Beyond Axion Discovery:

Distinguishing Different Axion Models and Further Searches with (Baby)IAXO

Daniel Heuchel (DESY)
daniel.heuchel@desy.de
FH Particle Physics Pizza Seminar
Hamburg, 26th June 2023

Mainly based on papers:

- JHEP05(2021)137
- JCAP06(2019)047
- JCAP03(2019)039
- Eur. Phys. J. C 82, 120 (2022)

HELMHOLTZ

DESY.

Outline

For this Talk

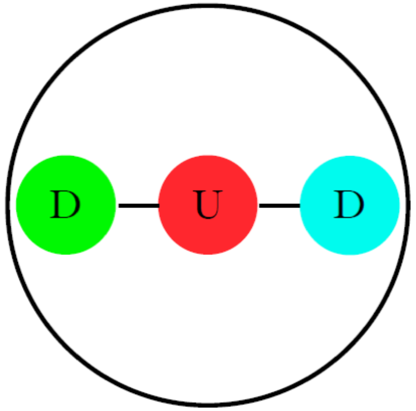
- Axions/ALPs & detection strategies
- Helioscopes: IAXO & BabyIAXO
- Physics prospects beyond (Primakoff)-axion discovery:
  - Axion-electron coupling
  - Axion-nucleon coupling
  - X-ray polarisation
  - Haloscope mode and further searches
- Summary and Outlook

Axions/ALPs

and how to detect them.

Why Axions/ALPs?

Physics Motivation



Most compelling solution to the strong CP problem

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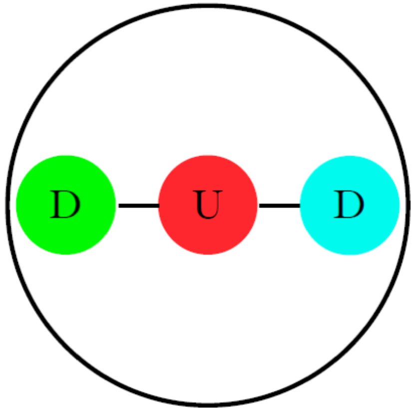

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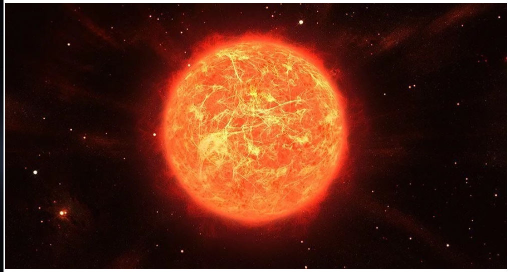

Astrophysical hints:
UHE γ transparency +
anomalous stellar cooling, …

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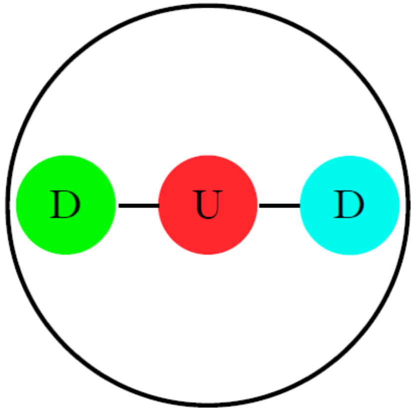

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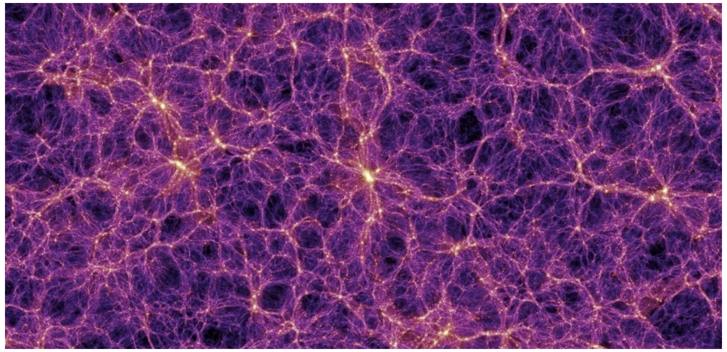

Cosmology:
Excellent cold dark matter candidate
(Not ad hoc solution to DM)

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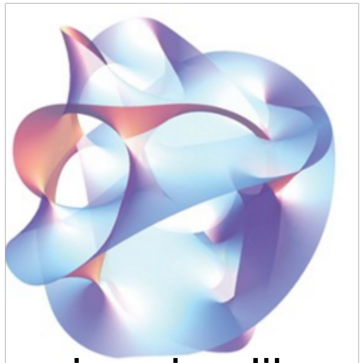
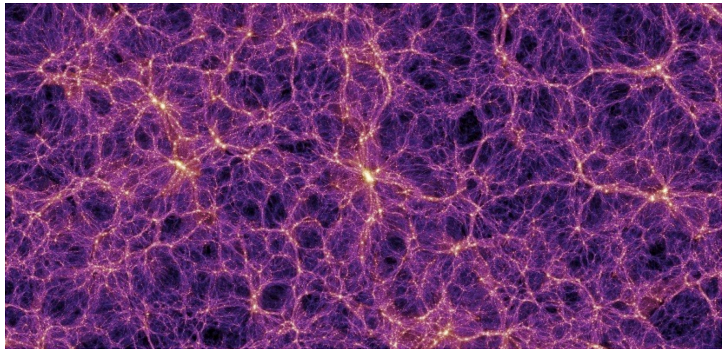


Theory:
More generic axion-like particles (ALPs) predicted by many extensions of SM (e.g. string theory)



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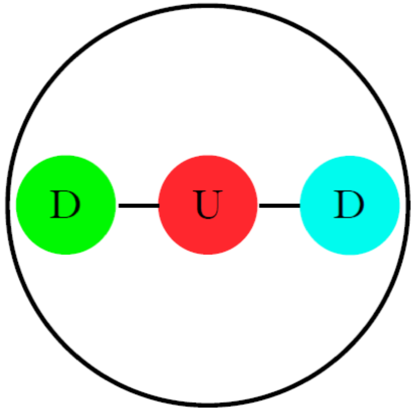

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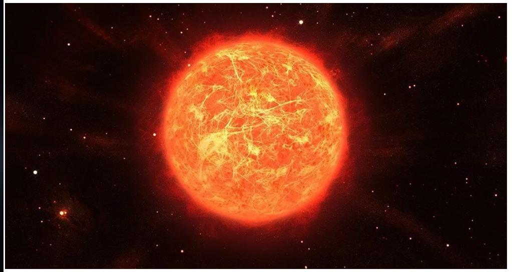

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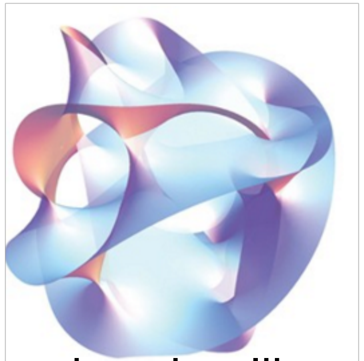

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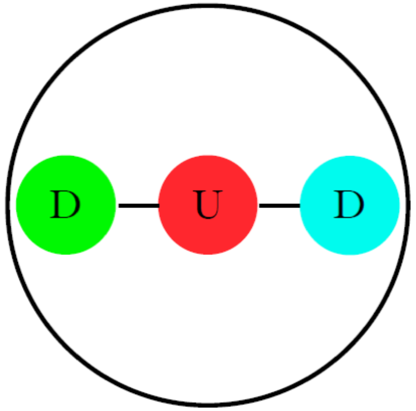

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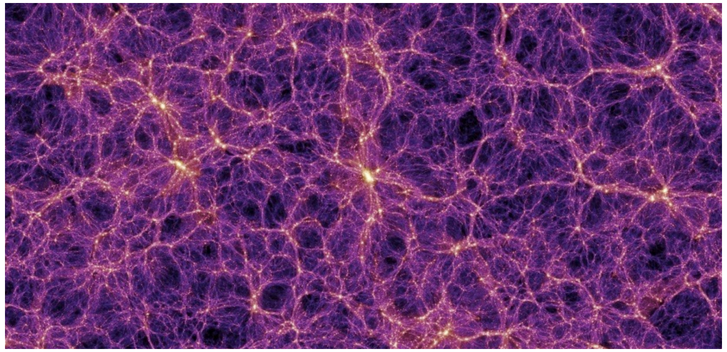

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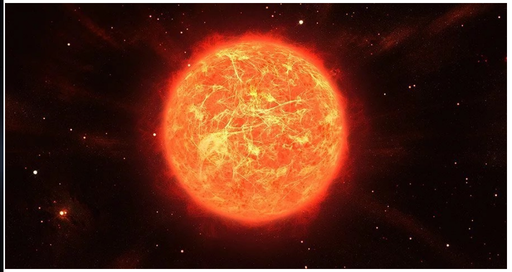

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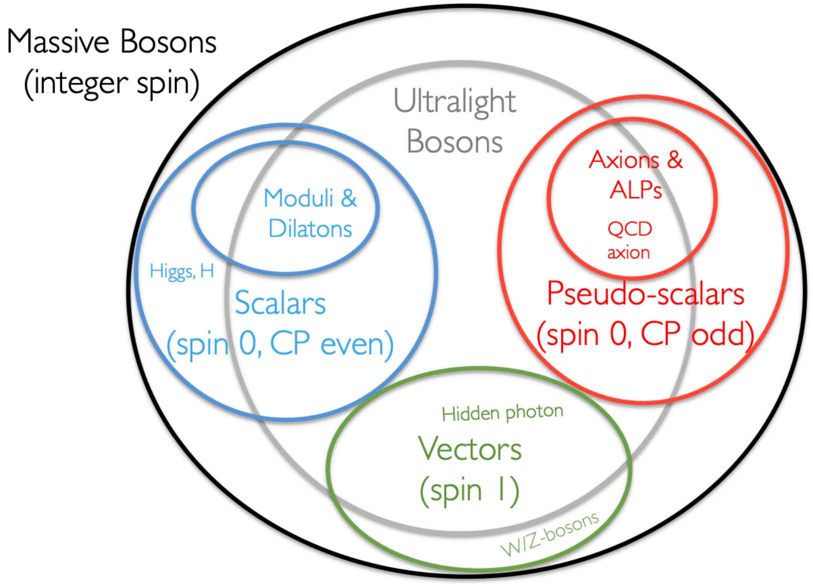
Detection of Axion/ALPs

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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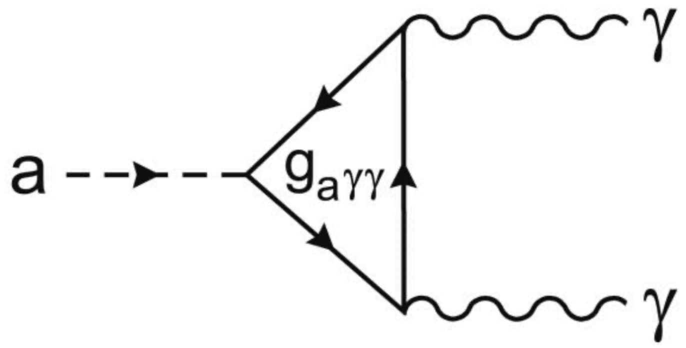

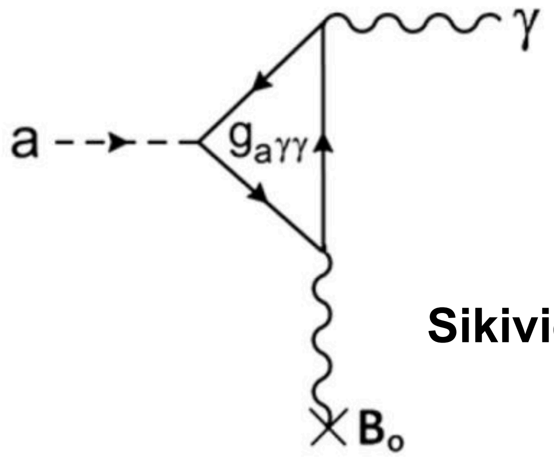

Sikivie effect

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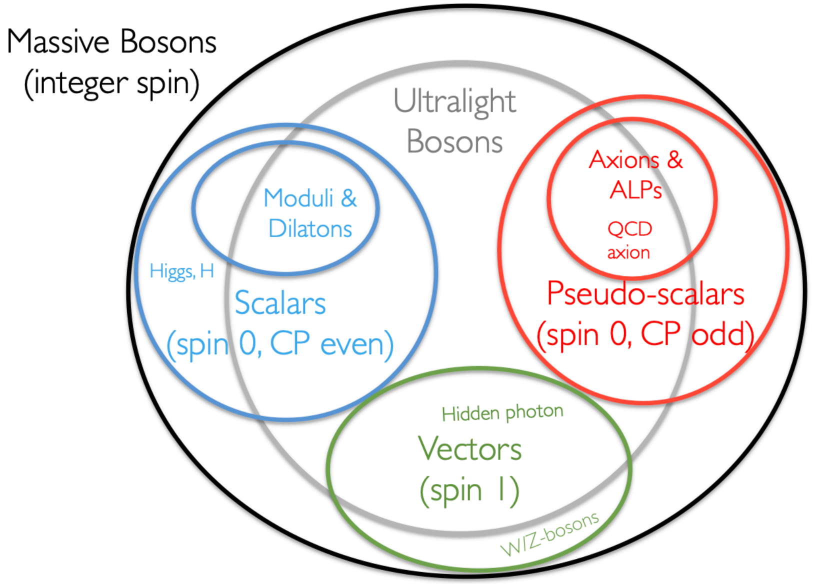

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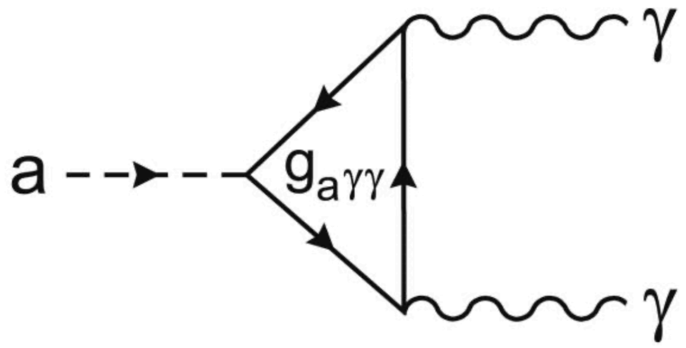
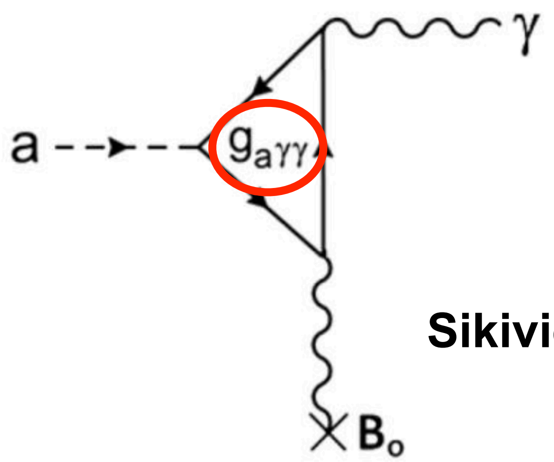
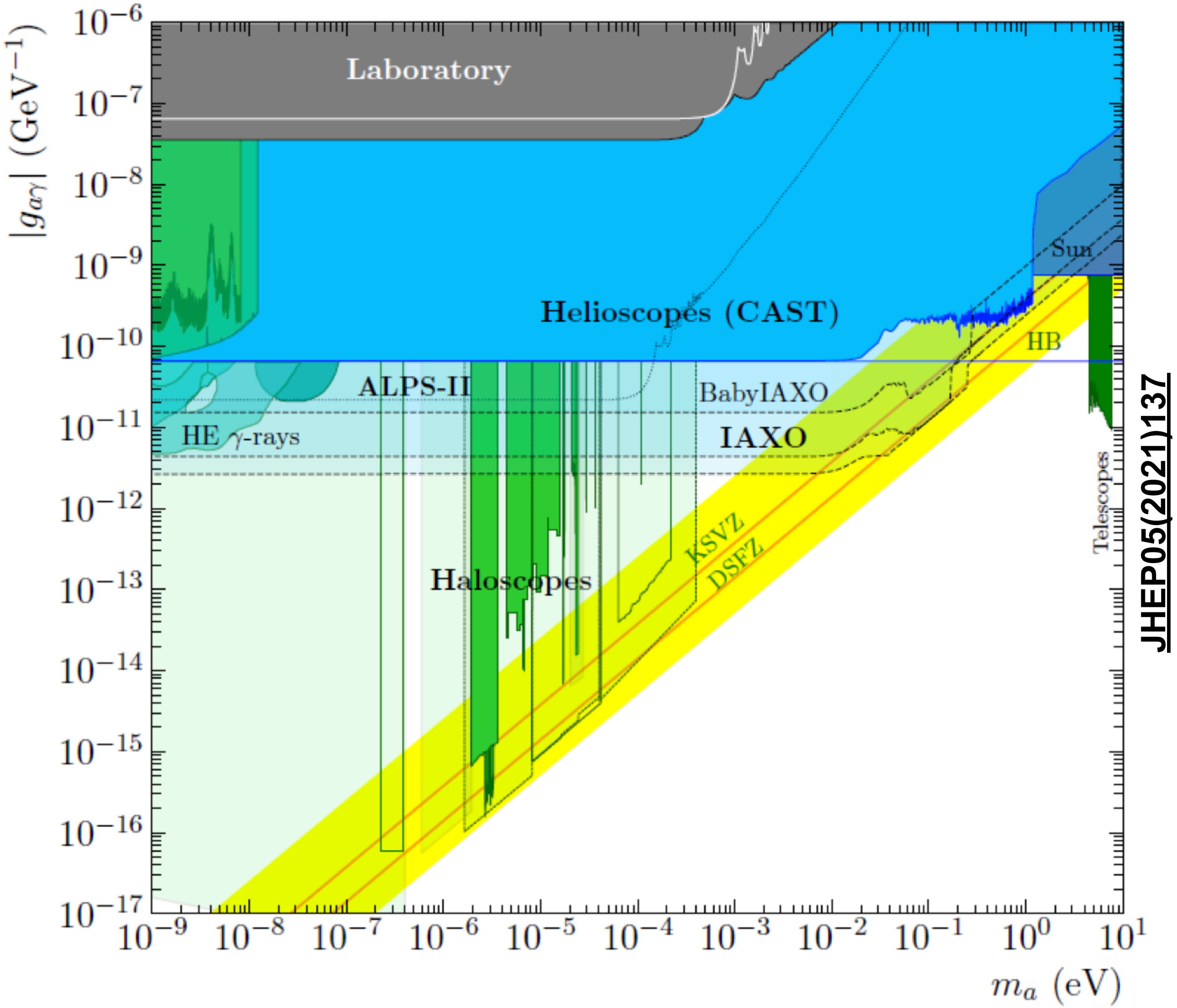




Sikivie effect

The Parameter Landscape

Theories and Experiments



JHEP05(2021)137

The Parameter Landscape

Theories and Experiments

- Yellow band: traditional QCD axion benchmarks
  - ➡ DFSZ (Dine, Fischler, Srednicki, Zhitniskii) axions couple to fermions
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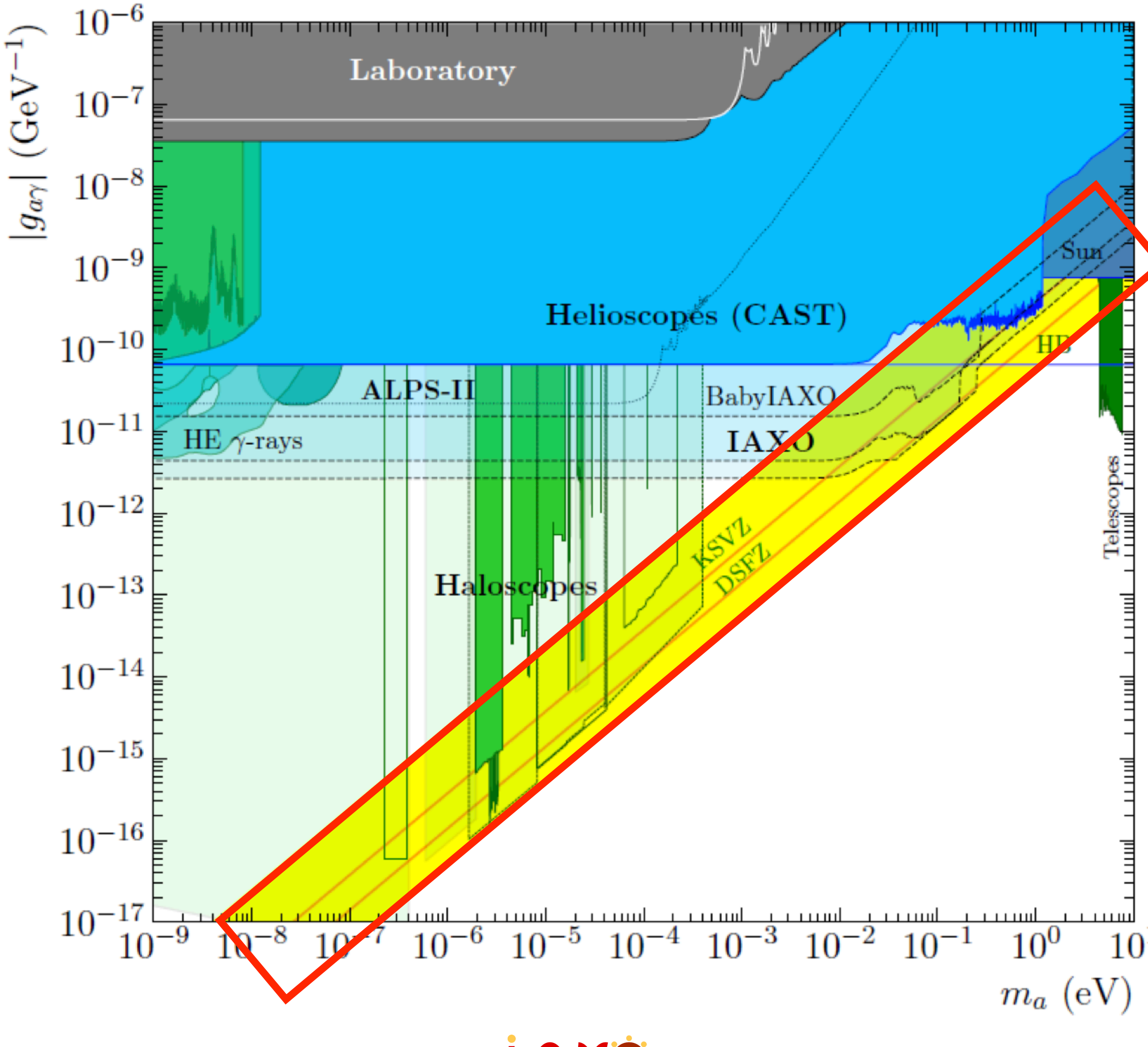

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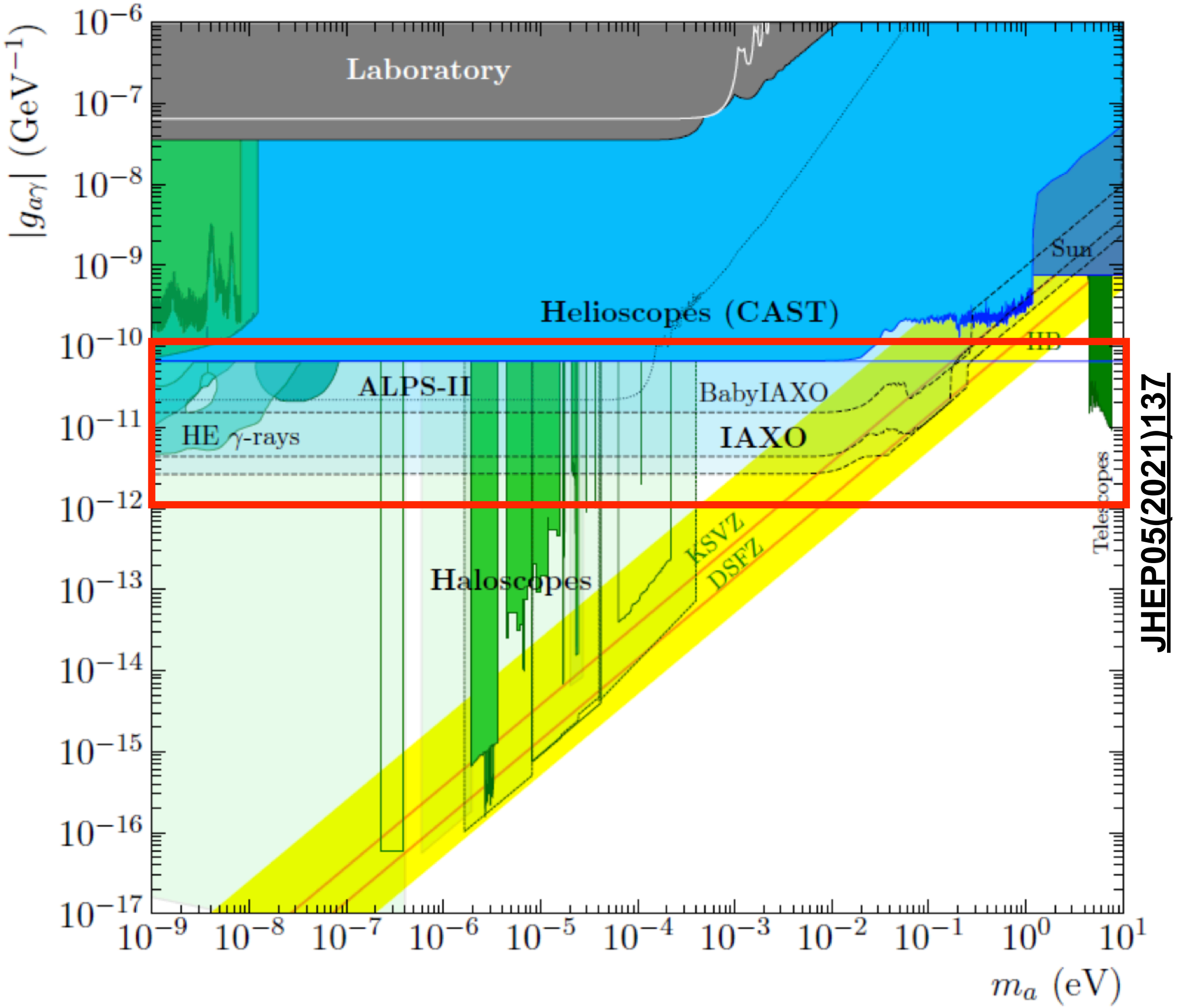

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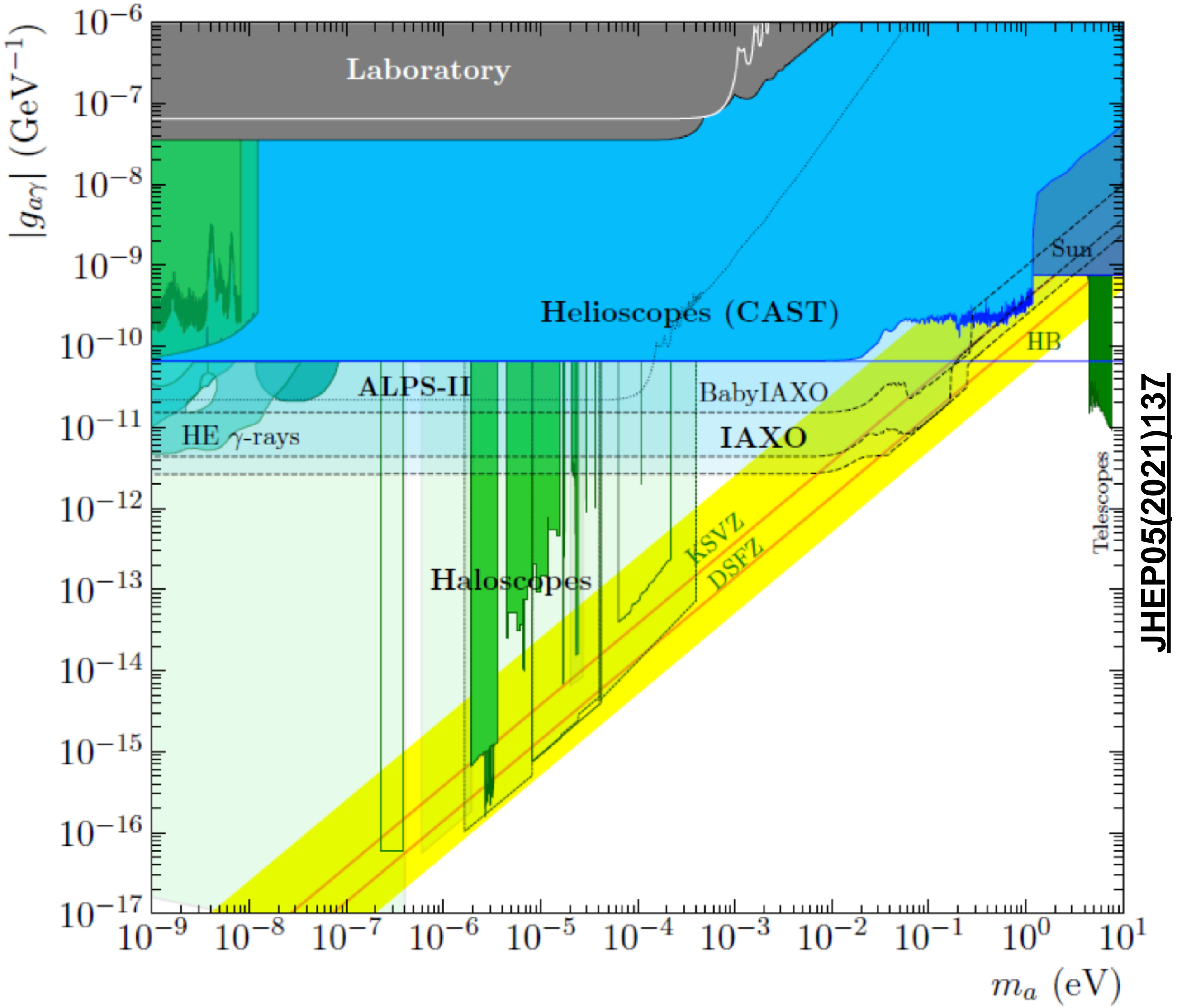

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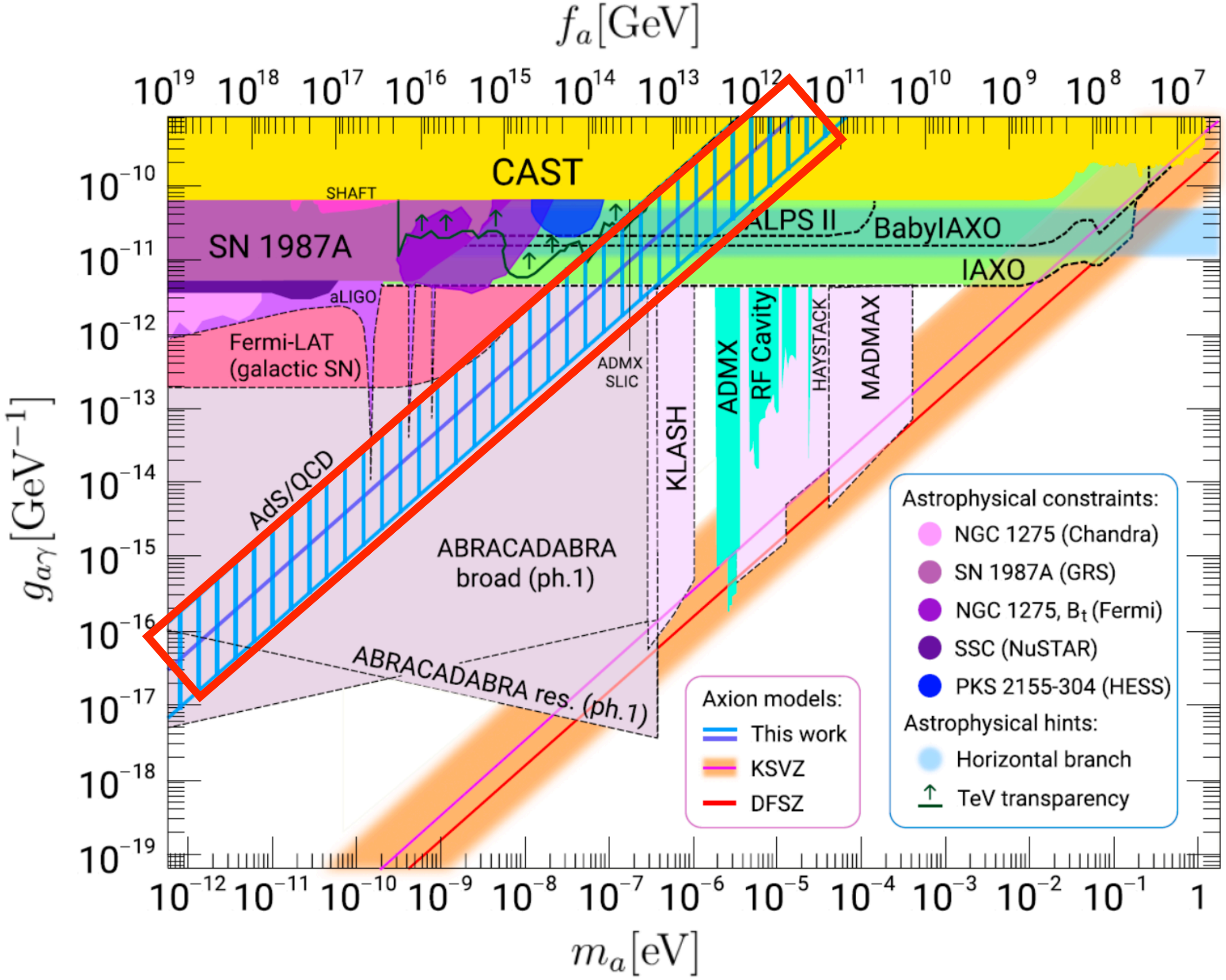

Sokolov-Ringwald: JHEP06(2021)123

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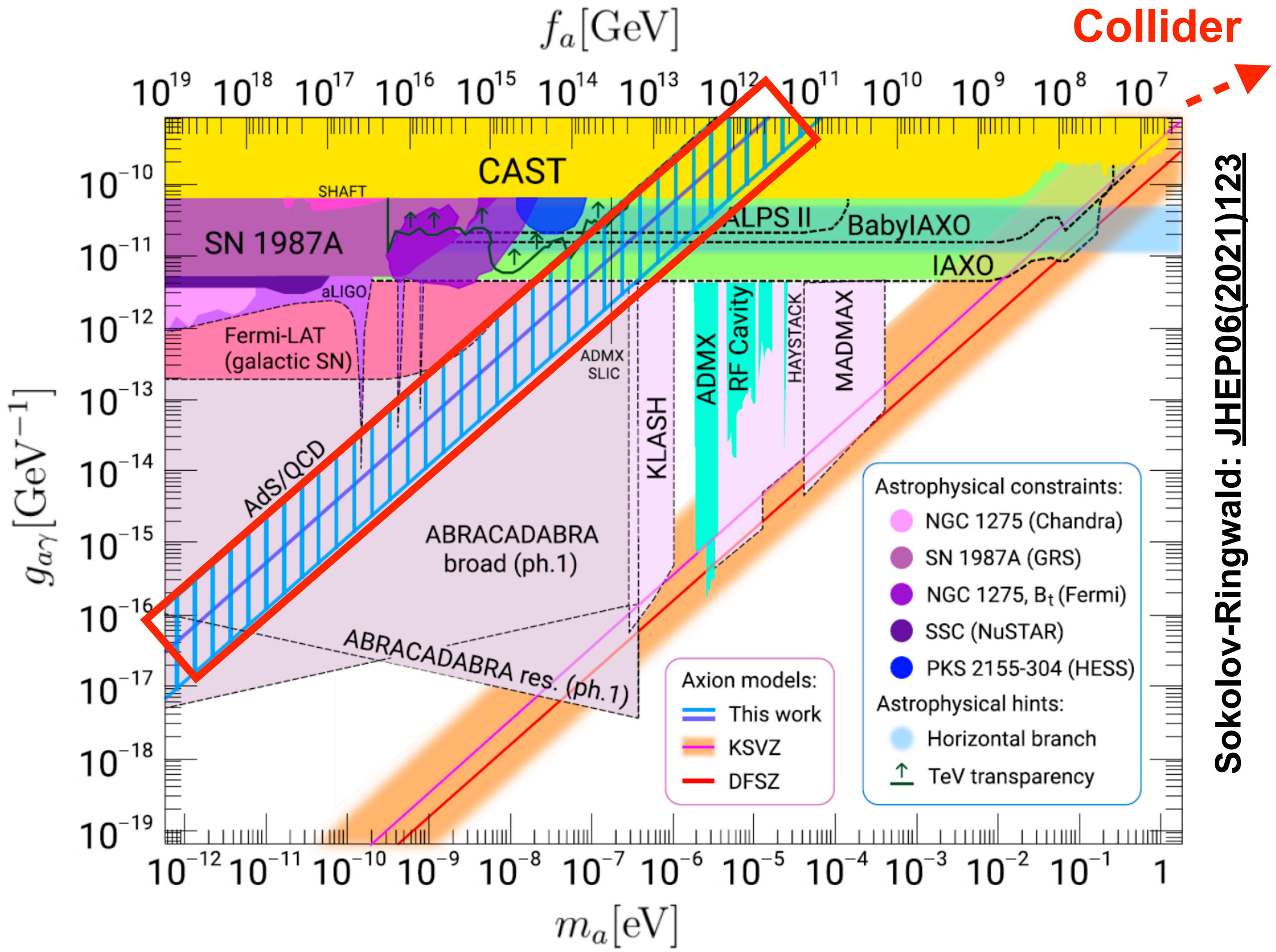
- **Reachable parameter space! Very interesting times for different types of axion experiments!**



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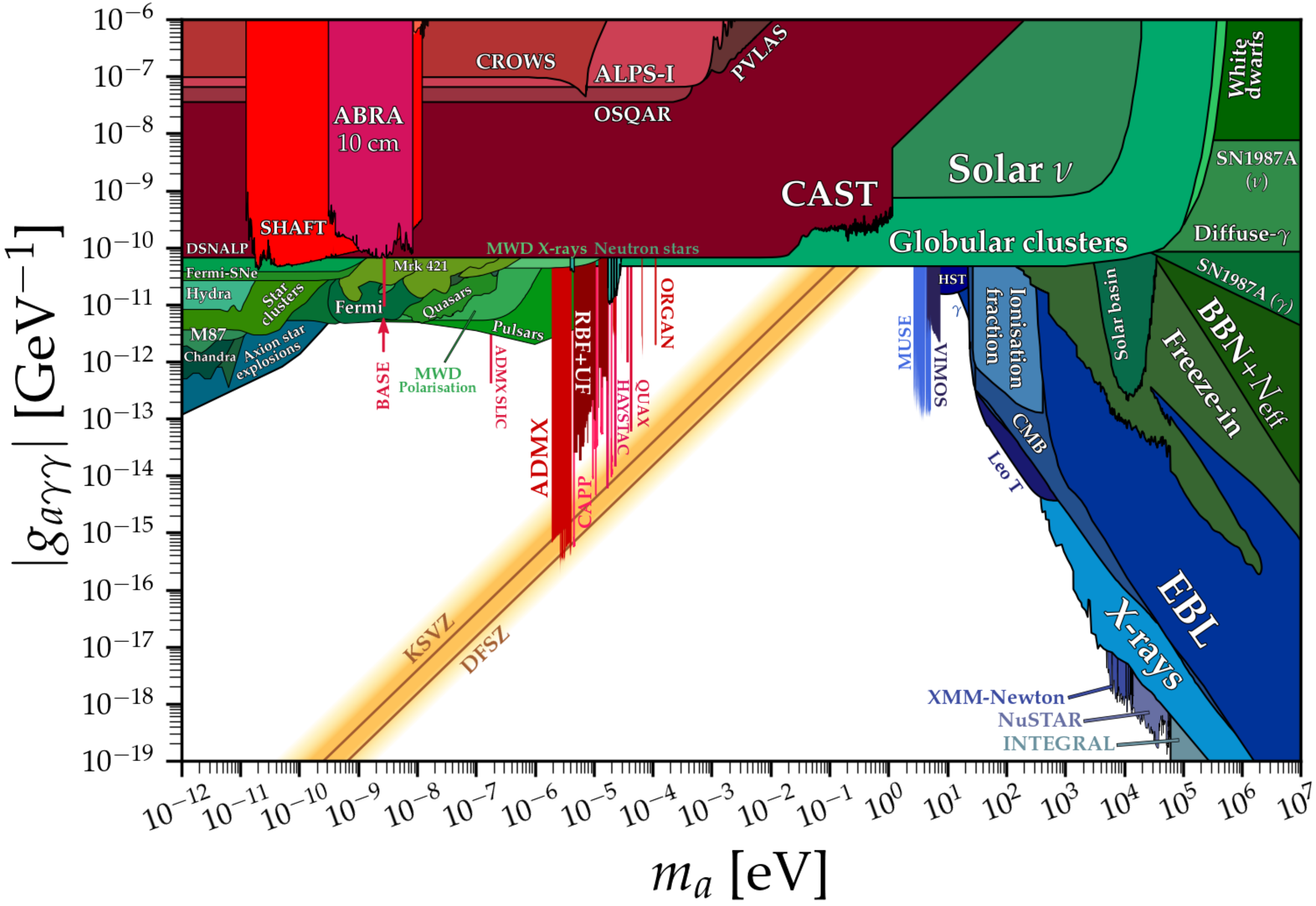
The Current Parameter Landscape

Experimental Exclusion Limits

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



The Current Parameter Landscape

Experimental Exclusion Limits + Projections

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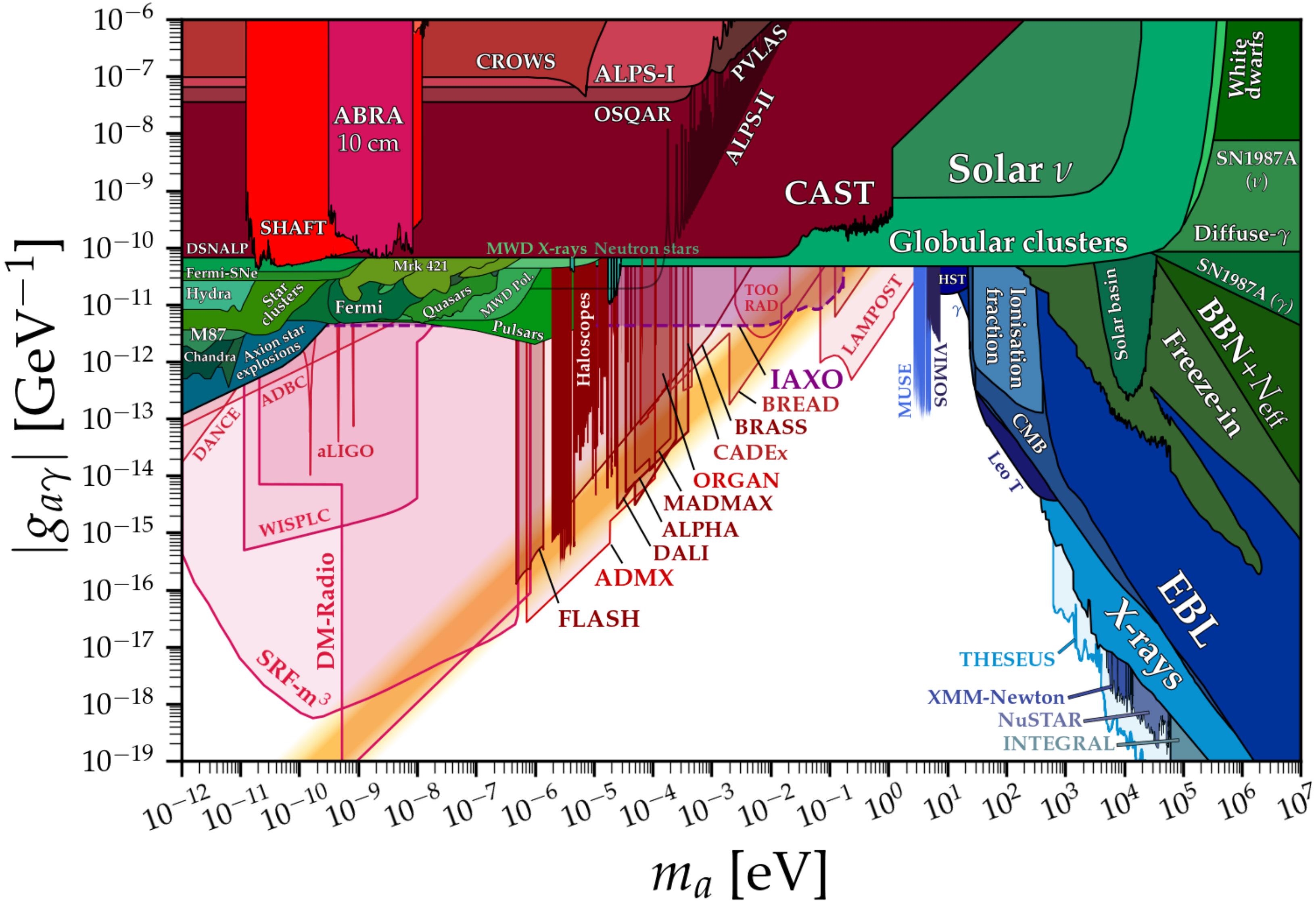
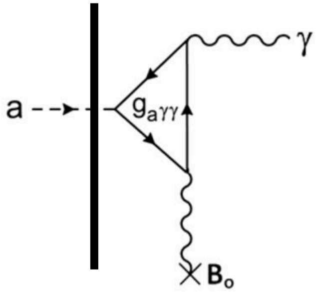


Experimental Approaches

Complementarity & Model Dependencies

Concept	Source	Detection	Model & Cosmology Dependency	Experiments
Haloscopes			High: axions cold dark matter constituents -> “monochromatic” microwave	ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…

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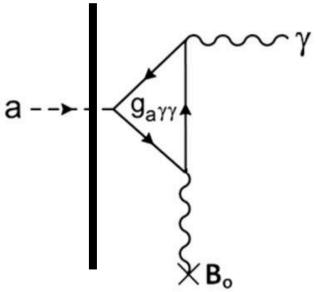
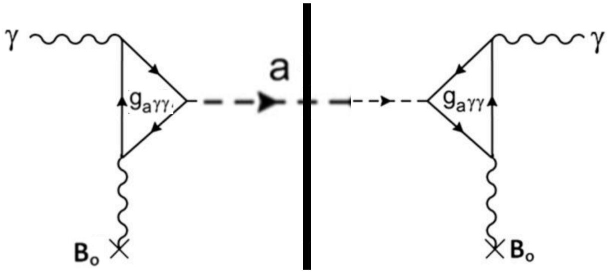
Haloscopes			High: axions cold dark matter constituents -> "monochromatic" microwave	ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…
Light-shining-through-walls experiments	 Lab axions		Model independent: "self-made" axions -> monochromatic microwave/optical	OSQAR, CROWS, ALPS, **ALPS II**,…

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

Just one Extra Slide…

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

Experimental Approaches

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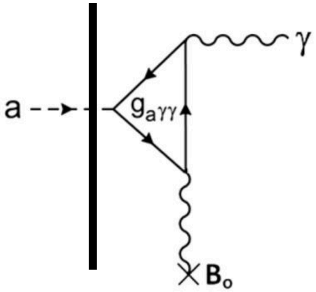
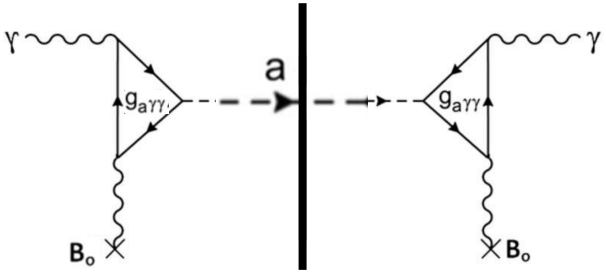
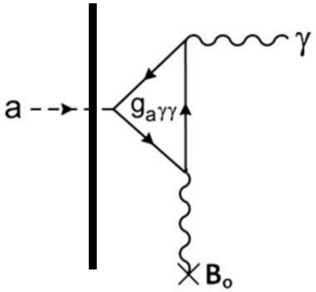
Haloscopes			High: axions cold dark matter constituents -> “monochromatic” microwave	ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…
Light-shining-through-walls experiments	 Lab axions		Model independent: “self-made” axions -> monochromatic microwave/optical	OSQAR, CROWS, ALPS, **ALPS II**,…
Helioscopes	 Solar axions		Low: but depending on production channel and solar model -> X-rays (relativistic axions!), non-monochromatic	SUMICO, CAST, **(Baby)IAXO**

Helioscopes
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

Solar Axions

Production Mechanisms

Solar Axions

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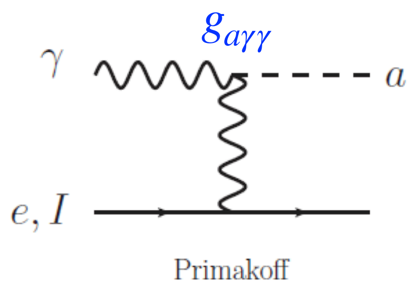
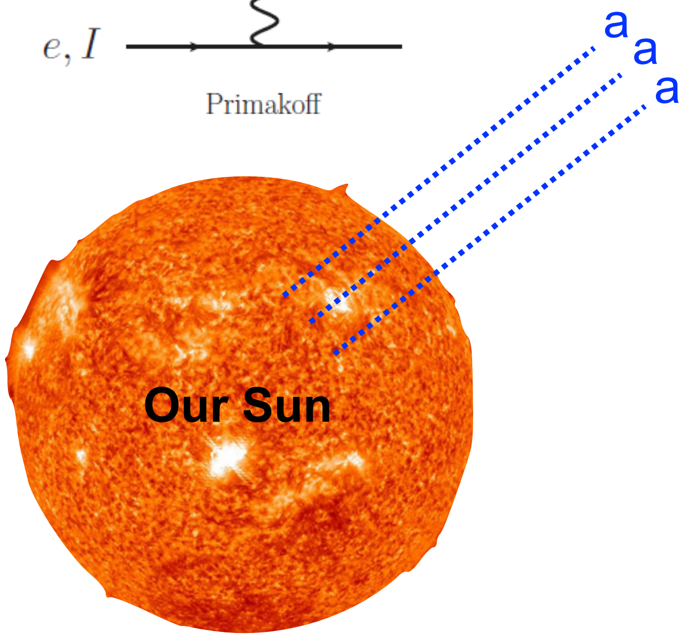
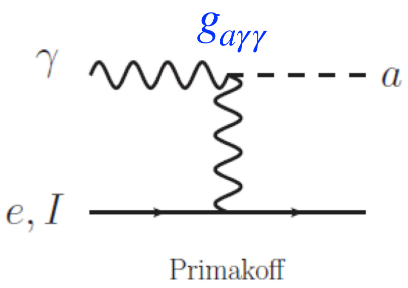


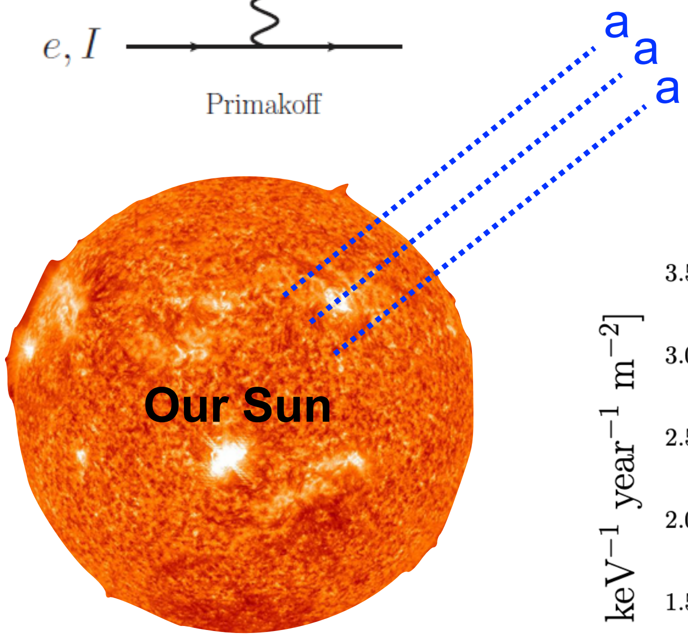


1. “Classical” Primakoff axions from solar plasma photons
   ➡ Generic prediction of most axion models
   ➡ Axion energy: thermal spectrum of sun

Solar Axions

Production Mechanisms





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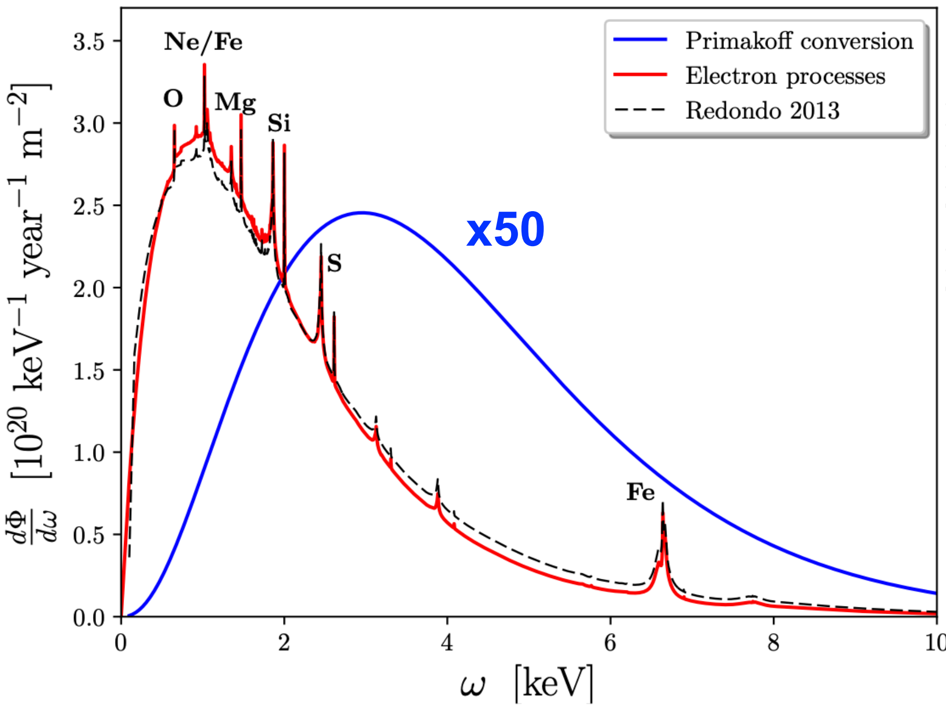
Differential axion flux at earth



Phys. Rev. D 100, 123020

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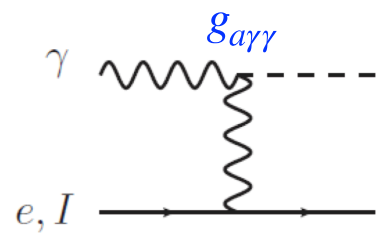
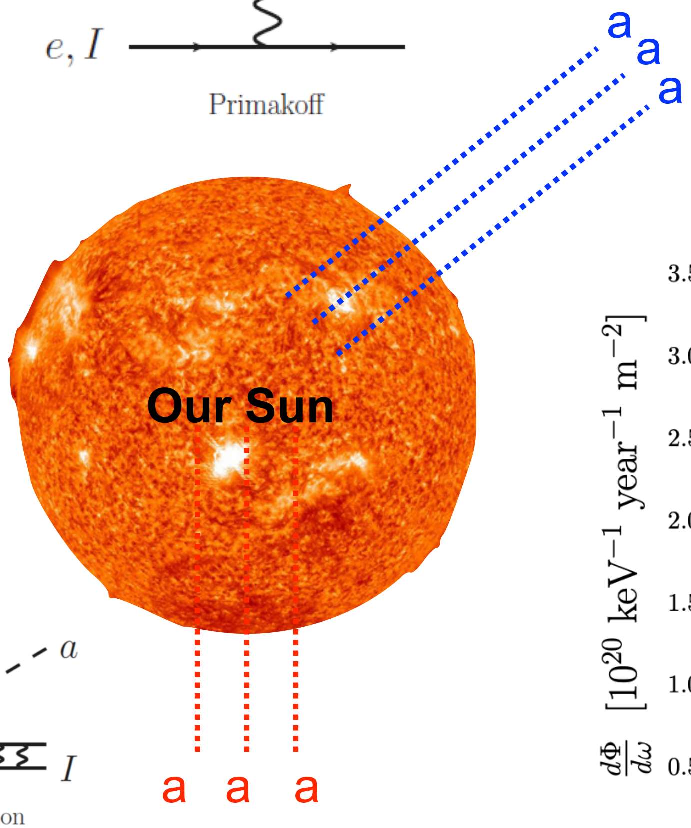
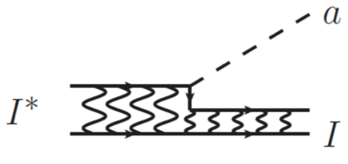
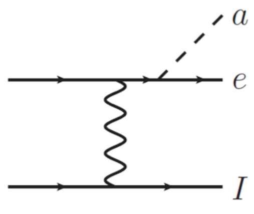


Primakoff

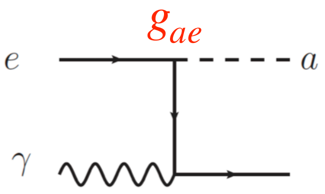




axio – deexcitation

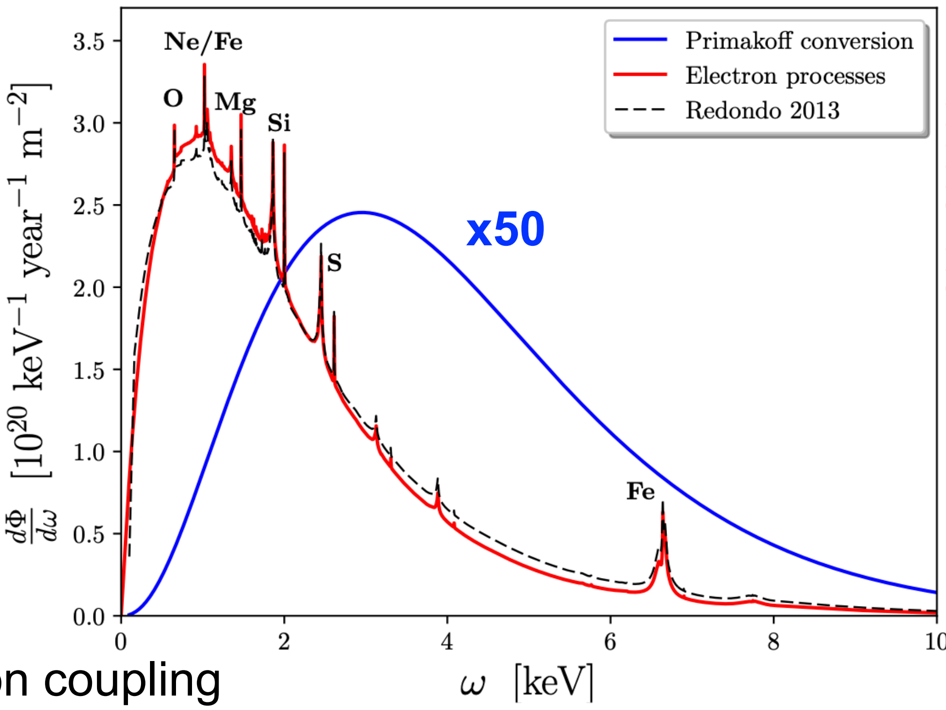


e – I bremsstrahlung



Compton

Differential axion flux at earth



Phys. Rev. D 100, 123020

2. “ABC” solar axions from axion-electron coupling
   ➡ Model dependent
   ➡ Axion energy: continuous spectrum + elemental peaks

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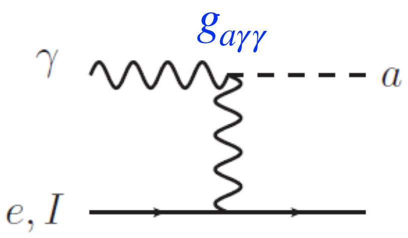
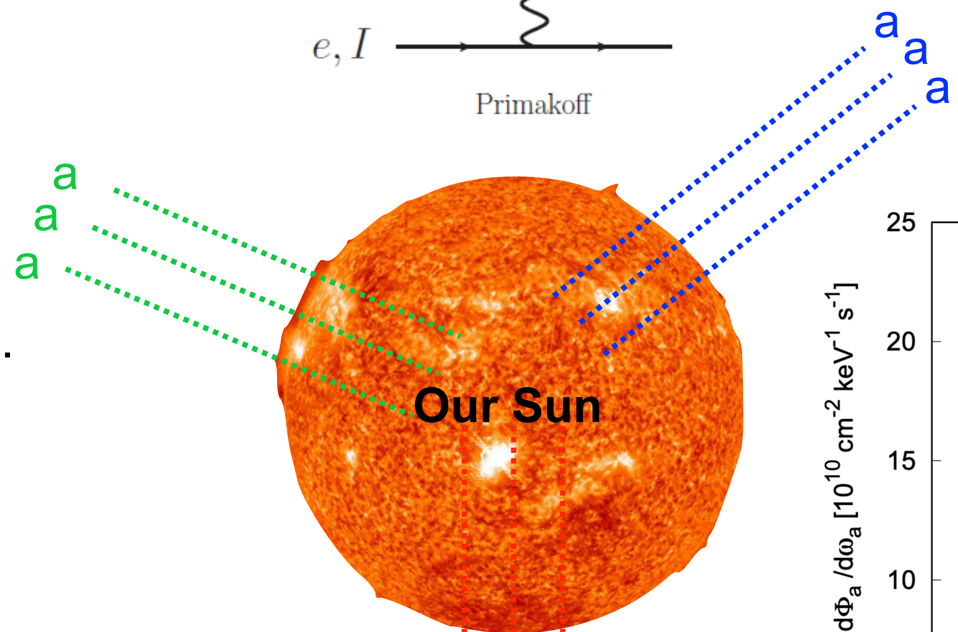
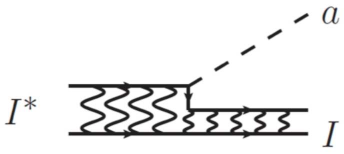


Primakoff

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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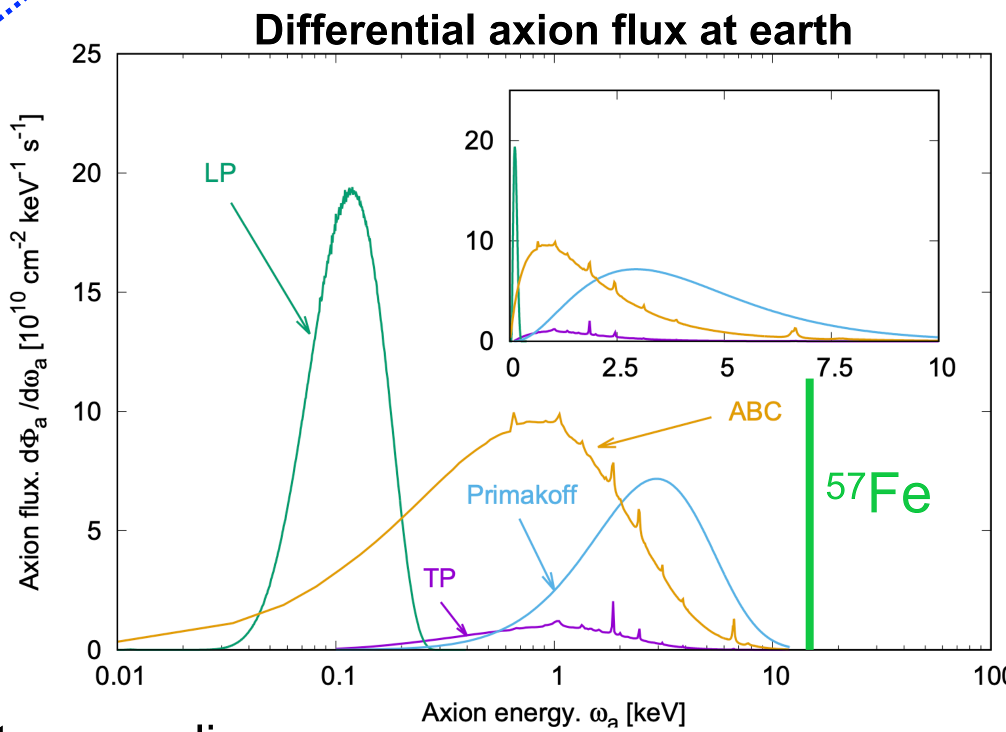

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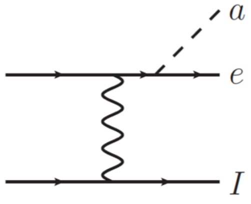

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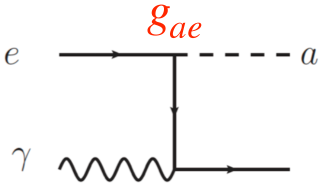

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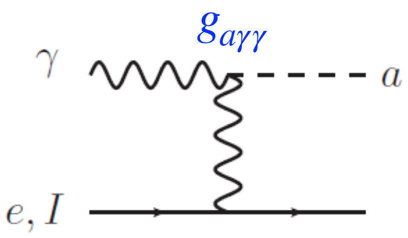
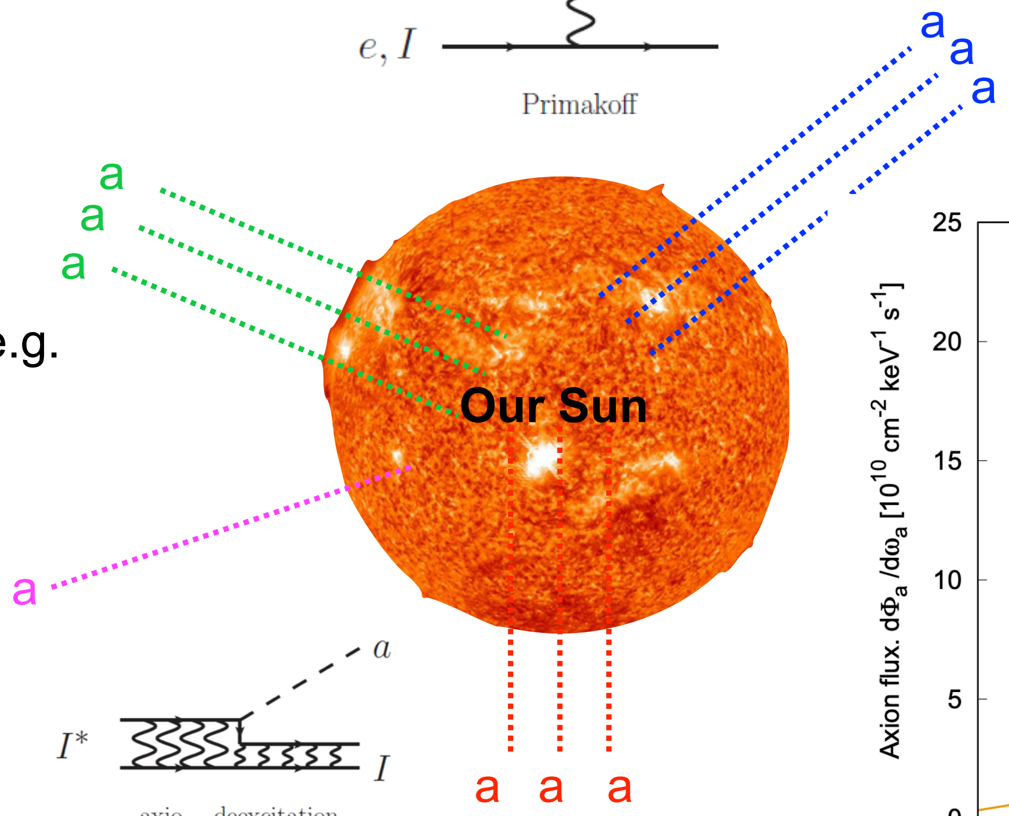
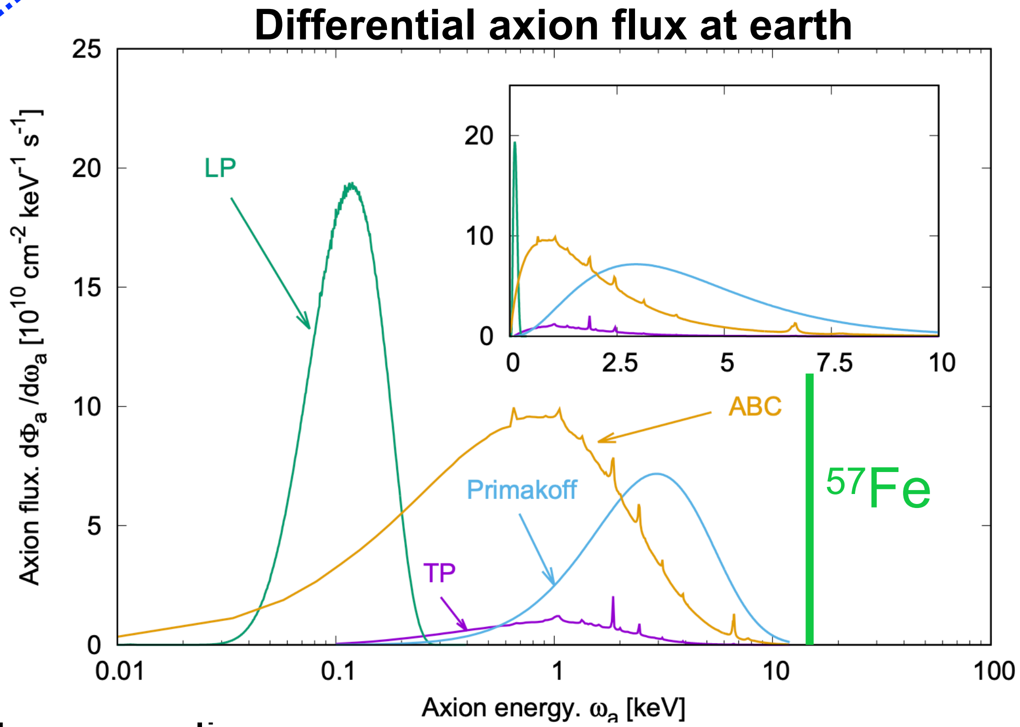


Primakoff

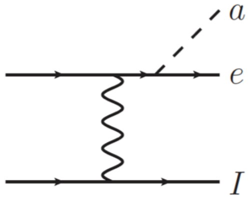
3. Solar axions from axion-nucleon coupling g_{an}
   ➡ Model dependent
   ➡ Fusion processes and nuclear transitions, e.g. most promising: ^{57}Fe
   ➡ Monochromatic lines: e.g. 14.4 keV (^{57}Fe)



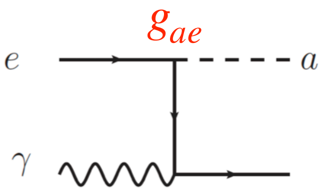


4. Other mechanisms:
➡ Photon-axion conversion in macroscopic B-field
➡ Plasmon-axion conversion
Phys. Rev. D 102, 123024
Phys. Rev. D 101, 123004

axio – deexcitation



e – I bremsstrahlung



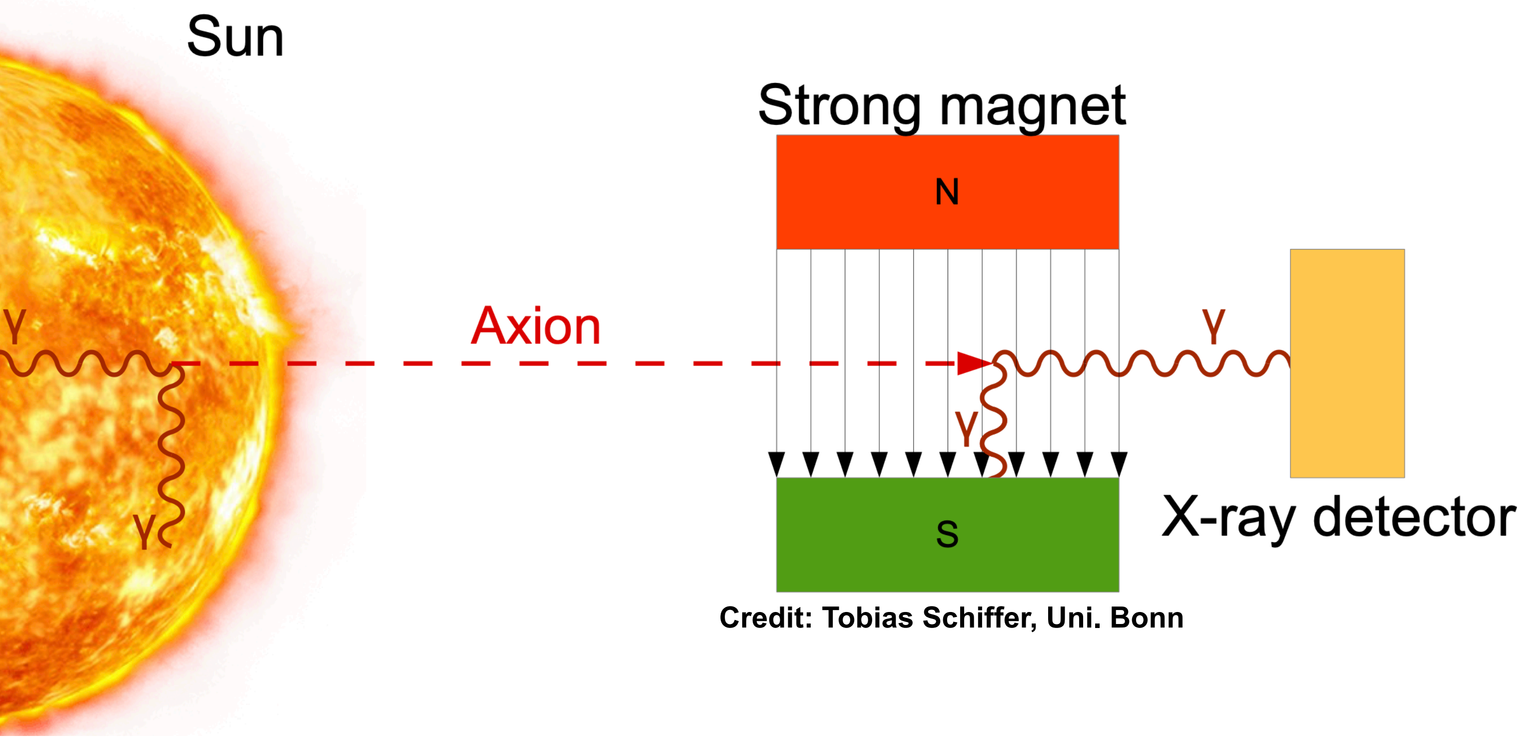
Compton

2. "ABC" solar axions from axion-electron coupling
   ➡ Model dependent
   ➡ Axion energy: continuous spectrum + elemental peaks

universe8010037

Helioscopes

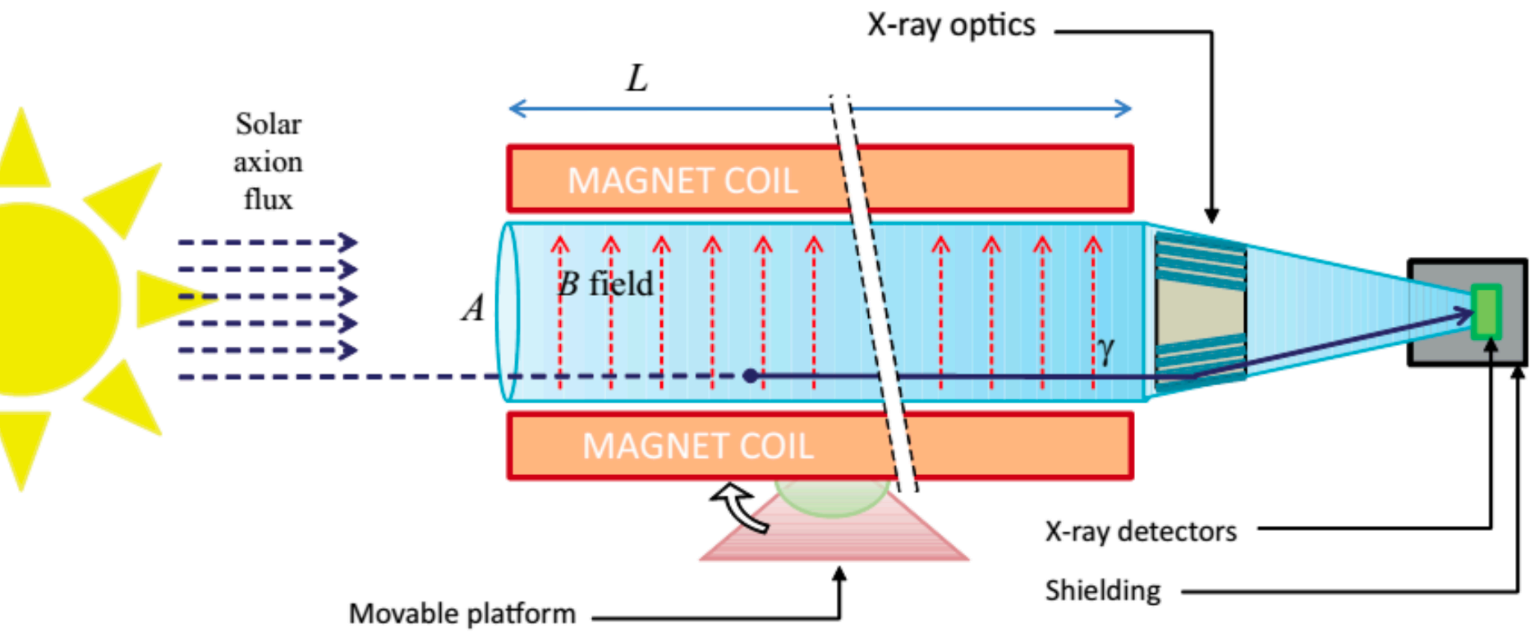
Basic Components, Detection Principle and Figure of Merit



Credit: Tobias Schiffer, Uni. Bonn

Helioscopes

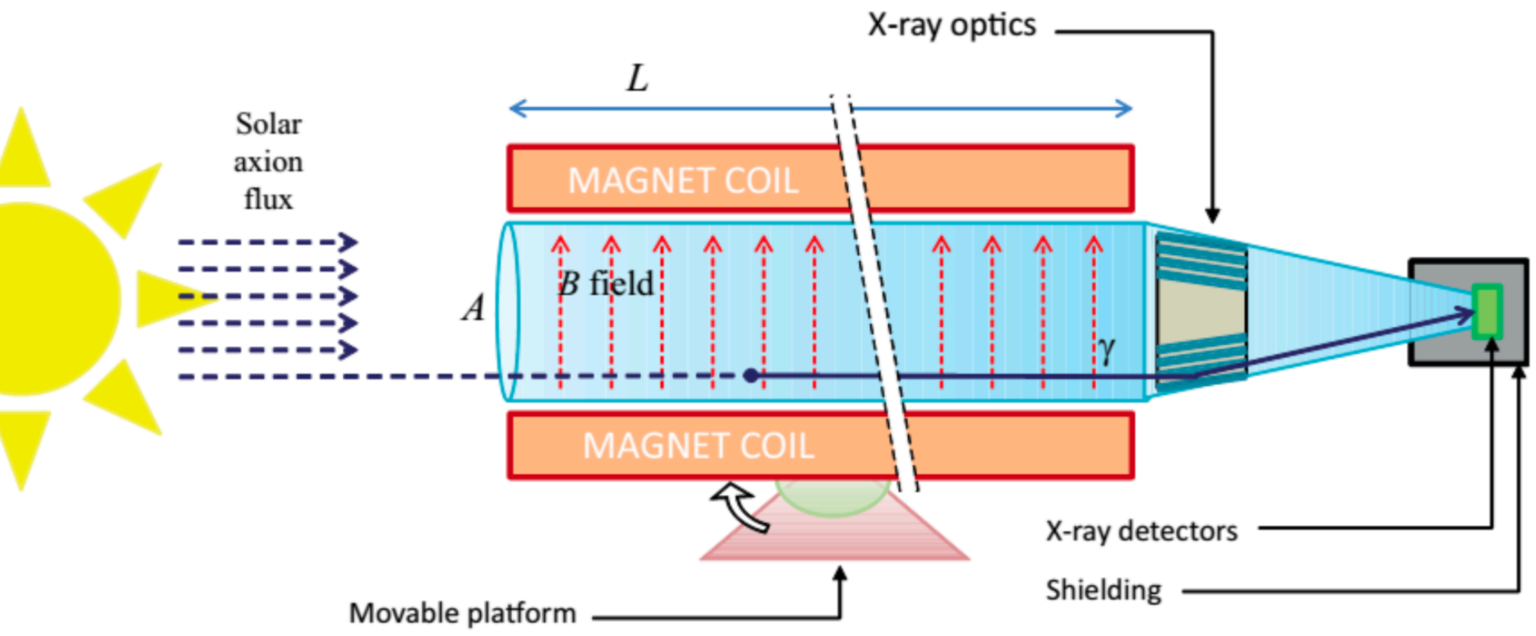
Basic Components, Detection Principle and Figure of Merit



- **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

Basic Components, Detection Principle and Figure of Merit

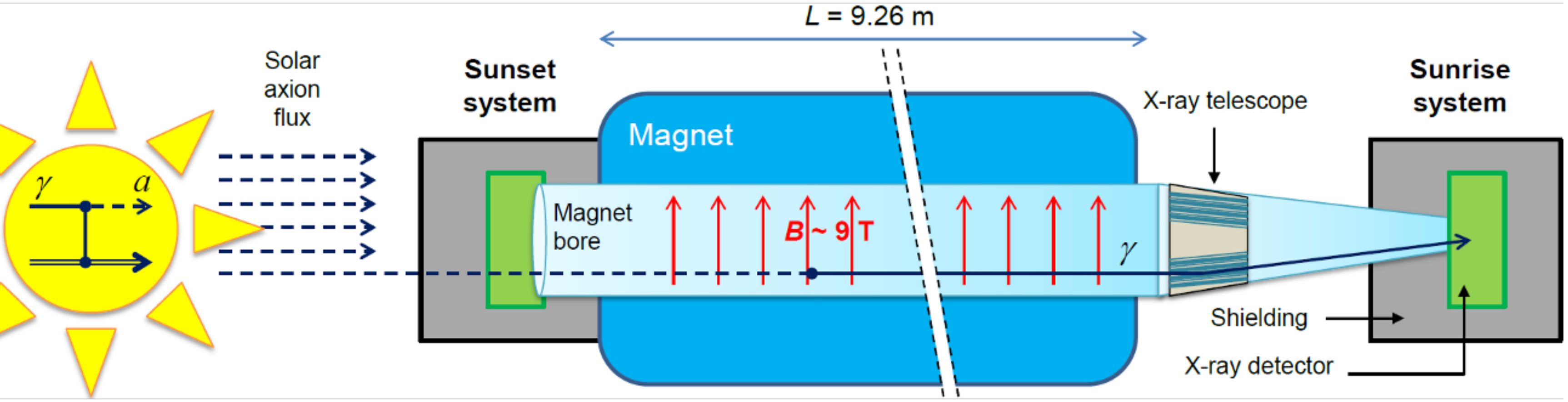


- **Structure & drive system**: precise and long sun tracking capability
- **Magnet**: large volume and high field strength
- **X-ray optics**: small focal spot and high throughput
- **X-ray detectors**: high efficiency and low background

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

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

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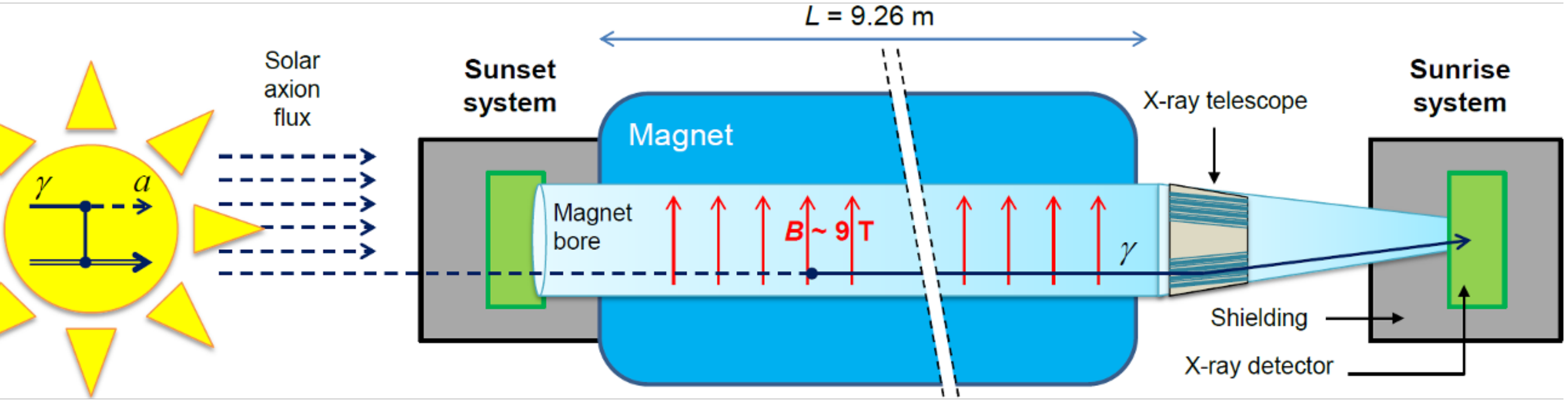

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- First helioscope using X-ray focusing and low background techniques
- Data taking ended 2021 after 20 years of fruitful operation

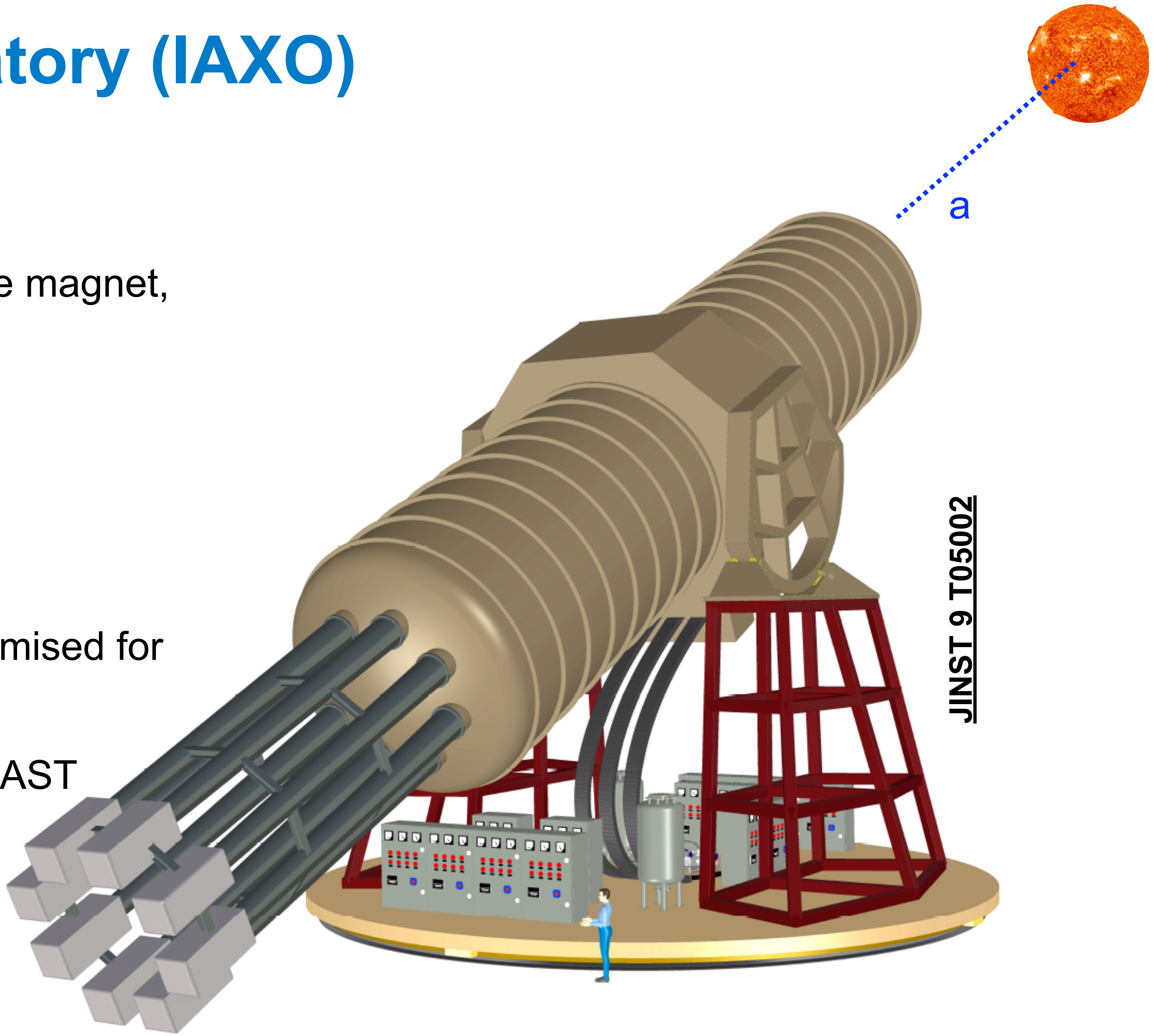
➡ Still state-of-the-art limits on $g_{a\gamma\gamma}$ vs. m_a and other parameter space

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

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
  - ➡ 4+ orders of magnitude better SNR than CAST



JINST 9 T05002

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BabyIAXO - The Intermediate Step

But indeed not a Baby…

New life arises in HERA hall south!

BabyIAXO - The Intermediate Step

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BabyIAXO - The Intermediate Step

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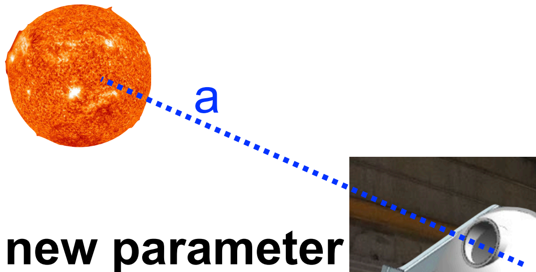

- Prototype for all IAXO sub-systems
- **Fully-fledged helioscope that will study new parameter space and deliver important physics results**

JHEP05(2021)137

BabyIAXO - The Intermediate Step

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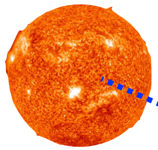


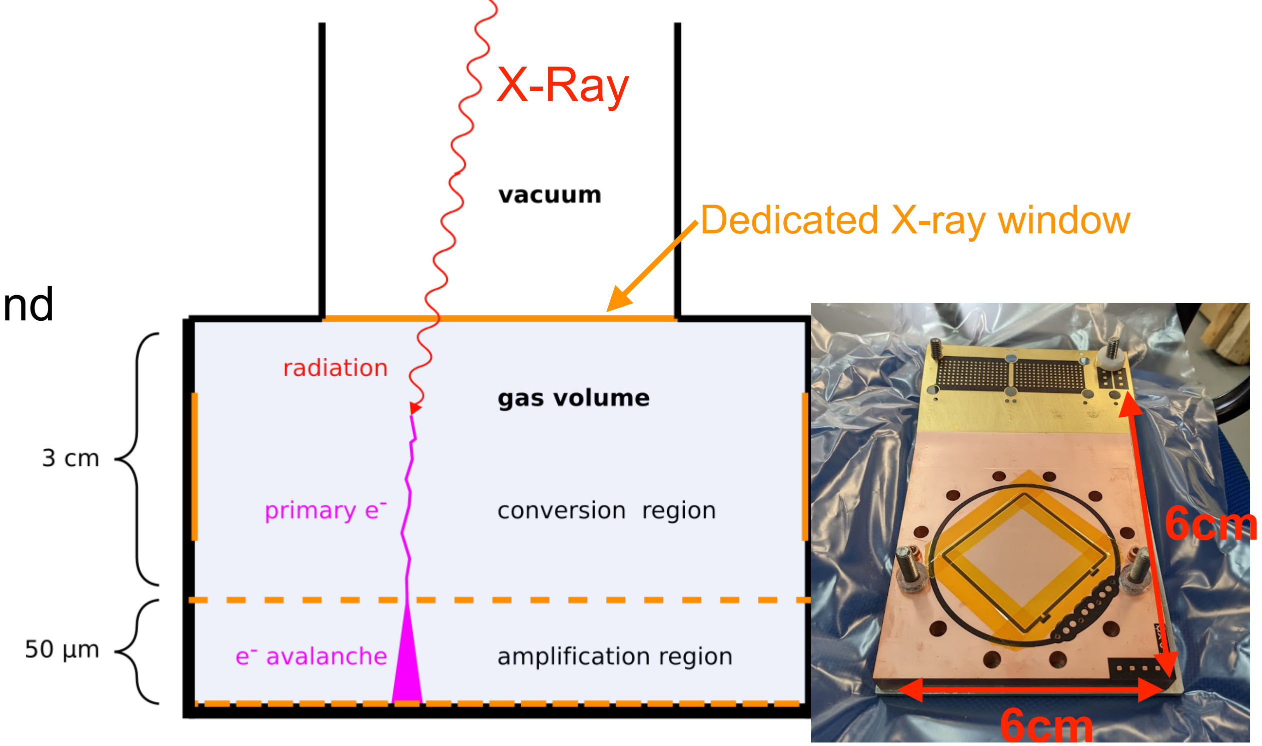
- Prototype for all IAXO sub-systems
- **Fully-fledged helioscope that will study new parameter space and deliver important physics results**
- 12 hours solar tracking per day
- 10 m superconducting purpose built large scale magnet, 2-3 T, 2 bores (d = 70 cm each)
  - ➡ $B^2 L^2 A = \sim 325\ T^2 m^4$ (>10x CAST)
- X-ray optics with ~0.2 cm^2 focal planes
- 2 detection lines
  - ➡ Complementary detector technologies optimised for different measurements
  - ➡ 2 orders of magnitude better SNR than CAST

JHEP05(2021)137

X-Ray Detectors

Discovery Technologies

- Requirements: High detection efficiency (1-10 keV) and ultra-low background levels
- Baseline option: Micromegas (Micro-Mesh) TPC



X-Ray Detectors

Discovery Technologies

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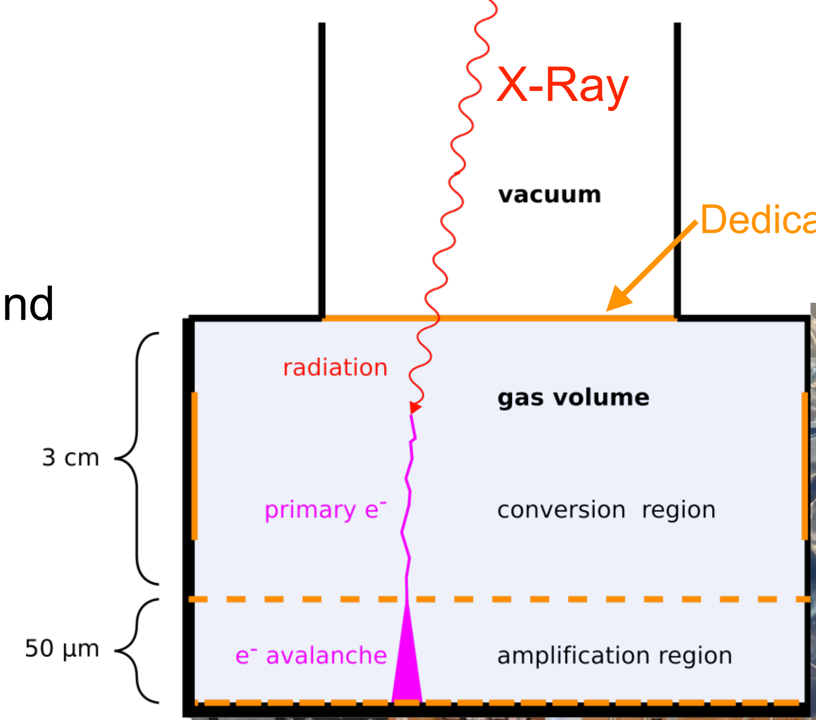
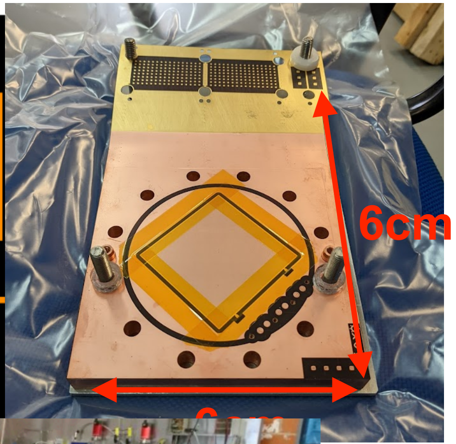
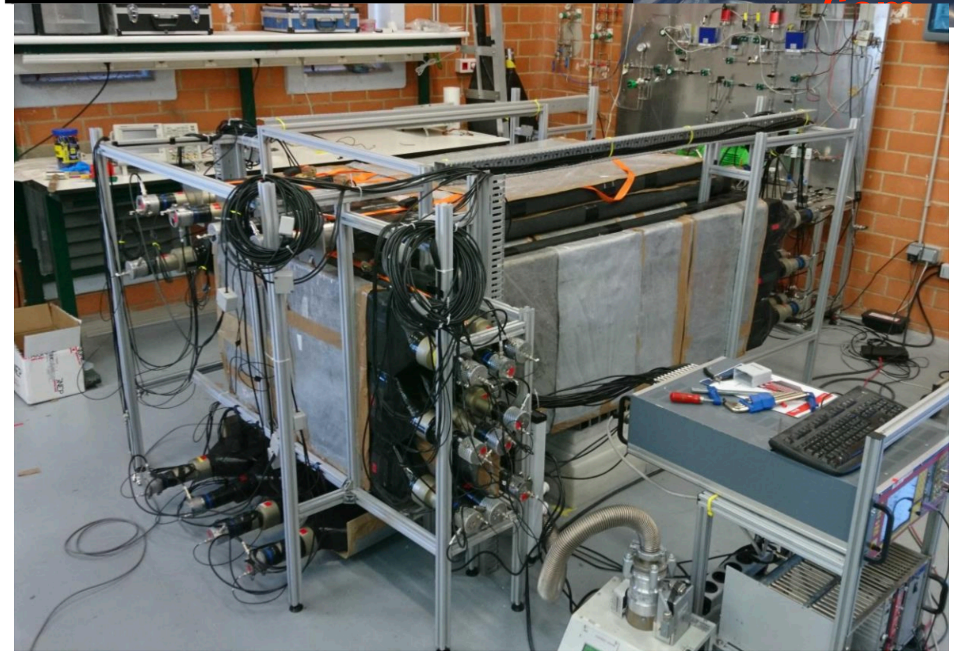


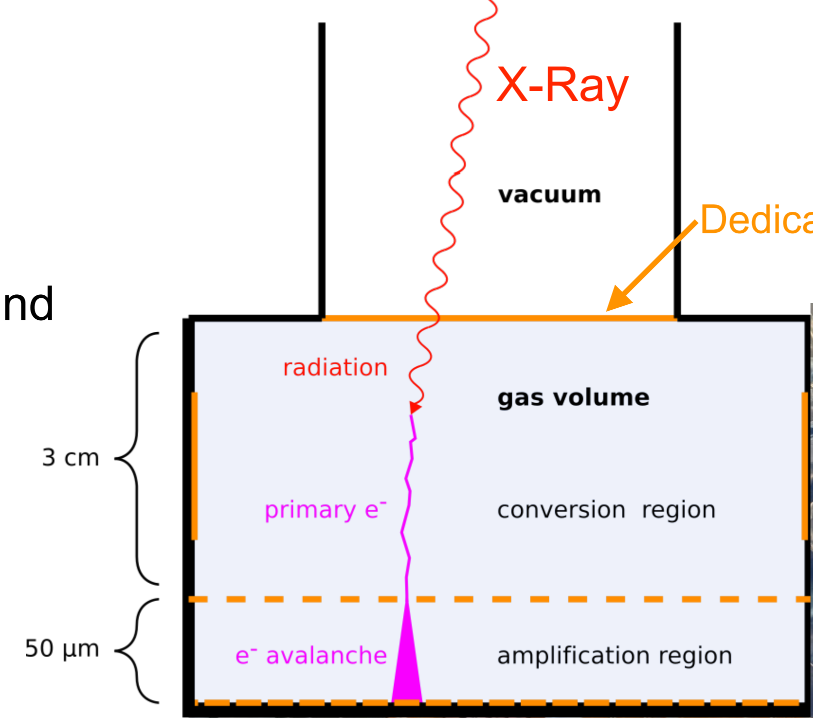


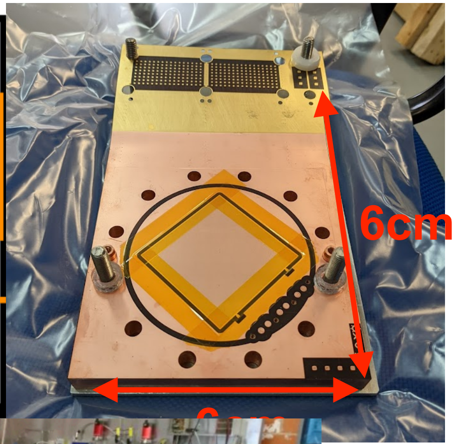


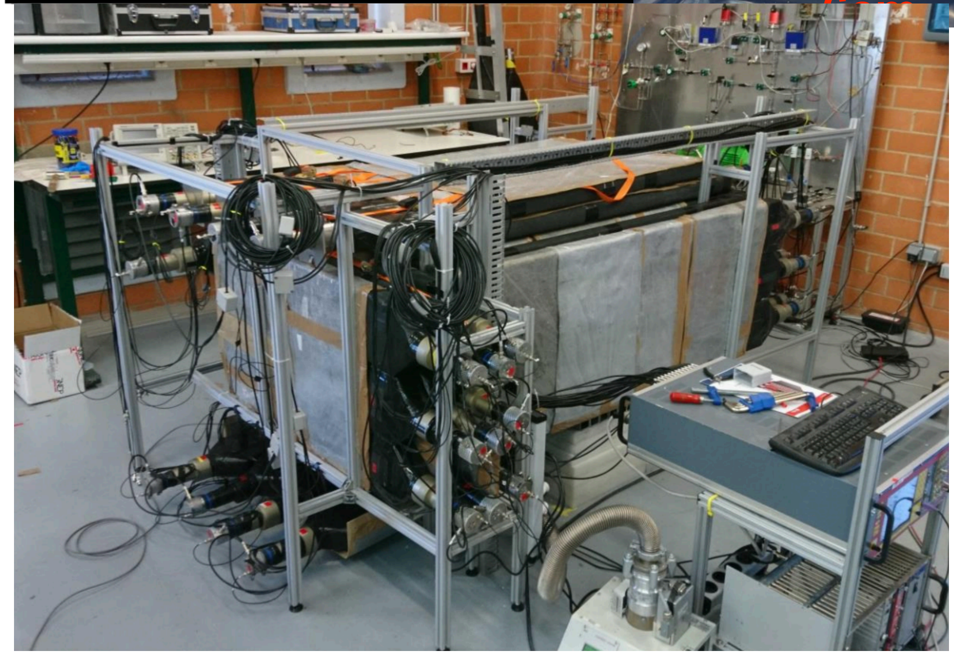
X-Ray Detectors

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)





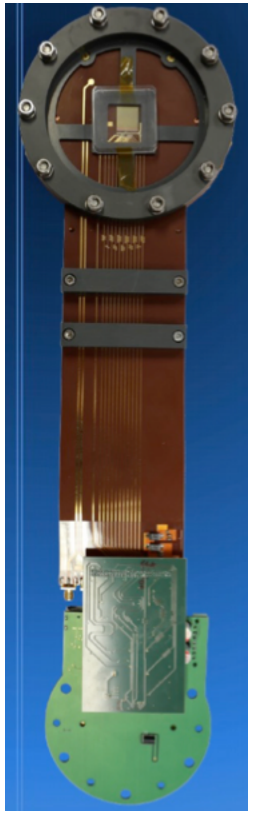


X-Ray Detectors

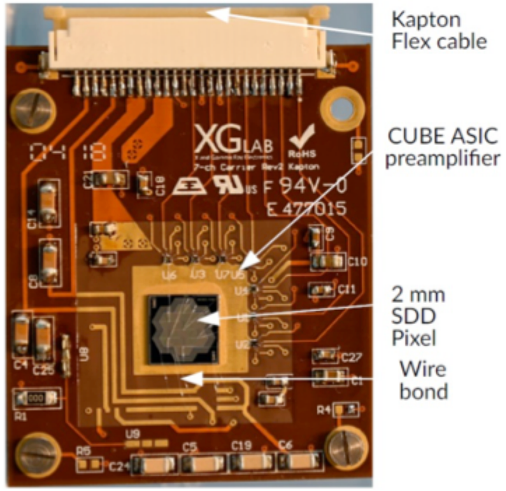
Post Discovery Technologies

- Beyond baseline: precision technologies
  - ➡ Better energy resolution: few eV - 100 eV
  - ➡ Lower energy threshold: ~ 0.1 keV
- Very active R&D ongoing: designs, materials, readout

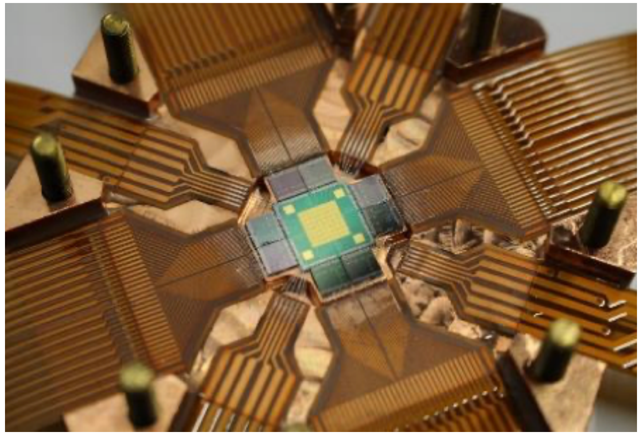
Keep in mind!



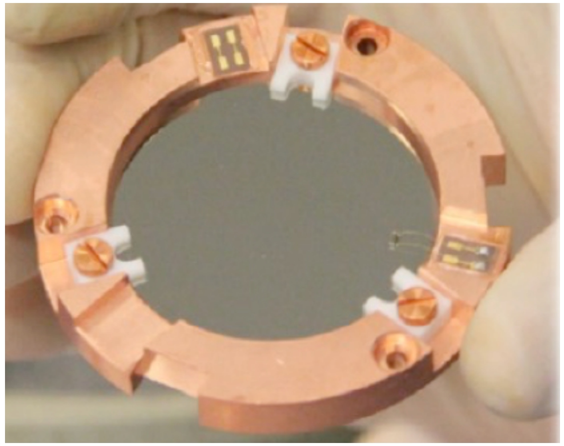
GridPix
(U. Bonn)



SDD: Silicon Drift
Detectors (TUM)



MMC: Metallic Magnetic
Calorimeters (U. Heidelberg)



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

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)

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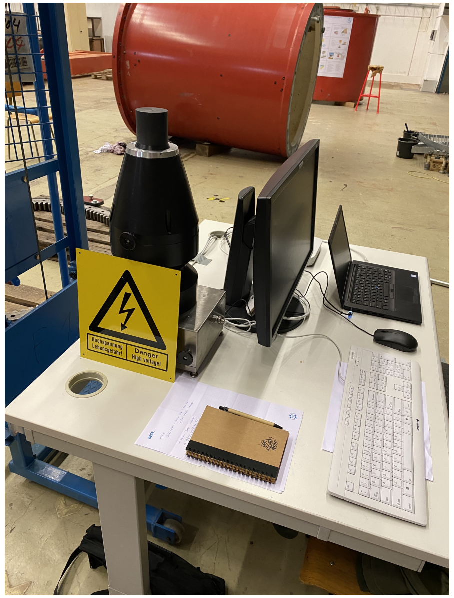
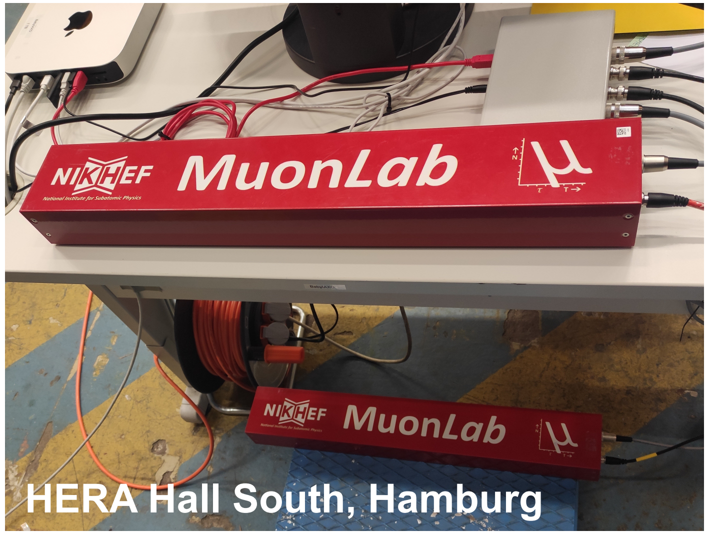
Canfranc (LSC), Spain

➡ 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





HERA Hall South, Hamburg

In-Situ Background Measurements

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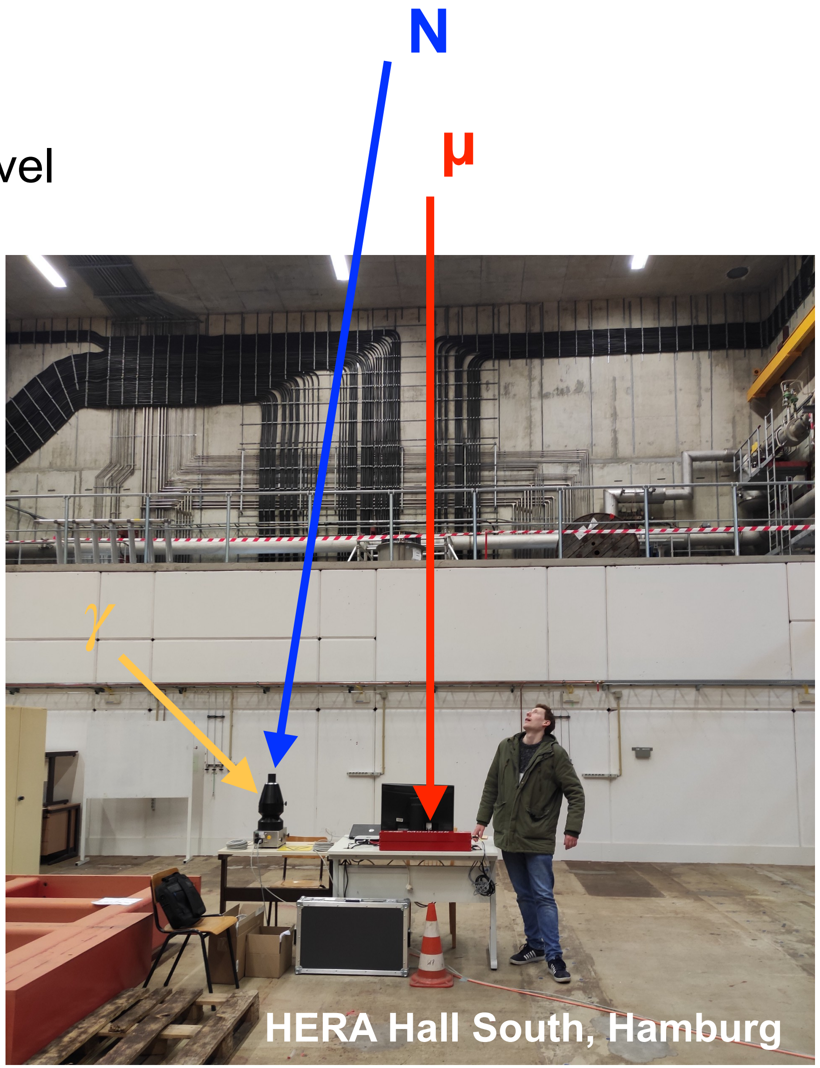


Background Simulation Campaigns

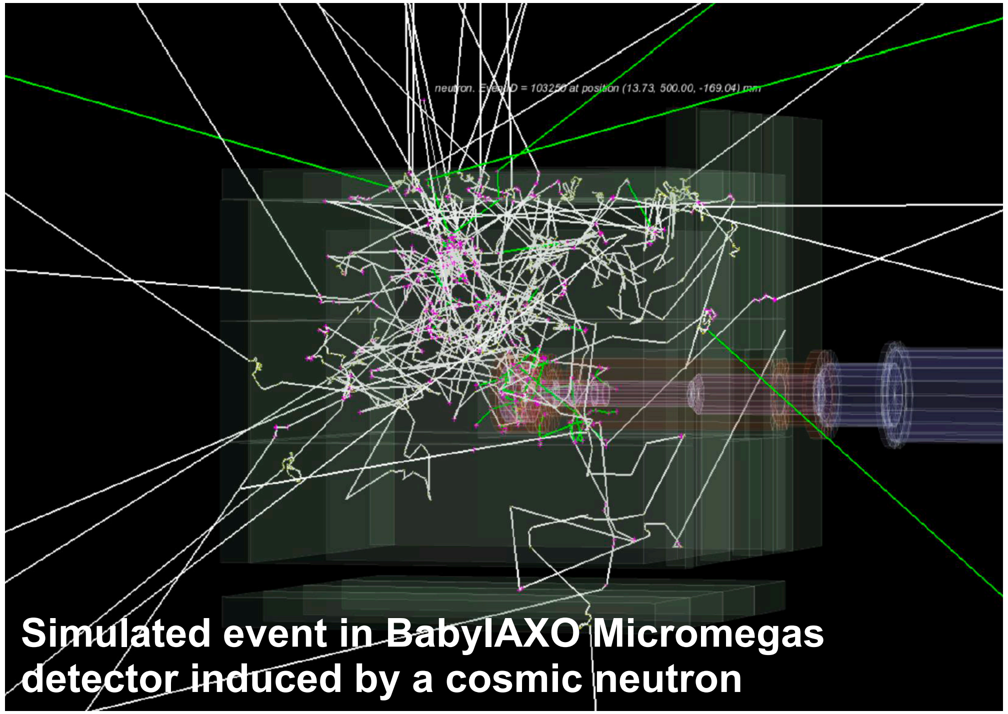
Distinguishing Signals and Background

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

- 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



Simulated event in BabyIAXO Micromegas detector induced by a cosmic neutron

Background Simulation Campaigns

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  - ➡ 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

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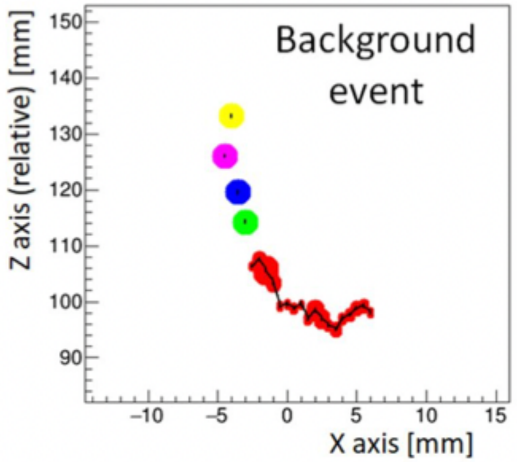
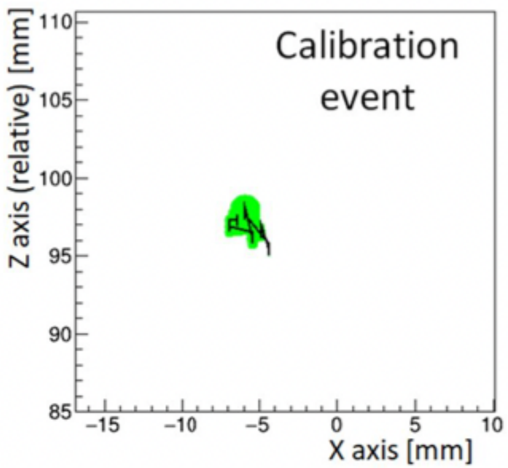
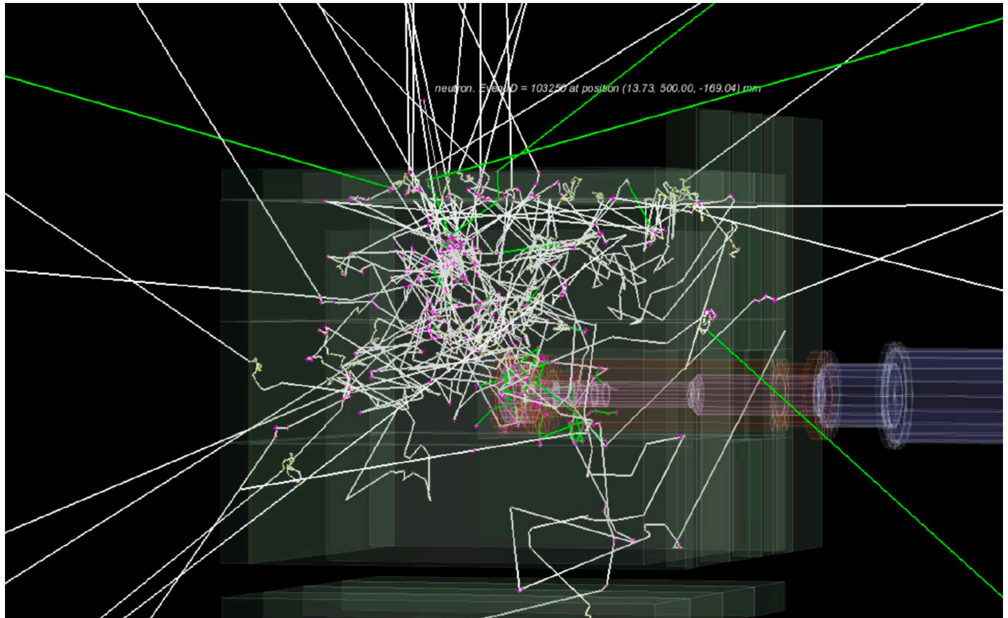






Simulated event in BabyIAXO Micromegas detector induced by a cosmic neutron

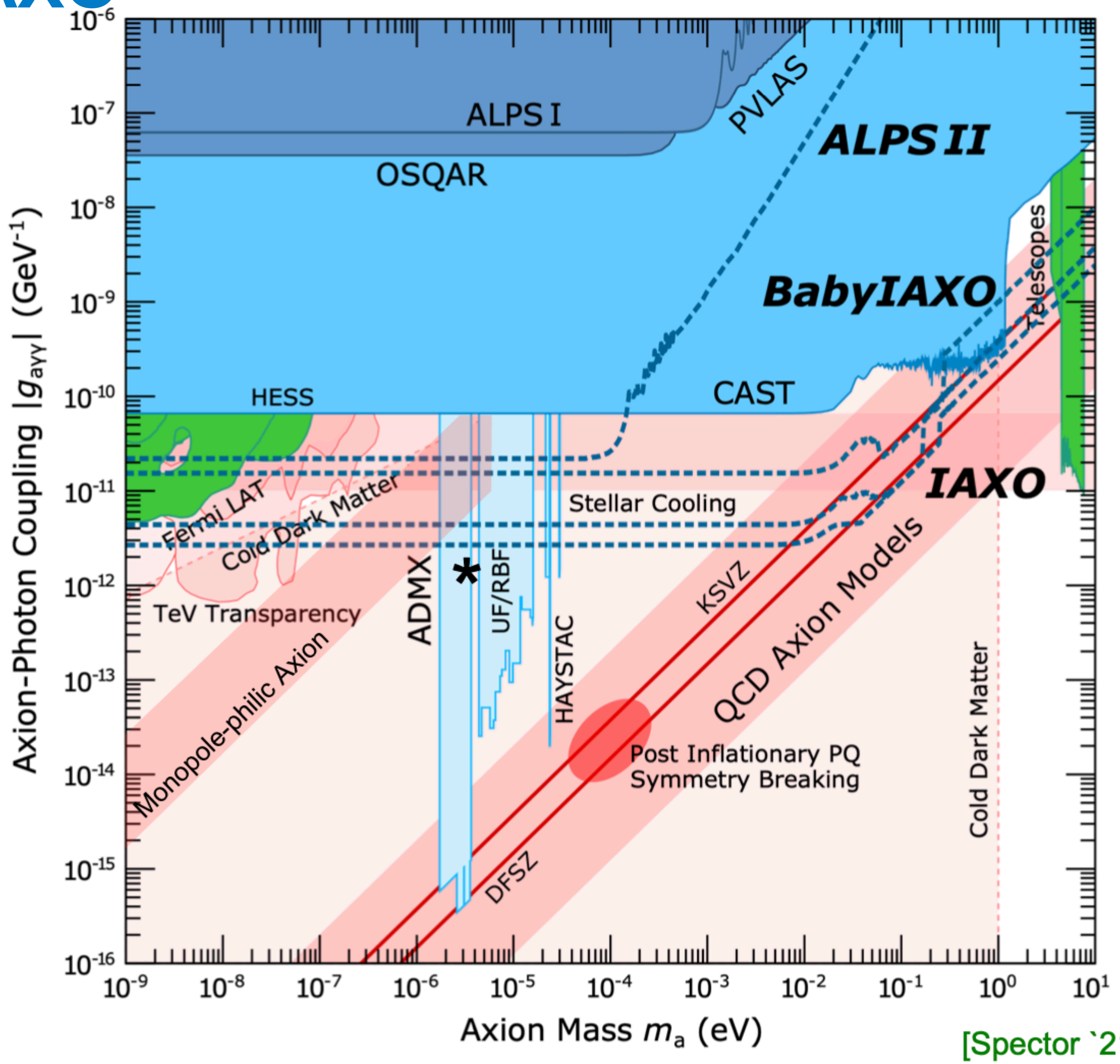
Primakoff-Axion Discovery:

Exploring the Axion-Photon Coupling.

Physics Prospects of (Baby)IAXO

Baseline (Primakoff-)Axion-Photon Coupling

- BabyIAXO will probe large generic unexplored ALPs parameter space:
  - ➡ Low masses: $g_{a\gamma\gamma}$ ~ few 10^{-11} GeV^{-1}
    - ➡ Hints from astrophysics and cosmologically interesting regions
  - ➡ **Vanilla QCD axion models** (meV - eV)



[Spector `21]

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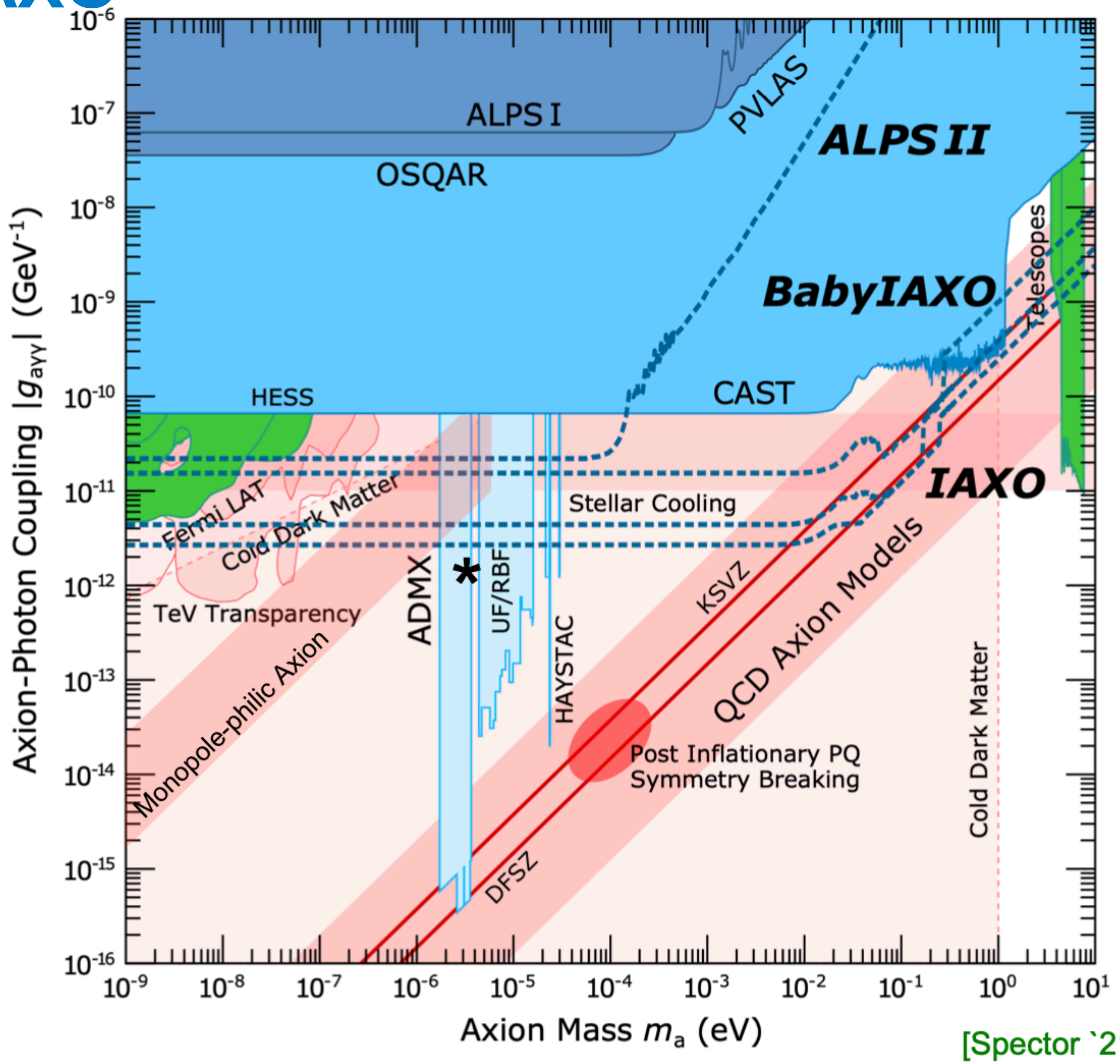
  - ➡ **Vanilla QCD axion models** (meV - eV)
- Independent of axion = DM hypothesis
- Synergy with ALPS II: $g_{a\gamma\gamma}$ would provide total solar (Primakoff-)axion flux
- IAXO(+) will dig deeper in parameter space



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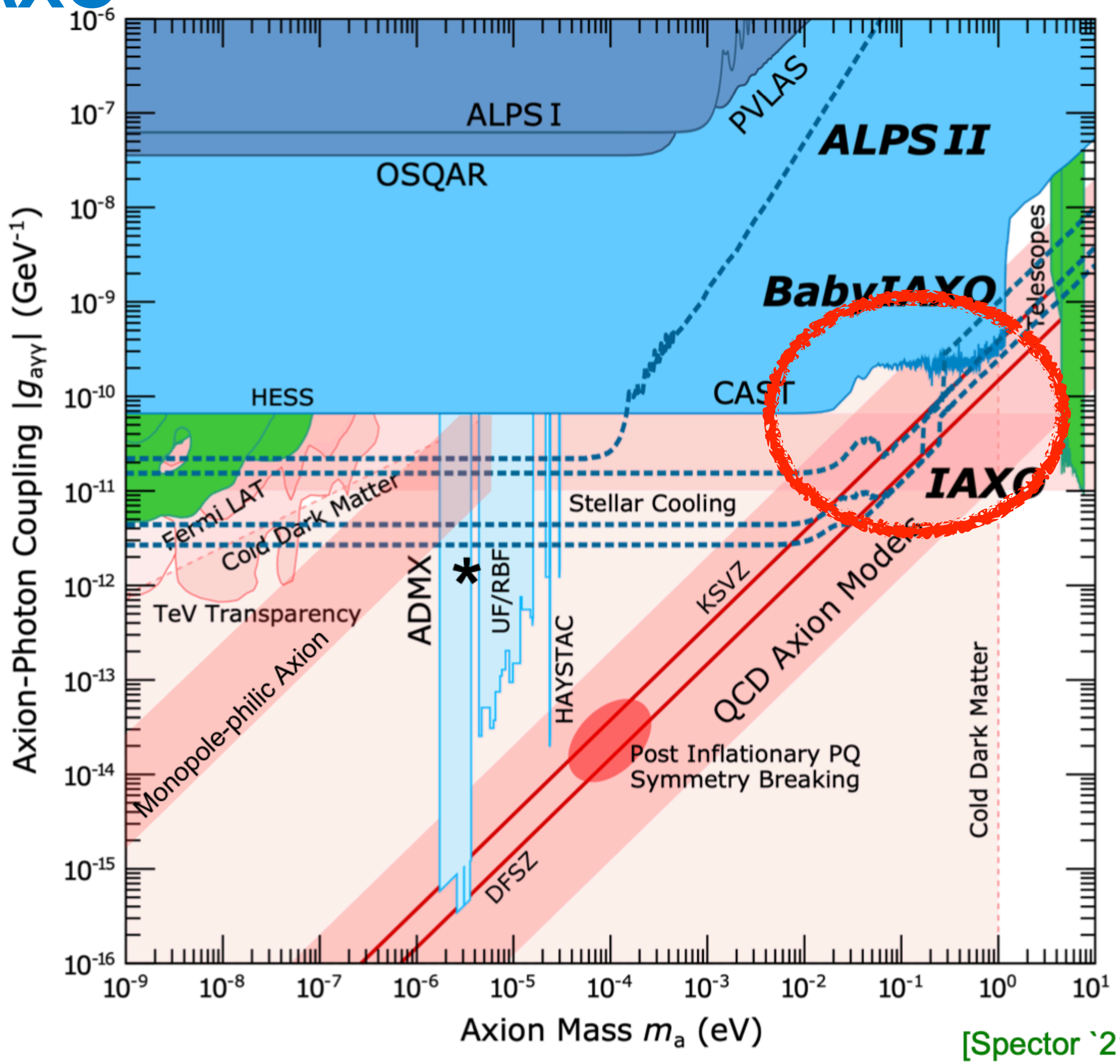

[Spector `21]

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

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

Coherence Gas Buffer Technique

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- 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

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  - ➡ 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

Beyond Axion Discovery I:

Axion-Electron Coupling.

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

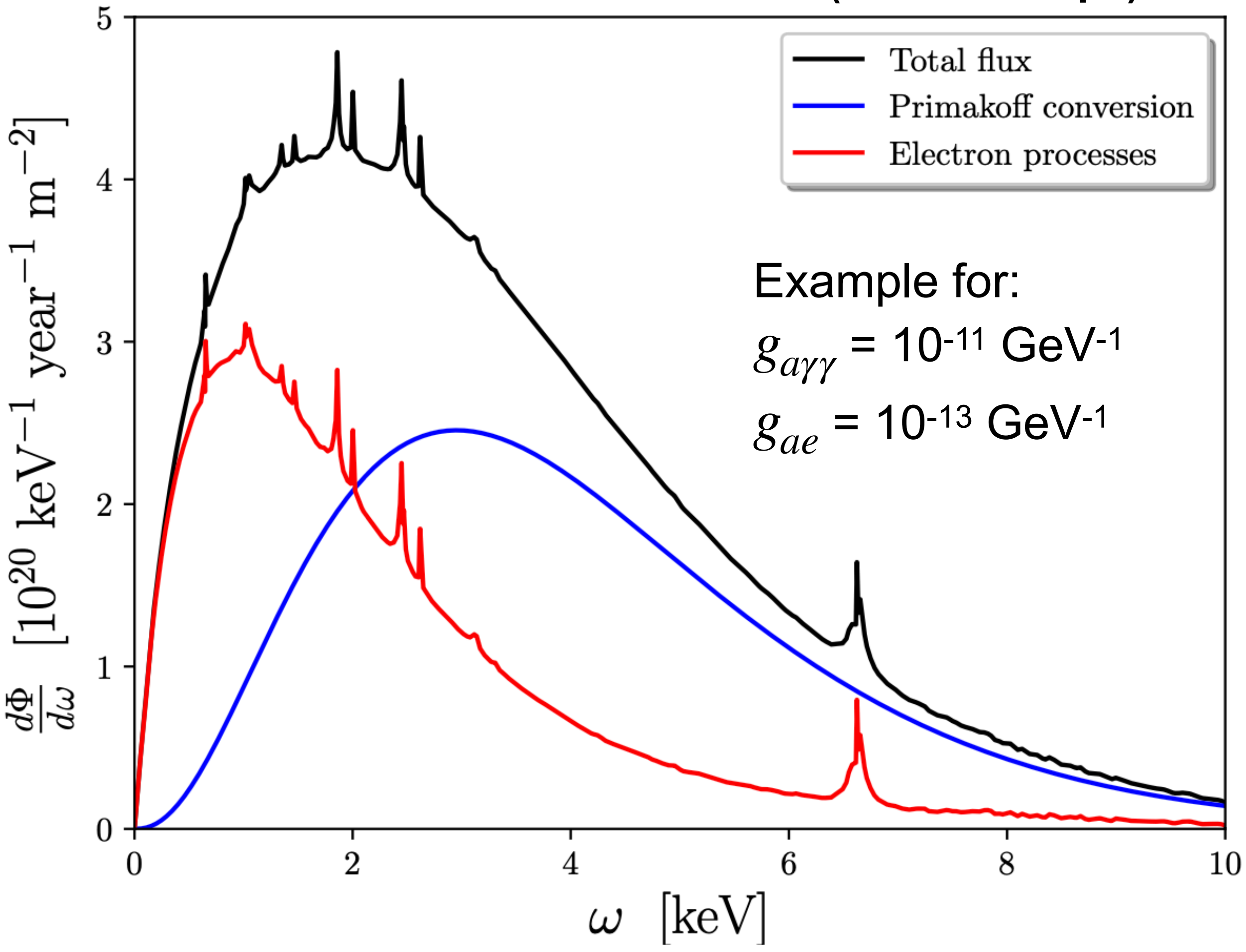
JCAP03(2019)039

Basic Idea and Strategy

- Main idea: measured axion spectrum contains axions from axion-photon and axion-electron coupling within the Sun

- Depending on the shape of the spectrum one can determine $g_{a\gamma\gamma}$ and g_{ae} individually in a specific range

Differential axion flux at earth (no helioscope)



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

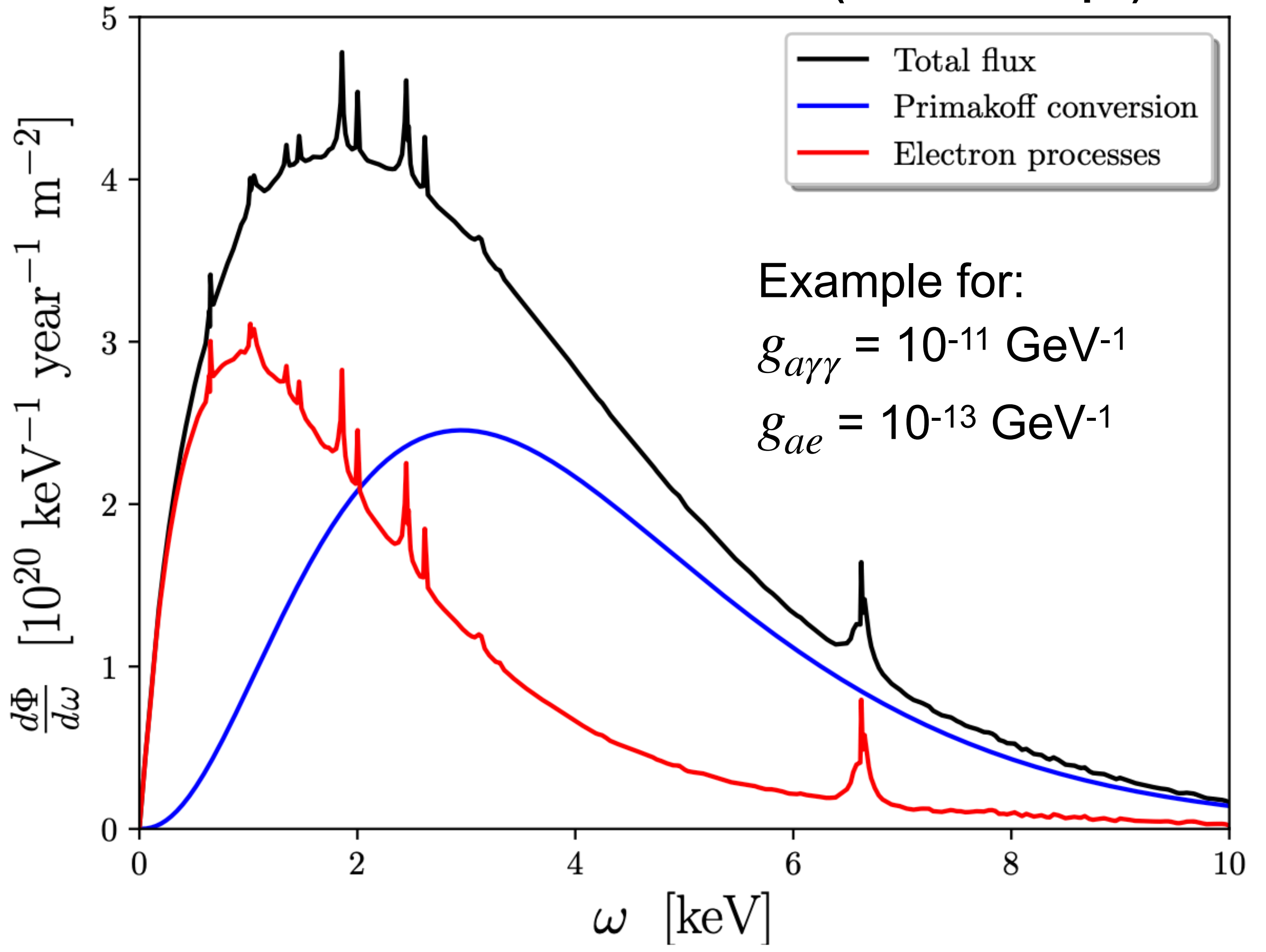
JCAP03(2019)039

Basic Idea and Strategy

- Main idea: measured axion spectrum contains axions from axion-photon and axion-electron coupling within the Sun
- Depending on the shape of the spectrum one can determine $g_{a\gamma\gamma}$ and g_{ae} individually in a specific range
  - ➡ Higher g_{ae} softens the spectrum
  - ➡ Higher g_{ae} pronounces atomic transition peaks

➡ For a large range the measurement of m_a is possible due to helioscope techniques

Differential axion flux at earth (no helioscope)



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 $\propto g_{ae}^2$

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JCAP03(2019)039

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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 $\propto g_{ae}^2$

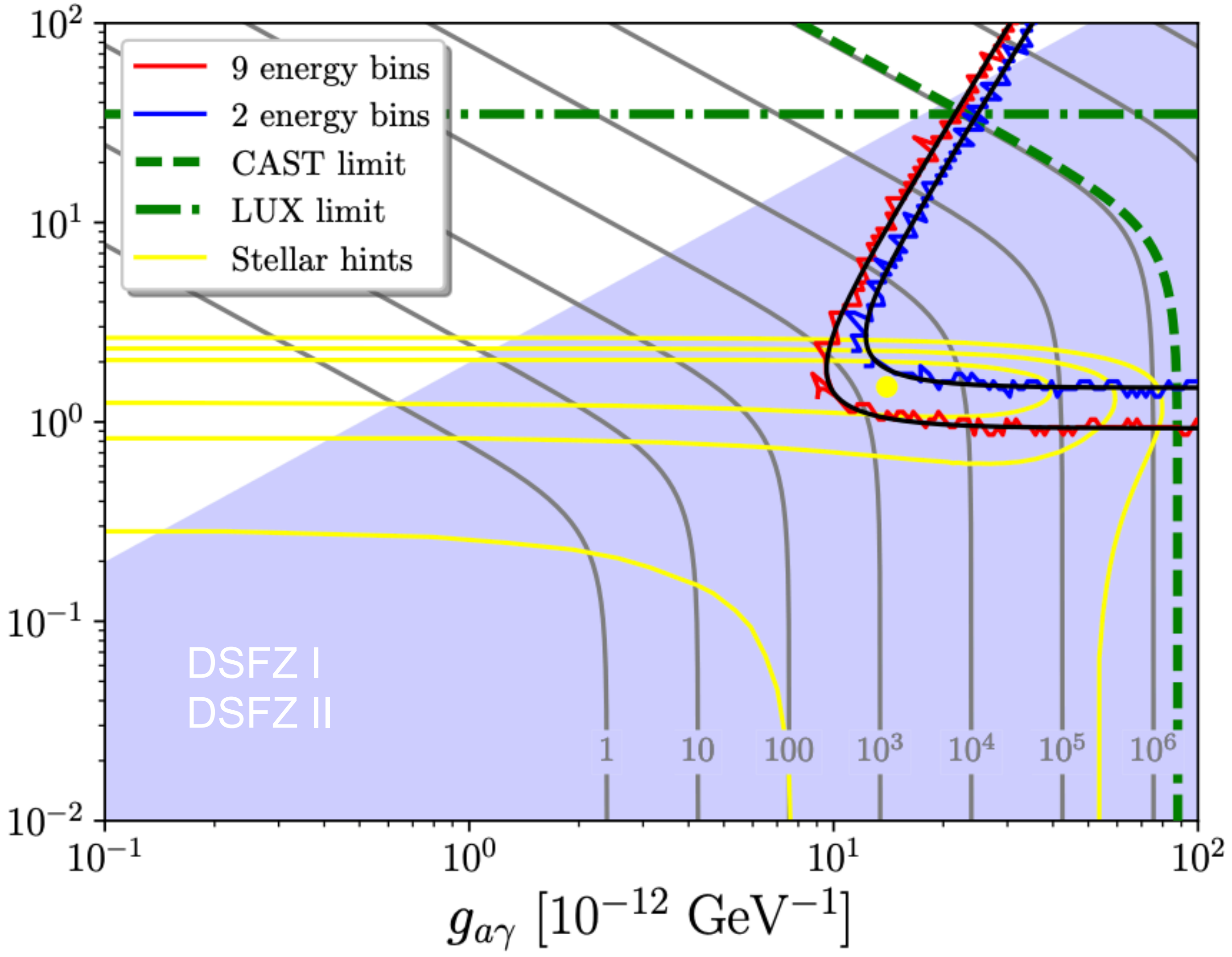
- Use Poisson statistics to simulate a binned signal for IAXO
  - ➡ Inputs I: numerical values from solar axion spectrum and helioscope parameters
  - ➡ Inputs II: g_{ae} between 10^{-15} - 10^{-10} GeV^{-1} and adapt $g_{a\gamma\gamma}$ to keep the same number of events
- Recover the two couplings by 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: Massless Case + Baseline IAXO

JCAP03(2019)039

Coherent Axion-Photon Conversion

- Large new parameter space beyond CAST limits accessible
- Large parameter space in DSFZ models accessible
  - ➡ Example, other models could be confronted as well with model-independent analysis
- Best fit for stellar hints accessible with 1 keV energy resolution (red) of IAXO detectors



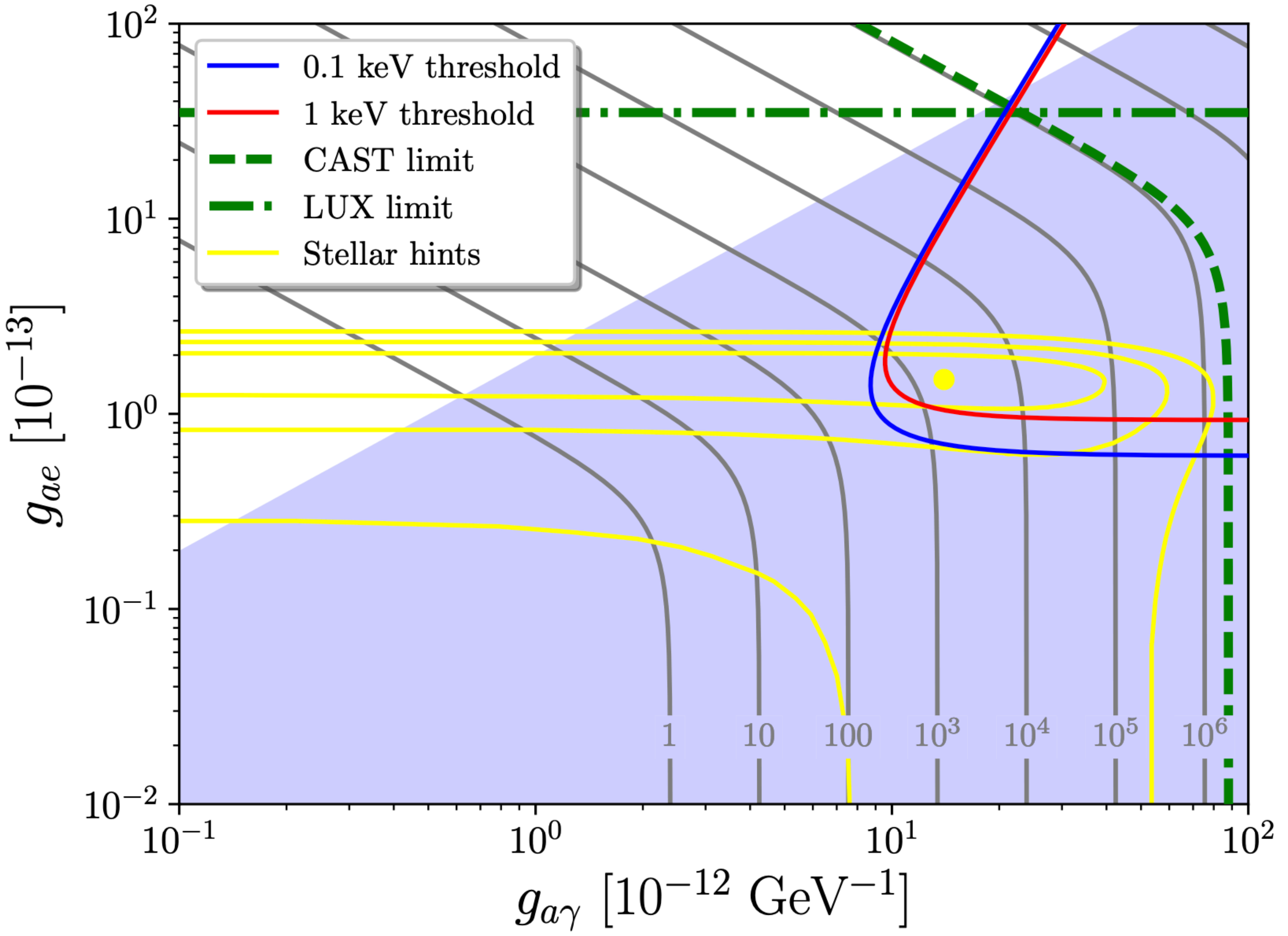
Results: Massless Case + Optimised IAXO

JCAP03(2019)039

Coherent Axion-Photon Conversion

- Detector technologies with lower energy thresholds help to increase sensitivity
  - ➡ More sensible to softer X-rays from electron processes
- Increased energy resolution is also expected to improve 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

- 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

Results: Massive Case

JCAP03(2019)039

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

Example for:

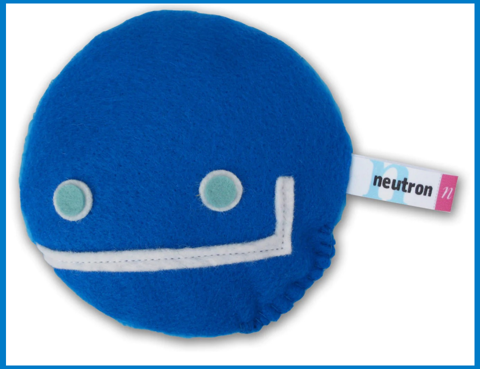
$g_{a\gamma\gamma}$ = 10^{-11} GeV^{-1}

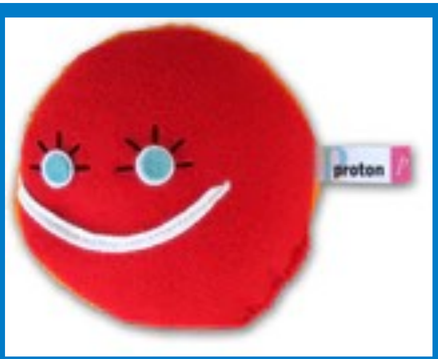
g_{ae} = 10^{-13} GeV^{-1}

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

Beyond Axion Discovery II:

Axion-Nucleon Coupling.



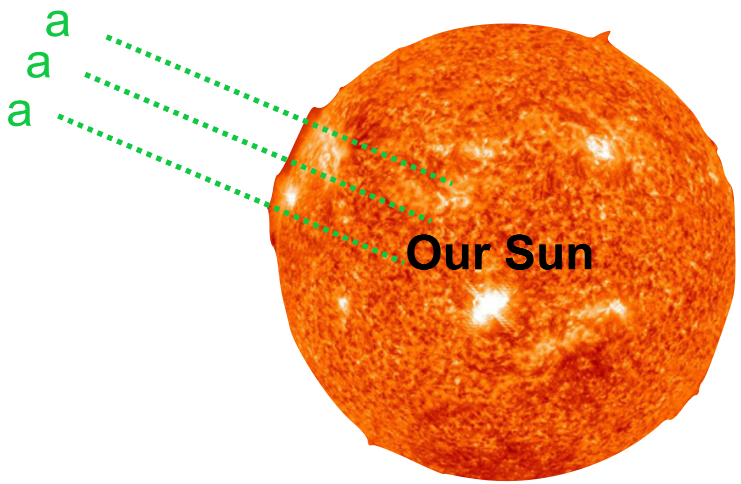


Solar Axions from Nuclear Processes

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

Model Dependencies and Fluxes

- If axions couple to nucleons, production in nuclear processes within the Sun (fusion, nuclear transitions)
- Flux dependent on solar model (T_{core}, isotope abundance, lifetimes of excited states, occupation numbers,…)



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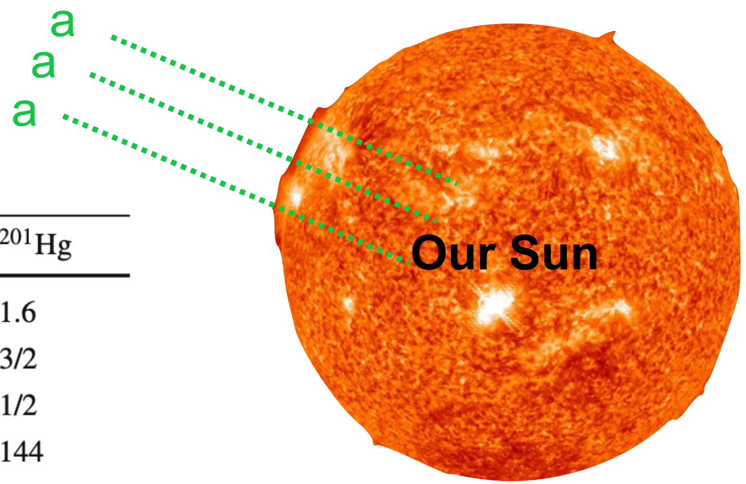
➡ Most promising candidate: M1 transition of ^{57}Fe at 14.4 keV



	^{57}Fe	^{83}Kr	^{169}Tm	^{187}Os	^{201}Hg
E^* [keV]	14.4	9.4	8.4	9.7	1.6
J_0	1/2	9/2	1/2	1/2	3/2
J_1	3/2	7/2	3/2	3/2	1/2
τ_0 [ns]	141	212	5.9	3.4	144
α	8.56	17.09	285	264	47,000
ϵ	$10^{-4.5}$	$10^{-8.75}$	$10^{-11.9}$	$10^{-10.6}$	$10^{-10.83}$
a [%]	2.14	11.55	100	1.6	13.2
$\mathcal{N}_a(r=0)$ [relative to ^{57}Fe]	1	1.8×10^{-3}	1.3×10^{-4}	3.0×10^{-5}	1.9×10^{-6}

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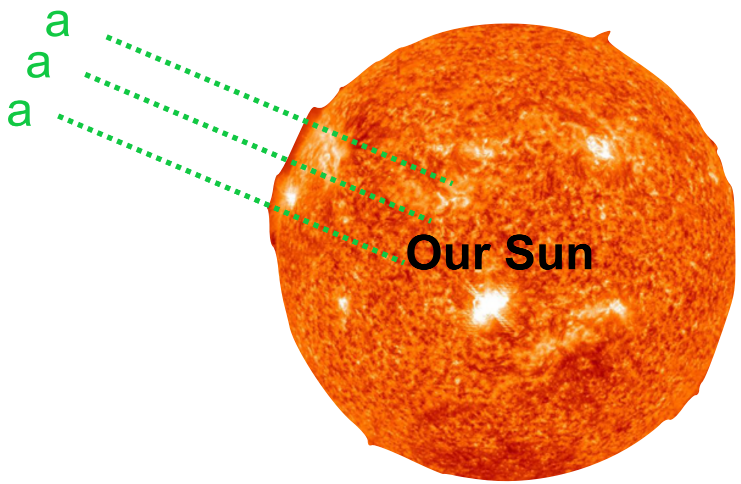
  ➡ Monochromatic: natural line width << Doppler broadening (~2 eV)



- Flux dependent on axion model g_{aN} ($g_{aN}^{eff} = 0.16 g_{ap} + 1.16 g_{an}$ for ^{57}Fe)

  ➡ $\frac{\Gamma_a}{\Gamma_\gamma} = 2.32 (g_{aN}^{eff})^2$. Example: $\left.\frac{\Gamma_a}{\Gamma_\gamma}\right|_{\mathrm{KSVZ}} = 5.81 \times 10^{-16} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^2$

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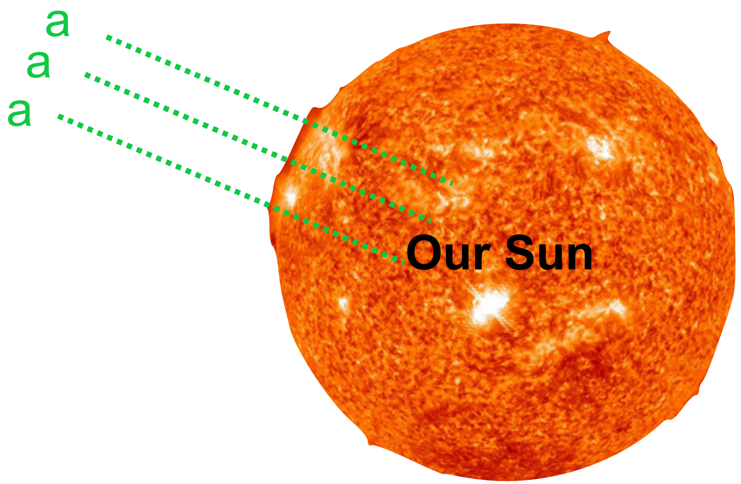

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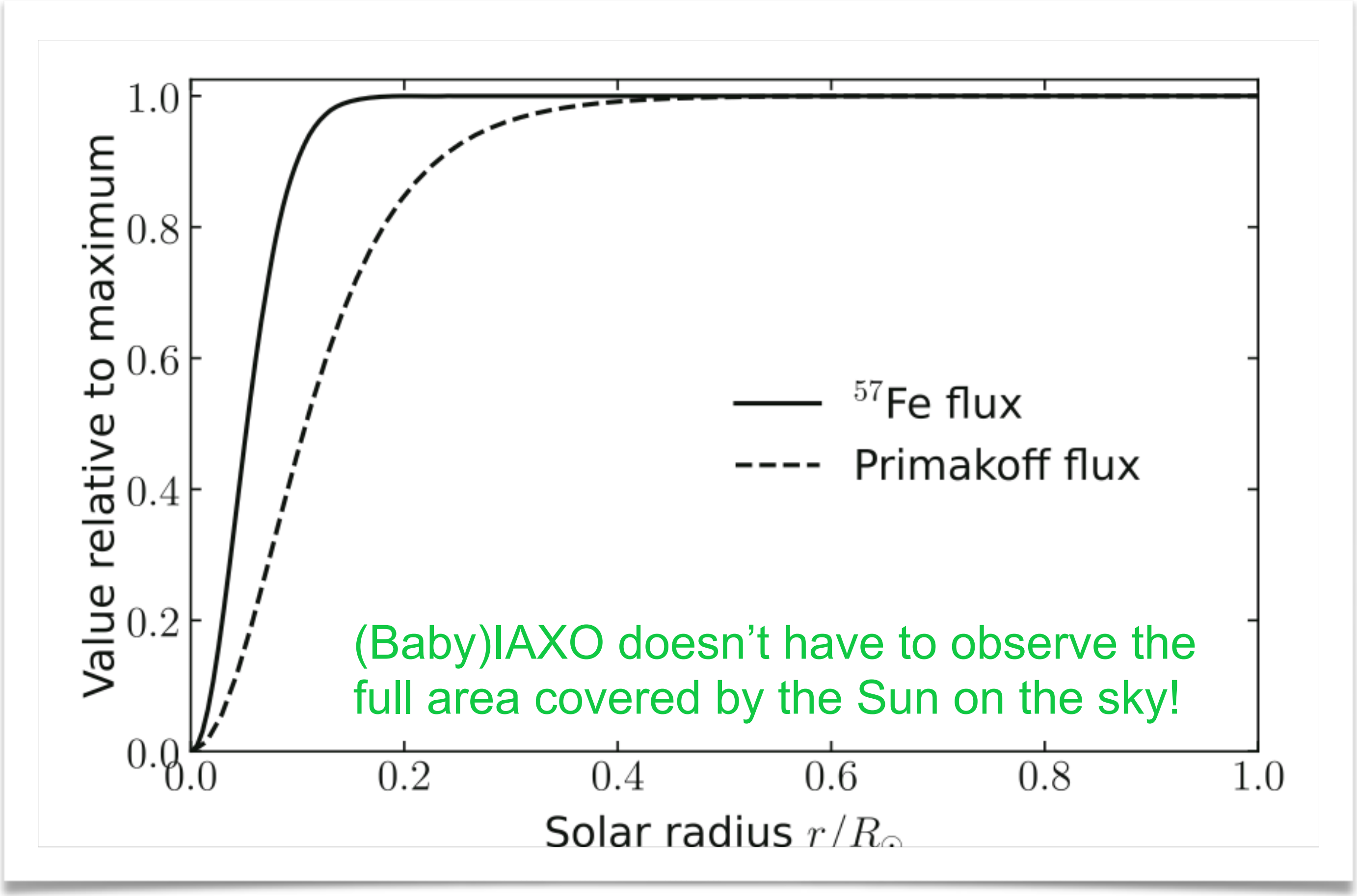
- Fixing a solar model (B16-AGSS09) and calculating the monochromatic solar axion flux of ^{57}Fe:

  ➡ $\boxed{\Phi_a = 5.06 \times 10^{23}\ (g_{aN}^{\mathrm{eff}})^2\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$

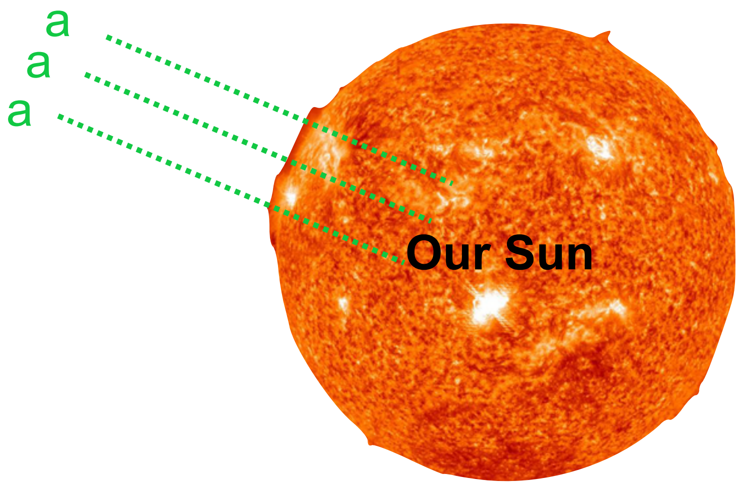
Solar Axions from Nuclear Processes

Model Dependencies and Fluxes

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



(Baby)IAXO doesn't have to observe the full area covered by the Sun on the sky!



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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

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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

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
	$\mathrm{BabyIAXO}_0$	$\mathrm{BabyIAXO}_1$	$\mathrm{BabyIAXO}_2$	$\mathrm{BabyIAXO}_3$	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

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

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

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

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

Results: Massless Axion

Coherent Axion-Photon Conversion

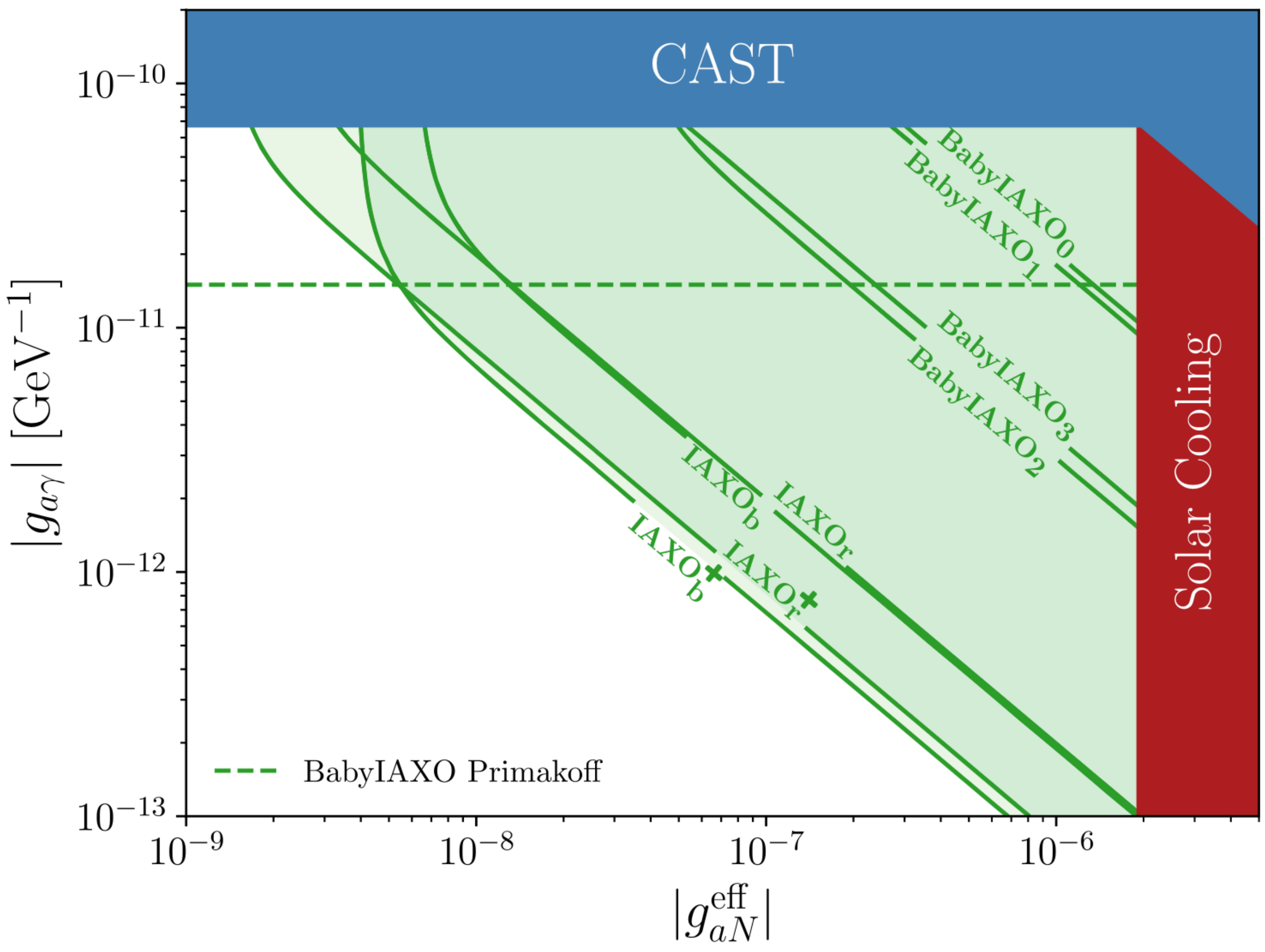
Eur. Phys. J. C 82, 120 (2022)

- BabyIAXO will probe new parameter space beyond solar and CAST bounds
  ➡ Optimised optic pays off

- Probing of DFSZ and M1 models in principle possible with gas buffer technique

- If axions have couplings above green dashed line: individual extraction of $g_{a\gamma\gamma}$ and g_{aN}^{eff} might be possible for BabyIAXO

- If axions have couplings below green line, axions from ^{57}Fe might be detected before Primakoff axions

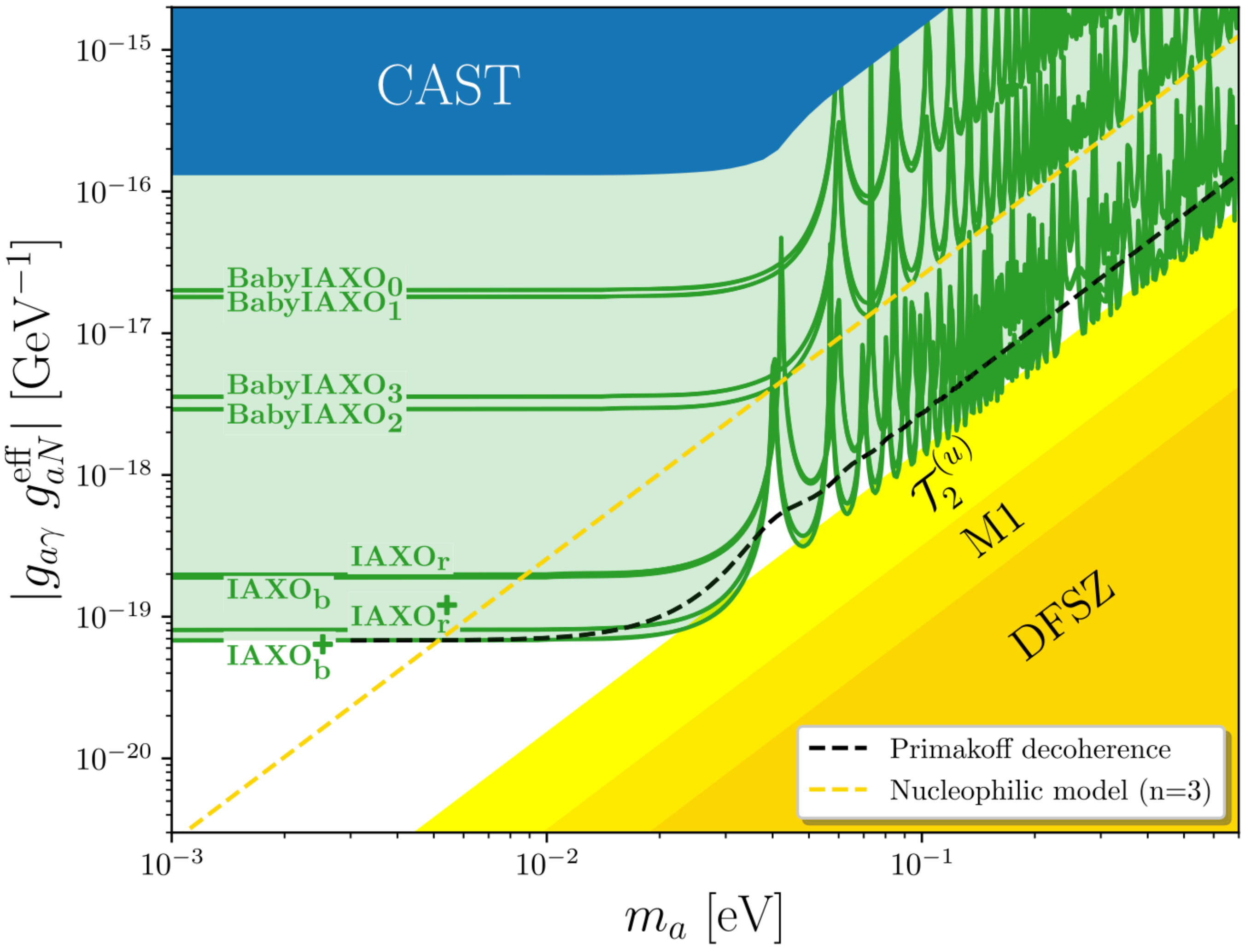


Results: Massive Case

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

Increasing Decoherence in Axion-Photon Conversion

- Worst case scenario shown here: no gas buffer technique at all, so increasing decoherence with increasing m_a
- No Primakoff background in signal bin, same statistical analysis as before
- Still BabyIAXO will reach new parameter space and might see axions described by nucleophilic models
- IAXO and IAXO+ will dig deeper in parameter space



Beyond Axion Discovery III:

X-Ray Polarisation.

Pseudo-scalar vs. Scalar

And the Polarisation of Converted Photons

Pseudo-scalar	Scalar
0^-	0^+

Effective Lagrangian density of interaction with an electromagnetic field $F_{\mu\nu}$:

$$\mathcal{L}_{int} = -\frac{1}{4} g_{\mathrm{A}\gamma\gamma}\ \mathcal{A}\ F_{\mu\nu}\widetilde{F}^{\mu\nu} = g_{\mathrm{A}\gamma\gamma}\ \mathcal{A}\ \vec{E}\cdot\vec{B}$$

$$\mathcal{L}_{int} = -\frac{1}{4} g_{\mathrm{A}\gamma\gamma}\ \mathcal{A}\ F_{\mu\nu}F^{\mu\nu} = g_{\mathrm{A}\gamma\gamma}\ \mathcal{A}\ \frac{1}{2}(\vec{E}^2 - \vec{B}^2)$$

Polarisation mode of linearly polarised photons after conversion in transversal magnetic field B_{ext}:

$E_\gamma \parallel B_{ext}$ (p-polarisation)

$E_\gamma \perp B_{ext}$ (s-polarisation)

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$E_\gamma \parallel B_{ext}$ (p-polarisation)

$E_\gamma \perp B_{ext}$ (s-polarisation)

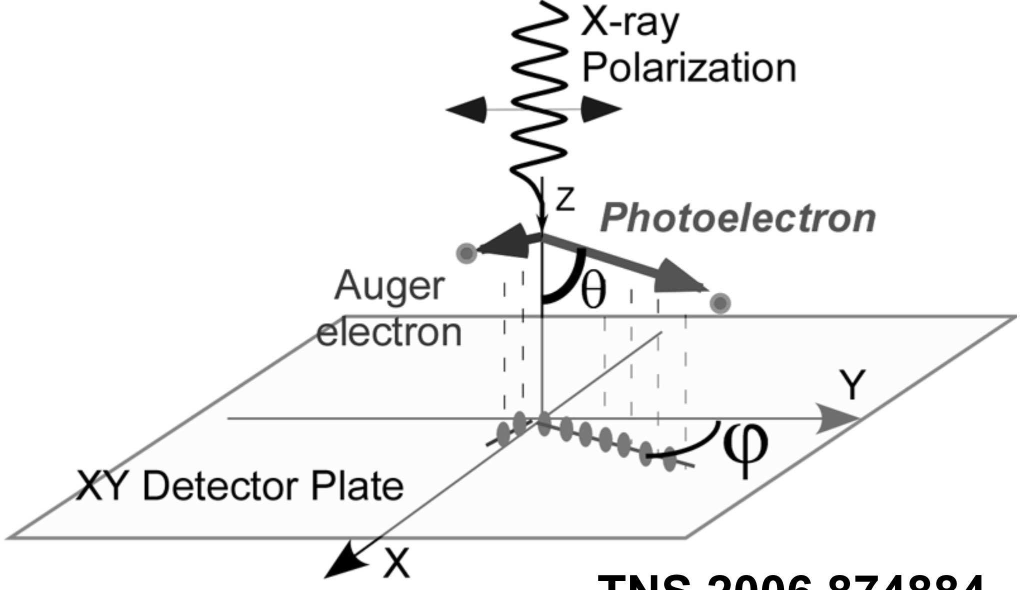
- ➡ ALPS II: depending on the polarisation of the laser, pseudo-scalar or scalar conversion mode
- ➡ **(Baby)IAXO: measuring the X-ray polarisation with respect to B_{ext} - pseudo-scalar or scalar?**

How to Measure X-Ray Polarisation

In a IAXO Gas-Based Detector

- Idea and concept actively developed in astrophysics and photoemission spectroscopy: polarisation measurement of X-rays by photoelectron emission angle

  ➡ Depending on the X-ray polarisation the angle spectrum of the emitted photoelectron changes



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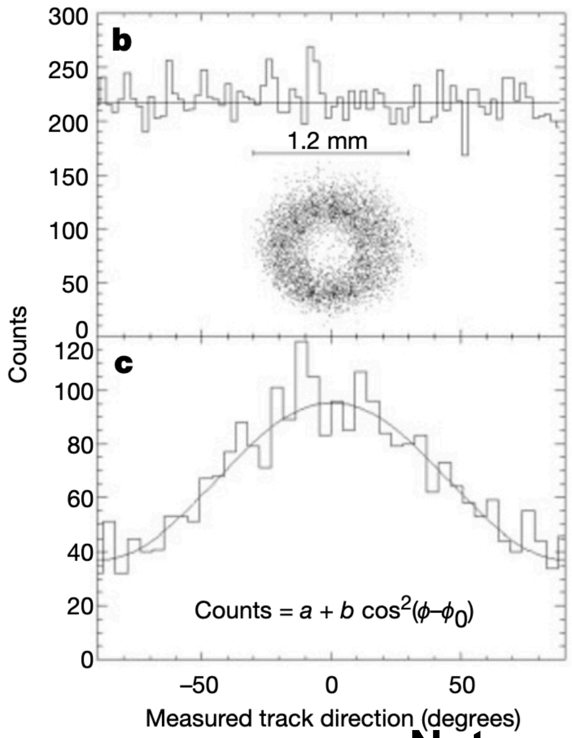

Un-polarised

p-polarisation

Nature 411, 662–665 (2001)

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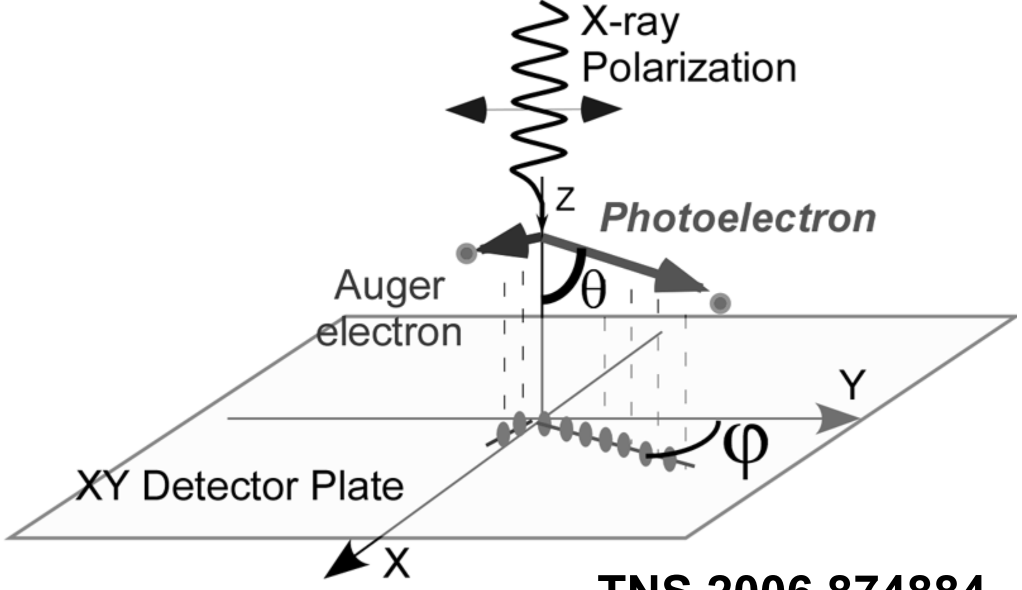
- Currently conceiving a study for sensitivity in BabyIAXO
  ➡ Impact by energy of X-rays (1-10 keV)?
  ➡ Optimal detector volume, gas type and pressure?
  ➡ Required readout granularity to resolve direction of photoelectron track? Gridpix?
  ➡ How many X-rays (axions/ALPS) required?
  ➡ May machine learning algorithms help?



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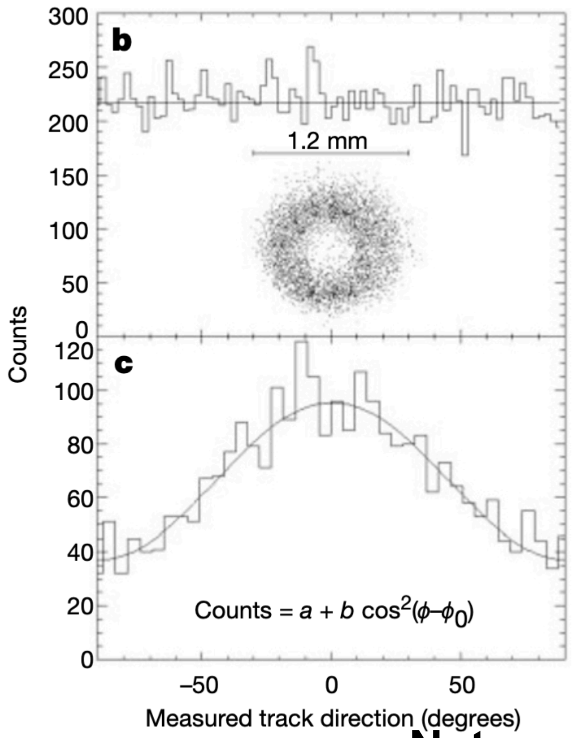

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p-polarisation

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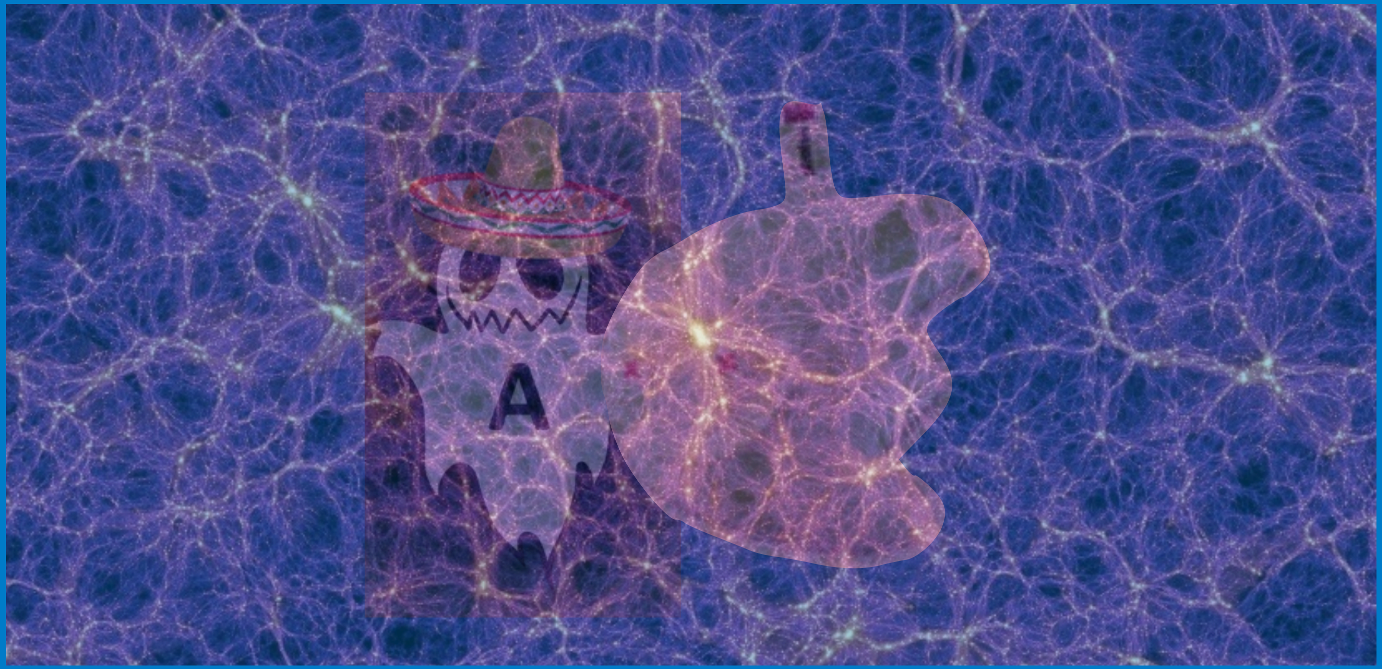
Beyond Axion Discovery IV:

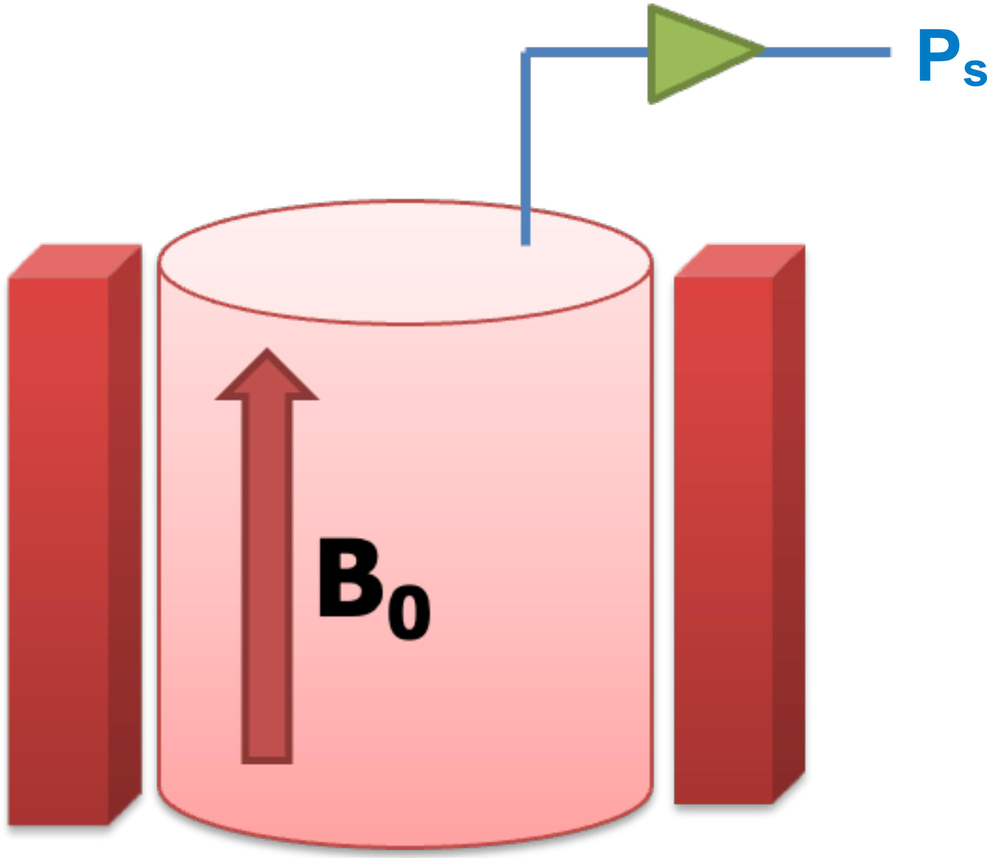
Haloscope Mode.



Haloscopes

Detecting Dark Matter Axions - In a Nutshell

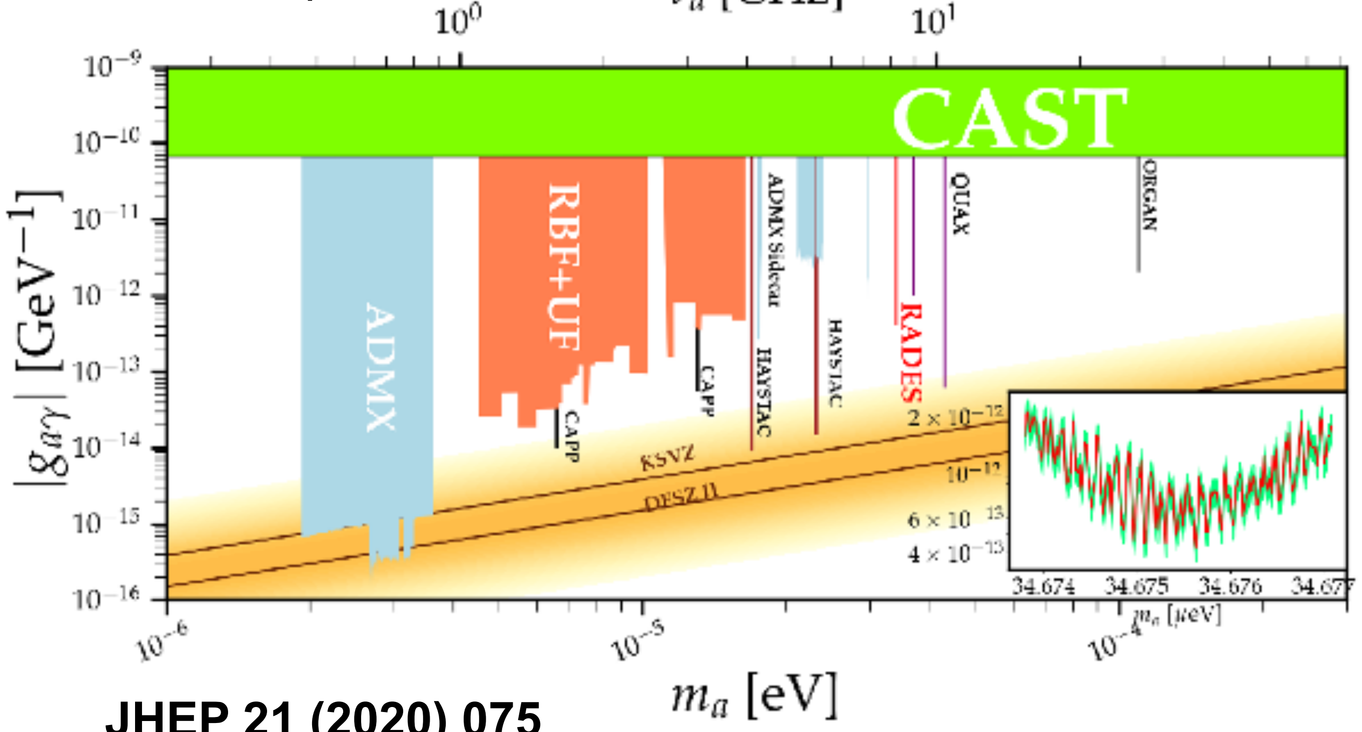
- Assumption for haloscope: DM halo is mostly made of axions
  - ➡ Axions non-relativistic: $m_a \rightarrow f_{a,\gamma}$
- Resonant “Sikivie” cavities
  - ➡ Axion-photon conversion in tunable resonant cavity
  - ➡ Typically in frequency ranges of microwaves
- If cavity is tuned to axion frequency: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



RADES

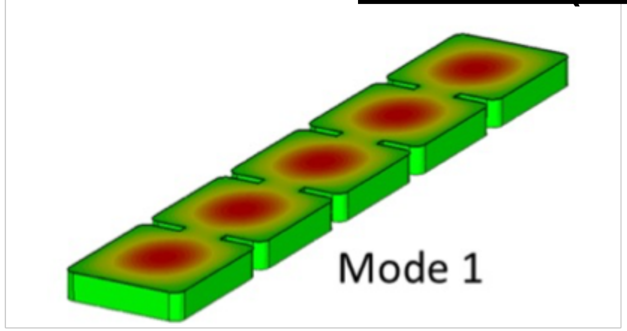
Helioscope as Haloscope Project

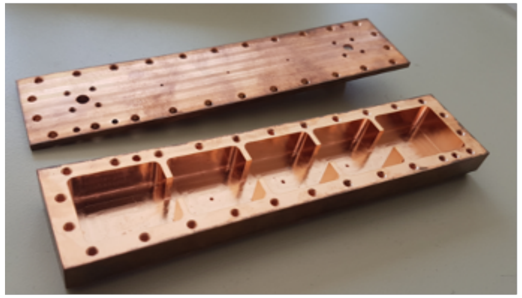
- During late years in the CAST experiment the RADES project emerged
  ➡ Reuse the magnetic volumes of helioscope for haloscope searches by integrating resonant cavity setups



JHEP 21 (2020) 075

JCAP 05 (2018) 040





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

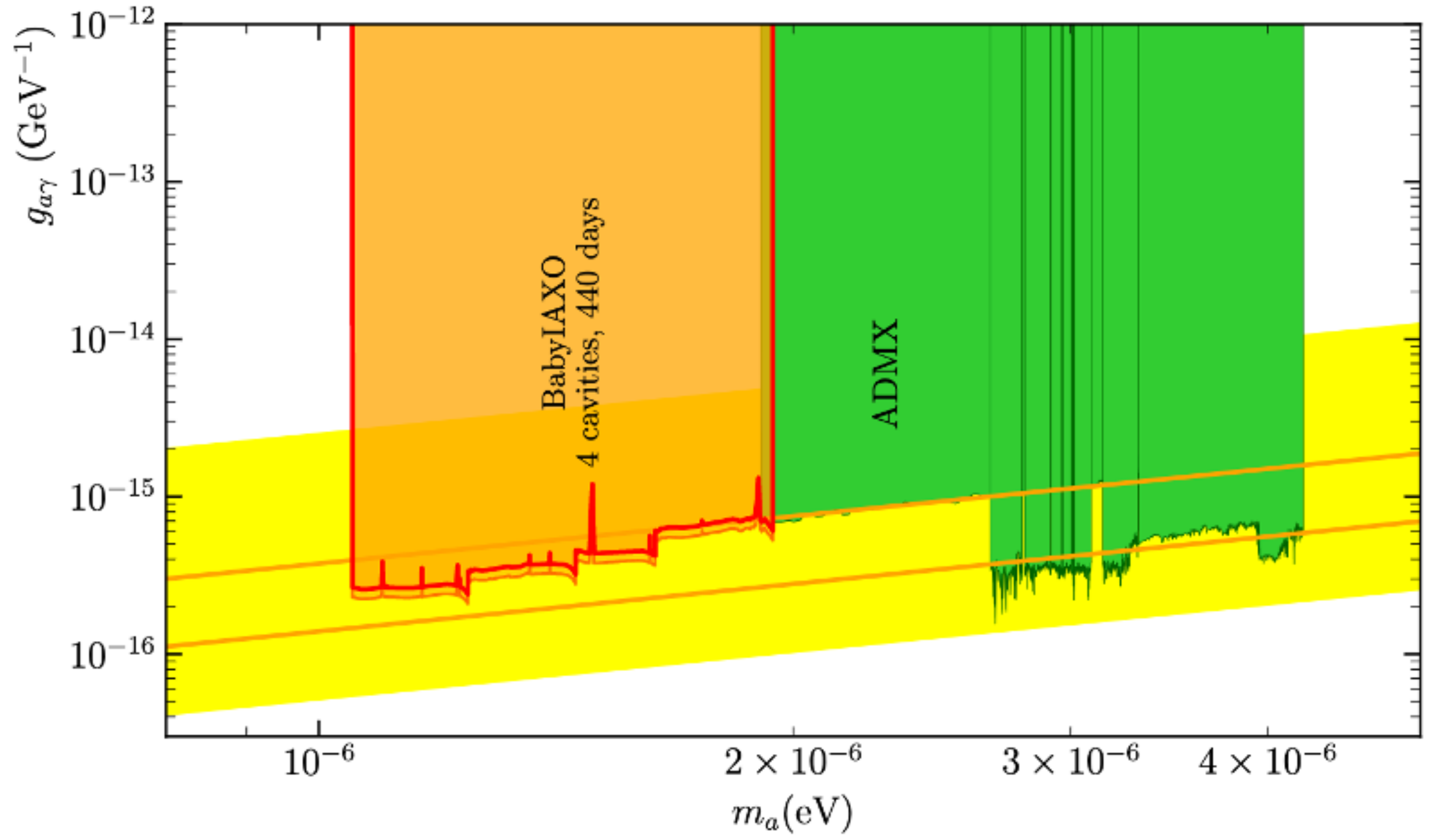
- Developments continued after CAST times
  ➡ Optimising geometries of cavities
  ➡ Improving coating for improving boost factor, etc.

BabyIAXO - Preliminary Projected Sensitivities

Haloscope Mode

- 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

RADES collaboration paper in preparation



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

Beyond Axion Discovery V:

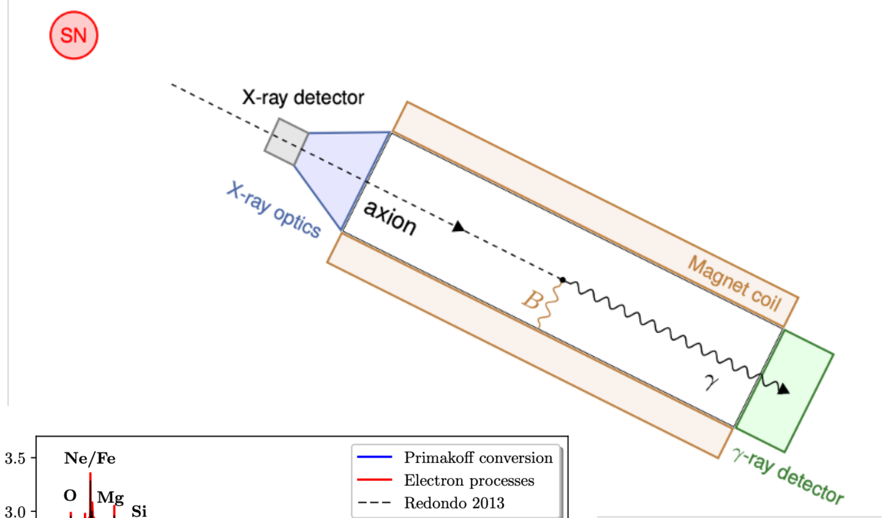
High Frequency Gravitational Waves and Other Searches.

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

Further Searches

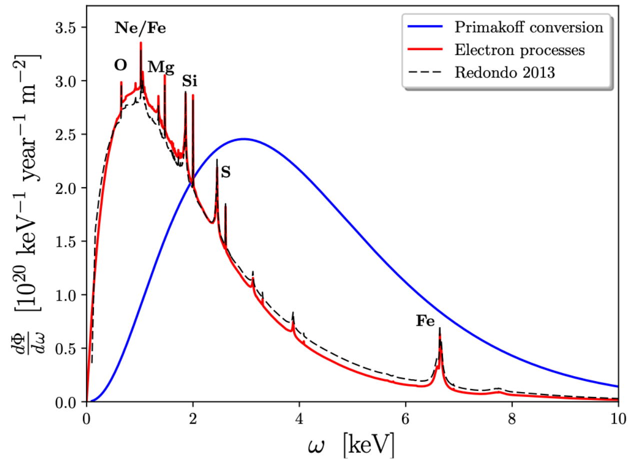
A Broad Spectrum of Ideas

- Axions from supernova explosions arXiv:2008.03924
  - ➡ Would require HE-γ detector at the opposite of X-ray detector

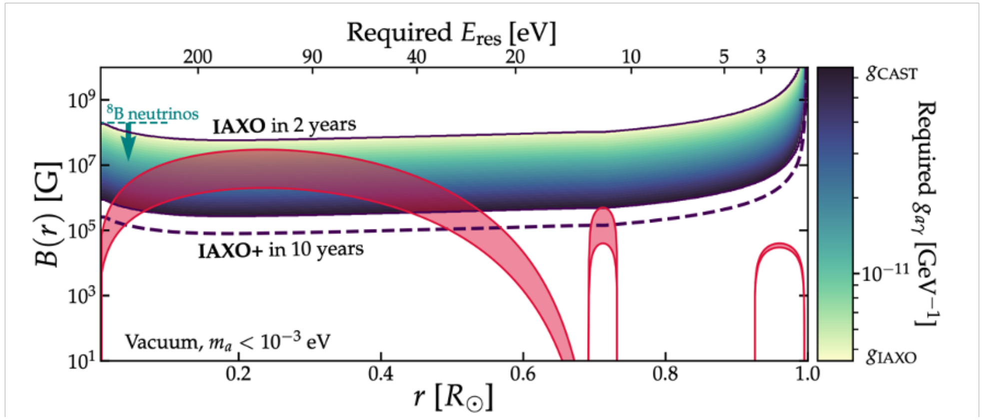


Phys. Rev. D 100, 123020

- If g_{ae} sufficiently high, characterisation of solar metallicity by measuring elemental peaks in ABC axion spectrum



- Helioscope as solar magnetometers Phys. Rev. D 102, 043019



- High frequency gravitational waves by primordial black holes

PhysRevD.106.103520

PhysRevD.106.063027

JCAP03(2021)054

Summary & Outlook

… and a Dream

- After ALPS II, BabyIAXO is the next in the line of local axion/ALPs experiment @ DESY
- BabyIAXO is prototype for IAXO, but will be a fully fledged helioscope with discovery potential in many channels!
- Helioscope searches offer unique environment to probe different couplings ($g_{a\gamma\gamma}$, g_{ae} , g_{aN}) and m_a individually for a significant part of the parameter space
  - ➡ Distinguishing of different axion models possible
- (Baby)IAXO might turn into a facility to search for more generic axion-related physics and beyond: DM axions, SN axions, dark photons, HFGW,…

Thank you for your attention!

IAXO Collaboration Meeting @ DESY, Hamburg, 12-15.03.2023
~125 scientists from 22 full member institutions + 5 associate institutions.
https://iaxo.desy.de

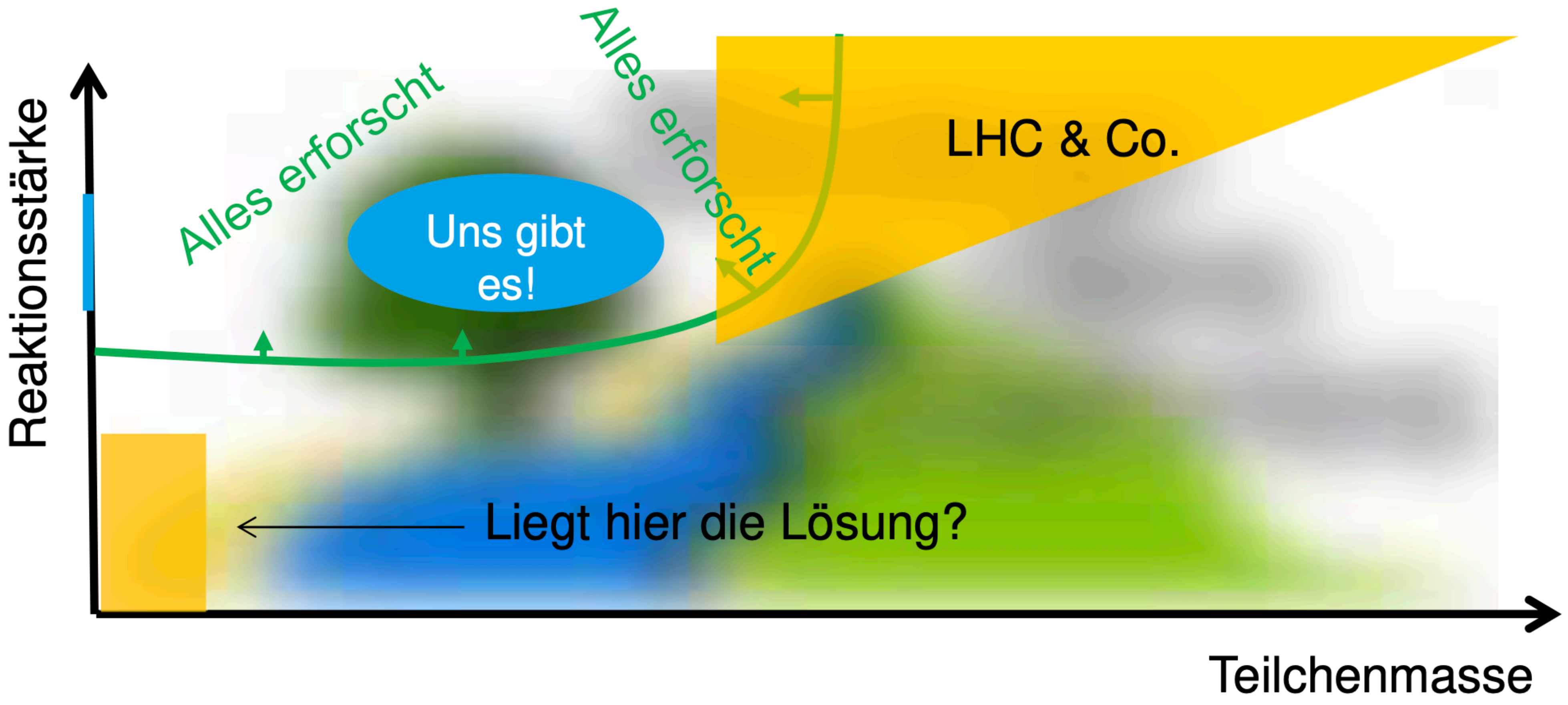
Backup

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

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

Collider vs. High Precision - Rare Event Search Experiments

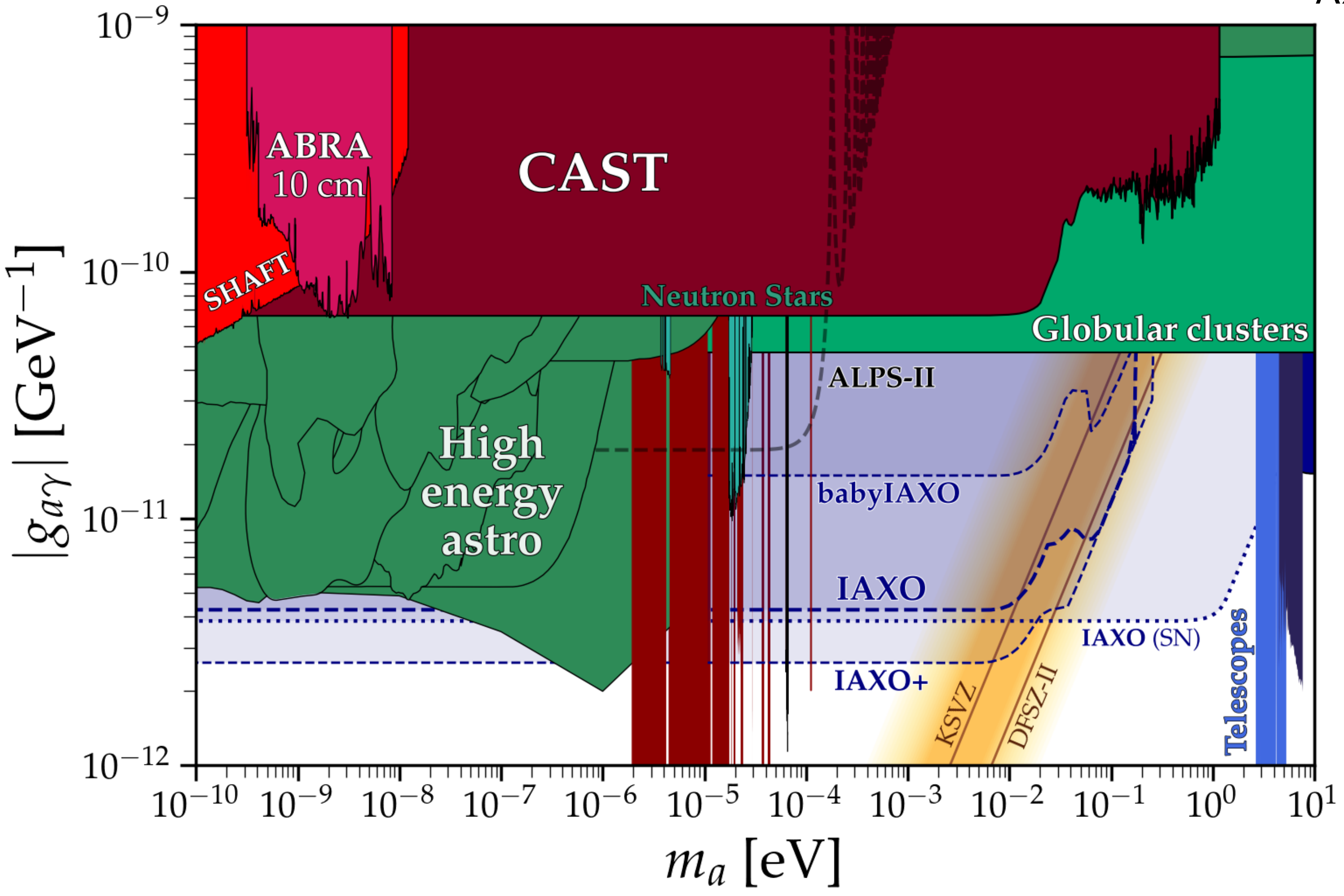
Different Parameter Spaces to Investigate!



Current Parameter Space - Axion-Photon Coupling

Experimental Limits + Projections Helioscopes

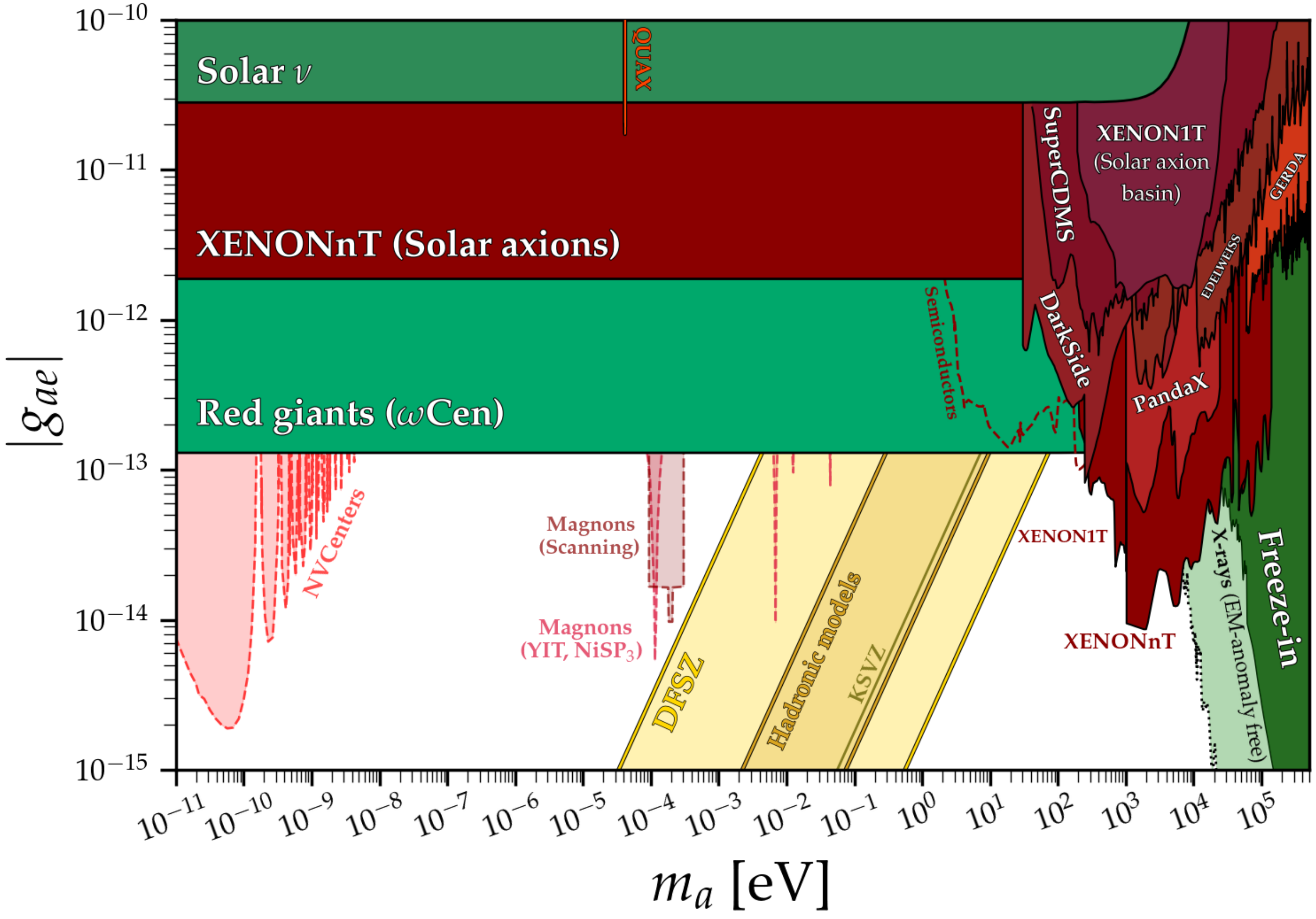
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Axion-Electron Coupling

Experimental Limits + Projections

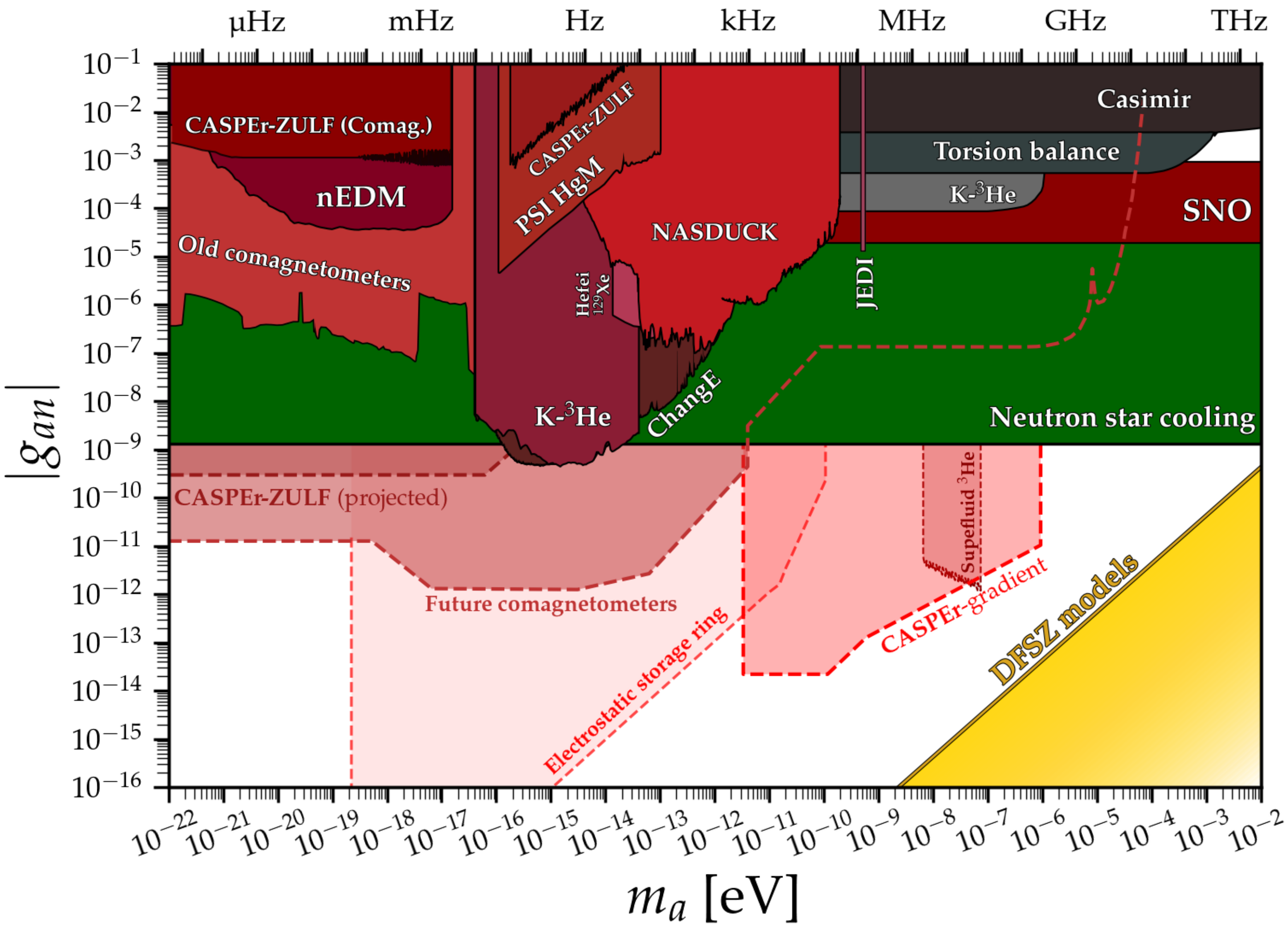
https://cajohare.github.io/AxionLimits/docs/ap.html



Current Parameter Space - Axion-Neutron Coupling

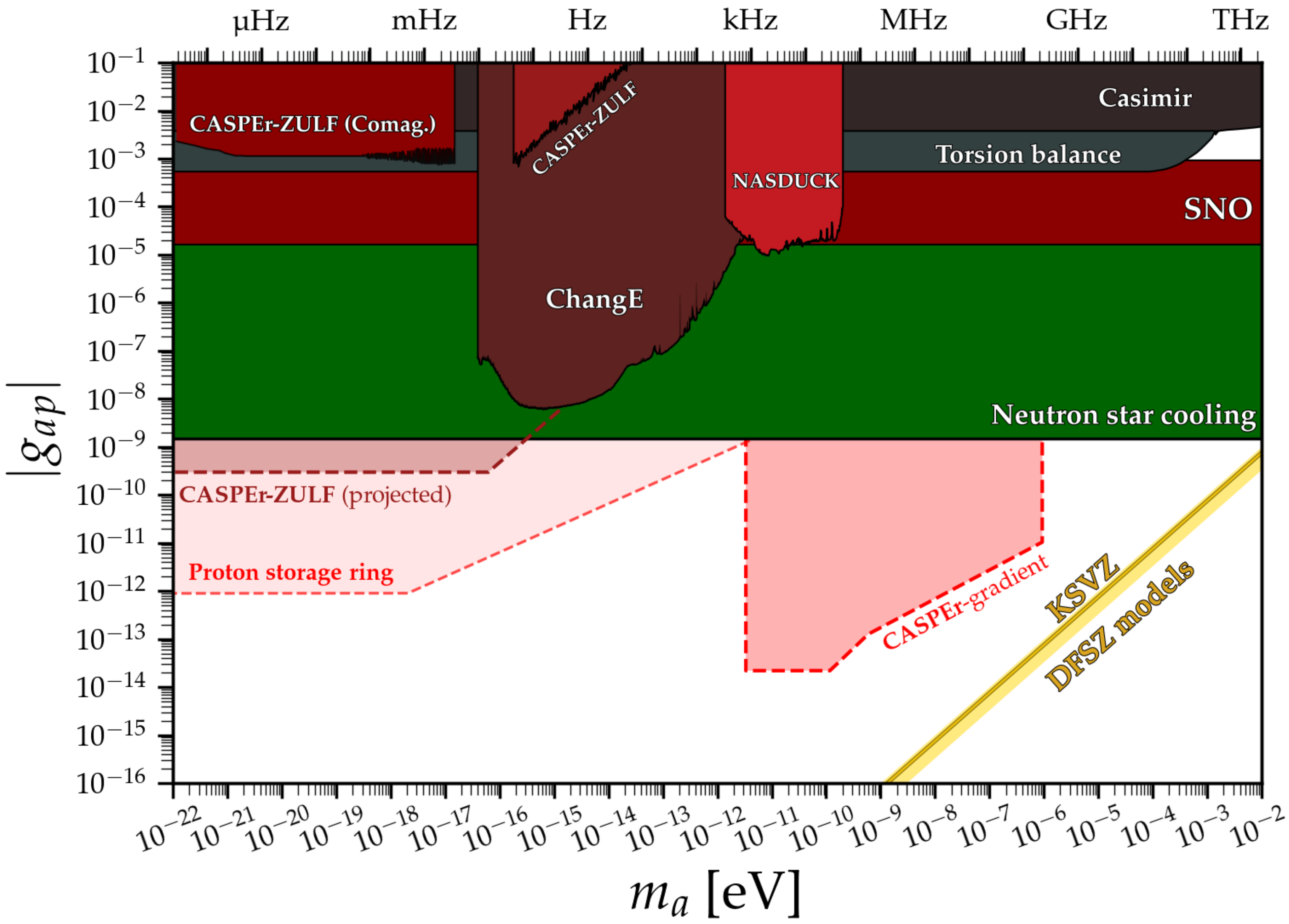
Experimental Limits + Projections

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



Current Parameter Space - Axion-Proton Coupling

Experimental Limits + Projections

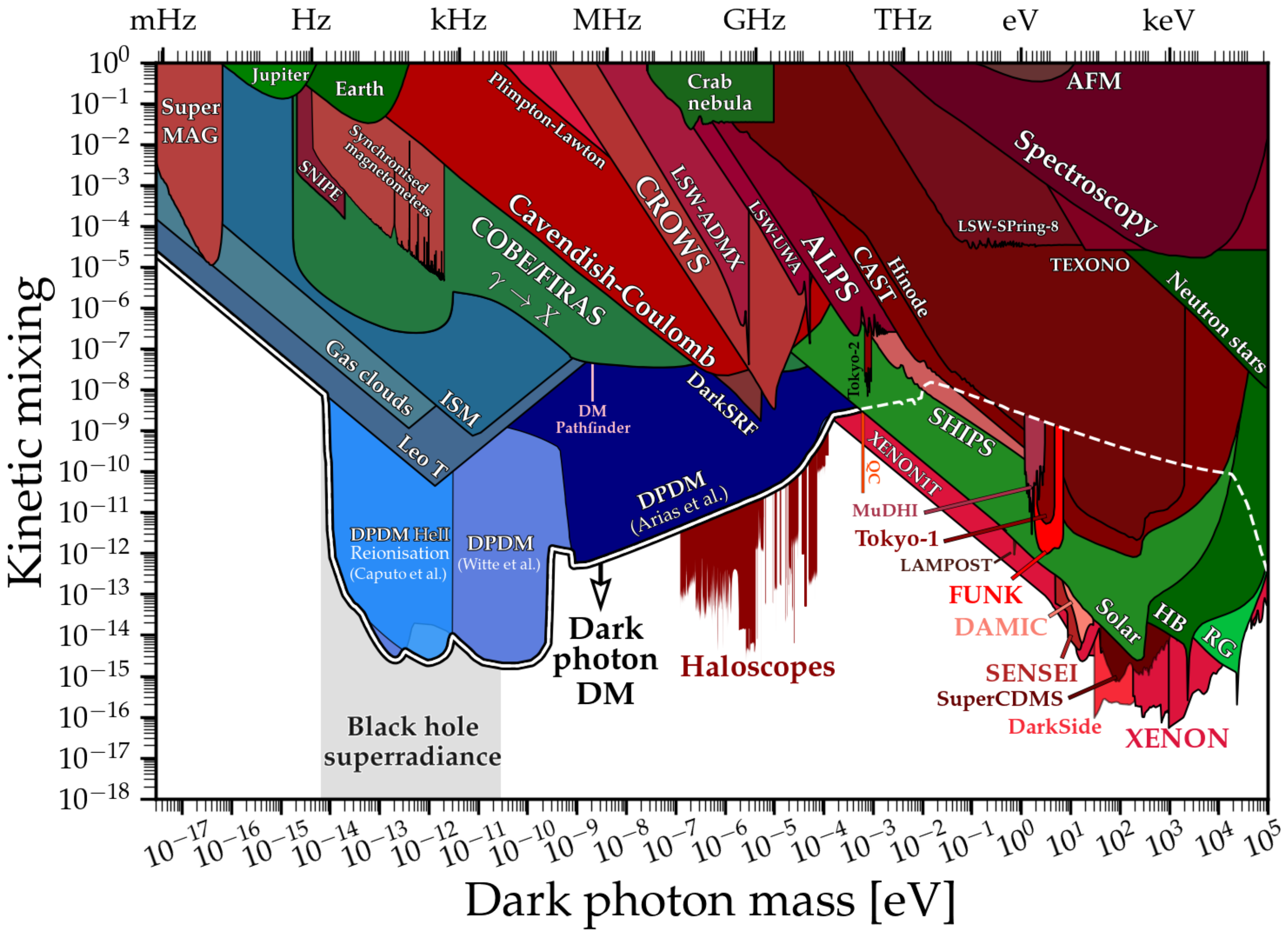


https://cajohare.github.io/AxionLimits/docs/ap.html

Current Parameter Space - Dark Photons

Experimental Limits + Projections

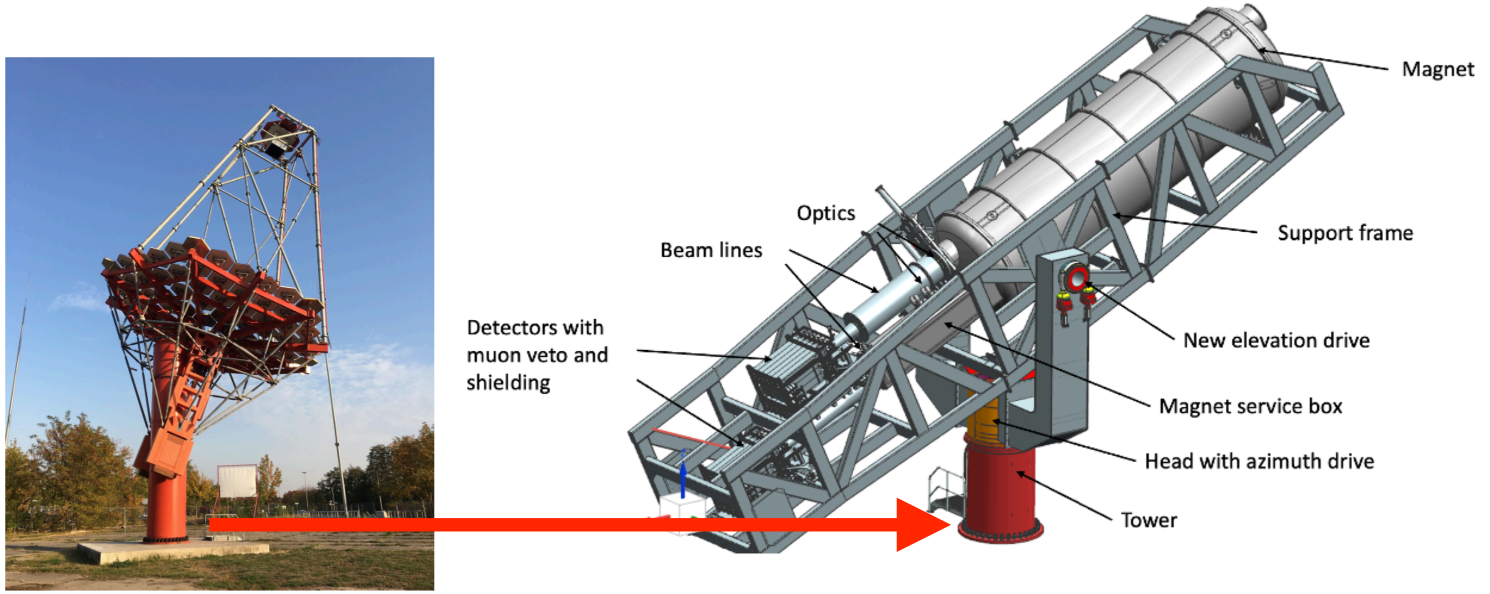
https://cajohare.github.io/AxionLimits/docs/ap.html

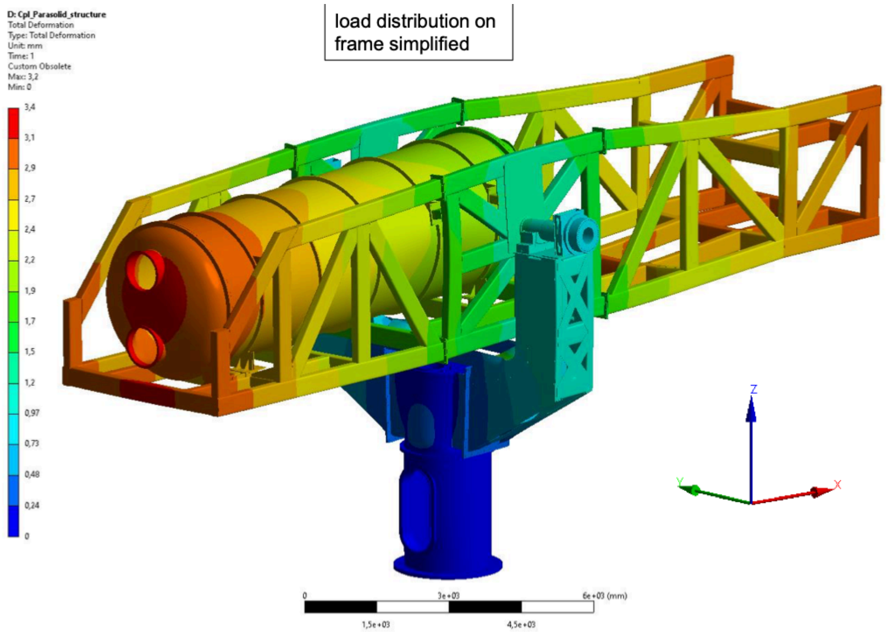


Structure & Drive System

And Alignment to the Sun

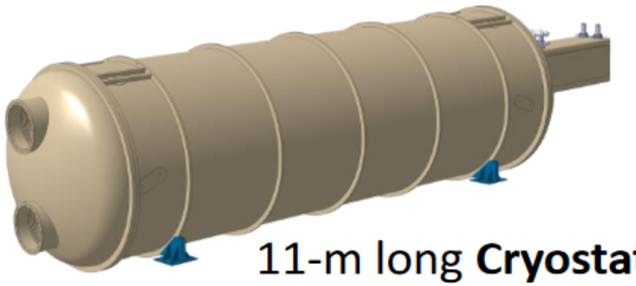
- Reusing parts of CTA/MST prototype from DESY Zeuthen
- Technical studies progressing well
  - ➡ Design almost finished
  - ➡ Rotation: 360°, Tilt: ±25°
  - ➡ Pointing precision < 0.01°
  - ➡ Extensive simulations of load distributions and deformations
  - ➡ Internal and external alignment studies

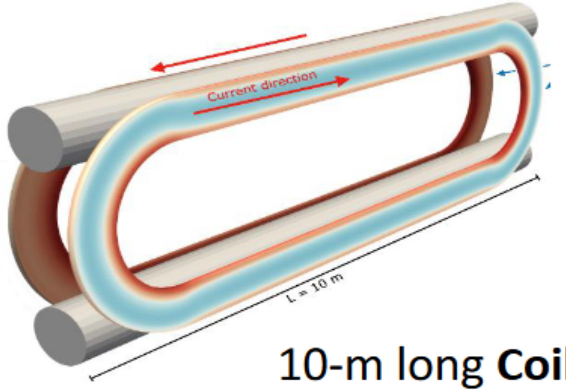


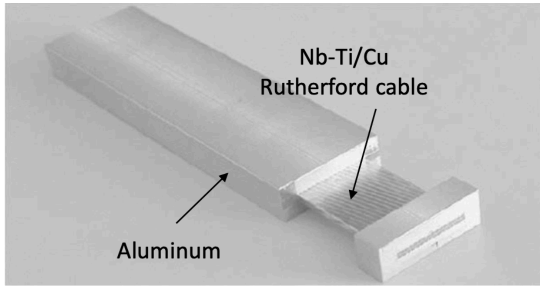


Magnet (Design by CERN)

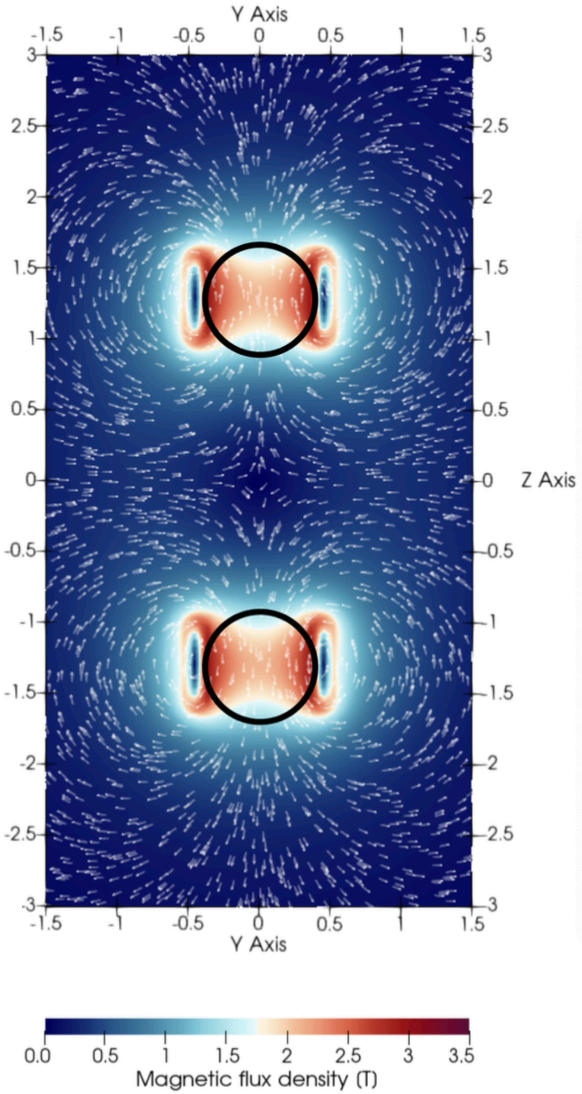
Prospects and Challenges







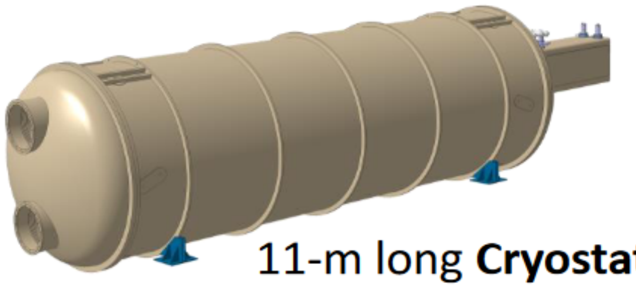
20-km long **Conductor**



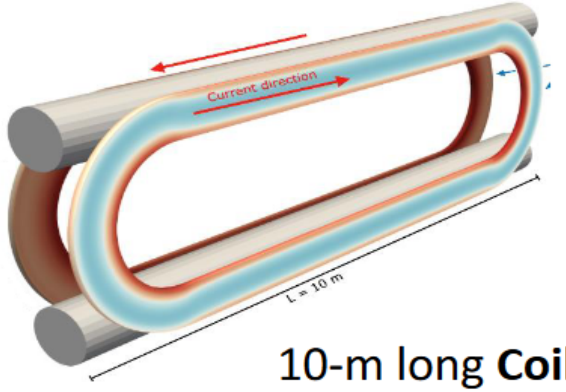
- Two 10 m long bores with common coil racetrack design, cryocooler concept

Magnet (Design by CERN)

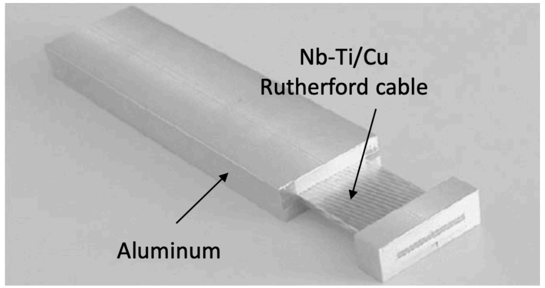
Prospects and Challenges



11-m long **Cryostat**



10-m long **Coils**



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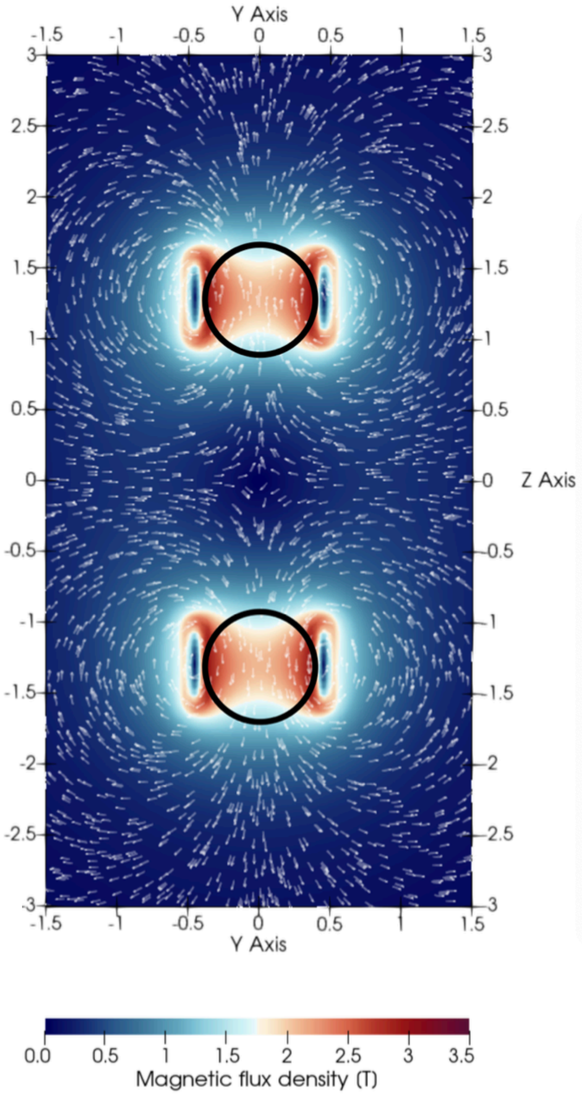

- Two 10 m long bores with common coil racetrack design, cryocooler concept

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

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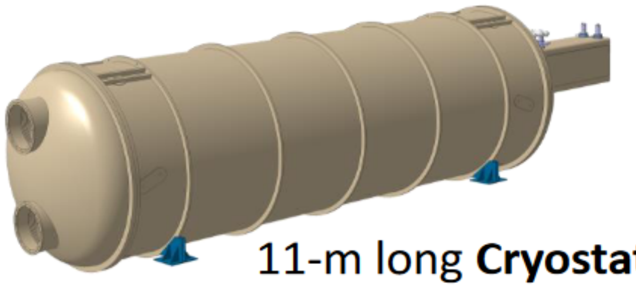

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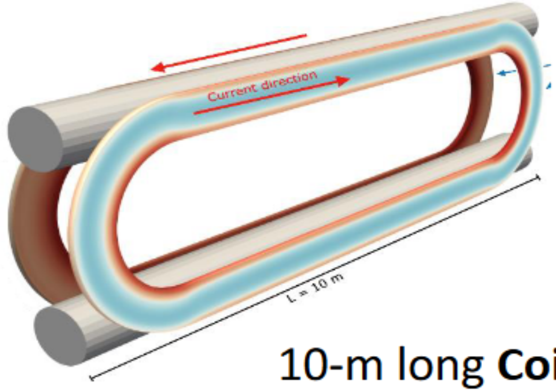

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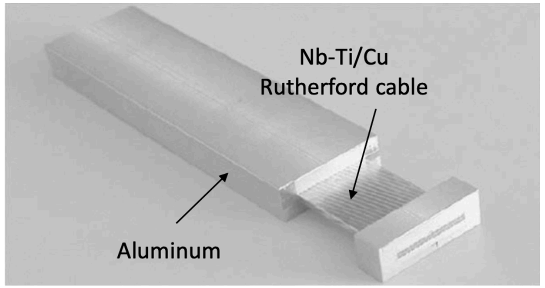

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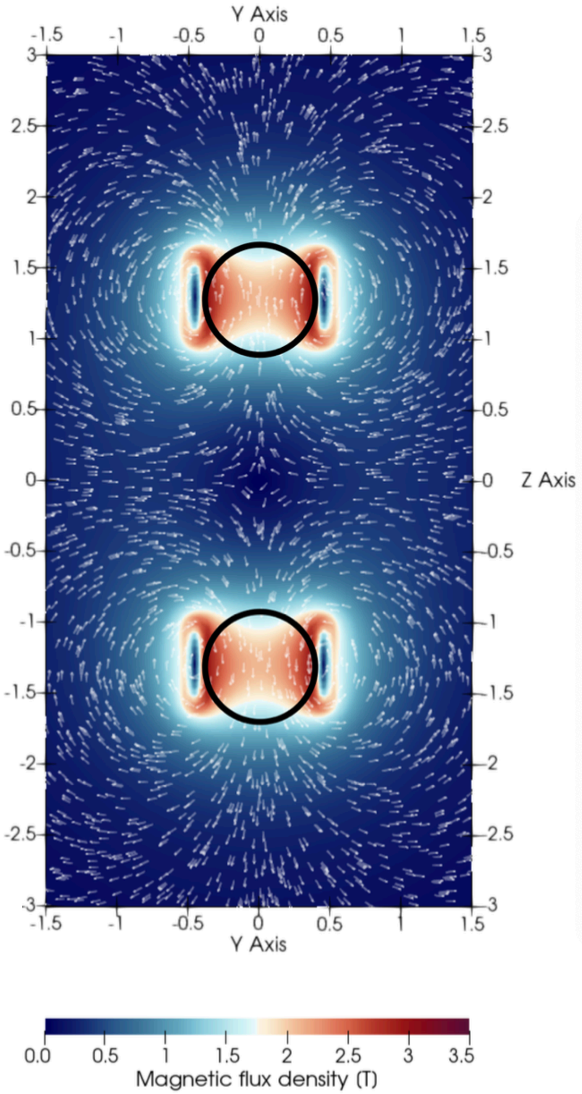


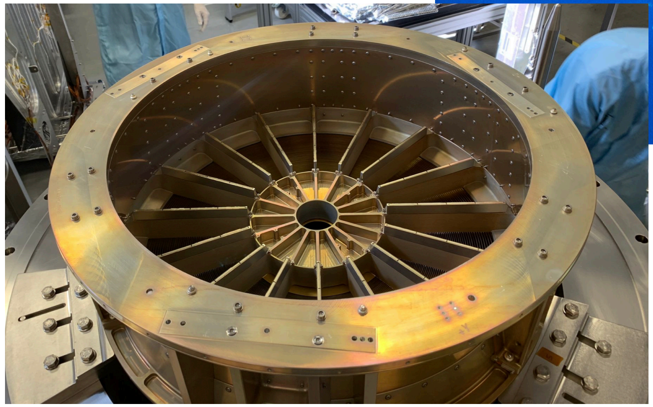
- Two 10 m long bores with common coil racetrack design, cryocooler concept
- Ongoing discussion mainly due to difficulties in building Al-stabilised superconducting cables, **critical item**
  - ➡ Potential Russian companies not available
  - ➡ Causing additional costs and delays
- Collaboration of magnet experts (DESY+CERN)
  - ➡ Build up competence to build cable at CERN or let it built by a suitable industrial partner
  - ➡ Constantly improving cryogenic system
  - ➡ 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



Optics

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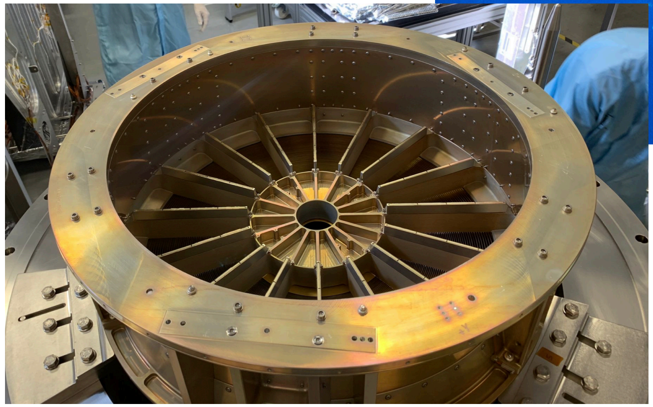
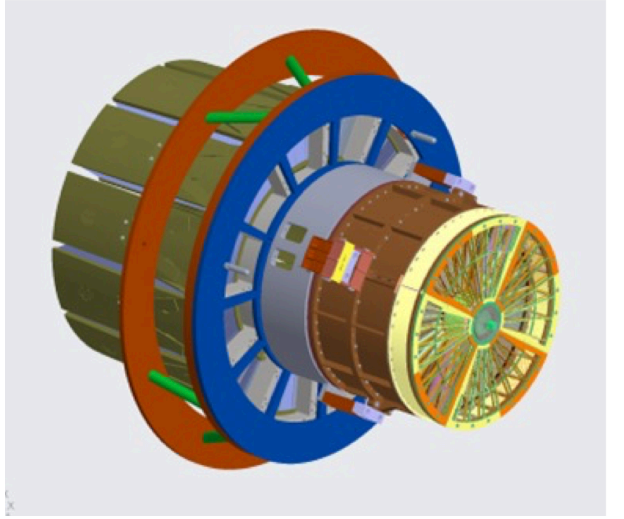


2. Custom optics (hybrid approach)
   ➡ Focal length: 5 m
   ➡ Significant progress in test for different mirror coating, design and calibration

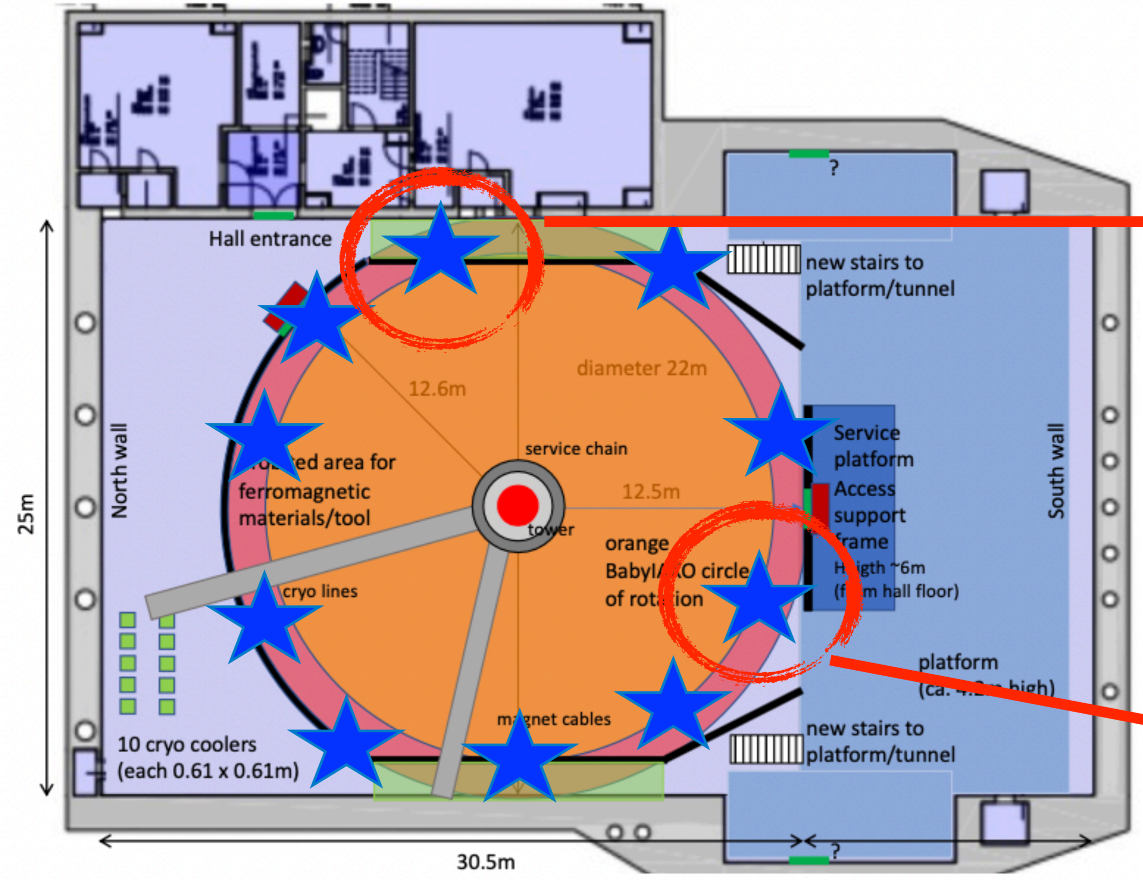


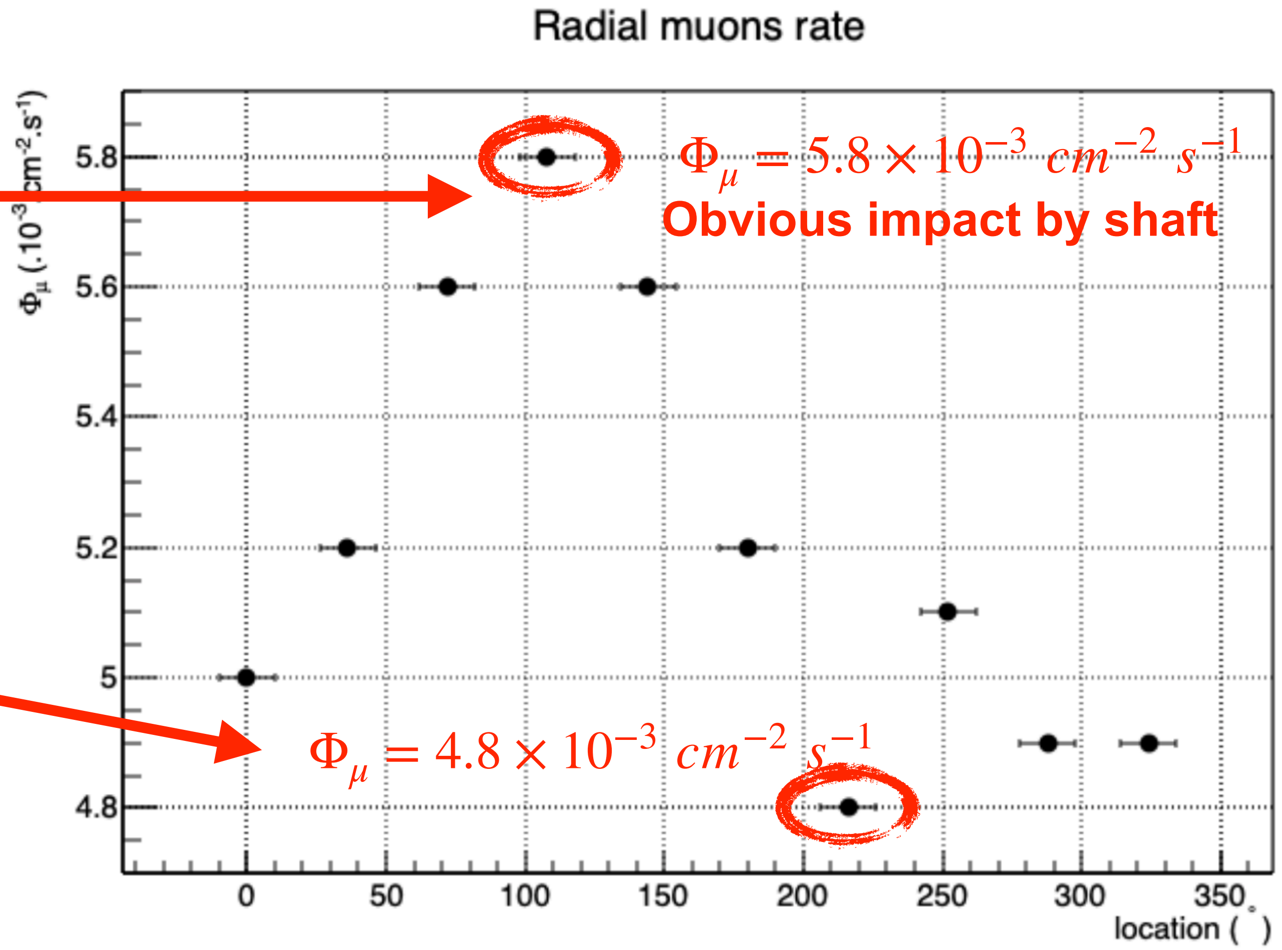
- Challenges: Throughput efficiency (40-60%) and focal area (0.2 cm^2)

Muon Measurements I

BabyIAXO Circle of Rotation + Shaft

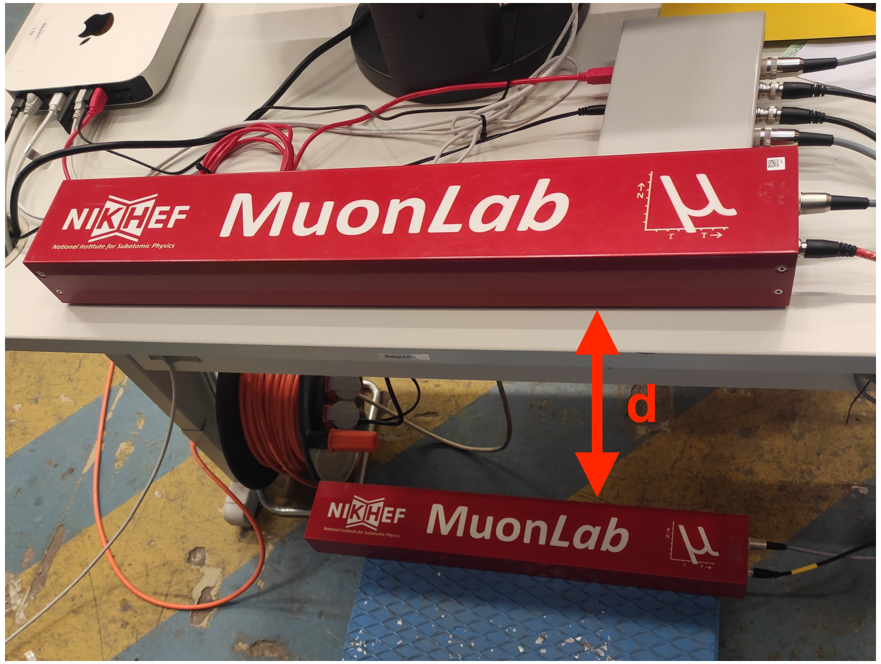
- Defined 10 measurement locations at the outer radius of the BabyIAXO circle of rotation

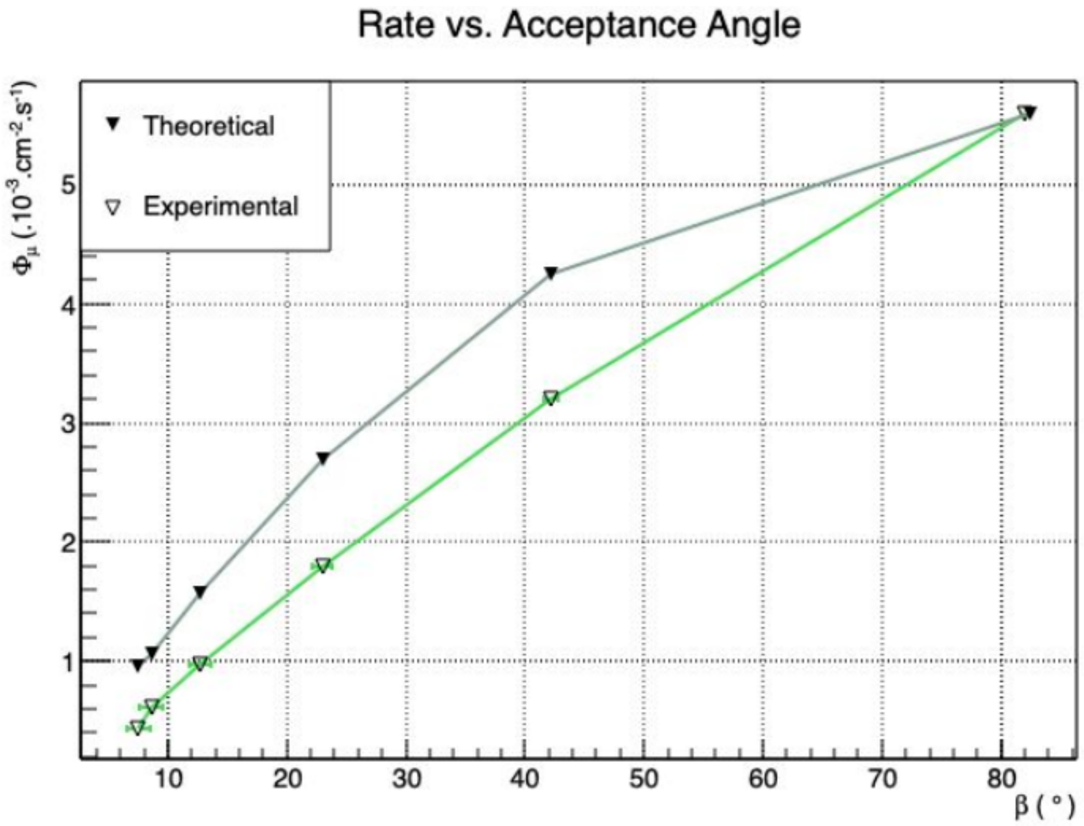




Muon Measurements II

Acceptance Angle

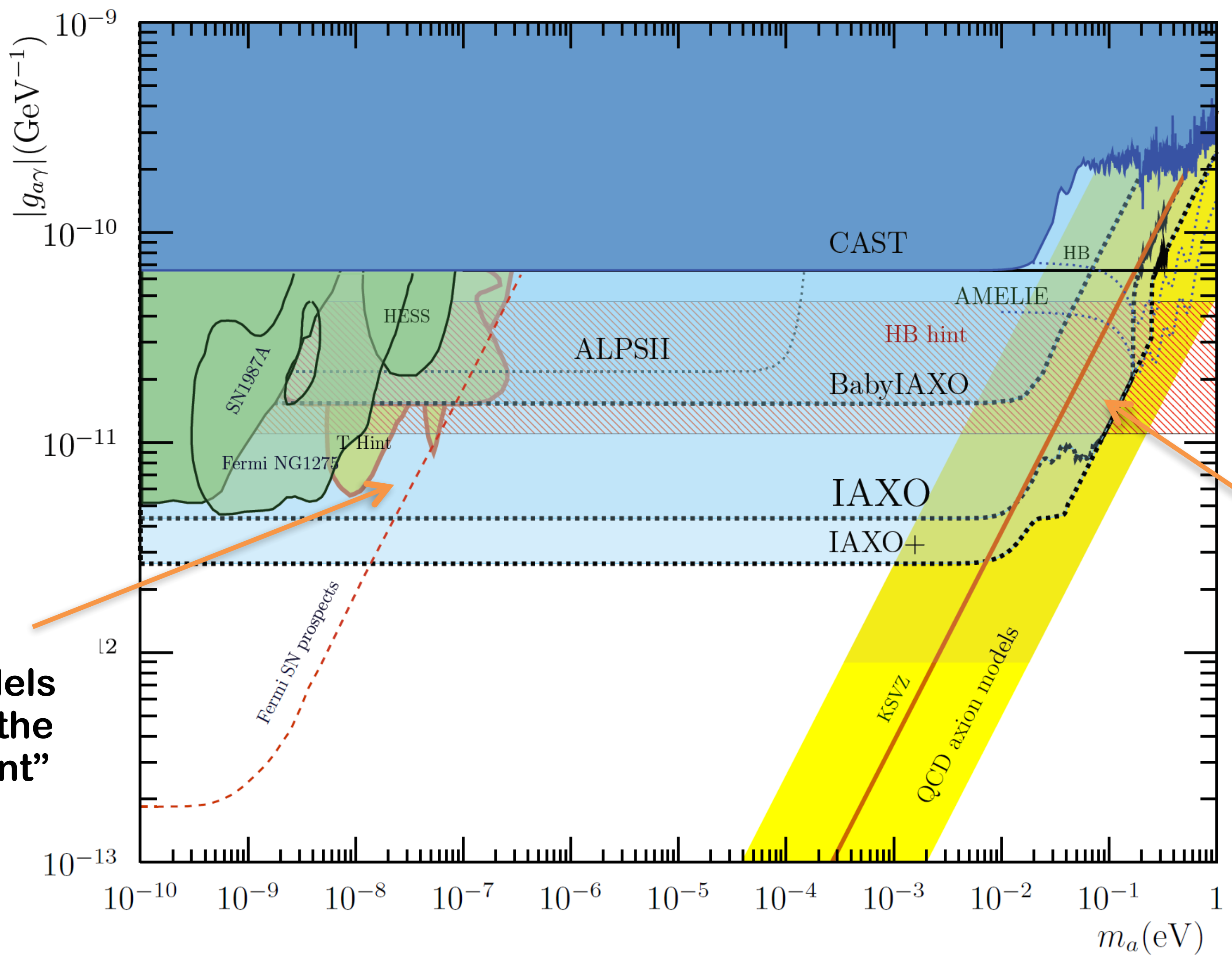




- Long time measurements below shaft with varying scintillator distance **d**
  - ➡ Calculation of acceptance angle β
  - ➡ Comparison to angular spectrum of cosmic rays and calculation of expected rates
  - ➡ Trend similar, but experimental values systematically lower: misalignment, bar size, layers of concrete,…

BabyIAXO & IAXO physics reach

BabyIAXO prospects: 10xMFOM + optics and detector from conservative scenario of LoI



IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

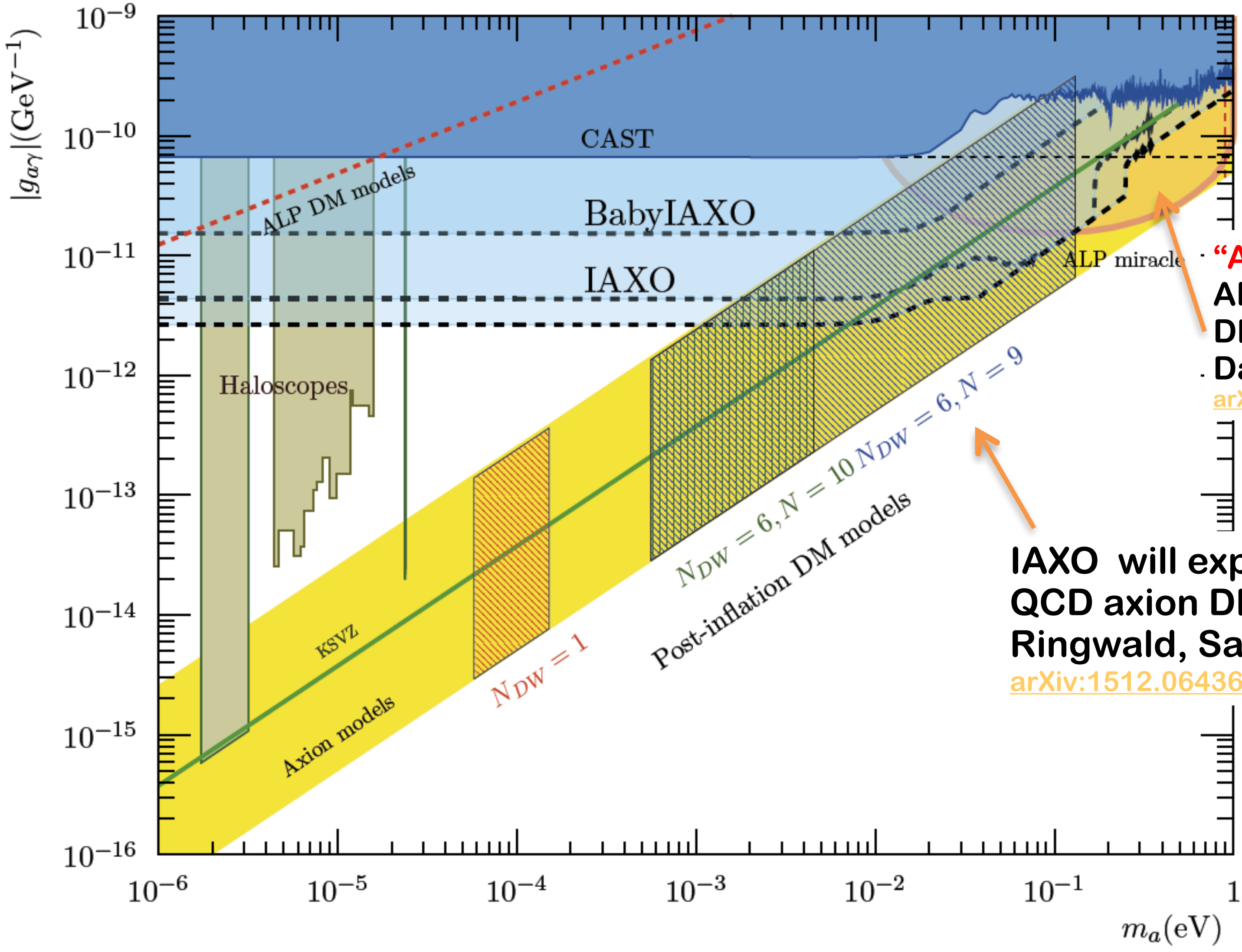
IAXO will fully explore ALP models invoked to solve the "transparency hint"

… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"

But for this the g_{ae} is particularly interesting

MFOM = Magnet FOM

IAXO & meV axion cosmology



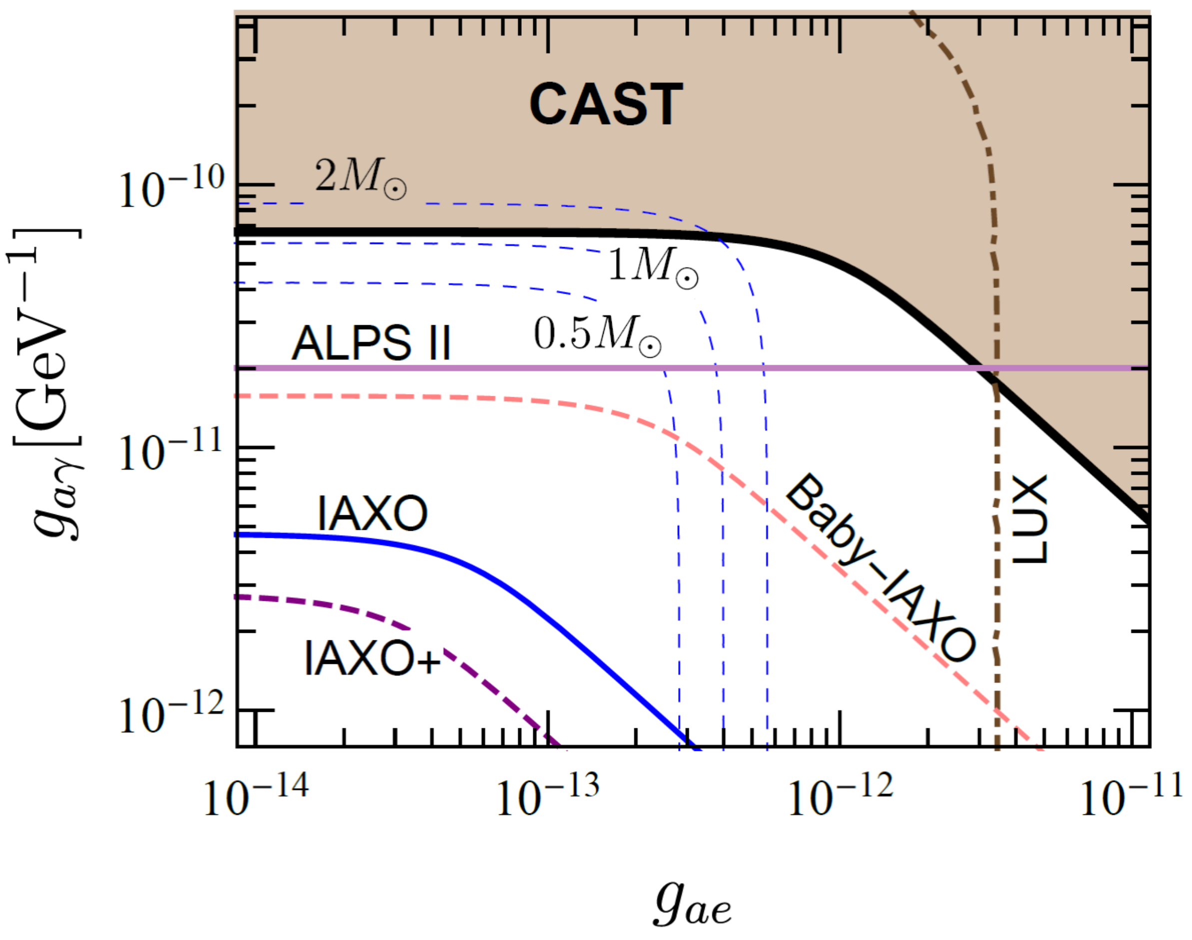
"ALP miracle" region
ALPs solving both
DM & inflation
Daido et al. 2017
arXiv:1710.11107

IAXO will explore viable
QCD axion DM models
Ringwald, Saikawa 2016
arXiv:1512.06436

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

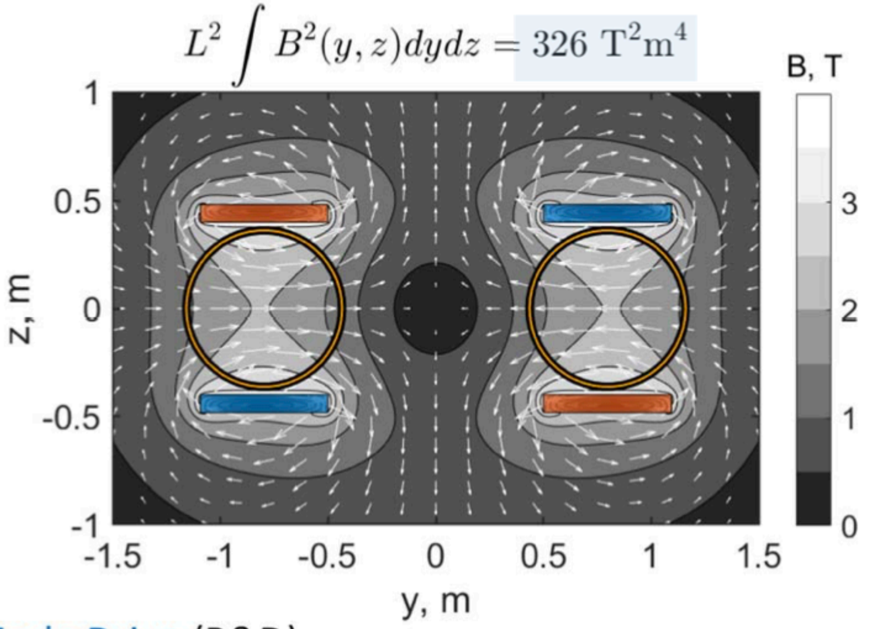
Baby-IAXO magnets (II)

- Two bores of 70 cm diameter (dimensions similar to final IAXO bores) and 10 m length
- Field in bore 2 – 3 T

  Magnetic figure of merit

  $f_M = B^2L^2A$

  About 10 times larger than in CAST



- Design of supporting structures

  Repelling force 34 MN

- Defining the electrical circuit:

  Direct drive (no risk) vs Persistent Mode Drive (R&D)

  Quench protection

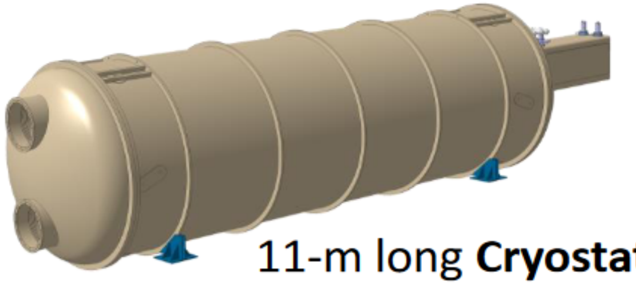
- Cryogenics:

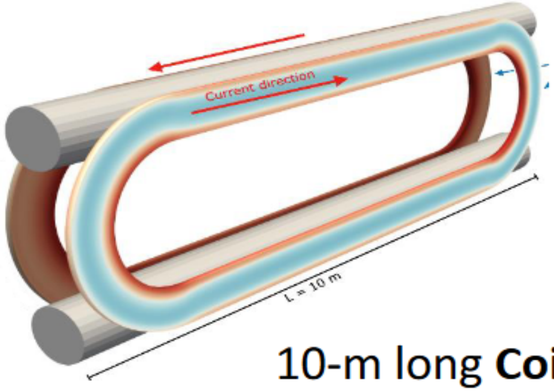
  cryocoolers based cooling system

  evaluation of the heat load

Magnet

Prospects and Challenges

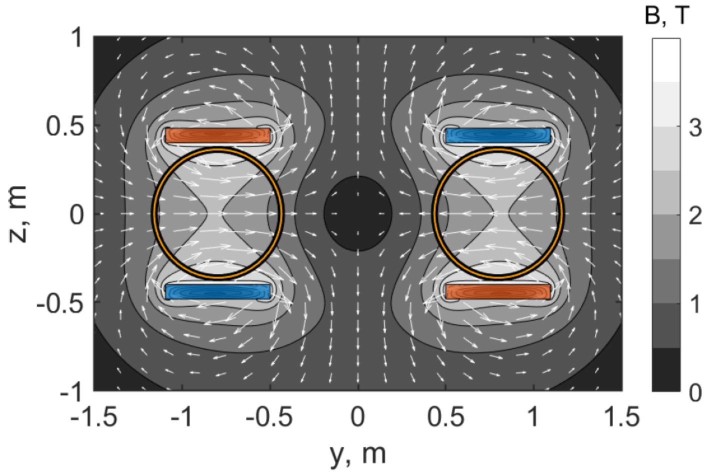

11-m long **Cryostat**



10-m long **Coils**


~35 km **Superconductor**

- Two 10 m long bores with 70 cm diameter each, magnetic field ~2 T
  - ➡ Common coil racetrack design with counter-flowing currents
- Dry detector magnet concept based on cryocoolers, cold mass 4.5 K



- Ongoing adaptations due to difficulties in obtaining Al-stabilised superconducting cables
  - ➡ Potential Russian providers not available
  - ➡ Critical item, causing delays
- Intense collaboration with magnet experts at CERN
  - ➡ Requests for quotations and tendering restarted recently
  - ➡ New review upcoming, conceptual design under preparation

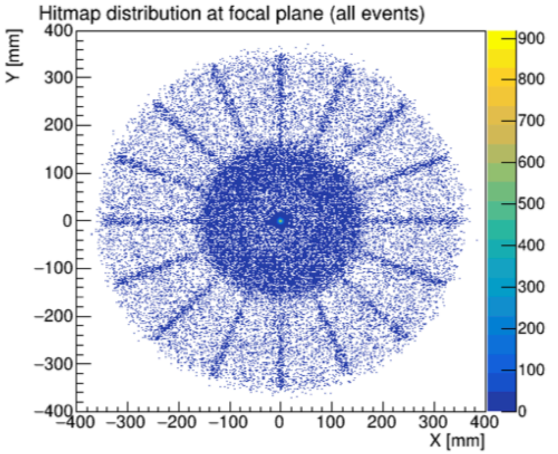
Optics

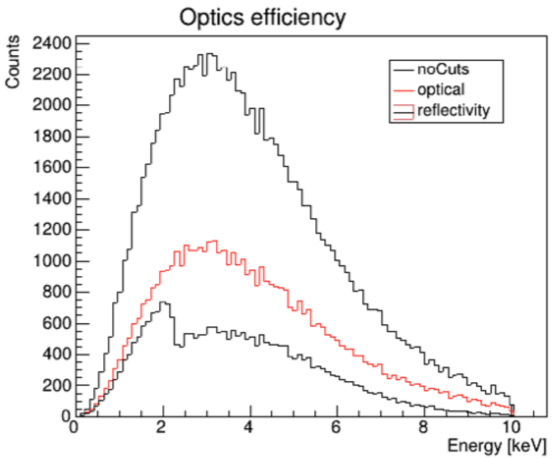
Focal Plane with Spot Events

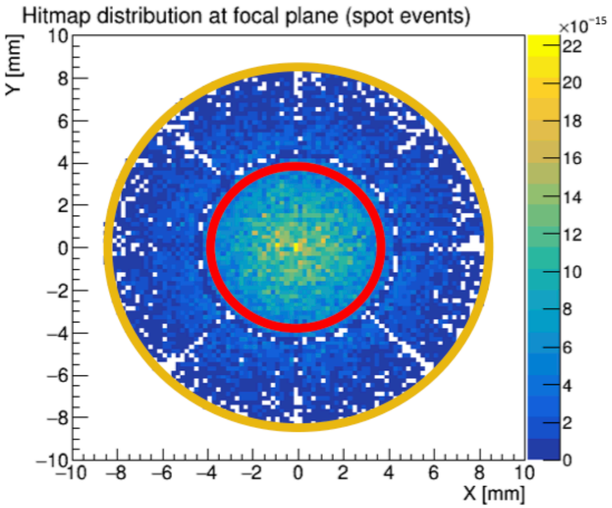
Run number : 17

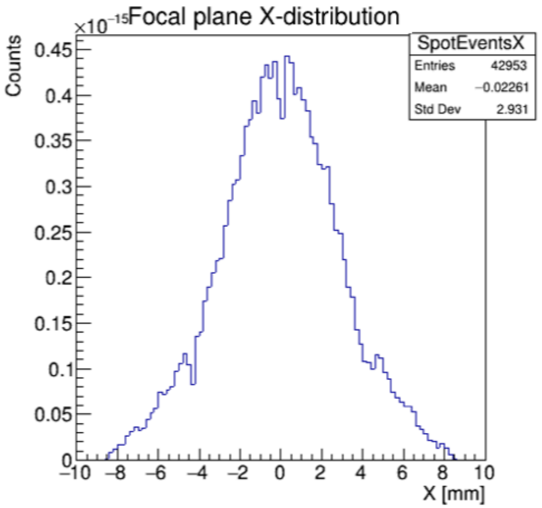
Run tag : Primakoff_XMM_Micromegas_Vacuum

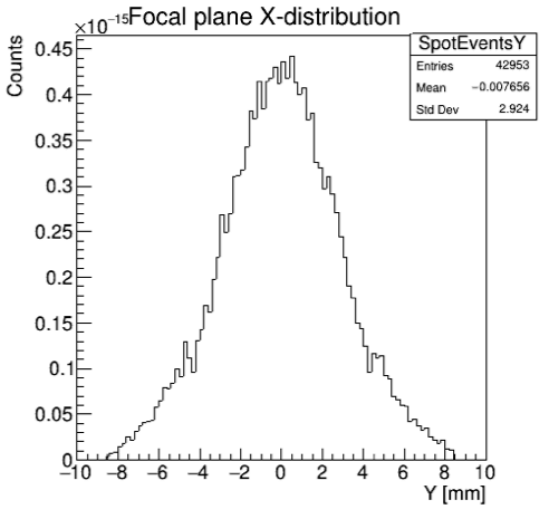
Entries : 100000







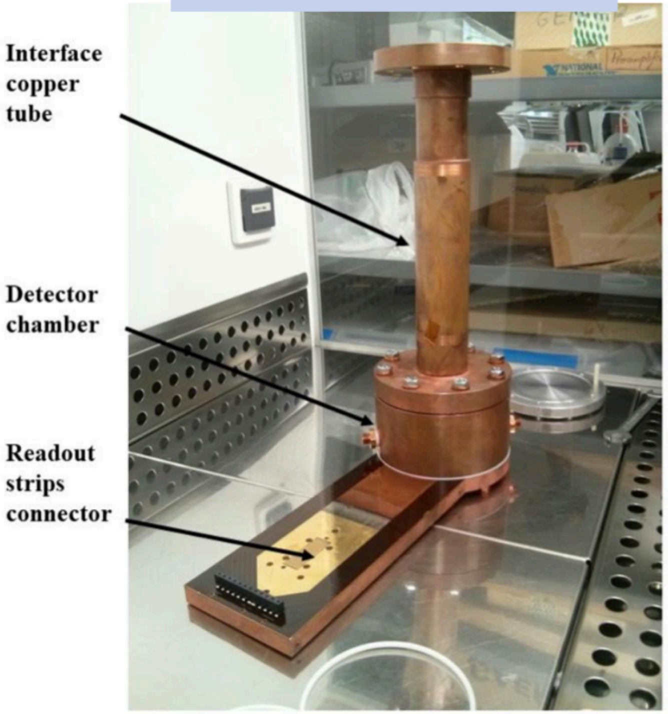




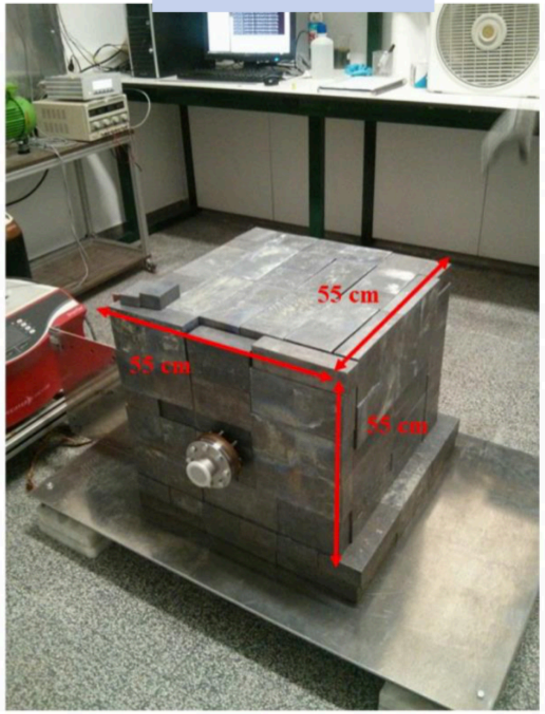
IAXO-D0: the Micromegas prototype at Unizar

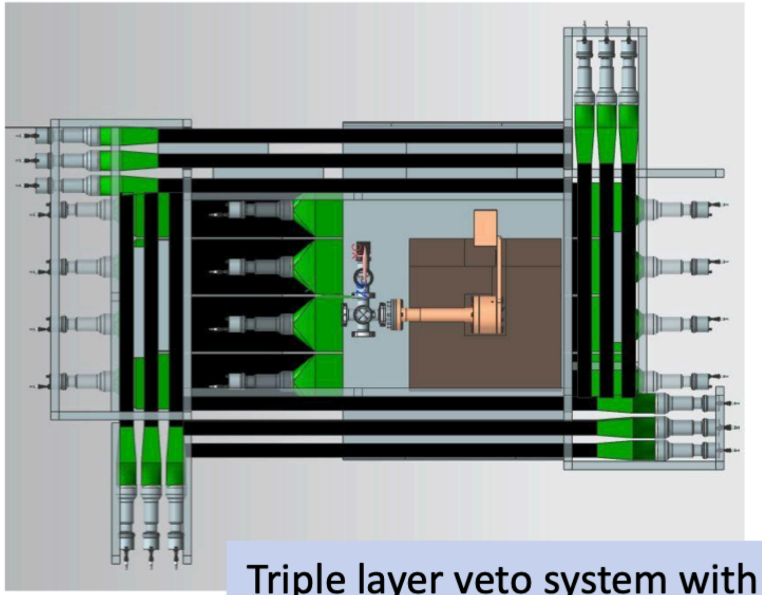
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Micromegas detector



Lead castle



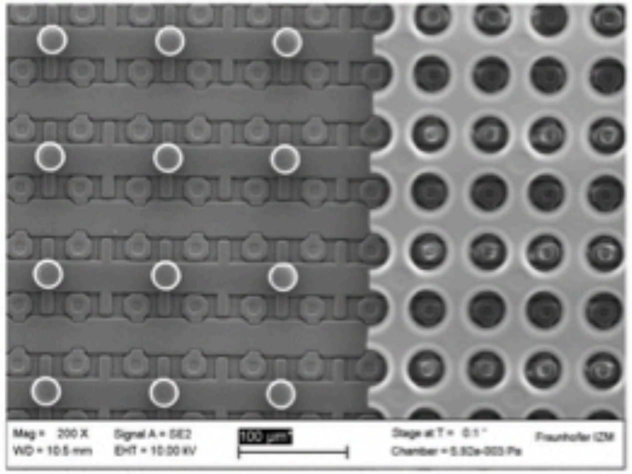


Triple layer veto system with cadmium sheets to discriminate neutron background

Prospective (Baby)IAXO X-ray detectors

GridPix

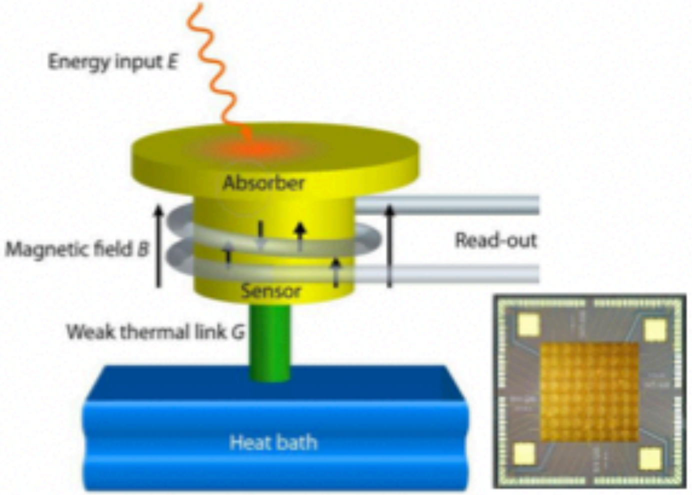
- Evolution of Micromegas detector
- CMOS chip in readout plane
- Single electron detection



Metallic magnetic calorimeters

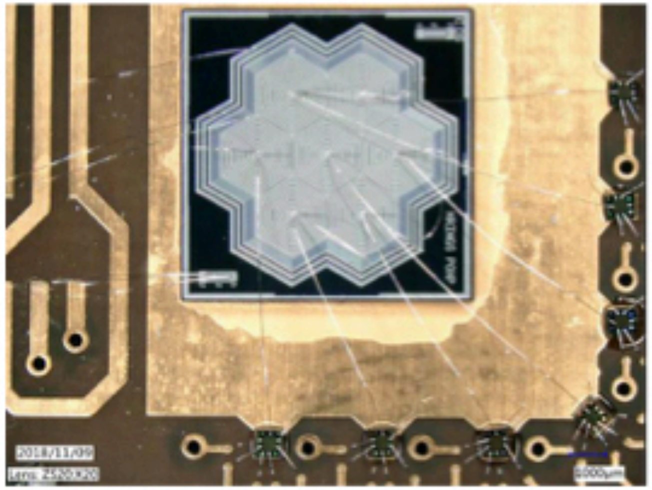
- high energy resolution ~1.6 eV fwhm
- "no" threshold from detector, but window necessary for cryostat

→ Especially useful for axion spectroscopy in case of signal



Silicon drift detectors

- Low threshold < 500 eV
- Good energy resolution ~ 130 eV fwhm
- no window necessary



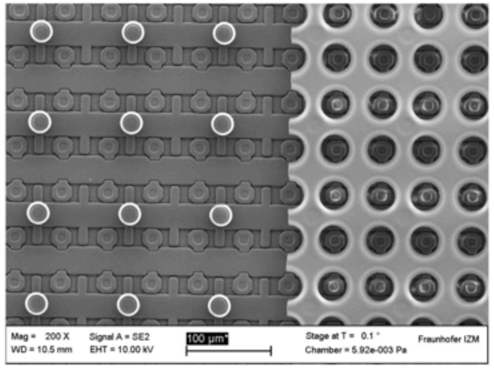
+ Transition Edge Sensors (TES) R&D

Other detectors under study

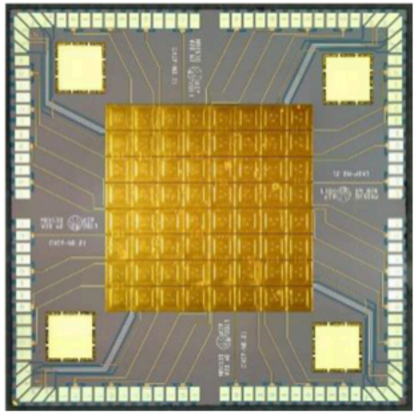
Many alternative detectors are being considered and are undergoing development for later stages of BabyIAXO data taking

- Other technologies under study
    - IAXO as a generic infrastructure for axions and ALPs physics
    - and R&D of alternative detectors with different properties
        - Excellent energy resolution, energy threshold, high efficiency and ultra-pure materials
        - Improve the energy threshold → investigation of fine structures in the axion spectrum

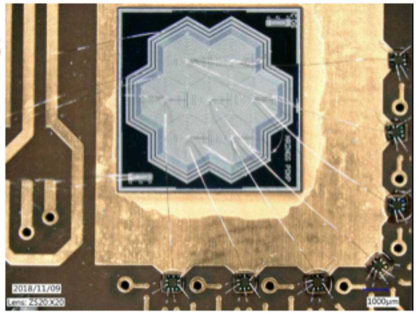
- Post-discovery scenario
    - If positive signal, low threshold + good energy resolution → possibility to determine m_a and g_{ae}
    - Minimization of systematics effects and reinforcement of the claim significance



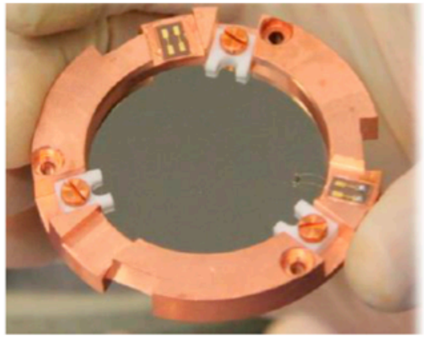
GridPix – evolution of Micromegas



Metallic magnetic calorimeters (MMC)



Silicon Drift Detectors (SDD)



Transition Edge Sensors (TES)

Simulation and Analysis Strategy

JCAP03(2019)039

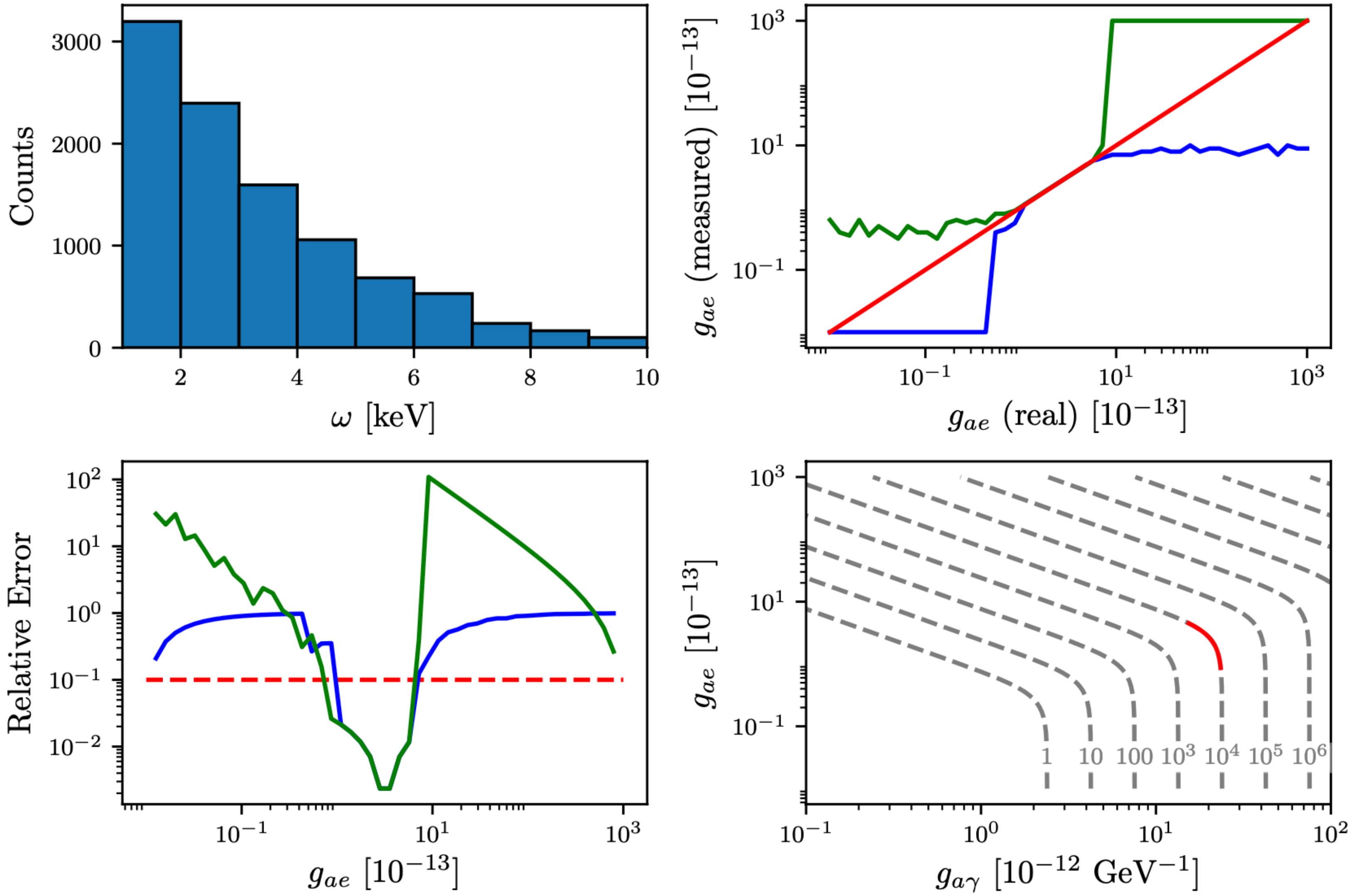
IAXO Parameters

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}	$1\,\mathrm{cm}^2$

Simulation and Analysis Strategy

JCAP03(2019)039

Example



Red: truth input values
Green: Upper value in 95% certainty interval
Blue: Lower value in 95% certainty interval

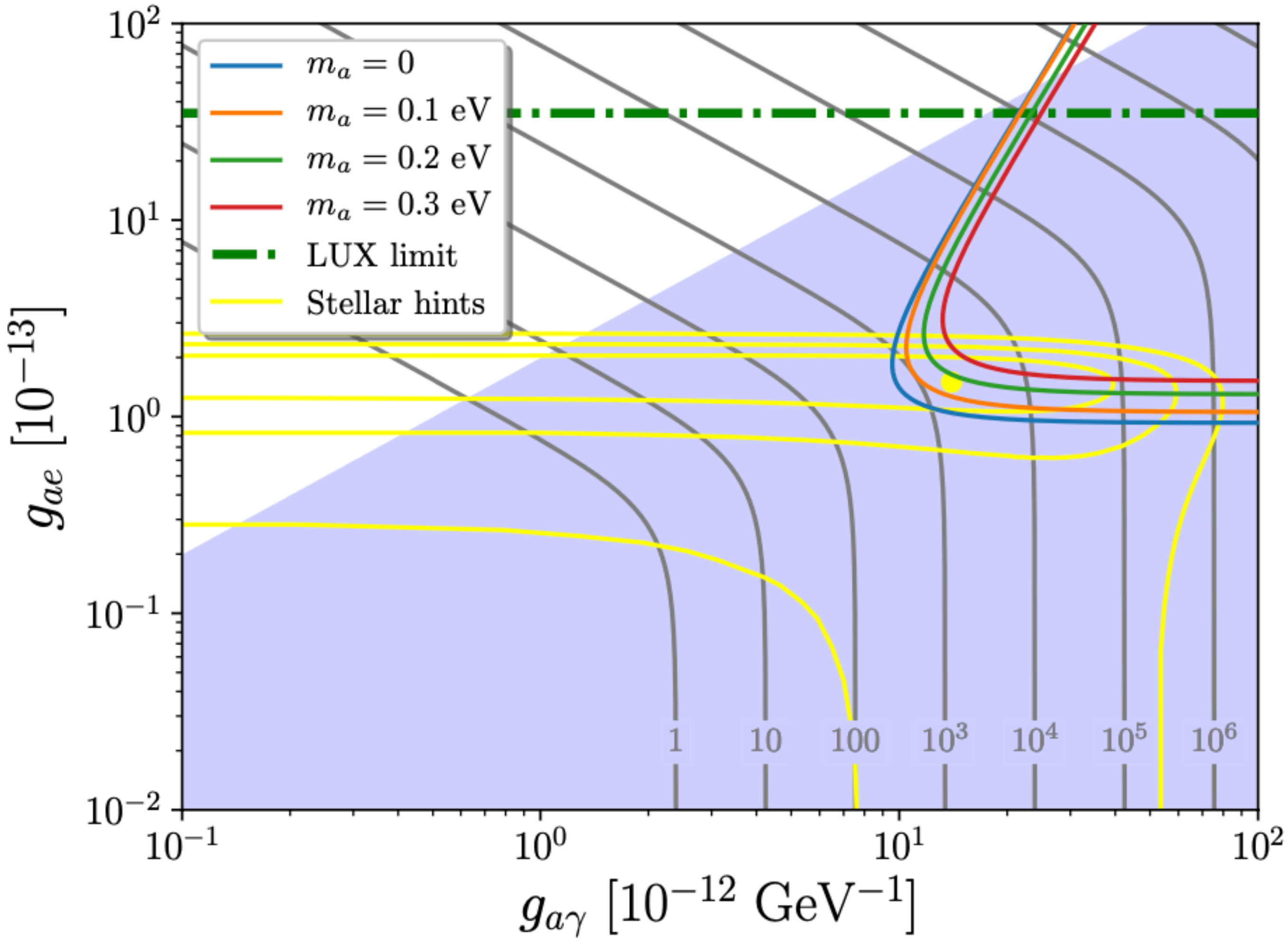
Procedure repeated for many other expectation values of g_{ae} to check accessible area in parameter space

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)



Studied Experimental Setups

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

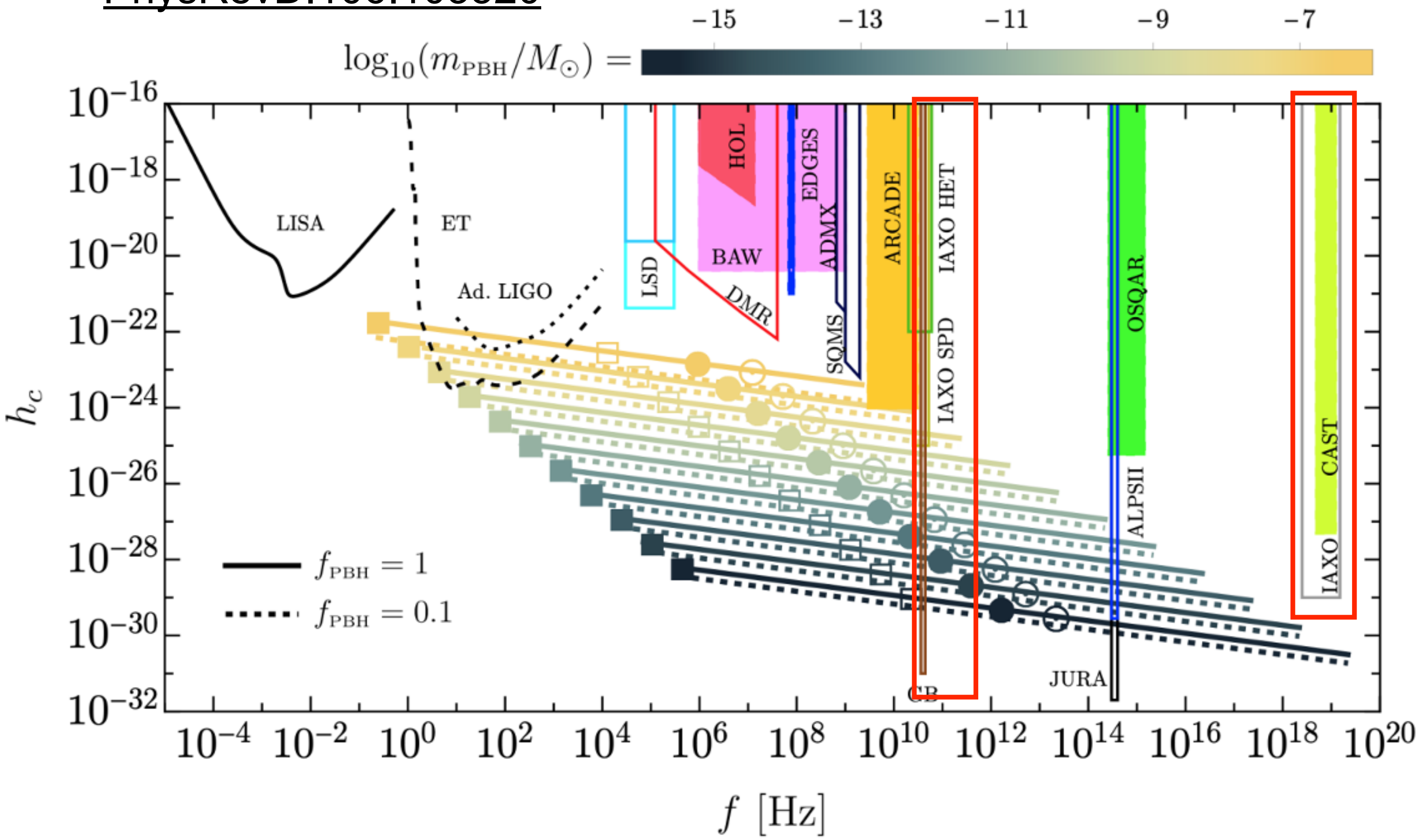
Optimising for 14.4 keV photons

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 IAXO_b	High energy resolution IAXO_r	Low background $\mathrm{IAXO}^+_\mathrm{b}$	High energy resolution $\mathrm{IAXO}^+_\mathrm{r}$
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	$\frac{5}{14400}$

(Baby)IAXO and HFGW

Detection Possible?

PhysRevD.106.103520



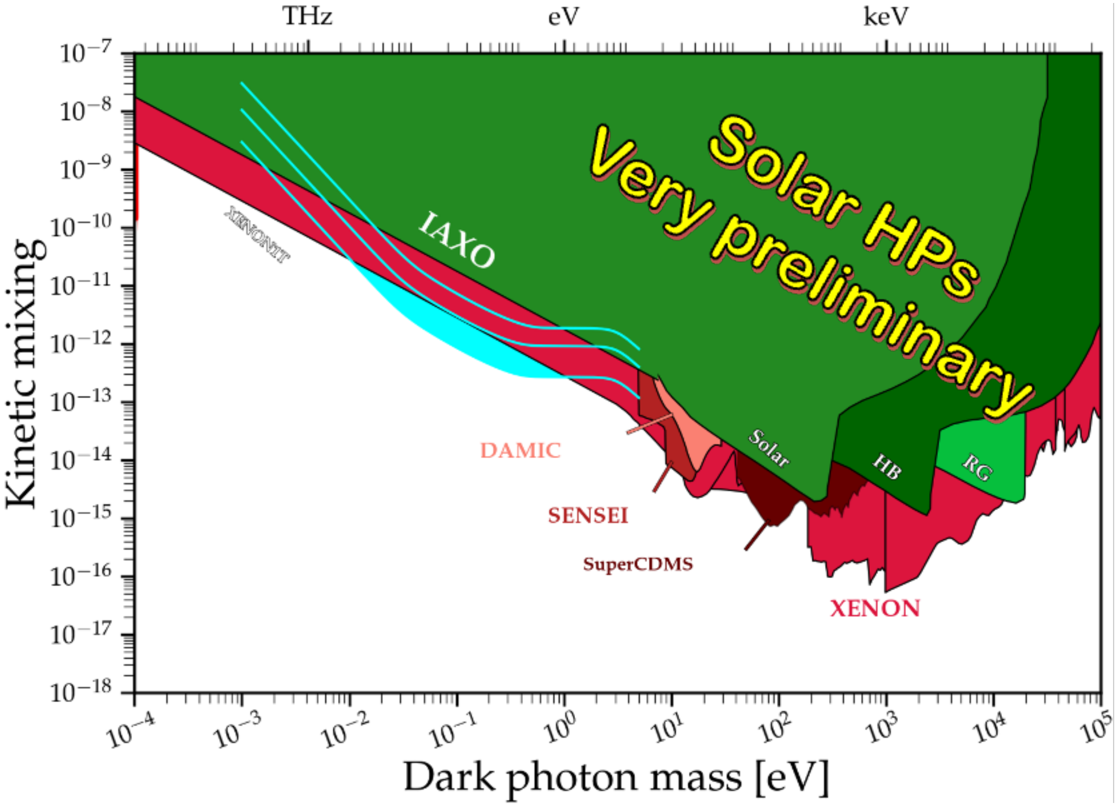
- High frequency gravitational waves are expected in non-standard scenarios, e.g. from primordial black holes
- Gravitational waves converted into photons by inverse Gertsenshtein effect in a strong magnetic field
  - ➡ (Baby)IAXO sensitive to specific frequencies?

➡ Emerging field of study, synergies?

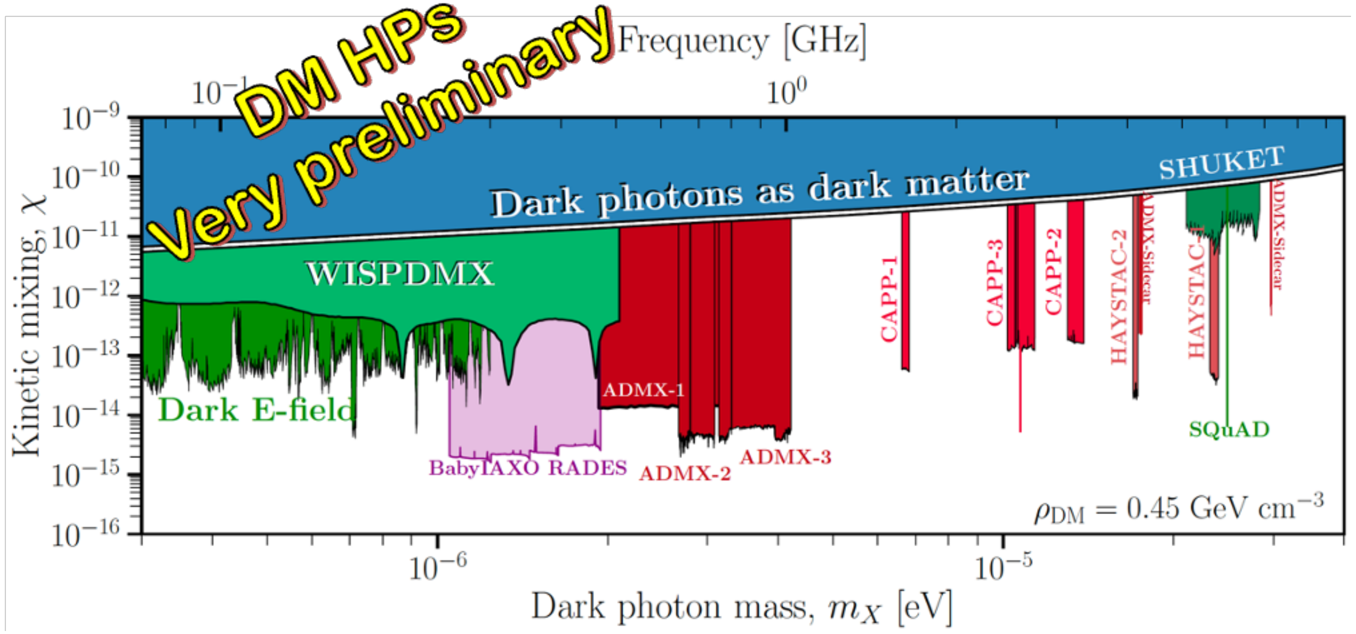
(Baby)IAXO sensitivities: PhysRevD.106.063027 + JCAP03(2021)054

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…