Axion and ALP searches at different massses - an unavoidably biased overview

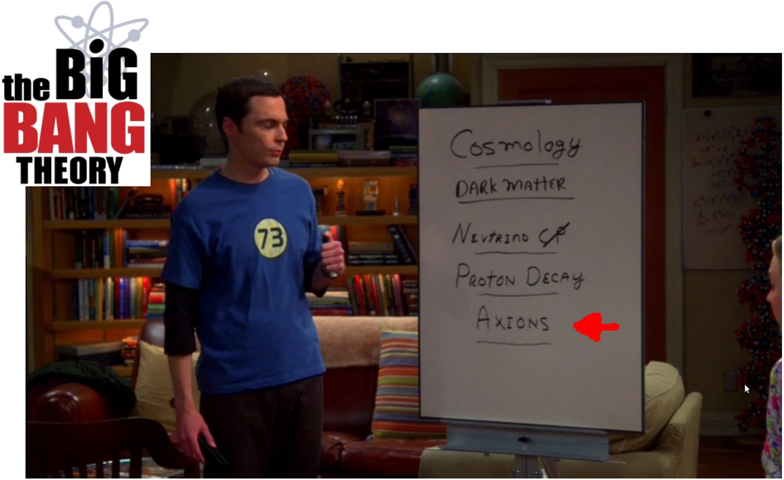
Babette Döbrich (CERN)

MPI, Garching, 5/11/19

European Research Council

Established by the European Commission

The axion in popular culture...



Sheldon looks for a new field of study... after BICEP 2 announcement
The Relationship Diremption, Aired April 10, 2014

The axion in (European) political culture...

CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

https://arxiv.org/abs/1910.11775

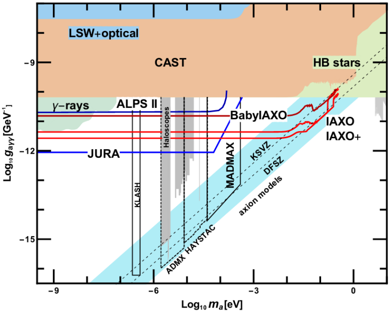


Fig. 9.7: Current exclusion of ALPs and axions coupling to photons in the sub-eV mass-scale (see, e.g., [349,614] for details) with experimental prospects. Astrophysical limits are shown in green, pure laboratory experiments are indicated in blue, helioscopes in red and haloscopes in black. The turquoise shaded region indicates the typical coupling range expected for QCD axion models. Couplings to other particles than photons are discussed in the supporting note [518].

QCD axion, white area: axion-like-particle, coupling-to-2-photons vs mass

The axion in (European) political culture...

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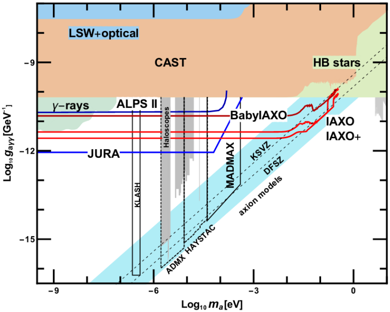

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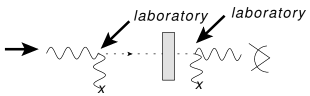
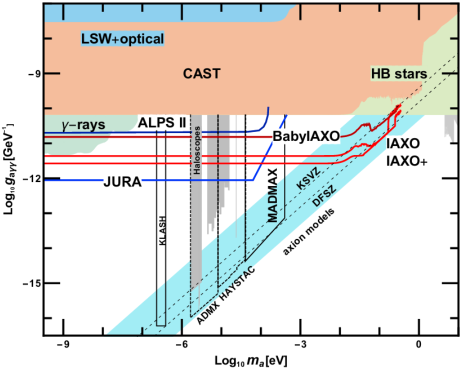
FlagShipExps: ALPS-II (LSW), IAXO (Helioscope), MADMAX (Haloscope)

why? difference in ALP/Axion source: disadvantages can cancel out

1) “Homemade” ALPs: production and detection in lab

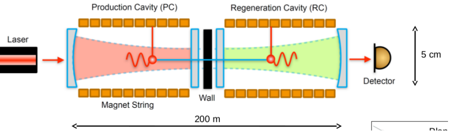


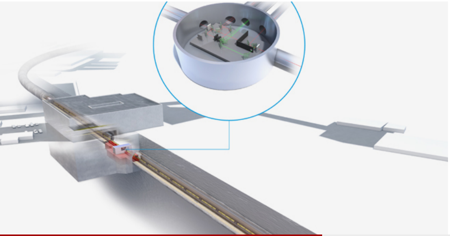
- light-shining-through-a wall [Anselm ’86]
    - ☺ full control over production mechanism, least model-dep.
    - ☹ large installation needed to compete with, e.g. Helioscopes
- “first generation”: ALPS-I (DESY) and OSQAR (CERN)



1) “Homemade” ALPs: production and detection in lab

[pictures courtesy A. Lindner]





- light-shining-through-a wall [Anselm '86]
  - ☺ full control over production mechanism, least model-dep.
  - ☹ large installation needed to compete with, e.g. Helioscopes
- “first generation”: ALPS-I (DESY) and OSQAR (CERN)
- second generation: ALPS-II [arXiv:1302.5647], main upgrades
  - 10 + 10 straightened HERA dipoles (200m!)
  - regeneration cavity (status: 20m prototype)
  - Transition Edge sensor
- foreseen start of data taking with full setup in the HERA tunnel at DESY ∼ 2021

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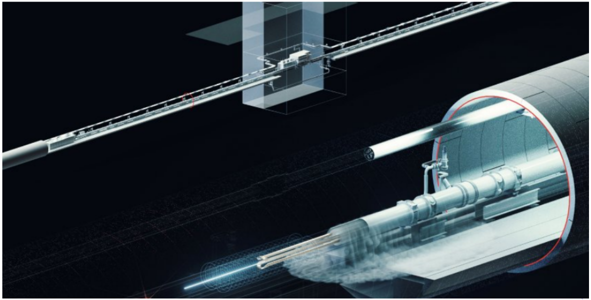
Nachrichten > Wissenschaft > Natur > Desy > Alps II am Desy: Kann Licht durch eine Wand scheinen?

Neues Experiment am Desy

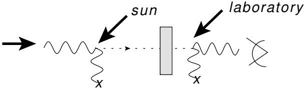
Kann Licht durch eine Wand scheinen?

Woraus besteht Dunkle Materie? Ein Experiment in Hamburg sucht nach besonders leichten Partikeln - ihre Entdeckung wäre eine Revolution in der Physik. Außerdem speziell: die Verwendung von recycelter Technik.

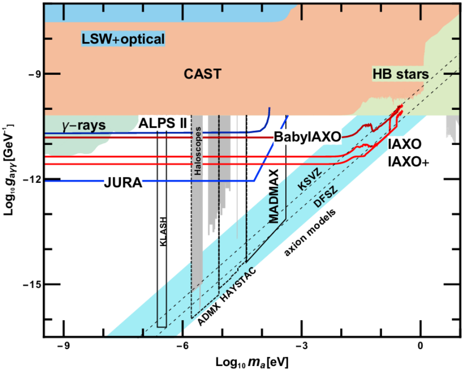


On the occasion of first magnet installation in tunnel

2) Production in the sun (Helioscopes)



- leading: CAST (20years!)
  - ☺ broadband, reaches QCD axion band at "high" mass
  - ☹ dependent on flux at source (nontunable and slightly model dep.)



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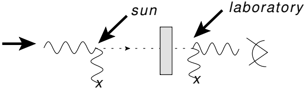
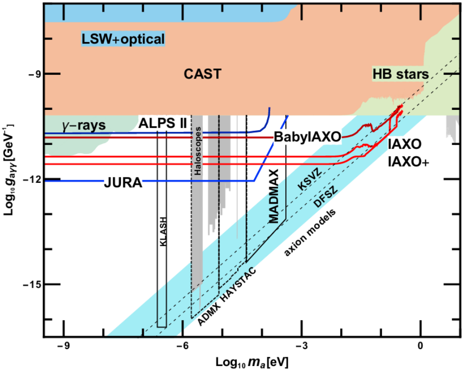
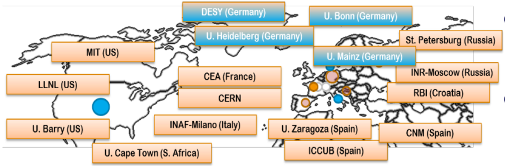




- leading: CAST (20years!)
  - ☺ broadband, reaches QCD axion band at "high" mass
  - ☹ dependent on flux at source (nontunable and slightly model dep.)
- last result (2013-2015 data) [Nature Physics 13, 584-590], competitive with most restrictive astrophysical results
- proposed 2020/2021 CAST program (besides solar tracking) includes direct DM searches (see later), density-dep. fields

2) Future Helioscopes: babyIAXO and IAXO(+)



- custom-made magnet for solar axion search: big $B^2 V$
- formal collaboration founding in 2017 at DESY (which has offered to host IAXO)

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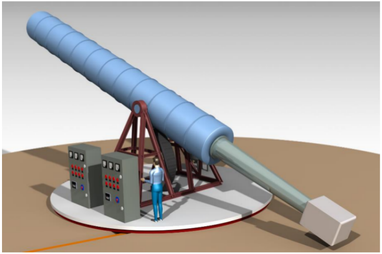
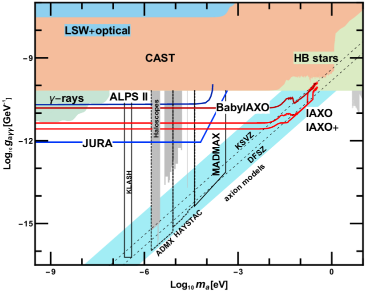
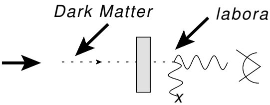




- custom-made magnet for solar axion search: big $B^2 V$
- formal collaboration founding in 2017 at DESY (which has offered to host IAXO)
- prototype babyIAXO: 2 bores (instead of 8), ERC adv. grant (I. Irastorza)
- Can probe an meV region which is compatible with DM as well as astrophysical hints (white dwarf cooling anomaly) JCAP 06/47 (2019)

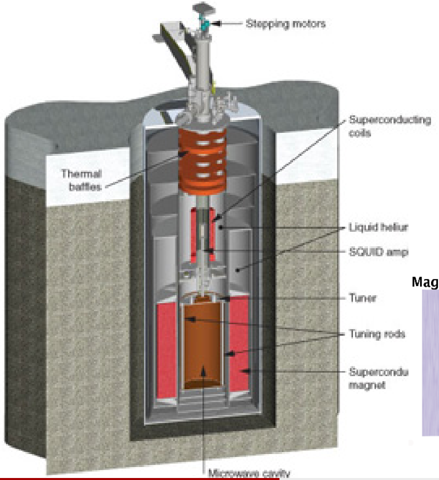
3) Dark Matter Axions (Haloscopes)

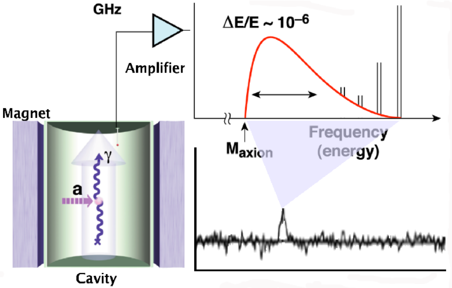


- Axions & ALPs $\rightarrow$ dark matter candidate $\rightarrow$ Haloscope [Sikivie '83] **resonant** technique

$f_{\rm cavity} \sim \omega_{\rm photon} \sim m_{\rm axion}$

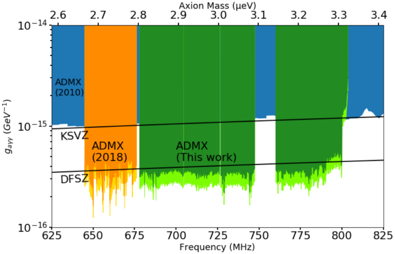
ADMX status cf [1403.5332]



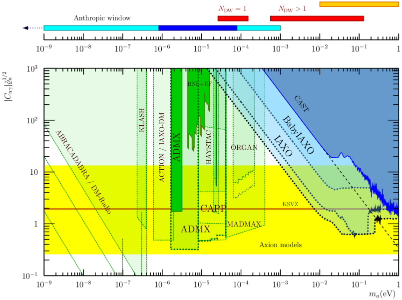


3) Dark Matter Axions (Haloscopes)

taken from [1910.08638]



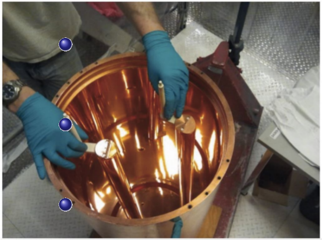
taken from [1801.08127]

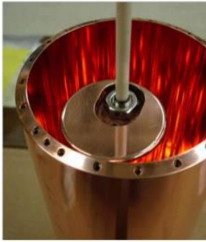


- Axions & ALPs → dark matter candidate → Haloscope [Sikivie '83] **resonant** technique

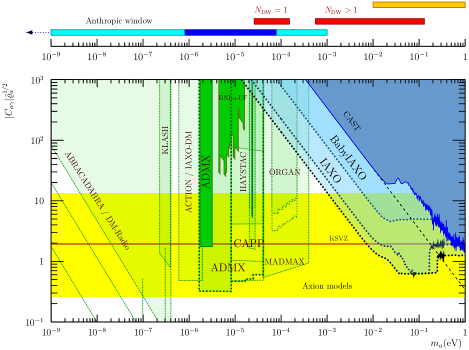
$f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$

- results obtained in Axion Band: ADMX and HAYSTACK
  - ☺ sensitive to axion DM
  - ☹ very narrow band (tuning)



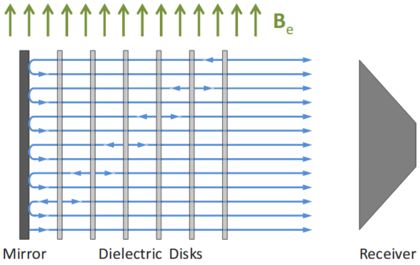


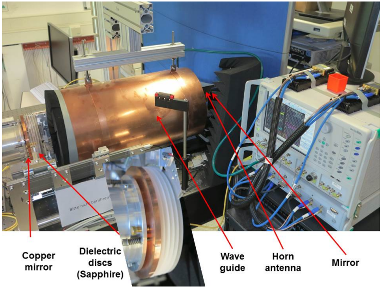
Interlude on 3): the problem with large axion masses



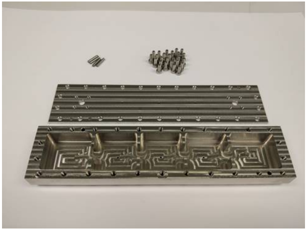
- Axion not overabundant above masses of $\sim 10^{-6}$eV
- naively: large $m \rightarrow$ higher resonance $f \rightarrow$ lower dimension
- Output power from cavity: $P \sim g^2 \frac{\rho}{m} B^2 \; V \; Q \; G$
- Quality factor $Q \sim 1/\Delta f \rightarrow$ long scan times
- $Q \sim \frac{V}{\delta S}$ Volume to surface ratio: gets bad at large Volumes
- proposed soln's: larger B (CAPP), superconducting cavity, very low T_{noise}, dielectric layers (MADMAX)

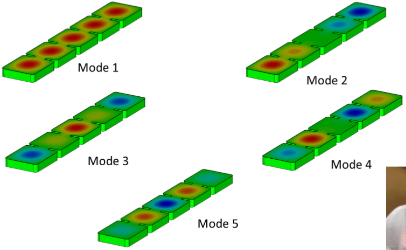
- rough explanation: "open resonator" i.e. constructively combine axion emission at dielectric surface by choice of plate separation and dielectric constant $\rightarrow$ allows to probe 'large' axion DM mass
- under review for running at DESY
- among challenges: 9T dipole with 1.35m bore



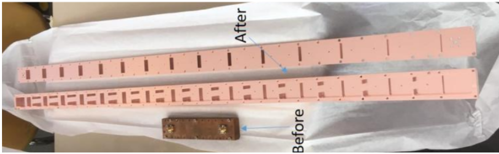


Interlude: RADES concept explored at CERN Melcon et al [1803.01243]





- RADES at CERN: retain large volume at high resonance frequencies large using subcavities
- sub-cavity sets resonance scale
- only first resonant mode couples to the axion
- prototype data on tape, long cavity installed in magnet



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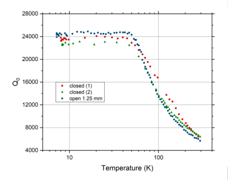
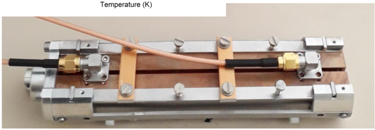
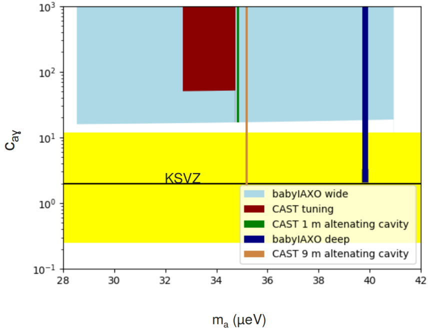


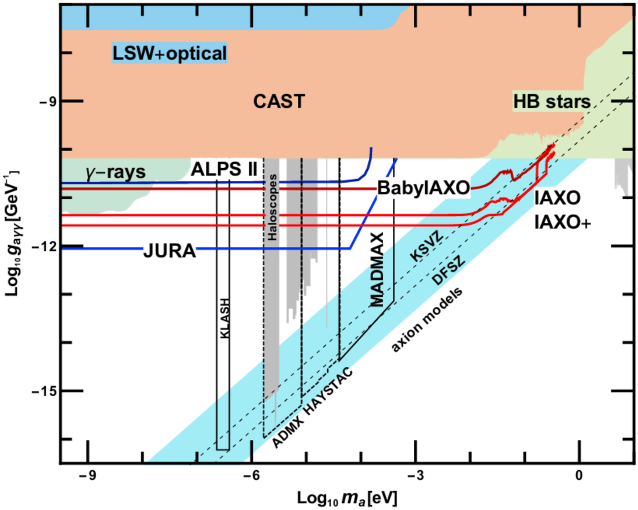




- RADES at CERN: retain large volume at high resonance frequencies large using subcavities
- sub-cavity sets resonance scale
- only first resonant mode couples to the axion
- prototype data on tape, long cavity installed in magnet
- **tuning** prototypes OK in cryolab, prospects with babyIAXO encouraging (after solar run, example 1 year, conservative)

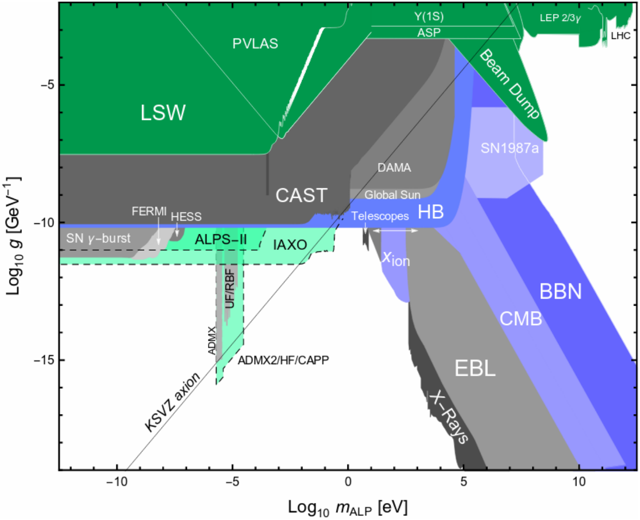
Putting things together

in ∼10 years, worst case: many more filled areas, case: discovery

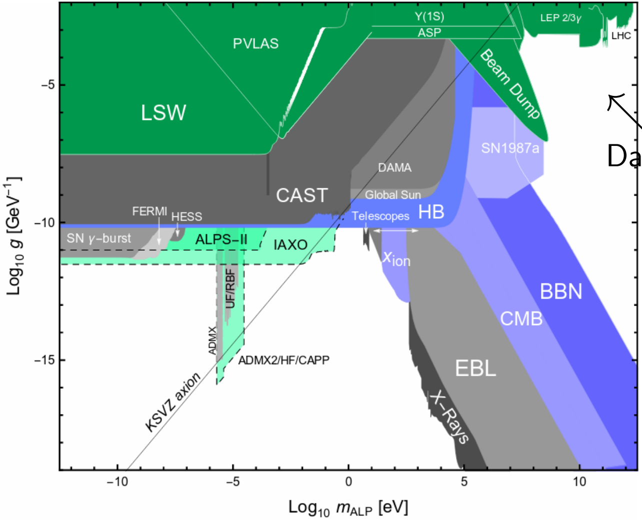


Putting things together

completing the story: the idea of 'Dark Sectors'

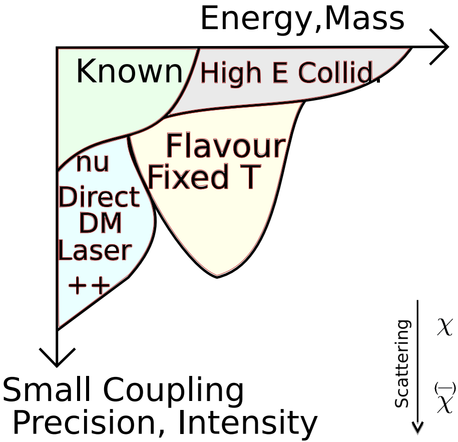


Putting things together

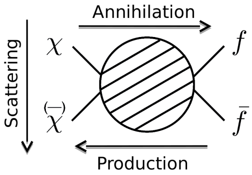


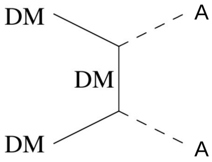
Dark Sector

Interlude: new physics at the MeV mass scale

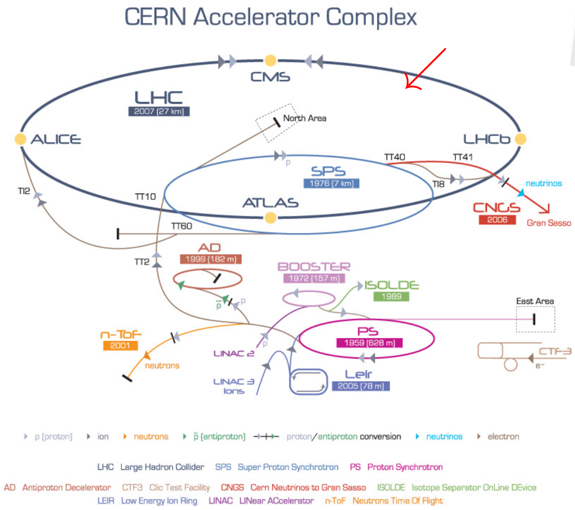


- From the previous slide: sub-eV is not the only open option
- some models of Dark Matter propose MeV mass, weakly-coupled particles [1502.06000] to act as a Mediator particle





NA62 at CERN



P326 NA62

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

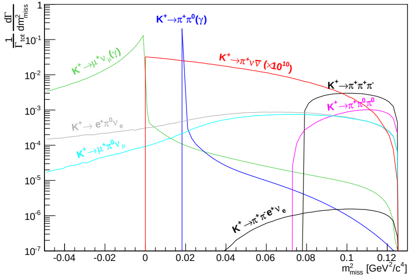
BR theory:

$$(8.4 \pm 1.0) \times 10^{-11}$$

Buras et al. JHEP 1511, 33

New Result 2017 data! https://indico.cern.ch/event/846814/

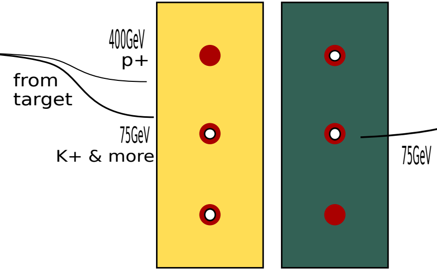
How to look for Axions at NA62

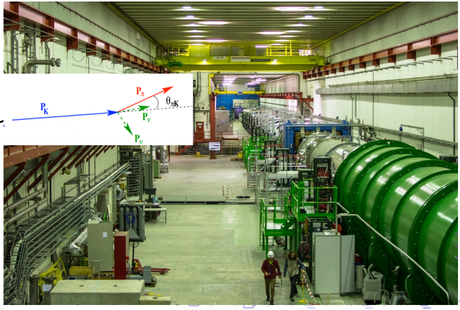


straightforward: flavored axion

$K^+ \to \pi^+ + a$

(almost by-product of $\pi^+ + \nu\bar{\nu}$)





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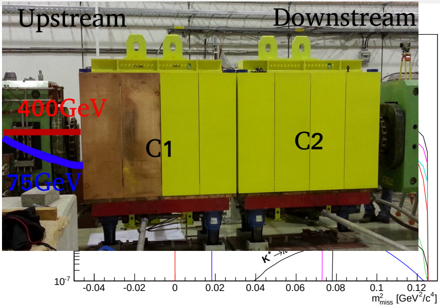


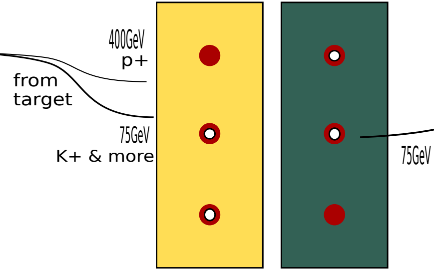
parasitic (charged) triggers not requiring an initial Kaon

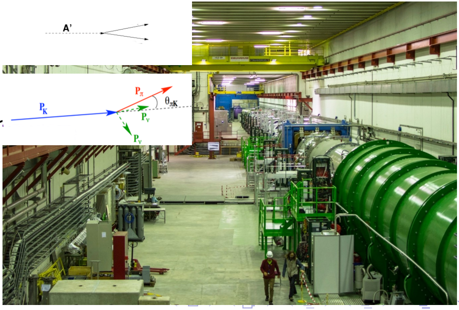
$\Rightarrow$ **upstream production**

60 % target interaction & 40 % direct p

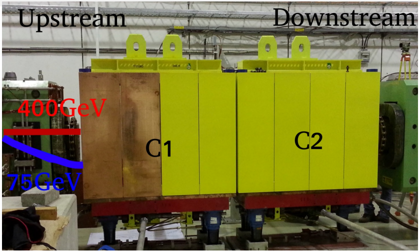
see e.g. 1711.08967

e.g. $\mu\mu$: $\mathcal{O}(10^{17})$ POT in 2017





Possibility to run NA62 as beam dump

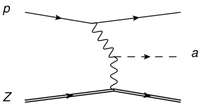


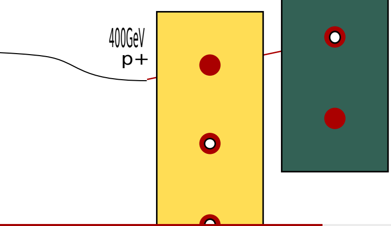
Primakoff production of MeV-GeV ALPs

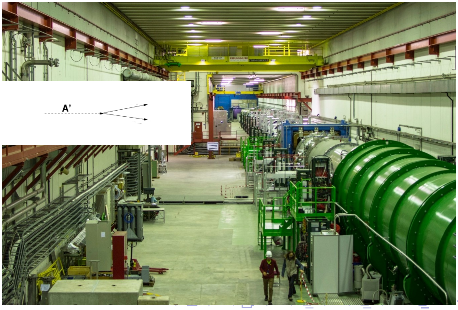
in upstream collimator: run as dump

critical for $\gamma\gamma$ final state

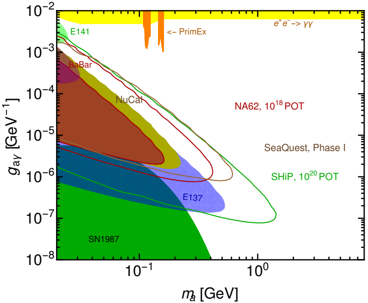
$\sim 2\times10^{16}$ POT collected so far

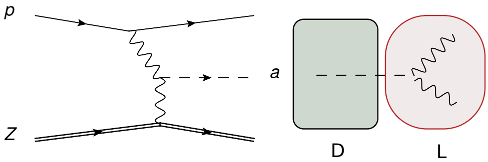






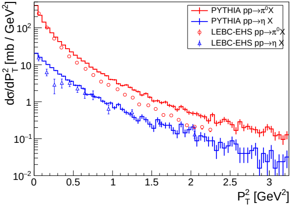
ALPs will be probed above the MeV





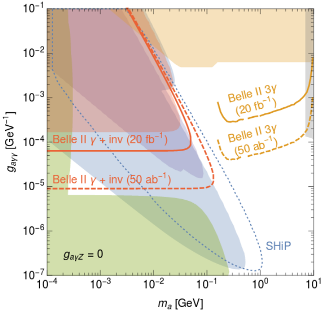
[BD et al, JHEP 1602, 018]

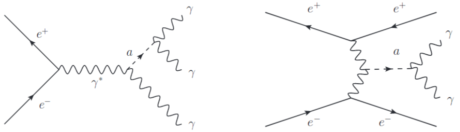
- Sensitivity prospect for 10^{18} POT at NA62 based on production via π^0 decay photons (also shown dedicated beam dumps called SHiP and Seaquest)



['light meson production archeology']
[BD et al JHEP 05(2019)213]

ALPs will be probed above the MeV

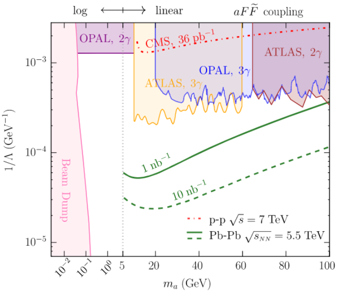


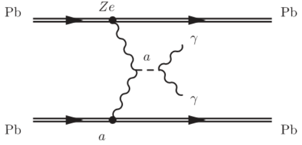


[Dolan et al, JHEP 1712, 094]

- Sensitivity prospect for 10^{18} POT at NA62 based on production via π^0 decay photons (also shown dedicated beam dumps called SHiP and Seaquest)
- Belle-II $\rightarrow$ photon-fusion and ALPstrahlung

ALPs will be probed above the MeV





[Knapen et al, PRL 118, 11]

- Sensitivity prospect for 10^{18} POT at NA62 based on production via π^0 decay photons (also shown dedicated beam dumps called SHiP and Seaquest)
- Belle-II $\rightarrow$ photon-fusion and ALPstrahlung
- LHC, e.g. lead-lead collisions very interesting through enhanced photon flux Z^4 (further collider options in case of hypercharge coupling [Bauer et al, JHEP 1712, 44])

Summary

- this was a lot but by far not exhaustive...
  - I did not mention searches for Axions/ALPs beyond using coupling to photons: coupling to photons has proven sensitive to QCD axion benchmark models. However exciting searches are going on, **CASPEr (Mainz), QUAX (Legnaro), ABRACADABRA ...**
  - have a look at the excellent review from 1801.08127 by Irastorza/Redondo for low masses
  - did not mention weakly coupled particles beyond pseudo-scalar (dark photons etc) case but often similar strategies as for Axion case (e.g. scalars: light-shining-through-wall: just turn polarization of laser w.r.t. magnetic field, Dark Photon: switch off mangetic field)
  - rushed over many experiments that all deserve their own talks
- **looking forward to your questions**

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