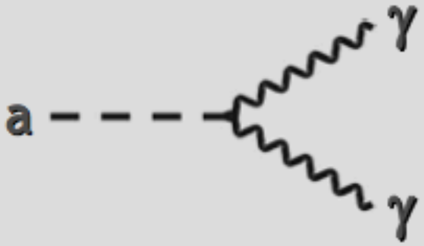
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

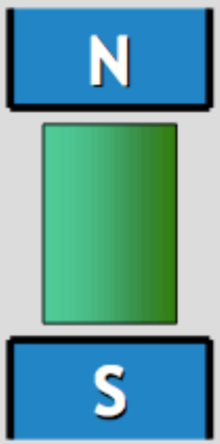
- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

Cosmology

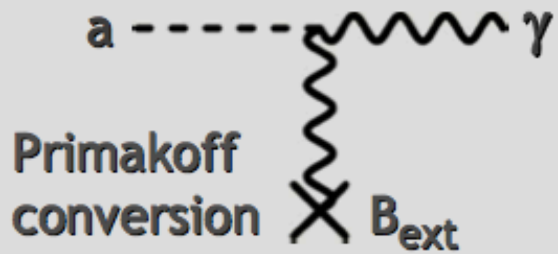
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

→ Cold dark matter candidate
$m_a \sim$ 1-1000 μeV

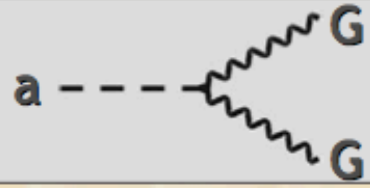
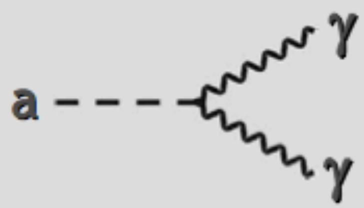
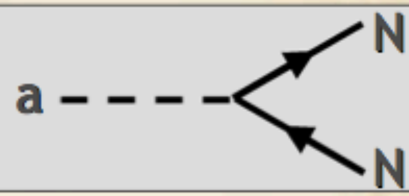
Search for Axion Dark Matter



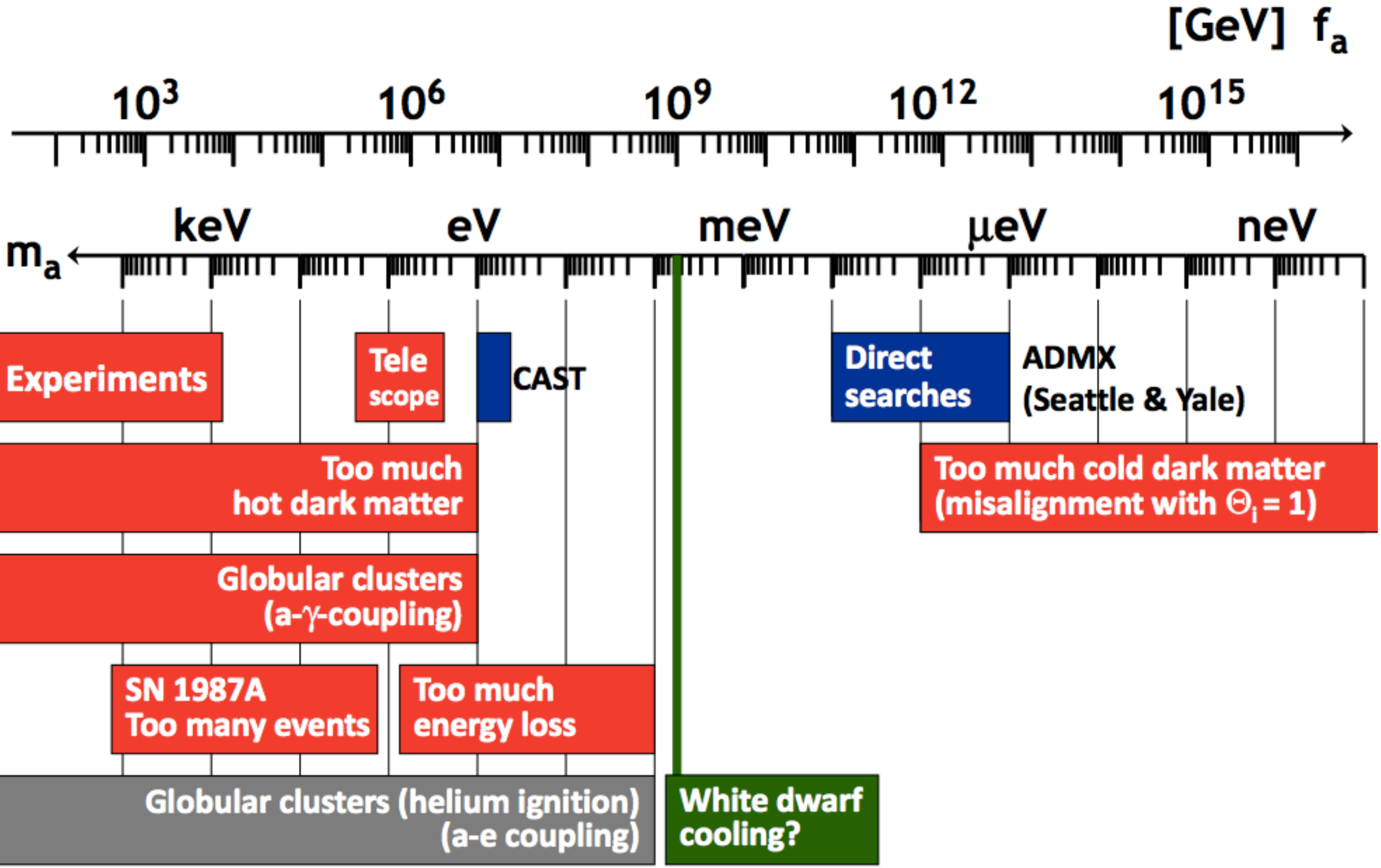
Microwave resonator (1 GHz = 4 μeV)



Axion Properties

Gluon coupling (Generic property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass	$m_a = \frac{0.6\,\text{eV}}{f_a / 10^7\,\text{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$	
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma} \vec{E}\cdot\vec{B}a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0 \pi^+ \partial_\mu \pi^- + \ldots)\partial^\mu a$	
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$	
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$	

Axion Bounds and Searches

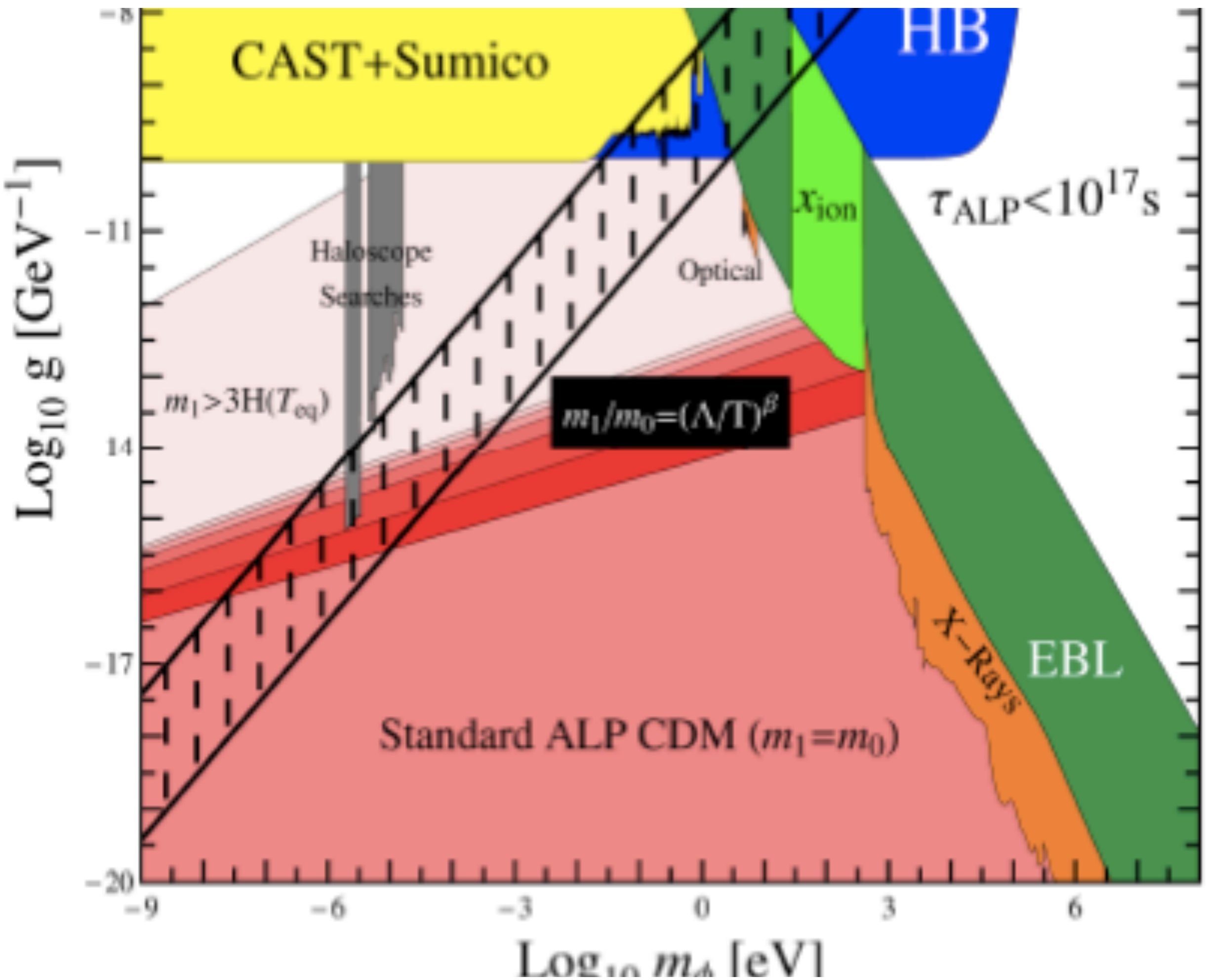


Current experimental limits

$$L = -\frac{1}{4} g_W \varphi F_{\alpha\beta} \tilde{F}^{\alpha\beta}$$

$$g_W \approx \frac{\alpha}{m_e} g_p$$

Primakov Conversion

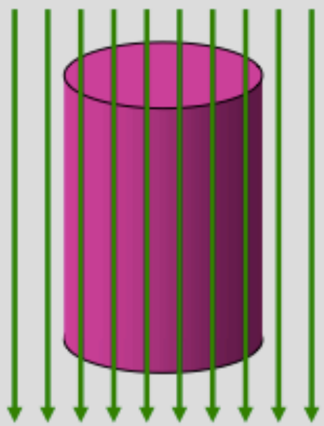


Search for Galactic Axions (Cold Dark Matter)

DM axions	m_a = 10-3000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$

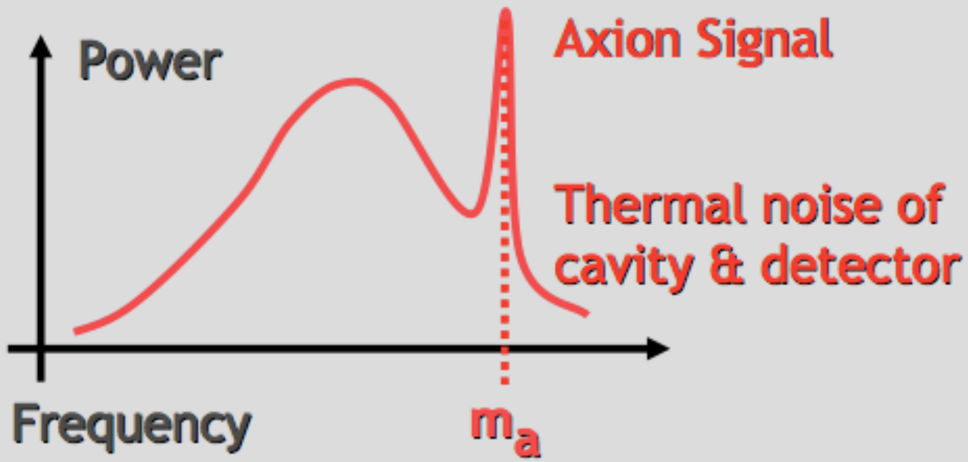
→ **Microwave Energies (1 GHz ≈ 4 μeV)**

Axion Haloscope (Sikivie 1983)

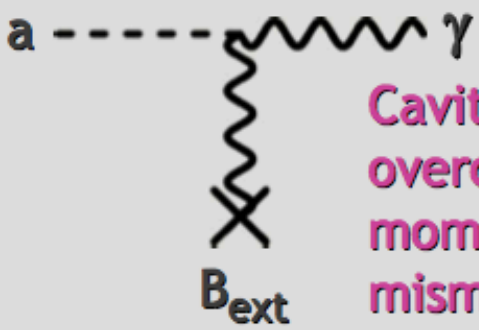


$B_{ext} \approx 8$ Tesla

Microwave Resonator
$Q \approx 10^5$



Primakoff Conversion

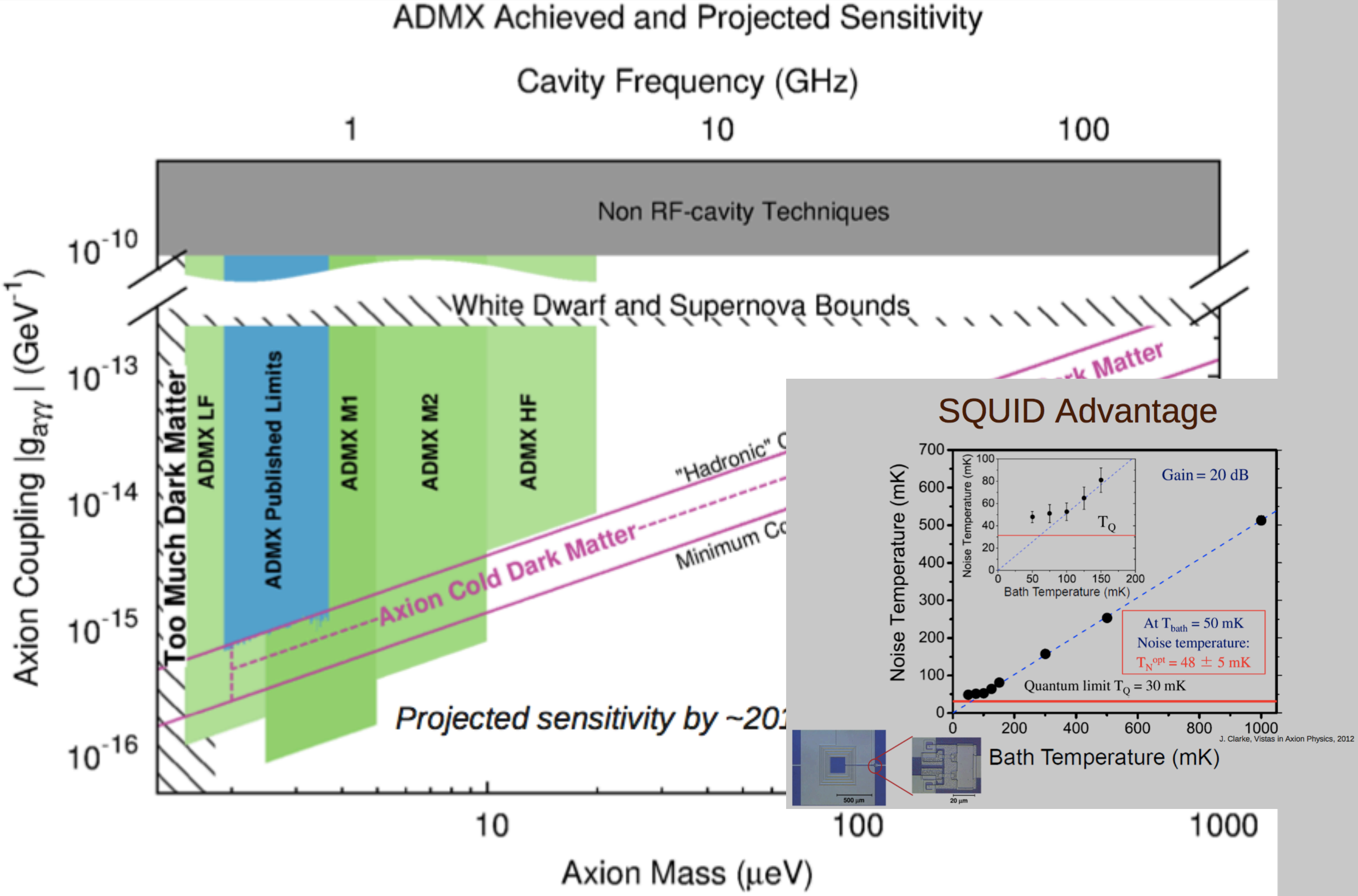


Cavity overcomes momentum mismatch

Power of galactic axion signal

$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm}^3}\right)$$

ADMX Near Term Targets



Search for galactic axion – new proposal

Exploit the axion-electron coupling

$$L_{ae} = \frac{C_e}{2f_a} \bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \, \partial_\mu a$$

Ce ≤ 10-13Gev-1

$$H_a = -\vec{S} \cdot \left[\frac{g_p}{m_e} \nabla a \right]$$

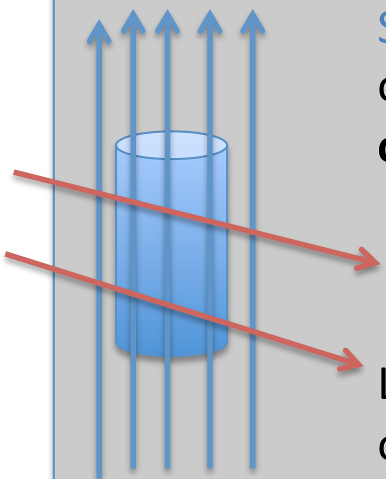
(only DFSZ axion)

Axion wind equivalent to magnetic field

$$B_E = \frac{2 g_p}{e} \frac{g_a}{g_J} \nabla_z a$$

$$B_{Ef} \approx \left(\frac{m_a}{10^{-4} eV} \right) 9.4 \times 10^{-23} T$$

Detection using EPR magnetometry

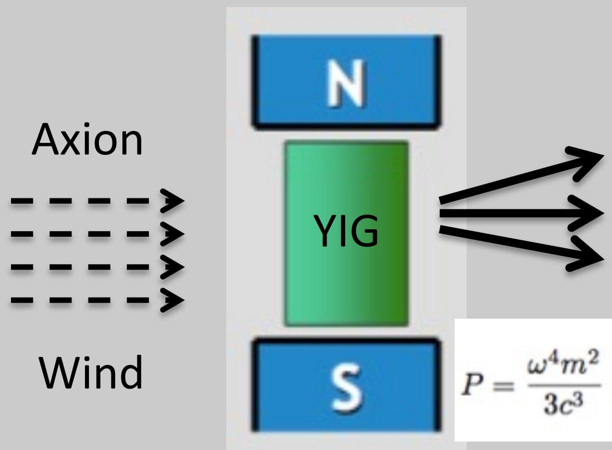


Static external field on **paramagnetic crystal sample**

Modulated RF field

Low frequency detection of **induced magnetization**

- Excess Noise in Magnetized Crystal
-Zeeman Transition in Optical Crystals



$$P = \frac{\omega^4 m^2}{3c^3} = M_0^2 \frac{\omega_H^4}{3c^3} \left(\frac{b}{H_0} \right)^2 Q^2$$

For both schemes **annual modulation expected**

ELECTRON – AXION interaction through SPIN

F. Wilczek, J.M. Martín, J. Leon, R. Barbieri, I.V. Kolokolov, G. Raffelt

$$L = \overline{\psi}(x)\,(i\hbar\,\not{\partial}_x - mc)\,\psi(x) - a(x)\overline{\psi}(x)\,(g_s + ig_p\gamma_5)\,\psi(x) \qquad (1)$$

The energy of interaction between spin and axion-field is

$$H_a = -\vec{S}\cdot\left[\frac{g_p}{m_e}\nabla a\right]$$

This looks like a **magnetic coupling** through electron spin

$$\Delta E_a = \frac{g_p}{m_e}\hbar g_a \nabla_z a$$

$$B_E = \frac{2g_p}{e}\frac{g_a}{g_J}\nabla_z a$$

Effective magnetic field for cosmological axion

$$B_{Ef} \approx \left(\frac{m_a}{10^{-4}\,eV}\right) 9.4\times10^{-23}\,T$$

DETECTION TECHNIQUES :

Electron Spin Resonance Magnetometry with Paramagnetic Materials

Optical Spectroscopy in Paramagnetic Crystals

Effective B RF field @ 10^-22 T seems feasible to attain

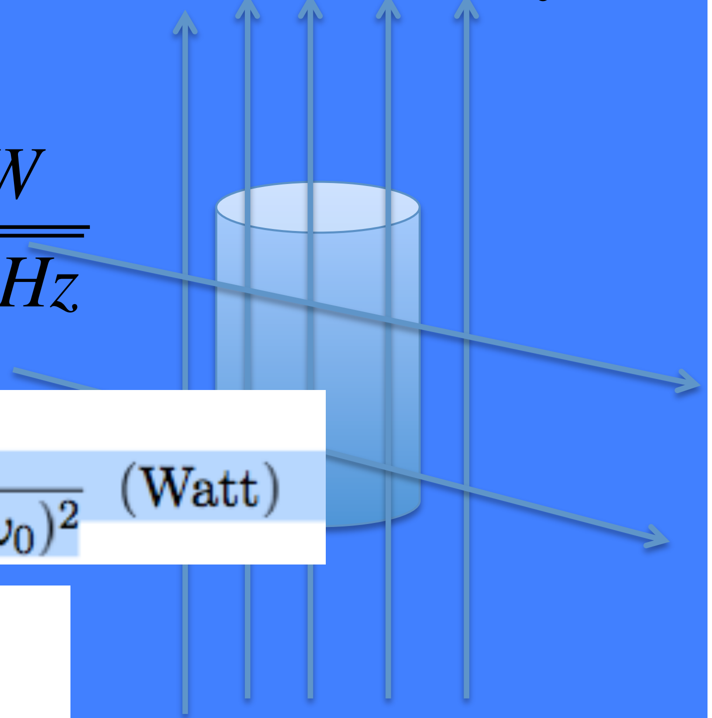
ESR Magnetometry/Zeeman Spectroscopy:

from 10μeV to meV (GHz to THz)

SAMPLE: DPPH , TbF3 , YIG, Ruby

$$m = M_0 \frac{b}{H_0} Q,$$

$$P_{\min RF} = 10^{-22} \frac{W}{\sqrt{Hz}}$$

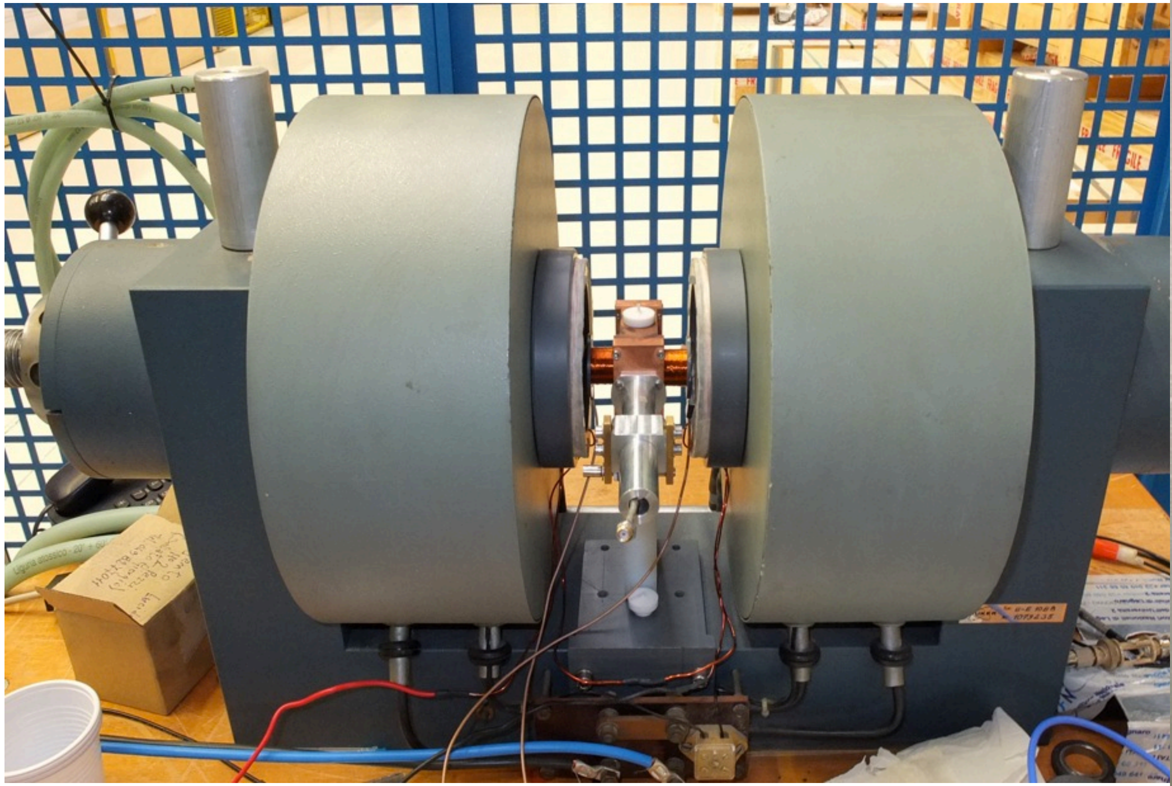


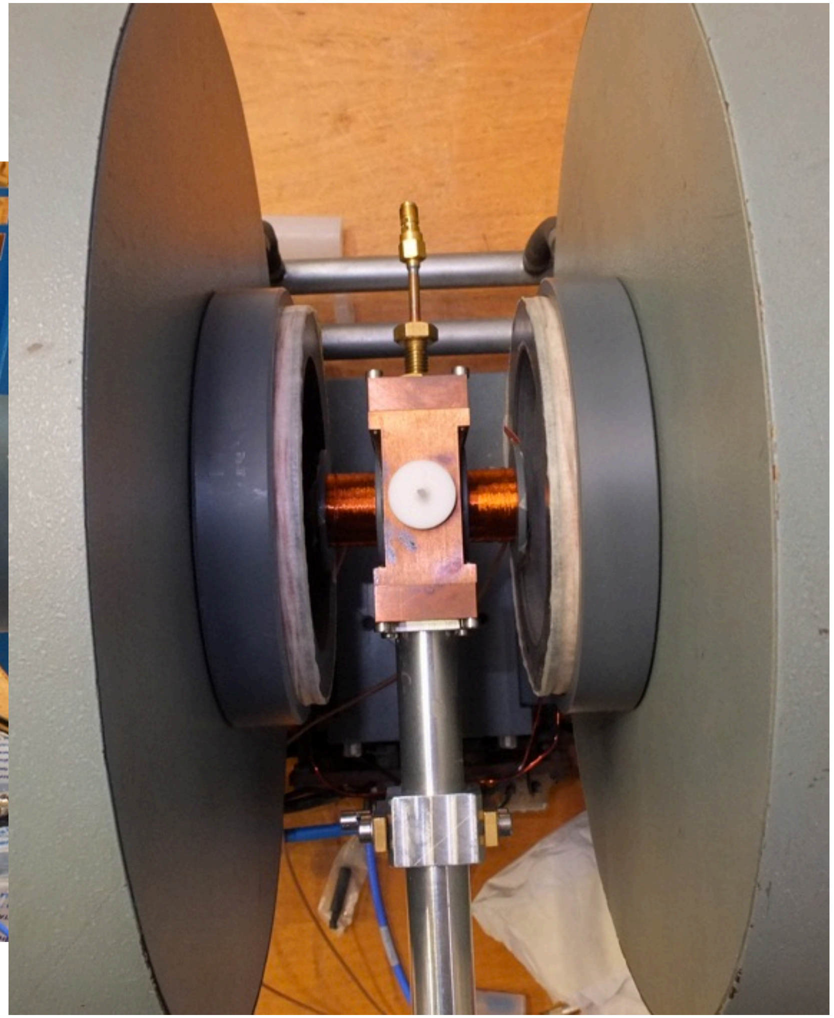
$$P_a(\omega) = \frac{\omega^2}{12\pi c^3}(\dot{m})^2 = \frac{1}{4\pi}\frac{\omega^4}{3c^3}\frac{B_a^2 V^2}{\mu_0}\frac{\gamma^2 M_0^2 \tau^2}{1+\tau^2(\omega-\omega_0)^2} \quad \text{(Watt)}$$

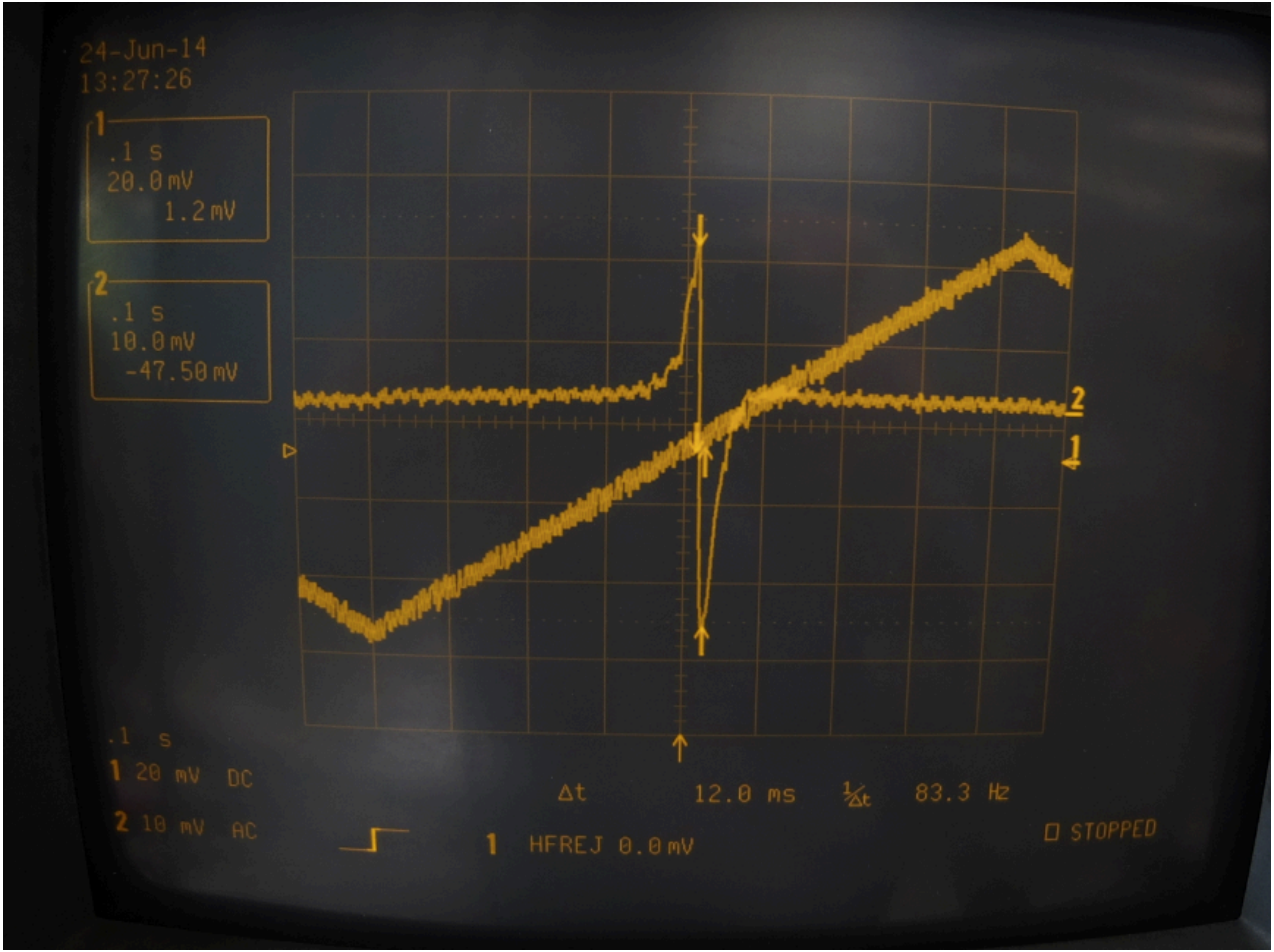
$$\mathrm{SNR}^2 = \frac{M_s^2(\nu)}{\mathcal{M}_n^2(\nu)}\frac{1}{\Delta\nu} = \frac{\gamma M_0 \tau B_a^2 V}{2\mu_0 \hbar \coth\left(\frac{\hbar\omega}{2k_B T}\right)}\frac{1}{\Delta\nu}$$

$$P_{\text{noise}} = \hbar\omega\sqrt{\frac{\Delta\nu}{t_{\text{int}}}} = 1.58 \cdot 10^{-23}\left(\frac{m_a}{10^{-4}\text{eV}}\right)\sqrt{\frac{\Delta\nu}{t_{\text{int}}}} \quad \text{W}$$

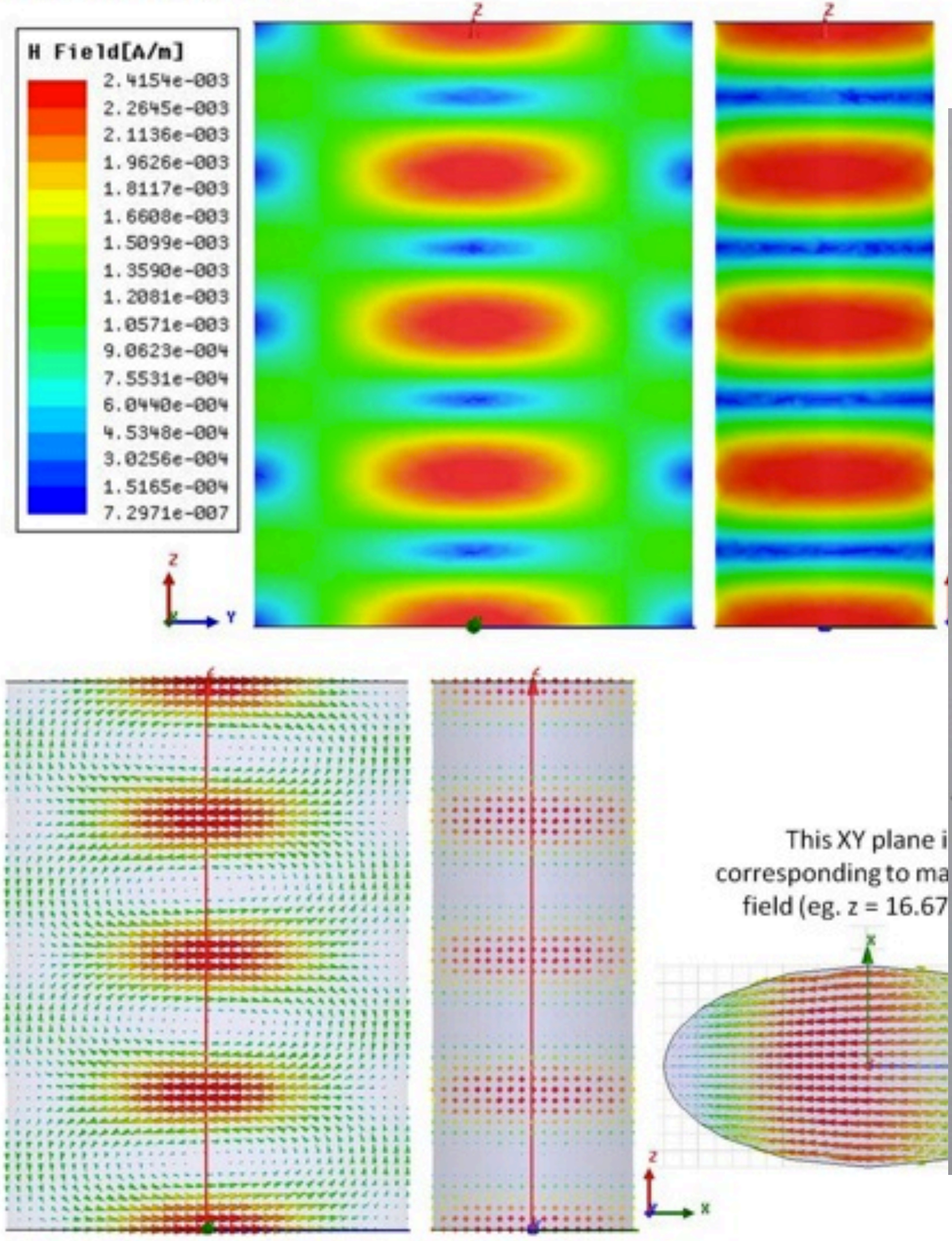
LNL EPR SET UP

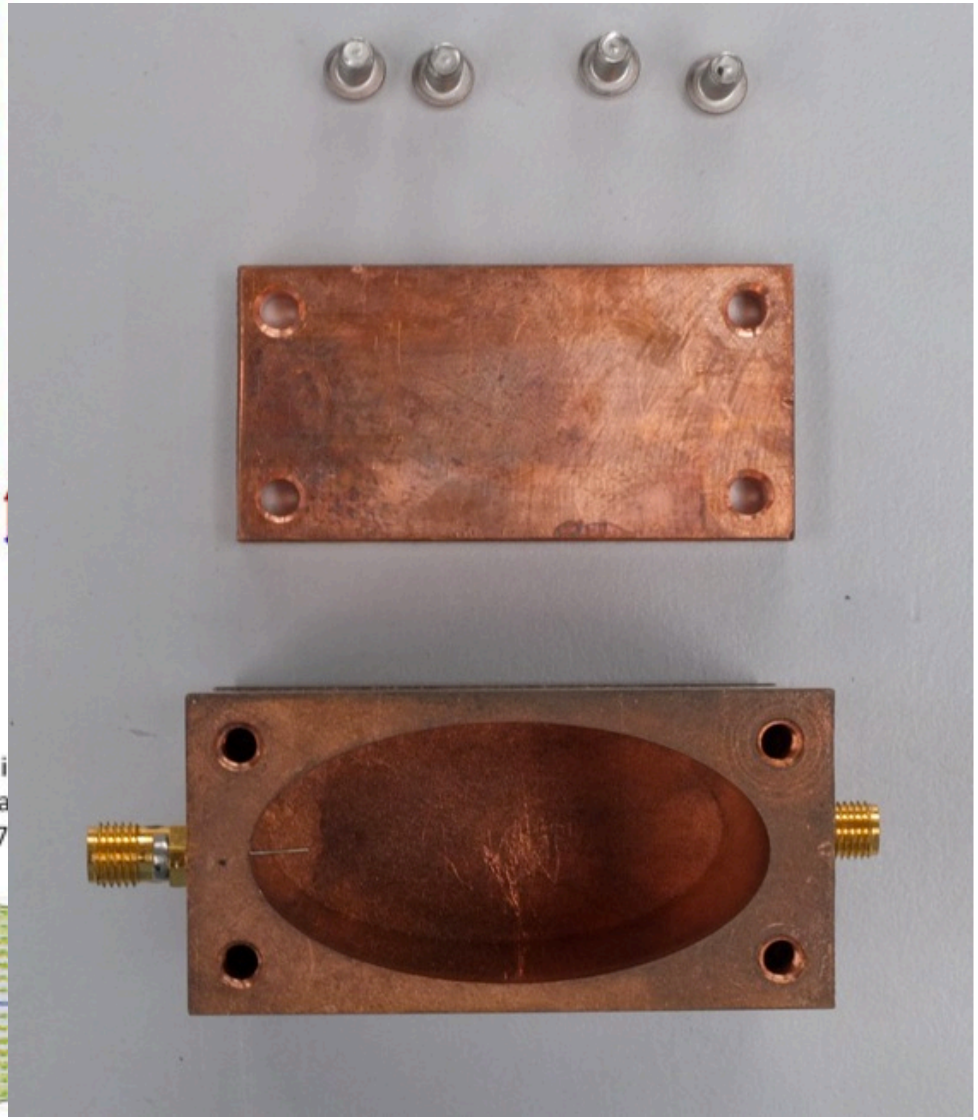




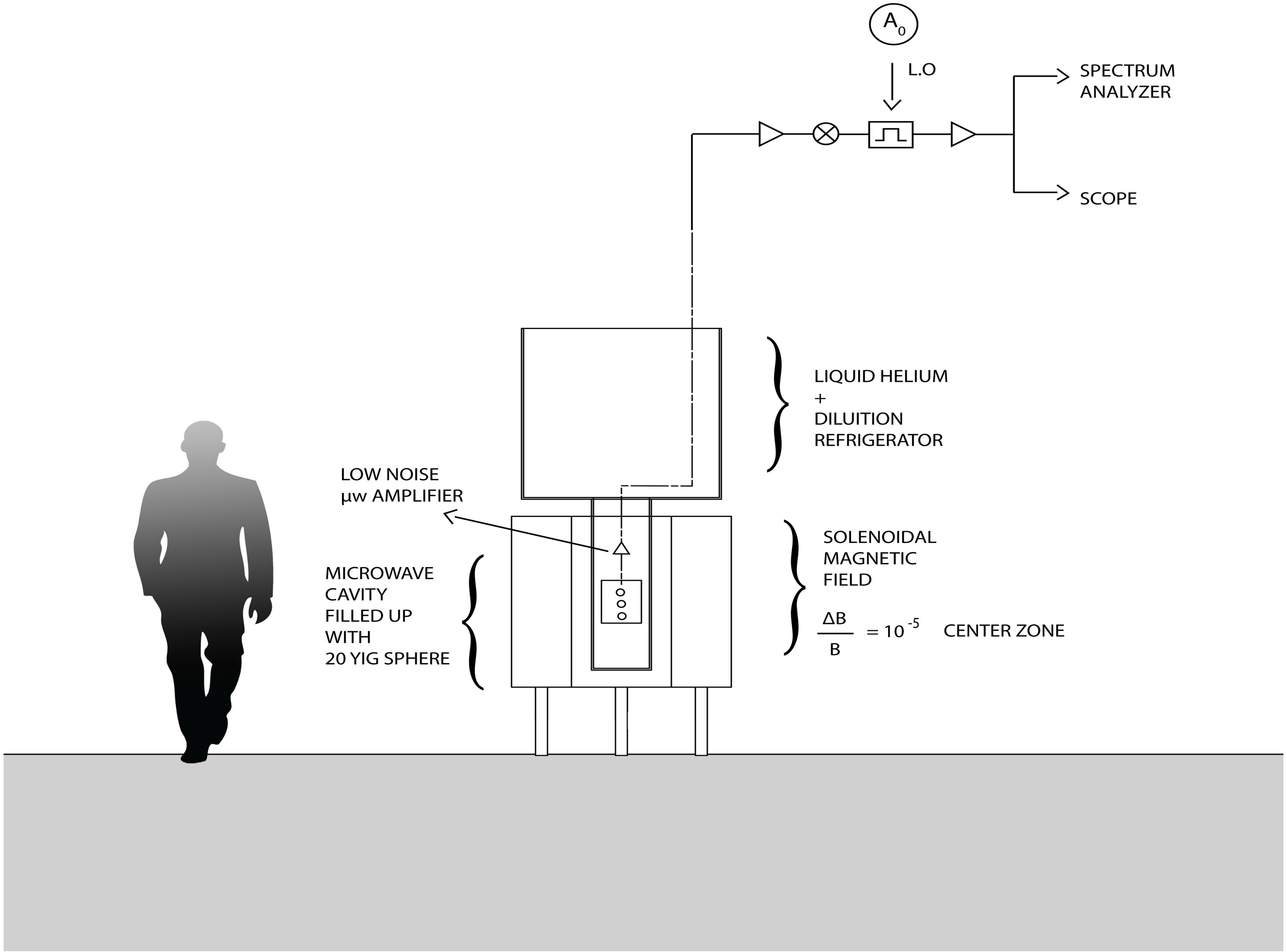

24-Jun-14
13:27:26
1
.1 s
20.0 mV
1.2 mV
2
.1 s
10.0 mV
-47.50 mV
.1 s
1 20 mV DC
2 10 mV AC
Δt 12.0 ms 1/Δt 83.3 Hz
1 HFREJ 0.0 mV
STOPPED

Magnetic field distribution





$Q_{UAERERE}$ - A_{XION} EXPERIMENTAL SET -UP



QUAX Activities (2015 – 2017/8) :

1) High Susceptivity Material , Low Dissipation (LNL-INRIM.TO)

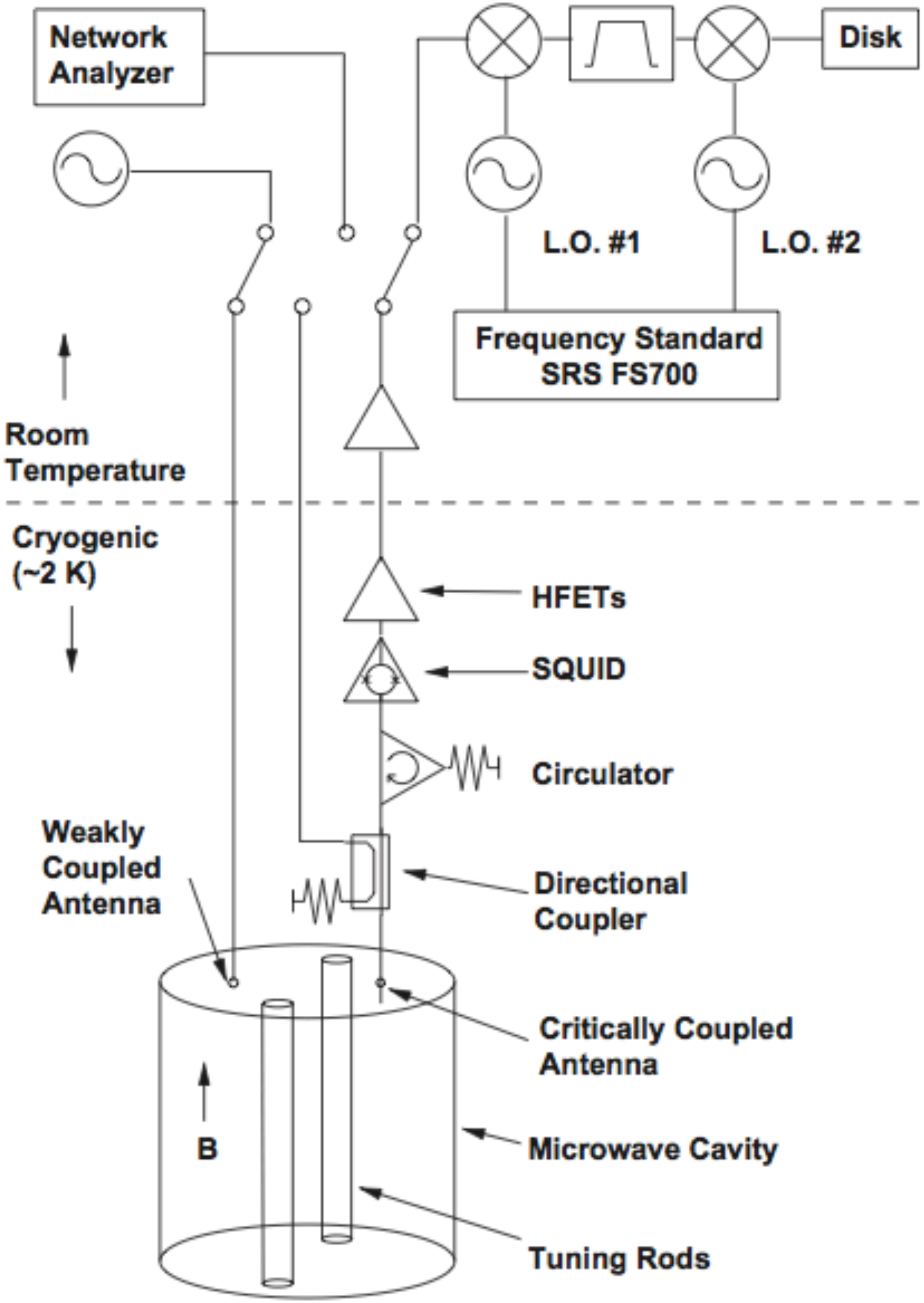
2) Low Noise Receiver : Linear / Quantum @ near QL(PD-LNL)

3) High Frequency High Q Microwave Cavity 10^5: (PD-LNL)

4) High Magnetic Field : 05-1 Tesla (GE-LNL)

5) Cryogenics @ 100 milliKelvin (TN-PD)

6) Optical Spectroscopy on Paramagnetic Single Crystals Zeeman



Network Analyzer
Disk
L.O. #1
L.O. #2
Frequency Standard SRS FS700
Room Temperature
Cryogenic (~2 K)
HFETs
SQUID
Circulator
Weakly Coupled Antenna
Directional Coupler
Critically Coupled Antenna
B
Microwave Cavity
Tuning Rods

“Hybrid” superconducting cavities may increase Q, and thus increase signal power

Open resonators may be the key to explore axion masses up to meV