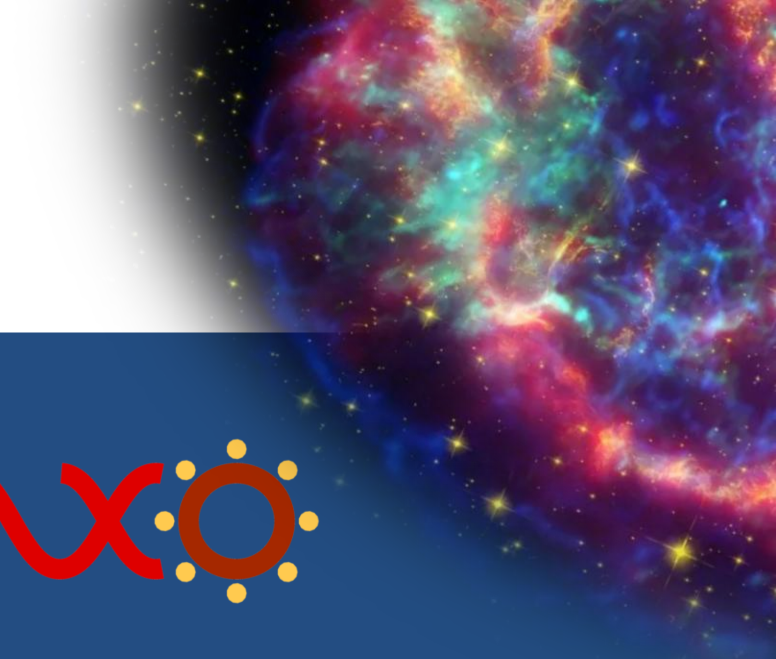


Centro de Astropartículas y
Física de Altas Energías
Universidad Zaragoza

Axion searches with IAXO from the Sun to Supernovae

María Jiménez Puyuelo maria.jimenez@unizar.es
on behalf of the IAXO group at Zaragoza

Saturnalia 2025: Dark topics for the Longest Nights
16-19 December 2025, Zaragoza

Contents

- Axions: searches
- The helioscope technique
- IAXO and BabyIAXO
- Micromegas detectors for BabyIAXO
- IAXO as a SN-Scope

Axions

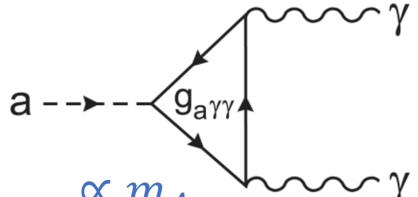
- Hypothetical particles proposed to solve the **strong CP problem** (Peccei-Quinn, 1977)
- **Pseudo Goldstone-boson**

Generic

- Gluon coupling
- Mass $m_A = 6\mu eV \dfrac{10^{12} GeV}{f_A}$

Generic (but value model dependent)

- Photon coupling

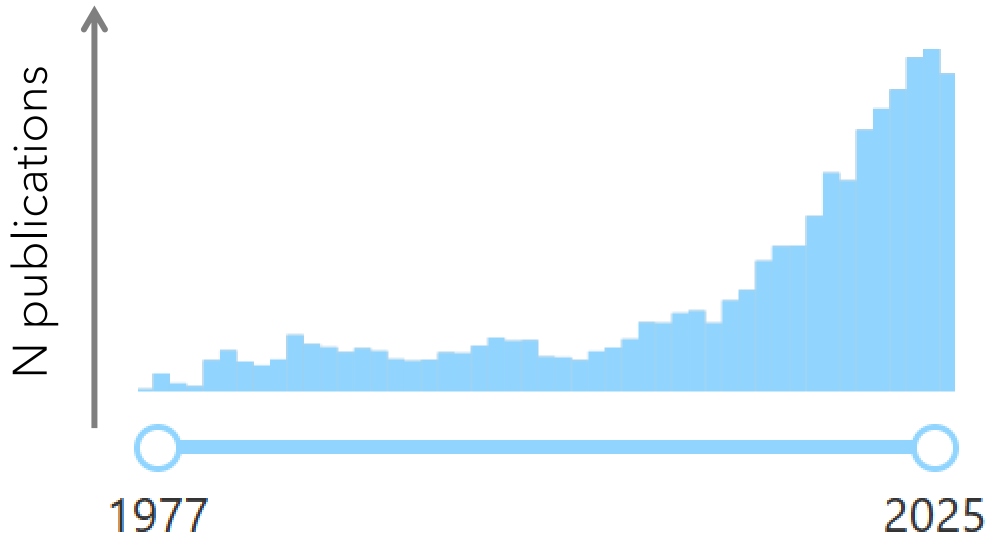


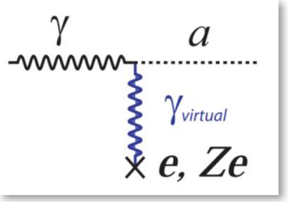
$g_{a\gamma\gamma} \propto m_A$

Electron, meson, nucleon couplings …

+ STRONG DM CANDIDATE!

Rapidly increasing interest and experimental efforts

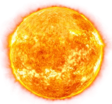




- Most experimental efforts based on the coupling with photons (Primakoff effect)

Large complementarity between different experimental approaches

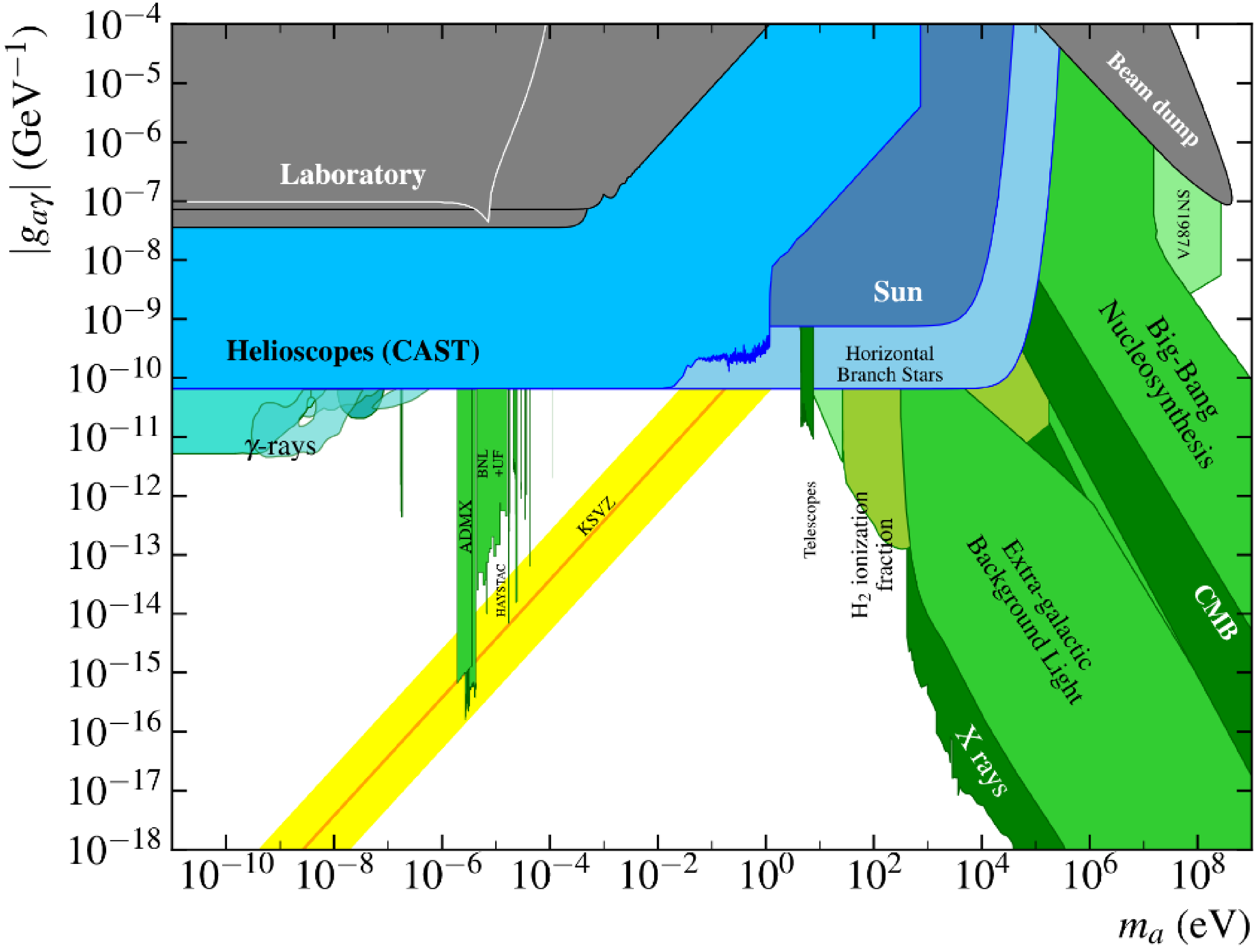

Lab axions: LSW Light Shining Through Wall
- Very low model dependent

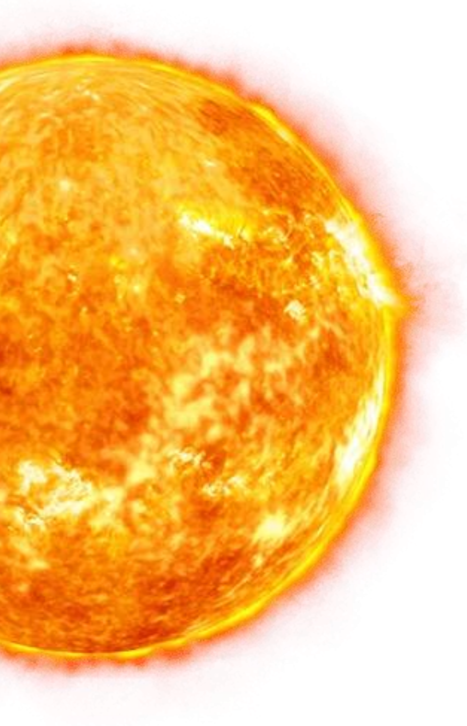

Solar axions: Helioscopes
- Low model dependent

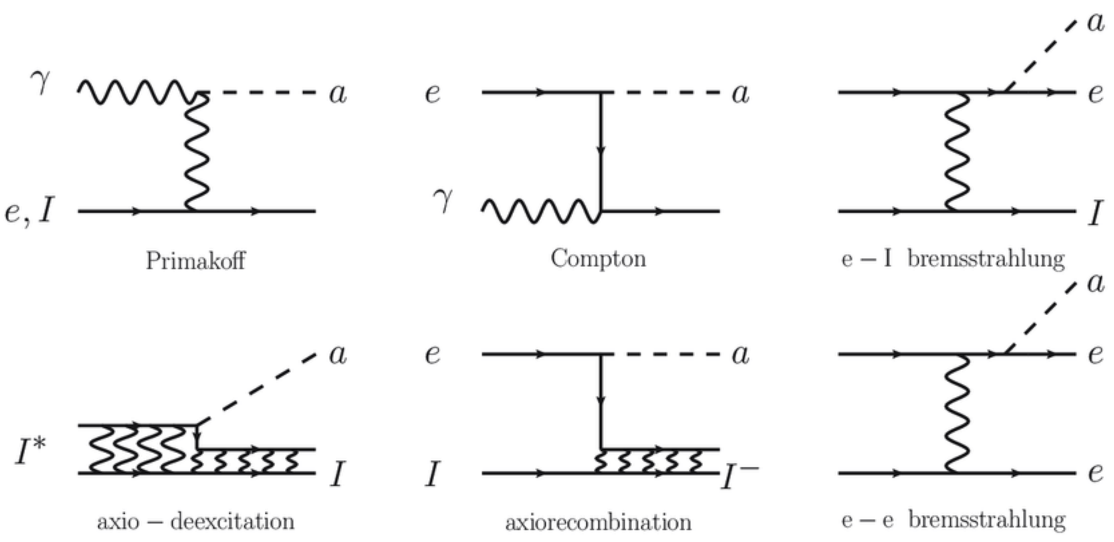

Relic axions: Haloscopes
- Highly model dependent

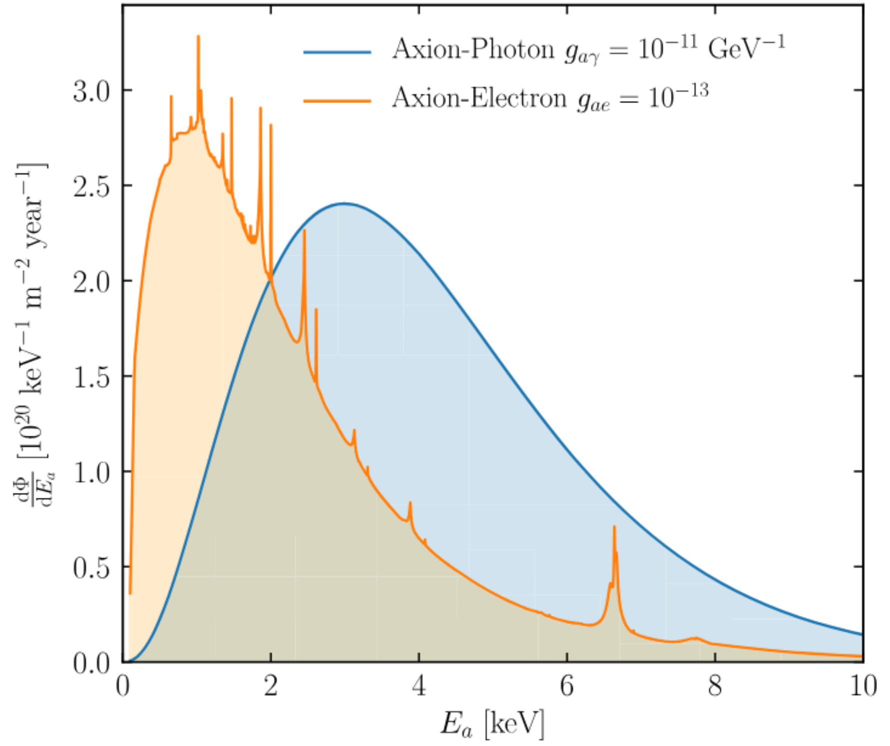
Axion like particles predicted by many extensions of the SM

$g_{a\gamma\gamma} \cancel{\propto} m_A$



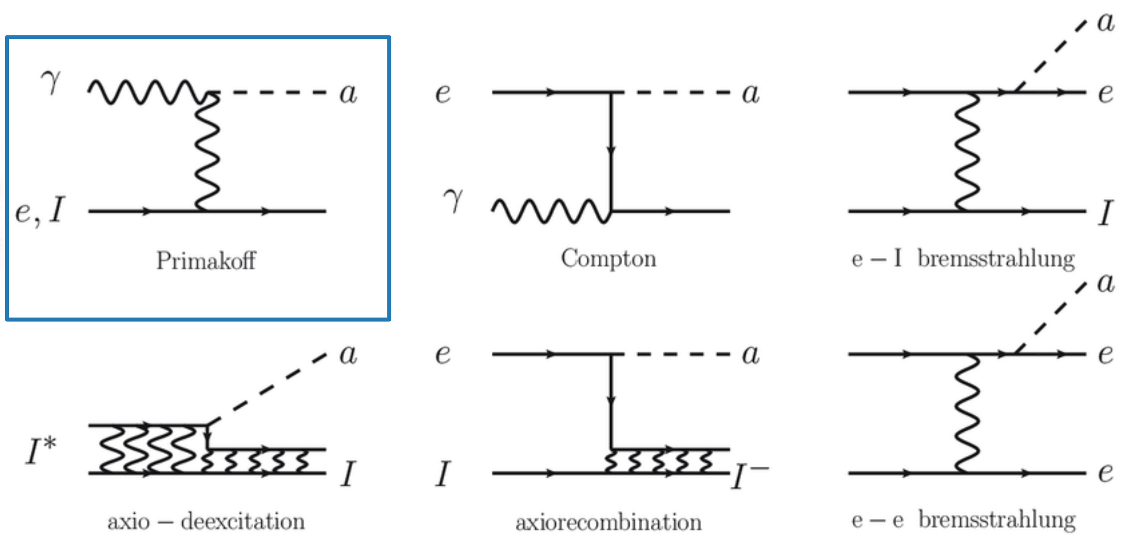


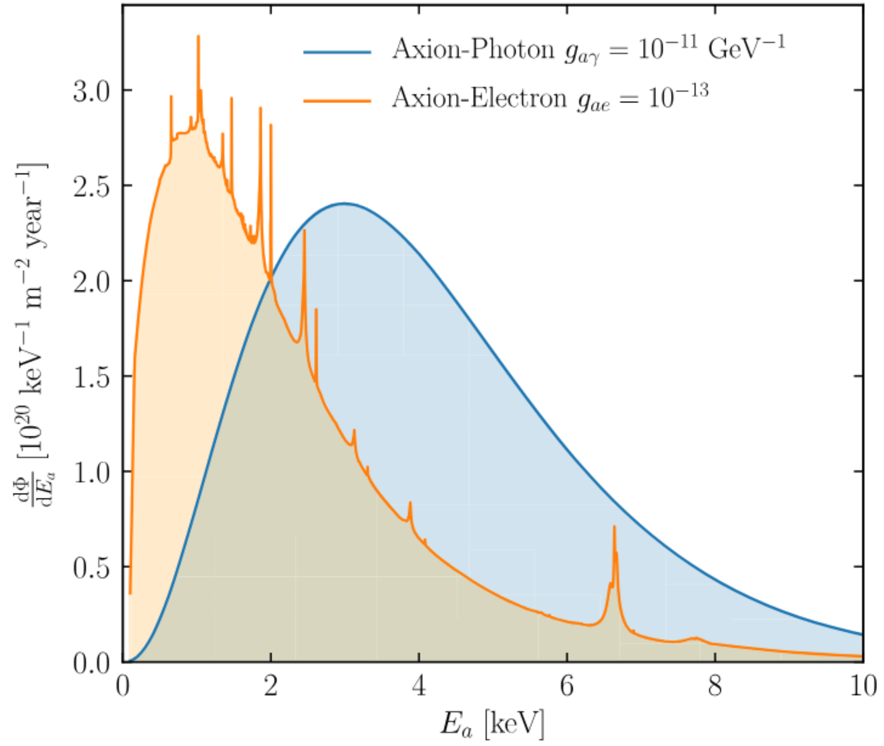




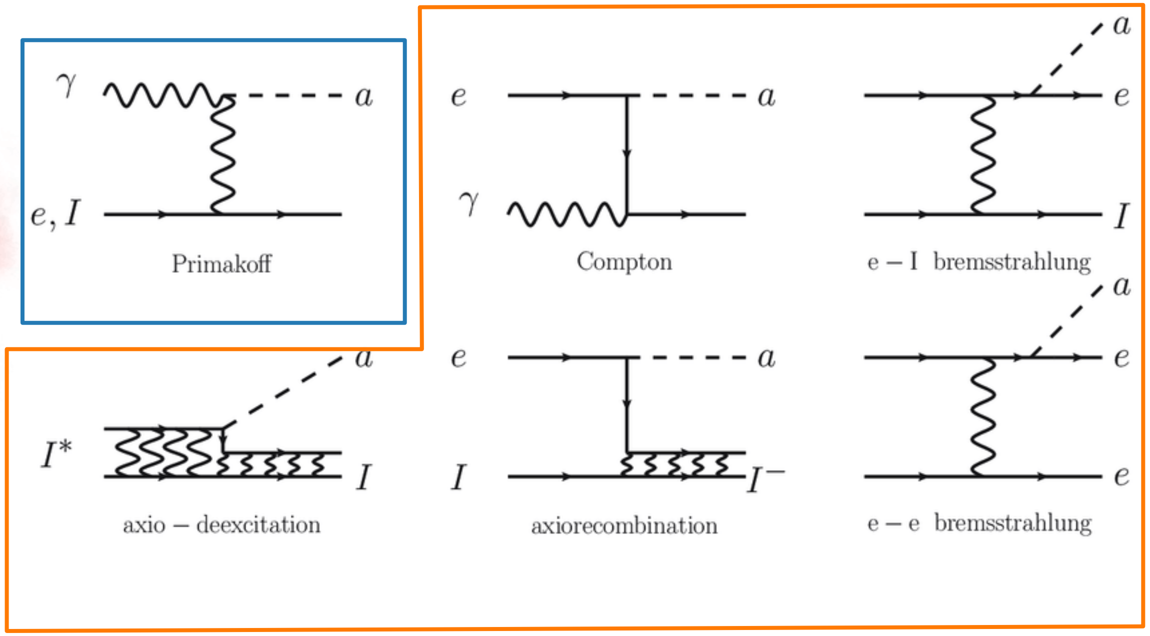
- Stars (like the Sun) are ideal environment for producing axions

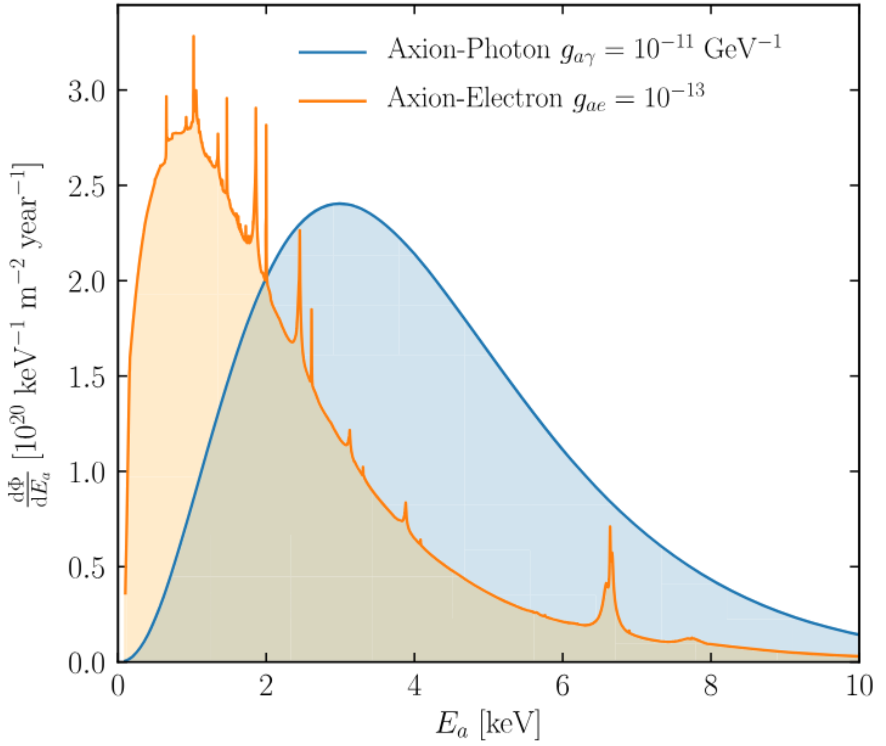
Solar axions



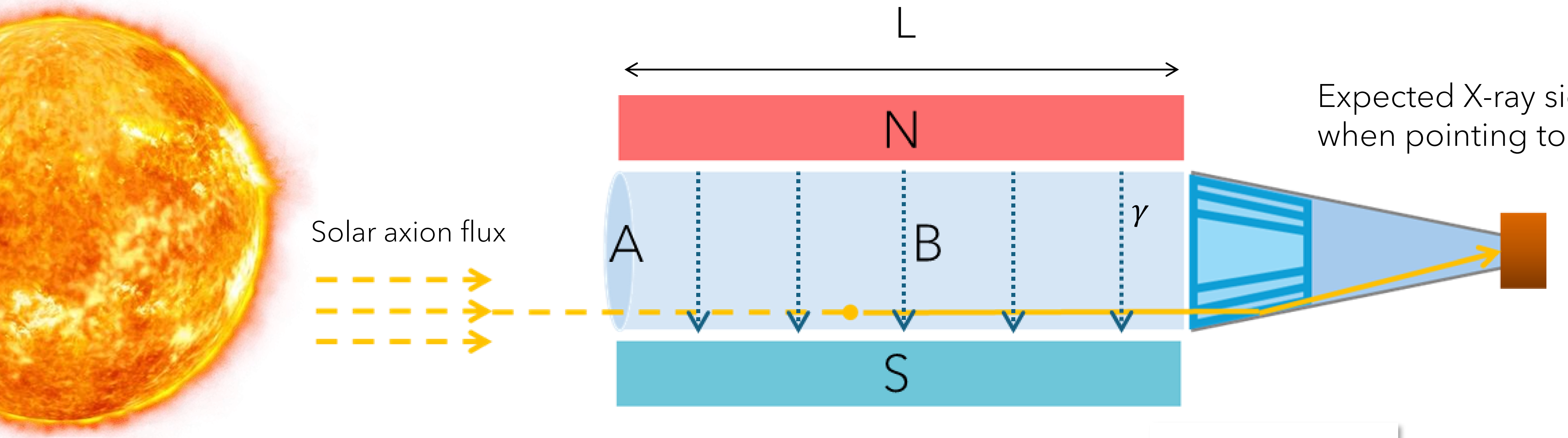


- Stars (like the Sun) are ideal environment for producing axions
- Blackbody photons (keV) can be converted into axions in presence of strong EM field in the plasma: Primakoff axions





- Stars (like the Sun) are ideal environment for producing axions
- Blackbody photons (keV) can be converted into axions in presence of strong EM field in the plasma: Primakoff axions
- If axions are coupled with electrons: ABC axions (non hadronic)



Detection: conversion of axions into photons in the presence of a magnetic field

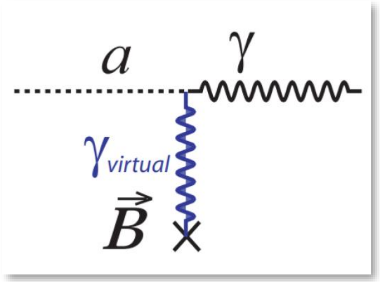
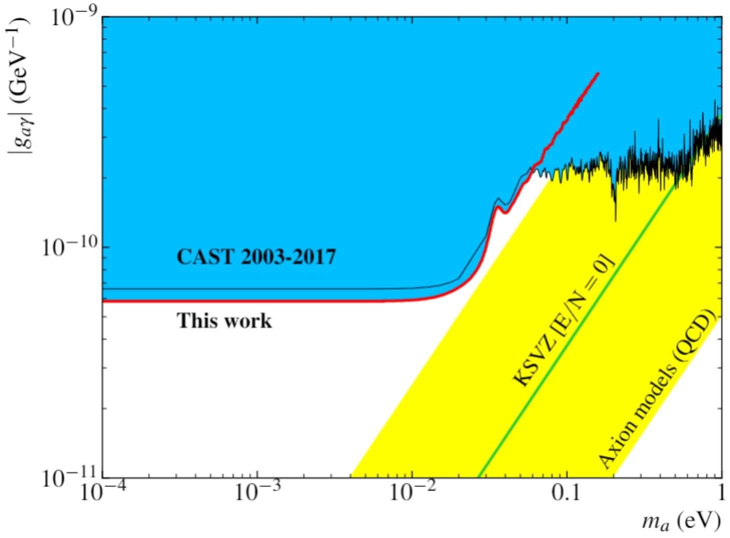


Figure of Merit (FOM)

	magnet		detectors		optics		exposure
Figure of Merit (FOM)	$B^2 L^2 A$	$\times$	$\varepsilon_d b^{-1/2}$	$\times$	$\varepsilon_0 \alpha^{-1/2}$	$\times$	$\varepsilon_t^{-1/2} t^{-1/2}$

Helioscope generations



CERN Axion Solar Telescope

- State of the art
- More than 20 years of experience
- LHC dipole magnet
  - L = 9.26 m
  - Magnetic field = 9 T
- Solar tracking during sunrise and sunset
- The most sensitive helioscope so far

↓

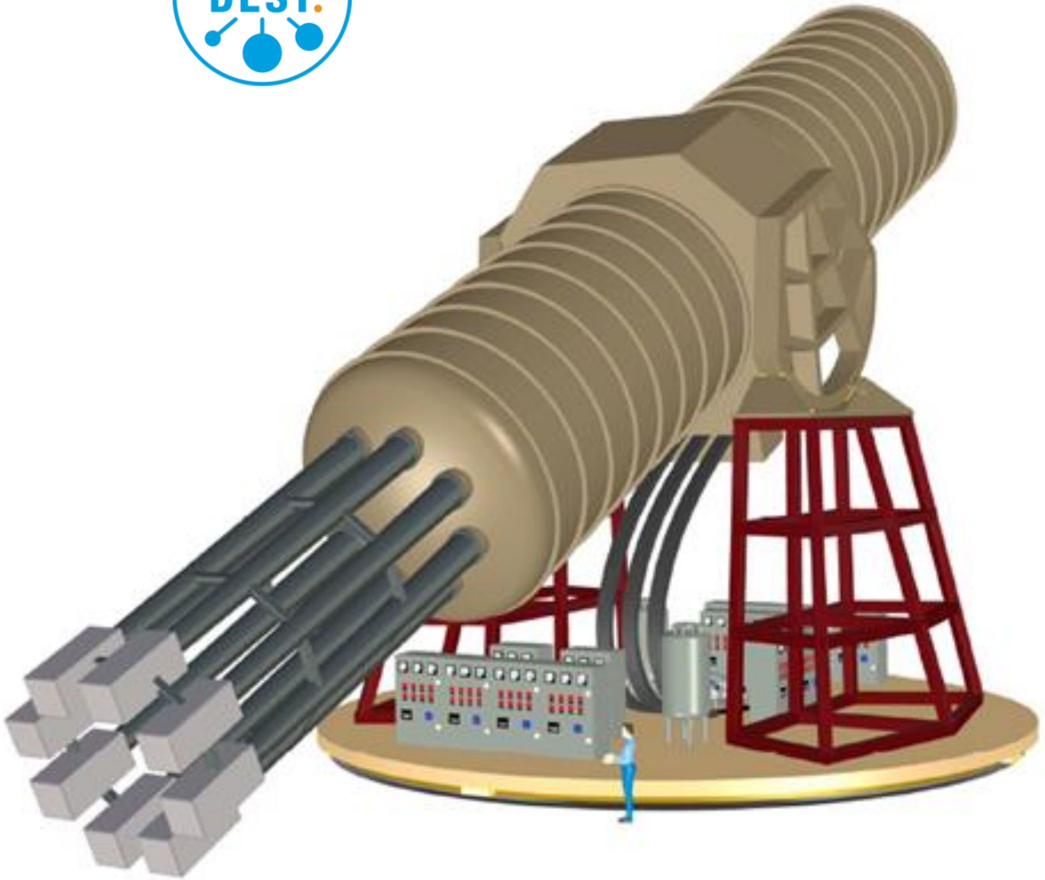
Coupling limit $m_a < 0.01$ eV

$$|g_{a\gamma}| < 0.58 \cdot 10^{-10}\ GeV^{-1}\ (95\%\ C.L)$$

Phys. Rev. Lett 133.22 (2024): 221005.

International Axion Observatory

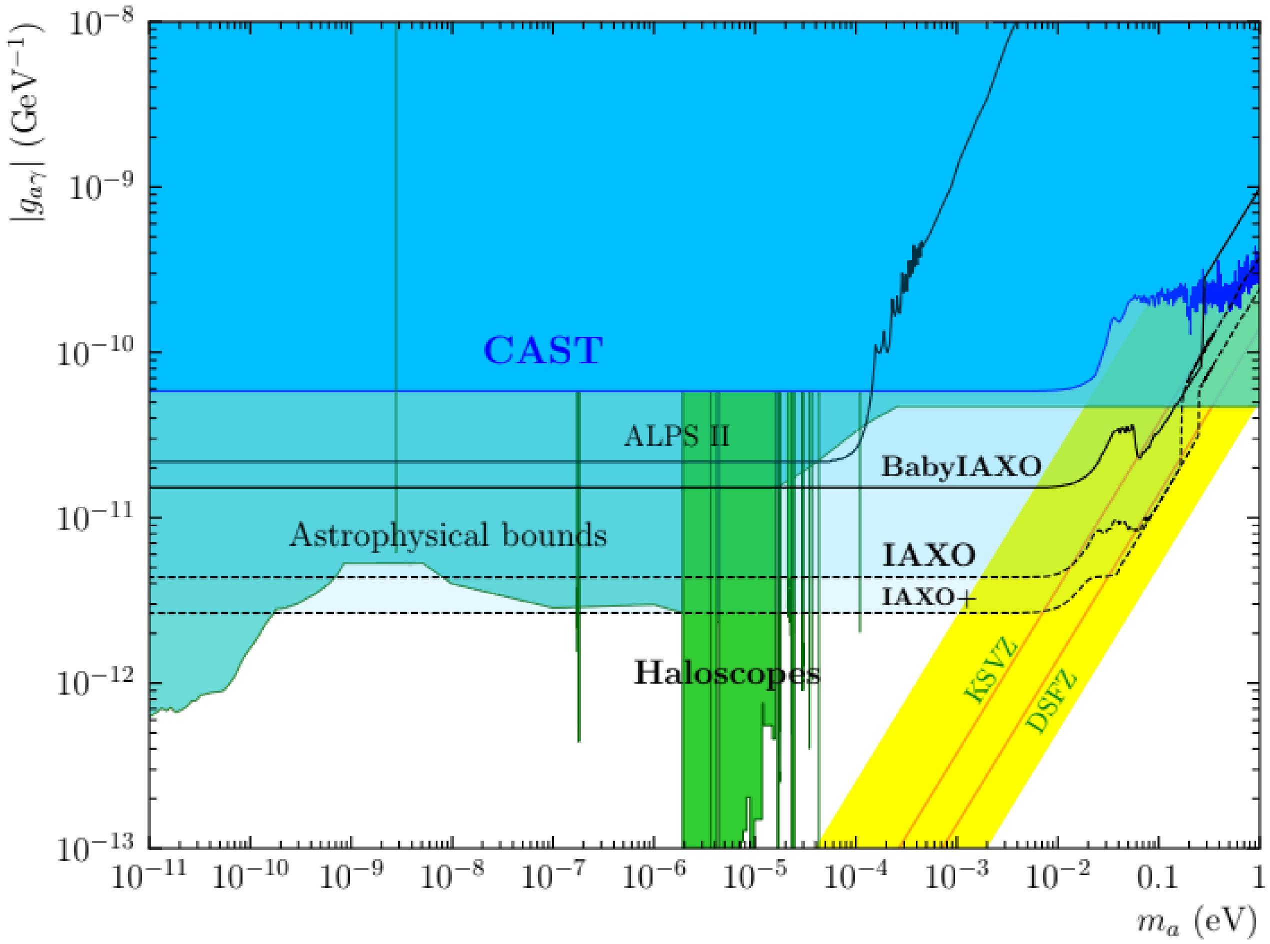
- Next generation axion helioscope
- Purpose-built magnet
  - L = 20 m, B = 5.4 T
  - 8 bores of 60 cm Ø
- Dedicated x-ray optics
  - Based on slumped-glass technique used in NuSTAR
  - 0.2 cm^2 focal spot
- Tracking system based on CTA
  - 50% Sun-tracking time
- 8 detection lines



10.1088/1748-0221/9/05/T05002

CAST

- The most sensitive helioscope so far
- Has reached similar level to HB stars bounds



IAXO

- x10^4 SNR better than CAST
- Improves CAST sensitivity to $g_{a\gamma}$ in more than a factor 10

Sensitivity prospects

CAST

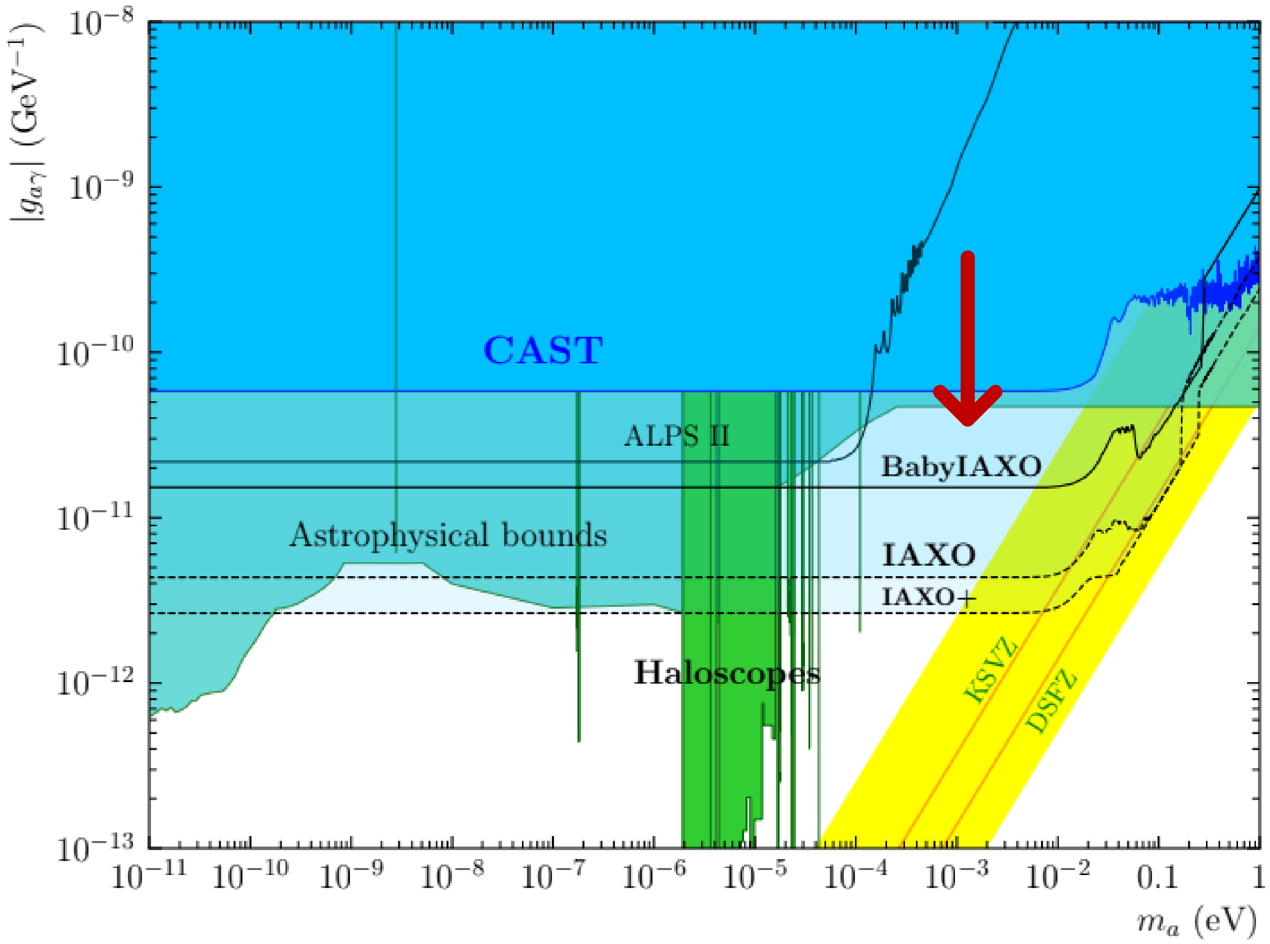
- The most sensitive helioscope so far
- Has reached similar level to HB stars bounds

But first: BabyIAXO!

- Prove of concept
- Has its own physics case
- Sensitive to realistic QCD axion models
- x10^2 SNR better than CAST

IAXO

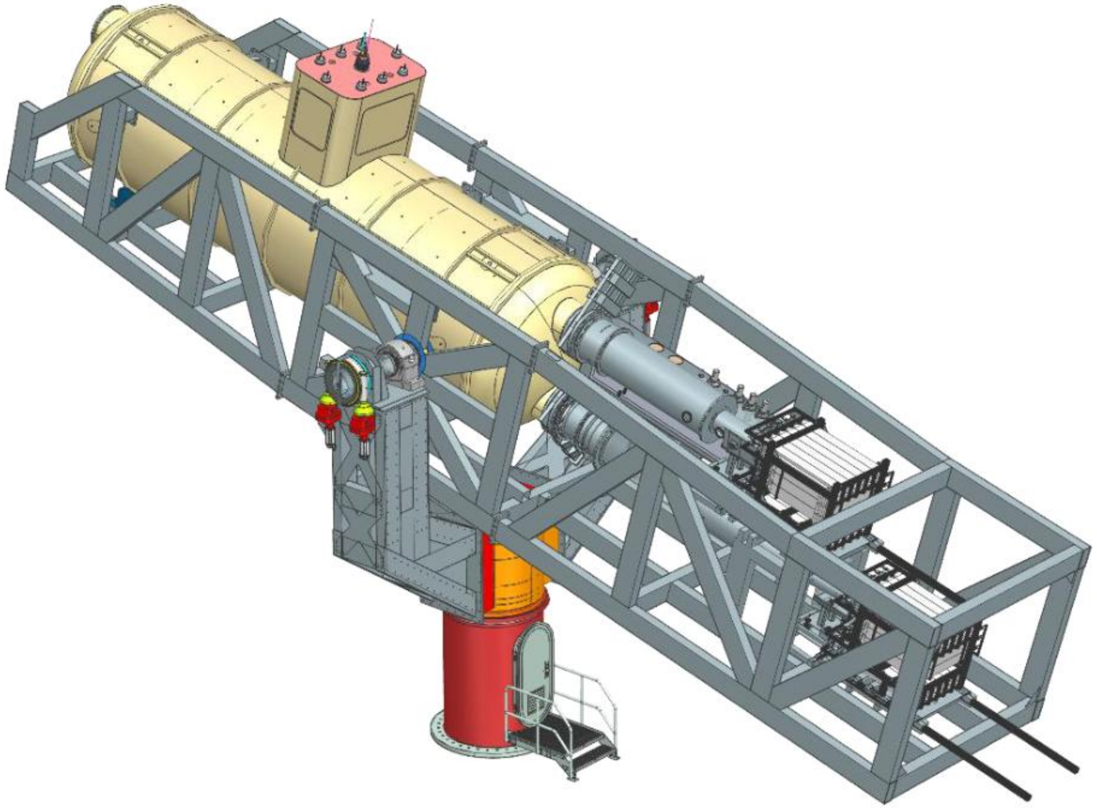
- x10^4 SNR better than CAST
- Improves CAST sensitivity to $g_{a\gamma}$ in more than a factor 10



BabyIAXO

- Intermediate experimental stage before IAXO
- Test and improve all systems

10.1007/JHEP05(2021)137

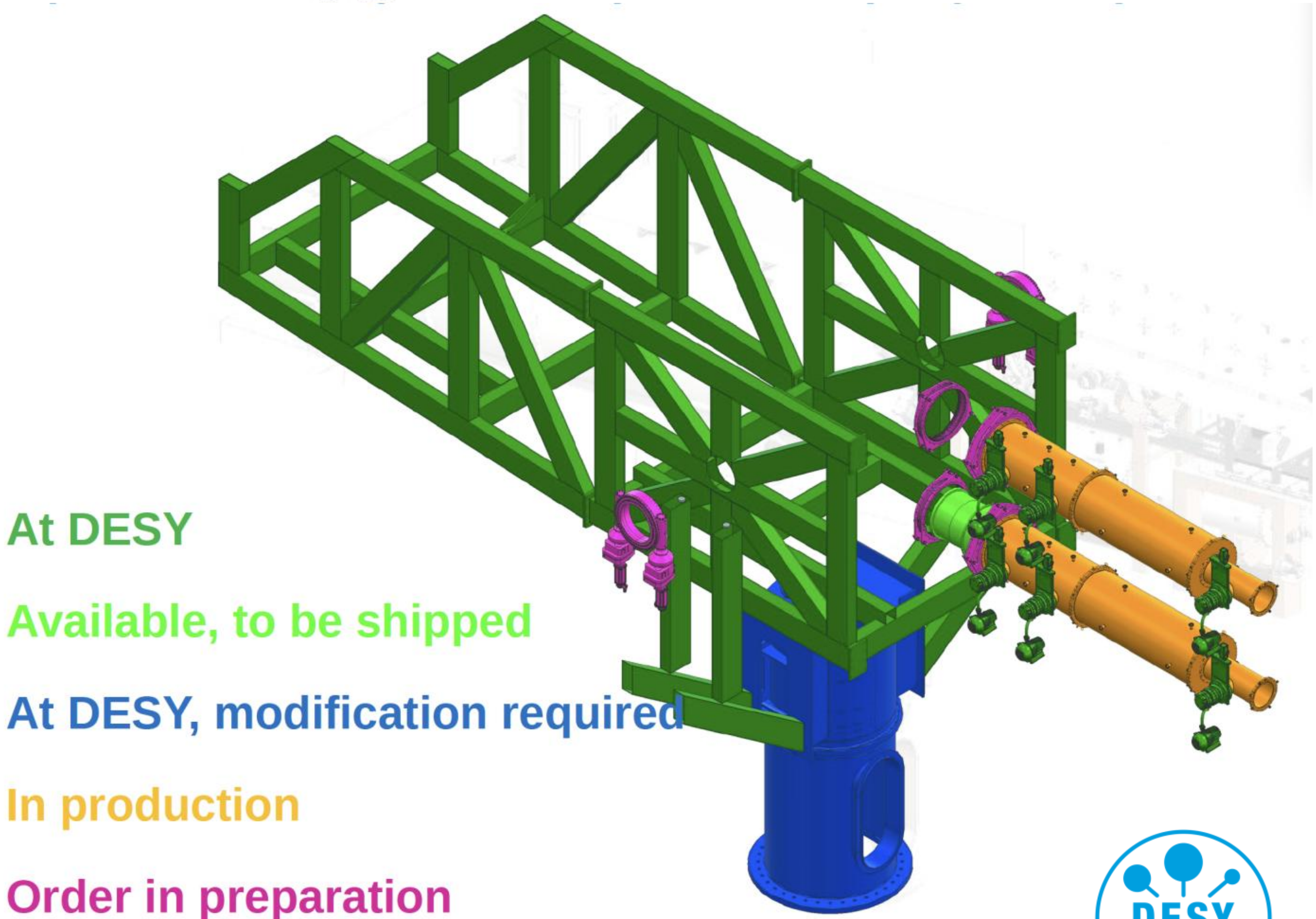


- Magnet will test design options of final IAXO magne
  - 2 bores of 70 cm Ø
  - L = 10 m, B = 3-4 T
- Dedicated x-ray optics
  - 0.2 cm^2 focal spot
- Detection lines representative of final ones
  - Micromegas baseline

BabyIAXO

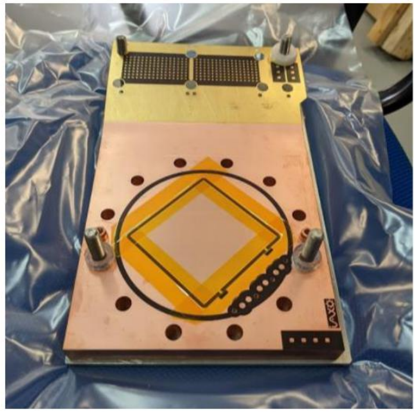
Currently under construction!

10.1007/JHEP05(2021)137



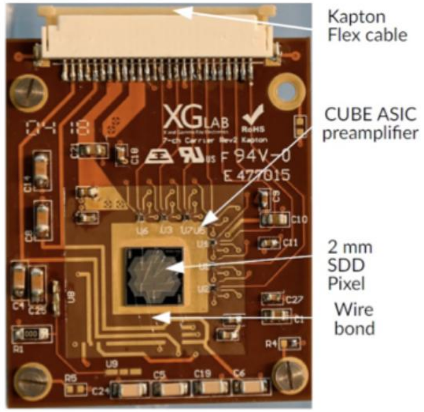
$$\text{FOM} = \varepsilon_d/\sqrt{b}$$

- BabyIAXO's required level of background is 10^{-7} c/keV/cm^2/s in the [1-10] keV ROI
- Different technologies are under study at different optimisation stages:

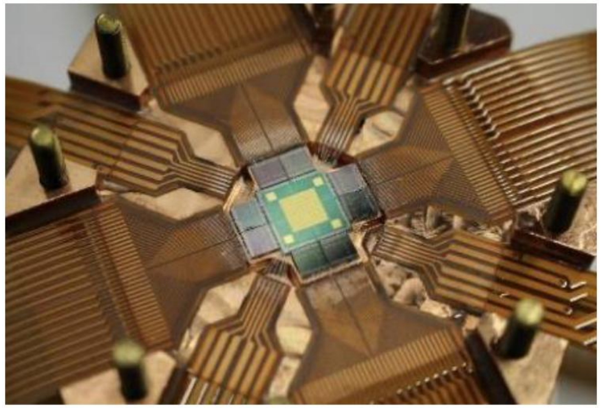


Microbulk Micromegas TPC
(U. Zaragoza and CEA-Saclay)

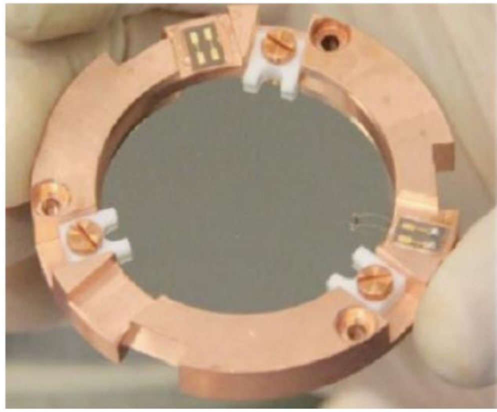
GridPix TPC
(U. Bonn)



SDD: Silicon Drift Detectors
(MPIFP)



MMC: Metallic Magnetic Calorimeters
(U. Heildeberg and CEA-Saclay)



TES: Transition Edge Sensors
(U. Zaragoza-INMA ICMAB-CSIC IJCLab)

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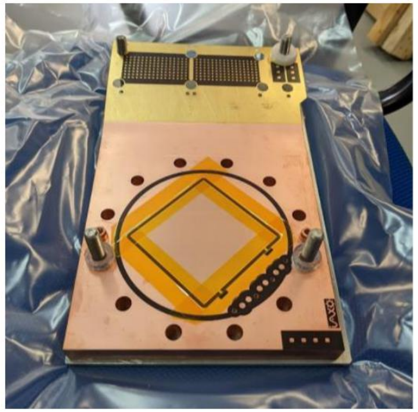
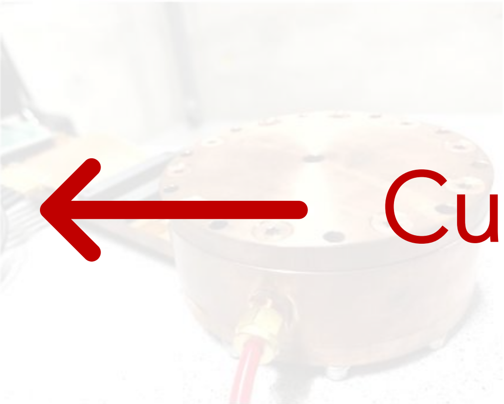


Microbulk Micromegas TPC
(U. Zaragoza and CEA-Saclay)

← Current baseline technology



GridPix TPC
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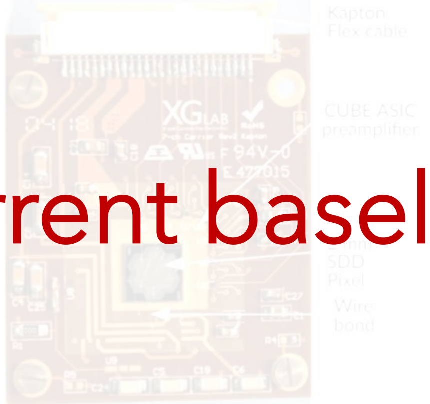

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$$\text{FOM} = \varepsilon_d/\sqrt{b}$$

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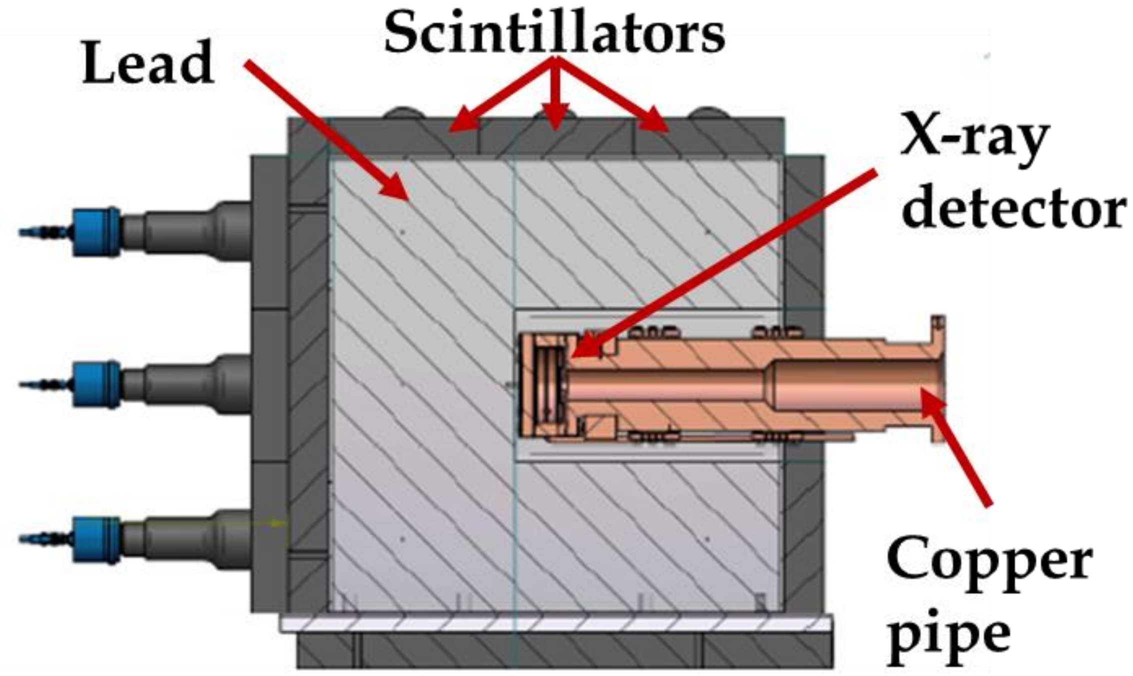
State of the art on ultra-low background techniques

- Radiopurity
- Shielding
  - Passive: 20 cm of lead
  - Radiopure copper: 2.5 cm
  - Active veto system (plastic scintillators) for cosmic rays and secondaries
- Event discrimination strategies
  - Micromegas: event topology (x-ray events)
  - Veto system: multiplicity



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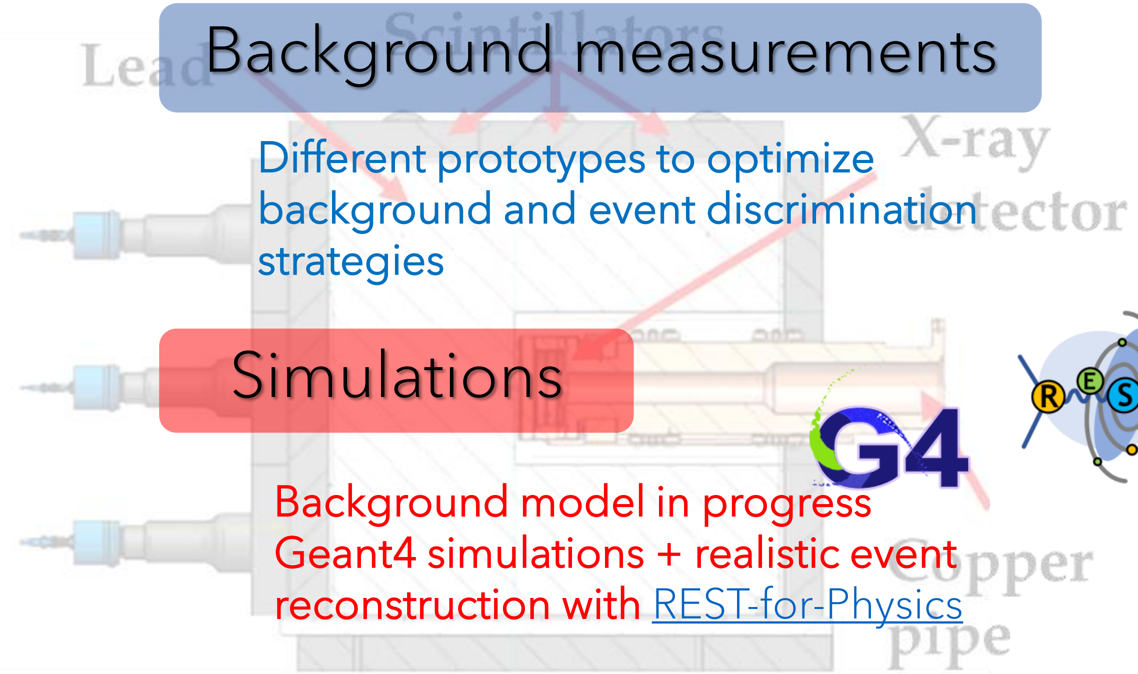


Background measurements

Different prototypes to optimize background and event discrimination strategies

Simulations

Background model in progress
Geant4 simulations + realistic event reconstruction with REST-for-Physics

BabyIAXO Micromegas detectors

Surface level

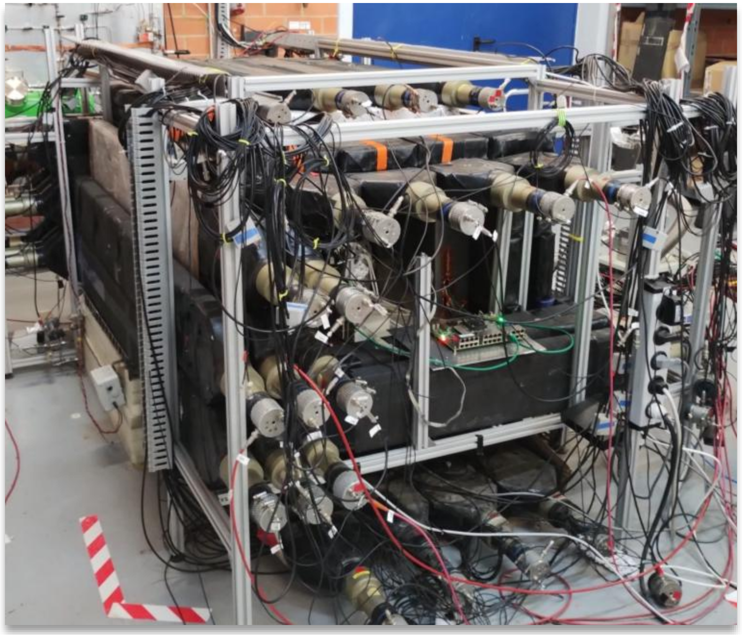
Underground

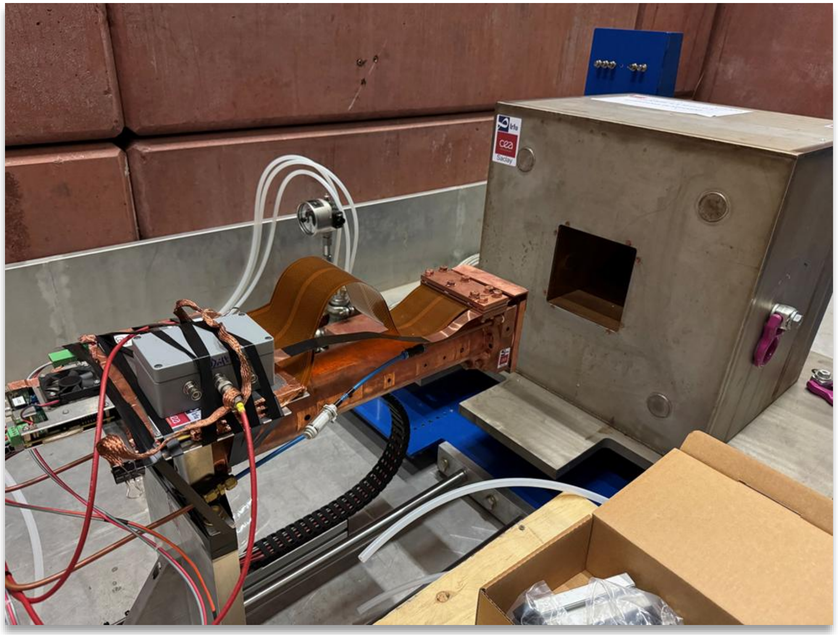
Laboratorio Subterráneo de Canfranc

Cosmic muon flux reduced by a factor 10^4

Zaragoza

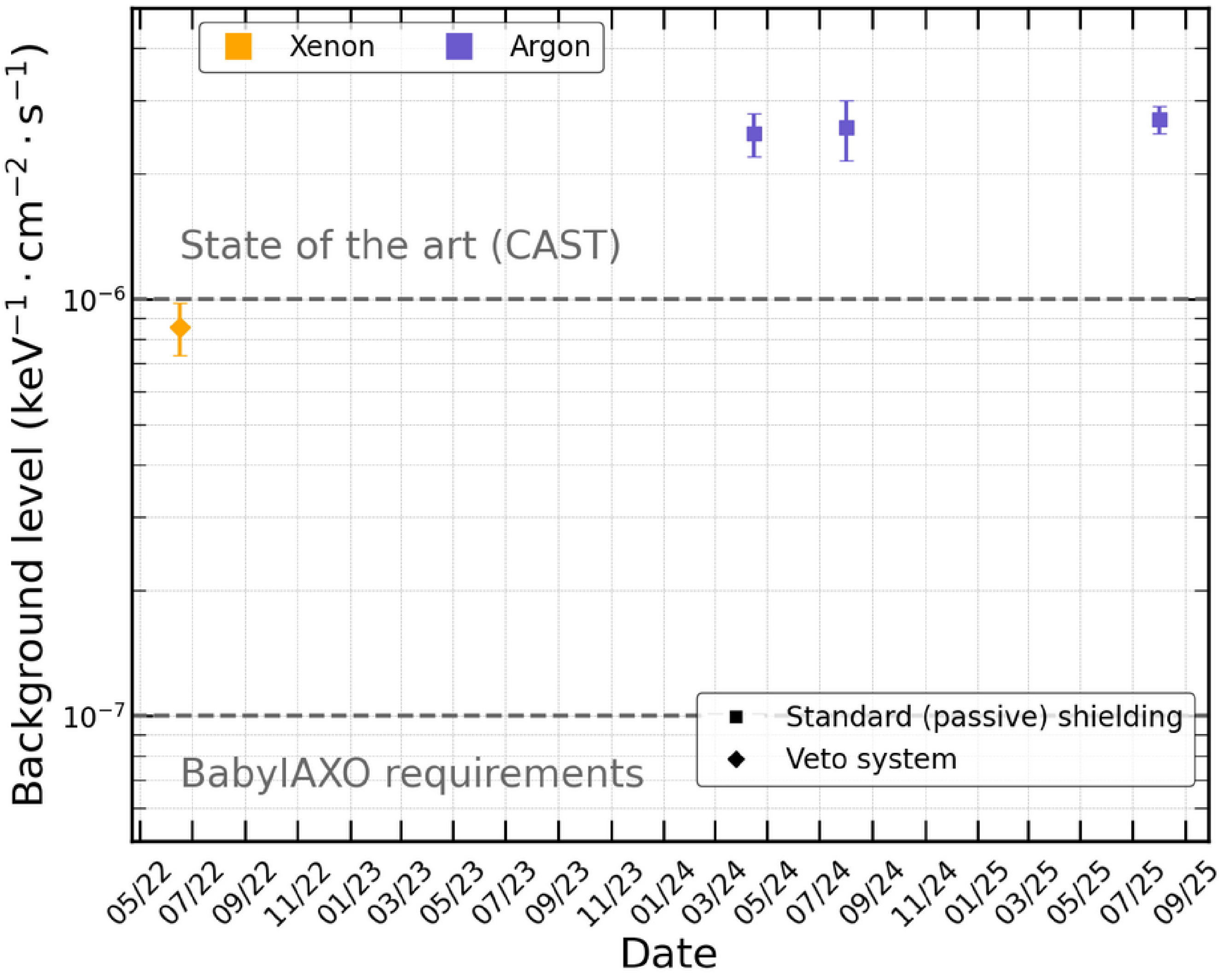
CEA-Saclay → Now in DESY!





- Effect of multi-layer veto system to tag cosmogenic neutrons (in addition to muons)
- Measure background on experimental site
- Intrinsic detector background
- Test of different gas mixtures

The Micromegas background puzzle



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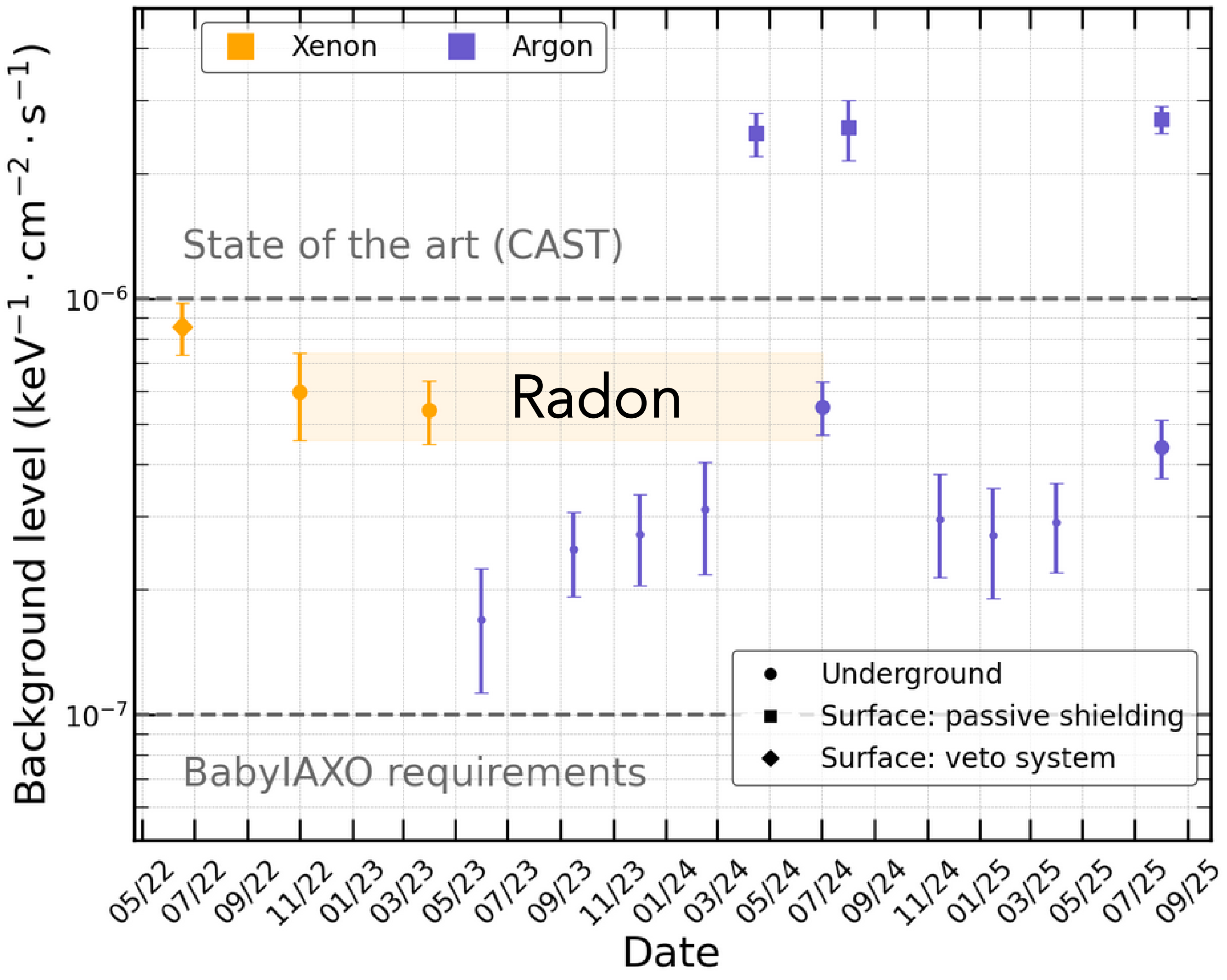
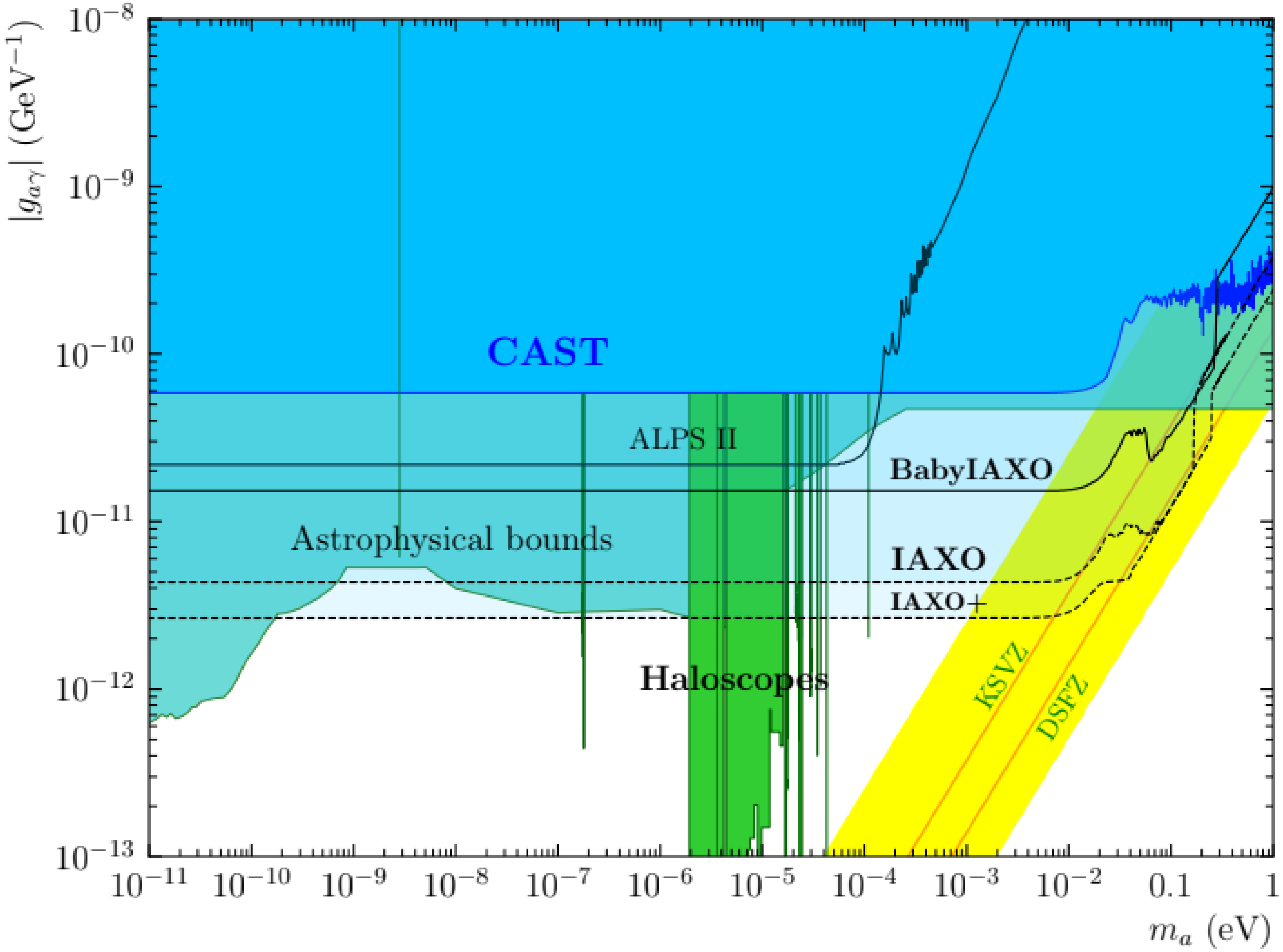


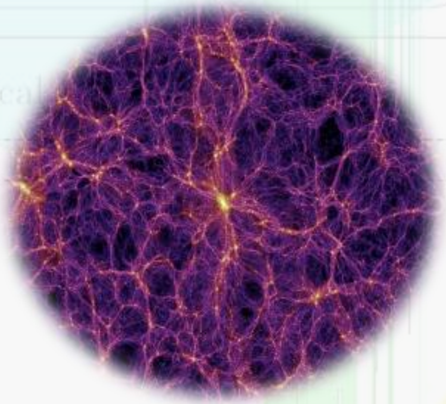
Physics potential



IAXO is a generic axion(-like) detection facility

(Baby)IAXO constitutes a great infraestructure that can be used to target other physics goals beyond Primakoff solar axions

Non-primakoff solar axions



DM axions: haloscope setups in (Baby)IAXO

Axions from close-by Supernovae

Physics potential

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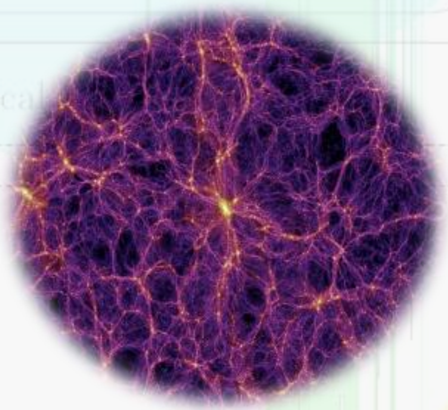

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Axions from close-by Supernovae

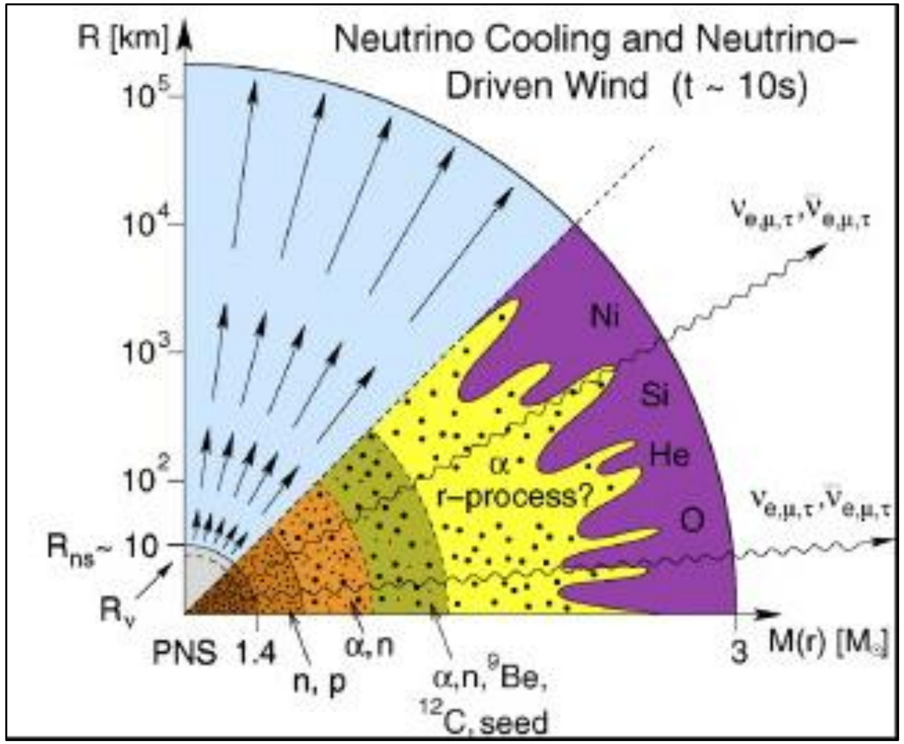
10.1088/1475-7516/2025/07/075

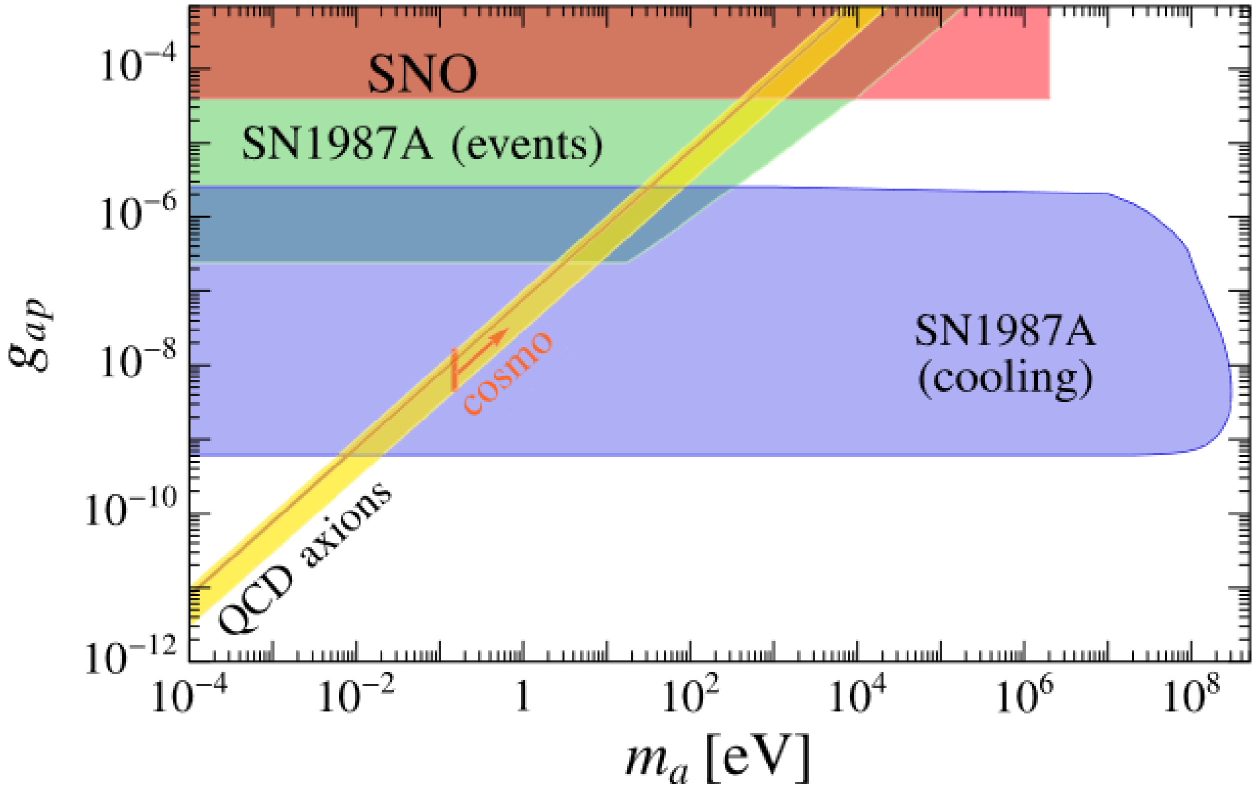
Phys. Rev. D 107 (2023) 103017 [2211.13760]
Phys. Rev. D 109 (2024) 023001 [2306.01048]

- Core collapse supernova (CCSN)
- Begining of the cooling phase
- Coupling with nuclear matter g_{aN}
- Free streaming regime: $g_{aN} < 5 \cdot 10^{-10}$

→

- T $\sim 30 - 40$ MeV
- $\rho \sim 10^{14}$ g·cm^{-3}





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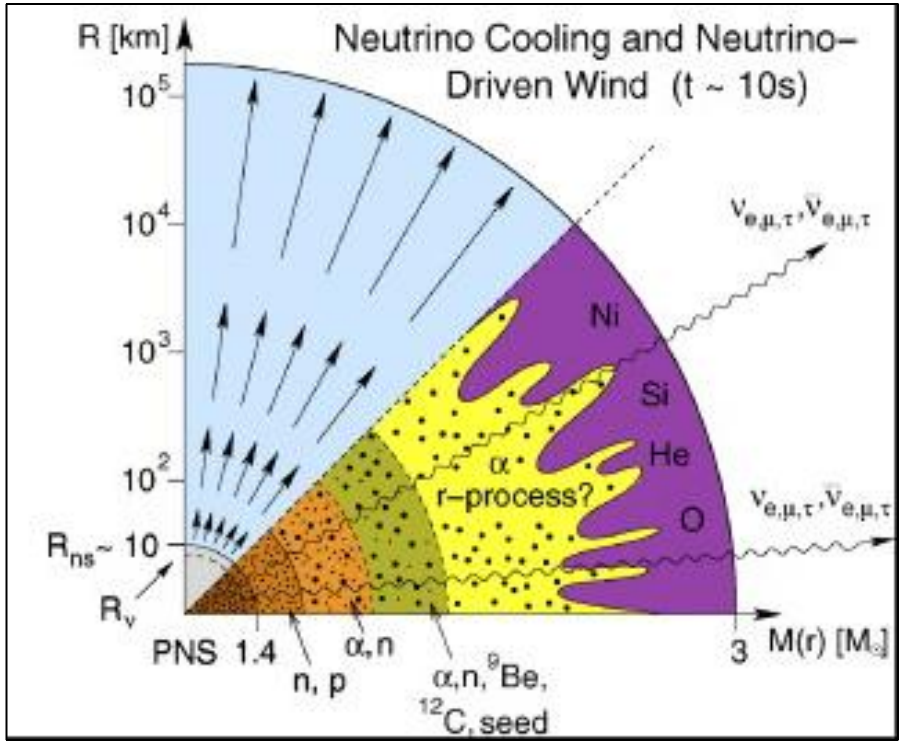
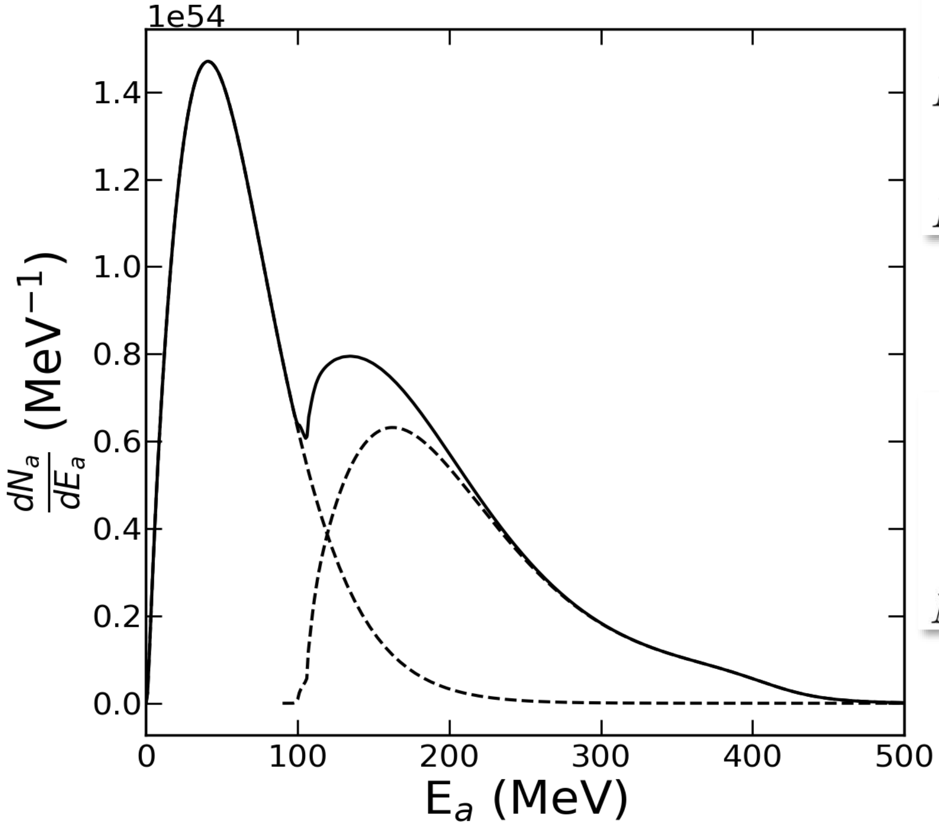
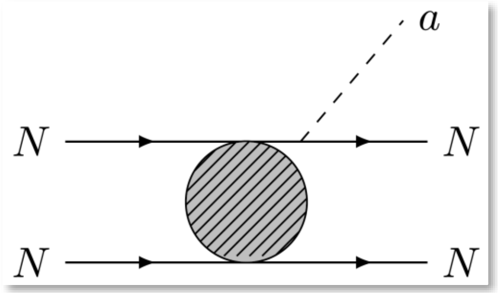
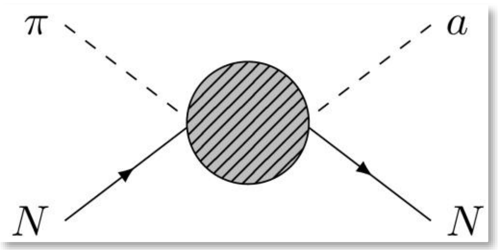




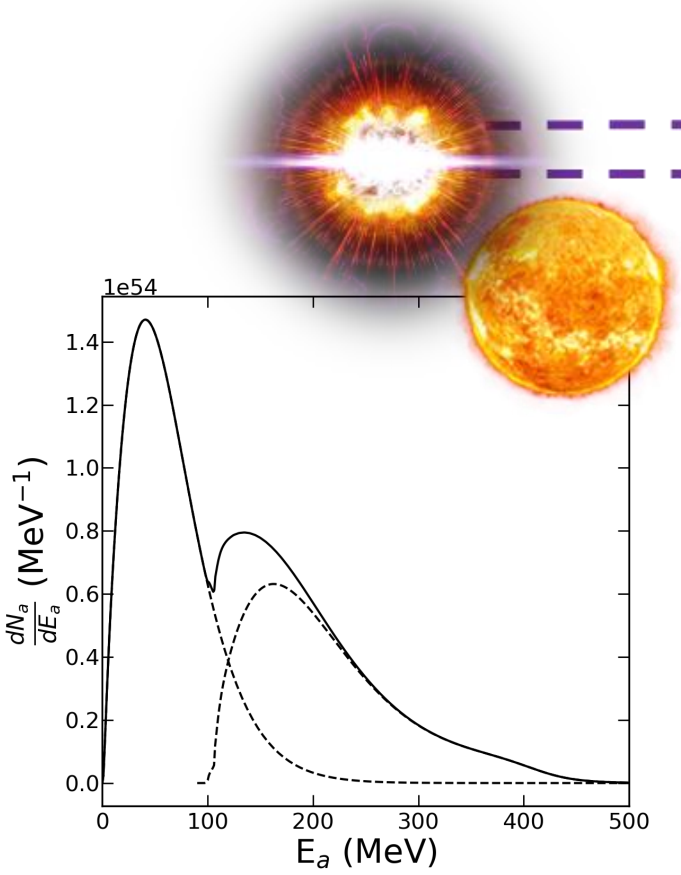
Bremsstrahlung



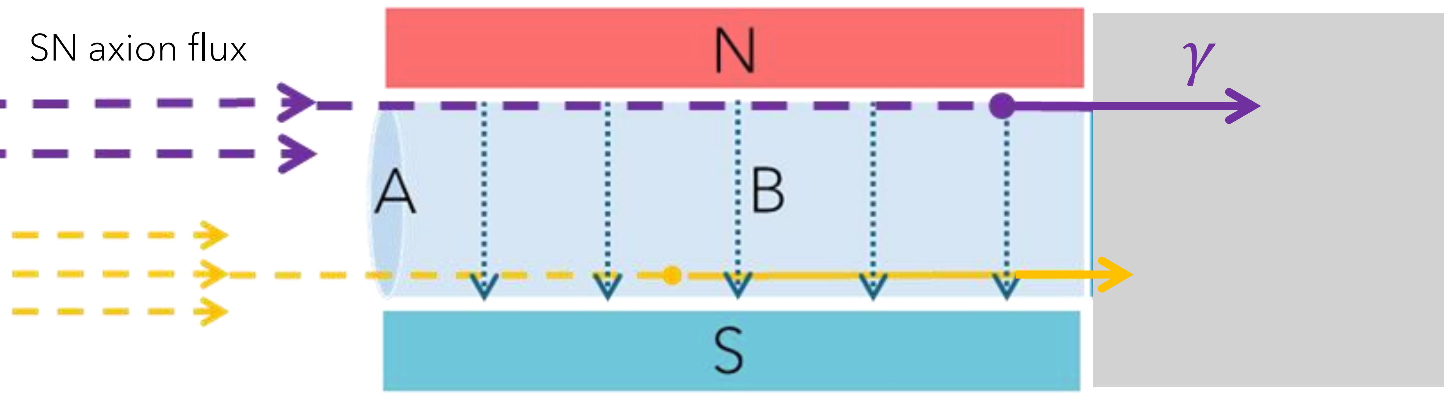
Pion Compton



$$\boxed{g_{a\gamma}^2 \cdot g_{aN}^2 \quad \propto \quad D^2 \quad \times \quad \epsilon^{-1} \quad \times (B \cdot L)^{-2} \cdot A^{-1}}$$

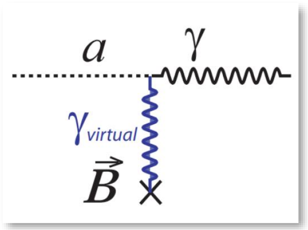


SN axion flux



High energy
gamma
detector

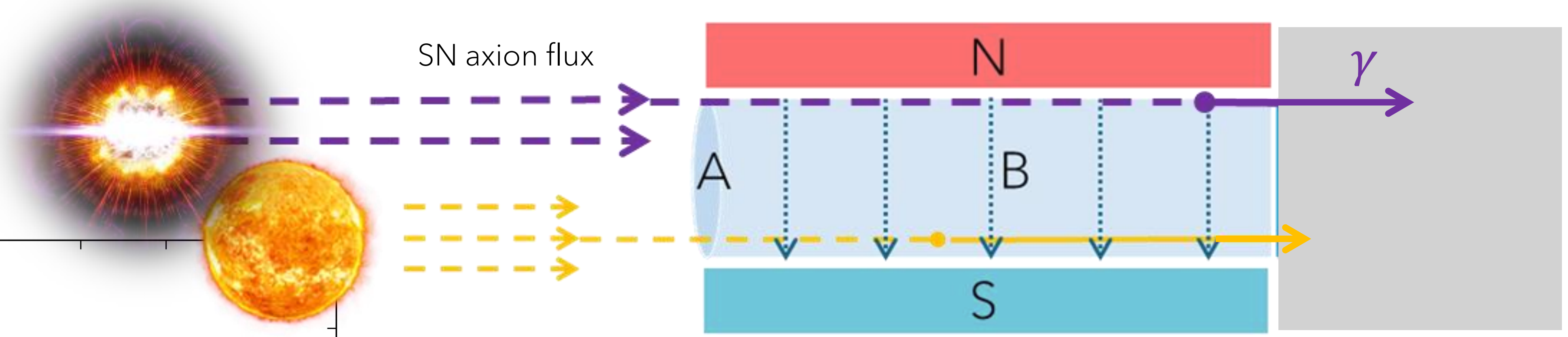
Detection: conversion of axions into photons in the presence of a magnetic field



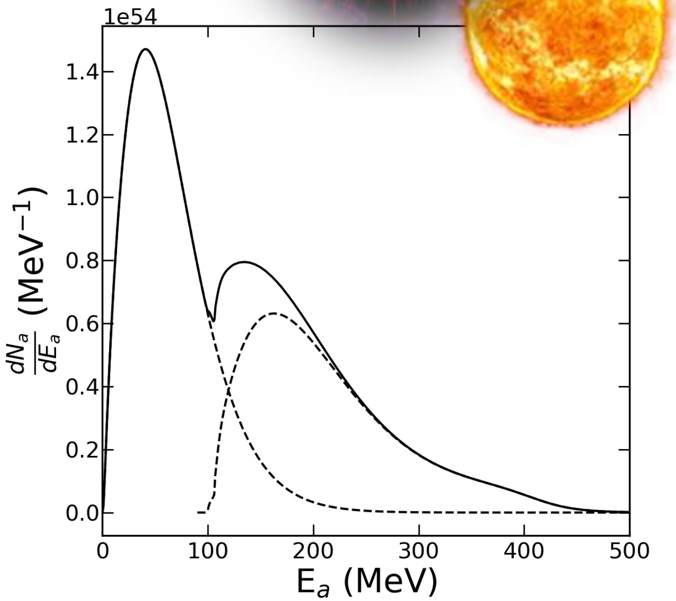
$$\boxed{P_{a\to\gamma} = \frac{1}{4}\left(g_{a\gamma}BL\right)^2}$$

*in vacuum

$$\boxed{g_{a\gamma}^2 \cdot g_{aN}^2 \propto \underbrace{D^2}_{\text{SN candidates } D<300\text{ pc}} \times \epsilon^{-1} \times (B\cdot L)^{-2} \cdot A^{-1}}$$



High energy gamma detector



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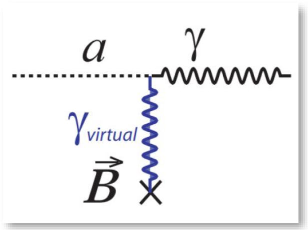

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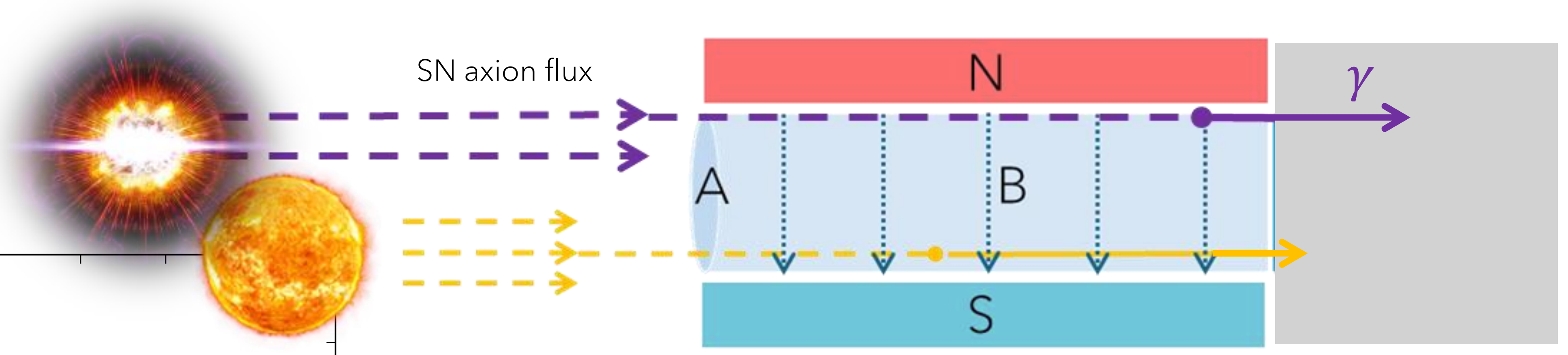
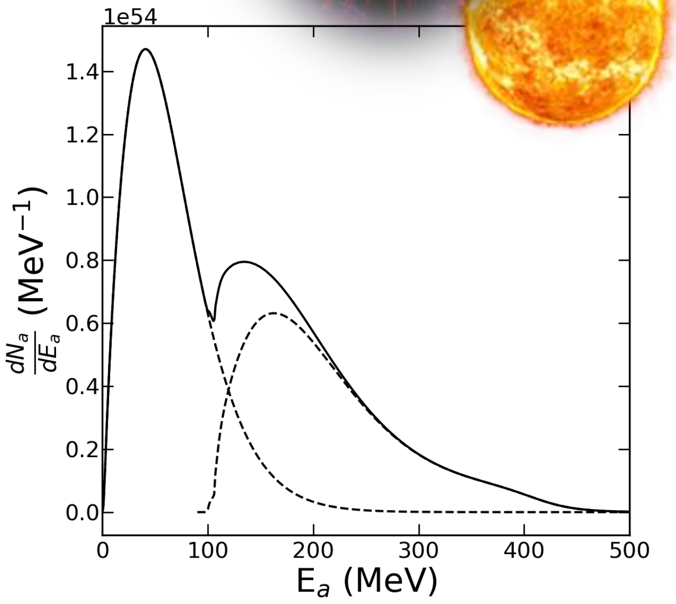
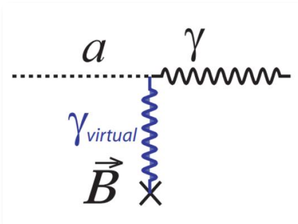


High energy gamma detector



Detection: conversion of axions into photons in the presence of a magnetic field



$$\boxed{P_{a\to\gamma} = \frac{1}{4}\left(g_{a\gamma} B L\right)^2}$$

*in vacuum

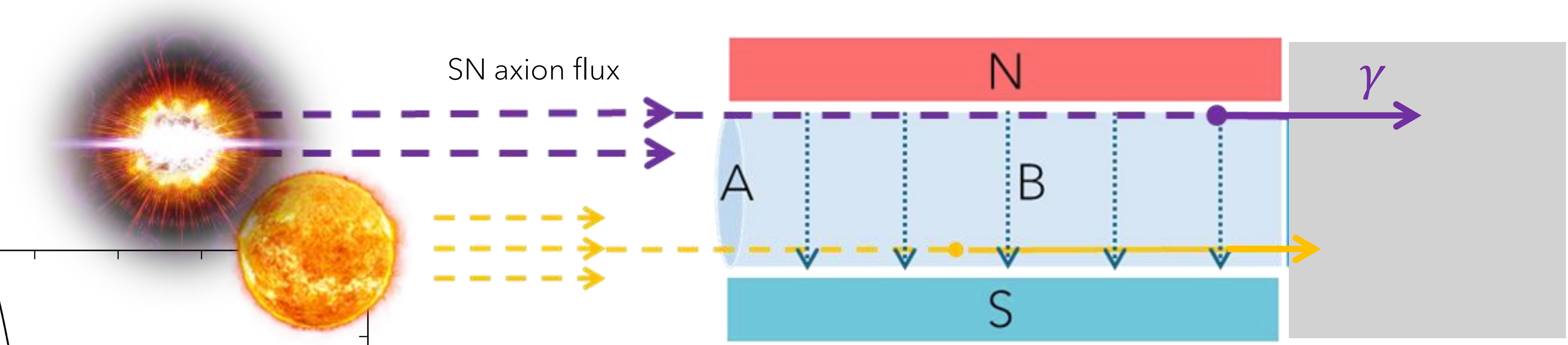
$$g_{a\gamma}^2 \cdot g_{aN}^2 \propto D^2 \times \epsilon^{-1} \times (B \cdot L)^{-2} \cdot A^{-1}$$

SN candidates D < 300 pc

detector

magnet

	B (T)	L (m)	A (m²)
BabyIAXO	2	10	0.77
IAXO	2.5	20	2.3
IAXO+	3.5	22	3.9



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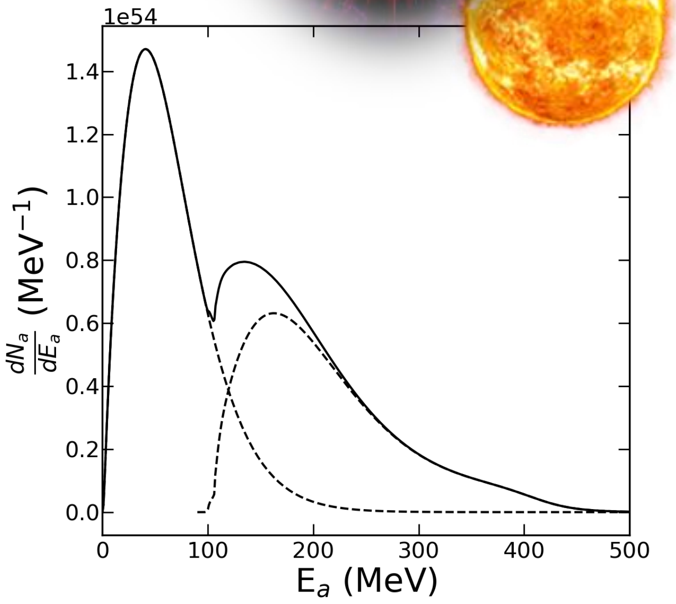

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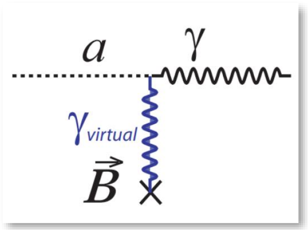


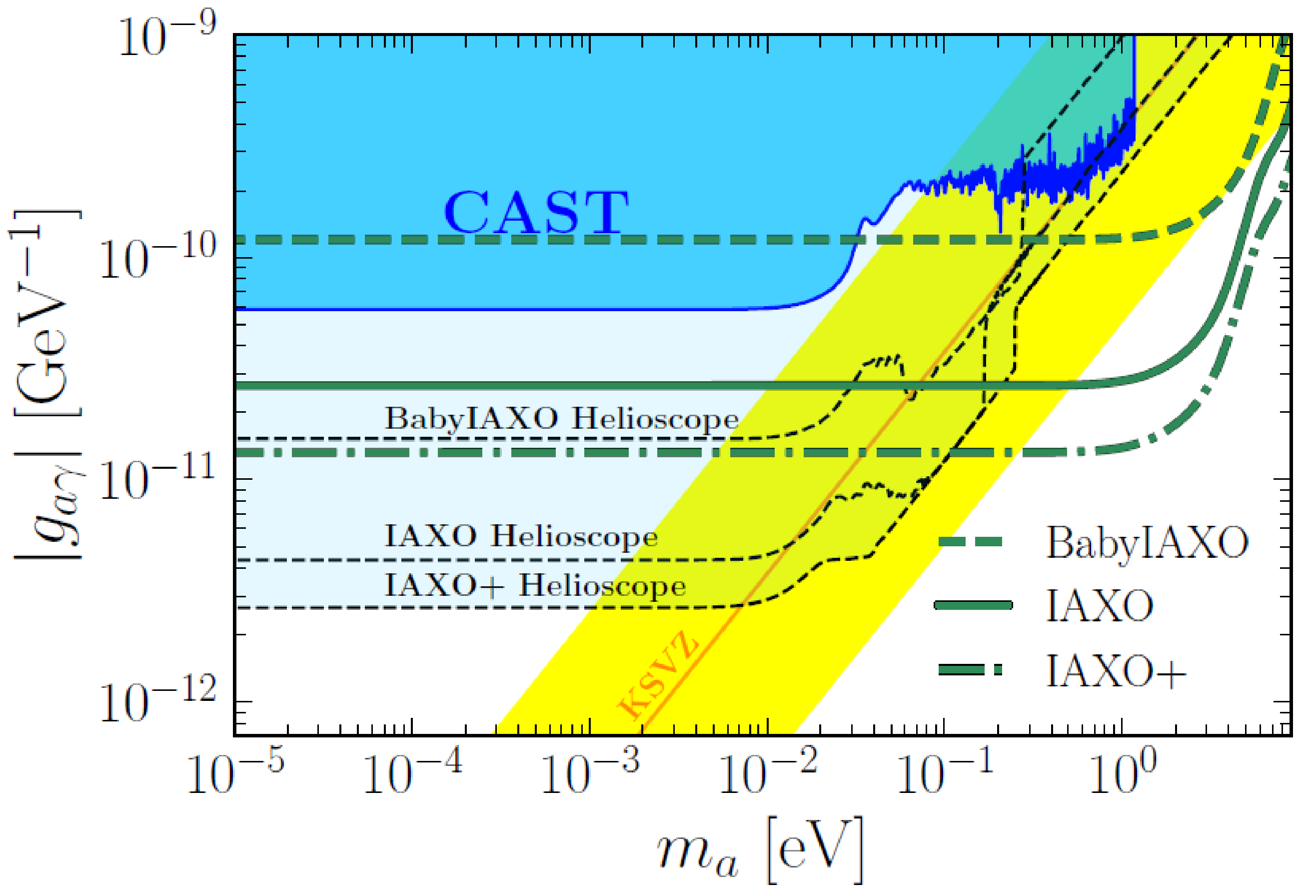
$$P_{a\rightarrow\gamma} = \frac{1}{4}\left(g_{a\gamma}BL\right)^2$$

*in vacuum

IAXO as a SN-Scope

- Detection potential outside the reach of solar axion searches
- Coherence region extends to 1 eV

(d) $NN + \pi N$: Spica D = 77 pc



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- NN as only production mechanism lead to more stringent limits

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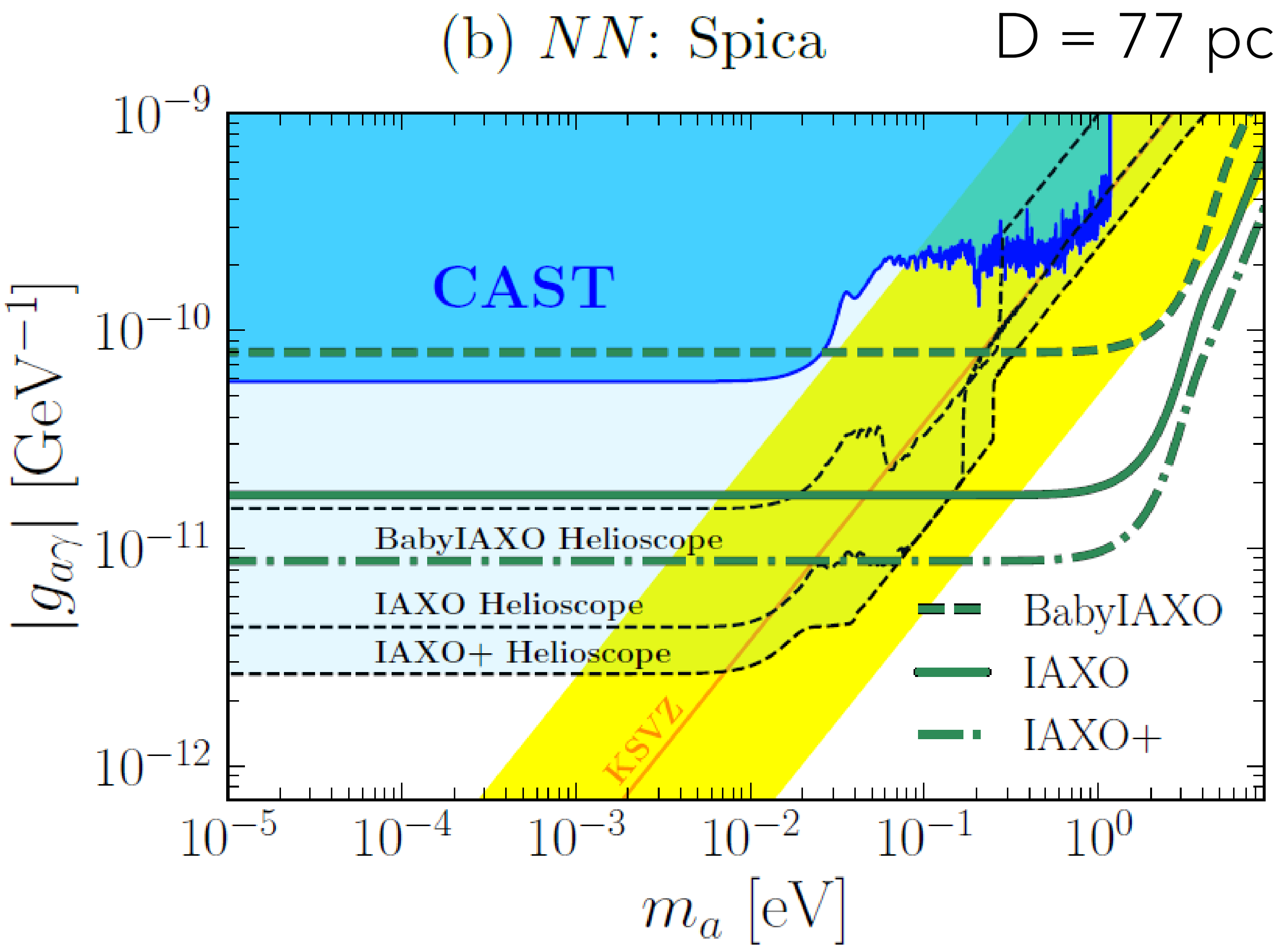


$$NN\colon\ g_{aN} = 10^{-9}$$

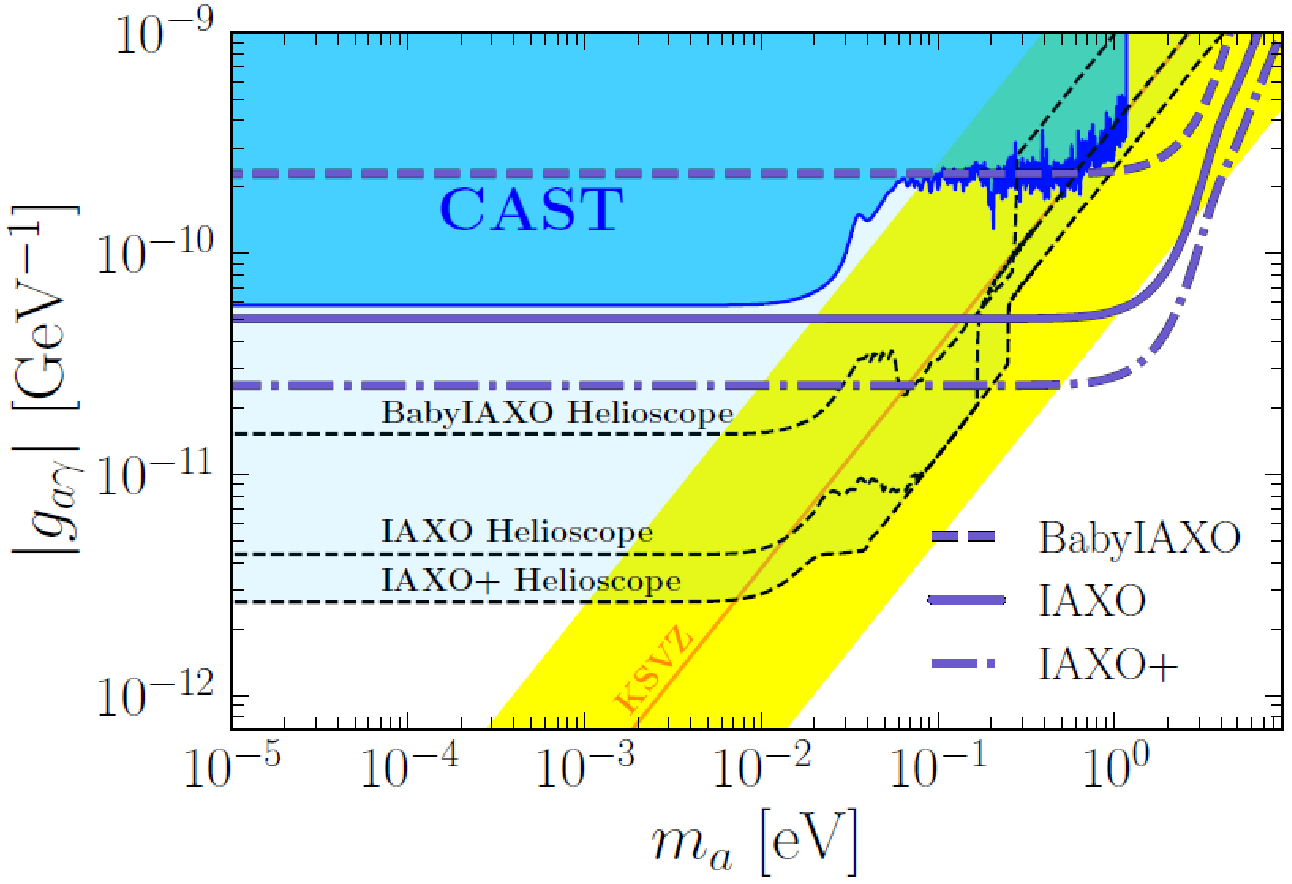
$$NN + N\pi\colon\ g_{aN} = 5 \cdot 10^{-10}$$

- Detection potential outside the reach of solar axion searches
- Coherence region extends to 1 eV
- NN as only production mechanism lead to more stringent limits
- The closest the candidate, more restrictive limits

$$NN\colon\ g_{aN} = 10^{-9}$$

$$NN + N\pi\colon\ g_{aN} = 5 \cdot 10^{-10}$$

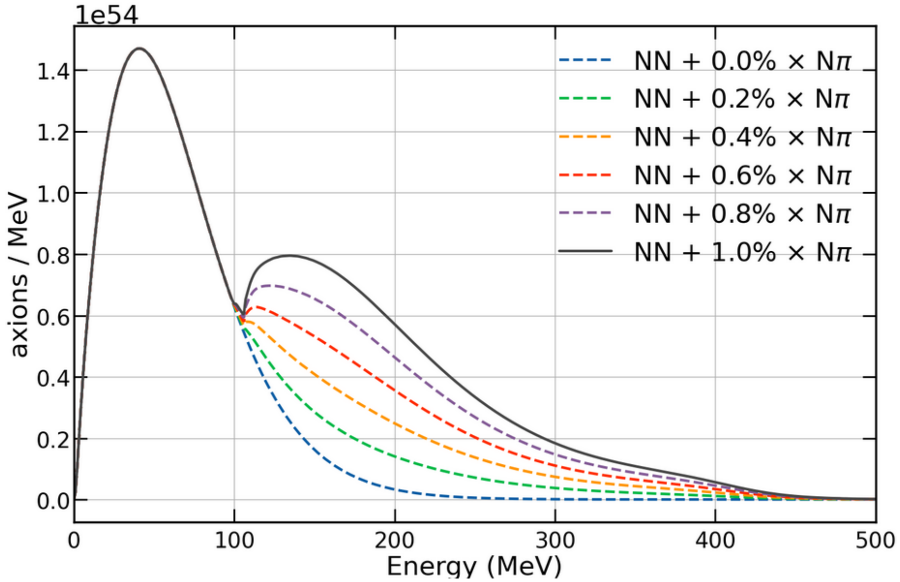
(a) NN: Betelgeuse D = 222 pc



- Fraction of pions in the PN star is still under investigation
- The number of axions emitted by pion conversion is highly dependent on the pion abundance in the SN core

$$\frac{dN_a}{dE} = A g_{aN}^2 [F_{NN}(E_a) + \boldsymbol{\delta} F_{\pi N}(E_a)]$$

Can we say something in case of detection?



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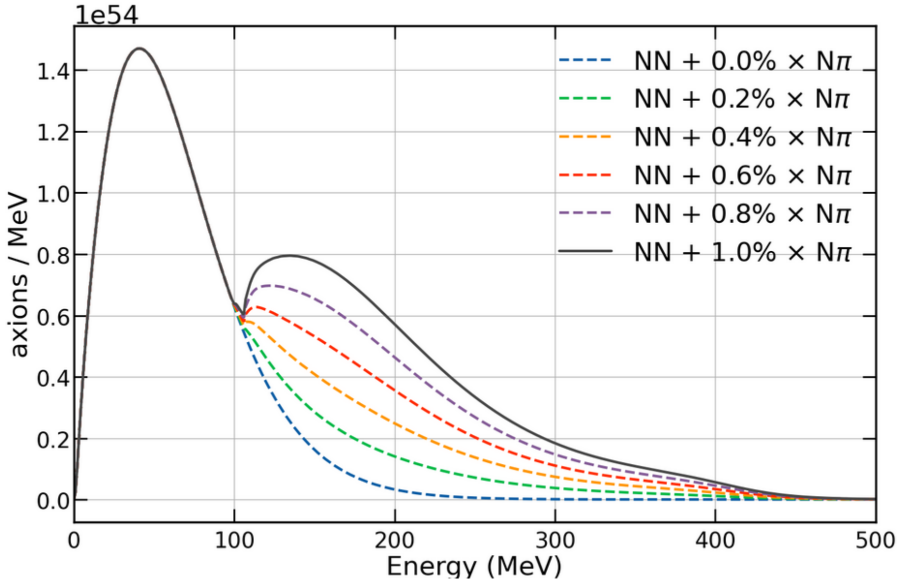

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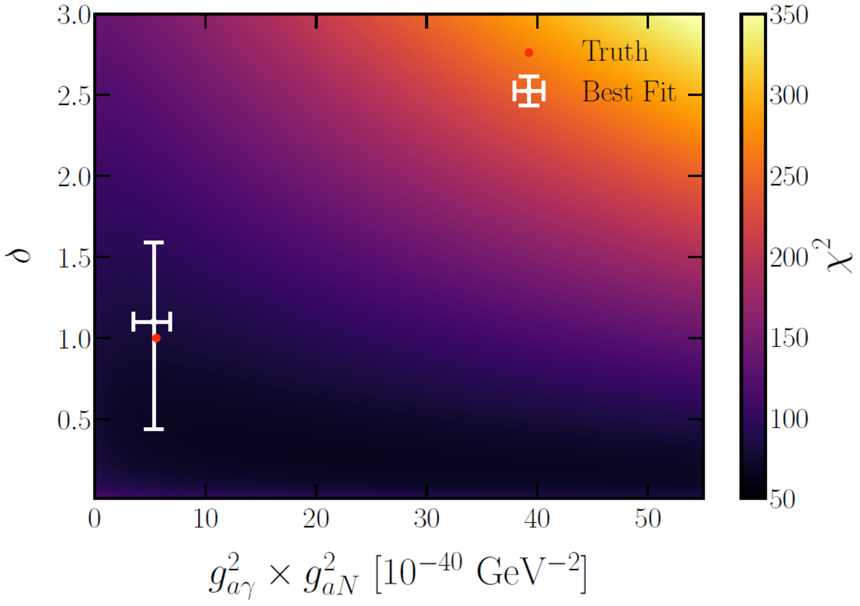

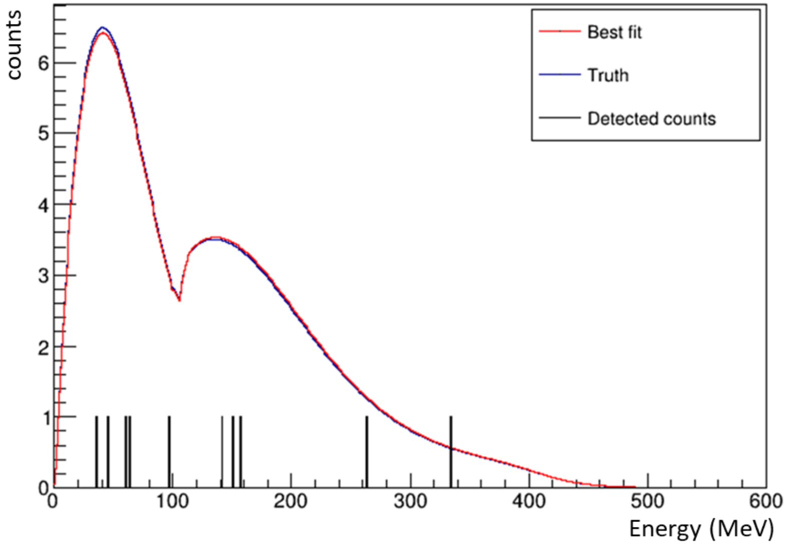

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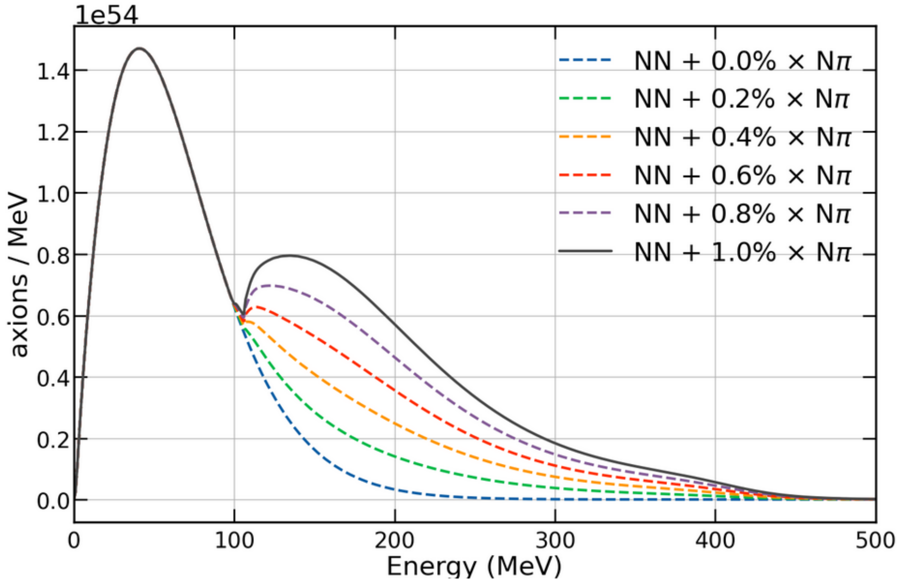

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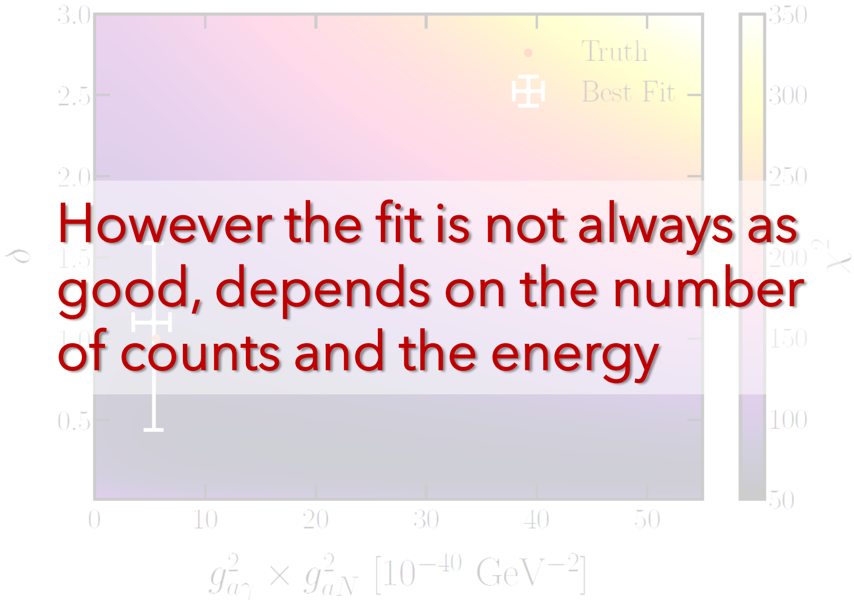
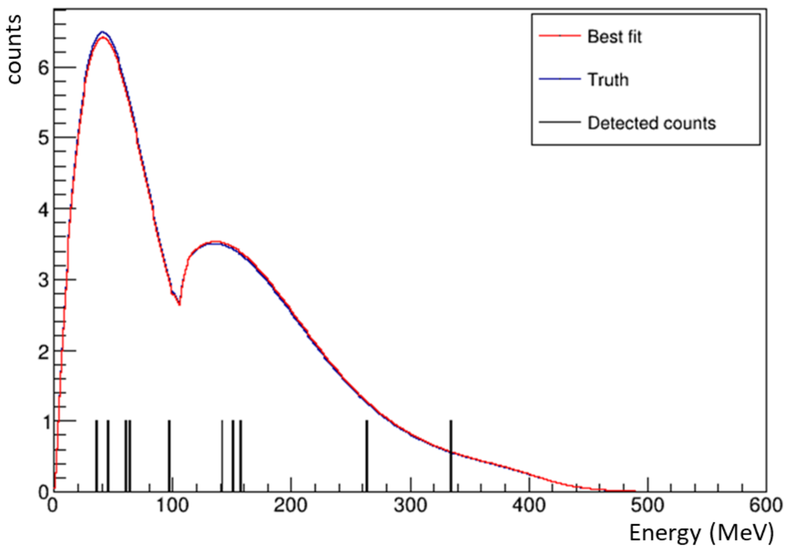
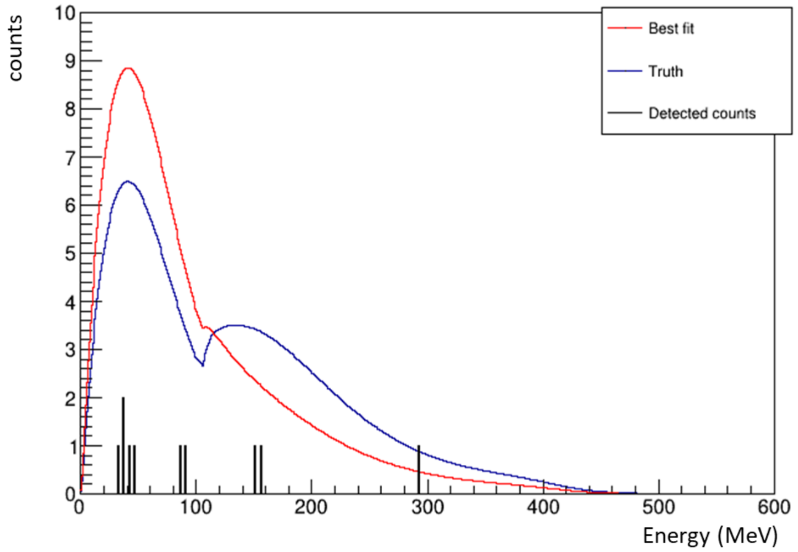


However the fit is not always as good, depends on the number of counts and the energy

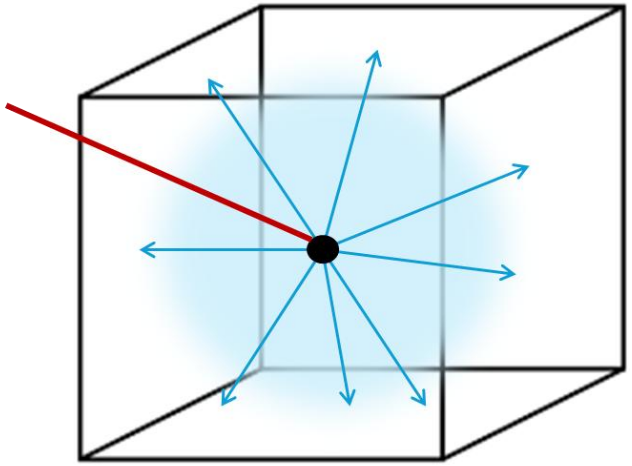


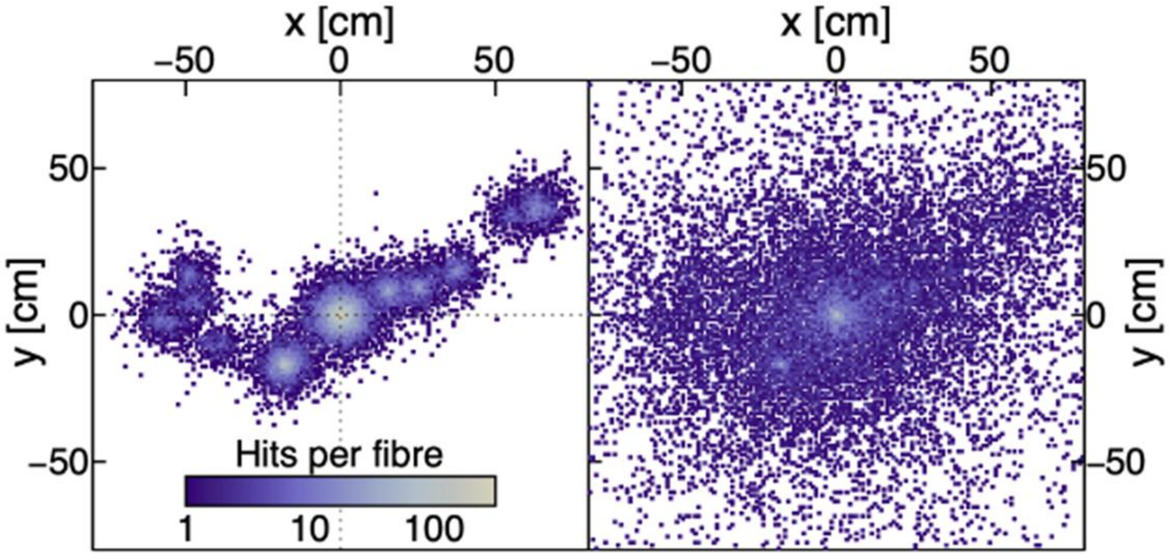


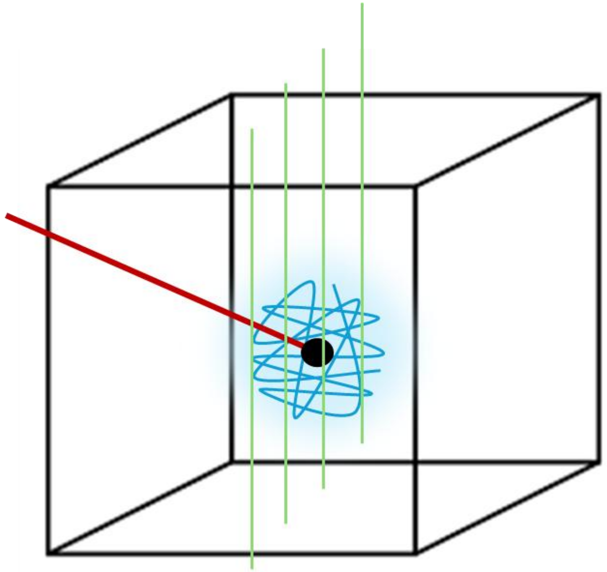
- Technology choice for the HE gamma detector: LiquidO

+ Active and passive shielding for cosmic rays/neutrons

- ❑ Short scattering length: light confinement
- ❑ Spatial resolution capabilities
- ❑ Particle identification
- ❑ Dopand to enhance efficiency

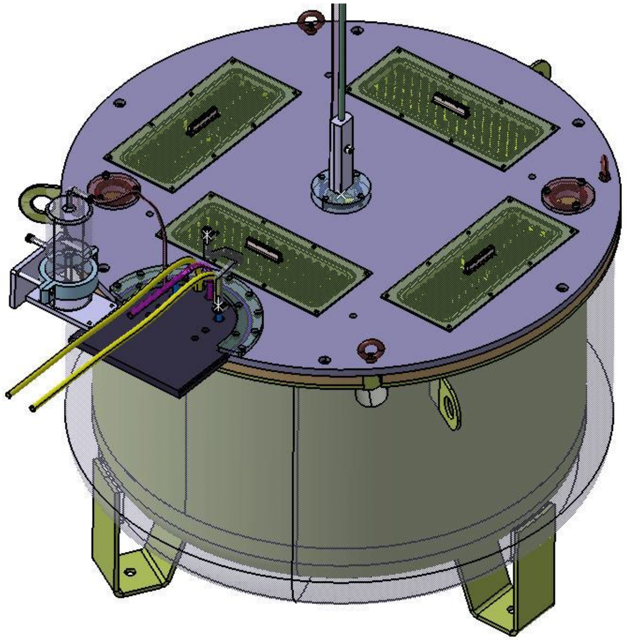






Development of a LiquidO prototype in Zaragoza

- Generic R&D in a medium size prototype (~250 l)
- 256/512 readout channels
- Test different fibre pitch and layout
- Study of different dopant loading



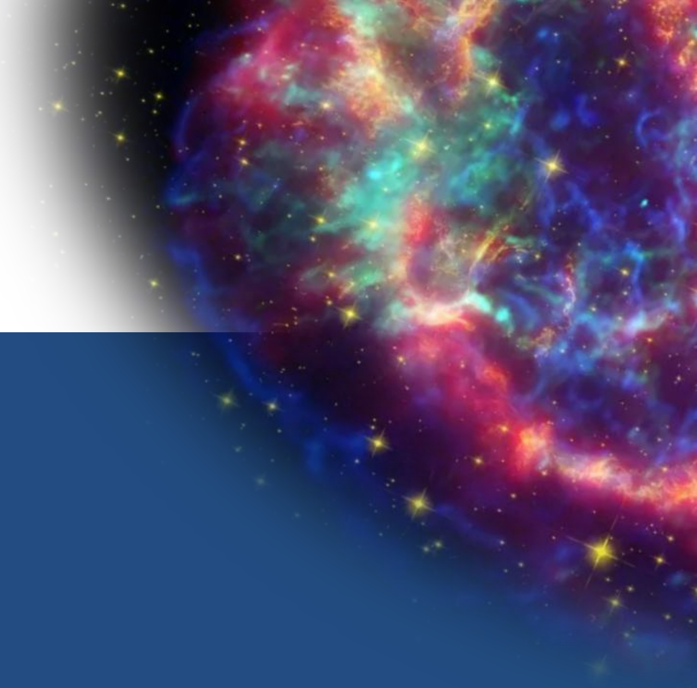
- ❑ Design completed
- ❑ Procurement and assembly of the mechanical parts on-going

Summary and conclusions

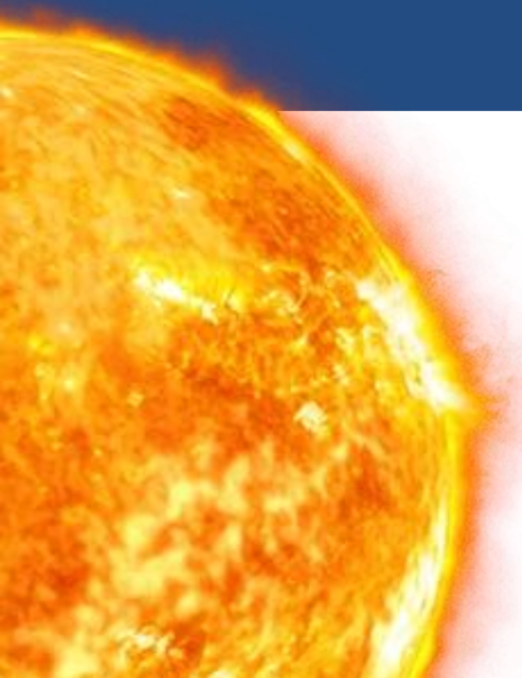
- IAXO will be a next generation helioscope with its intermediate stage BabyIAXO
- BabyIAXO will have competitive results on solar axions and could explore more physics cases

- Micromegas is the baseline technology for BabyIAXO
- On-going R&D with different prototypes to explore the necessary techniques to reach the ultra-low background goals for BabyIAXO

- Realistic capabilites of BabyIAXO and IAXO to detect SN axions
  - Discovery potential in m_a~eV
  - Access to regions of the parameter space not accessible through solar observation



Thank you!!



125 scientists from 21 full member institutes + 5 associate institutions

Full members: Kirchoff Institute for Physics, Heildelberg 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) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | MPP Munich (Germany) | U. Polytechnical of Cartegena (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)

Acknowledgements

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In particular, we acknowledge support from:

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European Research Council
Established by the European Commission

AGENCIA ESTATAL DE INVESTIGACIÓN

Funded by the European Union
NextGenerationEU

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

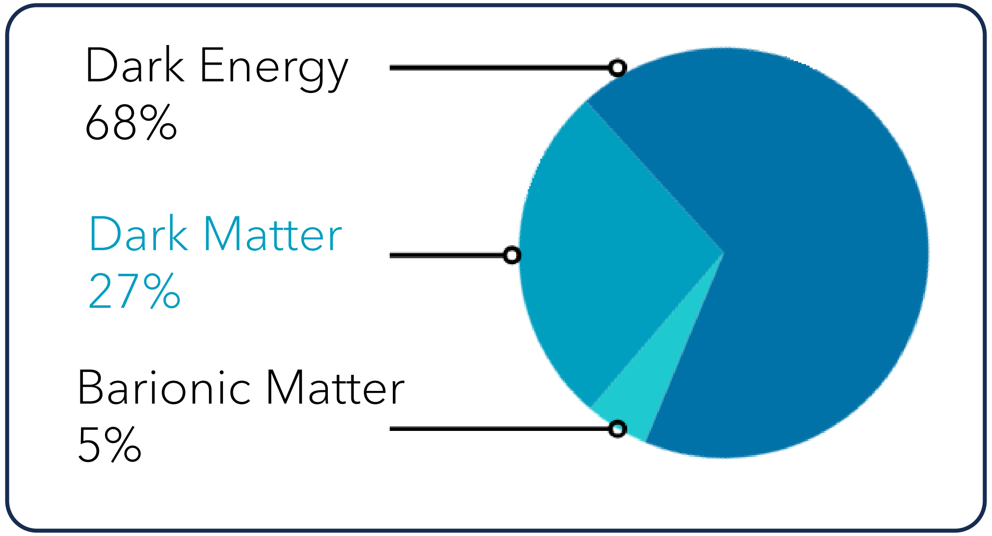
Plan de Recuperación, Transformación y Resiliencia

GOBIERNO DE ARAGON

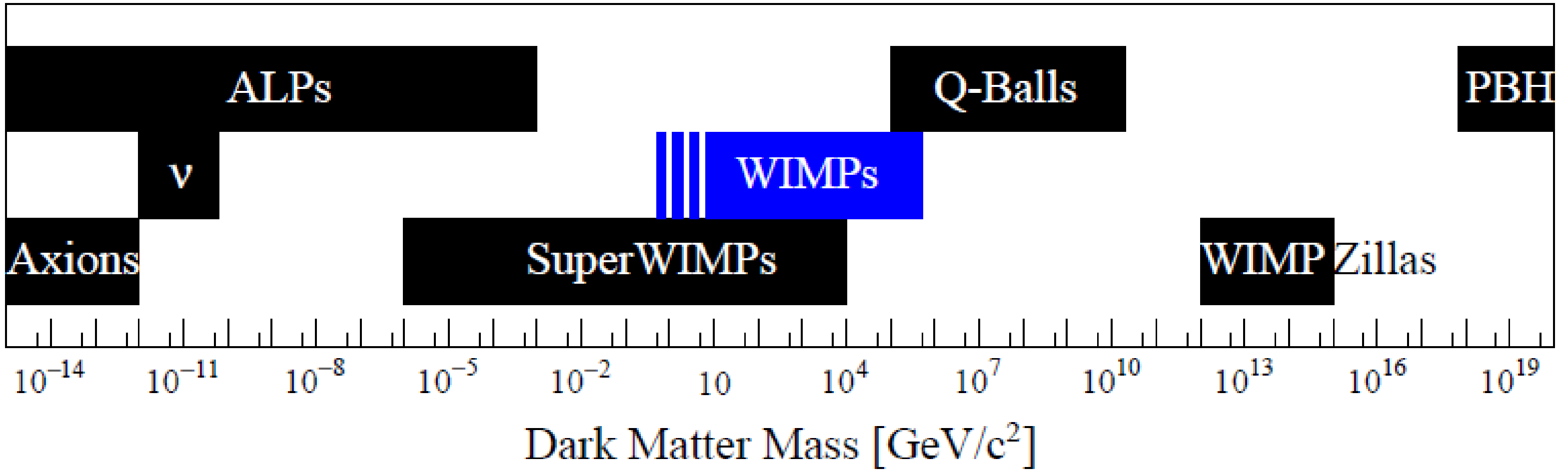
Backup slides

Dark matter

What we know about DM?



- Mass
- Non baryonic
- Weakly coupled to the photon
- Weakly interacting with baryons



Axions

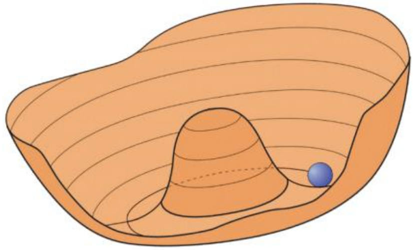
- Hypothetical particles proposed to solve the strong CP problem

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G_a^{\mu\nu}}$$

θ induces large nEDM not observed experimentally!

$$d_n < 2.9 \cdot 10^{-26} e \cdot cm$$

- Peccei-Quinn mechanism (1977): θ is a dynamical field → Axion
  - Pseudo Nambu-Goldstone boson
  - Spin = 0
  - Neutral

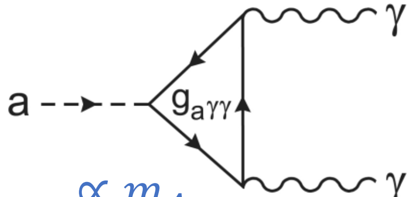


Generic

- Gluon coupling
- Mass $m_A = 6\mu eV \dfrac{10^{12} GeV}{f_A}$

Generic (but value model dependent)

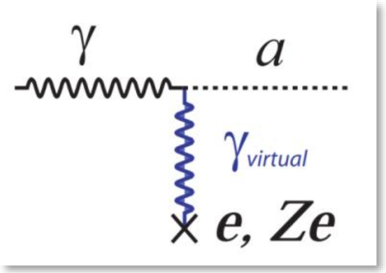
- Photon coupling



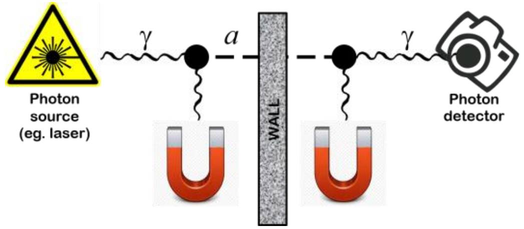
$g_{a\gamma\gamma} \propto m_A$

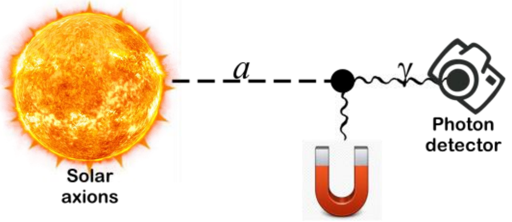
Electron, meson, nucleon couplings …

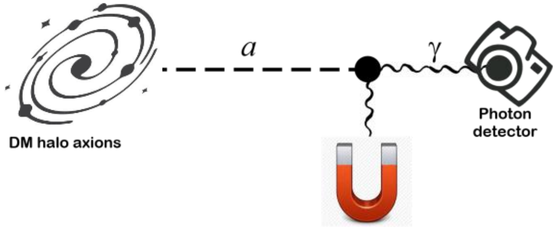
Most experimental efforts based on the coupling with photons (Primakoff effect)



Light-shining-through-wall experiments	OSQAR, CROWS, ALPS I, ALPS II …	Very low model dependent
Helioscopes	SUMICO, CAST, BabyIAXO, IAXO	Low model dependent
Haloscopes	ADMX, HAYSTAC, RADES, CAPP, ALPHA, CASPEr, ORGAN, MADMAX…	Highly model dependent



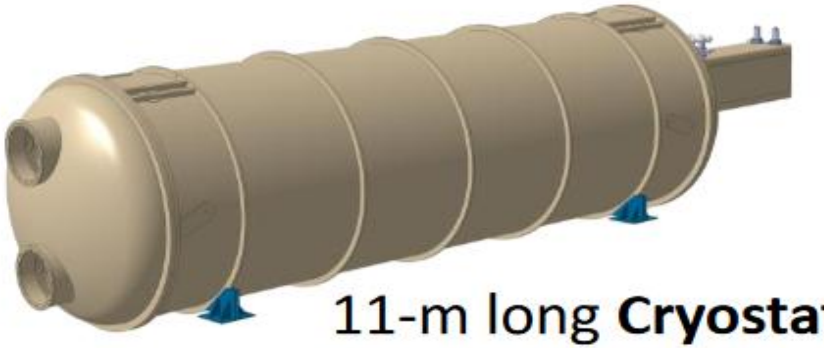


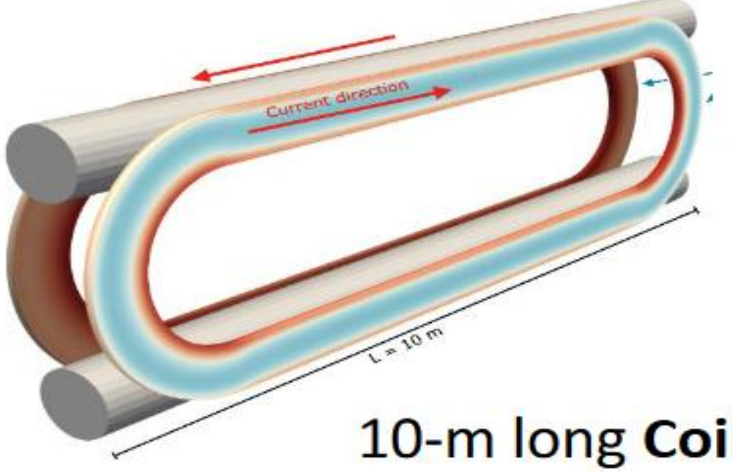


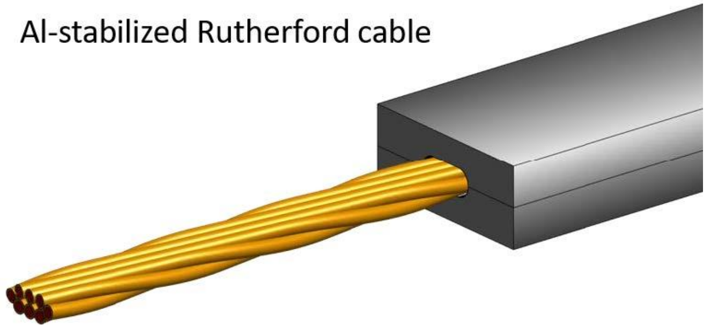
$$\boxed{P_{a\to\gamma} = \frac{1}{4}\left(g_{a\gamma}BL\right)^2}$$

*in vacuum

- Cold mass at 4.5 K
- Cryogenic system design by CERN and DESY
- Aluminium stabilized Rutherford cable
- STATUS: Cable parts are being tested





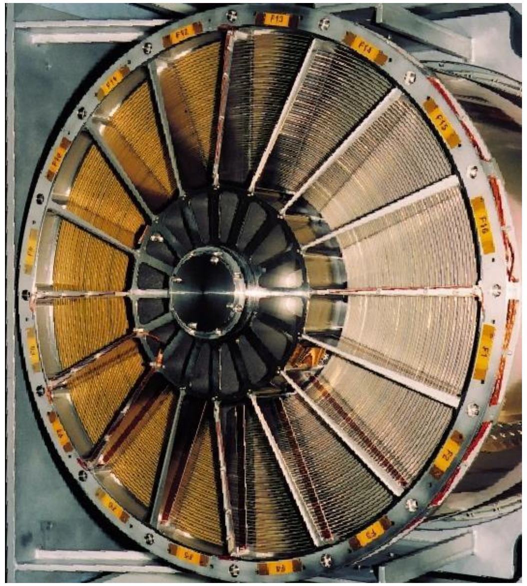


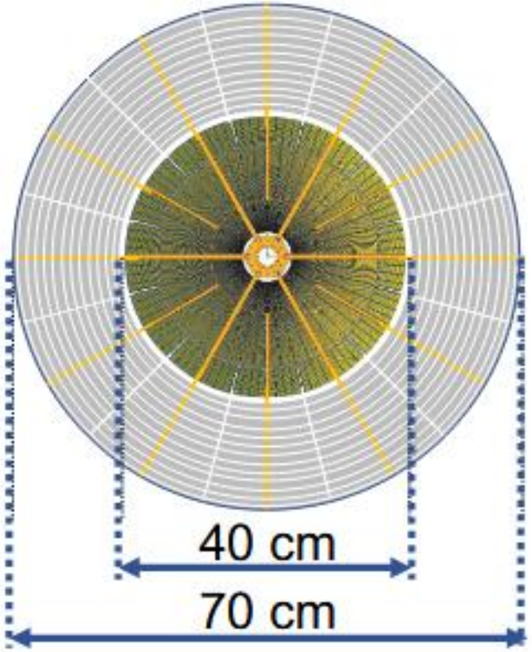
BabyIAXO optics

$$\boxed{\text{FOM} = \varepsilon_0 \alpha^{-1/2}}$$

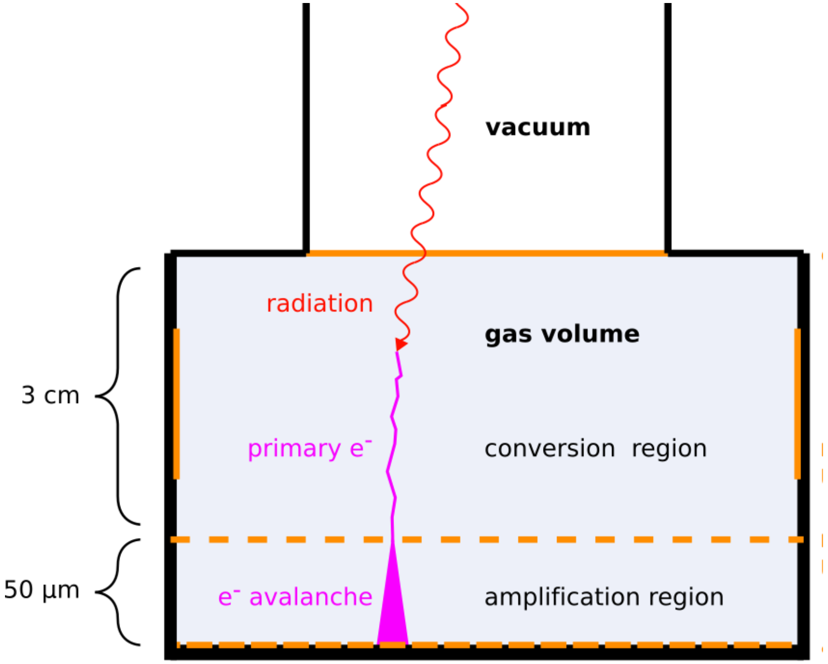
- XMM optics built for the XMM-Newton space mission (1999)
  - To be tested at PANTER
- Custom optics consisting of an inner optics and outer optics
  - Inner: NuSTAR-like optics from thermally formed glass
  - Outer: Wolter 1 optics from cold-slumped Willow glass

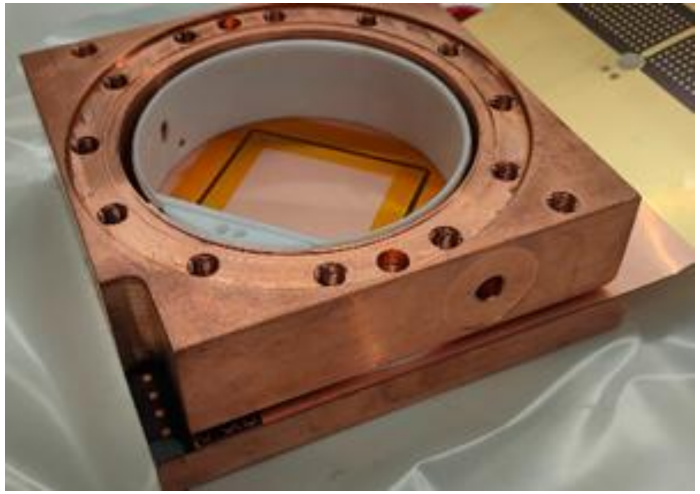
  - Glass inventory finalised and prototype manufacturing is on going





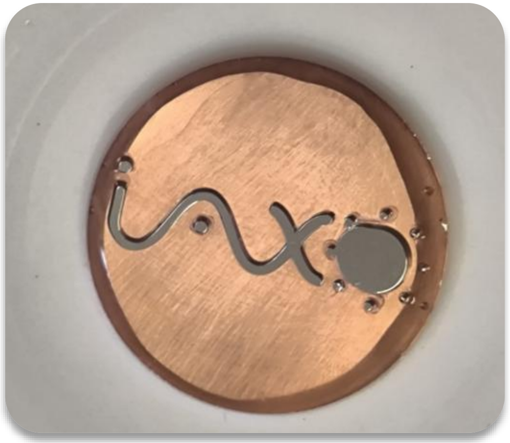
BabyIAXO Micromegas detectors

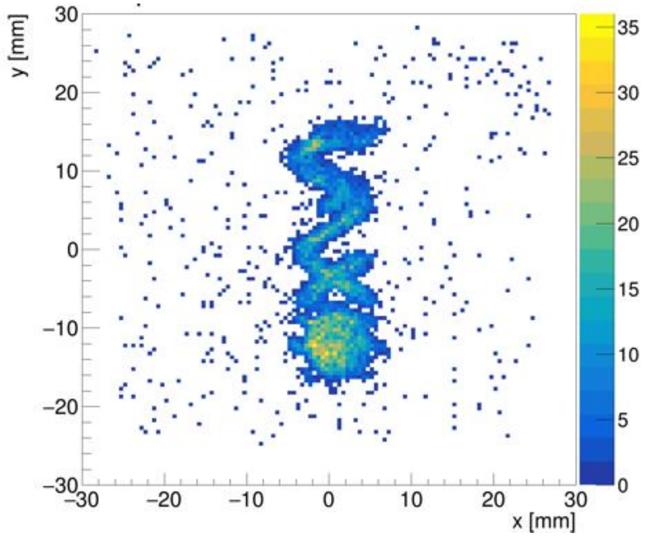




- 3 cm drift distance Gaseous Time Projection Chamber
- Microbulk Micromegas readout
  - 50 µm amplification gap
  - 120 x 120 strips (6 x 6 cm^2)

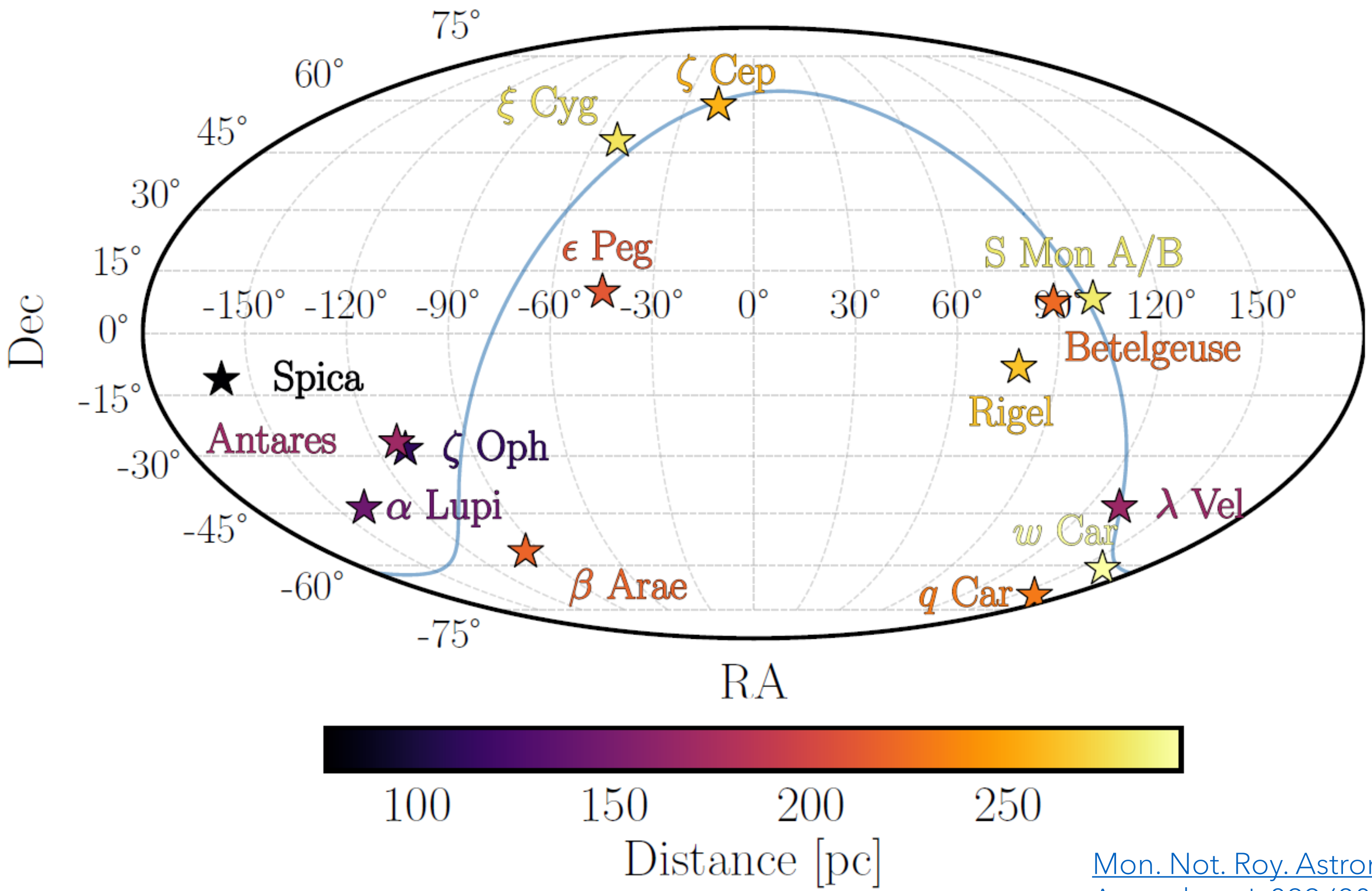
✓ Very homogeneous amplification gap, uniform gain
✓ Microbulk: intrinsically radiopure
✓ Good energy and spatial resolution
✓ Pixelized readout gives topological information





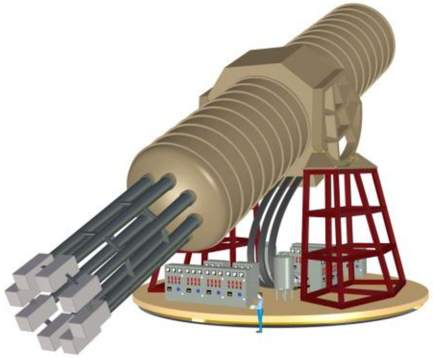
Supernova candidates

- SN axion flux very intense but short in time (~10 s)
- Considered SN candidates in D < 300 pc

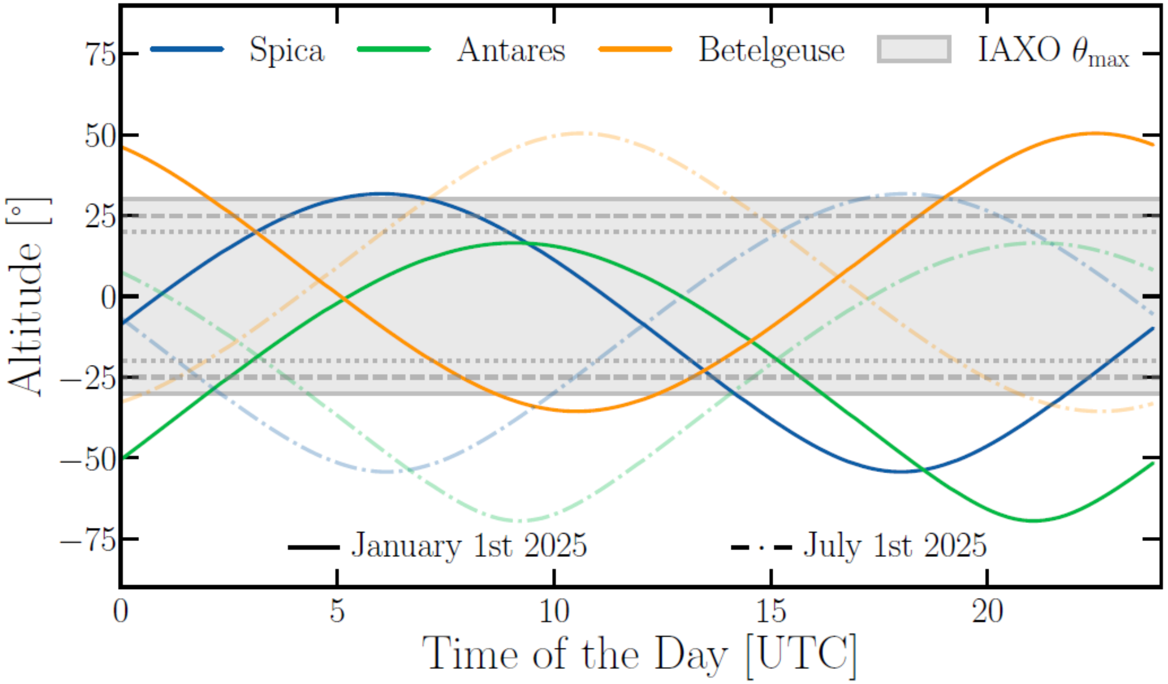


Mon. Not. Roy. Astron. Soc. 529 (2024) 3630 [2307.08785]
Astrophys. J. 899 (2020) 153 [2004.02045]

- Pointing to the Sun → SN
- IAXO tracking system based on CTA: fast response (90 s)



- Observation time fraction depends on the tracking range of IAXO



	Observation time fraction for IAXO		
	$\theta_{max} = 20°$	$\theta_{max} = 25°$	$\theta_{max} = 30°$
Spica 77 pc	43 %	63 %	70 %
Betelgeuse 222 pc	41 %	54 %	74 %

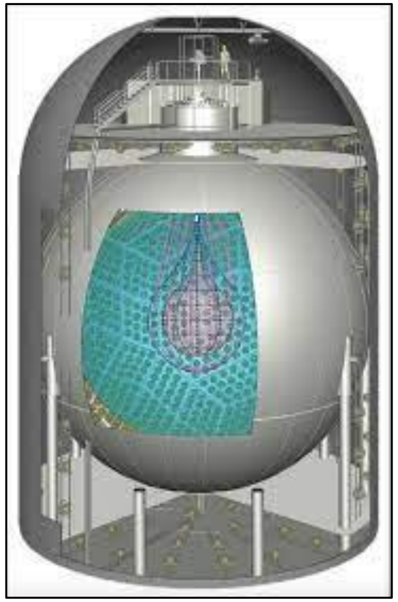
IAXO as a SN-Scope: Prediction

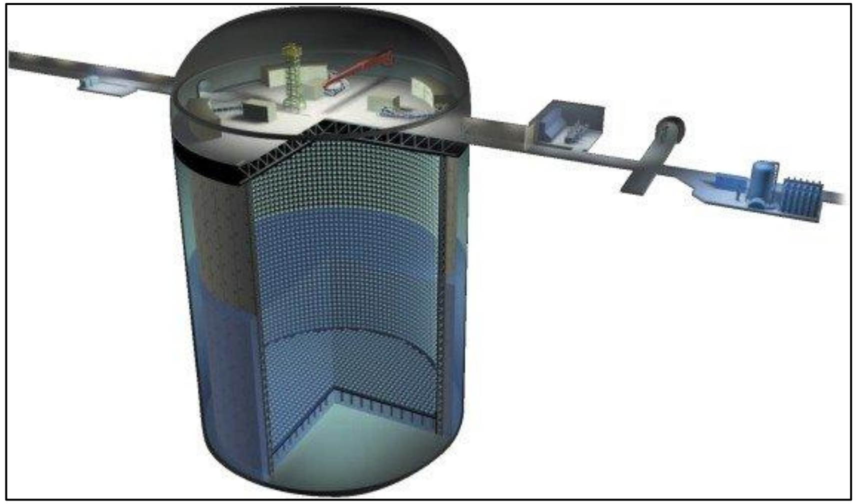
10.3847/1538-4357/ab99a6
2404.09920

- Observation of pre-SN neutrinos

- KamLAND + SuperKamiokande combined analysis could detect pre-SN neutrinos 12 h in advance
  - Directional information is more limited:
    - Inverse beta decay detectors
    - Angular resolution 60° for 200 events

- Future: SuperNova Early Warning System, SNEWS 2.0
  - Better directional information





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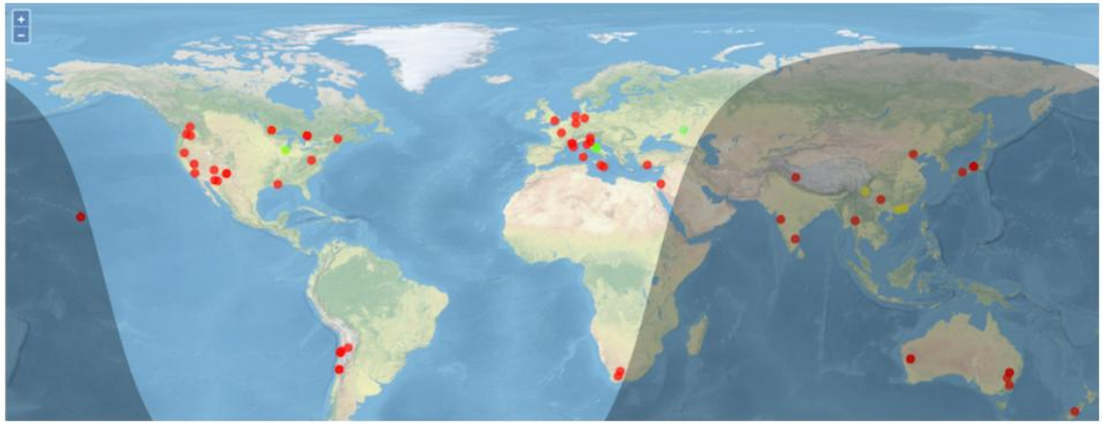
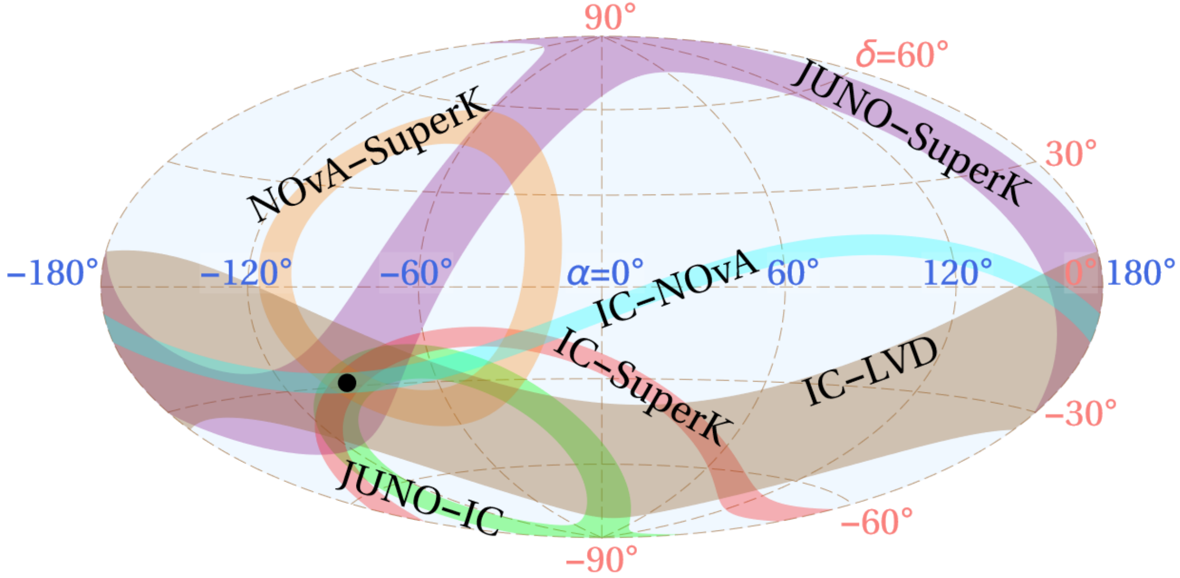
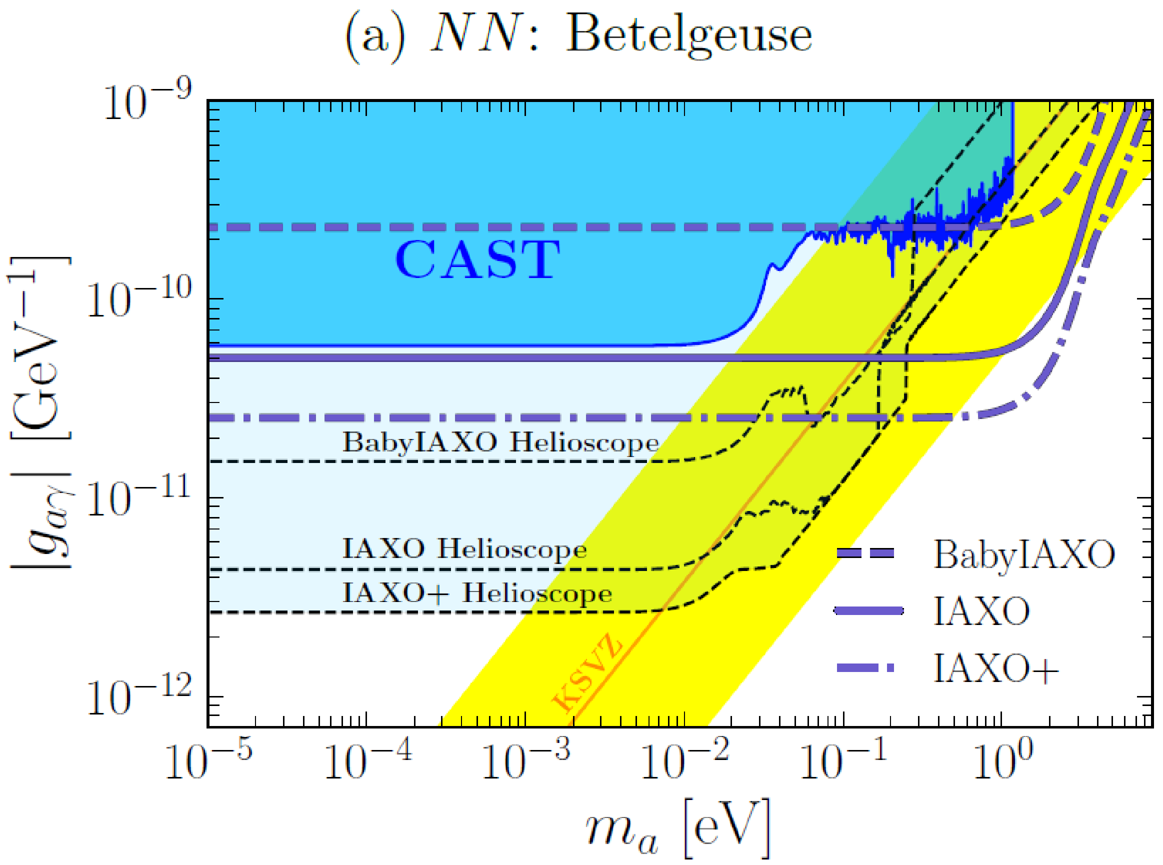
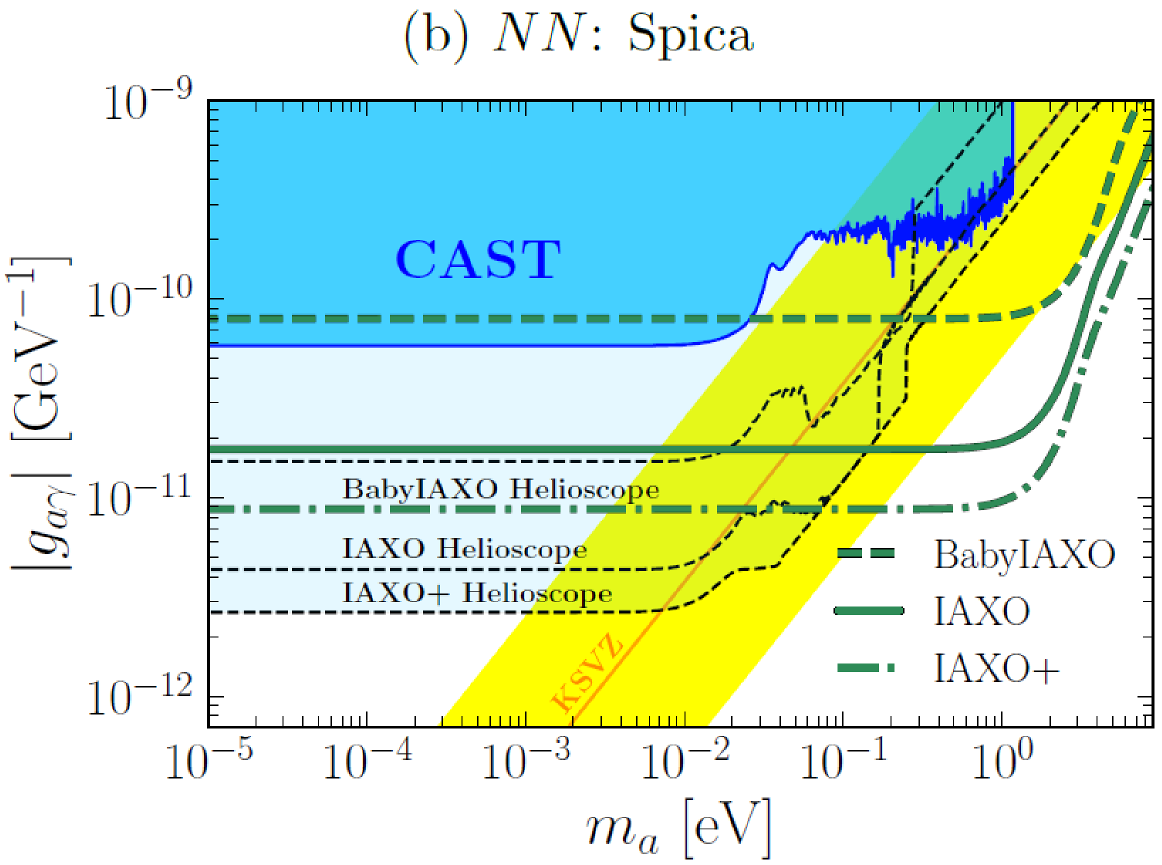




IAXO as a SN-Scope: Sensitivity prospects

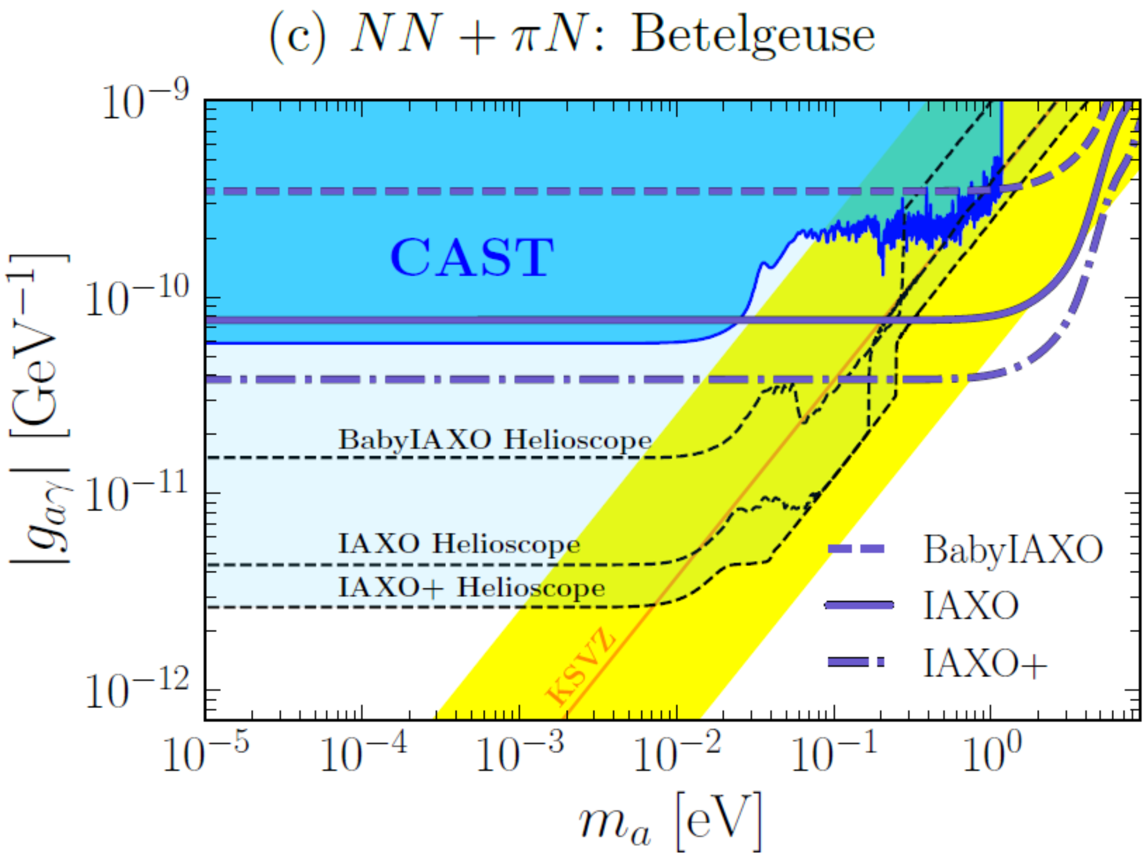
$g_{aN} = 10^{-9}$

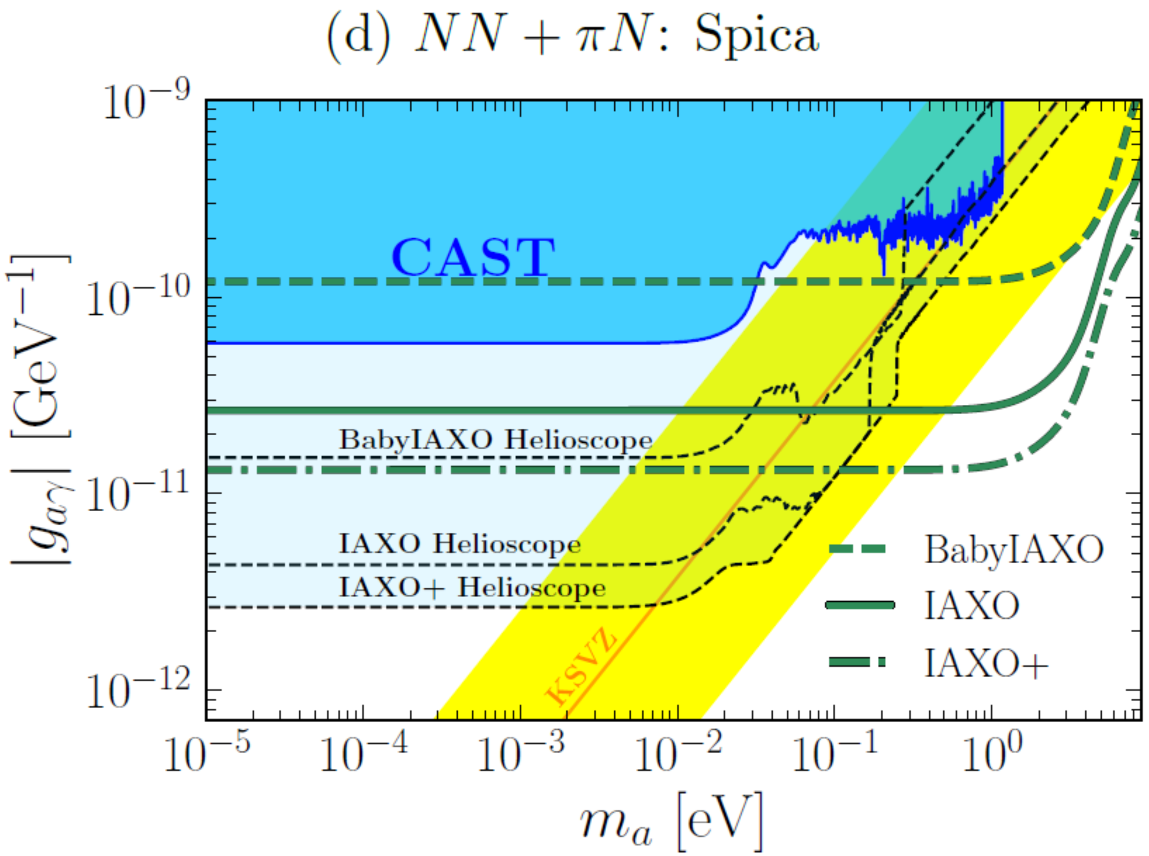


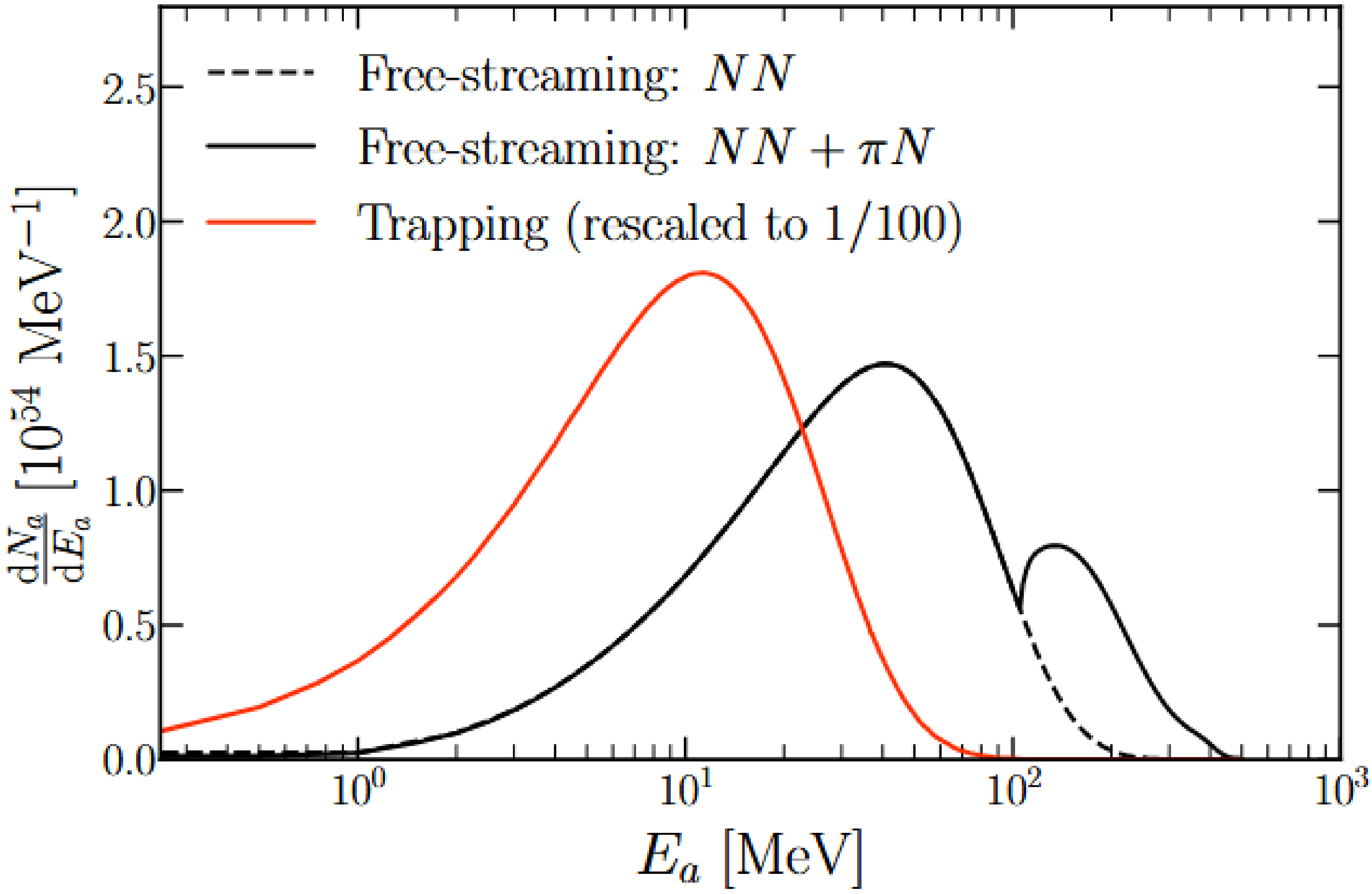


IAXO as a SN-Scope: Sensitivity prospects

$g_{aN} = 5 \cdot 10^{-10}$

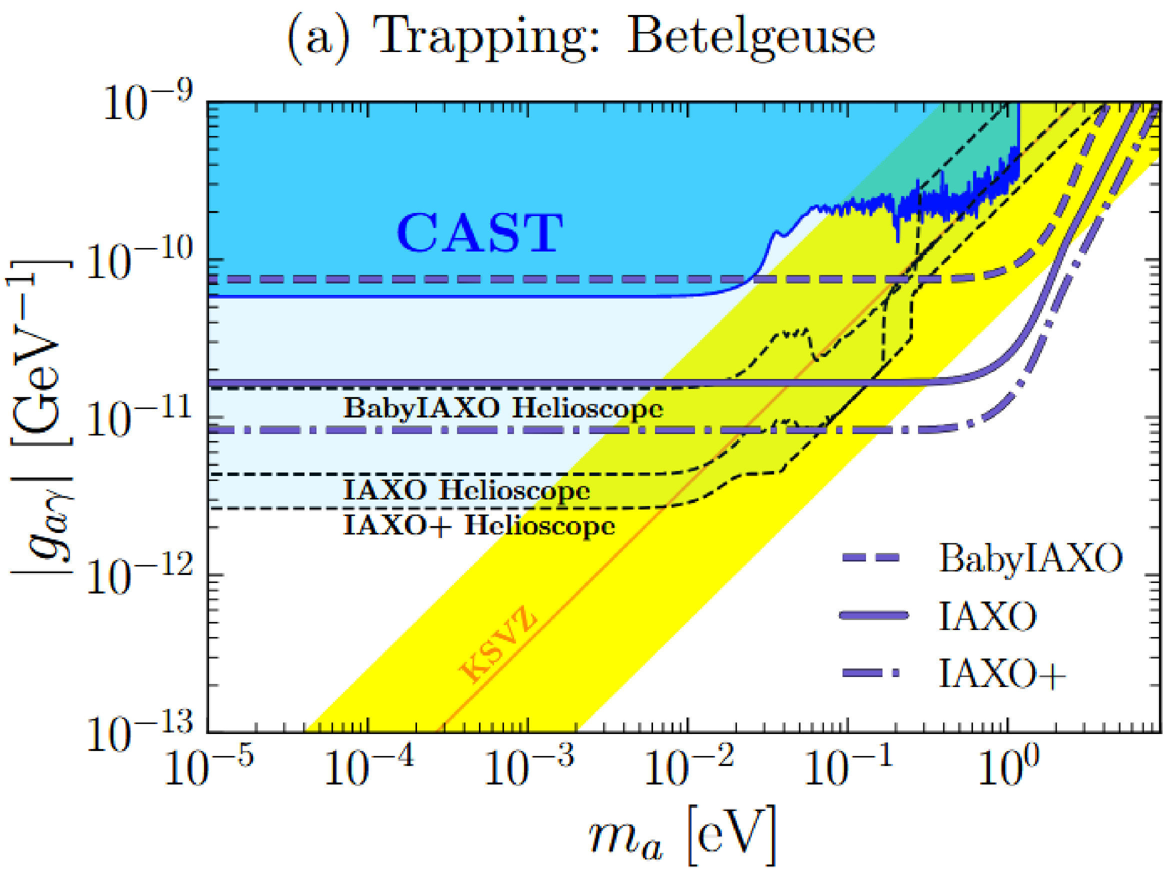


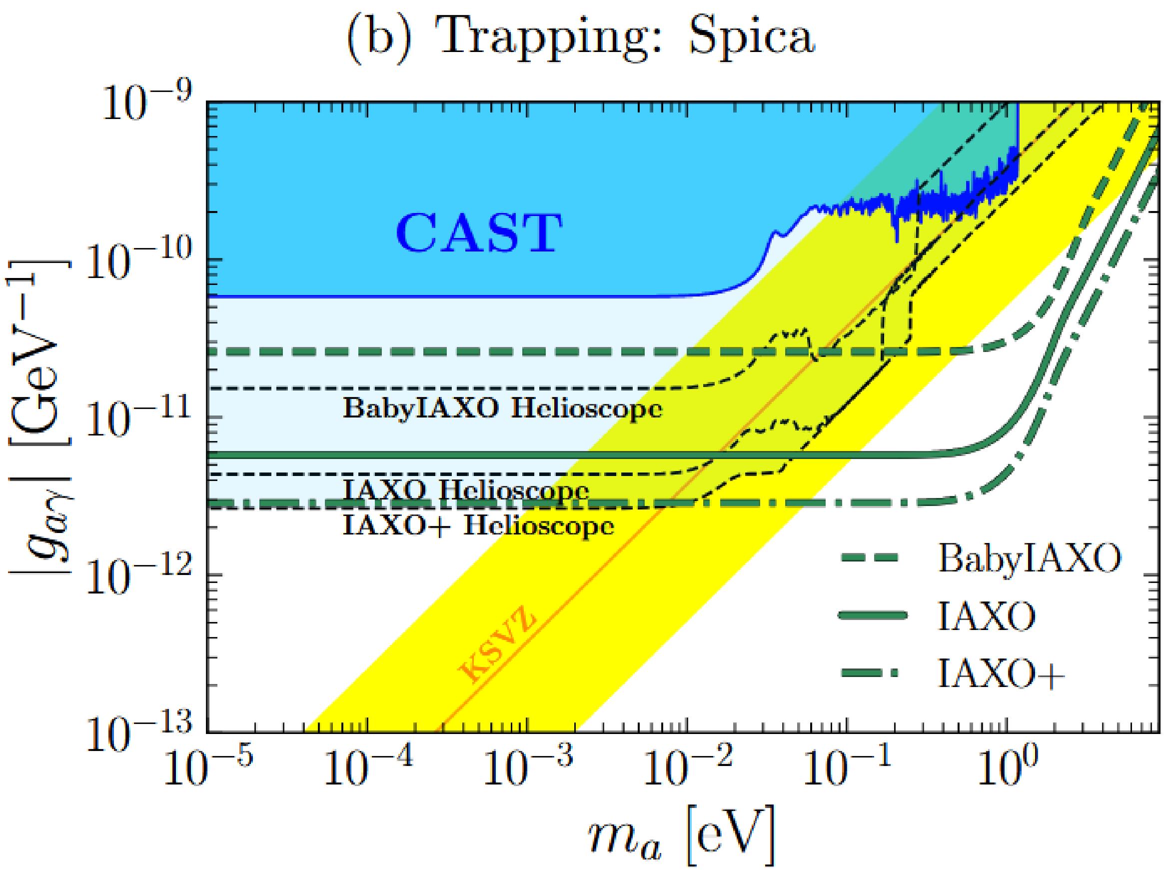


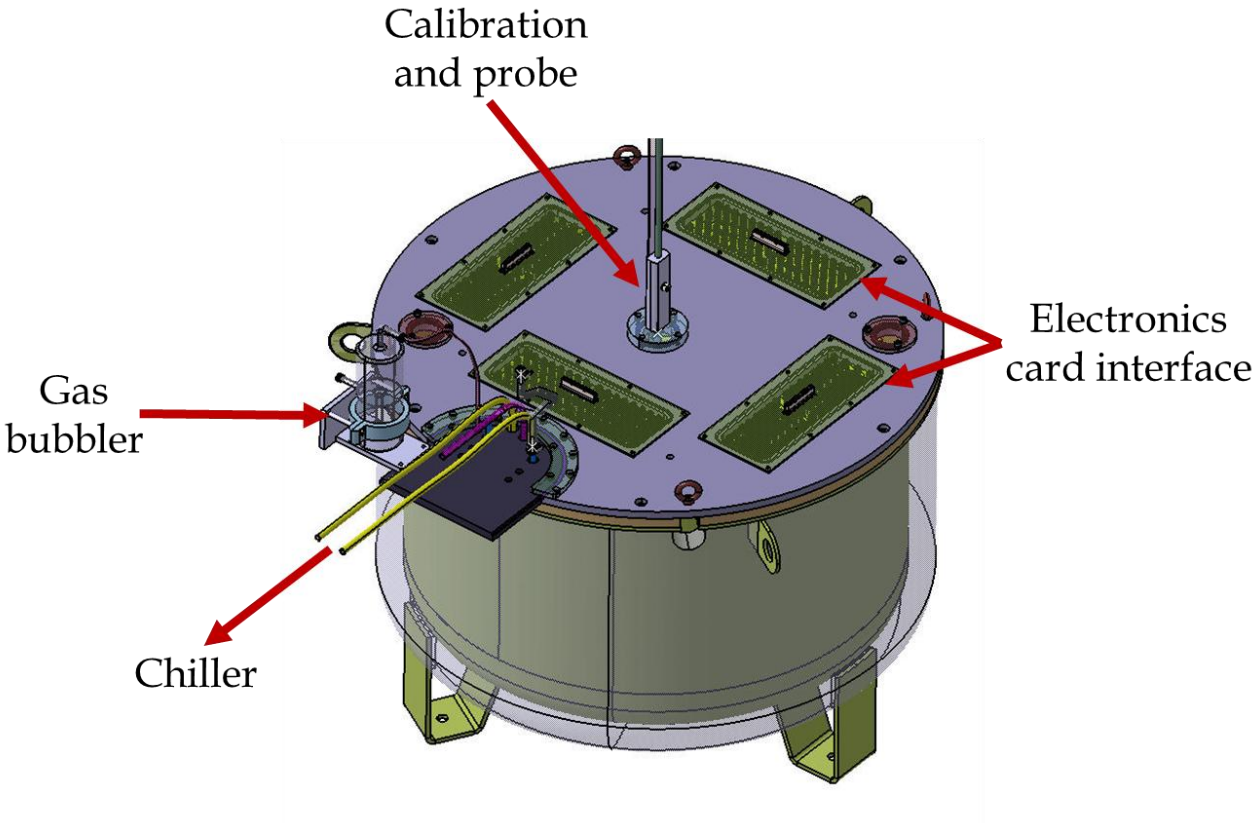

Free-streaming: NN
Free-streaming: $NN+\pi N$
Trapping (rescaled to 1/100)
$\frac{dN_a}{dE_a}$ [10^{54} MeV^{-1}]
2.5
2.0
1.5
1.0
0.5
0.0
10^0
10^1
10^2
10^3
E_a [MeV]

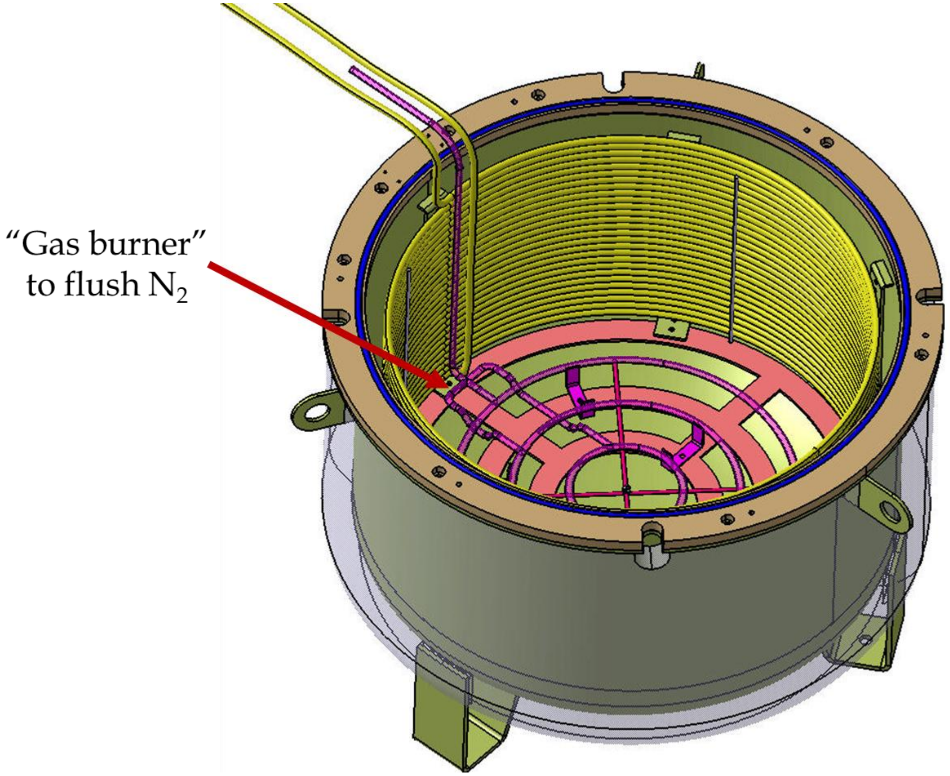
IAXO as a SN-Scope: Sensitivity prospects

$$g_{aN} = 3 \cdot 10^{-6}$$





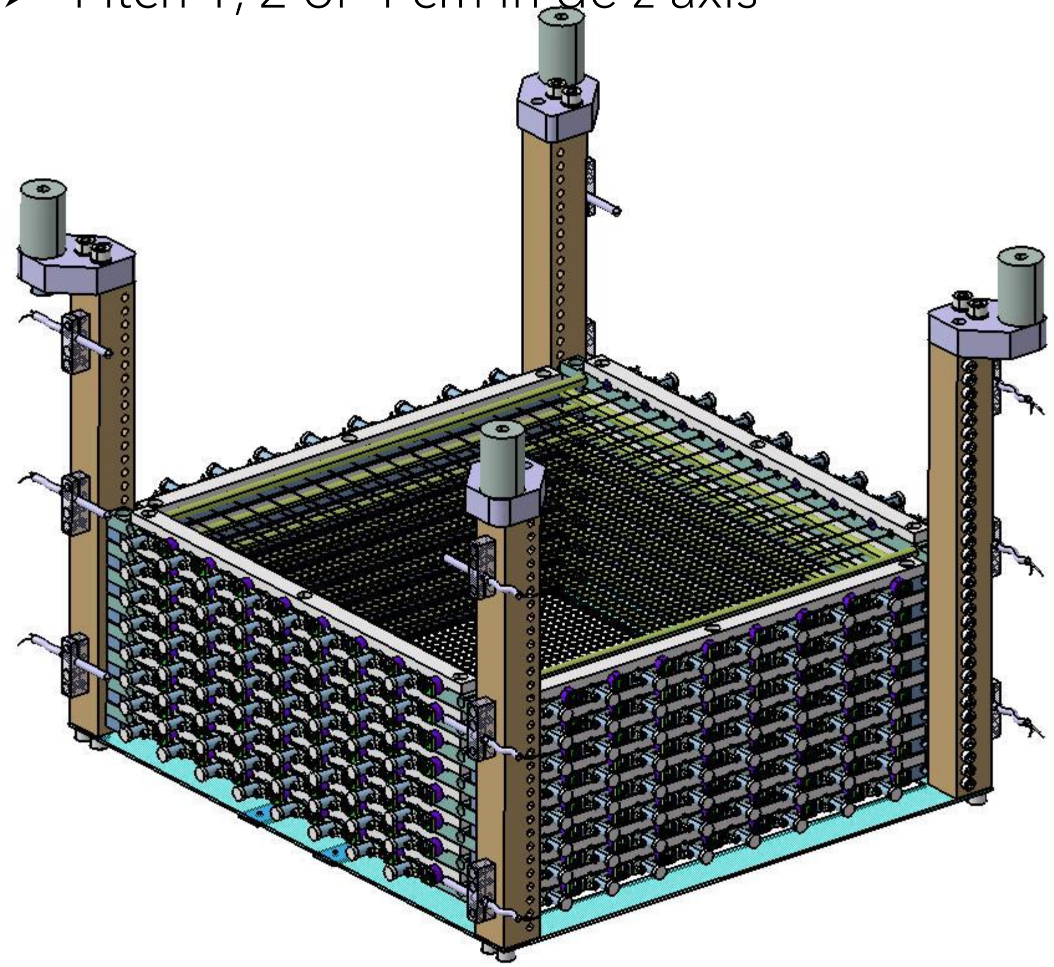

Calibration
and probe
Electronics
card interface
Gas
bubbler
Chiller

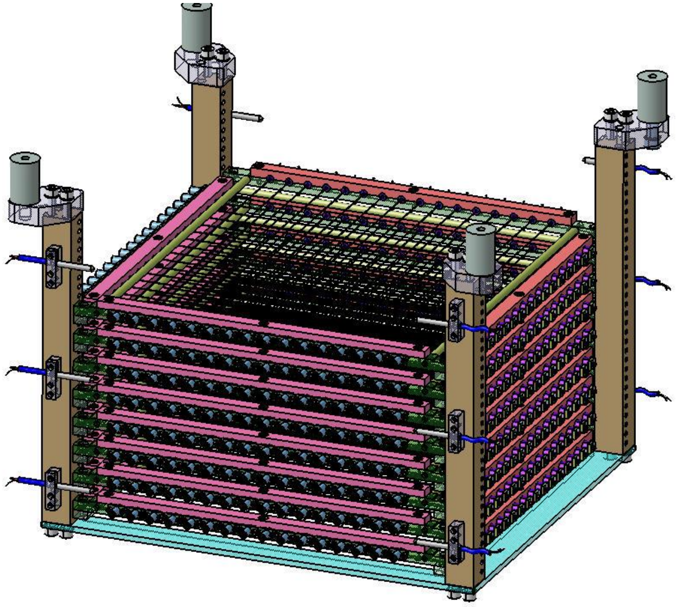

"Gas burner"
to flush N_2

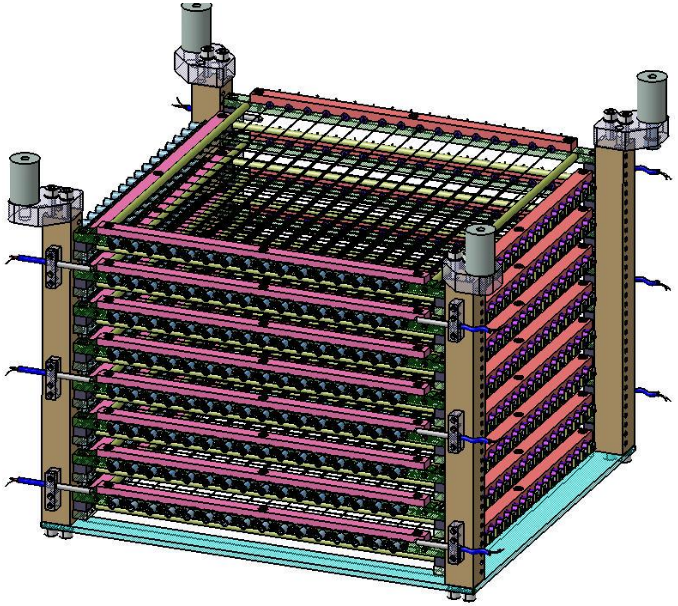
Support structure for frames

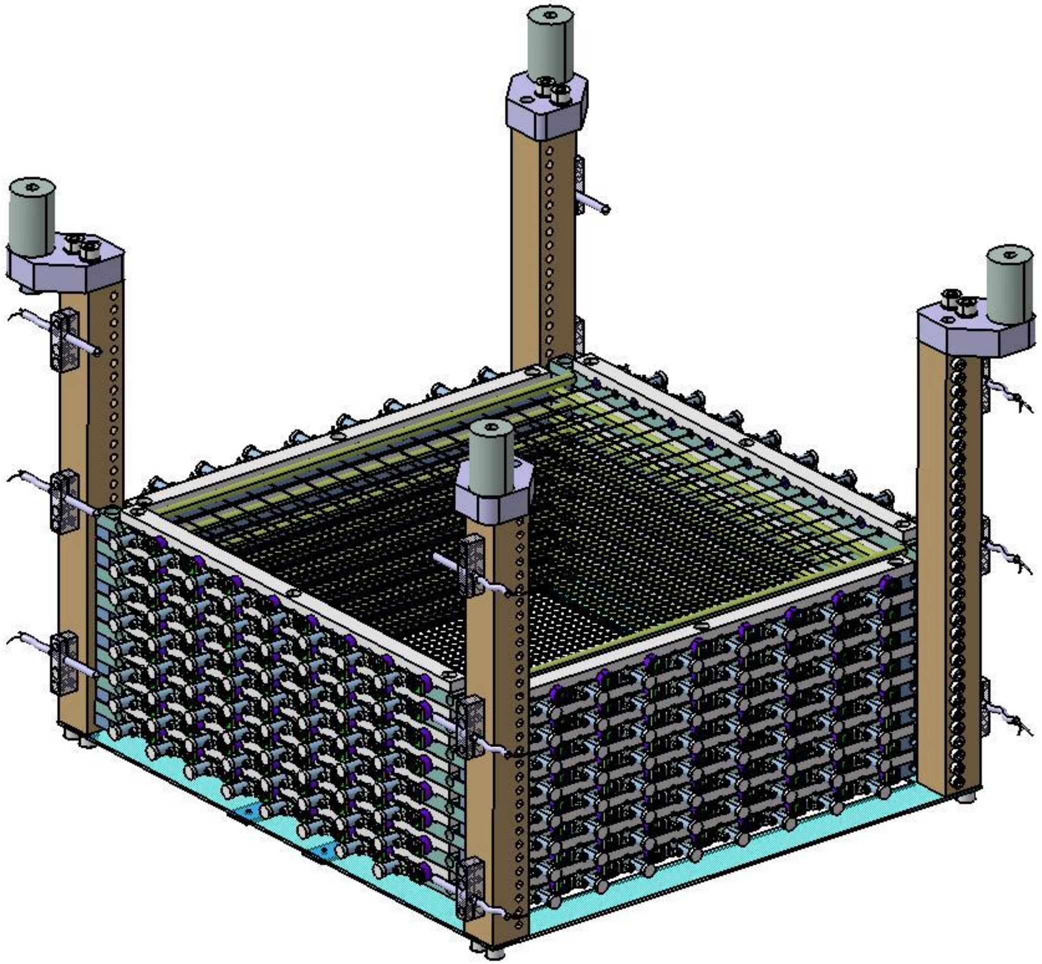
Three different layout configurations:

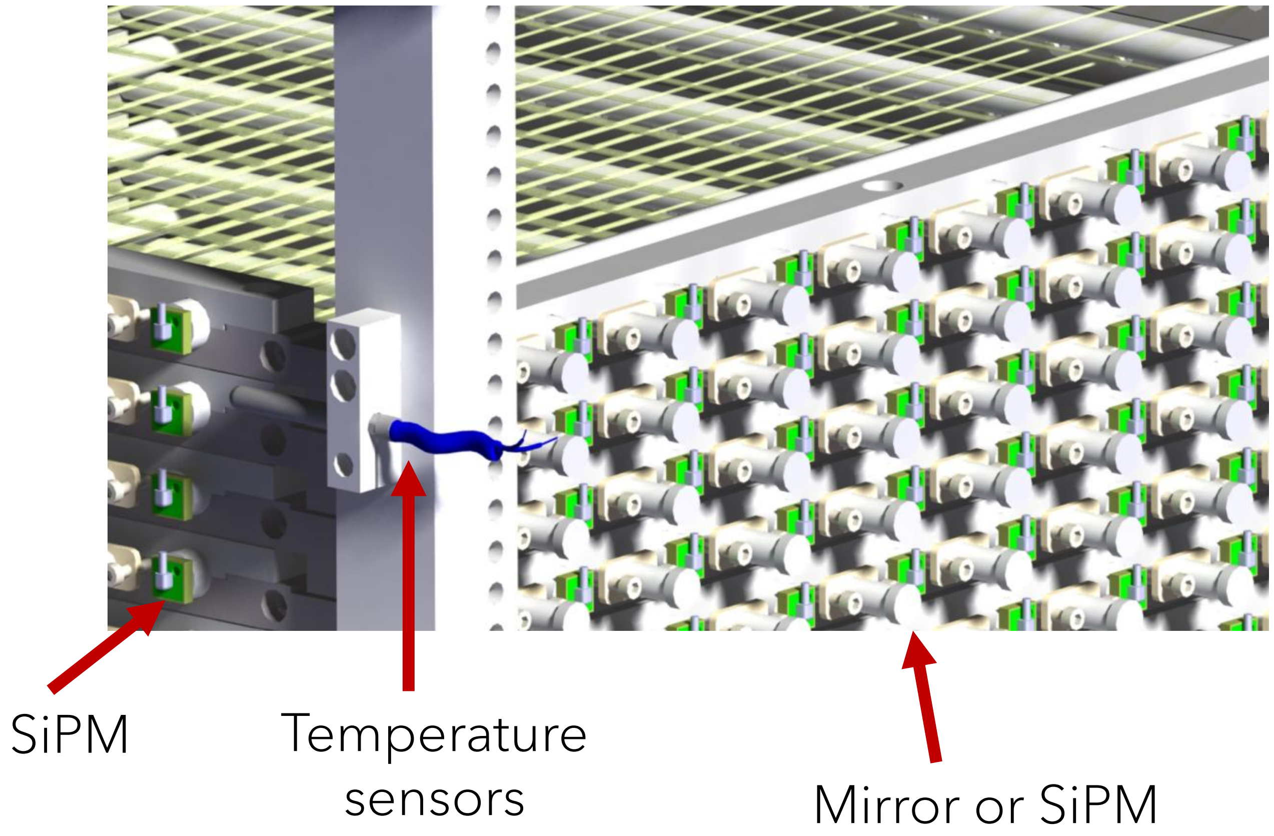
- Pitch 1, 2 or 4 cm in de z axis










SiPM
Temperature sensors
Mirror or SiPM