Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

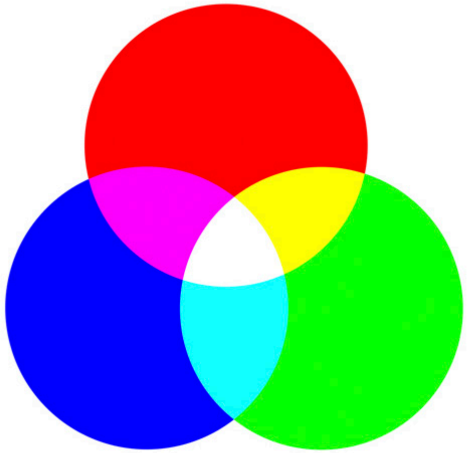
SEARCH FOR AXION AND AXION-LIKE-PARTICLES AT LNF

CLAUDIO GATTI, LABORATORI NAZIONALI DI FRASCATI - INFN

56th Scientific Committee Meeting, LNF November 5th 2018

OUTLINE

- Introduction on Axions and Axion Dark-Matter
- Axion Research at LNF
  a) COLD Lab @ LNF
  b) QUAX
  c) SIMP
  d) KLASH
- Publications
- Collaborations
- Conclusion



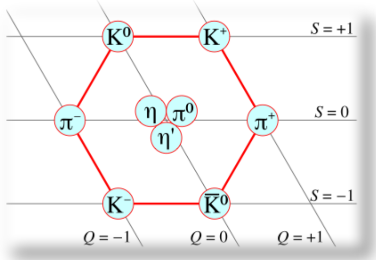
INTRODUCTION

AXIONS in one slide

U(1)$_A$ problem

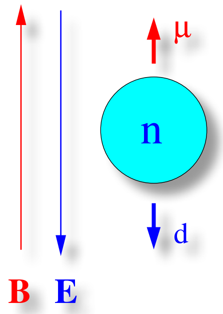
$$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$$

S.Weinberg U(1) problem PRD 11 (1975)



Strong CP problem

$$\mathcal{L}_{QCD}^{\not{CP}} = \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$



Phys Rev Lett 82, n.5 (1999) p.904

$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$\theta < 10^{-10}$$

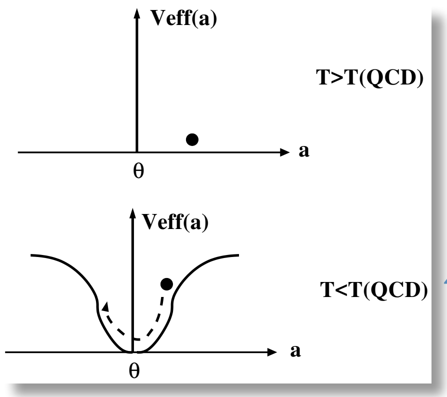
R.D.Peccei and H.R.Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977).
S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

Axions

$$\mathcal{L}_{QCD}^{\not{CP}} = \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

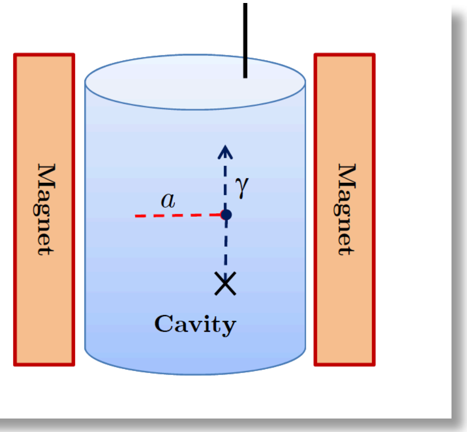
Axion Dark Matter

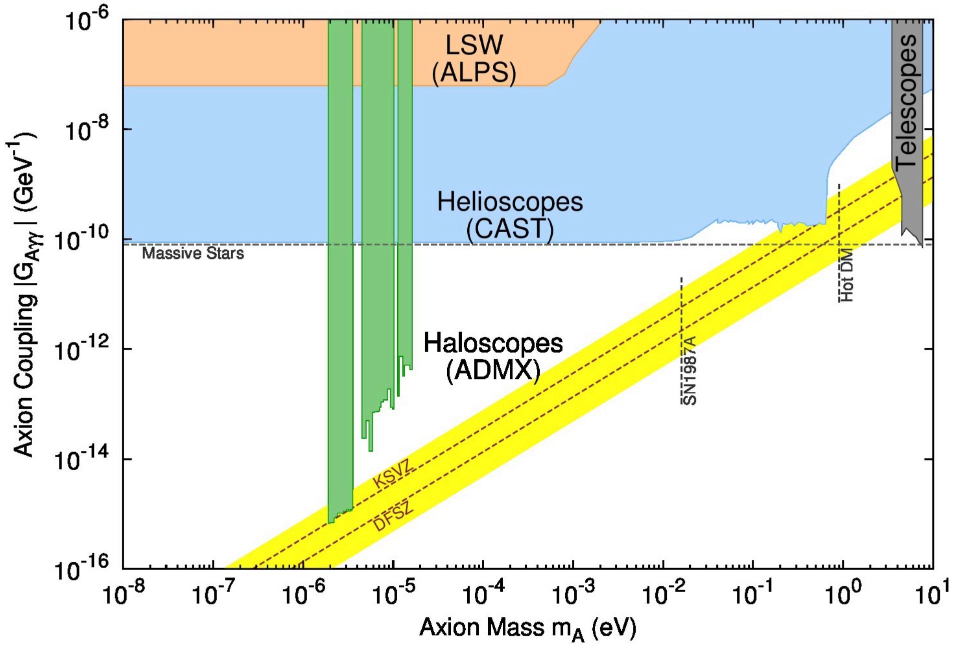
Misalignment mechanism



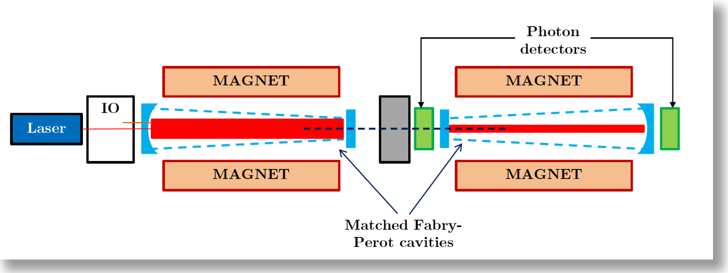
Axion Searches

Axion DM (Haloscopes):
ADMX, HAYTSTAC.

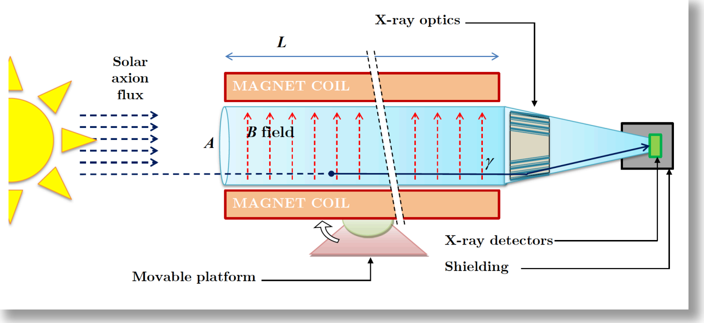




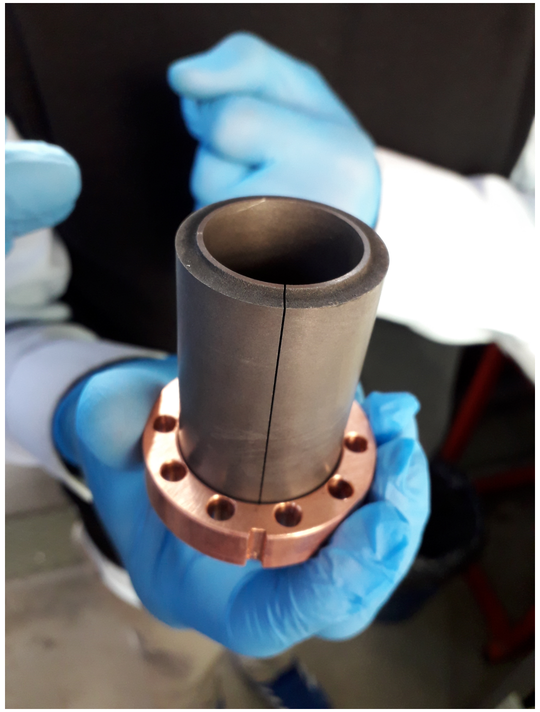
Laboratory searches (LSW):
PVLAS, ALPS, CROWS, OSQAR.



Axions from Sun (Helioscopes):
CAST, SUMICO.



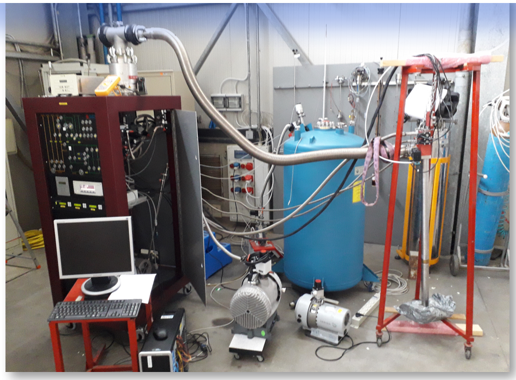
A recent review: Irastorza Redondo Arxiv:1801.08127

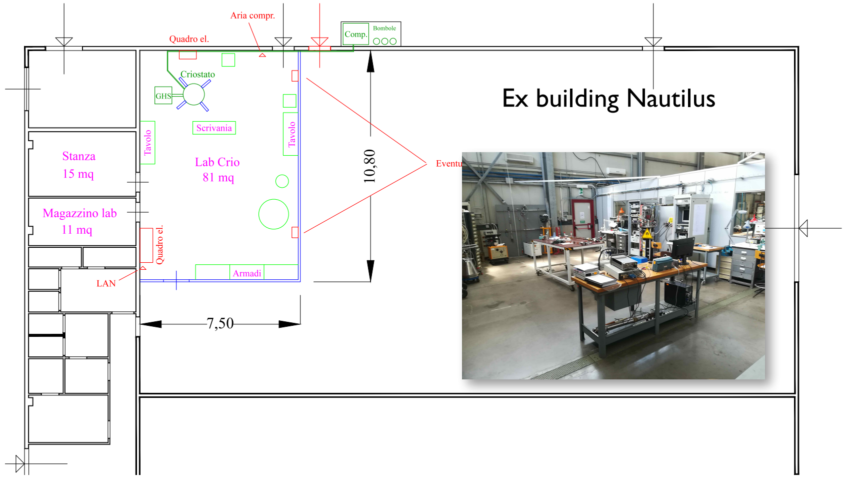


AXION RESEARCH AT LNF

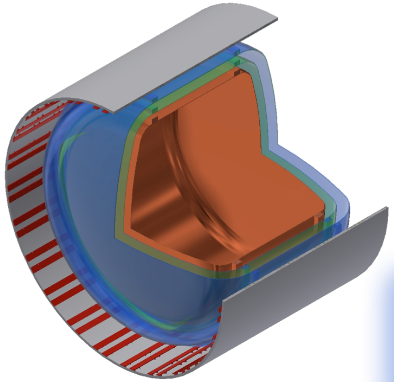
CryOgenic Laboratory for Detectors

SIMP (CSN5)
SIngle Microwave Photon detection





QUAX (CSN2)
QUest for AXions



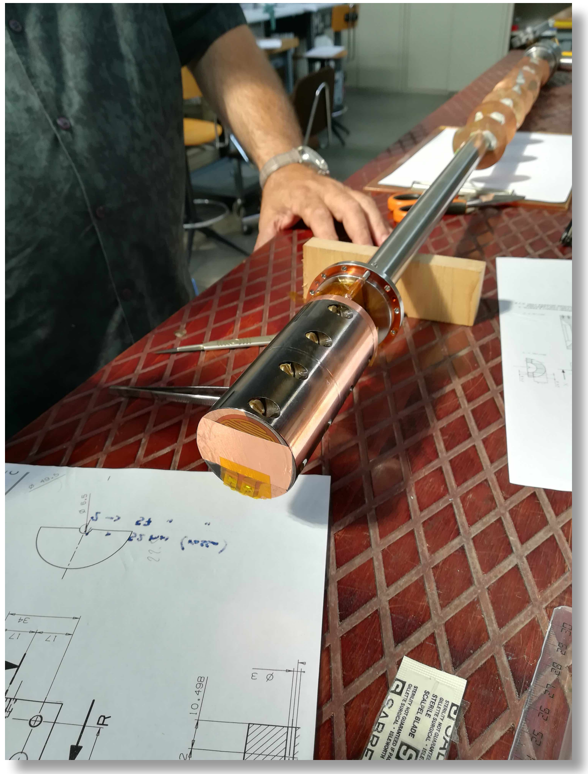
KLASH (CSN2)
KLoe magnet for Axion SearcH

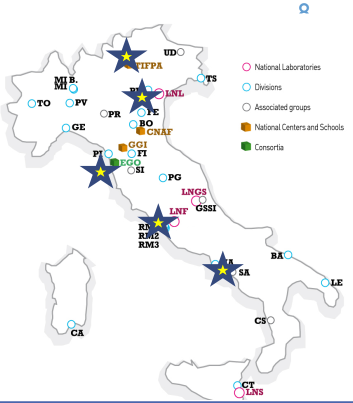
Nb-Island Device
(In collaboration with TERA CSN5)

QUAX: Quest for Axions

Quax: 3 years R&D (2017-2019) funded by CSN2 (total budget about 300 k€).

LNF 2019	FTE
C Gatti (R, Loc Resp)	0.5
D Di Gioacchino (R)	0.5
C Ligi (T)	0.2
D Alesini (PT)	0.1
G Lamanna (Uni Pi)	0.1
G Maccarrone (PR)	0.3
D Babusci (PR)	0.3
D Moricciani (R)	0.3
S Tocci (Research fellow)	1.0
A Rettaroli (PhD student)	1.0
Tot	4.3





Research Units
Padova (Nat Resp)
LNL (experiment site)
LNF
TIFPA FBK
Sa
Pi

QUAX: Quest for Axions

Quax Experimental Scheme

Use Electron Spin Resonance to absorb energy from Axion Wind and re-emit it as *e.m.* radiation.

$$i\hbar\frac{\delta\phi}{\delta t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p\hbar}{2m}\sigma\cdot\nabla a\right]\phi$$

$$B_0 = \frac{m_a c^2}{\gamma\hbar} = 1.7\left(\frac{m_a}{200\mu\mathrm{eV}}\right)\ \mathrm{T}$$

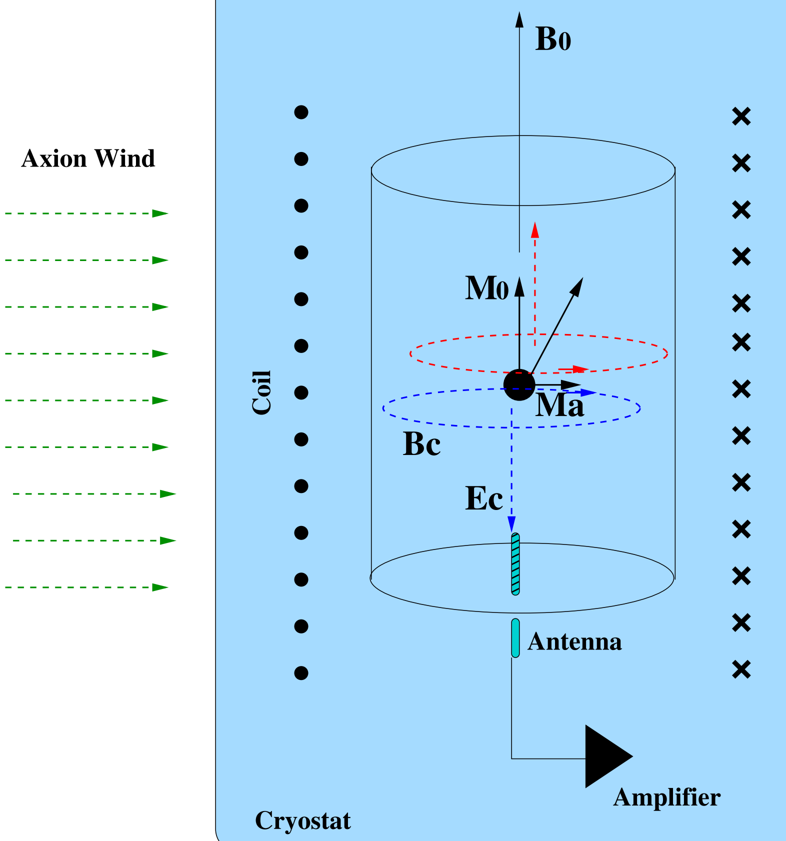
Tune Larmor frequency to Axion energy by changing DC field

$\gamma = e/m_e$

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

Axion frequency

Phys. Dark Univ. 15 (2017) 135

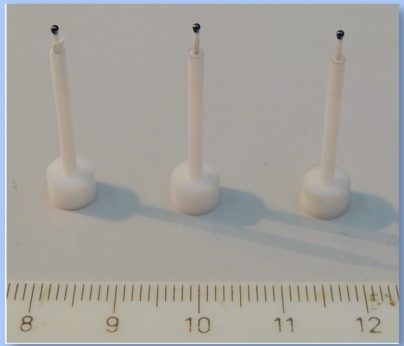


$$\lambda_a = \frac{h}{mv_a} \gg L_{detector}$$

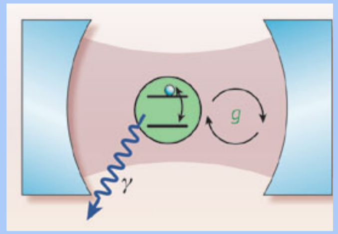
QUAX R&D

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

$$\tau_1 \gg \tau_2 \sim \mu\text{s}$$



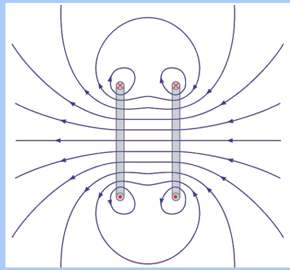
Magnetic material with:
n_s~$10^{28}/m^3$
τ_2~1 μs
Volume 100 cm^3



$$P_{out} = 3.8 \times 10^{-26} \text{ W}$$

Single microwave photon counter

$$\tau_B = \frac{1}{\omega_a}\frac{B_0}{\delta B_0} \sim 1\mu\text{s} \left(\frac{10\text{GHz}}{\omega_a}\right)\left(\frac{10^{-5}}{\delta B/B}\right)$$



SC magnet with:
Field up to 2 T
High uniformity
High stability

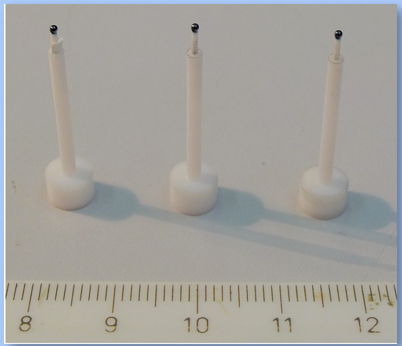
$$\tau_c = \frac{Q}{\omega_a} \sim 10\mu\text{s} \left(\frac{10\text{GHz}}{\omega_a}\right)\left(\frac{Q}{10^6}\right)$$

Resonant cavities with high Q~10^6 operated at 100mK in a magnetic field ~2T

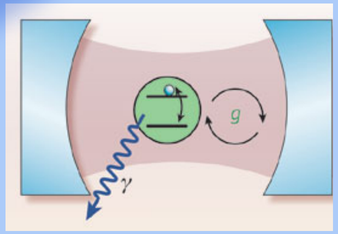
QUAX R&D

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

$$\tau_1 \gg \tau_2 \sim \mu\text{s}$$



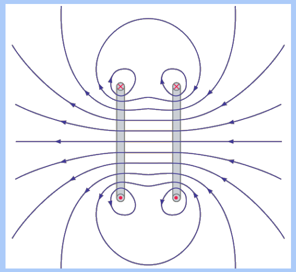
Magnetic material with:
n_s~$10^{28}/m^3$
τ_2~$1\,\mu s$
Volume 100 cm^3



$$P_{out} = 3.8 \times 10^{-26} \text{ W}$$

SIMP: Single microwave photon counter

$$\tau_B = \frac{1}{\omega_a}\frac{B_0}{\delta B_0} \sim 1\mu\text{s} \left(\frac{10\text{GHz}}{\omega_a}\right)\left(\frac{10^{-5}}{\delta B/B}\right)$$



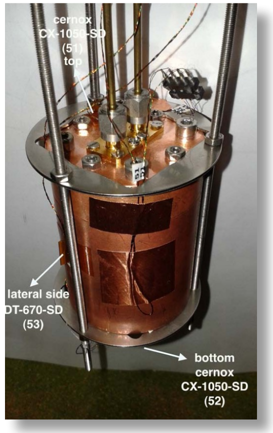
SC magnet with:
Field up to 2 T
High uniformity
High stability

$$\tau_c = \frac{Q}{\omega_a} \sim 10\mu\text{s}\left(\frac{10\text{GHz}}{\omega_a}\right)\left(\frac{Q}{10^6}\right)$$

Resonant cavities with high Q~10^6 operated at 100mK in a magnetic field ~2T

QUAX R&D: High-Q RF-Cavities operating in B field

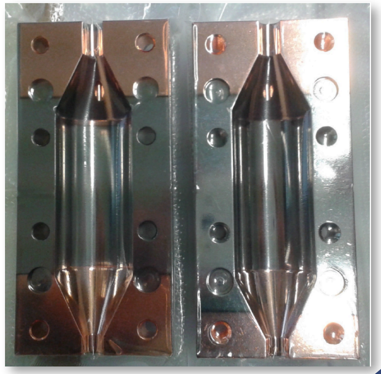
Copper cavity

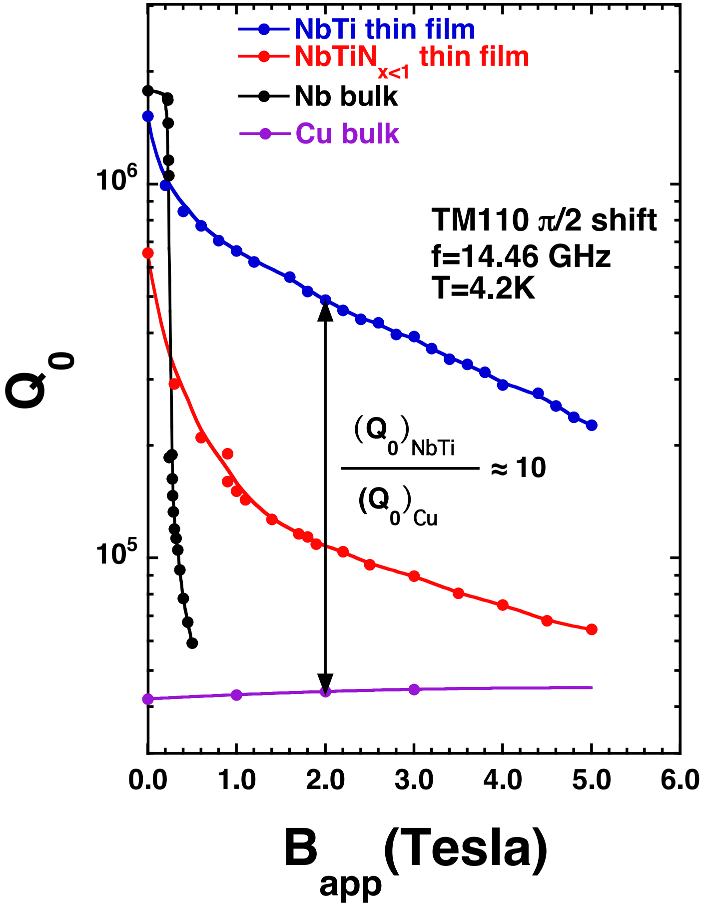


Bulk Nb cavity (H_{c2} 0.6 T)

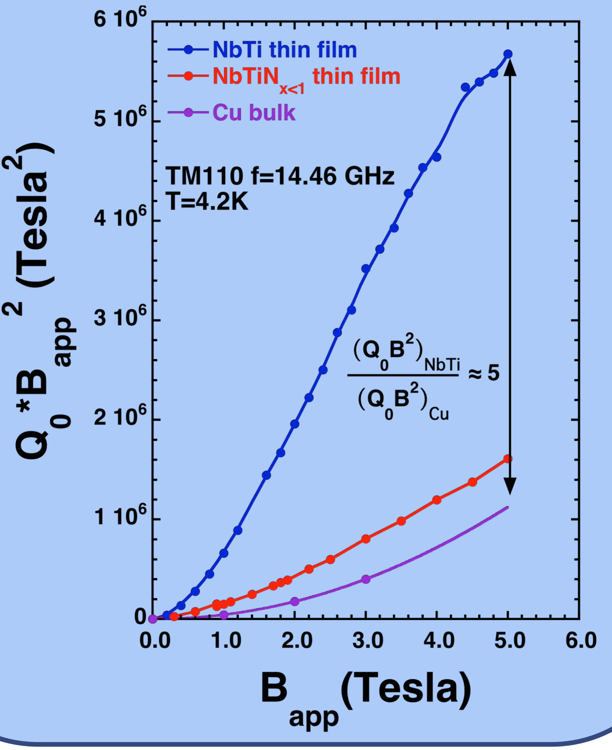
$$R_S^{SCtypeII} \propto \left(\frac{B}{B_{c2}}\right)^{\alpha}$$

Sputtered NbTi cavity (H_{c2} 13 T)

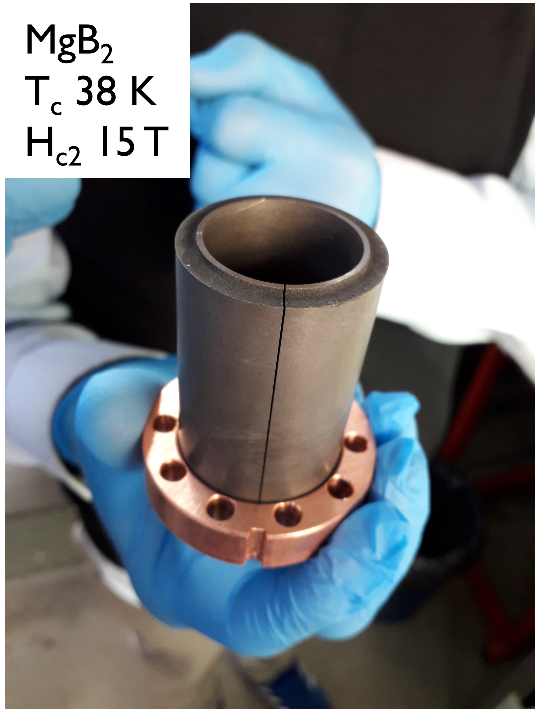




Gain factor 5 in power for Primakoff conversion at 5 T and14 GHz with NbTi cavity (paper in preparation)!

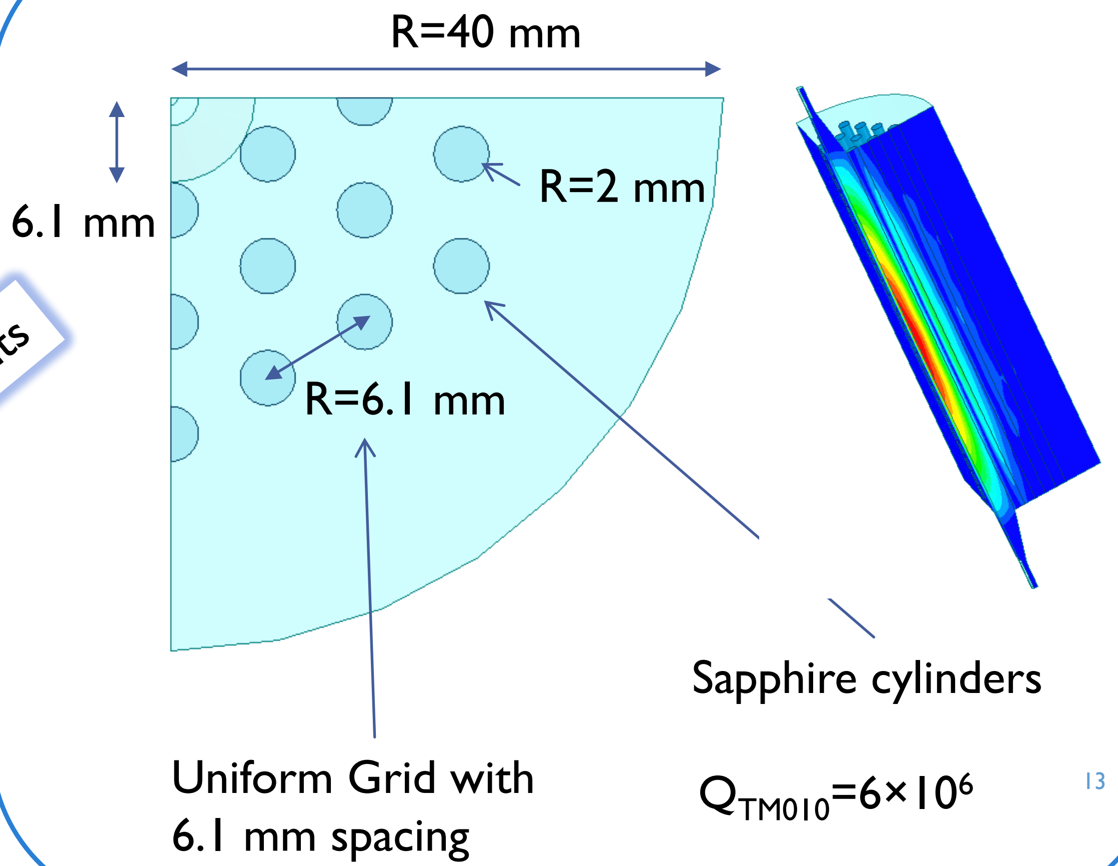


QUAX R&D: Type II SC and Photonic Band Gap RF-Cavities



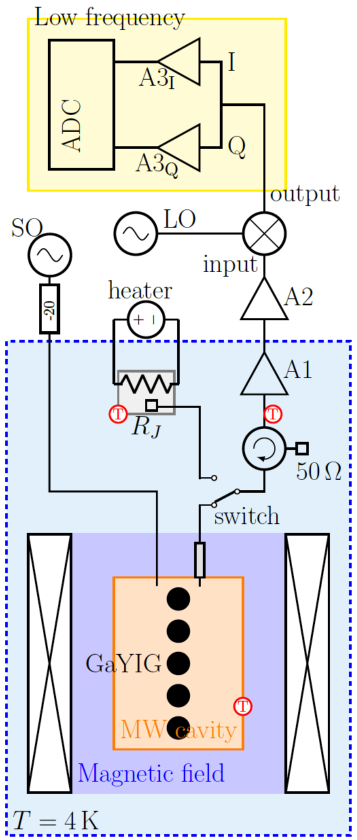
EDISON SPA (Milan) developed the reactive liquid infiltration technique to produce bulk MgB_2
G.Giunghi, Supercond. Sci. Tech. 20 (2007) L16-L19

Ongoing measurements



$Q_{TM010}=6\times10^6$

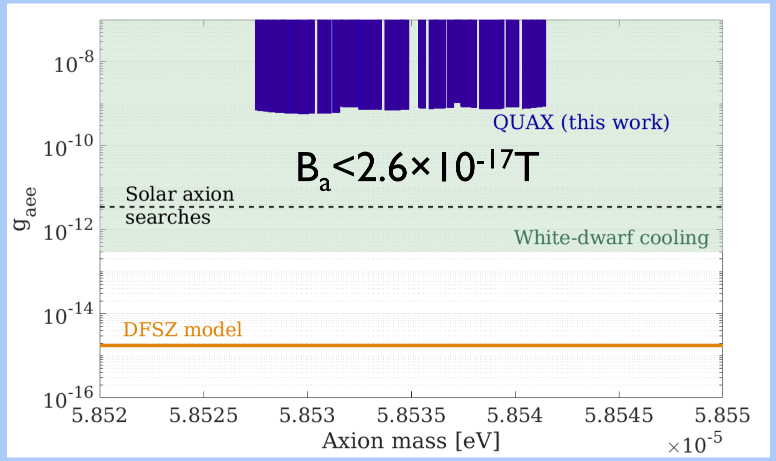
First Operation of a Ferromagnetic Axion Haloscope at m_a = 58μeV



QUAX demonstrator succesfully put in operation!

Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =1 mm)	5
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.11
Frequency [GHz]	13.98
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [K]	5.0

EPJC (2018) 78:703



- Next improvements (sensitivity gain 10^2):
  1. Larger sample volume
  2. Longer relaxation time
  3. Ultra cryogenic temperature
  4. Quantum limited amplifier (JPA).

SIMP: SIngle Microwave Photon detection

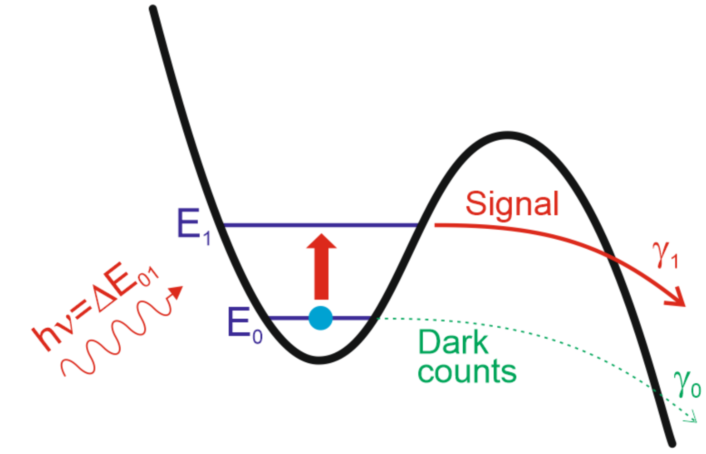
LNF 2019	FTE
C Gatti (R, Nat Resp)	0.5
D Di Gioacchino (R)	0.5
C Ligi (T)	0.3
D Alesini (PT)	0.1
G Felici (DR)	0.1
B Buonomo (T)	0.3
L Foggetta (T)	0.2
A Gallo (DT)	0.1
G Castellano (PR CNR)	0.1
F Chiarello (R CNR)	0.3
F Mattioli (R CNR)	0.3
G Torrioli (R CNR)	0.3
Tot	3.1

SIMP: 3 years R&D (2019-2021) funded by CSN5 (total budget about 300 k€)

Unità	FTE	Device
LNF	2.1	CBJJ
INFN Pi	1.3	TES
INFN Sa	1	CBJJ
TIFPA-FBK	0.6	TES
CNR Nano NEST	1.6	TES
CNR IFN	1	CBJJ
INRIM	0.6	TES
TOT	8.2	

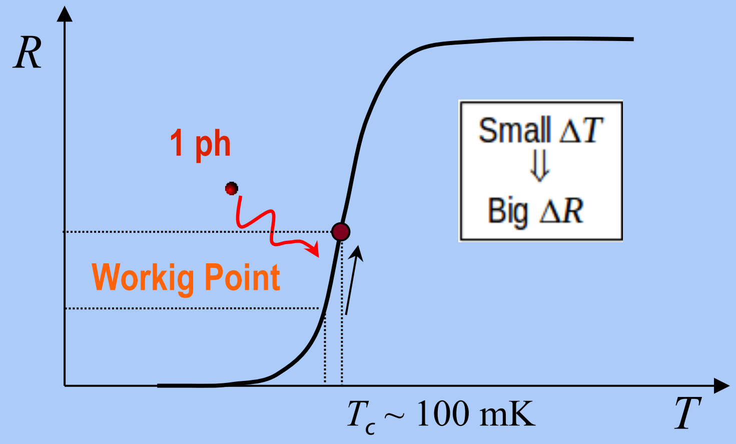
SIMP: Towards the Detection of Single Microwave Photons (10-100 GHz)

Current Biased Josephson junction



Following absorption of a photon, the voltage at the terminals of the Josephson junction passes from a null value to a few hundred microvolts, until the junction is reset.

Transition Edge Sensor

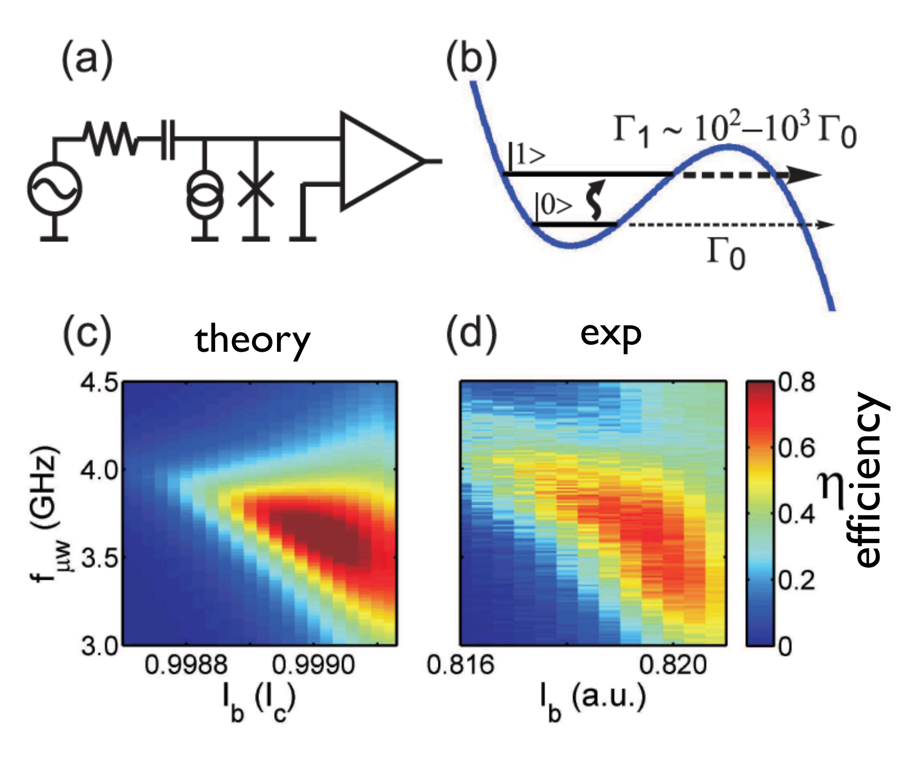


A TES detector is based on the steep transition to the resistive state of a superconducting film. Stability is guaranteed by thermo-electric effect.

CBJJ

State of Art

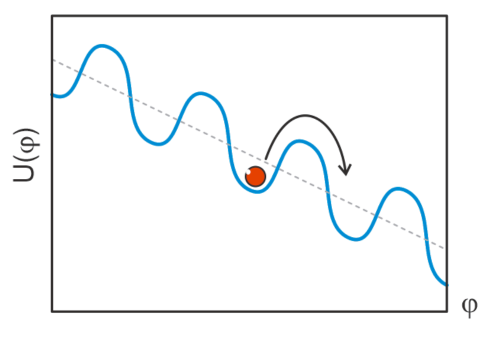
Al-AlOx-Al 1000 μm² junction



Chen et al. PRL 107, 217401 (2011)

Thermal activation process

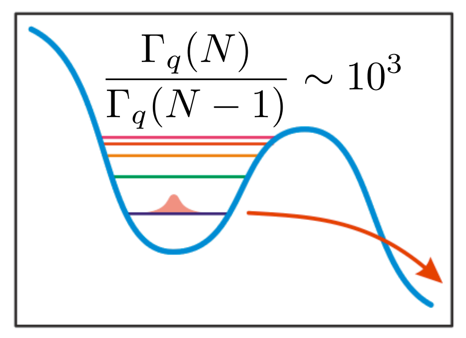
$$\Gamma_t = \frac{\omega_0}{2\pi} a_t \exp\left(-\frac{\Delta U}{k_B T}\right)$$



Macroscopic quantum tunneling

$$\Gamma_q \simeq \frac{\omega_0}{2\pi}\sqrt{\frac{7.2\Delta U}{\hbar\omega_0}} \exp\left(-\frac{7.2\Delta U}{\hbar\omega_0}\right)$$

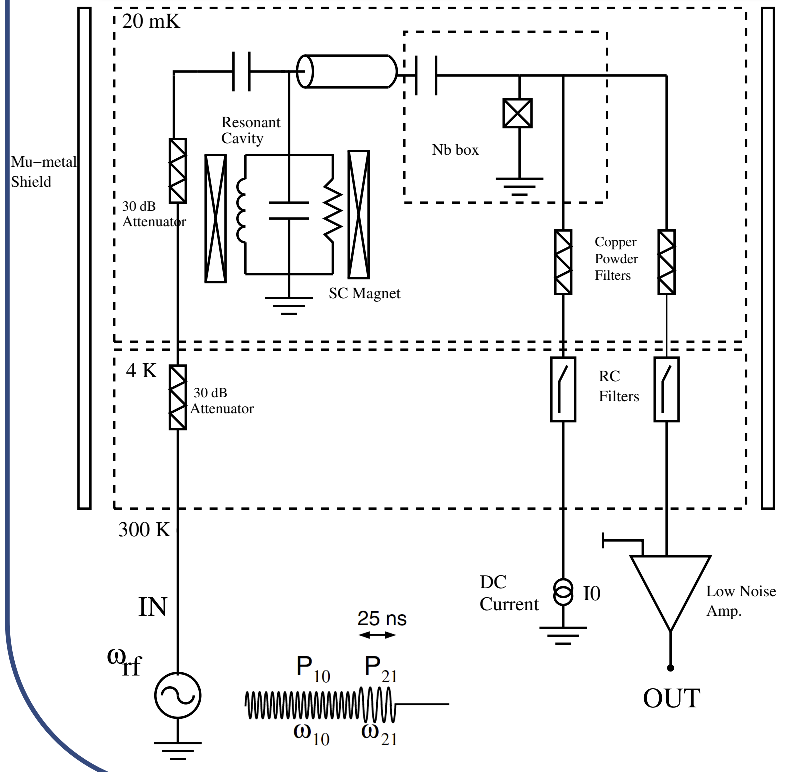
$$\Delta U = 2E_j\left[\sqrt{1-(I_0/I_c)^2} - (I_0/Ic)\arccos\left(I_0/I_c\right)\right]$$



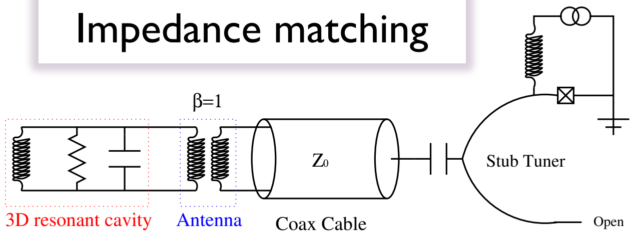
CBJJ at LNF

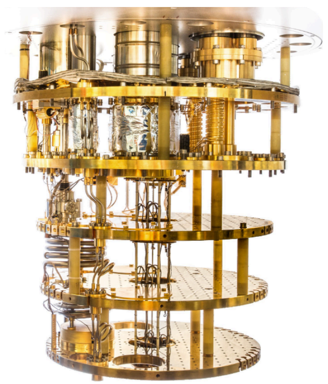
Setup of Cryogen-Free Dilution Refrigerator

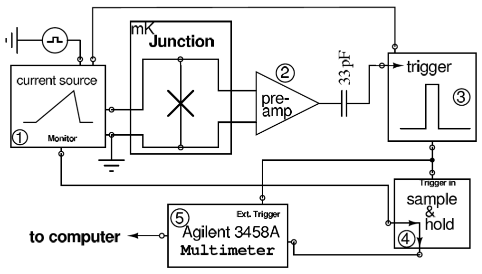
Model CF-CS110 Leiden Cryogenics



Impedance matching

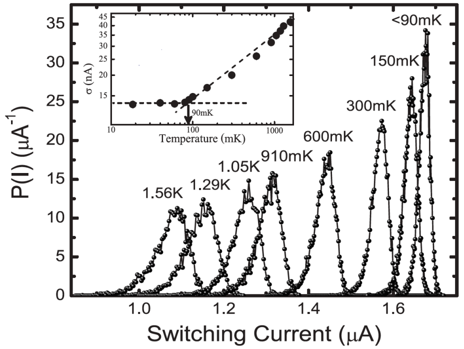




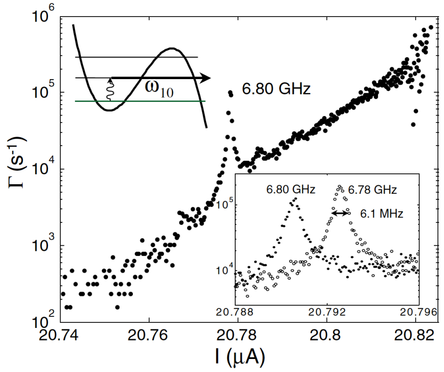


Device characterization

Measurement of switching currents



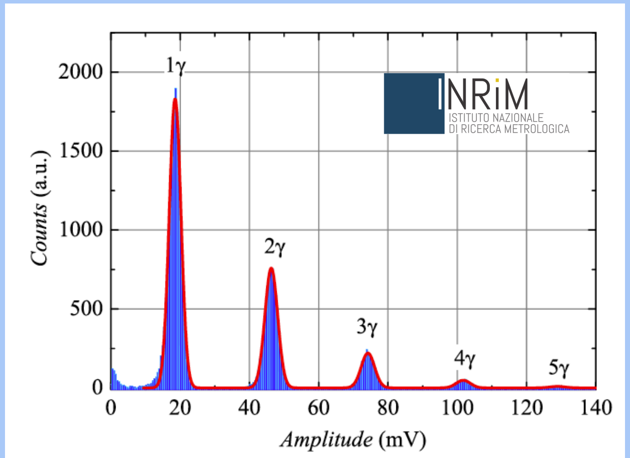
Spectroscopic measurements



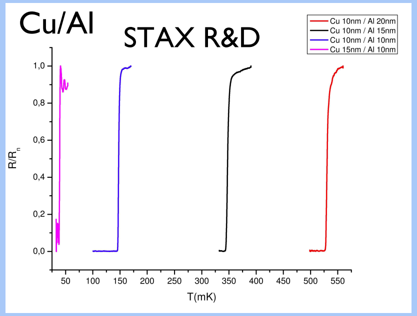
TES

State of Art

App.Phys.Lett. 103 041107 (2013)



Ti/Au, Tc~ 100 mK, 800 meV photons, resolution 100 meV.



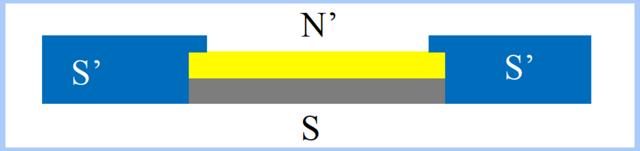
$$\sigma_E \propto \sqrt{k_B C T^2}$$

$$C = \gamma V T$$

Lower temperature

Reduce volume

Tune transition temperature by proximity effect



TiAu bilayer

$V \sim 300 \times 80 \times 35 \text{ nm}^3$

$\gamma \sim 10^{-22} \text{ mJ/K}^2/\text{nm}^3$

$T_c \sim 40 \text{ mK}$

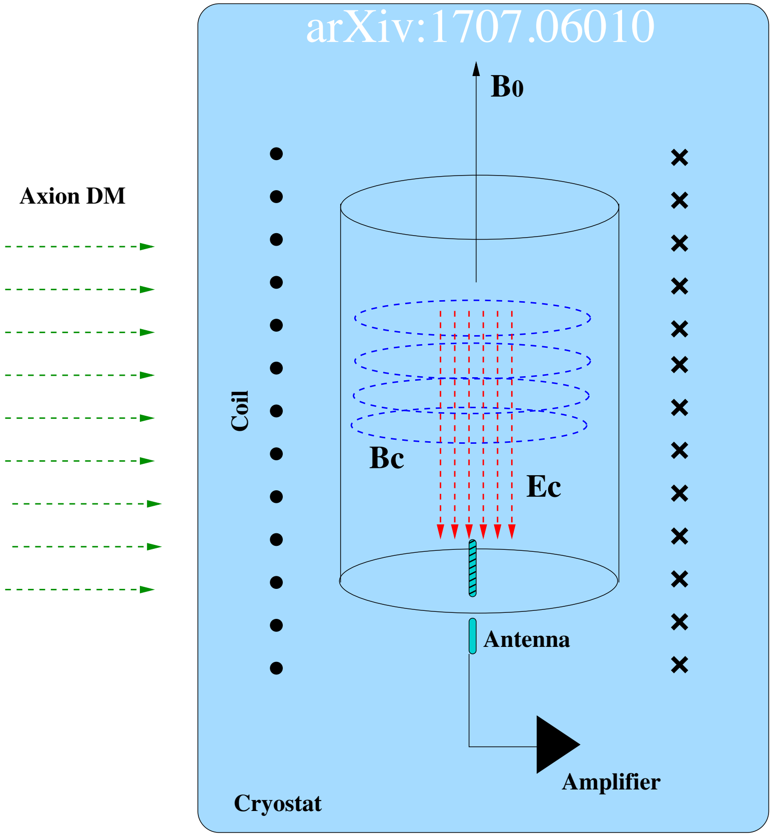
$\sigma_E \sim 20\ \mu\text{eV} \sim 5 \text{ GHz}$

FUTURE PROJECT

The KLASH Proposal

- KLASH - KLoe magnet for Axions SearcH
- Proposal of a large Haloscope
- Search of galactic axions in the mass range 0.3-1 μeV
- Large volume RF Cavity (33 m^3)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q~600,000
- T 4.5 K

Experiment	$\omega\ B^2 V\ Q_L$ (rad $T^2 m^3$/s) (×10^{15})
The KLASH	1
ADMX	4
HAYSTAC	0.05

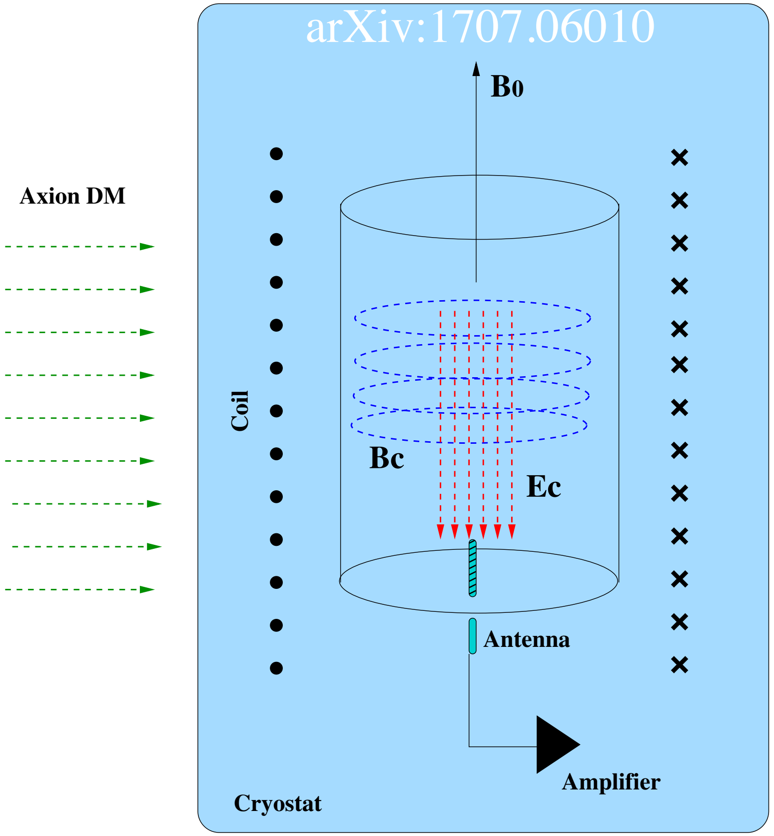


The KLASH Proposal

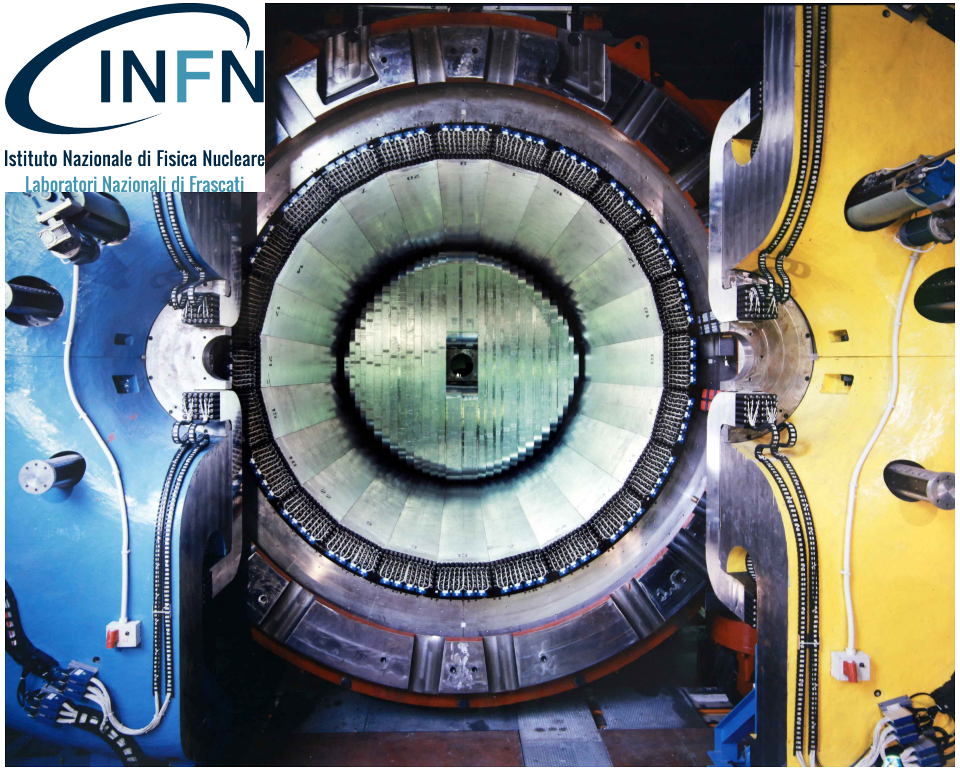
$$P_{\text{sig}} = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left(\frac{\beta}{1+\beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right)$$

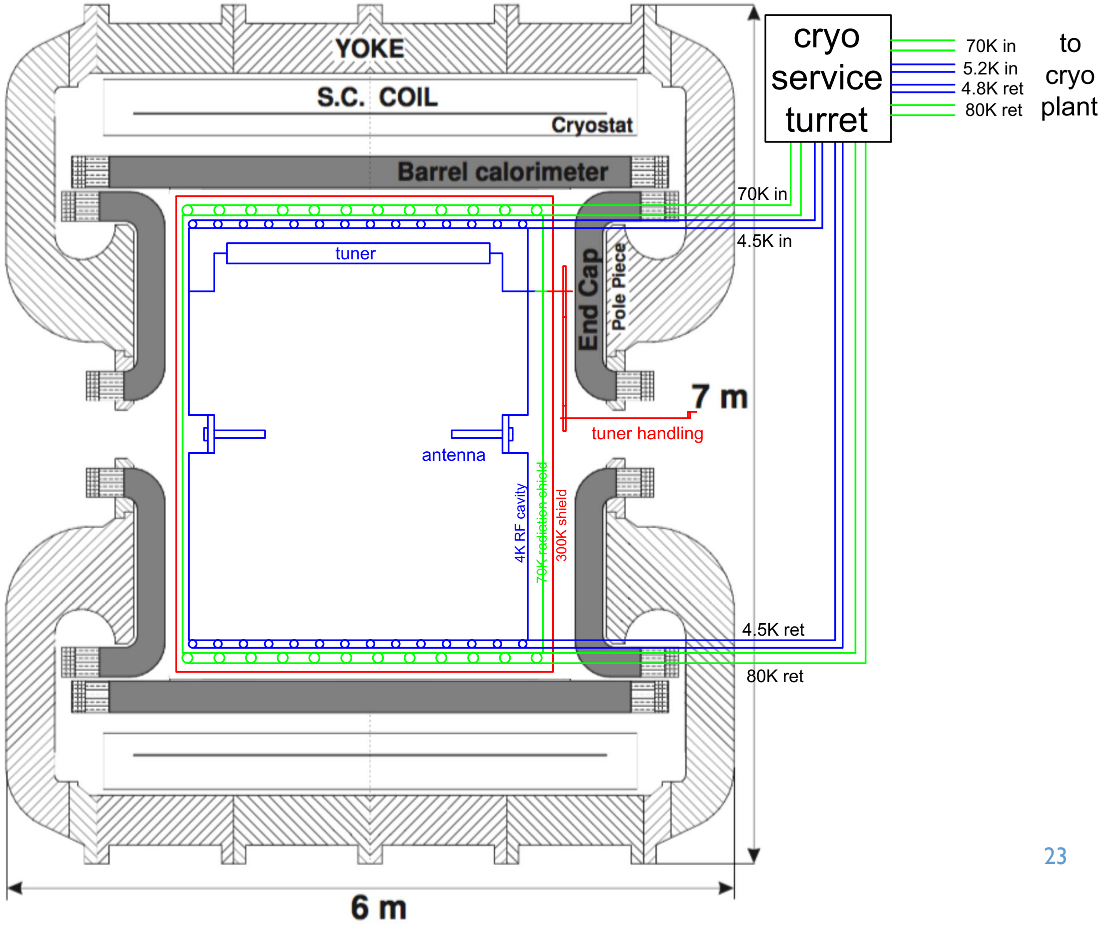
$$SNR = \frac{P_{\text{sig}}}{k_B T_{sys}} \sqrt{\frac{\tau}{\Delta \nu_a}}$$

Experiment	ω $B^2 V Q_L$ (rad $T^2 m^3/s$) ($\times 10^{15}$)
The KLASH	1
ADMX	4
HAYSTAC	0.05



The KLOE Detector





The KLOE Magnet

B(T)	0.6
D(m)	4.86
L(m)	4.4

The DAFNE Cryogenic Plant

LINDE TCF 50 liquid He liquefaction/refrigeration plant

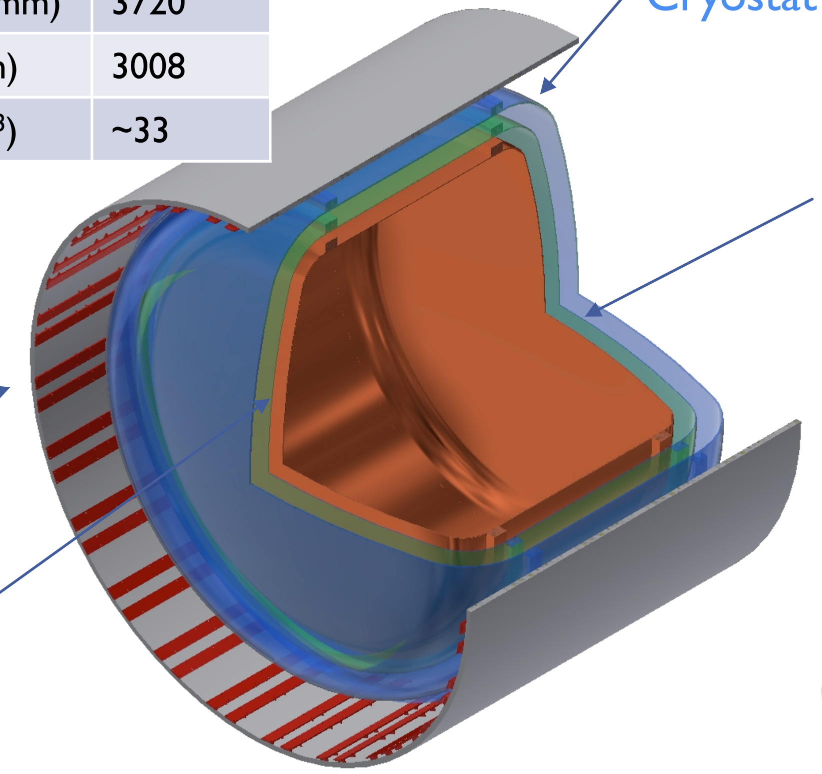
Running at DAFNE since 1996.
Perfectly working.
Located outside the DAFNE main ring.

4.5K refrigeration capacity	**99 W**
4.5K liquefaction capacity	1.14 g/s
70K refrigeration capacity	800 W
KLOE 4.5K refrig. load	55 W
KLOE 4.5K liquef. load	0.6 g/s
KLOE 70K refrig. load	530 W
cavity 4.5K refrig. availability	44 W
cavity 70K refrig. availability	270 W

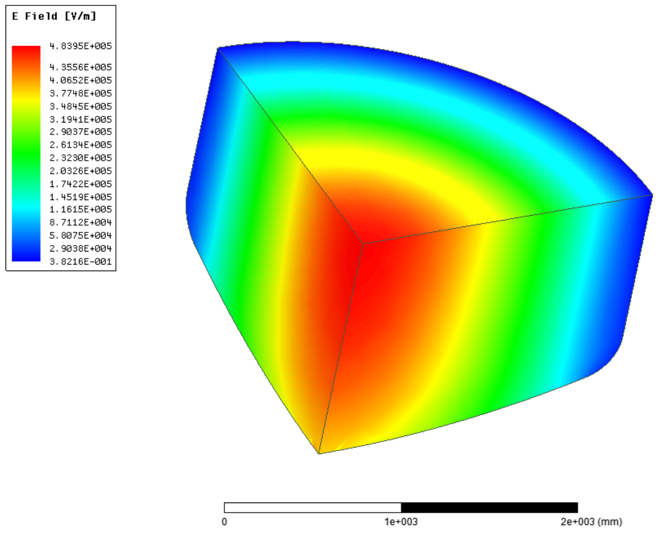
M. Modena LNF–97/046 (IR)

The KLASH Project

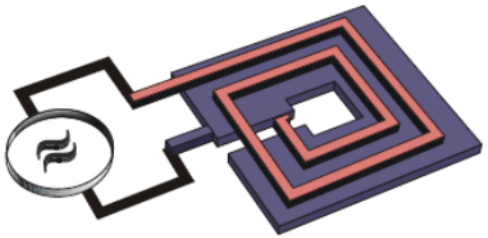
Cryostat Total Weight	~15 Ton
RF Cavity diameter (mm)	3720
RF Cavity length (mm)	3008
RF Cavity Volume (m^3)	~33



Mechanical project



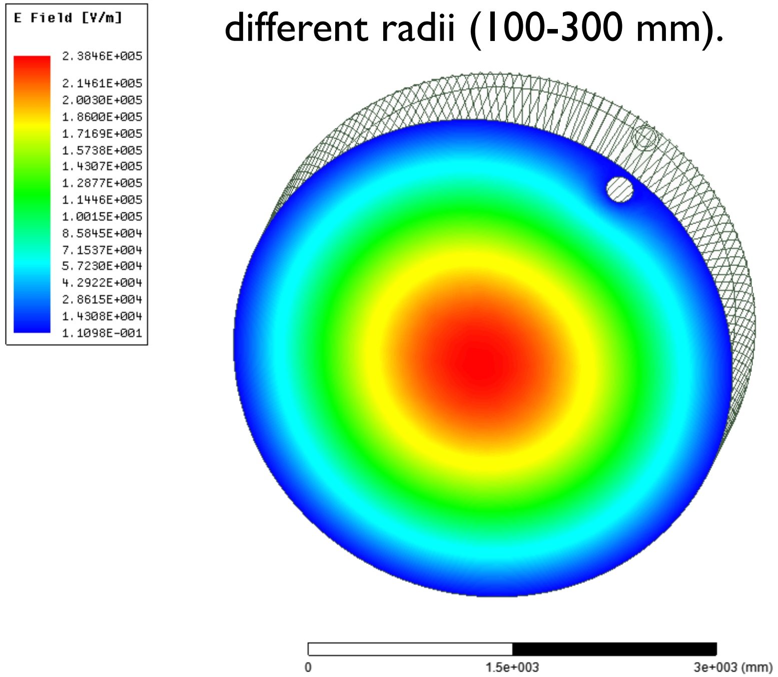
RF simulations

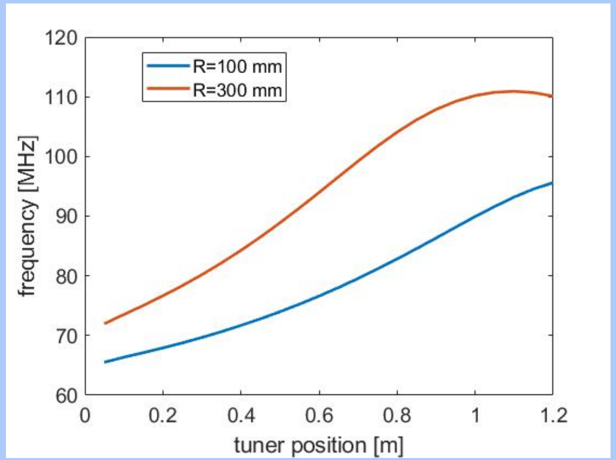


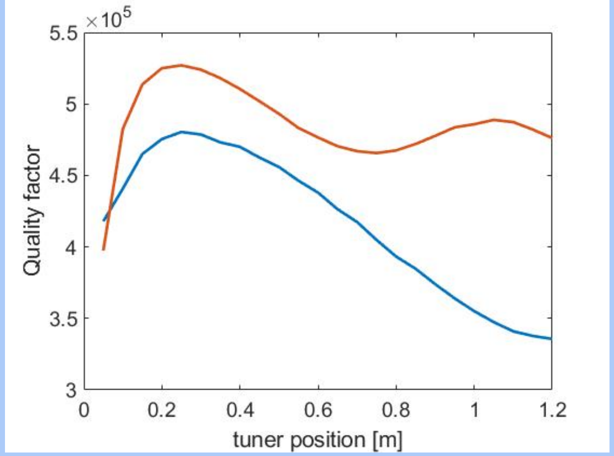
Signal amplification by MSA

Frequency (Axion-Mass) Tuning

Simulation with tuning rods of different radii (100-300 mm).





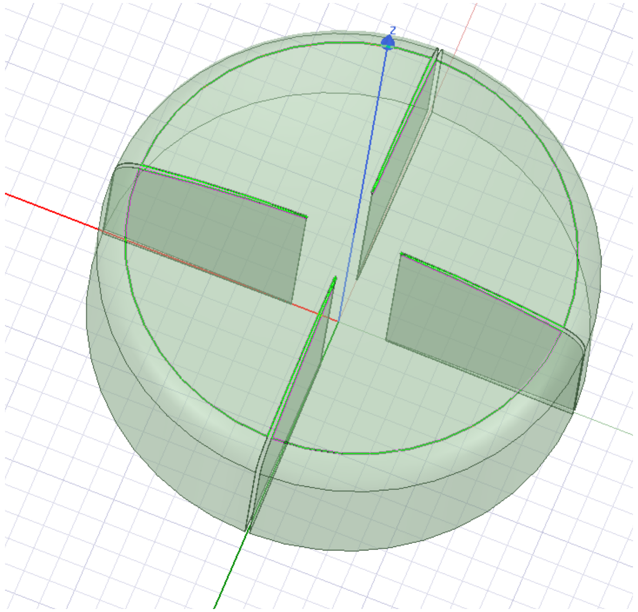


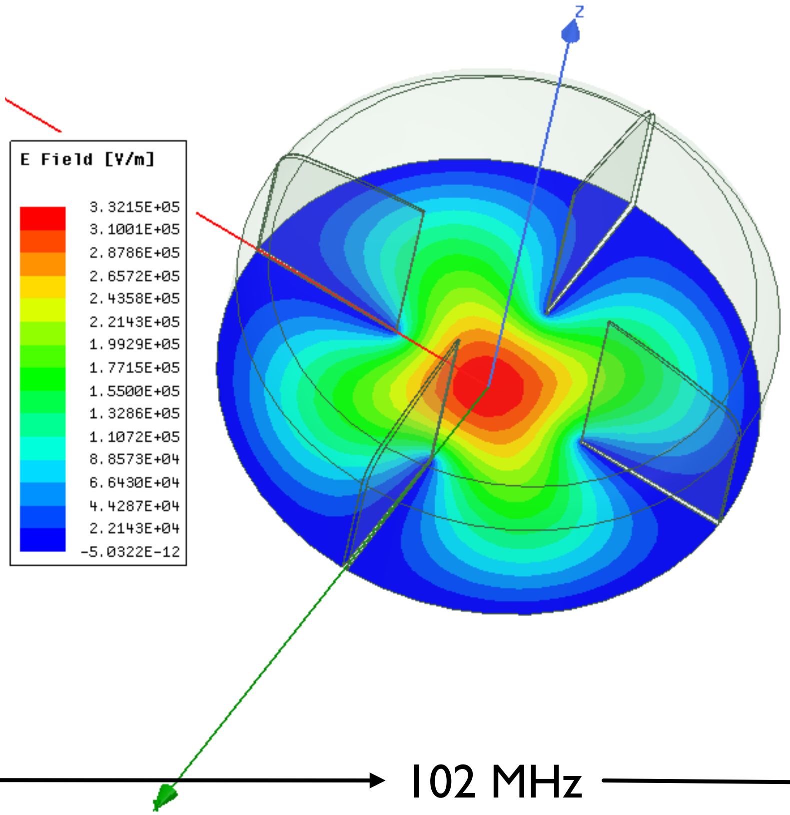
Tuning from 70 to 110 MHz (0.3 to 0.45 μeV) with 2 rods of 300 mm radius and Q about 500,000.

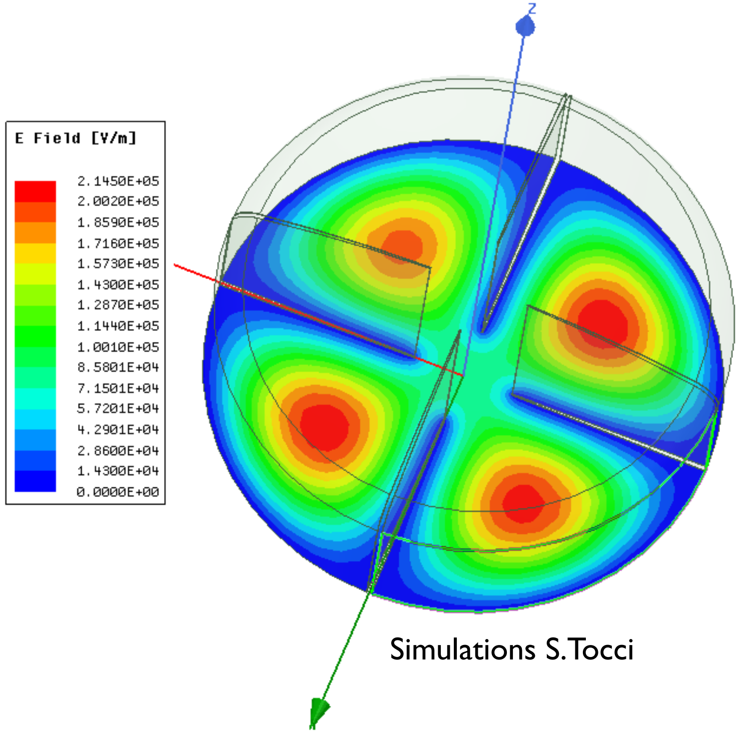
Tuning: Multiple-cell "Pizza" cavity

J.Jeong et al, Phys Lett B 777 (2018) 412

Gain in the effective mode volume



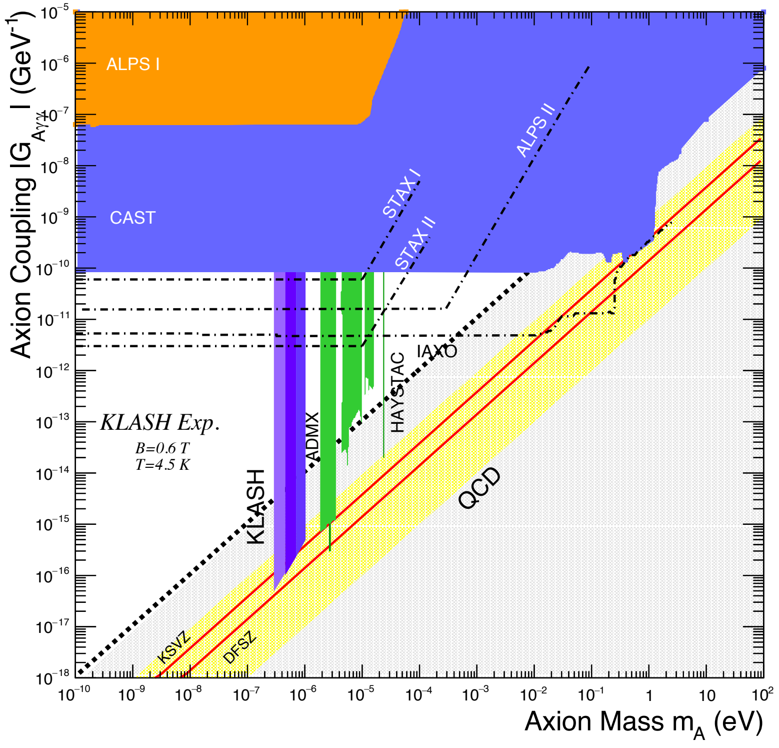




Simulations S.Tocci

70 MHz → 102 MHz → 130 MHz

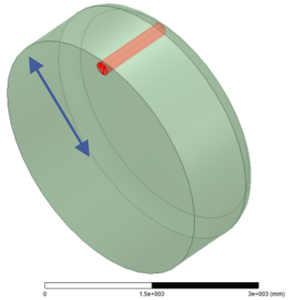
Expected Sensitivity



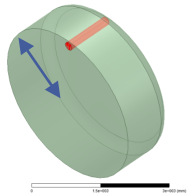
*Gray band PRL 118, 031801 (2017)

	3 years data taking
Radius [m]	1.9 → 1.2 → 0.9
Frequencies [MHz]	70 → 250
Q (70-170MHz)	550,000 → 375,000
Power [W] (KSVZ)	1.3×10^{-22} → 4.3×10^{-23}
Rate [kHz] (KSVZ)	2.8 → 0.38
Integration time (min)	10 → 15
T_{sys} [K]	4.8

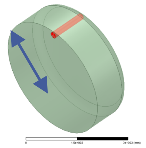
R=1.9m



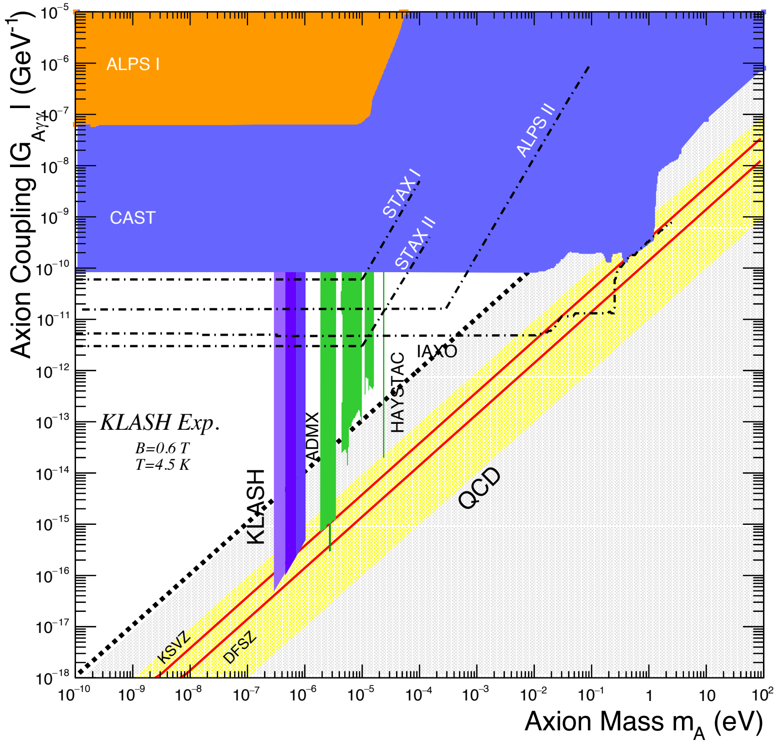
R=1.2m



R=0.9m



Expected Sensitivity



*Gray band PRL **118**, 031801 (2017)

Laboratori Nazionali di Frascati

INFN-18-09-LNF
September 18, 2018

The KLASH – Letter of Intent

D.Alesini[1], D.Babusci[1], F.Bossi[1], P.Ciambrone[1], G.Corcella[1], D.Di Gioacchino[1], P.Falferi[2], C.Gatti[1], A.Ghigo[1], G.Lamanna[3], C.Ligi[1], G.Maccarrone[1], A.Mirizzi[4], D.Montanino[5], D.Moricciani[1], A.Mostacci[6], E.Nardi[1], A.Paoloni[1], L.Pellegrino[1], A.Rettaroli[1], R.Ricci[1], L.Sabbatini[1],S.Tocci[1].

[1] Laboratori Nazionali di Frascati - INFN
[2] TIFPA e FBK
[3] Università di Pisa e INFN Sezione Pisa
[4] Università “Aldo Moro” e INFN Sezione Bari
[5] Università del Salento e INFN Sezione Lecce
[6] Università “La Sapienza” e INFN Sezione Roma1

INFN CSN2 funded with 30 k€ one year study for KLASH-CDR

Estimated construction cost about 1-2 M€

In conclusion … (running out of time)

Several "COLD LAB" publications …

arXiv:1707.06010

The KLASH Proposal

Axion Calling

D. Alesini[1], D. Babusci[1], D. Di Gioacchino[1], C. Gatti[1], G. Lamanna[2], C. Ligi[1]
[1)] *INFN, Laboratori Nazionali di Frascati*
[2)] *Università di Pisa and INFN*

Patras 2018 Proceedings

The Klash Proposal: Status and Perspectives

C. Gatti[1], D. Alesini[1], D. Babusci[1], C. Braggio[6,7], G. Carugno[6,7], N. Crescini[5,7], D. Di Gioacchino[1], P. Falferi[3,4], G. Lamanna[2], C. Ligi[1], A. Ortolan[5], L. Pellegrino[1], A. Rettaroli[1], G. Ruoso[5], S.Tocci[1]

Eur Phys J C (2018) 78:703

Operation of a ferromagnetic axion haloscope at $m_a = 58\,\mu\text{eV}$

N. Crescini[1,2,a], D. Alesini[3], C. Braggio[1,4], G. Carugno[1,4], D. Di Gioacchino[3], C. S. Gallo[2], U. Gambardella[5], C. Gatti[3], G. Iannone[5], G. Lamanna[6], C. Ligi[3], A. Lombardi[2], A. Ortolan[2], S. Pagano[5], R. Pengo[2], G. Ruoso[2,b], C. C. Speake[7], L. Taffarello[4]

arXiv:1802.05552 Patras 2017 Proceedings

Searching for galactic axions through magnetized media: QUAX status report

G. Ruoso[1], D. Alesini[2], C. Braggio[3,4], G. Carugno[3,4], N. Crescini[1,4], D. Di Gioacchino[2], P. Falferi[5,6], S. Gallo[3,4], U. Gambardella[8], C. Gatti[2], G. Iannone[8], G. Lamanna[9], C. Ligi[2], A. Lombardi[1], R. Mezzena[6,7], A. Ortolan[1], R. Pengo[1], C. C. Speake[10]

IEEE Trans Appl Superc 28 (2018)

Single Photon Counter based on a Josephson Junction at 14 GHz for searching Galactic Axions

Leonid Kuzmin, Alexander S. Sobolev, Claudio Gatti, Daniele Di Gioacchino, Nicolò Crescini, Anna Gordeeva, Eugeni Il'ichev

J Supercond Nov Magn (2017) 30:359-363

A Novel Particle/Photon Detector Based on a Superconducting Proximity Array of Nanodots

Daniele Di Gioacchino[1] · Nicola Poccia[2,3] · Martijn Lankhorst[2] · Claudio Gatti[1] · Bruno Buonomo[1] · Luca Foggetta[1] · Augusto Marcelli[1,4] · Hans Hilgenkamp[2]

Submitted to IEEE Trans Appl Superc

Microwave losses in a dc magnetic field in superconducting cavities for axion studies

D. Di Gioacchino, C. Gatti, D. Alesini, C. Ligi, S. Tocci, A. Rettaroli, G. Carugno, N. Crescini, G. Ruoso, C. Braggio, P. Falferi, C.S. Gallo, U. Gambardella, G. Iannone, G. Lamanna, A. Lombardi, R. Mezzena, A. Ortolan, R. Pengo, E. Silva, N. Pompeo

First QUAX-LNF Thesis …

ROMA TRE
UNIVERSITÀ DEGLI STUDI

DIPARTIMENTO DI MATEMATICA E FISICA
CORSO DI LAUREA MAGISTRALE IN FISICA

MASTER DEGREE THESIS

Characterization of superconducting resonant RF cavities for axion search with the QUAX experiment

October 23, 2018

Author:
Alessio Rettaroli

Supervisor:
Prof. **Giuseppe Salamanna**

Supervisor:
Dott. **Claudio Gatti**

New collaborations …

In Italy

- CNR-IFN Roma
- CNR-NEST Pisa
- INRIM Torino
- FBK
- Department of Engineering Roma 3 University

Abroad

- Center for Axion and Precision Physics (CAPP) (South Korea)
- Chalmers University of Technology (Sweden)

Daejeon South Korea October 2018

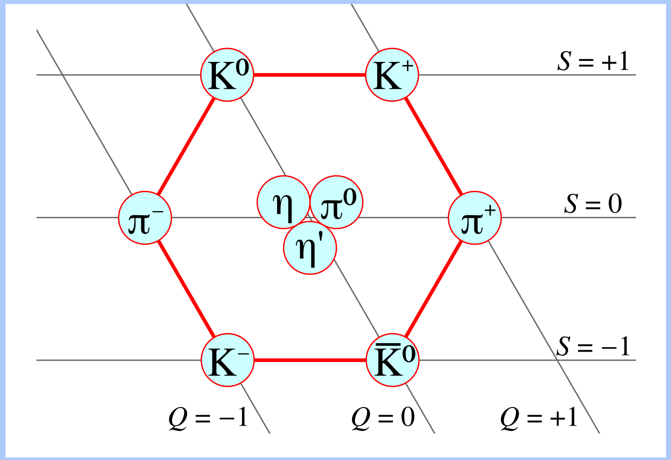
Conclusion

Well motivated extensions of the Standard Model of particle physics predict the existence of light particles such as axions or axion-like particles. Their discovery requires skills and infrastructures typical of a laboratory such as LNF. With this in mind, we set up the COLD laboratory, a CryOgenic Laboratory for Detectors. The are obviously problems: our technician Iannarelli just retired; ^{4}He world shortage and aging of our apparatus of liquefaction; etc. etc..
But, QUAX gave us the right boost, SIMP was approved and KLASH maybe in the future.
Thank you.

LNF - ADONE Cavity
Winter 2017-2018

BACK UP SLIDES

WHY AXIONS? The η′ problem and the CP violation in QCD



Mass spectrum of lighter mesons reflects the underlying flavour symmetry (u↔d↔s, with $m_u = m_d \ll m_s$), summarized in the Gell-Mann Okubo relation:

$$M_\eta^2 = \left(4M_K^2 - M_\pi^2\right)/3$$

The similar relation for the η' is badly broken and

$$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$$

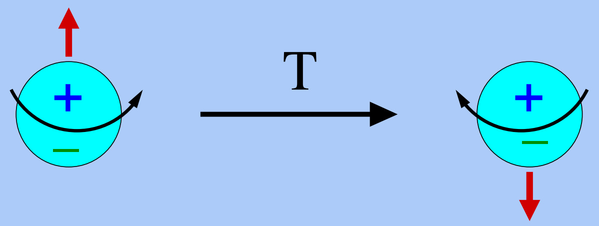
S.Weinberg U(1) problem PRD 11 (1975)

This symmetry violation is accounted by the "anomaly" term in the interaction lagrangian …

$$\mathcal{L}_{QCD}^{\not{CP}} = \theta_{QCD} \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$$

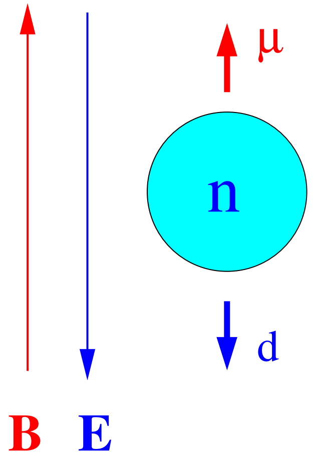
… this term is **CP violating!**

Responsible for an *electric dipole moment* of neutron



$$d_n \simeq \theta \frac{m_q}{M_n} \frac{e}{M_n} \sim \theta \times 10^{-16} e \text{ cm}$$

Neutron EDM

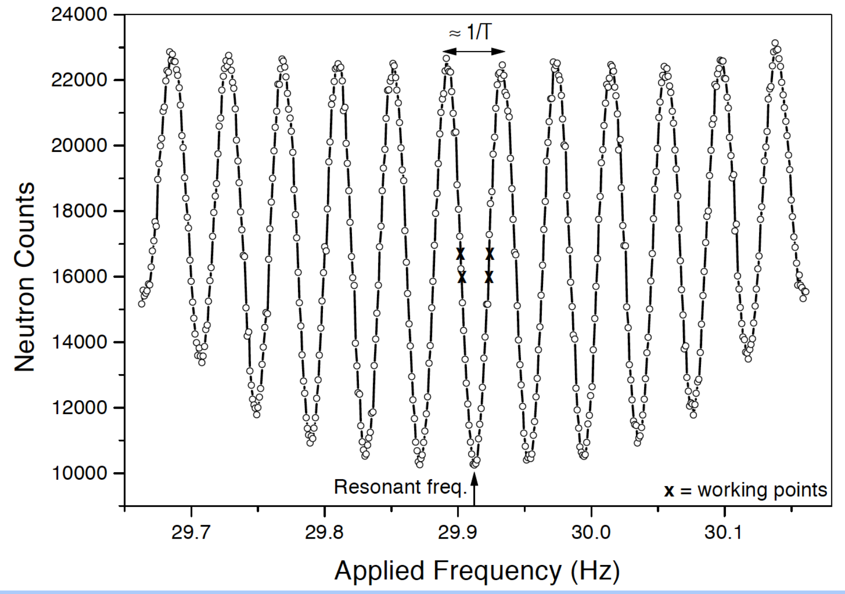


Measurement of the resonant depolarization frequency of neutrons:

$$h\nu = |2\mu_n \cdot B \pm 2d_n \cdot E|$$

$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$\theta < 10^{-10}$$



ILL Grenoble (Fr)

Phys Rev Lett 82, n.5 (1999) p.904

The Axion Solution to the Strong CP Problem

$$\theta = \theta_{QCD} + arg\ det\ M_q$$

Why so small?

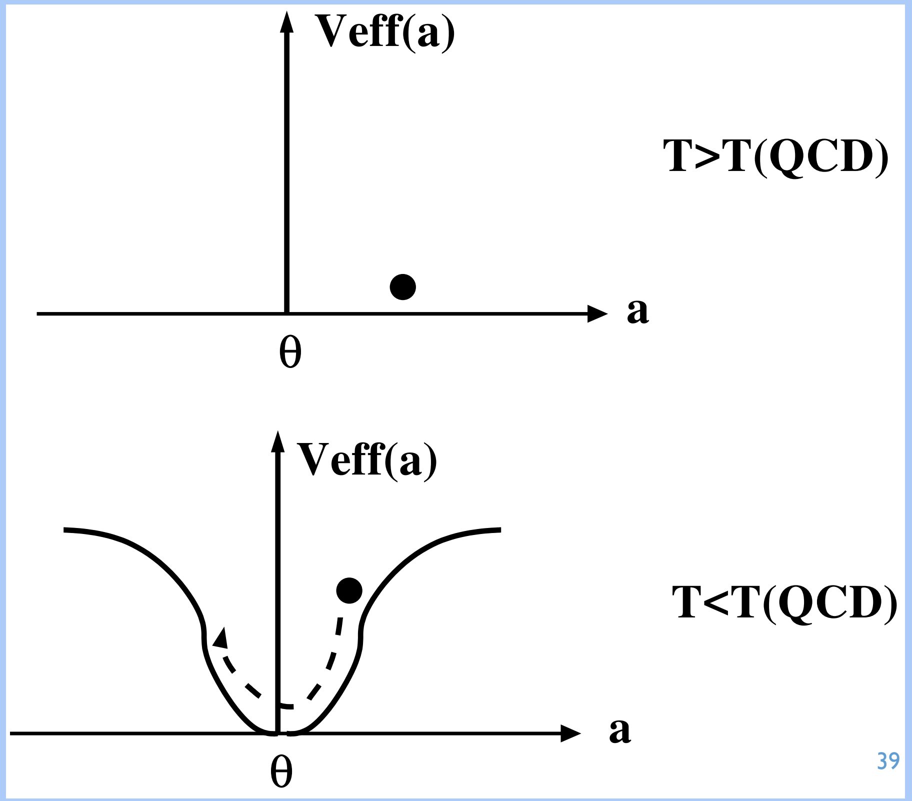
Why so small?

The Axion is a new scalar field that cancels dinamically the θ term.

$$\mathcal{L}_{QCD}^{\not{CP}} = \left(\theta - \frac{a}{f_a}\right)\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

This *misalignment* mechanism naturally produces axion cold dark matter

Misalignment mechanism



AXION DARK MATTER

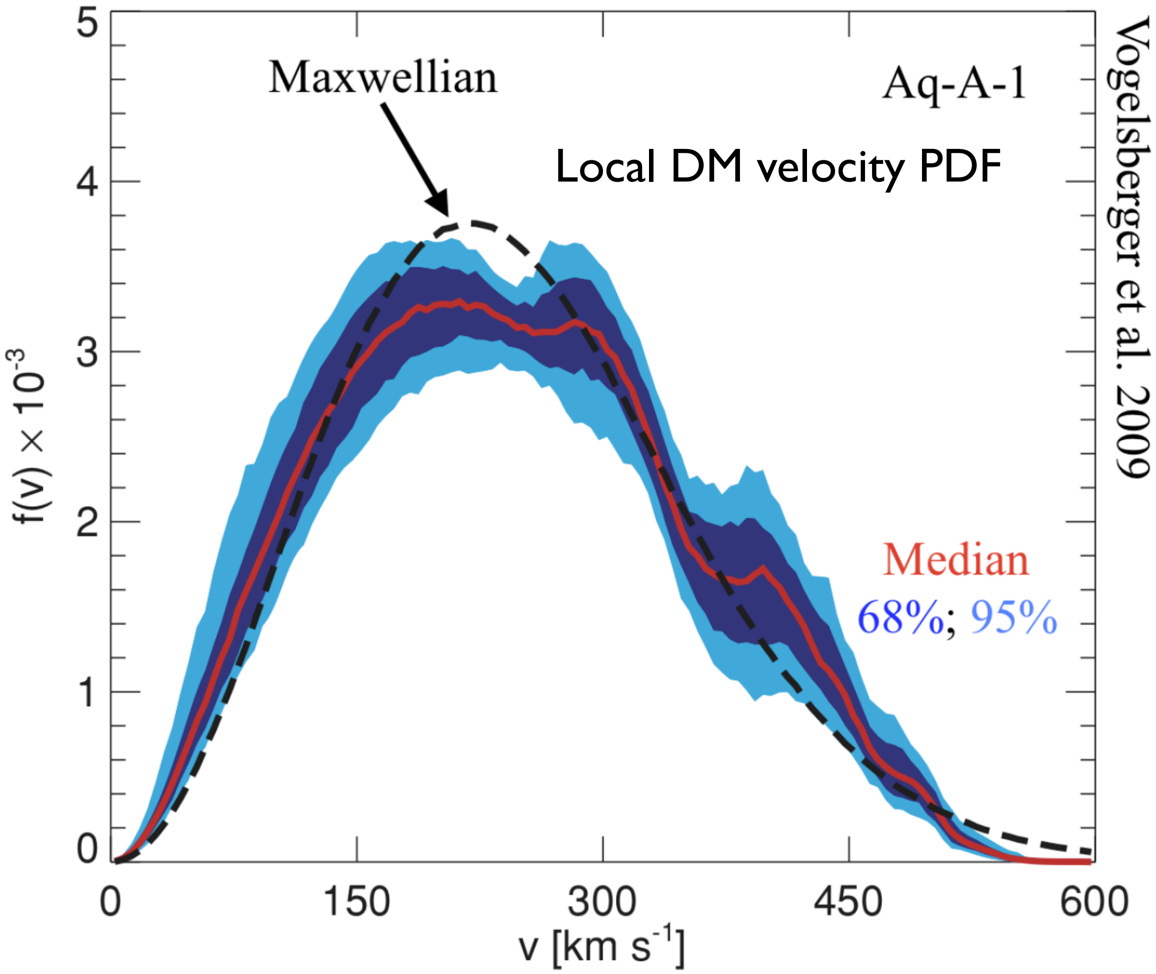
Standard Halo Model predicts Maxwell-Boltzman distribution of DM halo

$$f(v)d^3v = n_0 \left(\frac{1}{\pi v_0}\right)^{3/2} e^{-(v/v_0)^2} d^3v$$

$$v_0 = 270\ \mathrm{Km/s}$$ Velocity spread

Energy spread

$$\delta E/E = \frac{1}{2}\left(\frac{v_0}{c}\right)^2 \sim 5 \times 10^{-7}$$



AXION DARK MATTER

Local Dark Matter density

$$\rho \simeq 0.3 GeV/cm^3$$

Axion density

$$n_a \simeq 3 \times 10^{12} \left(\frac{100\mu eV}{m_a}\right) 1/\text{cm}^3$$

Axion-Earth relative speed

$$\beta_a \sim 10^{-3} \qquad \hbar\omega \simeq m_a c^2$$

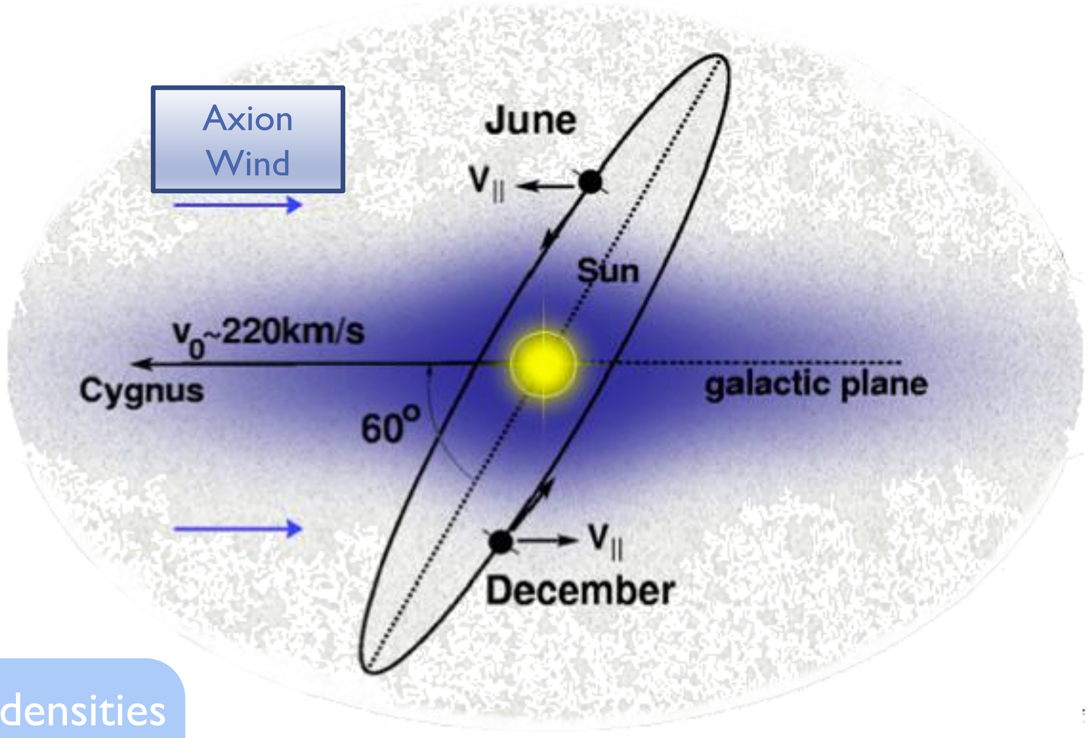
Treat axion as a classical field

$$a = a_0 \cos\left(\omega t - kx\right)$$

$$a_0 = \sqrt{\frac{n_a \hbar^3}{m_a c}}$$

Equating field energy and DM densities

$$\frac{1}{2\hbar c}\left[\dot{a}^2 + \left(mc^2/\hbar\right)^2 a^2\right] = \rho_{DM}$$



$$v_a = v_{Halo} - v_{Earth}$$

QUAX: Interaction of Axions with Electron Spin

$$\mathcal{L}_{int} = -ig_p a(x)\bar{\psi}(x)\gamma_5\psi(x)$$

Interaction lagrangian

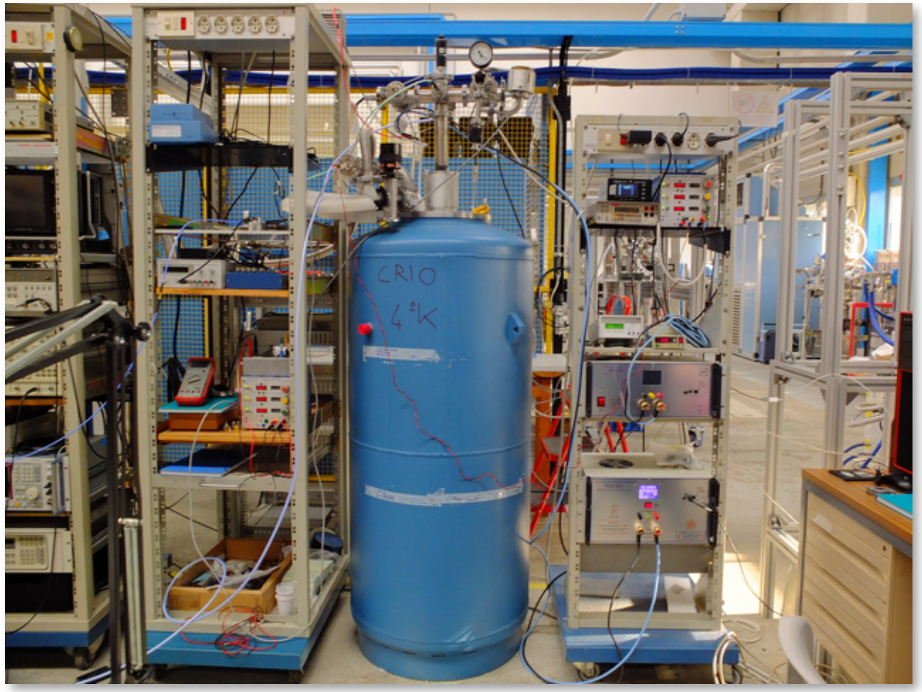
$$i\hbar\frac{\delta\phi}{\delta t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p\hbar}{2m}\sigma\cdot\nabla a\right]\phi$$

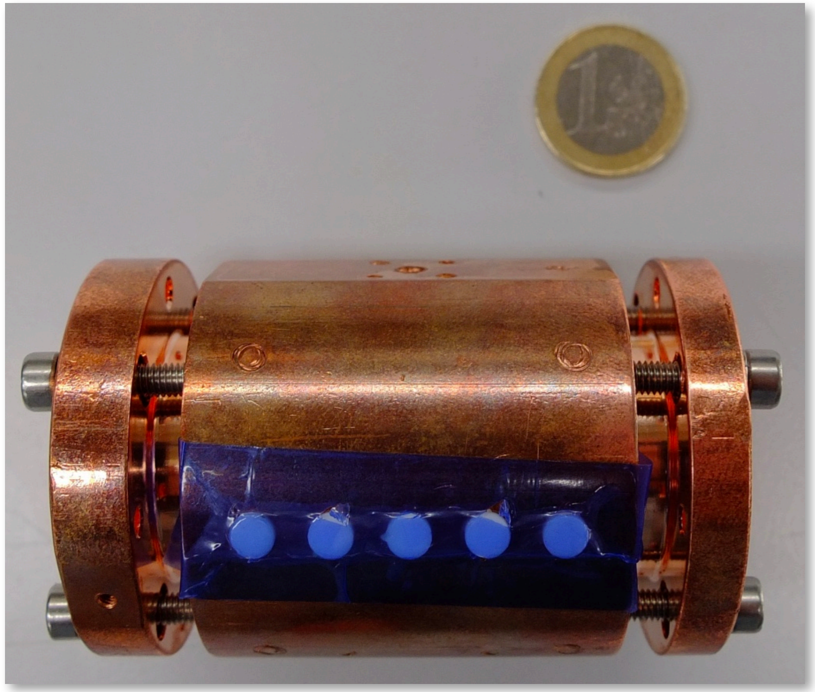
Non relativistic limit

Interaction between electron magnetic moment
and
effective magnetic field

$$B_a \equiv \frac{g_p}{2e}\nabla a$$

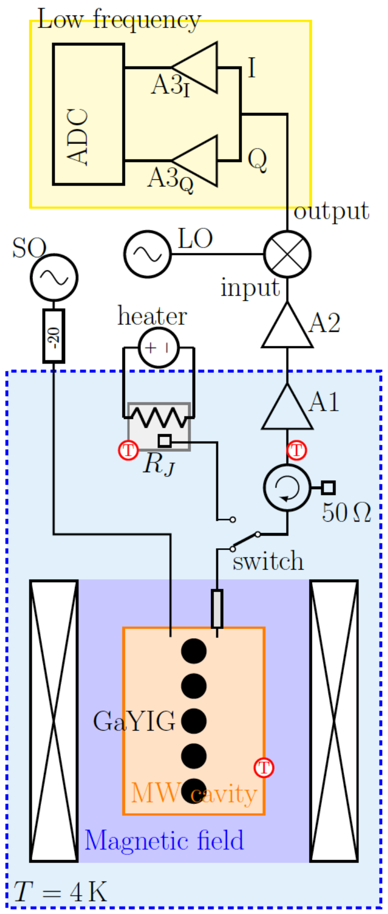
QUAX R&D





Measurement setup at LNL

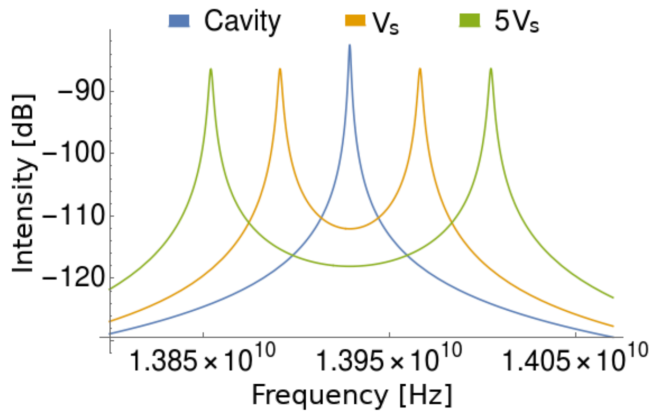
First Operation of a Ferromagnetic Axion Haloscope at m_a = 58μeV



Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =1 mm)	5
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.11
Frequency [GHz]	13.98
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [K]	5.0

$$P_{\rm out} = \frac{P_{\rm in}}{2} = 1.4\times10^{-33}\left(\frac{m_a}{58.5\,\mu\mathrm{eV}}\right)^3 \times \times \left(\frac{n_s}{2\cdot10^{28}/\mathrm{m}^3}\right)\left(\frac{V_s}{2.6\,\mathrm{mm}^3}\right)\left(\frac{\tau_{\rm min}}{0.11\,\mu\mathrm{s}}\right)\mathrm{W}$$

EPJC (2018) 78:703



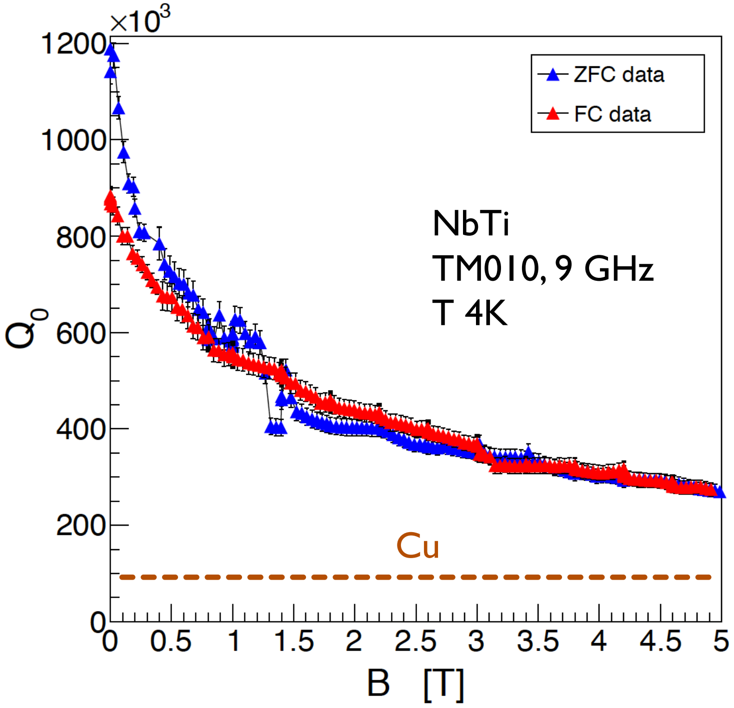
Hybridization of Cavity and Kittle modes

Expected power from DFSZ axion.
No way to detect it at this stage!

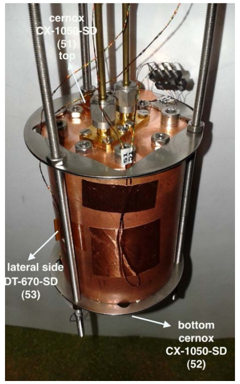
QUAX R&D: Type II SC RF-Cavities

Quality factor of a copper cavity sputtered with NbTi (13T H_{c2}) measured at 4K, for:

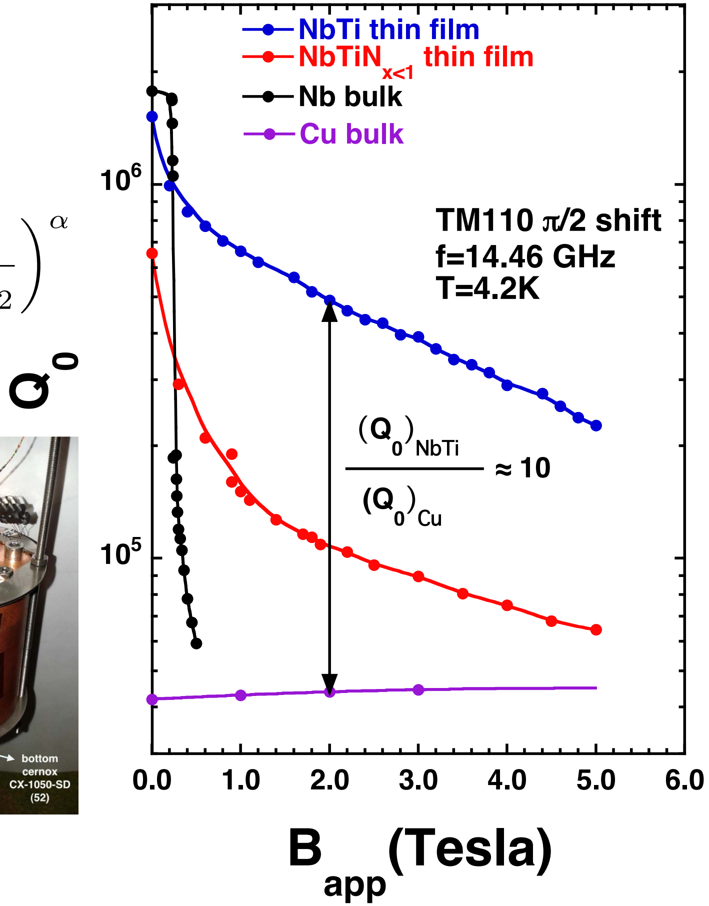
1. TM010 mode at 9 GHz
2. TM110 mode at 14 GHz



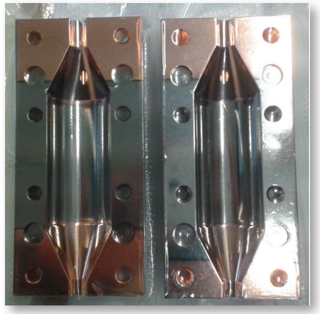
$$R_S^{SCtypeII} \propto \left(\frac{B}{B_{c2}}\right)^{\alpha}$$



Cu



Nb



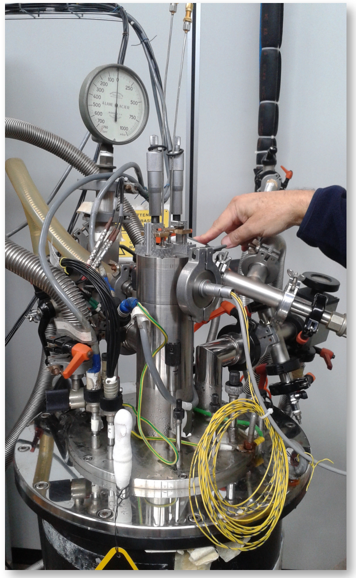
NbTi

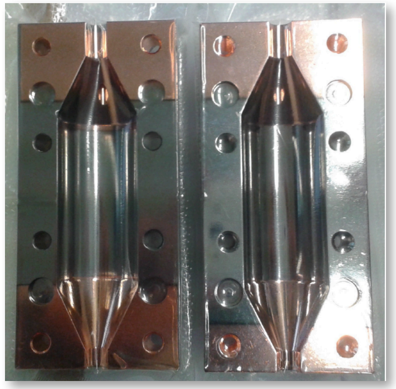
QUAX R&D: Type II SC RF-Cavities

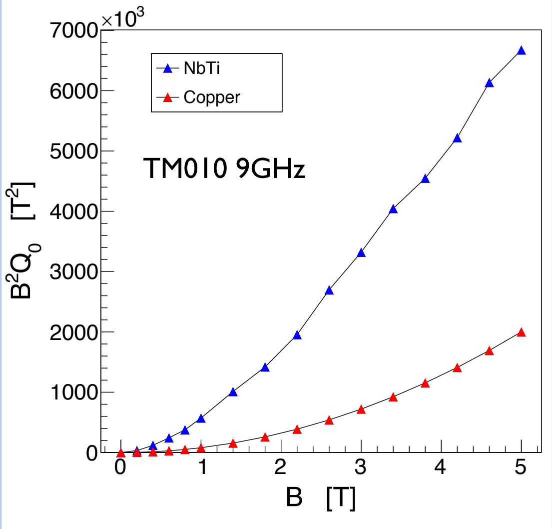
Quality factor of a copper cavity sputtered with NbTi (13T H_{c2}) measured at 4K, for:

1. TM010 mode at 9 GHz
2. TM110 mode at 14 GHz

Gain of factor 4-5 in the expected signal power, for Primakoff conversion, at both frequencies when B=5 T.

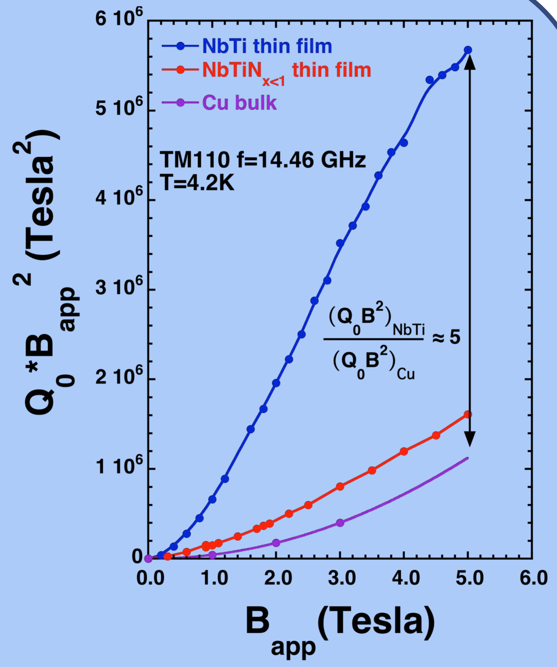




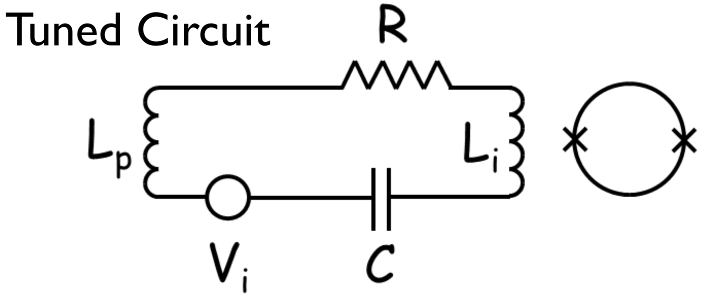


$$R_S^{Cu,an} \propto \omega^{2/3}$$

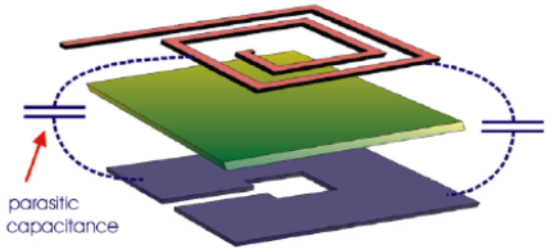
$$R_S^{SCtypeII} \propto \left(\frac{B}{B_{c2}}\right)^{\alpha}$$



THE DC SQUID AS A RADIOFREQUENCY AMPLIFIER



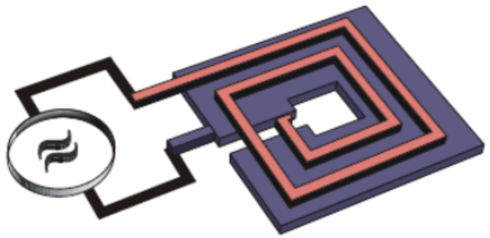
At frequencies higher than a few MHz it is convenient to use a tuned circuit:
e.g. Noise Temperature T_N=1.7K @93MHz and @4.2K
C. Hilbert and J. Clarke, J. Low Temp. Phys. **61**, 263 (1985).



but

In a conventional square-washer SQUID the parasitic capacitance between the input coil and the square washer can lower the gain to useless levels at frequencies around 100 MHz

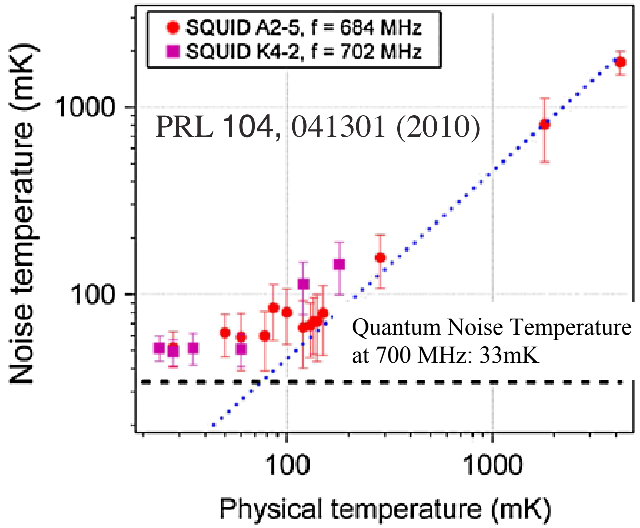
then

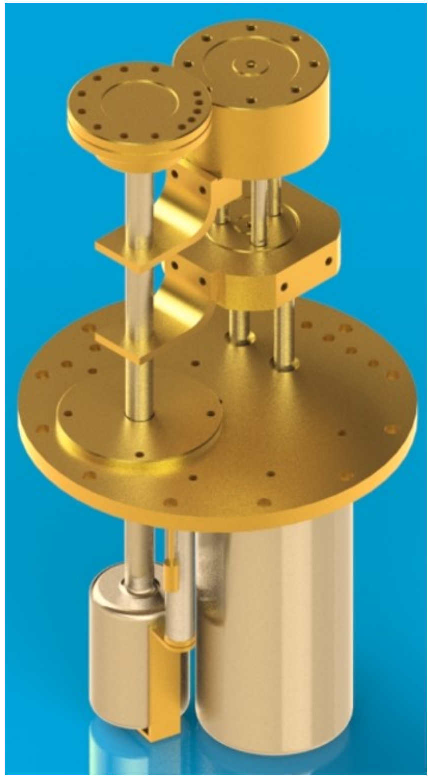


Possible solution: in contrast to the conventional input scheme the signal is applied between one end of the coil and the washer (the other end of the coil is left open).
e.g. T_N=52mK @538MHz and @0.1K (Quantum Limited T_N=26mK) M. Muck et al. Appl. Phys. Lett **78,** 967, (2001)

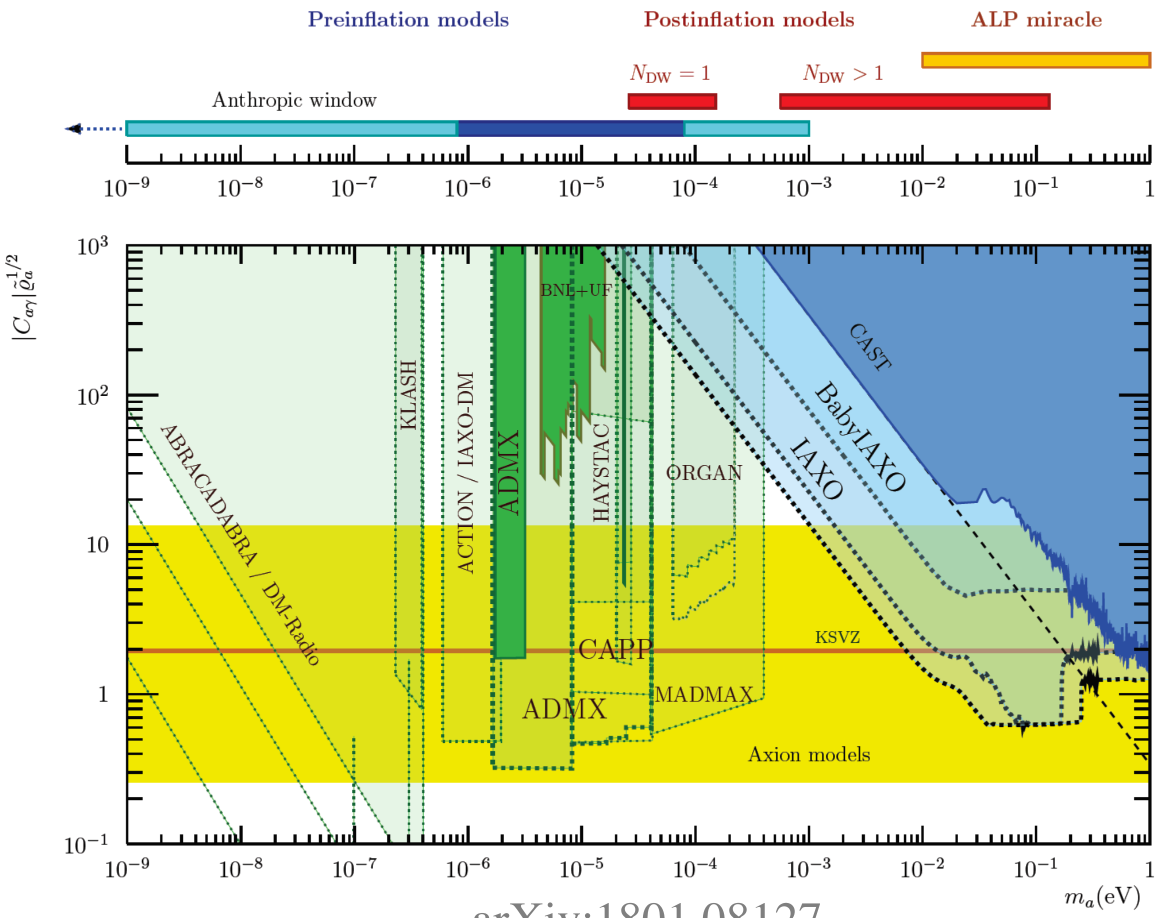
300 mK COOLING FOR SQUID

- SQUID can be cooled at about 0.3 K using a ^{3}He fridge
- The simplest solution foresees a coupled ^{4}He/^{3}He fridges
- Compact and quite easy to operate
- $T_{base} \approx 300$ mK, cooling power ≈ few tens of μW
- Single shot condensation allows a 80÷90% duty cycle operation
- Two ^{3}He fridges and a thermal switch allow continuous operation, but requires developement





COMPETITORS



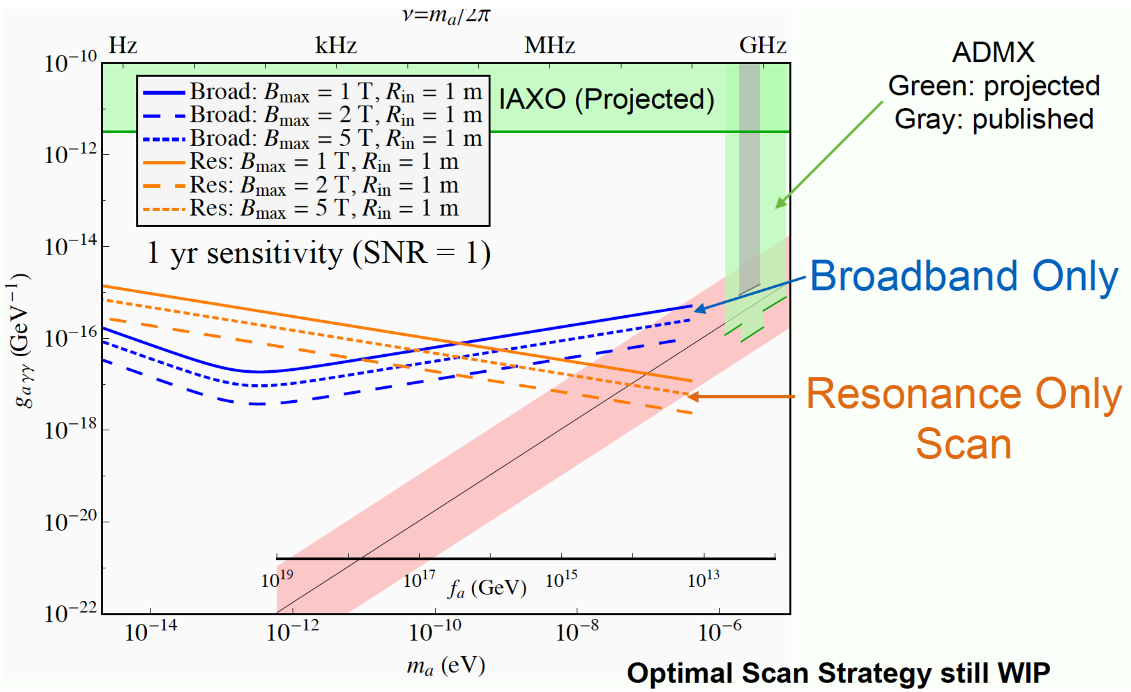
arXiv:1801.08127

COMPETITORS

ABRACADABRA-10cm	
Dilution Refrigerator	✓
SQUID Readout System	✓
Magnet	\$80k
Shielding	
ABRACADABRA 1m	
Cooling System:	
Dilution refrigerator systems	O(≤\$1M)
Larger system to cool the toroid	
SQUID Readout Systems	
Custom system with larger bandwidth and resonator	O(≤\$1M)
Shielding	
To be determined	
Magnet	
Typical scaling number (cost driver)	\$250k/MJ
R_{min}=1m, R_{max} = 2m, h = 3m, B_{max} = 1T	\$1.2M
R_{min}=2.2m, R_{max} = 4.5m, h = 6.7m, B_{max} = 1T	\$6M
R_{min}=1m, R_{max} = 2m, h = 3m, B_{max} = 5T	\$30M

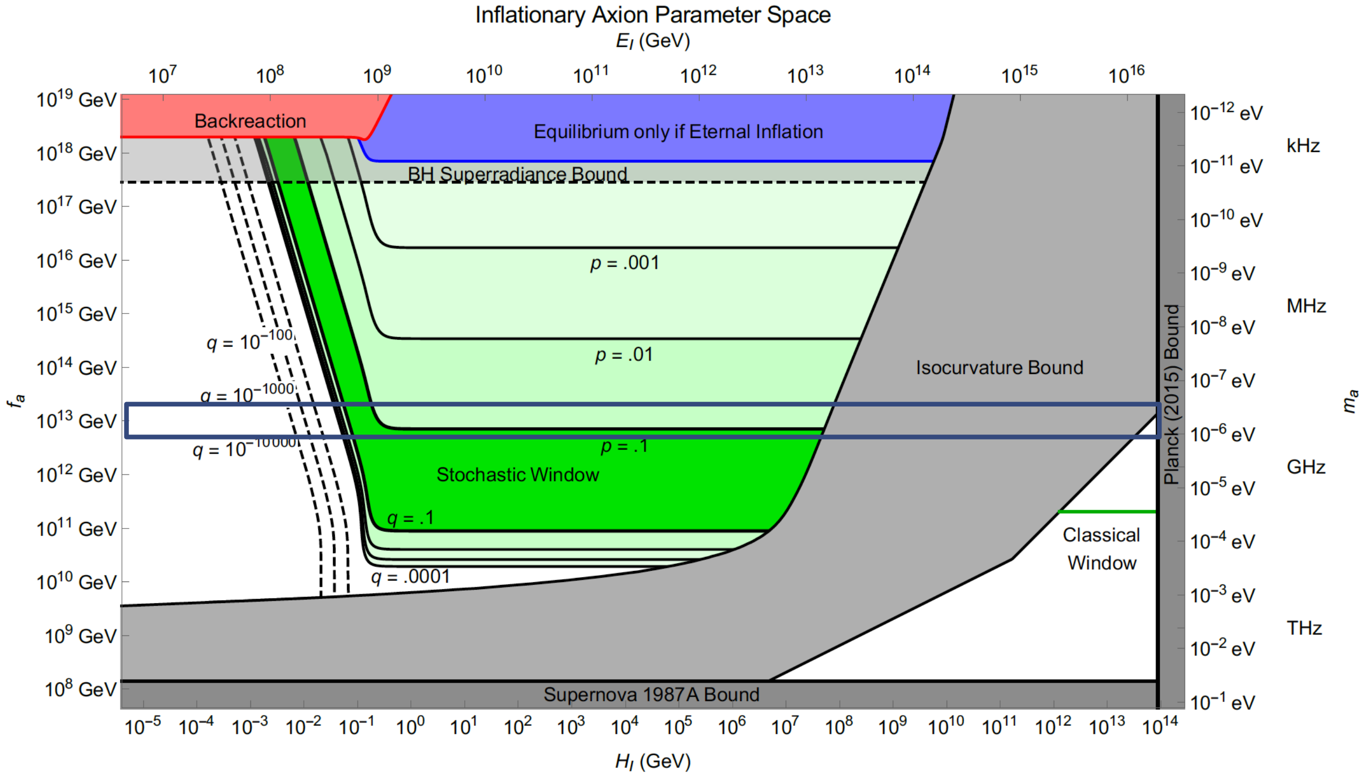
Same Sensitivity

* All numbers are ballpark estimates



Optimal Scan Strategy still WIP

COSMOLOGICAL LIMITS



Other models:

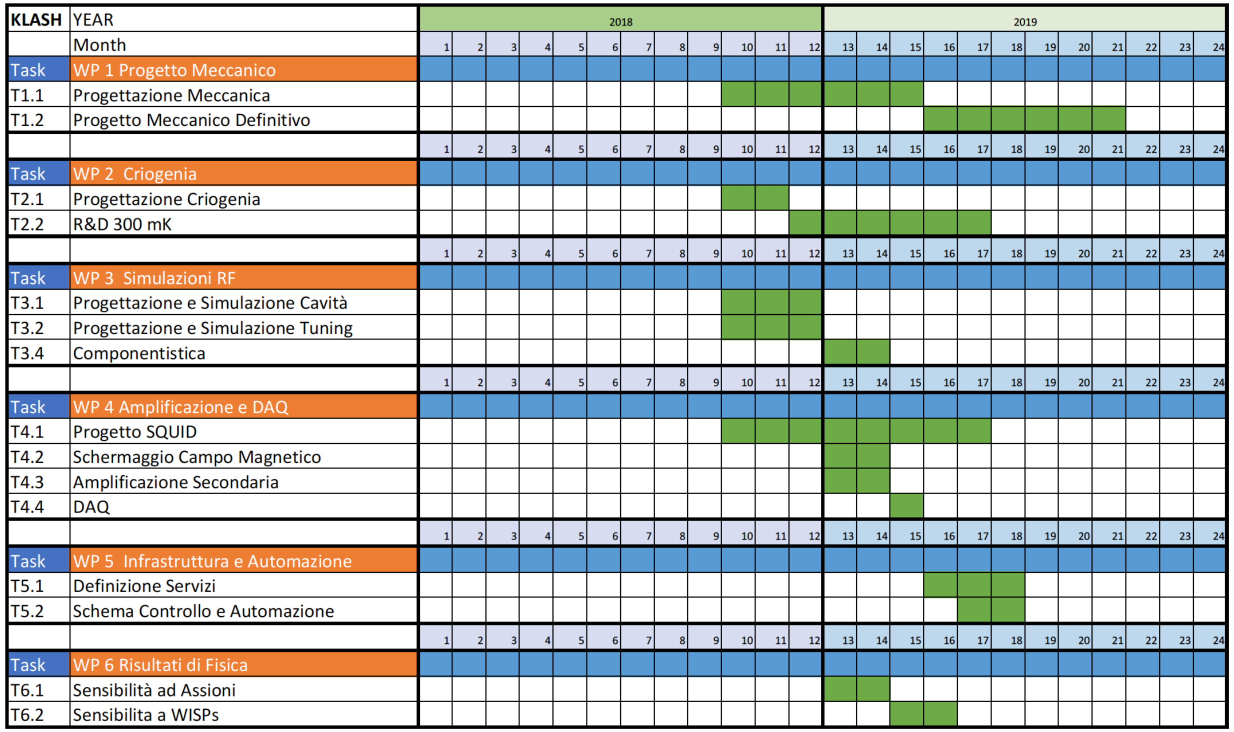
arXiv:1406.0660

arXiv:1304.7270

arXiv:1705.01134

arXiv:1805.07362

REQUESTS FOR CDR



CDR I anno	Costo (k€)	Mesi Persona (R,T, Tecnici Serv.)
Progettazione Meccanica (LNF) e progetto esecutivo (Ditta esterna)	25	6
Progetto criogenia. Prototipo refrigeratore 300 mK	5	3
Simulazioni RF	-	4
Amplificazione e DAQ	-	3.5
Infrastruttura e automazione	-	1
Risultati di Fisica	-	2

Estimated construction cost about 1-2 M€