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Axions and ALPs Beyond Discovery

--

Measuring their Properties 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[*], W. Yin[T] 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, [T]Tohoku U.

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The Axion and its ALPs

Axion/ALP couplings

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{4} g_{a\gamma\gamma} a (F^{\mu\nu})^2 + \frac{1}{2} g_{agg} a (G^{\mu\nu})^2 + \sum_f g_{aff} a \bar{f} \gamma^5 f$$

Couplings contain model information!

E.g. QCD axion $g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$

The QCD axion, precisely
Giovanni Grilli di Cortona (INFN, Trieste and SISSA, Trieste), Edward Hardy (ICTP, Trieste), Javier Pardo Vega (SISSA, Trieste and INFN, Trieste and ICTP, Trieste), Giovanni Villadoro (ICTP, Trieste) (Nov 9, 2015)
Published in: *JHEP* 01 (2016) 034 • e-Print: 1511.02867 [hep-ph]

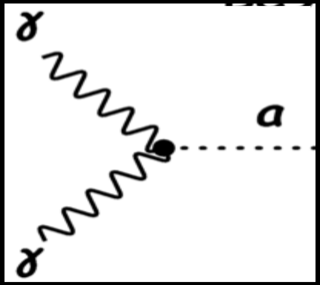
The landscape of QCD axion models
Luca Di Luzio (DESY), Maurizio Giannotti (Barry U.), Enrico Nardi (Frascati), Luca Visinelli (U. Amsterdam, GRAPPA) (Mar 2, 2020)
Published in: *Phys.Rept.* 870 (2020) 1-117 • e-Print: 2003.01100 [hep-ph]

Contains charges etc. of heavy particles

Couplings fixed by scale of symmetry breaking: f_a

- Photon coupling

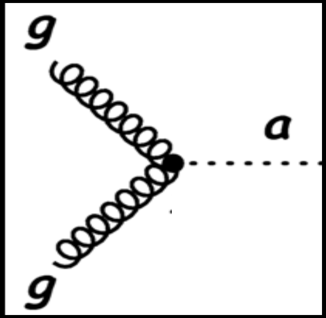
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$



small → $$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$ ← large

- Gluon coupling

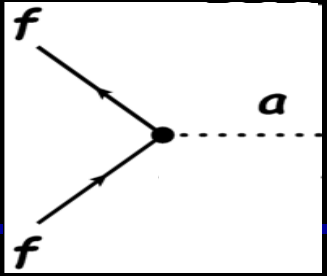
$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu} \tilde{G}_{\mu\nu}$$



small → $$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$ ← large

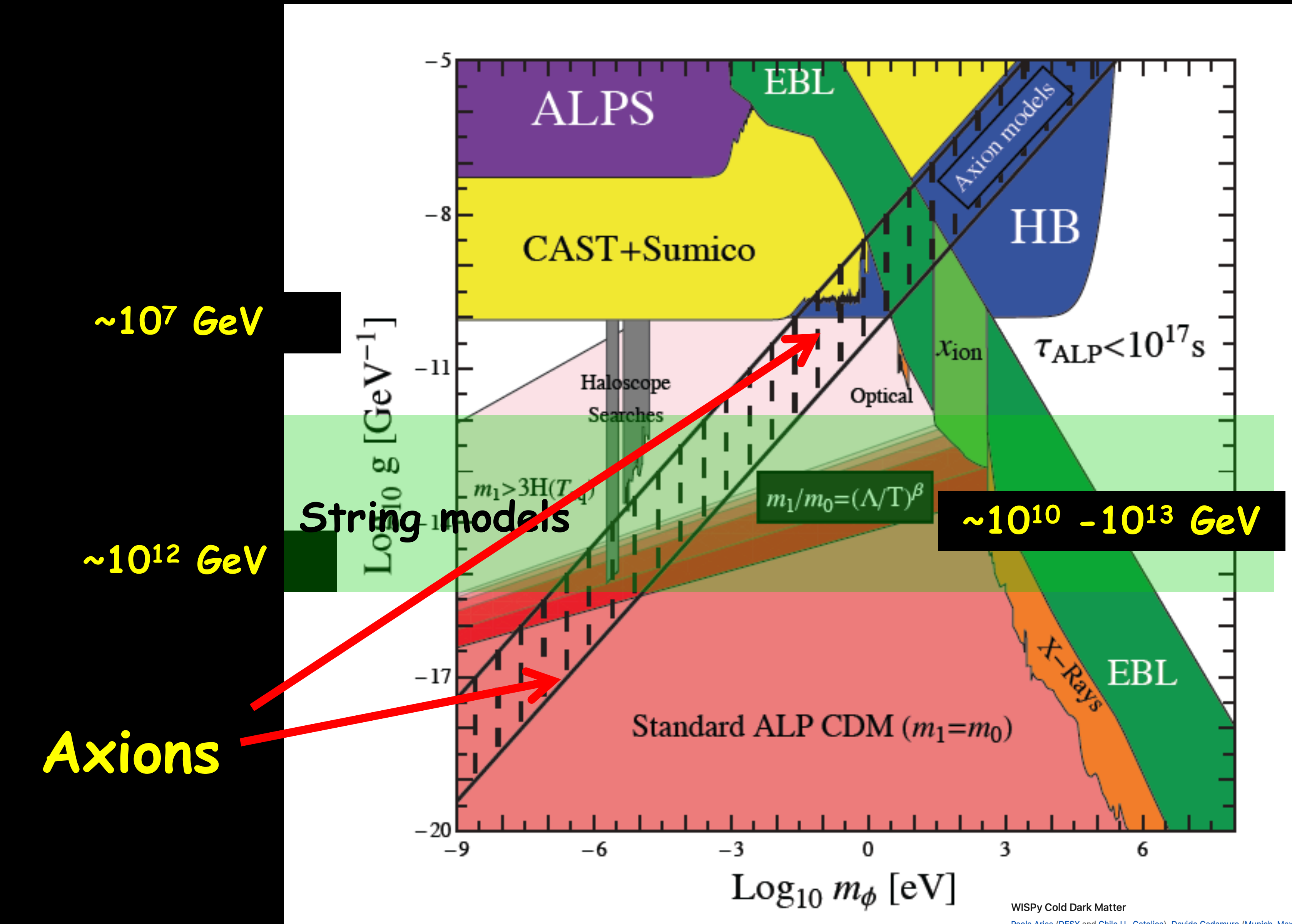
- Fermion couplings

$$\mathcal{L} \supset g_{a\psi\psi} a \bar{\psi} \gamma^5 \psi$$



small → $$g_{a\psi\psi} \sim \frac{m_\psi}{f_a}$$ ← large

Axion(-like particle)s: Photon cloupling



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]

Dark Matters

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
- Axions can be a probe of deep UV physics

Axions are the Best DM candidate ;-)

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Heidelberg University

- Axions are motivated by SM problem
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Axion(-like particle) Dark Matter

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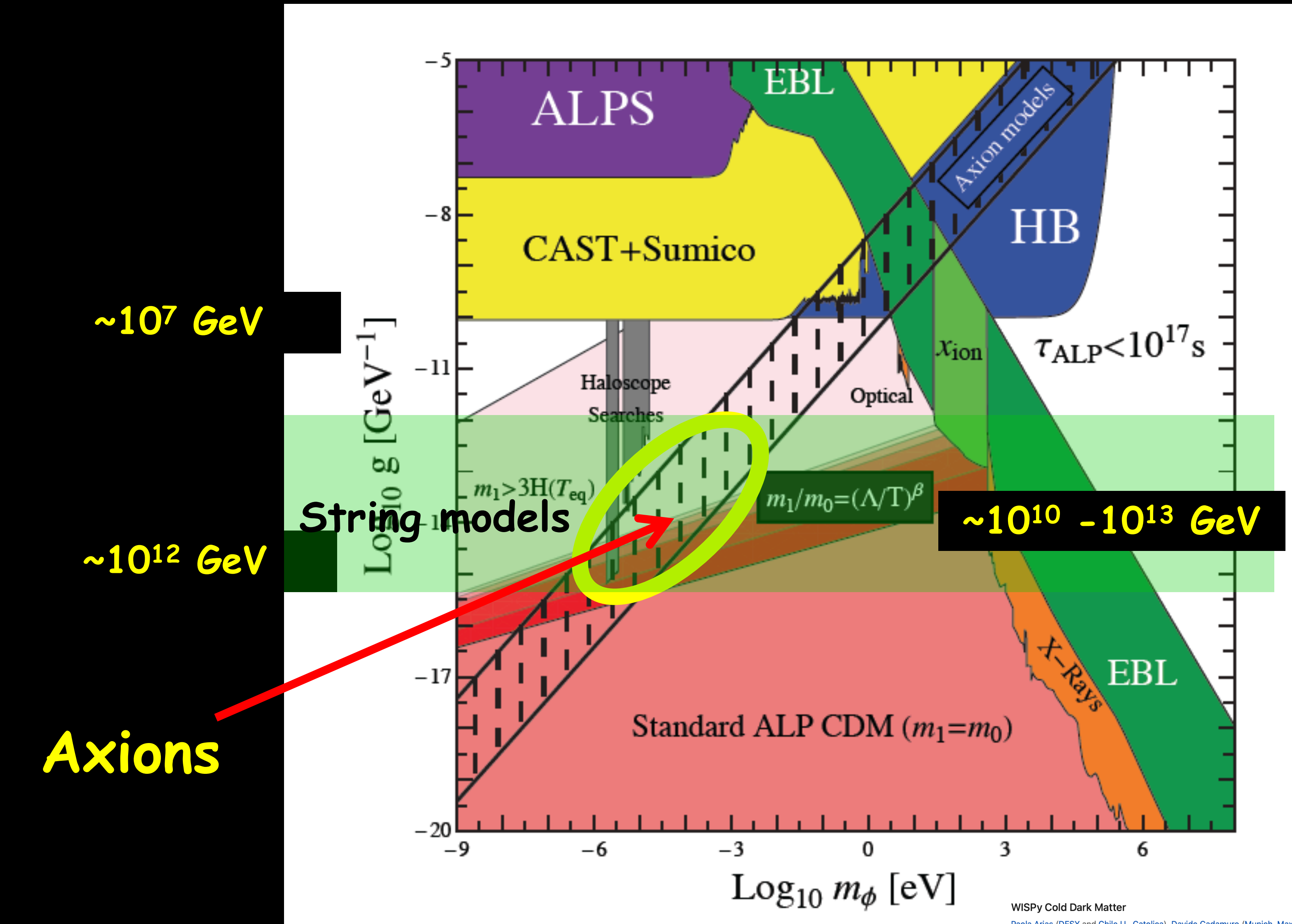

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Axion(-like particle) Dark Matter

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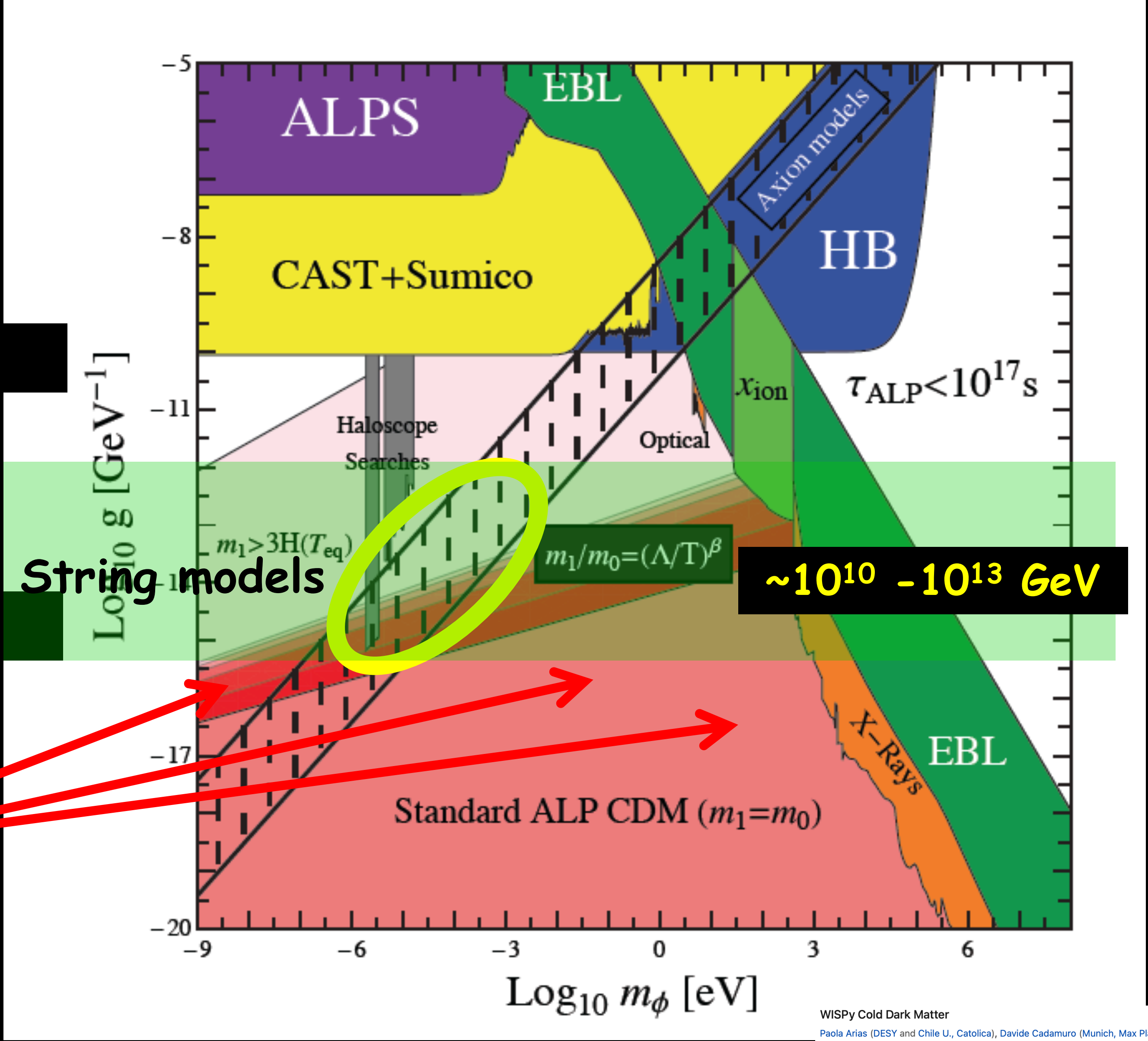
~10^7 GeV

~10^12 GeV

String models

~10^10 -10^13 GeV

ALPs



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

Detecting Axion/ALP DM

→ Probably much more on this in Gray's talk on Thursday

Use a plentiful source of axions

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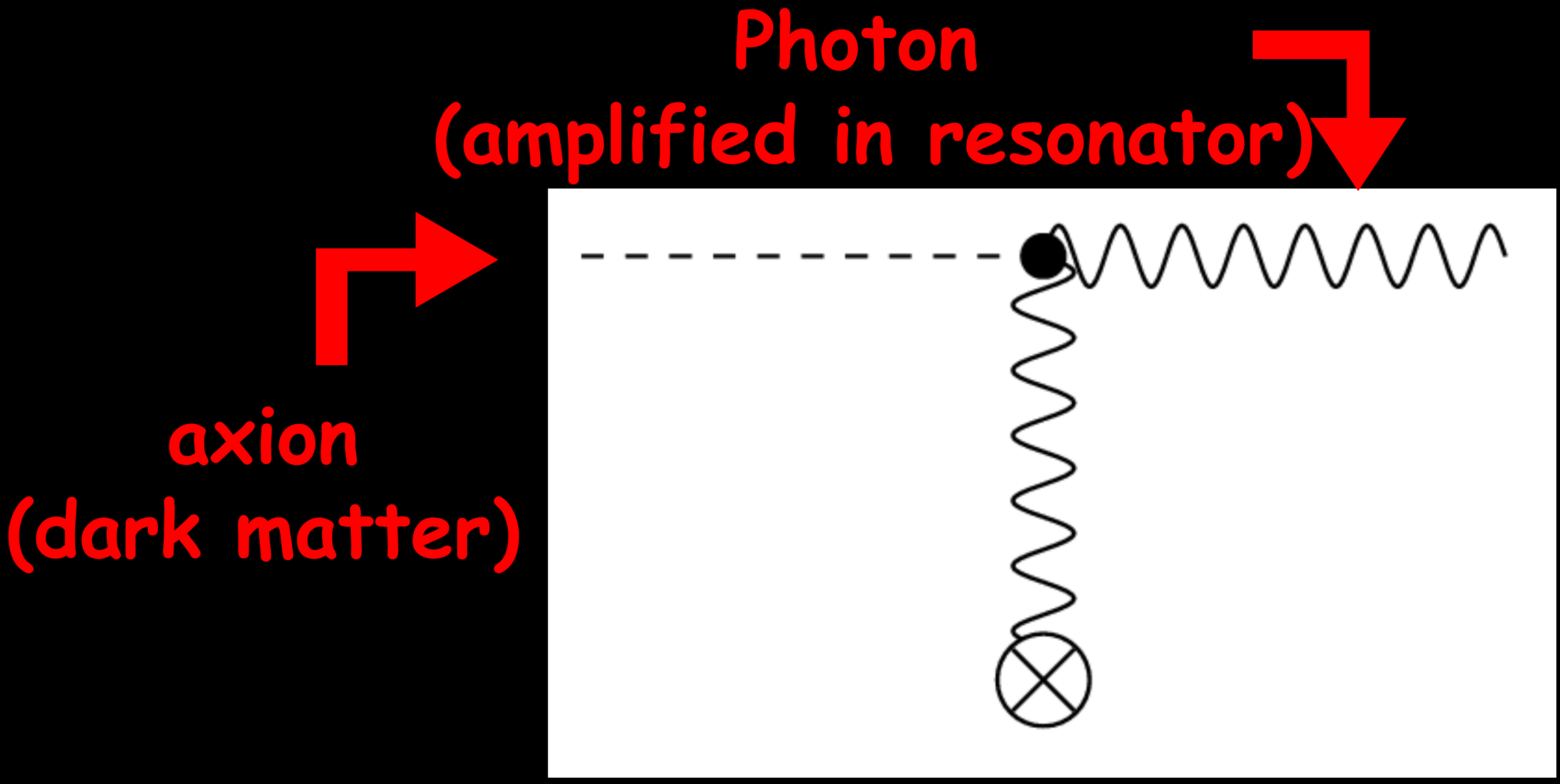
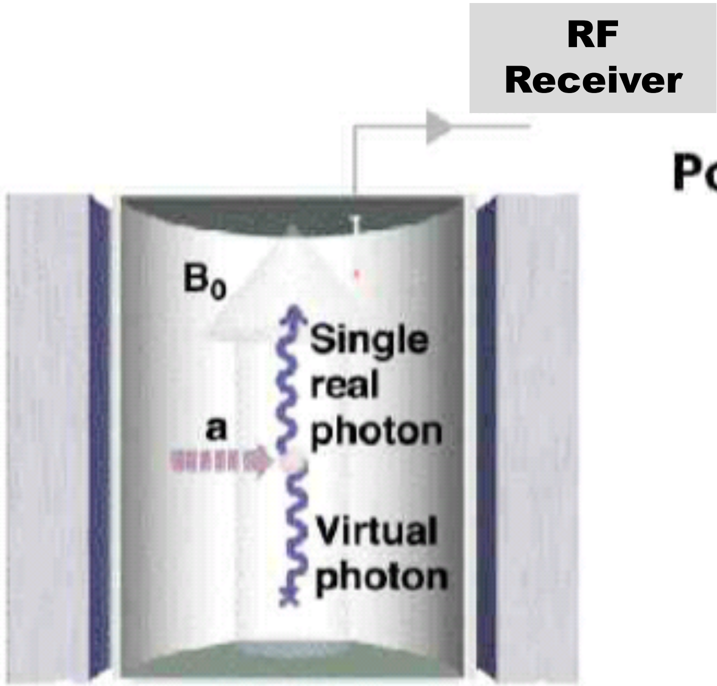
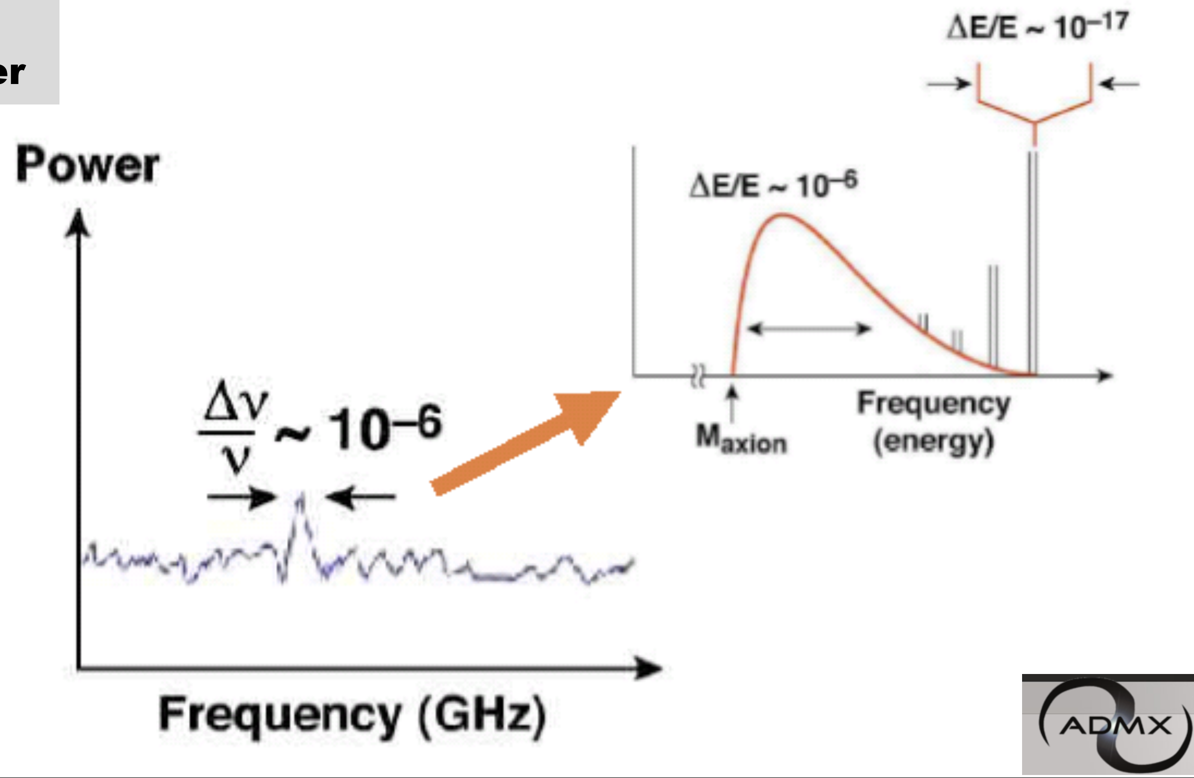
- Photon Regeneration



Signal: Total energy of axion





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

Virial velocity in galaxy halo!

An extremely sensitive probe!!!

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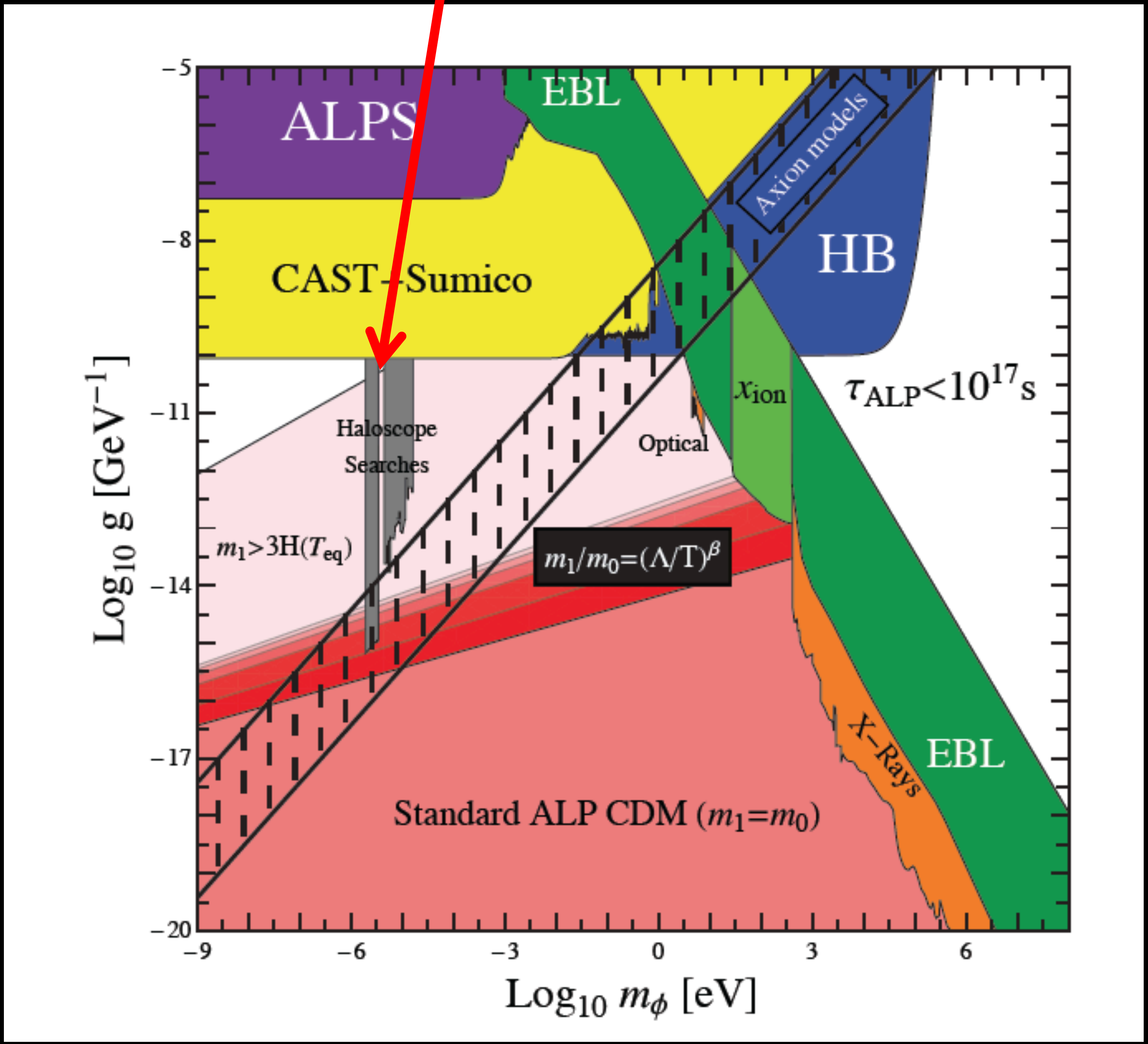

A discovery possible any minute!

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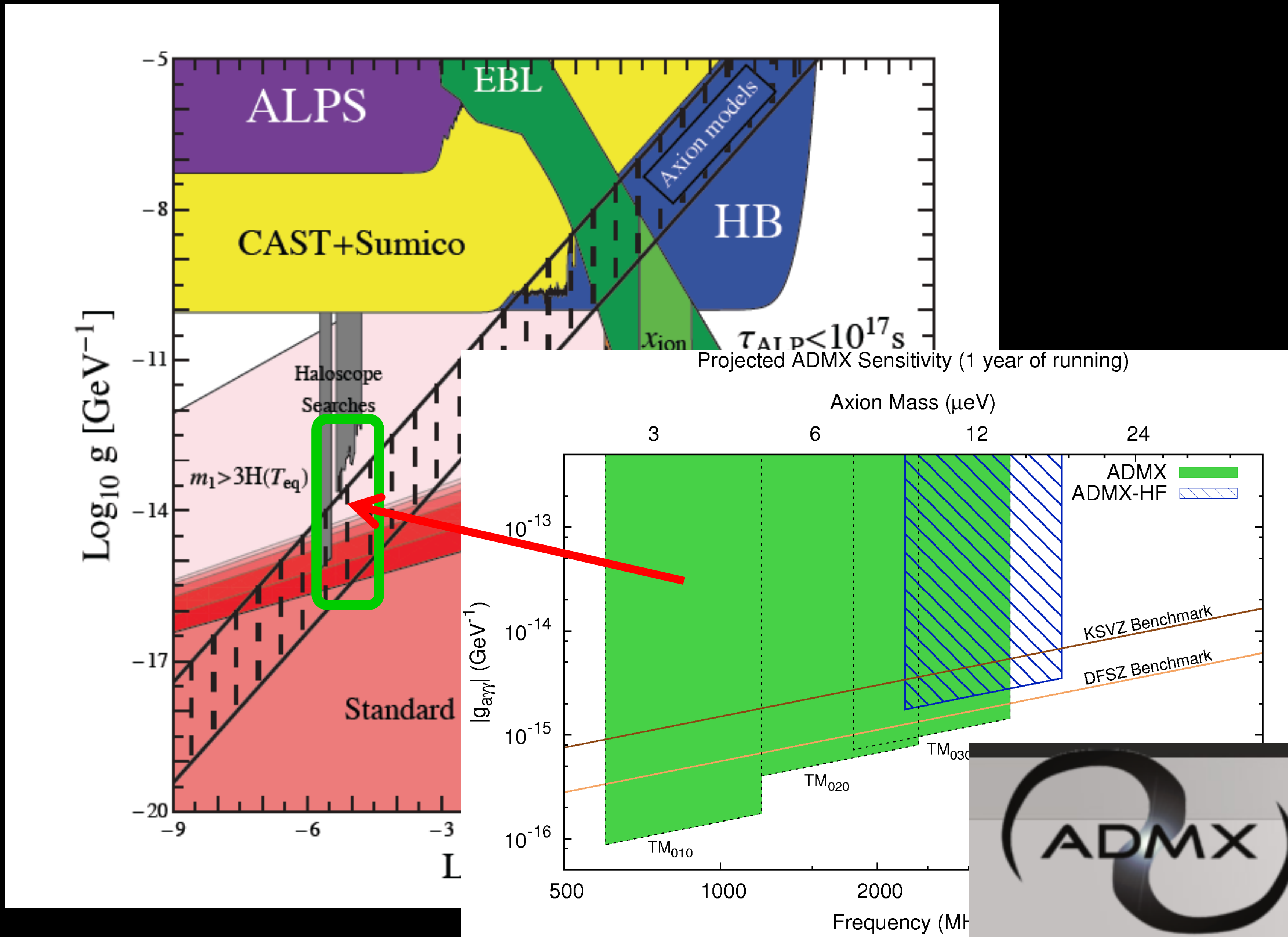
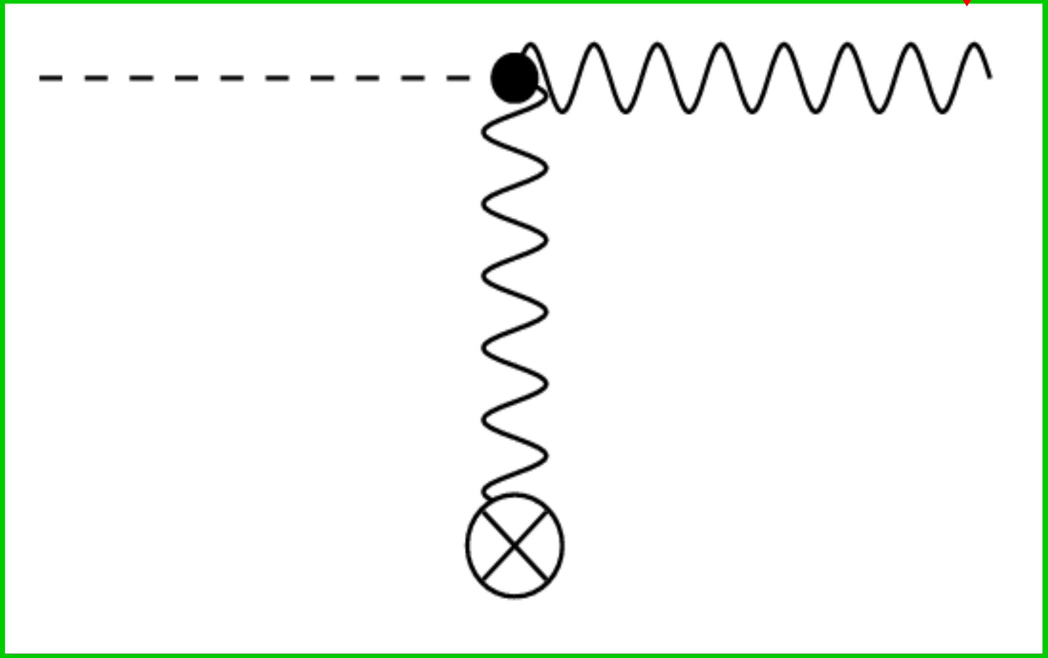


Electricity from Dark Matter ;-).

- 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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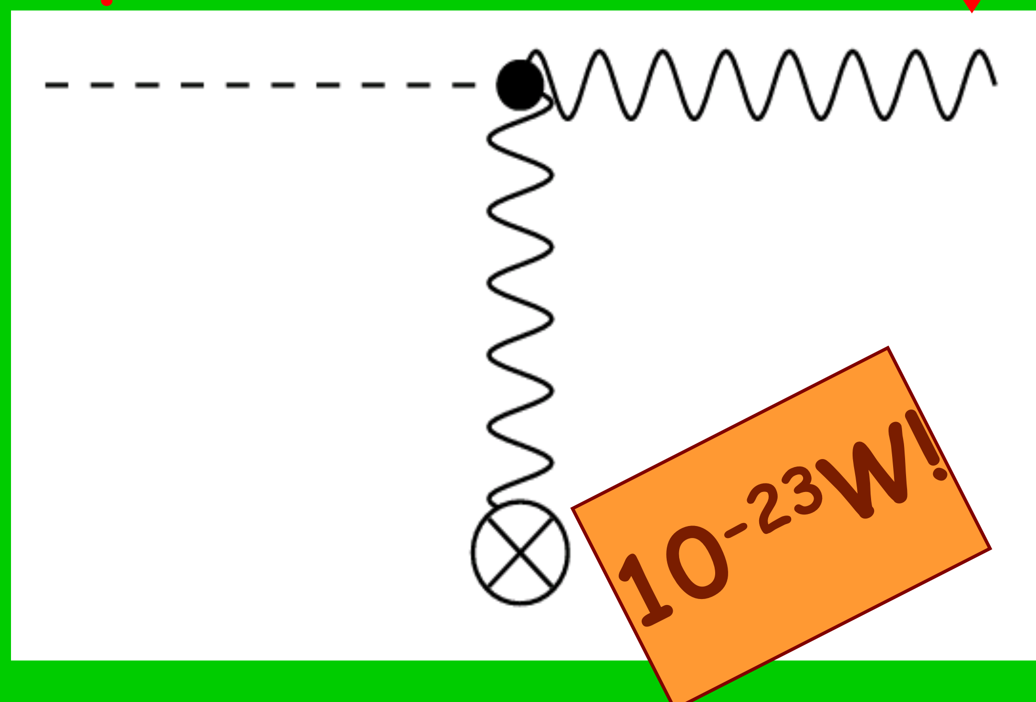
- Photon Regeneration

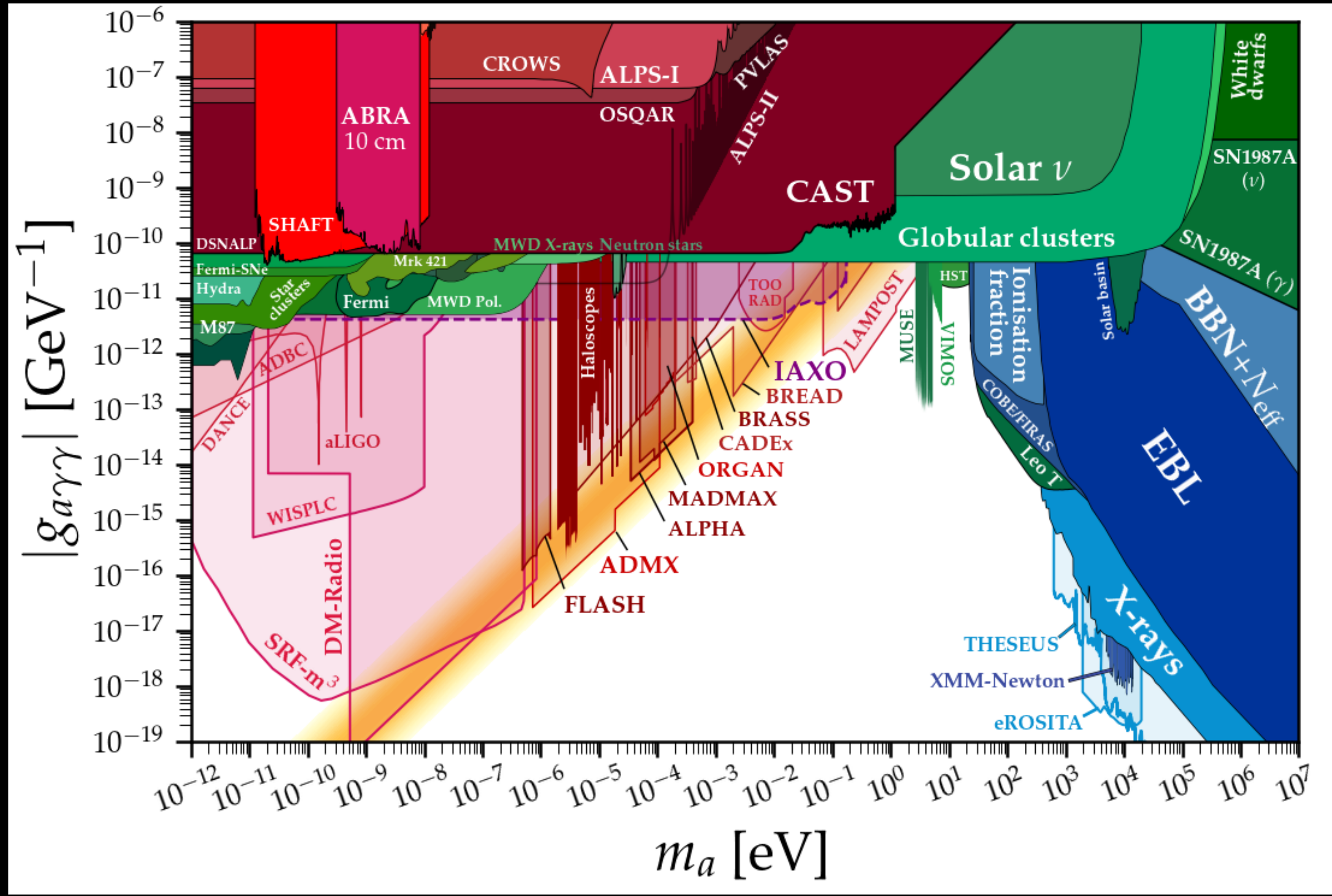
Photon
(amplified in resonator)

axion
(dark matter)



Many more experiments…

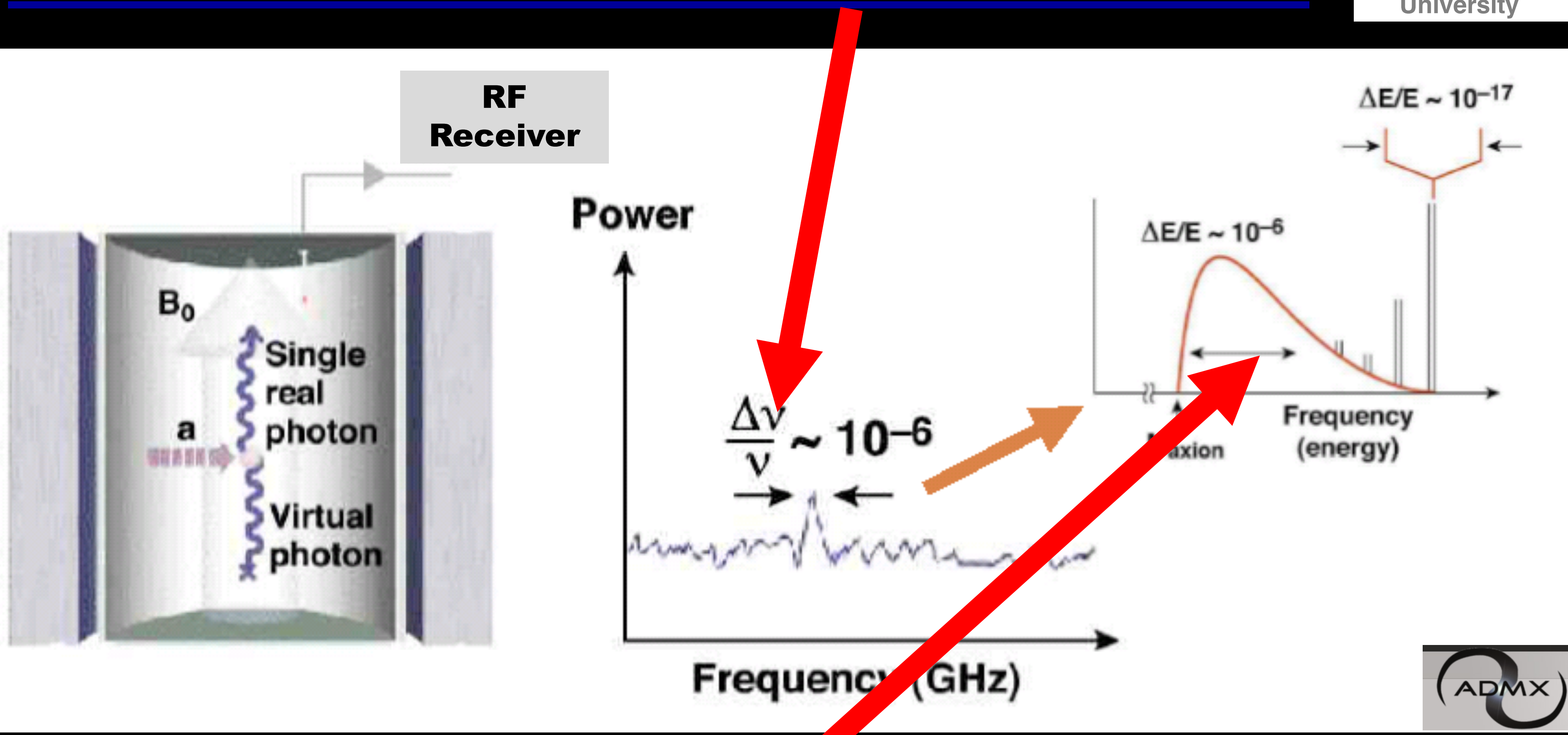
- Abracadabra
- BRASS
- Bread
- Cultask
- DMRadio
- EDM ring
- Haystac
- Lamppost
- Organ
- SRFcavities
- TooRad
- Quax
- …



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

DM Astrophysics

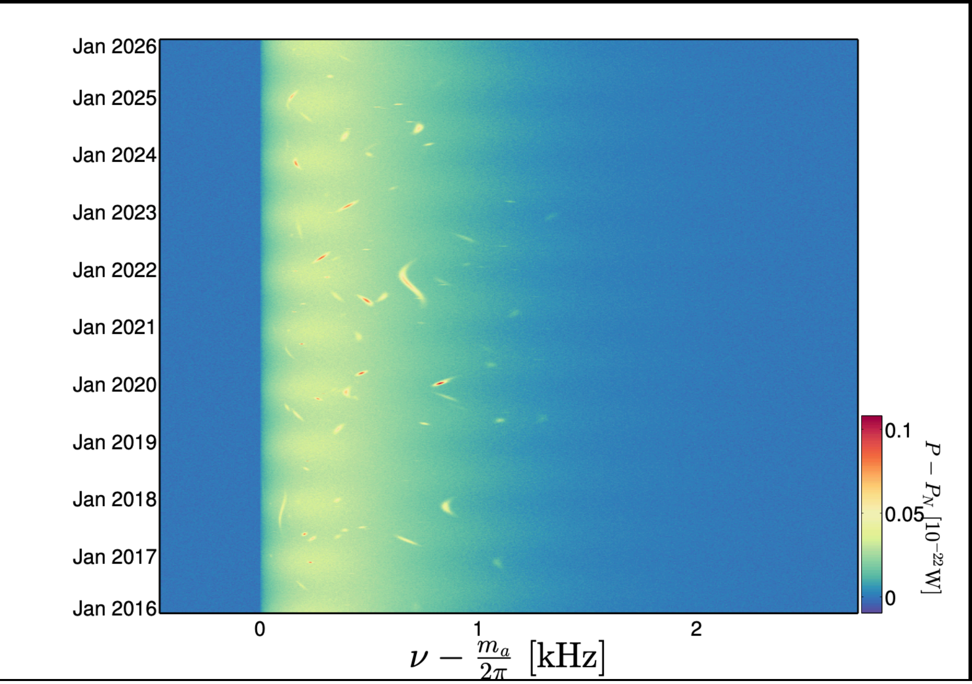
Signal: High resolution possible



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

Axion Astronomy...

Streams and local objects...

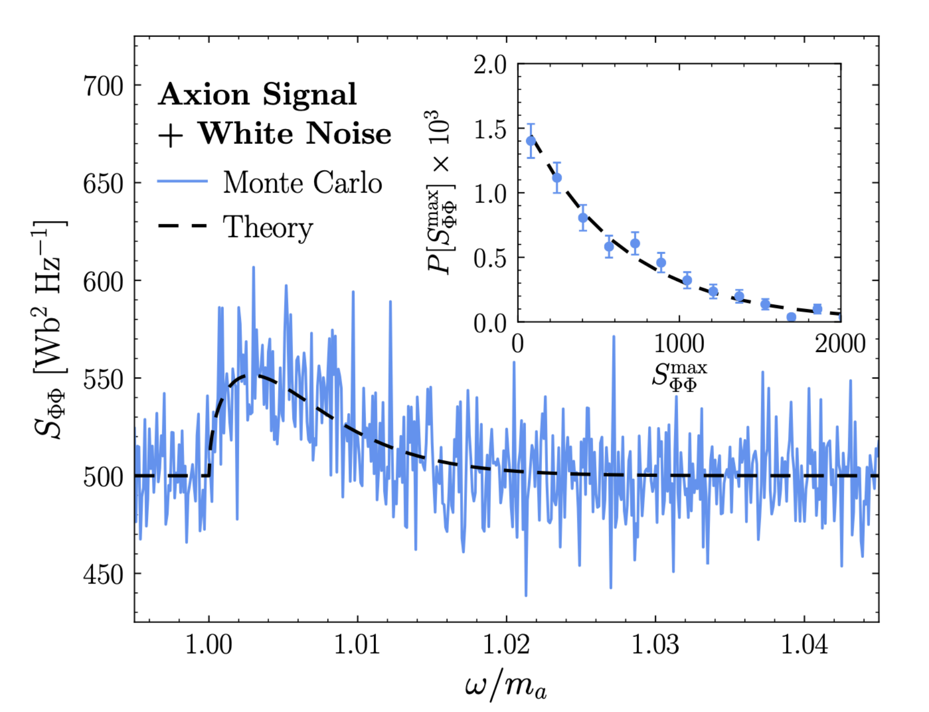


Axion astronomy with microwave cavity experiments

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

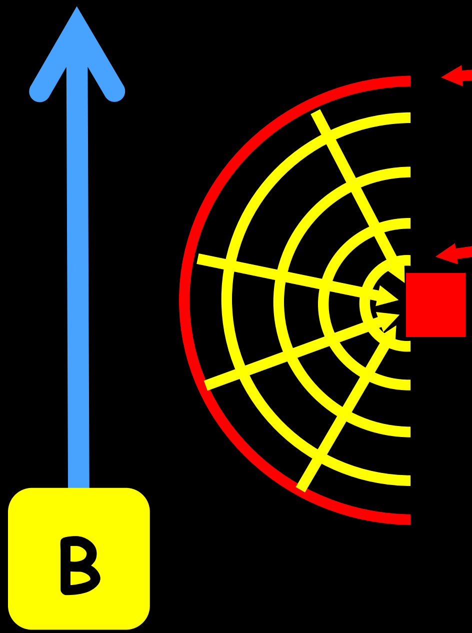
- Networks of multiple detectors can give directional sensitivity

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

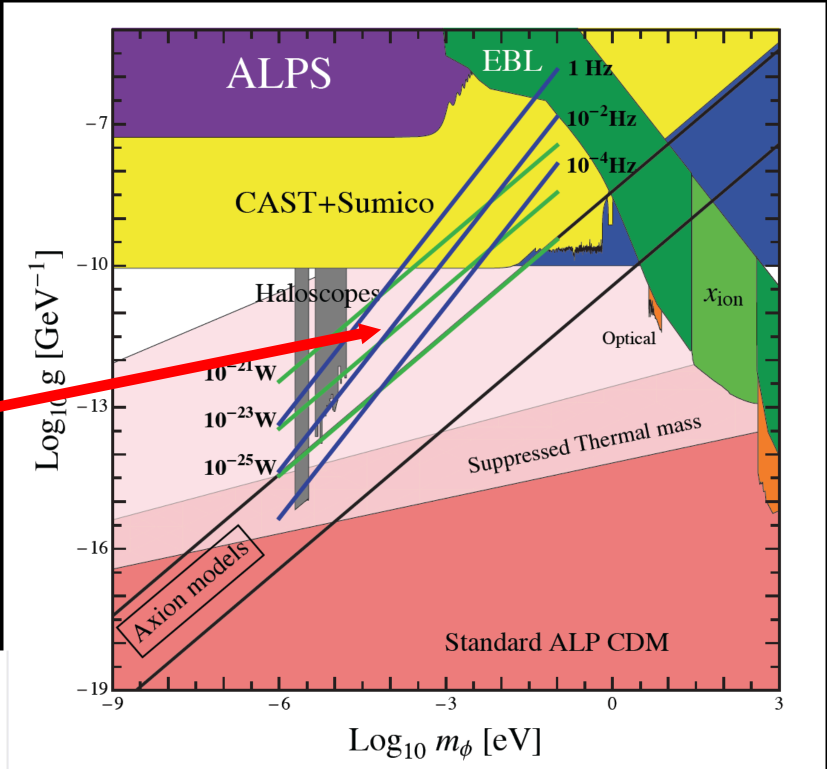


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



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

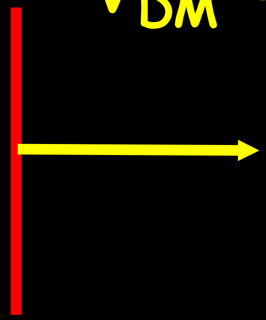
Dieter Horns (Hamburg U.), Joerg Jaeckel (Durham U., IPPP and Heidelberg U.), Axel Lindner (DESY), Andrei Lobanov (Bonn, Max Planck Inst., Radioastron.), Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.) et al. (Dec, 2012)

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

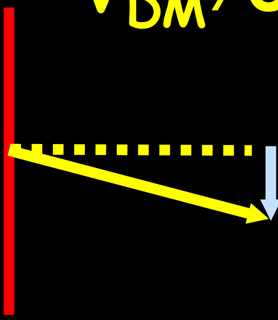
Taking a picture of the DM velocity

- Emission from moving dark matter

$V_{DM} = 0$



$V_{DM} \neq 0 =$ ↓

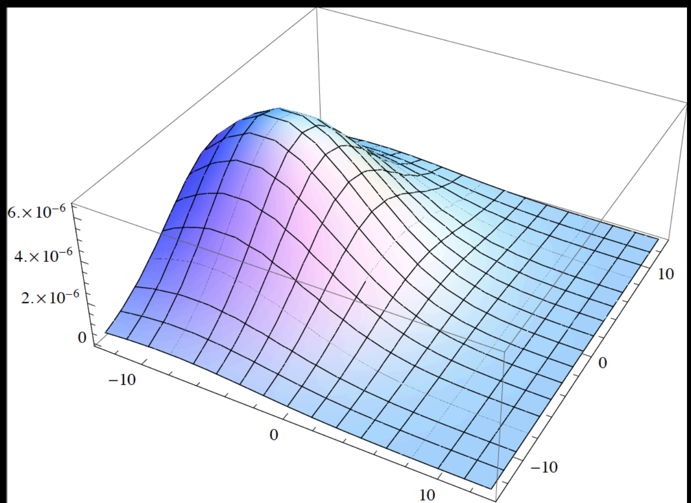


An antenna for directional detection of WISPy dark matter
Joerg Jaeckel (Heidelberg U.), Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.) (Jul 26, 2013)
Published in: *JCAP* 11 (2013) 016 • e-Print: 1307.7181 [hep-ph]

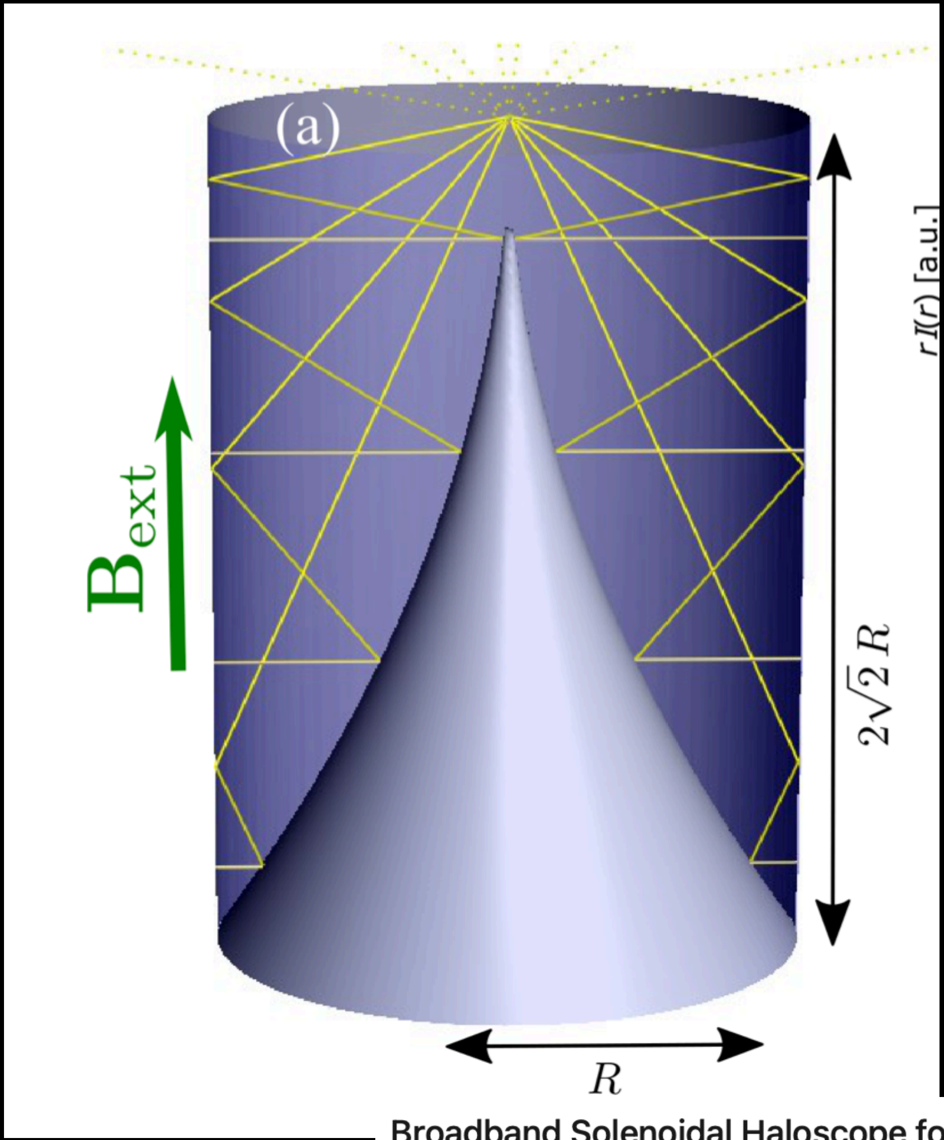
Directional Resolution of Dish Antenna Experiments to Search for WISPy Dark Matter
Joerg Jaeckel (Heidelberg U.), Stefan Knirck (Heidelberg U.) (Sep 1, 2015)
Published in: *JCAP* 01 (2016) 005 • e-Print: 1509.00371 [hep-ph]

- A picture of the DM-velocity distribution

Screen



Can also use cool geometries: BREAD



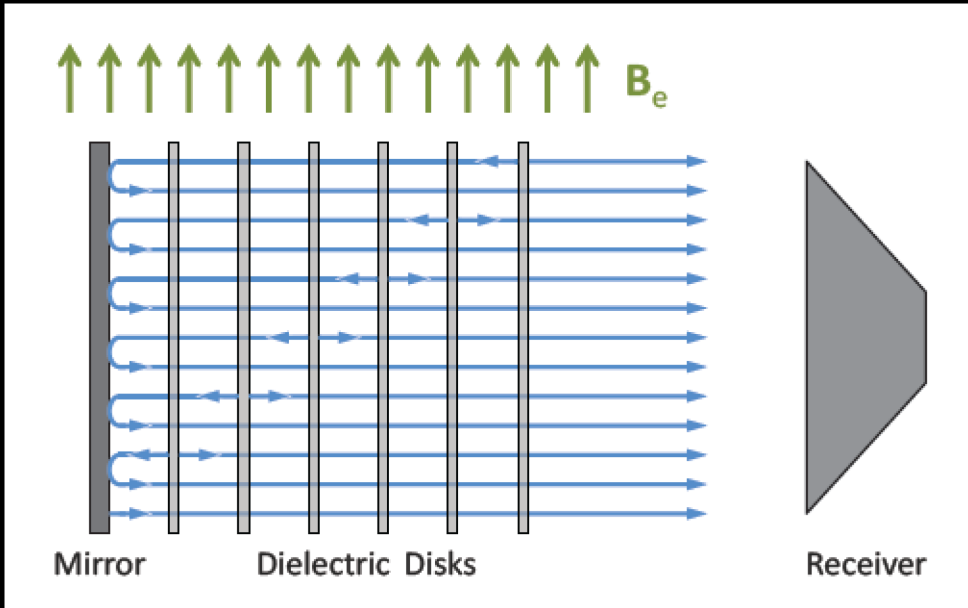
Broadband Solenoidal Haloscope for Terahertz Axion Detection

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 project at MPP



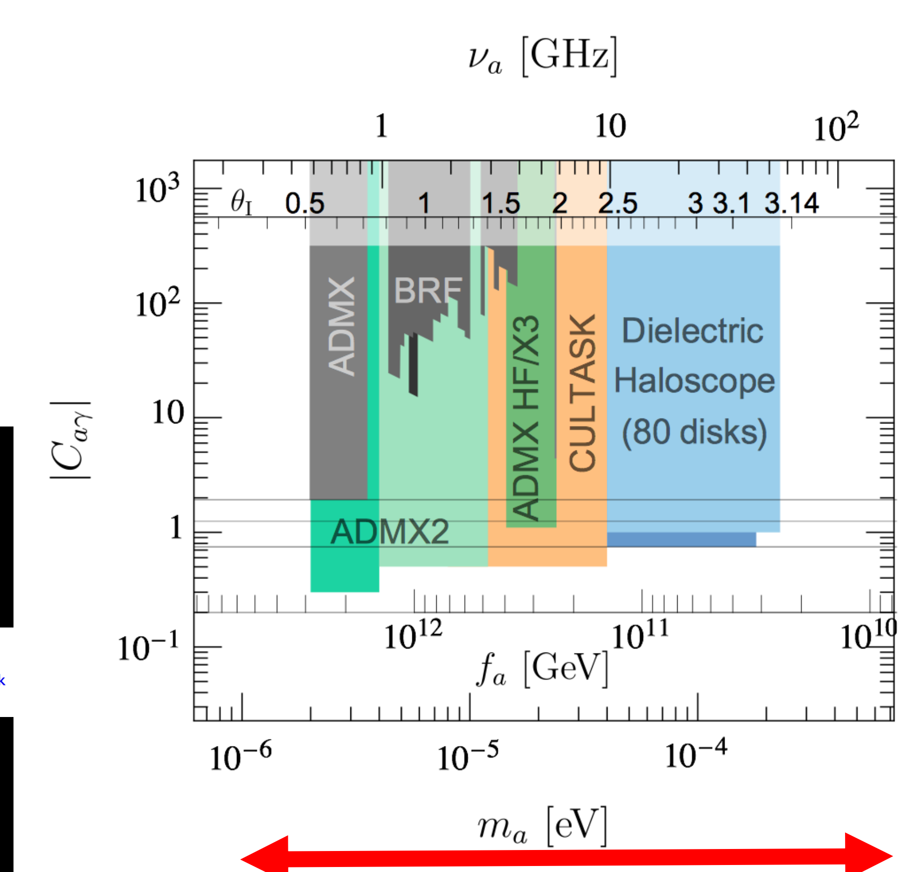
Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

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

Establishing Axions as "The Dark Matter"

A signal does not yet establish DM

- 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...

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e-Print: 2307.11871 [hep-ph]

Let's find an Axion Mini-cluster

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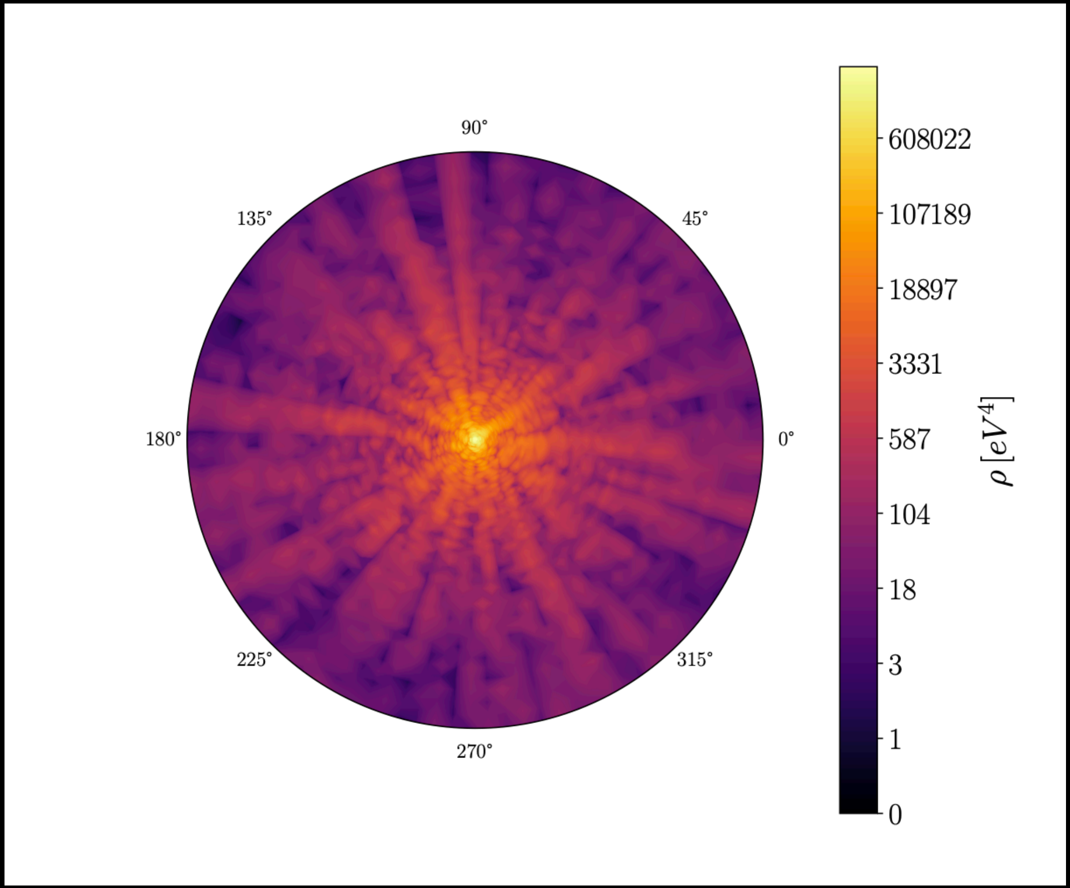

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...and fly through it

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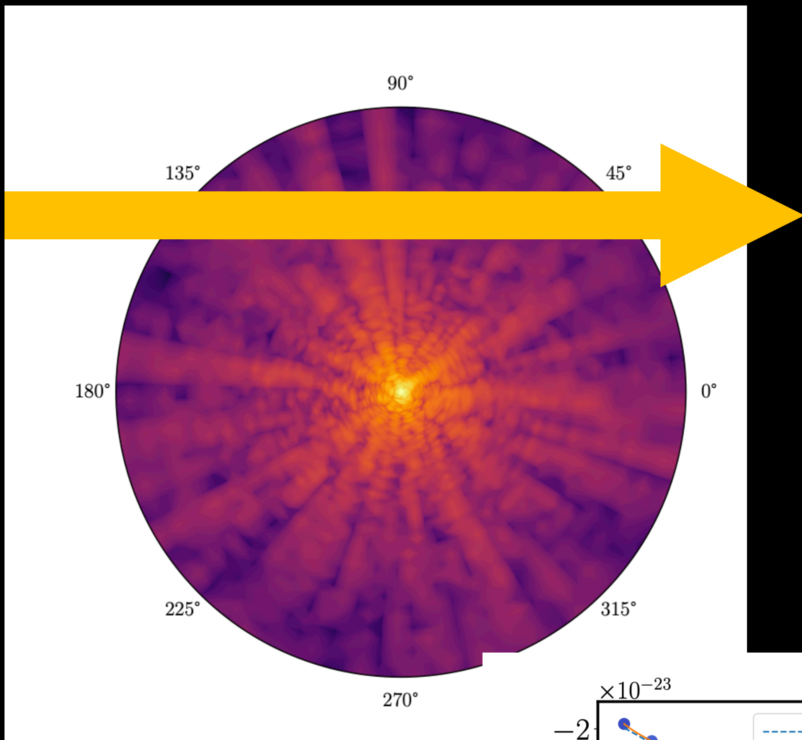
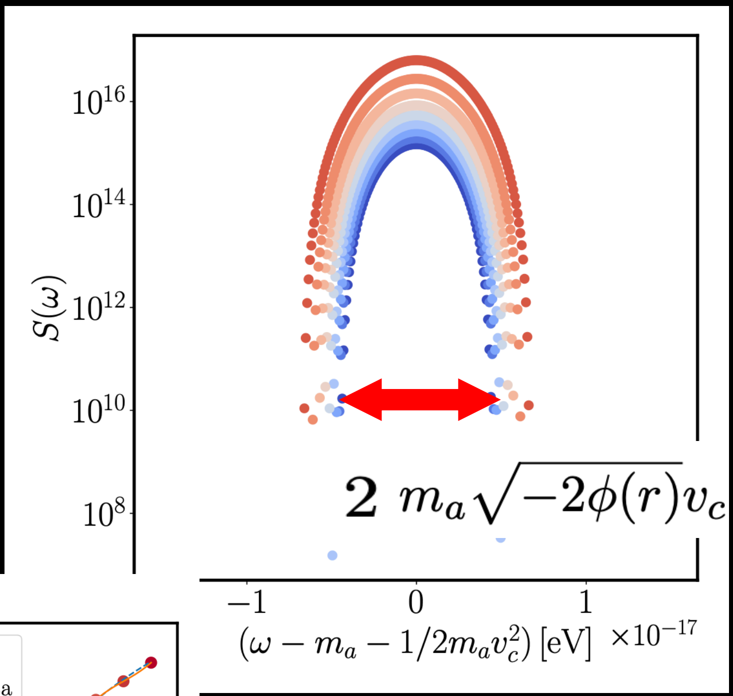
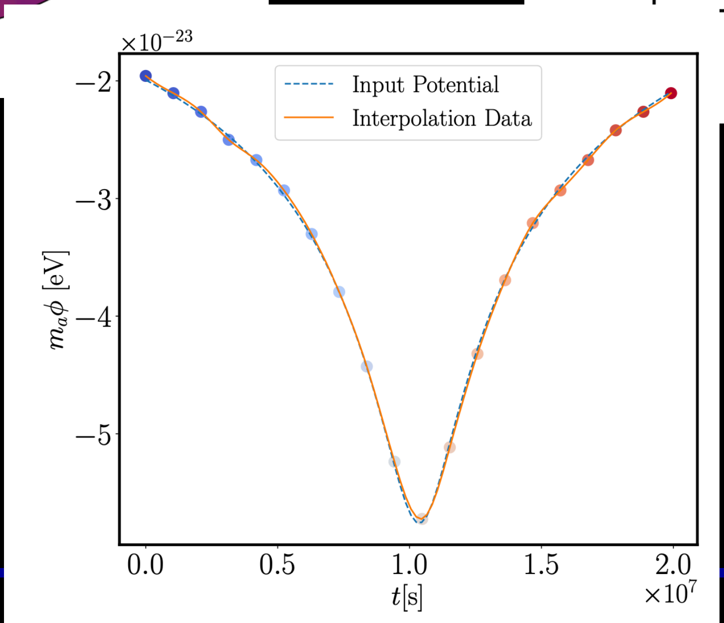


Power spectrum along the path





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Reconstruct minicluster density...

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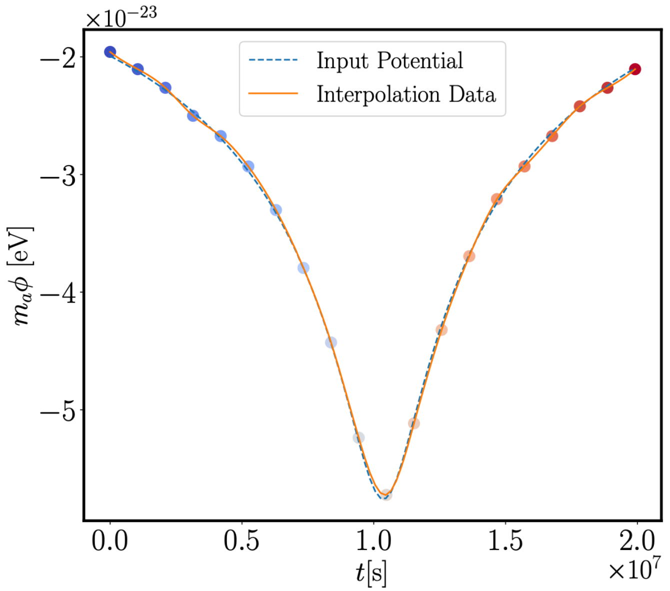
- Poisson equation (along path)

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

\+



Determined

Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density
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e-Print: 2307.11871 [hep-ph]

Measure coupling...

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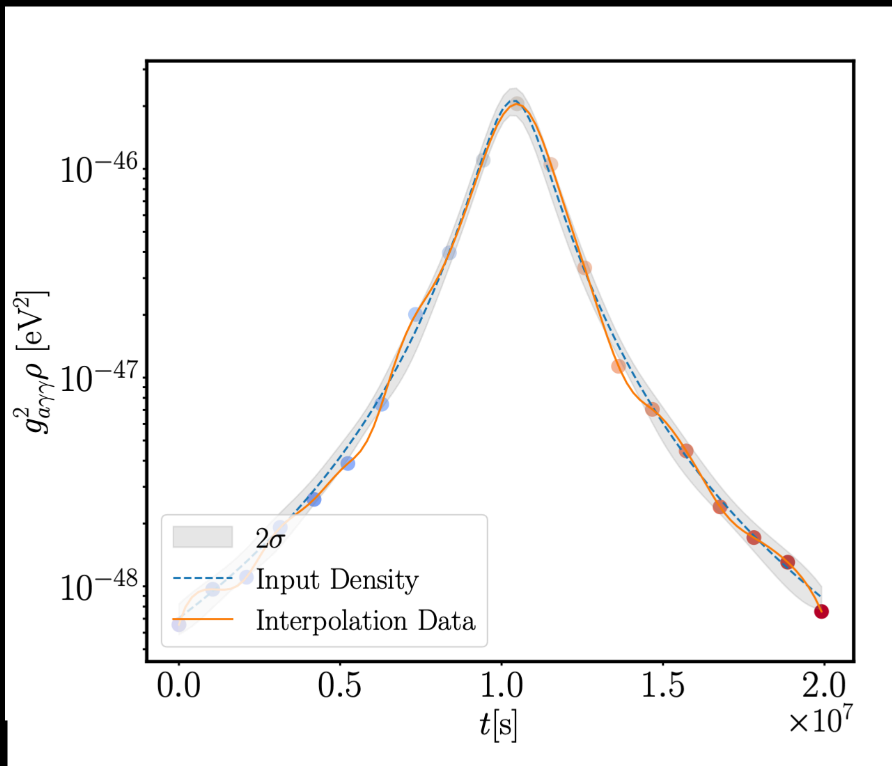
- Power along the path



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

Already known

➔ Obtain g

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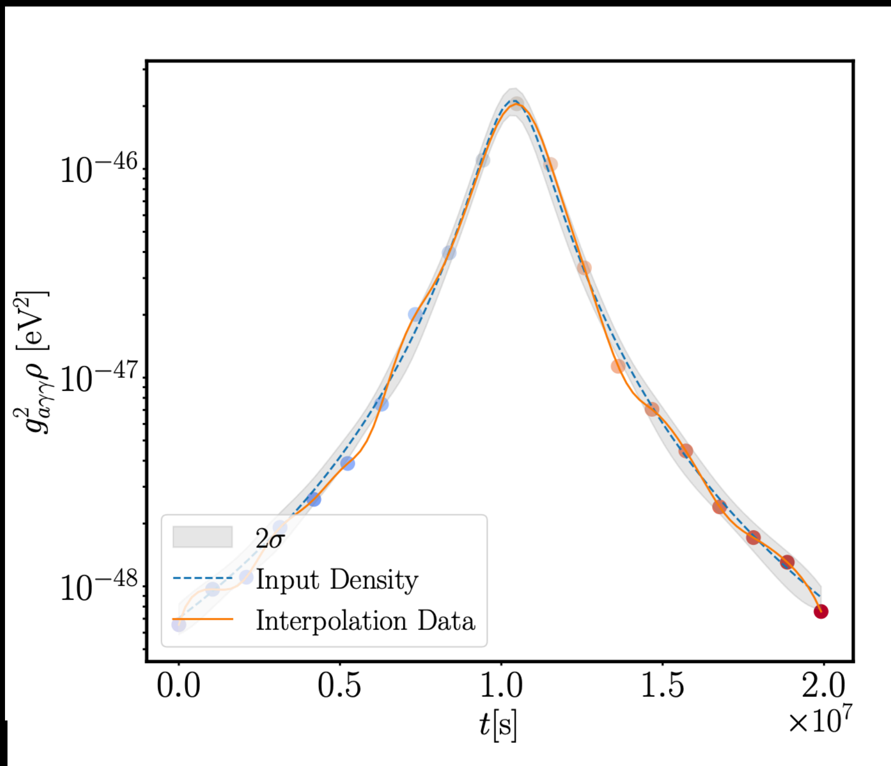
Measure coupling...

- 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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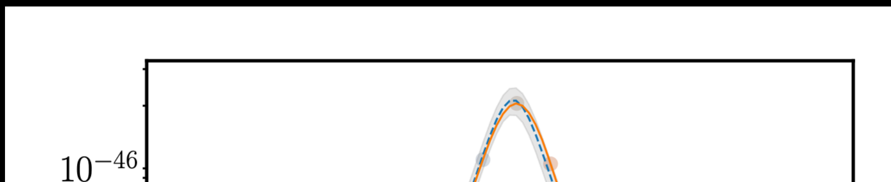
- Power along the path



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

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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e-Print: 2307.11871 [hep-ph]

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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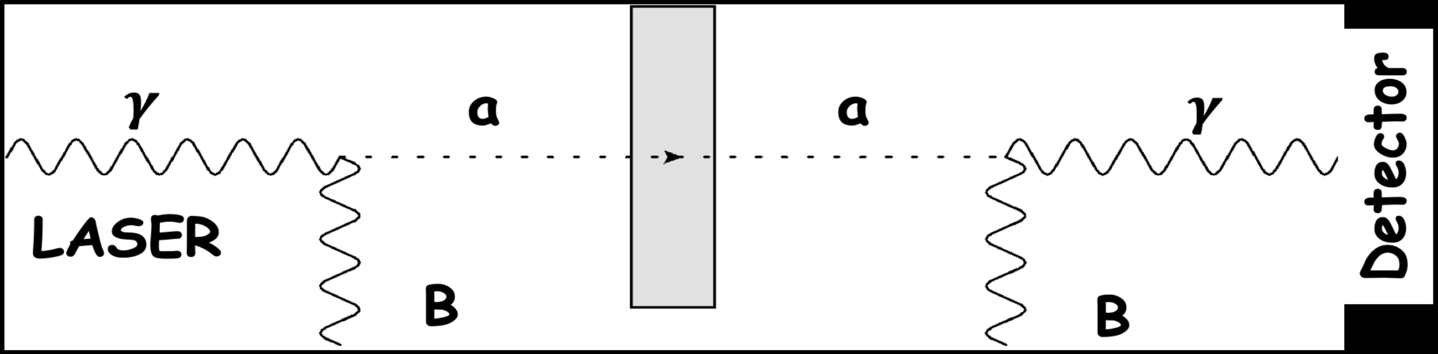
- What is an LSW experiment?

Light shining through walls

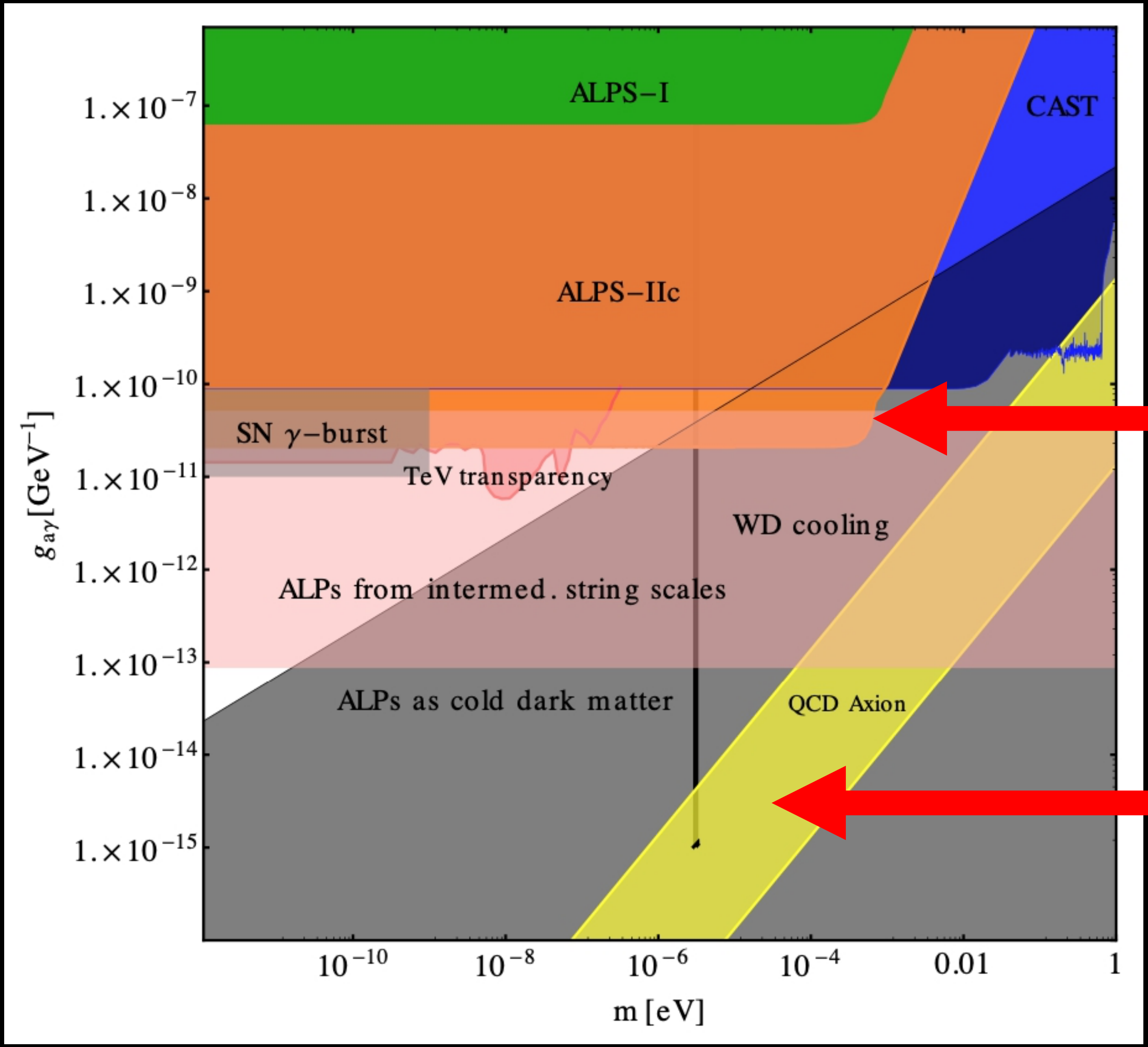


- Probability to see the light

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

Purely laboratory based → determine g

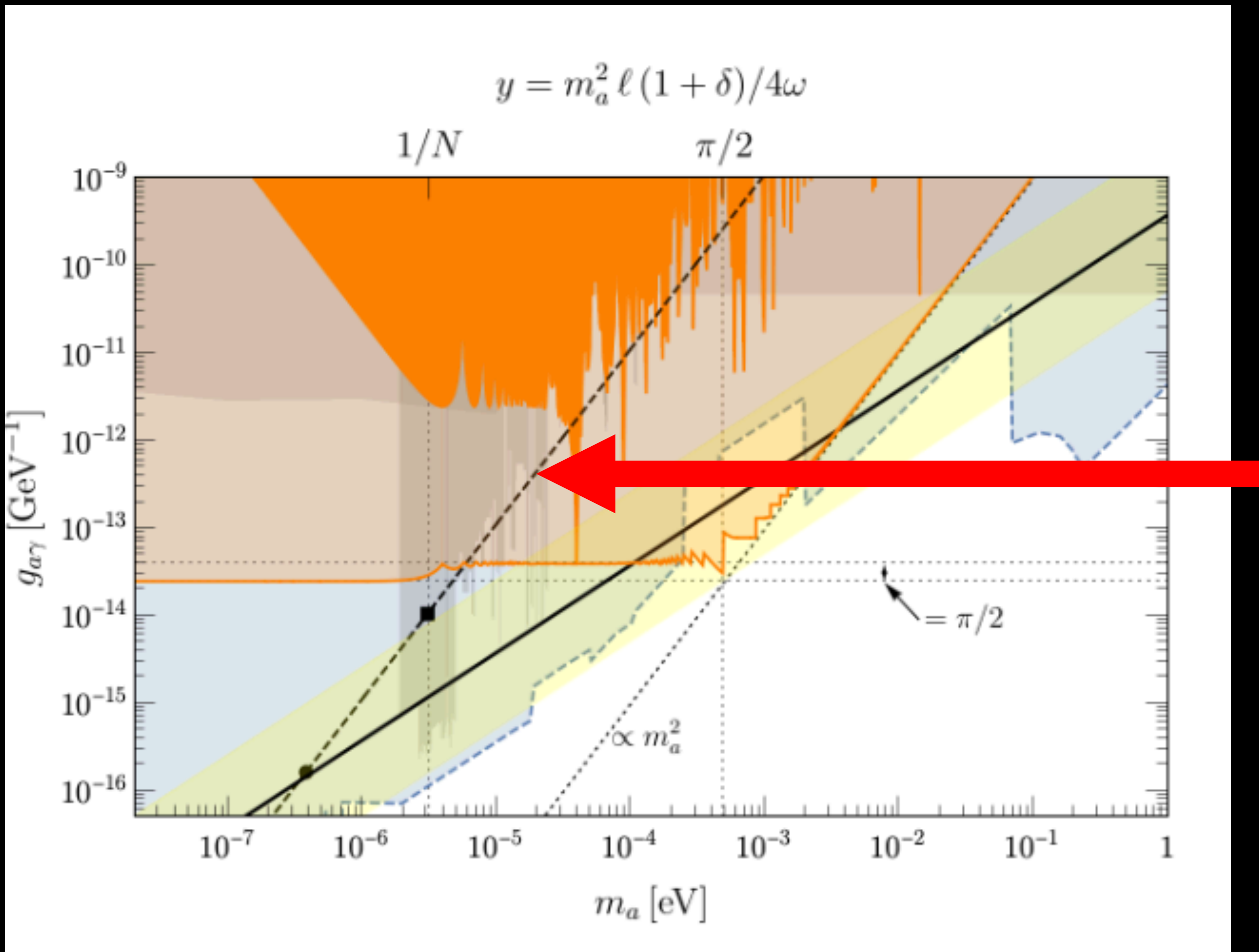
Not so easy... ALPS II



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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Optimize magnet configuration

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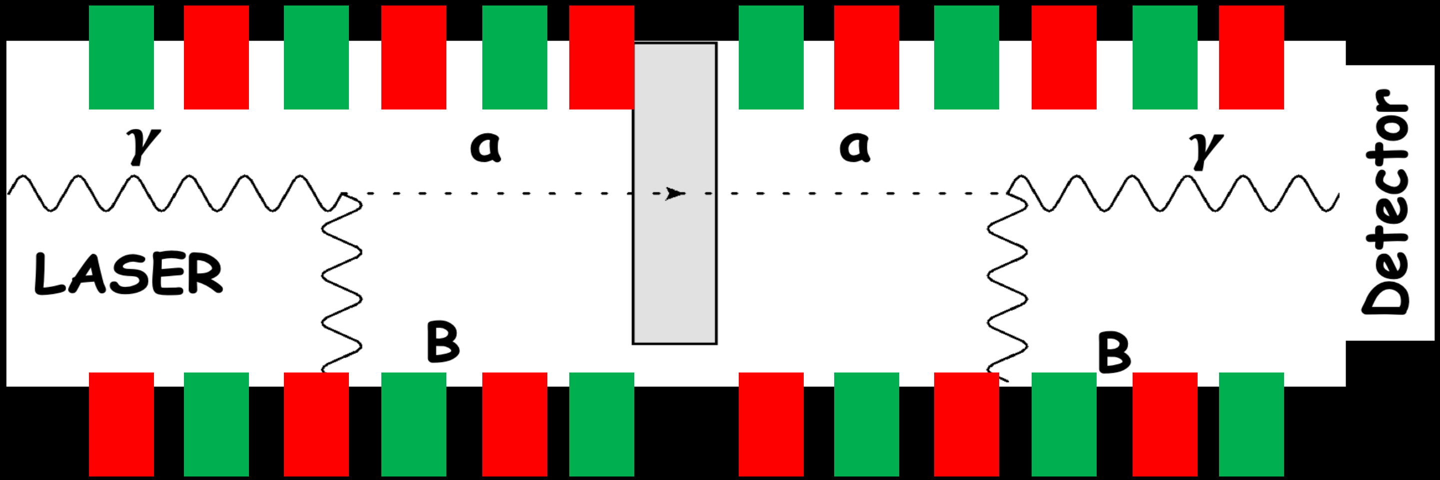

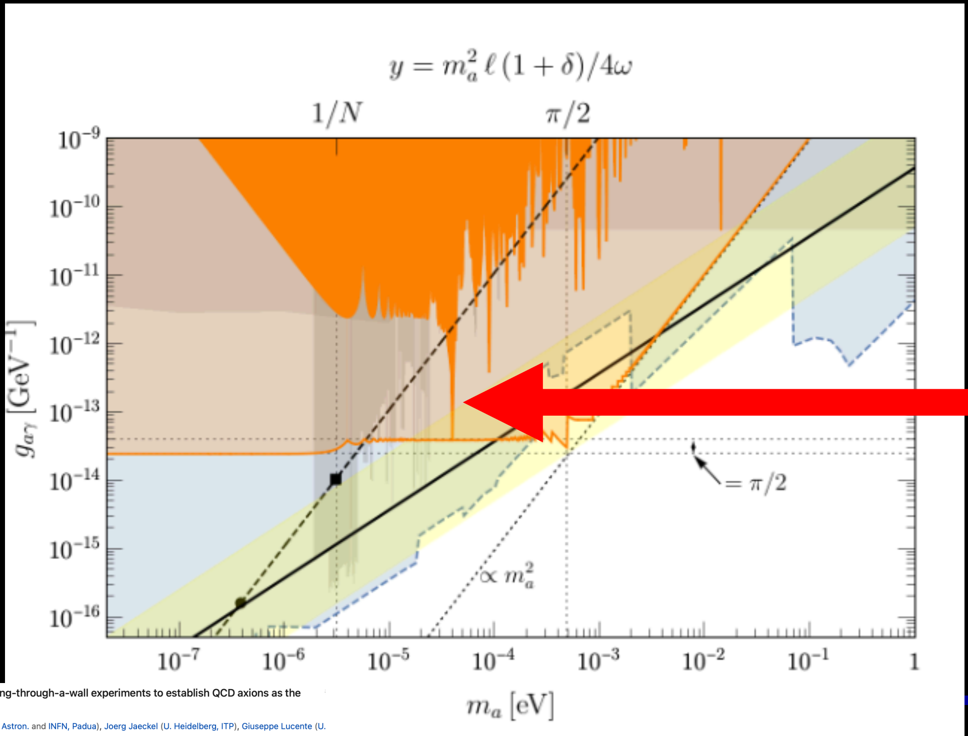

Alternating magnets

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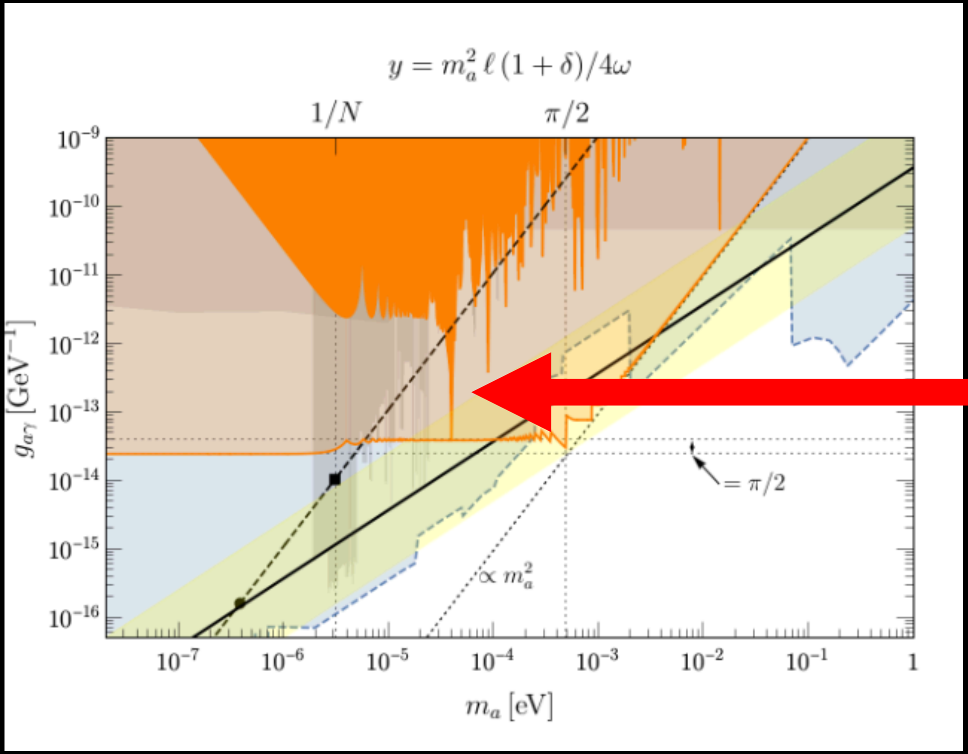
Sebastian Hoof (U. Padua, Dept. Phys. Astron. and INFN, Padua), Joerg Jaeckel (U. Heidelberg, ITP), Giuseppe Lucente (U. Heidelberg, ITP and Kirchhoff Inst. Phys.) (Jul 5, 2024)

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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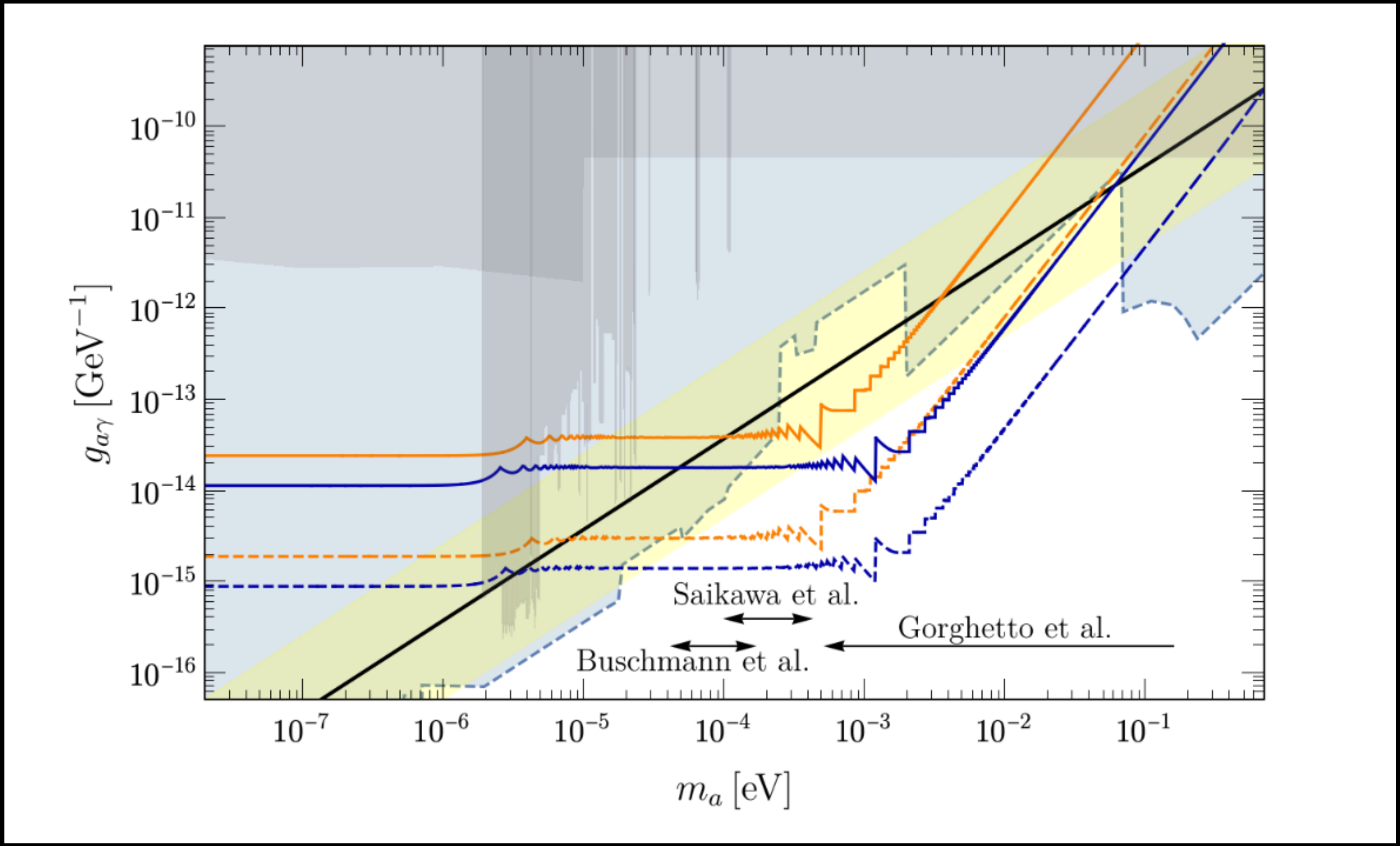
Discovery region



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Price tag...

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

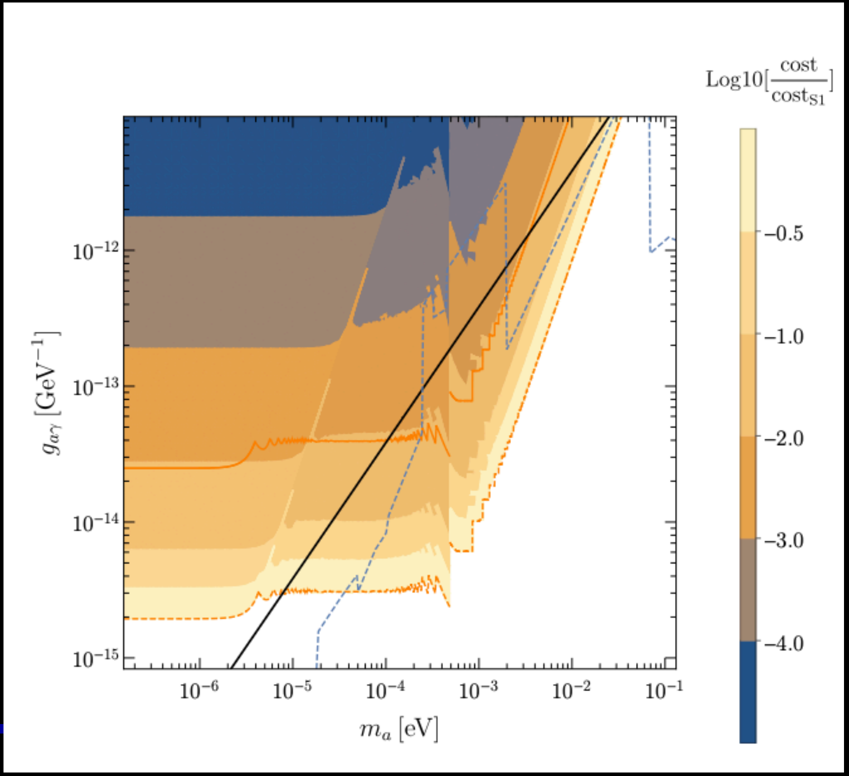
+

many strong magnets

~

few x 100 GEuro

➔Pick cheapest option



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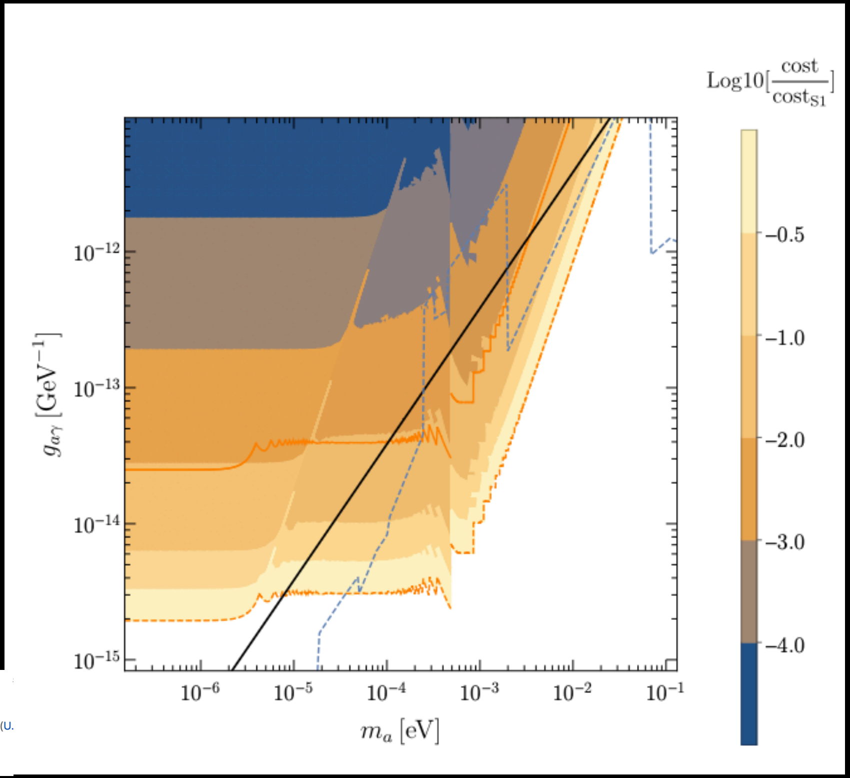

TimeWarp

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e-Print: 2407.04772 [hep-ph]

Dark Astrophysics

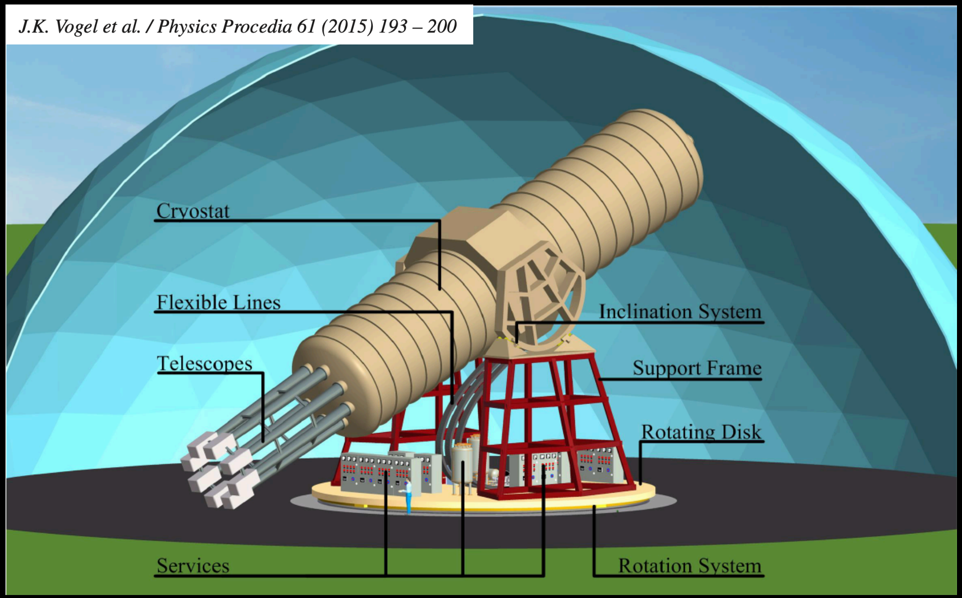
Taking the sun's temperature

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)

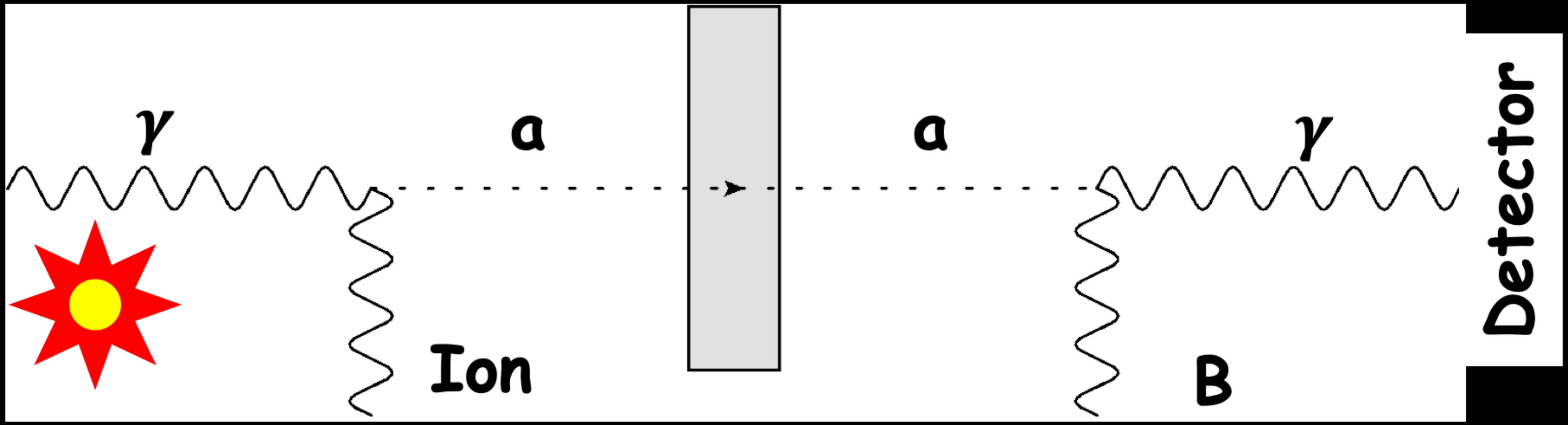
Published in: *JCAP* 10 (2023) 024 • e-Print: 2306.00077 [hep-ph]

Helioscope:
International Axion Observatory = IAXO

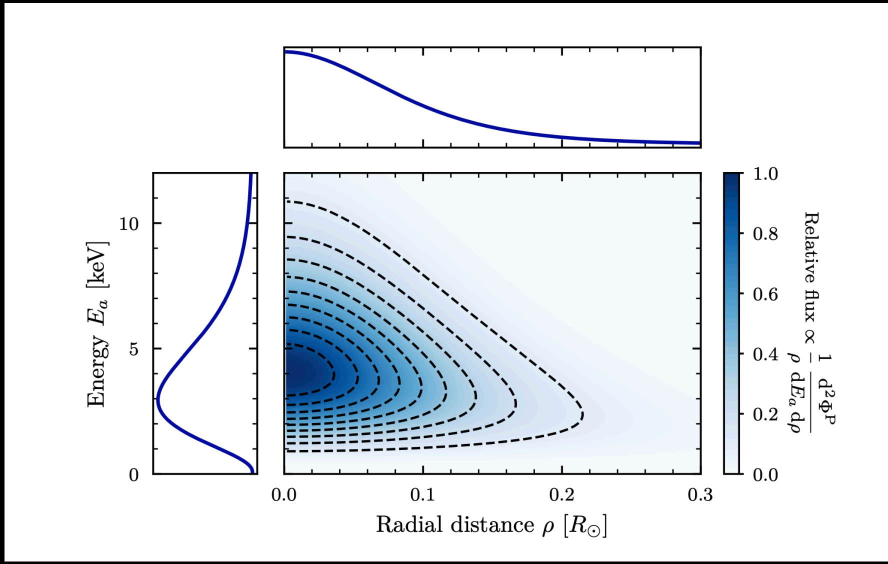


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

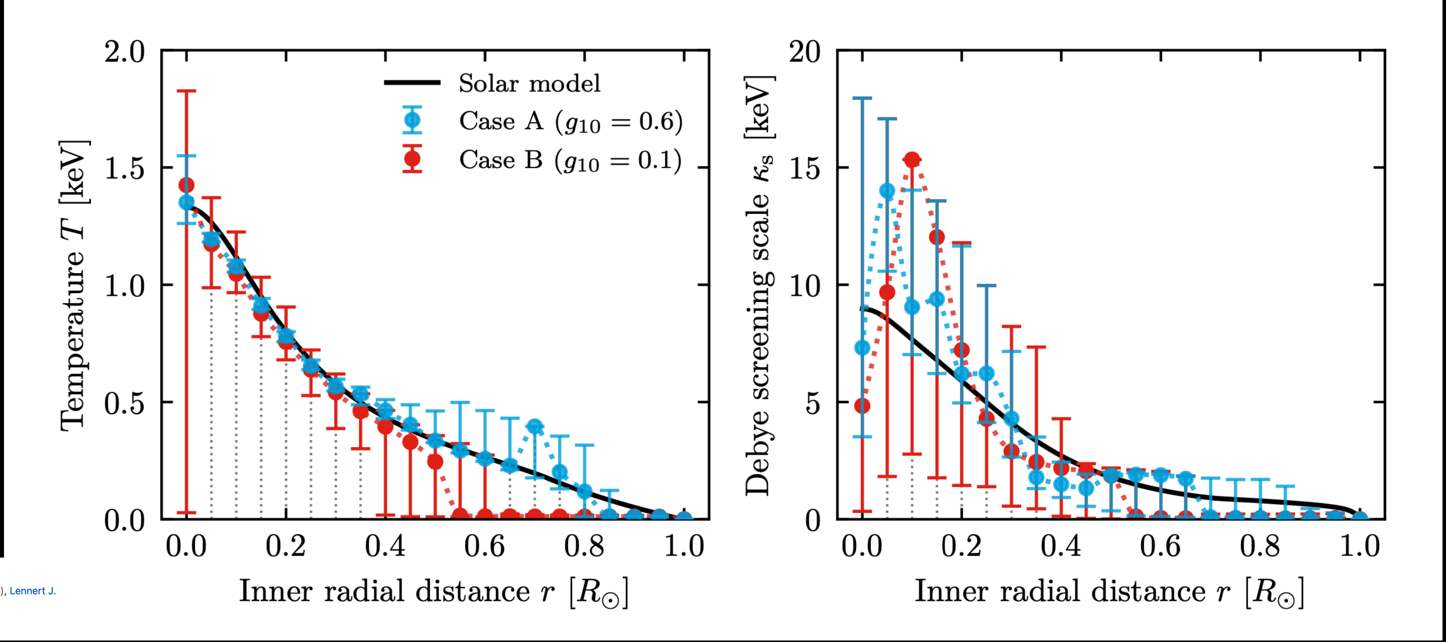
Light shining through walls



Temperature measurement



Measure axion flux and spectrum along the solar disc



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]

Theory
+
Astrophysics

Learning about models (axion and solar)

Could also tell us about axion models...

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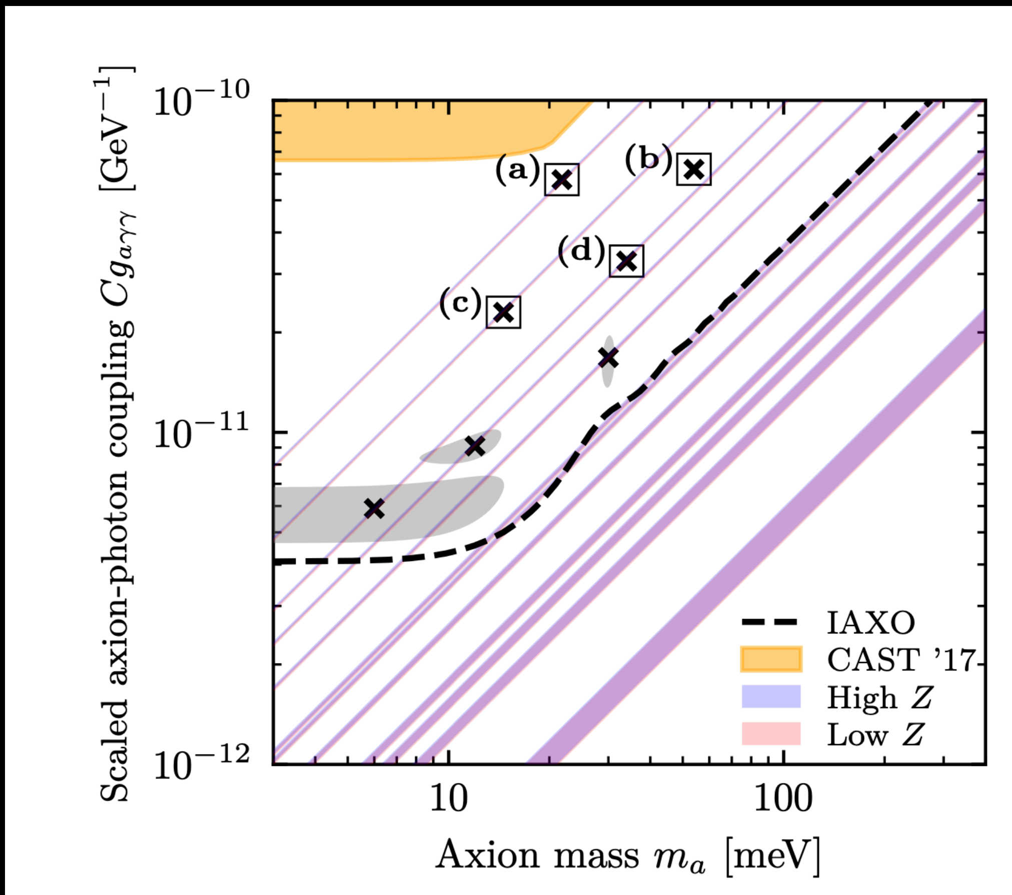
QCD axion models live on "lines" in parameter space
→ mass + coupling also tells us about model



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

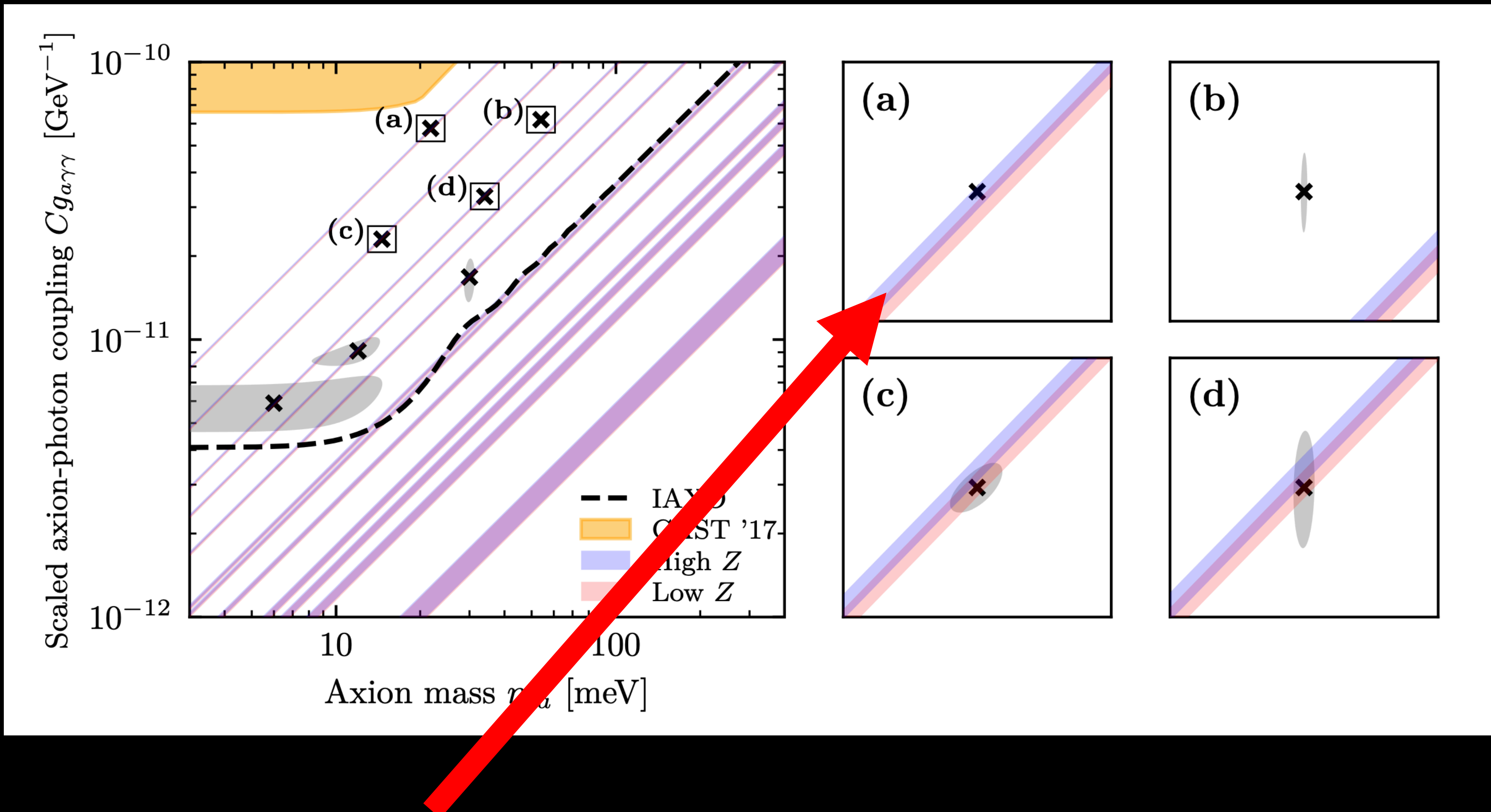
Charges of heavy particles in axion model

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...



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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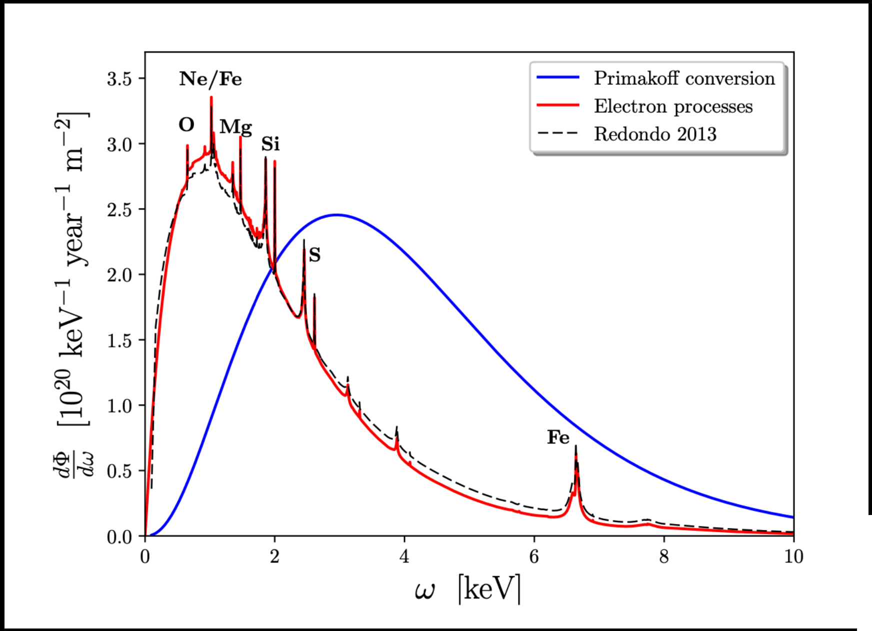
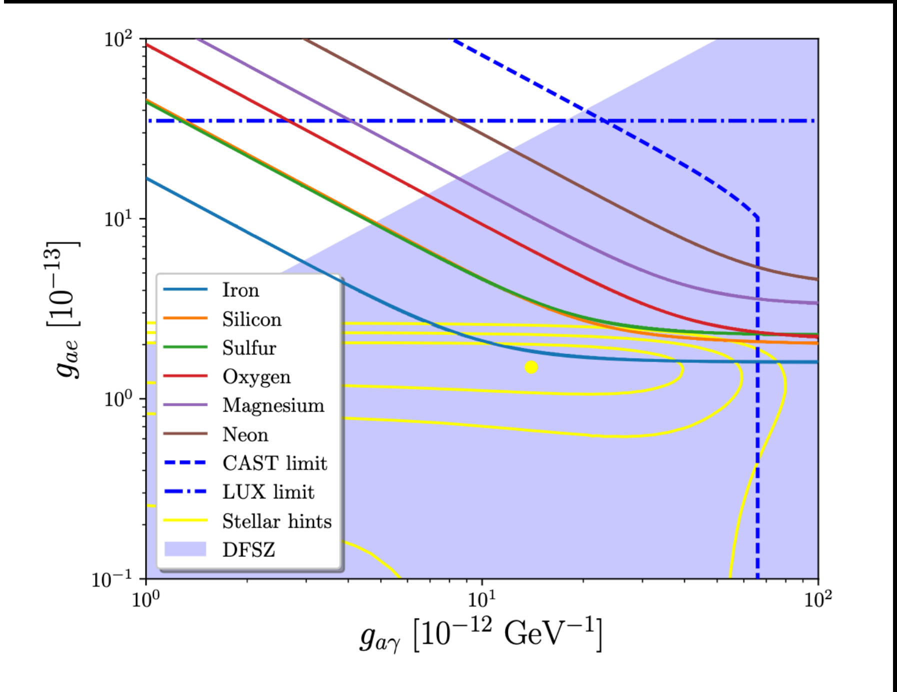




Axions as a probe of solar metals

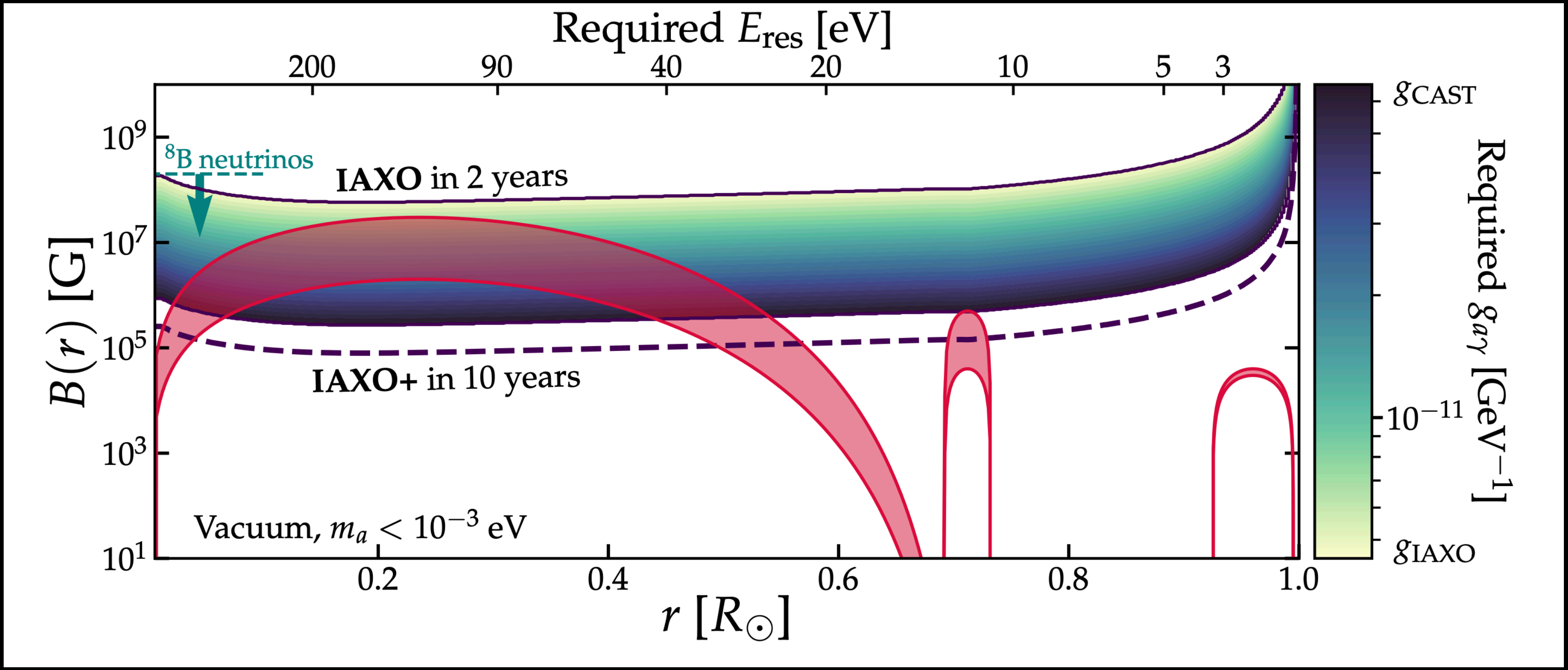
Joerg Jaeckel (U. Heidelberg (main)), Lennert J. Thormaehlen (U. Heidelberg (main)) (Aug 28, 2019)

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



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
- Axions tell us about the sun

  ➔ Temperature + Composition
- Axion coupling and mass ➔ Axion model?
- Axion dark radiation may even tell us about reheating!