MAX-PLANCK-INSTITUT
FÜR PHYSIK

RADES

DETECTING AXION DARK MATTER WITH RESONANT CAVITIES: THE **RADES** COLLABORATION

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Saturnalia 2025 - Universidad de Zaragoza

SUMMARY

- Dark Matter?
- Dark matter QCD axion motivation (The short story)
  - The Strong CP Problem (For experimentalists)
  - Relic axions as dark matter
- Haloscopes: Dark matter axion detection
- The CAST-RADES experiment (RADES is born)
- RADES search with high temperature superconductors
- Present and future of RADES

THE DARK MATTER PUZZLE

DARK MATTER (DM)

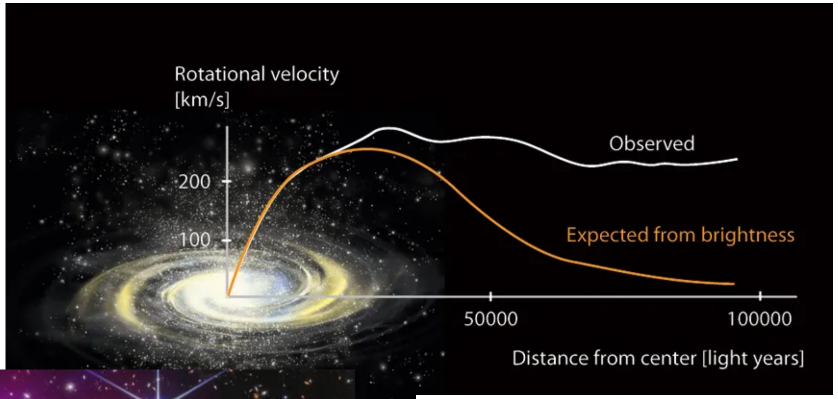
Large scale of the Universe and its evolution is given by:

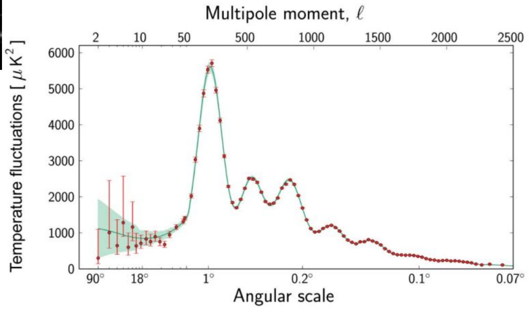
- Einstein's equations of General Relativity
- Matter-Energy content split into:
  - 5% Ordinary matter
  - 27% Cold dark matter
  - 68% Dark energy

ΛCDM Model

After decades of astronomical observations we have accumulated evidence of DM:

- Flatness of galaxy rotation curves
- Missing mass on galaxy mergers
- CMB Anisotropies
- …





DARK MATTER PUZZLE

The Standard Model of particle physics does not provide a viable candidate for DM

DARK MATTER PUZZLE

The Standard Model of particle physics does not provide a viable candidate for DM

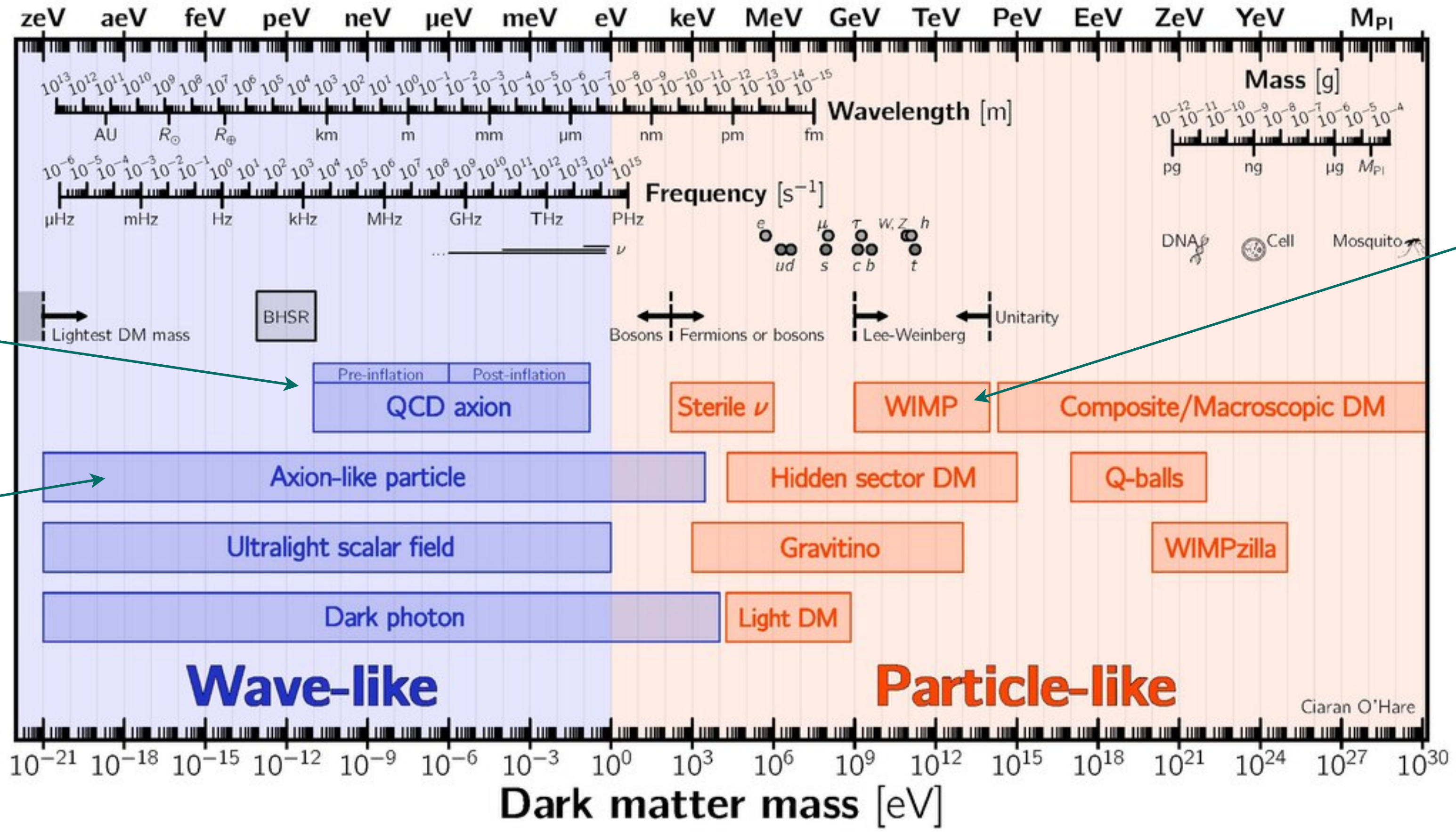
However...

Different extensions of BSM physics offer several candidates

Main focus of this talk

More on this in the next talk

Talks tomorrow and Friday



QCD AXION DARK MATTER

STRONG CP PROBLEM

Main idea: The existence of a θ-vacuum term for QCD has observational implications

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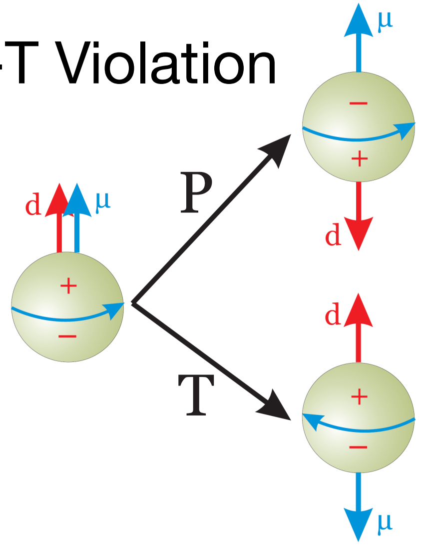
Direct experimental test: Electric dipole moment for neutron

$$\mathcal{L}_\theta = \frac{\bar{\theta} g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

Implies: $|d_n| \simeq 4.5 \times 10^{-15}\, \bar{\theta}\, e\,\mathrm{cm}$

P-T Violation



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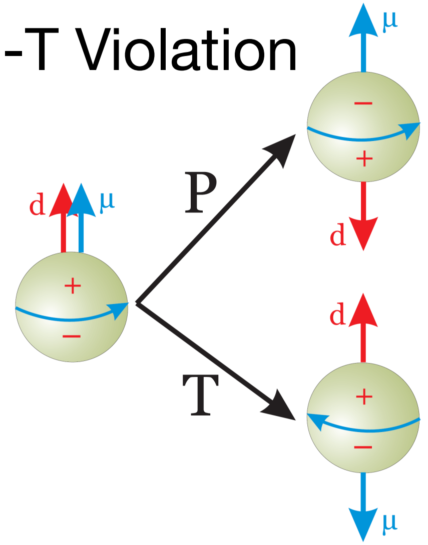

Experimental limit:

$$|d_n| < 2.9 \times 10^{-26}\,e\,\mathrm{cm}$$

Limit on $\bar{\theta} < 10^{-11}$ → Why is $\bar{\theta}$ so small?

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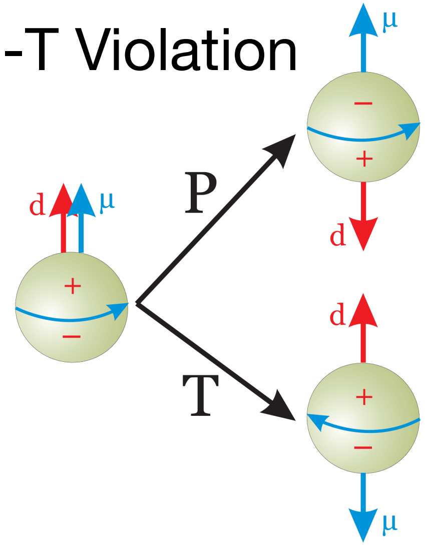

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Strong CP problem: Why is CP-symmetry preserved in QCD?

PECCEI-QUINN SOLUTION

1) $\bar{\theta}$ is promoted from a parameter into a dynamical field: $\bar{\theta} = \frac{a}{f_a}$

2) This new field exhibits a minimum at $\bar{\theta}_0 = 0$ and so it relaxes to the CP preserving value.

3) This new field *a* (**the Axion**) is a pseudo scalar that corresponds to the pseudo Nambu-Goldstone boson of a $U(1)_{PQ}$ extra symmetry of the QCD lagrangian.

We are left with a new particle, the axion, and a new energy scale

Axion decay constant :	$f_a \longrightarrow$	Energy scale at which $U(1)_{PQ}$ is spontaneously broken

$$f_a \gg 246\,\mathrm{GeV}$$

(Above the electroweak scale)

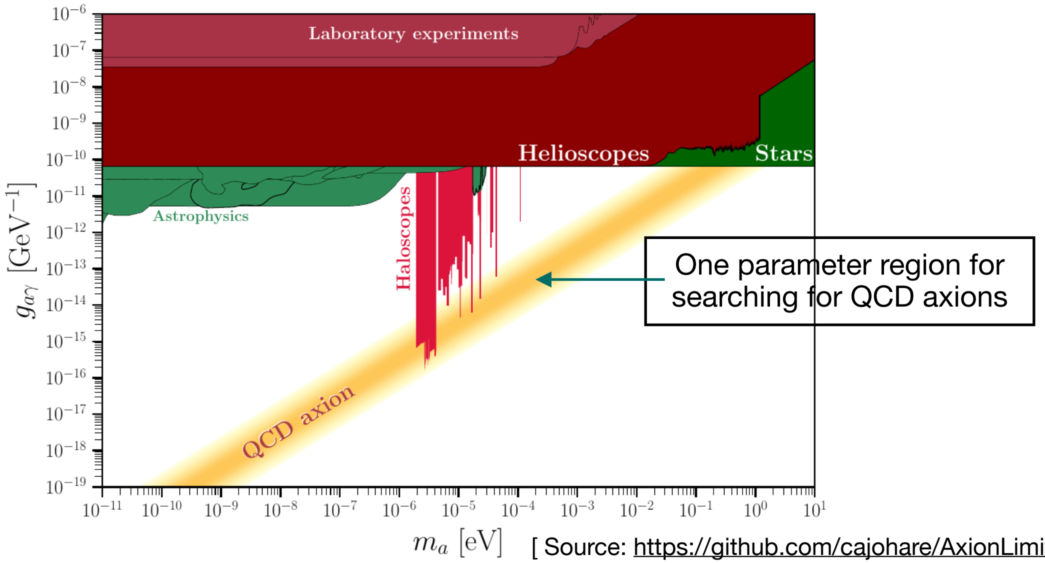
QCD AXION

The energy scale f_a plays a role in the mass and the couplings

1) The mass and energy scale are related → $m_a \approx \frac{10^{12}\,\text{GeV}}{f_a} 5.69\,\mu\text{eV}$

2) Axion-photon coupling dependency → $g_{a\gamma} \propto \frac{1}{f_a}$ **Big role in axion detection**

3) Same suppression for other couplings → $g_{af} \propto \frac{1}{f_a}$ (fermions) ; $g_{an} \propto \frac{1}{f_a}$ (neutrons)



[Source: https://github.com/cajohare/AxionLimits]

RELIC AXIONS AS CDM CANDIDATES

Do axions fulfil the requirements for being CDM?

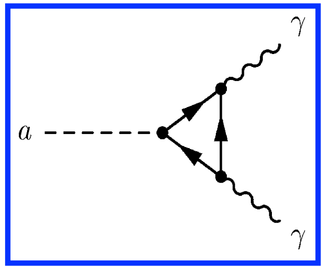
- ✓ 1) Having mass ⟶ $\mathcal{L}_{axion} = \frac{1}{2}\left((\partial_\mu a)(\partial^\mu a) - m_a^2 a^2\right)$
- ✓ 2) Weakly interacting with SM particles ⟶ $\frac{1}{f_a}$ suppression
- ✓ 3) Production mechanisms for cold relic density
  - → The theta vacuum relaxes to $\theta_i \to 0$ radiating axions
  - → Decay of topological defects

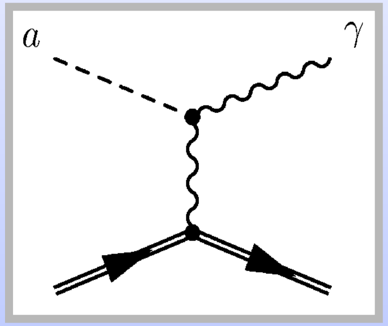
HALOSCOPES

AXION-PHOTON CONVERSION

- Axion-photon coupling appears in the EFT below QCD energy scale

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a \qquad g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$





- Axion-photon conversion in the presence of an electromagnetic field (Inverse Primakoff effect)

Probably the most relevant of axion properties for detection purposes.

Most axion detection strategies are based on the axion-photon coupling

HALOSCOPES

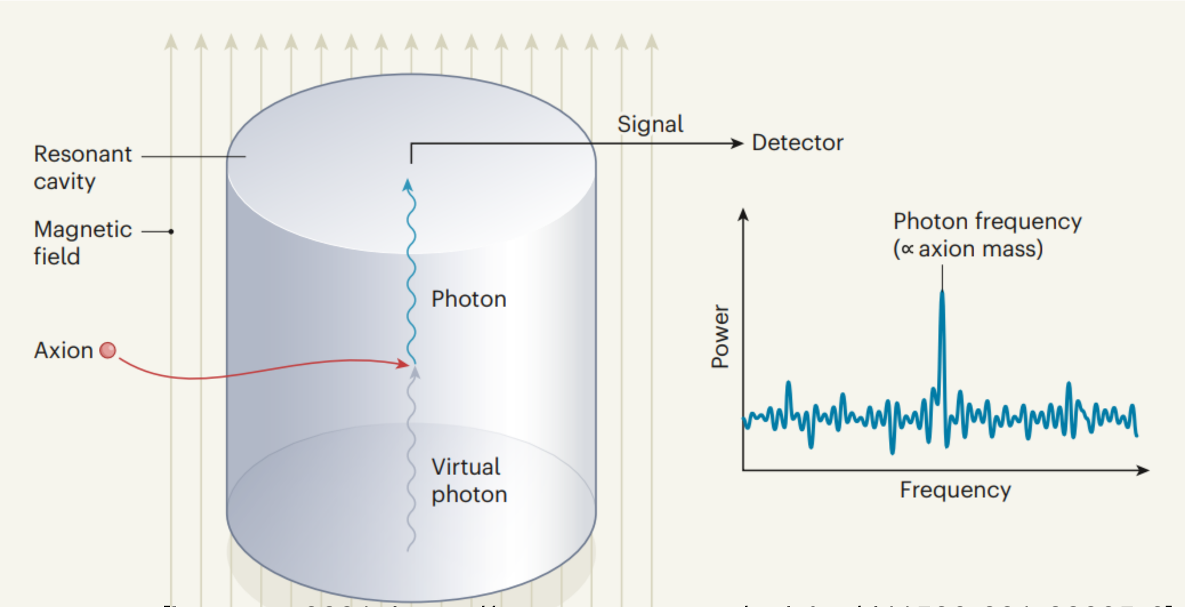
- For CDM axions the most common detection scheme relies on coherent conversion under a strong static B-field

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = g_{a\gamma}\mathbf{B}\dot{a} \rightarrow \dot{\mathbf{E}} = a_0 g_{a\gamma} m_a B_0 \cos(m_a t)\ \mathbf{z}$$

Extremely small

- Axion-photon signal can be enhanced inside of a resonator

If the induced E-field matches one of the resonator eigenmodes: its energy is stored, and the signal is enhanced



[Irastorza 2021, https://www.nature.com/articles/d41586-021-00295-6]

HALOSCOPE SENSITIVITY

Signal power → $$P_s = \kappa g_{a\gamma}^2 V B_e^2 \mathcal{C}_m^2 Q_m \frac{\rho_{DM}}{m_a}$$

(For a single mode m)

Resonator coupling → κ

Geometric factor → $\mathcal{C}_m = \frac{1}{VB_e}\int_V \mathbf{B}_e \cdot \mathbf{e}_m(\mathbf{r})\mathrm{d}\mathbf{r}$

Resonant mode of the cavity

Quality factor of the resonator → $Q_m = \frac{\omega_m}{\Gamma_m}$

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- With thermal background noise, the signal to noise ratio (SNR) is

$$\mathrm{SNR} = \frac{P_s \sqrt{\Delta\nu t}}{P_N}$$

(Johnson thermal noise)

t $\longrightarrow$ acquisition time

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- And the sensitivity for axion-photon coupling (for QCD axions) is given by:

$$g_{a\gamma}^2 = \frac{\mathrm{SNR}\, T_{\mathrm{sys}}}{\kappa \rho_{DM} B_e^2 Q_m V C_m^2}\sqrt{\frac{m_a^3}{tQ_a}}$$

$Q_a \longrightarrow$ width of axion signal (based on halo model)

HALOSCOPE SENSITIVITY

GOAL: Maximizing the sensitivity (Reach lower values of g)

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Options:

- Reduce T_{sys} → Advanced cryogenic systems
- Increase acquisition time → Very stable acquisition system and well understood background
- Increase the quality factor → Maximizing conductivity of cavities
- Increase the volume → Needs clever ideas not to compromise the resonant frequency

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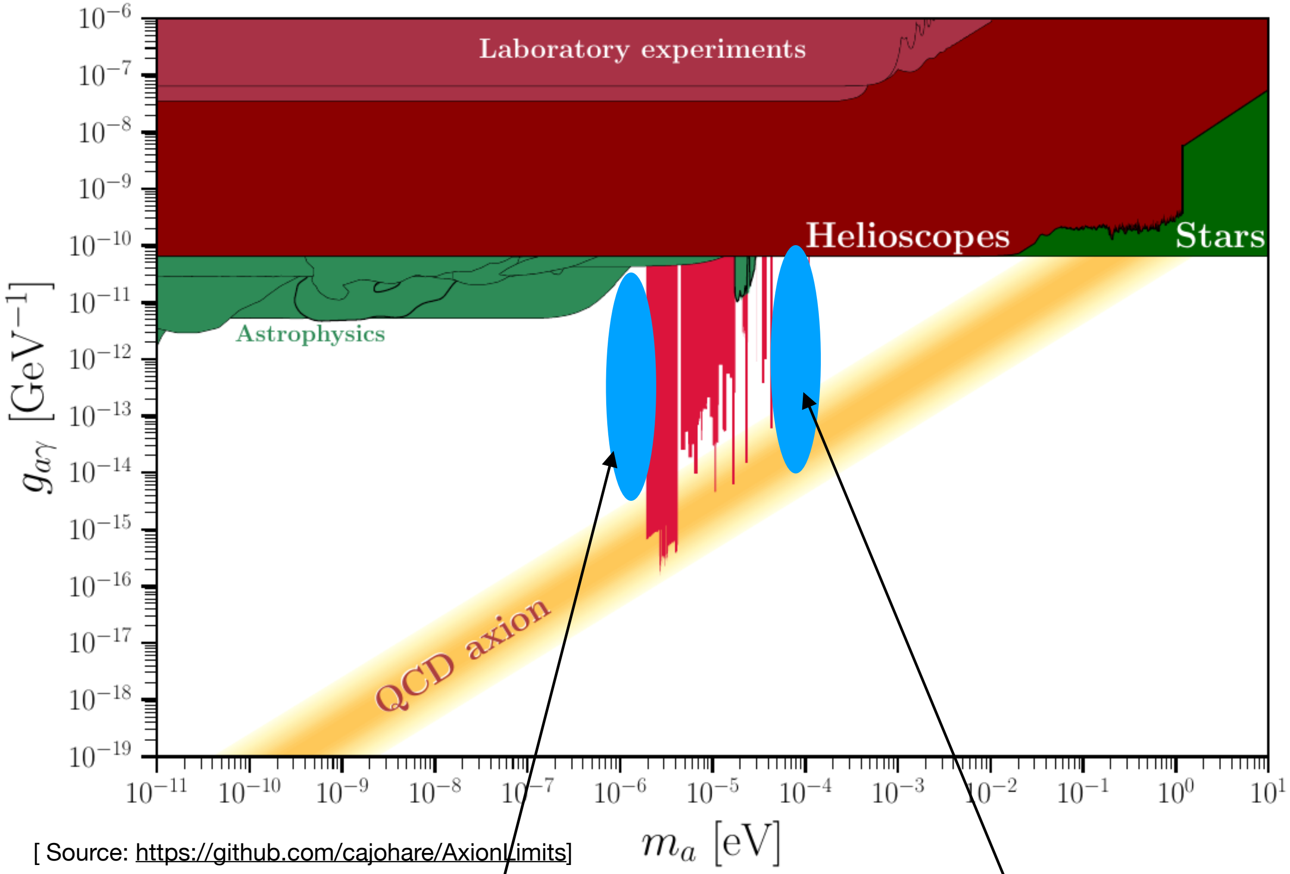
Extra complication:

The requirement of a mass scanning implies the need of implementing a tuning mechanism

HALOSCOPE SENSITIVITY

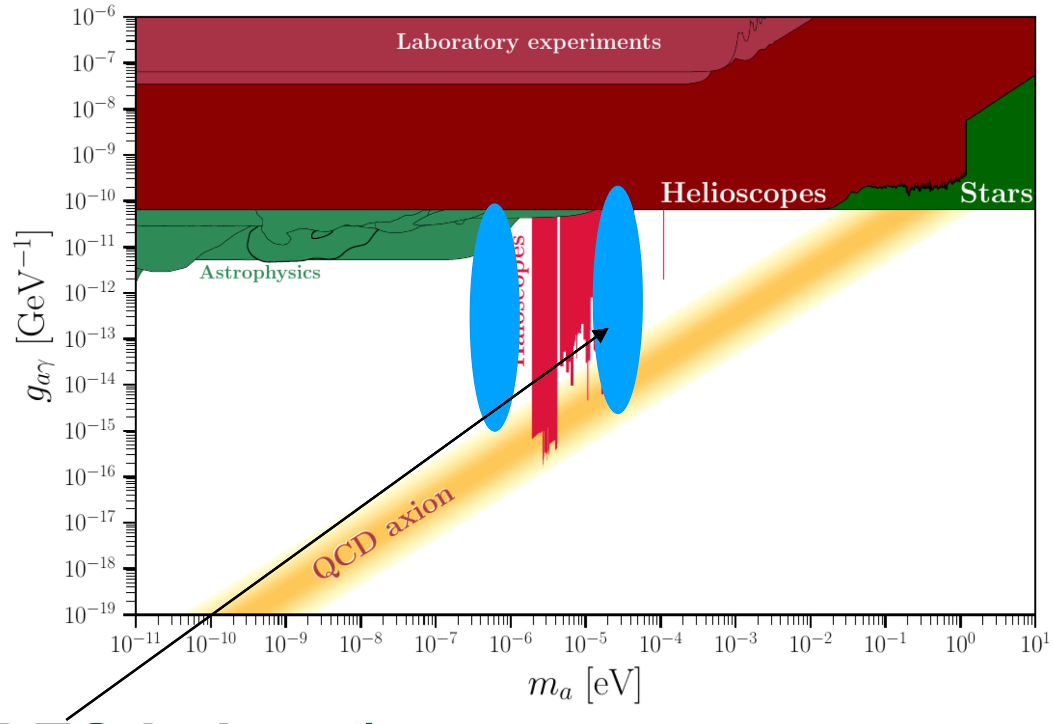


[Source: https://github.com/cajohare/AxionLimits]

Larger resonators: Need large magnets

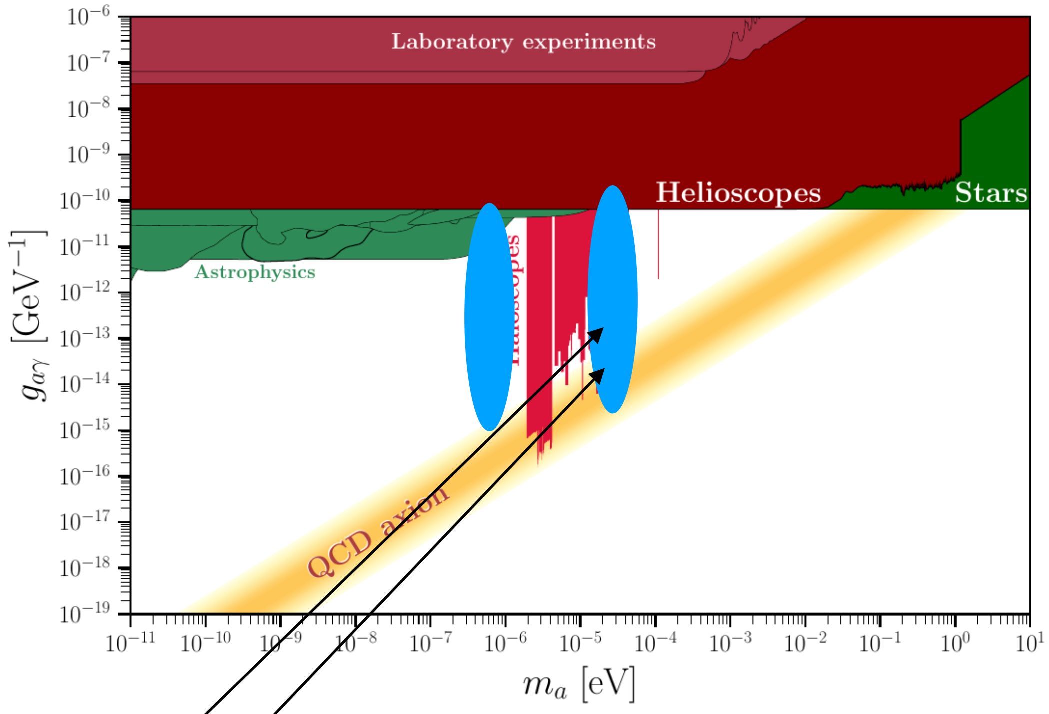
Smaller resonators: Small signal → **Need for alternative approach**

SUMMARY



- **The CAST-RADES experiment (RADES is born)**

SUMMARY



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- RADES search with high temperature superconductors

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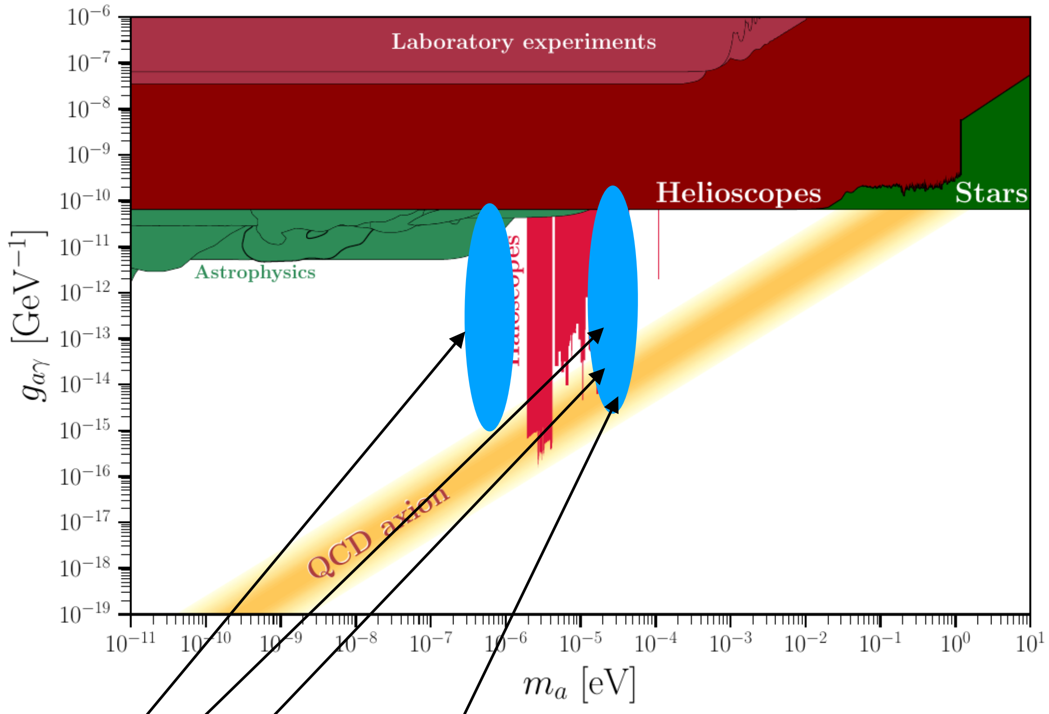

- The CAST-RADES experiment (RADES is born)
- RADES search with high temperature superconductors
- Present and future of RADES: DQLF and DQHF

THE CAST-RADES EXPERIMENT

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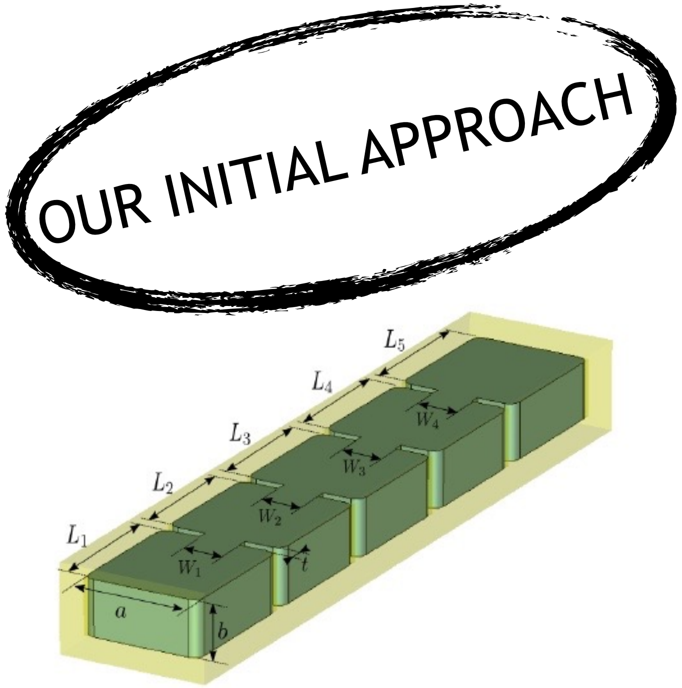
Increasing the frequency at which the structure resonates, decreases the volume of the cavity.

Strong inconvenience:

The figure of merit for detection experiments involving haloscopes depends on $B^2VQ^{1/2}$

RADES experiment basis:

A series of cavities connected by irises can behave as a single resonating cavity with all sub-cavities resonating coherently

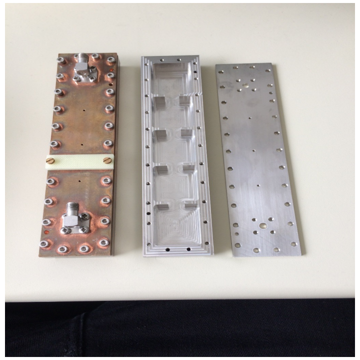


Filter-like structures

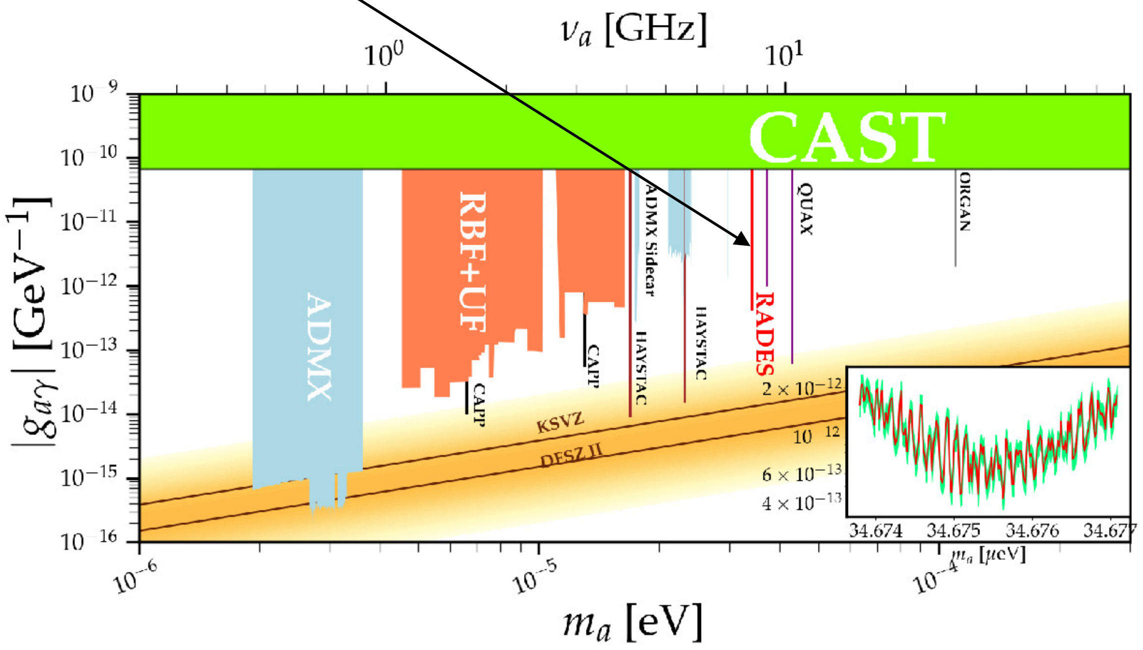
Axion Searches with Microwave Filters: the RADES project
A. Alvarez Melcon et al. (arXiv:1803.01243)

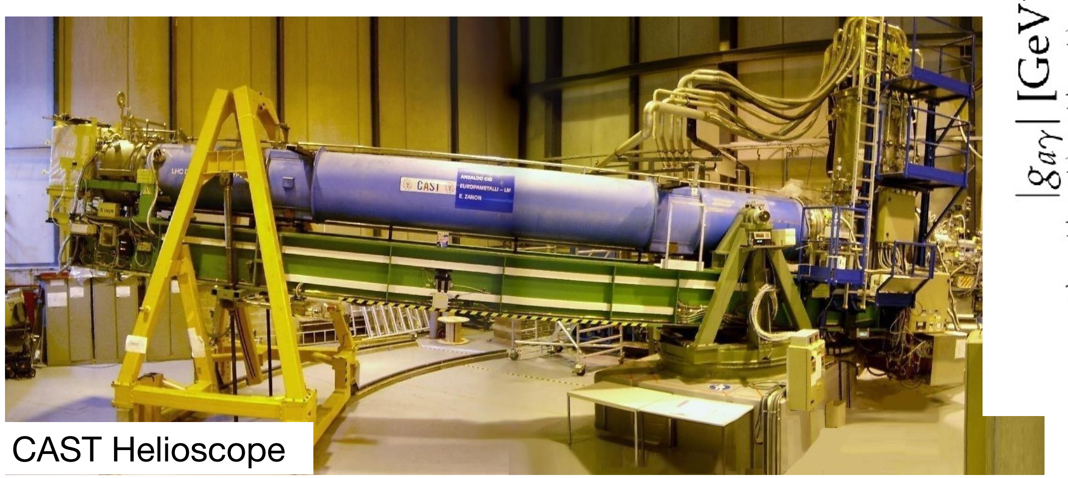
THE CAST-RADES EXPERIMENT

In 2017 we installed our first cavity inside the CAST magnet for the 2017/2018 data taking campaign



First RADES limits with a multi cavity published in 2021





CAST Helioscope

(More about Helioscopes on Maria's talk this Thursday!)

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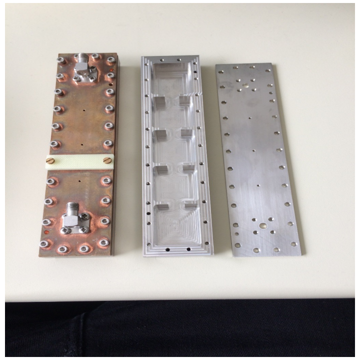

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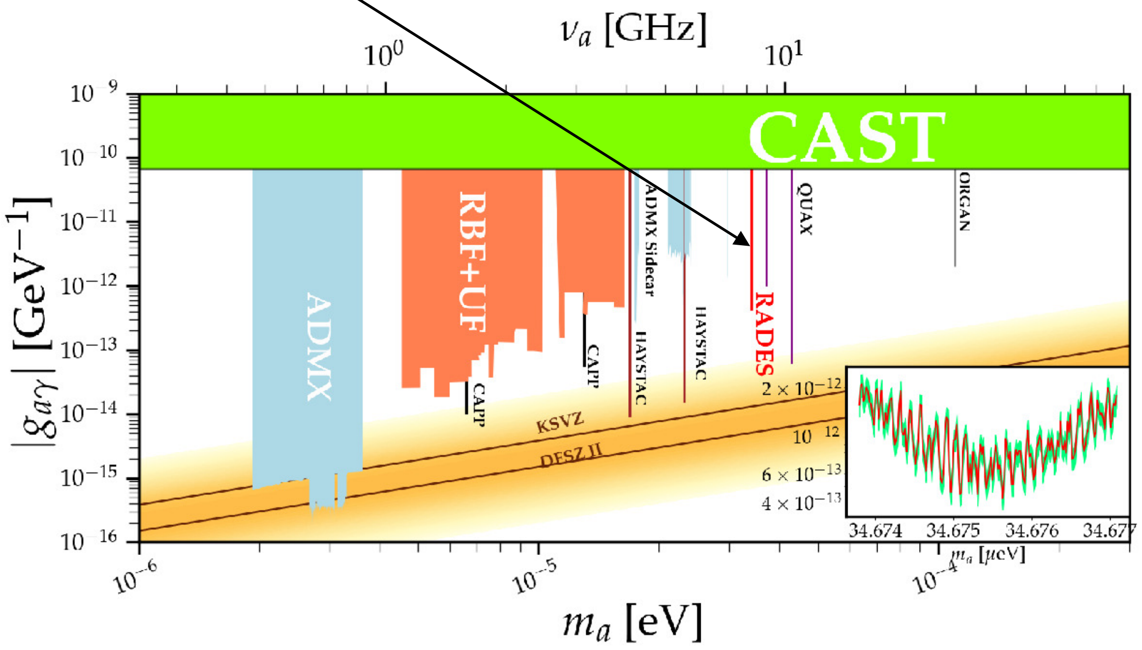

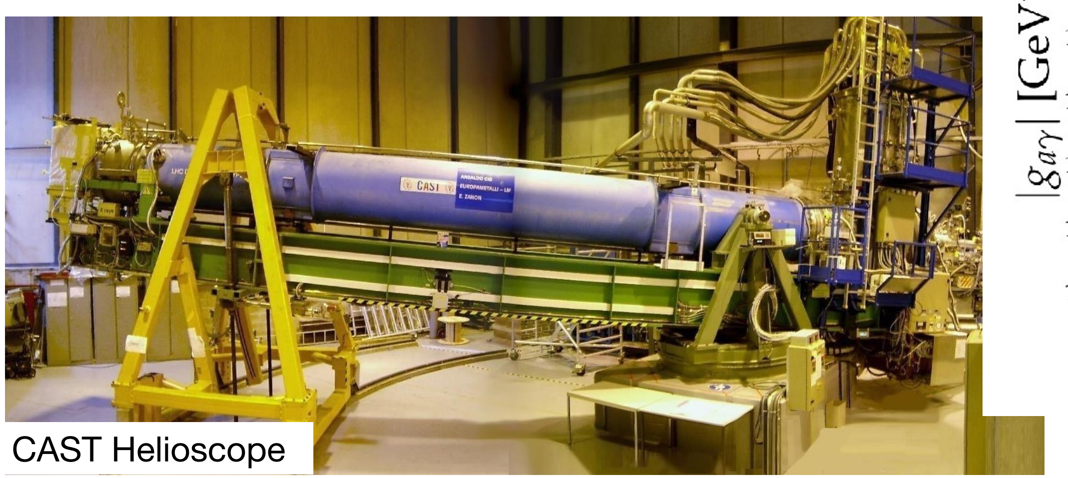
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Conclusion: Obtaining very competitive results is possible but tuning is very difficult

HTS COATED CAVITIES

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- To compensate decreasing the volume one can increase the Q-factor

$$P_s = \kappa g_{a\gamma}^2 V B_e^2 \mathcal{C}_m^2 Q_m \frac{\rho_{DM}}{m_a}$$

- Specifically: A better conductivity of the material translates directly on a better Q-factor

- Can we use superconductors?

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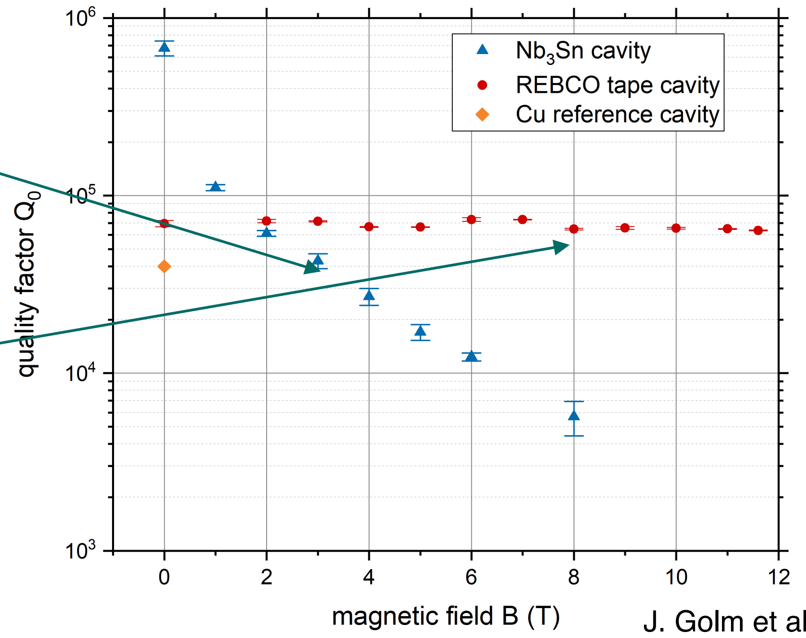
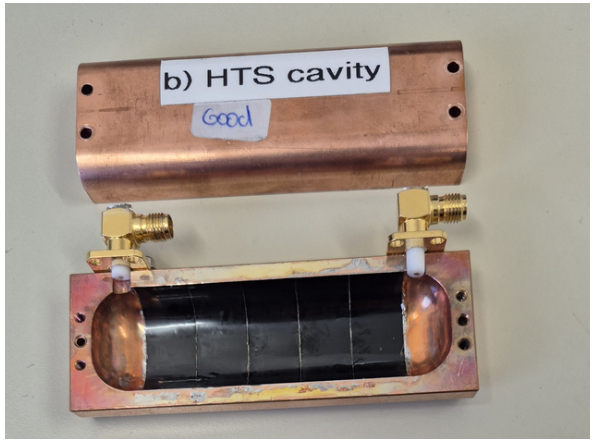
Type I superconductors performance degrades under strong B-fields

Type II superconductors (HTS) have been proven to work under strong B-fields



J. Golm et al., [arxiv:2110.01296]

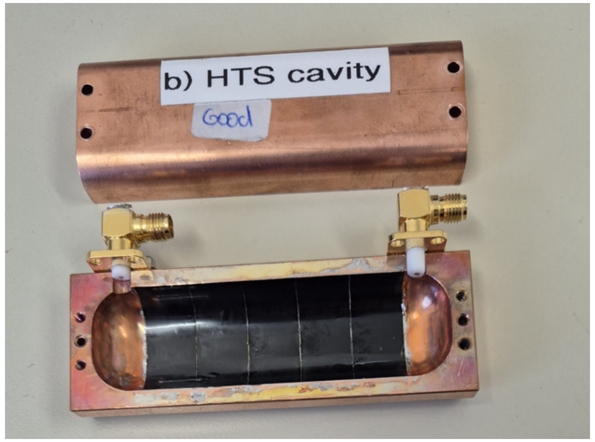
HTS COATED CAVITIES

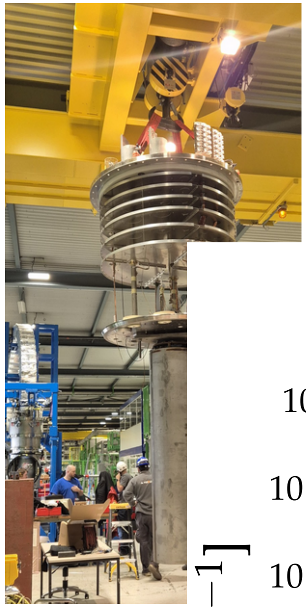


2021 -> first data taking with a copper cavity coated with RebCo tapes

The cavity was installed inside a 11.7 T dipole magnet at the magnet testing facility at CERN.

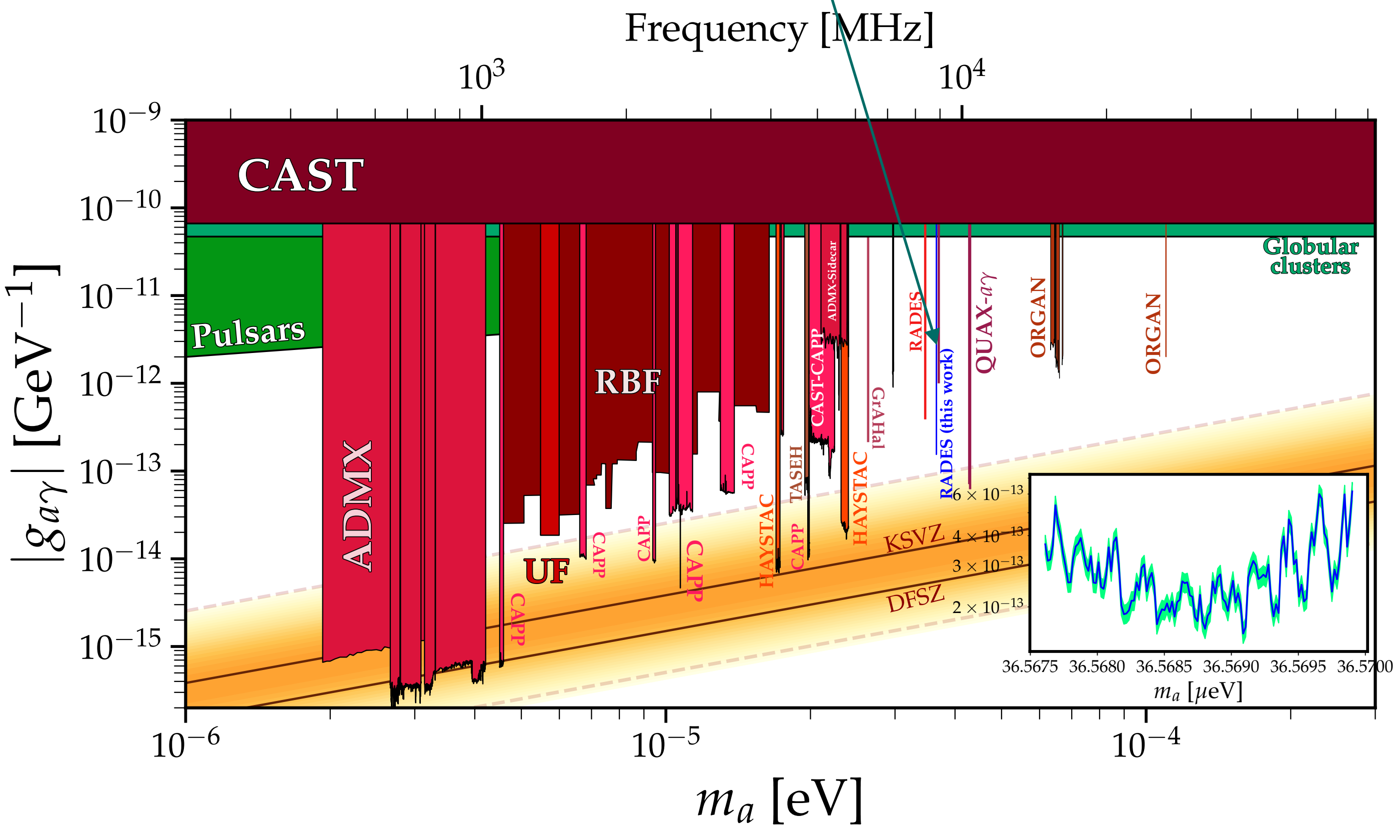
HTS COATED CAVITIES





2021 -> first data taking with a copper cavity coated with RebCo tapes

After analysing a dataset of 27 hours we obtained competitive results at higher masses than our previous 2018 search



CURRENT RESEARCH LINES

RADES AS OF TODAY

The RADES Collaboration:

Collaboration Meeting at Valencia last February

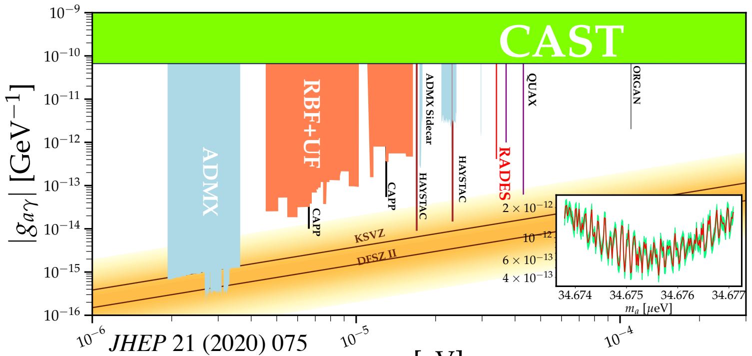
~ 30 people from different institutes all around the world

Funding currently secured through different European grants:

- ERC-Stg
- QUANTERA Project
- Lise Meitner Excellence Program
- ERC-Syg

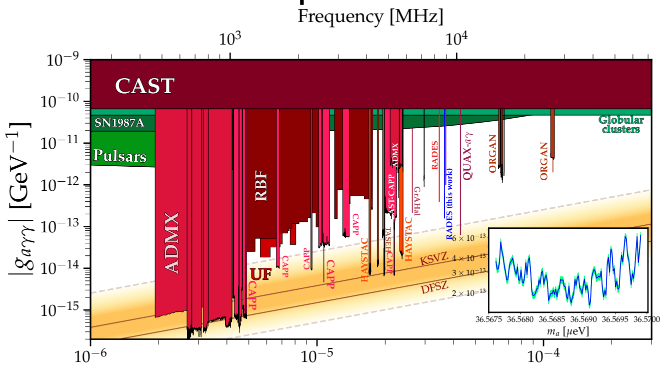
Three physics runs so far:

1st - High frequency multi-cavity in 2018 at CAST (CERN)



JHEP 21 (2020) 075
arXiv:2104.13798

2nd - HTS coated cavity in 2021 in a 12T dipole at CERN



arXiv:2403.07790

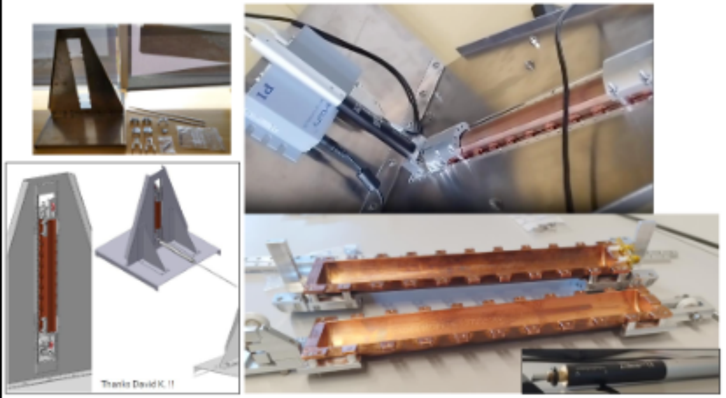
3rd - HTS coated cavity in 2024 in a 12T dipole at CERN

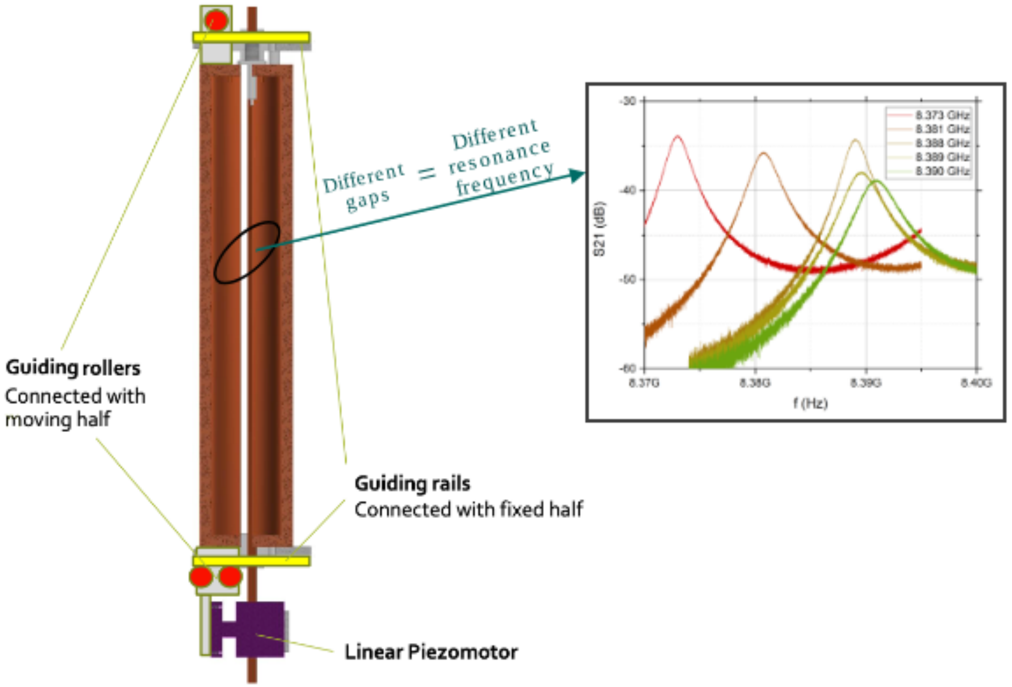
(Ongoing analysis)

RADES AT MPP: TUNABLE PROTOTYPE

- Resonant cavity split in two halves
- Separating the halves tunes the resonance frequency
- Cryogenic motor implemented
- First tests performed inside of a 4K cryostat

Room temperature proof of principle (developed at MPP):





Basic concept published in Frontiers in Physics 12 (2024) 1372846

[2312.13109]

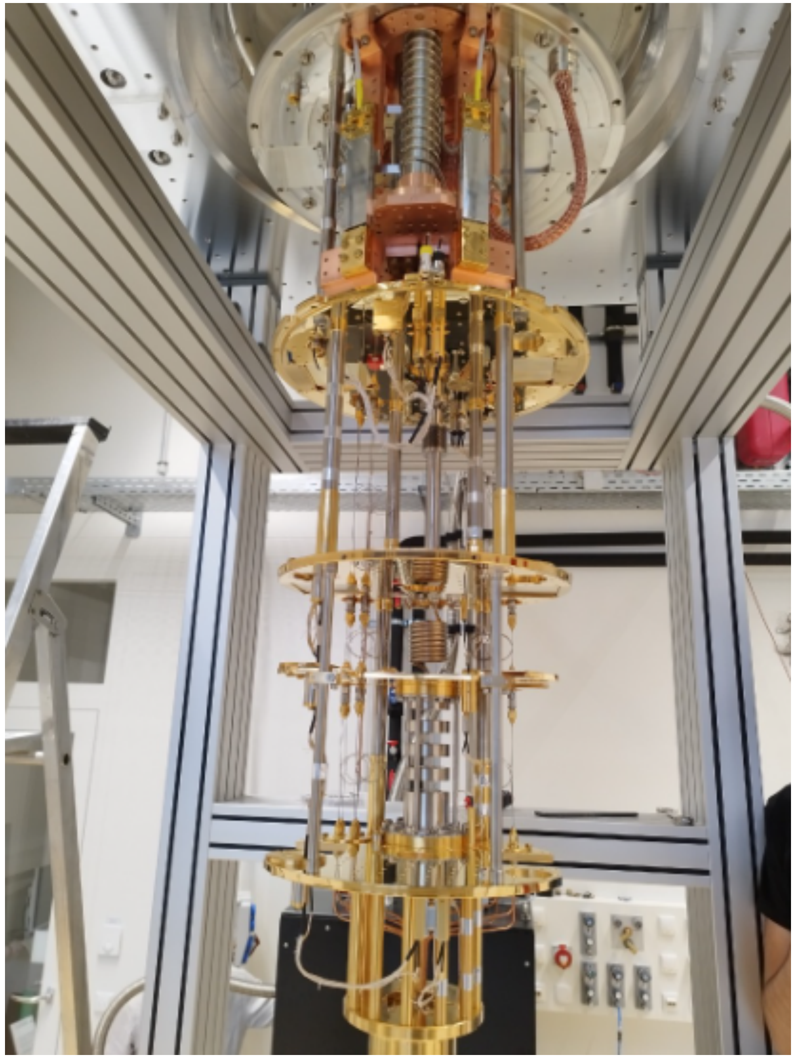
RADES AT MPP: mK CRYOSTAT WITH MAGNET

Technical specifications:

- Dilution fridge with 6.5 mK base temperature
- Cold volume of 294 mm ⌀ below the mixing chamber
- Equipped with a solenoid magnet: 12T, 65 mm ⌀, ~400 mm L

Goals:

- Implementation of quantum noise limited amplifiers
- Exploring new detection schemes, e.g. single photon counting
- Possibility of a first physics run at MPP

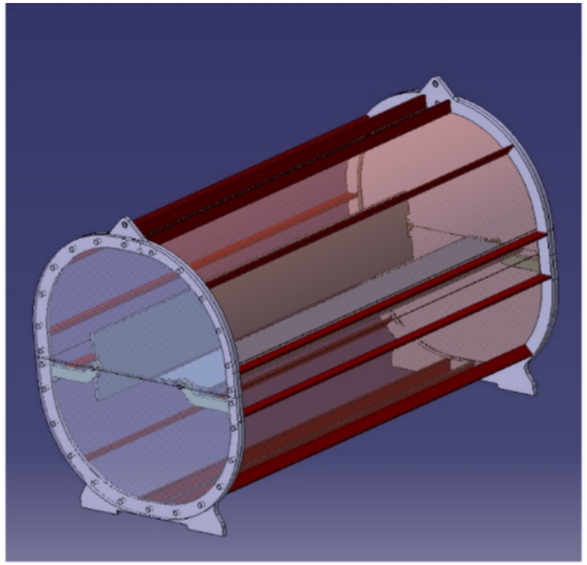


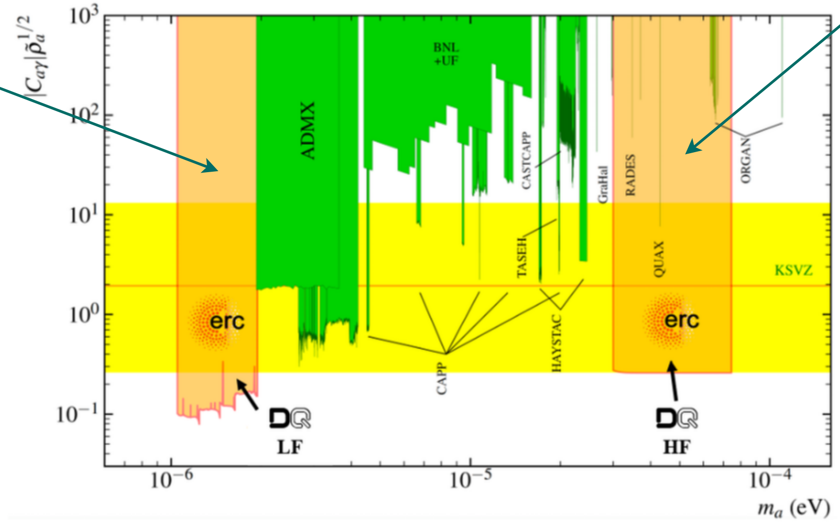
DARK QUANTUM

- ERC Synergy grant awarded on 2023

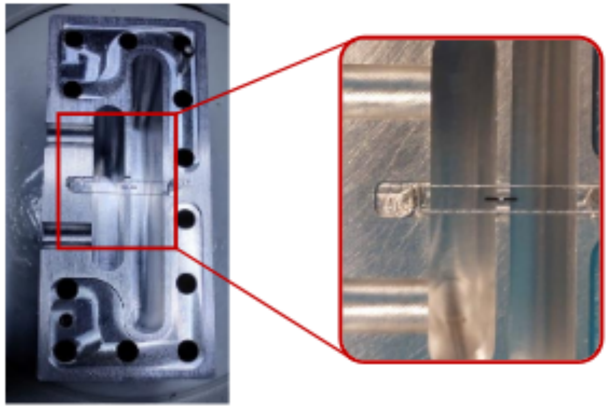
For developing cryogenics & quantum-limited readout for two different quantum-enhanced haloscopes

DQ Low Frequency:
Longer cavities to be installed in the BabyIAXO magnet





DQ High Frequency:
Superconducting qubits as quantum sensors



SUMMARY AND OUTLOOK

- The QCD axion is a well motivated extension of standard model
- Axions could solve the strong CP problem and be the dark matter
- Conventional haloscopes are limited for going to both higher and lower masses
- Covering unexplored regions of the parameter space require both innovative approaches and the development of cutting edge technologies.
- In the RADES collaboration we have performed three different axion searches at higher frequencies
- With more than 30 members from different institutions in Europe we are exploring novel technologies for axion detection
- Recently secured funding will allow us to develop technologies for reaching unexplored areas of the axion parameter space both at higher and lower masses than conventional haloscopes

THANKS FOR YOUR ATTENTION AND HAPPY HOLIDAYS