Searches for axion dark matter

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On Behalf of the following contributors:

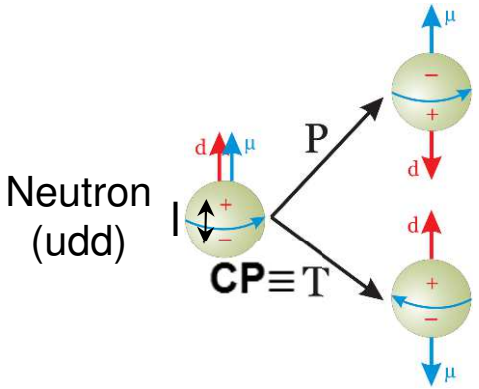
https://indico.in2p3.fr/event/19776/contributions/75431/ (MADMAX - F. Hubaut *et al*)
https://indico.in2p3.fr/event/19776/contributions/75425/ (GrAHal - T. Grenet *et al*)
https://indico.in2p3.fr/event/19776/contributions/75434/ (BMV - C. Rizzo *et al*)

Thanks to all contributors for useful discussions

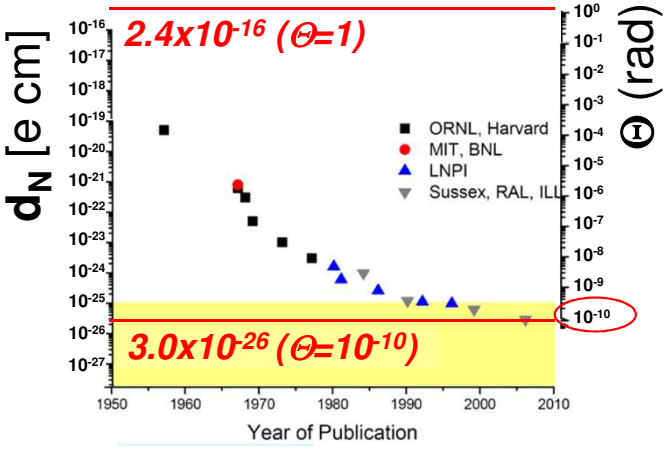
Prospectives IN2P3 - GT06, 28 october 2019

(Short) Theoretical motivations

- Studies of C,P, T symmetries in particle physics : major subject since >60 years
- CP violation in weak interaction: observed in 1964 in kaon system
  - ✓ Associated phase in quark-mixing CKM matrix measured ➔ δ_{13} ~ **1.2 rad**
  - ✓ Phase still to be measured in lepton sector (PMNS matrix) ➔ T2K, DUNE, Super-ORCA, …
- CP violation in strong interaction ?
  - ✓ CP-violating term in QCD Lagrangian (controlled by Θ) **is allowed and should exist**
  - ✓ … but **Θ < 10^{-10}** from neutron electric dipole moment



- Electric dipole moment: $d_N = e \cdot l$
- If strong CP : $d_N \sim \Theta \times 10^{-16}$ e·cm
- Experimental results today:
  → $d_N < 3 \times 10^{-26}$ e·cm → $\Theta < 10^{-10}$



➔ **Strong CP Problem = naturalness problem. Why is Θ so small ?**

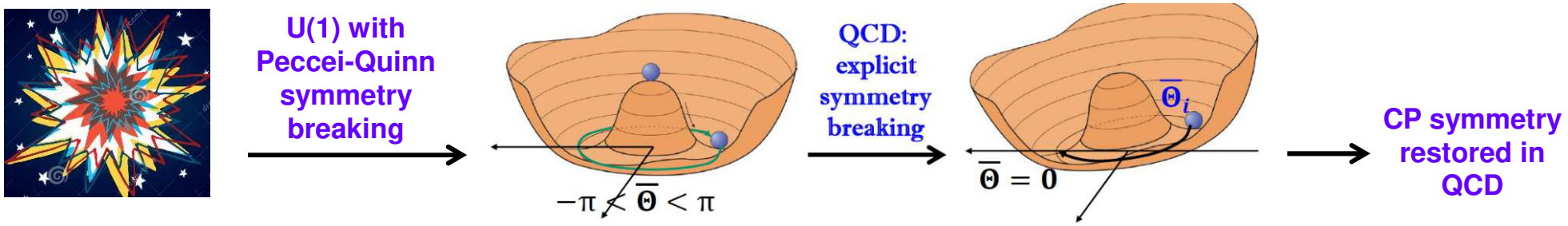
(Short) Theoretical motivations

❑ Solution to Strong CP problem ➔ Axion = motivated by particle physics

- Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale $f_a >> f_{EW}$
  - ➔ Makes Θ a dynamical field ($\Theta = a/f_a$), with a = pseudo-scalar boson
  - ➔ Suppress CP-violating term in Lagrangian ($\Theta_{eff} \rightarrow \Theta - a/f_a$) : explains absence of CP strong

- Consequence: Goldstone boson of the new theory = **axion** *(Weinberg-Wilczek, 1978)*
  - ➔ Properties are all known given the scale of symmetry breaking f_a [mass $\mathbf{m_a} \approx m_\pi f_\pi / \mathbf{f_a}$ << eV]
  - ➔ Couplings to SM particles suppressed by f_a : very weak interaction with SM

- Cosmology: Non-thermal axion production at $T \sim f_a$ *(can occur before or after inflation)*



➔ Axion = natural candidate for DM for m_a=1-10^3 μeV ***(i.e. $f_a = 10^{12}$ -10^9 GeV >> f_{EW})***

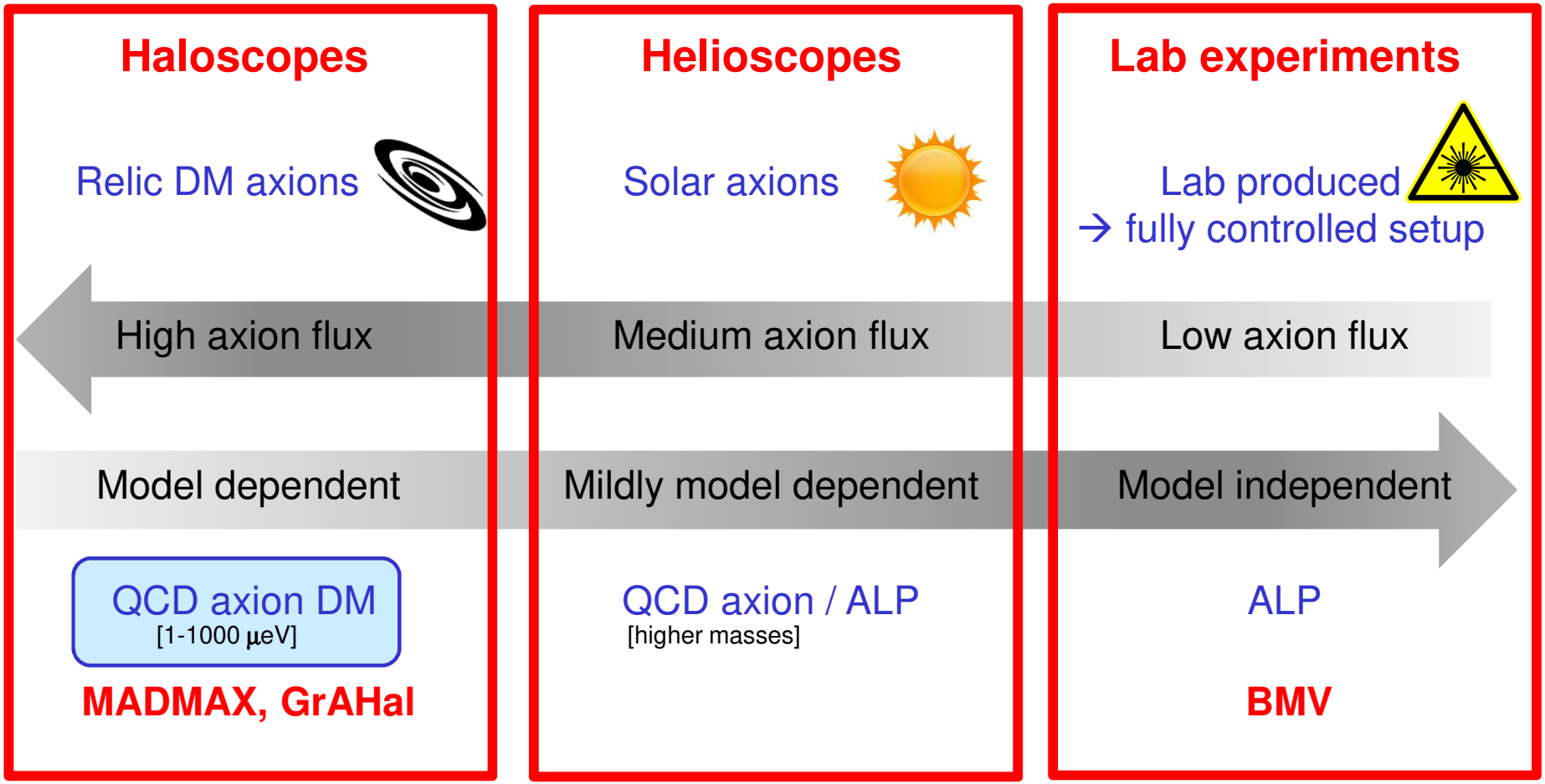
Remark: ALP (Axion Like Particle) = scalar not solving strong CP problem but potential DM candidate

Axion/ALP searches

Haloscopes	Helioscopes	Lab experiments
Relic DM axions 	Solar axions 	Lab produced  → fully controlled setup
High axion flux	Medium axion flux	Low axion flux
Model dependent	Mildly model dependent	Model independent
QCD axion DM [1-1000 μeV]	QCD axion / ALP [higher masses]	ALP
MADMAX, GrAHal		**BMV**

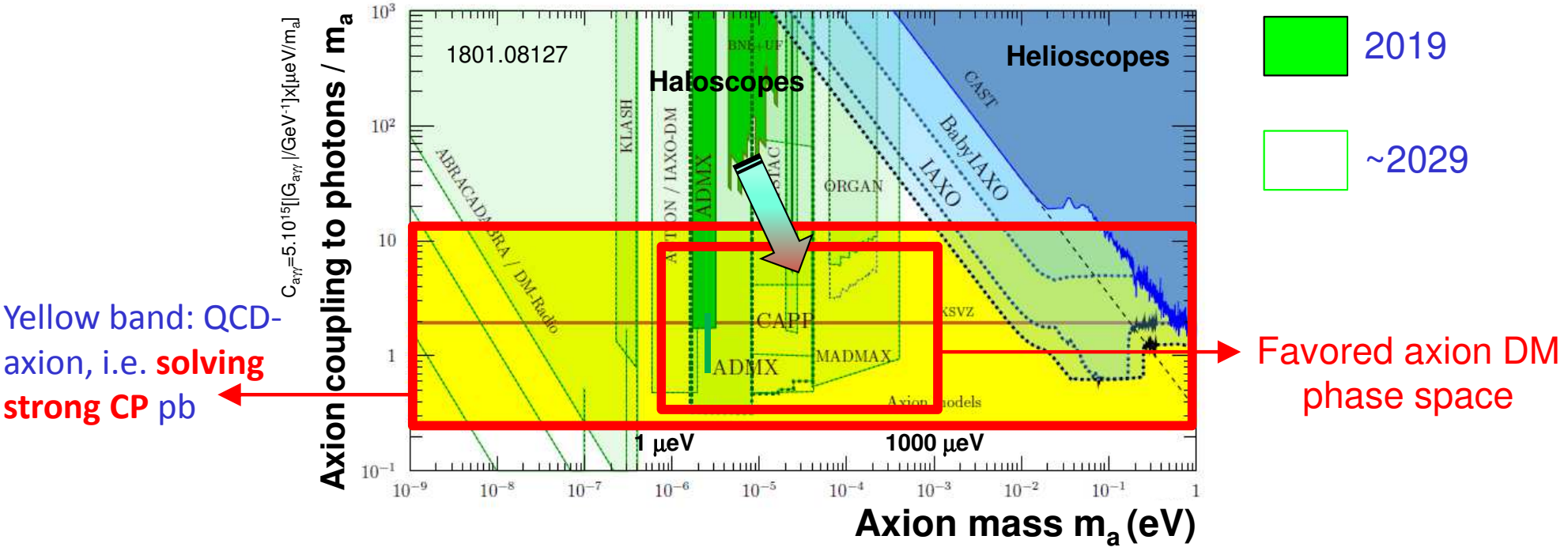
→ Complementarity between 3 mature experimental approaches

Axion/ALP searches



Axion DM search: status / prospects

- Extremely challenging because of extraordinary weak coupling of axions [muucchh lower than neutrinos]

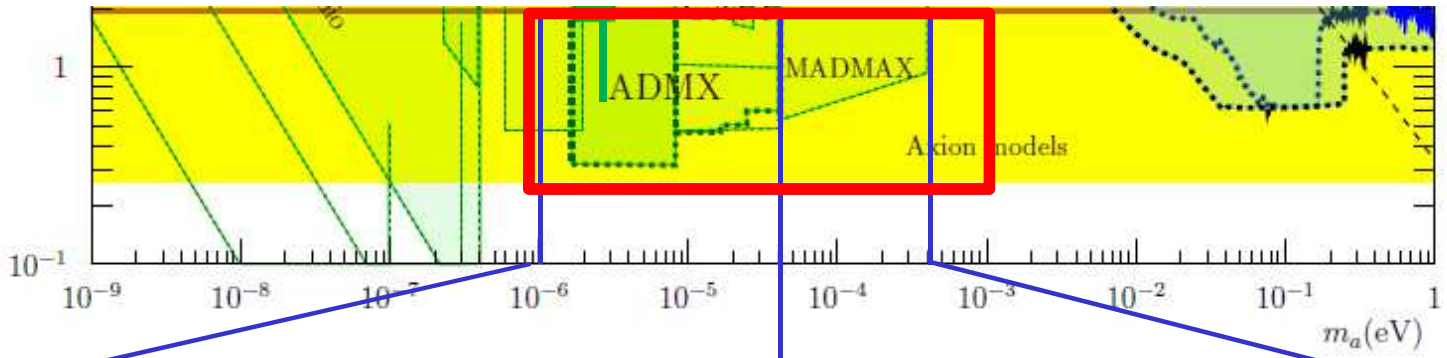


- Only 1 experiment (ADMX) currently probe a (very small) part of the favored phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

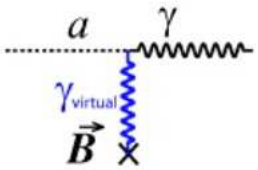
➔ Next decade will be decisive, probing axion DM most favorable region

Axion DM search: how?

- Convert axions into photons *[E field of O(10^{-12}. $\frac{B}{10\ T}$) V/m]* ➔ high magnetic field >> 1T
- Boost photon field *[up to P~10^{-22} W]* ➔ resonant cavities or emission at dielectric interfaces
- Scan over range of axion mass ➔ need tunable set-up



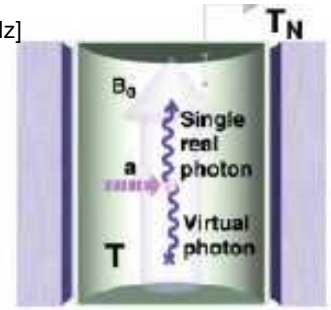
Primakoff effect $a\gamma^* \rightarrow \gamma$



1 μeV [0.25 GHz] **40 μeV** [10 GHz] **400 μeV** [100 GHz]

[$\nu_a=\nu_\gamma$] → Microwave regime

Cavities

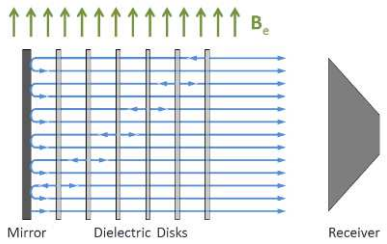


ADMX, HAYSTACK, CAPP

Multicavities, Very High B

RADES, ADMX-SideCar, CAPP, GrAHal

Cavity size too small + high noise



MADMAX

Dielectric haloscopes

[novel concept 2013]
Phys.Rev. D88 (2013) 115002

➔ **New ideas of last decade coming to maturity to scan preferred mass range**

MADMAX contribution

https://indico.in2p3.fr/event/19776/contributions/75431/

- **Only experiment capable to explore m_a=40-400 μeV** *(favored by post-inflation theory)*

Search for axion dark matter with a novel approach used by the MADMAX experiment

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➔ **CPPM initiates experimental axion DM search at IN2P3**

MADMAX experiment

White Paper [EPJC 79 (2019) 186, 1901.07401]

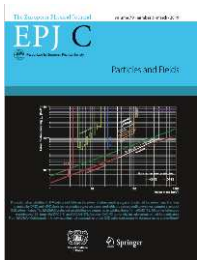
❑ **~40 collaborators** e.g. from MPI-Münich, U-Hamburg, DESY, CEA/IRFU, I. Néel + CPPM

Associate members since 2019

	2019	2020	2021	2022	2023	2024	2025	≥2026
MadMax	Preparation prototype	Construction prototype		Exploitation prototype		Construction final detector		Exploitation final detector

@DESY axion hub
(IAXO, ALPS, MadMax)

Cover page of EPJC in March' 19



Booster → 80 dielectric disks (lanthanum aluminate ε~24) of ∅=1m (thickness 1 mm), few kgs, positioned at O(10 μm)
[spacing 15 mm for 40 μeV and 1.5 mm for 400 μeV]

Dipole magnet B~10 T → **$B^2.A$ ~ 100 $T^2.m^2$**

Cryostat → T~4 K

Parabolic Mirror → T<100 mK

Horn Antenna + Receiver

Mirror

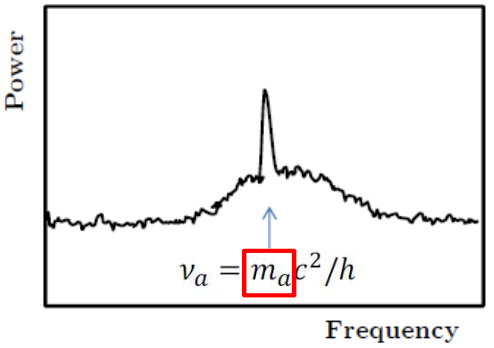
L= 0(1) m

Φ = 1m

Φ = 4.5m

H1 Yoke L=6m

Picture not to scale



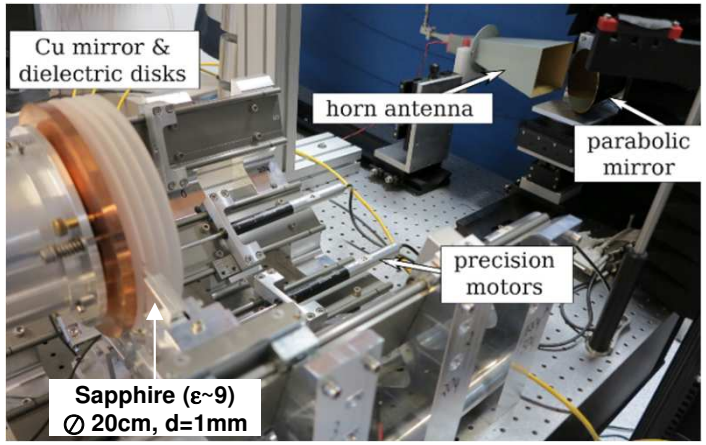
➔ Many challenges ➔ Innovative R&D ongoing ➔ many technical opportunities

MADMAX: Technical opportunities

❑ Axion DM experiment at the technological frontier, e.g.

1. Need to control disk thickness **(10 μm)** and position precisely disks (**10 μm**)

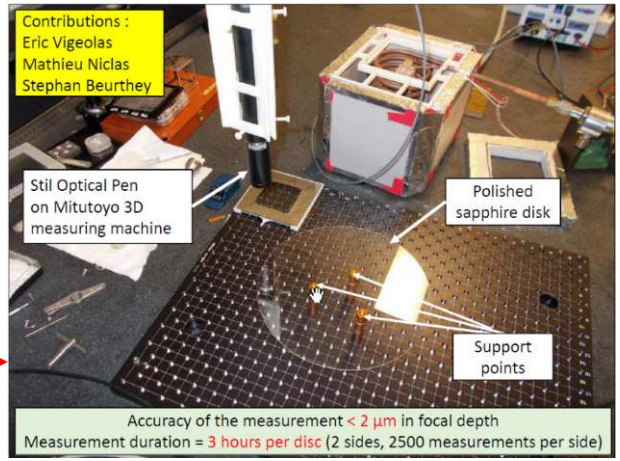
➔ Profit from the precision measurement infrastructure at CPPM [ATLAS pixels] to control disk planarity and thickness with 3 different set-ups with O(μm) precision



Proof of principle setup at MPI

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Disk measurement setup at CPPM



➔ First CPPM/IN2P3 contributions on MADMAX precision mechanics

➢ CPPM involvement in next years → Prototype to validate technology

- Concentrate on booster, composed of **20** disks of **30 cm** diameter (1/4th of final detector)
- Operated at CERN (>2021) in ATLAS testbeam magnet [under CPPM impulsion → SPSC LoI]
- Can already probe unexplored region of phase space (ALPs) ➔ physics in next 3-4 years

MADMAX: Technical opportunities

❑ **Axion DM experiment at the technological frontier, e.g.**

1. Need to control disk thickness **(10 μm)** and position precisely disks (**10 μm**)
2. Need high magnetic fields over large apertures
3. Need ultra-low noise amplifiers (e.g. Josephson Parametric Amplifier) and cryogenic temperatures

- CEA-Saclay: full member of MADMAX collaboration **[also involved in IAXO and Shuket projects]**
- LNCMI-Grenoble: expert for MADMAX magnet review [P. Pugnat]
- Institut Néel Grenoble: associate member of MADMAX collaboration [N. Roch, L. Planat]

➔ **Synergies with GrAHal project**

GrAHal contribution

https://indico.in2p3.fr/event/19776/contributions/75425/

GrAHal : un projet d'Haloscope à Grenoble pour détecter la Matière Noire axionique

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➔ **Project based on local synergetic expertises**

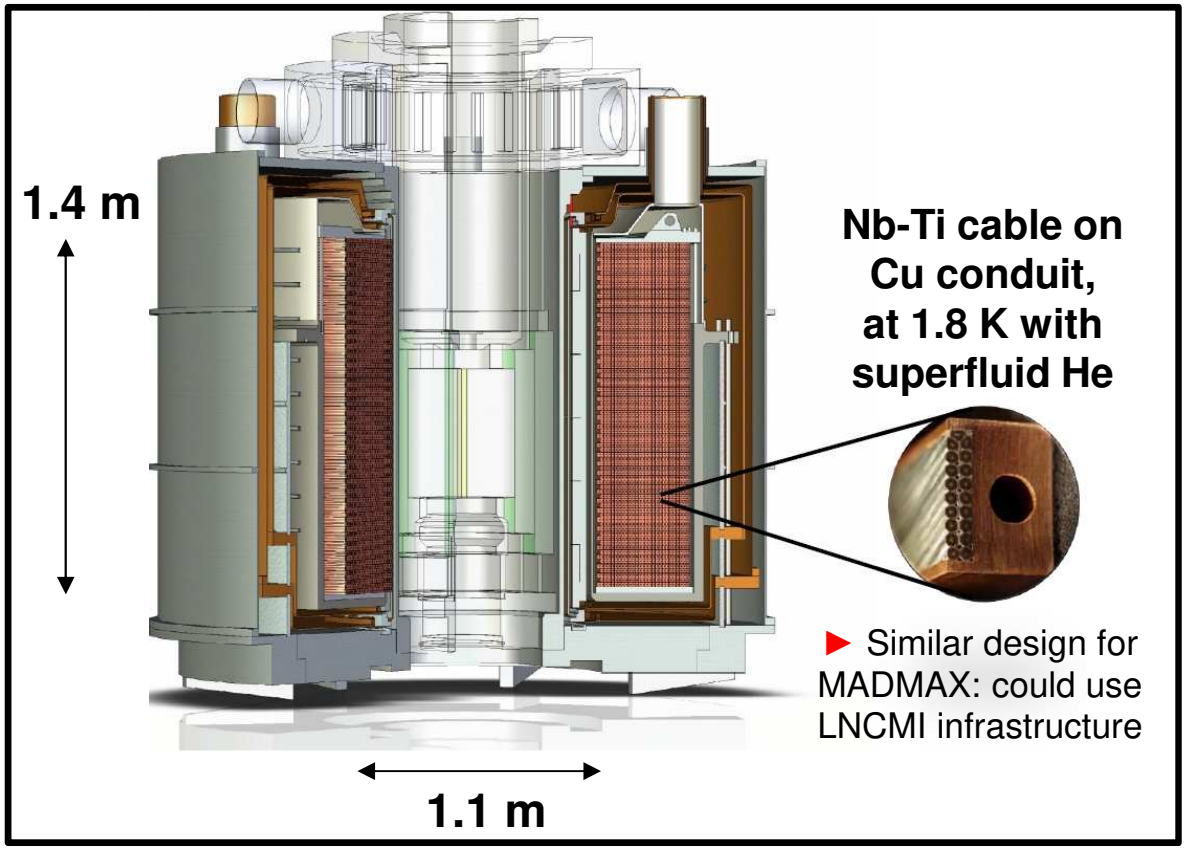
GrAHal: hybrid magnet

❑ High magnetic fields and fluxes

- Large bore superconducting solenoid in construction at LNCMI-Grenoble
- Possible hybrid configurations in association with resistive coils
- Modular magnet platform ➔ B/∅= 9T/800mm –17T/375mm – 27T/170mm – 43T/34mm

B^2V~40 T^2m^3 [~8 for latest ADMX result]

$$P = g_{A\gamma\gamma}^2 (\rho_{halo}/m_A) B^2 V C Q/2$$

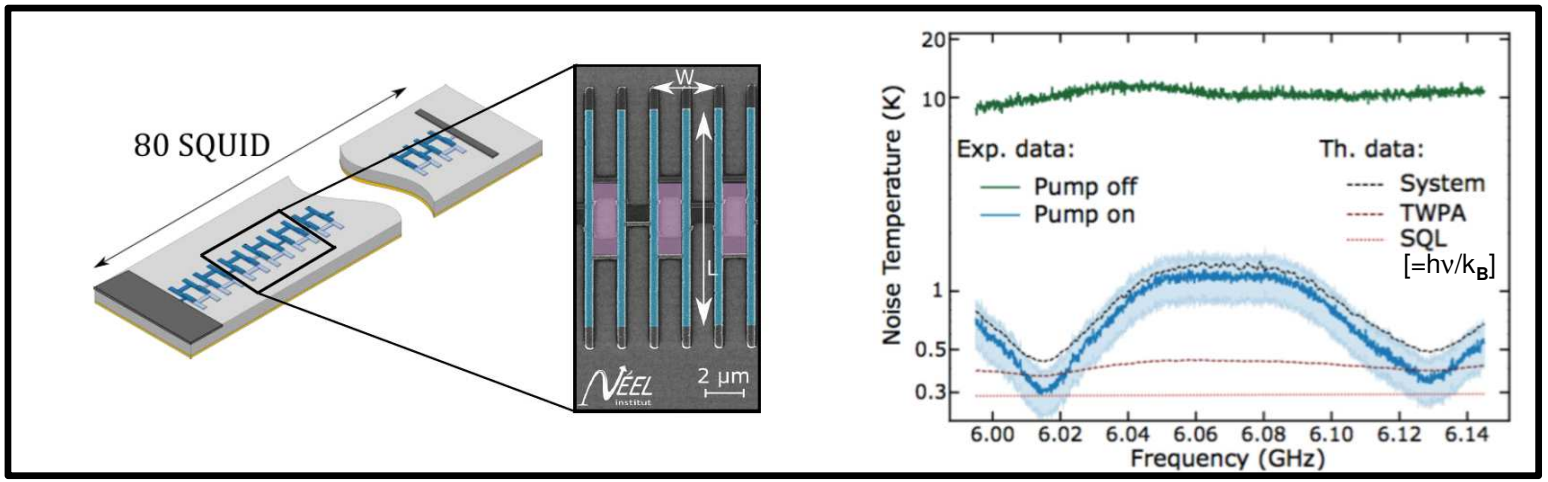


- ➢ Collaboration with CEA and Noell GmbH [as MADMAX magnet]
- ➢ Should be operational in 2021

GrAHal: low noise amplifiers

- **High magnetic fields and fluxes**
- **Ultra-low-noise microwave receivers**
  - Ultra-low noise microwave amplifiers based on Josephson jonctions (JPA) in development at Néel institute ➔ microwave signal power readout
  - Allows to work at quantum noise limit over a large bandwidth in >GHz regime

[i.e. better than High Electron Mobility Transistors HEMT and Superconducting Quantum Interference Device SQUID amplifiers]



- Requires ultra-low temperatures (also for the RF cavities)

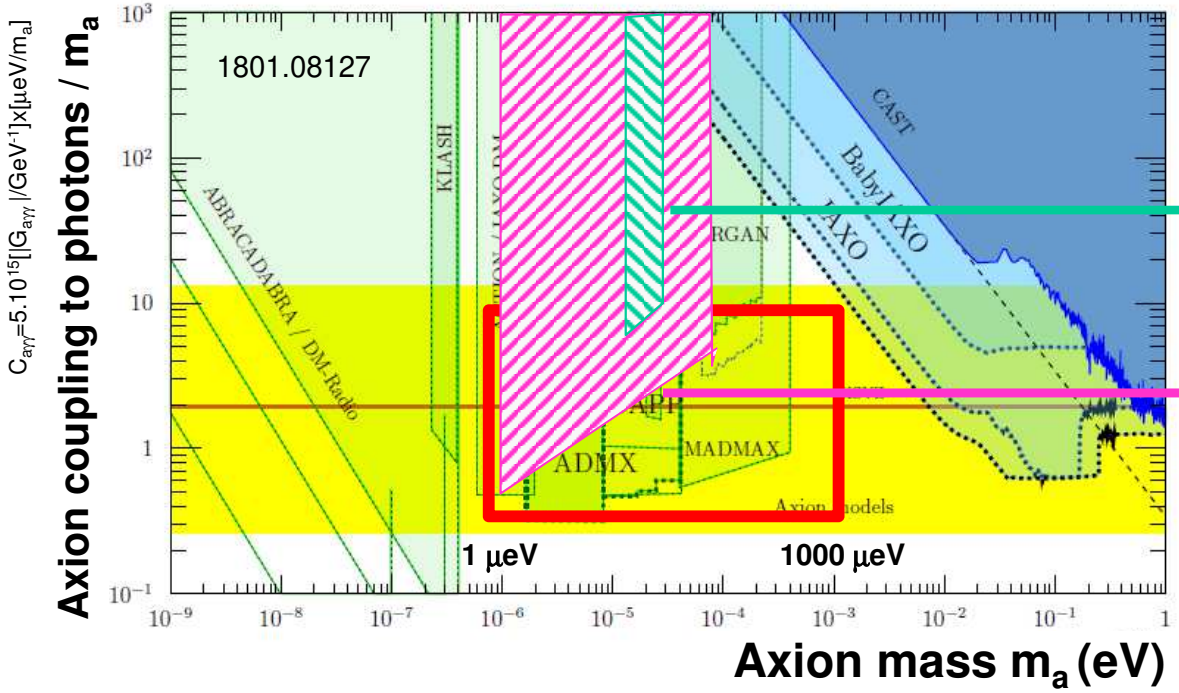
➔ expertise at Néel institute with ^{3}He/^{4}He dilution refrigerators (<50 mK) [used e.g. for Edelweiss, Planck]

GrAHal: physics goals

- ❑ **High magnetic fields and fluxes**
- ❑ **Ultra-low-noise microwave receivers**
- ❑ **Theoretical and analysis activities**

+ discussions with people at CERN & IBS/CAPP (South Korea) for development of RF cavities

[First sensitivity estimates based on scaling wrt ADMX results using existing techno]



Phase 0 (~now) → ~20 μeV with B/∅=16T/50mm, T~2K

Phase 1 → 17-30 μeV with B/∅=14T/77mm, T~50mK

Phase 2 (>2021) → extend potential mass reach at maximum using modular platform

→ Synergy with MADMAX

BMV contribution

https://indico.in2p3.fr/event/19776/contributions/75434/

Vacuum Magnetic Birefringence: QED & WISPS

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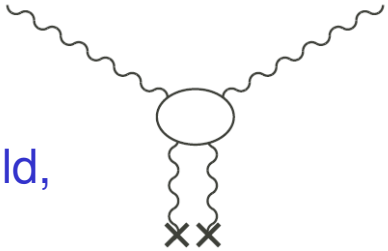
➔ Axion search as by-product of very precise test of QED

BMV: physics goals

❑ Vacuum magnetic birefringence…



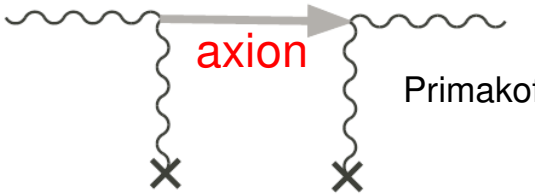
- Macroscopic effect predicted by QED but never observed
- Vacuum refraction index depends on light polarization to external B field, because of quantum vacuum polarization
- Very precise test of QED through interaction of vacuum fluctuations and real γ

QED 1st order prediction: $\Delta n = n_{\parallel} - n_{\perp} \approx 4 \times 10^{-24} \frac{{B_0}^2}{\mathrm{T}^2}$

- Best current sensitivity at O(10) times QED prediction [PVLAS 1510.08052]

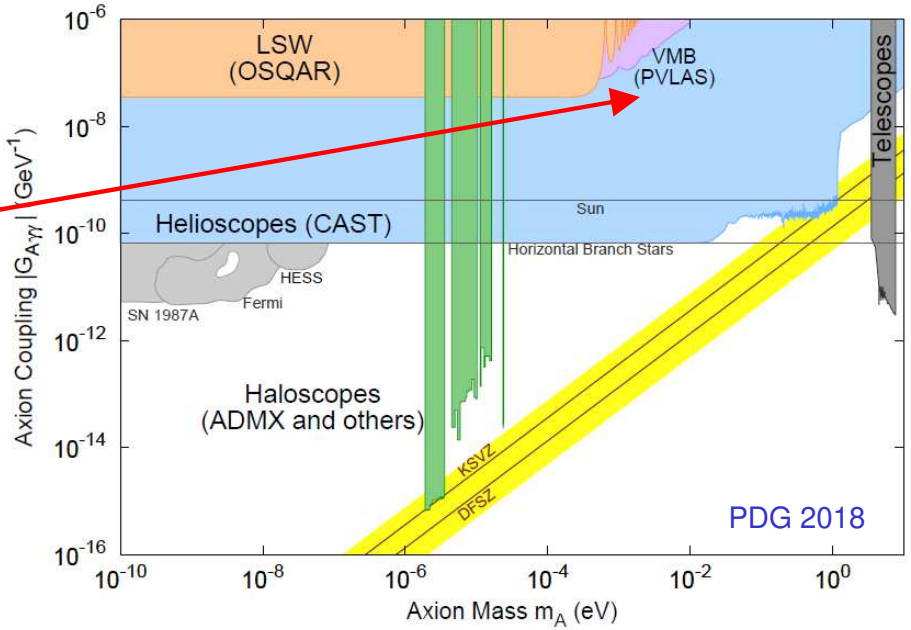
❑ … allows to probe axions

- QED prediction sensitive to BSM effects
- in particular to Axions-Like Particles



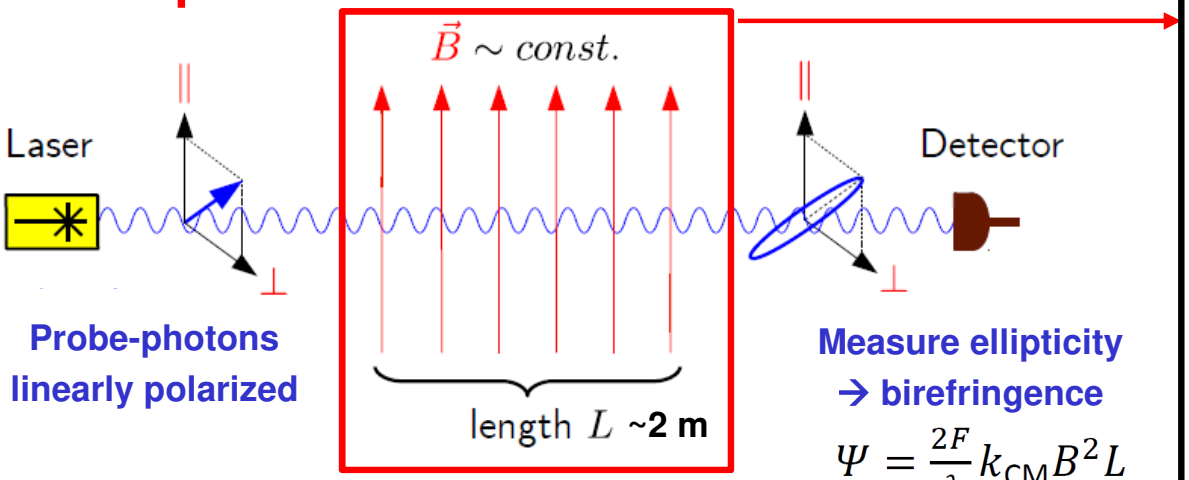
Primakoff effect

- Complementary to other searches: no cosmological / astrophysical assumptions



BMV: experiment & status

Lab experiment



Probe-photons linearly polarized

Measure ellipticity → birefringence

$$\Psi = \frac{2F}{\lambda} k_{CM} B^2 L$$

Photon propagation in vacuum
→ Fabry-Pérot cavity (long optical path)

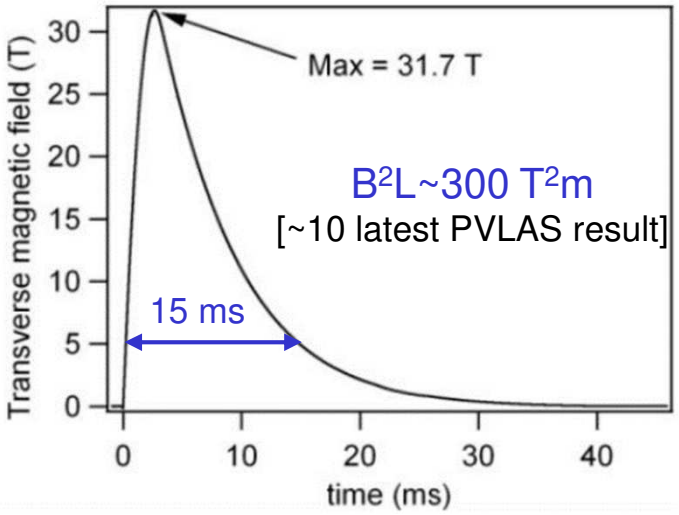
1. High pulsed magnetic field B^2L
   ➔ LNCMI-Toulouse expertise
2. High finesse F optical cavity
   ➔ collaboration with IP2I (LMA) for cavity mirrors F ~ 500 000

LNCMI

iP2i LES 2 INFINIS LYON

- Very small effect ➔ enormous experimental challenge
- BMV world-class result in 2014 ➔ validate technical choices **[Eur. Phys. J. D 68, 16 (2014)]**
- 2nd generation experiment under commissioning ➔ observation of VMB at reach (S/N~1)
- Next decade: precise measurement of VMB effect ➔ increased sensitivity to dark matter ALPs

XXL-Coil



B^2L~300 T^2m
[~10 latest PVLAS result]

Conclusions and prospects

- **Axion = DM candidate motivated by particle physics since 40 years …**
  - Very low mass wrt WIMPs (factor ~10^{-15})
- **… can be discovered / excluded in the next O(10) years …**
  - Sensitivity entered last year in the theory-favored region
  - Will now be extended to most of the interesting range with novel experiments
  - Initiate this field at IN2P3 in complement with direct searches for WIMPs
- **… with strong associated technical opportunities for IN2P3 (at low cost)**
  - Needs for precise instrumentation in extreme conditions (high B, cryo temperature, vacuum)
  - Recognised expertise in other CNRS labs (LNCMI, Institut Néel) and CEA/IRFU ➔ synergies
  - Many innovative opportunities for technical departments ➔ lots of room for IN2P3 visibility

Opportunities for IN2P3 in next decade (**scientific & technical**) on a **fundamental question** of particle physics with a **strong discovery potential**