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Heidelberg University

From Axion Dark Matter to Dark Astronomy + Dark Cosmology

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[*], W. Yin[T], The FUNK Collaboration

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

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The Axion

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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Axion(-like particle) Dark Matter

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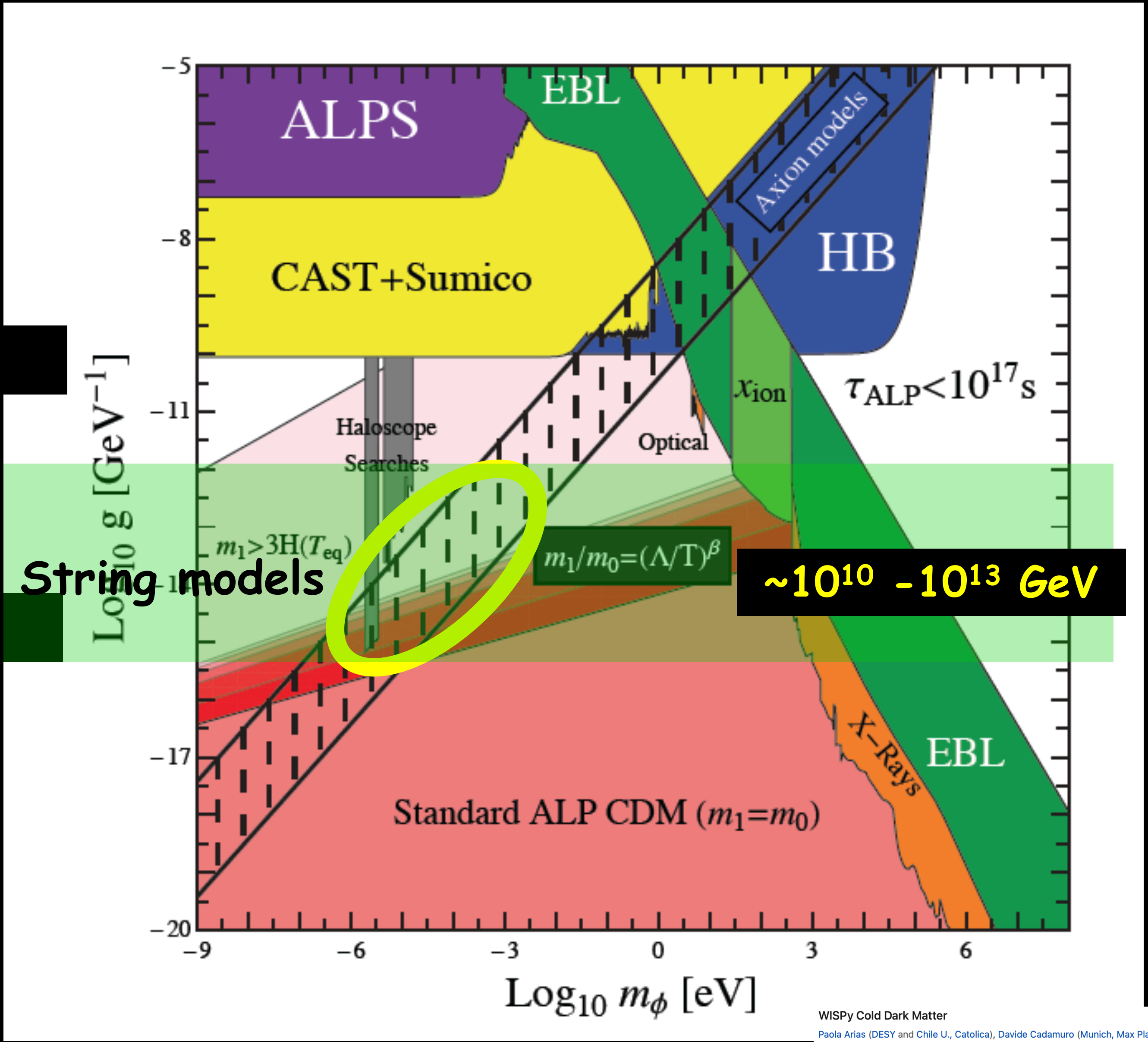
~10^7 GeV

~10^{12} GeV



~10^{10} -10^{13} GeV

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]

Detecting Axion DM

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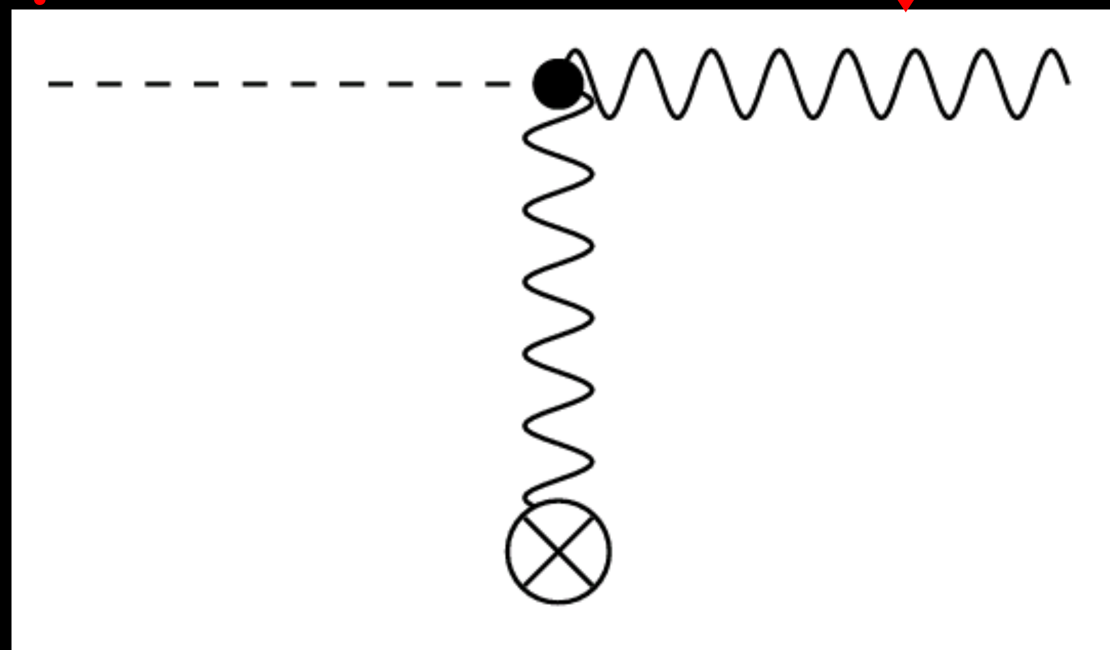
Use a plentiful source of axions

- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Signal: Total energy of axion

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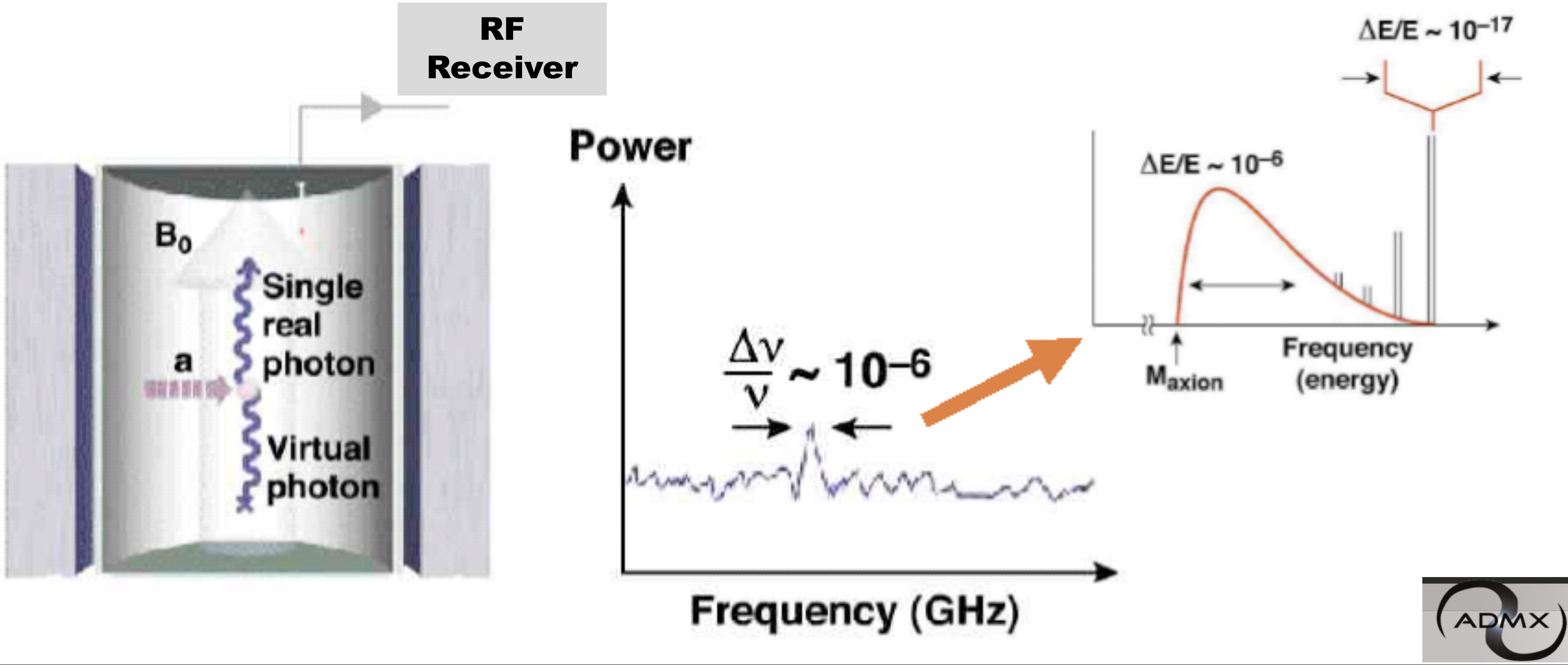
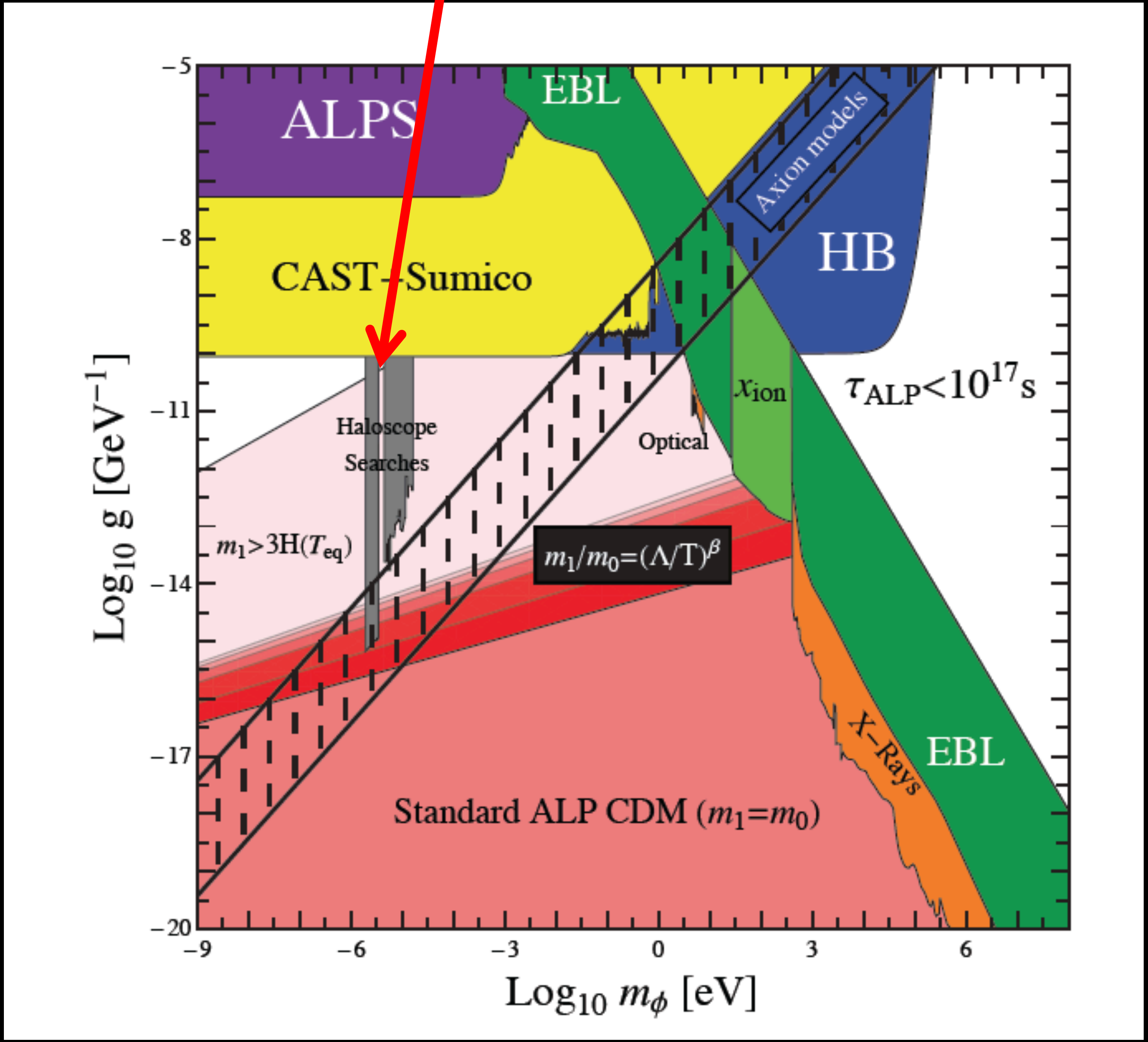


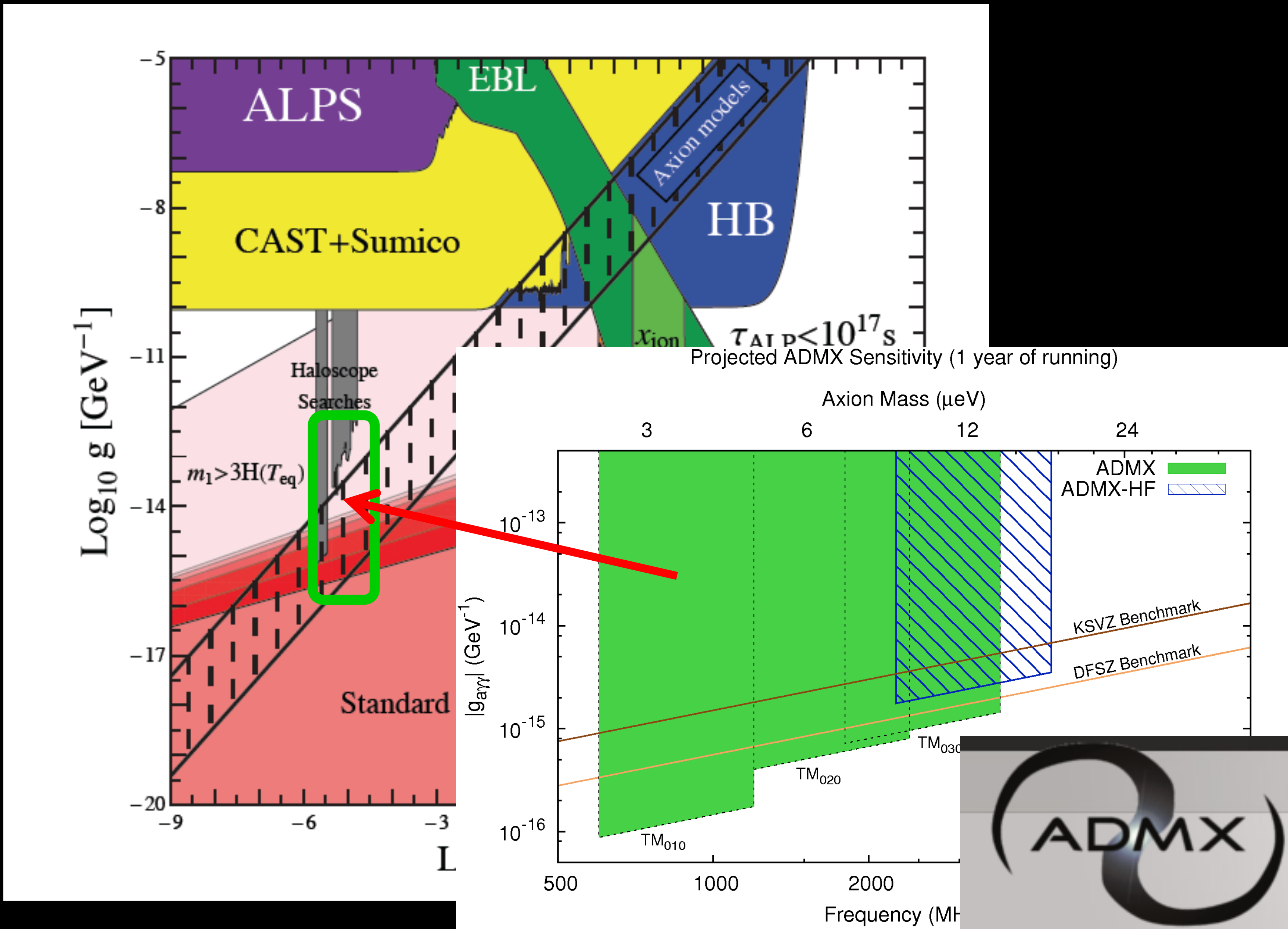
$$h\nu = m_a c^2[1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity
in galaxy halo!

An extremely sensitive probe!!!



A discovery possible any minute!



Electricity from Dark Matter ;-).

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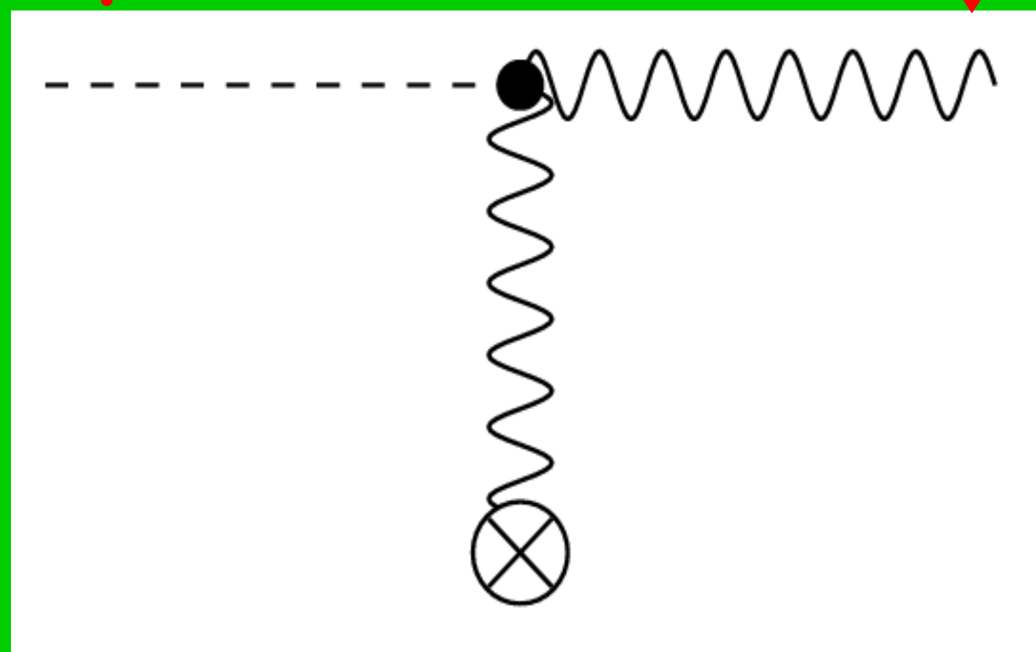
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Really sustainable Energy

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- 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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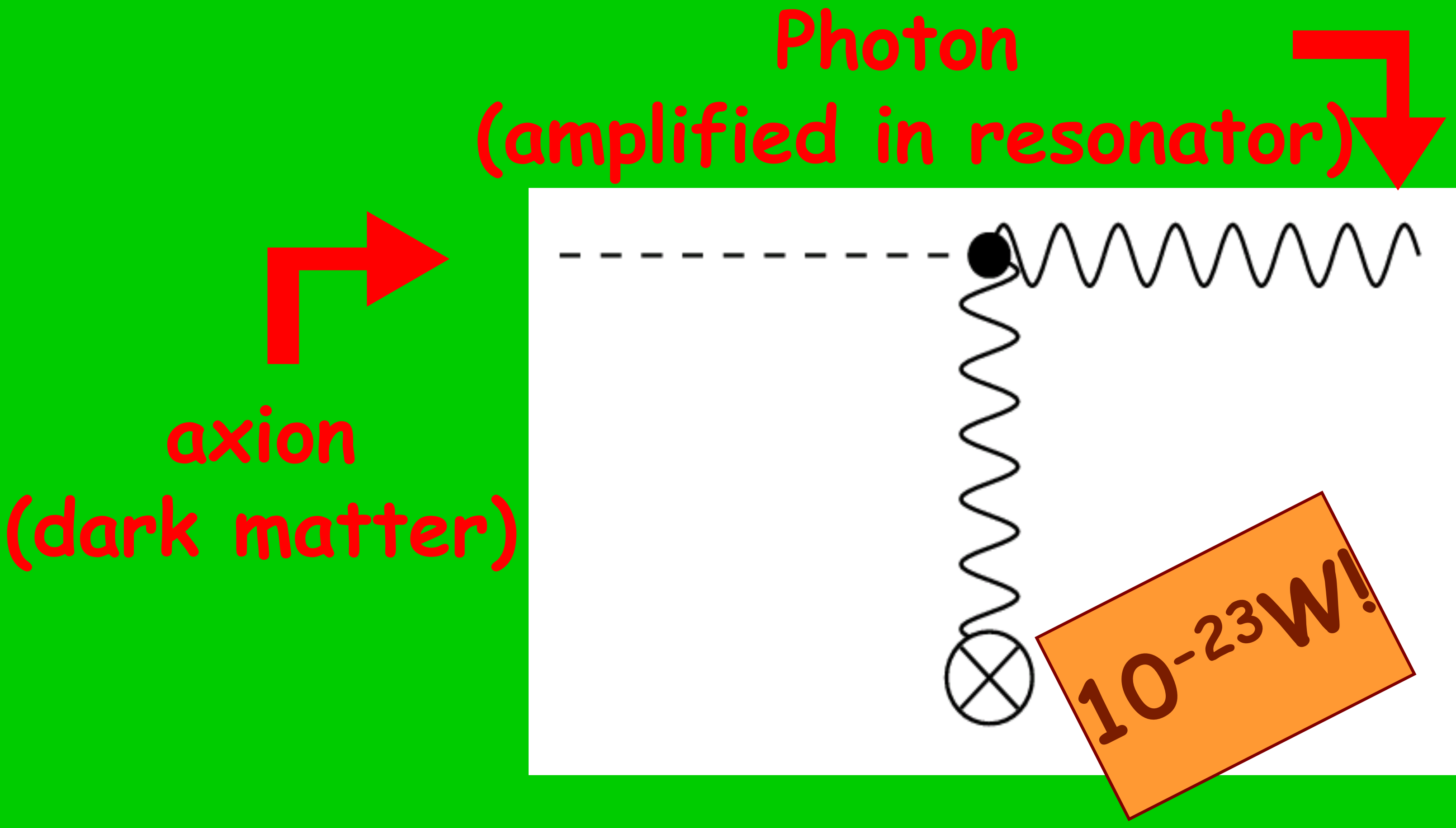
- Photon Regeneration



Many more experiments...

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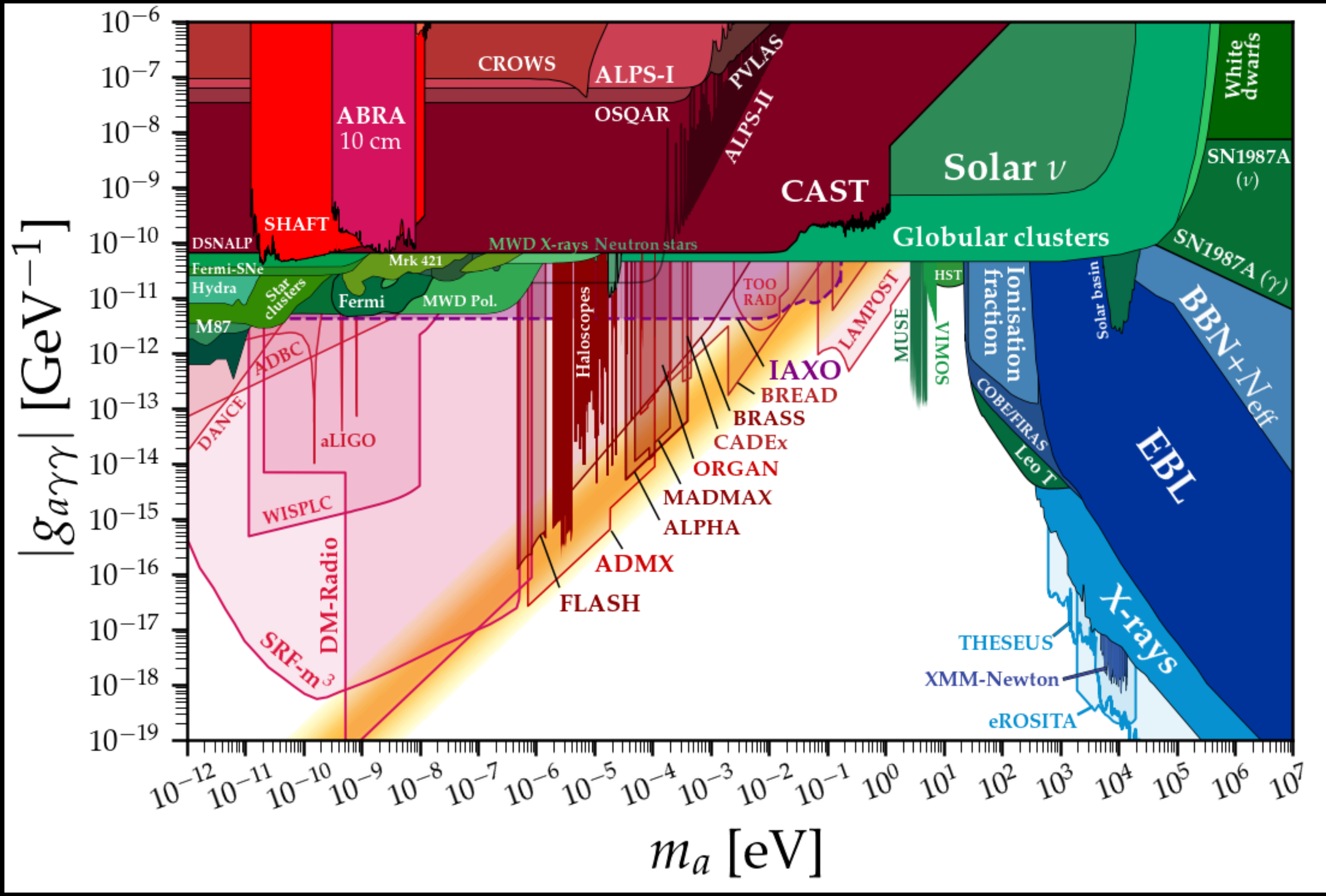
- Abracadabra
- BRASS
- Bread
- Cultask
- DMRadio
- EDM ring
- Haystac
- Lamppost
- Organ
- SRFcavities
- TooRad
- Quax
- ...



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

DM Astrophysics

Signal: High resolution possible

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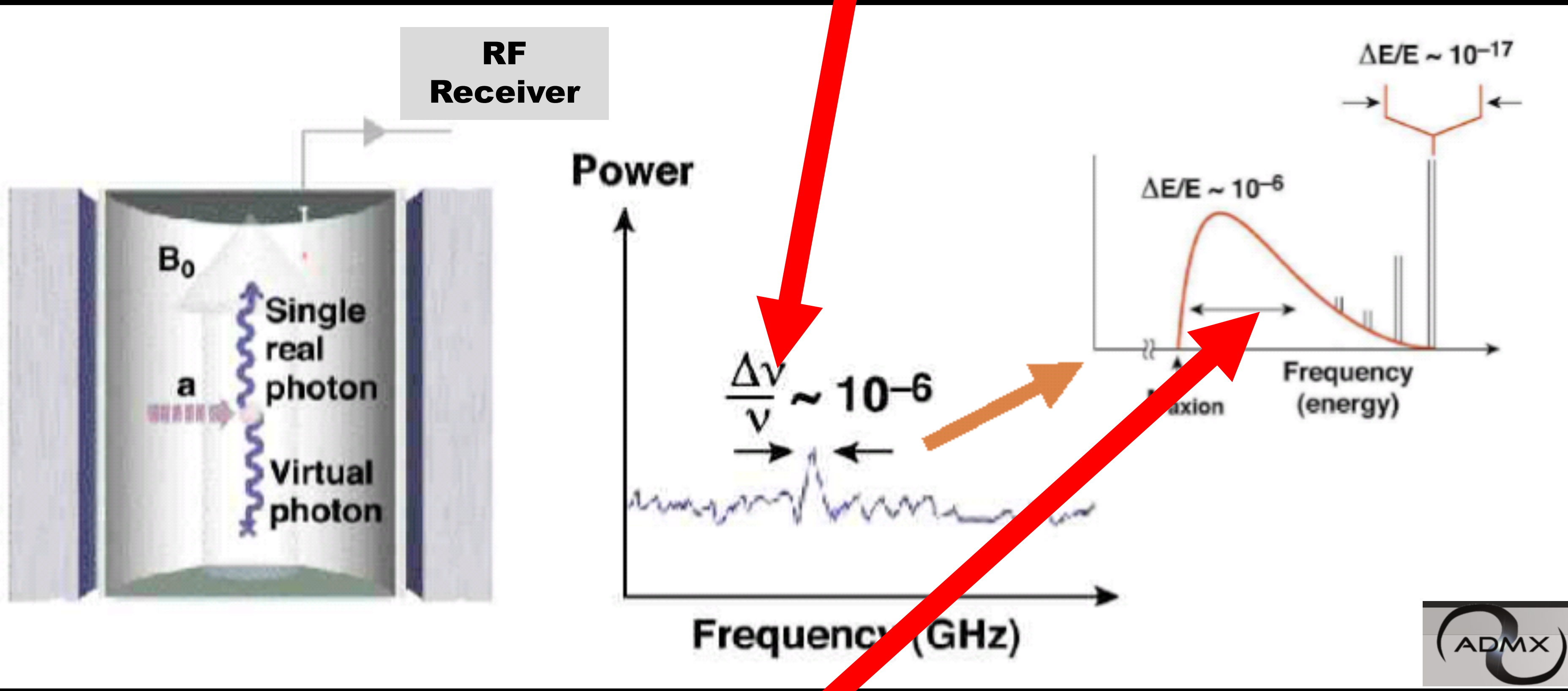
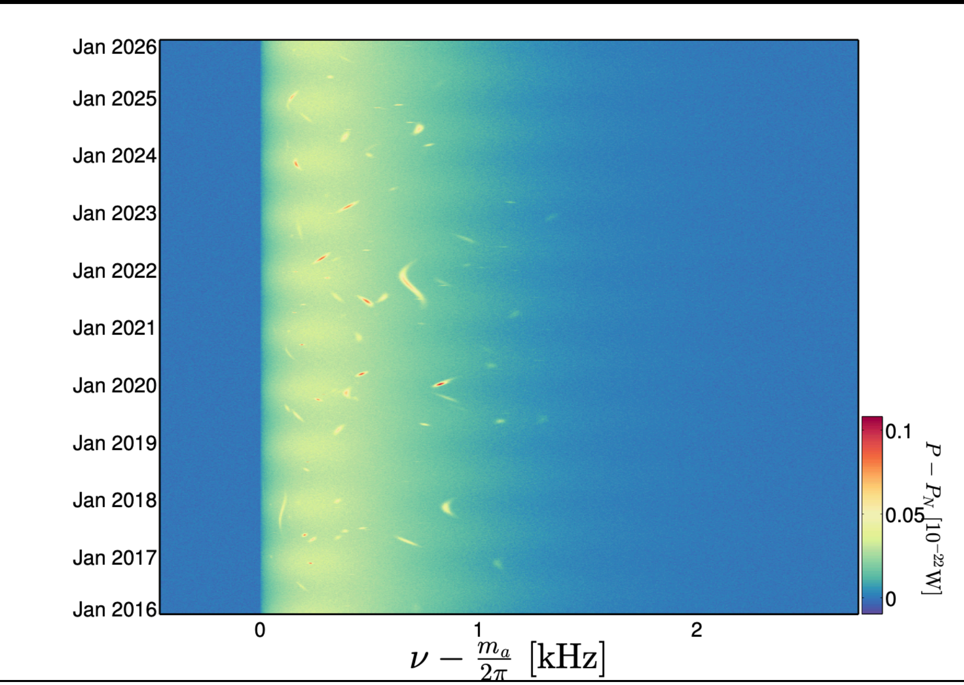


$$h\nu = m_a c^2[1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Axion Astronomy...

Streams and local objects...

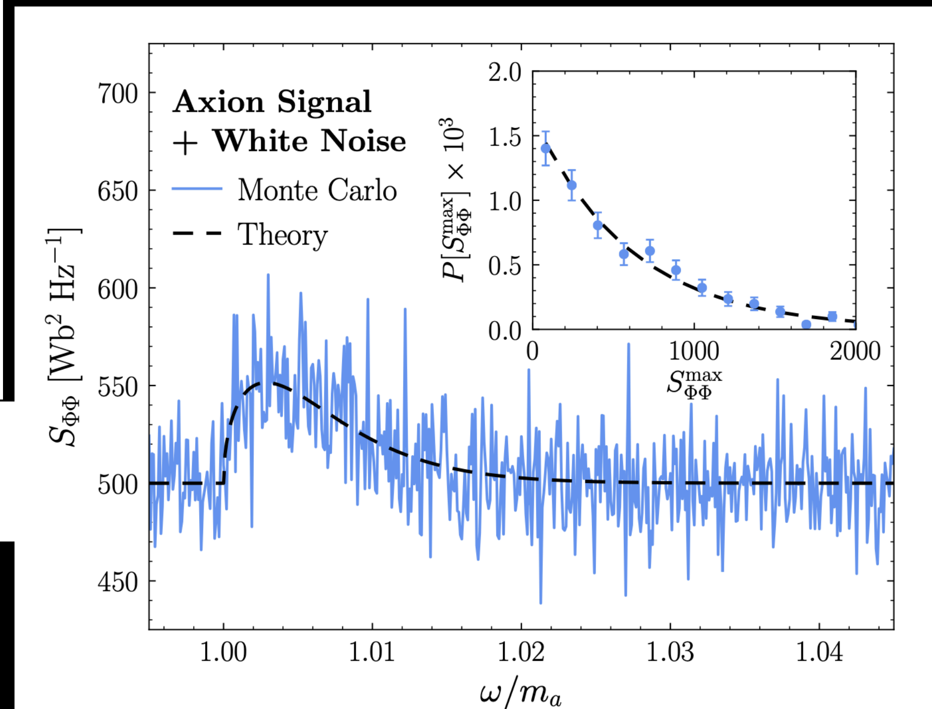


Axion astronomy with microwave cavity experiments

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

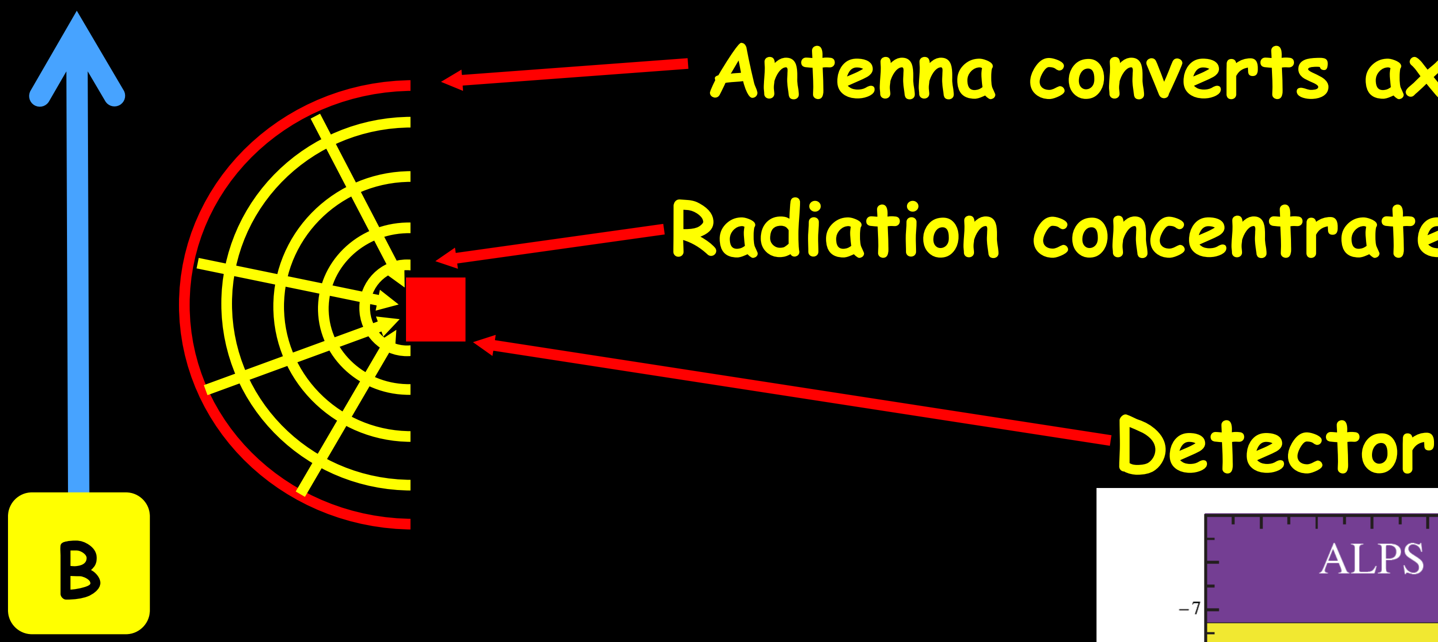
- Networks of multiple detectors can give directional sensitivity

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]

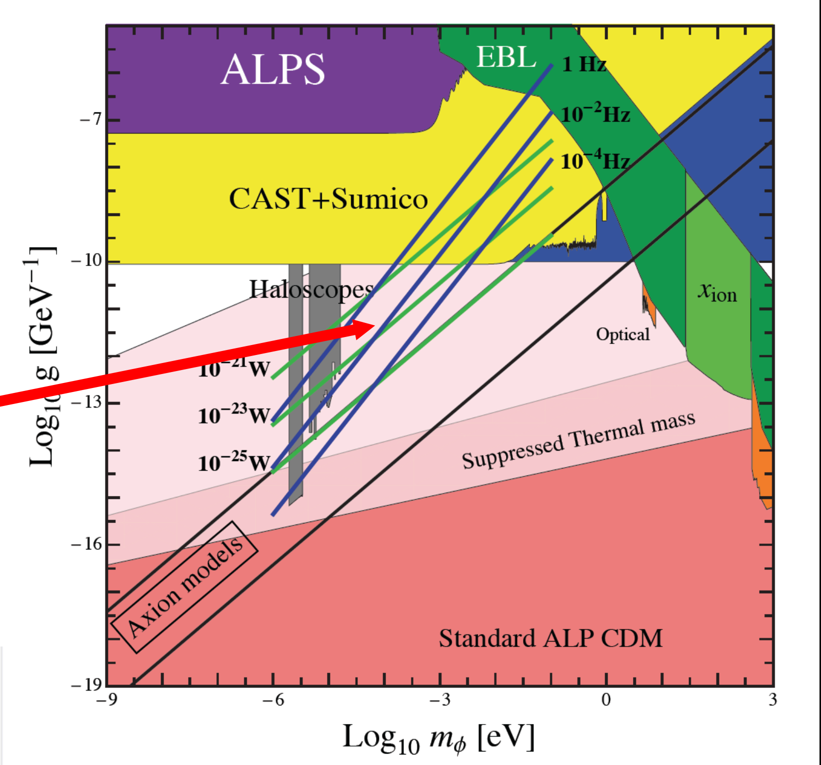
- But even suitably shaped cavities can already give some sensitivity to that

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



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

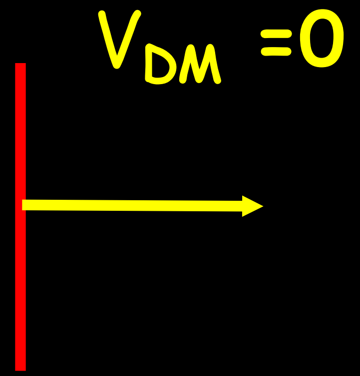
Recycle Auger mirror

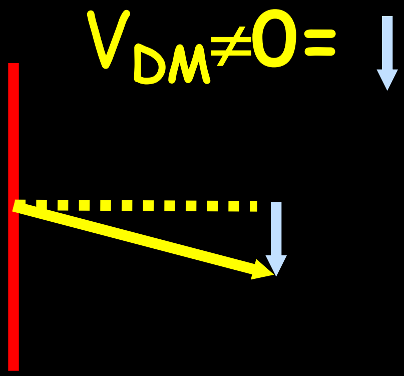
Detector

No magnet:
Only sensitive to hidden photons

Taking a picture of the DM velocity

- Emission from moving dark matter

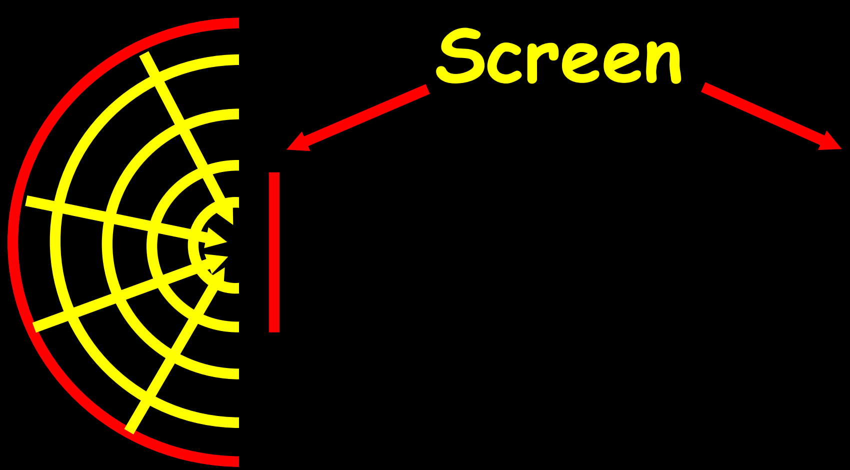


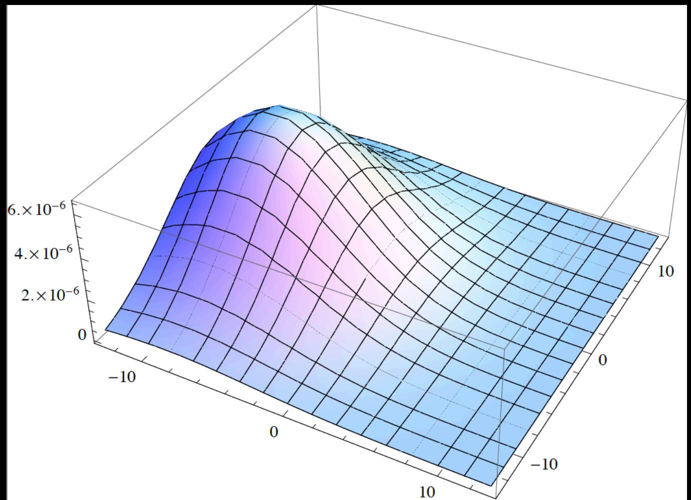


An antenna for directional detection of WISPy dark matter
Joerg Jaeckel (Heidelberg U.), Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.) (Jul 26, 2013)
Published in: *JCAP* 11 (2013) 016 • e-Print: 1307.7181 [hep-ph]

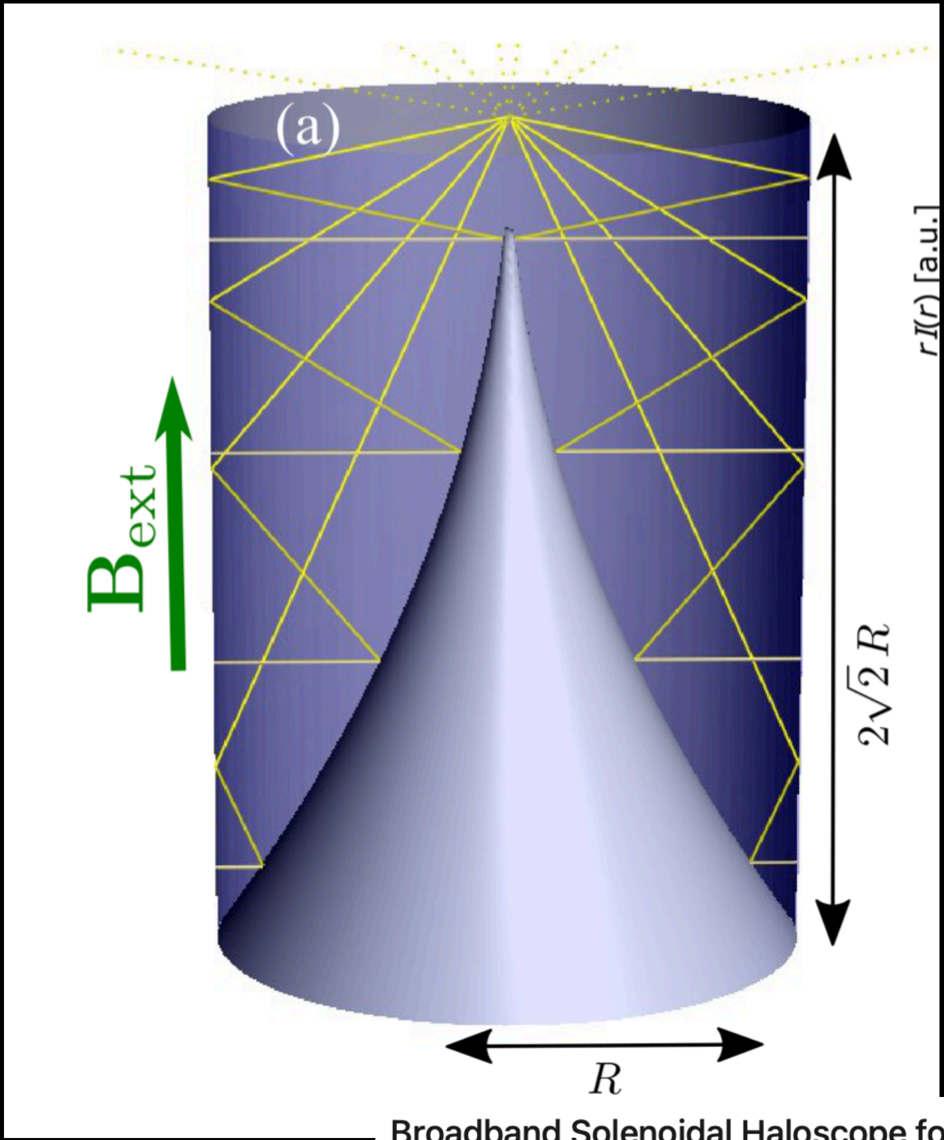
Directional Resolution of Dish Antenna Experiments to Search for WISPy Dark Matter
Joerg Jaeckel (Heidelberg U.), Stefan Knirck (Heidelberg U.) (Sep 1, 2015)
Published in: *JCAP* 01 (2016) 005 • e-Print: 1509.00371 [hep-ph]

- A picture of the DM-velocity distribution





Can also use cool geometries: BREAD



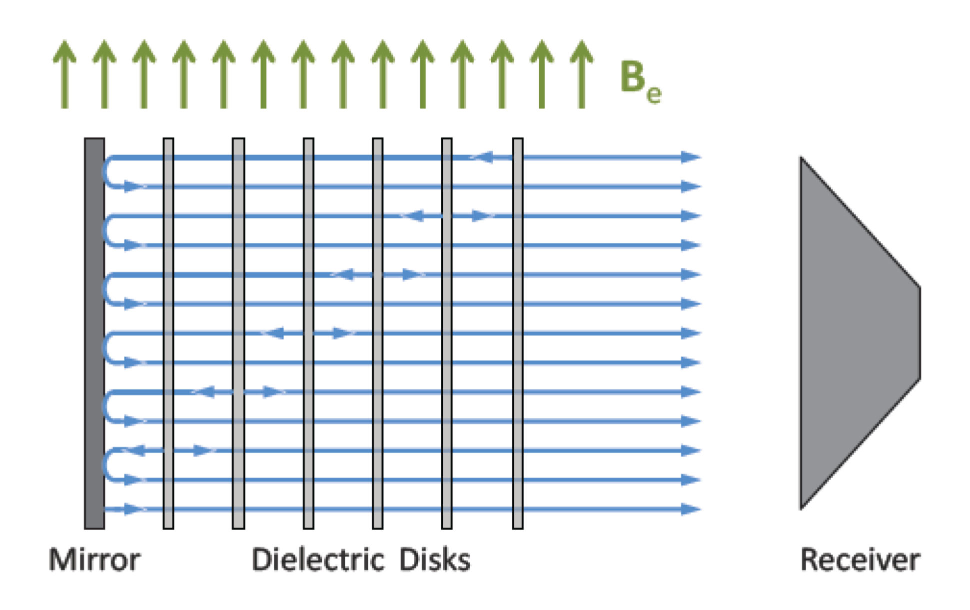
Broadband Solenoidal Haloscope for Terahertz Axion Detection

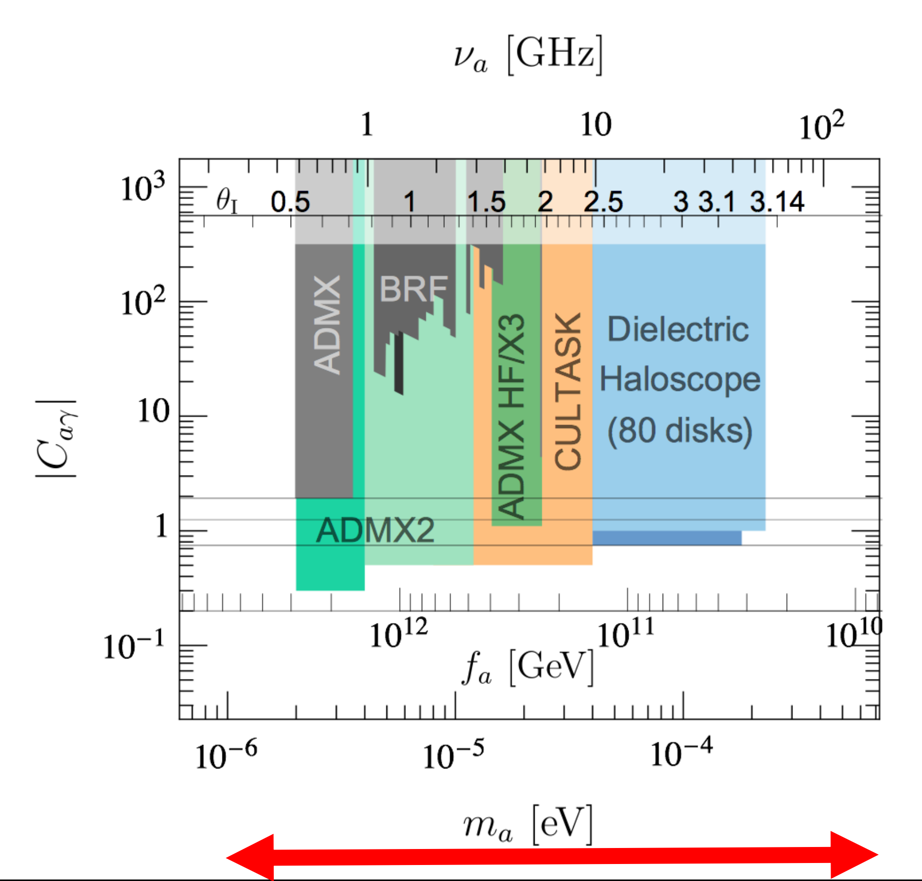
BREAD Collaboration • Jesse Liu (Cambridge U. and Chicago U.) et al. (Nov 23, 2021)

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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New Observables for Direct Detection of Axion Dark Matter
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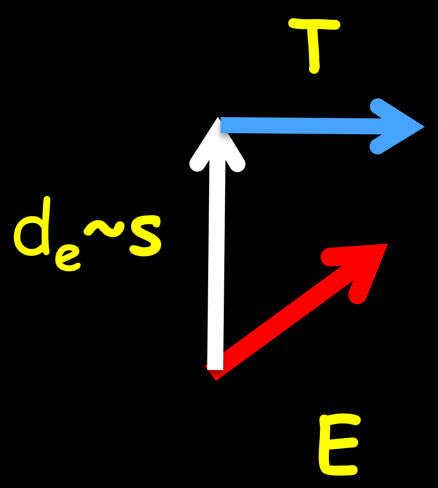
Published in **Phys.Rev. D88 (2013) 035023**
DOI: 10.1103/PhysRevD.88.035023
e-Print: **arXiv:1306.6088 [hep-ph]** | PDF

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

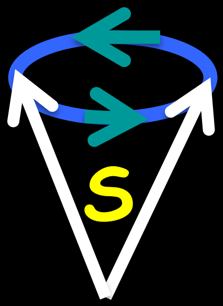
Problem: the dipole moment is rapidly oscillating ~m_a

➔ Danger of cancellation

Solution: Rotate spin to compensate

➔ Use Spin Precession in magnetic field

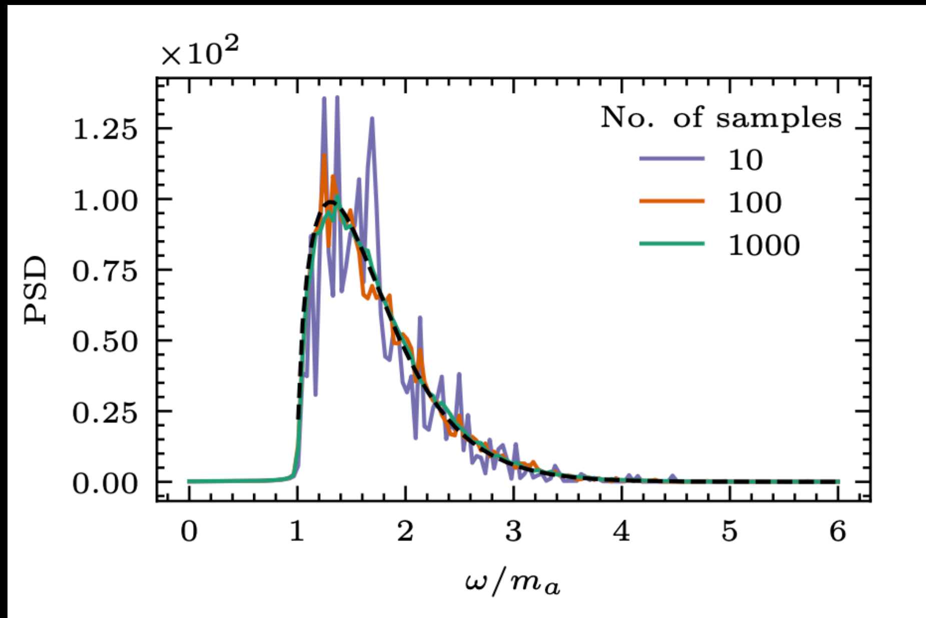
$$\omega_L = 2\mu B$$

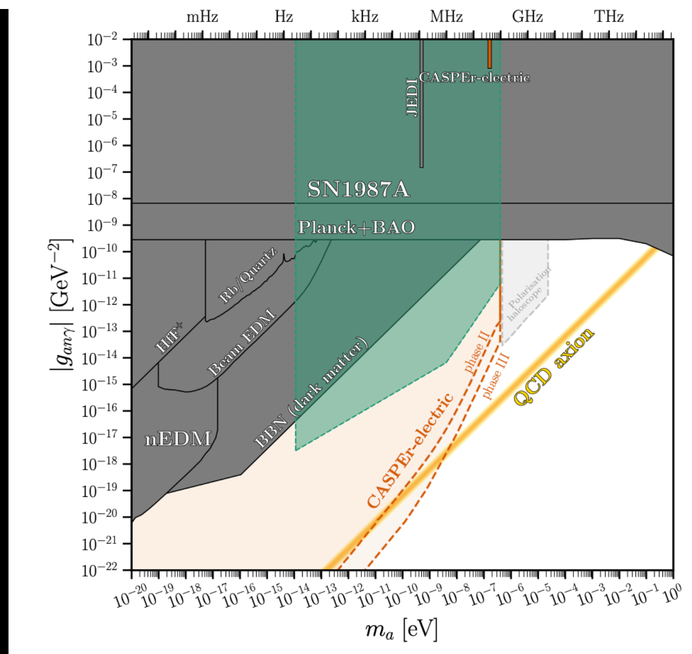


Resonance when $\omega_L = m_a$

Measure velocity^2 distribution?

- Yes





JJ, C. Quint (in preparation)

Establishing Axions as “The Dark Matter”

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]

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?

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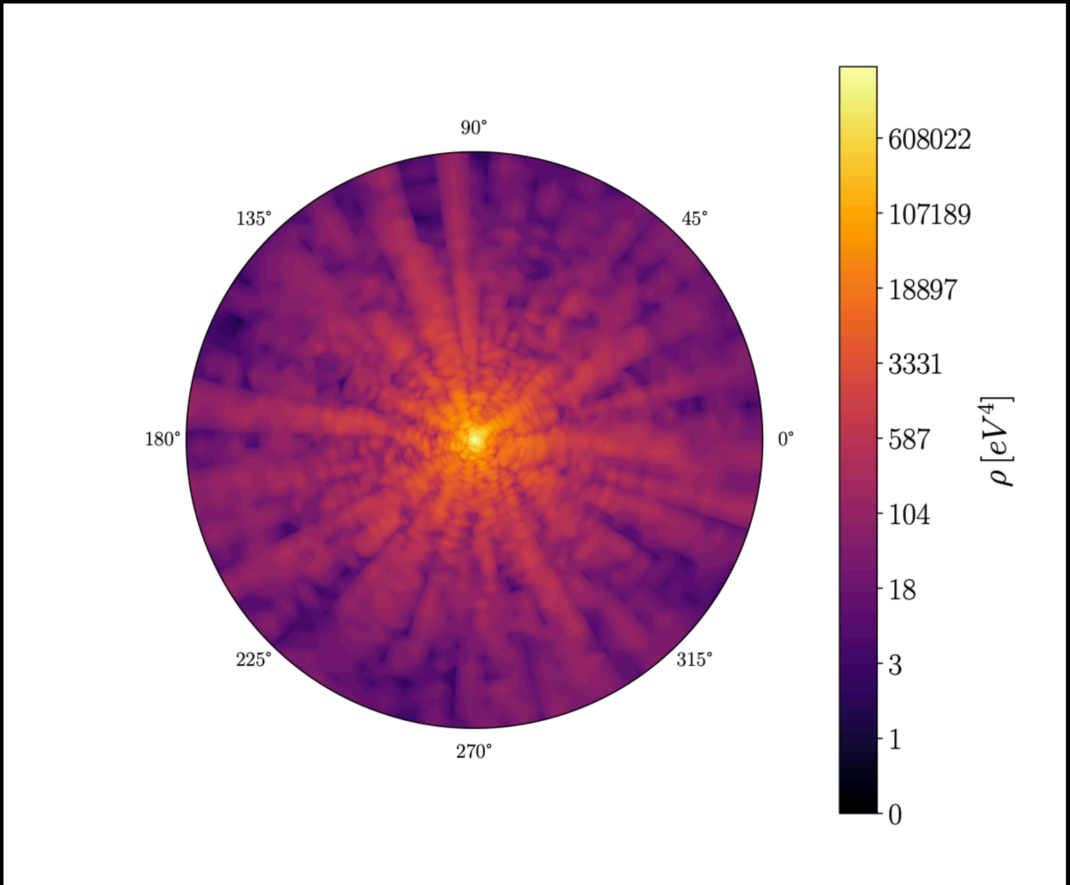
Let's find an Axion Mini-cluster



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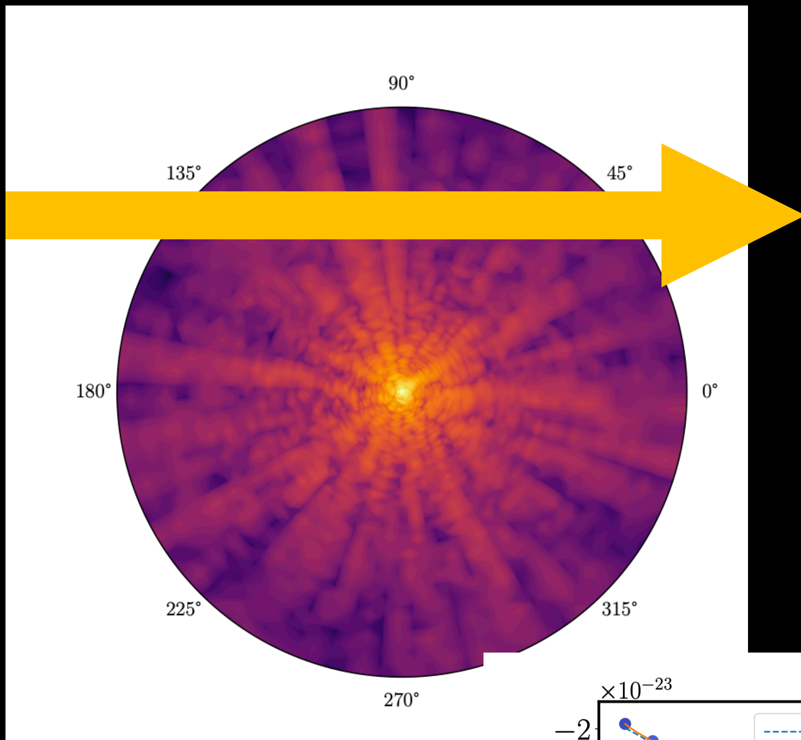
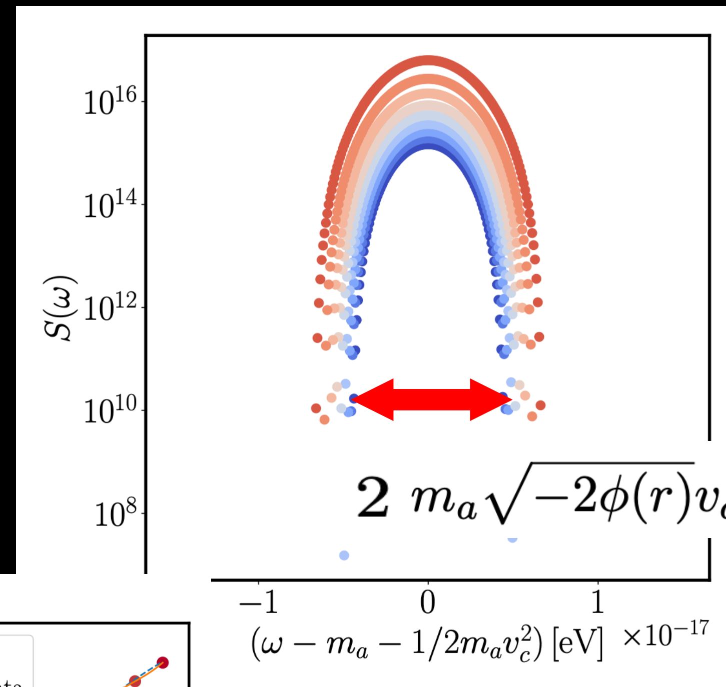
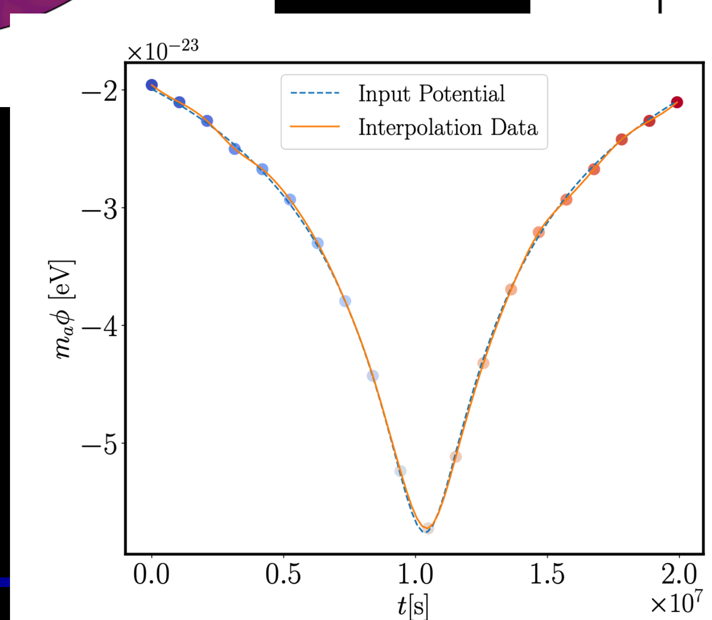
...and fly through it

Power spectrum along the path







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Reconstruct minicluster density...

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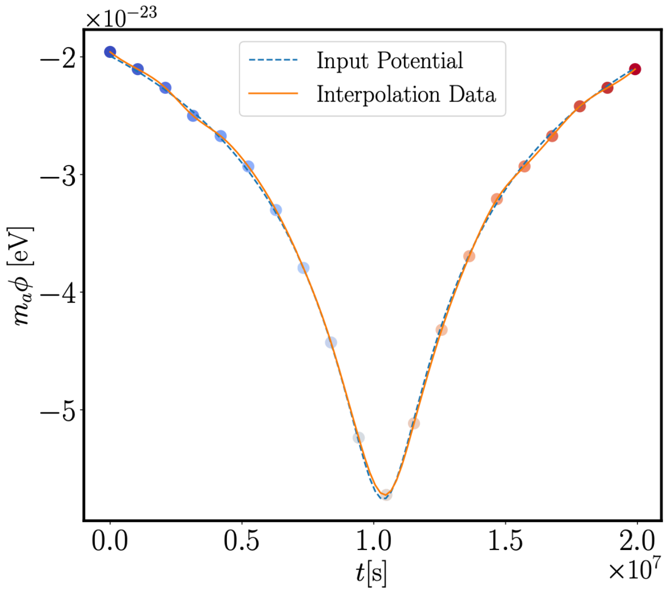
- Poisson equation (along path)

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

+



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...

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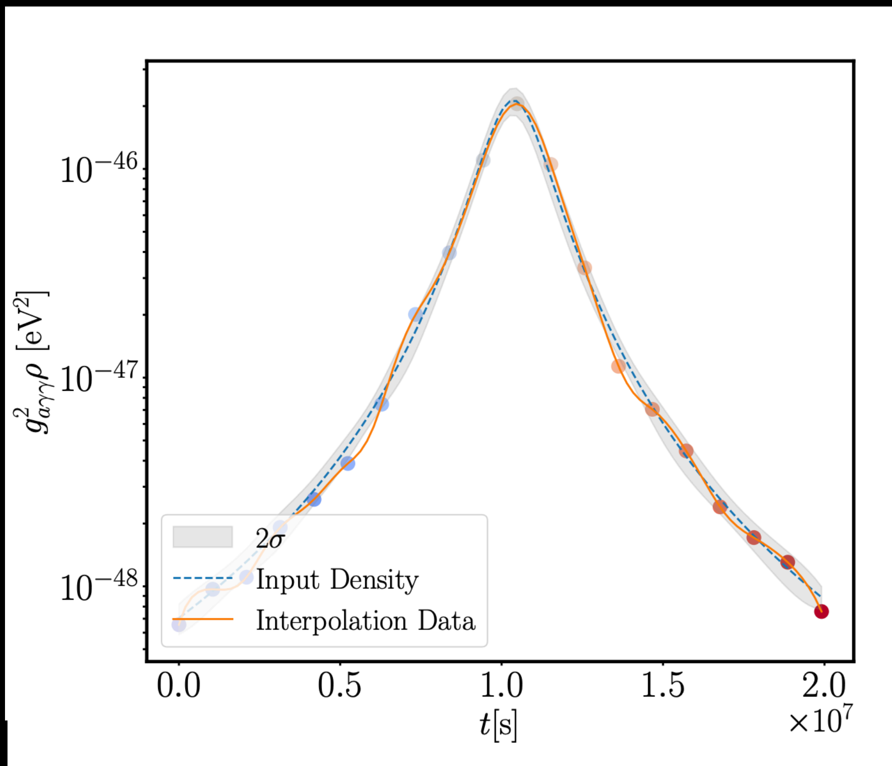
- Power along the path



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

Already known

➔ Obtain g

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

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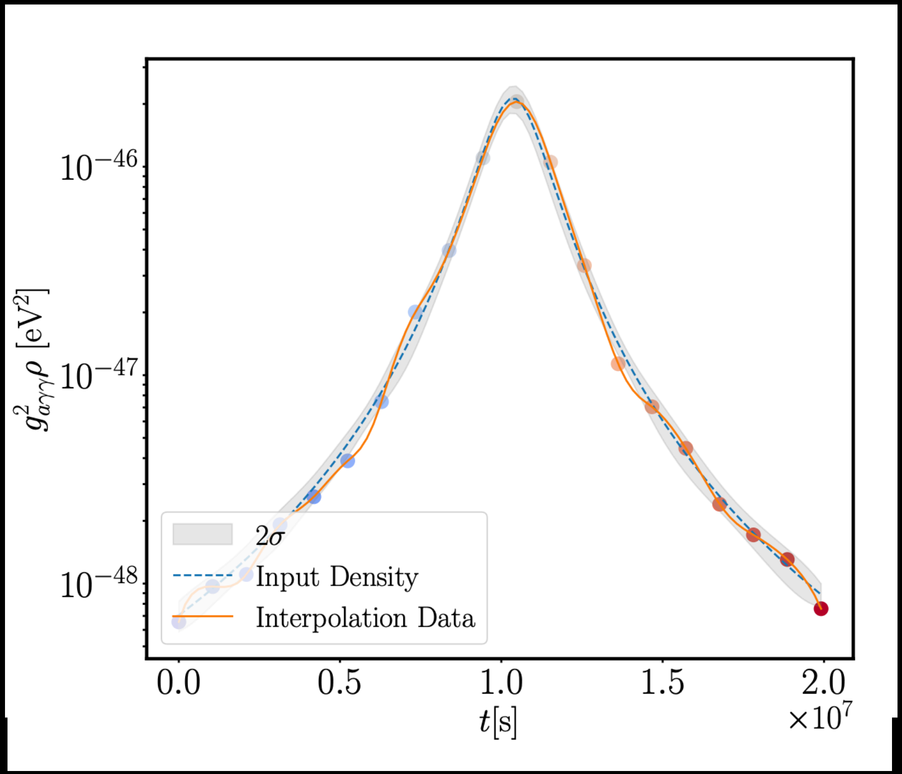
- Power along the path



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

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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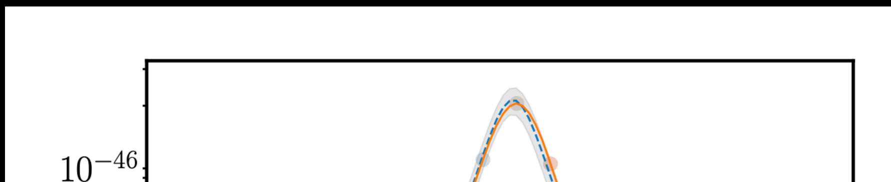
Heidelberg University

- 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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e-Print: 2307.11871 [hep-ph]

Part II
If we are dedicated...

JJ, G. Lucente, S. Hoof in preparation

We build HyperLSW ☺

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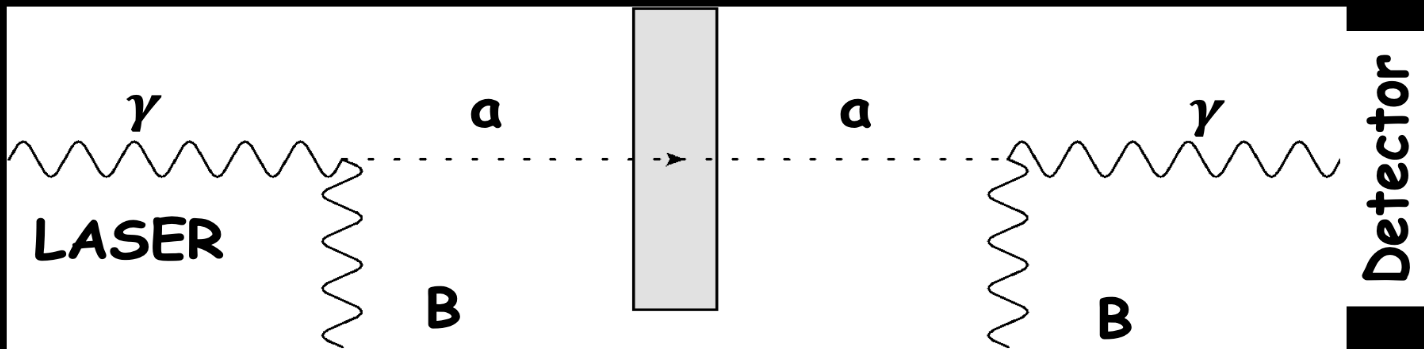
- What is an LSW experiment?

Light shining through walls

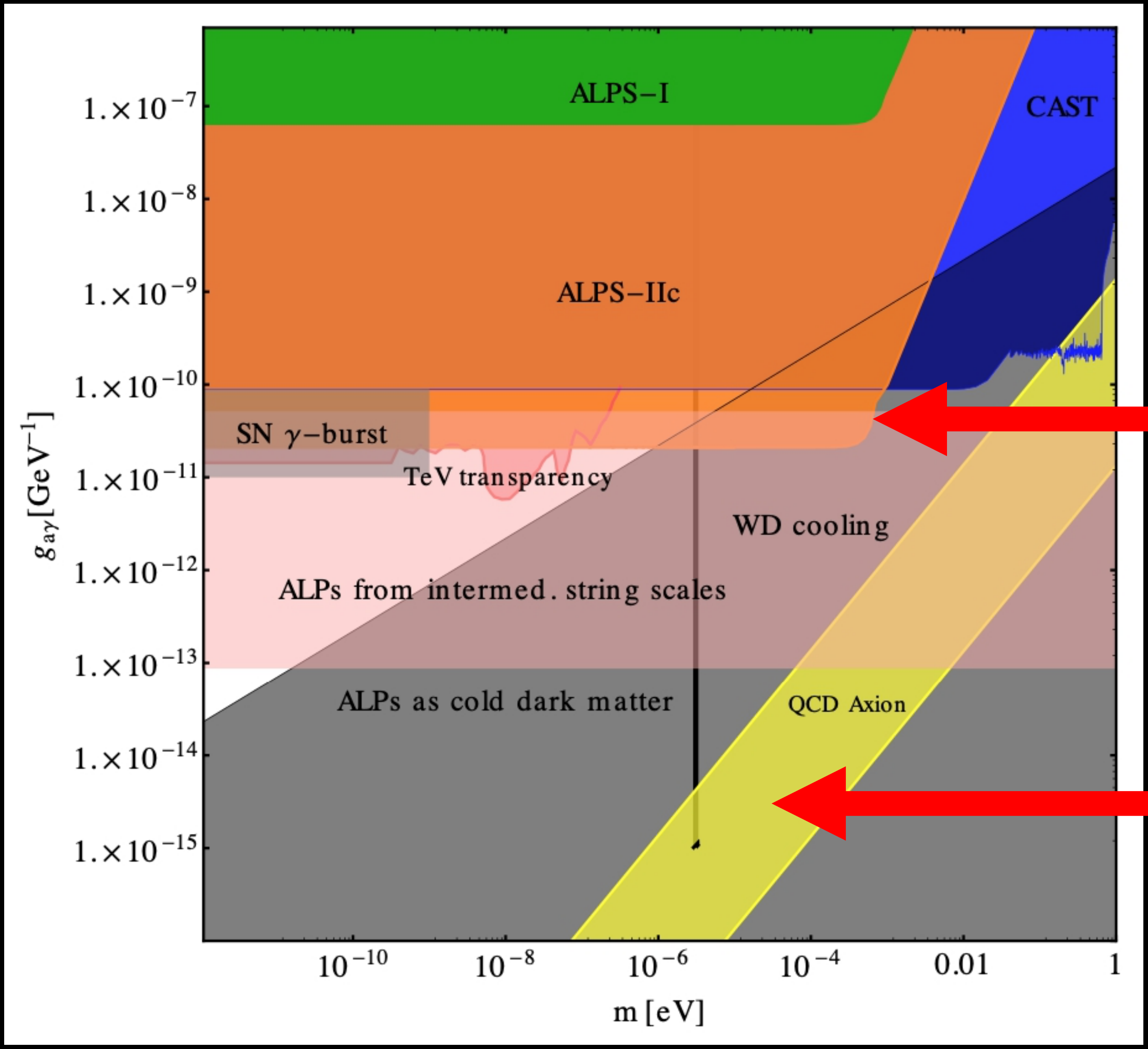


- Probability to see the light

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

Purely laboratory based → determine g

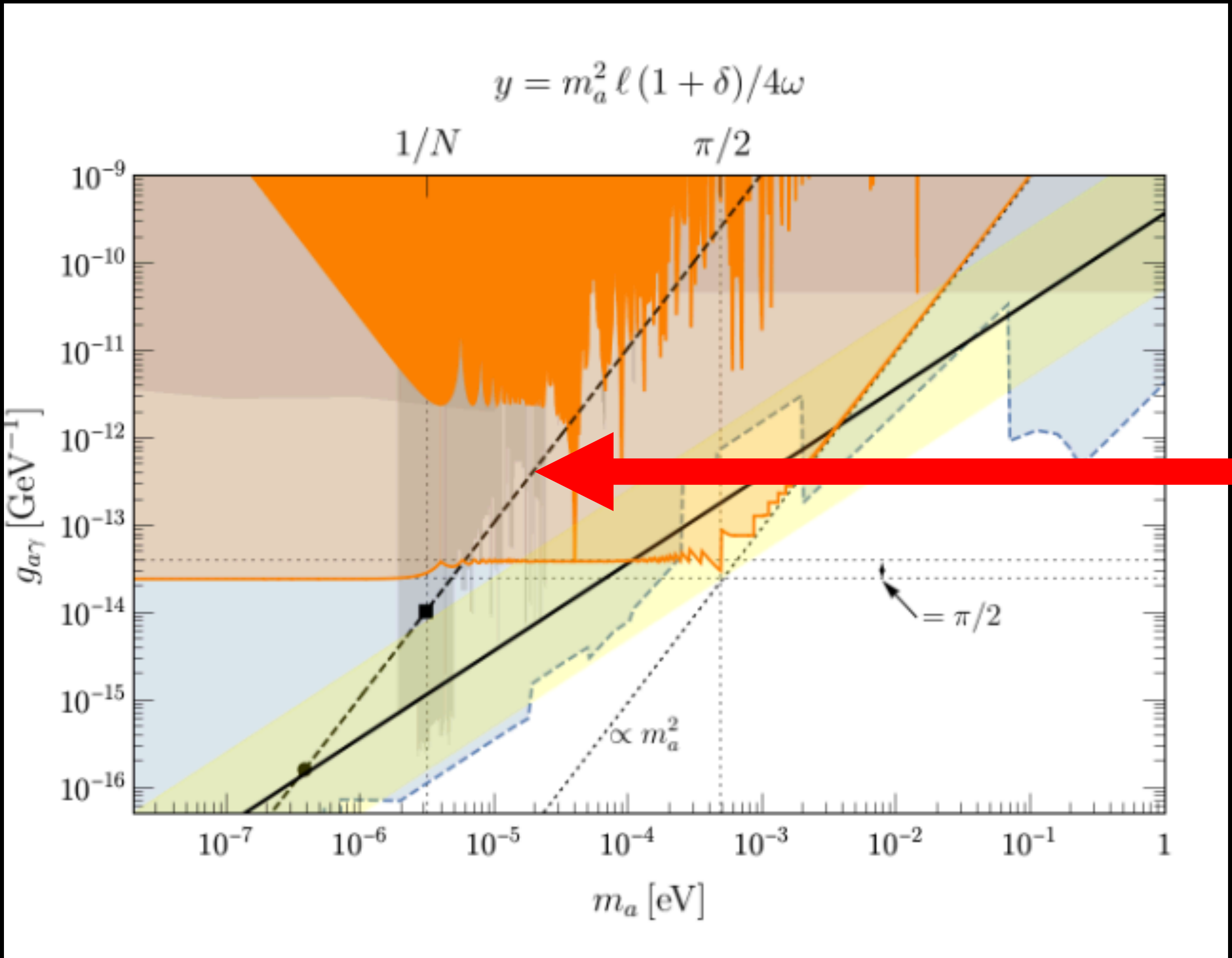
Not so easy... ALPS II



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

Optimize magnet configuration

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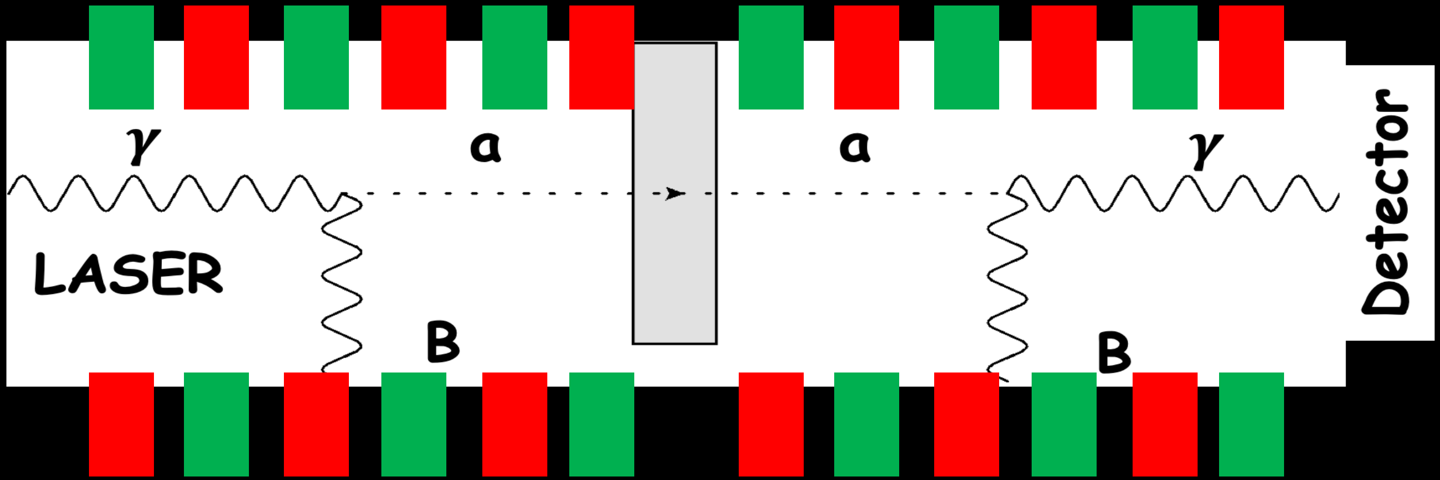
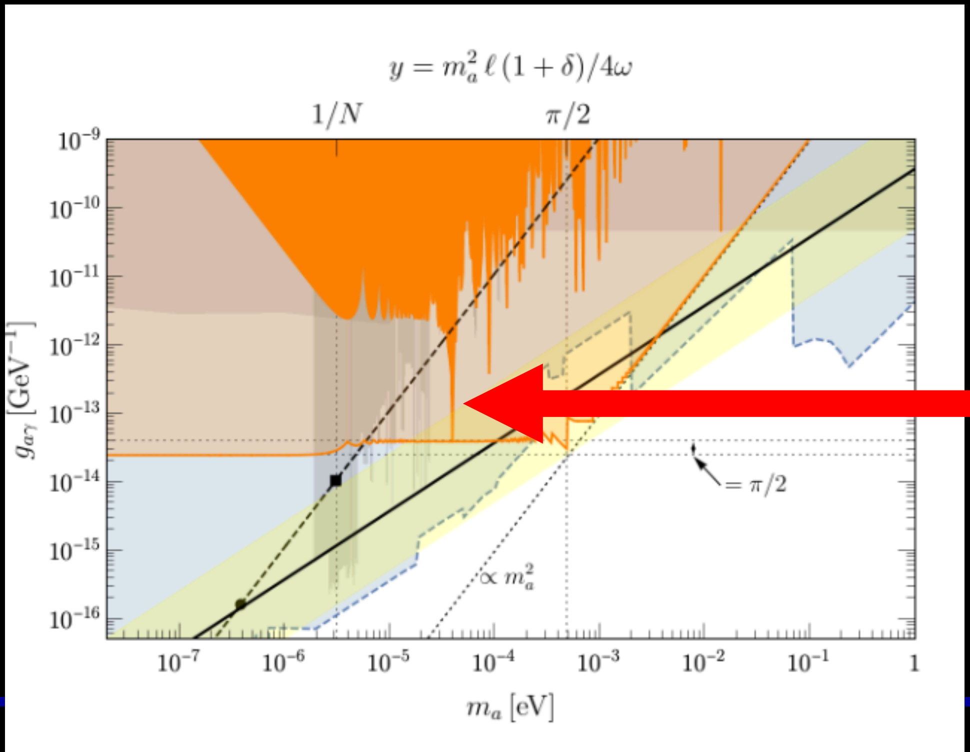
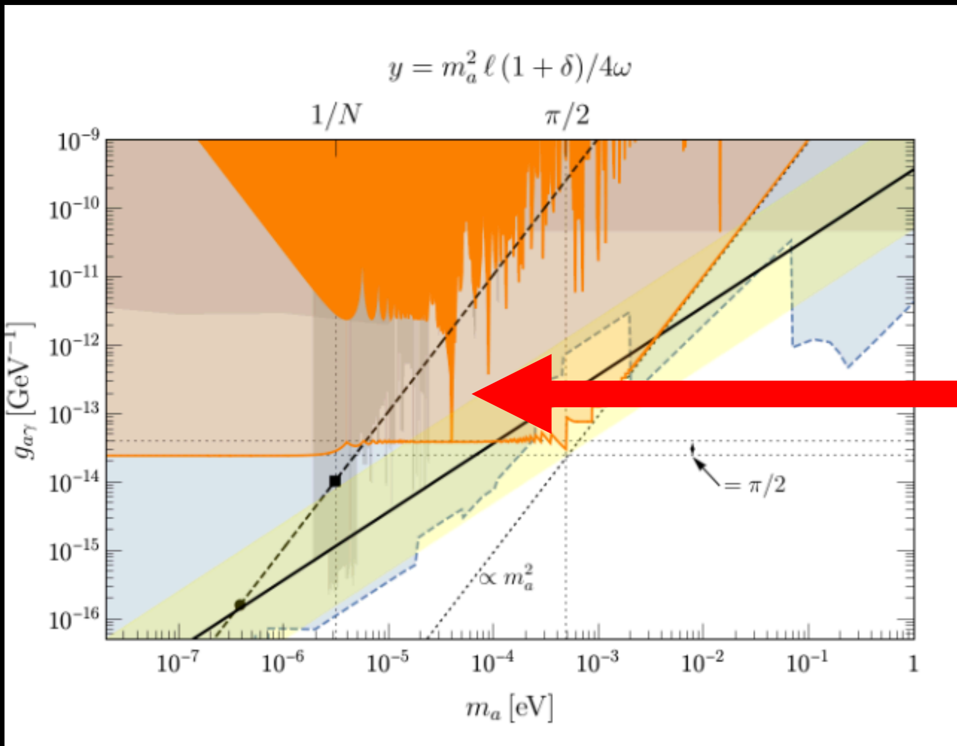




Alternating magnets

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

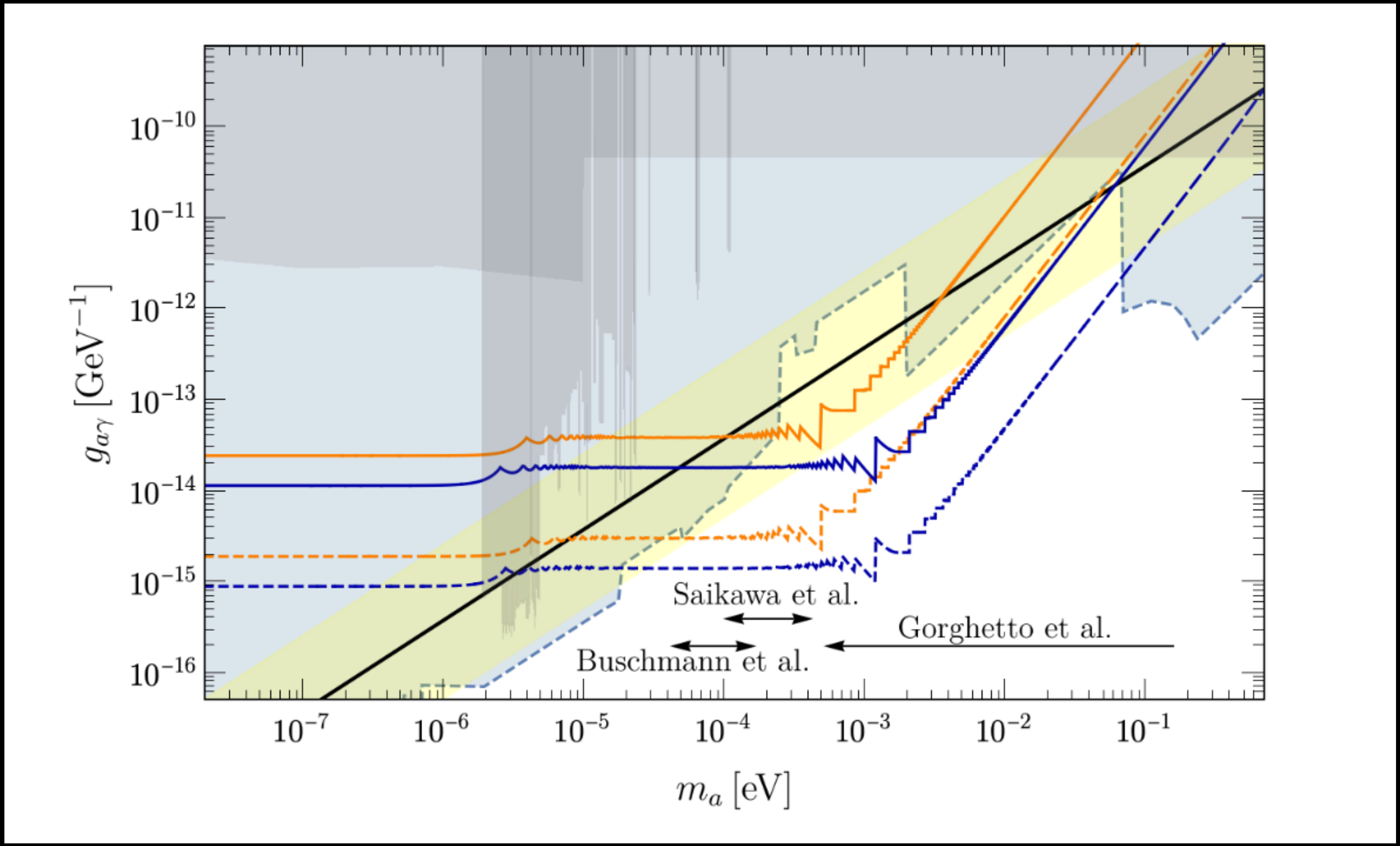
Optimizing Light-Shining-through-a-Wall Experiments for Axion and other WISP Searches
Paola Arias (DESY), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (Munich, Max Planck Inst.), Andreas Ringwald (DESY) (Sep, 2010)
Published in: Phys.Rev.D 82 (2010) 115018 • e-Print: 1009.4875 [hep-ph]



Very narrow?

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

Discovery region



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Price tag...

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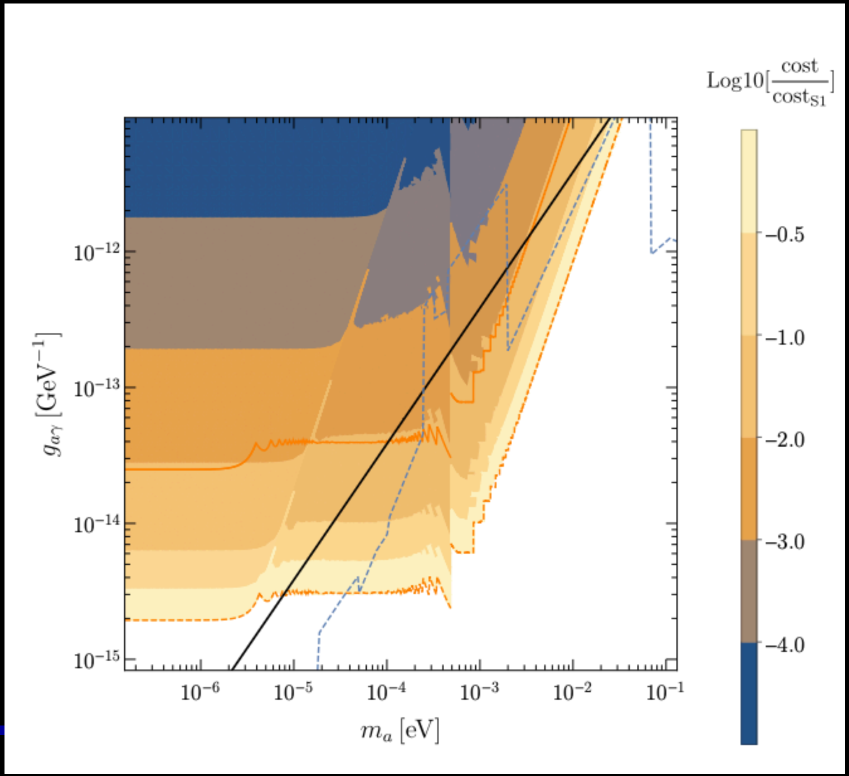
Setup	B [T]	a [m]	ℓ [m]	$\Delta_{\min}$ [m]	P_λ [W]	β_g	β_r	λ [nm]	$\varepsilon_{\rm eff}$	τ [h]	b [s^{-1}]	$2\,z_{\rm opt}$ [km]	$\mathcal{S}_{\rm crit}$
S1	10	1.3	4.0	2.0	3	10^5	10^5	1064	0.95	100	10^{-4}	2×94	186.42
S2	12	2.0	0.5	0.5	3	10^5	10^5	1064	0.95	100	10^{-4}	2×220	186.42
O1	10	1.3	4.0	2.0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



going full

Astronomy

Taking the sun's temperature

Axion helioscopes as solar thermometers

Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Lennert J. Thormaehlen (U. Heidelberg, ITP) (May 31, 2023)

Published in: *JCAP* 10 (2023) 024 • e-Print: 2306.00077 [hep-ph]

Helioscope:
International Axion Observatory = IAXO

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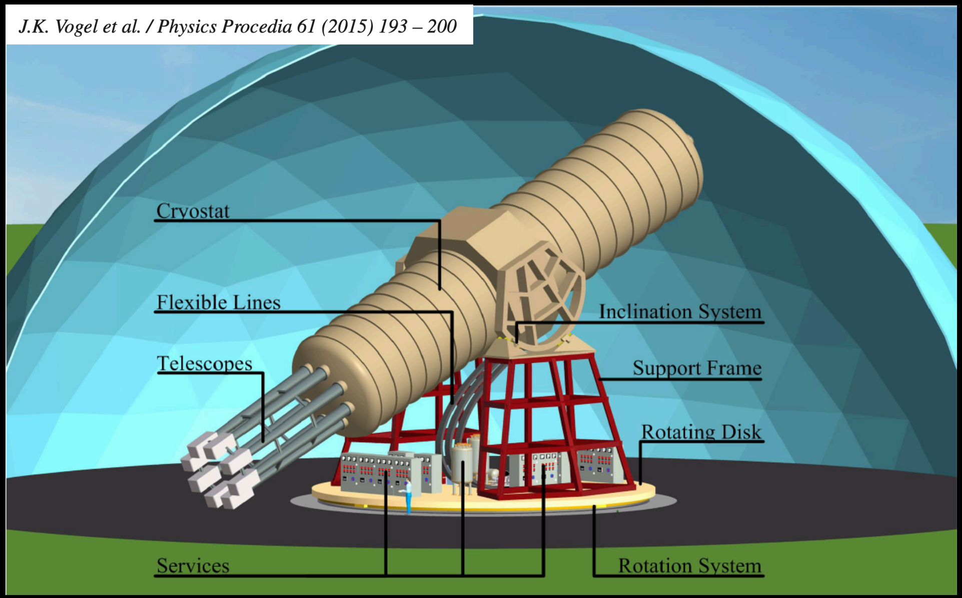
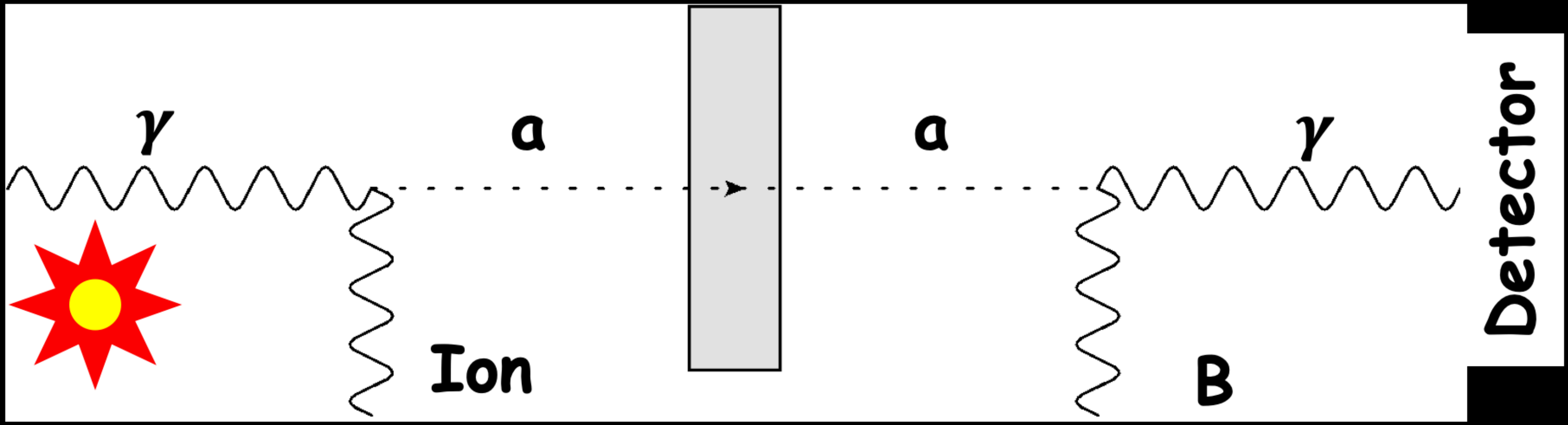
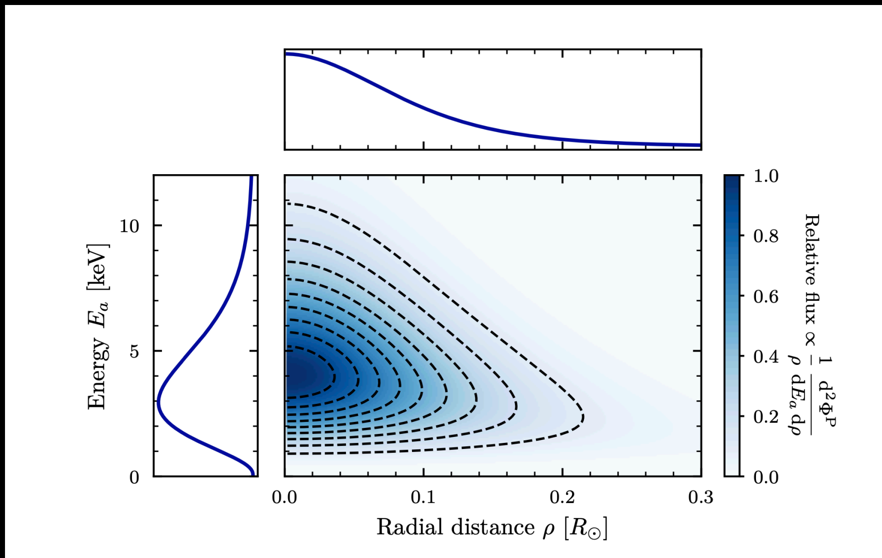


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

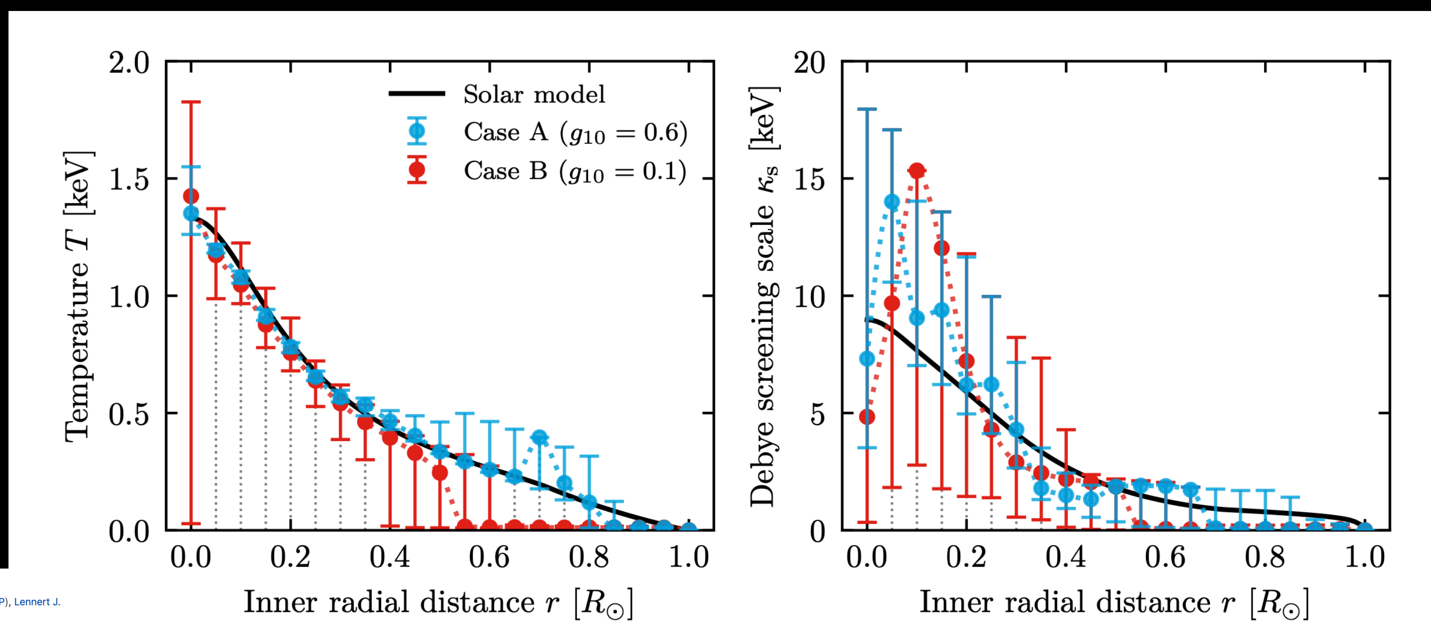
Light shining through walls



Temperature measurement



Measure axion flux and spectrum along the solar disc



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Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Lennert J. Thormaehlen (U. Heidelberg, ITP) (May 31, 2023)

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Theory
+
Astrophysics

Learning about models (axion and solar)

Could also tell us about axion models...

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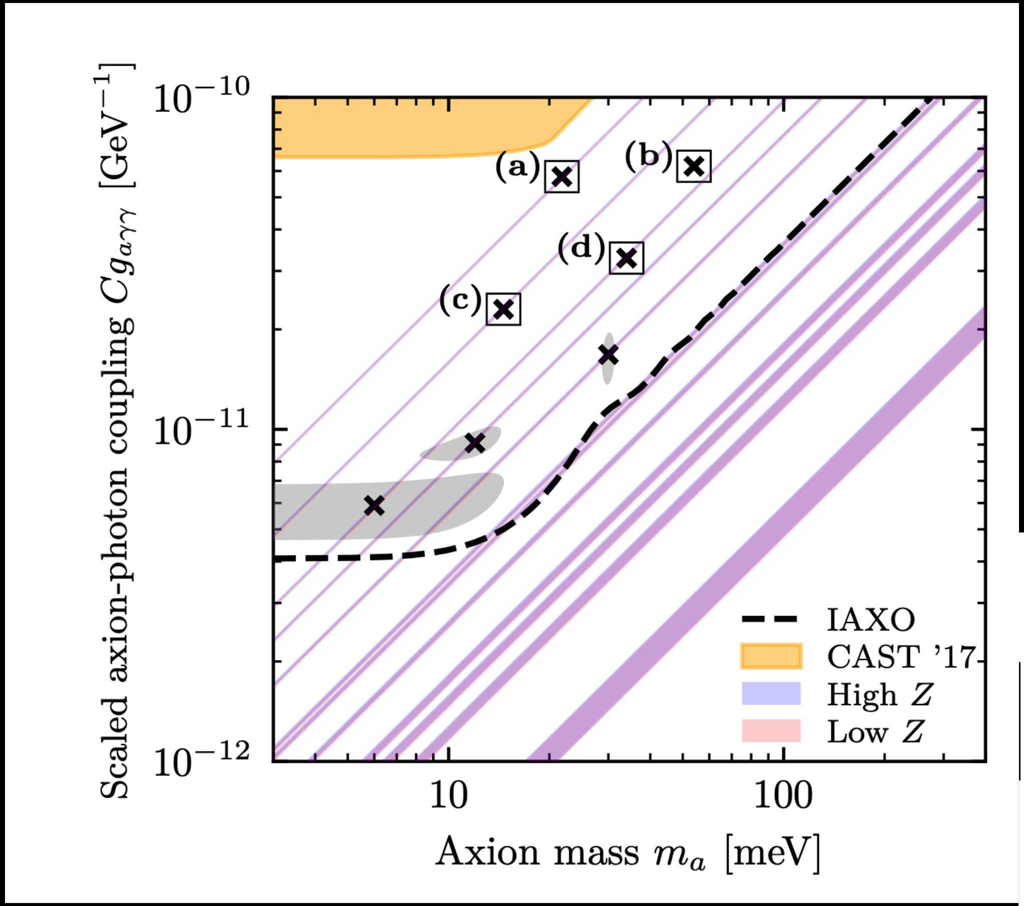
QCD axion models live on "lines" in parameter space
→ mass + coupling also tells us about model



$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} C_{a\gamma} = \frac{\alpha}{2\pi f_a} \left| E/N - C_{a\gamma,0}^{\rm NLO} \right|,$$

Charges of heavy particles in axion model

Distinguishing Axion Models with IAXO

Joerg Jaeckel (Heidelberg U.), Lennert J. Thormaehlen (Heidelberg U.) (Nov 22, 2018)

Published in: *JCAP* 03 (2019) 039 • e-Print: 1811.09278 [hep-ph]

Weighing the solar axion

Theopisti Dafni (Zaragoza U.), Ciaran A.J. O'Hare (Zaragoza U.), Biljana Lakić (Boskovic Inst., Zagreb), Javier Galán (Zaragoza U.), Francisco J. Iguaz (Zaragoza U. and SOLEIL, Saint-Aubin) et al. (Nov 22, 2018)

Published in: *Phys.Rev.D* 99 (2019) 3, 035037 • e-Print: 1811.09290 [hep-ph]

Quantifying uncertainties in the solar axion flux and their impact on determining axion model parameters #3

Sebastian Hoof (Inst. Astrophys. Gottingen), Joerg Jaeckel (Heidelberg U.), Lennert J. Thormaehlen (Heidelberg U.) (Jan 21, 2021)

Published in: *JCAP* 09 (2021) 006 • e-Print: 2101.08789 [hep-ph]

But also about solar models...

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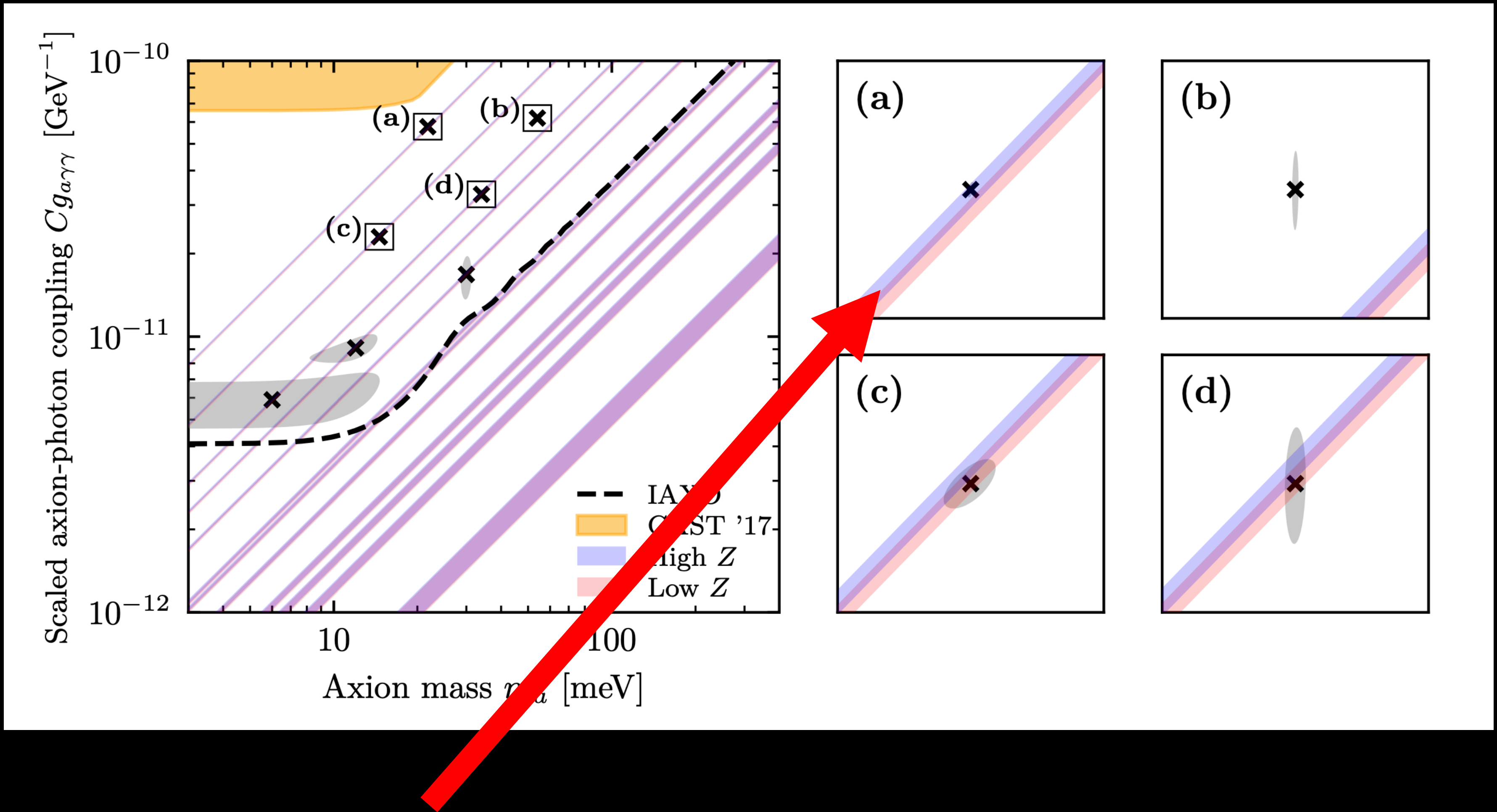

Different solar models

Quantifying uncertainties in the solar axion flux and their impact on determining axion model parameters

Sebastian Hoof (Inst. Astrophys. Gottingen), Joerg Jaeckel (Heidelberg U.), Lennert J. Thormaehlen (Heidelberg U.) (Jan 21, 2021)

Published in: JCAP 09 (2021) 006 • e-Print: 2101.08789 [hep-ph]

Probing solar „metals“

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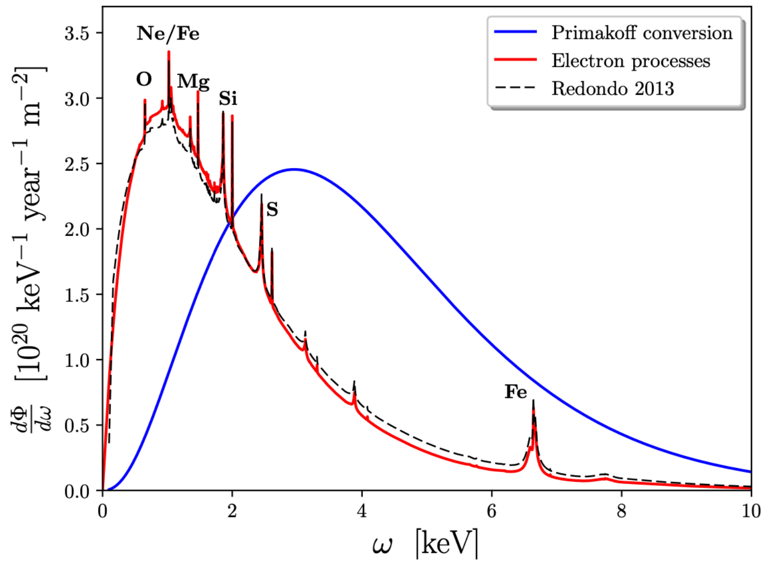
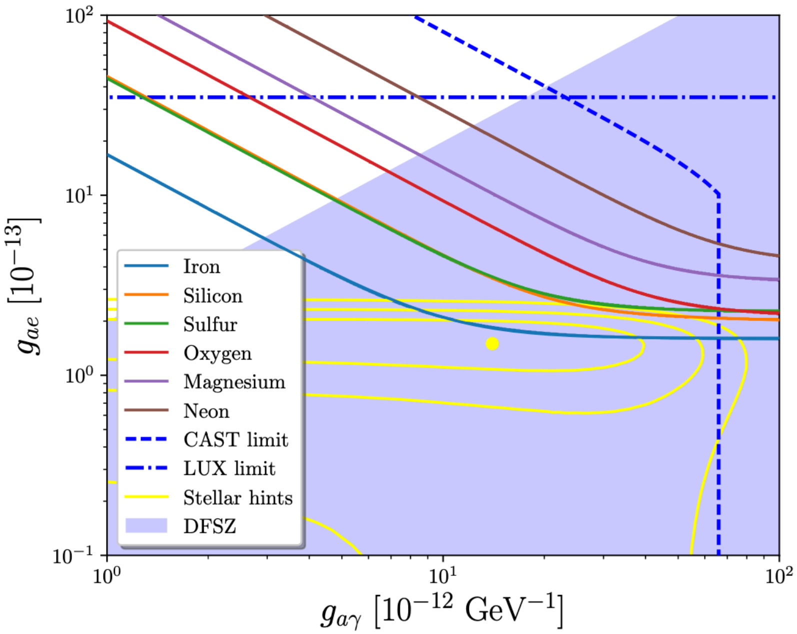




Axions as a probe of solar metals

Joerg Jaeckel (U. Heidelberg (main)), Lennert J. Thormaehlen (U. Heidelberg (main)) (Aug 28, 2019)

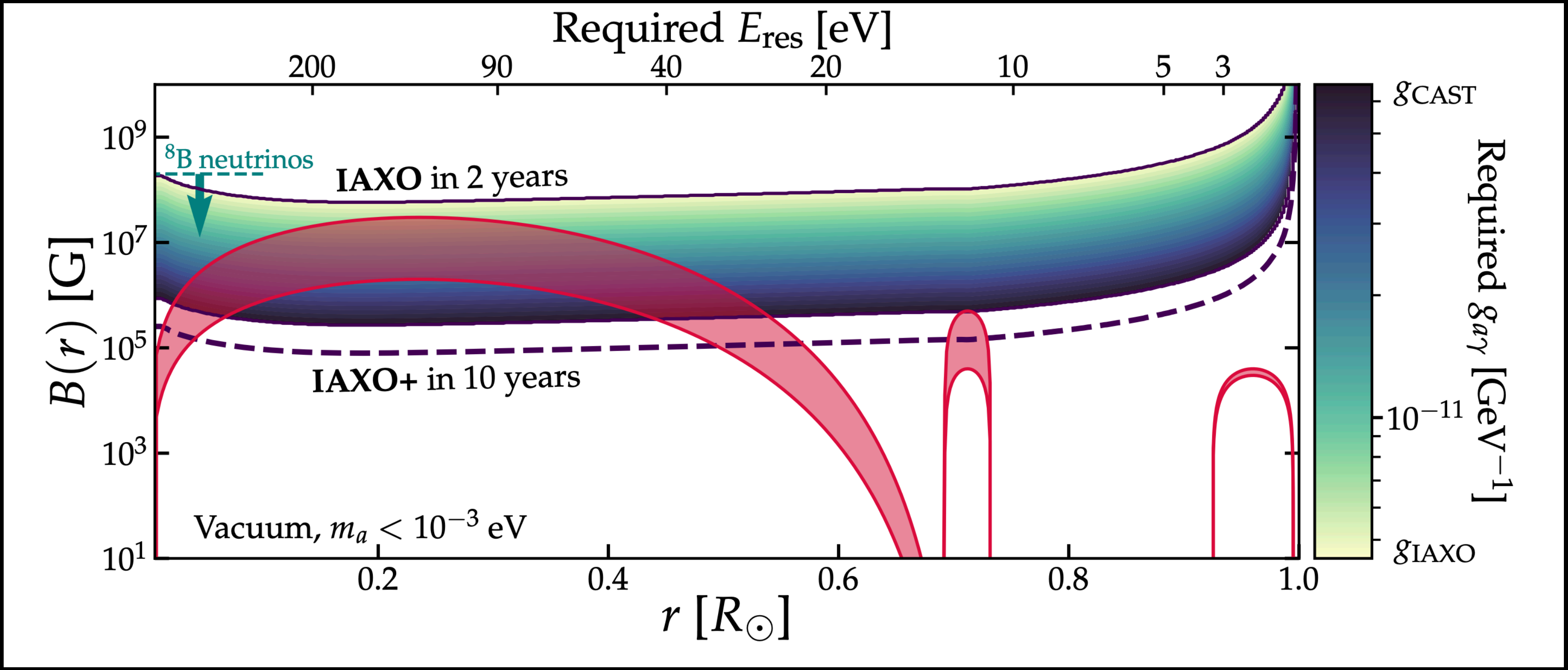
Published in: *Phys.Rev.D* 100 (2019) 12, 123020 • e-Print: 1908.10878 [astro-ph.SR]

Axions as solar magnetometers

Axion helioscopes as solar magnetometers

Ciaran A.J. O'Hare (Sydney U.), Andrea Caputo (Valencia U., IFIC and Valencia U.), Alexander J. Millar (Stockholm U., OKC and Nordita and Royal Inst. Tech., Stockholm), Edoardo Vitagliano (UCLA)

Jun 18, 2020



Dark Cosmology

Axionic/ALPy Dark Radiation

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- Many (string) models feature a long-lived modulus Φ
- This reheats the Universe $\Phi \rightarrow SM$
- Significant branching ratio into axions/ALPs $\Phi \rightarrow a + a$
- These a are effective degrees relativistic of freedom visible in BBN and CMB
- often dangerous „Dark Radiation Problem"

A. Hebecker, P. Mangat, F. Rompineve, and L. T. Witkowski, "Dark Radiation predictions from general Large Volume Scenarios," JHEP 09 (2014) 140, arXiv:1403.6810 [hep-ph].

S. Angus, "Dark Radiation in Anisotropic LARGE Volume Compactifications," JHEP 10 (2014) 184, arXiv:1403.6473 [hep-ph].

M. Cicoli, J. P. Conlon, and F. Quevedo, "Dark radiation in LARGE volume models," Phys. Rev. D 87 no. 4, (2013) 043520, arXiv:1208.3562 [hep-ph].

T. Higaki and F. Takahashi, "Dark Radiation and Dark Matter in Large Volume Compactifications," JHEP 11 (2012) 125, arXiv:1208.3563 [hep-ph].

- Can be addressed but leaves some DR

Axions in string theory — slaying the Hydra of dark radiation

Michele Cicoli (Bologna U. and INFN, Bologna), Arthur Hebecker (U. Heidelberg, ITP and Heidelberg U.), Joerg Jaeckel (U. Heidelberg, ITP and Heidelberg U.), Manuel Wittner (U. Heidelberg, ITP and Heidelberg U.) (Mar 16, 2022)

Published in: JHEP 09 (2022) 198 • e-Print: 2203.08833 [hep-th]

We expect some dark radiation

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$$\Delta N_{\text{eff}} \sim 6.1 \left(\frac{11}{g_\star^4 g_{\star,S}^{-3}} \right)^{1/3} BR(\phi \to aa) \simeq 0.3 \left(\frac{11}{g_*^4 g_{*,S}^{-3}} \right)^{1/3} \simeq 0.14$$

$$g_* = g_{*,S} = 106.75$$

This dark radiation is made from axions.
A significant part is QCD axions

↓

Detectable

Axions in string theory — slaying the Hydra of dark radiation
Michele Cicoli (Bologna U. and INFN, Bologna), Arthur Hebecker (U. Heidelberg, ITP and Heidelberg U.), Joerg Jaeckel (U. Heidelberg, ITP and Heidelberg U.), Manuel Wittner (U. Heidelberg, ITP and Heidelberg U.) (Mar 16, 2022)
Published in: JHEP 09 (2022) 198 • e-Print: 2203.08833 [hep-th]

Dark Radiation may be detectable + useful

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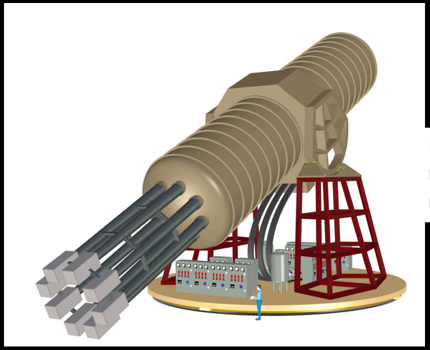
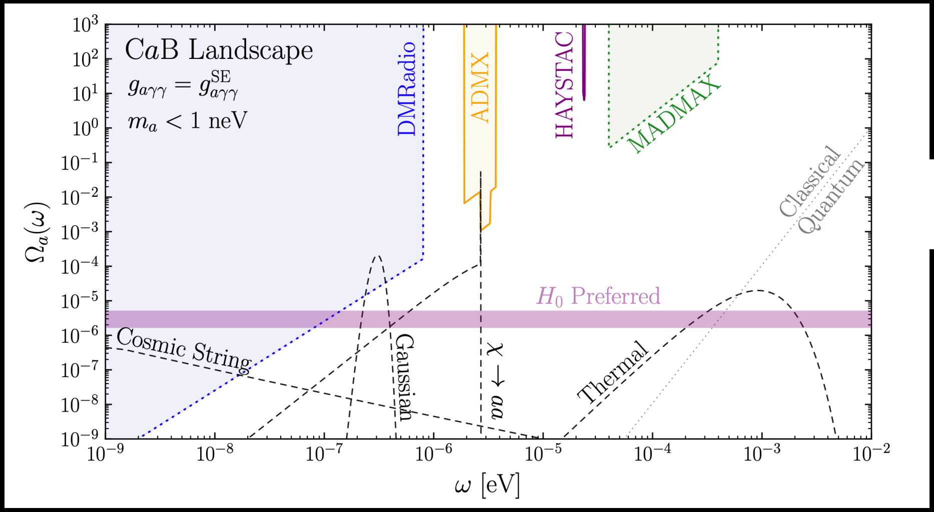
- For example in IAXO



Physics potential of the International Axion Observatory (IAXO)
IAXO Collaboration • E. Armengaud (IRFU, Saclay) et al. (Apr 19, 2019)
Published in: *JCAP* 06 (2019) 047 • e-Print: 1904.09155 [hep-ph]

- But also other experiments



Cosmic axion background
Jeff A. Dror (UC, Santa Cruz and UC, Santa Cruz, Inst. Part. Phys. and UC, Berkeley and LBNL, Berkeley), Hitoshi Murayama (UC, Berkeley and LBNL, Berkeley and Tokyo U., IPMU), Nicholas L. Rodd (UC, Berkeley and LBNL, Berkeley)

- Might be interesting to think beyond scalar photon couplings!

New tool to probe Reheating

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- This dark radiation may allow to get access to information about reheating

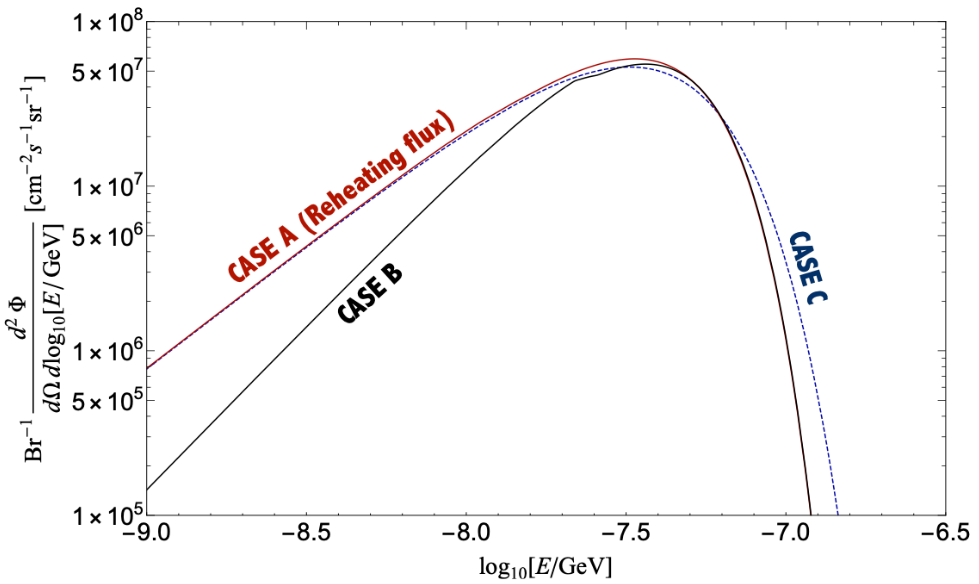

Figure. 1. The differential flux of the messenger particle, $d^2\Phi/d\log_{10} E d\Omega$. CASE A ($\phi$ once dominated the Universe) and CASE B (ϕ never dominates the Universe and decay in the radiation dominant epoch) are shown in red and black lines, respectively. We also show the flux for CASE C where a subdominant ϕ decays in the matter dominant era as the blue dashed line.

https://arxiv.org/pdf/2102.00006.pdf

New tool to probe Reheating

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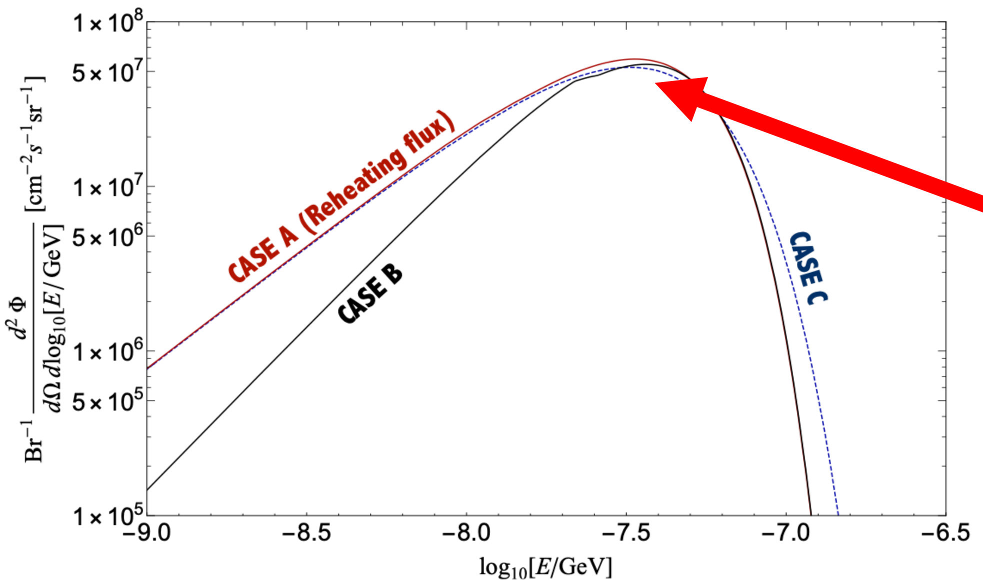

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Measures

$$\frac{m_\Phi}{T_\Phi}$$

https://arxiv.org/pdf/2102.00006.pdf

Measure reheating temperature

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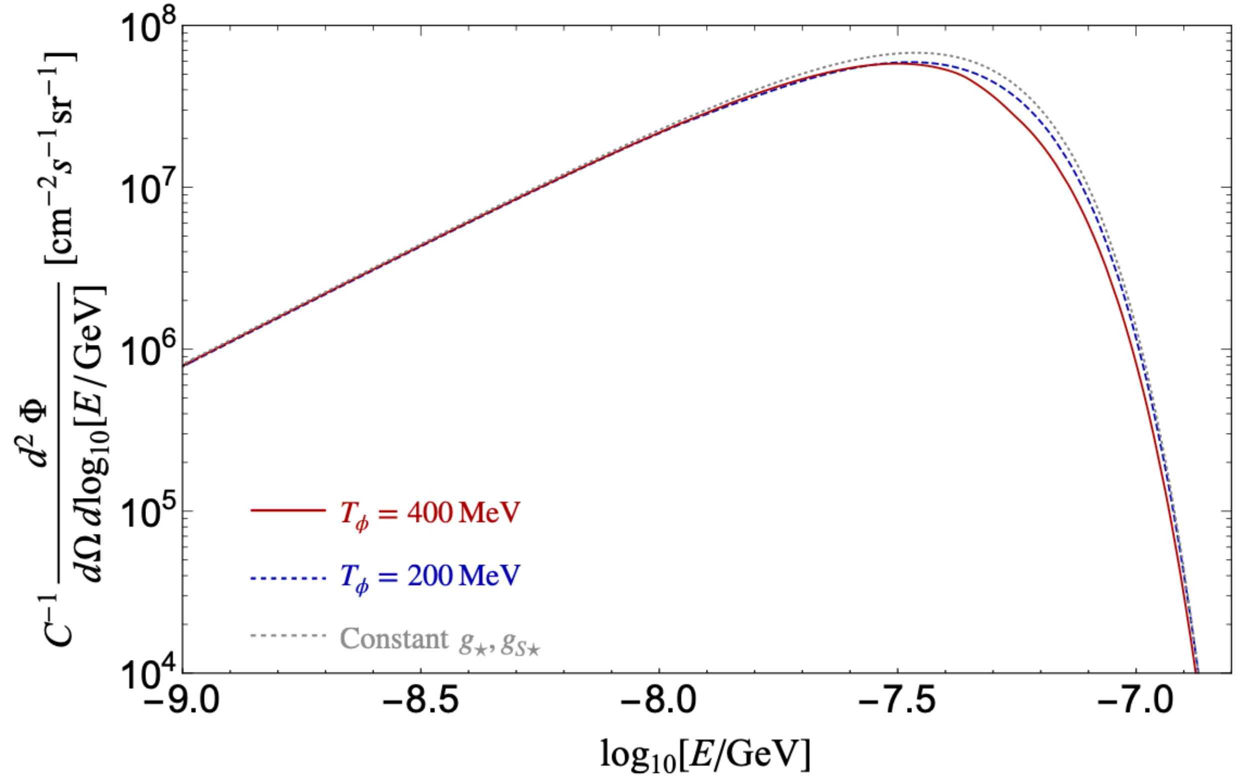

Figure. 2. The reheating flux dependence on the decoupling effect: $T_\phi = 400\,\mathrm{MeV}$ (red-solid line) and $T_\phi = 200\,\mathrm{MeV}$ (blue-dashed line, CASE A). We take $g_\star, g_{s\star}$ temperature in-

https://arxiv.org/pdf/2102.00006.pdf

Conclusions

Conclusions

- 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
- Axions tell us about the sun
  → Temperature + Composition
- Axion coupling and mass → Axion model?
- Axions can be a messenger of Inflation and Reheating

A little survey

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- Looking for potentially wrong or problematic papers
- (focused on experiments/experimental proposals)

Please participate!