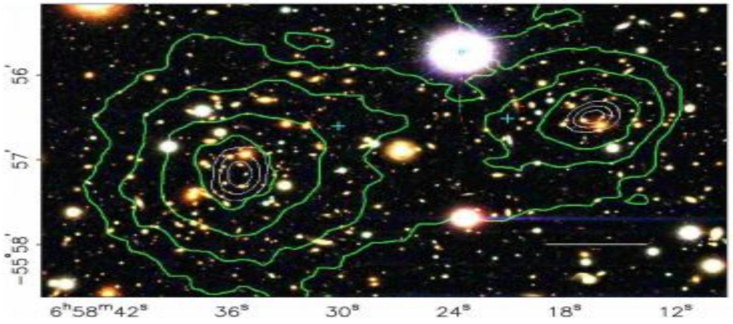
Search for new light-weight physics — opportunistically and strategically —

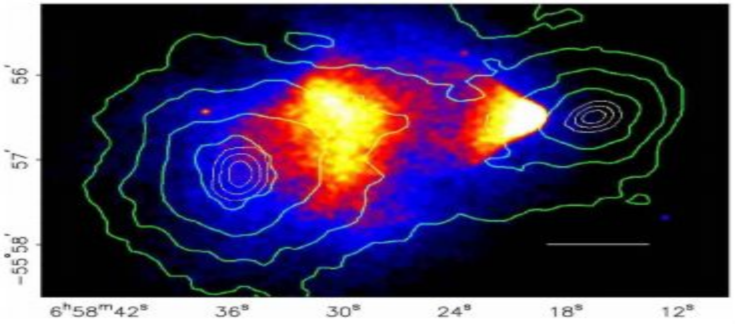
Babette Döbrich
(Max Planck Institute for Physics)

European Research Council
Established by the European Commission

We know about the gravitational effects of smth called “Dark Matter”

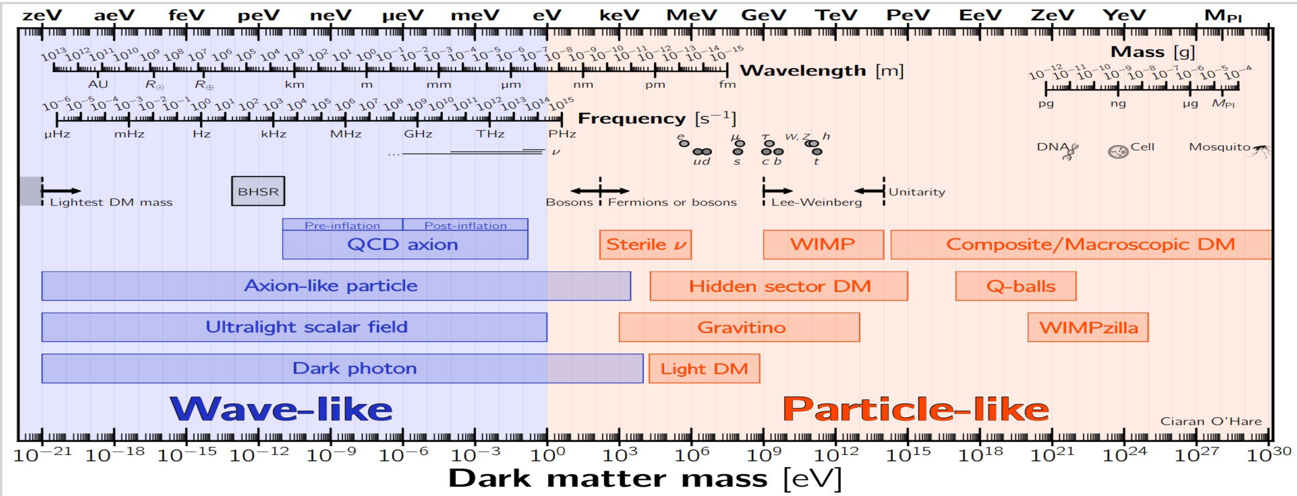
- **Assuming this is due to a particle we haven’t seen yet understand the composition of 80% of the matter in the universe!**
- **There is a plethora of evidence supporting this statement, maybe the most famous example is the “bullet cluster”**
- **Most importantly evidence exists on a <u>plentitude of length scales</u>**
  - CMB
  - Structure formation
  - Galaxy rotation curves …..



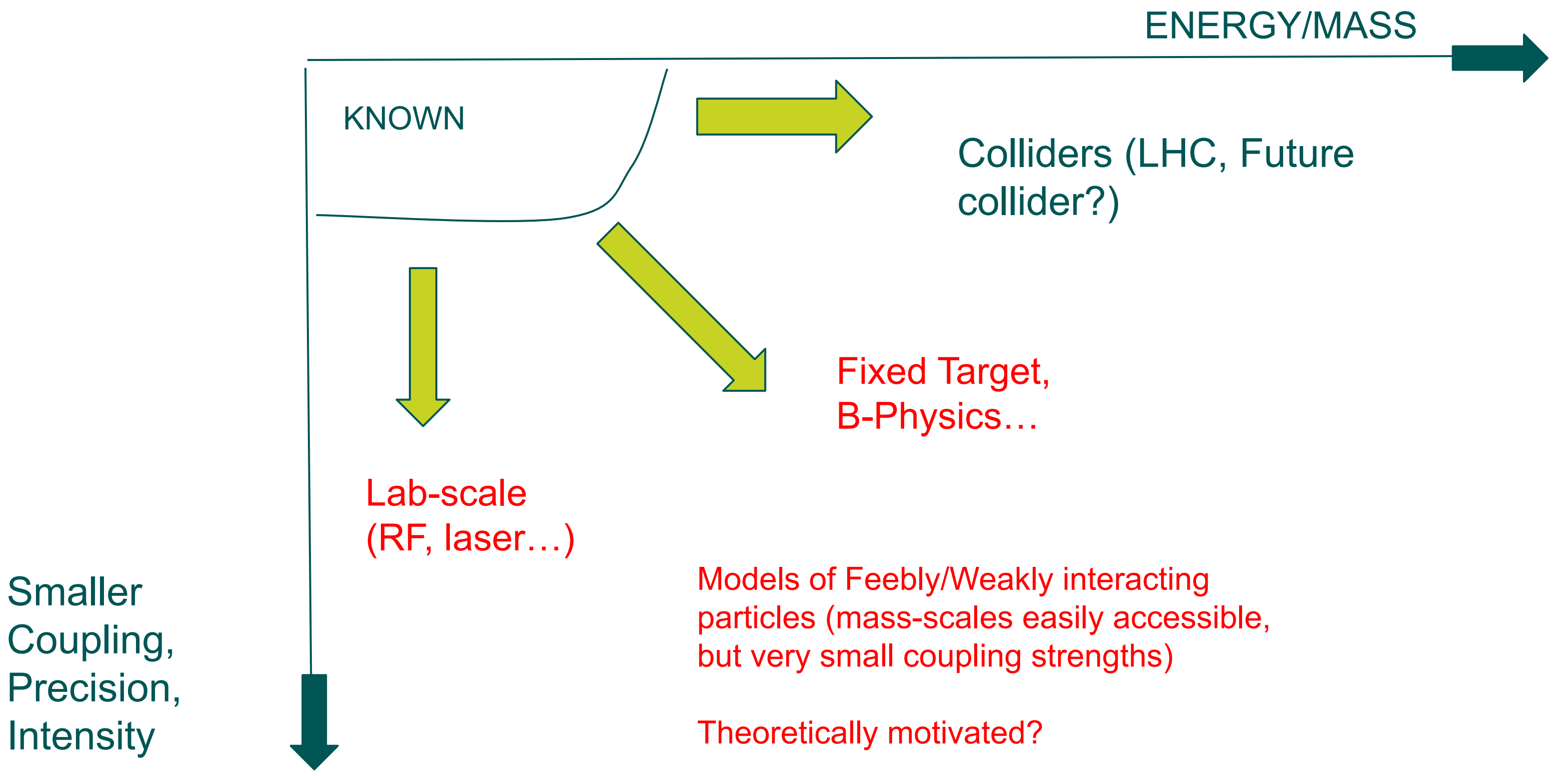


We know about the gravitational effects of smth called “Dark Matter”

- **Unfortunately our models of Dark Matter, also span multiple orders of magnitude in mass….**
- **We should have a healthy mix of strategies to probe the various possibilities**
  - Opportunistically: Test novel hypotheses quickly, with modest resources, possibly getting lucky! (train students from “A to Z”, try out new ideas that find no room in more formal projects)
  - Strategically: Think long-term and build or exploit collaboratively the best machines to get sensitivity to even the more “pessimistic models” among those who are most “well-motivated”



How to improve our understanding (non-comprehensive!)



The axion(-like-particle): A prime example for a weakly interacting particle

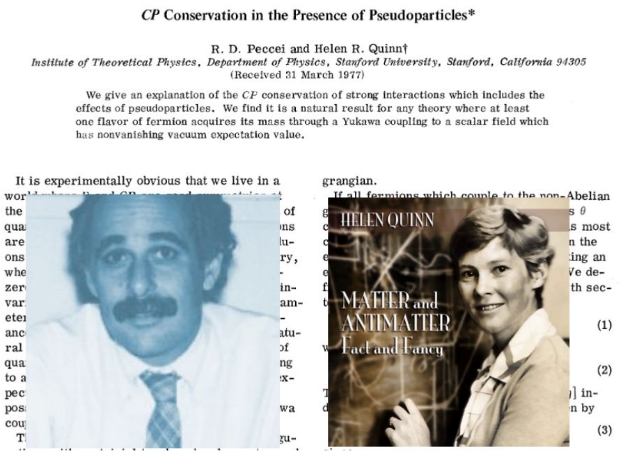
- “Vanilla axion”: solve the strong CP problem & be cold Dark matter
- QCD vacuum allows for a CP violating term to which one has topological + EW contribution
- Physical observable: Neutron EDM

Naively $e/2m_n \sim 10^{-14}$ e cm

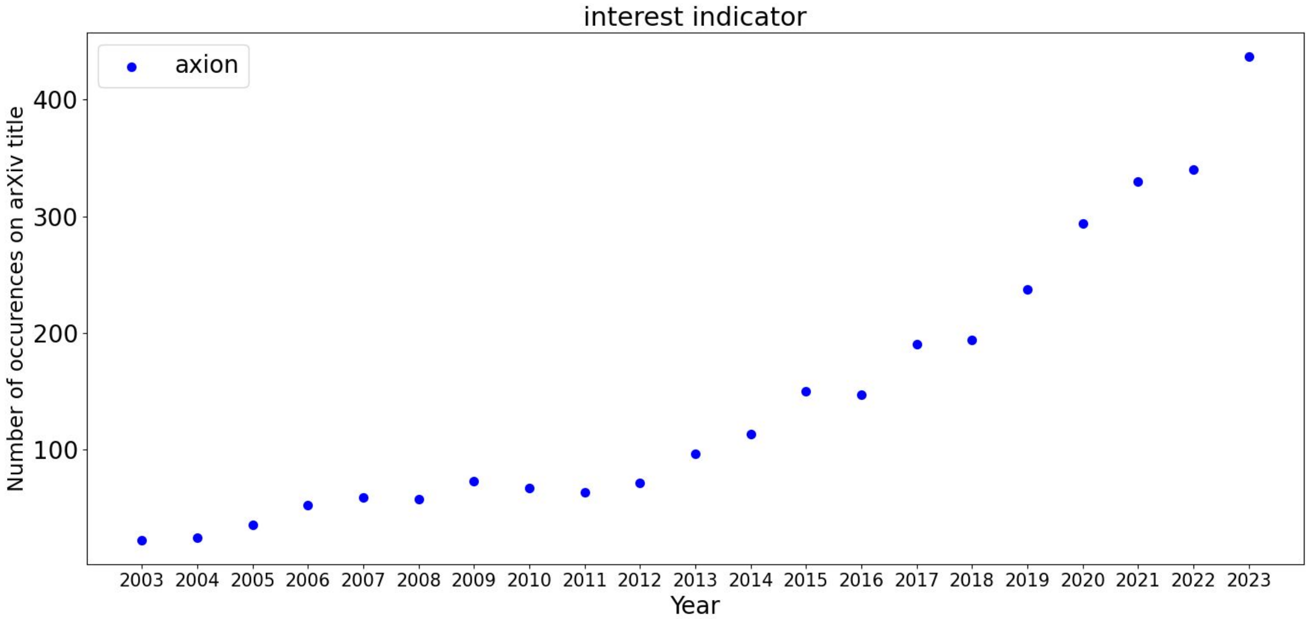
Measured $|d_n| < 10^{-26}$ e cm

→ fine-tuning $\theta < 10^{-10}$

This can be considered a problem, unless θ is related to a <u>dynamical field, the axion</u>



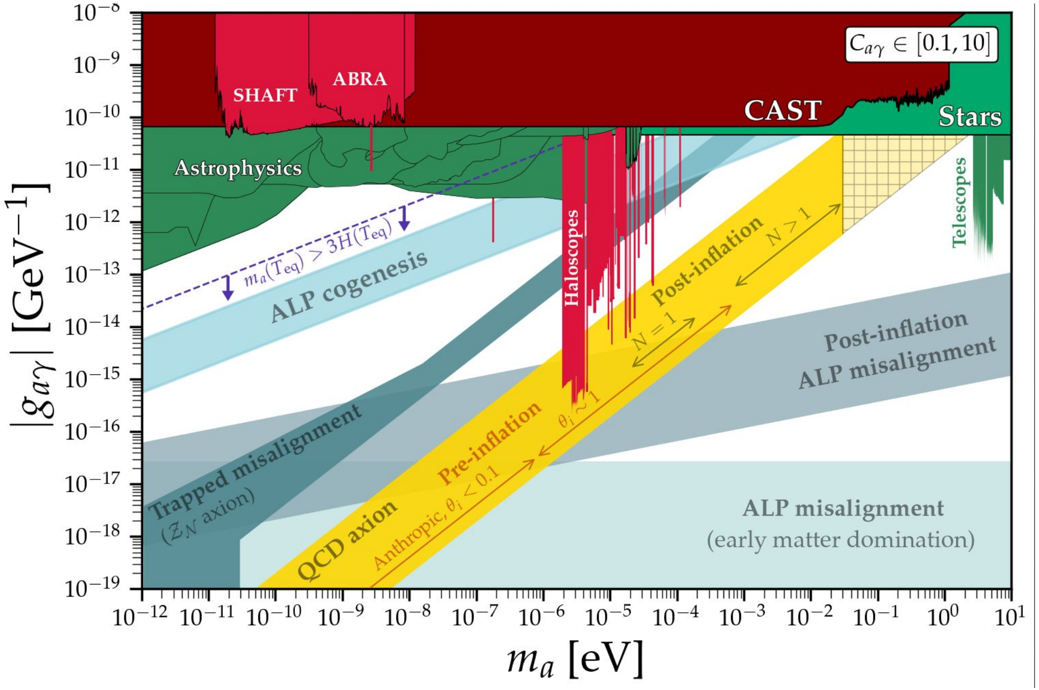
I assume that this is not the only axion talk you have heard lately…



1) Given this (exponential?) trend, we should hope to be able to confirm or rule out the axion as DM
2) Caveat: the term axion is not always used in its ``vanilla version''

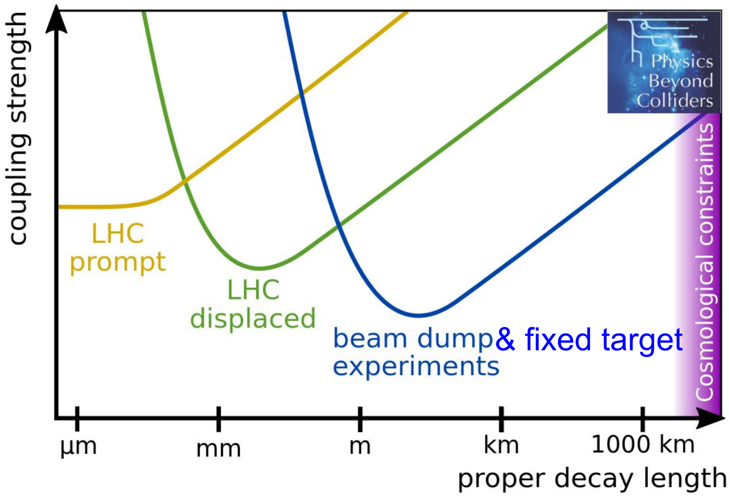
Community Glossary: axion, axion-like and axion-DM

- The `vanilla' axion lives in the yellow region
- The axion-DM lives below approx ~10^-2 eV
- The axion-like particle lives anywhere that experiments/astro-probes haven't probed yet (and may in some regions still be DM). It is phenomenologically motivated & appears in SM extensions (e.g. string theory)



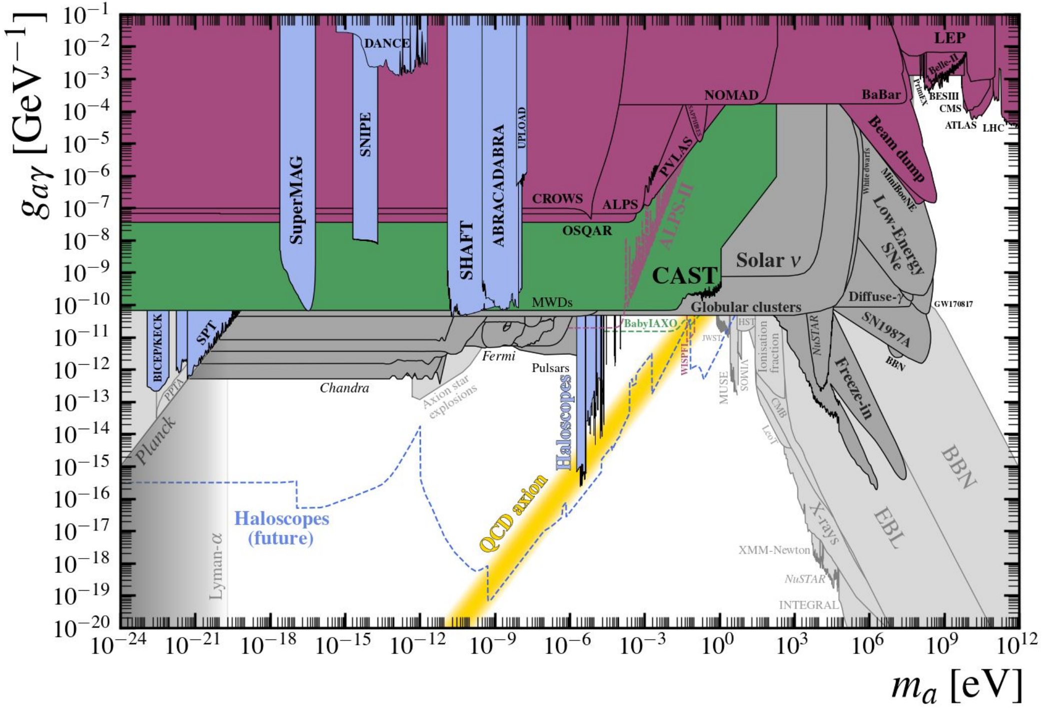
Why are heavier axion-like particles also interesting?

- In fact, poor constraints in that region (see next slides), fixed target can be very complementary to collider sensitivities
- Possible connection to anomalies in particle physics, (X17 Boson) [Hostert & M. Pospelov, Phys. Rev. D105 (2022) 015017]
- ``WIMPless miracle” e.g. [Feng, Kumar]: DM can be a thermal relic but significantly lighter than TeV without overproducing it. This can be achieved by “portal” mediators that are BSM states



adapted from [2310.17726]

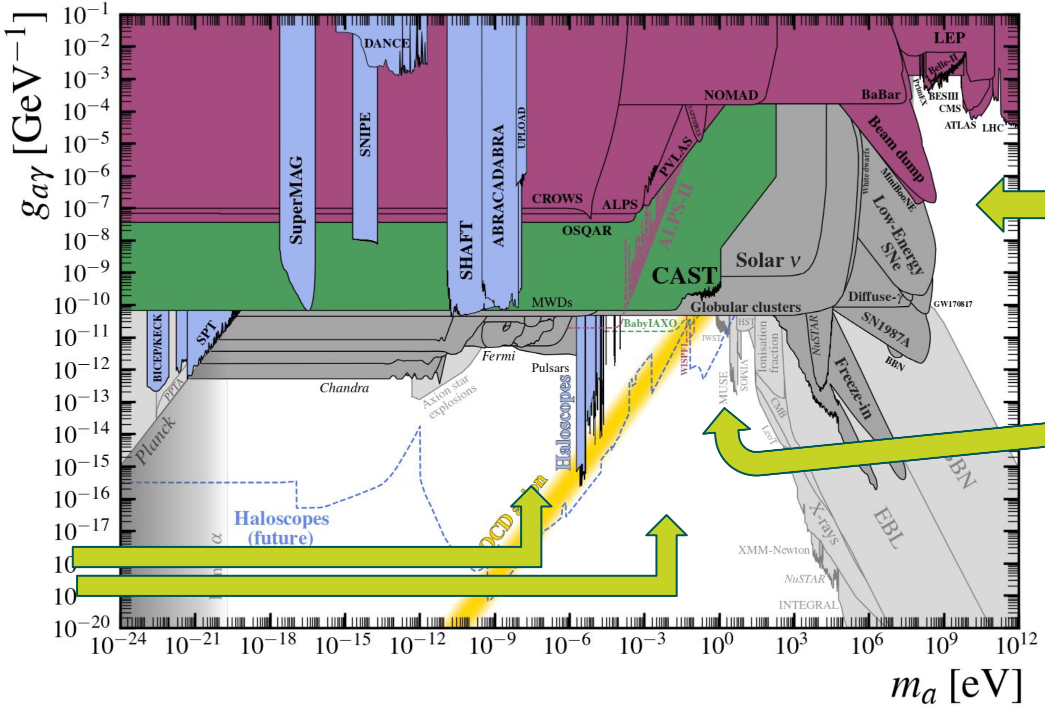
Summarizing what I said so far: the Axion (and ALP) parameter space



[this and most overview limit plots taken from Ciaran Github]

Summarizing what I said so far: the Axion (and ALP) hide-outs

Classical and (quantum-limited?) Haloscope searches with



RADES

Beam-Dump/ Fixed Target Searches

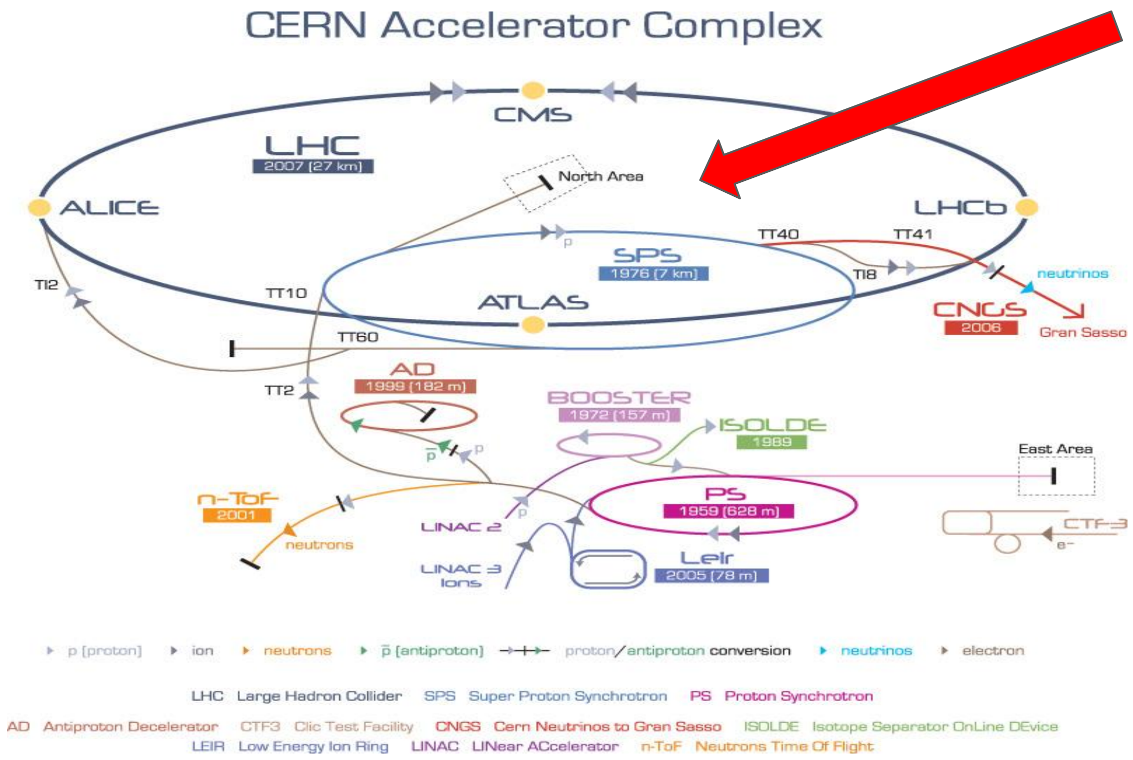
And Kaon decays

at

NA62

[this and most overview limit plots taken from Ciaran Github]

NA62 @ CERN/Prevessin



- Fixed target experiment at CERN's north area (NA) with ~200 participants
- Primary proton beam of 400GeV from the SPS
- secondary Kaon beam of ~75GeV
- **Main goal:** measure branching ratio

$$K^+ \to \pi^+ \nu \bar{\nu}$$

- Precisely predicted in theory, experimentally not (yet) well-known
- Requires some space due to the comparably long Kaon lifetime

NA62 experiment: timeline and impressions

2008 NA62 approval → 2009-2014 detector R&D, installation → 2016-2018 Physis Run → 2019-2021 LS2 upgrades → 2021-2025 Physics Run

"Run 1" (2016-2018) "Run 2" (2021-2025)

<- View of the ECN3 hall

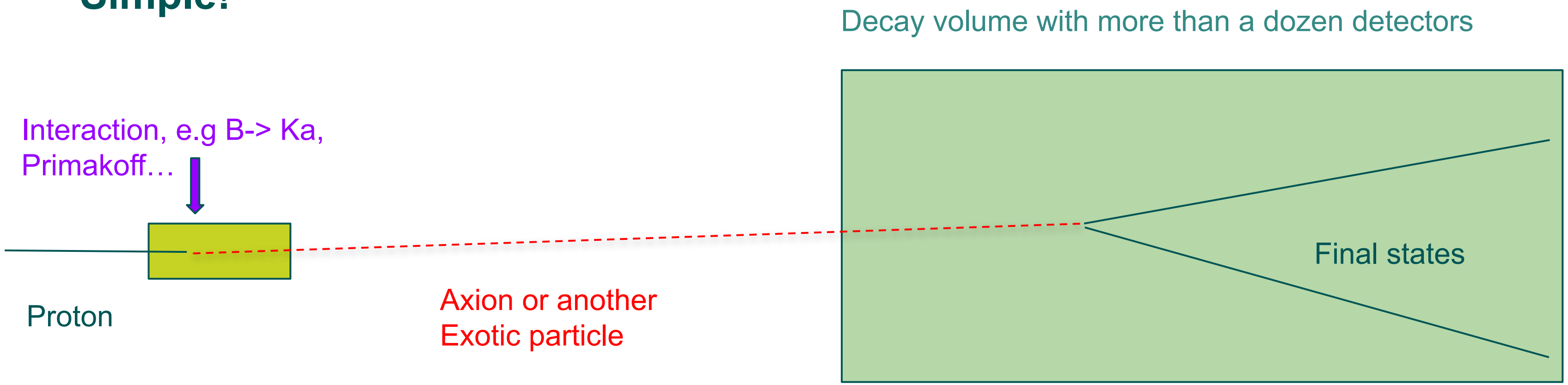
Axions & ALPs @NA62

Besides the main measurement, collaboration organized in 3 Working groups, all of which have results on axions, see those examples:

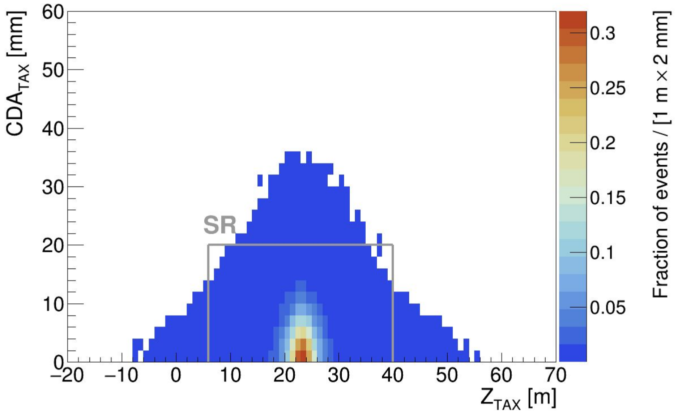
- Precision measurements (sensitive to light non-flavor-diagonal axions in $K^+ \to \pi^+ a$)
- Rare and forbidden decays (e.g. $K^+ \to \pi^+ aa \to \pi^+ e^+ e^- e^+ e^-$)

- **Beam dump/Exotics (remove the target in which Kaons created & shoot the protons directly into a dump. Then, axions created in the proton-dump interaction can reach the decay volume and their decay products recorded)**

Simple!

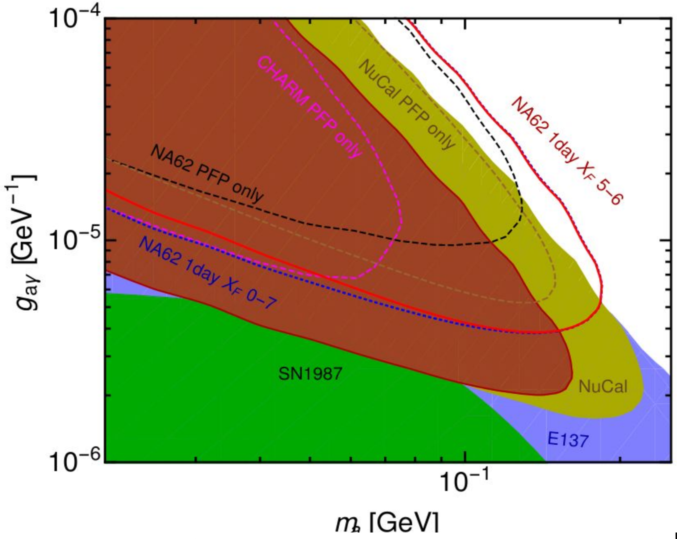


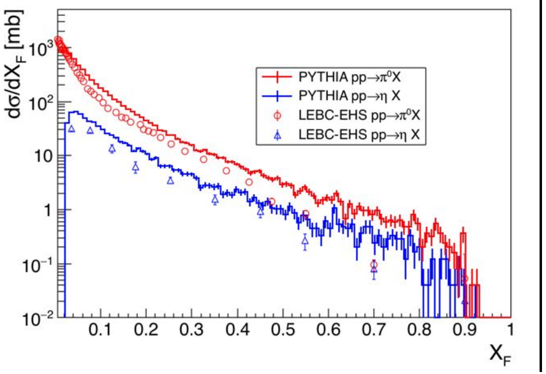
Example of Monte Carlo signal event distribution for exotic particle to di-muon final state



The devil is in the details

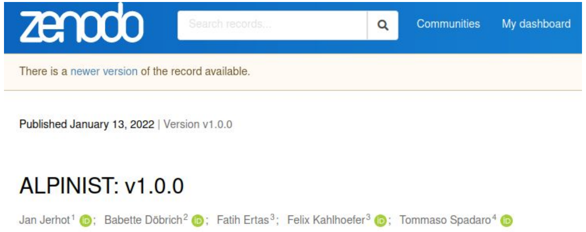
- Conceptual idea and first public sensitivity estimates for beam-dump searches in 2015 [BD et al, *JHEP* 02 (2016) 018], focussing on di-photon final state
- Convince the collaboration!
- Assess relevant production mechanisms, sometimes the dominant ones were/are not (properly) evaluated in literature
- How to model the signal (mesons) [BD et al, *JHEP* 05 (2019) 213]





The devil is in the details

- Is what you do really novel? Recheck/recast previous experiments in modern models in a reproducible & transparent fashion, allow for additions [Jerhot et al, *JHEP* 07 (2022) 094], used in community studies

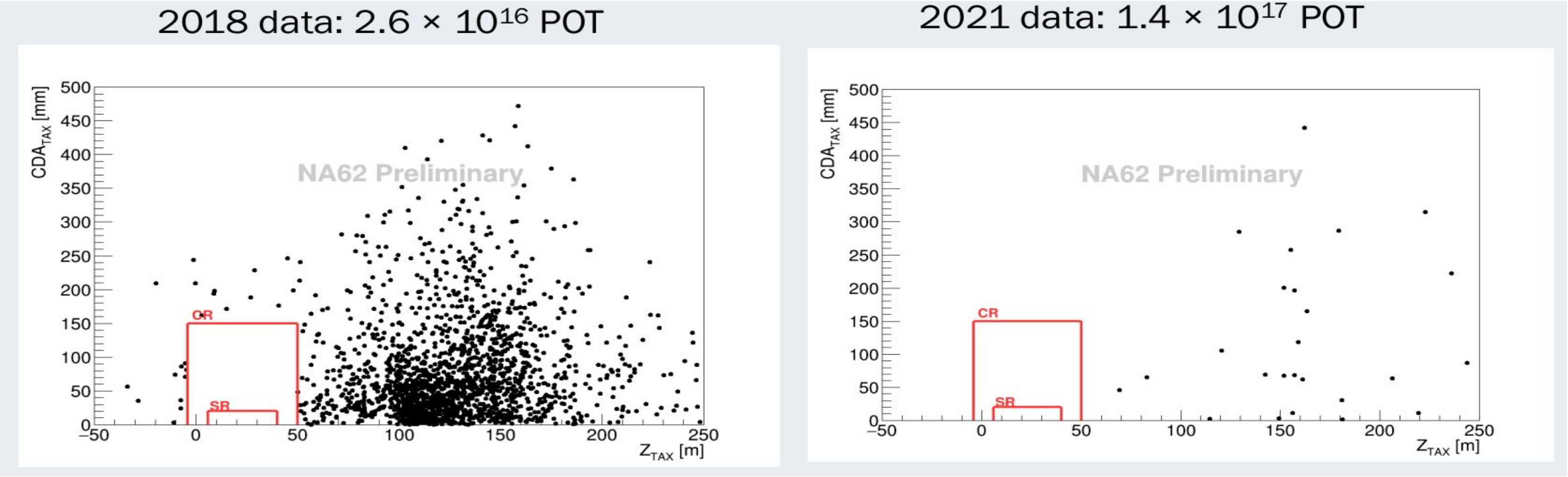


Experimentally:

- How to suppress background (following slide?)
- How to model/understand the background (for the equivalent statistics of 10^{17} Protons shot on target!)

Background reduction 2018 vs 2021

- **Naively switching from Kaon to dump-mode in 2018**
- **upstream magnet tuned subsequently** to increase muon sweeping
- In 2021, compared to 2018, background rejection was increased by **O(200)** on most 2-track channels despite higher intensity (example below: $\mu^+\mu^-$)

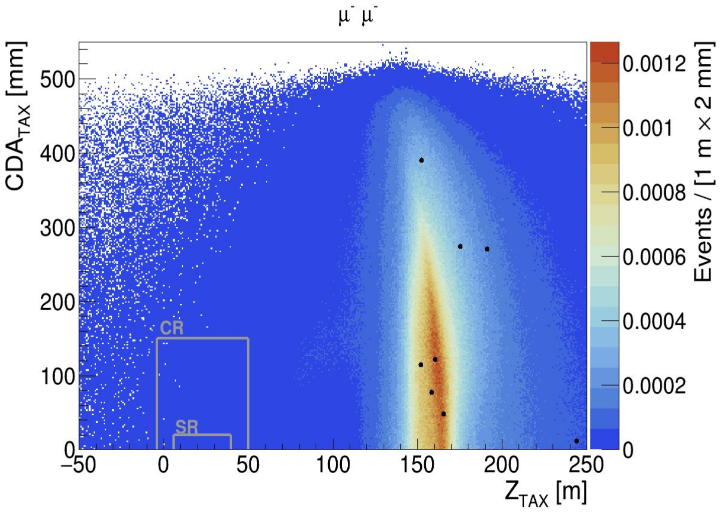


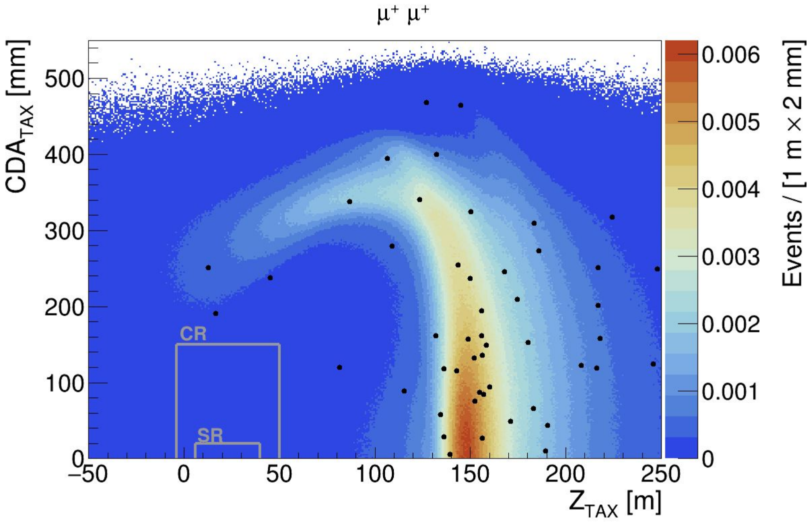
Towards analysing the 2021 data: same-sign control sample

- Background greatly reduced in 2021
- Still for a believable analysis, say the decay of an axion into $\mu^+\mu^-$ we need to be able to understand all remaining events, this includes accidental (not-in-time) as well as prompt (in-time) contributions

Towards analysing the 2021 data: same-sign control sample

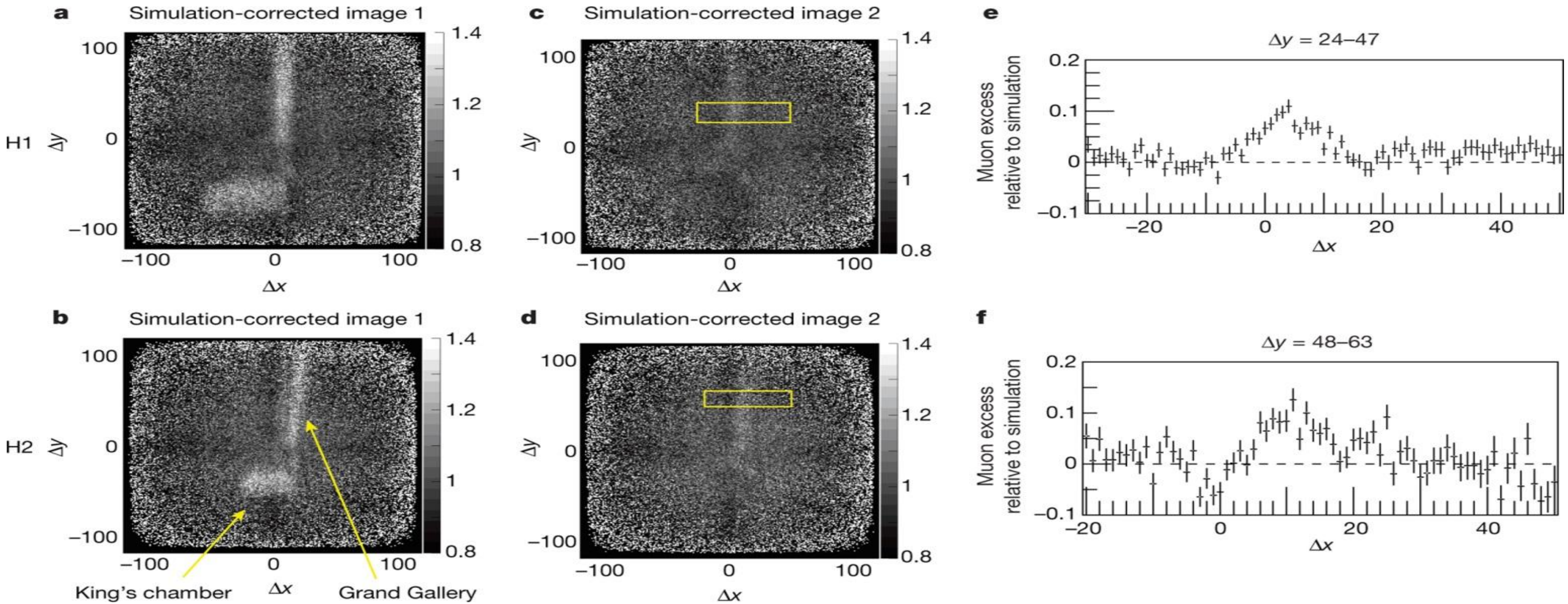
Out-of-time background: Collect event single track sample sample from independent trigger line and overlay!





This handles the accidental contribution, how about in-time backgrounds (i.e. events from interaction)?

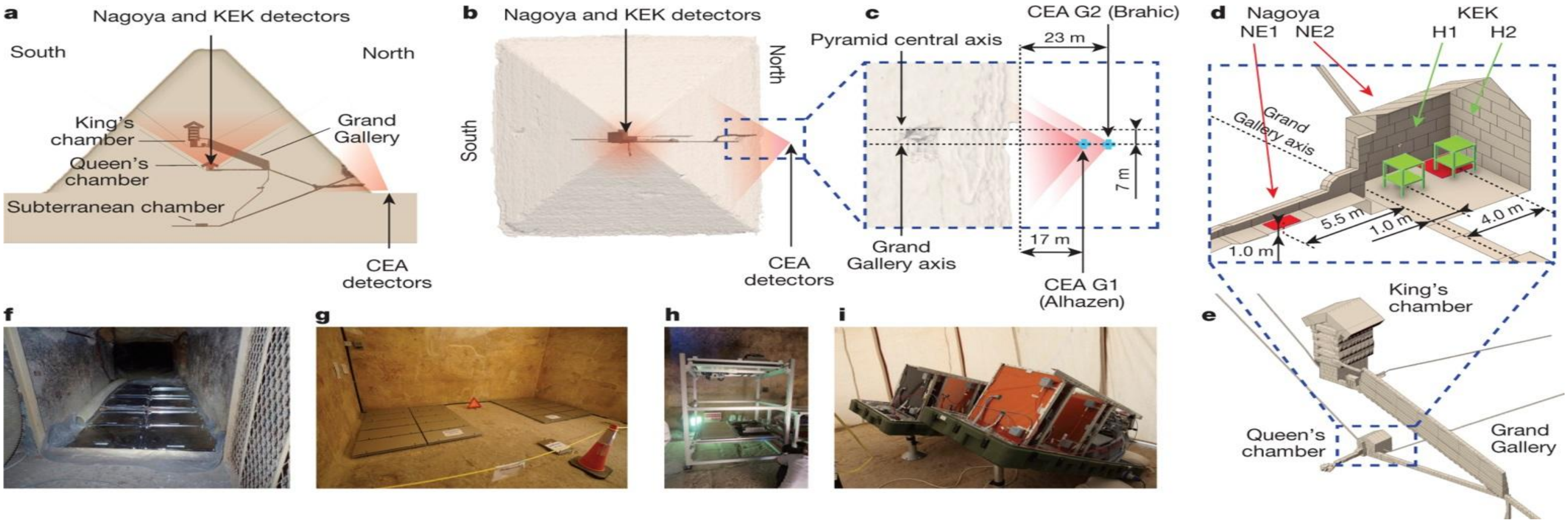
Digression: your turn! world news in 2017



K Morishima *et al. Nature* **552,** 386–390 (2017) doi:10.1038/nature24647

nature

Muography for Khufu's Pyramid



K Morishima *et al.* *Nature* **552,** 386–390 (2017) doi:10.1038/nature24647

nature

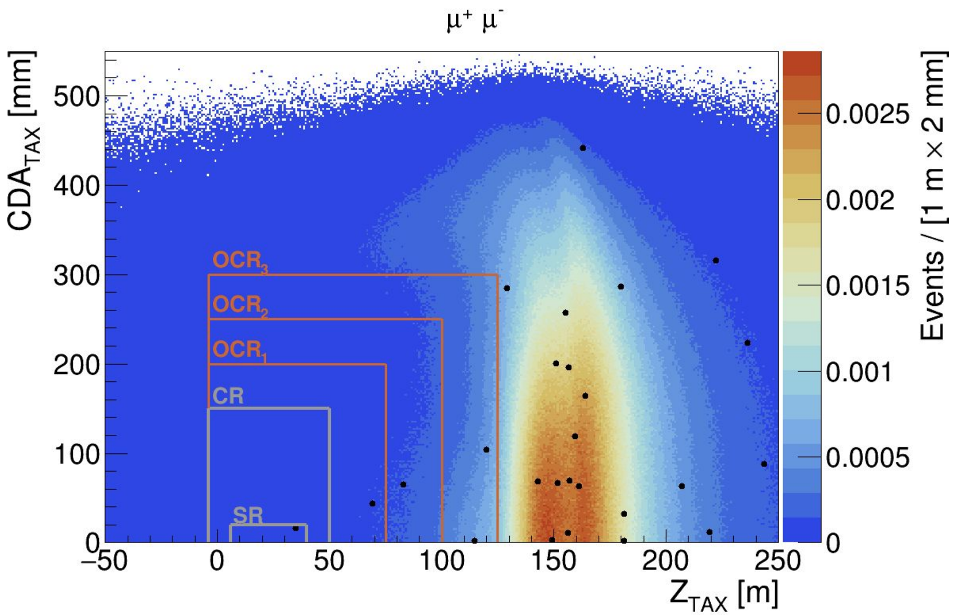
Data-MC comparison: Signal Region open $\mu^+\mu^-$

- For in-time (prompt) background: **backward muon MC** - PUMAS: Propagate Muons back in time (adding Energy) to a given plane, then forward to study muon interaction with material

Blind up to now:

OK for Box-opening

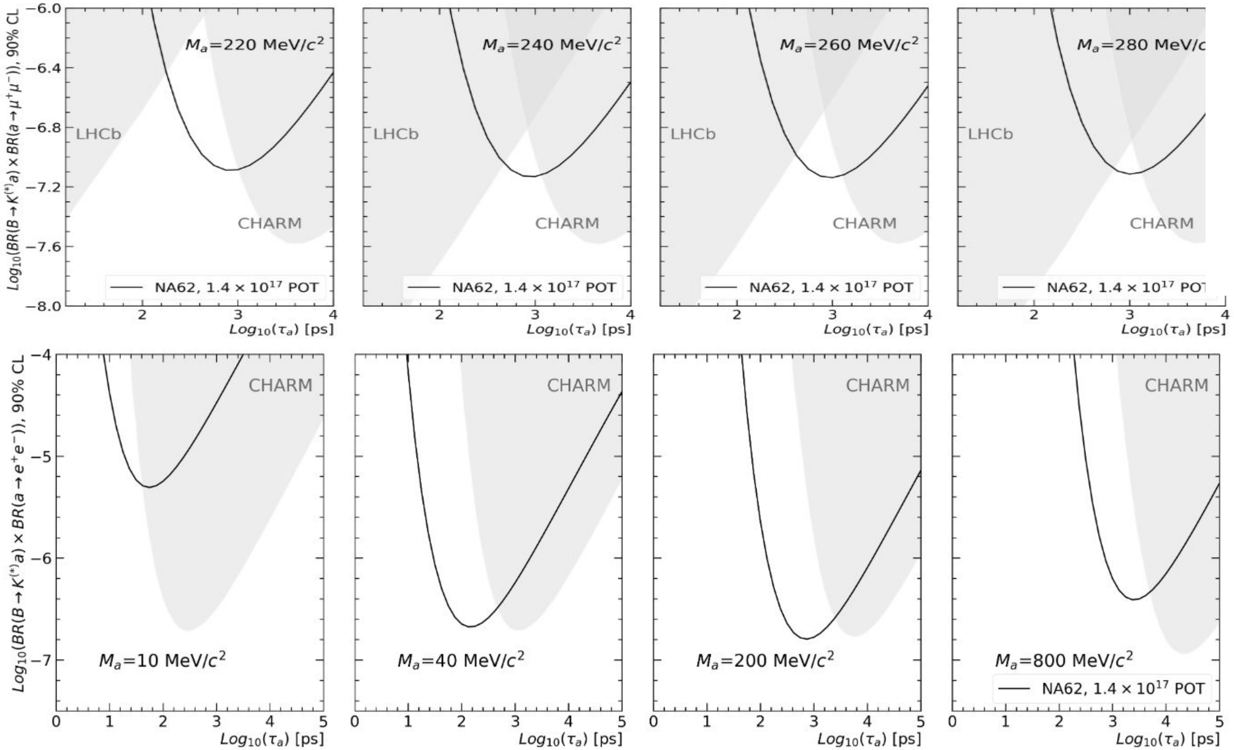
- Color scale: Expected background
- 1 event observed in (geometric and timing far tail of) SR

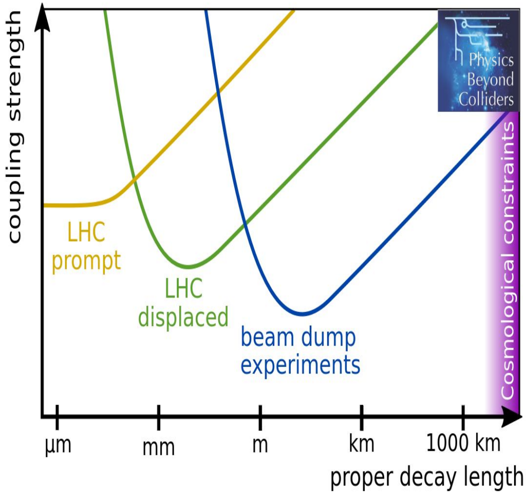


- (later analysis: No events when opening SR in e^+e^-)

… result for axion-like particles

di-muon published in JHEP 09 (2023) 035, di-electron accepted in PRL [2312.12055]





Top: $\mu^+\mu^-$,
bottom: e^+e^-

Assuming mass, lifetime and coupling to be independent parameters
see BD et al. , PLB 790 (2019) 537

CERNCOURIER | Reporting on international high-energy physics

SEARCHES FOR NEW PHYSICS | NEWS

Searching for dark photons in beam-dump mode

24 April 2023

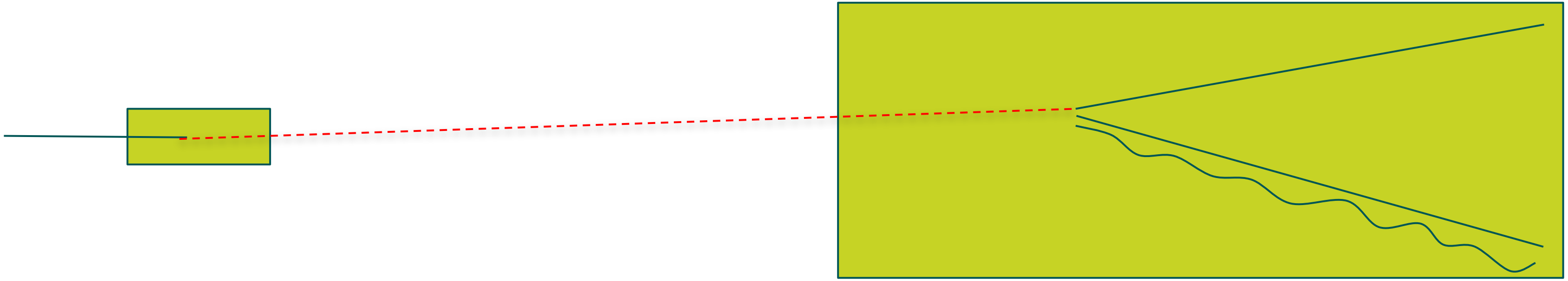
Intense Part of the NA62 detector in the ECN3 experimental hall in Prevessin, where beam travels from right to left. On the right-hand side is the STRAW spectrometer, with the analysing magnet in blue. Four large-angle vetoes serving to clean the samples from non-forward events are visible in white, while the green region houses the RICH detector. Credit: CERN-PHOTO-202104-059-6

Faced with the no-show of phenomena beyond the Standard Model at the high mass and energy scales explored so far by the LHC, it has recently become a much considered possibility that new physics hides "in plain sight", namely at mass scales that can be very easily accessed but at very small coupling strengths. If this were the case, then high-intensity experiments have an advantage: thanks to the large number of events that can be generated, even the most feeble couplings corresponding to the rarest processes can be accessible.

Such a high-intensity experiment is NA62 at CERN's North Area. Designed to measure the ultra-rare kaon decay $K \to \pi\nu\bar{\nu}$, it has also released several results probing the existence of weakly coupled processes that could become visible in its apparatus, a prominent example being the decay of a kaon into a pion and an axion. But there is also an unusual way in which NA62 can probe this kind of physics using a configuration that was not foreseen when the experiment was planned, for which the first result was recently reported.

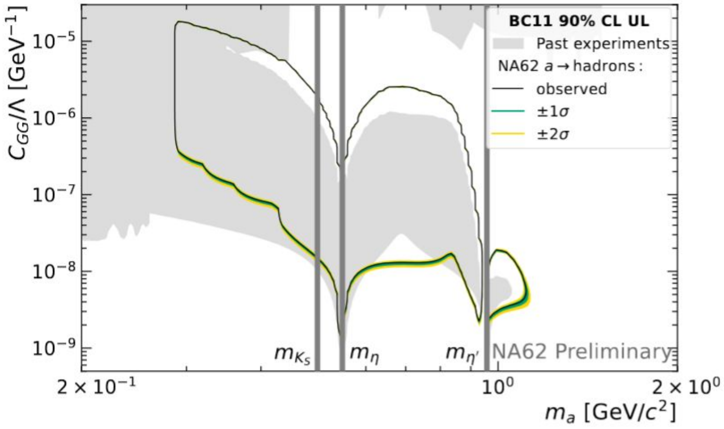
Article in CERN courier from April 24th 2023:
link

Other results: Hadronic decays (with photons)

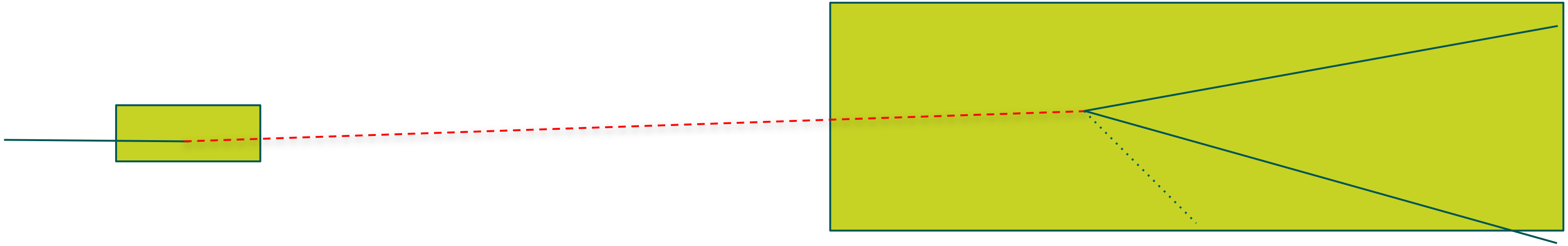


ALP to $\pi^+\pi^-, \pi^+\pi^-\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\eta, K^+K^-, K^+K^-\pi^0$

- Recently presented at Moriond 2024, limits set on ALP-Gluon coupling, first since the 90s!
- Upgraded PID (NN) + Refined box-opening strategy (from more complicated to simpler topologies)
- Low Background from “beam Kaons”

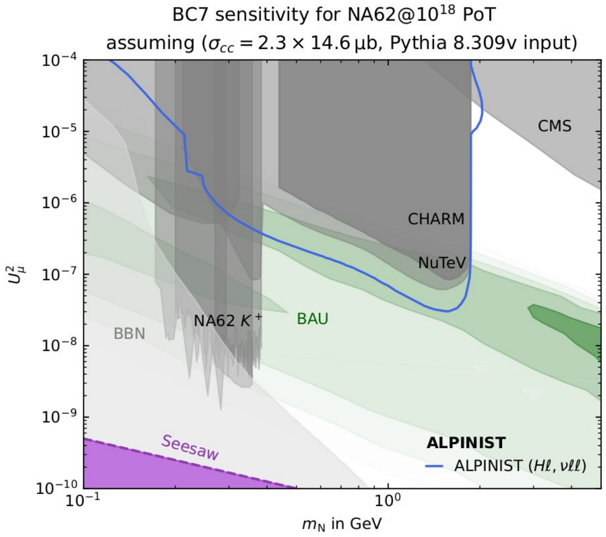


Ongoing work (example): open final states involving a neutrino



- Cannot detect neutrino but can use correlation of momenta from production point
- (delicate process to validate heavy meson spectra)
- very competitive prospects to possibly discover a Heavy neutral Lepton related to explain the Baryon asymmetry in the universe (BAU) (among the most prominently advertised models to be studied in such a setting)

[Schubert et al, in preparation]

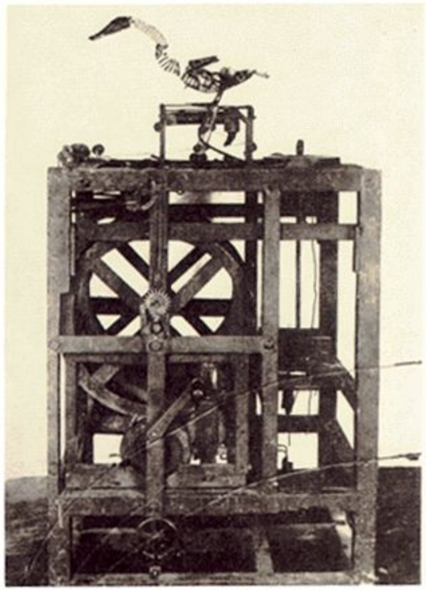


What's next at the MeV-GeV scale?

- **Taking data at NA62 as we speak & next year, poised to complete several additional analyses that will either set a competitive limit (or much preferred: discover new physics), models to test keep on coming in (e.g. G. Perez 2405.06744)**
- **We proposed to continue with the NA62 physics programme (with 4x intensity) after LS3** **(MPP team was/is involved for a scintillator-based veto…)**
- **CERN management decided in favor of the SHiP proposal (beam-dump only from ~203x, no more charged Kaon decays in foreseeable future).**
- **In any case, our work already had a big impact on the field**
  - First results in relevant parameter regions since the 80s (together with FASER@LHC)
  - Strategies to understand & mitigate remaining rare backgrounds at 10^17 POT
  - Fundamental work on validation and completion of phenomenological input for these searches

Now, a bit lighter (in mass!)

- We could discover a (stable or unstable) axion at NA62
- Even if it looks `dark', we would still need to prove that this can be related to Dark Matter or better:
  CONSTITUTE the dark matter
- We should also work on direct detection!
- For axions, it turns out this is done in a most straightforward way using their coupling to photons



RADES collaboration meeting

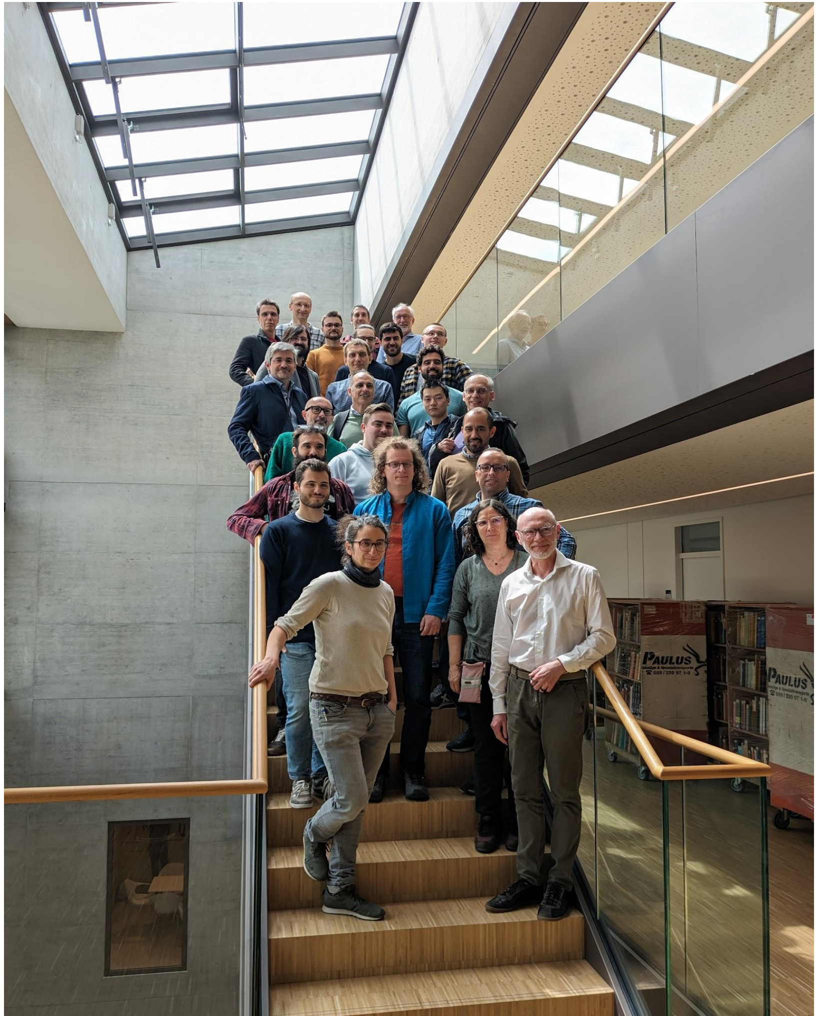
(& ERC-SYG DarkQuantum kick-off)

May 7 & 8, 2024 at MPP

RADES = Relic Axion Detector Exploratory Setup

Members from: Aalto, Barcelona (x3), Cartagena-UPCT, CERN, KIT, MPP, Mainz, OAN Yebes, ENS-Paris, TRIUMF, Valencia, Zaragoza

*axion/particle *quantum *cryo *HTS *RF *radiopure



What is RADES? (overview)

- Started as “opportunistic idea” with a handful of people to use the CAST dipole as haloscope* in order to discover (or exclude) the axion in a so-far untackled mass region (will explain in the next slides)
- Several R&D strains to improve the individual terms Figure of Merit for such haloscopes*
- Grown into a larger collaboration that intends to strategically search for axions & develop single photon detectors
- Support secured through ERC-Stg, ERC-SYG and QUANTERA

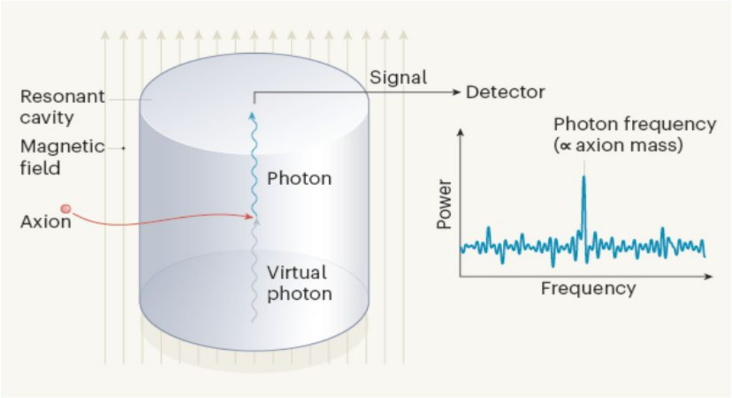
erc
European Research Council
Established by the European Commission

QUANTERA

The programme
QuantERA ERA-NET Cofund in Quantum Technologies

- * Jargon that will be explained momentarily

*The classical (Sikivie) haloscope



*Principle scheme of a cavity haloscope (from I. G. Irastorza, Nature **590**, 226-227 (2021))*

- Resonantly convert the Axion Dark matter into RF signal by placing em resonator (appropriate mode overlap parameterized in G, volume V) in a strong external magnetic field B
- m ~ f_resonance (cold Dark Matter)
- Advantage: profits from with amplification Q
- Disadvantage: scanning needed, usually performed via rotating rods inside the cavity
- Leading results by ADMX (US) and CAPP (Korea)

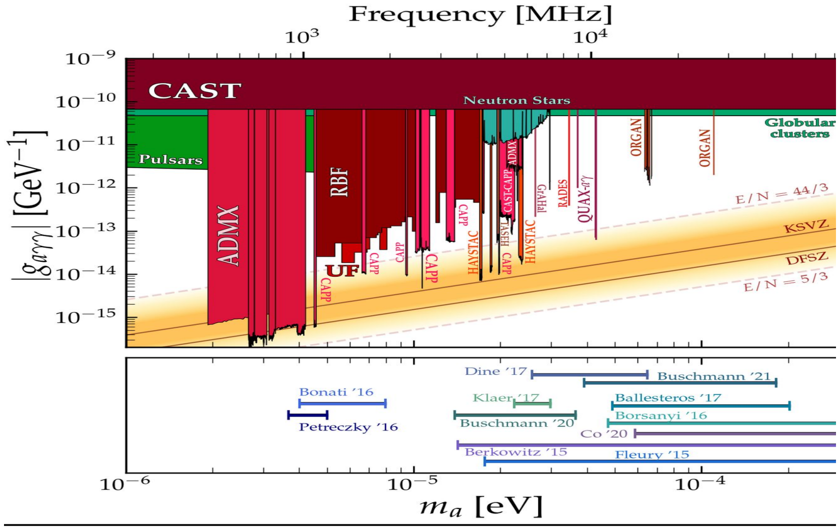
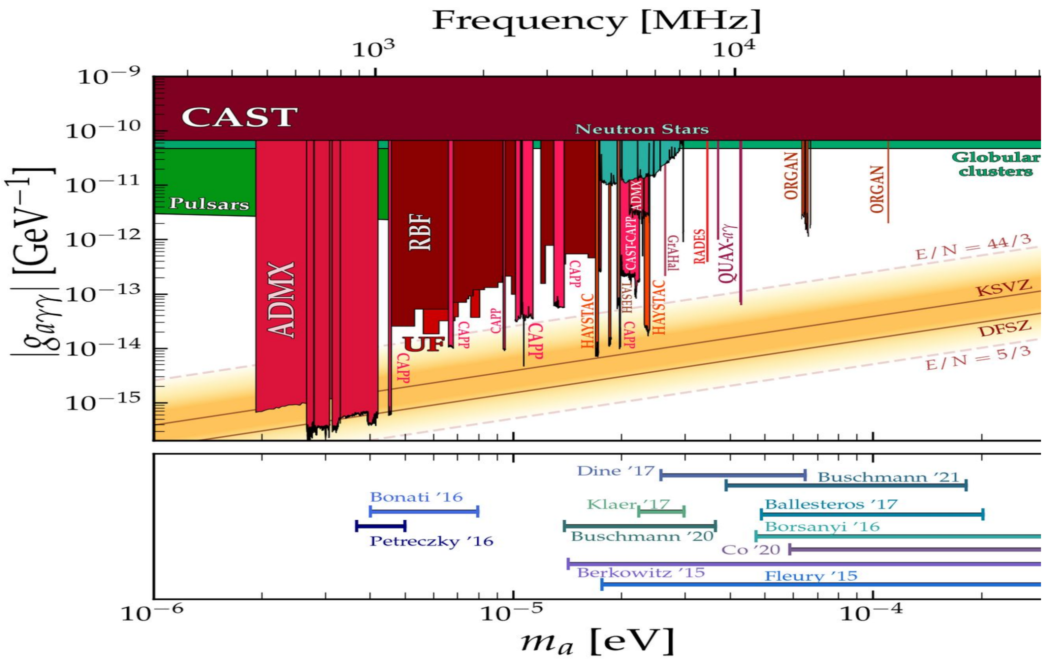


Figure of merit:

$$F \sim g^4 m^2 B^4 V^2 T_{\rm sys}^{-2} \mathcal{G}^4 Q$$

The classical (Sikivie) haloscope, II



$$F \sim g^4 m^2 B^4 V^2 T_{\mathrm{sys}}^{-2} \mathcal{G}^4 Q$$

- Volume and Quality factor decrease at “larger” Axion masses (cavities become smaller, naively)
- Particularly unfortunate as for the “post-inflationary regime”, the axion mass can be computed “in principle”
- One workaround: ``give up” on haloscope principe, use dielectric layers coherently (MADMAX)
- Another option: stick to general idea, but change some of the established worklines (RADES & many others)

Exploitation of the CAST LHC dipole for a high-mass axion search

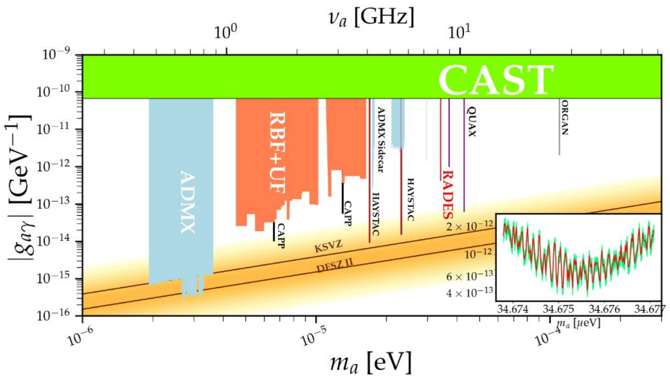
RADES "kick-off" in 2018:

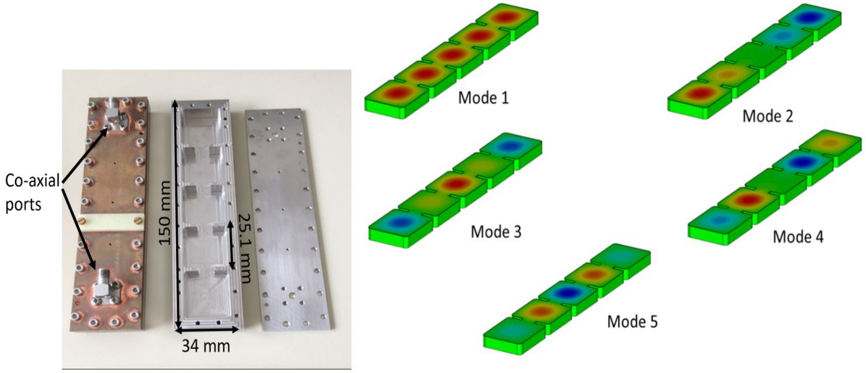
CAST magnet offered a magnetic dipole field in a very long (straight!) tube, originally used to search axions from the sun

RADES R&D example : innovative cavity geometries

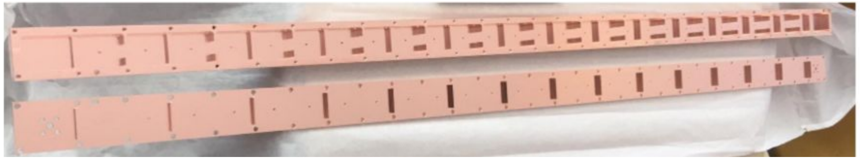
$$F \sim g^4 m^2 B^4 V^2 T_{\text{sys}}^{-2} \mathcal{G}^4 Q$$

Break Volume-frequency relation to probe higher masses than usually possible





Data-taking result; *JHEP* 21 (2020) 075, scaling up posible:



RADES R&D example: HTS

Superconducting tapes can increase Quality factor by a large factor (as also proven by CAPP/QUAX)*

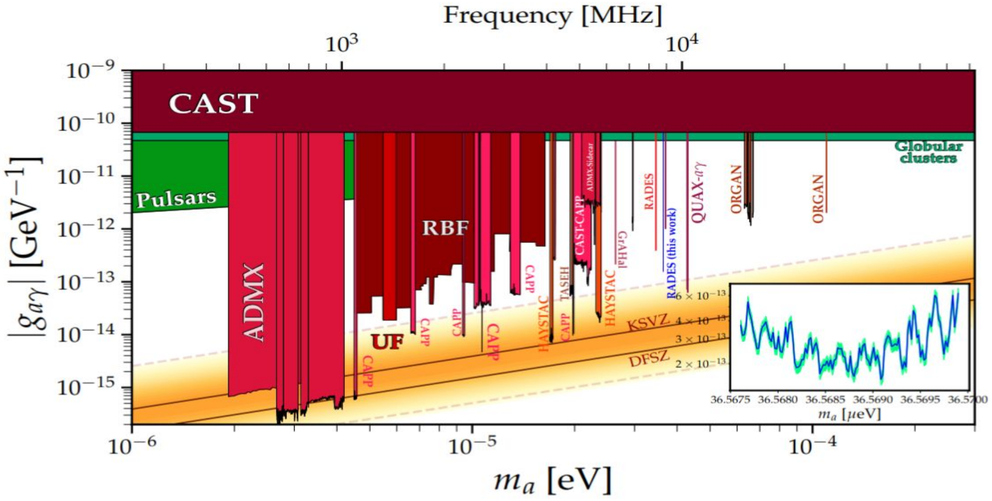
$$F \sim g^4 m^2 B^4 V^2 T_{\rm sys}^{-2} \mathcal{G}^4 Q$$

Tape attached at ICMAB by G. Telles, N. Lamas, X. Granados, T. Puig, J. Gutierrez

Axion data taking at CERN performed at 12T, new data-taking later this year (~September)

[2403.07790]

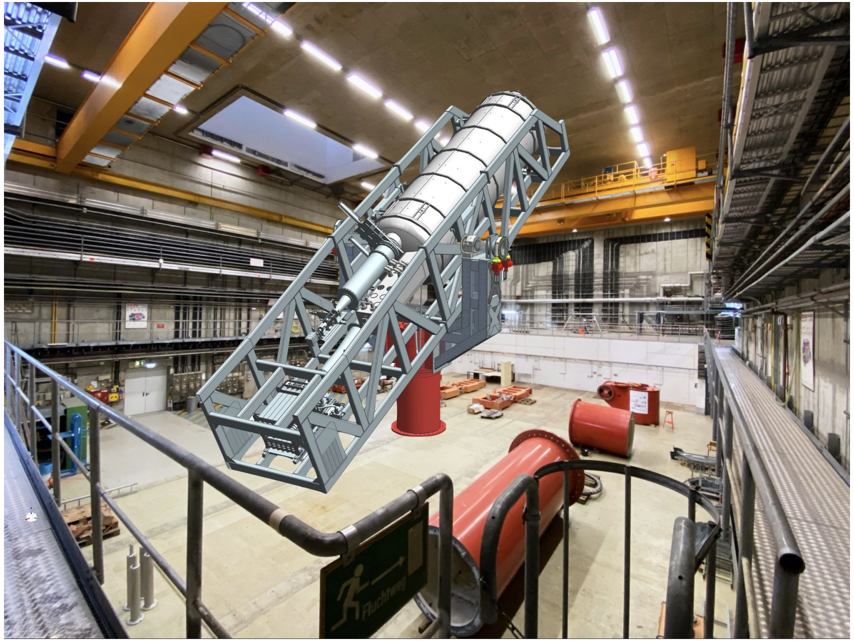
* Expert comment: demonstrated also a viable possible tuning mechanism for such cavities (which is difficult to be based on the conventional mechanical copper rod mentioned [Golm et al, Frontiers, 12, 2024])



Having build up this expertise in cavity design, RF technology, data analysis, what can we do to maximise our potential?

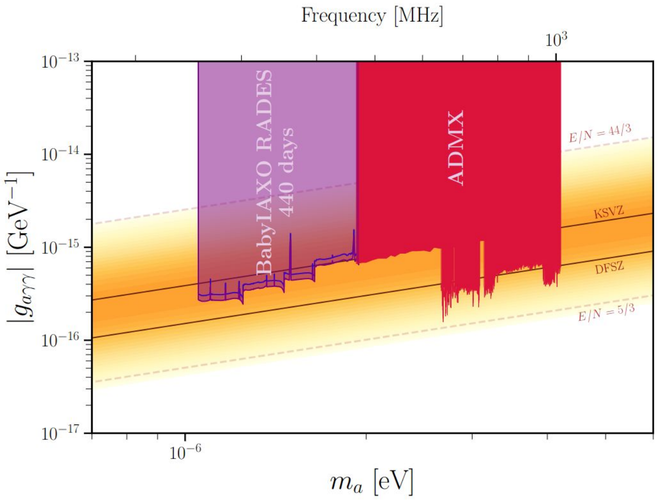
Beyond R&D: long-term #1: exploit the babyIAXO magnet infrastructure

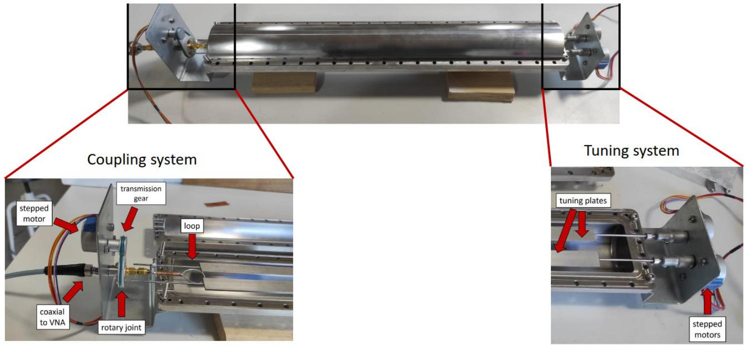
- Foreseen successor of CAST is the proposed babyIAXO experiment @DESY, also a dipole: Primary goal to act as `helioscope' , like CAST (axions from sun)
- babyIAXO would lend itself also to a cavity search (haloscope) at few hundreds of MHz (or act as a generic platform for other axion search concepts such as MADMAX)
- Exceptional magnetic volume (2 bores of 70cm, with 10m length at ~2T)
- Project status updates: process to purchase Rutherford cable from external vendor
- Timeline to be defined after this step



Future prospects for RADES@babyIAXO

- Projection with 440 days exposure time (in large parts complementary to FLASH)
- (see Ann.Phys. 535, 12 for details)
- Cryogenic tests of prototype RADES cavity (~50cm, i.e. ~factor 10 downsized) started April 2024 at KIT/Germany to check tuning, modes…





Beyond R&D: long-term #2: development of Single Photon detection

- Axion search: Lever arms exploited: magnetic field, volume, Quality factor
- Let's look at the detection scheme: normally, linear amplifiers are used which suffer from phase/amplitude zero point fluctuation noise.
- In principle, as a single-photon detector is sensitive only to the photon number (not the phase), such limitation can be overcome, noise counts exponentially suppressed (limited by shot noise eventually or by thermal noise/dark count)
- [Lamoreaux et al (2013)]: with other parameters fixed as in typical axion experiments, single-photon detectors become competitive and ultimately favored, when compared to quantum-limited linear amplifiers, above ~ 10GHz
- If such technology can be successfully developed, one may gain not only be factors, but by orders of magnitude in sensitivity!

A wish-list: Single photon detection, an example

Viable technologies (oversimplified):

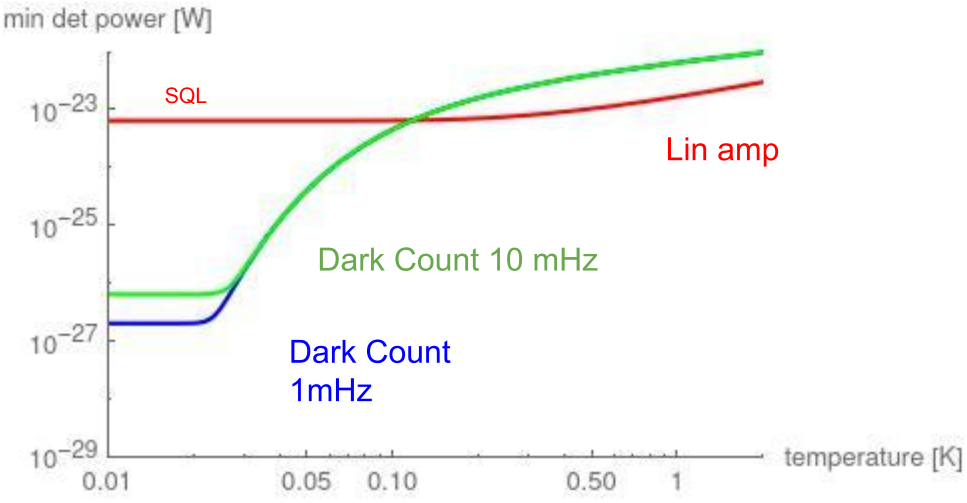
nano-TES e.g. [2007.08320] (QUAX group) or

QBITs (reading+sensing cavity) e.g. [2008.12231] (Chicago, Dixit et. al) and recently 2403.02321 (Braggio et al.)

Challenges:

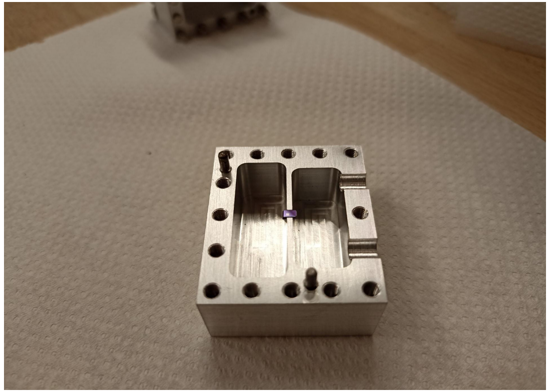
- **Achieving good coupling between photon and sensor**
- **Going broadband while maintaining resolution**
- **Functionality in/near strong magnetic fields**
- **….**

f= 10GHz, Q =10000, t= 10^4 s

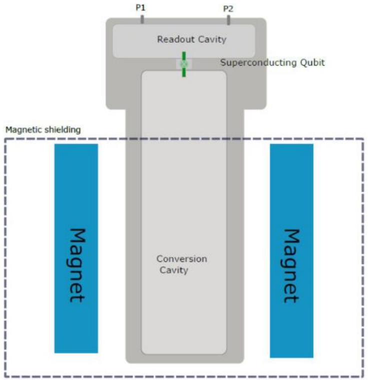


QBIT activities started in RADES

- qubit transition dependent on photon number
- Currently testing cavity & QBIT behaviour in RADES
- MPP works currently on DAQ, monitoring, integration, dilfridge arrives in October 2024
- RADES in application to take experiment underground (EoI @ Canfranc)

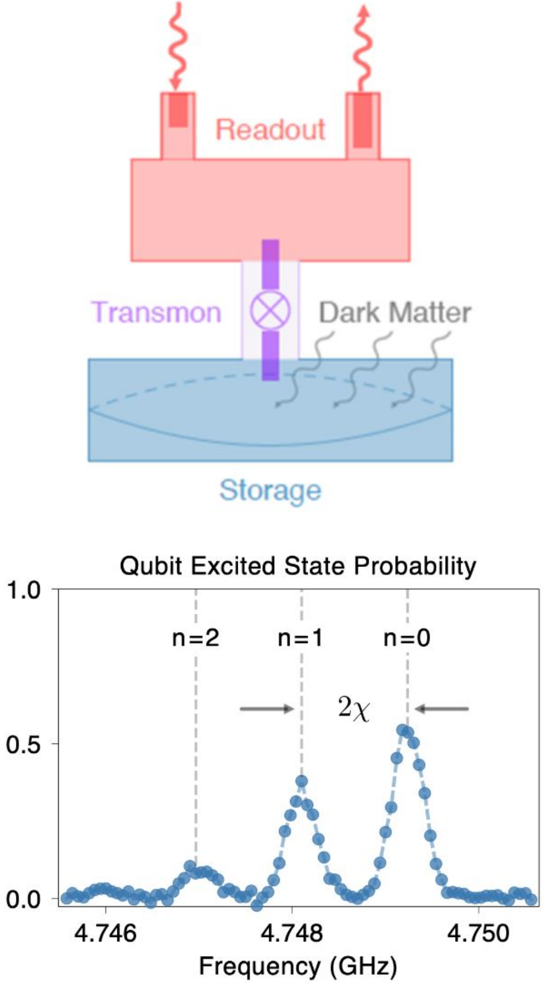


Test currently at Aalto, Paris, Zaragoza



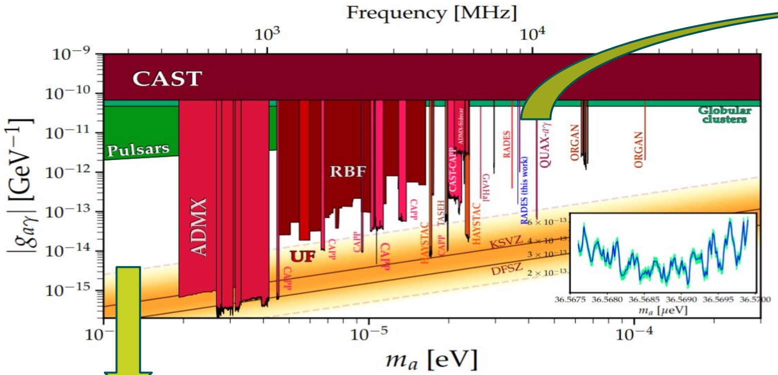
Dixit el al.

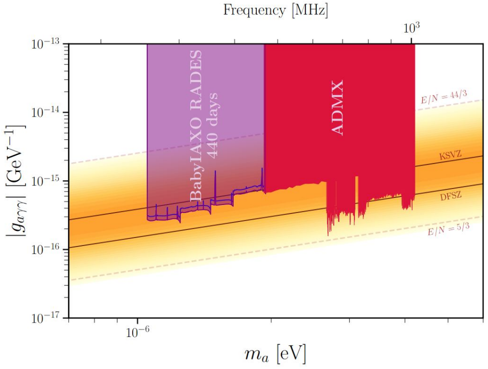
PRL.126.141302



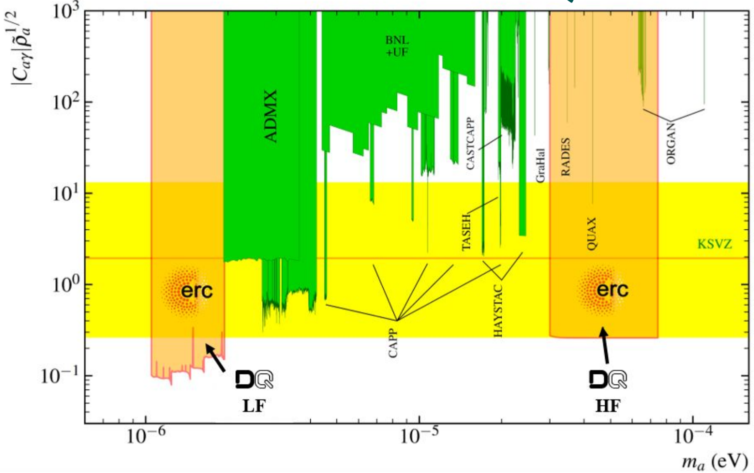
Summary of perspectives with RADES (QRADES and DarkQuantum projects)

2024





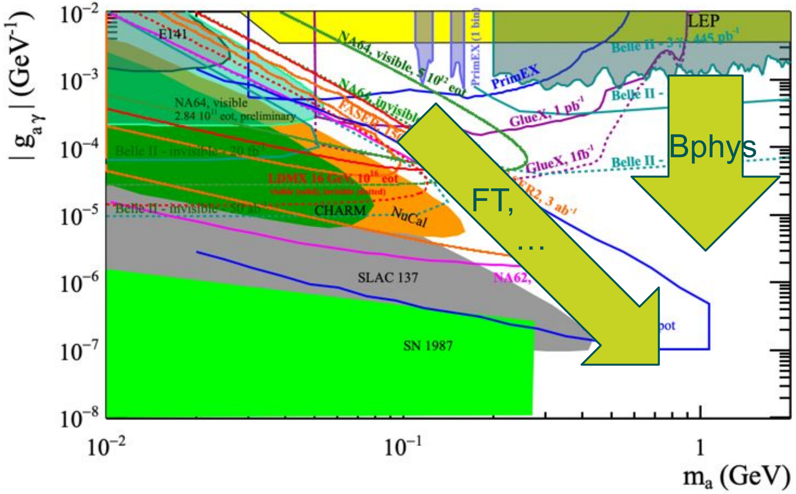
Scan time 800 days (multiple cavities)



ERC-SYG Dark Quantum: cryogenics & quantum-limited readout: Irastorza, Wernsdofer, Kontos, Paraoanu (MPP is partner)
QRADES project in Quantera: MPP among the PIs

Take away I

- A broad program that includes also small- and medium-size set-ups is needed in particle physics: New physics may very well be light-weight but very weakly coupled, such as the axion, lively field
- The NA62 experiment provides a number of channels to search such particles at the MeV to GeV scale, a number of results in exotics searches released and ~2 more years of data to come!
- Excellent sensitivity to such kind of physics also, with ongoing experiments (Belle2, Seaquest/DarkQuest, FASER, PADME…) novel ideas (downstreamtracks at LHCb?), and those planned for the future (FASER2, FPF, SHiP)

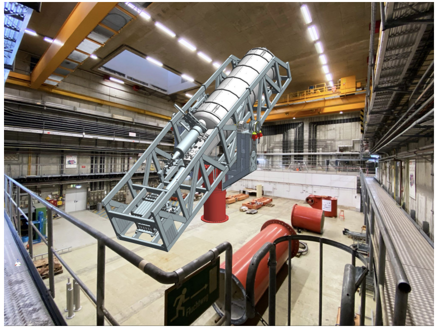


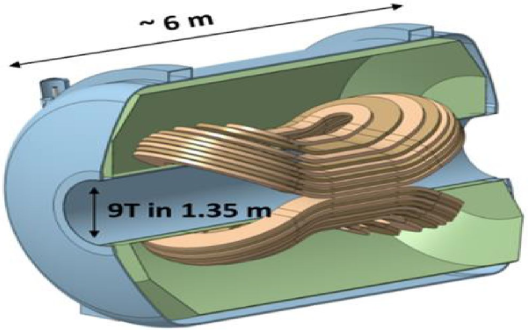
Collection from https://pbc.web.cern.ch/fpc-results

To be taken as indicative (2020!)

Take away II

- **The axion as Dark matter candidate has a clear target parameter region. Excellent prospects to probe it (but strong field magnets like the future babyIAXO and MADMAX magnets are a prerequisite!)**
- **If challenges can be overcome, an interesting technological avenue in axion searches could be single photon detection in the >10 GHz regime**





Thanks to you for listening and thanks to…

Work presented impossible without the local team and external collaborators from NA62 (~200) and RADES (~30)

MPP team:

<u>NA62:</u> Samet Lezki, Jan Jerhot, Sri Vrushank Ayyagari, Jonathan Schubert

<u>RADES:</u> Louis Herwig, David Kittlinger, Cristian Cogollos, José María García Barceló, Samridh Dev Singh

<u>Student still employed at CERN:</u>

Jessica Golm

BACKUP

Quantera/

QRADES

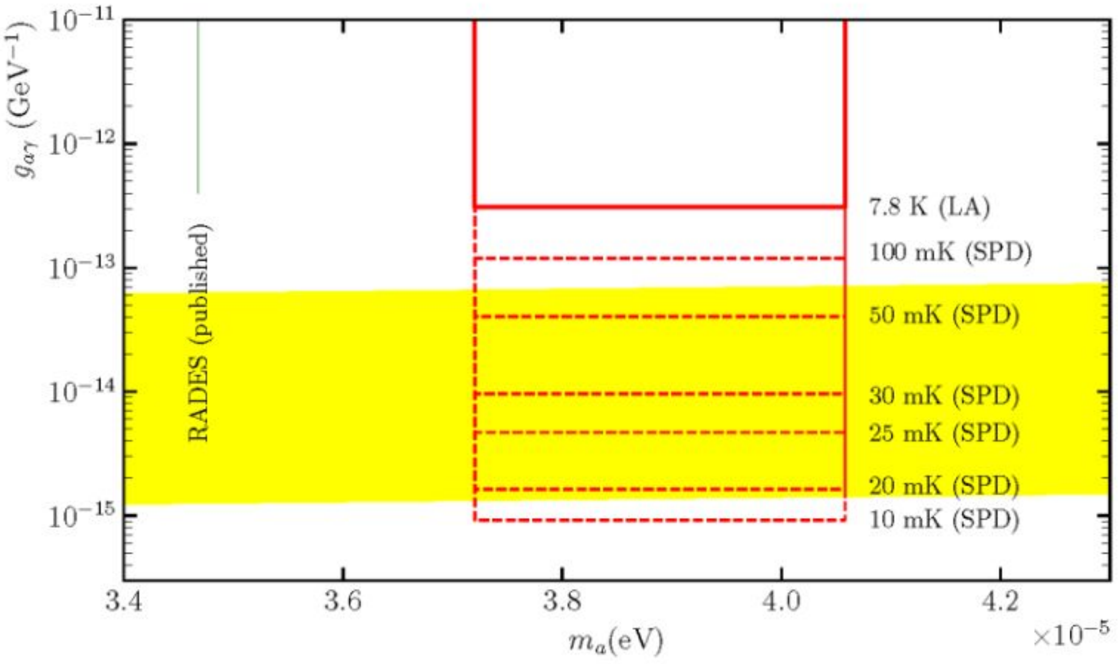


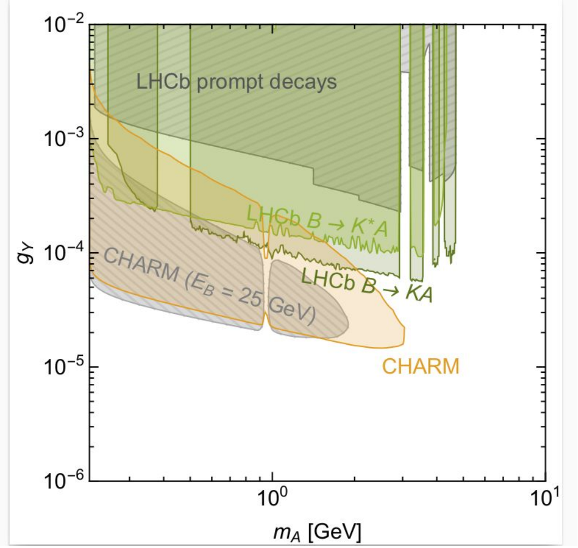
Figure 4: Potential sensitivity to axion DM of a quantum-enhanced RADES experiment (dashed red lines), equipped with a SPD, compared with a reference sensitivity (solid red line) from current LA-equipped RADES at $T_{sys} = 7.9K$. The various lines correspond to several assumed dark count rate of the SPD. The span in frequency of the regions is assumed to be 10% of the central value and is composed of 1000 consecutive steps of 10 h integration time each. See text for details.

Beware of model-dependencies, introduction

BD et al. PLB 2019

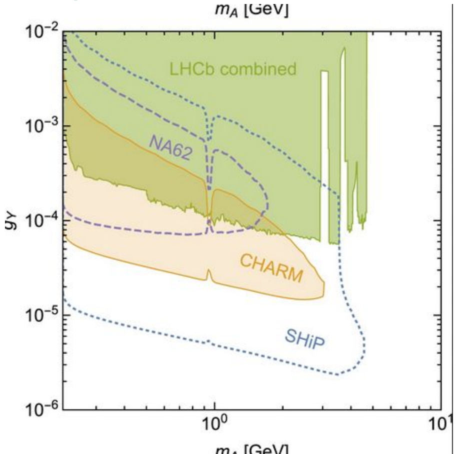
- **Example: light pseudoscalar with fermion coupling:**
- $$\mathcal{L} = i\, g_Y \sum_{f=q,\ell} \frac{m_f}{v} A\, \bar{f}\gamma^5 f\,,$$

Past literature (re-cast) bound based on monochromatic (sic!) spectrum of B-meson decays (see previous discussion)



- **Re-evaluation:**

  Seemingly no good prospect For NA62 to compete ,
- **BUT**

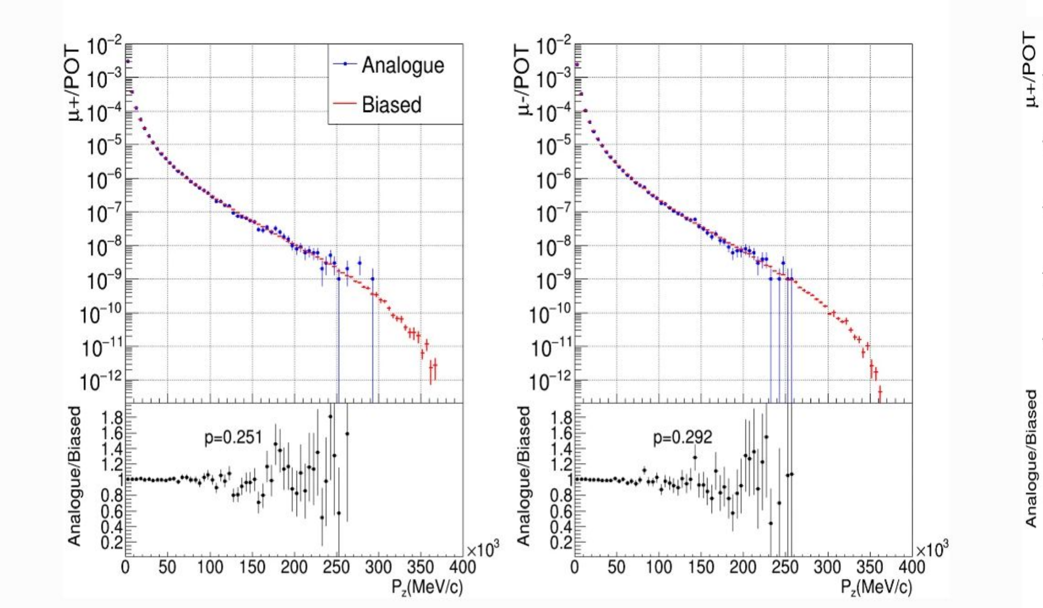


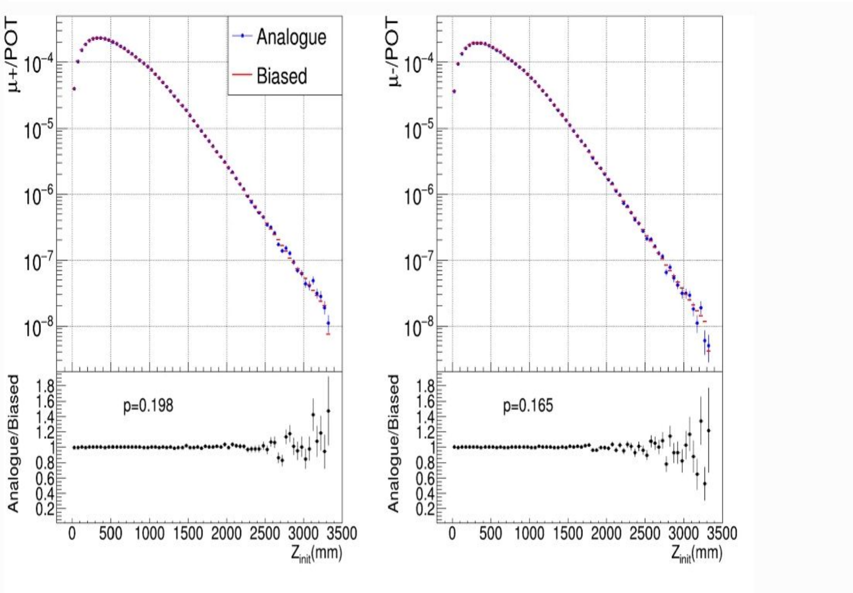
©

sufficient statistics in MC: several attempts…

Biasing: Clone particle that would be killed (analogue), keep propagating

- Apply appropriate weights according to interactions that could have occurred. see [EPCJ 81,767] for more details





Hadronic final states $\pi\pi$ x

- Analysis strategy similar to completed two-track studies (upper rhs), PID differs (BDT based)
- Complication 1: Soft radiated photon from track can be present, which would lead to mis-labelling of simpler topologies
- Complication 2: Lost photon allow more complicated topologies polluting simpler topologies (rhs bottom)
- Refine strategy as follows:
- [ ] Require minimum photon energy, acceptable signal loss for more complicated topologies (while removing a significant background)
- [ ] Open boxes starting from more complicated topologies to simpler ones to avoid any pollution

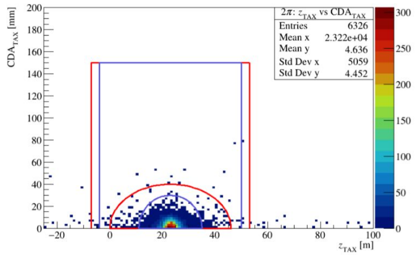


Figure 2: Closest distance of approach between the primary proton beam and the reconstructed exotic particle from a $\pi^+\pi^-$ event simulated with NA62 Monte Carlo. The red ellipse and box define the signal and control regions used in this analysis, compared to the blue signal and control regions used in [13].

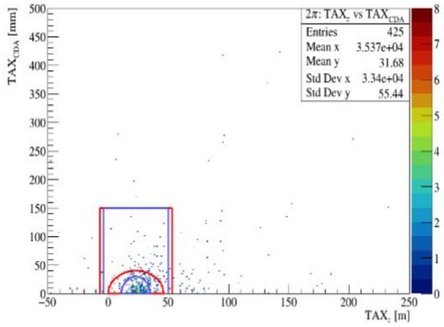


Figure 4: Closest distance of approach between the primary proton beam and the reconstructed exotic particle from a $\pi^+\pi^-\gamma$ event mis-reconstructed as $\pi^+\pi^-$ event.

Background studies

Combinatorial

- Build artificially from single tracks (orthogonal to analysis sample - different trigger line)
- Statistical accuracy from combinatorial enhancement
- Weight to account for analysis time window

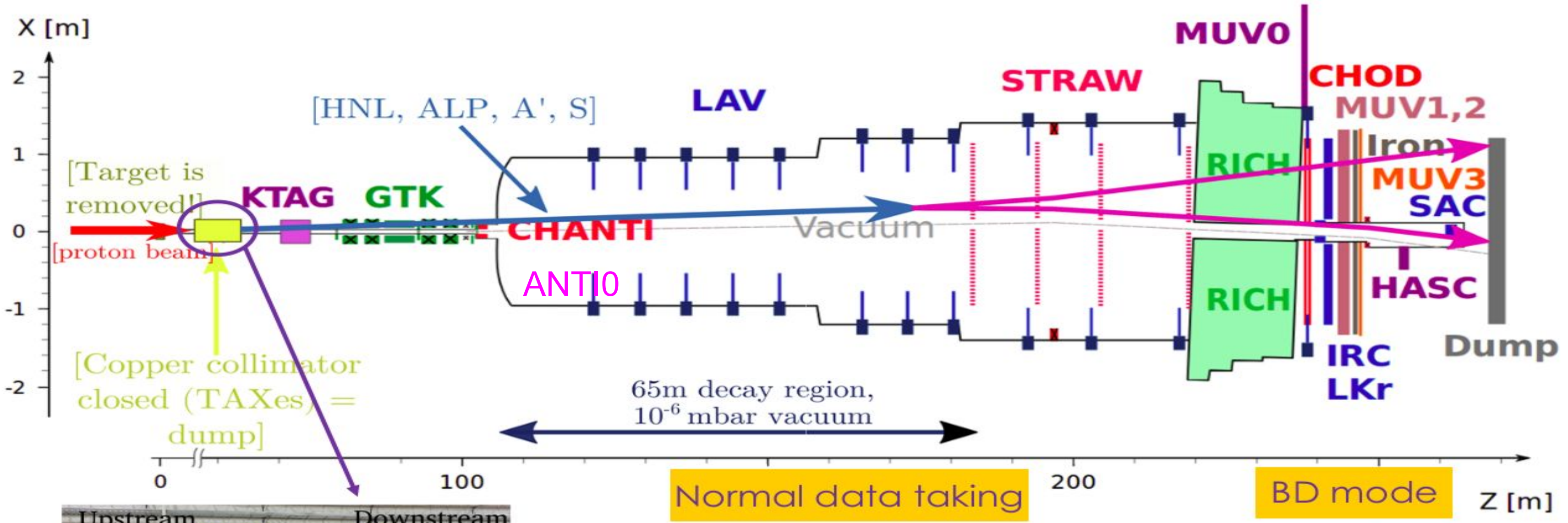
Prompt

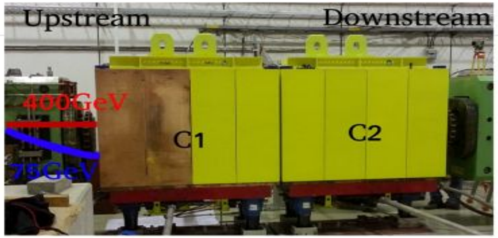
- Secondaries of a muon interaction in traversed material (usual π with consecutive decay to μ)
- Kinematics extracted from single tracks (backward MC - PUMAS)
- Relative uncertainty of MC expectation ~50%

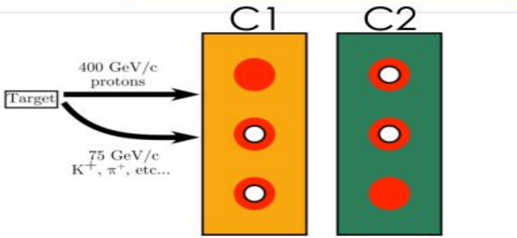
Table 4: Summary of expected numbers of background events for the search of $A' \to \mu^+\mu^-$ with the related uncertainty. The limits reported are defined with a 90% CL.

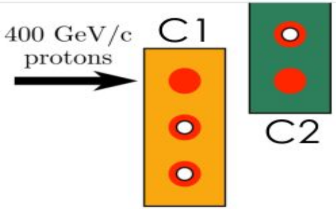
Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

The NA62 experiment in Beam-Dump mode









Atomki

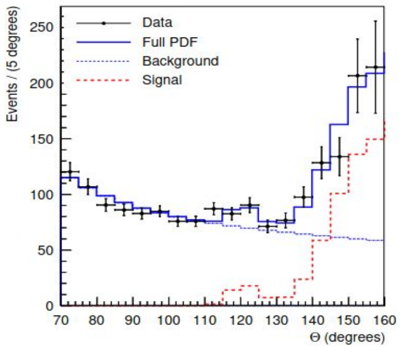


FIG. 7. Experimental angular correlations of the e^+e^- pairs fitted by the contributions from the E1 IPC and from the contributions coming from the e^+e^- decay of the X17 particle.

SUMMARY

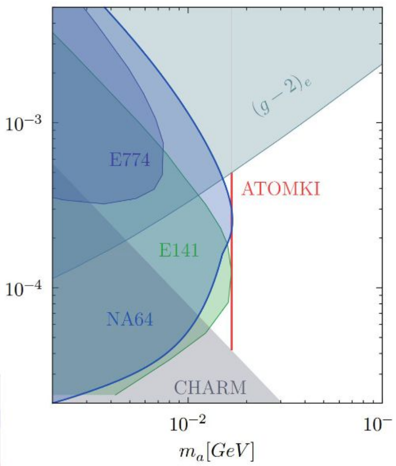
We reported on a new direction of X17 research. For the first time, we successfully detect this particle in the decay of the Giant Dipole Resonance (GDR). Since this resonance is a general property of all nuclei, the study of GDR may extend these studies to the entire nuclear chart.

We have studied the GDR ($J^\pi = 1^-$) E1-decay to the ground state ($J^\pi = 0^+$) and to the first excited state ($J^\pi = 2^+_1$) in ^{8}Be. The energy-sum and the angular correlation of the e^+e^- pairs produced in the ^{7}Li(p,e^+e^-)^{8}Be reaction was measured at a proton energy of $E_p = 4.0$ MeV. The gross features of the angular correlation can be described well by the IPC process following the decay of the GDR. However, on top of the smooth, monotonic distribution of the angular correlation of e^+e^- pairs, we observed significant anomalous excess at about 120° and above 140°.

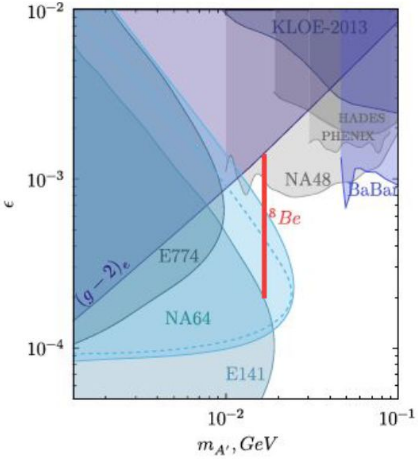
The e^+e^- excess can be well-described by the creation and subsequent decay of the X17 particle, which we have recently suggested [1, 8, 9]. The invariant mass of the particle was measured to be ($m_X c^2$ = 16.95 ± 0.48(stat.) MeV), which agrees well with our previous results.

<- arXiv:2308.06473 [nucl-ex], for an overview cf. talk by V Kozhuharov @ Vulcano 2024

Phys. Rev. D 101, 071101(R)

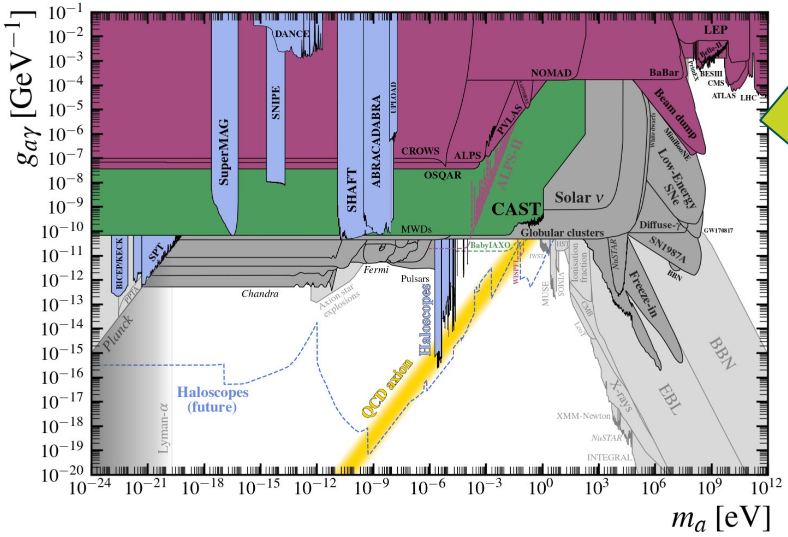


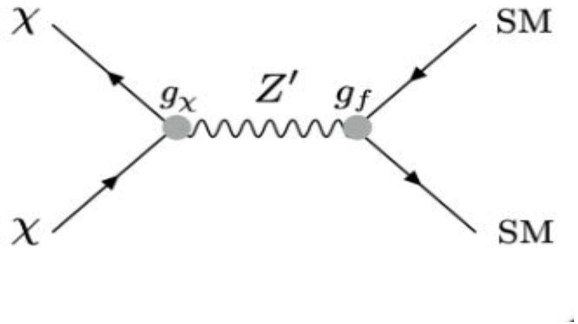
arXiv:2104.13342 [hep-ex]



- Similar physics observables as in the ^{8}Be, ^{4}He and ^{12}C experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)

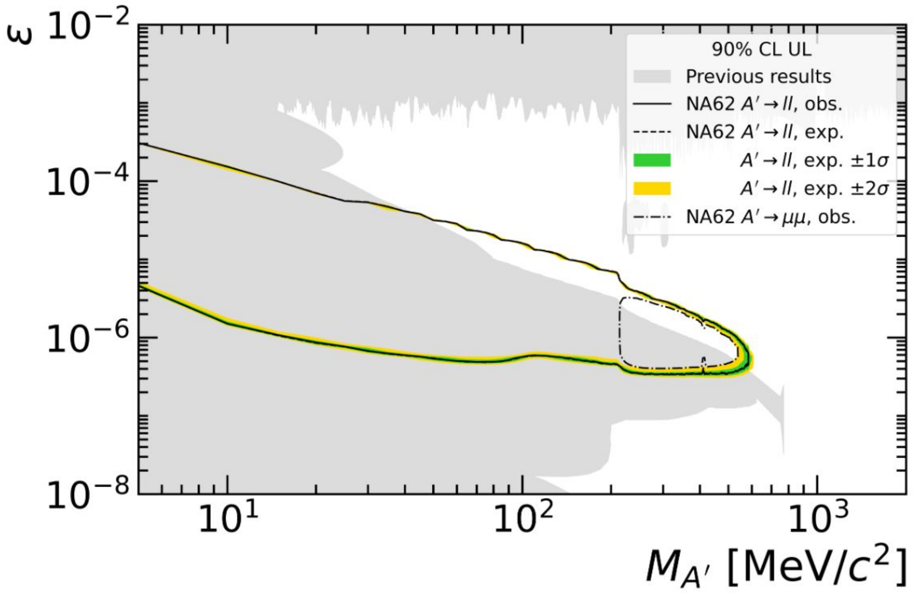
Portal Dark Matter





Also other portals are possible, Z’ as the probably most well-known

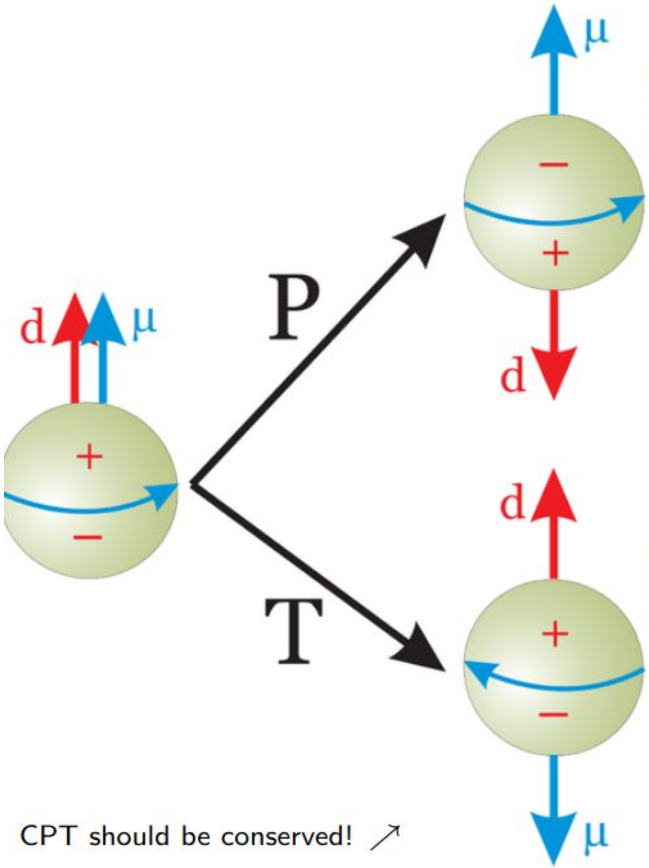
Complete picture: Leptonic decay of Dark Photons



Together with FASER@LHC, first new limits in this region since the 80s!

in JHEP for muons
https://link.springer.com/article/10.1007/JHEP09%282023%29035

And on the arxiv for electrons
[2312.12055]



CPT should be conserved! $\nearrow$

Theory

- QCD vacuum CP- violating term: $\mathcal{L}_\Theta \sim \alpha_s \bar{\Theta} G^a_{\mu\nu} \tilde{G}^{a\ \mu\nu}$
- QCD topological + EW contribution $\bar{\Theta} = \Theta + \mathrm{Arg}\det M$, M quark mass matrix

Experiment

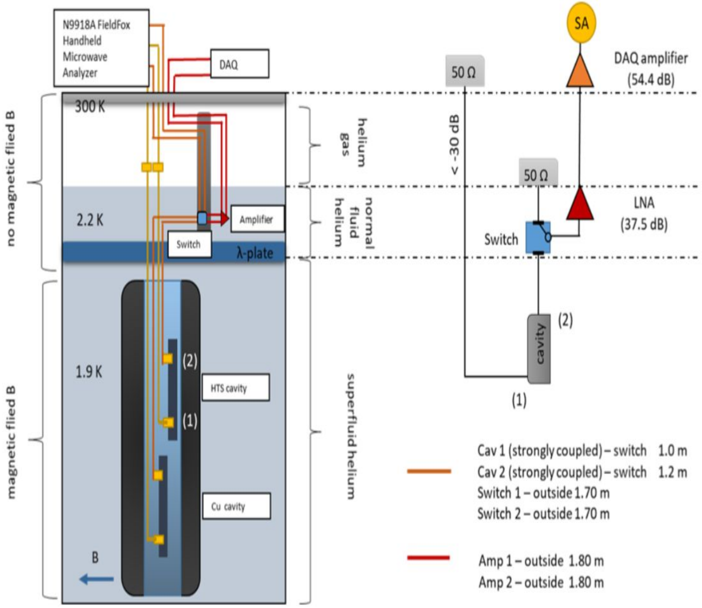
- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_\mathrm{n}(\bar{\Theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

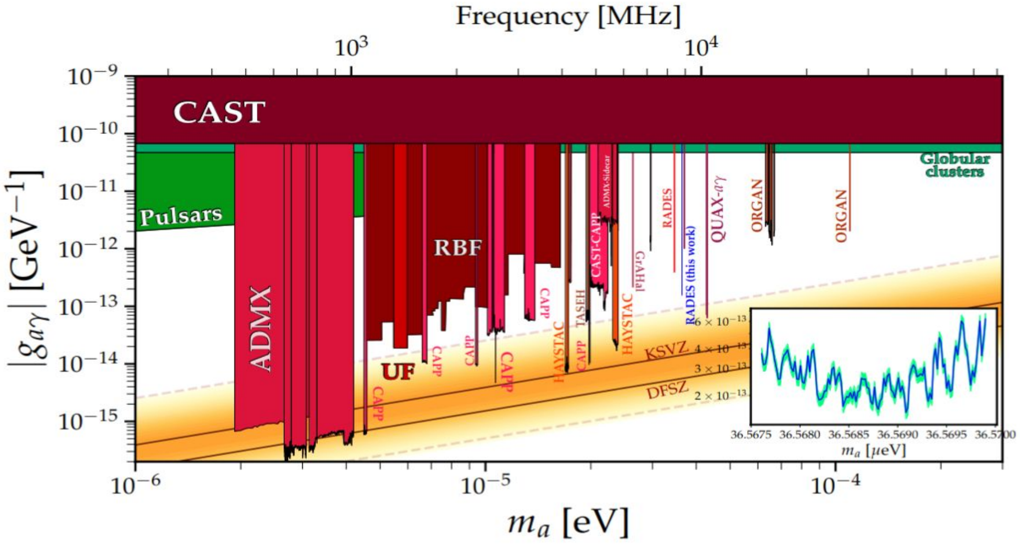
angle $\bar{\Theta} \lesssim 10^{-10}$ $\rightarrow$ **naturalness/finetuning problem!**

hadrons

model	production channels	decay channels
DP	Bremsstrahlung	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
		$K^+K^-\pi^0$
	light meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
DS	B meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
ALP	Primakoff mixing ($\pi^0/\eta/\eta'$) B meson decay	$\pi^+\pi^-\gamma$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
		$K^+K^-\pi^0$

Results of HTS data-taking at 11.7T dipole in SM18





$$\frac{dm_a}{dt} = \frac{Q_a}{Q_l}\left(\frac{P_d}{\frac{S}{N}k_B T_{sys}}\right)^2 = Q_a Q_l \kappa^2 g_{a\gamma}^4 \left(\frac{\rho_a}{m_a}\right)^2 B_e^4 C^2 V^2 \left(\frac{S}{N}k_B T_{sys}\right)^{-2}$$

copper reference cavity to directly compare performance when ramping field see [2110.01296]
-> NEW SLOT IN SEPTEMBER