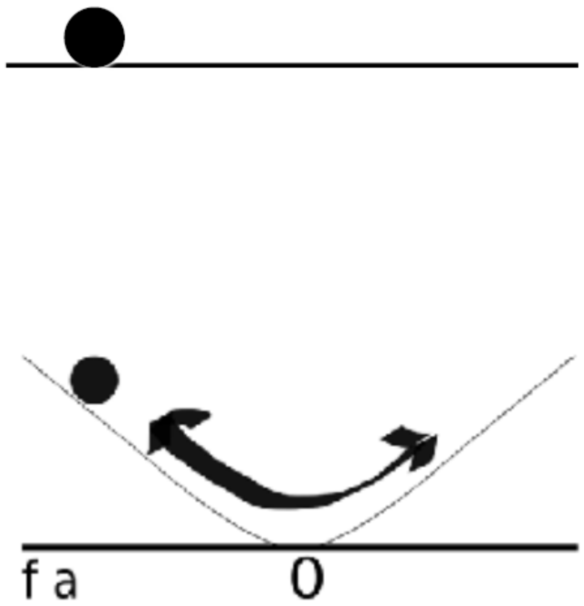
Axion/ALP search program introduction

APPEC Direct Dark Matter Detection Report
Community Feedback Meeting
February 2, 2021

Béla Majorovits
Max-Planck-Institut für Physik, München



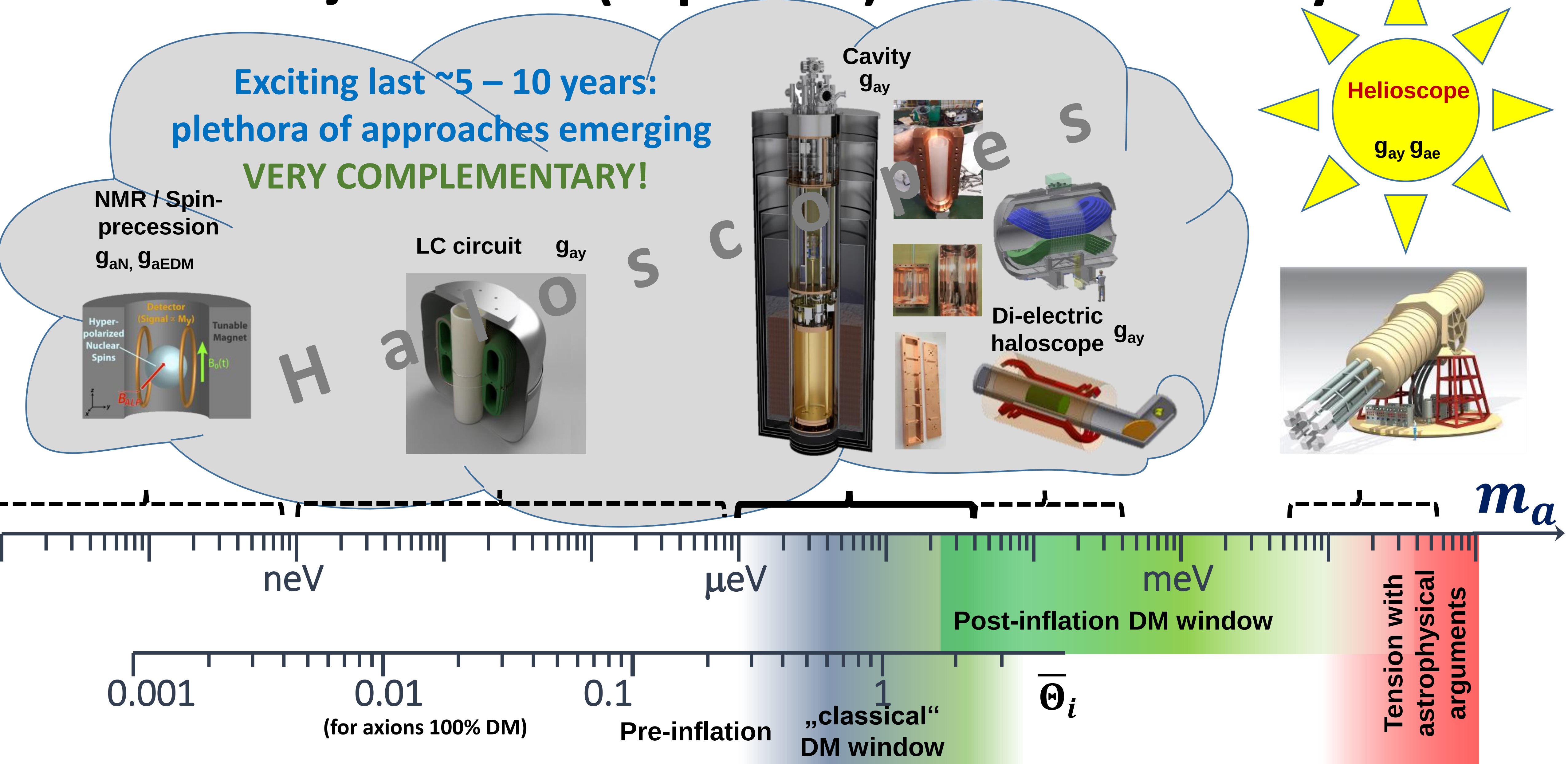
Laura, phsicist

Anna, 13

Ella, 11

Emöke, 6

Projects with (expected) axion sensitivity



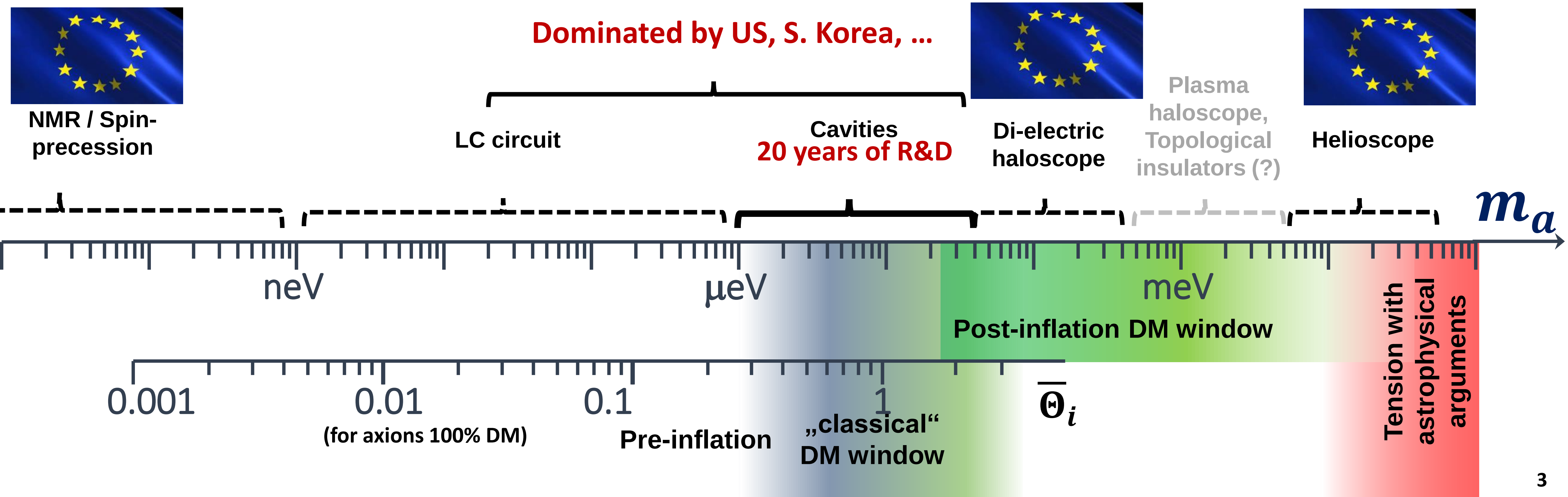
Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Axion experiments: next ~decade prospect:

Close the gap: haloscopes + helioscopes

cover whole axion mass range compatible with dark matter!

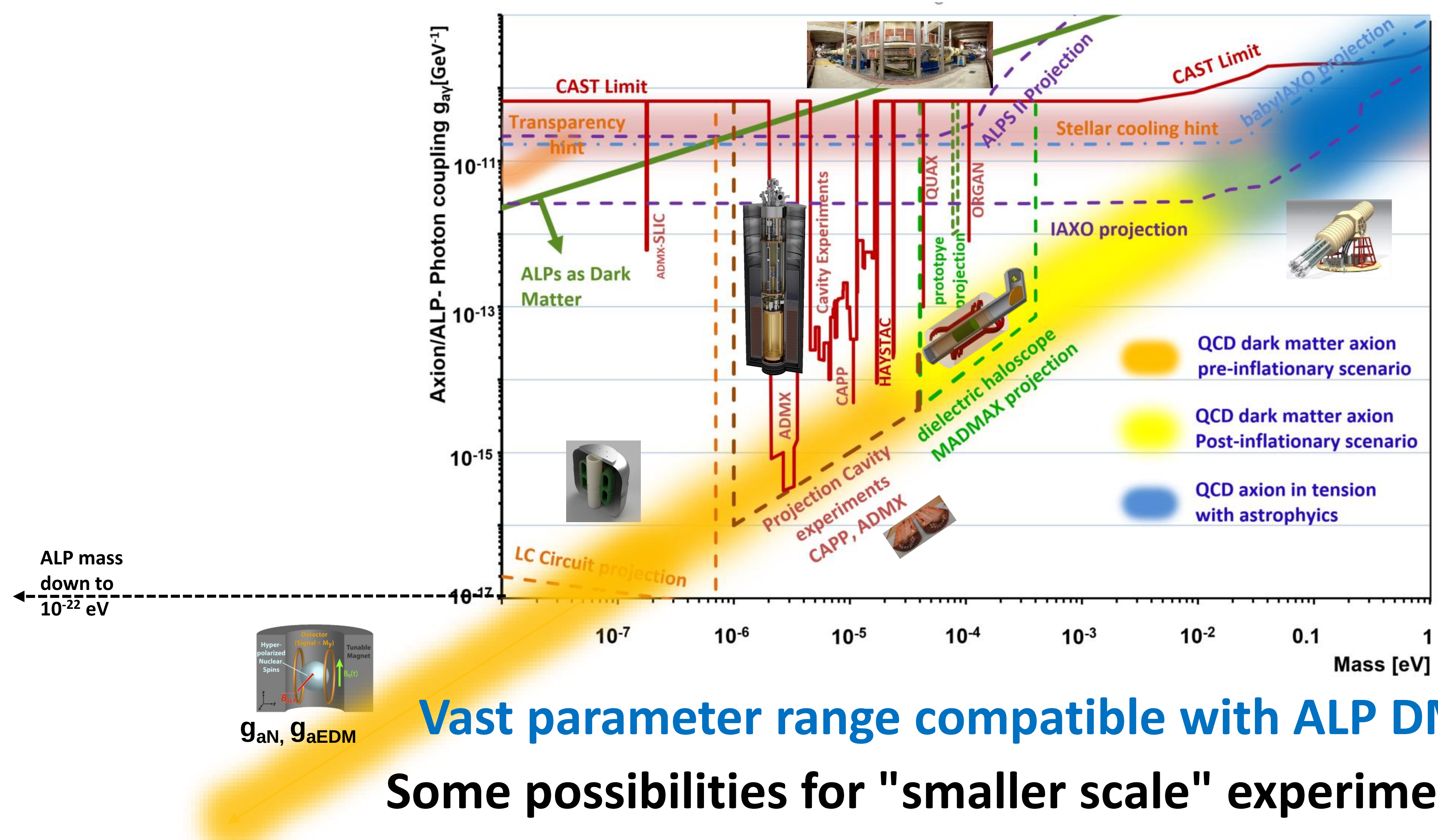
~ 10 orders of magnitude! → Find the DM axion!



Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Axion & ALP experiments

Axion search prototypes: very good ALP searches

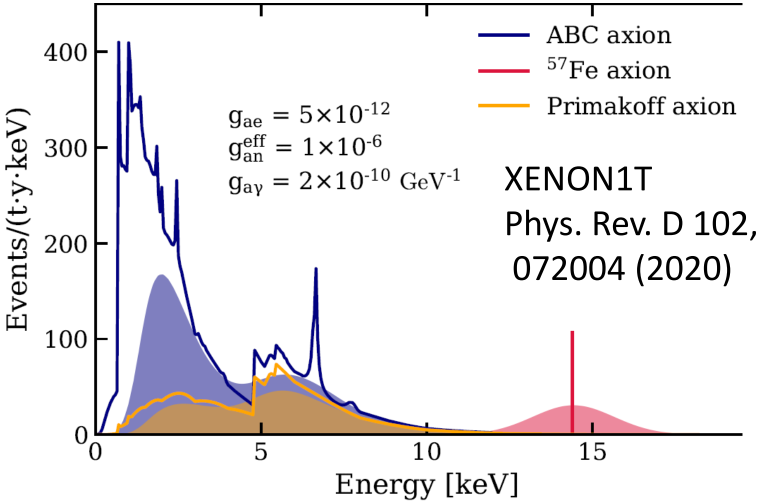


Vast parameter range compatible with ALP DM

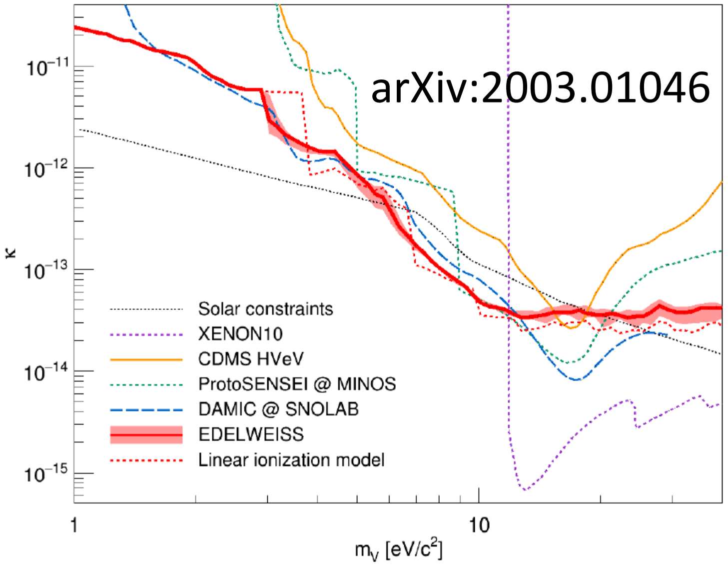
Some possibilities for "smaller scale" experiments

Sensitivity of "low background" experiments

Solar axions - **ALPs**



Hidden Photons



Sensitivity "for free" to

(solar) ALPs, Hidden Photon or Vector Boson dark matter with "high masses"

No QCD axion sensitivity

compatible with astrophysical observations

But: Independent limits for axions from sun!

Some ALP sensitivity:

Some "fine tuning needed" for g_{ae} vs $g_{a\gamma}$

Hidden Photons/Vector bosons:

sensitive to parameter range not yet excluded

DM & neutrino experiments: **sub eV thresholds**!

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

S W O T table axion, ALP and HP experiments

	Strengths	Weaknesses	Opportunities	Threats
haloscopes	can cover "classical" mass region in next decade(s)	DM abundace relies on cosmological models	profit from R&D on quantum computing	what if axions sub dominant DM contribution?
	partly already sensitive to QCD axion	high field magnets needed	straight forward to adapt to precise frequency	potentially supressed signal due to axion miniclusters
	precise mass measurement		possibility of transients	
	easy to switch off signal			
helioscopes	all required technologies available	signal not related to DM halo density	could carry payload experiment	non DM related signal could deviate efforts
	easy to switch off signal			
	senstivity to g_ae and g_aN			
LSW	no model dependence of ALP source	QCD axion not accessible	can soon cover astrophysical hints	
		not related to DM halo densitys	R&D synergies with other fields	
Low background	comes for free	not senstivie to QCD axion and large parts of ALP parameter range	exploitation of some new parameter range	
	can probe g_ae	not necessarily related to DM halo densitys		

Axions ALP HPs

ALP HPs

HPs

Experiment	Type	Techn.	$g\_$	Mass range	Status	Limits	Location	Timescale
Experiments with expected sensitivity to DM axion benchmark models								
CASPEr-e[a]	∅	NMR	aN	10^{-13} eV – 1 neV	R&D	ALP	BU	
DM Radio[b]	∅	LC	$a\gamma$	20 neV – 0.8 μeV	R&D	HP	Stanford	2025-30
ADMX[c]	∅	C	$a\gamma$	2 μeV – 40 μeV	running	**axion**†	UW	2017-30
HAYSTAC	∅	CS	$a\gamma$	15 μeV – 35 μeV	running	axion‡	Yale	2015-25
CULTASK	∅	SC/MC	$a\gamma$	3 μeV – 70 μeV	running	axion⋆	CAPP	2021-30
QUAX[d]	∅	SC/DC	$a\gamma$	30 μeV – 50 μeV	in prep.	ALP*	INFN	2021-25
MADMAX[e]	∅	DH	$a\gamma$	40 μeV – 400 μeV	prototype		DESY	2025-35[f]
ORGAN[d]	∅	DC/CS	$a\gamma$	60 μeV – 210 μeV	prototype	ALP	UWA	2025-35[f]
IAXO[g]	⊙	XR	$a\gamma, ae$	1 meV – 10 eV	in prep.		DESY	2023-35
ALP experiments								
CASPEr-w[a]	∅	NMR	ALPN	10^{-22} eV – 1 μeV	running	ALP	HIM/UCB	
GNOME	∅	NMR	ALPN	10^{-21} eV – 10^{-10} eV	running	ALP	global	2017-24
DANCE	∅	OC	ALPγ	$\lesssim 10^{-10}$ eV	R&D	ALP	Tokyo	
Up/Download	∅	MO	ALPγ	10^{-10} eV – 10^{-7} eV	prototype	ALP	UWA	
ABRA[b]	∅	LC	ALPγ	1 neV – μeV	in prep.	ALP	MIT	
SHAFT	∅	LC	ALPγ	$\lesssim$ 10 neV	R&D	ALP	BU	
ADMX-SLIC	∅	LC	ALPγ	$\lesssim$ 0.2 μeV	R&D	ALP	UFL	
ALPS II	$\mathcal{L}$	LSW	ALPγ	$\lesssim$ 0.1 meV	constr.		DESY	2021
RADES	∅	MC	ALPγ	∼30 – 50 μeV	R&D		CERN	
QUAX	∅	e^-S	ALPe	30 μeV – 80 μeV	R&D	ALP	INFN	2021-25
BRASS	∅	DA	ALPγ	1 μeV – 1000 μeV	in prep.		UH	2022-23
IAXO[g]	⊙	XR	ALPγ	$\lesssim$ 1 eV	in prep.		DESY	2025-35
Hidden photon experiments (no axion or ALP coupling)								
SHUKET	∅	DA	ϵ	20 μeV – 30 μeV	in prep.	HP	CEA	2024
FUNK	∅	DA	ϵ	2 eV – 8 eV	upgrade	HP	KIT	

+ low background experiments

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Recommendation 6: Axion/ALP experiments

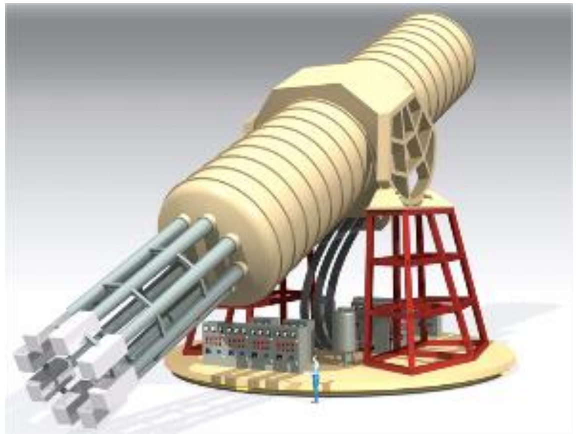
European-led efforts should **focus on axion and ALPs mass ranges** that are **complementary to the established cavity approach**

and this is where **European teams** have a **unique opportunity to secure the pioneering role** in achieving sensitivities **in axion/ALP mass ranges** not yet explored by experiments conducted elsewhere.

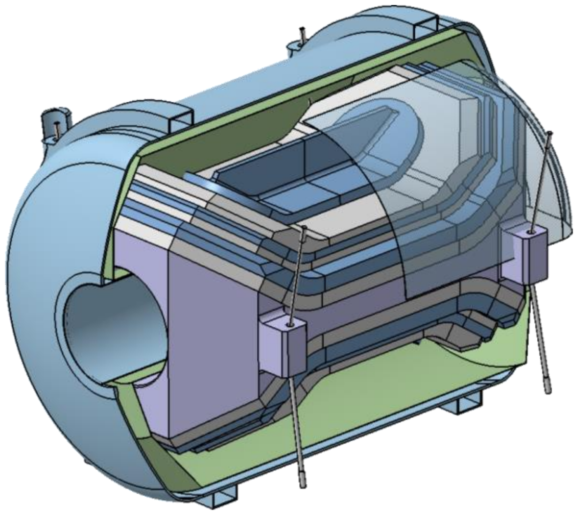
In parallel, **R&D efforts to improve experimental sensitivity** and to extend the accessible mass ranges should be supported.

Technologies

Magnets



IAXO magnet: based on existing **CERN technology** from accelerator magnets



MADMAX dipole magnet: being developed in terms of **EU-innovation partnership** between MPP, Bilfinger-NOELL and CEA-Irfu Sacly

Development of **strong (dipole) magnets paramount** for reaching goal of **covering axion DM mass range**

Main challenges:

- **Huge superconducting dipole magnets large stored energy** (helioscopes, dielectric haloscopes, dish antenna) → **Infrastructure**
- **Solenoids (cavity experiments)**

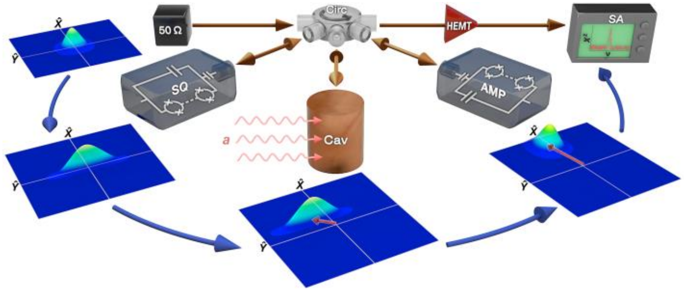
Potential **synergies:**

- **accelerator magnets,**
- **medical physics,**
- **fusion reactors,**
- some aspects of solid state physics,
- …

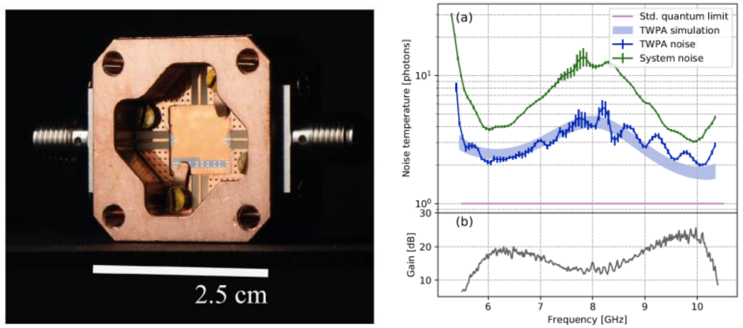
Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Technologies

Photon detection



HAYSTAC: squeezed statesarXiv:2008.01853



MADMAX TWPA arXiv:2101.05815

Improve detector sensitivity
→ increases mass range that can be covered in given time

Main challenges:

- **quantum detectors** (frequency < 100GHz):
  with broad bandwidth (JPA, TWPA)
  or beat quantum limit by squeezing
- **Single photon detectors** (frequency > 10 GHz):
  extremely low threshold, low background: (QMONs, TES)

Potential **synergies:**

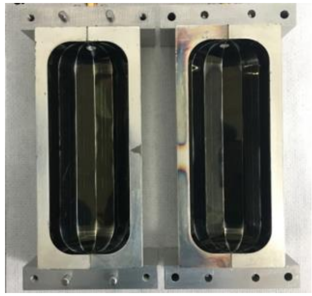
- **Quantum computing**
- **neutrino experiments & other light DM searches**
- …

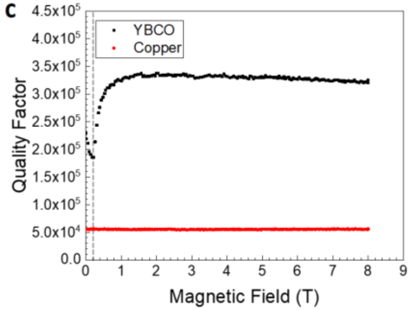
Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Technologies

Low loss dielectrics for **MADMAX** arXiv:1901.07401

Photonic crystal **QUAX** arXiv:2002.01816





Superconducting cavities: **CAPP** arXiv:2002.08769

Low loss dielectrics and cavities

Minimize RF losses in cavities/booster, etc.
→ maximize signal

Main challenges:

- Grow large **single crystals** or produce **amorphous materials** low enough dielectric loss (tan delta)
- Develop suitable **superconducting cavities,**
- Develop **meta-materials**
  (plasma haloscope – topological insulators)

Potential **synergies:**

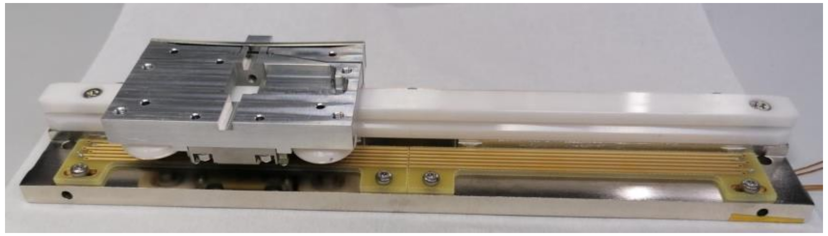
- **Radio astronomy**
- **Quantum computing**
- **RF engineering – telecommunication**
- **…**

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Technologies

Cryogenic precision engineering in B-field

JPE
Driven by innovation



Piezo linear stage developed for **MADMAX** by https://www.jpe-innovations.com/

Contact made by: Technology forum APPEC

Precision displacement with large stroke at low temperature & strong B-field surrounding
tune frequency , minimizing noise, maximize signal

Main challenges:

- Precision machining of large objects
- Precision displacement at extreme conditions
- Macroscopic stroke at cryogenic temperature
- Reliability

Potential **synergies**

- **Cryo-electron microscopy**
- **Gravitational wave detectors**
- **Precision displacement technology in general**
- **…**

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Infrastructure
for experiments with axion sensitivity

Infrastructure for projects with QCD axion reach:

similar **to particle physics – accelerator R&D** needs:
space in **well-equipped large (enough) experimental halls**
with good **cryogenic infrastructure**

Necessary boundary conditions:

- operation of **large aperture superconducting magnets**,
- operating **ultra-sensitive quantum detectors**,
- **minimize** (thermal) **RF noise & stable ground** in detector surrounding.

MORPURGO magnet at CERN

ALPSII at DESY

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Infrastructure

for axion & ALP experiments

Projects benefit from lab vicinity with world-leading knowledge:

- accelerator technology,
- superconducting magnet R&D,
- detector research,
- low loss RF-technologies,
- cryogenic engineering.

Very strong players in 

CERN DESY. cea KIT Karlsruher Institut für Technologie INFN Istituto Nazionale di Fisica Nucleare MAX PLANCK GESELLSCHAFT ....

+ top universities

Benefit of support of large European and national labs demonstrated: e.g. by CAST & OSQAR experiments at CERN and ALPS at DESY

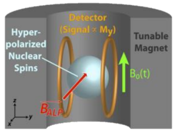
Potential of fundamental discoveries with small(er) scale experiments

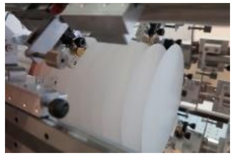
Opportunities for research program complementary to large scale - for example accelerator - projects

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Concluding words:

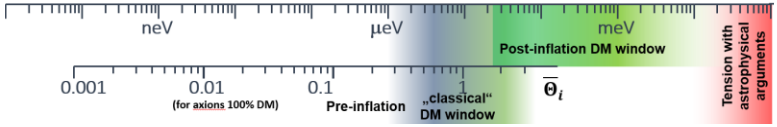
- **Axions** naturally emerge as **excellent DM candidate** from natural solution to standard model strong CP problem



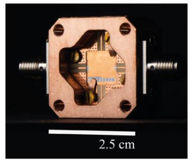


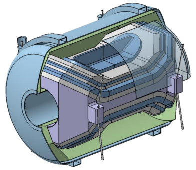
- Last decade: **new innovative initiatives - many within EU**:
  → possibility to **cover full mass range** by complementary efforts!
  → tentatively **high probability of success**!

- **Unique possibility for European community** to take leadership in covering significant part of well motivated mass range!

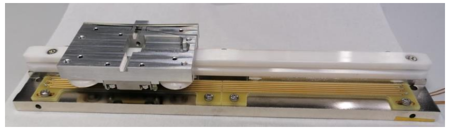


- Challenging **technologies to be developed** within axion community but also outside!





- DESY becoming **"axion hub"**?
- EU **has all prerequisites** to find axion in **next ~ decade** and **solve the DM puzzle**!



- **Cross fertilization** between EU INDUSTRY & Scientific research!

Lets take the opportunity, acquire the resources and DO IT ….