



Axion dark matter searches

Yannis K. Semertzidis, IBS/CAPP & KAIST

✓ This decade belongs to axion dark matter experiments!

The question to answer:

Are axions a significant part of the local dark matter?

The Strong CP-problem, Axion parameters, Dark Matter

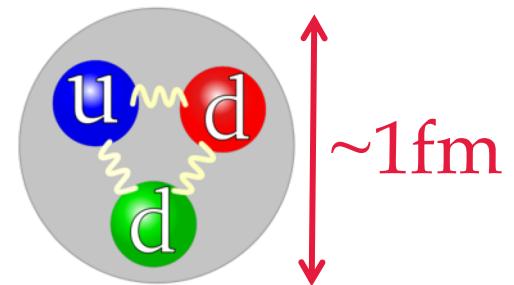
Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta} \frac{g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

The QCD Lagrangian contains a theta-term violating both P-parity and T-time reversal symmetries.

Strong CP-problem and neutron EDM

$$L_{QCD, \bar{\theta}} = \bar{\theta} \frac{g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n(\bar{\theta}) \sim \bar{\theta} \frac{e}{m_n} \frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta} \cdot (6 \times 10^{-17}) \text{ e}\cdot\text{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n(\bar{\theta}) \approx -d_p(\bar{\theta}) \approx 3.6 \times 10^{-16} \bar{\theta} \text{ e}\cdot\text{cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

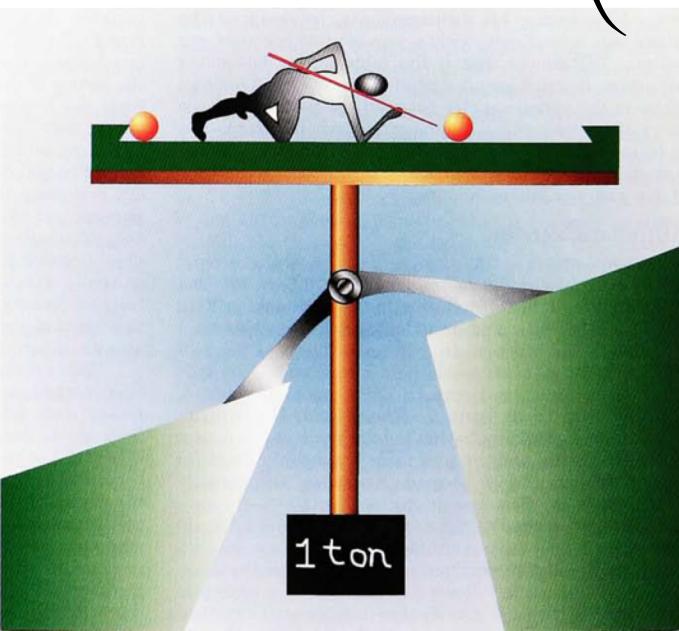
$$\text{Exp.: } d_n < 3 \times 10^{-26} \text{ e}\cdot\text{cm} \rightarrow \bar{\theta} < 10^{-10}$$

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least $\sim 9\text{-}10$ orders of magnitude less! WHY?

Strong CP-problem

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally

$$L_{QCD, \bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$



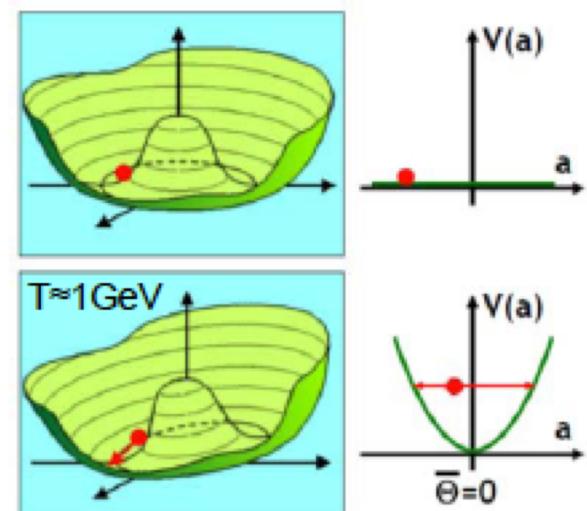
The Pool-Table Analogy with Axion Physics, Pierre Sikivie
Physics Today **49**(12), 22 (1996);
<http://dx.doi.org/10.1063/1.881573>

Strong CP-problem

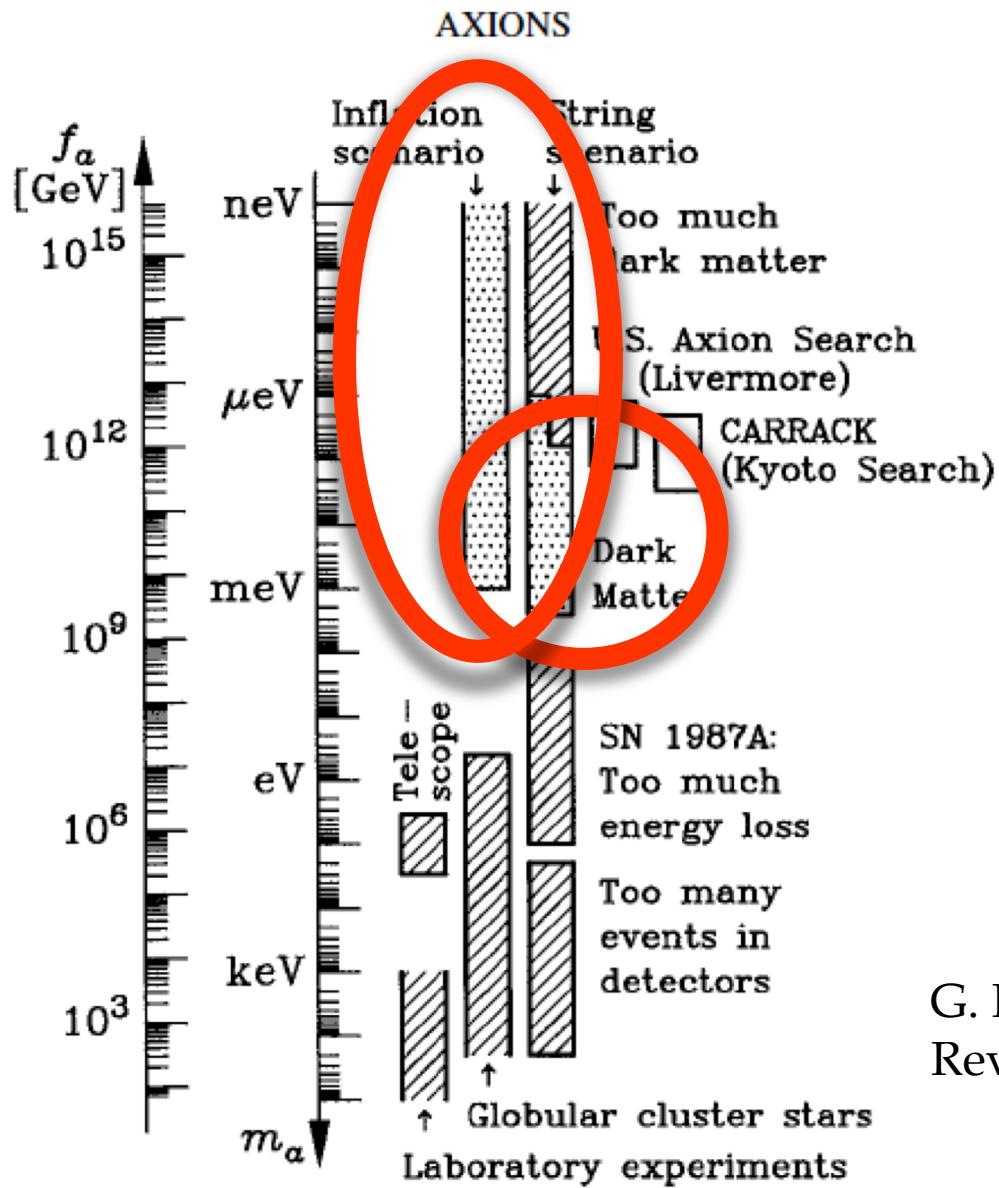
- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally
- Wilczek and Weinberg: axion particle (1977)
- J.E. Kim: Hadronic axions (1979)

- Axions: pseudoscalars,
light cousins of neutral pions

$$m_a \approx 6 \times 10^{-6} \text{ eV} \frac{10^{12} \text{ GeV}}{f_a}$$

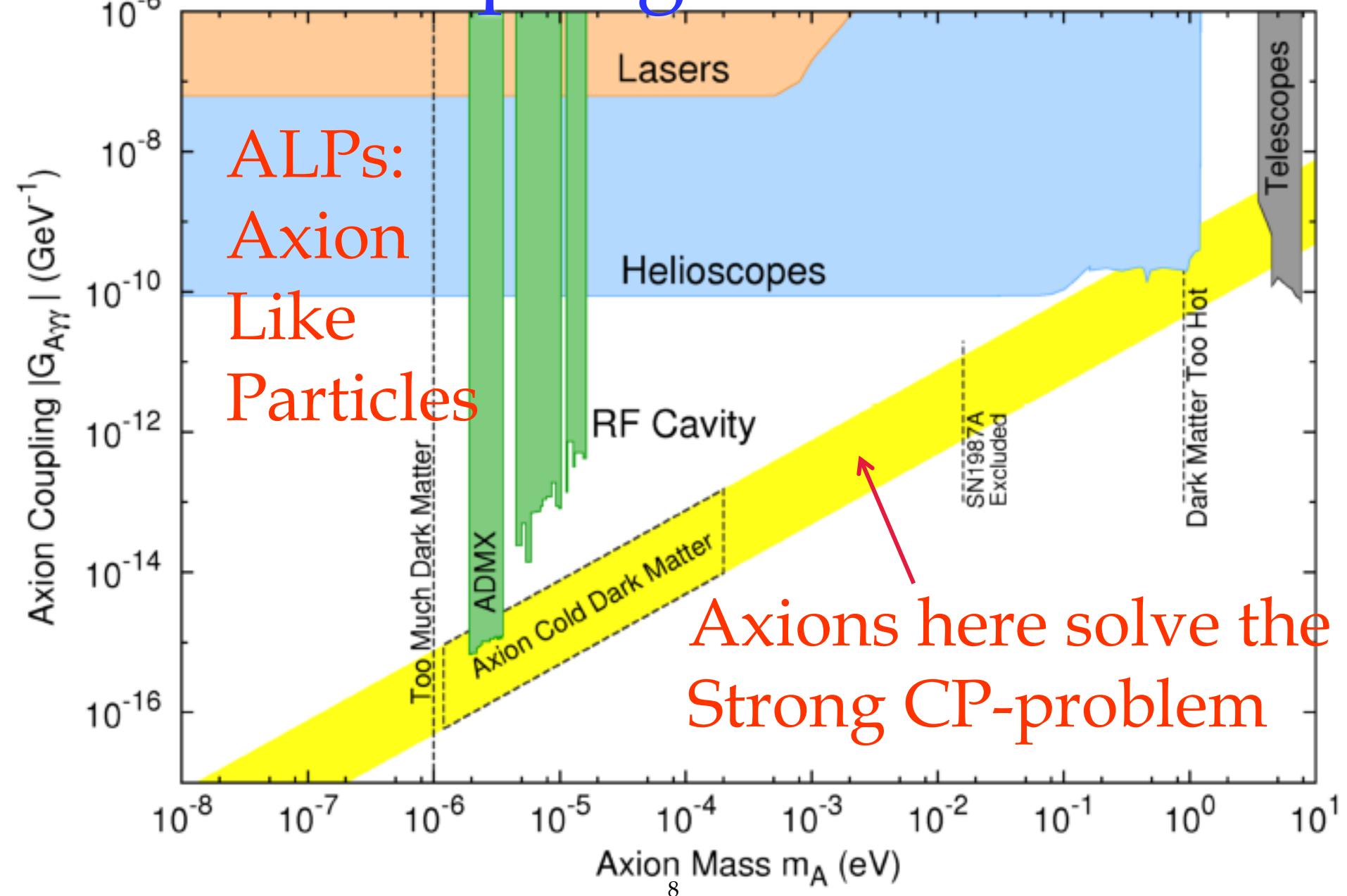


Axion parameters range



G. Raffelt, Space Science
Reviews 100: 153-158, 2002

Axion coupling vs. axion mass



Axion Dark matter

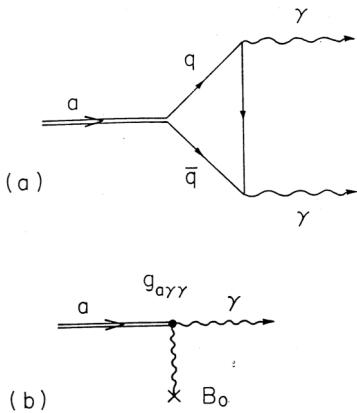
- Dark matter: $0.3\text{-}0.5 \text{ GeV/cm}^3$
- Axions in the $1\text{-}300 \mu\text{eV}$ range: $10^{12}\text{-}10^{14}/\text{cm}^3$, classical system.
- Lifetime $\sim 7 \times 10^{44} \text{s}$ ($100 \mu\text{eV} / m_a$) 5
- Cold Dark Matter ($v/c \sim 10^{-3}$), Kinetic energy $\sim 10^{-6} m_a$, very narrow line in spectrum.

Axion Dark matter

- Velocity range: $< 10^{-3}c$ (bound in galaxies)
- Mass range: $> 10^{-22}\text{eV}$ (size of galaxies)
- Coherence length (De Broglie wavelength):

$$l_{DB} \approx 1\text{m} \times \left(\frac{1\text{meV}}{m_a} \right)$$

Axion Couplings



- Gauge fields:

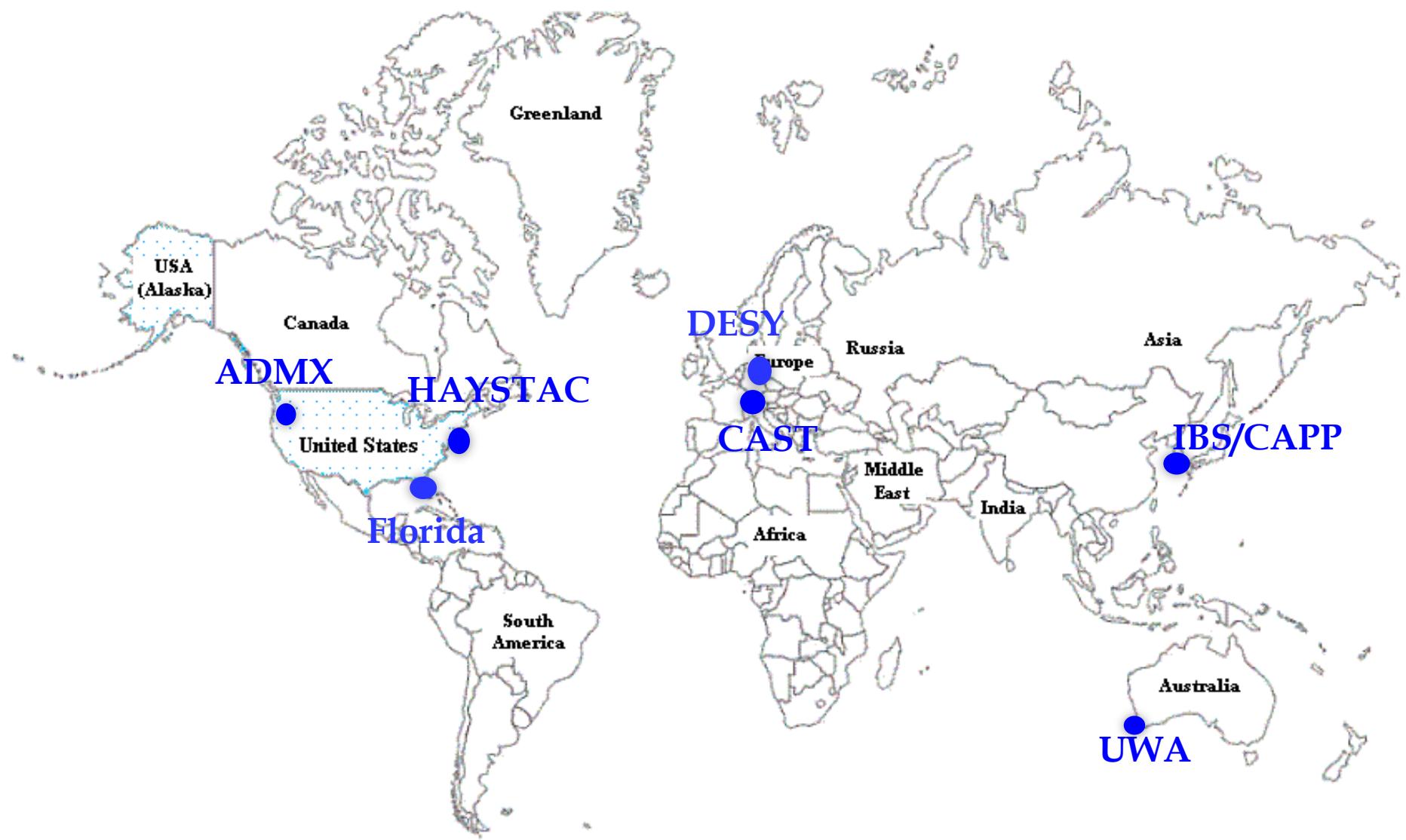
- Electromagnetic fields $L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$
-
- Gluon Fields (Oscillating EDM,...)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Major Axion activities



>>100 participants, 12th Patras Workshop on AXIONs, WIMPs, and WISPs,
Jeju Island/Korea, 20-24 June, 2016.



>>100 participants, 13th Patras Workshop on AXIONs, WIMPs, and WISPs,
Thessaloniki, Greece, 15-19 May, 2017.



>150 participants, 14th Patras Workshop on AXIONS, WIMPs, and WISPs,
DESY/Hamburg, Germany, 18-22 June, 2018.



Major activities

- ADMX (UW, microwave cavity)
- HAYSTAC (Yale, microwave cavity)
- IBS/CAPP (CULTASK, multiple microwave cavities)
- ORGAN (UWA, high frequency)
- KLASH (KLOE magnet in Frascati, microwave cavity)
- MADMAX (DESY, dielectric interfaces)
- ALPs (DESY, coupled FP resonators)
- CAST-CAPP (CERN, rectangular cavities-TE modes)
- ABRACADABRA (MIT, toroidal)
- Dark Matter RADIO (Looking for collaborators w/ large magnet...)

Major activities

- CASPEr electric (Boston Univ.)
- CASPEr axion-wind (MAINZ)
- Oscillating neutron-EDM (PSI)
- Axion-EDM (JEDI at Juelich)

Major activities

- GNOME (Axion domain walls, stars; International network)
- ARIADNE (Axion-mediated long-range forces; No dark matter needed)

Axion detection method

Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	Model dependency
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×			×		×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)				×	×				DM
Spin precession in cavity		×							DM
Atomic transitions	×	×							DM

Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also “DM” when searching for ALP DM signals, see section 6.2

Nice overview: Irastorza, Redondo 1801.08127v2

Figure of merit in various experiments

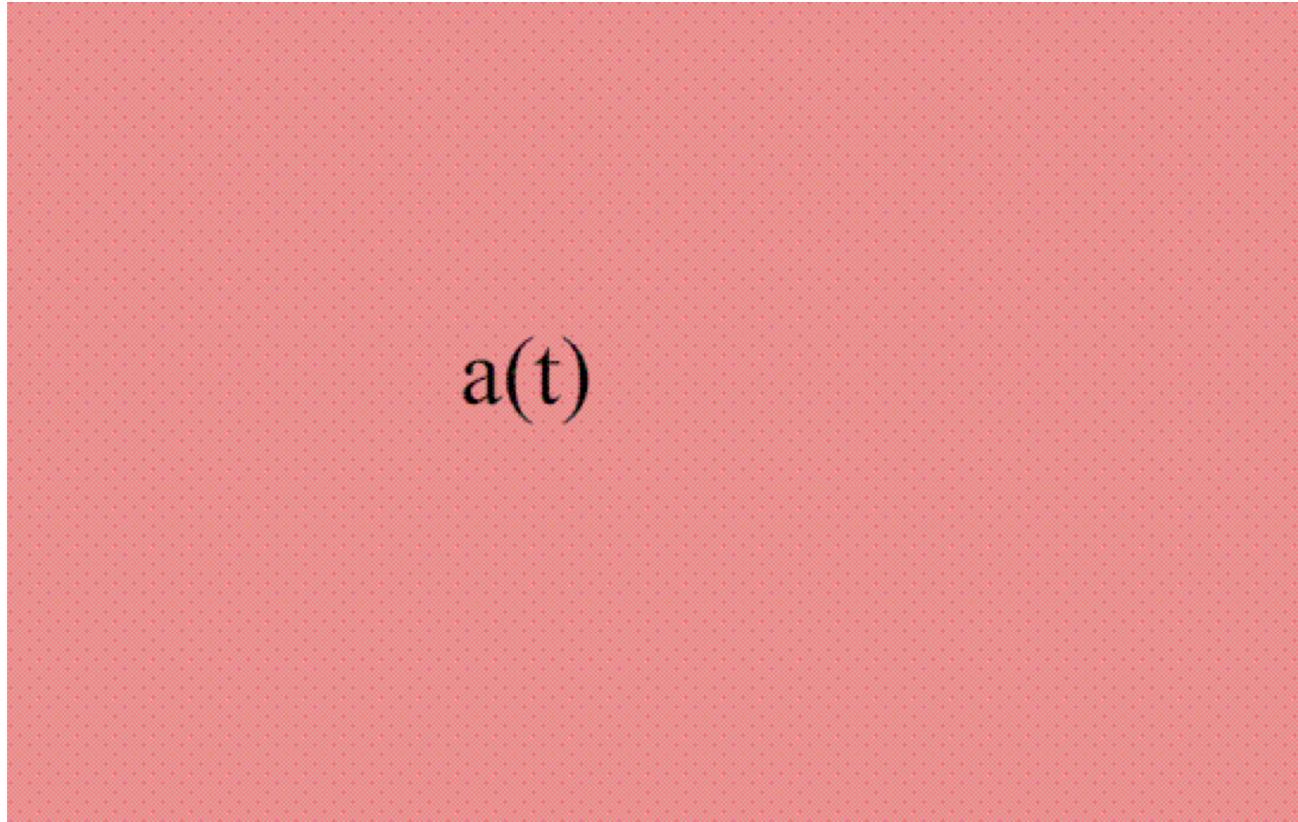
R. Battesti *et al.*, Phys. Rep. (2018)

Table 3. Figure-of-merit (FOM) for various fundamental-physics experiments. L , A and V are the characteristic length, transverse area and volume of the magnetic-field region. The last column lists the sections of this paper where the corresponding experiments are discussed.

Experiment	FOM	Examples	Section
Vacuum birefringence	$B^2 L$	BMV, PVLAS, OVAL	2.1
Light shining through wall	$B^4 L^4$	ALPS, OSQAR, ...	2.2.1
Helioscope	$B^2 L^2 A = B^2 V L$	CAST, IAXO	2.2.2
Haloscope (Primakoff)	$B^2 V$	ADMX, HAYSTAC, ORGAN, CULTASK ...	2.2.3
Haloscope (other)	None of the above	CASPER, QUAX, ...	2.2.3

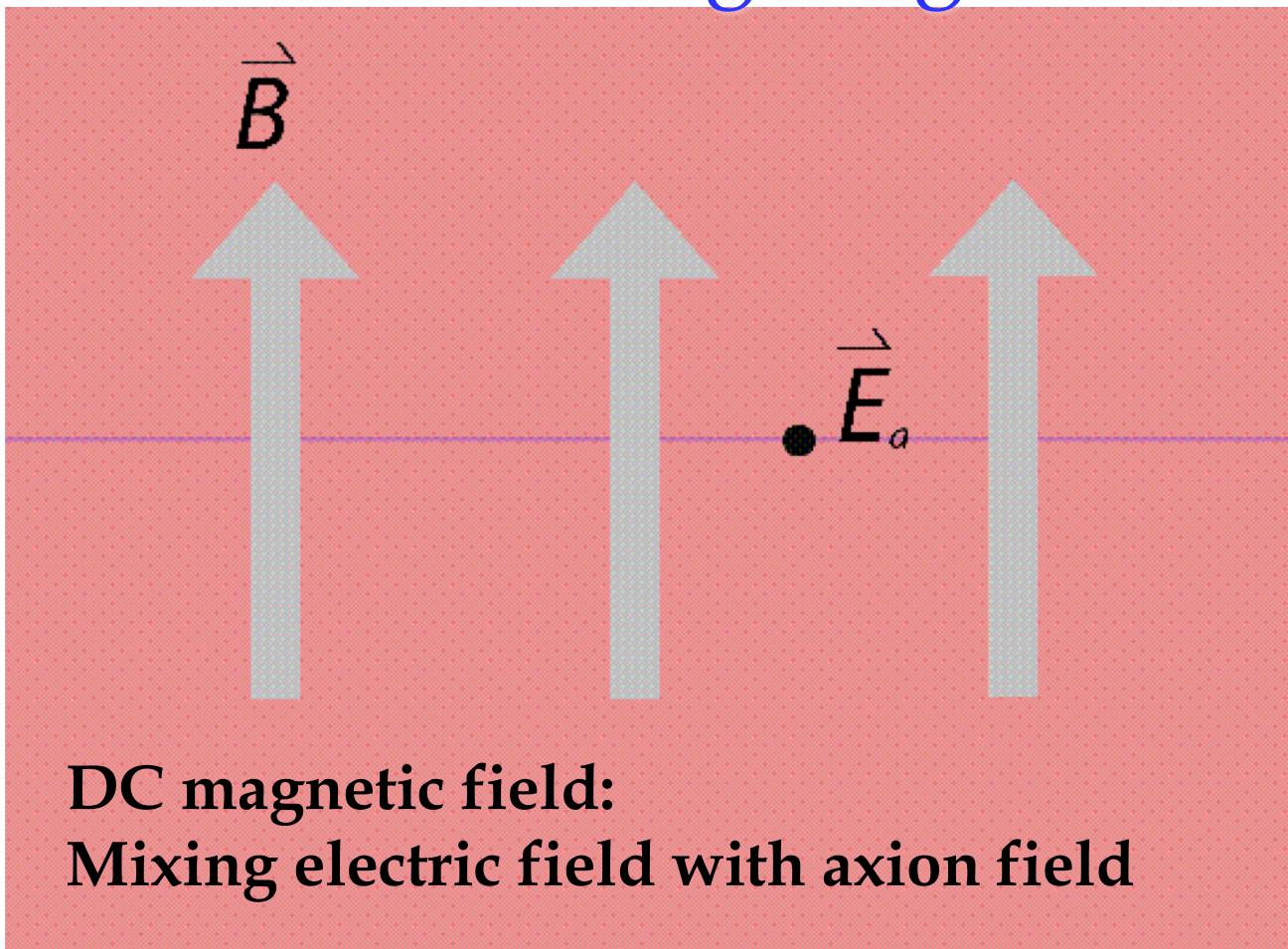
Measure nothing but frequency!

Axion (Higgslet) dark matter: Imprint on the vacuum since soon after the Big-Bang!



Animation by Kristian Themann

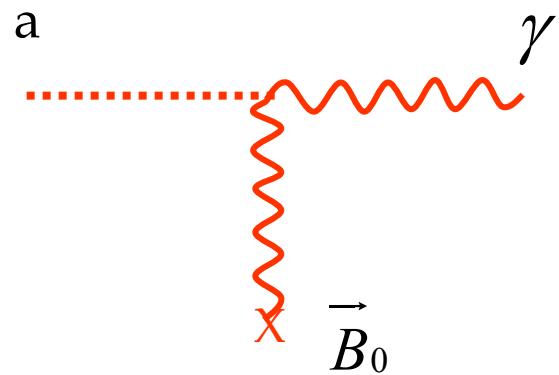
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



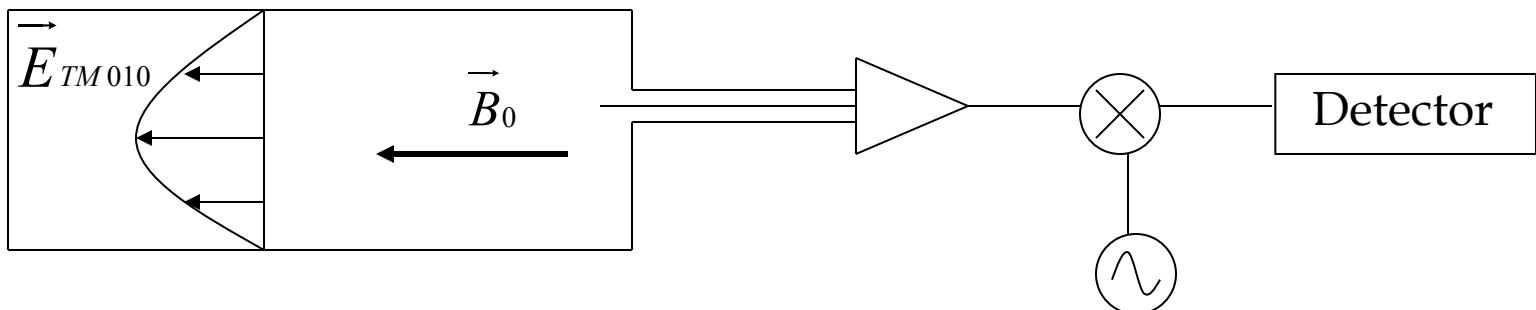
Animation by Kristian Themann

J. Hong, J.E. Kim, S. Nam, YkS
hep-ph: 1403.1576

P. Sikivie's method: Axions convert into microwave photons in the presence of a DC magnetic field (Primakov effect)



$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



Need to tune the cavity over a vast frequency range

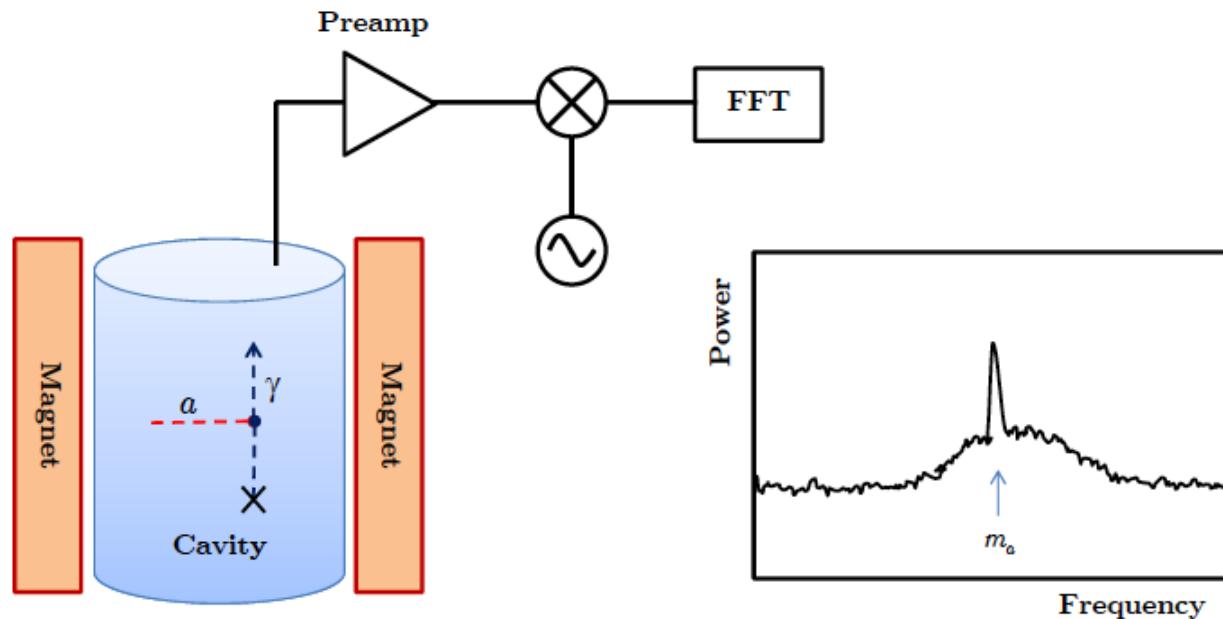
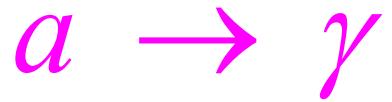


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.



The conversion power on resonance

$$\begin{aligned}
P &= \left(\frac{\alpha g_\gamma}{\pi f_a} \right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L \\
&= 2 \cdot 10^{-22} \text{ Watt} \left(\frac{V}{500 \text{ liter}} \right) \left(\frac{B_0}{7 \text{ Tesla}} \right)^2 \left(\frac{C}{0.4} \right) \\
&\quad \left(\frac{g_\gamma}{0.36} \right)^2 \left(\frac{\rho_a}{5 \cdot 10^{-25} \text{ gr/cm}^3} \right) \left(\frac{m_a c^2}{h \text{ GHz}} \right) \left(\frac{Q_L}{10^5} \right)
\end{aligned}$$

The axion to photon conversion power is very small.

If you don't know the axion mass need to tune

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q} \frac{1}{t} \approx \frac{1 \text{ GHz}}{\text{year}} \left(g_{a\gamma\gamma} 10^{15} \text{ GeV} \right)^4 \left(\frac{5 \text{ GHz}}{f} \right)^2 \left(\frac{4}{SNR} \right)^2 \left(\frac{0.25 \text{ K}}{T} \right)^2$$

The equation is shown with three terms circled in colored circles: a red circle around the first term $\left(\frac{B}{25T}\right)^4$, a green circle around the second term $\left(\frac{c}{0.6}\right)^2$, and a blue circle around the third term $\left(\frac{Q}{10^5}\right)^2$.

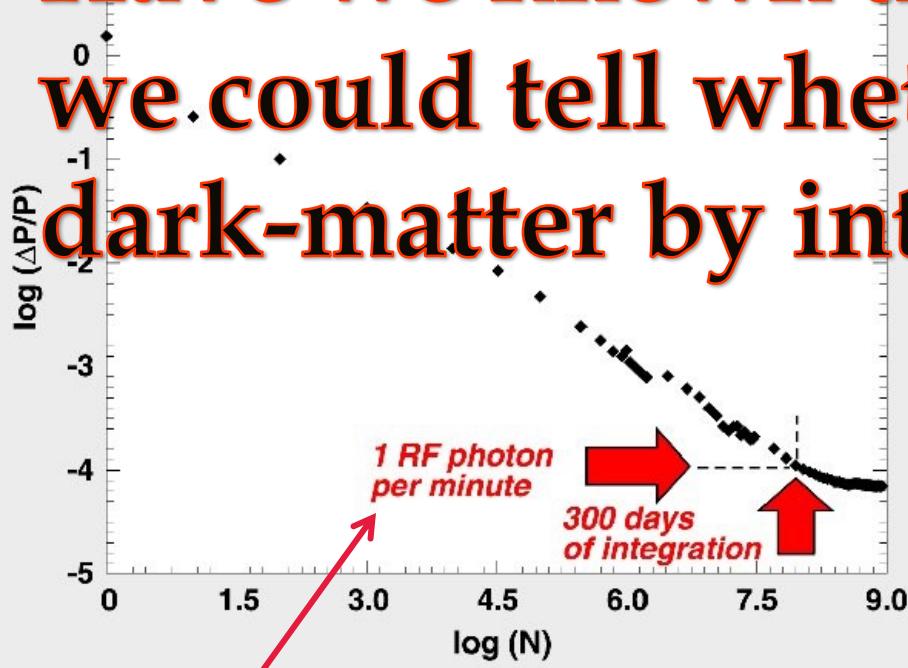
$$T = T_N + T_{ph}$$

SQUID Amplifier Noise (ADMX)

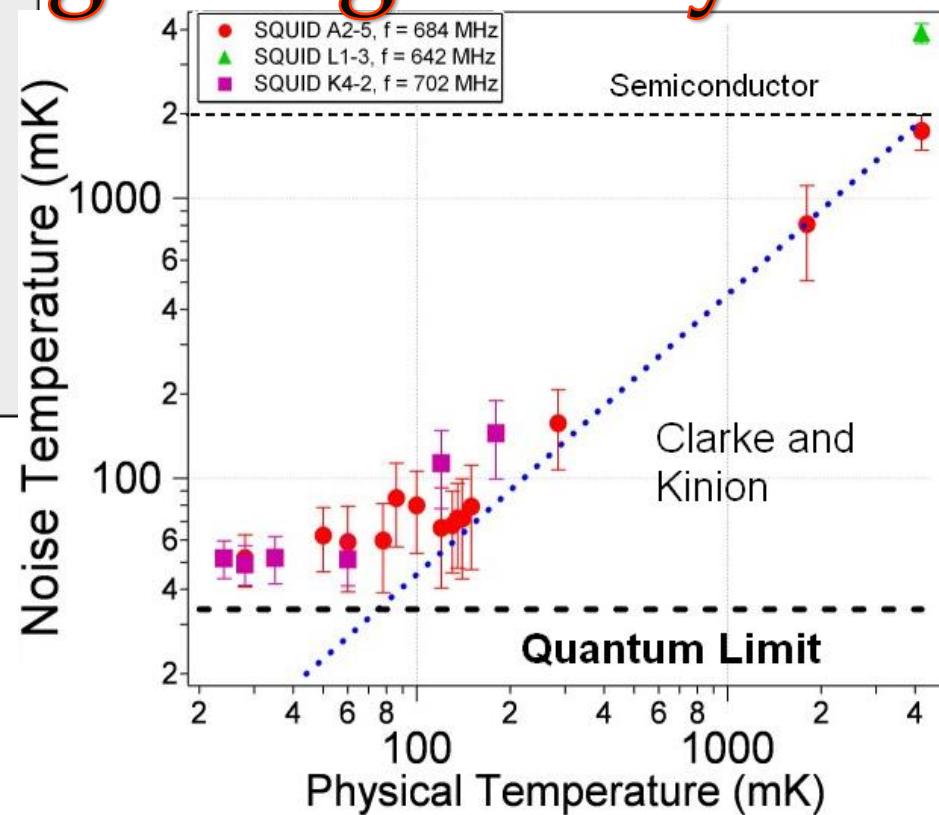
Have we known the axion mass

we could tell whether it's the

dark-matter by integrating ~ 1 day!



10^{-26} W



Axion dark matter search

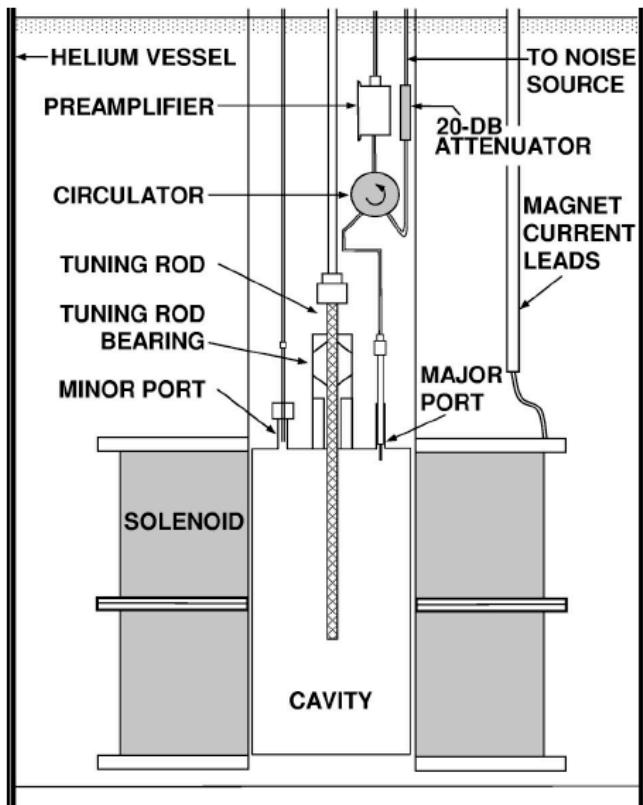
- The axion mass is unknown
The way we look for it:



- Once it's discovered, anyone will be able to dial in... and talk to it.

The first-generation axion-dark-matter experiment Rochester Brookhaven Fermilab, at BNL – 1980's

W. Wuensch *et al.*, Phys. Rev.
D40 (1989) 3153



First PhD Thesis
Joe Rogers
(1957-2004)



RBF axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Support from BNL
- Questions often asked: existence of DM and axions!



Axion dark detection mechanism

- Sikivie invented a method to detect the “invisible” axions utilizing the inverse Primakoff effect

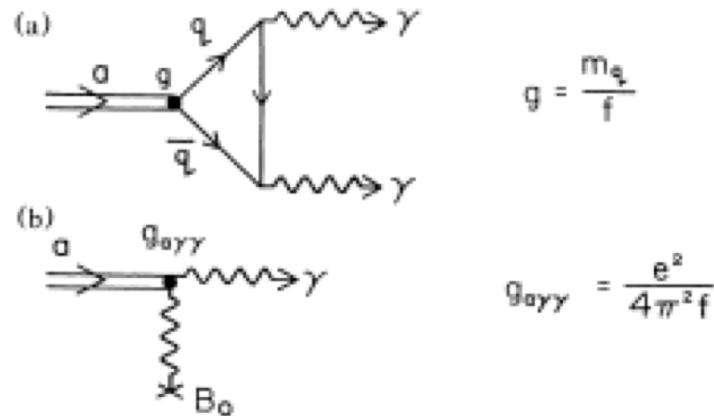


FIG. 1. (a) The coupling of axions to two photons. (b) The Primakoff effect.

$$R_{a \rightarrow \gamma} = (\epsilon_0 c^2 / \hbar^2) g_{a\gamma\gamma}^2 \omega^{-1} Q B_0^2 G_f^2.$$

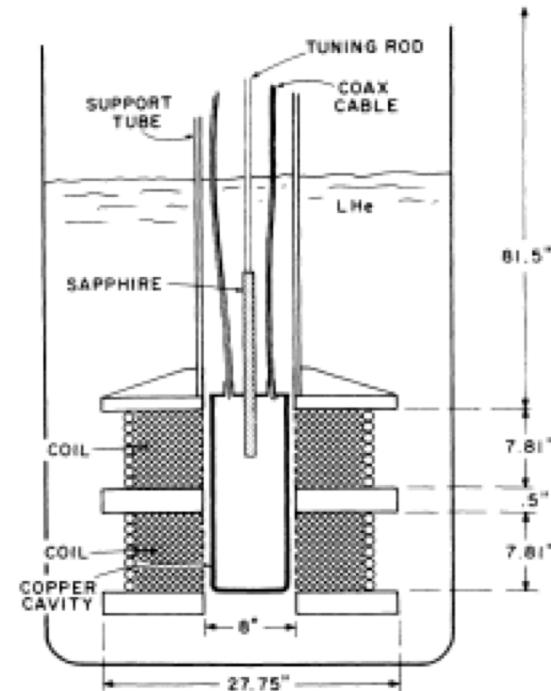
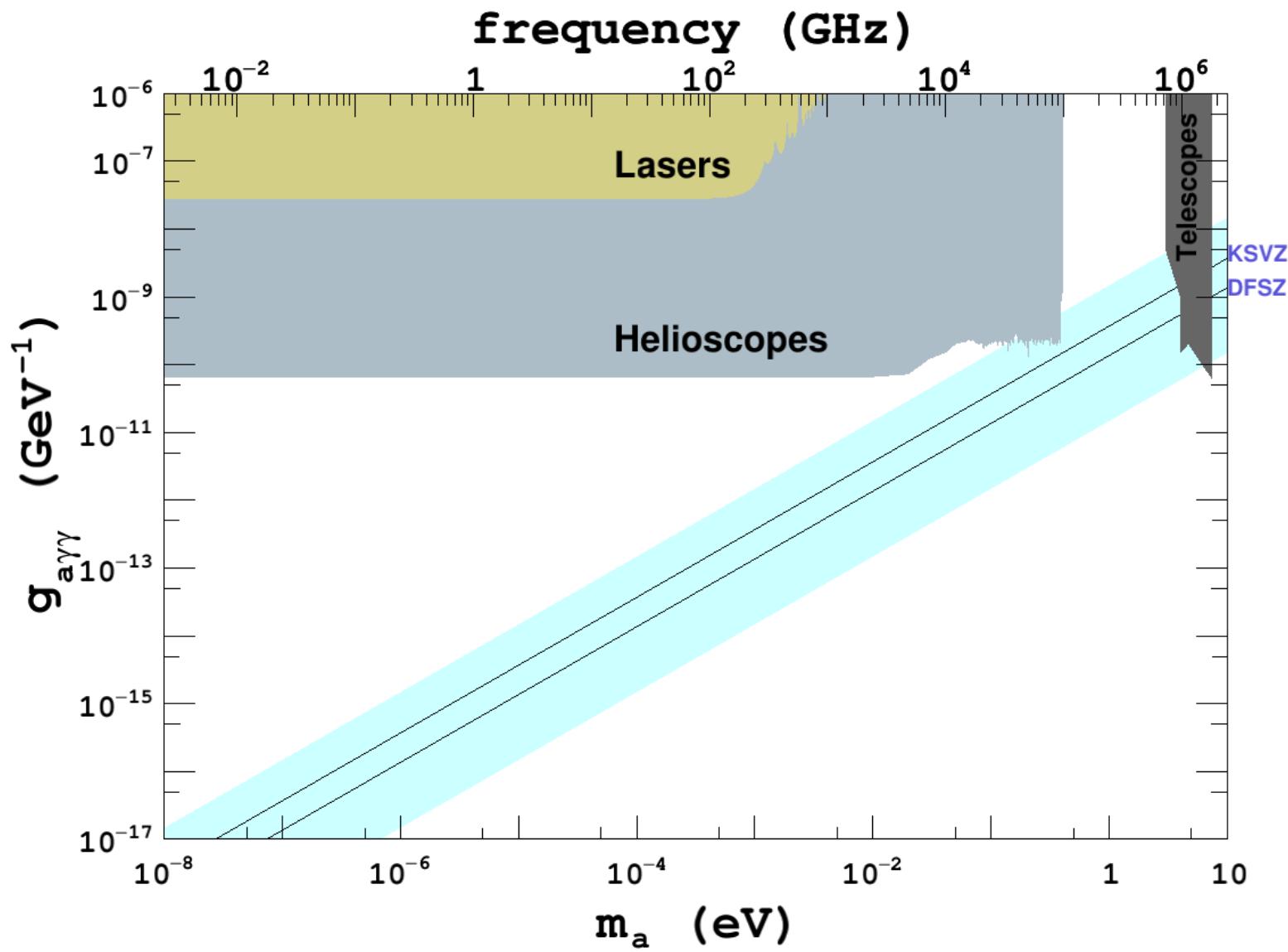
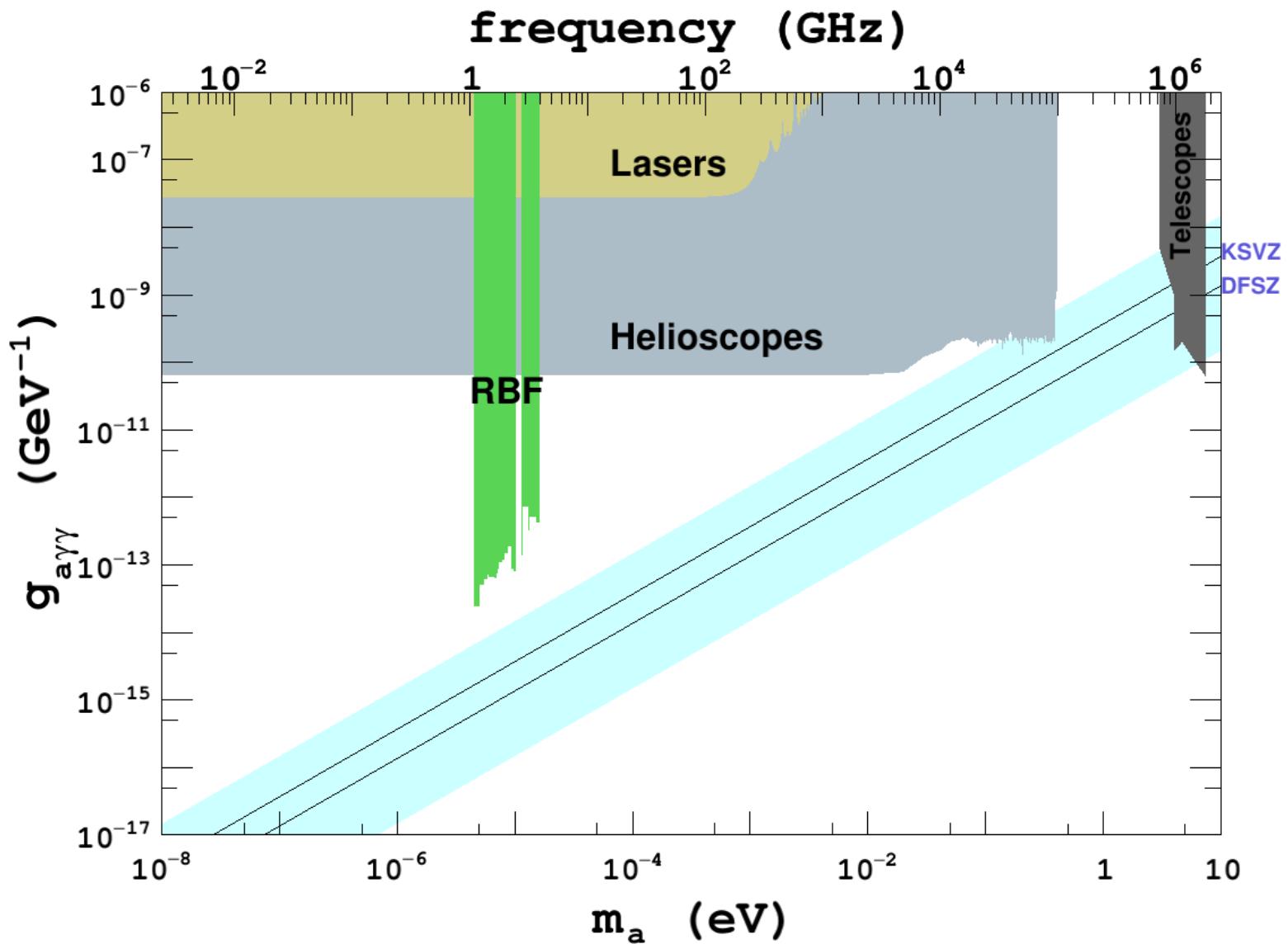
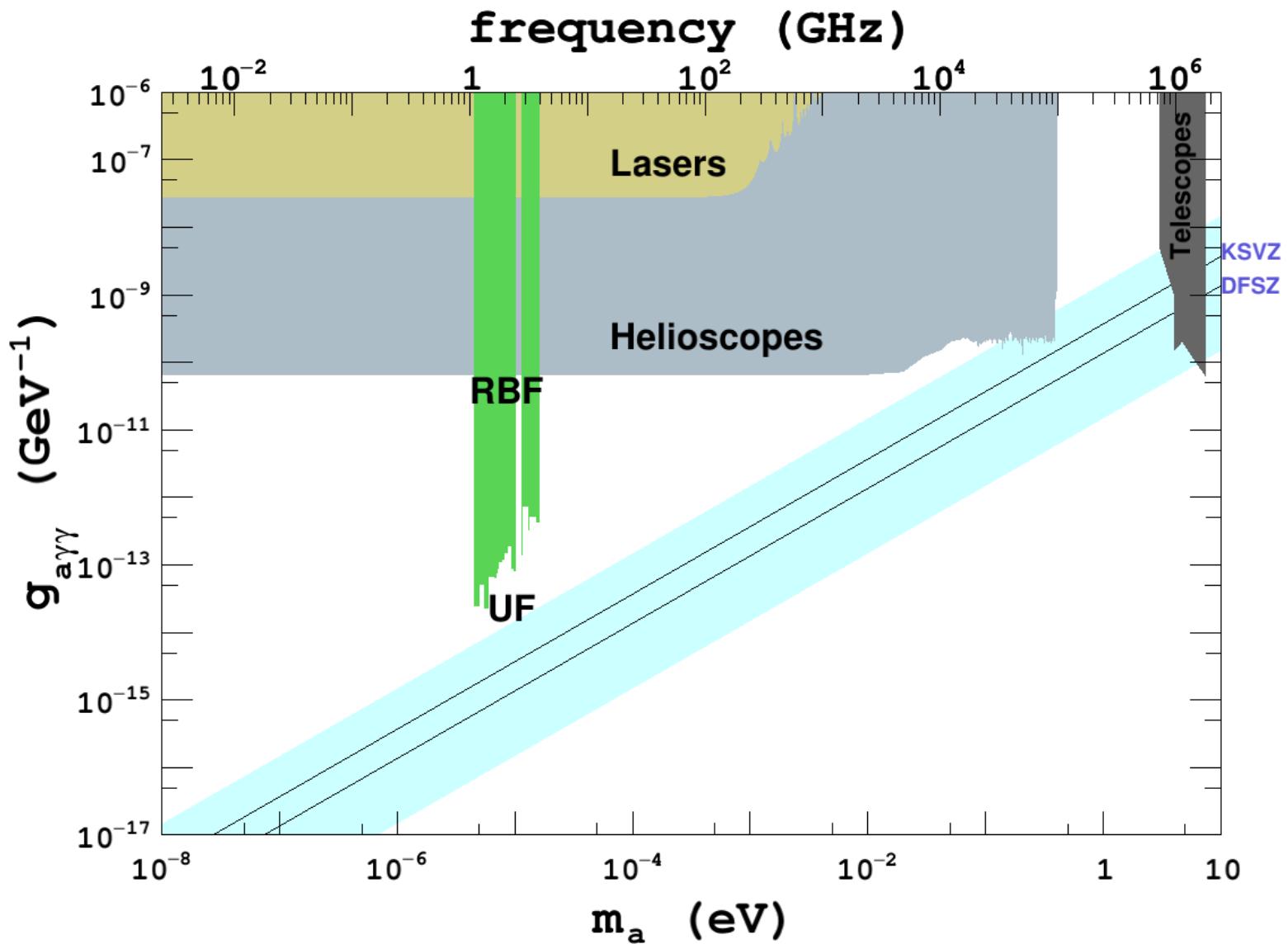


FIG. 2. Schematic diagram of the apparatus.







ADMX, longest in the game

ADMX: Recent results at the DFSZ frontier

N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L.J. Rosenberg, and G. Rybka

University of Washington

G.P. Carosi, N Wollett,
Livermore

A.S. Chou, A. Sonnenschein, and W. Wester
FNAL

C. Boutan and N. Oblath
PNNL

John Clarke, S. O'Kelley, Karl van Bibber
UC Berkeley

Leanne Dufffy
Los Alamos

Richard Bradley
NRAO

Ed Daw
Sheffield

Nicole Crisosto, Jeff Hoskins, J. Gleason,
R. Jois, I. Stern, Jihee Yang,

Pierre Sikivie, Neil Sullivan, D.B.T.
University of Florida



Axion Dark Matter eXperiment

The ADMX-dark matter axion group, 2012



ADMX results

ADMX “G2” Dark Matter Search: Find Dark Matter Axions



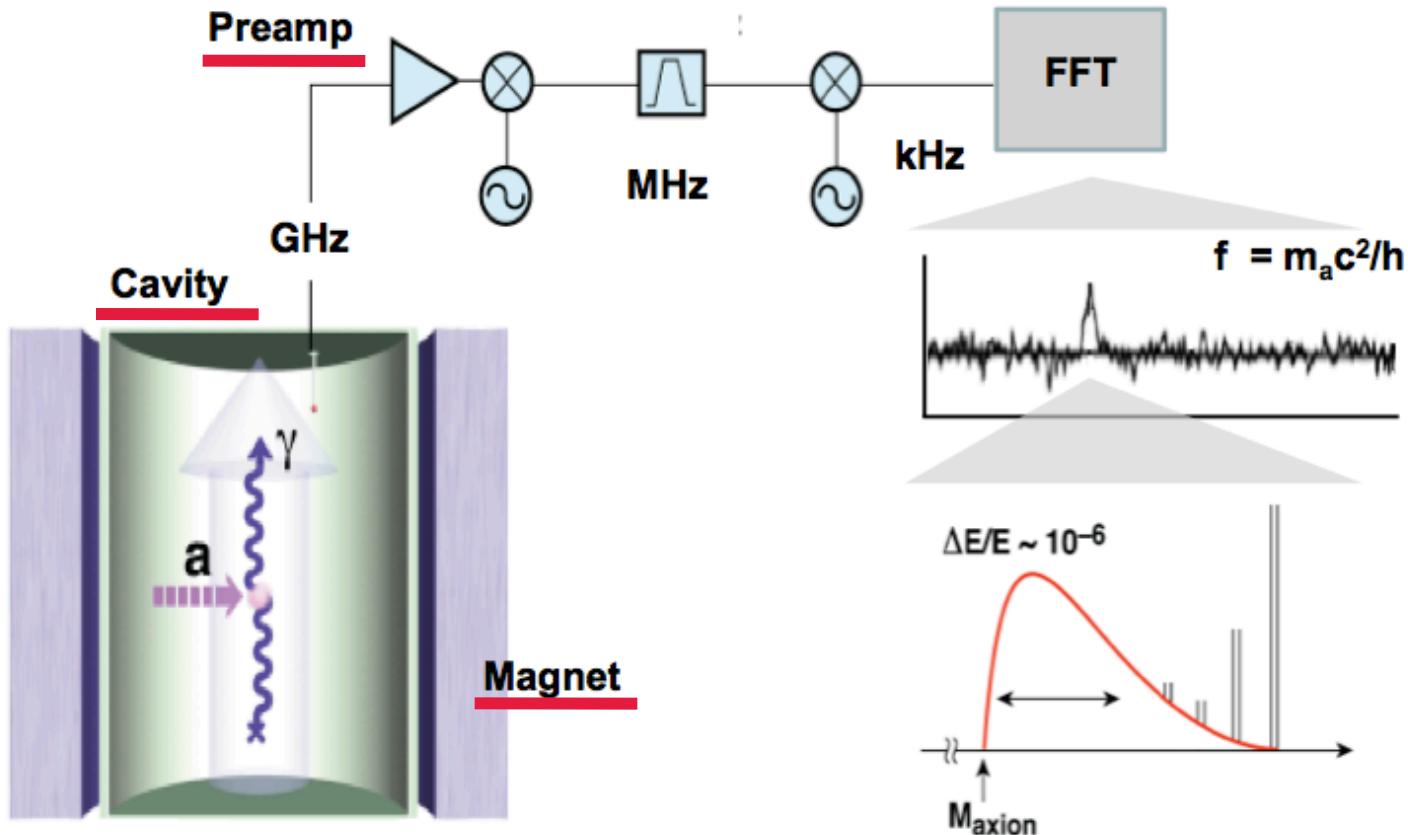
ADMX collaboration meeting, April 2018

Collaborating Institutions:
UW, UFL, LLNL
FNAL, UCB, PNNL
LANL, NRAO, WU, Sheffield

The ADMX collaboration gratefully acknowledges support from the US Dept. of Energy, High Energy Physics DE-SC0011665 & DE-SC0010280 & DE-AC52-07NA27344

Also support from LLNL and PNNL LDRD programs
and R&D support the Heising-Simons institute

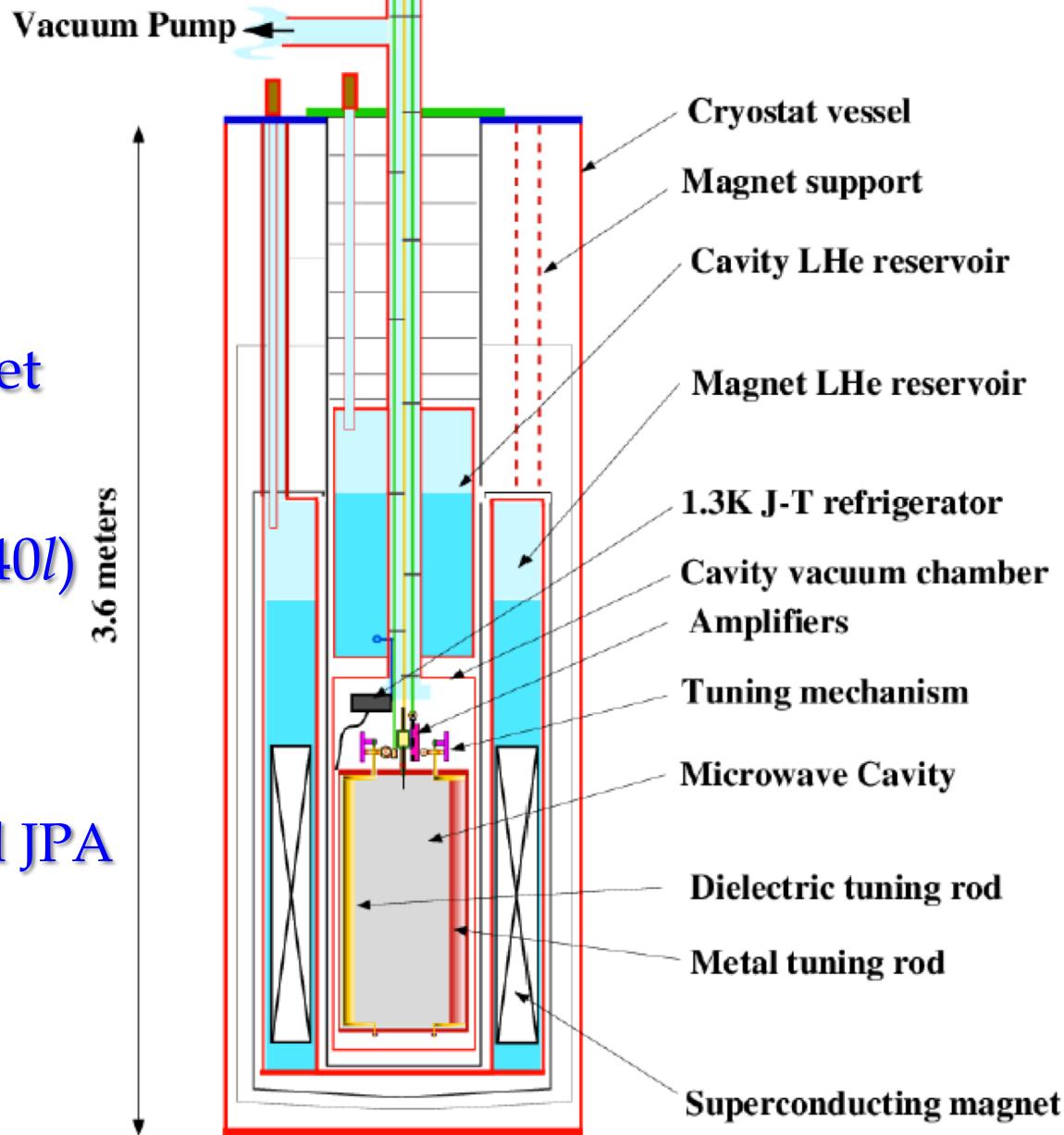
The full ADMX receiver



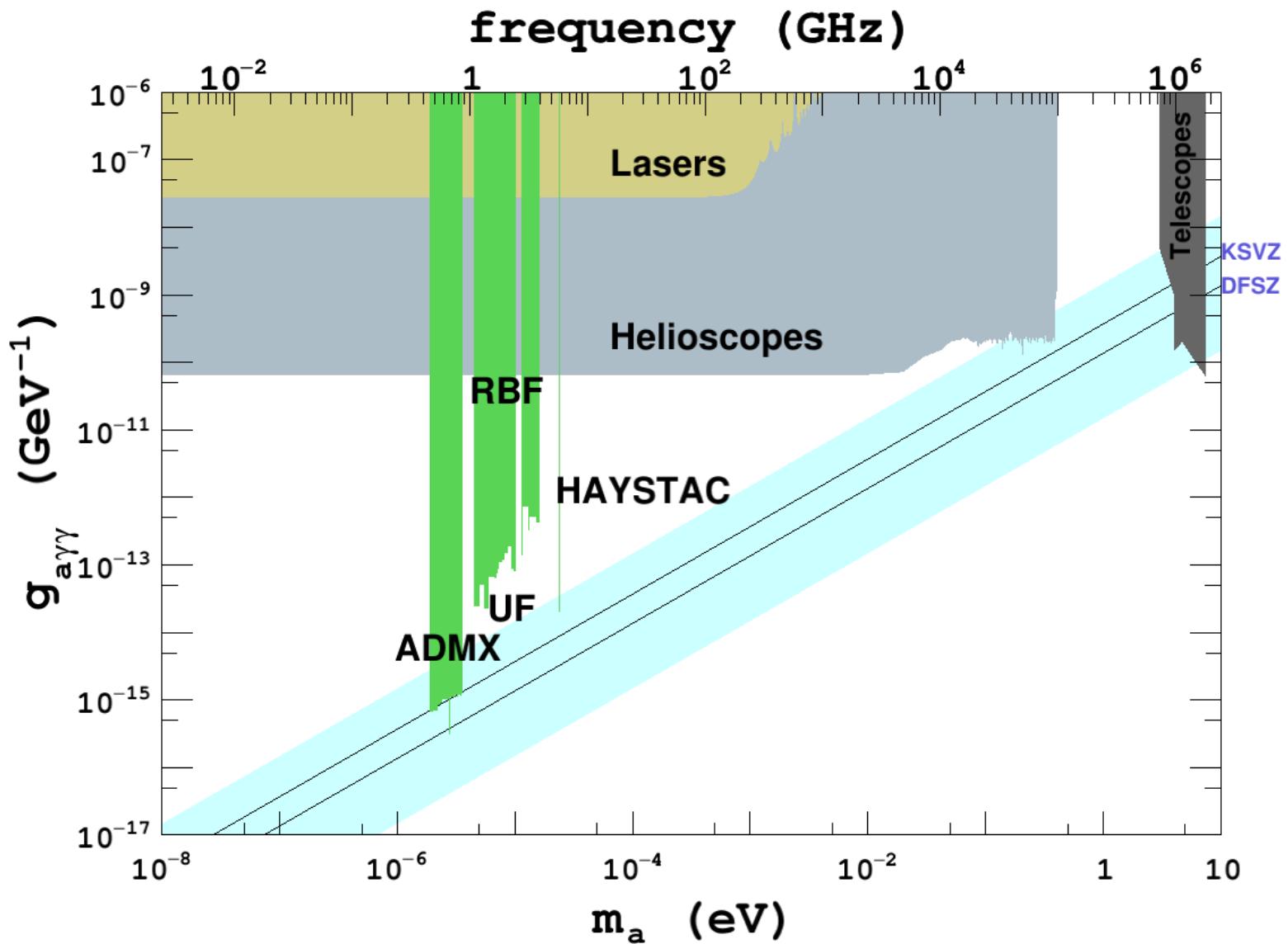
$$P_{\text{sig}} \propto (B^2 V Q_{\text{cav}})(g^2 m_a \rho_a) \sim 10^{-23} \text{ W}$$
$$s/n = \frac{P_{\text{sig}}}{kT_{\text{sys}}} \sqrt{\frac{t}{\Delta\nu}}$$

Axion Dark Matter eXperiment

Stepping motors

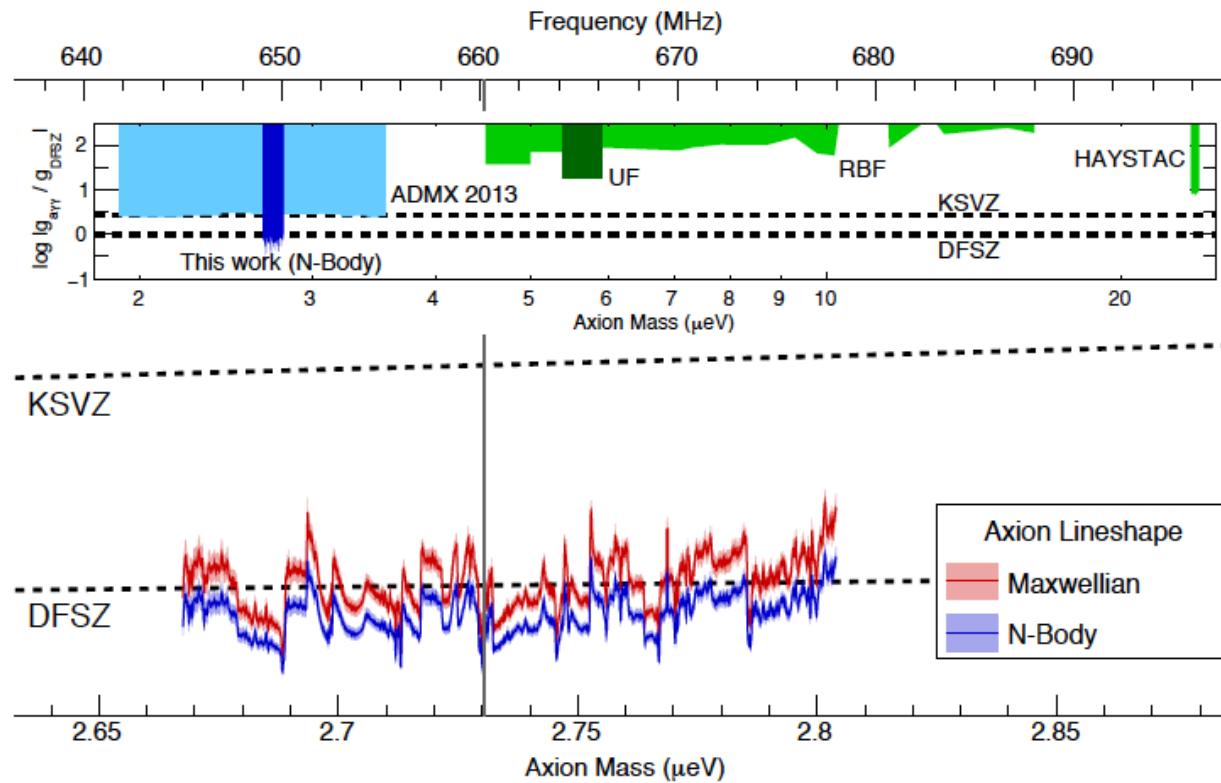


- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity ($140l$)
- Low noise amplifiers
 - From 12K to 1K
 - Currently SQUID and JPA (<1K)



ADMX results

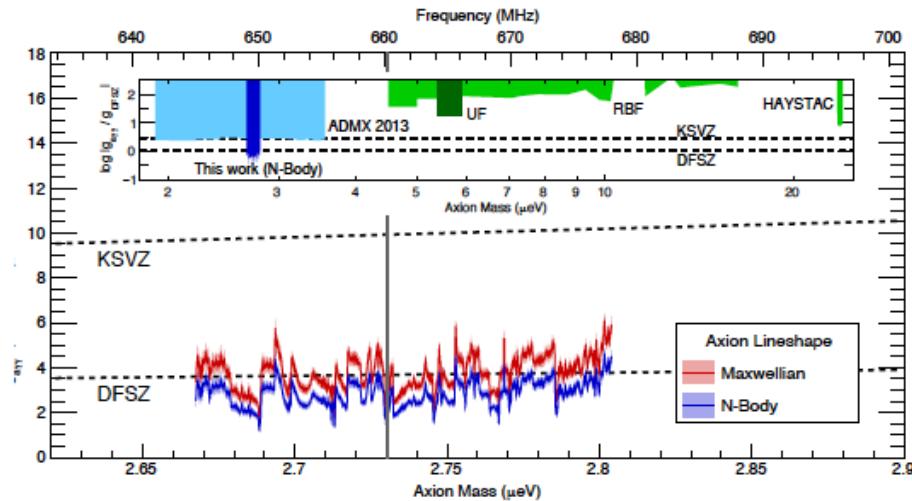
ADMX Exclusion Limits 2017



N. Du *et al.* (ADMX Collaboration), “Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment,” [Phys. Rev. Lett. 120, 151301 \(2018\)](#).

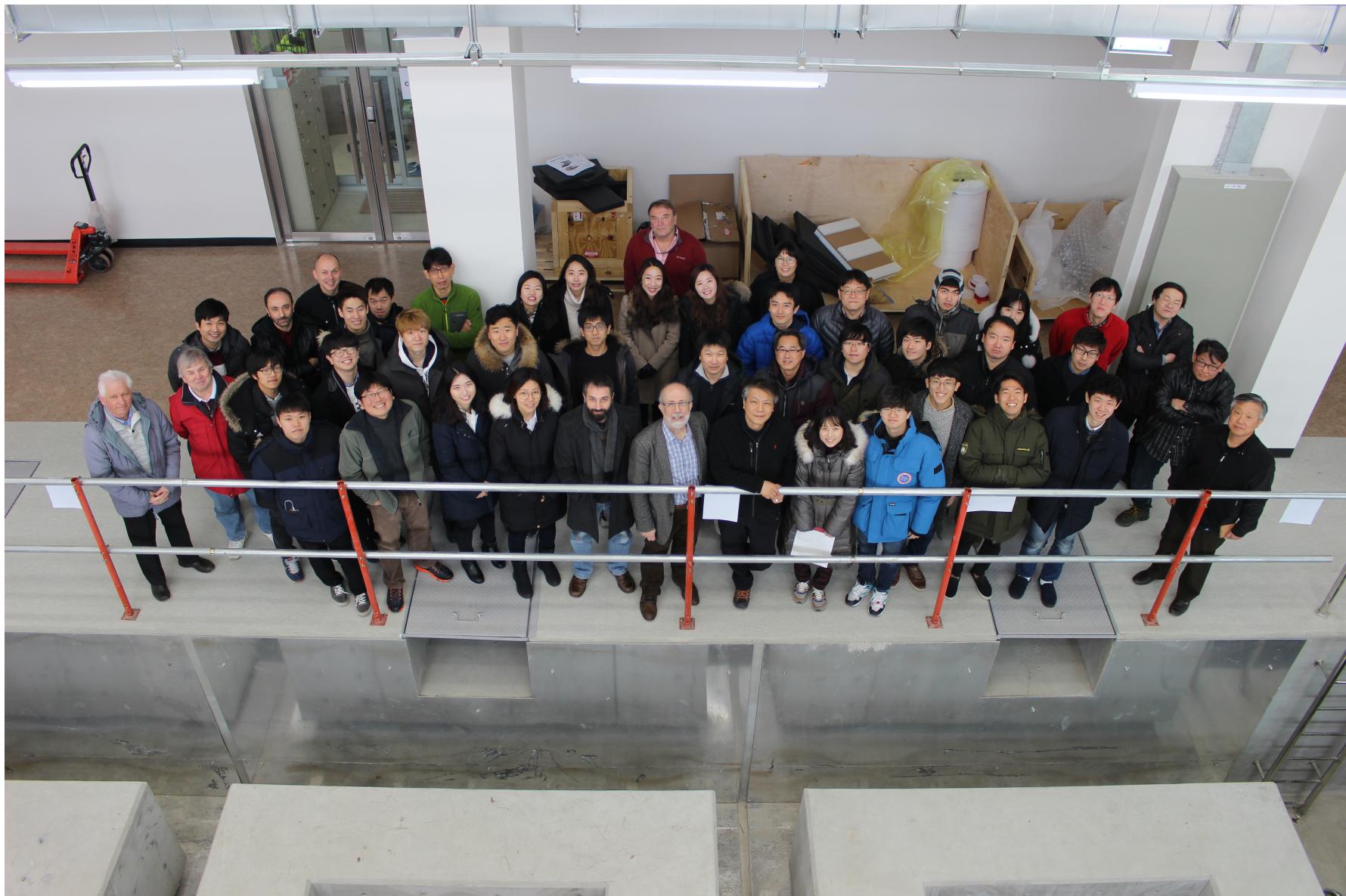
ADMX results

ADMX Exclusion Limits 2017



We didn't find an axion over this narrow range.
More importantly, we could have. This is the first
exploration into the plausible DFSZ coupling in the prime
mass range for Dark Matter. A discovery could come at any
time.

IBS/CAPP at Munji Campus, KAIST, January 2017.



CAPP Experimental Hall (LVP)



June 19th 2018

14th PATRAS Workshop, DESY

Woohyun Chung's slide

CULTASK Refrigerators and Magnets

Refrigerators					Magnets				
Vendor	Model	T _B (mK)	Cooling power	Installation	B field	Bore (cm)	Material	Vendor	Delivery
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016	26T	3.5	HTS	SUNAM	2016
BlueFors (BF4)	LD400	10	18μW@20 580μW@100	2016	18T	7	HTS	SUNAM	2017
Janis	HE3	300	25μW@300mK	2017	9T	12	NbTi	Cryo-Magnetics	2017
BlueFors (BF5)	LD400	10	18μW@20mK 580μW@100K	2017	8T	12	NbTi	AMI	2016
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100K	2017	8T	16.5	NbTi	AMI	2017
Leiden	DRS100	100	1mW @100mK	2018	25T	10	HTS	BNL/CAPP	2020
Oxford	Kelvinox	<30	400 @120mK	2017	12T	32	Nb ₃ Sn	Oxford	2020

CAPP's base plan

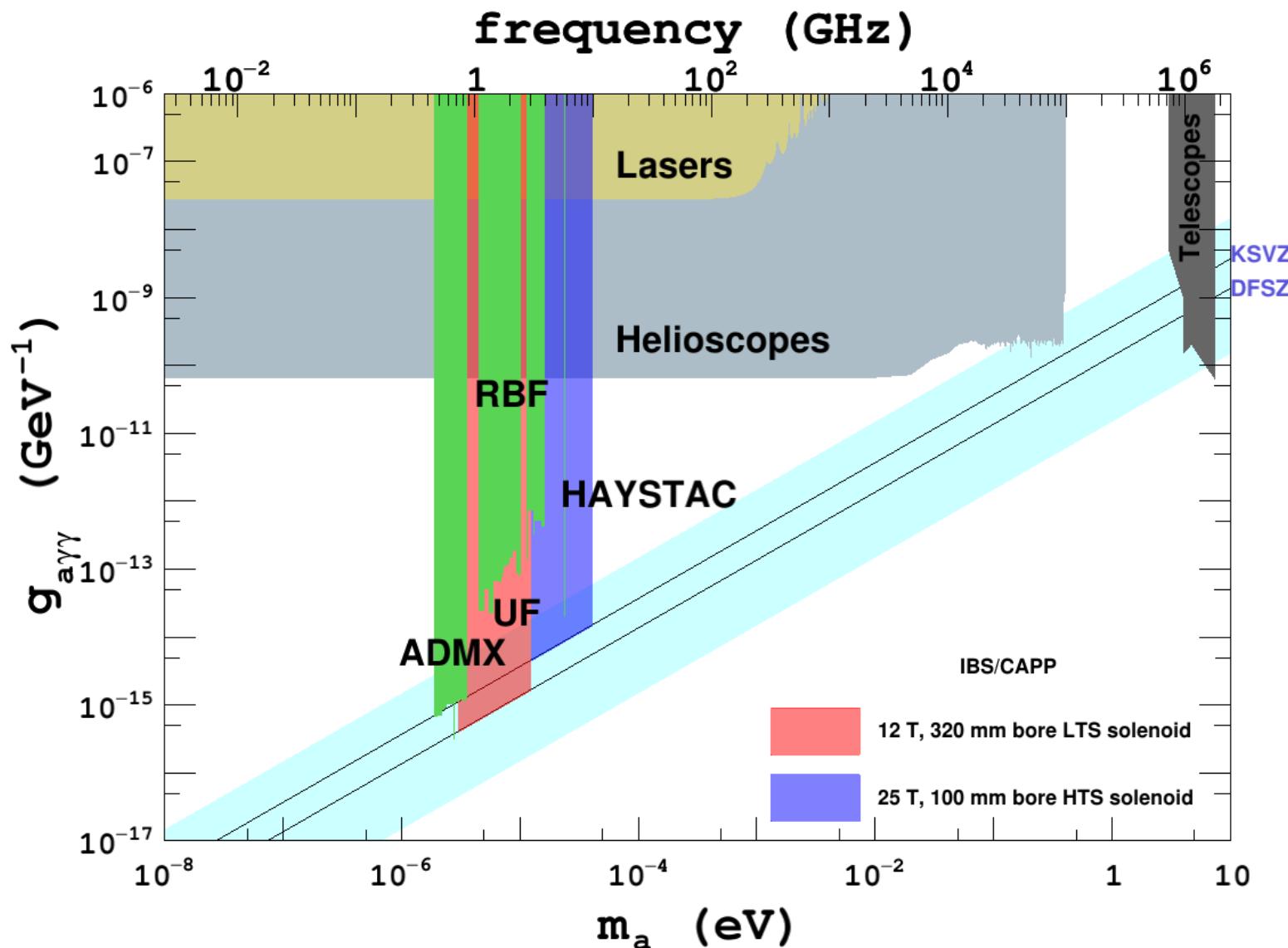
- Microwave cavities 0.7-20 GHz, using 25T/10cm and 12T/32cm magnets
- Combine the two magnets to obtain 37T
- Phase-lock two or more axion dark matter exps.
- Open resonators R&D for higher frequency
- GNOME
- Wide band axion-mass network...

CAPP's base plan

- Delivery of 25T/10cm and 12T/32cm magnets in 2020 (**funding limited**).
- In the meantime, we are getting ready for it:
 - Quantum noise limited SQUID-amplifiers
 - Cryo-expertise, reach lowest physical temperature (down to <50mK)
 - Demonstrate efficient high-frequency, high-volume operation
 - Efficient DAQ
 - Prepare systems for large magnets

Potential shown based on single cavities

Possible to extend to >10GHz



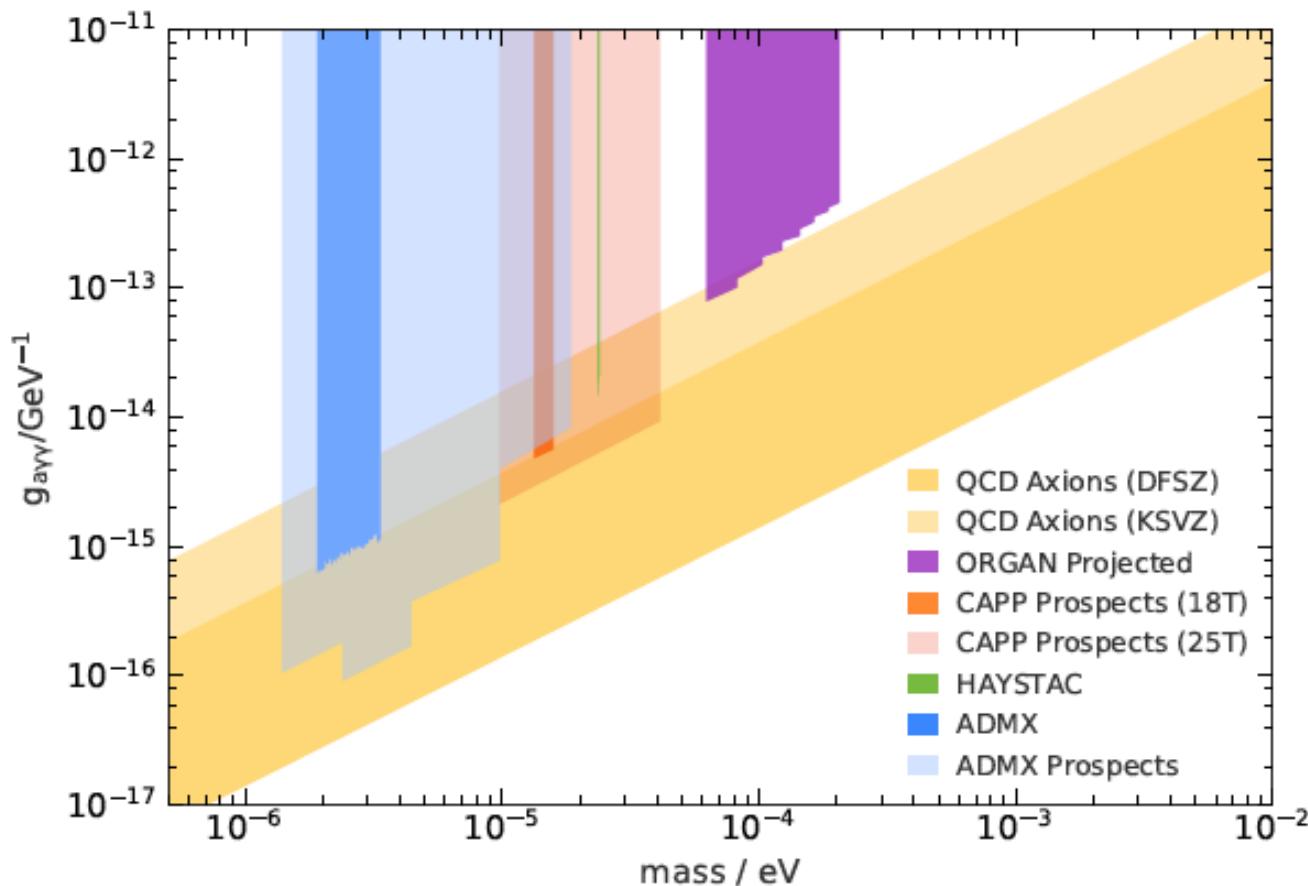


Fig. 13. Current and projected limits on the axion-photon coupling constants from Primakoff-haloscope experiments under the assumption that dark matter is dominated by a single-species of axions or ALPs. This overview plot was created with ALPlot (<https://alplot.physik.uni-mainz.de>).

Haloscope axion searches

$$\text{FOM} = B^4 V^2 Q/T^2$$

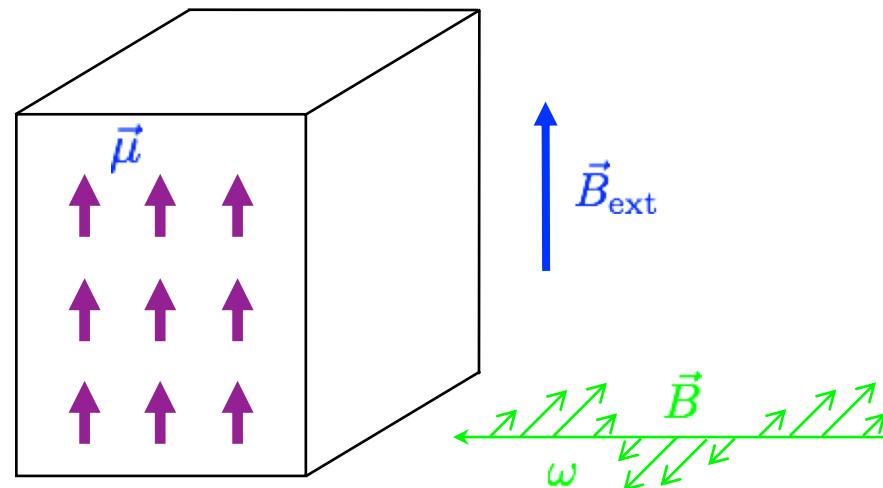
Experiment	References	Status	B (T)	V (m^3)	$B^2 V$ ($\text{T}^2 \text{m}^3$)	Multiple Cavities	Axion/ALP mass range (μeV)
ADMX	[95]	present	7.4	0.14	7.4	no	2-3.5-5.8
		future	7.4	0.08	4.4	yes	5.8-8.3
		considered	24	0.008	4.8	no	
		considered	32	0.008	8	no	4.2-8.4
						yes	8.4-25
HAYSTAC	[94]	present	9.4	0.0015	0.12	no	23-24
ORGAN	[96]	present	7	0.003	0.16	no	110
		future	14	0.0014	0.27	yes	60-210
CAPP	[97]	commission	12	0.033	4	no	3 - 12.5
		present	18	0.001	0.3	no	15-26
		commission	25	0.0025	1.4	no	12-42
						yes	> 85
Grenoble	[98]	proposal	9/17.5/27/ 40/43	0.49/0.05/0.0029/ $2.9 \cdot 10^{-5}/0.45 \cdot 10^{-5}$	13-0.01	yes/no	1.3-200

Table 7. Present and future haloscopes based on the Primakoff production of microwave photons by dark-matter axions/ALPs. In this case, V refers to the volume within microwave cavities placed into magnetic field. After CAPP runs the 12 T and the 25 T magnets, they plan to combine them and reach 37 T within the volume of the 25 T magnet, with a significant boost in the sensitivity of the axion/ALP search.

Haloscopes using spins!

Dima Budker, CASPER

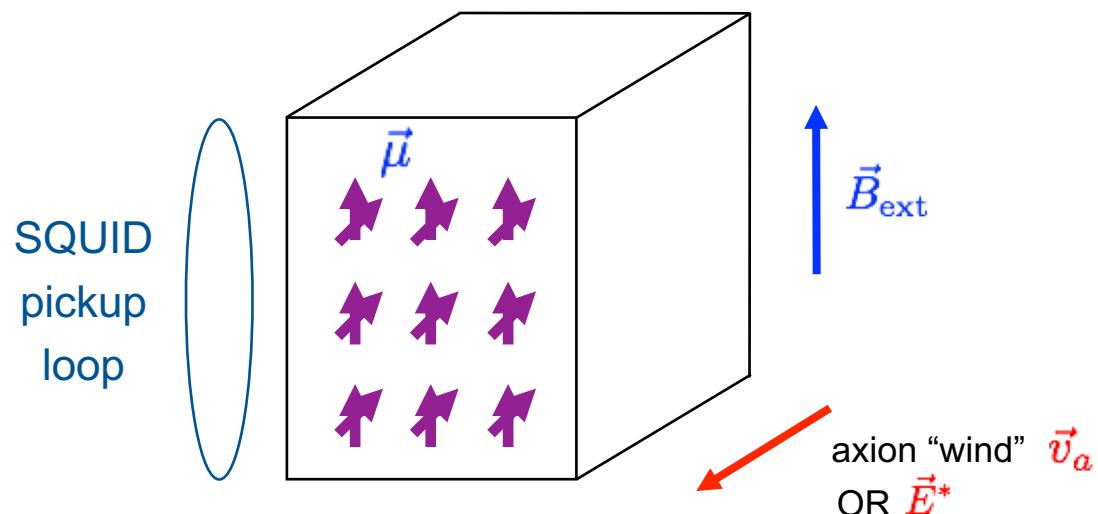
Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\text{ext}} = \omega$

Dima Budker

CASPER



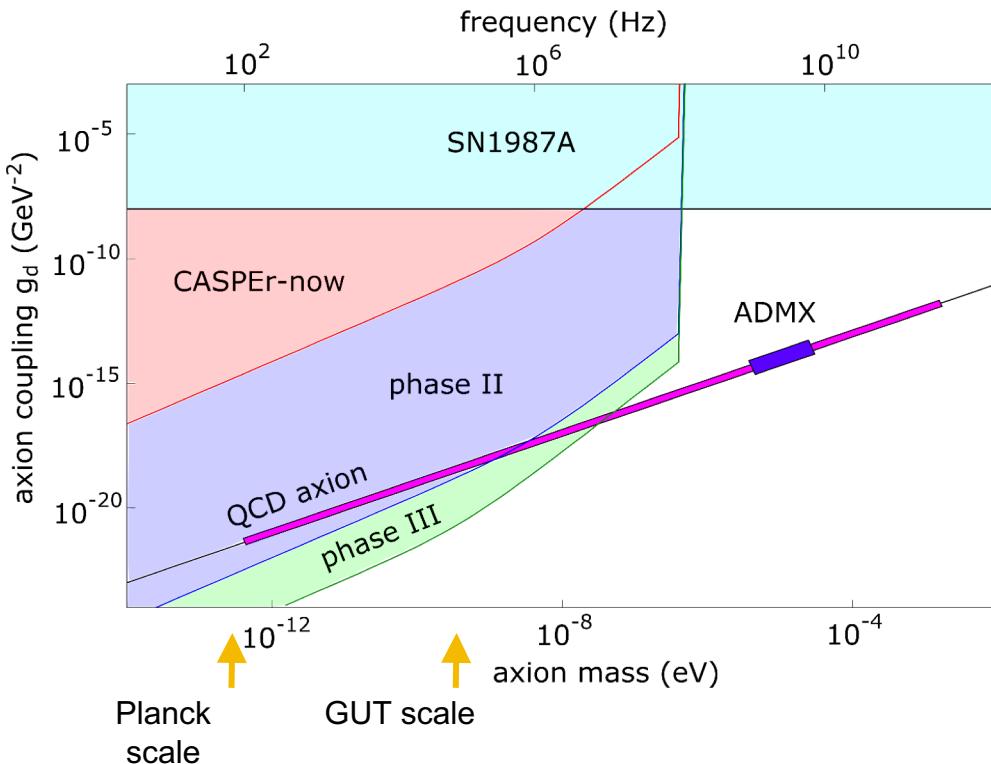
Larmor frequency = axion mass \rightarrow resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe , ferroelectric PbTiO_3

Dima Budker

The experimental reach of CASPER



CASPER-now at BU:

- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

phase II:

- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

phase III:

- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

[*Phys. Rev. X* **4**, 021030 (2014)]



Slide by Alex Suskov (adapted)

Solar Axions

R. Battesti *et al.*, Phys. Rep. (2018)

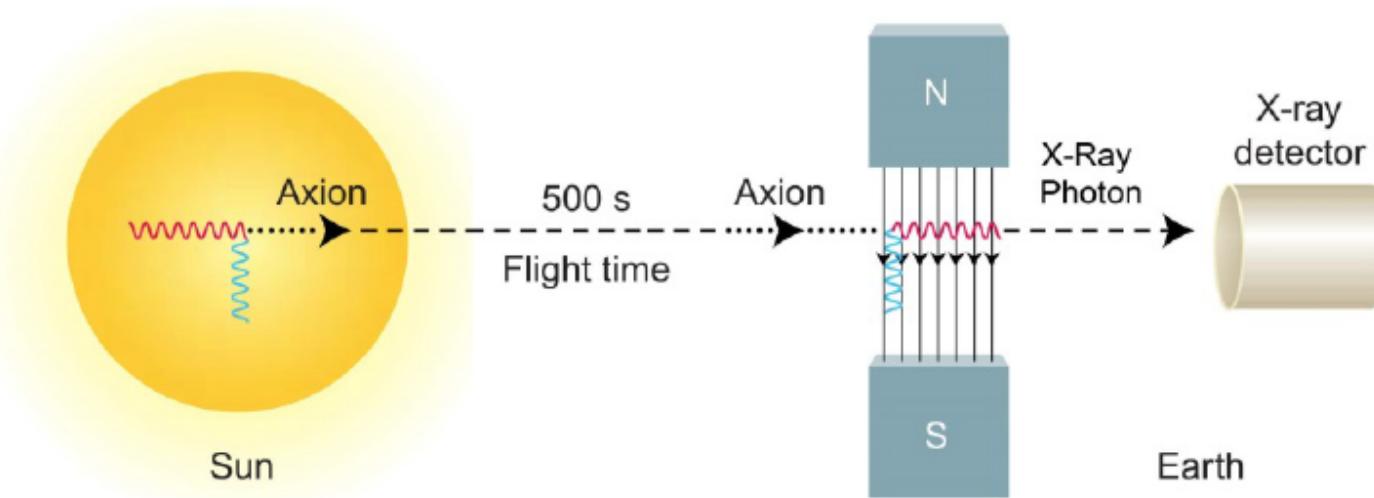


Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.

Experiment	References	Status	B (T)	L (m)	A (cm ²)	Focusing	$g_{\alpha\gamma}$ (10 ⁻¹⁰ GeV ⁻¹)
Brookhaven	[80]	past	2.2	1.8	130	no	36
SUMICO	[81, 82]	past	4	2.5	18	no	6
CAST	[83, 84, 85, 86, 87]	ongoing	9	9.3	30	yes	0.66
TASTE	[79]	in design	3.5	12	2.8×10^3	yes	0.2
BabyIAXO	[88]	in design	~ 2.5	10	2.8×10^3	yes	0.2
IAXO	[89, 74]	in design	~ 2.5	22	2.3×10^4	yes	0.04

Solar axion spectrum

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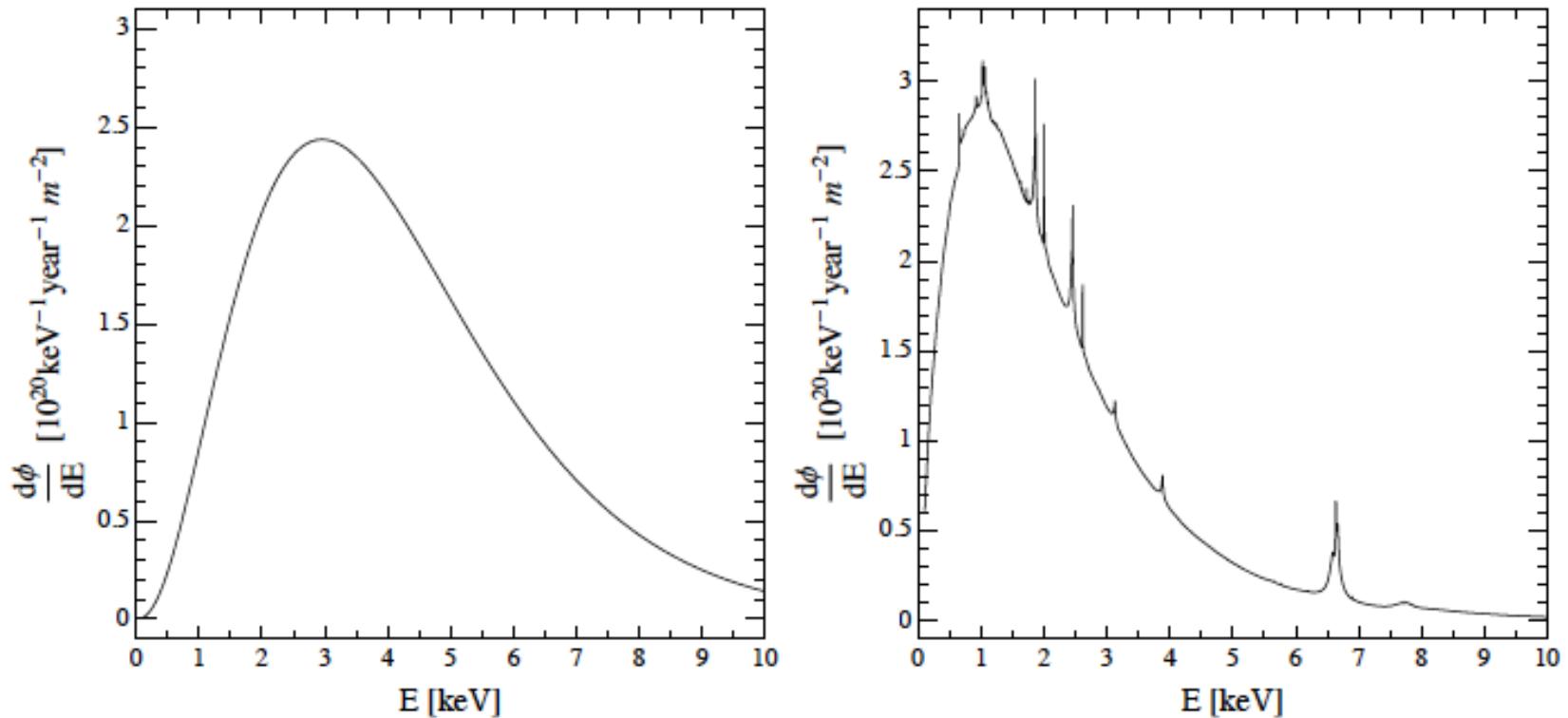
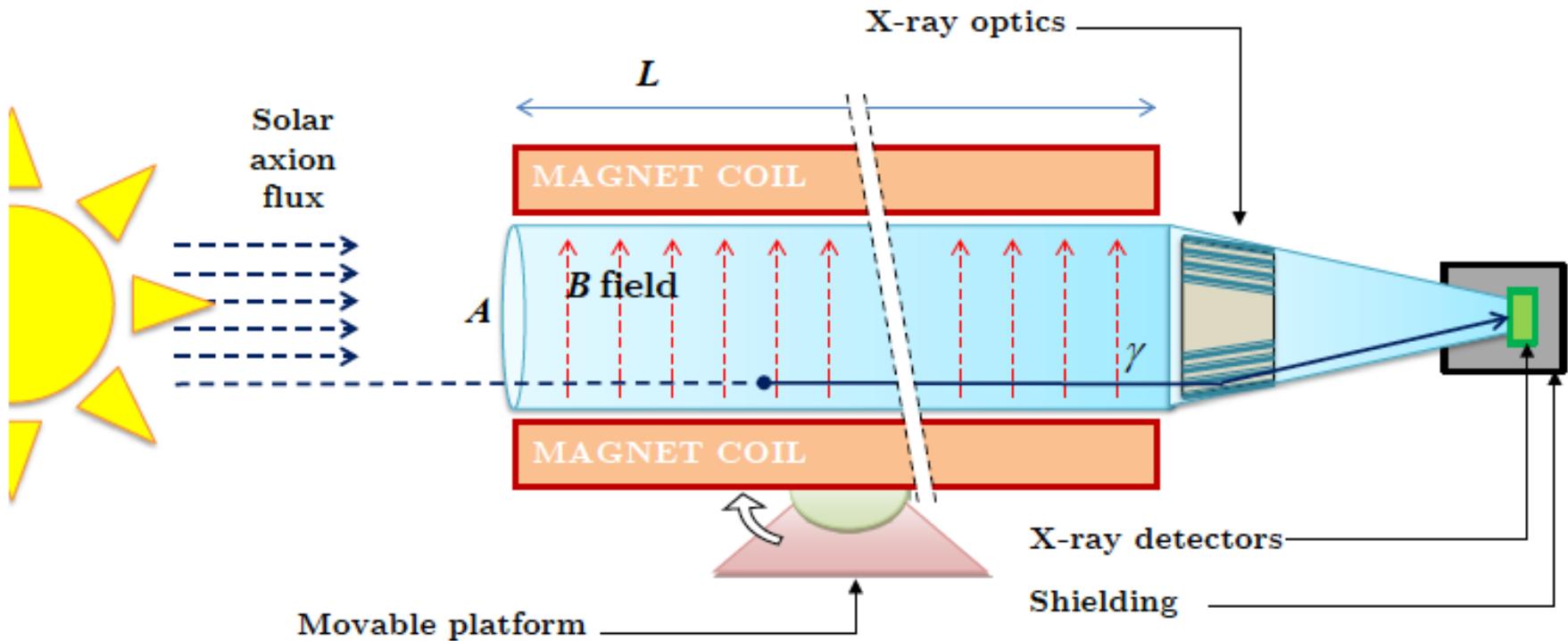


Figure 9: Solar axion flux spectra at Earth by different production mechanisms. On the left, the most generic situation in which only the Primakoff conversion of plasma photons into axions is assumed. On the right the spectrum originating from processes involving electrons, bremsstrahlung, Compton and axio-recombination [323, 395]. The illustrative values of the coupling constants chosen are $g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}$ and $g_{ae} = 10^{-13}$. Plots from [480].

Solar Axions

$$\text{FOM} = B^2 l^2 A = B^2 V l^{1801.08127v2}$$



Solar Axions

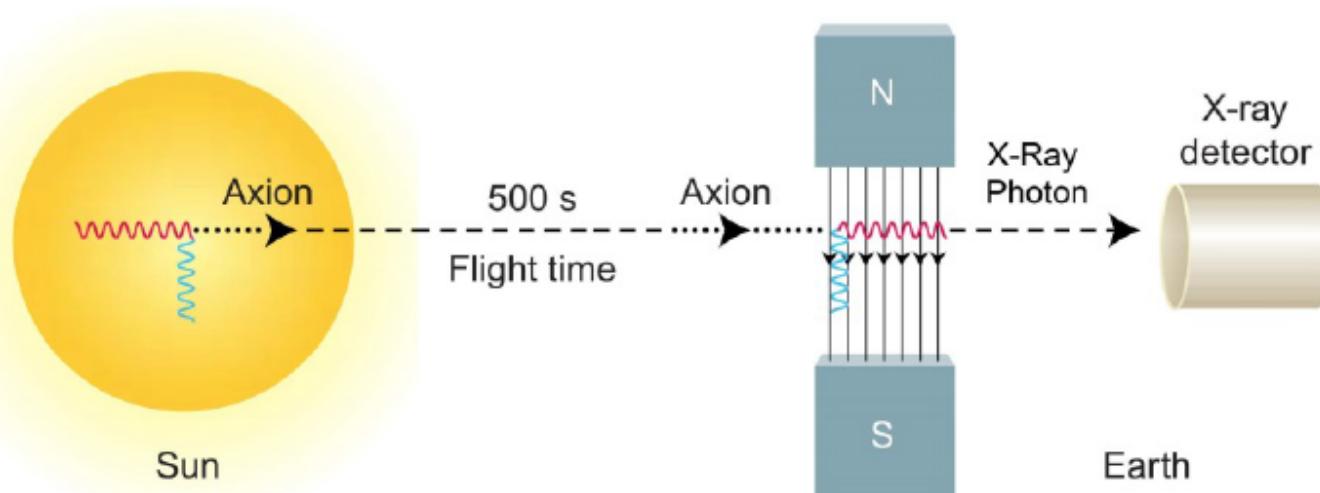


Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.



CAST: LHC prototype
magnet

Solar Axions

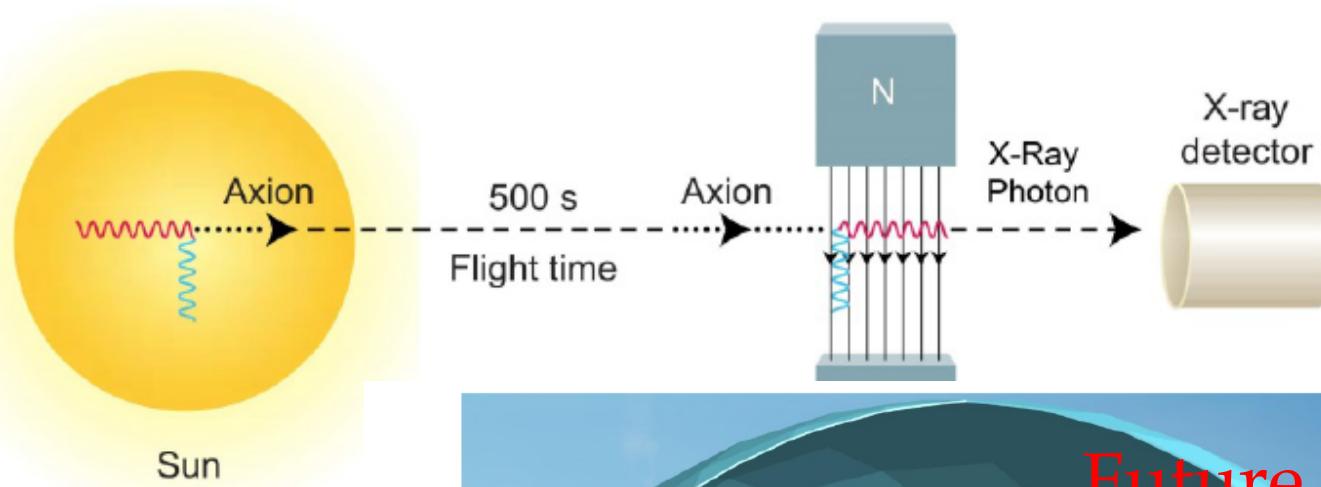


Fig. 9. The axion-helioscope concept. Axions a field in the haloscope (corresponding to the blt spectrum of the x-ray photons corresponds to

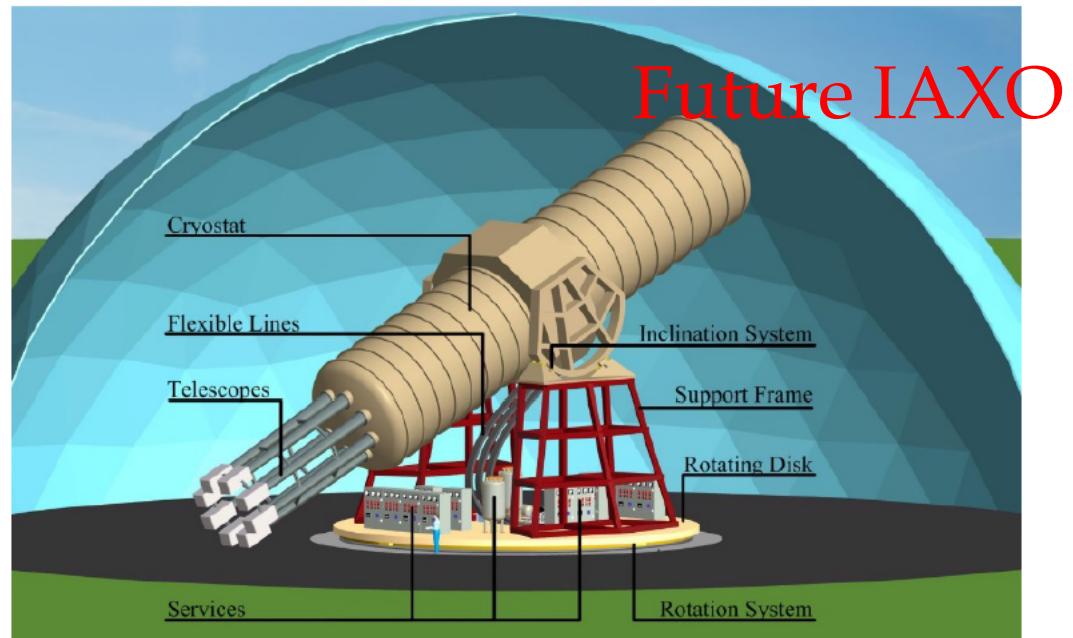
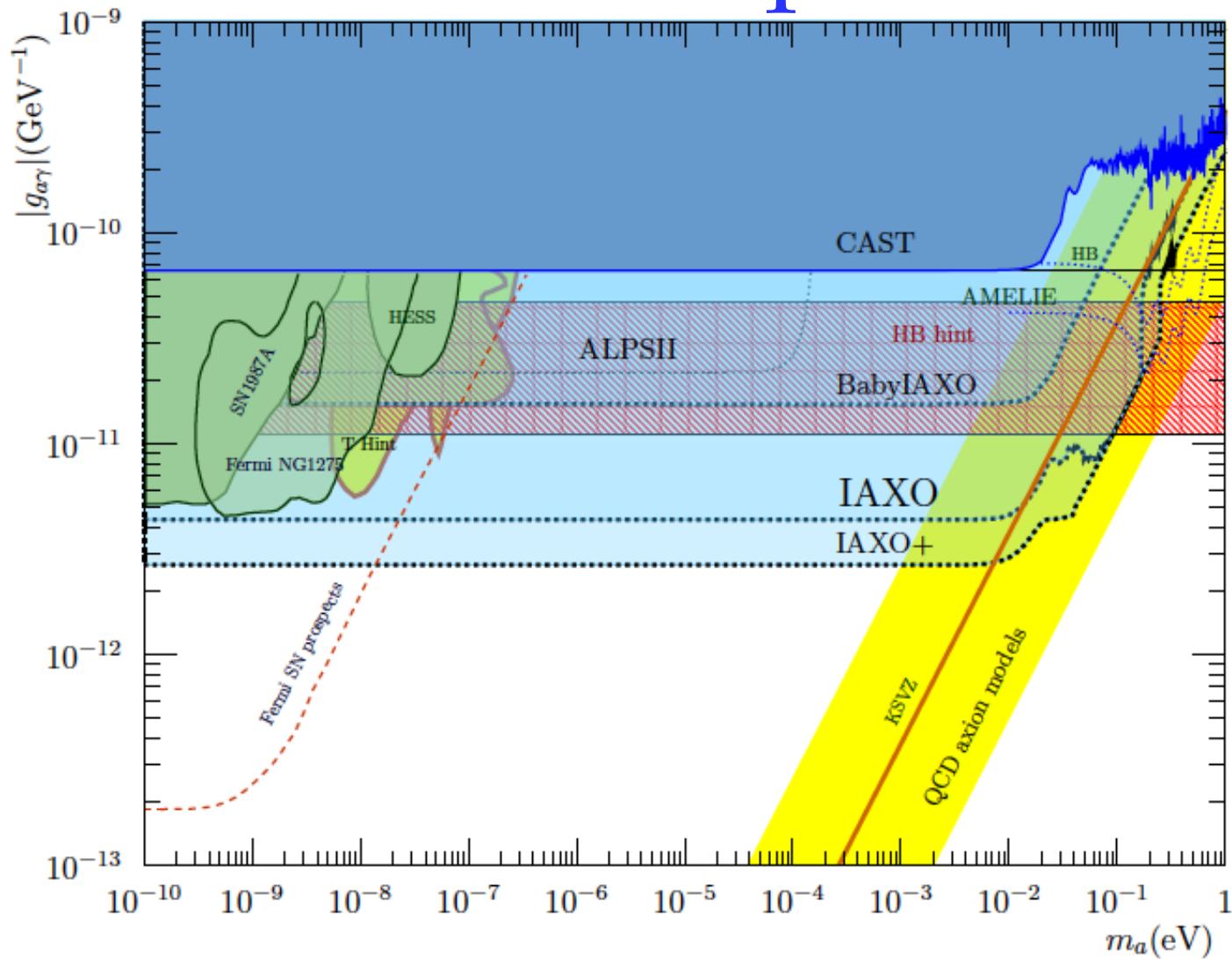
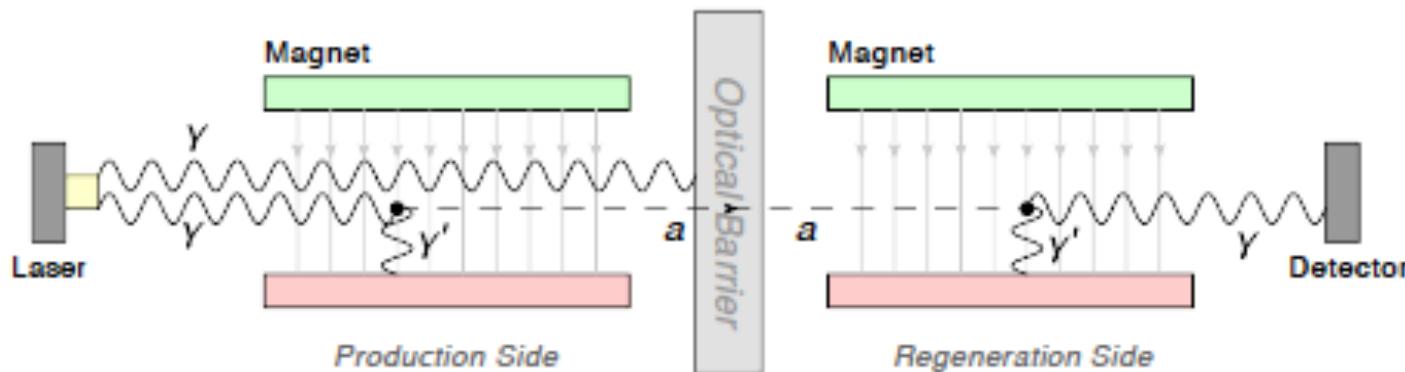


Fig. 10. General view of the IAXO design whose key part is a 22 m long eight-coil toroidal magnet enclosed in a 25 m long cryostat. Figure from [74].

CAST and planned axion Helioscopes



ALPS



$$P_{\gamma \rightarrow a \rightarrow \gamma} = \frac{1}{16} (g_{a\gamma\gamma} B L)^4 = 6 \cdot 10^{-38} \left(\frac{g_{a\gamma\gamma}}{10^{-10} \text{ GeV}^{-1}} \frac{B}{1 \text{ T}} \frac{L}{10 \text{ m}} \right)^4,$$

For sufficiently small
axion mass

Experiment	Reference	Photon energy [eV]	Laser power	Power buildup	Magnetic field strength B [T]	Magnetic field length L [m]	$(BL)^4$ [Tm] ⁴
ALPS	[66]	2.33	4 W	$P_p = 300$	5	4.3	$2 \cdot 10^5$
BRFT	[21]	2.47	3 W	$P_p = 100$	3.7	4.4	$7 \cdot 10^4$
BMV	[67]	1.17	$8 \cdot 10^{21} \gamma/\text{pulse}$ (14 pulses)	-	12.3	0.4	$6 \cdot 10^2$
GammeV	[68]	2.33	$4 \cdot 10^{17} \gamma/\text{pulse}$ (3600 pulses)	-	5	3	$6 \cdot 10^4$
OSQAR	[69]	2.33	18.5W	-	9	14.3	$3 \cdot 10^8$
ALPS-II	[70]	1.16	30W	$P_p = 5000$ $P_r = 40000$	5	100	$6 \cdot 10^{10}$
LSW with X-Rays	[71]	50200 90700	10mW 0.1 mW	-	3	0.150 and 0.097	0.017
LSW with Pulsed Magnets and Synchrotron X Rays	[72]	9500	46 mW	-	8.3 T and 5.7 T pulsed (duration 1ms)	0.8	10^3

Table 5. Overview of experimental parameters of previous and future LSW experiments: the photon energy, the initial laser power, the power-buildup in the production and regeneration side (P_p and P_r), as well as the magnetic field strength and length in production and regeneration sides (B_p , B_r , L_p , L_r). For all the cases, $B = B_p = B_r$ and $L = L_p = L_r$.

Light shining through walls

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma} [\text{GeV}^{-1}]$
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	$9.9 \times 10^{-8} (*)$
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a . For microwave LSW (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, see Figure 6

ALPS II at DESY, Start data taking 2020

ALPS II Optical System

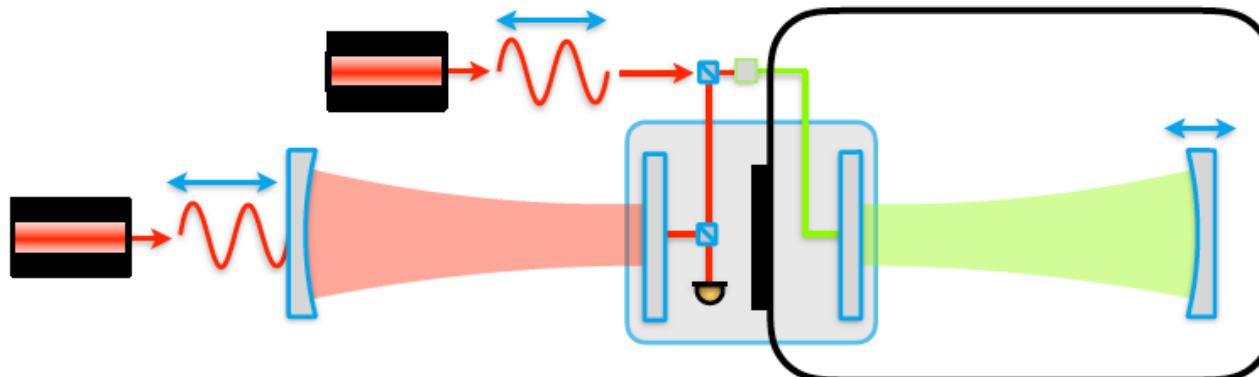
A unique set of challenges

Two 100m optical resonators

- 30 W amplified NPRO input laser
- PC: 150 kW circulating power
- RC: 120,000 finesse

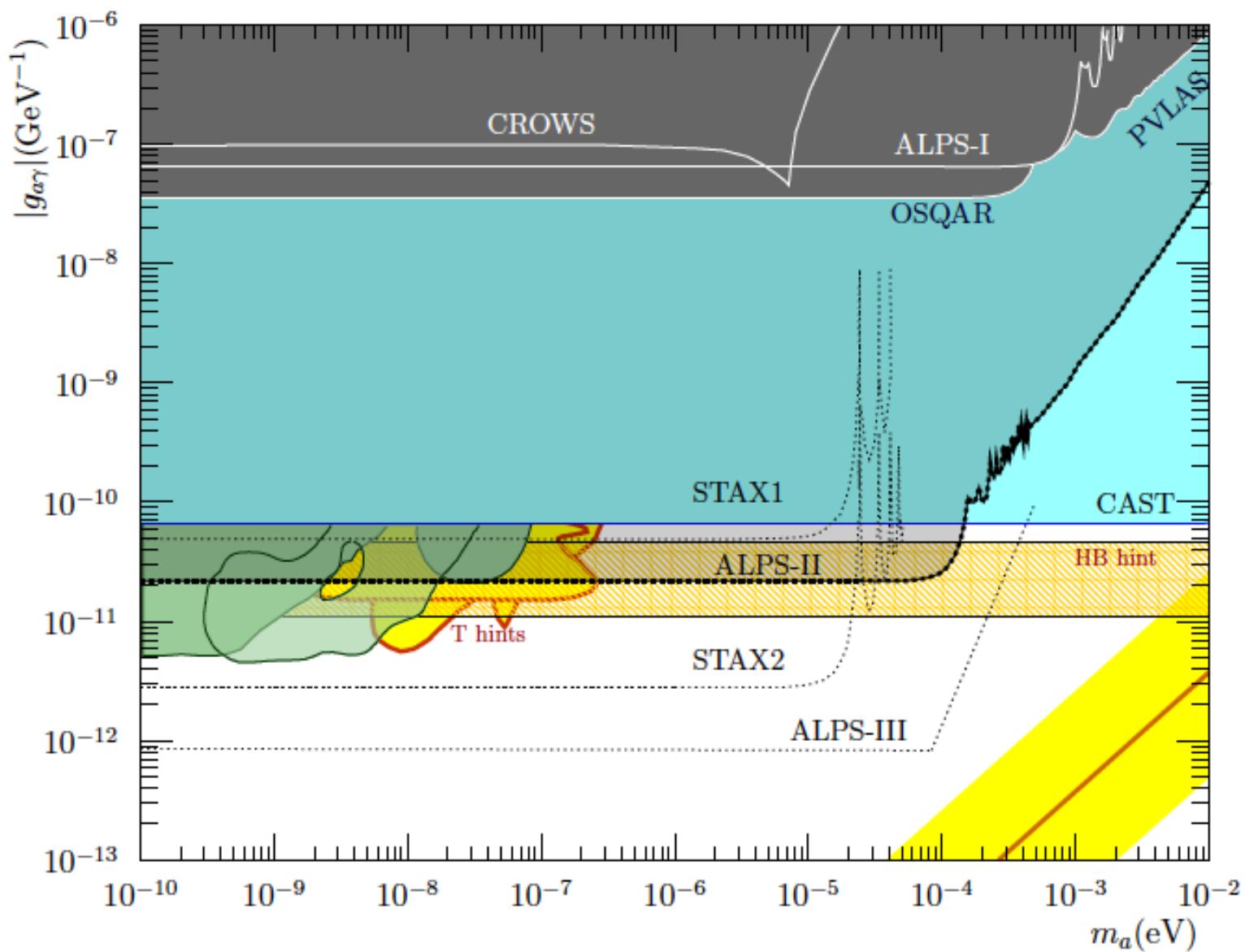
Challenges

- Maintenance of dual resonance
- Maintenance of spatial overlap
- Light tightness 1 photon / 2 weeks



ALPS

1801.08127v2



Axion dark matter: open resonators, MADMAX

1801.08127v2

Dielectrics for high frequency-short wavelength

Dielectrics to
suppress negative
E-field

Reverse direction
of B-field

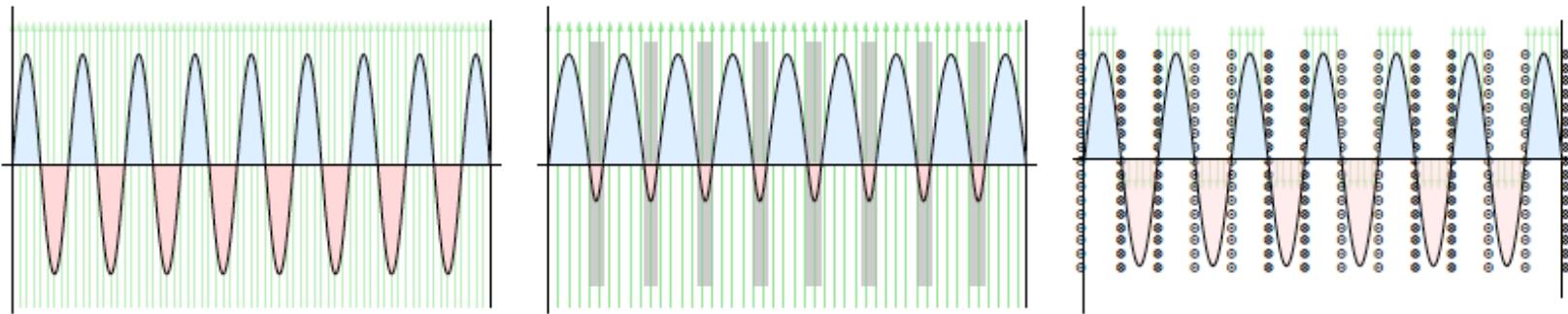
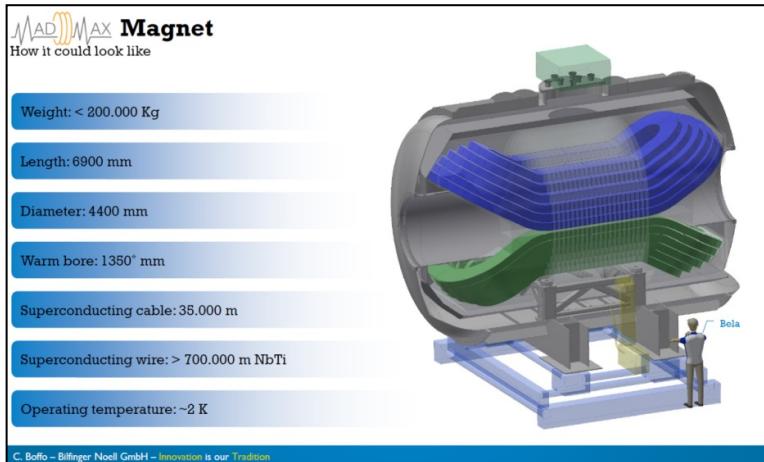


Figure 19: The geometric factor of an ideal 1D cavity in a homogeneous B -field (green arrows) cancels between crests and valleys of a high mode (left). The cancellation can be avoided by placing high- n dielectrics –grey regions– in the valleys (centre) or by alternating the polarity of the external B_e field to track the mode variations (right). This case can be done by introducing wire planes with suitable currents [563].

MADMAX: Physics at the interface

MADMAX - search for dark matter axions



MADMAX (dark matter)

- Site in HERA hall north being prepared
- Magnet studies by Bilfinger-Noell and CEA Saclay, aim for magnet decision in late 2018

MADMAX collaboration

- Founded at DESY in 2017

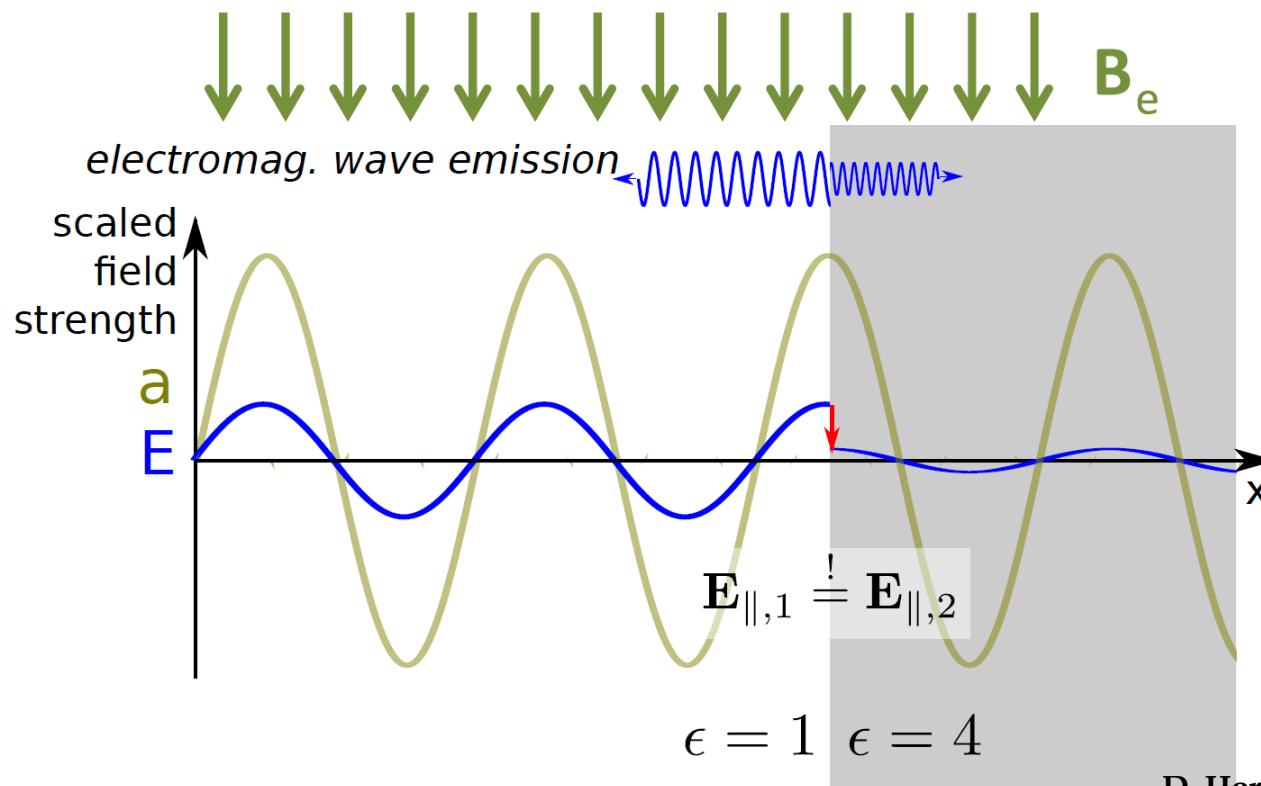
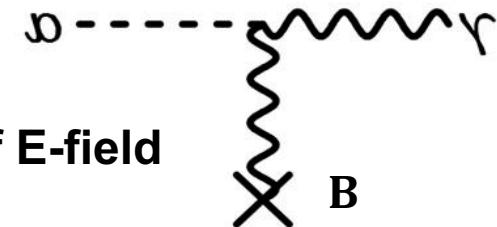
Experimental approaches: Effect of Dielectric

Mixing of axion with photon in extremal B-field

→ Sources oscillating E-field

At surfaces with transition of ϵ : Discontinuity of E-field

→ Emission of photons



$$\left(\frac{P}{A}\right)_{\text{mirror}} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{\parallel}}{10 T}\right)^2 (g_{a\gamma\gamma} m_a)^2$$

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald
JCAP 1304 (2013) 016
[arXiv:1212.2970].

Axion dark matter: MADMAX

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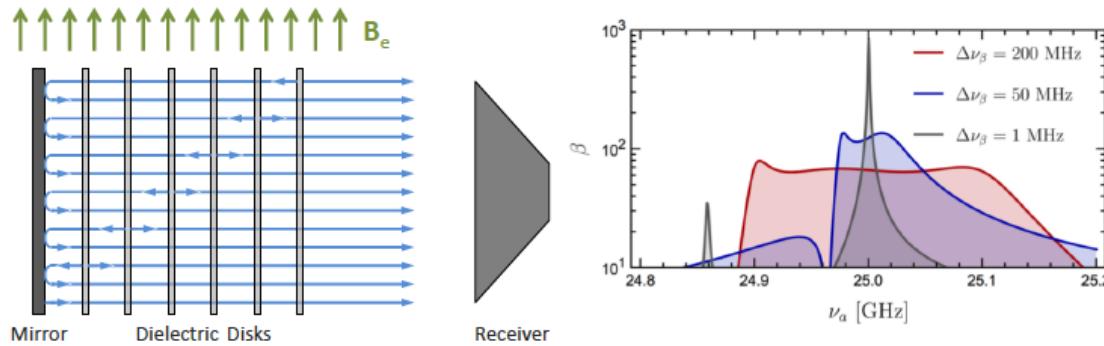


Figure 21: Left: sketch of the dielectric haloscope experiment. Photons in the B_e field are emitted from the dielectric surfaces and reflected in the leftmost mirror and other surfaces to be measured coherently by a receiver, from [585]. Right: Adjusting the distances between the layers, the frequency dependence of the boosted sensitivity can be adjusted to different bandwidths, from [590].

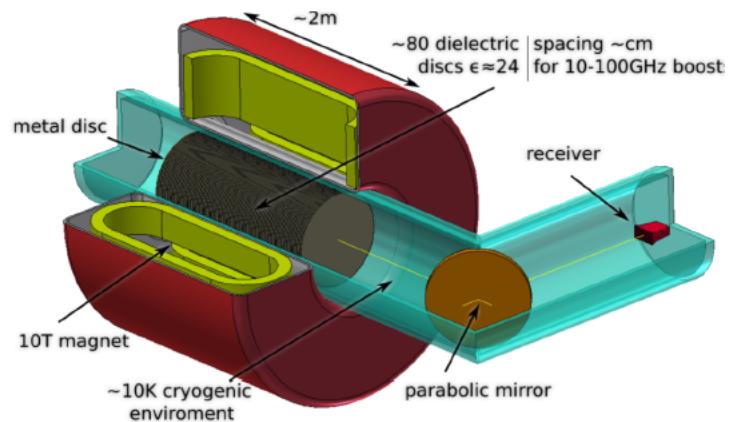
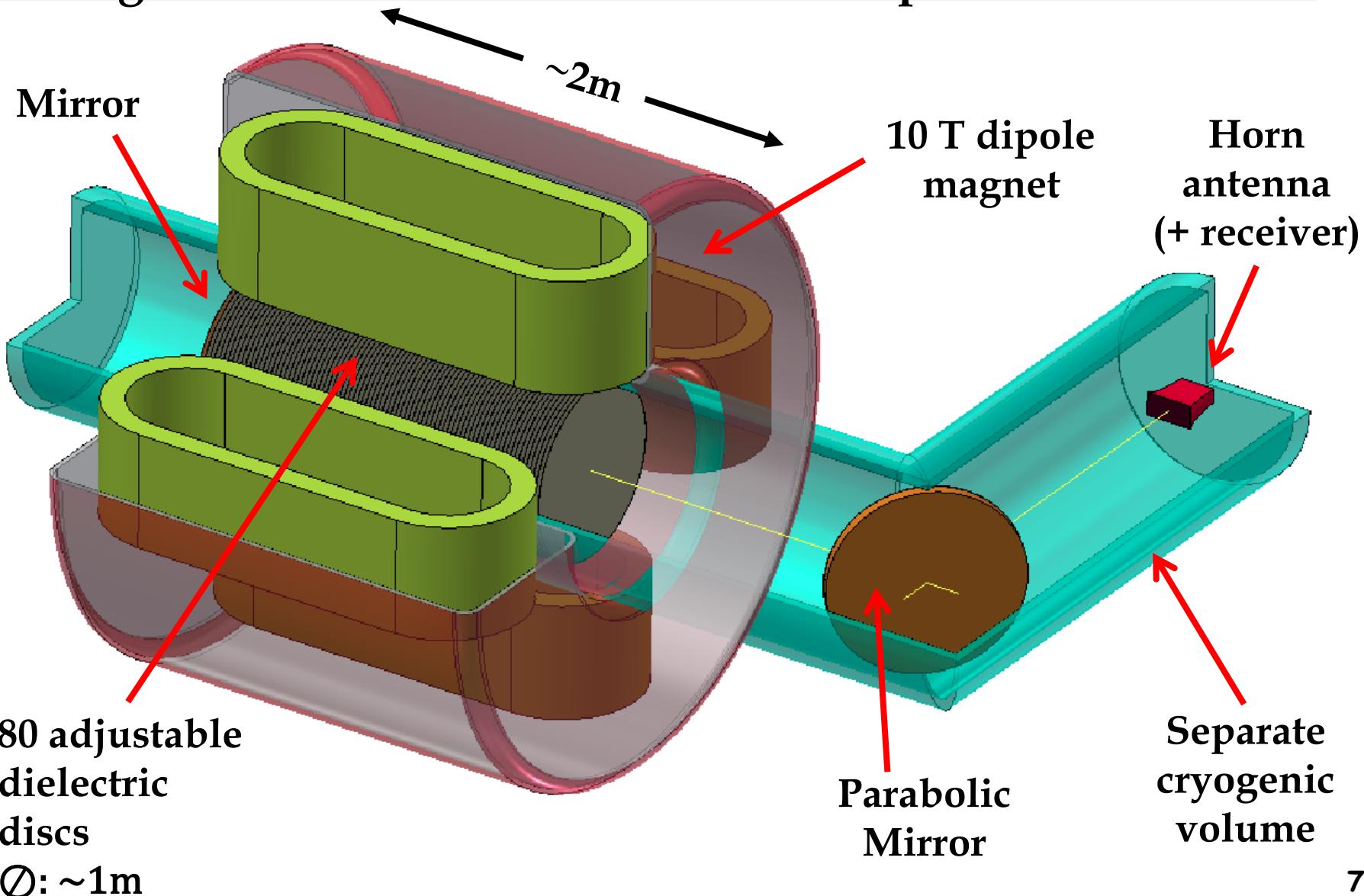
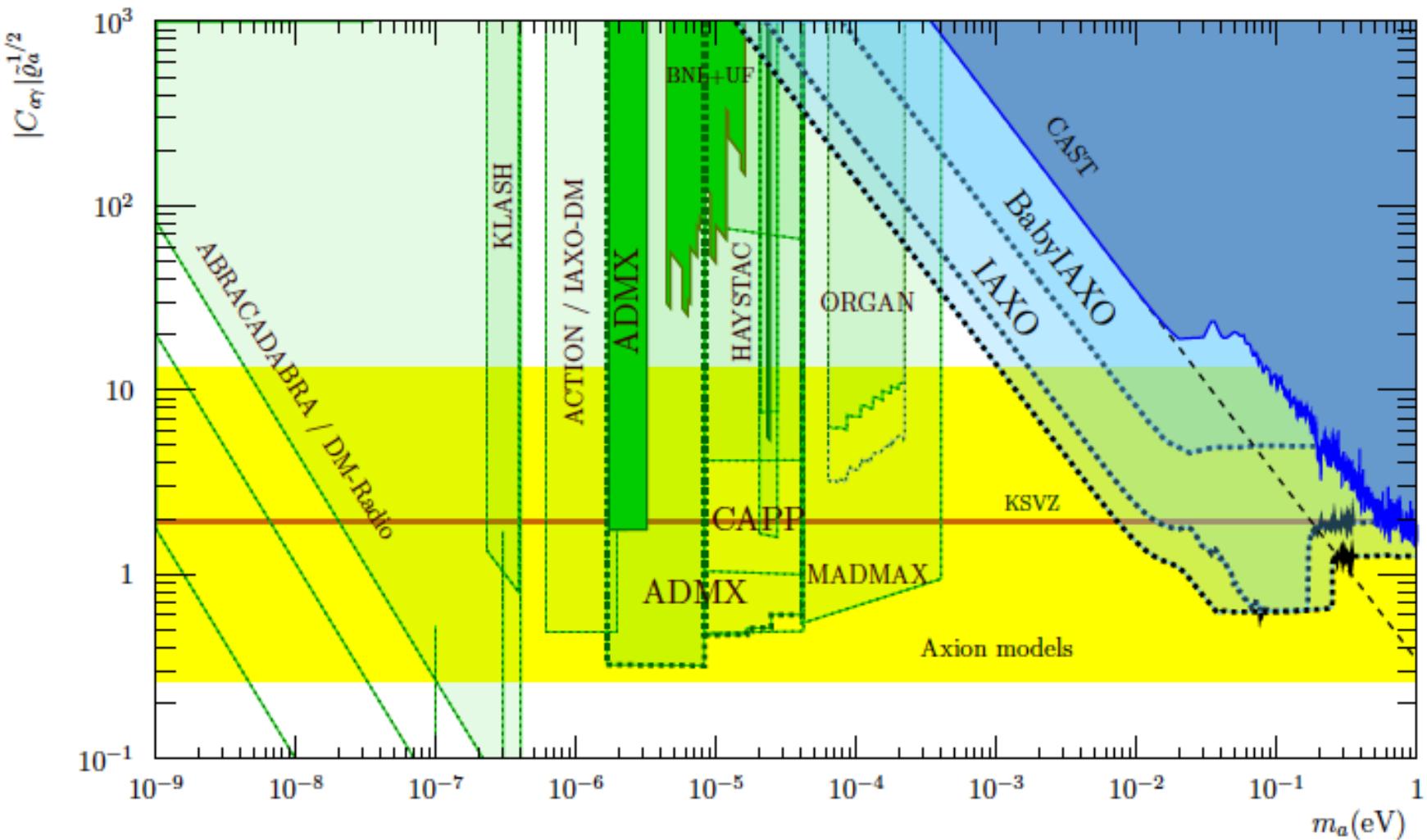


Figure 22: The concept of the MADMAX experiment, see text for details. From [590].

Magnetized Disc and Mirror Axion eXperiment



Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

L_{ight}

A_{xion}

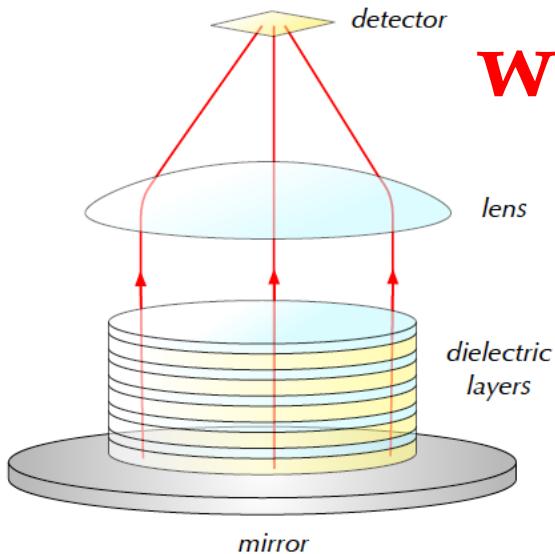
M_{ultilayer}

P_{eriodic}

O_{ptical}

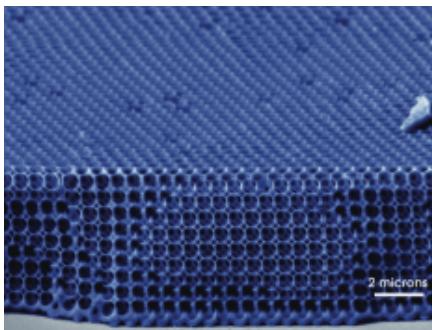
S_{canning}

T_{argets}



Optical range with photonic crystals

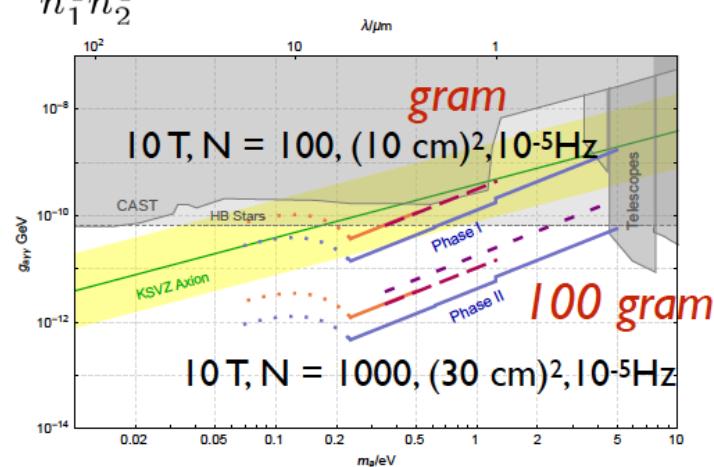
J. Huang, Perimeter Institute
1803.11455



- Axion-photon coupling $g_{a\gamma\gamma} a E \cdot B$ requires background magnetic field
- Existing constraints stronger; need larger target / better detectors

$$8g^2 B_0^2 \frac{\rho_{\text{DM}}}{m_0^2} AN^2 \frac{(n_1^2 - n_2^2)^2}{n_1^4 n_2^4}$$

1 week run time



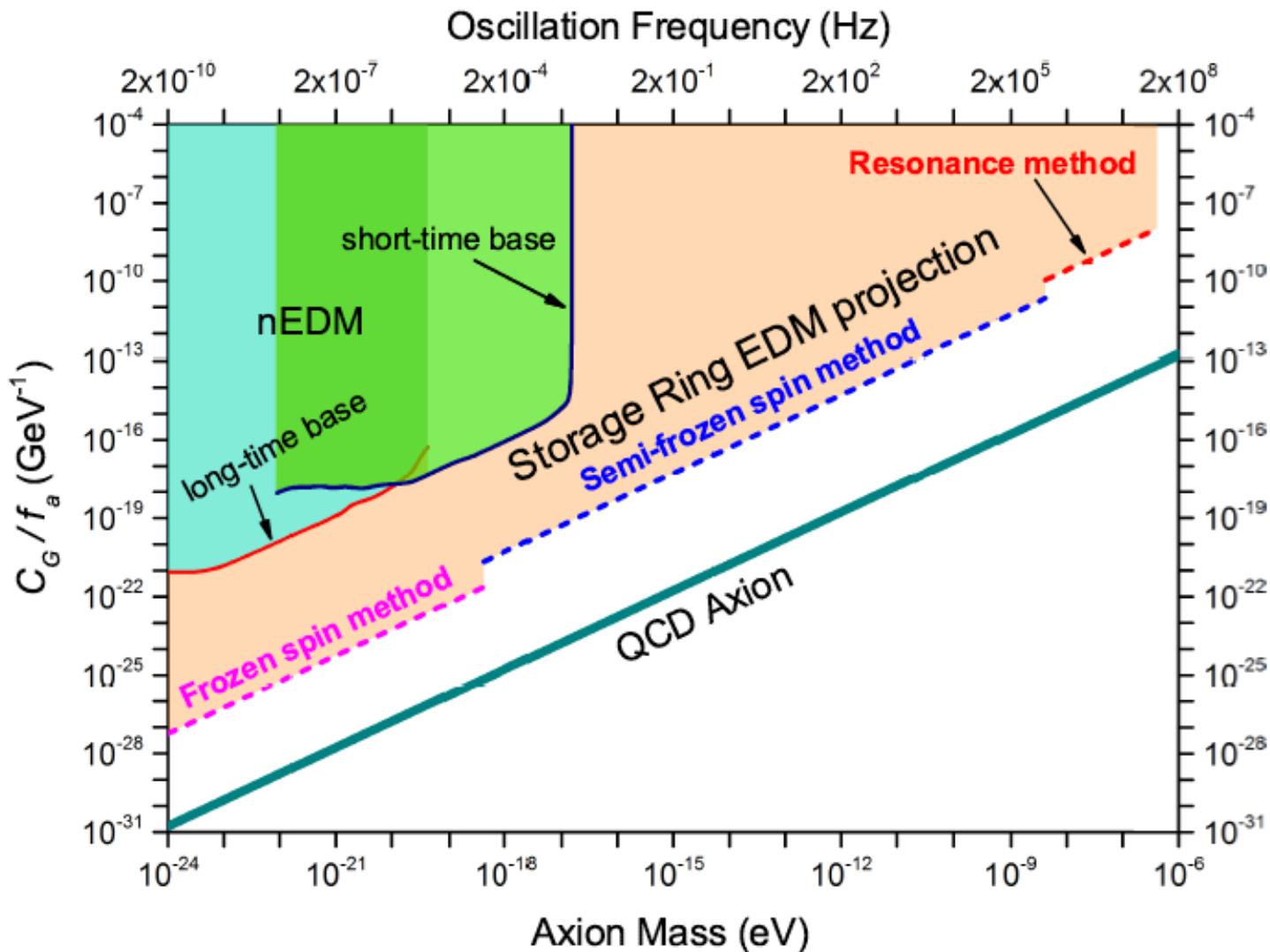
Sub-component of DM

Summary

- Axion-dark-matter efforts are becoming very exciting
- A discovery can be announced at any moment (depending on the frequency number!)
- Within the next five to ten years we may very well know whether axions are 100% of the dark matter...

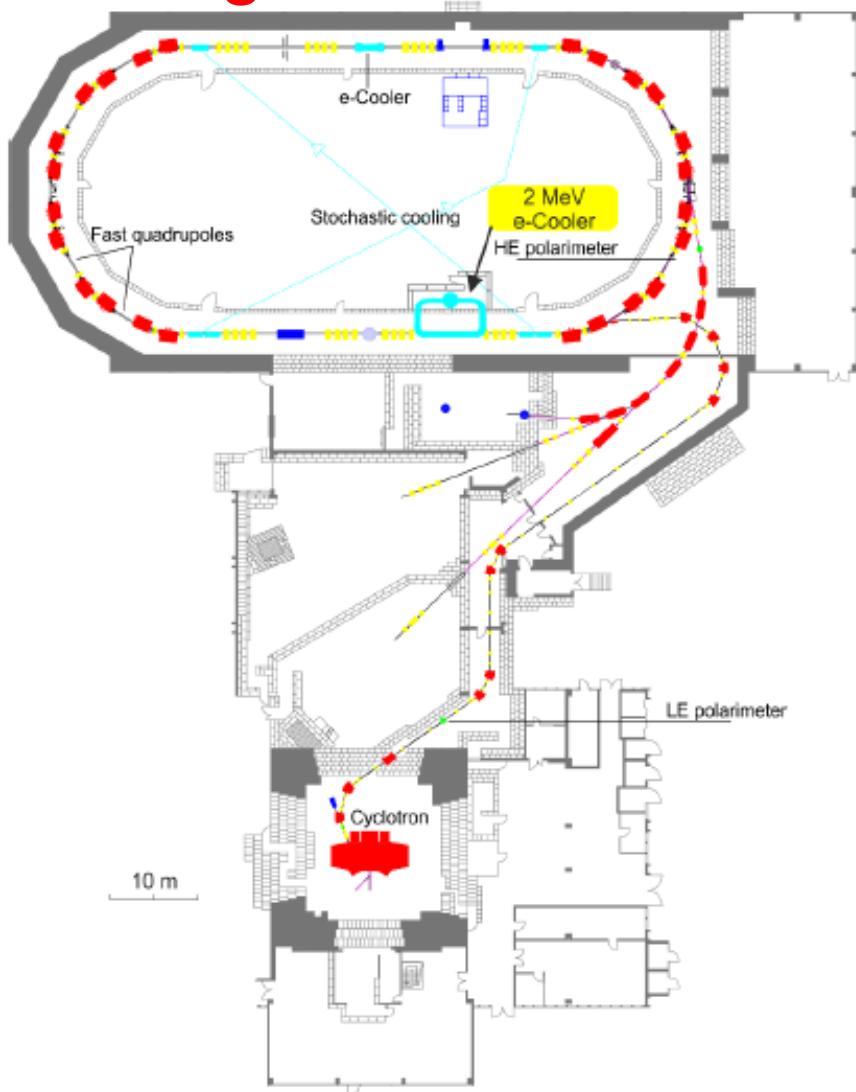
Extra Slides

Projected, preliminary



De Broglie wavelength $> 1\text{km}$, whole ring within axion-field coherence

The right machine for the resonance method!



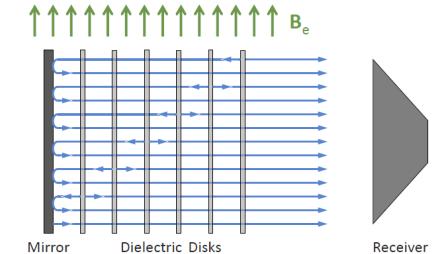
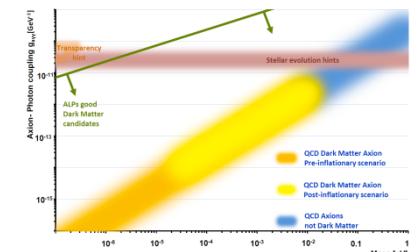
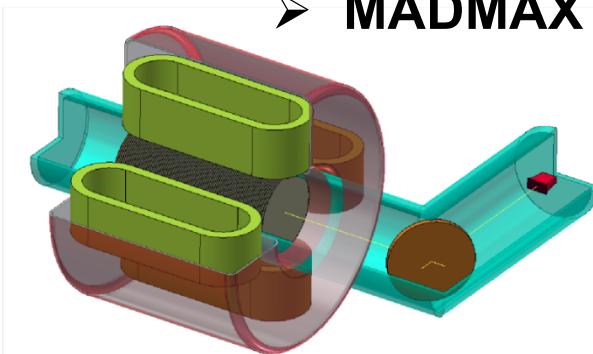
- **184 m circumference**
- **Protons and Deuterons**
- **Polarized or un-polarized**
- **p: 295 MeV/c - 3,65 GeV/c**
- **Stochastic and electron cooling**
- **2 e⁻ cooler: 100 keV and 2 MeV**
- **Typ. amount of stored particles: 10^{10}**
- **Internal experiments and 3 external beam lines**
- **H⁻ stripping injection**



A new road to axion dark matter detection?

Béla Majorovits (MPI für Physik)
for the  collaboration

- Axions and ALPs as DM candidates
- The axion detection method
- Dielectric haloscope
- MADMAX status and plans





Collaboration forming at DESY, Hamburg



**8 Institutes from France,
Germany, Spain
Site: DESY Hamburg,
hall north**



David Tanner

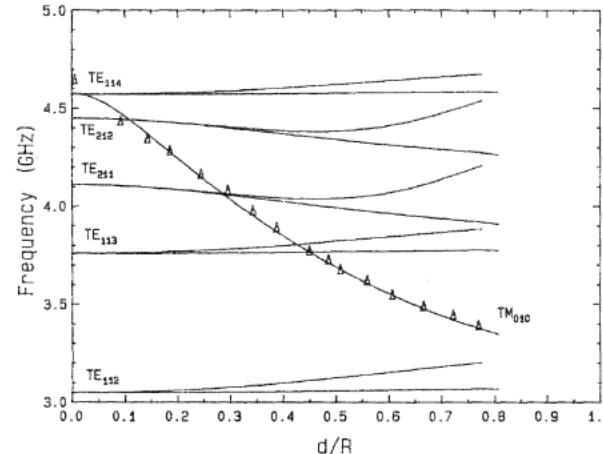
Strawman: Single cavity

- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130 \text{ yW} \left(\frac{1 \text{ GHz}}{f} \right)^{2.67}$$

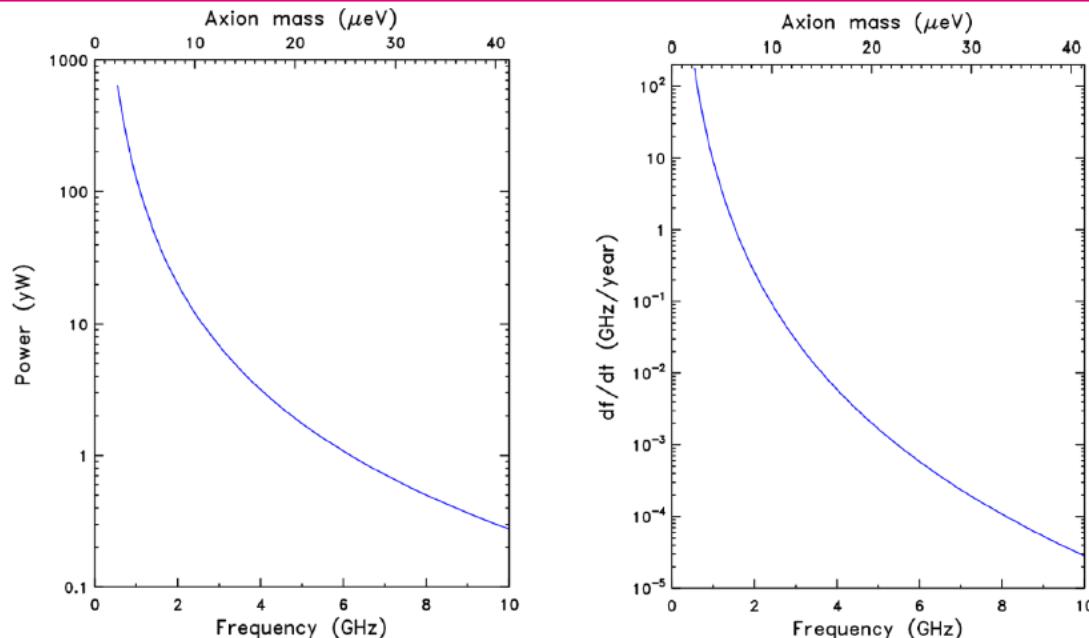
- Volume decreases as f^{-3} , the Q decreases as $f^{-2/3}$ while the mass increases as f
- Length as well as diameter changes because the cavity cannot get too long
 - The longer the cavity, the more TE/TEM modes there are
 - Typically:

$$L \sim 4.4r$$



David Tanner

Strawman 2: Single cavity



- Power and scan rate decrease as frequency goes up 😞
- Just the opposite of what we want.

KLASH

THE KLASH PROPOSAL

arXiv:1707.06010 (Alesini, Babusci, Di Gioacchino, Gatti, Lamanna, Ligi)

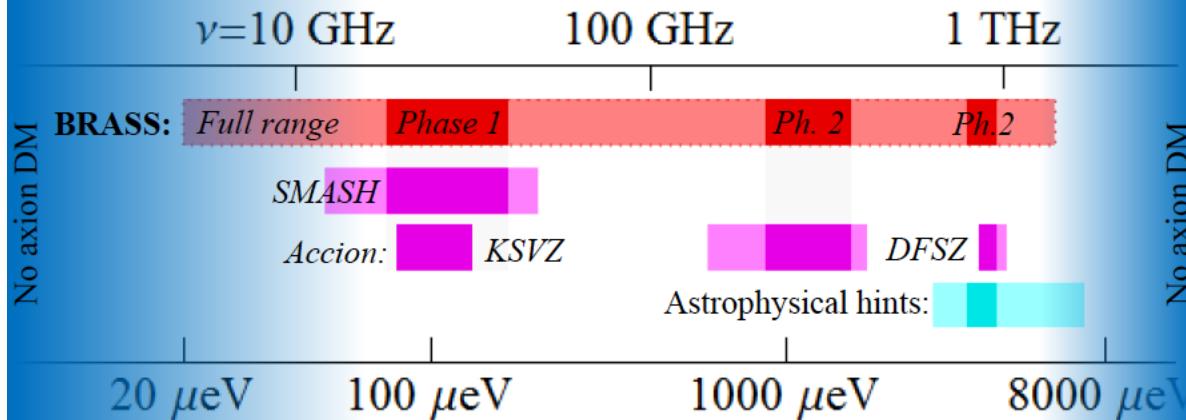
- KLASH - KLoe magnet for Axions SearchH
- Proposal of a large Haloscope
- Search of galactic axions in the mass range 0.3-1 μeV
- Large volume RF Cavity (35 m^3)
- Moderate magnetic field (0.6 T)
- Copper rf cavity $Q \sim 600,000$
- T 4.2 K

$$P_{\text{sig}} = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left(\frac{\beta}{1 + \beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnL} Q_L \right)$$

$$SNR = \frac{P_{\text{sig}}}{k_B T_{\text{sys}}} \sqrt{\frac{\tau}{\Delta\nu_a}}$$

Experiment	$\omega B^2 V Q (\text{rad T}^2 \text{m}^3/\text{s}) (\times 10^{15})$
The KLASH	1
ADMX	4
HAYSTAC	0.5

BRASS: **Broadband Radiometric Axion/ALP** **Searches**



D. Horns¹, P. Freire², E. Garutti¹, A. Jacob³, M. Kramer¹, A.P. Lobanov^{1,2},
K. Menten², J. Liske¹, L.H. Nguyen¹, A. Ringwald⁴, G. Sigl¹, J.A. Zensus²

1 – University of Hamburg. 2 – Max-Planck Institute for Radioastronomy, Bonn.
3 – Hamburg University of Technology. 4 – Deutsches Elektronen Synchrotron (DESY).

Superconducting materials

Material Name	Class	Critical Temperature (K)	Critical Field B_{c2}	Critical Field@2.2 K	Geometry
NbTi	LTS	9.8	9.5 T @ 4.2 K	11.5 T	Multi-filamentary round & rectangular wire
Nb ₃ Sn	LTS	18.1	20 T @ 4.2 K	23 T	Multi-filamentary round wire
MgB ₂	MTS	39	5–10 T @ 4.2 K 1–3 T @ 10 K	N/A	Multi-filamentary round wire
Bi–2212	HTS	90–110	40 T @ 4.2 K 10 T @ 12 K	N/A	Multi-filamentary round wire
Bi–2213	HTS	90–110	40 T @ 4.2 K 8 T @ 20 K 4 T @ 65 K	N/A	Tape
YBCO	HTS	92–135	45 T @ 4.2 K 12 T @ 20 K 8 T @ 65 K	N/A	Tape

Table 8. Superconducting materials. LTS, MTS, and HTS stand for low-, medium-, and hight-temperature superconductors. N/A means that these materials as are typically not used below 4.2 K. They can operate at lower temperatures but without particular advantage.

Superconducting materials

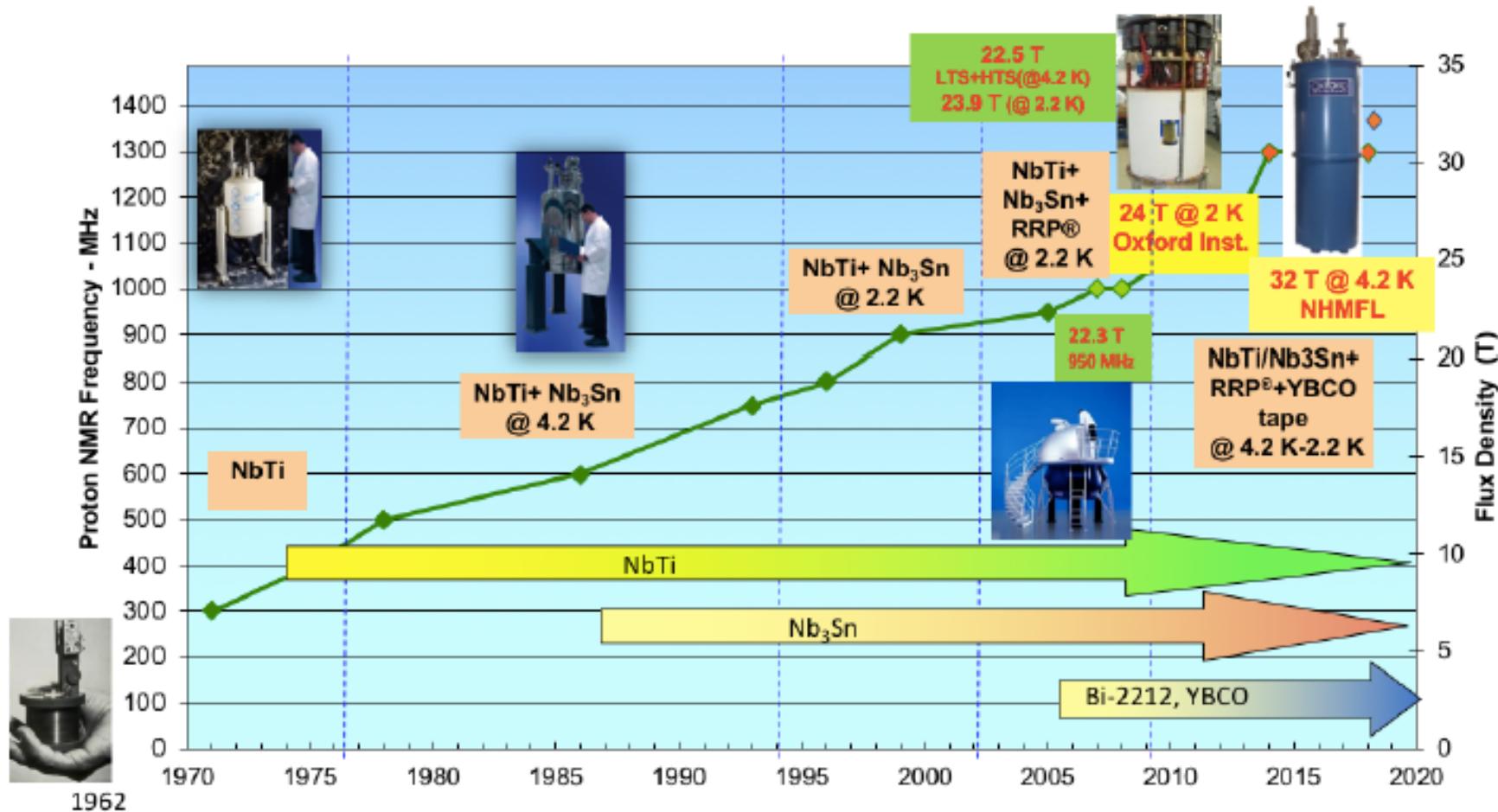


Fig. 22. Solenoid magnets for NMR as a representative example of the progress in magnet technology. NHMFL: National High Magnetic Field Laboratory, Tallahassee, Florida.

Superconducting materials

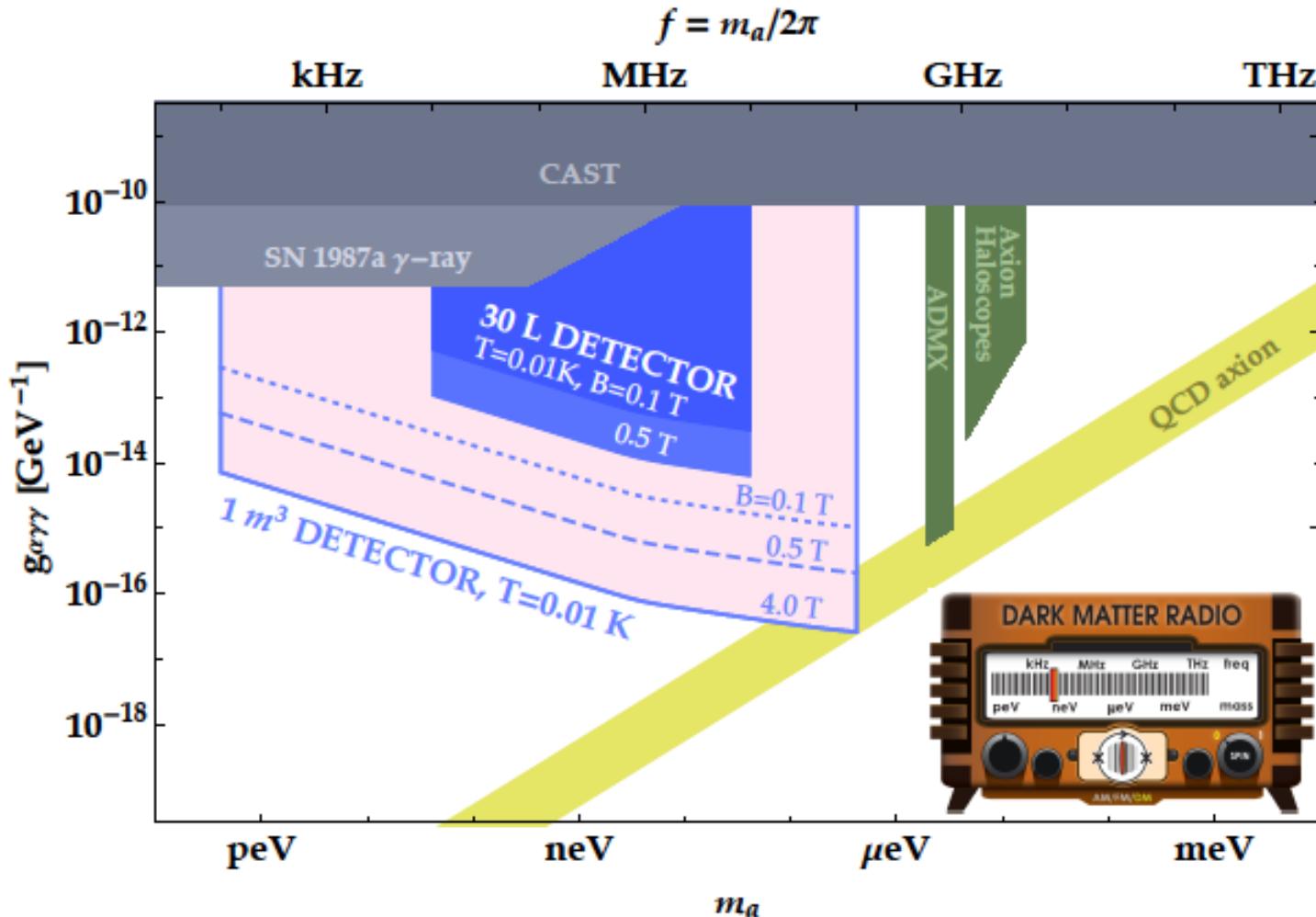
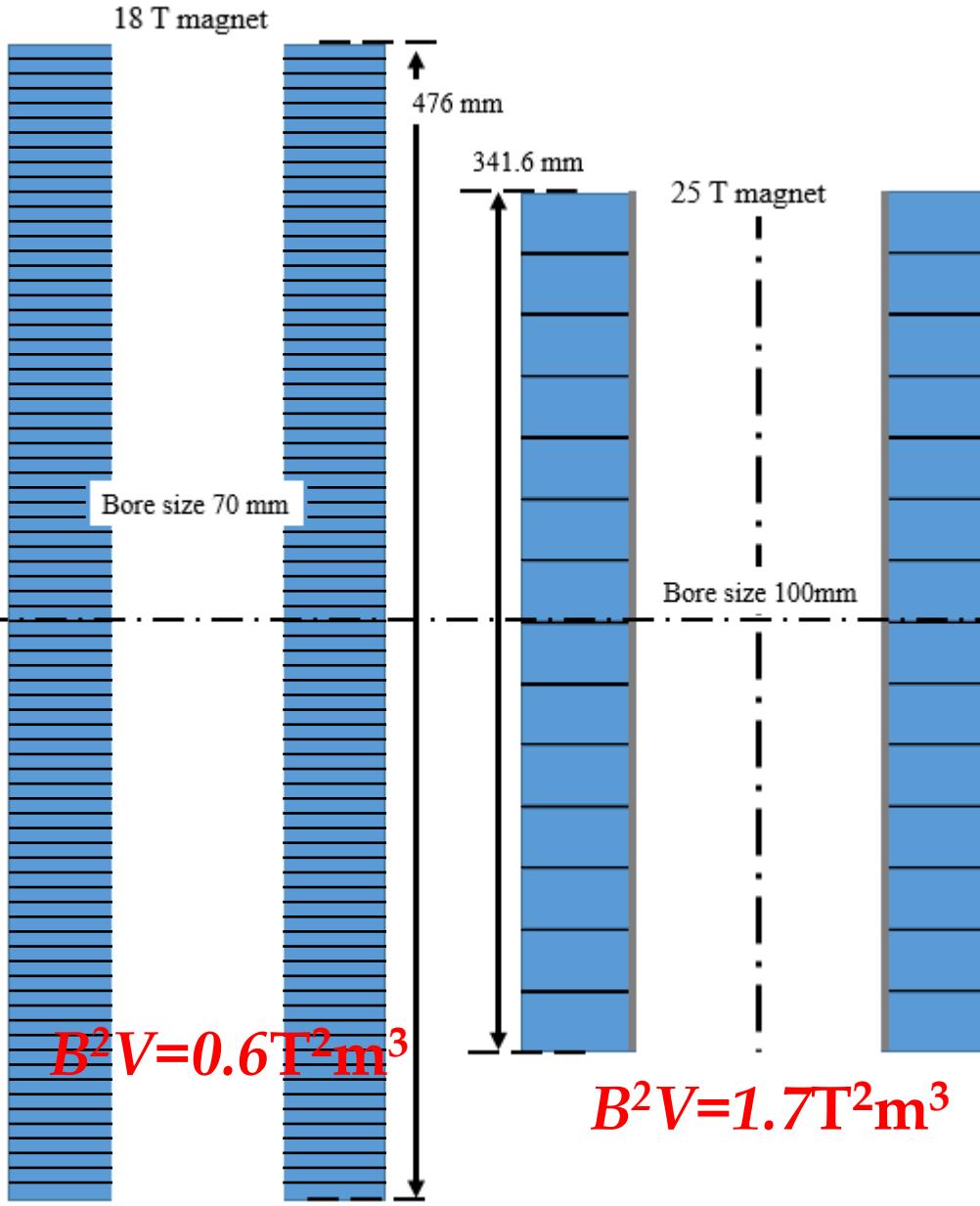
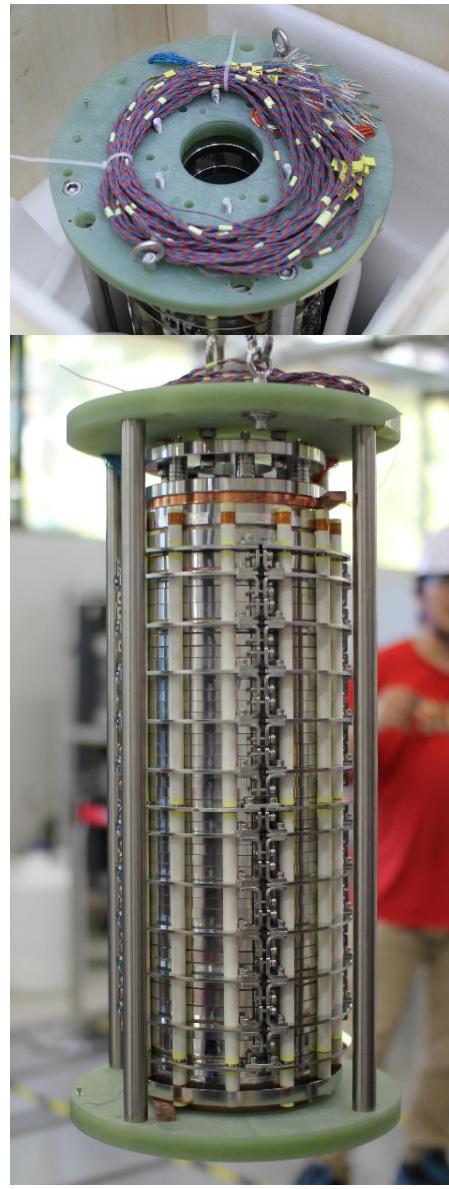


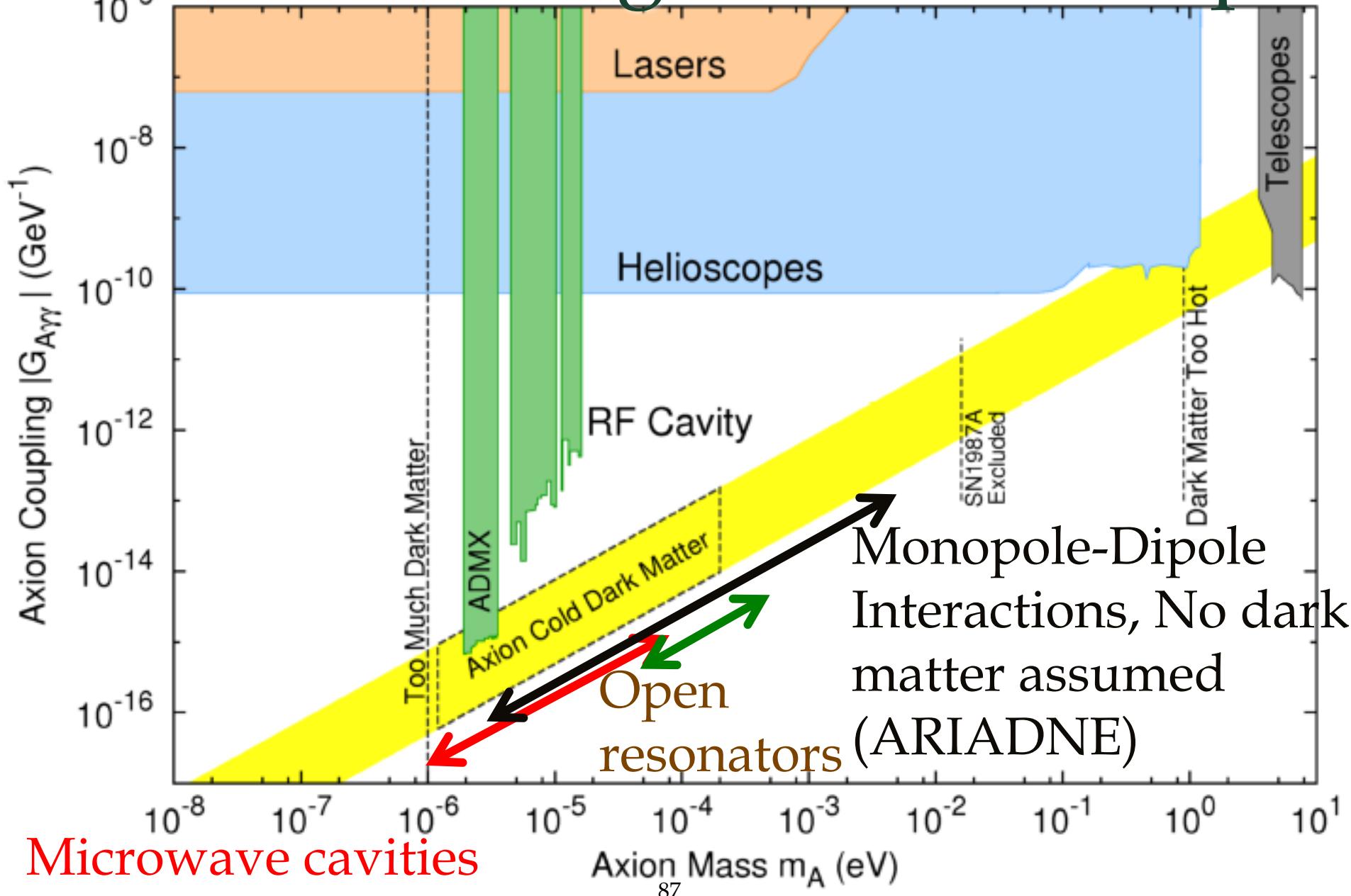
Fig. 14. Projected sensitivity of various stages of the Dark Matter radio (DM radio) experiment to axion-photon coupling. The inset at the lower right shows an emblem of the experiment accurately capturing some of the essential features. Figure courtesy DM radio collaboration.

18 T no insulation magnet



1st coil
for 25 T magnet
1/28

Axion mass target and technique



CASPER-Electric, CASPER-Wind

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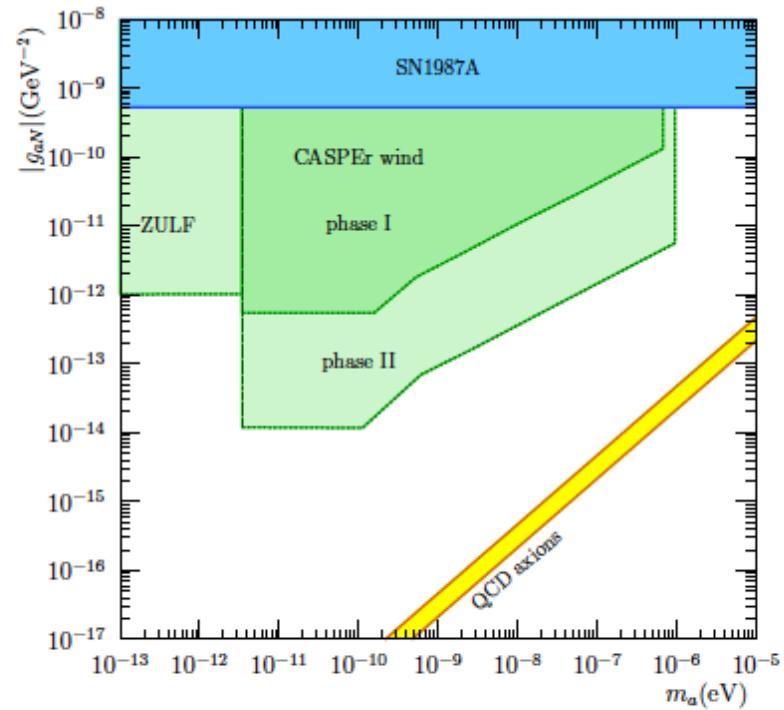
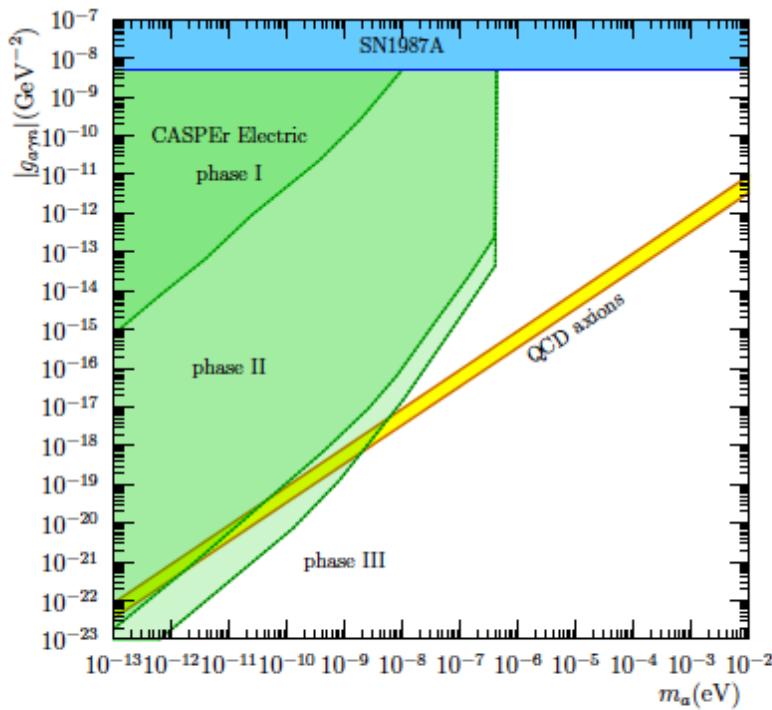
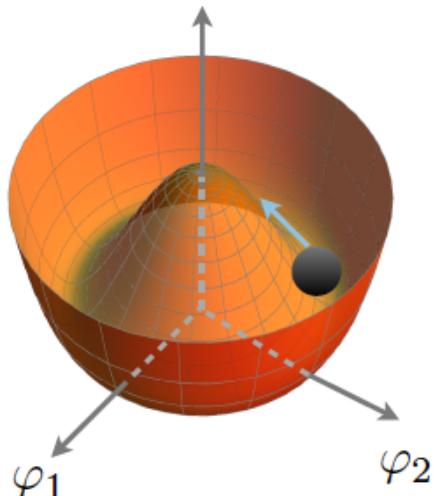


Figure 24: Left: limits on $g_{a\gamma n}$ and prospects for CASPER-Electric. Right: Limits on g_{aN} and prospects of CASPER “wind” experiments. From [600].

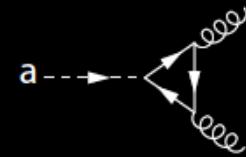
Daniel Grin, Patras2018 workshop

WHAT ARE AXIONS?

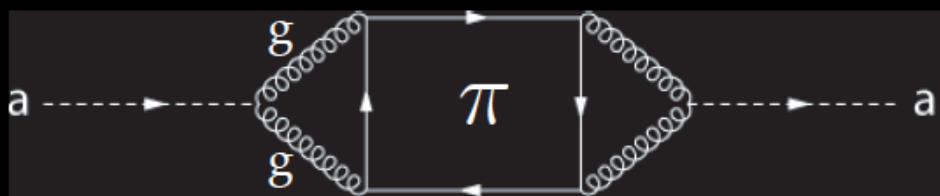


New scalar field with global $U(1)$ symmetry!

$$\mathcal{L}_{\text{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_a} g^2 G\tilde{G}$$



- * Couples to SM gauge fields (via fermions)
- * Dynamically erases QCD CP-violation
- * Mass through pion mixing



Peccei + Quinn (1977), Weinberg + Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)