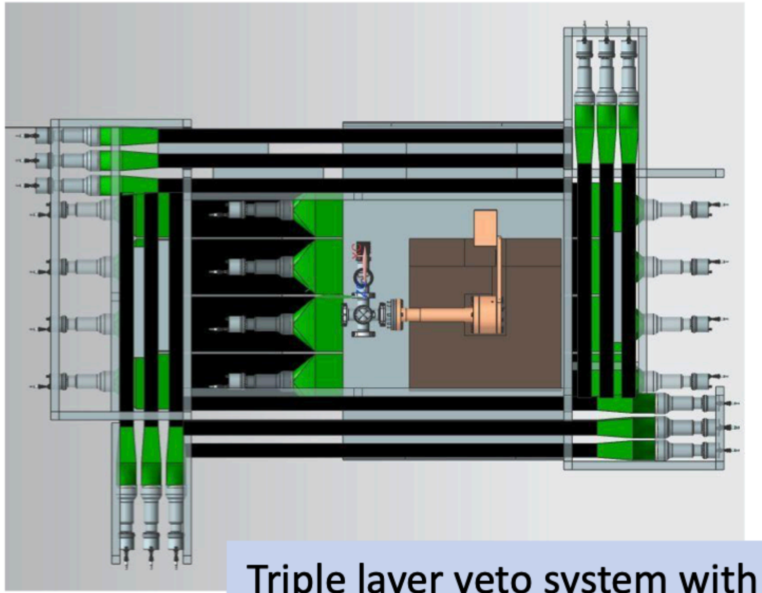
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Micromegas detector



Lead castle





Triple layer veto system with cadmium sheets to discriminate neutron background

In-Situ Background Measurements

And Detector System Integration

- **Goal BKG level: ~1 photon keV^{-1} cm^{-2} year^{-1}**

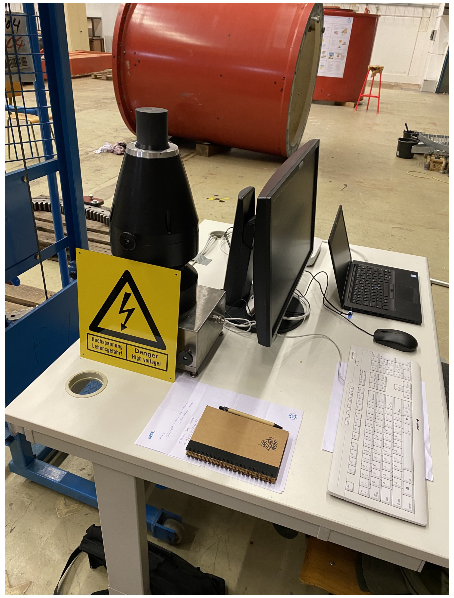
➡ Extensive background measurement campaigns at individual detector level

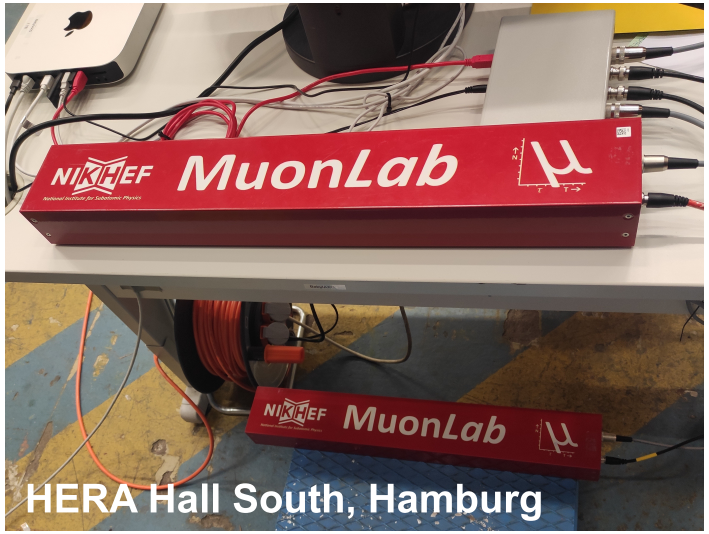
➡ Extrinsics (cosmics, radioactivity) vs. Intrinsics (internal radioactivity)

➡ In-situ background measurement campaigns in HERA hall south with small scale and prototype IAXO detectors

➡ Characterise local background sources and levels

➡ Full system level integration of detectors and BabyIAXO components for potential “dry runs” without magnet





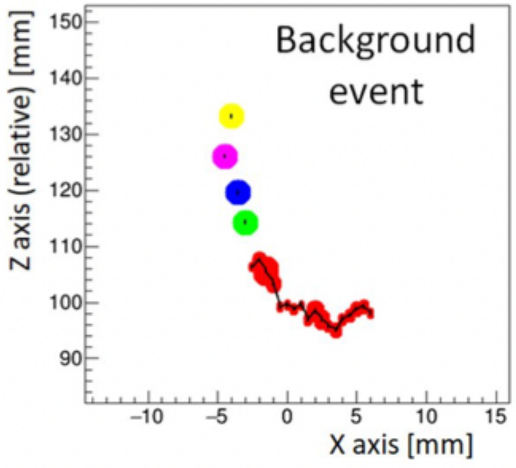
Background Simulation Campaigns

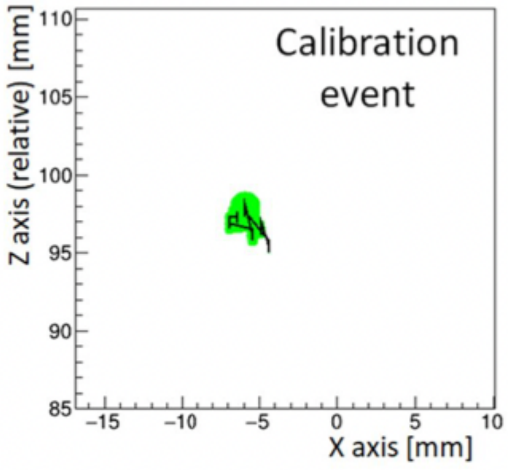
Distinguishing Signals and Background

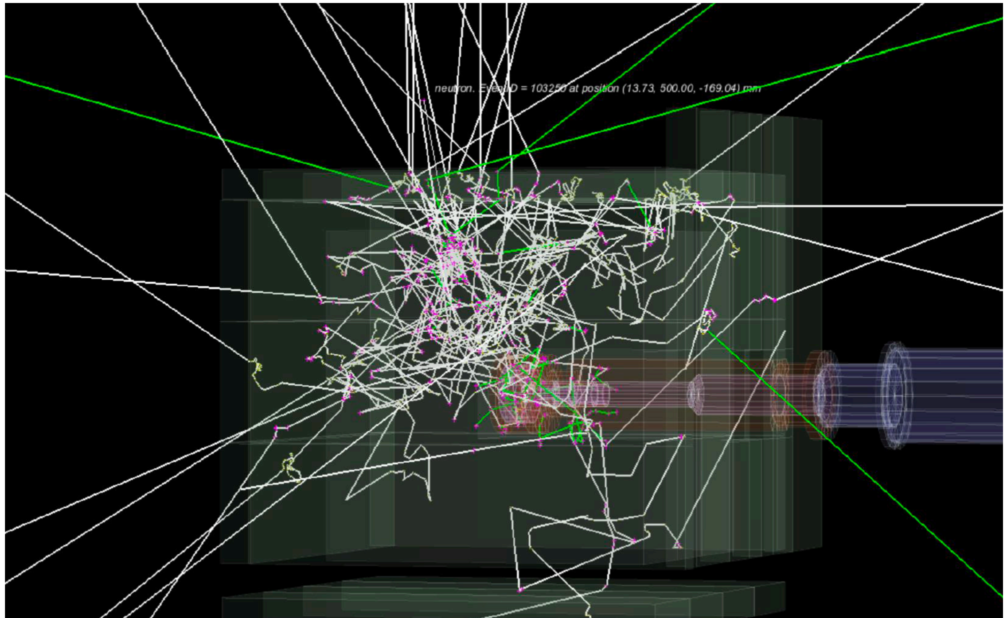
- Extensive MC Geant4 simulation campaigns with REST for different detector technologies and backgrounds
  - ➡ Characterise and quantify response by different backgrounds e.g. BKG induced by cosmic neutrons
  - ➡ More generic studies: distinguish BKG from signal events by topology, signal shape, timing,…
    - ➡ Machine learning algorithms

Studies are powered by REST-for-Physics (Rare Event Searches Toolkit) Framework for data analysis and Geant4 MonteCarlo simulation.

https://github.com/rest-for-physics







Simulated event in BabyIAXO Micromegas detector induced by a cosmic neutron

Coherence Gas Buffer Technique

Pushing the Sensitivity to high Axion Masses

"Massless" case $m_a < 20$ meV

$$P_{a\to\gamma} = \frac{g_{a\gamma}^2 B^2 L^2}{4}$$

Constant

Finite mass case $m_a > 20$ meV (IAXO)

$$P_{a\to\gamma} = \frac{g_{a\gamma}^2 B^2 L^2}{4} \times \frac{2(1-\cos(qL))}{(qL)^2}$$

Oscillates and rapidly drops with axion mass and L of conversion volume (Decoherence of axion and photon field)

Transfered momentum

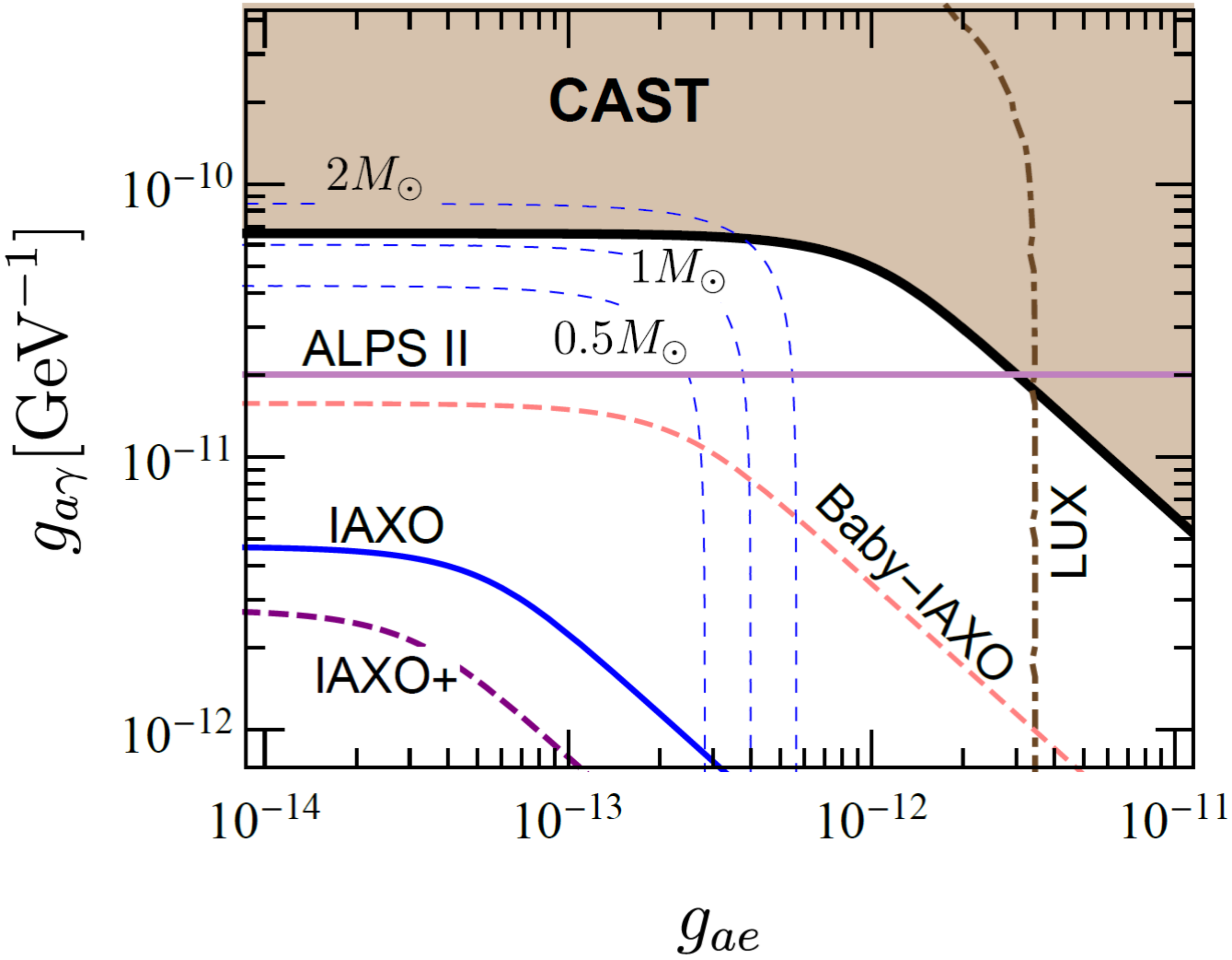
$$q = \frac{1}{2\omega}(m_a^2 - m_\gamma^2)$$

- Counter-act: Introduce a buffer gas in the magnetic bores
  - ➡ Introducing n and therefore a change in m_γ
  - ➡ Tune gas type & pressure: effective coherent conversion again for a specific m_a
- Scan with different pressure settings: extend m_a reach with high sensitivity to $g_{a\gamma\gamma}$
  - ➡ Successfully demonstrated in CAST and to be used in (Baby)IAXO as well
  - ➡ Limit: Condensation of gas in bore and X-ray absorption

Axion Search Sensitivity

Couplings

O. Straniero et al.



IAXO sensitive to axion – photon and axion – electron coupling, in contrast to light-shining-through-a-wall experiments and haloscopes

Simulation and Analysis Strategy

JCAP03(2019)039

IAXO Parameters

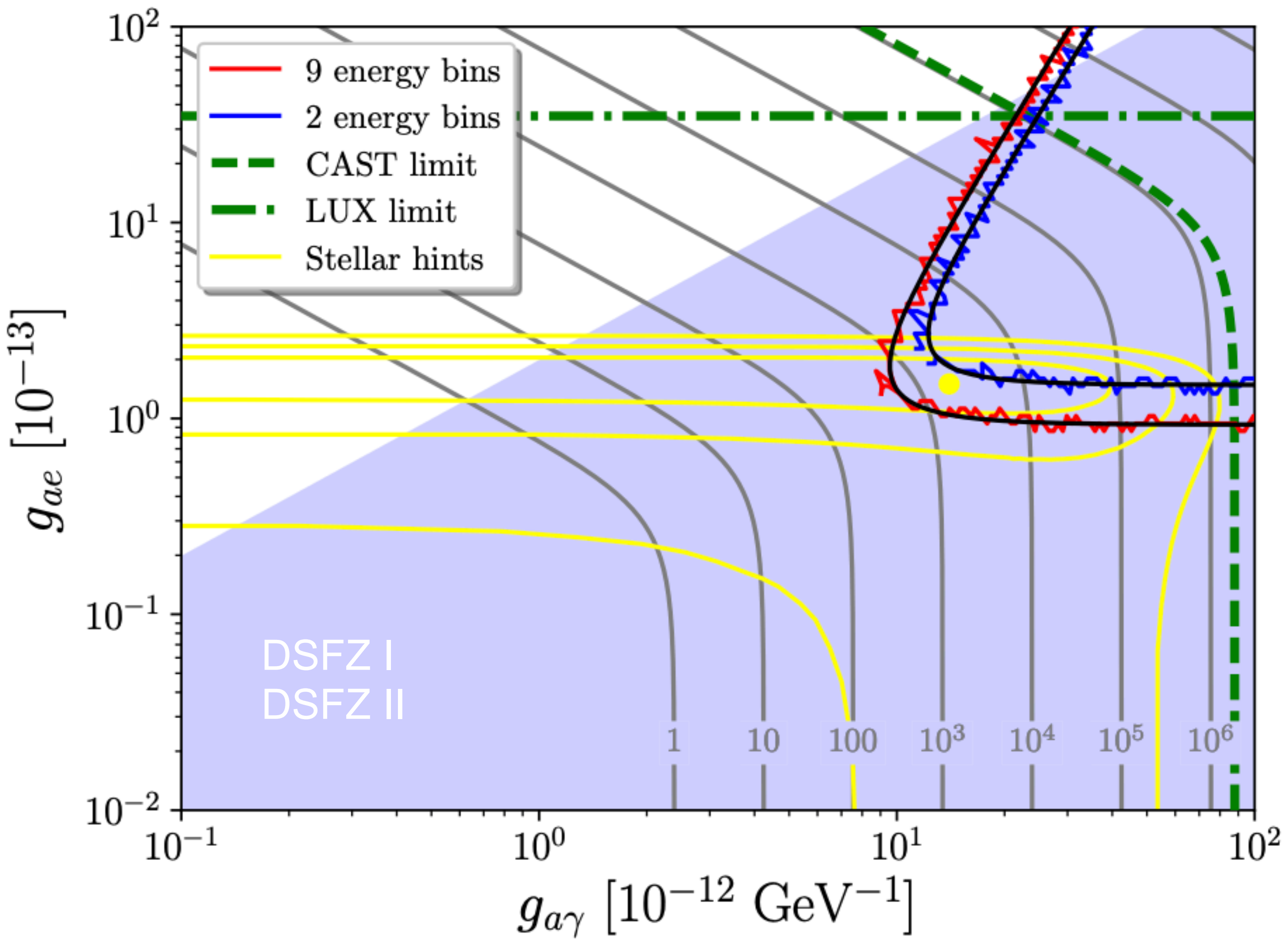
Parameter	Value
Magnetic field strength B	$2.8\,\mathrm{T}$
Length of conversion volume L	$20\,\mathrm{m}$
Cross-section of conversion volume A	$2\,\mathrm{m}^2$
Figure of merit (B^2L^2A)	$6272\,\mathrm{T}^2\,\mathrm{m}^4$ $(\sim 300 \times \mathrm{CAST})$
Total tracking time t	100 days
Bandwidth	(1–10) keV
Energy resolution $\Delta\nu$	1 keV
Inverse absorption length Γ	0 (vacuum)
Efficiency of telescope Q	0.5
Background level	$10^{-7}\,\mathrm{keV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$
Detector area A_{detect}	$1\,\mathrm{cm}^2$

Results: Low Mass Axions + Baseline IAXO

JCAP03(2019)039

Coherent Axion-Photon Conversion

- Large unexplored parameter space beyond CAST limits accessible
- Best fit for stellar hints accessible with 1 keV energy resolution (red) IAXO detectors
- Large parameter space in DSFZ I and II models accessible
  - ➡ Other models can be confronted as well with model-independent analysis



Results: Low Mass Axions + Baseline IAXO

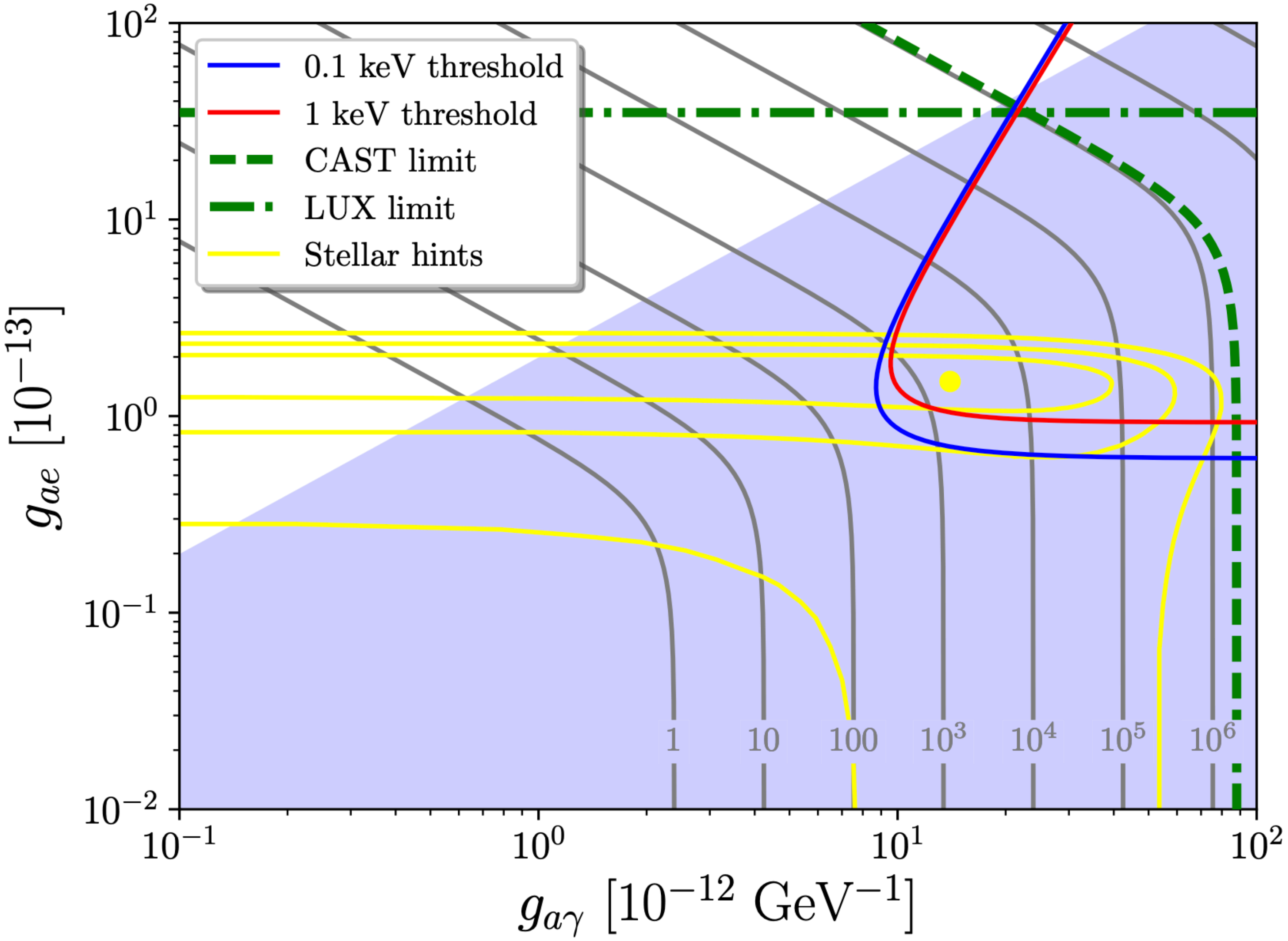
JCAP03(2019)039

Coherent Axion-Photon Conversion

- Lower energy threshold helps to increase sensitivity to softer X-rays from electron processes

- Increased energy resolution is also expected to improve resolving sensitivity limits
  - ➡ Soft vs. harder X-rays and resolving peaks?

➡ IAXO SDD, MMC, TES, Gridpix!

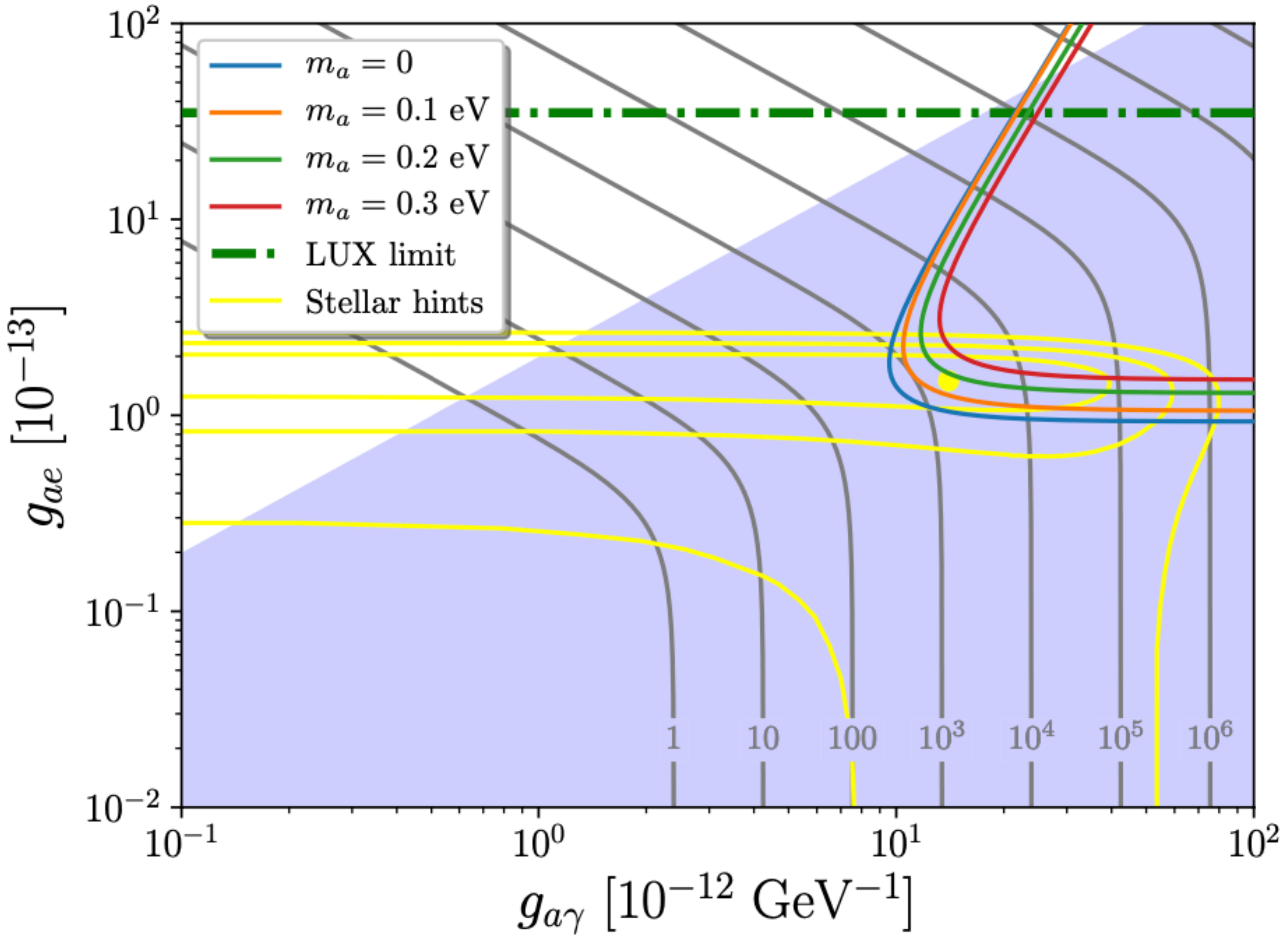


Results: Massive Case

JCAP03(2019)039

Increasing Decoherence in Axion-Photon Conversion

➡ Lower sensitivity due to higher photon absorption with increasing gas pressure (higher m_a)



Simulation and Analysis Strategy

JCAP03(2019)039

Overview

Measured energy spectrum of photons in helioscope:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}\omega} = Q(\omega) P_{a\to\gamma}(\omega) \frac{\mathrm{d}\Phi_a}{\mathrm{d}\omega}.$$

Combined efficiencies of X-ray window, optics & detectors

Axion-photon conversion probability (shown before) depending on magnet and $\propto g_{a\gamma\gamma}^2$

Solar axion energy spectrum calculated in detail: $\propto g_{a\gamma\gamma}^2$ and $\propto g_{ae}^2$

- Use Poisson statistics to simulate a binned signal for IAXO
  - ➡ Inputs I: numerical values from solar axion spectrum and helioscope parameters
  - ➡ Inputs II: g_{ae} between 10^{-15} - 10^{-10} GeV^{-1} and adapt $g_{a\gamma\gamma}$ to keep the same number of events
- Recover the two couplings by using a maximum likelihood method (likelihood-ratio test)
  - ➡ For each value 95% certainty interval for g_{ae} calculated
  - ➡ Couplings defined as resolved if relative error on g_{ae} < 10%

Results: Massive Case

JCAP03(2019)039

Increasing Decoherence in Axion-Photon Conversion

- If finite axion mass: decoherence effect
  - ➡ Gas buffer technique to counteract
  - ➡ Allows to measure m_a in addition for specific ranges!
  - ➡ **But:** photon absorption: lower number of events and therefore sensitivity to individual couplings

#	m_a	Detection	m_a resolved	$(g_{a\gamma}, g_{ae})$ resolved	Method
0	$\lesssim 2\,\mathrm{meV}$	✓	✗	✓	vacuum only
1	$\sim(2\text{–}5)\,\mathrm{meV}$	✓	✓	✓	on/off resonance
2	$\sim(5\text{–}20)\,\mathrm{meV}$	✓	✓	✓	vacuum only
3	$\sim(20\text{–}200)\,\mathrm{meV}$	✓	✓	✓	scanning m_γ
4	$\sim(0.2\text{–}1)\ \mathrm{eV}$	✓	✓	✗	scanning m_γ
5	$\gtrsim 1\,\mathrm{eV}$	✗	✗	✗	-

Example for:
$g_{a\gamma\gamma}$ = 10^{-11} GeV^{-1}
g_{ae} = 10^{-13} GeV^{-1}

➡ **For a broad range of $g_{a\gamma\gamma}$, g_{ae} and m_a: individual measurements possible! Info about axion model!**

Studied Experimental Setups

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

Optimising for 14.4 keV photons

Label	BabyIAXO				IAXO		IAXO+	
	Baseline $BabyIAXO_0$	No optics $BabyIAXO_1$	Optimized optics $BabyIAXO_2$	High energy resolution $BabyIAXO_3$	Low background $IAXO_b$	High energy resolution $IAXO_r$	Low background $IAXO_b^+$	High energy resolution $IAXO_r^+$
B [T]	2	2	2	2	2.5	2.5	3.5	3.5
L [m]	10	10	10	10	20	20	22	22
A [m^2]	0.77	0.38	0.38	0.38	2.3	2.3	3.9	3.9
t [year]	0.75	0.75	0.75	0.75	1.5	1.5	2.5	2.5
$b\ [\frac{1}{\mathrm{keVcm^2s}}]$	10^{-7}	10^{-6}	10^{-7}	10^{-5}	10^{-8}	10^{-6}	10^{-9}	10^{-6}
ϵ_d	0.15	0.9	0.5	0.99	0.99	0.99	0.99	0.99
ϵ_0	0.013	1	0.3	0.3	0.3	0.3	0.3	0.3
a [cm^2]	0.6	3800	0.3	0.3	1.2	1.2	1.2	1.2
$r_\omega = \frac{\Delta E_d}{14.4\,\mathrm{keV}}$	0.12	0.12	0.12	0.02	0.02	$\frac{5}{14400}$	0.02	$\frac{5}{14400}$

Sensitivity Estimates and Backgrounds

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

How to Optimise Sensitivity

- Two type of background in signal bin (14.4 keV) expected:
  - ➡ Conventional backgrounds: cosmics, radioactivity
  - ➡ Primakoff photons

Efficiencies of X-ray optics and detectors

Figure of merit:

$$f \propto \frac{S}{\sqrt{B}} \propto \frac{\epsilon_o \epsilon_d \, g_{a\gamma}^2}{\sqrt{\Delta E_d}\sqrt{ba + g_{a\gamma}^4 \kappa \epsilon_o \epsilon_d}}$$

Quantifying Primakoff background flux

Energy resolution of X-ray detectors

Signal spot area after focusing

Conventional background rate per area

Studied Experimental Setups

Optimised for 14.4 keV photons

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

Label	BabyIAXO				IAXO		IAXO+	
	Baseline	No optics	Optimized optics	High energy resolution	Low background	High energy resolution	Low background	High energy resolution
	$\mathrm{BabyIAXO}_0$	$\mathrm{BabyIAXO}_1$	$\mathrm{BabyIAXO}_2$	$\mathrm{BabyIAXO}_3$	IAXO_b	IAXO_r	$\mathrm{IAXO}_\mathrm{b}^+$	$\mathrm{IAXO}_\mathrm{r}^+$

No optics, full coverage of magnetic bore with a Micromegas gas detectors (high pressure Xenon)

Optimised optics (14.4 keV) and SDD

Optimised optics and Cadmium-Zinc-Telluride semiconductor detector (Optimised to ~14.4 keV)

$\mathrm{IAXO}_\mathrm{b}^{(+)}$: benchmark configuration parameters + fully optimised optics

$\mathrm{IAXO}_\mathrm{r}^{(+)}$: benchmark configuration parameters + fully optimised optics + per-mille level energy resolving detectors (MMCs)

Analysis Strategy

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

Determining Sensitivity Limits for g_{aN}^{eff} vs. $g_{a\gamma\gamma}$

Expected number of signal events: $\mu_{\text{signal}} = \Phi_a \, P_{a\to\gamma} \, A \, t \, \epsilon_o \, \epsilon_d \quad \propto (g_{a\gamma} \, g_{aN}^{\text{eff}})^2$

Expected number of background events: $\mu_{\text{back}} \simeq \left(g_{a\gamma}^4 \kappa \epsilon_o \epsilon_d + ba \right) \Delta E_d t$

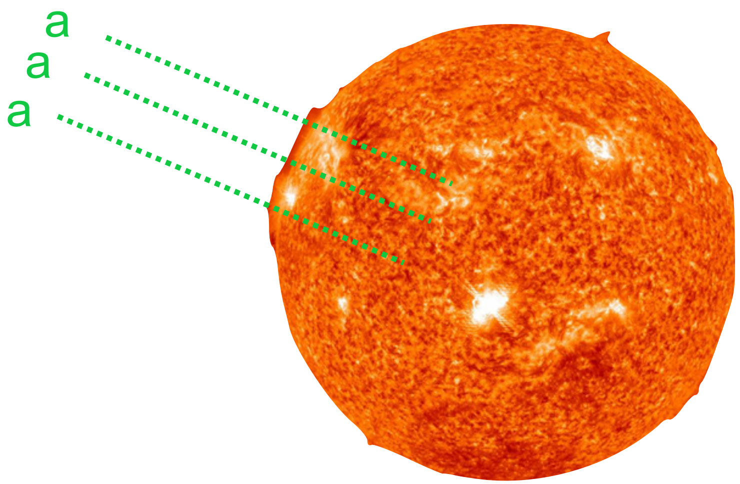
- Scan all combinations of $g_{a\gamma\gamma}$ and g_{aN}^{eff} and calculate $\mu = \mu_{signal} + \mu_{back}$
  - ➡ Assume Poisson distribution of counts in signal bin and calculate expectation value of p (only background hypothesis)
  - ➡ If <p> < 0.05 (2 sigma anomaly) sensitivity to $g_{a\gamma\gamma}$ and g_{aN}^{eff} is claimed

Solar Axions from Nuclear Processes

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

Model Dependencies and Fluxes

- If axions couple to nucleons, production via nuclear processes within the Sun (fusion, nuclear transitions)
  - ➡ Flux dependent on solar model (T_{core}, isotope abundance, τ of excited states, occupation numbers,…)
  - ➡ Most promising candidate: M1 transition of ^{57}Fe at 14.4 keV
  - ➡ Monochromatic: natural line width << Doppler broadening (~2 eV)



- Total flux dependent on axion model (g_{aN})
  - ➡ Example: $$\left.\frac{\Gamma_a}{\Gamma_\gamma}\right|_{\mathrm{KSVZ}} = 5.81 \times 10^{-16} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^2$$

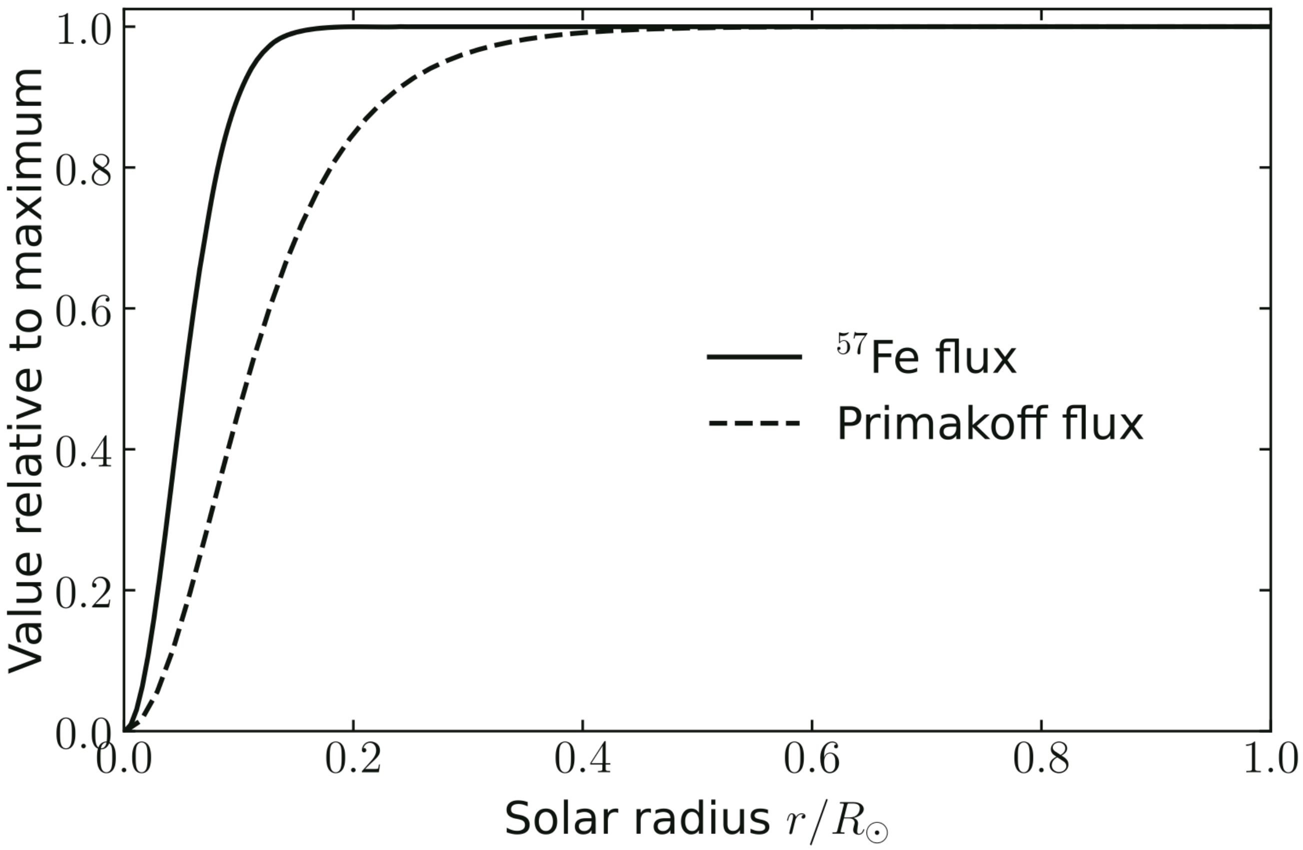
- Fixing a solar model (B16-AGSS09) and calculating the monochromatic solar axion flux of ^{57}Fe:

$$\Phi_a = 5.06 \times 10^{23} \left(g_{aN}\right)^2 cm^{-2}\ s^{-1}$$

Solar Axions from Nuclear Processes

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

Model Dependencies and Fluxes



Solar model: B16-AGSS09

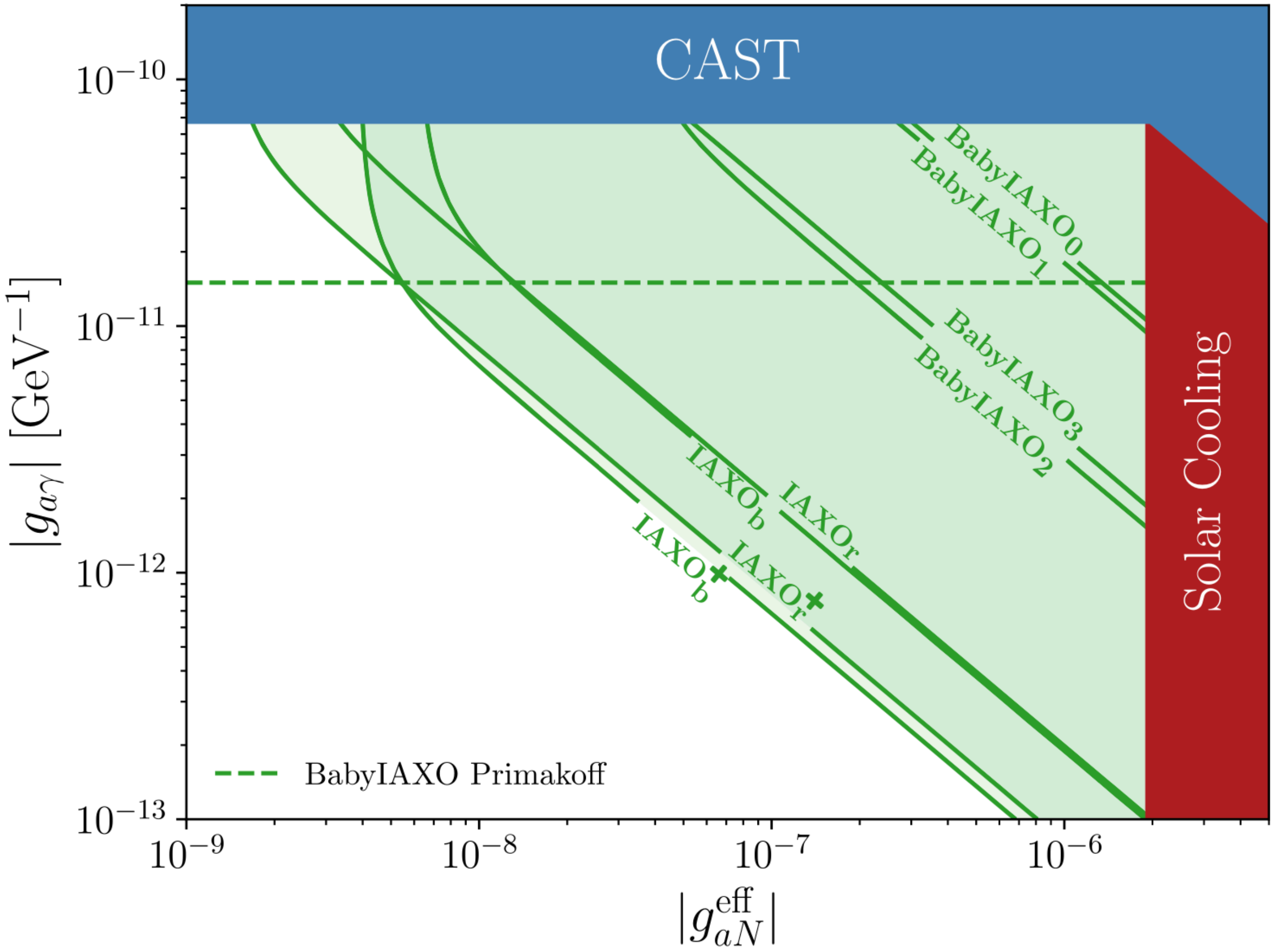
- A precise measurement of the 14.4 keV solar axion rate will allow to:
  - ➡ Determine g_{aN} (next to an individually determined $g_{a\gamma\gamma}$ in the best case) and therefore help to constrain the underlying BSM model
- A spatial measurement of the 14.4 keV solar axion rate will allow to:
  - ➡ Take X-ray images of the sun and help to test different solar models

Results: Low Mass Axions

Coherent Axion-Photon Conversion

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

- BabyIAXO will probe unexplored parameter space beyond solar and CAST bounds
- If axions have couplings above green dashed line: individual determination of $g_{a\gamma\gamma}$ and g_{aN} possible for BabyIAXO
- If axions have couplings below green dashed line, axions from ^{57}Fe might be detected before Primakoff axions

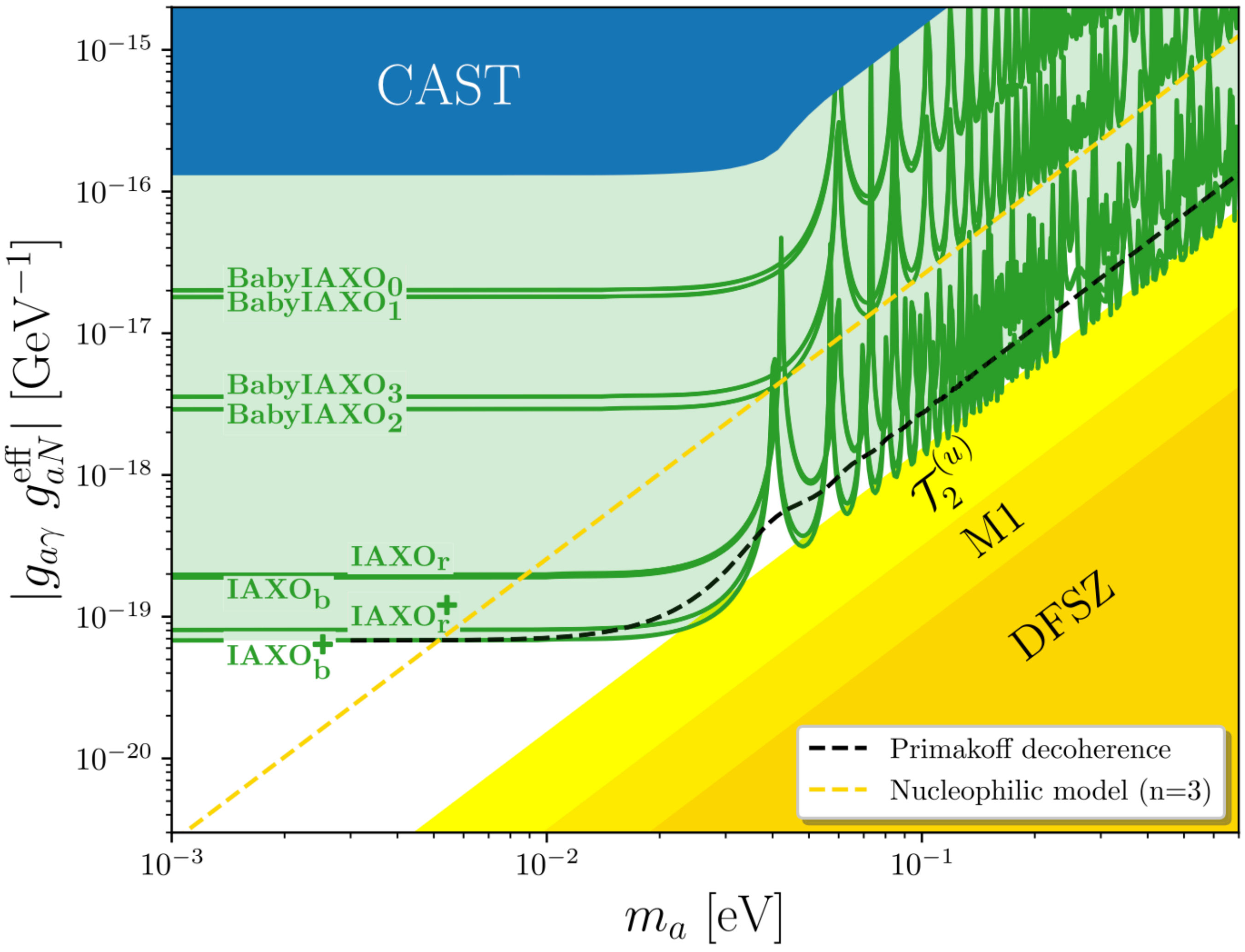


Results: Massive Case

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

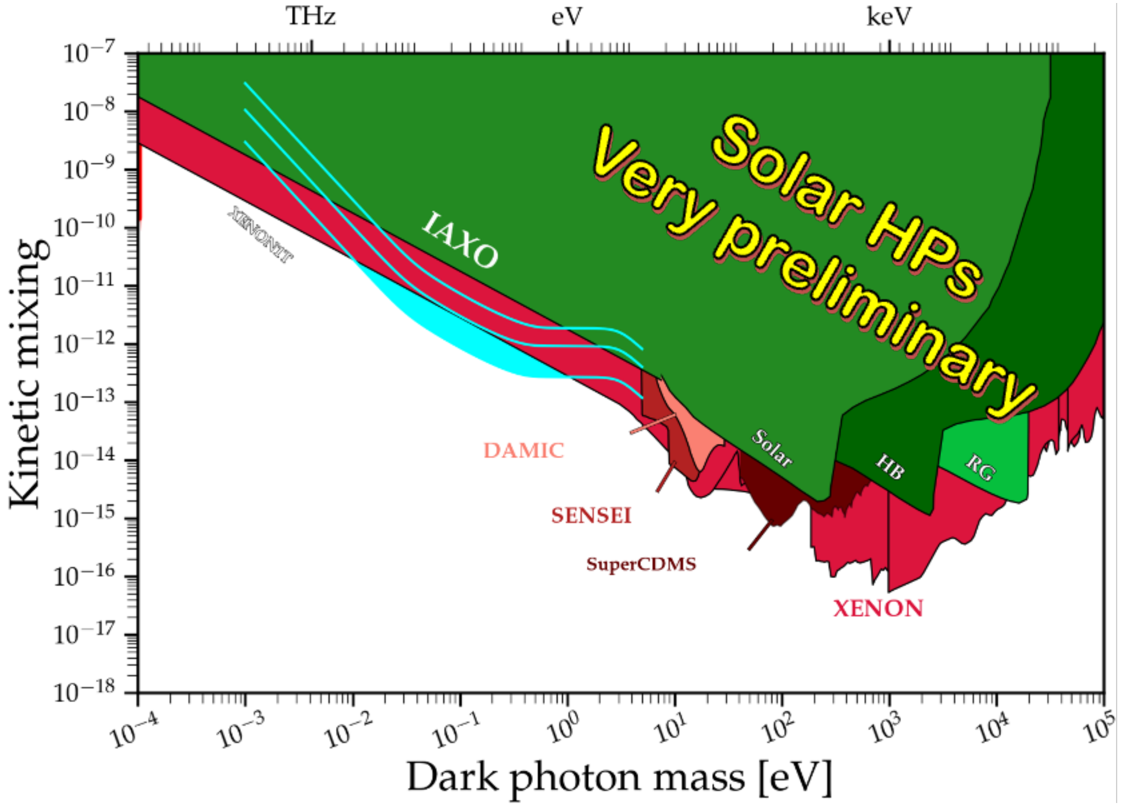
Increasing Decoherence in Axion-Photon Conversion

- Worst case scenario shown: increasing decoherence with increasing m_a (no gas buffer technique)
- Still BabyIAXO will explore new parameter space and might see axions described by nucleophilic models
- IAXO and IAXO+ will dig deeper in parameter space

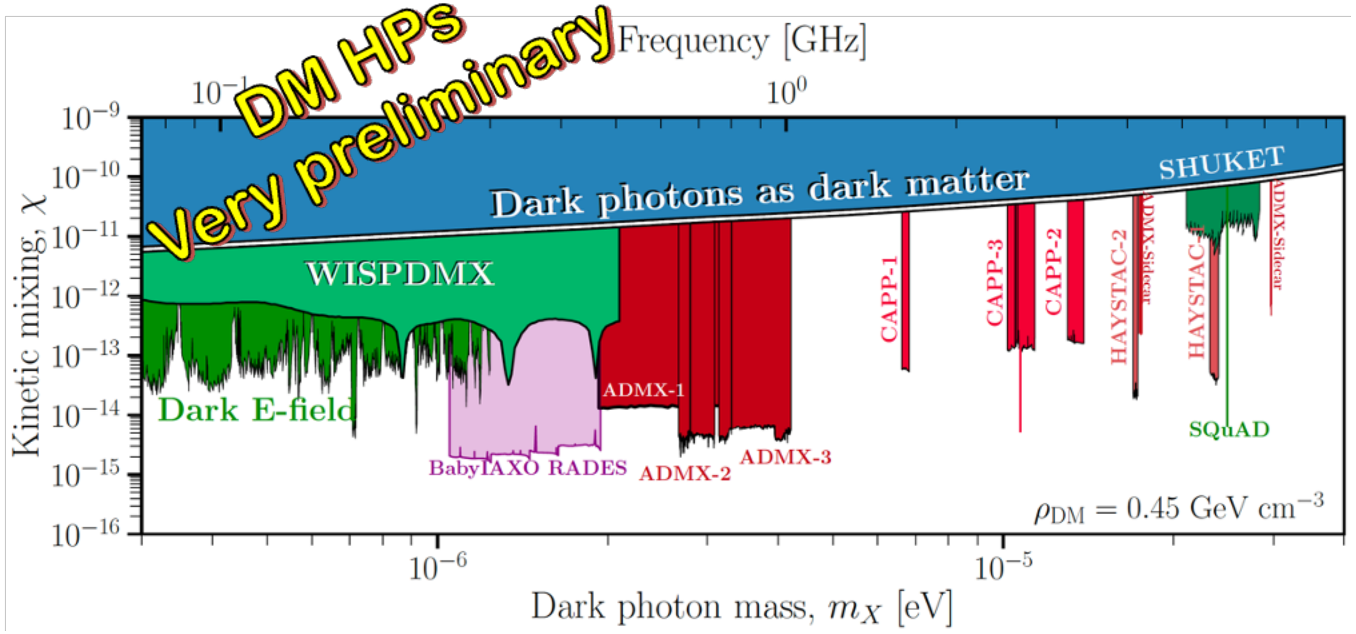


Hidden photons at IAXO

- **Search for hidden photons, both solar and DM. Same configuration as with axions but without B-field.**



Computed by T. O'shea. Paper in preparation…



Computed by C. Cogollos. Paper in preparation…

Backup

Haloscopes

Axions of Cosmic Origin

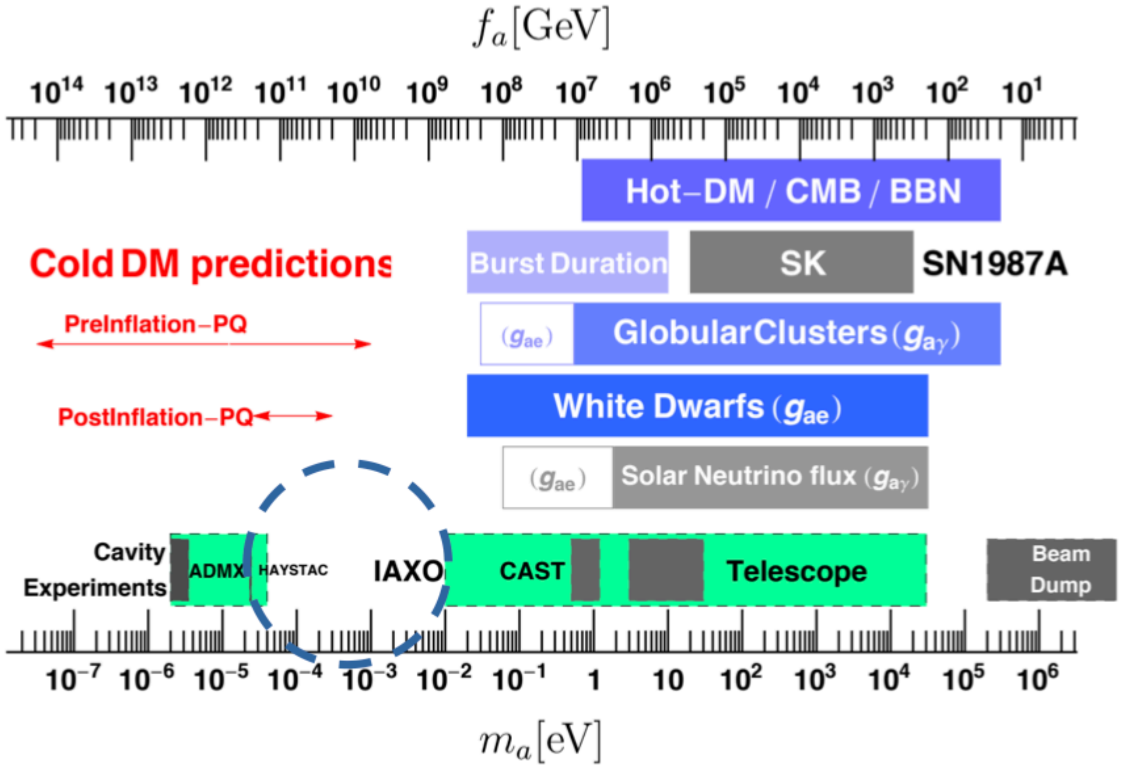
Thanks to Todd Kozlowski!

Axions as Cold Dark Matter

- pre-inflationary PQ-symmetry breaking scenario:
  - allows entire CDM to be cold axions with mass below ~ 500 µeV
- post-inflationary PQ-symmetry breaking scenario:
  - average of local variations in initial misalignment
  - complicated by topological defects, but nevertheless motivates a mass range:

$$26\ \mu eV < m_a < 1\ meV$$

- a **window of opportunity** appears around **~ 100 µeV** to search for axion CDM from either scenario



MADMAX Collaboration., Brun, P., Caldwell, A. *et al.* A new experimental approach to probe QCD axion dark matter in the mass range above 40µeV. *Eur. Phys. J. C* 79, 186 (2019).

MAgnetized Disk and Mirror Axion eXperiment

Thanks to Todd Kozlowski!

A Dielectric Haloscope

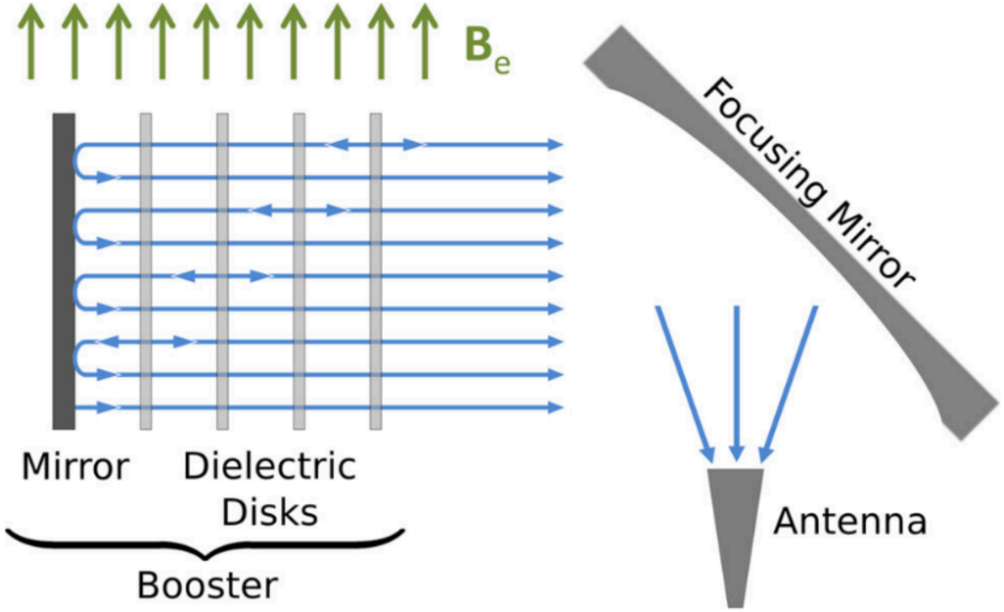
- generates an axion-induced electromagnetic wave from the **E-field discontinuity at the disk's dielectric boundary** in a magnetic field:

$$P_0 = 2.2 \times 10^{-27}\mathrm{W} \left(\frac{A}{1\ \mathrm{m}^2}\right) \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right) C_{a\gamma}^2$$

- adding multiple dielectric media leads to a tunable "boost" factor, where the emissions from the different surfaces sum constructively:

$$P = P_0 \cdot \beta^2(\nu) = 1.1 \times 10^{-22}\ \mathrm{W} \left(\frac{\beta^2(\nu)}{5 \times 10^4}\right) \left(\frac{A}{1\ \mathrm{m}^2}\right) \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right) C_{a\gamma}^2$$

- boost factor tunable via the disk separations, in order to scan sensitivity to the axion dark matter mass



Egge, J., Knirck, S., Majorovits, B. et al. Eur. Phys. J. C 80, 392 (2020).

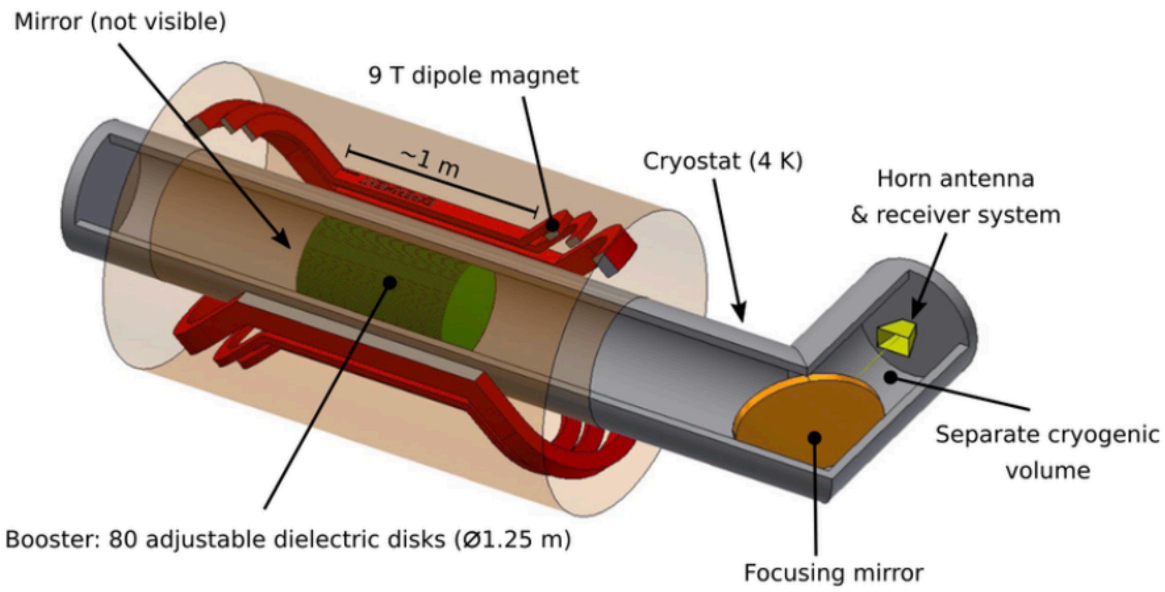
Graphic courtesy of Christoph Krüger

MAgnetized Disk and Mirror Axion eXperiment

Thanks to Todd Kozlowski!

MADMAX Design Concept

- arrangement of 80x 1.25 m diameter dielectric disks placed inside a purpose-built superconducting 9 T wide-bore magnet
- each dielectric disk (6 kg) need to be positioned to 10 µm accuracy to allow the electromagnetic fields to add coherently and optimize the boost factor
- entire detector is cryogenically cooled (4 K) to reduce background and improve sensitivity
- optimized to probe in the range of $m_a \sim 100$ µeV down to contemporary models



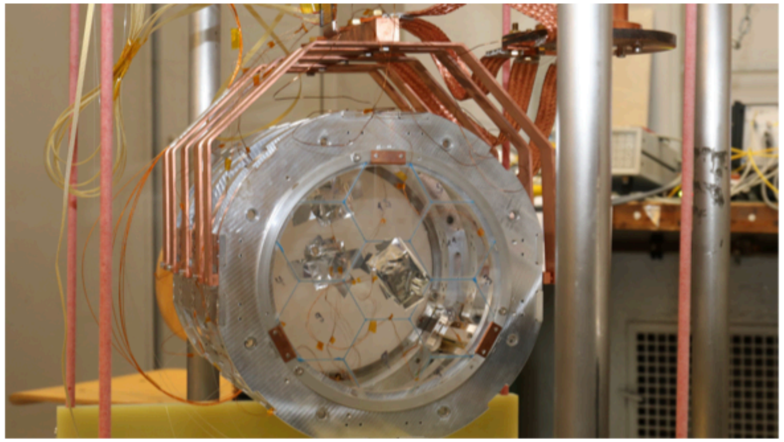
Xiaoyue Li and for the MADMAX Collaboration (2020) J. Phys.: Conf. Ser. 1468 012062

Images courtesy of: https://madmax.mpp.mpg.de/ and Alberto Martini

Phased Prototypes and R&D

Closed Boosters

- CB100: 3 x fixed ⌀100mm Al_2O_3 disks
  - **initial measurements** in CERN MORPURGO magnet (pictured)
  - test read-out electronics, booster modeling, noise
- CB200: 3 x fixed ⌀200mm Al_2O_3 disks
  - **under development** to investigate scaling



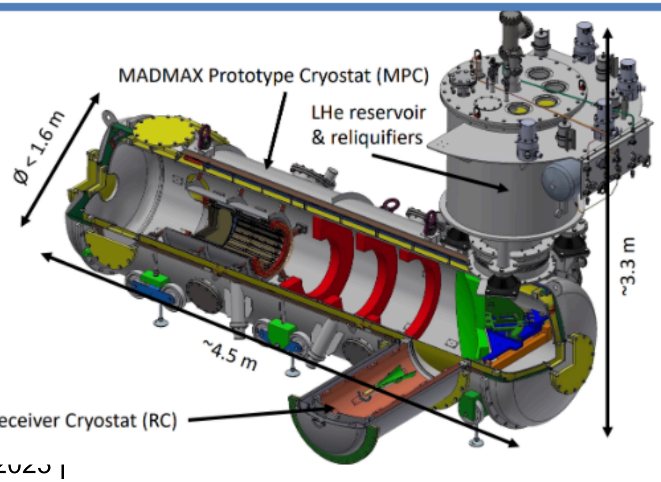
Open Boosters

- OB200: 2 x adjustable ⌀200mm Al_2O_3 disks
  - testbed for mechanical disk positioners (pictured)
  - linear motors **successfully tested** in 5 K / 5.3 T / UHV @ DESY
- OB300: 3 x adjustable ⌀300mm disks
  - under construction, room temp. end of year, cryo 2024-2025

E. Garutti *et al* 2023 *JINST* 18 P08011

MADMAX Prototype Cryostat

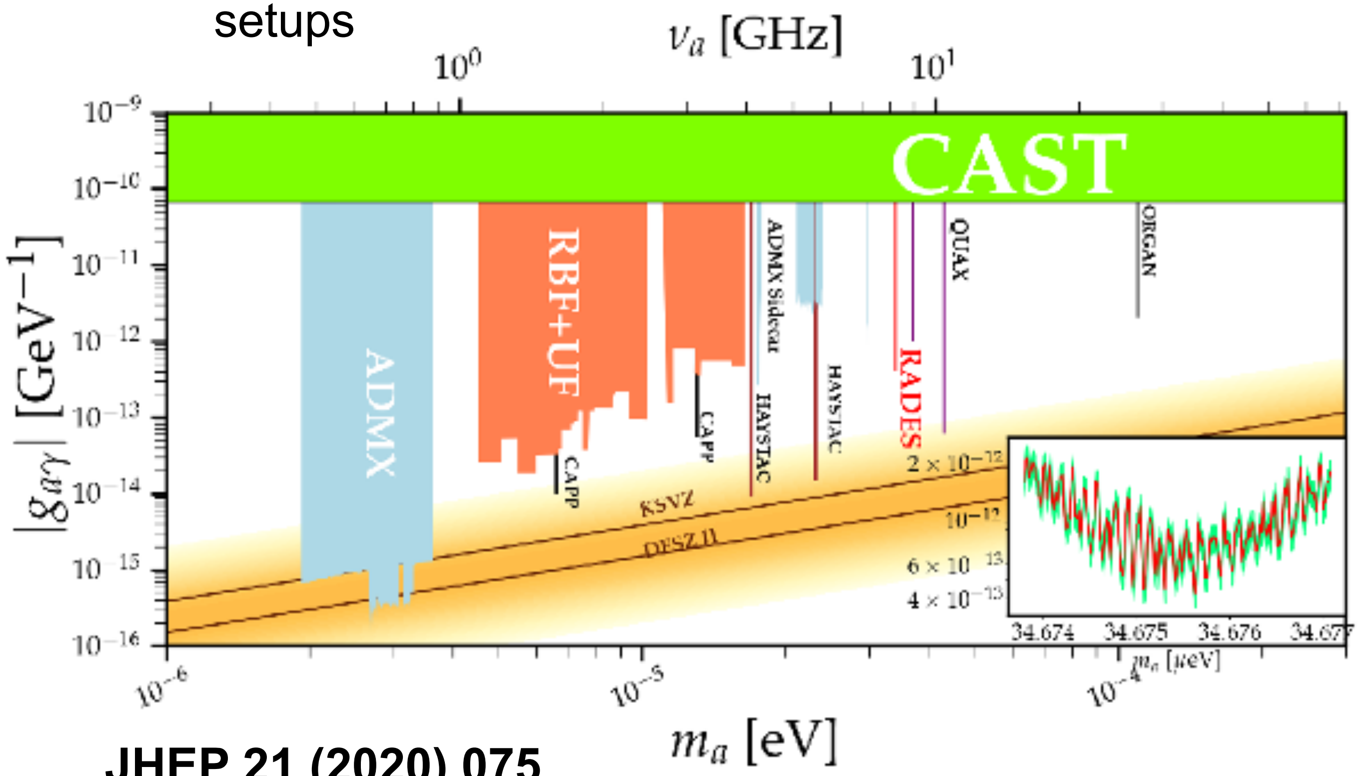
- Prototype liquid helium (4 K) cryostat
- ⌀760mm large bore to accommodate all prototype booster designs
  - fits into MORPURGO magnet bore
- **to be delivered / commissioned @ DESY 2024**



RADES

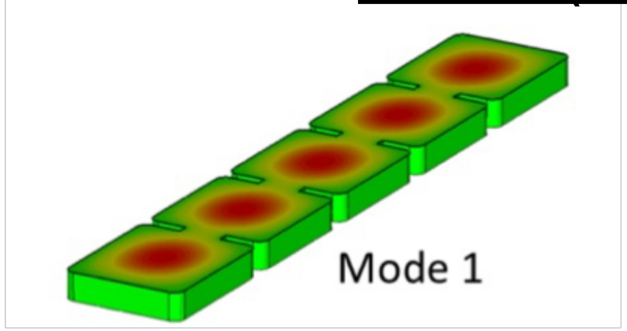
Helioscope as Haloscope Project

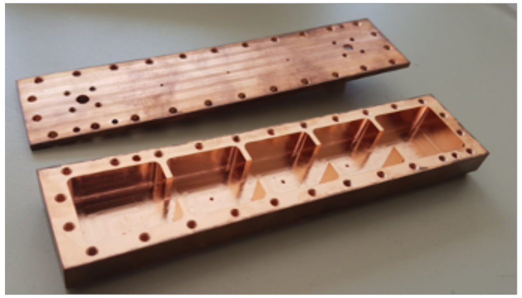
- During late years in the CAST experiment the RADES project emerged
  - ➡ Reuse the magnetic volumes of helioscope for haloscope searches by integrating resonant cavity setups



JHEP 21 (2020) 075

JCAP 05 (2018) 040





- Single frequency point measurement at 37 μeV in the CAST experiment

- Developments continued after CAST times
  - ➡ Optimising geometries of cavities
  - ➡ Improving coating for improving boost factor, etc.

BabyIAXO - Haloscope Mode

Preliminary Projected Sensitivities

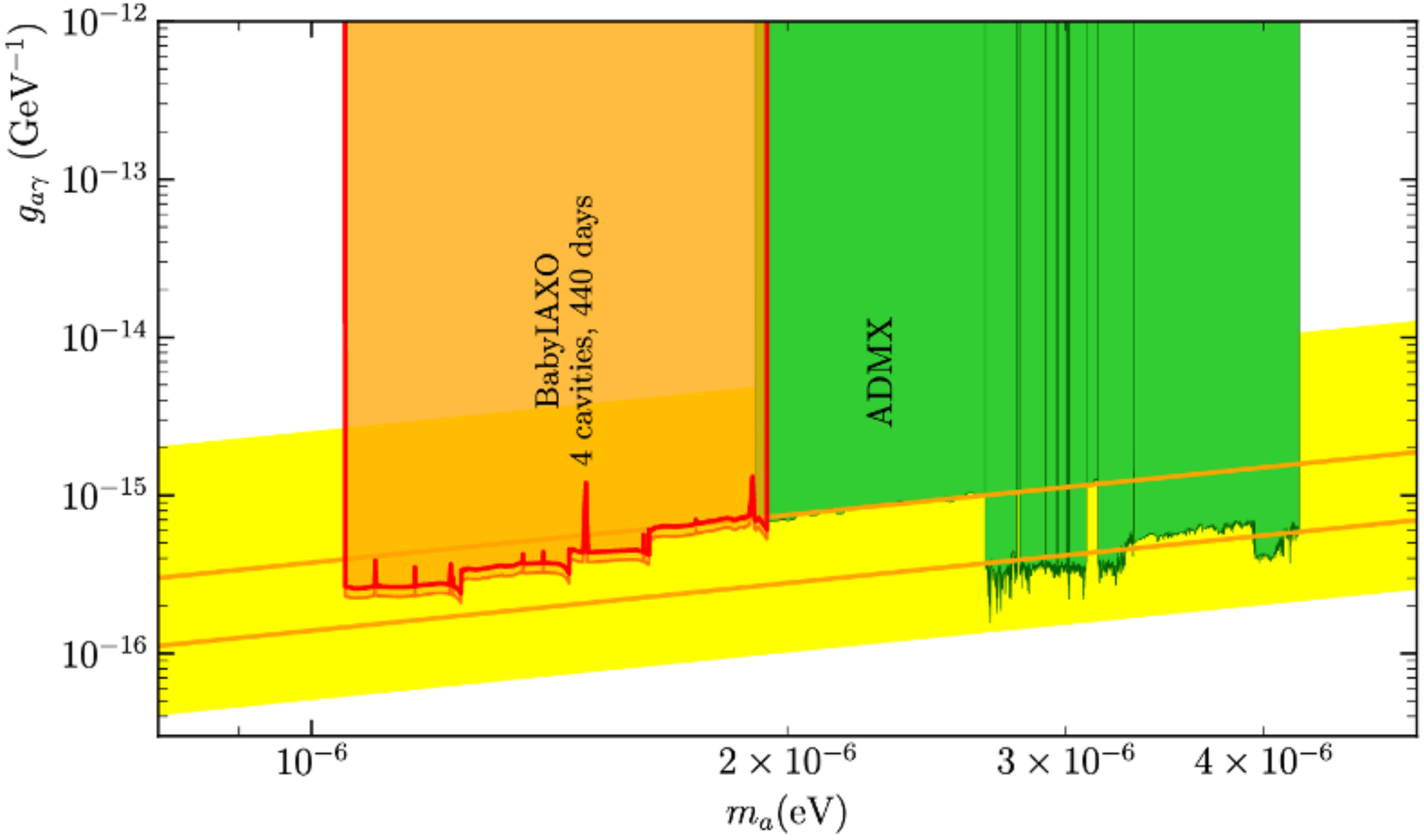
- Use 4 x 5m long cavities in the BabyIAXO magnetic bores

  ➡ May enable sensitivity to **1-2 μeV DM axions** close to ADMX limits

  ➡ Within 2 years of data taking reaching the KSVZ band

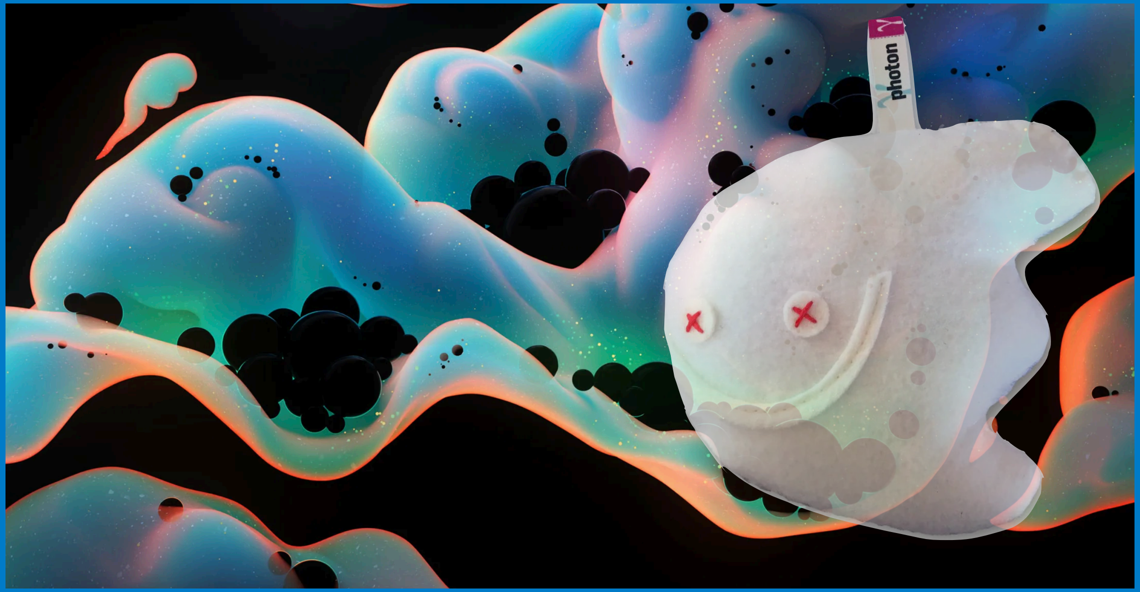
- Further implementations actively being discussed by collaboration

<u>RADES collaboration paper in preparation</u>

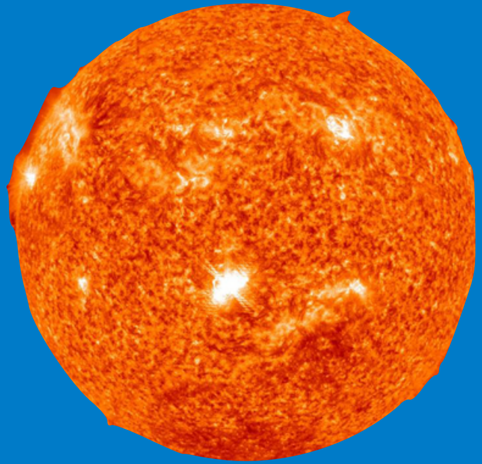


*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

Further Searches with ALPS II & BabyIAXO

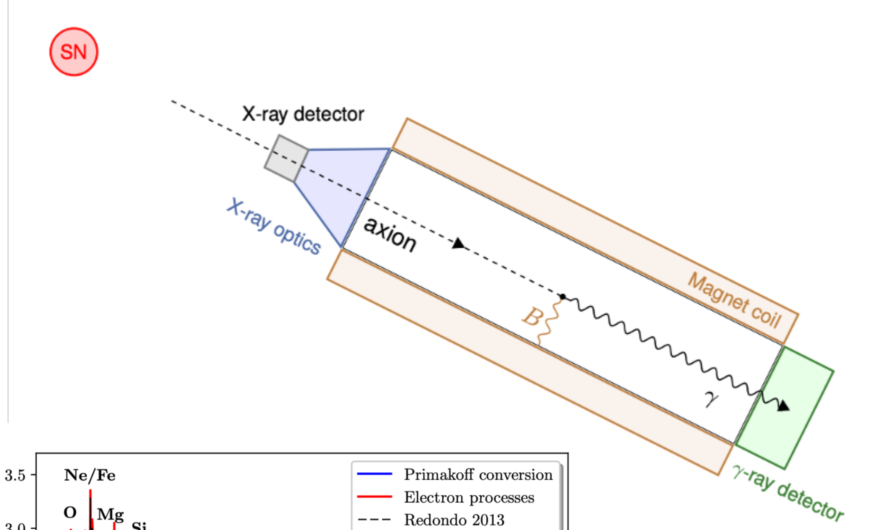


https://www.wired.com/story/is-dark-matter-just-black-holes-made-during-the-big-bang/



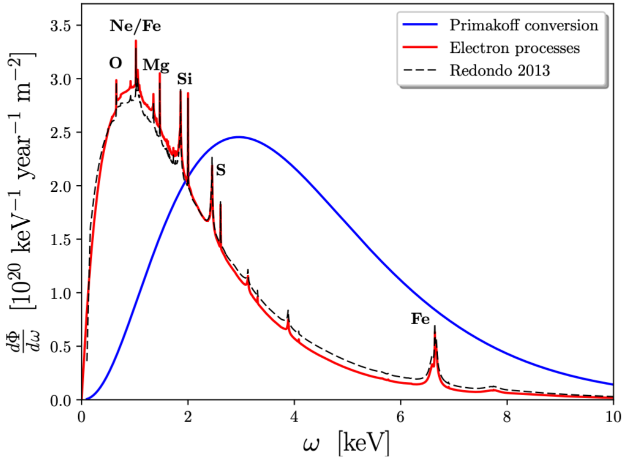
BabyIAXO & ALPS II Further Searches

A Broad Spectrum of Ideas



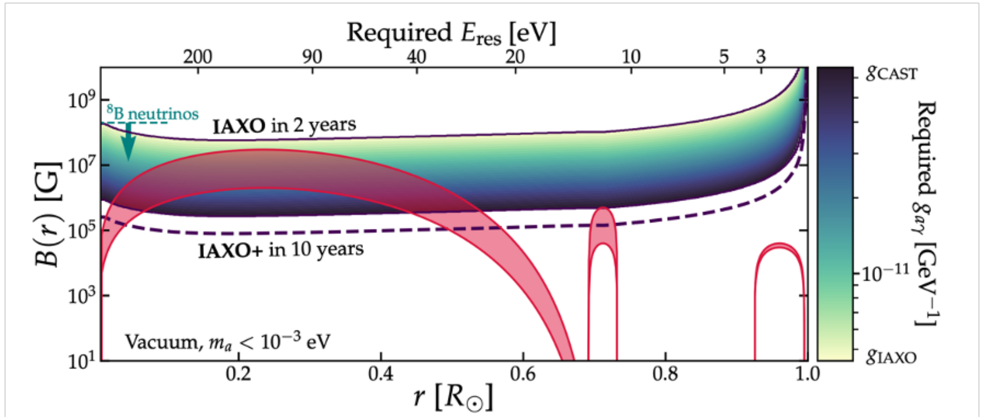
Solar & Supernovae Physics

- Axions from supernova explosions
  - ➡ Would require HE-γ detector at the opposite of X-ray detector
    arXiv:2008.03924
- If g_{ae} sufficiently high, characterisation of solar metallicity by measuring elemental peaks in ABC axion spectrum
  Phys. Rev. D 100, 123020
- Helioscope as solar magnetometers
  Phys. Rev. D 102, 043019



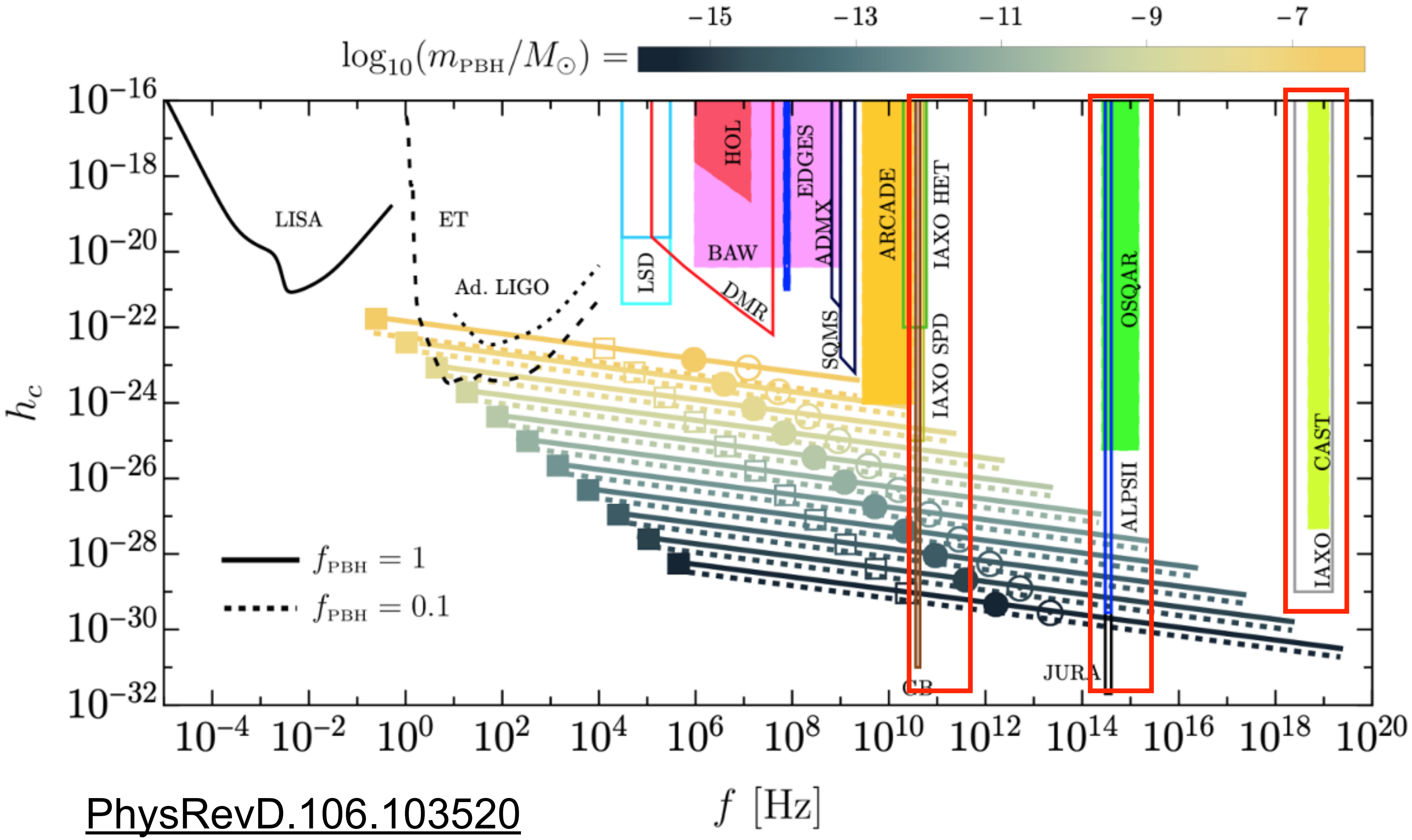
Standard Model Precision Tests:

- Measurement of Vacuum Magnetic Birefringence (VBM)
  - ➡ Using ALPS II magnet string and profit from laser interferometry infrastructure



High Frequency Gravitational Waves

Detection Possible with ALPS II and BabyIAXO?



PhysRevD.106.103520

(Baby)IAXO sensitivities: PhysRevD.106.063027 + JCAP03(2021)054

- High frequency gravitational waves are expected in non-standard scenarios, e.g. from primordial black hole formation
- Gravitational waves converted into photons by inverse Gertsenshtein effect in a strong magnetic field
  - ➡ ALPS II and BabyIAXO sensitive to specific frequencies?

➡ Emerging field of study, synergies?