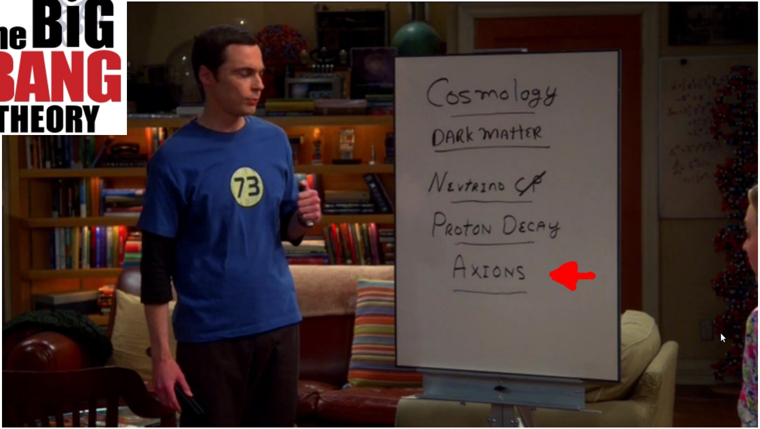
(Somewhat) New ideas in ultralight DM searches: FUNK & RADES

Babette Döbrich (CERN) based on work within the FUNK and the RADES teams

BNL, 10/01/18

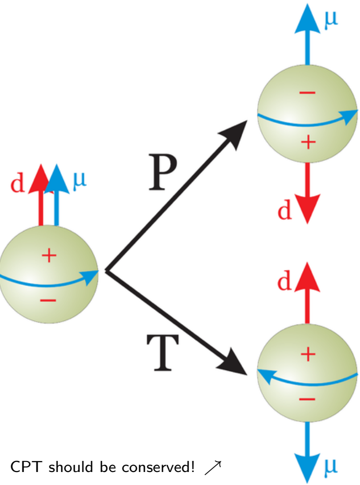
1. brief recap: QCD axions and ALPs
2. Axion Searches with Haloscopes and RADES
3. Dark Photons and FUNK

The axion in popular culture...



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

Why Axions? The strong CP problem!



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

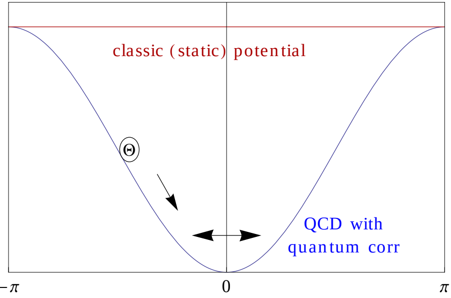
- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_\mathrm{n}(\bar{\theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

angle $\bar{\Theta} \lesssim 10^{-10} \rightarrow$ **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 $U(1)_{\mathrm{PQ}}$ spontaneously broken at f_a, the axion is phase (Goldstone boson) of this symmetry

  Weinberg, Wilczek, 78



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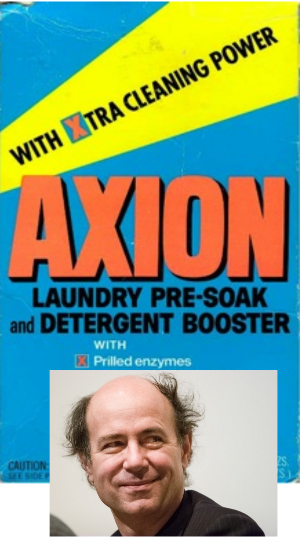

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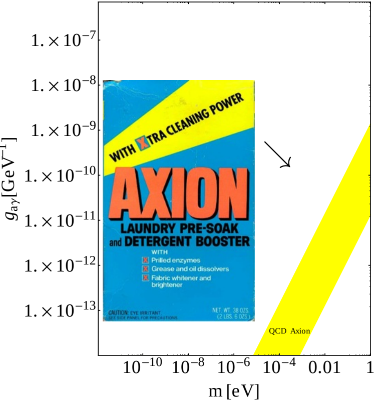
- $f_a \gg \Lambda_{\rm EW}$ 'invisible axion models' 'KSVZ' & 'DFSZ' Kim, Shifman, Vainshtein, Zakharov

  & 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) see, e.g. 0807.3125



[good reading: 9506229 Sikivie's Pooltable]

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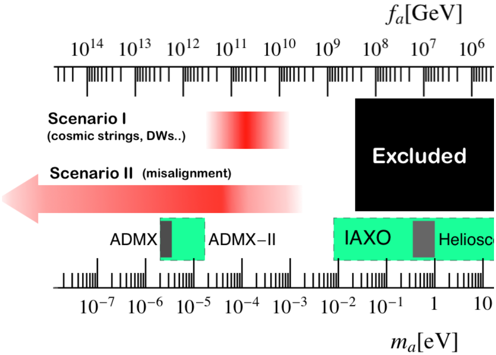
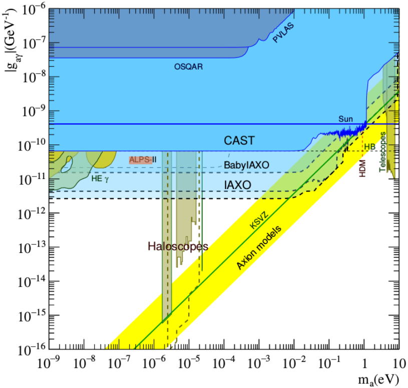
- $m \sim 0.6\mathrm{meV}/(f_a/10^{10}\mathrm{GeV}) \to$ pseudo-Goldstone boson
- couple to photons (π^0 mixing): Primakoff effect $\to$ most experiments

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



[plot taken from review: 1801.08127 by Irastorza/Redondo]



- Axion ColdDM misalignment, $m \gtrsim 1\mu$eV

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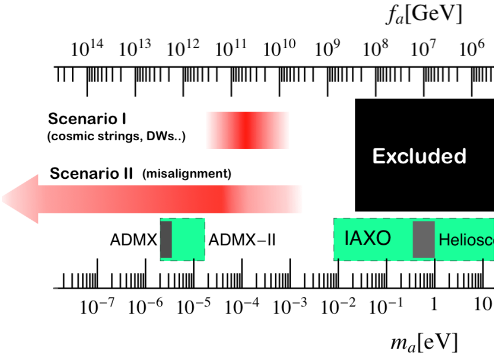

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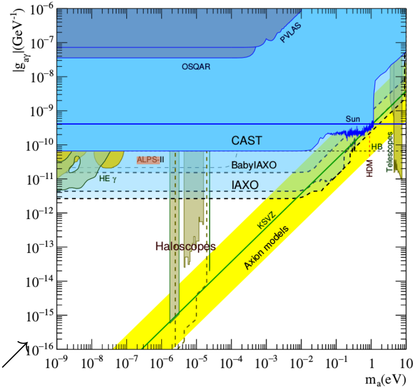

difference between filled and shaded areas ↗

- Axion ColdDM misalignment, $m \gtrsim 1\mu$eV

interlude: Axion-Like particles (ALPs)

- in previous slide, blue search-regions often do not cover the yellow axion band
- The axion is a pseudo-NGSB. Global symmetry of axion: Peccei Quinn, explicit breaking: QCD effects at scale f_π

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- in previous slide, blue search-regions often do not cover the yellow axion band
- The axion is a pseudo-NGSB. Global symmetry of axion: Peccei Quinn, explicit breaking: QCD effects at scale f_π
- other global symmetries may be broken, create an ALP (Axion-Like particles), e.g. in string theories it is not unusual to have an entire 'axiverse' outside the yellow band
- the axion itself may be more complicated than thought, find models e.g. 1709.06085 in which an axion solving strong CP lies outside the yellow band
- pheno-hints: TeV transparency [1612.01864] and stellar cooling e.g. [1512.08108] could be related to ALPs
- be open-minded!

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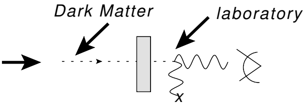
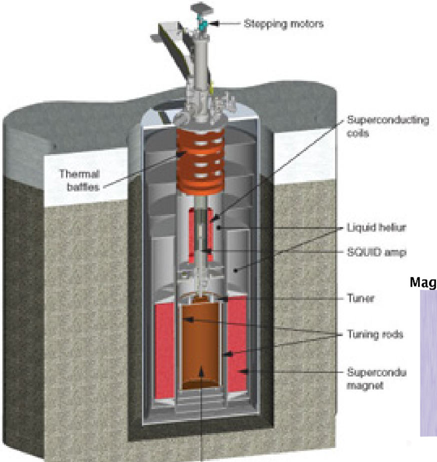
Dark Matter Axions (Haloscopes) [Sikivie '83]

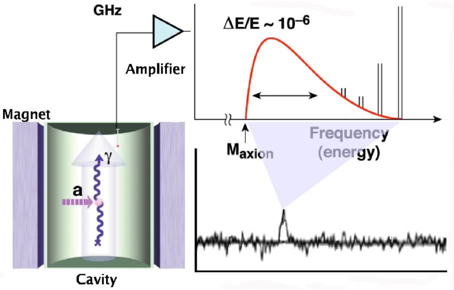


- Axions & ALPs $\rightarrow$ dark matter candidate $\rightarrow$ Haloscope [Sikivie '83] **resonant** technique

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

Pioneer: ADMX status cf [1612.08296]





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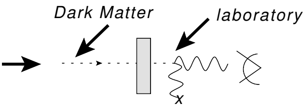

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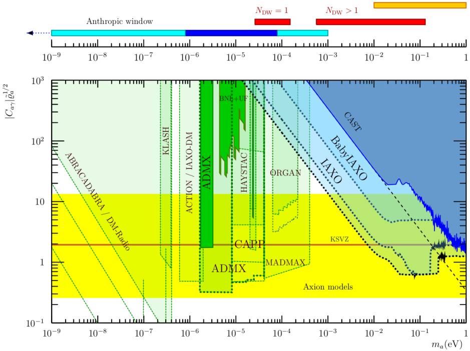
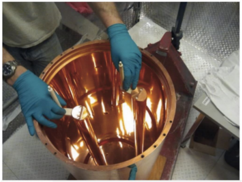
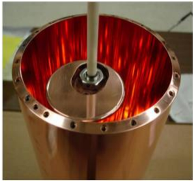
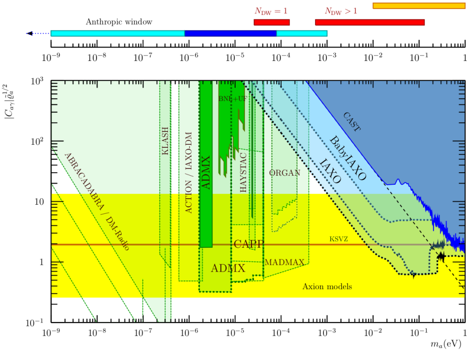


- Axions & ALPs → dark matter candidate → Haloscope [Sikivie '83] **resonant** technique $f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$
- results obtained in Axion Band: ADMX and HAYSTAC [1803.03690]
  - ☹ $\vec{E}\,.\,\vec{B}$ (only certain cavity modes OK)
  - ☹ very narrow band (tuning)





Interlude: the problem with large axion masses



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

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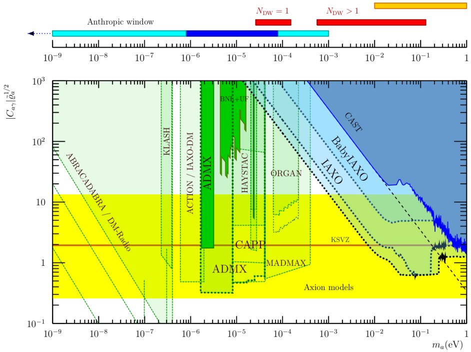

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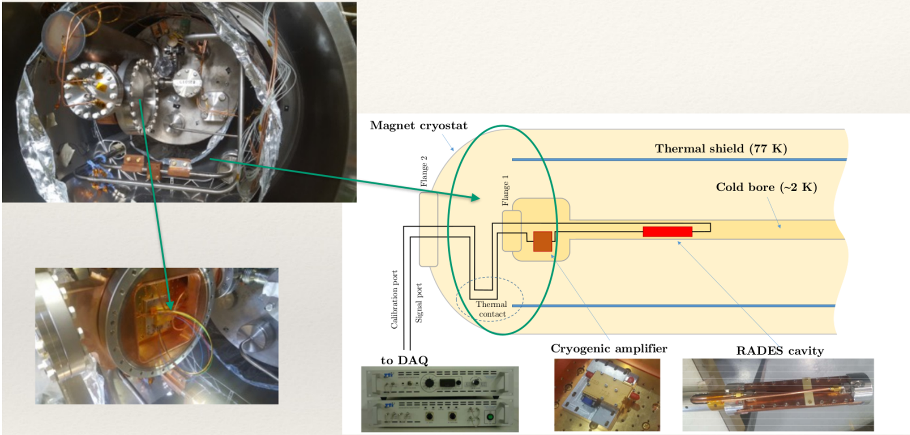
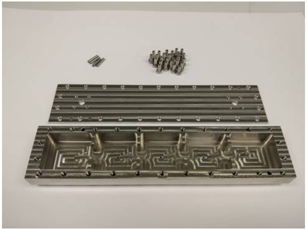
- RADES at CERN: retain large V (at high f) by using dipoles (not quite that one)

RADES prototype at CAST winter 2017/2018

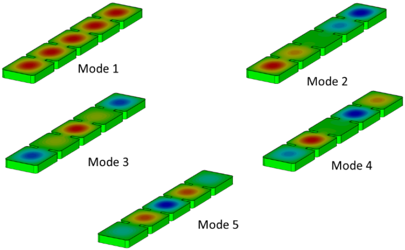
← the CAST magnet



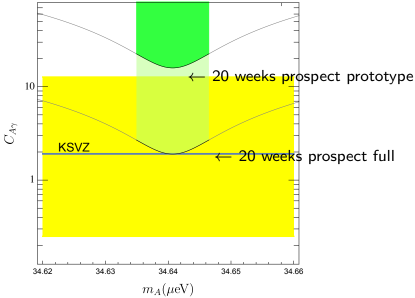
RADES concept explored at CERN Melcon et al [1803.01243]



15cm test cavity run in Winter 2017/2018



- RADES at CERN: retain large volume at high resonance frequencies large using subcavities $m \sim 34\mu$eV
- sub-cavity sets resonance scale
- only first resonant mode couples to the axion



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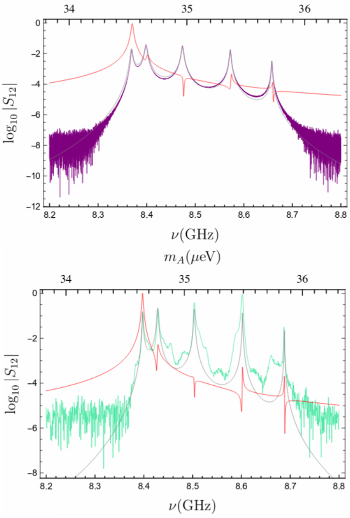
top: room, bottom 2.3K

red: coupling to axion

green/purple: data

gray: analytical fit



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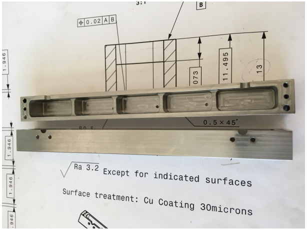

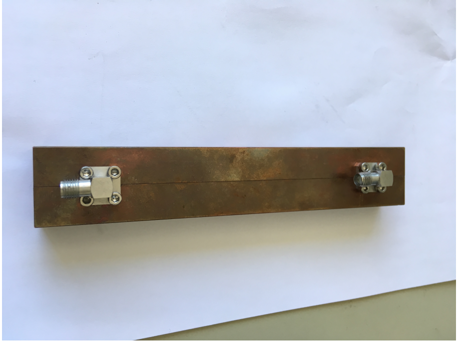

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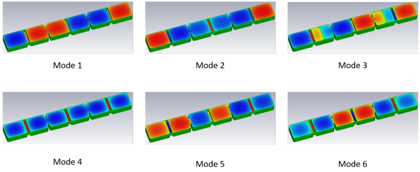
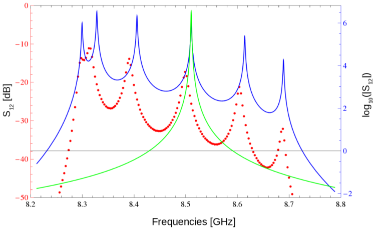


Analytical model vs Simulations (Preliminary results)



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- and an alternating irises structure to **enhance length**

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Holdom, 1986, PLB

$$\mathcal{L} \sim \underbrace{\chi}_{\text{mixing}} \underbrace{F_{\mu\nu}}_{\text{SM U(1)}} \underbrace{X^{\mu\nu}}_{\text{hid U(1)}} + \underbrace{\frac{m_{\tilde{\gamma}}^2}{2} X_\mu X^\mu}_{\text{mass}}$$

Frascati Physics Series Vol. LVI (2012)
DARK FORCES AT ACCELERATORS
October 16-19, 2012

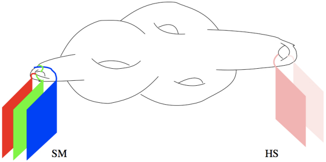
A force beyond the Standard Model
–
Status of the quest for hidden photons

Joerg Jaeckel
Institut für theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany

pheno: diagonalize $X^\mu \to X^\mu - \chi A\mu$

analogous to ν oscillation

experimentally no need for the external field (contrasting axions)



from string scenarios [1206.0819]

Extra U(1) gauge bosons: Hidden/Dark Photons $\tilde{\gamma}$

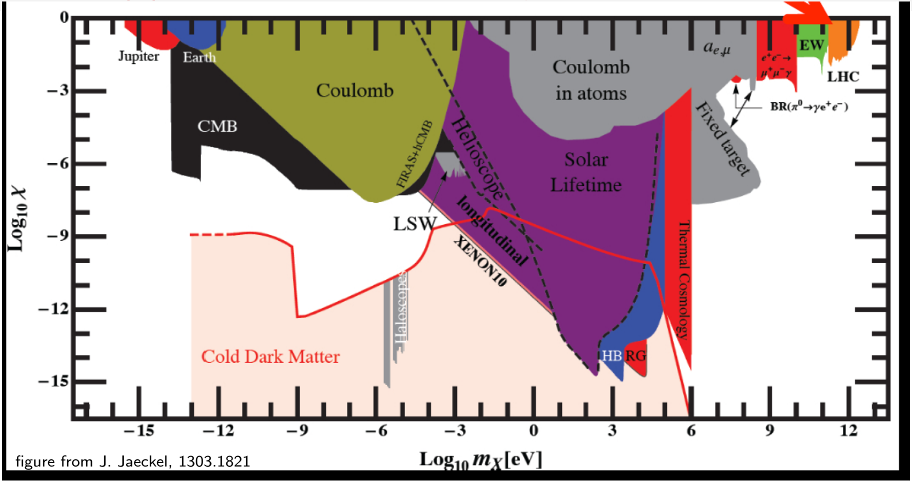


figure from J. Jaeckel, 1303.1821

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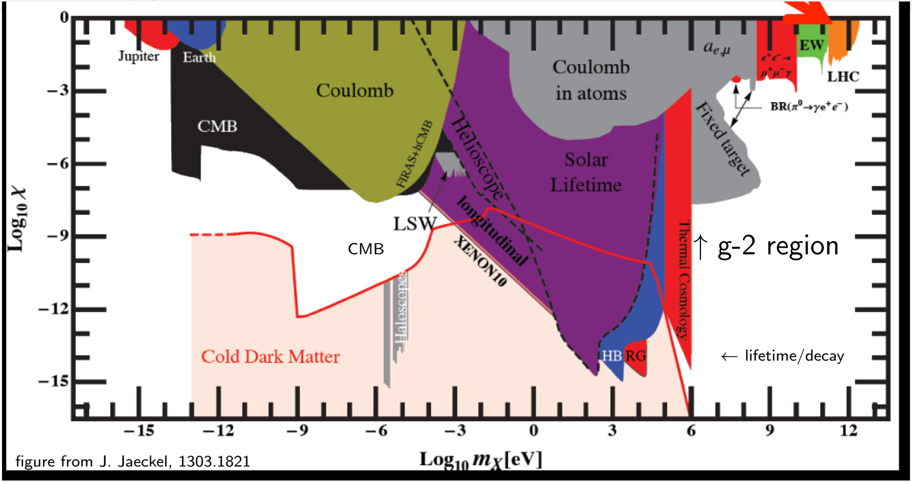

the HP can be cold Dark Matter

Misalignment mechanism: JCAP 1206, 013 & PRD 84 103501

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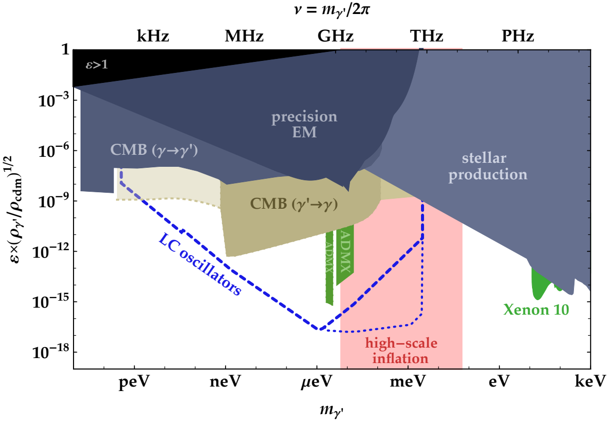

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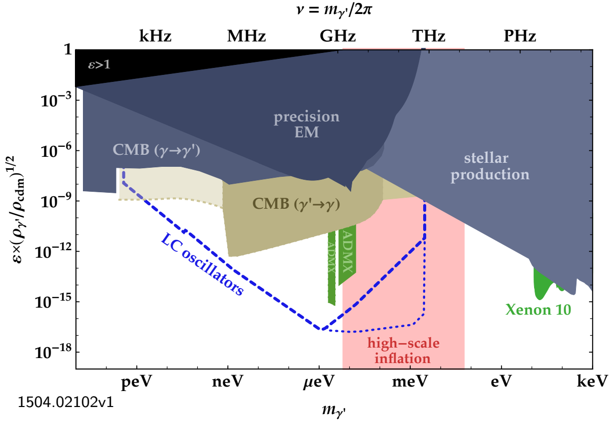

1504.02102v1

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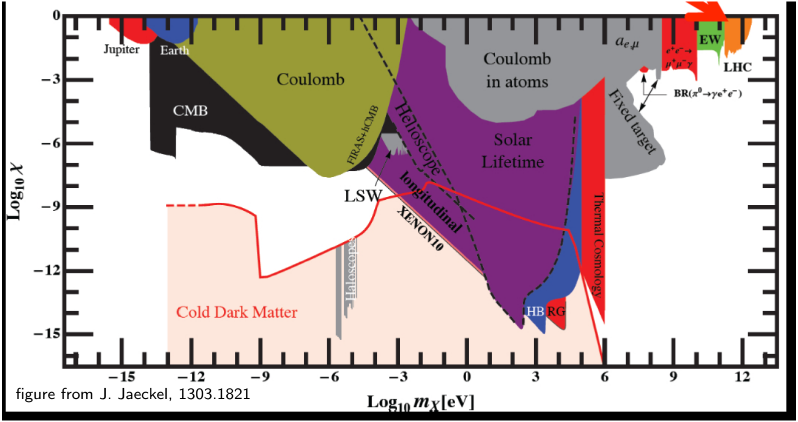
$\Rightarrow$ variety of experiments

Selected current experimental efforts



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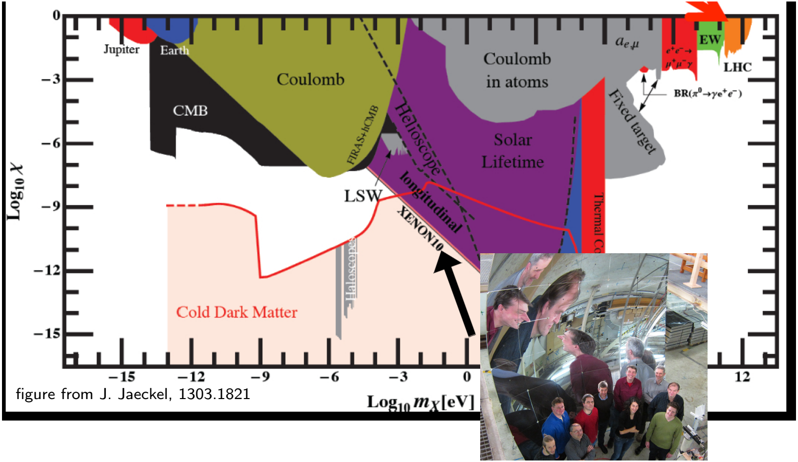

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mirror search
(in the following)

→ μeV-eV: Dish (nonresonant) Idea: Horns et al. JCAP 1304, 016; Japan: 1509.00785, FUNK: 1410.0200

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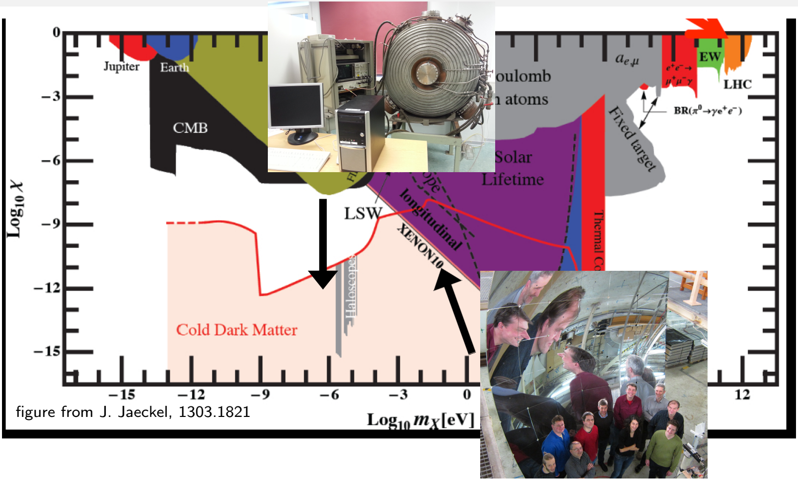

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→ up to 100 μeV? resonators, LSW [Horns et al 1410.6302+ Graham PRD90 7, 075017 + ADMX!]

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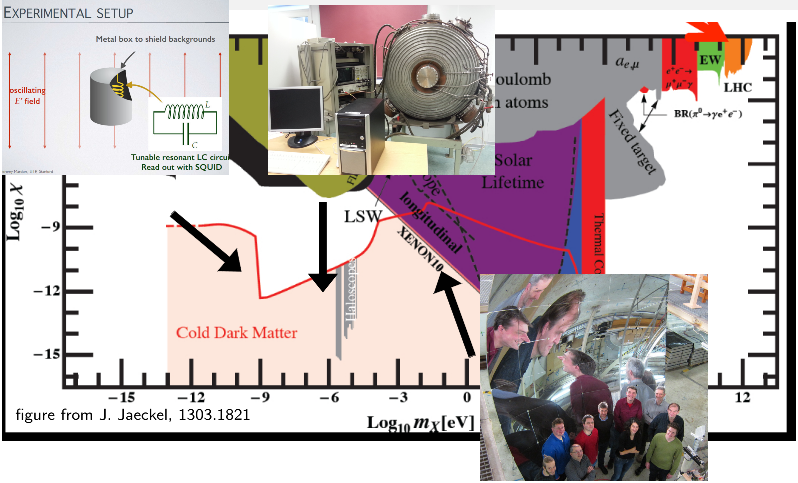

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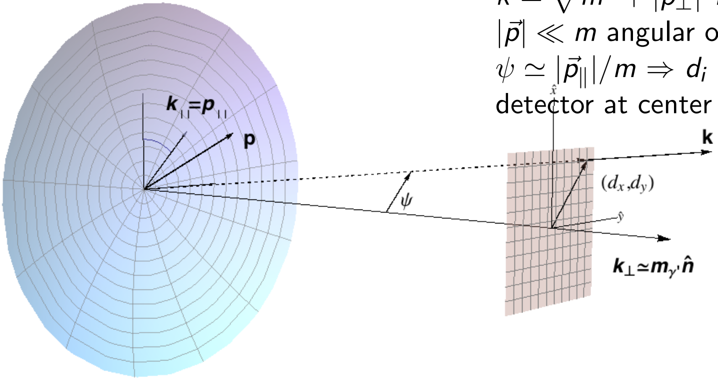
→ neV + tunable LC [(Arza... BD et al. EPJC 75,7); Chaudhuri 1411.7382]

more → Direct detection An et al. Phys.Lett. B747

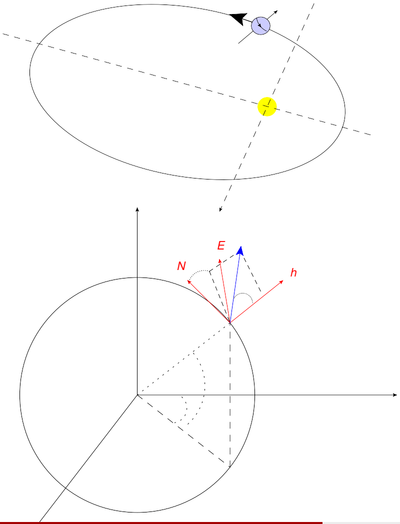
Hidden Photon Dark Matter Signal from mirror JCAP 1311 (2013) 016

- $\vec{p}$ incoming, $\vec{k}$ outgoing, along $k_{\parallel} = p_{\parallel}$ no boundary change
- with energy conservation $\vec{k} = \sqrt{m^2 + |\vec{p}_{\perp}|^2}\vec{n} + \vec{p}_{\parallel} \Rightarrow$ $|\vec{p}| \ll m$ angular off-set $\psi \simeq |\vec{p}_{\parallel}|/m \Rightarrow d_i \simeq \frac{p_i}{m}R$, detector at center R



DM @ 60° to ecliptic ↘

see, eg. 1307.5323]



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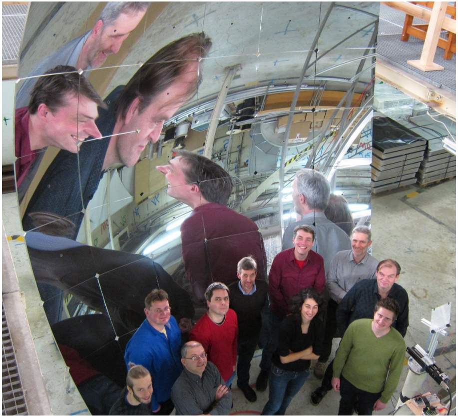
- spot-**broadening** DM velocity distribution $\Delta d \sim 1\mathrm{mm}(\frac{R}{\mathrm{m}})$ (if $\Delta v \sim 10^{-3}$) +**movement** (in DM frame)

HP Dish DM at KIT: FUNK! concept JCAP 1304 (2013) 016, res: PoS ICRC2015 (2015) 1191



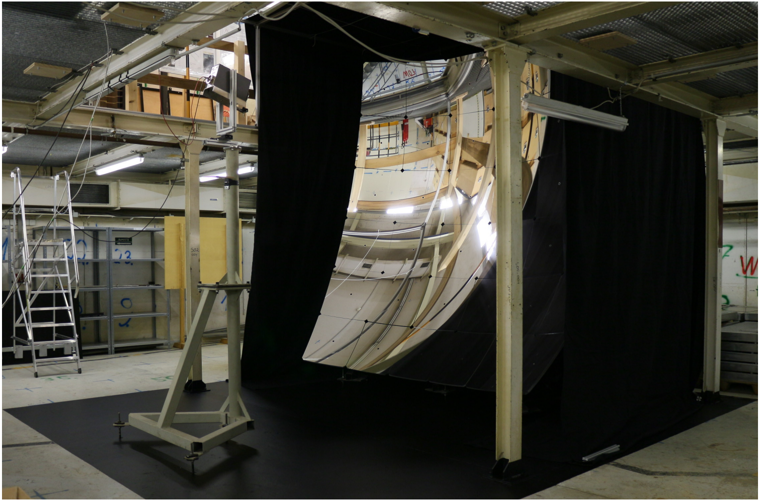
- HP DM effectively move electrons $\rightarrow$ radiation, $m_{\rm HP} \sim 1/\lambda$
- background-supressed at dish/mirror $\rightarrow$ collect light at center of LARGE reflecting sphere
- Finding U(1)s of a Novel Kind at KIT, north campus 1410.0200

PROCEEDINGS OF SCIENCE

Search for dark matter in the hidden-photon sector with a large spherical mirror

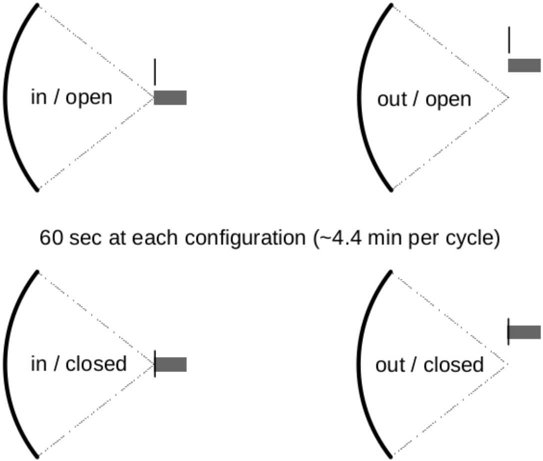
Darko Veberič*[a], Kai Daumiller[a], Babette Döbrich[b], Ralph Engel[a], Joerg Jaeckel[c]
Marek Kowalski[de], Axel Lindner[d], Hermann-Josef Mathes[a], Javier Redondo[f],
Markus Roth[a], Christoph Schäfer[a], Ralf Ulrich[a] [The FUNK Experiment]

Measurement scheme: shutter and background focus



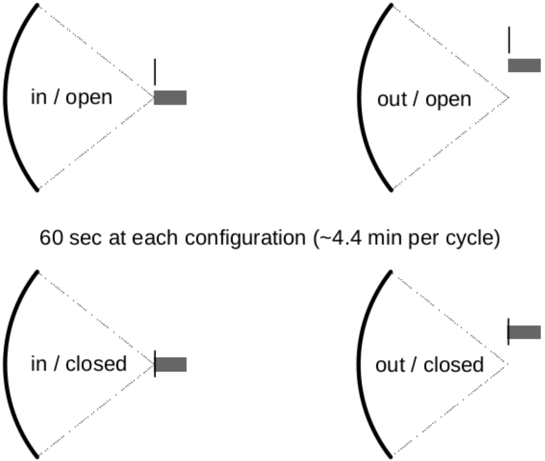
Windowless hall with $\sim$2m thick walls, complete curtain cover

Measurement scheme: shutter and background focus



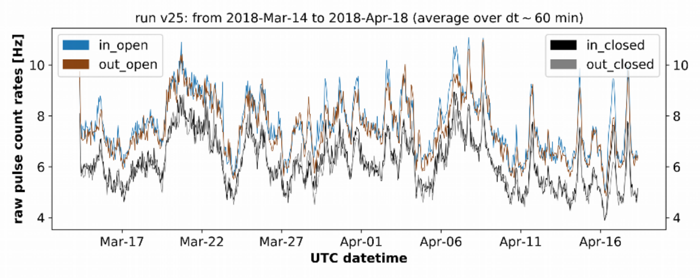
Detector: Test phase CCD, Now: low-noise PMT (UV-visible)

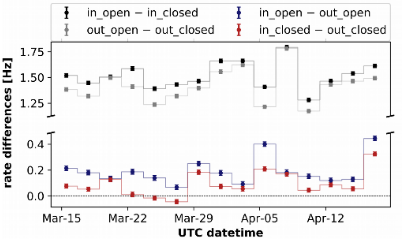
Measurement scheme: shutter and background focus



Problem: shutter tight only up to ϵ (due to "edges")

A look at the raw data





$$\left[\frac{\text{in open} - \text{in closed}}{\text{in closed}}\right] \sim 24.6\,\% \qquad \left[\frac{\text{out open} - \text{out closed}}{\text{out closed}}\right] \sim 23.4\,\%$$

$$\left[\frac{\text{in open} - \text{out open}}{\text{in open}}\right] \sim 2.5\,\% \qquad \left[\frac{\text{in closed} - \text{out closed}}{\text{out closed}}\right] \sim 1.5\,\%$$

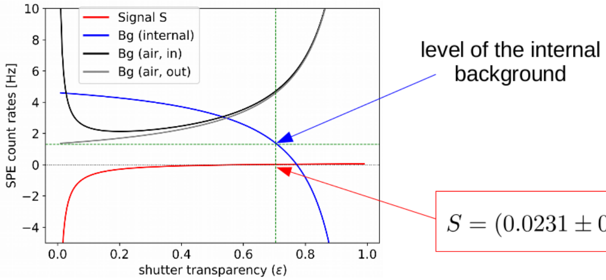
The differences ***in / out*** for the two statuses ***open / closed*** are compatible.

signal selection proceeds after "flasher calibration"

Signal extraction

- Possible signal extracted by modeling the four measurement configurations

$$\begin{aligned}
\Phi_{\mathrm{in/open}} &= S + B_{\mathrm{int}} + B_{\mathrm{air/in}} \\
\Phi_{\mathrm{in/closed}} &= B_{\mathrm{int}} + \epsilon B_{\mathrm{air/in}} \\
\Phi_{\mathrm{out/open}} &= B_{\mathrm{int}} + B_{\mathrm{air/out}} \\
\Phi_{\mathrm{out/closed}} &= B_{\mathrm{int}} + \epsilon B_{\mathrm{air/out}}
\end{aligned}$$

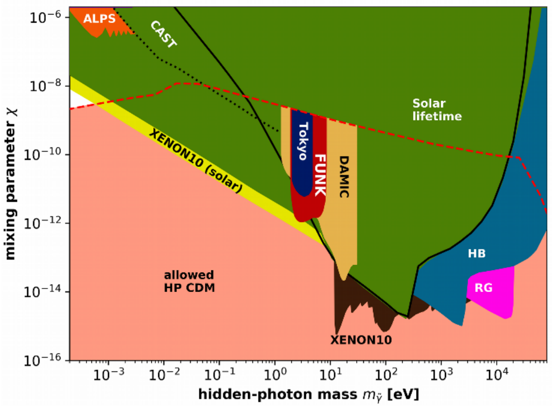


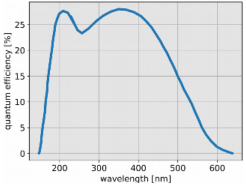
$S = (0.0231 \pm 0.0260)\mathrm{Hz}$

Selection proceeds after Flasher calibration

PRELIMINARY results

$$\chi = 4.1 \times 10^{-12} \left(\frac{\Phi_{\gamma,\mathrm{det}}}{\mathrm{Hz}}\frac{m}{\mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{1}{\eta(m)}\right)^{\frac{1}{2}} \left(\frac{1\,\mathrm{m}^2}{\mathcal{A}_{\mathrm{eff}}}\right)^{\frac{1}{2}} \left(\frac{0.3\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{CDM}}}\right)^{\frac{1}{2}} \left(\frac{2/3}{\langle\cos^2\alpha\rangle}\right)^{\frac{1}{2}}$$





$1.9 \lesssim m/\mathrm{eV} \lesssim 7.8$

$\chi < 1.12 \times 10^{-12}$
at 99.7 %CL

To do: some cross-checks with new digitizer, go to lower frequency range

Thanks for listening :-)

ultralight DM searches: QCD axions, ALPs, Hidden Photons

- FUNK: broadband search with mirror at KIT, Germany: about to publish first results, future measurements in GHz and THz range planned
- RADES: high-mass axion R&D at CERN, re-starting data taking next week, improvement of DAQ behavior and noise temperature
- lots of other experiments in that field (Please talk to me if interested)

Please come to my talk on October 5th to hear about my actual main work with NA62! Also searching axions :-)

DI2018: `https://indico.bnl.gov/event/3478/`

Credits (students highlighted)

FUNK at KIT is the work of

A. Andrianavalomahefa, K. Daumiller, BD, R. Engel, J. Jaeckel, M. Kowalski, A. Lindner, H-J. Mathes, J. Redondo, M. Roth, T. Schwetz-Mangold, C. Schäfer, R. Ulrich, D. Veberic

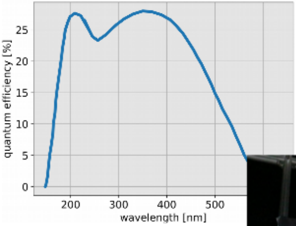
RADES at CERN is the work of

Alejandro Alvarez Melcon, Sergio Arguedas Cuendis, Cristian Cogollos, Alejandro Diaz-Morcillo, BD, Juan Daniel Gallego, Benito Gimeno, Igor G. Irastorza, Antonio Jose Lozano-Guerrero, Chloe Malbrunot, Pablo Navarro, Carlos Pena Garay, Javier Redondo, Theodoros Vafeiadis and Walter Wuensch

Additional slides/backup

FUNK DAQ

Sensor



- Model 9107QB (low noise)
- Spectral coverage (160, 630) nm
- Active diameter 25 mm

Data acquisition

- Model PS 6000 series
- ADC resolution 8 bits
- Sampling period 0.8 ns

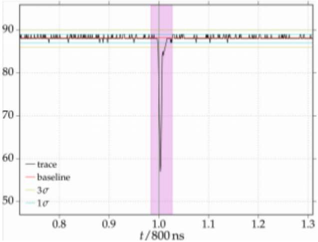
Computer

Save:

- Trace of 1600 ns (1000 bins before and after trigger)
- Environmental data (T, p)
- Configurations

In parallel:

- Muon monitoring



Free field

- A hidden, light U(1) in addition to the SM

$$-\mathcal{L}_{\rm eff} \supset \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{m^2}{2} X_\mu X^\mu + \frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$$

- Modified Maxwell equations in vacuum

$$\nabla \cdot \mathbf{E} = \rho + \chi m^2 X^0 + \mathcal{O}(\chi^2)$$
$$\nabla \cdot \hat{\mathbf{E}} = -m^2 X^0 - \chi\rho + \mathcal{O}(\chi^2)$$

- Field solution in free-space

$$\begin{pmatrix} \mathbf{E} \\ \hat{\mathbf{E}} \end{pmatrix} = \mathbf{E}_m \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{i(\omega t - \mathbf{k}\cdot\mathbf{x})} + \hat{\mathbf{E}}_m \begin{pmatrix} -\chi \\ 1 \end{pmatrix} e^{i(\omega t - \mathbf{p}\cdot\mathbf{x})}$$

oscillating at $\nu \sim 240\,\mathrm{THz}\left(\frac{m}{\mathrm{eV}}\right)$

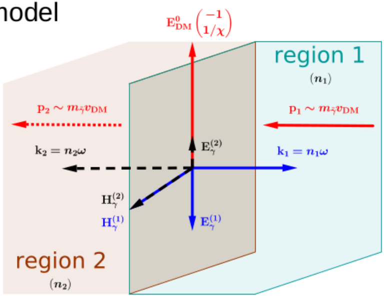
Matter

- Field solution in matter

$$\begin{pmatrix}\mathbf{E}\\ \hat{\mathbf{E}}\end{pmatrix} = \mathbf{E}_\gamma \begin{pmatrix}1\\ \chi_{\rm eff}-\chi\end{pmatrix} e^{i(\omega t-\mathbf{k}\cdot\mathbf{x})} + \mathbf{E}_{\rm DM}\begin{pmatrix}-1\\ 1/\chi_{\rm eff}\end{pmatrix} e^{i(mt-\mathbf{p}\cdot\mathbf{x})}$$

$$\chi_{\rm eff} = \chi\frac{m^2}{m^2+(n^2-1)\omega^2}$$

- Toy model



- Continuity of the parallel components
- Outgoing ordinary electric field

$$E^{(1)}_{\gamma,||} = \frac{\chi_1-\chi_2}{\chi_1}\frac{n_2}{n_1+n_2}E^0_{\rm DM,||}$$