Instrumentation for axion searches

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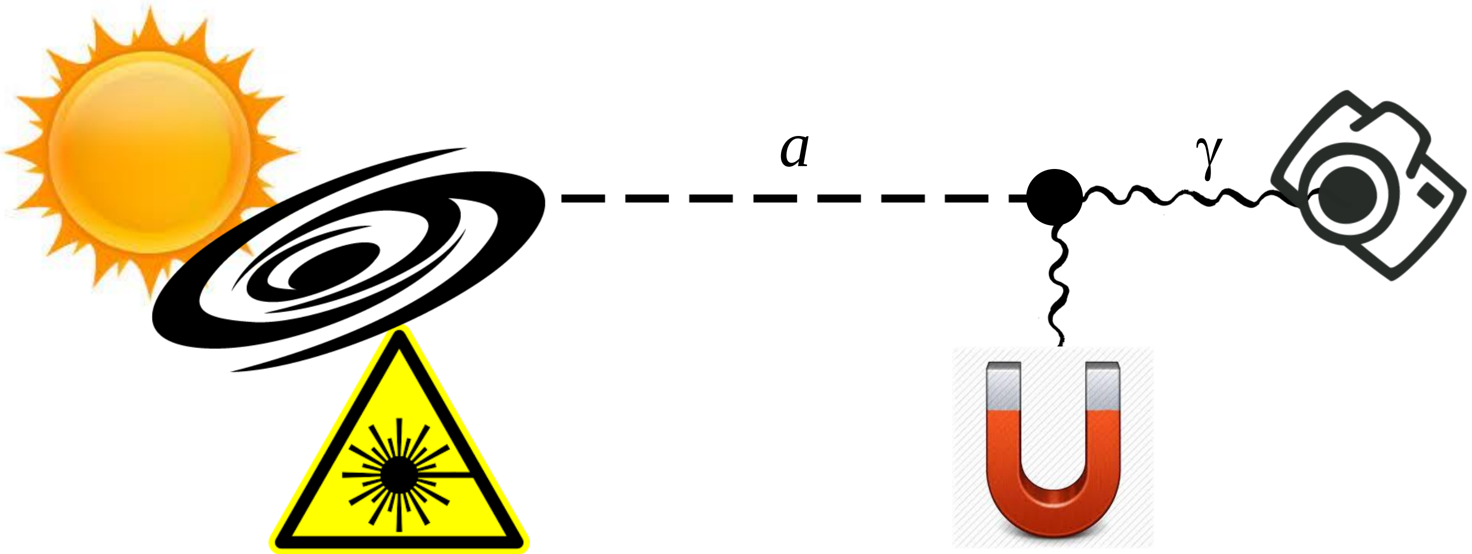
IFIC-Valencia, 15-26 June-2026

CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza



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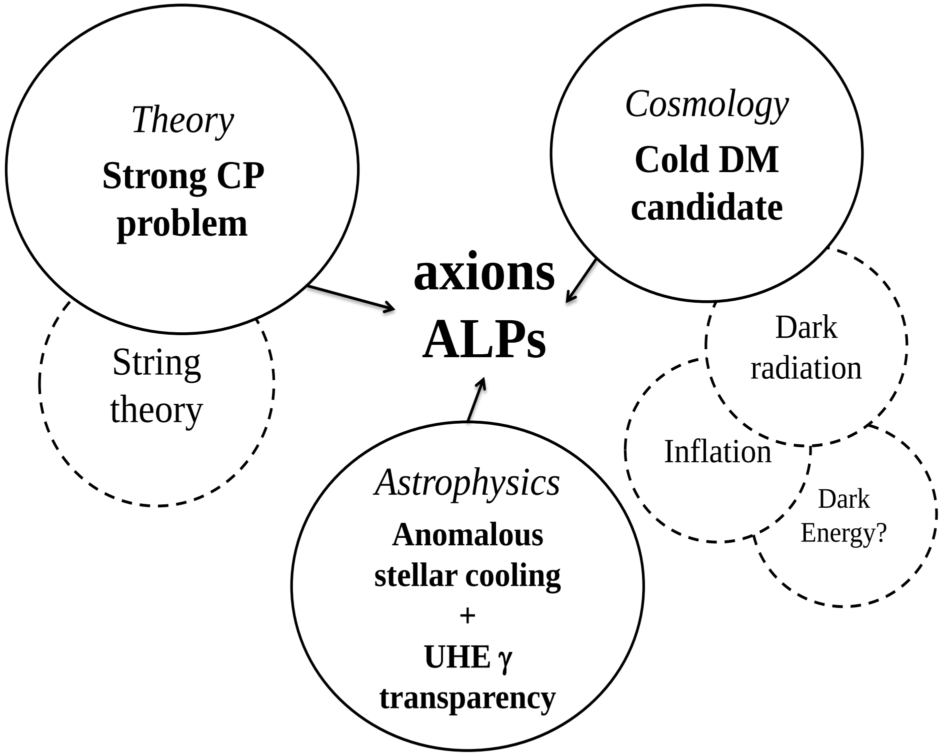
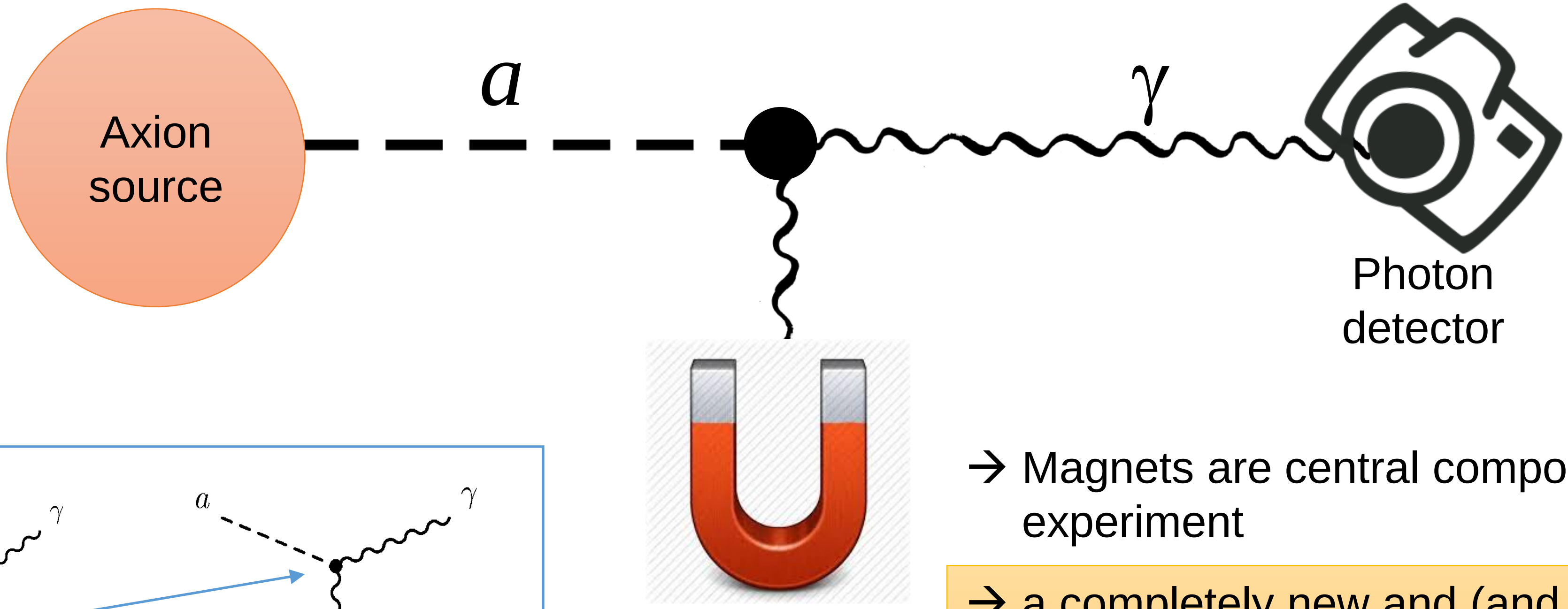
Why axions?

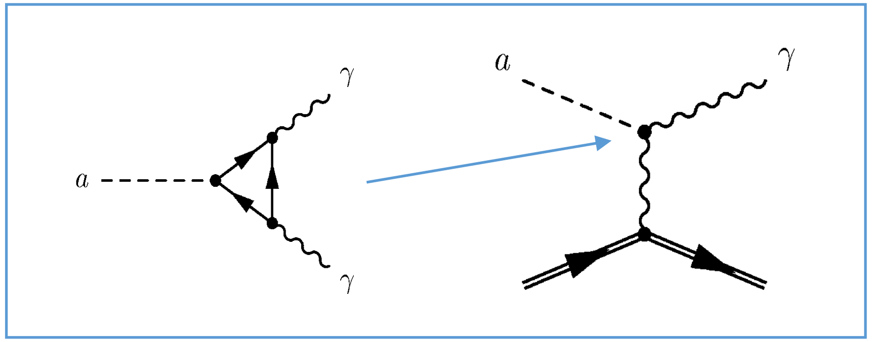
- Most compelling solution to the **Strong CP problem** of the SM
- Axion-like particles (ALPs) **predicted by many extensions** of the SM (e.g. string theory)
- Axions, like WIMPs, may **solve the DM problem** *for free*. (i.e. not *ad hoc* solution to DM)
- **Astrophysical hints** for axion/ALPs?



- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Rapidly increasing interest & experimental efforts devoted to axions

How to detect an axion?





→ Magnets are central components in axion experiment

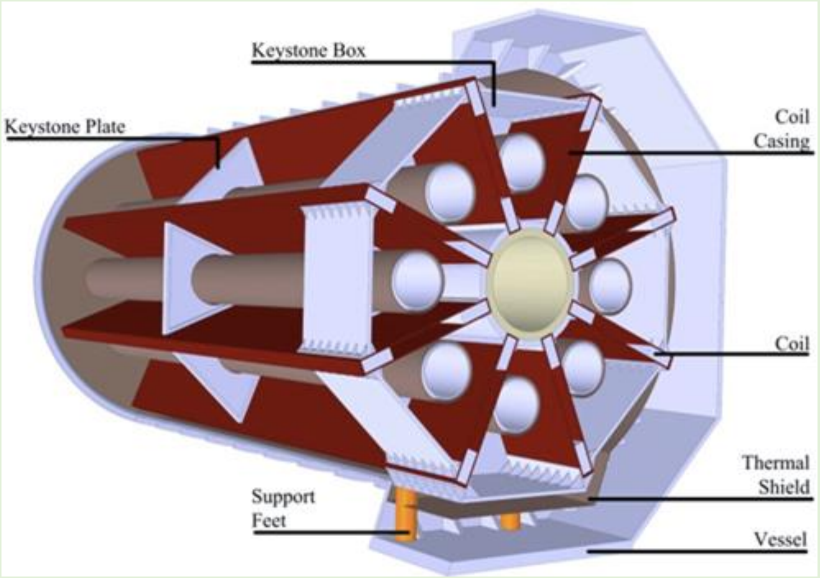
→ a completely new and (and even more?) important role for magnets in the low mass frontier of particle physics

Magnets for axions

- In axion experiments, the magnet *is* the detector.
- Most FOMs increase with B and size of magnet.
  - Helioscopes ~ B^2L^2
  - Haloscopes ~B^2V
- Large magnets are expensive. Most axion experiments piggyback on existing infrastructure. Some modern projects aim at purpose-made magnets (IAXO, MADMAX,…).
- Synergies with HEP accelerator & detector magnets. Technologies associated with large HEP magnets (see later)

IAXO magnet

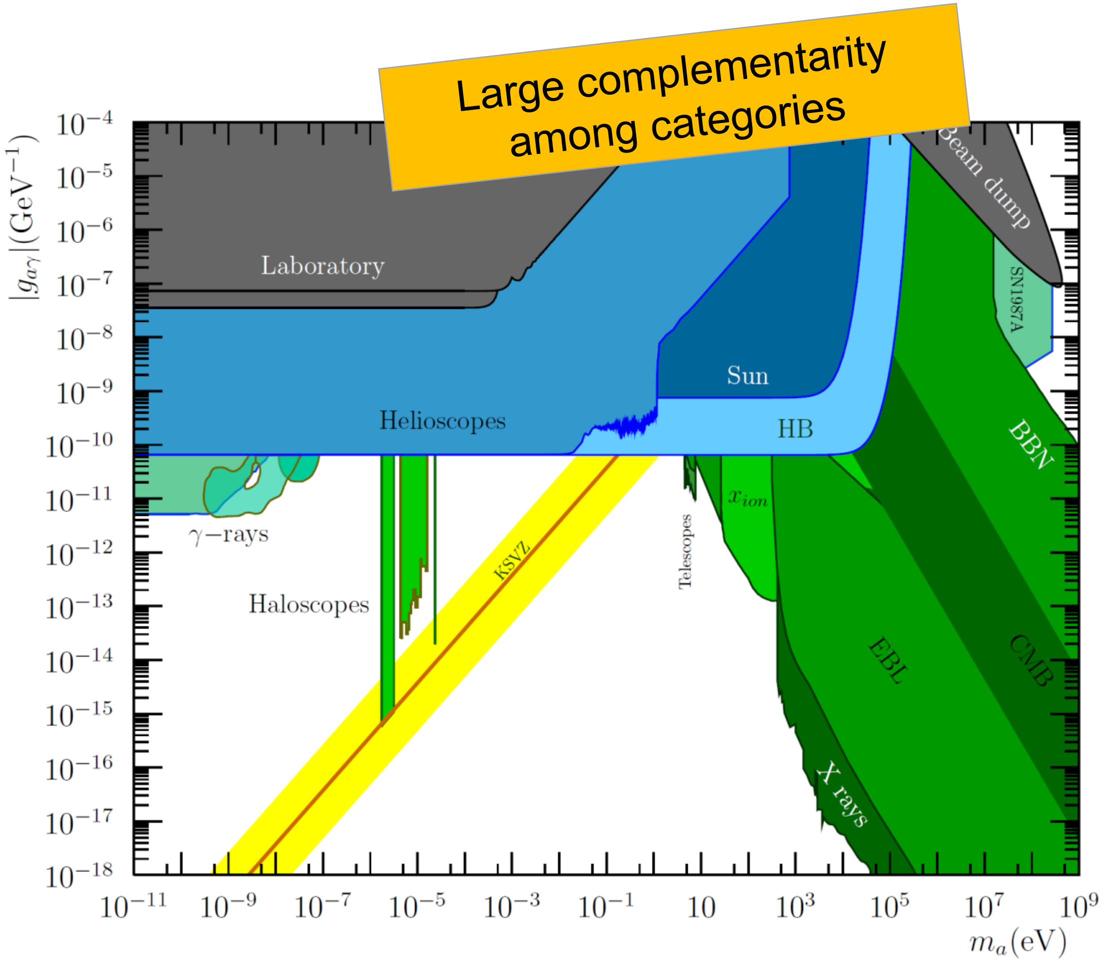
- Superconducting "detector" magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore



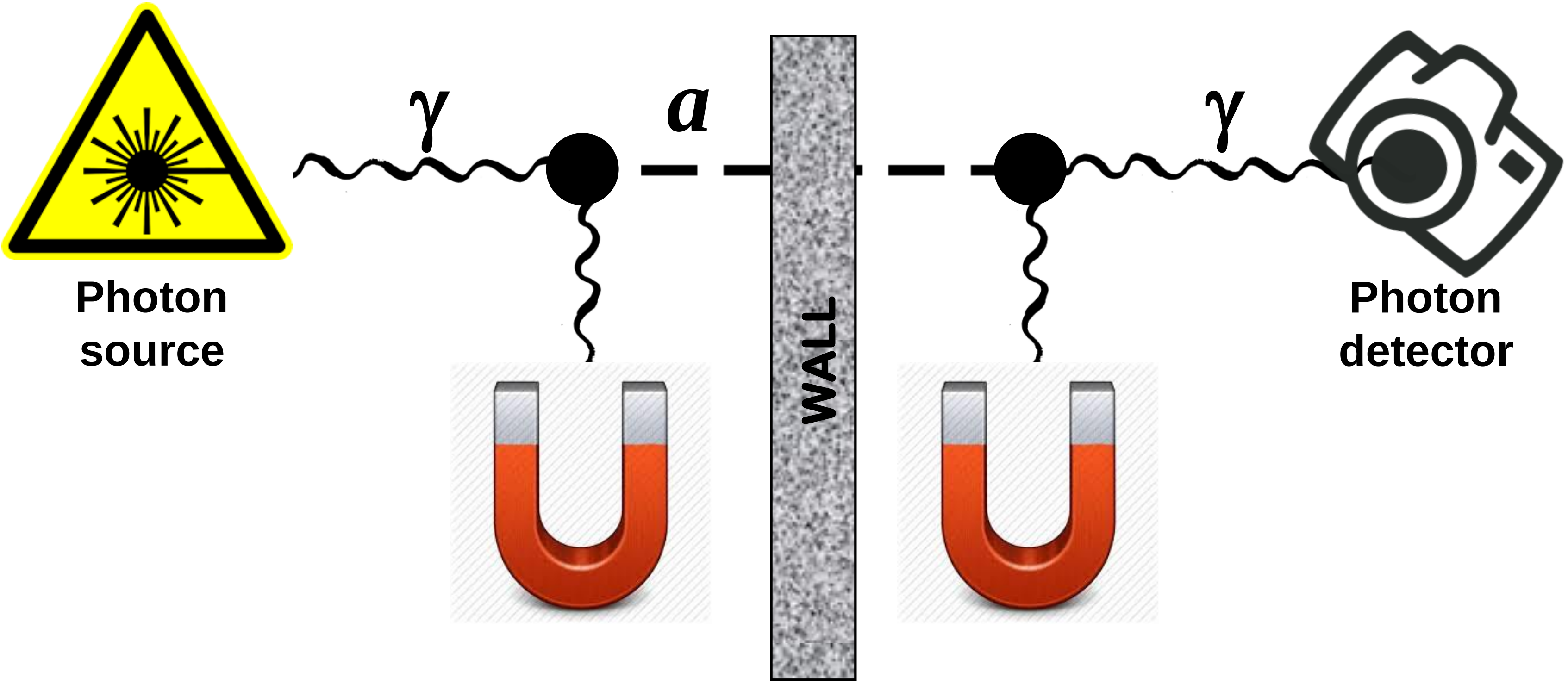
Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

Detection of axions

Source	Experiments	Model & Cosmology dependency
Relic axions 	ADMX, HAYSTAC, CASPEr, CAPP, MADMAX, QUAX, RADES, ORGAN, …	High
Lab axions 	ALPS, OSQAR, ARIADNE,…	Very low
Solar axions 	SUMICO, CAST, (Baby)IAXO	Low

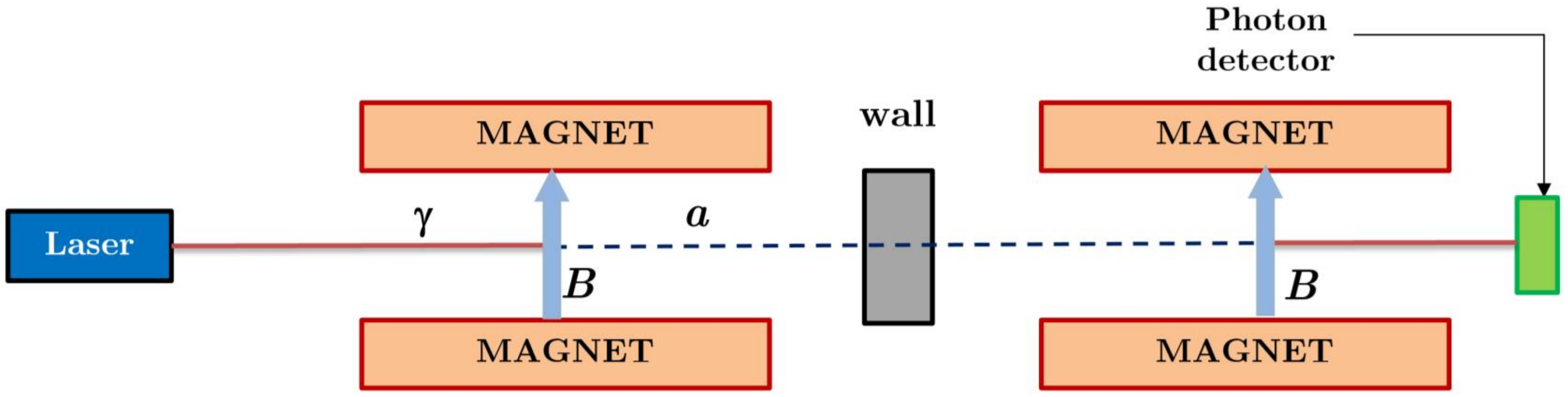


Laboratory axions

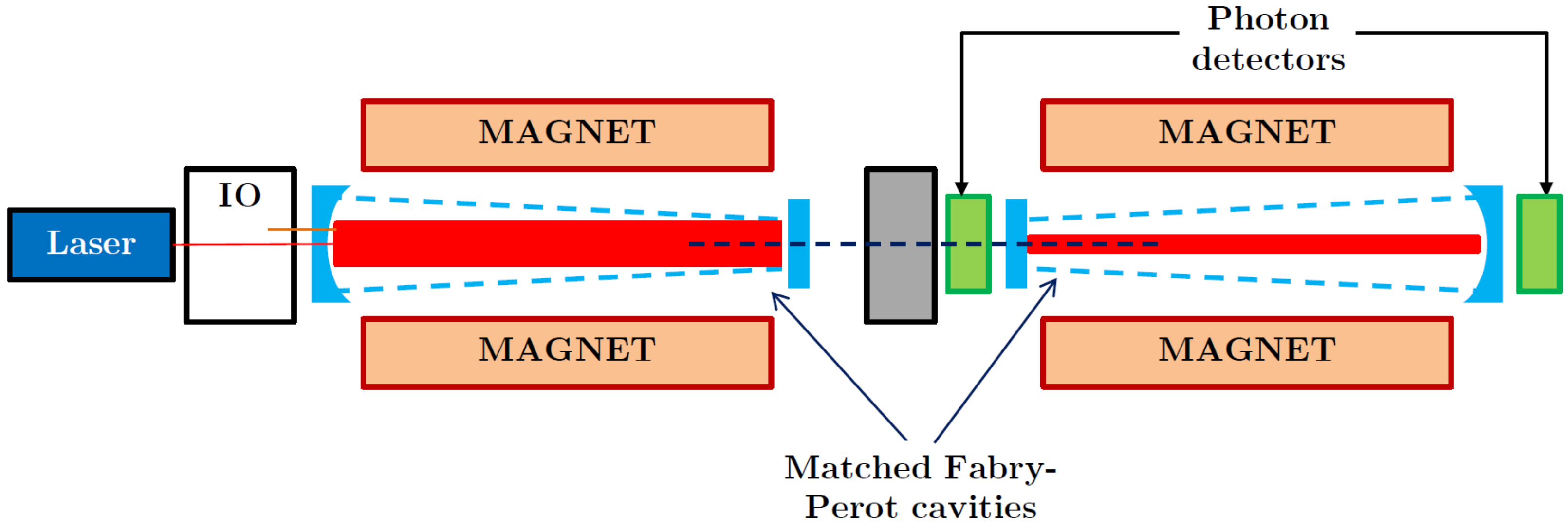


Light-shining-through-wall (LSW)

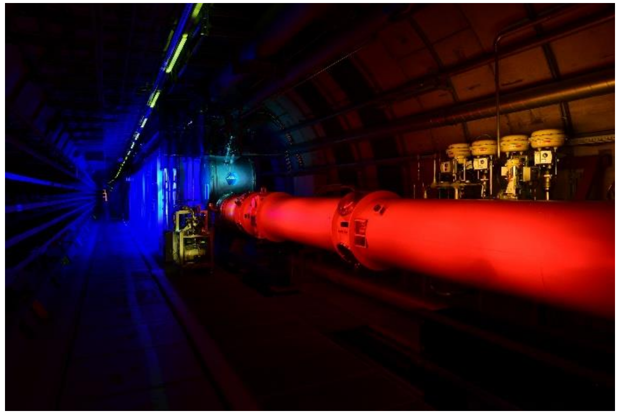
Standard configuration →



Enhanced “resonant” configuration (future) →



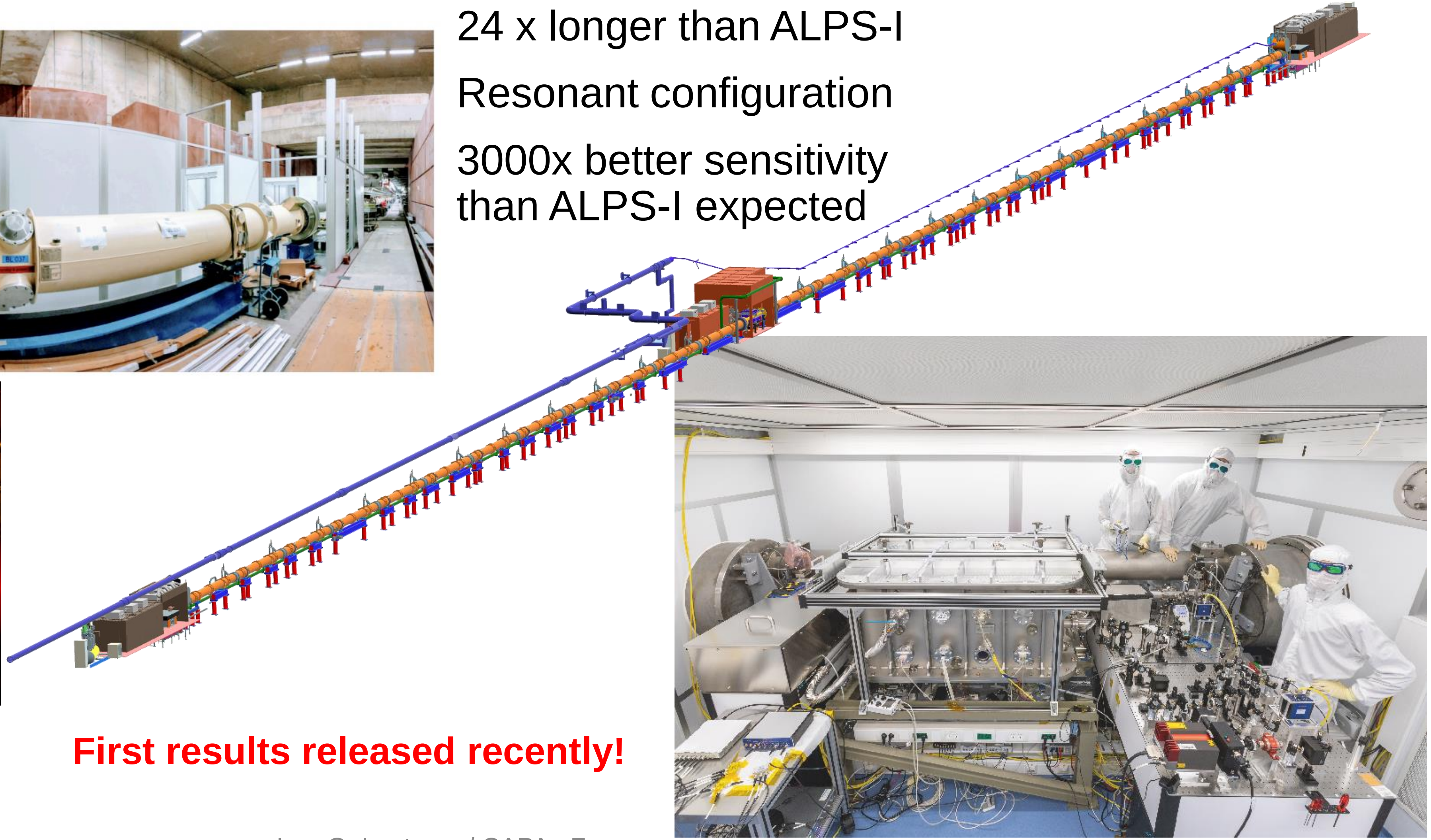
ALPS-II @ DESY



24 x longer than ALPS-I

Resonant configuration

3000x better sensitivity than ALPS-I expected

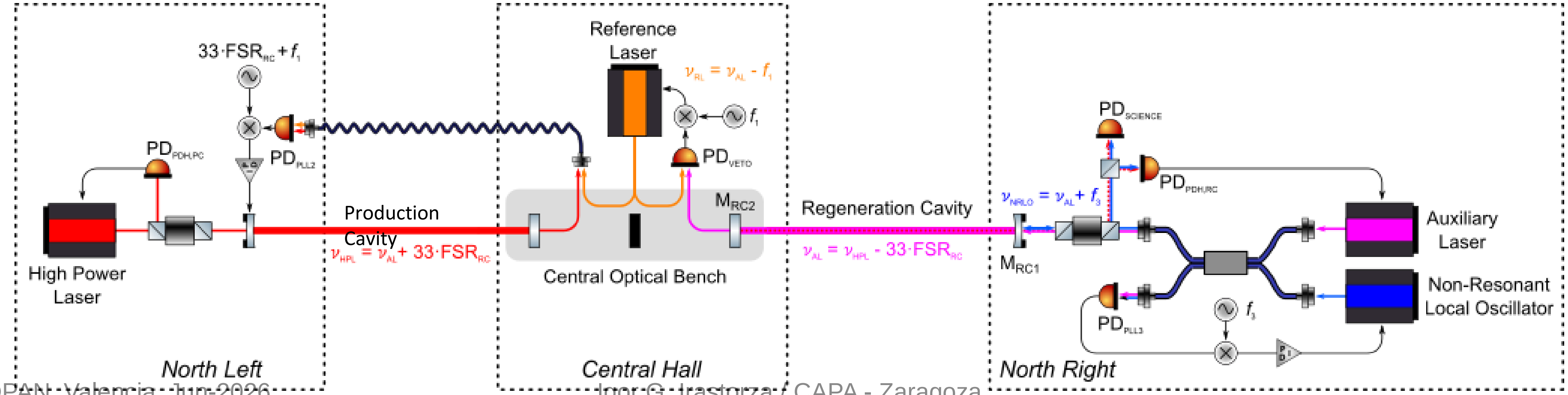


First results released recently!

High precision optics

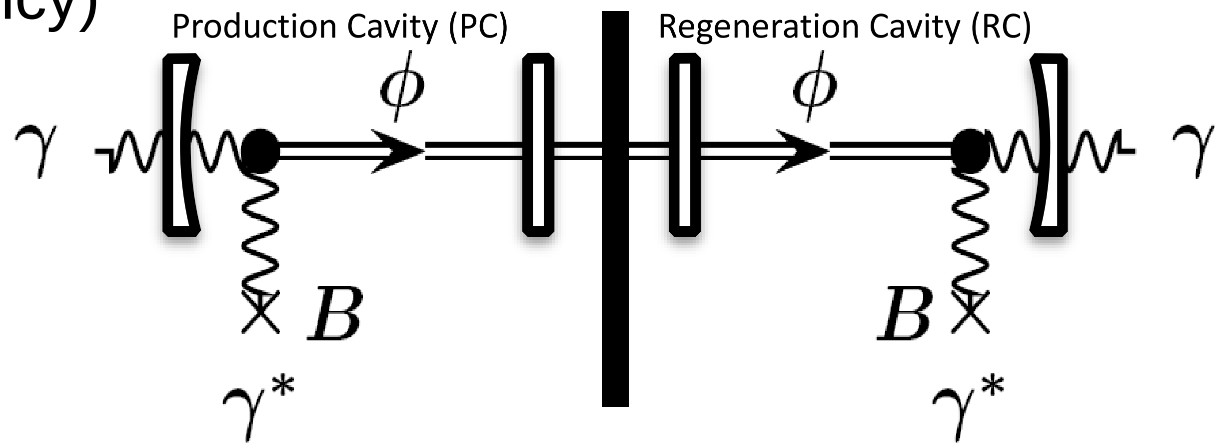
ALPS-II: extreme precision optical metrology

- Sub-μHz stabilization of laser frequency differences (20 order of magnitude lower than laser frequency - 282 THz)
- Picometer-level control of coupled optical cavities.
- Active feedback with kHz bandwidth to compensate seismic disturbances.
- Interferometric sensing and control of the Production and Regeneration cavities.

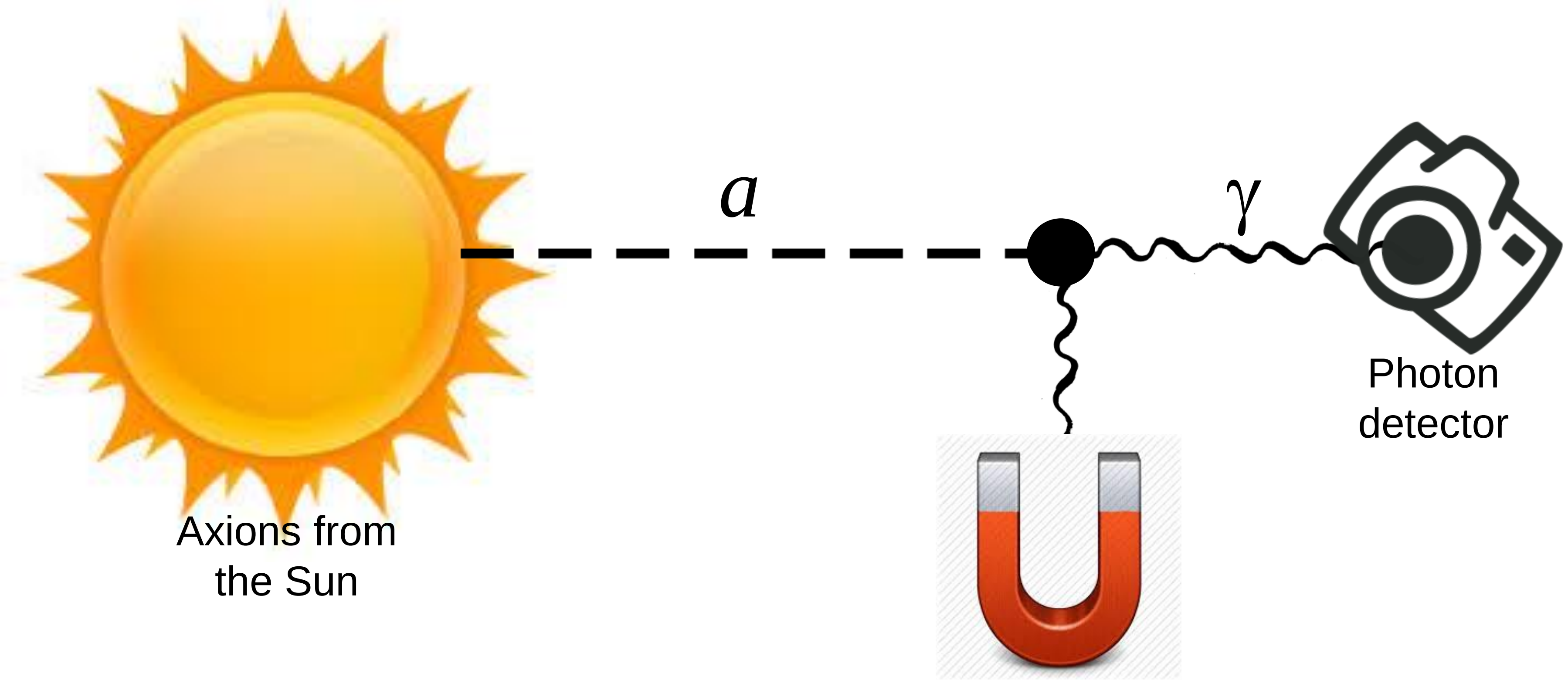


Ultra-low background optical detection

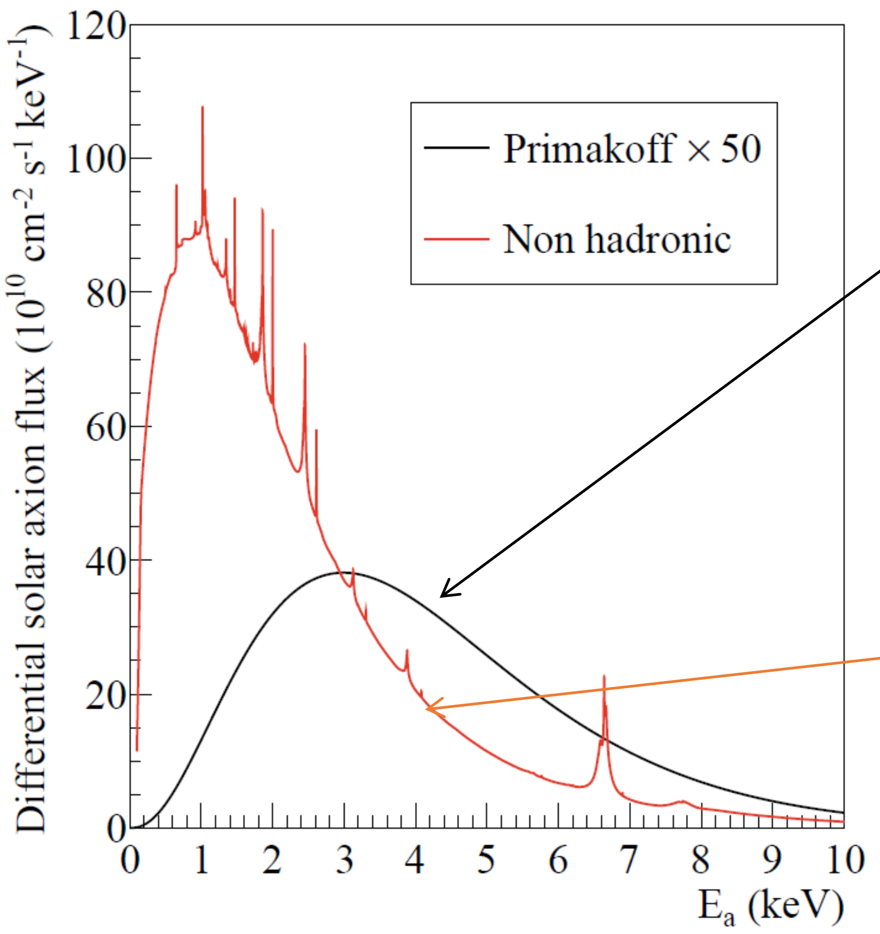
- Shot-noise-limited heterodyne detection with sensitivity approaching the single-photon level.
- Doppler-shifted stray-light backgrounds rejected through frequency discrimination.
  - Future run will reduce the stray-light background to > 1 photon per measurement time (10^6 seconds). Currently 200 photons in signal frequency bin (stray light)
- Operation with ~10^{29} photons circulating in the production cavity. Optical system designed to suppress leakage and backgrounds by ~30 orders of magnitude (at the signal frequency)

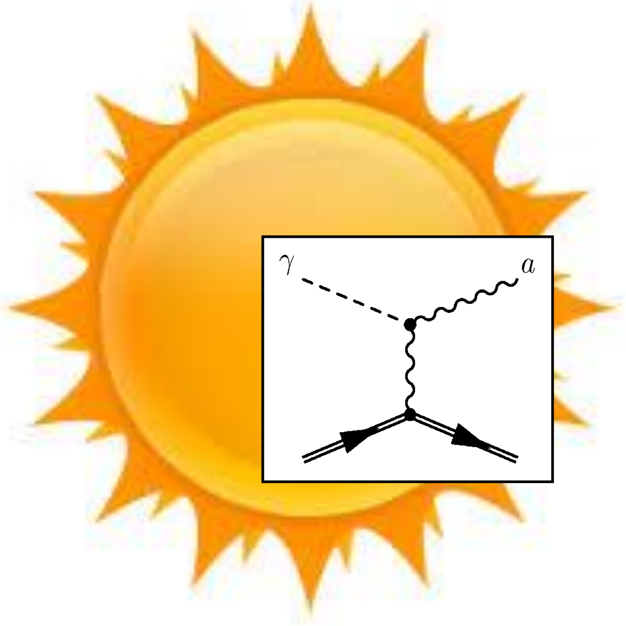


Solar axions



Solar Axions





Standard Primakoff spectrum

Robust prediction from axion models. Conversion of solar plasma fotons into axion (only axion-photon coupling involed)

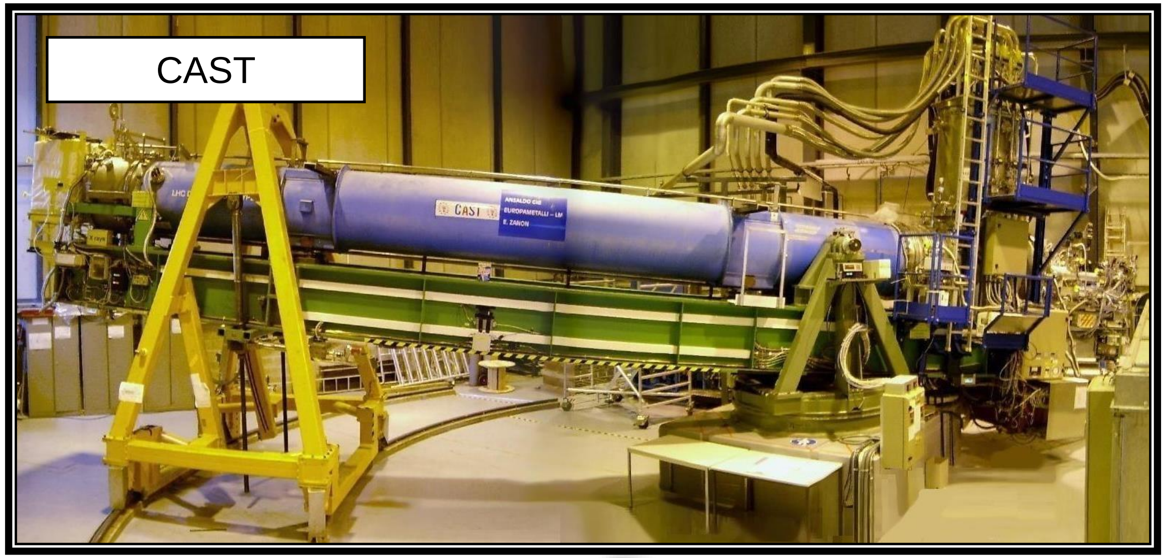
van Bibber PRD 39 (89)
CAST JCAP 04(2007)010

Non-hadronic “ABC” Solar axion flux at Earth
(only if axion couples to electron)

Redondo, JCAP 1312 008

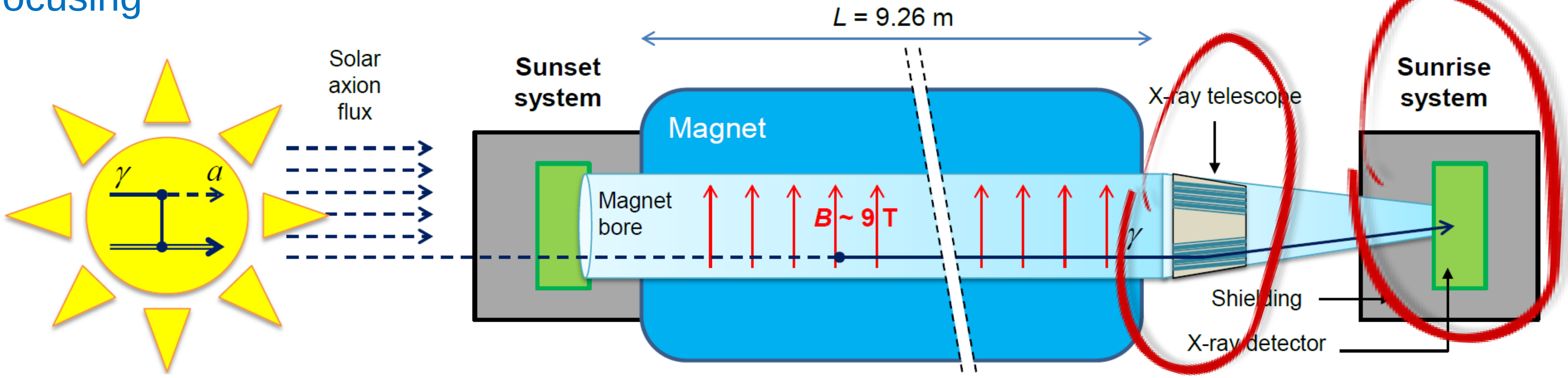
CAST: state-of-the-art "axion helioscope"

Axion helioscope concept
P. Sikivie, 1983
+ K. van Bibber, G. Raffelt, et al. (1989) (use of buffer gas)



Current state-of-the-art:
CERN Axion Solar Telescope (CAST)

First helioscope using low background techniques & x-ray focusing

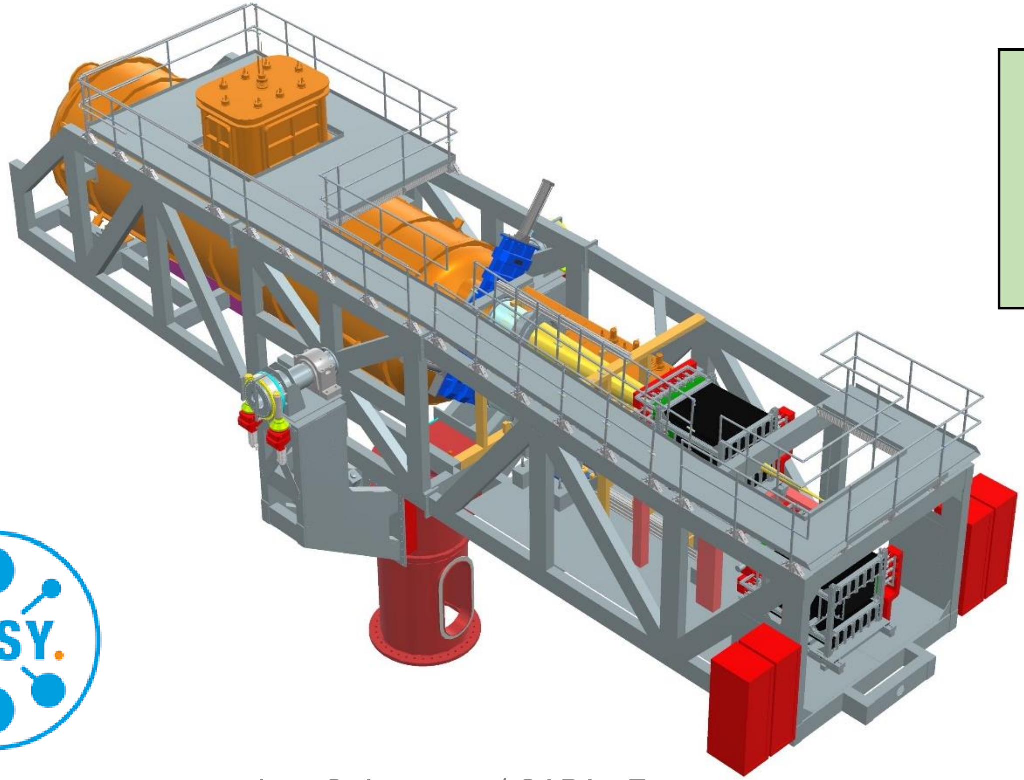


IAXO & BabyIAXO in a nutshell

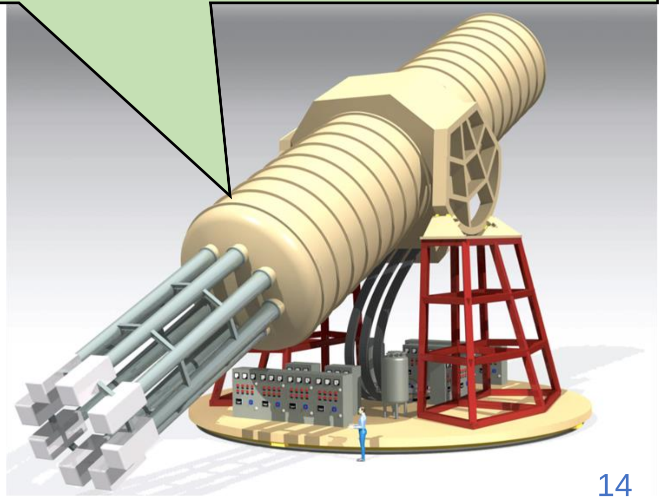
BabyIAXO: intermediate scale between CAST & IAXO. Prototype for IAXO. Relevant physics reach in itself
SNR ~100 x that of CAST

- Primary physics goal: detection of solar axions. Additional physics program→ *IAXO as a generic ALP facility*
- BabyIAXO under construction at DESY. Dedicated magnet → Time-critical item, experiment timetable driven by magnet: important delays due to cable and funding issues

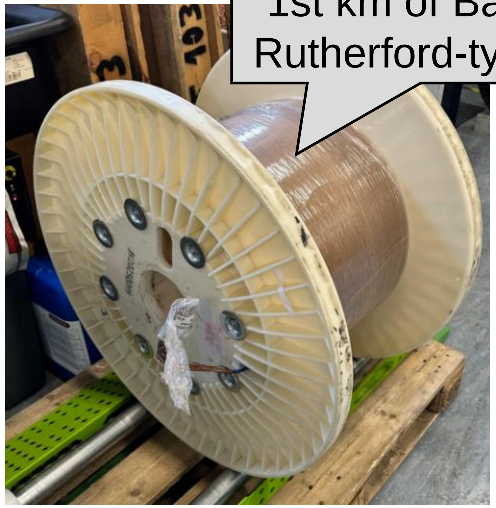
CAST @ CERN: current state-of-the-art.
Finished in 2021.
Best upper bound on axion-photon coupling



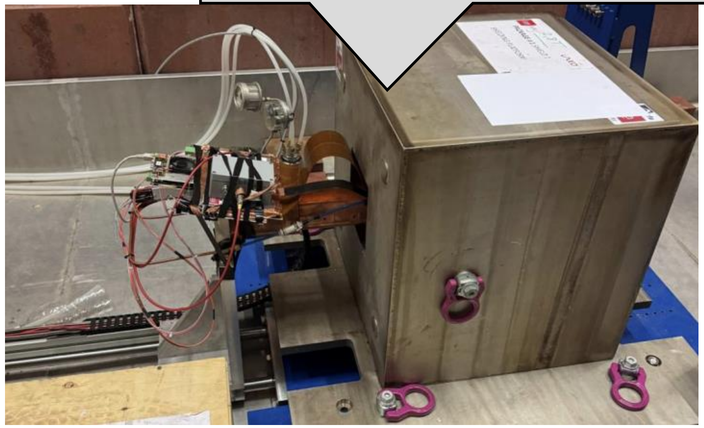
IAXO: longer-term goal of the community.
First concept established in 2014
SNR ~10^5 x CAST



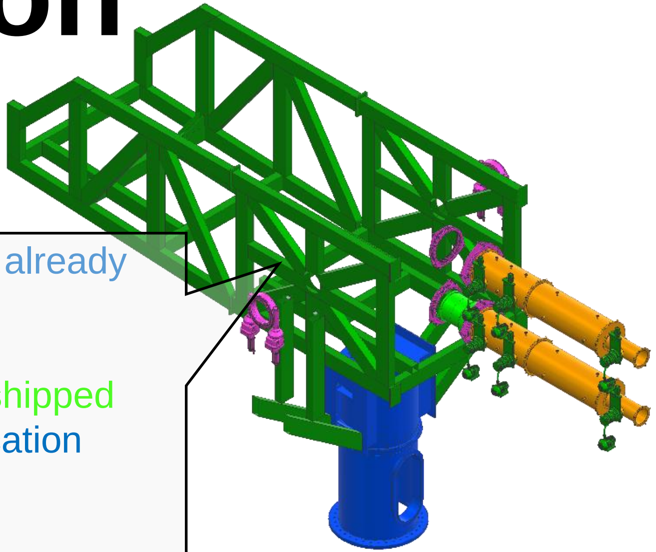
BabyIAXO – under construction



1st km of BabyIAXO Rutherford-type cable



1st Micromegas x-ray detector (with shielding) taking background data at DESY



Parts of BabyIAXO already built:
- At DESY
- Available, to be shipped
- At DESY, modification required
- In production
- Order in preparation

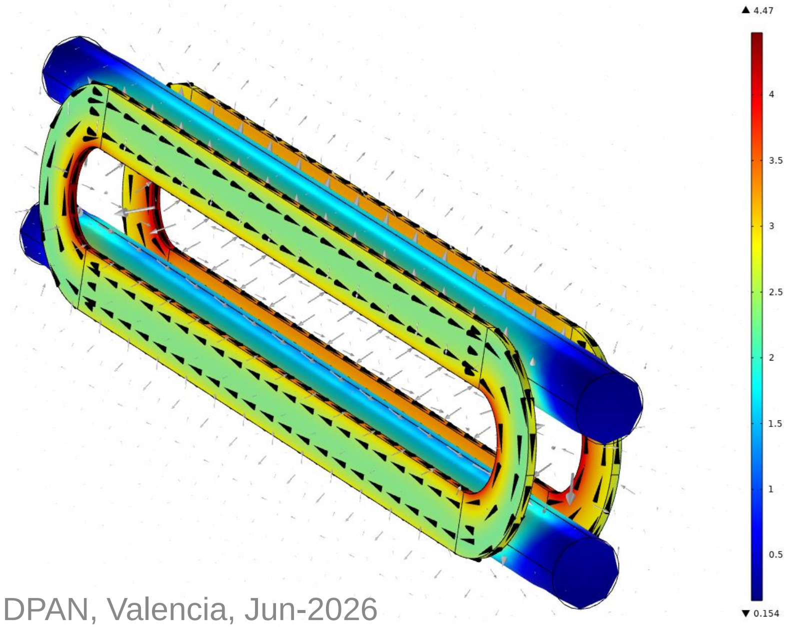
Large vacuum beamlines just finished

Current BabyIAXO timeline:
- **2026**: Site activation
- **2027**: *magnetless*-commissioning
- **2028**: dark photon run
- **2029**: magnet installation
- **2030**+: commissioning + axion runs

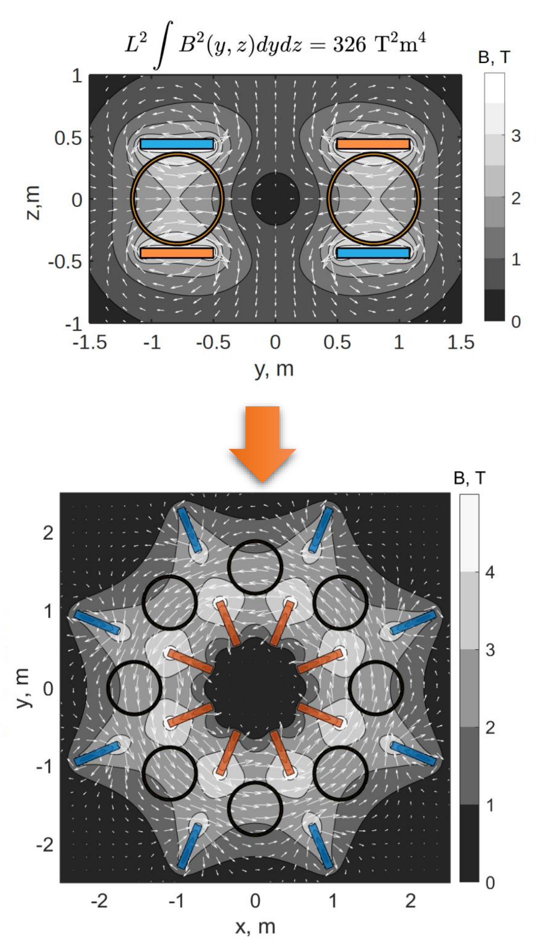
BabyIAXO magnet

Magnet design led by CERN-EP (M. Mentink), with support from DESY, Elytt, and CAPA (cable)

- “Common coil” configuration
  - Reduce risk: known design choices as much as possible
  - Cost-effective: Best use of existing infrastructure and experience at CERN
  - Prototyping character: winding layout very close to that of IAXO toroidal design.

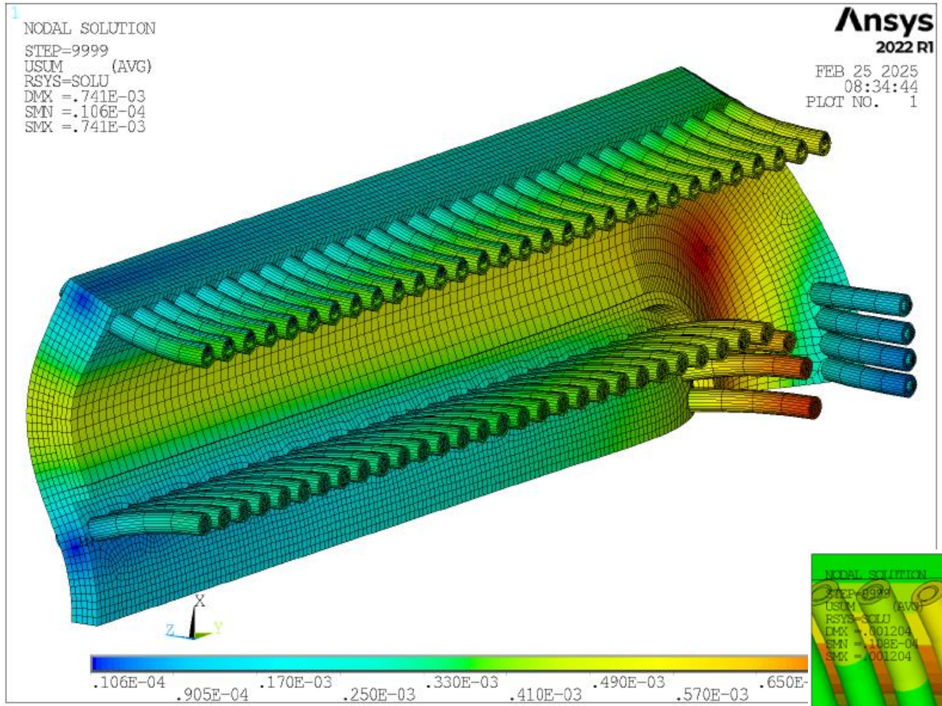


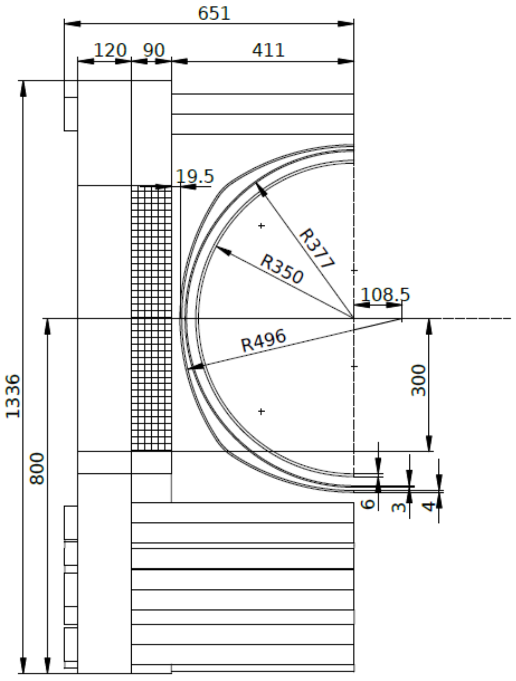
Parameter	Value
Operating current [kA]	6.0
Free bore diameter	0.7
Transverse magnetic field during operation [T]	2.1
Stored magnetic energy [MJ]	56
Inductance [H]	3.1
Cold mass weight (preliminary) [tons]	38
Energy density (preliminary) [kJ/kg]	1.5
Overall coil conductor length [km]	22
Conductor length per pancake [km]	2.5
Peak magnetic field magnitude on the Rutherford cable [T]	4.7



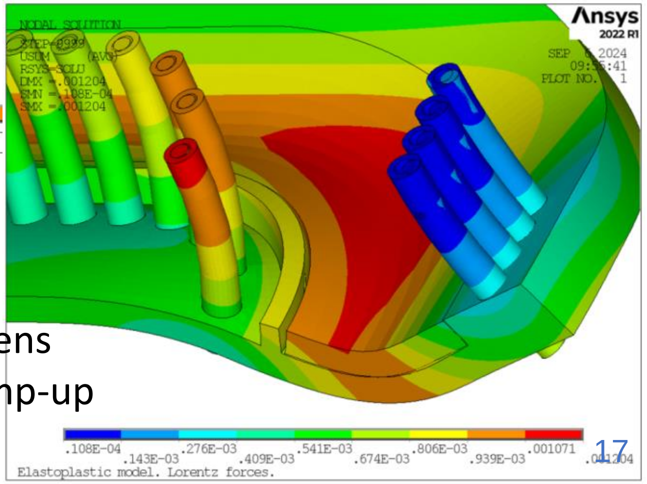
BabyIAXO magnet: cold-mass

- Al alloy support structure to hold considerable forces
- Coil bonded to structure
  - Four layers stack
  - Requirement on conductor: transverse yield strength of >50 MPa at 4K
- System of pretensioned tie rods to hold repulsion forces (also vertical ones due to mech. tolerances)
- Extensive 3D simulations to evaluate deformations/ displacements





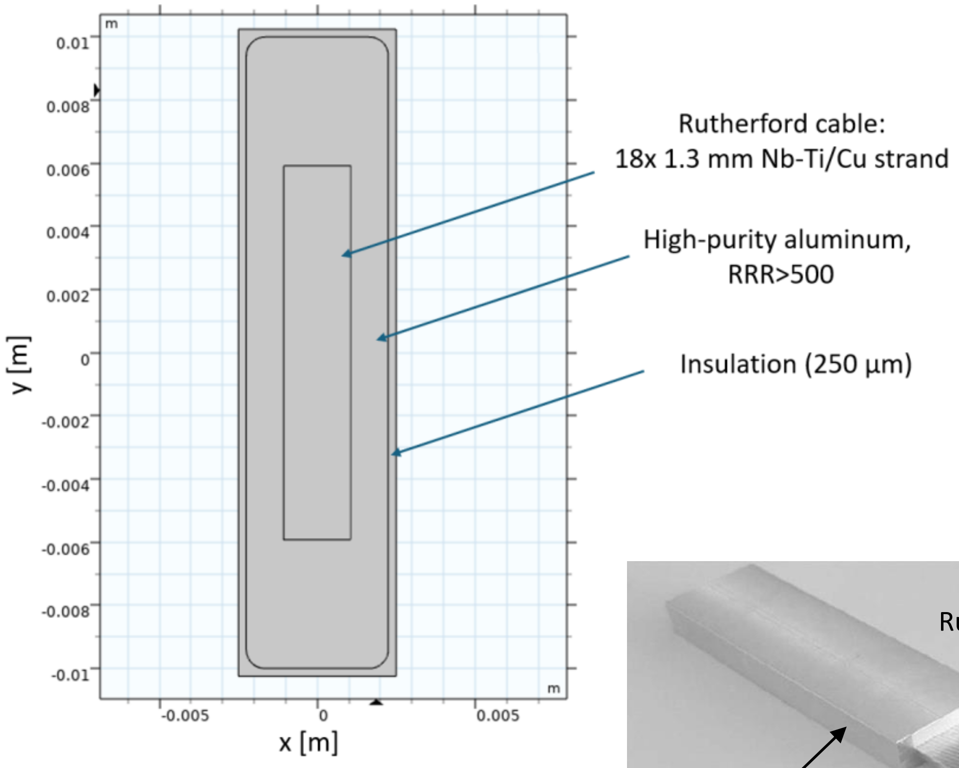
Dimensions

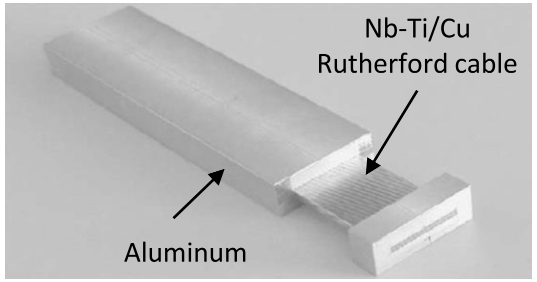


Gap opens during ramp-up

Conductor for large scale coils

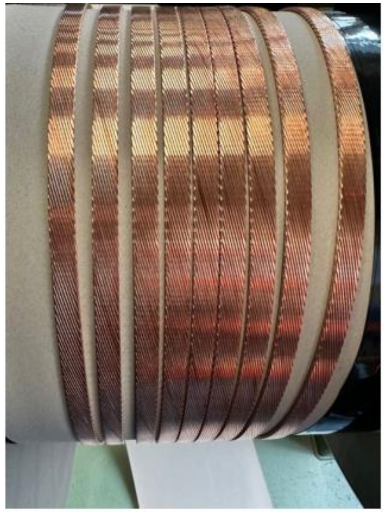
Aluminum-stabilized Nb-Ti/Cu conductor:





- Conventional technology but no providers in recent years! (+ Russian war) → causing delay to project
- Rutherford cable already under production
- CERN-TE support in quality control & cabling
- Al co-extrusion: possible provider found in China, first trials…
- Cold-working needed to meet yield strength specs

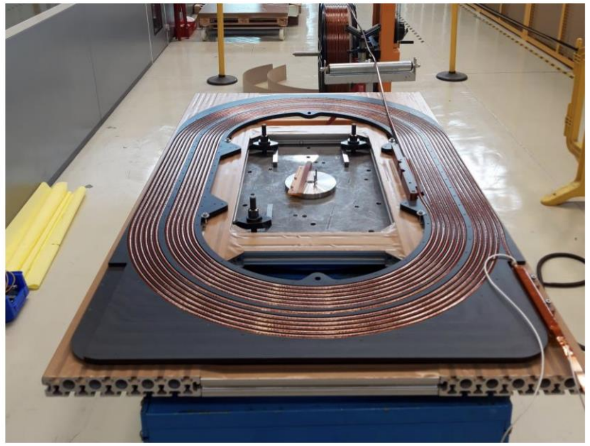
CERN Rutherford cabling machine



NbTi Rutherford cable (NbTi RC) produced at CERN (72 m)

Future: HTS cables

SHiP
Search for Hidden Particles



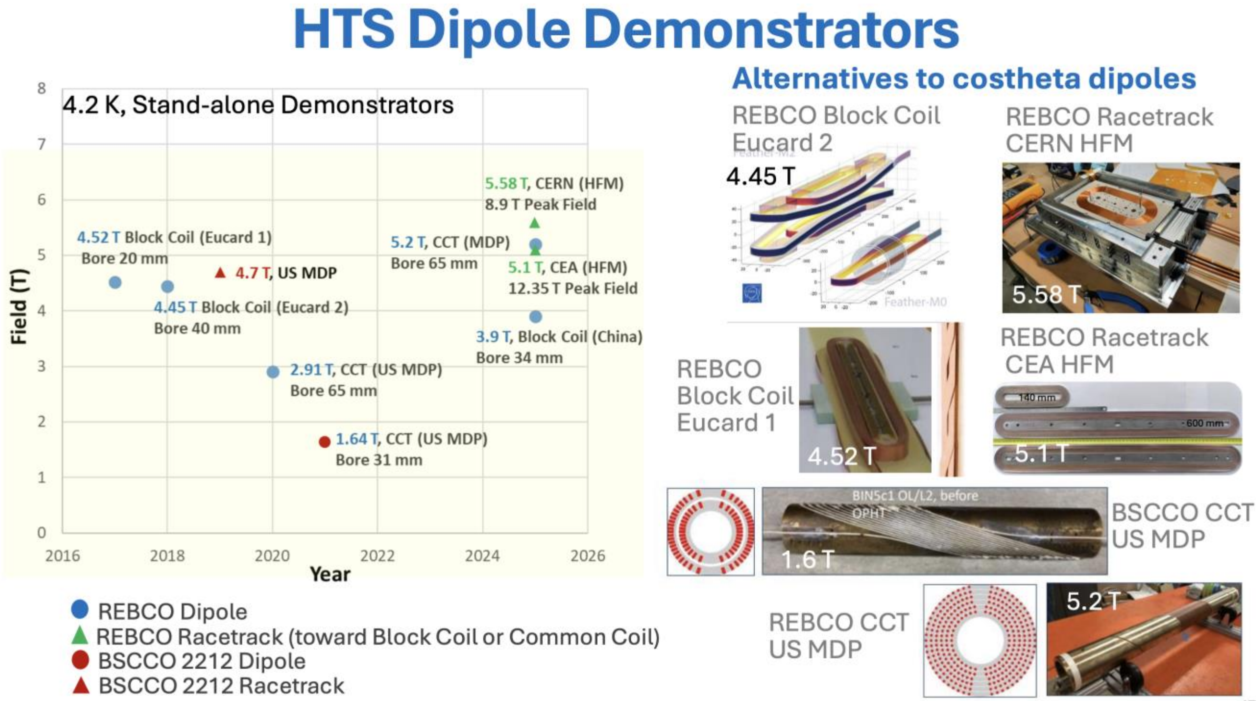
SHiP also explores at the Karlsruhe Institute of Technology an **active REBCO muon shield**

HTS-based conductors would allow for more powerful magnets, and/or simpler cryognenics

Its use in large magnets are already a reality in **fusion** projects and HEP demonstrators

Lack of reliable HTS ”cable”.Industrial reality rapidly evolving.

See recent seminar by A. Ballarino at CERN: https://indico.cern.ch/event/1562652/



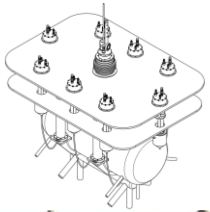
Large scale (few K) cryogenics

- BabyIAXO will be the first large-scale magnet using cryo-coolers integrated into the magnet vacuum vessel itself (no external plant).
- Cold items:
  - Cold mass at < 5 K.
  - Two concentric thermal shields, 25 K and 50 K, to mitigate low cooling budget at 4.5 K
  - HTS-based lead currents at 50K, to limit heat-load to cold-mass

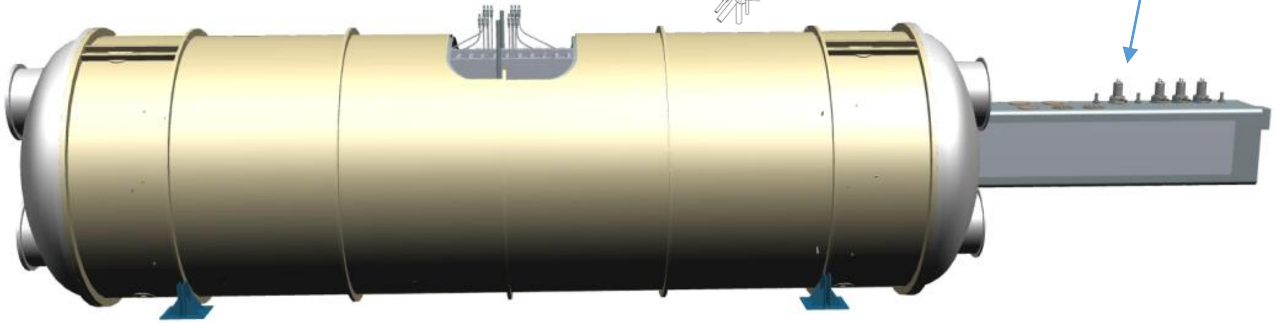
PROS
No need of external plant Good for movable magnet Less space Modularity, redundancy Less He consumption

CONS
Complexity Innovative design Modest power, less efficient

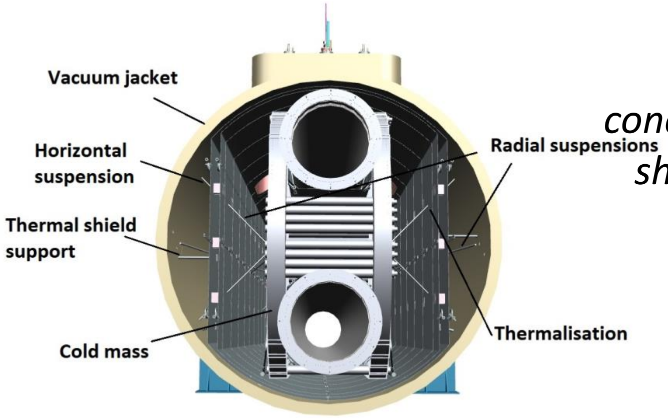
Cryogenic turret (phase separator)



Service box



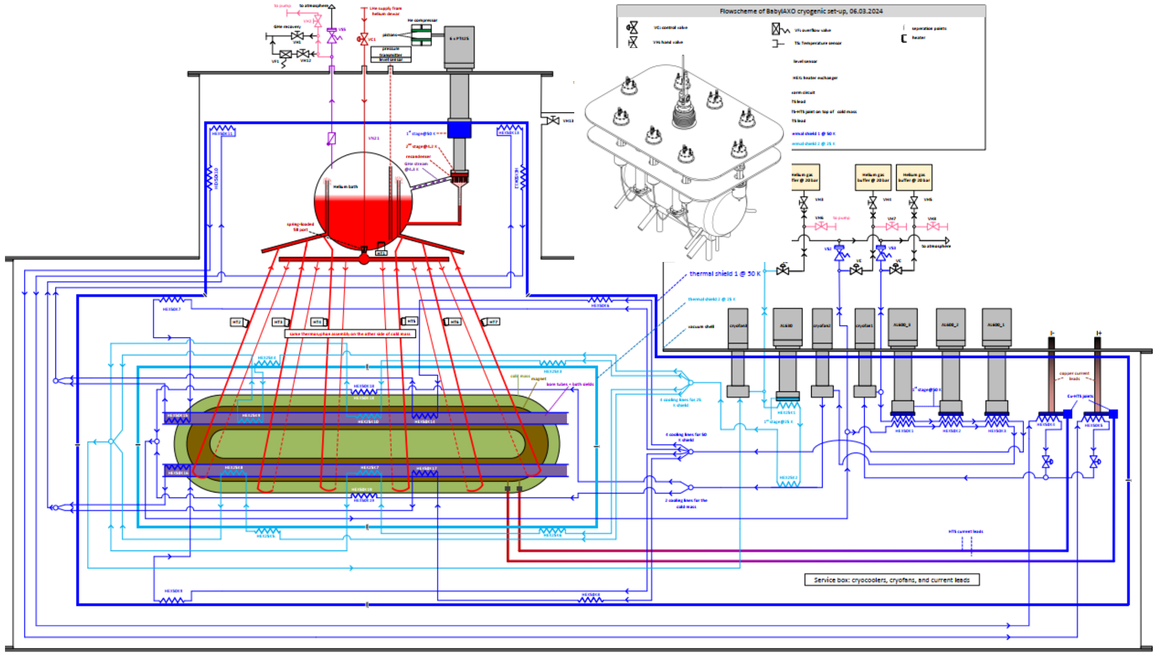
Concentric thermal shields (25 and 50 K)

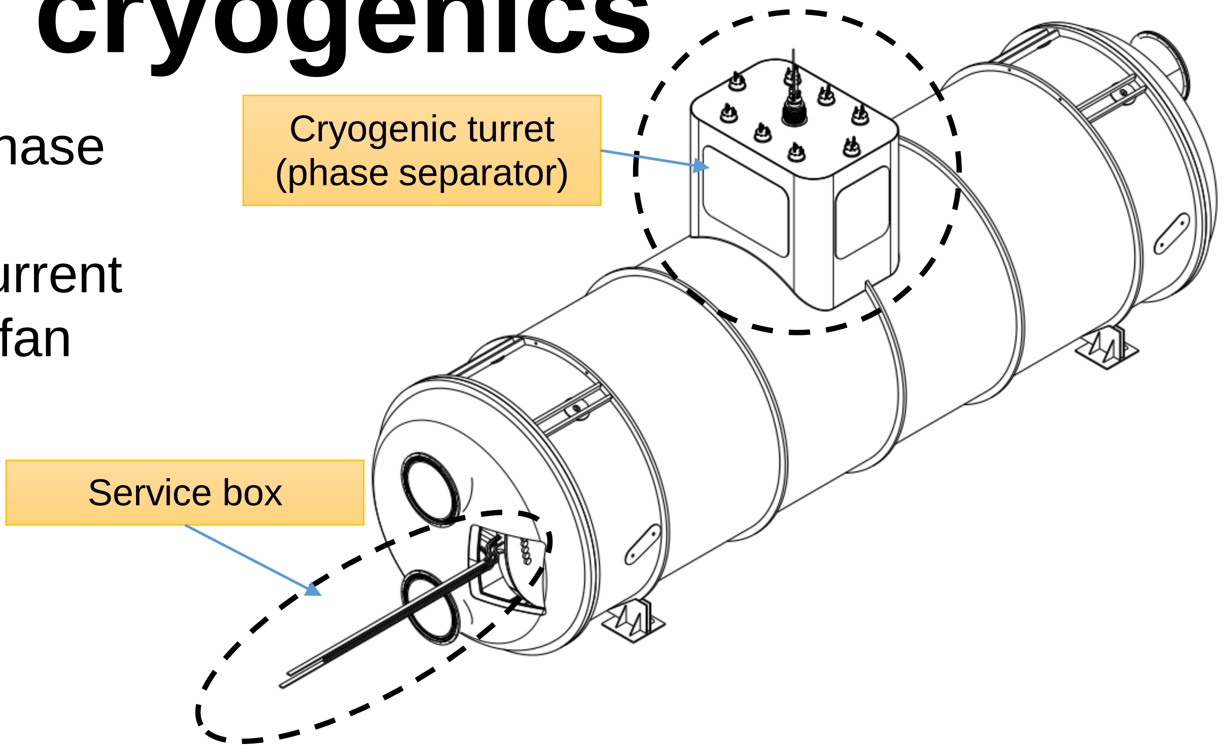


Cold mass, concentric thermal shields and coil suspension

BabyIAXO magnet: cryogenics

- Cold mass (<5K), Cooled with liquid He from phase separator via thermosiphon (cryo turret)
- 50 K & 25 K thermal shields and HTS-based current leads, cooled with He gas circulation with cryo fan (service box).





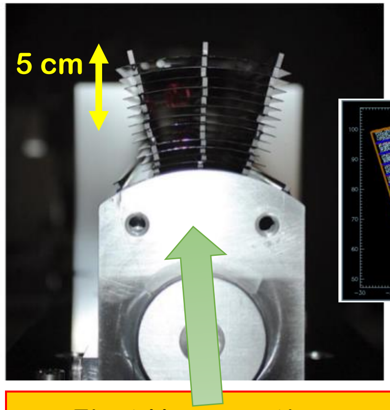
A number of demonstrating setups & tests ongoing at CERN-EP

He gas circulation with cryocoolers & cryofan
HTS high-efficiency current leads.
Local cryocooler-based He liquefaction and thermal syphon.
Compact Zero-boil-off cryogenics
Custom-designed heat exchanger

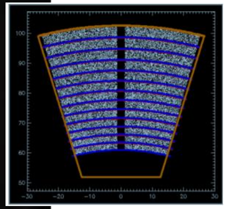
X-ray optics for axion helioscopes

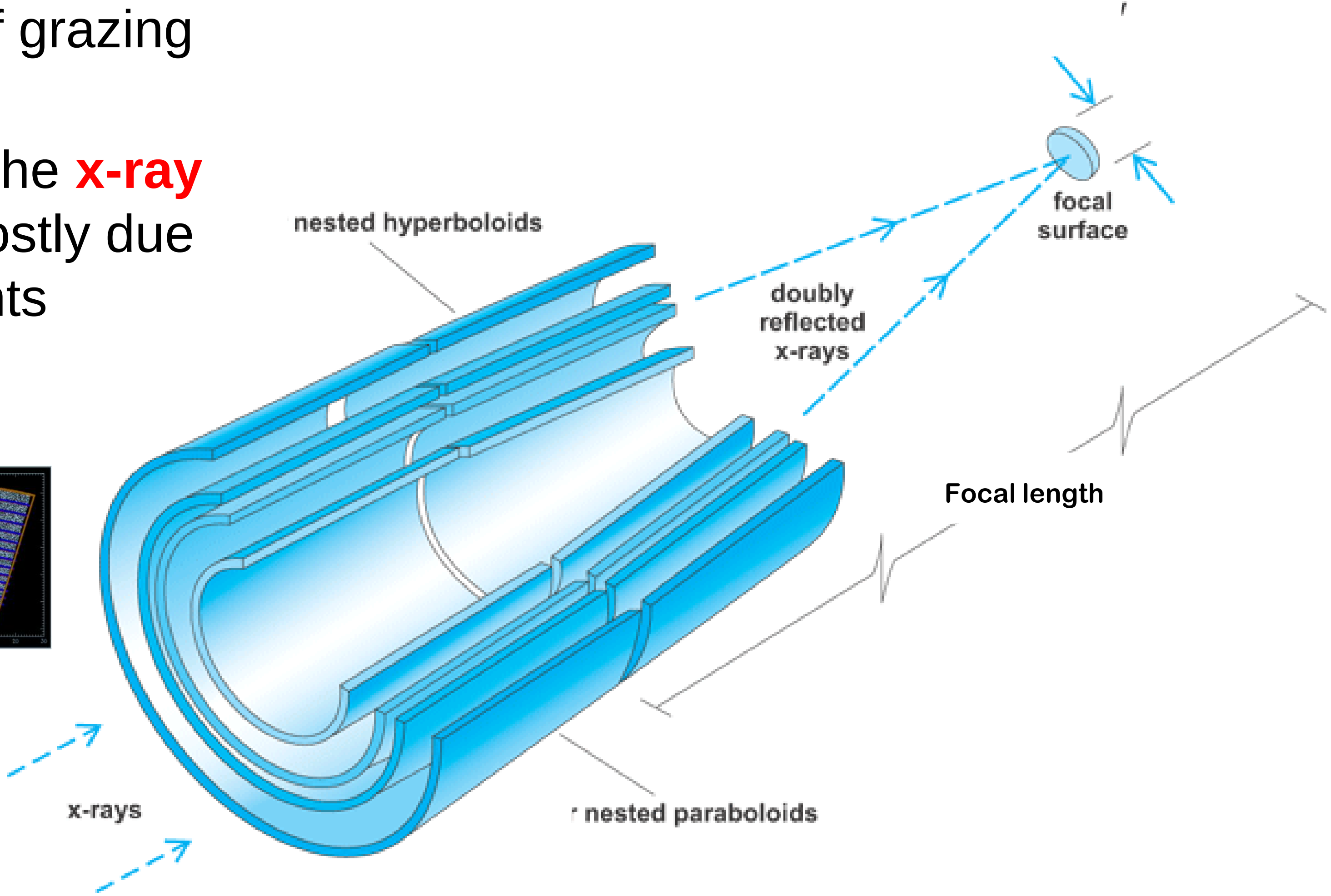
- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the **x-ray astronomy field**. But usually costly due to exquisite imaging requirements

ABRIXAS spare telescope, used in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)



First X-ray optics specifically built for axions in CAST (LLNL)



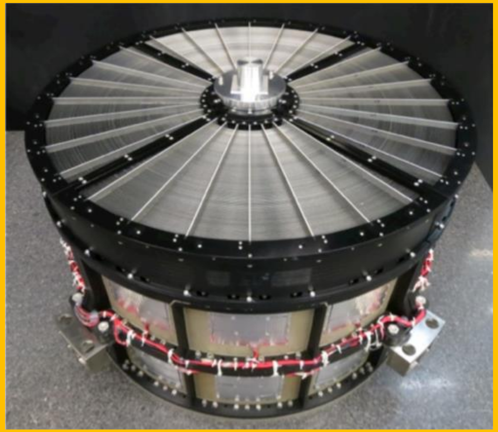


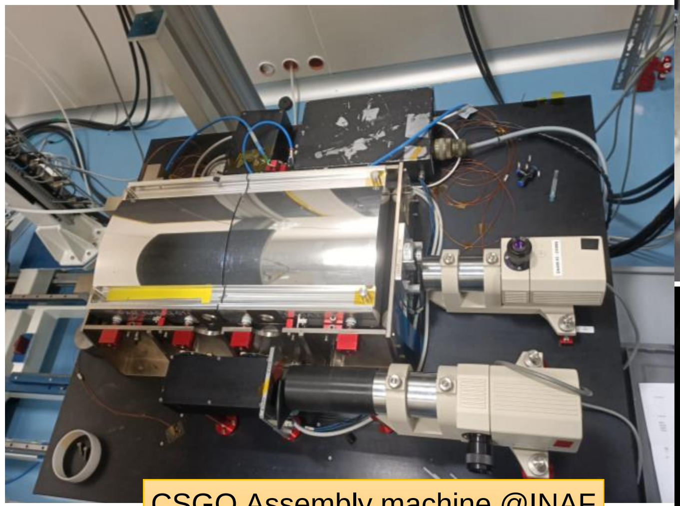
Cost-effective large-scale X-ray optics

- Various technologies successfully used in X-ray astronomy:
  - Slumped glass (NUSTAR)
  - Aluminium foil (XRISM)
- Also existing flight spare modules can be used →

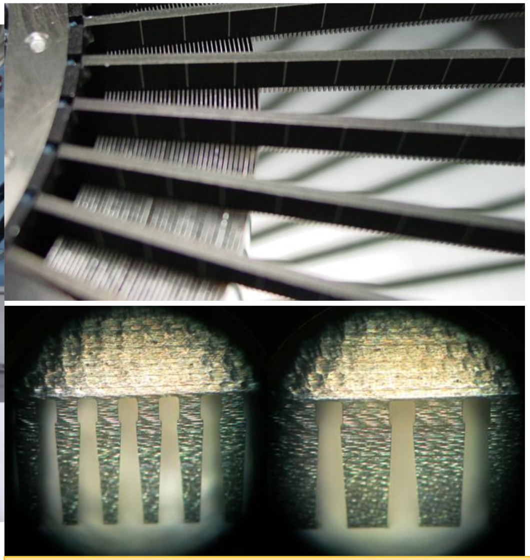
XMM Flight Spare x-ray telescope

Property of ESA, loaned to be used in BabyIAXO. 70 cm diameters, 7 m focal length

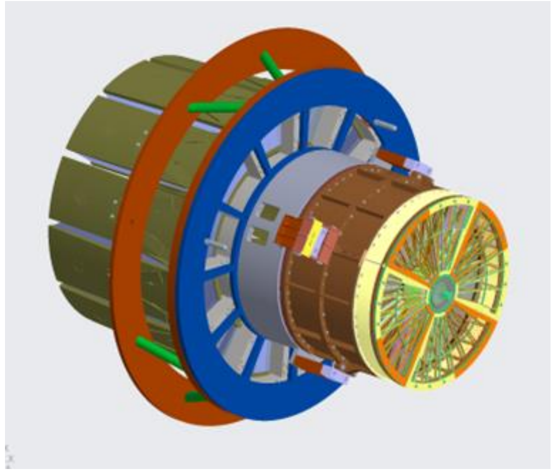




CSGO Assembly machine @INAF



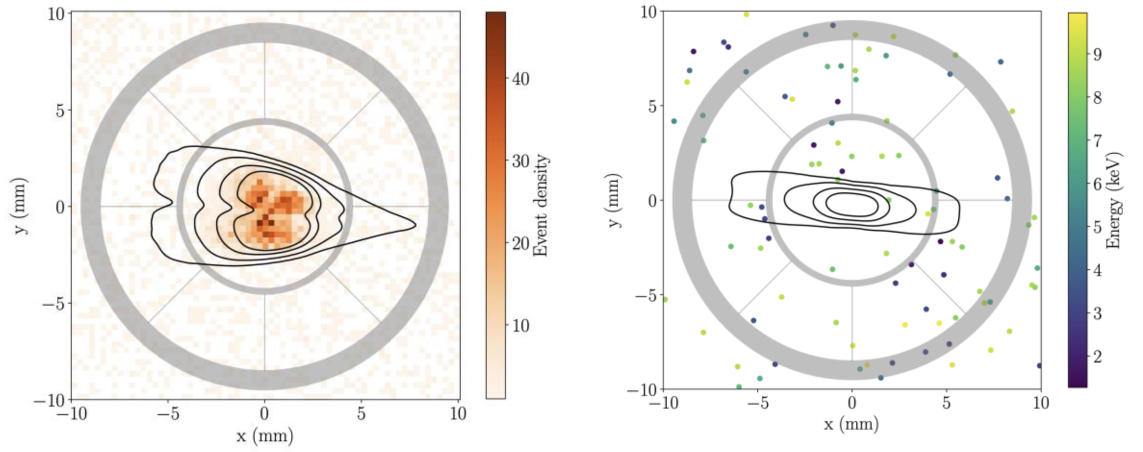
XRISM XRT and alignment bars @NASA GSFC



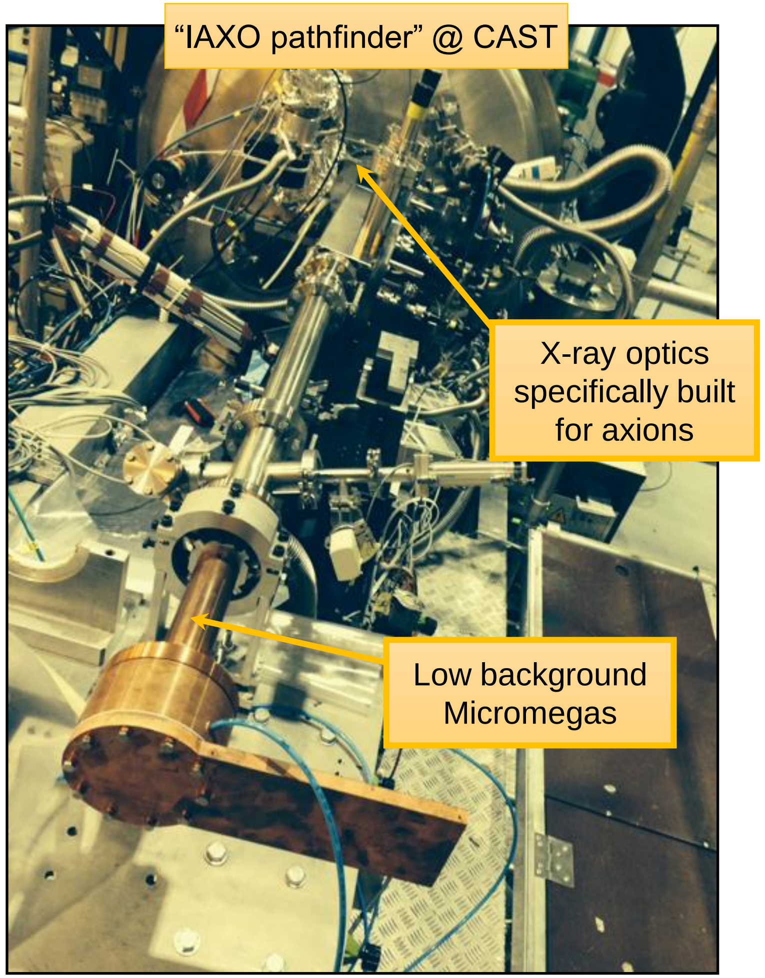
Conceptual design for BIAXO co-mount need to be finalized and constructed

Ultra-low background x-ray detectors

- To be placed at the focal plane of optics
- Pixelization to properly image the axion signal
- Lowest possible background

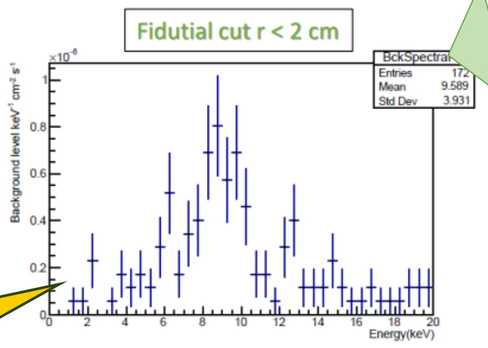


Phys. Rev. Lett. 133 (2024)



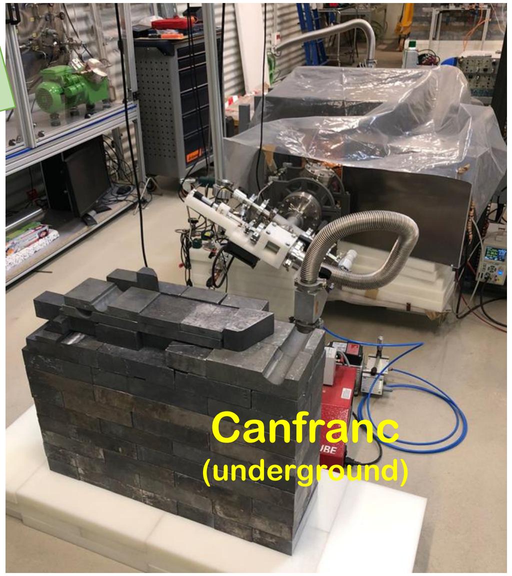
Ultra-low background x-ray detectors

- Low background techniques similar to underground DM experiments:
  - Radiopure components & materials
  - Shielding of external radiation
  - Detailed simulations
  - Offline cuts

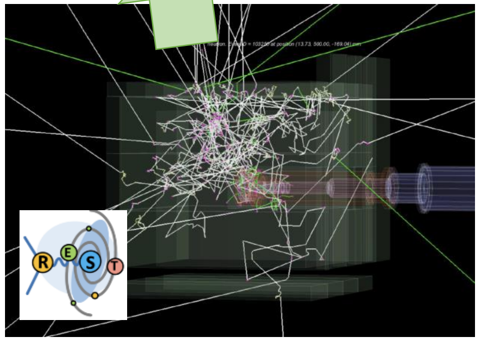


~1 count/month background in the RoI!

[2 – 7] keV 32 counts:
(1.84 ± 0.33) x 10^{-7} c·keV^{-1}·cm^{-2}·s^{-1}



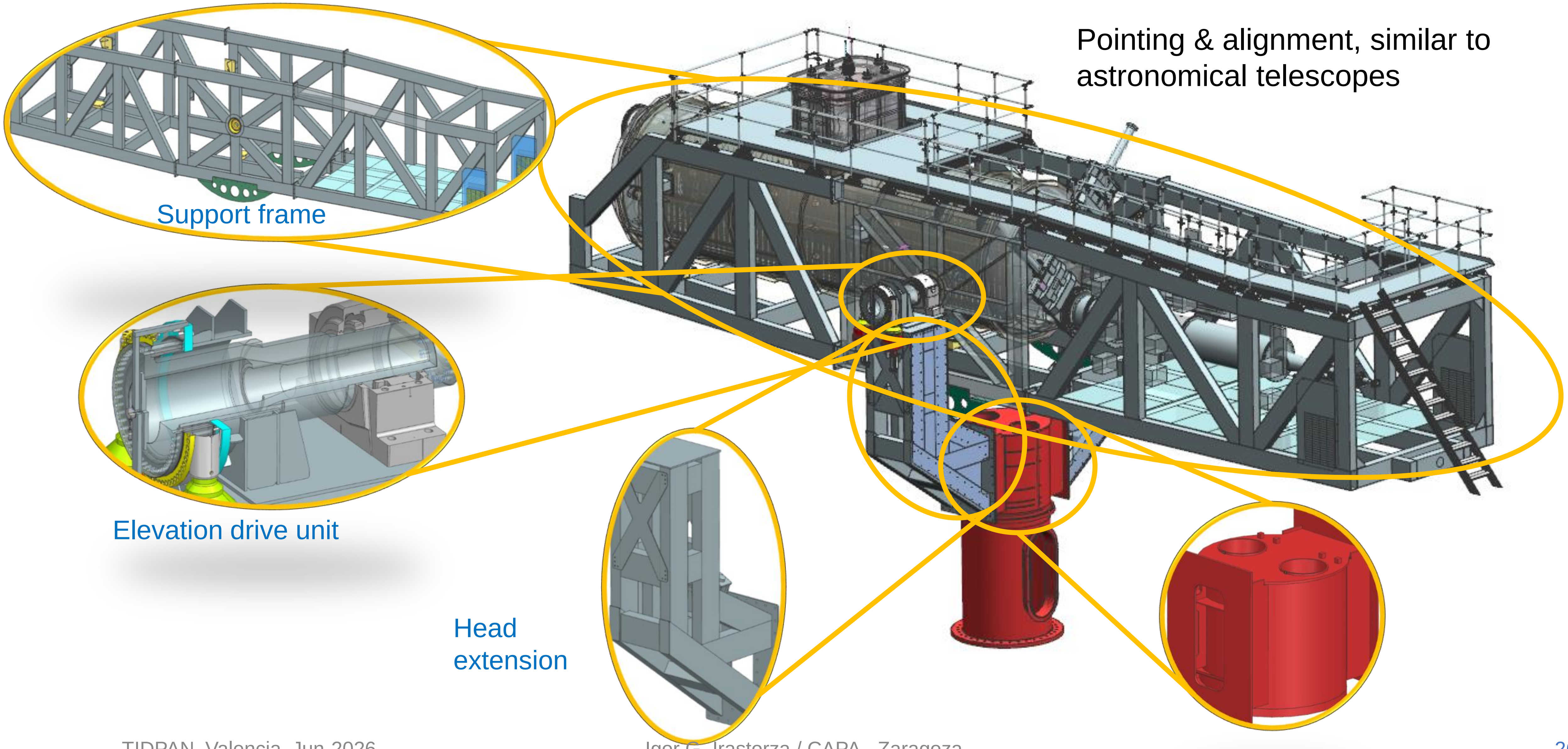
Simulation studies (neutron event)



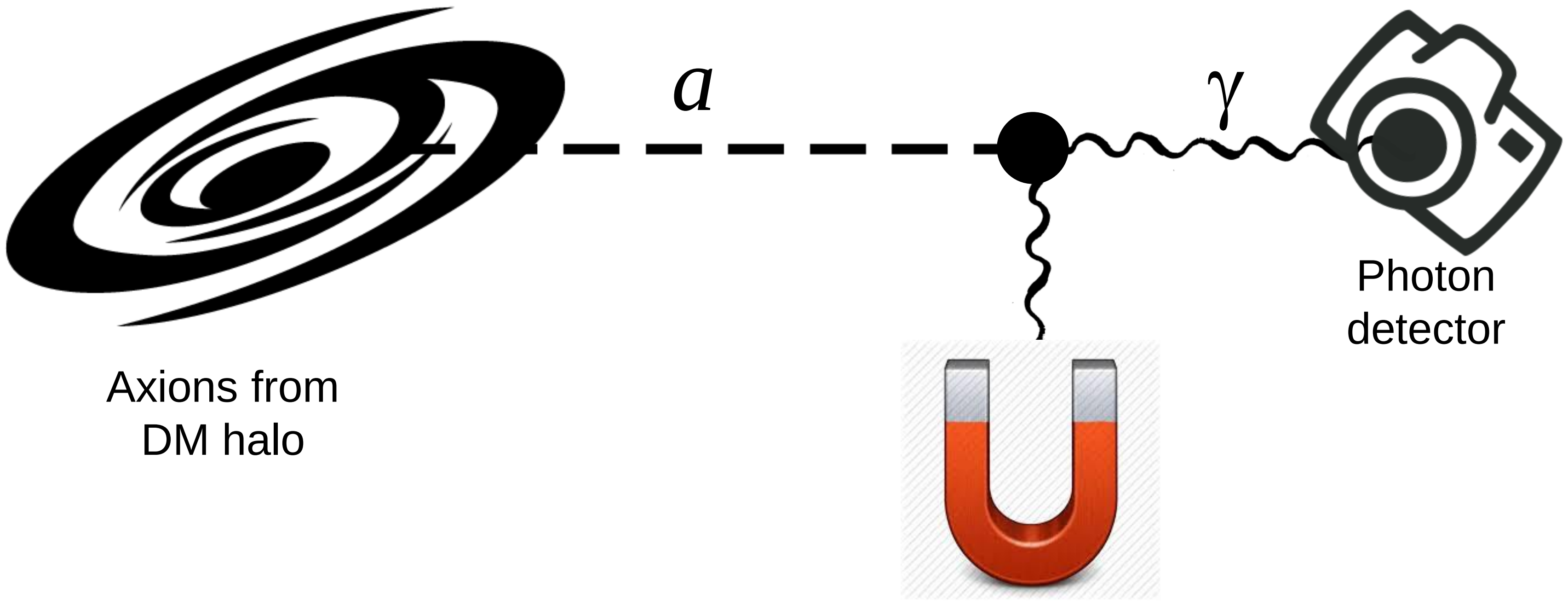
System on suface to test active shielding concepts (cosmic neutron tagging)

Support and drive system (SDS)

Pointing & alignment, similar to astronomical telescopes



Dark matter axions



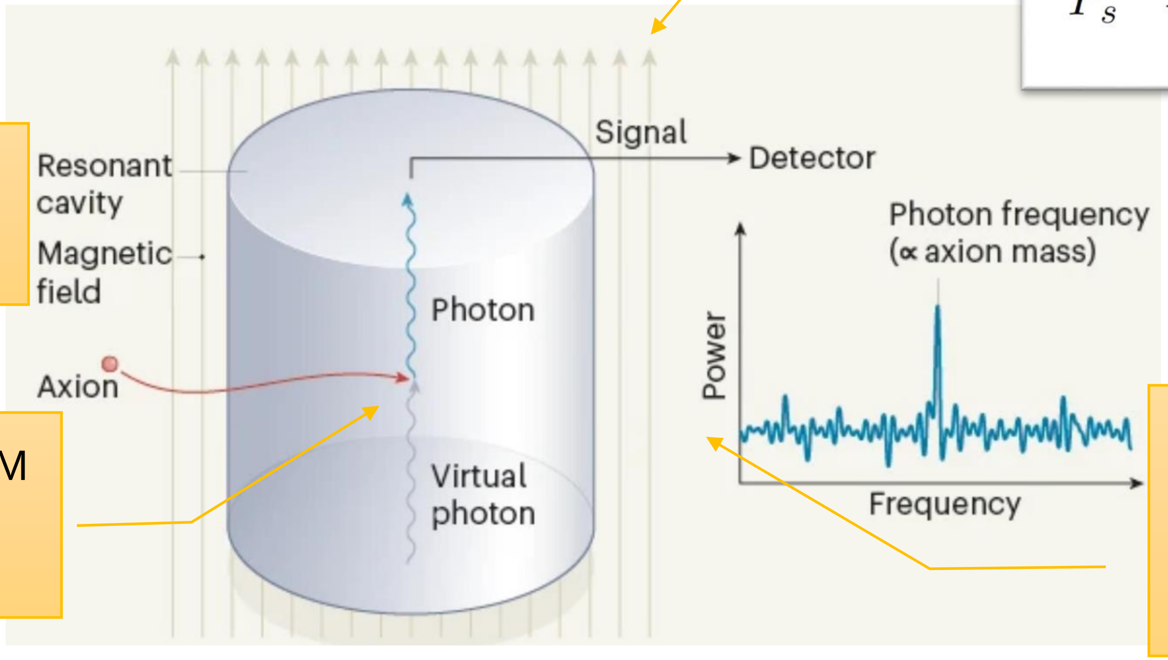
Detecting DM axions: “axion haloscopes”

- Assumption: DM is mostly axions
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$

Cavity dimensions smaller than de Broglie wavelength of axions

$$P_s = \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a$$

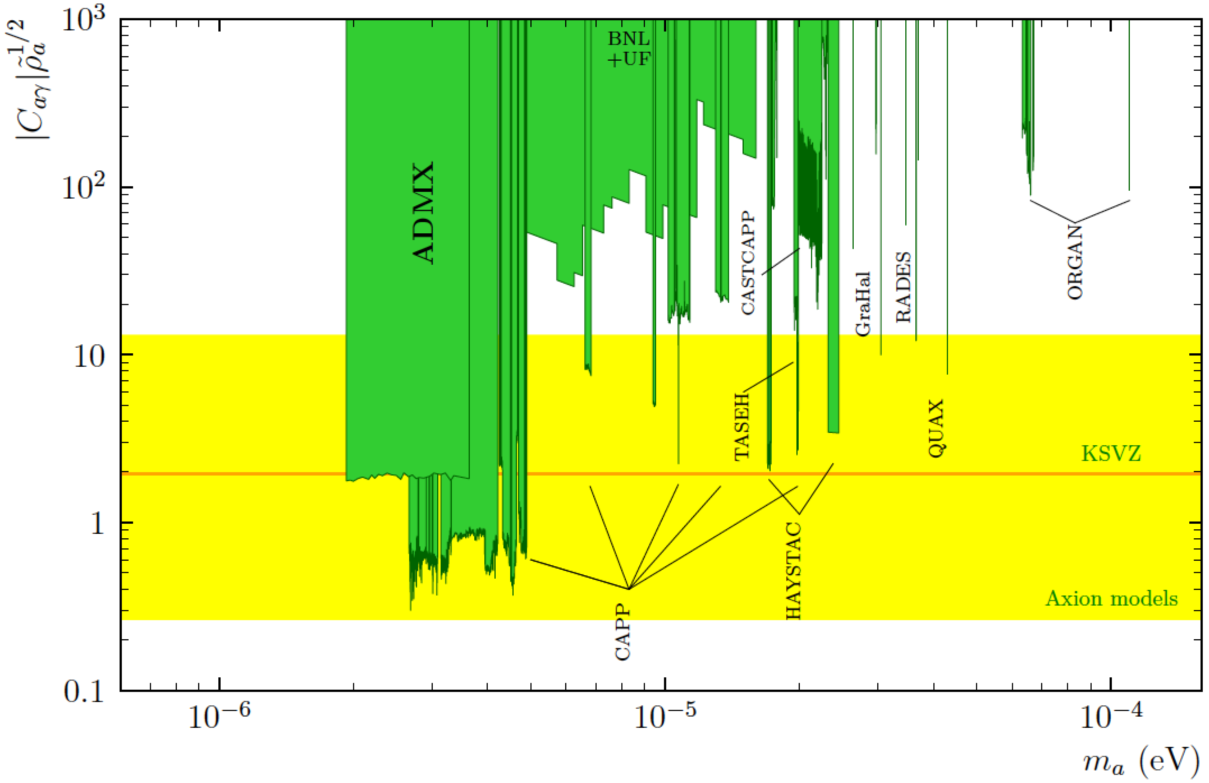
Axion DM field
Non-relativistic
Frequency ← axion mass

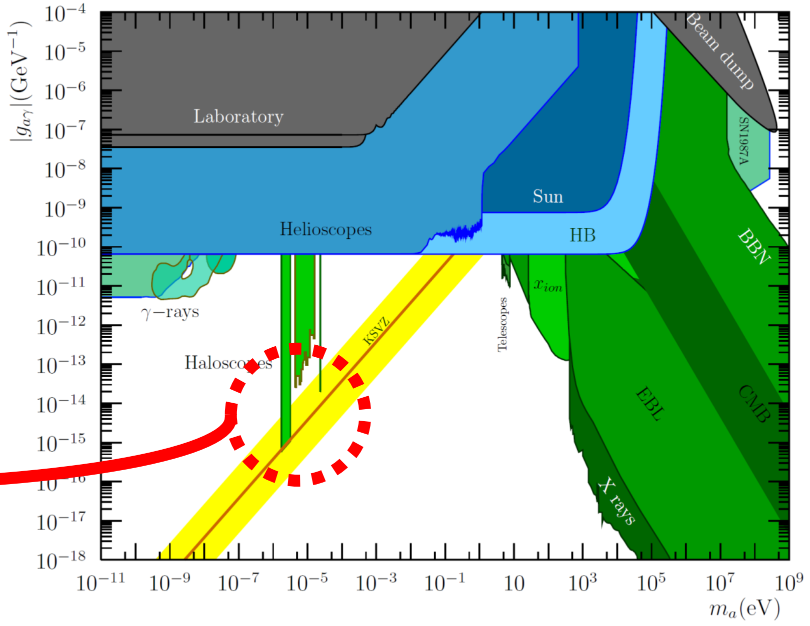


Primakoff conversion of DM axions into microwave photons inside cavity

If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)

Haloscopes: current results

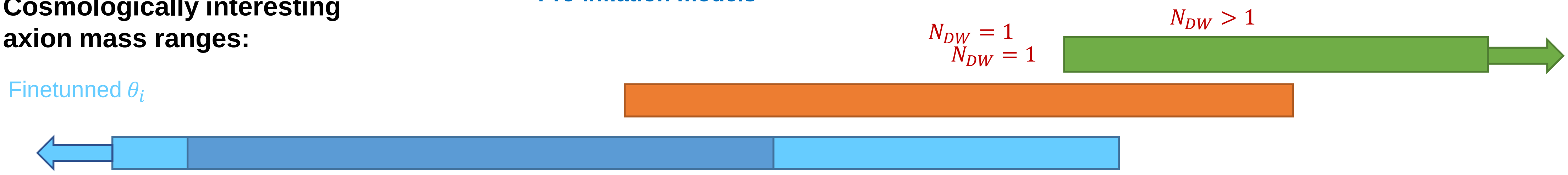




Cosmologically interesting axion mass ranges:

Pre-inflation models

Post-inflation models

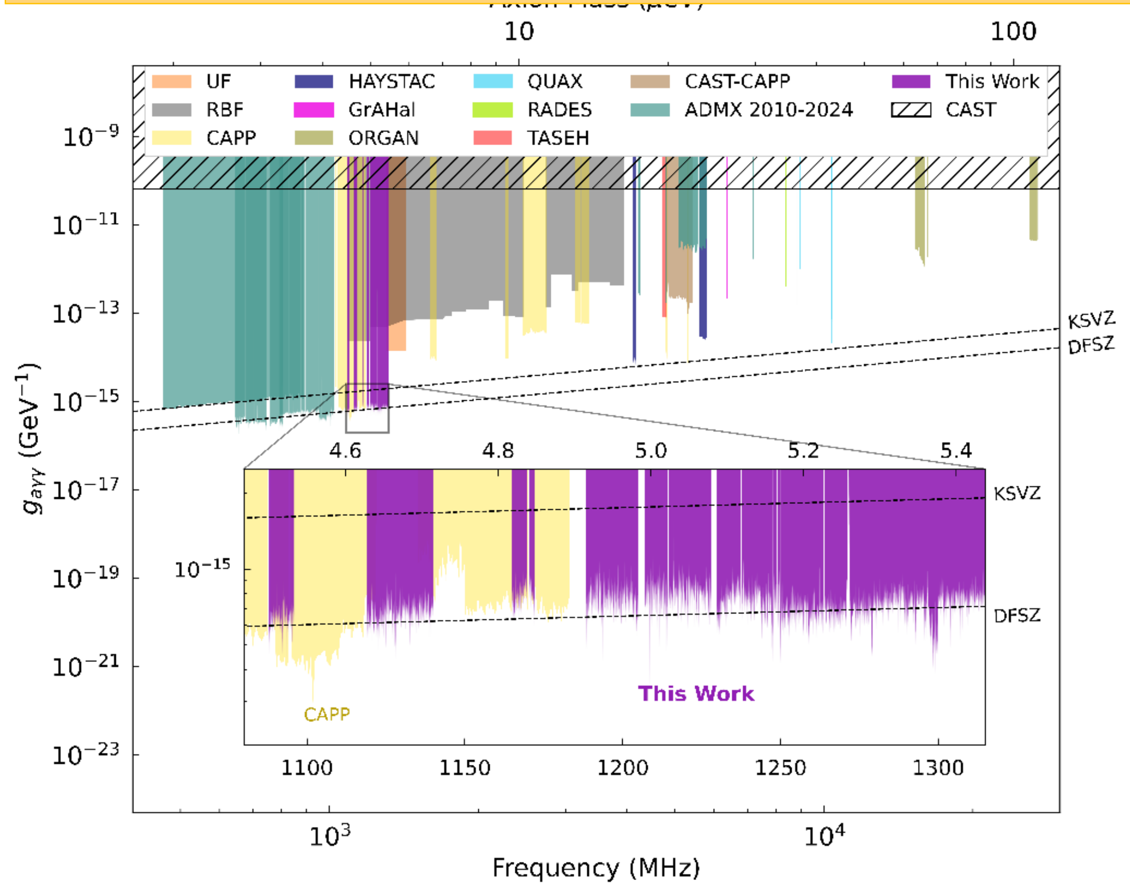


ADMX

- Paradigmatic axion haloscope. Long track of R&D and physics results. Sited at U. of Washington
- Tuning achieved by set of movable rods
- Sensitivity to **few μeV** proven

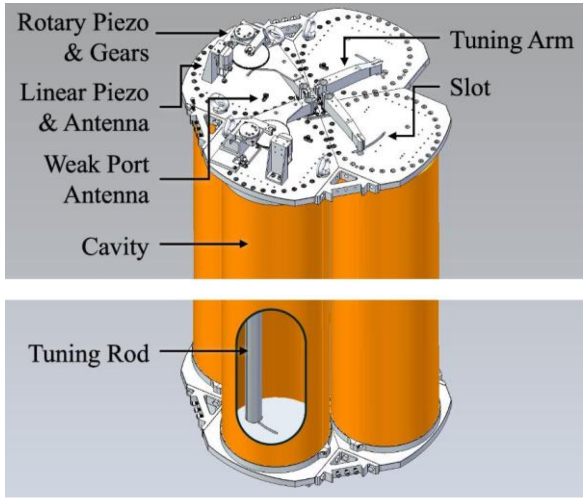
Last results (2024): KSVZ Axion Model at nominal dark matter density excluded at 90% confidence between 1 GHz and 1.3 GHz. DFSZ Axion Model at slightly higher densities excluded

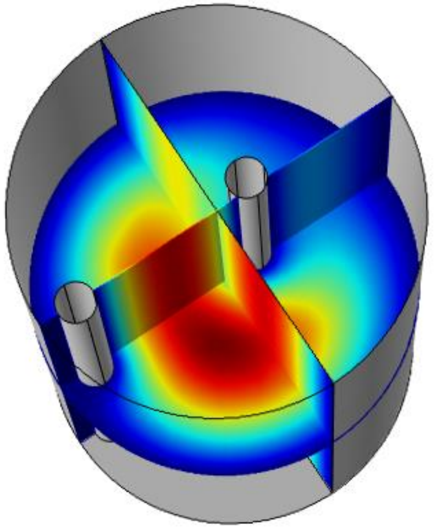
- High Q cavity $\sim 10^5$
- Large volume: $1\text{m} \times 60\text{cm}\ \text{Ø}$
- Suited for resonance at few $\times\ \mu\text{eV}$
- 8T superconducting magnet

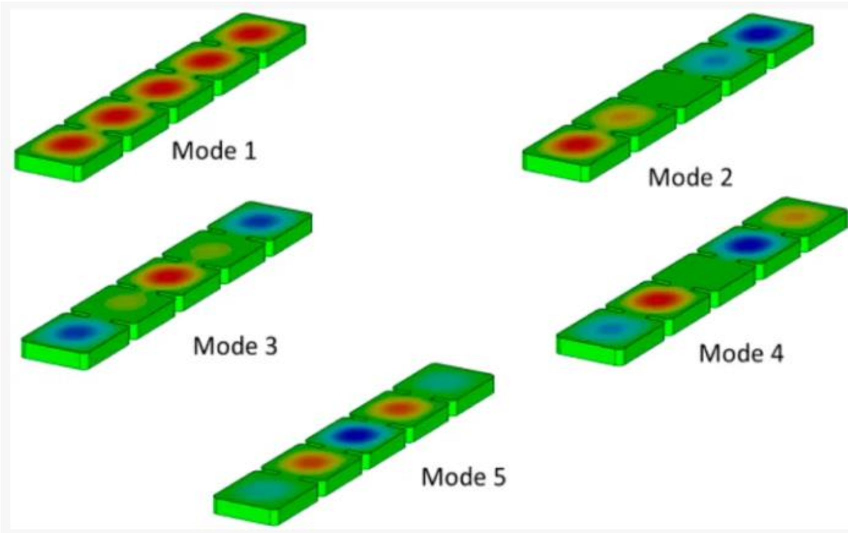


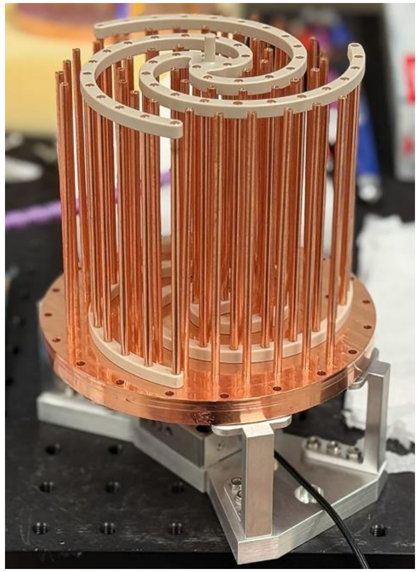
RF design & engineering

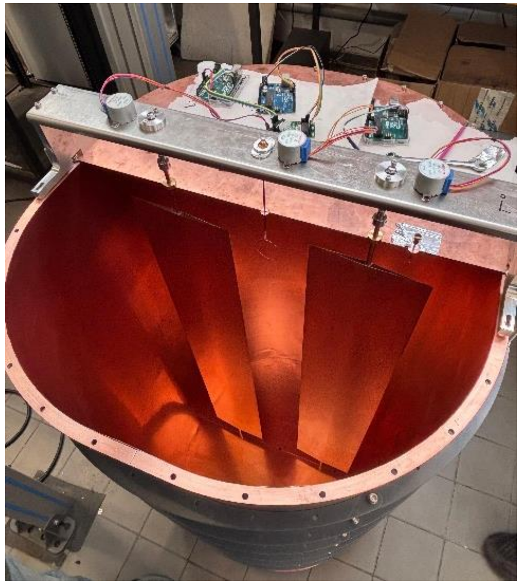
- As the expected signal are at RF, we need expertise in:
  - Passive elements design and FEM simulation (resonant cavities and structures)
  - RF components, circuits, characterization, etc…











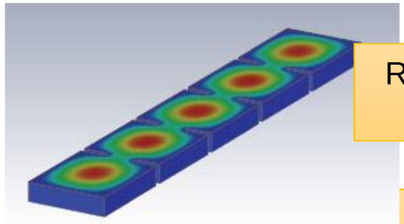
Haloscope FOM

- **High-m_a challenges:**

higher m_a → lower V → lower sensitivity

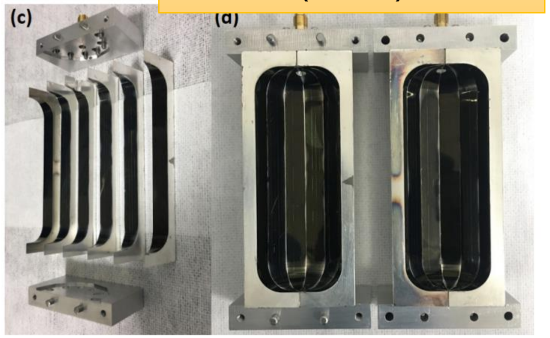
$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$

- **R&D to go to:**
  - Higher B magnets
  - Larger instrumented volumes
  - Lower noise sensors
  - Higher Q cavities



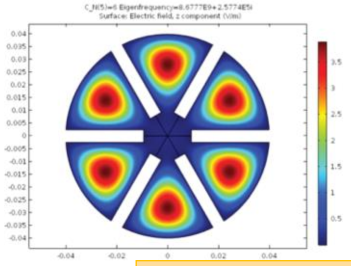
RADES project in CAST

HTS coated cavity (CAPP)



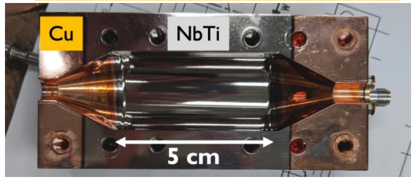
Very active R&D in many groups!

- More powerful magnets
- Multicell structures:
  - Phase-matched
  - Filter-like
  - Dielectric loading
  - Photonic bandgap
  - …
- SC deposited cavities
- Lowering T with cryogenics and novel sensing techniques



"Pizza cavity" at CAPP
→ 2008.10141

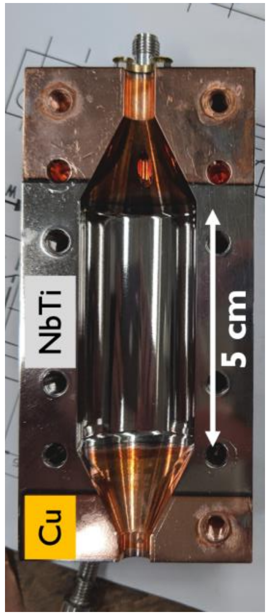
QUAX at LNL



Superconducting coatings

- Coating the walls of the cavity with a superconductor material will increase Q (decreases the losses on the walls)
- Technological challenges: the material must remain SC in the magnetic field.
- Novel high-T superconductor (HTS) are difficult to handle (brittle materials, etc.)
- Physical limit to improving Q: above $Q_a \sim 10^6$ it does not translate in improved FOM (the axion peak must fit in the cavity bandwidth!)

NbTi coated cavity
(QUAX experiment)

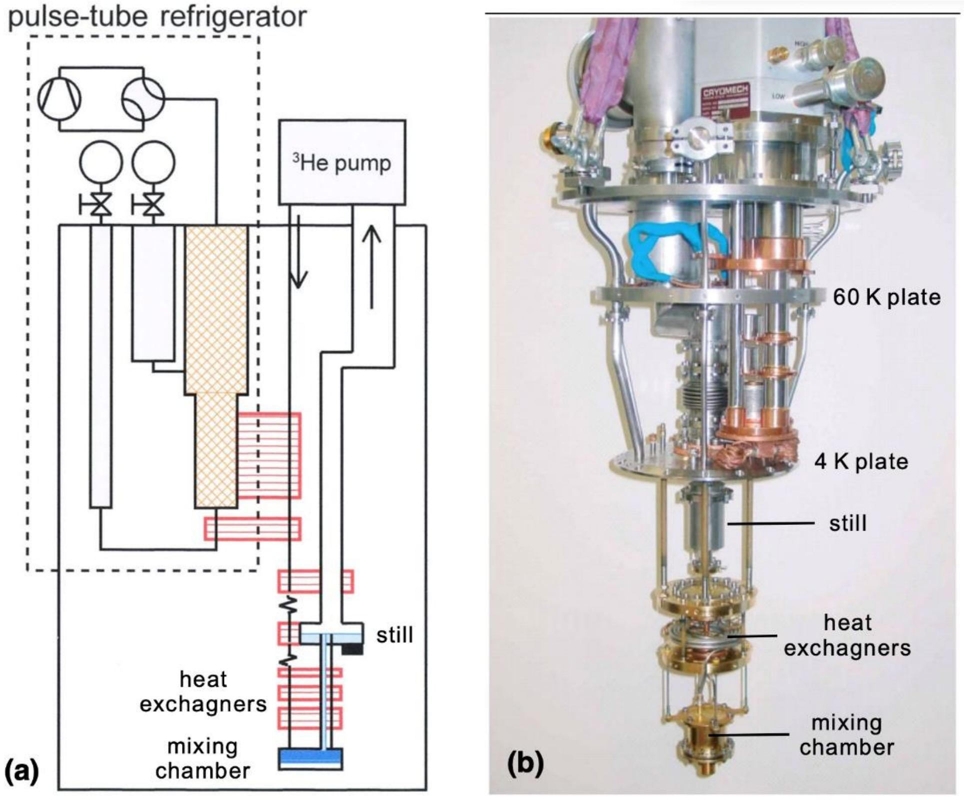


HTS coated cavity
(CAPP)

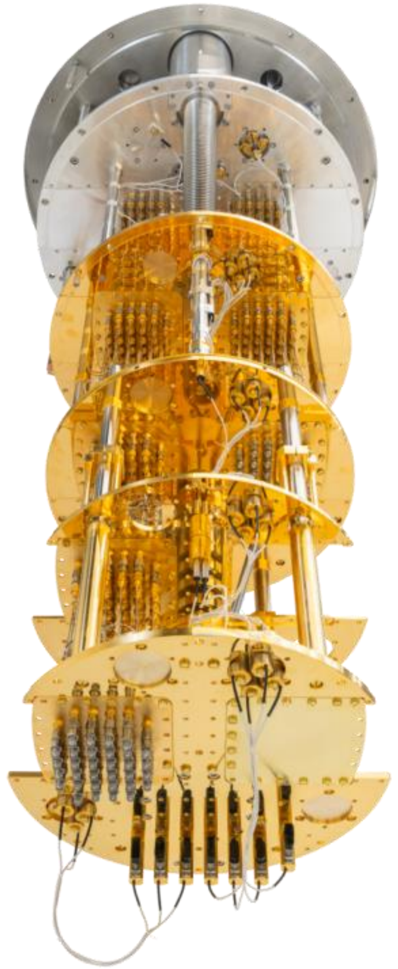
HTS coated cavity
(RADES)

Millikelvin cryogenics

- Dilution refrigerators use evaporation of He3 from a mixture He3/He4 mixturesto reach mK temperaturas
- Commercial availability has expanded dramatically, driven by advances in quantum technologies.



https://www.insight-ihbar.com/QC_hardware_en/F.html



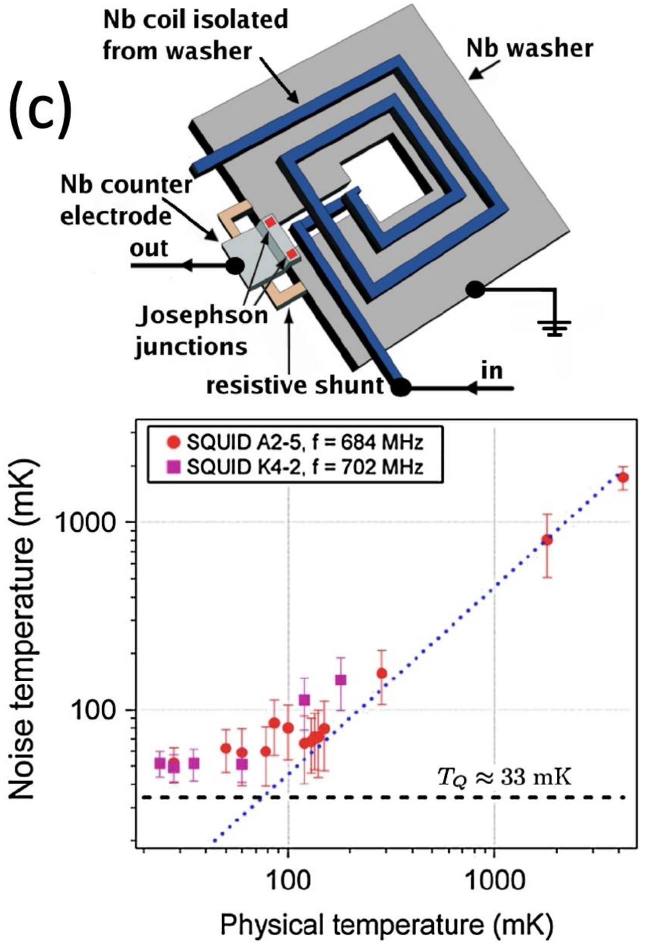
Commercial dilfridge BlueFors LD

Quantum technologies to lower T_{sys}

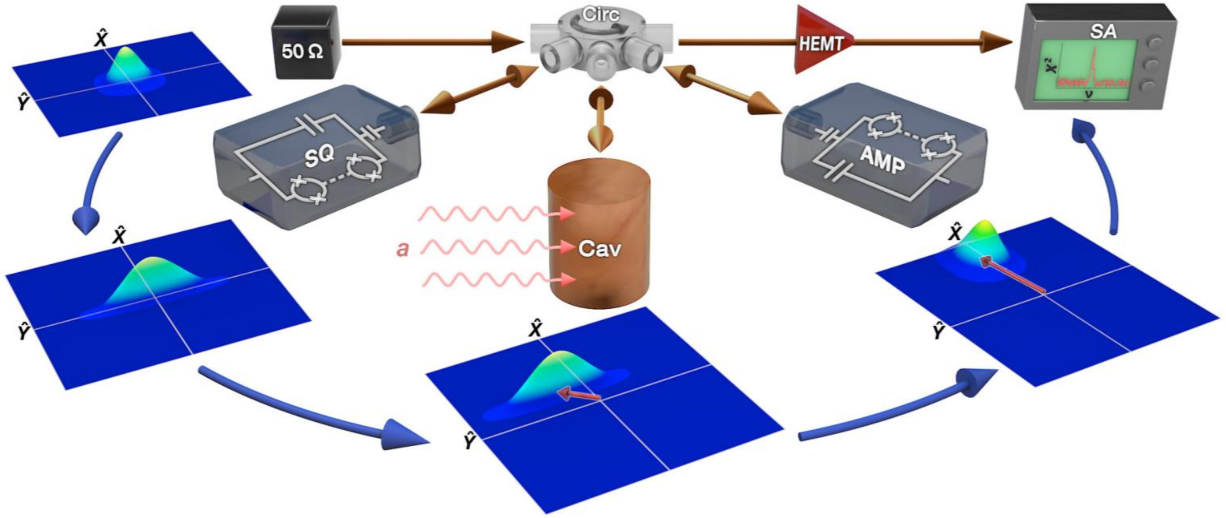
SQUID amplifier from ADMX collaboration

$$F_{\text{halo}} \propto \rho_a^2 g_{a\gamma}^4 m_a^2 B^4 V^2 T_{\text{sys}}^{-2} |\mathcal{G}|^4 Q$$

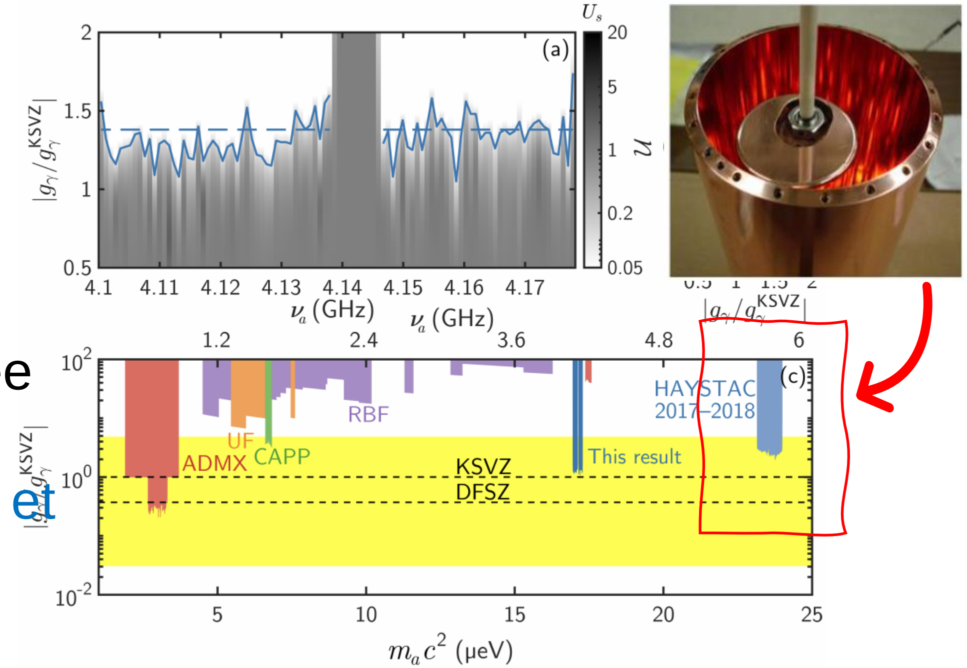
- Leading haloscopes use cryogenics to cool down well below $T_{phys} \ll 1$ K.
- But $T_{sys} = T_{phys} + T_{sen}$ (contribution from the sensor technology). New technologies with lower T_{sen} are also needed. Quantum technology needed to profit from T_{phys} at reach by dilution refrigerators
- But Standard Quantum Limit (SQL): when T_{phys} approaches $\sim h\nu$, irreducible noise from vacuum fluctuations.
- Quantum circuits to achieve quantum-limited amplification: SQUIDs, JPA, TWPA,…



Beyond the SQL: photon squeezing



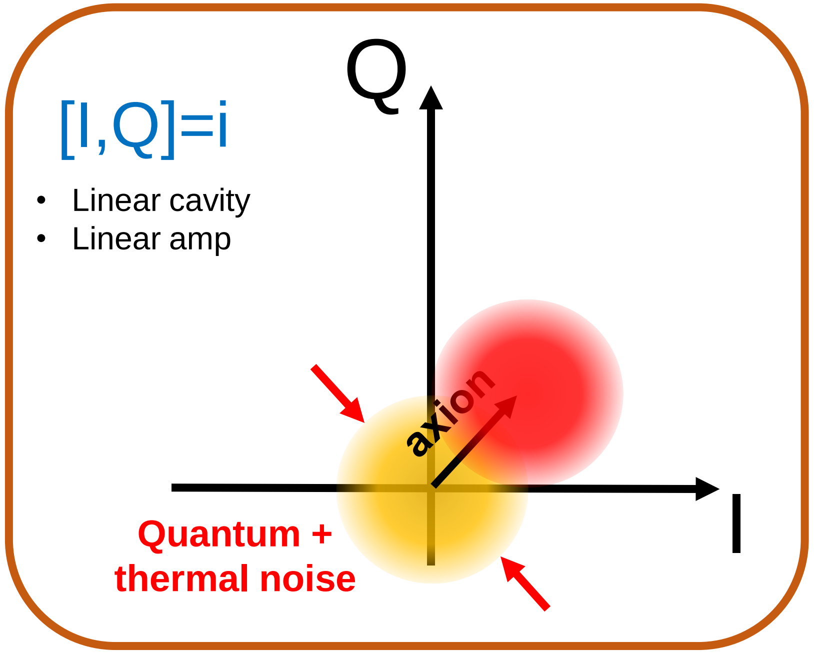
HAYSTAC experiment:
Quantum information technologies for axion searches

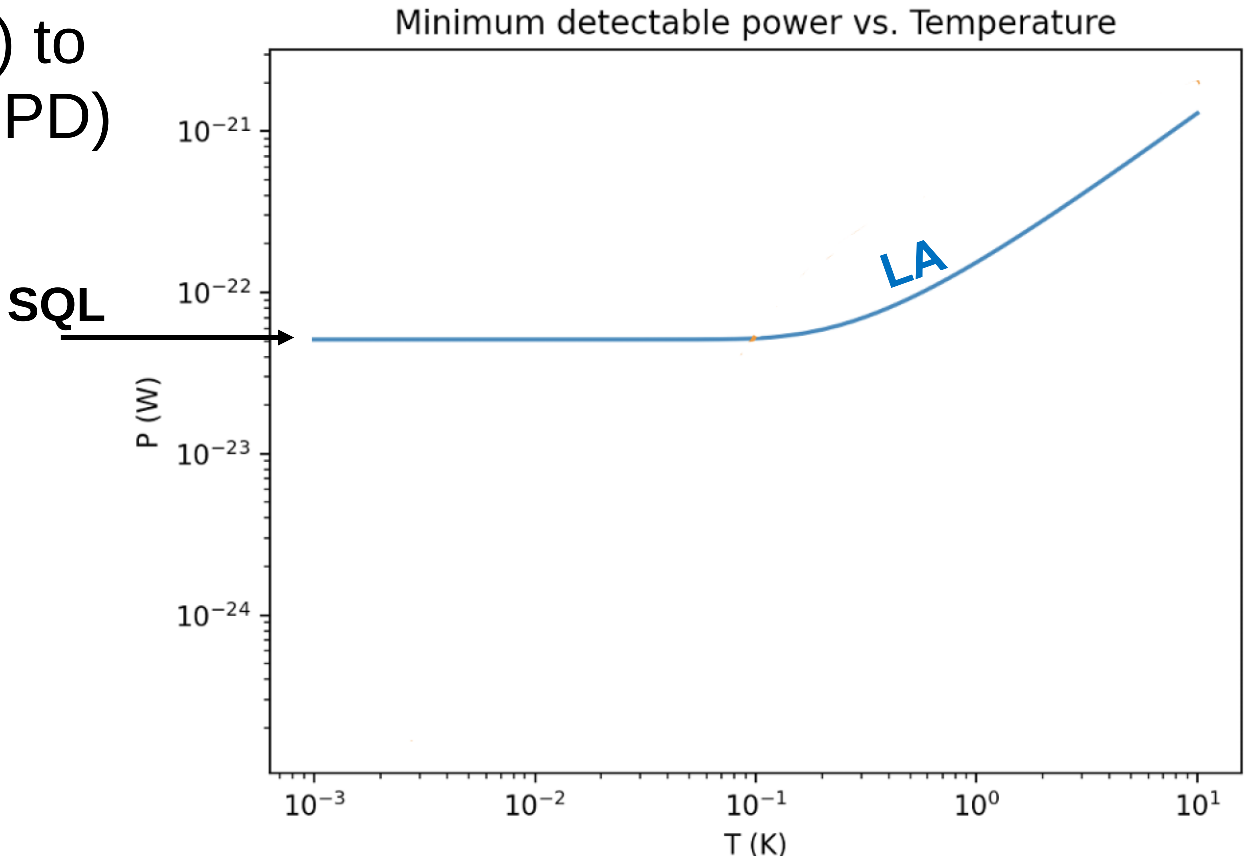


- If the cavity vacuum is prepared in a squeezed state, the axion signal can be read with a noise that is effectively lower than the SQL in an amount dependent of the degree of squeezing. Concept studied in Malnou et. al 2018
- First experimental application HAYSTAC at Yale (Backes et al 2021). Factor x2 effective faster scan rate obtained

Beyond the quantum limit

- From linear amplification (LA) to ***counting single photons*** (SPD)

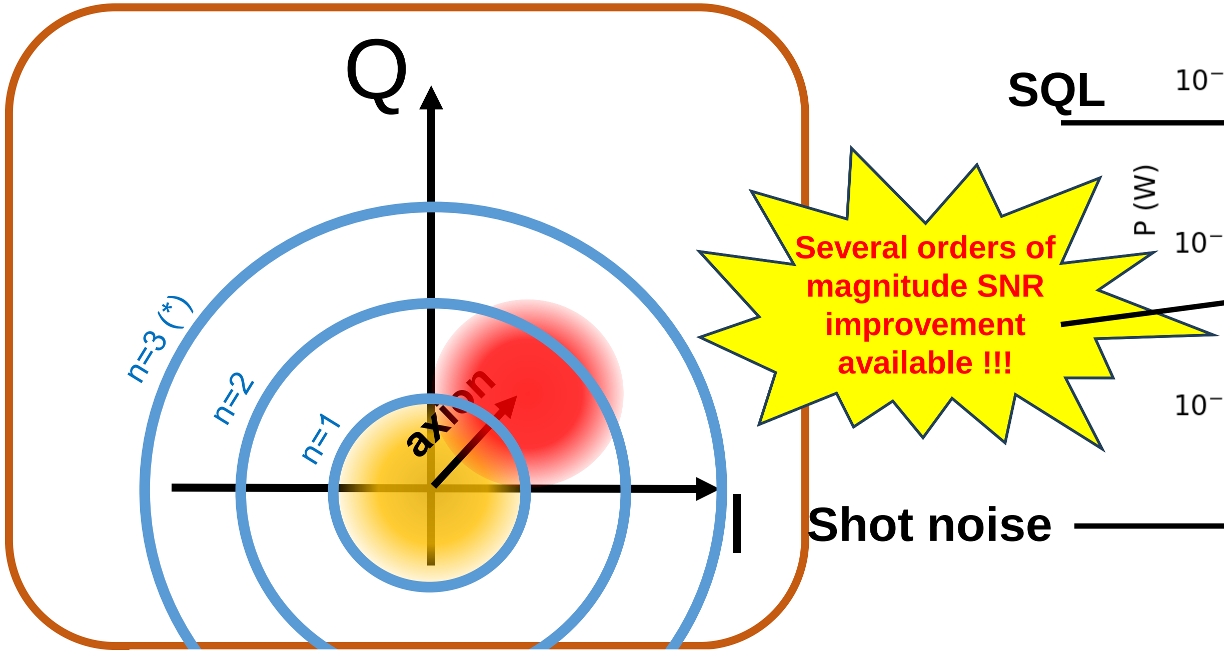




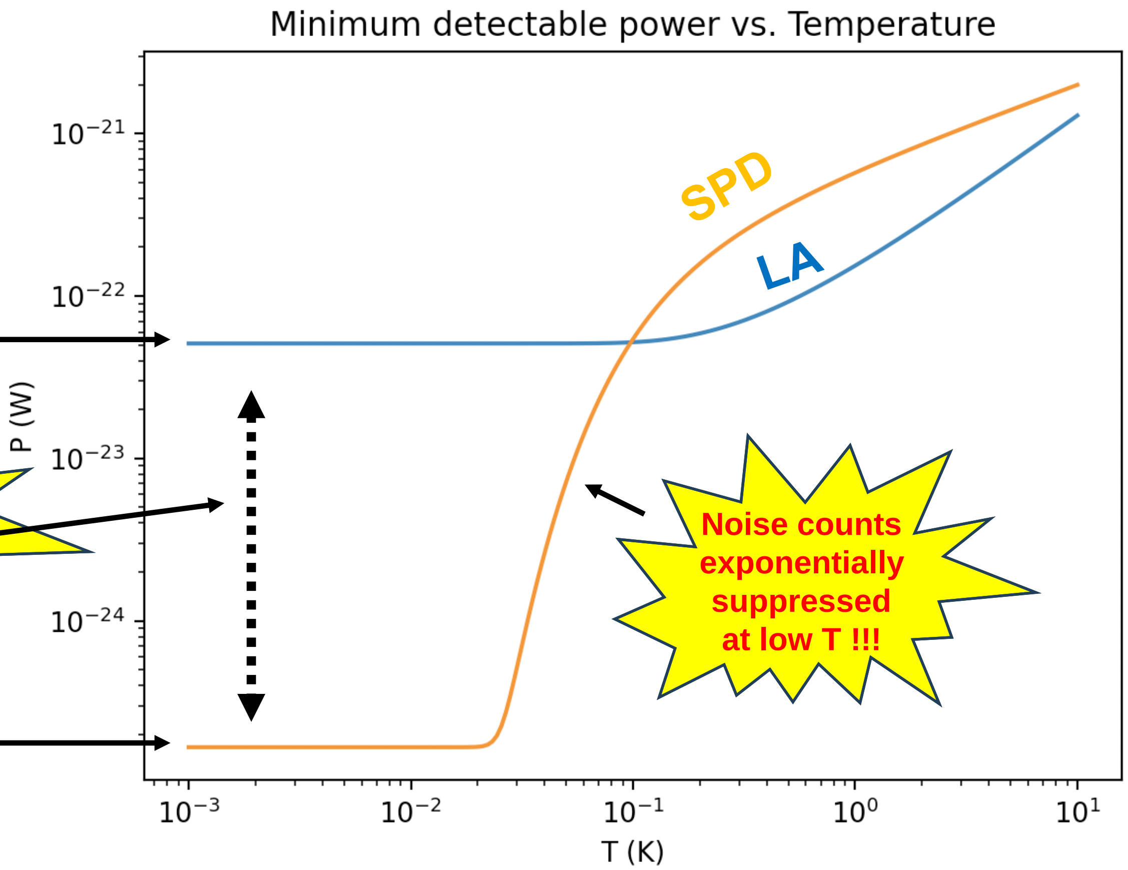
Conventional haloscope: In-phase(I) and Out of phase (Q) conjugates **limited by SQL**

Beyond the quantum limit

- From linear amplification (LA) to ***counting single photons*** (SPD)



(*) heuristic simplified picture



Single-photon detector (SPD) vs Linear Amplifier (LA)

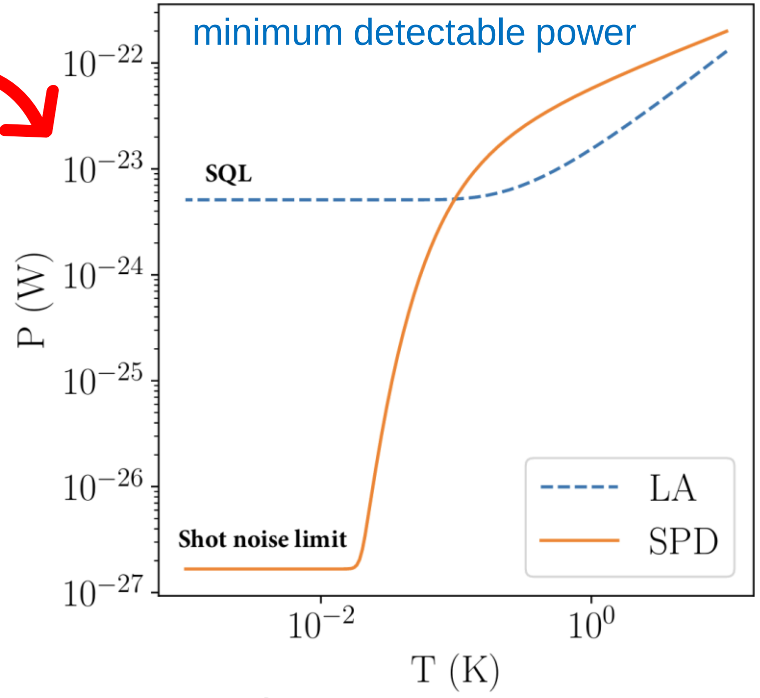
Displaced vacuum state leaks into non-zero Fock number.

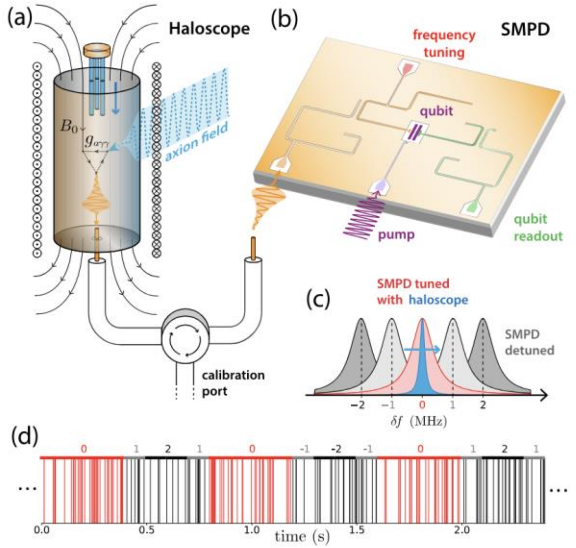
Detect displacement by counting the photon.

Beyond the SQL: photon counting

Counting photons (versus phase preserving readout):
SQL is evaded as phase uncertainty is maximal…

- But, how to implement photon counters at these energies? → quantum technologies Several promising ideas. Some examples:
- **QUAX+Saclay** group: 2403.02321 (x20 better than SQL)

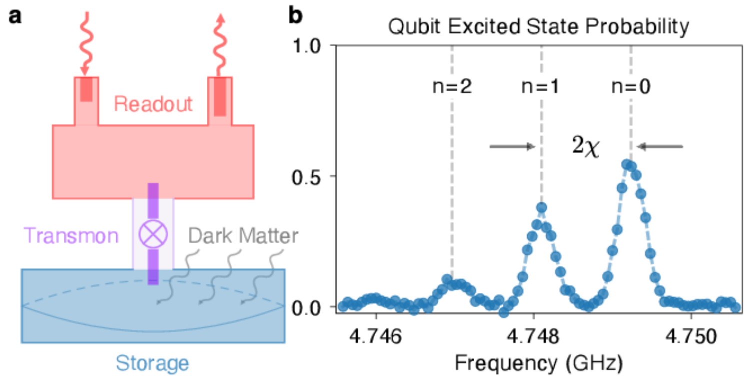




- **Dixit et al** (PRL 126)
- **RADES** / DarkQuantum ERC-SyG project

DarkQuantum

erc

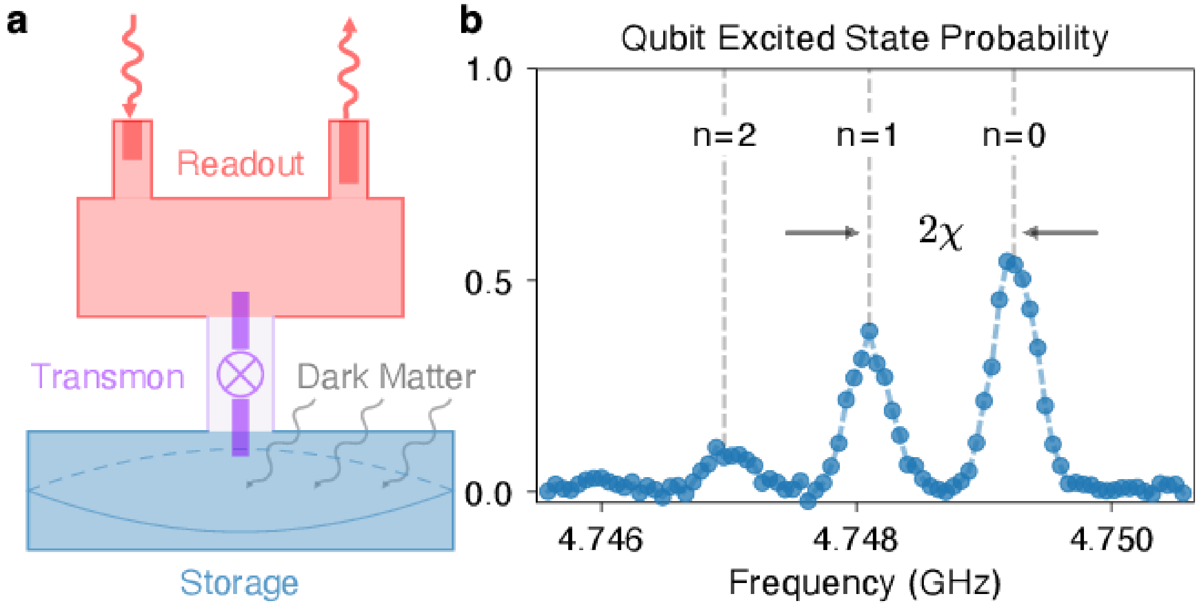


Qubit-based Single Photon Detector (SPD)

- Superconducting qubit (trasmon) dispersively coupled to cavity:

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z$$

Cavity *Qubit* *Coupling*

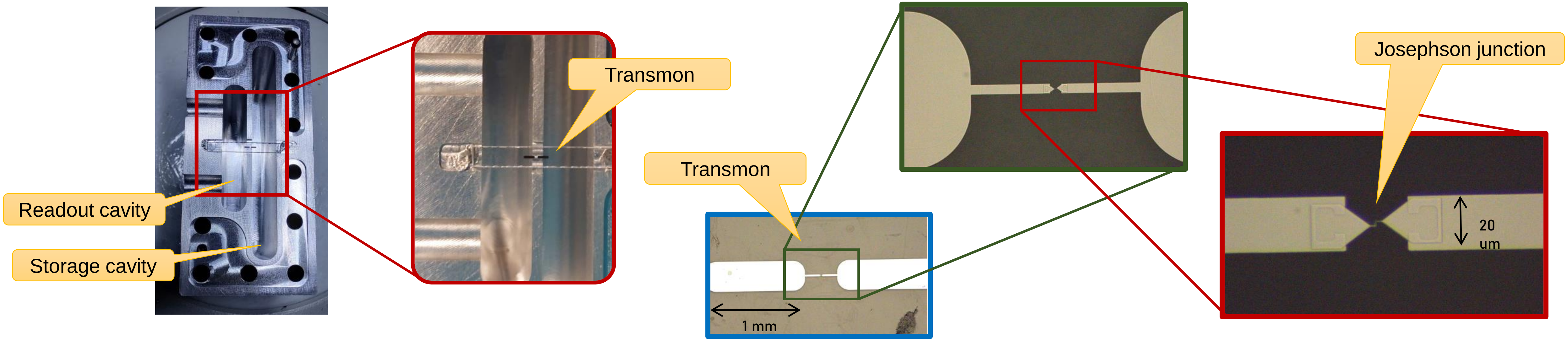


- Presence of photons in cavity shifts frequency of qubit.
- Interrogating the qubit "senses" the presence of single photon
- **Quantum-non-demolition measurement** → photon not absorbed, measurement can be repeated on the same photon!

- Concept proposed in the context of axions by Dixit et al. PRL126 (2021) → O(Hz) dark count rate measured, 10^3 better than SQL!!!

First implementation in RADES

- Double cavity with transmon coupled to both:



- Second version with cylindrical storage cavity geometry just built at CAPA/Zaragoza →

Conclusions

- Boosting interest in experimental search for axions
- Singular portfolio of technologies, many of them not present in conventional HEP groups/institutions
  - Technologicaly exciting field
- Importance of networking with neighboring fields
  - Astronomical observatories and missions (e.g. x-ray telecopes)
  - Precision optics, material science,…
  - RF technologies and astronomy
  - Quantum physics and technologies
- Potential for impact of new ideas, or new synergic connections, etc…
- Large fraction of parameter space at reach of near-future experiments
  - chances of discovery!

Good times for axions… stay tuned

Acknowledgements

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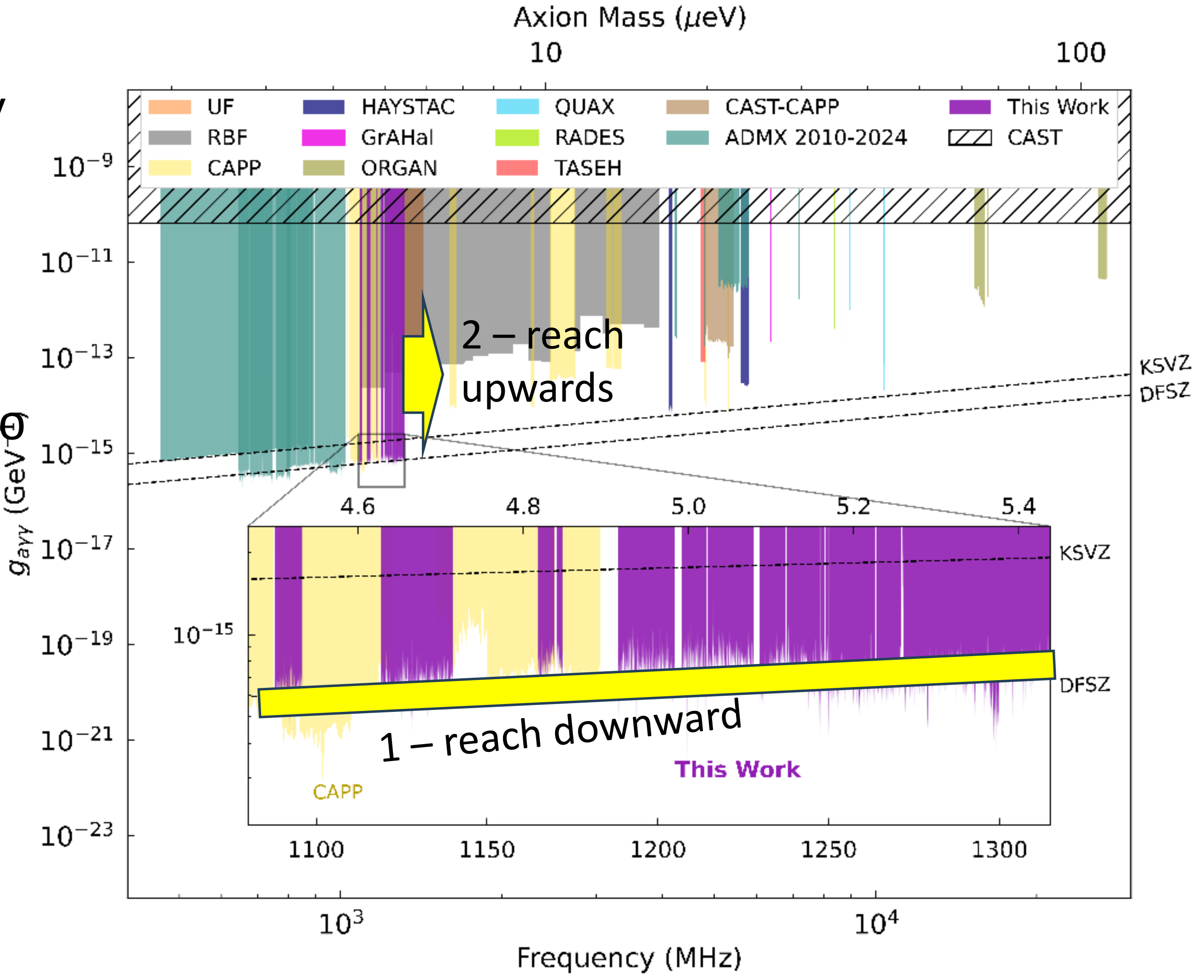
Thank you for your attention

→ Backup slides

ADMX: next plans

- Plan: Extend reach down to DFSZ at below-nominal dark matter density, by improving amplifiers to lower system noise temperature. [Started data taking in 2026)

- Beyond next year: Extend sensitivity to higher masses using a multicavity system. Method: Multiple cavity system



Lower-m_a haloscopes

- Large V haloscopes are technologically simpler, but expensive → huge magnet needed.
- Use of existing magnets could be an effective strategy

Some proposals:

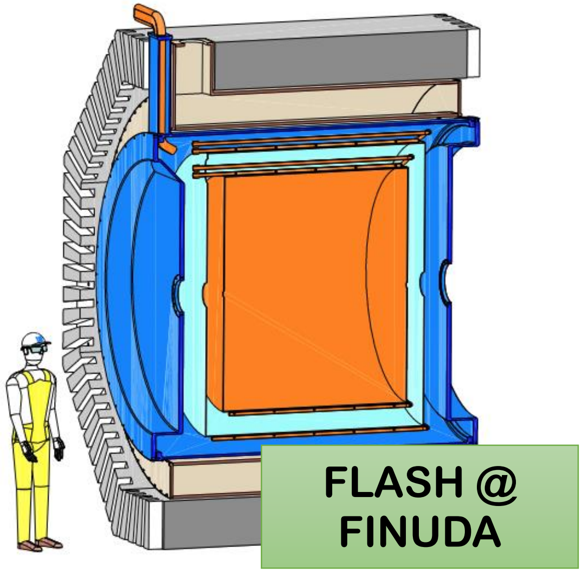
- **RADES** DarkQuantum - low frequency: aiming at BabyIAXO magnet, but first prototypes could take data at CERN’s M1
- **FLASH** proposal to use FINUDA magnet at LNF

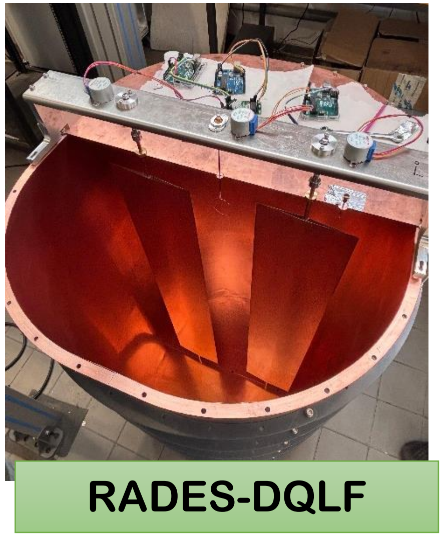
Also

- **GraHal** in Grenoble
- **ADMX** plans for lower masses (EFR)

Lowest possible frequency ultimately limited but realistic magnet/cavity size → move to different concepts

- Pick-up coil and resonant circuit (DM-Radio, see next slide)
- NMR resonances (CASPEr), but not sensitive to other than $g_{a\gamma}$



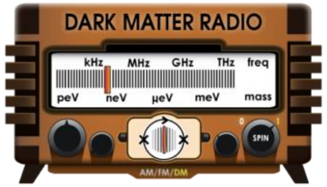


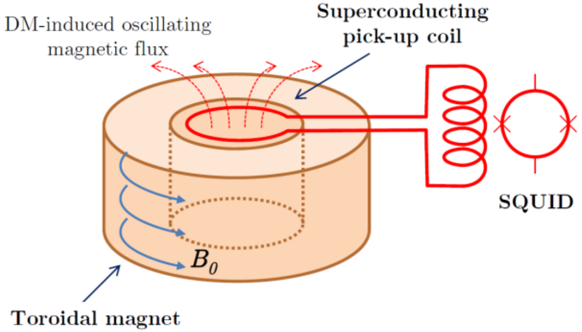
Plasma haloscopes: ALPHA

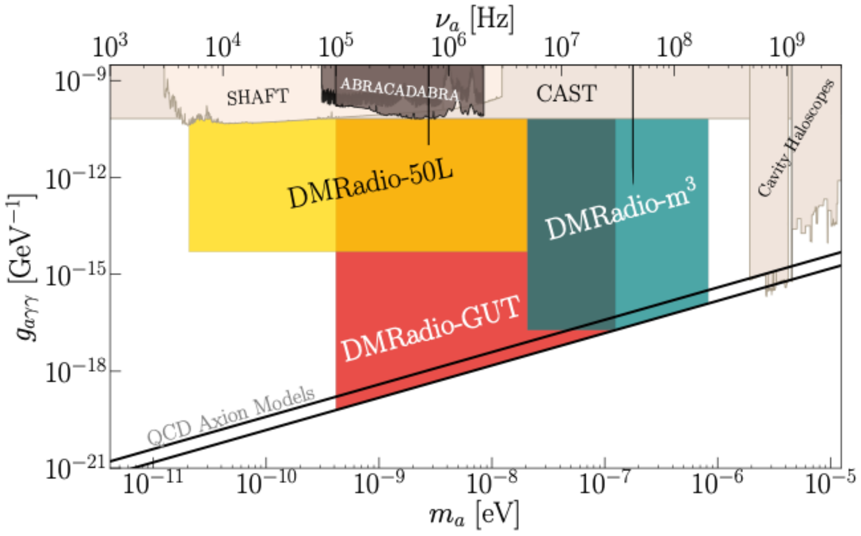
- bal

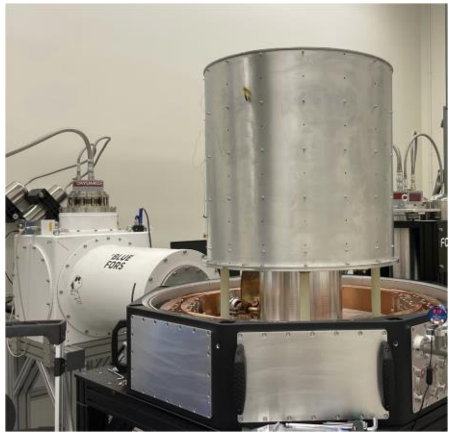
Pick-up loop & resonant circuit: DM-Radio

- A program to make a definitive search for GUT-scale axions and find a pre-inflation relic!
- Now commissioning DMRadio-50L
- While working on a staged R&D program for DMRadio-GUT.





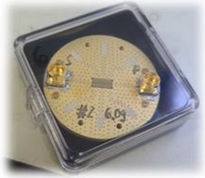


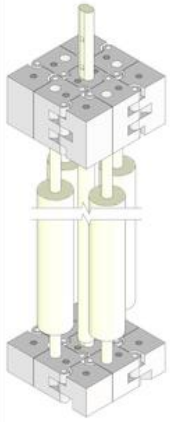


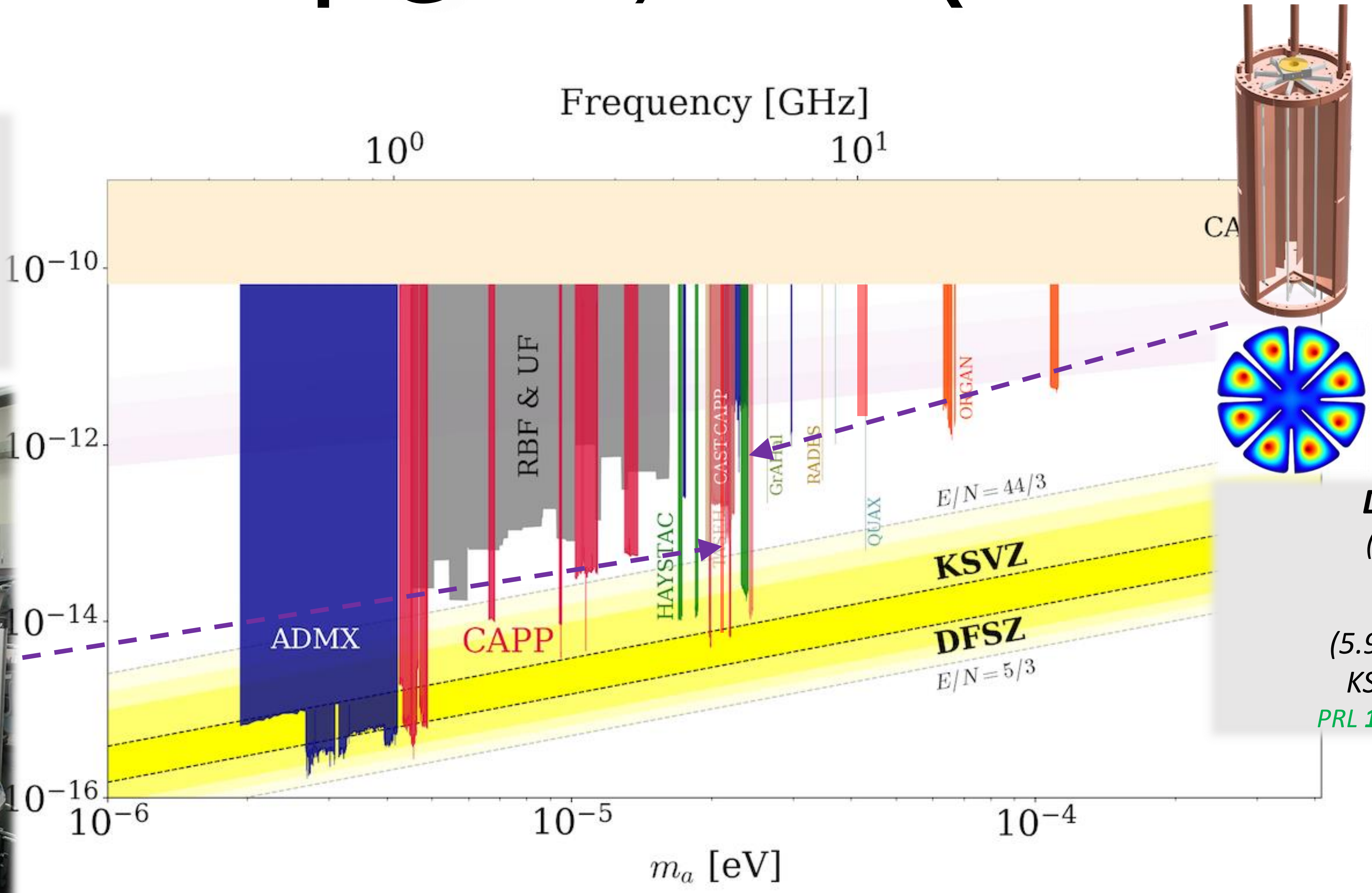
DM Axion Group @ IBS, Korea (former CAPP)

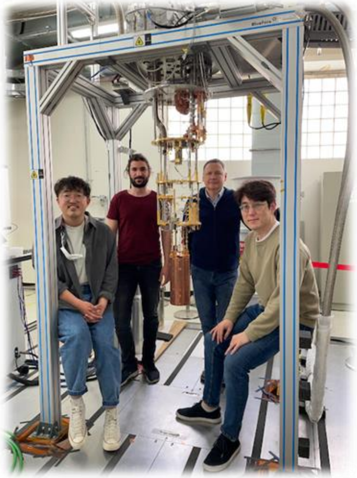
DMAG-12T
(12T/96m)

TM_{020} + auxetic + JPA
(5.1 GHz)
Near KSVZ sensitivity
*PRL **135** 091804 (2025)*









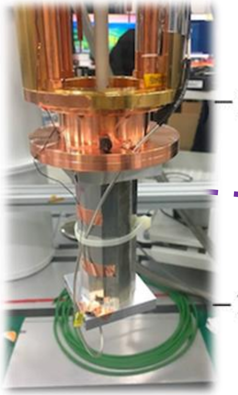
DMAG-8TB
(8T/165mm)

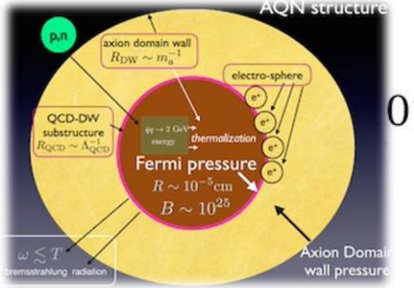
8-cell + JPA
(5.9 GHz, 400 mK)
KSVZ sensitivity
*PRL **135** 211801 (2025)*

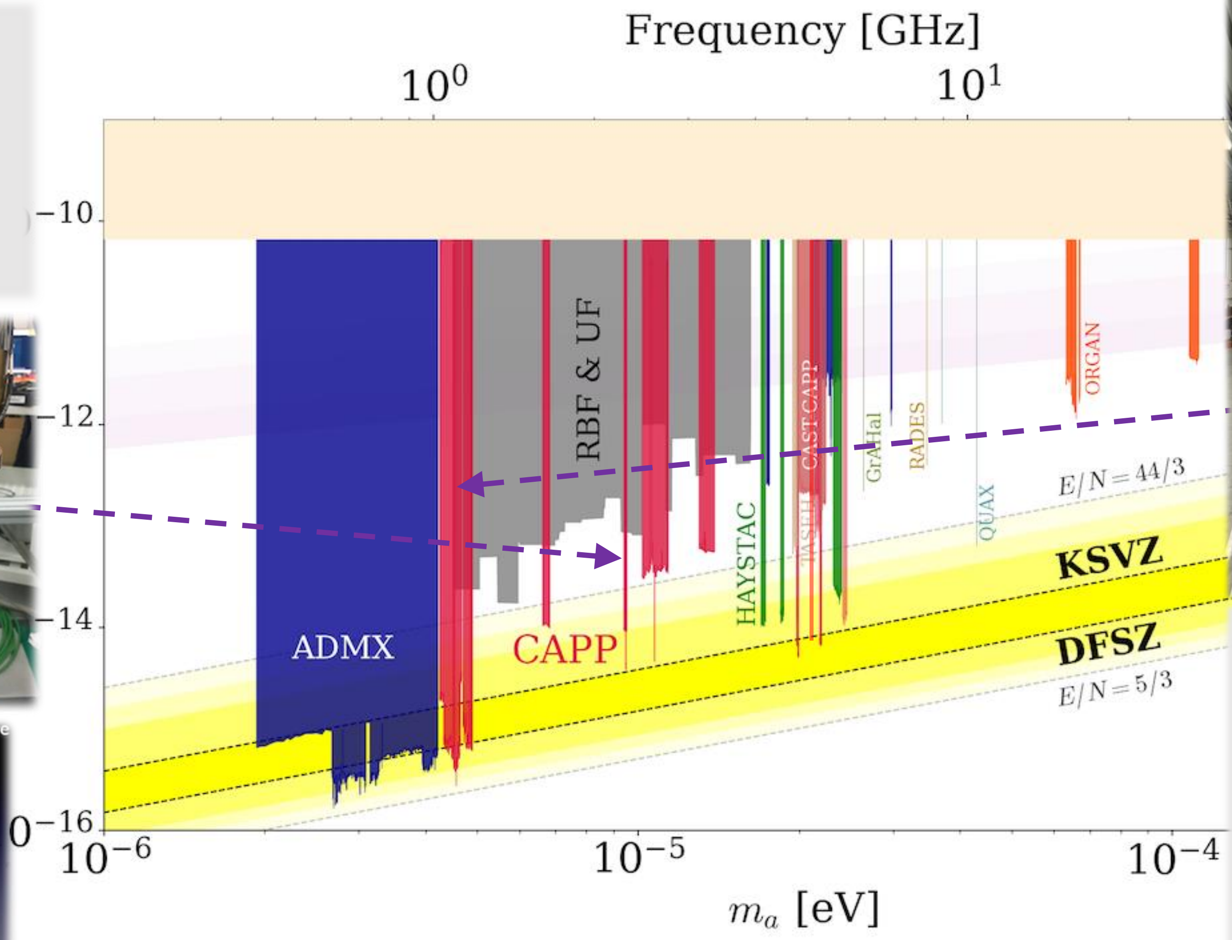
DM Axion Group @ IBS, Korea (former CAPP)

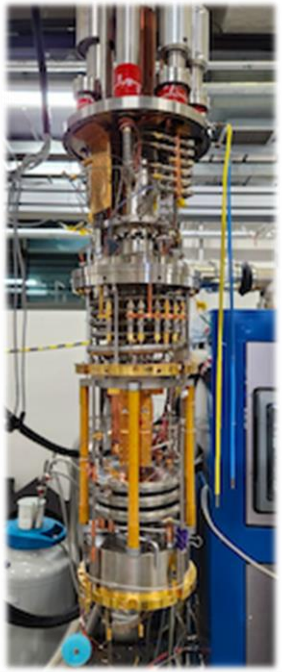
CAPP-8T
(8T/125mm)

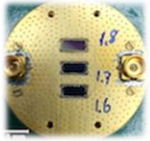
HTS SC cavity + JPA
(2.3 GHz, Q ~ 3.5 M)
AQN search
PRD 112, L121305 (2025)







DMAG-12TB *(12T/320mm)*

f > 1 GHz, V = 32 L, T_{sys} ~ 200 mK
df/dt ~ 2 MHz/day @ DFSZ
*PRX **14** 031023 (2024)*

Hybrid cavity
(Cu cavity + HTS tuning rod)
DAQ since Nov. 2025 (1.3–1.5 GHz)

Magnetized dish antenna

- DM field + B field + boundary condition in the dish → photon emission normal to surface
- No resonance (loss a factor Q) BUT may be compensated with very large areas ?

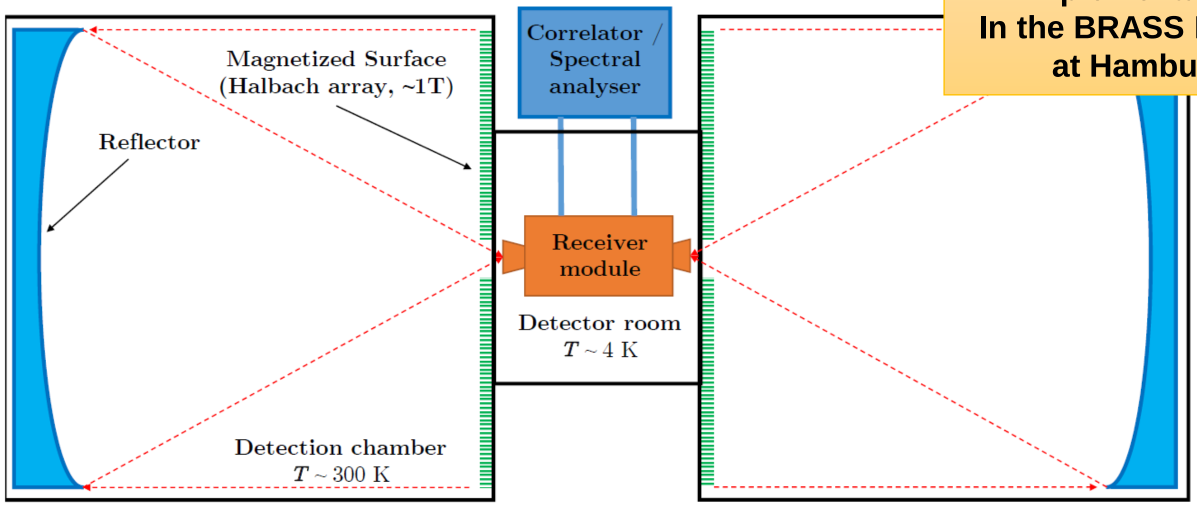
Horns et al. JCAP 1304 (2013) 016
Jaeckel , Redondo JCAP 1311 (2013)

Resonance versus area

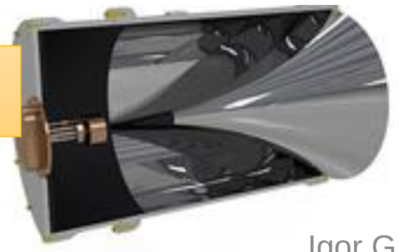
$$\frac{P_{\rm dish}}{P_{\rm haloscope}} \propto \frac{m_a^2 \mathcal{A}}{Q},$$

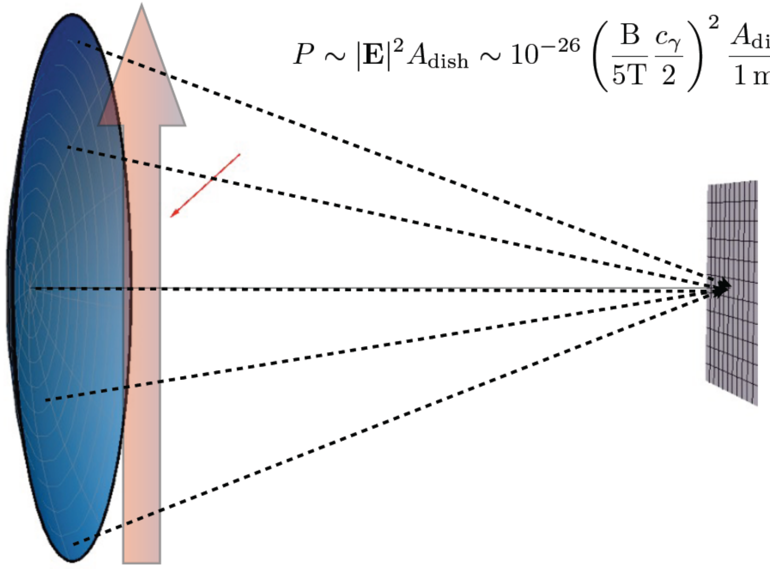
$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26}\left(\frac{\rm B}{5\rm T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,\rm m^2}\,{\rm Watt}$$

Implementation In the BRASS Project at Hamburg



Also BREAD Project @ US Variation: solenoidal geometry

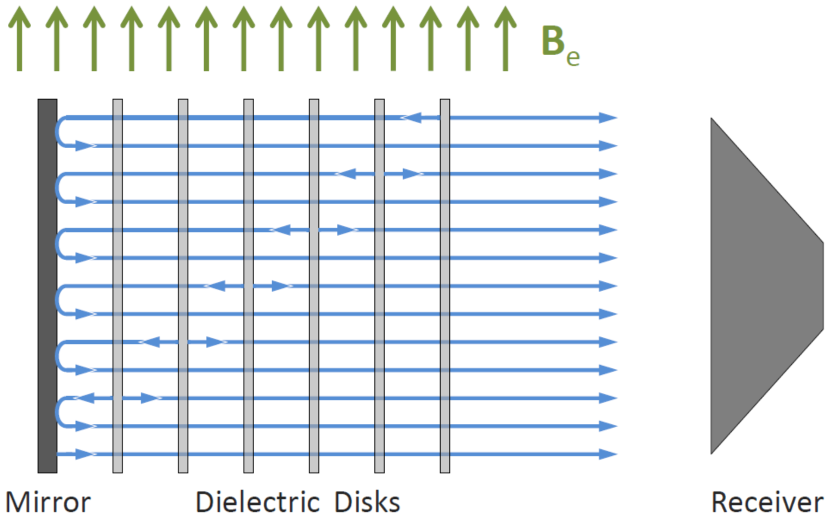




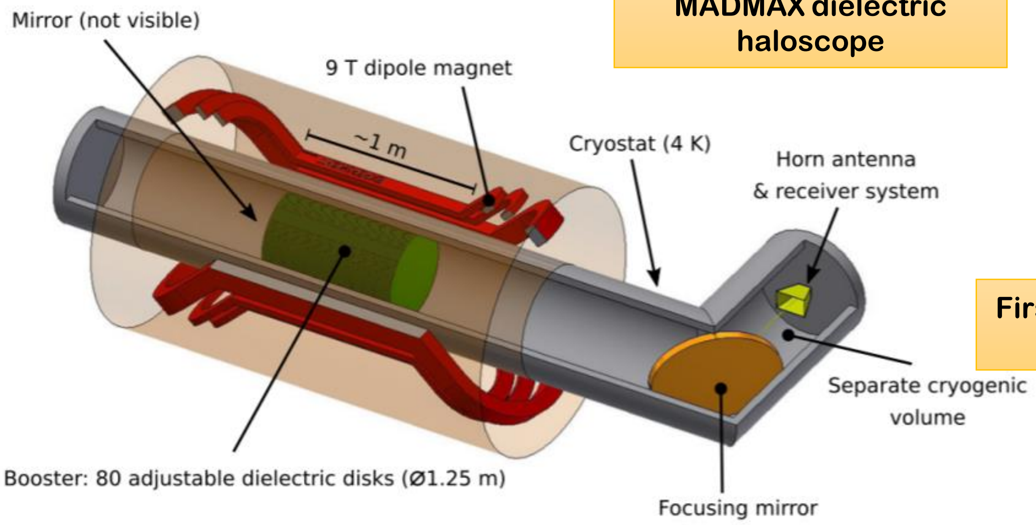
spherical reflecting dish

Dielectric haloscopes: MADMAX

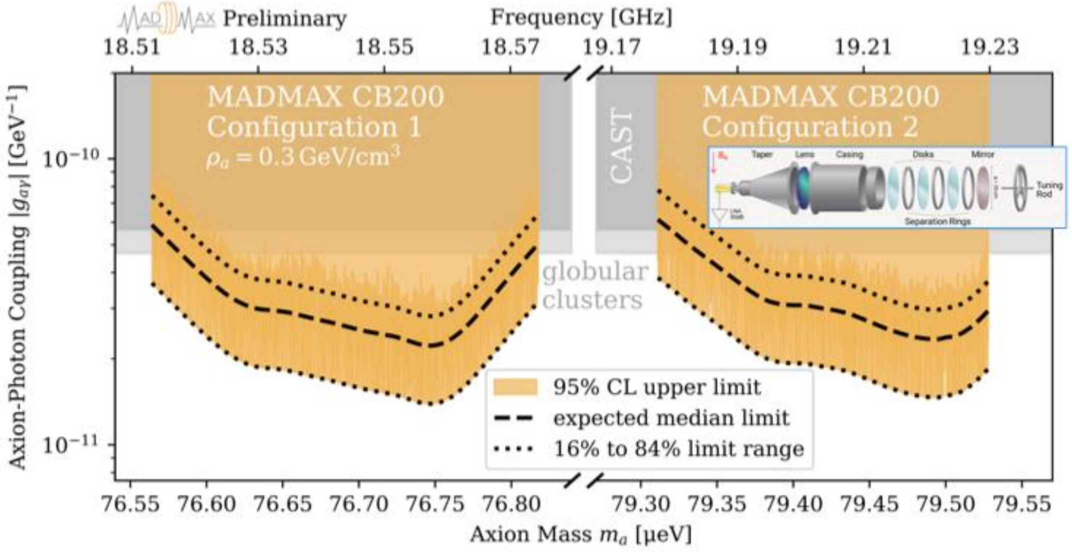
- Effect of dish antenna “boosted” by the addition of many dielectric disks
- Some “mild” resonance
  - Concept between a haloscope and a dish antenna
  - It needs tuning! (challenging)
- Relevant sensitivity in the 10^{-4} eV ballpark for a ~m^3 10T experiment (80 disks)



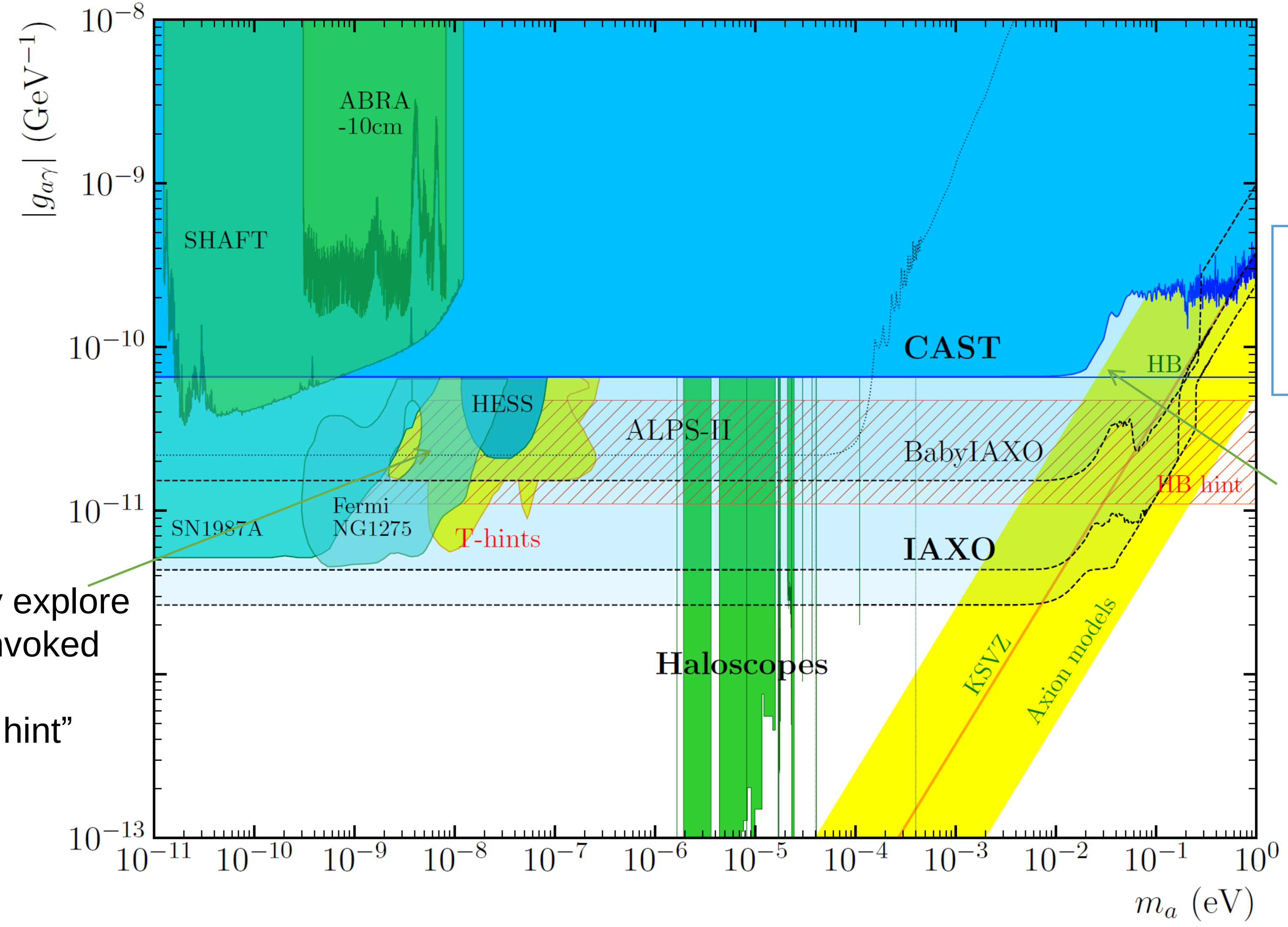
MADMAX dielectric haloscope



First results with a 3 disk prototype



Helioscopes & astrophysics



IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect to 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 (see backup slides)

MFOM = Magnet FOM

BabyIAXO: beyond baseline

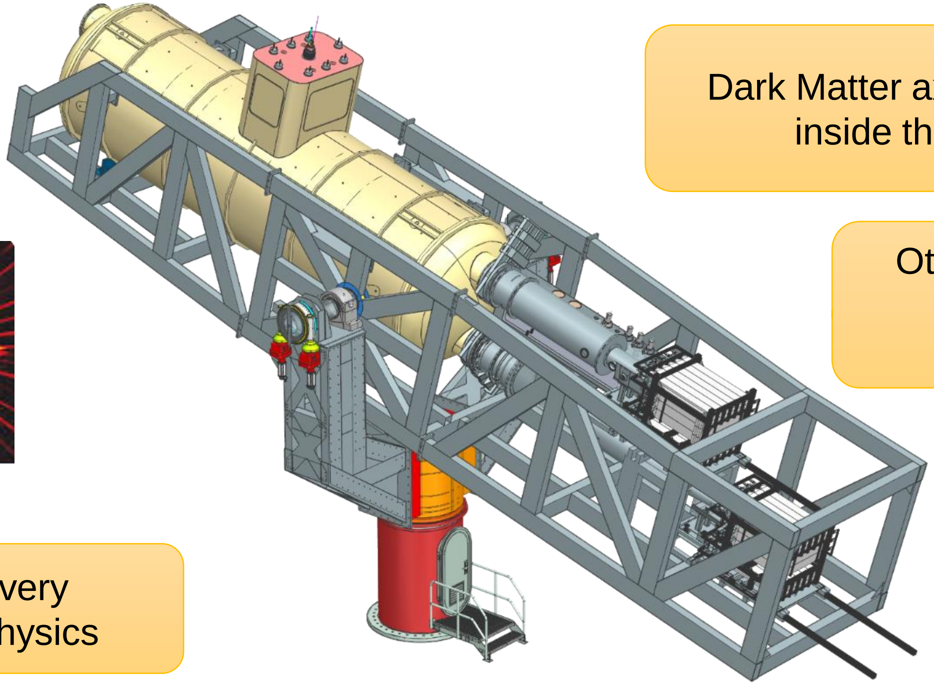
BabyIAXO as a generic axion(-like) facility

- BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

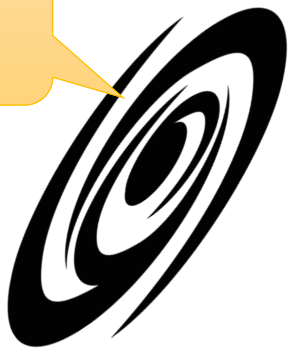
Other (non-Primakoff) solar axion production mechanisms

Axions from SN

post-Discovery "precision" physics

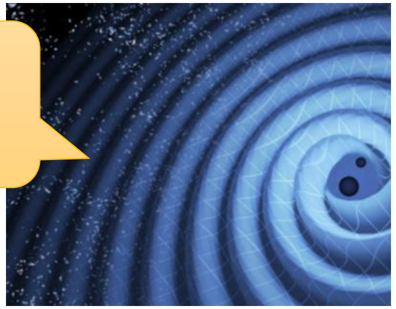


Dark Matter axions: haloscope setups inside the BabyIAXO bores



Other WISPs: hidden (dark) photons, chameleons, …

…And also high-frequency grav. waves!!

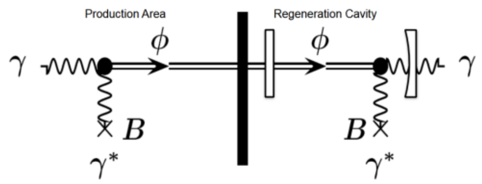


ALPS-II @ DESY: status & plans

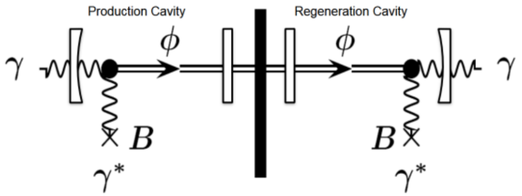
arXiv:2512.14110 [hep-ex]
arXiv:2601.18684 [hep-ex]

- Results of first axion search science campaign published!

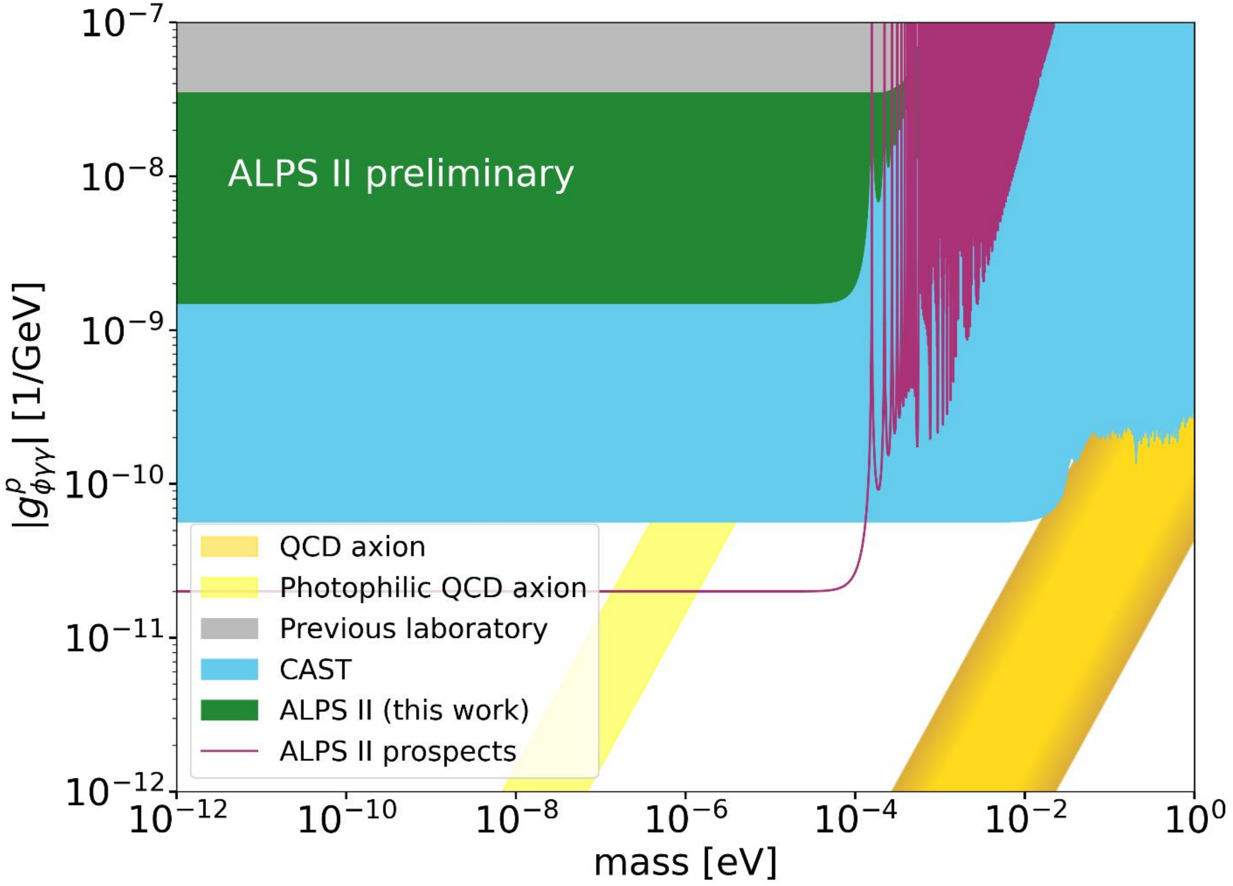
- Optics upgrade for axion searches under way.



$N_i \sim 10^{26}$ photons $(10^6$ seconds$)$
$N_b \sim 200$ photons $(10^6$ seconds$)$



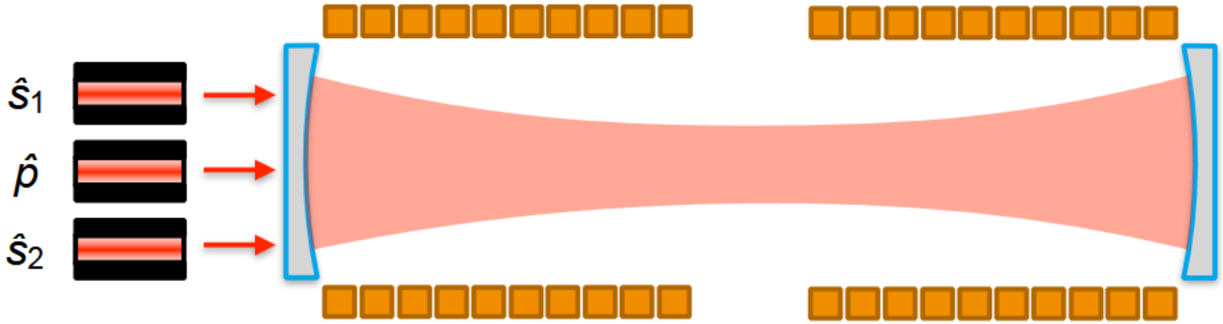
$N_i \sim 10^{30}$ photons $(10^6$ seconds$)$
$N_b \sim 1$ photon $(10^6$ seconds$)$

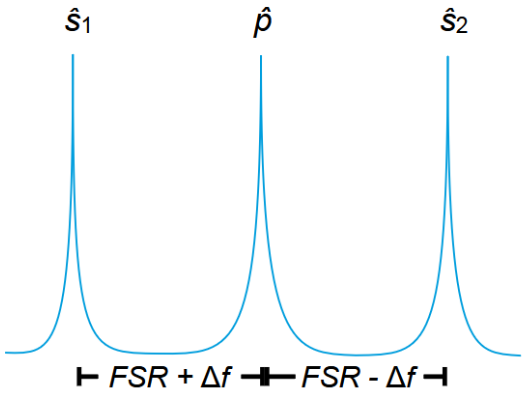


ALPS II @ DESY: beyond axion searches

- Expected signal at ALPS II 600 times larger than at PVLAS.
- Measure changes in the cavity resonances for orthogonally polarized states when modulating magnetic field strength at mHz frequencies.

Measure Vacuum Magnetic Birefringence

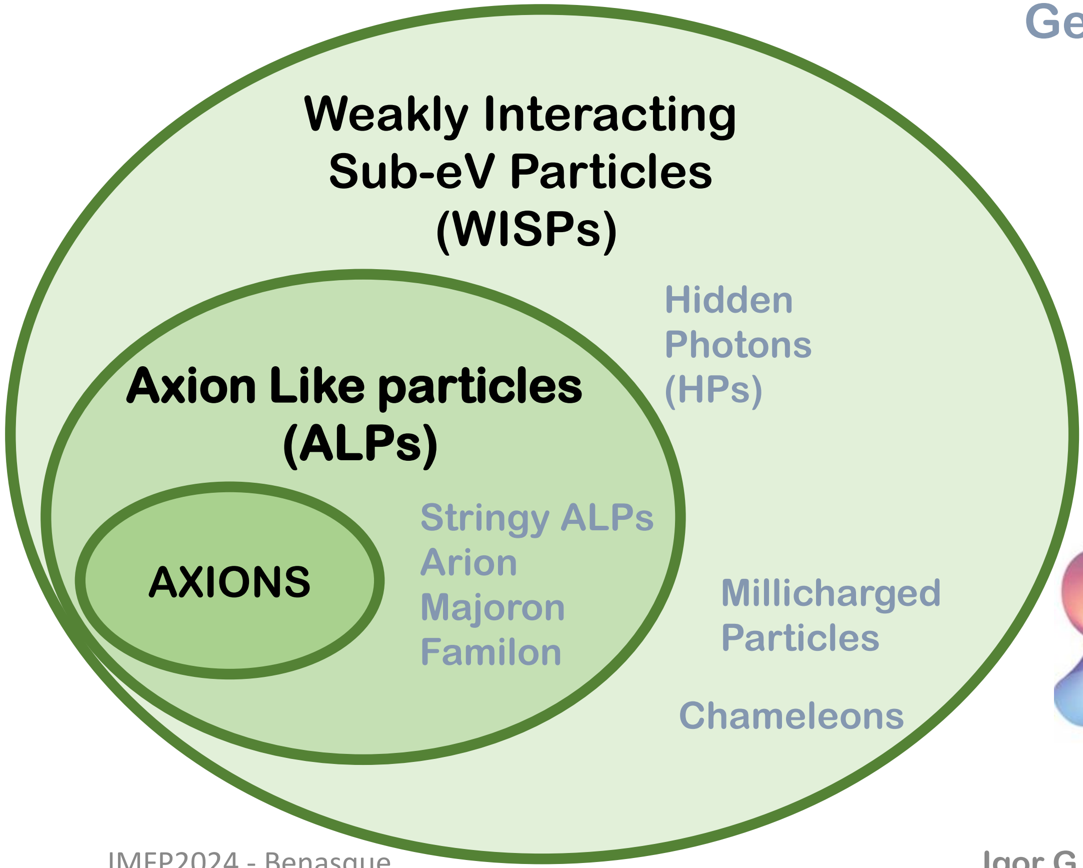




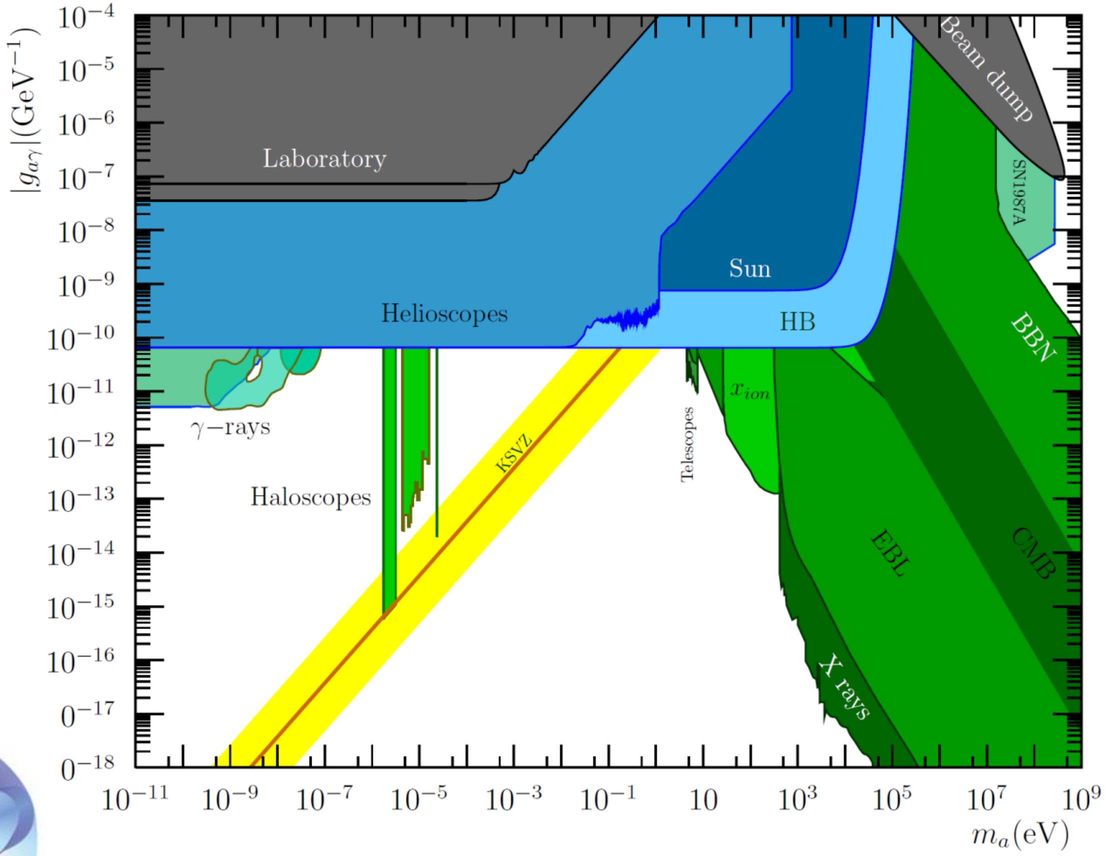
Results from 19m prototype published: arXiv:2510.14064 [physics.optics].

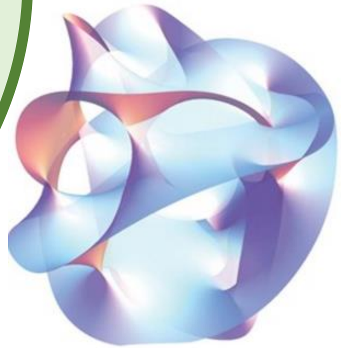
Beyond axions

- **Many extensions of SM predict axion-like particles**
  - **Higher scale symmetry breaking**



Generic ALPs parameter space →





String theory predicts a plenitude of ALPs

Axion phenomenology

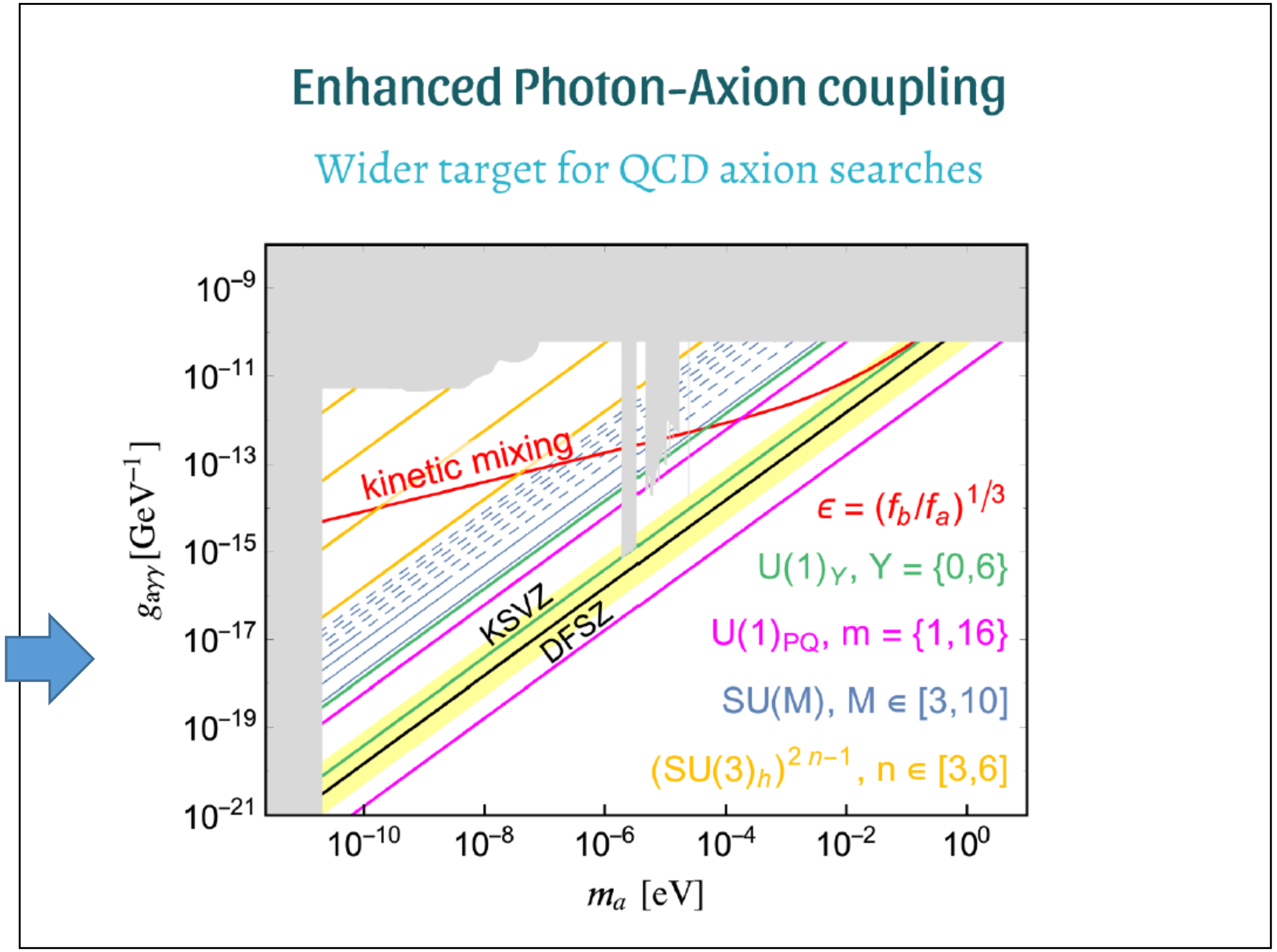
- Some phenomenology depends on the **“axion model”**, e.g.
  - KSVZ axions are “hadronic axions” (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$	$m_A = 5.70(7)\mu\mathrm{eV} \times \left(\frac{10^{12}\mathrm{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron coupling Nucleon coupling …
generic	*generic*	*generic but value model dependent*	*Model dependent*

Axion models

- Conventional QCD axion models lie on the "yellow band"
  - KSVZ, DSFZ benchmarks
- Outside the band typically ALPs

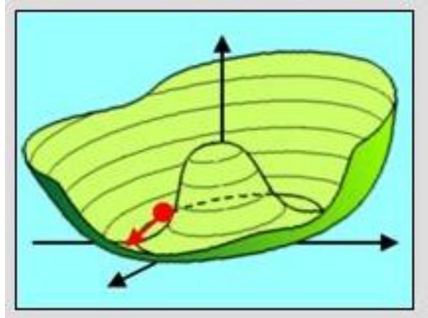
- BUT a lot of "model building" activity in recent years, leading to QCD axion models outside the conventional band…
  - Normally populating higher $g_{a\gamma}$.
  - Very interesting for experiments!



P. Agrawal, ESPP 2019 Granada

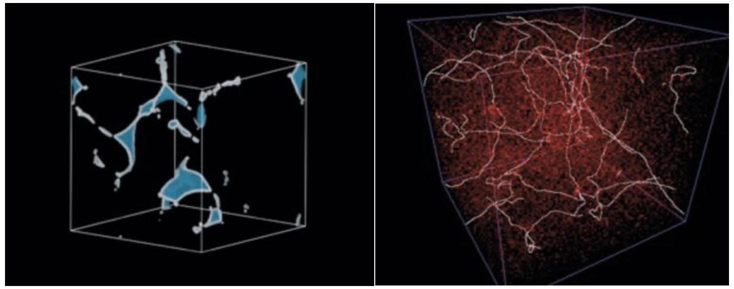
Axions as cold dark matter

Axion realignment… (AR)



PQ before or after inflation?

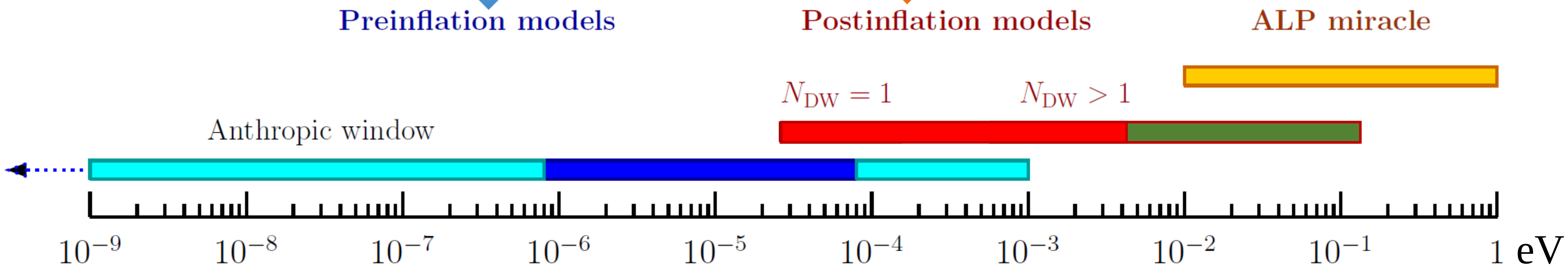
… AND decay of topological defects. (TD)



- Only well-known AR
- BUT, initial misalignment angle unknown…
- Large range of masses possible, even very low ones (→ anthopically finetuned?)

- TD contributes, potentially dominating…
- Not initial AR uncertainty
- BUT TD computation very complex
- Still large range of masses possible

ALP as inflaton AND dark matter?

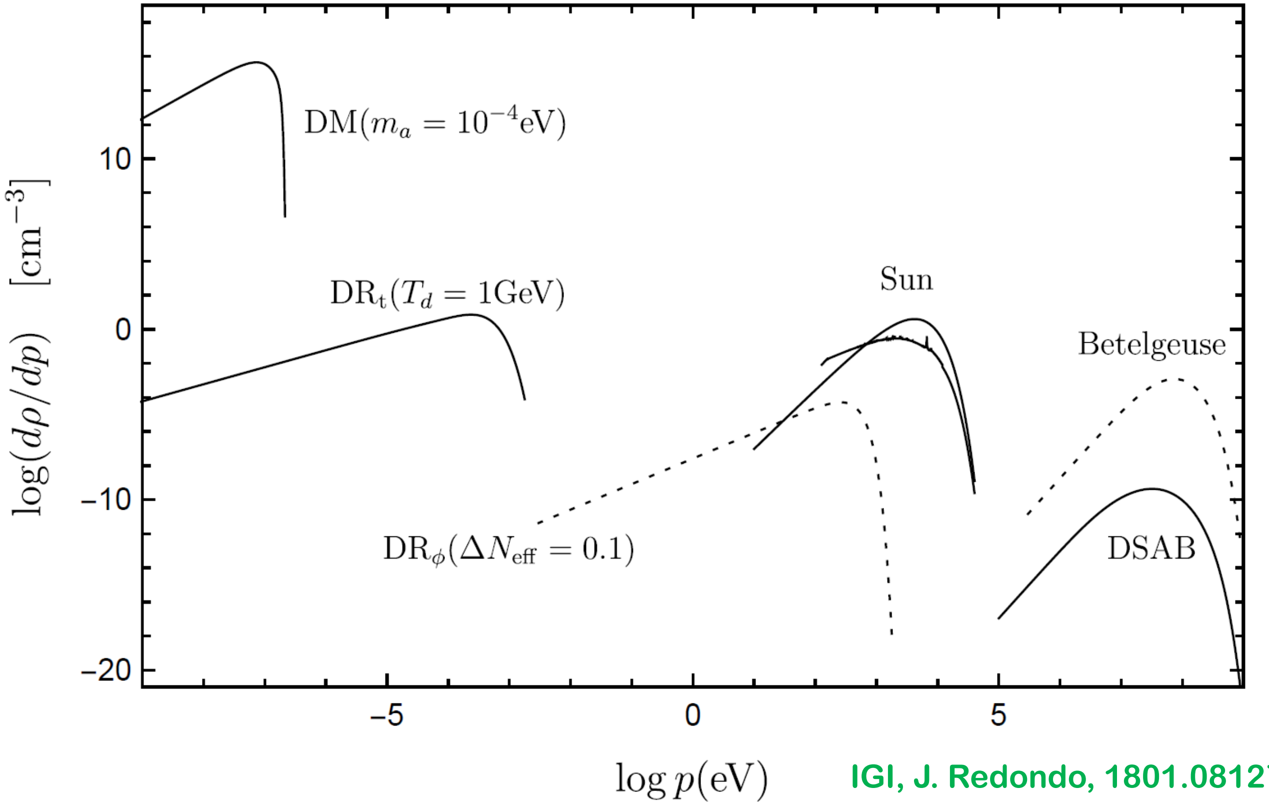


→ **Right axion DM density is possible for a wide range range of masses**

Sources of axions

Natural sources

Dark matter Dark radiation Stellar



IGI, J. Redondo, 1801.08127

Laboratory sources

- Photon-ALP conversion in strong magnetic fields (axion-photon coupling)
- ALP fields from macroscopic bodies (fermionic couplings)

Other purely laboratory searches

Other LSW experiments active in the past, some at different photon energies:

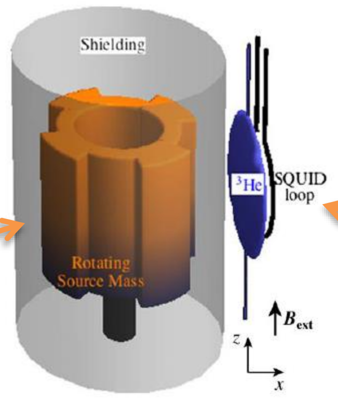
OSQAR@CERN, CROWS@CERN, GammeV & REAP @ Fermilab, US, BMV @ Toulouse,…

Possible future extrapolation: JURA (& also STAX with MW)

Laser polarization experiments (sensitive to VMB): PVLAS @ Ferrara, … Future (project): VMB@CERN

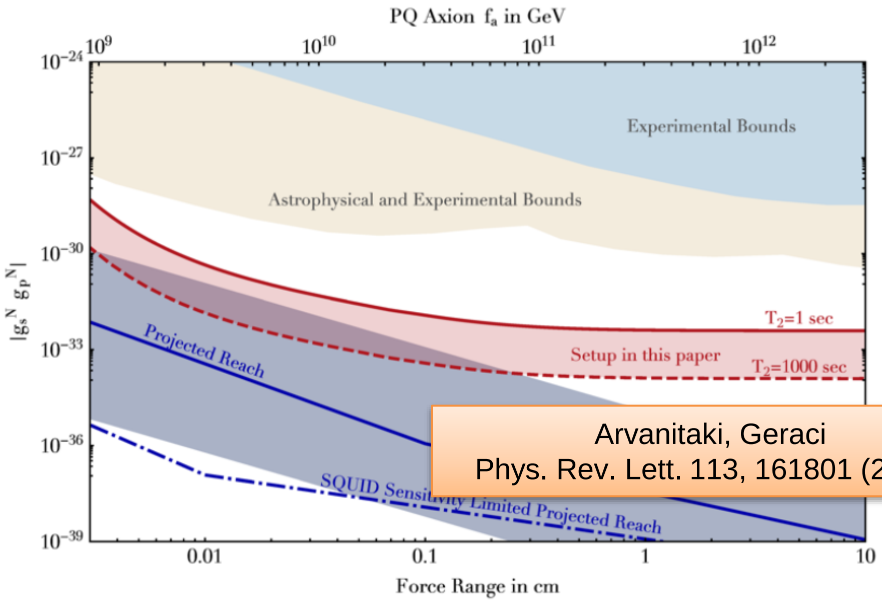
Short-range axion-mediated macroscopic forces: ARIADNE

- NMR techniques
- Sensitive to (products of) fermion couplings
- Good prospects for sub-meV axion



Rotating source mass

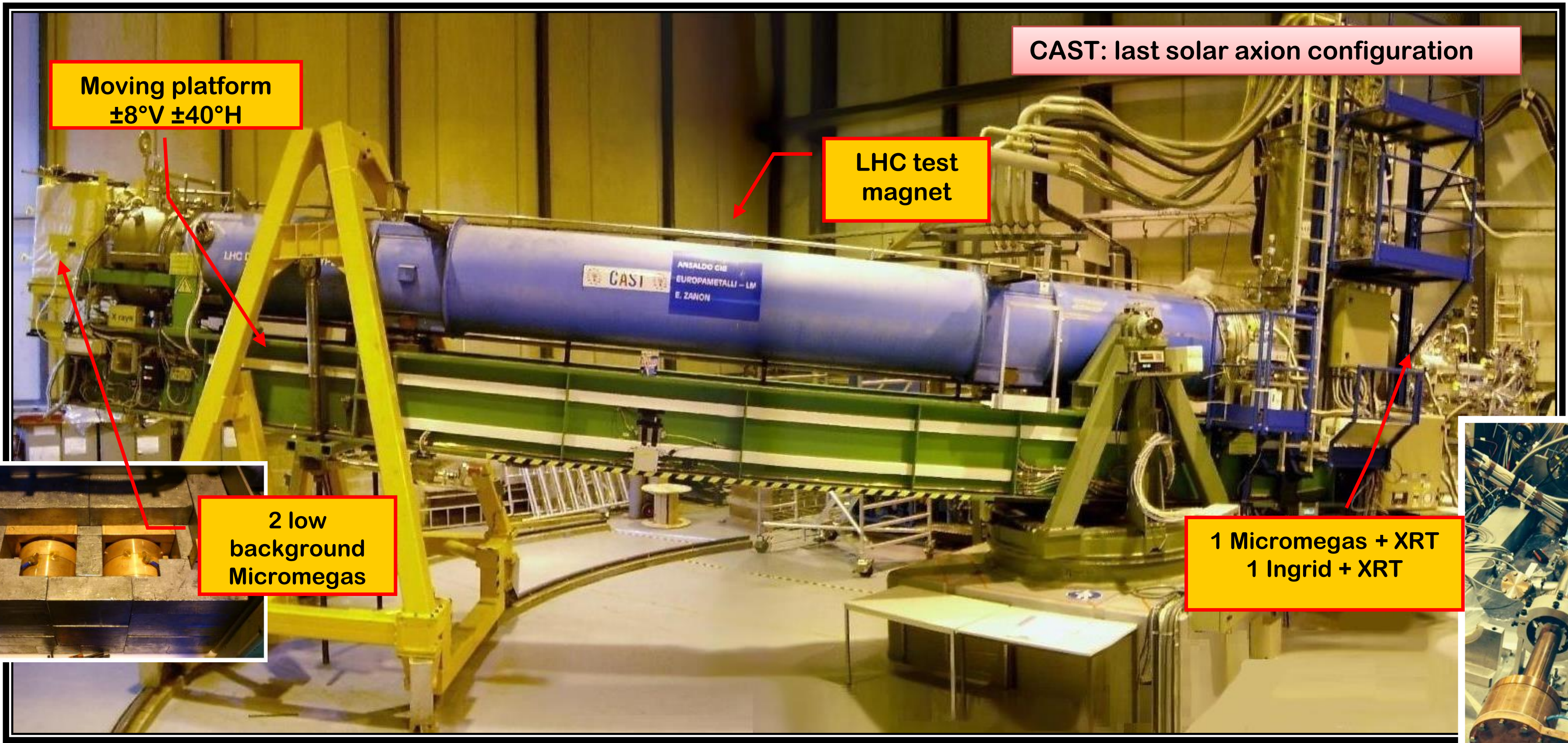
NMR sample

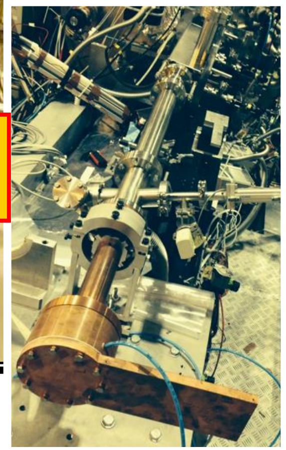


Arvanitaki, Geraci
Phys. Rev. Lett. 113, 161801 (2014)

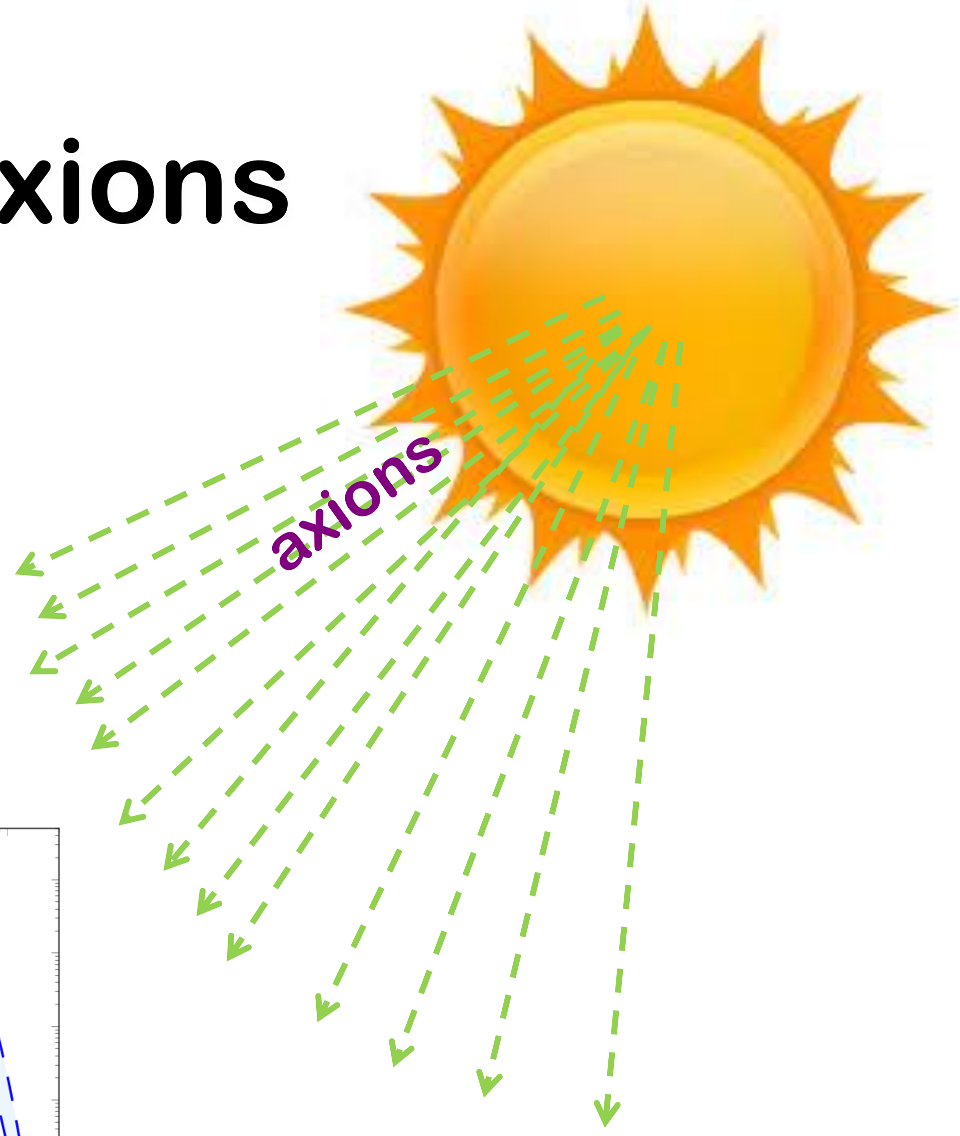
CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes used.
- X ray Focusing System to increase signal/noise ratio.





...and more solar axions

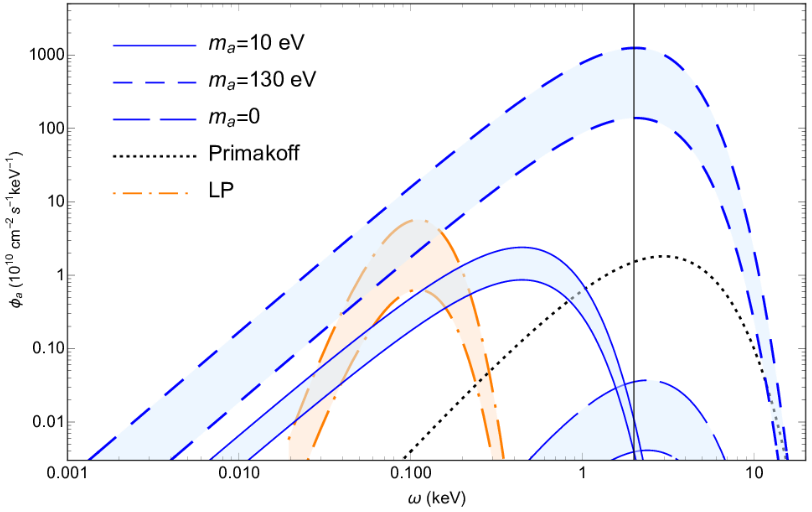


- Via axion-nucleon couplings: monochromatic lines from nuclear transitions:
  - E.g. 14.4 keV axions emitted in the M1 transition of Fe-57 nuclei, MeV axions from 7Li and D(p;γ)^{3}He nuclear transitions or Tm-169.

- More recently proposed: photons interacting with macroscopic solar B-fields.

See recent study Di Luzio et al, EPJC 82, 2111.06407 [hep-ph]

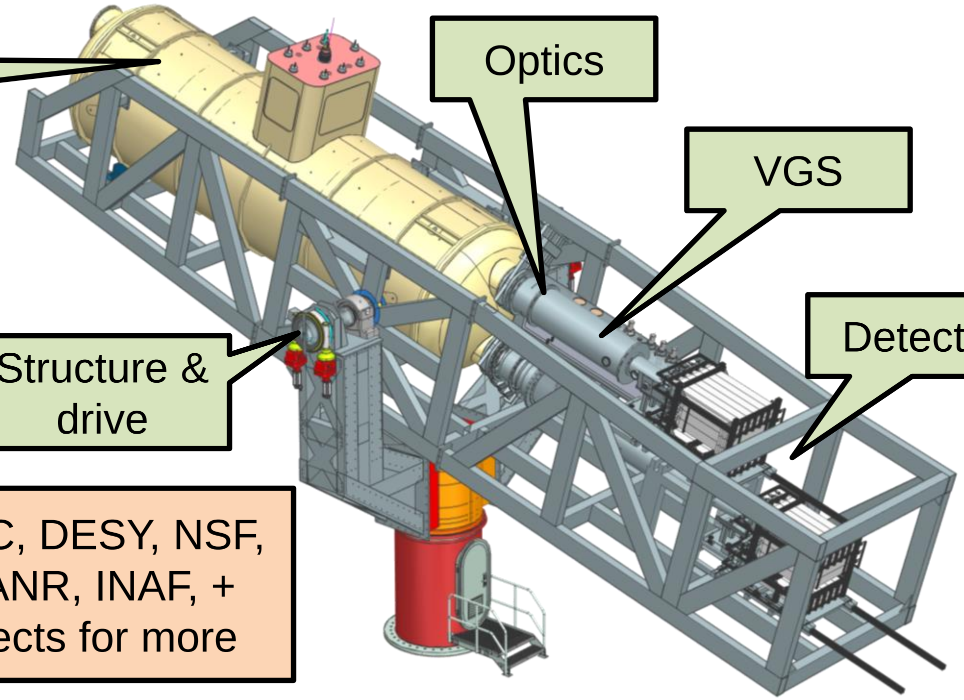
- longitudinal and transversal plasmons conversion.
- Depend on $g_{a\gamma}$!
- TP depend on m_a too
- Depend on solar B-field. Poorly known but constrained:



See e.g. Caputo et al 2005.00078, Guarini et al. 2010.06601

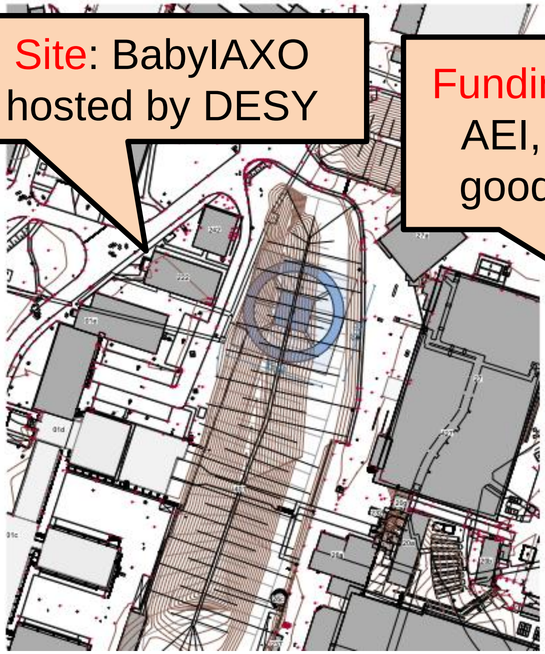
BabyIAXO – superbrief status

- Technologies involved: Large detector magnets, x-ray optics & detectors, low-background, vacuum, astronomical alignment, link with quantum technologies,…



Collaboration consolidated: 120 (150) members, 20 (24) institutions (associated)

Site: BabyIAXO hosted by DESY



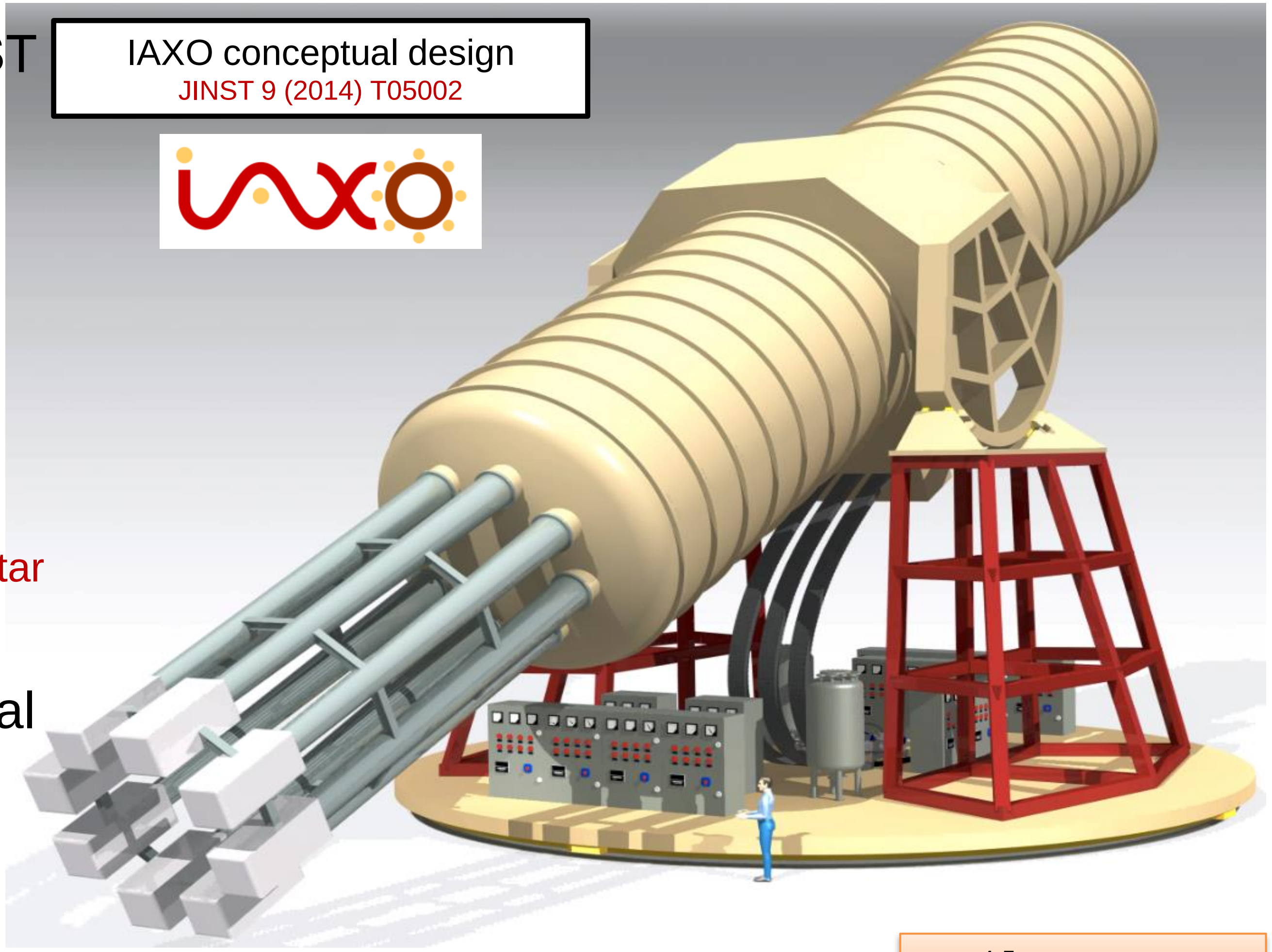
Funding: ERC, DESY, NSF, AEI, DFG, ANR, INAF, + good prospects for more

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

Promising DFG GG application

IAXO experiment - summary

- Next generation "axion helioscope" after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar
- ~50% Sun-tracking time
- Large magnetic volume available for additional "axion" physics (e.g. DM setups)



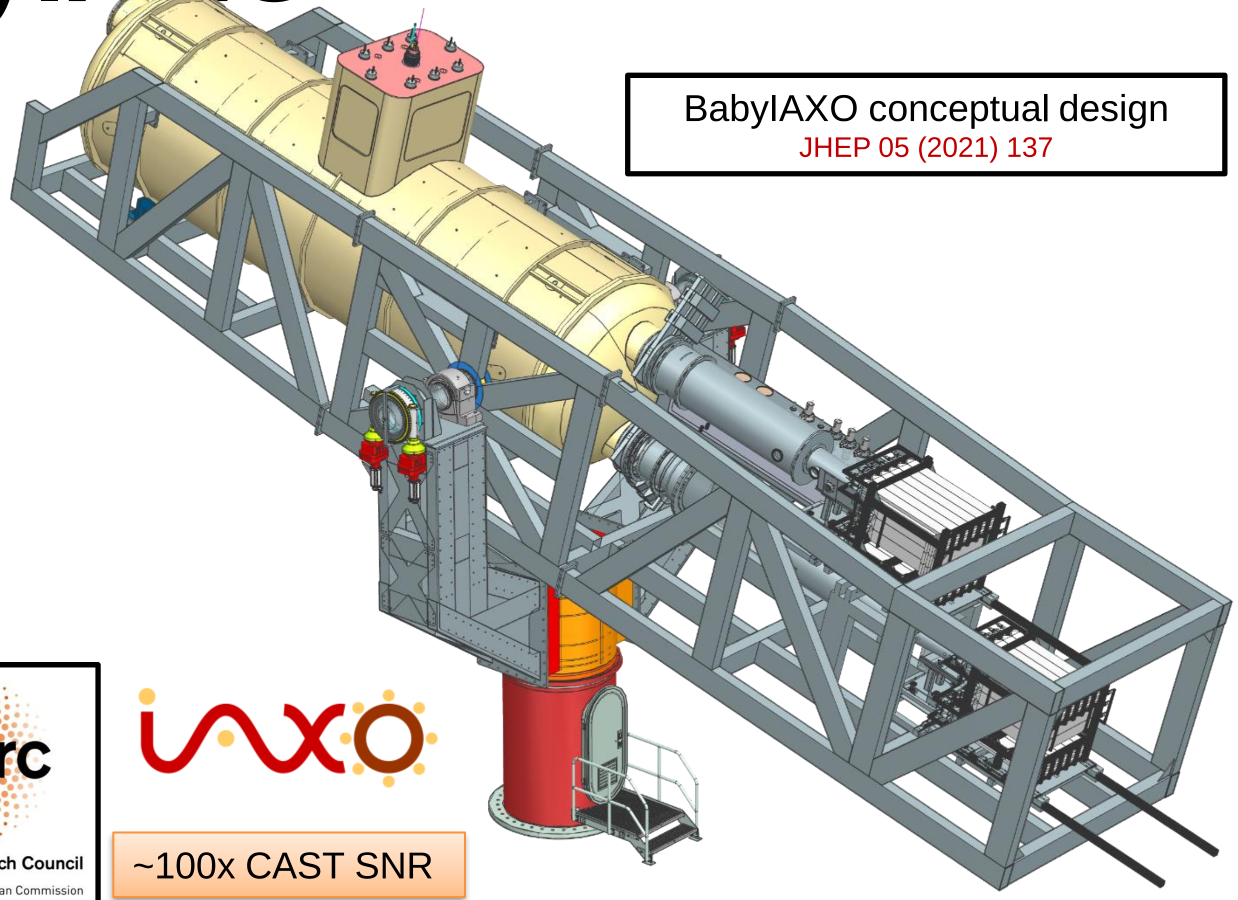
IAXO conceptual design
JINST 9 (2014) T05002

~10^{4-5} x CAST SNR

BabyIAXO

- Prototype: Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO
- Physics: will also produce relevant physics outcome

  (~100 times larger FOM than CAST)



BabyIAXO conceptual design
JHEP 05 (2021) 137

European Research Council
Established by the European Commission

~100x CAST SNR

ERC-AvG 2017 IAXO+

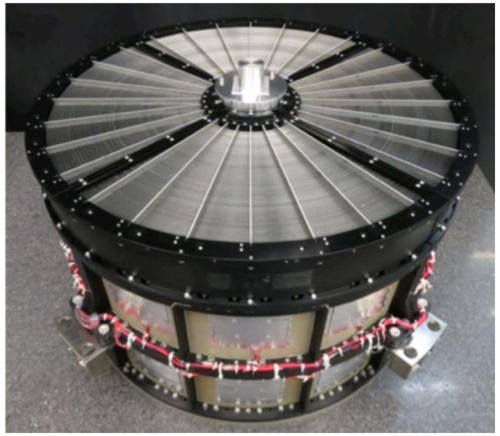
BabyIAXO status

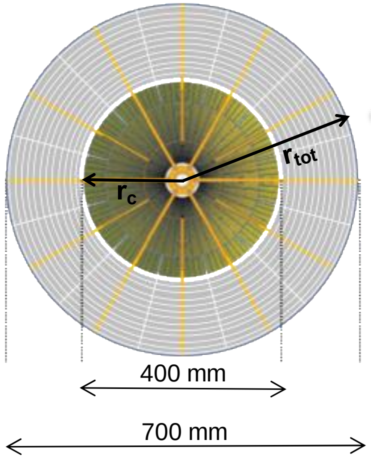
X-ray Optics

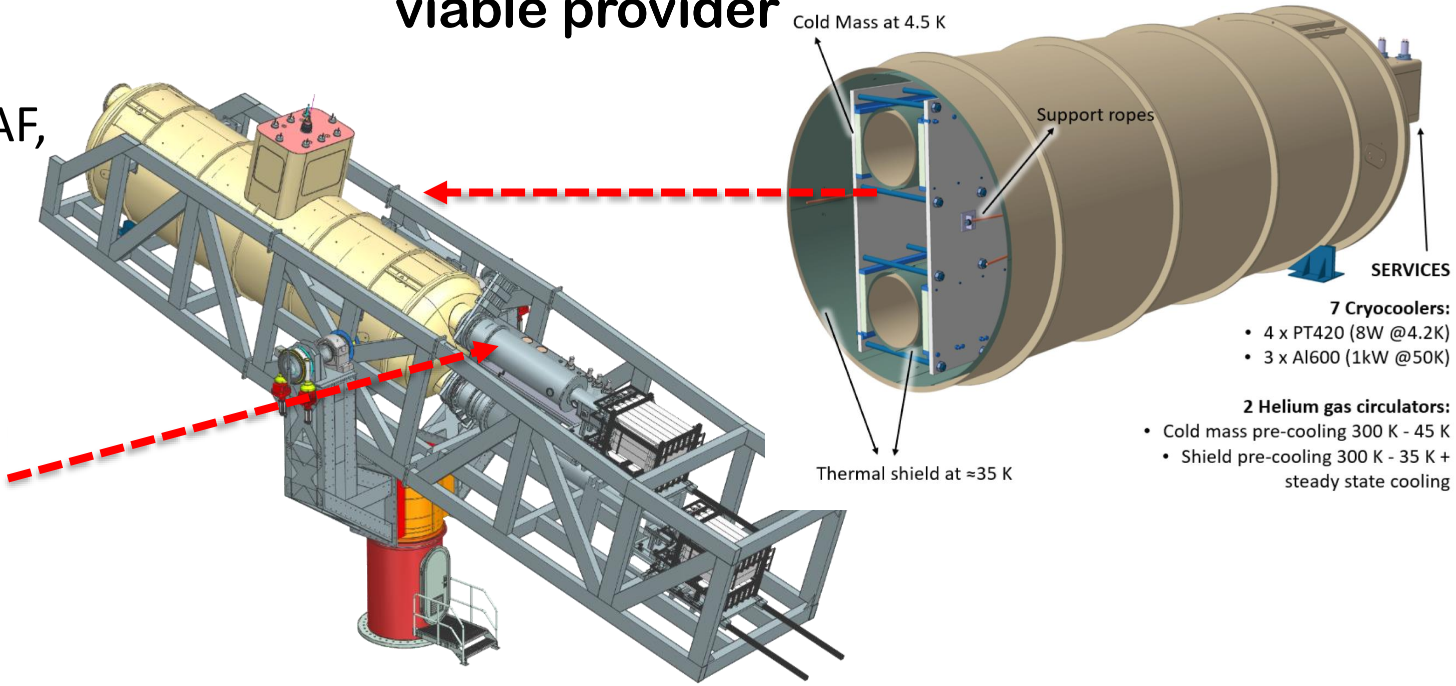
- 2 detection lines in BabyIAXO with different solutions: existing XMM spare + custom-made slumped glass optics
- Collaboration effort: CAPA, Columbia, INAF, DTU, MPE-Panter
- First prototype sectors built!

Magnet

- Technical in-depth review of magnet design successfully passed at DESY PRC last april. Progress towards TDR
- Magnet cable procurement: critical item, causing delays. Good progress in finding viable provider

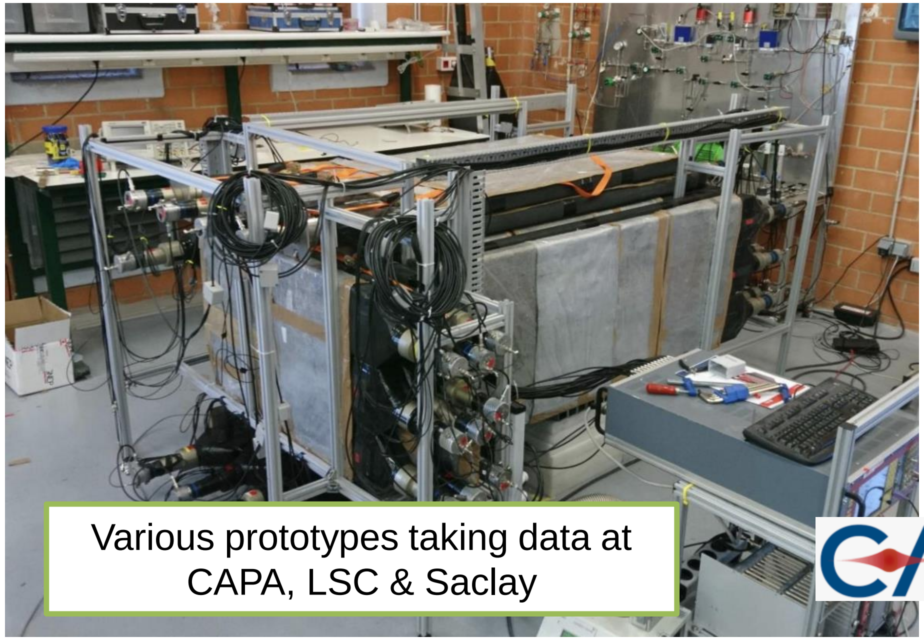




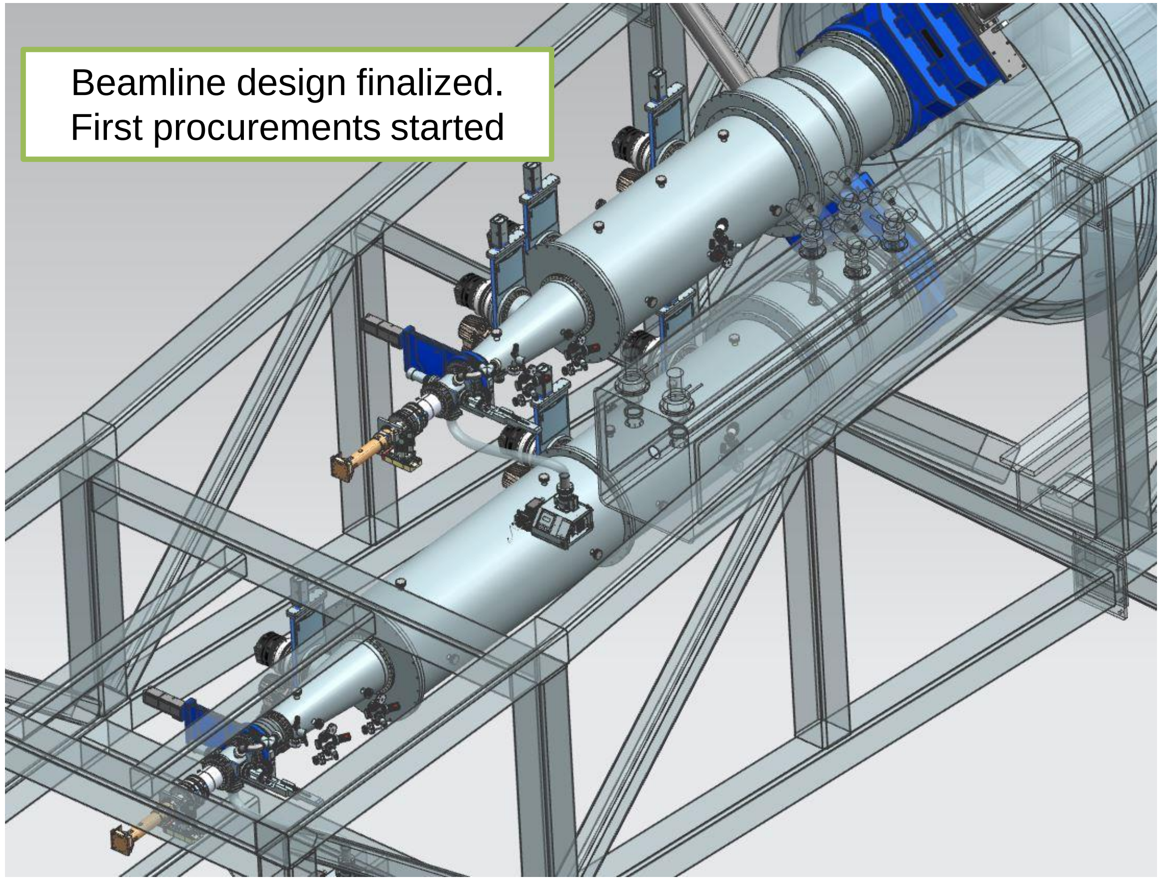


BabyIAXO detectors and beamlines

- Baseline detectors: Low background Micromegas detectors of *microbulk* type.
- Various alternative technologies being explored in te collaboration: TES, MMC, GridPix, SDDs,…

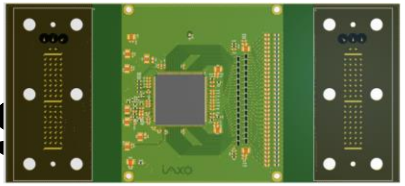


Various prototypes taking data at CAPA, LSC & Saclay



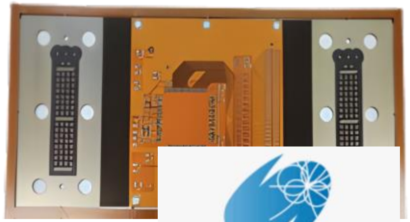
Beamline design finalized.
First procurements started

BabyIAXO Micromegas detectors



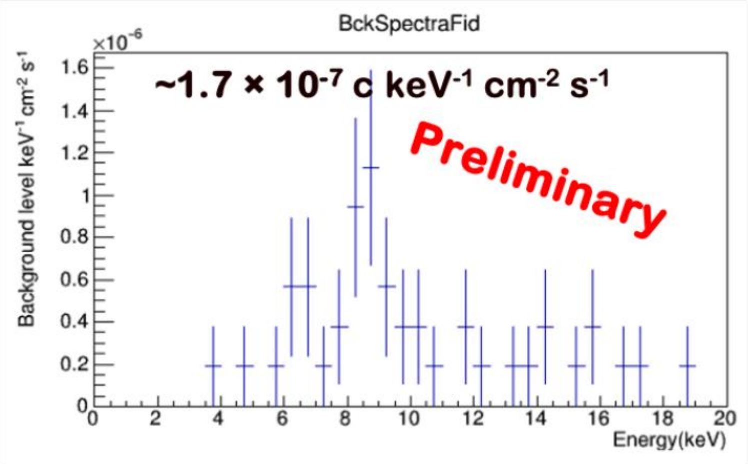
- Goal is to reach 10^{-7} c/keV/cm^2/s
- Achieved underground
- Prototypes aboveground (CAPA) and underground (LSC) to test intrinsic limits
- Simulation effort: background model
- Cosmic neutrons study: collaboration with **HENSA**

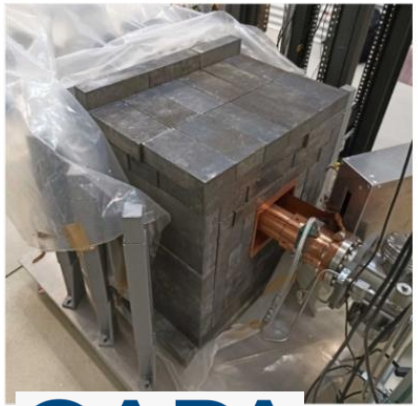
Development of new radiopure electronics & low EM noise



ICCUB

ita

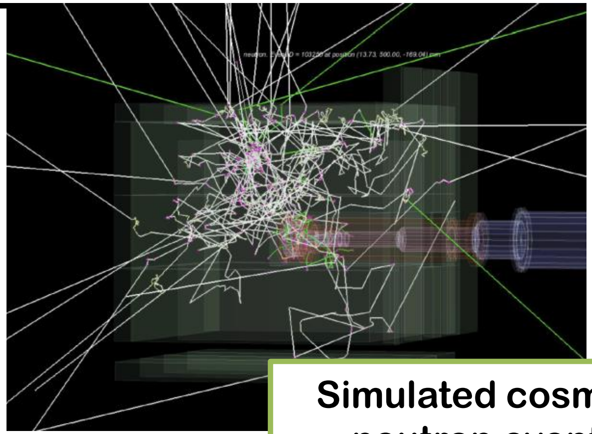




CAPA

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

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



Simulated cosmic neutron event

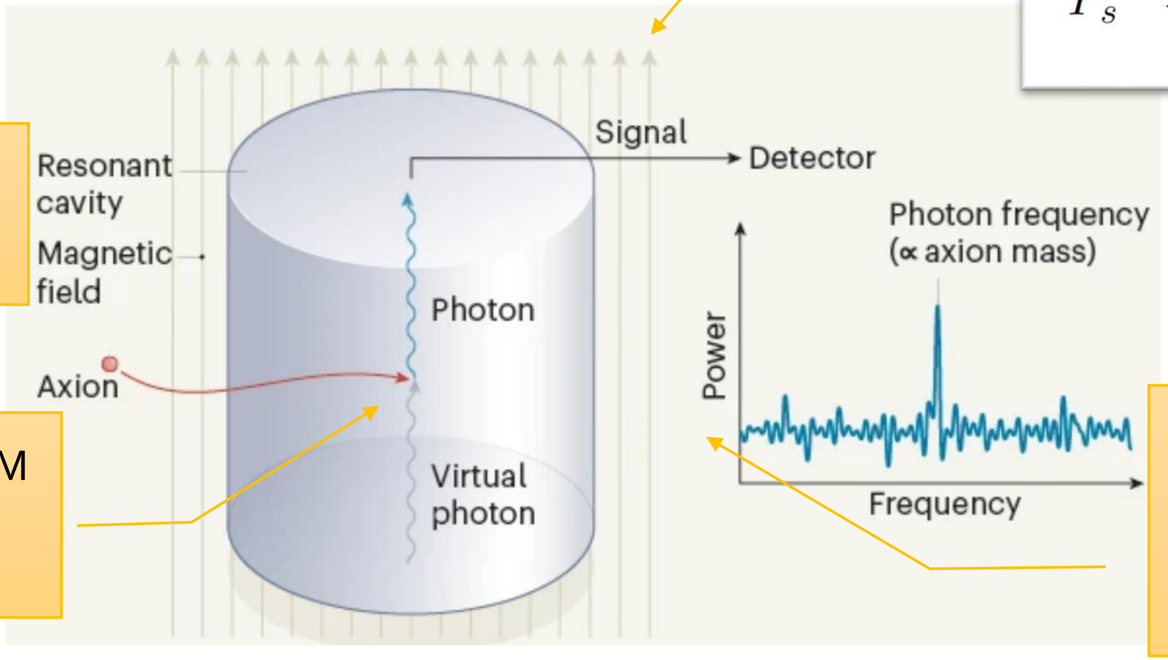
Detecting DM axions: “axion haloscopes”

- Assumption: DM is mostly axions
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$

Cavity dimensions smaller than de Broglie wavelength of axions

$$P_s = \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a$$

Axion DM field
Non-relativistic
Frequency ← axion mass

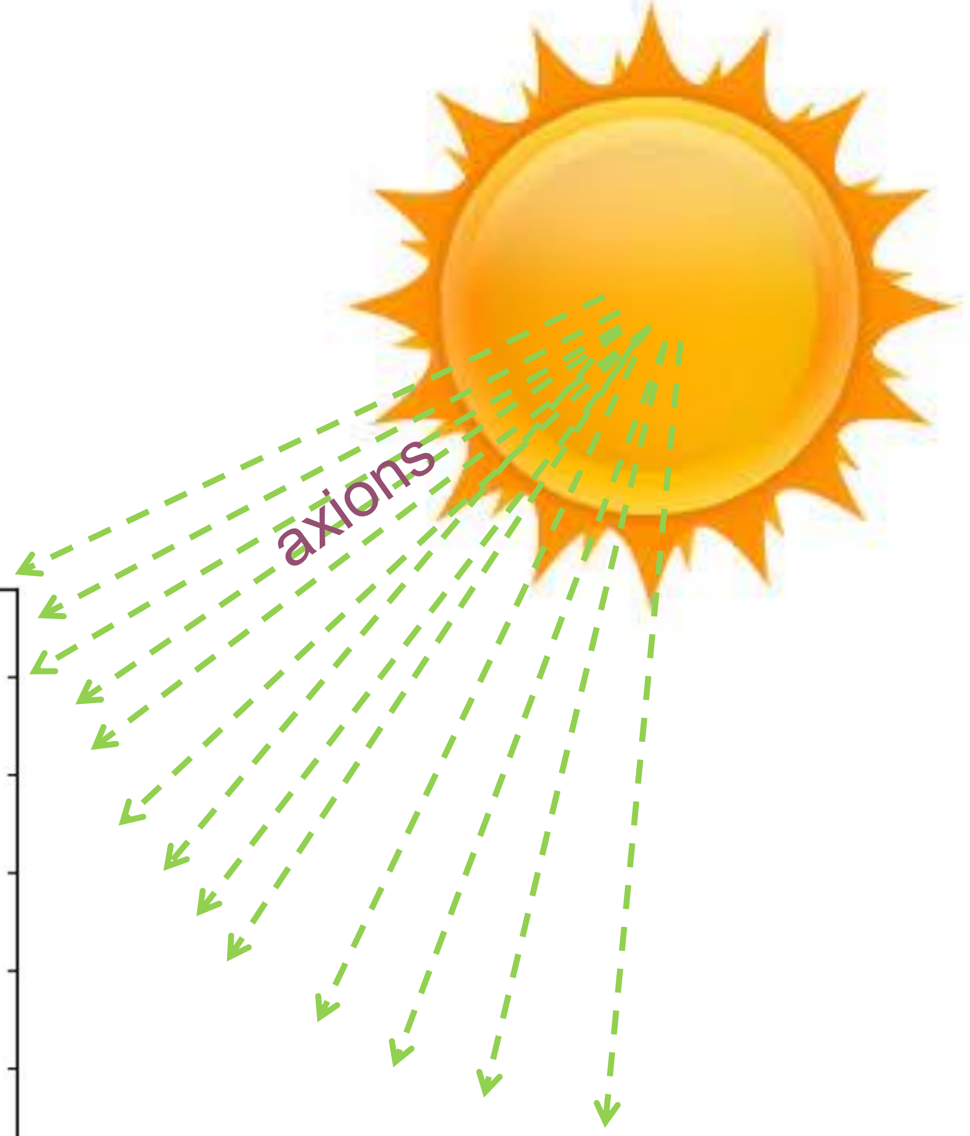


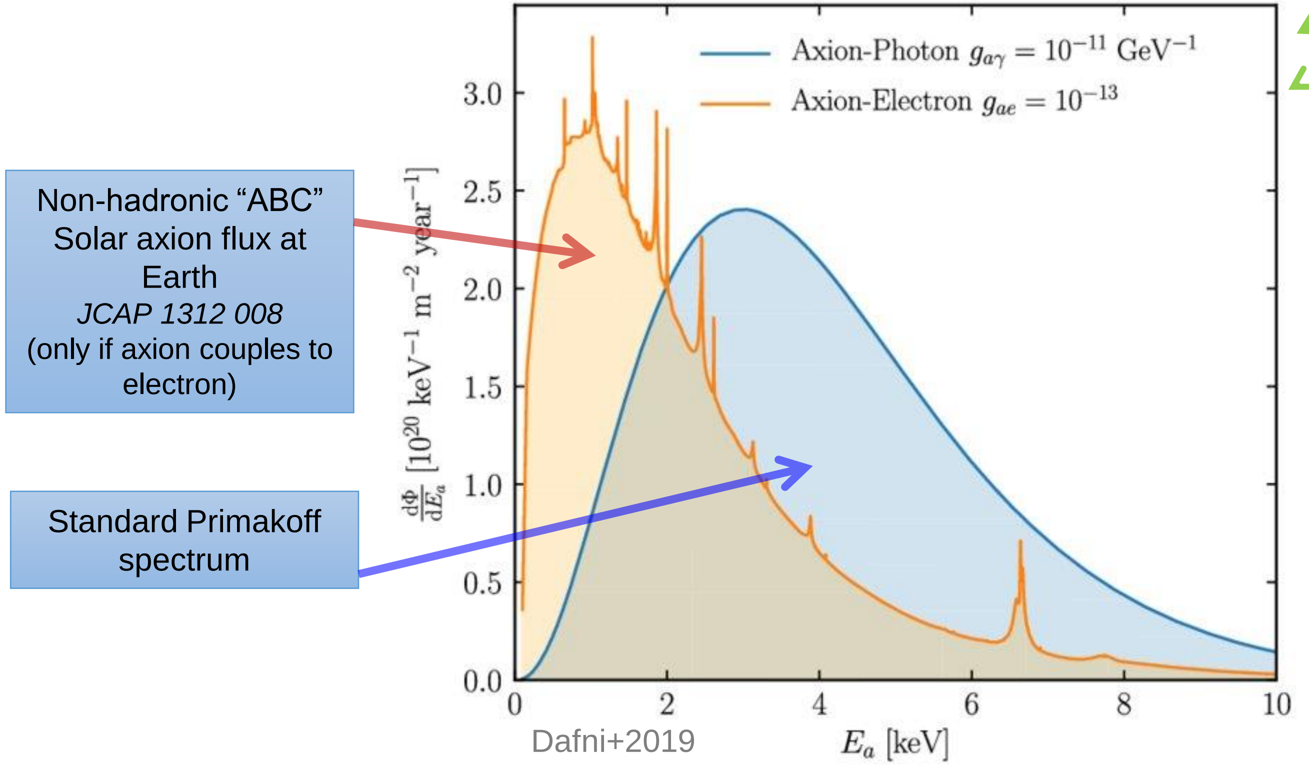
Primakoff conversion of DM axions into microwave photons inside cavity

If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)

Solar Axions

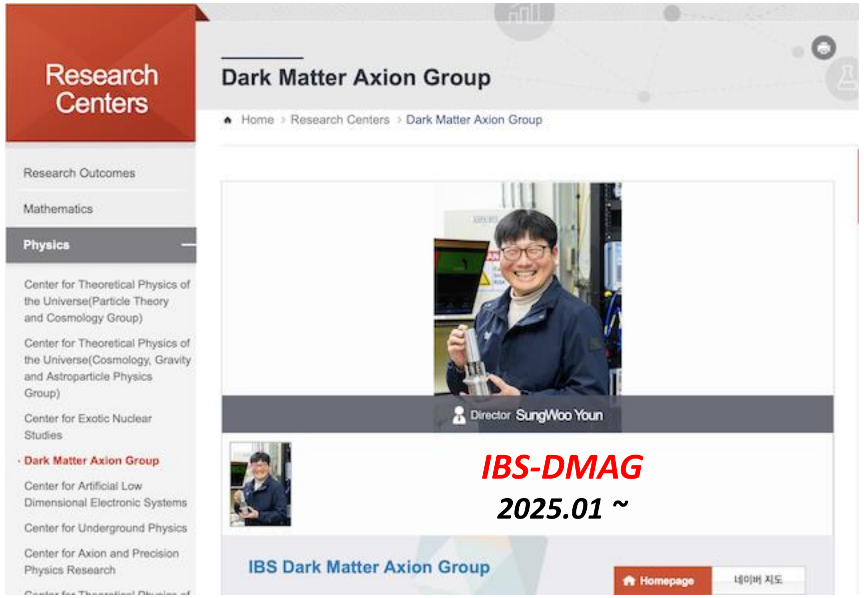
- Primakoff conversion of solar plasma photons → generic prediction of most axion models
- In addition, g_{ae}-mediated axions (model dependent)





CAPP to DMAG

Research Centers
Center for Axion and Precision Physics Research
Home › Research Centers › Center for Axion and Precision Physics Research
Research Outcomes
Mathematics
Physics
Center for Theoretical Physics of the Universe(Particle Theory and Cosmology Group)
Center for Theoretical Physics of the Universe(Cosmology, Gravity and Astroparticle Physics Group)
Center for Exotic Nuclear Studies
Dark Matter Axion Group
Center for Artificial Low Dimensional Electronic Systems
Center for Underground Physics
Center for Axion and Precision Physics Research
Director Yannis SEMERTZIDIS
IBS-CAPP
2013.10 ~ 2024.12
Searching for dark matter axions to explain the formation
Homepage



Research Centers
Dark Matter Axion Group
Home › Research Centers › Dark Matter Axion Group
Research Outcomes
Mathematics
Physics
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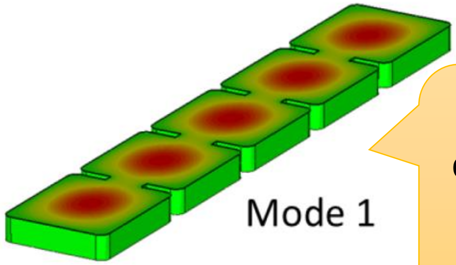
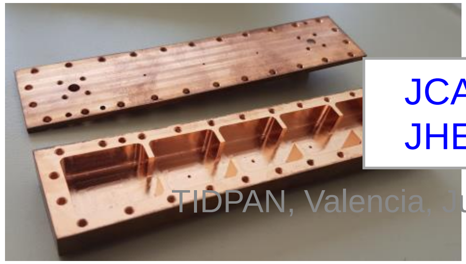
Dark Matter Axion Group
Center for Artificial Low Dimensional Electronic Systems
Center for Underground Physics
Center for Axion and Precision Physics Research
Director SungWoo Youn
IBS-DMAG
2025.01 ~
IBS Dark Matter Axion Group
Homepage
네이버 지도

RADES

- Exploratory project emerged at a later stage of CAST: use of "helioscope" magnets for "haloscope" searches
- Various R&D and physics results
- Strong boost by ERC-StG (B. Dobrich) in 2018
- Now ultra-cryogenic setup being built at MPP-Munich
- DarkQuantum ERC-SyG started 2024 (Irastorza, Kontos, Paraoanu, Wernsdorfer)

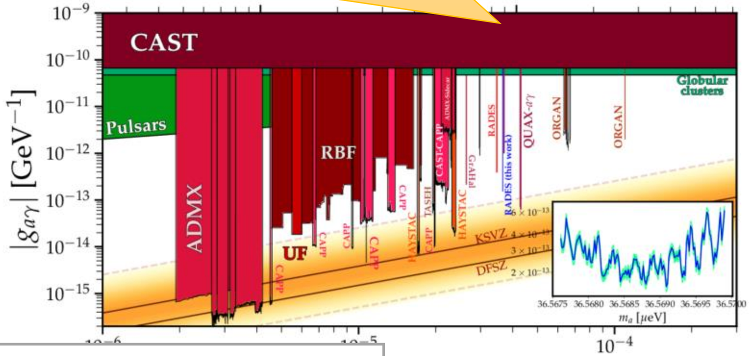


New geometry concepts to scale in V but keeping high resonant *f*



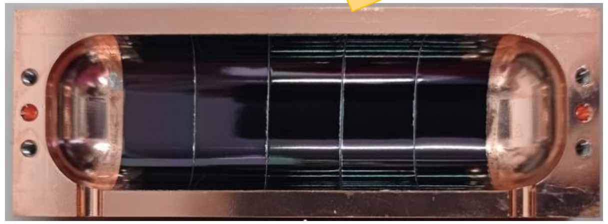
JCAP 05 (2018) 040
JHEP 07 (2020) 084

Physics result at single *f* point in CAST and in SM18 magnets



JHEP 21 (2020) 075
JHEP 04 (2025) 113

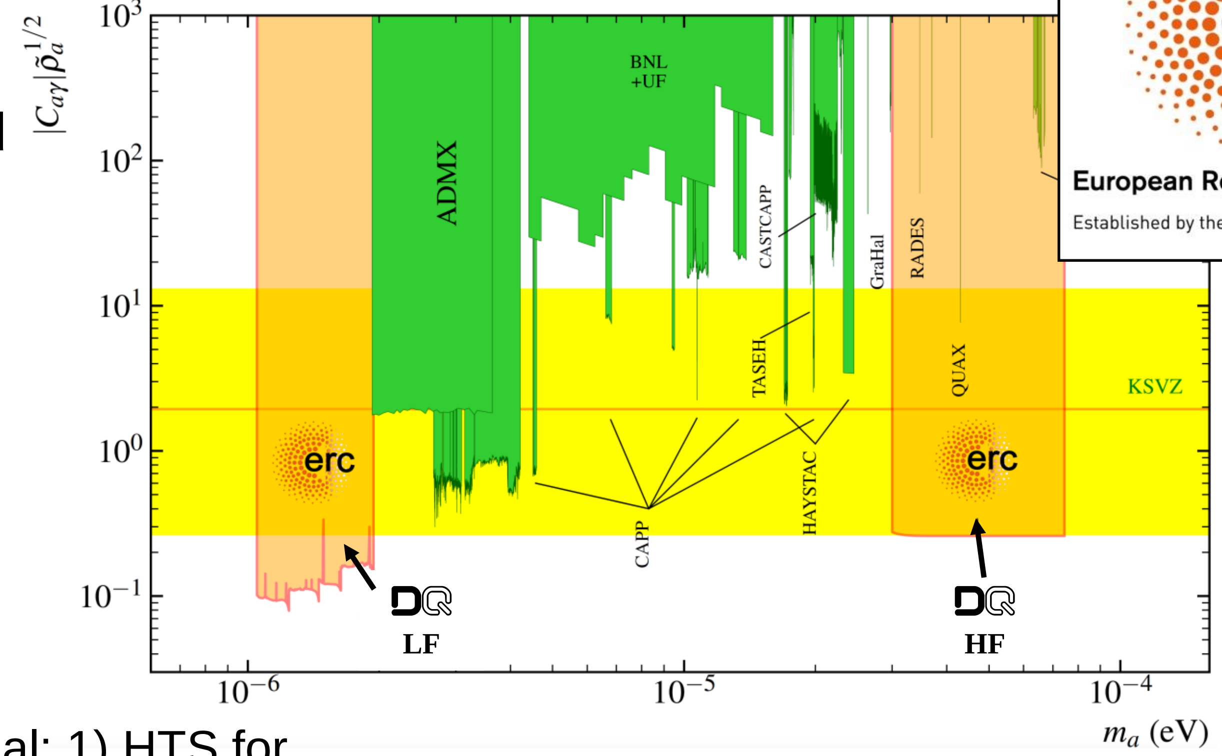
Inner HTS coatings to improve Q factor



IEEE Trans. Appl. Supercond. 32 (2022) 45

DarkQuantum: quantum-enhancing RADES

- Built on RADES plans. Add "quantum" ingredient.
  - Establish link with key experts and bring them to the axion field.
- Well defined roadmap of technical and physics outcome (→ impact)
  - Low frequency search in RADES@BabyIAXO
  - High frequency search in RADES@LSC

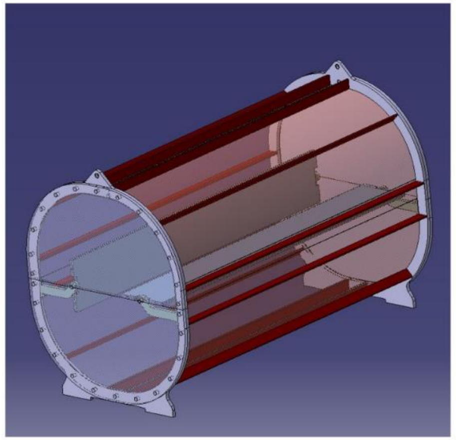


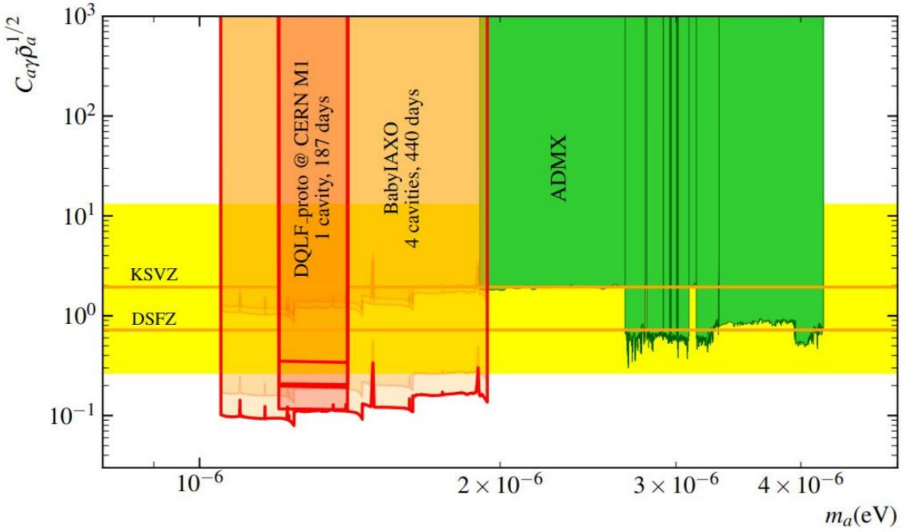
Additional exploratory lines with great potential: 1) HTS for increasing Q, 2) low radioactive techniques / underground, 3) Machine learning, 4) Magnonics for tuning

Also **QRADES** project from Quantera call, further strengthen the quantum development for RADES

RADES/DQ low frequency

- Large V haloscopes are technologically simpler, but expensive → huge magnet needed. Use of existing magnets could be an effective strategy
- **RADES**: use of BabyIAXO Use of (Baby)IAXO large magnetic volume for axion DM setups.
  - Various 5-m long 50-cm diameter cavities
- Very competitive prospects for 1-2 μeV axion searches.
- First prototypes under construction (1 m long)
- Could already get physics from them: using M1 magnet at CERN North Area? → **recent EoI to CERN SPSC submitted**

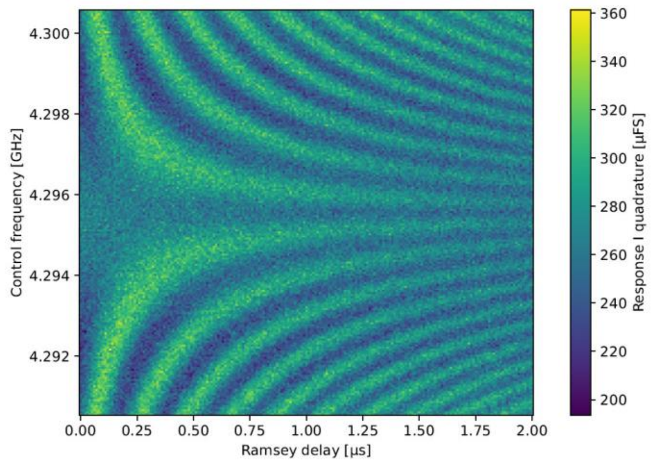


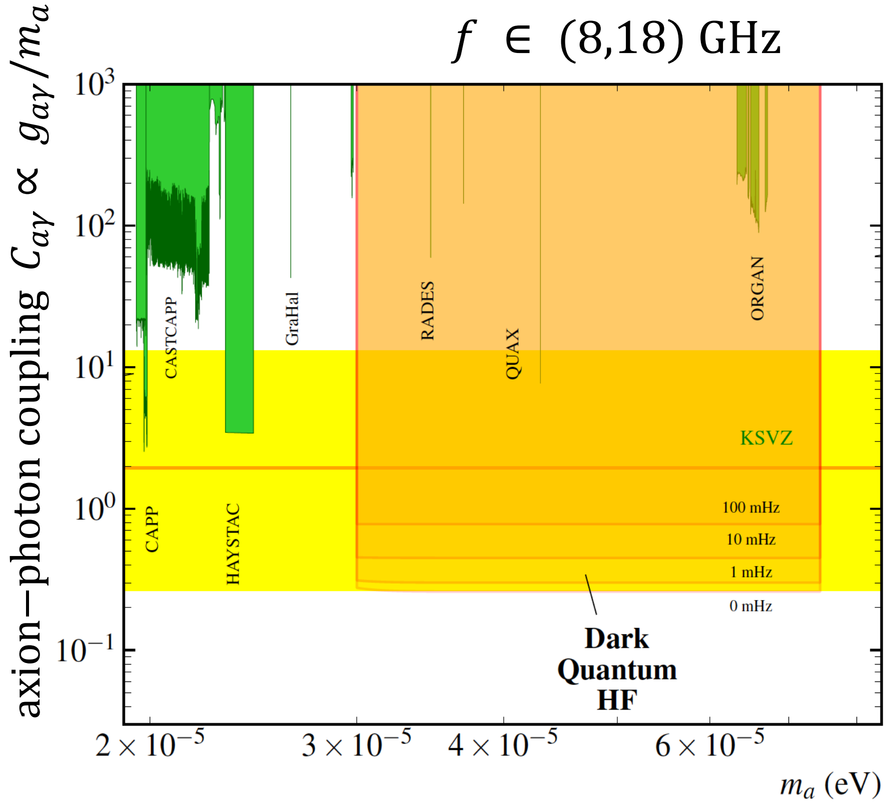


RADES-DQ high frequency

Beyond the standard quantum limit by counting ~10 GHz photons:

- SC qubit (transmon) based sensor
- Quantum non-demolition measurement
- Magnonics for frequency tuning
- HTS for increasing cavity Q
- Going underground to reduce darkcount rate → **EoI to LSC recently submitted**





SPD dark count rate

DarkQuantum: quantum-enhancing RADES

Main “rationale”:

- Built on RADES plans, high-frequency and low-frequency (BabyIAXO)
- Add “quantum” ingredient. Establish link with key experts and bring them to the axion field.

DarkQuantum

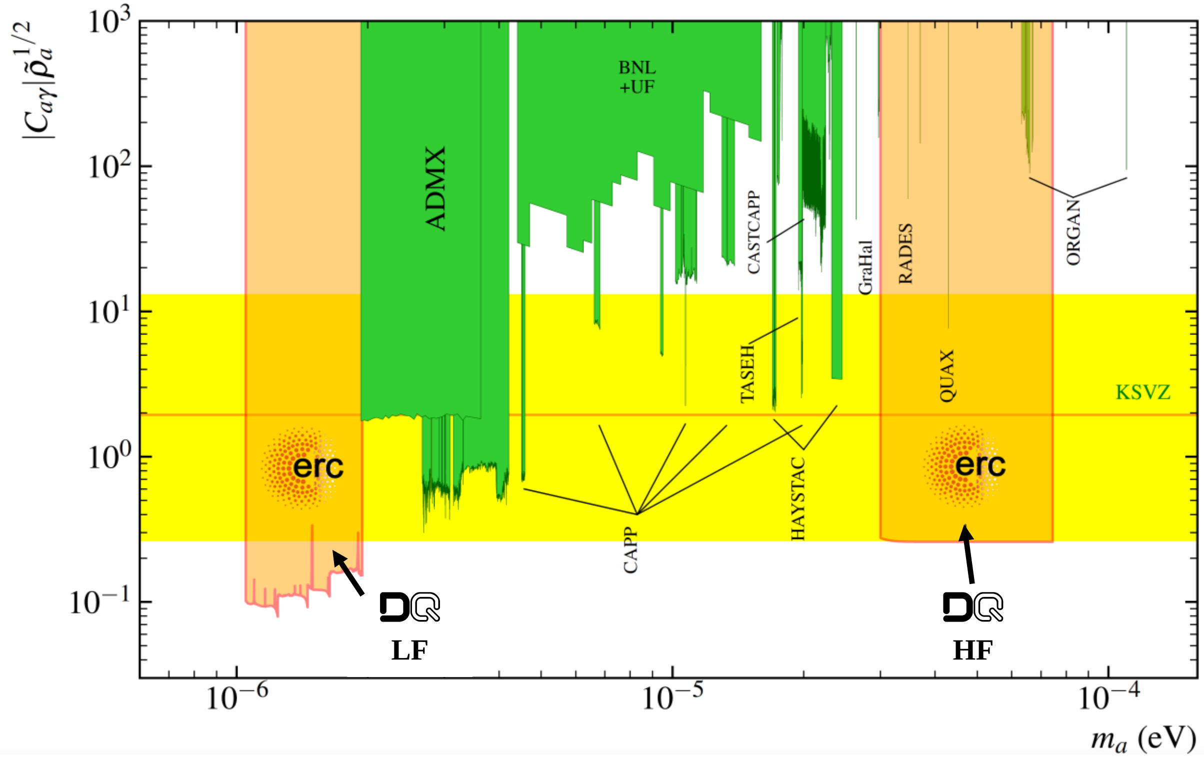
European Research Council
Established by the European Commission

3rd RADES Coll. Meeting &
DarkQuantum KICKOFF Meeting
1 month ago @ MPP-Munich

Also **QRADES** project from Quantera call, further strengthen the quantum development for RADES

DarkQuantum: quantum-enhancing RADES

- Well defined roadmap of technical and physics outcome (→ impact)
  - Low frequency search in RADES@BabyIAXO
  - High frequency search in RADES@LSC
- Development & implementation of quantum sensors.
- Very novel synergies: remain open for new ideas, unforeseen byproducts, etc…



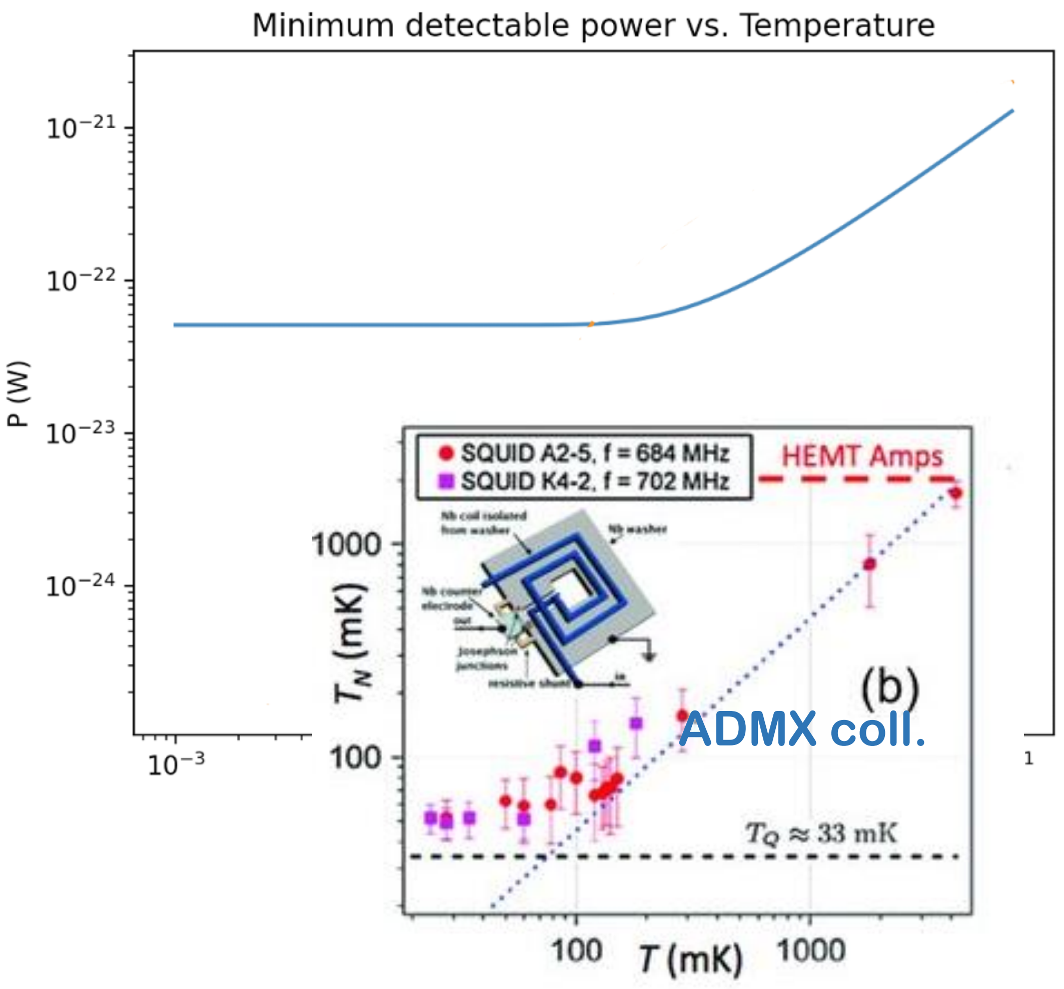
Haloscopes & quantum technologies

$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$

- Reducing T_{sys} implies:
  - 1) reducing physical temperature &
  - 2) improving sensing technology (quantum sensing)

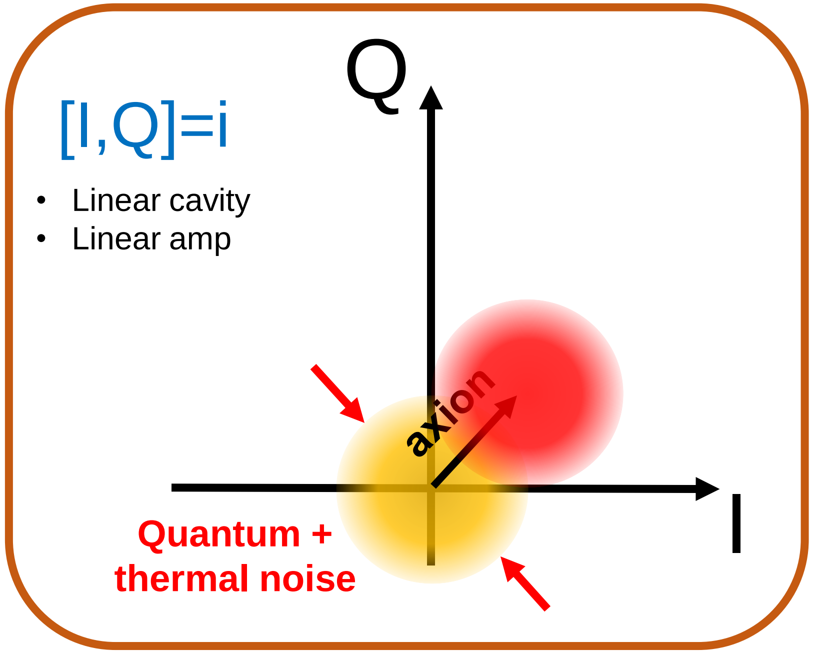
- Quantum amplification technologies are needed if one want to profit from cryogenics…

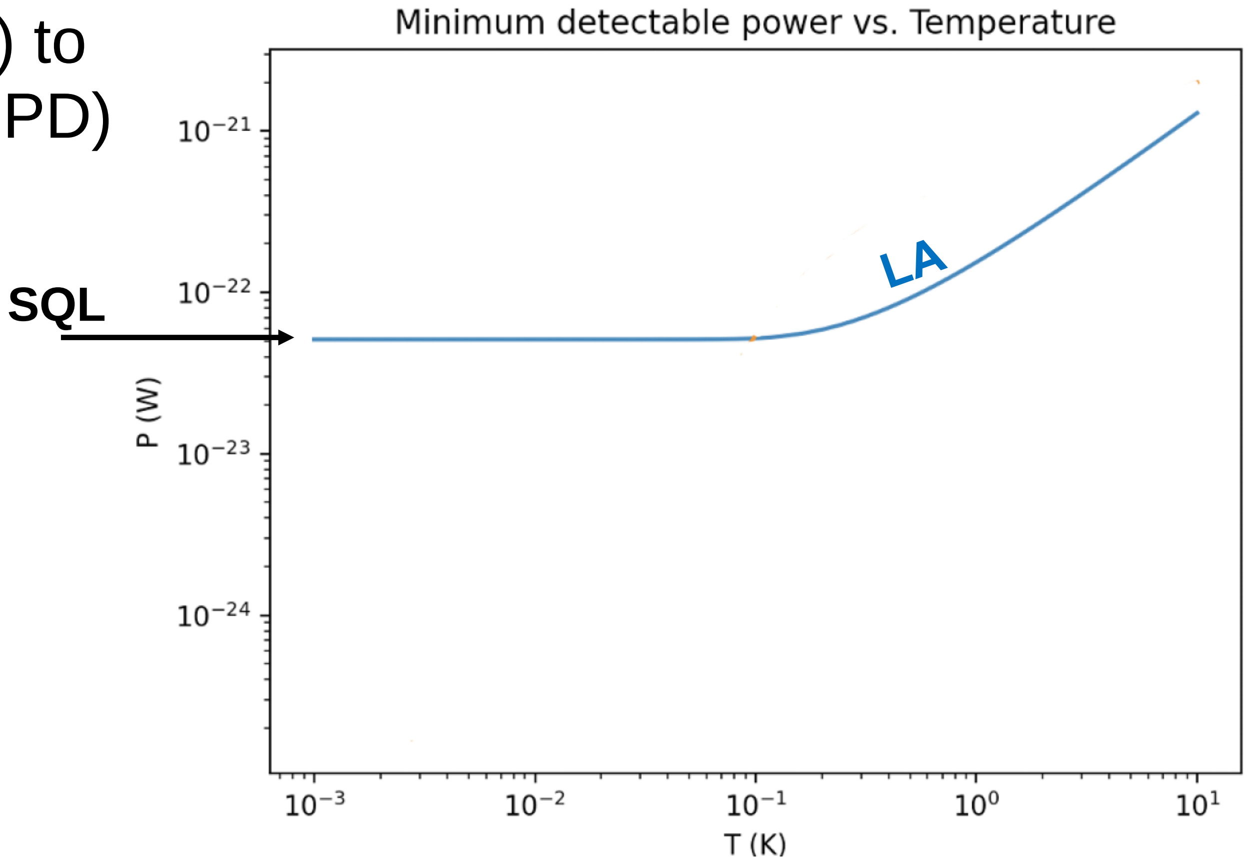
- But, even doing 1) and 2) the improvement suggested in above expression does not continue indefinitely: standard quantum limit SQL



Beyond the quantum limit

- From linear amplification (LA) to ***counting single photons*** (SPD)

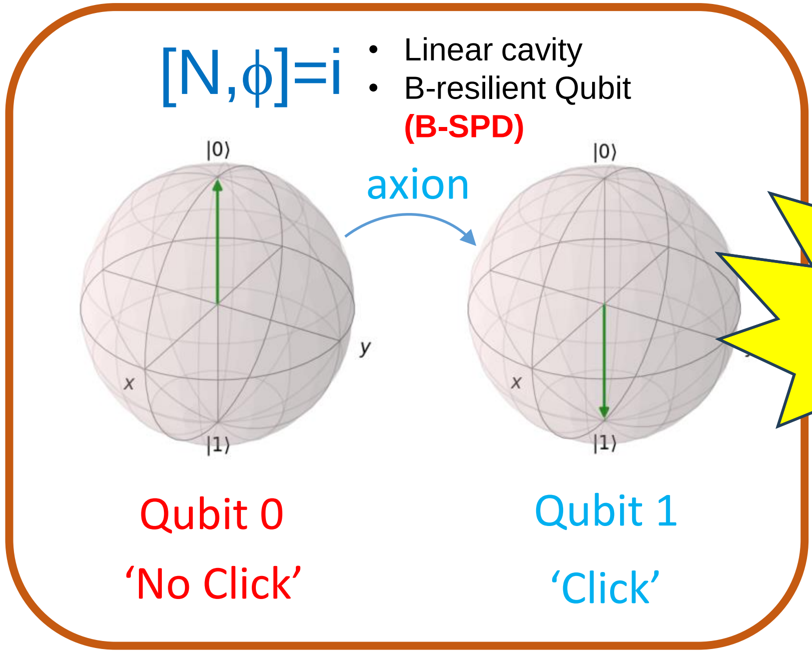




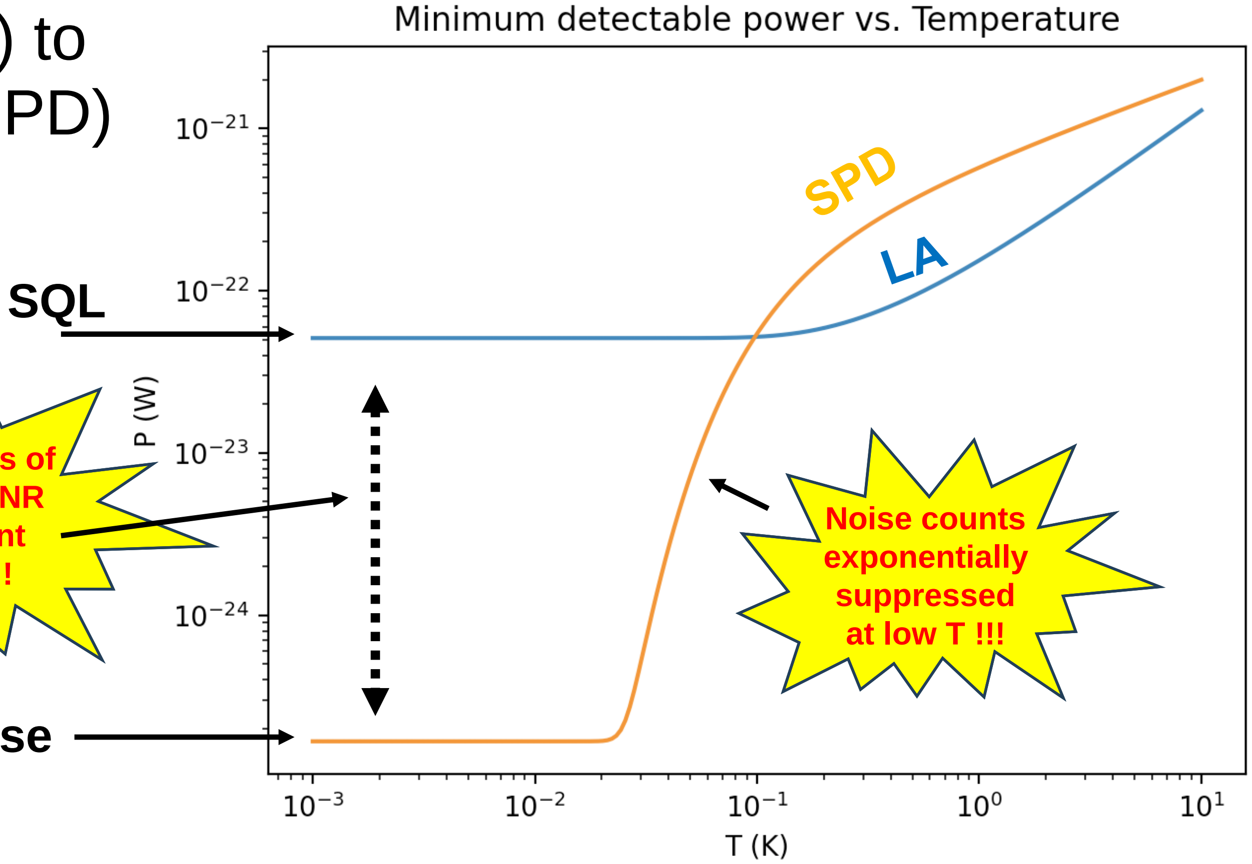
Conventional haloscope: In-phase(I) and Out of phase (Q) conjugates **limited by SQL**

Beyond the SQL: “counting photons”

- From linear amplification (LA) to ***counting single photons*** (SPD)



Several orders of magnitude SNR improvement available !!!

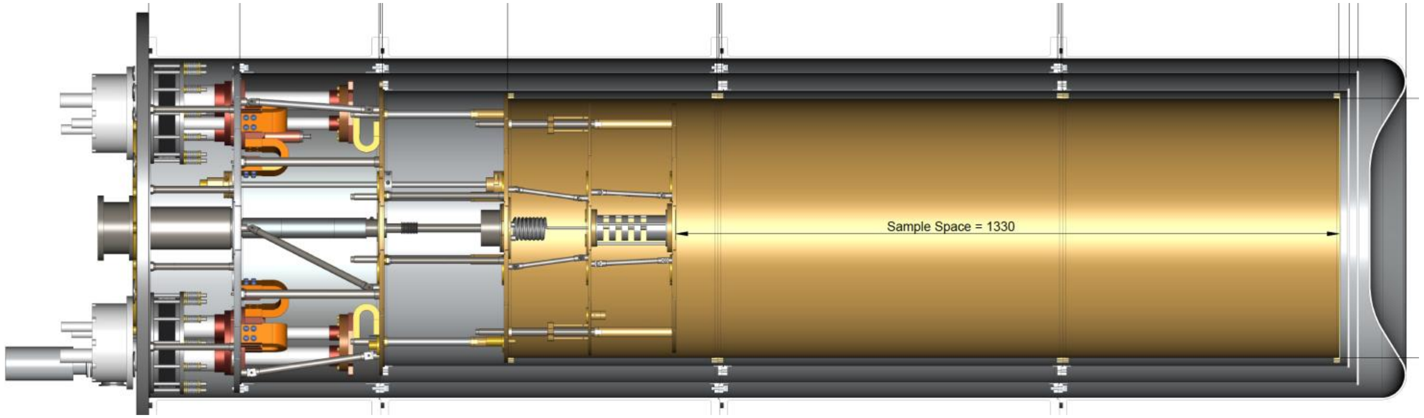


Single-photon detector (SPD) vs Linear Amplifier (LA)

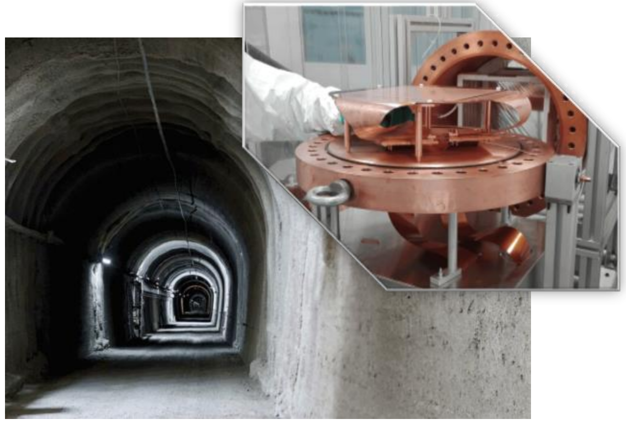
DQ change of paradigm → Number-Phase conjugates evade the SQL

DarkQuantum synergies

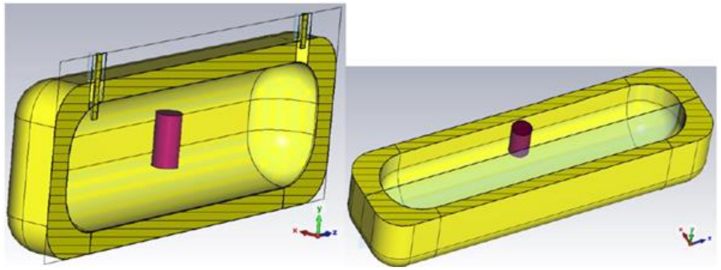
- Large-scale cryogenics



- Low radioactivity techniques and underground operation

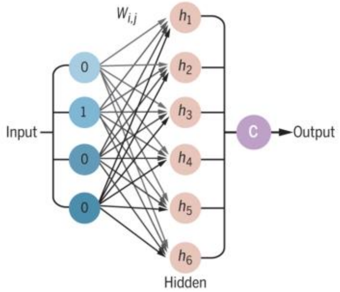


- Magnonics for tuning



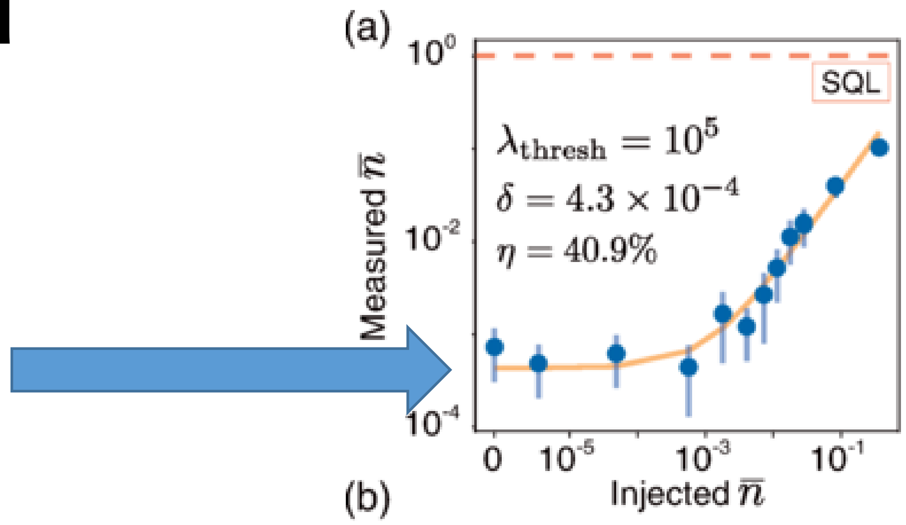
- HTS coatings

- Machine learning for quantum sensing



Why going underground

- Going underground to further reduce dark count rate?
  - EoI to LSC recently submitted
- Large scale cryogenics to cool down BabyIAXO bores
- Machine What is its origin? Could radiation play a role?
- Suggestive link to evidence of radiation affecting qubits properties. Synergies with ARQ/MIRQ project already operating at Canfranc (led by P.Forn IFAE) ?
- QRADES: Quantera project share goals with DarkQuantum, includes P. Forn

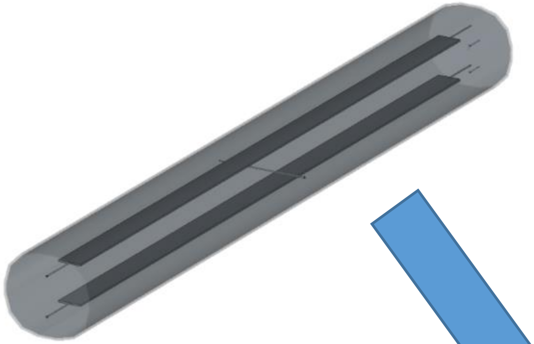


DarkQuantum could open an innovative link between "low background techniques & underground labs" and "axion haloscopes":

RADES at LSC the first underground axion haloscope?

Haloscopes inside BabyIAXO

- **Use of (Baby)IAXO large magnetic volume for axion DM setups.**
- **Very competitive prospects for 1-2 μeV axion searches.**
  - 4 x 5m long cavities with tuning slabs.
  - Low noise (standard) amplification + DAQ
  - Bores cooled down to 4-5 K
  - Sensitivity to KSVZ in < 2year data.
  - Other implementations (more speculative) are being discussed, BASE-like setups to much lower masses



RESEARCH ARTICLE

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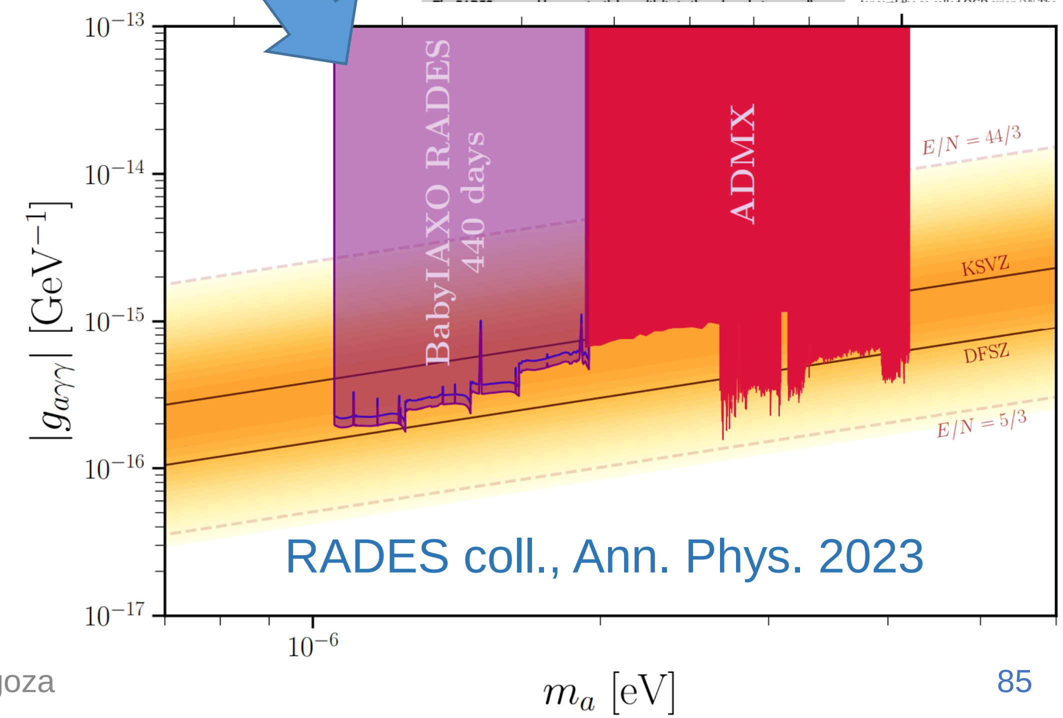
A Proposal for a Low-Frequency Axion Search in the 1–2 μeV Range and Below with the BabyIAXO Magnet

Saiyd Ahyoune, Alejandro Álvarez Melcón, Sergio Arguedas Cuendis, Sergio Calatroni, Cristian Cogollos, Jack Devlin, Alejandro Díaz-Morcillo, David Díez-Ibáñez, Babette Döbrich, Javier Galindo, Juan Daniel Gallego, Jose María García-Barceló, Benito Gimeno, Jessica Golm, Yikun Gu, Louis Herwig, Igor Garcia Irastorza, Antonio Jose Lozano-Guerrero, Chloé Malbrunot, Jordi Miralda-Escudé, Juan Monzó-Cabrera, Pablo Navarro, Jose Ramón Navarro-Madrid, Javier Redondo, José Reina-Valero, Kristof Schmieden, Tim Schneemann, Marc Siodlaczek, Stefan Ulmer, and Walter Wuensch*

In the near future BabyIAXO will be the most powerful axion helioscope, relying on a custom-made magnet of two bores of 70 cm diameter and 10 m long, with a total available magnetic volume of more than 7 m³. In this document, it proposes and describe the implementation of low-frequency axion haloscope setups suitable for operation inside the BabyIAXO magnet.

1. Introduction

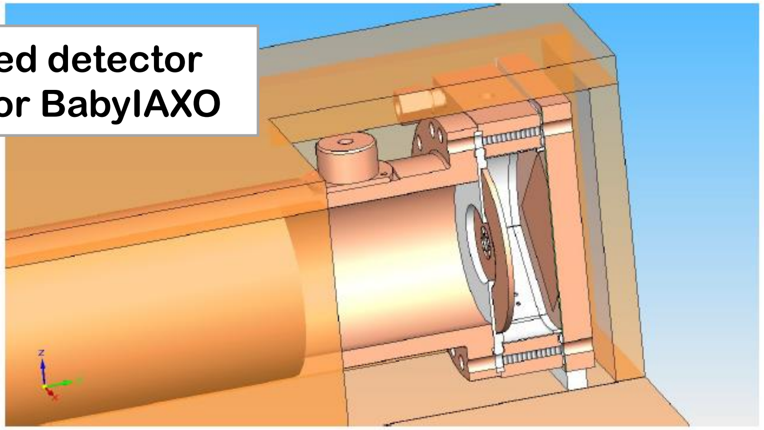
Two of the most pressing issues of fundamental particle physics, the strong CP problem[1–3] and the identification of the nature of the Dark Matter (DM) of the Universe,[4] could be solved by the exis-



RADES coll., Ann. Phys. 2023

BabyIAXO detectors

- Baseline detectors:
  - Low background Micromegas detectors of *microbulk* type
  - “Discovery detectors” (priority to low background).
  - Experience in CAST
  - Low background capability, radiopurity, shielding.
  - Goal is to reach 10^{-7} c/keV/cm^2/s

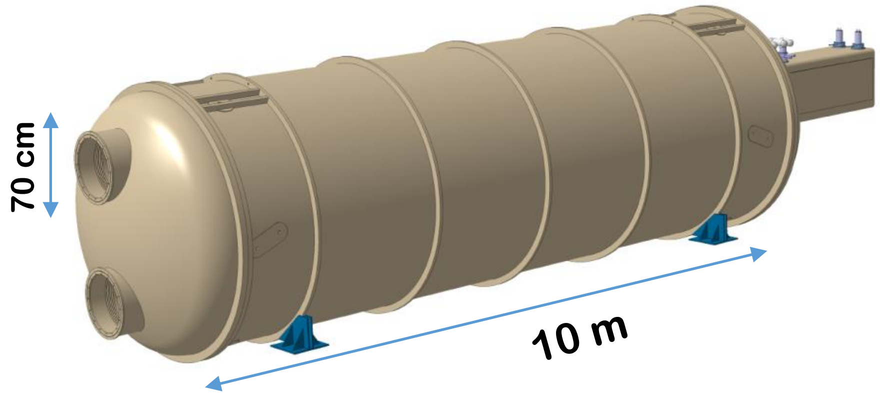


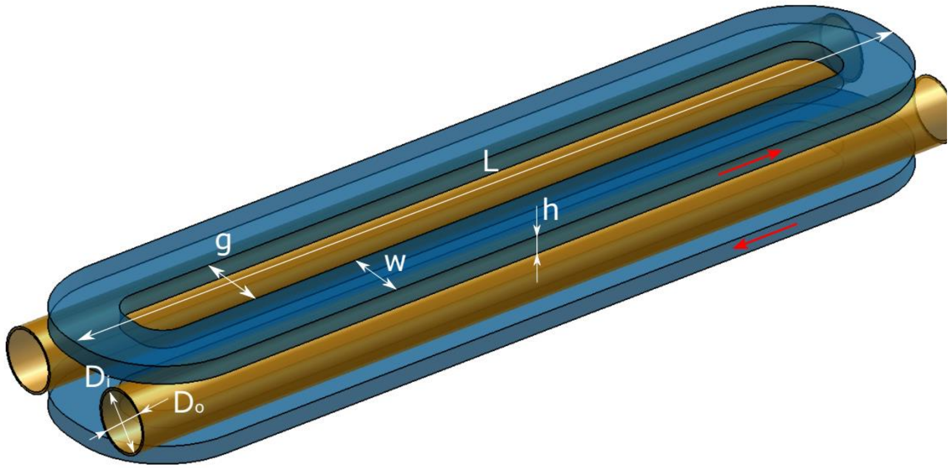
Improved detector design for BabyIAXO

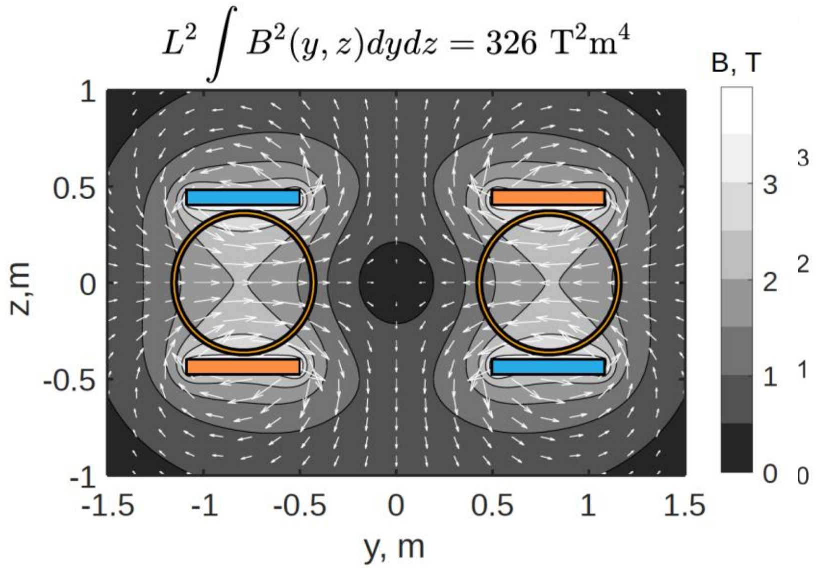
IAXO-D0 prototype in its shielding

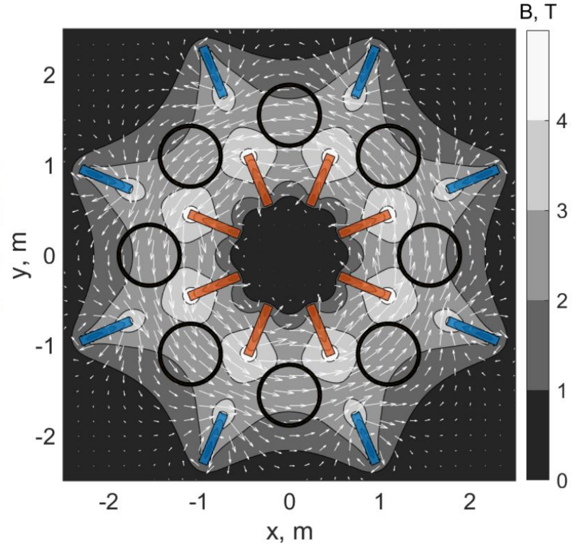
BabyIAXO magnet

- "Common coil" configuration
  - Minimal risk: conservative design choices
  - Cost-effective: Best use of existing infrastructure and experience at CERN
  - Prototyping character: winding layout very close to that of IAXO toroidal design.



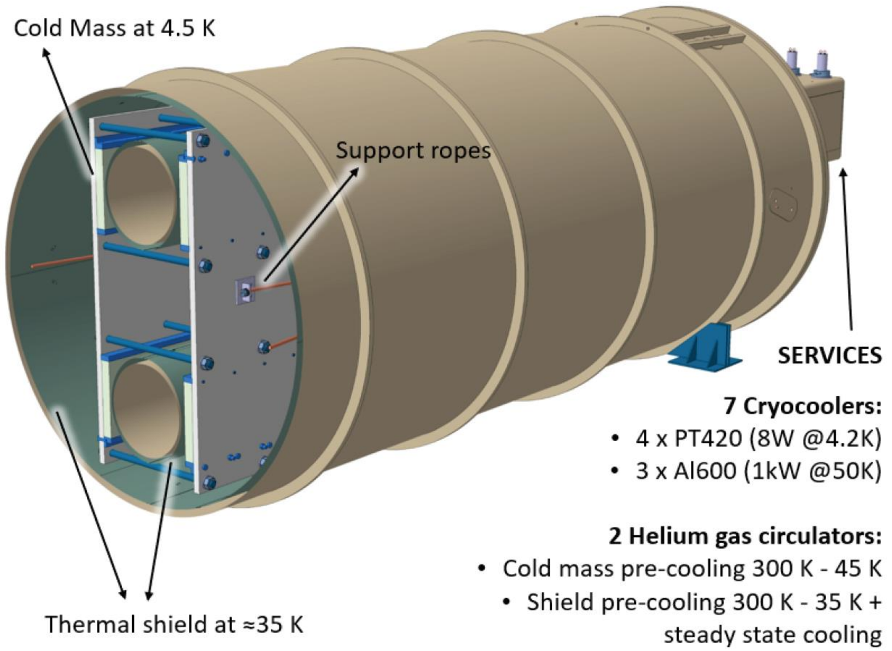


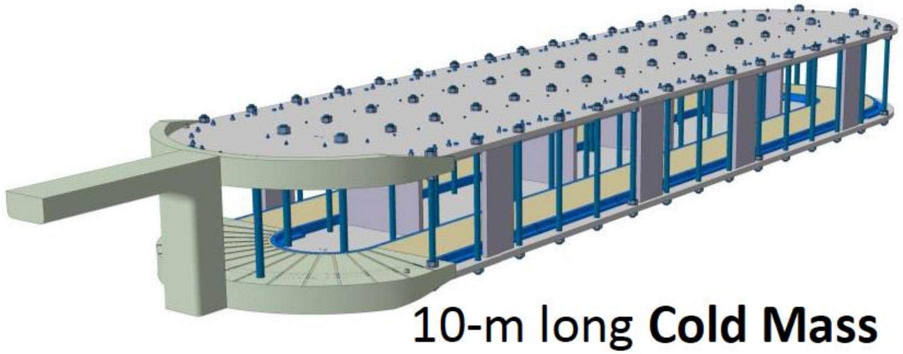




BabyIAXO magnet

- Technical in-depth review of magnet design successfully passed at DESY PRC already in 2020.
- Now ongoing adaptations derived from difficulties to procure Al-stabilized SC cable:
  - Original cable not usable
  - Potential Russian providers not available
  - Need to re-activate know-how in industry.
  - New review planned for end of year
- Request for quotations & tendering started for some subsystems.
- Critical item, causing delays.



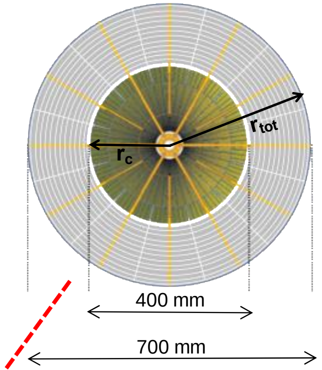


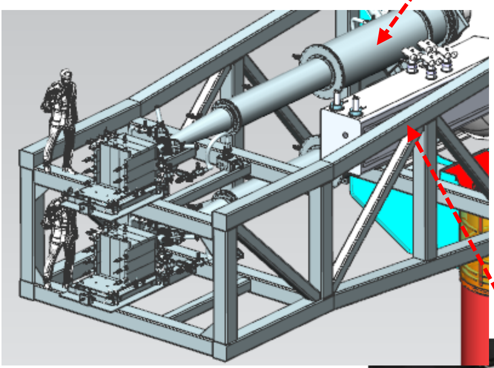
BabyIAXO optics

2 detection lines in BabyIAXO with different solutions:

Hybrid approach for custom BabyIAXO optic

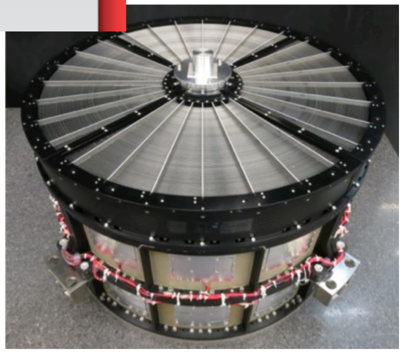
- **Inner part Al-foil or segmented glass optic**
- **Outer part cold-slumped Willow-glass technology**
- **First coating test (10 & 30 nm Ir) on NuSTAR flight glass and Willow glass satisfactory agreement with expectations**
  - **→ Henriksen et al, Appl. Opt. 60 (2021)**
- **Design of support structure and vessel to hold, co-align and calibrate both underway**





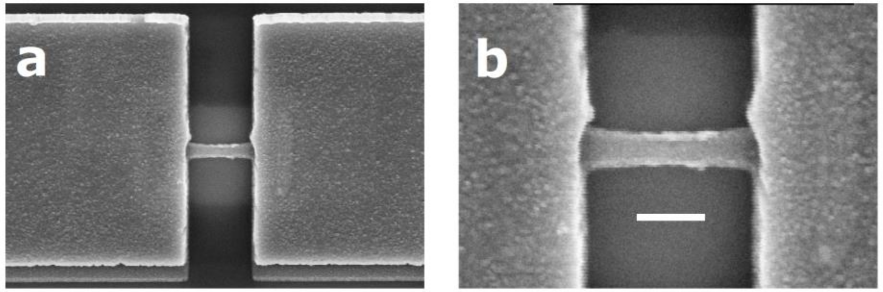
XMM Flight Spare XRT

- **Engineering model sent to DESY, actual optic currently at PANTER (Munich). MPE/PANTER formally joined IAXO.**
- **ESA letter received in 2019. Now operational requirements and loan agreement in preparation**
- **Calibration at PANTER scheduled soon**



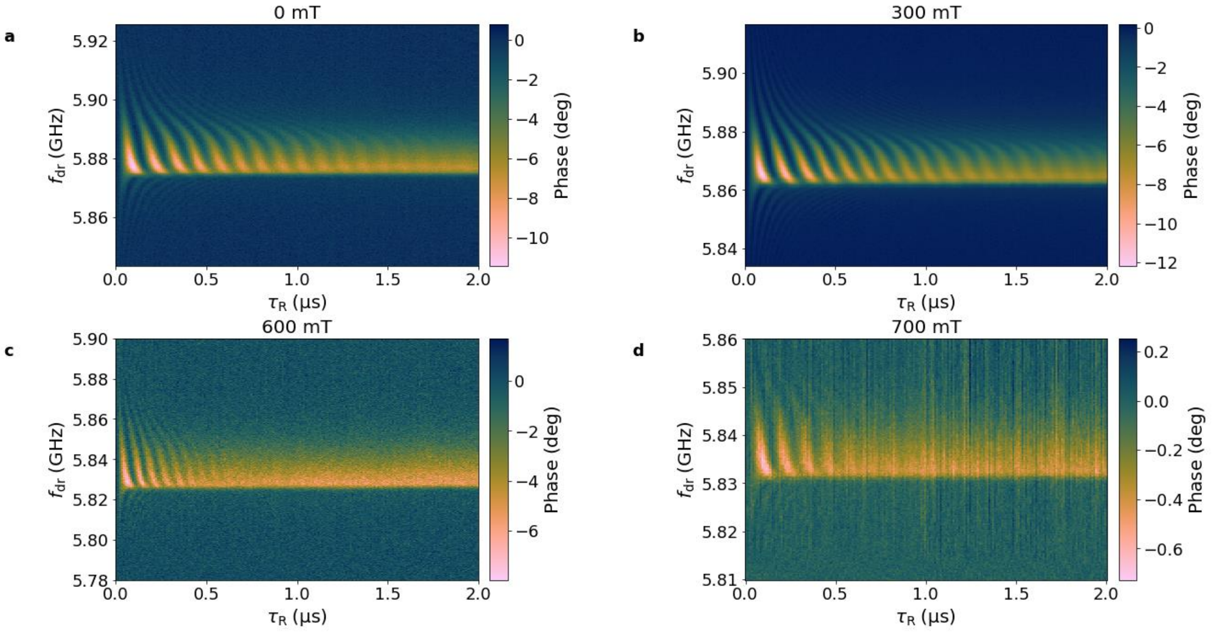
B-resilient transmons using graAl

Preliminary results from T. Kontos' group (ENS-Paris)



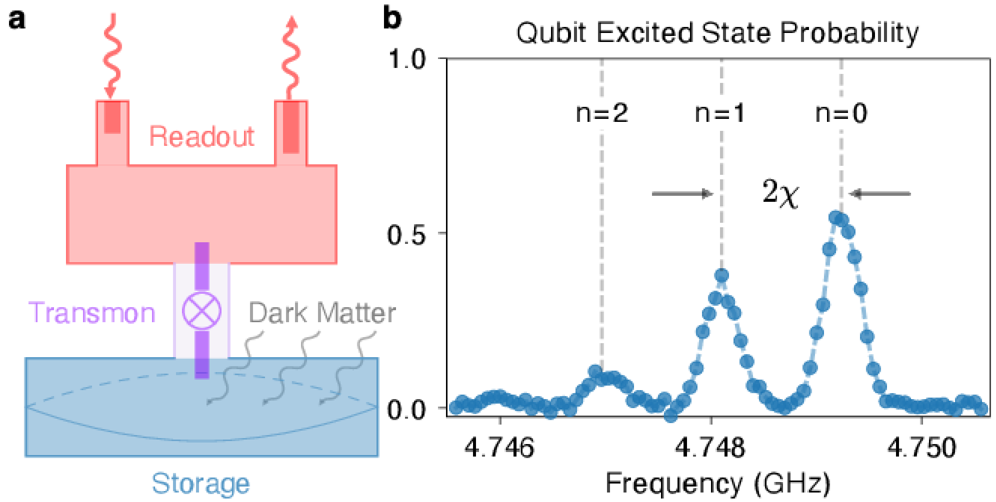
- Magnetic field resilient superconducting quantum circuits with granular aluminium, A. Théry et al. submitted to PRL'23

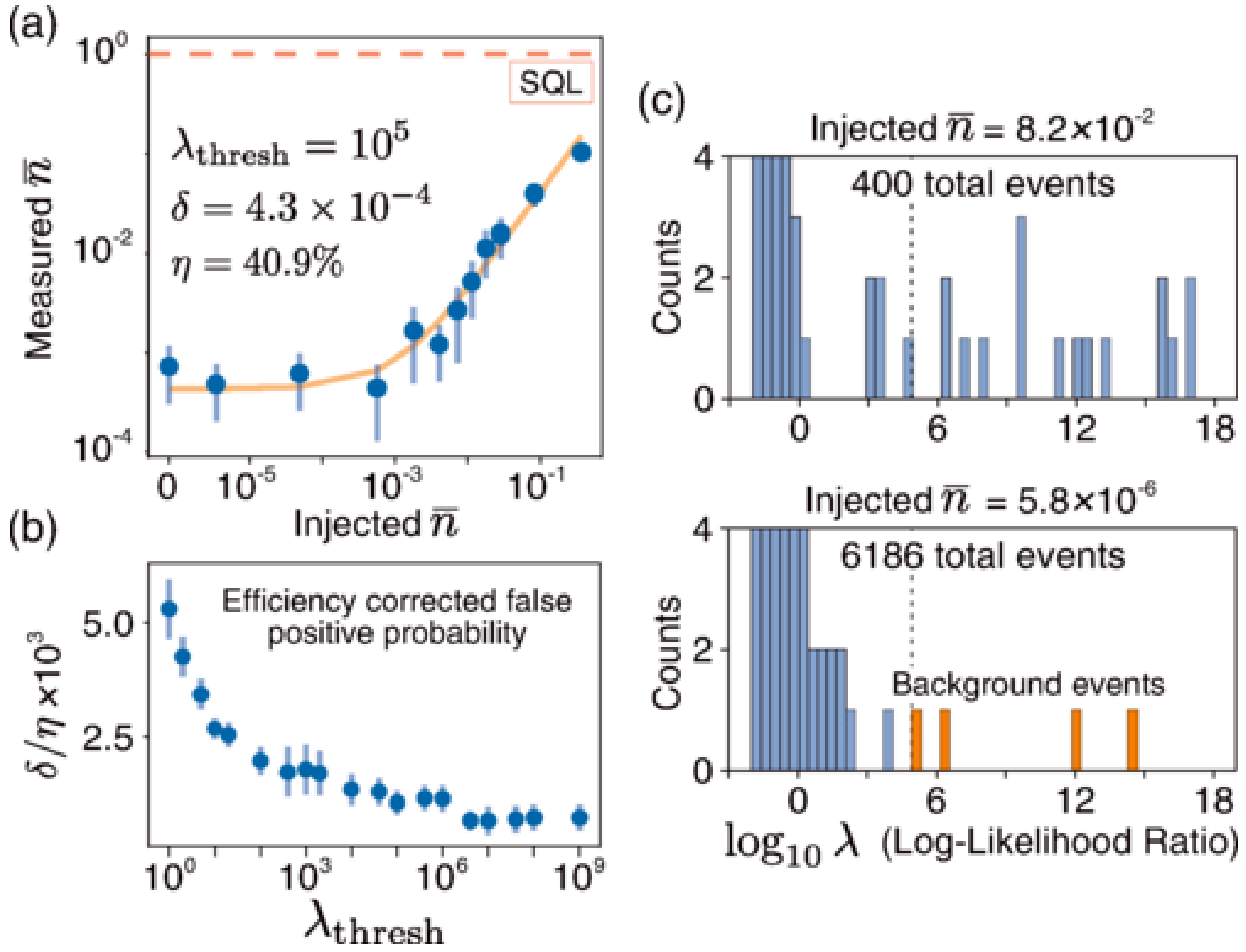
Rabi-like drive at finite B-field



T=20mK

Qubit-based Single Photon Detector (SPD)





- Dixit et al. Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126
- Other SC devices/layouts possible (*)

- **Problem**: transmons are supersensitive to B-fields!

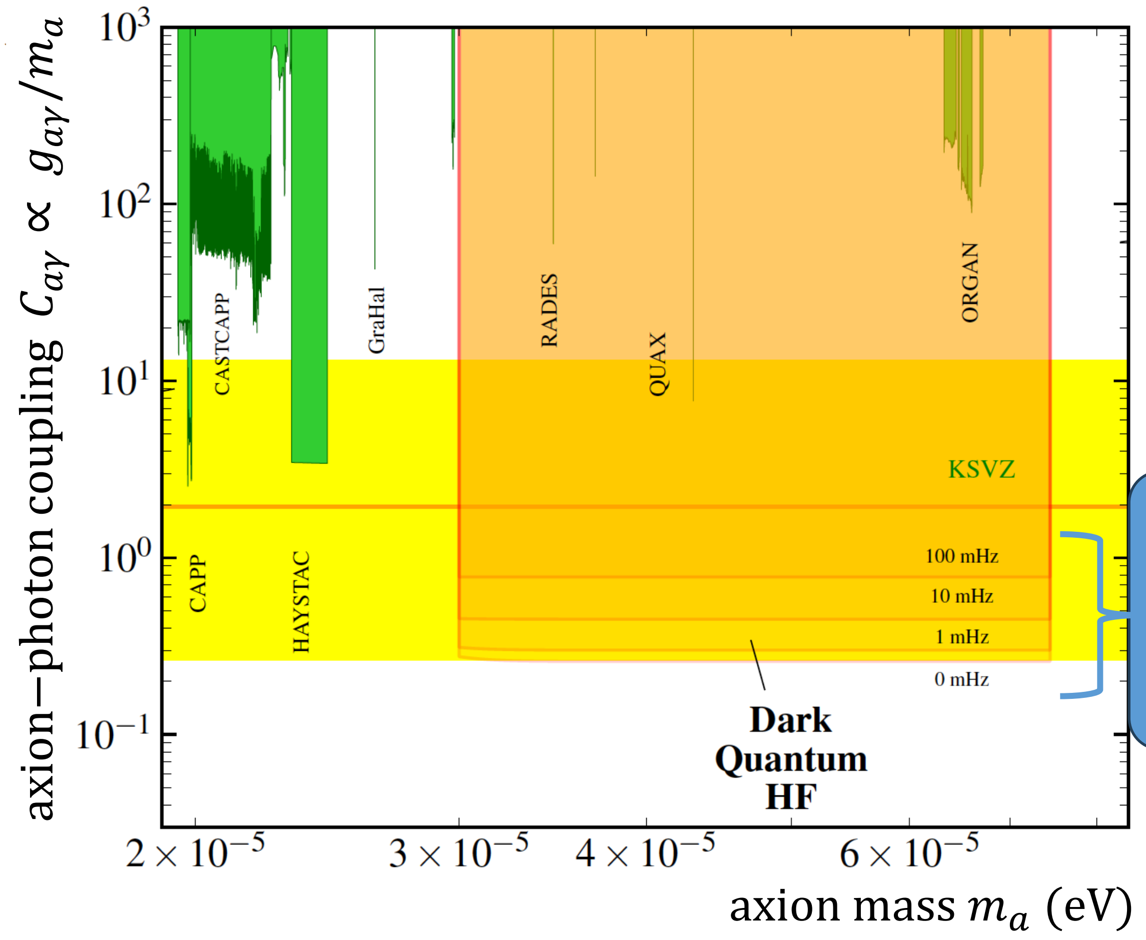
Potential impact in high-freq RADES setup

+ single-photon counter
+ reasonable tunability

Other parameters conservative – current RADES numbers:

V ~ 0.03 liters
Q ~ 10^4
B ~ 9 T
Time per m_a-step = 2 h
Total effective exposure time = 800 days
(can be distributed in a few cavities)

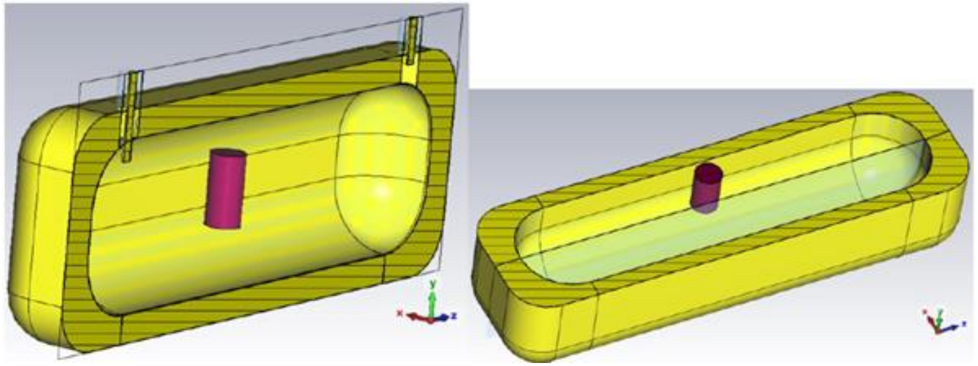
$f \in (8,18)$ GHz



SPD dark count rate

Magnonics for tuning

- Magnetic crystals (e.g. YIG or GdVO4) can modify the mode geometry and frequency in a B-dependent way
- Varying B to tune cavity: avoid messy and challenging mechanical systems! And maybe increase range?
- Challenge: how to implement without affecting Q or mode coupling



- Plan B: we go back to mechanical tuning

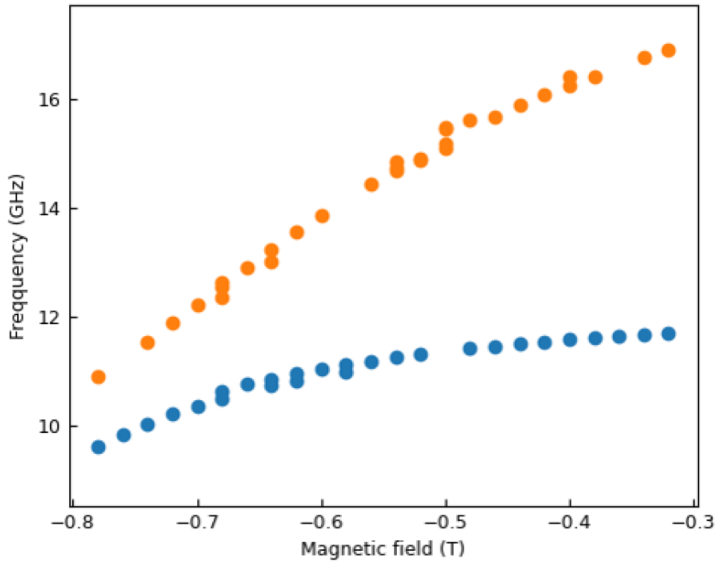


Figure 7: Evolution of two magnetic modes of a $GdVO_4$ crystal in a cavity-GraAl transmon-magnon setup. The two modes span a frequency of 9 GHz to 17 GHz, which corresponds to most of the range envisioned in the DarkQHF detectors.

Preliminary results from T. Kontos' group (ENS-Paris)

RADES groups

- MPP-Munich
- CAPA-Zaragoza
- JGU-Mainz
- CERN
- ICCUB, Barcelona
- IFIC, Valencia
- TRIUMF, Vancouver
- UPCT, Cartagena
- ITA, Zaragoza
- OAN, Yebes
- LSC

Large expertise in axion haloscopes and related know-hows

- **ENS-Paris**
- **KIT**
- **Aalto**

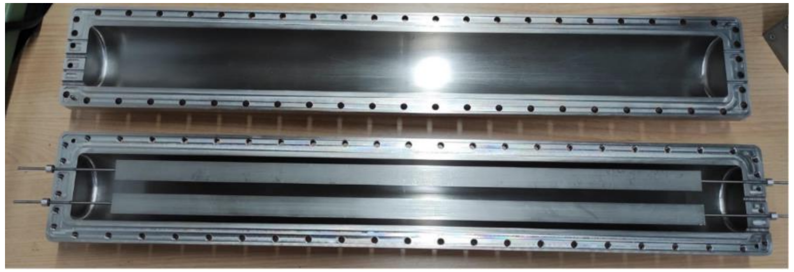
+ **IFAE** (P.Forn) via QRADES

"Quantum tech" experts via DarkQuantum

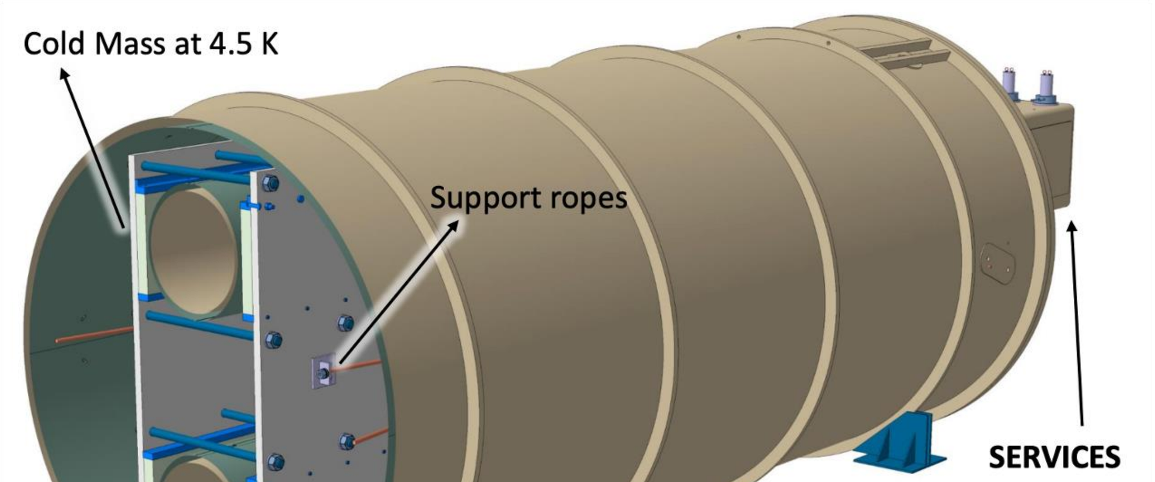
Low frequency: pushing BabyIAXO to SQL

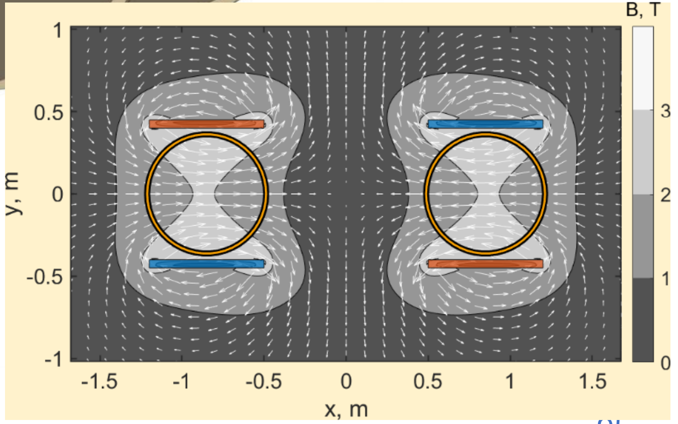
- Unprecedented magnetic volume
- Available to axion community
- We need:
  - Ultra-cryogenics for unorthodox size and dimensions: challenging but possible.
  - SQUID-based quantum-limited amplifier

First scaled-down prototype built and tested:



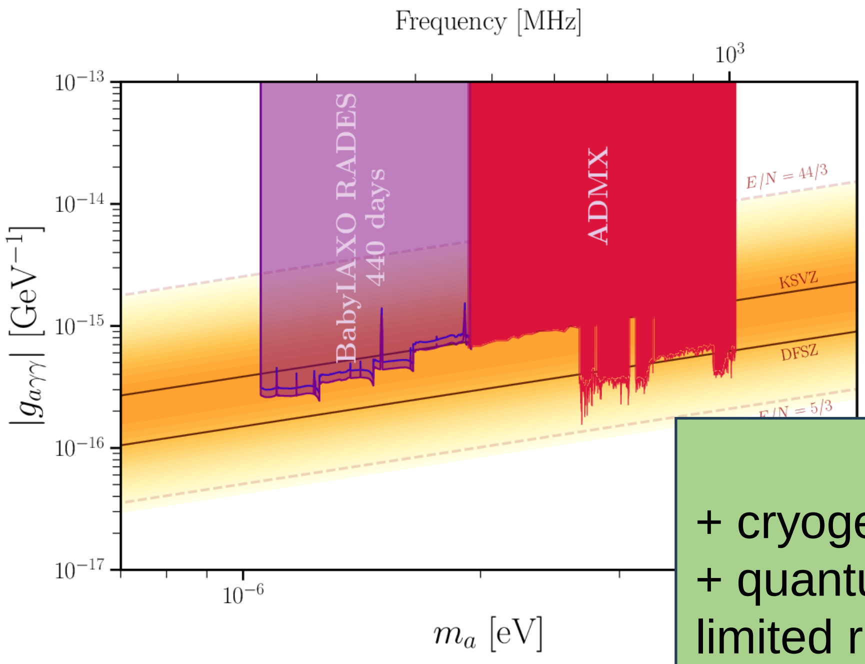
2 x 10-m long 70-cm diameter magnet bores



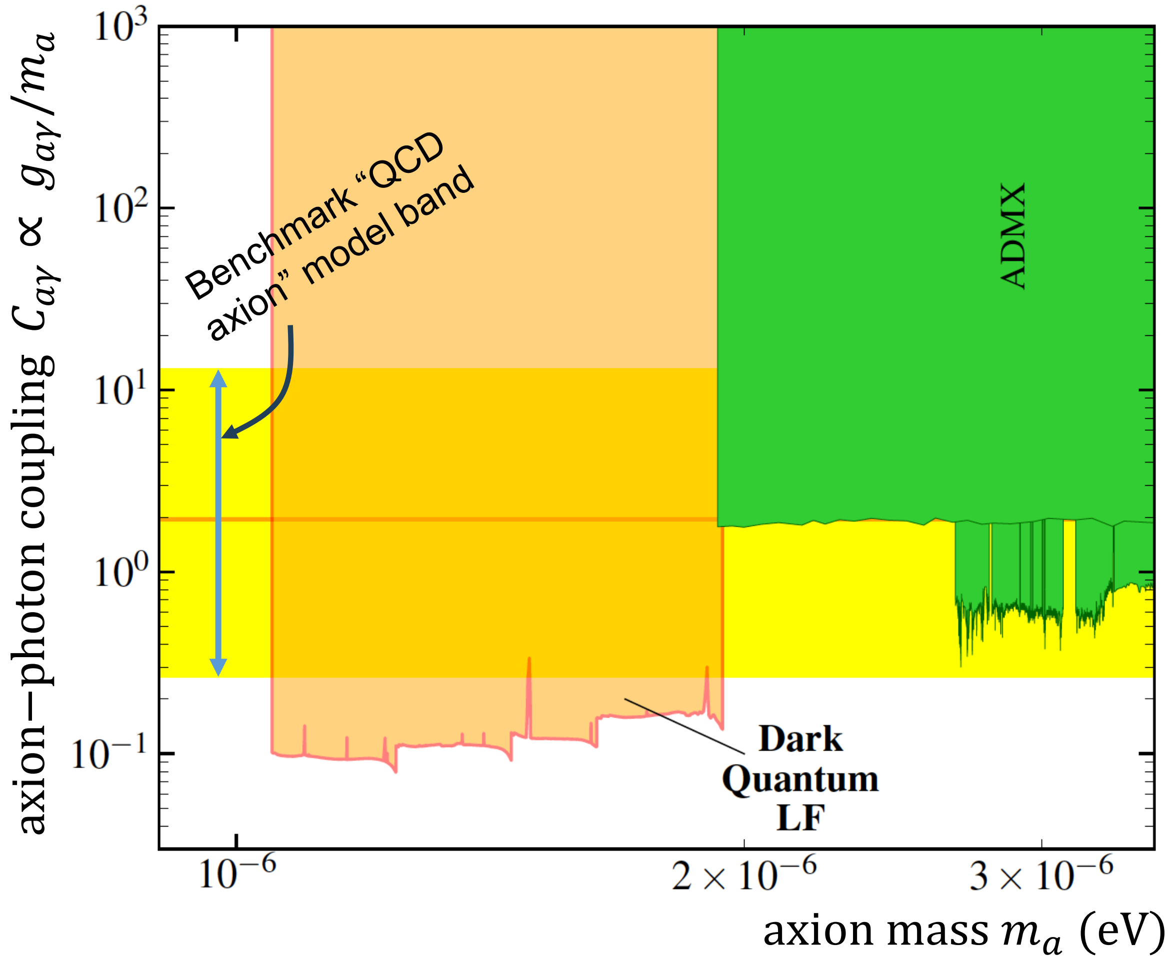


Enhanced sensitivity prospects

From our recent RADES@BabyIAXO paper:



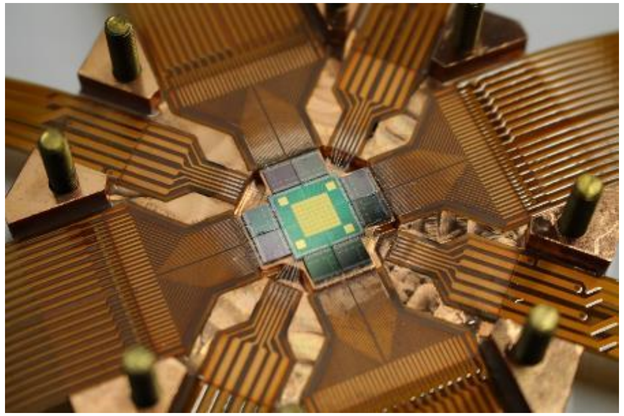
+ cryogenics
+ quantum-limited readout



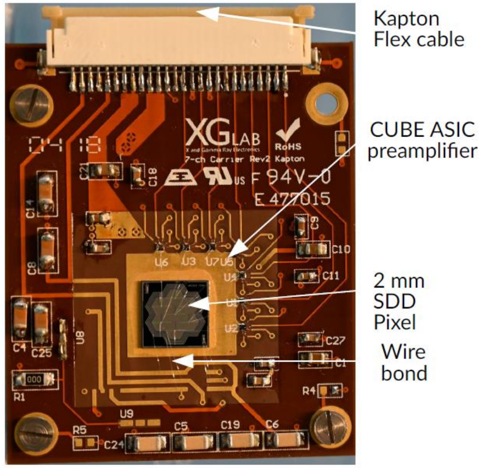
BabyIAXO complementary technologies

- **Beyond baseline, "high precision" detectors**
  - **Better threshold & energy resolution**
  - **Design and material optimization ongoing in all fronts**
  - **Background studies with different shielding configurations**
  - **DALPS project (French ANR)**

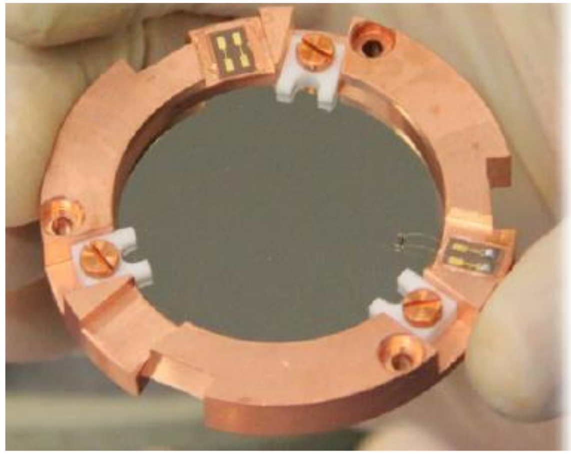
ERC-StG (2020)
M.Meyer
To understand bkg in TES



MMC: Metallic Magnetic calorimeters



SDD: Silicon Drift Detectors

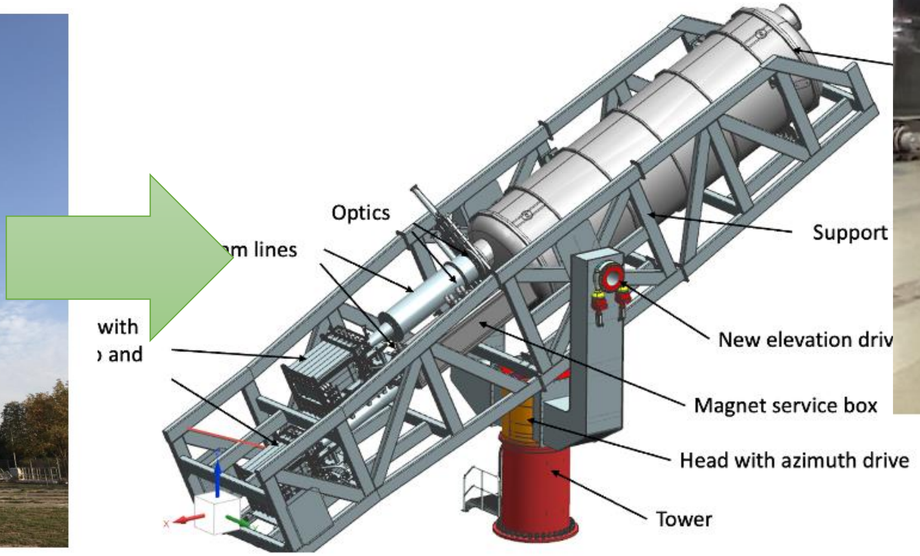


TES: Transition Edge senstors

Gridpix

Technical coordination at DESY

- **Site**: **HERA South Hall, former ZEUS detector hall: 43 x 25m**
- **Support and Drive System**: **Reusing (parts of) CTA MST Prototype from Berlin.**
- **Technical coordination and project office** **very active, WBS, PBS, …**



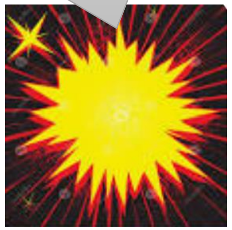
BabyIAXO: beyond baseline

BabyIAXO as a generic axion(-like) facility

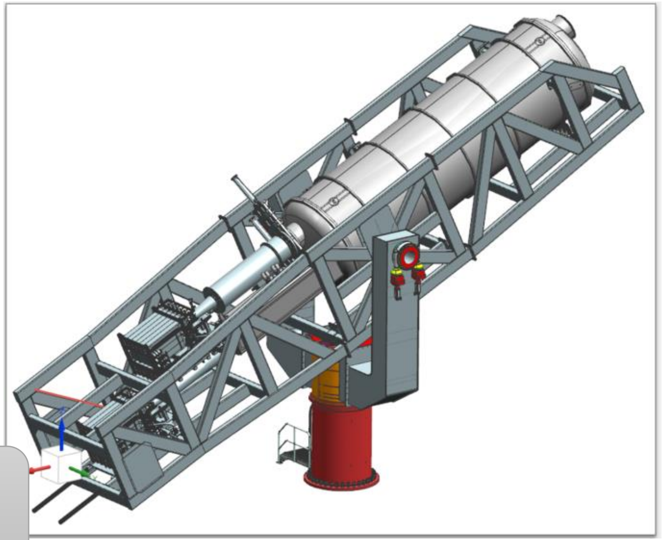
- BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

Other (non-Primakoff) solar axion production mechanisms

Axions from SN



post-Discovery “precision” physics

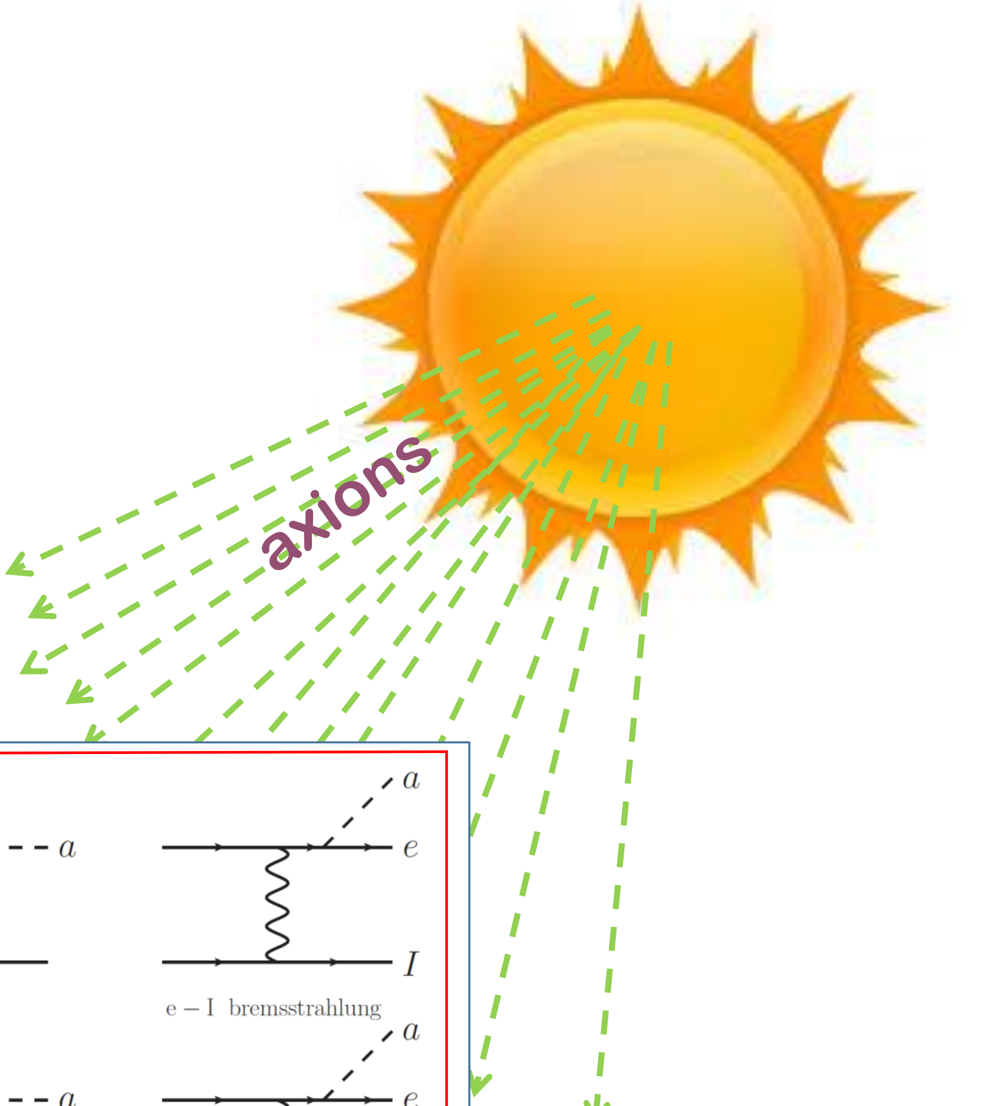


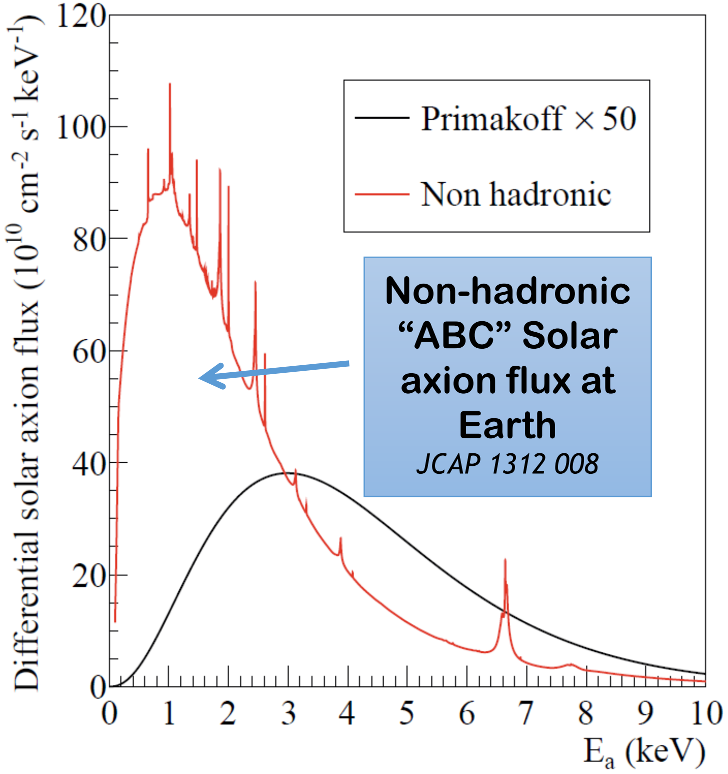
Dark Matter axions: haloscope setups inside the BabyIAXO bores

Other WISPs: hidden (dark) photons, chameleons, …

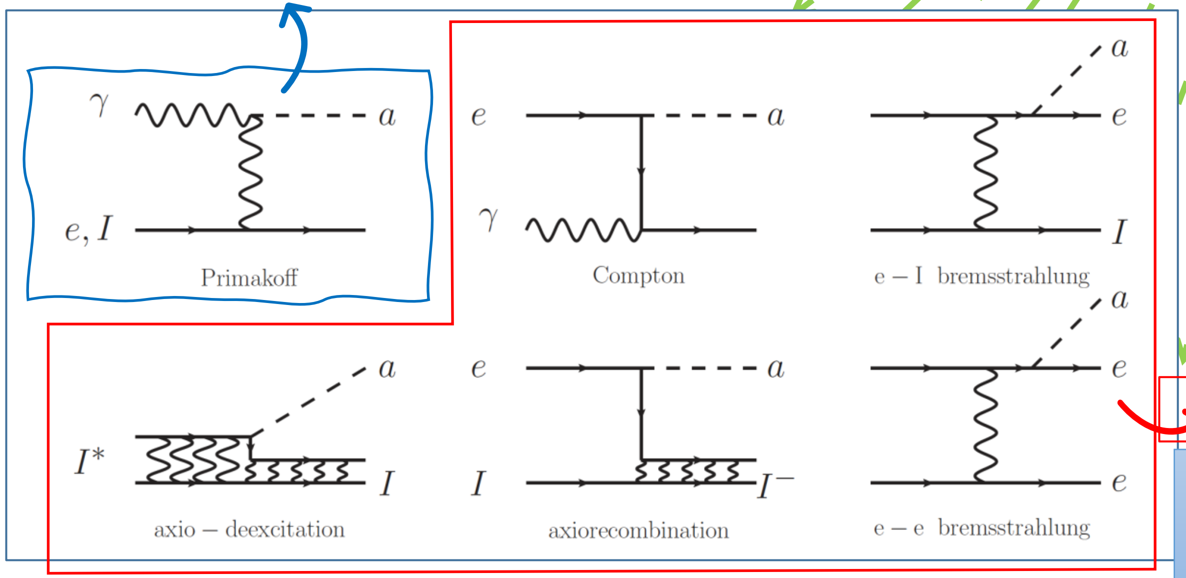
Other solar axion sources

- **In addition to Primakoff, “ABC axions” may be x100 more intense… but model-dependent.**





Primakoff



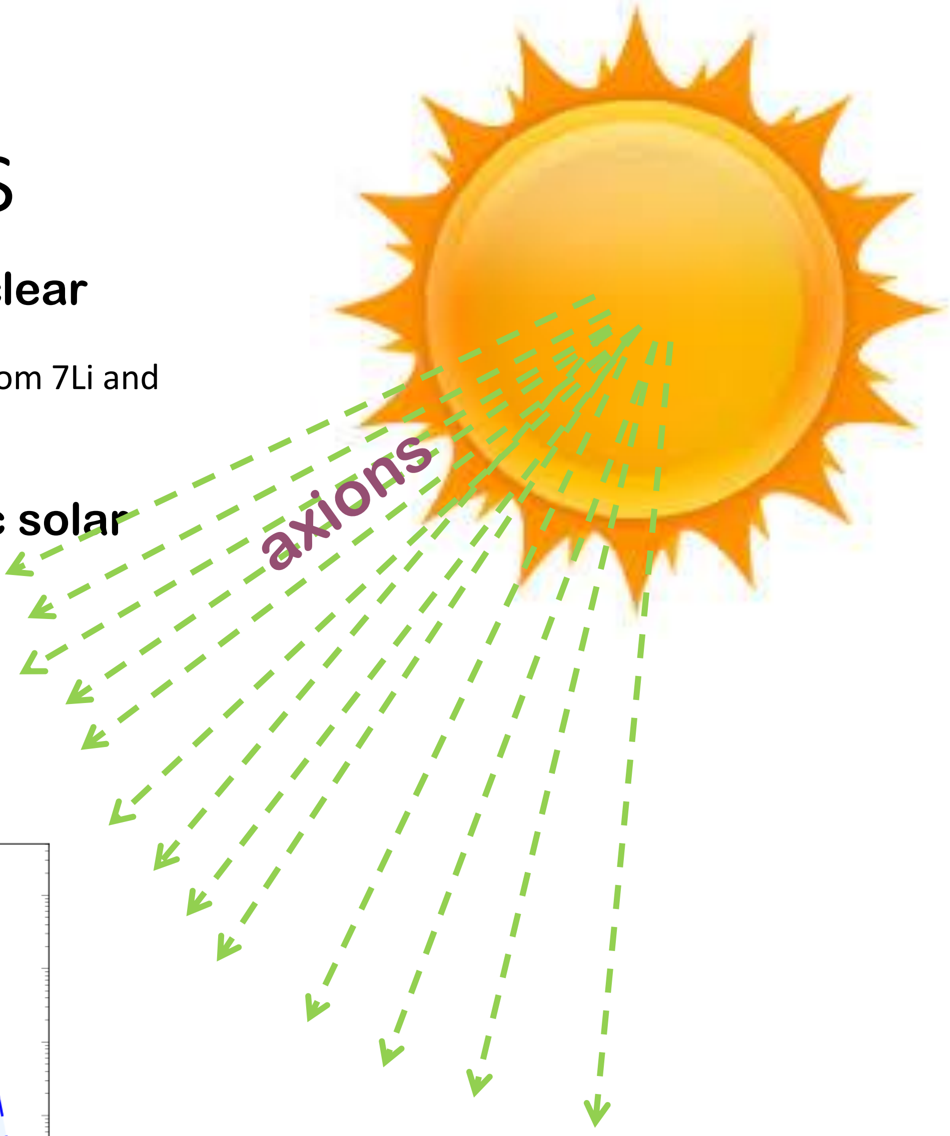
“ABC” axions (*)

* if the axion couples with the electron (g_{ae})
(non hadronic axion)

Other solar axion sources

- **Via** axion-nucleon couplings**: monochromatic lines from nuclear transitions:**
  - E.g. 14.4 keV axions emitted in the M1 transition of Fe-57 nuclei, MeV axions from 7Li and D(p;γ)^{3}He nuclear transitions or Tm-169. Di Luzio et al. 2111.06407

- **More** recently proposed: p**hotons interacting with macroscopic solar** B-**fields.** e.g. Guarini et al. 2010.06601



- **longitudinal and transversal plasmons conversion.**
- **Depend on $g_{a\gamma}$!**
- **TP depend on m_a too**
- **Depend on solar B-field. Poorly known but constrained:**