Experimental Hunts for Axions and Axion-Like Particles.

Andreas Ringwald (DESY)

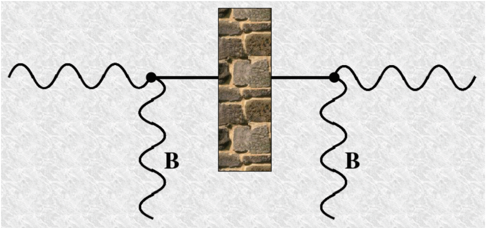
Mini-Workshop “Theory meets experiment”
NIKHEF
Amsterdam
The Netherlands
27 January 2017

HELMHOLTZ
ASSOCIATION

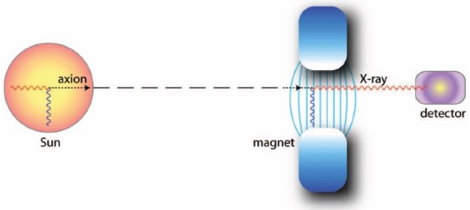
DESY

Different Search Methods

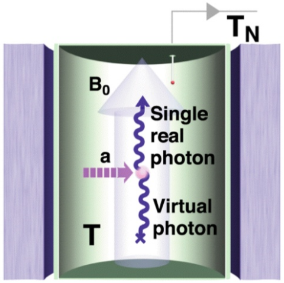
- Light-shining-through-walls



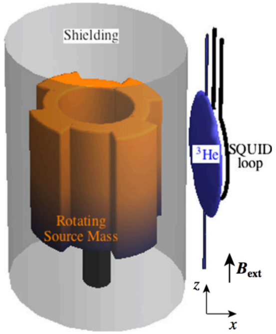
- Helioscopes



- Haloscopes

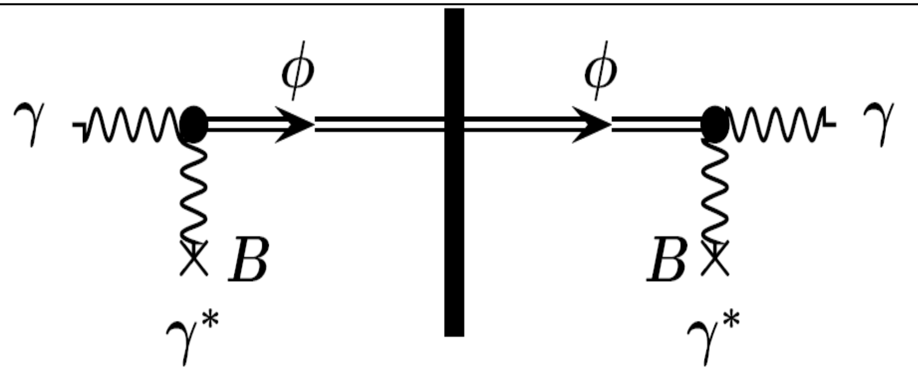


- Fifth-force searches



Light-shining-through-a-wall Searches

- Axion/ALP so weakly interacting, that it passes any barrier
- Light-shining-through a wall:



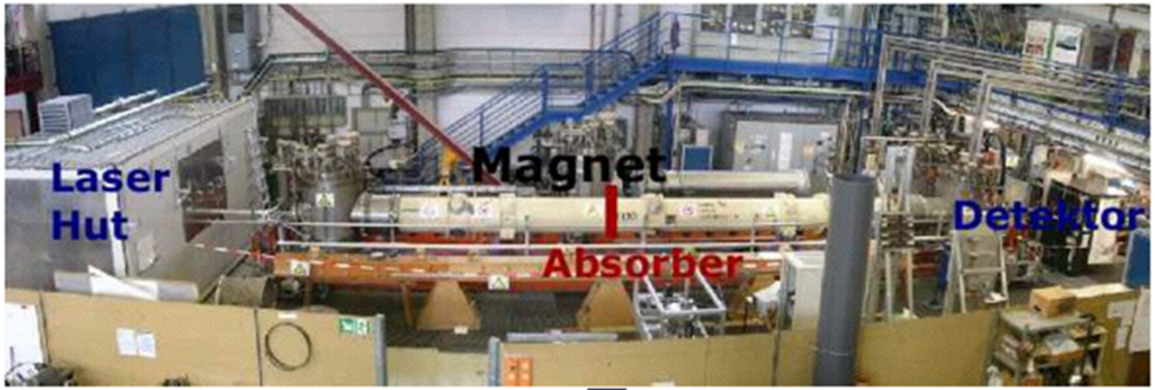
[Okun 1982, Sikivie 1983, Ansel‘m 1985, van Bibber et al. 1987]

- Oscillation probability:

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

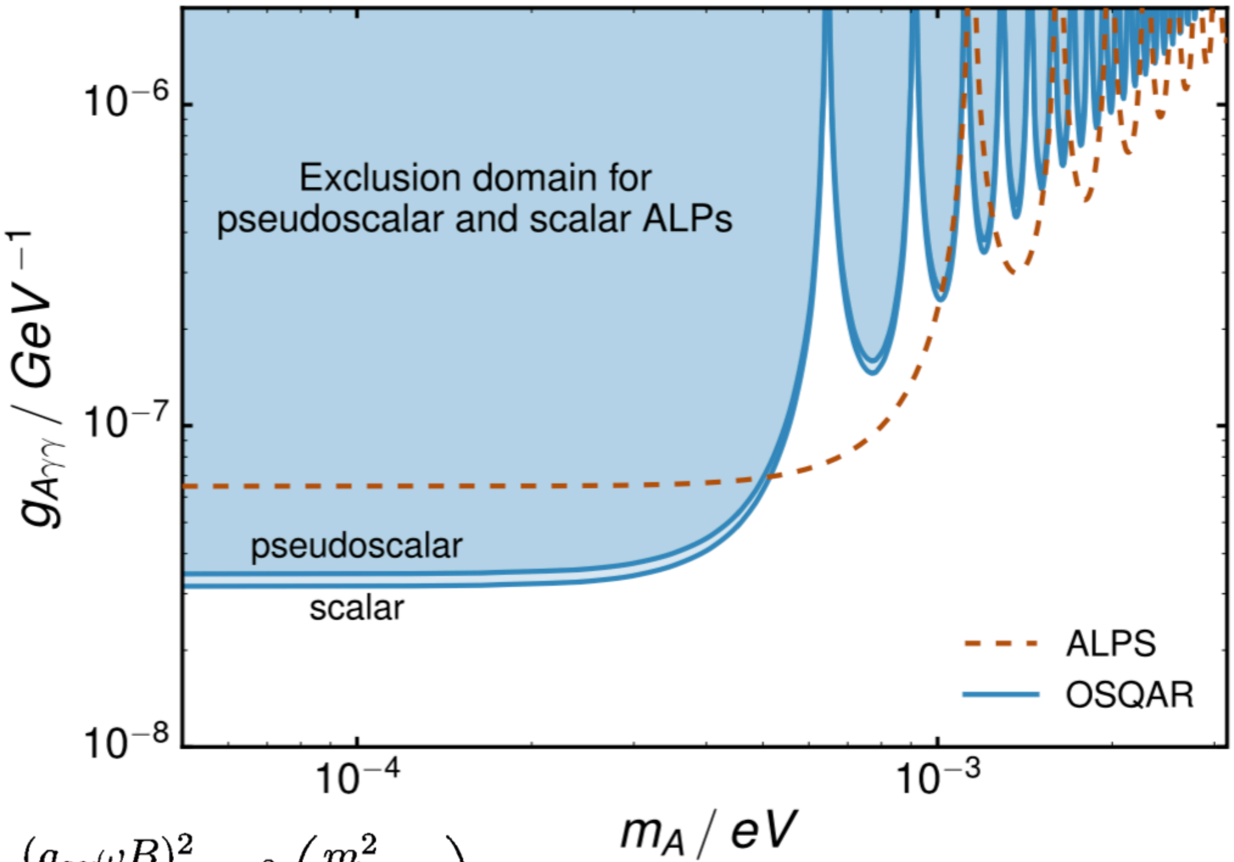
Light-shining-through-a-wall Searches

- Any Light Particle Search (ALPS) at DESY (in coll. with AEI, UHH)



Light-shining-through-a-wall Searches

- Currently best limits from LSW: ALPS (DESY) and OSQAR (CERN)

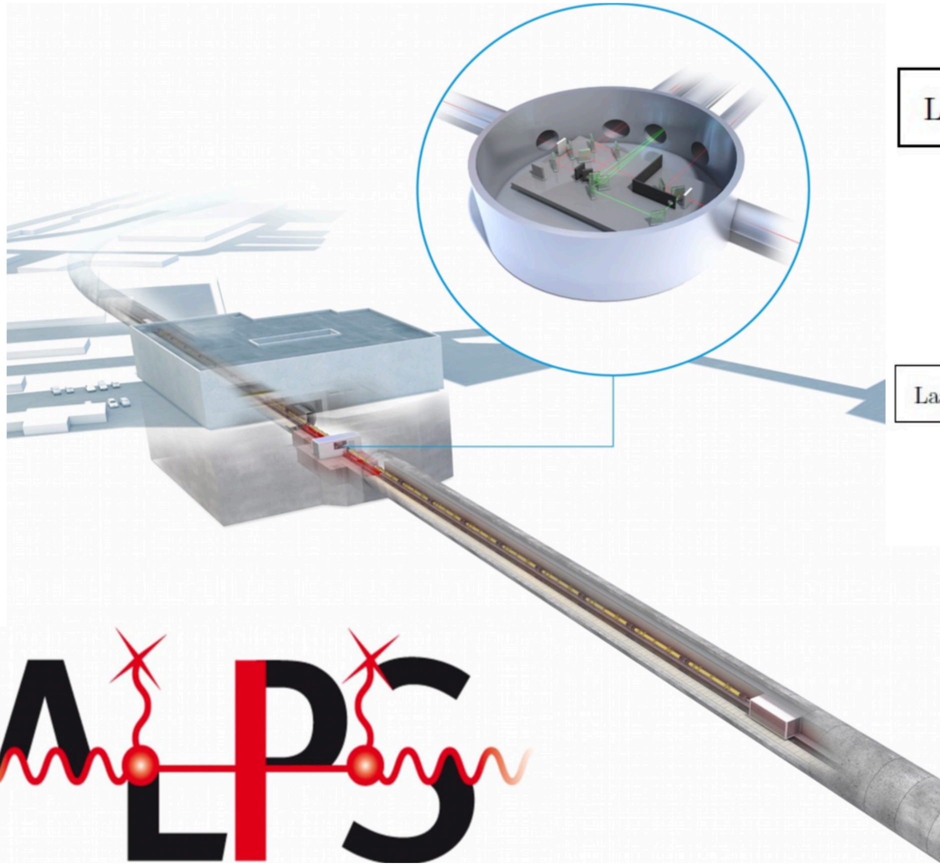


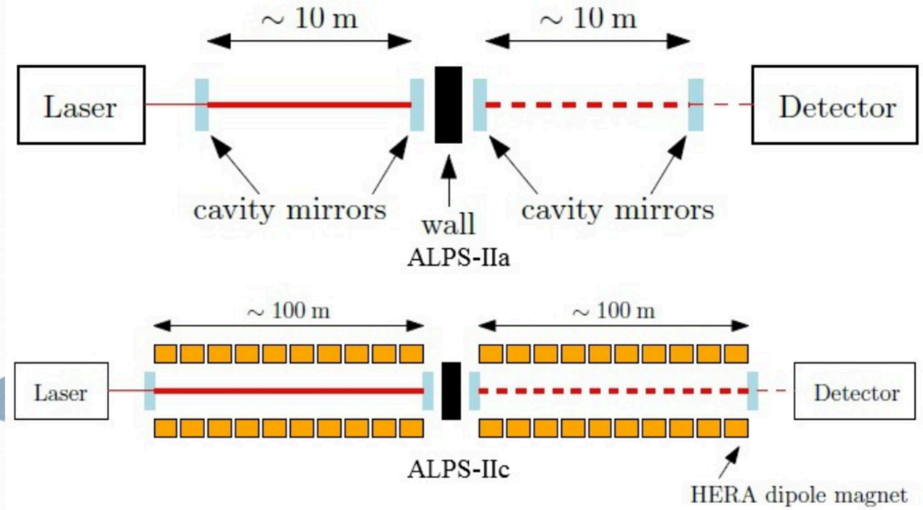
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

[Ballou et al. 15]

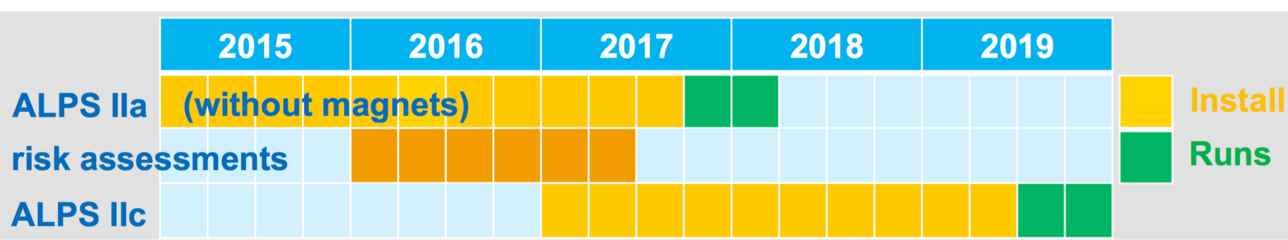
Light-shining-through-a-wall Searches

> ALPS II at DESY (in coll. with AEI, UFL, U Mainz)





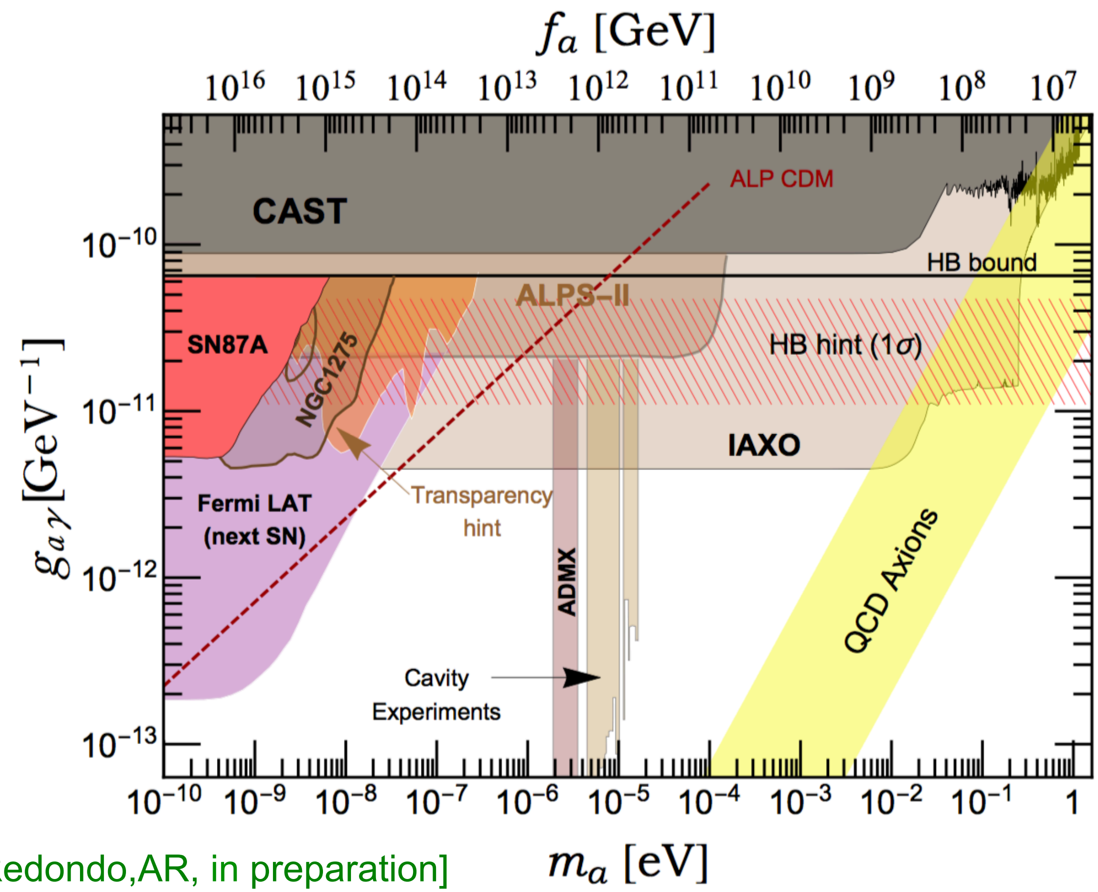
Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power $P_{\rm laser}$	$g_{a\gamma} \propto P_{\rm laser}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC $P_{\rm RC}$	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,{\rm s}^{-1}$	$0.000001\,{\rm s}^{-1}$	2.6
Combined improvements				3082



[Bähre et al (ALPS II TDR) 13]

> ALPS II

- First pure laboratory experiment to surpass stellar bounds
- Can probe part of parameter space relevant for astro hints



[Giannotti,Irastorza,Redondo,AR, in preparation]

Light-shining-through-a-wall Searches

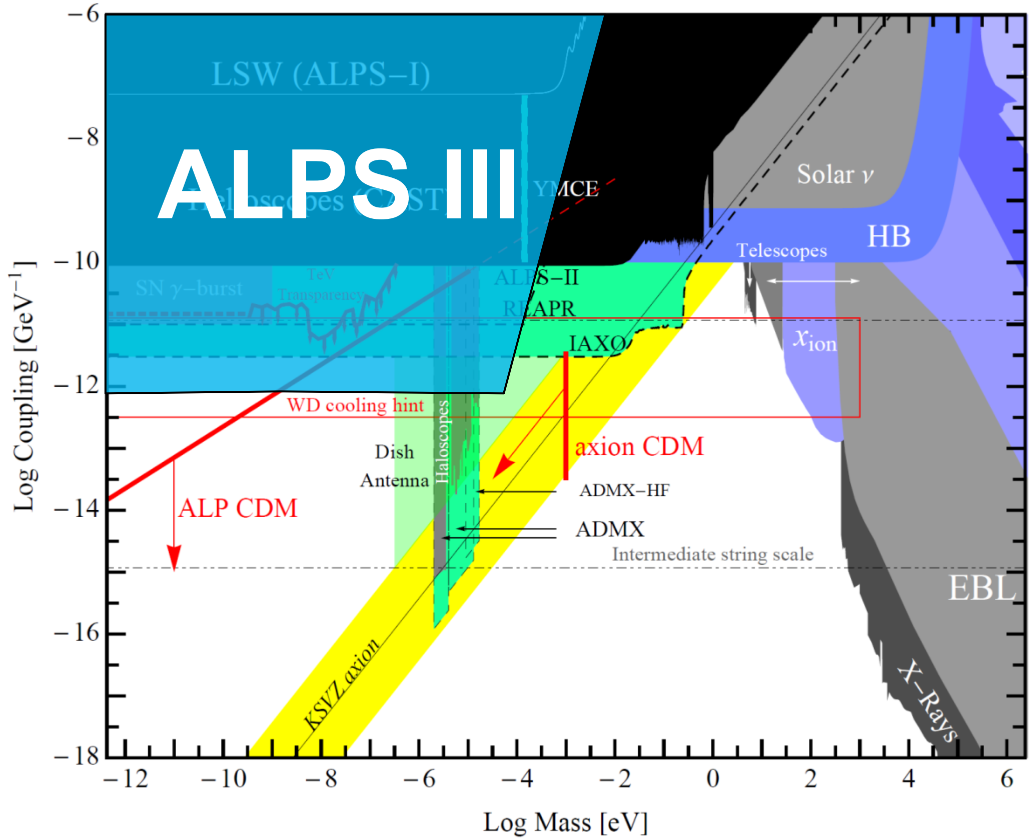
> Beyond ALPS II?

Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)	Mass reach (eV)
ALPS I	$3.5\cdot10^{21}$	2.3	5.0	4.4	22	1	0.0003	0.001
ALPS II	$1\cdot10^{24}$	1.2	5.3	106	468	40,000	1	0.0002
"ALPS III"	$3\cdot10^{25}$	1.2	13	400	5200	100,000	27	0.0001

[Lindner 14]

Light-shining-through-a-wall Searches

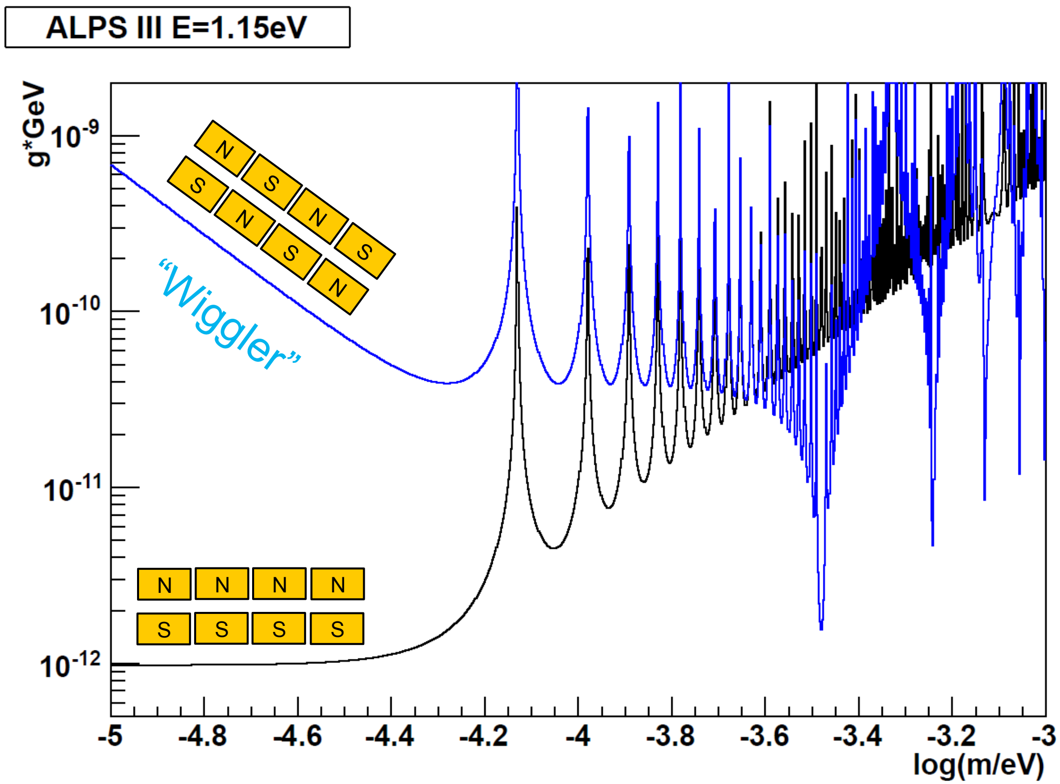
- ALPS III could completely cover astro hints



[Lindner `16]

Light-shining-through-a-wall Searches

- ALPS III could completely cover astro hints and even touch axion band



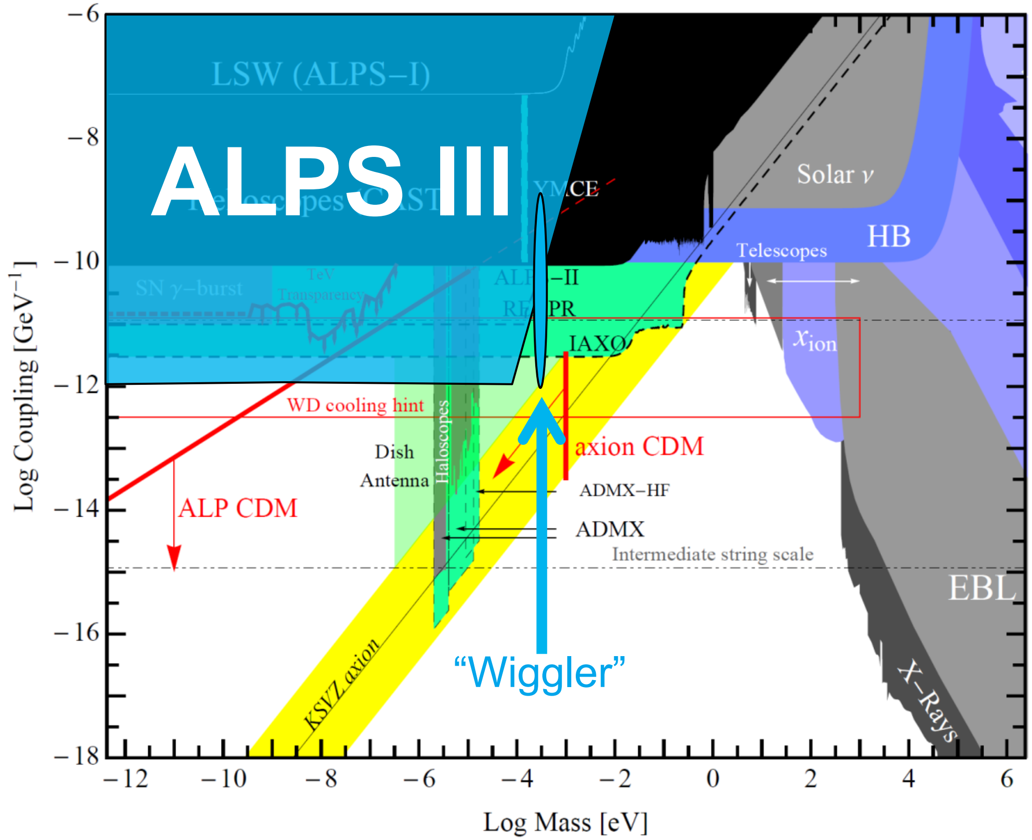
[Lindner `16]

Light-shining-through-a-wall Searches

- ALPS III could completely cover astro hints and even touch axion band

However:

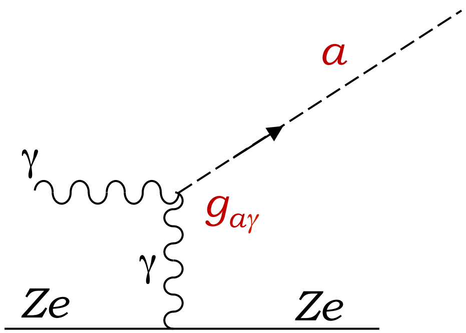
- It is to be shown first that ALPS II performs as expected
- Magnets as being developed for an LHC energy upgrade are essential
- “ALPS III” not before 2025



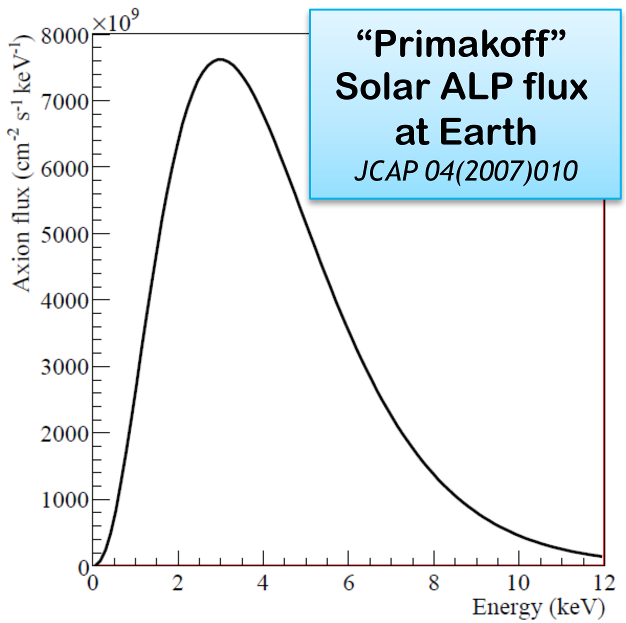
[Lindner `16]

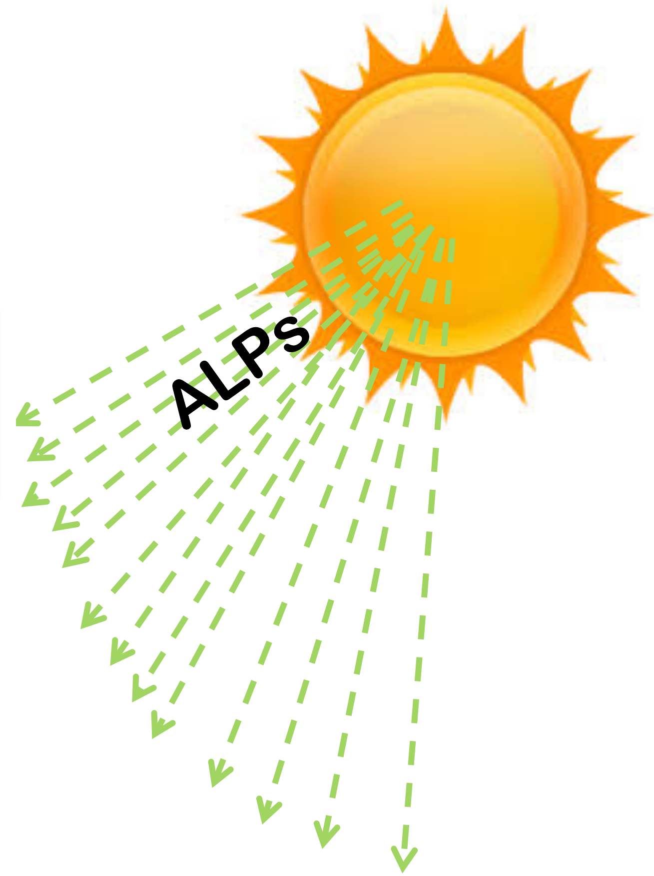
Helioscope Searches

> Appreciable flux of solar ALPs produced by Primakoff process in core:



[Giannotti `16]

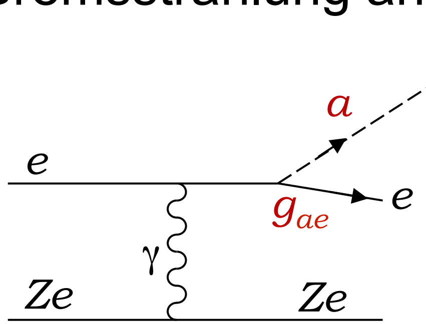




[Irastorza `16]

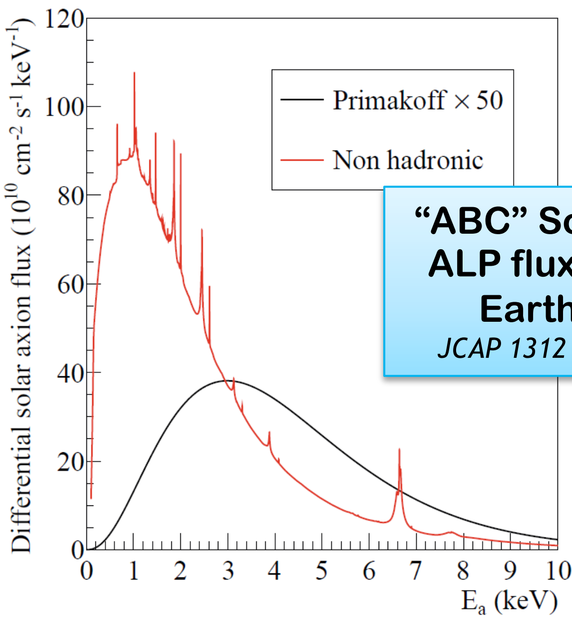
Helioscope Searches

> Even higher flux of solar ALPs produced by Atomic Recombination, Bremsstrahlung and Compton (ABC) processes:

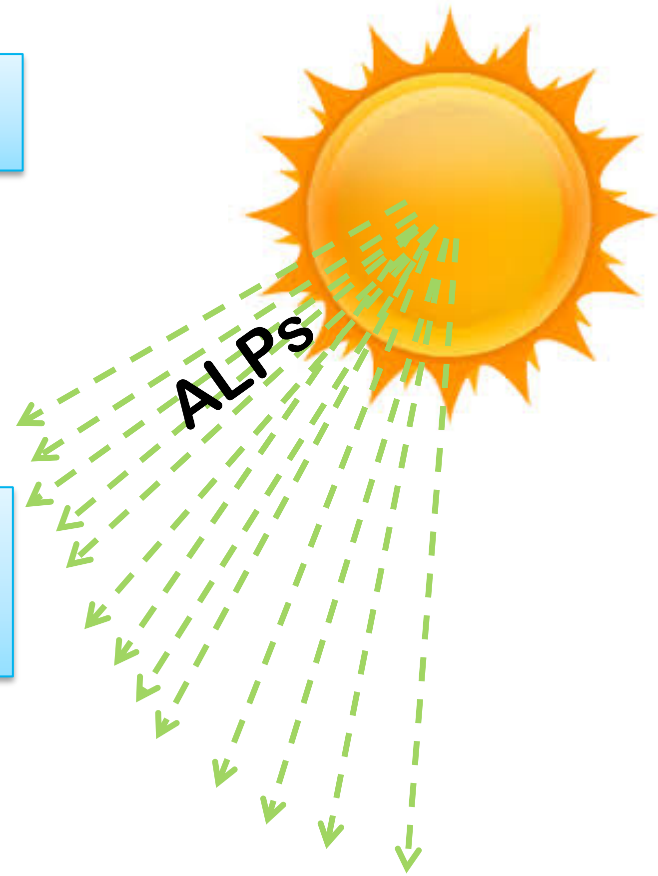


[Giannotti `16]

*** if the ALP couples with electron (g_{ae})**



"ABC" Solar ALP flux at Earth
JCAP 1312 008

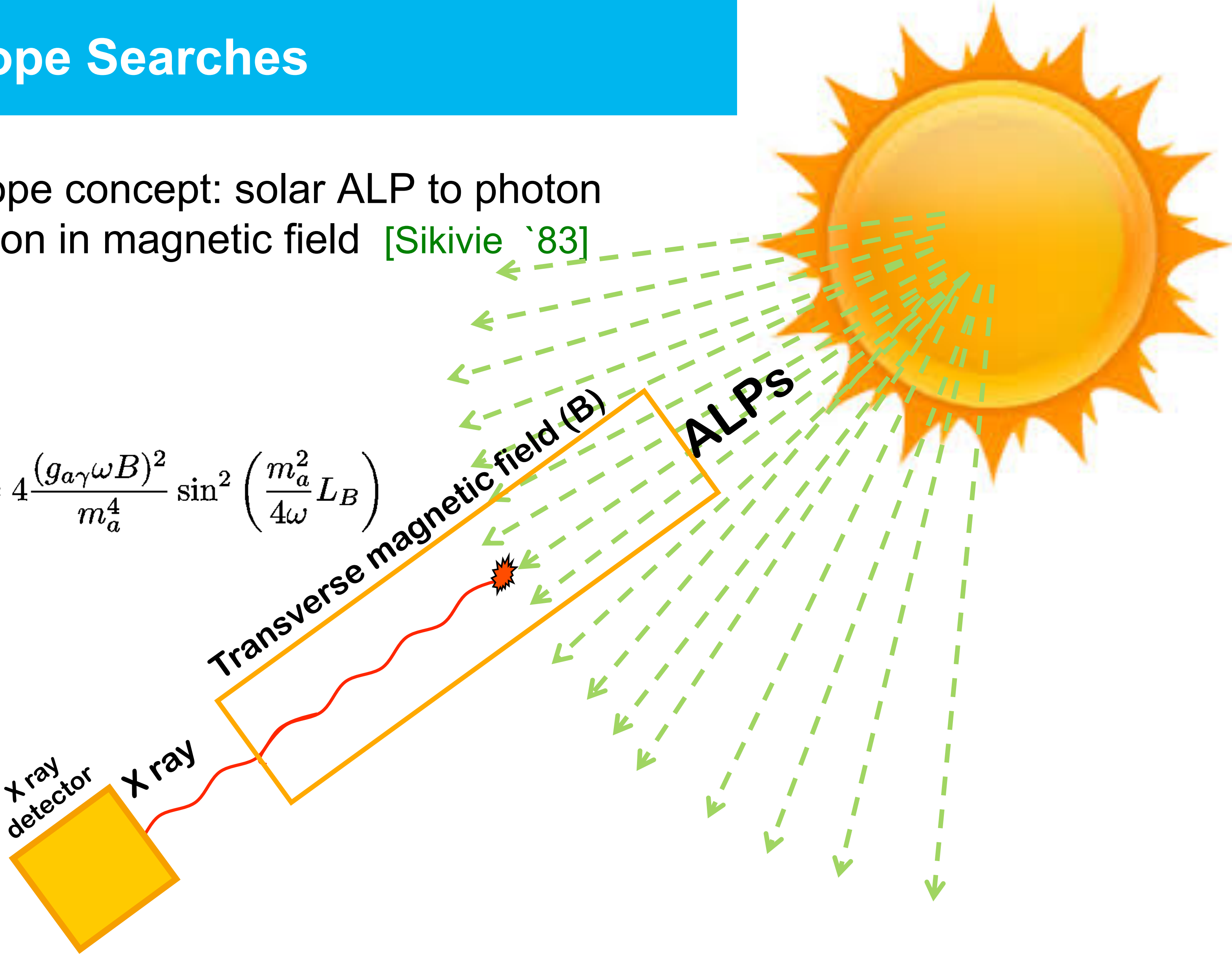


[Irastorza `16]

Helioscope Searches

- Helioscope concept: solar ALP to photon conversion in magnetic field [Sikivie `83]

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



[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)

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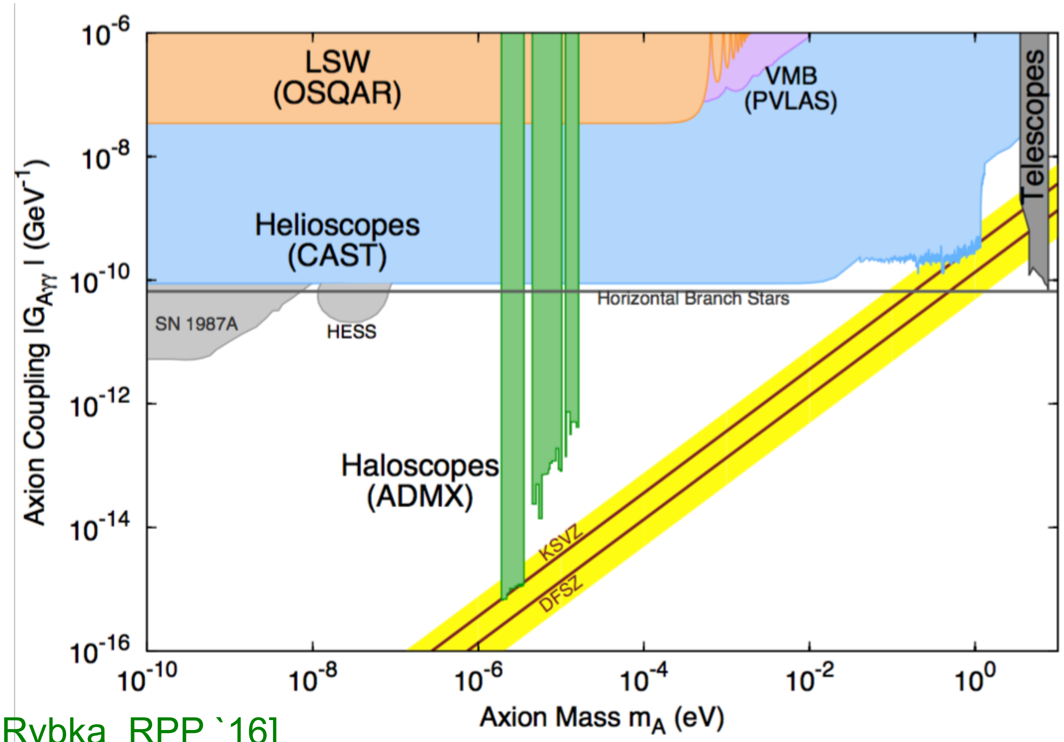
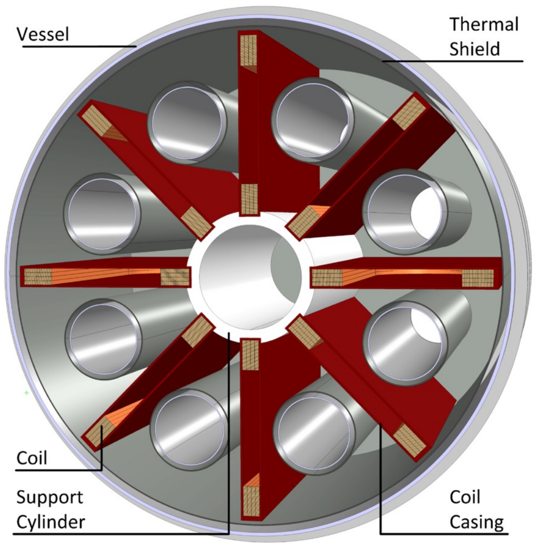
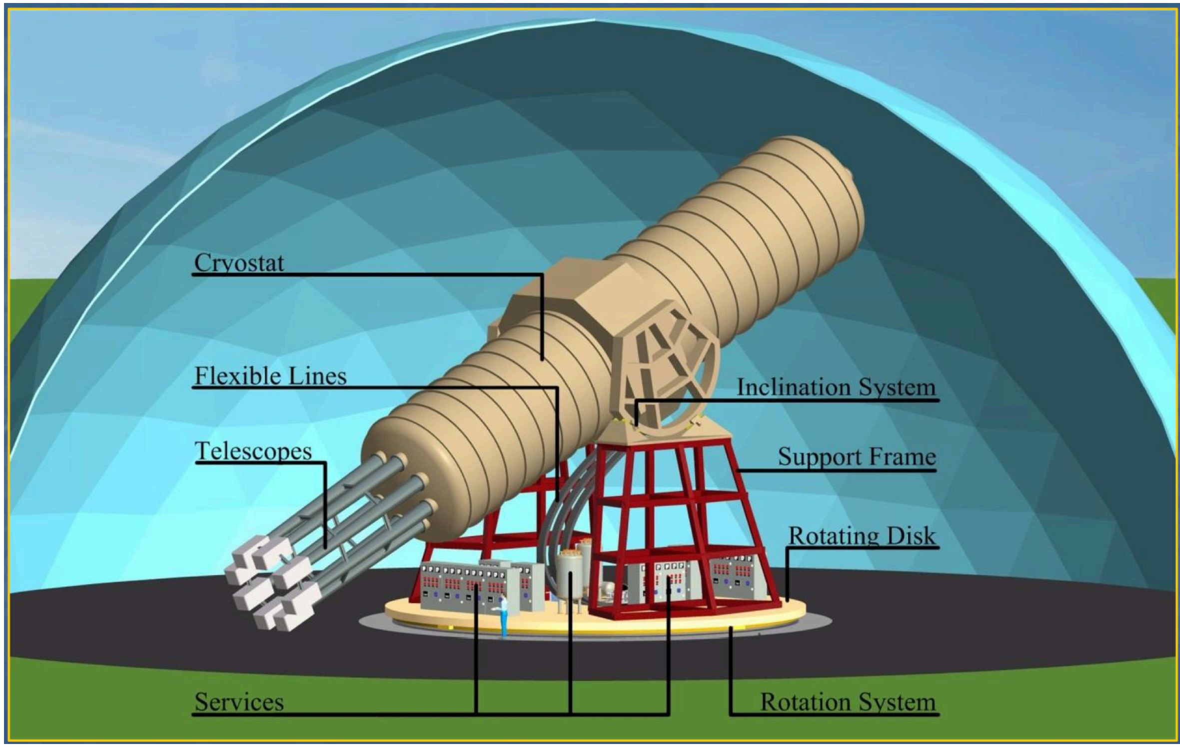


[AR, Rosenberg, Rybka RPP `16]

Helioscope Searches

- Proposed successor: International Axion Observatory (IAXO)
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors



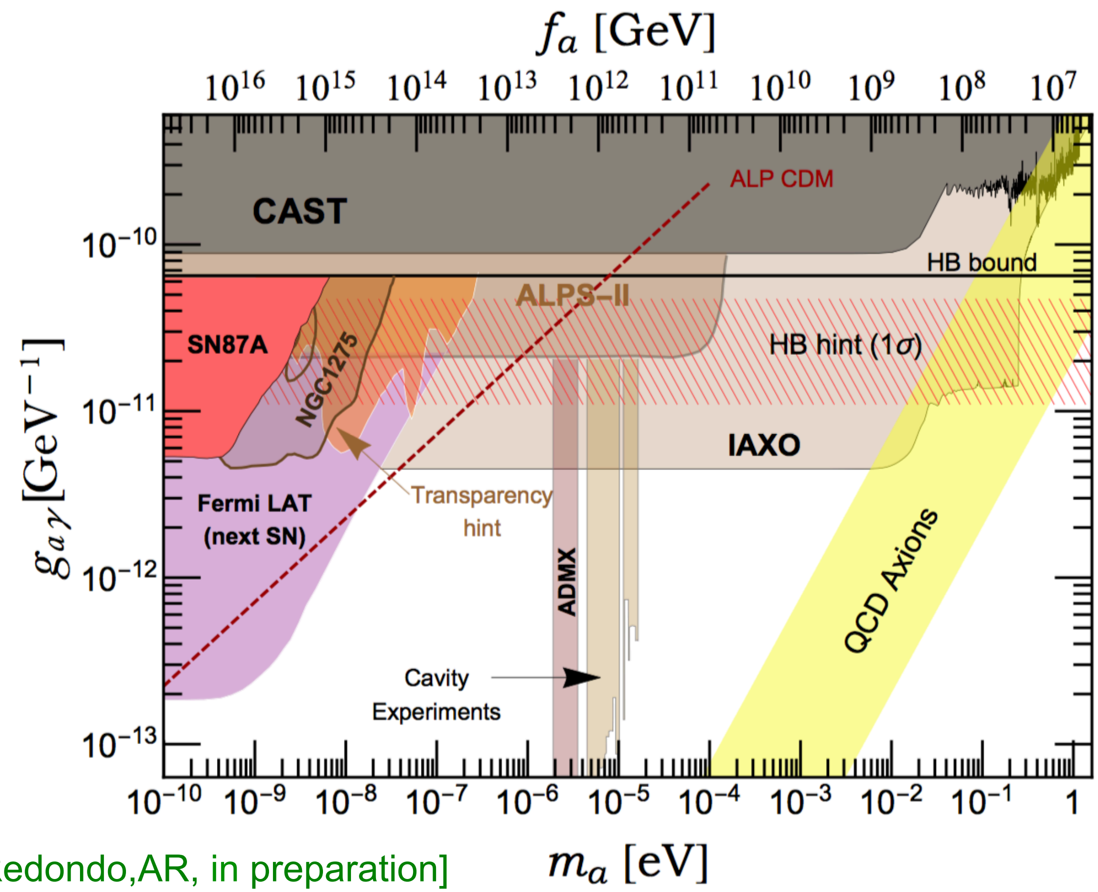


[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope Searches

> IAXO

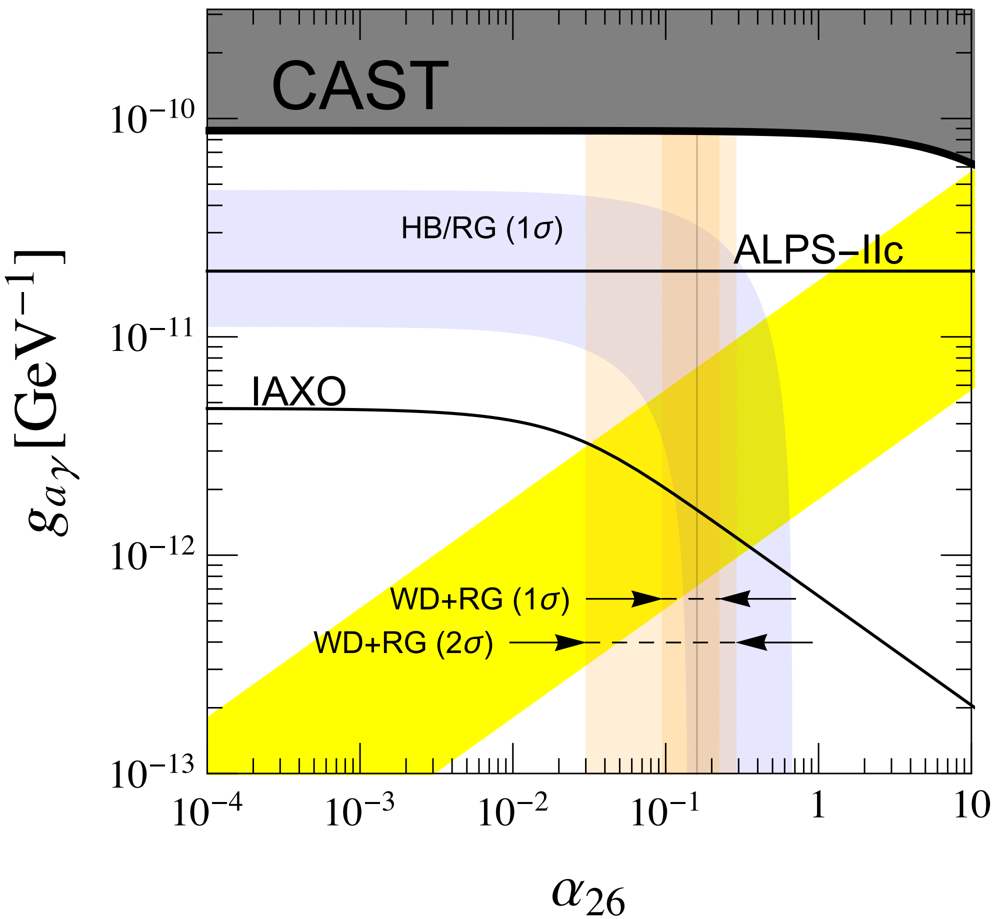
- Covers most of parameter space relevant for astro hints
- Able to probe meV mass axion



[Giannotti,Irastorza,Redondo,AR, in preparation]

Helioscope Searches

- IAXO also sensitive to electron coupling hinted by stellar energy losses:

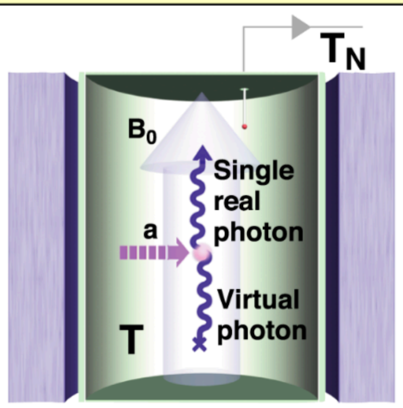


[Giannotti,Irastorza,Redondo,AR `16]

Haloscope Searches: Microwave Cavities

- Direct detection of axion/ALP dark matter!
- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]

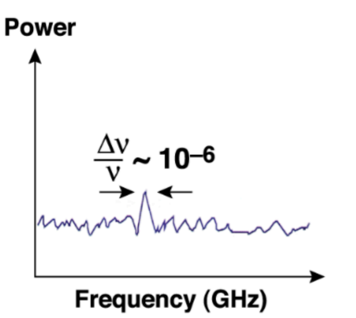
Primakoff Conversion



- **The conversion is resonant, i.e. the frequency must equal the mass + K. E.**
- **The total system noise temperature $T_S = T + T_N$ is the critical factor**

$$m_A = 2\pi\nu \simeq 4\ \mu\text{eV}\ (\nu/\text{GHz})$$

Signal



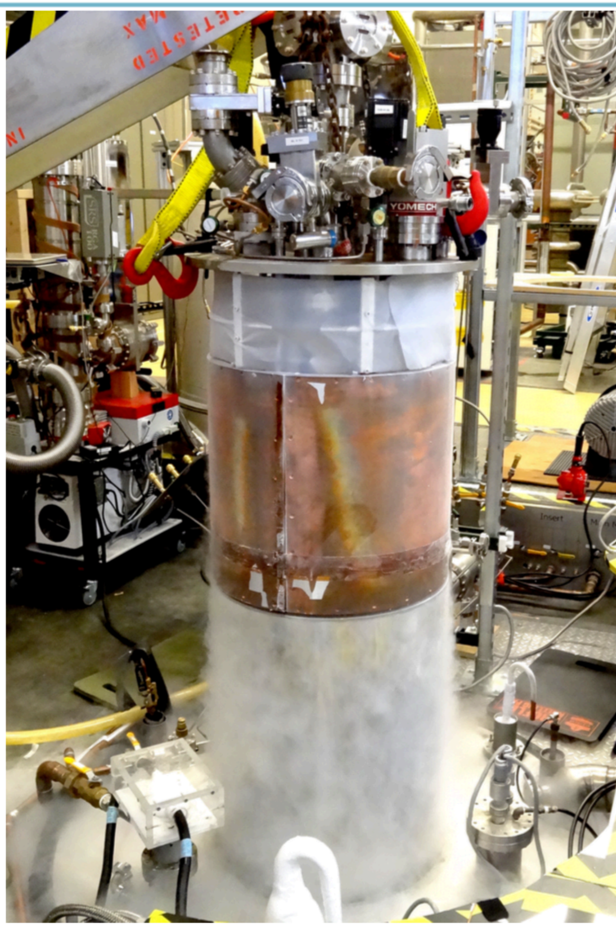
Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

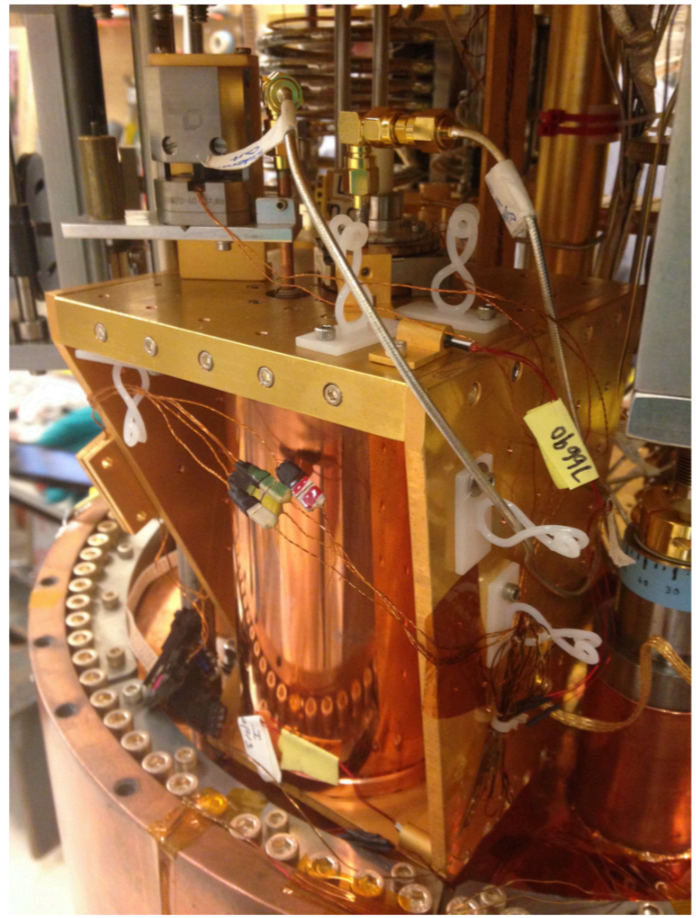
[Rosenberg `16]

Haloscope Searches: Microwave Cavities

> Ongoing: ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid

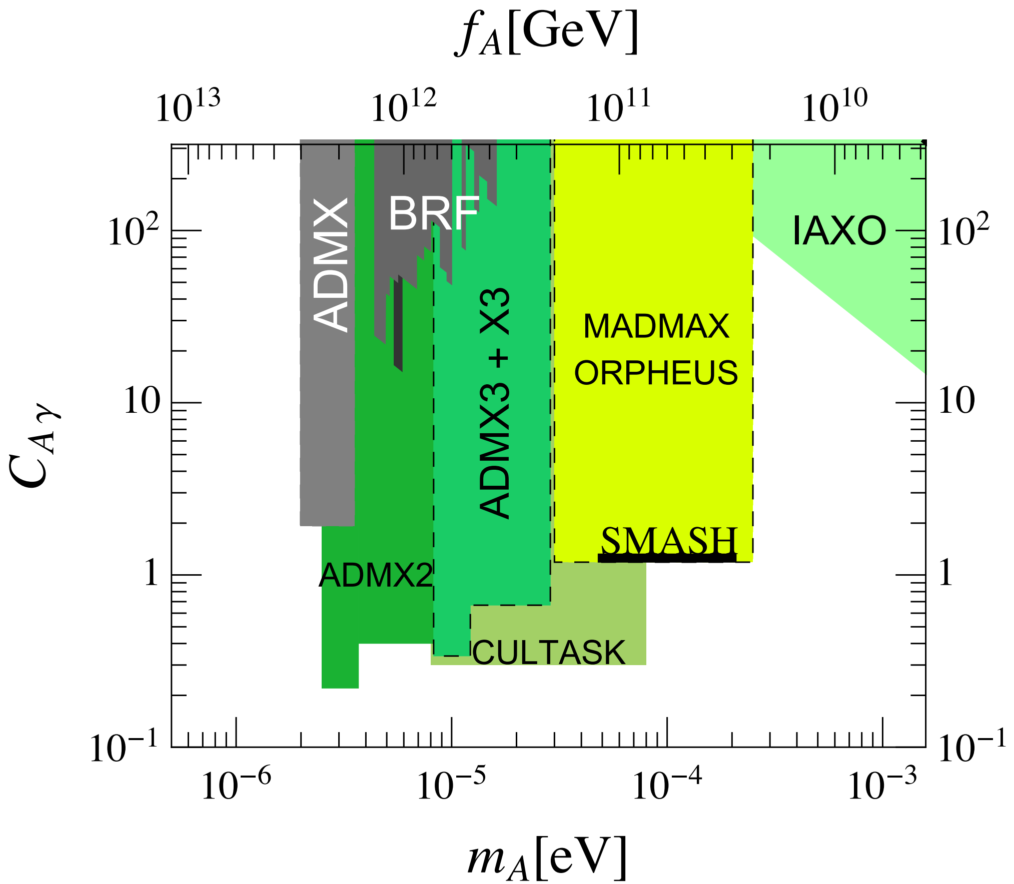
The ADMX experiment insert [Rosenberg `16]





Haloscope Searches: Microwave Cavities

- Projected sensitivities of microwave cavity based experiments (ADMX (Seattle), X3 (Yale), CULTASK (South Korea)):

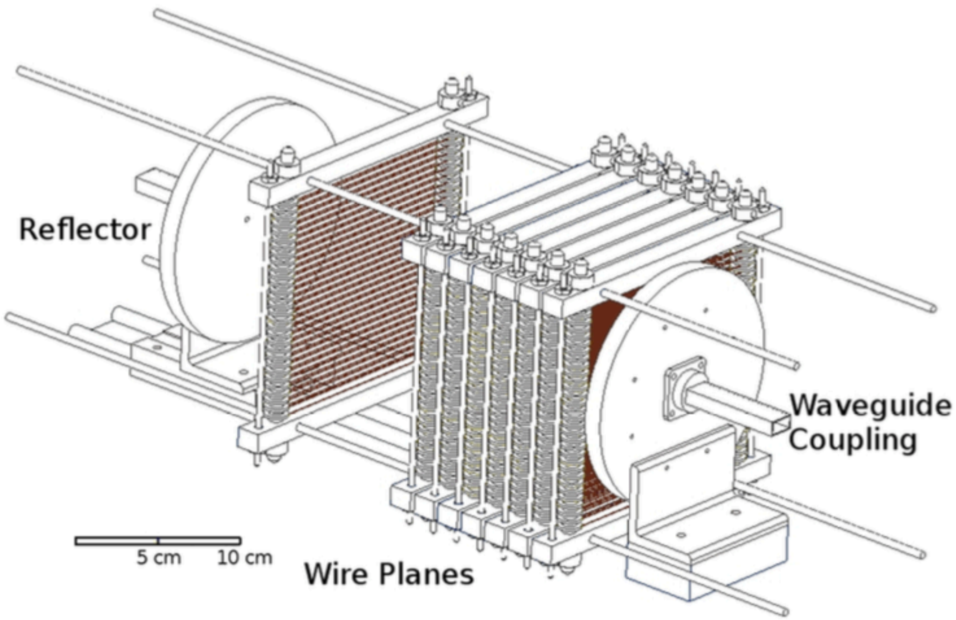


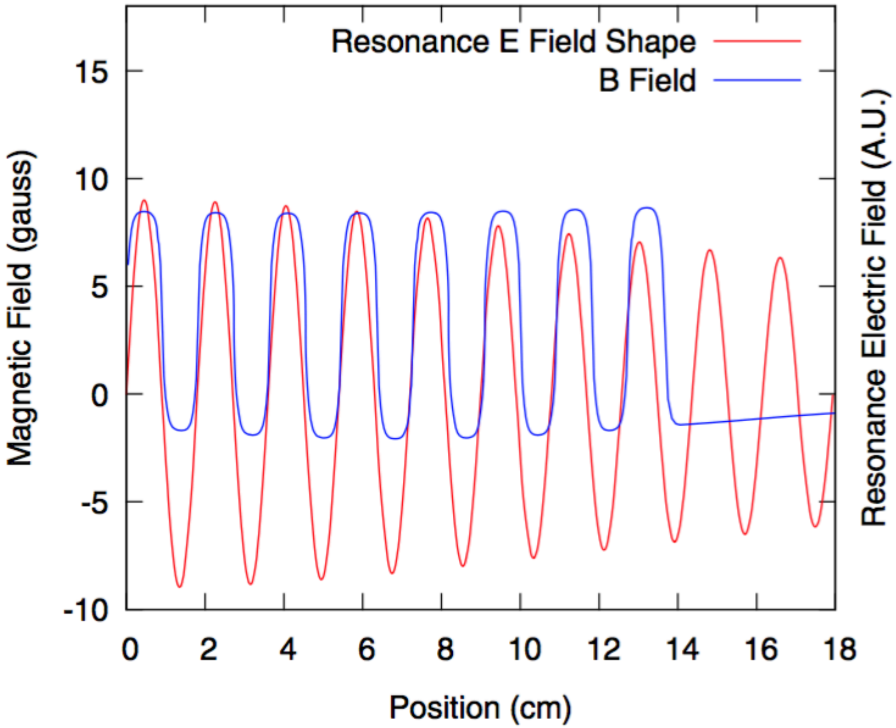
[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

Haloscope Searches: Fabry Perot Resonator

> ORPHEUS (Seattle): [Rybka et al. 15]

- Exploit Fabry-Perot resonator and series of current wire-planes [Sikivie,Tanner,Wang `92]



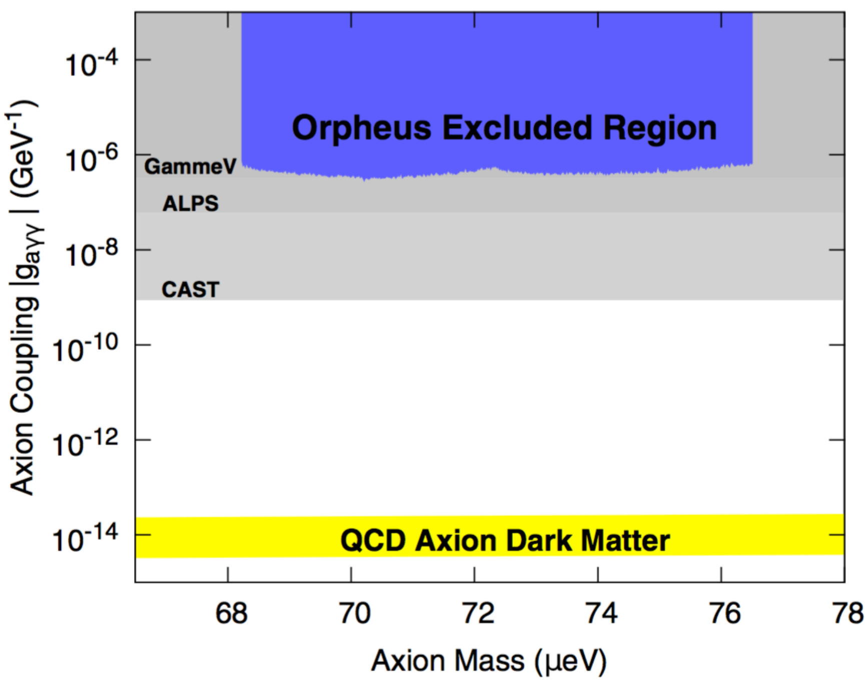


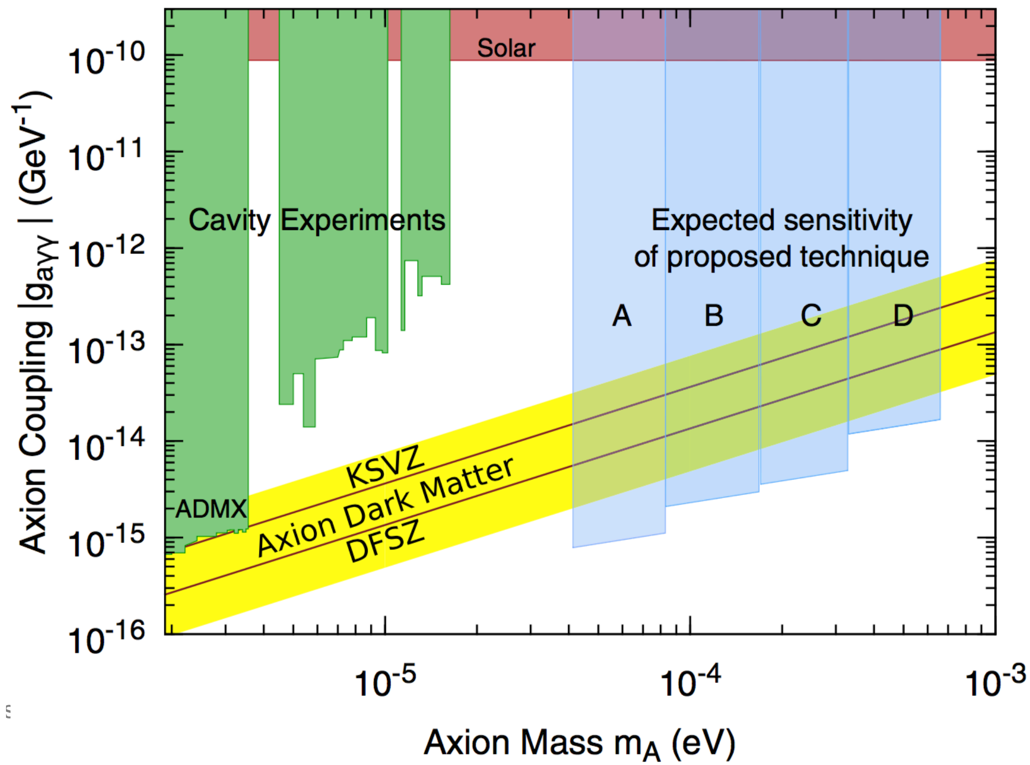
Haloscope Searches: Fabry Perot Resonator

> ORPHEUS (Seattle): [Rybka et al. 15]

- Exploit Fabry-Perot resonator and series of current wire-planes [Sikivie,Tanner,Wang `92]
- Technique may allow to probe masses of interest in post-inflationary SB scenario

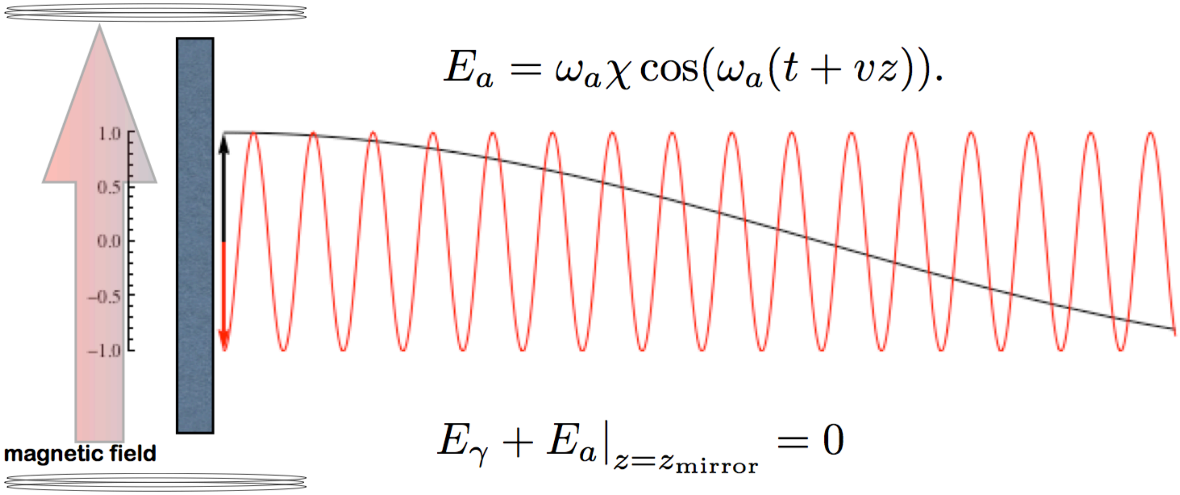
Experiment	Mass target (μeV)	Frequency (GHz)	B field (T)	Q	Volume	Noise temperature	Run time (yr)
A	52	15	3	10^6	1×10^6 cm^3	750 mK	1
B	103	30	3	10^6	8×10^5 cm^3	1.5 K	1
C	207	60	6	10^6	4×10^5 cm^3	3 K	1
D	414	120	6	10^6	2×10^5 cm^3	6 K	1





Haloscope Searches: Dish Antenna

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



$$E_a = \omega_a \chi \cos(\omega_a(t + vz)).$$

$$E_\gamma + E_a|_{z=z_{\mathrm{mirror}}} = 0$$

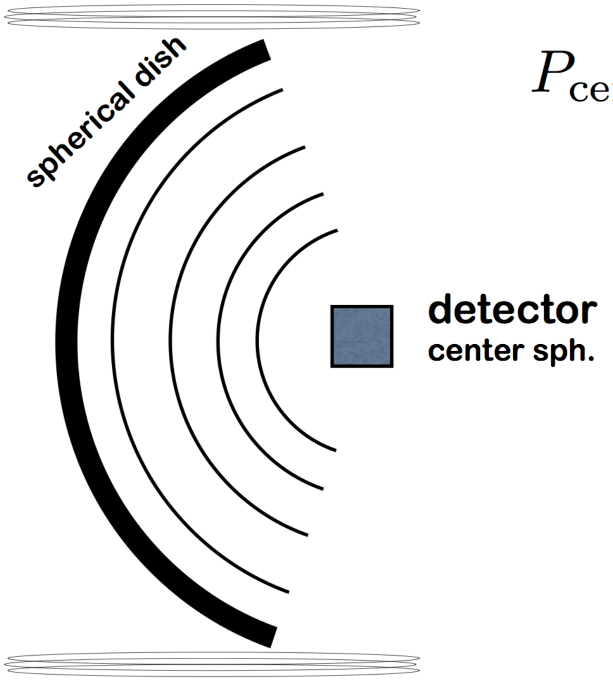
Radiated photon wave $$E_\gamma = -\omega_a \chi \cos(\omega_\gamma(t - z)).$$

whose frequency is $$\omega_\gamma = \omega_a = m_a(1 + v^2/2)$$

[Redondo: talk at DESY 14]

Haloscope Searches: Dish Antenna

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



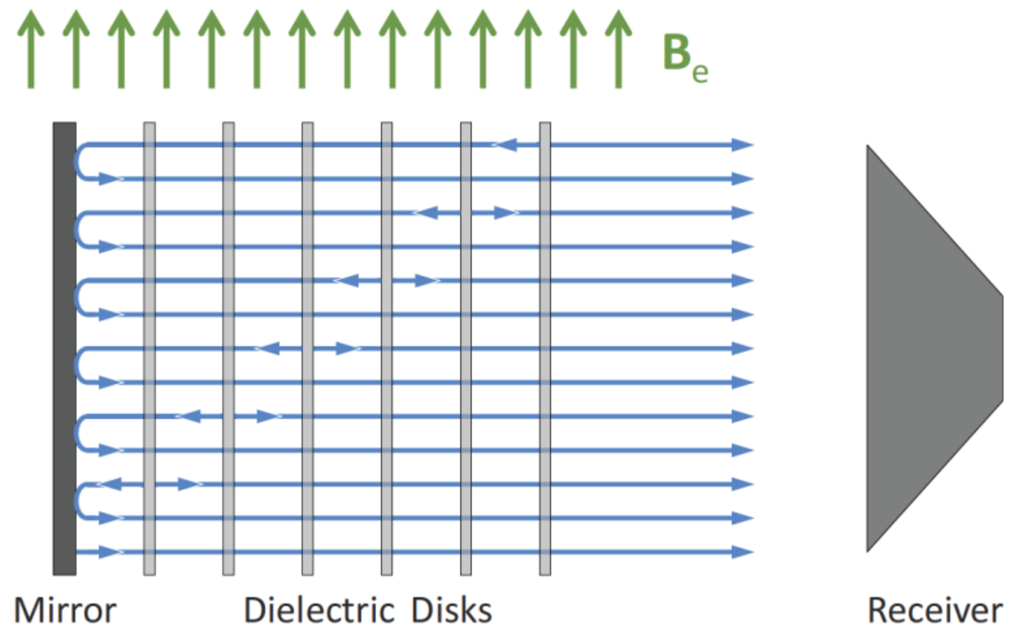
$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

$$\sim 10^{-26} \left(\frac{\rm B}{\rm 5T} \frac{c_\gamma}{2} \right)^2 \frac{\rm A}{\rm 1m^2} {\rm Watt}$$

[Redondo: talk at DESY 14]

Haloscope Searches: Open Dielectric Resonator

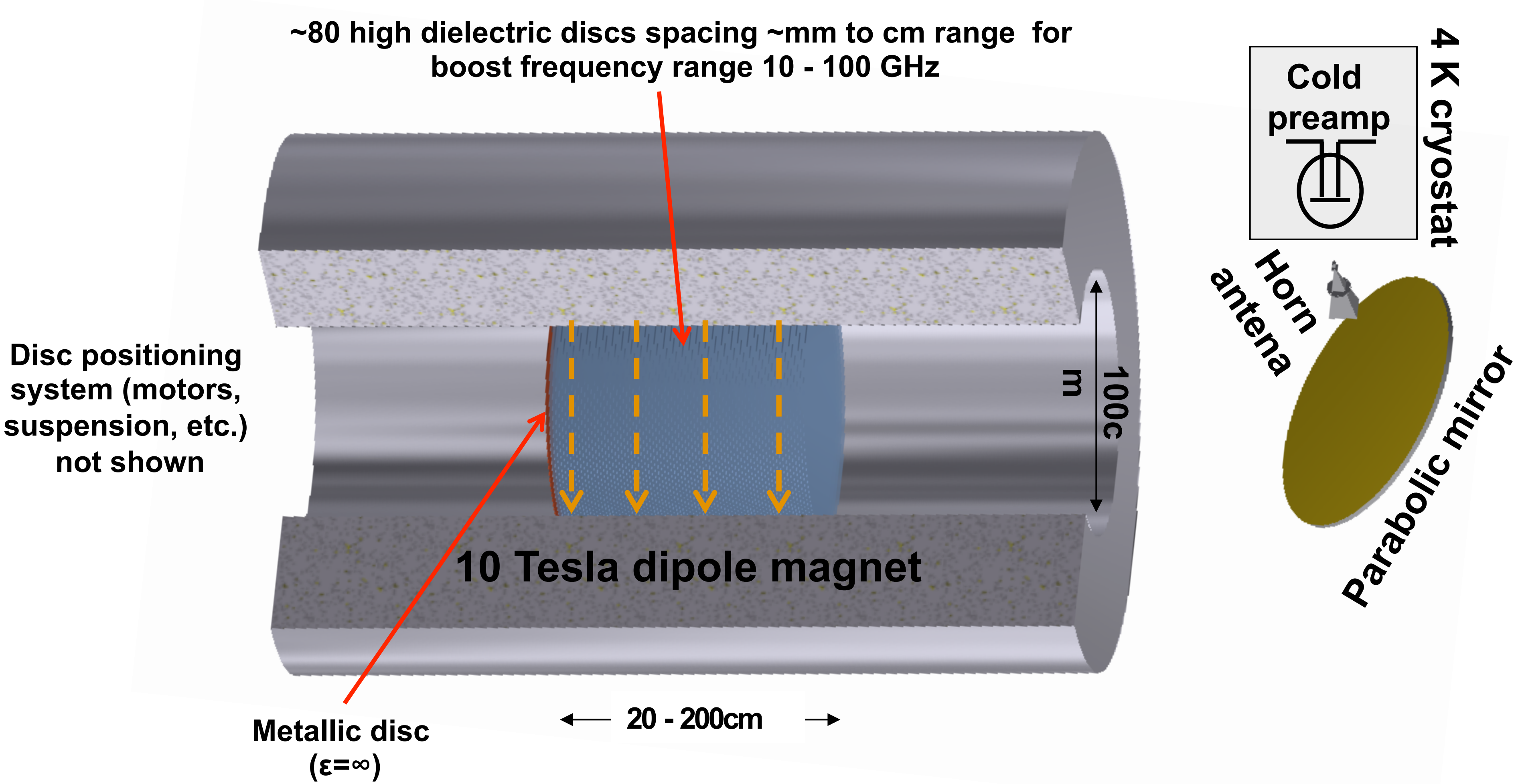
- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- A magnetised mirror in axion/ALP DM background radiates photons
- Spherical dish antenna
- Dielectric resonator
  - Add stack of dielectric layers in front of mirror
  - Contribution for photon emission from all surfaces
  - Constructive interference of photon part of wave function



[Caldwell et al. `16]

Haloscope Searches: Open Dielectric Resonator

- Proposed experiment: MADMAX (possible site: DESY)

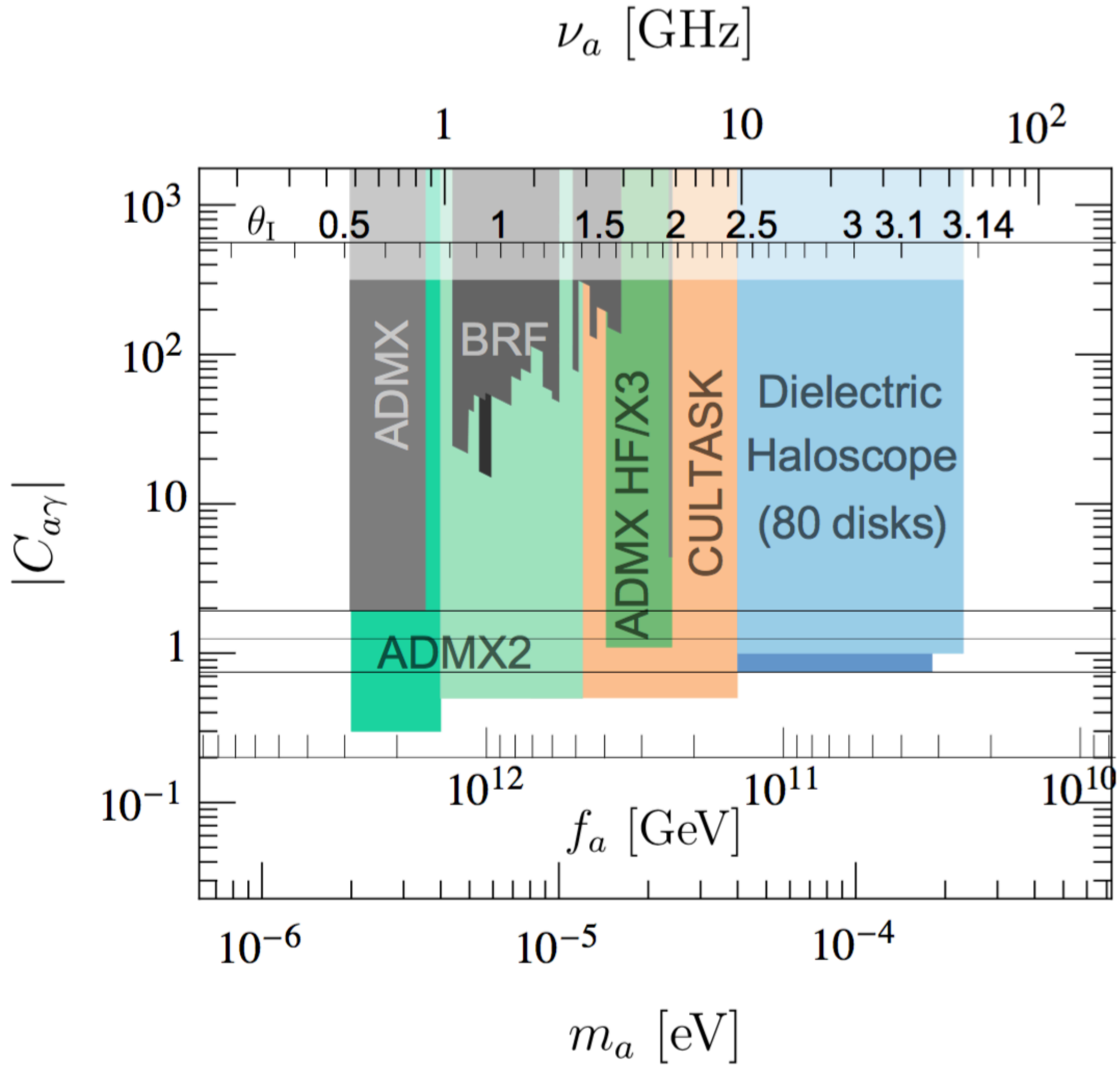


[Majorovits`16]

Haloscope Searches: Open Dielectric Resonator

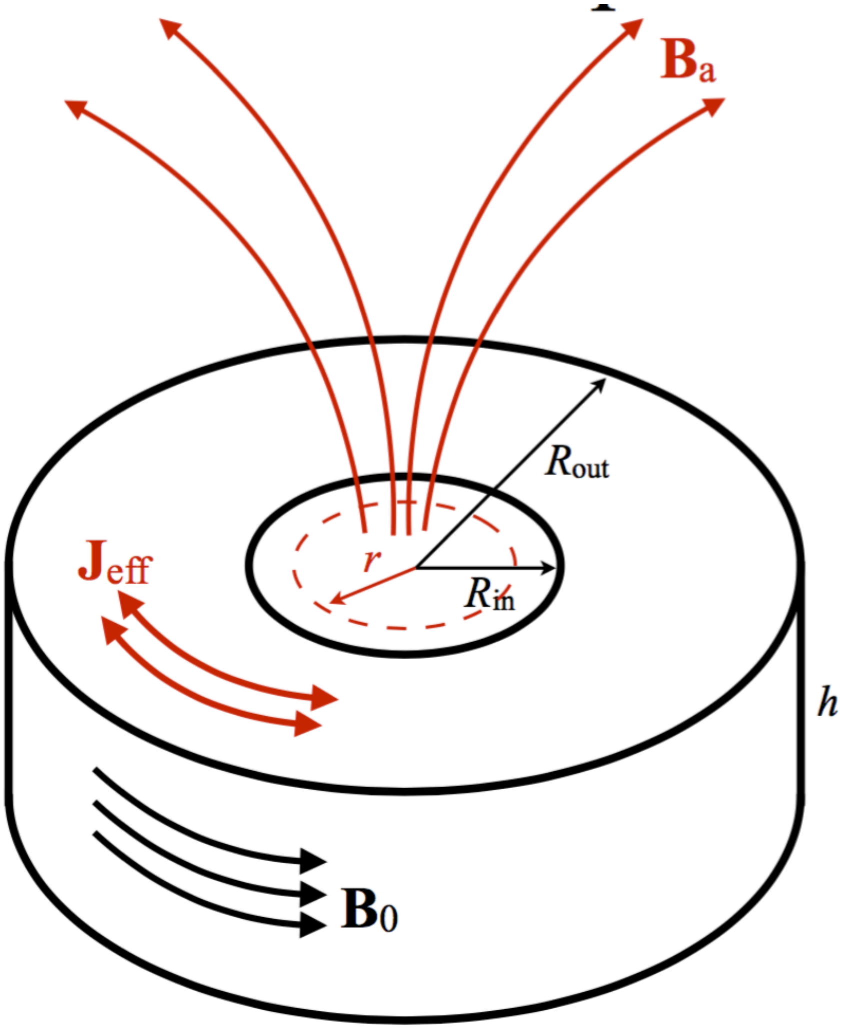
- MADMAX may allow to probe mass range of interest in post-inflationary SB scenario:

[Caldwell et al. `16]



Haloscopes: Toroidal Magnet as Oscillating Current Ring

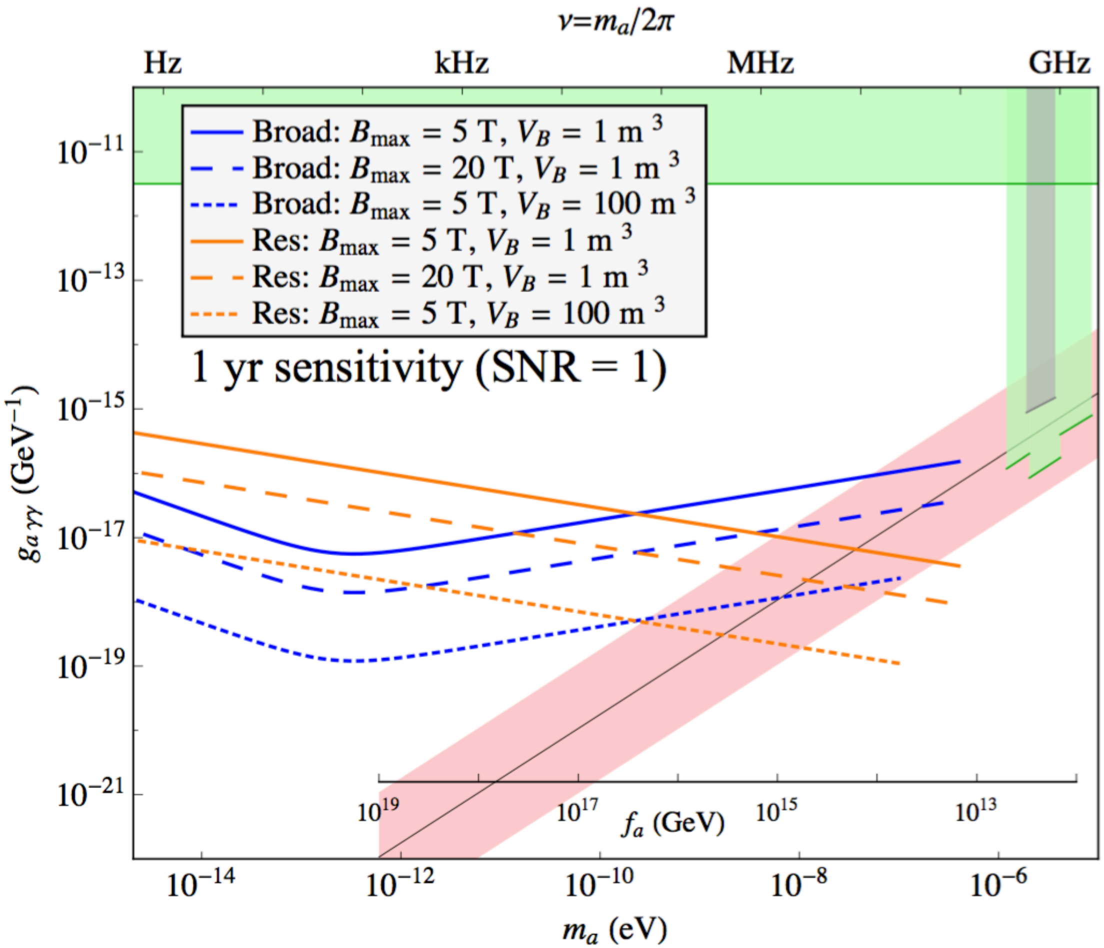
- Toroidal magnet with fixed magnetic field
- Axion DM generates oscillating effective current around ring
- ... this generates oscillating magnetic field through center
- Can be detected by pickup loop



[Ouellet `16]

Haloscopes: Toroidal Magnet as Oscillating Current Ring

- ABRACADABRA (MIT) can probe masses below range of ADMX:



[Kahn,Safdi,Thaler `16]

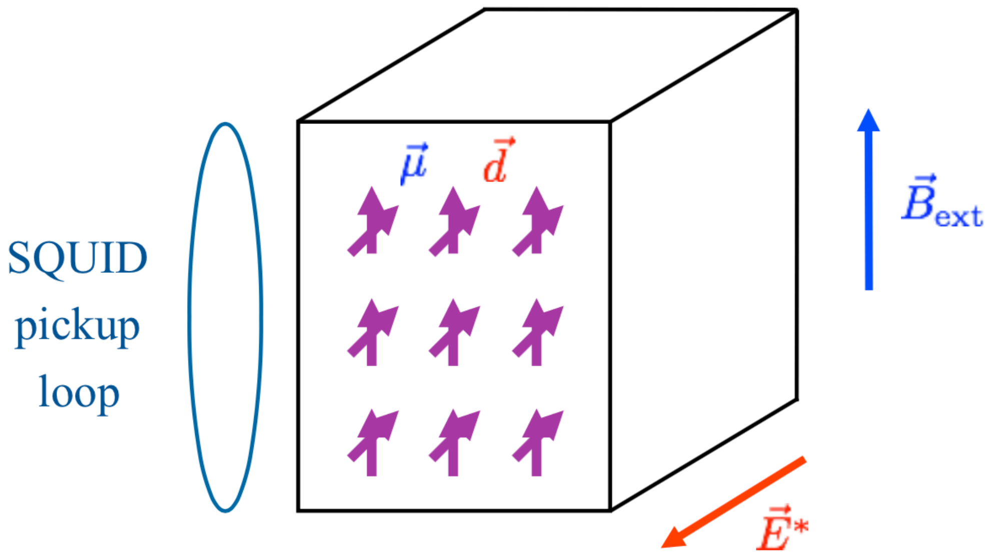
Haloscopes: Magnetic Resonance Searches

- Galactic axion DM field induces oscillating nuclear EDMs:

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

- CASPEr (Mainz):

  MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in presence of eletric field



$$M(t) \approx n p \mu E^* \epsilon_S d_n \frac{\sin[(\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar})t]}{\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar}} \sin\left(2\mu B_{\rm ext} t\right)$$

[Budker et al. 14]

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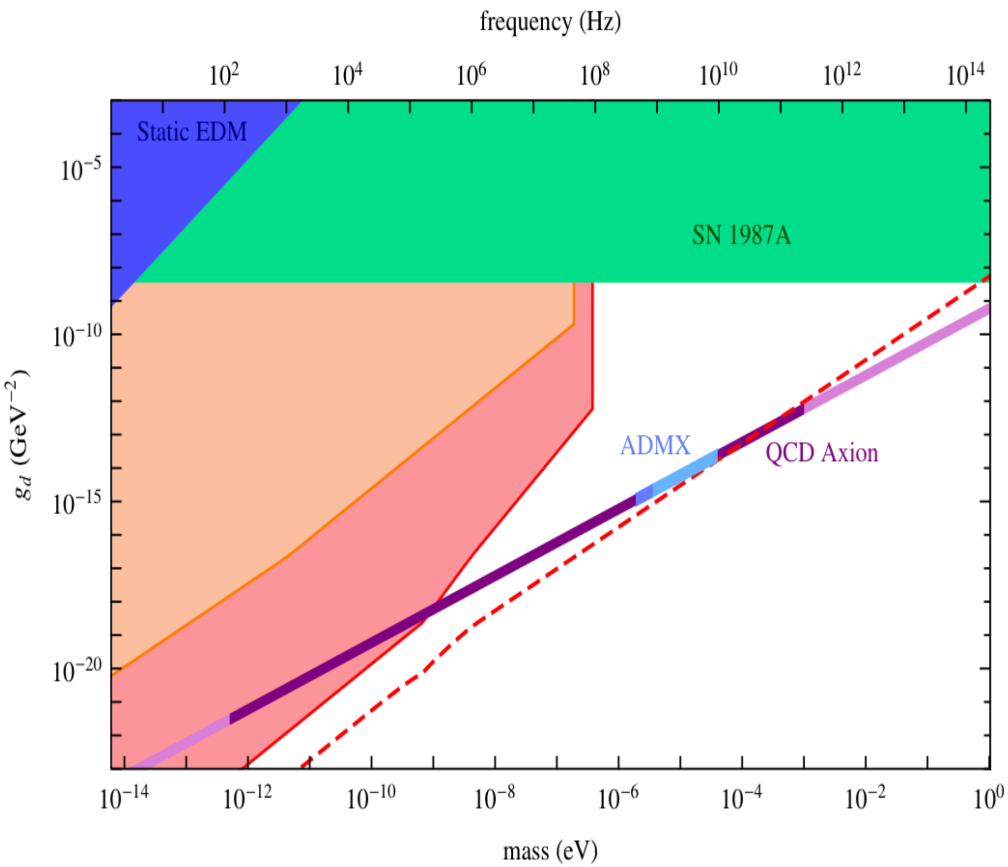


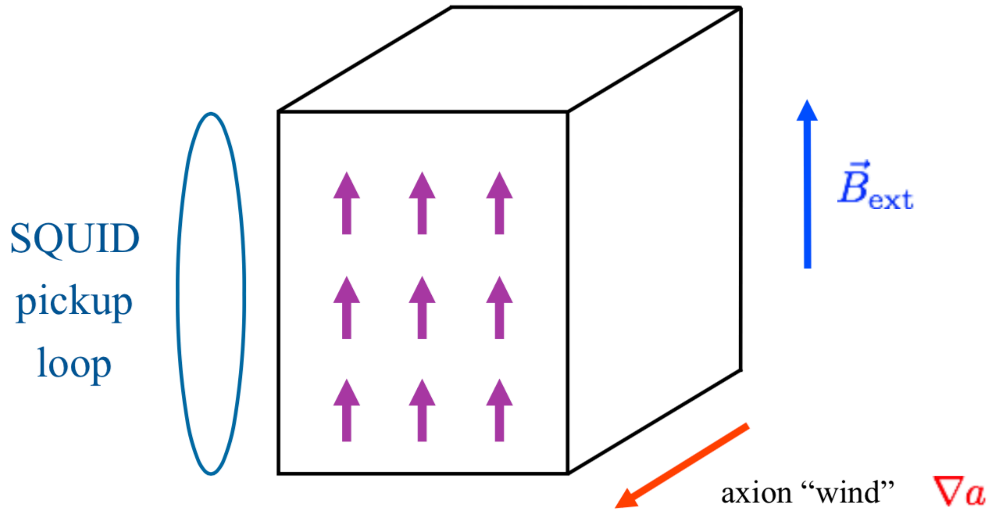
[Budker et al. 14]

	n	E^*	p	T_2	Max $B_{\rm ext}$
Phase 1	10^{22} cm^{-3}	3×10^8 V/cm	10^{-3}	1 ms	10 T
Phase 2	10^{22} cm^{-3}	3×10^8 V/cm	1	1 s	20 T

Haloscopes: Magnetic Resonance Searches

- Axion/ALP nucleon/electron coupling leads to nucleon/ electron spin precession about galactic axion/ALP DM wind
- CASPEr (Mainz):

  MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in DM wind



[Graham,Rajendran 13]

$$M(t) \approx n p \mu \left(g_{\rm aNN} \sqrt{2 \rho_{DM}} v \right) \frac{\sin\left(\left(2\mu B_{\rm ext} - m_a \right) t \right)}{2\mu B_{\rm ext} - m_a} \sin\left(2\mu B_{\rm ext} t \right)$$

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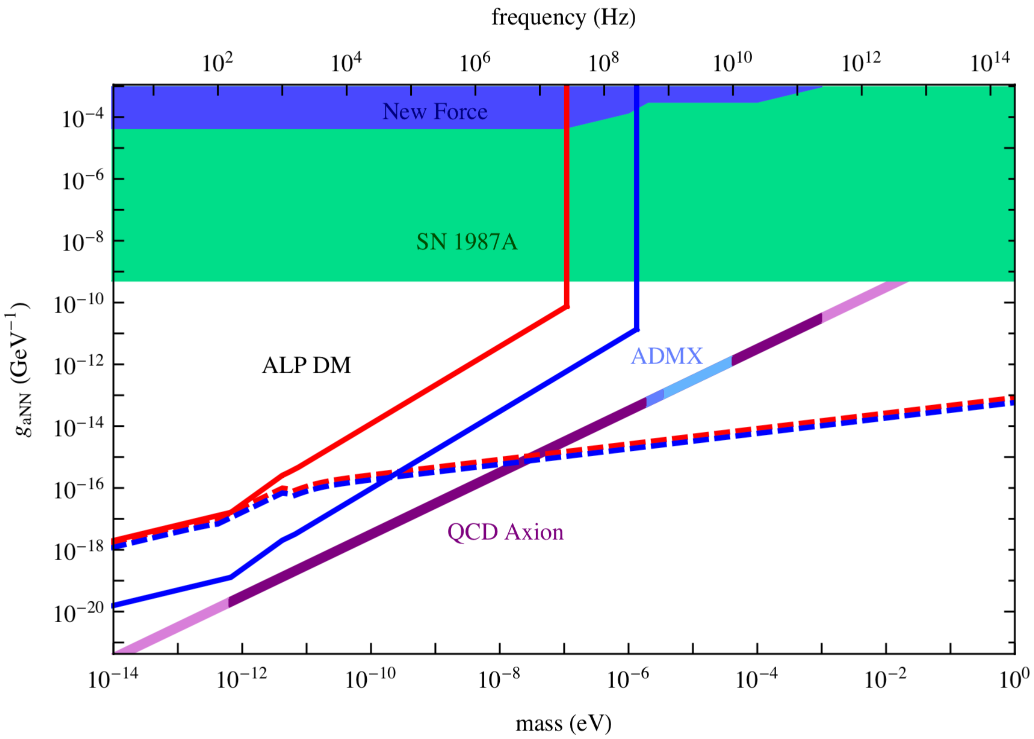

[Graham,Rajendran 13]

$$M(t) \approx np\mu \left(g_{aNN}\sqrt{2\rho_{DM}}v\right) \frac{\sin\left(\left(2\mu B_{\text{ext}} - m_a\right)t\right)}{2\mu B_{\text{ext}} - m_a} \sin\left(2\mu B_{\text{ext}}t\right)$$

	Element	Density (n)	Magnetic Moment (μ)	T_2	Max. B	Magnetometer Sensitivity
1.	Xe	$1.3 \times 10^{22}\,\frac{1}{\text{cm}^3}$	$0.35\,\mu_N$	100 s	10 T	$10^{-16}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$
2.	^{3}He	$2.8 \times 10^{22}\,\frac{1}{\text{cm}^3}$	$2.12\,\mu_N$	100 s	20 T	$10^{-17}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

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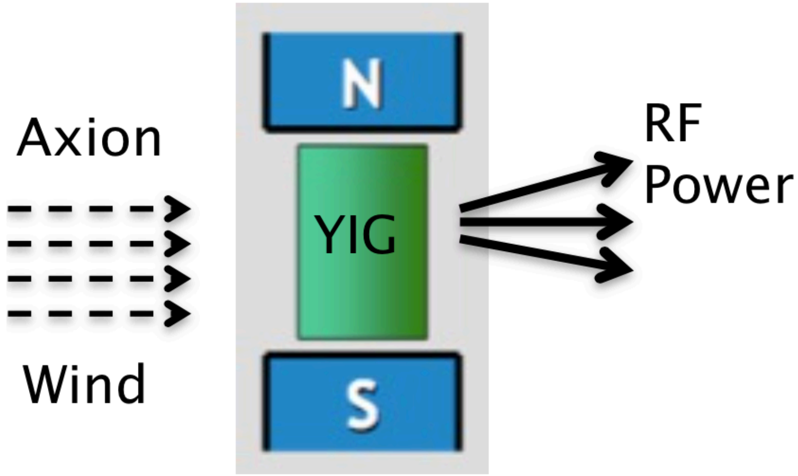
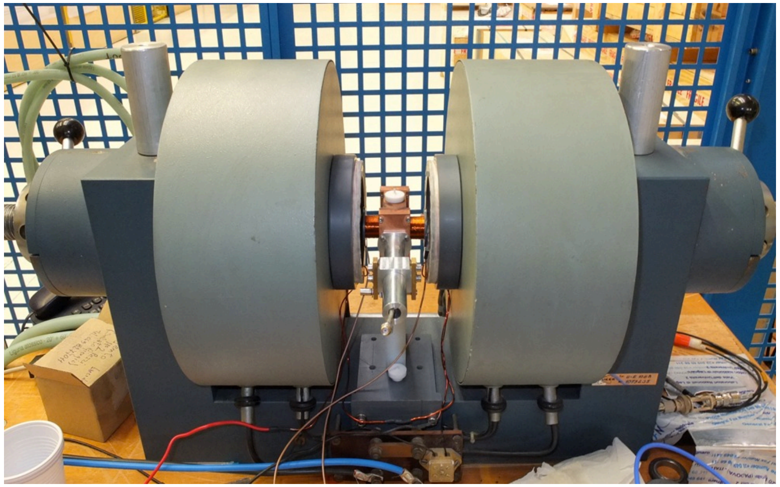
- QUAX (INFN):

  ESRT search





[Ruoso et al. 15]

Fifth Force: Search for Axion-Mediated Forces

- ARIADNE: Proposed experiment based on precision magnetometry to search for axion-mediated spin-dependent forces
- Combining techniques used in NMR and short-distance tests of gravity

[Arvanitaki, Geraci 14]

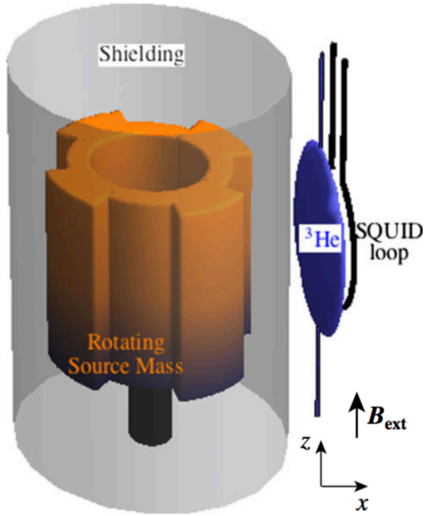


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N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

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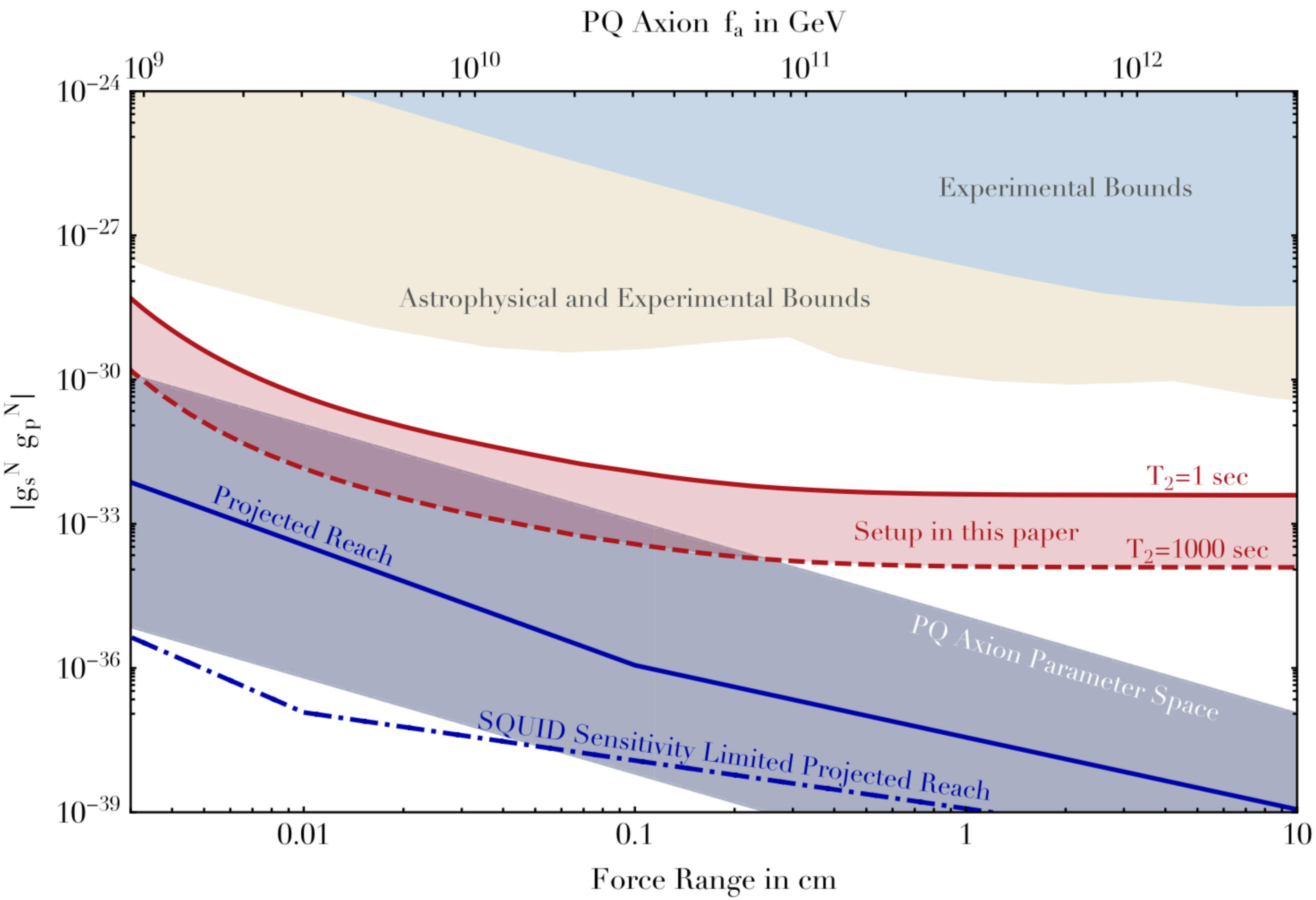

[Arvanitaki, Geraci 14]

Conclusions

- Large parts in axion and ALPs parameter space can be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Helioscopes (IAXO, ...)
  - Haloscopes (ABRACADABRA, ADMX, CASPEr, CULTASK, MADMAX, ORPHEUS, QUAX, ...)
  - Fifth-force experiments (ARIADNE, ...)
- Stay tuned!