Preliminary Study for a New Axion Dark-Matter Haloscope

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12th Patras Workshop on Axions, WIMPs and WISPs

20 - 24 June 2016
Jeju Island, South Korea

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Outline

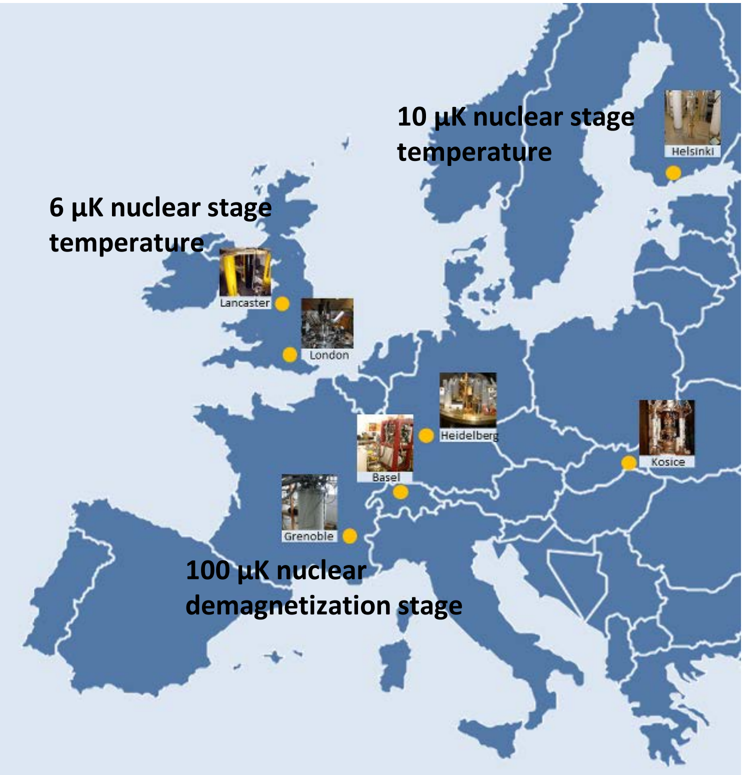
- High Field Magnet & Ultra Low Temperature Laboratories in Europe
- Status of the Axionic Dark Matter Search
- The Haloscope Principle in a Nutshell
- Key ingredients & existing/ongoing developments
  - High field / high flux magnets (CNRS-LNCMI)
  - RF cavities (KAIST-CAPP, CNRS-IN & CERN?)
  - SQUIDs *vs.* Parametric Amplifiers (CNRS-IN)
  - Very low temperature < 20 mK & cryostat (CNRS-IN)
- Summary & Conclusion

Some Geo-Physical considerations to start…

European Microkelvin Platform

20 leading ultralow temperature physics & technology Institutes in Europe including 7 submilliK facilities

http://emplatform.eu/about/facilities



10 µK nuclear stage temperature

6 µK nuclear stage temperature

100 µK nuclear demagnetization stage

EMFL

European Magnetic Field Laboratory

Dresden/LNCLI-Toulouse, pulsed up to 95/91 T, 1-10 ms
Nijmegen/LNCMI-Grenoble, DC up to 38/36 T, Projects 45/43 T

https://emfl-users.lncmi.cnrs.fr/SelCom/proposals.shtml

If you need Extreme Low Temperatures together with High magnetic fields, CNRS-Grenoble is the right place…

Le Laboratoire National des Champs Magnétiques Intenses

(UPR-CNRS, conventionné UPS-INSAT-UJF)

LNCMI

135 Employees

European Magnetic Field Laboratory

33 000 Employees
1 100 UPR & UMR

Missions

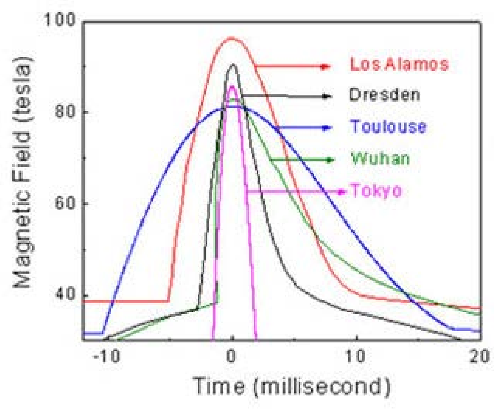
-R&D for the production and use of high magnetic fields, *i.e. Applied and Fundamental sciences*

- Laboratory open to the scientific community

-1980: Discovery of the integer quantum Hall effect at LCMI/GHMFL by Klaus von Klitzing (Nobel Prize in 1985)

- 1987: World record in the production of DC magnetic field 31.35 T in 50 mm dia.

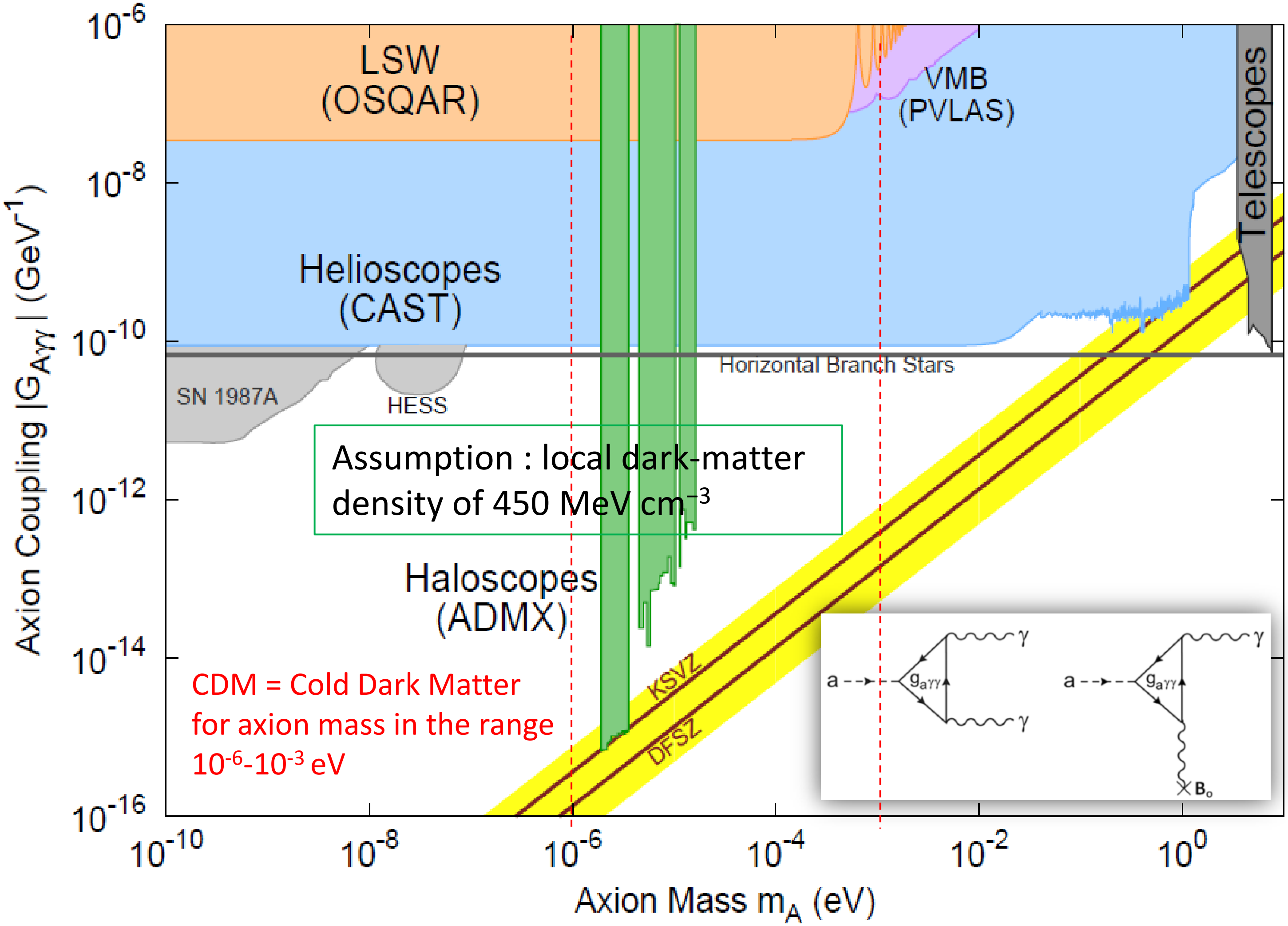
Grenoble: DC High Magnetic Field 36 T and 43 T (project) in 34 mm dia. (24 MW)



BMV Experiment
C. Rizzo et al.

Toulouse: Pulsed High Magnetic Field 90.8 T in 1-10 ms

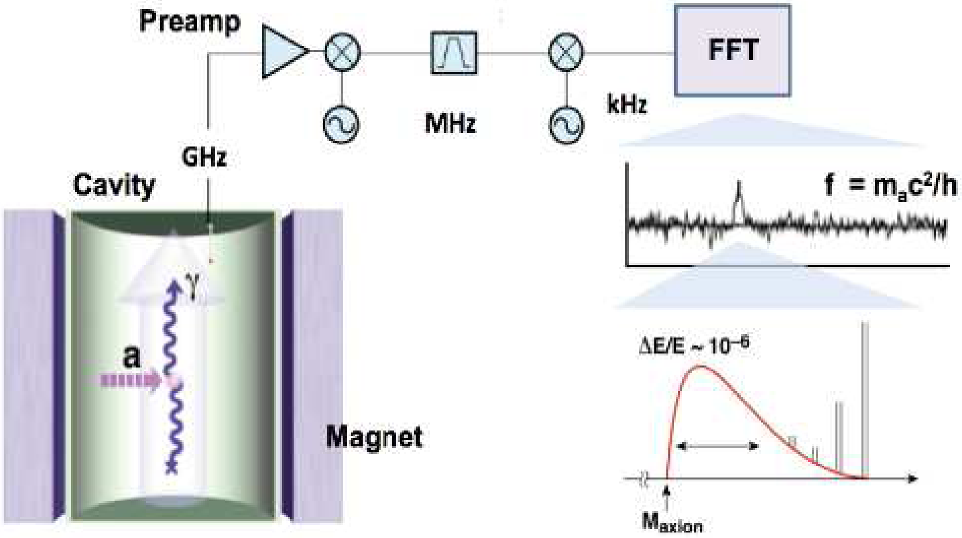
Exclusion plots for Axion/ALP particles (rpp2015-rev-axions, Revised January 2016)



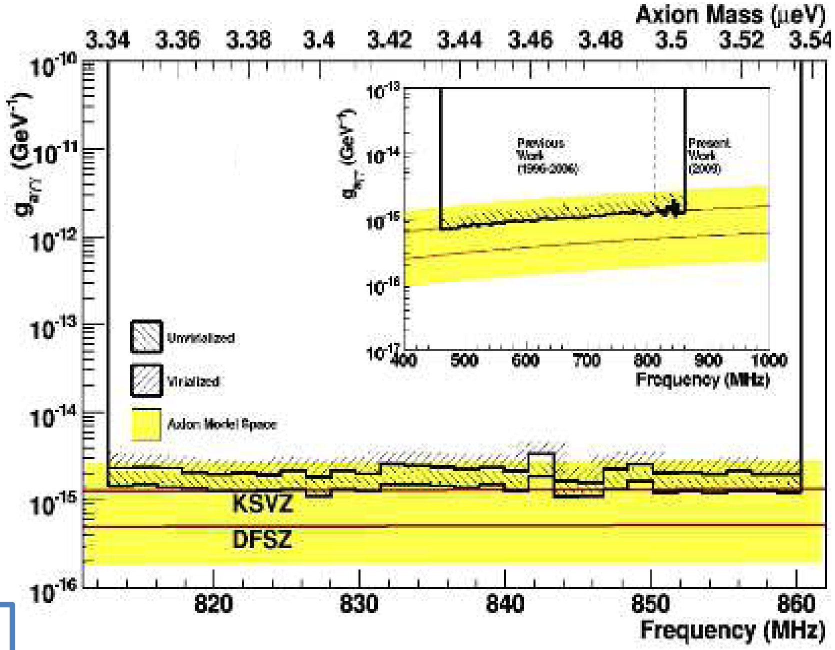
Assumption : local dark-matter density of 450 MeV cm^{-3}

CDM = Cold Dark Matter for axion mass in the range 10^{-6}-10^{-3} eV

Haloscope: A road paved by ADMX, following the pioneering idea of P. Sikivie



(From K. van Bibber, Patras 2012)



1.9 - 3.5 µeV (460 - 860 MHz)

From P. Sikivie Phys. Rev. Lett, 51 (1983), the power *P* to be detected is in the range of 10^{-23} W

$\rho_{halo} \sim 450\ MeV/cm^3$

$m_A \sim 10^{-6}\text{-}10^{-3}\ eV$

$$P = g_{A\gamma\gamma}^2(\rho_{halo}/m_A)\boxed{B^2 V\, C\, Q/2}$$

Figure of merit

$B^2V \sim$ 8-14 T^2m^3 (ADMX)

$C \sim 0.5$ (cavity mode form factor)

$Q \sim 10^5$ (cavity quality factor)

$$S/N = (P/k_B T_{syst})(t/\Delta f)^{1/2} \text{ with } T_{syst} = T + T_N$$

To scan various *f* as fast as possible requires to lower T as much as possible…

Need of a “High Flux” Magnet

In construction at LNCMI-Grenoble for a large spectrum of scientific experiments including DE & DM searches

The Grenoble Hybrid Magnet in construction phase
Expected in operation for 2019

PROJET LaSUP

Equipex

MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE

COMMISSARIAT GÉNÉRAL À L'INVESTISSEMENT

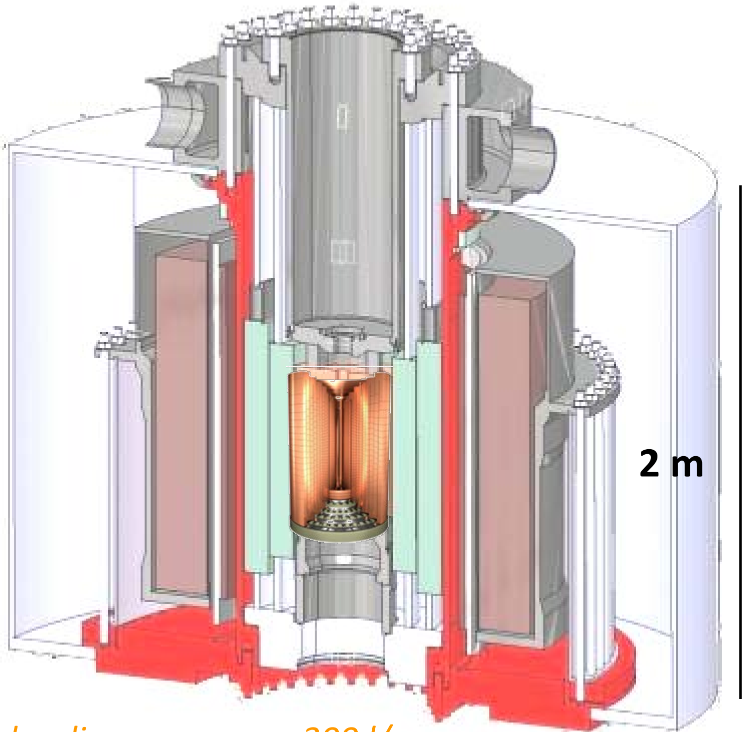
Modular Plateform for the production of High Magnetic Fields

- 43 T/34 mm hybrid magnet 24 MW
  ► 8.5 + 9 + 25.5 T / Supra + Bitter + Poly-helix
- 34 T/34 mm hybrid magnet 12 MW
  ► Energy saving !
- 27 T/170 mm hybrid magnet 18 MW
- 17.5 T/375 mm hybrid magnet 12 MW
- 9 T/800 mm superconducting magnet alone

High Flux Magnets

Under study & open to collaborations

- ADMX type Experiment
- RF-LSW Experiment



Hydraulics : 300 l/s
Total stored Energy : 108 MJ (~ 23 kg de TNT)

P. Pugnat *et al., IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)

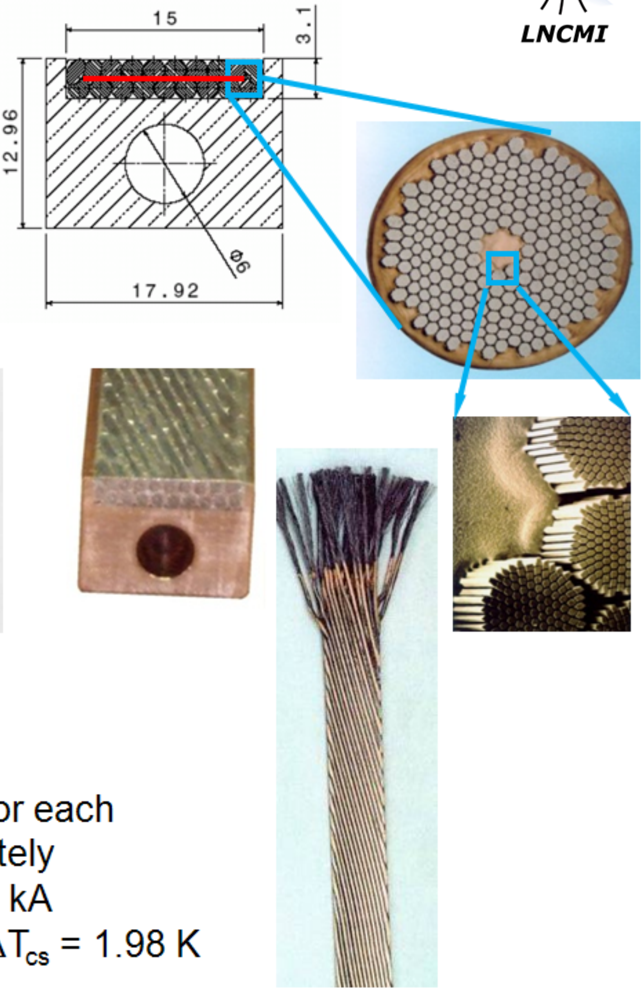
Superconducting Outsert Nb-Ti : 8.5 T / 9T @ 1.8 K

CEA - CNRS Collaboration

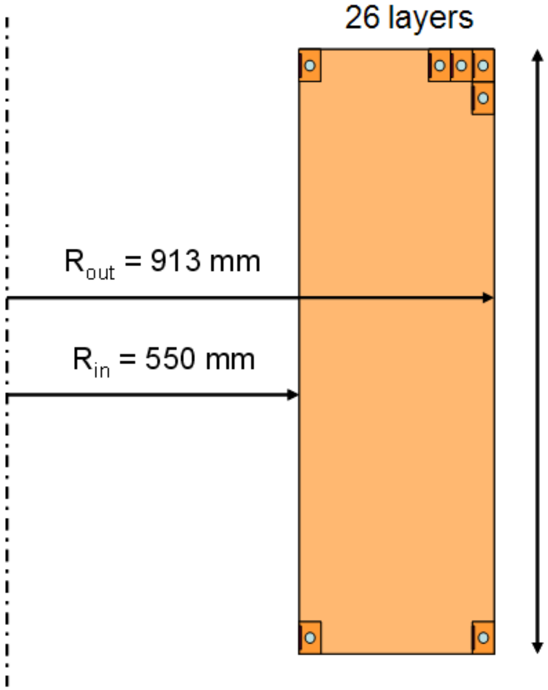
LNCMI

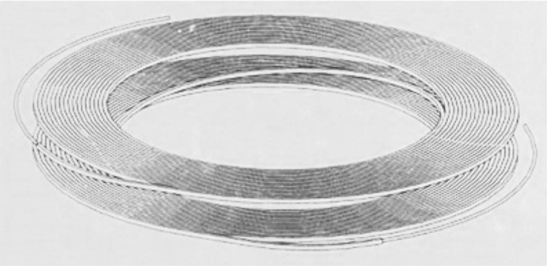
RCOCC : "Rutherford Cable On Conduit Conductor "

- Flat Rutherford cable, 19 strands Ø = 1.62 mm
  - ► Flat stainless steel core (50 μm)
- 6264 filaments/strand, Ø ≈ 14 μm
- Extruded Stabiliser in Cu-$Ag_{0.05\%}$ (RRR ≤ 60)



Coil : 37 double-pancakes (260 m long) series connected



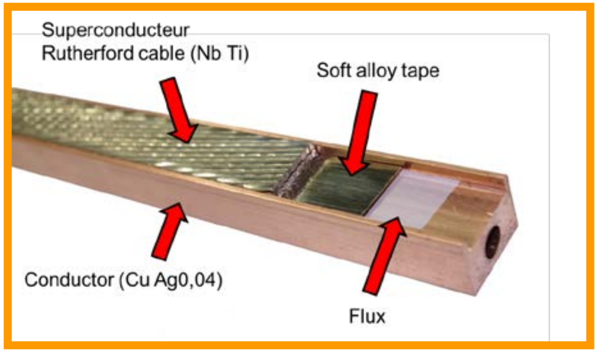


- Coil weight = 17 tons
- Vacuum impregnation for each double-pancake separately
- I (8.5 T / 9 T) = 7.1 / 7.5 kA
- $\Delta I/I_c$ = 19 % at 7.1 kA, ΔT_{cs} = 1.98 K
- L = 3 H, E = 76 / 84 MJ

P. Pugnat, *et al. IEEE Trans. on Appl. Supercond.* **22**, 6001604 (2012)

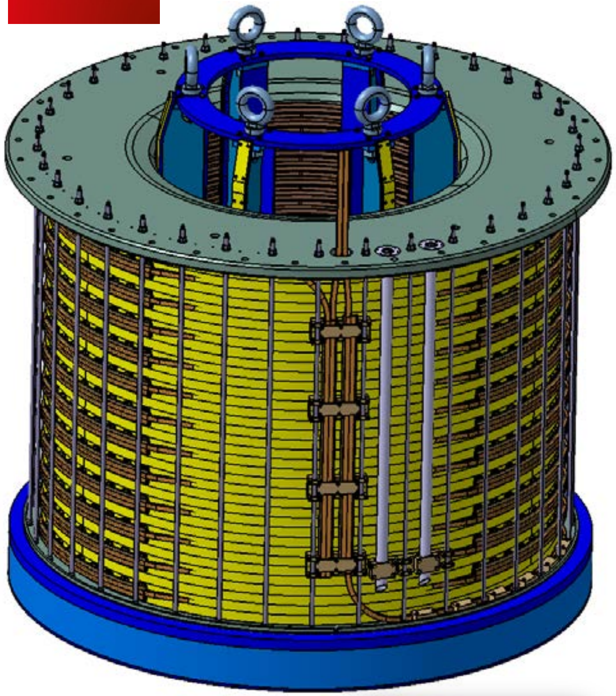
Some ongoing activities

"In Lab." assembly of the superconducting conductor



Coil winding & VPI in industry from

cea SACLAY Irfu **Design**



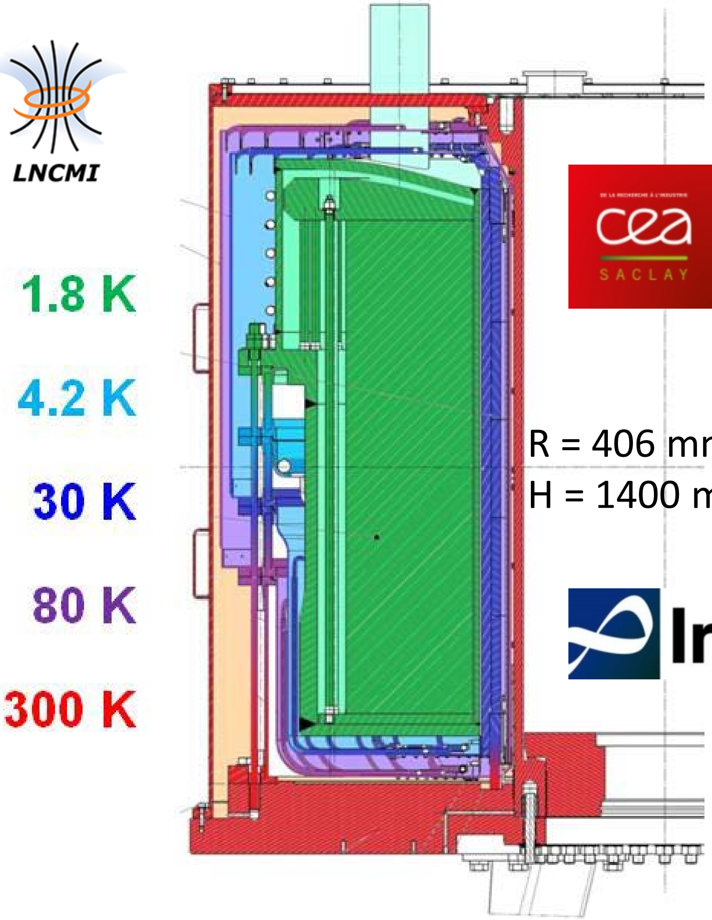
Contract signed January 11th 2016

BILFINGER
Babcock Noell GmbH

- From warm bore + cryostat, $(B^2V)_{magnet}$ up to 40 $T^2\,m^3$ is achievable, *i.e.* about 2 times larger than ADMX & even 5-3 times / 1st ADMX cavity volume

- Can we further increase $(B^2V)_{magnet}$ say up to 75 $T^2\,m^3$?

  . Difficult with quite significant modifications of the design not in line with a multi-user experimental platform…



R = 406 mm
H = 1400 mm

Mass @ 1.8 K	**24 060 kg**
- Superconducting coil	16 300 kg
- Helium vessel	5 380 kg
- Mechanical structure	2 380 kg
Mass @ 4.2 K	**100 kg**
- Thermalisation loop	
Mass @ 30 K	**2 900 kg**
- Eddy-current shield	2 280 kg
- Thermal screens	620 kg
Mass @ 80 K	**710 kg**
- Thermal screens	

High-Q RF Cavities, coupling & tuning

LNCMI

NÉEL institut

Center for Axion and Precision Physics Research

ibs Institute for Basic Science

KAIST

CERN ?

cea SACLAY ?

Possible strategies based on existing RF cavity technologies in Cu

- Several possibilities to optimize B^2V focusing on the TM_{010} mode with the largest form factor knowing that

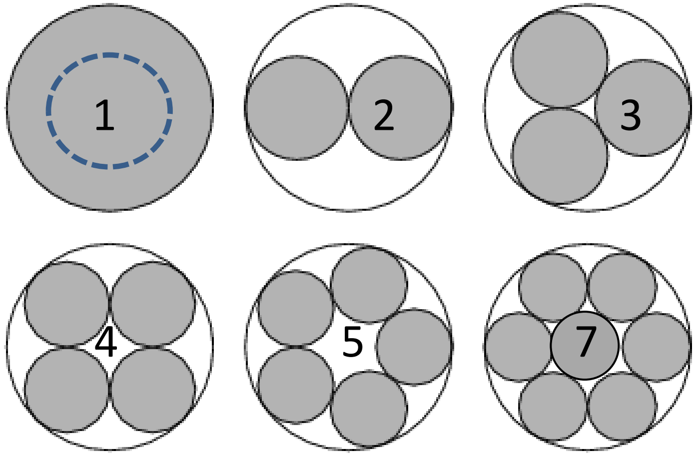
$$R/1\ cm = 11.5\ GHz/f$$

340 MHz 1.4 µeV

1': 640 MHz 2.6 µeV

1.3 GHz 5.4 µeV

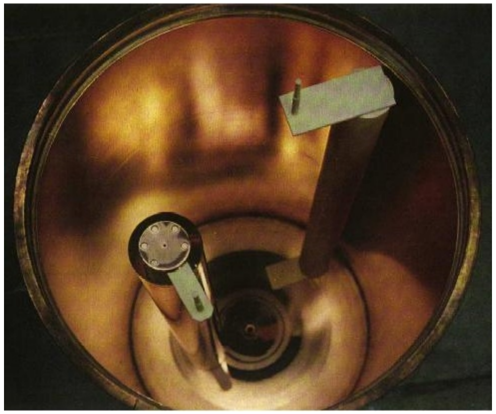
1.4 GHz 5.7 µeV



Cavities in array tuned at the same frequency & phase matching
(See presentation of SungWoo Youn)

1.9 GHz
7.8 µeV

- Frequency tuning with conducting rodes



Borrowed from D. Tanner presentation Vistas in Axion Physics , April 2012

- Adding the conducting rods increases the resonant frequency

- The frequency of the TM010 mode increases as the rods approach the center of the cavity typically 500-800 MHz as for ADMX

Worldwide R&D efforts required to develop RF cavities with $Q \sim 10^6$ (ADMX on the track)

- Presently $Q \sim 10^5$ for Cu cavities, this opens already some interesting opportunities within our large bore superconducting magnet.

- Aiming for $Q \sim 10^6$ with superconducting/Cu cavity, but shall wisthand a 9 T magnetic field; for bulk Nb, $H_{c2}(0) \sim 0.4$ T & can reach 1 T in thin film but not enough, other superconducting materials needed…

- Possible options among others
  - MgB_2 with $T_c \sim 39$ K and $H_{c2}(0) \sim 13$ T
  - Nb-N with $T_c \sim 10$ K and $H_{c2}(0) \sim 13.2$ T

Rq . Larger value reported in thin film geometry or $H_{c3}(0)$?
for Nb-N $H_{c2or3}(0) \sim 20$ T

. Also to be considered, the anisotropy of the $H_{c2}(T)$;
for Nb-N the reported anisotropy is opposite to what is expected,
i.e. $H_{c2//}(0) < H_{c2\perp}(0)$

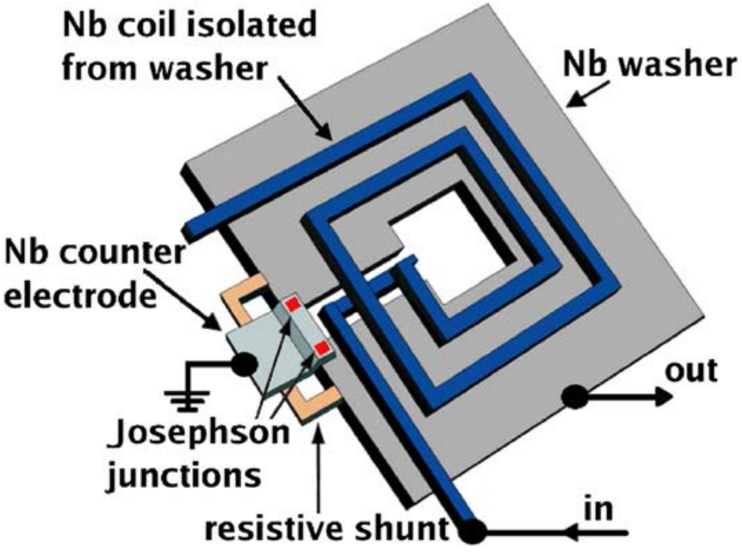
RF Detectors/Amplifiers

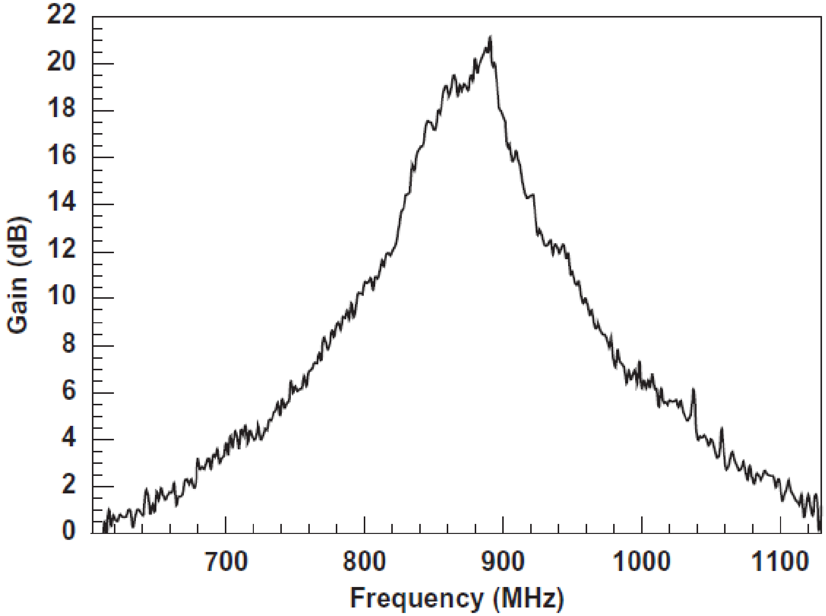
SQUID *vs.* Josephson Parametric Amplifier

& Field-cancellation Magnet

?

SQUID





SQUID + Nb coil = high gain resonator
1 x 1 mm^2 Nb washer
with a hole of 0.2 x 0.2 mm^2

$\Phi_0 = h/(2e) \approx 2.067833758(46)\times10^{-15}$ Wb
$\approx 2.067833758(46)\times10^{-7}$ Mx

More suitable at “low” frequencies

For SQUID cooled to 20 mK
$T_N = 52 \pm 20$ mK at 538 MHz
Quantum limited noise = 26 mK

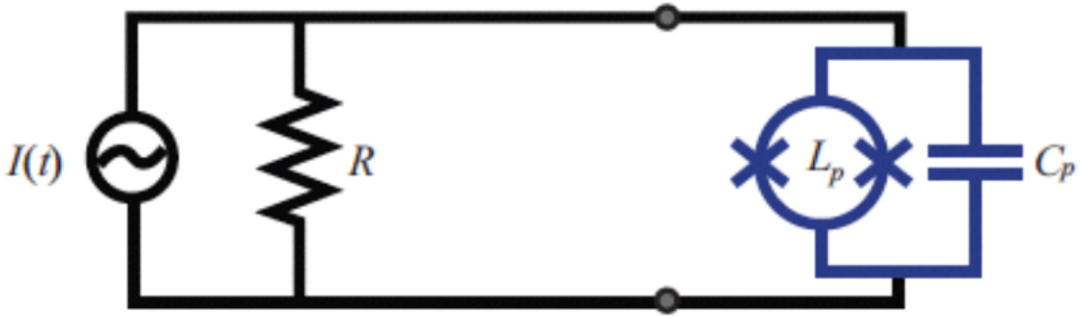
ADMX & J. Clark, NIMA 656 (2011) 39-44

Josephson Parametric Amplifiers (JPAs)

B. Yurke, *et al.*, PRL 60 (1988) 764 (Observation of 4.2-K equilibrium-noise squeezing…)

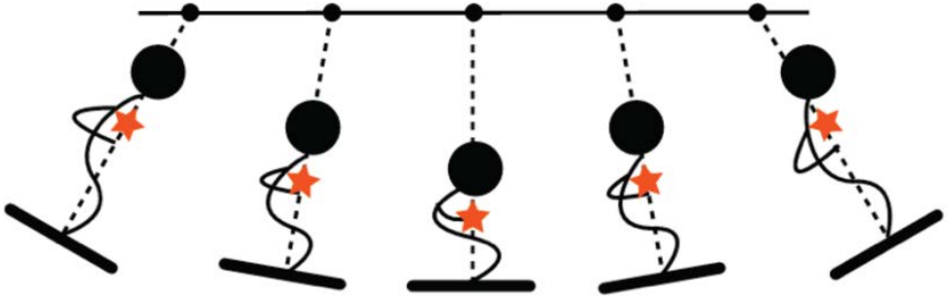
Operating principle

SQUIDs embedded in a cavity form a parametric amplifier



non-linear driven oscillator

$$\frac{d^2\delta_s(t)}{dt^2}+\kappa_0\frac{d\delta_s(t)}{dt}+\Omega_p^2(1-\varepsilon)\left(1-\frac{\varepsilon}{1-\varepsilon}\sin(2\Omega_d t-2\theta)\right)\delta_s(t)=A_s(t)$$



Like a swing

JPA Worldwide Achievements

N. Roch

$$1\ \mathrm{GHz} < f_o < 10\ \mathrm{GHz}$$

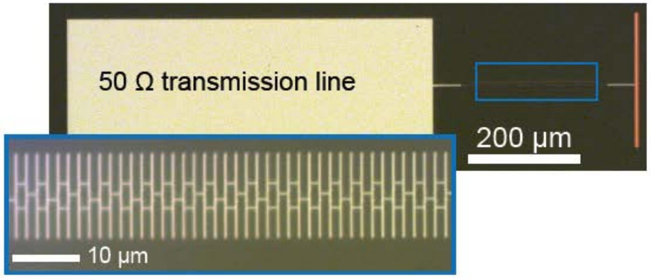
$$G \geq 20\ \mathrm{dB}$$

$$BW \sim 100\ \mathrm{MHz}$$

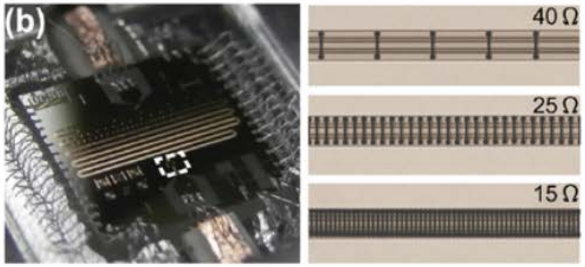
$$T_N \gtrsim \frac{hf_o}{2k_\mathrm{B}}$$

$$P_{1\mathrm{dB}} \sim -100\ \mathrm{dBm}$$

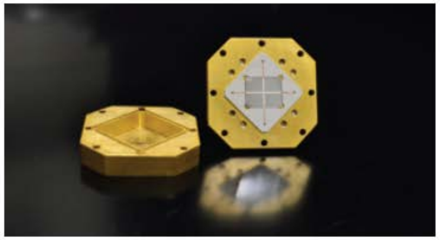
More suitable at "high" frequencies



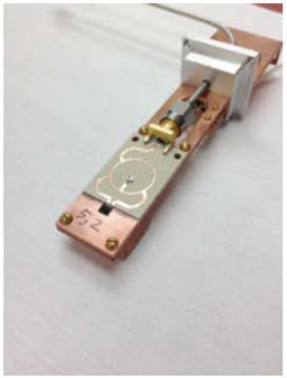
Grenoble



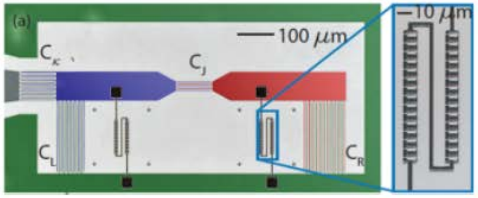
Santa Barbara



Yale

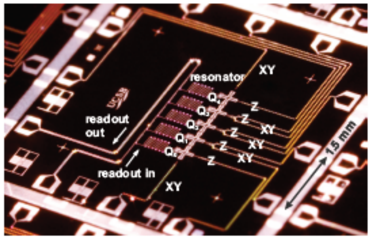


Berkeley



ETHZ

Also ENS-Paris, Boulder, TIFR, Saclay, RIKEN, Technion, Munich, Alto…



Barends et al., **Nature** (2014)

Ex. for High-fidelity readout & Multiplexing

Santa Barbara, Berkeley, Yale,
Delft, ENS-Paris, ETHZ, Wisconsin, Princeton, IBM…

N. Roch, *et al.*
PRL 108 (2012) 147701

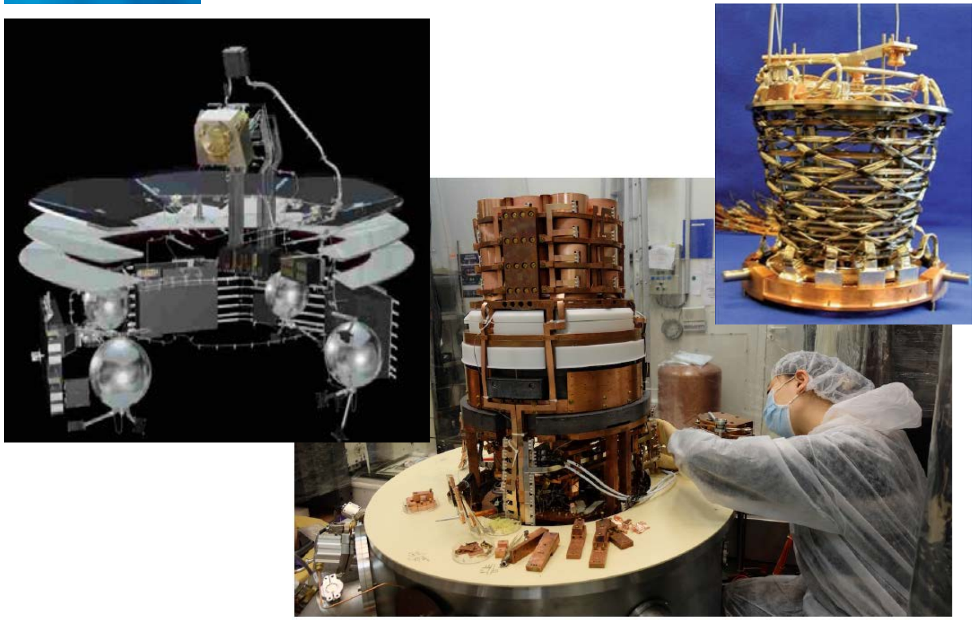
Dilution Refrigerator & Cryostat for RF cavity & Amplifier @ T ≈ 20 mK

Pre-design Considerations

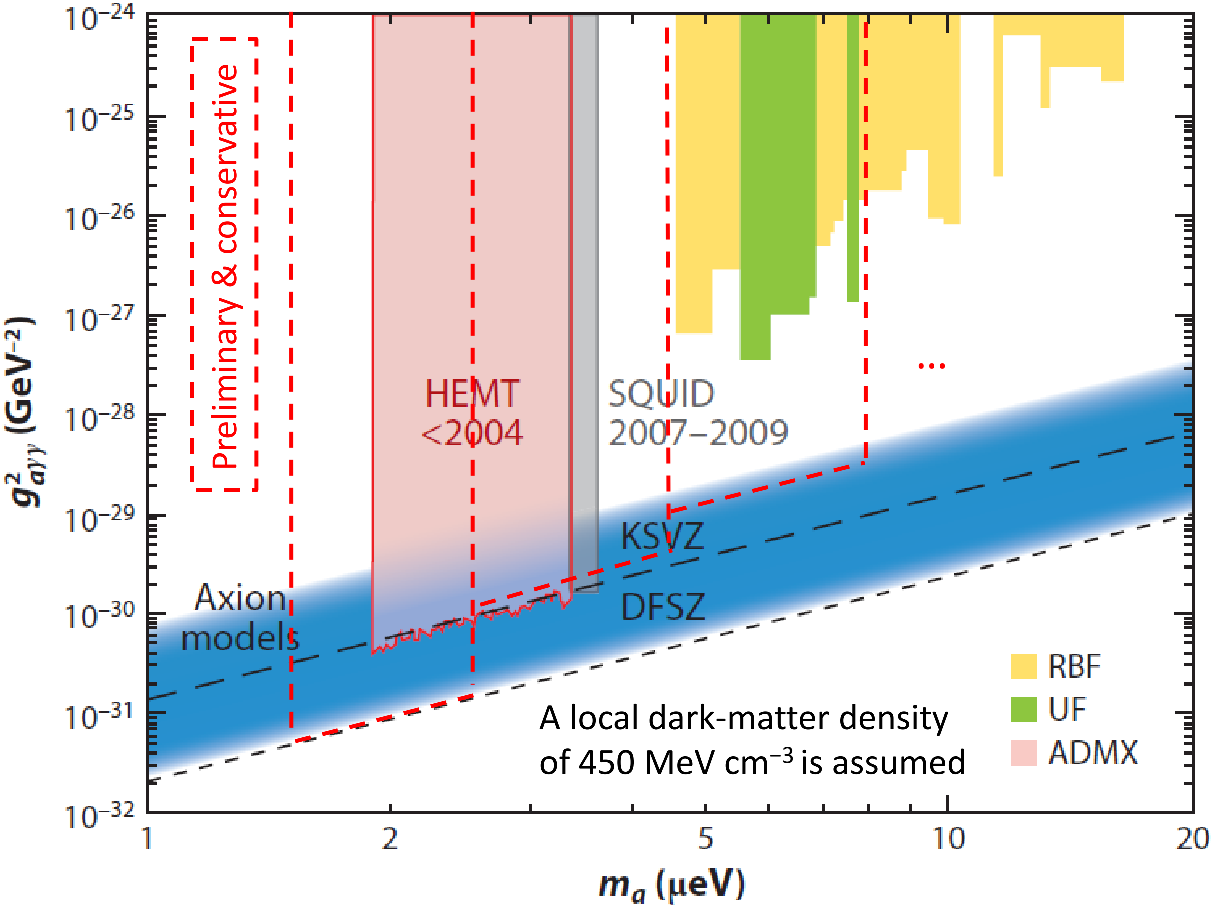
- The warm magnet aperture need to be filled with a dilution cryostat optimizing the 20 mK volume for the RF cavity
- 5 temperature stages from 300 K down to 20 mK, with 10 mm space in between, *i.e.* at least 40 mm in radius lost
- Cryostat with LHe flow or bath, see the most compact & convenient solution
- Custom dilution fridge
- No issues from the know-how @ Néel Institute

http://neel.cnrs.fr/UserFiles/file/faits-marquants/2009/Faits_Marquants1_2009.pdf

- Examples of dilution cryostats & fridges developed @ Néel Institute/Ph. Camus
  - Planck cryogenics (100 mK @ zero-gravity)
  - Edelweiss cryogenics (100 kg @ 15 mK)
  - CUTE (8 kg @ 20 mK – Test for SuperCDMS for which 400 kg @ 20 mK – SNOLAB Canada)



Summary



Model dependant diphoton coupling constant

$g^{KSVZ}_{a\gamma\gamma} = 0.38\ m_a/GeV$

(Kim-Shifman-Vainshtein-Zakharov)

$g^{DFSZ}_{a\gamma\gamma} = 0.14\ m_a/GeV$

(Dine-Fischler-Srednicki-Zhitnitsky)

- As a first step, possibilities of exploring new territories with Cu RF cavities

- In a 2nd step, DFSZ limit extended to larger m_A with High-Q RF cavities (sc or not sc ?)
- And more, but this requires to squeeze the quantum noise (see presentation of A. Chou)…

Conclusion

- **The preliminary study for the development of a new haloscope from a CNRS/CAPP-IBS collaboration is very promising**. The target is to be competitive with ADMX & go beyond, reaching the DFSZ limit for axion mass range compatible with CDM, *i.e.* typically 10^{-6}-10^{-4} eV.

- **Disclaimer:** Although the construction of the large bore superconducting magnet, which is fully funded, is well engaged, **not all institutes & laboratories listed in this presentation have been yet officially informed about this project**… We are at the feasibility study stage, in the *know-how* inventory & team building.

- **Expected Next Steps**
  - MoU between collaborating institutes (CNRS/CAPP-IBS, others ?)
  - Feasibility study including funding issues
  - Technical Design Review
  - Final Design Review
  - Installation at LNCMI-Grenoble in ~ 2020, it's the right time to start the design & construction of RF cavities…

Disclaimer

On High Magnetic Fields ;-) …