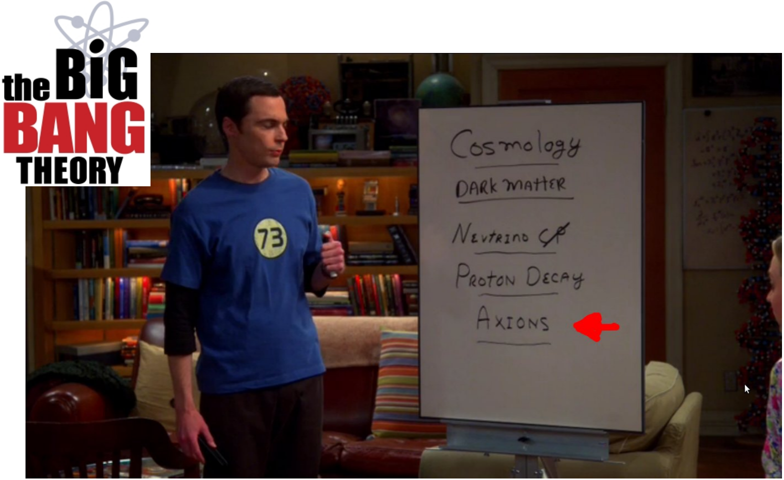
Phenomenology of Axions, ALPs and Dark Photons

in a Dark Matter context

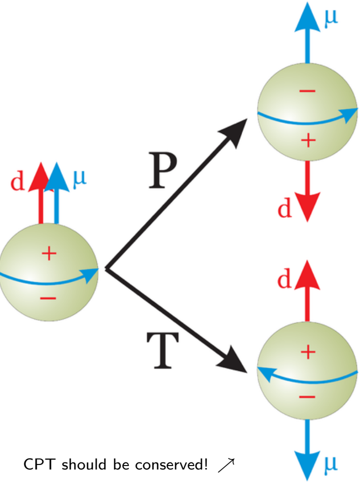
Babette Döbrich (CERN), HAP DM 2015

A popular view on axions...



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

The strong CP problem and Axions



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

... meets experiment

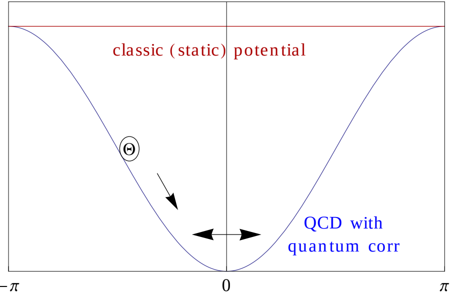
- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_\mathrm{n}(\bar{\theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

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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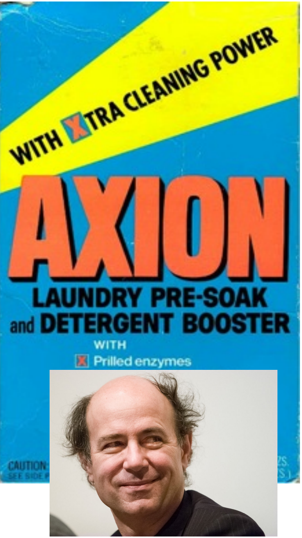

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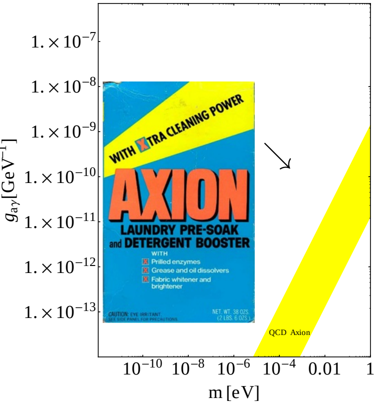
- $f_a \gg \Lambda_{\mathrm{electroweak}}$ 'invisible axion models' 'KSVZ' & 'DFSZ' Kim, Shifman, Vainshtein, Zakharov

  & 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

$$m_a = \frac{m_u m_d}{m_u + m_d} \frac{m_\pi f_\pi}{f_a}$$



[good reading: 9506229 Sikivie's Pooltable]

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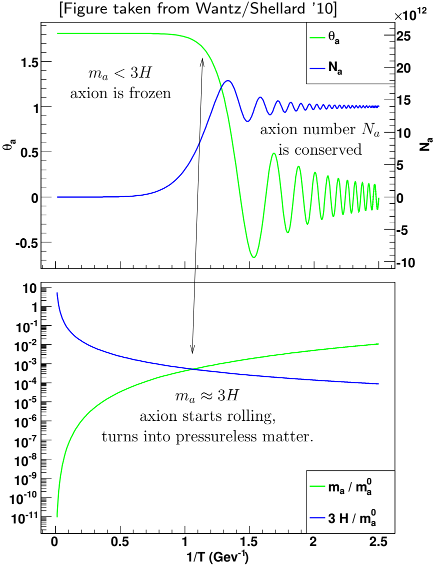
- $m \sim 1/f_a \rightarrow$ pseudo-Goldstone boson (explicit symmetry breaking)
- couple to photons through quark $\triangle$
- how to become (cold) Dark Matter? different ways, depending on f_a

Some selected aspects of Axion cosmology more see, e.g. Kolb & Turner

[Figure taken from Wantz/Shellard '10]



- low m Axion → CDM candidate (lifetime ≫ age of universe)
- $\ddot{\theta} + 3H\dot{\theta} + m^2(T)\theta = 0$ → EOS non-rel DM

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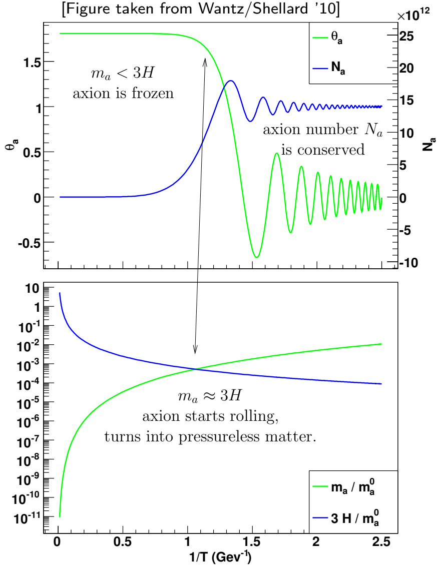

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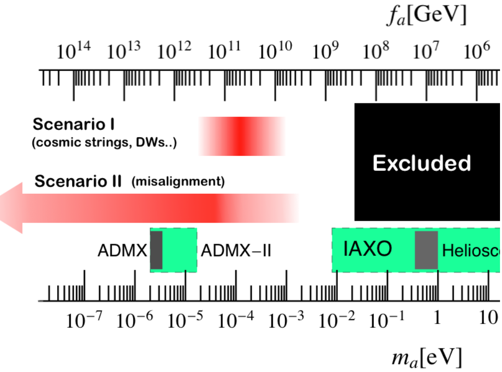

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- omitted: production through axionic strings, domain walls
- phase transition f_a in principle before or after inflation $H_I/(2\pi)$

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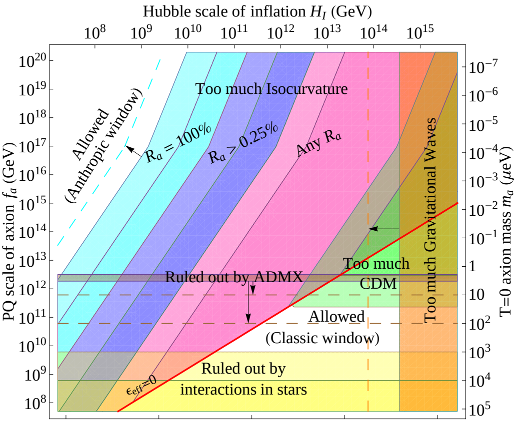
[Figure taken from Hertzberg et al '08]



red line $f_a = H_I/(2\pi)$

fixed H_I → small prefered region

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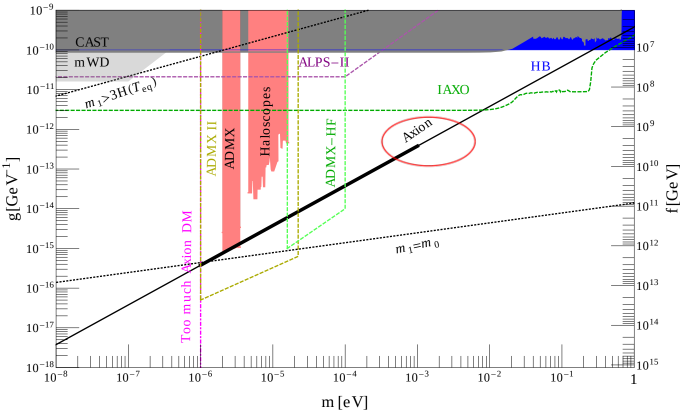
- phase transition f_a in principle before or after inflation $H_I/(2\pi)$
- isocurvature, measure H_I → constraints (remember Sheldon)
- Bose-Einstein today? 0901.1106 Relaxation? 1504.07551 + follow ups

Selected current experimental QCD axion efforts (→ A.Lindner)



→ exploit axion-photon coupling → [Sikivie '83]

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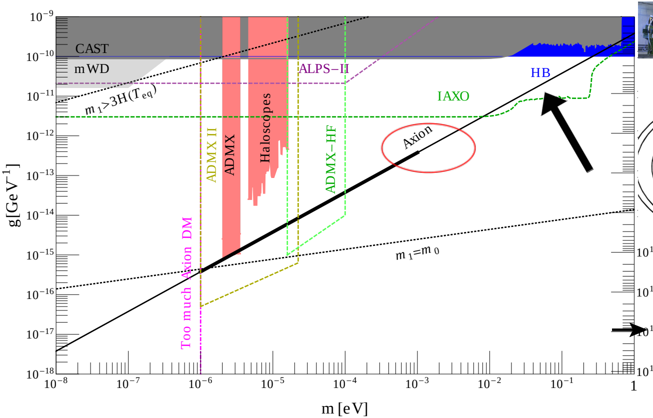

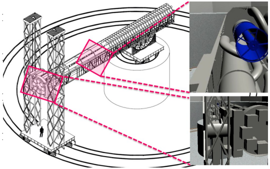

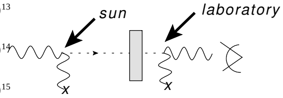

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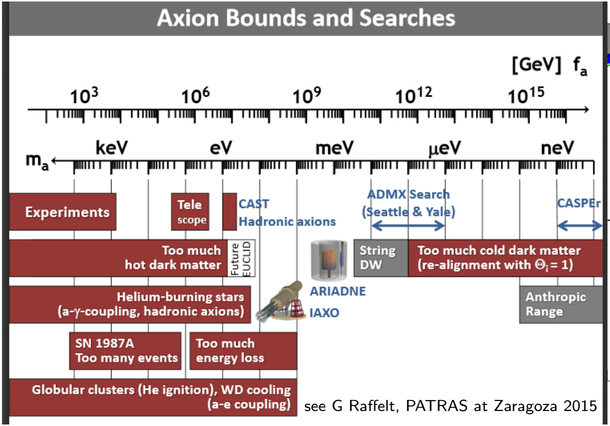
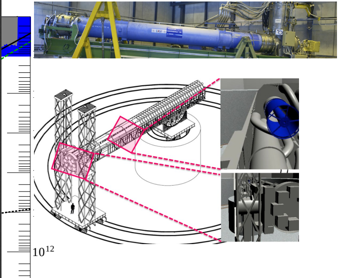
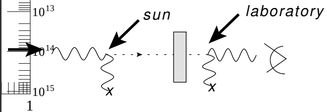


see G Raffelt, PATRAS at Zaragoza 2015





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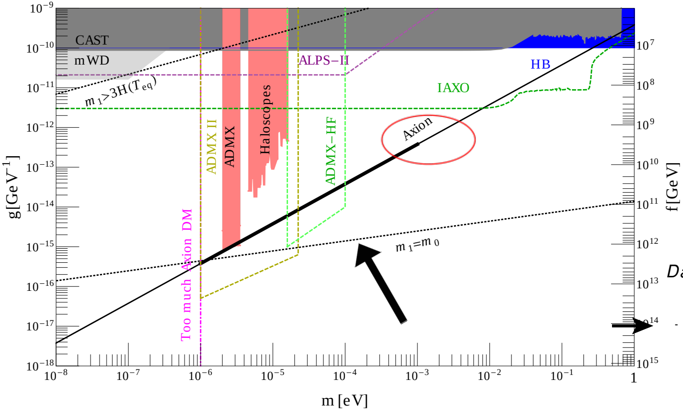

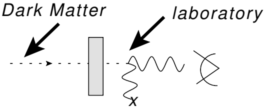

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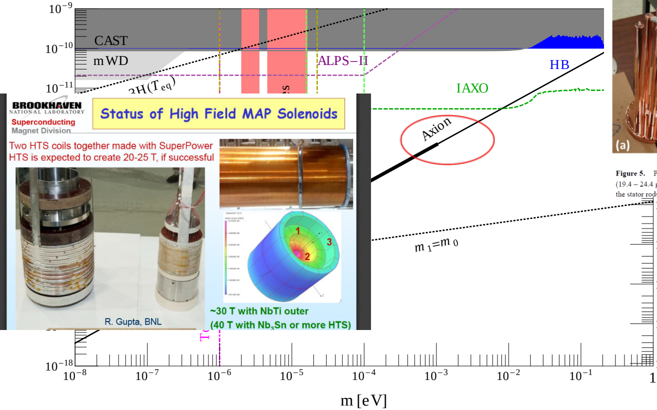


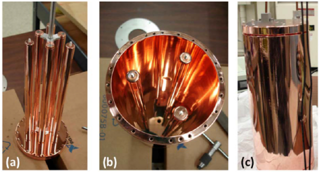
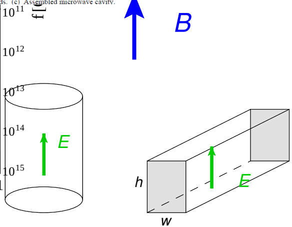


Figure 5. Photographs of the first ADMX-HF cavity, covering the frequency range 4.7 – 5.9 GHz (19.4 – 24.4 μeV). (a) Stator and rotor on the lower end-cap. (b) View of the cavity interior with the stator rods. (c) Assembled microwave cavity.



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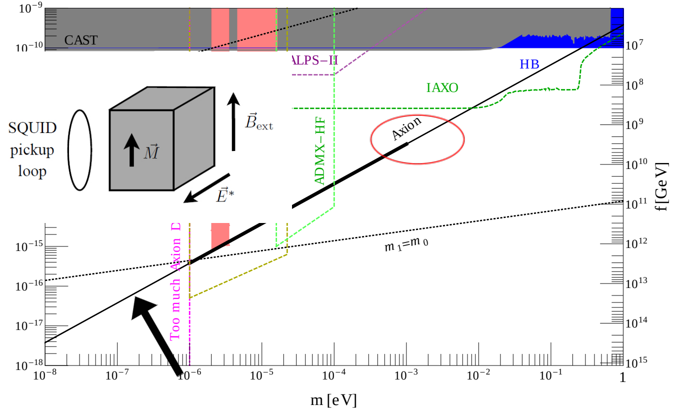

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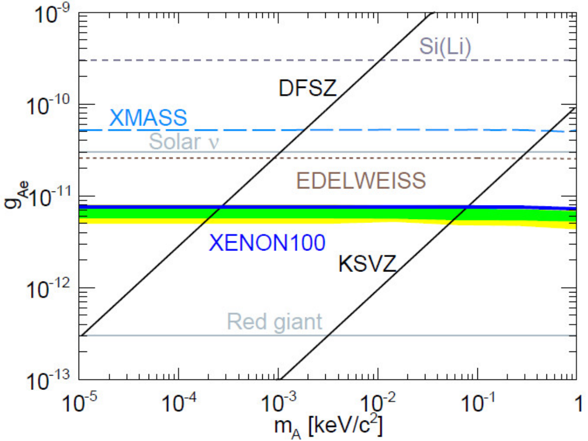
→ CASPEr osc. EDM Phys. Rev. X 4, 021030 +other NMR techniques PRL. 113, 161801

Dual use of WIMP DM direct detection setups

taken from Xenon100 PRD90 6, 062009



see talk Rafael Lang

constraints axion-electron coupling (axio-electric effect)

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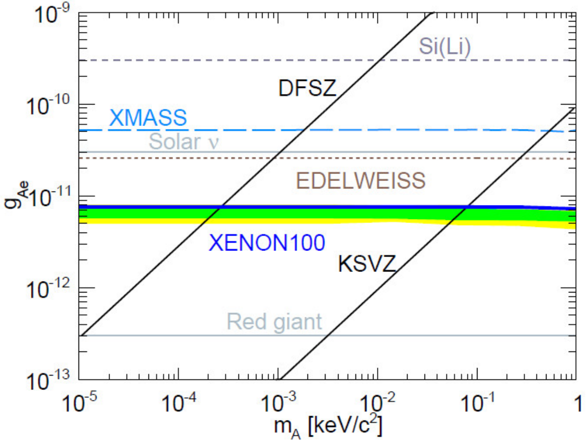
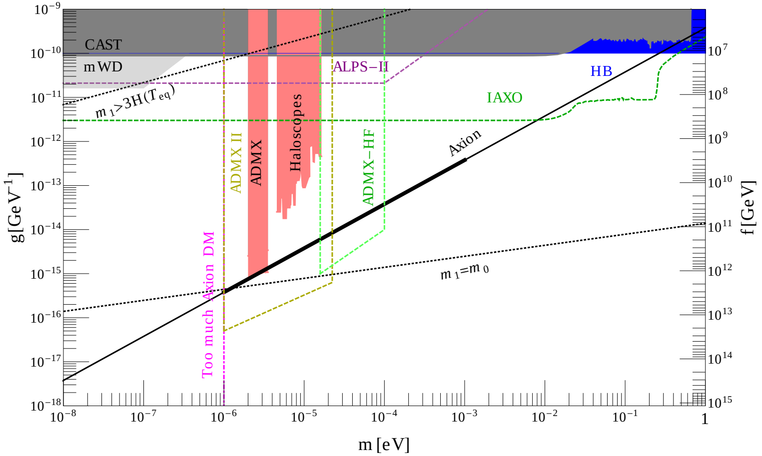


see talk Rafael Lang

constraints axion-electron coupling (axio-electric effect)

solar axions, expectation of DM beyond axion DM mass range?

Axion-like particles as Dark Matter



arbitrary relation between mass and coupling → not strong CP

arise, e.g. in stringy models JHEP06(2014)037, 'axiverse', generally as PNGSBs

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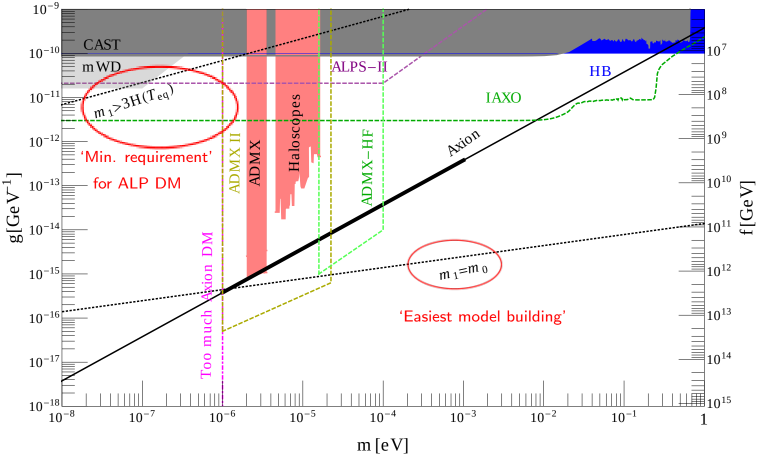

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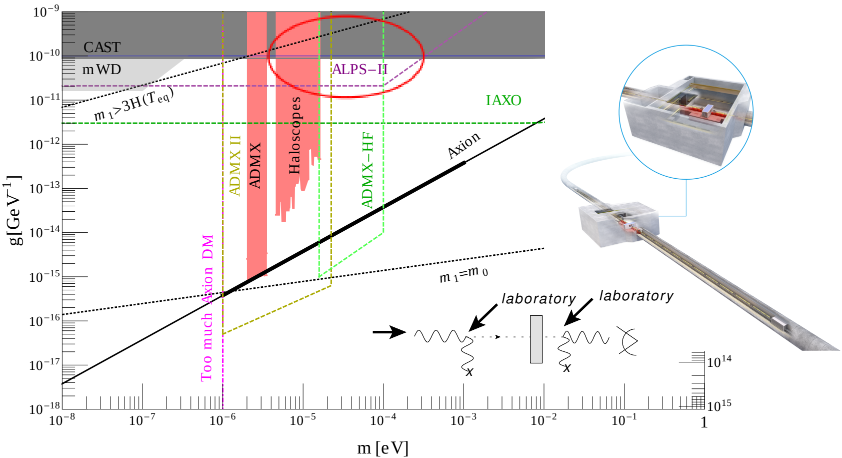
Dark Matter? misalignment as seen before! JCAP 1206, 013

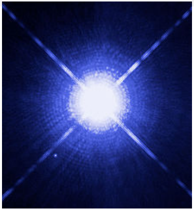
Selected ALP DM (candidate) searches → A. Lindner

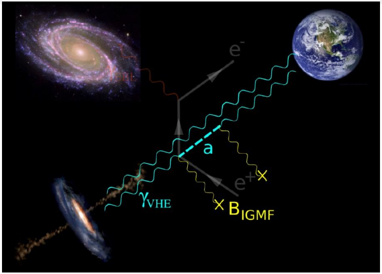


all efforts searching for QCD axion DM, additional examples:

ALPS-II light-shining-through-wall → candidate (indirect) search

One slide on ALPs motivated beyond Dark Matter





Searching for a $0.1 - 1$ keV Cosmic Axion Background

Joseph P. Conlon* and M.C. David Marsh†
Rudolph Peierls Centre for Theoretical Physics, University of Oxford,
1 Keble Road, OX1 3NP, Oxford, United Kingdom

(Dated: May 26, 2014)

Primordial decays of string theory moduli at $z \sim 10^{12}$ naturally generate a dark radiation Cosm

- ALPs motivated phenomenologically also by astrophysical observations (possible, but not necessary DM connection)
- TeV transparency of the universe e.g. 1302.1208, Cosmic Axion Background (observable: soft X-ray excess), White dwarf cooling e.g. 1304.7652...

Axion-Like-Particles as Dark Matter mediators

Why pseudoscalars?

> Pseudoscalar mediators are also attractive from a purely phenomenological point of view, because they predict a strong suppression of the event rate in direct detection experiments, due to three separate effects:

- In the non-relativistic limit, scattering via pseudoscalar exchange is momentum suppressed. Event rates are proportional to $q^4/(m_\chi^2\, m_N^2)$ where $q \sim \mu\, v$ and $v \simeq 10^{-3} c$.
- Moreover, in contrast to scalars pseudoscalars couple to the nucleus spin rather than its mass, so that there is no large enhancement for heavy target nuclei.
- Finally, it turns out that for typical coupling structures pseudoscalars have strongly suppressed couplings to neutrons, further reducing the sensitivity of experiments with unpaired neutrons (in particular xenon-based experiments).

$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q} \left[g_q - \sum_{q'=u,\ldots,t} g_{q'} \frac{\overline{m}}{m_{q'}} \right] \Delta_q^{(N)}$$

For Yukawa-like couplings:

$$-0.4 \lesssim g_n/g_p \lesssim 0$$

Freytsis & Ligeti, arXiv:1012.5317

Felix Kahlhoefer | A Taste of Dark Matter | 2-27 February | Page 5

DESY

stolen from F.Kahlhoefer, MIAPP workshop

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Mainz Institute for Theoretical Physics

NA62 Kaon Physics Handbook

11-22 January 2016
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

- Axion-like particle as ‘mediator’: why is DM evading direct detection? Couple DM to a mediator which is coupled weakly to the SM, pseudoscalars from Higgs sector extension or PNGSB as before
- of course, many other mediators possible (vector, e.g.)
- discovery potential for proton beam dumps (see recent proposal for new SHiP experiment at SPS see 1504.04956)
- also accessible through rare Meson decays , see e.g. 1406.5542 (working on this? please see covert advertisement on the left)

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

Holdom, 1986, PLB

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

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

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

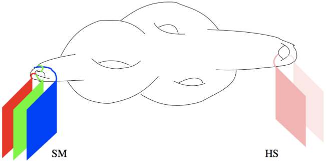
analogous to ν oscillation

→ 

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

experimentally no need for the external field (contrasting axions)



from string scenarios [1206.0819]

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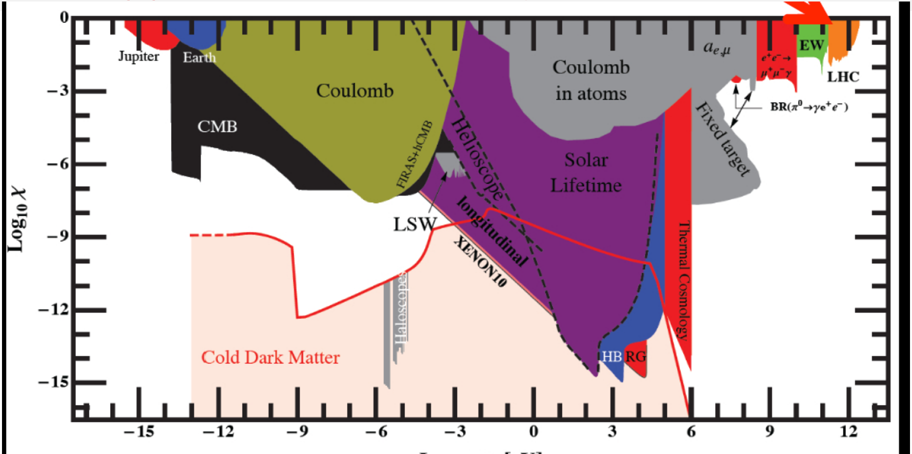

figure from J. Jaeckel, 1303.1821

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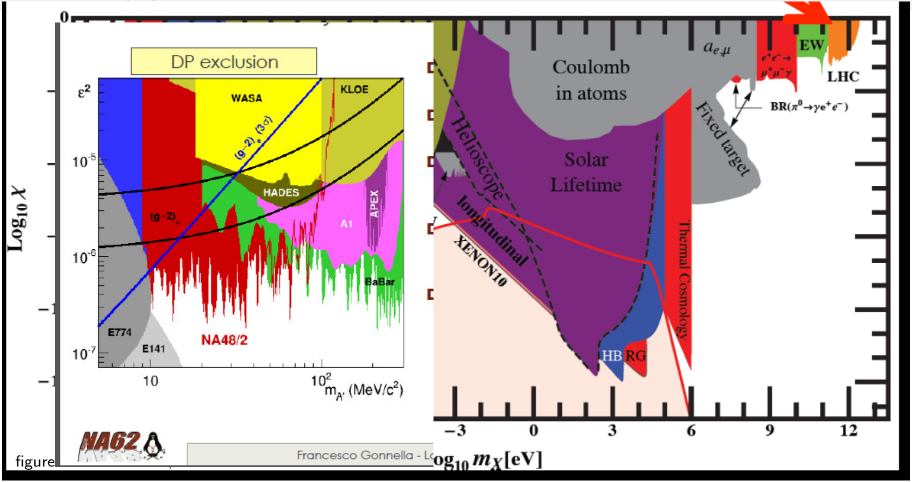


a lot of recent interest in the sub-GeV region muon g-2 anomaly

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

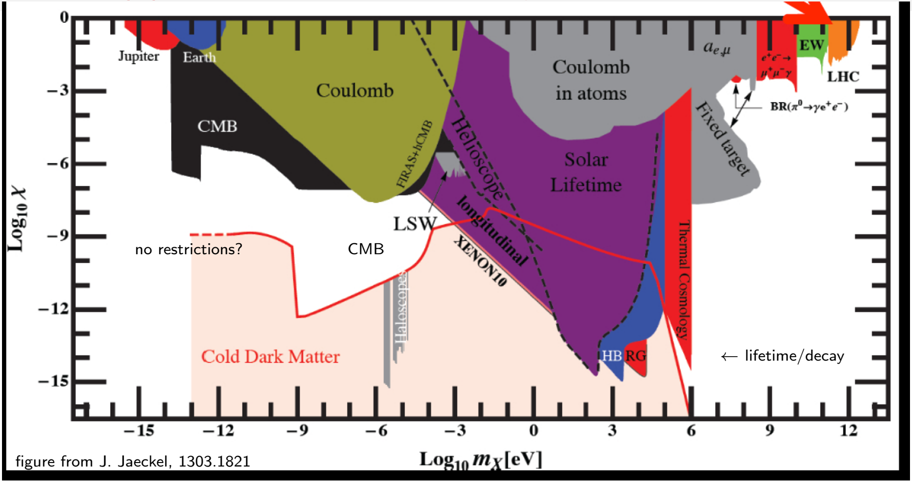
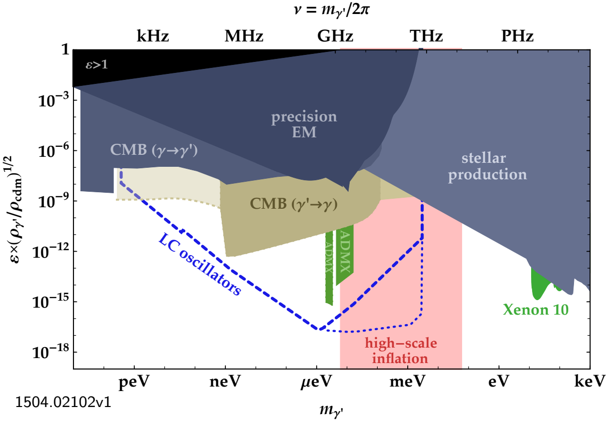


figure from J. Jaeckel, 1303.1821

the HP can be cold Dark Matter

Misalignment mechanism: JCAP 1206, 013 & PRD 84 103501

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



1504.02102v1

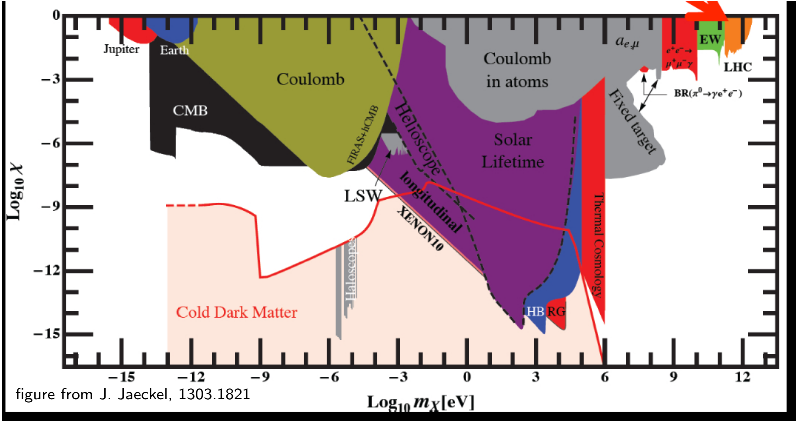
the HP can be cold Dark Matter

Misalignment mechanism: JCAP 1206, 013 & PRD 84 103501

Inflationary fluctuation: Graham et al 1504.02102

$\Rightarrow$ neat experiments

Selected current experimental efforts (→ A.Lindner)



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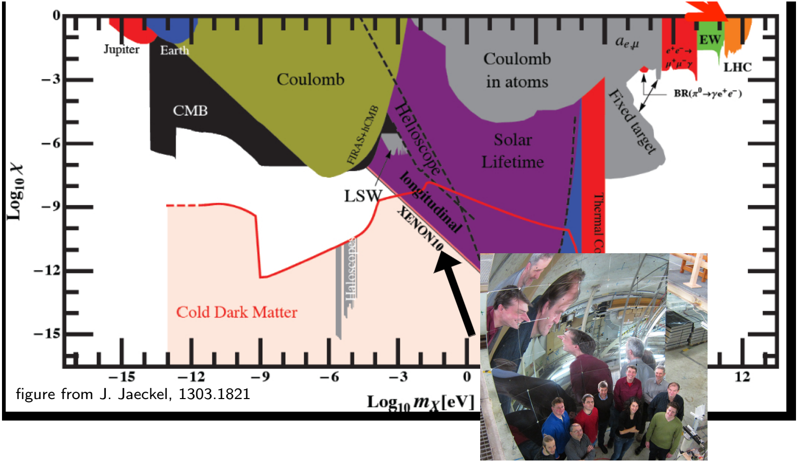

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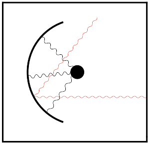

mirror search

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

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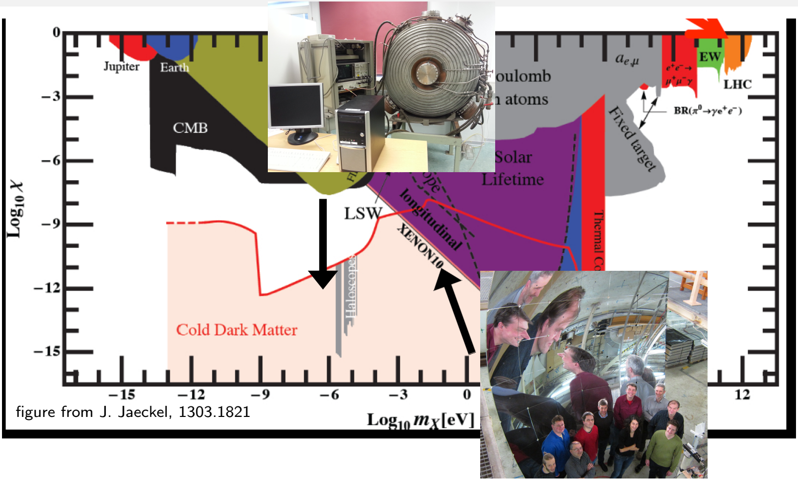

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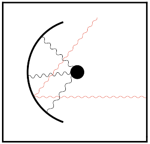

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→ up to 100 μeV? resonators, LSW [Horns et al 1410.6302+ Graham PRD90 7, 075017 + ADMX!]

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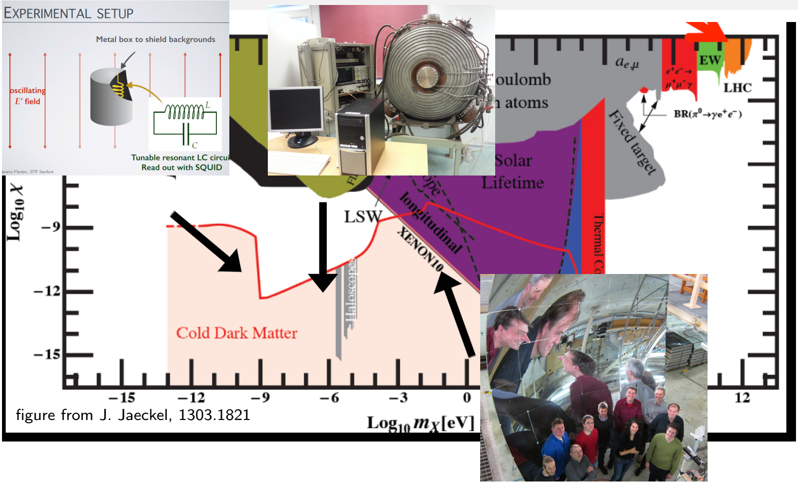

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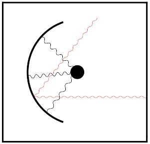


mirror search

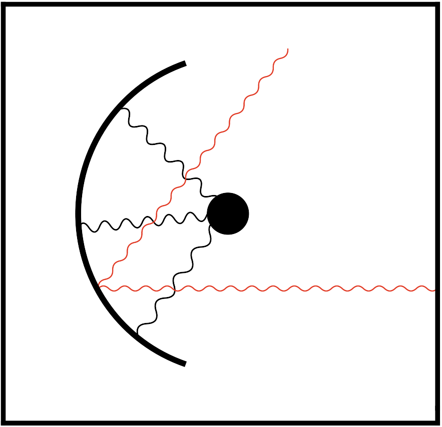
→ μeV-eV: Dish (nonresonant) Idea: Horns et al. JCAP 1304, 016; Japan: 1509.00785, FUNK: 1410.0200

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

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

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

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

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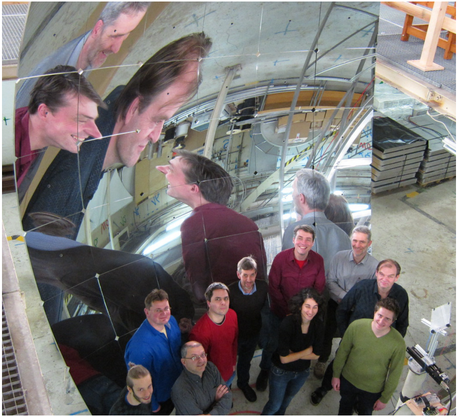
your thesis here?:-)



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- Finding U(1)s of a Novel Kind at KIT, north campus 1410.0200

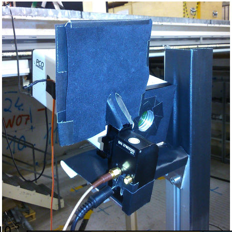
PoS PROCEEDINGS OF SCIENCE

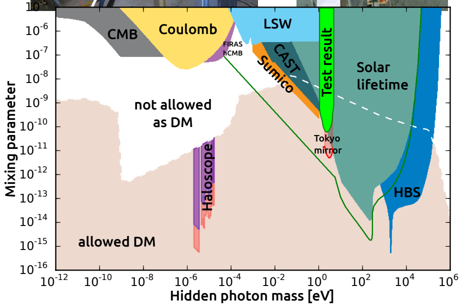
Search for dark matter in the hidden-photon sector with a large spherical mirror

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]

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

PMT kindly financed by HAP





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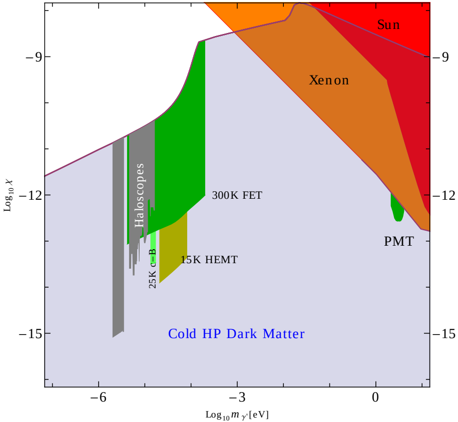
- test results with CCD run, results in Tokio: 1504.00118, run with PMT at FUNK forthcoming



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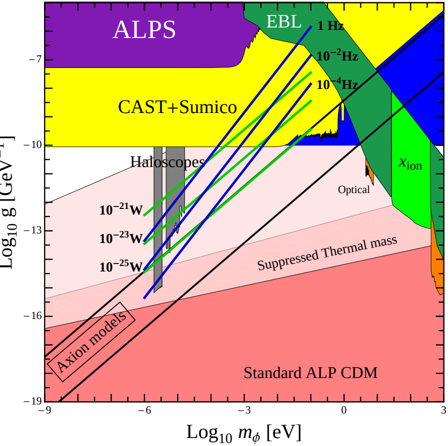
HP Dish DM at KIT: FUNK! concept JCAP 1304 (2013) 016, res: PoS ICRC2015 (2015) 1191

For $1m^2$ at 5T



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- ALPs/axions need *strong* $\vec{B} \parallel$ surface, unlikely with that config, remember: $\mathcal{L}_{\mathrm{Ax}} \sim g\phi\vec{B}\vec{E}$

Summary

Phenomenology of axions, ALPs and HPs as DM

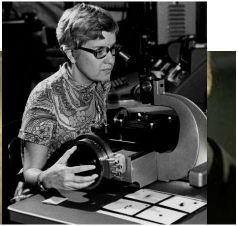
- Dark Matter particles could be very light (sub-eV)
- QCD axion very well motivated & attractive as DM
- Dark Matter possibiliy for ALPs (also as mediator) and HPs. Motivated from SM extensions, DM constraints/pheno being worked out, many (new) experiments en route
- Experiments (more details in the upcoming talk): diverse, interdisciplinary, fun :-)

Prospect

- Axion DM Q can be answered (if not $\Omega_a \ll \Omega_{DM}$), finite parameter space, technology is feasible, vital increase in funding lately (ADMX Gen2, CAPP Korea...)
- ALPs and HP (as DM or else) parameter space somewhat wider $\Rightarrow$ care to join in the quest th/pheno/exp ? :-)

Thanks + acknowledgements

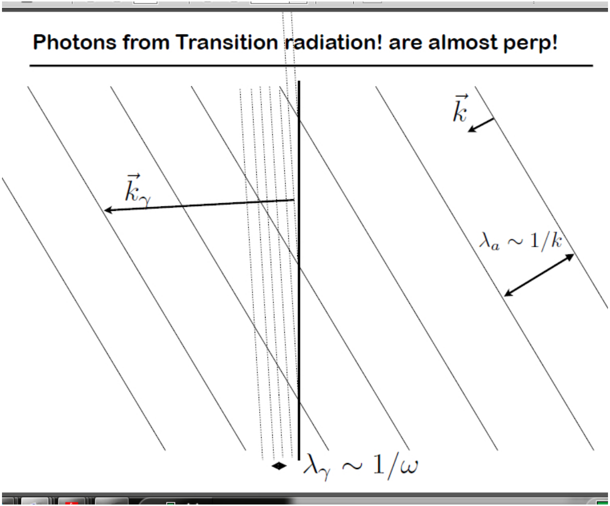
Thank you for your attention!



I am indebted to many colleagues for discussions and collaboration on the above topics. Any list of names would very likely be incomplete and not fit on the slide, so I thank the experimentalists and theorists 'close to' ALPS-II, FUNK, IAXO, CAST and NA62

start of backup

Radiation to mirror center



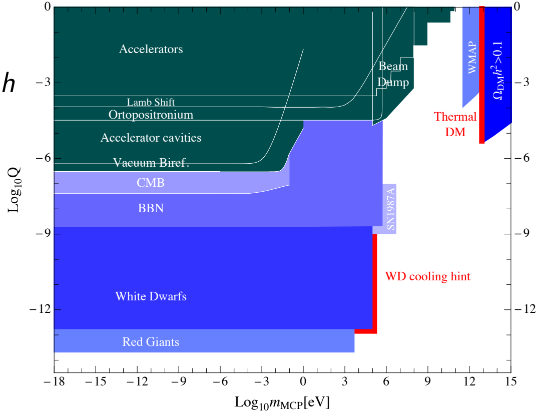
courtesy J. Redondo

Massles extra U(1) + Fermions = minicharged

$$\mathcal{L} \sim \underbrace{\chi}_{\text{mixing}} \underbrace{F_{\mu\nu}}_{\text{SM U(1)}} \underbrace{X^{\mu\nu}}_{\text{hid U(1)}}$$

$$+ \mathcal{L}_{\text{ferm}} \sim e\bar{\psi}\not{A}\psi + e_{\text{h}}\bar{h}\not{X}h$$

$$\rightarrow Q = \chi e_h / e$$

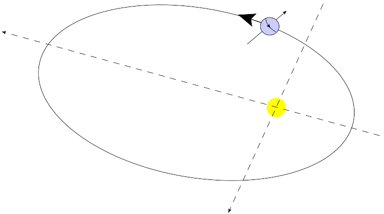


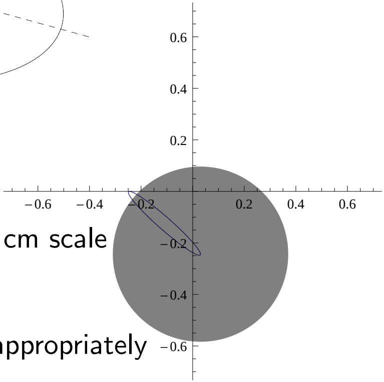
minicharged Dark Matter

Phys.Rev.D75:115001,2007 JHEP 0703:120,2007

Directionality for $\lambda \ll$ dish scale general: Jae/Red, JCAP 1311 (2013) 016

DM @ 60° to ecliptic ↘



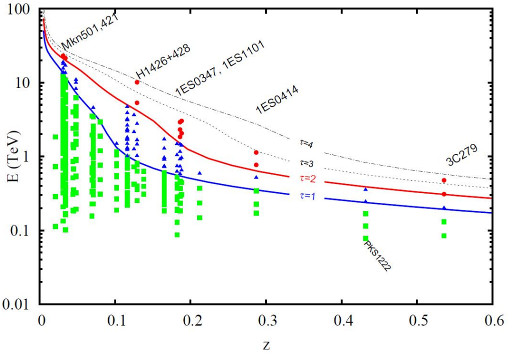


example R=3.4m

choose detector size appropriately

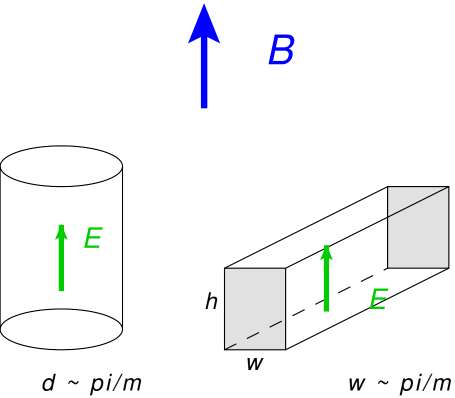
- spot-radius-**broadening** DM velocity distribution $\Delta d \sim 1\mathrm{mm}(\frac{R}{\mathrm{m}})$ (if $\Delta v \sim 10^{-3}$) +**movement** (in DM frame)
- point spread $\sim$ mm and daily mod $\sim$ mm, yearly mod negligible. dependent on exact orientation

TeV transparency [e.g. 1201.4711] M. Meyer, D. Horns et al



- fit spectral sample (left from [e.g. 1201.4711]) in optically thin region
- extrapolate into thick region
- not 'compatible with fit' at $\sim 4\ \sigma$
- explanation through secondary processes difficult (cascade would wash out the intrinsic variability of the source)

Further Haloscopes at higher masses?



- decouple resonant frequency from V [1110.2180], long rectangular cavities? perfect for dipoles
- two proposals for CAST magnet as axion haloscope: CAPP and RADES
- problems: close mode spacing... and more