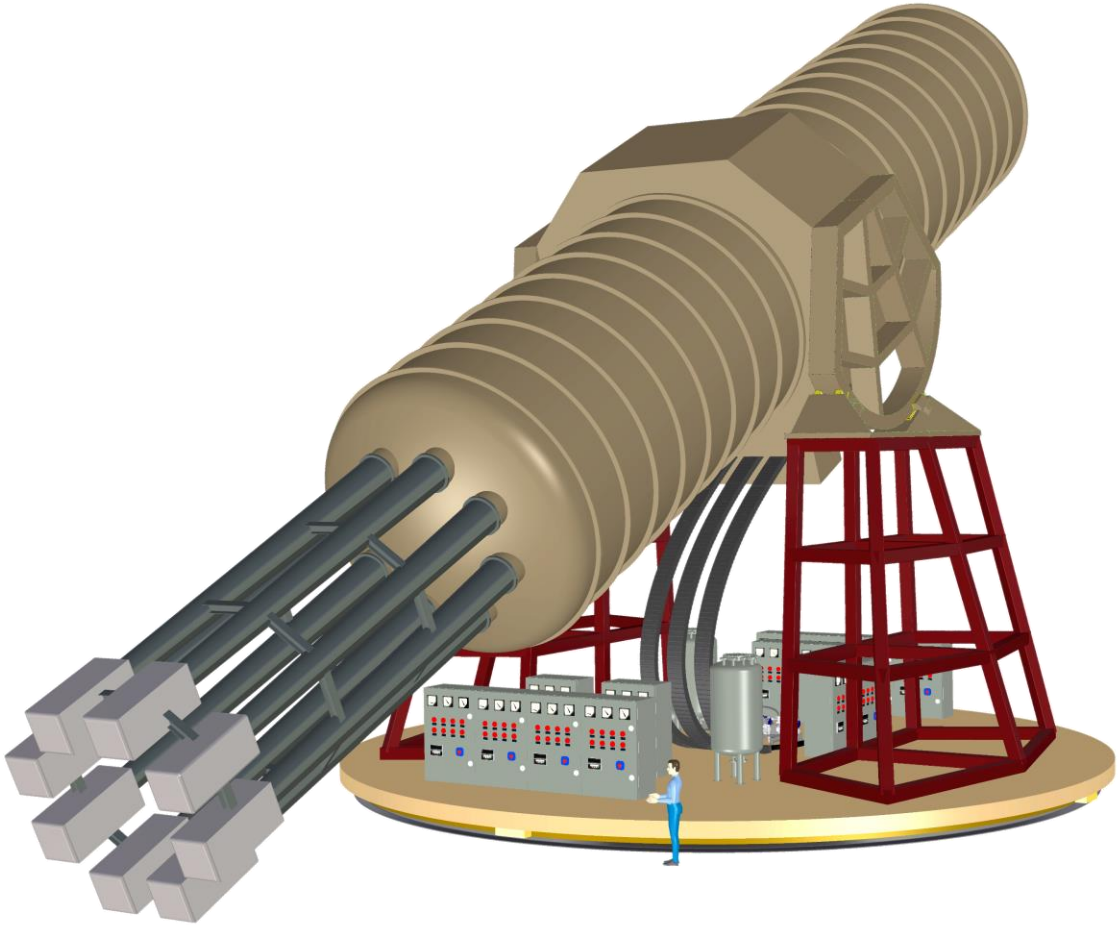
Axion Searches with IAXO and BabyIAXO



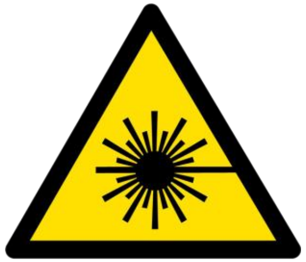
Johanna von Oy

On behalf of the IAXO Collaboration

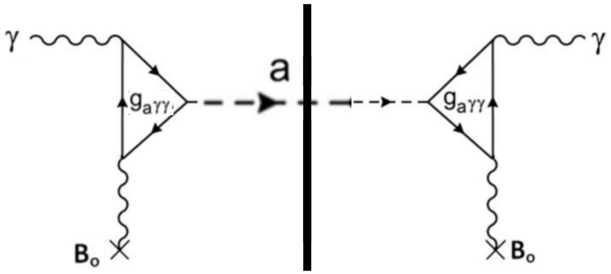
19th Patras Workshop

DETECTION OF AXIONS

Light-shining-through-wall experiments

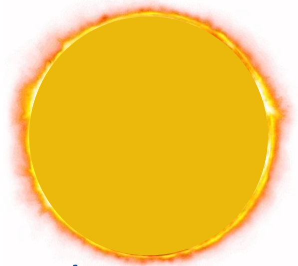


Lab Axions

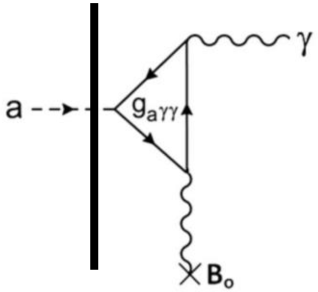


OSQAR, CROWS, ALPS I, ALPS II, STAX

Helioscopes



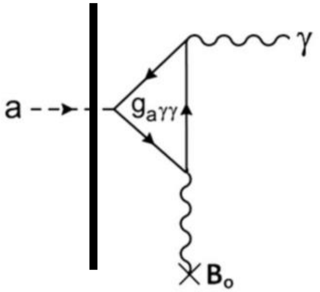
Solar Axions



SIMICO, CAST, BabyIAXO, IAXO

Haloscopes

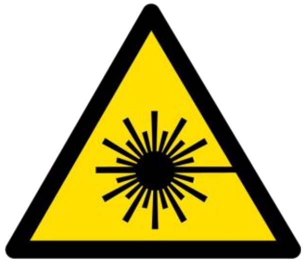
Relic Axions



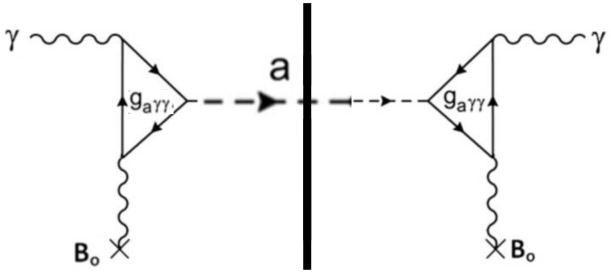
ADMX, HAYSTAC, RADES, CAPP, ALPHA, CASPEr, ORGAN, MADMAX…

DETECTION OF AXIONS

Light-shining-through-wall experiments



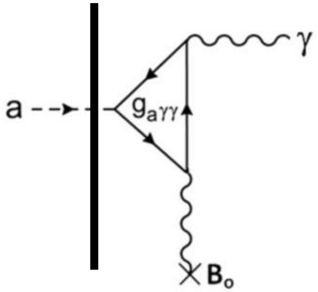
Lab Axions



OSQAR, CROWS, ALPS I, ALPS II, STAX

Helioscopes

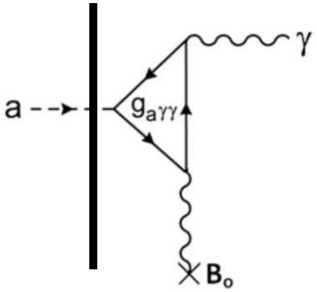
Solar Axions



SIMICO, CAST, BabyIAXO, IAXO

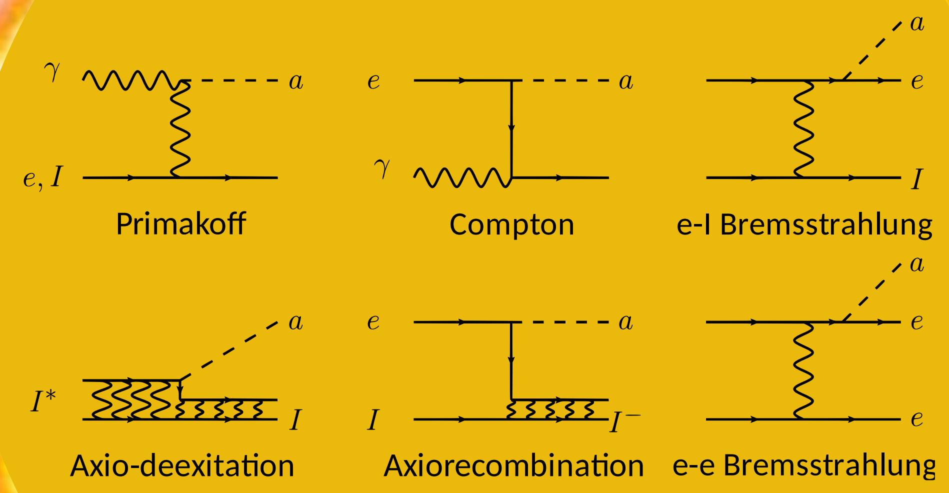
Haloscopes

Relic Axions



ADMX, HAYSTAC, RADES, CAPP, ALPHA, CASPEr, ORGAN, MADMAX…

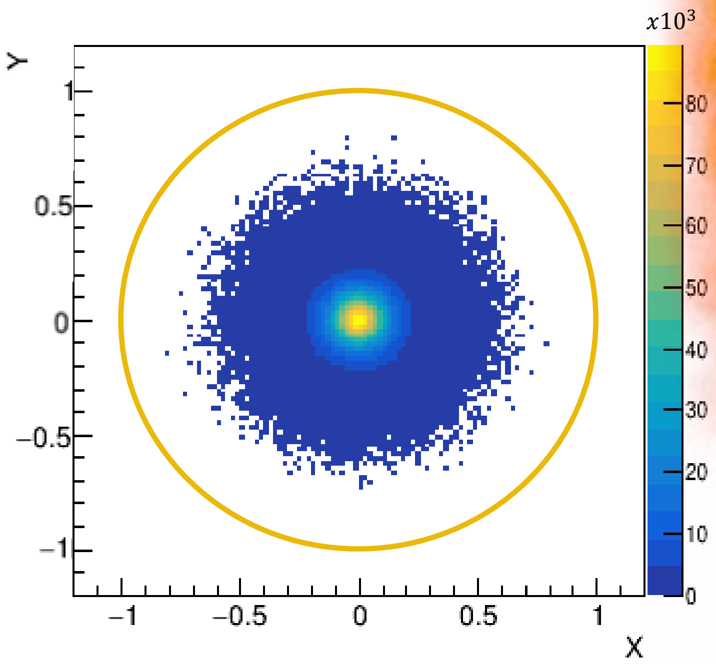
SOLAR AXIONS



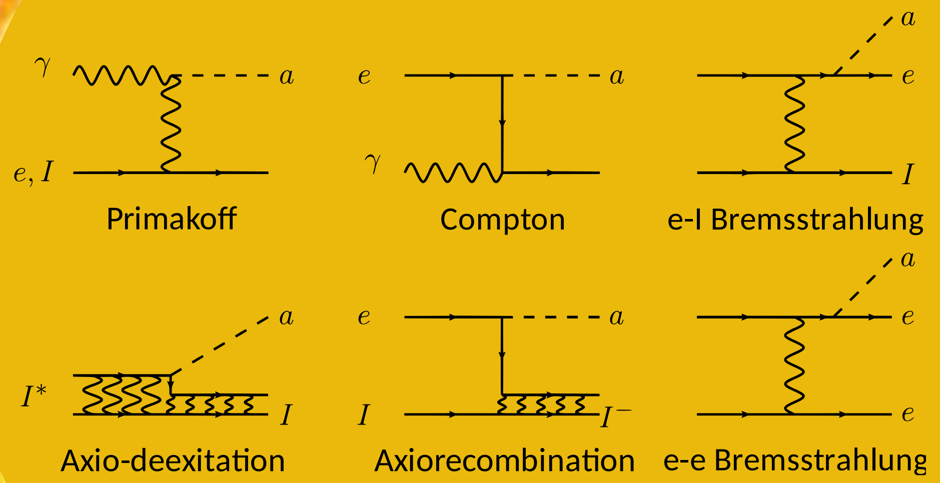
J. Redondo, JCAP 12 (2013) 008

SOLAR AXIONS

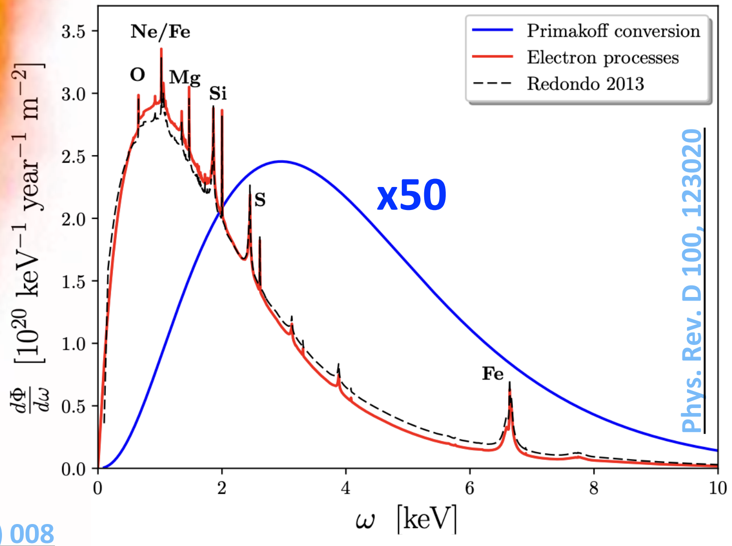
Axion Origin



Axion couplings

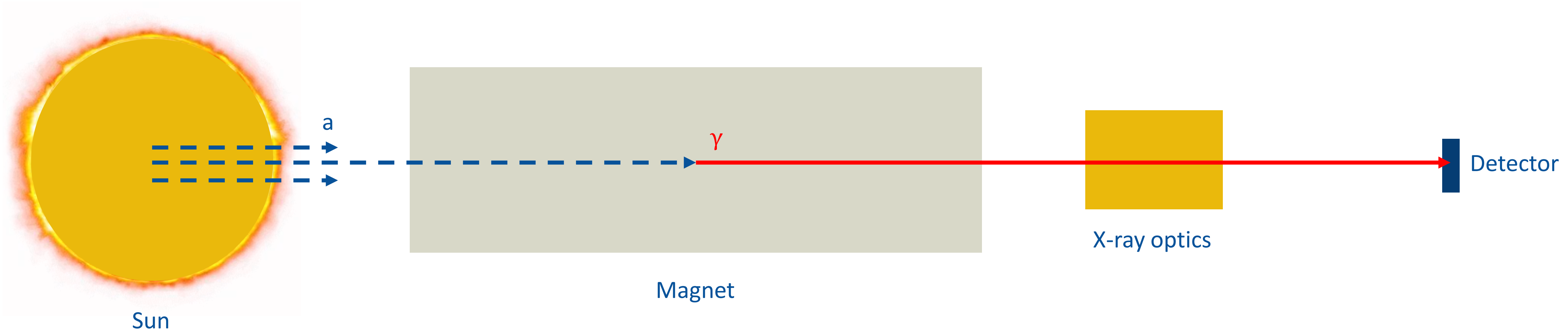


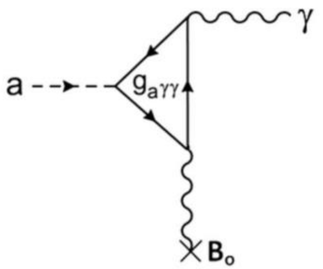
Axion Energy



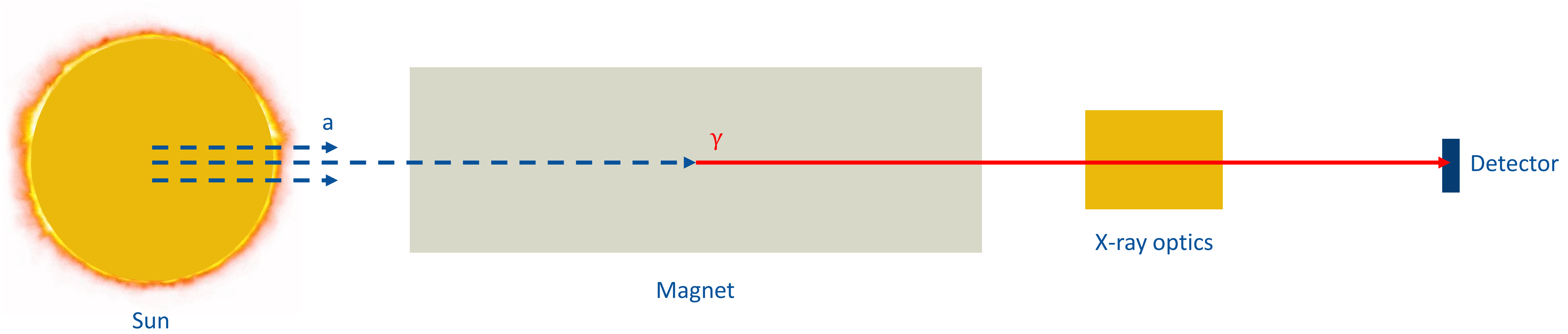
J. Redondo, JCAP 12 (2013) 008

HELIOSCOPE PRINCIPLE



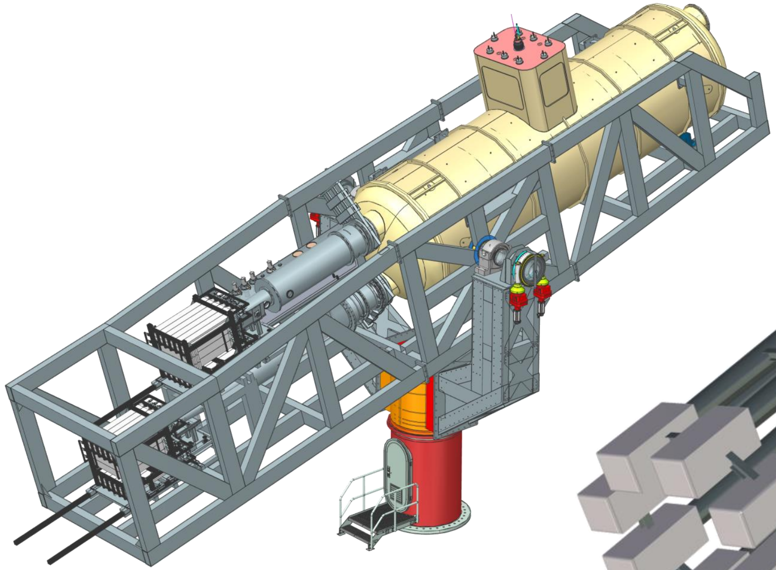


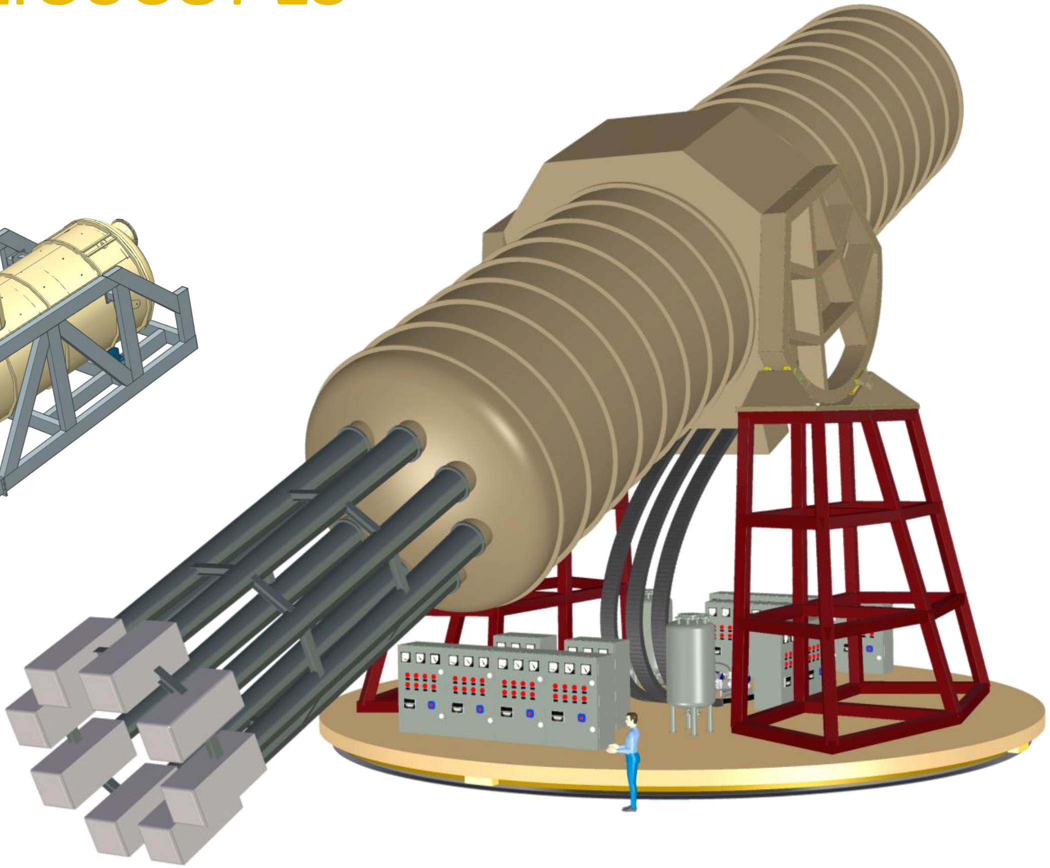
HELIOSCOPE PRINCIPLE



$$FoM \sim B^2 L^2 A \cdot \epsilon_o \alpha^{-1/2} \cdot \epsilon_d \, b^{-1/2} \cdot \epsilon_t^{1/2} t^{1/2}$$

GENERATIONS OF HELIOSCOPES

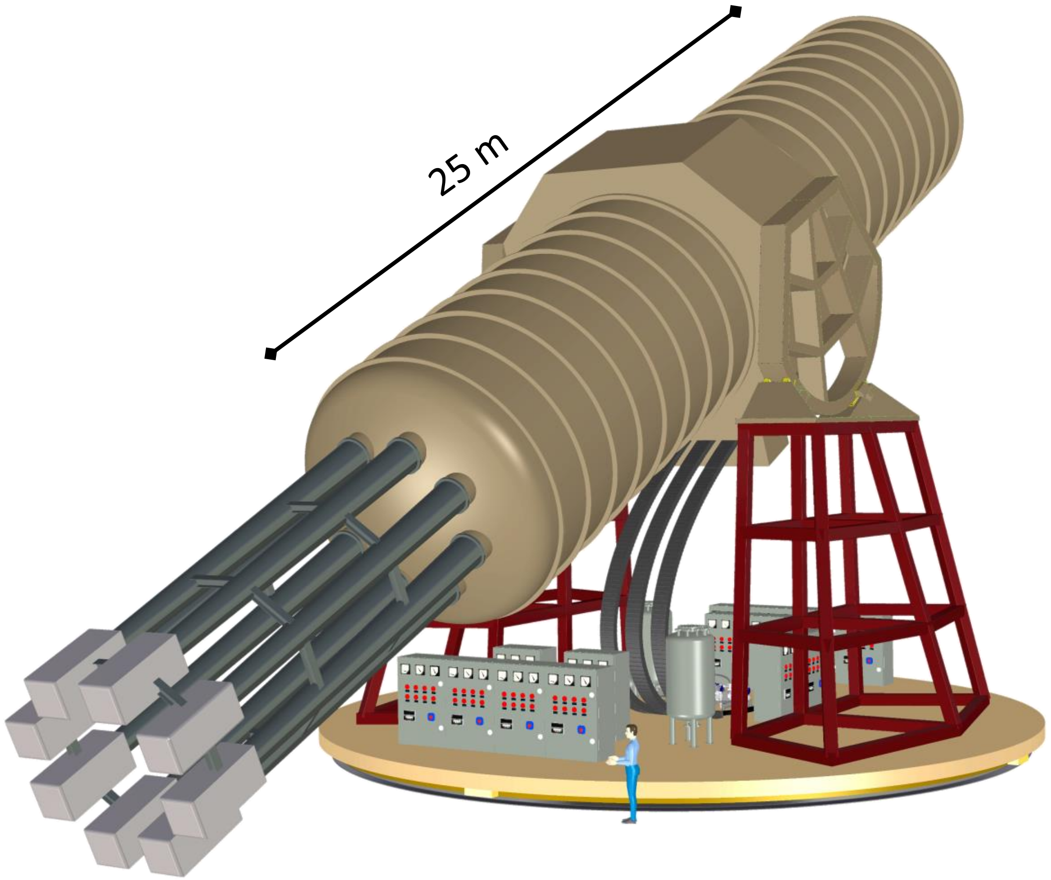




IAXO collaboration 2014, arXiv:1401.3233v1

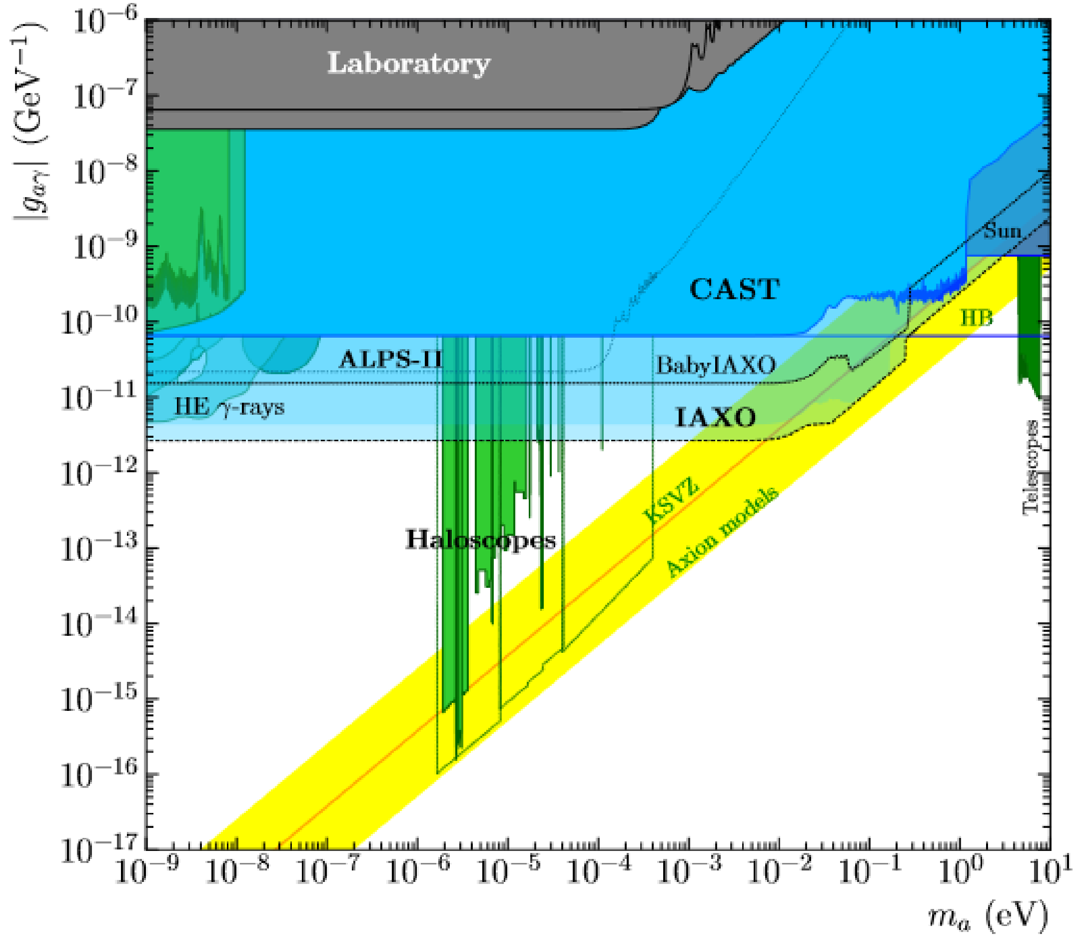
Previous experiments — CAST — BabyIAXO — IAXO

THE INTERNATIONAL AXION OBSERVATORY



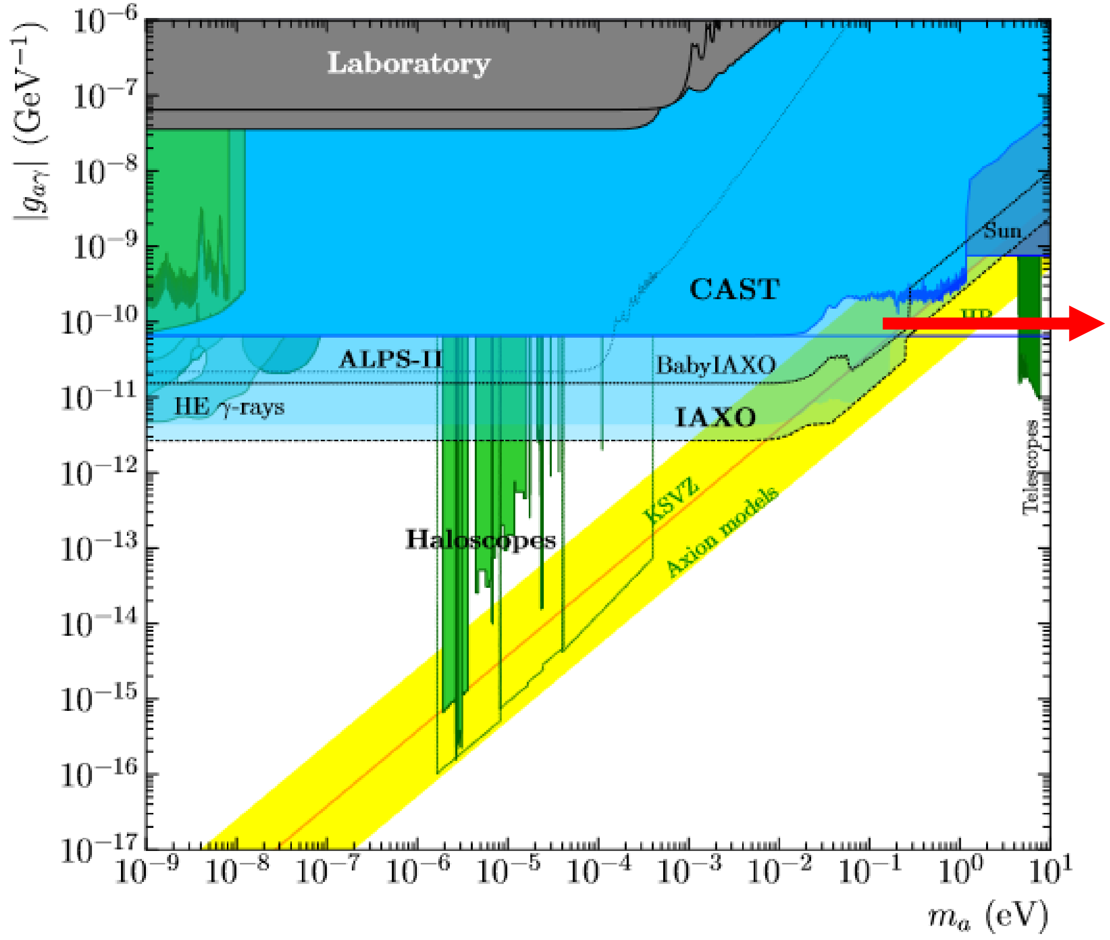
- Proposed to be built at DESY
- 8 magnet bores for optics and detector setups
- 25 m long magnet
- Peak magnetic field of 5.4 T
- 12 h of data taking a day
- Aims for a $FoM \sim$ 10000 times higher than CAST

PHYSICS CASE



IAXO collaboration 2020, arXiv:2010.12076

PHYSICS CASE



IAXO collaboration 2020, arXiv:2010.12076

But first: BabyIAXO

- Prove of concept for IAXO
- Has ist own physics case

BUT FIRST: BABYIAXO

- 2 magnet bores for optics and detector setups
- 10 m long magnet
- Peak magnetic field of 3.2 T
- 12 h of data taking a day
- $FoM \sim$ 100 times higher than CAST

BUT FIRST: BABYIAXO

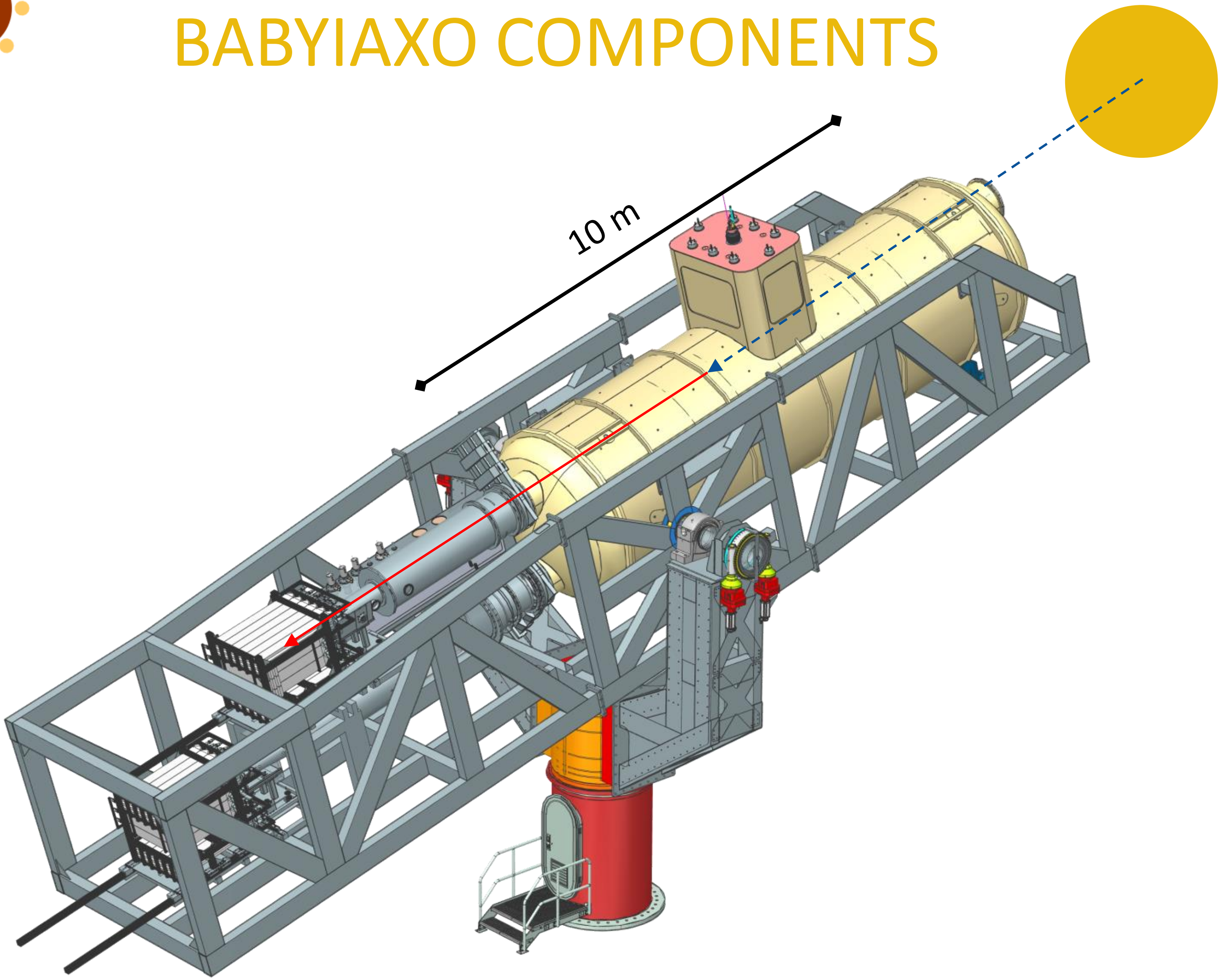
- First parts already in Hera South Hall at DESY
- Construction of components on going/ planned

BUT FIRST: BABYIAXO

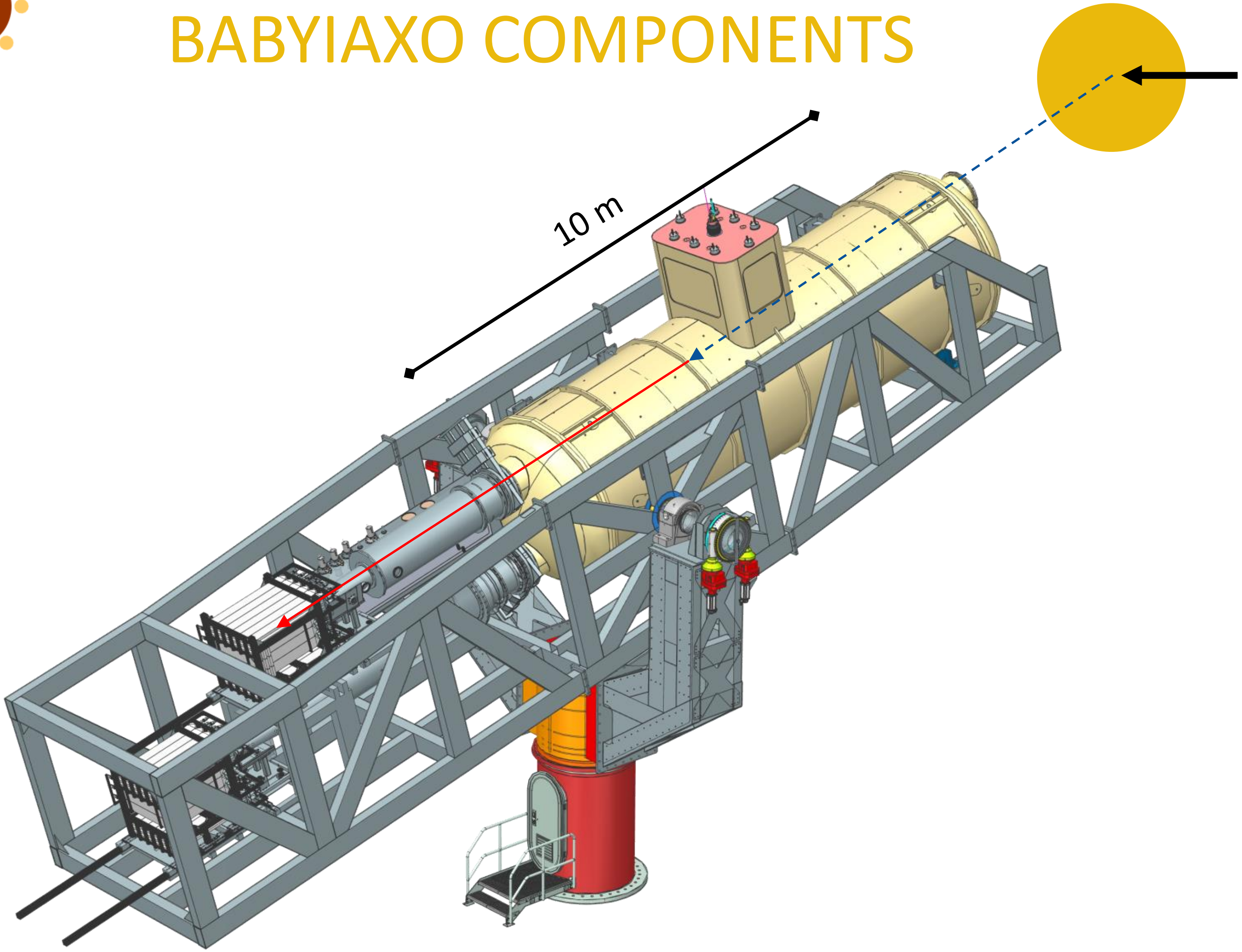
- First parts already in Hera South Hall at DESY
- Construction of components on going/ planned

- Structure & Drive system:
  - ➢ Reuse parts from the CTA/MST prototype

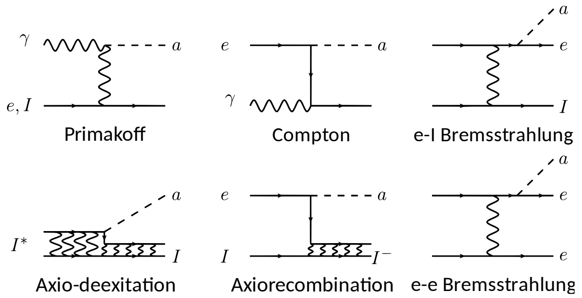
BABYIAXO COMPONENTS



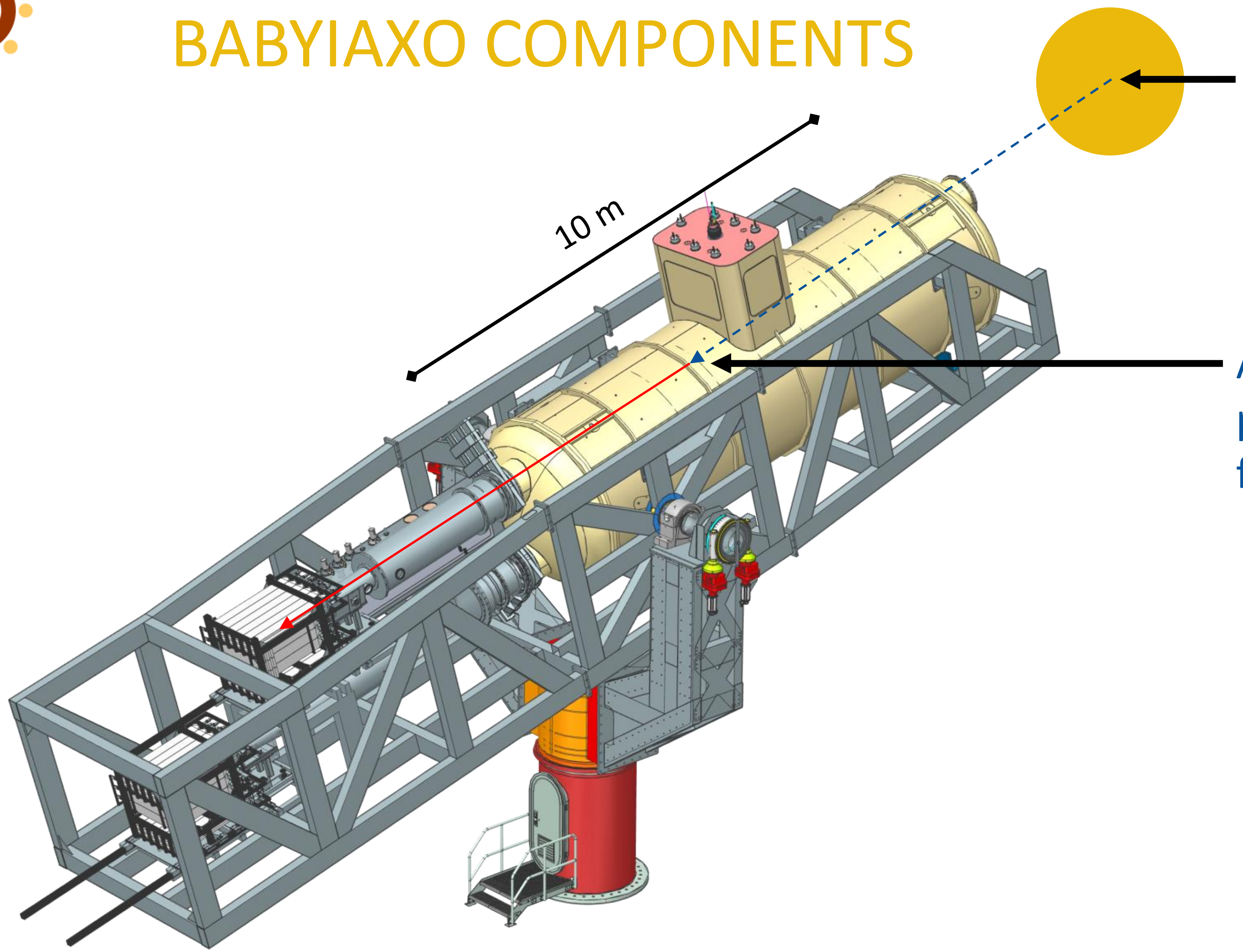
BABYIAXO COMPONENTS



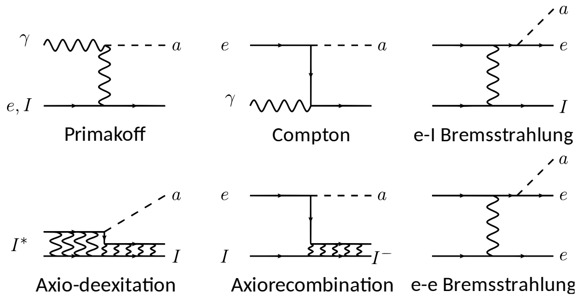
Axion production in the sun



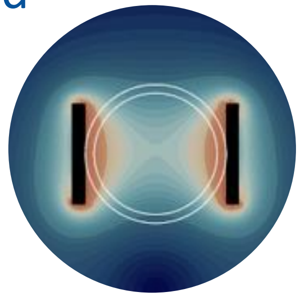
BABYIAXO COMPONENTS



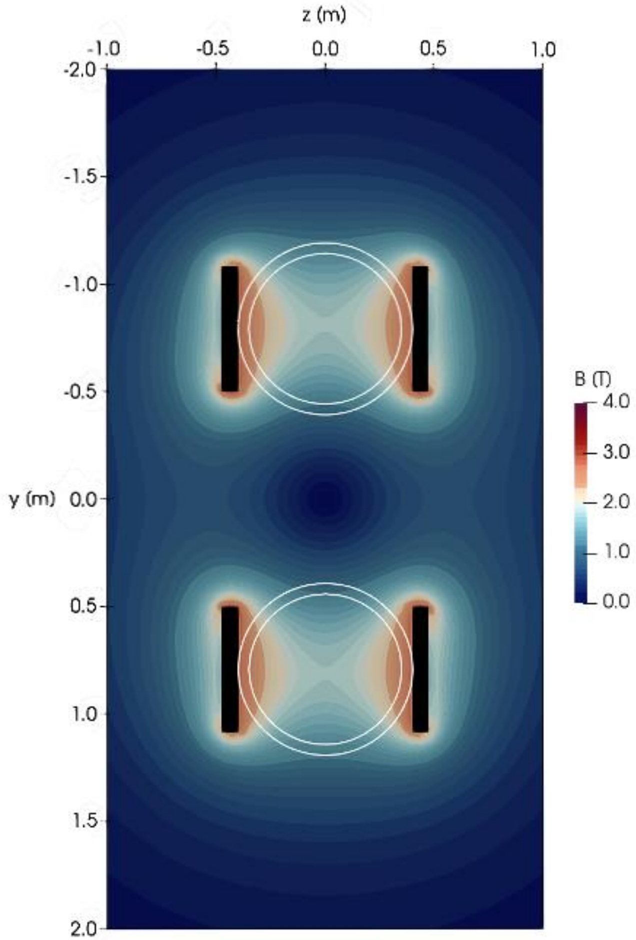
Axion production in the sun

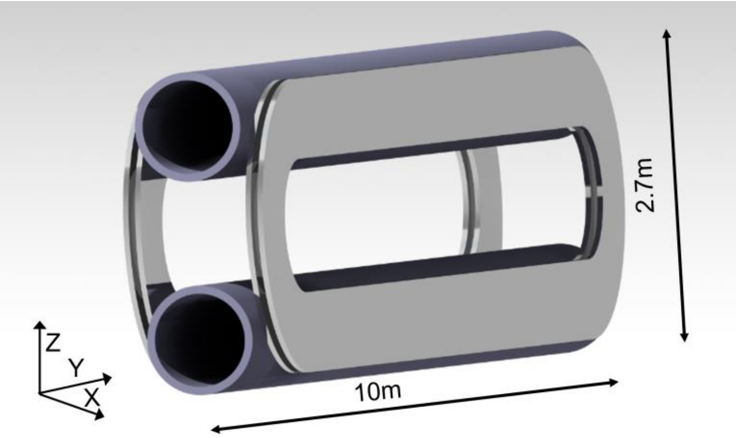


Axions couple to photons in magnetic field

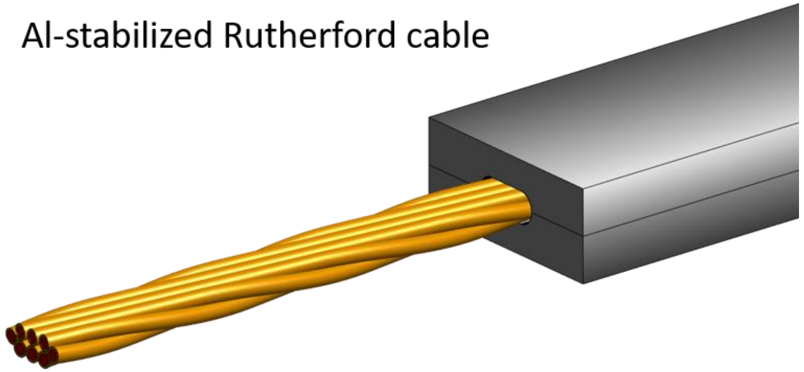


MAGNET





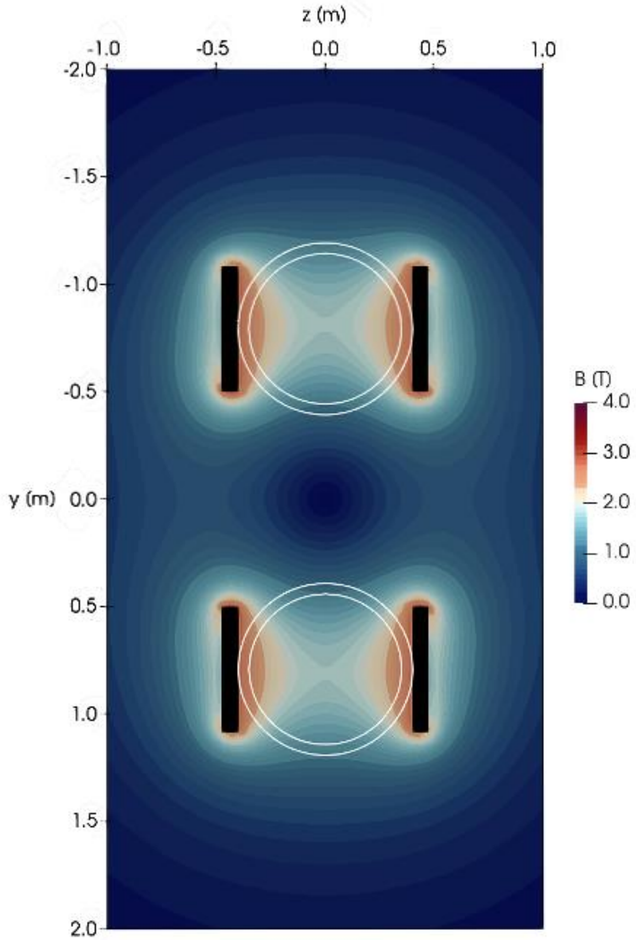
Al-stabilized Rutherford cable

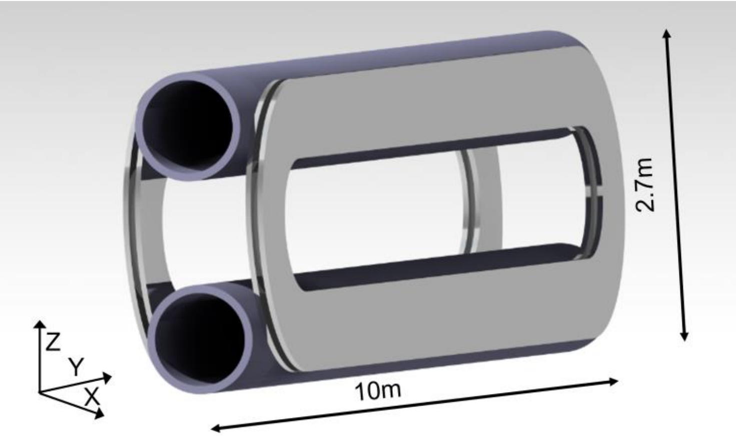


- Cryogenic system designed by CERN and DESY
- Aluminum stabilized Rutherford cable
- Photon production probability:

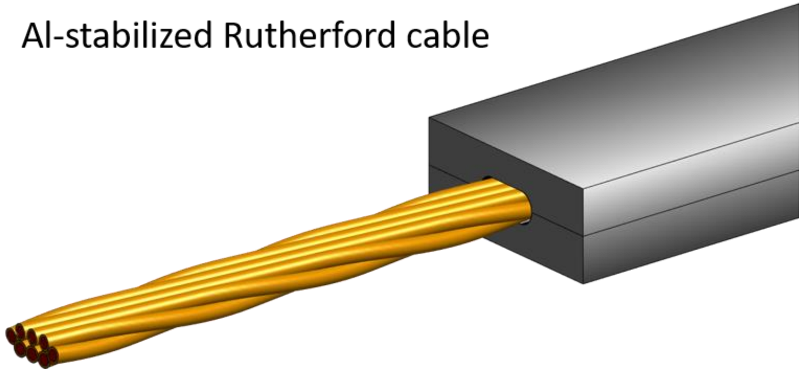
$$P_{a\to\gamma} = \frac{1}{4}(g_{a\gamma}BL)^2$$

MAGNET





Al-stabilized Rutherford cable



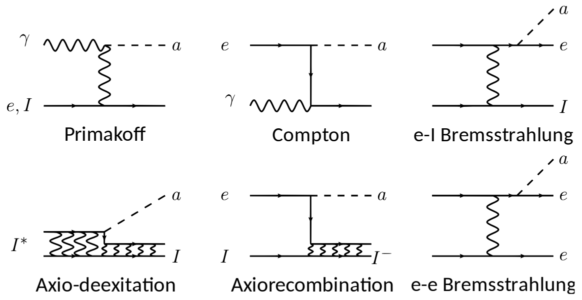
- Cryogenic system designed by CERN and DESY
- Aluminum stabilized Rutherford cable
- Photon production probability:

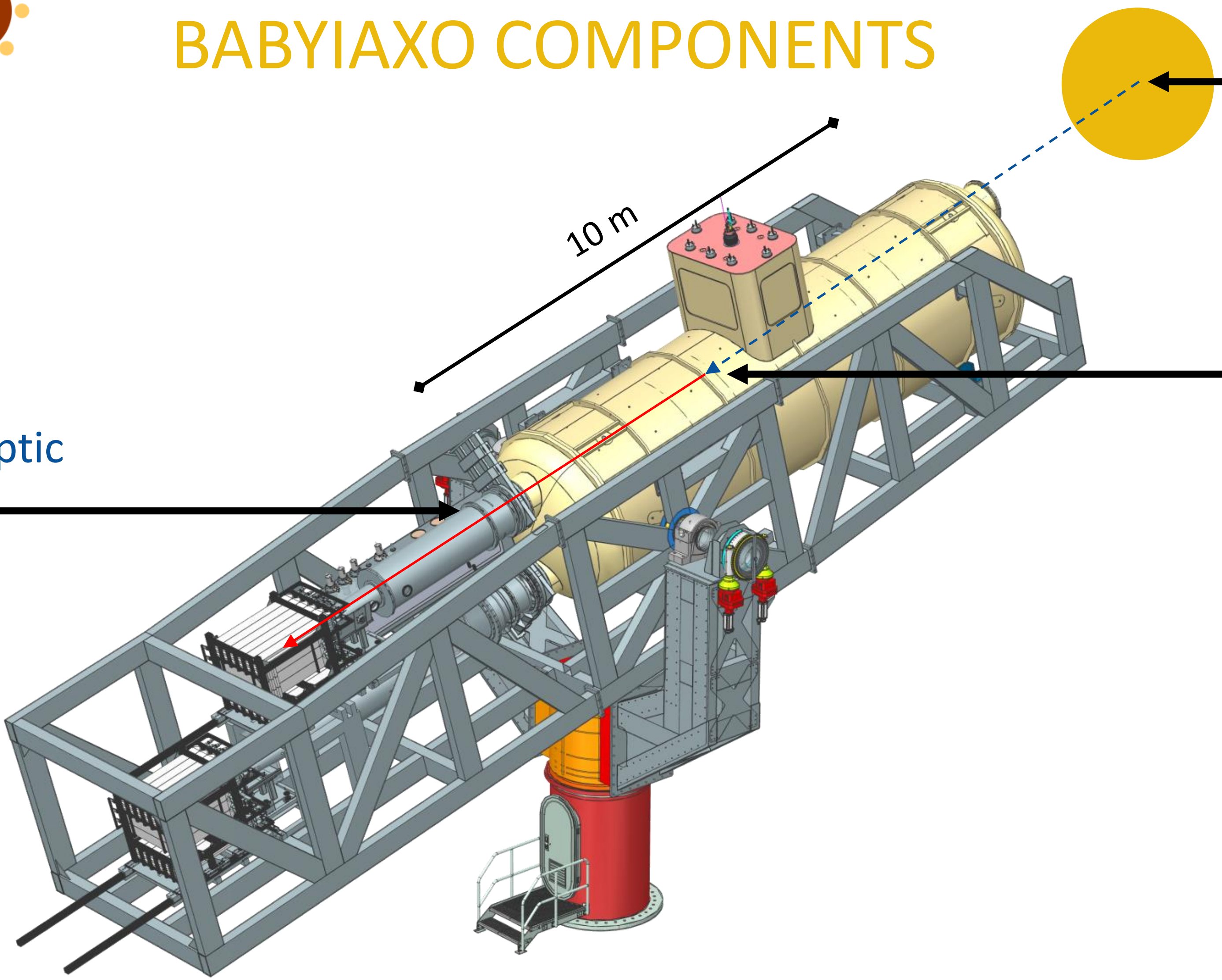
$$P_{a\to\gamma} = \frac{1}{4}(g_{a\gamma}BL)^2$$

Status: Cable parts are being tested

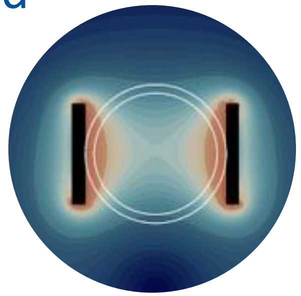
BABYIAXO COMPONENTS

Axion production in the sun

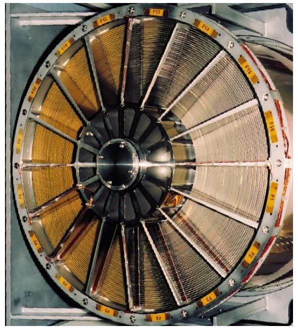




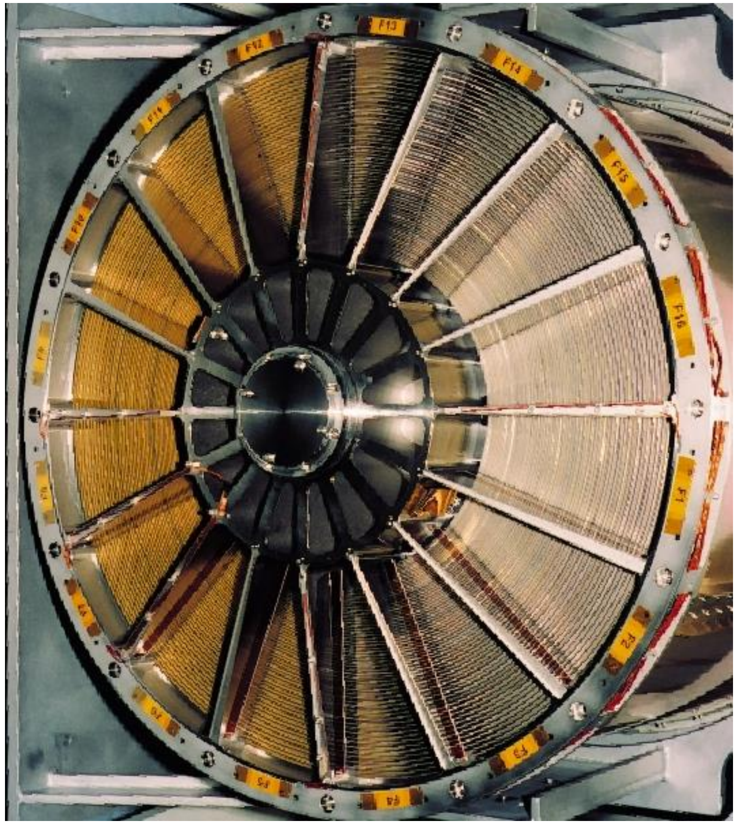
Axions couple to photons in magnetic field



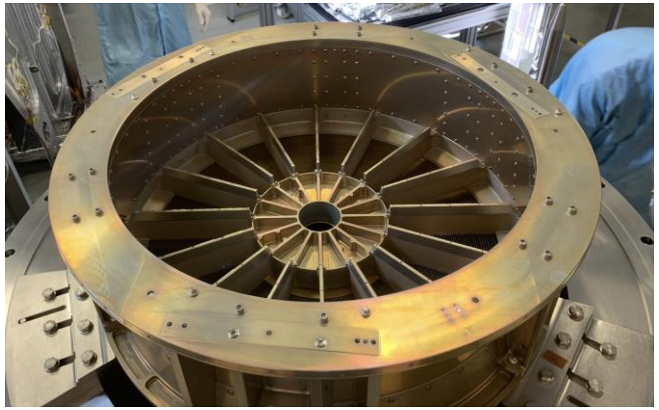
Focus of X-rays in optic



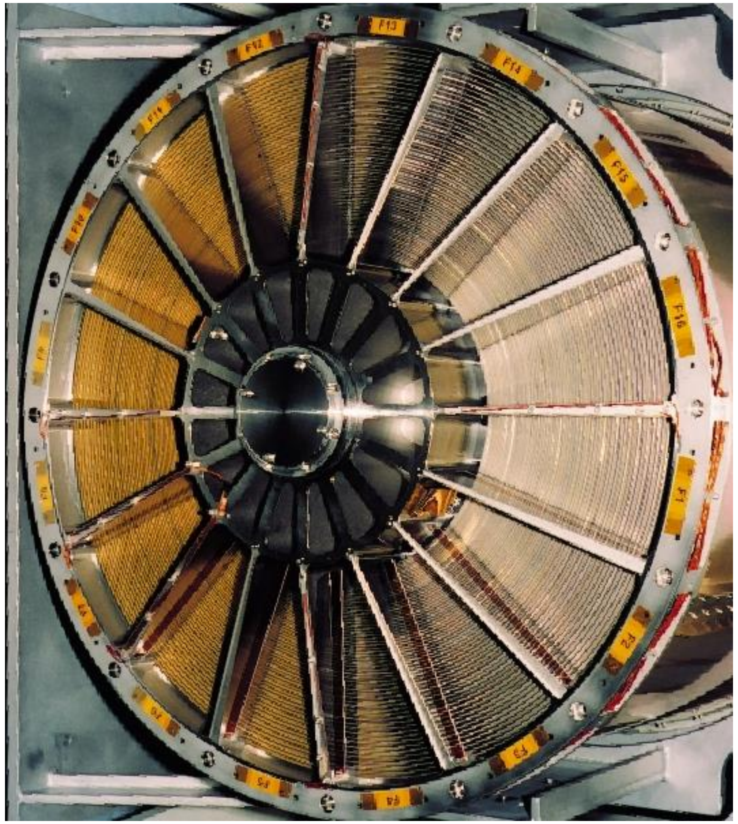
X-RAY OPTICS: XMM NEWTON



- XMM optics built for the XMM-Newton space mission (1999)
- Flight Module 5 will be loaned by ESA
- Wolter I X-ray optics from gold-coated nickel shells

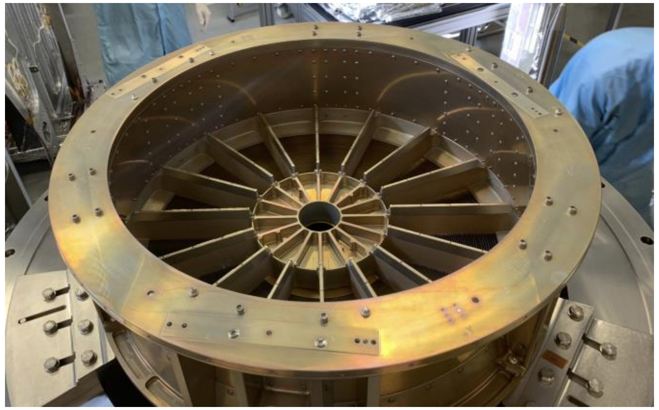


X-RAY OPTICS: XMM NEWTON

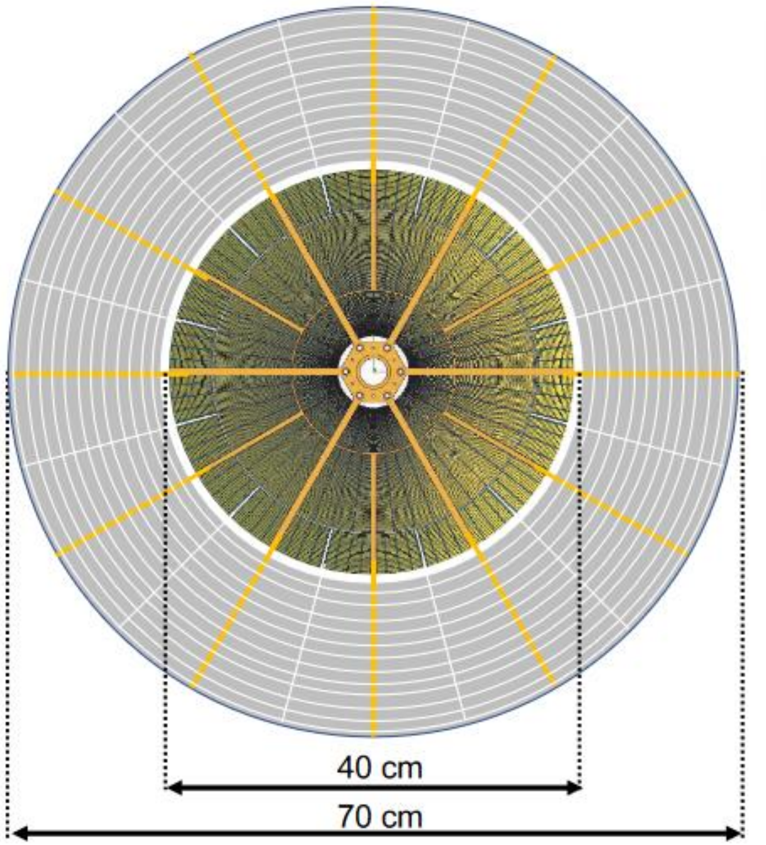


- XMM optics built for the XMM-Newton space mission (1999)
- Flight Module 5 will be loaned by ESA
- Wolter I X-ray optics from gold-coated nickel shells

Status: has been unpacked after 20 years and is ready to be tested at PANTER

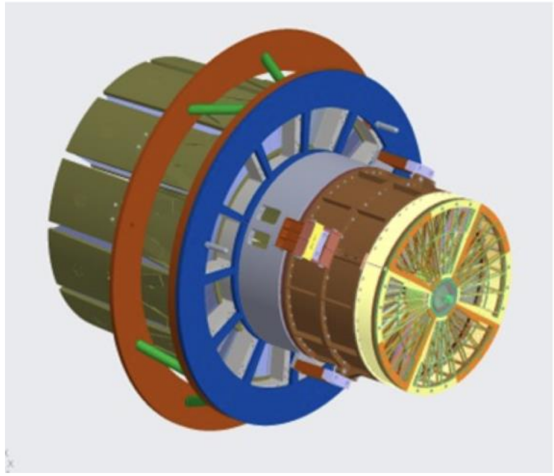


X-RAY OPTICS: CUSTOM OPTICS

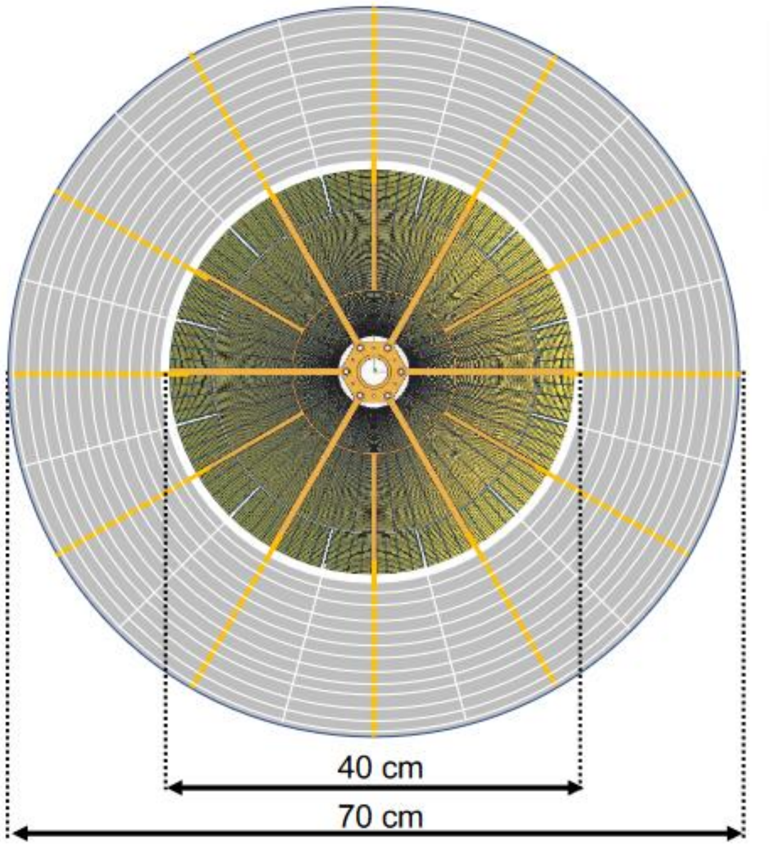


IAXO collaboration 2020, arXiv:2010.12076

- Custom BabyIAXO optics consisting of an inner optics and outer optics
- Inner: NuSTAR-like optics from thermally formed glass
- Outer: Wolter 1 optics from cold-slumped Willow glass



X-RAY OPTICS: CUSTOM OPTICS



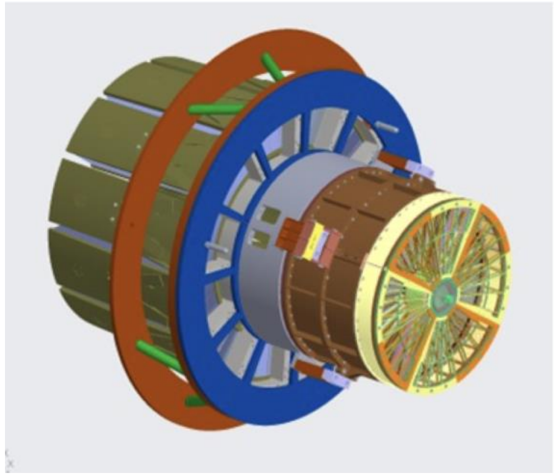
IAXO collaboration 2020, arXiv:2010.12076

- Custom BabyIAXO optics consisting of an inner optics and outer optics
- Inner: NuSTAR-like optics from thermally formed glass

Status: Glass inventory is being tested

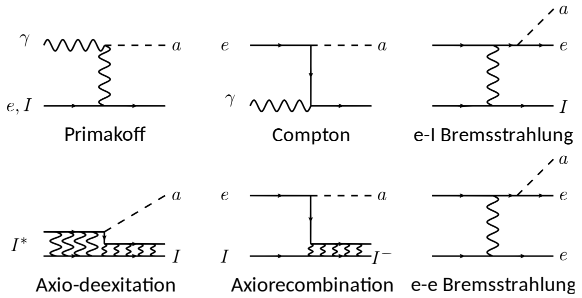
- Outer: Wolter 1 optics from cold-slumped Willow glass

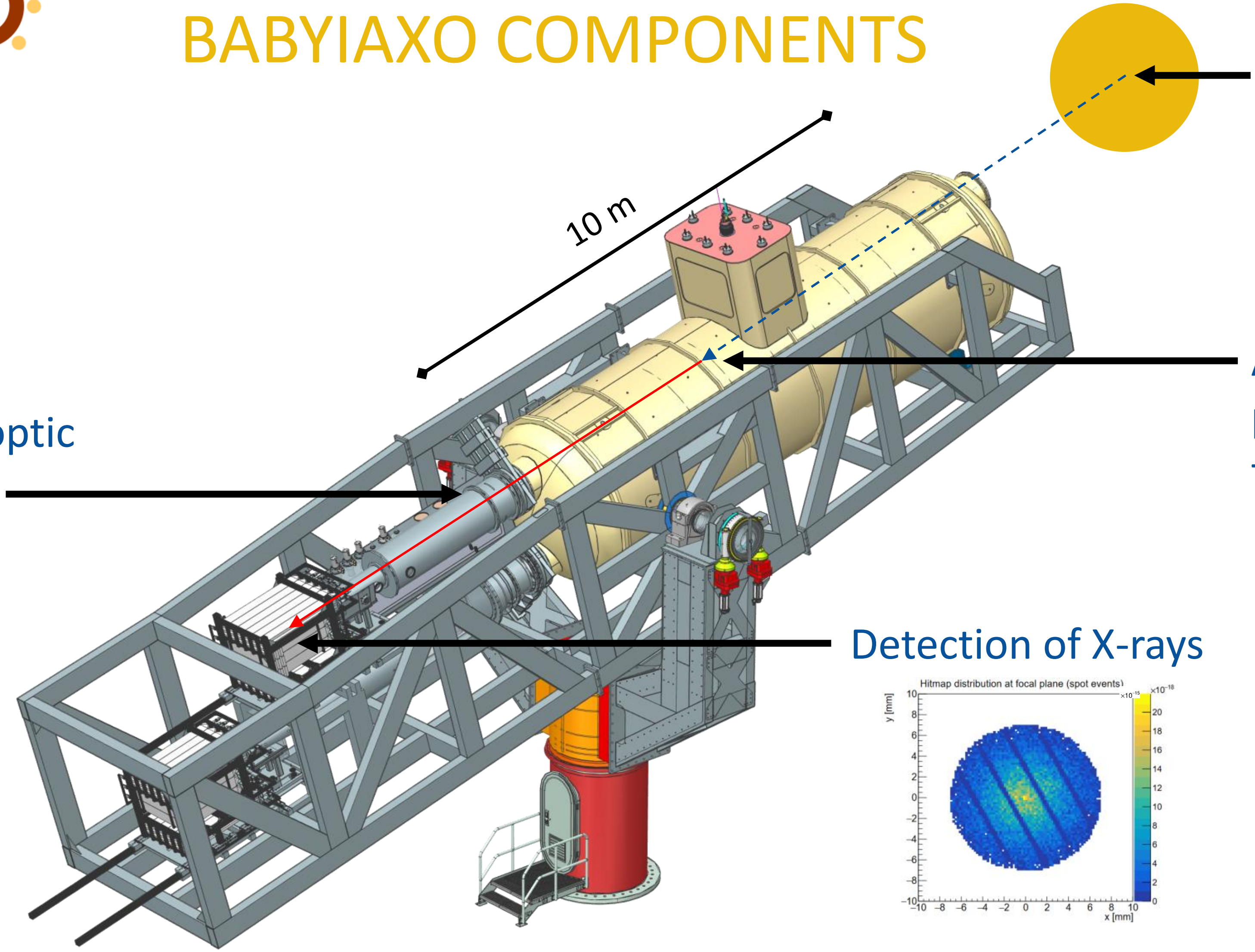
Status: 2nd prototype is going to be built soon



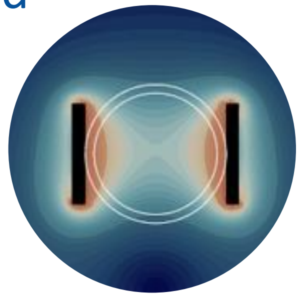
BABYIAXO COMPONENTS

Axion production in the sun

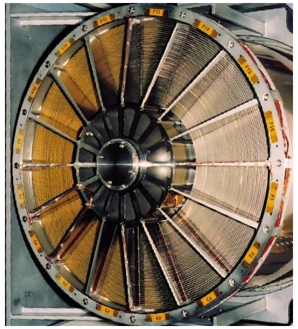




Axions couple to photons in magnetic field



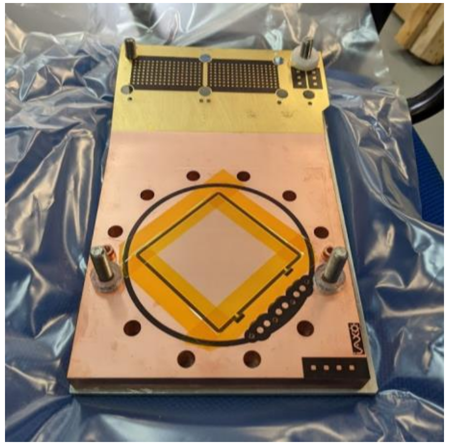
Focus of X-rays in optic



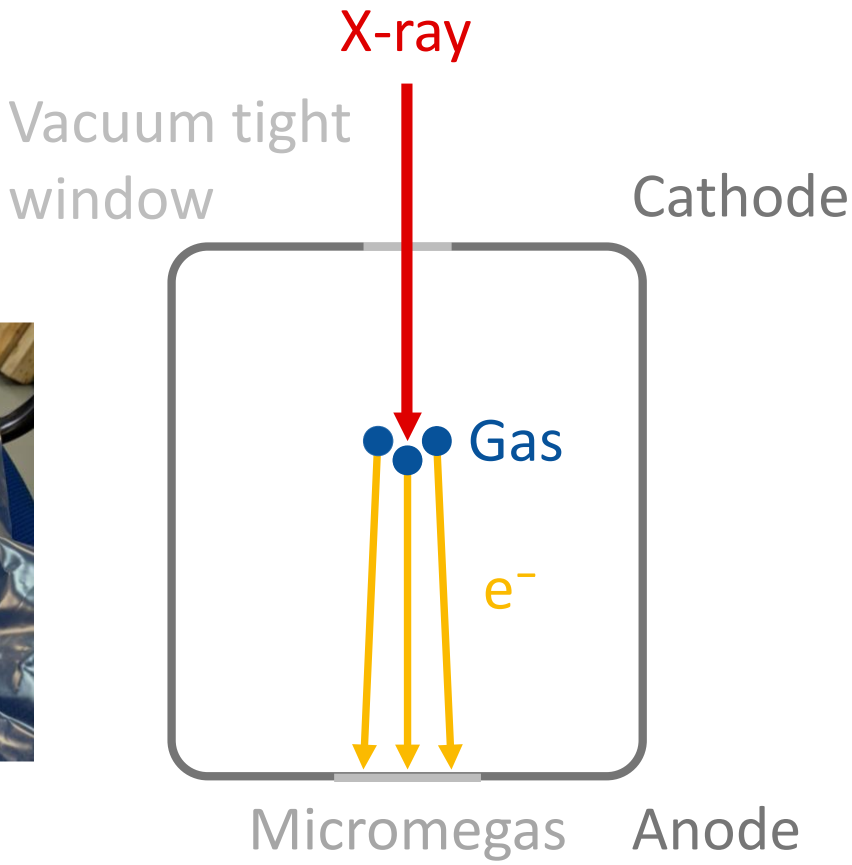
Detection of X-rays

MICROMEGAS DETECTOR AND MUON SHIELDING

- Detector requirements:
  - Sensitive to 1 – 10 keV X-rays
  - Ultra-low background < 10^{-7} counts keV^{-1} cm^{-2} s^{-1}



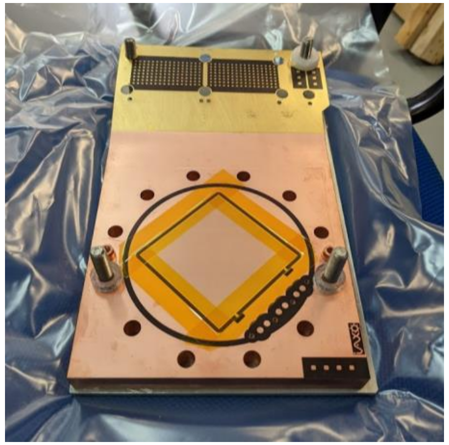
Micromegas (U. Zaragoza & CEA Saclay)



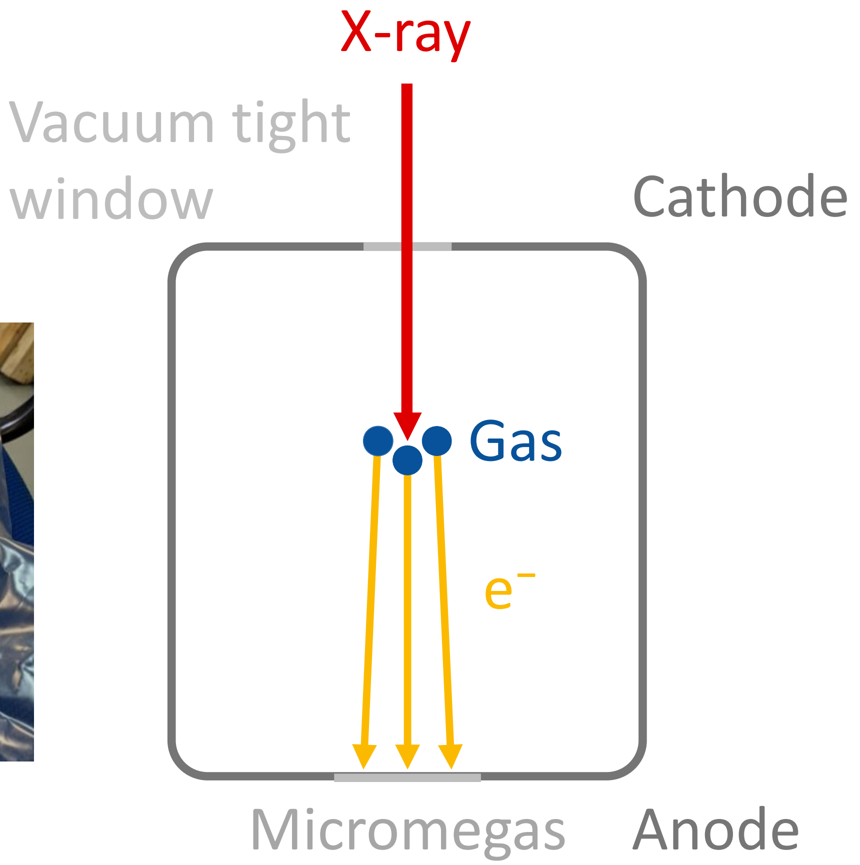
MICROMEGAS DETECTOR AND MUON SHIELDING

- Detector requirements:
  - Sensitive to 1 – 10 keV X-rays
  - Ultra-low background < 10^{-7} counts keV^{-1} cm^{-2} s^{-1}

Status: Getting close to desired background in underground lab

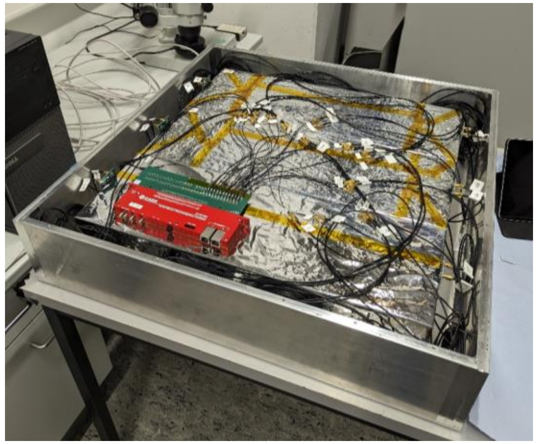


Micromegas (U. Zaragoza & CEA Saclay)

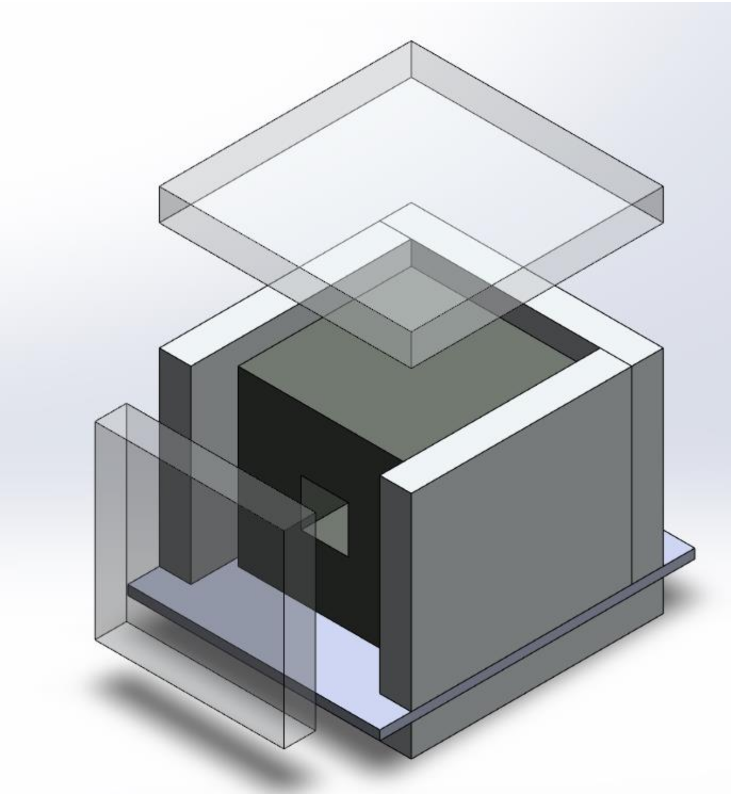


MICROMEGAS DETECTOR AND MUON SHIELDING

- Detector requirements:
  - Sensitive to 1 – 10 keV X-rays
  - Ultra-low background < 10^{-7} counts keV^{-1} cm^{-2} s^{-1}
- Additionally: cosmic background suppression necessary

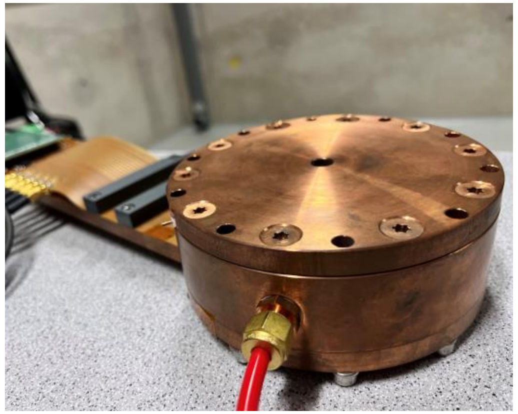


Muon veto (U. Mainz)

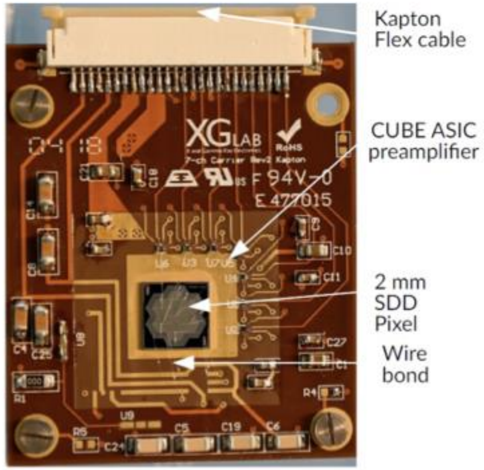


OTHER DETECTORS

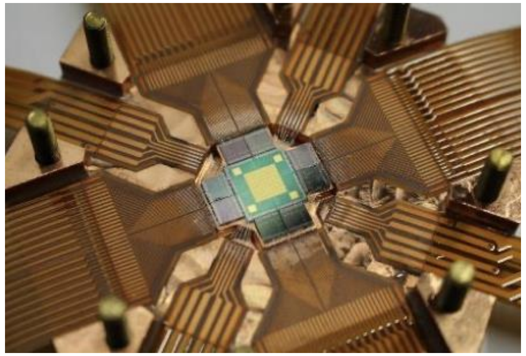
- Similar requirements
- Different advantages: Sensitive to very low or high energies, high efficiency, high energy resolution



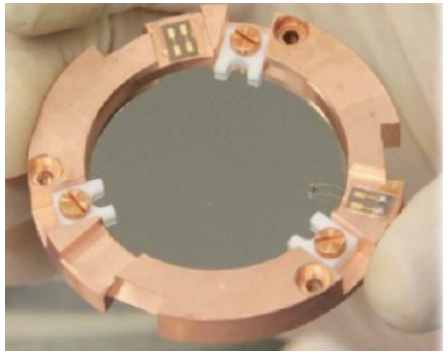
GridPix detector (Uni Bonn)



SDD: Silicon Drift Detector (TUM)



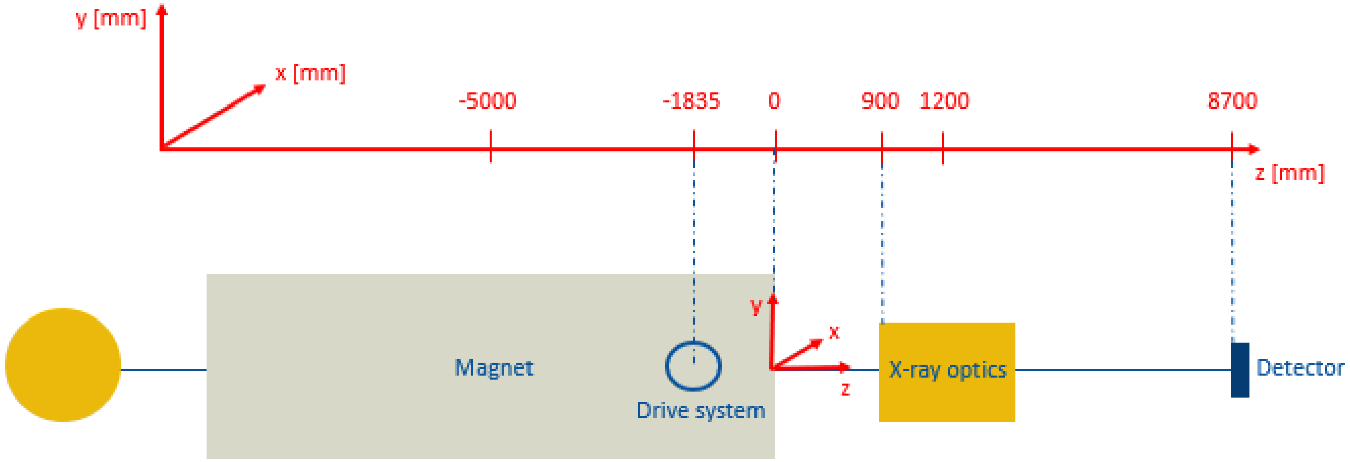
MMC: Metallic Magnetic Calorimeters (U. Heidelberg)

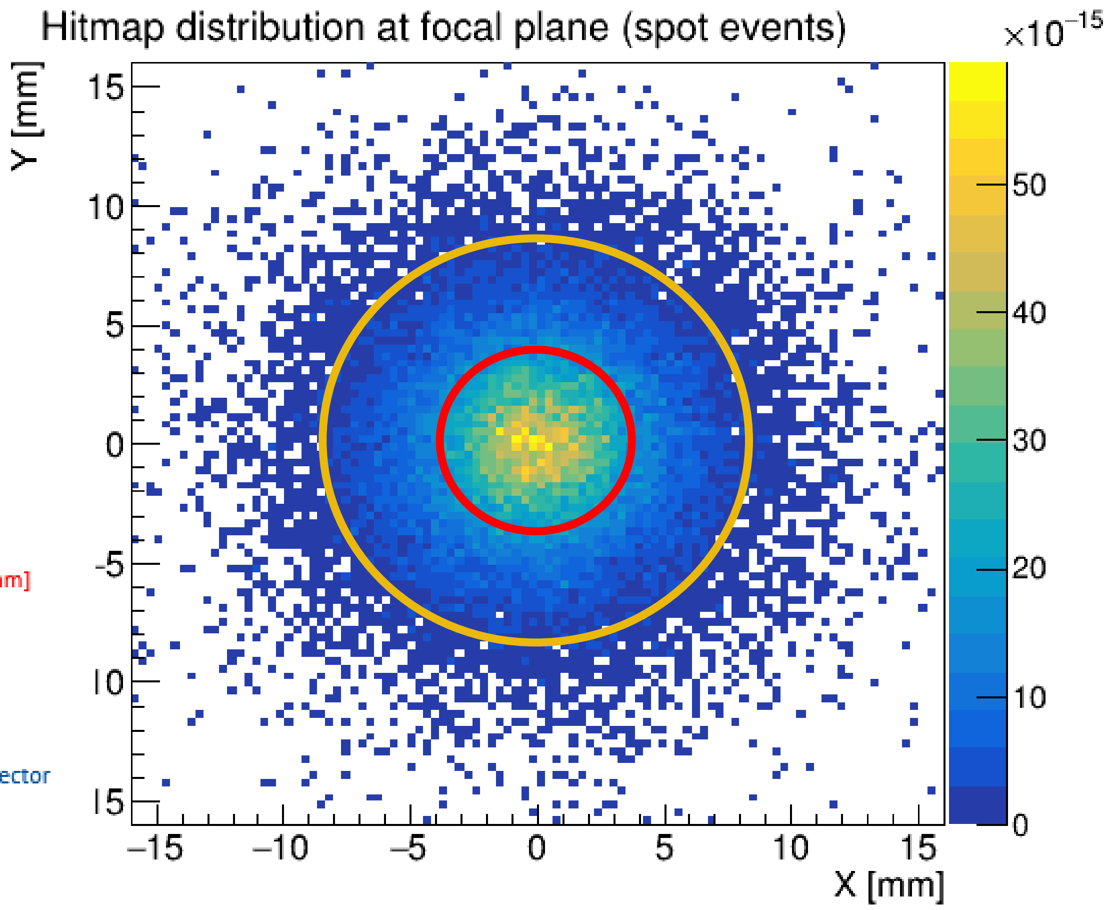


TES: Transition Edge Sensors (INMA-ICMAB CSIC)

SIMULATIONS

- Ray tracing including all components
- Simulation of gravitational effects
- Background simulations



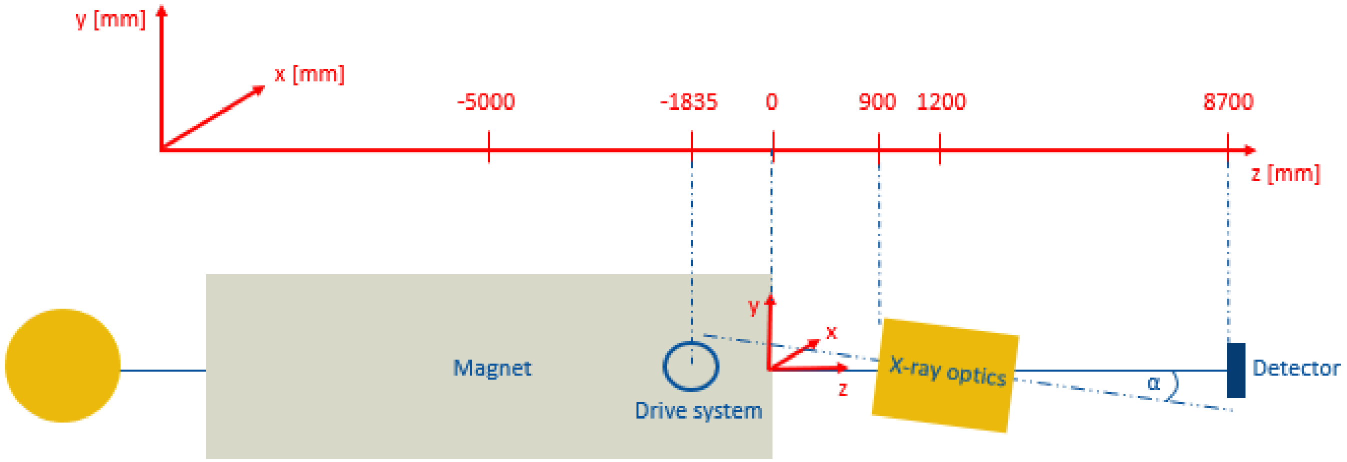


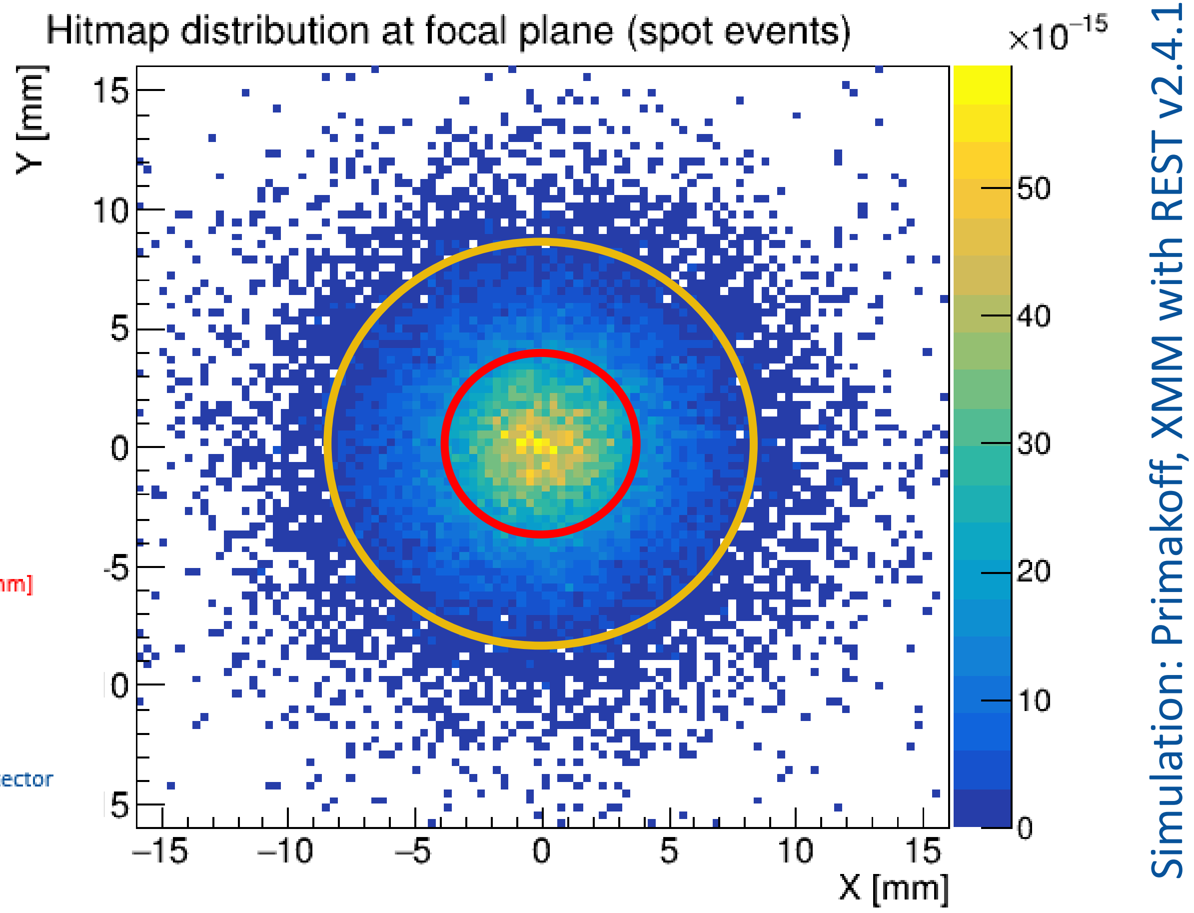
HEW=7.83mm W90=16.83mm

Simulation: Primakoff, XMM with REST v2.4.1

SIMULATIONS

- Ray tracing including all components
- Simulation of gravitational effects
- Background simulations

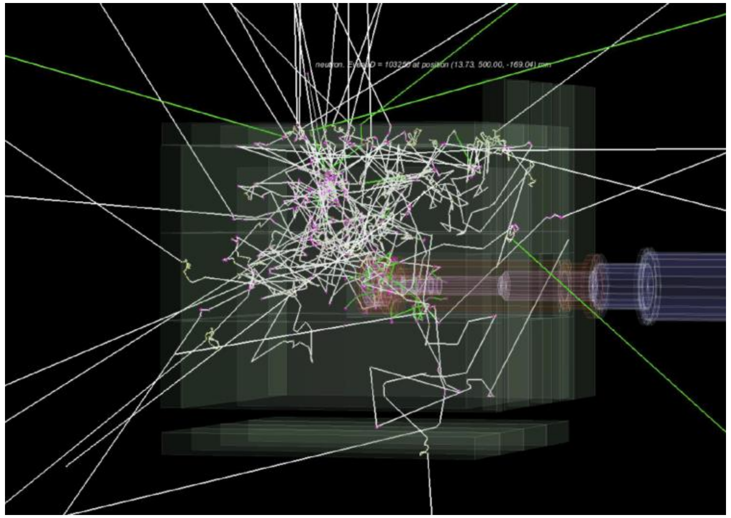




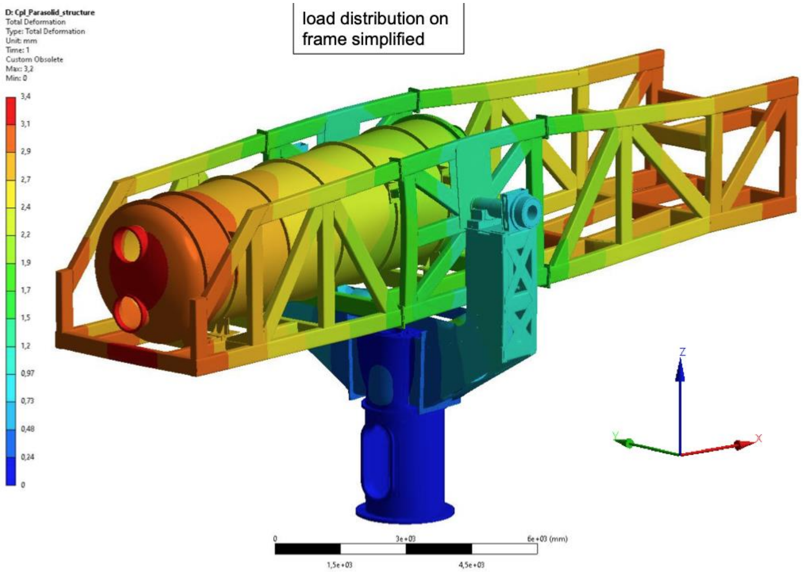
HEW=7.83mm W90=16.83mm

SIMULATIONS

- Ray tracing including all components
- Simulation of gravitational effects
- Background simulations

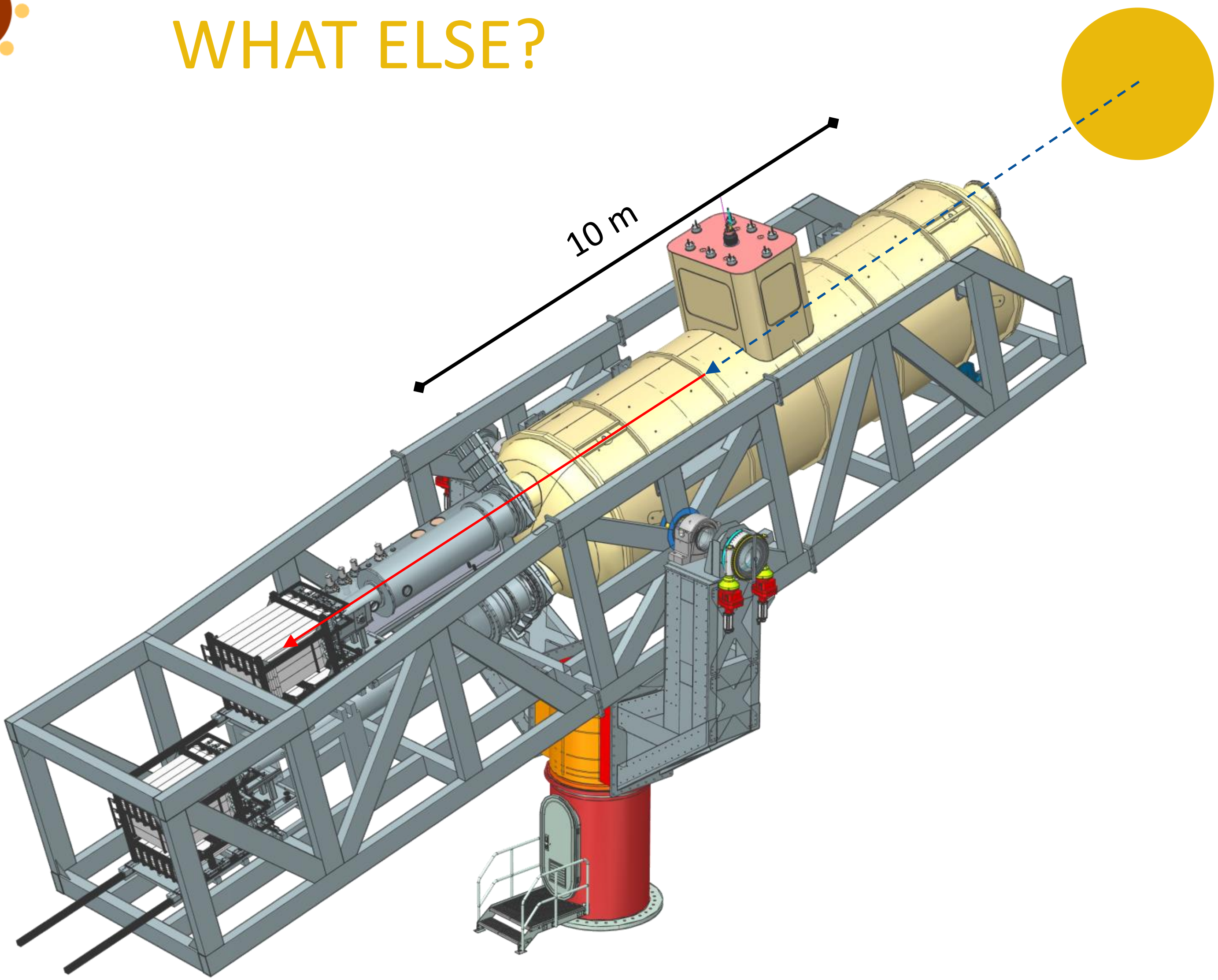


Cosmic neutron simulations



Gravitational effects

WHAT ELSE?



MAGNET – GAS STAGE

- For axions with $m_a > 20$ meV the photon production probability becomes:

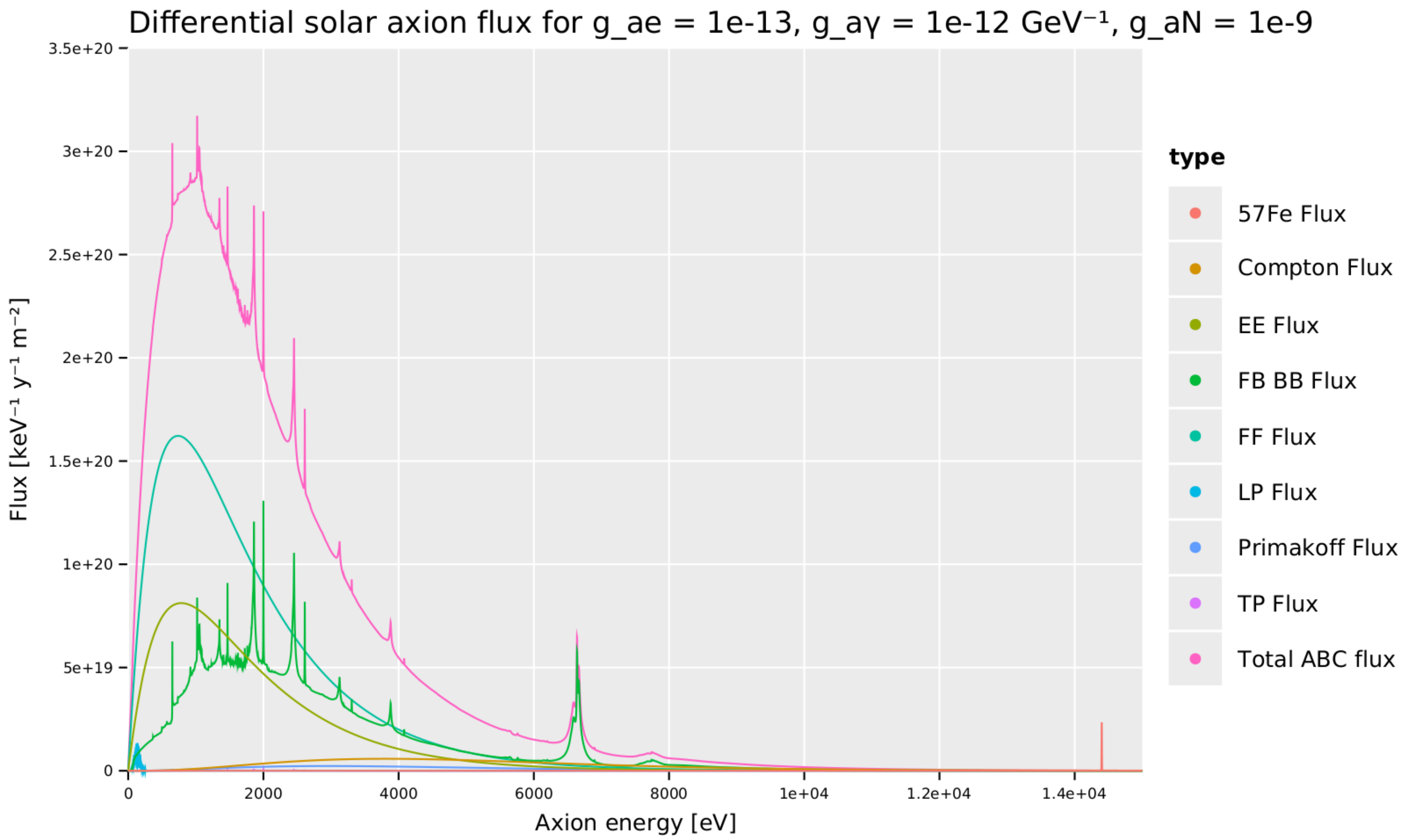
$$P_{a\to\gamma} = \frac{1}{4}(g_{a\gamma}BL)^2 \times \frac{2(1-\cos(qL))}{(qL)^2}$$

- With the momentum exchange:

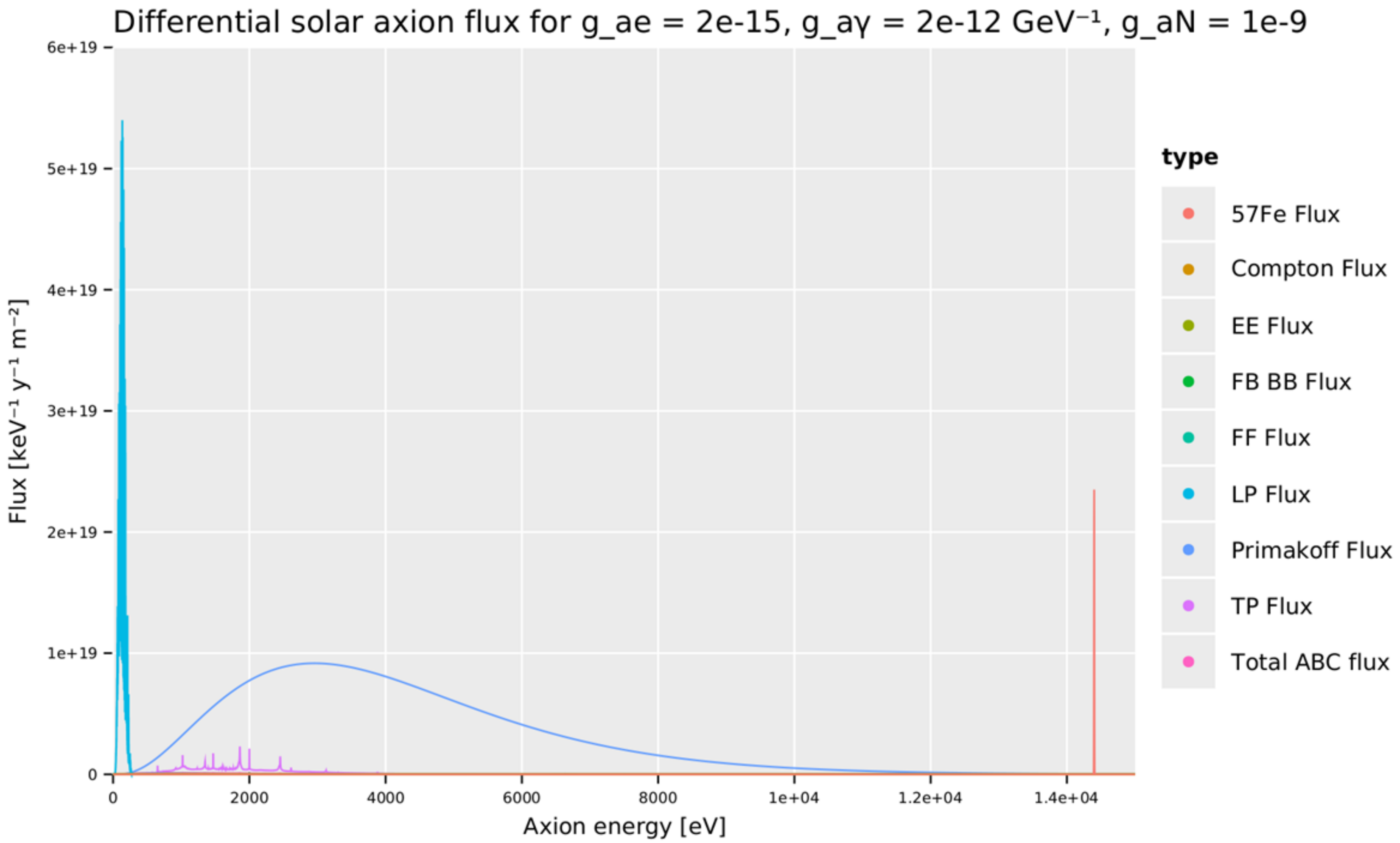
$$q = \frac{m_\gamma^2 - m_a^2}{2\omega} \quad \text{with} \quad m_\gamma = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \quad \text{for helium}$$

- Introducing a buffer gas to restore coherence of fields but also increasing X-ray absorption

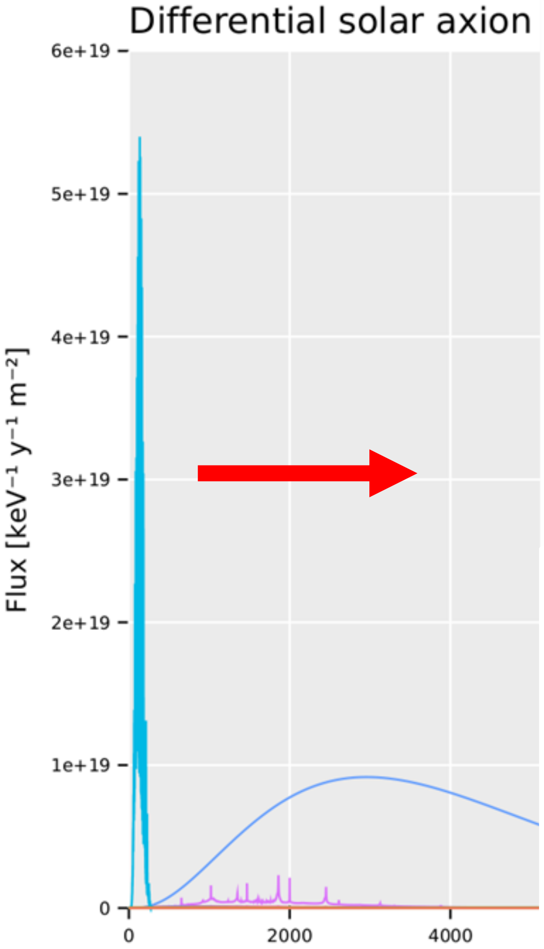
DFSZ SOLAR AXIONS WITH OTHER EFFECTS

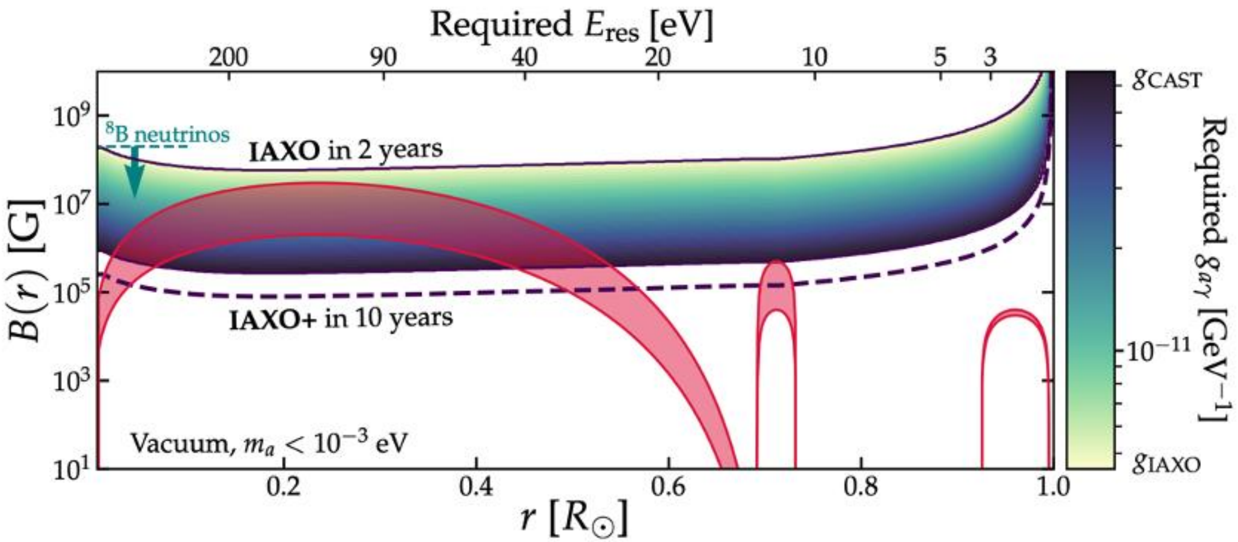


KSVZ SOLAR AXIONS WITH OTHER EFFECTS



KSVZ SOLAR AXIONS WITH OTHER EFFECTS



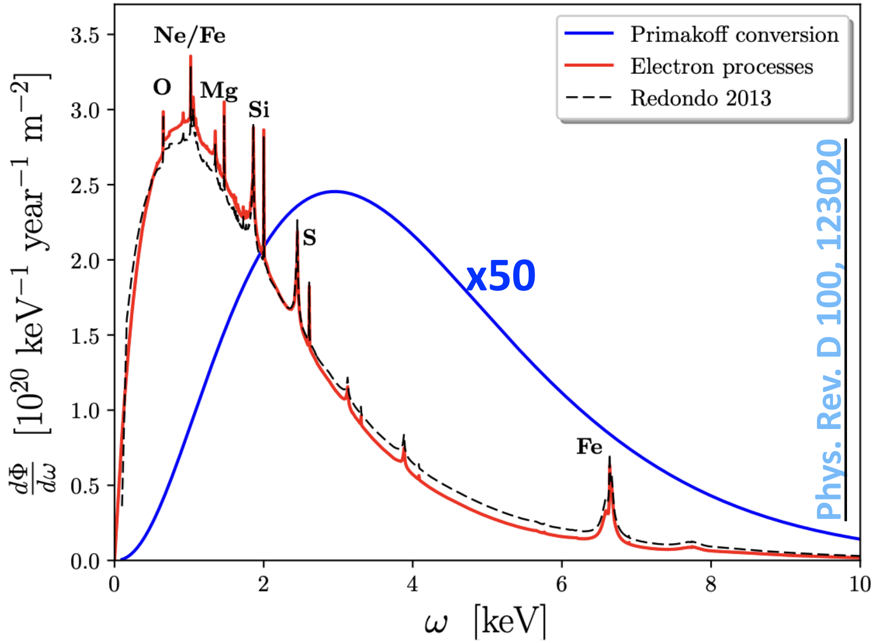


Turn helioscopes into solar magnetometers post discovery

Phys. Rev. D 100, 123020

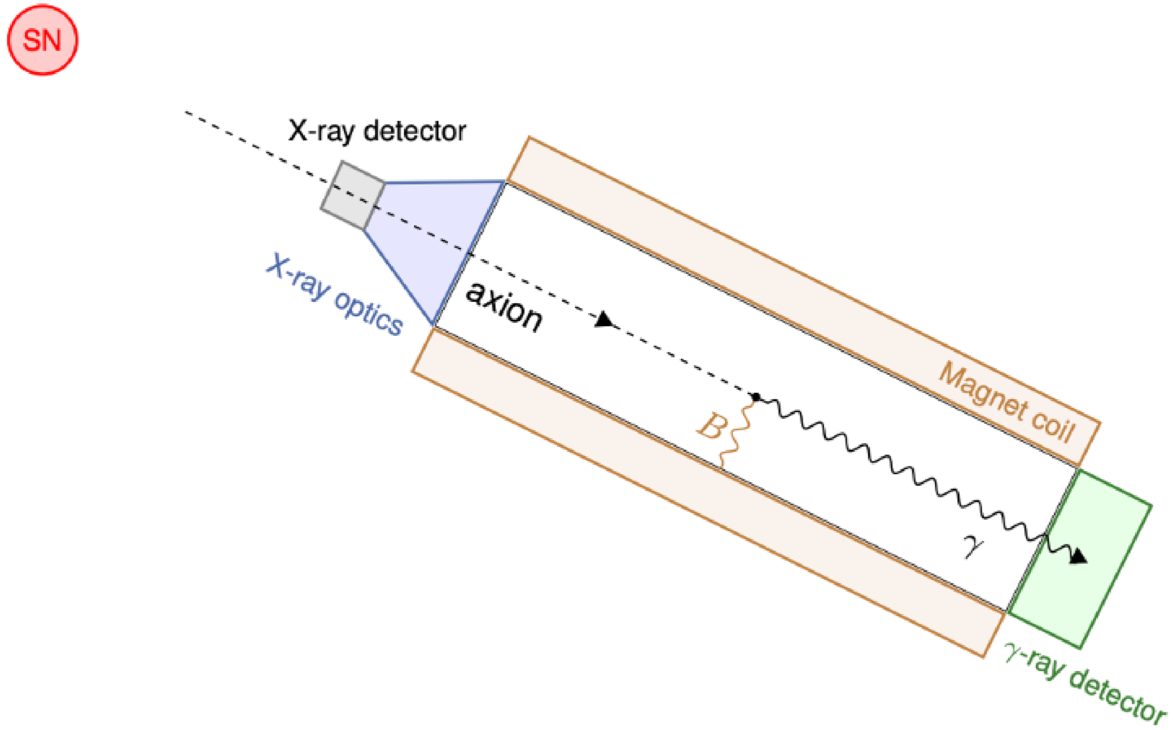
POST DISCOVERY

- Turn helioscopes into solar magnetometers Phys. Rev. D 102, 043019
- Measure solar metalicity with the ABC flux Phys. Rev. D 100, 123020
- Turn helioscopes into solar thermometers arXiv:2306.00077



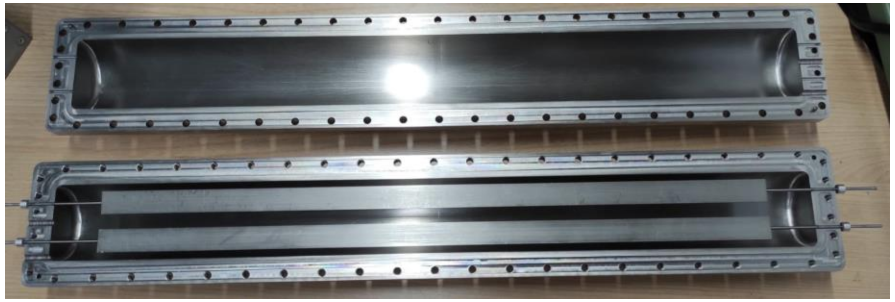
OTHER AXION SOURCES

- Measure supernova axions from an exploding galactic SN arXiv:2008.03924
- Use a He-γ detector that coveres the whole magent bore

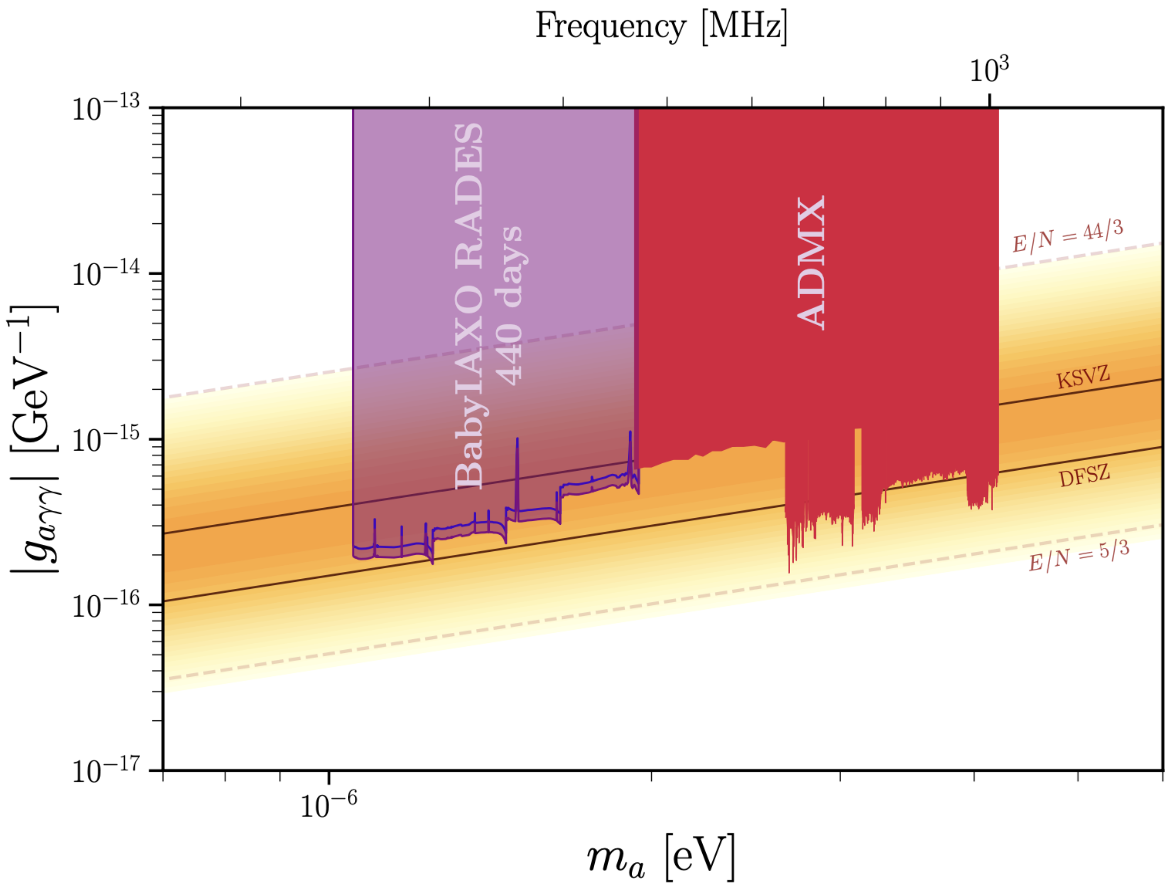


OTHER AXION SOURCES - RADES

- Reuse magnet by integrating resonant cavities
- BabyIAXO magnet bore dimension suitable for 4x 5m cavities



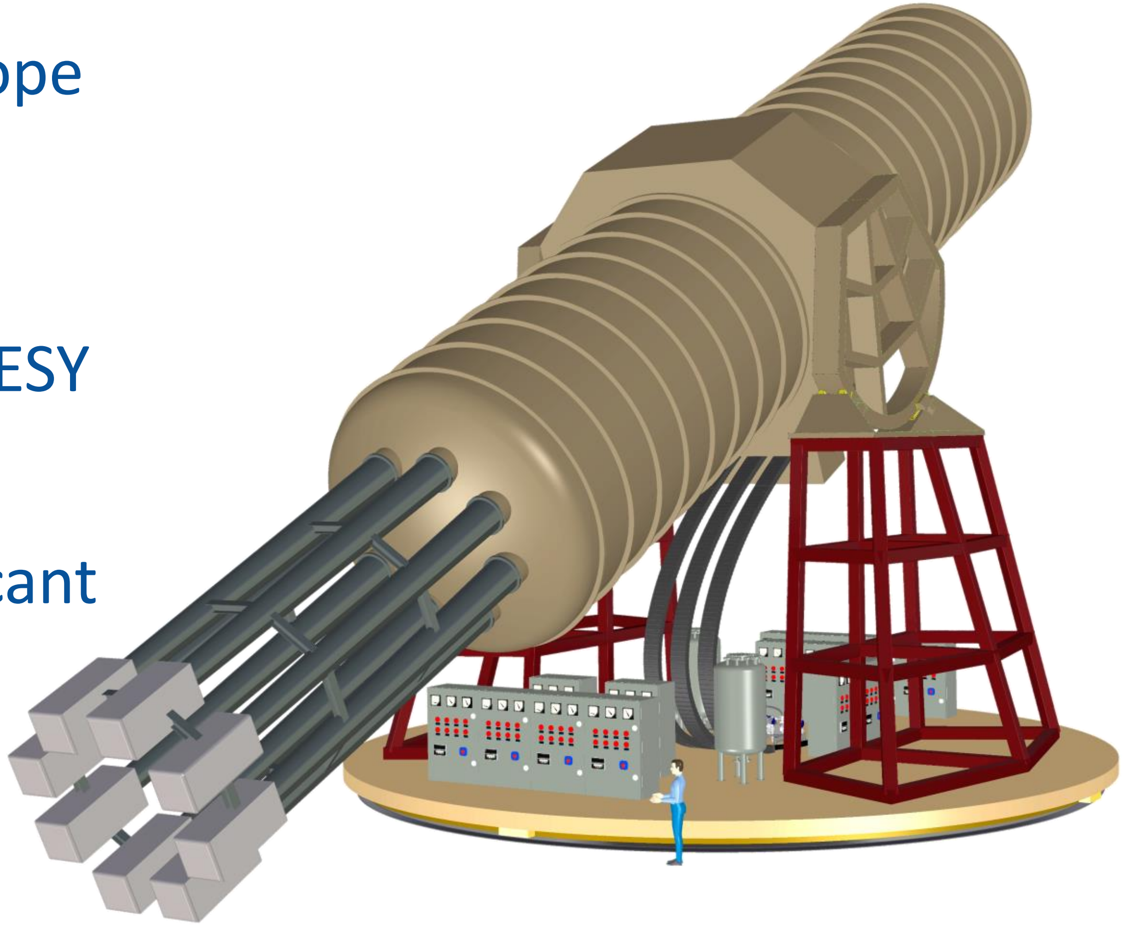
RADES-BabyIAXO Prototype



arXiv:2306.17243

CONCLUSIONS

- IAXO will be a next generation helioscope with its intermediate stage BabyIAXO
- BabyIAXO‘s components are in development and Hera South hall at DESY is being prepared
- BabyIAXO will be able to scan a significant axion energy and mass range and distinguish between models



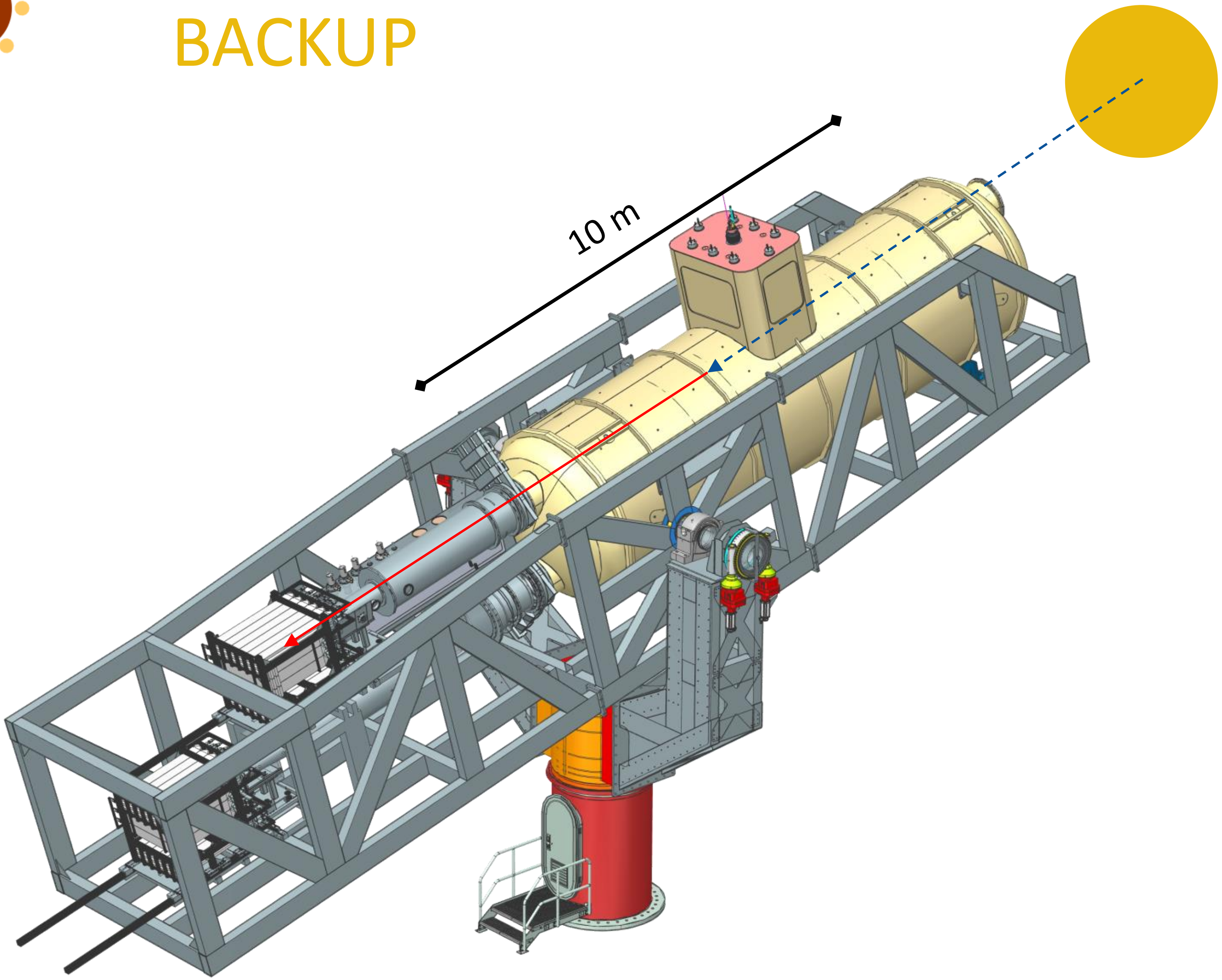
IAXO COLLABORATION

125 scientists from 21 full member institutions + 5 associate institutions

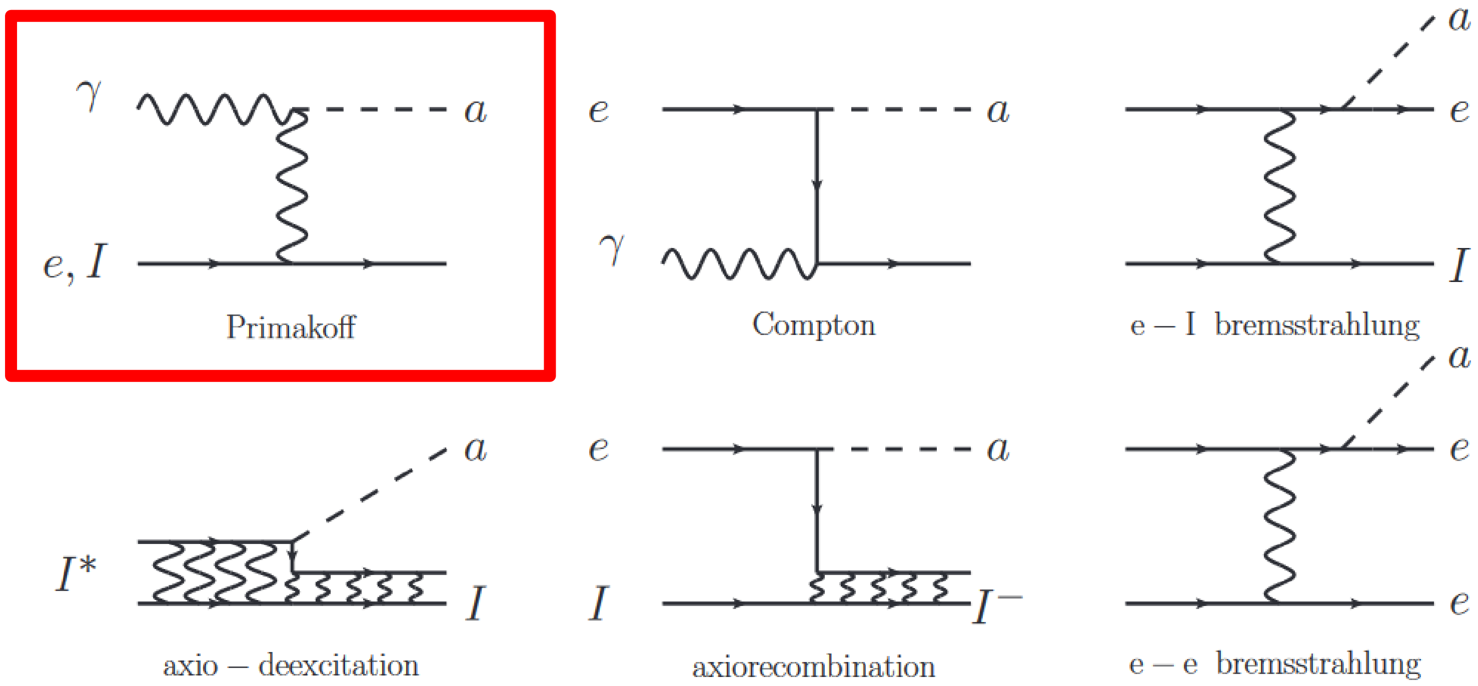
Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | CERN (Switzerland) | INAF-Brera (Italy) | ICCUB-Barcelona (Spain) | Siegen University (Germany) | Barry University (USA) | CEFCA-Teruel (Spain) | University of Bonn (Germany) | DESY (Germany)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

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

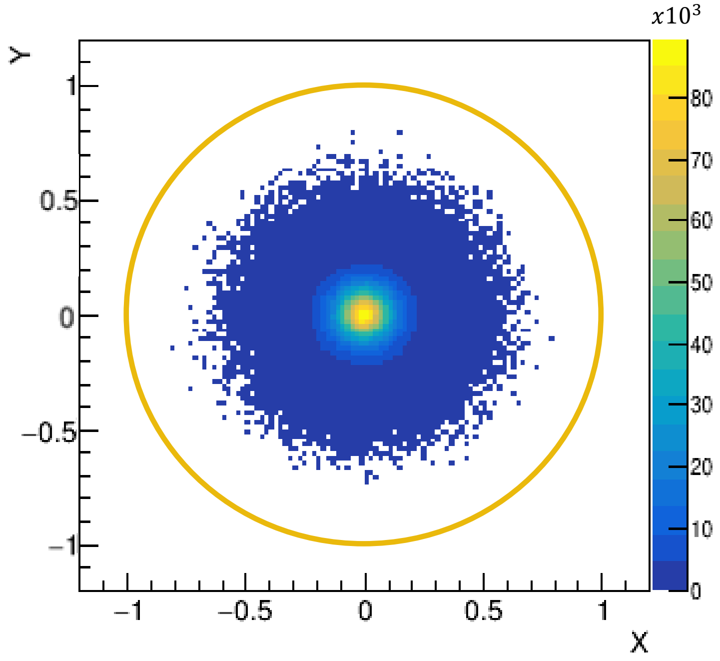
BACKUP



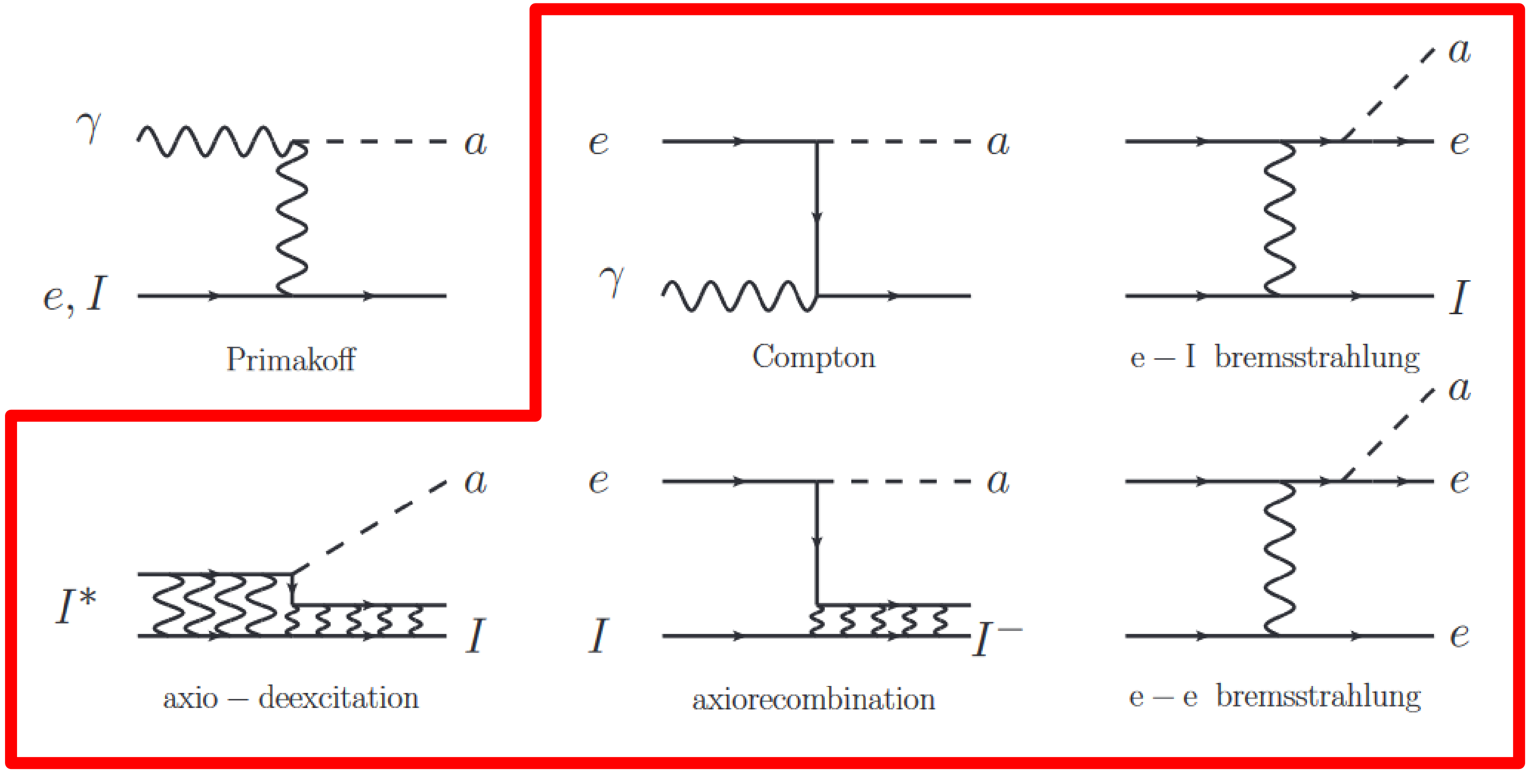
SOLAR AXIONS – RADIAL DISTRIBUTION



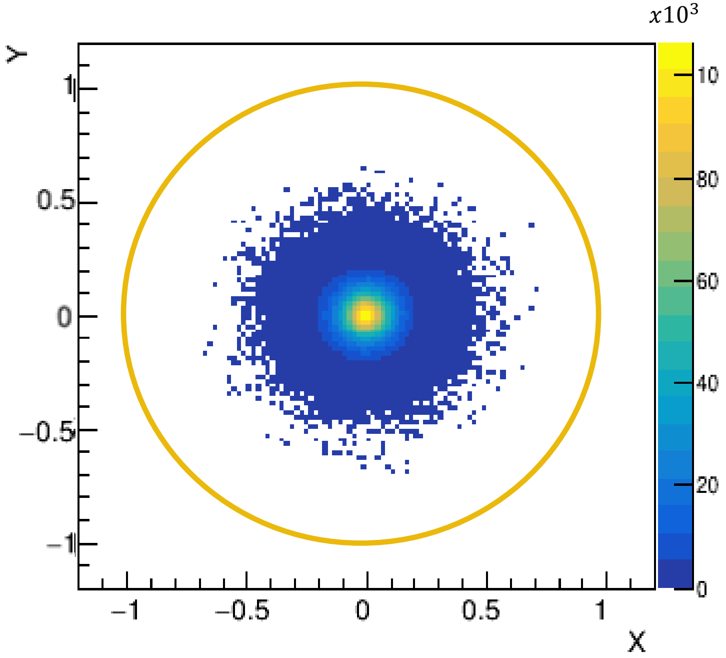
Radial distribution of Primakoff axion flux in sun



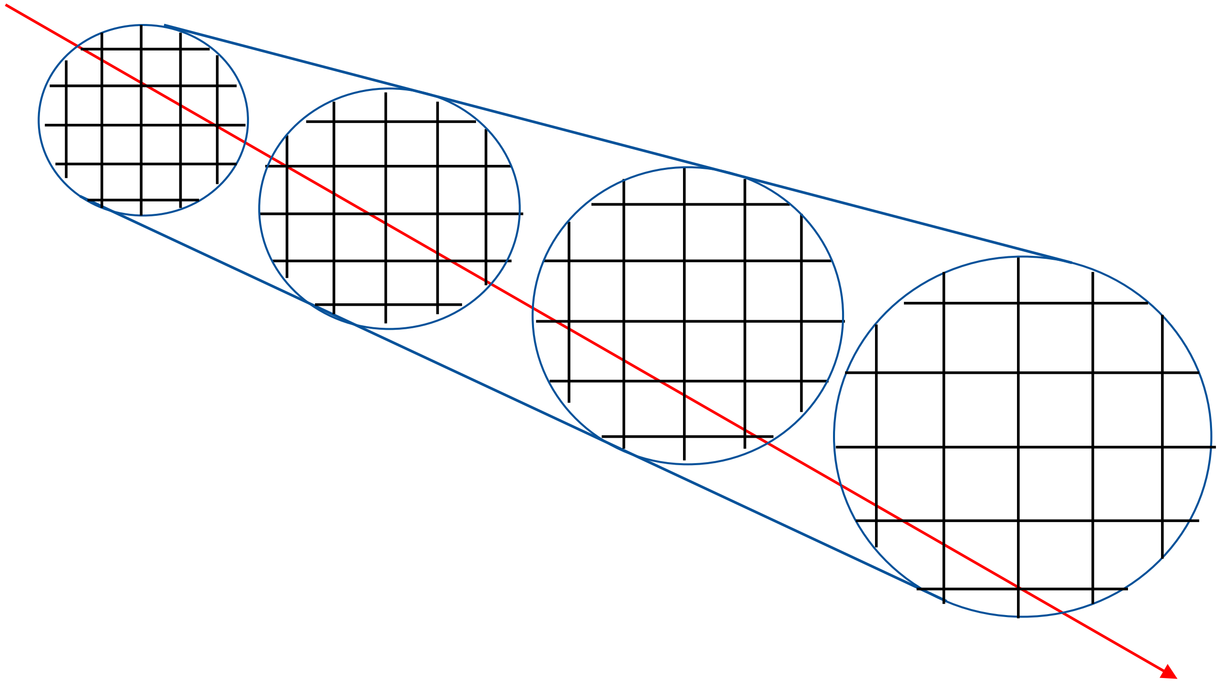
SOLAR AXIONS – RADIAL DISTRIBUTION



Radial distribution of ABC axion flux in sun



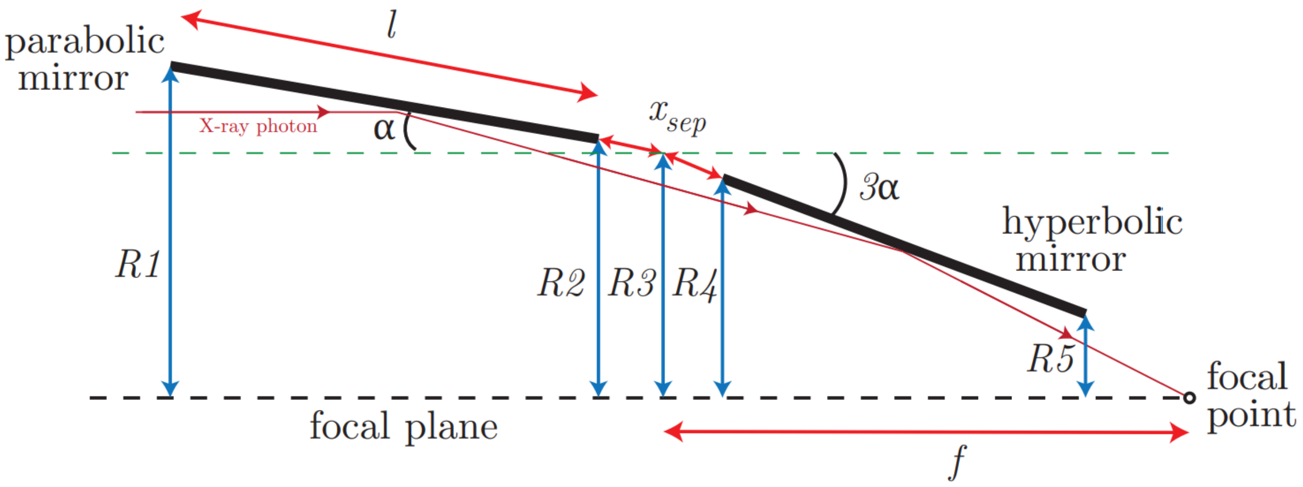
MAGNETIC FIELD IMPLEMENTATION



1. Get magnetic field on grid-vector intersection points
2. Integrate magnetic field over vector
3. Photon production probability: $P_{a\rightarrow\gamma} = \frac{1}{4}(g_{a\gamma}BL)^2$

WOLTER I OPTICS

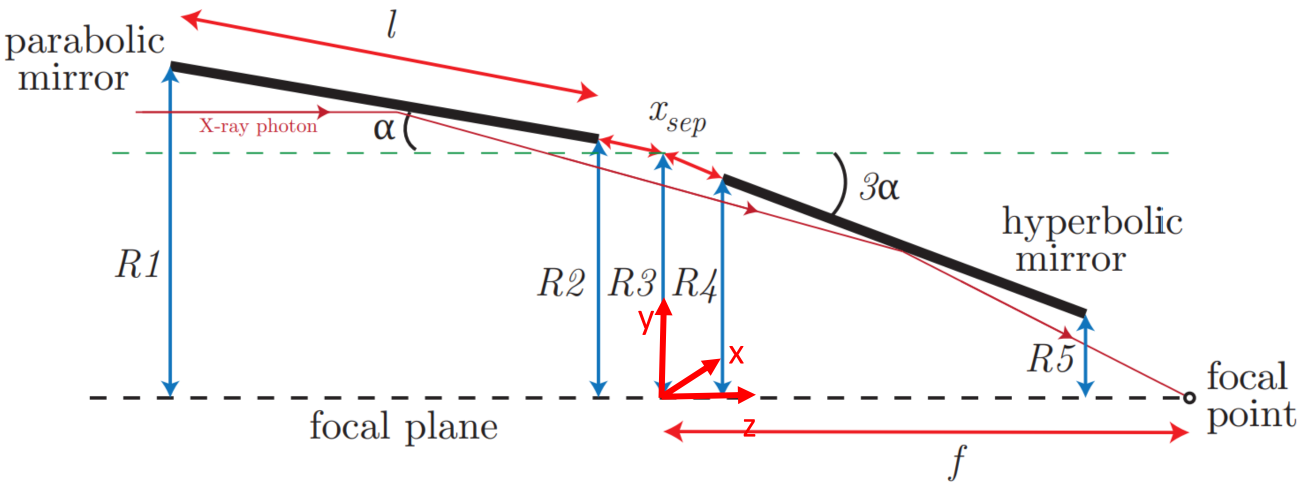
A Wolter I optic principle from the side



1. Find interaction point
2. Turn X-ray vector in regards to the respective normal vector

WOLTER I OPTICS

A Wolter I optic principle from the side



1. Find interaction point
2. Turn X-ray vector in regards to the respective normal vector

Wolter I: Parabolic mirror function

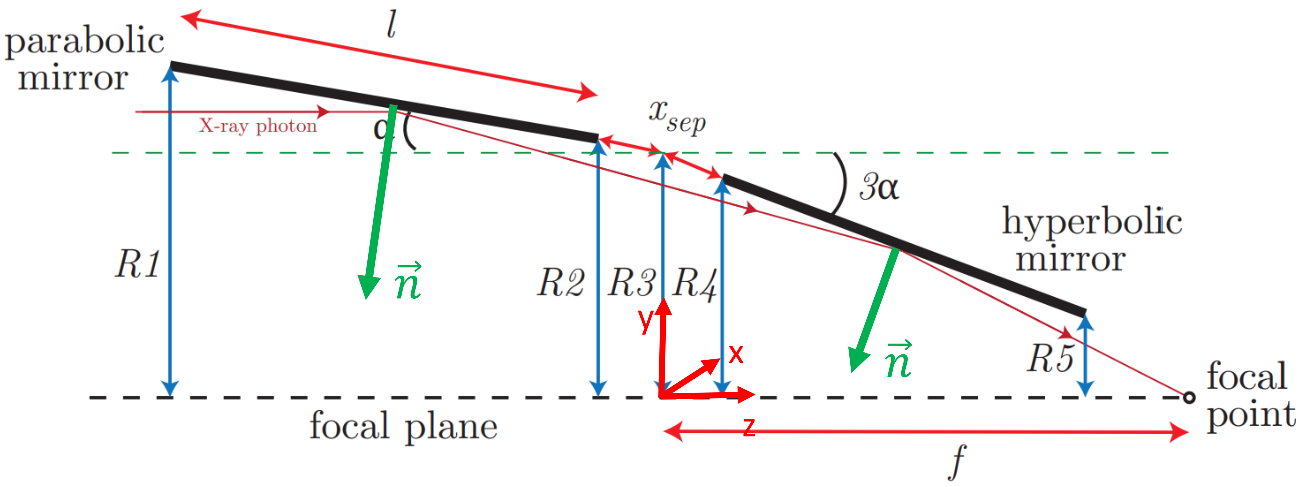
$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(\alpha) \cdot z$$

Wolter I: Hyperbolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(3\alpha) \cdot \left(z + \frac{z^2}{f + R3 \cdot \cot(2\alpha)}\right)$$

WOLTER I OPTICS

A Wolter I optic principle from the side



1. Find interaction point
2. Turn X-ray vector in regards to the respective normal vector

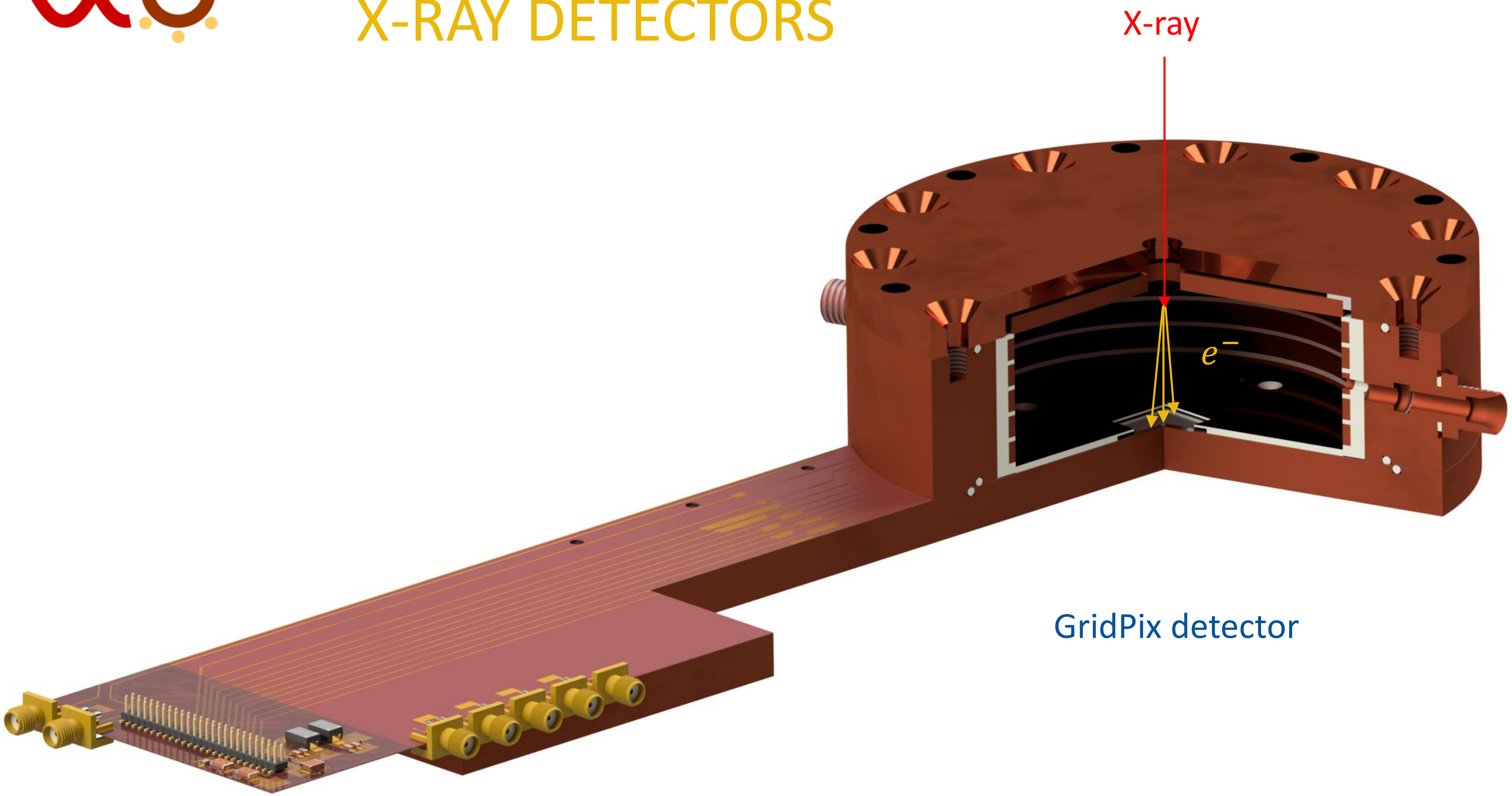
Wolter I: Parabolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(\alpha) \cdot z$$

Wolter I: Hyperbolic mirror function

$$R^2(z) = R3^2 - R3 \cdot 2 \cdot \tan(3\alpha) \cdot \left(z + \frac{z^2}{f + R3 \cdot \cot(2\alpha)}\right)$$

X-RAY DETECTORS



GridPix detector