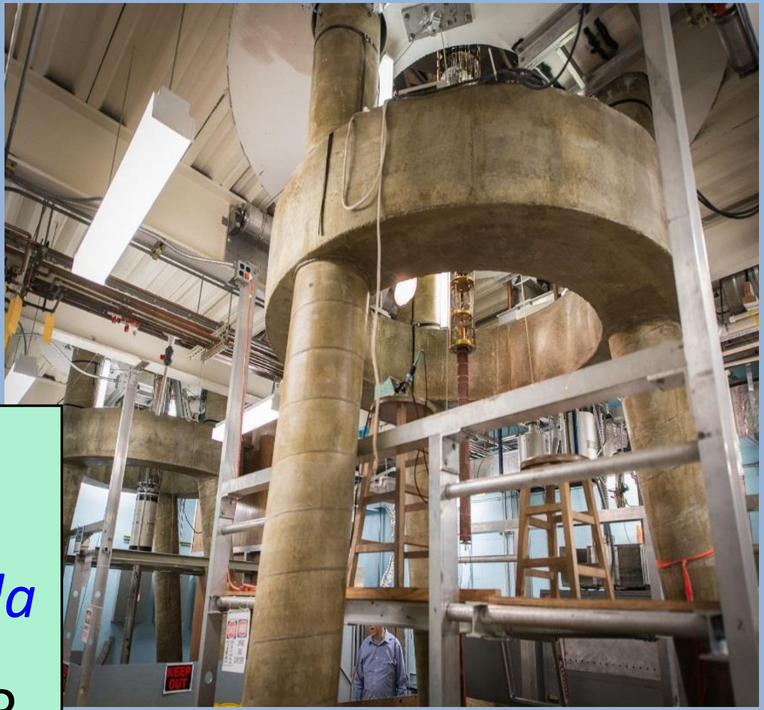
# Experiments at Ultra-Low Temperatures (T<0.01K)



How  to produce    T< 1 mK

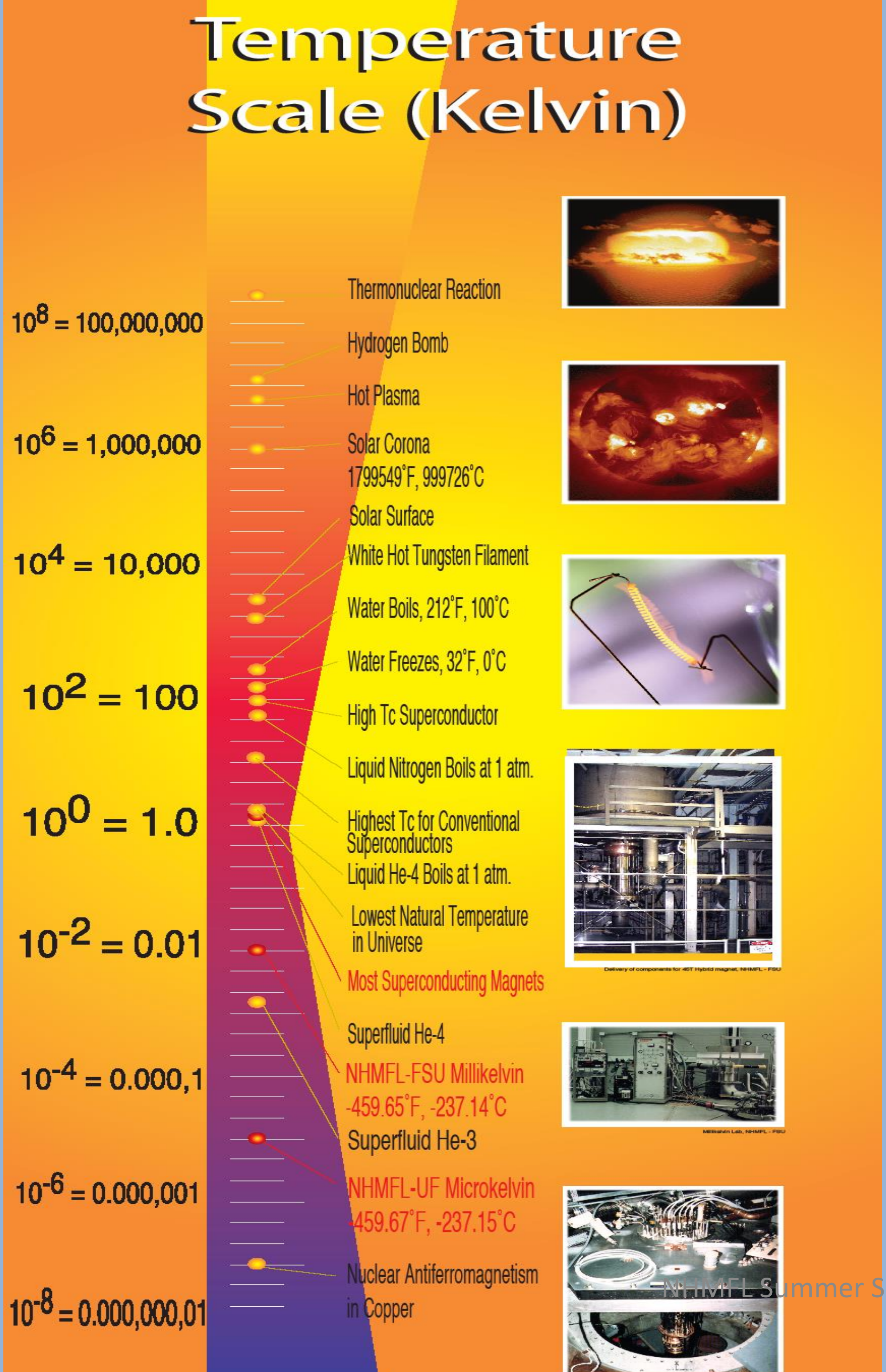
Where?   *High B/T Facility Univ. of Florida*

What types of Experiments are Possible?

How to conduct Experiments?

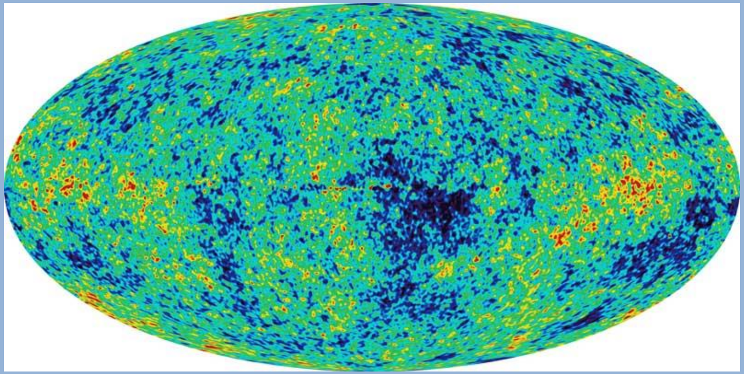
NHMFL  Summer School  2018

*N. Sullivan,  J. S. Xia, N. Masuhara, C. Huan, A. Woods*



## Coldest Temperature

## in Nature?  T = 2.725 K



**WMAP Resolves the Universe**
**Credit:** WMAP Science Team, NASA

# HOW ?

(i) 1st stage: Powerful (high-circulation rate) dilution refrigerator

(ii) 2$^{nd}$ Stage: a few tens of moles of metal = nuclear refrigerator

(iii) Cool nuclear spins to 10 mK in 10 Tesla and then isolate (superconducting switch)

(iv) Demagnetize nuclear spins (isentropic process)

(v) Cooling power for 20 moles ~ nanowatts

FACILITY provides (i) --- (v)

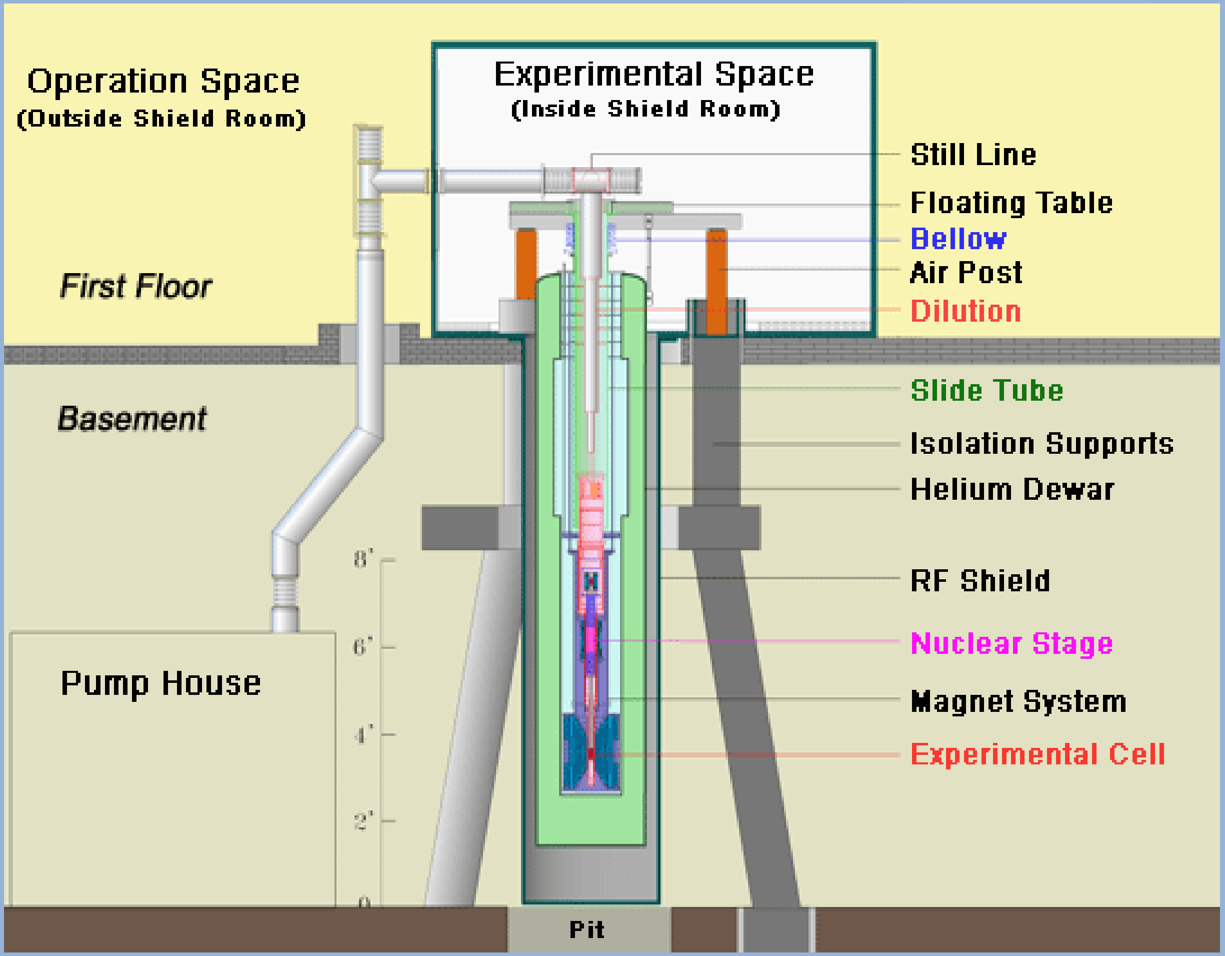
(vi) Must minimize spurious heat ---- can stay cold for weeks

**USER MUST DESIGN EXPERIMENT VERY CAREFULLY --- consult local staff early**

# UF High B/T Facility

Available to users worldwide

T < 1mK , B up to 16 T



## Research

Nuclear spin ordering
2D Electron gas
Bose-Einstein Condensation
Quantum critical behavior

# Nuclear Refrigerator

Relies on fact that B/T for a ‘good” paramagnet remains constant If perfectly isolated.

M= F(B/T)

(1) Cu: Precool to ~ 10mK in B =10 T

Isolate (open superconductor switch)

(2) Demagnetize to 0.03 T (very carefully)

T drops from 10 mK to 300 microK

Good design

-- stay cold for several weeks

Cu or PrNi5

demagnetization

e.g.

(a) $PrNi_5$:

cool from 30mK to 0.3mK

high cooling power

(b) Cu:

Cool from 30 mK to 0.03mK

Low cooling power

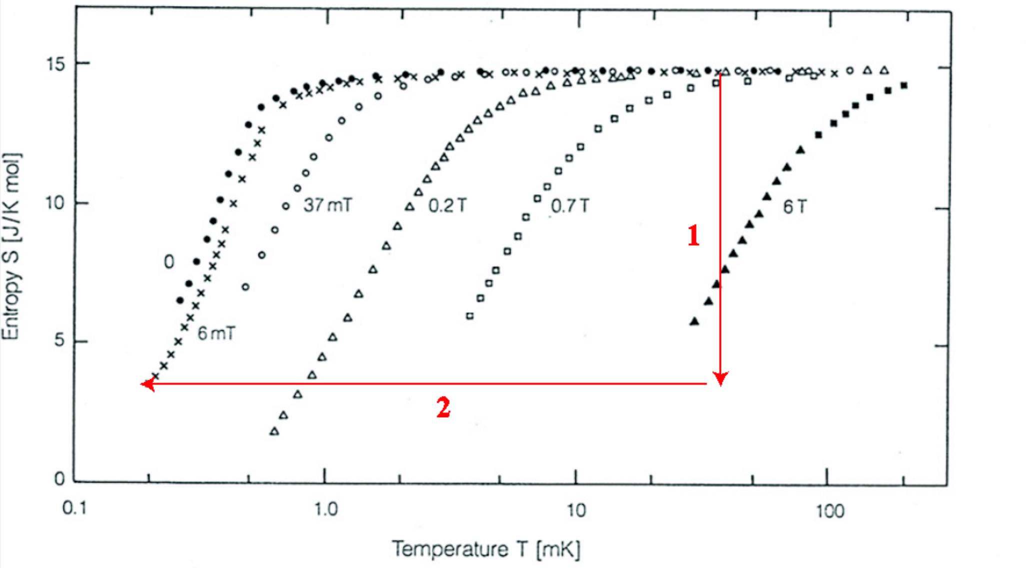
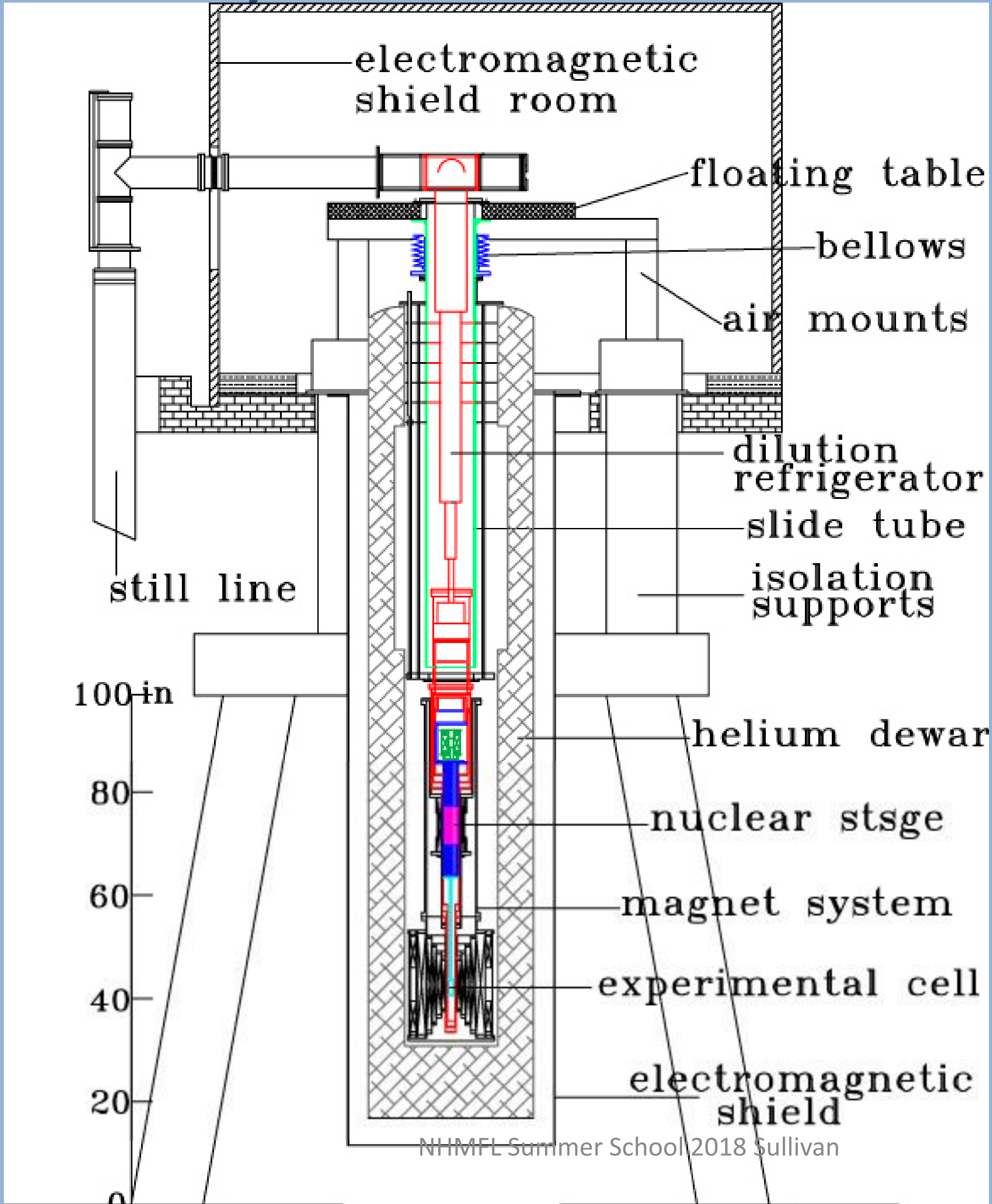


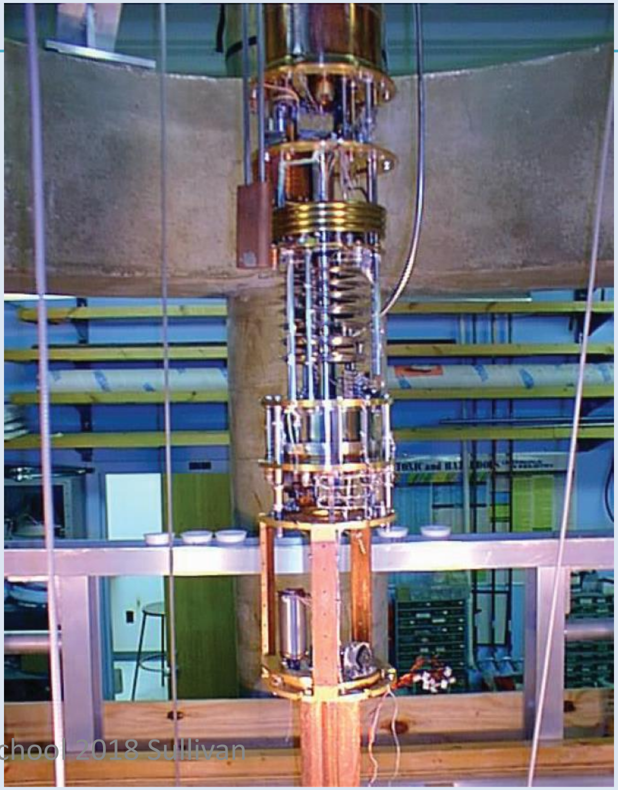
**Fig.10.13.** Nuclear spin entropy of $PrNi_5$ as a function of temperature in the indicated fields [10.55] *F. Pobell: Ultra-Low Temperatures*

# NHMFL HIGH B/T FACILITY



# MAGNET SYSTEMS AND AVAILABLE TEMPERATURES

| Superconducting Magnets | Refrigerator |
|---|---|
| Bay 3, Microkelvin Laboratory<br>**15.5 T at 4K (16.5 T at 1.2K**<br>**2 cm DSV experimental space** | **$PrNi_5$ nuclear refrigerator**<br>0.3 mK, 10 nW cooling power |
| Bay 2, Microkelvin Laboratory<br>**8 T at 4K (10 T at 1.2 K)**<br>**3.2 cm DSV experimental space** | **Cu nuclear refrigerator**<br>0.07 mK, 0.1 nW cooling power<br>(lowest attained temperature 0.04 mK) |
| Williamson Hall Annex<br>**10 T, 2.5 cm DSV experimental space** | **Dilution refrigerator 40 mK** |



# Current capabilities

Electrical Transport Measurements
AC magnetic and electric susceptibility
High frequency NMR/NQR (2.0 MHz – 1.2 GHz)
Ultrasound absorption
Precision pressure/thermodynamic measurements

# Specialized Instruments

High sensitivity bridges
Vibrating-wire viscometers
Sample rotator (–10° to +90°, with a liq-$^4$He actuator)
RF and DC SQUIDs (commercial)
Broadband low temperature amplifier (noise T < 1 K)

# Thermometry

| | |
|---|---|
| Pt NMR | T < 20 mK, in a low-field region |
| $^3$He melting curve thermometer | 0.4 mK < T |
| Dilute $^3$He vibrating-wire thermometer | 1.7 mK < T |
| Kapton capacitance thermometer | 4 mK < T |
| CMN susceptibility thermometer | 15 mK < T, in the low-field space |
| RuO resistor (all commercial) | 20 mK < T, in the low-field space |

# 1. Measuring Magnetic and Electric Susceptibilities at Ultra-Low T.

## CHALLENGES

(i) Must adequately thermalize sample
… best to immerse in liquid 3He (otherwise not reliable below 15 mK.)

(ii) All electrical leads must be heat sunk to avoid conduction losses via electrons …. very hard to cool electrons in metals

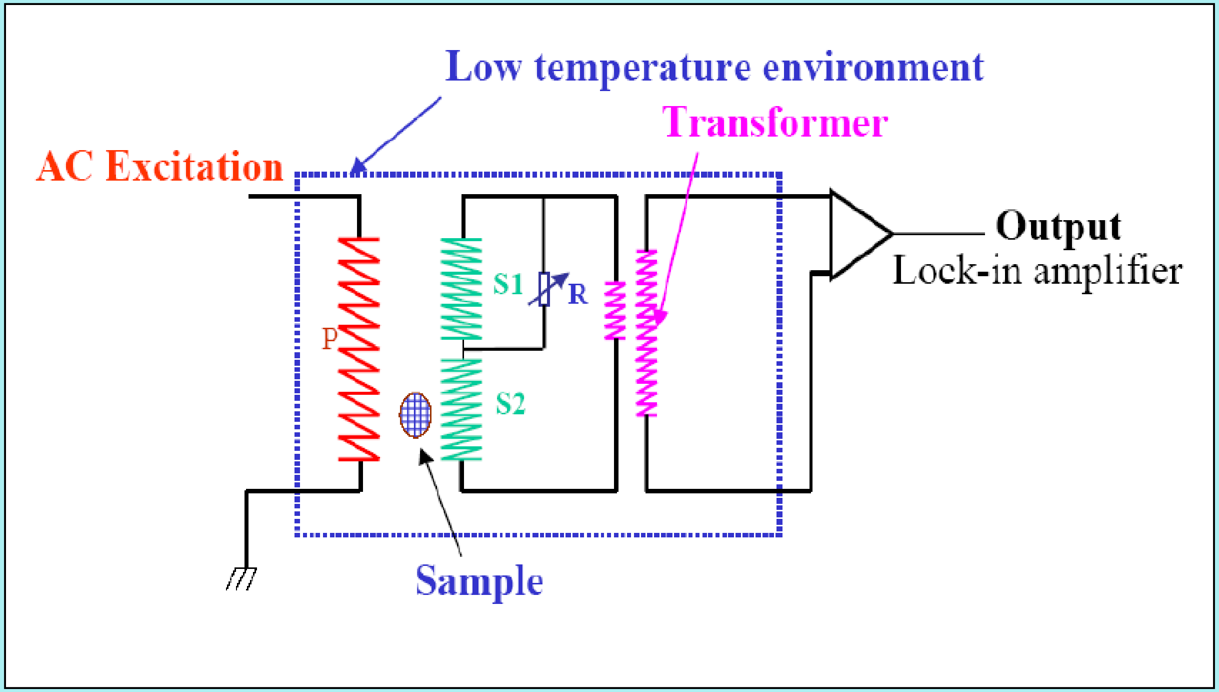
(iii) Low temperature transformers not very reliable
…… basically air core, hand wound and tailored to experiment

(iv) Careful grounding of all leads, and avoid ground loops at all costs.

**(v) TEST experimental cell in 10 mK/10T facility BEFORE using High B/T**

# AC Magnetic Susceptibility Measurements

Use modified version of standard mutual inductance bridge with counter wound secondary coils (sample positioned in one):

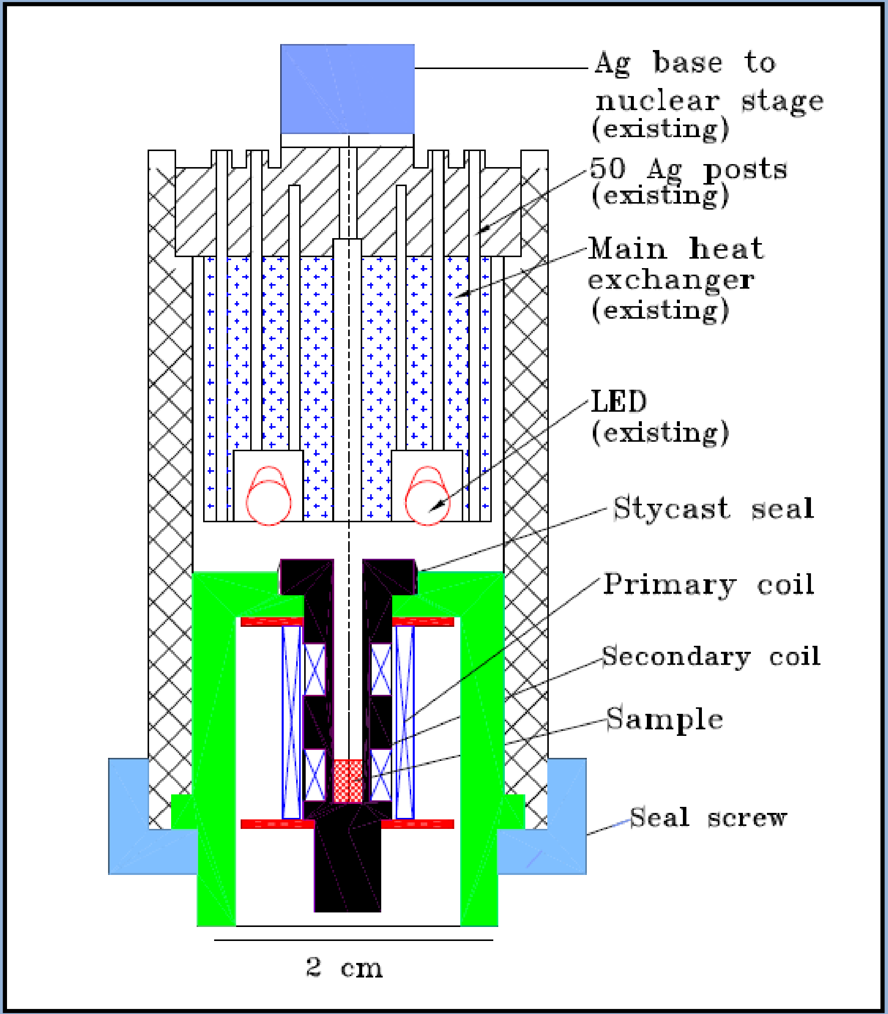


(i) Primary: Superconductor… reduces heating

(ii) Add low temperature transformer to impedance match to achieve lowest $T_{noise}$

**L. Yin *et al*. J. Low Temp. Phys., 158, 710-715 (2010)**

# Magnetic Susceptibility Cell

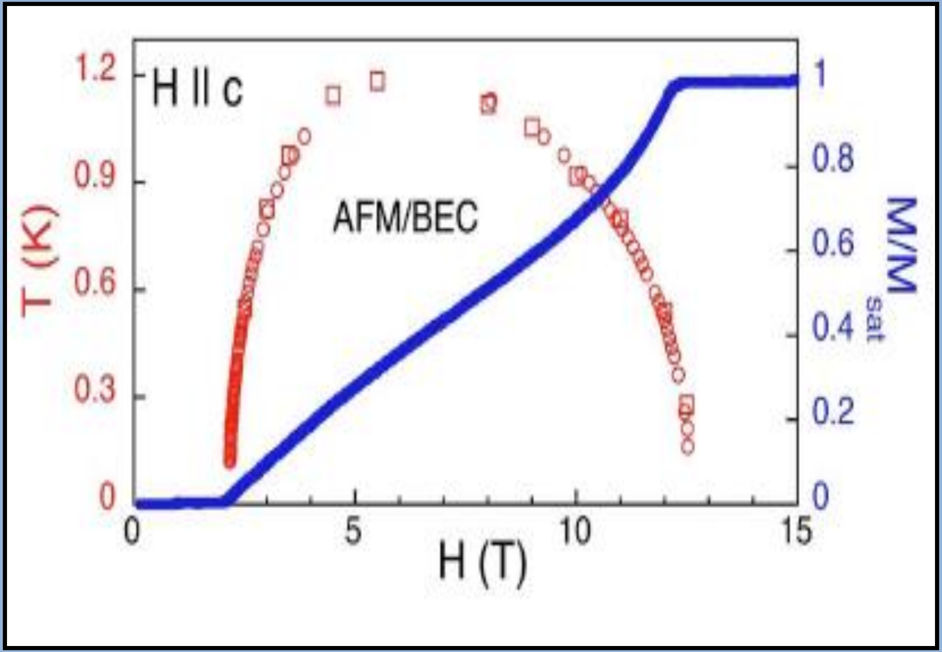


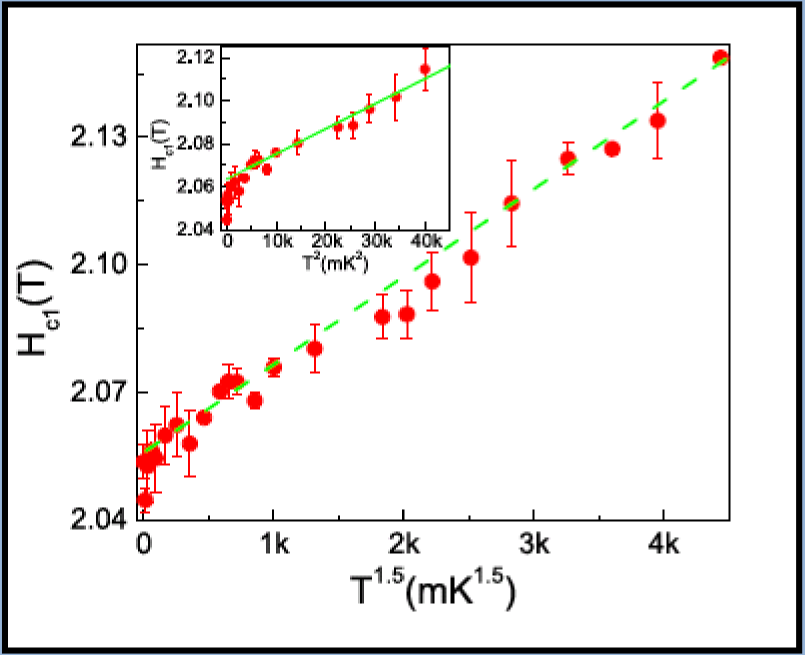
- Note heat exchangers for input leads to reduce heat leaks
- Annealed Ag wire used for secondary coil
- Superconducting wire for primary coil

L. Yin *et al.*, J. Low Temp. Phys., **158**, 710-715 (2010)

# Example:  BEC in Organic Quantum Magnets

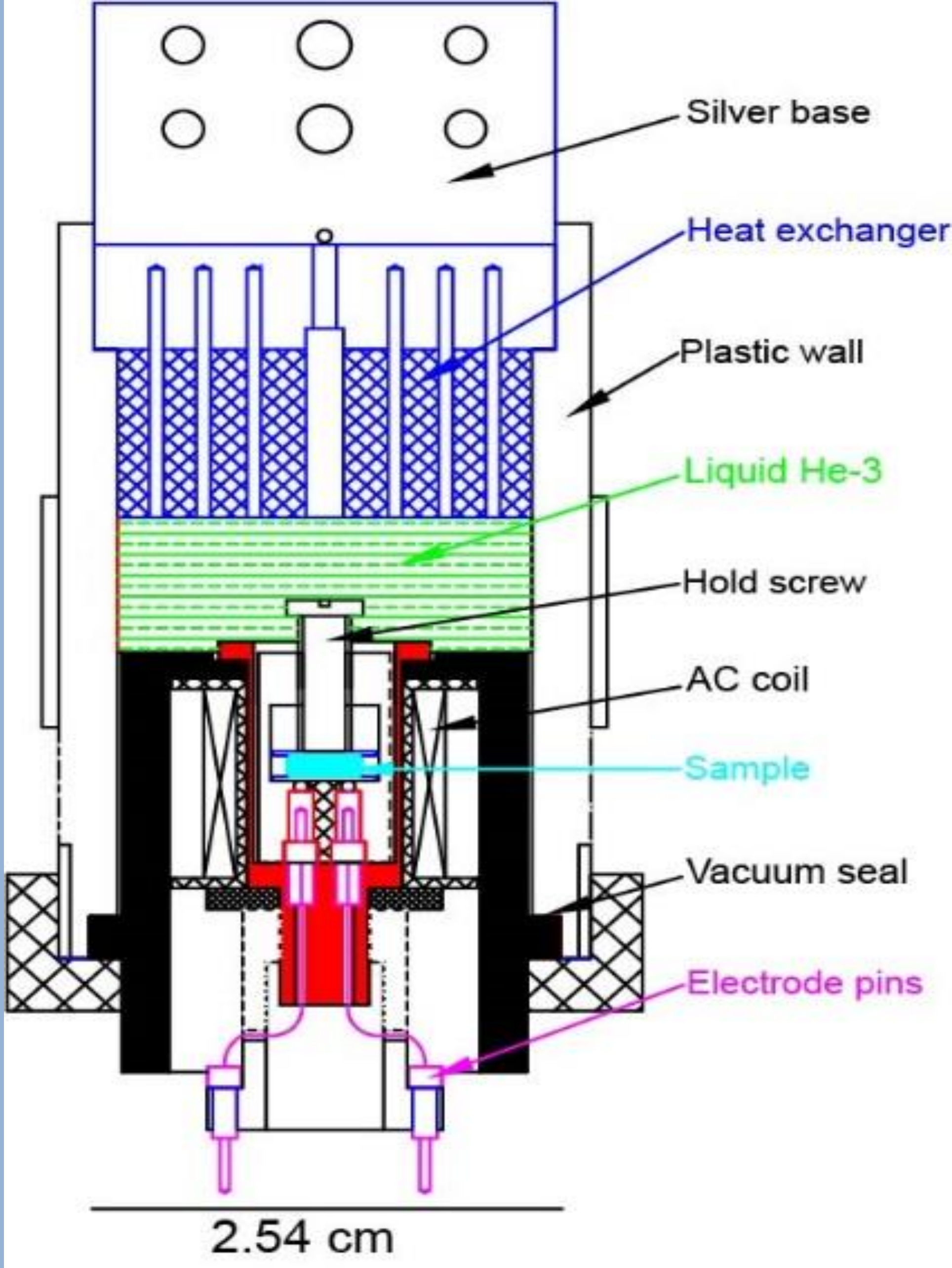
*AC susceptibility  as function of H*





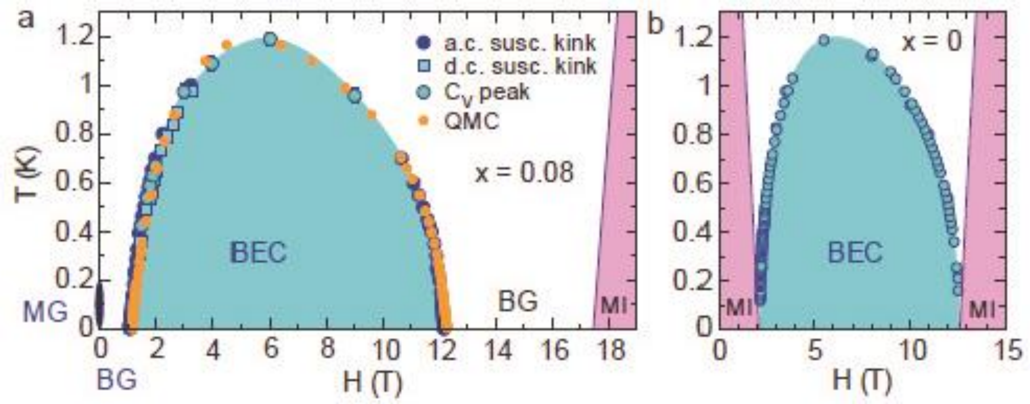
**L. Yin, V. Zapf et al.,**
**J. Low Temp. Phys.  158,  710-715 (2010).**

# Dielectric Susceptibility Cell

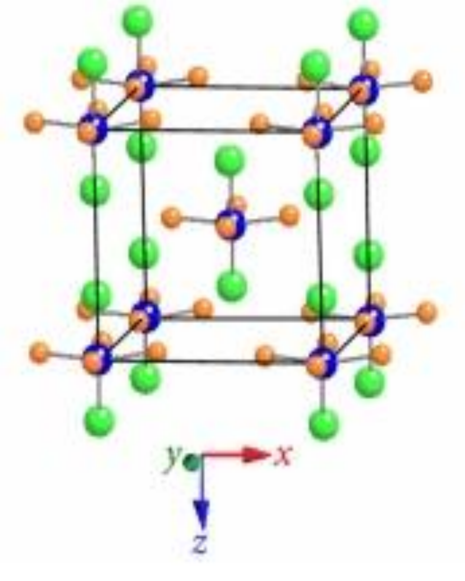


- Sintered silver heat exchangers for input leads to reduce heat leaks
- Superfluid 3He for reliable thermal contact
- Additional AC magnetic field to measure magneto-electric effects

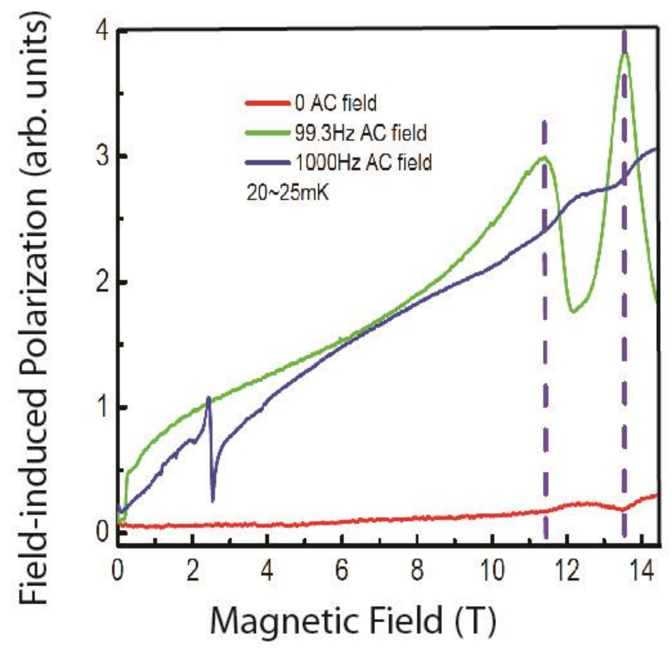
# Example: Magneto-electric Effects in DTN



**Low temperature phase diagrams for (a) BEC condensed DTN,**
**(b) Bose glass state in Br-doped (15%) DTN**



**Crystal structure :**
**Ni spins blue,**
**Cl separators green**



I. **strong frequency dependent induced polarization**

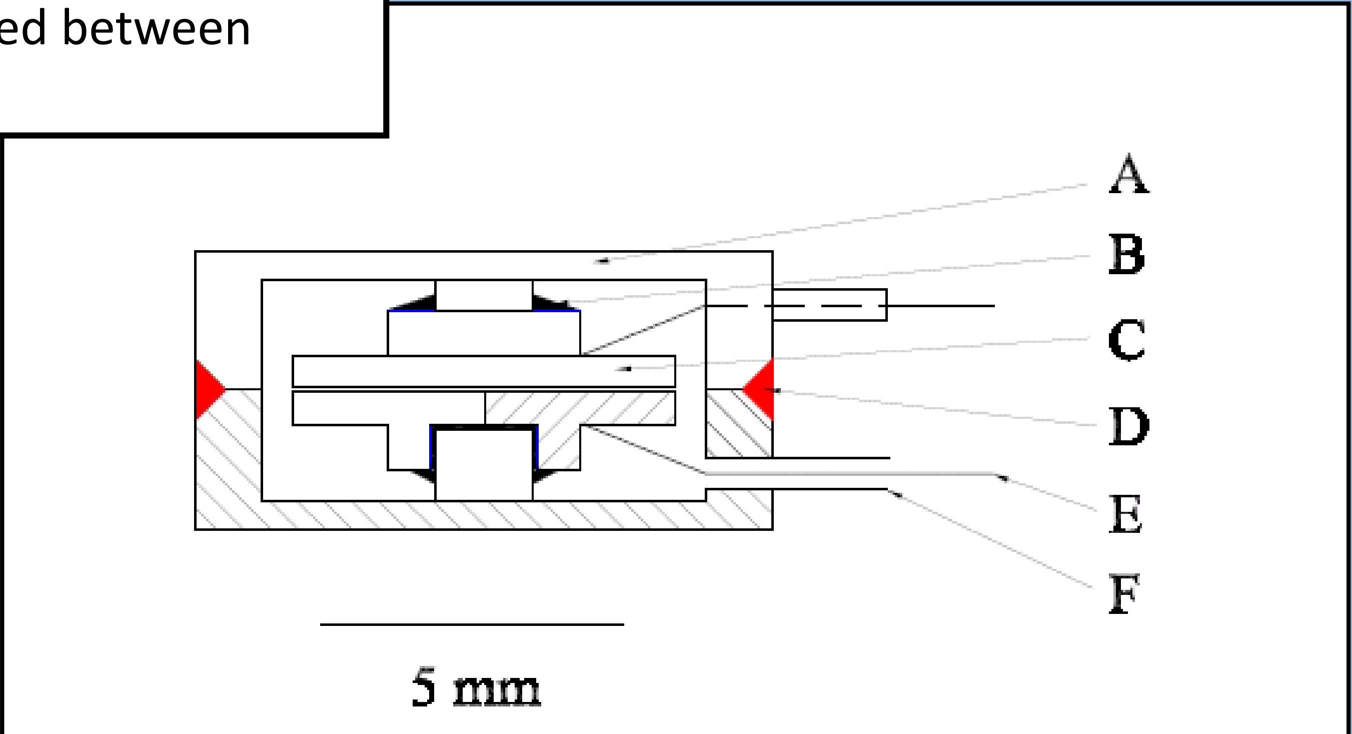
II. **clear indications of the transitions: BG state to BEC phase**

# 2. Measuring Pressure
# Capacitive Strain Gauge

**Xia *et al*. J. Phys. Conf. Series, 150, 012054 (2009).**

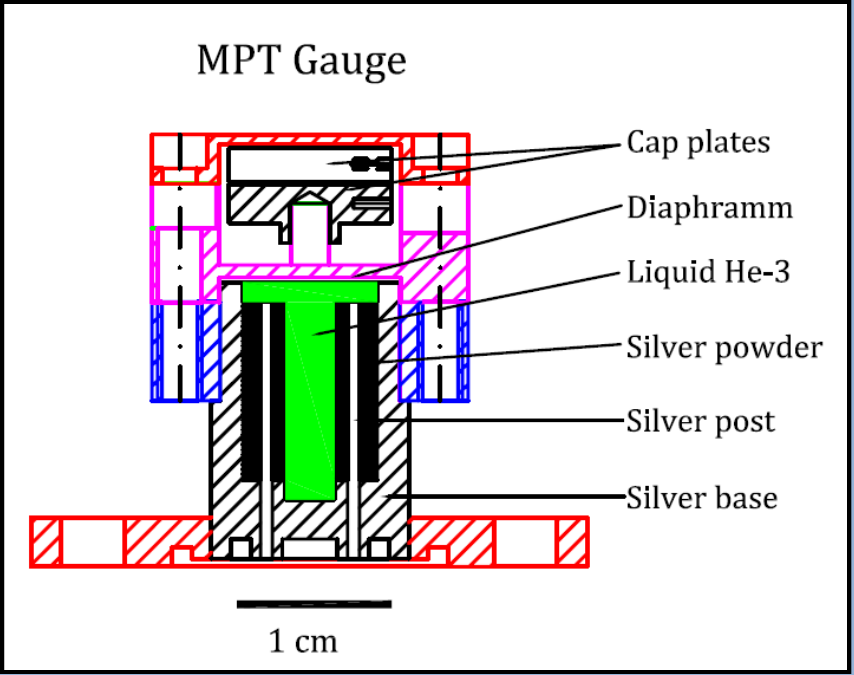
Motion of flexible diaphragm (A) transmitted to moving electrode (C)

Capacitance measured between C and the stator E



# 3. Ultra-Low T Thermometry

## (a) $^3$He Melting Curve Thermometer



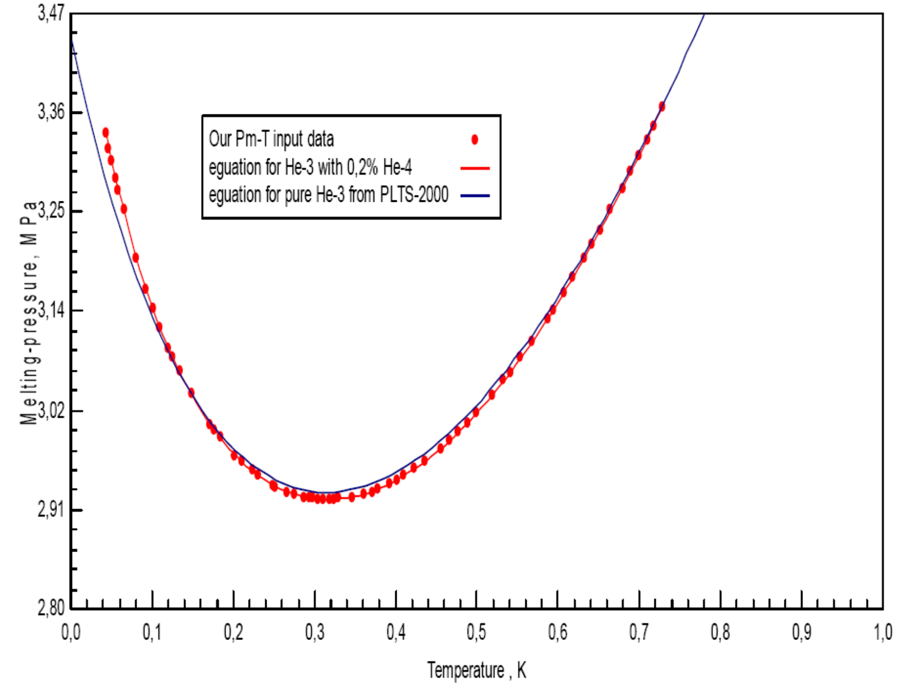


Figure 2. $^3$He melting curve with 0.2% $^4$He impurity.

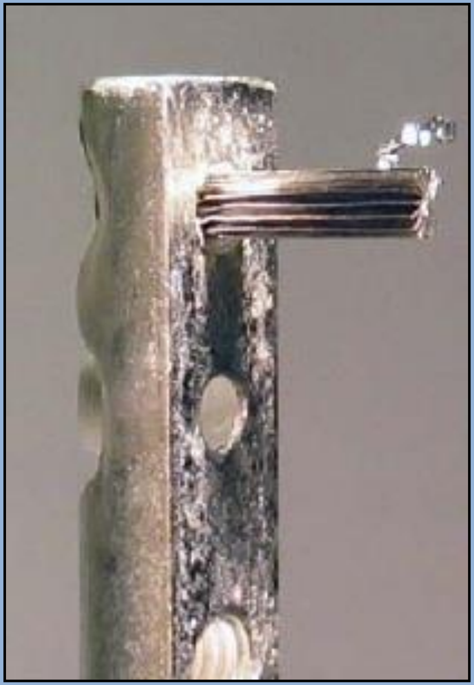
**References**

D. S. Greywall, Phys. Rev. B33,7520 (1986)
W. Ni *et al*., J. Low Temp. Phys. 99,167 (1995).

**$^3$He Pressure unique thermodynamic function of T**

**Most reliable: 0.5 --- 200 mK**

# (b) NMR $^{195}$Pt Thermometer



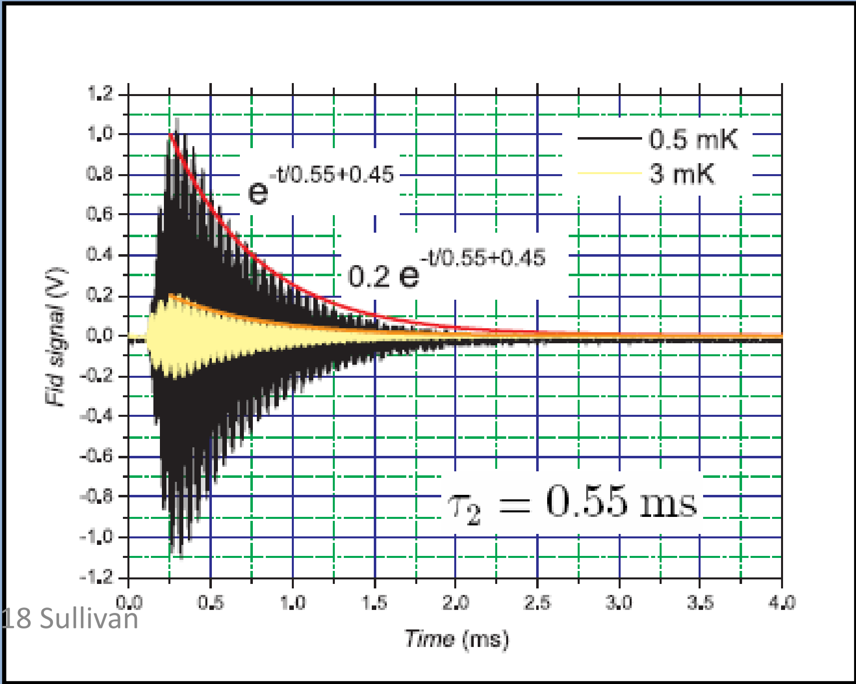
Anssi Salmela
*Helsinki Univ. of Technology*

Product of relaxation time $T_1$ and T a constant (Korringa Relation)

$T_1$ T=0.030 s K for $^{195}$Pt

$T_1$ = 5 min at 0.1 mK

Use brush of annealed fine Pt wires



# 4. NMR Capabilities

**Pulsed NMR Spectrometry to 1200 MHz**

(a) High Frequency (> 300 MHz):
---- Birdcage resonator

(b) Low Frequency (few MHz)
---- Crossed-coil probe with integrated low temperature preamplifier

(c ) Intermediate Frequency (hybrid-tee design)

**General technique**: Operate NMR circuit (coil etc.) at mK
----- sample at sub-mK temperatures

# HIGH FREQUENCY NMR Cell

Re-entrant cavity with walls at relatively high temperature and sample in cold finger inside cavity

**D. Candela *et al.* Phys. Rev. B 44, 7510 (1991).**

Application:

NMR at 14.8 T to study quantum diffusion of $^3$He in superfluid $^4$He.

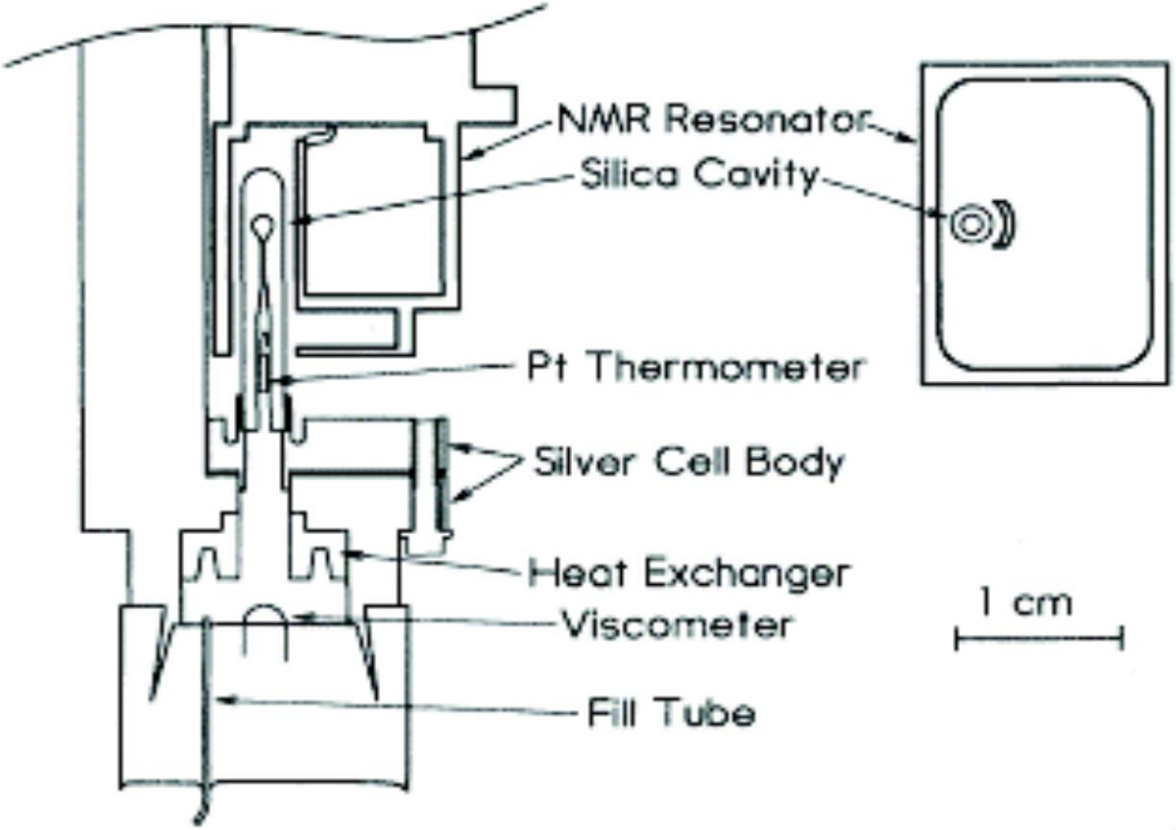


FIG. 3. Vertical cross section through the second sample cell. Inset at right shows a horizontal cross section through the inductive section of the $^3$He NMR resonator at the level of the spherical cavity.

Small Birdcage Resonator for Low Temperature NMR 793

**H. Akimoto, D. Candela**
**JLTP 121, 791 (2000)**

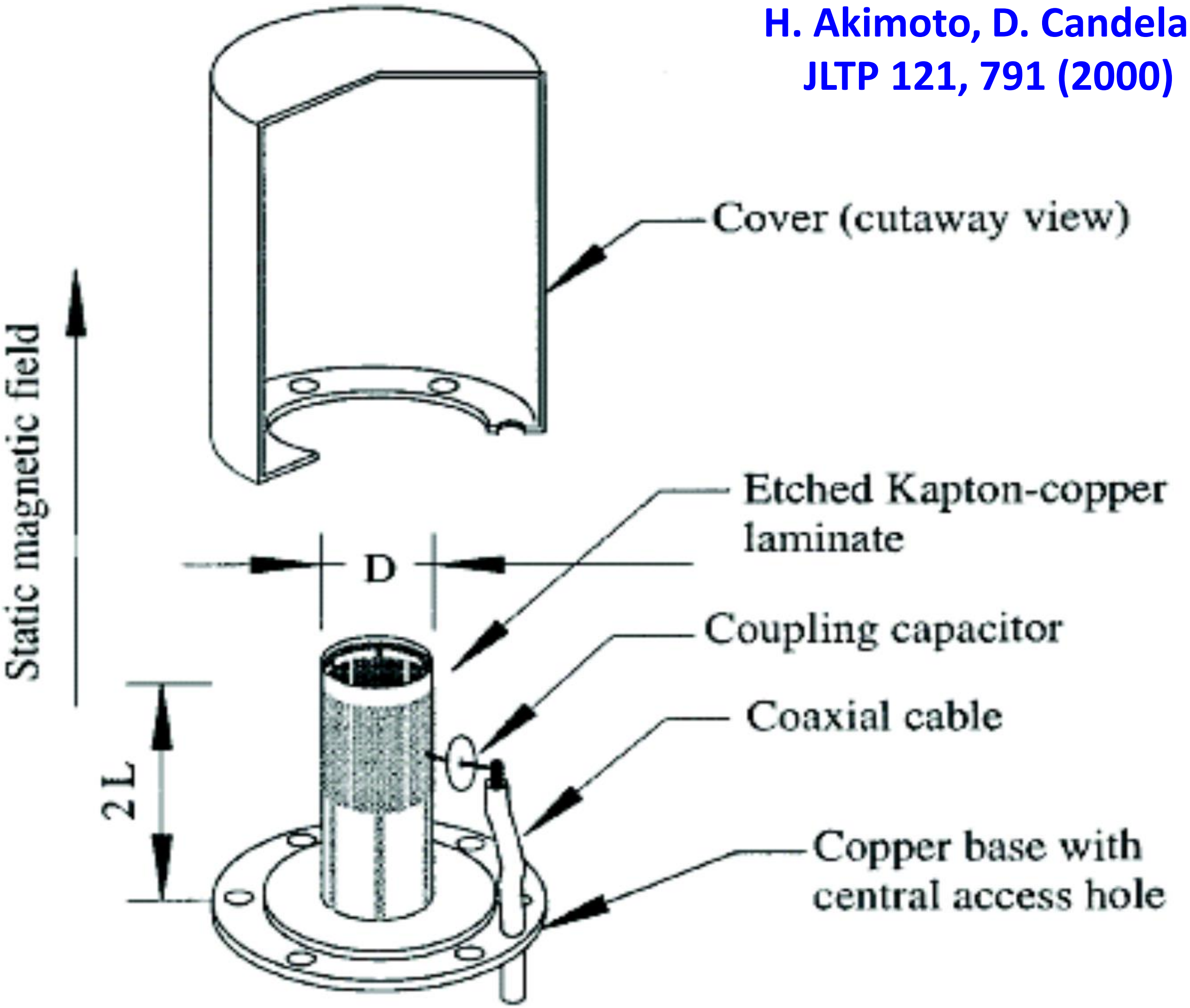


Fig. 1. Perspective drawing of the resonator. Dimensions are given in Table 1. The sample should be centered in the lower half of the etched circuit.

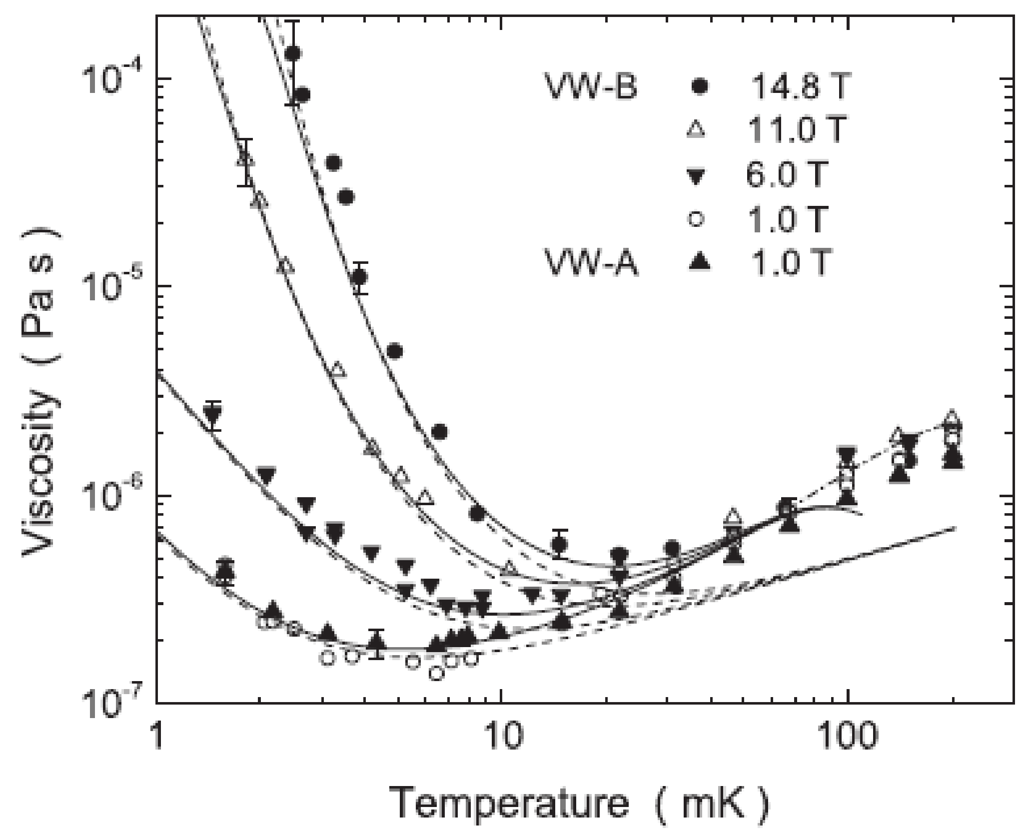
**Ideal Fermi Liquid**: 150 ppm $^3$He in $^4$He
Very dilute, weakly interacting $^3$He atoms
D. Candela *et al*.,

**Quantum Transport:**
**viscosity increase rapidly with B**

**Spins align in strong B**

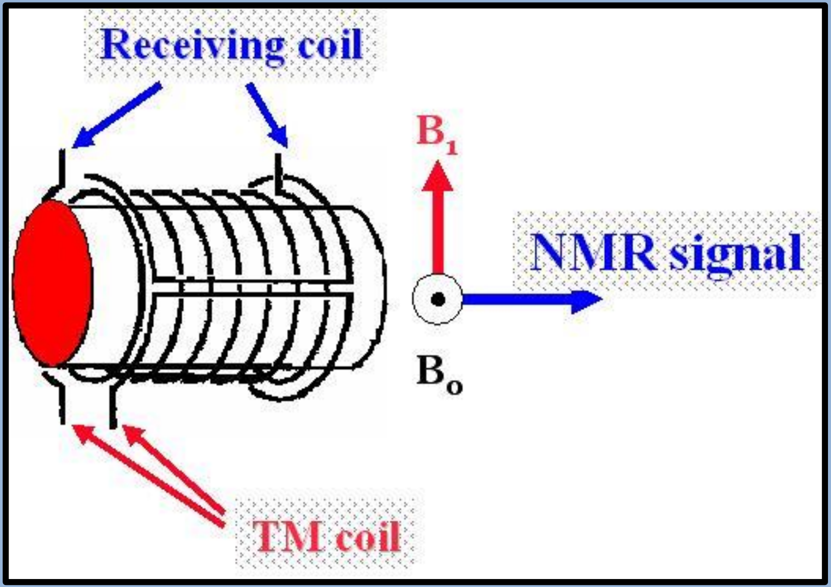
**↑↑ high scattering interaction**
**↑↓ low scattering interaction**

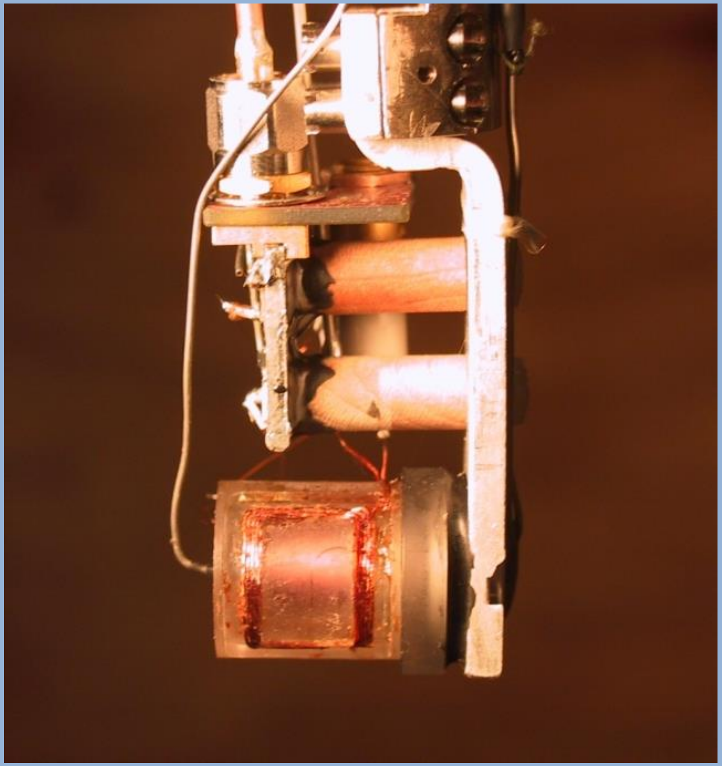
**Measure spin diffusion directly with NMR (15 T)**



# Crossed-Coil NMR Probe

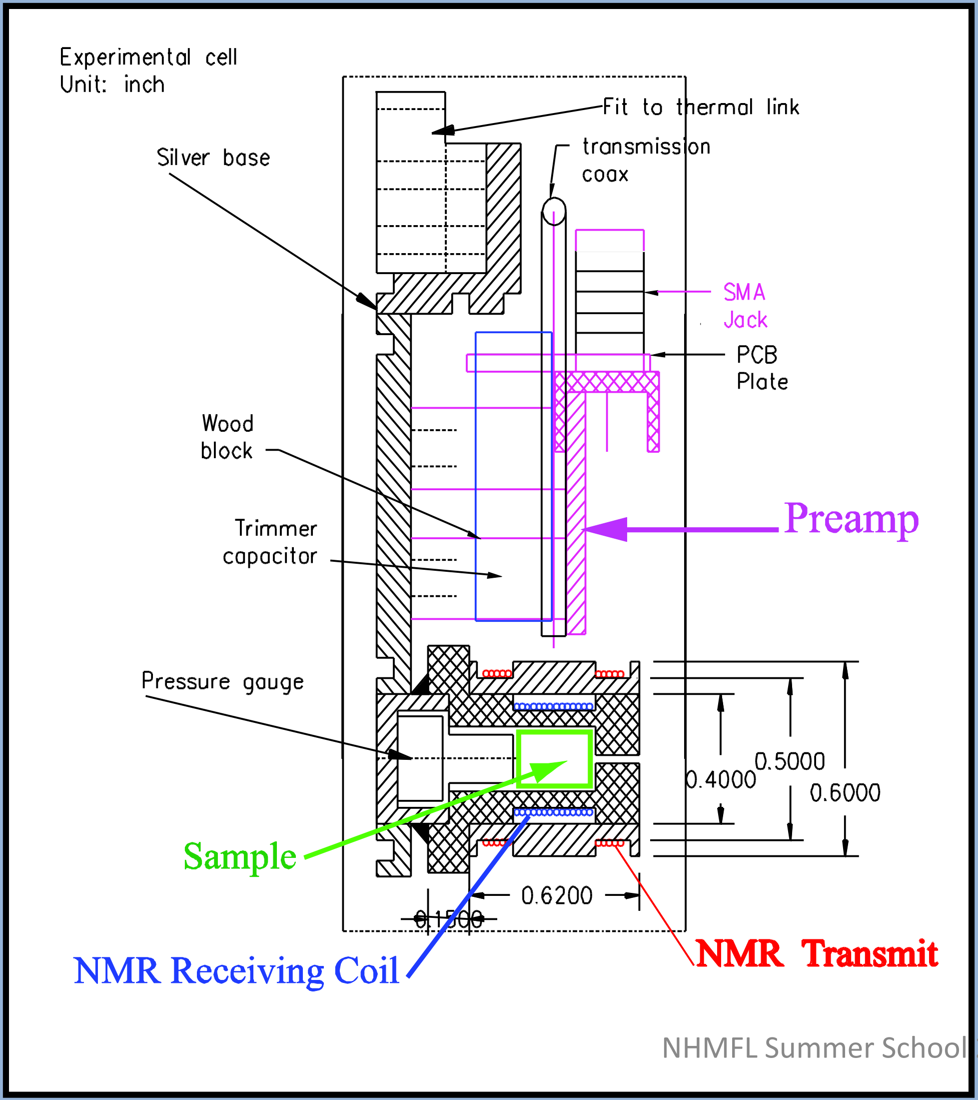
**C. Huan *et al.***
**J. Low Temp. Phys. 158, 692-696 (2010).**



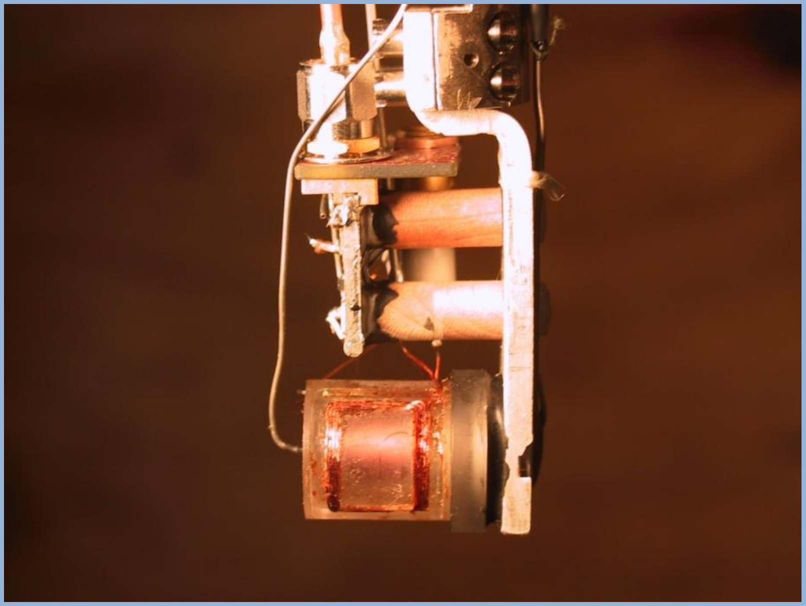


Pulse B1, create transverse
Magnetization in receiving coil

# Details: Crossed-Coil NMR Probe



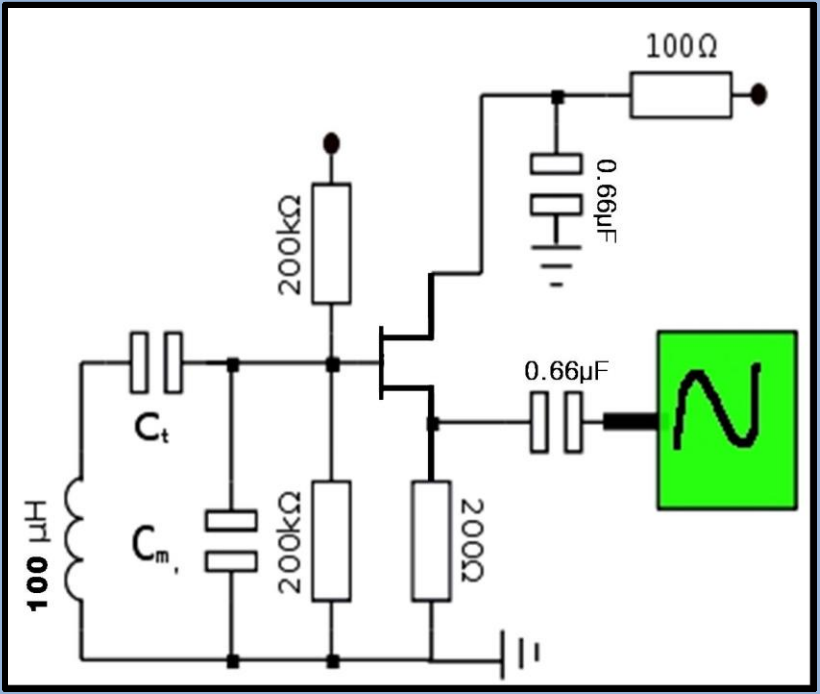
**S. Chao, S.S. Kim**
**J. Low Temp. Phys. 158, 692 (2010).**



# Circuit Diagram of Preamplifier

Uses HEMT transistor (simple source follower) operating at about 0.3 K

$T_{\text{Noise}} \leq 1$ K



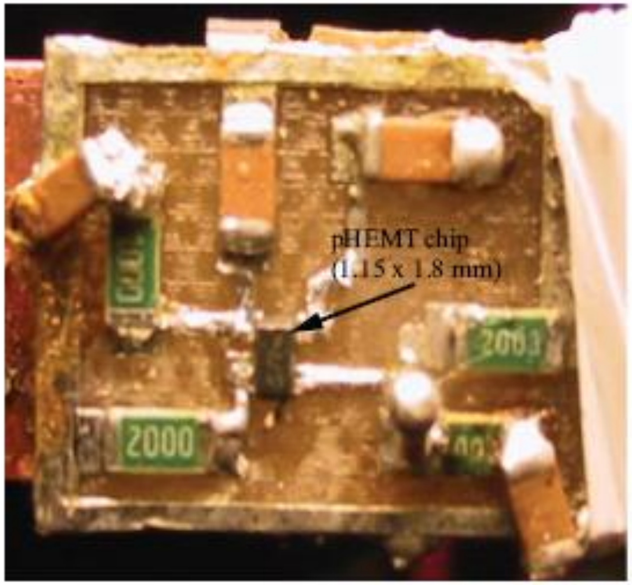
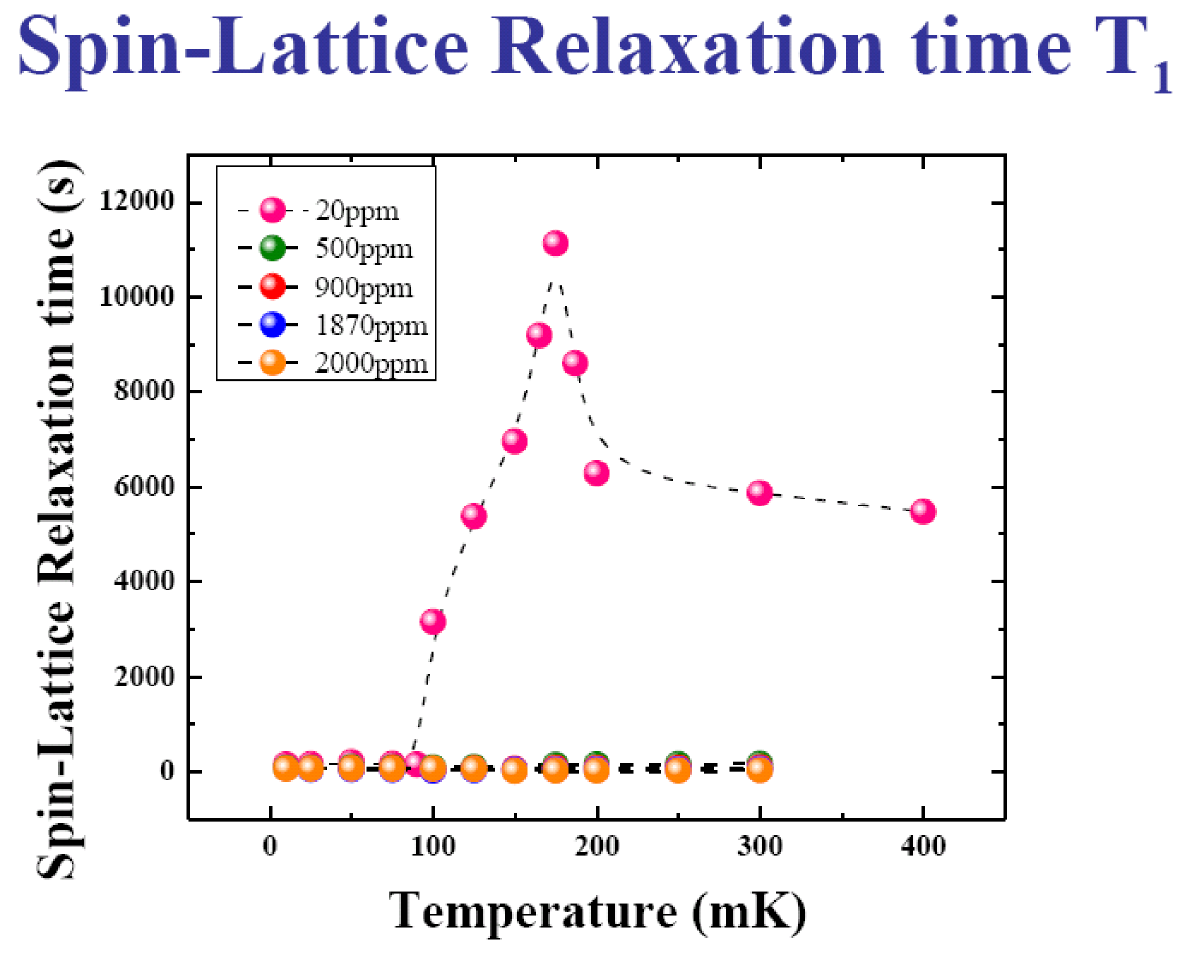


Fig. 1. Top view of the source follower circuit (full width of circuit board, 11mm)

**S. S. Kim, C. Huan *et al.***
**J. Low Temp. Phys. 158, 692 (2010).**

# Example: NMR Probe of Quantum Plasticity $^4$He

## *Dynamics of $^3$He Impurities*


Spin-Lattice Relaxation time $T_1$

# 5. Transport Measurements

**(i) Standard 4-wire techniques**

**(ii) Twisted pair and shielded leads, heat sunk at critical places**

**(iii) Use low noise high sensitivity NF Corporation Lock-in detectors**

**(iv) Thermal link to sample critical**

**Immerse sample in liquid helium**

**Can rotate sample:**

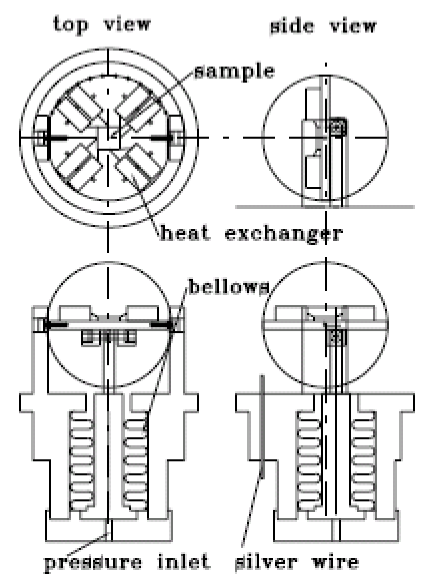
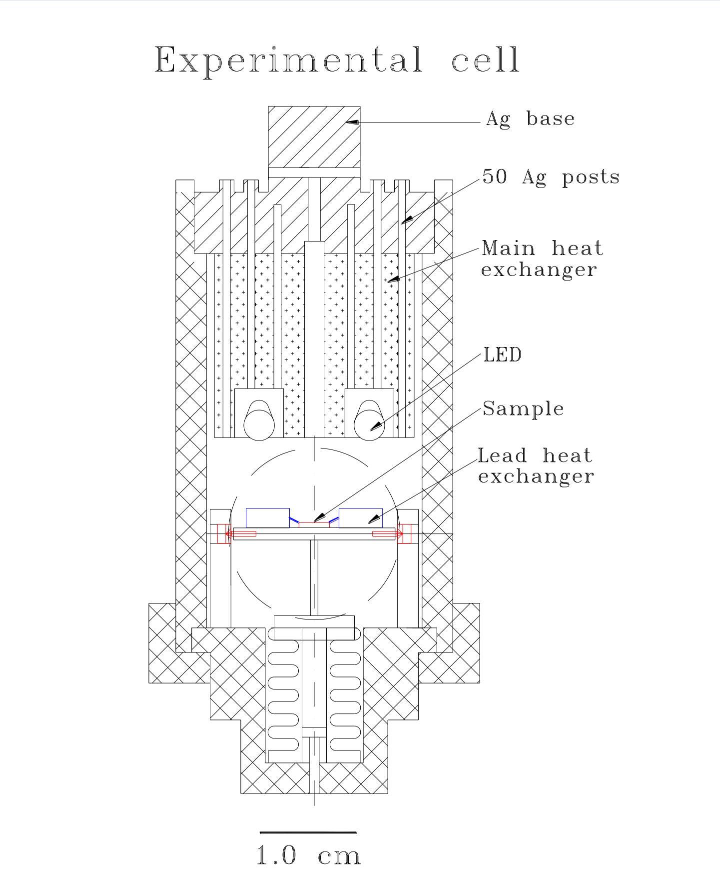


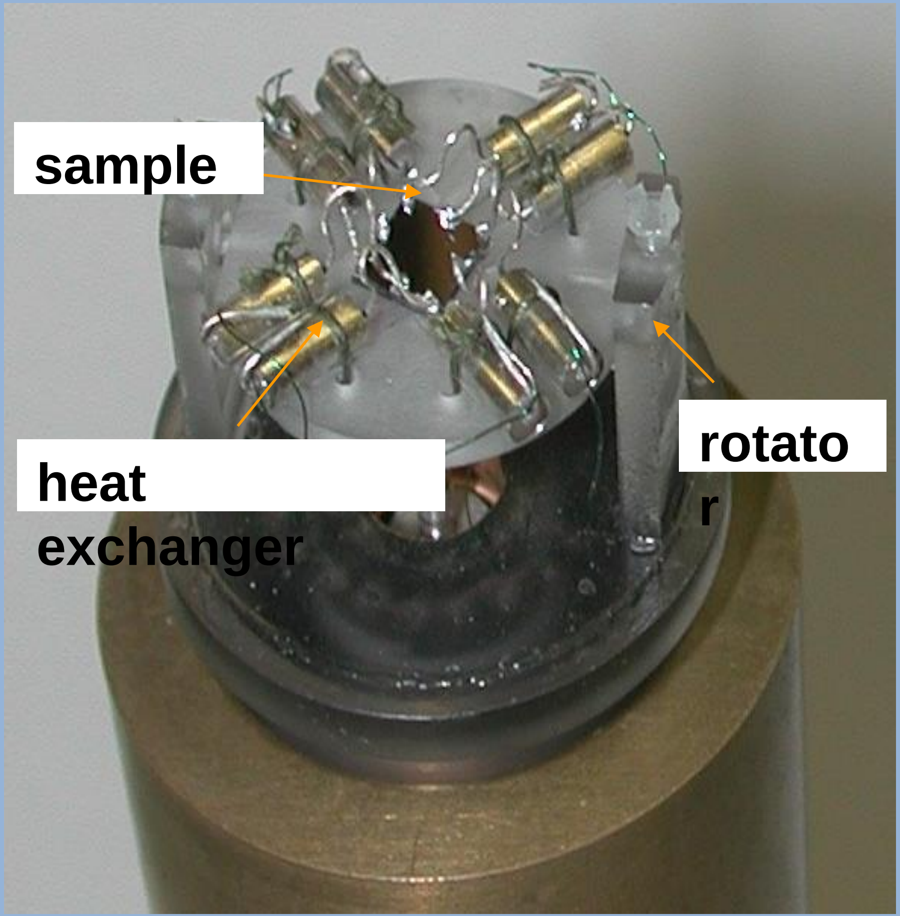
Fig. 1. Construction details of rotator.

**Xia et al., Physica E 18 , 109 (2003).**

# HIGH B/T Transport: Ultra-Low T ROTATOR



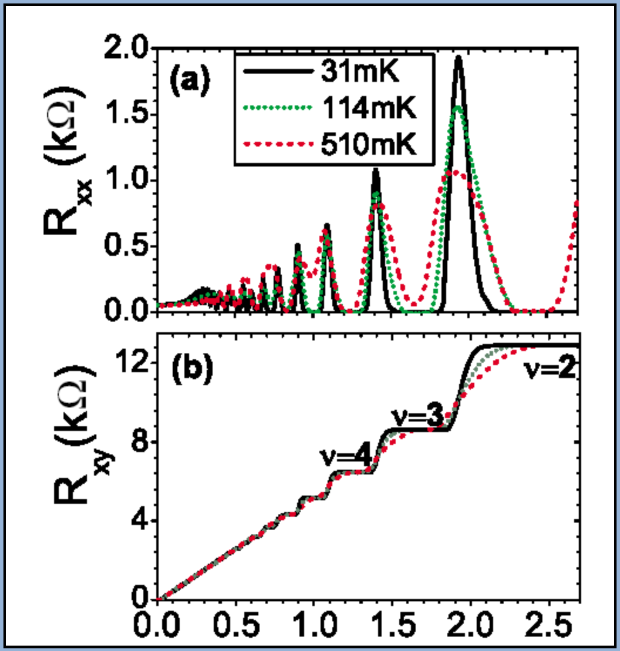
**J. S. Xia *et al.***

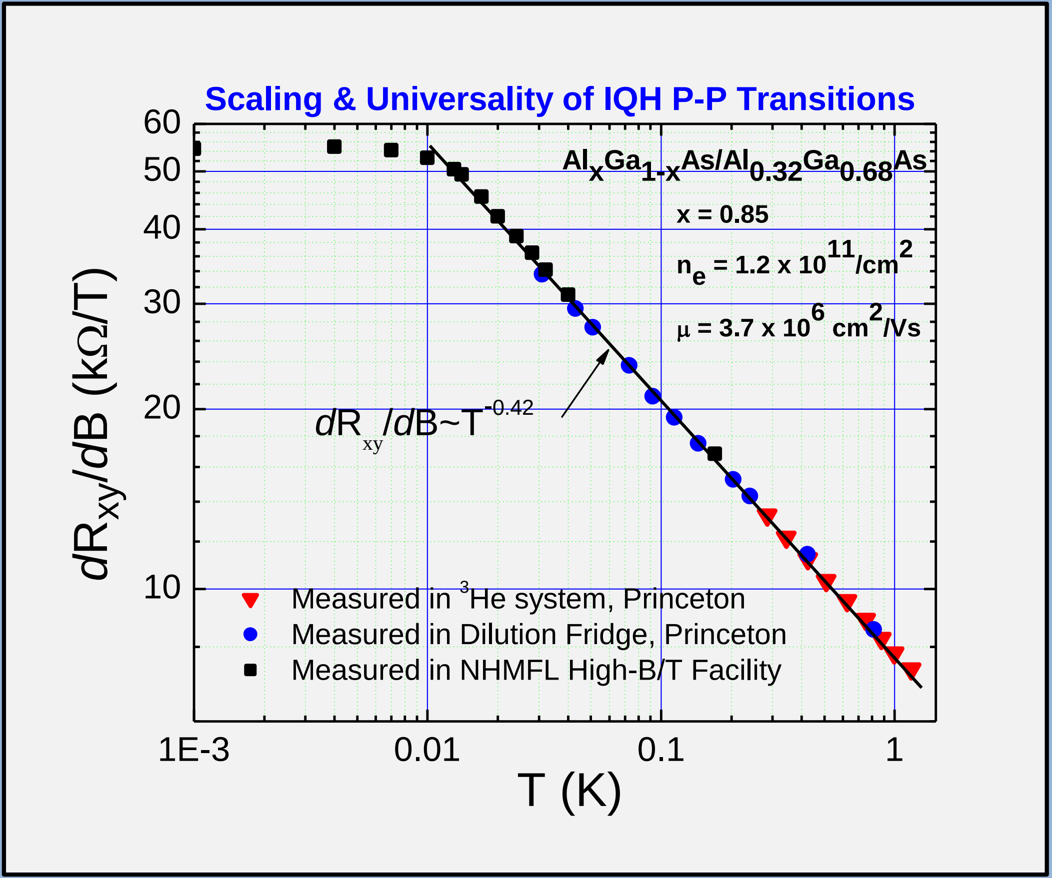


Xia et al., Physica E 18 , 109 (2003).

# Example: Quantum Hall Effect

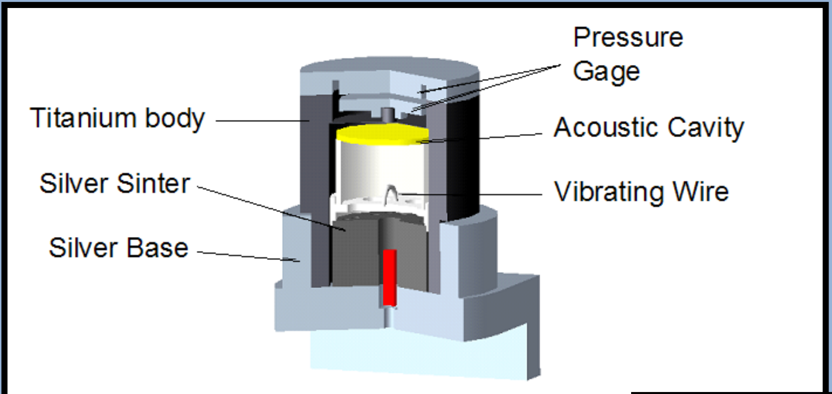
## *Scaling at mK temperatures*



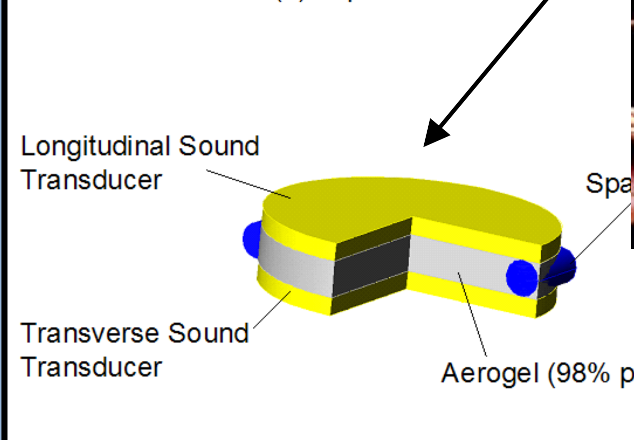


W. Li, G. A. Csathy, D. C. Tsui
(Princeton)

# 6. Ultrasound Measurements



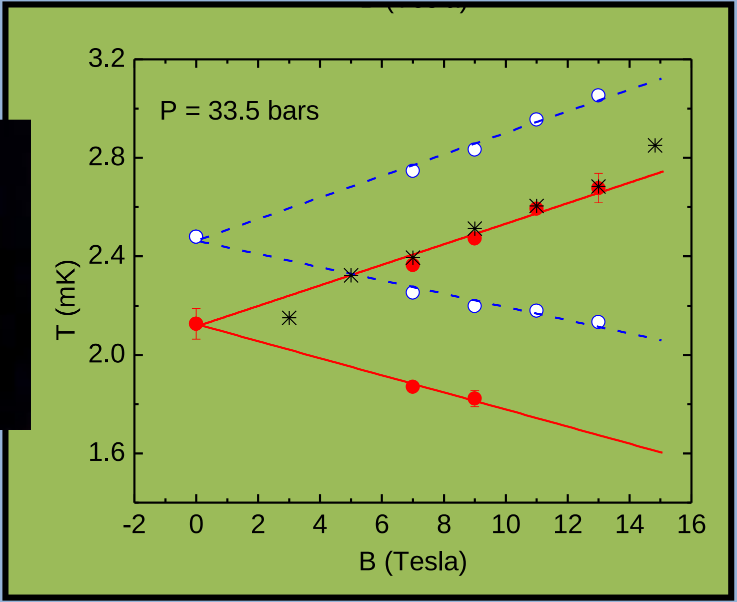
(a) Experimental Cell



(b) Acoustic Cavity

E

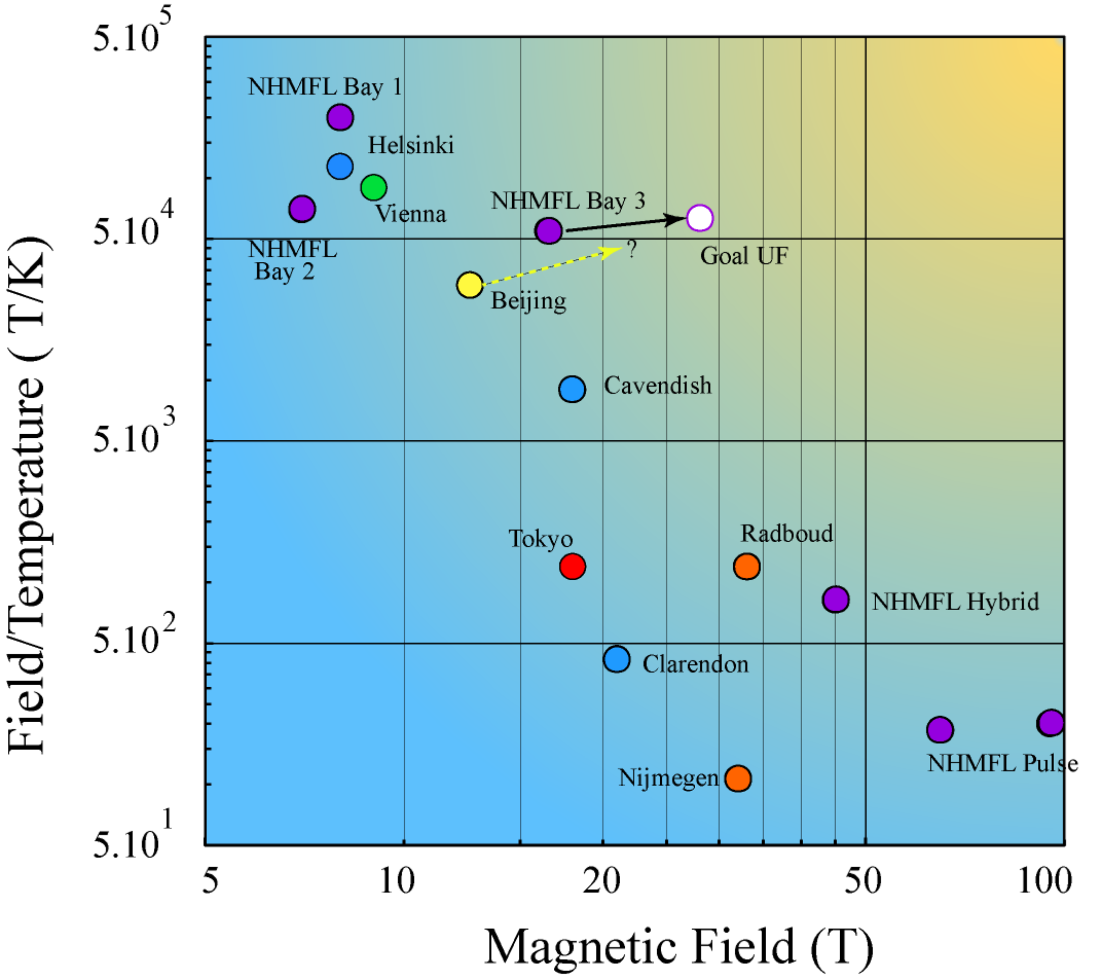
**Effect of strong magnetic field superfluid $^3$He in 98% porosity aerogel**



**The normal-A and A-B transitions suppressed due to the scattering of $^3$He quasiparticles (fermions)**

**Y. Lee *et al*.**

# Comparison International Facilities



# SEARCH FOR AXIONS (COLD DARK MATTER)

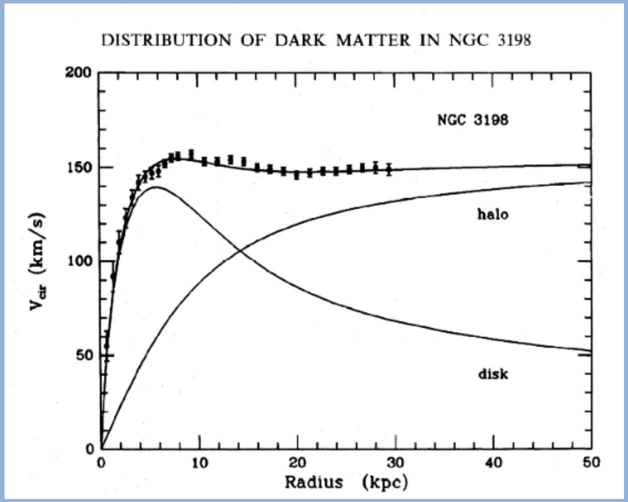
## *--- High B, Low T, ultra-quiet*

Leading question(s) in Astrophysics/Cosmology today:
***origin and composition of dark matter and dark energy***

**Dark Matter** -- must be non-baryonic, cold (non-relativistic)

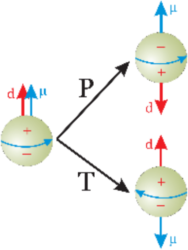
*responsible for*

- *anomalous rotation curves of matter in galaxies,*
- *motions of galaxy clusters, lensing….*



**Axions** (originally postulated to solve strong CP problem in strong interactions) QCD strongly CP violation

*Expect neutron dipole moment*
*Not seen*

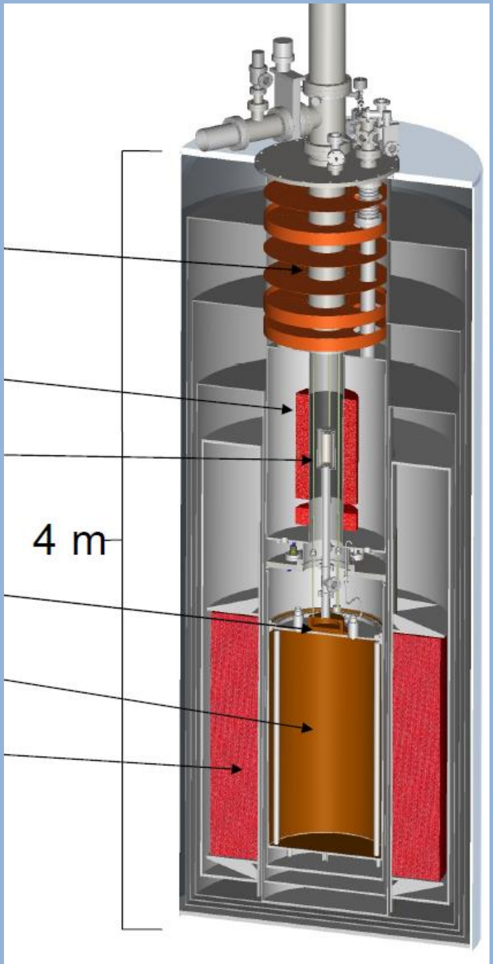


*born cold in early universe, should exist as halos around galaxies,*
*mass ~ 10-1000 $\mu e$*

*-- possible to detect expected abundance in lab. experiments*

# Milky Way axions can be detected by **Primakoff effect**:

*decay in a strong B field to microwave photons*



Baffling

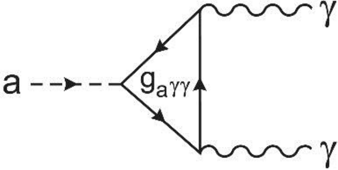
Bucking Magnet

SQUID

“1K”Pot

Microwave Cavity

Main Magnet
8 Tesla
600 mm Bore
13 ton



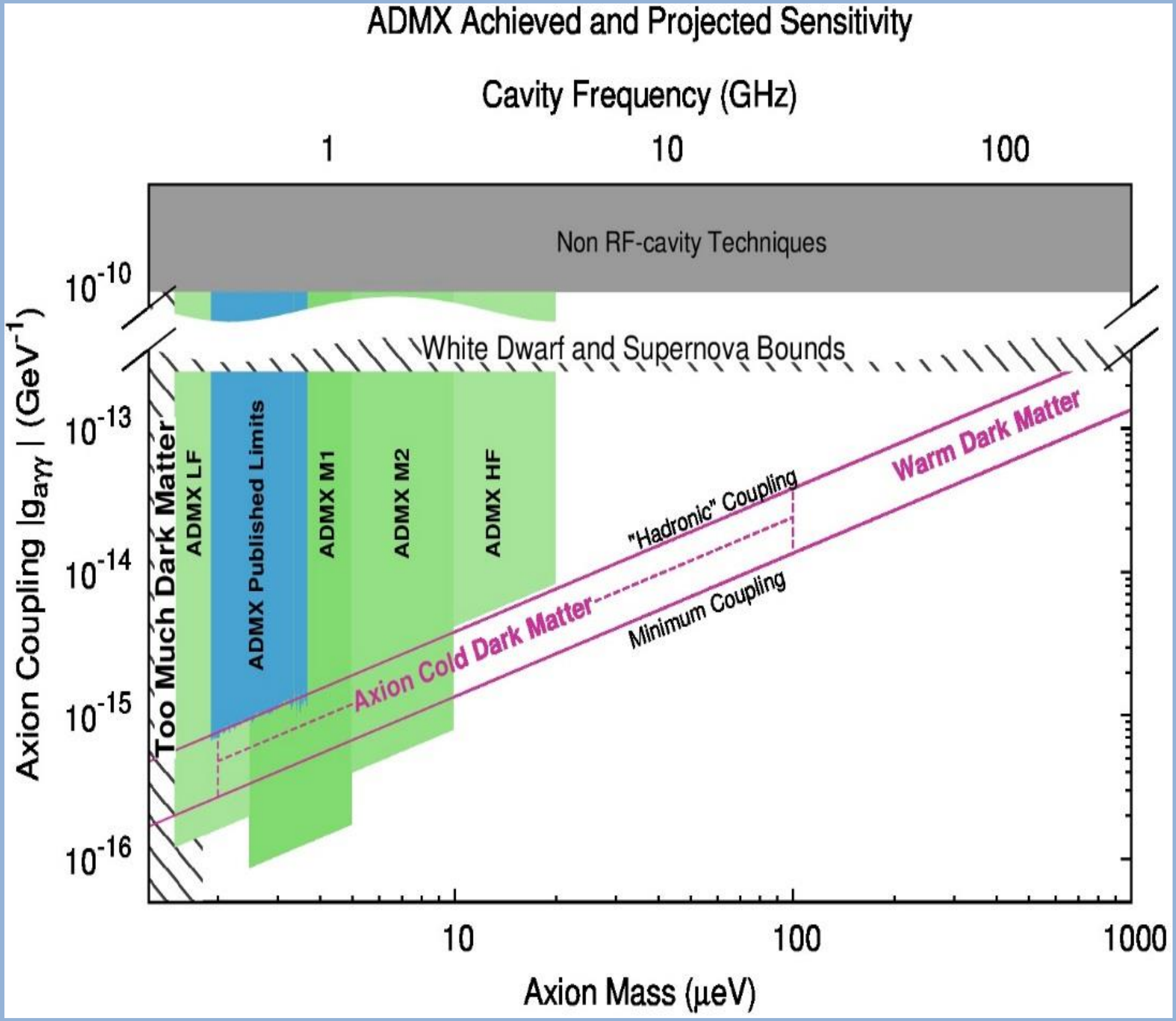
strong B

microwave photon

(Detect with high Q microwave cavity)

For B = 7T, V = 500 L, m ~ 2 GHZ, all DM = axions, Q ~$10^5$

Power emitted = $10^{-26}$ W


ADMX Achieved and Projected Sensitivity
Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
$10^{-10}$
White Dwarf and Supernova Bounds
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV$^{-1}$)
Too Much Dark Matter
ADMX LF
ADMX Published Limits
ADMX M1
ADMX M2
ADMX HF
"Hadronic" Coupling
Warm Dark Matter
Axion Cold Dark Matter
Minimum Coupling
10
100
1000
Axion Mass (μeV)

# Acknowledgements

NHMFL High B/T Staff

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Chao Huan(NHMFL)
Elizabeth Webb (NHMFL)
Andrew Woods (NHMFL)

National Science Foundation

State of Florida

# Comparison International Facilities