Small Scale experiments for fundamental physics

ICTP Summer School on Particle Physics, June 12-15

Part 3

A. Geraci, University of Nevada, Reno

Syllabus

- Introduction
- New (scalar) forces
- Gravitational Waves and Ultralight Dark Matter
- New (spin-dependent) forces

(relation to axions, EDMS, Cosmic DM experiments)

Ultralight field DM (cont'd)

Spin	Type	Operator	Interaction	Oscillating DM Effects	Searches
0	scalar	$\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$	Higgs portal / dilaton	m_e, m_p, α variation	Atomic clocks [51]
				acceleration	$\star$
	pseudo-scalar	$a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$	axion-QCD	nucleon EDM	CASPEr [18]
		$a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$	axion-E&M	EMF along B field	ADMX [13]
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	axion-fermion	spin torque	CASPEr [18]
1	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	minimally coupled	acceleration	$\star$
		$F'_{\mu\nu}F^{\mu\nu}$	vector–photon mixing	EMF in vacuum	DM Radio [32], ADMX
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole operator	spin torque	CASPEr [18]
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	minimally coupled	spin torque	CASPEr [18]
2 (?)	tensor	$h'_{\mu\nu}T^{\mu\nu}$ (?)	gravity-like	grav. wave-like	grav. wave detectors?

Arxiv: 1512.06165(2015)

Axions

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP problem $\theta_{QCD} < 10^{-10}$
- Dark matter candidate

Experiments: e.g. ADMX, CAST, LC circuit, Casper

- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978);
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

Axion couplings

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$ ← Coupling to electromagnetic field

ADMX, DM Radio, LC Circuit

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ ← Coupling to gluon field

CASPEr Electric

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$ ← Coupling to fermions

CASPEr Wind, QUAX

Axion mass

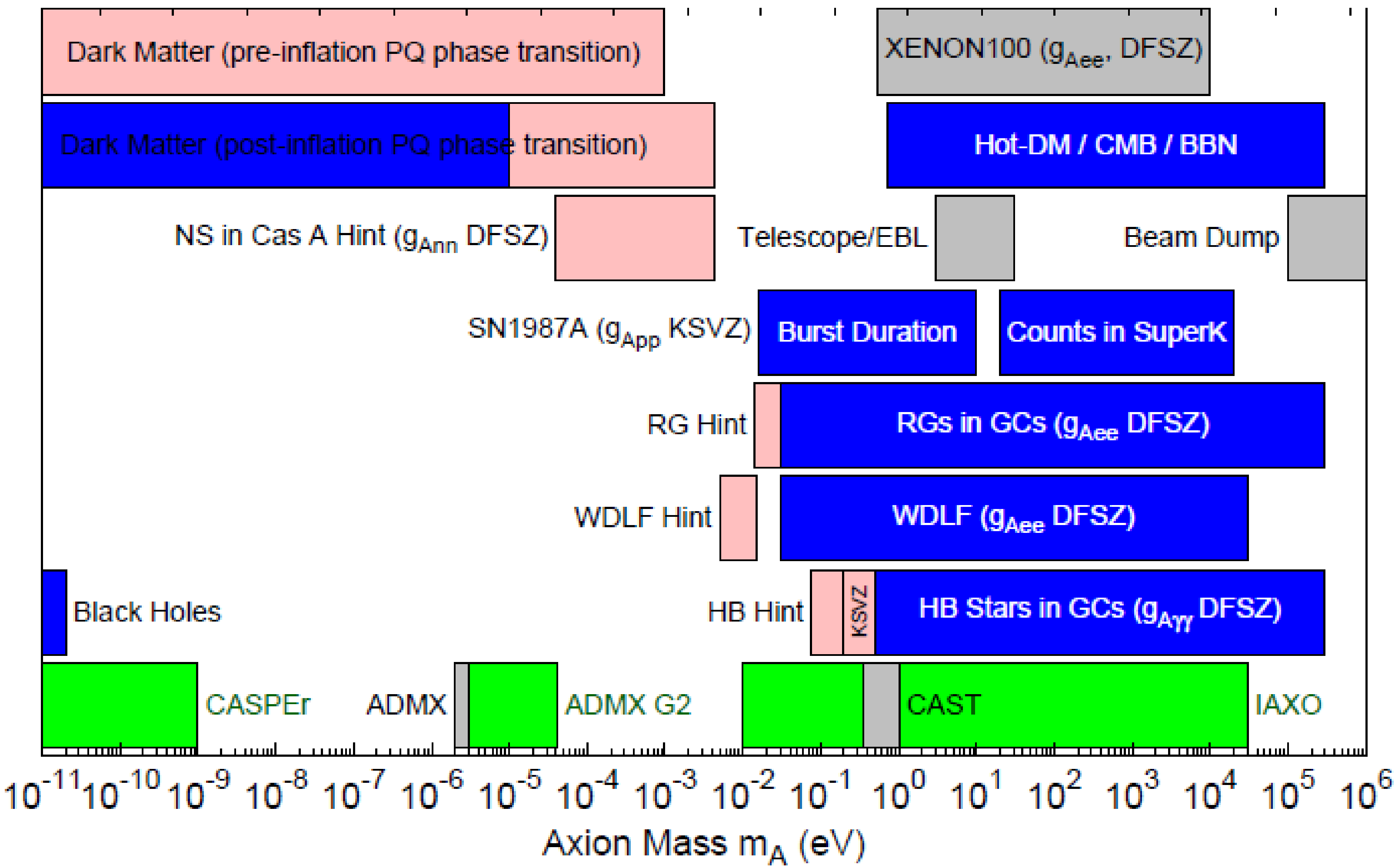
The QCD axion mass is given by:

$$m_a \sim \frac{{\Lambda_{\rm QCD}}^2}{f_a} \; .$$

$\Lambda_{\rm QCD}$ ~ 200 MeV is the QCD confinement scale.

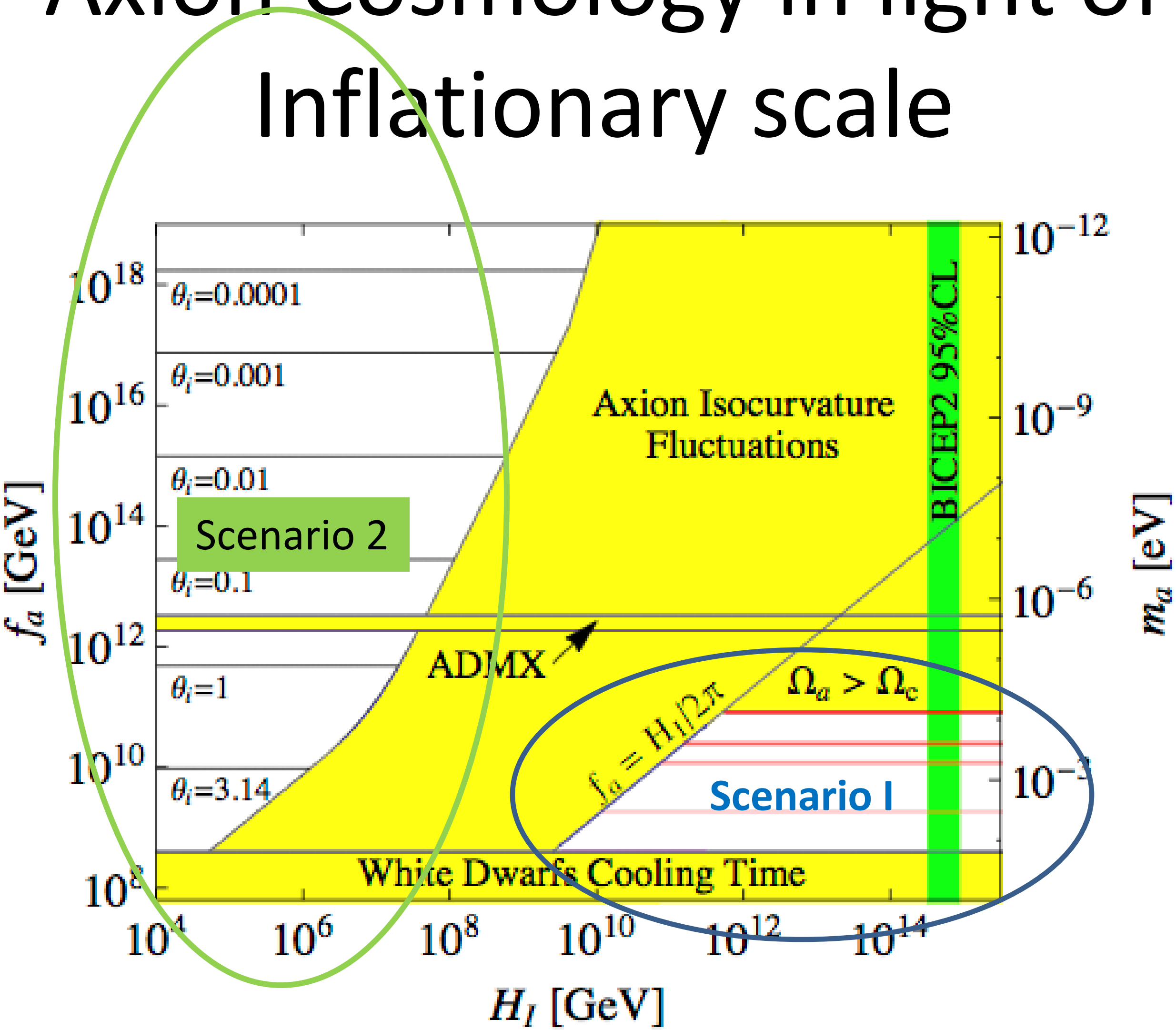
ALPs may have different Λ and f.

QCD Axion parameter space



Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion Cosmology in light of Inflationary scale



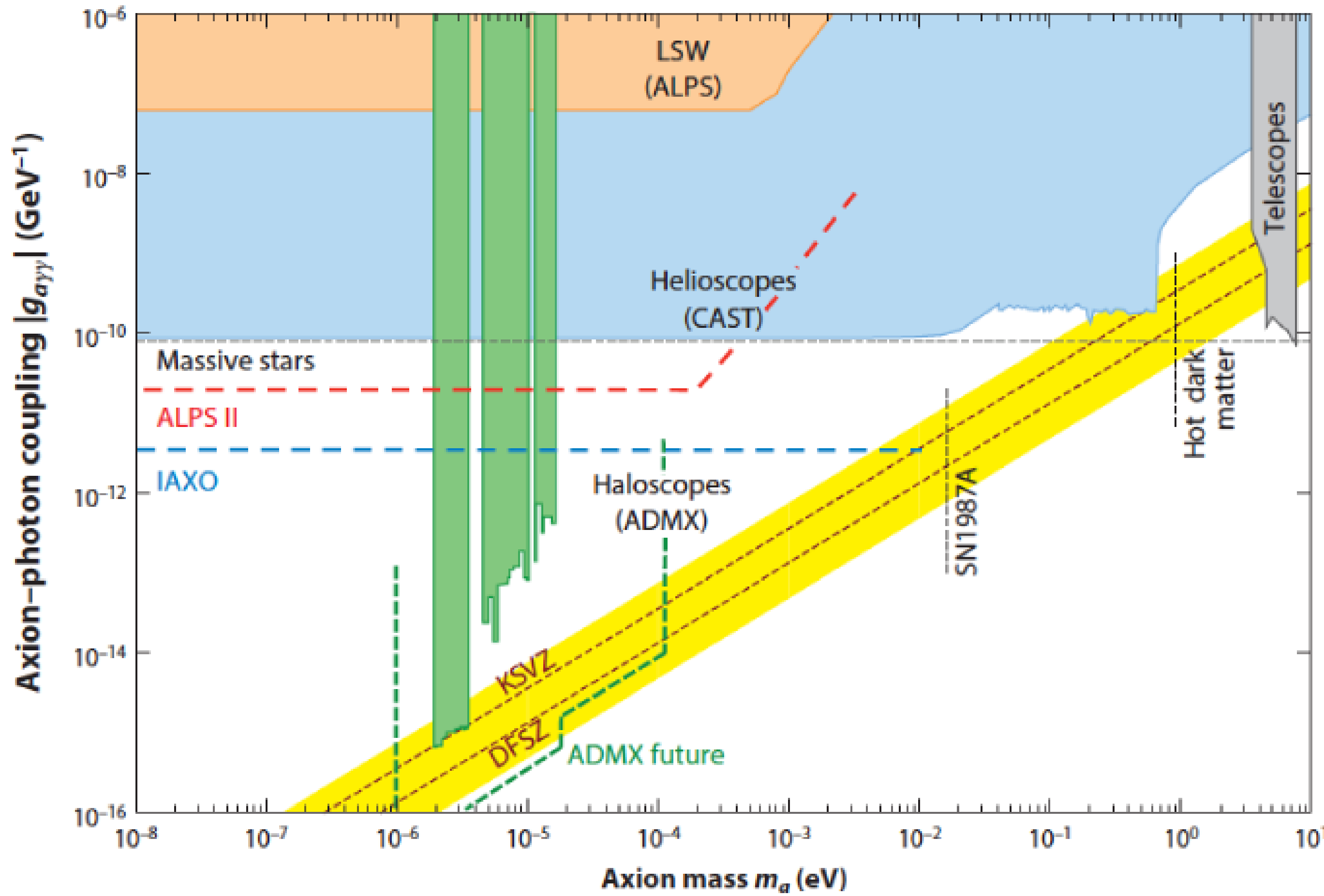
from: Luca Visinelli and Paolo Gondolo, arxiv: 1403.4594v2

Axion Dark Matter experiments

- ADMX, ADMX-HF, ORGAN, CULTASK, Orpheus
- DM Radio/ABRACADABRA/LC Circuit
- CAST, IAXO (Solar axions)
- ALPS, ALPS-II (produces axion-like particles in lab)
- Casper-Electric
- Casper-Wind
- QUAX

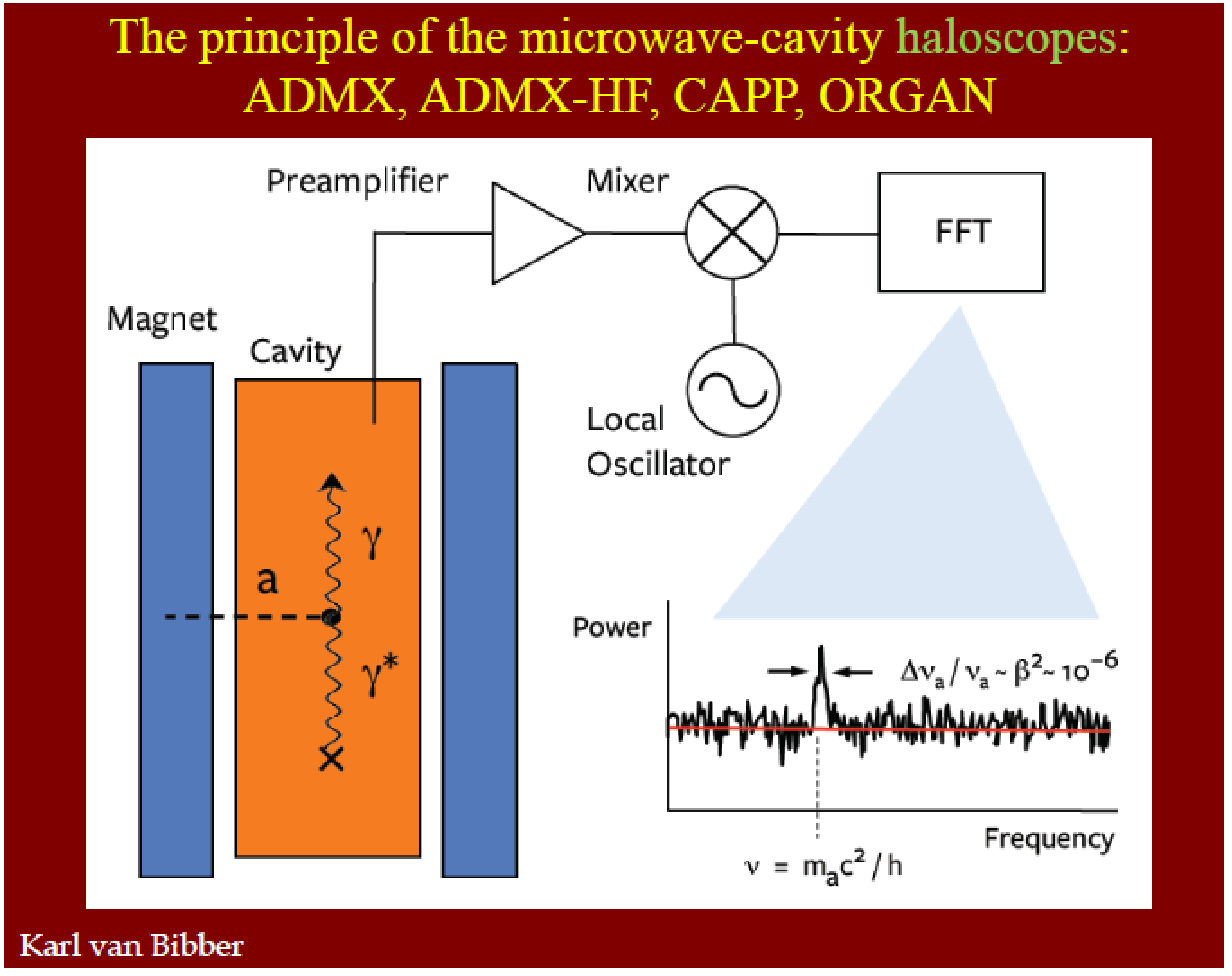
Axion-Photon coupling parameter space

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



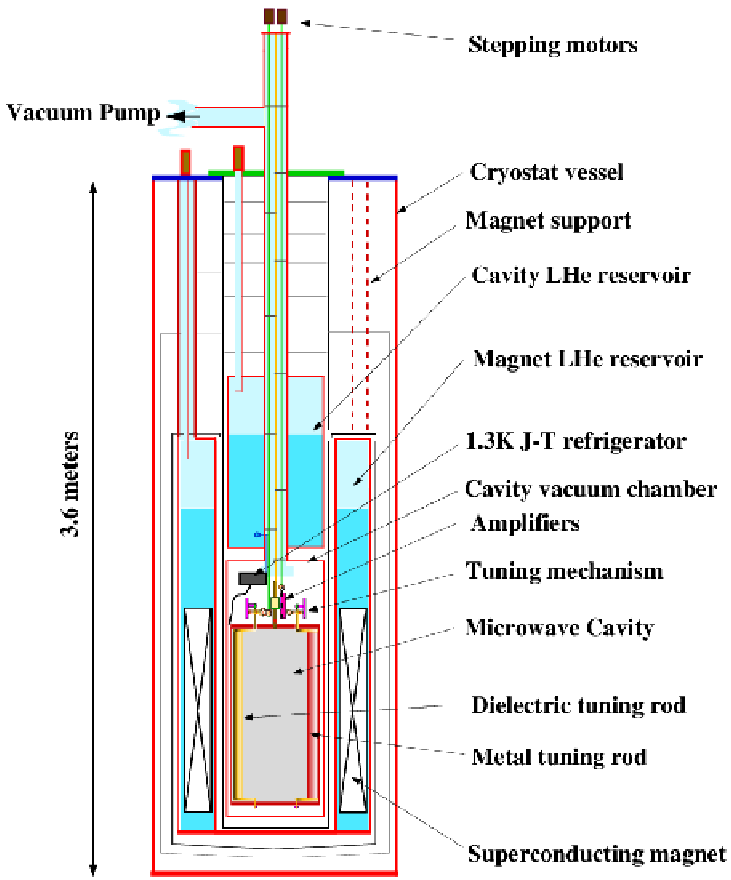
Karl van Bibber

Haloscopes


The principle of the microwave-cavity haloscopes:
ADMX, ADMX-HF, CAPP, ORGAN
Preamplifier
Mixer
FFT
Magnet
Cavity
Local
Oscillator
γ
a
γ*
Power
Δν_a / ν_a ~ β² ~ 10⁻⁶
Frequency
ν = m_a c² / h
Karl van Bibber

ADMX experiment

Axion couples to 2 photons $g_{a\gamma\gamma}$ → Resonant axion to photon conversion in Microwave cavity in background magnetic field



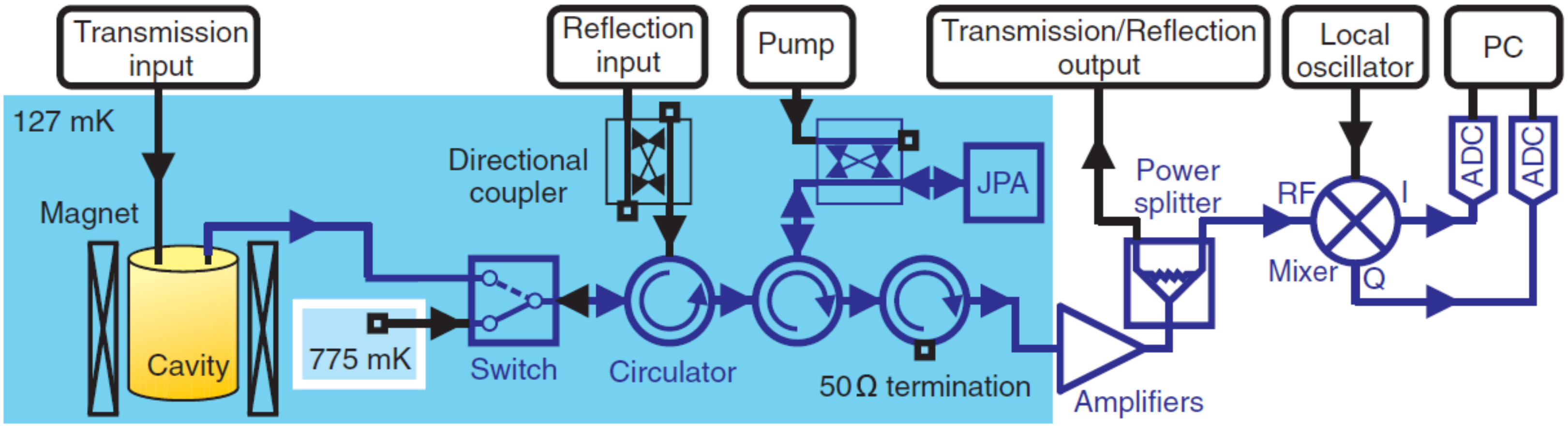
Cavity resonance tuned to match oscillation frequency of cosmic axion field

http://www.phys.washington.edu/groups/admx/home.html

Another experiment underway in Korea with similar concept! [https://capp.ibs.re.kr]

ADMX-HF (new results 2017)

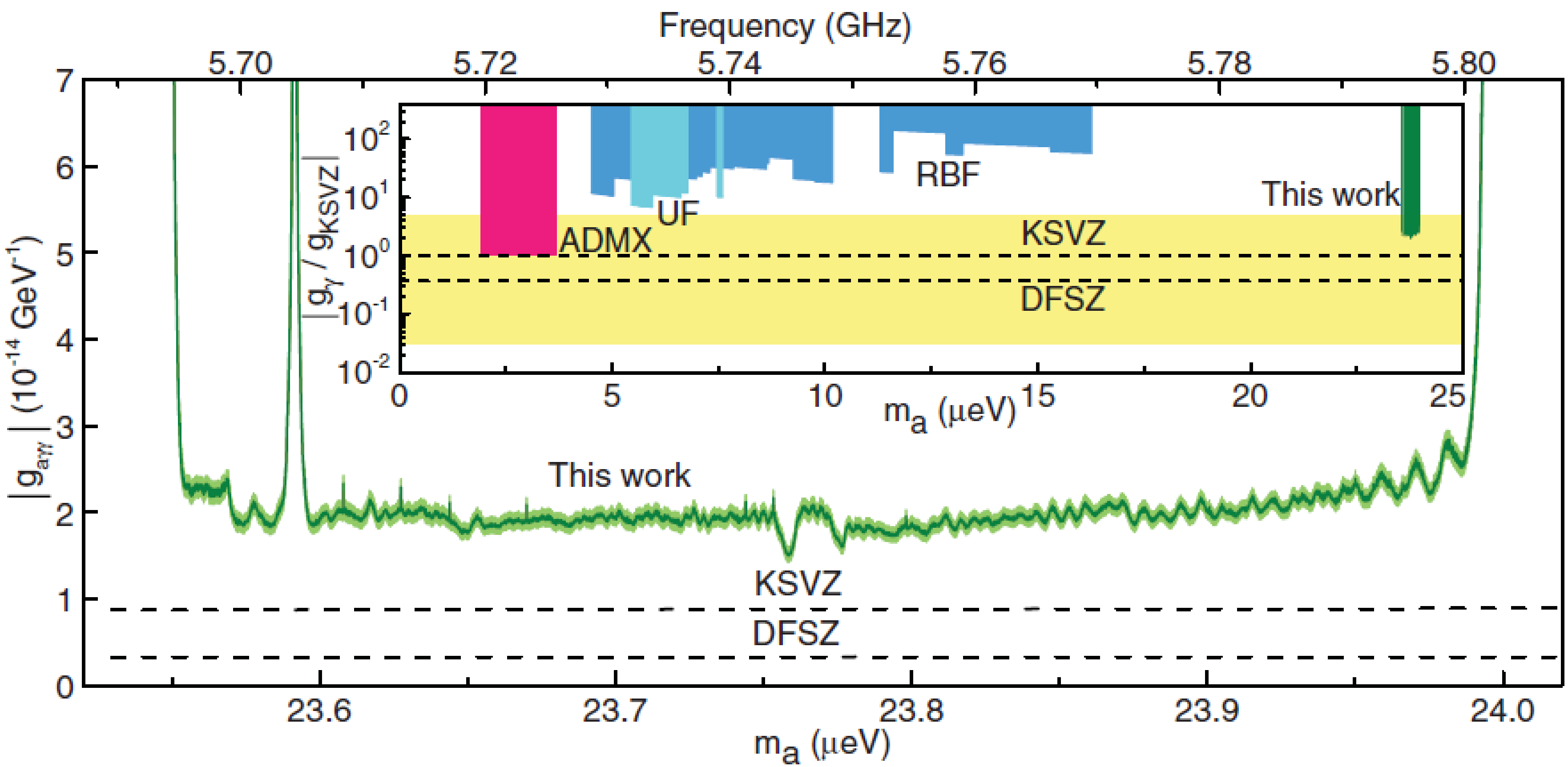
- Smaller (higher-freq 5GHz) cavity, JPA (quiet) amplifiers



Brubaker et.al, PRL 118, 061302 (2017)

ADMX-HF (new results 2017)

- Smaller (higher-freq) cavity, JPA (quiet) amps



Brubaker et.al, PRL 118, 061302 (2017)

Sensitivity of Axion Haloscopes

Mode coupling to receiver

Power deposited by axions: $$P_S = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\rho_a}{\Lambda^4}\right) \left(\omega_c B_0^2 V C_{mn\ell} Q_L \frac{\beta}{1+\beta}\right)$$

Properties of axion, DM

Properties of cavity

Model dependent coupling g_γ = -0.97, 0.36, for KSVZ, DFSZ models, resp.

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Physical coupling in Lagrangian: $g_{a\gamma\gamma} = (g_\gamma \alpha / \pi \Lambda^2) m_a$

Signal to Noise ratio: $$\Sigma = \frac{P_S}{k_B T_S} \sqrt{\frac{\tau}{\Delta\nu_a}}$$

Integration time

Axion linewidth

Noise temperature limits scan rate: $$k_B T_S = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_A\right)$$

Amplifier noise

Brubaker et.al, PRL 118, 061302 (2017)

Challenge at higher frequency

$$P = \frac{2\pi\hbar^2 g_{a\gamma\gamma}^2 \rho_{\rm DM}}{m_a^2 c} \cdot f_\gamma \cdot \frac{1}{\mu_0} B^2 V_{nlm} \cdot Q$$

Cavity parameters: Volume, Magnetic Field, Q

- Volume of resonant cavity shrinks as EM mode gets higher frequency
- Q of cavity tends to become worse at higher frequency

Ideas for higher mass axions

- Orpheus (open resonators)
- MADMAX (J. Redondo lecture!)

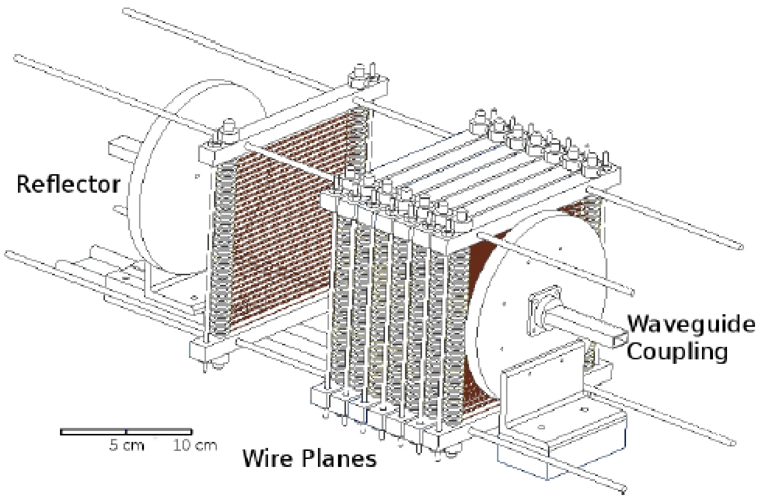
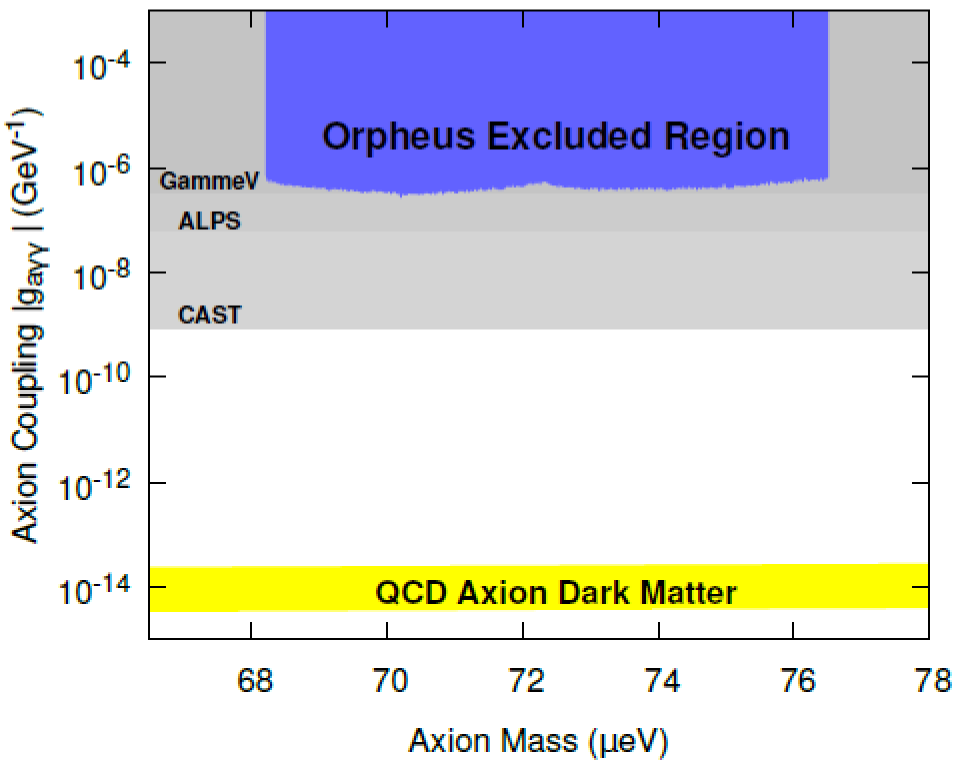


FIG. 1. Model of the Orpheus experiment. The experiment consists of a regular grid of wires braced by a pair of reflectors forming a Fabry-Pérot resonator. The wire planes and reflectors are supported on rails permitting the frequency of the resonator to be adjusted with optimal alignment of the magnetic field supplied by the wires.



Orpheus experiment: G. Rybka et. al., Phys. Rev. D 91, 011701(R) (2015)

Challenges at lower frequency

- Axion signal is getting weaker
- Larger volumes, magnets get expensive
- Can use high-Q LC circuit resonators rather than cavity

B. Cabrera, S. Thomas (Workshop Axions 2010, U. Florida, 2010)

LC Resonant Circuit

- Axion electrodynamics

F. Wilczek, PRL 58, 1977 (1987)

$$\Delta \mathcal{L} = \kappa a \mathbf{E} \cdot \mathbf{B}$$

$$\nabla \cdot \mathbf{E} = \tilde{\rho} - \kappa \nabla a \cdot \mathbf{B},$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t,$$

$$\nabla \cdot \mathbf{B} = 0,$$

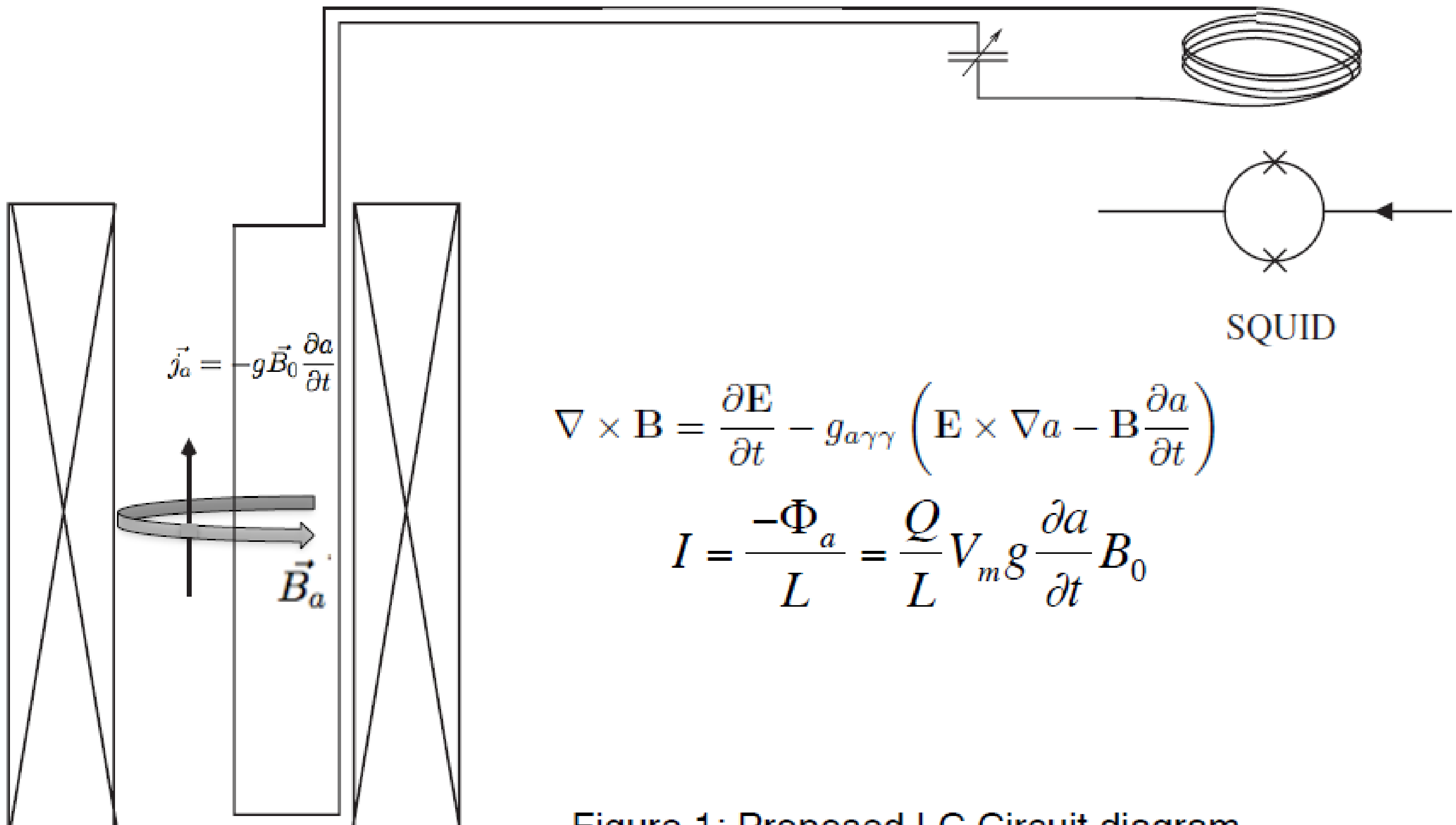
$$\nabla \times \mathbf{B} = \partial \mathbf{E}/\partial t + \tilde{\mathbf{j}} + \kappa(\dot{a}\mathbf{B} + \nabla a \times \mathbf{E})$$

In the presence of an external magnetic field $\vec{B}_0$

$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a = -g\vec{B}_0 \frac{\partial a}{\partial t}$$

B. Cabrera, S. Thomas (Workshop Axions 2010, U. Florida, 2010)

LC Resonant Circuit



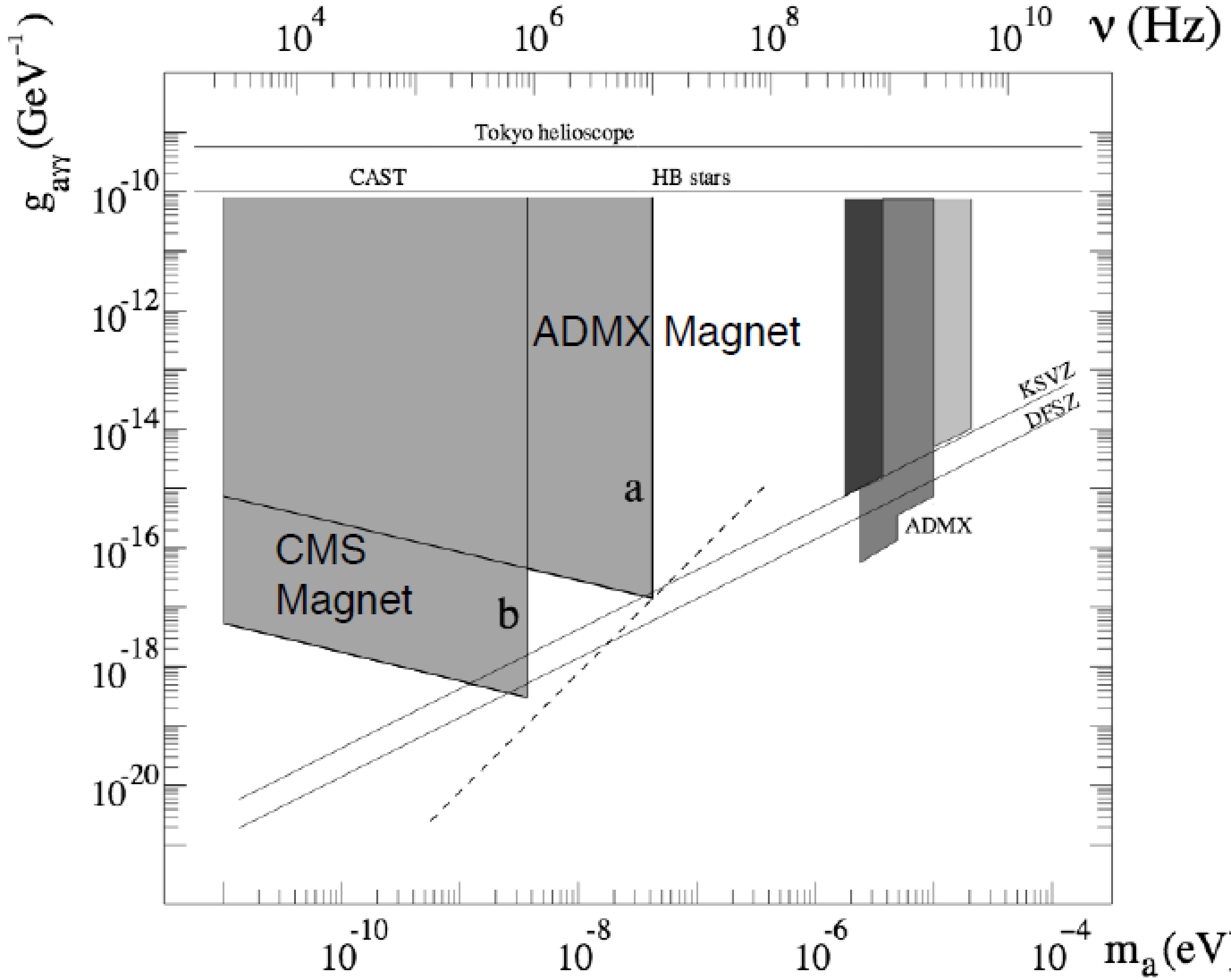
$$\nabla \times \mathrm{B} = \frac{\partial \mathrm{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathrm{E} \times \nabla a - \mathrm{B}\frac{\partial a}{\partial t}\right)$$

$$I = \frac{-\Phi_a}{L} = \frac{Q}{L} V_m g \frac{\partial a}{\partial t} B_0$$

Figure 1: Proposed LC Circuit diagram, adapted from [1] Sikivie et al.

Sikivie, Sullivan, Tanner, PRL 112, 131301 (2014)
B. Cabrera, S. Thomas, Workshop Axions 2010, U. Florida (2010)

Search reach



Sikivie, Sullivan, Tanner, PRL 112, 131301 (2014)

ABRACADABRA

- Toroidal geometry

Search reach

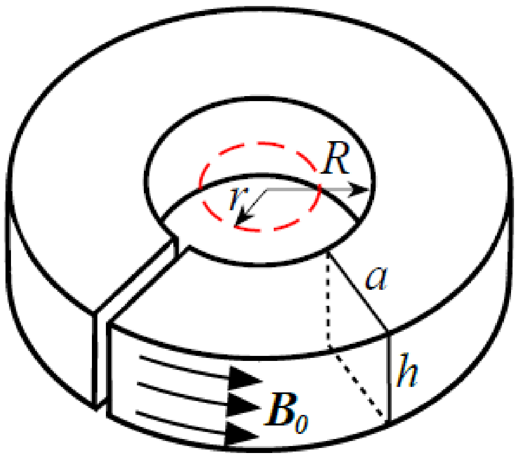
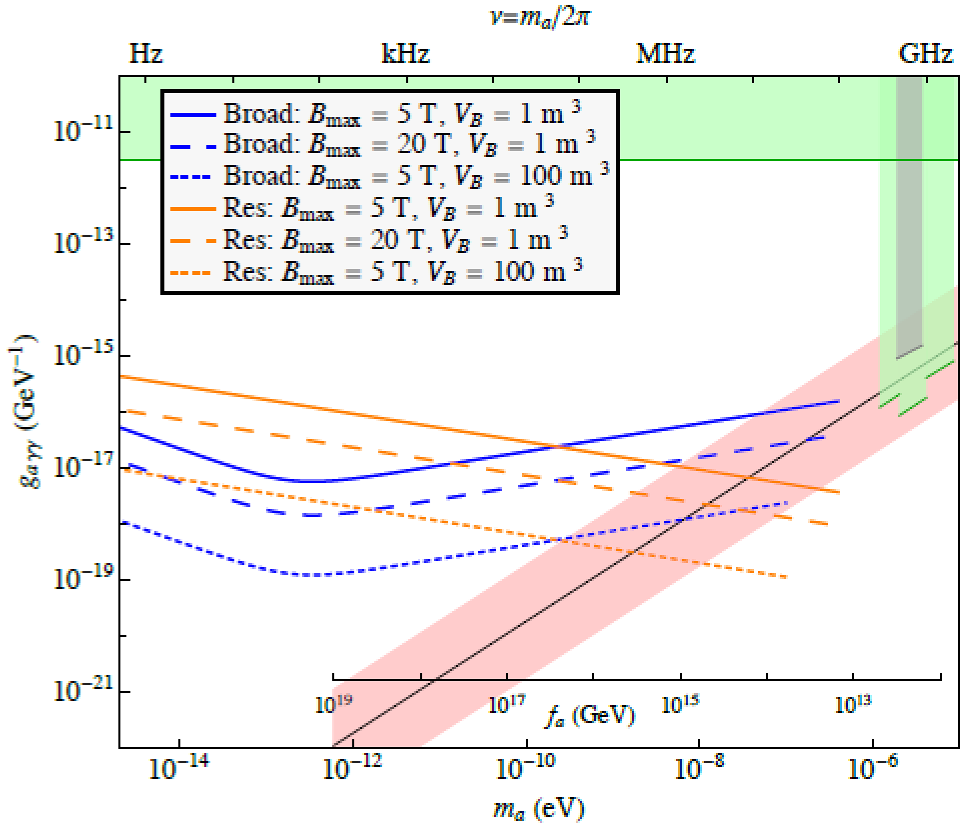
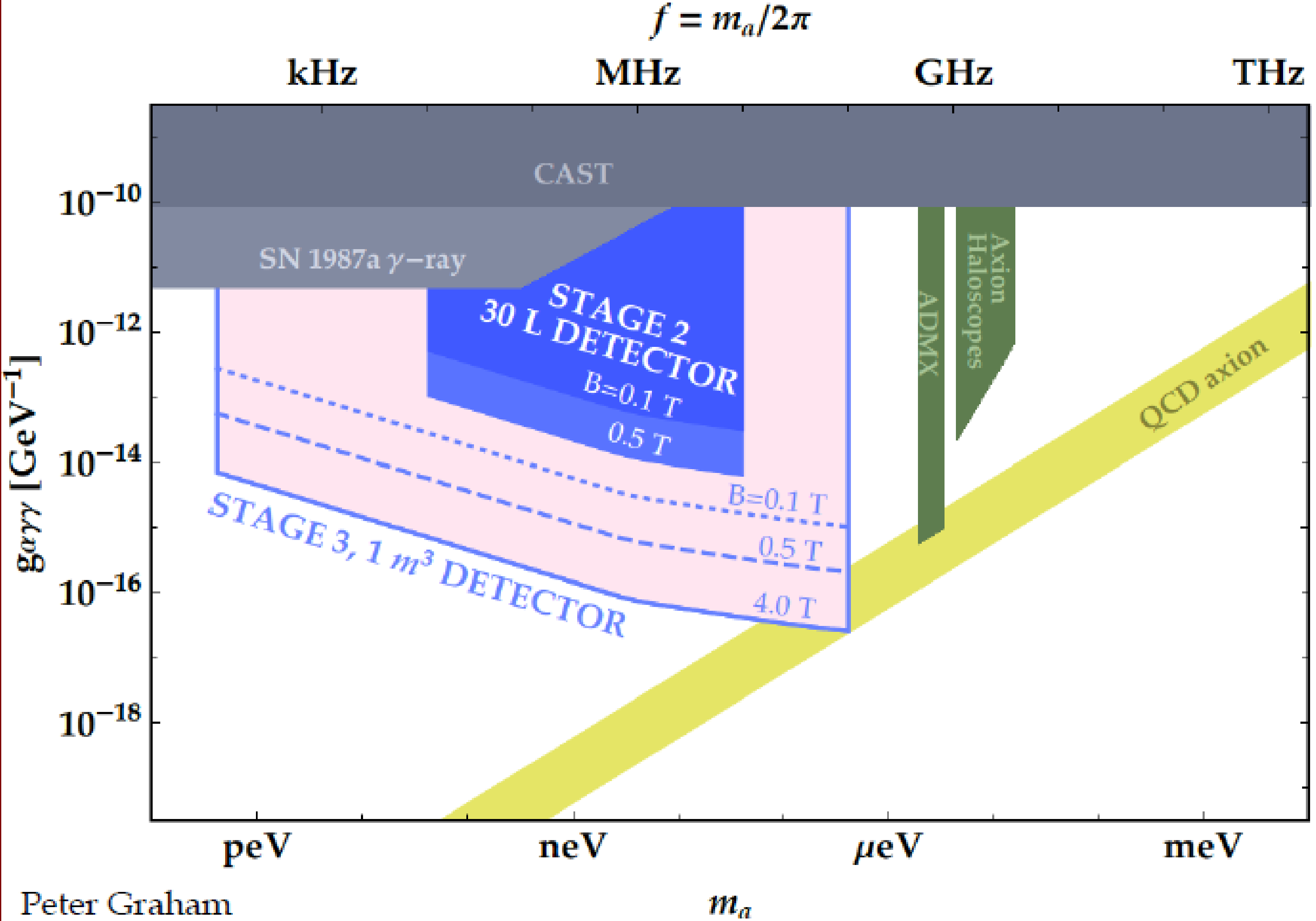


Figure 1. A (gapped) toroidal geometry to generate a static magnetic field $\mathbf{B}_0$. The dashed red circle shows the location of the superconducting pickup loop of radius $r \leq R$. The gap ensures a return path for the Meissner screening current; see discussion in main text.



Kahn, Safdi, Thaler, Arxiv 1602.01086

New Haloscope Proposals: ABRACADABRA (MIT) and DM Radio



Peter Graham

Other searches for axion-photon coupling (non-DM)

- Helioscopes (no assumptions about DM density at Earth, relies on solar physics)
- Light-shining-thru-walls (LSW) (model independent, direct conversion of lab photons into ALPS and back again

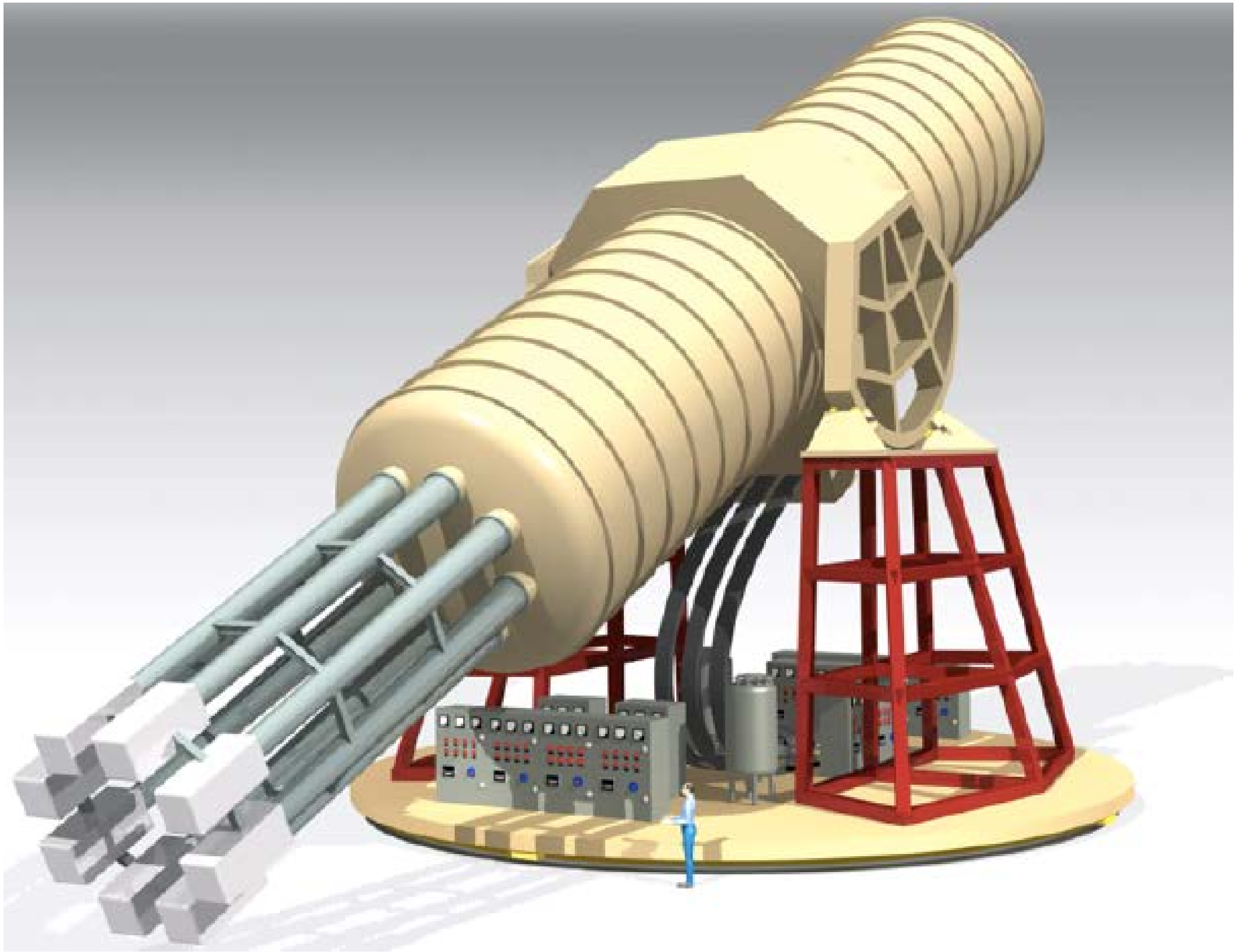
→ Good experimental control over system

→ However only sensitivity for ALPS, not QCD axion

Helioscopes: CAST experiment

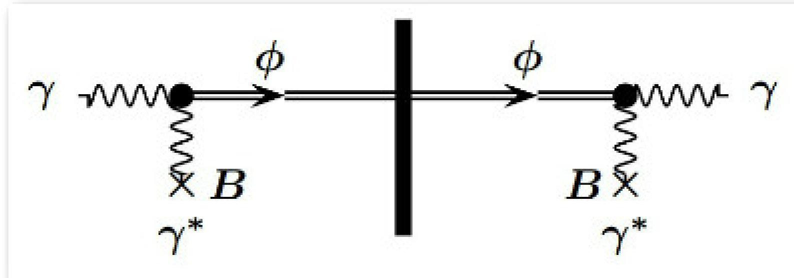
Conversion of solar axions to x-rays in background B field

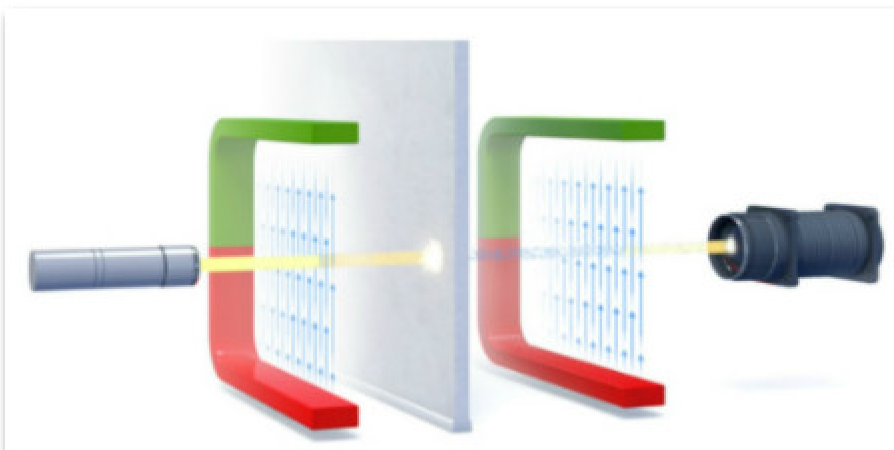
Helioscope of the future (IAXO)



ALPS & ALPS-II (Any light particle search)

Light shining through walls!



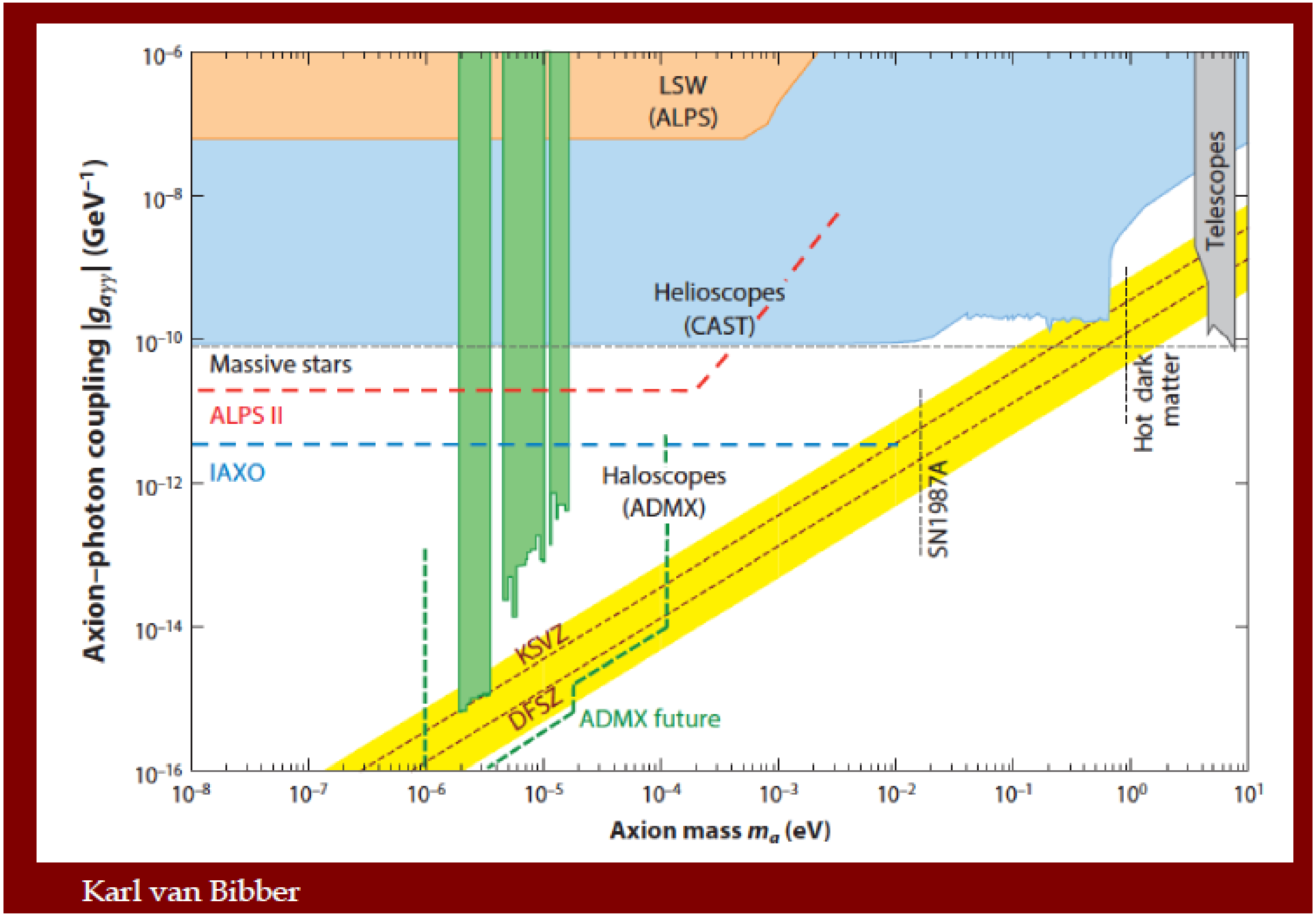


$$P_{a\leftrightarrow\gamma} = 2.6\cdot 10^{-17}\left(\frac{B}{10\,\mathrm{T}}\right)^2\left(\frac{L}{10\,\mathrm{m}}\right)^2\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2$$

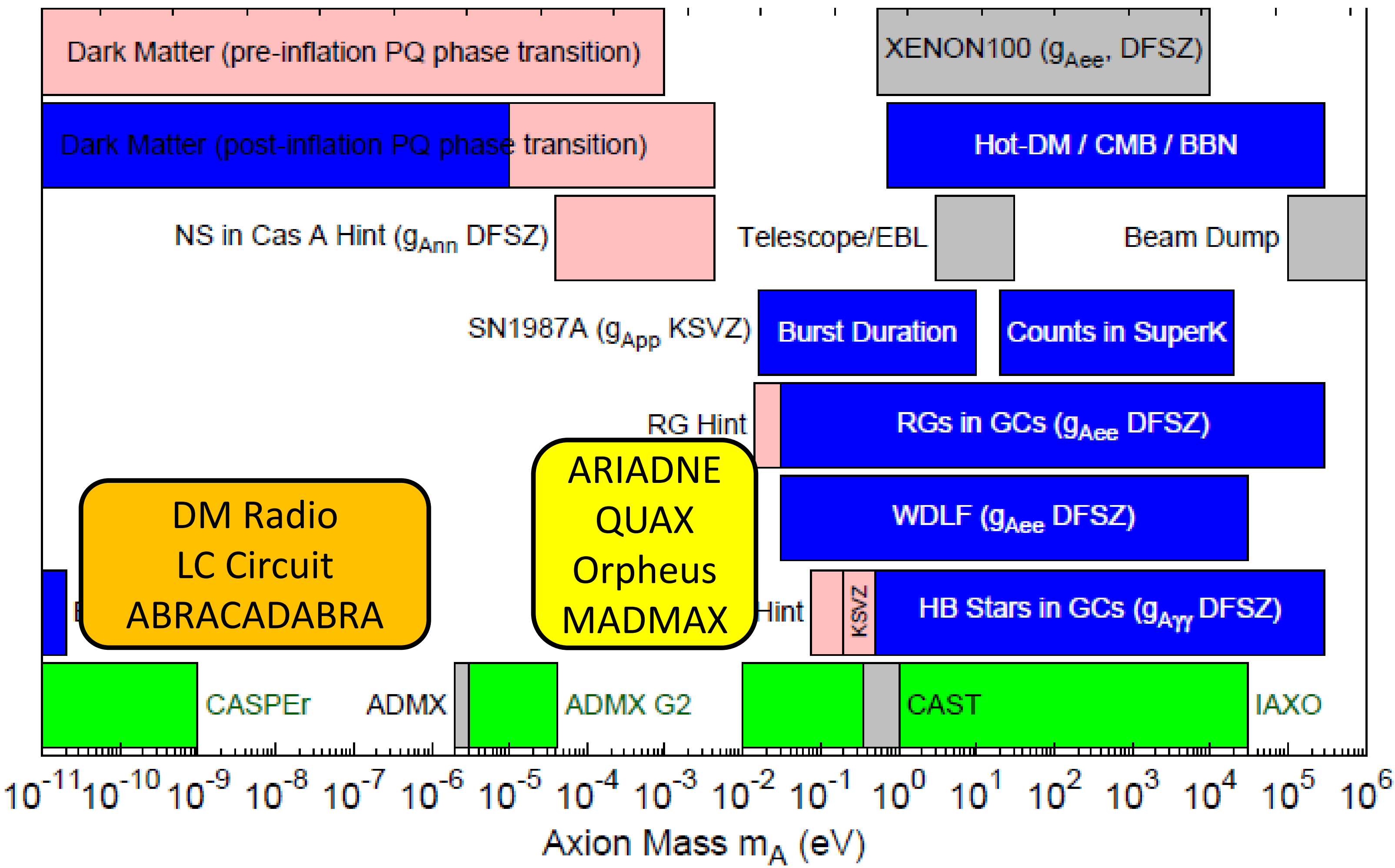
https://alps.desy.de/

Axion-Photon coupling parameter space

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

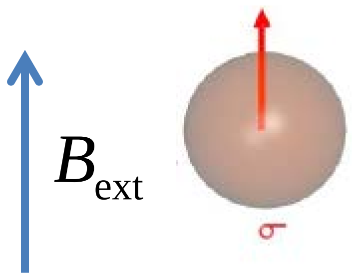


QCD Axion parameter space



Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion coupling to nuclei



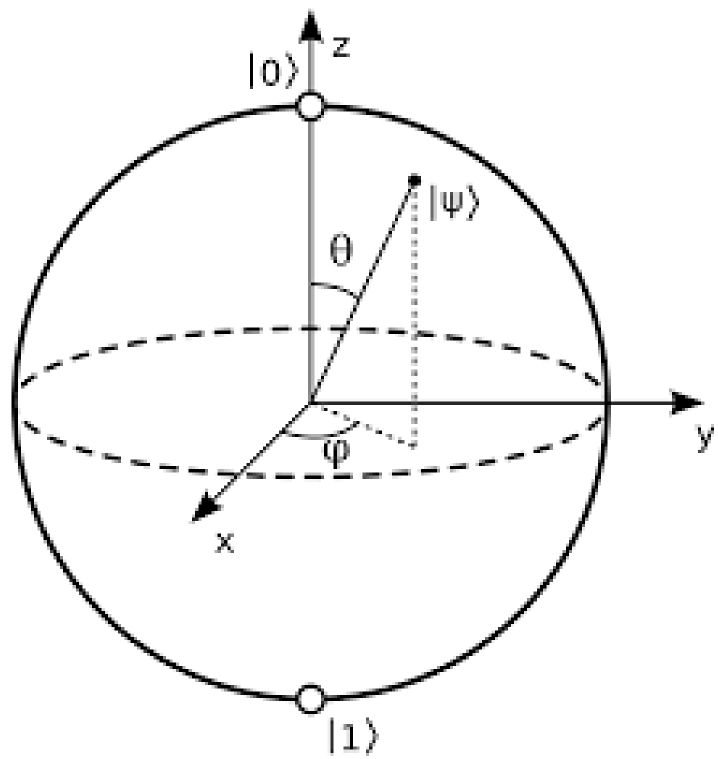
$$U = \mu \cdot B_{ext}$$

$|\uparrow\rangle$

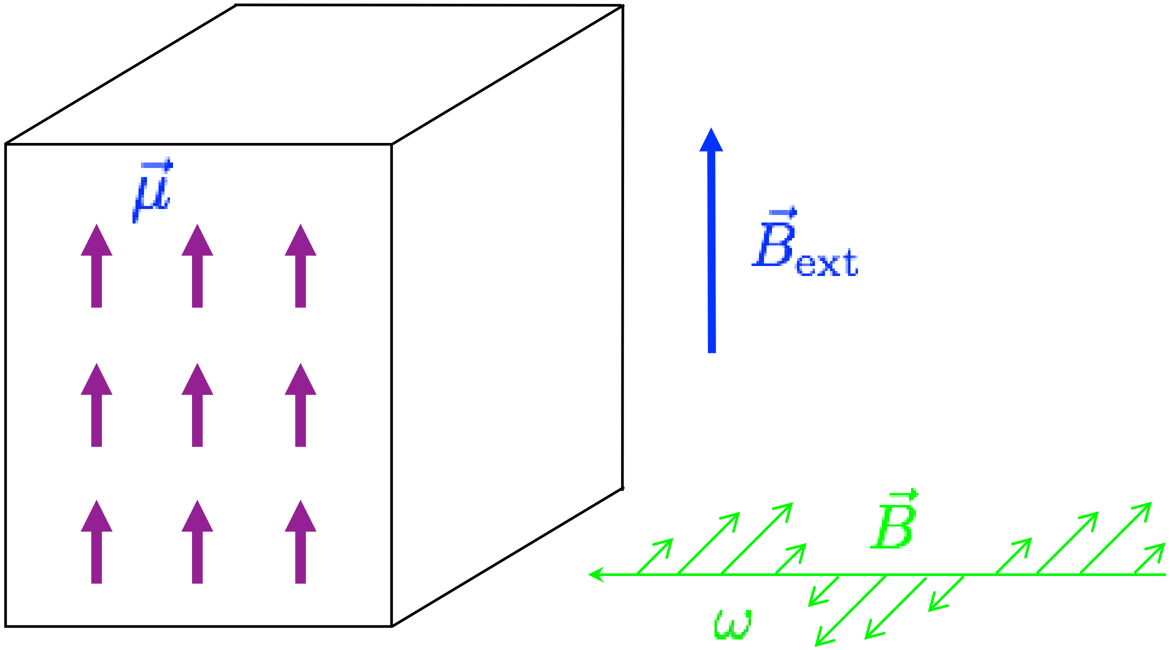
$$\omega = \frac{2\mu_N \cdot B_{ext}}{\hbar}$$

$|\downarrow\rangle$

Bloch Sphere for 2 level system



Nuclear Magnetic Resonance (NMR)



NMR resonant spin flip when Larmor frequency

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

PHYSICAL REVIEW X **4**, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

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(Received 9 July 2013; published 19 May 2014)

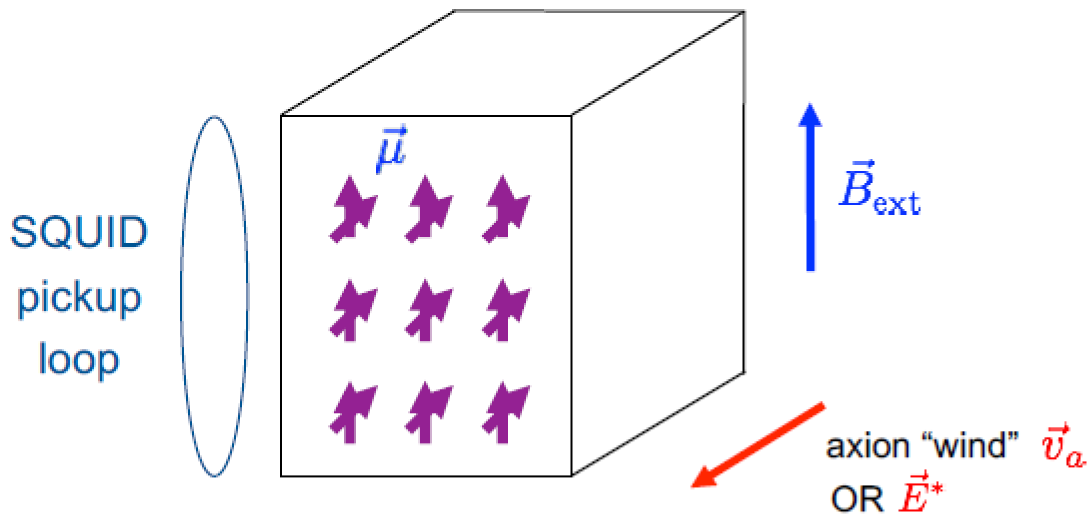
We propose an experiment to search for QCD axion and axionlike-particle dark matter. Nuclei that are interacting with the background axion dark matter acquire time-varying *CP*-odd nuclear moments such as an electric dipole moment. In analogy with nuclear magnetic resonance, these moments cause precession of nuclear spins in a material sample in the presence of an electric field. Precision magnetometry can be used to search for such precession. An initial phase of this experiment could cover many orders of magnitude in axionlike-particle parameter space beyond the current astrophysical and laboratory limits. And with established techniques, the proposed experimental scheme has sensitivity to QCD axion masses $m_a \lesssim 10^{-9}$ eV, corresponding to theoretically well-motivated axion decay constants $f_a \gtrsim 10^{16}$ GeV. With further improvements, this experiment could ultimately cover the entire range of masses $m_a \lesssim \mu$ eV, complementary to cavity searches.

DOI: 10.1103/PhysRevX.4.021030 Subject Areas: Cosmology

D. Budker et al., Phys. Rev. X **4**, 021030 (2014).

Principle of CASPER experiments

CASPEr



Larmor frequency = axion mass → resonant enhancement

SQUID measures resulting transverse magnetization

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

Axion-induced electric dipole moments (EDMs)

Nuclear EDM from the strong interaction (strong CP problem):

$$d \approx 3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm} \times \theta_{\mathrm{QCD}}\ .$$

Nuclear EDM from axion field:

$$d \approx 3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm} \times \frac{a}{f_a}\ ,$$

$$\approx \frac{3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm}}{f_a} \times a_0 \cos\left(m_a t\right)\ .$$

Can be thought of as an oscillating θ_{QCD}.

Axion oscillation frequency

Determined by the axion mass, related to the global symmetry breaking scale f_a :

$$m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz} \times \left(\frac{10^{16}\ \mathrm{GeV}}{f_a} \right) .$$

f_a at GUT scale $\rightarrow$ MHz frequencies,

f_a at Planck scale $\rightarrow$ kHz frequencies.

Axion-induced oscillating EDM

Assuming axions are the dark matter, the dark matter density fixes the ratio a_0/f_a:

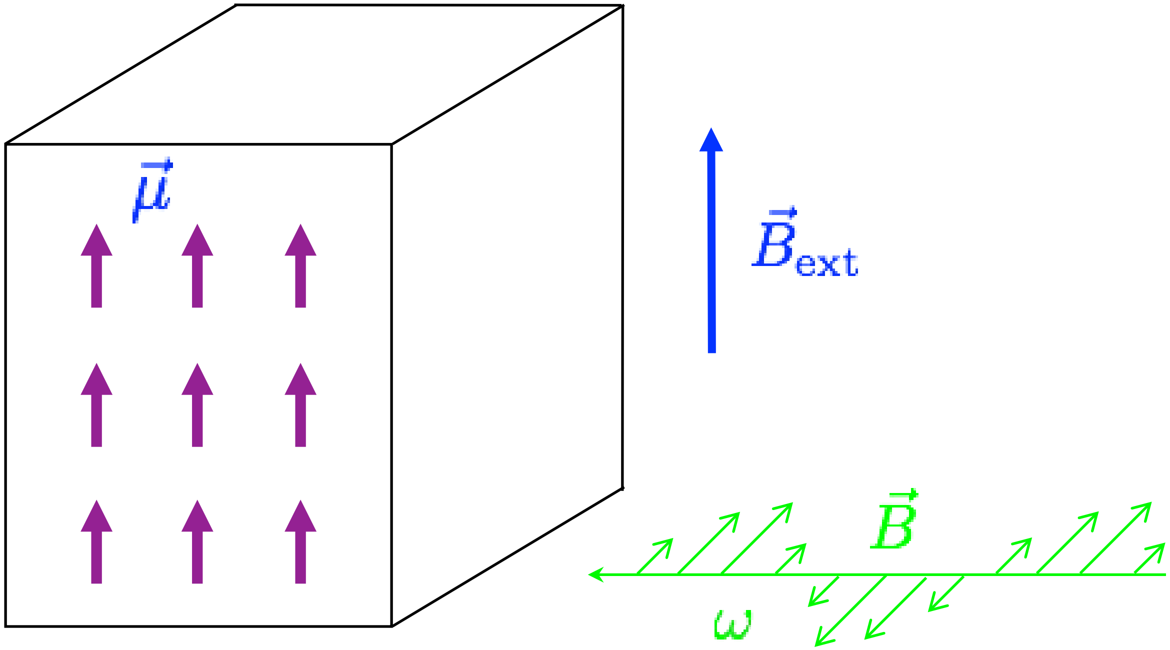
$$\rho_{\mathrm{DM}} \sim m_a^2 a_0^2 \sim \frac{(200\ \mathrm{MeV})^4}{f_a^2} a_0^2 \sim 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}\ ,$$

$$\frac{a_0}{f_a} \sim 3 \times 10^{-19}\ .$$

This generates an oscillating EDM:

$$d \sim 10^{-34}\ \mathrm{e} \cdot \mathrm{cm} \times \cos\left(m_a t\right)\ .$$

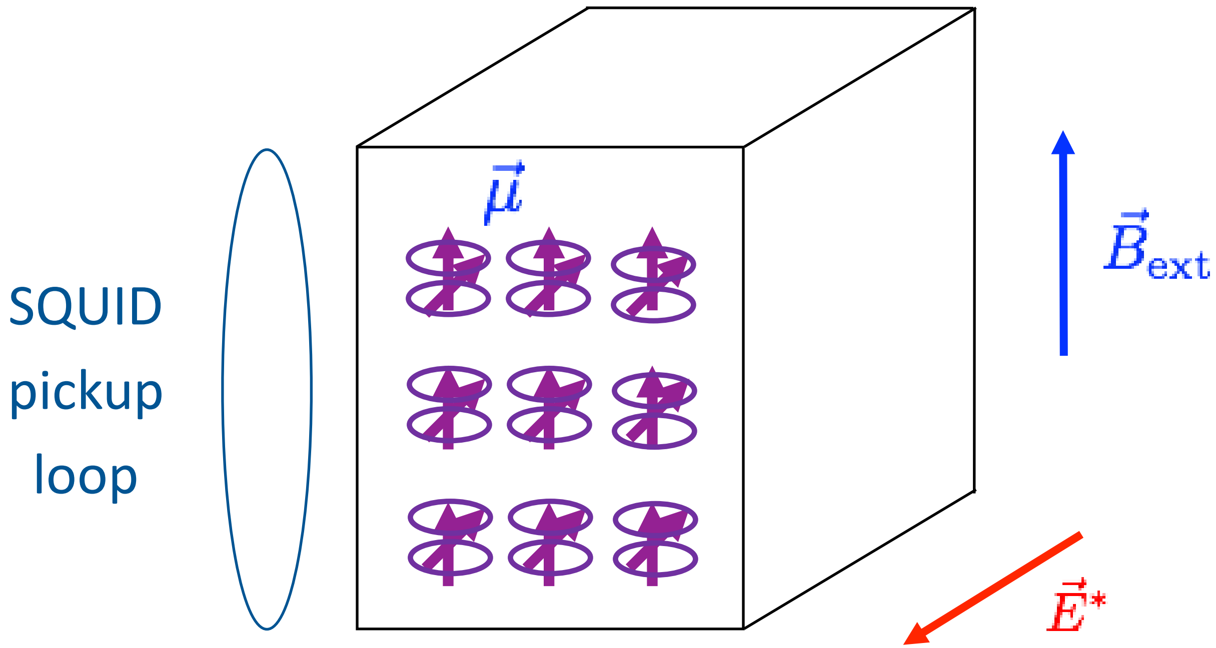
Nuclear Magnetic Resonance (NMR)



NMR resonant spin flip when Larmor frequency

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

EDM coupling to axion plays role of oscillating transverse magnetic field



Larmor frequency = axion Compton frequency

➔ resonant enhancement.

Signal estimate

$$\frac{\sin\left[(\Omega_L - m_a)t\right]}{\Omega_L - m_a} \approx T_2$$

$$M(t) \approx (np\mu) \times (\epsilon_S d E^*) \times \frac{\sin\left[(\Omega_L - m_a)t\right]}{\Omega_L - m_a} \sin\left(\Omega_L t\right)\ ,$$

n = atomic density;
p = nuclear polarization;
μ = magnetic moment;
E^* = effective electric field;
ε_S = Schiff suppression;
Ω_L = Larmor frequency.

D. Kimball

Sample choice

$$E^* \approx 3 \times 10^8 \ \frac{\mathrm{V}}{\mathrm{cm}} \ !$$

Need maximum n, p, E*, and ε_S, and long T_2.

For the first generation CASPEr-Electric experiment, we plan to use a ferroelectric crystal, likely $PbTiO_3$ or PMN-PT.

PHYSICAL REVIEW A **77**, 022102 (2008)

Nuclear-spin relaxation of ^{207}Pb in ferroelectric powders

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(Received 15 November 2007; published 4 February 2008)

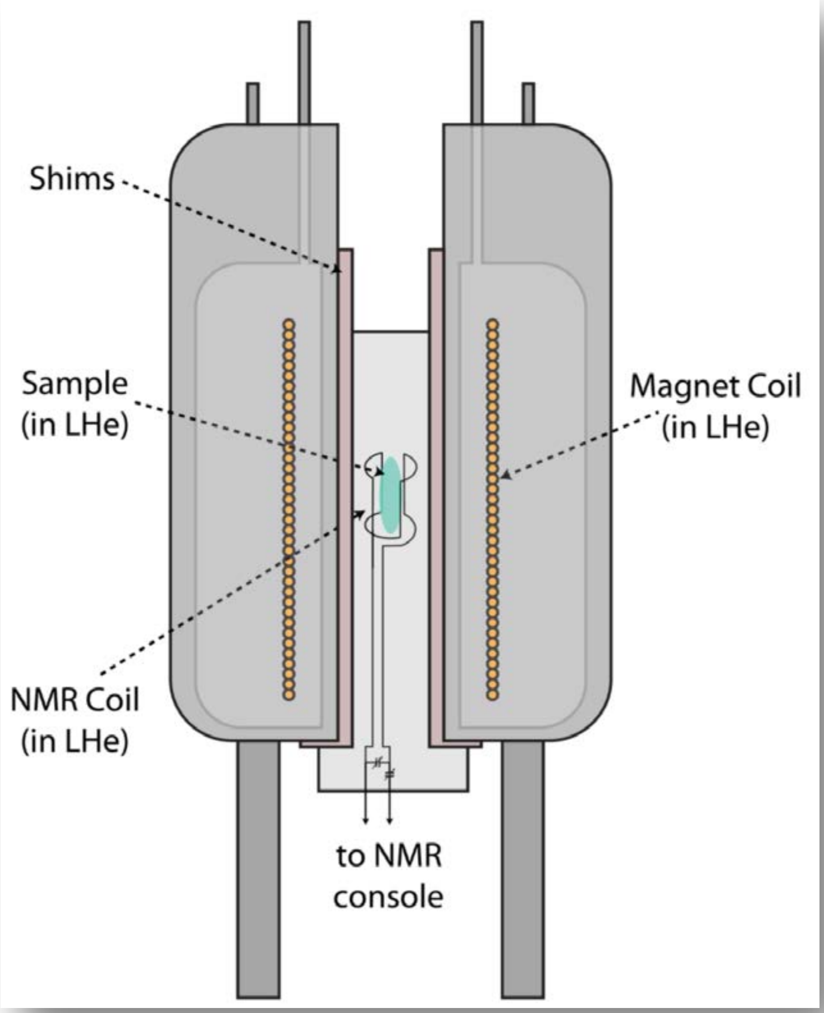
D. Kimball

Experimental strategy

(1) Thermally polarize spins in a cryogenic environment at high magnetic field (~ 10 T);

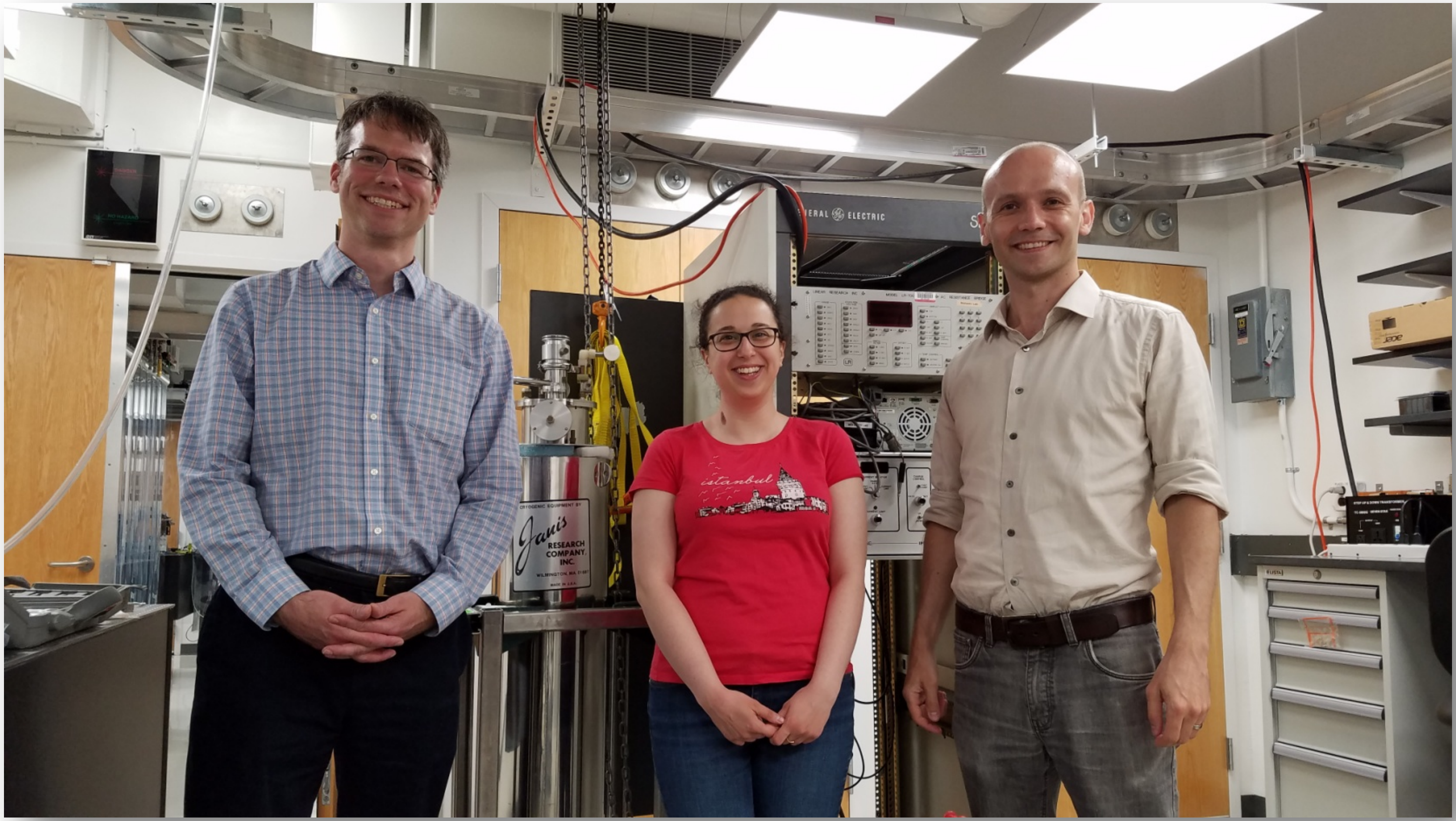
(2) Scan magnetic field down from 10 T -- Larmor frequency decreases from ~ 50 MHz;

(3) Integrate for ~ 10 ms at each frequency, complete scan takes around 1000 s $\approx T_1$ to complete.



D. Kimball

Experiments beginning!



D. Kimball

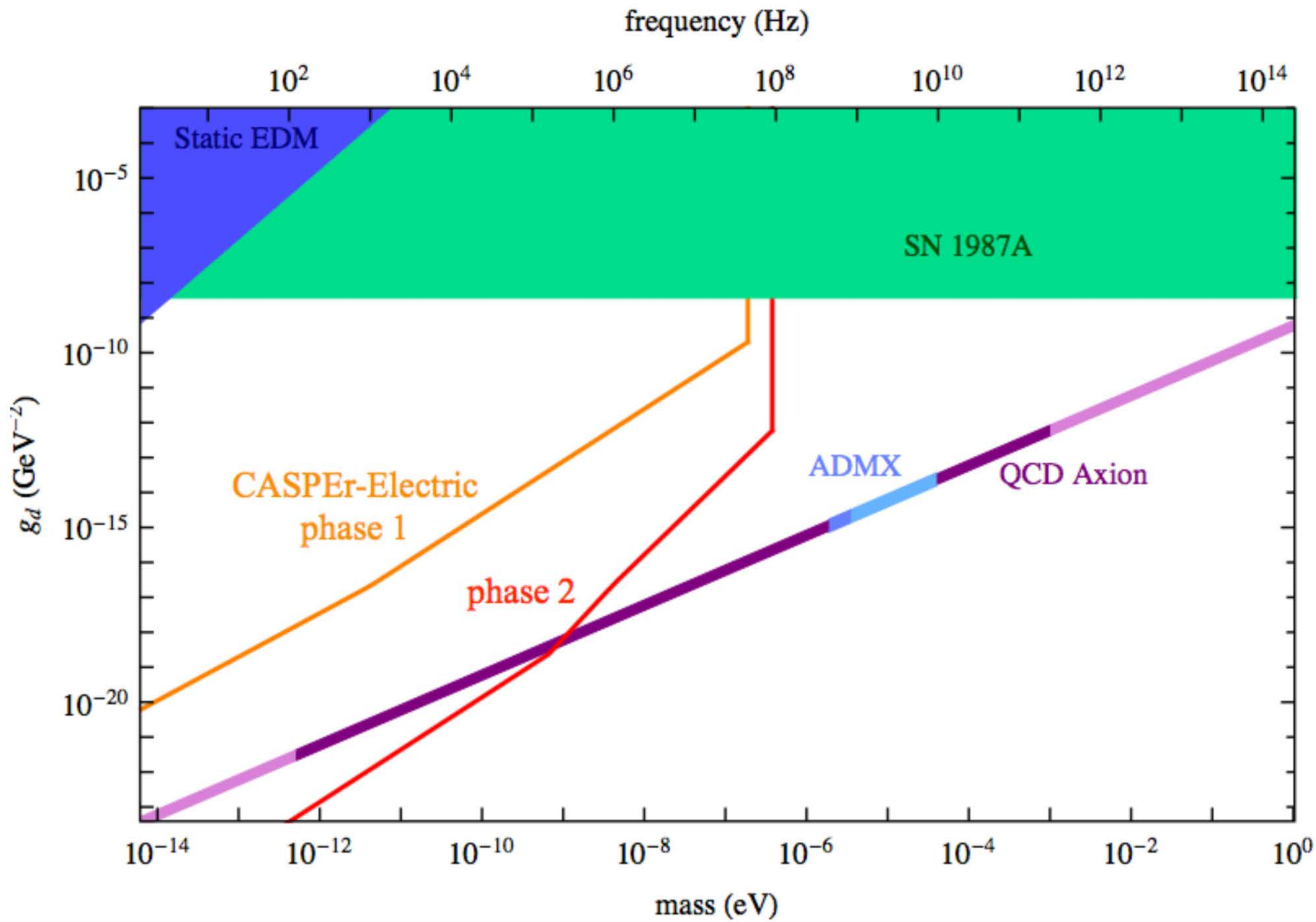
Challenges

(1) T_1 acquires field dependence due to paramagnetic impurities – long T_1 at high fields, short T_1 at low fields:
this is a problem for duty cycle and maintaining polarization at low fields: recent measurements look promising!

(2) The chemical shift anisotropy (CSA) can broaden the resonance.

(3) Vibrations can be an issue for low frequencies/fields.

- Estimates of thermal drifts and magnetic field fluctuations indicate that they shouldn't be a major problem.



Experimental sensitivity

Phase 2 requirements

(1) Longer coherence time: $T_2 \approx 1$ s.

(2) Hyperpolarization: $p \approx 1$.

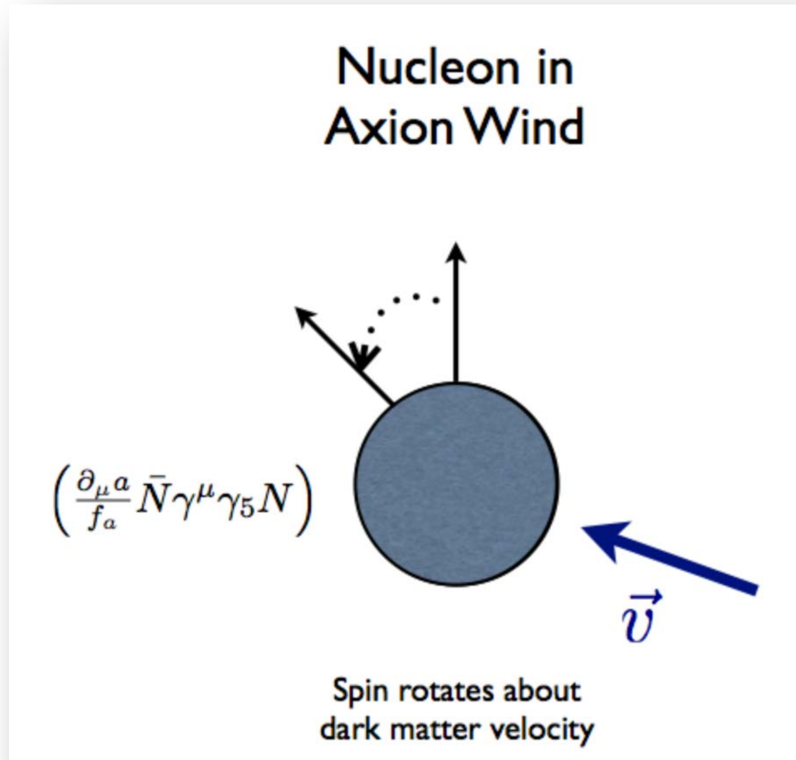
(3) Larger sample size: $V \approx$ 100-1000 cm^3.

R&D required!

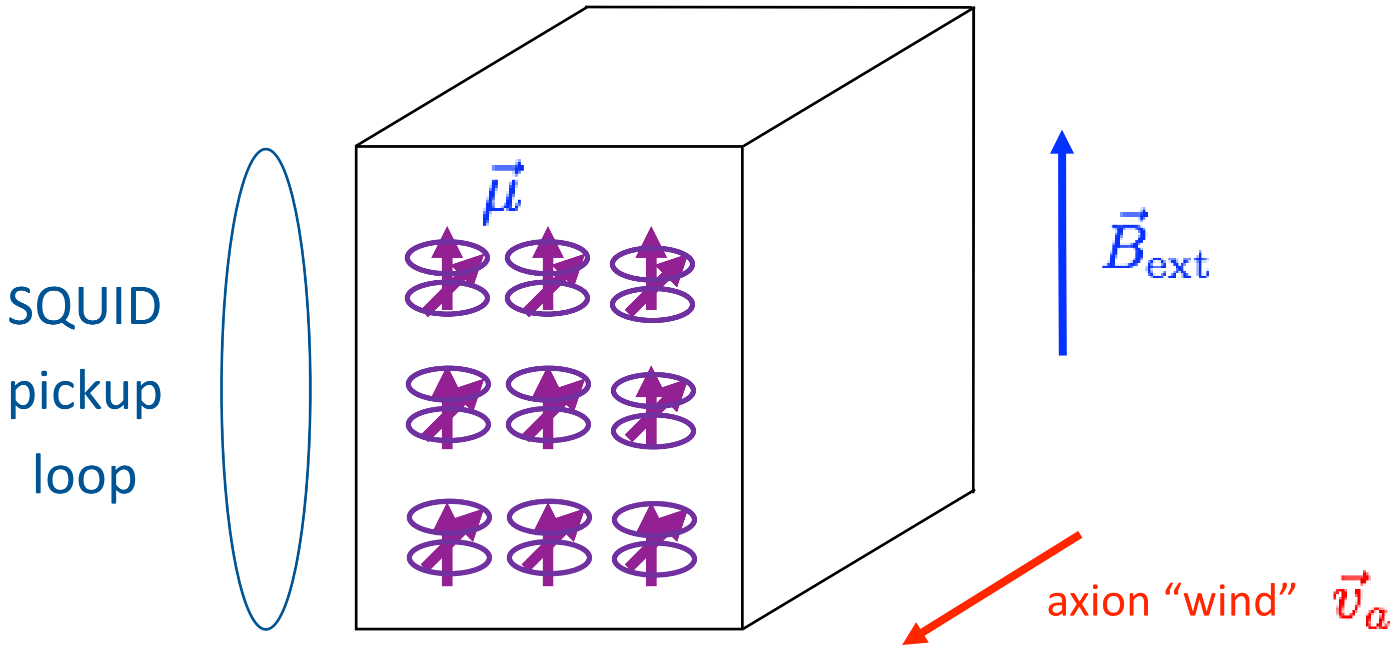
Axion/ALP-induced spin precession (axion wind)

Nonrelativistic limit of the axion-fermion coupling yields a Hamiltonian:

$$H_{\text{wind}} \approx g_{aNN} \nabla a \cdot \boldsymbol{\sigma}_N \ .$$



Axion wind detection



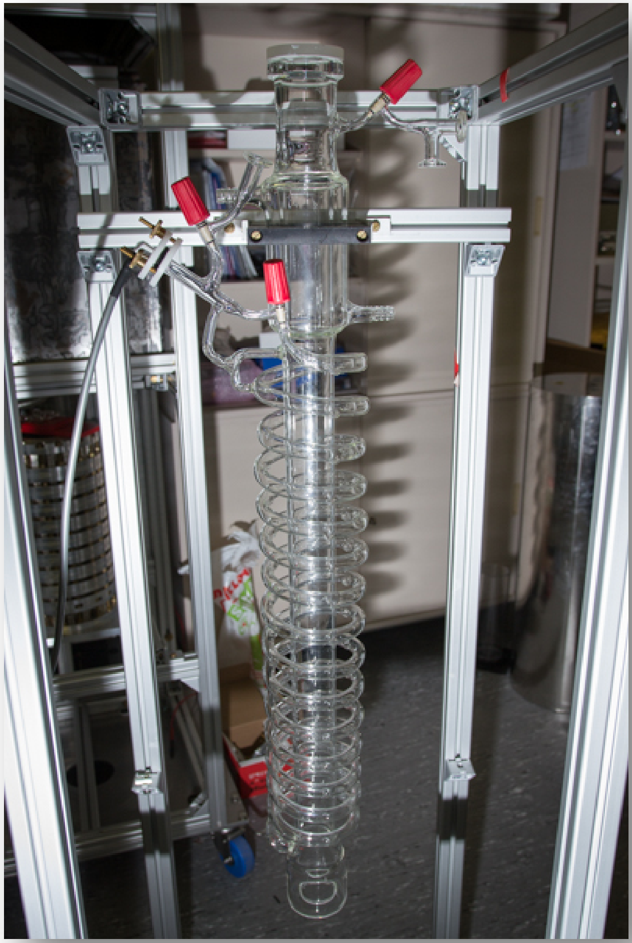
Larmor frequency = axion Compton frequency
➔ resonant enhancement.

Sample choice: liquid Xenon

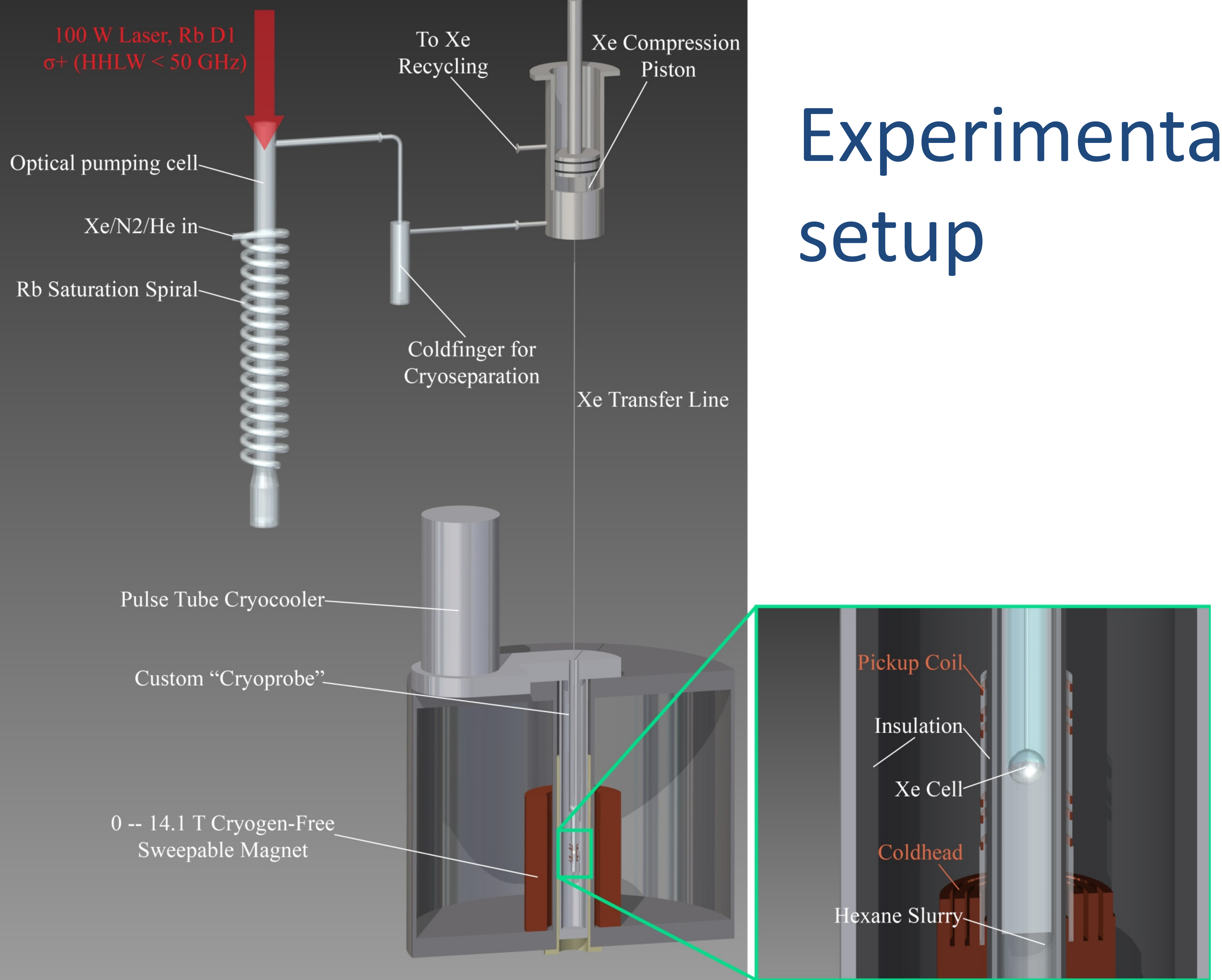
Density (n)	Magnetic Moment (μ)	T_2
$1.3 \times 10^{22}\,\frac{1}{\mathrm{cm}^3}$	$0.35\,\mu_N$	1300 s

Relatively large sample can be hyperpolarized.

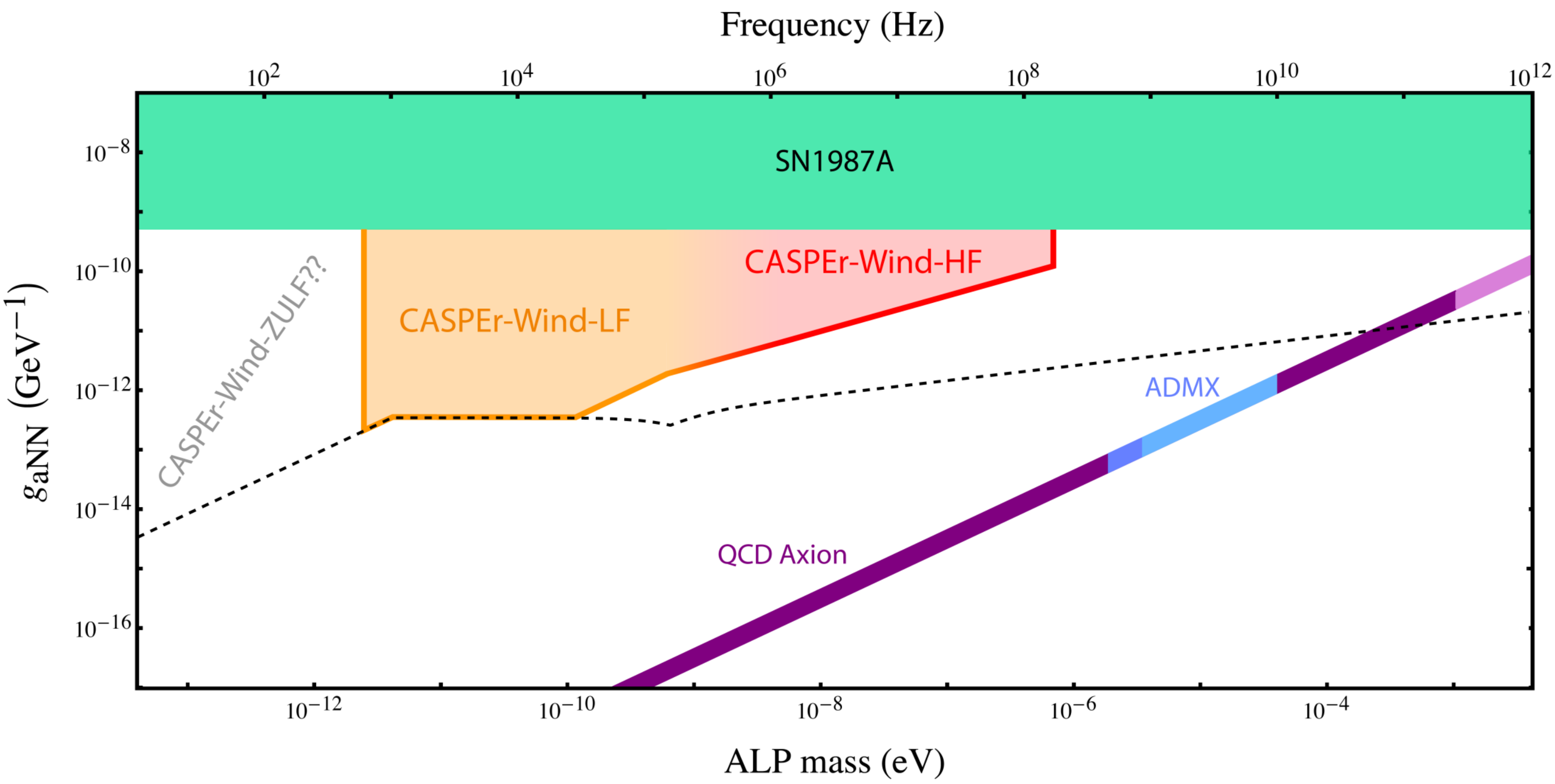
The enhancement factor can be on the order of 10^6.



Experimental setup

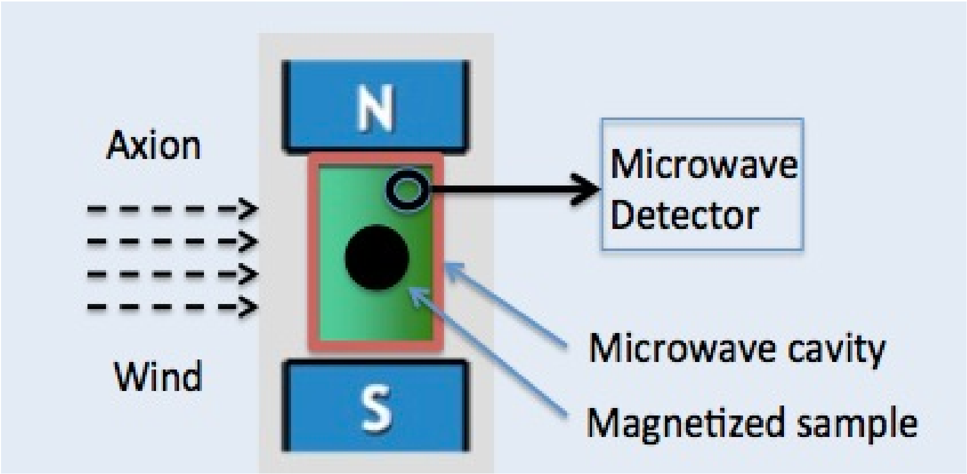


Experimental sensitivity



The QUAX (QUest for AXion) experiment

- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin** via **electron-axion coupling**
- This field excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**



The effective magnetic field associated with the axion wind

$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a v_E$$

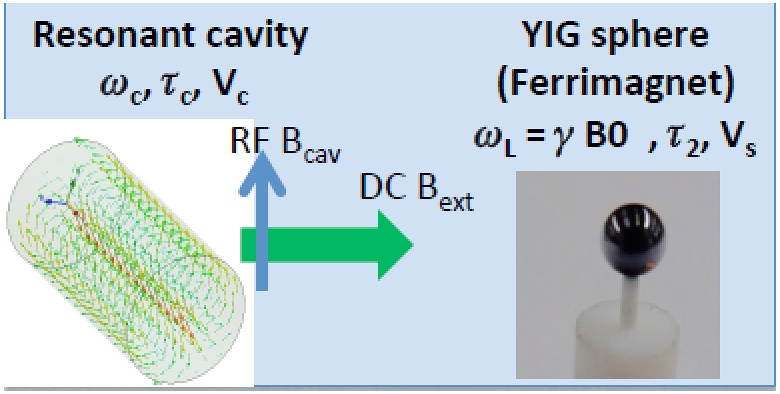
$$B_a = 2.0 \cdot 10^{-22}\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{T},$$

$$\frac{\omega_a}{2\pi} = 48\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \quad \mathrm{GHz},$$

- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

QUAX: Axion induced rf emission

A **volume V_s of magnetized material, strong coupled in a microwave resonant cavity,** will absorb energy from the axion wind and **re-emit as rf power**



With magnetizing field
B0 = 1.7 T => 48 GHz

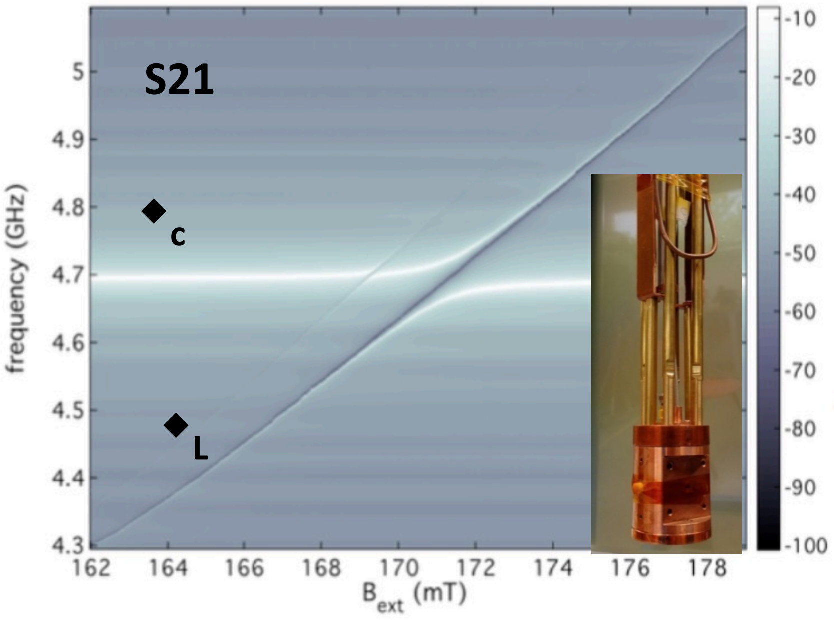
$$P_{\rm out} = \frac{P_{\rm in}}{2} = \mathbf{3.8\times 10^{-26}} \left(\frac{m_a}{200\,\mu{\rm eV}}\right)^3 \left(\frac{V_s}{100\ {\rm cm}^3}\right)\left(\frac{n_S}{2\cdot 10^{28}/{\rm m}^3}\right)\left(\frac{\tau_{\rm min}}{2\ \mu s}\right)\ {\rm W}$$

R & D in progress

Niobium Cavity

T = 300K
f_c = 13.964 GHz
Q_0 = 5.0*10^3

T = 4.2K
f_c = 13.960 GHz
Q_0 = 5.0*10^5



Summary

- Variety of ways to search for axions and axion like particles – Goal should be to cover allowed parameter space since mass/coupling is unknown!
- Coupling to photons

(DM axions [haloscopes], Solar axions [helioscopes], Lab axions [LSW])

- Coupling to nucleons

(DM axions [Casper-E, Casper-Wind, QUAX],

Lab axions [ARIADNE – next lecture])