# Axions and Axion-like particles
## — selected recent results —

MAX PLANCK GESELLSCHAFT

European Research Council
Established by the European Commission

Babette Döbrich
(Max Planck Institute for Physics)


Axion exists. Found the axion on the way to a winter conference in Italy! At an ice kart racing place in Livango

Finished. :-)

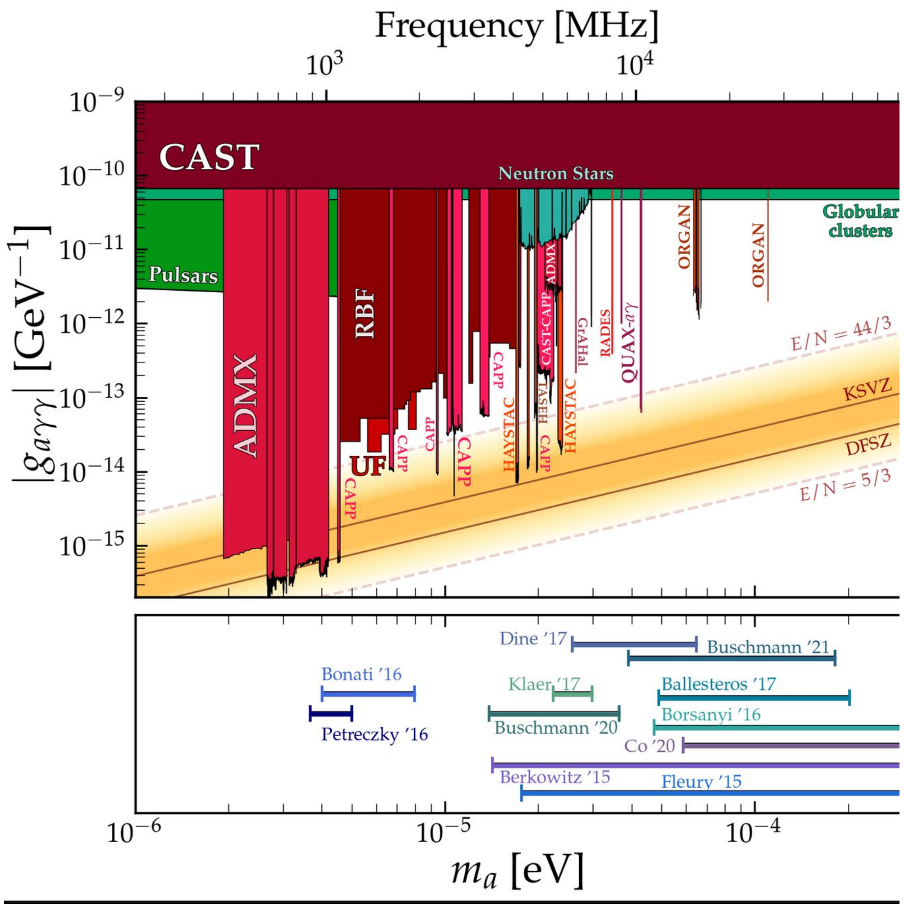
…

Realize the diversity of the audience. Feel free to ask, even if it means we won't make it through all my slides!

# Before we start, let's start with a small glossary:

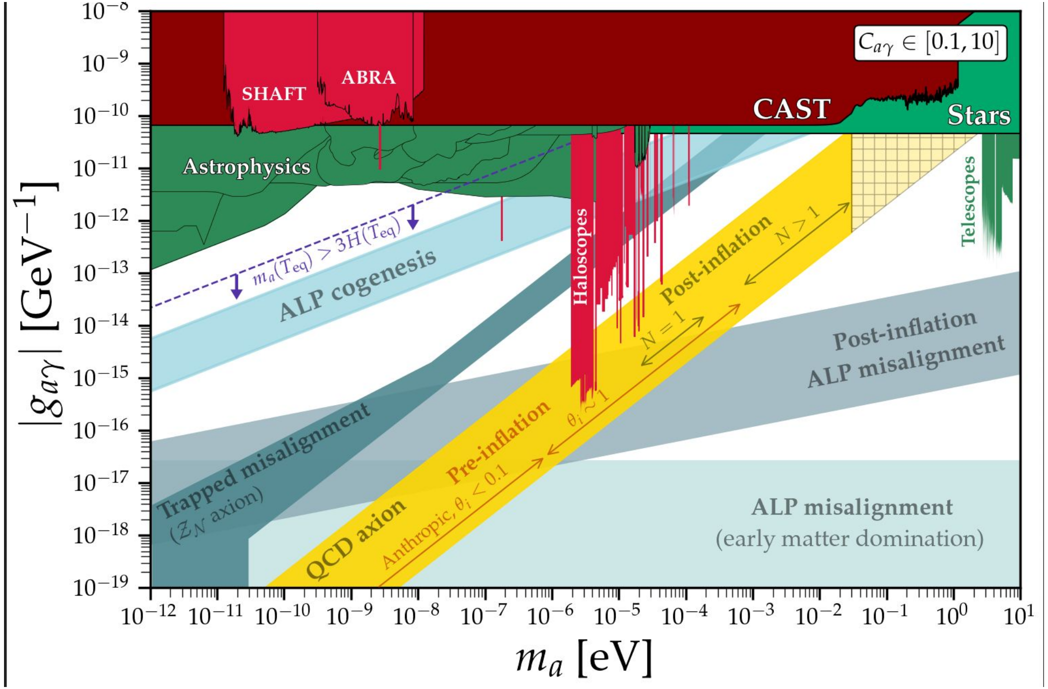
## 1. The axion

- Could solve the **strong CP problem (finetuning problem of 10 orders of magnitude, see backup)**
- Ideally, **could constitute all of the Dark Matter** (non-thermally produced!)
- Vanilla `QCD axion Dark Matter': KSVZ and DFSZ models, with fixed mass-to-coupling ratio (here shown only for 2-photon-coupling)
- typically scanned in narrow mass-points with electromagnetic resonators in strong magnetic fields, see red areas on right-hand side [status nicely maintained at O'Hare GitHub]



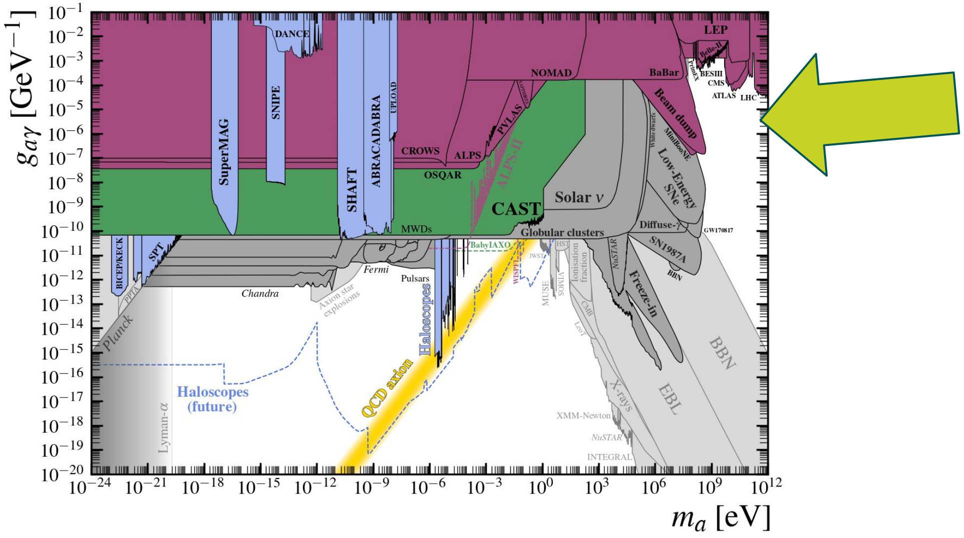
# Before we start, let's start with a small glossary:
## 2. The axion-like particle (ALP)

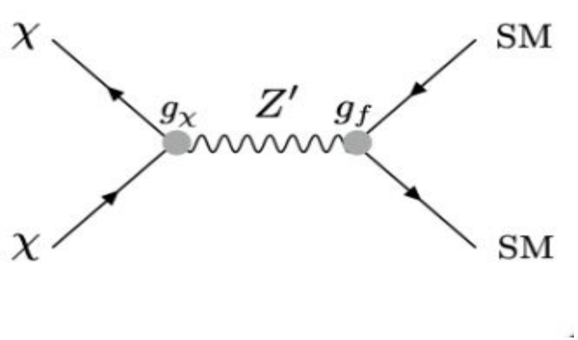
- Note the larger mass and coupling range with respect to the previous plot
- Theoretically interesting: relaxed/modified mass-to-coupling ratio: non-vanilla models
- Experimentally interesting: Novel approaches typically first sensitive to ALPs, before becoming sensitive enough to "proper axions"
- Preferred parameter range dependant on model behavior in early universe early universe
- References also maintained at [O'Hare GitHub]



# Before we start, let's start with a small glossary:
## 3. The axion-like particle as a DM `portal'

- Much larger couplings are still viable at high mass
- WIMPless miracle [see for example: Feng, Kumar] : thermally produced DM can be significantly lighter than GeV without overproducing it:
- Mediators that are BSM states -> "Portal"
- ALPs can constitute such a portal, in this case **they make sense also at MeV-GeV scale**



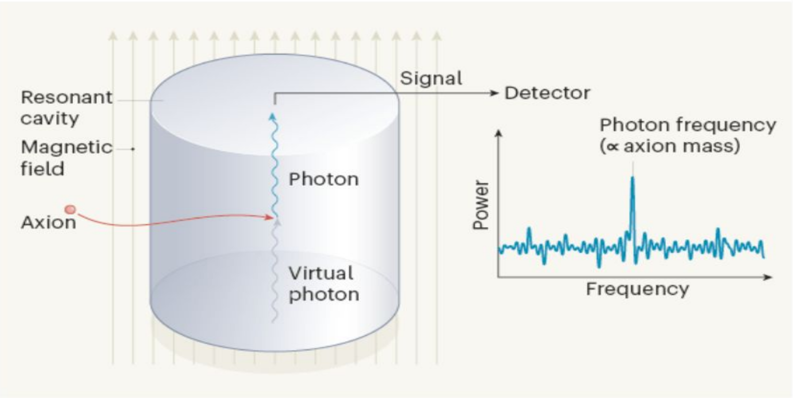




Also other portals are possible, Z' as the probably most well-known

# Almost ready, just one more thing

- In the literature, axion and ALP (non-portal and portal) are used interchangeably
- Given the breadth of the before-mentioned physics, only some examples can be presented (which necessarily vary with personal taste)
- Personally I find most exciting the results/ developments in
    a. **QCD axion searches, particularly aimed at directly detecting Dark Matter**
    b. Techniques that tackle couplings other than the photon coupling. Particularly for **ultra-light axions**, opens field to methods from a variety of communities: NMR, storage rings, magnetometers… see this collection for an overview
    c. **Flavor-non-diagonal axions**: Relate the axion to SM flavor parameters and motivate smallness and hierarchy of such parameters, see e.g. [2006.04795],
    d. **Ultra-heavy axions (portal axions)**

# a.) The classic (Sikivie) haloscope

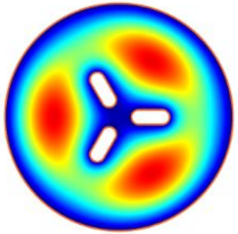


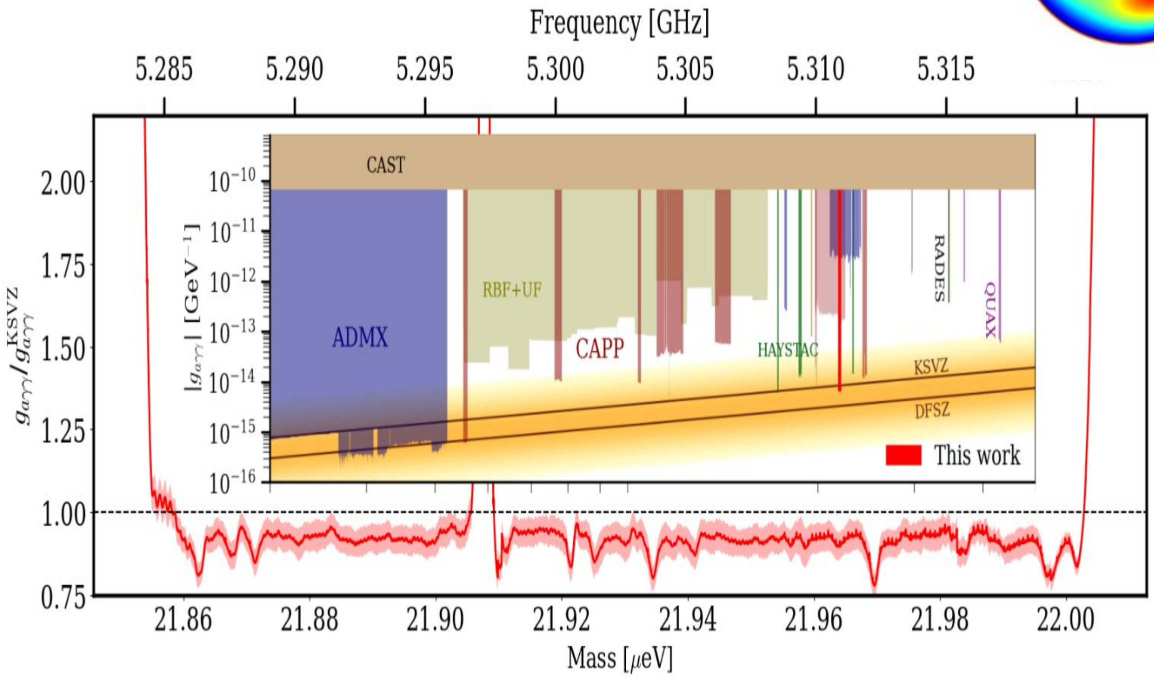

*Principle scheme of a cavity haloscope (from I. G. Irastorza, Nature **590**, 226-227 (2021) )*

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

- **Resonantly convert the Axion Dark matter into RF signal by placing electromagnetic resonator ( appropriate mode overlap parameterized in G, volume V) in a strong external magnetic field B**
- **m ~ f_resonance**
- **Advantage: profits from with amplification Q**
- **Disadvantage: scanning needed: <u>Volume and Quality factor decrease at larger Axion masses (cavities become smaller, naively)</u>**

# (vanilla) Benchmark sensitivity: ADMX & CAPP

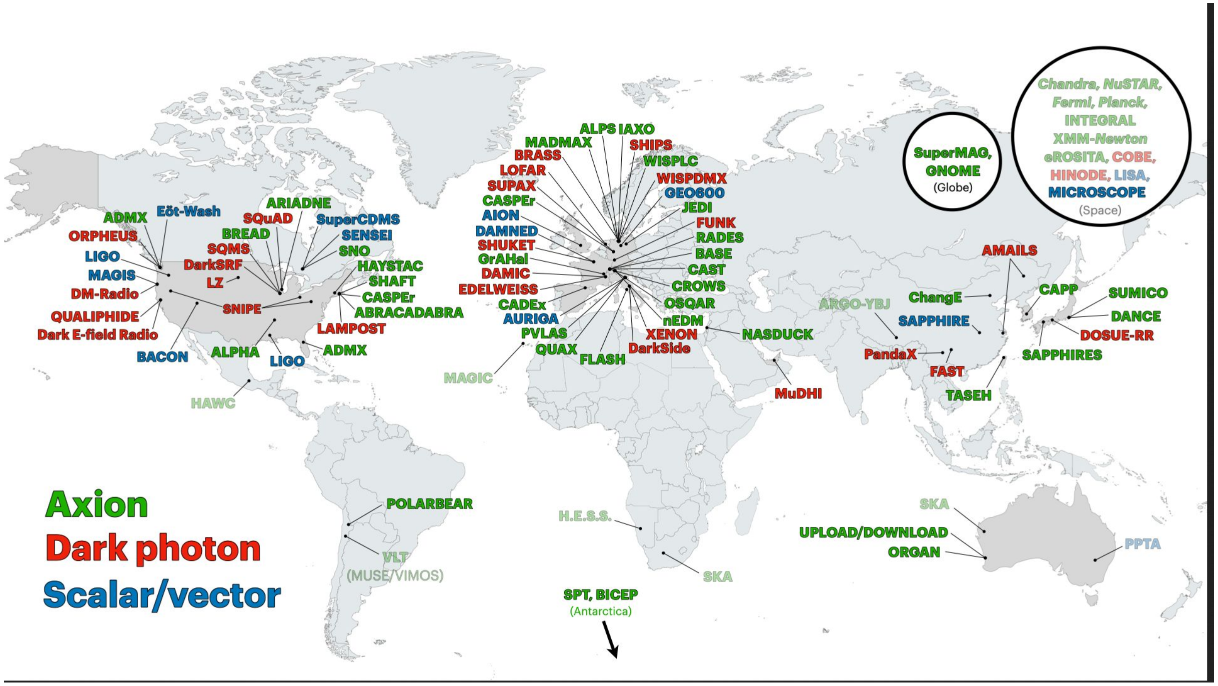





ADMX (US): key player since ~2010 with proven sensitivity to benchmark models using the classic Sikivie Haloscope

- Impressive pace of CAPP/Korea (started from scratch in 2013 (!)) exemplified by result on lhs from December 2023
- Peculiar cavity structure to reach larger masses (“Pizza-structure”, pls keep in mind)
- Still rather narrow mass range (35Mhz)

# Plenty of room for R&D, newcomers and small groups

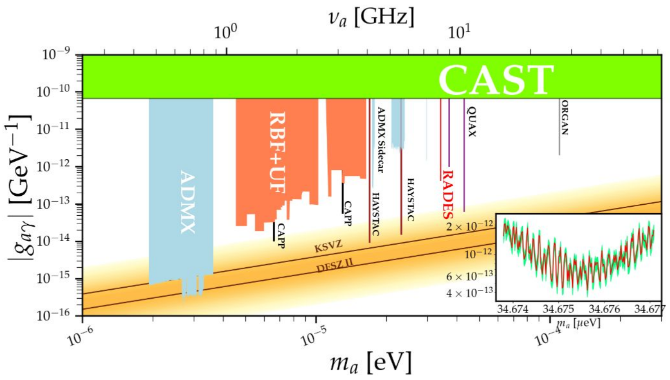


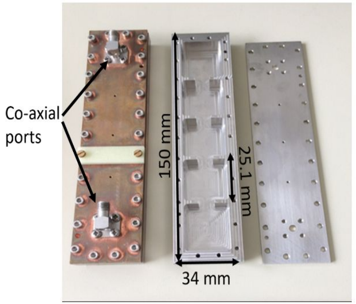

- R&D often immediately sensitive to novel axion-LIKE particles
- Map [O'Hare] contains dedicated efforts as well as parasitic sensitivity
- Not displayed are ad-hoc collaborative efforts which are common
- Excellent platform to train students in analysis, hardware and phenomenology
- Example: RADES

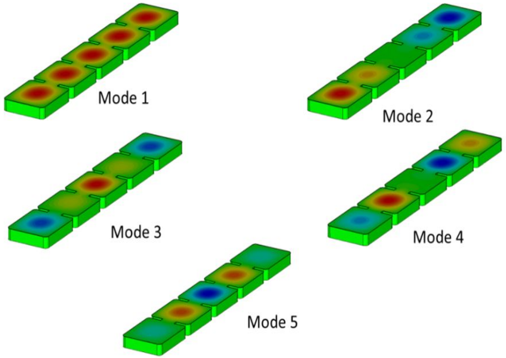
# RADES R&D example: innovative cavity geometries

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

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




Data-taking results *JHEP* 21 (2020) 075

# RADES R&D example: HTS

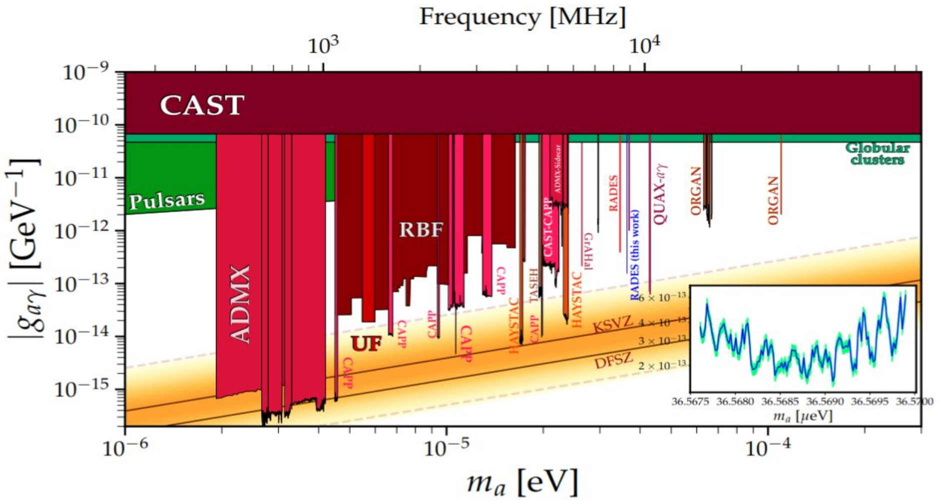
Superconducting tapes can increase Quality factor by a large factor*

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

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

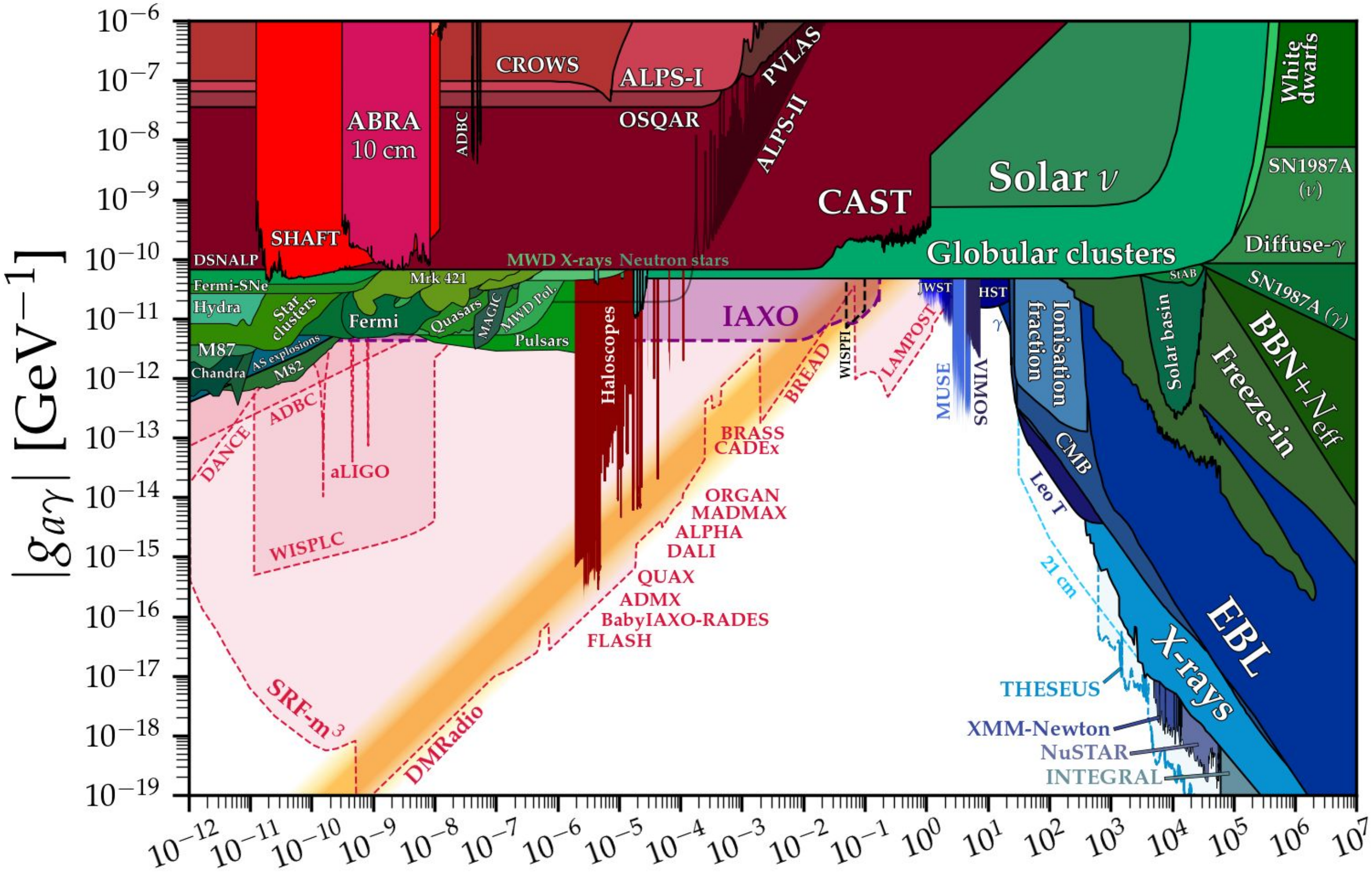
Data taking at CERN performed at 12T in 2021, new data-taking foreseen in September 2024

[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]

# The next 10-15 years?




I talked about a very small selection of efforts (notably I left out the main MPP axion experiment MADMAX)!

Interesting prospects to test `vanilla axion' models in the coming decade

REMINDER

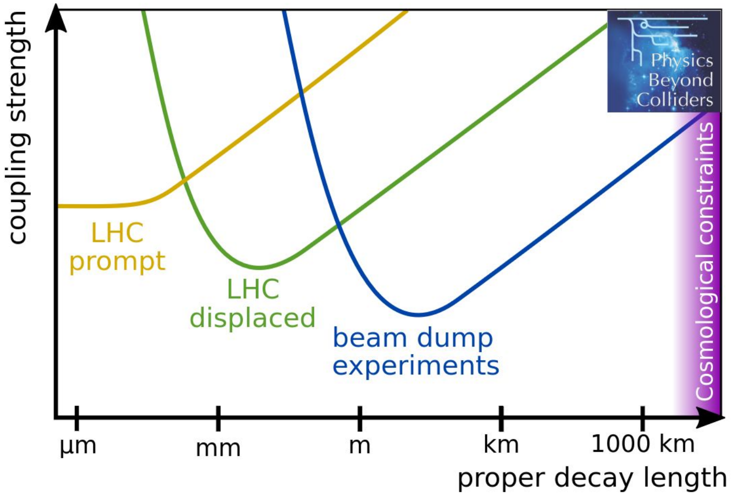
- Personally I find most exciting the results/ developments in

  a. **QCD axion searches, particularly aimed at directly detecting Dark Matter**
  b. …
  c. **…**
  d. **Ultra-heavy axions (portal axions)**

# d.) Ultra-heavy axions (MeV-GeV)

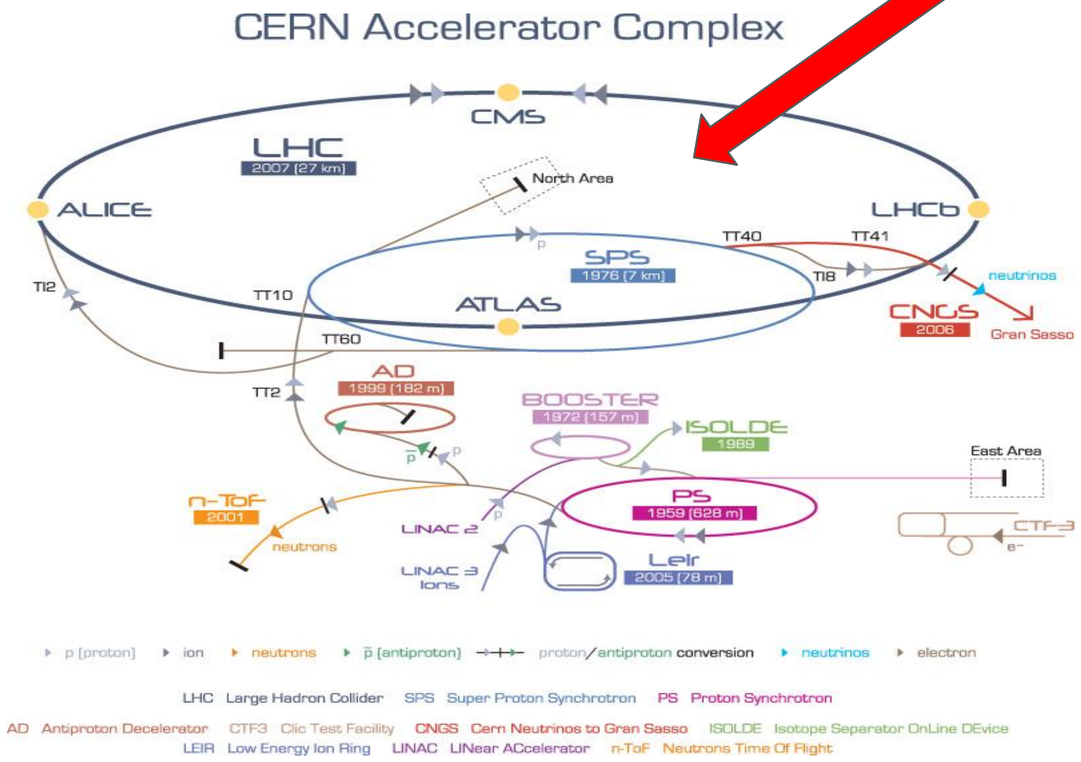
- Typically interesting in the `portal-type' models as mentioned in the Introduction (ALPs themselves not stable and thus not the Dark Matter)
- Sensitivity at detectors removed from interaction point very much complementary to collider-searches
- Lead to renewed interest in recent years (last beam-dump limits on Axions in the 80/90s!)

- Proposed & approved experiments dedicated to Feebly Interacting Particles (FIPs): SHiP, Mathusla, Forward physics facility… see FIPs 2022 report
- Here will present a recent result of existing set-ups: NA62 in beam-dump




from [2310.17726]

# 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
- **Talks by T. Spadaro and J. Swallow on NA62 results**

# 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)

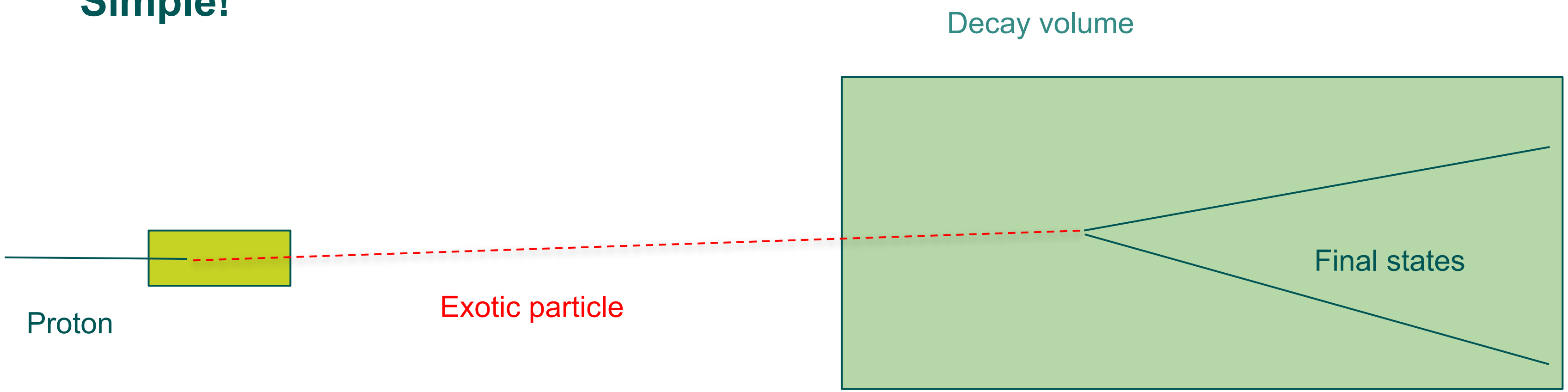
<- View of the ECN3 hall

# Axions @NA62

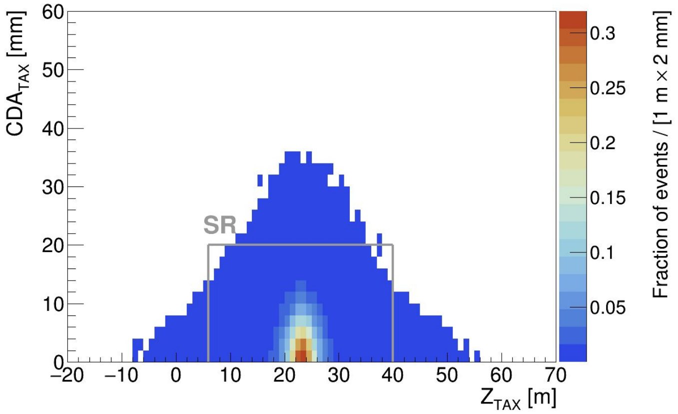
Besides the main measurement, collaboration organized in 3 Working groups, all of which have results on axions, see those examples:

- 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!

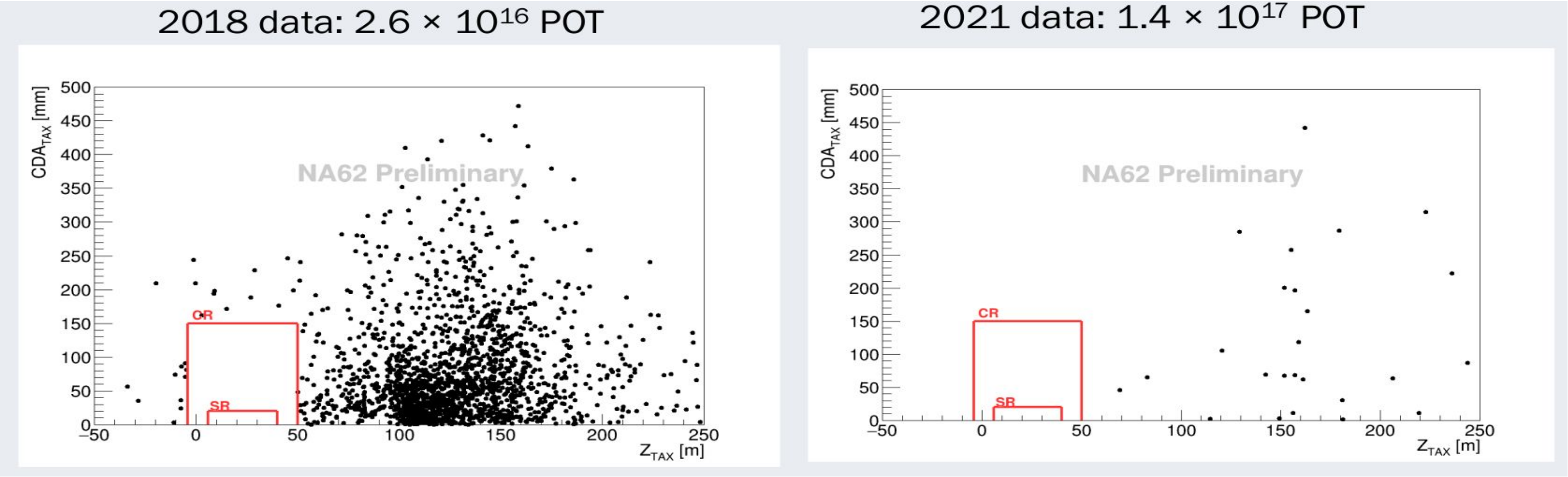



**Example** of Monte Carlo signal event distribution for exotic particle to di-muon final state



# Background reduction 2018 vs 2021

- **Naively switching from Kaon to dump-mode in 2018**
- **upstream magnet tuned** 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: $\mu^+\mu^-$)

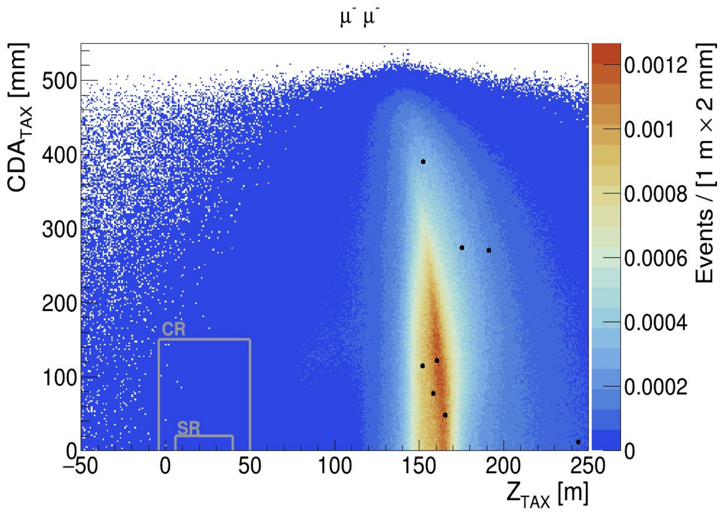


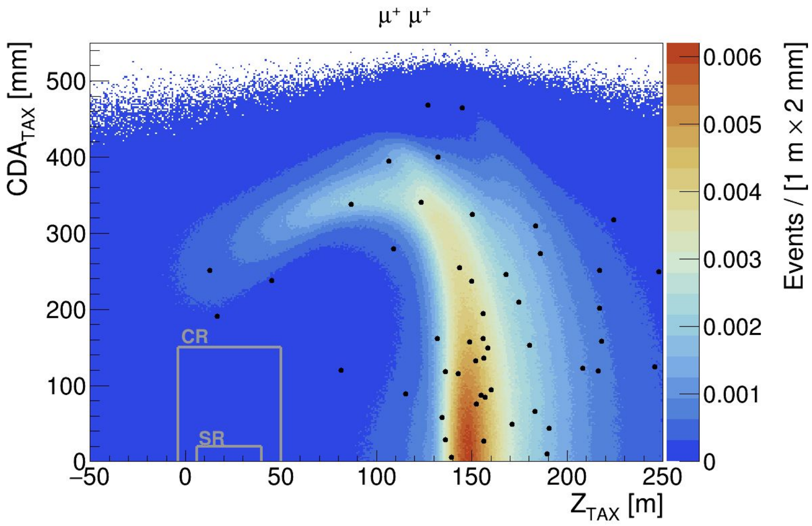
# Towards analysing the 2021 data: same-sign control sample

- 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

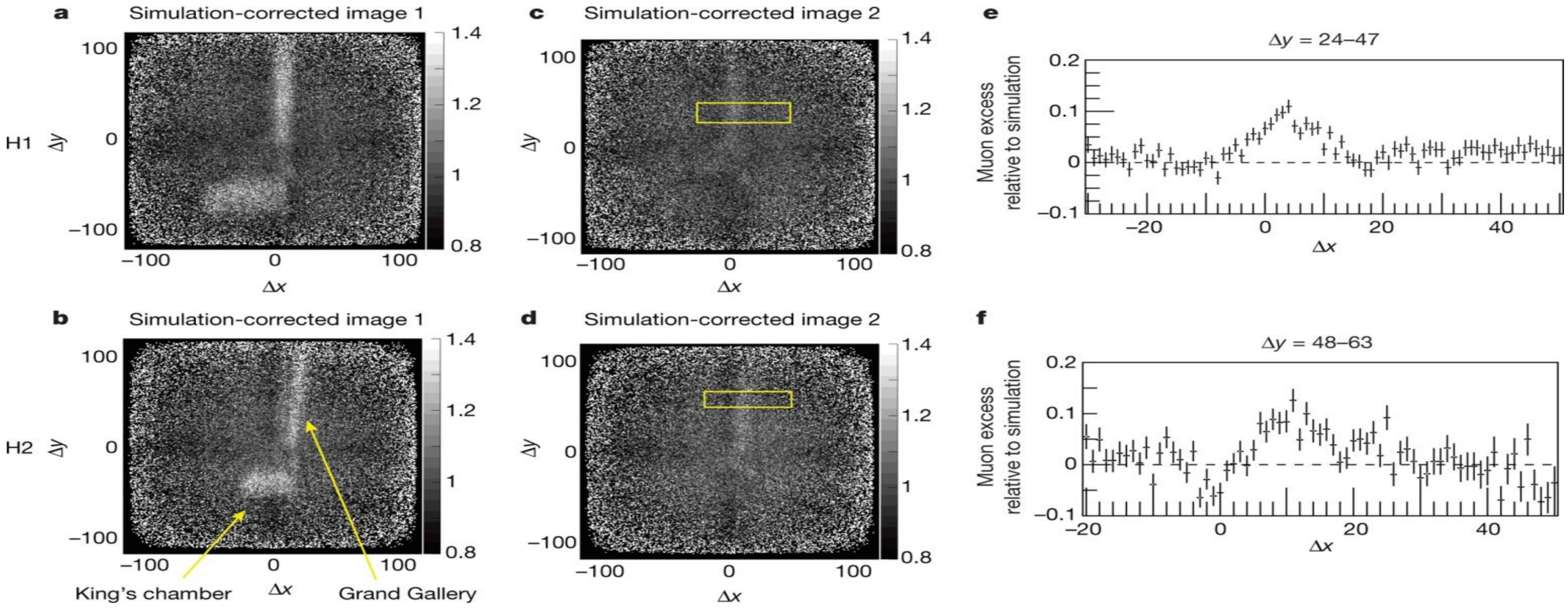
Collect event single track sample sample from independent trigger line and overlay!




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

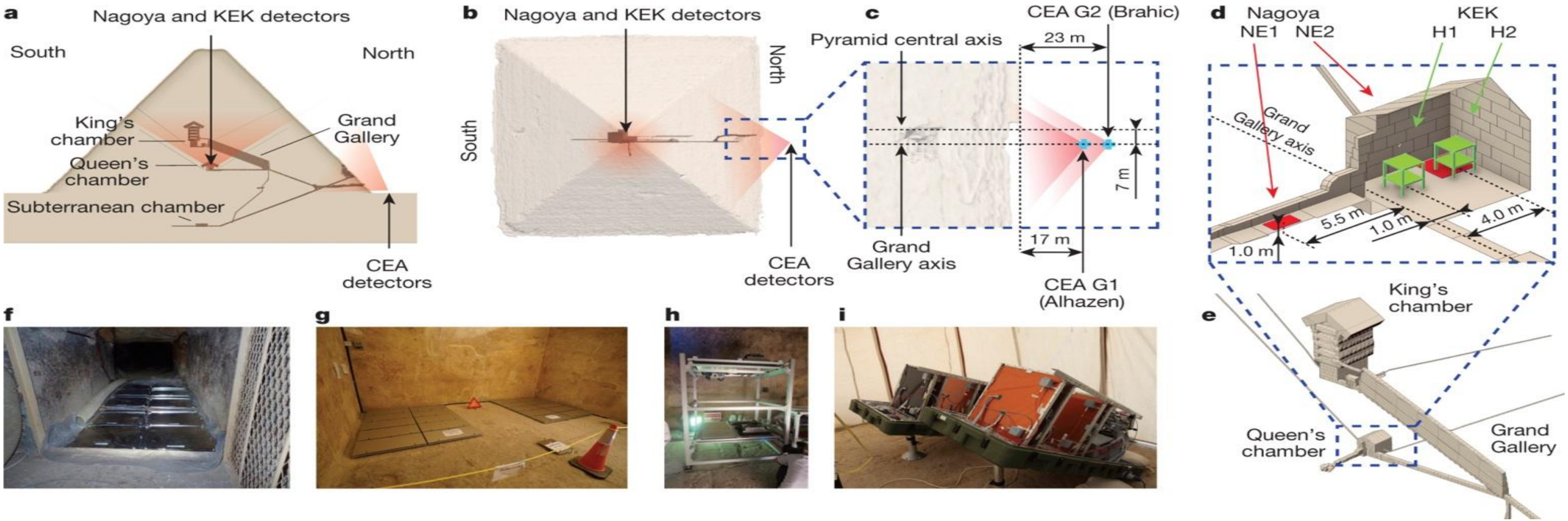
# **Digression: your turn!** world news in 2017




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

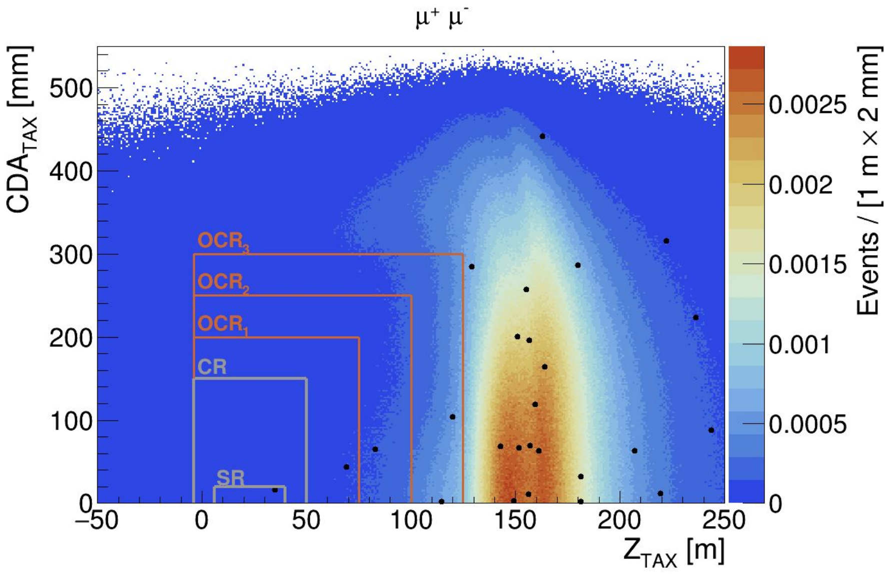
nature

# Data-MC comparison: SR open $\mu^+\mu^-$

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

## OK for Box-opening

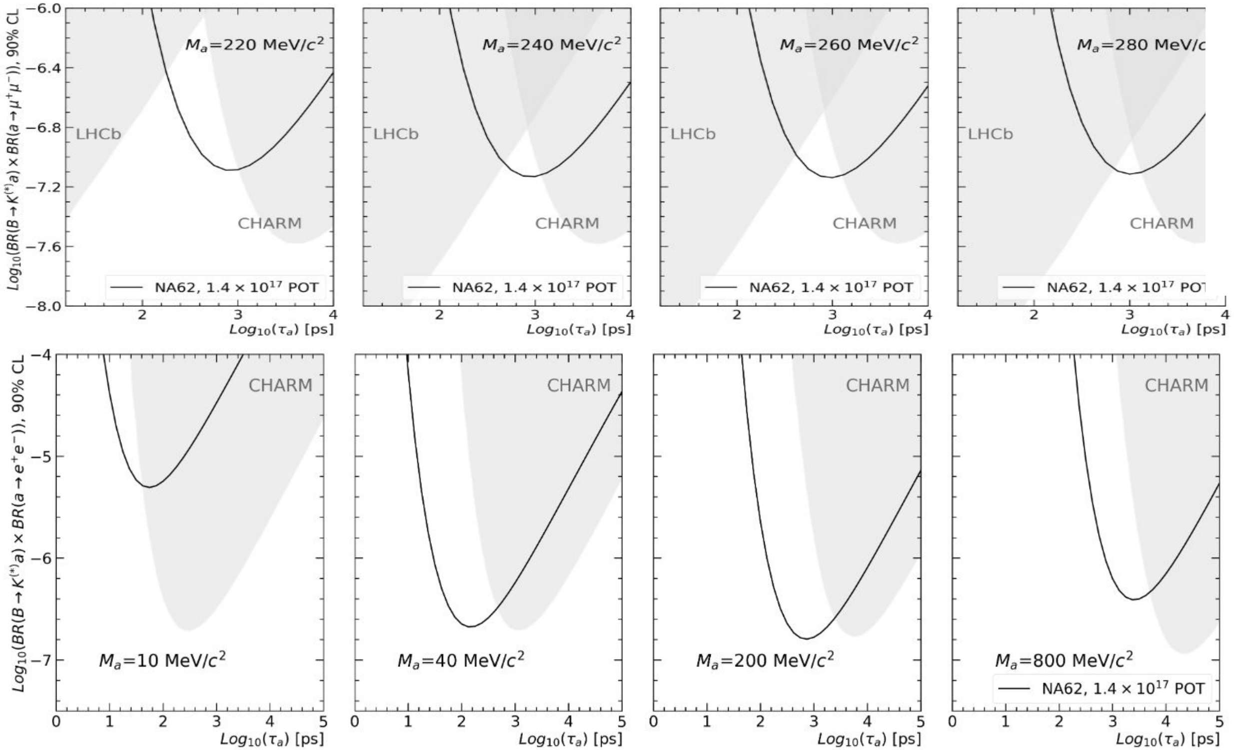
- Color scale: Expected background
- 1 event observed in (geometric and timing far tail of) SR

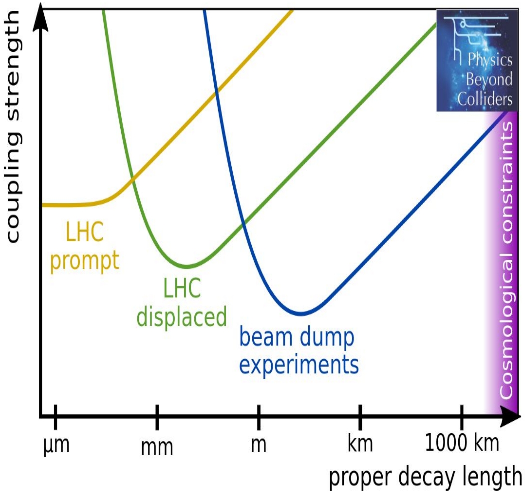



- (later analysis: No events when opening SR in $e^+e^-$)

# … result for axion-like particles

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



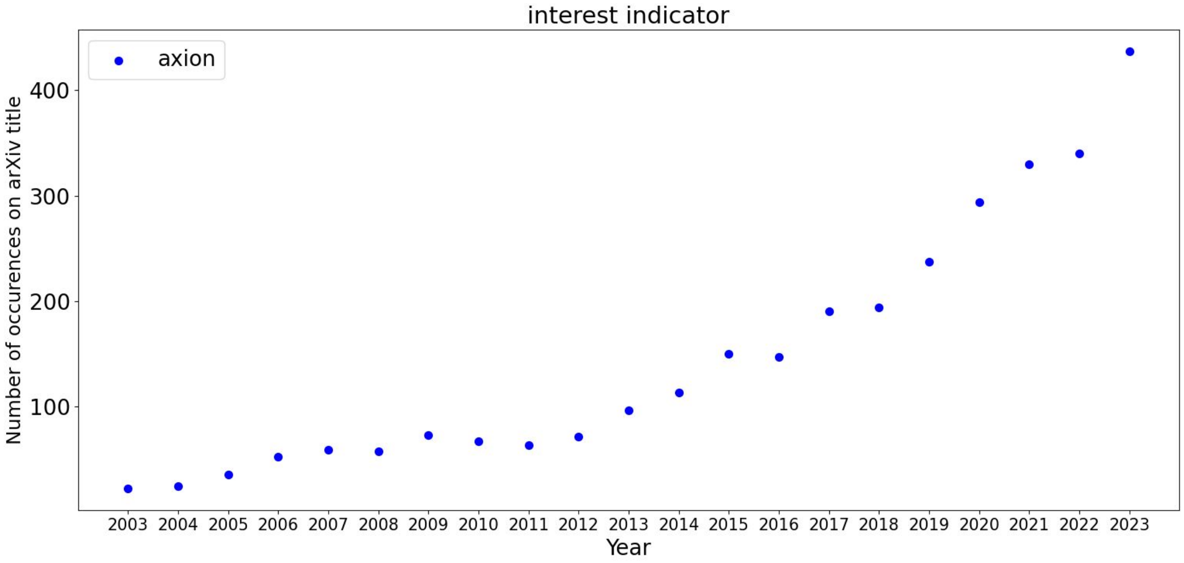

Top: $\mu^+\mu^-$ ,
bottom: $e^+e^-$

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

## Conclusions

- Axions have gone from “niche” to “main-stream”, see rhs
- in principle there is a vast parameter range which is motivated
- Direct axion Dark Matter detection for vanilla models in reach
- Heavy axions can be connected to rich phenomenology
- Hopefully, the increased attention can be rewarded with a proper discovery
- **THANK YOU for your attention**

Interest indicator:



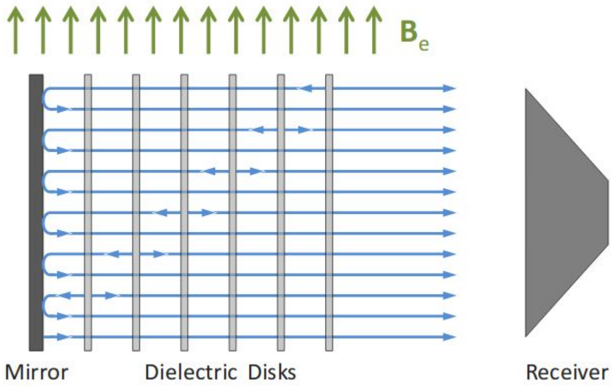

Credit to: NA62, especially their Exotics WG, and my colleagues in RADES

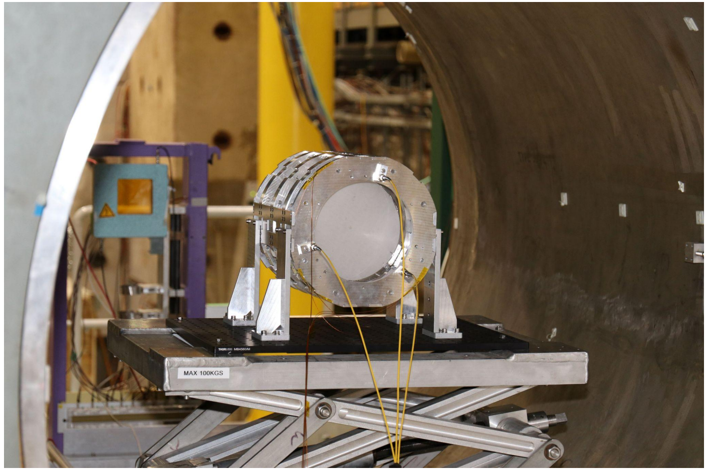
# Backup

- Here starts the backup

# Another scheme for larger masses: dielectric Haloscope, e.g. MADMAX

- Elegant solution to fix the m ~ f_resonance problem
- Simply spoken: add index of refraction (adding coherently) to go to large resonance frequencies and broadband (by moving the disks) at the same time!
- Plan: ~9T magnet at 1.3m diam-> scan significant portion of “large DM axion mass” parameter space
- Prototype campaign in CERN’s morpurgo magnet in 2023/2024 at 1.6 T (results expected soon):



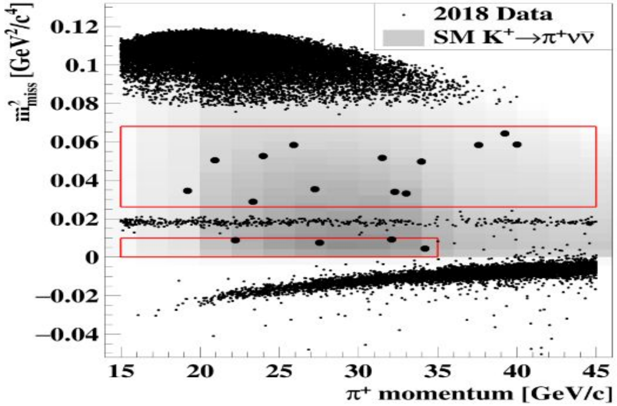



Recent SPSC status report (G. Ruggiero, May 11th 2023)

# $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ from RUN1

$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$

| | |
|---|---|
| $\mathcal{O}(100\text{ ps})$ | Timing |
| $\sim 10^3$ | Kinematic background suppression |
| $\sim 10^8$ | Muon suppression |
| $\sim 10^8$ | $\pi^0$ suppression |




$N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$,

$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$.

$N_{obs} = 20$

3.4$\sigma$ evidence $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

$BR = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$

JHEP06(2021)093

**"Random Veto"**

Probability of signal loss when rejecting photons

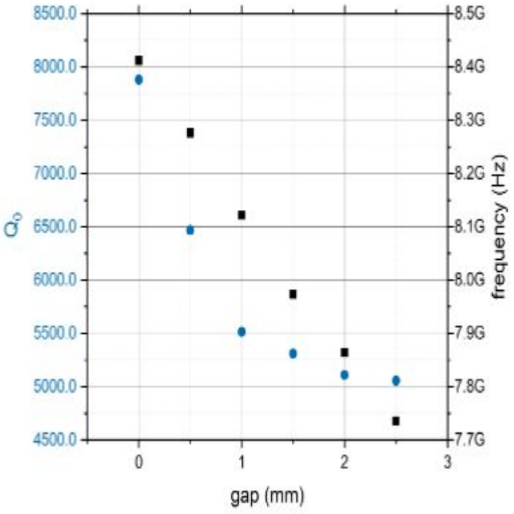
Loss due to random veto induced by accidental activity

**"Upstream" background**

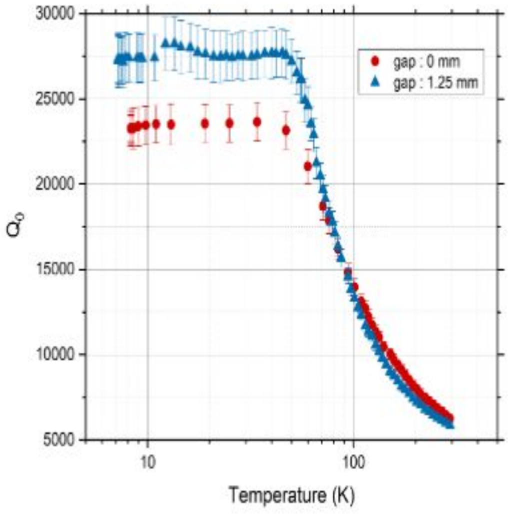
$K^+$ decays upstream

Problem: lack of vetoes along the beam line

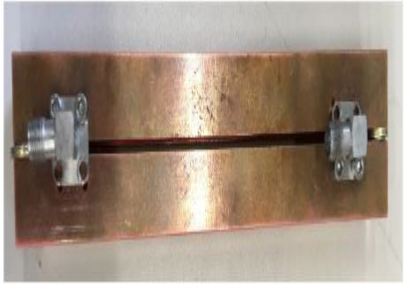
# Ctd.: “Pizza structure” (larger masses with classical scheme), (different experiment, RADES)




Golm et al. [2312.13109]

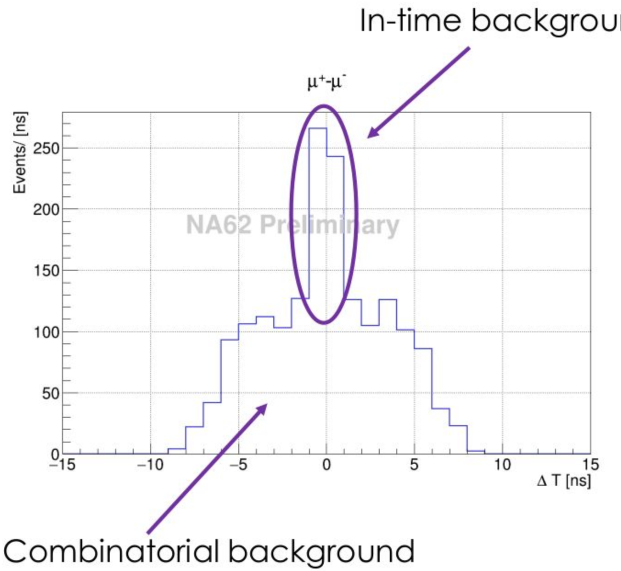


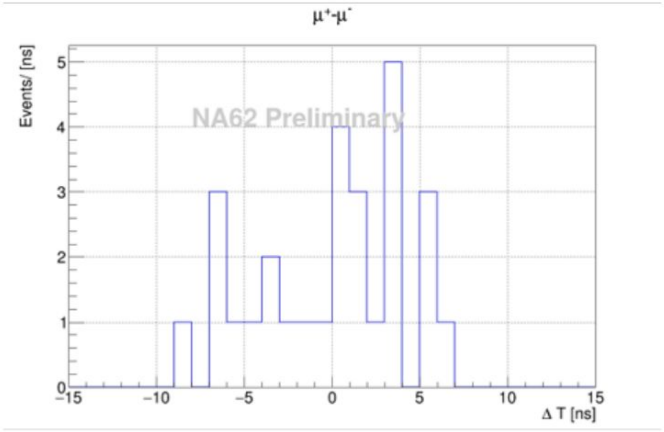

Tunable over 700Mhz in principle!



# Observed track time difference

Suggests two main background mechanisms




Before LAV veto (CR & SR blind)

Final events selected (CR & SR blind)

# 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 $\pi$ with consecutive decay to $\mu$ )
- Kinematics extracted from single tracks (backward MC - PUMAS)
- Relative uncertainty of MC expectation ~50%

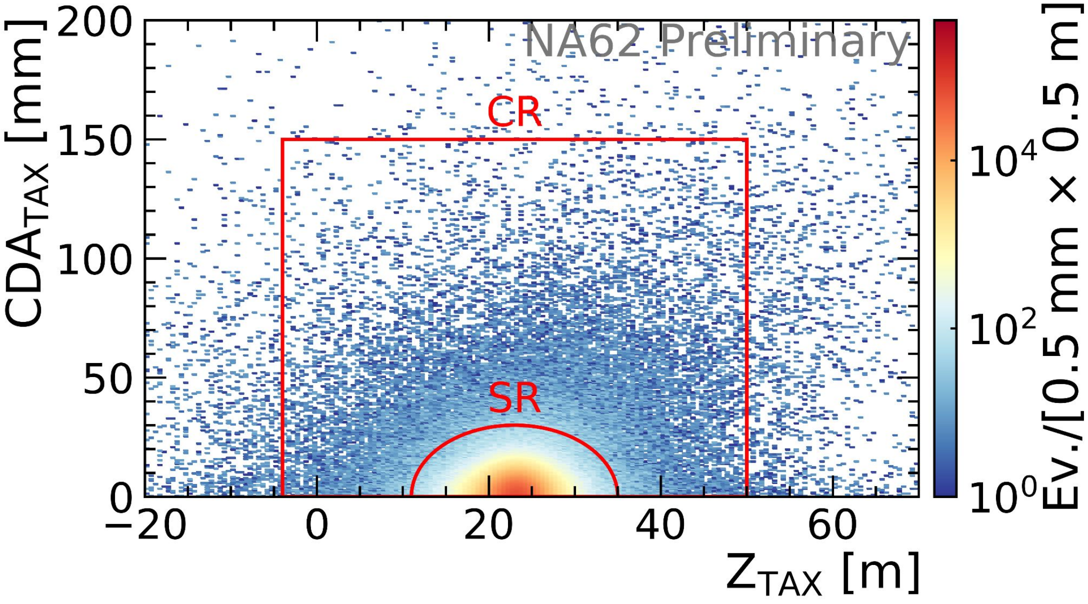
Table 4: Summary of expected numbers of background events for the search of $A' \to \mu^+\mu^-$ with the related uncertainty. The limits reported are defined with a 90% CL.

| Region | Combinatorial | Prompt | Upstream-prompt |
|---|---|---|---|
| CR | $0.17 \pm 0.02$ | $< 0.004$ | $< 0.069$ |
| SR | $0.016 \pm 0.002$ | $< 0.0004$ | $< 0.007$ |

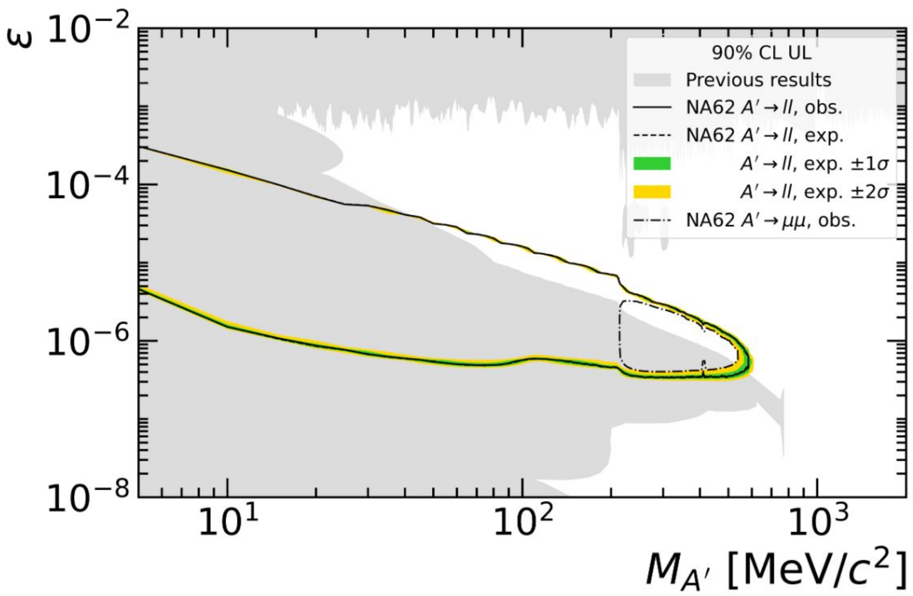
# … the $e^+e^-$ channel [very fresh from the arxiv: 2312.12055]

**Differences** with respect to $\mu^+\mu^-$

- Decay region optimization (cone-shape)
- PID optimization
- Inclusion of **ANTI0** detector
- New signal region definition (shown from bremsstrahlung on rhs)
- Background studies in backup slides



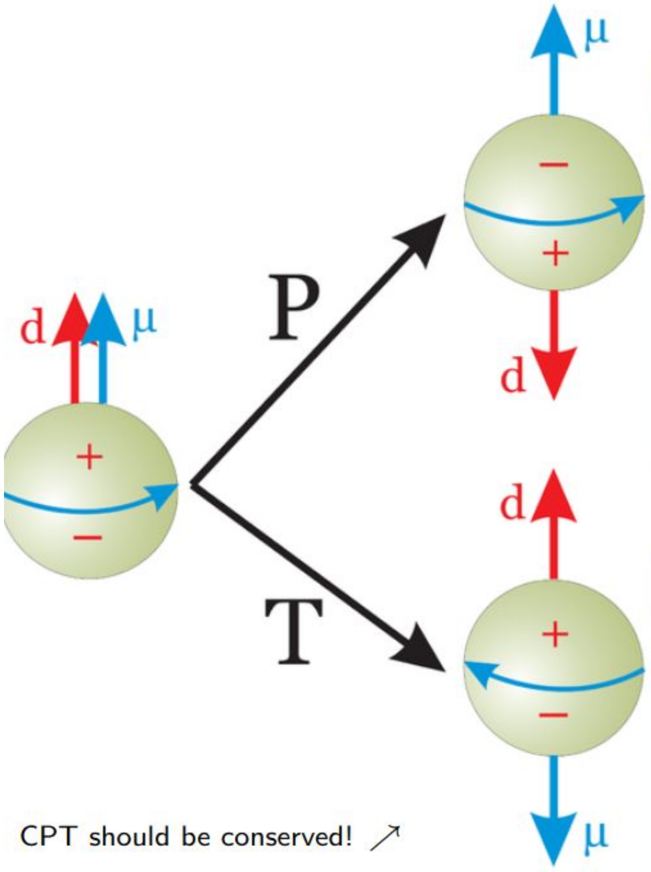
# Completeness: Leptonic decay of Dark Photons




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! ↗

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