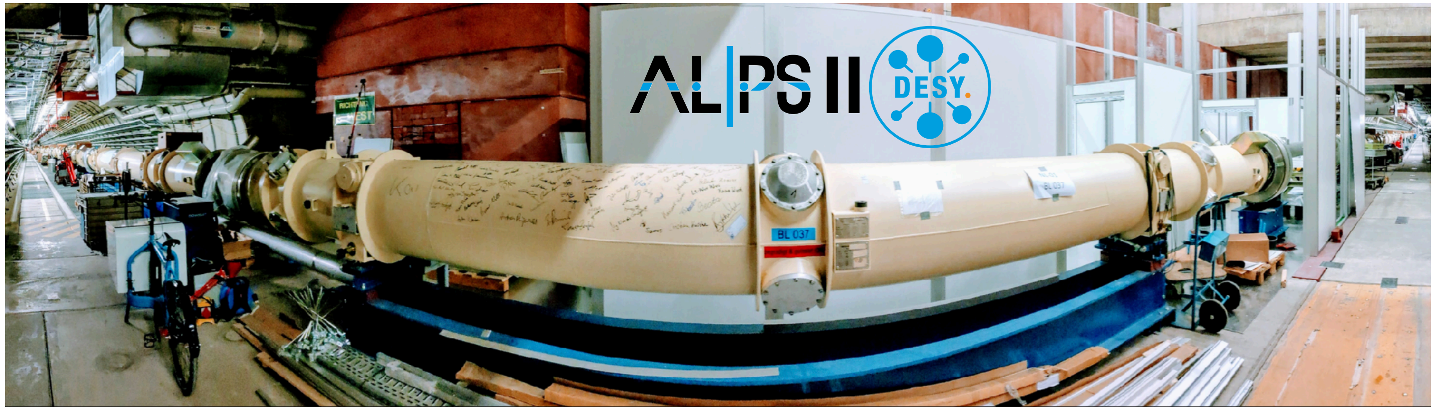
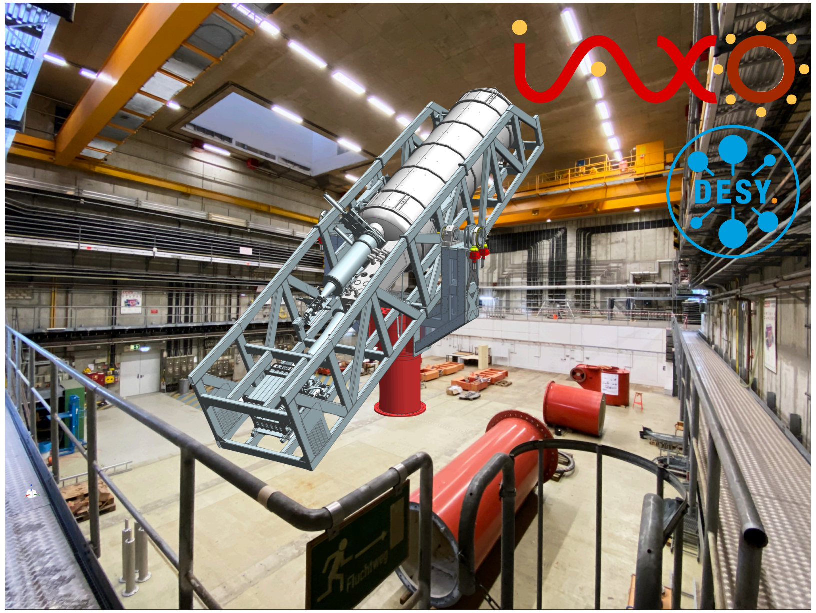
Axion & ALP Searches at DESY

Independent of the Dark Matter Paradigm



Daniel Heuchel (DESY)
daniel.heuchel@desy.de
3rd DMLab Meeting
KIT, Karlsruhe, 16th November 2023



Outline

For this Talk

- Motivation & detection strategies for axions/ALPs
- ALPS II and BabyIAXO:
  - ➡ Status
  - ➡ Axion/ALP physics prospects
  - ➡ Beyond axions/ALPs
- Summary and outlook

Axions/ALPs

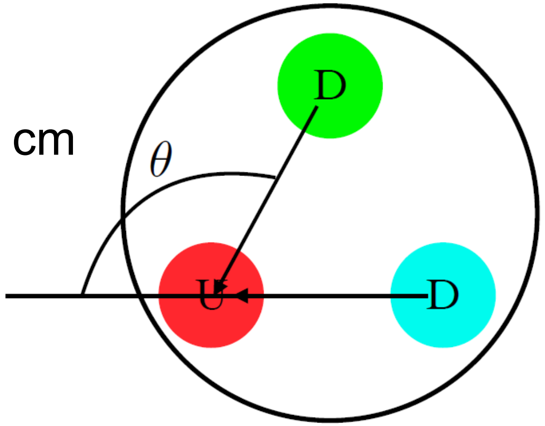
and how to detect them.

Why Axions/ALPs?

Physics Motivation

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

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



Most compelling solution to the strong CP problem

Credit: K. Altenmüller

Why Axions/ALPs?

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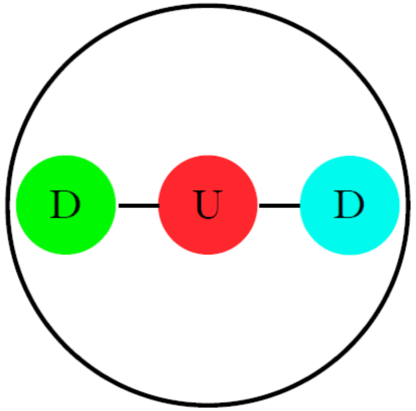

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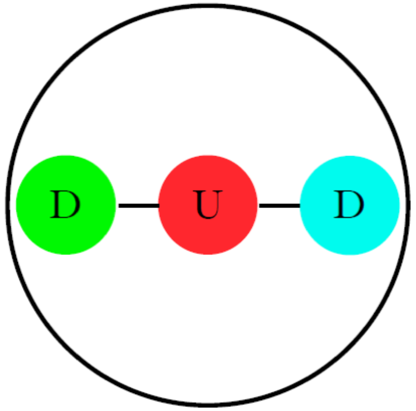

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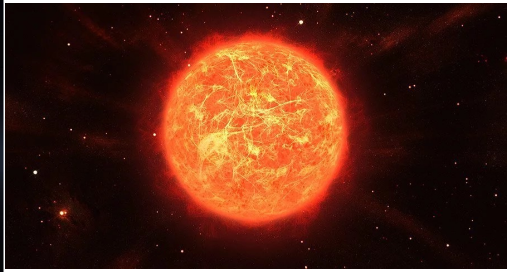

Astrophysical hints:
UHE γ transparency,
anomalous stellar cooling,
solar evolution …

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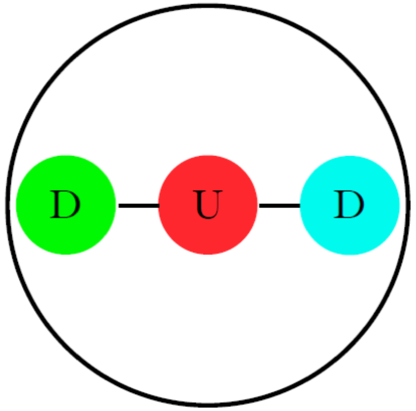

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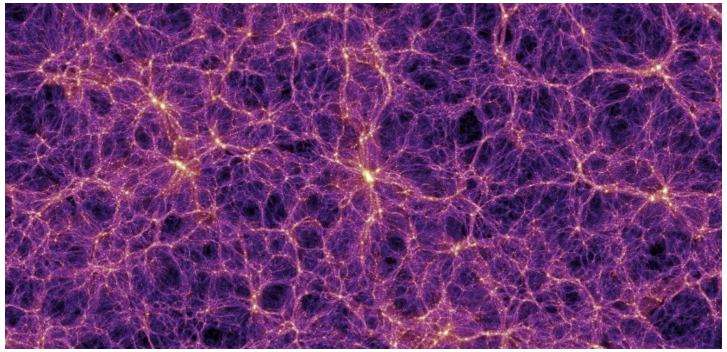

Cosmology:
Excellent cold DM candidate

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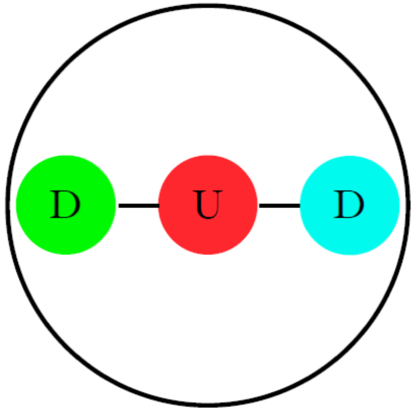
Why Axions/ALPs?

Physics Motivation

Theory:
ALPs predicted by many extensions of SM (e.g. string theory)



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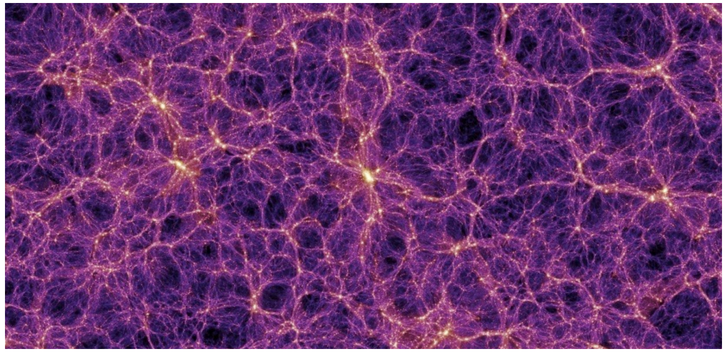

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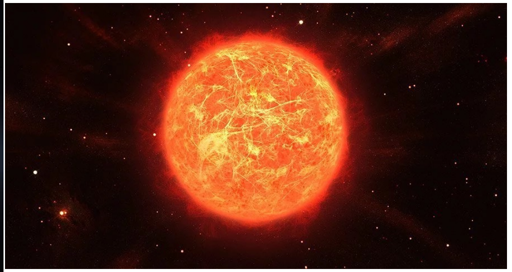

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Why Axions/ALPs?

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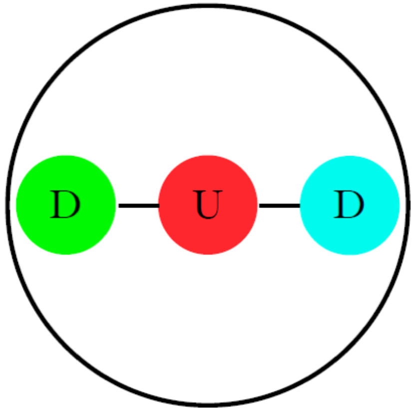
One particle to clean it all…



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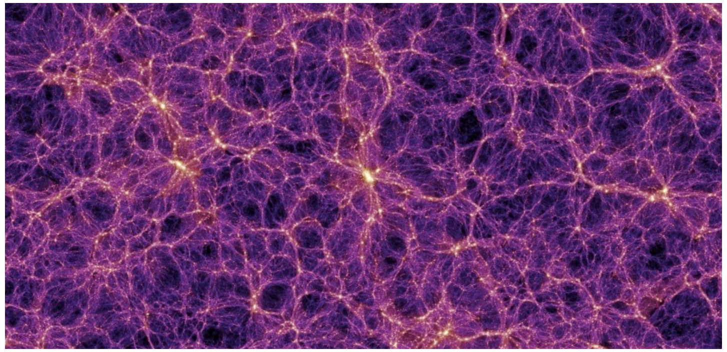

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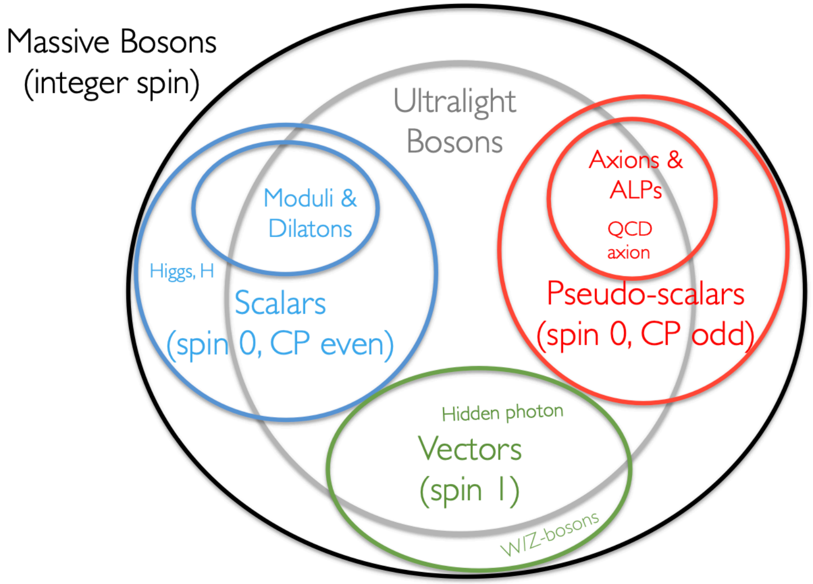
Detection of Axion/ALPs

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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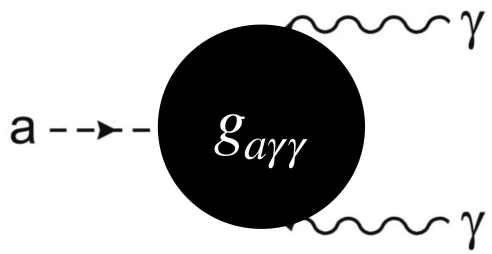

Axion decay to photons

Detection of Axion/ALPs

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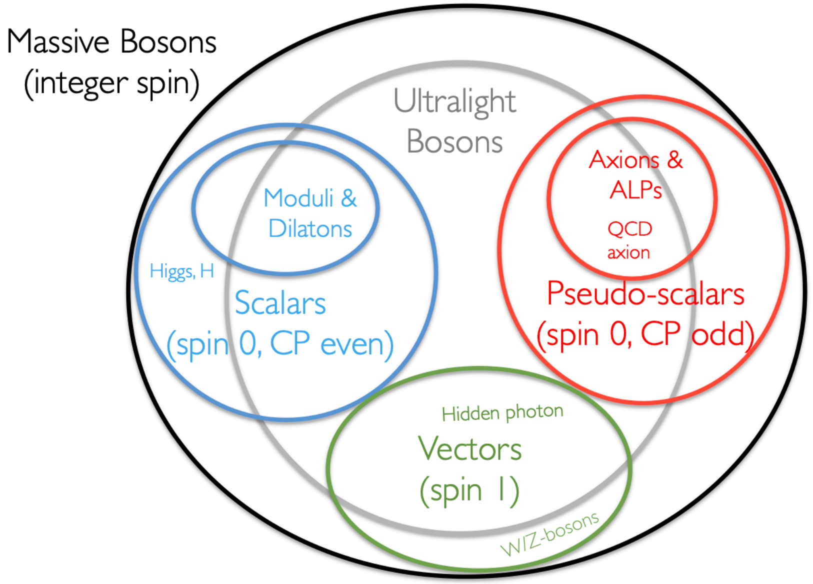
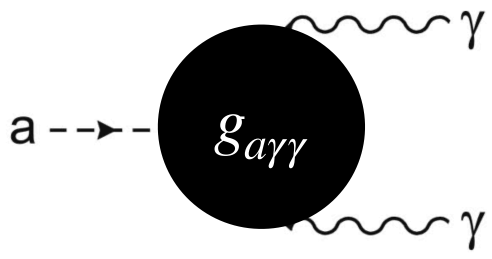


sciadv.abj3618



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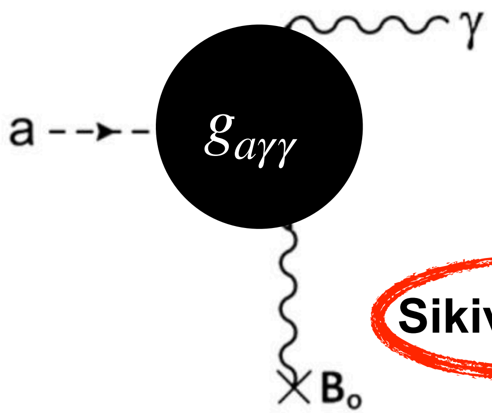
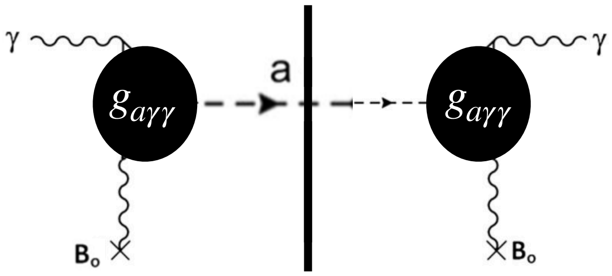


Sikivie effect

Experimental Approaches

Complementarity & Model Dependencies

Concept	Source	Detection	Model & Cosmology Dependency	Experiments
Light-shining-through-wall experiments	 Lab axions		**Independent** "self-made" axions	OSQAR, CROWS, ALPS, **ALPS II,** STAX

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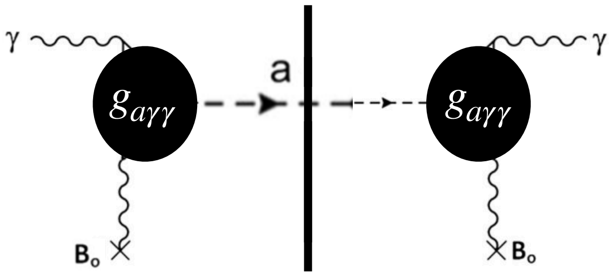
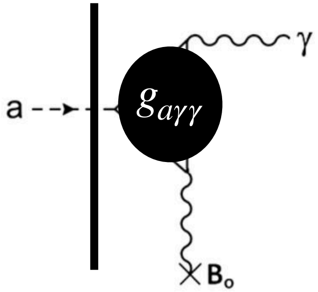
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	SUMICO, CAST, **(Baby)IAXO**

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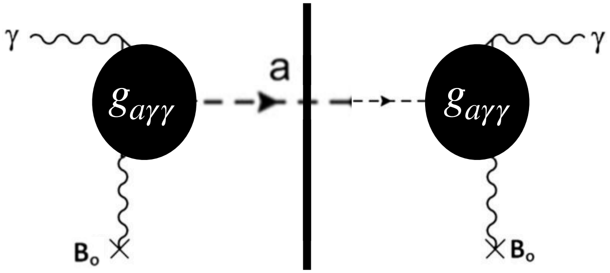
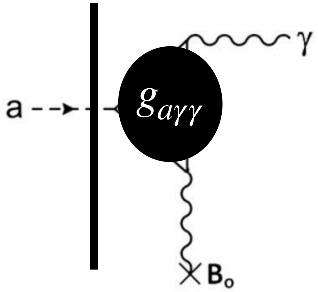
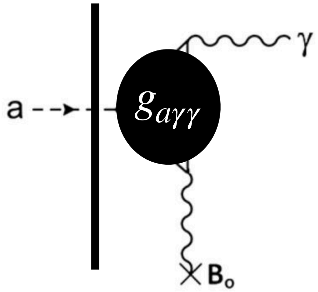
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	SUMICO, CAST, **(Baby)IAXO**
Haloscopes			**High** Axions = cold dark matter constituents	ADMX,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

Experimental Approaches

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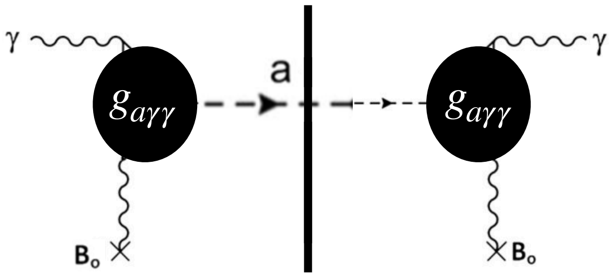
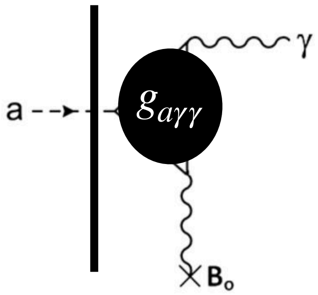
Light-shining-through-wall experiments	 Lab axions		**Independent** “self-made” axions	OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	SUMICO, CAST, **(Baby)IAXO**

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

Illustration: Parameter Landscape

Axion-Photon Coupling, Experiments & Theories

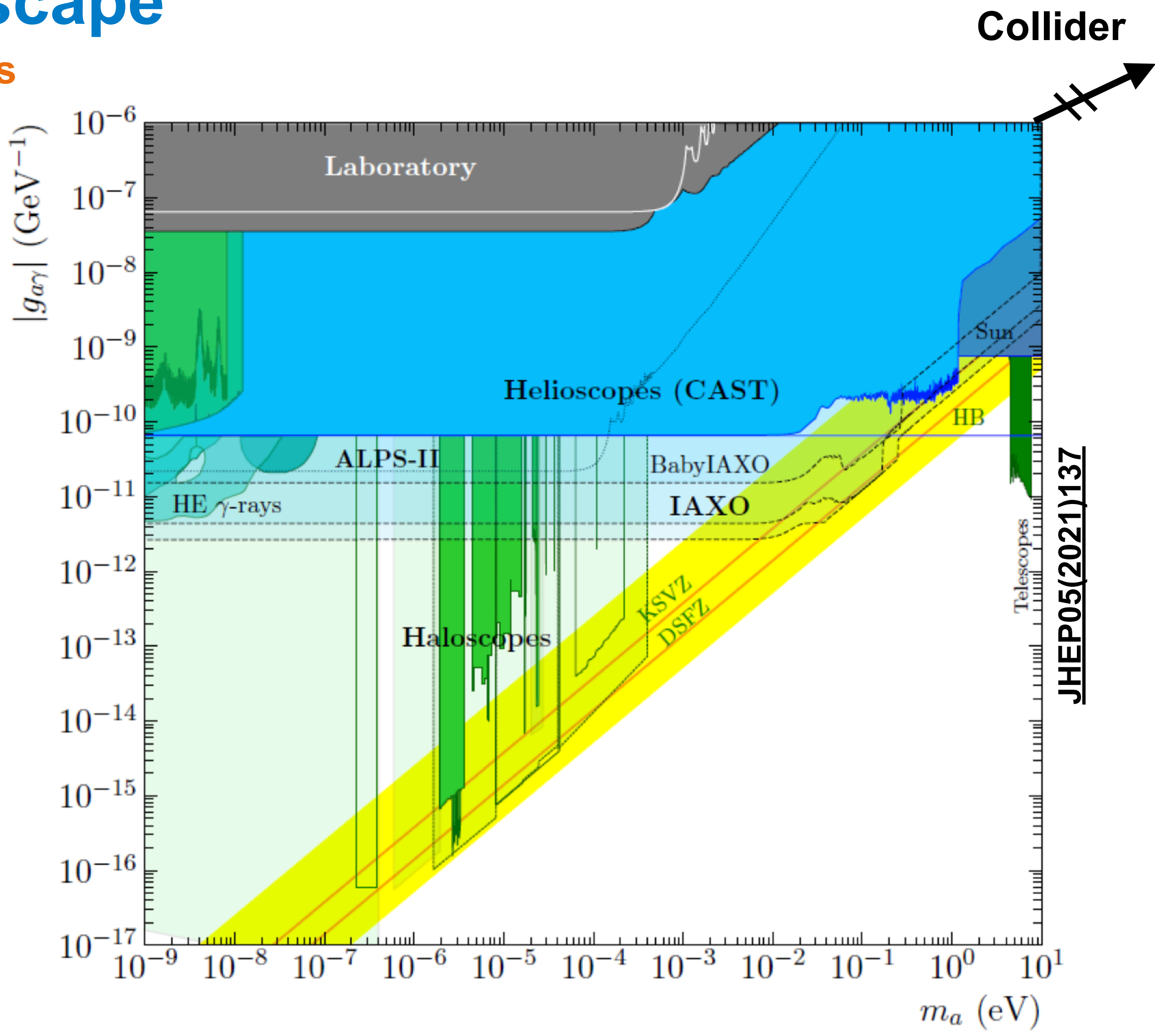
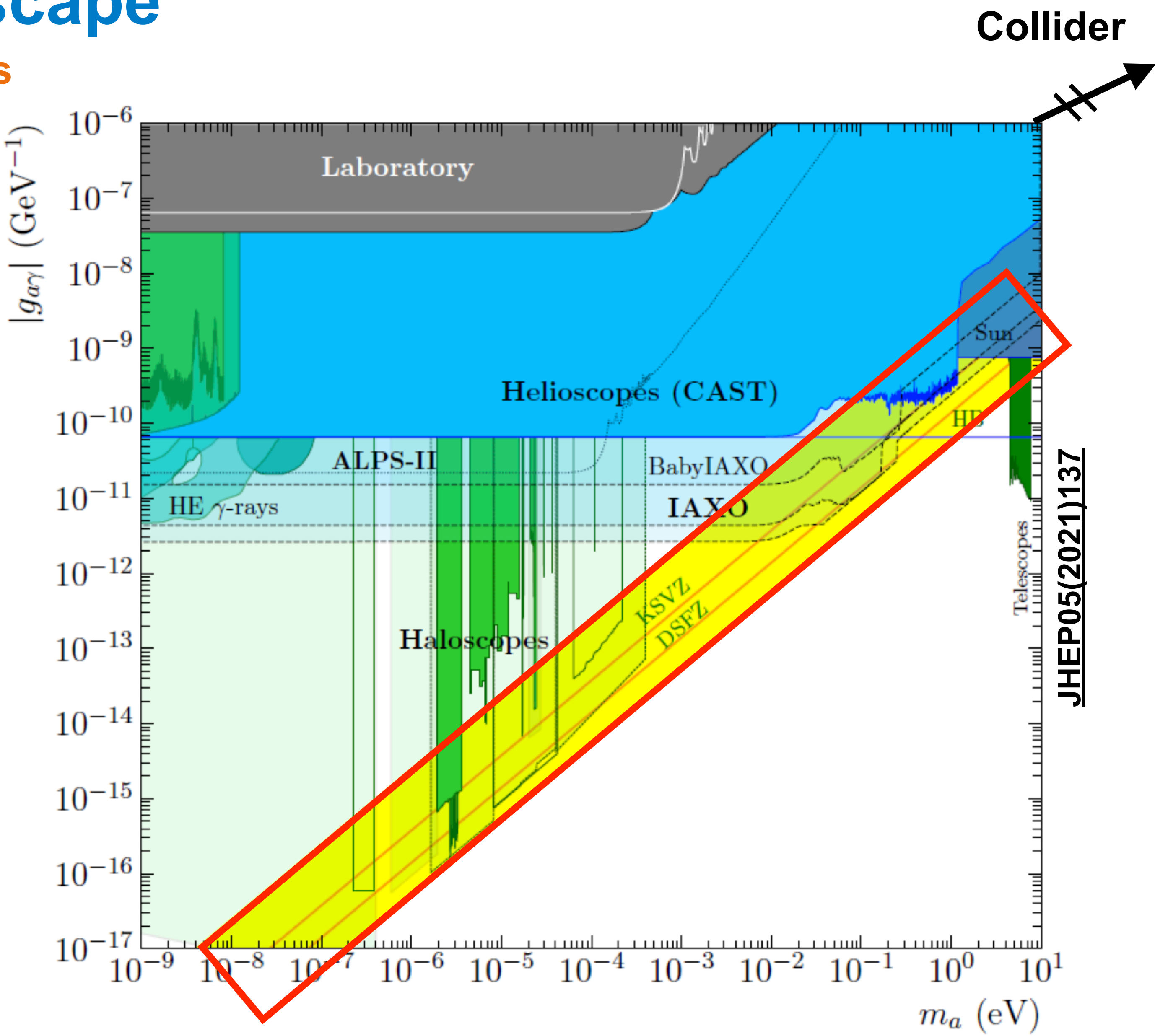


Illustration: Parameter Landscape

Axion-Photon Coupling, Experiments & Theories

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



JHEP05(2021)137

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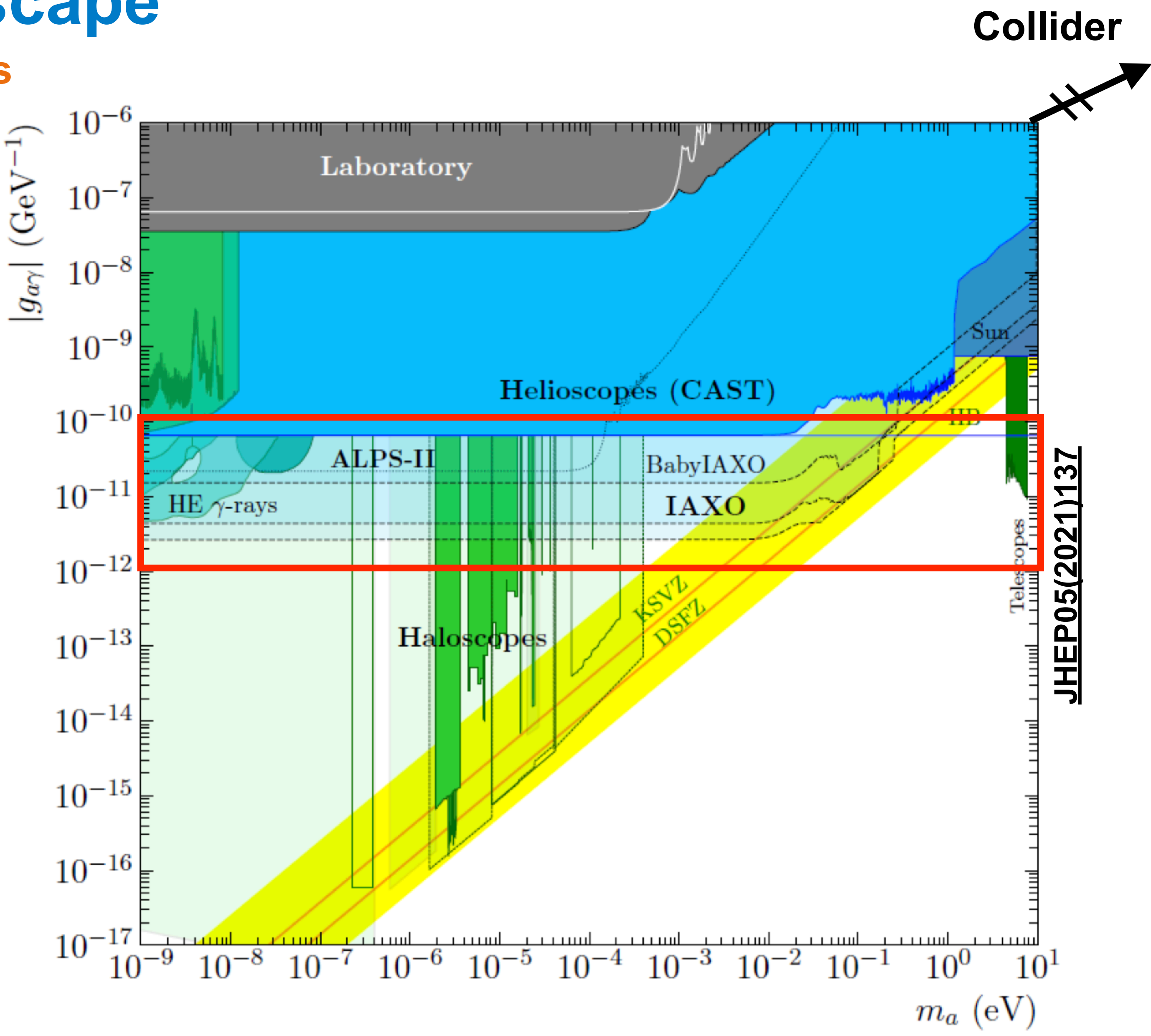

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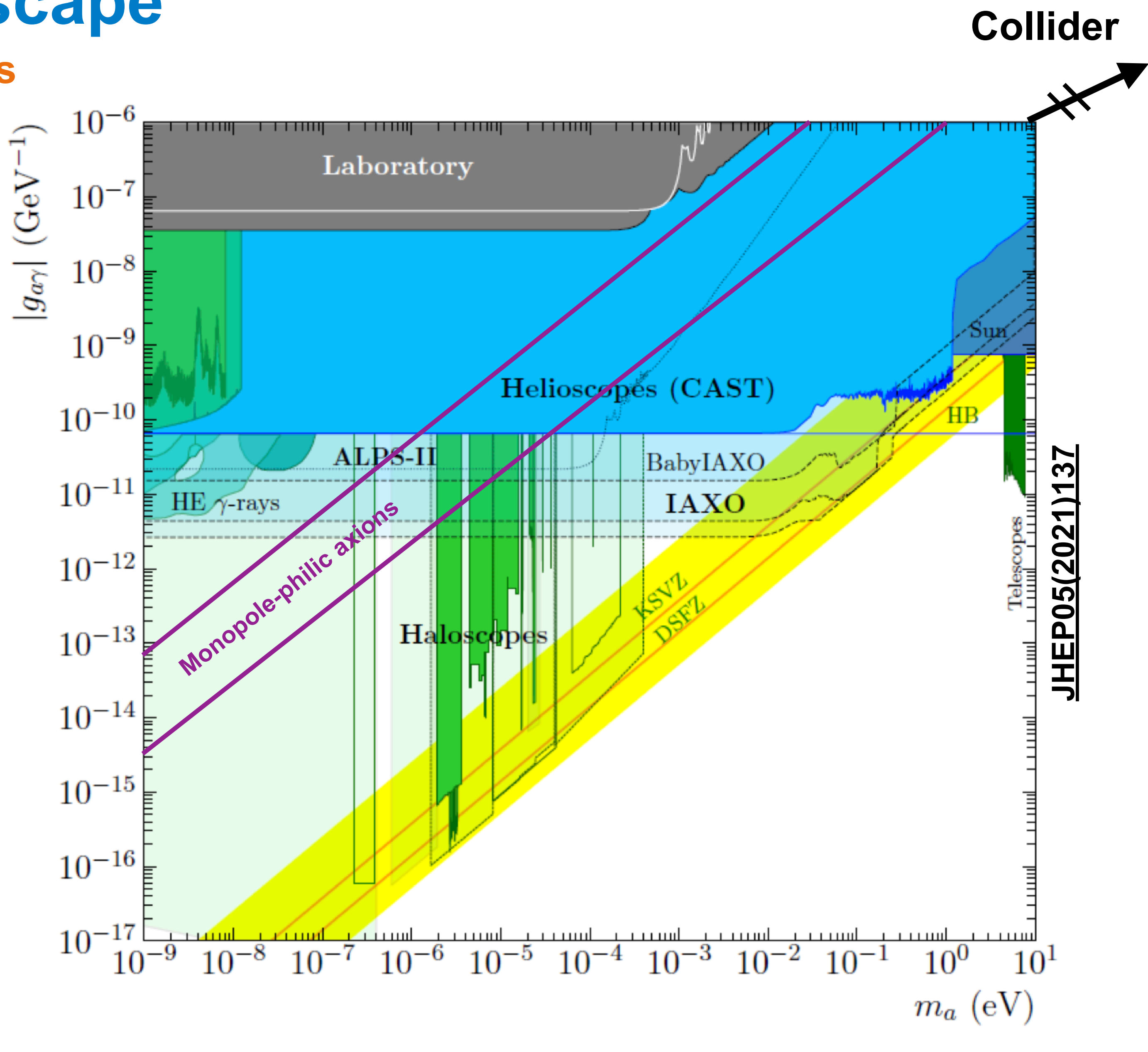
  - ➡ **But**: QCD axion models outside the band e.g. recent benchmark by Sokolov-Ringwald: JHEP06(2021)123



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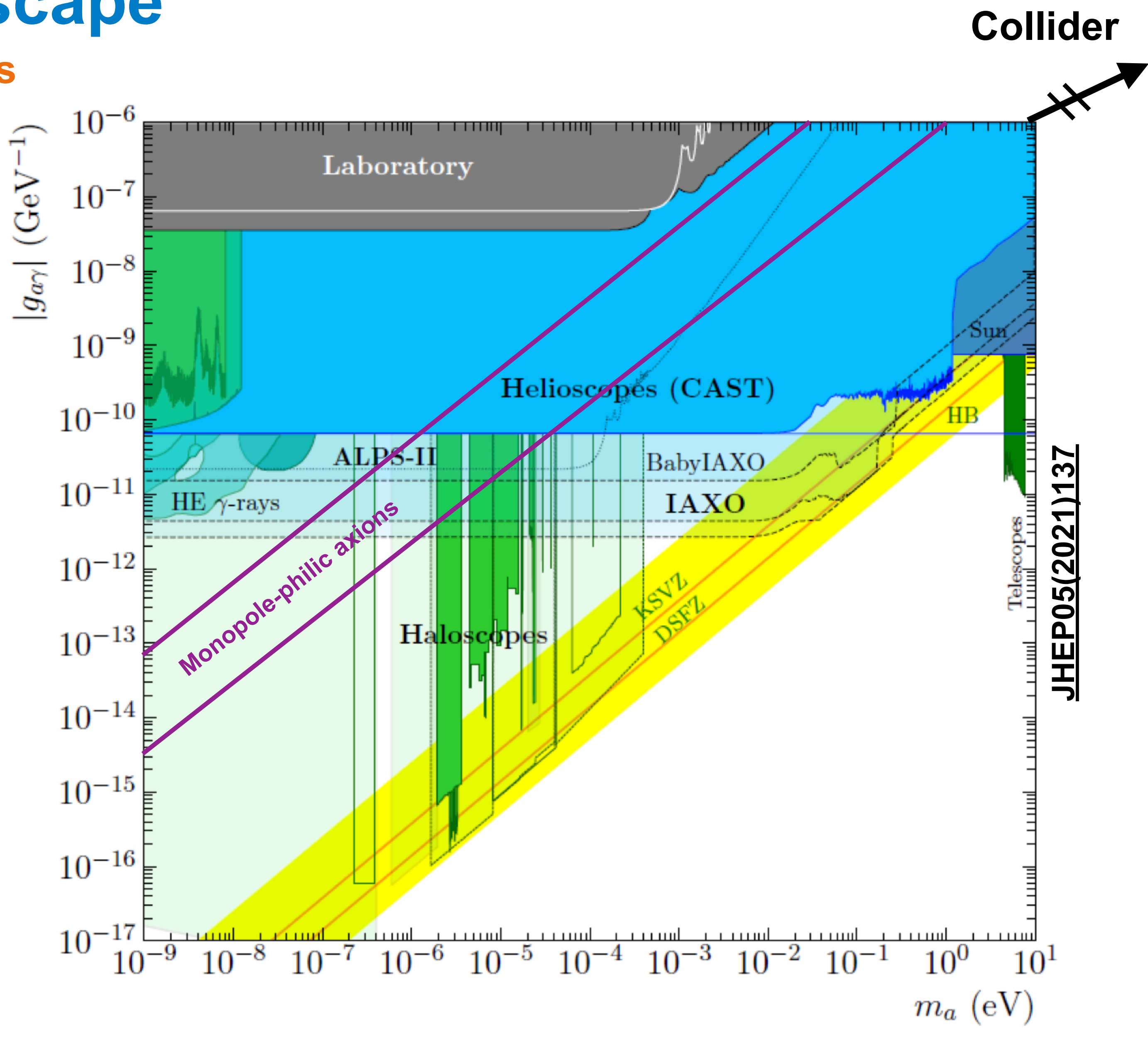
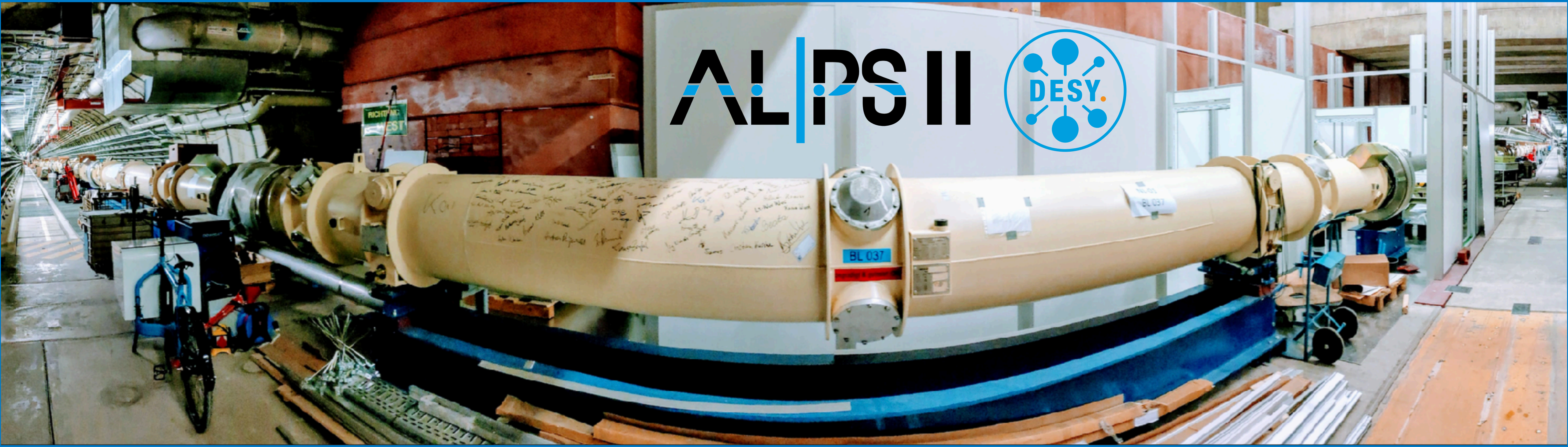
➡ **Reachable parameter space! Very interesting times for different types of axion experiments!**

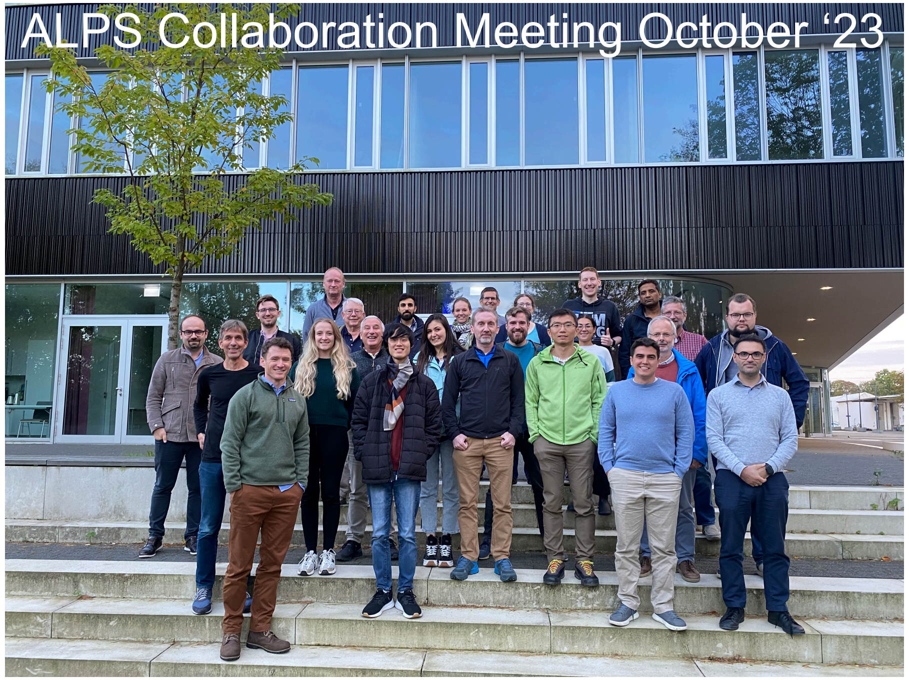


Shining light through a wall with ALPS II



The ALPS II Collaboration

Overview



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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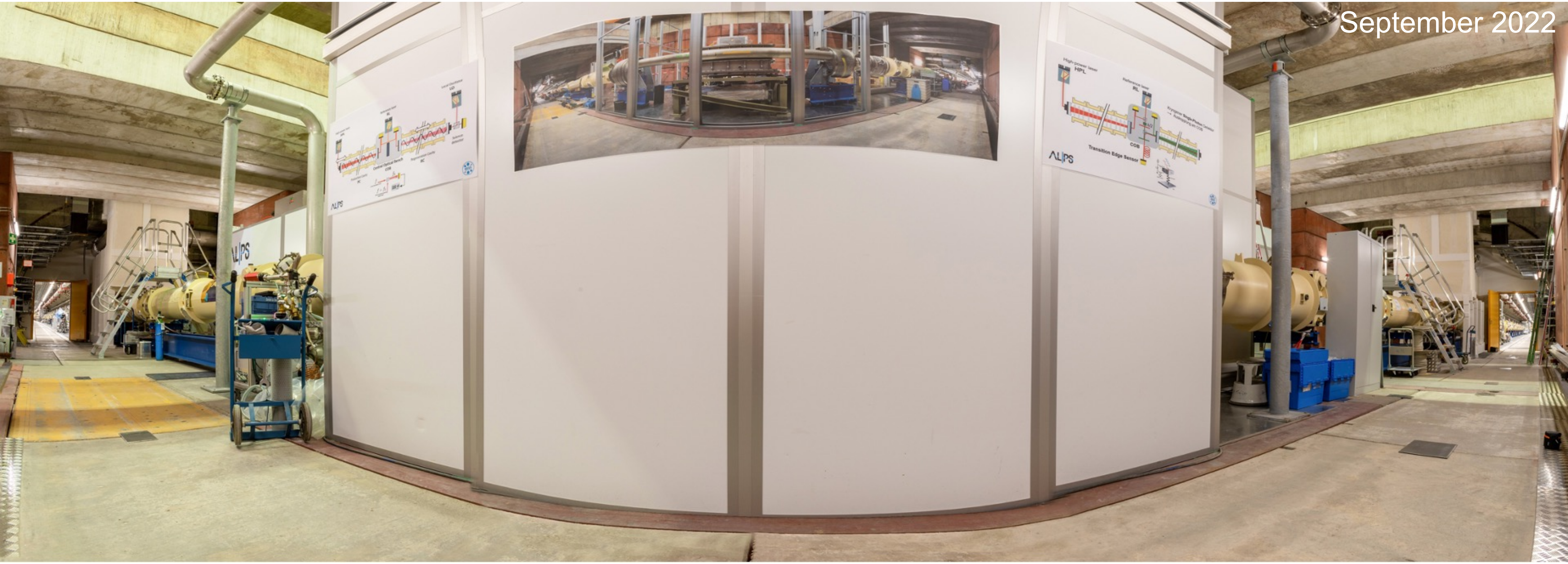

Recipe for Any Light Particle Search II (ALPS II)

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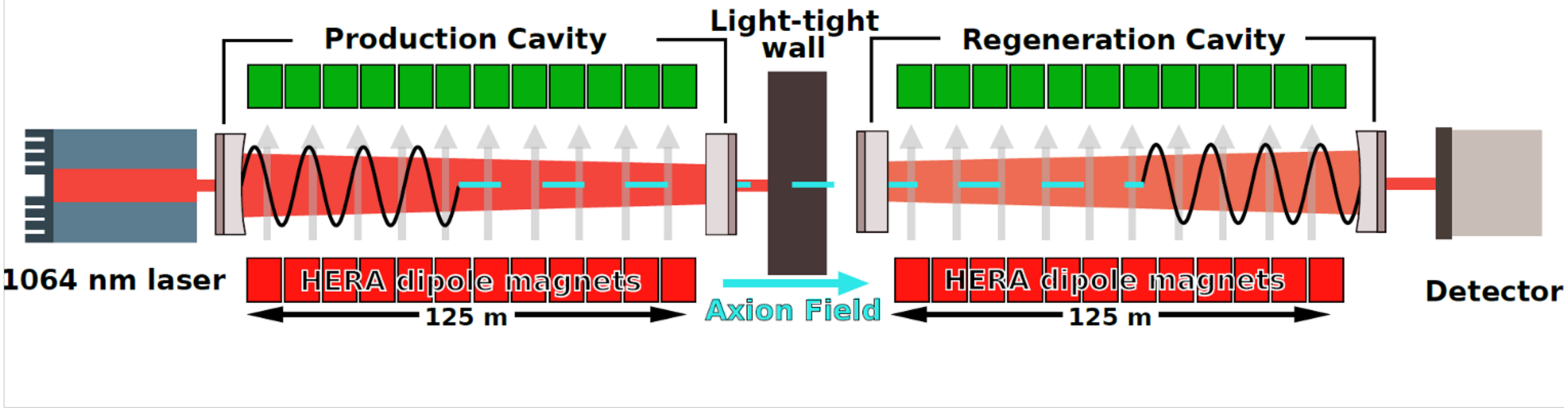
- DESY HERA infrastructure: 2x12 HERA dipole magnets, cryogenic lines, tunnel & 3 clean-rooms
- High power laser system (40 W)
- Optical cavities both before and after wall (key: dual resonance and phase stability)
- Central optical bench



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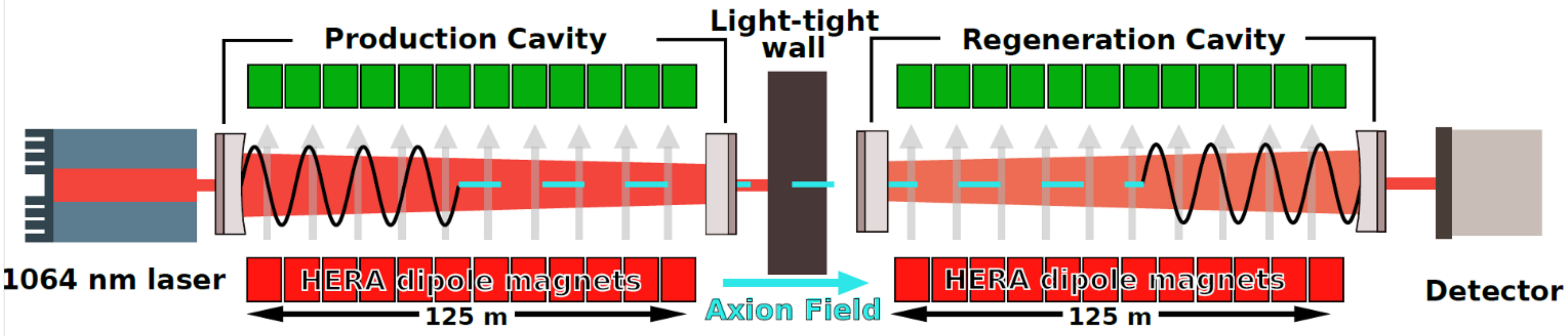


- With benchmark parameters expected: **~2 photons / day (5×10^{-24} W)**

➡ Heterodyne detection system, later single photon counting with transition edge sensor (TES)

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

We are Taking Data!

- Regeneration cavity + mod. optics system
  - ➡ Stray light hunting
- Scalar search: 150,000 s

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

ALPS II - Next Steps

New Milestones Ahead!

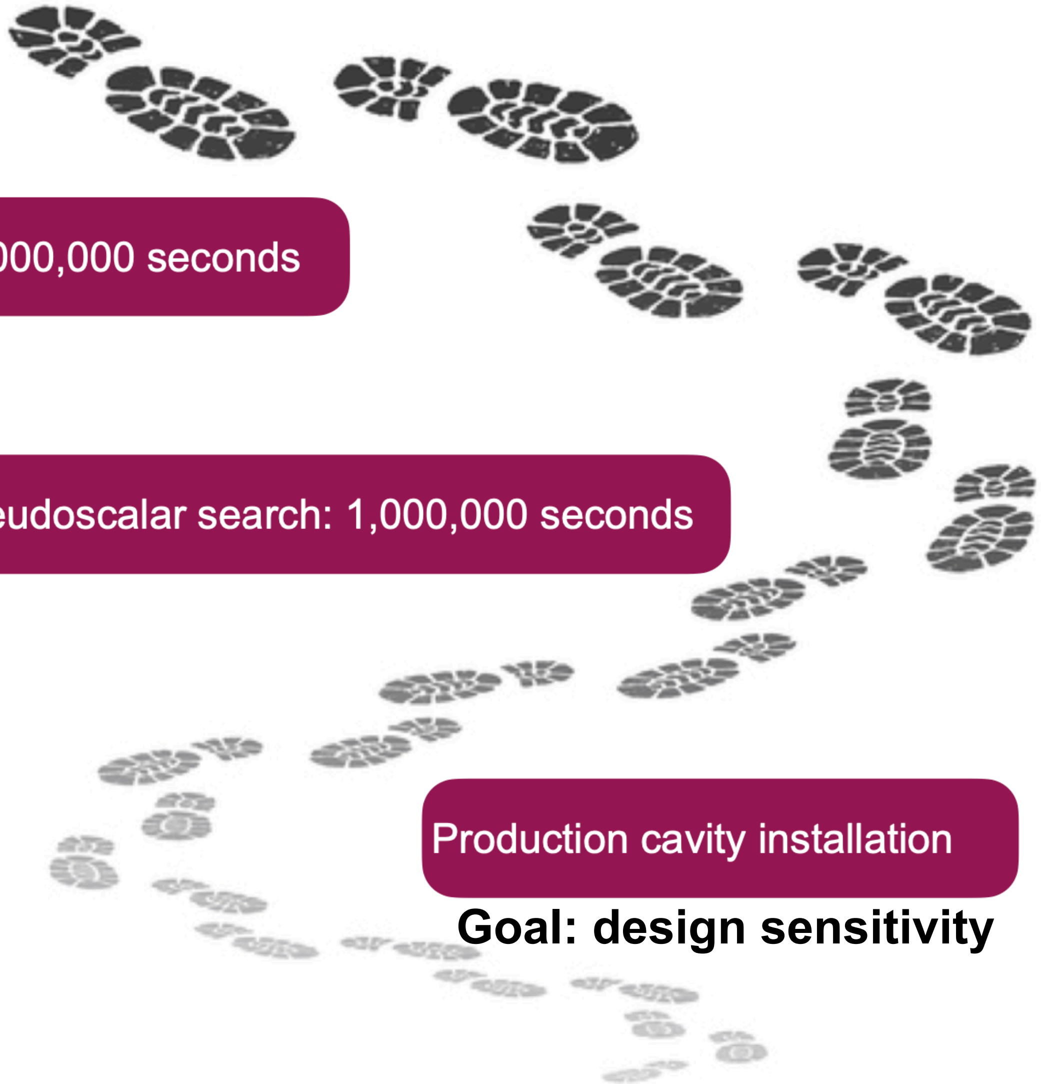
Started: 03.11.2023

Scalar search: 1,000,000 seconds

Pseudoscalar search: 1,000,000 seconds

Production cavity installation

Goal: design sensitivity

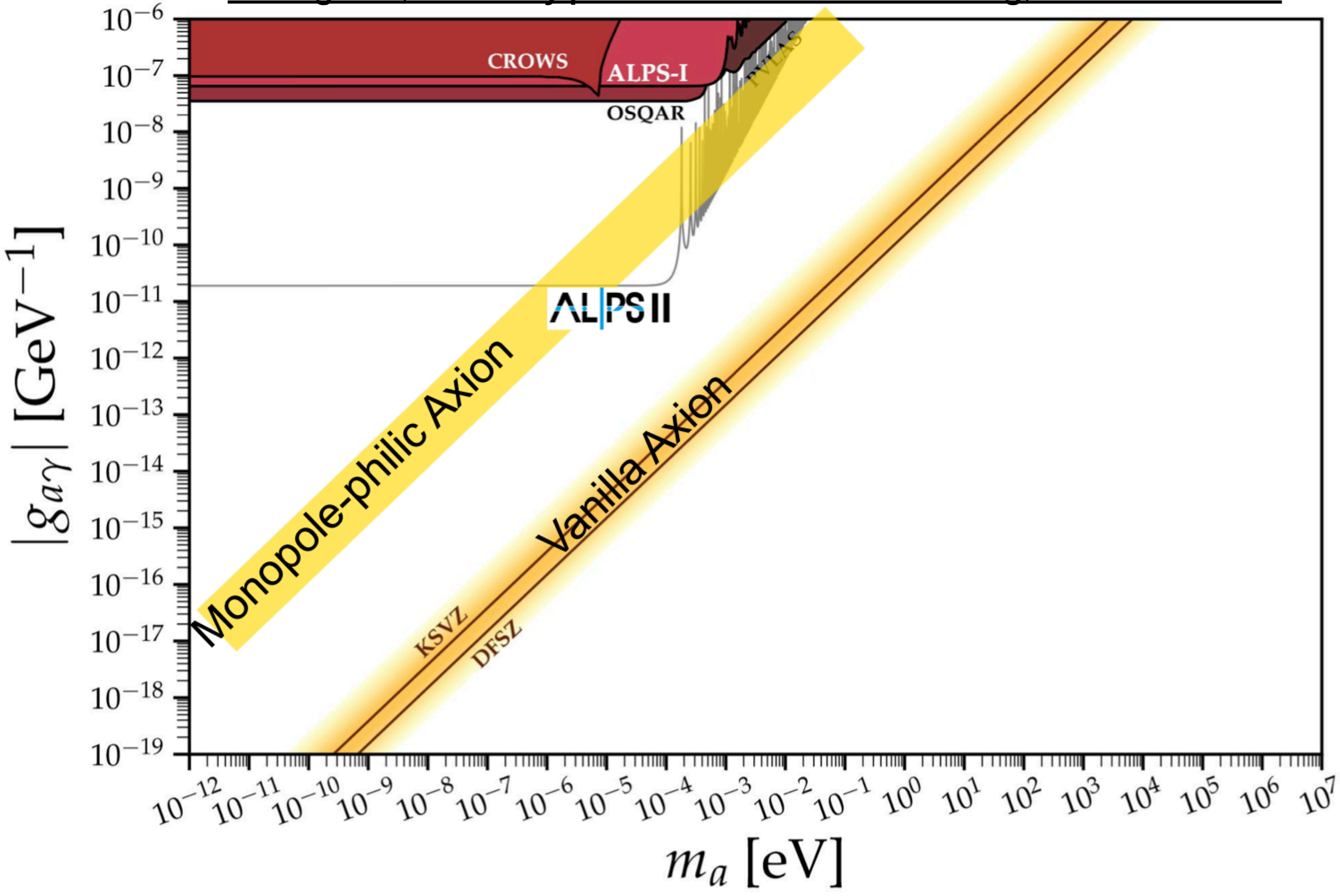


What is ALPS II Aiming for?

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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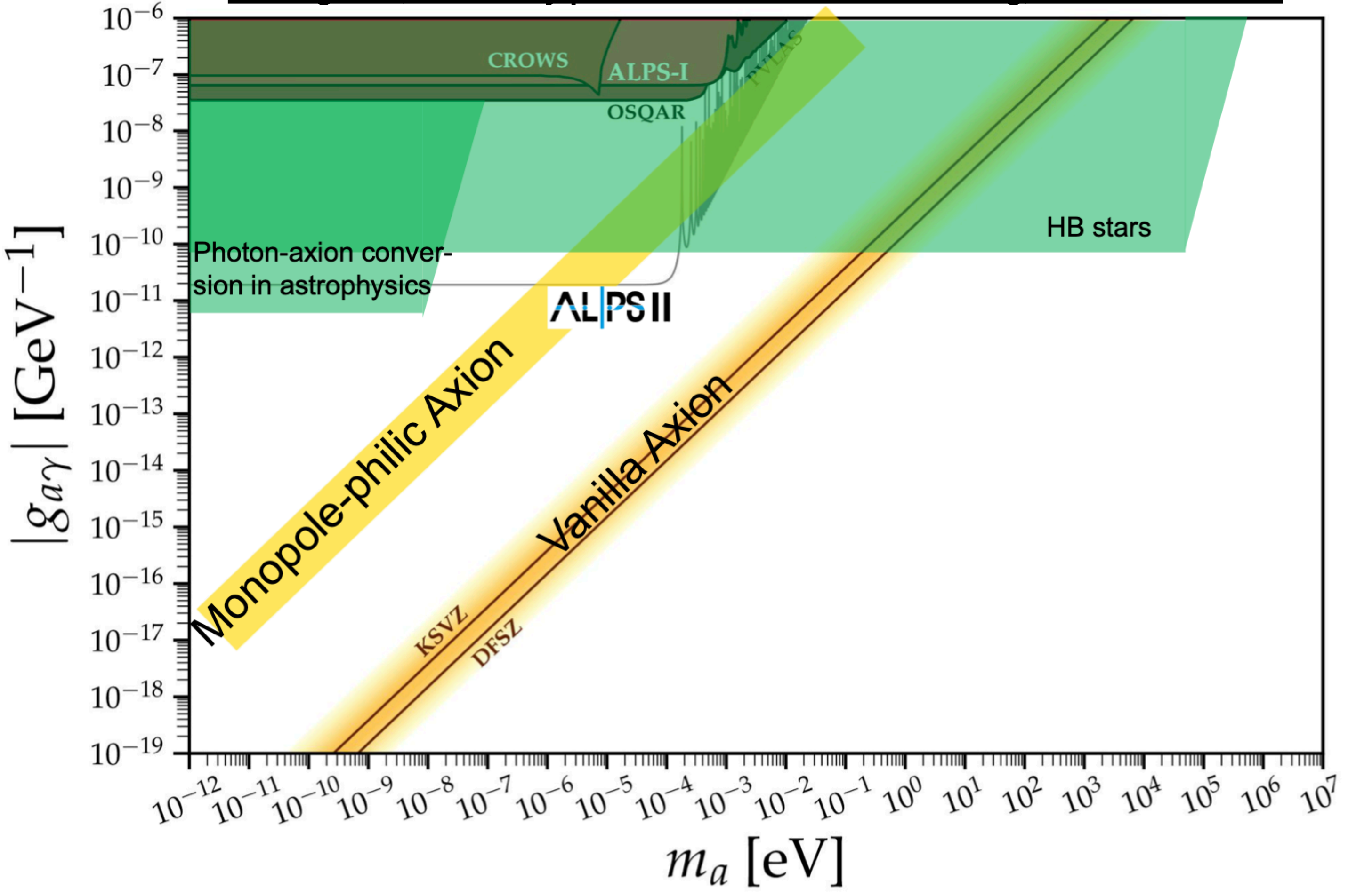

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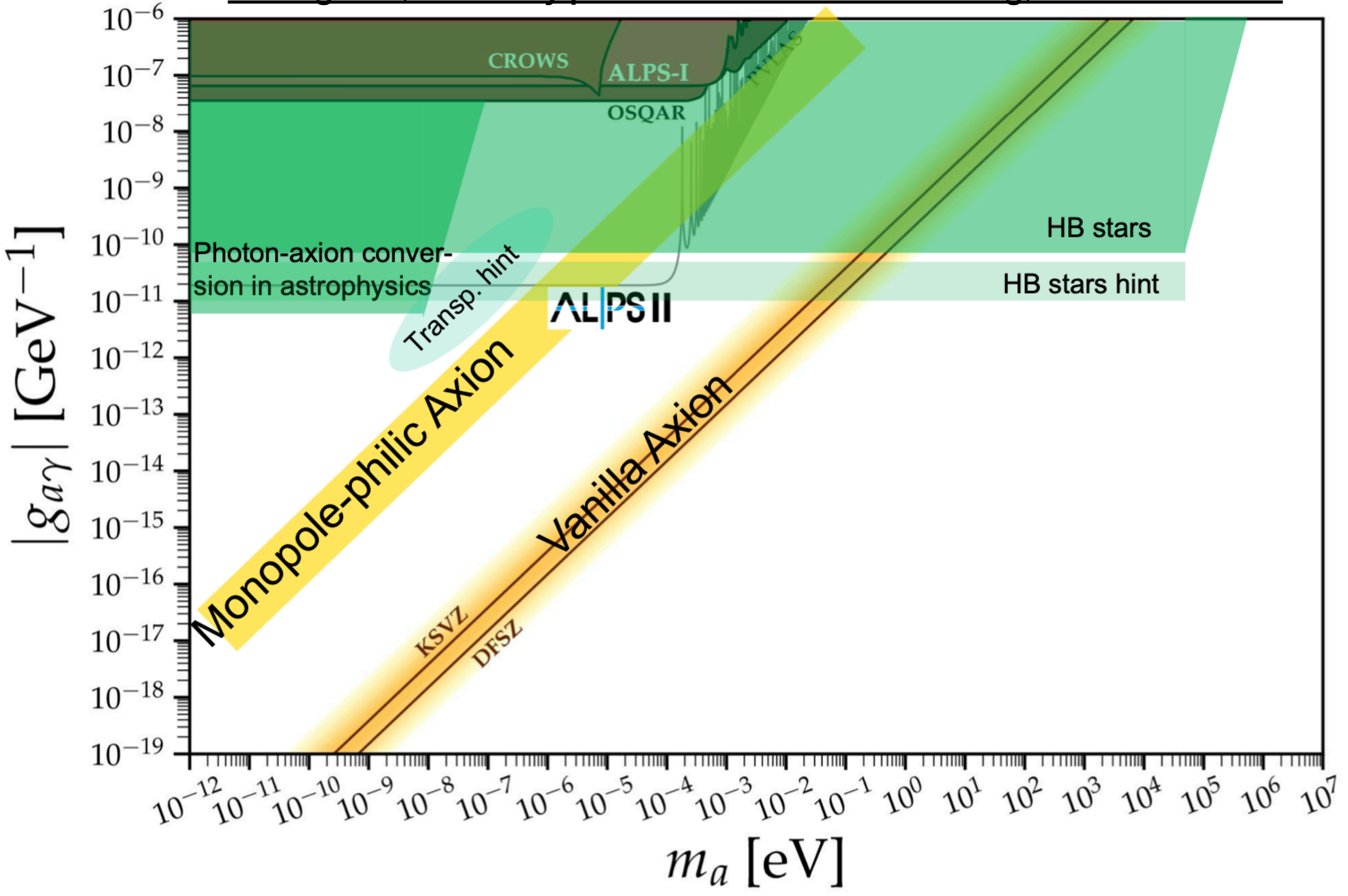

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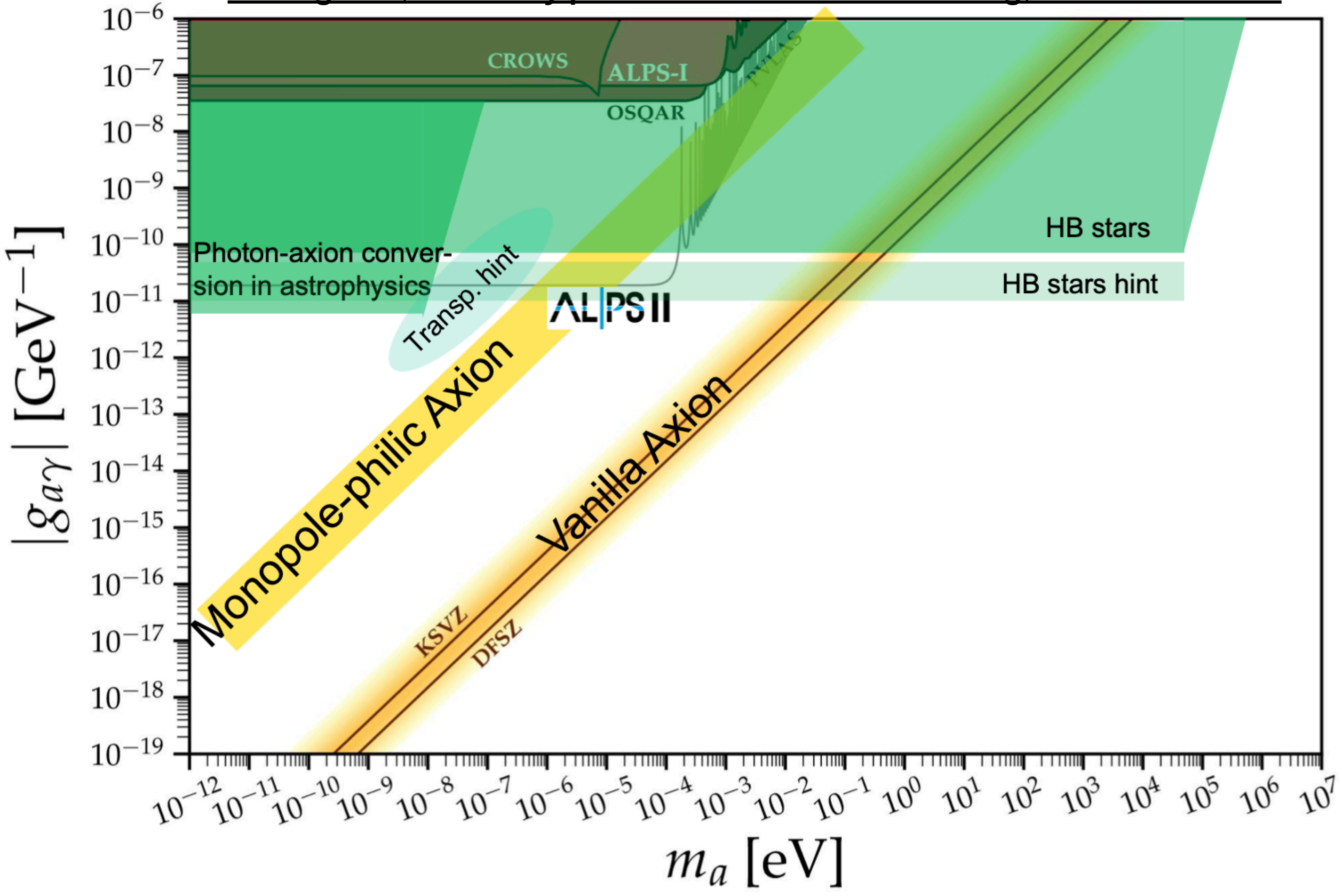

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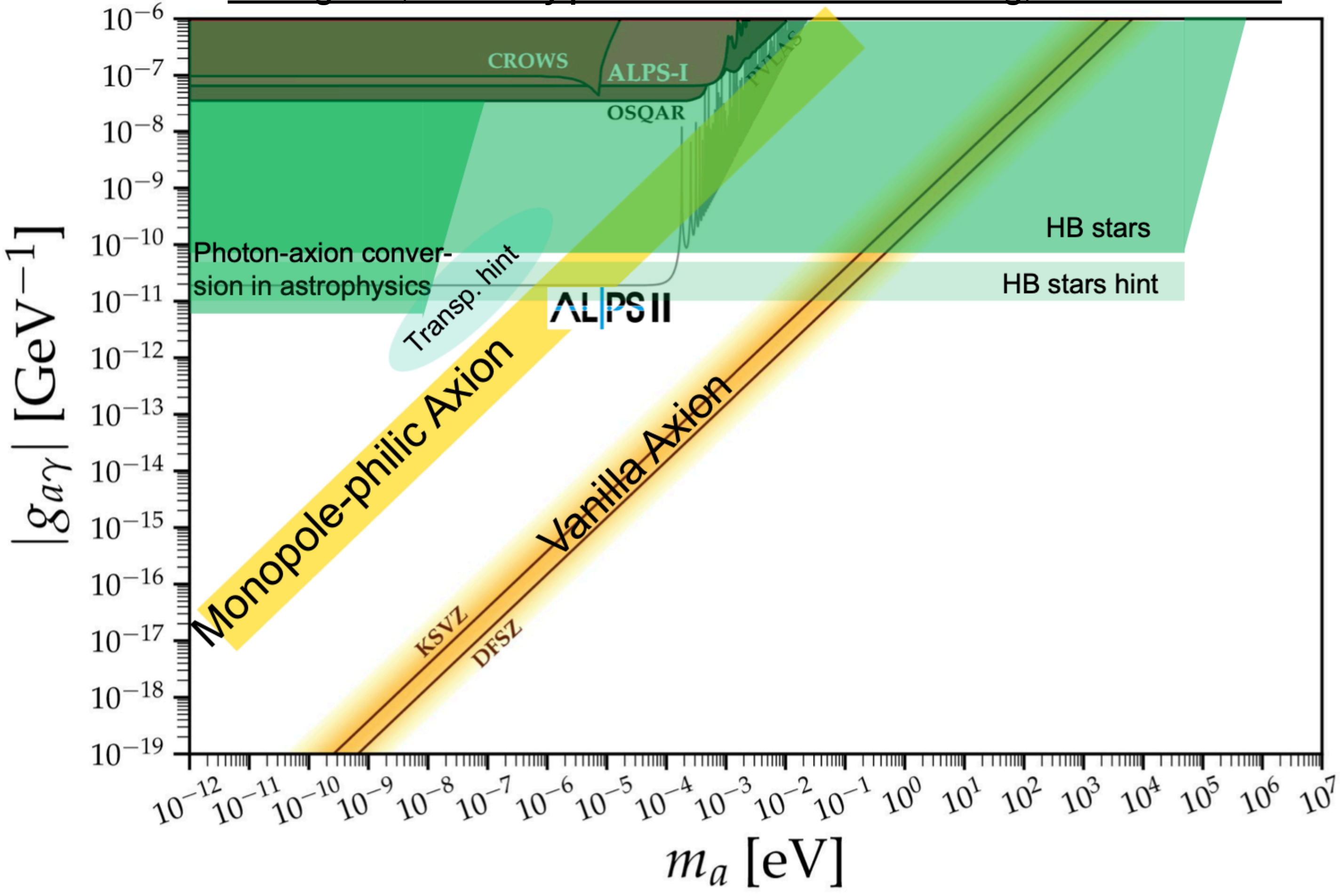
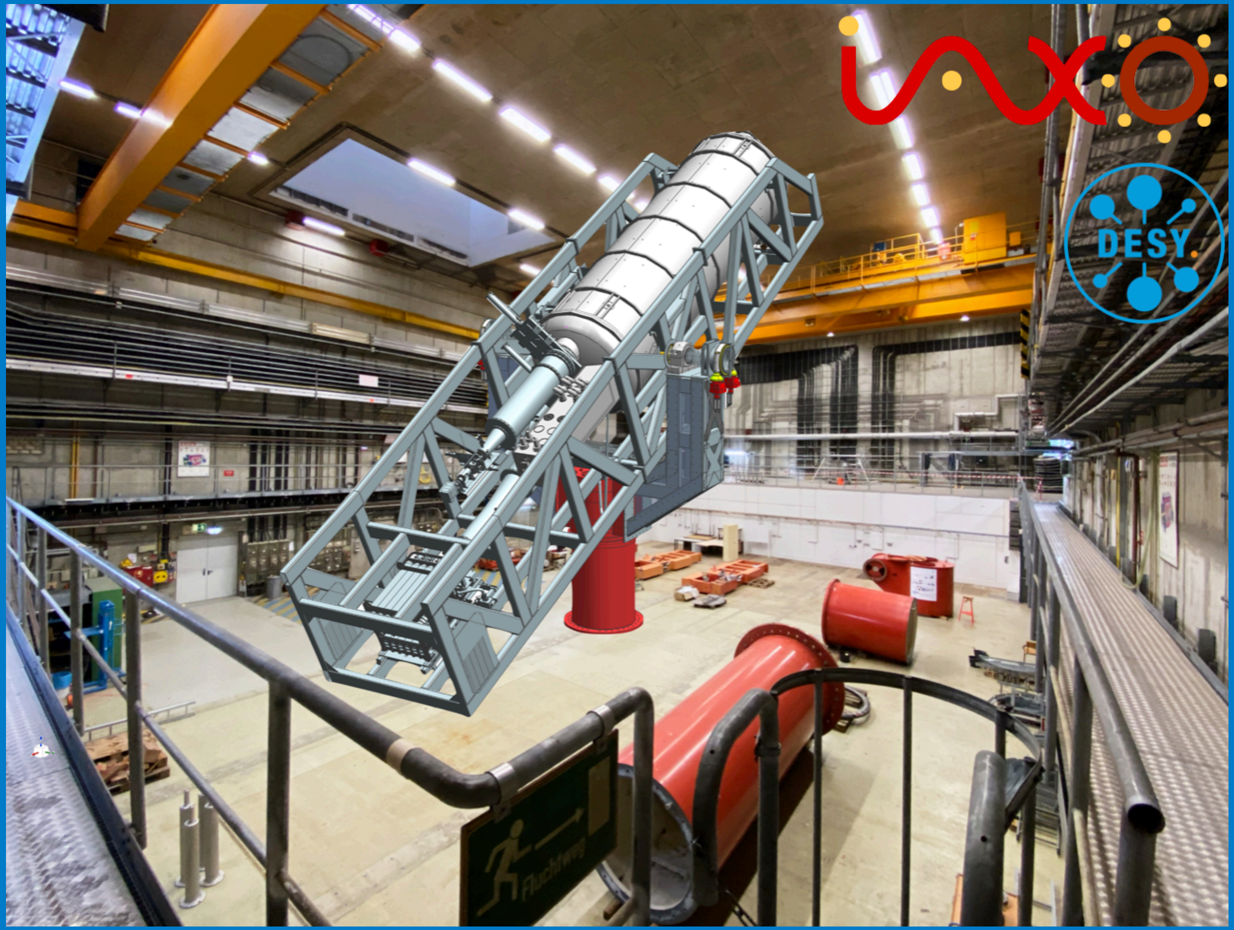
  - ➡ Uncharted parameter space well motivated by astrophysical anomalies
  - ➡ Covers parameter space of monopole-philic QCD axions outside of benchmark vanilla QCD axion band
- Goal: axion/ALP discovery and model-independent measurement of $g_{a\gamma\gamma}$
- And then?
  - ➡ Probe nature of the underlying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

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



The sunny side of life with (Baby)IAXO.

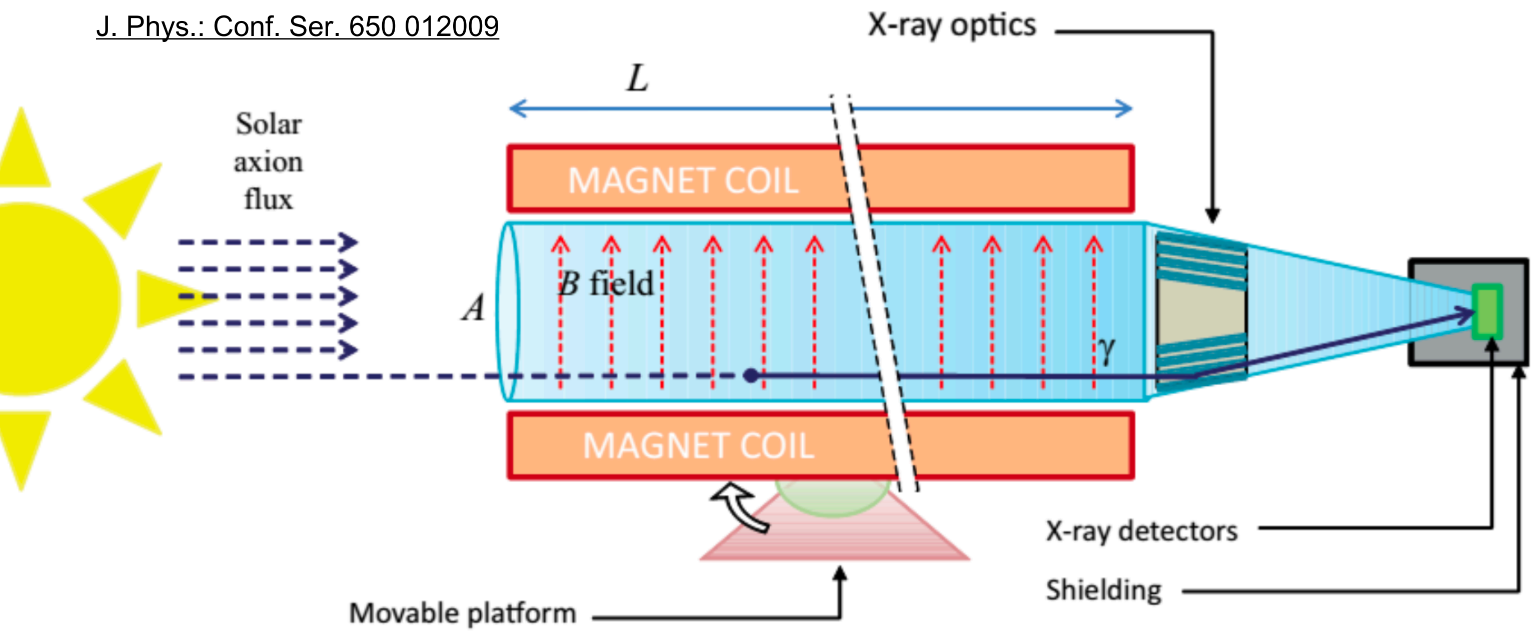
https://www.stern.de/kultur/tv/-teletubbies---so-sieht-das-baby-auf-der-sonne-heute-aus-32610940.html



Helioscopes - Basics

Components, Detection Principle and Figure of Merit

J. Phys.: Conf. Ser. 650 012009



- **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

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

The IAXO Collaboration

World's Largest Axion Collaboration

IAXO Collaboration Meeting @ Teruel, Spain, 11-14.09.23

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) | MPP Munich (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)

➡ >125 scientists from 23 full member institutions + 5 associate institutions

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World’s Largest Axion Collaboration

IAXO Collaboration Meeting @ Teruel, Spain, 11-14.09.23

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) | MPP Munich (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)

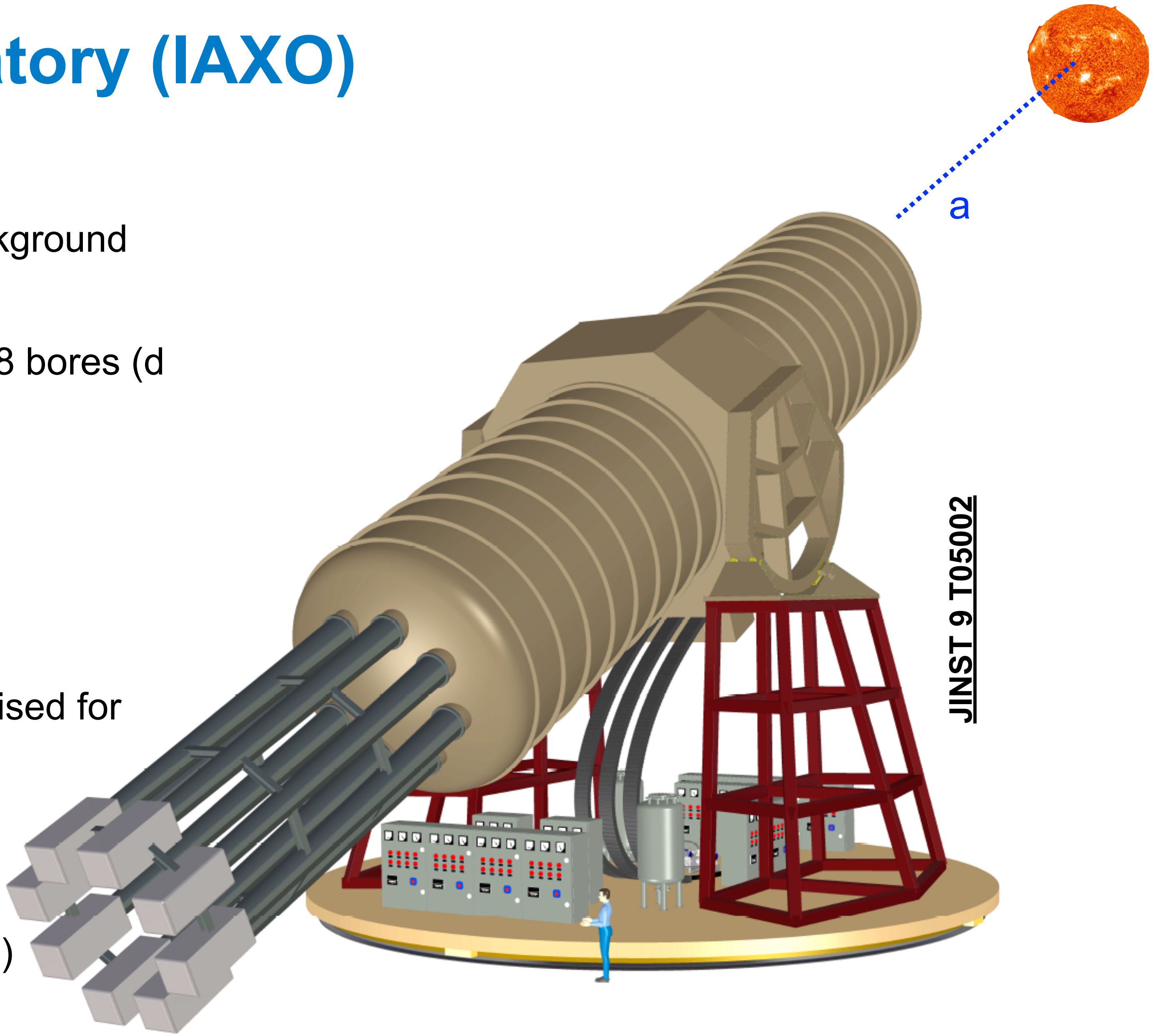
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

➡ >125 scientists from 23 full member institutions + 5 associate institutions

International AXion Observatory (IAXO)

The Next Generation Axion Helioscope

- 12 hours solar tracking + 12 hours off-sun for background measurements per day
- 20 m superconducting large scale magnet, 2-3 T, 8 bores (d = 60 cm each)
- X-ray optics with ~0.2 cm^2 focal spots
- 8 detection lines
  ➡ Complementary detector technologies optimised for different measurements
- Sensitivity FOM: **~10.000x CAST** (**C**ERN **A**xion **S**olar **T**elescope - predecessor exp.)



BabyIAXO - The Intermediate Step

But indeed not a Baby…

New life arises in HERA hall south!

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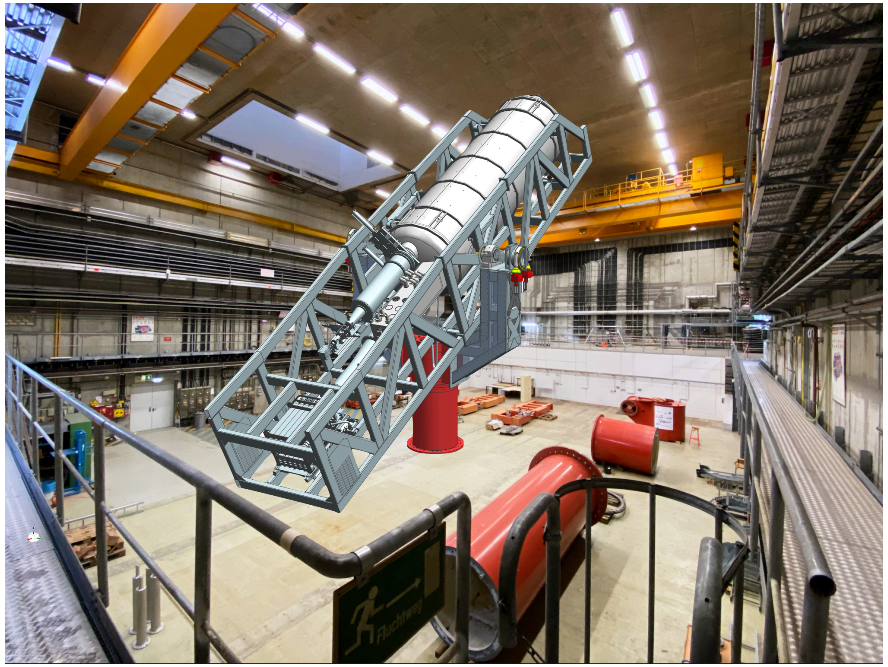


New life arises in HERA hall south!

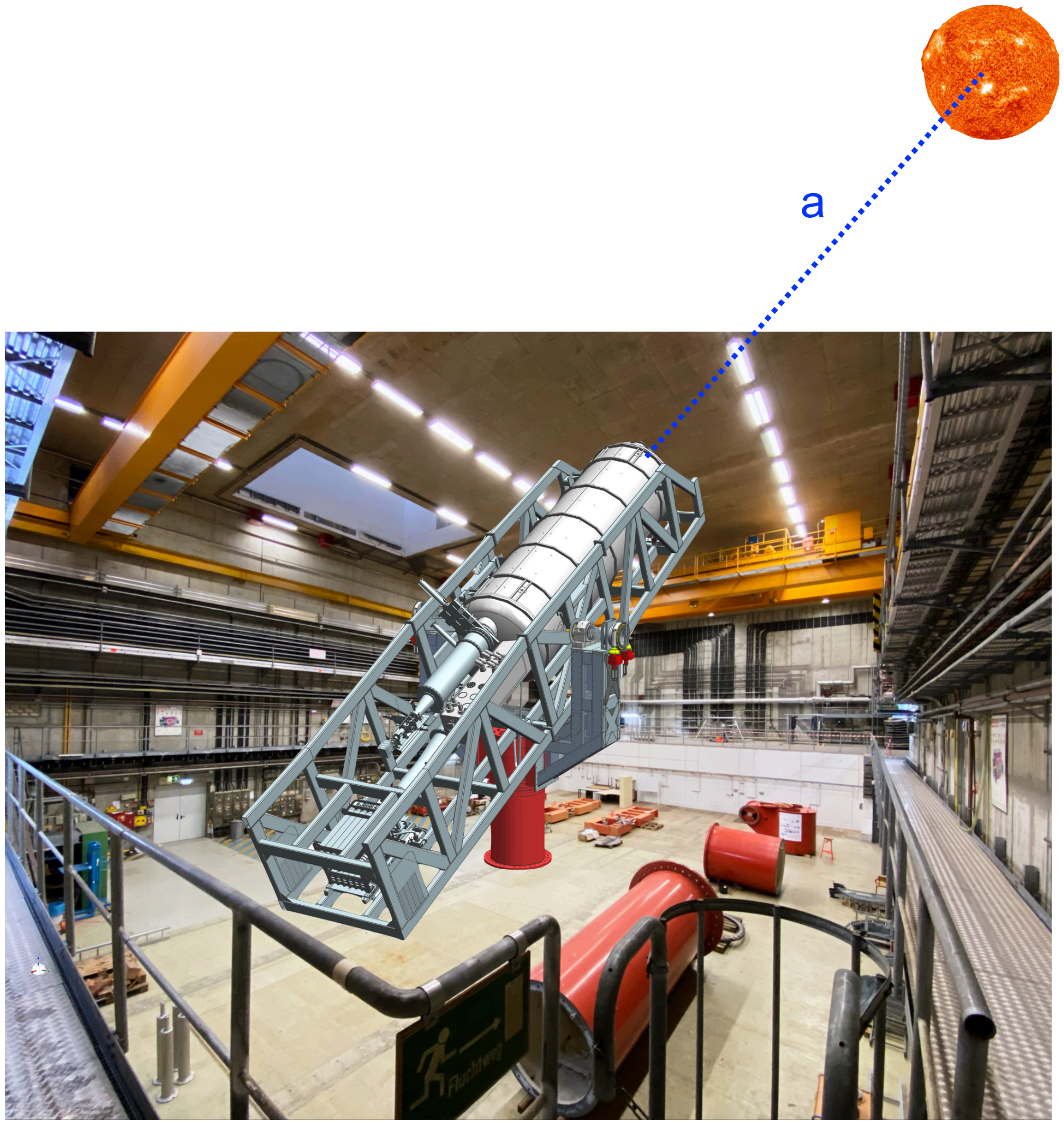
BabyIAXO - The Intermediate Step

But indeed not a Baby…

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

- Sensitivity FOM: **~100x CAST**

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



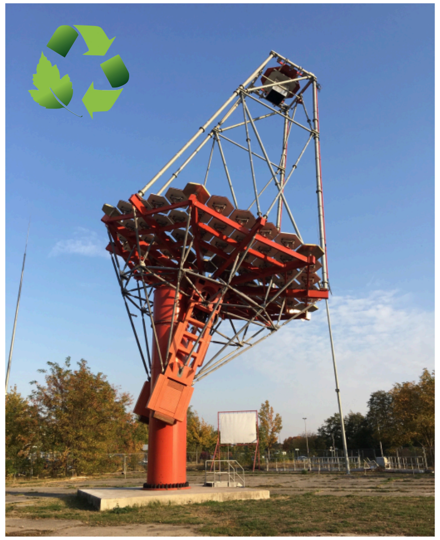
BabyIAXO - Recipe

Individual Components

- Structure & drive system: Reusing parts of CTA/MST prototype from DESY Zeuthen

    ➡ Duty cycle at least 50%

    ➡ Pointing precision < 0.01°



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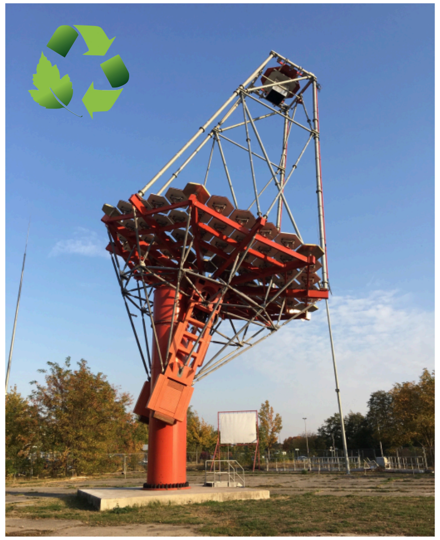

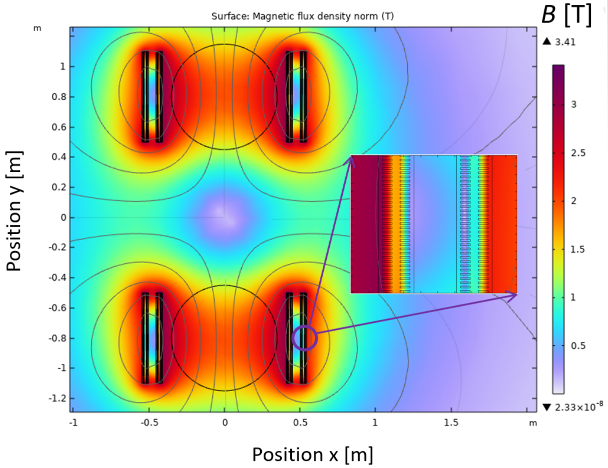

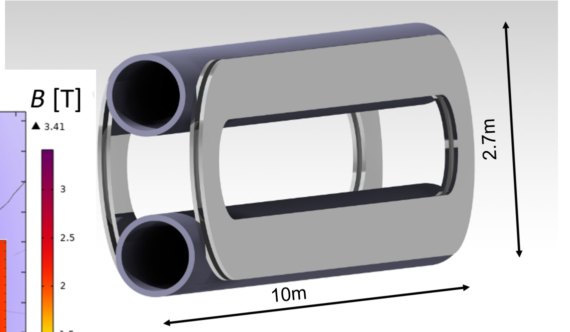

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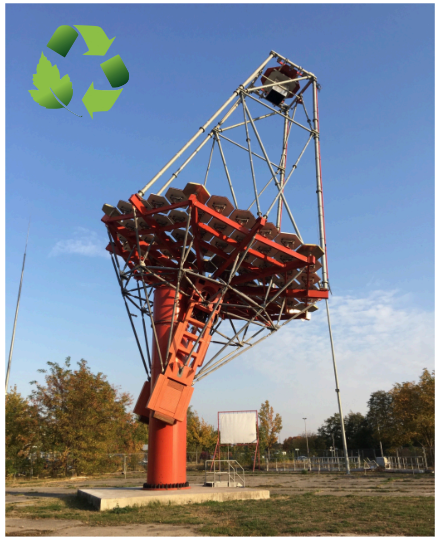

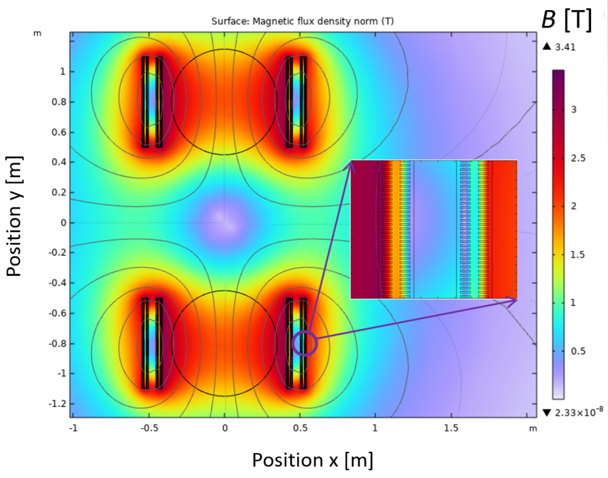

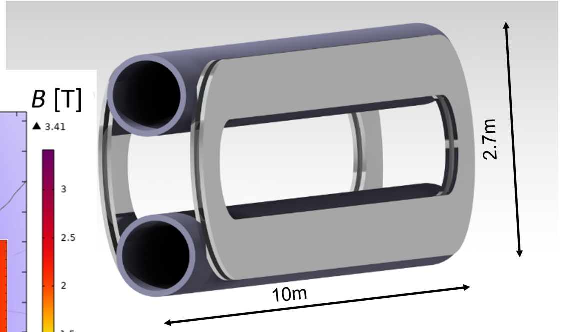

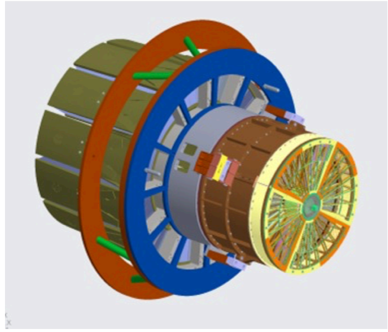

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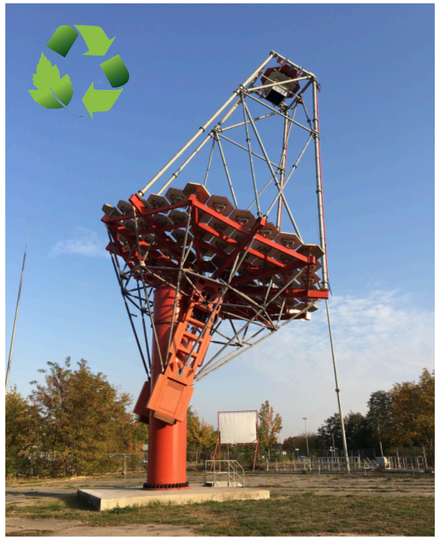

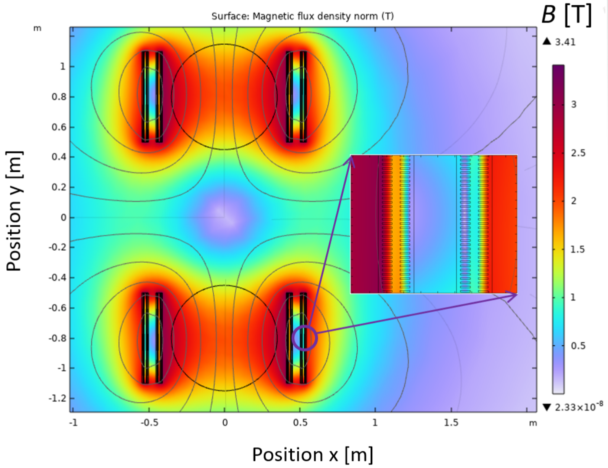

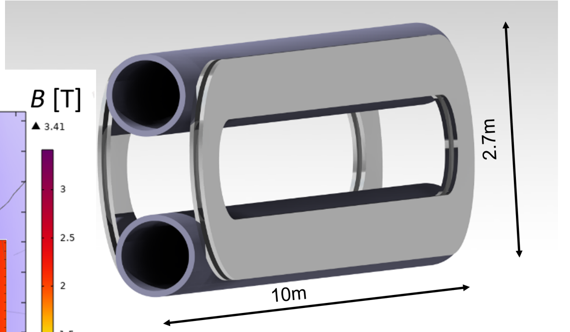

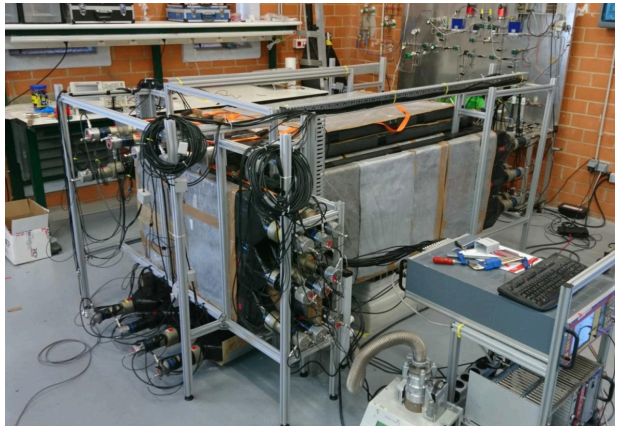

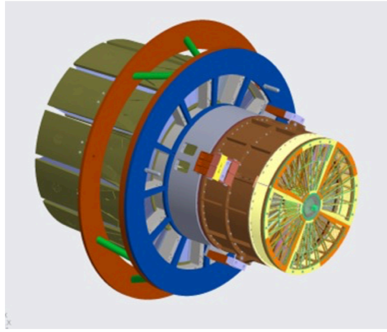

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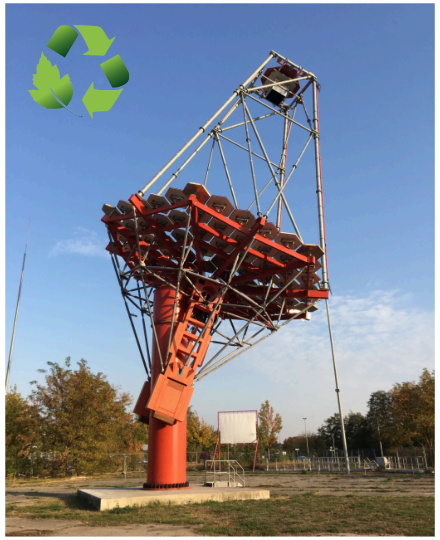
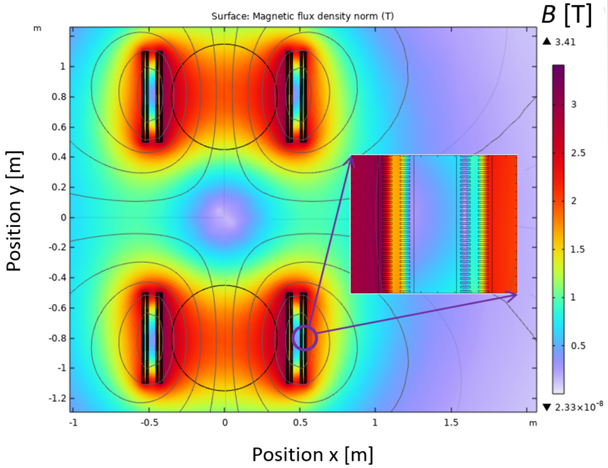
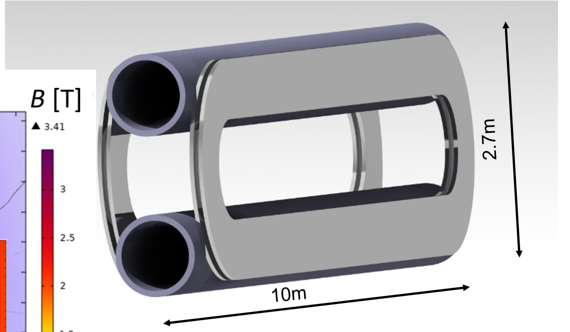
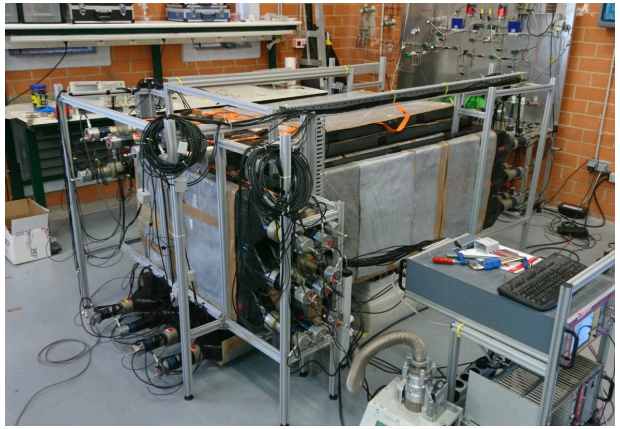
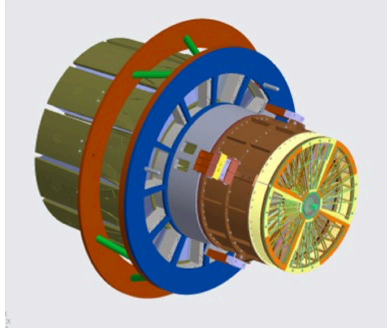
- Discovery detector: Micromegas (Micro-Mesh) TPC + shielding + veto systems
- Complementary precision detectors: optimised energy resolution and energy threshold: Gridpix TPC, SDD, TES, MMC

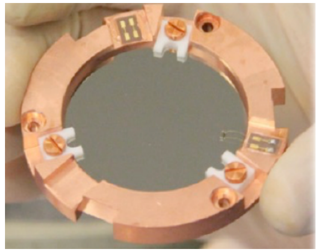


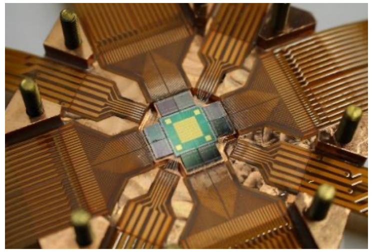


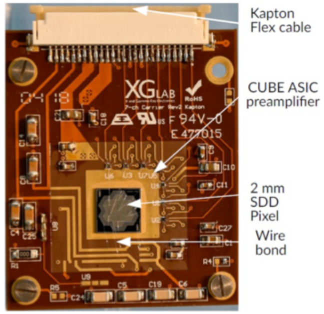












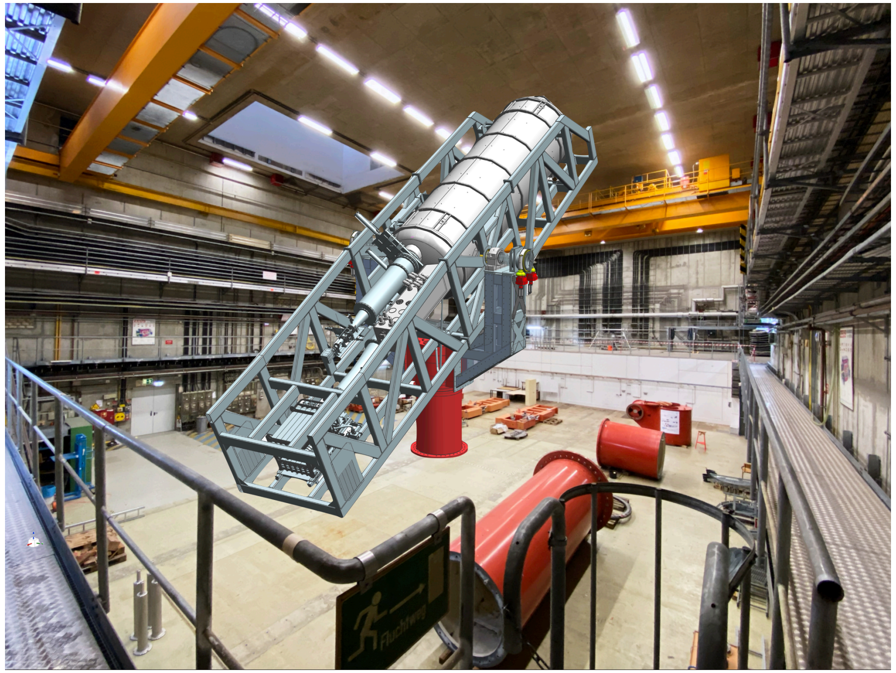
BabyIAXO - Status

Individual Components

Component / Status	Technical	Funding
Structure & Drive system	(✓)	(✓)
Vacuum & Gas System	✓	✓
Magnet	(✓)	(?)
X-ray Telescopes	✓	✓
Detectors	✓	✓

- Very good technical progress for all components

- In principle ready to start construction
  ➡ "Dry run" installation currently under discussion: install everything **expect for magnet**
    ➡ Early commissioning, alignment surveys, background measurements, initial physics runs,…



BabyIAXO - Status

Individual Components

Additional funding for magnet secured by achievement of **ERC synergy grant *DarkQuantum*** by I. Irastorza, T. Kontos, S. Paraoanu, W. Wernsdorfer, et al.

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Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

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2023/10/26

Back

ERC project to provide quantum detectors for DESY dark matter experiment

European Research Council (ERC) Synergy project to develop quantum sensors and apply them in dark matter experiments

The European Research Council (ERC) has bestowed a prestigious Synergy grant that will develop novel quantum sensors for experiments searching for dark matter. The DarkQuantum project, which is coordinated by the University of Zaragosa in Spain, has been funded with almost 13 million euros. The aim of which is the development of new quantum sensors and their application in experiments to search for axions, hypothetical particles that could make up dark matter. One of the experiments benefitting from this effort is the experiment BabyIAXO, a dark matter observatory under construction at DESY.

Download [3.0 MB, 2032 x 1530]

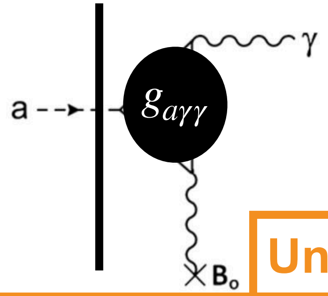
A visualisation of the BabyIAXO experiment in the underground chamber where it will be located. The quantum detectors that will be

The ERC's “Synergy” projects aim to bring together the expertise of several principal investigators (between 2 and 4) to tackle very ambitious research, which could not be carried out individually. The researcher Igor García Irastorza, professor of physics at the University of Zaragoza and leader of the DESY-based International Axion Observatory (IAXO), will lead the DarkQuantum project. The project is based on the Irastorza's extensive experience with this type of experiment, exploiting recent innovations in the field of quantum technologies. In addition to Irastorza, three other international experts in different aspects of quantum technologies are contributing, namely Takis Kontos of the École Normale Supérieure de Paris, Sorin Paraoanu of Aalto University in Finland, and Wolfgang Wernsdorfer of the Karlsruhe Institute of Technology.

Full article: here

Physics Prospects of BabyIAXO - Initial Remarks

Complementarity & Model Dependencies

Concept	Source	Detection	Model & Cosmology Dependency	Experiments
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	SUMICO, CAST, **(Baby)IAXO**

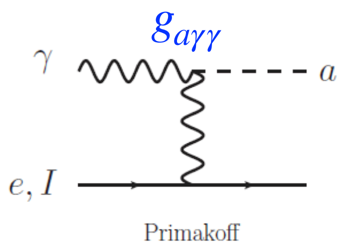
Unique environment and physics prospects!

Helioscope experiments search for WISPs independent of the Dark Matter paradigm!

Helioscopes offer a rich and unique post discovery physics program e.g. by exploiting the different solar production channels!

Solar Axions

Production Mechanisms



1. “Classical” Primakoff axions from solar plasma photons
   ➡ **Generic prediction** of most axion models
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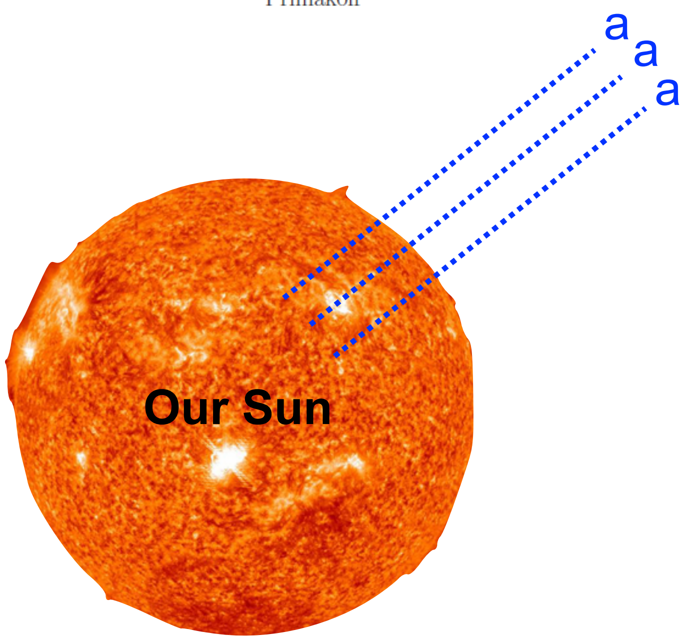
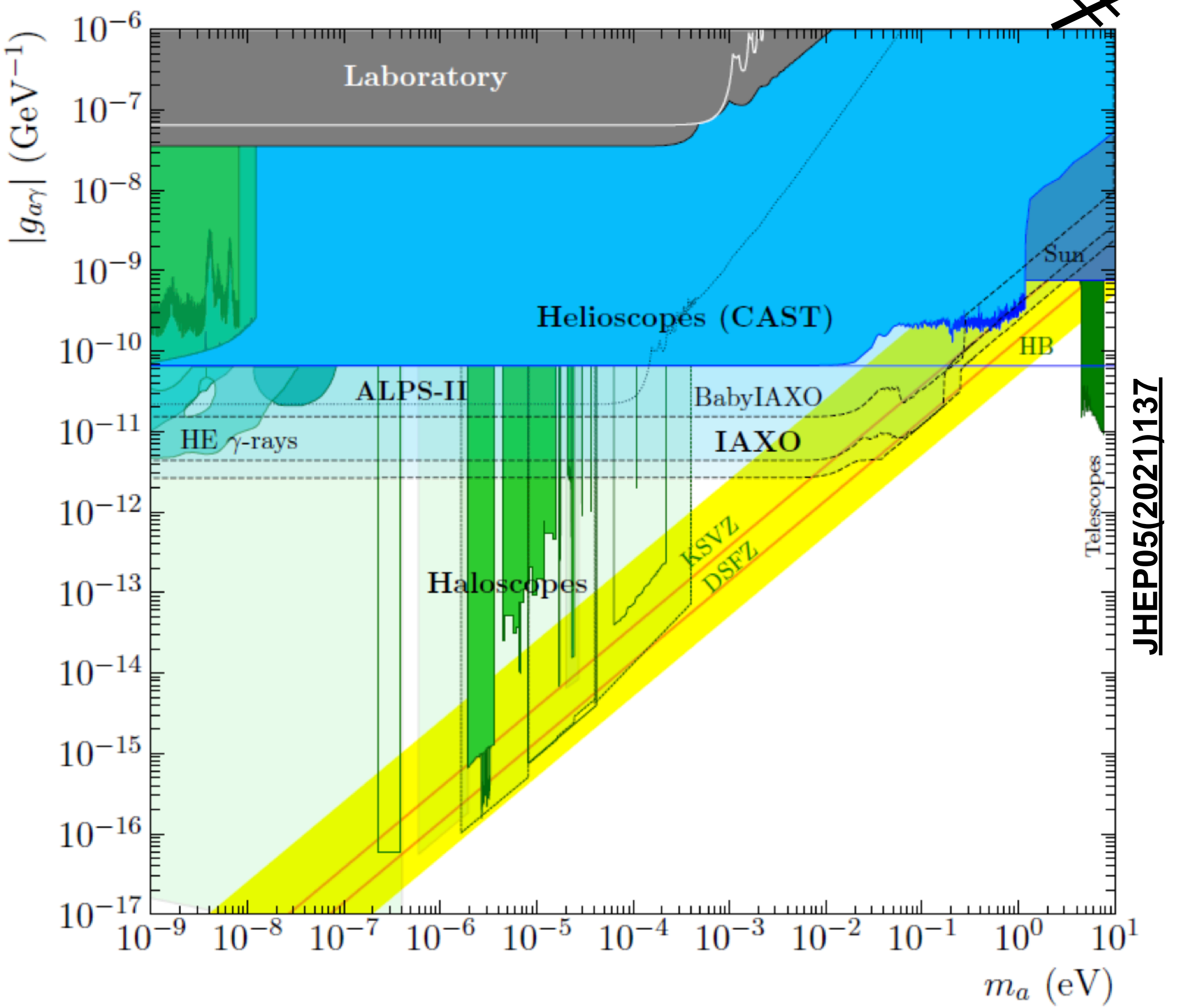


What is BabyIAXO Aiming for?

Classical (Primakoff-)Axion-Photon Coupling

- Improve $g_{a\gamma\gamma}$ sensitivity (~3x better than CAST):

Collider



JHEP05(2021)137

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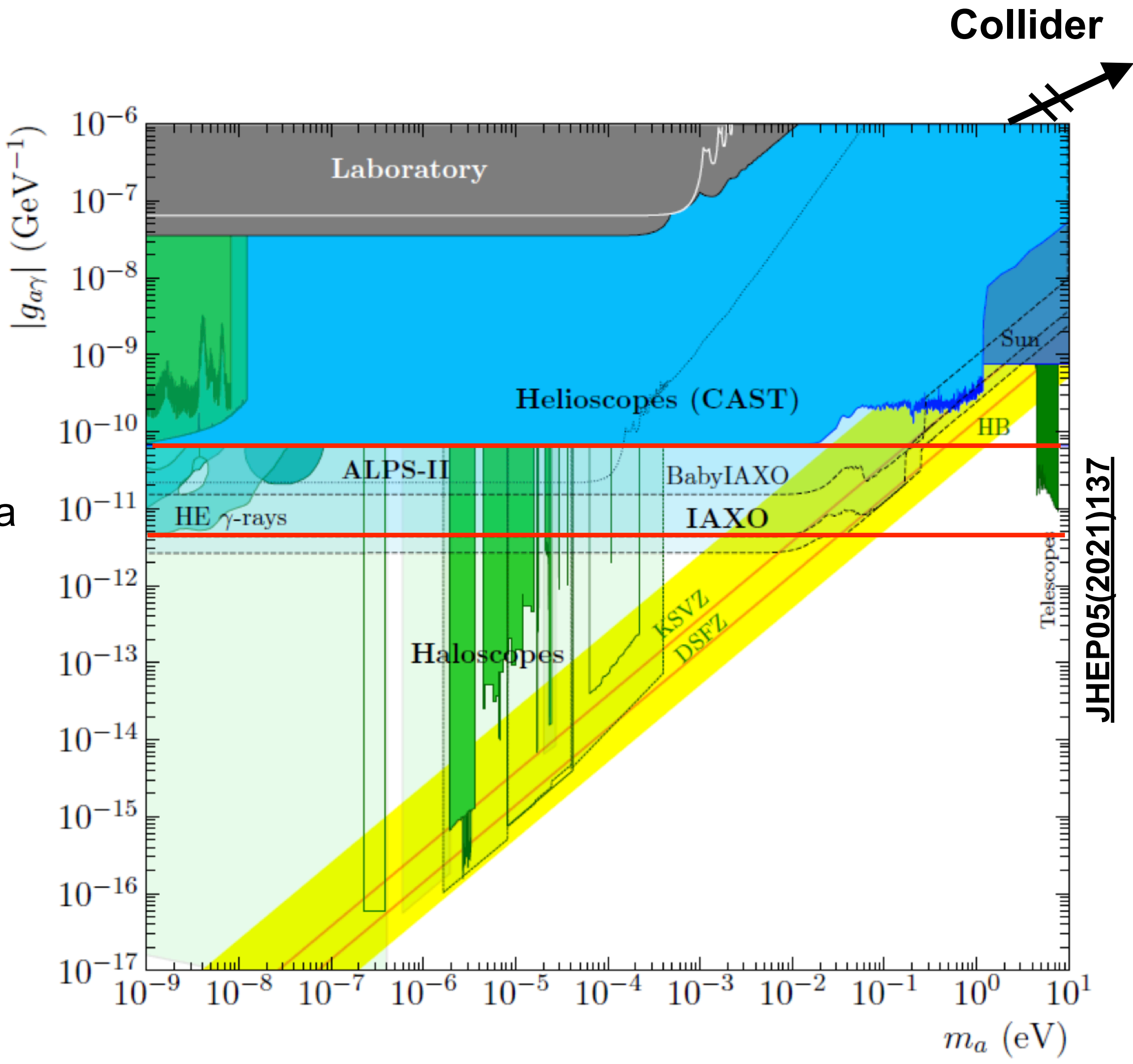
      - ➡ Compare $g_{a\gamma\gamma}$: vacuum and solar plasma



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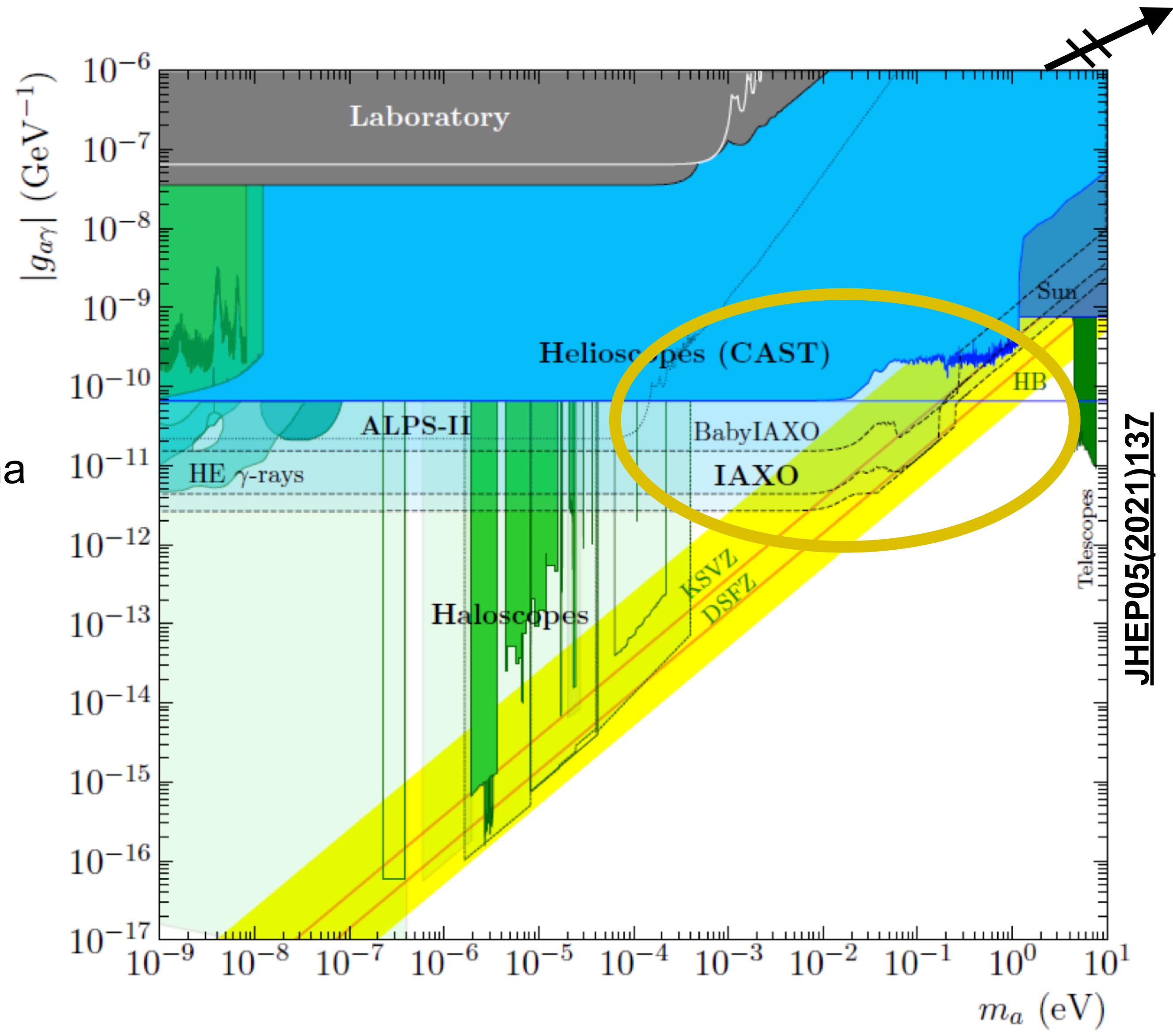

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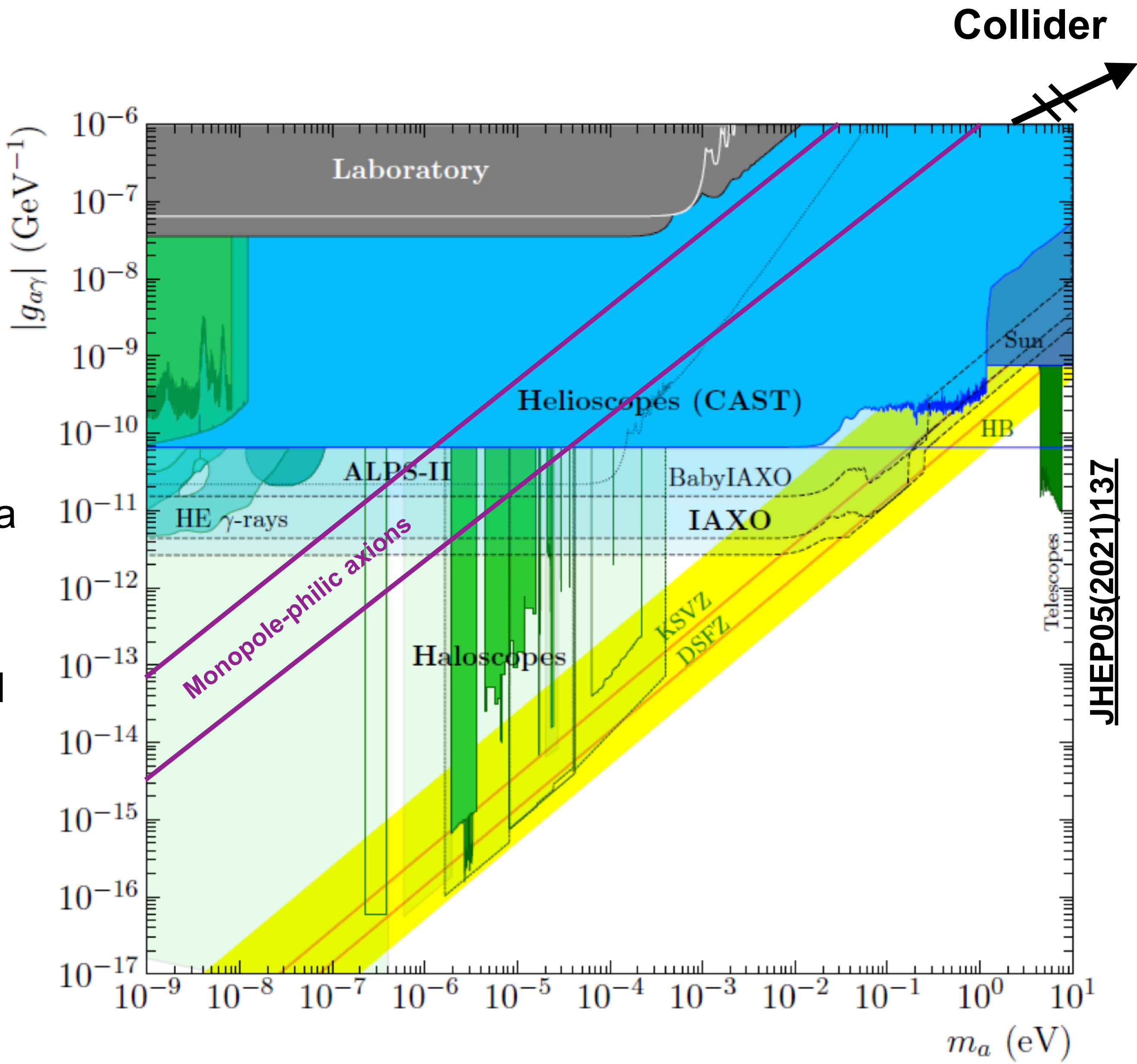
    e.g. recent benchmark by Sokolov-Ringwald:
    JHEP06(2021)123



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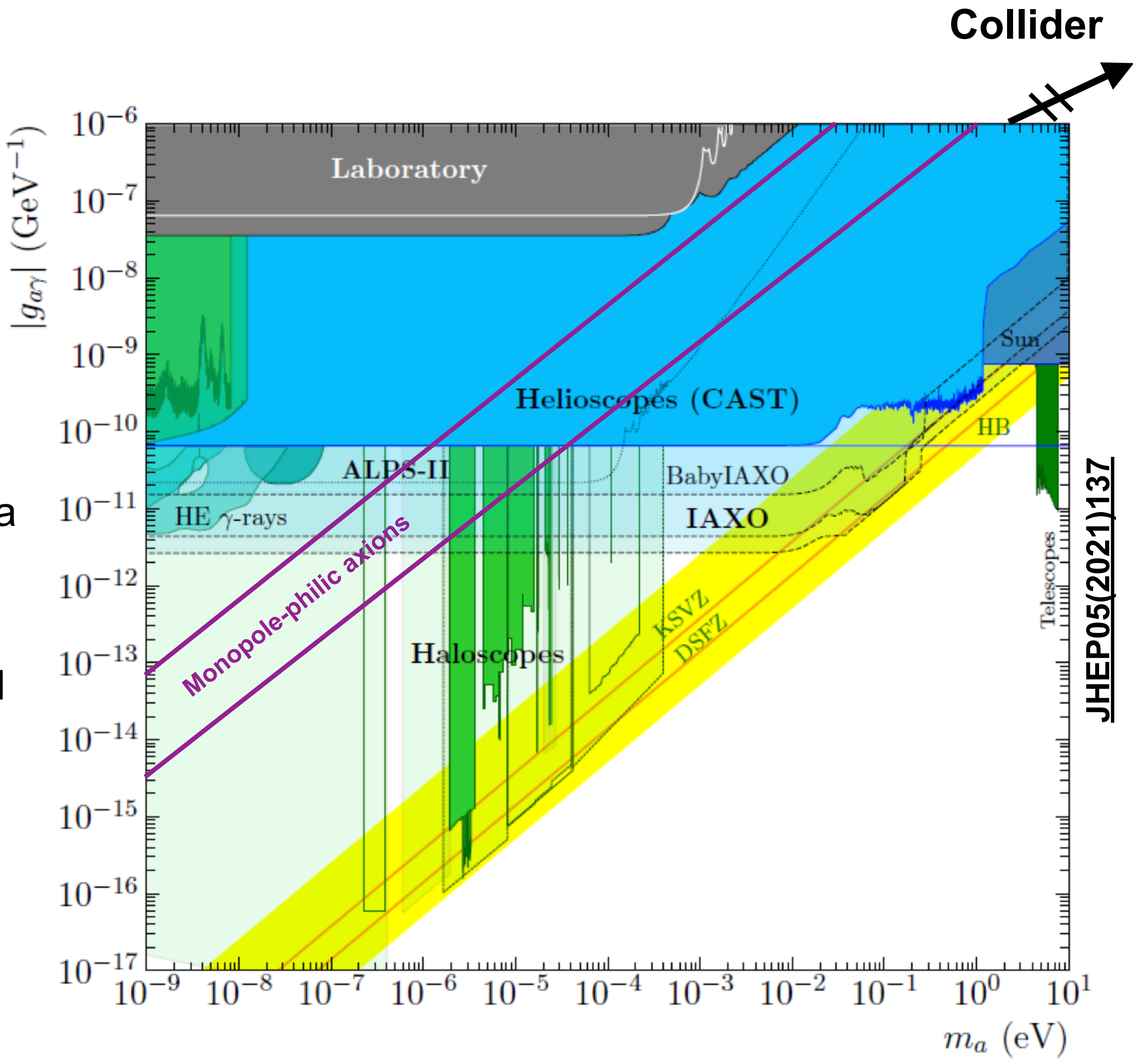
➡ Let's assume a discovery. Next goal: constrain the BSM model with (Baby)IAXO!



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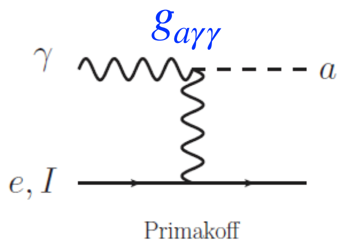
Solar Axions

Production Mechanisms



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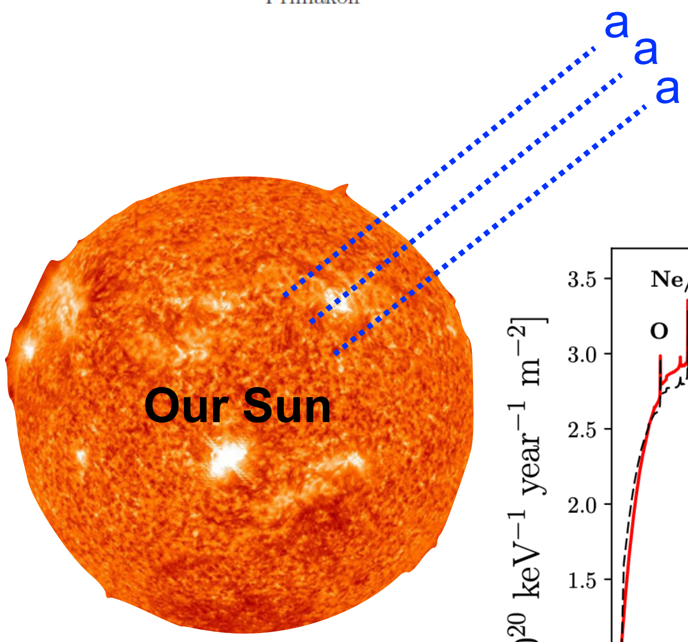

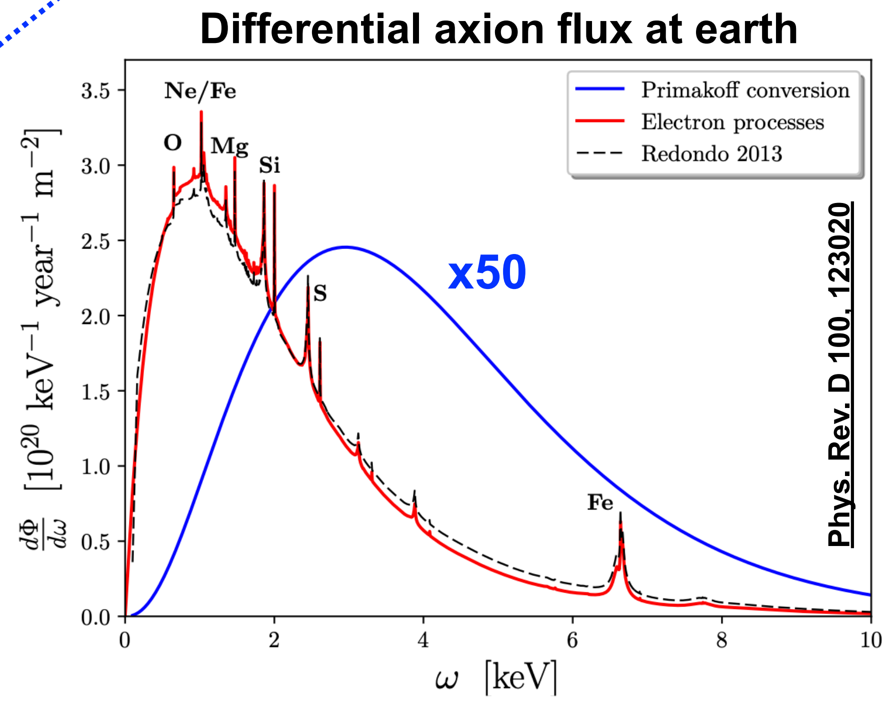

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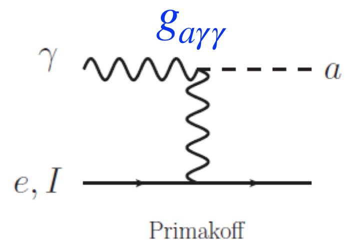

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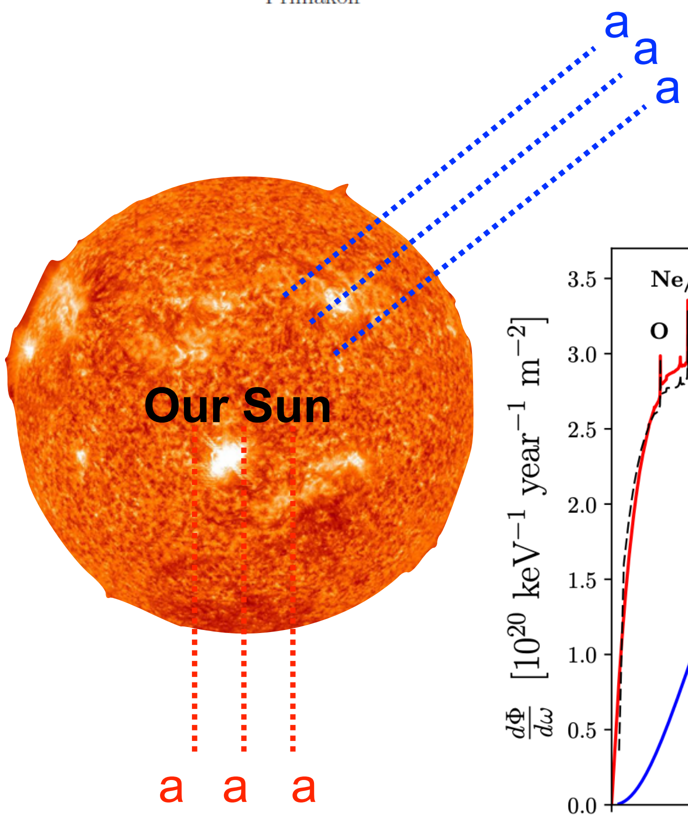

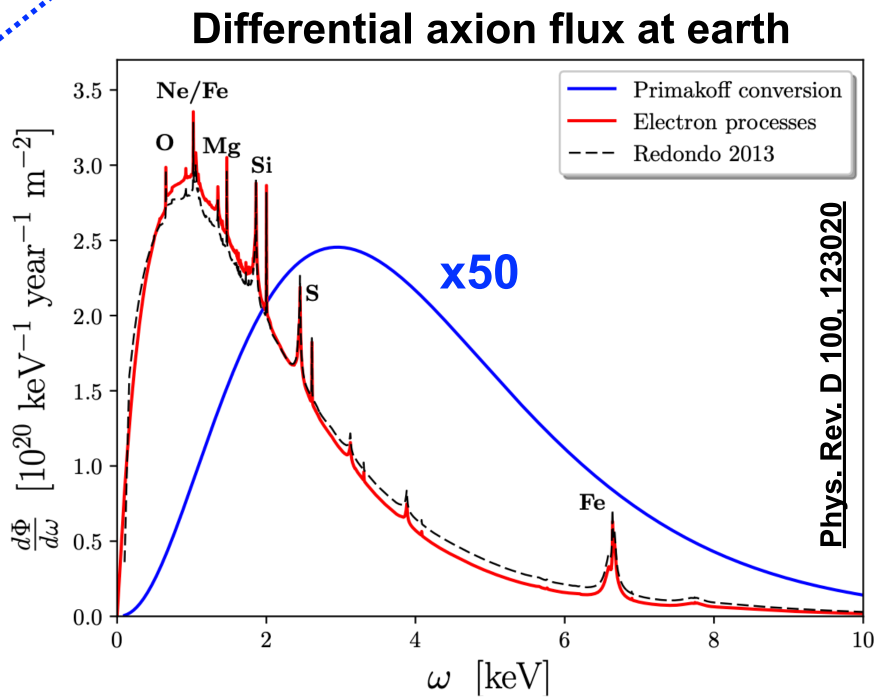

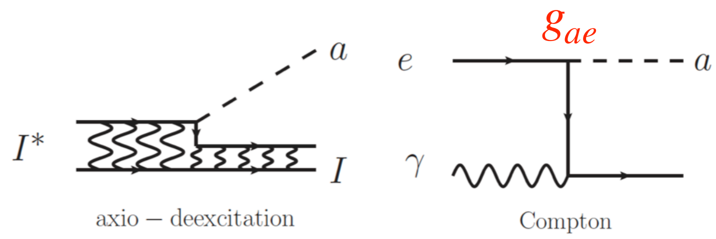

"ABC" solar axions from axion-electron coupling
- ➡ **Model dependent**
- ➡ Energy: continuous spectrum + elemental peaks

Solar Axions

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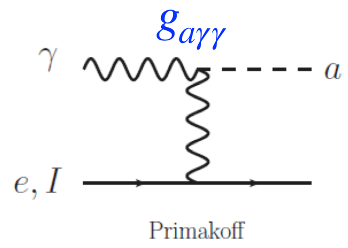

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3. Solar axions from axion-nucleon coupling g_{an}
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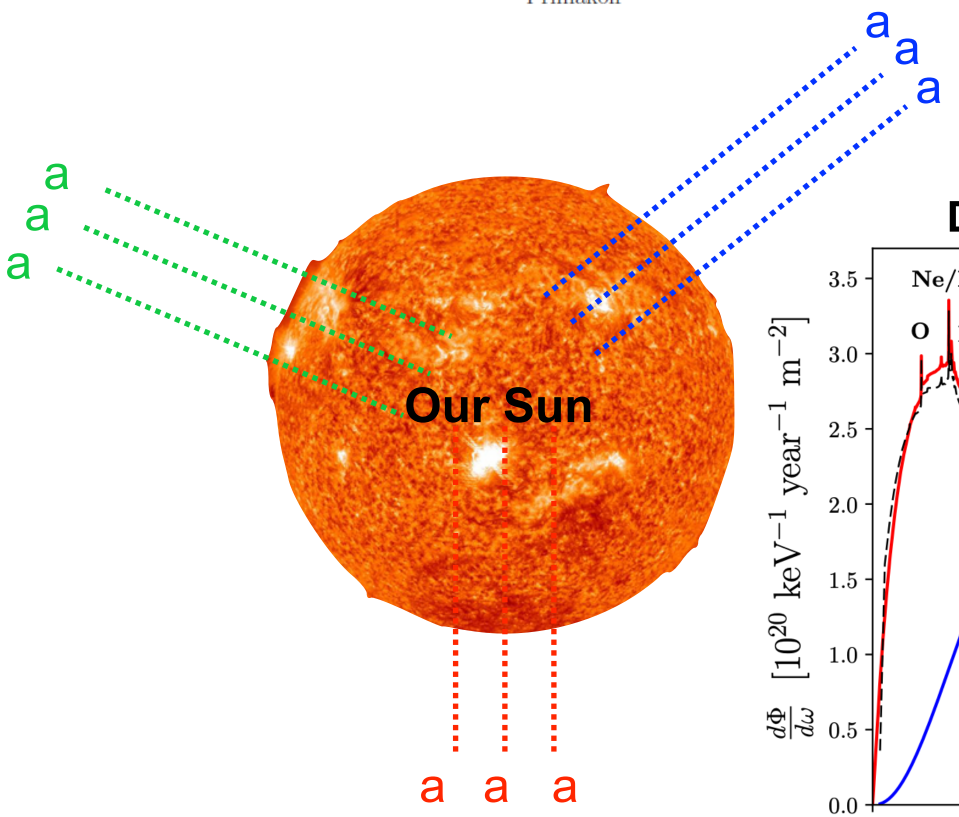
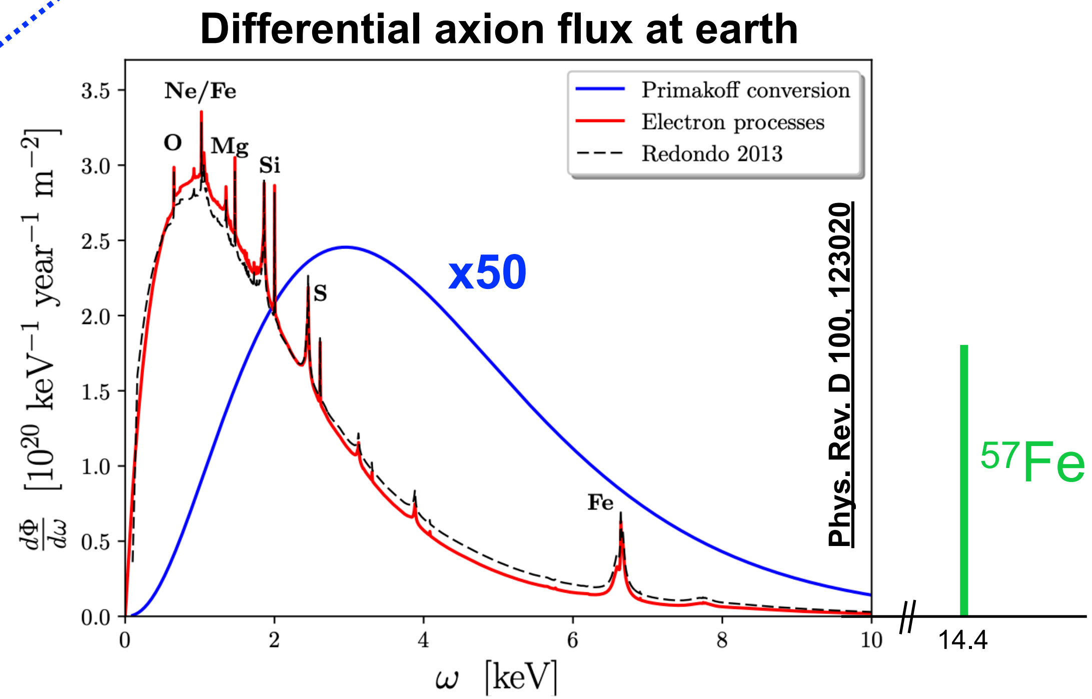
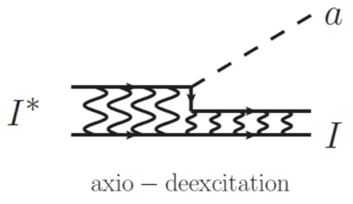
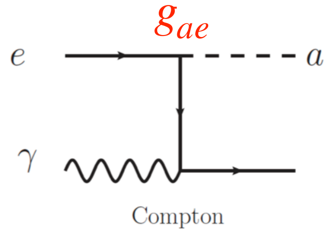
   ➡ Most promising: nuclear transition ^{57}Fe (14.4 keV)









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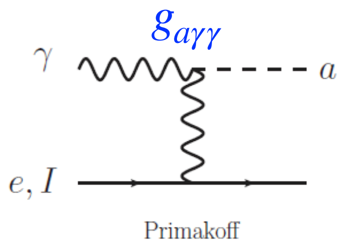

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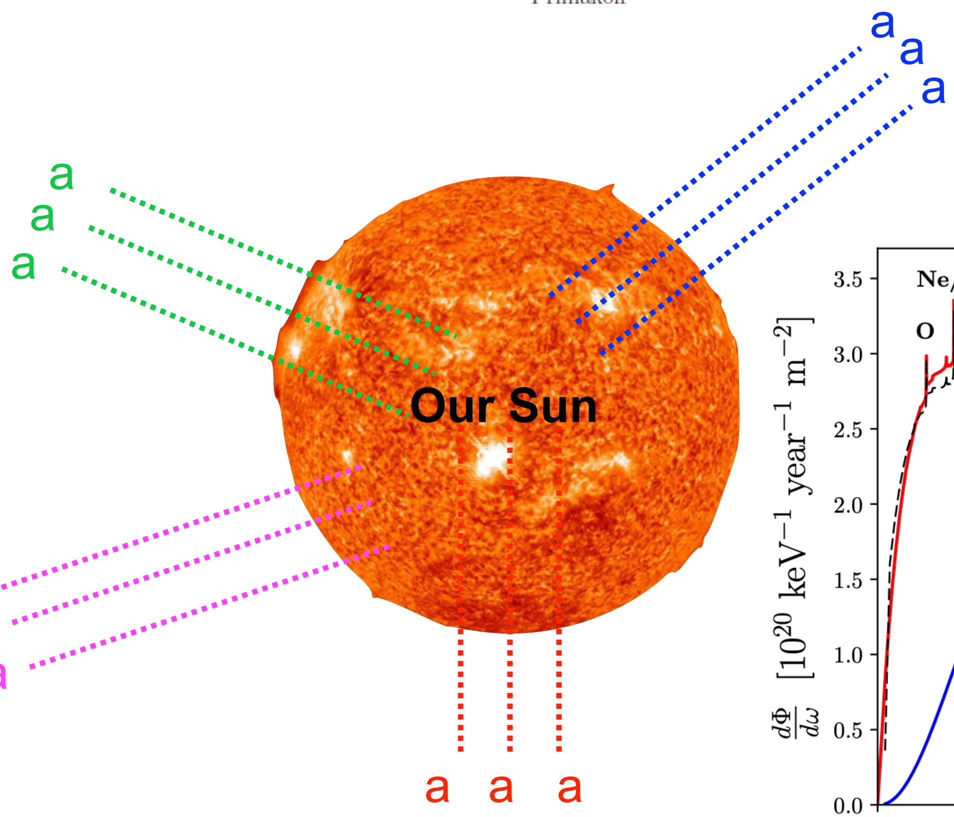
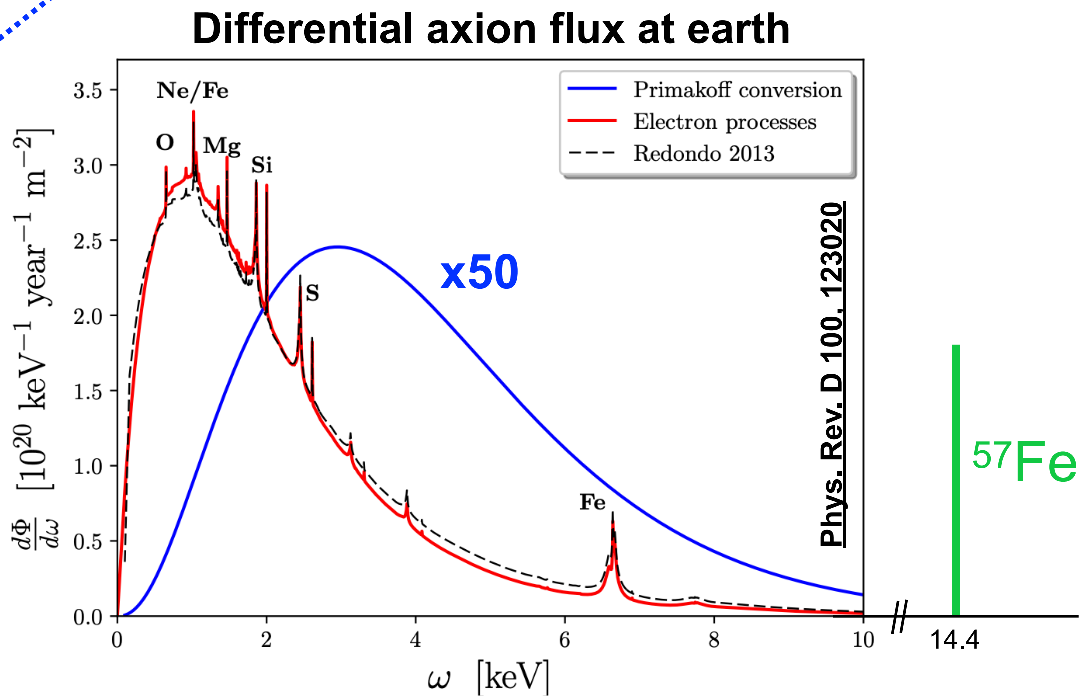
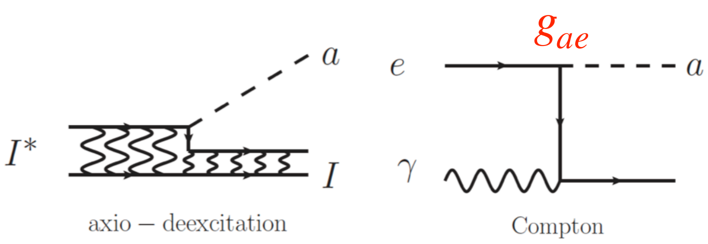




4. Other channels:

<u>**Phys. Rev. D 101, 123004**</u>

<u>**Phys. Rev. D 102, 123024**</u>



"ABC" solar axions from axion-electron coupling
➡ **Model dependent**
➡ Energy: continuous spectrum + elemental peaks

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

Basic Idea and Strategies

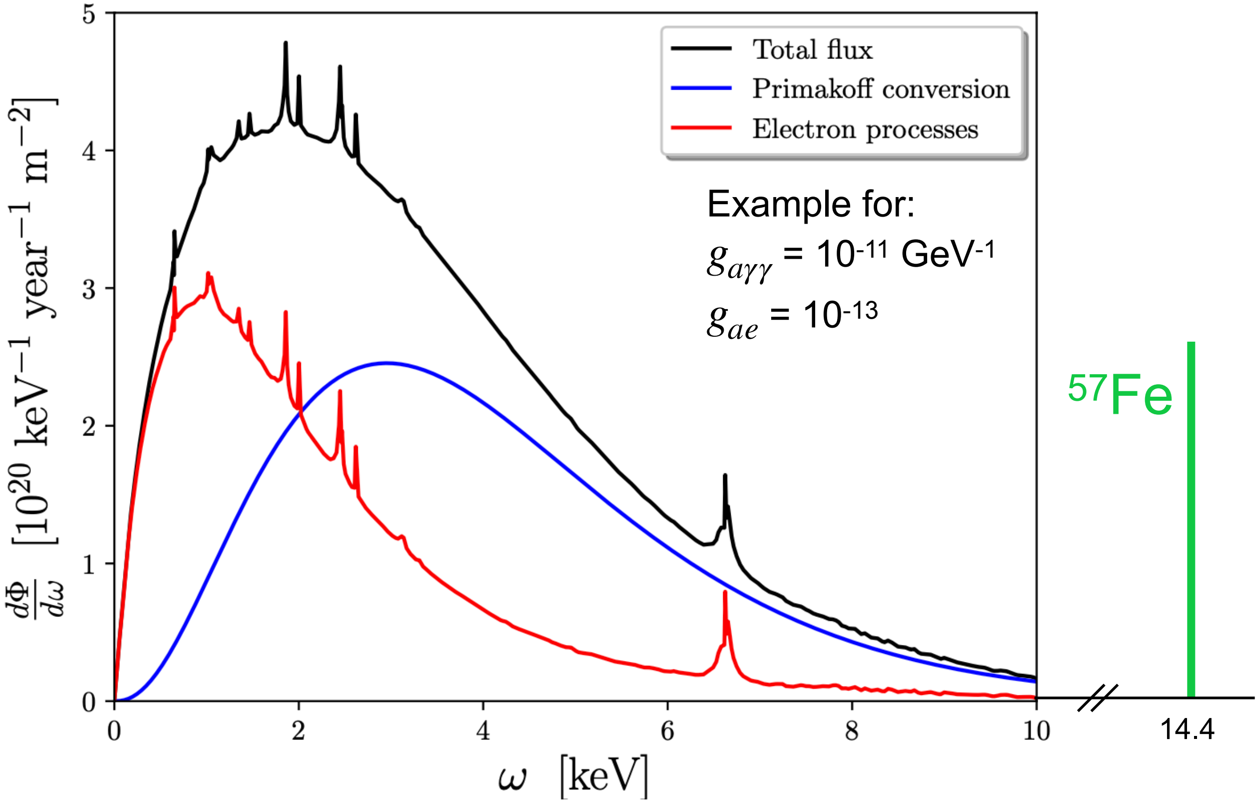
- Main idea: measured axion spectrum contains axions from different couplings

- 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



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

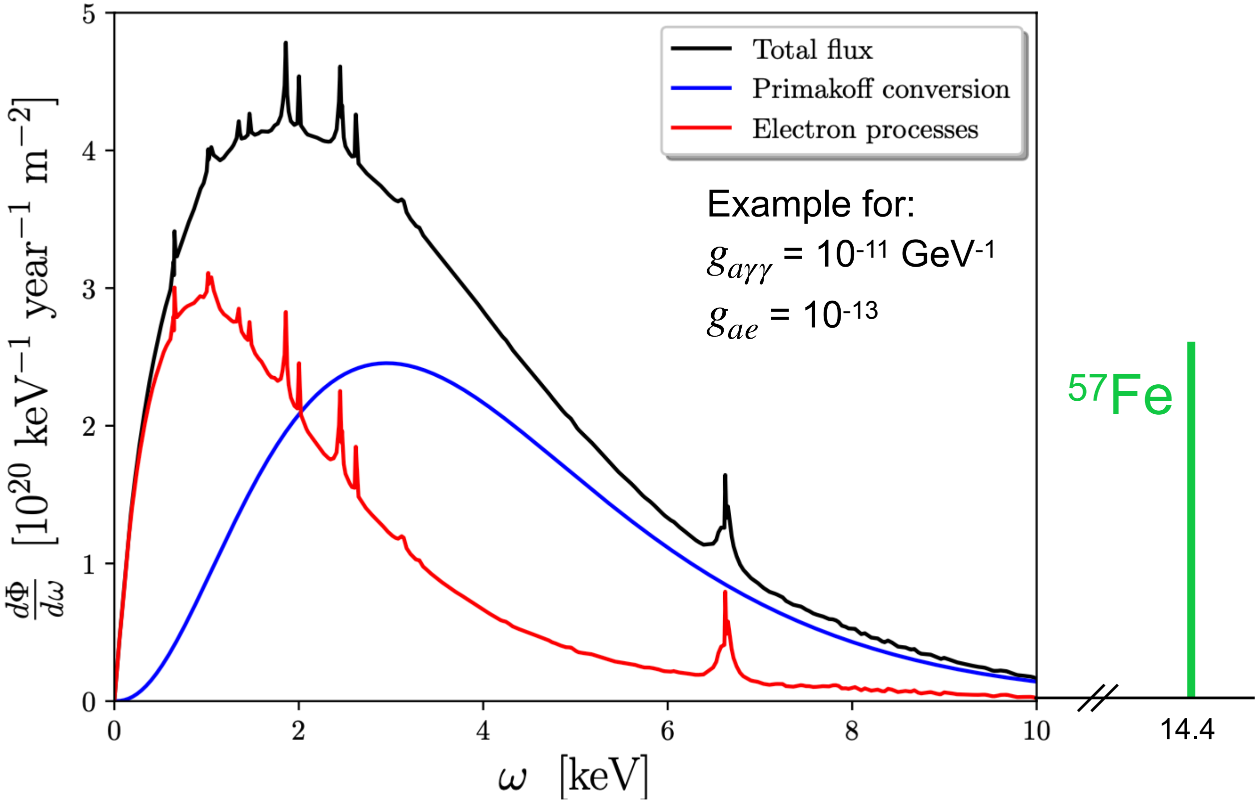
- Helioscope-specific techniques (e.g. buffer gas) allow m_a measurement in large range

- Detailed studies conducted to investigate potential sensitivities with different optics, detectors, etc.

JCAP03(2019)039

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

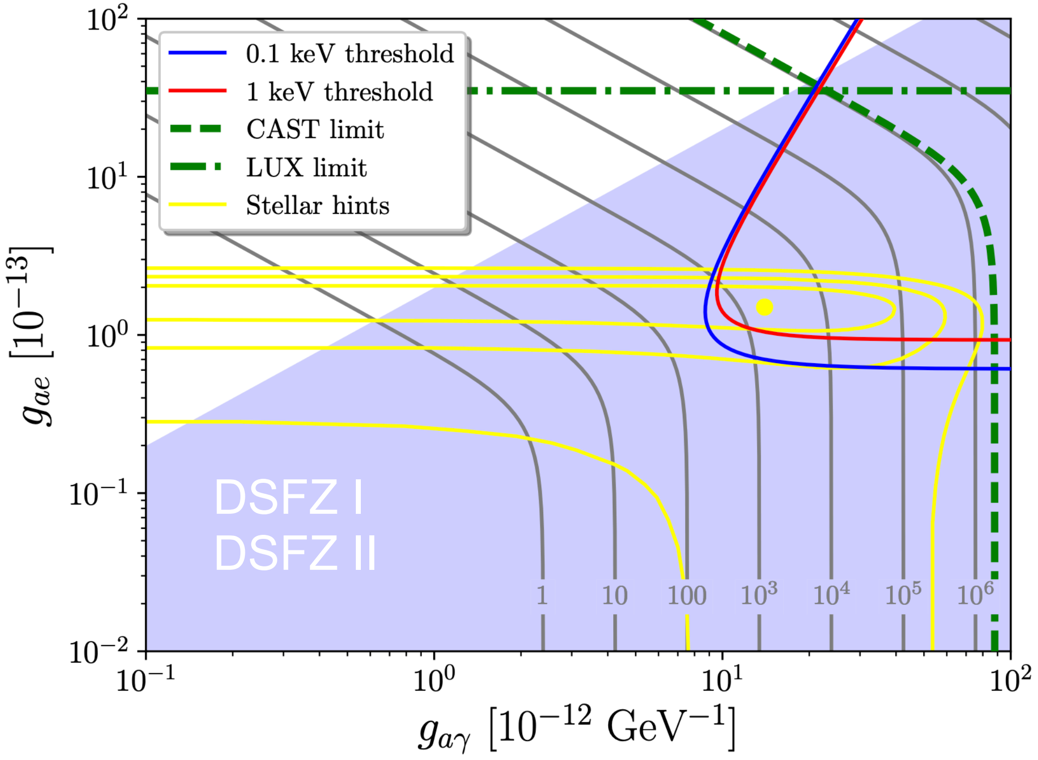
Differential axion flux at earth



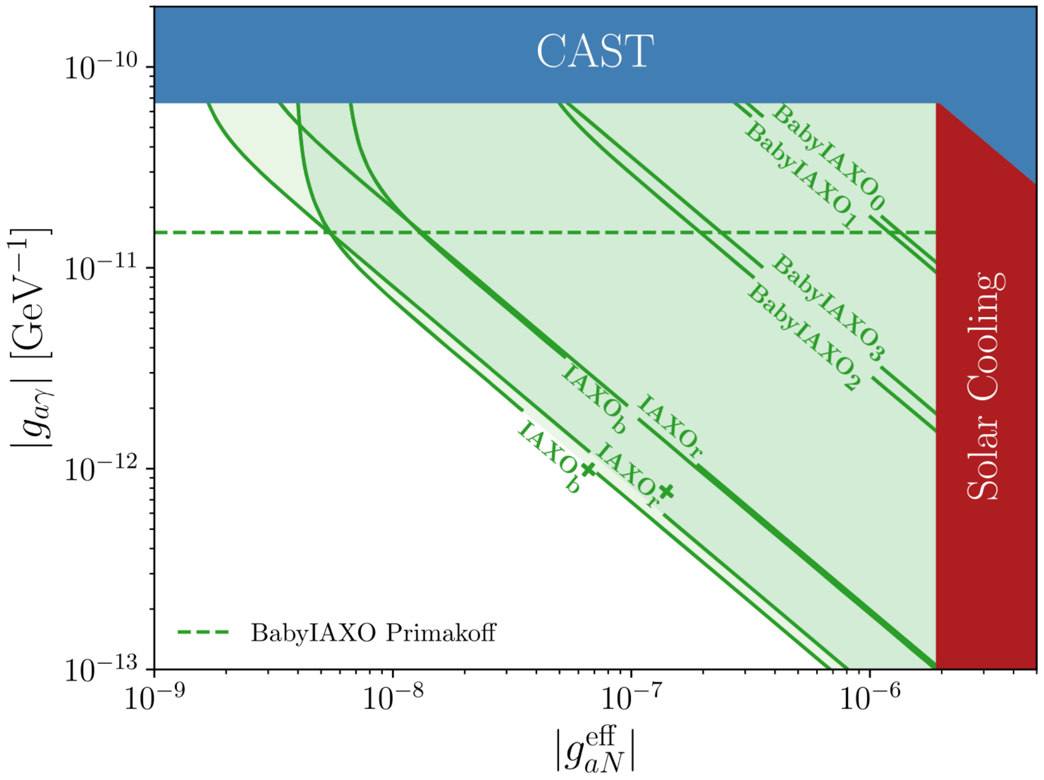
Testing Axion Models with (Baby)IAXO

Studied Sensitivity Examples

JCAP03(2019)039



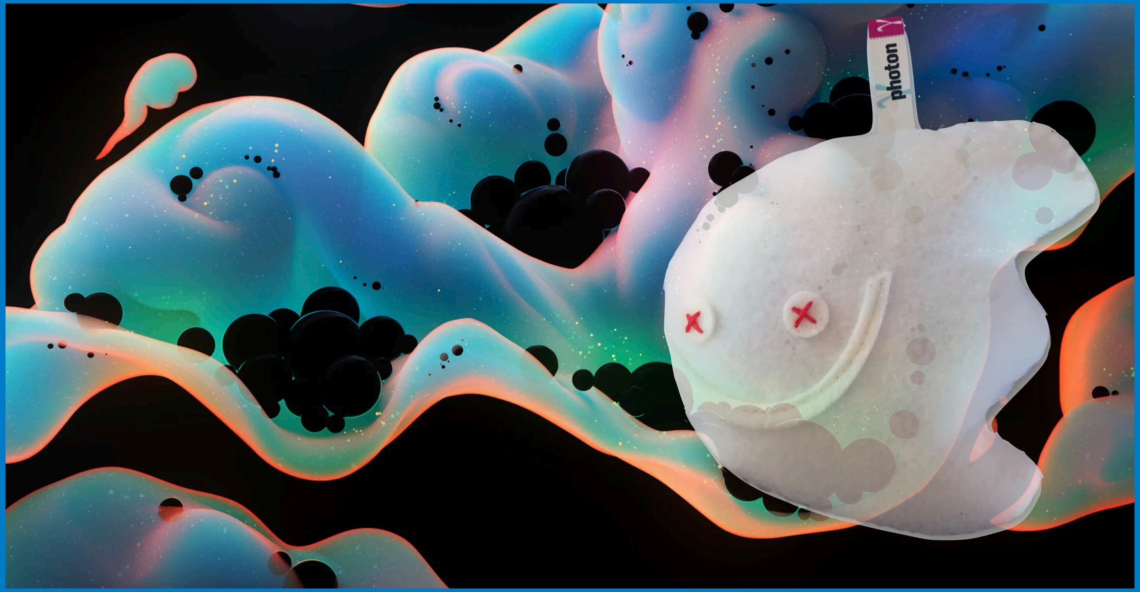
➡ Already BabyIAXO will be able to **confront different axion models**!



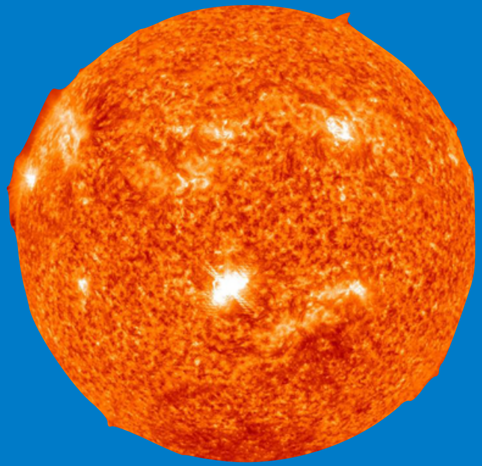
- Studies help to guide optimisation of sub-systems for specific channels
  - ➡ IAXO & IAXO+ will deliver higher statistics

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

Further Searches with ALPS II & BabyIAXO



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



And What About Dark Matter?

Haloscope Approaches with BabyIAXO Magnet

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

Let's assume…

…ALPS II discovers an axion/ALP
+
(Baby)IAXO confirms and constrains the underlying model

Or

…(Baby)IAXO discovers an axion/ALP
+
constrains the underlying model

Next question: does the discovered particle contribute to or constitute Dark Matter?

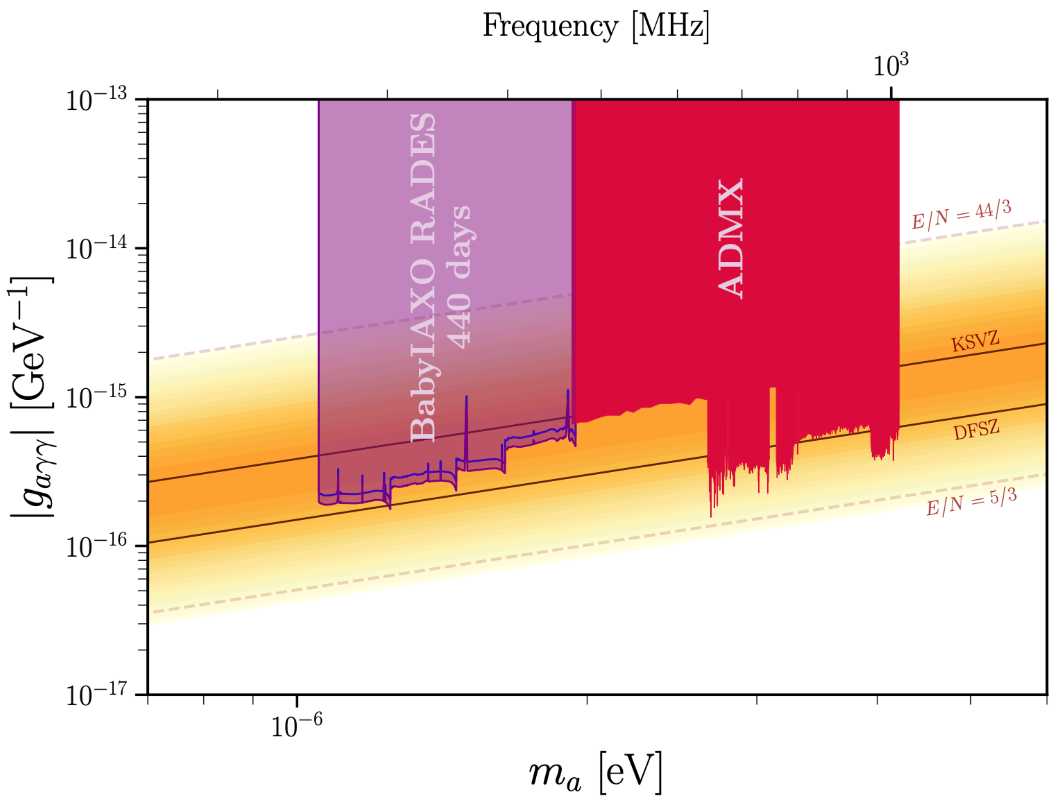
BabyIAXO as Haloscope

Searching for DM Axions

Strongly backed up by achievement of **ERC synergy grant *DarkQuantum*** by I. Irastorza, T. Kontos, S. Paraoanu, W. Wernsdorfer, et al.

- Main idea: Use BabyIAXO magnet for haloscope searches
  - ➡ BabyIAXO magnet bore: e.g. 4x 5m cavities to target 1-2 μeV range down to vanilla QCD axion band!
  - ➡ Multiple concepts under development and discussion

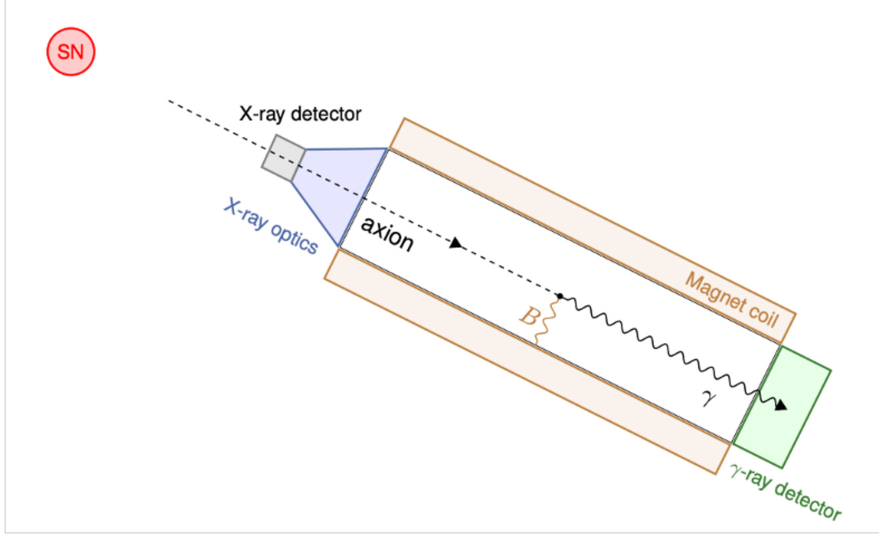
RADES-BabyIAXO Prototype



arXiv:2306.17243
(Submitted to AdP)

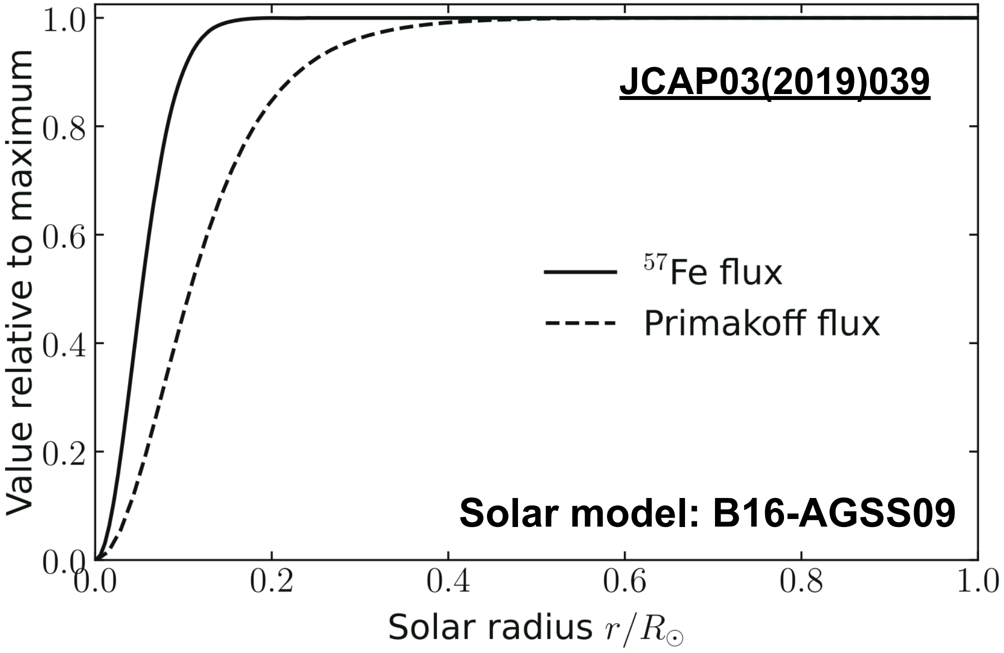
BabyIAXO & ALPS II Further Searches

A Broad Spectrum of Ideas and Studies



Solar Physics and Supernovae Axions with (Baby)IAXO

- 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 measurements to map magnetic fields, temperature and chemistry within Sun Phys. Rev. D 102, 043019

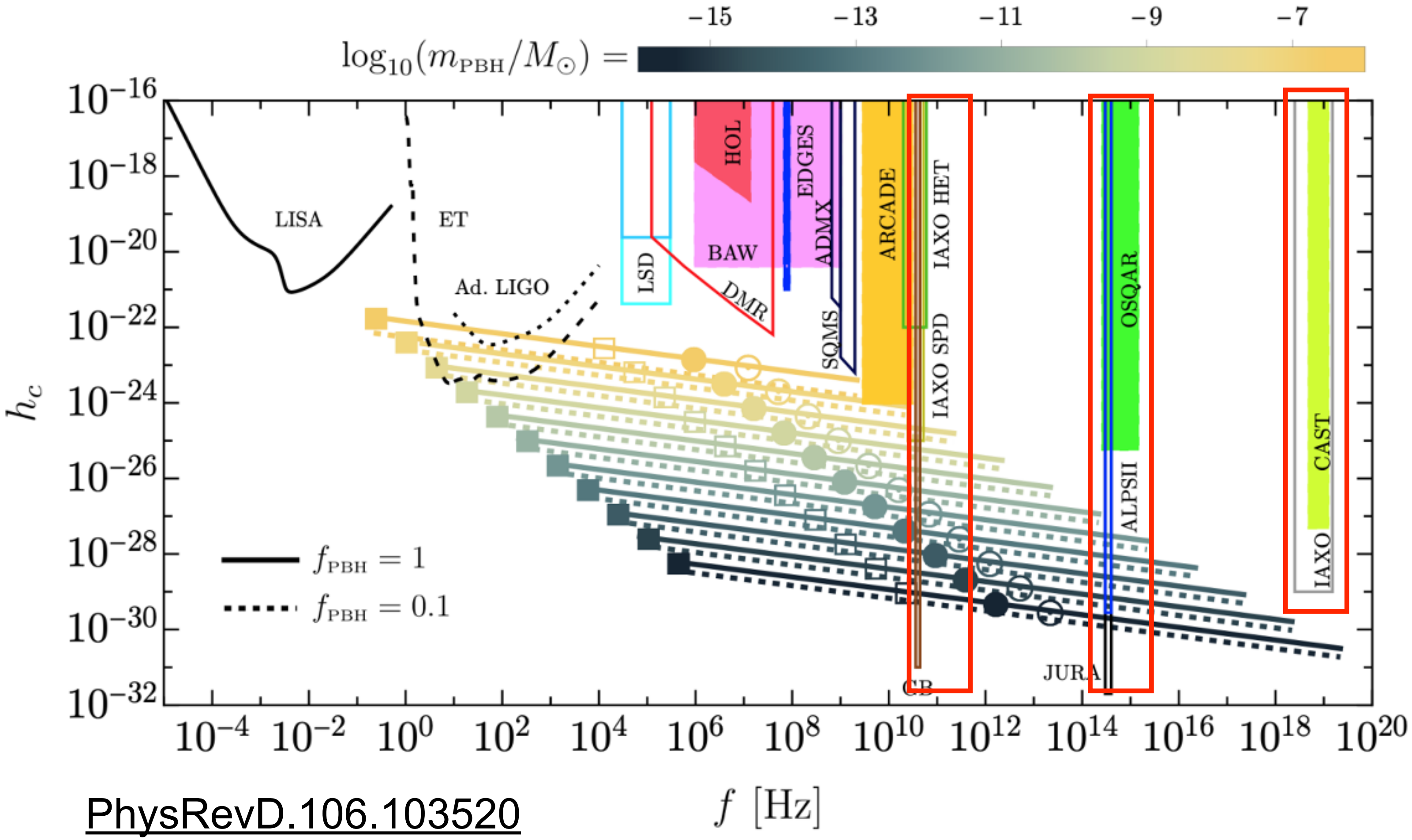


Standard Model Precision Tests with ALPS II:

- 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?

Summary & Outlook

… and a Dream

- DESY hosts a rich and complementary axion/ALP program over the next two decades

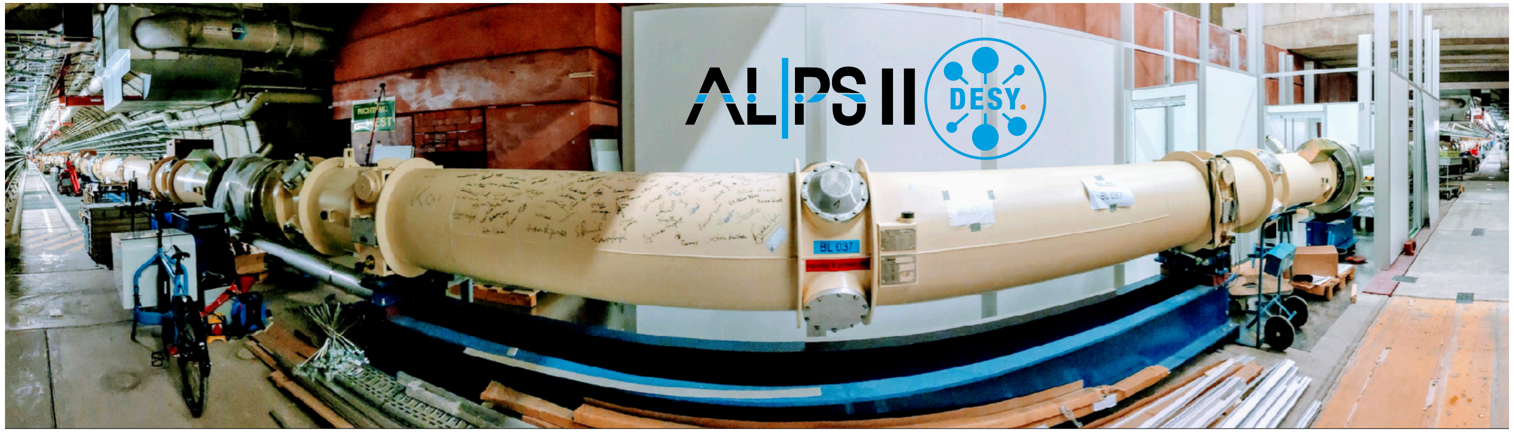
- ALPS II started data taking in May 2023 and is currently running
  - ➡ Discover axion/ALP and determine the ALP-photon coupling model-independently

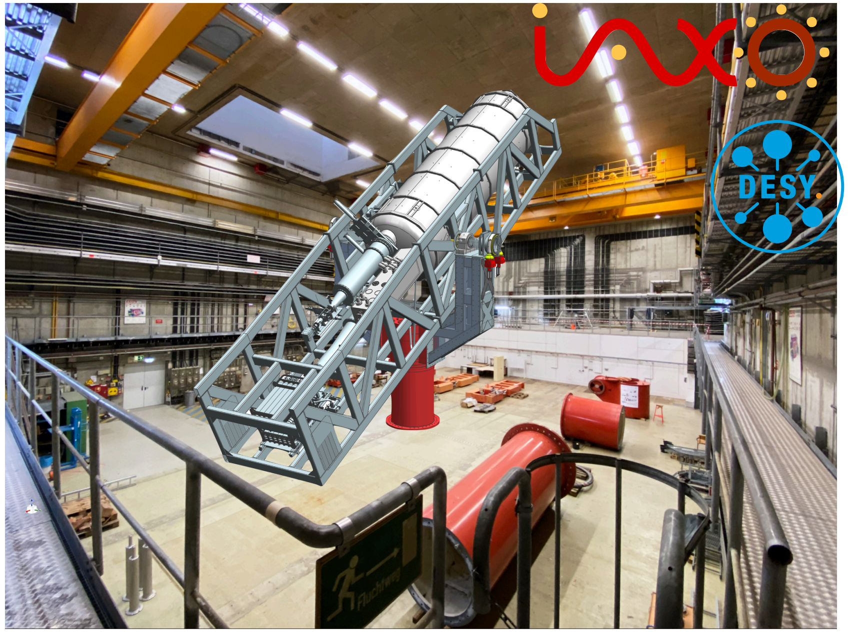
Independent of the DM paradigm

- Significant progress towards the construction of BabyIAXO:
  - ➡ Confirm ALPS II discovery (and compare $g_{a\gamma\gamma}$ measurement) or discover the axion/ALP
  - ➡ Constrain the nature of the underlying BSM model by probing $g_{a\gamma\gamma}$, g_{ae} , g_{aN} and m_a

- Expanding physics case: haloscope searches (complementary to MADMAX @ DESY), VBM, solar physics, supernovae axions, HFGW,…

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





Test our recent BabyIAXO augmented reality model! (Tested only for iOS)

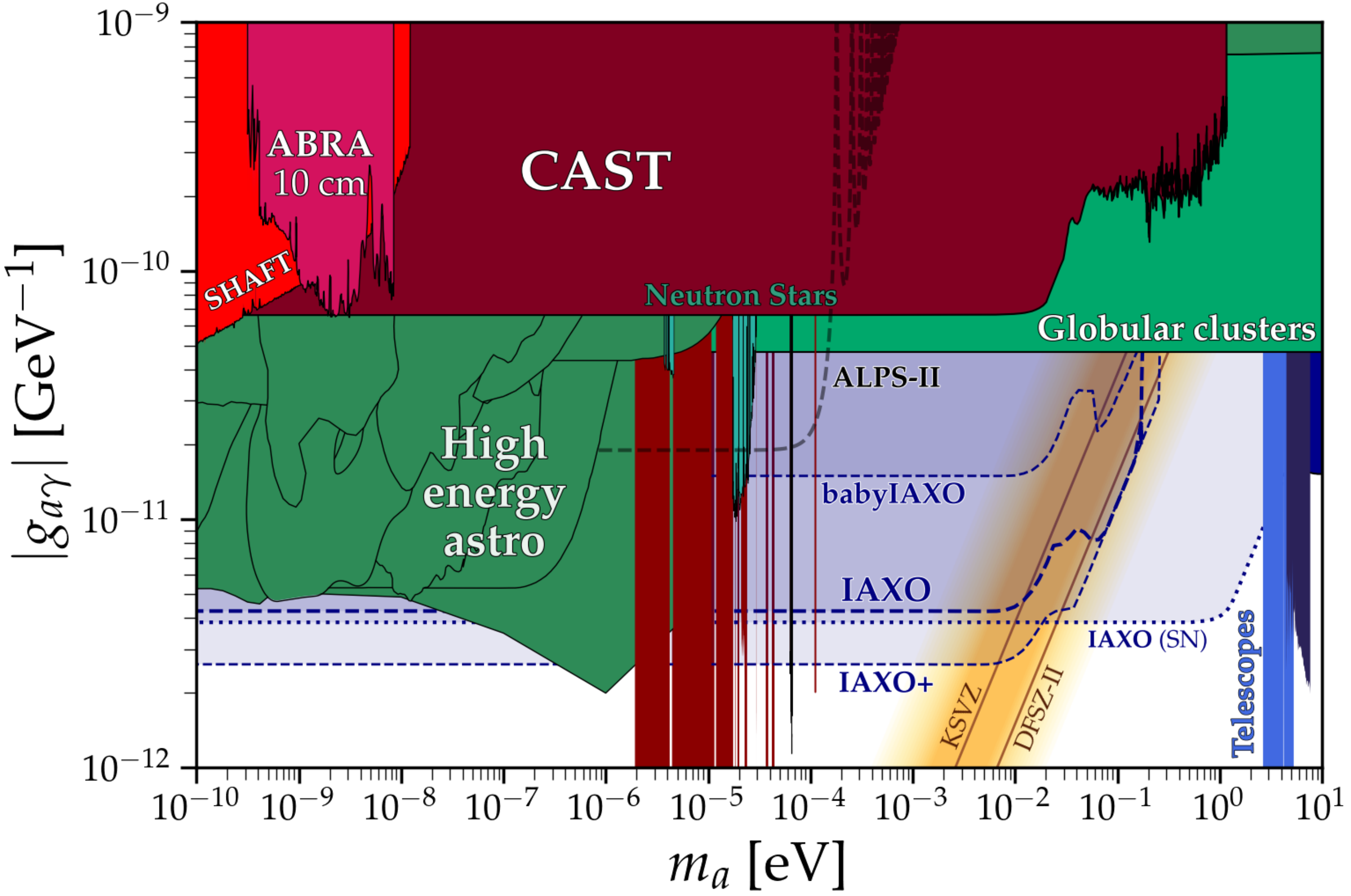
Thank you for your attention!

Backup

Landscape

Current Parameter Space - Axion-Photon Coupling

Experimental Limits + Projections Helioscopes

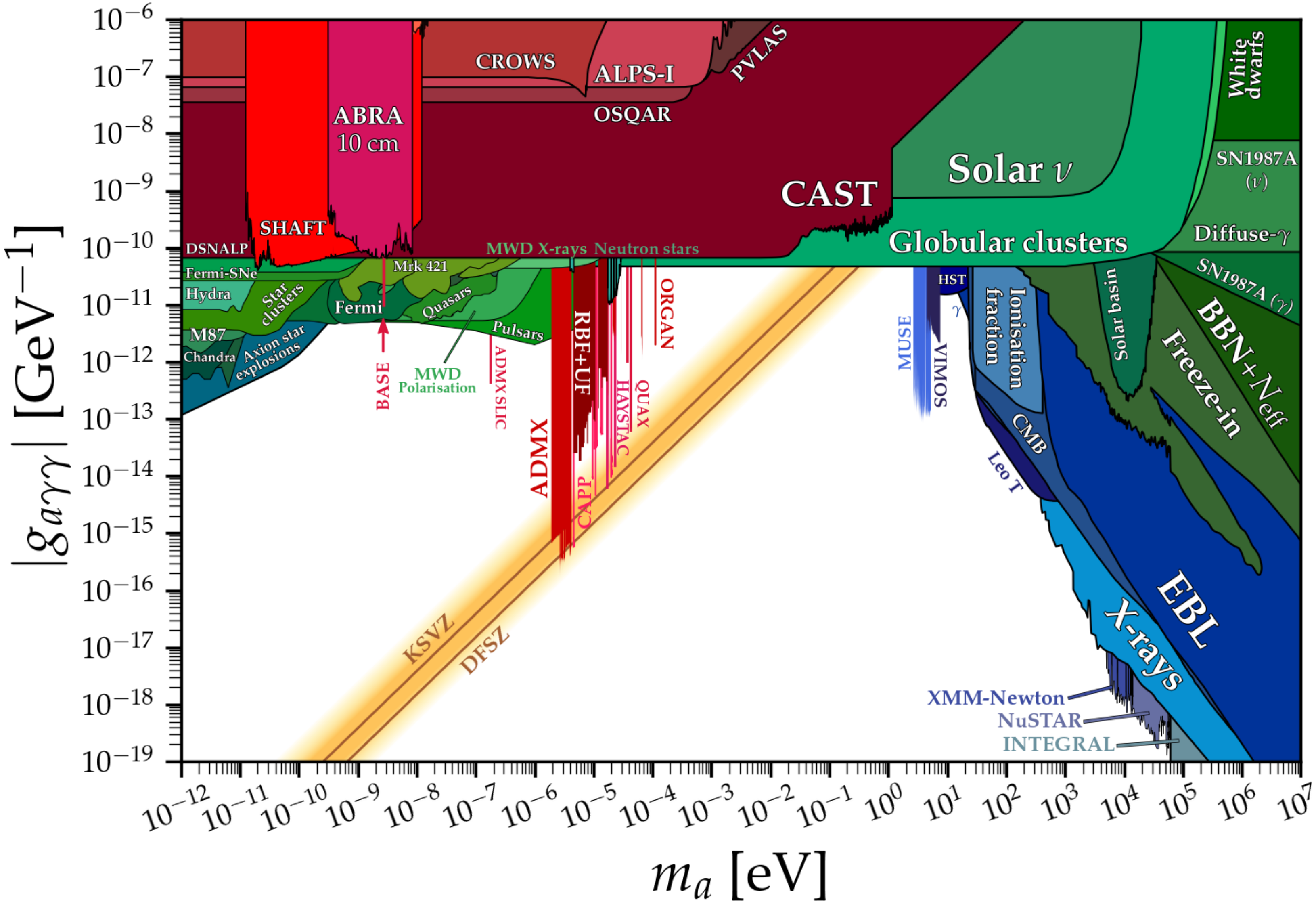


https://cajohare.github.io/AxionLimits/docs/ap.html

The (Future) Landscape I

Other Direct Dark Matter Searches & Beyond

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



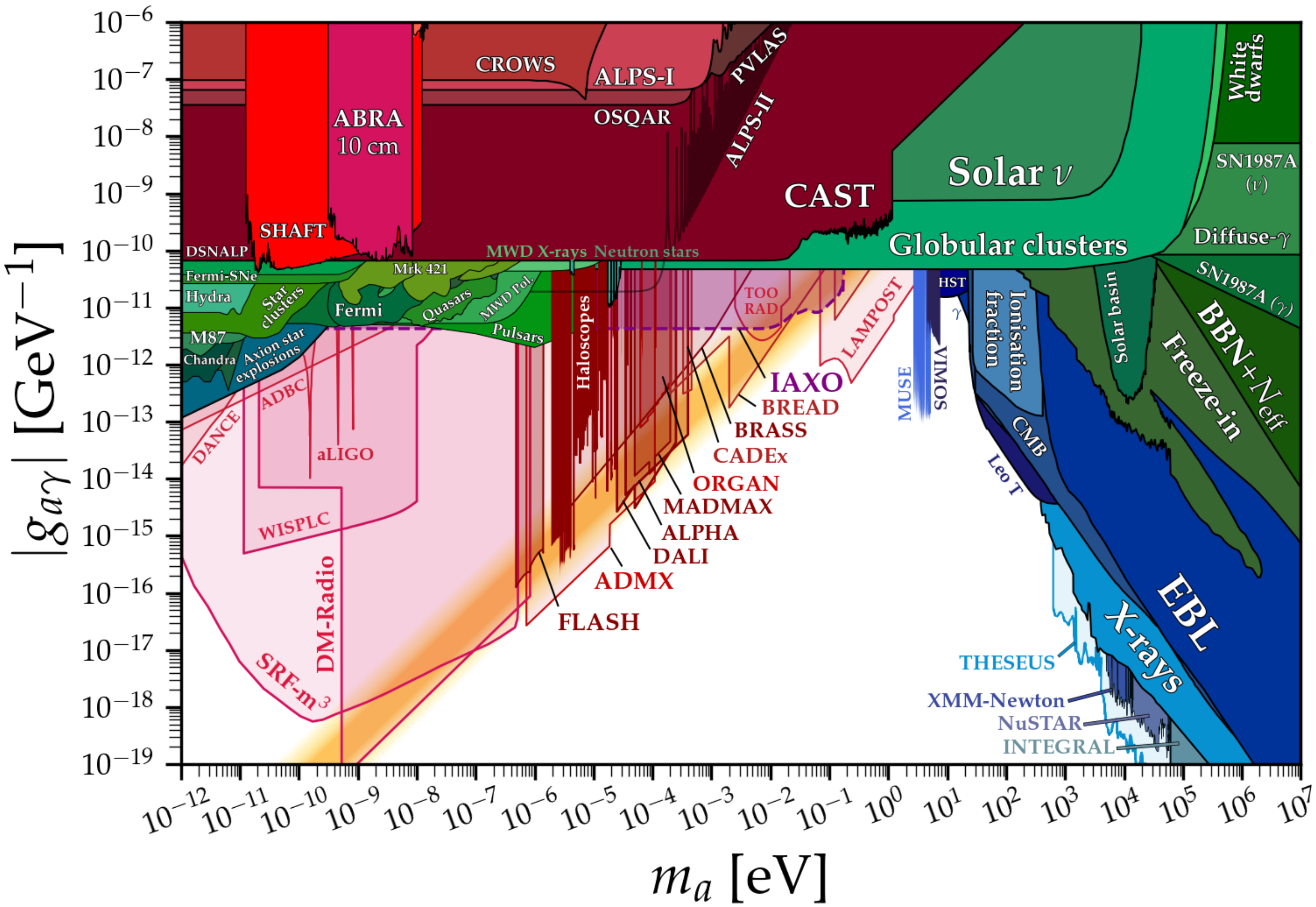
- Current experimental exclusion limits for DM and model-independent experiments

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

The (Future) Landscape I

Other Direct Dark Matter Searches & Beyond

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



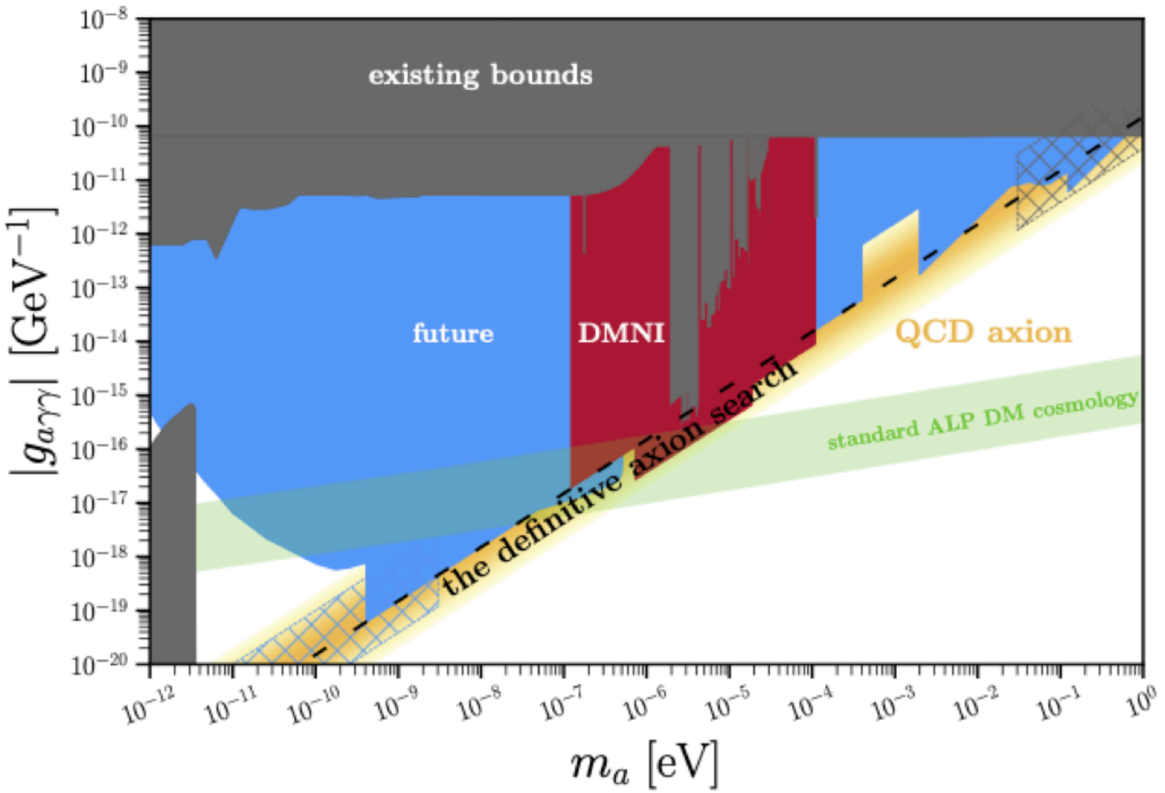
- Current experimental exclusion limits for DM and model-independent experiments + projections
  - ➡ Huge efforts ongoing to reach the benchmark QCD axion band with different types of experiments
  - ➡ Exciting times ahead!

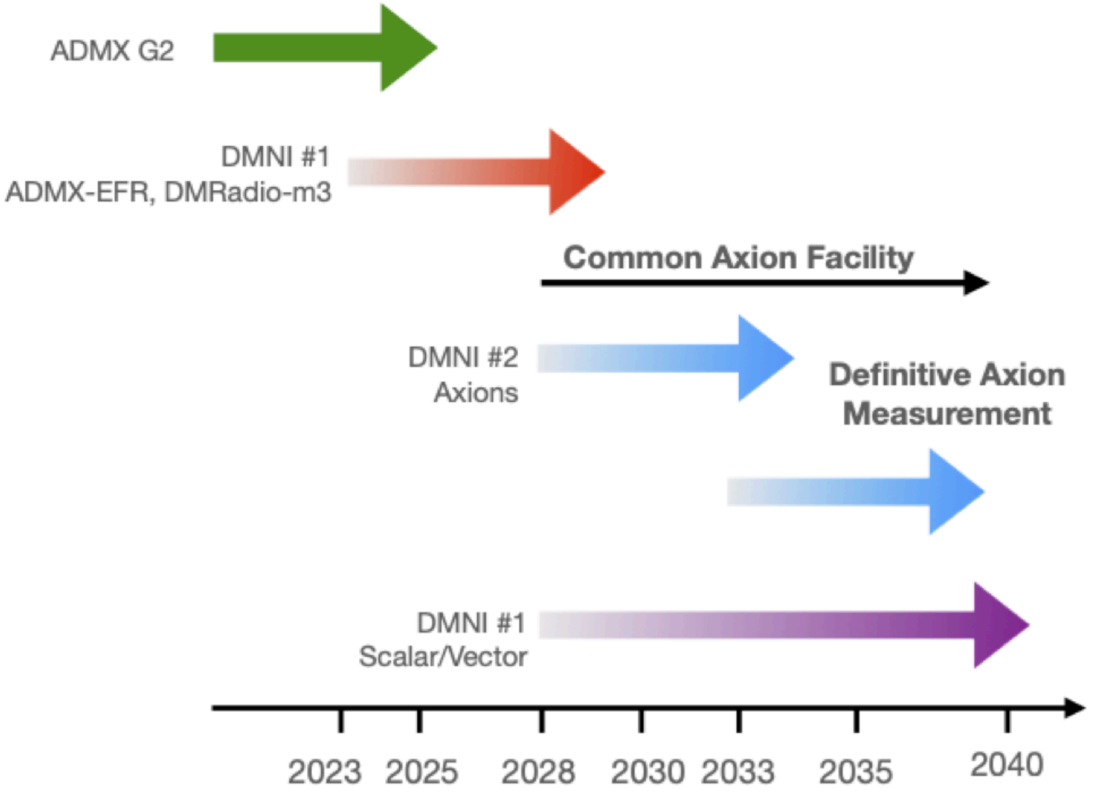
*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

The (Future) Landscape II

Direct Dark Matter Searches

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



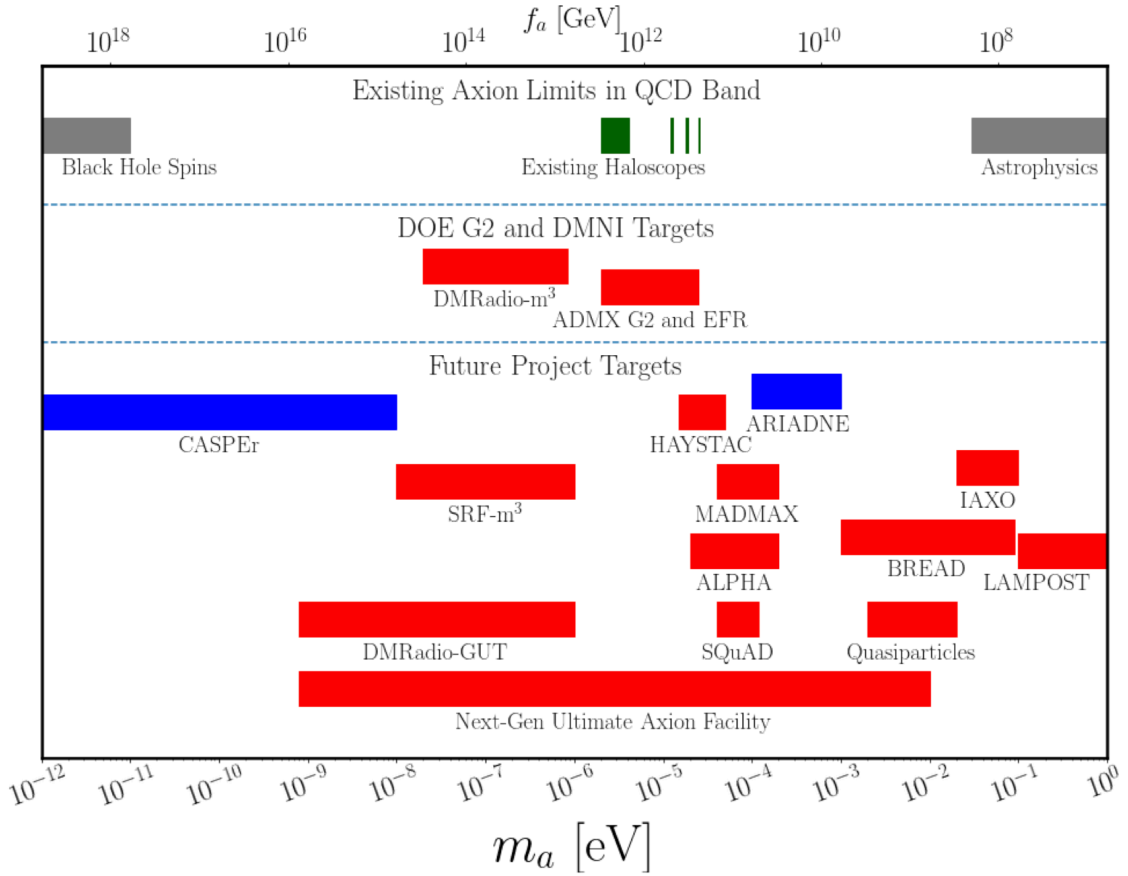


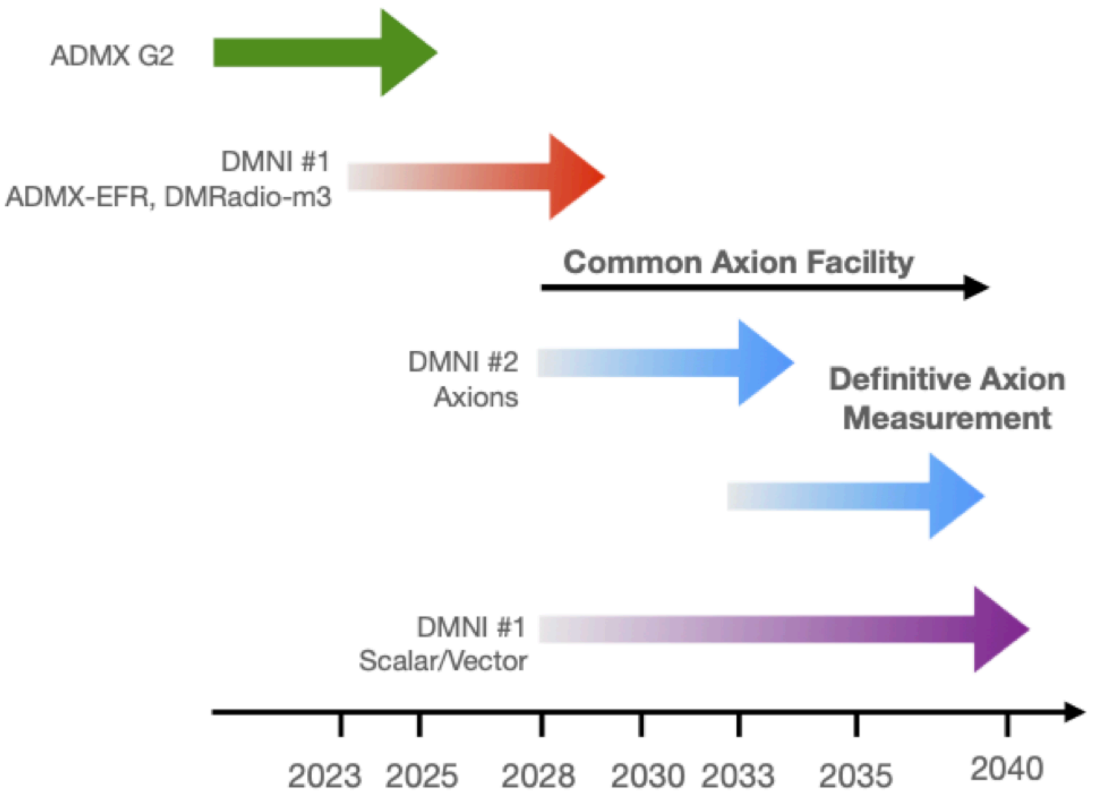
- Until ~2030: DMNI #1 aims to reach the QCD axion benchmark band for m_a: 10^{-7} - 10^{-4} eV
- Afterwards: DMNI #2, the definitive axion search, aims for basically full bandwidth

The (Future) Landscape II

Direct Dark Matter Searches

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





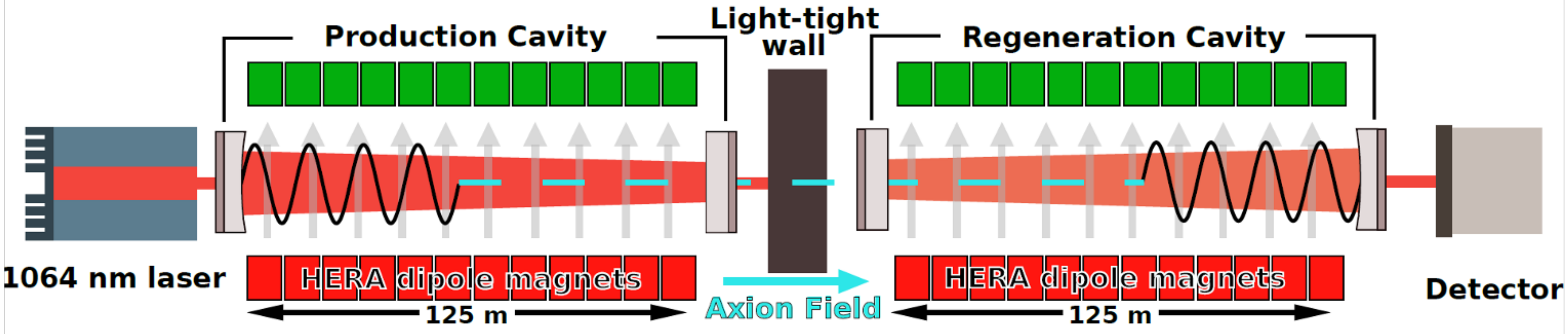
- Until ~2030: DMNI #1 aims to reach the QCD axion benchmark band for m_a: 10^{-7} - 10^{-4} eV
- Afterwards: DMNI #2, the definitive axion search, aims for basically full bandwidth
  - ➡ Various experiments up to a next-gen ultimate axion facility

Backup

ALPS II

ALPS II

Exploiting Mode Matched Optical Cavities



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

5,000 40,000 0.2 5.3 10.56

$= 10^{-25}$

Motivated by astrophysics

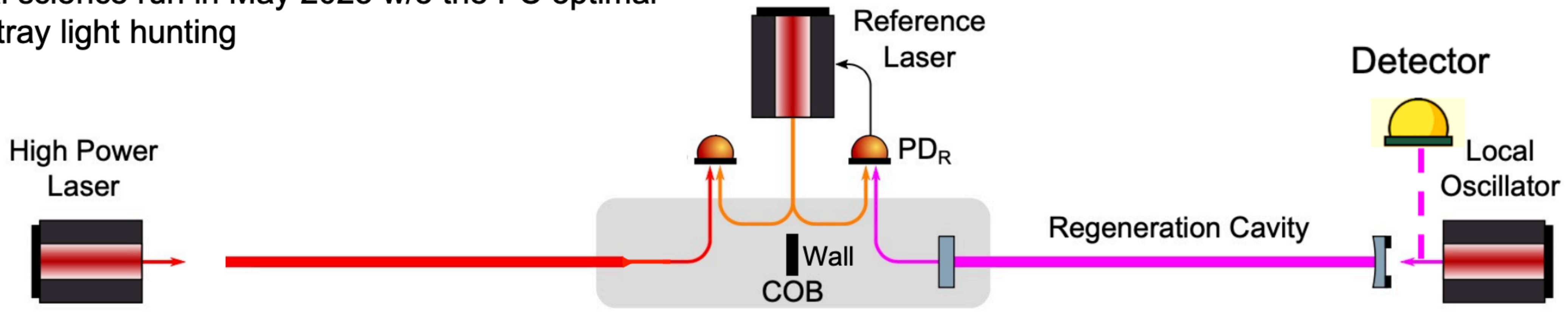
30 W cw Laser 1064 nm: $3\cdot 10^{-5}$ Photonen / s ($5\cdot 10^{-24}$ W).

Optic system

Initial science run

Thanks to I. Oceano!

- Initial science run in May 2023 w/o the PC optimal for stray light hunting



Phase stability as a **key detection point**

- Demodulation signal must be coherent with the measured signal
- LO must be coherent with regenerated field
  - HPL must be coherent with LO over the full run

Resonant Enhancement

- Amplification of regeneration cavity (RC) only works if the regenerated field is resonant
- Cannot directly interfere HPL and LO fields → too much stray light!
- Use of a reference laser with cascaded phase-locked loops as a “go-between” → HPL and LO never see each other directly

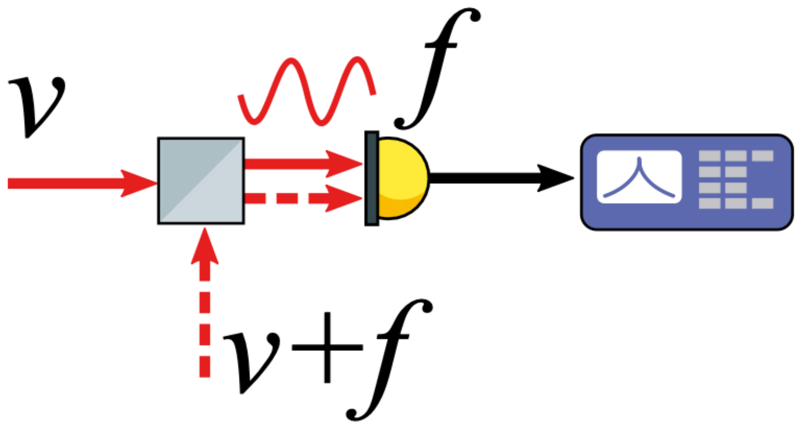
Heterodyne detection system

Measuring single photon power levels over days

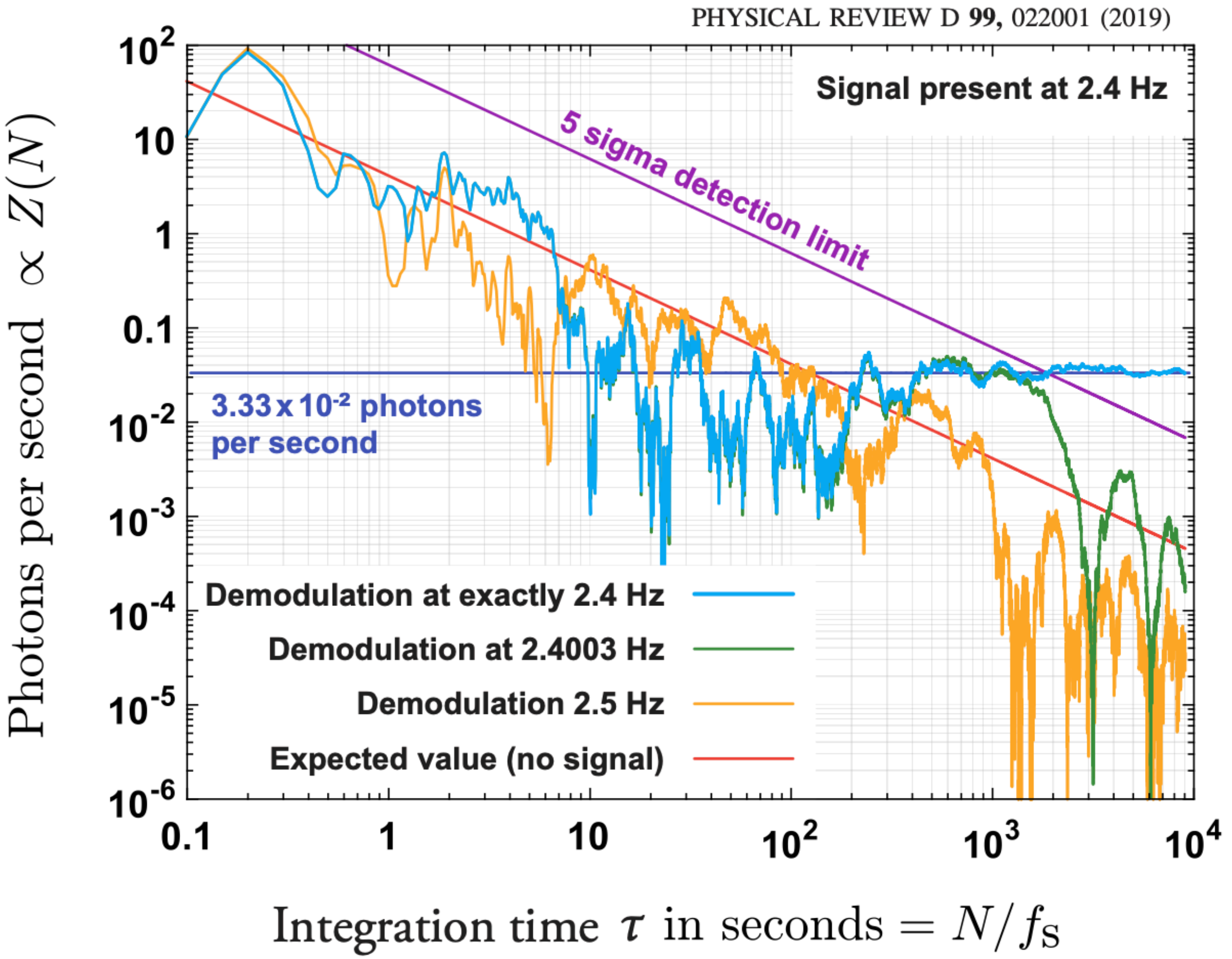
Thanks to A. Spector!

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



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



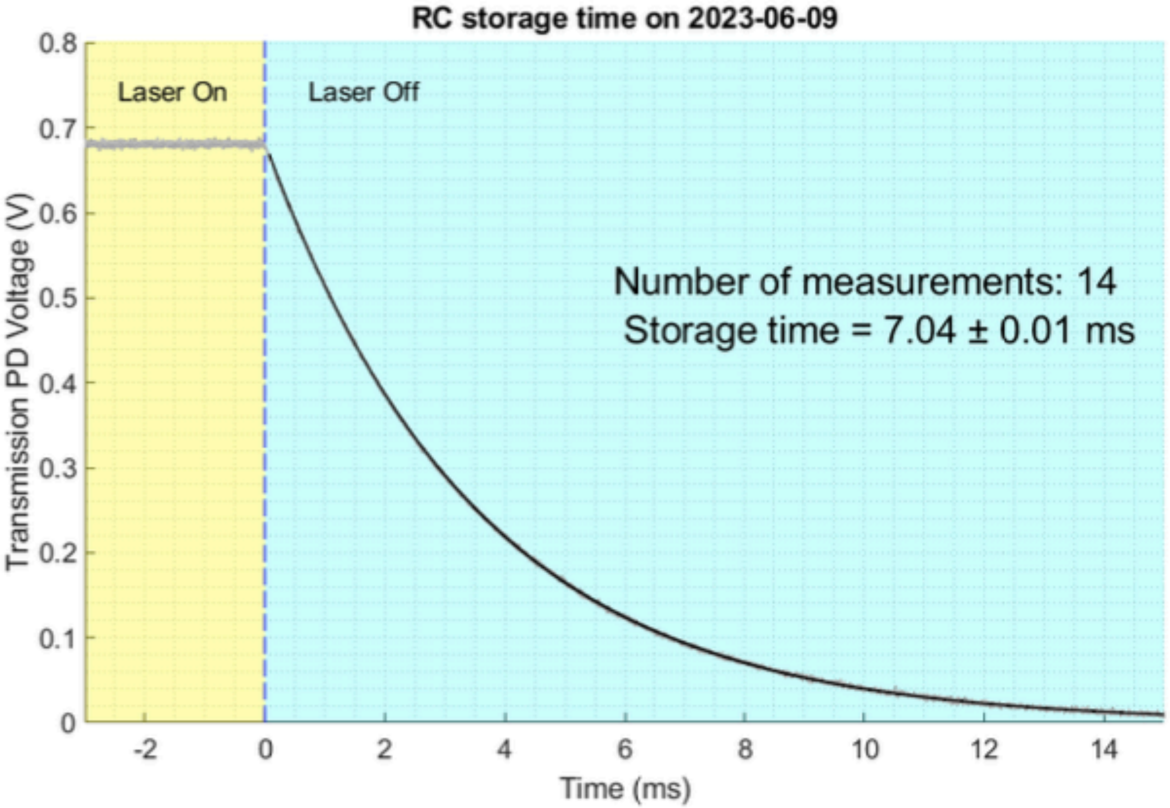
Regeneration Cavity

Reconverting axion-like particles back to photons

Thanks to A. Spector!

Longest storage time Fabry Perot cavity ever!

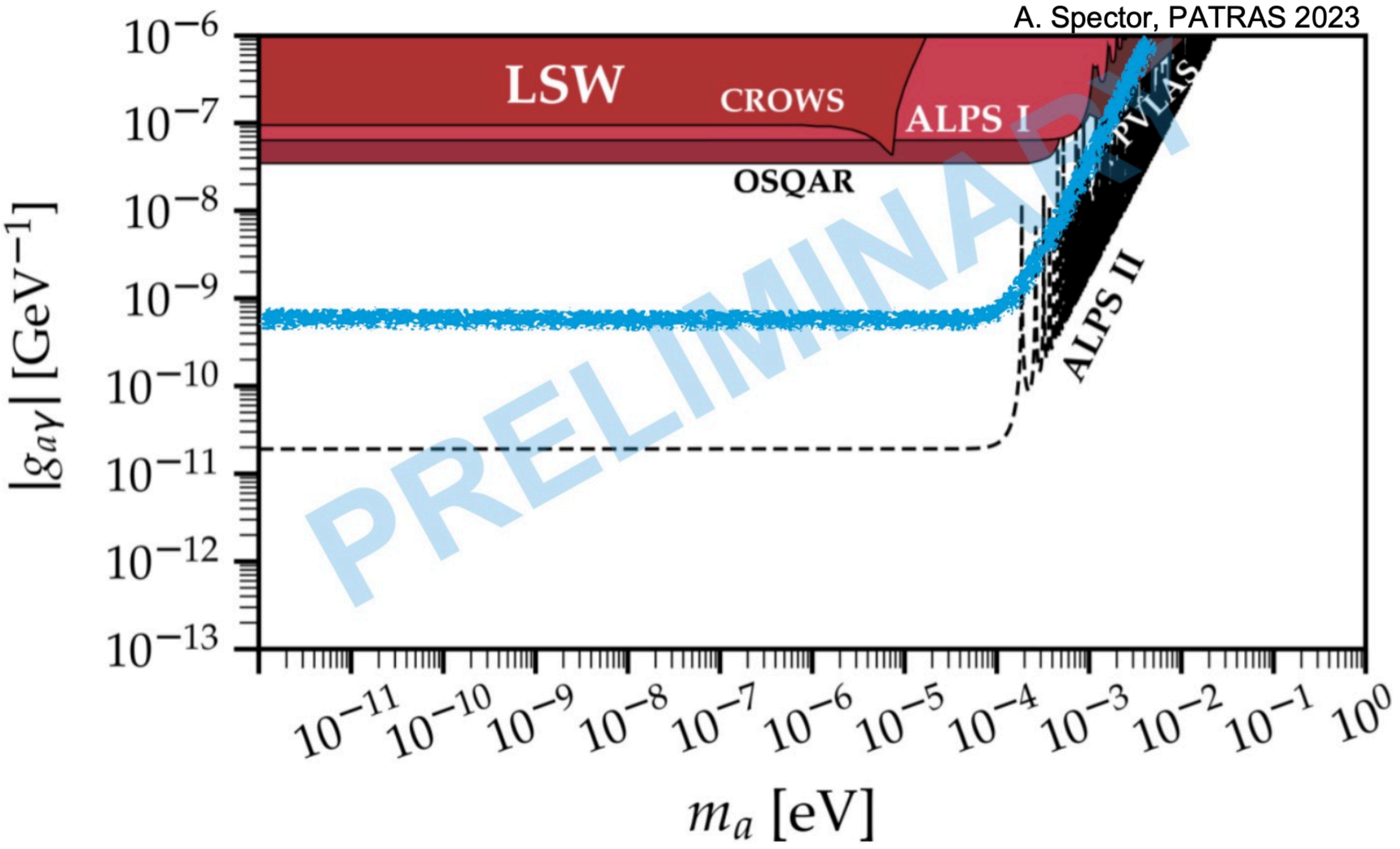
- Power build up factor: $\beta = 7700$
- PDH frequency stabilization, alignment control
- Multiple week locks demonstrated



Preliminary sensitivity estimate

Preliminary results

Thanks to I. Oceano!

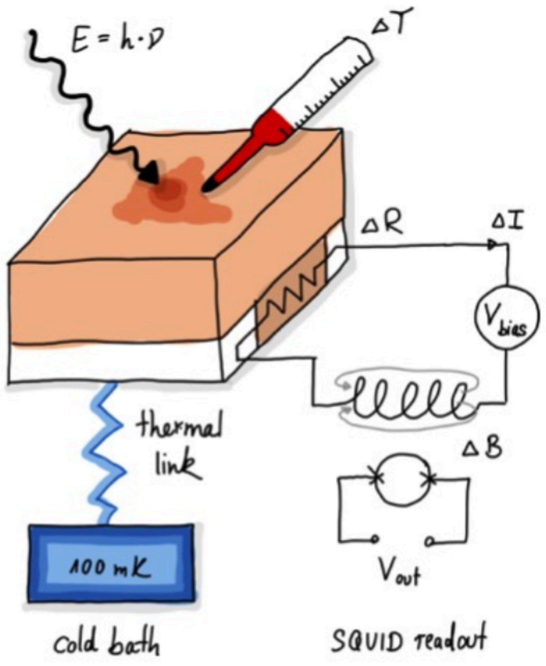


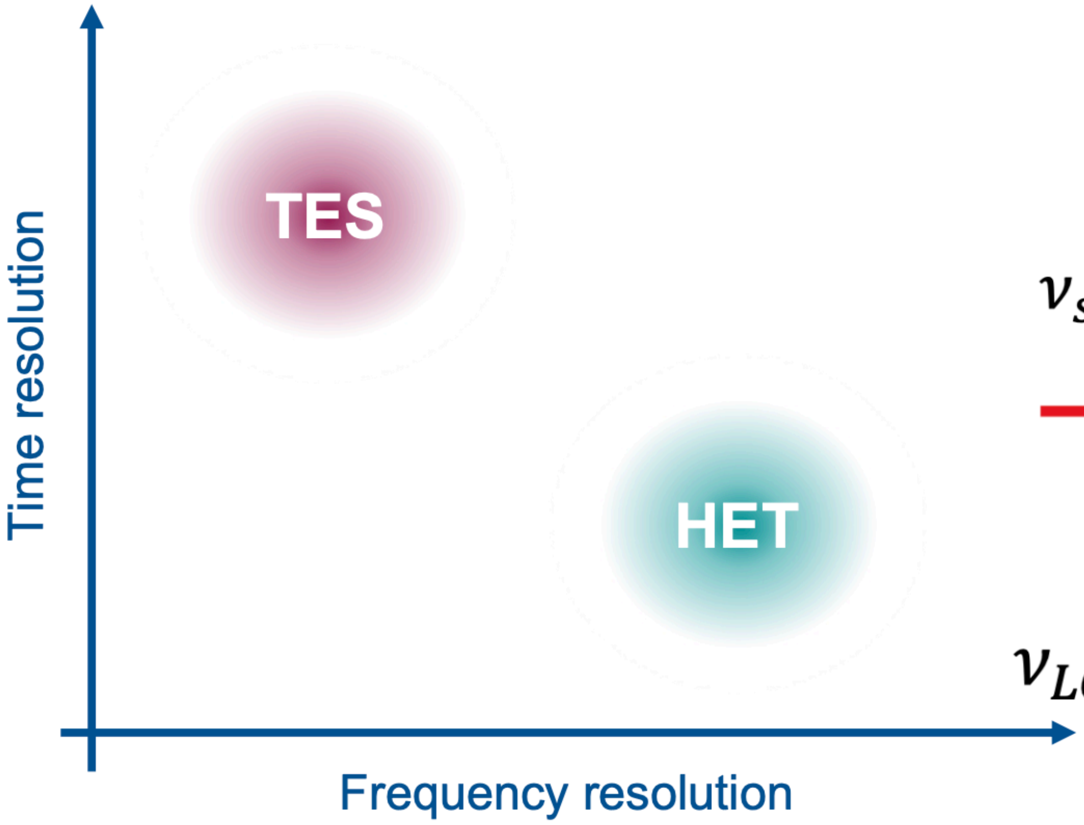
- Scalar search
- 150000 s (~45 h) integration time

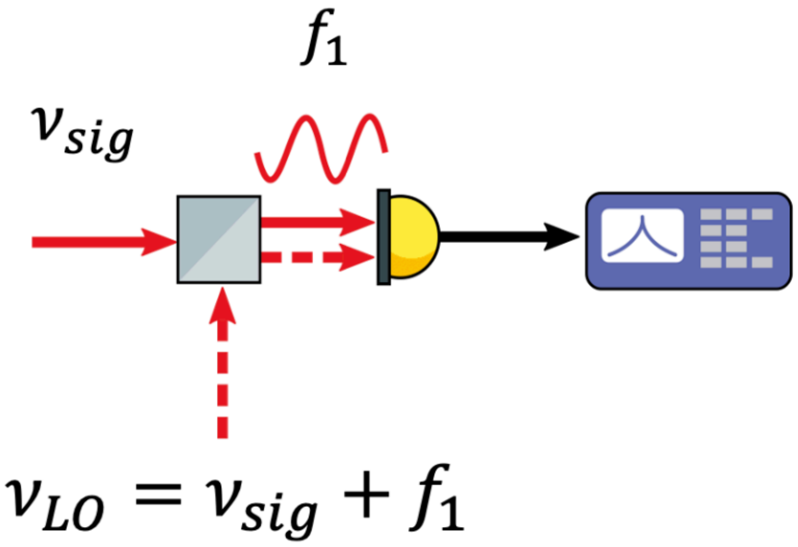
Regenerated photon detection

Exploiting two different techniques

Thanks to I. Oceano!







TES

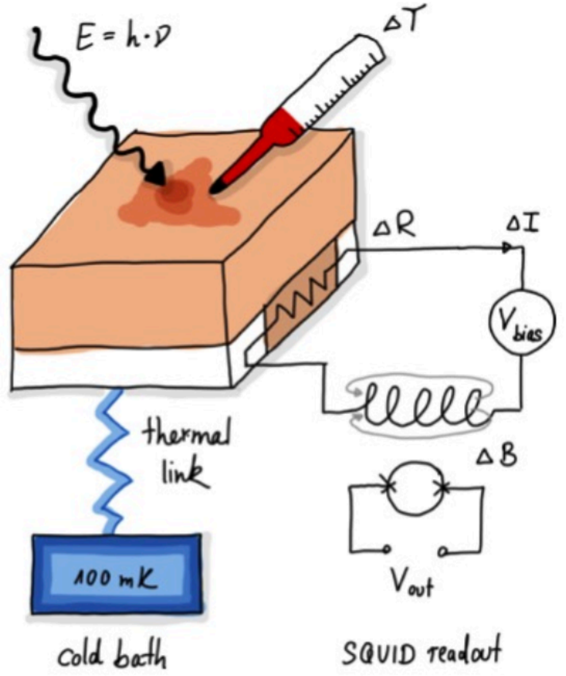
Transition Edge Sensor

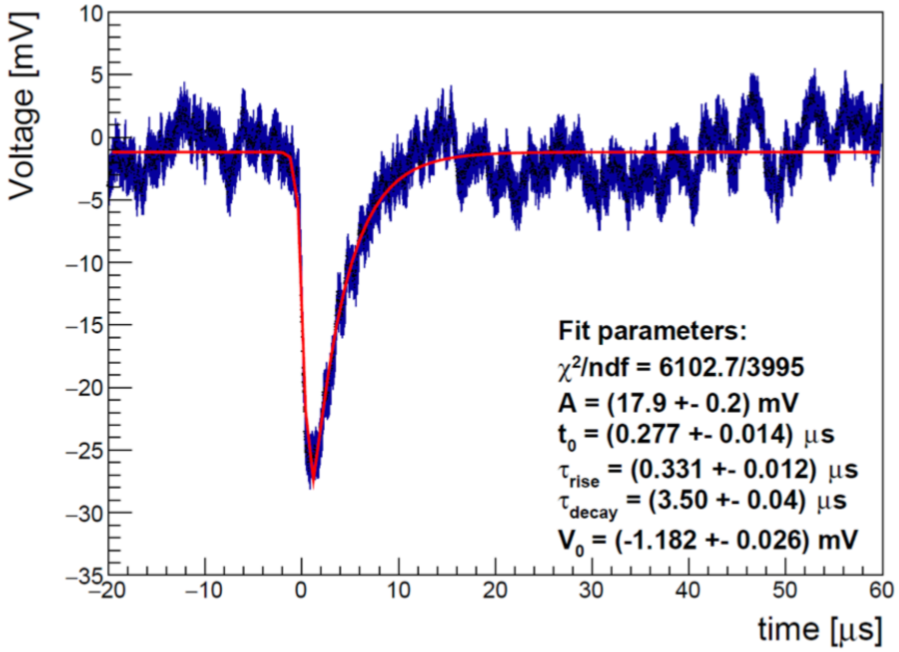
Thanks to I. Oceano!

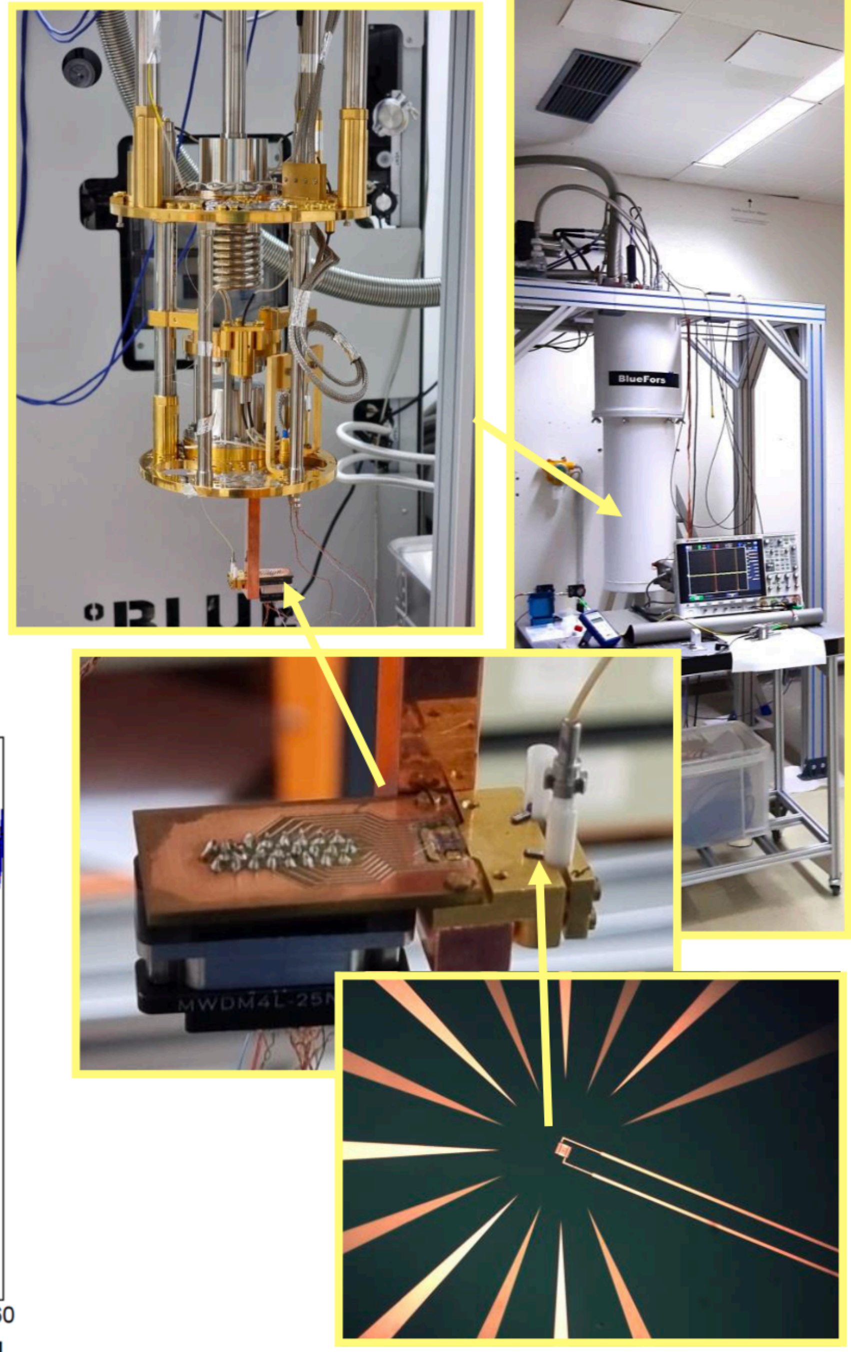
- Using a superconducting Transition Edge Sensor (TES) operated at about 100 mK.
- Already have demonstrated:
  - Low-backgrounds (μHz)
  - Good energy resolution (~10%)
  - Long-term stability (~20 days)

A tungsten microchip provided by NIST and a SQUID readout by PTB ($25\mu\mathrm{m} \times 25\mu\mathrm{m} \times 20\mathrm{nm}$) operated in the transition region ($\sim 140\mathrm{mK}$)

TES data-taking requires a different optics setup.





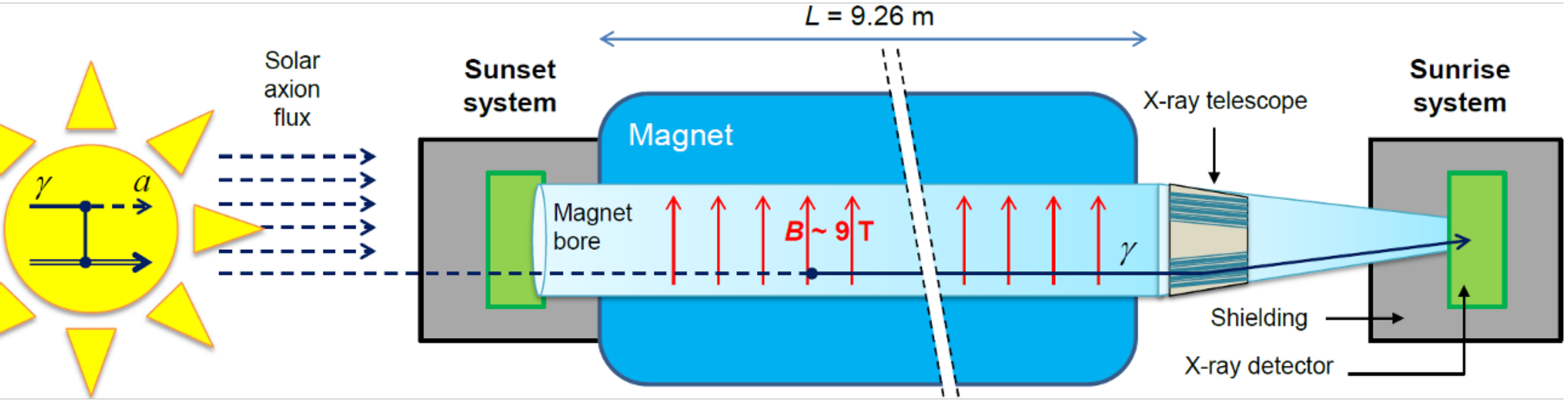


Backup

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

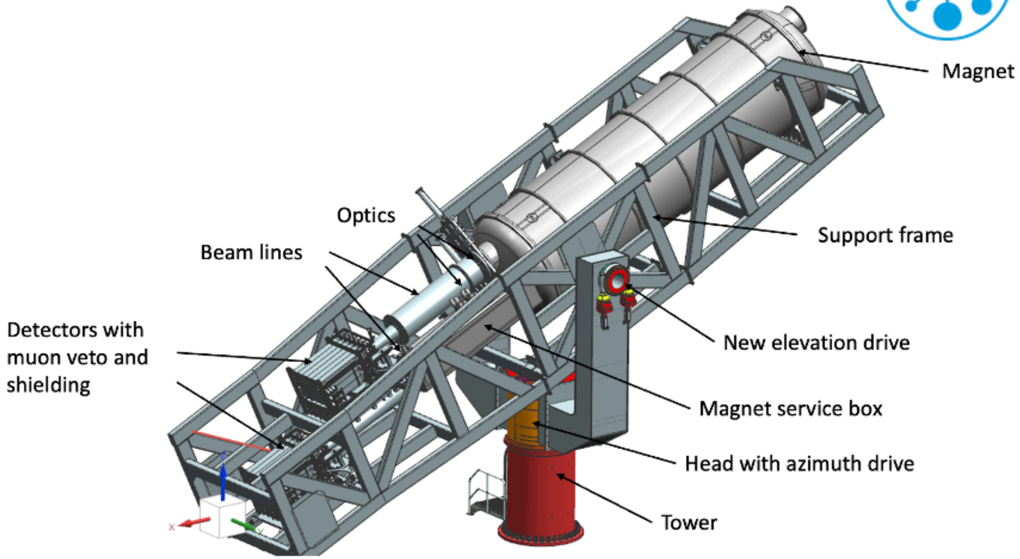
➡ Still state-of-the-art limits on $g_{a\gamma\gamma}$ vs. m_a and other parameter space

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

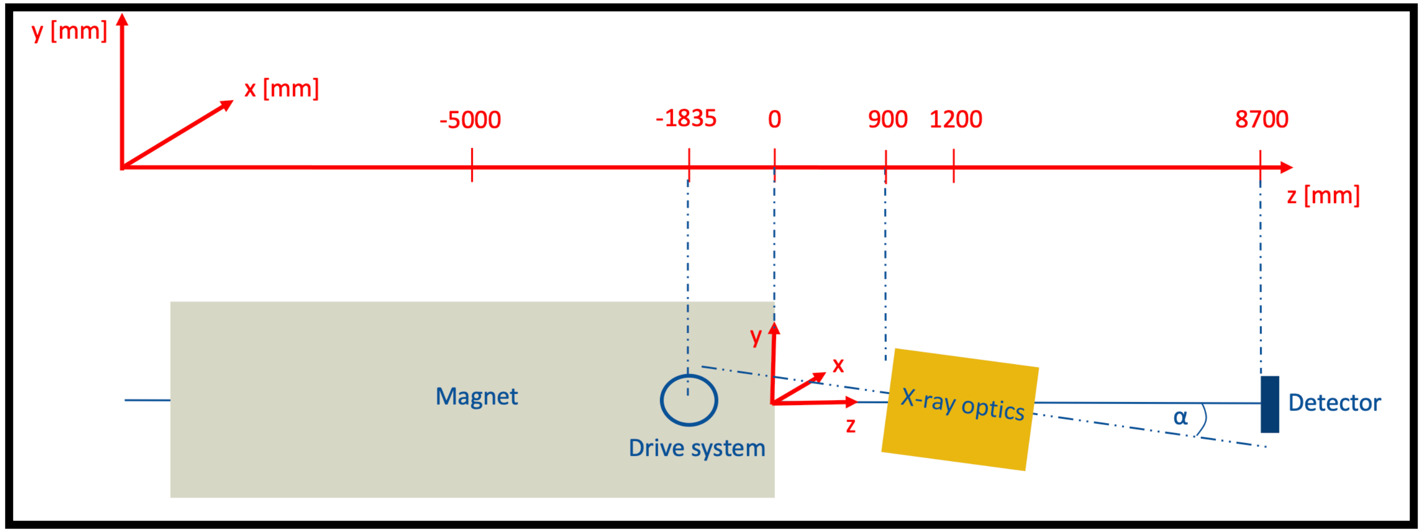
Structure & Drive System

And Alignment

- Reusing parts of CTA/MST prototype from DESY Zeuthen
  - ➡ Duty cycle at least 50%
  - ➡ Pointing precision < 0.01°

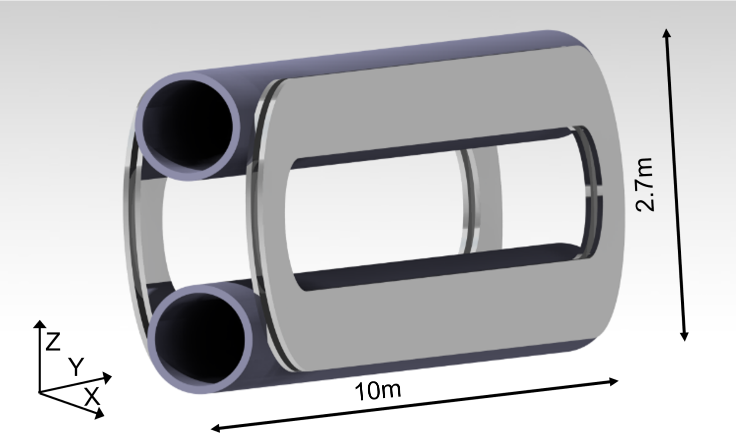


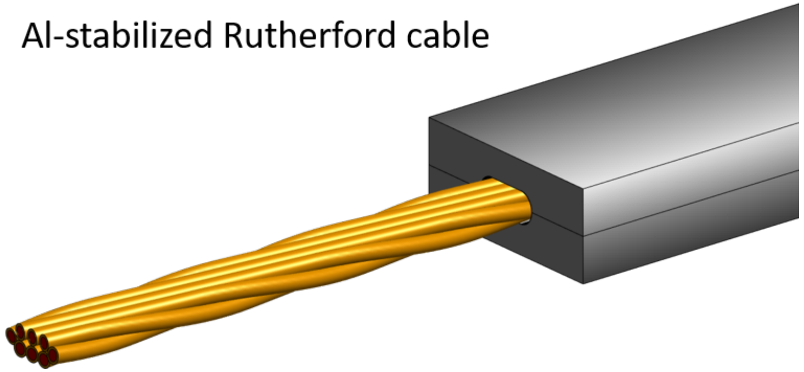
- **Significant progress**:
  - ➡ Design close to be finished
  - ➡ Extensive mech. simulations
  - ➡ External alignment: studied by CEFCA + DESY
  - ➡ Internal alignment: Complete MC study performed, manufacturing tolerances currently derived



Magnet

Challenges and Progress





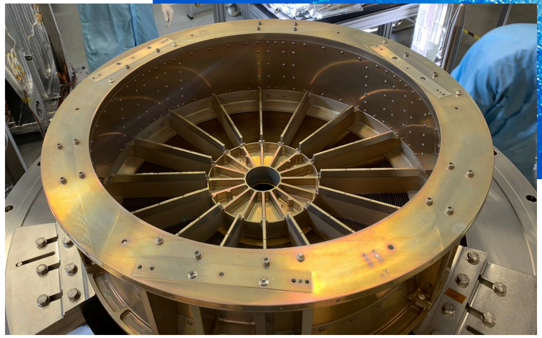
- Common coil racetrack design, cryocooler concept
- **Magnet efforts have gained significant momentum:**
- Redesign of cryogenic system
  - ➡ Design work by DESY & CERN teams progressing well
  - ➡ Company Elytt contracted: work on conceptual design
    - ➡ Funding by Zaragoza, Bonn and Mainz
  - ➡ CDR to be finished soon… in progress
- Al-stabilised SC cable (co-extrusion technique)
  - Became unavailable due to Russian invasion into Ukraine
  - ➡ CERN & KEK synergies: setup of co-extrusion facility?
  - ➡ Very promising cable samples from Chinese company
  - ➡ First part of Rutherford cable ordered

Optics

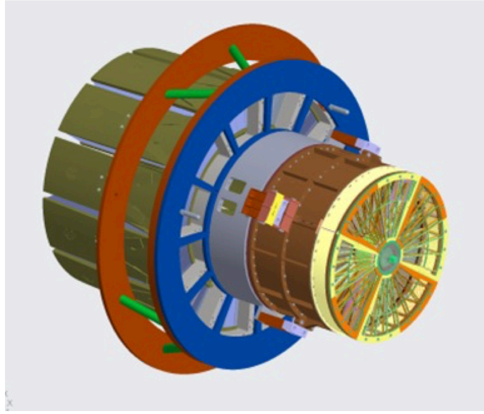
Focusing X-Rays

- Two different X-ray focusing optics planned for BabyIAXO

1. XMM Newton flight spare from ESA
   - ➡ Two modules at MPI/PANTER **to be recalibrated**
   - ➡ Work towards finalisation of loan agreement ESA-DESY



2. Custom-made hybrid optics
   - ➡ First prototype of coronal optics module successfully tested at PANTER
   - ➡ Progress with preparations for inner core optics construction
     - ➡ **Funding milestones: grants for both sub-systems (at INAF and Columbia U.)**

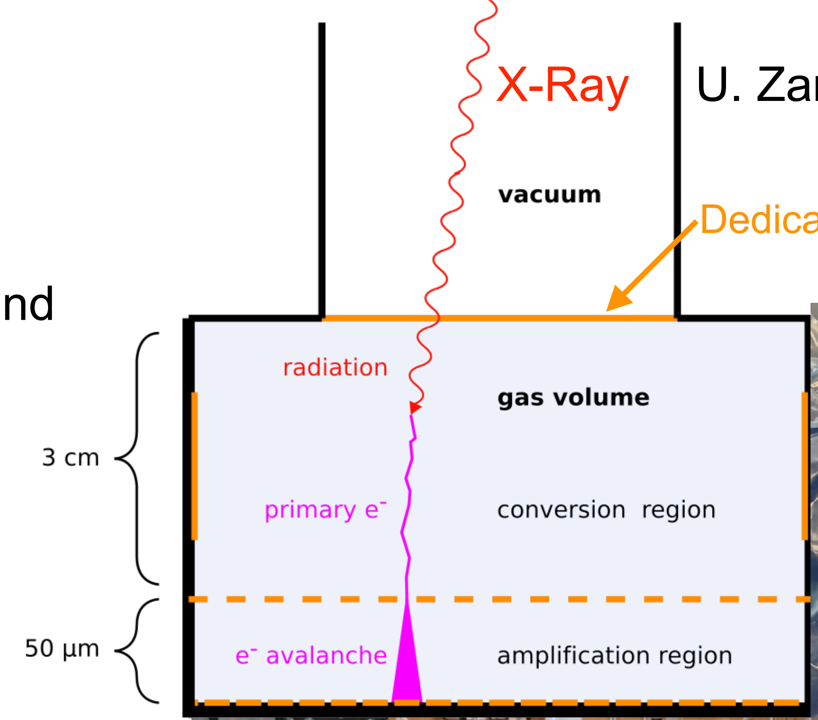


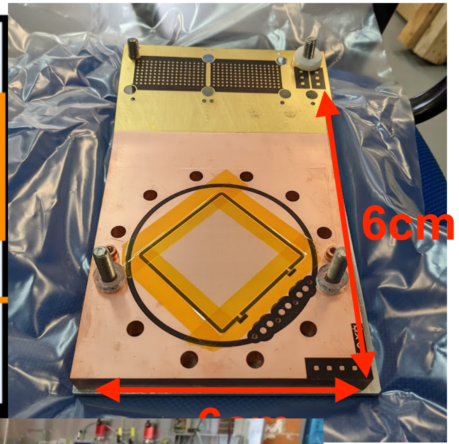
X-Ray Detectors

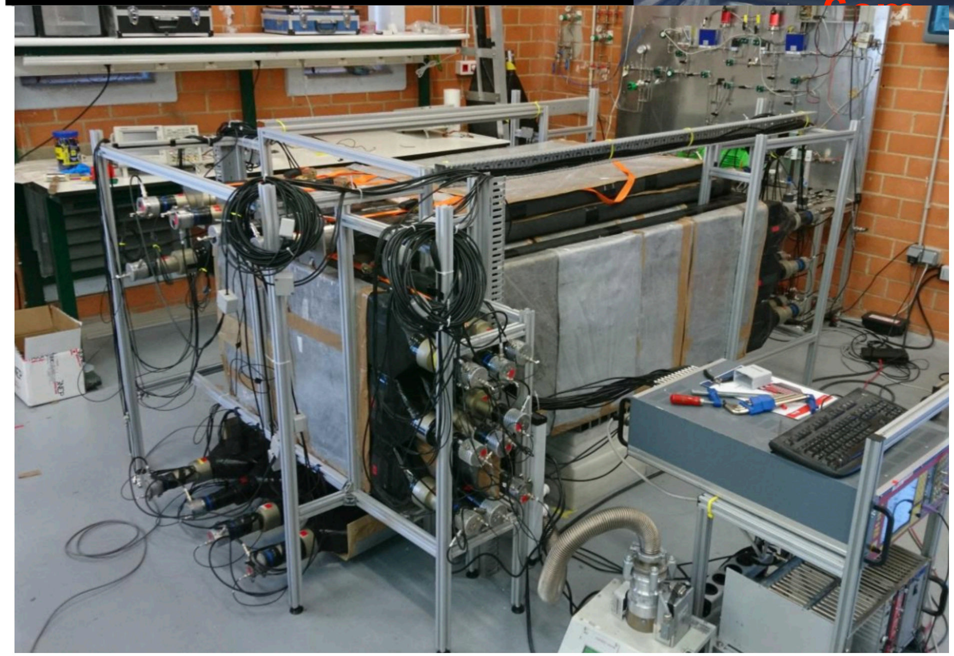
Discovery Technologies

- 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)

U. Zaragoza & CEA Saclay







X-Ray Detectors

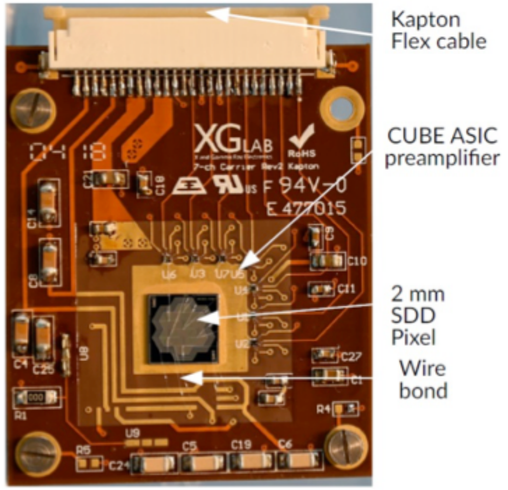
Complementary Technologies

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

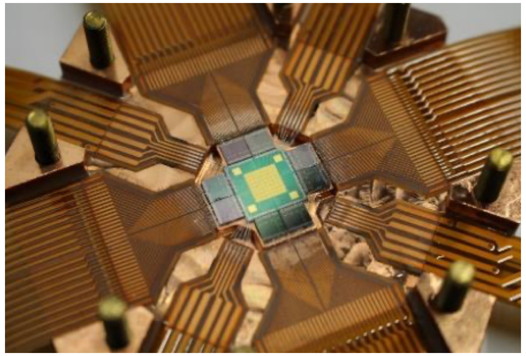
Precision / post-discovery:

- 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

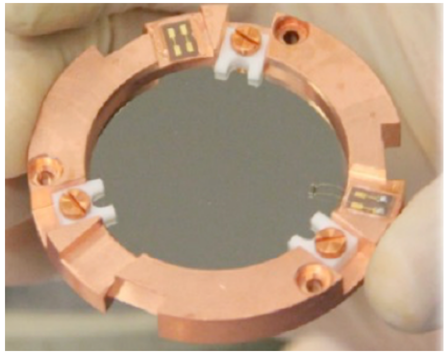


SDD: Silicon Drift Detectors (TUM)

GridPix (U. Bonn)



MMC: Metallic Magnetic Calorimeters (U. Heidelberg)



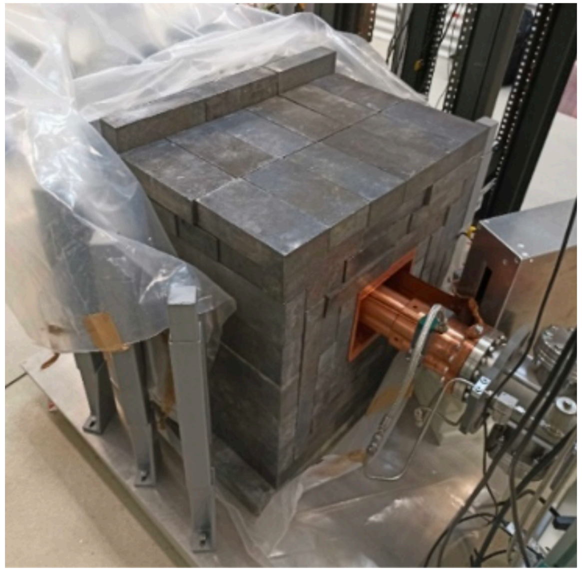
TES: Transition Edge Sensors (INMA-ICMAB CSIC)

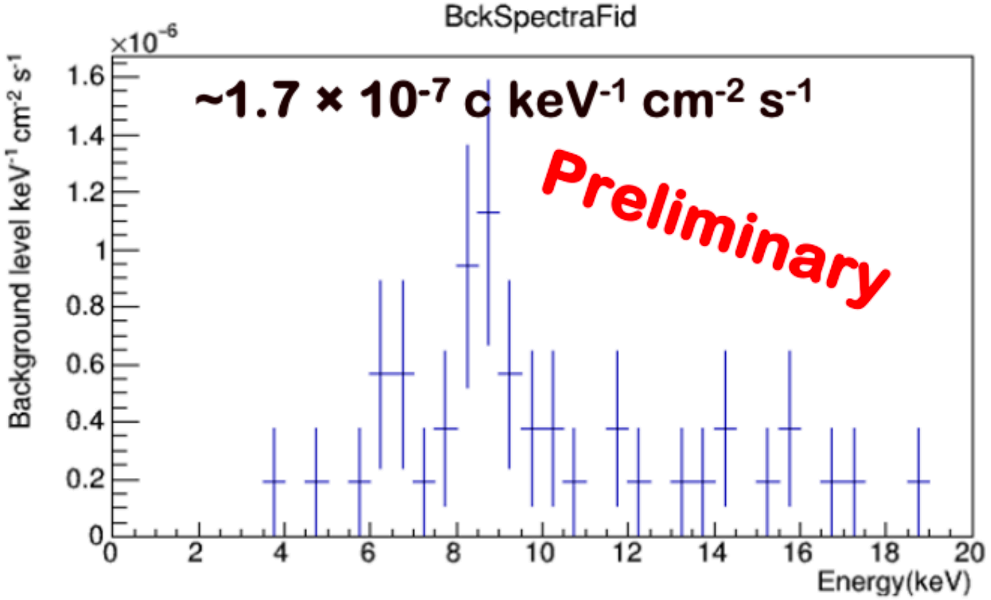
X-Ray Detectors - Highlight

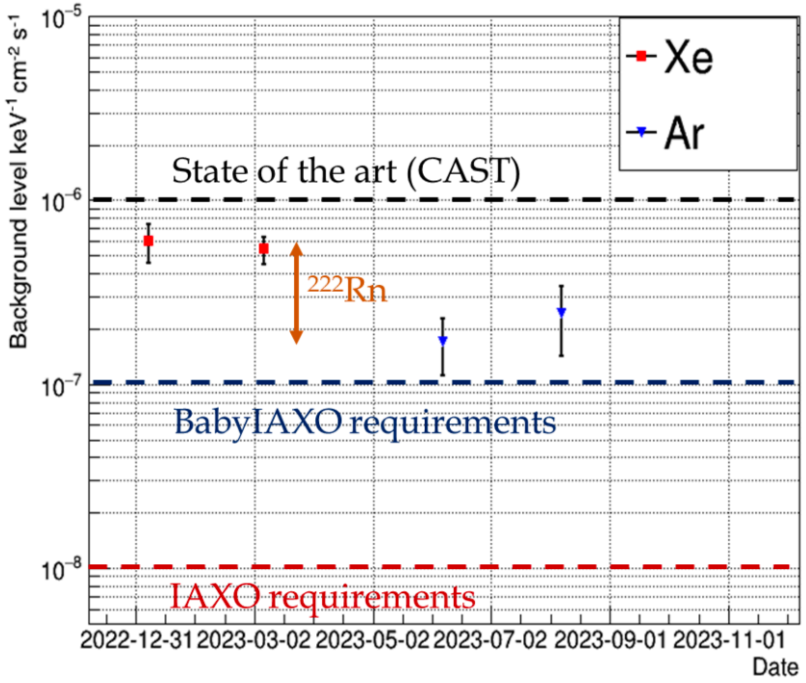
Towards Desired Background Levels

- May 2023: ~38 days of data taking with IAXO-D1 Micromegas prototype (Ar-Isobutane) in Canfranc underground laboratory (LSC)

Achieved lowest background level ever with this type of detector!







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 (BabyIAXO)

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

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

Transfered momentum

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

Axion energy

- 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

Coherence Threshold

Examples

"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 (BabyIAXO)

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

Transfered momentum

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

Axion energy Ea

Coherence condition approximation: $m_a \lesssim \sqrt{4\pi E_a/L}$

With $\hbar = c = 1$
[L] = [1\E]
1m = 1/197 GeV^{-1}

BabyIAXO: Ea = 3keV and L = 10m

$$m_a = \sim 25\ meV$$

ALPSII: Ea = 0.1 eV and L = 125m

$$m_a = \sim 0.05\ meV$$

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)	$6272\,\mathrm{T}^2\,\mathrm{m}^4$ ($\sim 300 \times$ 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}	$1\,\mathrm{cm}^2$

Studied Experimental Setups

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

Optimising for 14.4 keV photons

Label	BabyIAXO				IAXO		IAXO+	
	Baseline $\mathrm{BabyIAXO_0}$	No optics $\mathrm{BabyIAXO_1}$	Optimized optics $\mathrm{BabyIAXO_2}$	High energy resolution $\mathrm{BabyIAXO_3}$	Low background $\mathrm{IAXO_b}$	High energy resolution $\mathrm{IAXO_r}$	Low background $\mathrm{IAXO_b^+}$	High energy resolution $\mathrm{IAXO_r^+}$
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
$b\ [\frac{1}{\mathrm{keV cm^2 s}}]$	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	$\frac{5}{14400}$

Studied Experimental Setups

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

Optimised for 14.4 keV photons

Label	BabyIAXO				IAXO		IAXO+	
	Baseline	No optics	Optimized optics	High energy resolution	Low background	High energy resolution	Low background	High energy resolution
	BabyIAXO$_0$	BabyIAXO$_1$	BabyIAXO$_2$	BabyIAXO$_3$	IAXO$_b$	IAXO$_r$	IAXO$_b^+$	IAXO$_r^+$

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)

IAXO$_b^{(+)}$: benchmark configuration parameters + fully optimised optics

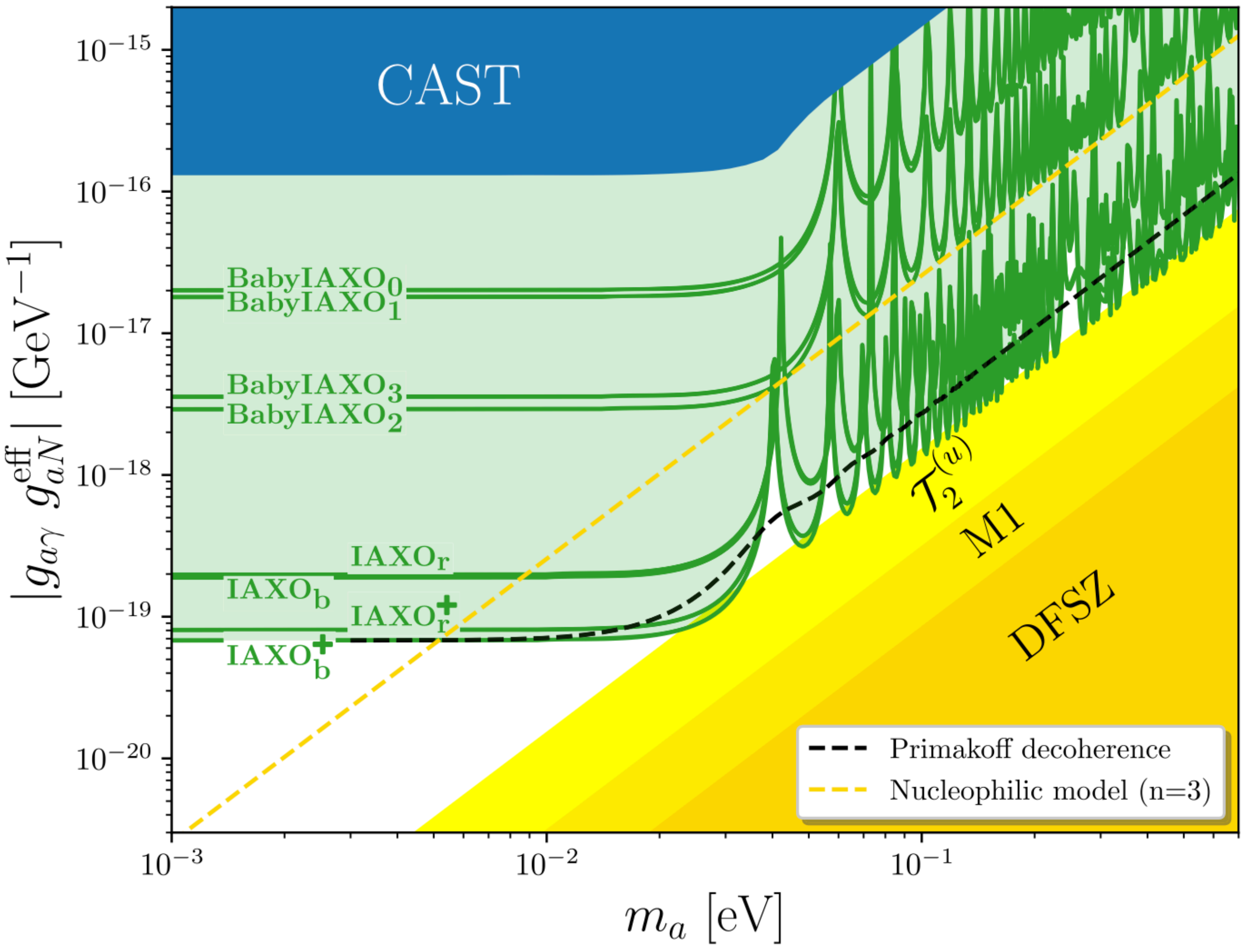
IAXO$_r^{(+)}$: benchmark configuration parameters + fully optimised optics + per-mille level energy resolving detectors (MMCs)

Results: Massive Case

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

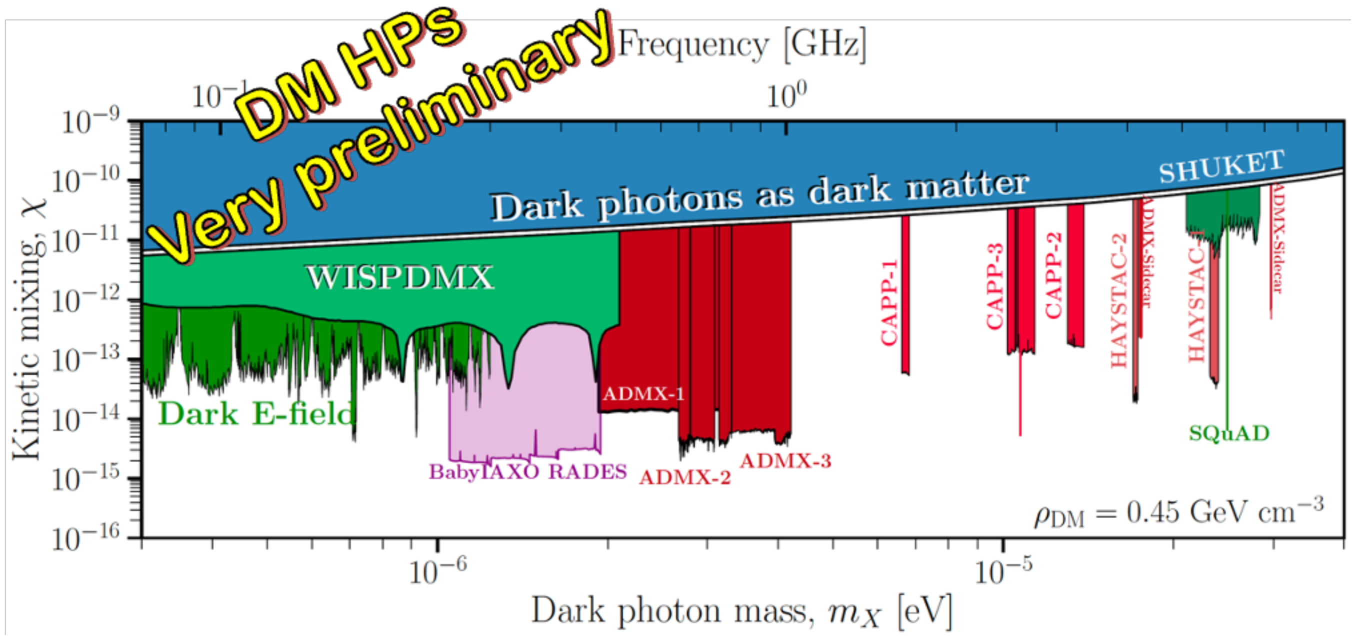
Increasing Decoherence in Axion-Photon Conversion

- 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

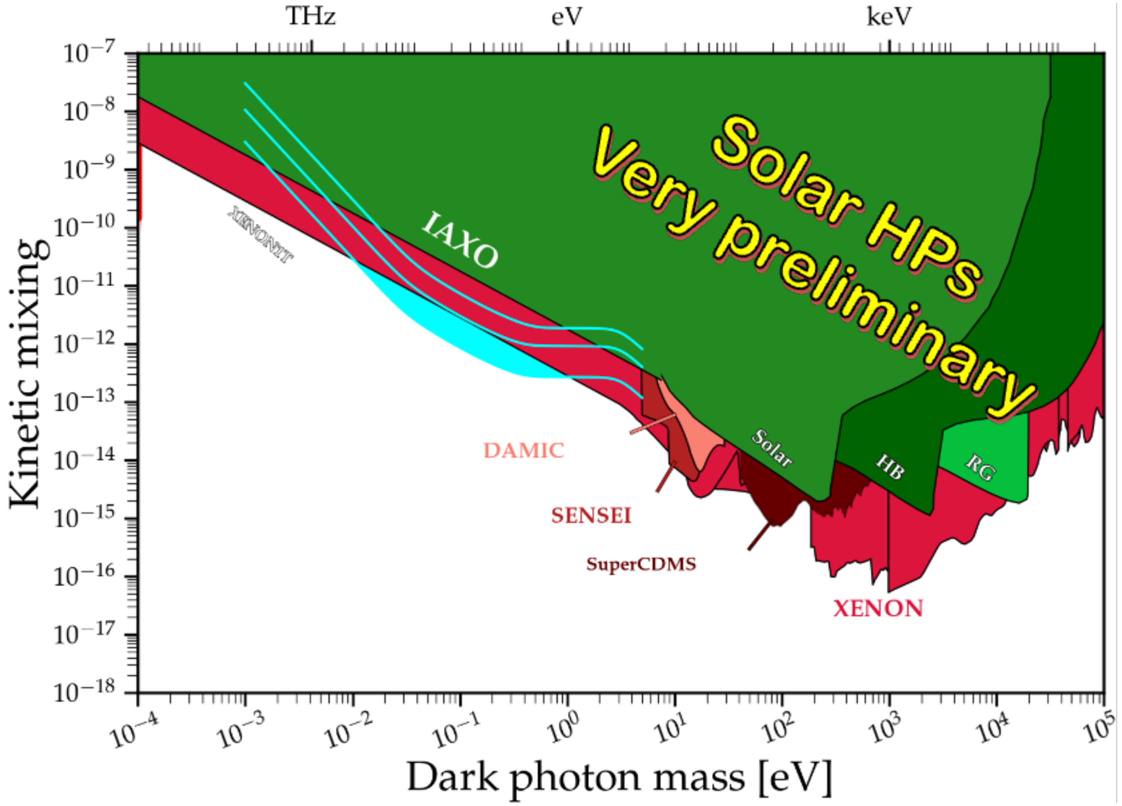


Hidden photons at IAXO

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



Computed by C. Cogollos. Paper in preparation…



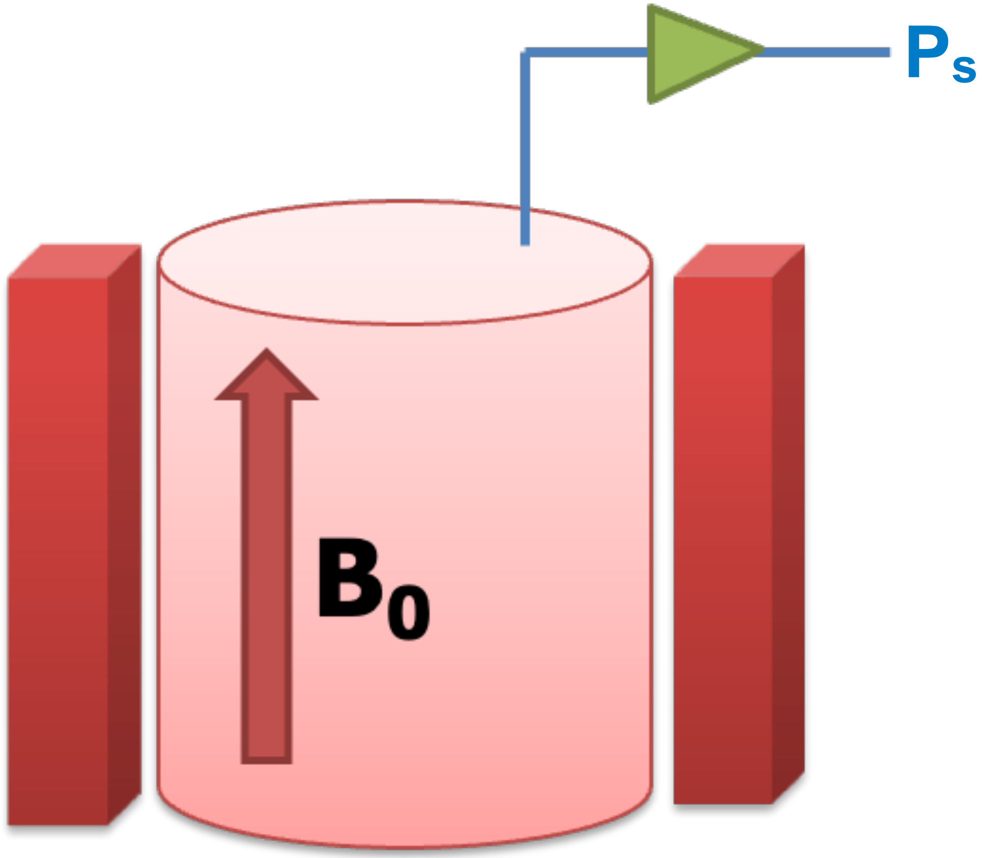
Computed by T. O'shea.
Paper in preparation…

Backup: Dark Matter with Haloscopes

Haloscopes

Detecting Dark Matter Axions - In a Nutshell

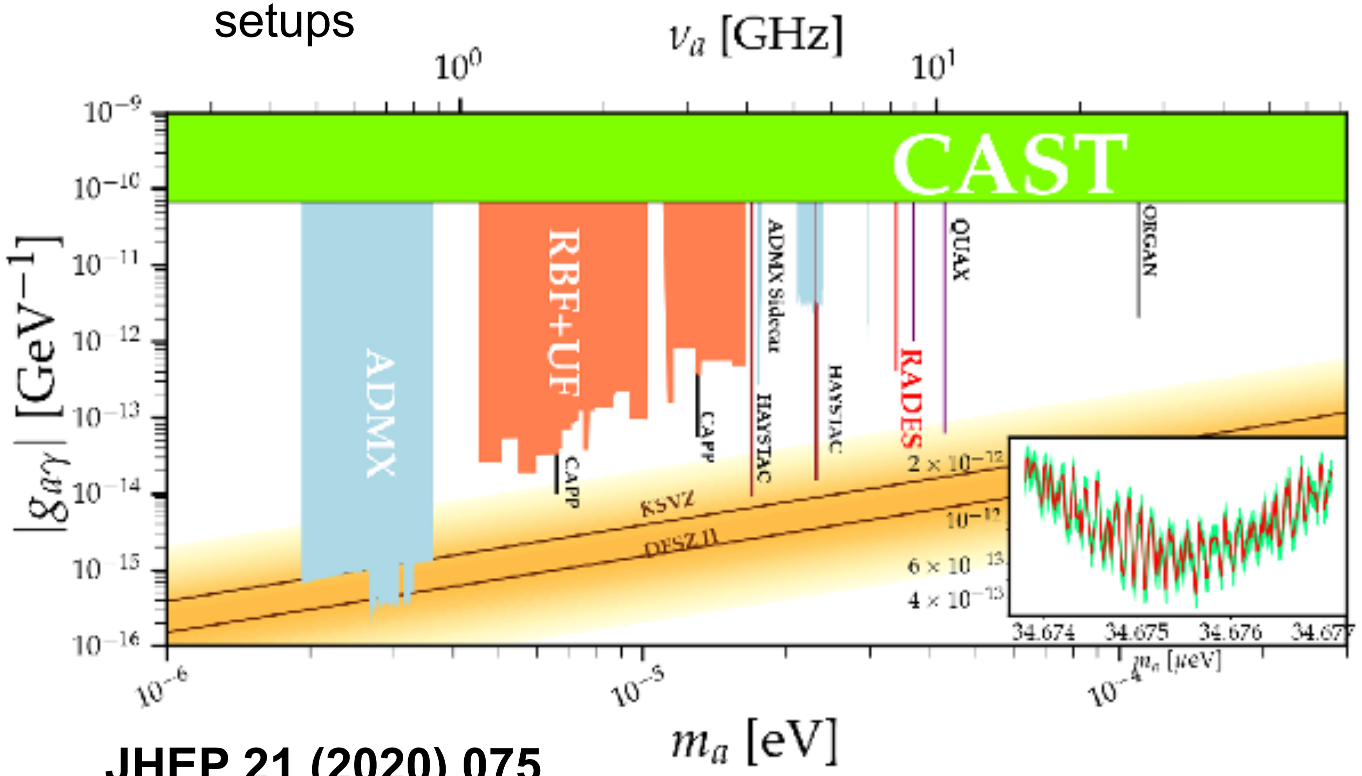
- Assumption for haloscope: DM is mostly made of axions
  - ➡ Axions non-relativistic: $m_a \rightarrow f_{a,\gamma}$
- Resonant "Sikivie" cavities
  - ➡ Axion-photon conversion in tunable resonant cavity
  - ➡ Typically in microwave ranges
- If cavity is tuned to axion frequency: Boost of conversion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



RADES

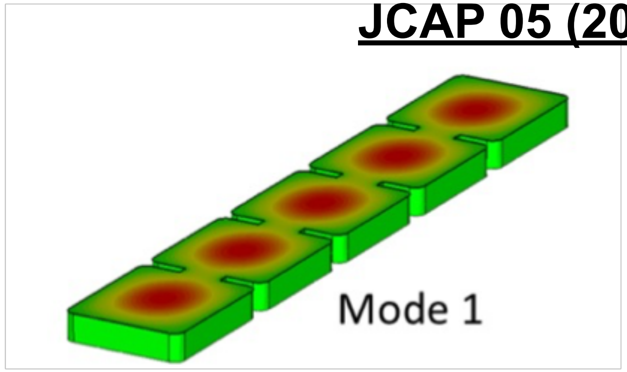
Helioscope as Haloscope Project

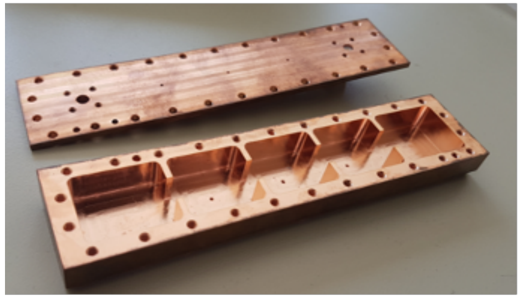
- During late years in the CAST experiment the RADES project emerged
  - ➡ Reuse the magnetic volumes of helioscope for haloscope searches by integrating resonant cavity setups



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 as Haloscope

Searching for DM Axions

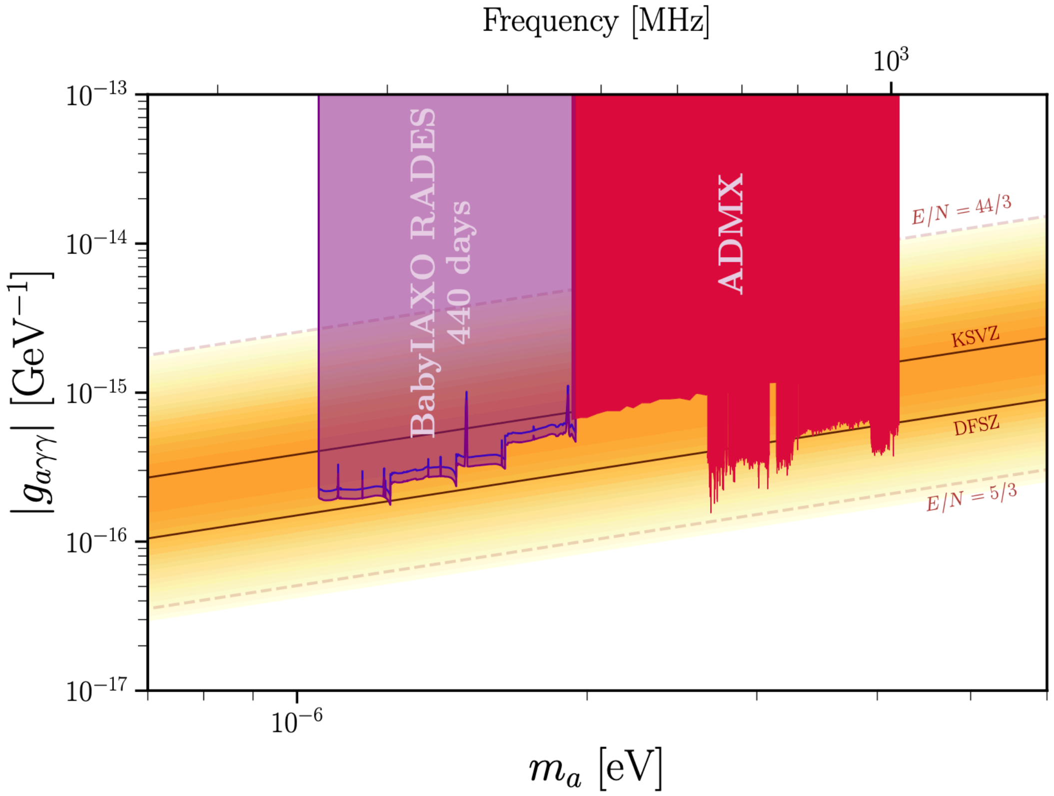
Strongly backed up by achievement of **ERC synergy grant *DarkQuantum*** by I. Irastorza et al.

- Main idea: Use BabyIAXO magnet for haloscope searches

➡ BabyIAXO magnet bore: e.g. 4x 5m cavities to target 1-2 µeV range down to vanilla QCD axion band!

➡ Multiple concepts under development and discussion

RADES-BabyIAXO Prototype



arXiv:2306.17243
(Submitted to AdP)

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

Direct Dark Matter Searches at DESY & Collaboration

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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

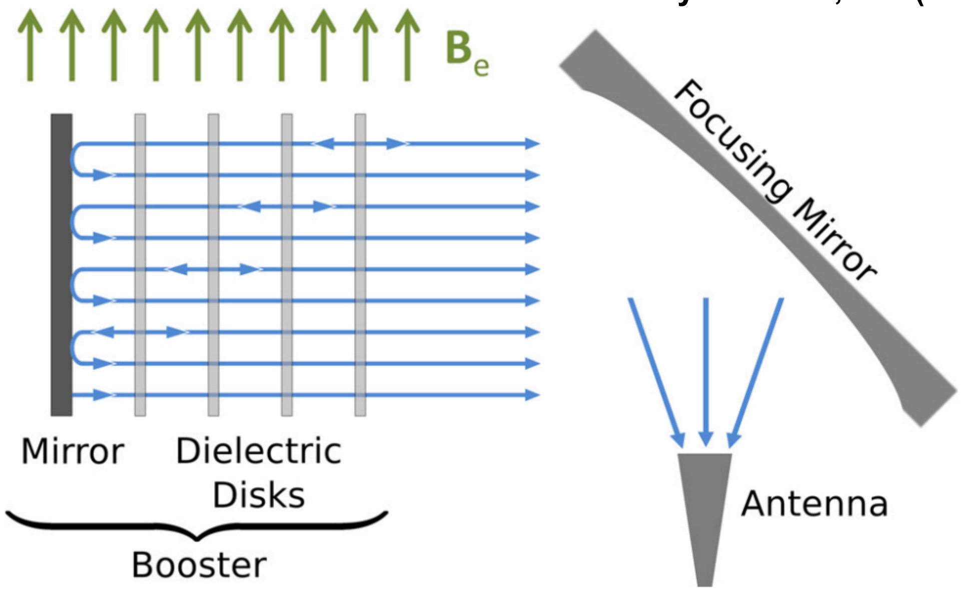
MAgnetized Disc and Mirror Axion eXperiment

A Dielectric Haloscope

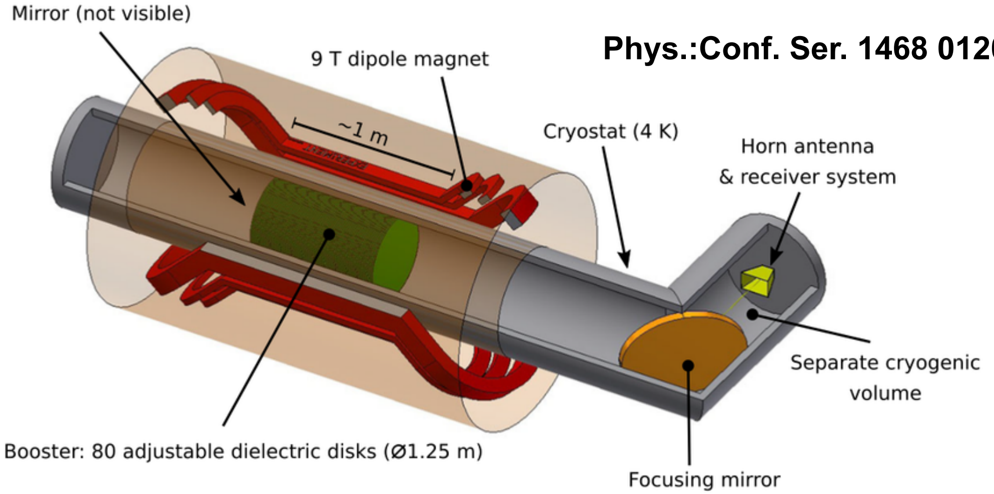
- Principle: boosted dish antenna, open dielectric resonator
  - ➡ Axion-induced EM wave from the E-field discontinuity at dielectric boundary in B-field
  - ➡ Multiple dielectric disks lead to “boost” factor: emissions sum constructively
  - ➡ Precise disk separation: boost factor tunable for specific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

- 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



MAgnetized Disc and Mirror Axion eXperiment

R&D and Status

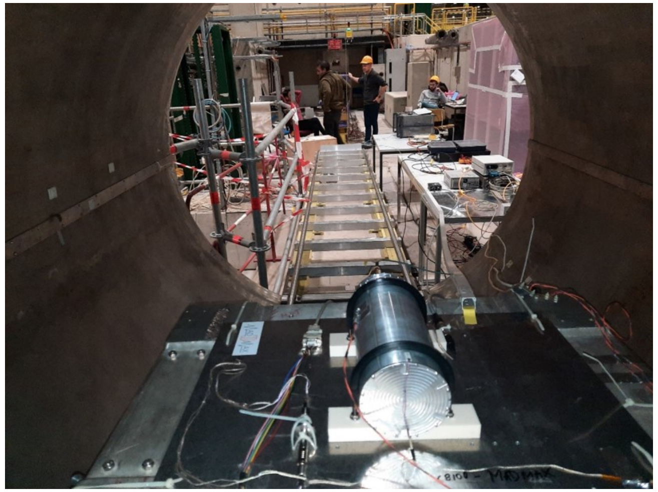
- Magnet: conceptual design + successful conductor tests (quench velocity) @ CEA / Saclay

- Enabling technologies:
  - ➡ Dielectric disk mounting and handling
  - ➡ Piezo motor tests (vacuum, B-field, cryogenics)
    - ➡ **Successfully tested** in UHV / 5.3 T / 5 K @ DESY/UHH

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

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

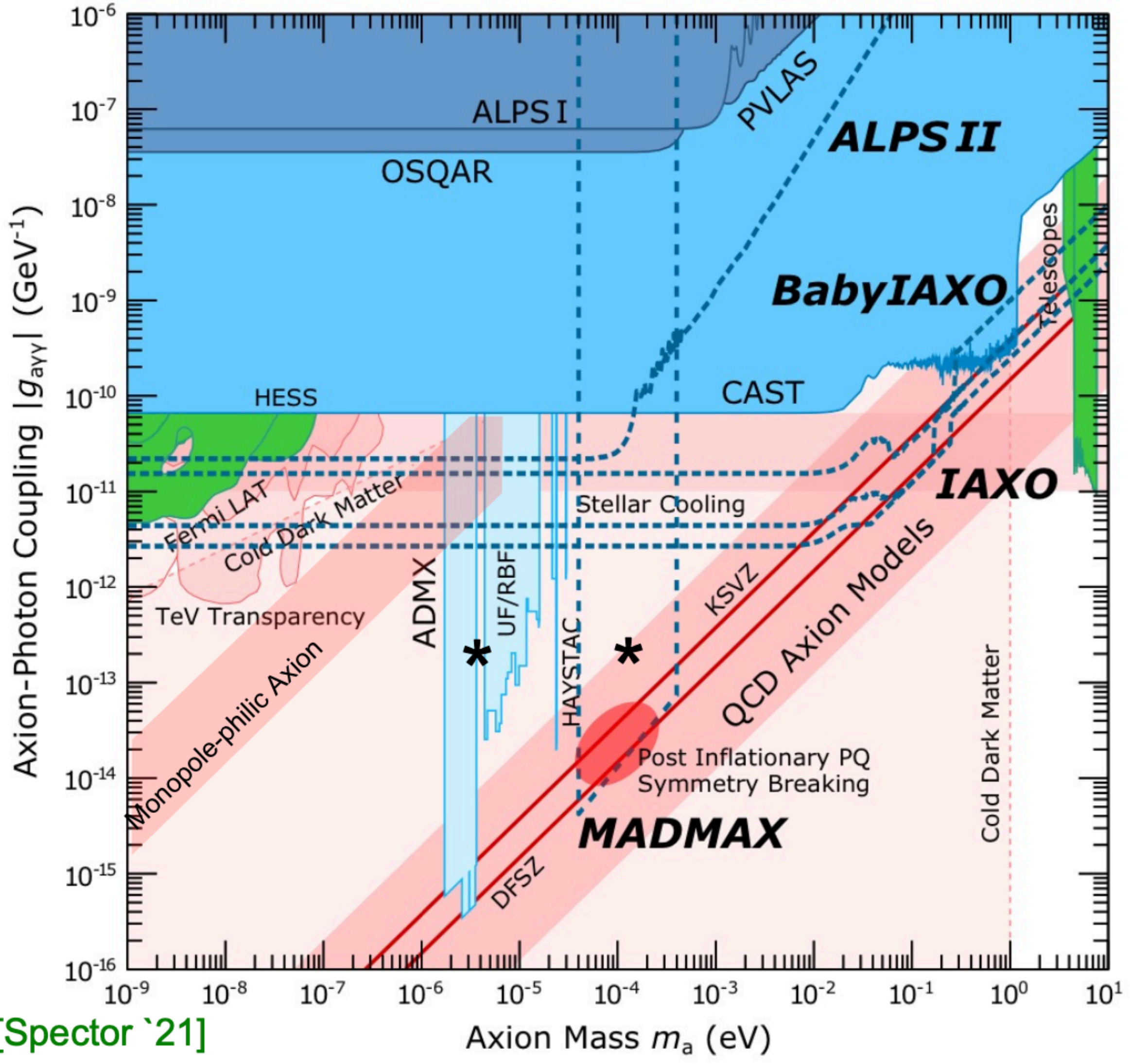
➡ MADMAX potential ~2030 @ DESY?




Prototype at MORPURGO / CERN

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 $\sqrt{\rho_{\mathrm{DM}}/\rho_a}$