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Axion and ALP Dark Matter Measuring its Abundance and More

J. Jaeckel*

P. Arias[C], M. Cicoli[B], V. Dandoy[kk], B. Doebrich[yy], S. Hoof[P] A. Hebecker*, S. Knirck[ff], G. Lucente*, V. Montoya*, J. Redondo[x], A. Ringwald**, C., Quint*, M. Wittner*, The FUNK Collaboration

*Heidelberg University, [C]Universidad de Santiago de Chile, [x]U. Zaragoza, [B]Bologna U.,**DESY, †IPPP Durham, [kk]Brussels University, [yy]MPI Muenchen+CERN, [ff]Fermilab, [P]University of Padua

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[B]Bologna U., [**]DESY, [†]IPPP Durham, [kk]Brussels University,
[yy]MPI Muenchen+CERN, [ff]Fermilab, [P]University of Padua

The Axion and its ALPs

Axions are the Best DM candidate ;-)

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- Axions are motivated by SM problem ✓
- Axions are dark and cold matter ✓
- Axions are produced in the early Universe ✓
- Axion's scale makes sense ✓
- Axions are testable in reasonable experiments ✓
- Axions can tell us a lot about astro and cosmo ✓

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Axions can tell us a lot about astro and cosmo ✓

Axion(-like particle) Dark Matter

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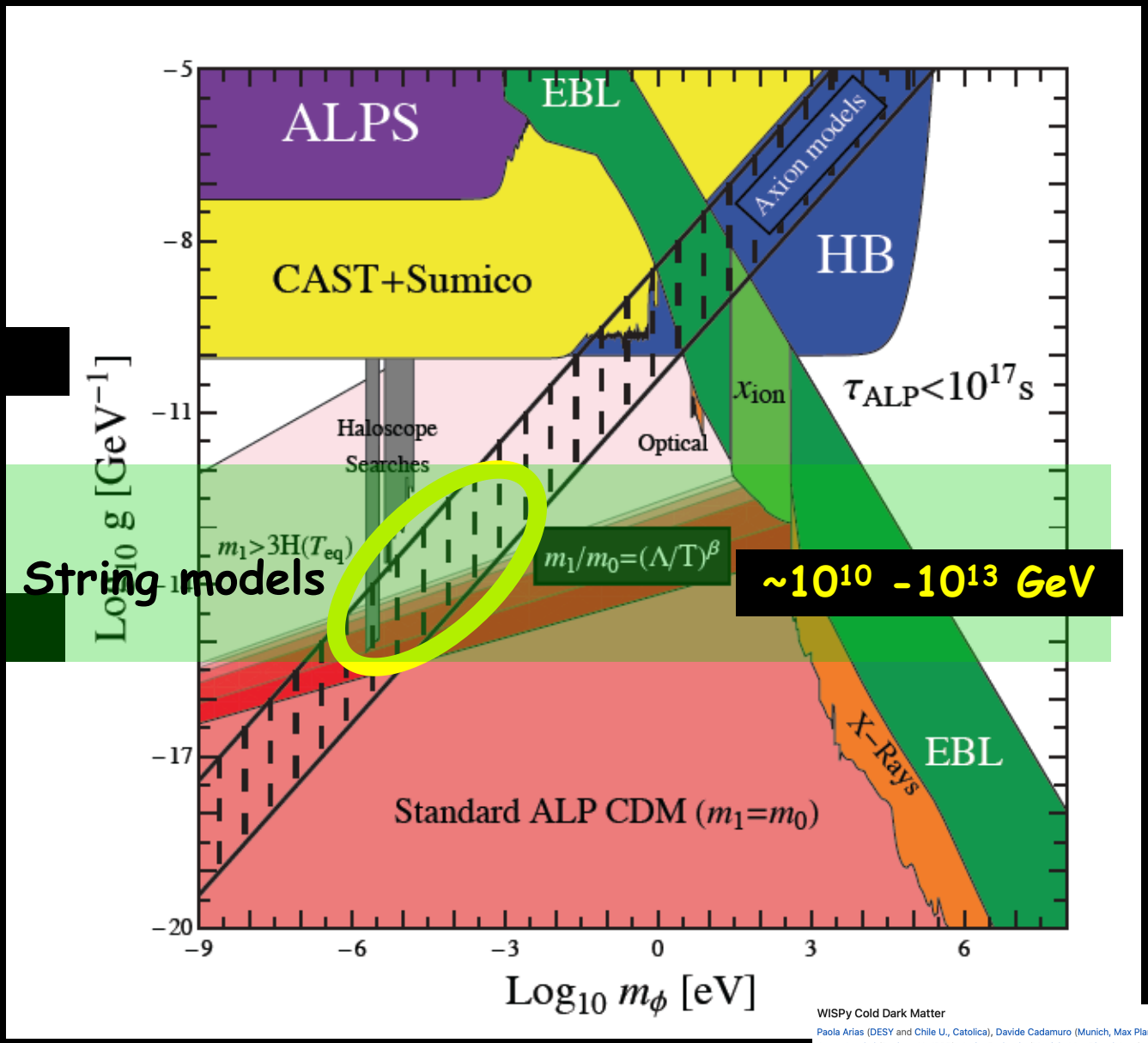
~10^7 GeV

~10^{12} GeV

String models



WISPy Cold Dark Matter

Paola Arias (DESY and Chile U., Catolica), Davide Cadamuro (Munich, Max Planck Inst.), Mark Goodsell (DESY and CERN), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (Munich, Max Planck Inst.) et al. (Jan, 2012)

Published in: *JCAP* 06 (2012) 013 • e-Print: 1201.5902 [hep-ph]

Axion(-like particle) Dark Matter

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~10^7 GeV

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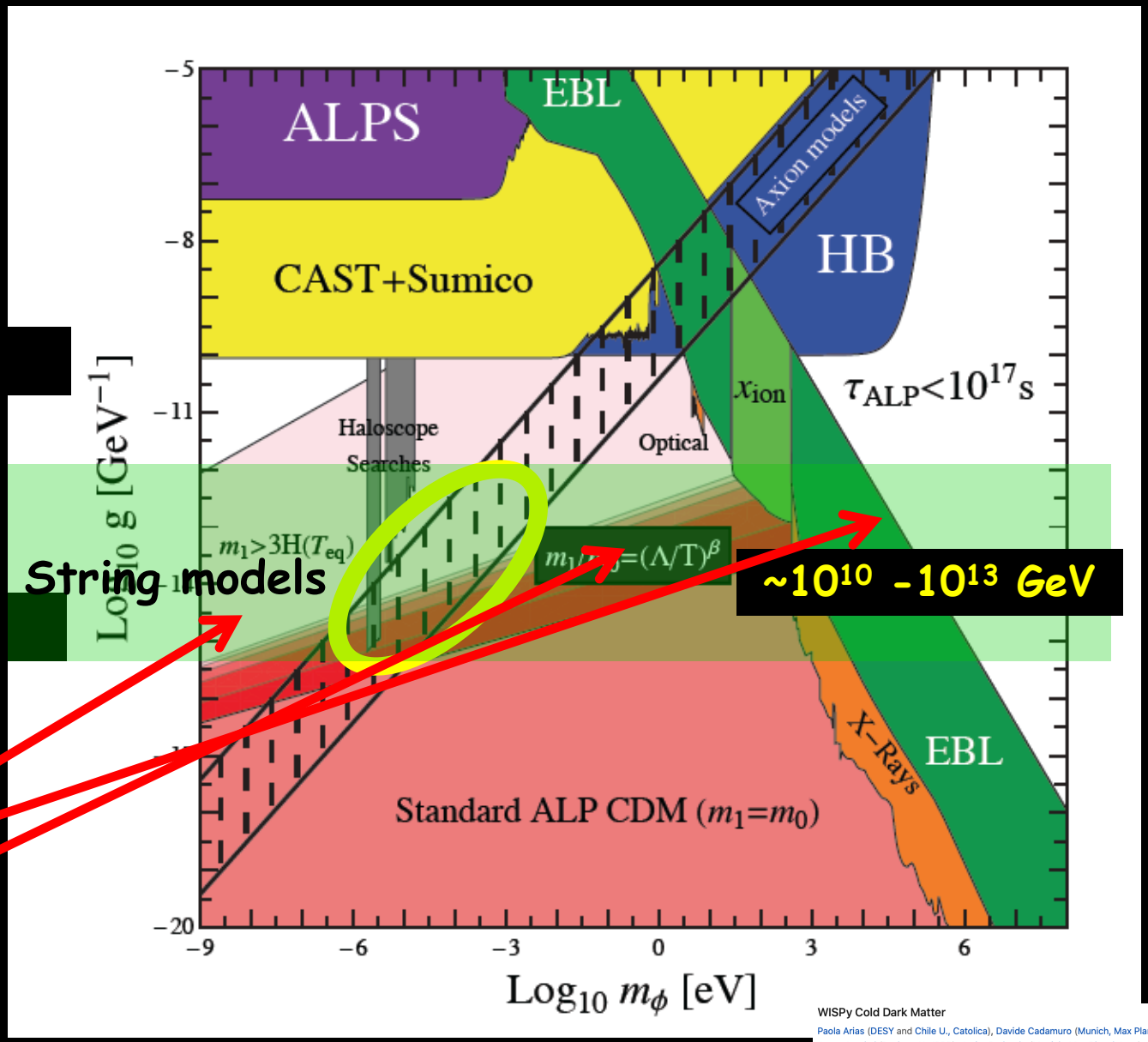
ALPs



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Published in: *JCAP* 06 (2012) 013 • e-Print: 1201.5902 [hep-ph]

Detecting Axion/ALP DM

Use a plentiful source of axions

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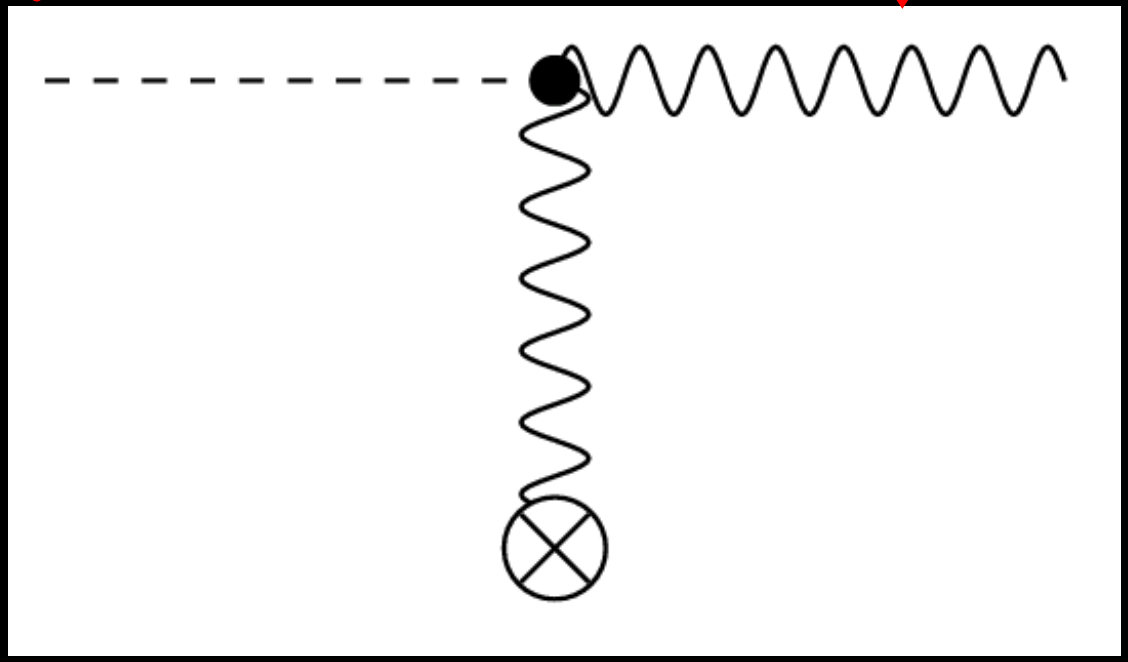
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Signal: Total energy of axion

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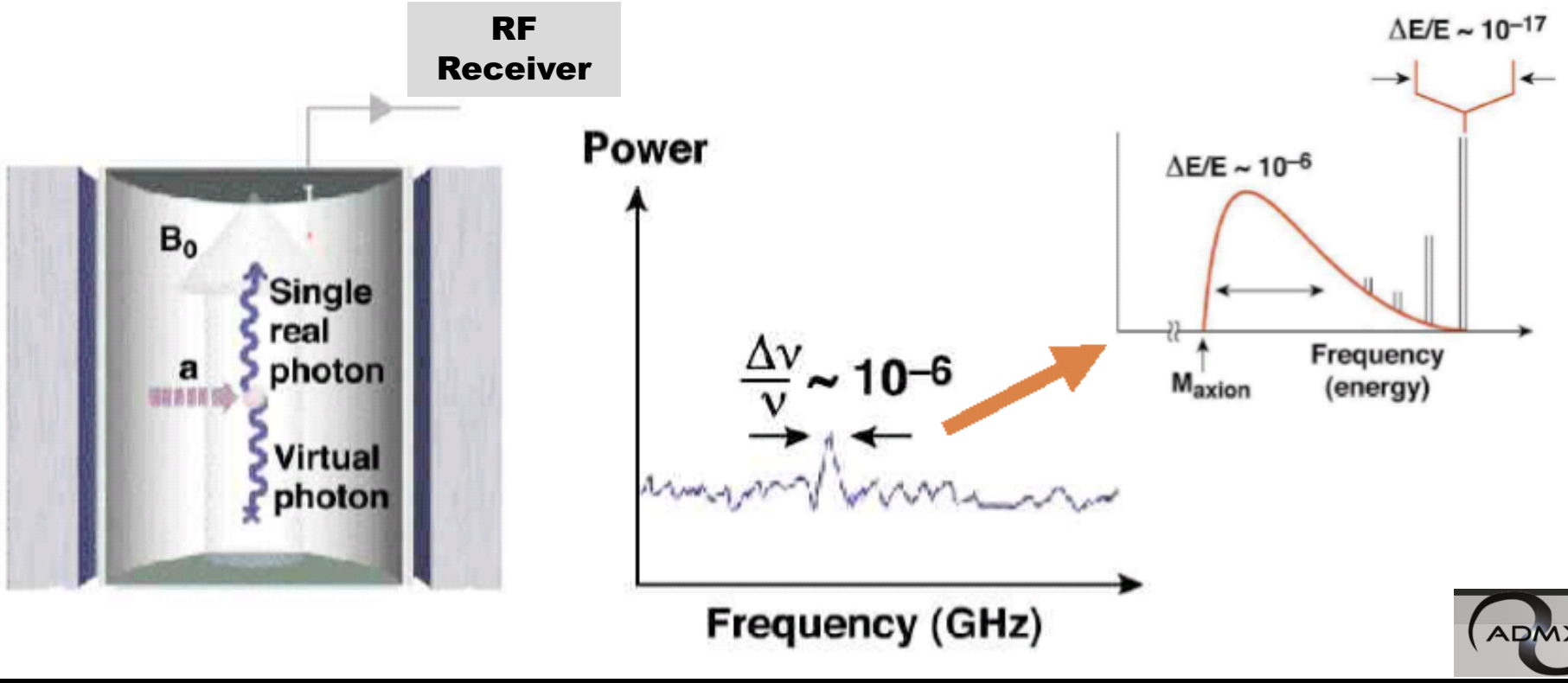

$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

An extremely sensitive probe!!!

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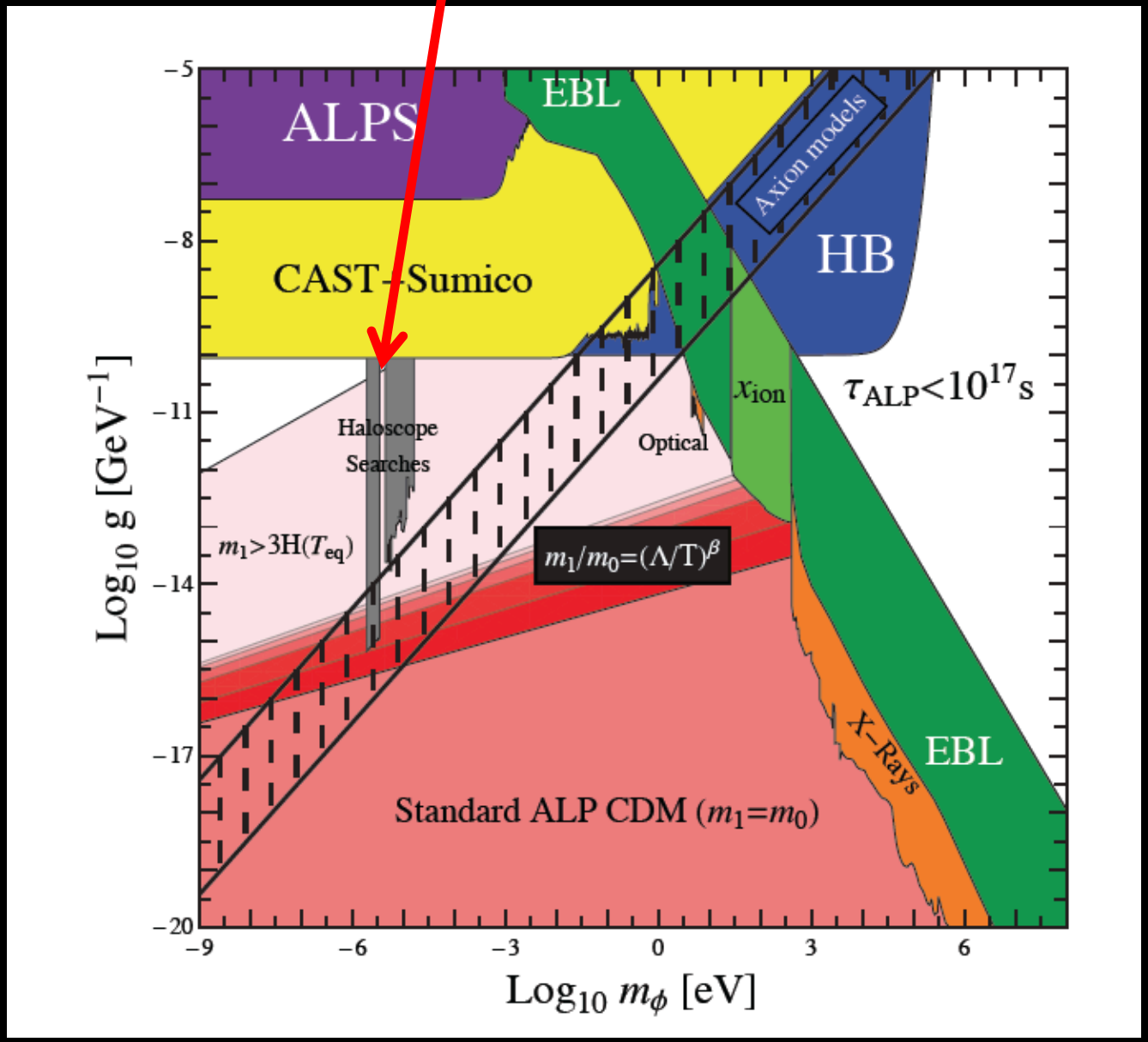

A discovery possible any minute!

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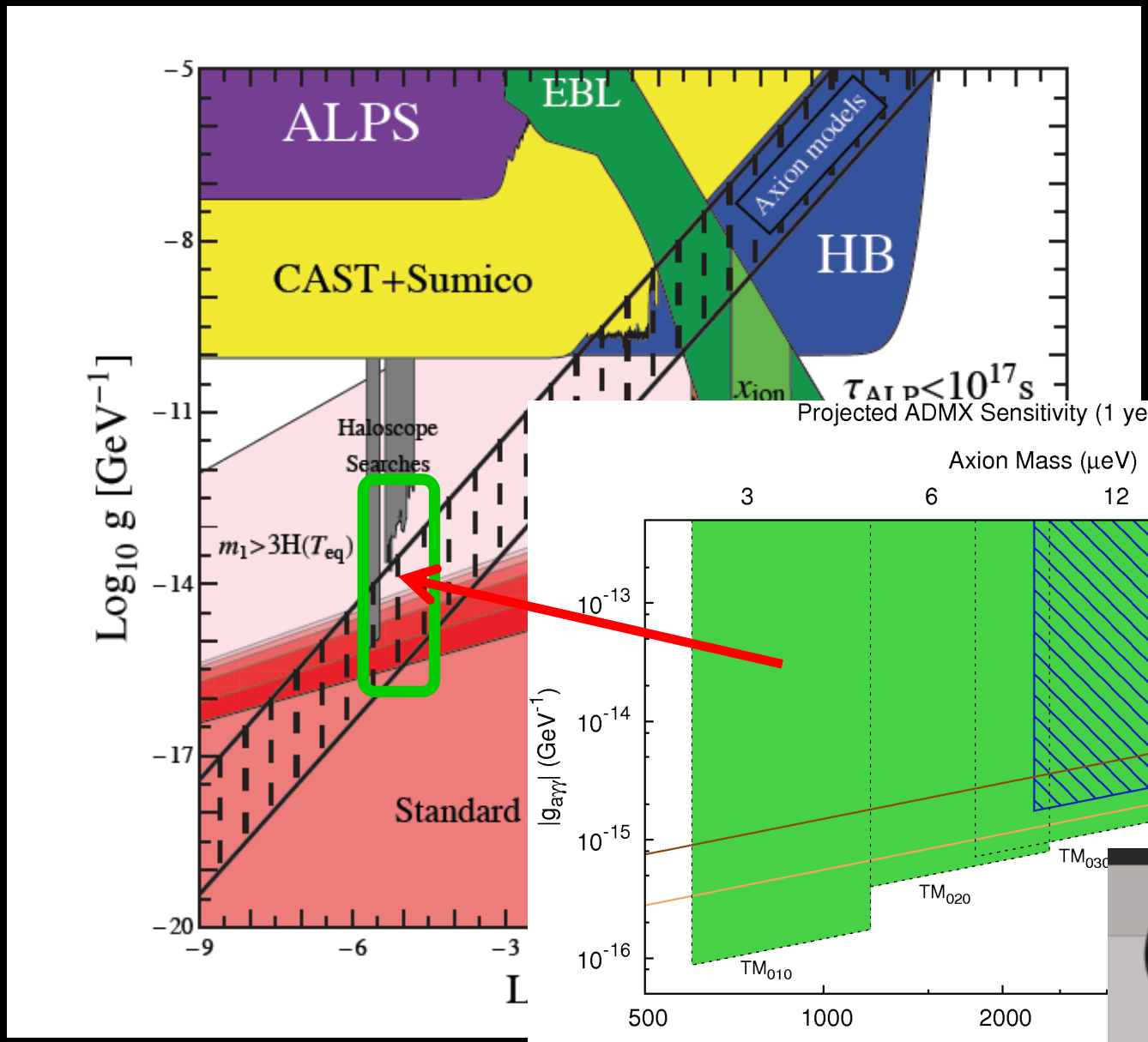

Electricity from Dark Matter ;-).

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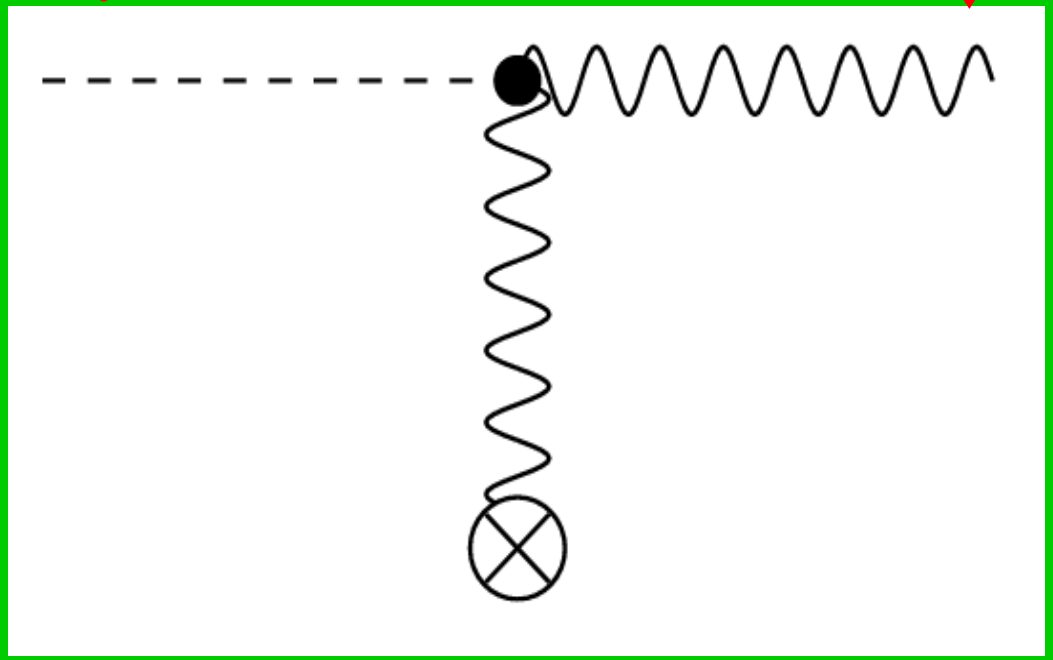
Heidelberg University

- Photon Regeneration

Photon
(amplified in resonator)



axion
(dark matter)

Really sustainable Energy

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Heidelberg University

- Galaxy contains (6-30)x10^{11} solar masses of DM

  ➔ (3-15)x10^{43} TWh

@100000 TWh per year (total world today)

  ➔ 10^{38} years ☺

DM power

ρ*v~300 MeV/cm^3*300km/s~10 W/m^2

compared to 2W/m^2 for wind

Electricity from Dark Matter ;-).

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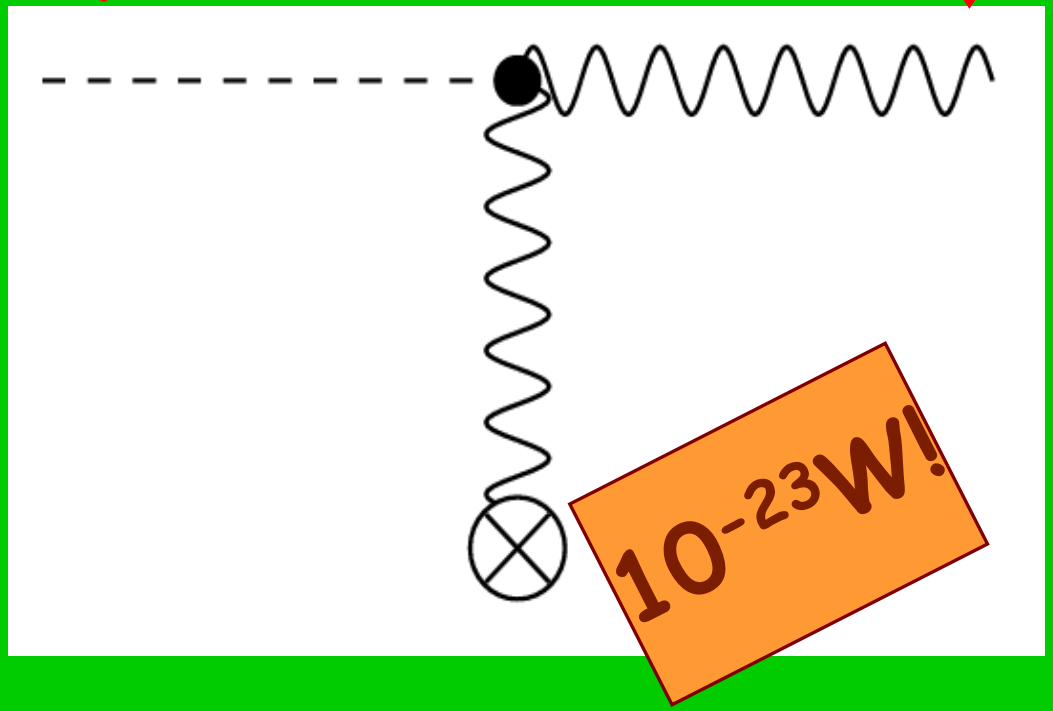
- Photon Regeneration

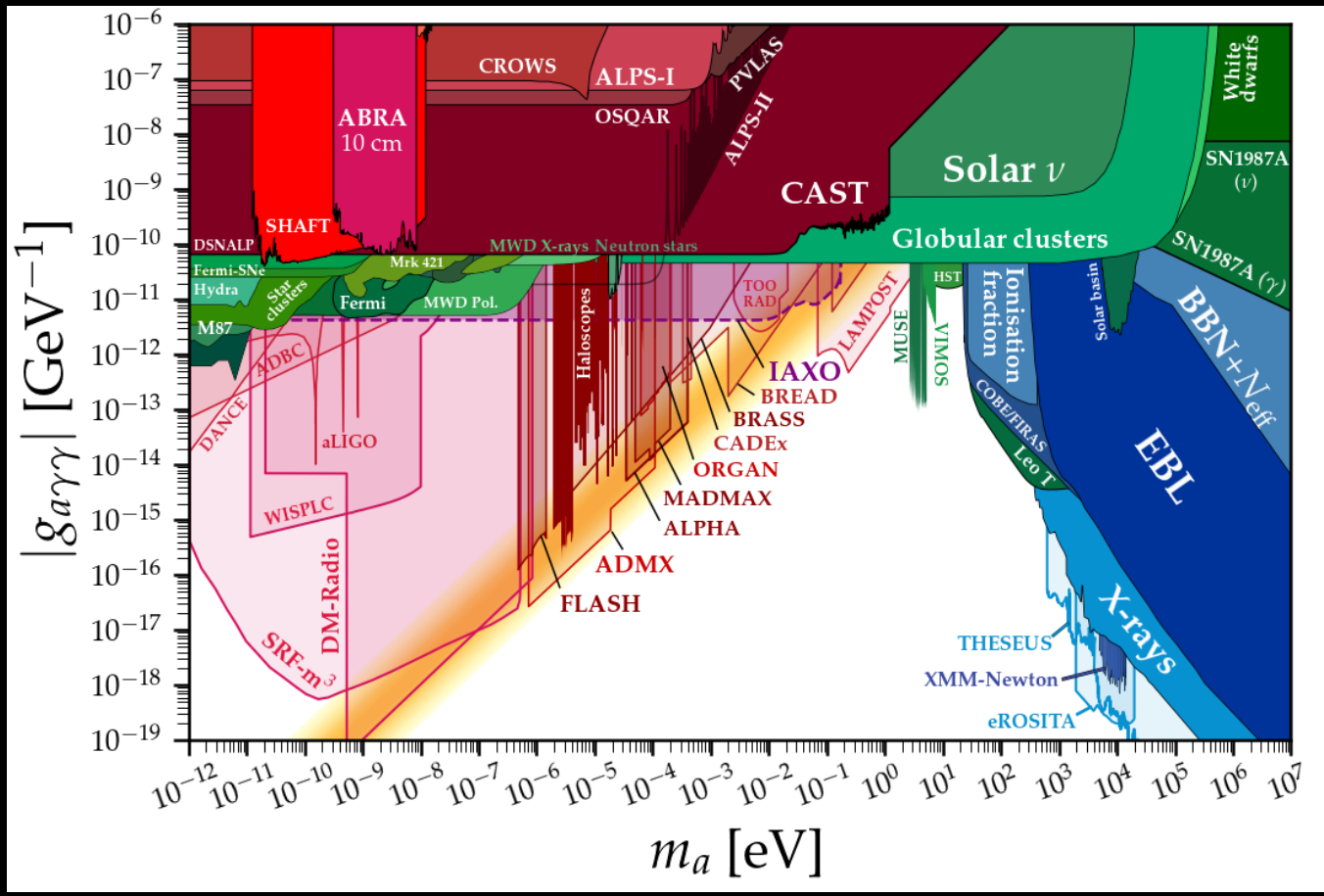
Photon
(amplified in resonator)

axion
(dark matter)



Many more experiments…

- Abracadabra
- BRASS
- Bread
- Cultask
- DMRadio
- EDM ring
- Haystac
- Lamppost
- Organ
- SRFcavities
- TooRad
- Quax
- …



Plot from super-useful website by Ciaran O'Hare
https://cajohare.github.io/AxionLimits/

DM Astrophysics

Signal: High resolution possible

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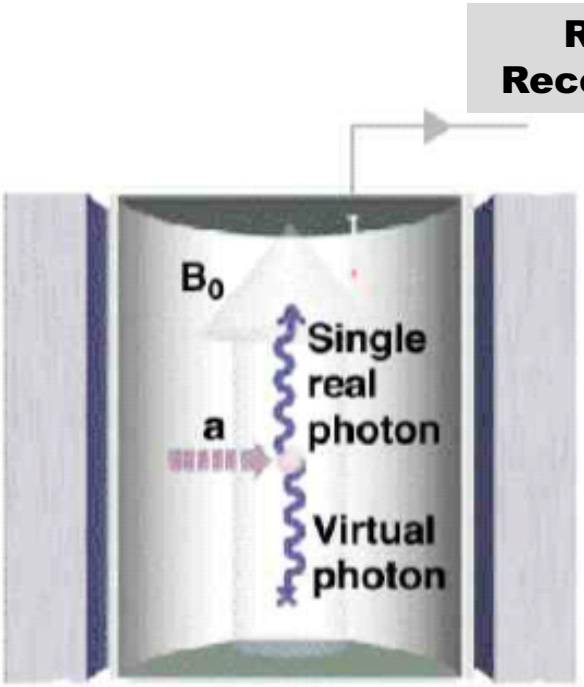

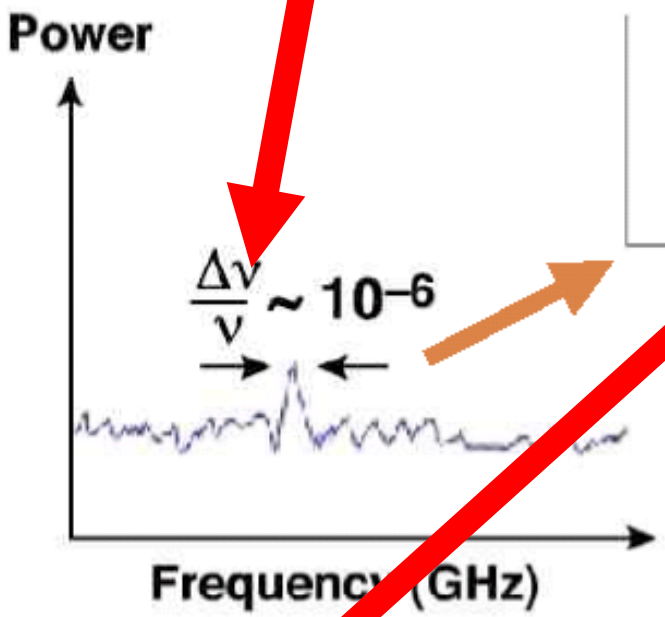

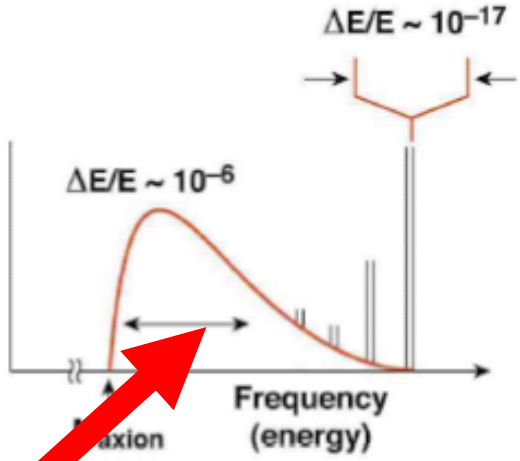

ADMX

$$h\nu = m_a c^2[1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Axion Astronomy...

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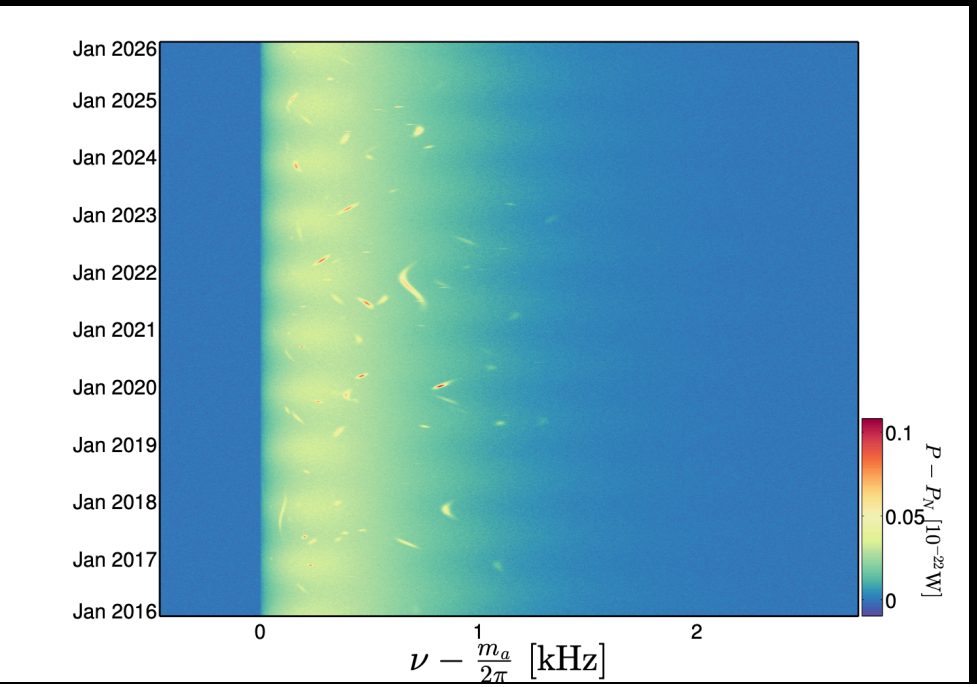
Streams and local objects...

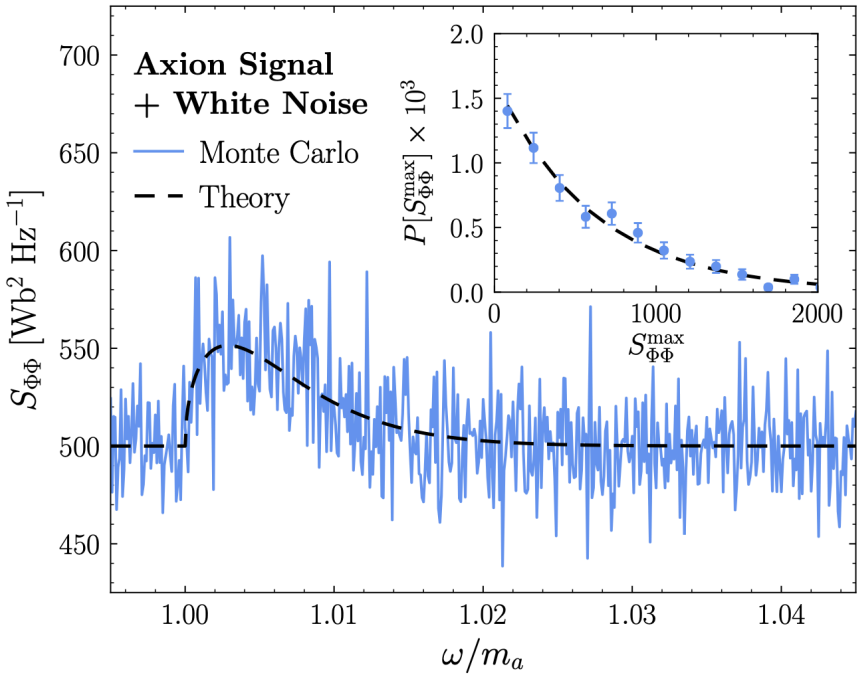


Axion astronomy with microwave cavity experiments

Ciaran A. J. O'Hare (Nottingham U.), Anne M. Green (Nottingham U.) (Jan 11, 2017)

Published in: *Phys.Rev.D* 95 (2017) 6, 063017 • e-Print: 1701.03118 [astro-ph.CO]

The Axion DM distribution...



Revealing the Dark Matter Halo with Axion Direct Detection

Joshua W. Foster (Michigan U., MCTP), Nicholas L. Rodd (MIT, Cambridge, CTP), Benjamin R. Safdi (Michigan U., MCTP) (Nov 28, 2017)

Published in: *Phys.Rev.D* 97 (2018) 12, 123006 • e-Print: 1711.10489 [astro-ph.CO]

Axion interferometry

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- Networks of multiple detectors can give directional sensitivity

Dark Matter Interferometry #2

Joshua W. Foster (Michigan U., LCTP and UC, Berkeley and LBL, Berkeley), Yonatan Kahn (Illinois U., Urbana), Rachel Nguyen (Illinois U., Urbana), Nicholas L. Rodd (UC, Berkeley and LBL, Berkeley), Benjamin R. Safdi (Michigan U., LCTP and UC, Berkeley and LBL, Berkeley) (Sep 29, 2020)

Published in: *Phys.Rev.D* 103 (2021) 7, 076018 • e-Print: 2009.14201 [hep-ph]

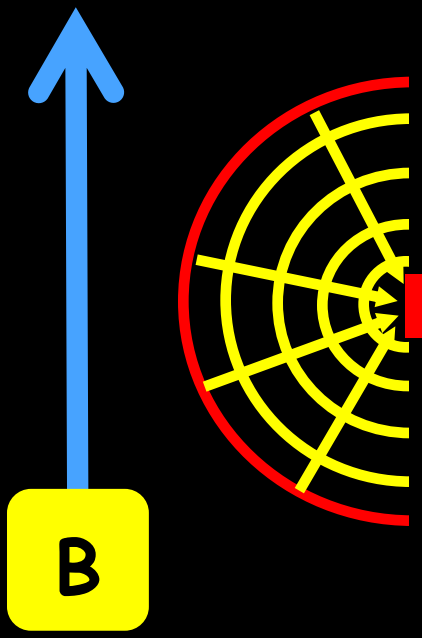
- But even suitably shaped cavities can already give some sensitivity to that

Direct detection of dark matter axions with directional sensitivity

Igor G. Irastorza (Zaragoza U.), Juan A. Garcia (Zaragoza U.) (Jul, 2012)

Published in: *JCAP* 10 (2012) 022 • e-Print: 1207.6129 [physics.ins-det]

Dark Matter Antenna

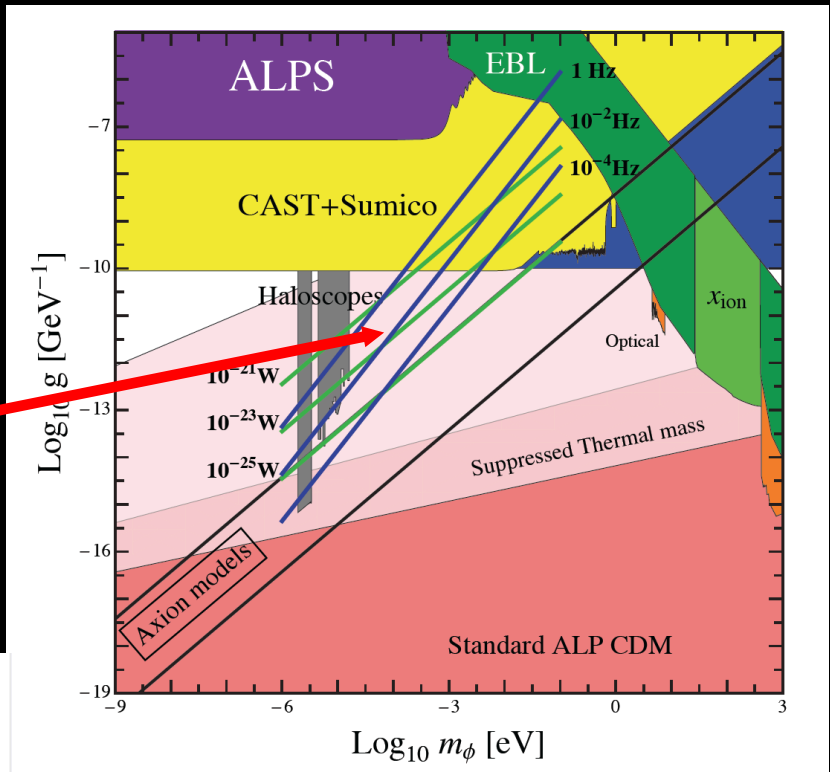


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



Searching for WISPy Cold Dark Matter with a Dish Antenna #21

Dieter Horns (Hamburg U.), Joerg Jaeckel (Durham U., IPPP and Heidelberg U.), Axel Lindner (DESY), Andrei Lobanov (Bonn, Max Planck Inst., Radioastron.), Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.) et al. (Dec, 2012)

Published in: *JCAP* 04 (2013) 016 • e-Print: 1212.2970 [hep-ph]

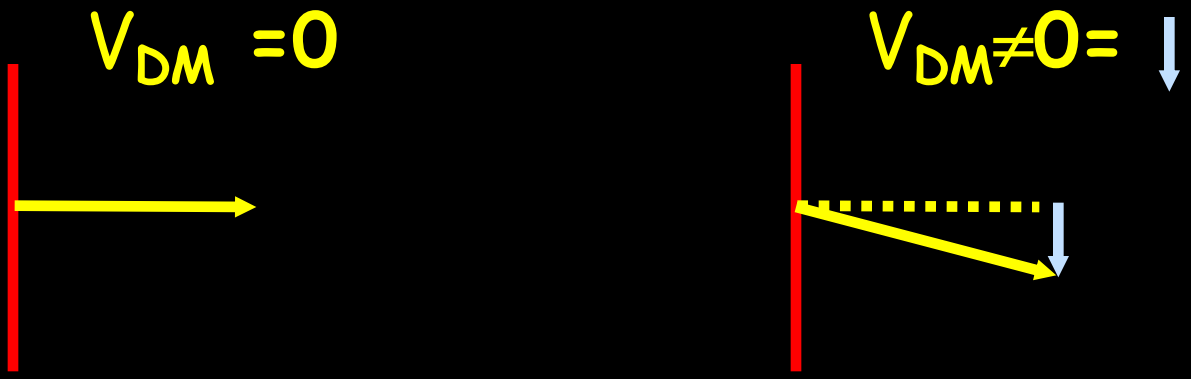
The FUNK Experiment

Recycle Auger mirror

No magnet:
Only sensitive to hidden photons

Taking a picture of the DM velocity

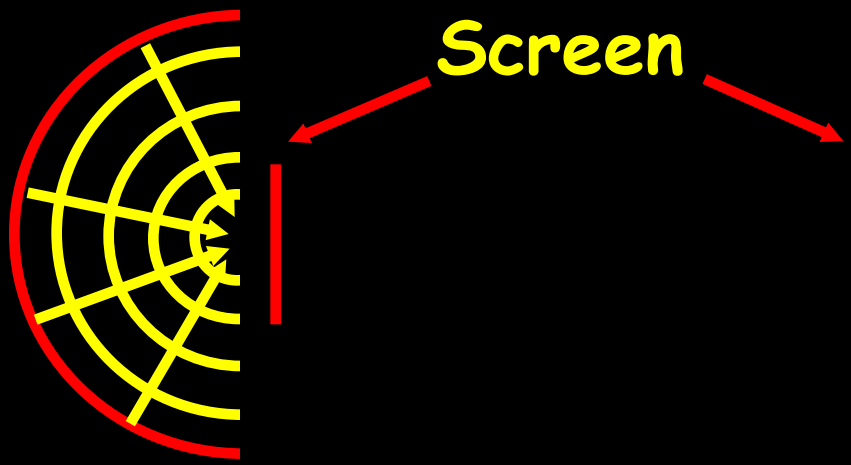
- Emission from moving dark matter

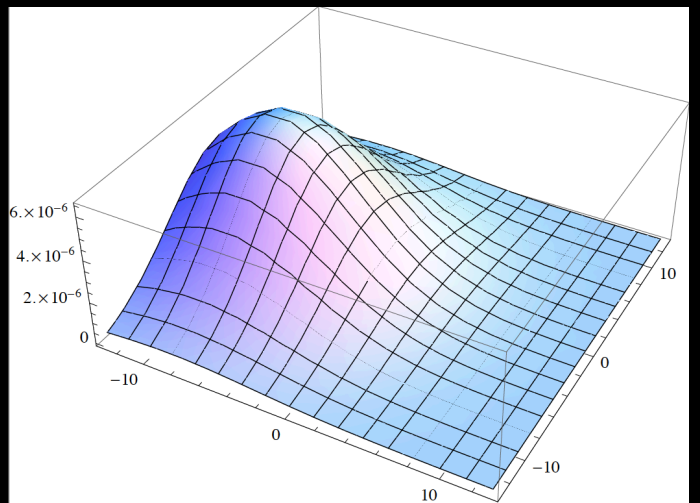


An antenna for directional detection of WISPy dark matter
Joerg Jaeckel (Heidelberg U.), Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.) (Jul 26, 2013)
Published in: *JCAP* 11 (2013) 016 • e-Print: 1307.7181 [hep-ph]

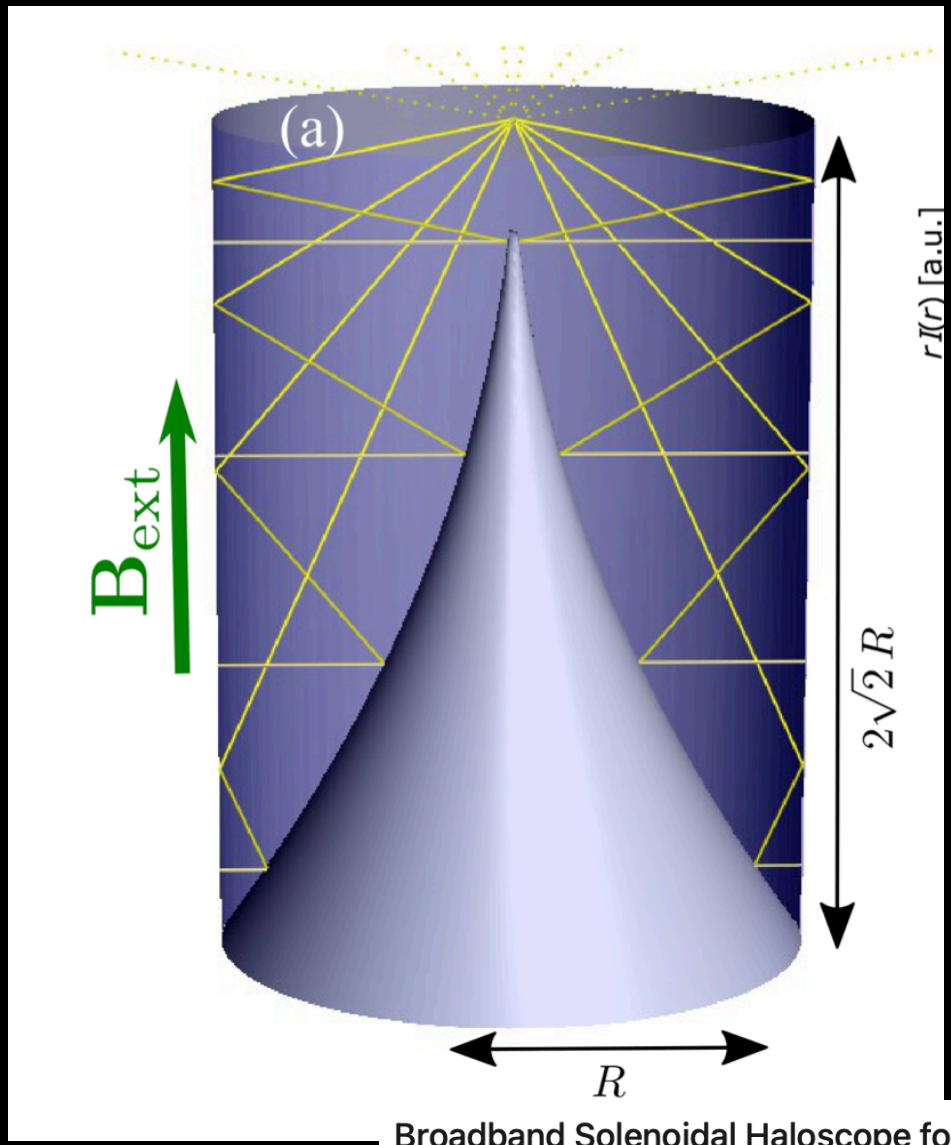
Directional Resolution of Dish Antenna Experiments to Search for WISPy Dark Matter
Joerg Jaeckel (Heidelberg U.), Stefan Knirck (Heidelberg U.) (Sep 1, 2015)
Published in: *JCAP* 01 (2016) 005 • e-Print: 1509.00371 [hep-ph]

- A picture of the DM-velocity distribution





Can also use cool geometries: BREAD



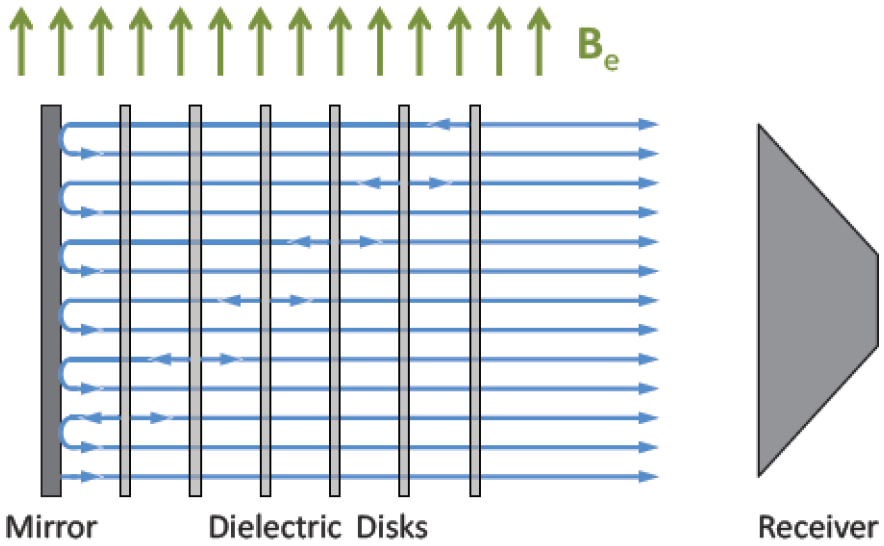
Broadband Solenoidal Haloscope for Terahertz Axion Detection

BREAD Collaboration • Jesse Liu (Cambridge U. and Chicago U.) et al. (Nov 23, 2021)

Published in: *Phys.Rev.Lett.* 128 (2022) 13, 131801 • e-Print: 2111.12103 [physics.ins-det]

Going Mad(Max)

Ambitious new project at MPP



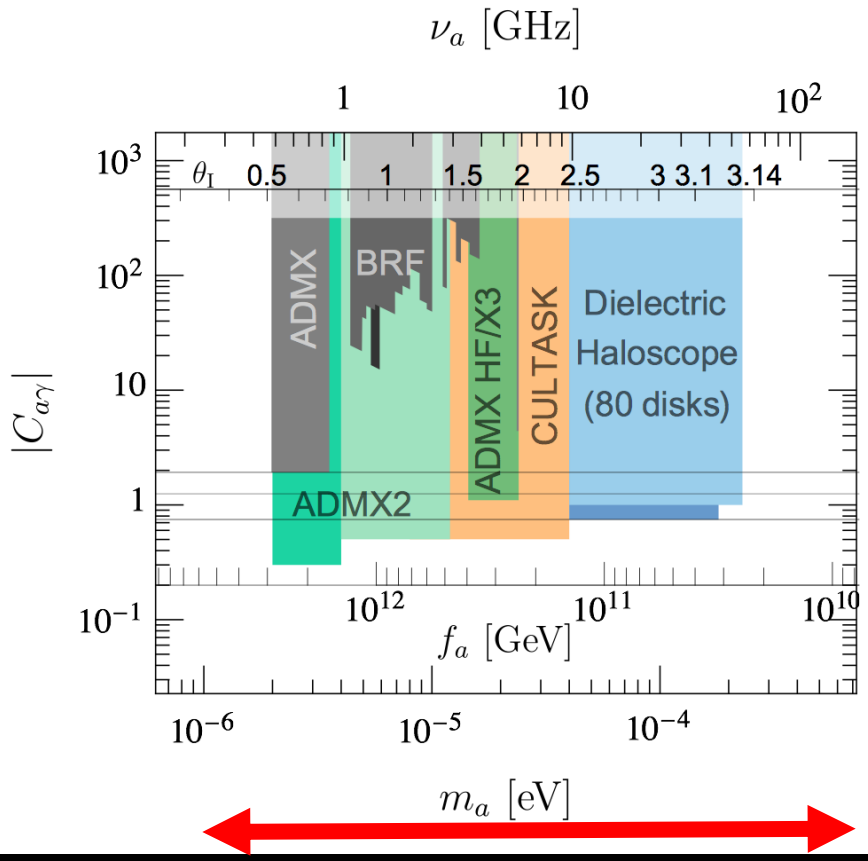
Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

The MADMAX Working Group: Allen Caldwell, Gia Dvali, Bela Majorovits, Alexander Millar, Georg Raffelt, Javier Redondo, Olaf Reimann, Frank Simon, Frank Steffen

Directional axion detection #22

Stefan Knirck (Munich, Max Planck Inst.), Alexander J. Millar (Munich, Max Planck Inst.), Ciaran A.J. O'Hare (U. Zaragoza (main)), Javier Redondo (Munich, Max Planck Inst. and Zaragoza U.), Frank D. Steffen (Munich, Max Planck Inst.) (Jun 15, 2018)

Published in: *JCAP* 11 (2018) 051 • e-Print: 1806.05927 [astro-ph.CO]



Natural DM

Also with other couplings?

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker (UC, Berkeley and LBNL, NSD), Peter W. Graham (Stanford U., ITP), Micah Ledbetter (Unlisted, US, CA), Surjeet Rajendran (Stanford U., ITP), Alex Sushkov (Harvard U., Phys. Dept.) (Jun 25, 2013)

Published in: *Phys.Rev.X* 4 (2014) 2, 021030 • e-Print: 1306.6089 [hep-ph]

New Observables for Direct Detection of Axion Dark Matter

Peter W. Graham (Stanford U., ITP), Surjeet Rajendran (Stanford U., ITP) (Jun 25, 2013)

Published in: *Phys.Rev.D* 88 (2013) 035023 • e-Print: 1306.6088 [hep-ph]

Looking for oscillating dipoles

- **Remember:**

  Axion field controls electric dipole moment:

$$d_e \sim \theta \sim \frac{a}{f_a}$$

- **Dipole moments follow the oscillating axion field**

  ➔ Tiny oscillating electric dipole

$$d_e \sim 10^{-35} e\,\mathrm{cm}\cos(m_a t)$$

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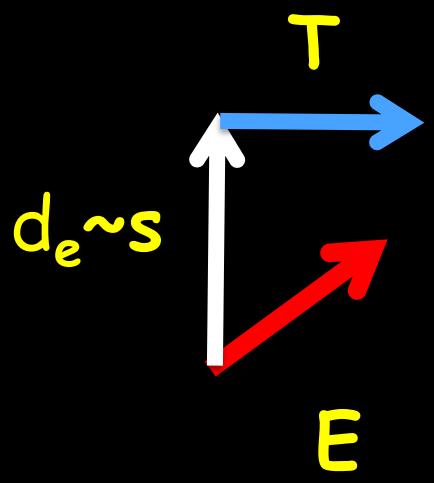
Published in **Phys.Rev. D88 (2013) 035023**

DOI: 10.1103/PhysRevD.88.035023

e-Print: arXiv:1306.6088 **[hep-ph]** | PDF

In an electric field



Energy in an electric field

$$H = -\mathbf{d} \cdot \mathbf{E} = -c_E \mathbf{s} \cdot \mathbf{E}.$$

Torque tries to tilt dipole moment/spin

$$\mathbf{T} = \mathbf{d} \times \mathbf{E} = c_E \mathbf{s} \times \mathbf{E}.$$

Dealing with oscillation

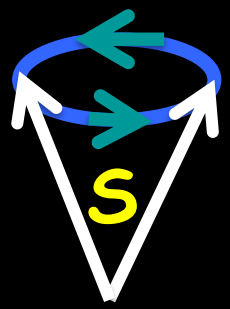
Problem: the dipole moment is rapidly oscillating ~m_a

➔ Danger of cancellation

Solution: Rotate spin to compensate

➔ Use Spin Precession in magnetic field

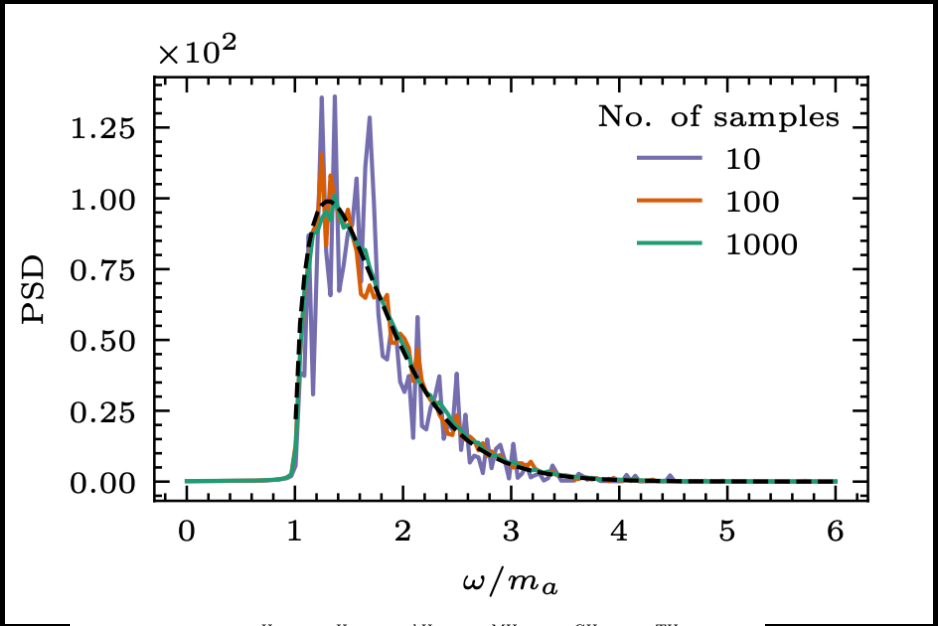
$$\omega_L = 2\mu B$$

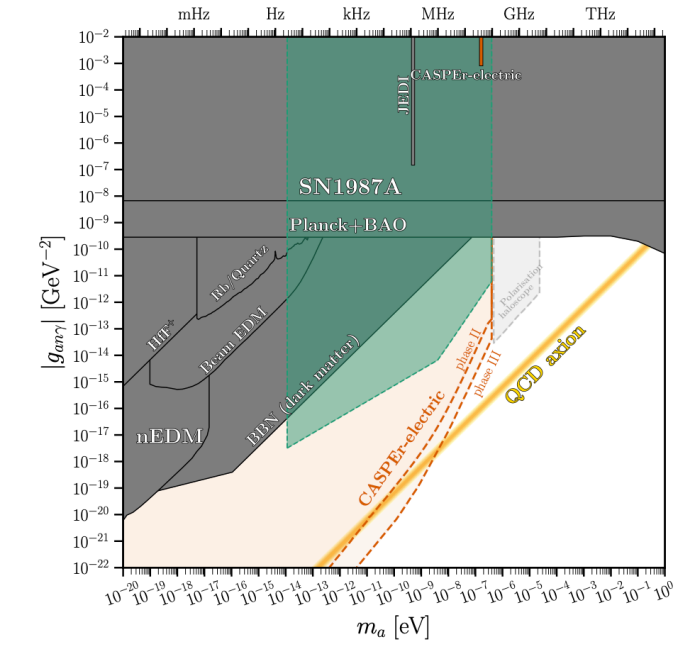


Resonance when $\omega_L = m_a$

Measure velocity^2 distribution?

- Yes





JJ, C. Quint (in preparation)

Establishing Axions as "The Dark Matter"

A signal does not yet establish DM

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- Once we have a signal...

$$P_{\text{signal}} \sim g^2 \rho$$

- g and ρ not independently measured

- We could have detected a sub-dominant DM

$$\rho \ll \rho_{DM}$$

➔ Can we disentangle?

Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density
Virgile Dandoy (KIT, Karlsruhe, IAP), Joerg Jaeckel, Valentina Montoya (Jul 21, 2023)
e-Print: 2307.11871 [hep-ph]

Part I
If we are lucky...

Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density

Virgile Dandoy (KIT, Karlsruhe, IAP), Joerg Jaeckel, Valentina Montoya (Jul 21, 2023)

e-Print: 2307.11871 [hep-ph]

Let's find an Axion Mini-cluster

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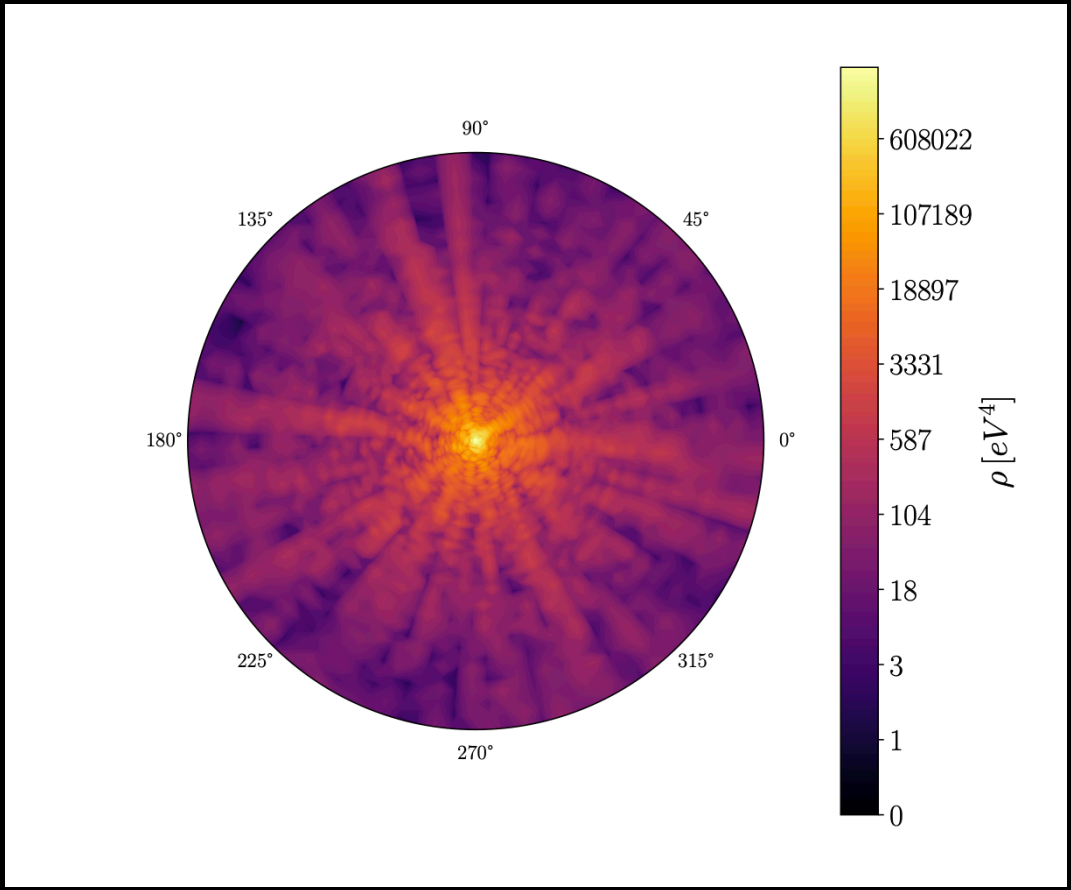

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...and fly through it

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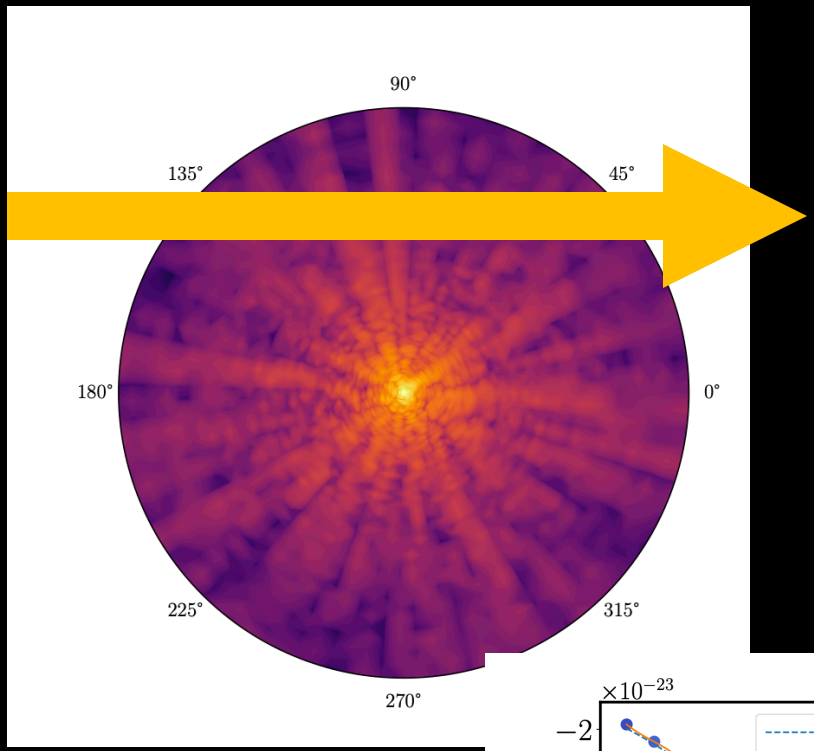
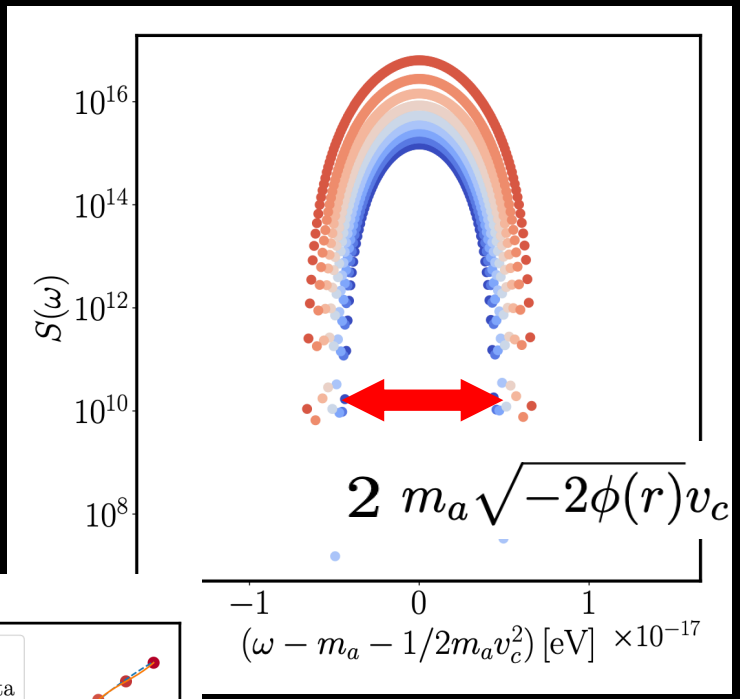
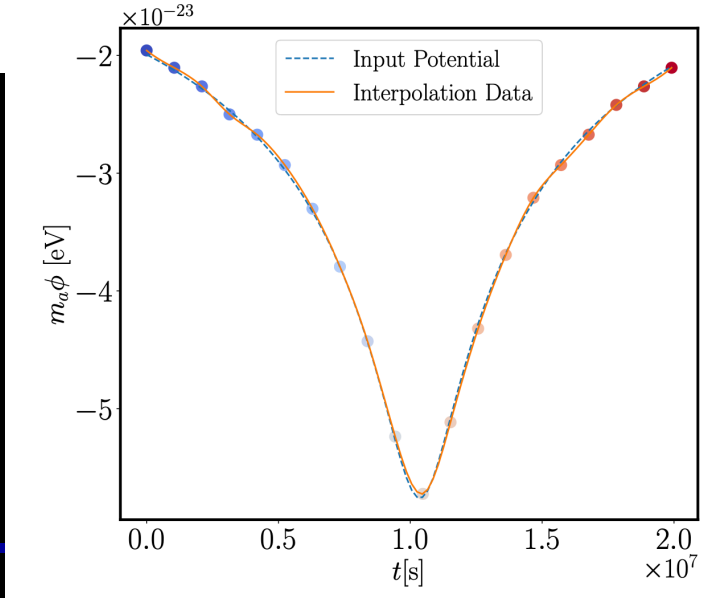


Power spectrum along the path





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e-Print: 2307.11871 [hep-ph]

Reconstruct minicluster density...

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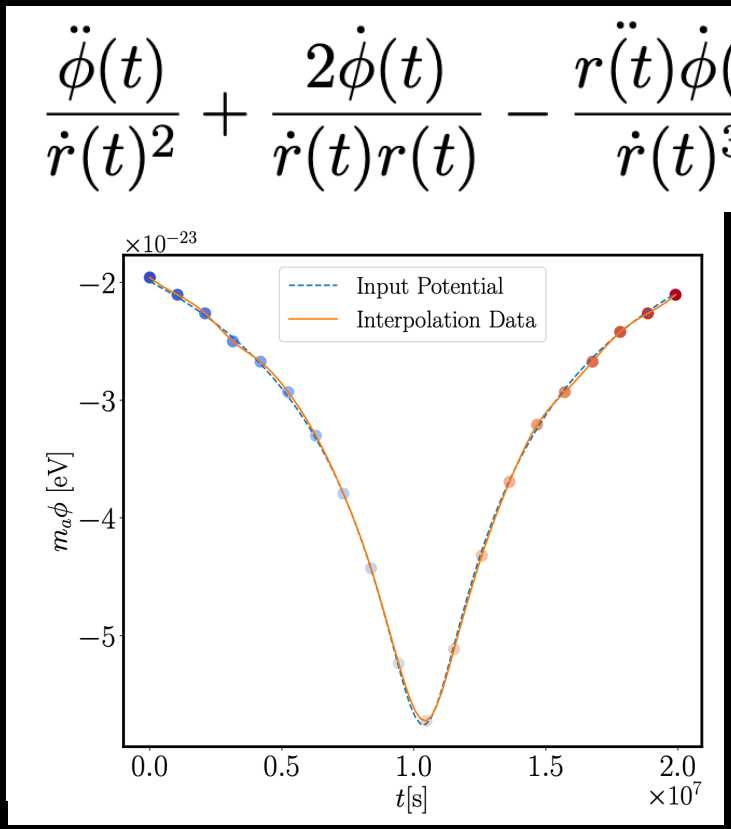
- Poisson equation (along path)

$$\frac{\ddot{\phi}(t)}{\dot{r}(t)^2} + \frac{2\dot{\phi}(t)}{\dot{r}(t)r(t)} - \frac{\ddot{r}(t)\dot{\phi}(t)}{\dot{r}(t)^3} = 4\pi G\rho(t)$$

+

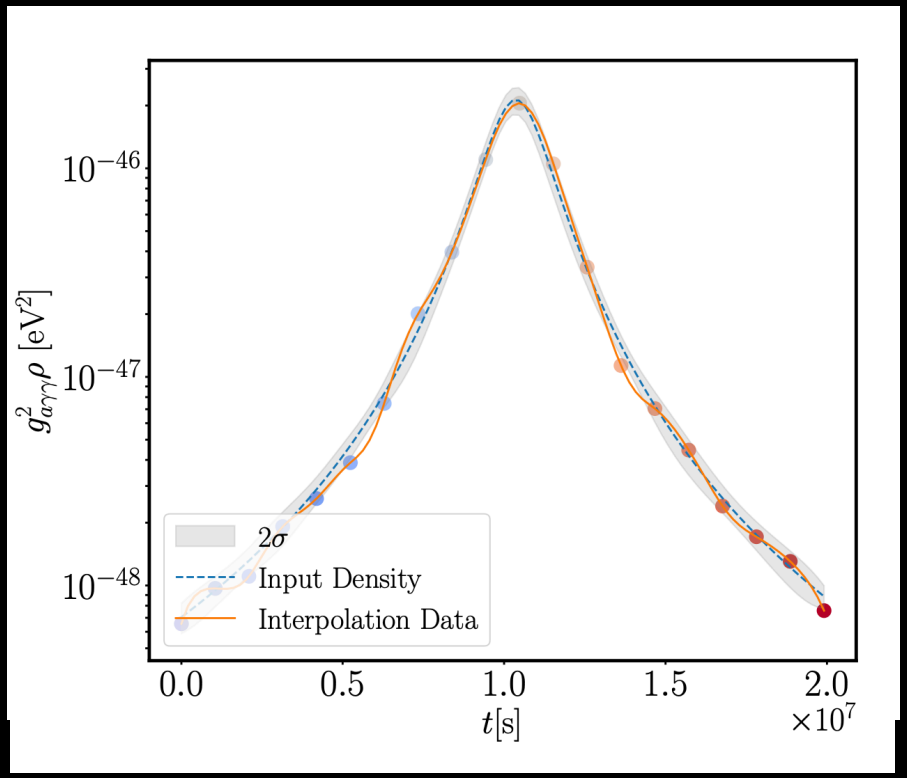


Determined

Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density
Virgile Dandoy (KIT, Karlsruhe, IAP), Joerg Jaeckel, Valentina Montoya (Jul 21, 2023)
e-Print: 2307.11871 [hep-ph]

Measure coupling...

- Power along the path



$$P_{\text{signal}} \sim g^2 \rho$$

Already known

➔ Obtain g

Measure coupling...

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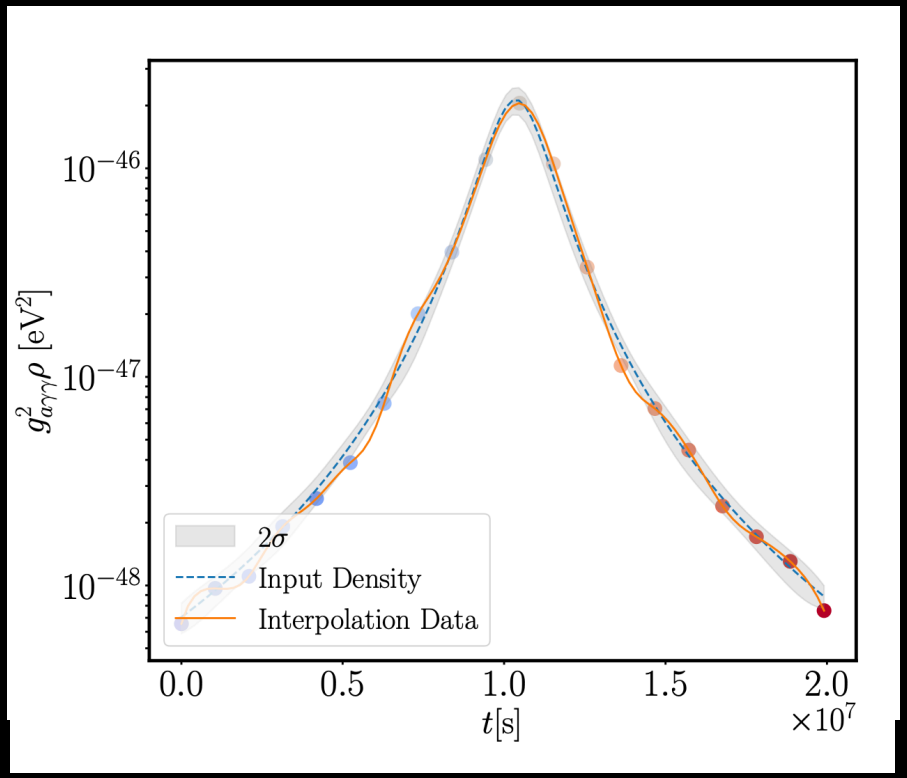
- Power along the path



$$P_{\text{signal}} \sim g^2 \rho$$

Already known

➔ Obtain g

+ Measure $P_{\text{signal}} \sim g^2 \rho_{\text{outside}}$ outside minicluster

➔ $\rho_{\text{outside}} \sim \rho^{\text{expected}}_{\text{local}}$?

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Measure coupling...

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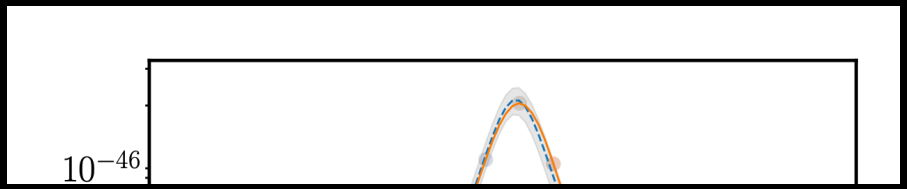
- Power along the path



$$P_{\text{signal}} \sim g^2 \rho$$

BUT:

Need to be lucky ~10^{-3}/year (and cluster not too destroyed)

+

➔ $\rho_{\text{outside}} \sim \rho_{\text{local}}^{\text{expected}}$?

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Part II
If we are dedicated...

HyperLSW: Ultimate light-shining-through-a-wall experiments to establish QCD axions as the dominant form of dark matter

Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Giuseppe Lucente (U. Heidelberg, ITP and Kirchhoff Inst. Phys.) (Jul 5, 2024)

e-Print: 2407.04772 [hep-ph]

We build HyperLSW ☺

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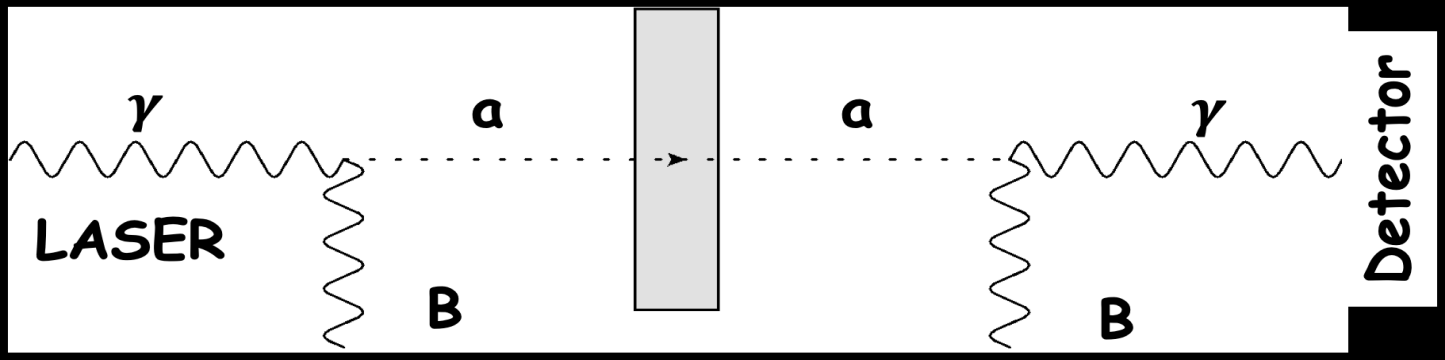
- What is an LSW experiment?

Light shining through walls



- Probability to see the light

$$p^2_{\gamma\leftrightarrow a} = \frac{\omega^2}{\omega^2 - m_a^2}\left(\frac{g_{a\gamma}BL}{2}\right)^4 |F|^4,$$

Purely laboratory based ➔ determine g

Not so easy... ALPS II

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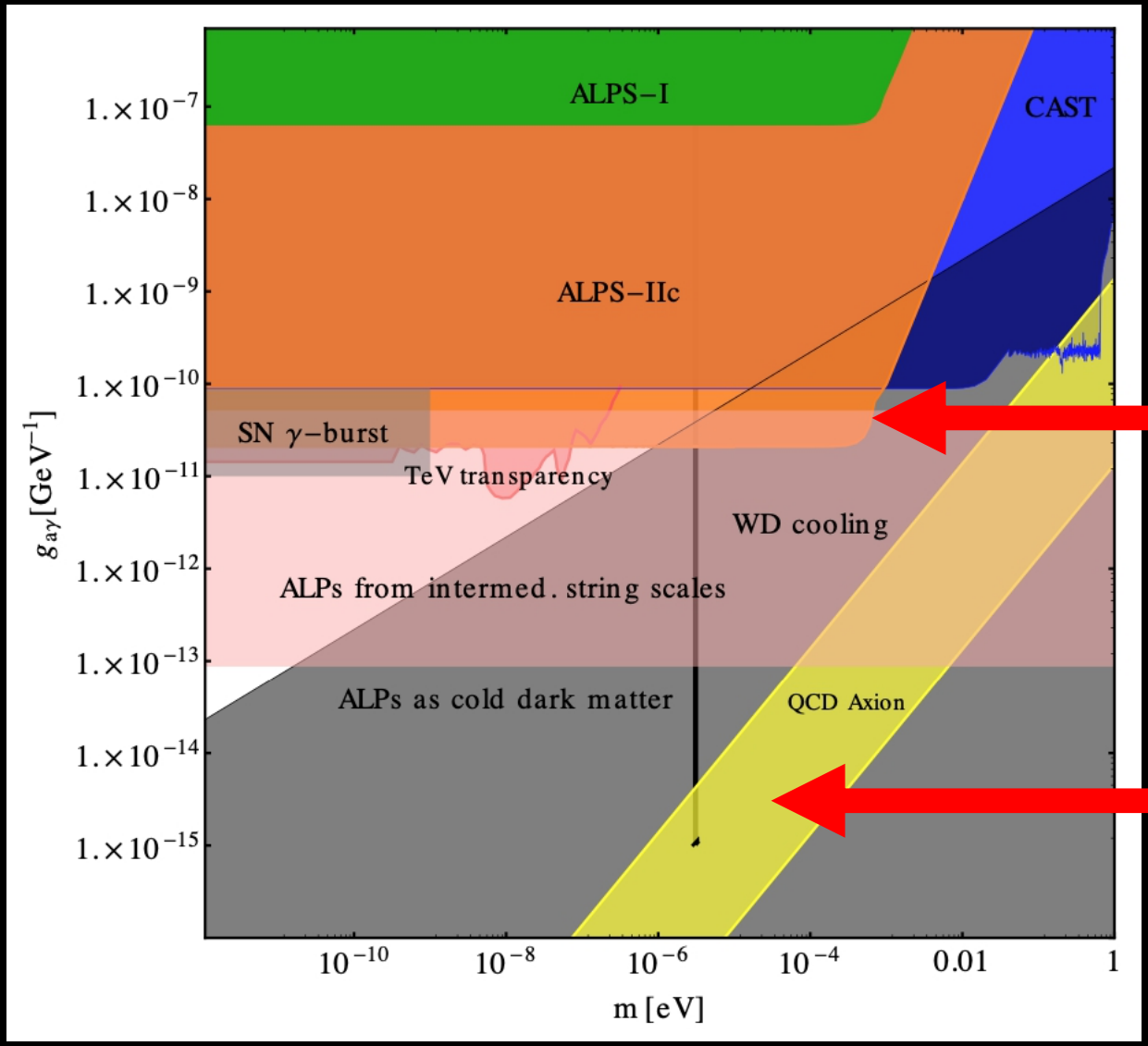
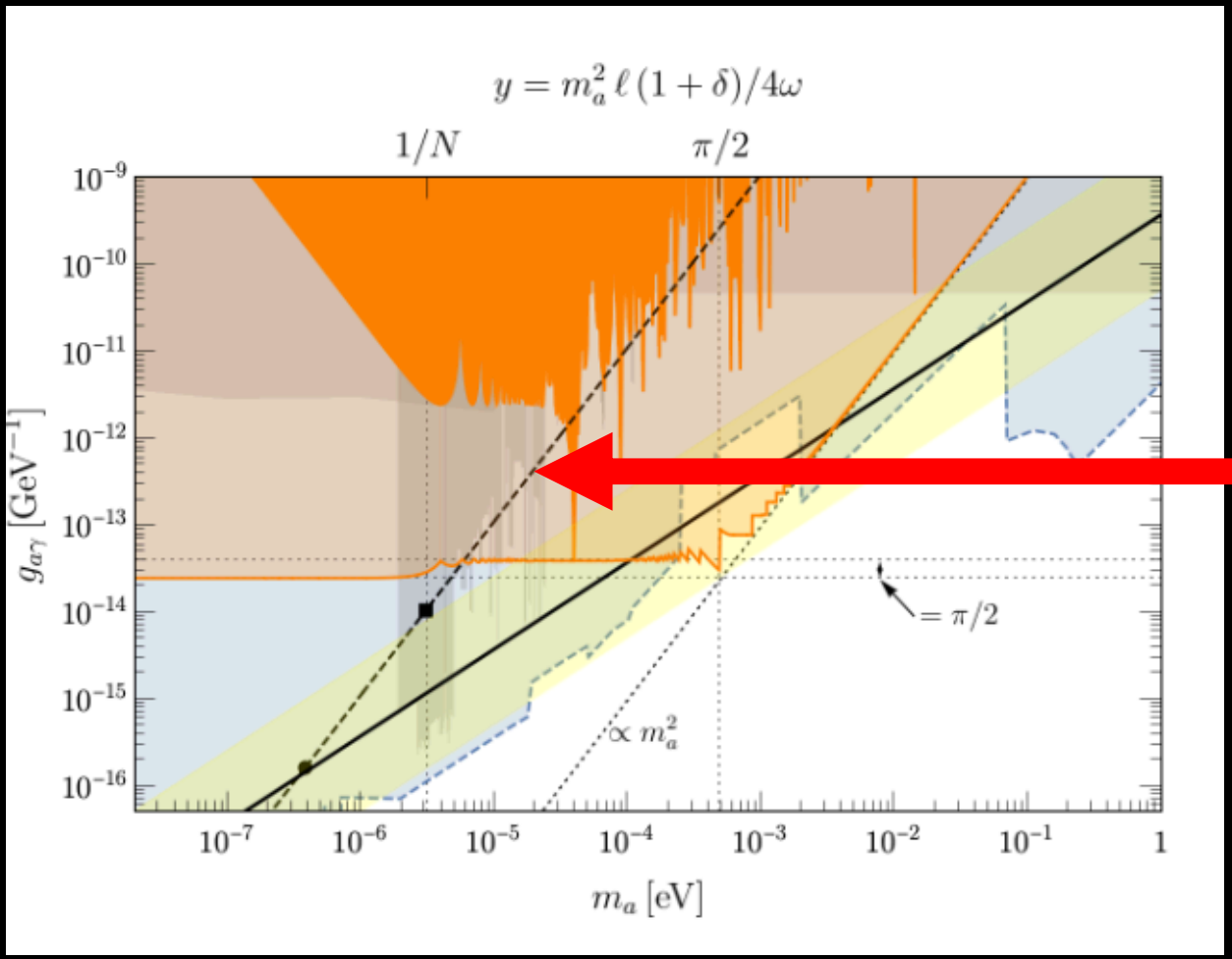


Does not quite reach axion masses

A few orders in sensitivity to go

ALPS II homepage: https://alps.desy.de/our_activities/axion_wisp_experiments/alps_ii



Making magnets longer is not sufficient

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Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Giuseppe Lucente (U. Heidelberg, ITP and Kirchhoff Inst. Phys.) (Jul 5, 2024)

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Optimize magnet configuration

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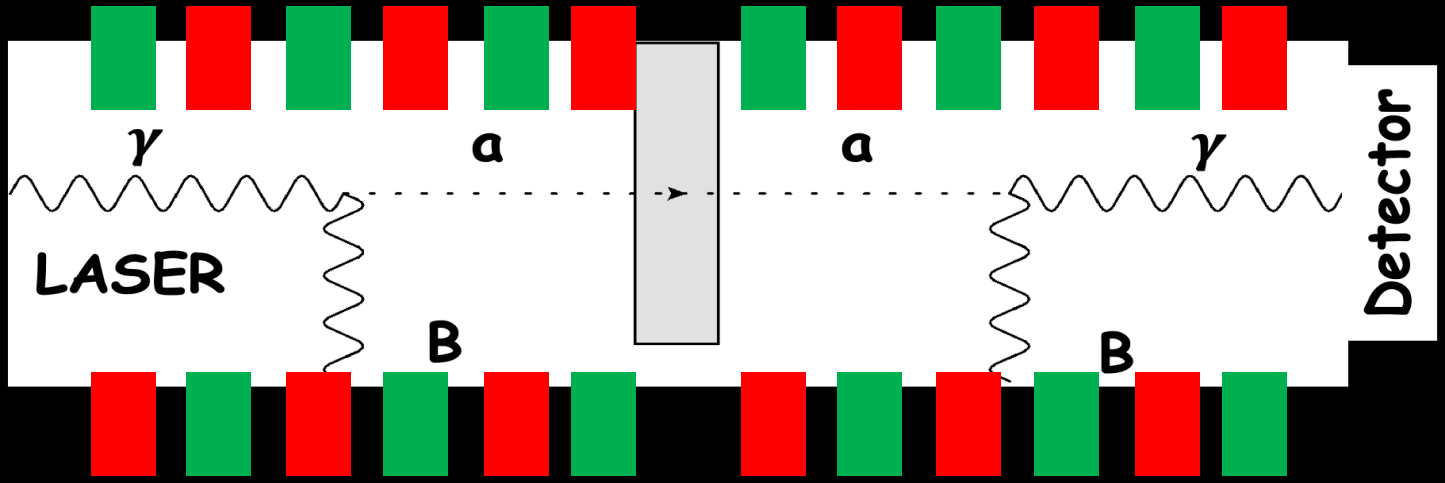
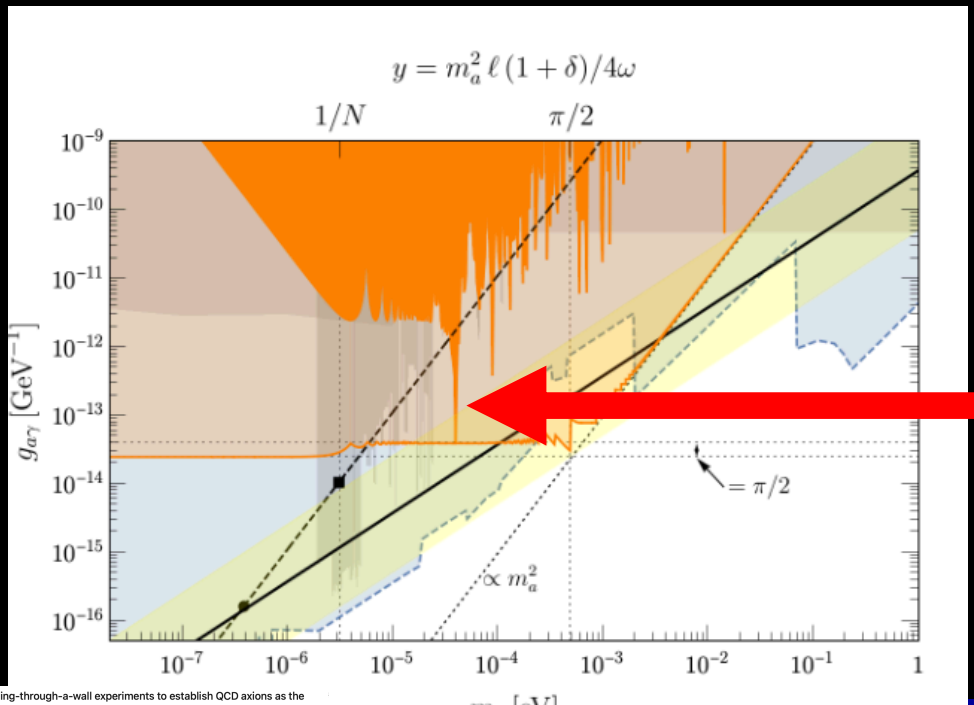


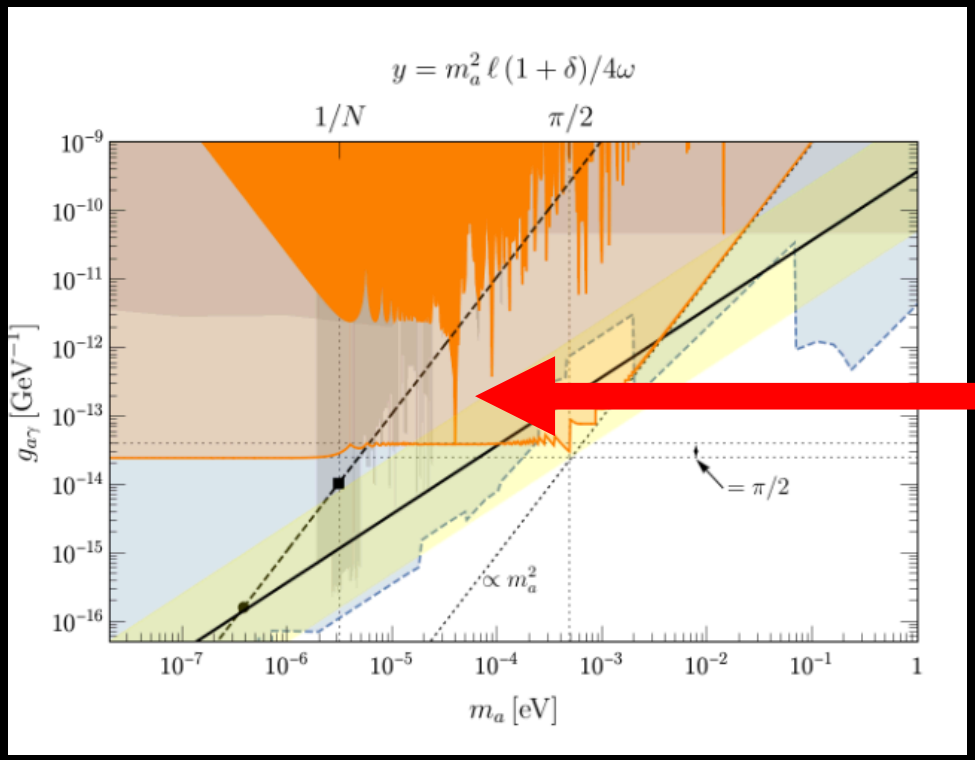


Alternating magnets

HyperLSW: Ultimate light-shining-through-a-wall experiments to establish QCD axions as the dominant form of dark matter
Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Giuseppe Lucente (U. Heidelberg, ITP and Kirchhoff Inst. Phys.) (Jul 5, 2024)

Proposed experiment to produce and detect light pseudoscalars
K. Van Bibber (LLNL, Livermore), N.R. Dagdeviren (Caltech), S.E. Koonin (Caltech), A. Kerman (MIT, LNS), H.N. Nelson (Stanford U., Phys. Dept. and SLAC) (May, 1987)
Published in: *Phys.Rev.Lett.* 59 (1987) 759-762

Optimizing Light-Shining-through-a-Wall Experiments for Axion and other WISP Searches
Paola Arias (DESY), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (Munich, Max Planck Inst.), Andreas Ringwald (DESY) (Sep, 2010)
Published in: *Phys.Rev.D* 82 (2010) 115018 • e-Print: 1009.4875 [hep-ph]



Very narrow?

➔Not a problem. DM discovery tells us mass with better than 10^{-10} accuracy

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Discovery region

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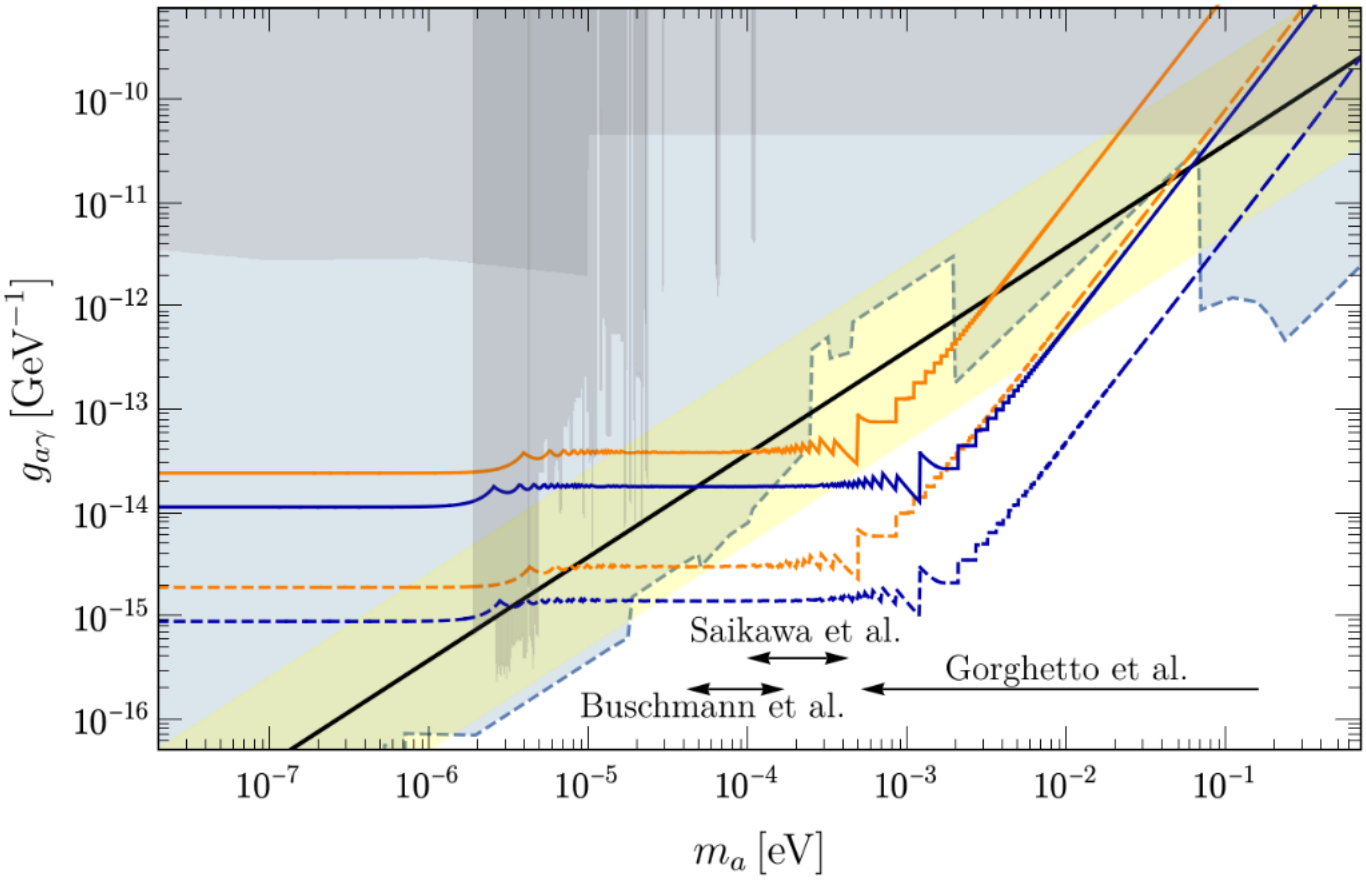

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Price tag...

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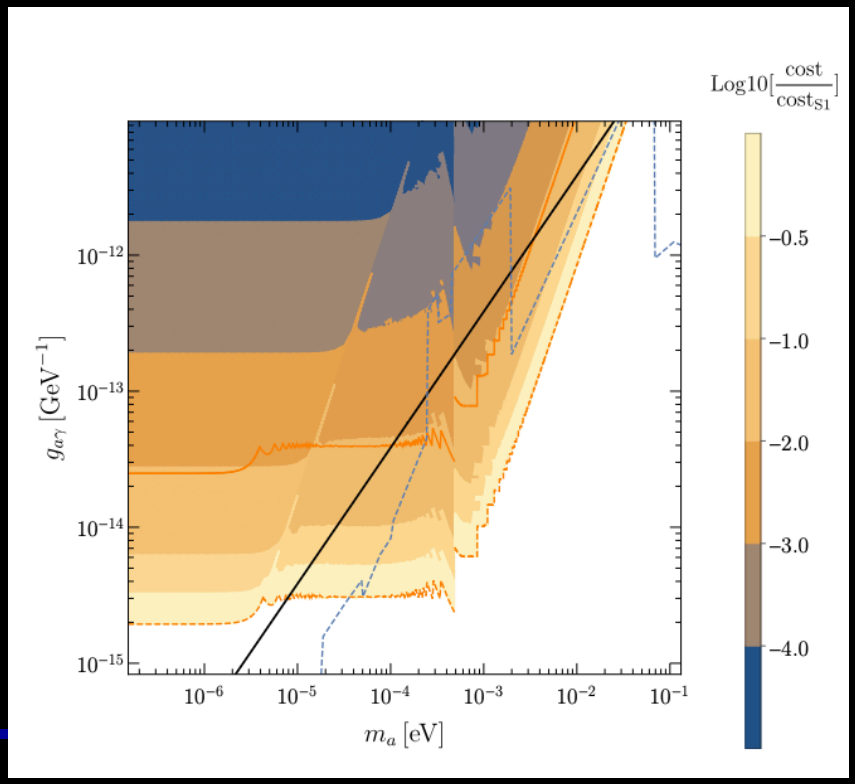
Setup	B [T]	a [m]	ℓ [m]	$\Delta_{\min}$ [m]	P_λ [W]	β_g	β_r	λ [nm]	ε_{eff}	τ [h]	b [s^{-1}]	$2\,z_{\text{opt}}$ [km]	$\mathcal{S}_{\text{crit}}$
S1	10	1.3	4.0	2.0	3	10^5	10^5	1064	0.95	100	10^{-4}	2×94	186.42
S2	12	2.0	0.5	0.5	3	10^5	10^5	1064	0.95	100	10^{-4}	2×220	186.42
O1	10	1.3	4.0	2.0	300	10^5	10^6	1064	0.95	5000	10^{-6}	2×79	172.55
O2	12	2.0	0.5	0.5	300	10^5	10^6	1064	0.95	5000	10^{-6}	2×188	172.55

Long tunnel
+
many strong magnets
~
few x 100 GEuro

➔Pick cheapest option



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Conclusions

Conclusions

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- Axion coolest Dark Matter ☺

- Current and near future experiments probe best motivated parameter space

- Axion DM can give us much more information:
  - DM density ➔ Is it THE Dark Matter
  - DM velocity