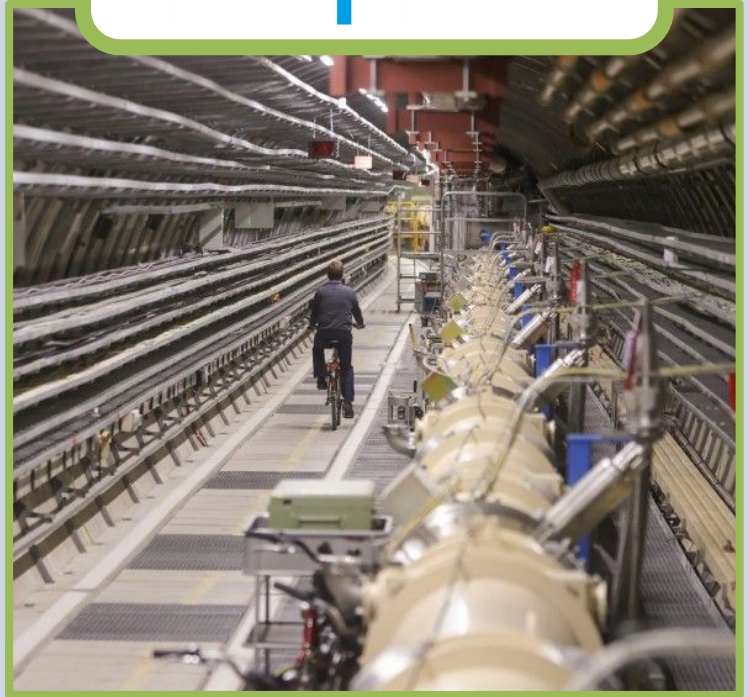
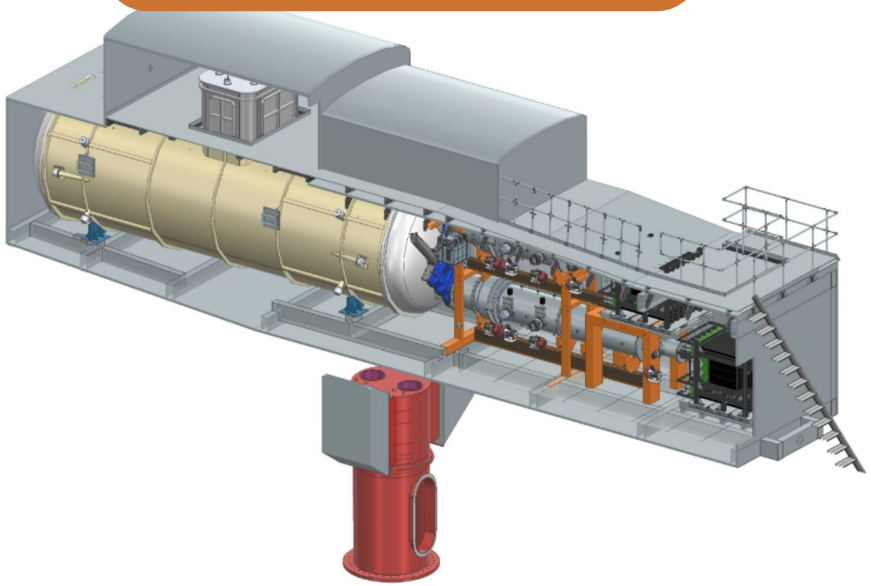
ALPS II



Todd Kozlowski

IAXO



Daniel Heuchel

MADMAX

Jacob Egge

On-site Axion Search Prospectives for PoF V

PoF V MU-FPF Retreat
20.06.2025

Particle physics motivation

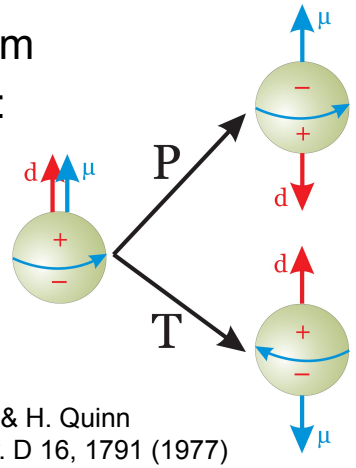
Strong CP problem

- QCD vacuum angle upper bound from measurements of neutron dipole moment:

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

C. Abel et al.
Phys. Rev. Lett. 124, 081803 (2020)

- solved by introducing a new field with $U(1)_{PQ}$ symmetry: the **axion**



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Axions as Dark Energy

- ultralight (<10^{-33} eV) axions could be the dynamical dark energy / cosmological constant
  - DES: https://doi.org/10.48550/arXiv.2503.18120
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Axions as Dark Matter

- axions are a natural cold dark matter candidate

DOI: 10.1126/sciadv.abj3618

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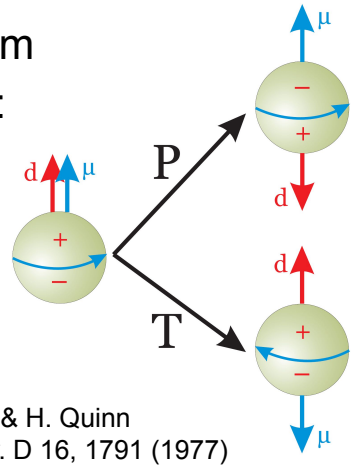

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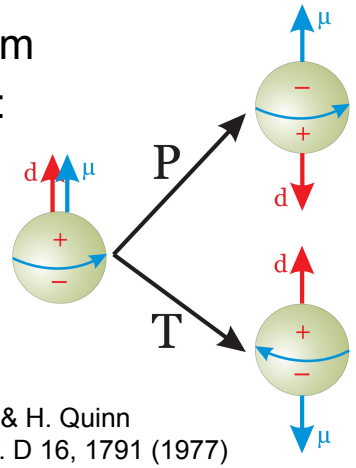

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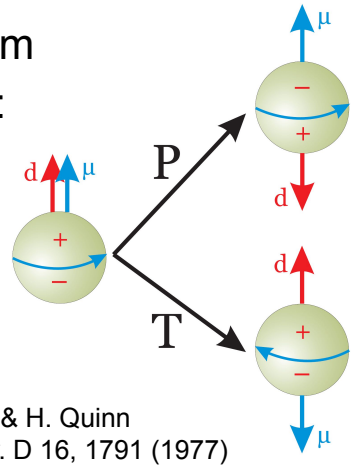

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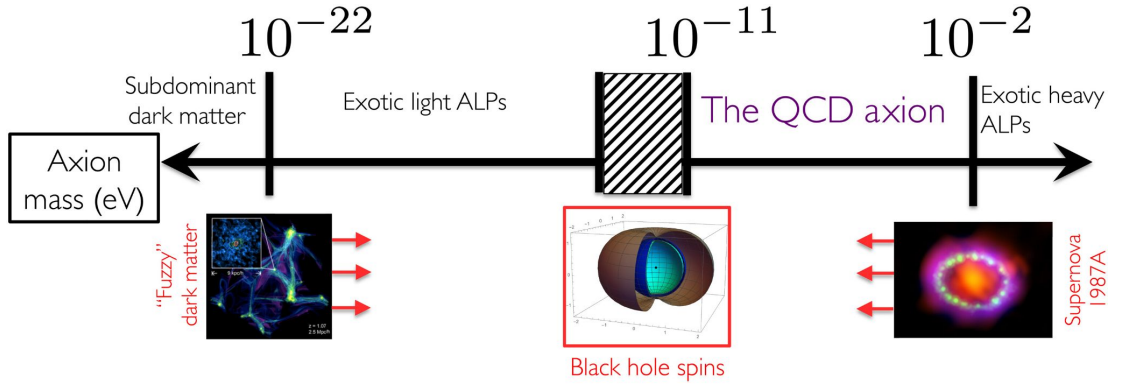

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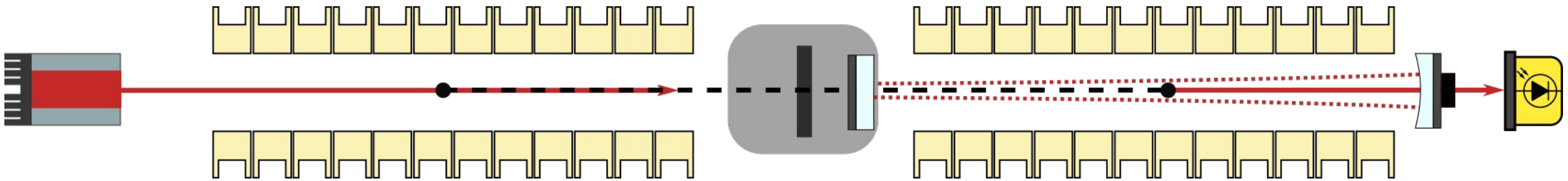
Todd Kozlowski

ALPS II: Status and Next Steps

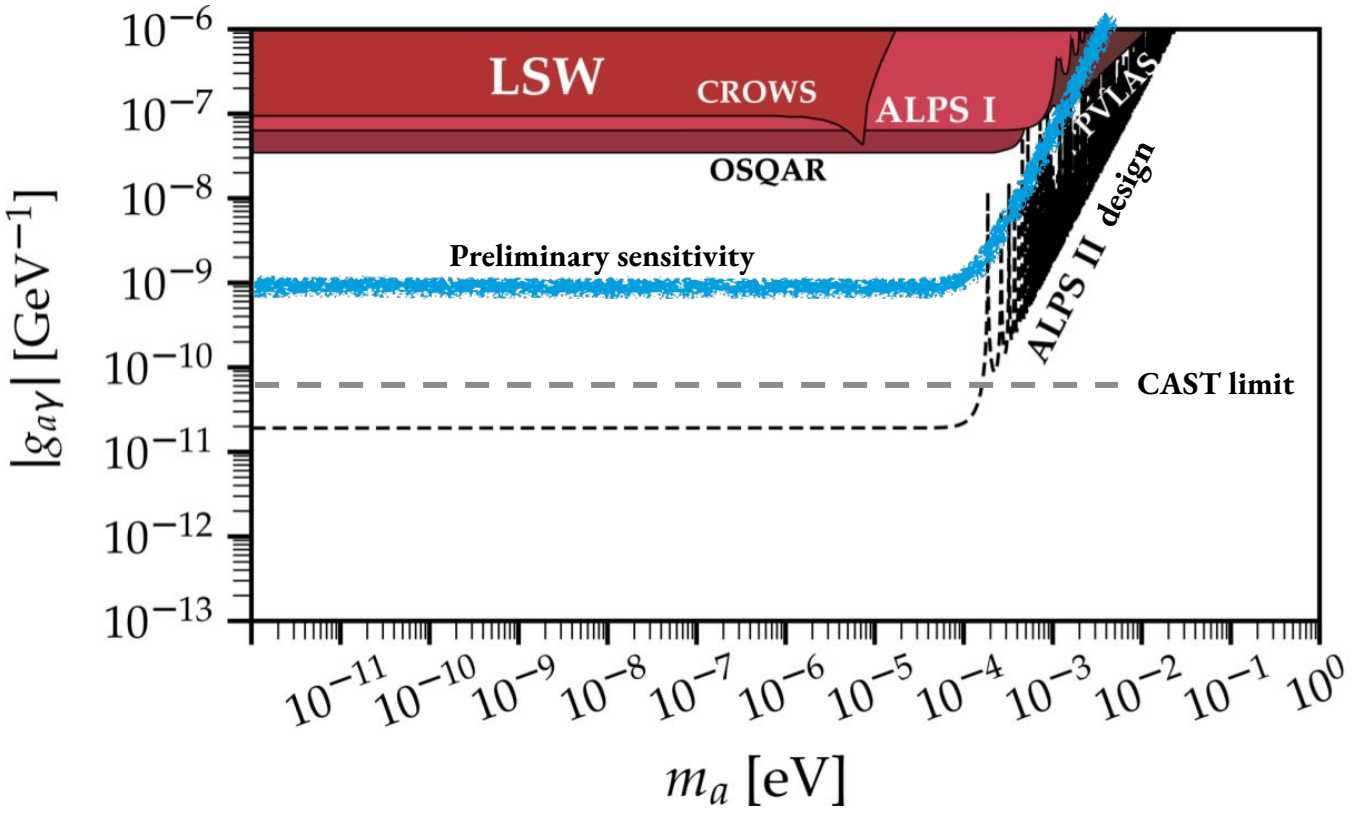


Status:

- first search for (pseudo)scalars 26.01 - 05.05.2024
- factor 30 better coupling sensitivity and 1,000,000 better signal rate than previous LSW experiments

Next steps (2025-2027, PoF IV):

- installation of production cavity to increase signal rate by a factor of 3,000
- upgrade cavity optics to further improve sensitivity



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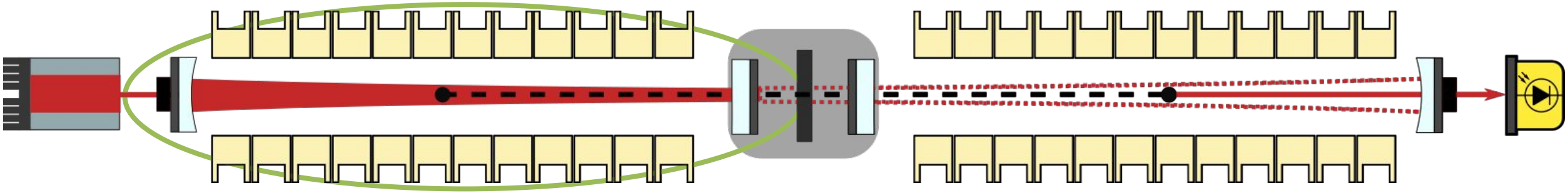

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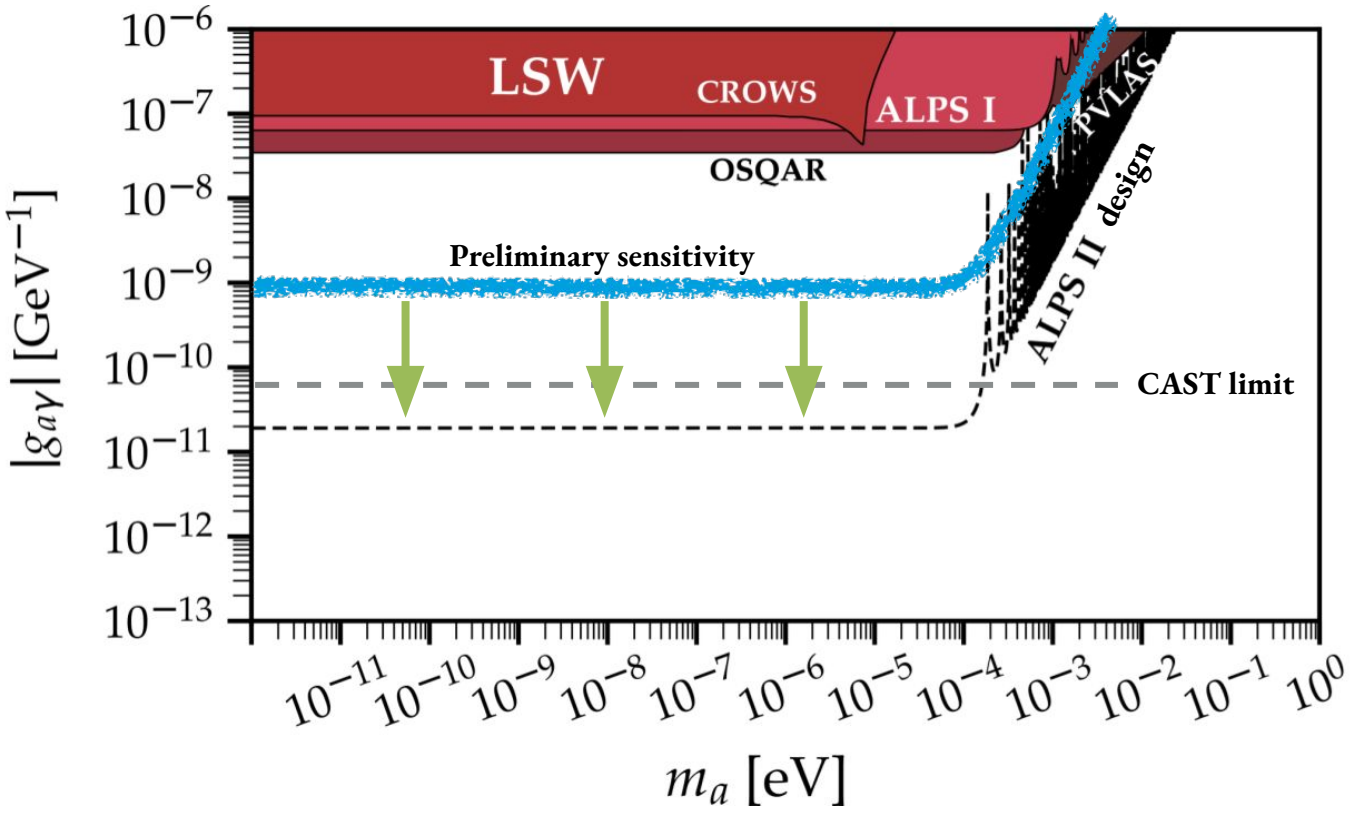


ALPS II Follow-up: Vacuum Magnetic Birefringence

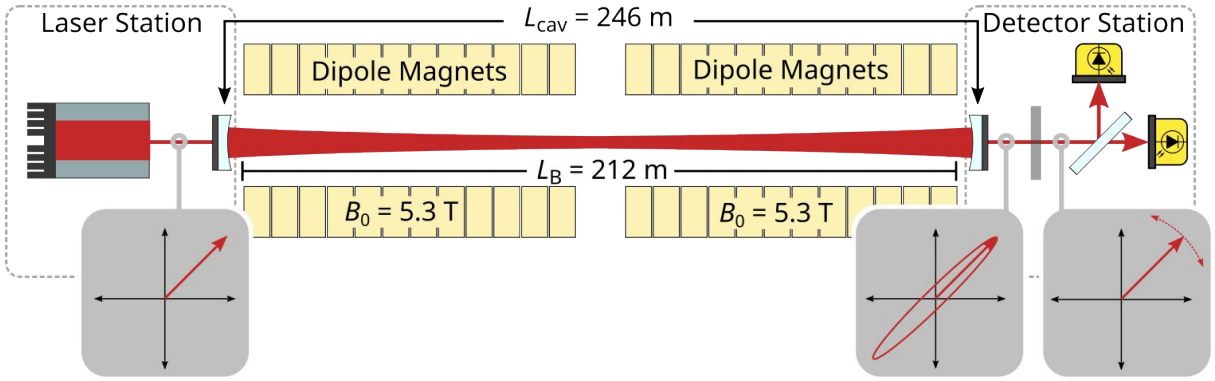
- 90-year-old prediction of quantum electrodynamics [1]
- in a magnetic field, the vacuum becomes birefringent:

$$\Delta n^{(\mathrm{VMB})} = n_{\parallel}^{(\mathrm{VMB})} - n_{\perp}^{(\mathrm{VMB})} = 3A_e B_{\mathrm{ext}}^2$$

- achieving sensitivity to the predicted value for the VMB:
  - definite test of the Born-Infeld model [2]
  - probes the dark sector [3]

- VMB effect strength on the phase of light $\propto$ B^2L

Experiment	L_B	$\Delta B^2 L$
PVLAS	1.6 m	10 T^2m
BMV	0.14 m	5.8 T^2m
ALPS II	**212 m**	**6000 T^2m**



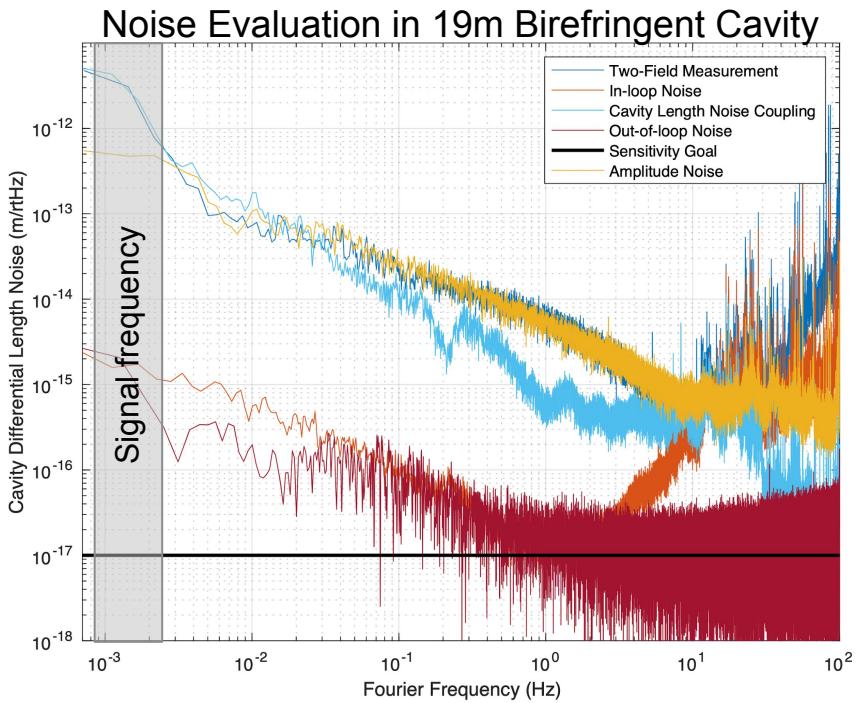
- relative phase shift between polarizations increased using an optical cavity [4]

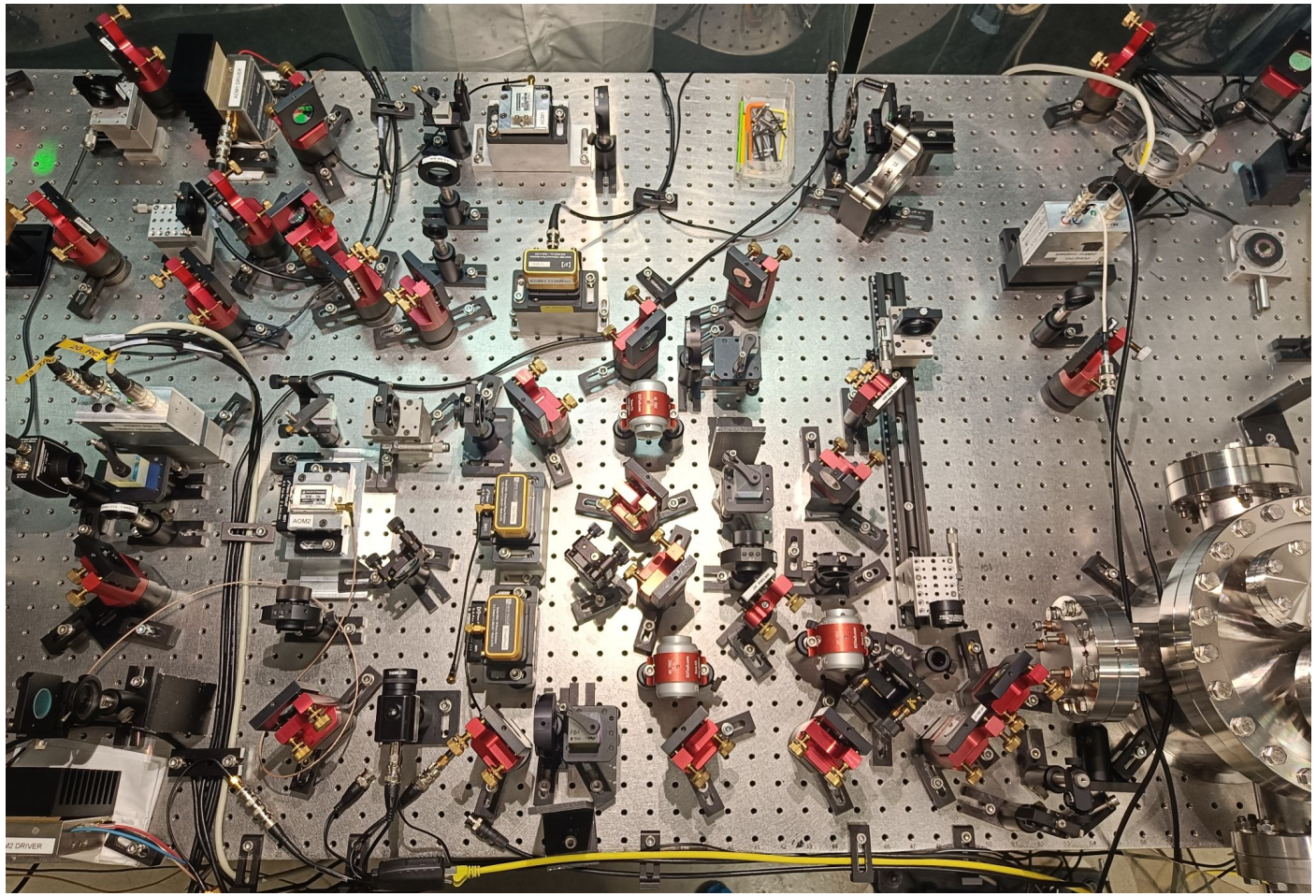
1. Euler and Kockel, Naturwissenschaften 23, 246–247 (1935)
2. Kadlecova, J. Math. Phys. 85, 012302 (2024)
3. Fan et al., Prog. Theor. Exp. Phys 6, 063B06 (2018)
4. Ejlli, et al., Physics Reports 871, 1-74 (2020)

ALPS II Follow-up: Vacuum Magnetic Birefringence

Development of a novel measurement scheme

- precision laser frequency / phase metrology
- based on a scheme proposed by *Hall et al.*
- evaluation of a 19m, low-loss optical cavity

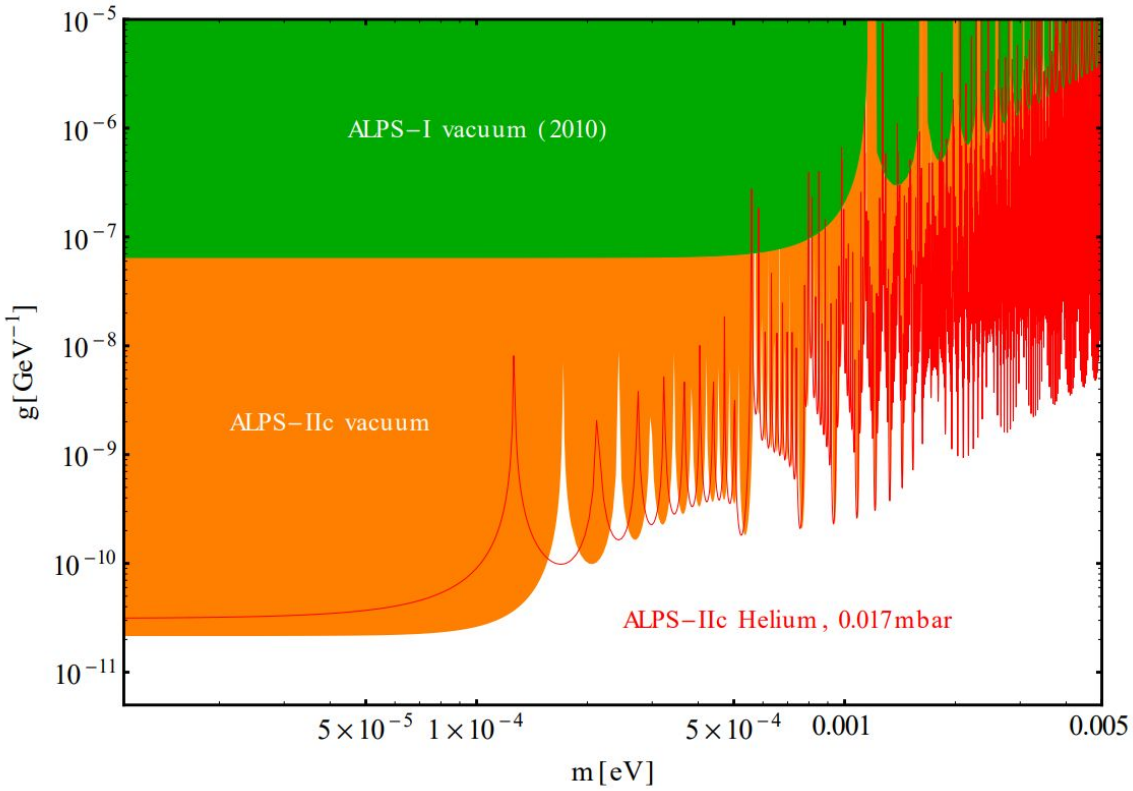




ALPS II Post-discovery potential: Expanding the parameter space

- essential to keep the ALPS II infrastructure in a “ready state” model-independent follow-up / verification
- only experiment which could give an exact coupling strength

- injecting inert gas can extend the accessible axion mass range of ALPS II in the case of a positive result from another experiment



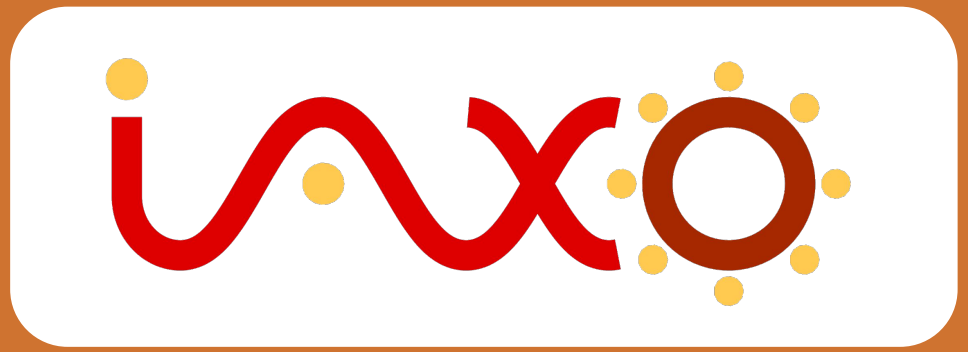
ALPS II reaches full sensitivity

VMB search in ALPS II infrastructure

2025 **2027** **2029** **2031**

19m Birefringence Lab R&D

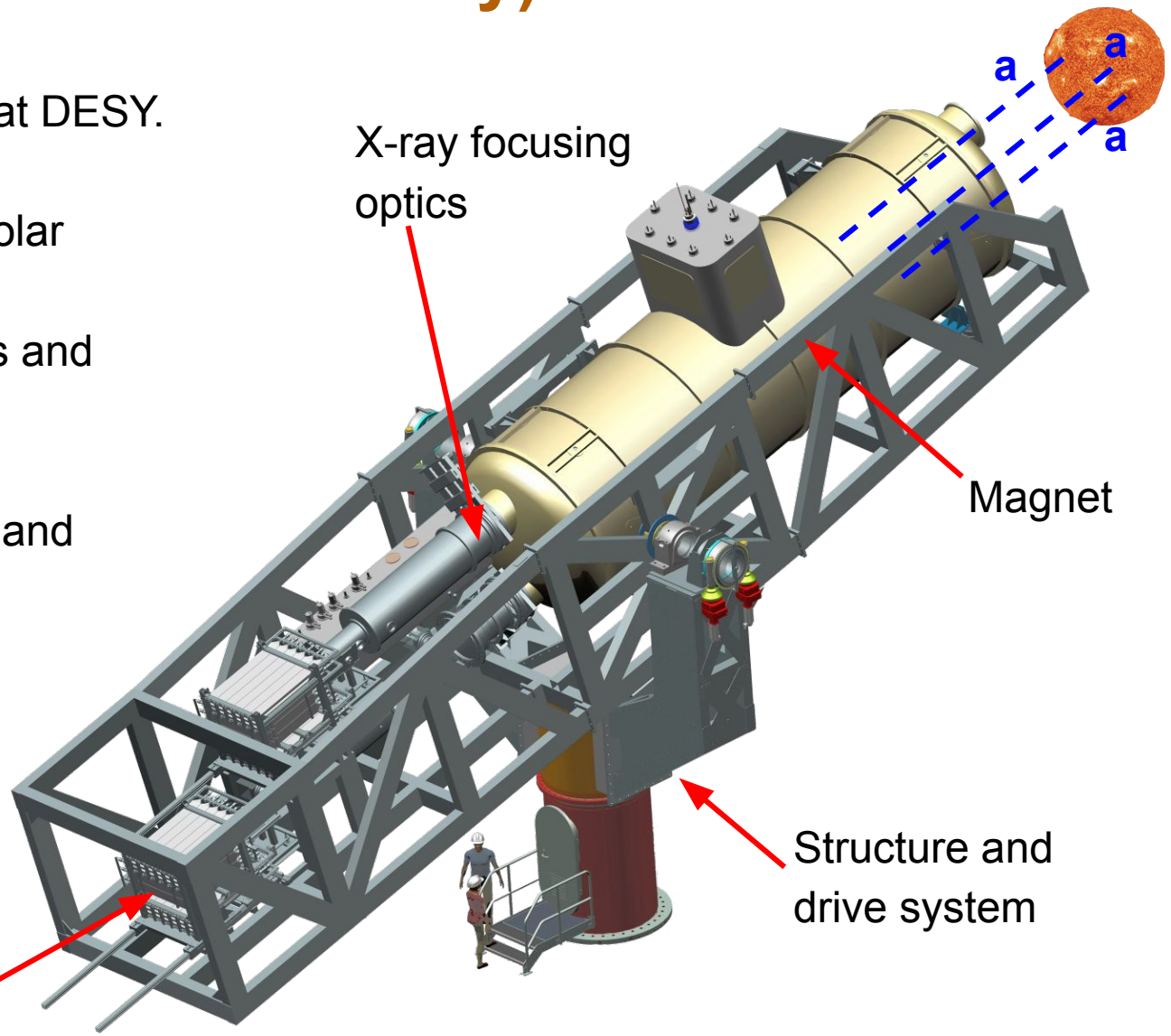
High-frequency gravitational waves / interferometric dark matter searches



Daniel Heuchel

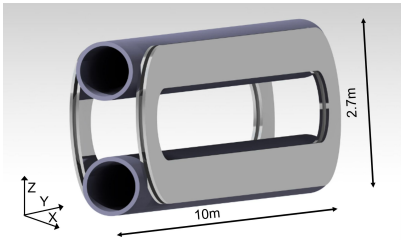
BabyIAXO (International AXion Observatory)

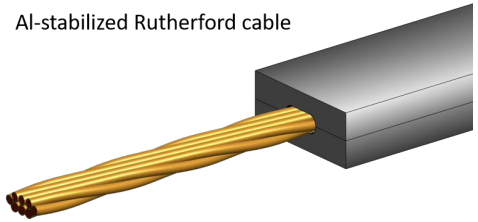
- The next generation state-of-the-art helioscope at DESY.
- Technological prototype for IAXO
- Sensitivity figure of merit: **~100x** CERN Axion Solar Telescope (CAST)
- Fully fledged helioscope to discover solar axions and more.
- Total cost: 19.8 M€.
- IAXO collaboration: 22 international universities and institutes from 10 countries.



BabyIAXO: Status and Timeline

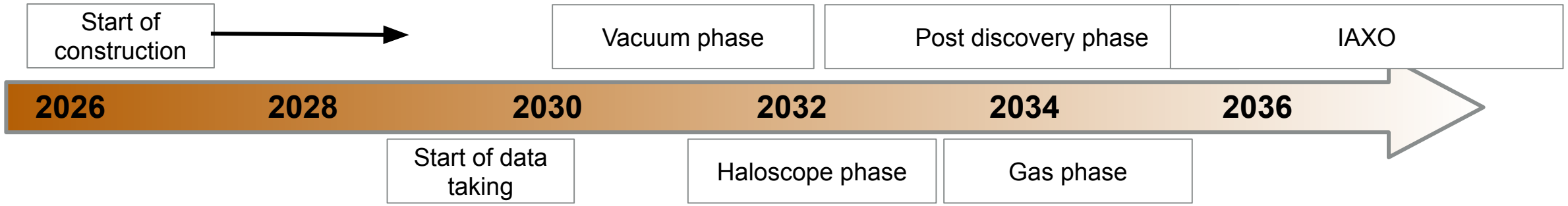
- Significant technical progress over last years
  - e.g. overall positive magnet review recently.
  - BabyIAXO ready to be constructed!





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

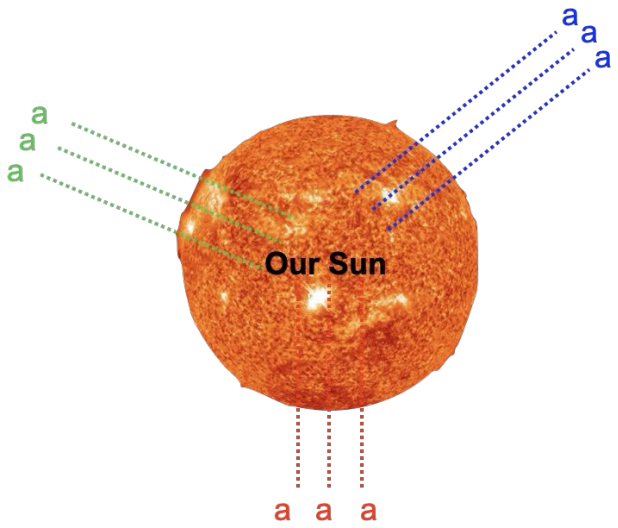
- Important funding milestones over the last years
  - ERC synergy grant “DarkQuantum” by I. Irastorza et al.
  - Excellence clusters Quantum Universe II and Color meets Flavor.
  - Next: DFG Forschungsgroßgeräte proposal.

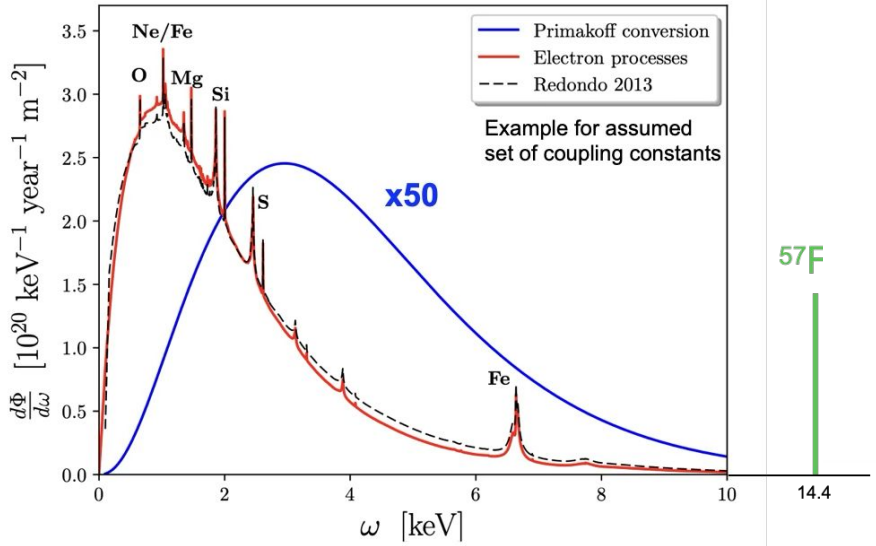


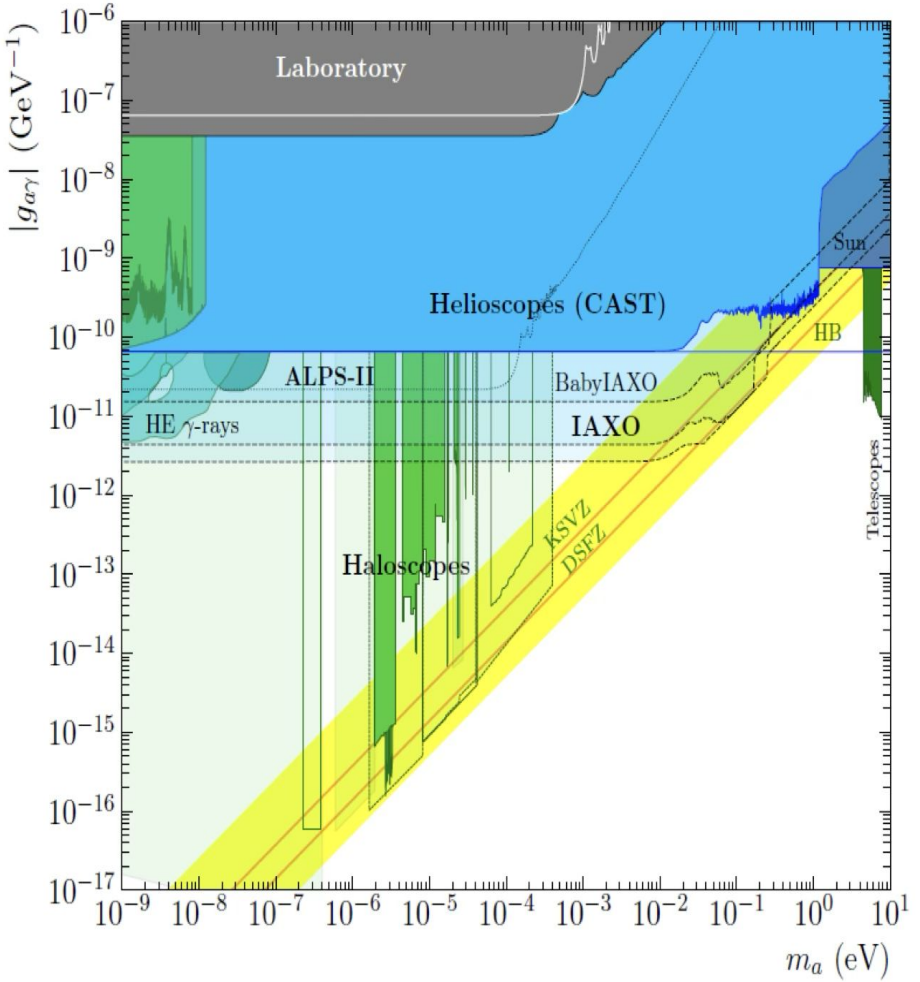
BabyIAXO: Going beyond Solar Axion Discovery I

- BabyIAXO will not only test uncharted parameter space exceeding ALPS II sensitivity (opportunities: comparison $g_{a\gamma\gamma}$, reach QCD band, probe lightweight axions).

- Helioscope have a unique physics case: by measuring energy spectrum access to different axion coupling constants (and mass).
  - Narrow down on BSM model!



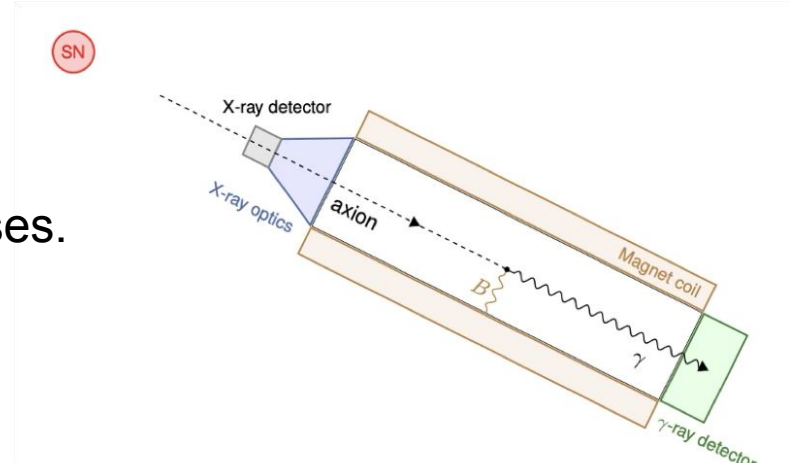




IAXO collaboration. *J. High Energ. Phys.* **2021**, 137 (2021)

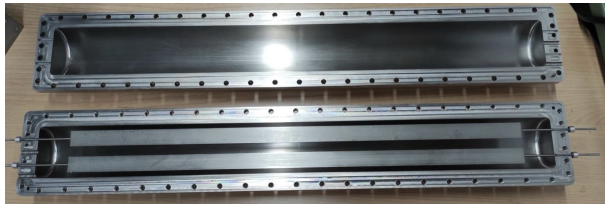
BabyIAXO: Going beyond Solar Axion Discovery II

- BabyIAXO features even more diverse physics case.
  - Solar physics (metallicity-, T- and B-mapping).
  - Search for supernova axions and axions from solar fusion processes.
  - High frequency gravitational waves.
  - Scalar or pseudo-scalar nature of particle.

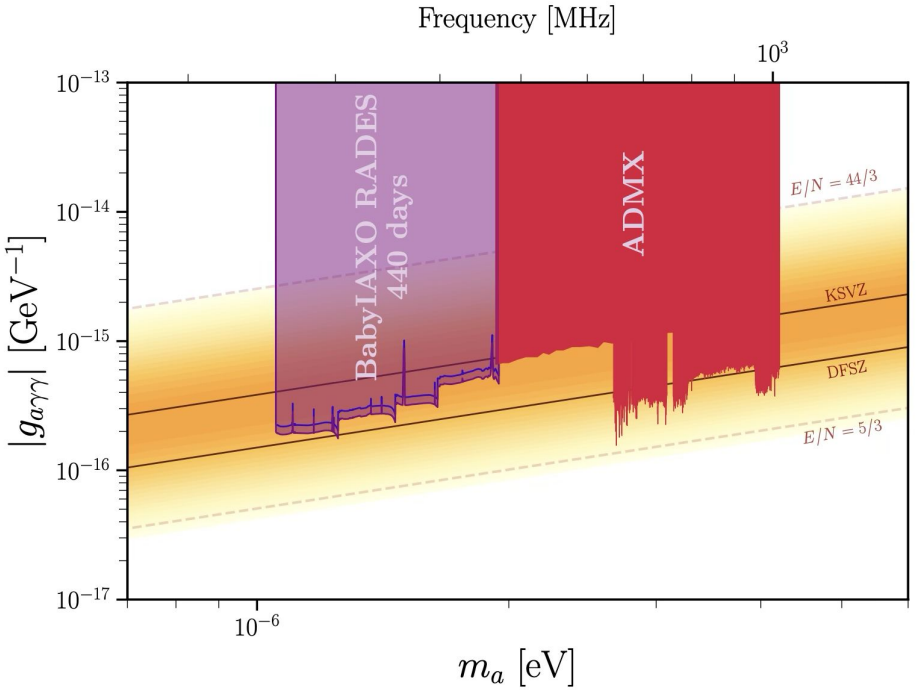


- BabyIAXO's dipole magnet will be used for dark matter searches.
  - Multi-use of infrastructure.
  - RADES haloscopes employing quantum sensing technologies.

Supported by ERC synergy grant DarkQuantum by I. Irastorza et al.



RADES-BabyIAXO Prototype




MAD MAX

Jacob Egge


DESY.
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UH
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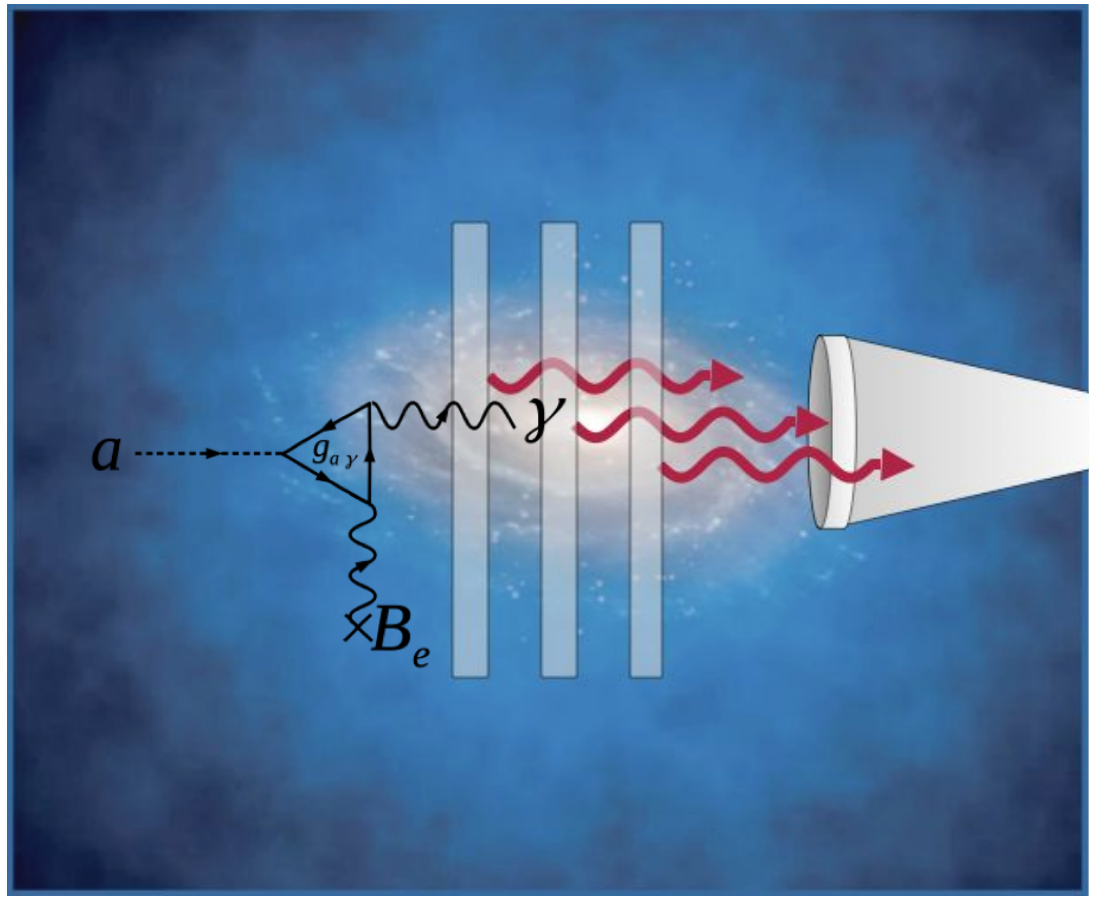
MADMAX: Dielectric haloscope



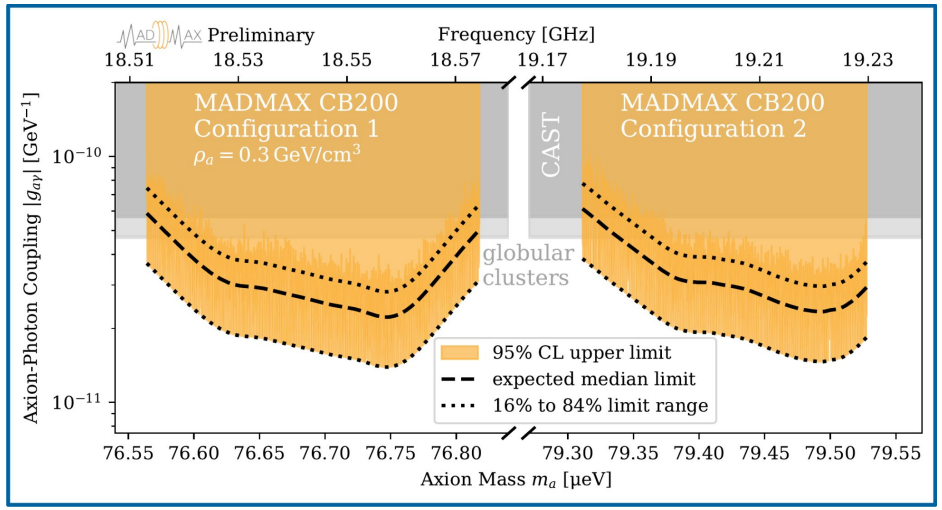
Concept

- Build a large resonator from many parallel dielectric disks
- 10 - 100 GHz
- Size of detector less dependent on wavelength
- $P_{sig} \propto V_{eff}$
- Effective volume **$O(10^6)\ \lambda^3$**
- RADES & other cavity haloscopes~10 λ^3

Current status and results

Axion run at CERN

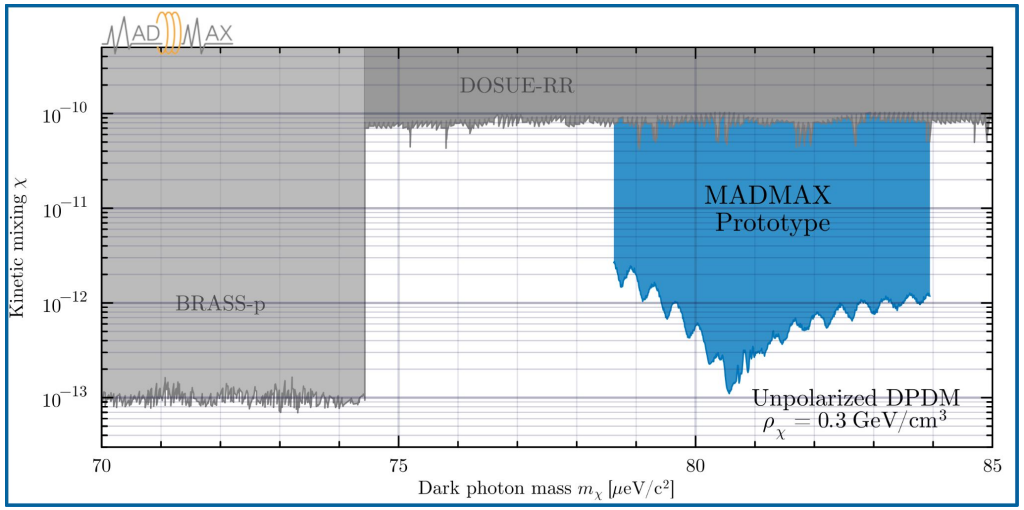
- 3 Disks, 200 mm diameter
- 1.5 T magnet
- effective volume ~200 λ^3



arXiv:2409.11777v1

Dark photon run at DESY/UHH

- 3 Disks, 300 mm diameter
- Without magnet
- effective volume ~500 λ^3

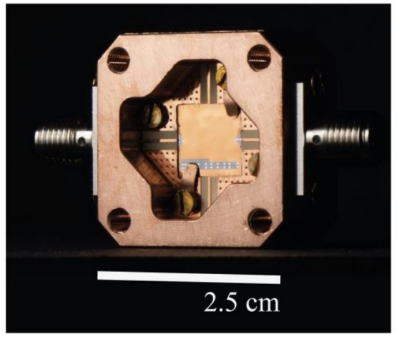


PhysRevLett.134.151004

Next steps: Reducing backgrounds

MADMAX Prototype Cryostat

- Reduce noise by going to cryogenic temperatures ~ 4K
- Cryostat on DESY campus right now
- Able to host current and future prototypes



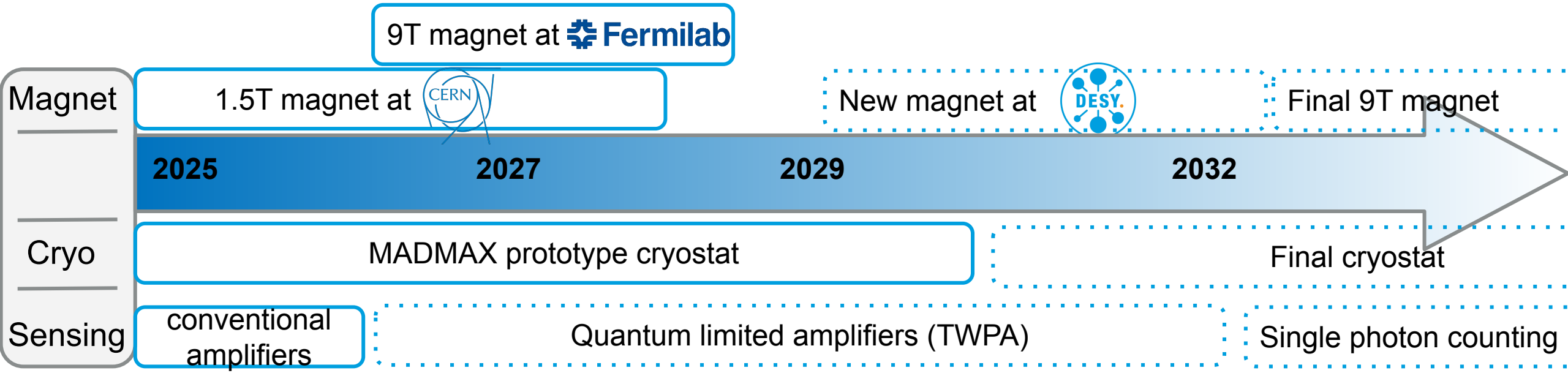
Quantum sensing

- Effective temperature due to standard quantum limit (SQL):
- ~0.5 to 5K (10 to 100 GHz)
- (Near) **quantum limited sensing**:
  - development of high frequency TWPA quantum amplifiers (Neel)
  - DarkQuantum ERC synergy grant
- Increasing operating frequency is a key research focus for **quantum technologies**
- Single photon detection to bypass SQL

Project timeline

MADMAX magnet

- Dedicated dipole magnet for MADMAX as early as 2029
- On DESY campus
- Cryostat+Magnet: strong platform for other axion experiments



The most exciting outlook

The **low energy, high precision** frontier will change in the next decade

- **Technological breakthroughs** (e.g. quantum sensing) can dramatically enhance sensitivities
- New astrophysical/cosmological **discoveries** could happen:
  - PTAs could find GW background due to cosmic phase transitions
  - DESI could confirm dynamical dark energy
  - New CMB observations could confirm cosmic birefringence
  - Large scale surveys could find signatures of wavelike dark matter
  - GW observatories could find evidence for black hole superradiance
  - A discovery by one the many world-wide axion experiments
- **Axions or other ultra light particles** could be involved in all of the above

We should be prepared with the right **infrastructure** and **key technologies**

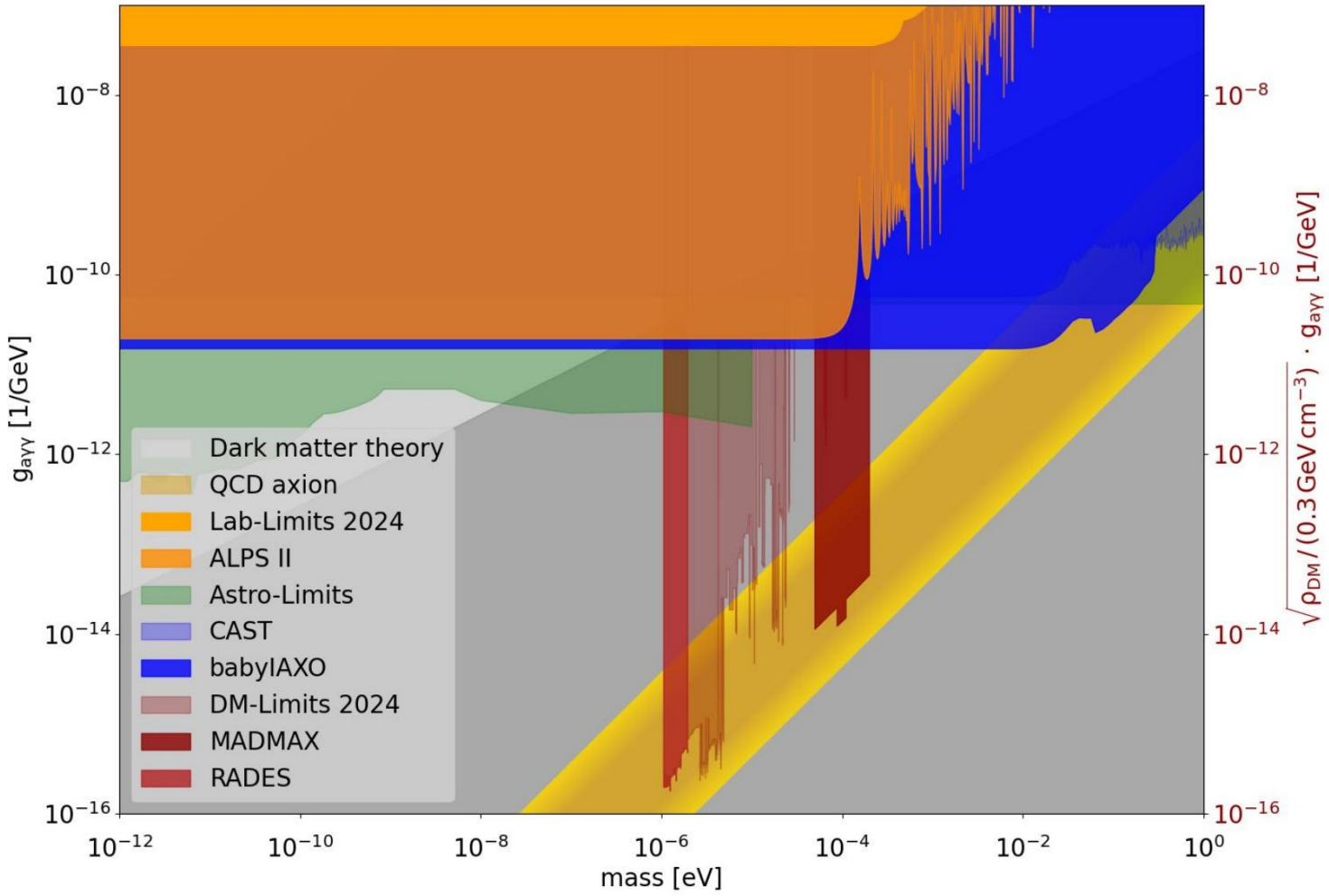
- **Complementarity** between ALPSII, BabyIAXO, MADMAX
  - Sensitive to different sources, different mass ranges
  - Axion astronomy
- High precision sensing from **microwaves to x-rays**
- Upcoming infrastructure (magnets+cryostats) offer many opportunities for axion experiments

ALPS II target sensitivity

MADMAX target sensitivity

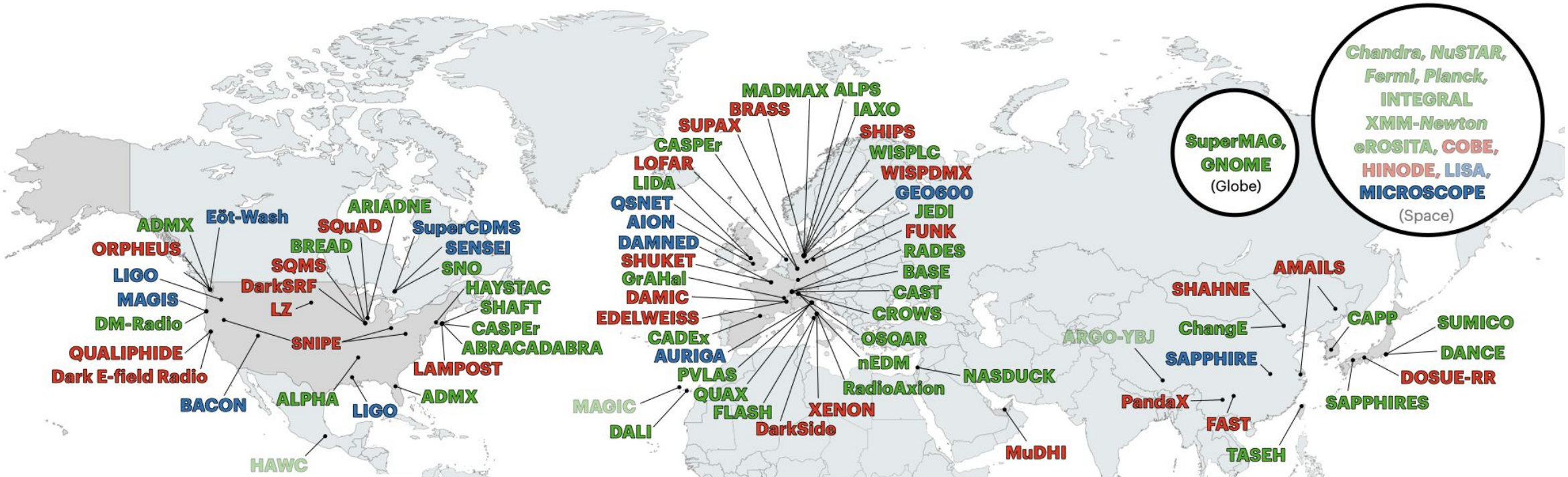
RADES target sensitivity (using the BabyIAXO magnet)

BabyIAXO target sensitivity



In case of discovery:

- **ALPS II:** Directly measure photon coupling
- **IAXO:** Study the cores of stars, axion astronomy
- **MADMAX:** Detect dark matter, probe the early universe


MADMAX
ALPS
BRASS
IAXO
SUPAX
SHIPS
CASPEr
WISPLC
LOFAR
WISPDMX
LIDA
GEO600
QSNET
JEDI
AION
FUNK
DAMNED
RADES
SHUKET
BASE
GrAHal
CAST
DAMIC
CROWS
EDELWEISS
OSQAR
CADEx
nEDM
AURIGA
NASDUCK
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RadioAxion
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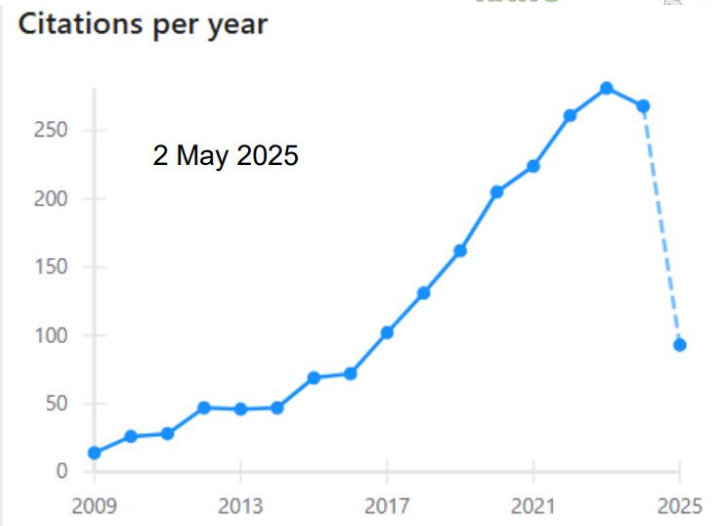
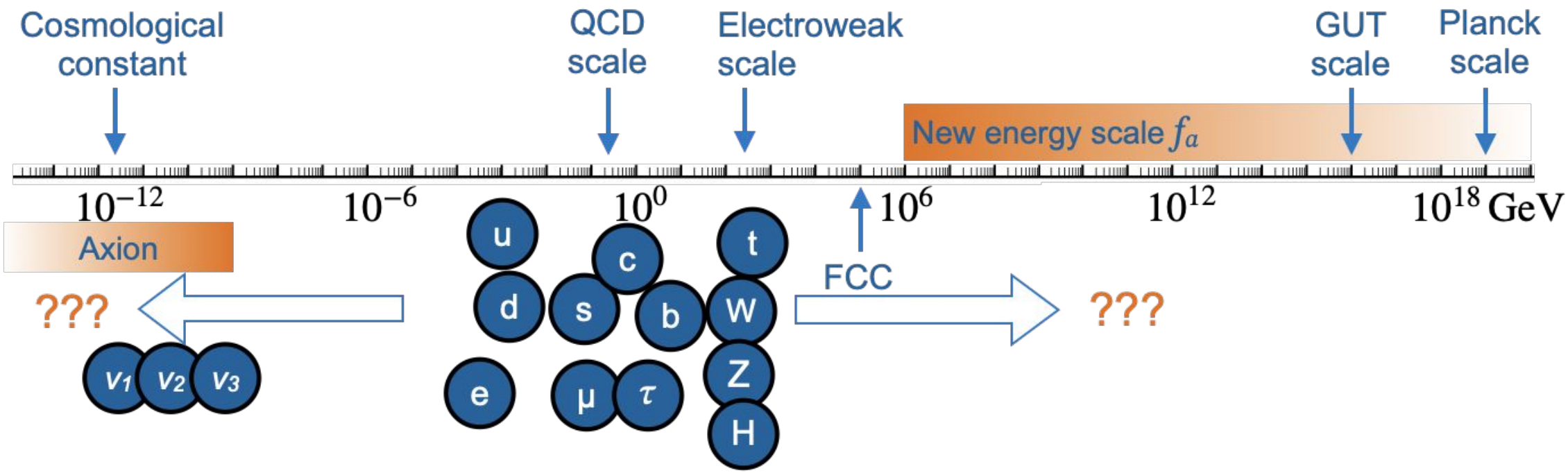
CASPEr
SNIPE
ABRACADABRA
QUALIPHIDE
LAMPOST
Dark E-field Radio
ADMX
BACON
ALPHA
LIGO
HAWC
SuperMAG,
GNOME
(Globe)
Chandra, NuSTAR,
Fermi, Planck,
INTEGRAL
XMM-Newton
eROSITA, COBE,
HINODE, LISA,
MICROSCOPE
(Space)
AMAILS
SHAHNE
CAPP
SUMICO
ChangE
ARGO-YBJ
DANCE
SAPPHIRE
DOSUE-RR
PandaX
SAPPHIRES
FAST
TASEH
POLARBEAR
VLT
(MUSE/VIMOS)
H.E.S.S.
SKA
SPT, BICEP
(Antarctica)
SKA
UPLOAD/DOWNLOAD
ORGAN
PPTA


Citations per year
2 May 2025
250
200
150
100
50
0
2009
2013
2017
2021
2025


Cosmological constant
QCD scale
Electroweak scale
GUT scale
Planck scale
New energy scale f_a
10^{-12}
10^{-6}
10^{0}
10^{6}
10^{12}
10^{18} GeV
Axion
???
FCC
???
ν_1 ν_2 ν_3
u
c
t
d
s
b
W
e
μ
τ
Z
H