Magnetometry for Gravitational Measurements of Antihydrogen

Nathan Evetts
for the ALPHA Collaboration
IMMW-21, June 2019

Outline

- How to measure the gravitational force on an anti-atom

- Existing ALPHA Magnetometry
  - Non-neutral plasmas
  - NMR system and performance

- Outlook: Low temperature NMR challenge

Asymmetry in the Universe

Why study antimatter?

What is ALPHA? *(Antihydrogen Laser PHysics Apparatus)*

Multidisciplinary group
~ 16 institutes
~ 50 people

A “small” group at CERN

Aarhus University, Denmark

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

Imperial College London

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, West Lafayette, USA

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

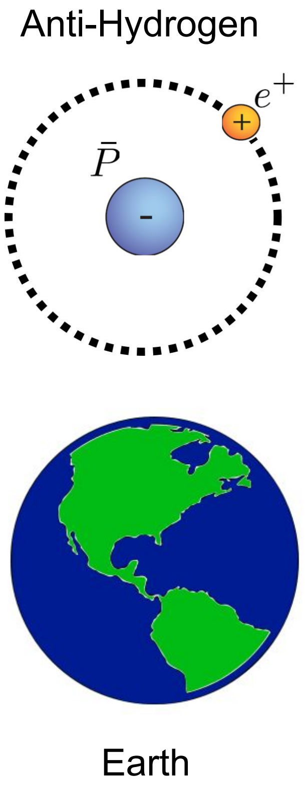
University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

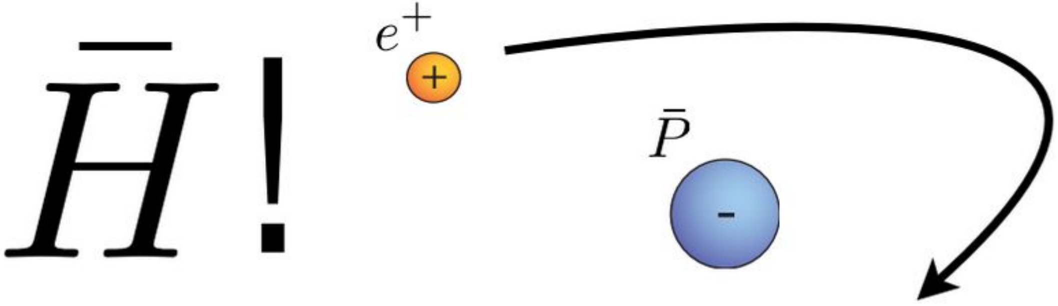
Matter - antimatter gravitational interaction

test of equivalence principle



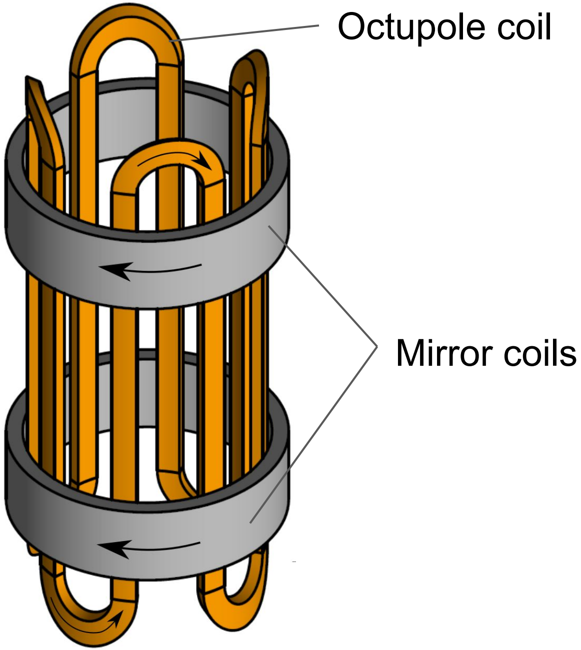
Antihydrogen recipe

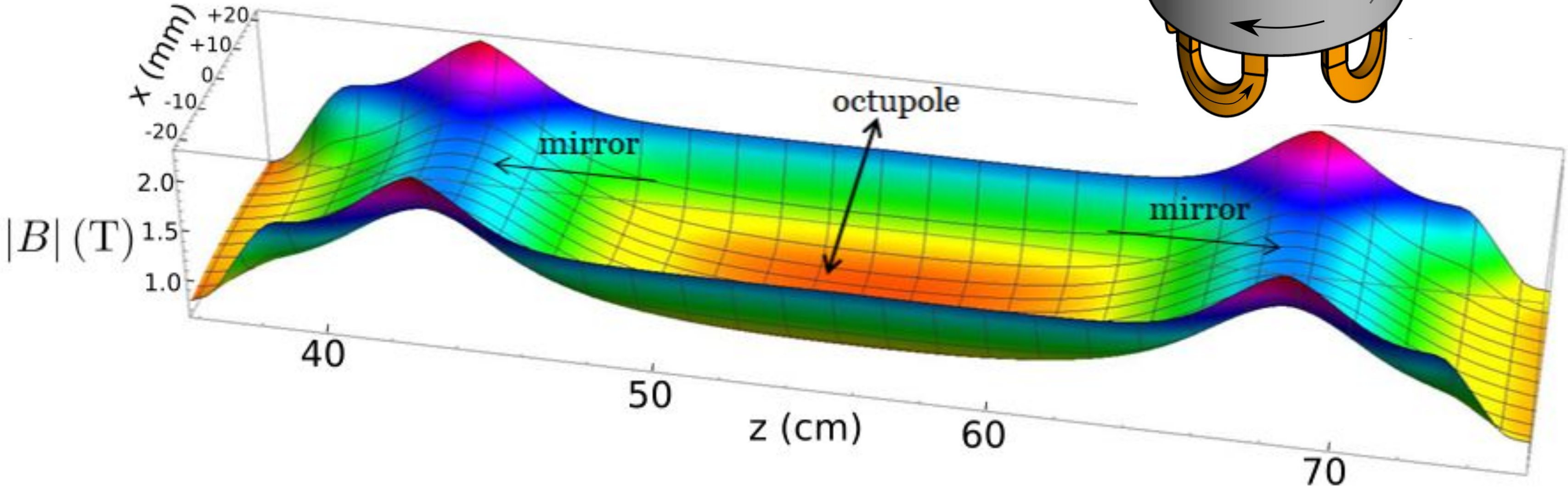
1. ~10^4 antiprotons *(from Antiproton Decelerator, CERN)*
2. ~10^6 positrons *(from beta decay , Na^{22} source)*
3. Cool to ~20 K *(the difficult part)*
4. Mix!



ALPHA-g Apparatus

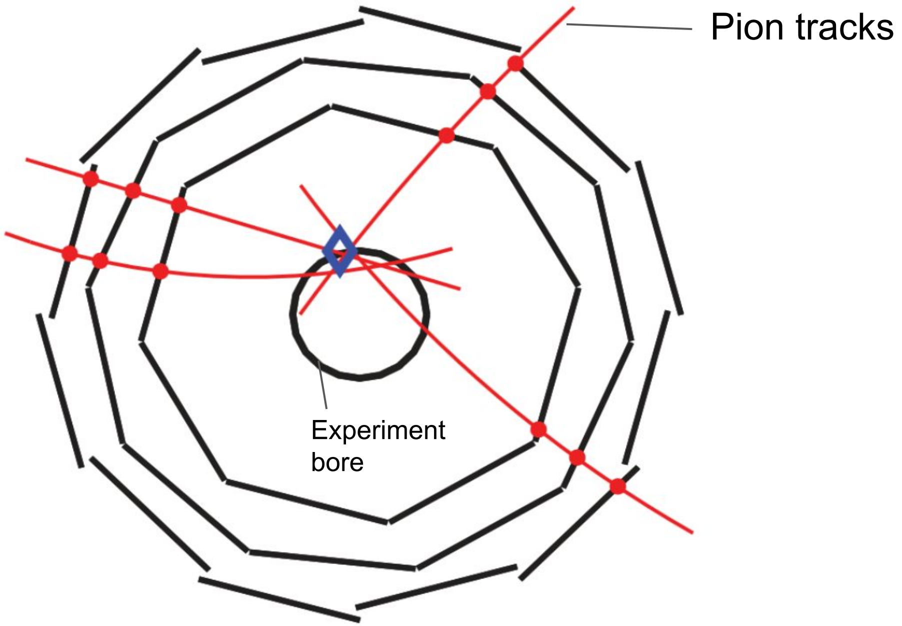
- Vertical Magnetic Trap $E = -\vec{\mu} \cdot \vec{B}$
- Trap depth ~ 0.5 K
- ~1000 anti-atoms trapped per day





ALPHA Apparatus

- Detection of single atoms
- Vertex resolution ~ 6mm

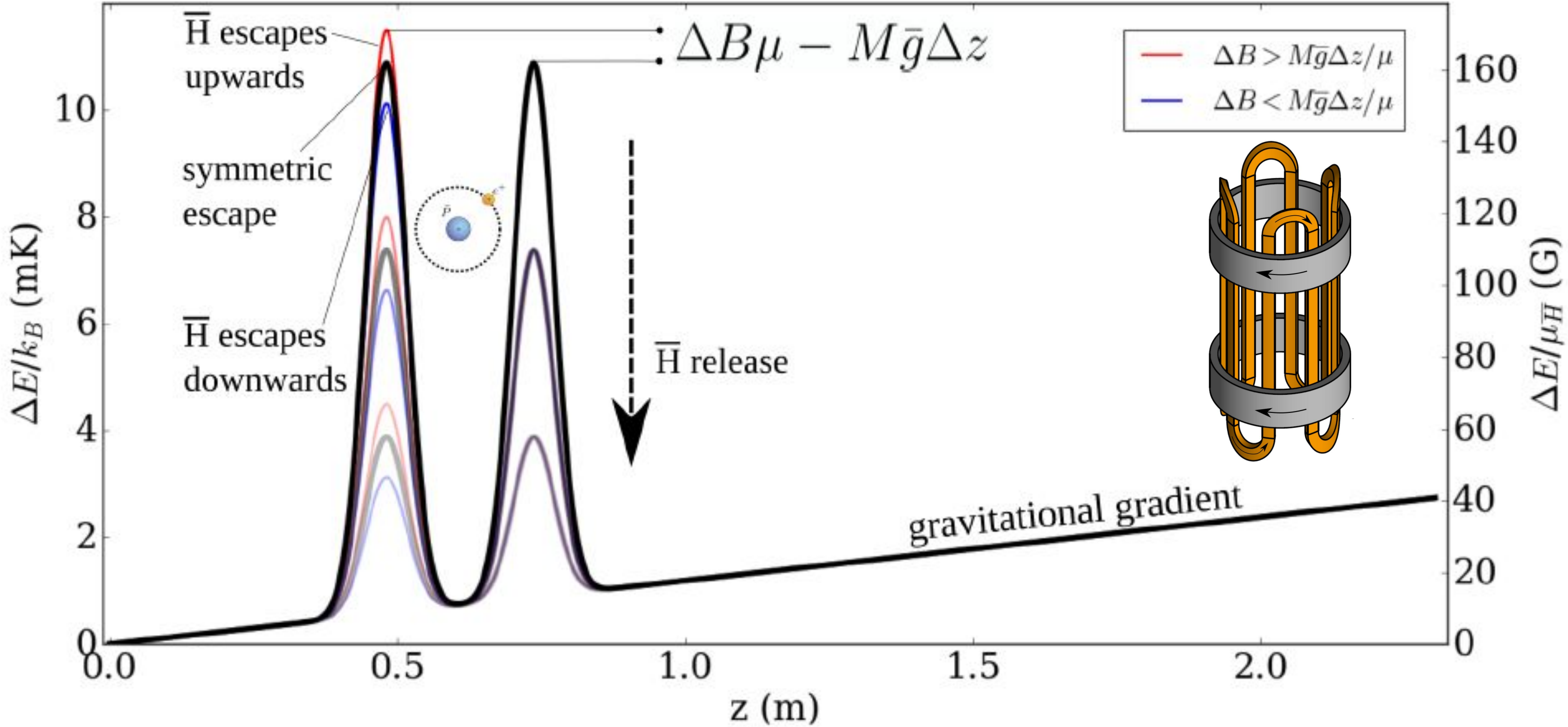


Antiproton annihilation

Antihydrogen Gravity Experiment

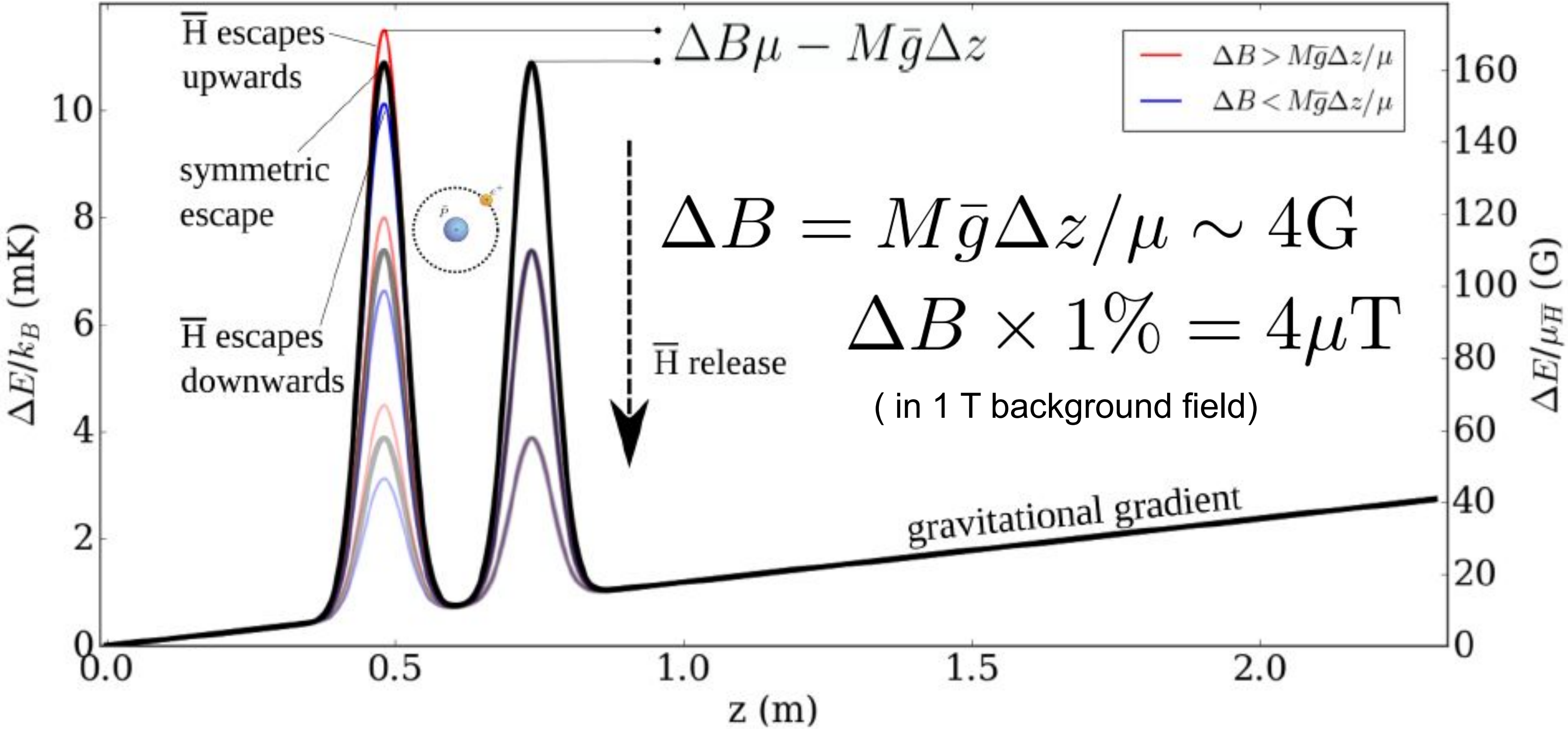
- Release antiatoms from magnetic trap, infer gravity from annihilation patterns

On-axis potential energy



Magnetometry precision goal: < 1ppm

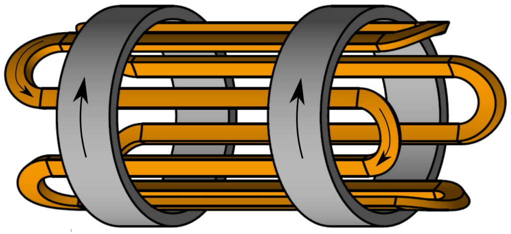
On-axis potential energy

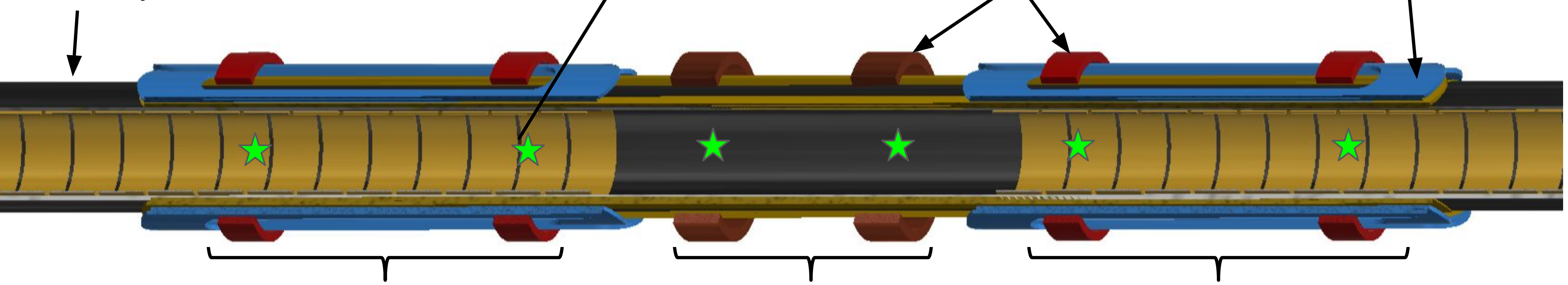


Challenging Environment for Magnetometry

- Field precision <1ppm , and...
  - Cryogenic
  - UHV
  - Poor physical access
  - Strong field non-uniformity
  - Field range 0.5 - 1.5 T

Cartoon antihydrogen trap

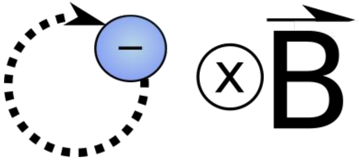




Magnetometry at ALPHA

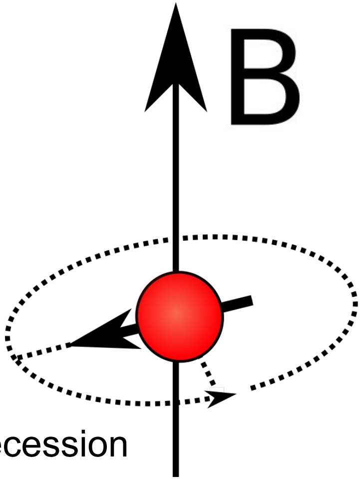
Magnetometry Overview

1. Electron cyclotron resonance
   - Pro: Measures field in-situ
   - Con: not fully understood



$$\omega_c = \frac{eB}{m}$$

2. Nuclear magnetic resonance (NMR)
   - Rubber samples
     - Pro: Sufficient resolution
     - Con: Best at room temperature
   - Aluminium micro-powder samples
     - Pro: Works at Low temperatures
     - Con: Weaker field resolution

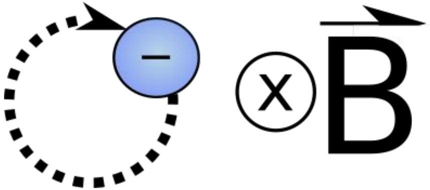


Spin precession

Magnetometry with Plasmas

- Working principle: plasmas heat when irradiated at the cyclotron frequency

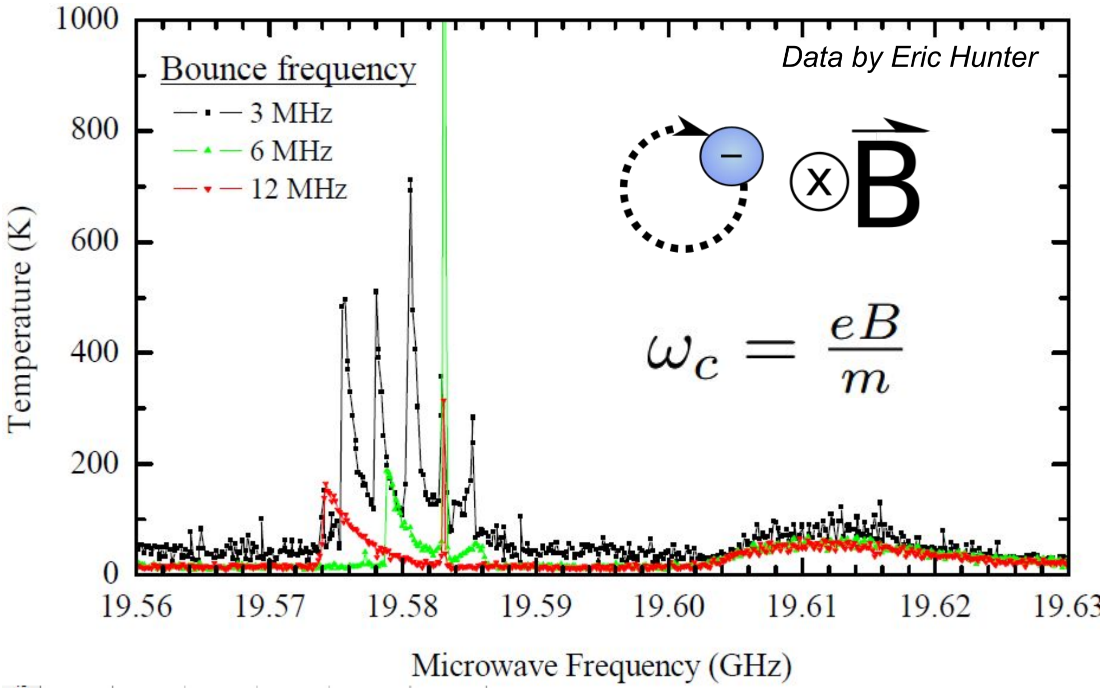
incoming microwave pulse

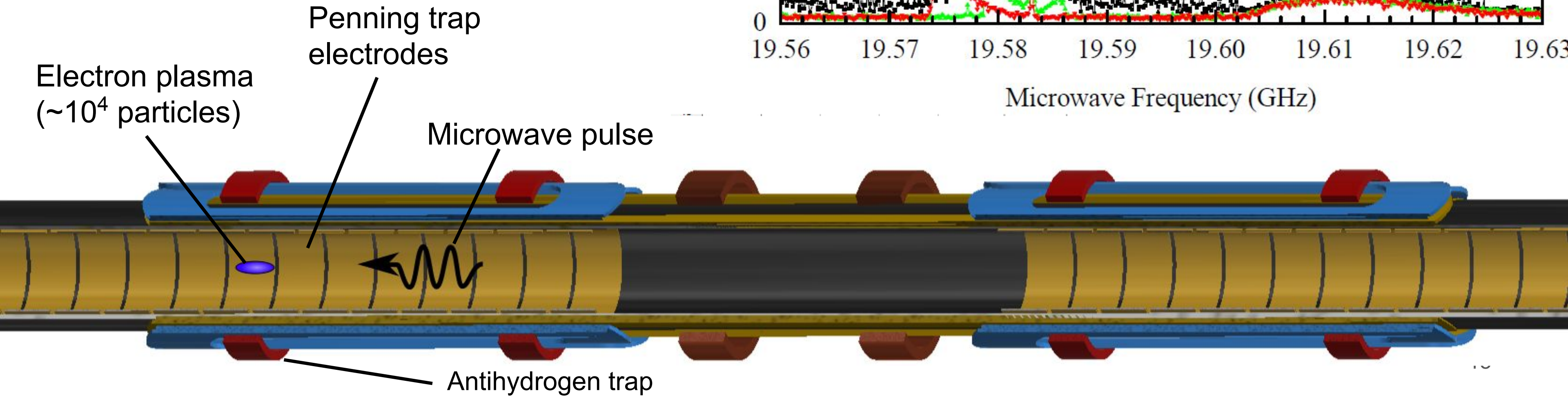


$$\omega_c = \frac{eB}{m}$$

Magnetometry with Plasmas

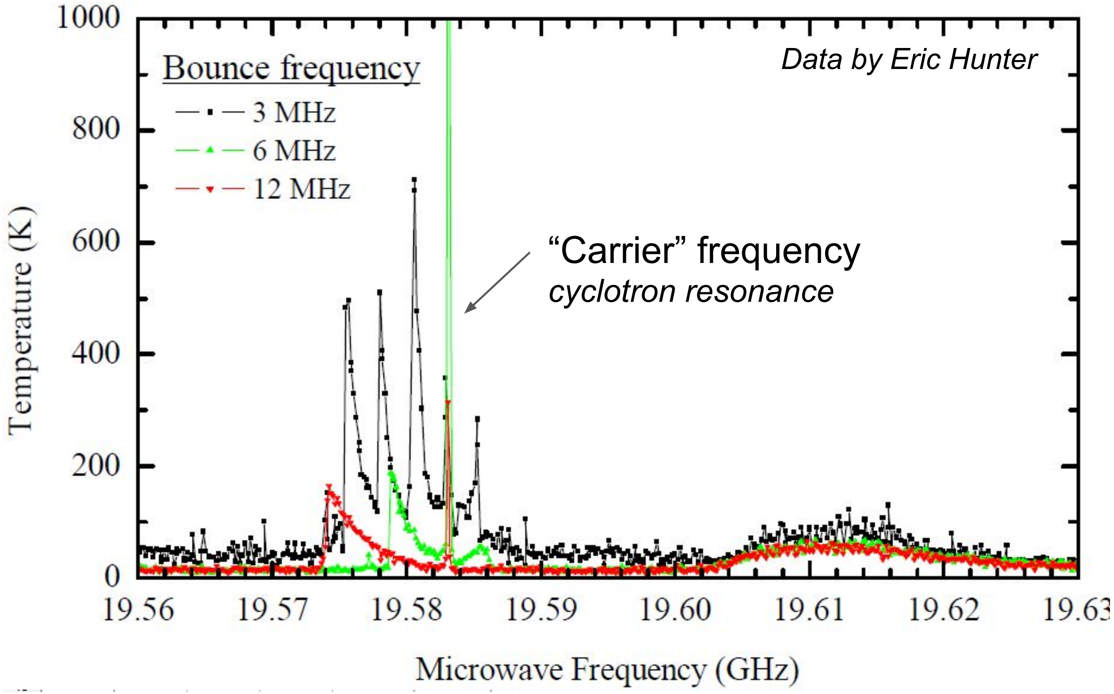
- Plasmas are “hot” when microwave frequency matches cyclotron frequency
- Technique to measure plasma temperature:
  Phys. Fluids B 4 3432–9 1992
  New J. Phys. 16 (2014) 013037.

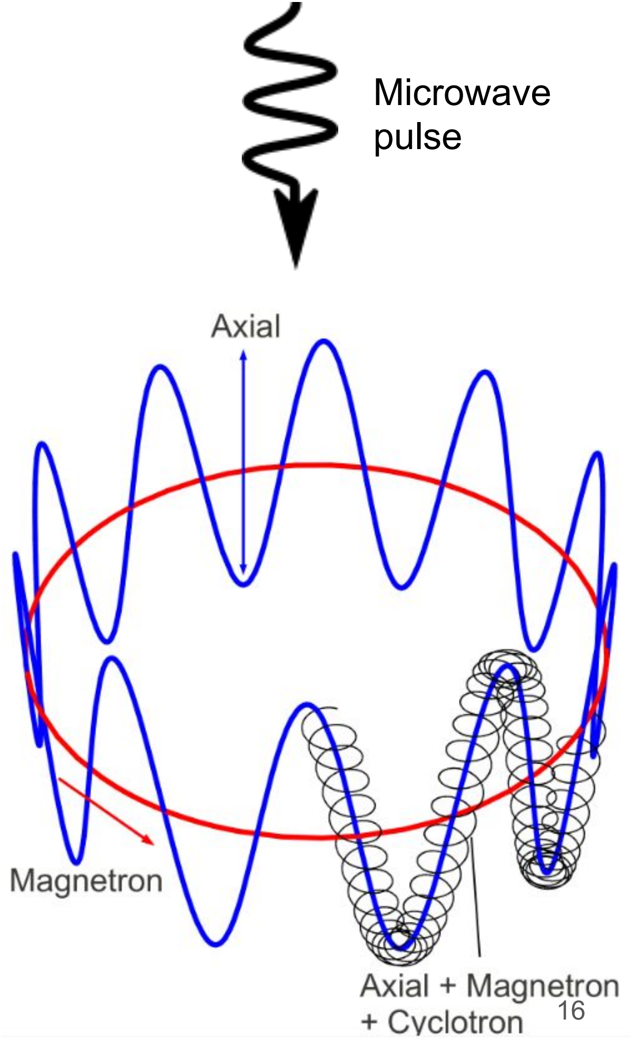




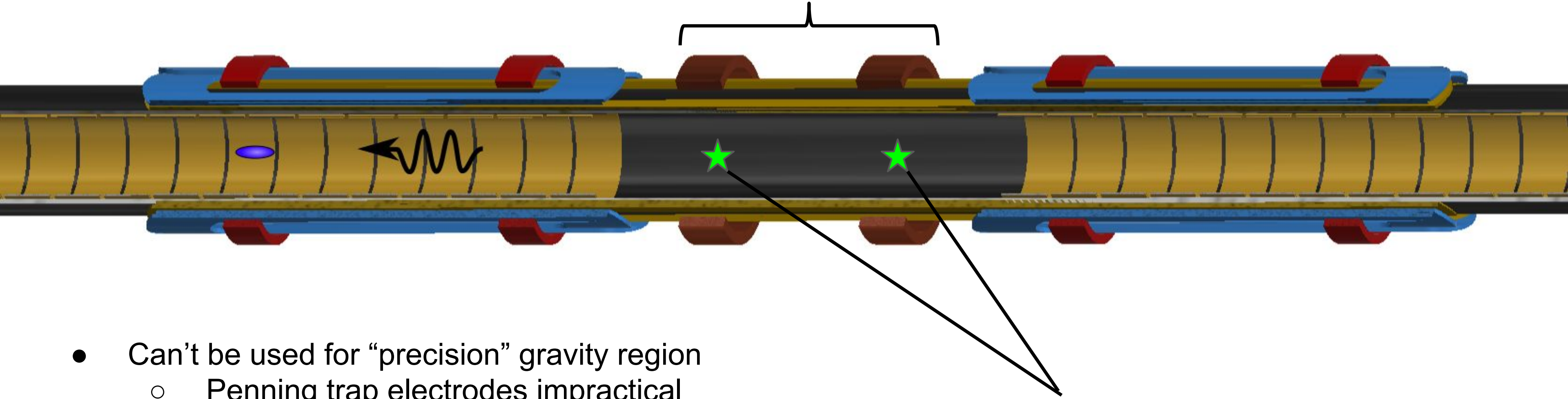
Magnetometry with Plasmas

- Complicated particle motion creates “side-bands”
  - Must identify “carrier” frequency
  - Preliminary resolution < 1ppm





Problem with Cyclotron Resonance Method



- Can’t be used for “precision” gravity region
  - Penning trap electrodes impractical

$$\Delta B \times 1\% = 4\mu\mathrm{T}$$

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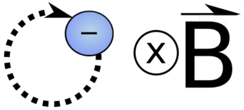

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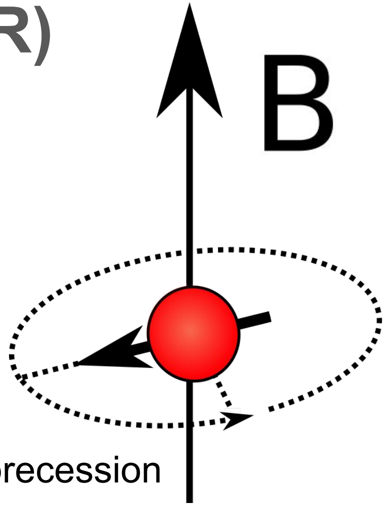
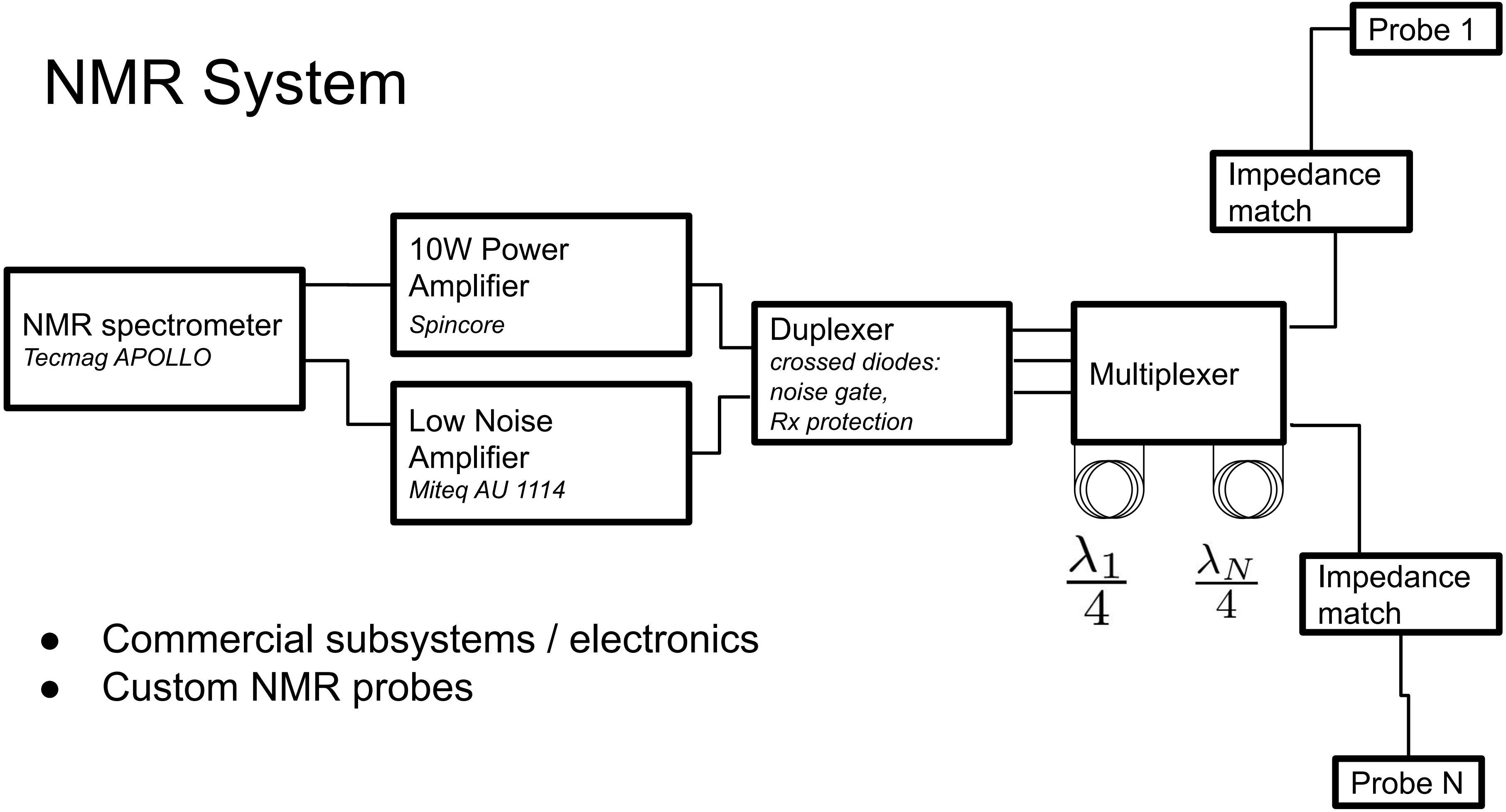


Spin precession

NMR System



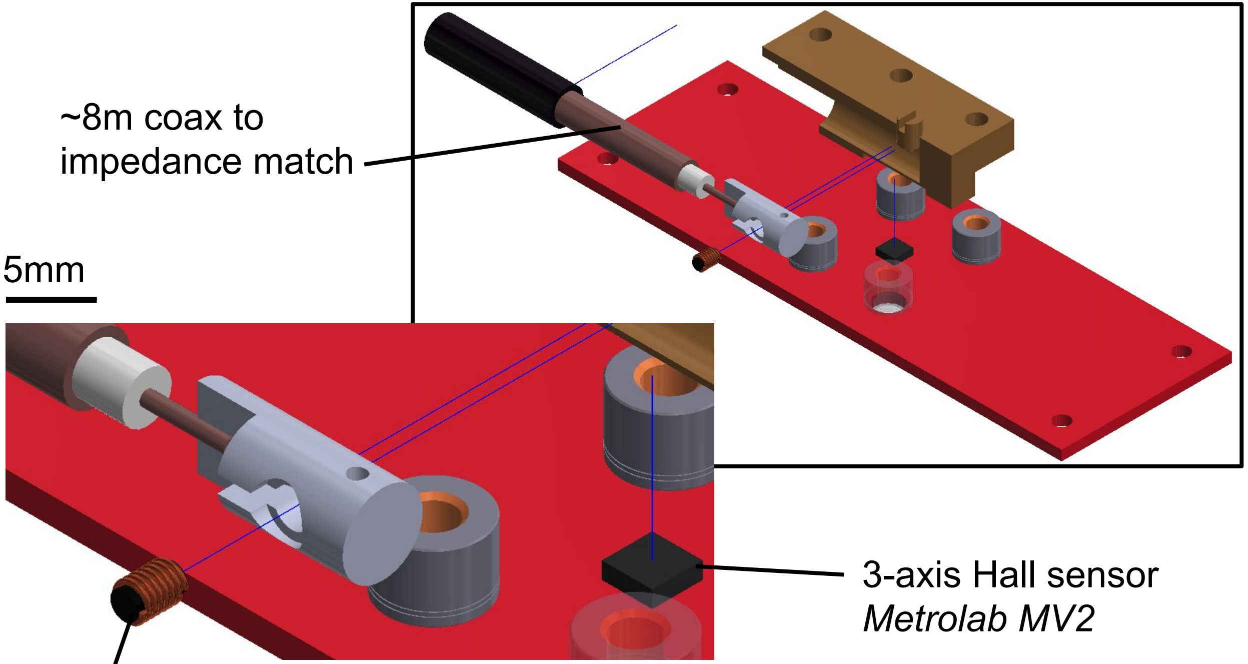
- Commercial subsystems / electronics
- Custom NMR probes

Room temperature NMR / Hall package

Environmental field monitor

~8m coax to
impedance match

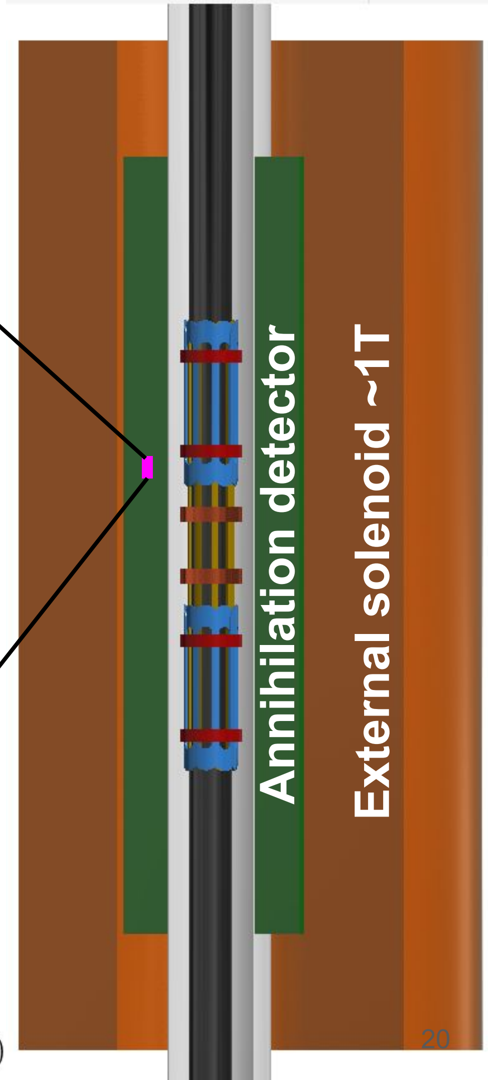
5mm



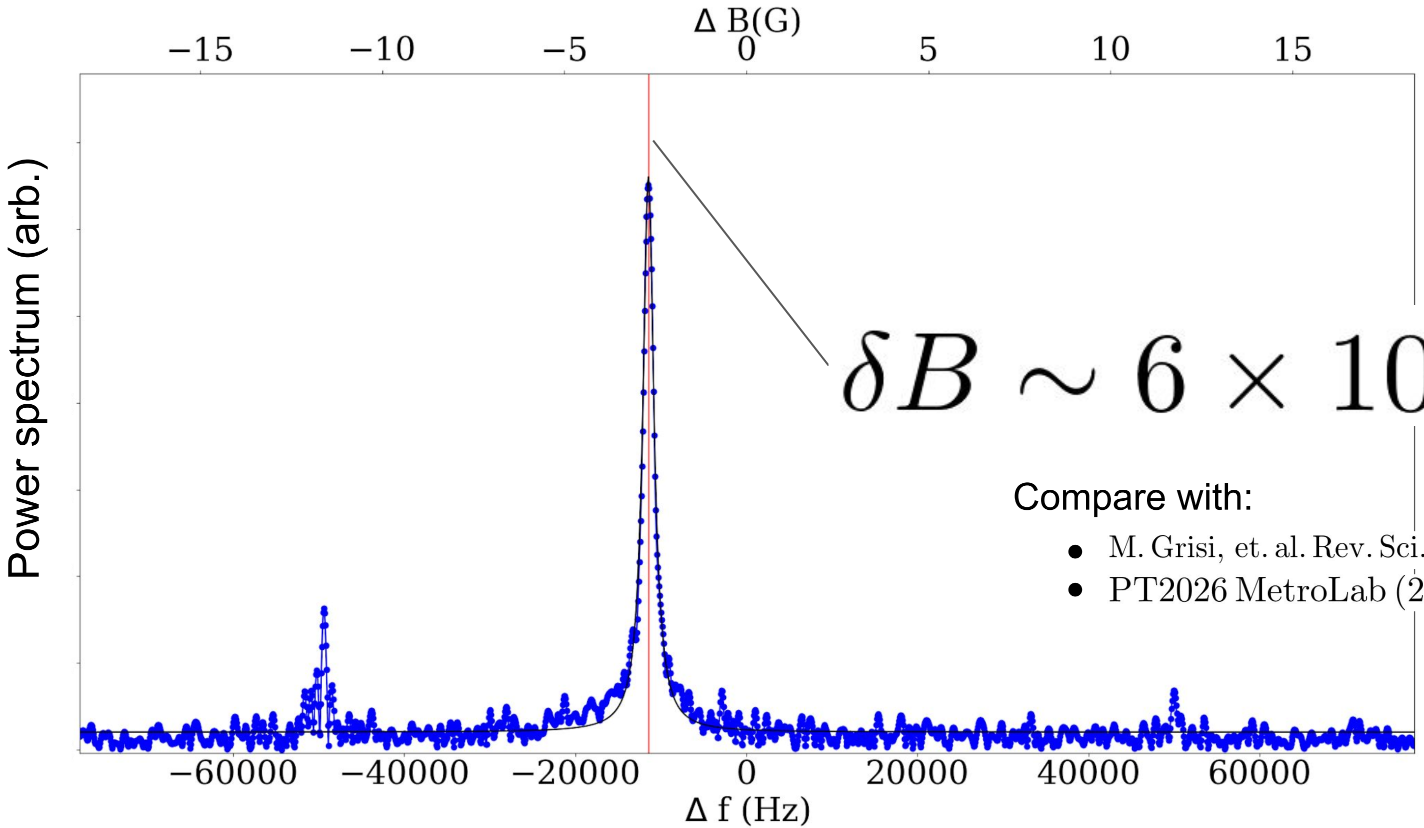
3-axis Hall sensor
Metrolab MV2

Natural Rubber NMR
sample V ~ 4mm^3

Possible improvement:
Remote Tuning of NMR Probe Circuits, J. Mag. Res. (2000)



Rubber NMR Probe Performance

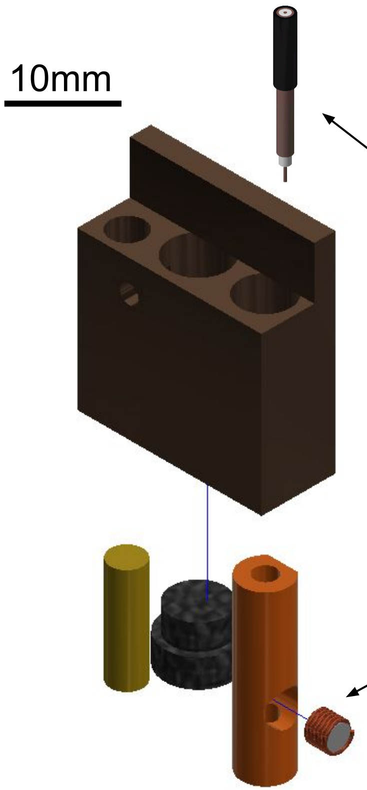


$$\delta B \sim 6 \times 10^{-7}\mathrm{T}$$

Compare with:

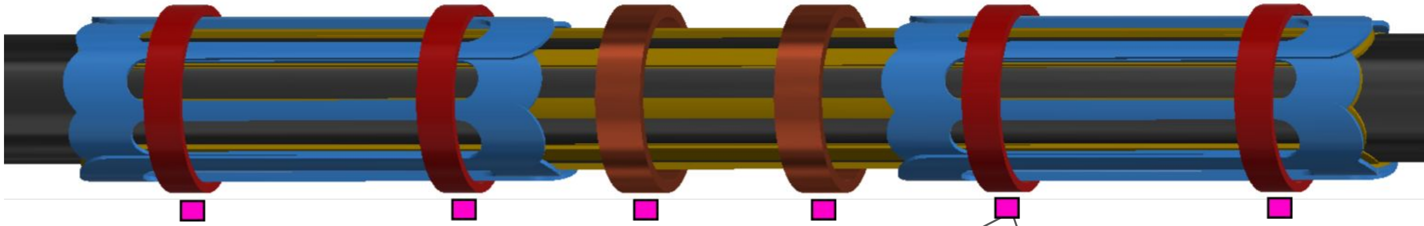
- M. Grisi, et. al. Rev. Sci. Instrum. (2019)
- PT2026 MetroLab (2019)

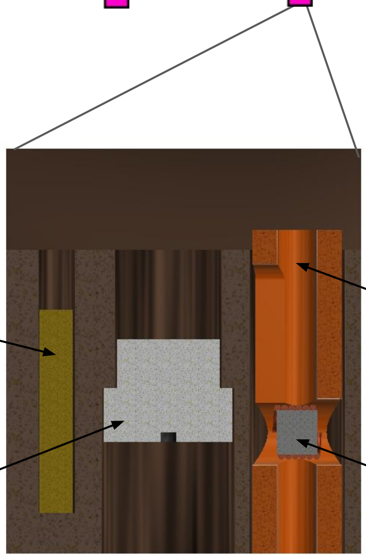
Cryogenic NMR probes *Mirror coil diagnostic*



~10m coax
1.4mm OD
double shielded

Hand wound
NMR coil





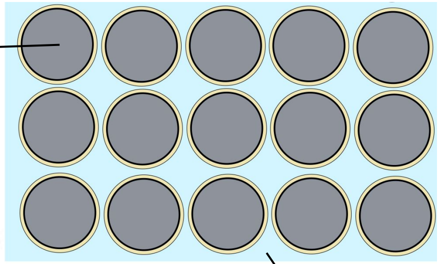
thermometer

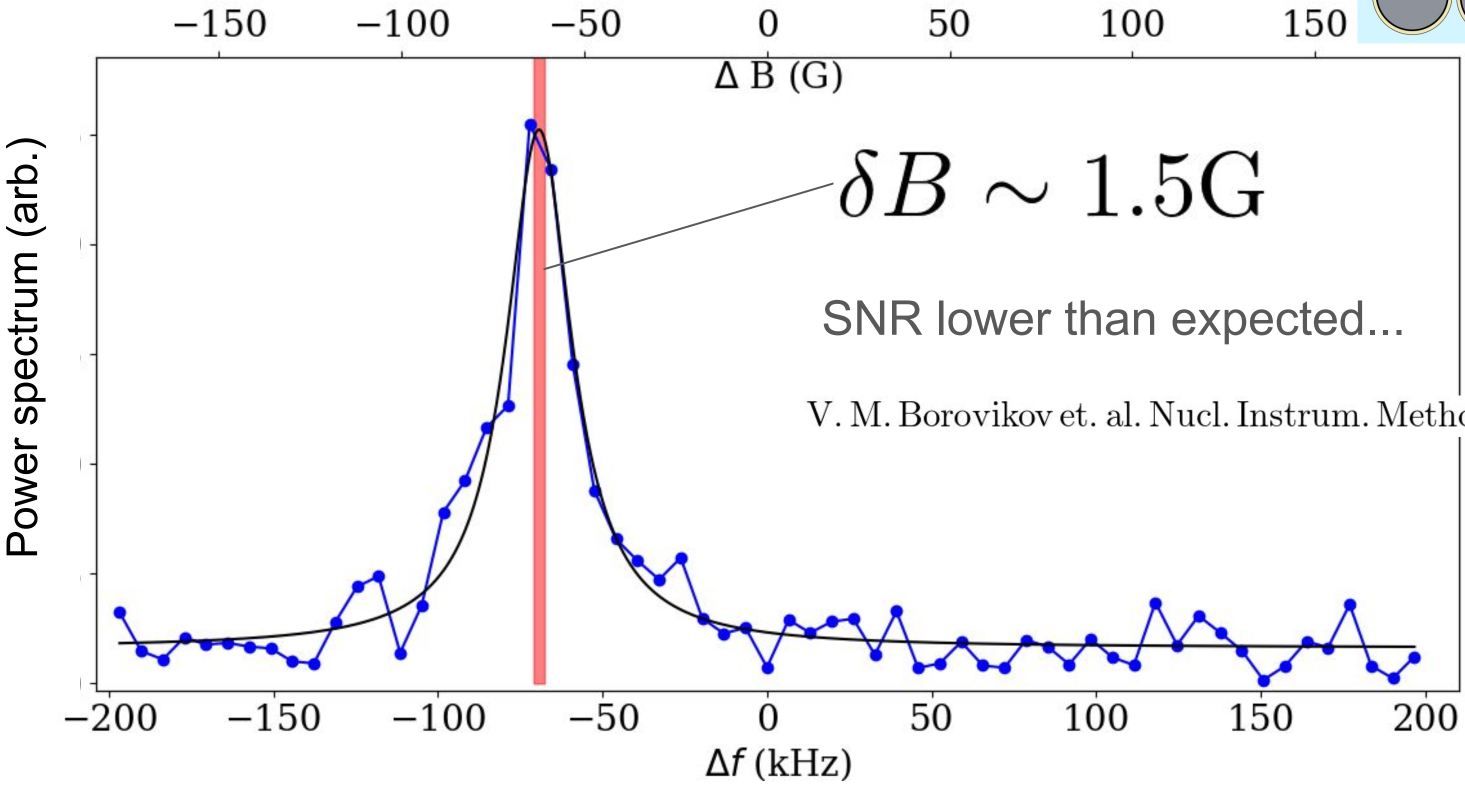
Phenolic
sample holder

NMR sample
aluminium
V ~ 8mm^3

Lakeshore HGCA 3020
Cryogenic Hall sensor

Aluminium NMR signal (at T~15K)





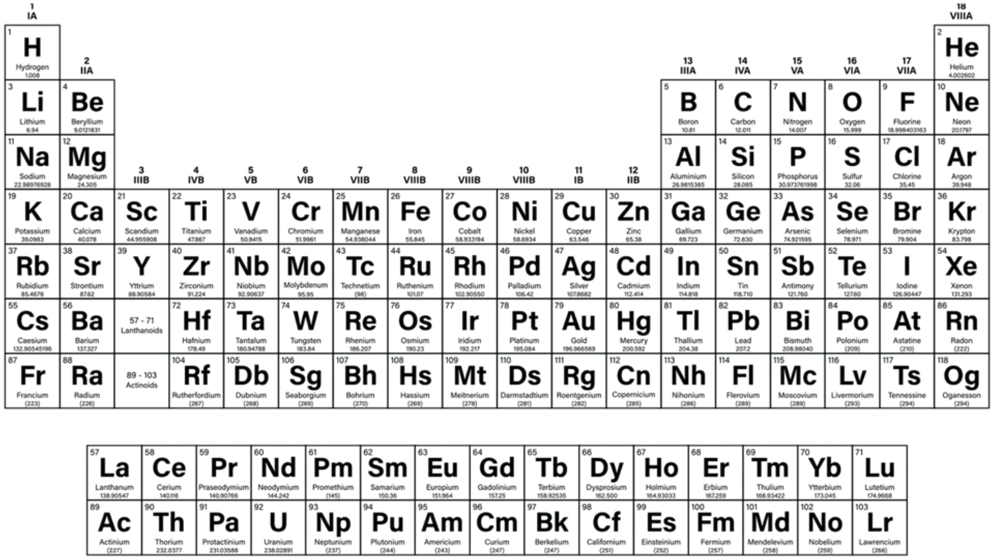
$\delta B \sim 1.5\mathrm{G}$

SNR lower than expected...

V. M. Borovikov et. al. Nucl. Instrum. Methods Phys. Res. A (2001)

Low Temperature NMR Sample Search *(improvement on aluminium)*

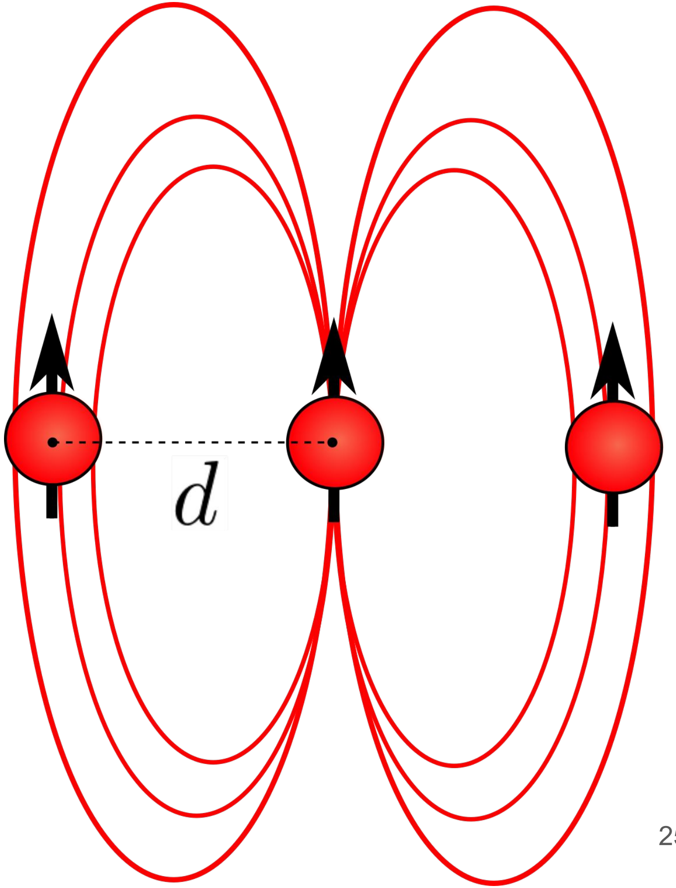
- Vast number of sample candidates
  - Elements, compounds, alloys….
- Search for:
  - Narrow NMR linewidth
  - Short T1 relaxation time (repetition time)



Low Temperature NMR Sample Search

- At 4K, almost everything is a solid
  - ie: has a broad linewidth
- Linewidth set by dipolar broadening

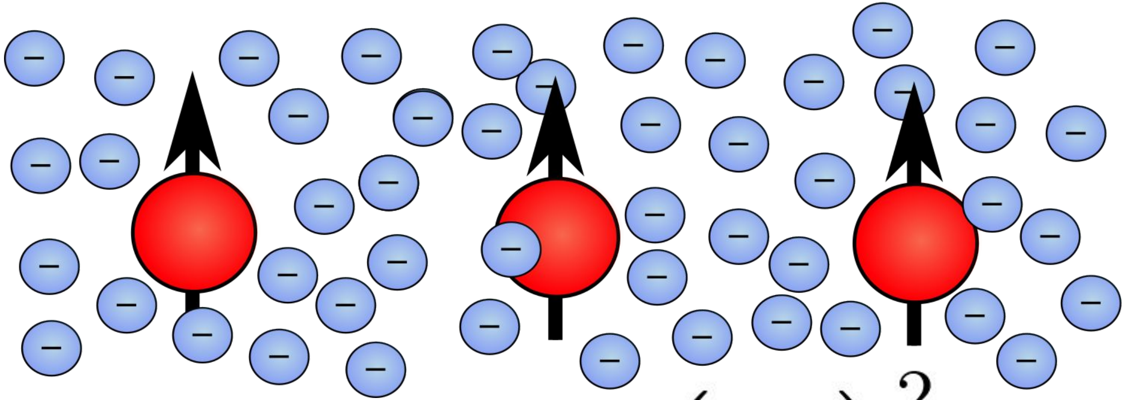
$$\Delta B \sim \frac{\sqrt{I(I+1)}\gamma\mu_o\hbar}{4\pi d^3}$$



A. Abragam, Principles of nuclear magnetism (Oxford Univ. Press, 1961)

Low Temperature NMR Sample Search

- T1: Spin-lattice relaxation time
  - Sets sensor repetition rate
- T1 short in metals due to interaction with conduction electrons (Korringa relation)

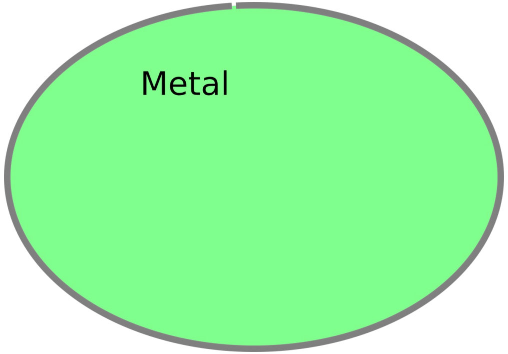


$$T_1 = \frac{\hbar}{4\pi T \mathscr{K}^2} \left(\frac{\gamma_e}{\gamma_N} \right)^2$$

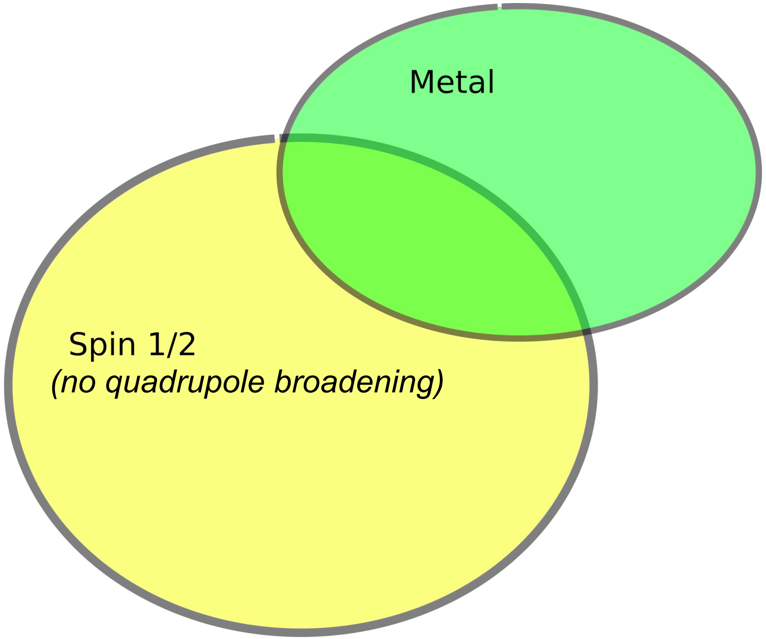
Aluminium T1 ~ 100ms
Helium-3 T1 ~ hours

C. P. Slichter, Principles of magnetic resonance (Harper and Row, 1963)

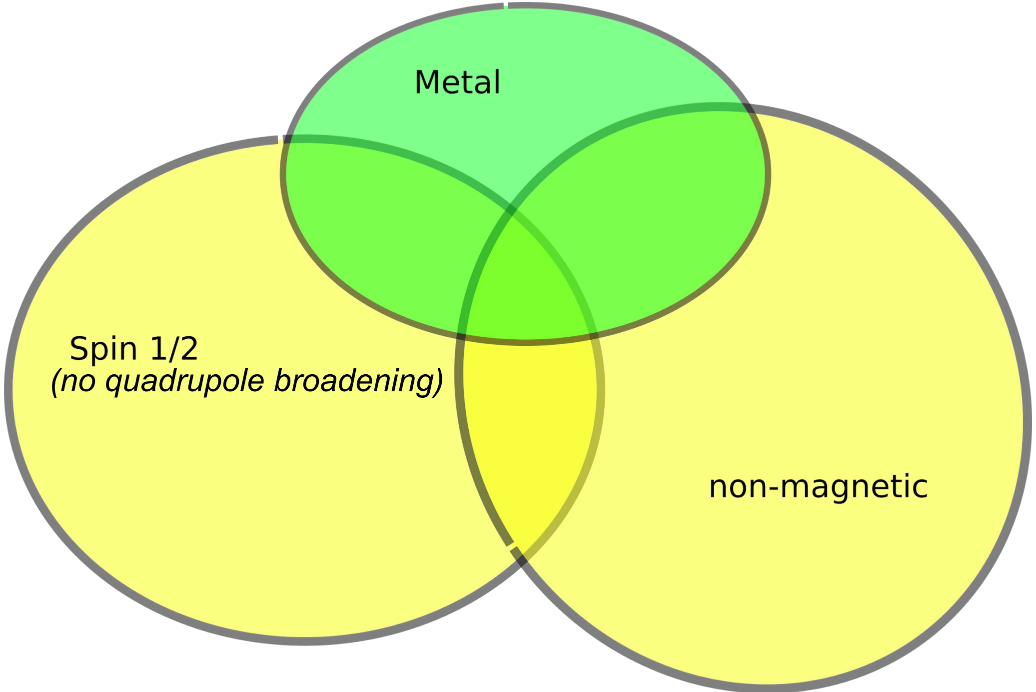
Low Temperature NMR Sample Search



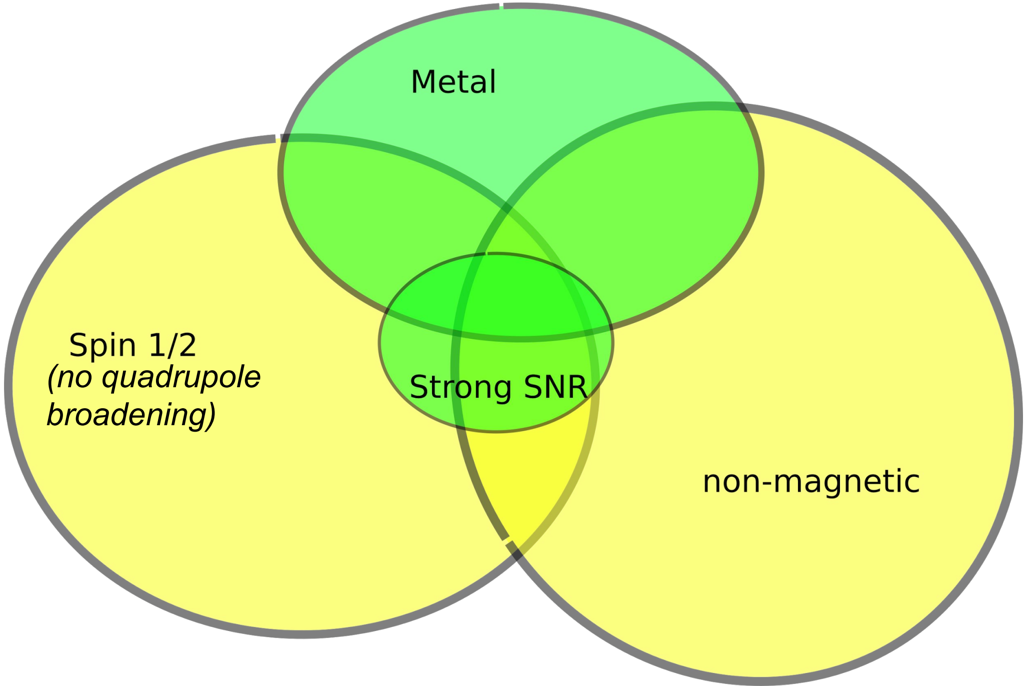
Low Temperature NMR Sample Search



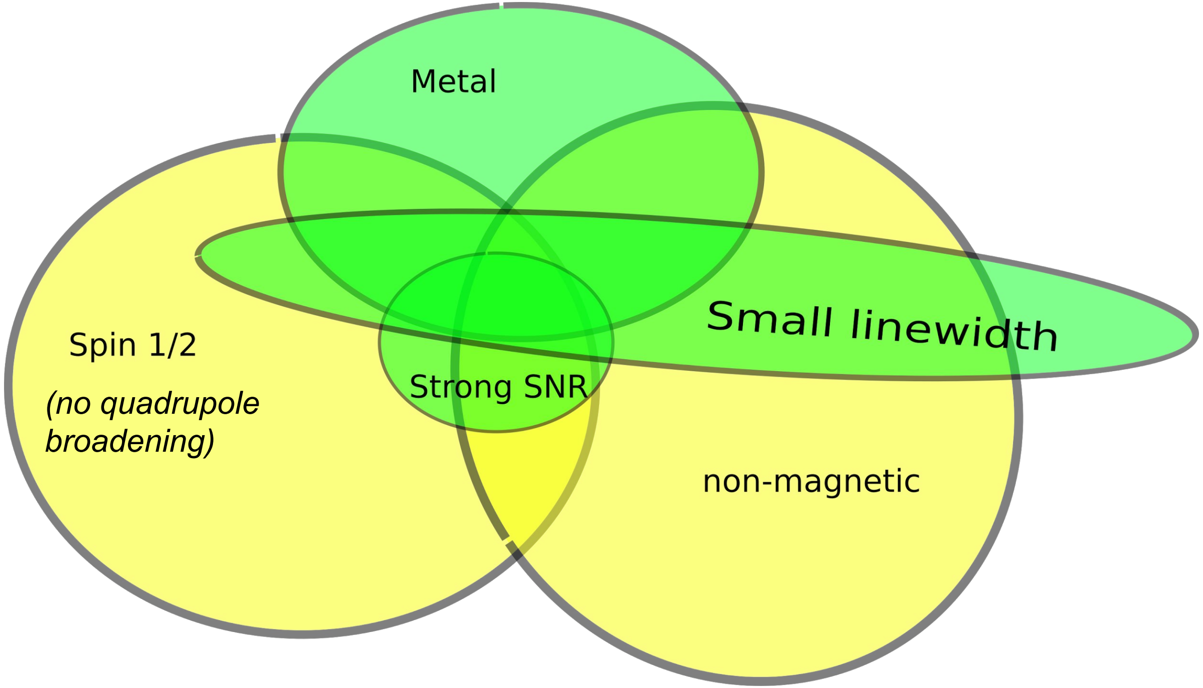
Low Temperature NMR Sample Search



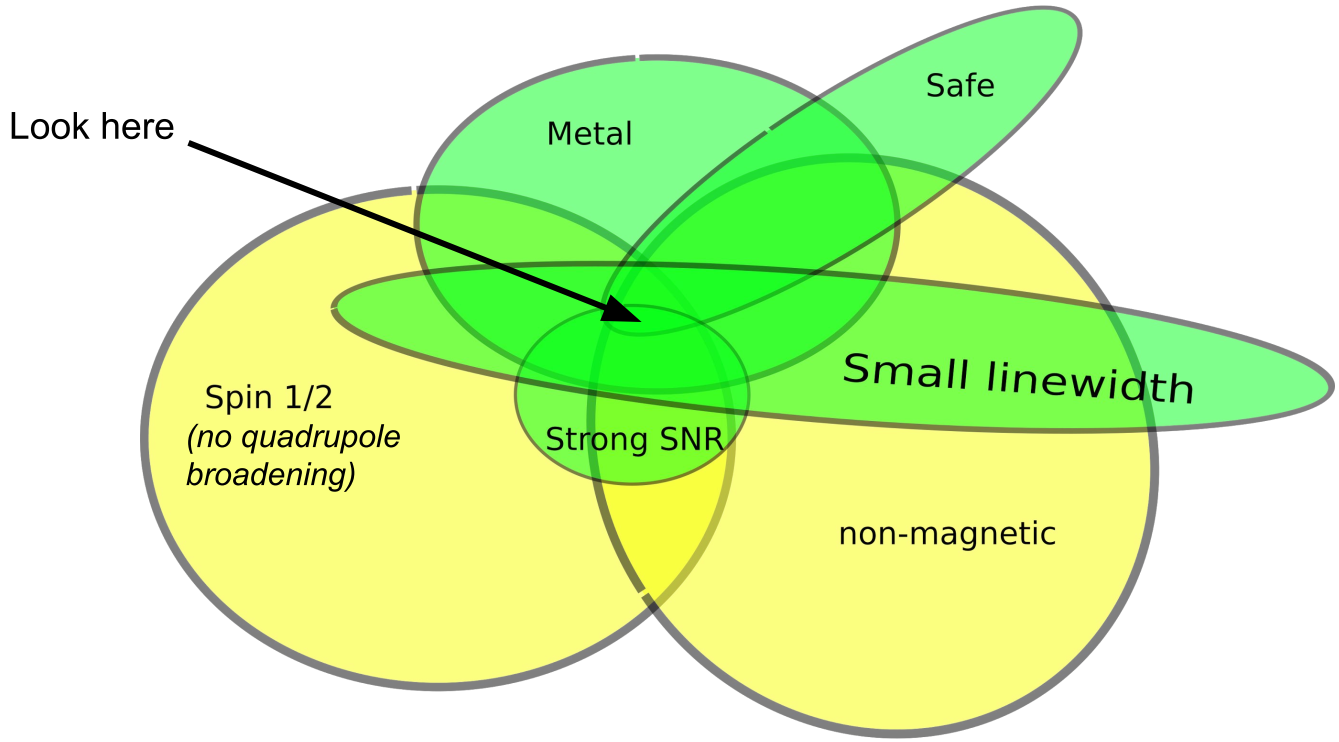
Low Temperature NMR Sample Search



Low Temperature NMR Sample Search

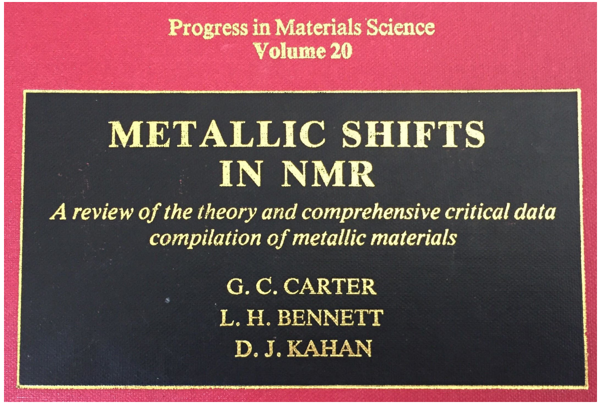


Low Temperature NMR Sample Search



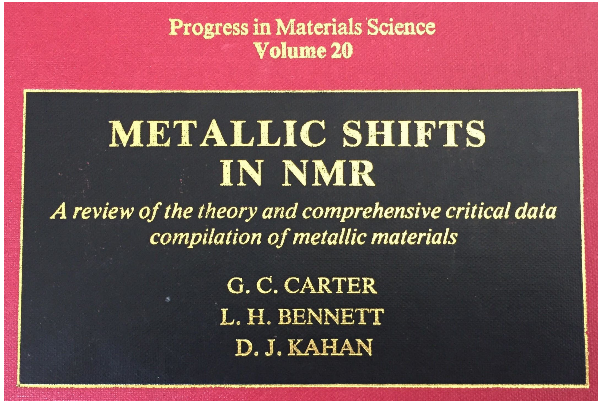
Low Temperature NMR Sample Search

- Check the literature!



Low Temperature NMR Sample Search

- Check the literature!
- Otherwise...estimate sensor performance:



Repetition time
$$T_1 = \frac{\hbar}{4\pi T \mathscr{K}^2}\left(\frac{\gamma_e}{\gamma_N}\right)^2$$

NMR linewidth
$$\Delta B \sim \frac{\sqrt{I(I+1)}\gamma\mu_o\hbar}{4\pi d^3}$$

Signal to noise ratio
$$SNR \propto \frac{\eta N Q^{1/2} V_c^{1/2}\gamma^{5/2} B^{3/2}}{f_{BW}^{1/2} T^{3/2}}$$
→ A. Abragam, Principles of nuclear magnetism (Oxford Univ. Press, 1961)

Sensor precision
$$\delta B_{CRLB} \geq \frac{\sqrt{12}}{SNR\sqrt{f_{BW}}T_o^{3/2}\gamma}$$
→ C. Gemmel, et. al. Eur. Phys. J. D (2010)

Low Temperature NMR Sample Search

Materials used as NMR magnetometers

Sample	Nucleus	Linewidth
Rubber	H-1	20 G
Aluminium	Al-27	20 G

$$\Delta B = M\bar{g}\Delta z/\mu \sim 4\mathrm{G}$$

$$\Delta B \times 1\% = 4\mu\mathrm{T}$$

Meets requirement of
1% gravity measurement?
(field precision <1ppm)

Low Temperature NMR Sample Search

Materials used as NMR magnetometers

Sample	Nucleus	Linewidth
Rubber	H-1	20 G
Aluminium	Al-27	20 G

Materials I'd like to characterize at 4K

Lead	Pb-207	1.6 G
Indium Phosphide	P-31	2.3 G
Titanium - Phosphide	P-31	2.0 G
Rubber	H-1	20 G

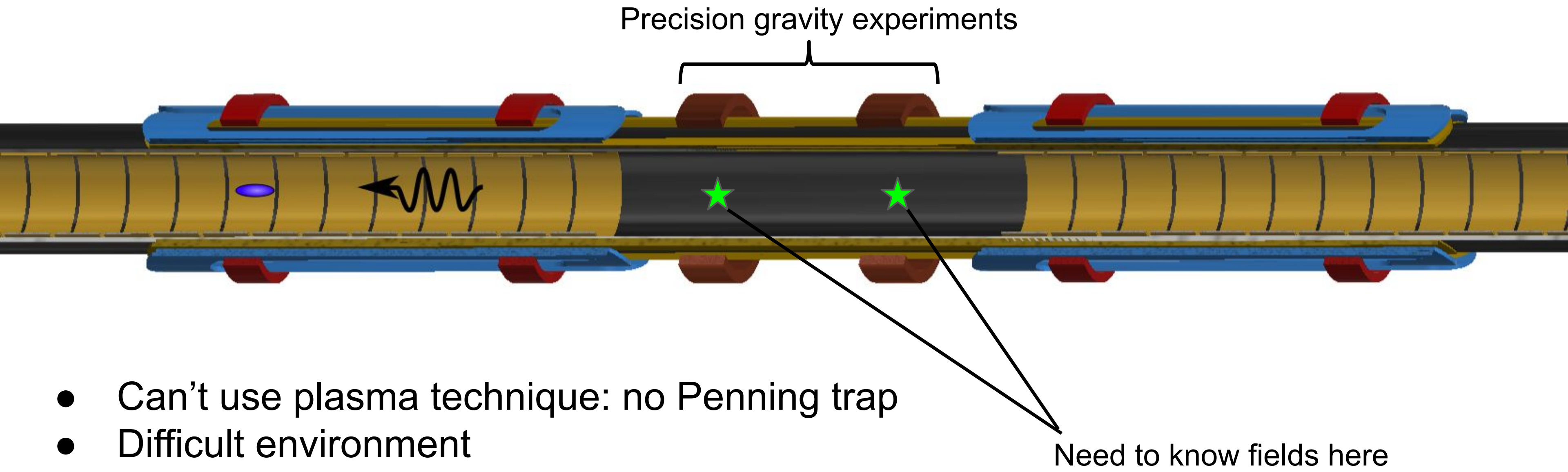
… and a dozen others...

$$\Delta B = M\bar{g}\Delta z/\mu \sim 4\mathrm{G}$$

$$\Delta B \times 1\% = 4\mu\mathrm{T}$$

Meets requirement of
1% gravity measurement?
(field precision <1ppm)

Present Magnetometry Problem



- Can't use plasma technique: no Penning trap
- Difficult environment
- Could NMR in metals work?
- **I am looking for solutions to this problem**

$$\Delta B \times 1\% = 4\mu\mathrm{T}$$

Thank you!

Field non-uniformity