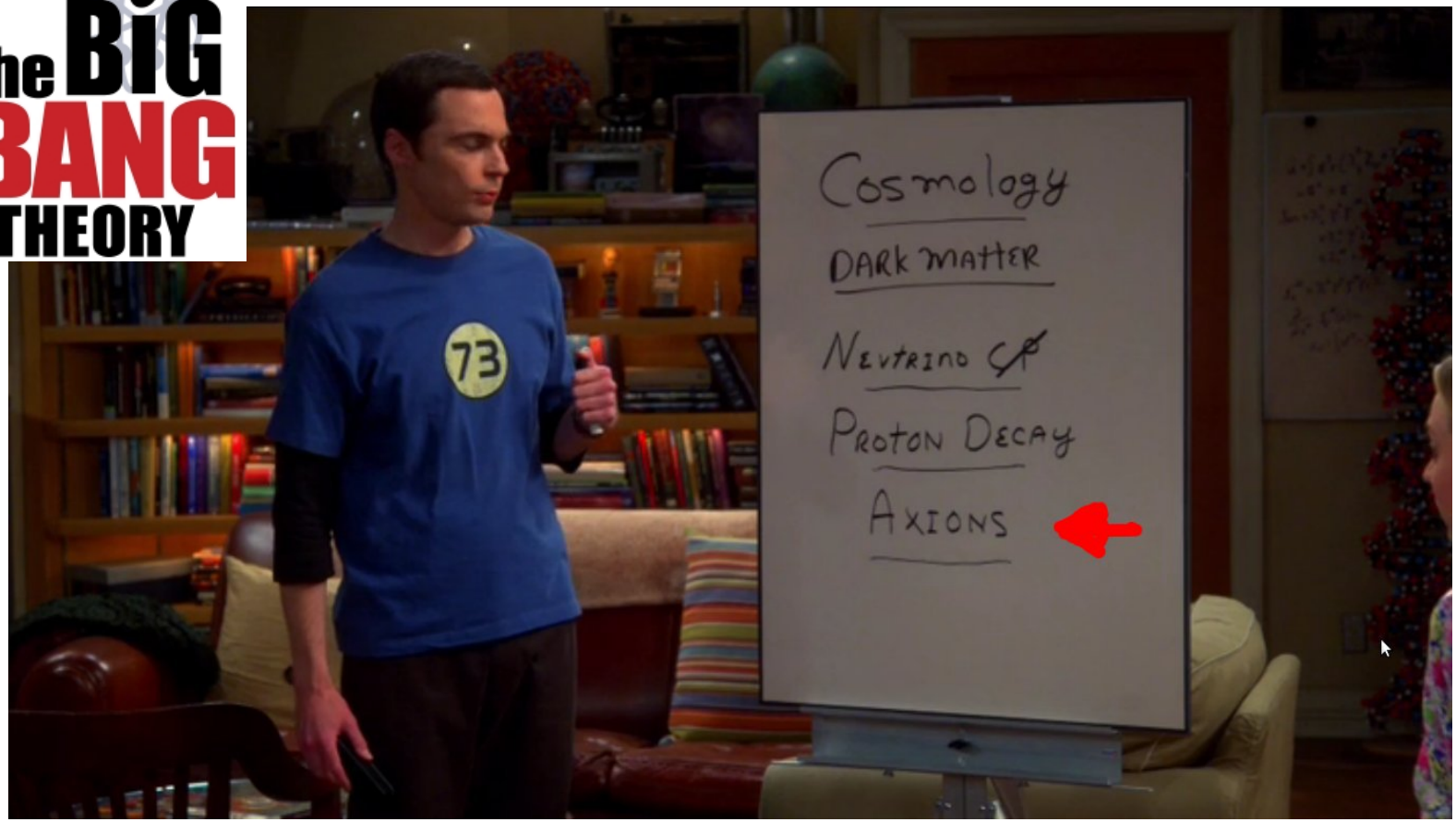
Axion and ALP searches at different massses - an unavoidably biased overview

Babette Döbrich (CERN)

virtual world, 09/10/20

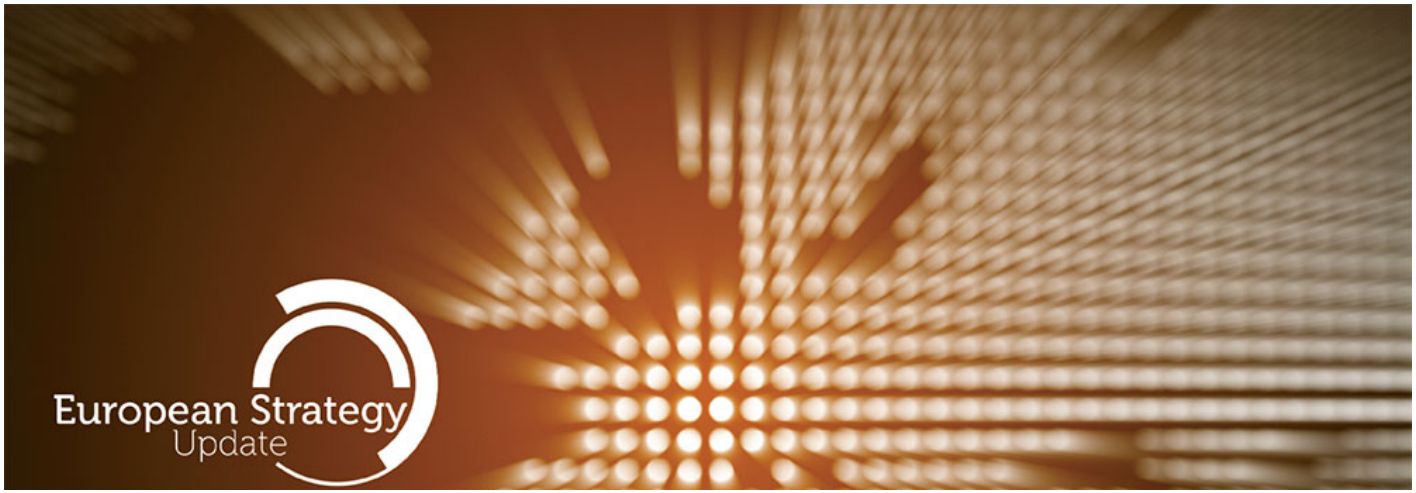
The axion in popular culture...



Sheldon looks for a new field of study... after BICEP 2 announcement

The Relationship Diremption, Aired April 10, 2014

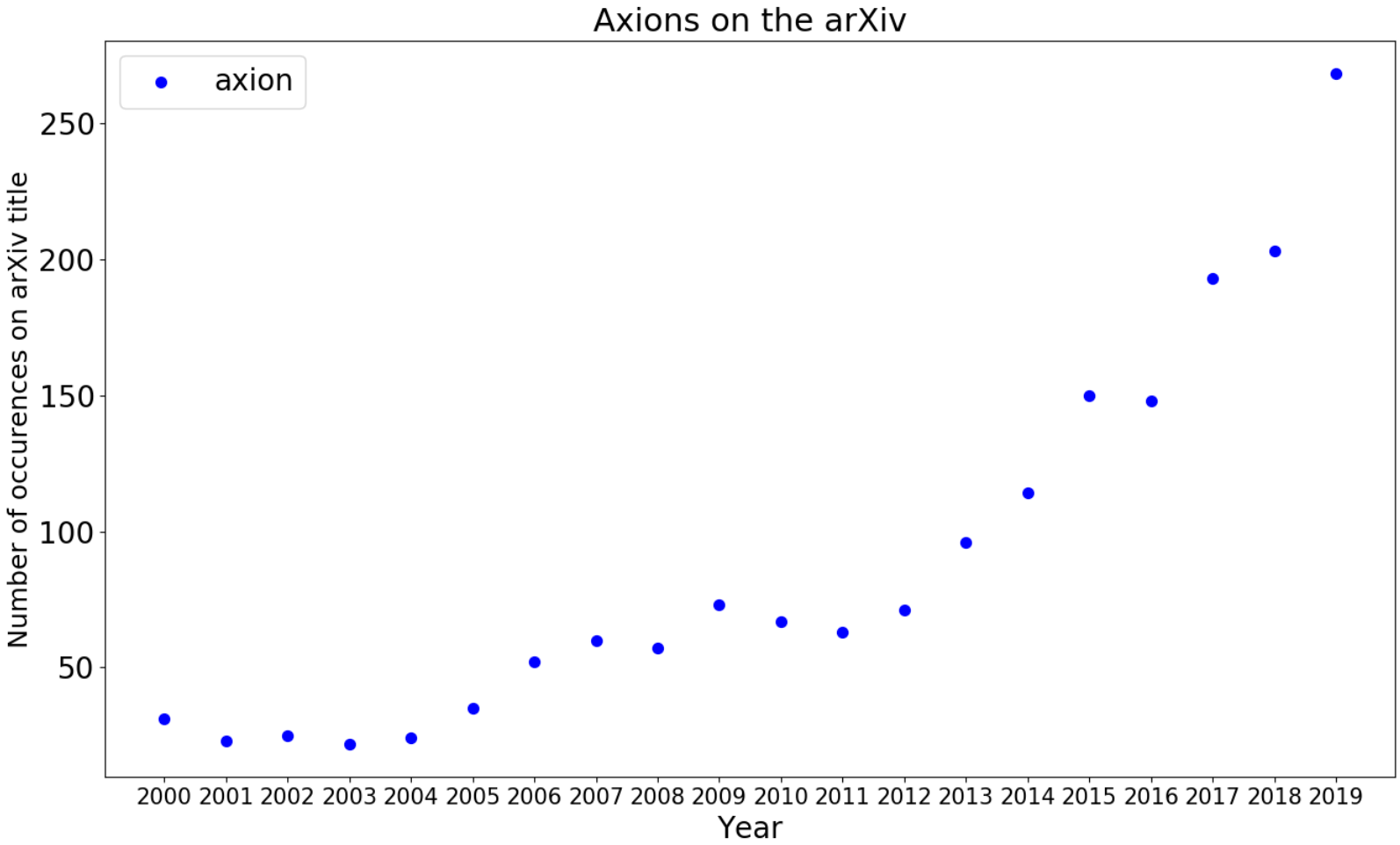
Also HEP is thinking what to do next...



The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

ESU-016 recommendation follows Sheldon! ;-)

... reflected/sparked by community interest:



Landscape: Let's have a look into the briefing book

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

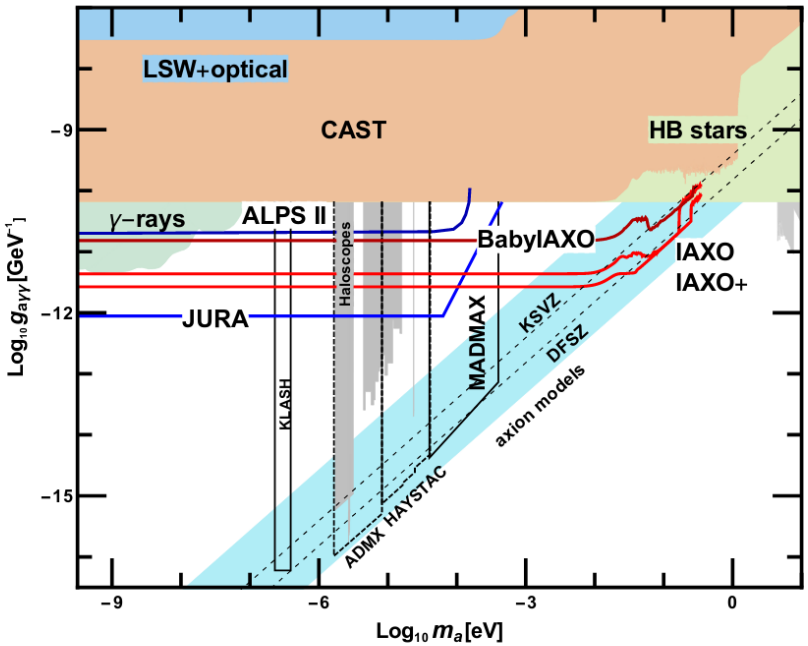


Fig. 9.7: Current exclusion of ALPs and axions coupling to photons in the sub-eV mass-scale (see, e.g., [349,614] for details) with experimental prospects. Astrophysical limits are shown in green, pure laboratory experiments are indicated in blue, helioscopes in red and haloscopes in black. The turquoise 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

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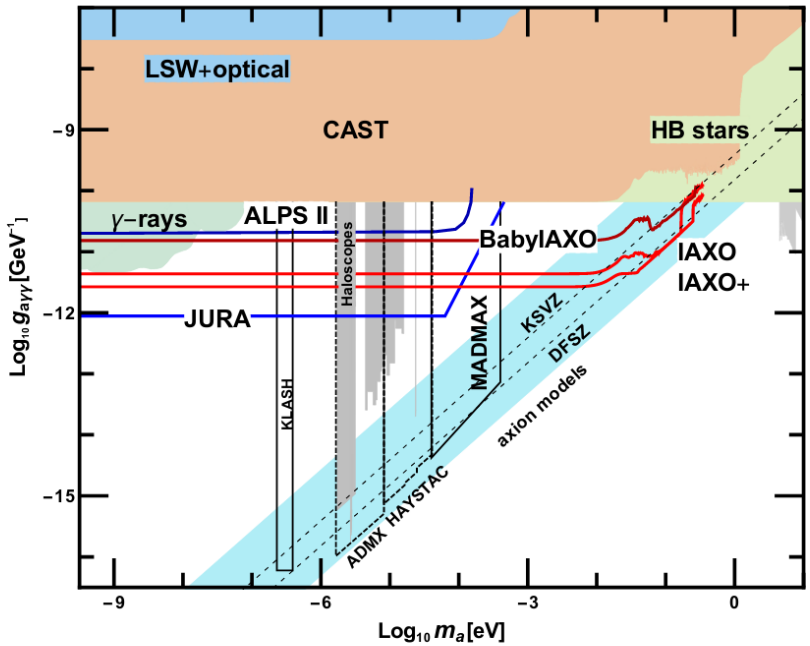

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FlagShipExps: ALPS-II (LSW), IAXO (Helioscope), MADMAX (Haloscope)

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

Why Axions? A brief dive into theory

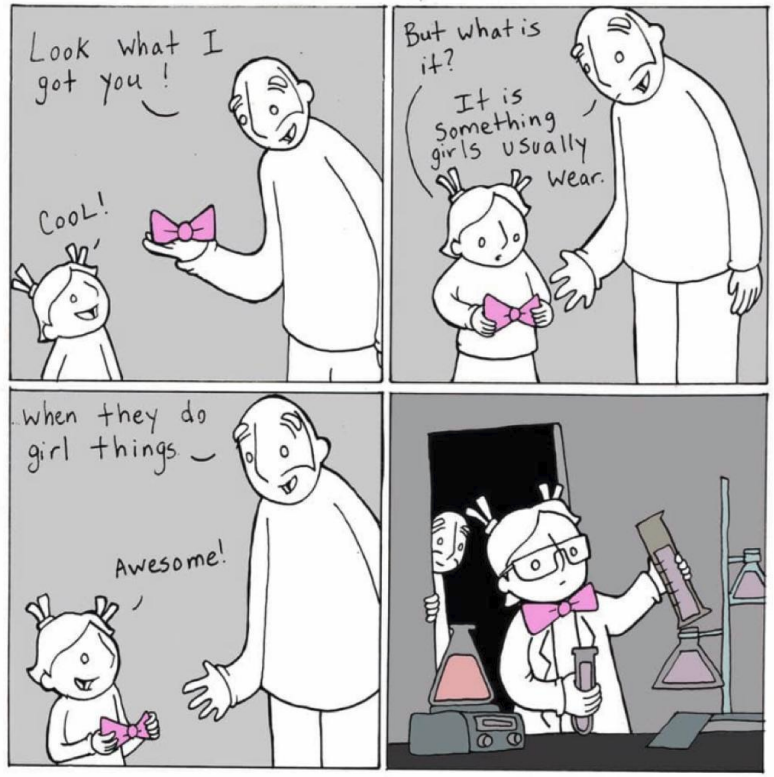
R. Peccei

H. Quinn

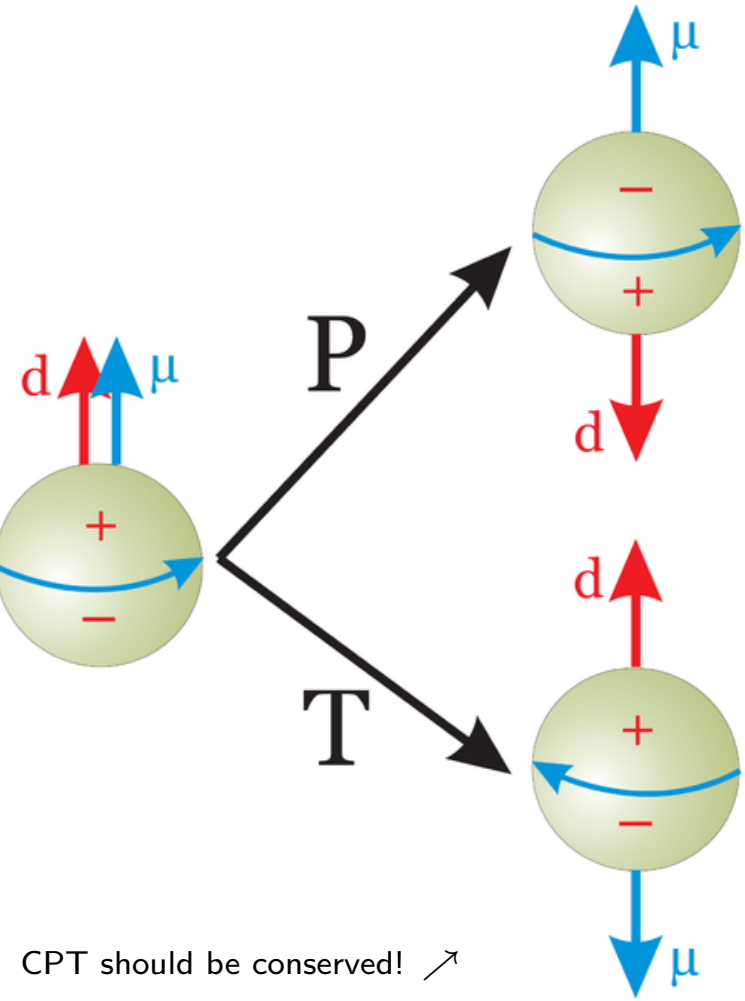
CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.



Why Axions? The strong CP problem!



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 $\bar{\Theta} = \Theta + \mathrm{Argdet} M$, M quark mass matrix

Experiment

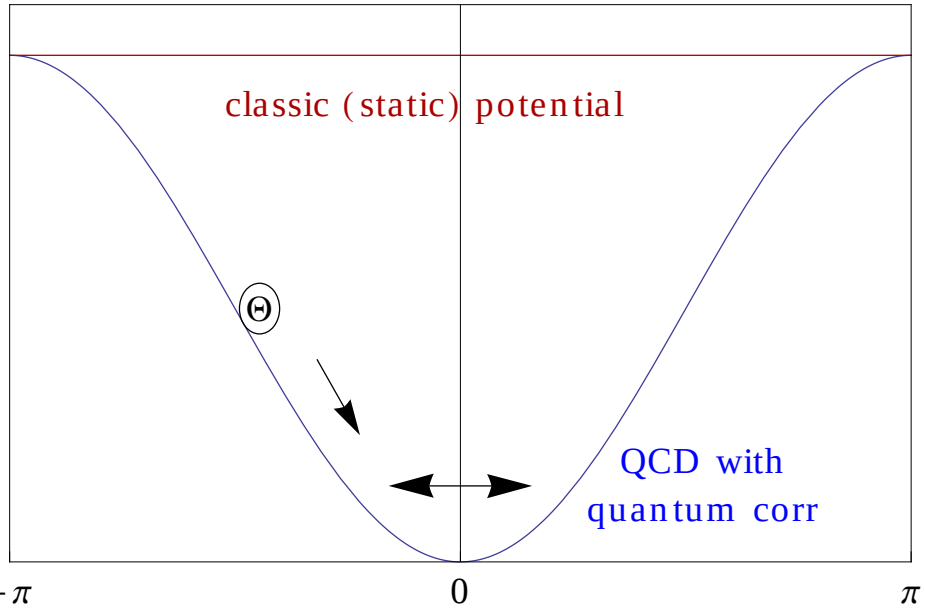
- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_n(\bar{\Theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

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

Axions in a (too small) nutshell see, e.g. 0807.3125

- make $\bar{\Theta} \equiv a(x)/f_a$ dynamical $\rightarrow$ zero through potential Peccei & Quinn, 77
- realized w global $U(1)_{\rm PQ}$ spontaneously broken at f_a, the axion is phase (Goldstone boson) of this symmetry

Weinberg, Wilczek, 78



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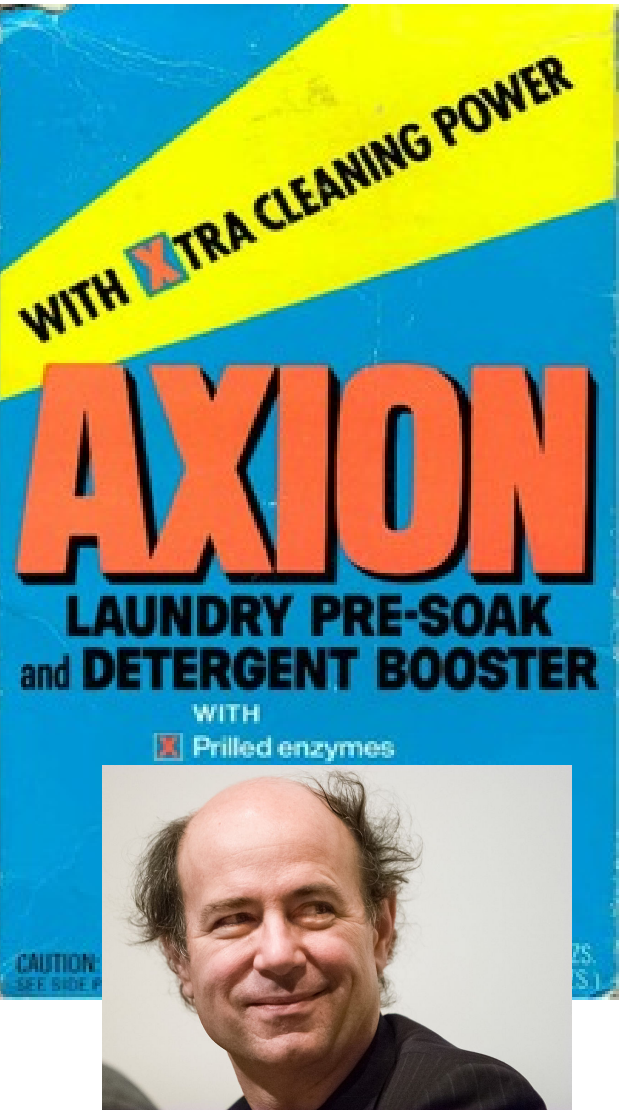

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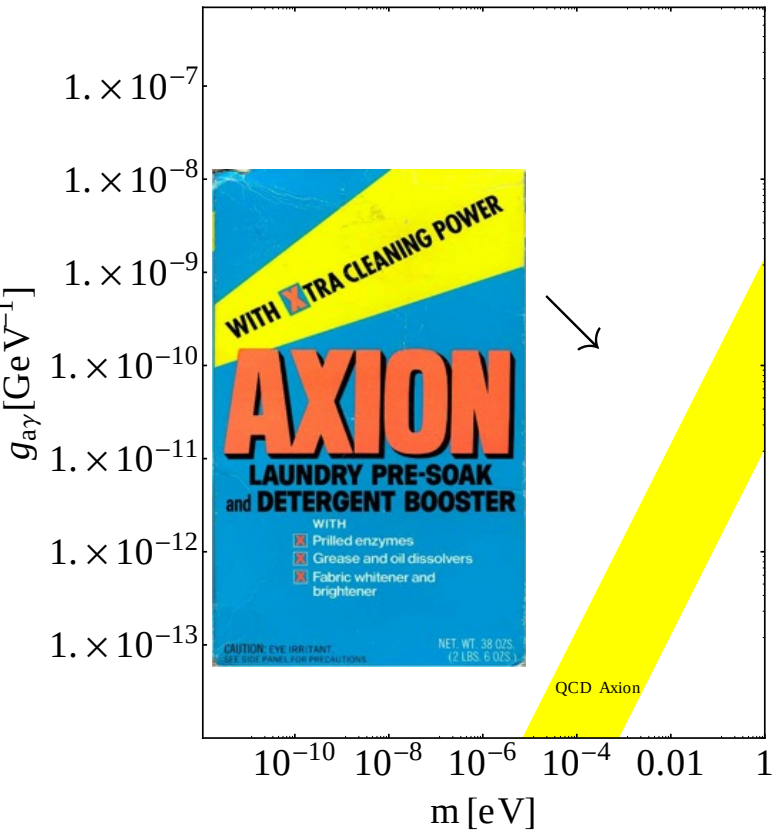
- originally $f_a \sim \Lambda_{\rm EW}$ (see arxiv:1710.03764 for revival)
- $f_a \gg \Lambda_{\rm EW}$ 'invisible axion models' 'KSVZ' & 'DFSZ' Kim, Shifman, Vainshtein, Zakharov & Dine, Fischler, Srednicki, Zhitnitsky

"I named them after a laundry detergent, since they clean up a problem with with an axial current." (Nobel lecture 2004)

Axions in a (too small) nutshell see, e.g. 0807.3125



[good reading: 9506229 Sikivie's Pooltable]

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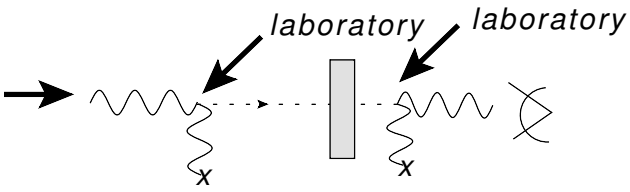
- $m \sim 0.6{\rm meV}/(f_a/10^{10}{\rm GeV}) \rightarrow$ pseudo-Goldstone boson
- couple to photons: Primakoff effect $\rightarrow$ basis of most experiments
- Axion ColdDM via 'misalignment'

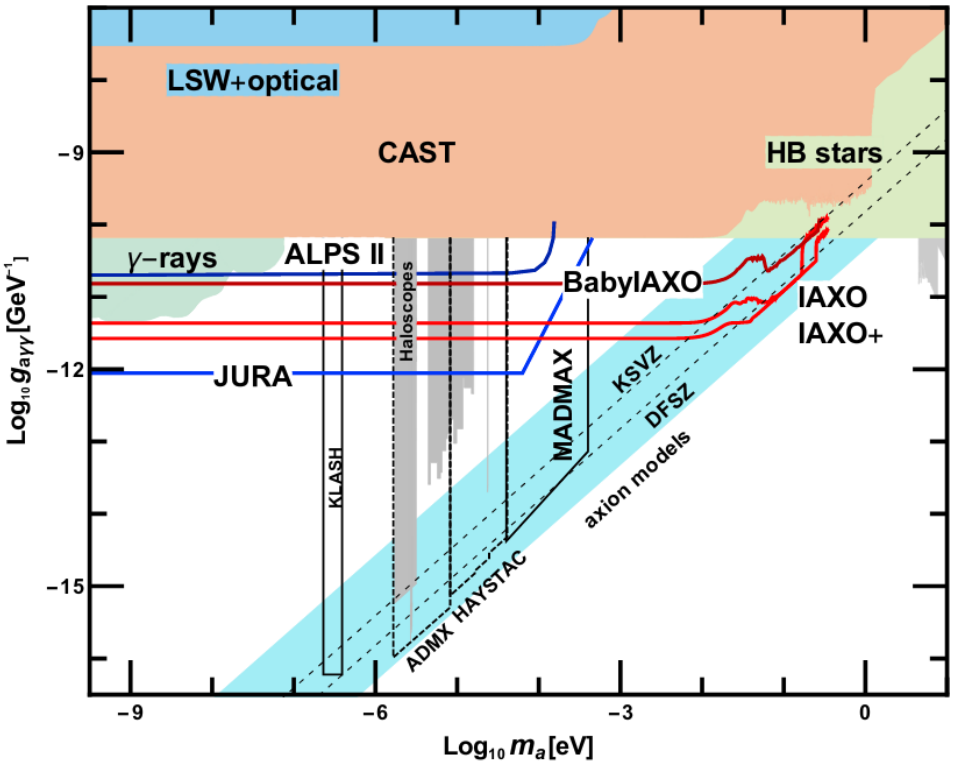
That's why Axions are theoretically appealing!

Need experiments to verify all of the above (Helps to have an AXION DETECTION SYSTEM)

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)



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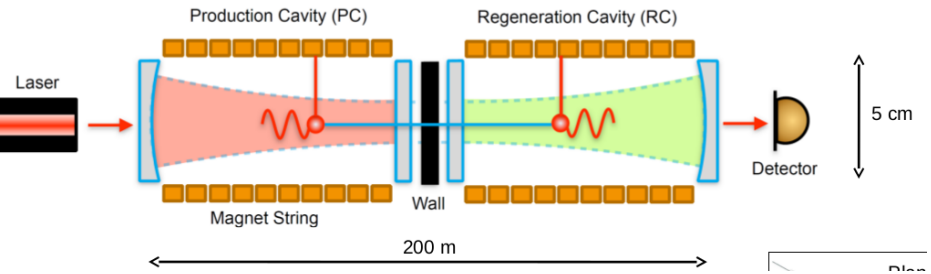
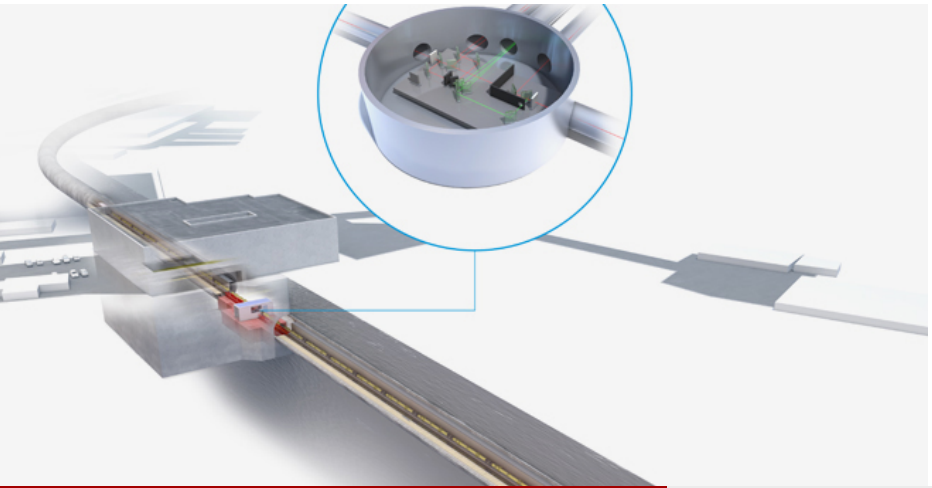
[pictures courtesy A. Lindner]





- 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 $\sim$ 2021

1) ALPS-II status

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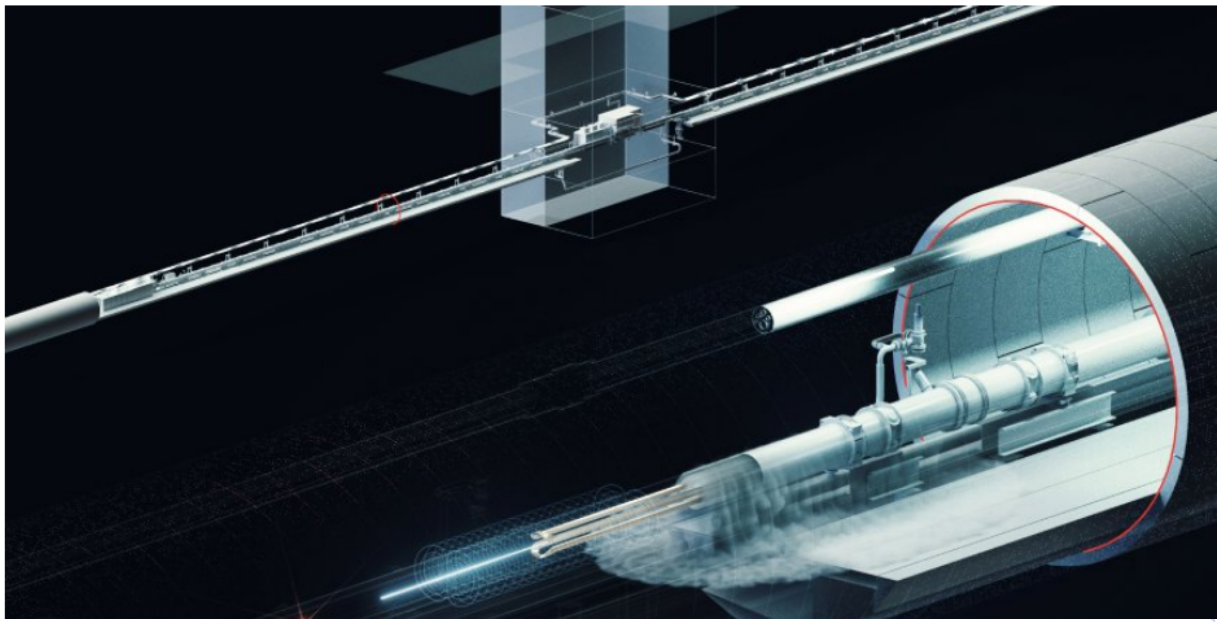
Nachrichten › Wissenschaft › Natur › Desy › Alps II am Desy: Kann Licht durch eine Wand scheinen?

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, 29.10.2019

1) ALPS-II status

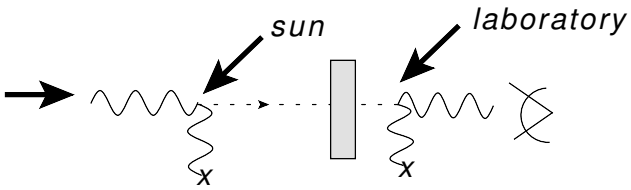
← status "now"

almost all magnets

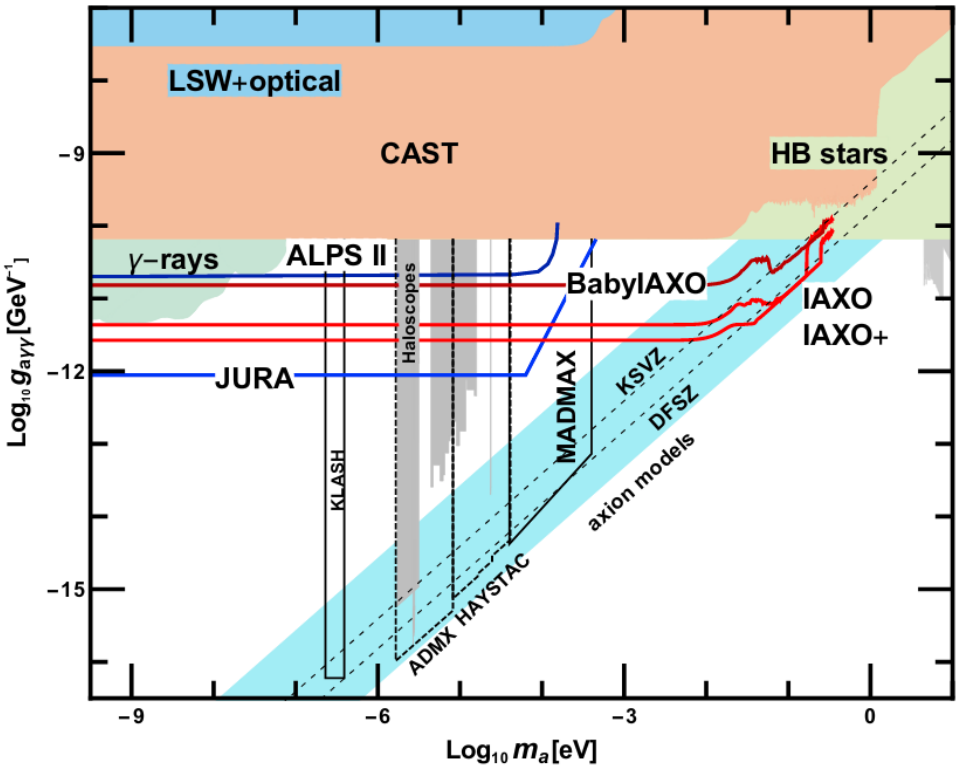
in straight (!) section

courtesy A. Lindner

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 dependent)



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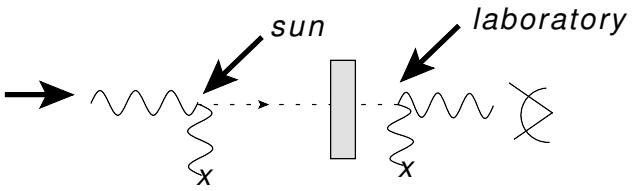
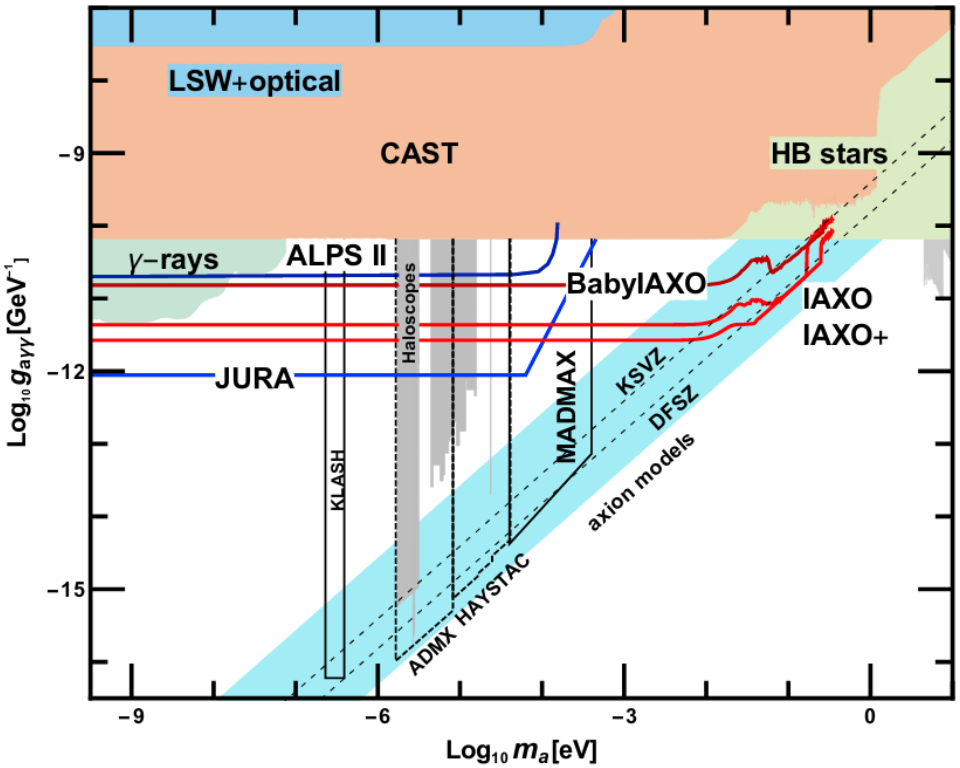
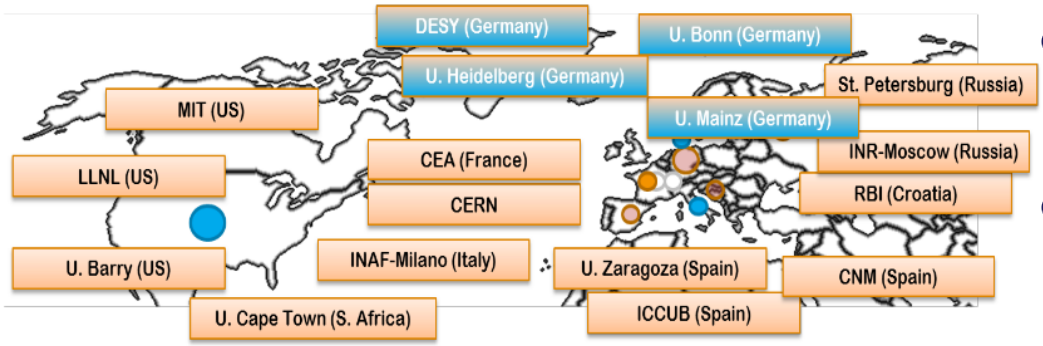




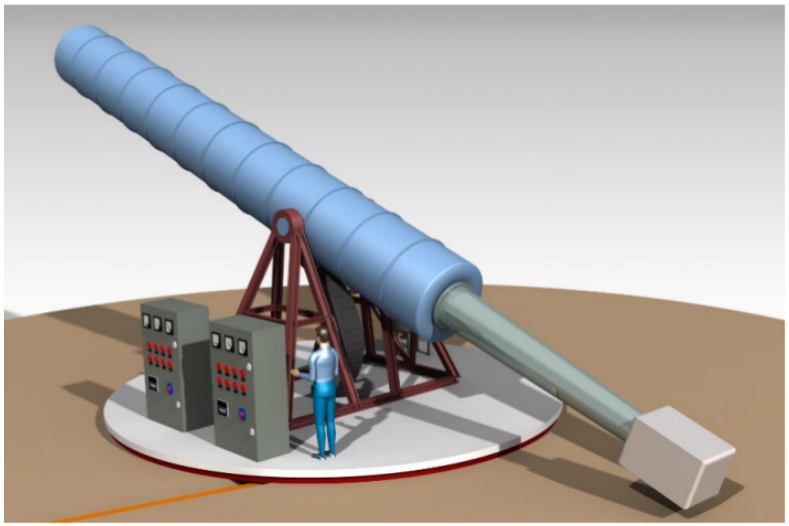
- leading: CAST (20years!)
  - ☺ broadband, reaches QCD axion band at "high" mass
  - ☹ dependent on flux at source (nontunable and slightly model dependent)
- last result (2013-2015 data) [Nature Physics 13, 584-590], competitive with most restrictive astrophysical results
- 2020 CAST program (besides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

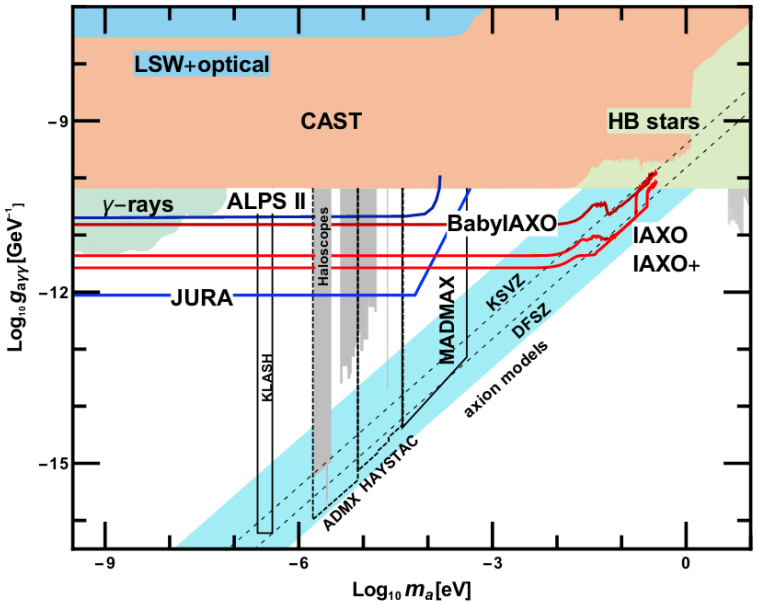
2) Future Helioscopes: babyIAXO and IAXO(+)



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

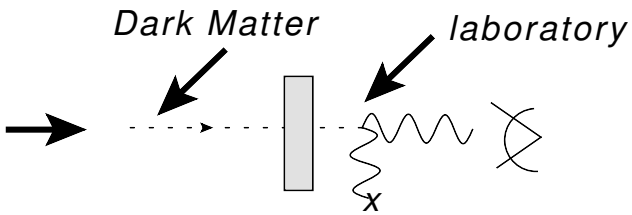
2) Future Helioscopes: babyIAXO and IAXO(+)





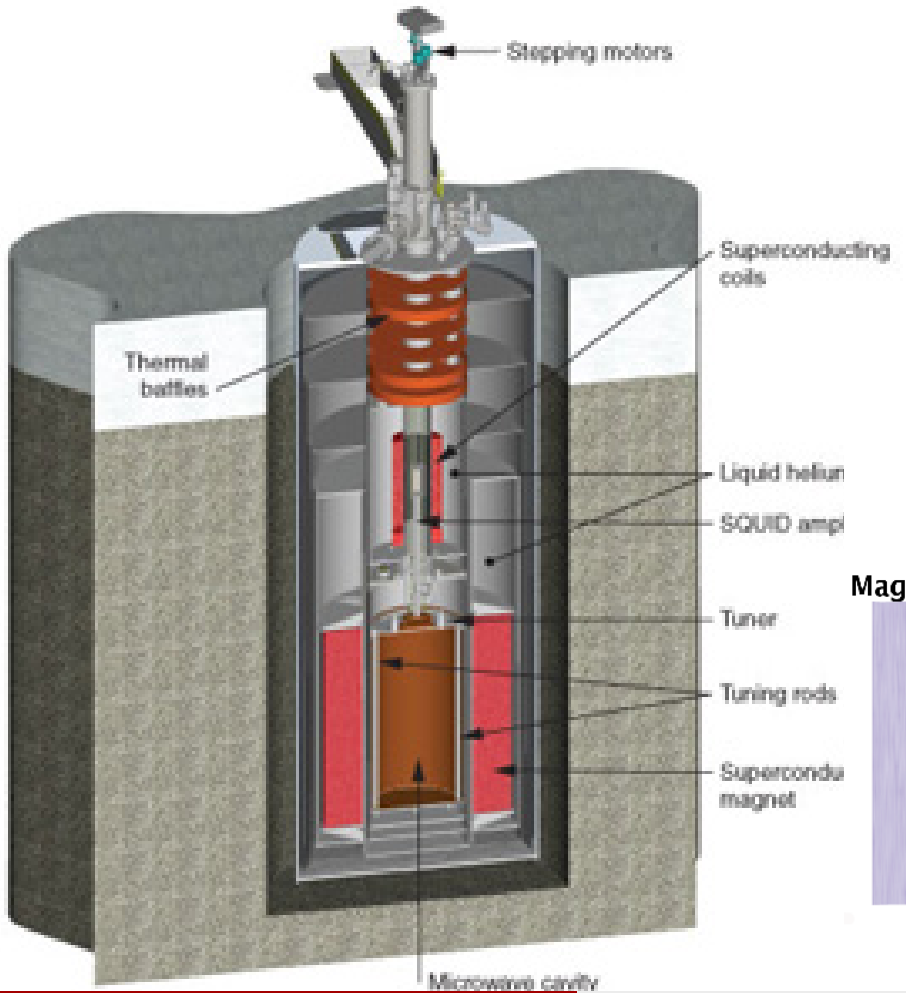
- custom-made magnet for solar axion search: big B^2V
- formal collaboration founding in 2017 at DESY (which has offered to host IAXO)
- prototype babyIAXO: 2 bores (instead of 8), ERC adv. grant (I. Irastorza)
- Can probe an meV region which is compatible with DM as well as astrophysical hints (white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

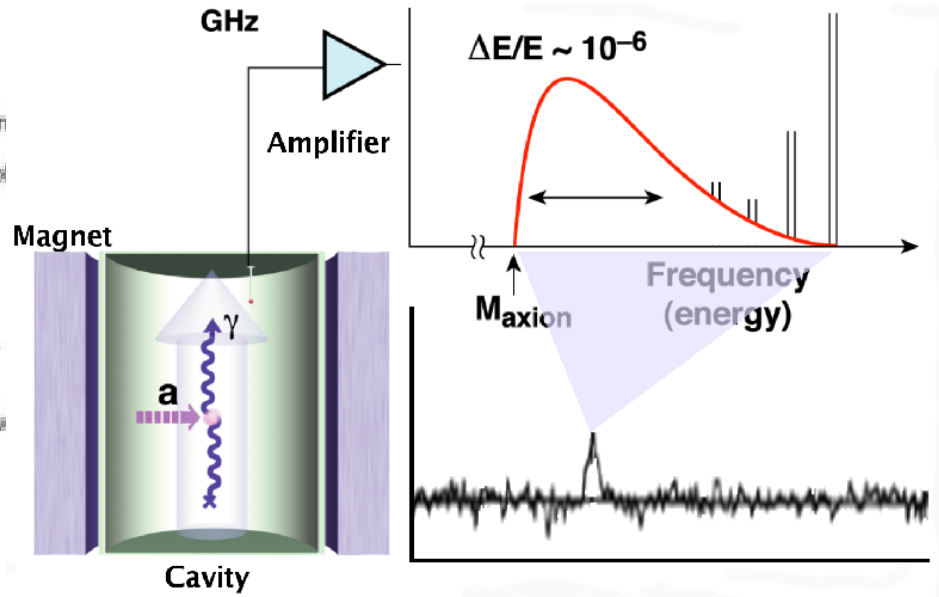
3) Dark Matter Axions (Haloscopes)



- Axions & ALPs → dark matter candidate → Haloscope [Sikivie '83]
  resonant technique
  $f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$

ADMX status cf [1403.5332]





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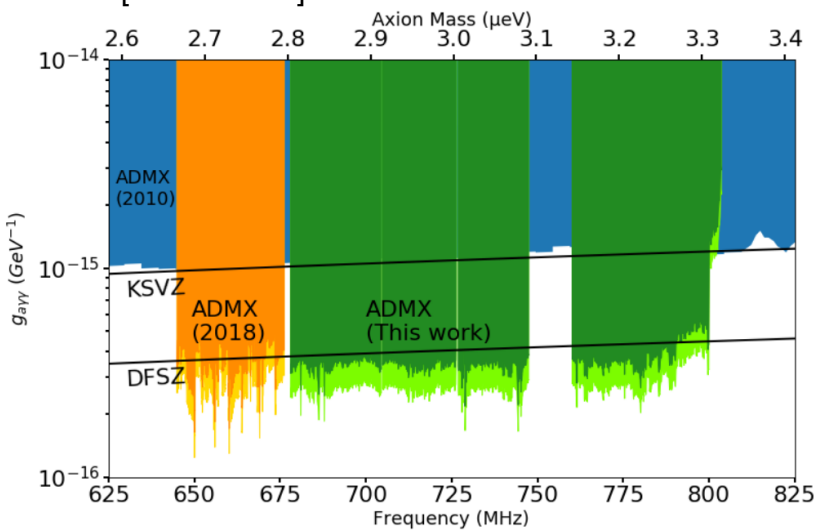
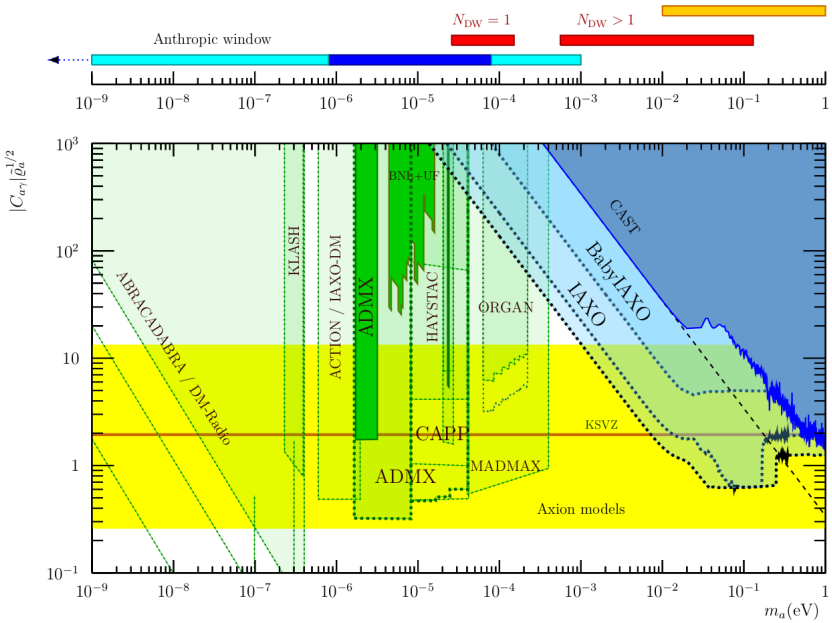
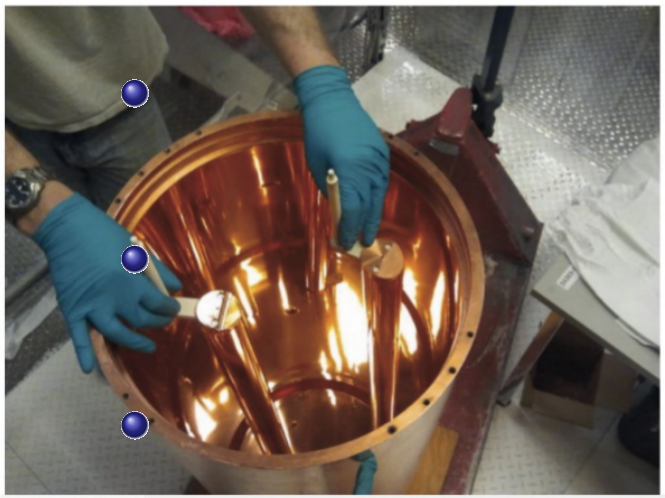
taken from [1910.08638]



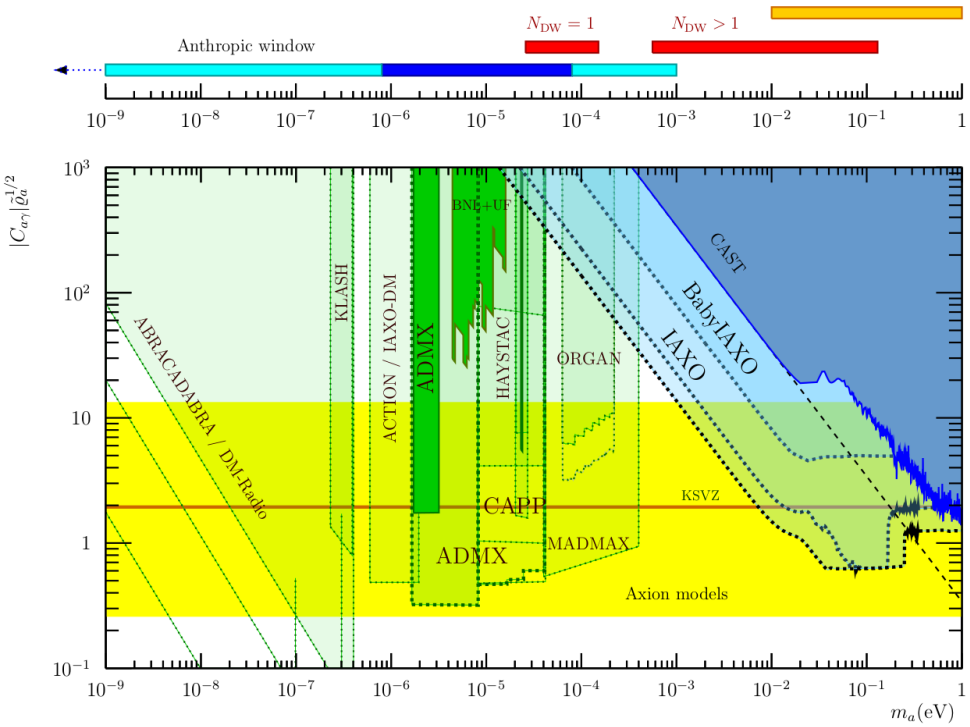
- Axions & ALPs $\rightarrow$ dark matter candidate $\rightarrow$ Haloscope [Sikivie '83]
  resonant technique
  $f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$
- results obtained in Axion Band: ADMX and HAYSTACK
  - ☺ sensitive to axion DM
  - ☹ very narrow band (tuning)

taken from [1801.08127]



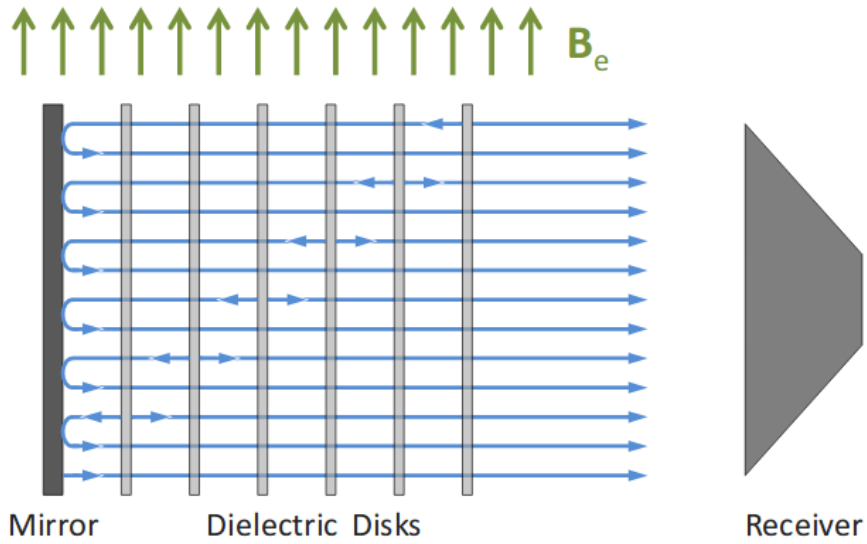


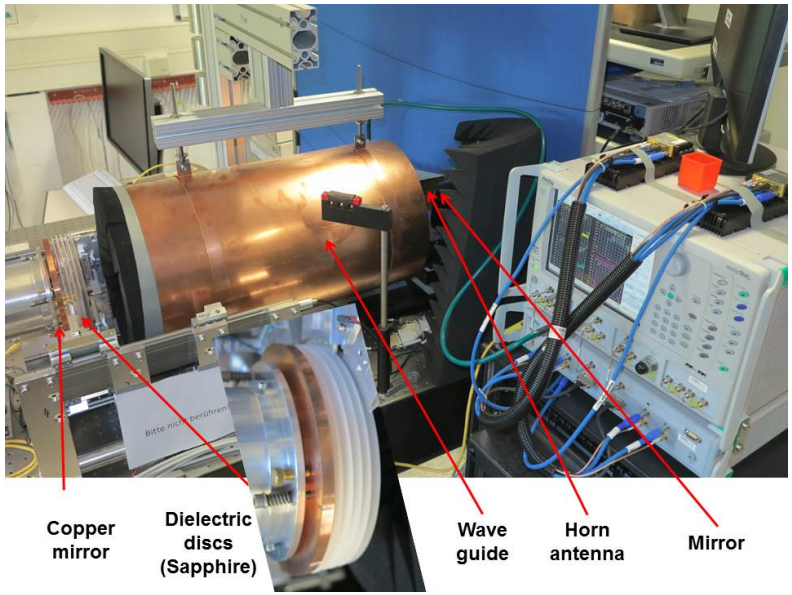
Interlude on 3): the problem with "large" axion masses



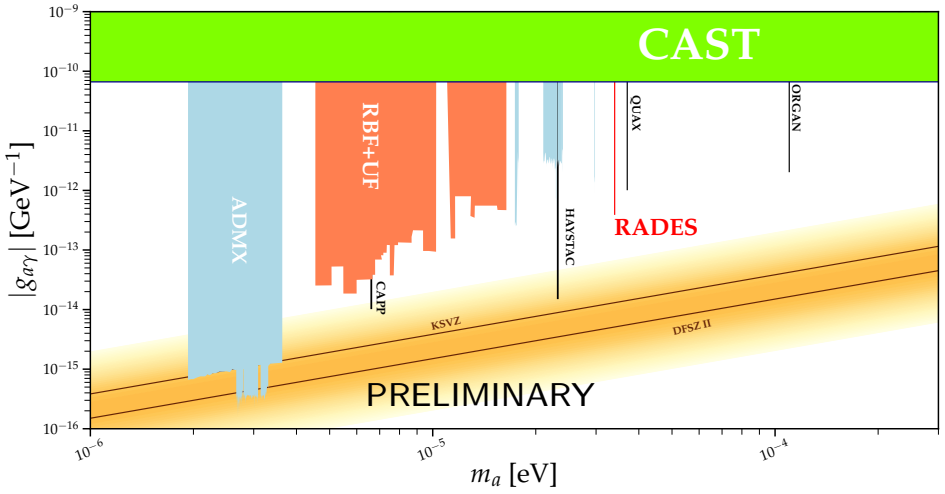
- naively: large $m \rightarrow$ higher resonance $f \rightarrow$ lower dimension
- Output power from cavity: $P \sim g^2 \frac{\rho}{m} B^2 \; V \; Q \; G$
- Quality factor $Q \sim 1/\Delta f \rightarrow$ long scan times
- $Q \sim \frac{V}{\delta S}$ Volume to surface ratio: gets bad at large Volumes
- proposed soln's: larger B (CAPP), superconducting cavity, very low $T_{\rm noise}$, 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
- amongst challenges: 9T dipole with 1.35m bore

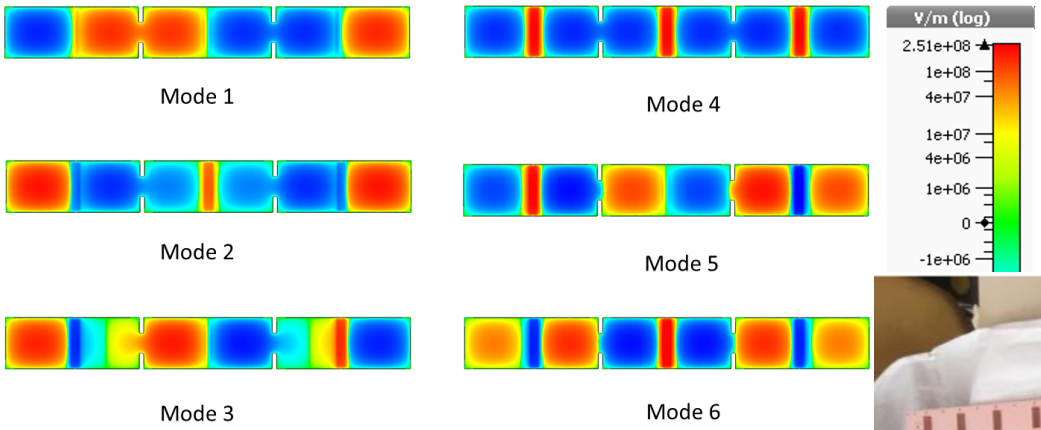


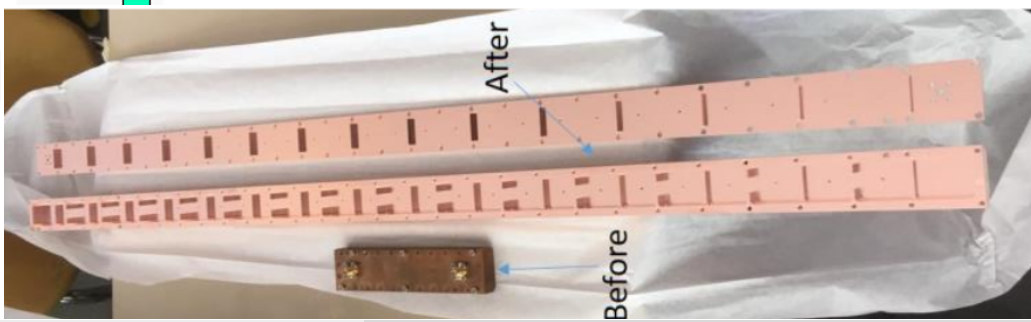


Interlude: RADES concept explored at CERN Melcon et al [1803.01243]



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





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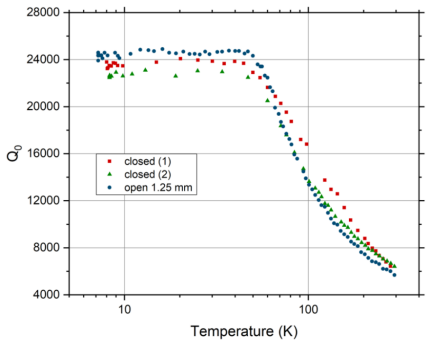

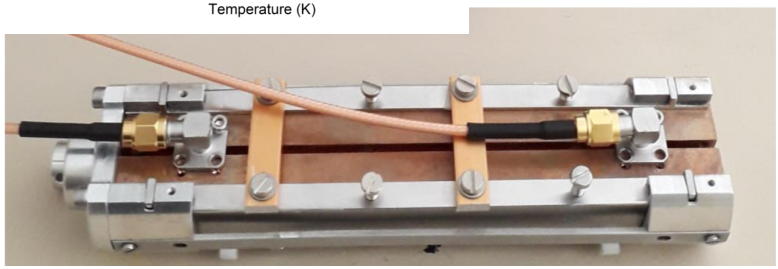

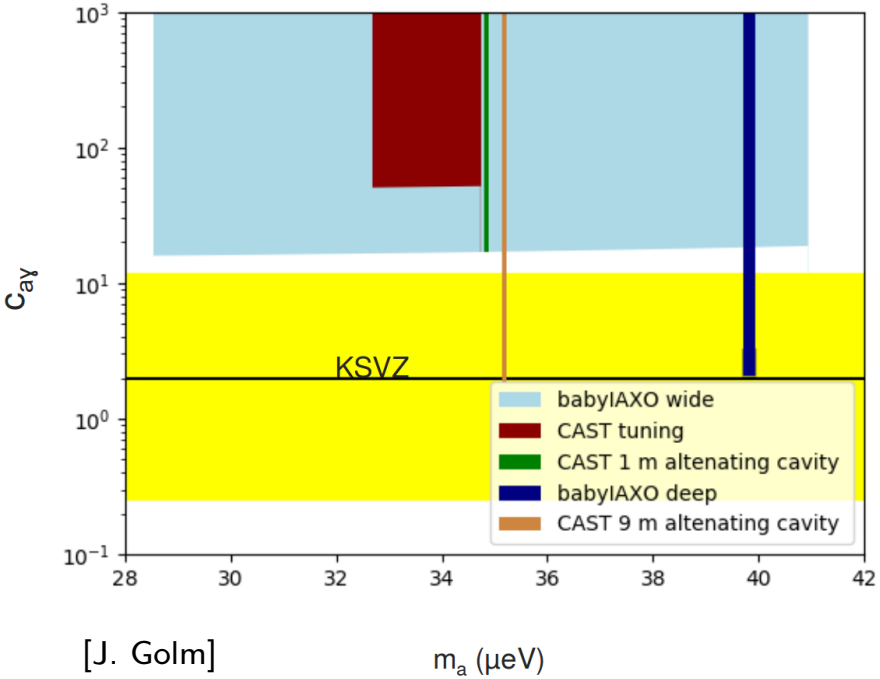

[J. Golm]

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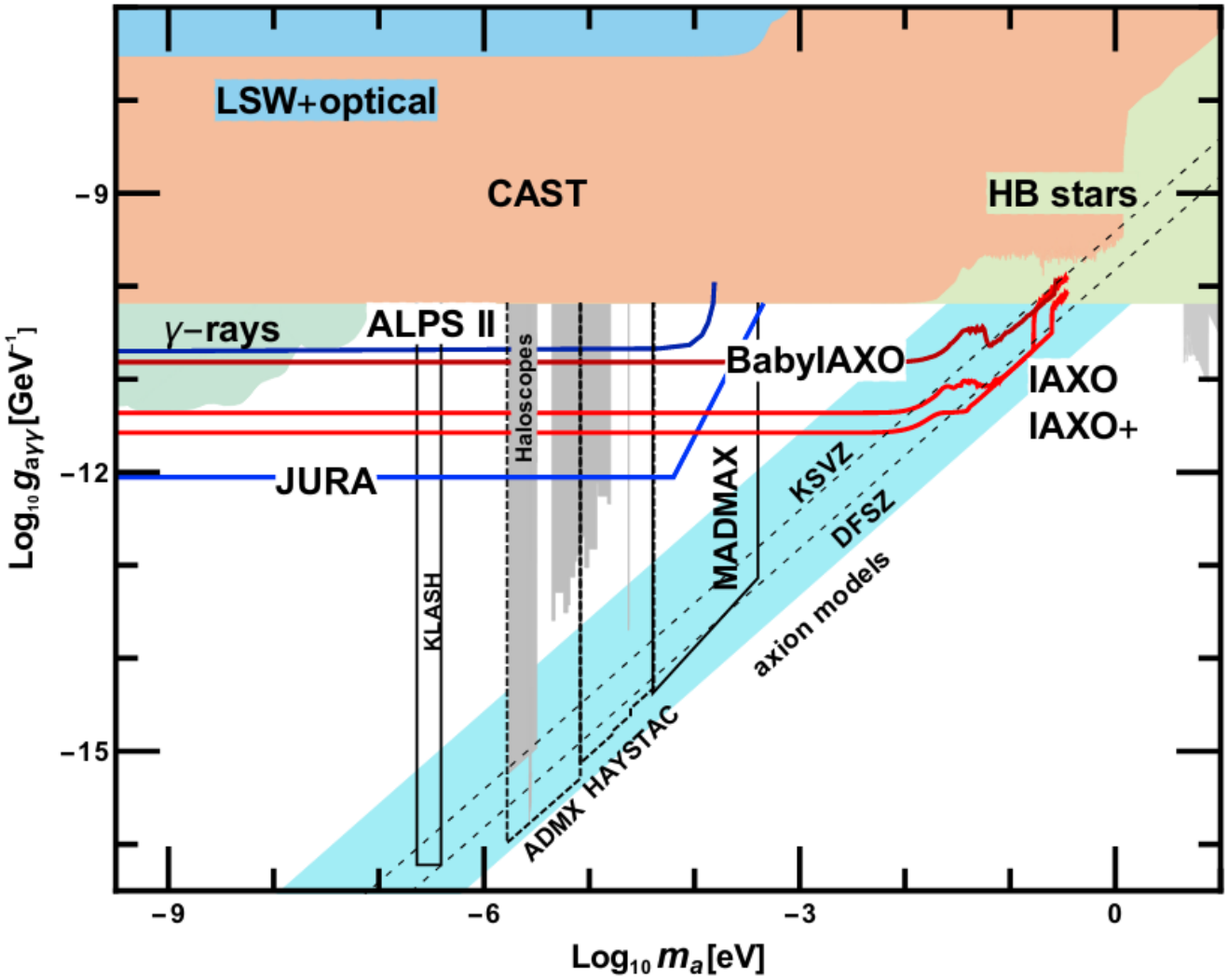
- sub-cavity sets resonance scale
- only one resonant mode couples to the axion
- prototype data almost ready to publish, long cavity installed in magnet
- **tuning** prototypes OK in cryolab, prospects with babyIAXO encouraging (after solar run, example 1 year, conservative)

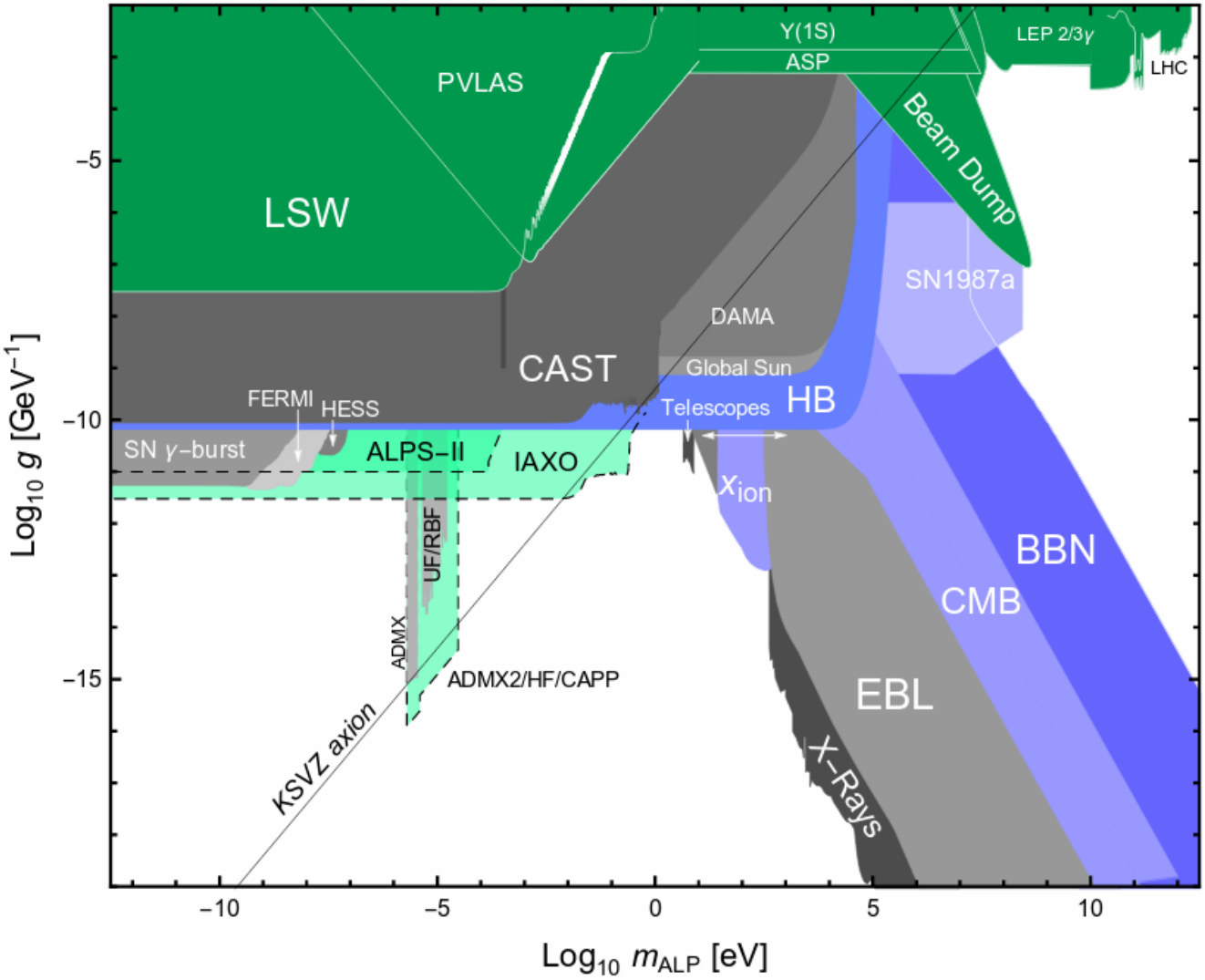
Putting things together...

in $\sim$10 years, worst case: many more filled areas, best case: discovery!

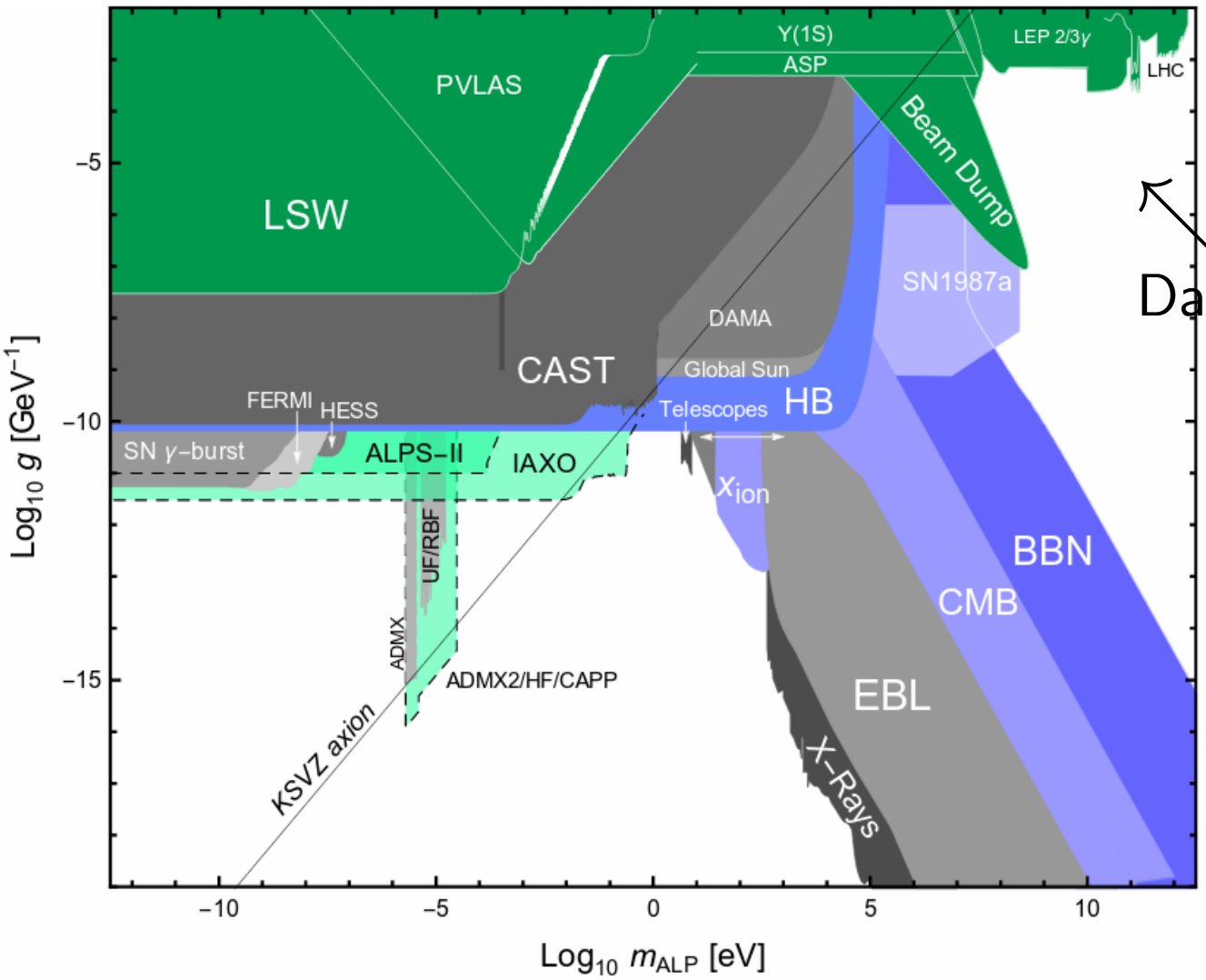


Putting things together...

completing the story: the idea of 'Dark Sectors'

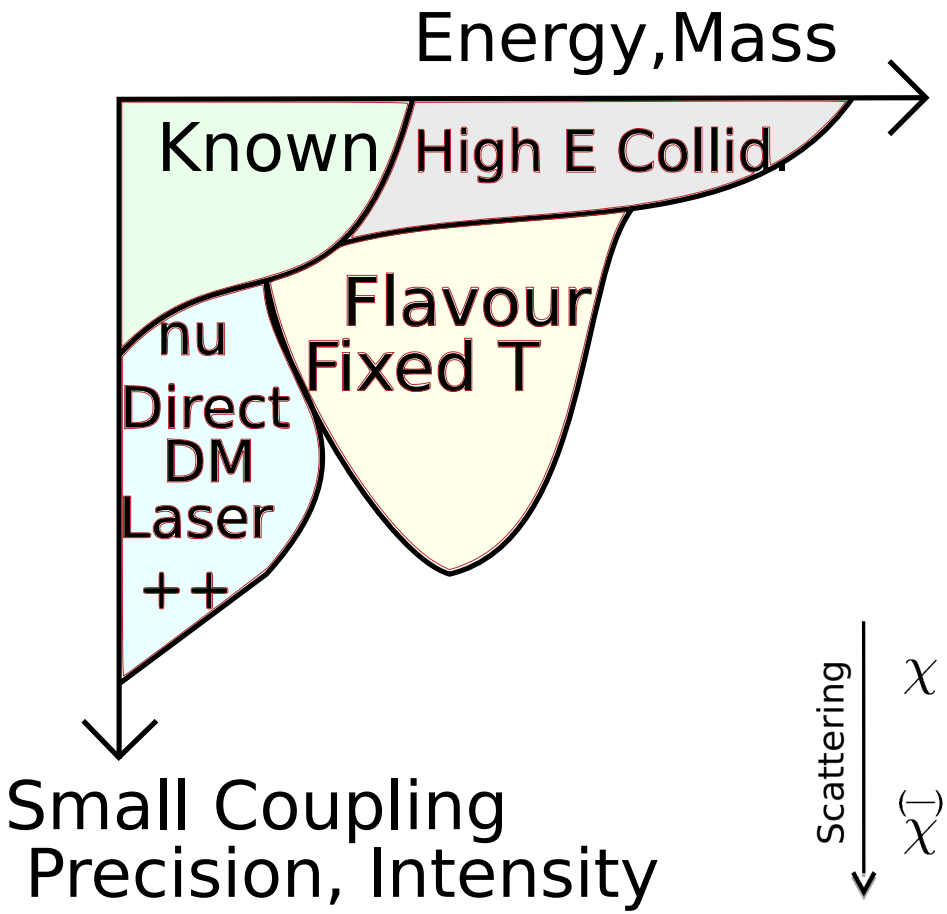


Putting things together...

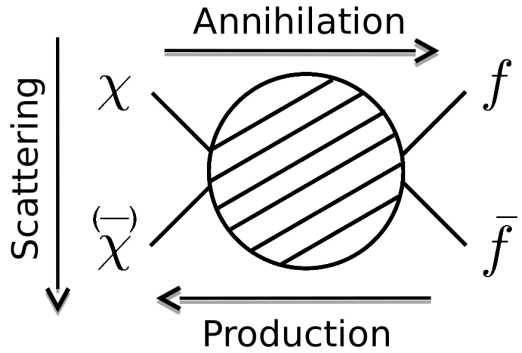


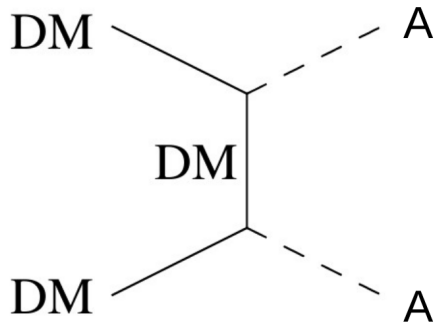
Dark Sector

Interlude: new physics at the MeV mass scale

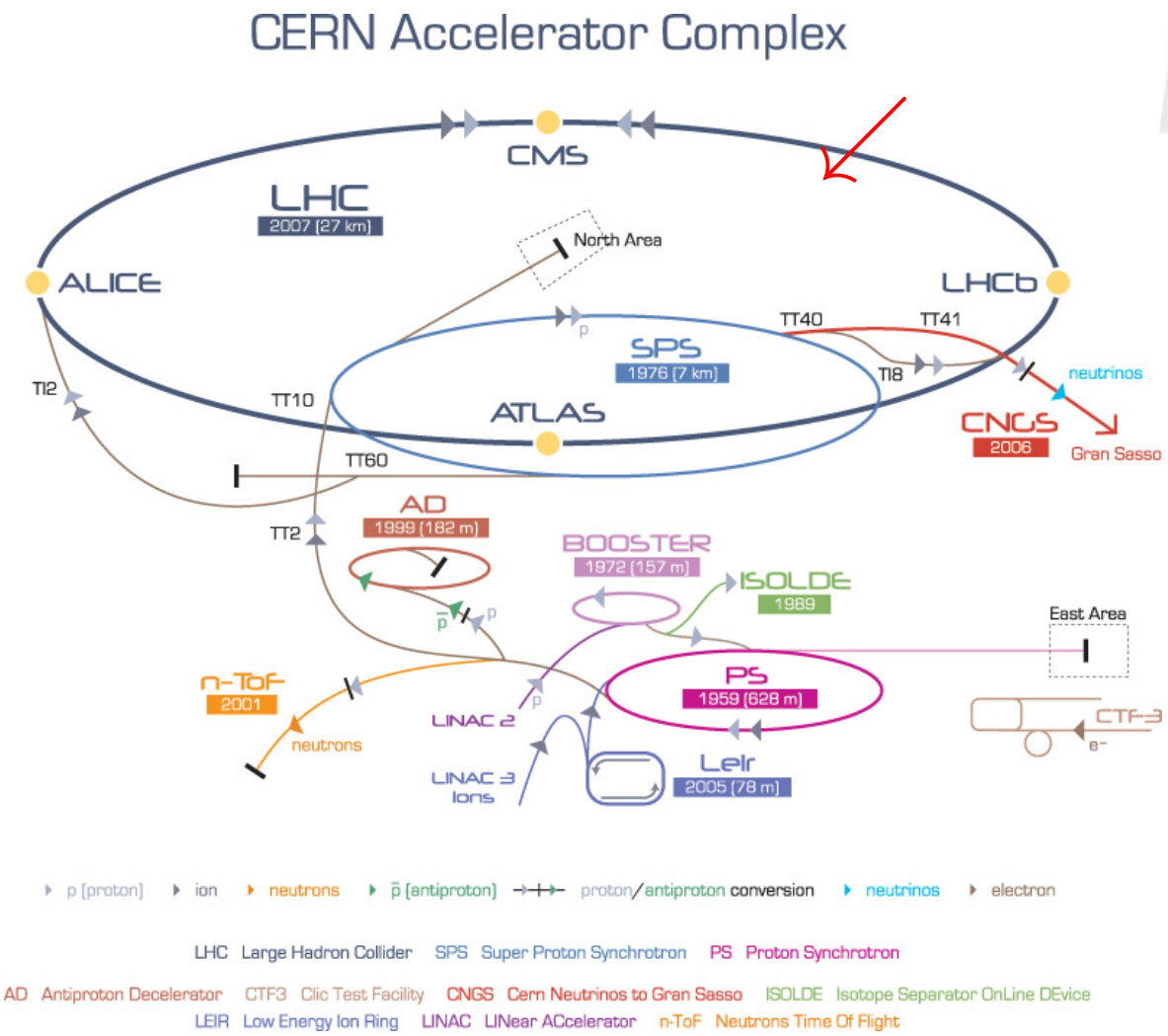


- From the previous slide: sub-eV ALP is not the only open option
- some models of Dark Matter propose MeV mass, weakly-coupled particles [1502.06000] to act as a Mediator particle





NA62 at CERN



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

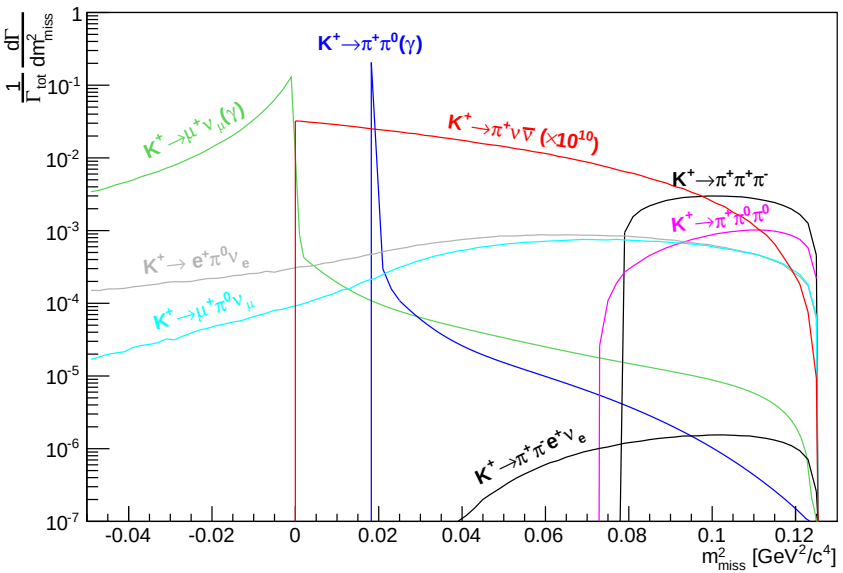
BR theory:

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

Buras et al. JHEP 1511, 33

New Result! `indico.cern.ch/event/868940/contributions/3815641`

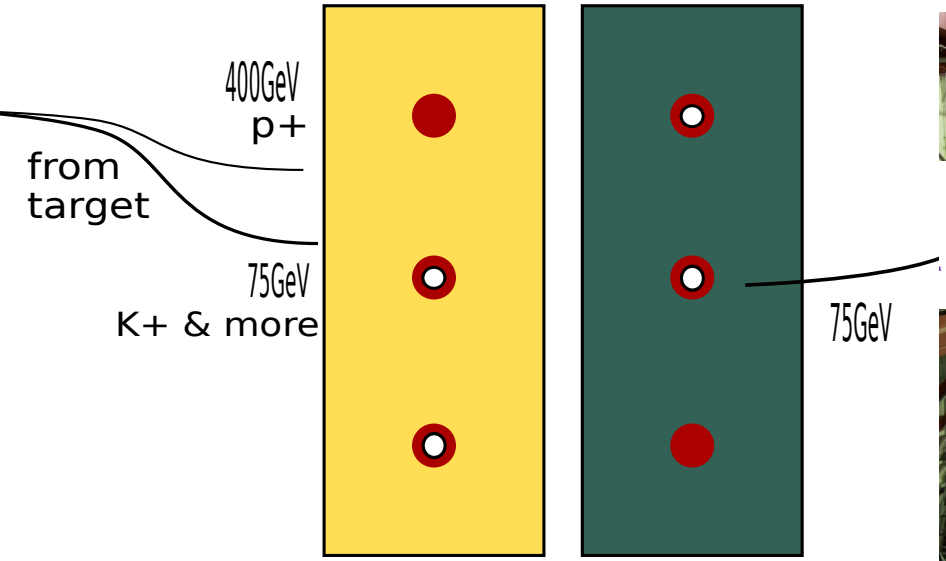
How to look for Axions at NA62

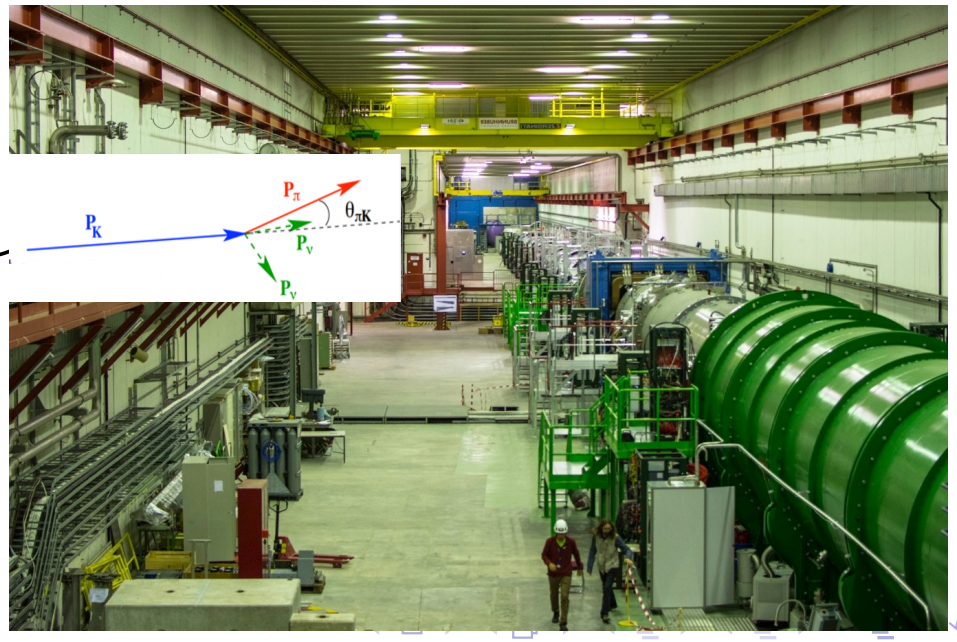


straightforward: flavored axion

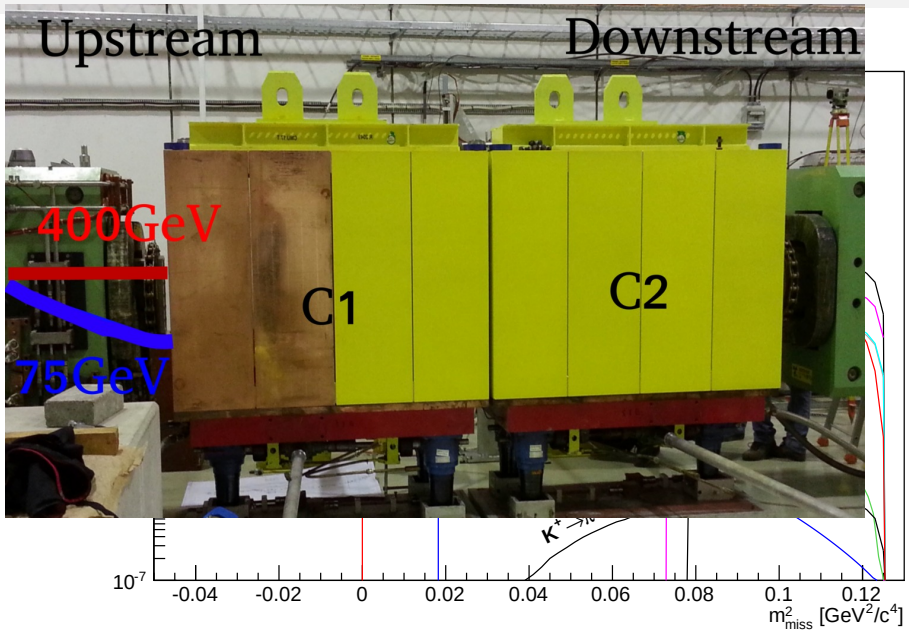
$K^+ \to \pi^+ + a$

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





How to look for Axions at NA62



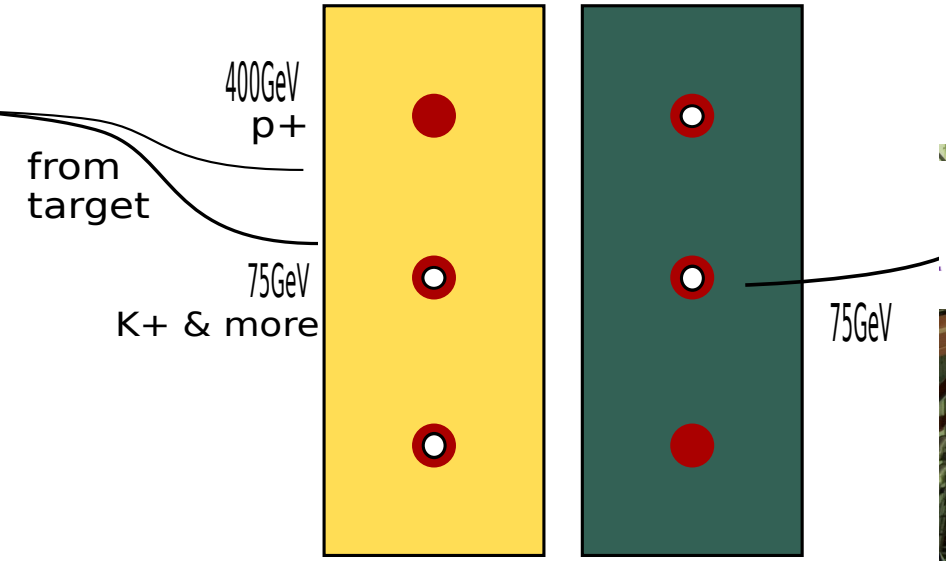
parasitic (charged) triggers not requiring an initial Kaon

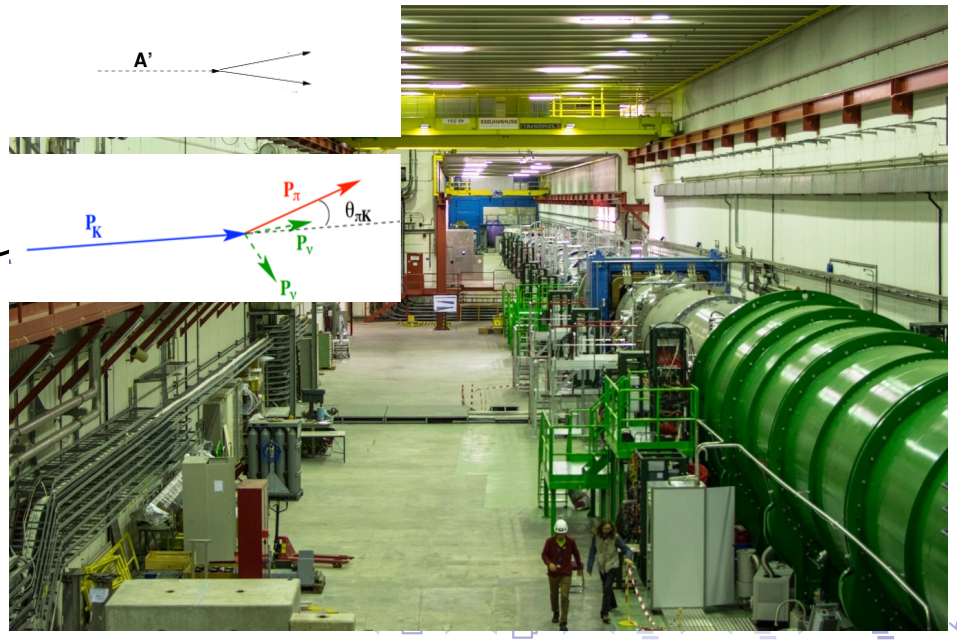
$\Rightarrow$ **upstream production**

60 % target interaction & 40 % direct p

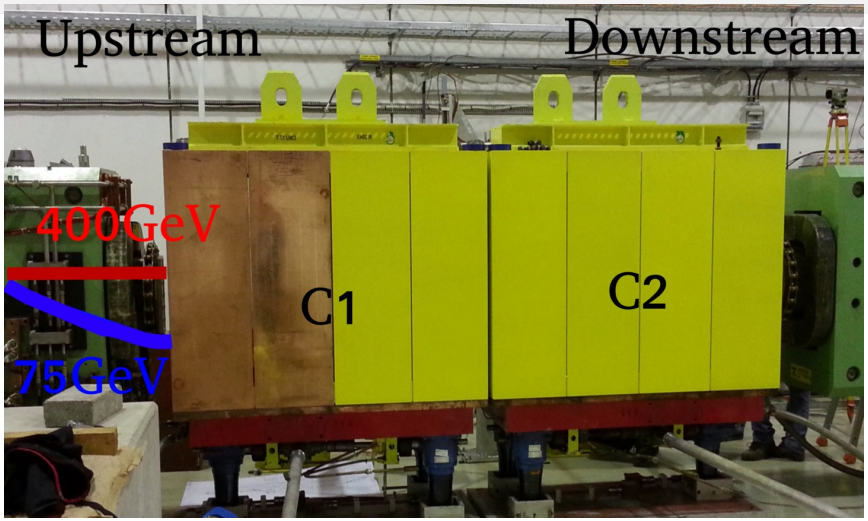
see e.g. 1711.08967

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





Possibility to run NA62 as beam dump

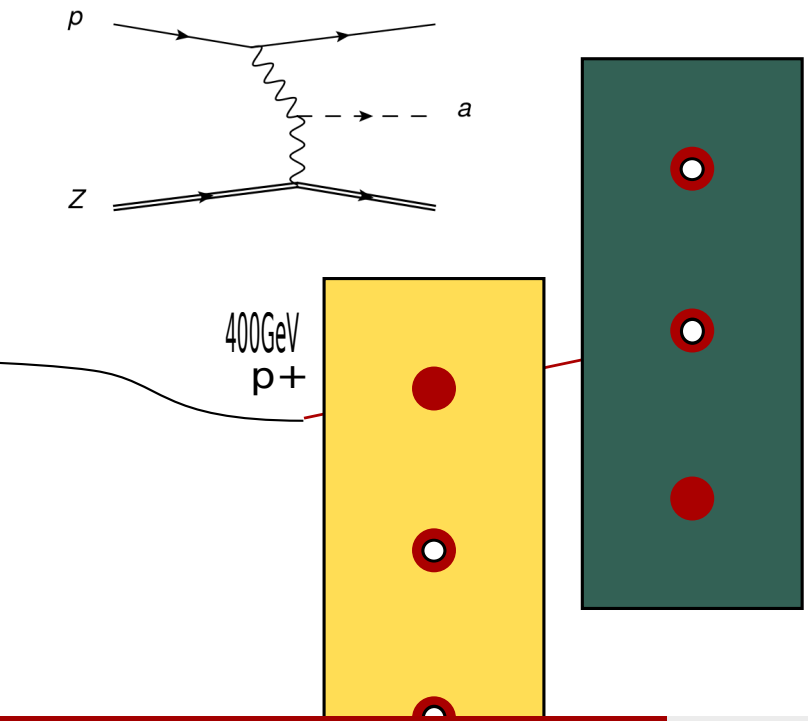


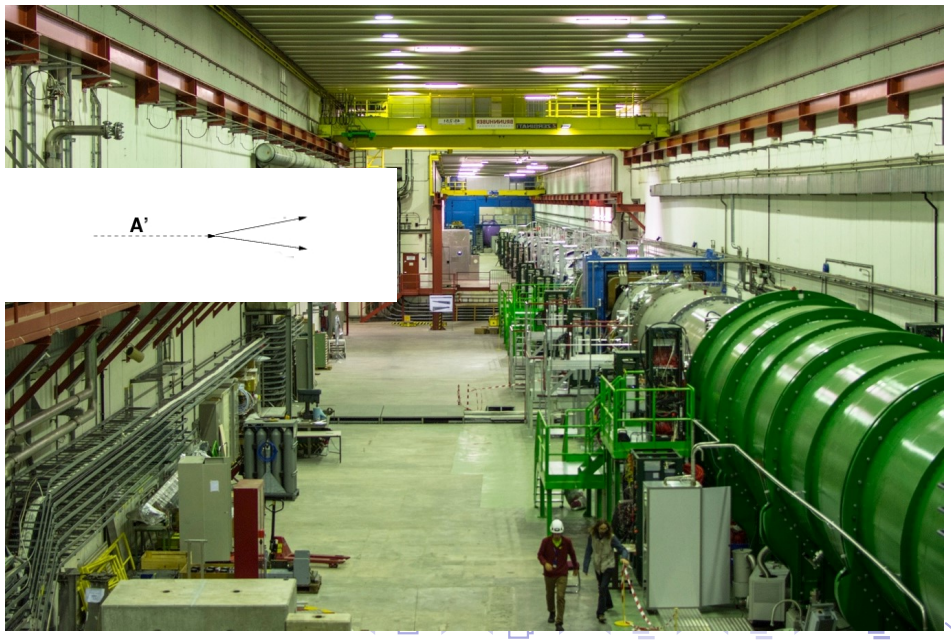
Primakoff production of MeV-GeV ALPs

in upstream collimator: run as dump

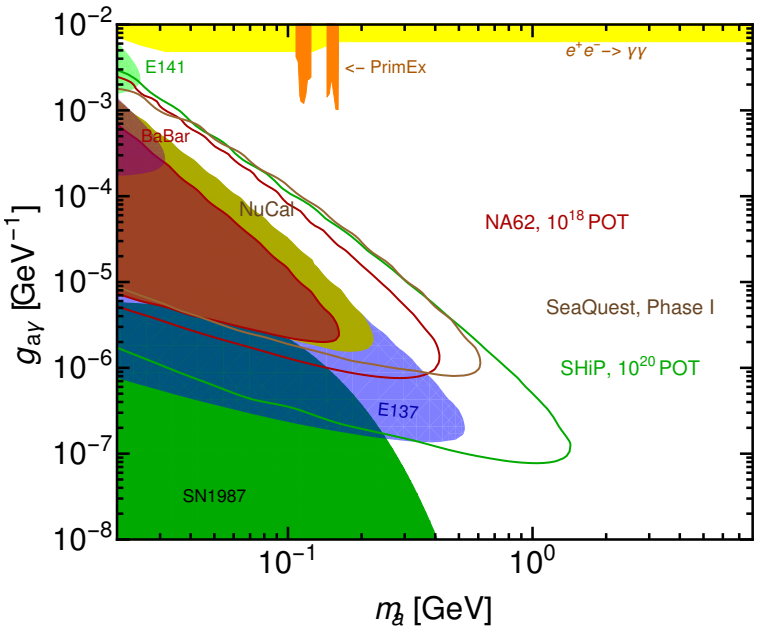
critical for $\gamma\gamma$ final state

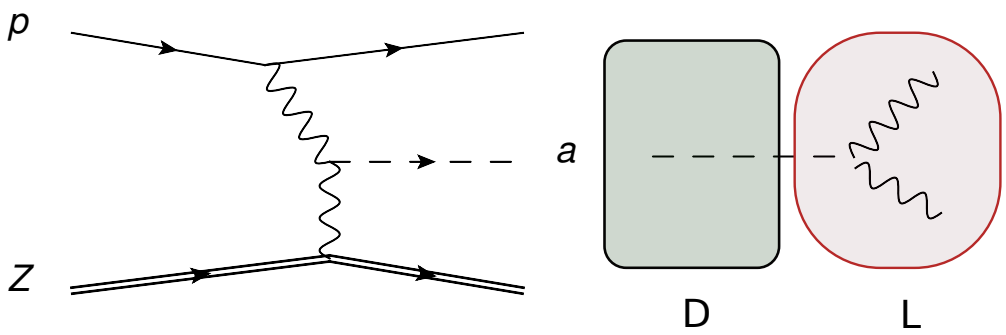
$\sim 2\times10^{16}$ POT collected so far





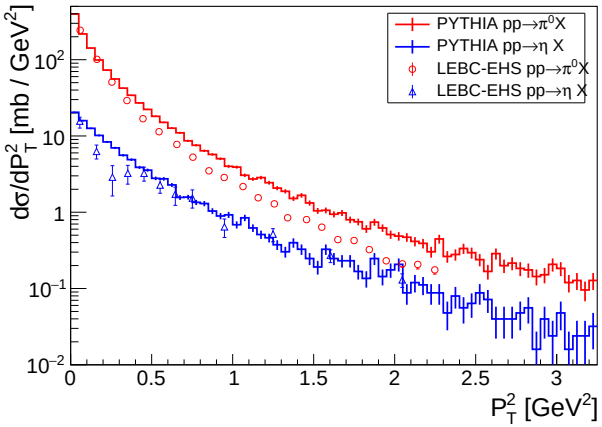
ALPs will be probed above the MeV





[BD et al, JHEP 1602, 018]

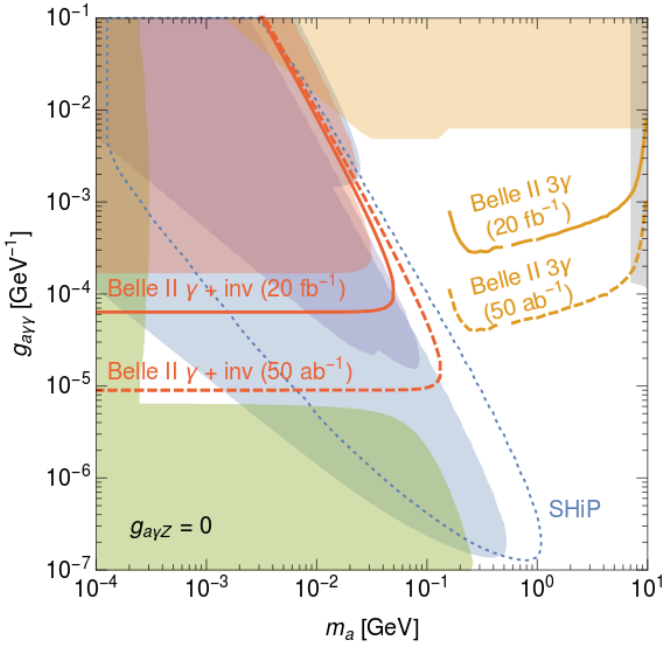
- Sensitivity prospect for 10^{18} POT at NA62 based on production via π^0 decay photons (also shown dedicated beam dumps called SHiP and Seaquest)

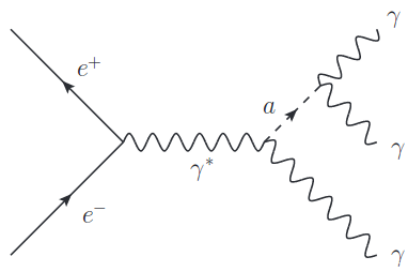


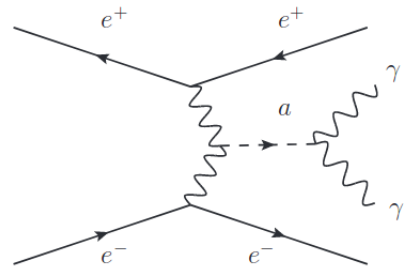
['light meson production archeology']

[BD et al JHEP 05(2019)213]

ALPs will be probed above the MeV



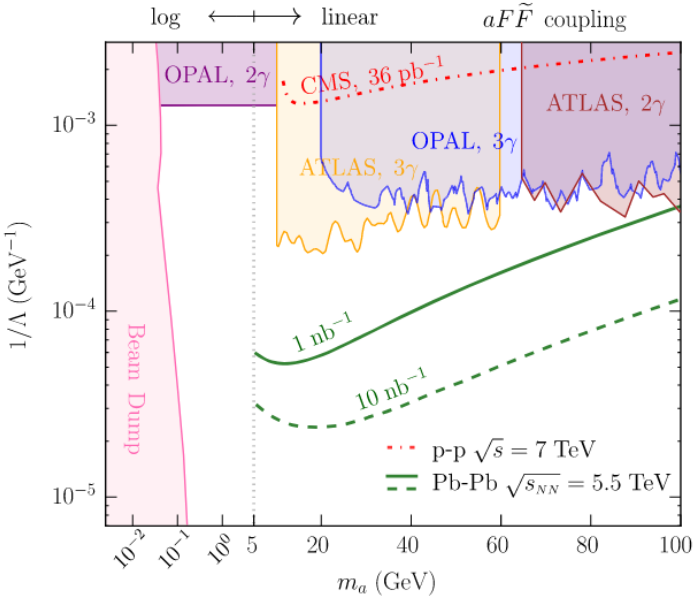


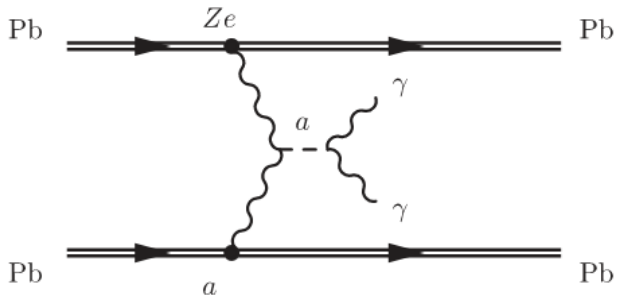


[Dolan et al, JHEP 1712, 094]

- 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 (first result: arXiv:2007.13071)

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 (first result: arXiv:2007.13071)
- 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 now**
- or later: babette@cern.ch

Acknowledgements: students and experiment collaborators

RADES team ($\sim$ 20):

my current/past students:

Jessica Golm, Sergio Arguedas Cuendis

Arefe Abghari

NA62 collaboration ($\sim$ 200):

my current/past students: Elisa Minucci, Diana Chamaki

Claudia Rella, Robert Circo, Samantha Davis, Carissa Cesarotti

Primary external collaborators on presented topics:

F. Kahlhoefer, J. Jaeckel, F. Ertas, A. Ringwald,

K. Schmidt-Hoberg, M. Rosenthal, T. Spadaro

+ ERC-2018-StG-802836 (AxScale project)

Thank you for your attention!

Backup

Dark Photons with Auger mirror

A magnetized mirror can be used to search for axions

arXiv:1212.2970.

Without magnetization, can be used for the search of hidden photons (light but massive extra U(1)): done at KIT!

Andrianavalomahefa et al, arxiv: 2003.13144

PhysRevD.102.042001

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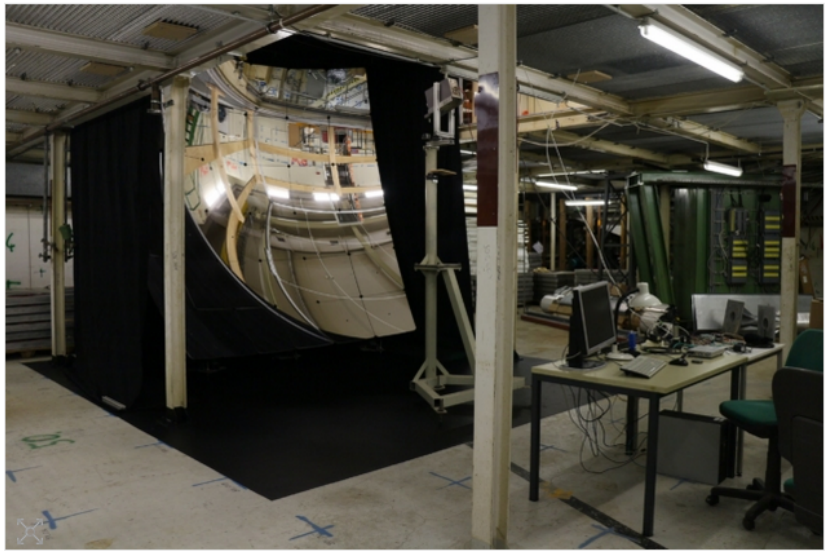
Funky physics at KIT

5 June 2020



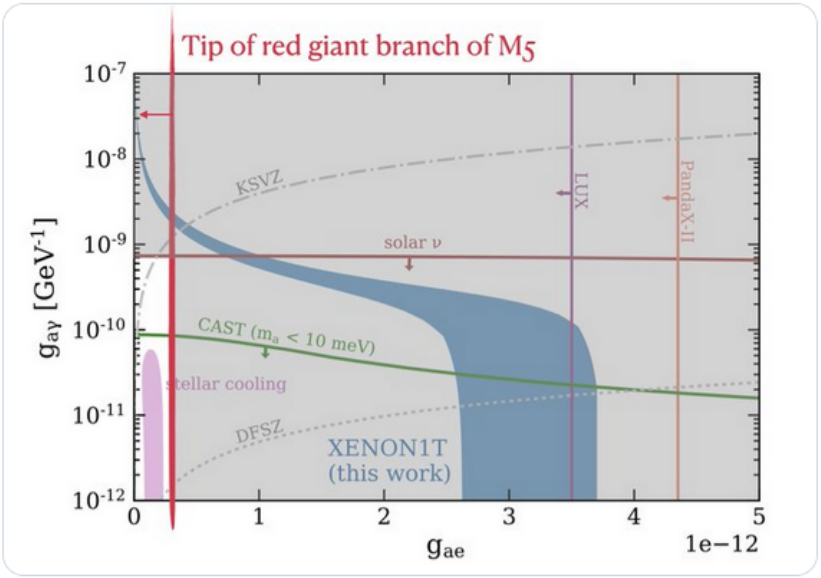
The FUNK experimental area, where the black-painted floor can be seen with the PMT-camera pillar at the centre and the mirror on the left. A black-cotton curtain encloses the whole area during running. Credit: KIT.

Xenon 1T & axions

Thread

Ciaran O'Hare
@cajohare

Not buying this solar axion interpretation of #Xenon1T excess. They show the stellar cooling global fit interpreted as a hint, but neglect to show the fact that you can just take the RGB of M5 and set a limit on g_ae that already excludes their entire confidence interval, e.g.:



in any case, babyIAXO should say something definitive if needed

Tuning in cryolab - eager to go in magnet!