Laboratory Searches of Axions and ALPs

Andreas Ringwald
Shoot for the Stars, Aim for the Axions
5th YOUNGST@RS Virtual Workshop
Mainz Institute for Theoretical Physics
Oct 4 - 7, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Axions and ALPs

Interactions with the Standard Model (SM)

- Pseudo Nambu-Goldstone bosons from spontaneous breaking of global U(1) symmetry at scale $f_a \gg v = 246\,\mathrm{GeV}$

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  - **Tiny mass** from anomalous or explicit breaking of global symmetry
    - Axion: breaking of $U(1)_{PQ}$ symmetry by axial anomaly $m_a \approx \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{z}}{1+z}$ $z = m_u/m_d$
    - ALP: lower limit from breaking of U(1) symmetry by effects from quantum gravity

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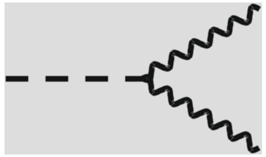
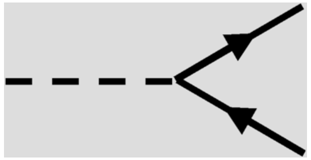
  - **Tiny couplings to SM** since they are suppressed by inverse power of symmetry breaking scale f_a :

$$\mathcal{L}_a \supset -\frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{af}}{f_a}\,\partial_\mu a\, \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f - \frac{i}{2}\frac{C_{a\gamma N}}{f_a}\, a\, \overline{\Psi}_N \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu}$$





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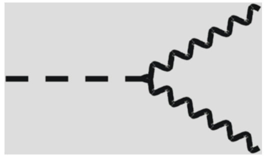

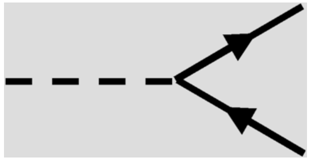

- Size of Wilson coefficients in benchmark axion models:
  - Photon coupling: $C_{a\gamma} = \frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}$ [Kaplan 85;Srednicki \`85; Grilli di Cortona et al. \`16]
  - Nucleon couplings: $C_{aN} = \mathcal{O}(1)$ [Grilli di Cortona et al. \`16]
  - EDM coupling: $C_{a\gamma N} = 2.4(1.0)\times 10^{-16}\,e\,\mathrm{cm}$ [Pospelov,Ritz \`00]

Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma}\right)$$

- Axion experiences mixing with photon in an external magnetic field

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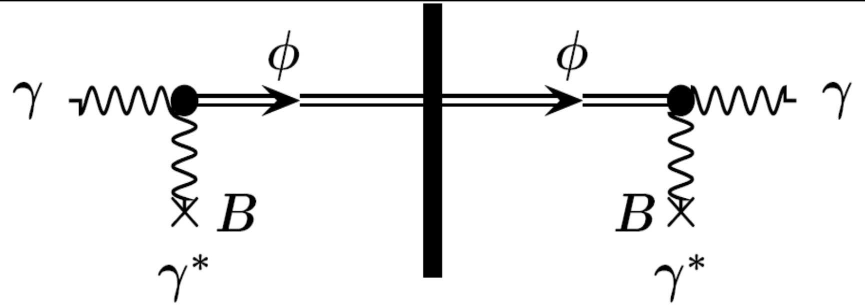

[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

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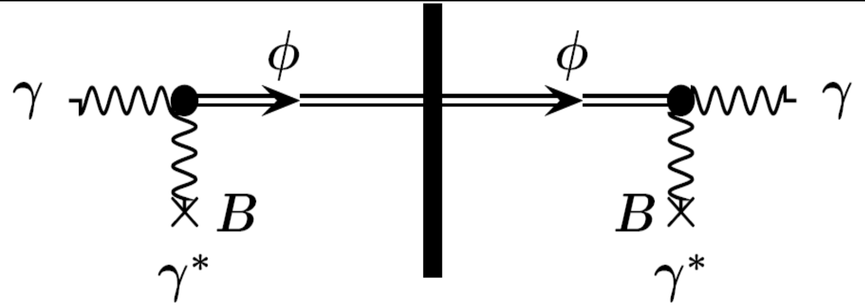

[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

- Probability, that photon ($\omega \gg m_a$) converts in axion after having traversed a distance L_B in magnetic field:

$$P(\gamma \leftrightarrow a) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$

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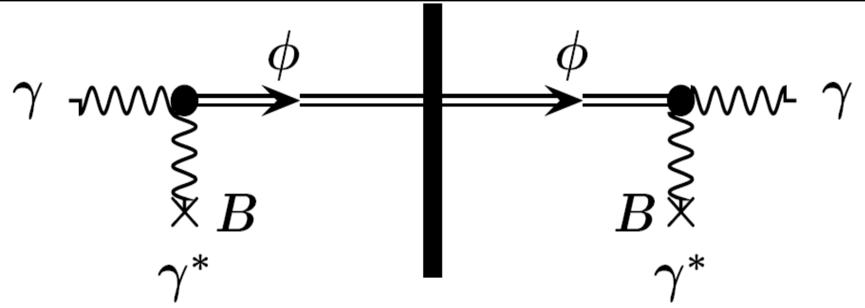

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- Best sensitivity for $m_a \ll \left(\frac{4\pi\omega}{L_B}\right)^{1/2}$:

$$P(\gamma \leftrightarrow a) \simeq \frac{1}{4}\left(g_{a\gamma} B L_B\right)^2$$

Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

- Proposal to recycle HERA dipoles for a light shining through a wall experiment: [AR 03]

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Physics Letters B 569 (2003) 51–56

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Production and detection of very light bosons in the HERA tunnel

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Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

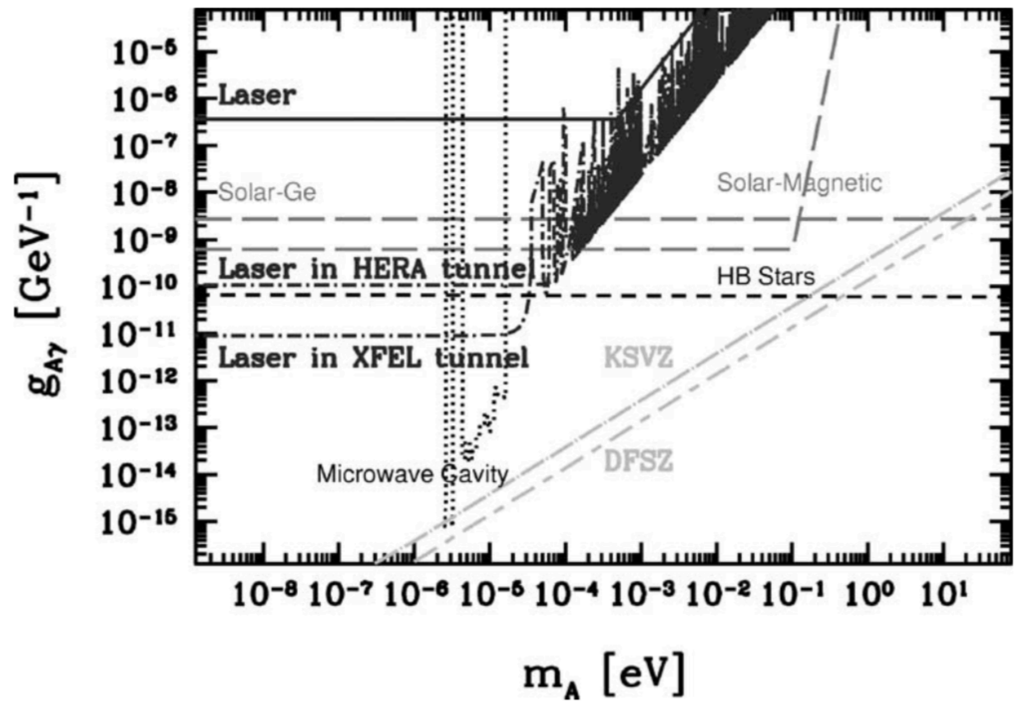
Received 17 June 2003; accepted 3 July 2003

Editor: P.V. Landshoff

Abstract

There are strong theoretical arguments in favour of the existence of very light scalar or pseudoscalar particles beyond the Standard Model which have, so far, remained undetected, due to their very weak coupling to ordinary matter. We point out that after HERA has been decommissioned, there arises a unique opportunity for searches for such particles: a number of HERA's four hundred superconducting dipole magnets might be recycled and used for laboratory experiments to produce and detect light neutral bosons that couple to two photons, such as the axion. We show that, in this way, laser experiments searching for photon regeneration or polarization effects in strong magnetic fields can reach a sensitivity which is unprecedented in pure laboratory experiments and exceeds astrophysical limits from stellar evolution considerations.

A. Ringwald / Physics Letters B 569 (2003) 51–56



Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

- Letter of Intent for ALPS experiment:

[Ehret et al.. 07]

DESY 07-014 Public version — 8.12.2006

Production and Detection of Axion-Like Particles in a HERA Dipole Magnet

– Letter-of-Intent for the ALPS experiment –

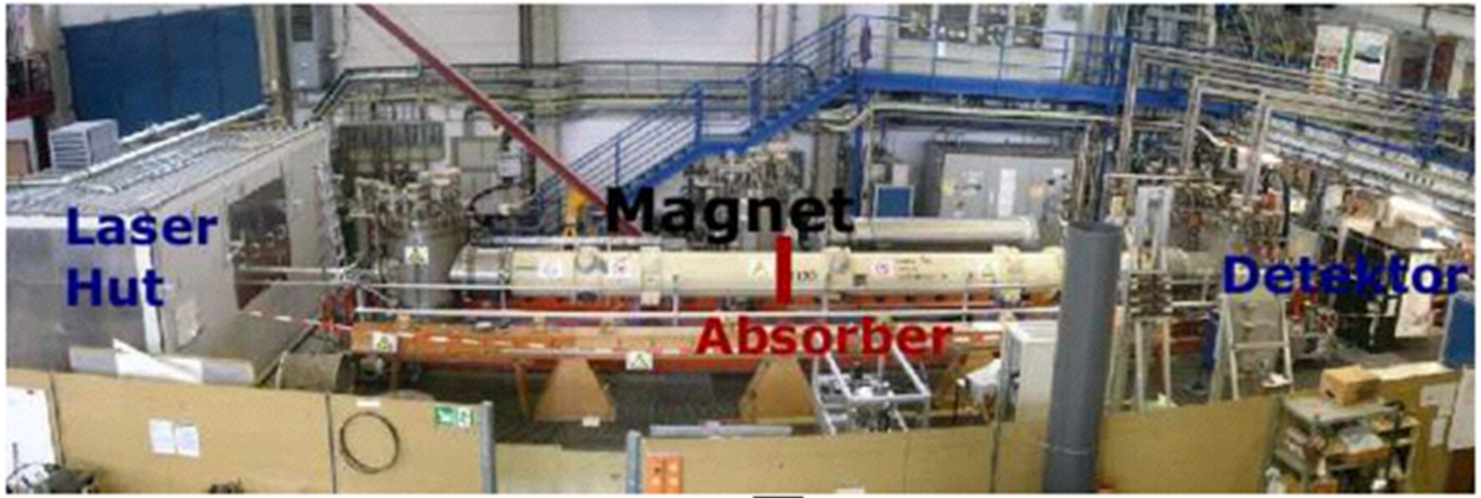
Klaus Ehret,[1] Maik Frede,[2] Ernst-Axel Knabbe,[1] Dietmar Kracht,[2] Axel Lindner,[1,*] Niels Meyer,[1] Dieter Notz,[1] Andreas Ringwald,[1,†] and Günter Wiedemann[3]

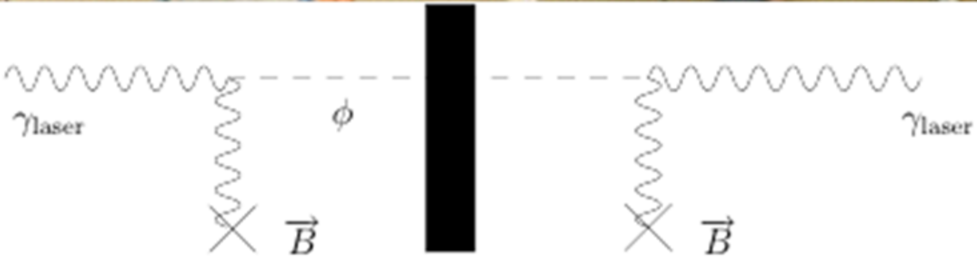
[1] *Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*
[2] *Laser Zentrum Hannover e.V., Hollerithallee 8, D-30419 Hannover, Germany*
[3] *Sternwarte Bergedorf, Gojenbergsweg 112, D-21029 Hamburg, Germany*

Recently, the PVLAS collaboration has reported evidence for an anomalous rotation of the polarization of light in vacuum in the presence of a transverse magnetic field. This may be explained through the production of a new light spin-zero (axion-like) neutral particle coupled to two photons. In this letter-of-intent, we propose to test this hypothesis by setting up a photon regeneration experiment which exploits the photon beam of a high-power infrared laser, sent along the transverse magnetic field of a superconducting HERA dipole magnet. The proposed[1] ALPS (Axion-Like Particle Search) experiment offers a window of opportunity for a rapid firm establishment or exclusion of the axion-like particle interpretation of the anomaly published by PVALS. It will also allow for the measurement of mass, parity, and coupling strength of this particle.

Light-Shining-through-a-Wall Searches

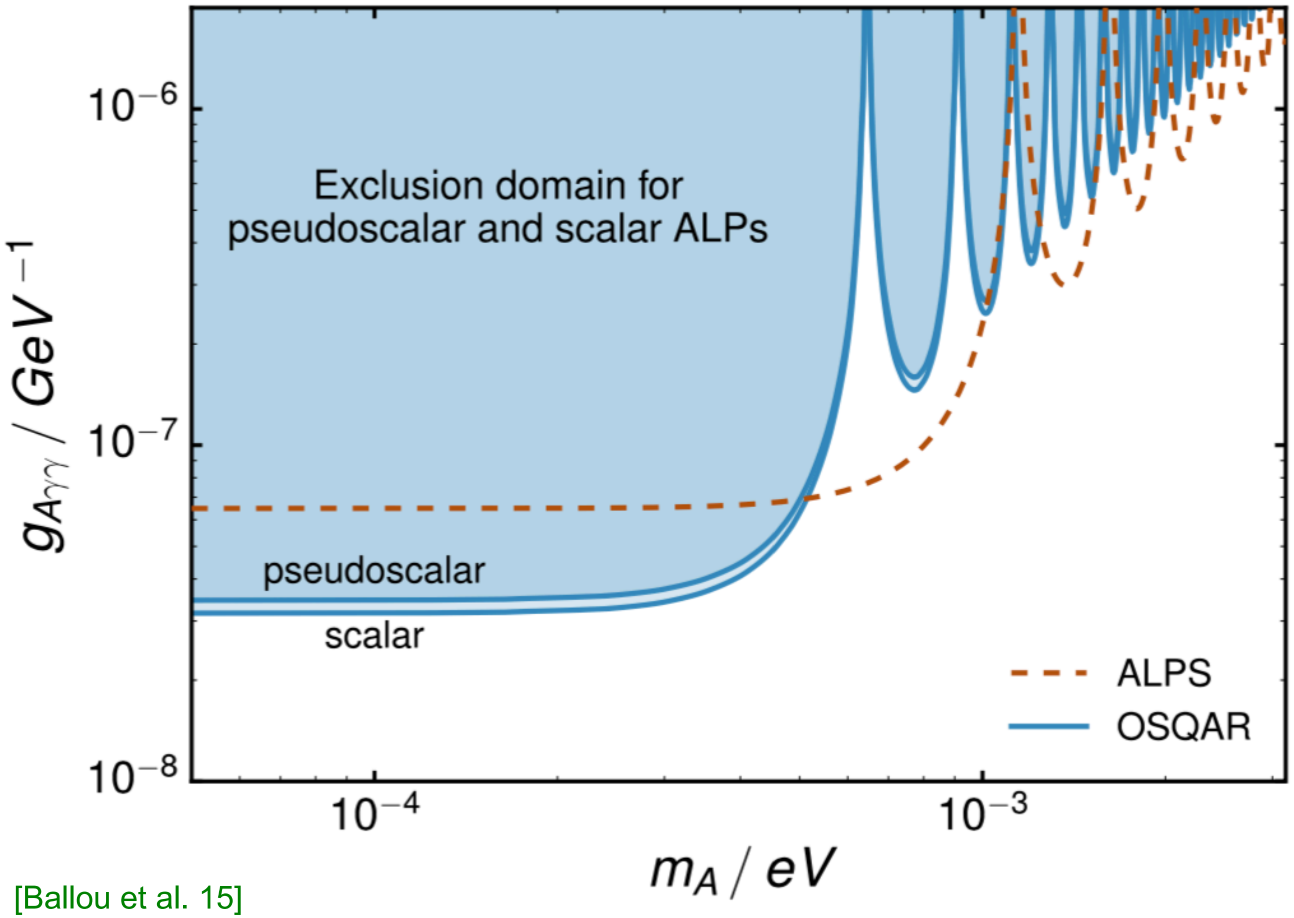
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;....;Ehret et al. 10]





Light-Shining-through-a-Wall Searches

- ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass ALPs:



[Ballou et al. 15]

Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]

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  - Increase sensitivity in photon coupling by a factor of more than 10^3

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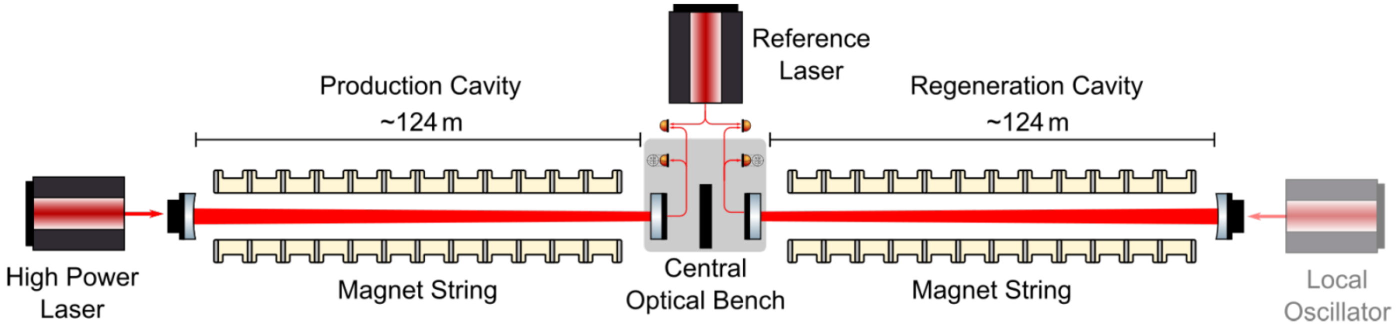

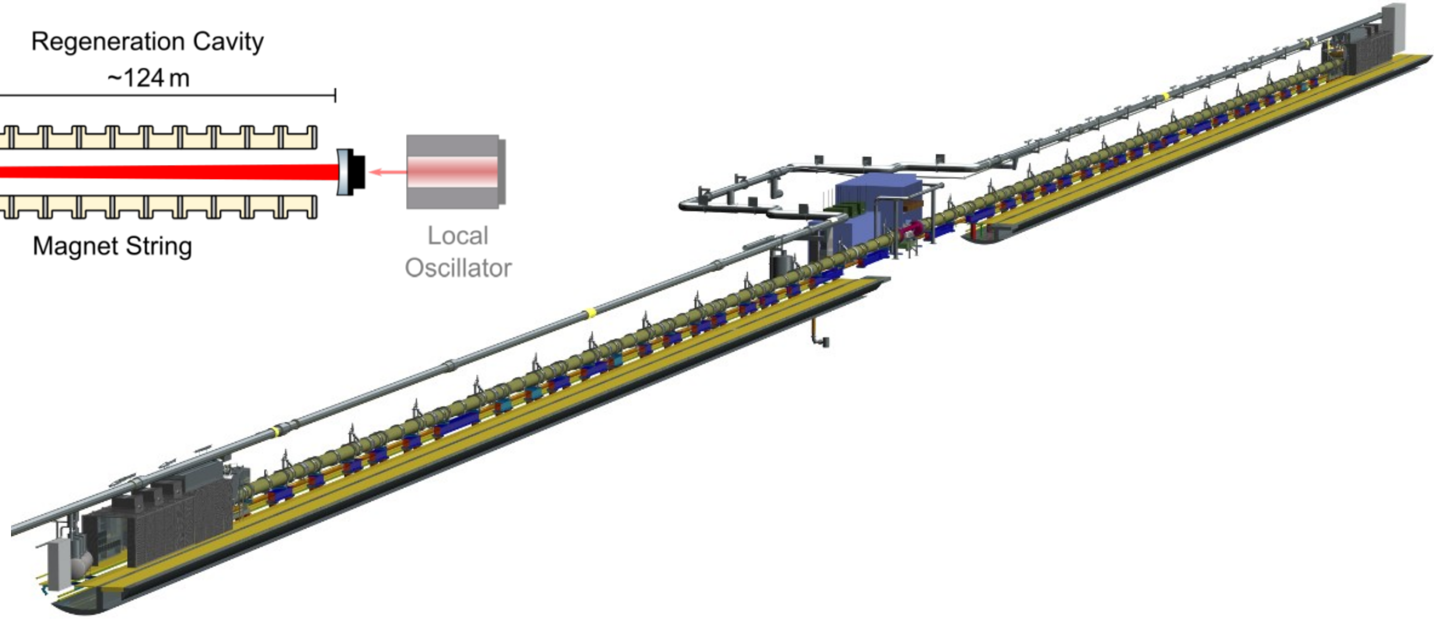

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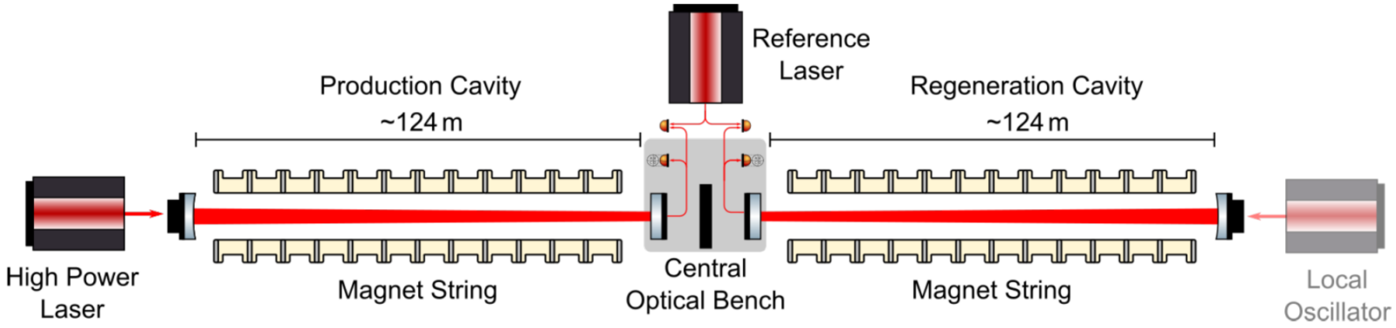

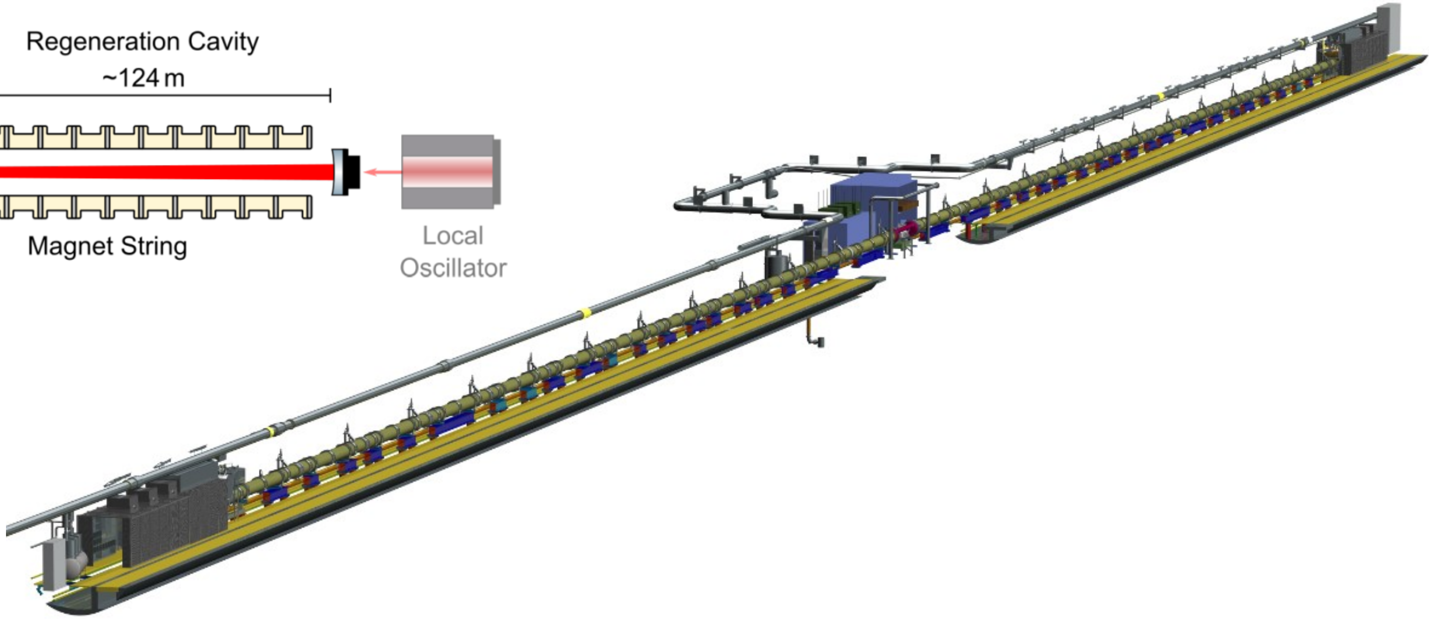

    - Optical cavities both at production and regeneration sites
      [Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]

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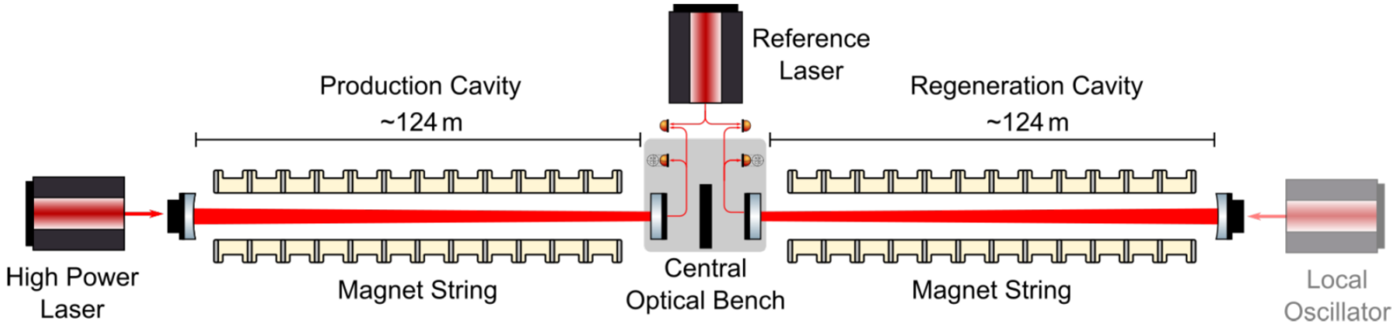
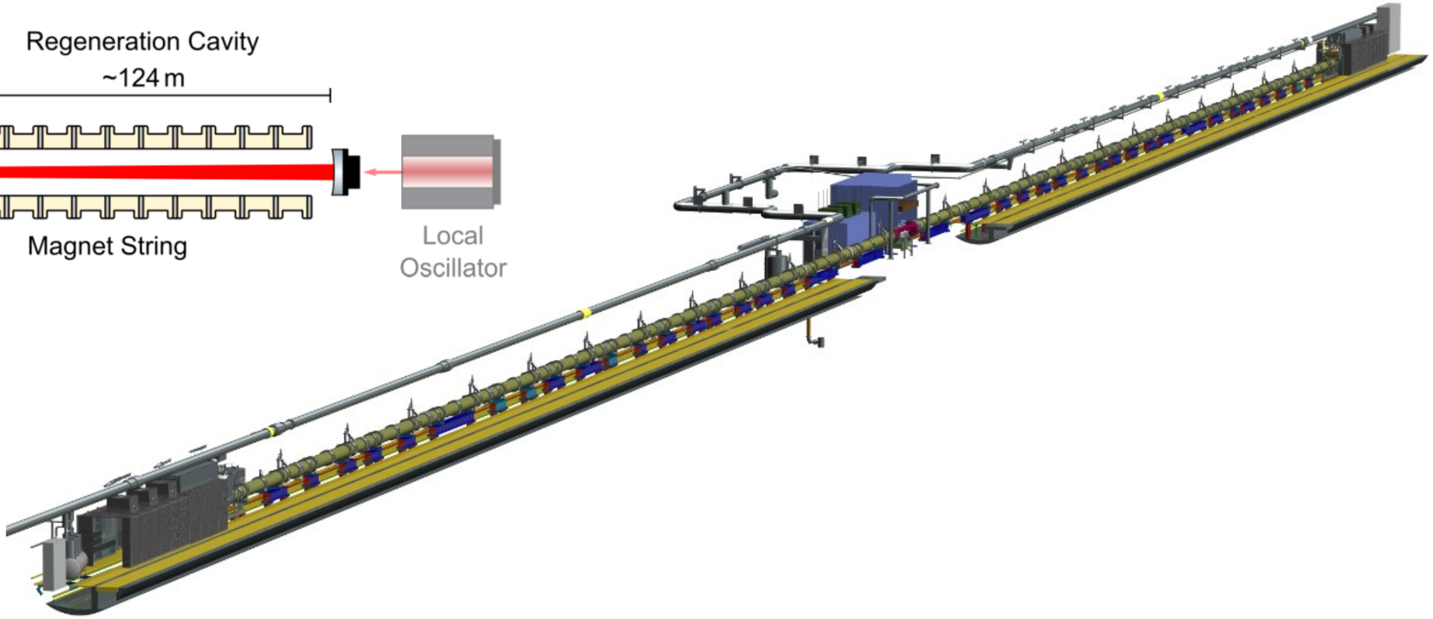
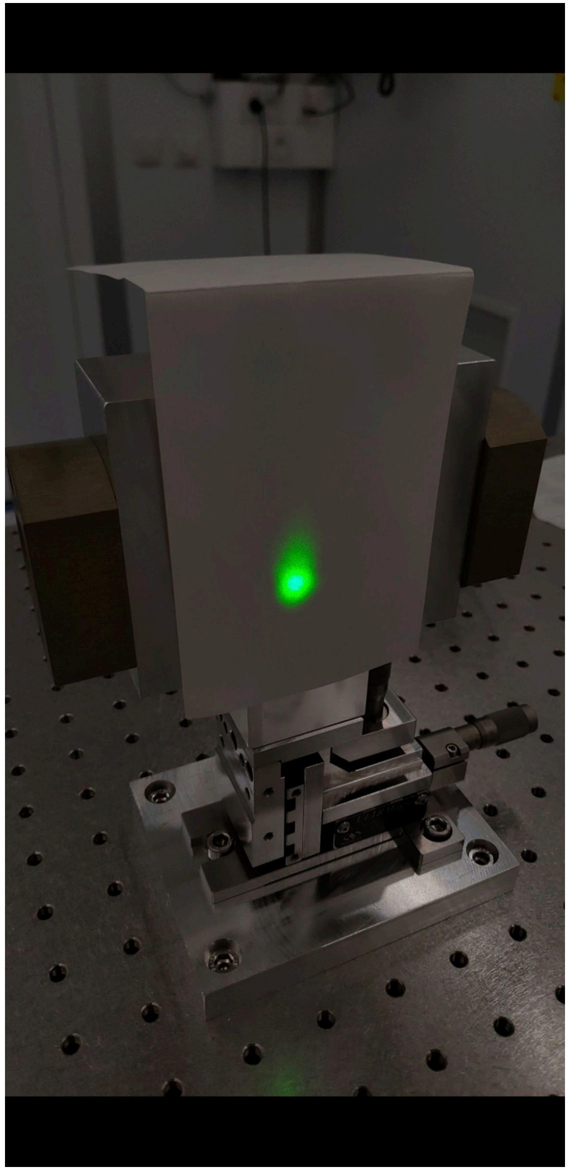




    - Optical cavities both at production and regeneration sites [Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]
    - Two detection techniques:
      - Heterodyne
      - Transition Edge Sensor (TES)

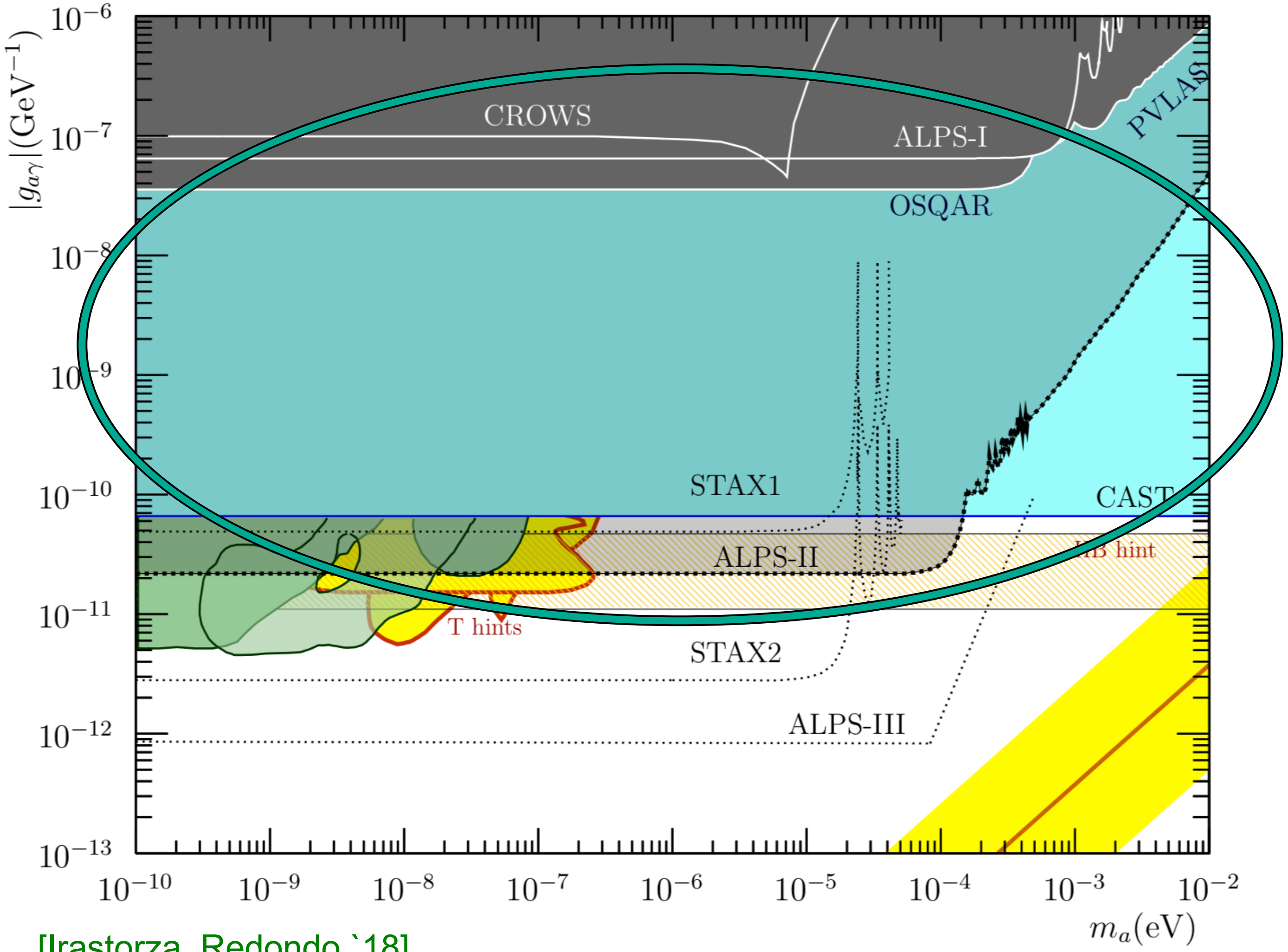
Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz)
  - Construction progressing:
    - All 24 magnets are installed and aligned and tested
    - Cleanrooms at end stations and center are operational
    - Commissioning of the optical system almost finished
  - First science run in early 2023



Light-Shining-through-a-Wall Searches

- ALPS II designed to beat astrophysical constraints and check astrophysical hints of axions:



[Irastorza, Redondo `18]

Light-Shining-through-a-Wall Searches

Impact of ALPS II for society has already started:

- Rumours that success of soccer team HSV (“Hamburger Sportverein”) depends on scientific activities in the HERA tunnel which is located beneath its stadium (“Volkspark Stadion”)

TV-STREAM INFOS ZU BILDPLUS WETTER MEDIATHEK BILD SHOP ZEITUNG SUCHE ANMELDEN

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SEIT BEI DESY WIEDER LASERLICHT DURCH RÖHREN SCHIESST, LÄUFT'S IM VOLKSPARK

Ist dieser Tunnel Grund für den HSV-Aufschwung?

Blick in den DESY-Tunnel unterm Volkspark: Rechts die auf - 269 Grad gekühlte Röhre mit Magneten, durch die Laserlicht schießen wird

Foto: Andreas Costanzo

Von: JÖRG KÖHNEMANN
05.10.2022 - 07:37 Uhr

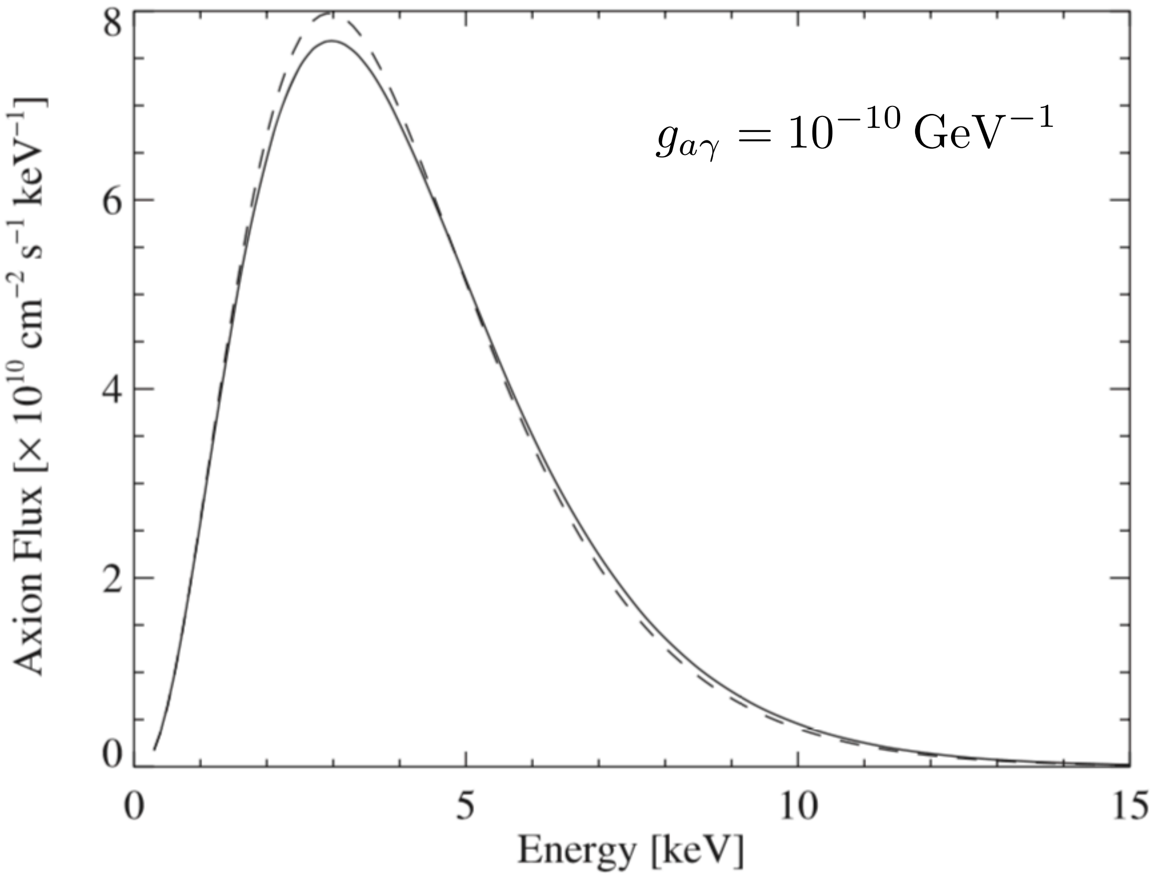
Hamburg – **20 Meter unterm Volkspark brennt wieder Licht im alten DESY-Tunnel.**

30 Physiker sind dort mit 24 Mega-Magneten (jeder 9 m lang, wiegt 10 Tonnen), durch vier Spiegel 10 000-fach verstärktem Laserlicht und Helium-Kühlung in einer schnurgeraden 250-Meter-Röhre geheimnisvoller „Dunkler Materie“, einem Axion Elementarteilchen, auf der Spur. Und schon ganz nah dran.

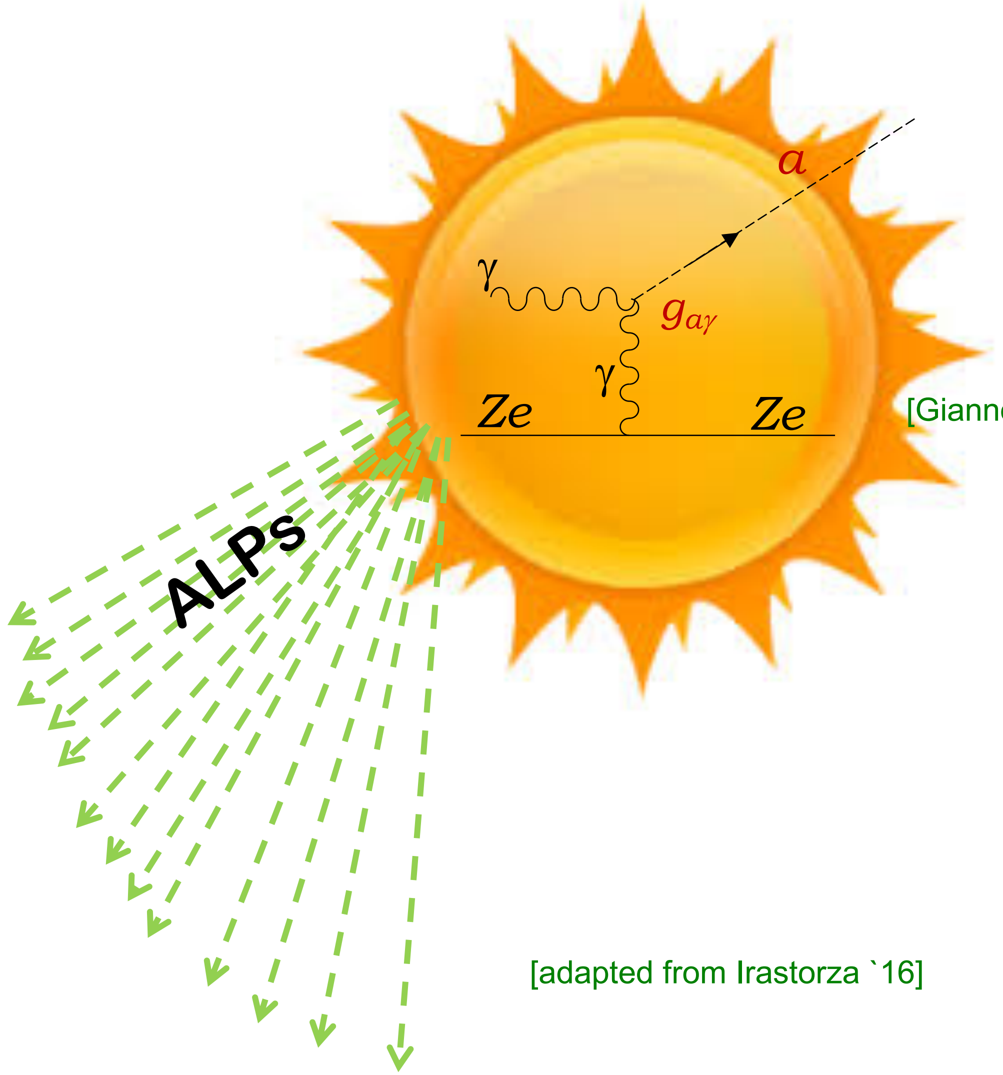
[Bild Hamburg, 5 Oct 2022]

Helioscope Searches

- Flux of solar axions/ALPs produced by two photon process in core:



[Adriamonje et al. `07]



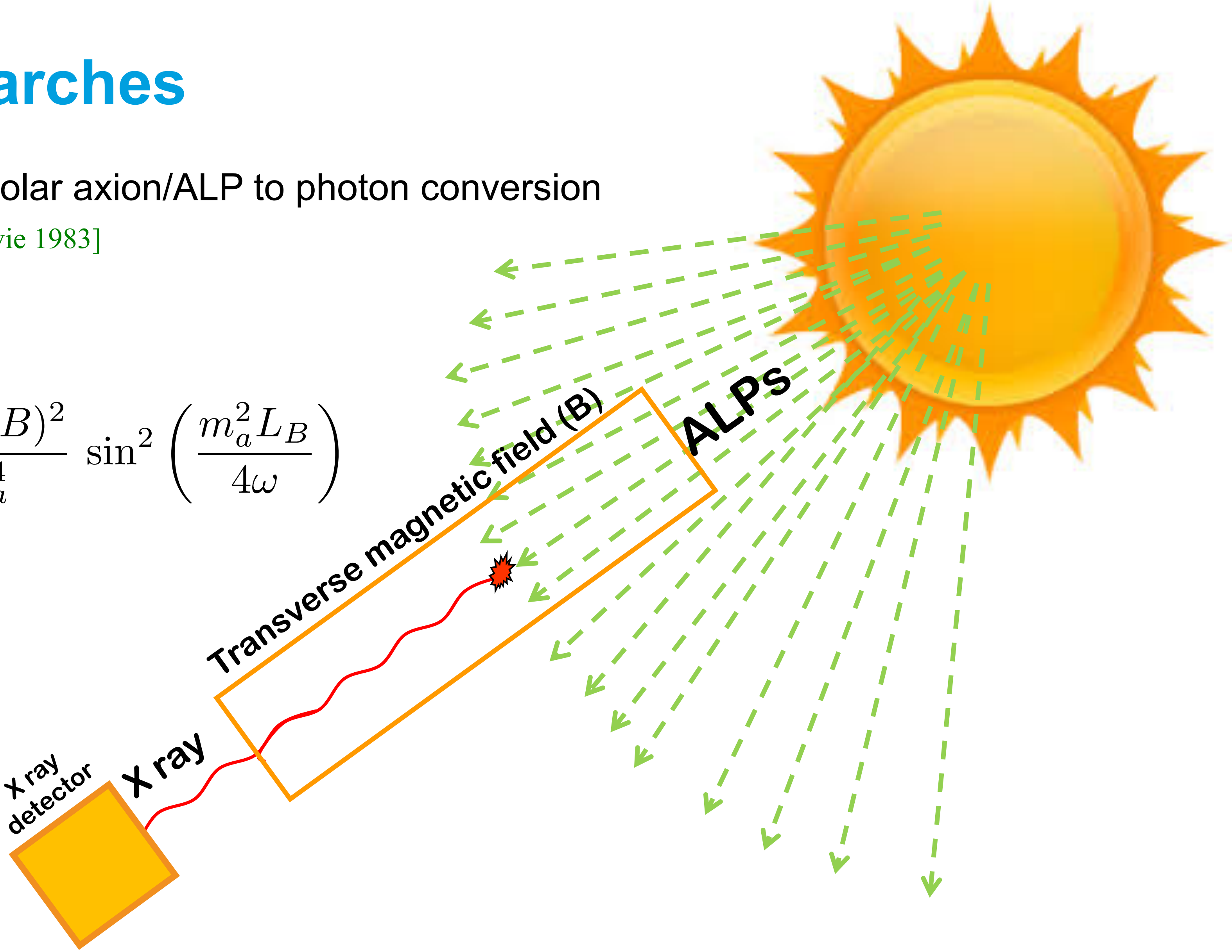
[Giannotti `16]

[adapted from Irastorza `16]

Helioscope Searches

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field [Sikivie 1983]

$$P(a \to \gamma) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$



[adapted from Irastorza `16]

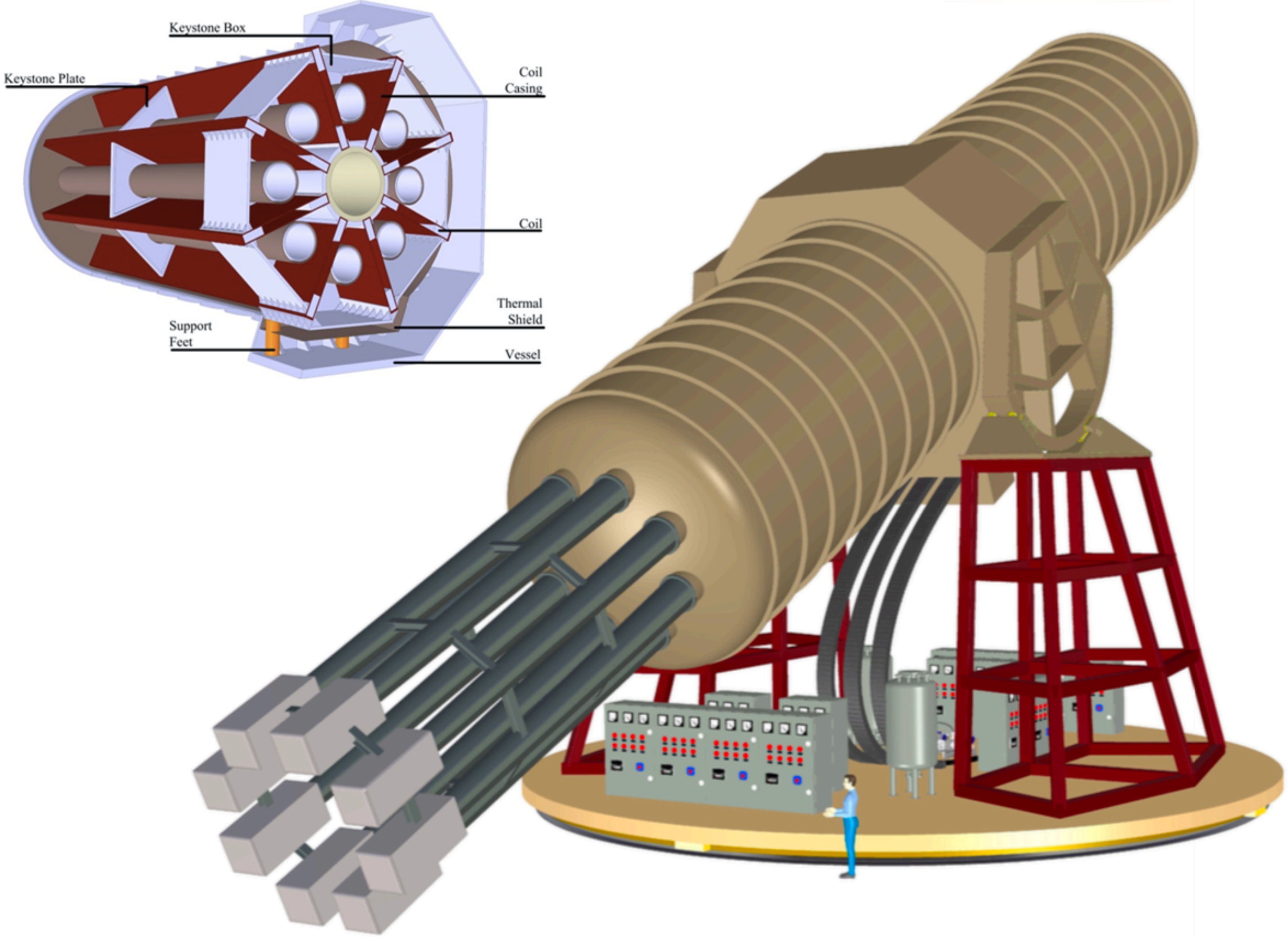
Helioscope Searches

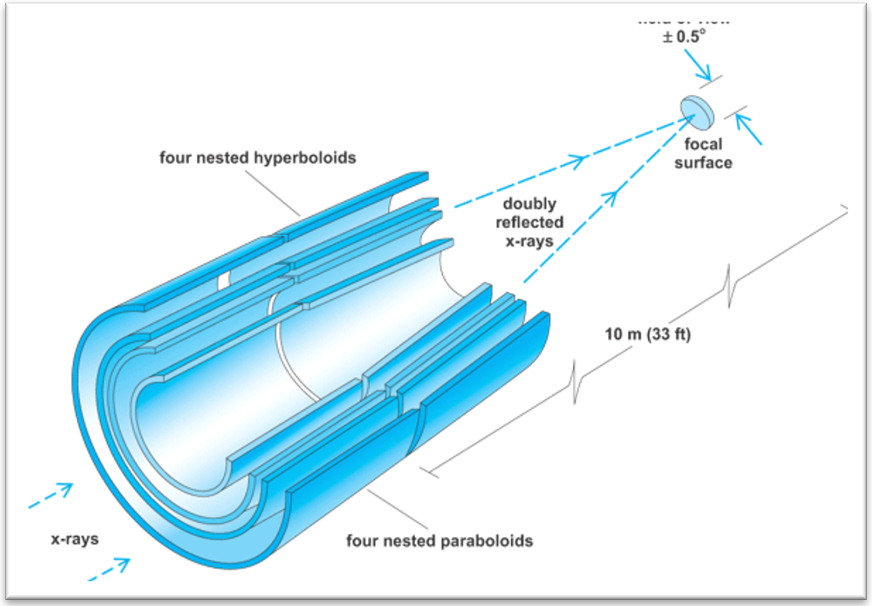
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Helioscope Searches

- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services

[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]





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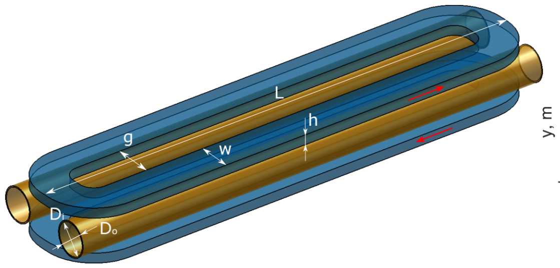
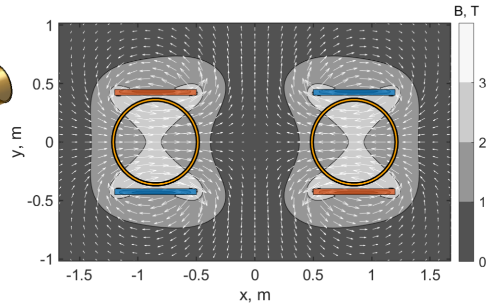
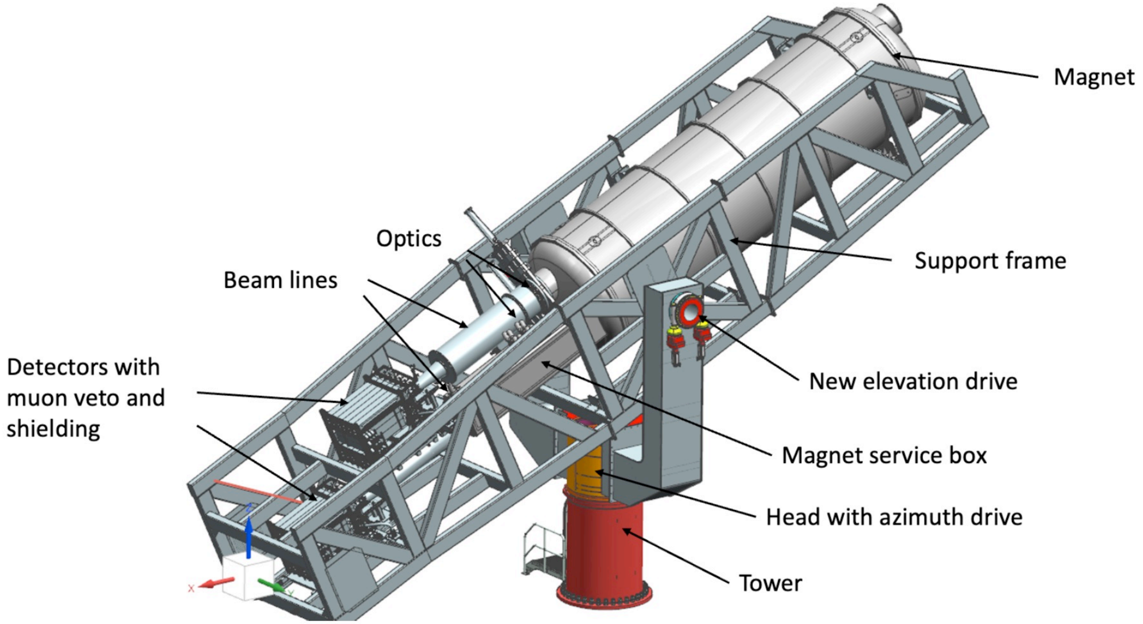
Helioscope Searches

- Prototype for IAXO: BabyIAXO
  - Two bores of dimensions similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
- Magnet technical design ongoing at CERN







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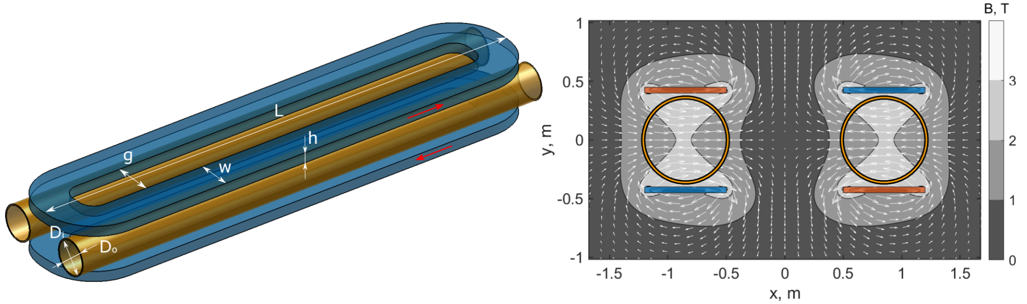
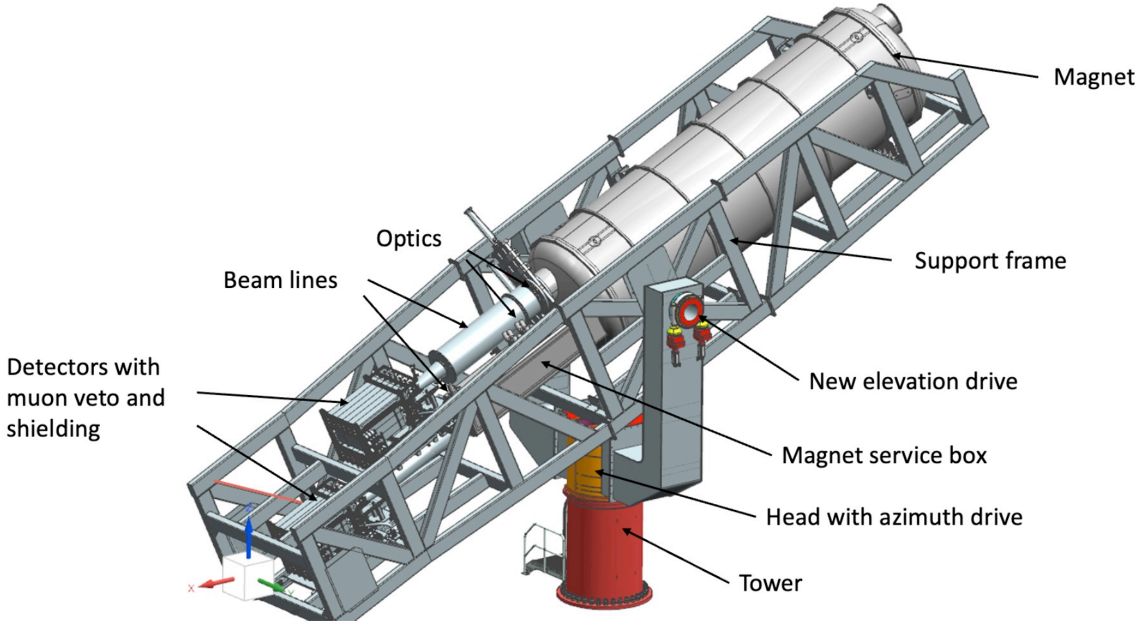
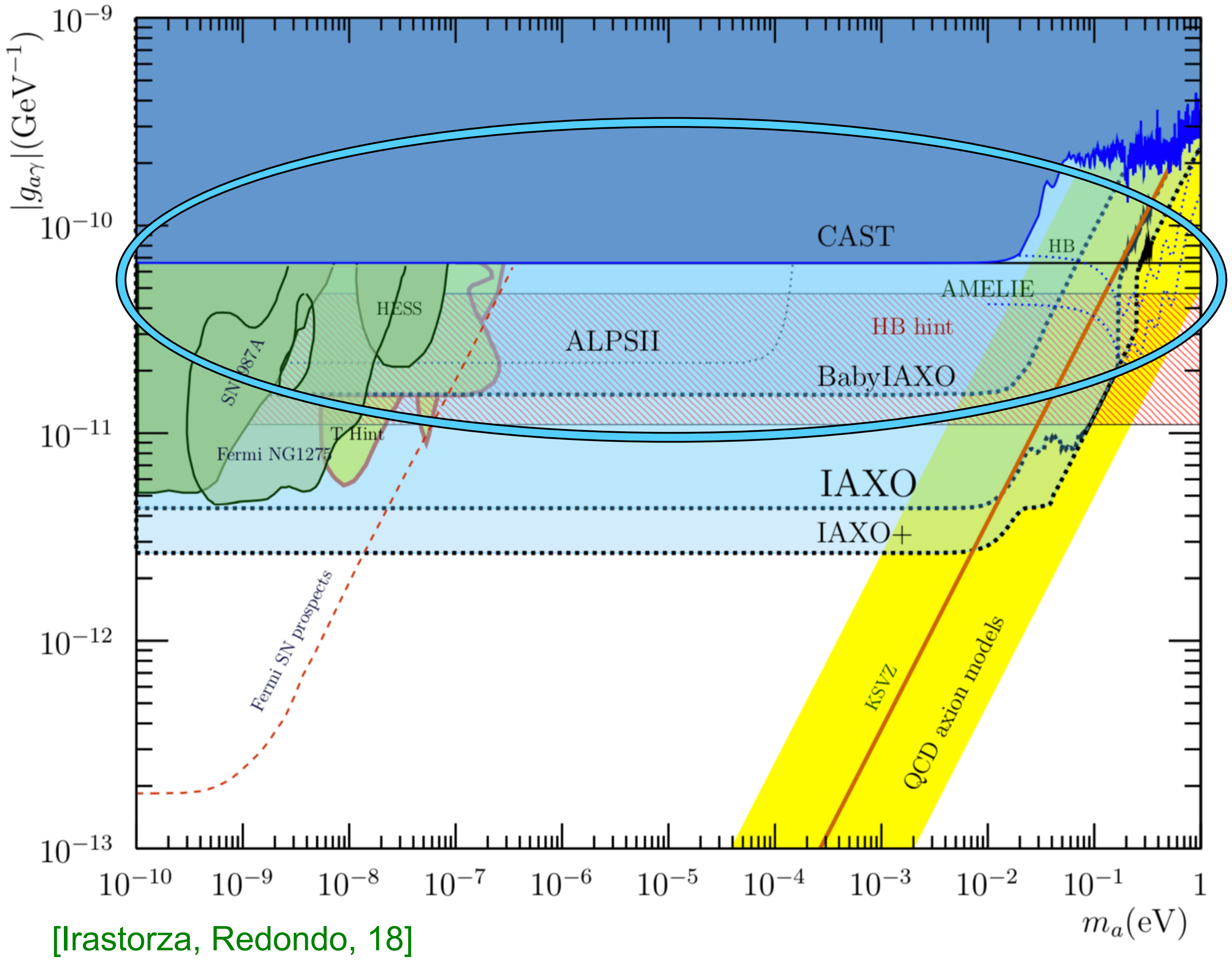


- Construction site: DESY
- Funded by CERN, DESY and Irastorza: ERC-AvG 2017 IAXO+
- Preparations have already started in 2020
- Start of data taking envisaged for 2026



Helioscope Searches

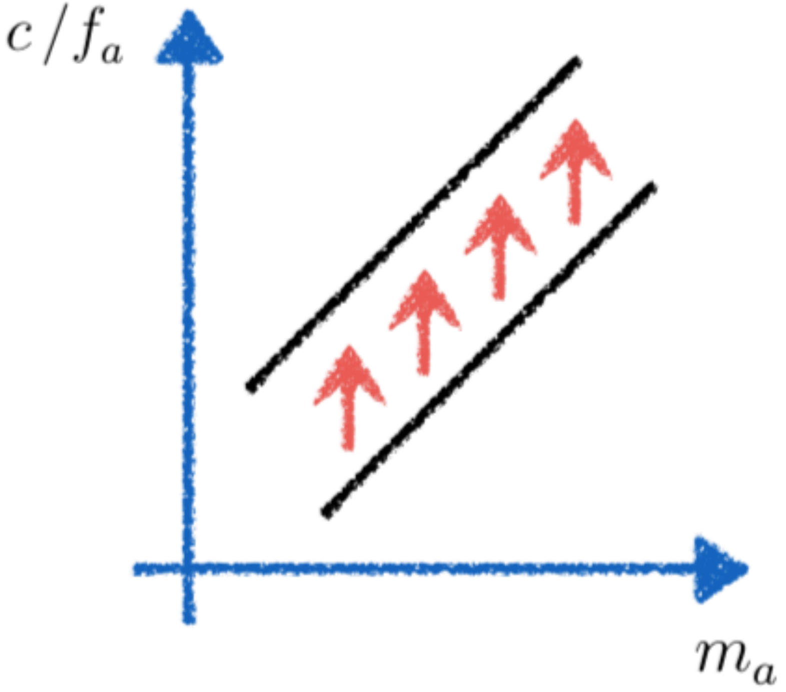
- (Baby)IAXO probes meV mass axion:

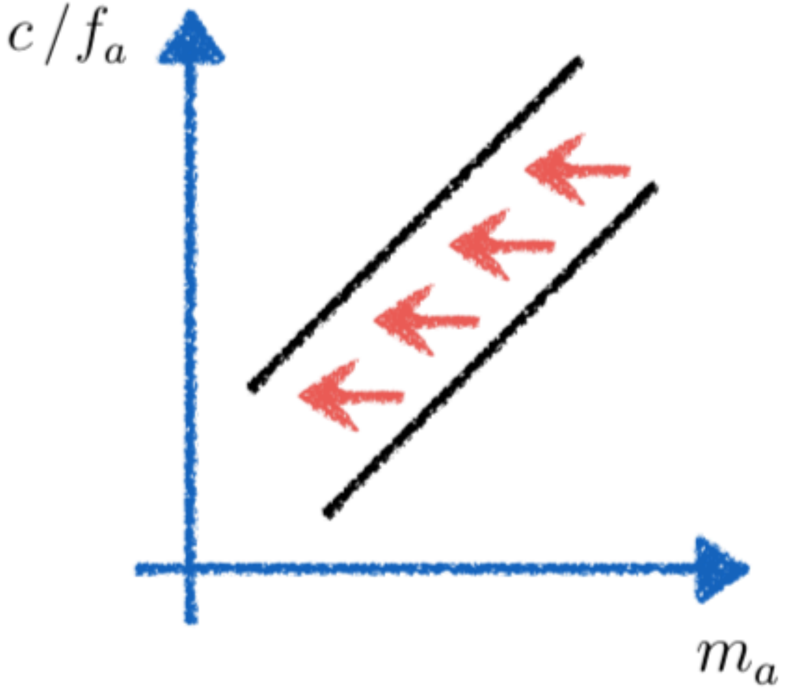


[Irastorza, Redondo, 18]

Axion or ALP?

- (Most of) Parameter range accessible by ALPS II (BabyIAXO) seems far away from expectation for axion
- In case of discovery by those experiments, it can still be the axion in models with
  - increased values of $C_{a\gamma}$, for fixed value of m_a [Di Luzio et al. 16, Farina et al. 16, Agrawal et al. 17, Sokolov,AR 21]
  - smaller values of m_a, for fixed values of $C_{a\gamma}/f_a$ [Hook 18, Di Luzio et al. 21]





[Di Luzio, Gavela, Quilez, AR 2102.00012]

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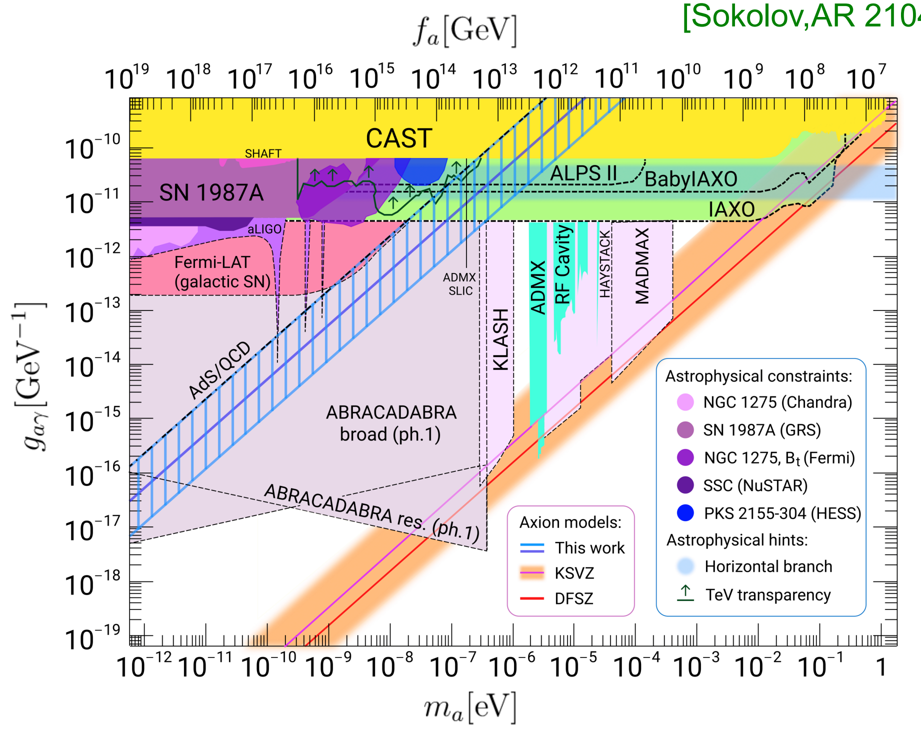
  - increased values of $C_{a\gamma}$, for fixed value of m_a [Di Luzio et al. 16, Farina et al. 16, Agrawal et al. 17, Sokolov,AR 21]
  - smaller values of m_a, for fixed values of $C_{a\gamma}/f_a$ [Hook 18, Di Luzio et al. 21]

KSVZ variant where exotic quark carries also magnetic charge:

[Sokolov,AR 2104.0257]



Axion or ALP?

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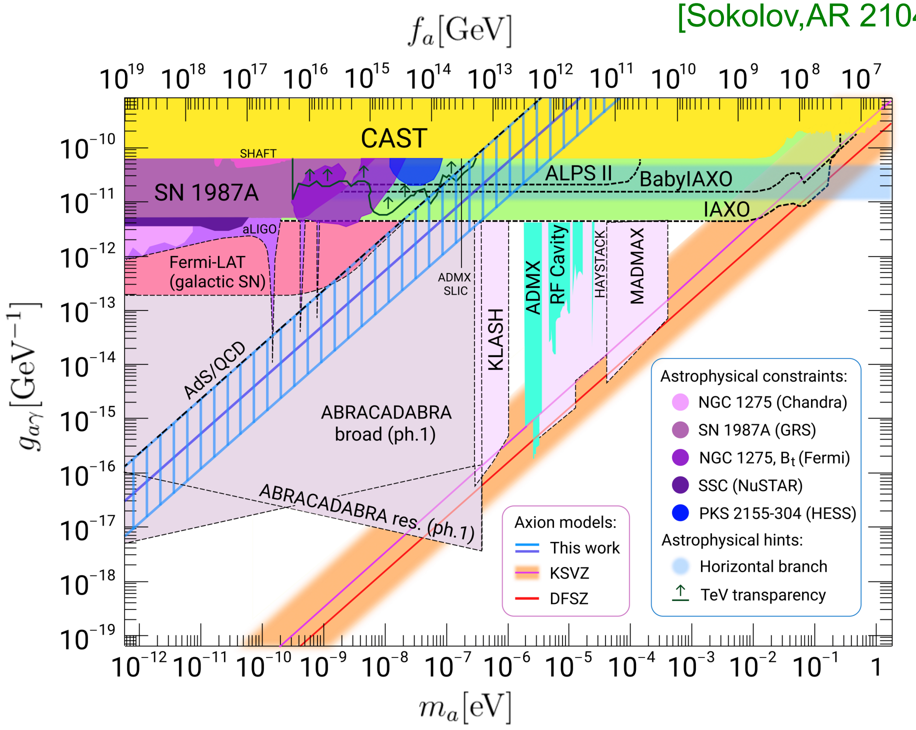
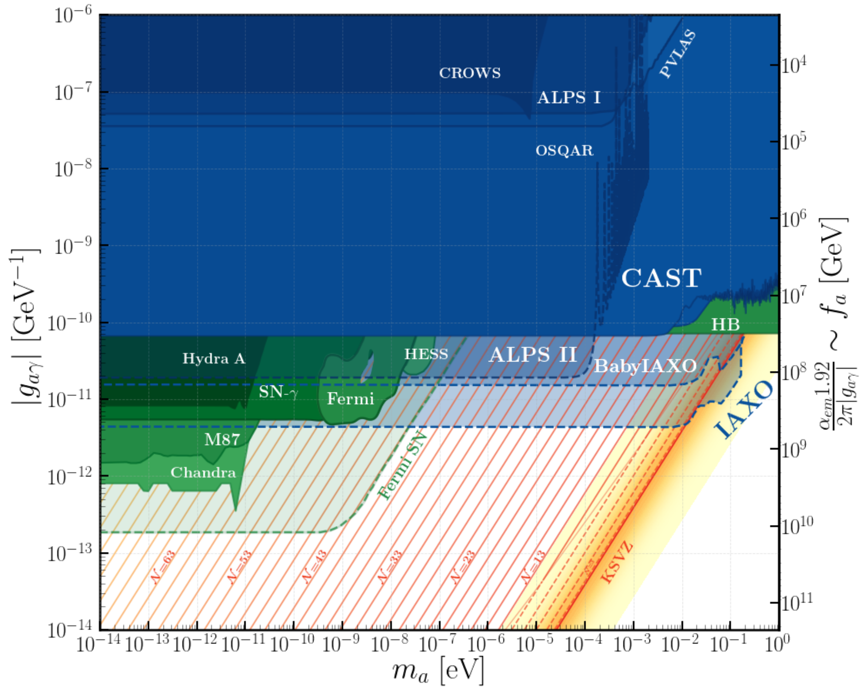


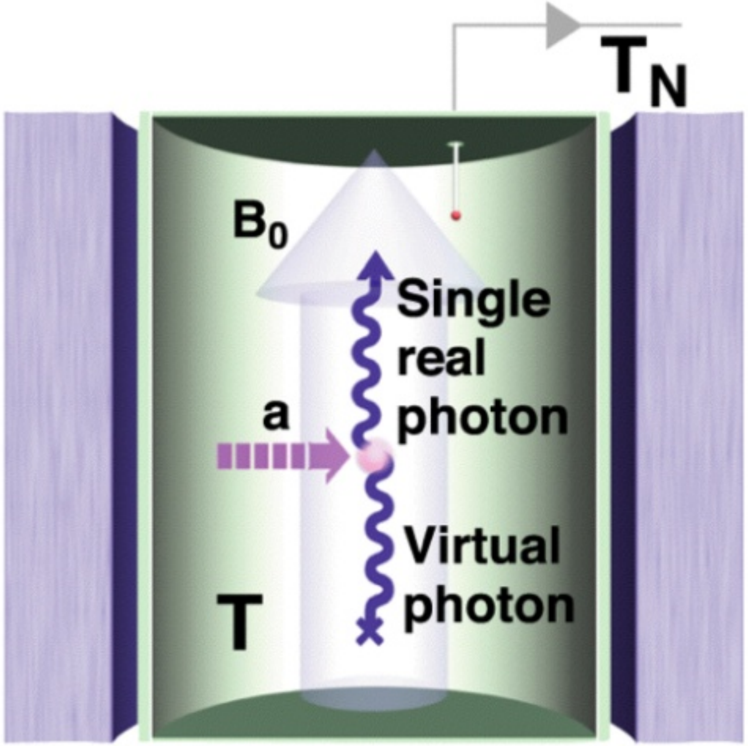
Z_N axion exploiting N copies of the SM: [Di Luzio et al., 2102.00012]



Axion Dark Matter Detection

Microwave Cavities

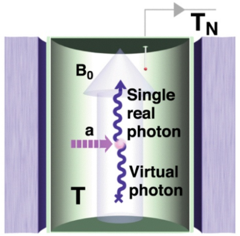
- Axion DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]

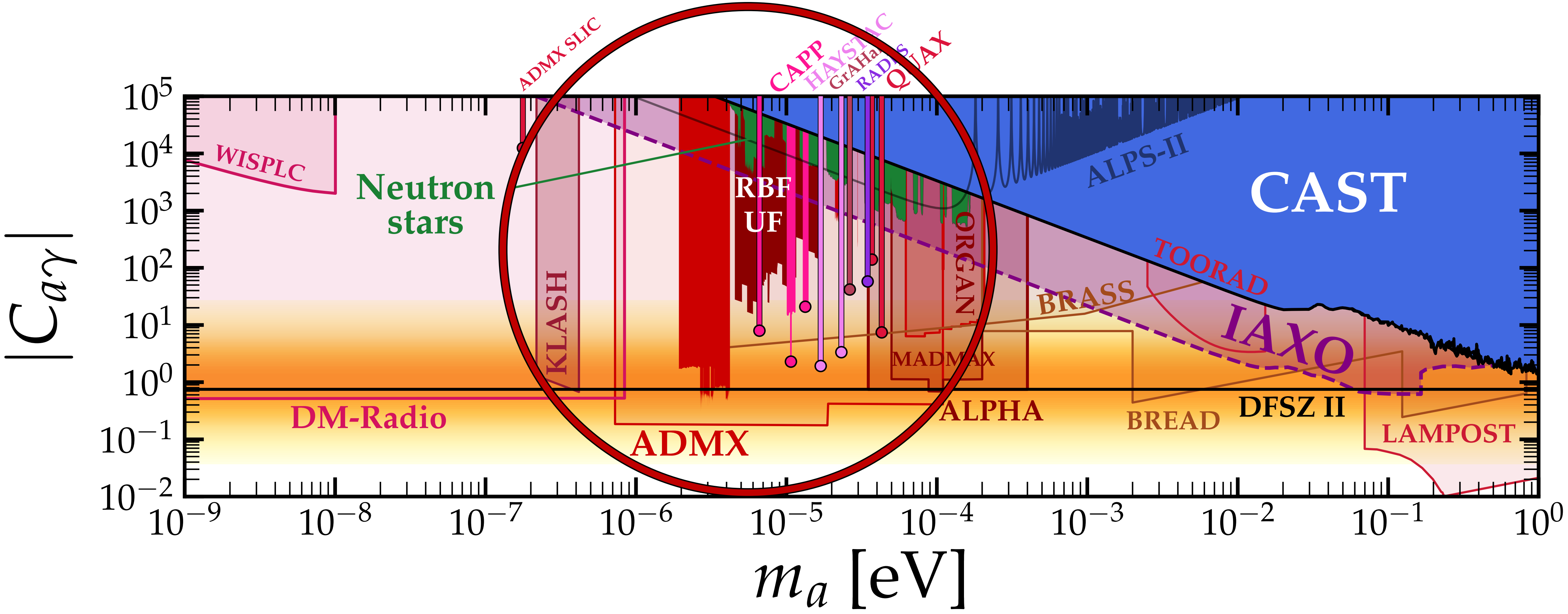


- Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\mathrm{eV}\left(\frac{\nu}{\mathrm{GHz}}\right)$
- Power output: $P_{\rm out} \sim g_{a\gamma}^2 \mid \mathbf{B}_0 \mid^2 \rho_{\rm DM} V Q / m_a$

Axion Dark Matter Detection

Microwave Cavities



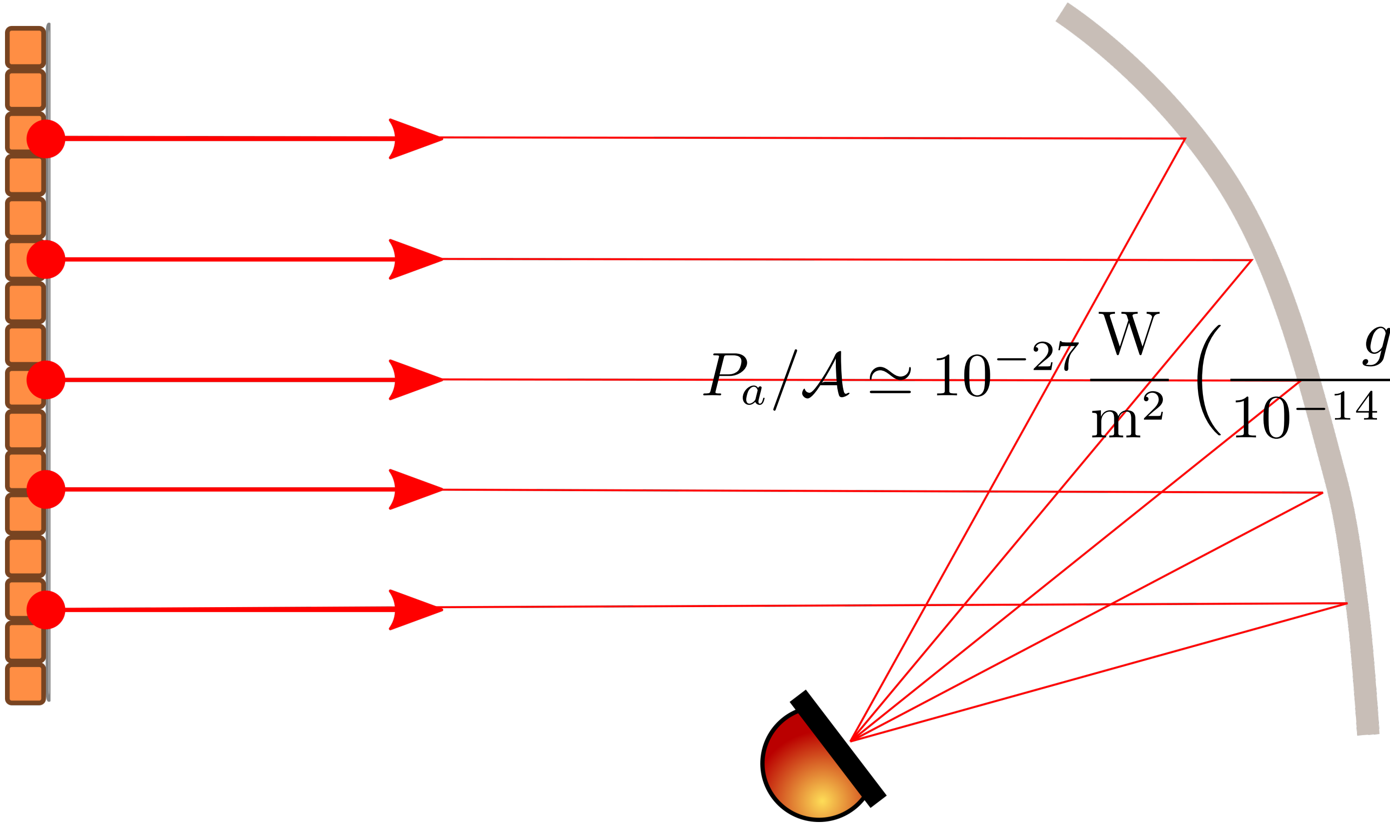


[https://github.com/cajohare/AxionLimits/blob/master/plots/AxionPhoton_Rescaled.pdf]

Axion Dark Matter Detection

Dish Antennas

- Oscillating axion DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]



$$P_a/\mathcal{A} \simeq 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{10^{-14}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\left(\frac{B}{10\,\mathrm{T}}\right)^2$$

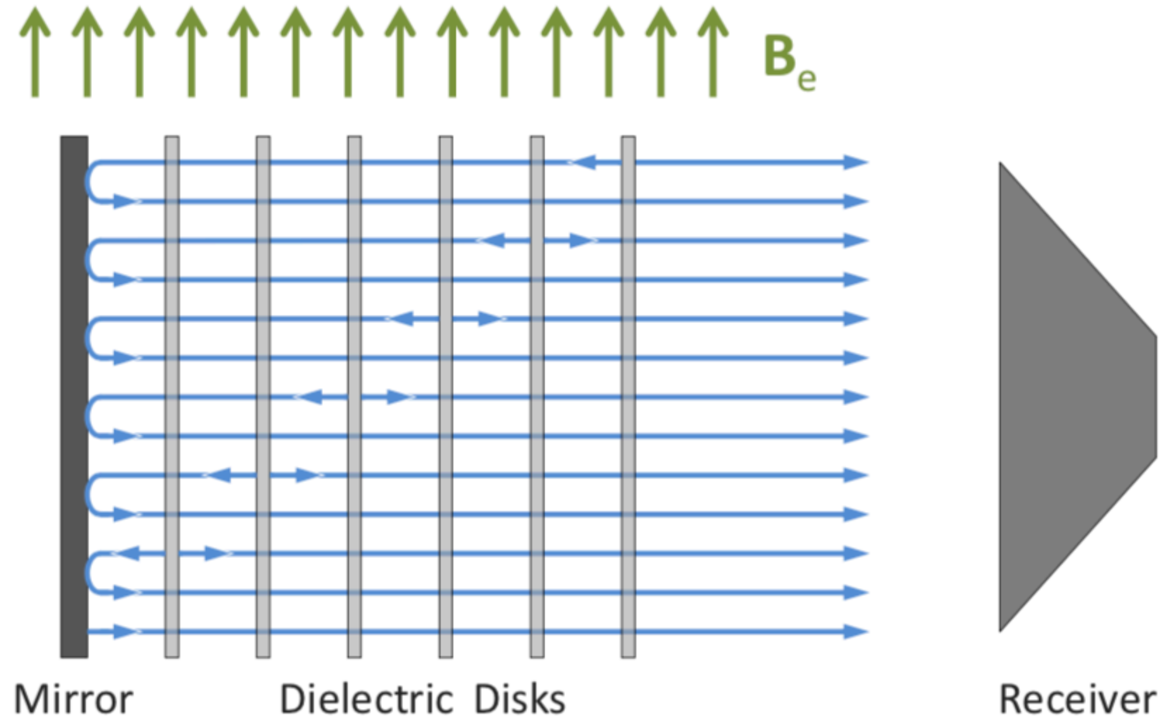
Axion Dark Matter Detection

Dish Antennas

- **Boosted dish antenna:** Open dielectric resonator
  - Add stack of dielectric disks with $\sim \lambda/2$ spacing in front of mirror (all immersed in magnetic field) [Jaeckel,Redondo 13]
  - Constructive interference of photon part of wave function

[Millar,Raffelt,Redondo,Steffen 16]

[Baryakhtar,Huang,Lasenby18]



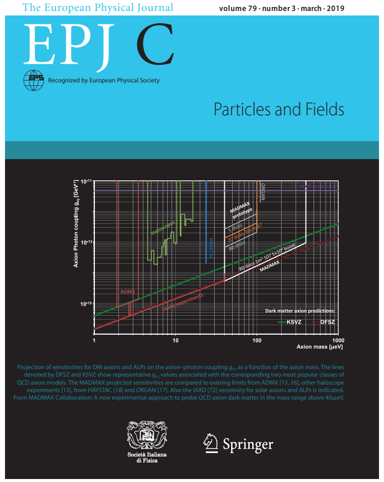
[Caldwell et al. `16]

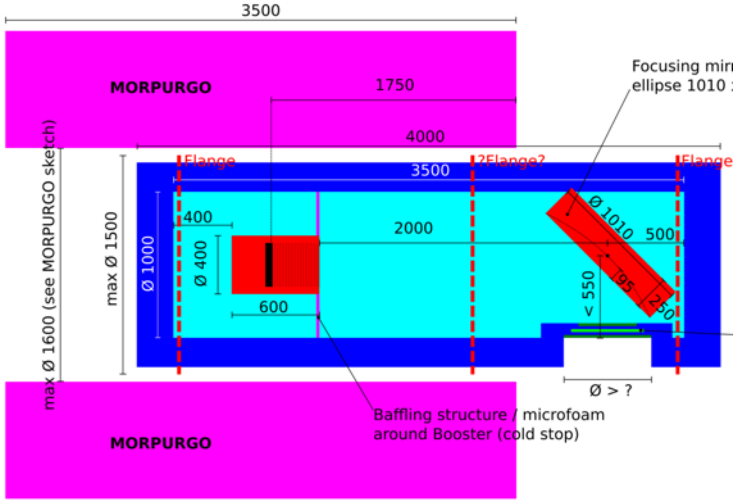
Axion Dark Matter Detection

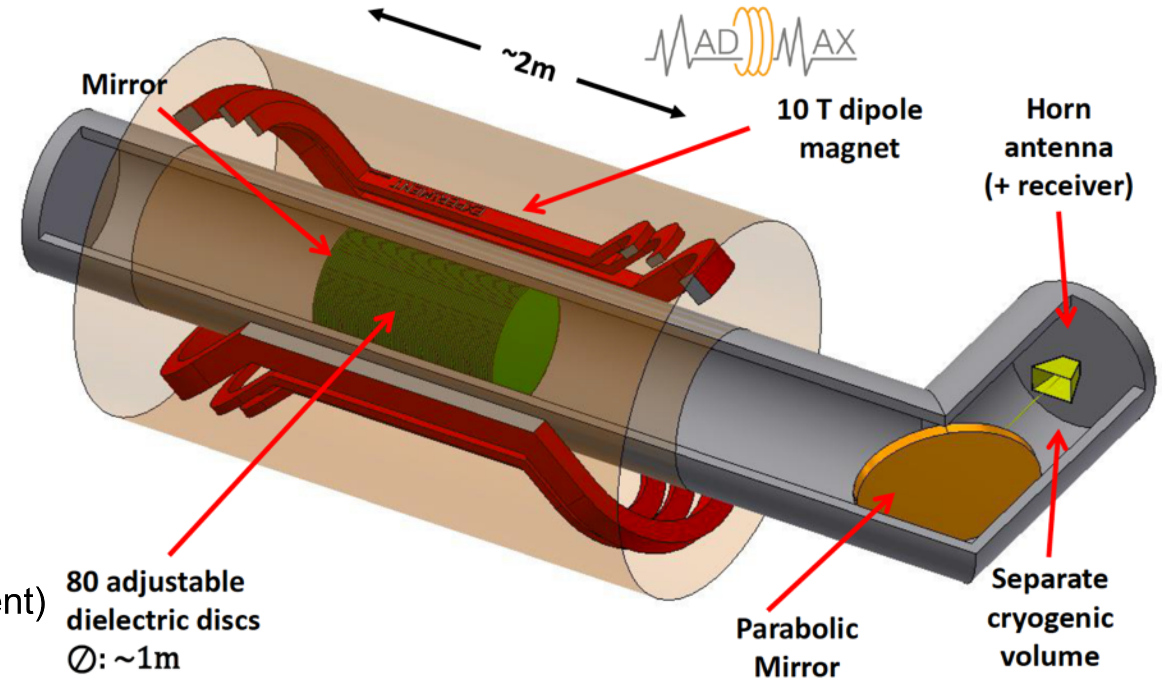
Dish Antennas

- **Boosted dish antenna: MADMAX** [Caldwell et al. `16; Bruns et al. 19]

2017 -2019	2020 -2028	2028 -2038
Design	Prototype	Experiment
	@CERN	@DESY







Scaling: (of final experiment)

Area	1/10
# discs	1/4
B [T]	1/5

Axion Dark Matter Detection

Dish Antennas

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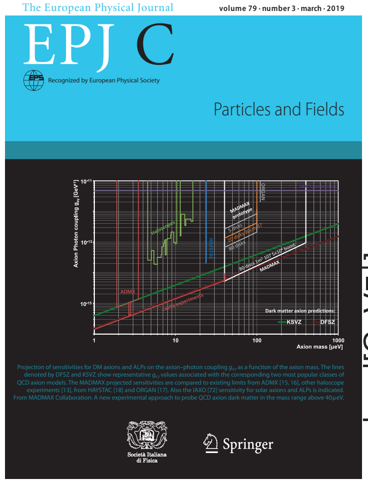
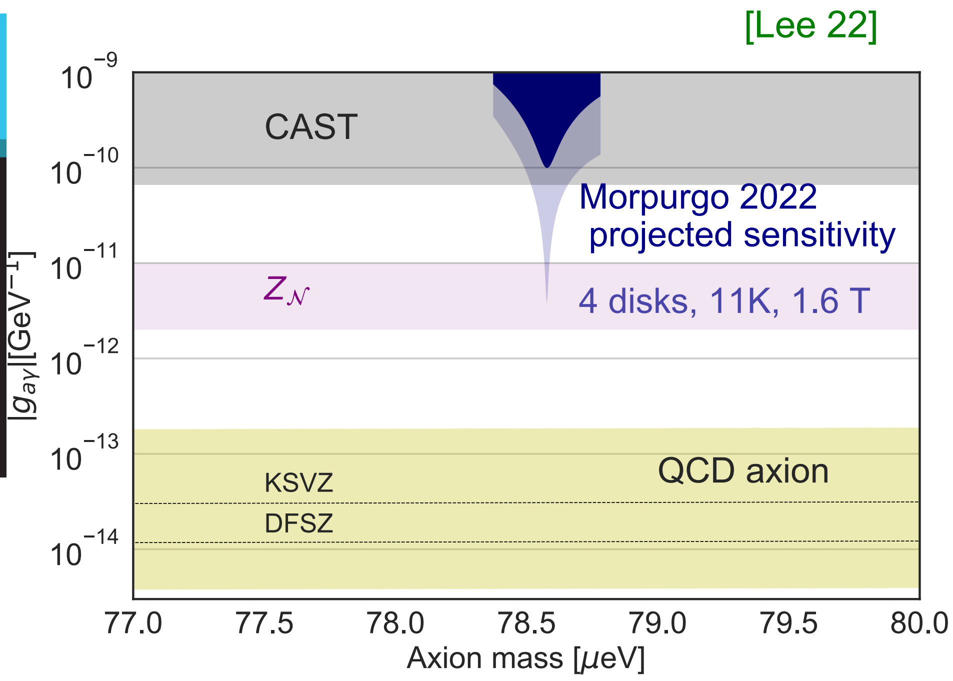
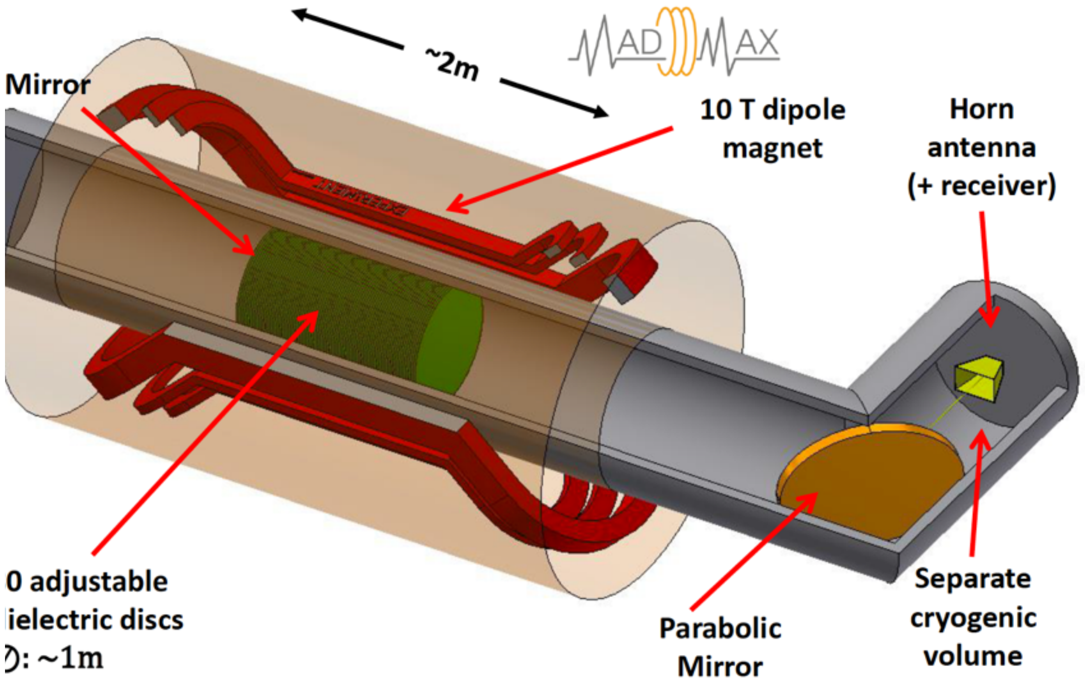
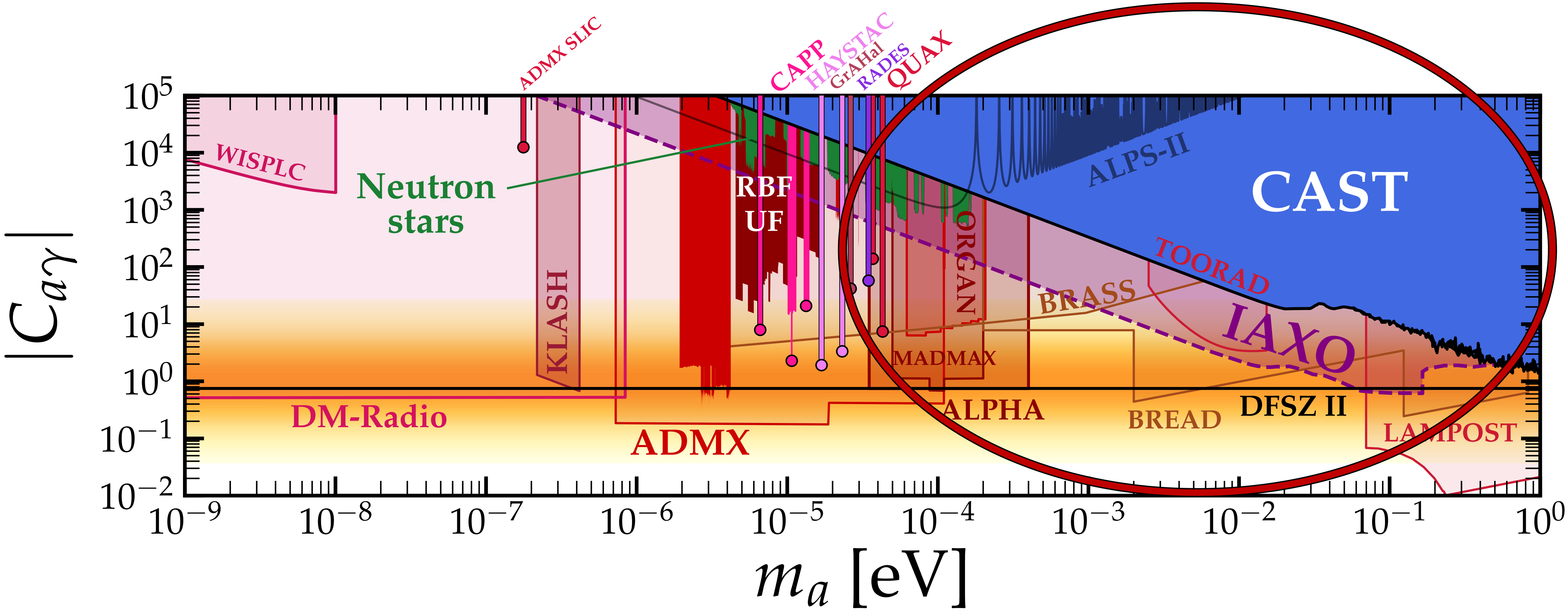






Axion Dark Matter Detection

Dish antennas



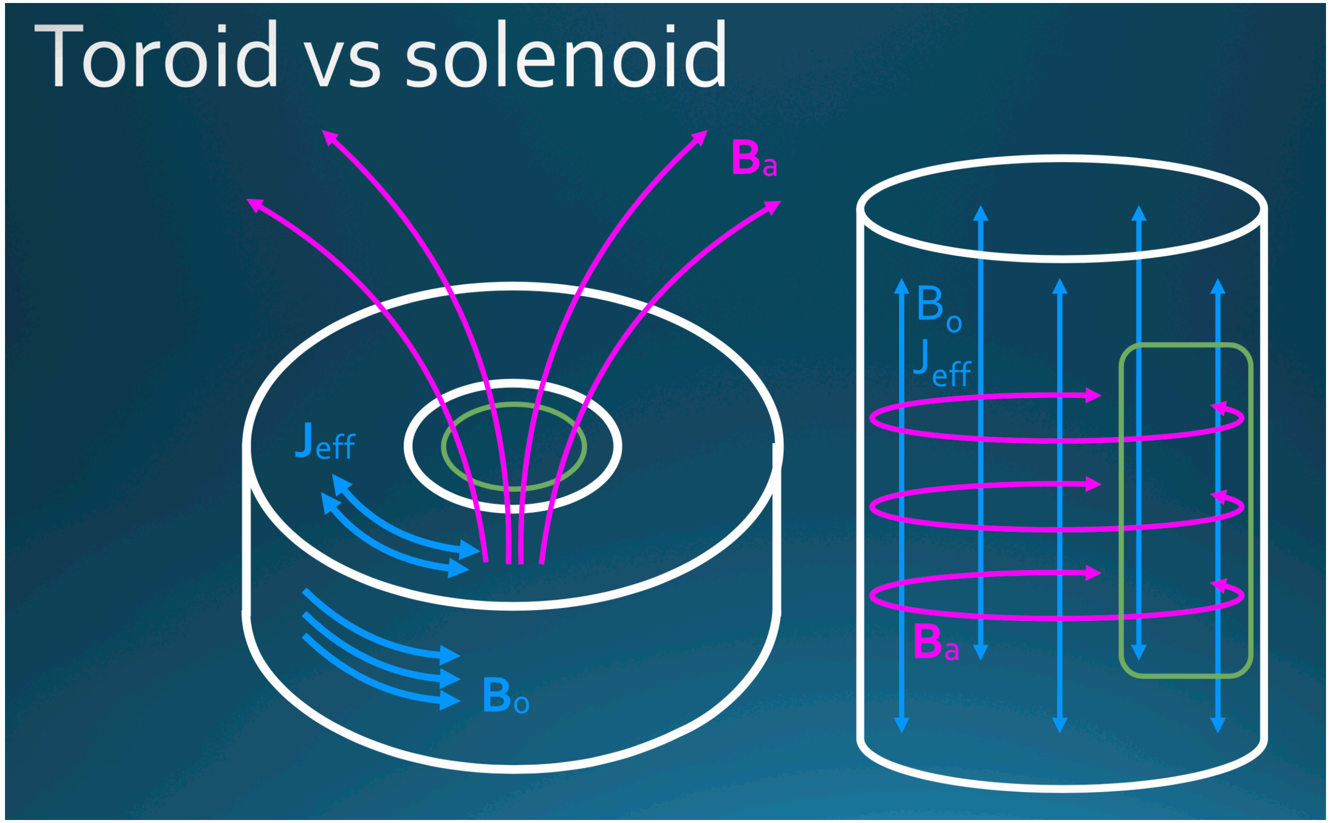
[https://github.com/cajohare/AxionLimits/blob/master/plots/AxionPhoton_Rescaled.pdf]

Axion Dark Matter Detection

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- Toroidal (solenoidal) magnet with fixed field B_0:
  - Axion DM generates oscillating effective current J_{eff} parallel to B_0
  - ... generating oscillating magnetic flux B_a through center (azimuthal magnetic flux)
  - ... which can be read out by pickup structure



$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

[Salemi '21]

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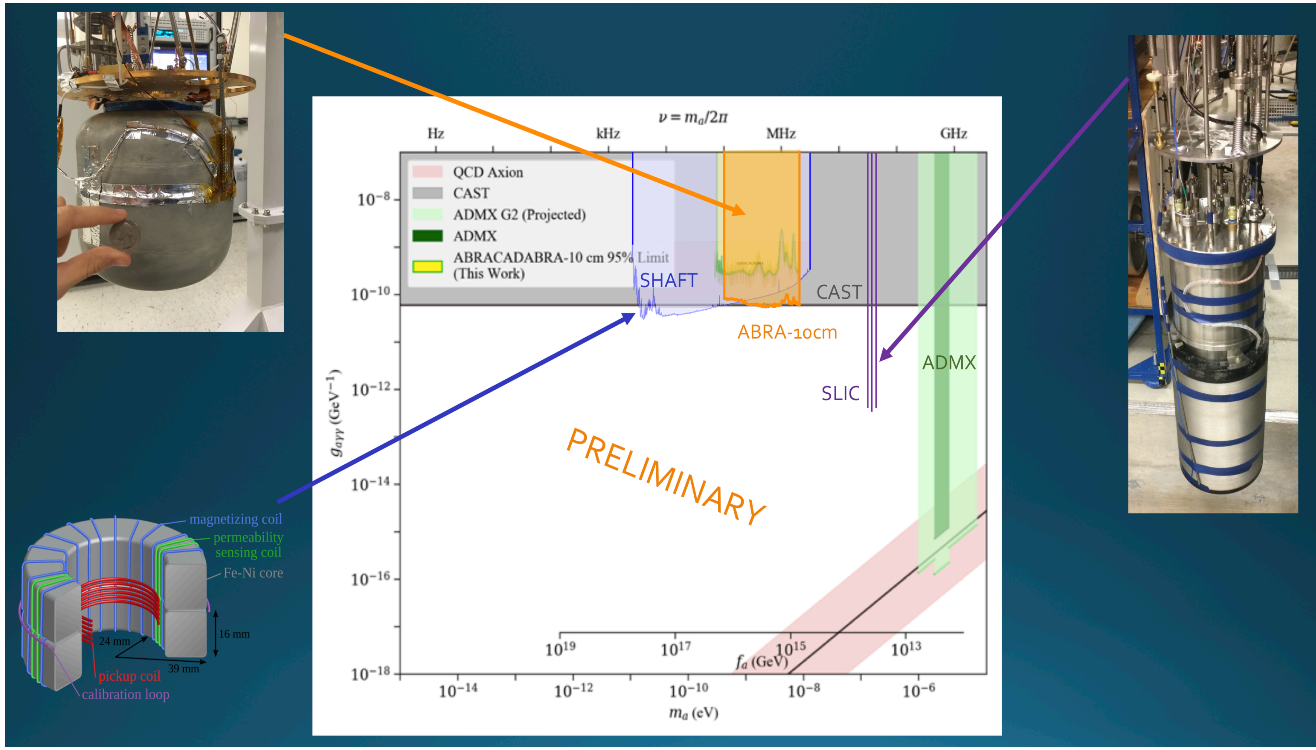

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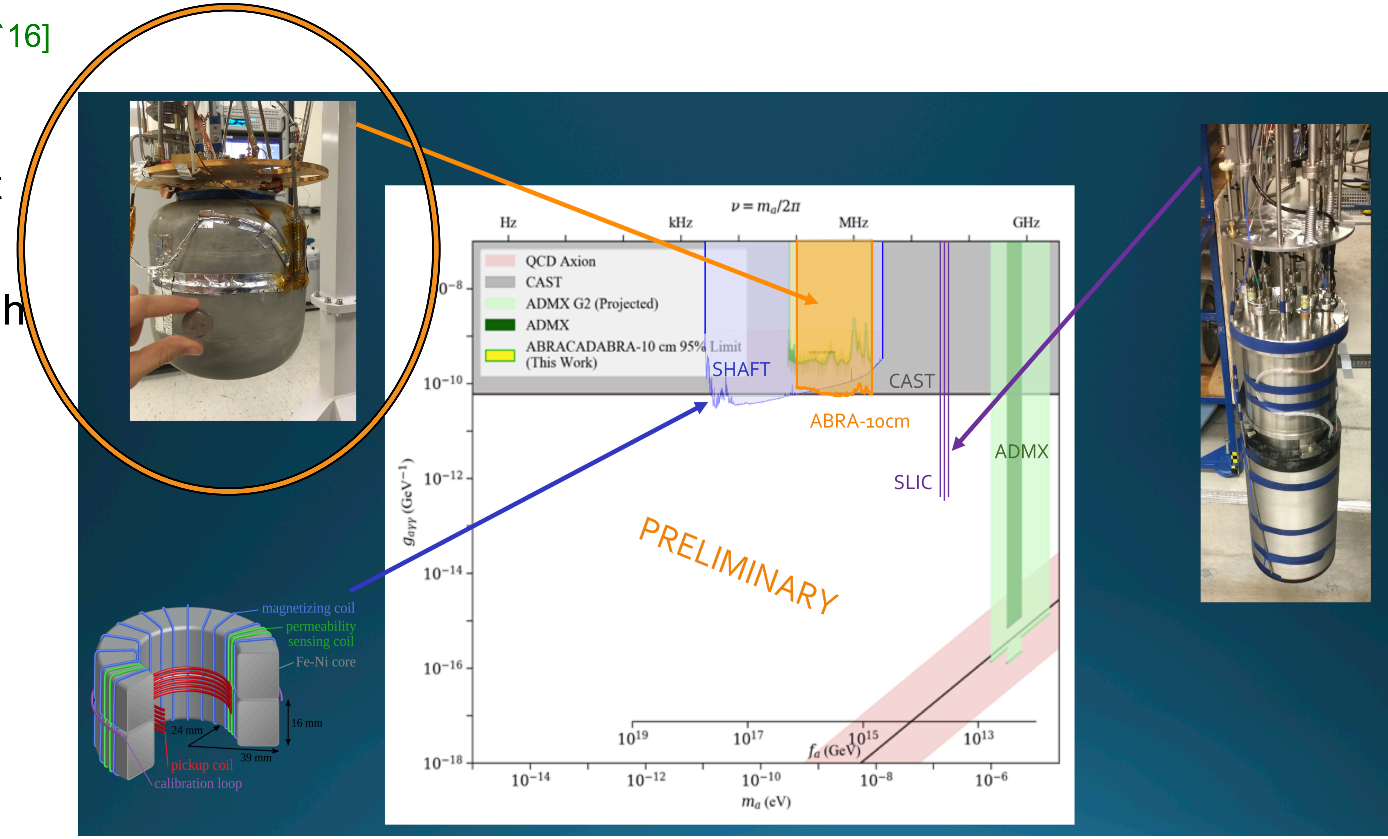

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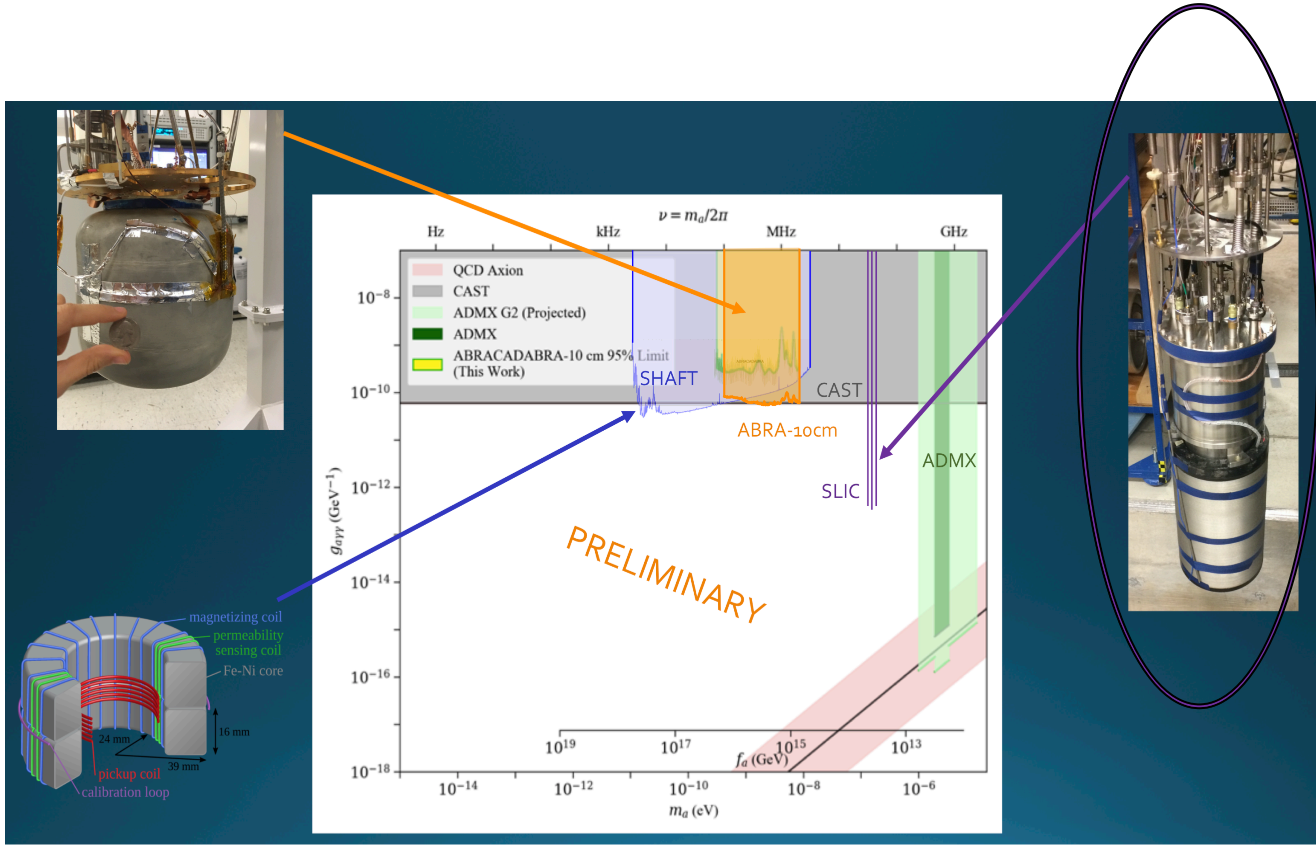

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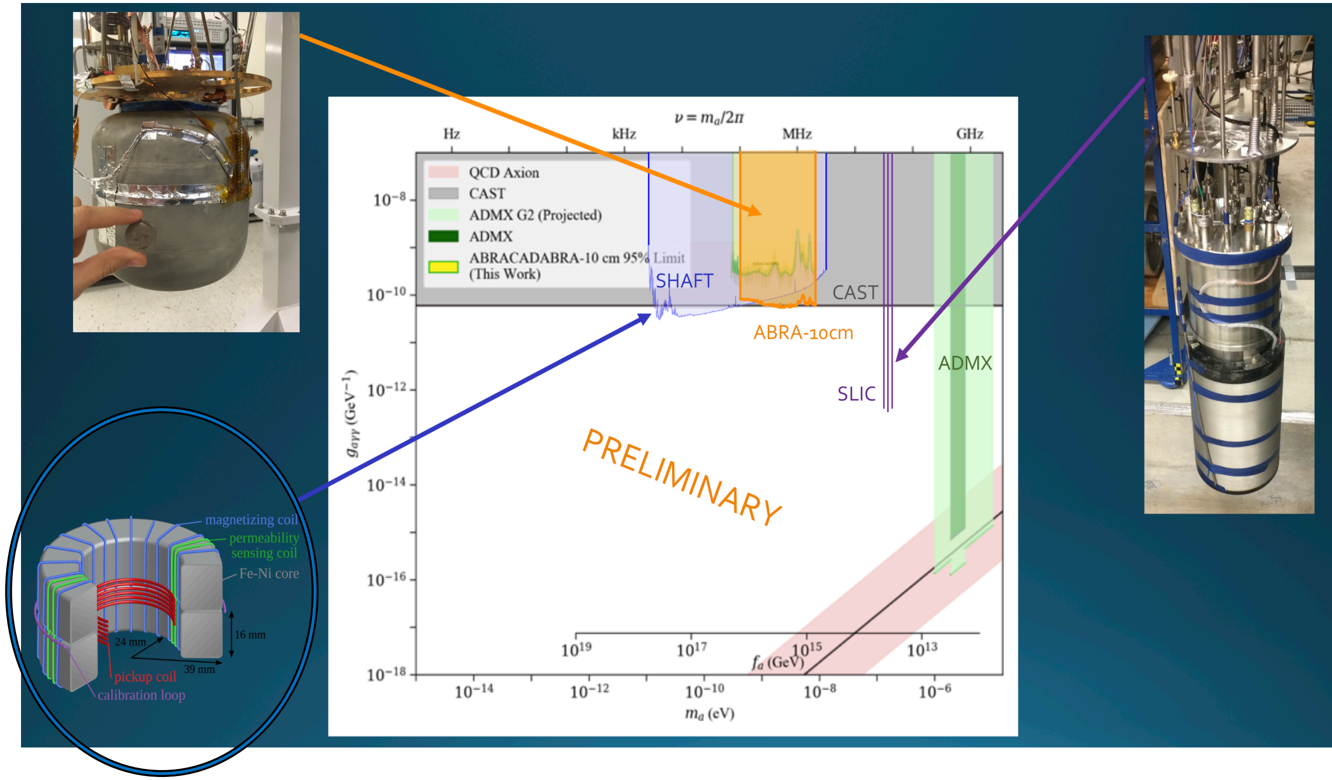

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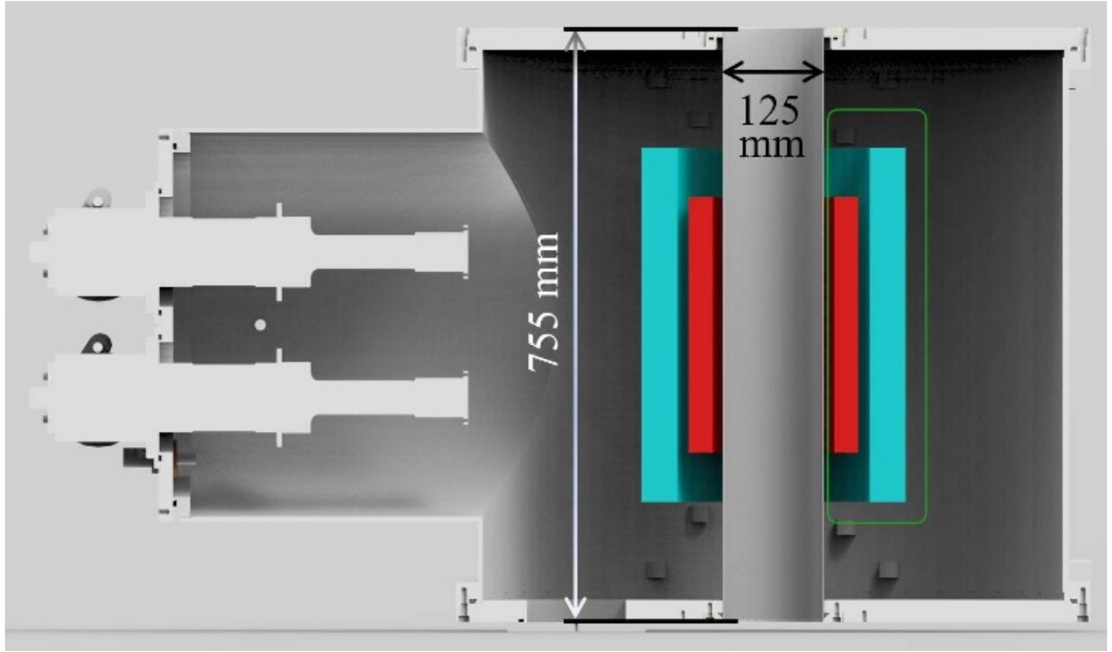
  - WISPLC [Zhang,Horns,Ghosh 21]



[Zhang,Horns,Ghosh 21]

TABLE I. Comparison of experimental parameters between WISPLC, ABRA. and SHAFT, $C = |\vec{B}_{max}| V_{magnet}\, \mathcal{G}_V$.

	$\lvert\vec{B}_{max}\rvert$ (T)	$\mathcal{G}_V$	V_{magnet} (m^3)	C/C_{SHAFT}
SHAFT[a]	1.5	0.108[b]	9.5×10^{-5}	1
ABRA.[c]	1	0.027	8.9×10^{-4}	1.55
WISPLC	14	0.074	2.4×10^{-2}	1.60×10^3

Axion Dark Matter Detection

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  - SHAFT [Gramolin et al. 21]
  - WISPLC
- DM-Radio Cubic Meter Consortium

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan

DARK MATTER RADIO

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC PRINCETON UNIVERSITY THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

DMRm3consortium v1 20191104

[Salemi '21]

Axion Dark Matter Detection

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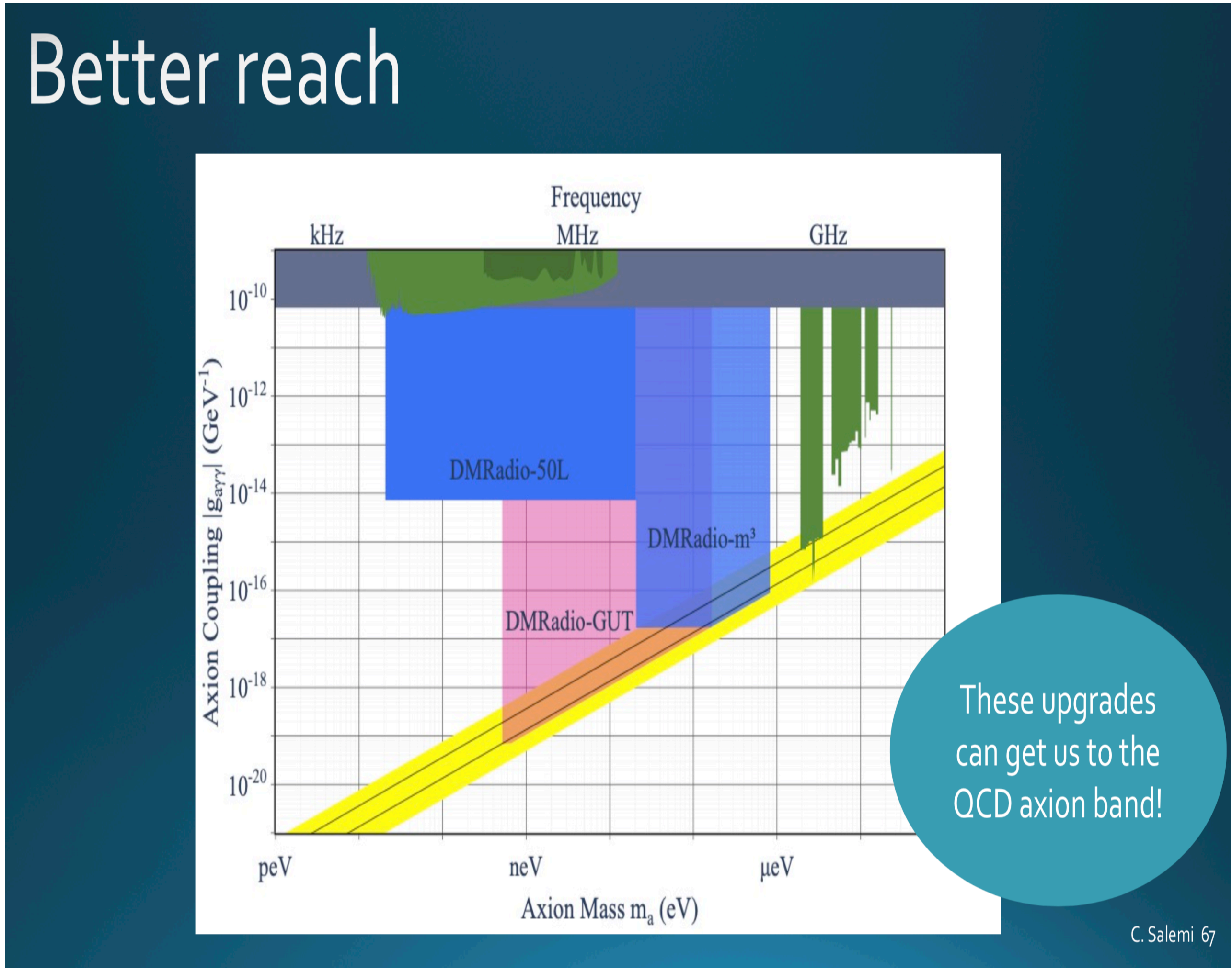
  - WISPLC
- DM-Radio Cubic Meter Consortium: aims to reach the canonical axion band, even reaching predictions from GUTs

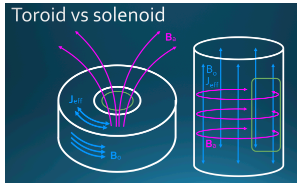
[Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]

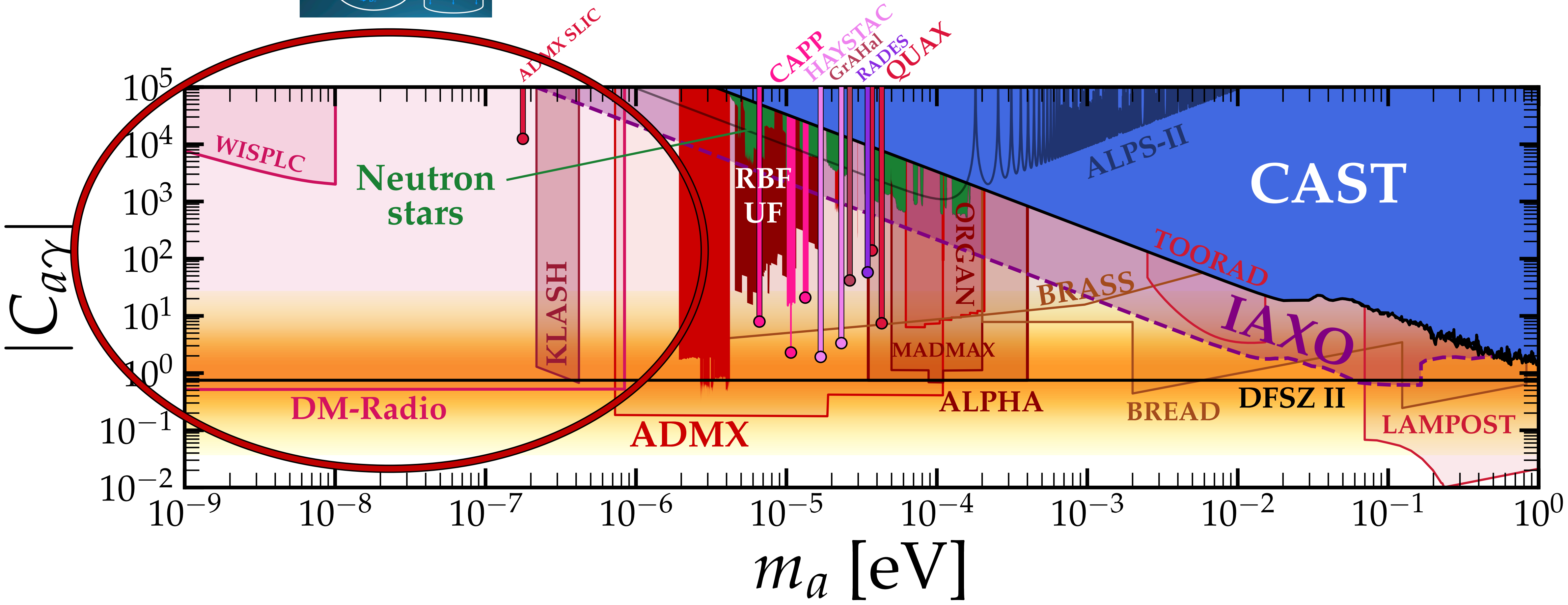


[Salemi '21]

Axion Dark Matter Detection

Searches employing lumped elements





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Axion Dark Matter Detection

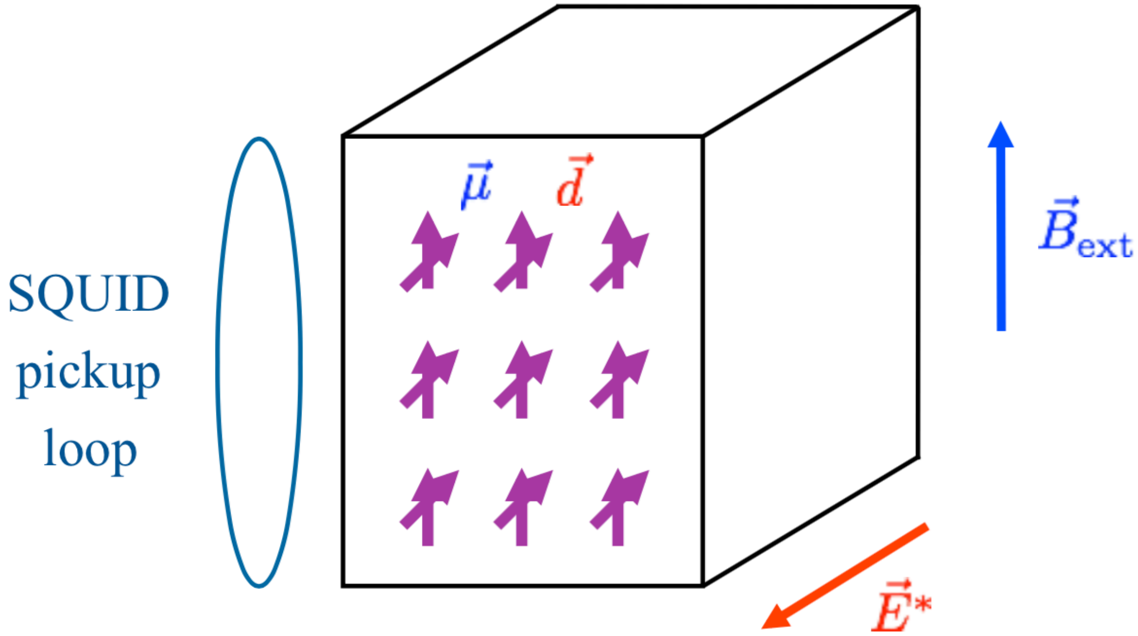
Magnetic Resonance Searches

- Axion DM field induces oscillating NEDMs:

$$d_N(t) = g_d\sqrt{2\rho_{\rm DM}}\cos(m_A t)/m_A$$

  - Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in external $\vec{B}_{\rm ext} \perp E^*$
  - Nuclear spins are polarised along $\vec{B}_{\rm ext}$ and precess at Larmor frequency $\omega_L = 2\mu_N B_{\rm ext}$
  - Interaction $\epsilon_S \vec{d}_N(t)\cdot\vec{E}^*$ of DM induced NEDM with the $\vec{E}^*$-field leads to resonant increase of transverse magnetisation of sample when $\omega_L = m_A$

[Graham,Rajendran 13; Budker et al. 14]



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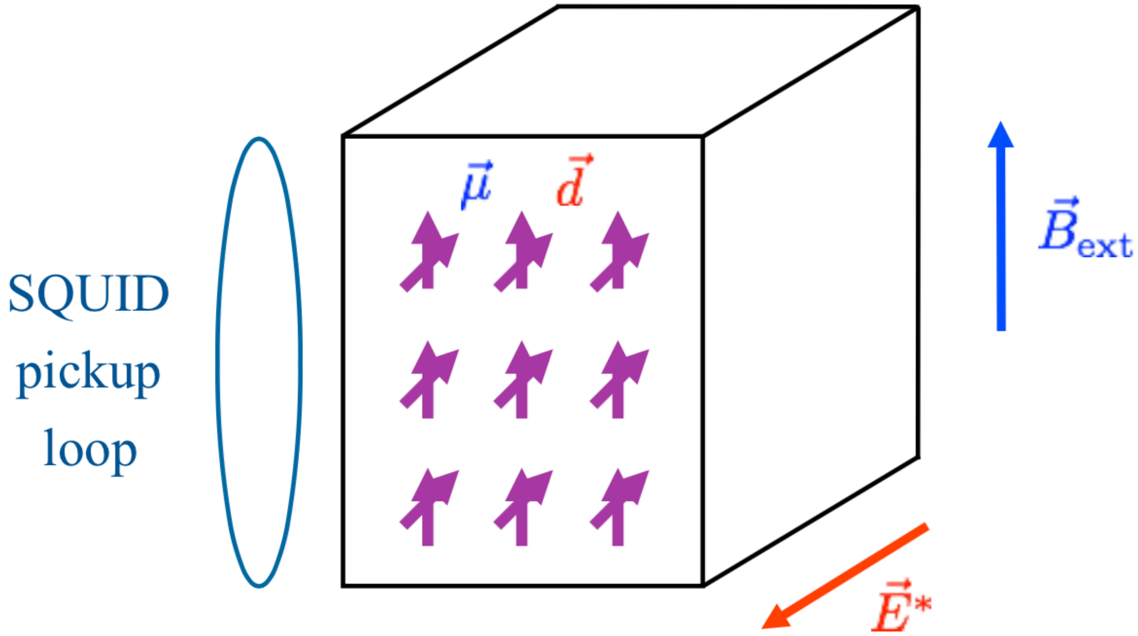

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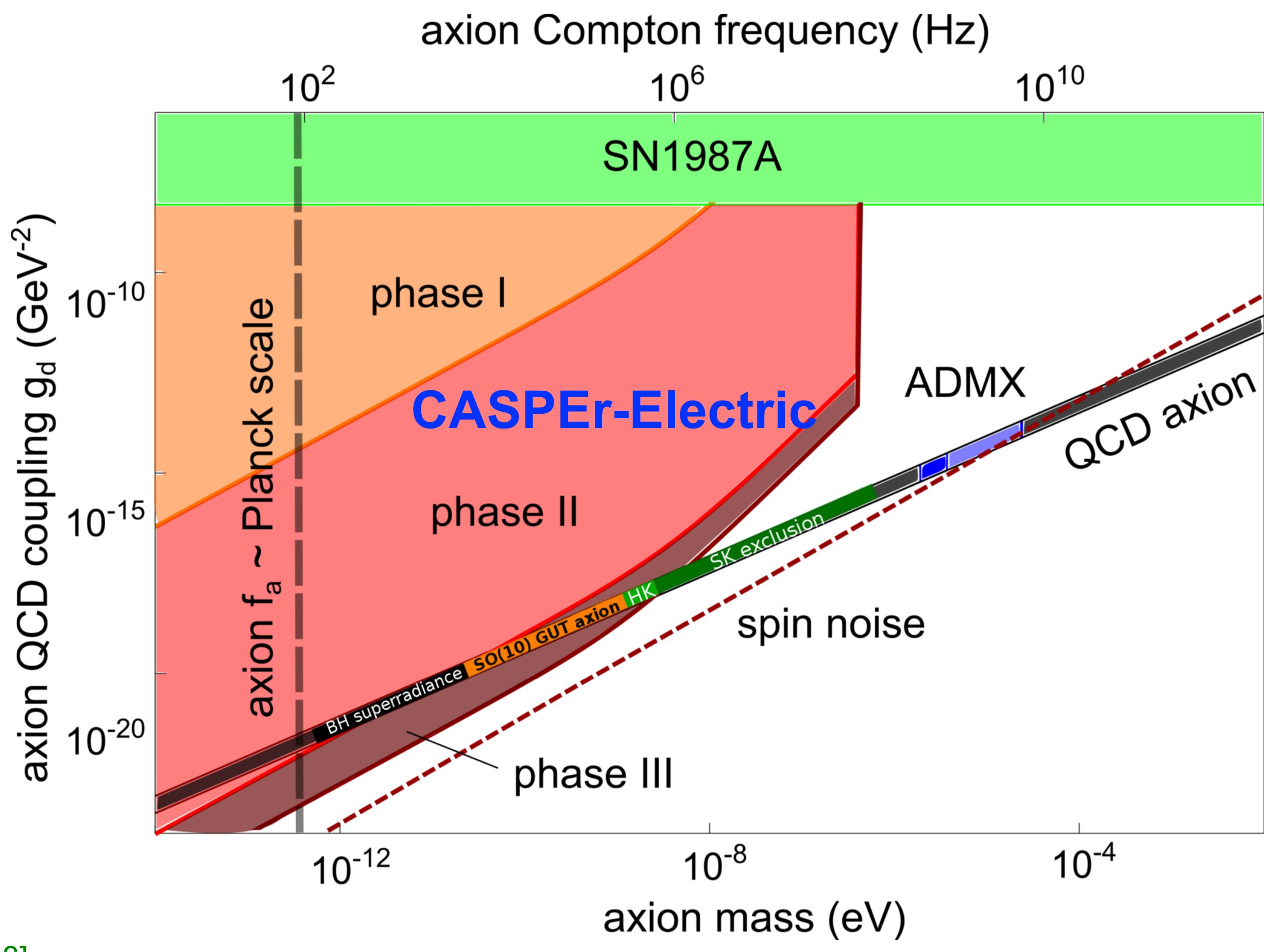

[Ernst,Di Luzio,AR,Tamarit 18]

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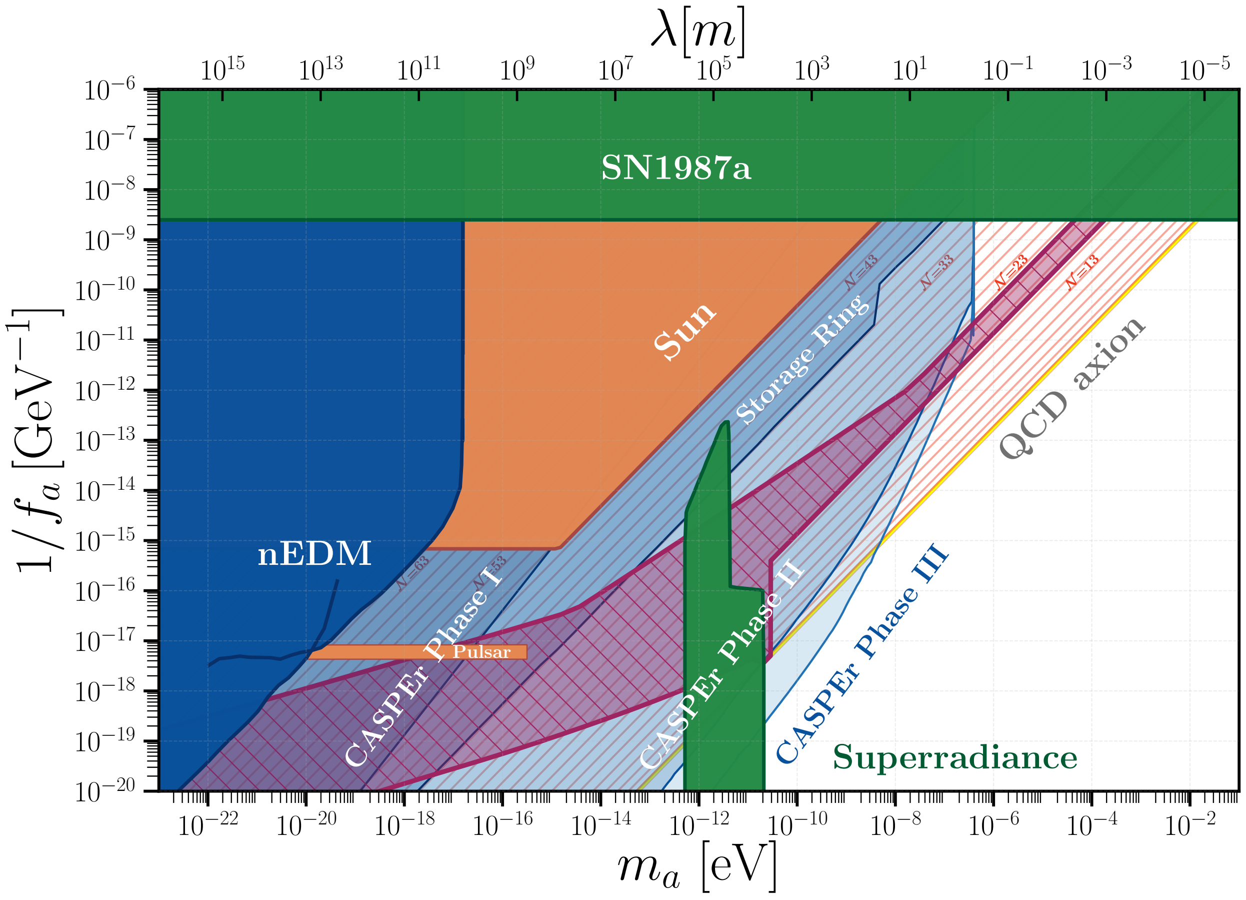
  - In phase I and II: probes Z_N axion dark matter

[Di Luzio, Gavela, Quilez, AR 2102.00012]



[Di Luzio, Gavela, Quilez, AR 2102.00012]

Conclusions

- Boom in axion searches!
- Large parts in axion parameter space will be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Solar axion searches ((Baby)IAXO, ...)
  - Axion dark matter searches (ADMX, BRASS, CAPP, CASPEr, DM RADIO, HAYSTAC, MADMAX, ORGAN, QUAX, ...)
  - Searches for axion-mediated forces (ARIADNE, ...)
- If 100 % of DM consists of QCD axions, one of the dark matter axion experiments likely to see a signal in the upcoming decade!

STAY TUNED!

Axion Dark Matter Search Based on NEDM Coupling

Storage ring EDM method

PHYSICAL REVIEW D **99**, 083002 (2019)

Axionlike dark matter search using the storage ring EDM method

Seung Pyo Chang,[1,2] Selçuk Hacıömeroğlu,[2] On Kim,[1,2] Soohyung Lee,[2] Seongtae Park,[2,*] and Yannis K. Semertzidis[1,2]

[1]*Department of Physics, KAIST, Daejeon 34141, Republic of Korea*

[2]*Center for Axion and Precision Physics Research, IBS, Daejeon 34051, Republic of Korea*

(Received 20 June 2018; revised manuscript received 28 January 2019; published 8 April 2019)

We propose using the storage ring electric dipole moment (EDM) method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of B and E fields to produce a resonance between the $g-2$ spin precession frequency and the background axion field oscillation to greatly enhance sensitivity to it. An axion frequency range from 10^{-9} Hz to 100 MHz can, in principle, be scanned with high sensitivity, corresponding to an f_a range of 10^{13} GeV $\le f_a \le 10^{30}$ GeV, the breakdown scale of the global symmetry generating the axion or axionlike particles.

DOI: 10.1103/PhysRevD.99.083002

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ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB188

NEW METHOD TO SEARCH FOR AXION-LIKE PARTICLES DEMONSTRATED WITH POLARIZED BEAM AT THE COSY STORAGE RING

S. Karanth*, Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
on behalf of the JEDI collaboration†

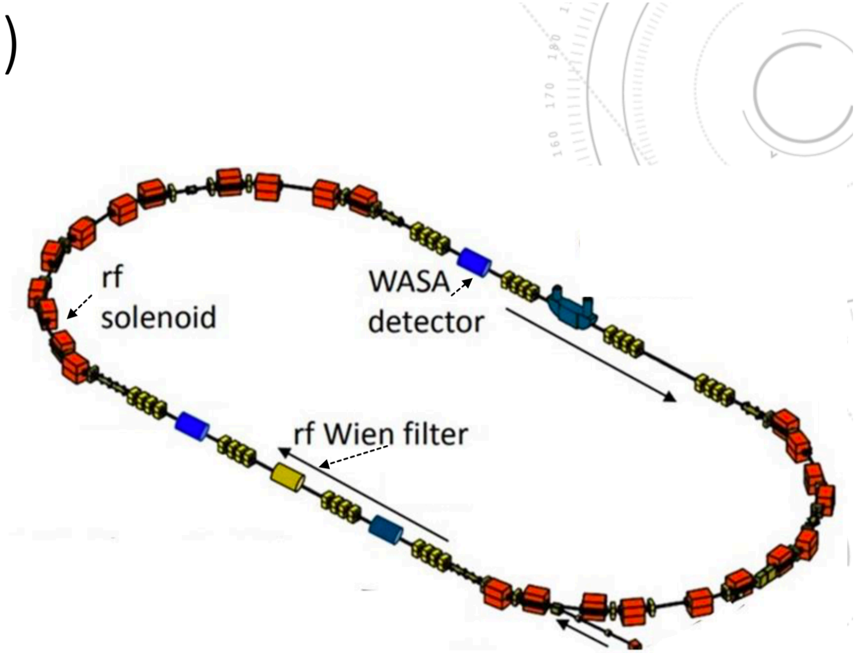
Abstract

The axion was originally proposed to explain the absence size of CP violation in quantum chromodynamics. Axions or axion-like particles (ALPs), when coupled to gluons, induce an oscillating Electric Dipole Moment (EDM) along the nucleon's spin direction. At the Cooler Synchrotron COSY in Jülich, this principle was used to perform a first test experiment to search for ALPs using an in-plane polarized deuteron beam. In COSY, the beam polarization vector precesses in the horizontal plane due to the presence of magnetic fields. If the spin precession frequency equals the EDM oscillation frequency, a resonance occurs that accumulates the rotation of the polarization out of the ring plane. Such a resonance is searched for by scanning beam revolution frequency, which is directly related to the spin precession frequency. At COSY, four beam bunches with different polarization directions were used to make sure that no resonance was missed because of the unknown relative phase between the polarization precession and the EDM oscillations. We scanned a frequency window of about 1.5 kHz width around the spin precession frequency of 121 kHz. This paper describes the experiment.

First demonstrator experiment at COSY

Cooler Synchrotron (COSY)

- A proof-of-principle experiment to search for ALPs
- Polarized deuterons
- WASA detector as the polarimeter



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NEW METHOD TO SEARCH FOR AXION-LIKE PARTICLES DEMONSTRATED WITH POLARIZED BEAM AT THE COSY STORAGE RING

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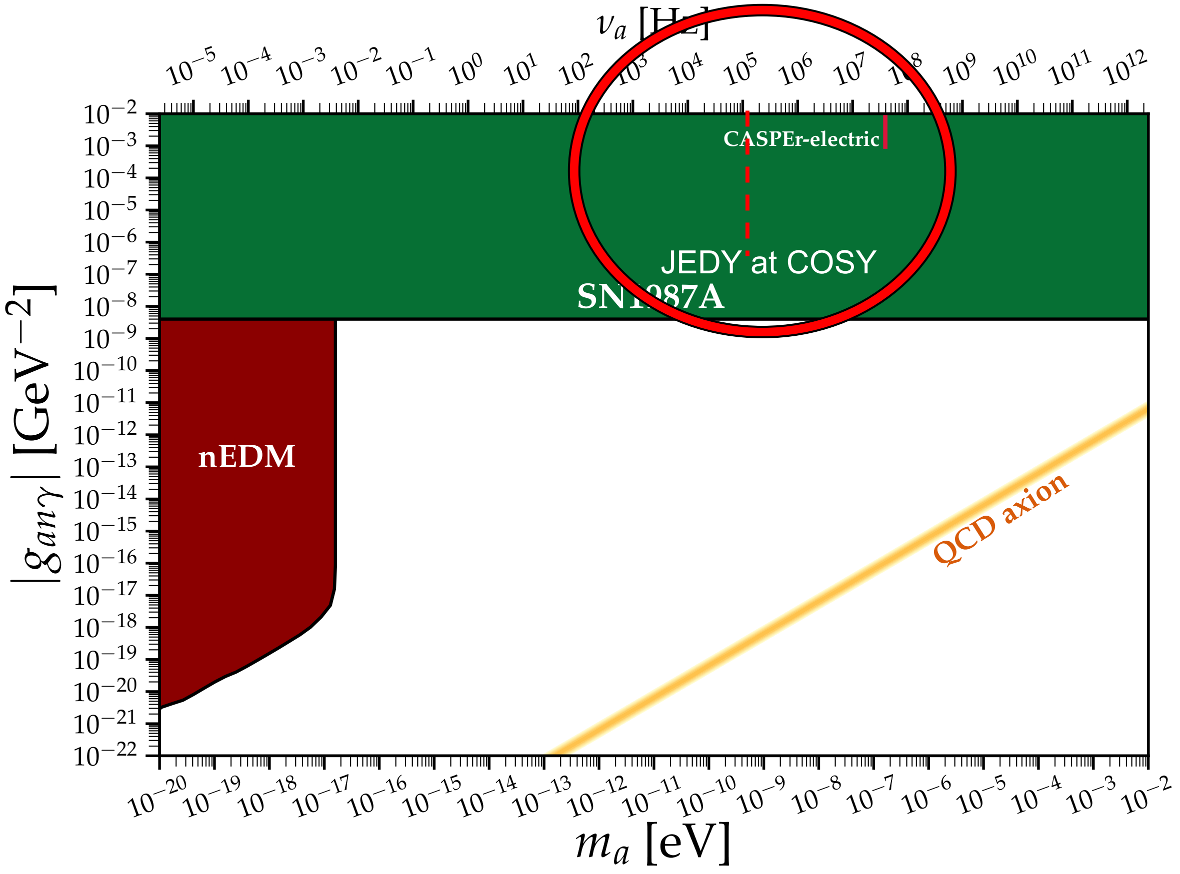
on behalf of the JEDI collaboration†

Abstract

The axion was originally proposed to explain the absence size of CP violation in quantum chromodynamics. Axions or axion-like particles (ALPs), when coupled to gluons, induce an oscillating Electric Dipole Moment (EDM) along the nucleon's spin direction. At the Cooler Synchrotron COSY in Jülich, this principle was used to perform a first test experiment to search for ALPs using an in-plane polarized deuteron beam. In COSY, the beam polarization vector precesses in the horizontal plane due to the presence of magnetic fields. If the spin precession frequency equals the EDM oscillation frequency, a resonance occurs that accumulates the rotation of the polarization out of the ring plane. Such a resonance is searched for by scanning beam revolution frequency, which is directly related to the spin precession frequency. At COSY, four beam bunches with different polarization directions were used to make sure that no resonance was missed because of the unknown relative phase between the polarization precession and the EDM oscillations. We scanned a frequency window of about 1.5 kHz width around the spin precession frequency of 121 kHz. This paper describes the experiment.



[adapted from https://github.com/cajohare/AxionLimits]

Axion Dark Matter Search Based on NEDM Coupling

Storage ring EDM method

The storage ring proton EDM experiment

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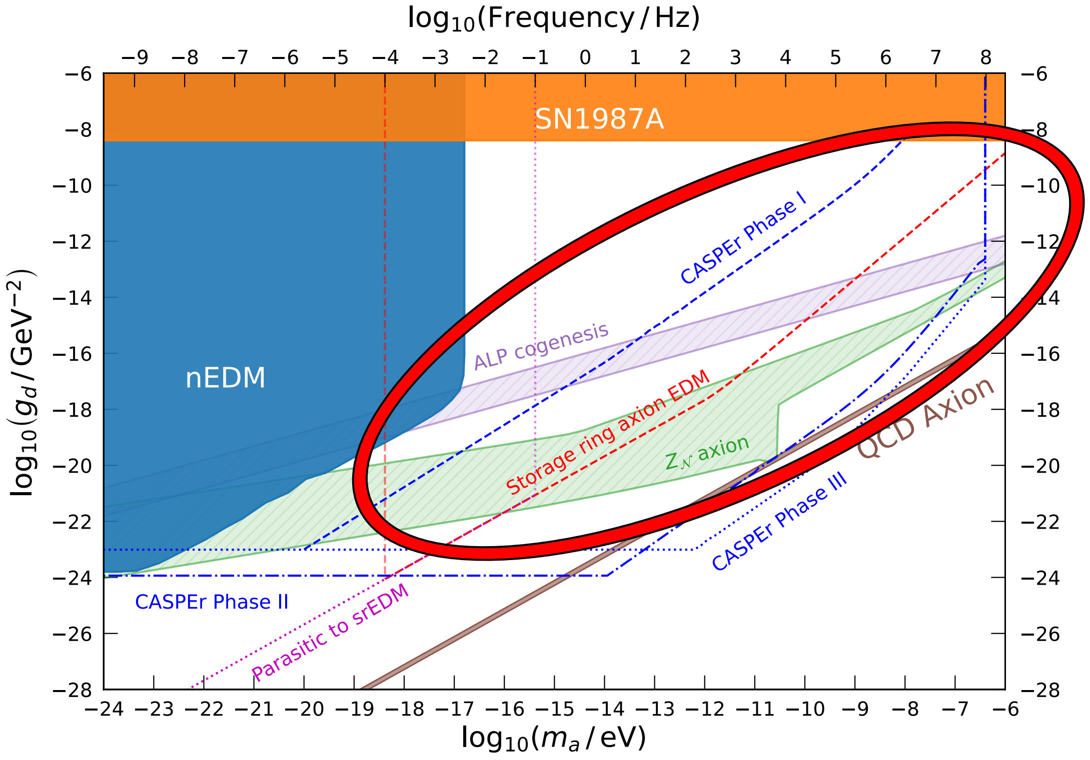
arXiv:2205.00830v1 [hep-ph] 25 Apr 2022



[Alexander et al., arXiv:2205.00830 [hep-ph]]

ALP with nEDM coupling in projected reach of storage ring EDM method is much lighter than a canonical QCD axion with the same nEDM coupling strength

Searches for Axion Mediated Forces

Magnetic Resonance Searches

- Experiments searching for axion mediated forces particularly effective in meV mass range
- Monopole-dipole interaction between nucleon and fermion:

$$U_{\mathrm{mon-dip}}(r) = \frac{g_{\overline{aN\bar{N}}}\, g_{af\bar{f}}}{8\pi m_f} \left(\frac{m_a}{r} + \frac{1}{r^2} \right) e^{-m_a r} \, (\hat{\sigma} \cdot \hat{r})$$

$$\mathcal{L}_{\mathrm{int}} = g_{\overline{aN\bar{N}}}\; a \bar{N} N - i\, g_{af\bar{f}}\, a \bar{f} \gamma_5 f$$

- Proposed ARIADNE experiment searches for forces between a rotating cylinder, made of unpolarized material, and a vessel containing hyperpolarized ^{3}He gas
  - Since ^{3}He magnetic moment dominated by neutron contribution: sensitive to monopole-dipole interaction between nucleus and neutrons, $\left| g_{\overline{aN\bar{N}}}\, g_{an\bar{n}} \right|$

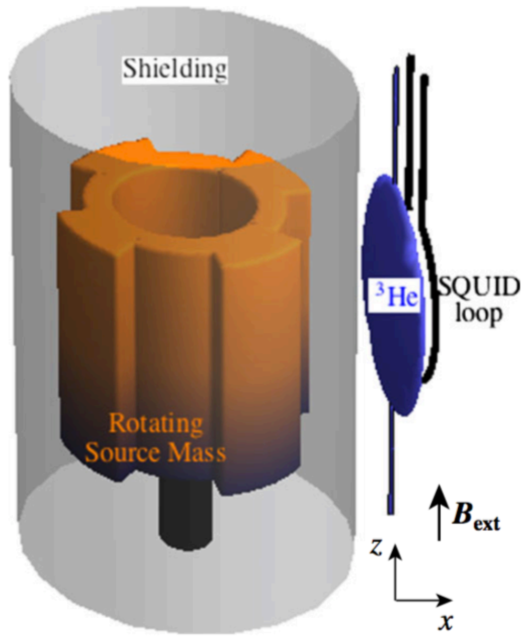


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{\mathrm{rot}}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{\mathrm{ext}}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

[Arvanitaki, Geraci 14]

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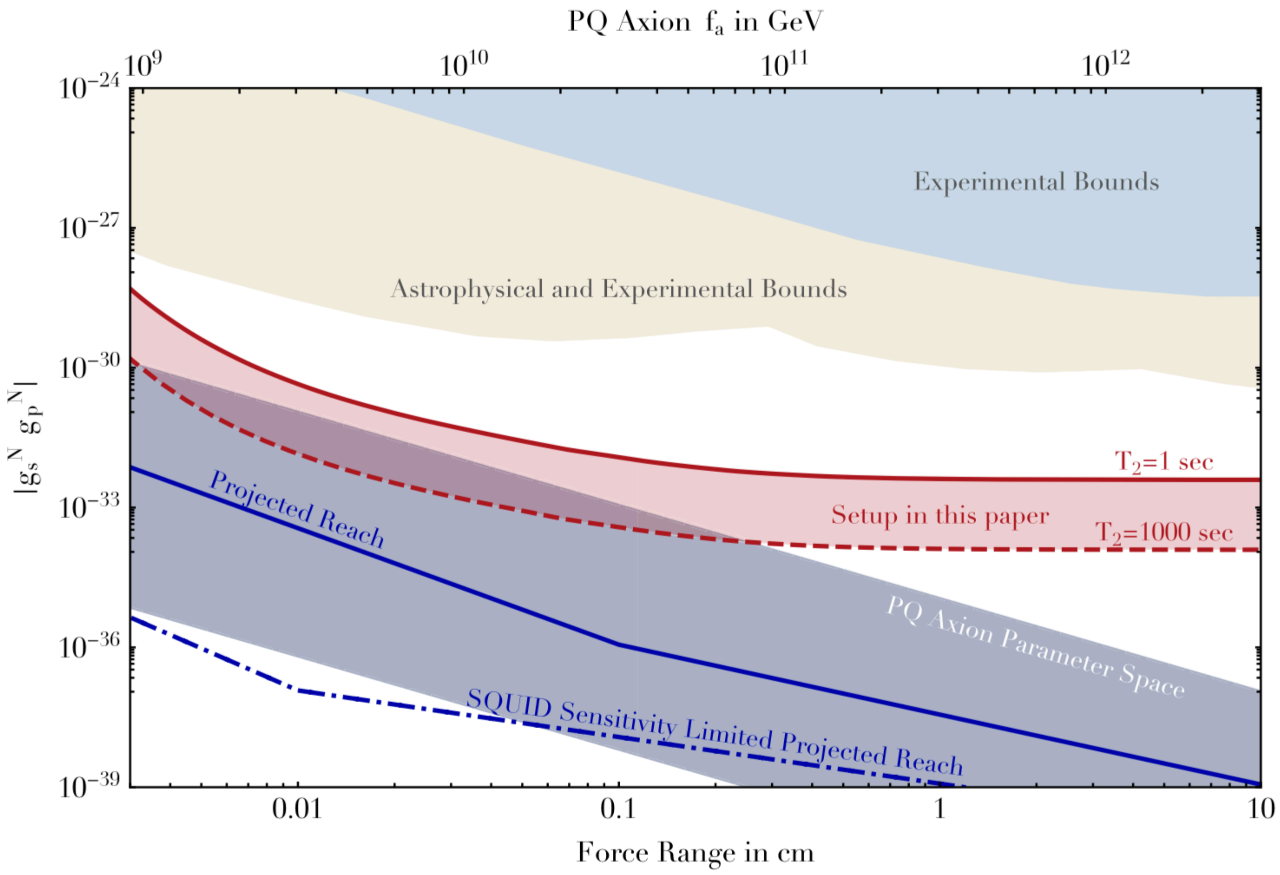
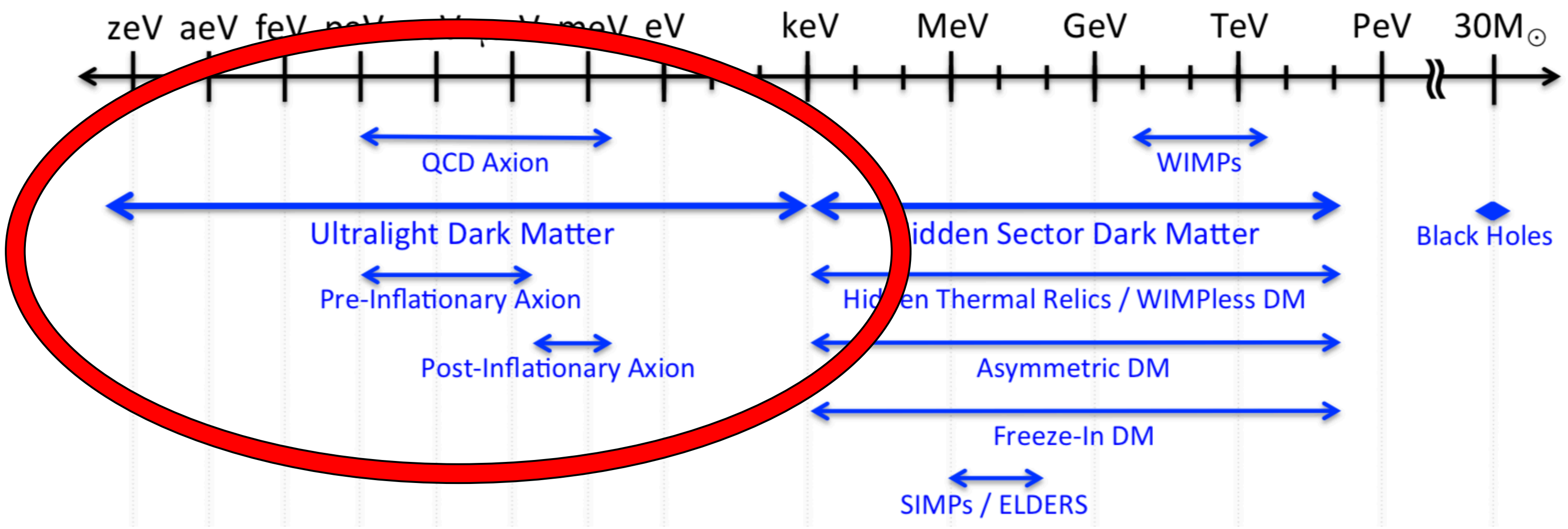


[Arvanitaki, Geraci 14]

Axion Dark Matter

Wavy dark matter

- “Invisible axion” ($f_a \gtrsim 10^9\,\mathrm{GeV} \leftrightarrow m_a \lesssim 6\,\mathrm{meV}$) [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Natural DM candidate
    - stable on cosmologically time scales
    - automatically produced in early universe by misalignment mechanism [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]
- Belongs to the generic class of **Ultralight Dark Matter** candidates



[US Cosmic Visions: New Ideas in Dark Matter 2017]

Axion Dark Matter

Wavy dark matter

- De Broglie wave length of dark matter in our neighborhood in Milky Way:

$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM}\, v_{\rm d}} = 1.49\,{\rm m}\,\left(\frac{\rm meV}{m_{\rm DM}}\right)\left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)$$

- For $m_{\rm DM} \ll 30\,{\rm eV}$, large occupation number per de Broglie volume in our neighborhood in Milky Way:

$$N_{\rm DM}\,|_{\rm dB} = n_{\rm DM}\,\lambda_{\rm dB}^3 = \frac{\rho_{\rm DM}}{m_{\rm DM}}\left(\frac{2\pi}{m_{\rm DM}\,v_{\rm d}}\right)^3 = 1.3\times 10^{18}\left(\frac{\rm meV}{m_{\rm DM}}\right)^4\left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3\left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

- Invisible axion dark matter ($f_a \gtrsim 10^9\,{\rm GeV} \leftrightarrow m_a \lesssim 6\,{\rm meV}$) best described by classical waves.

- Therefore also known as

Coherent-Field Dark Matter or **Wave Dark Matter**

- For $m_{\rm DM} \lesssim 10^{-22}\,{\rm eV}$, de Broglie wave length exceeds size of dwarf galaxies. Therefore,

Axion Dark Matter Candidates must have a mass $\gtrsim 10^{-22}\,{\rm eV}$