Searching for Ghosts with NMR:

Experimental Aspects of the Cosmic Axion Spin Precession Experiment (CASPEr)

Axions??

- Could be dark matter
- Could solve Strong CP problem
- Could do both
- Worth looking for

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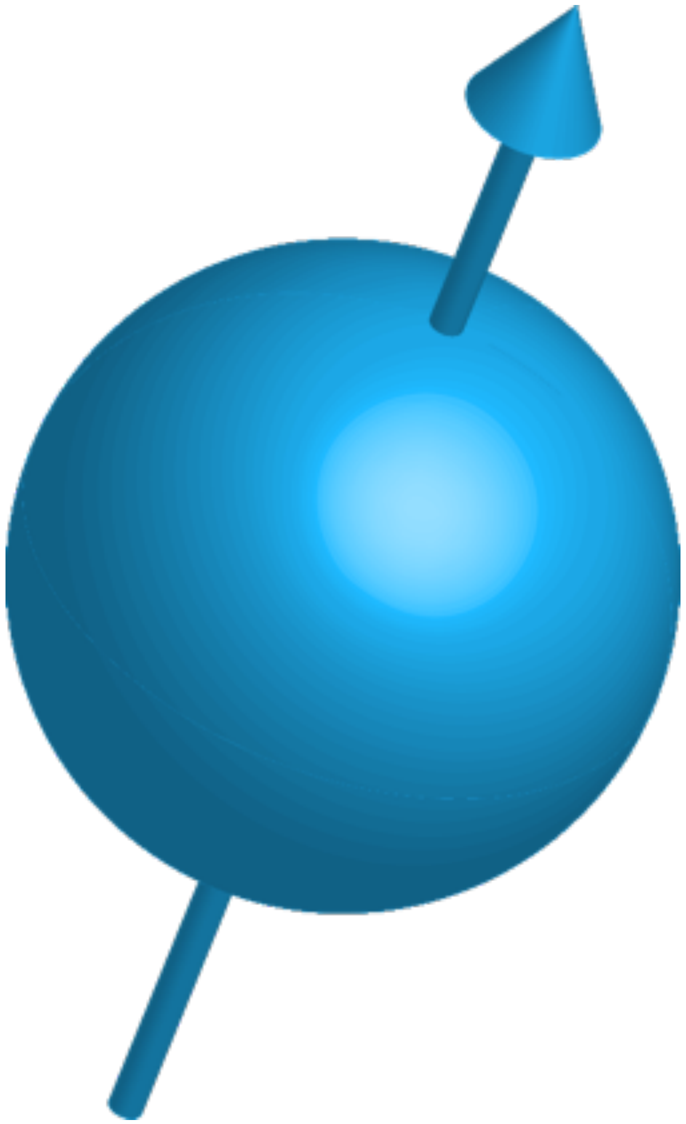
CASPEr

- Measure coupling of axions to nuclei
- Oscillating effect
- Leads to spin precession
- Resonant enhancement of spin precession makes detection possible

NMR

Parts of an NMR experiment:

- **Nuclear spins (sample)**
- Nuclear spin polarization
- Applied magnetic field (B_0)
- Excitation/Irradiation
- Detection



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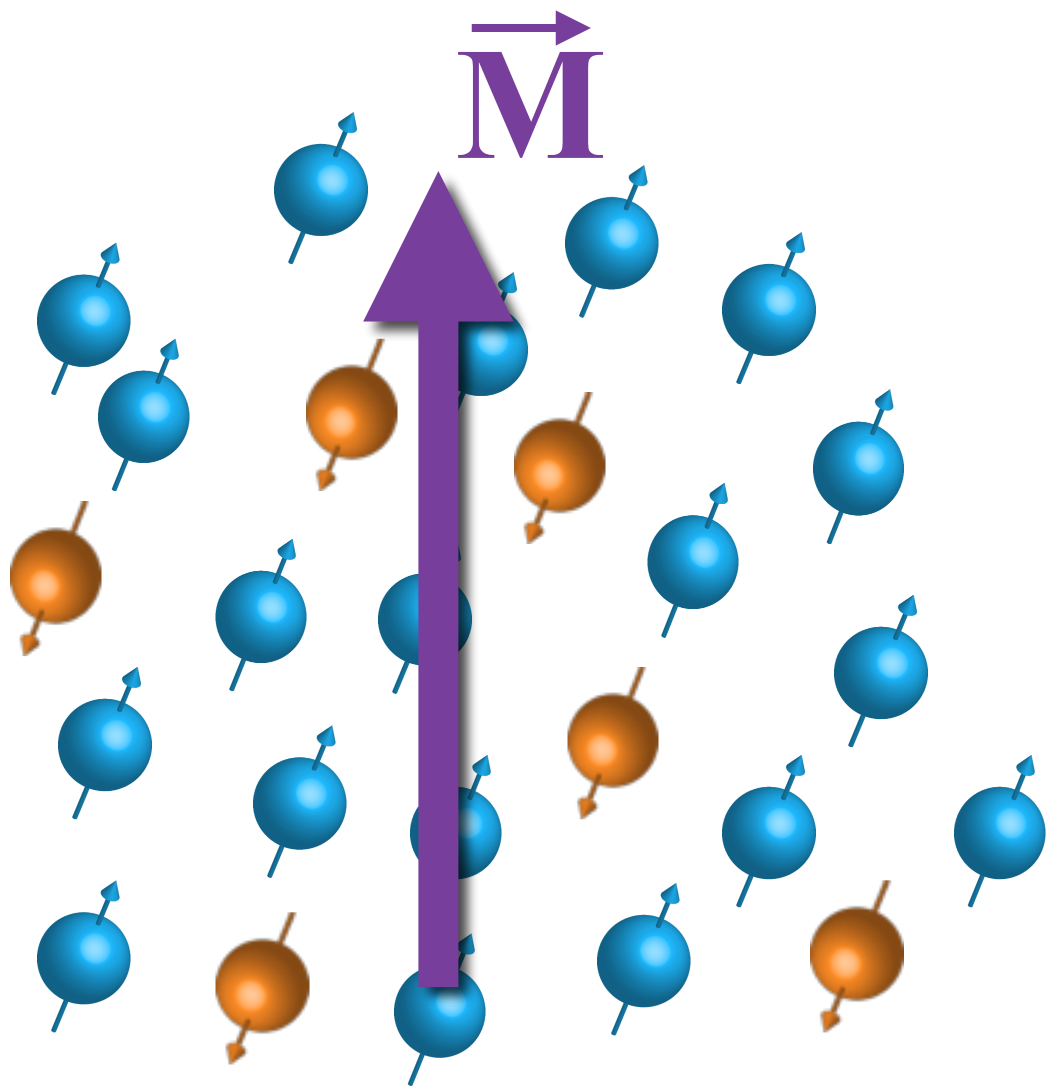

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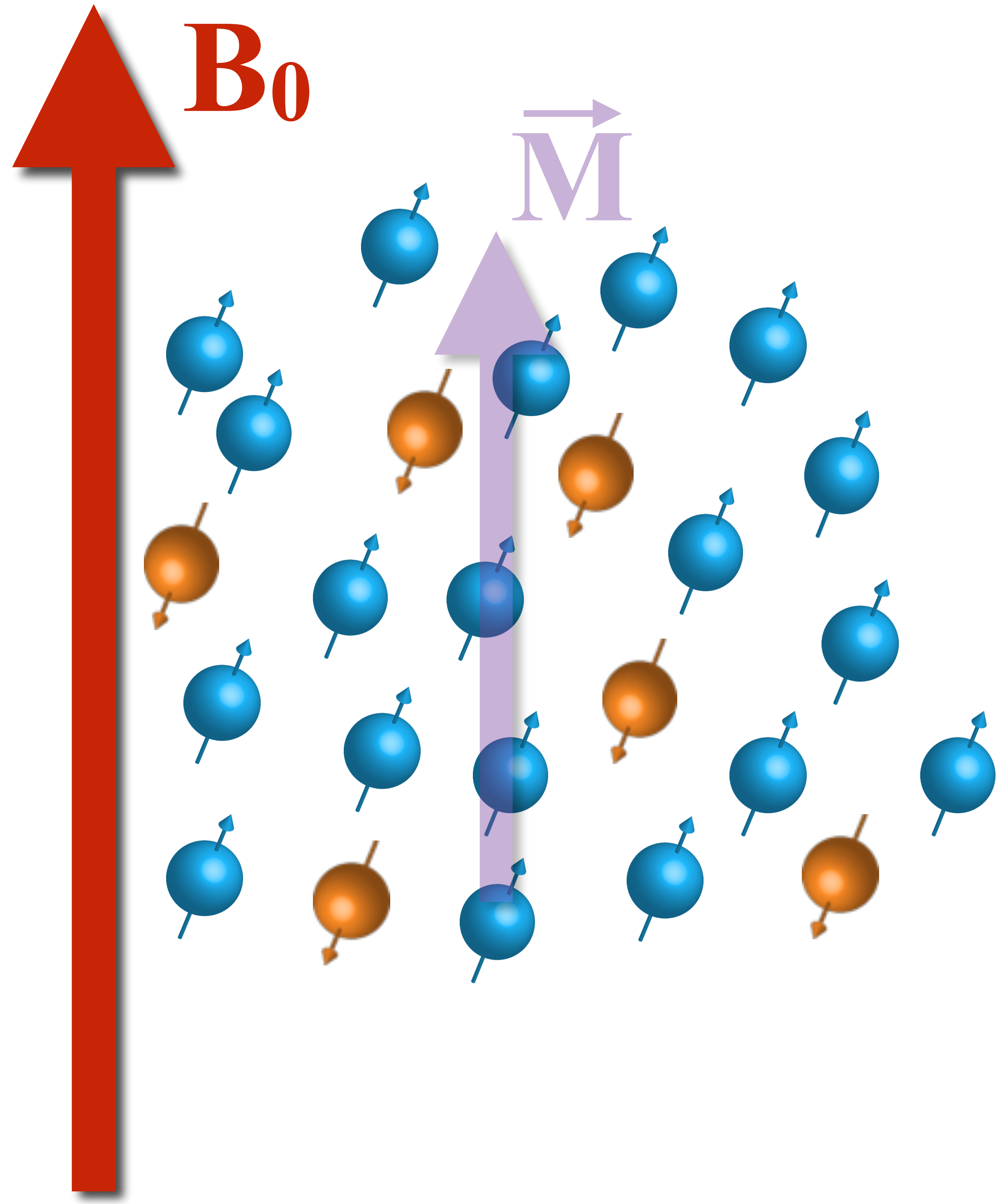

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- Applied magnetic field (B_0)
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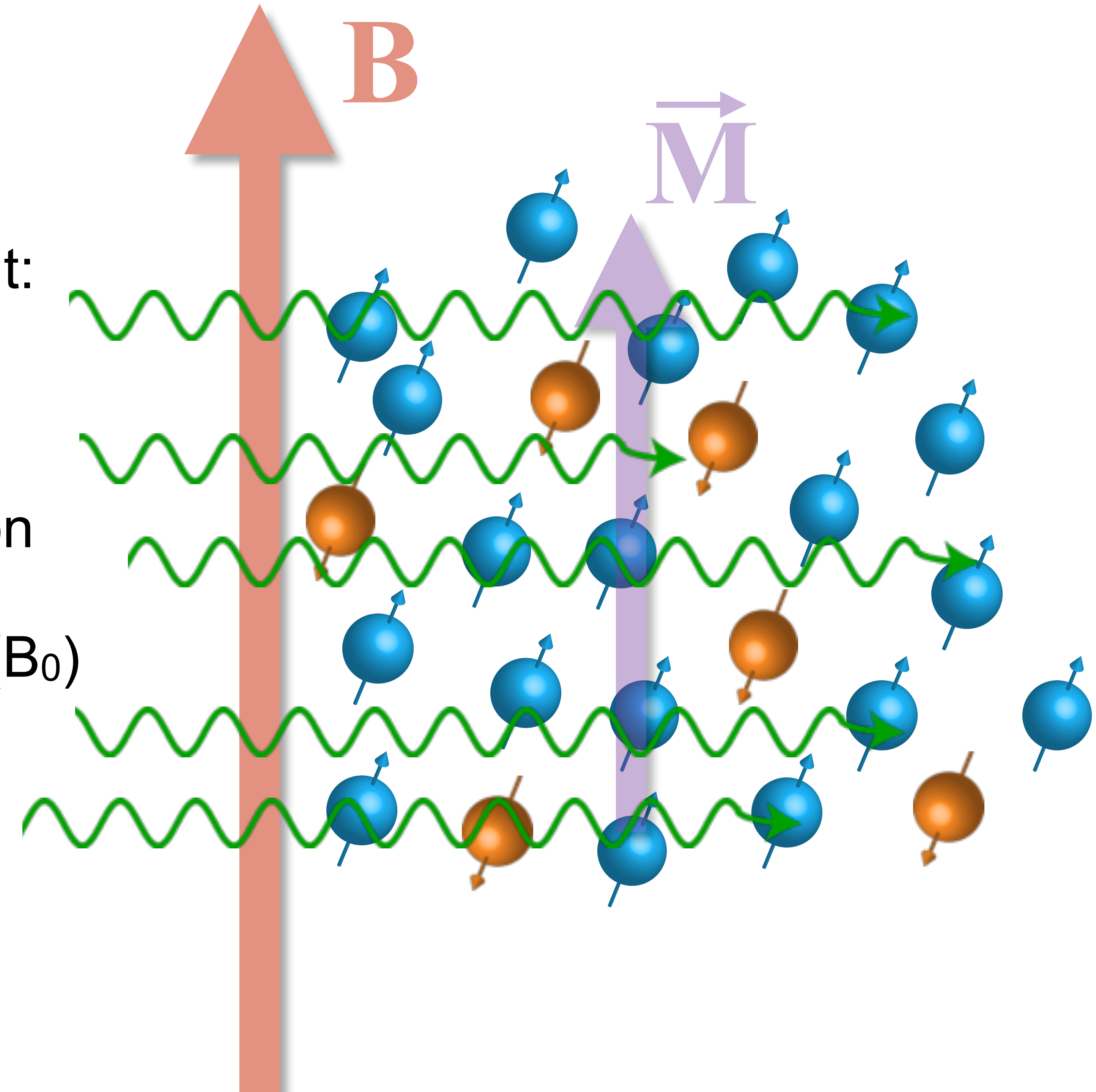

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NMR

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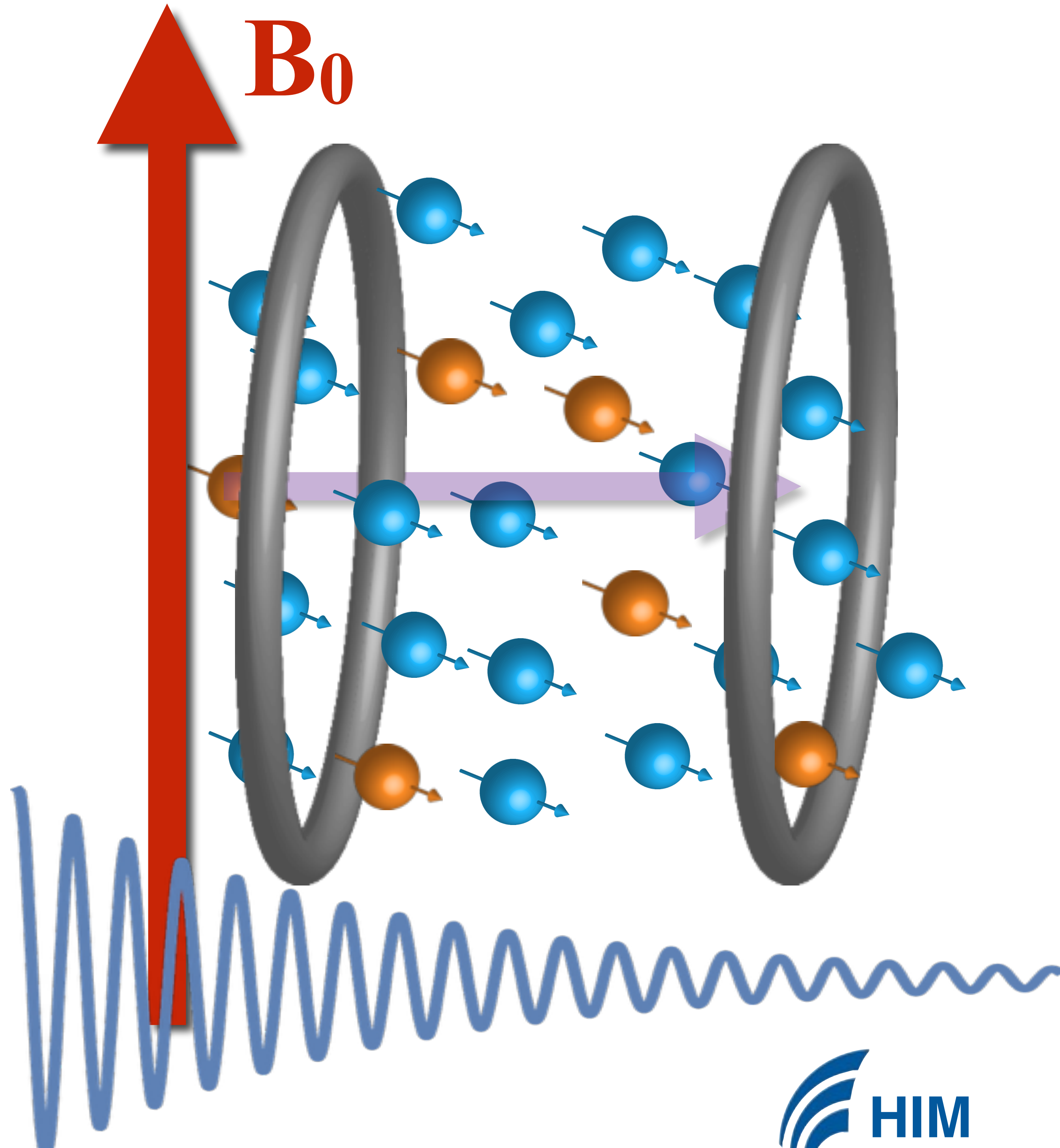
- **Detection**



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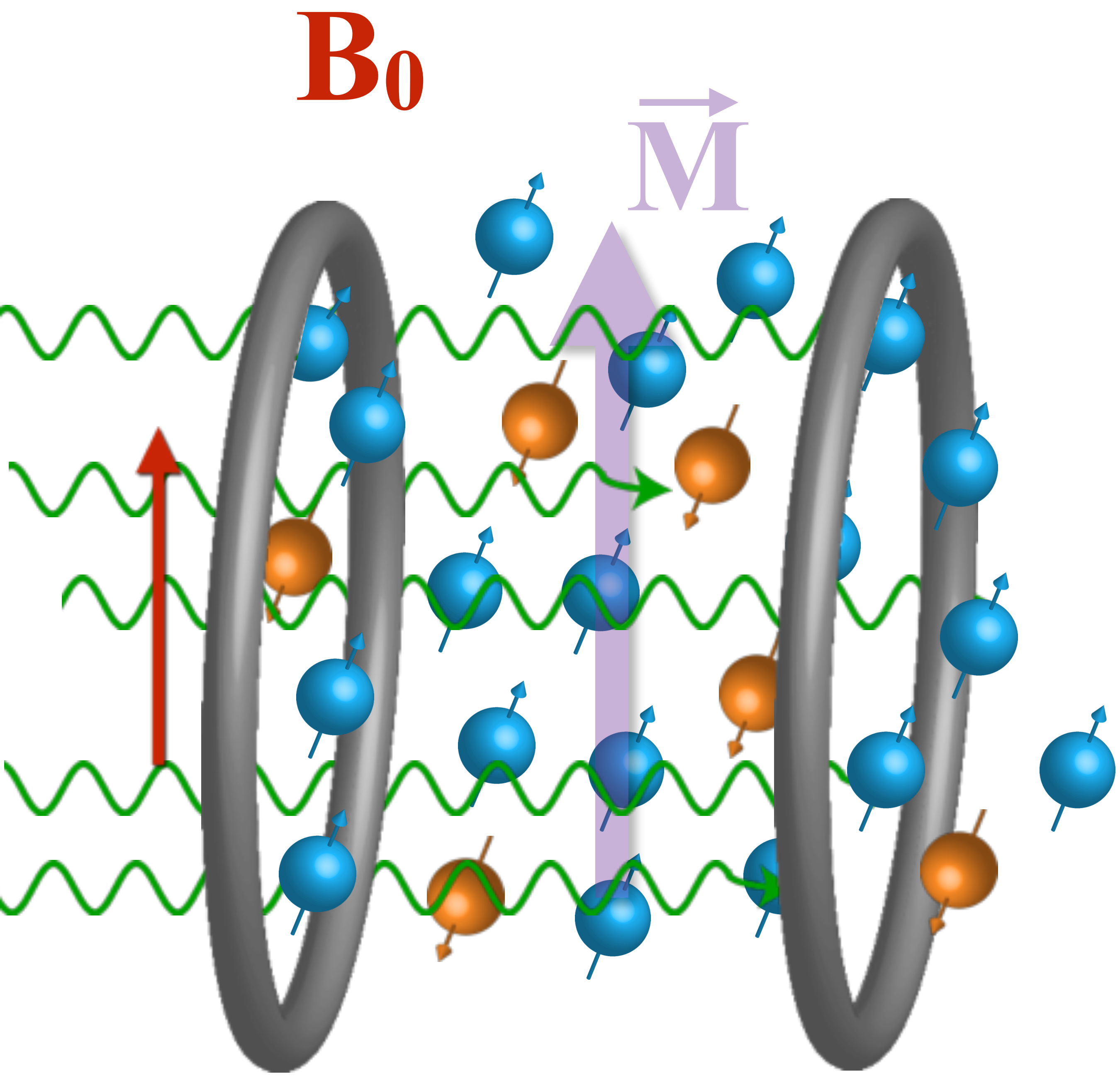
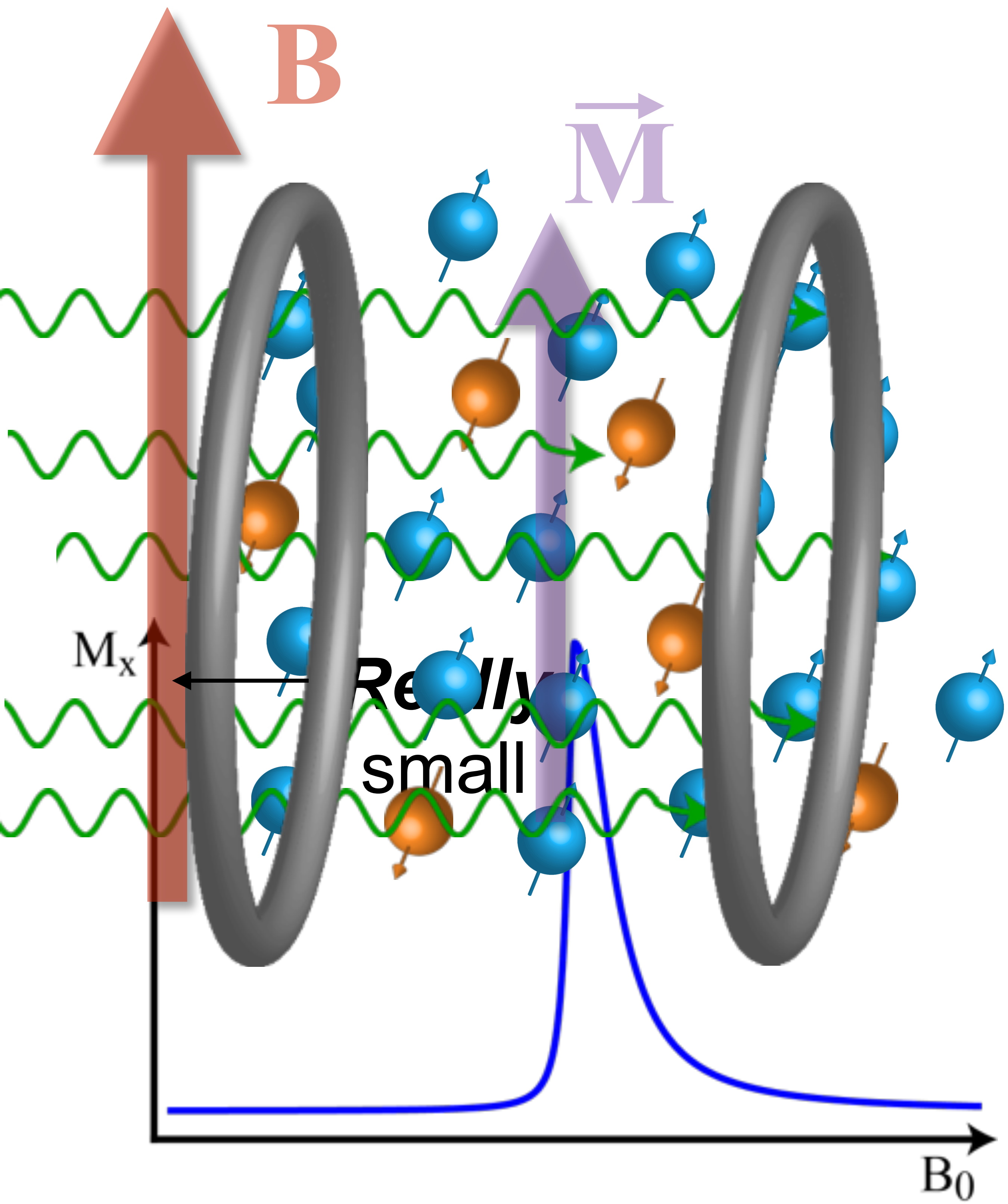
CW-NMR Radio Antenna



- Most modern NMR uses pulsed RF
- If you can't control your RF, you have to control the magnetic field instead
- But NMR suffers from sensitivity/polarization limitations
- Generally better to use a "normal" antenna (or a high-Q cavity)

CW-NMR Radio Antenna



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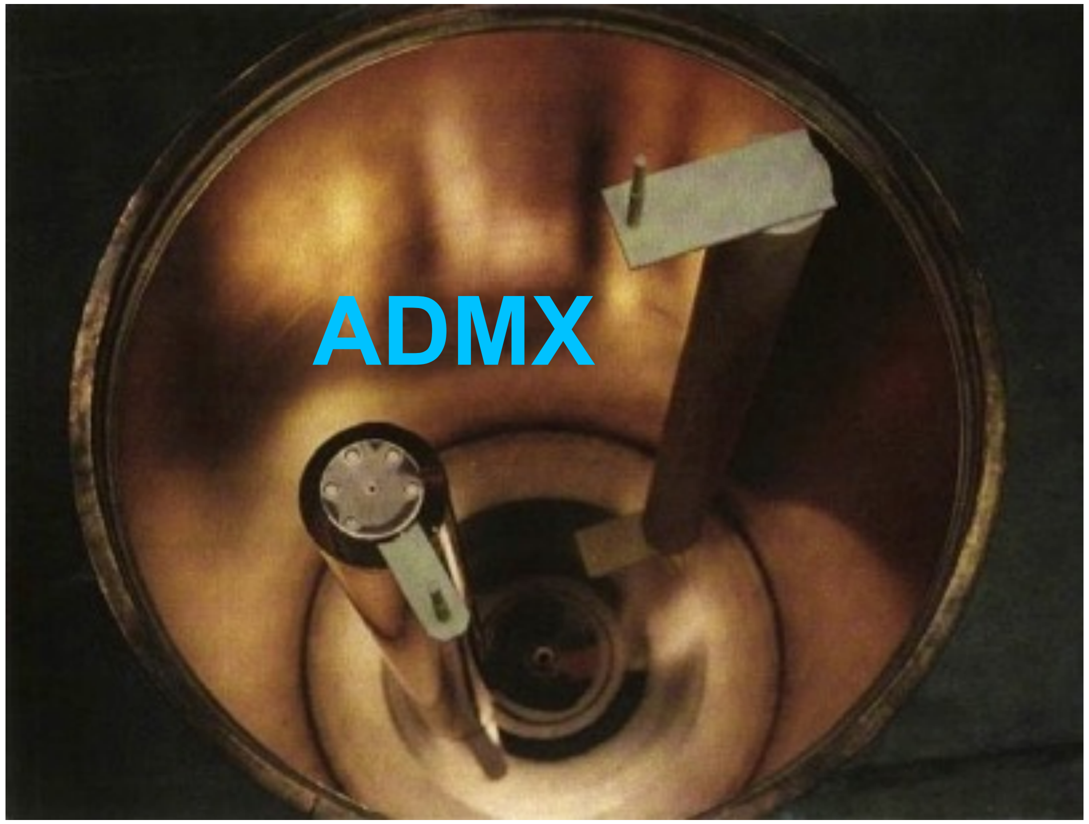

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- If you can't control your RF, you have to control the magnetic field instead
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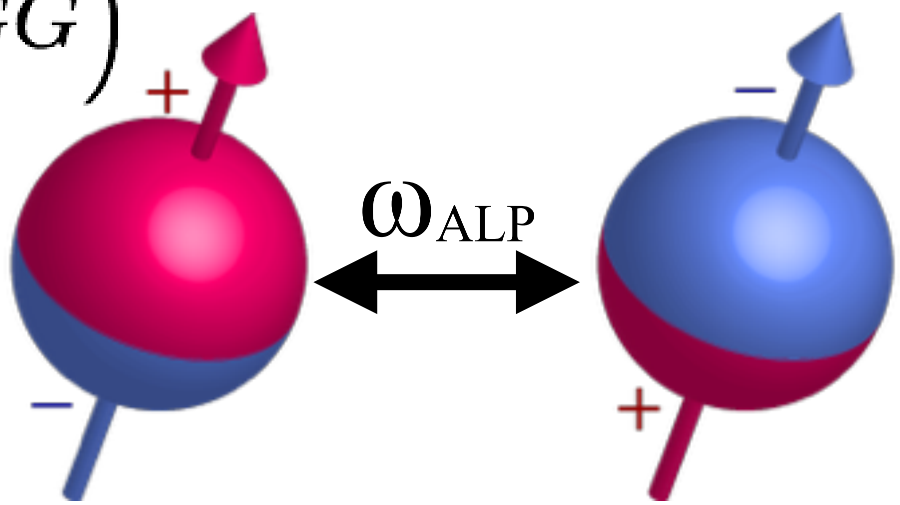
- Generally better to use a "normal" antenna (or a high-Q cavity)

CW-NMR (Ghost) Radio Antenna

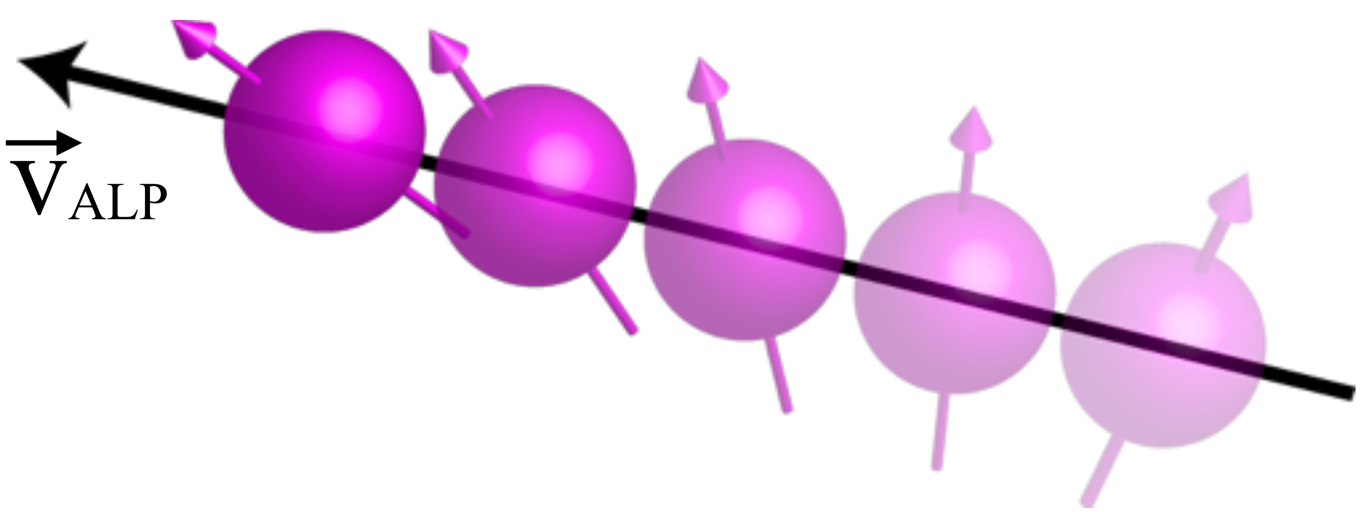
- To measure non-EM ALP couplings, you need a different kind of antenna
- Nuclear spin antenna:
  - ALP-induced EDM ➔ spin precession about applied electric field
  - Coupling of ALP to axial nuclear current ➔ spin precession about ALP velocity

CW-NMR (Ghost) Radio Antenna

$$\left(\frac{a}{f_a} G\tilde{G}\right)$$



$$\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$$



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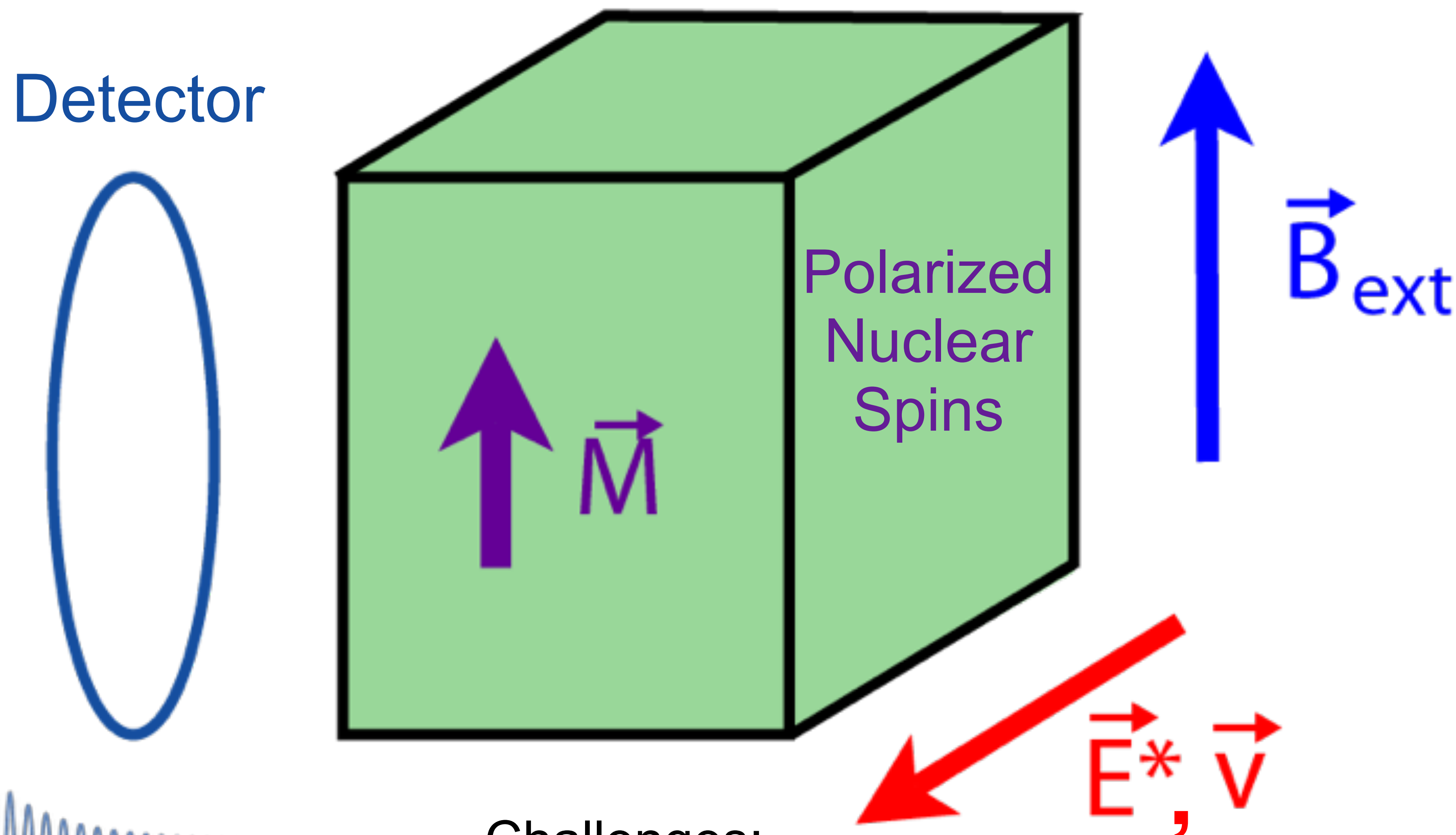
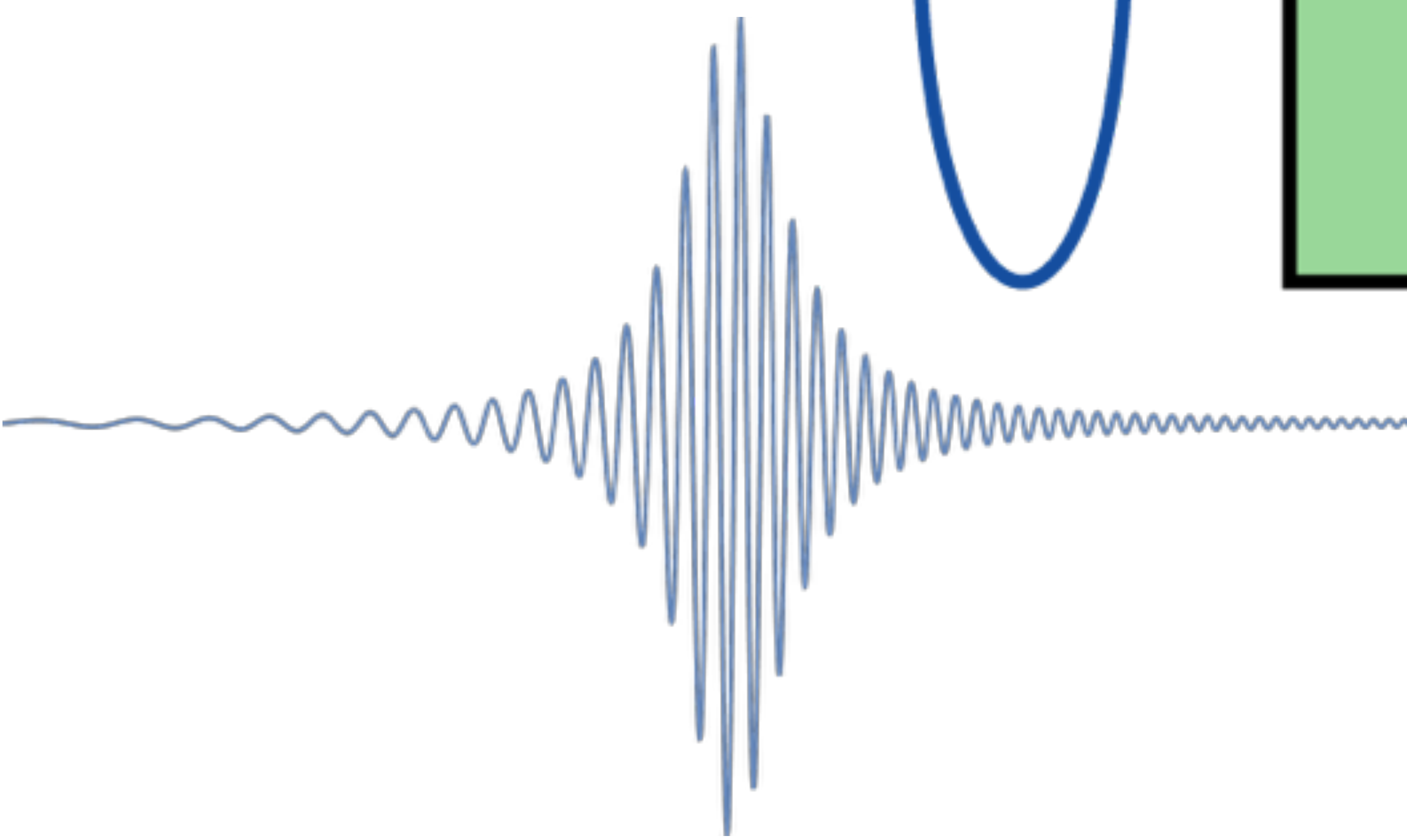
General CASPEr Experiment

1. Prepare polarized spin system
2. Sweep magnetic field
3. Detect sample magnetization

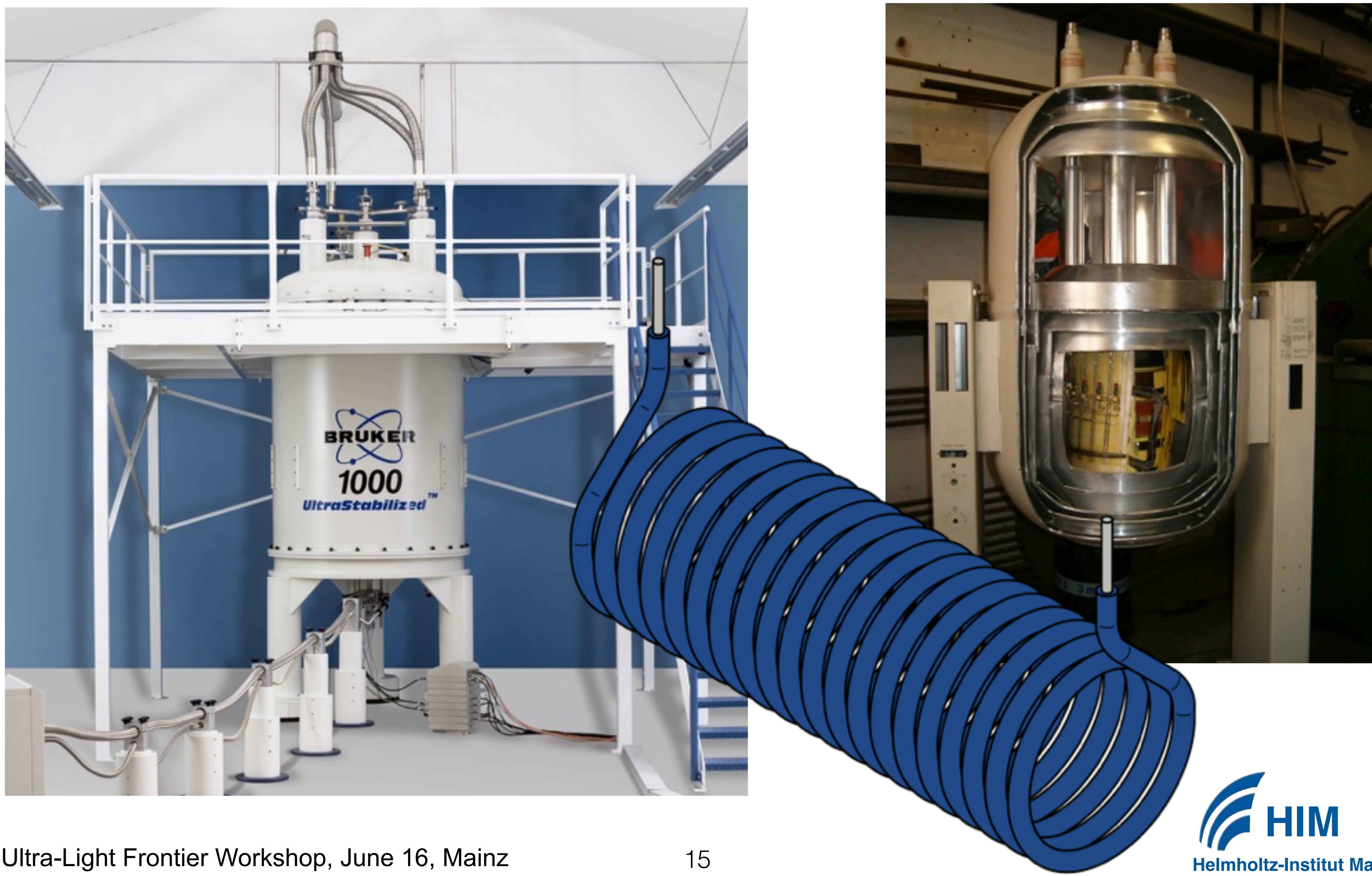




<u>Challenges:</u>

- Tunable homogeneous field
- Tunable sensitive detector
- Choosing the right nuclear spin antenna

Magnetic Field (B_0)

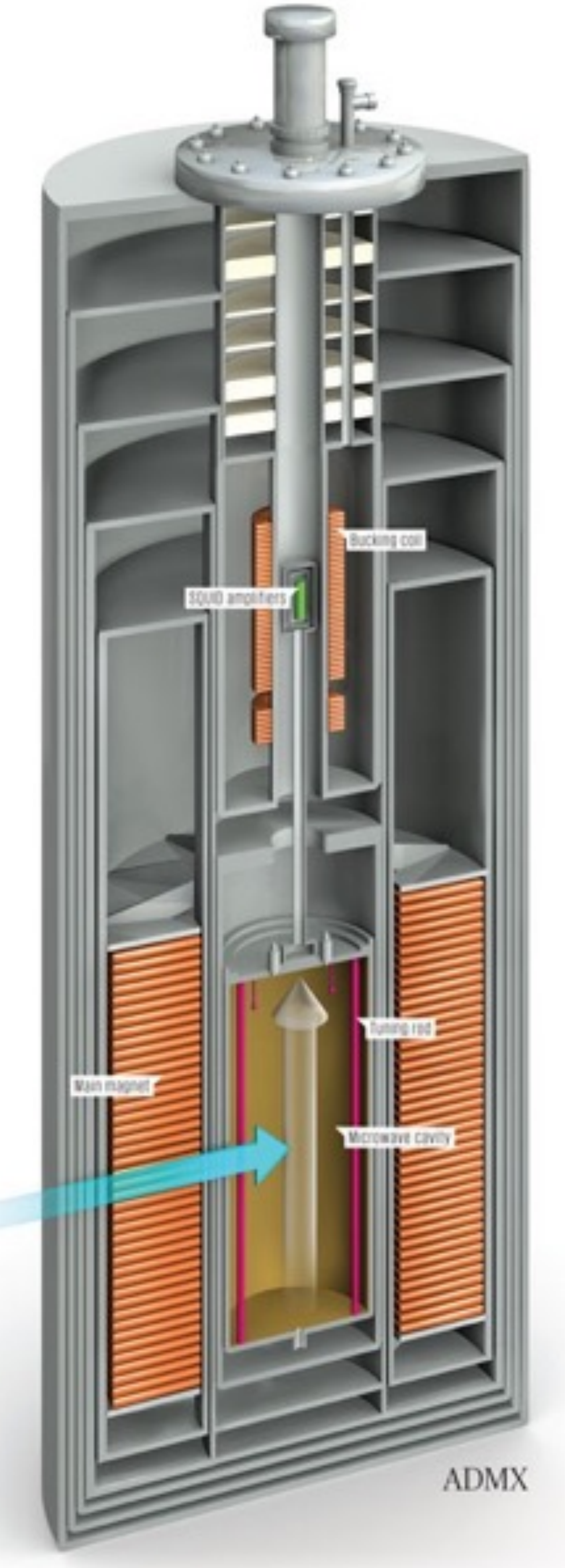


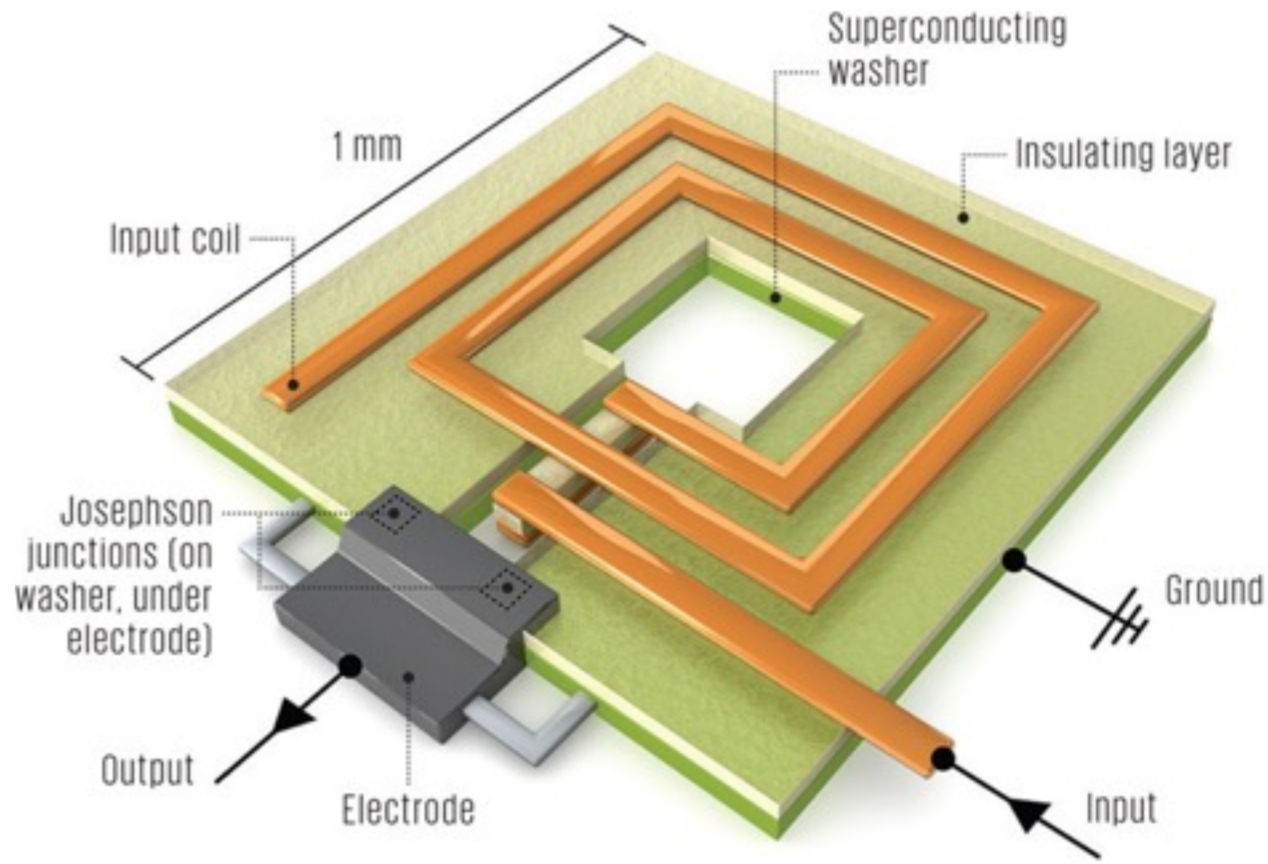
B_0 Field Homogeneity

Lots of shimming required

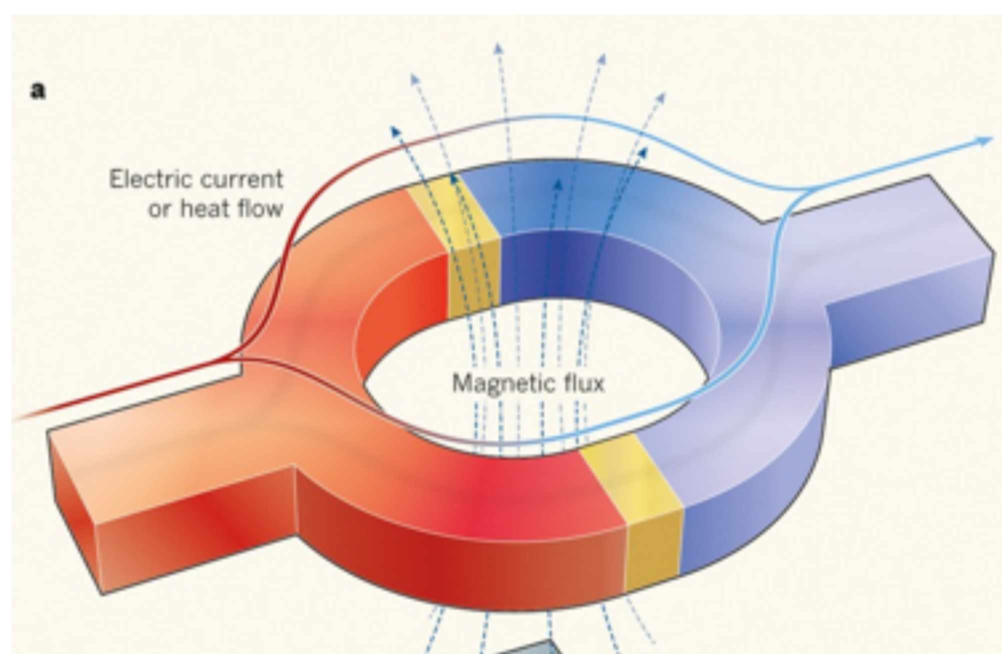
- automation?
- or grad student-powered

Detection: SQUIDS

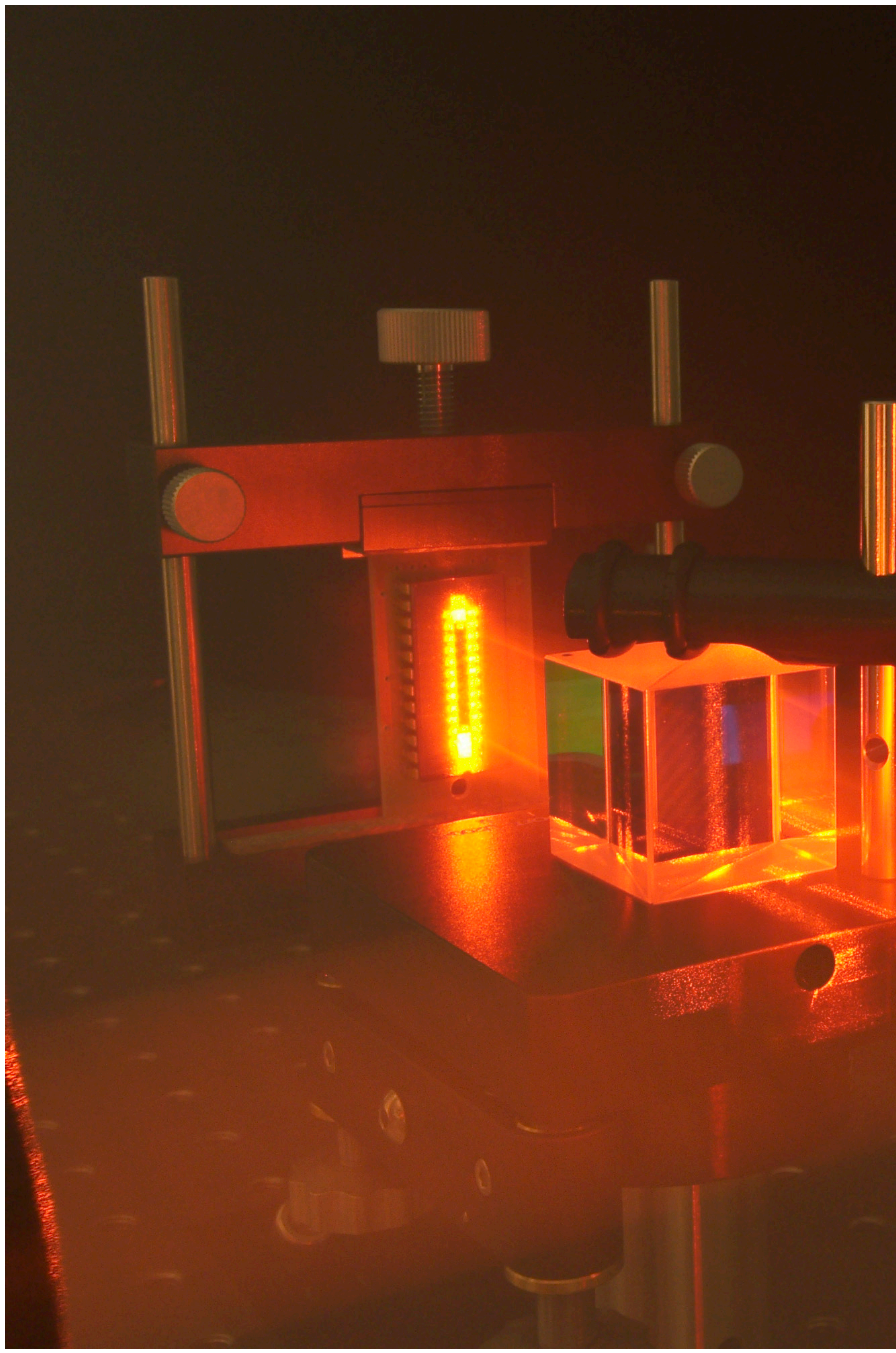


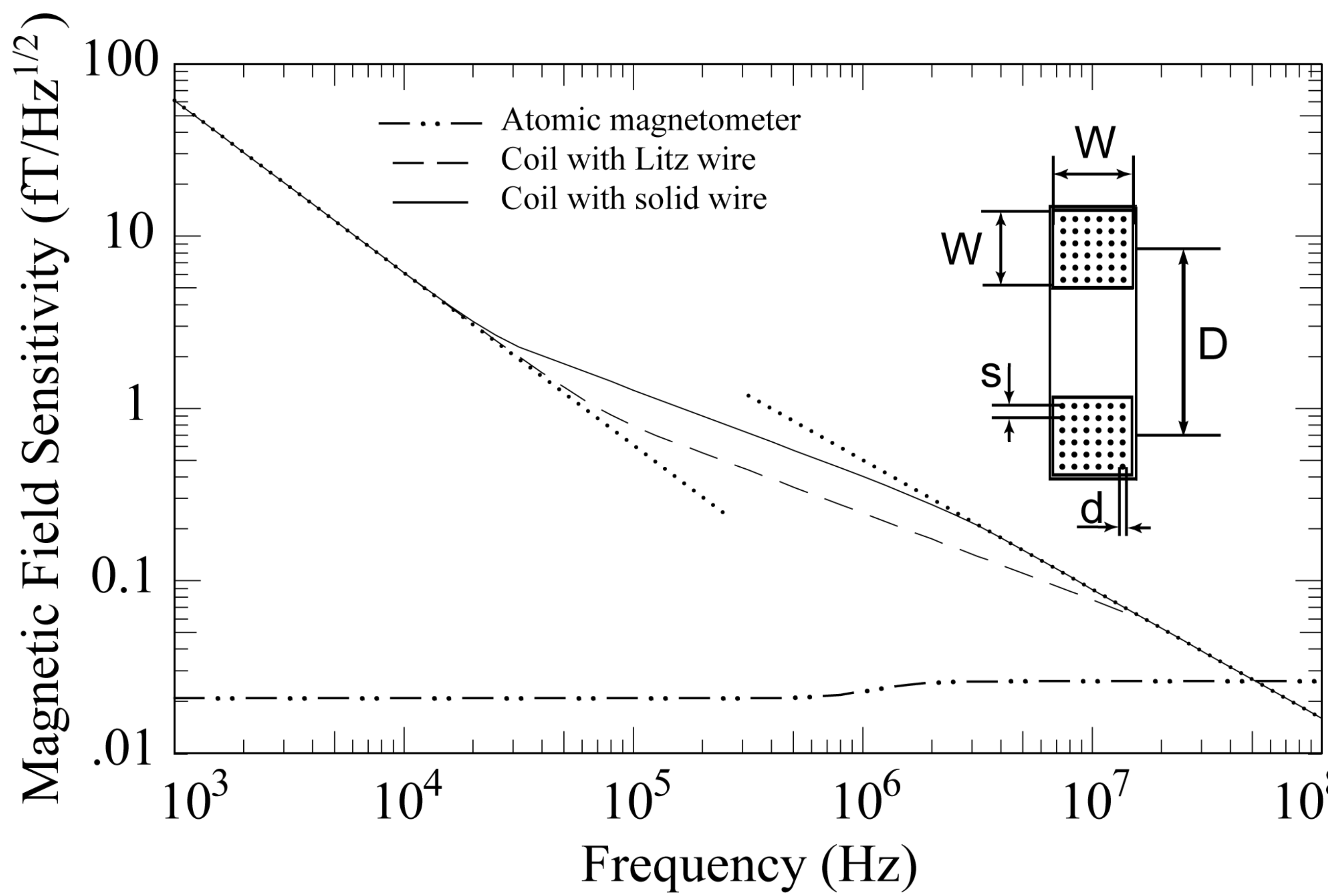


- Very sensitive (~ fT/√Hz)
- Wide bandwidth (up to MHz?)



Detection: SERF

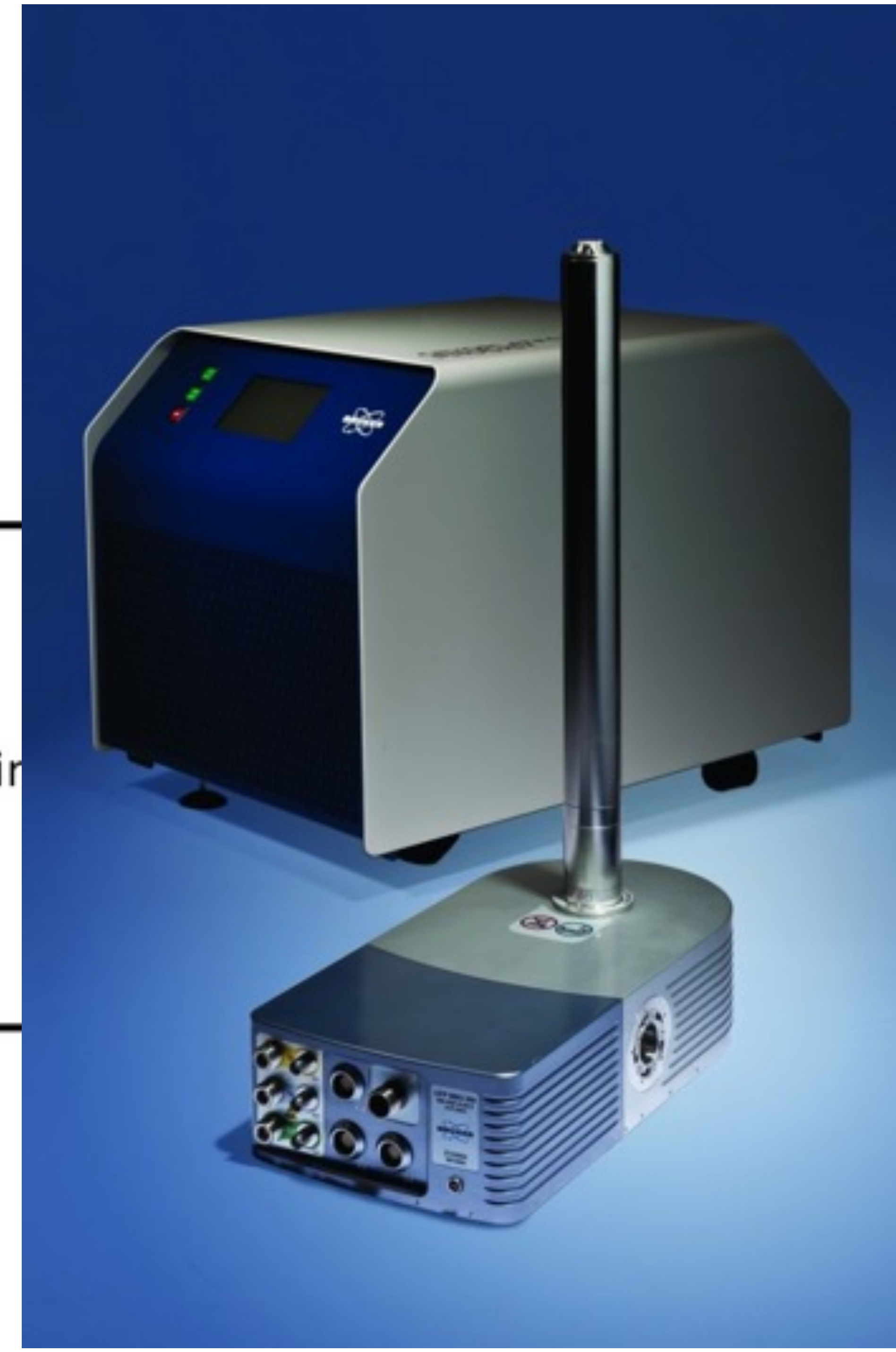




I. M. Savukov, S. J. Seltzer, and M. V. Romalis, *Journal of Magnetic Resonance* **185**, 214 (2007).

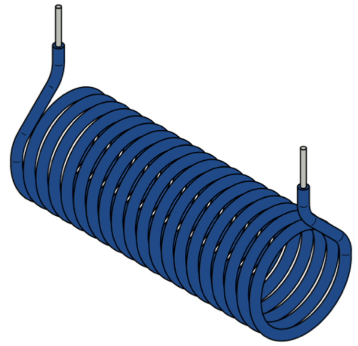
(Picture: T. W. Kornack)

Detection: Inductive



3 Field Regimes

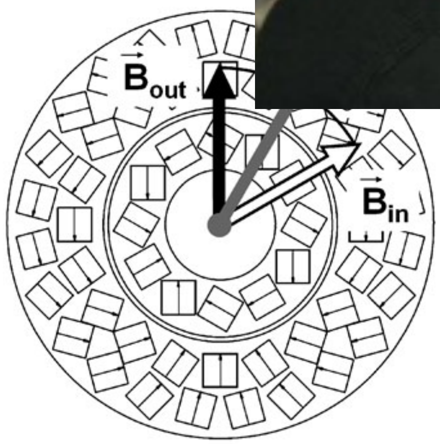
Low Field ($B_0 < 10^{-2}$ T)

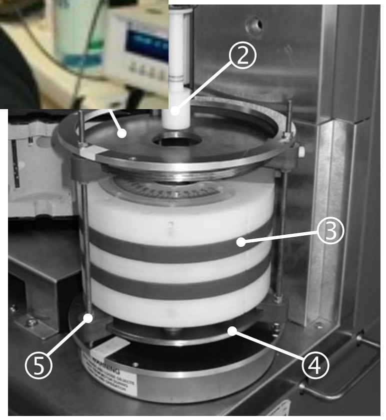


$

Intermediate Field ($10^{-2} < B_0 < 1$ T)

$$ (or free?)





High Field ($B_0 > 1$ T)

$$$$$$

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Sample Requirements

CASPEr-Wind

- High nuclear spin polarization (Field-independent)
- Long-ish coherence lifetime (T_2)
- Rapid repolarization OR long polarization lifetime (T_1)

CASPEr-Electric

- High nuclear spin polarization (Field-independent?)
- High Z
- Large (consistent) effective electric field
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? High nuclear spin polarization (Field-independent?)

- High Z
- Large (consistent) effective electric field

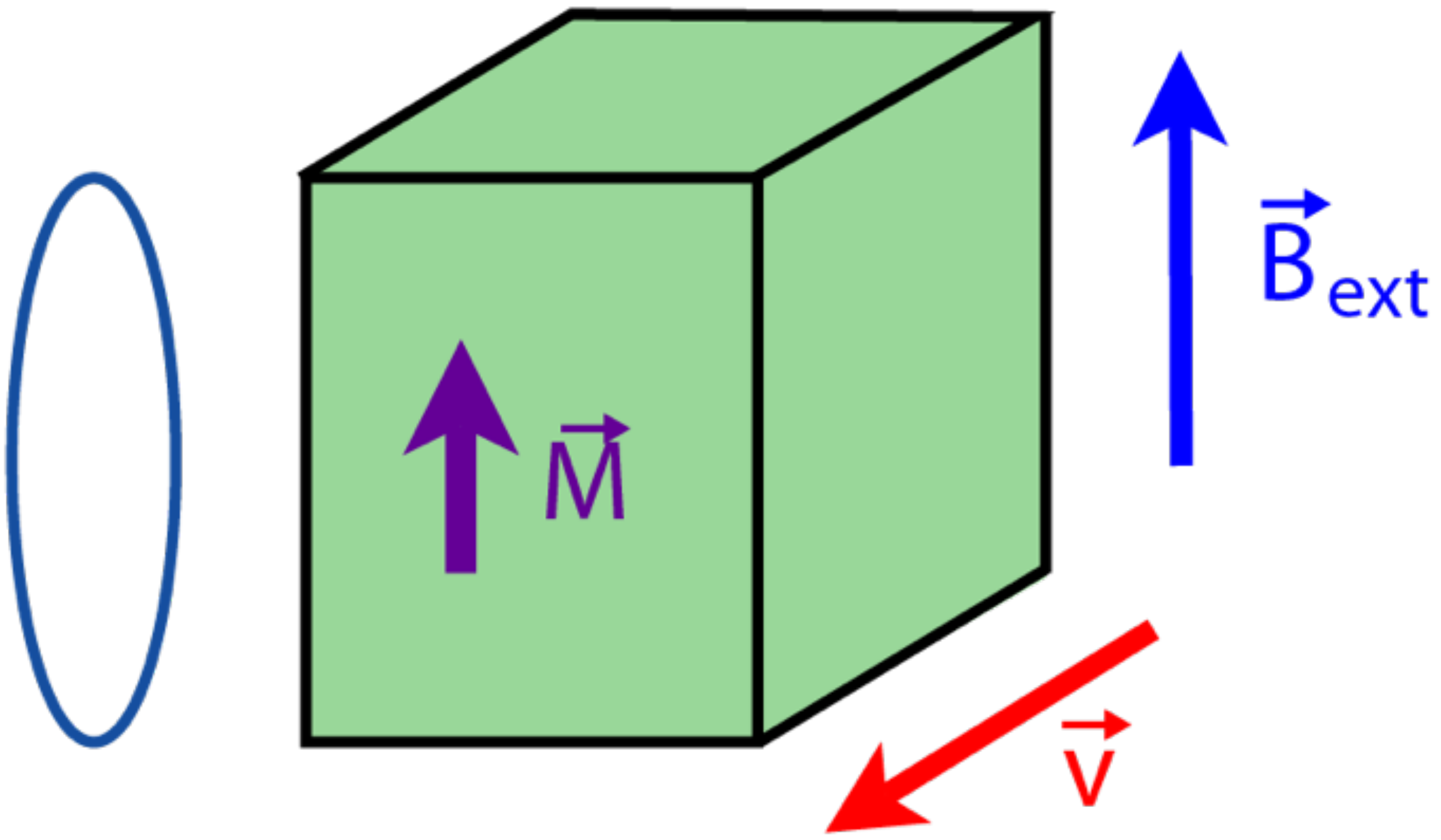
? Long-ish coherence lifetime (T_2)

- Rapid repolarization OR long polarization lifetime (T_1)

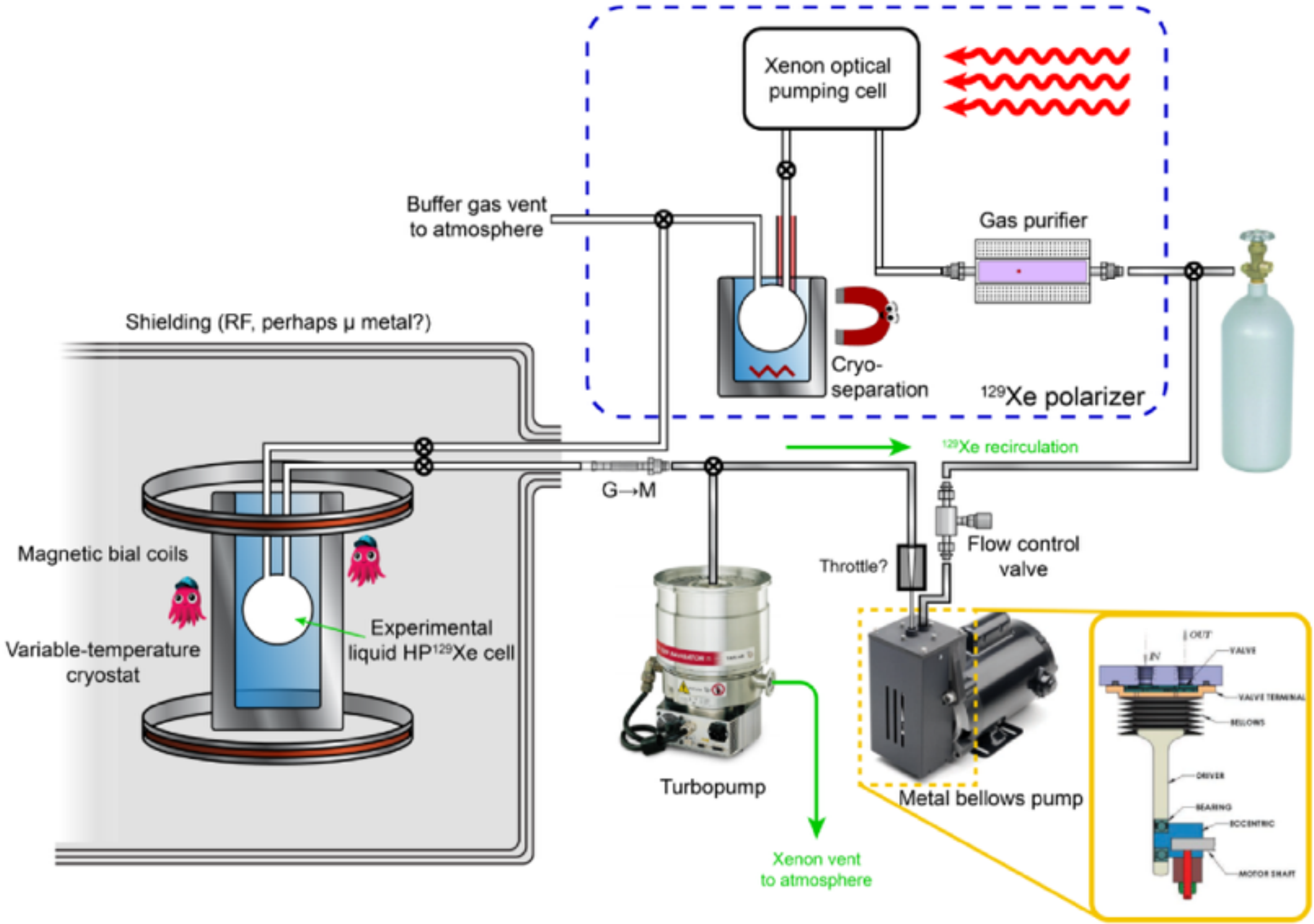
^{207}Pb in Ferroelectric Crystal

CASPEr-Wind

- Broadband Field-Sweep 129Xe NMR
- Requirements:
  - ✦ Hyperpolarized liquid Xe
  - ✦ Tunable B0
  - ✦ Sensitive detector(s)



CASPEr-Wind



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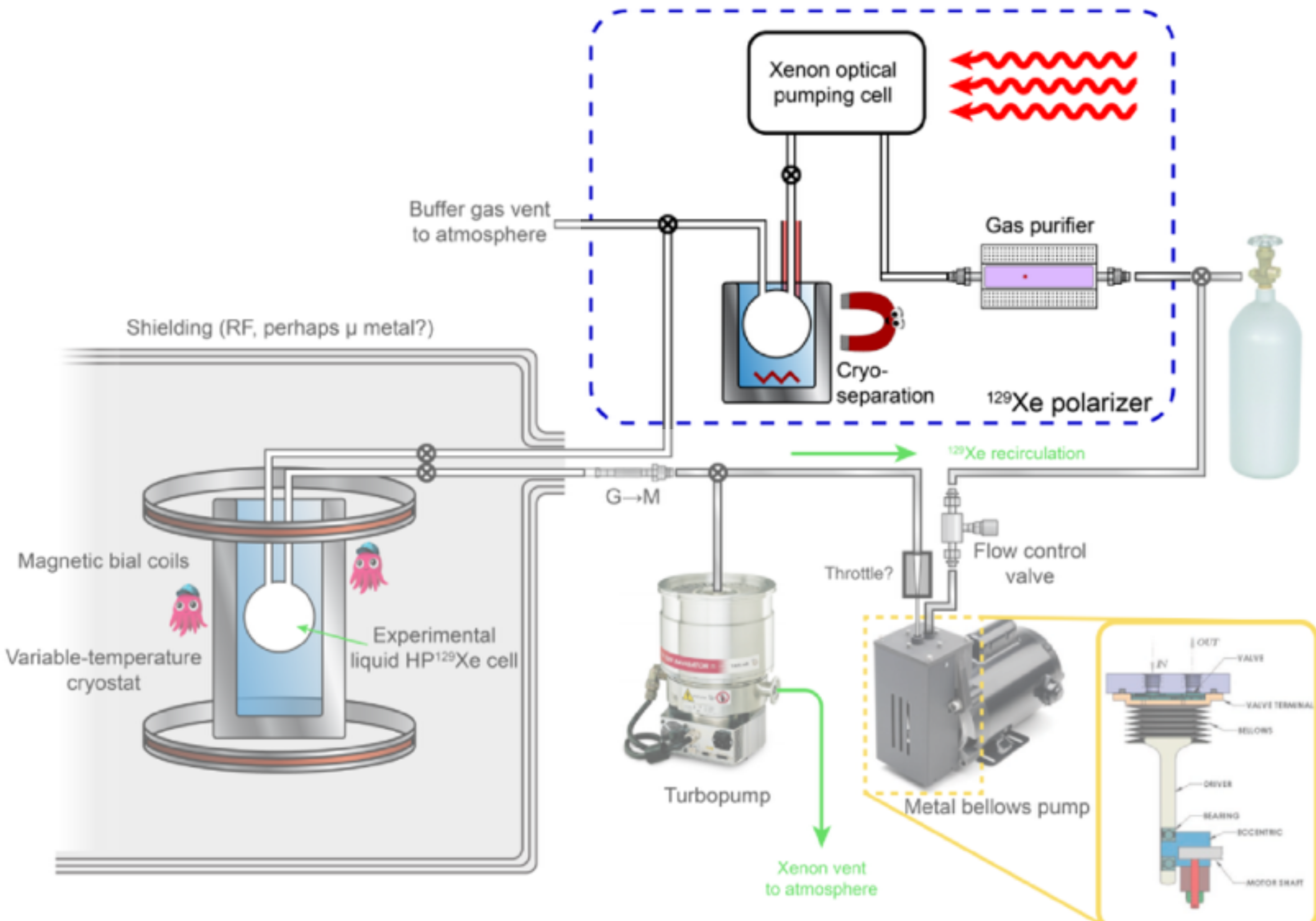
CASPEr-Wind



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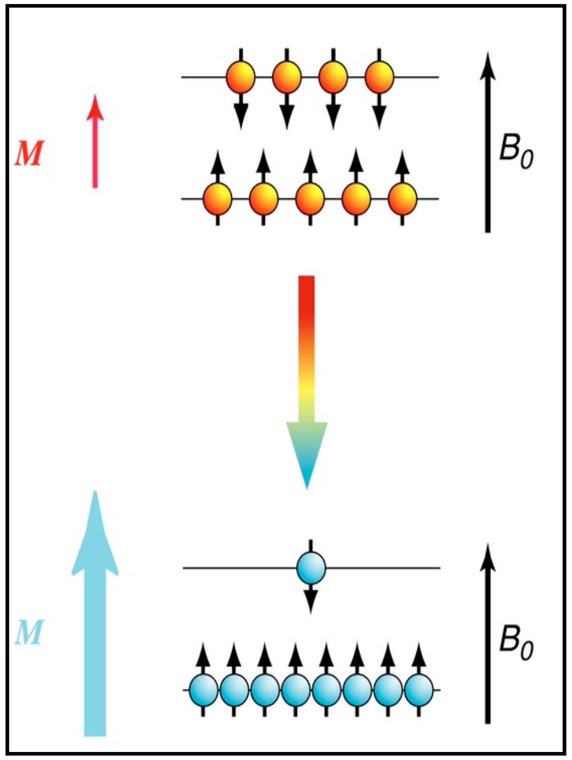
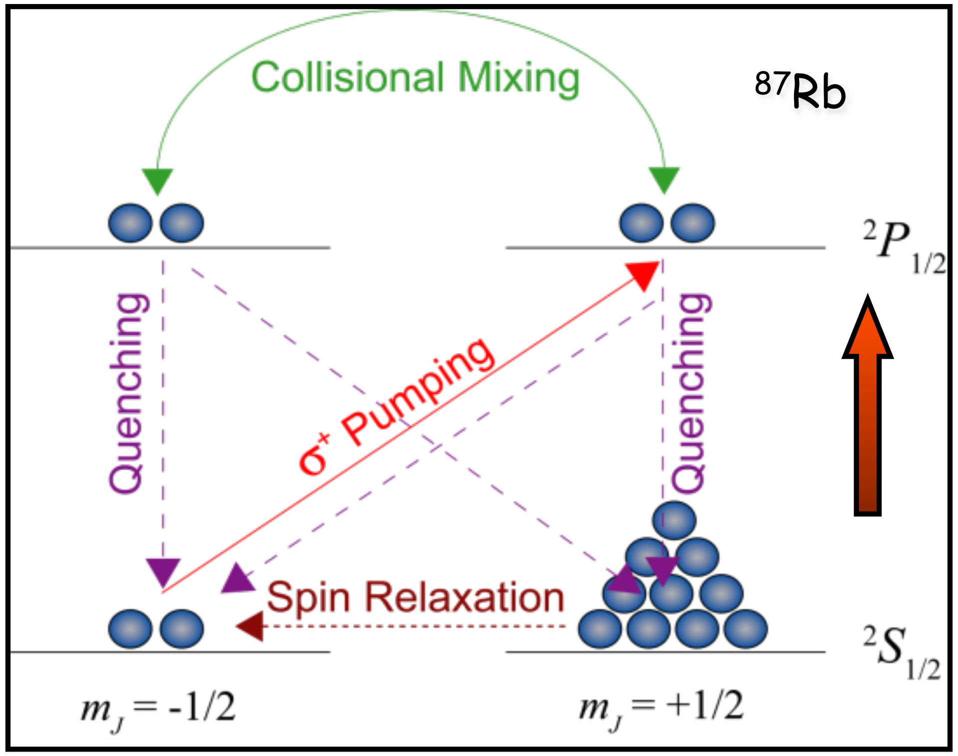
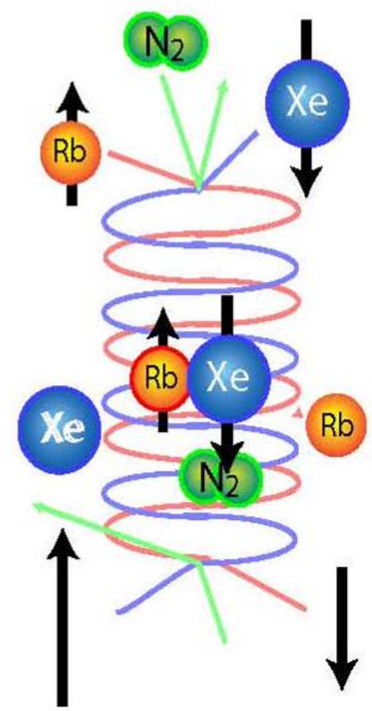
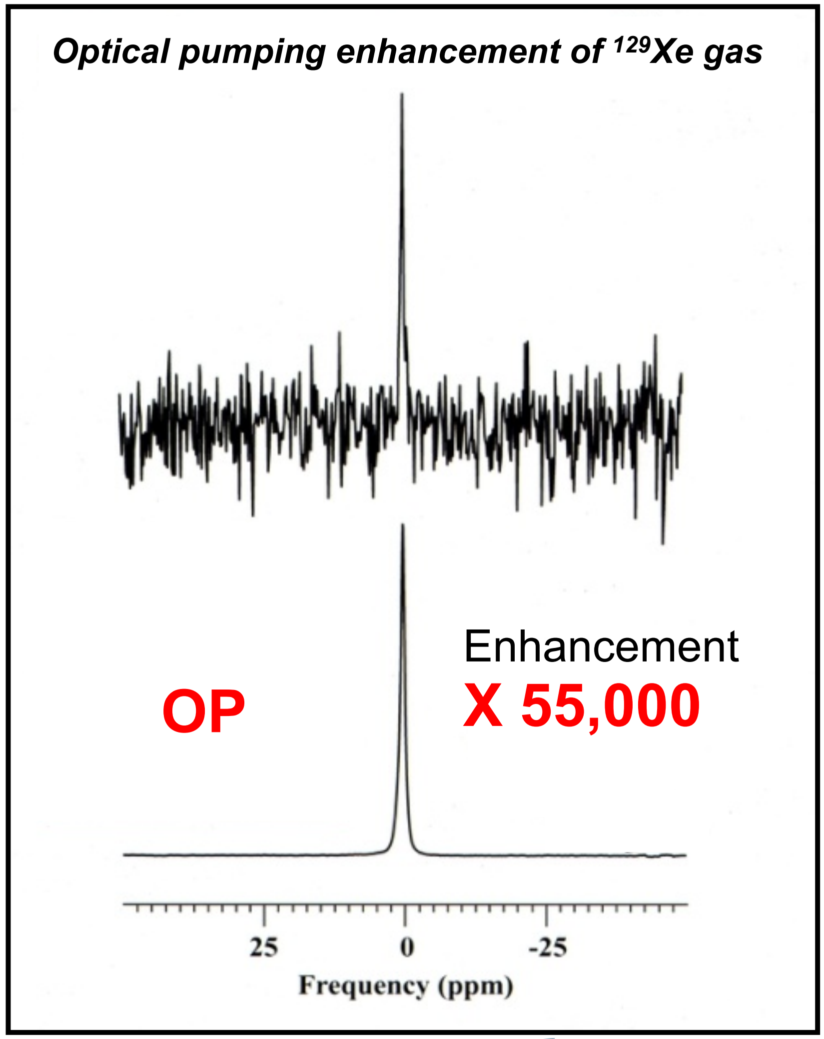
CASPEr-Wind: Xe SEOP







Xe polarization through Rb/Xe collisions and Fermi contact spin flips



- "Easy"
- Xe + Rb + γ = massive signal
- For large volumes (and high polarization) of LXe, we need a lot of laser power

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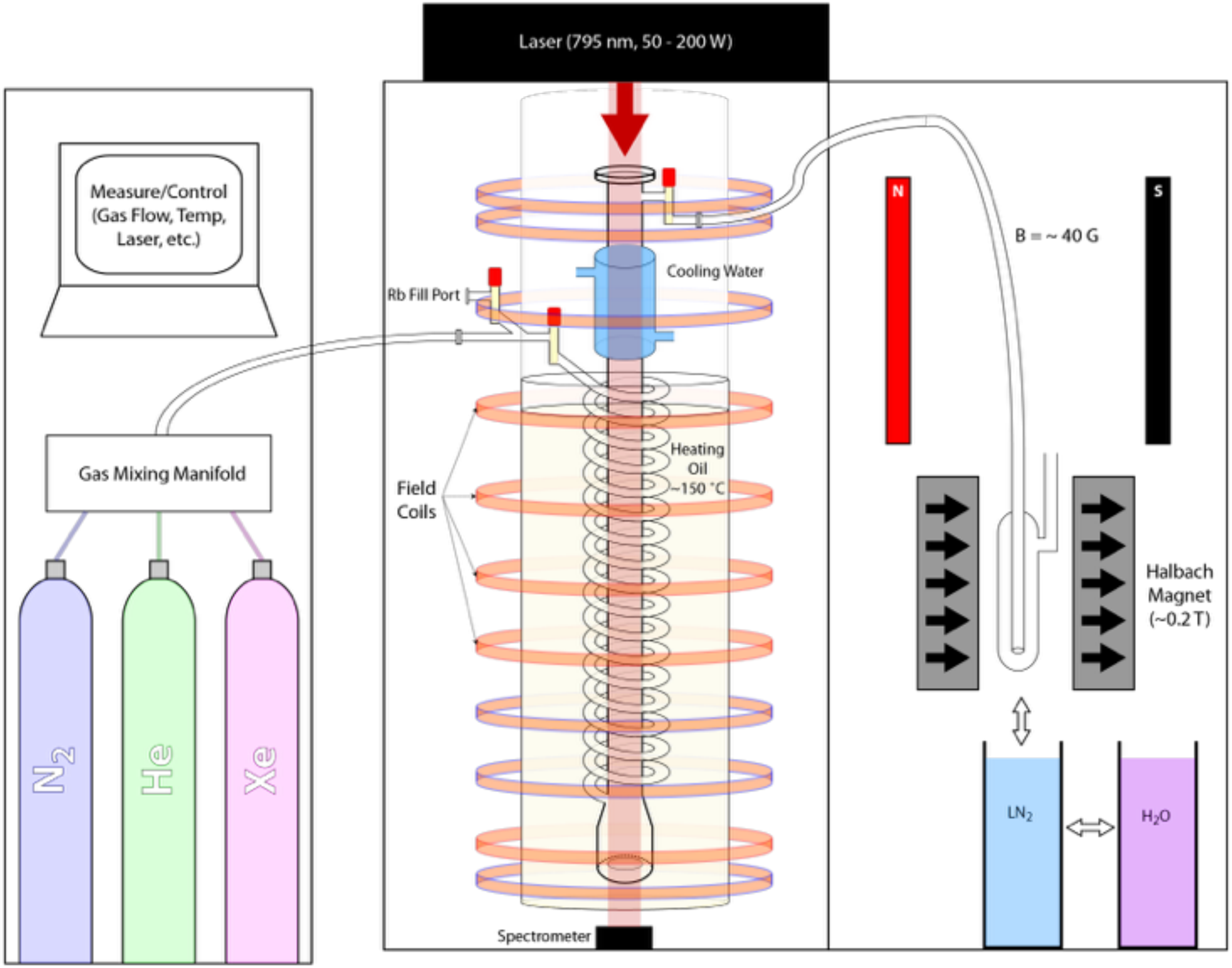
Mainz Xe Polarizer



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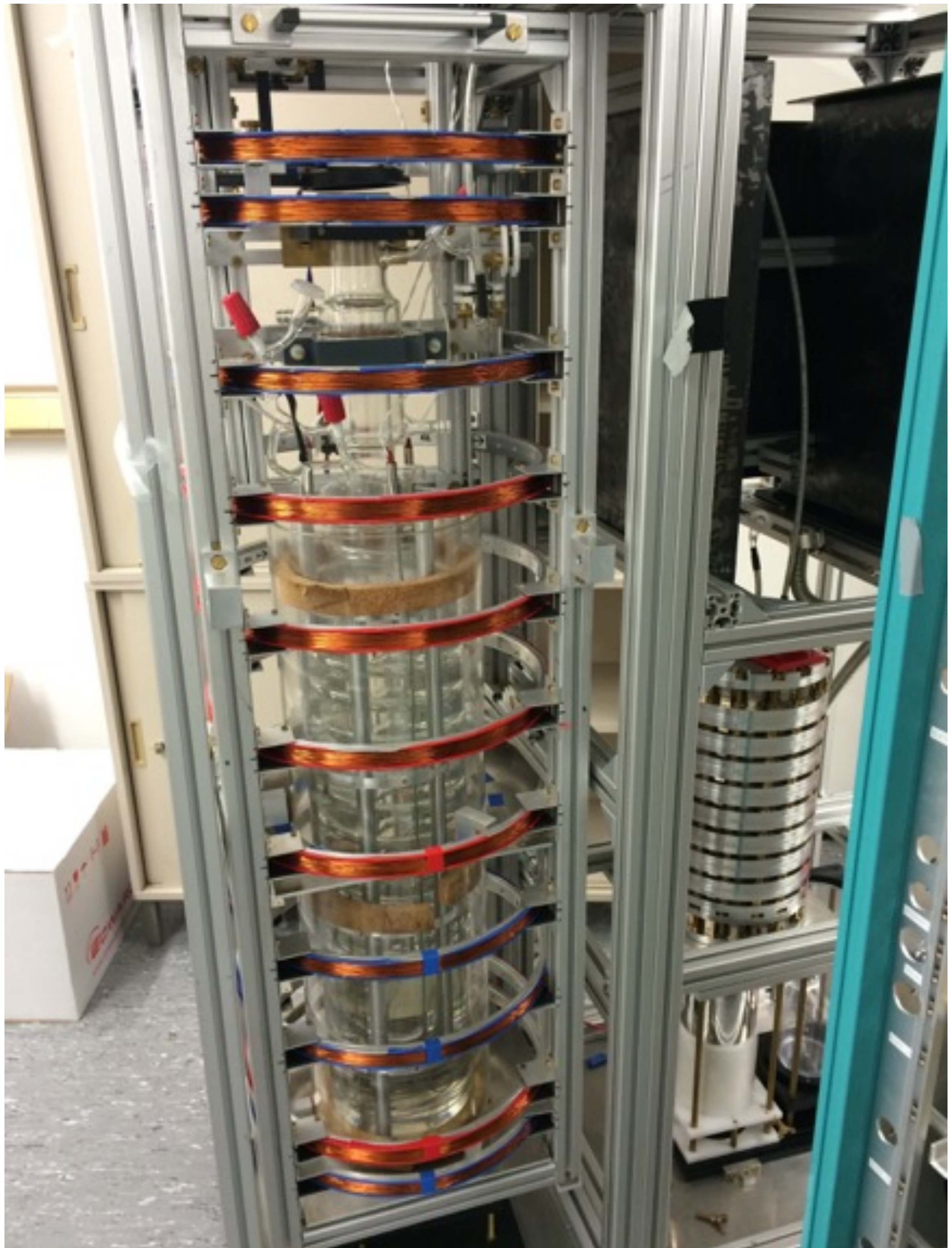
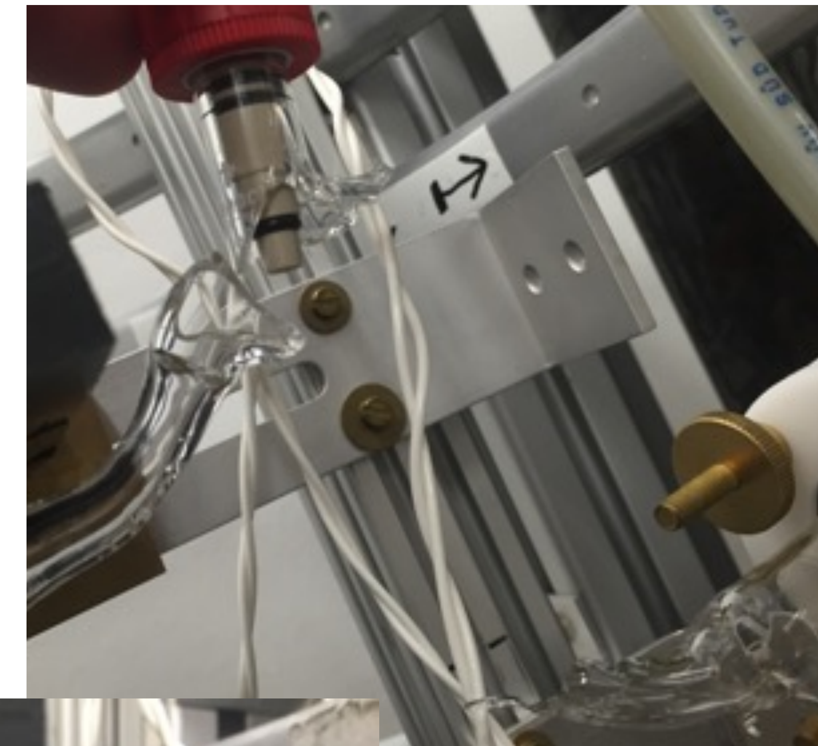
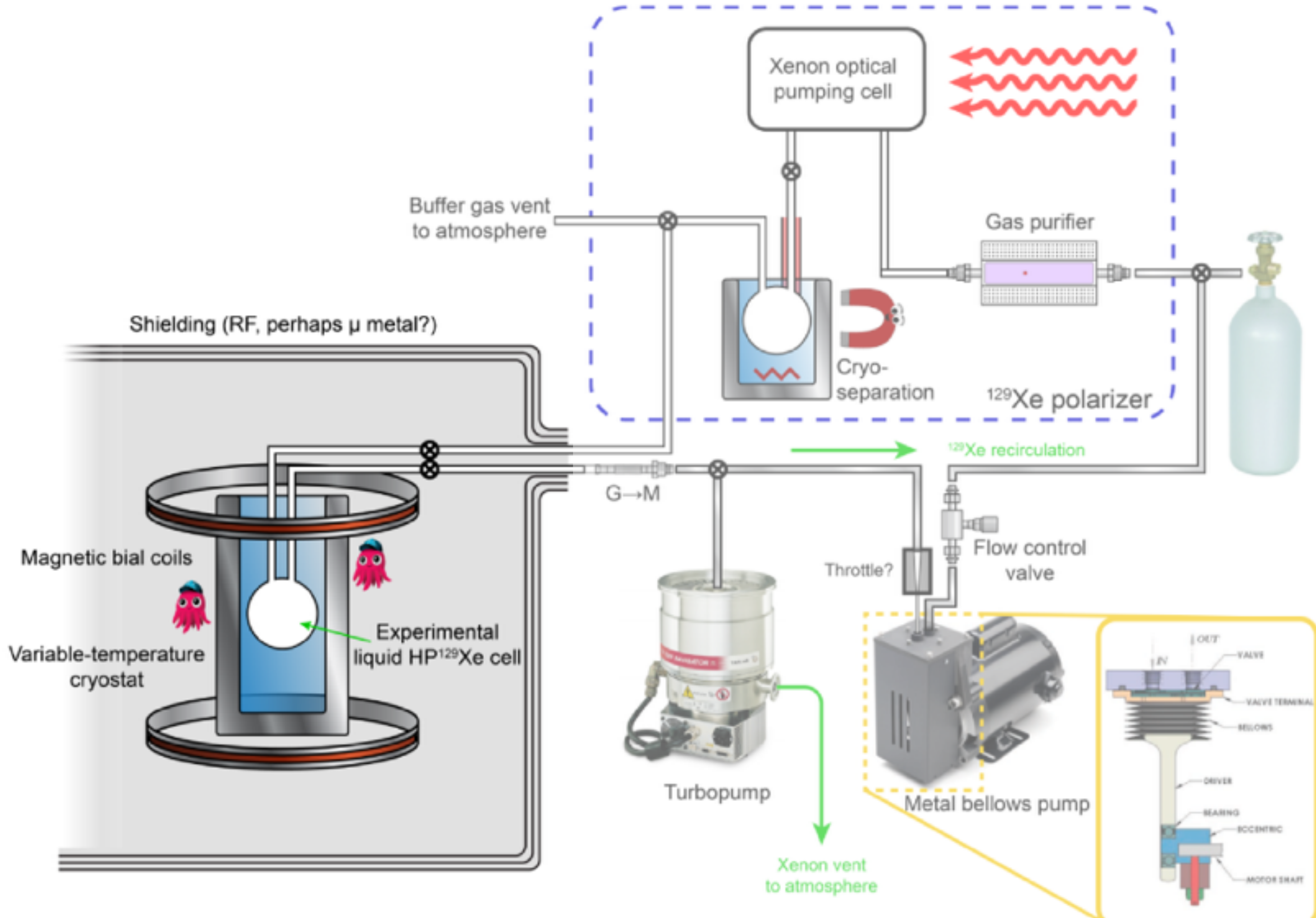
Mainz Xe Polarizer



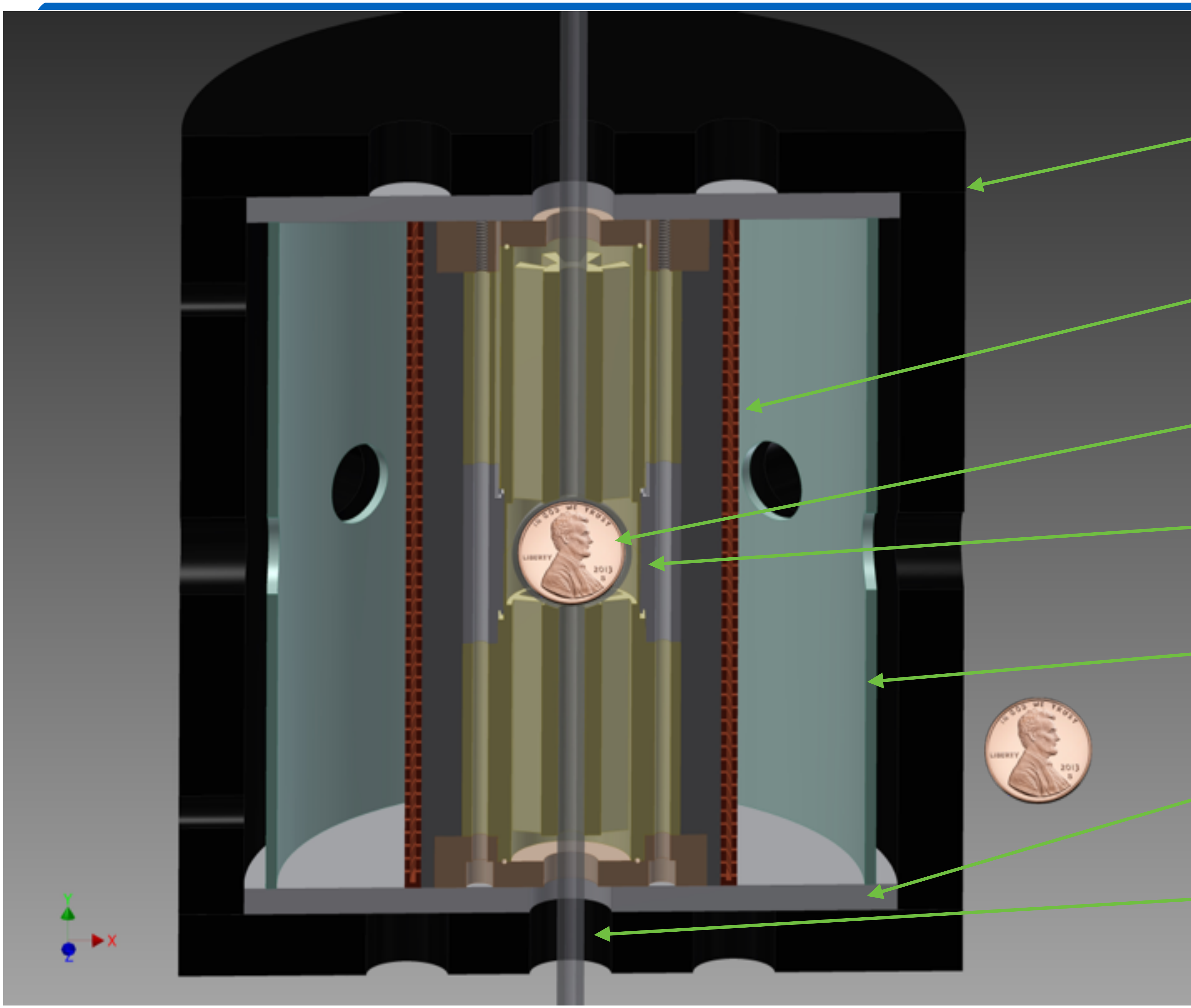


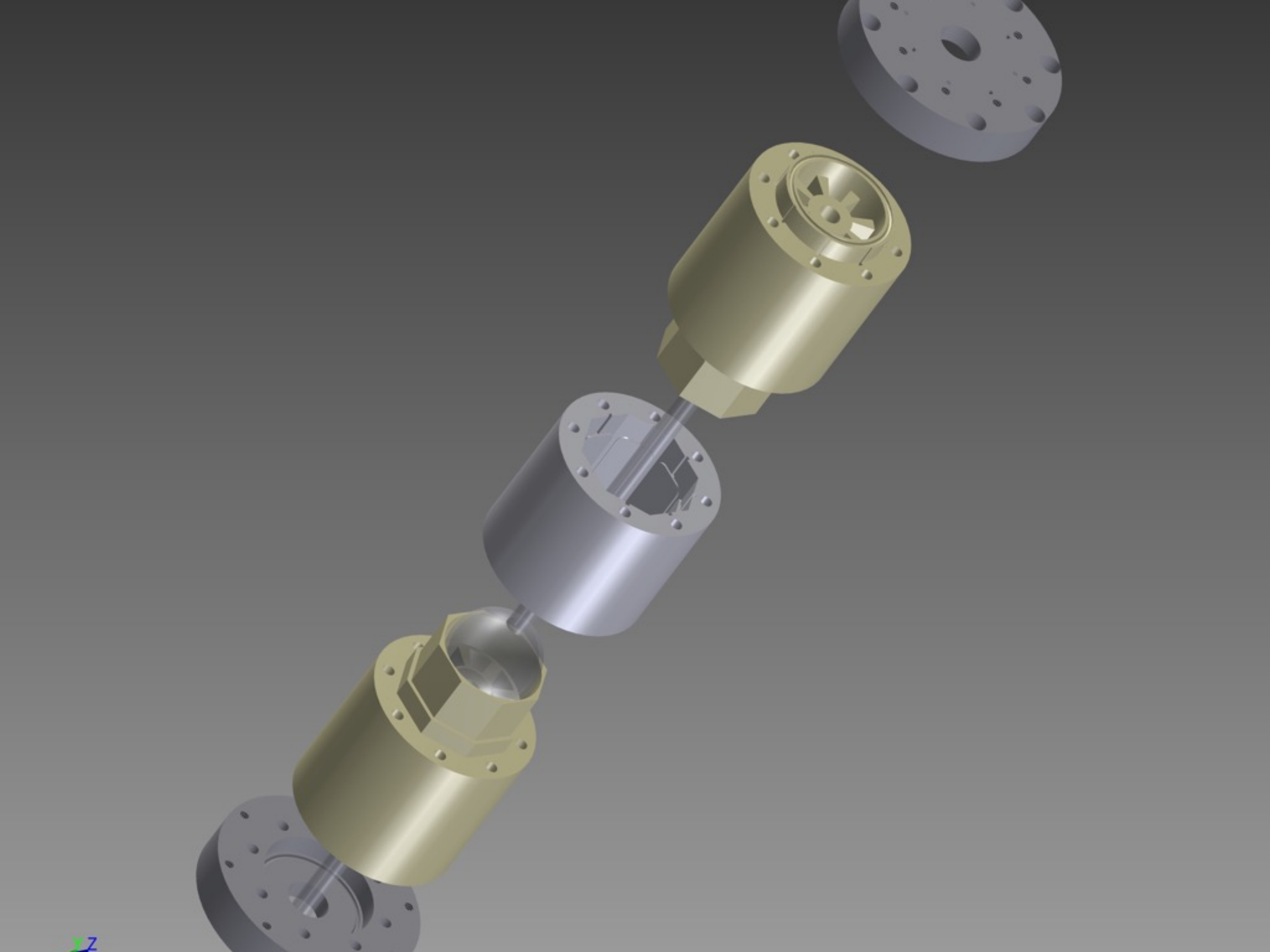
CASPEr-Wind



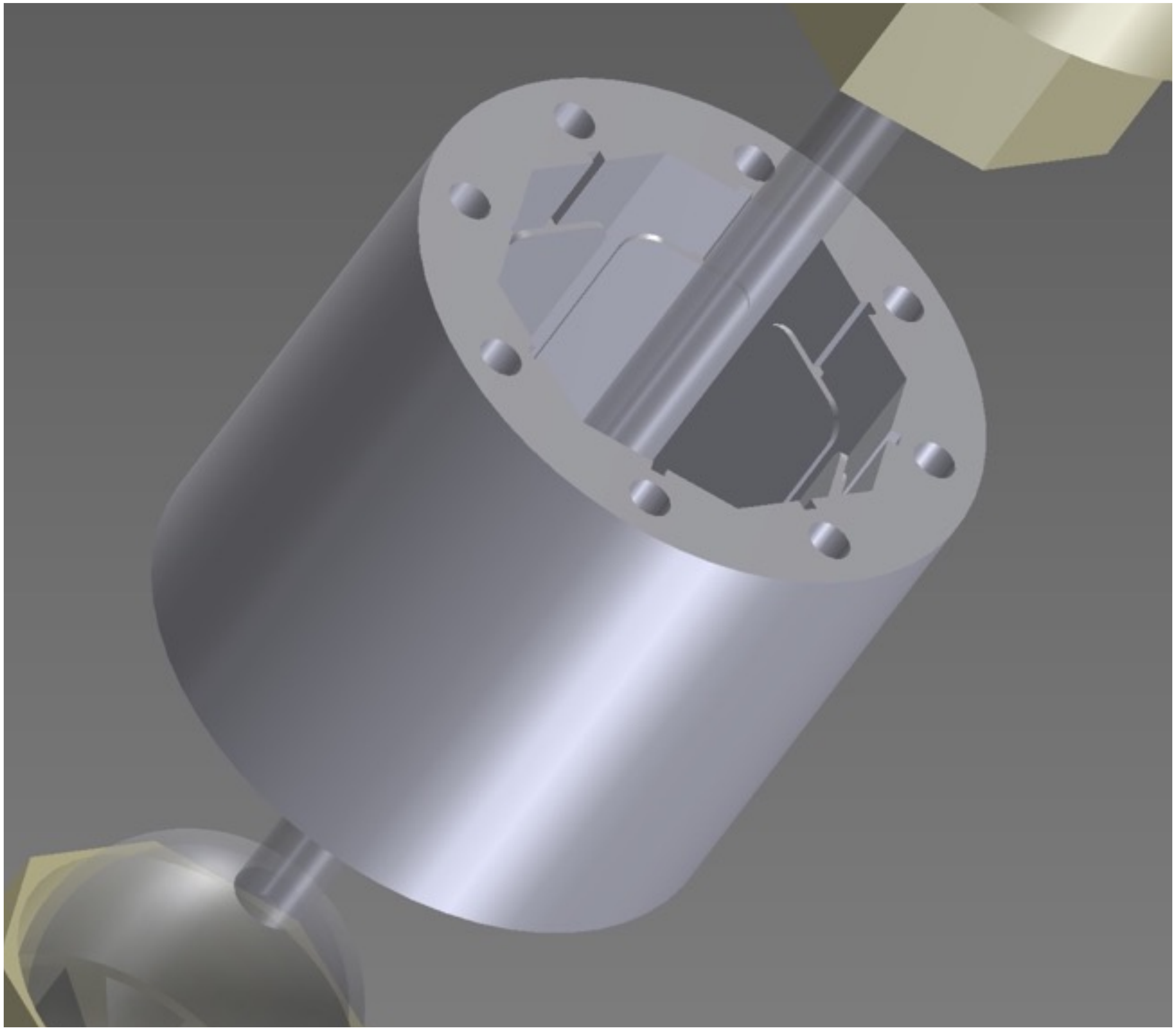
Xenon optical pumping cell
Buffer gas vent to atmosphere
Gas purifier
Shielding (RF, perhaps μ metal?)
Cryo-separation
129Xe polarizer
129Xe recirculation
G→M
Magnetic bial coils
Throttle?
Flow control valve
Experimental liquid HP129Xe cell
Variable-temperature cryostat
Turbopump
Metal bellows pump
Xenon vent to atmosphere

Low-Field CASPEr-Wind





Low-Field CASPEr-Wind



- Simple design
- 3D printed prototypes will arrive … tomorrow …
- Rough design — if you know about SQUIDs, please point out our mistakes!

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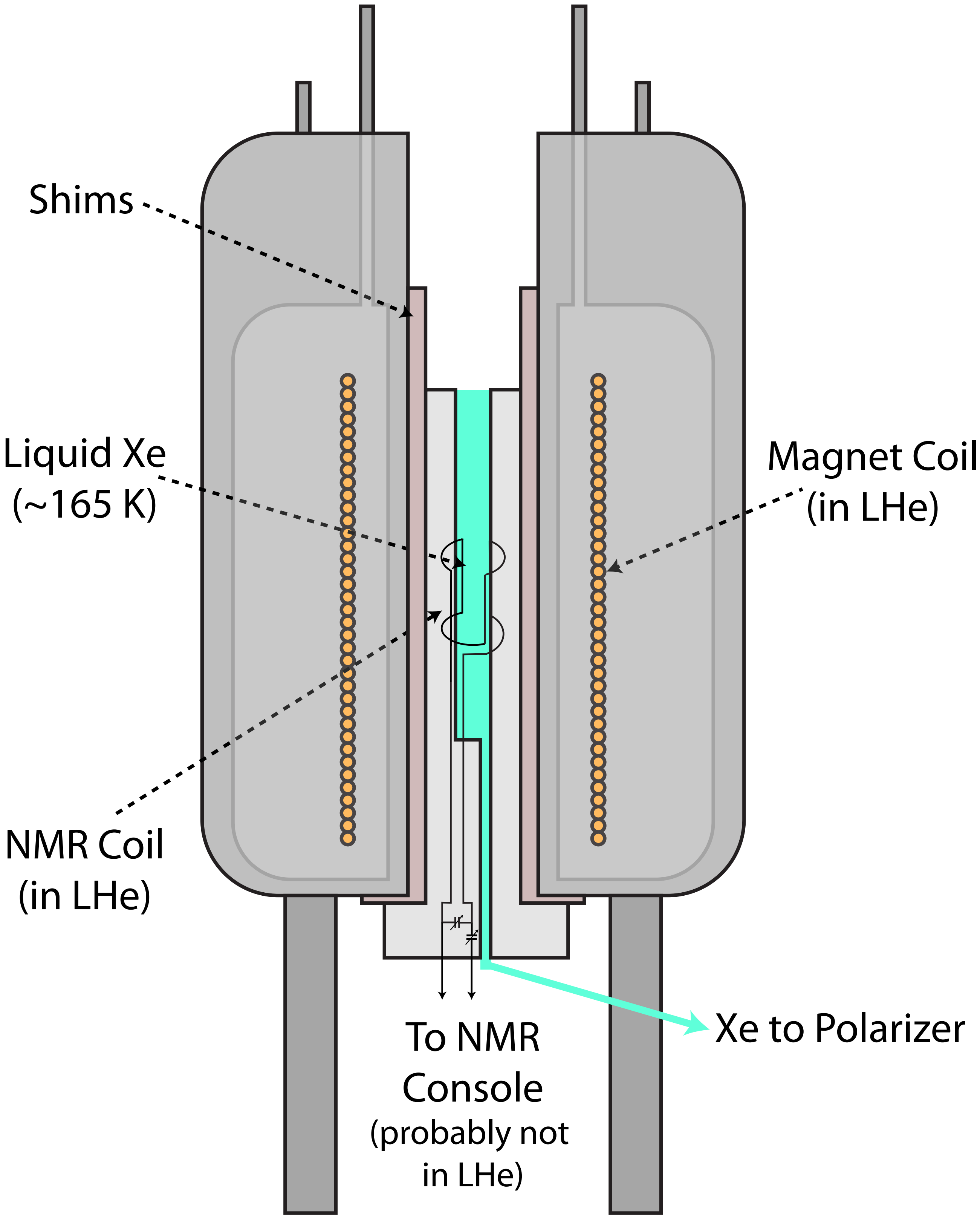
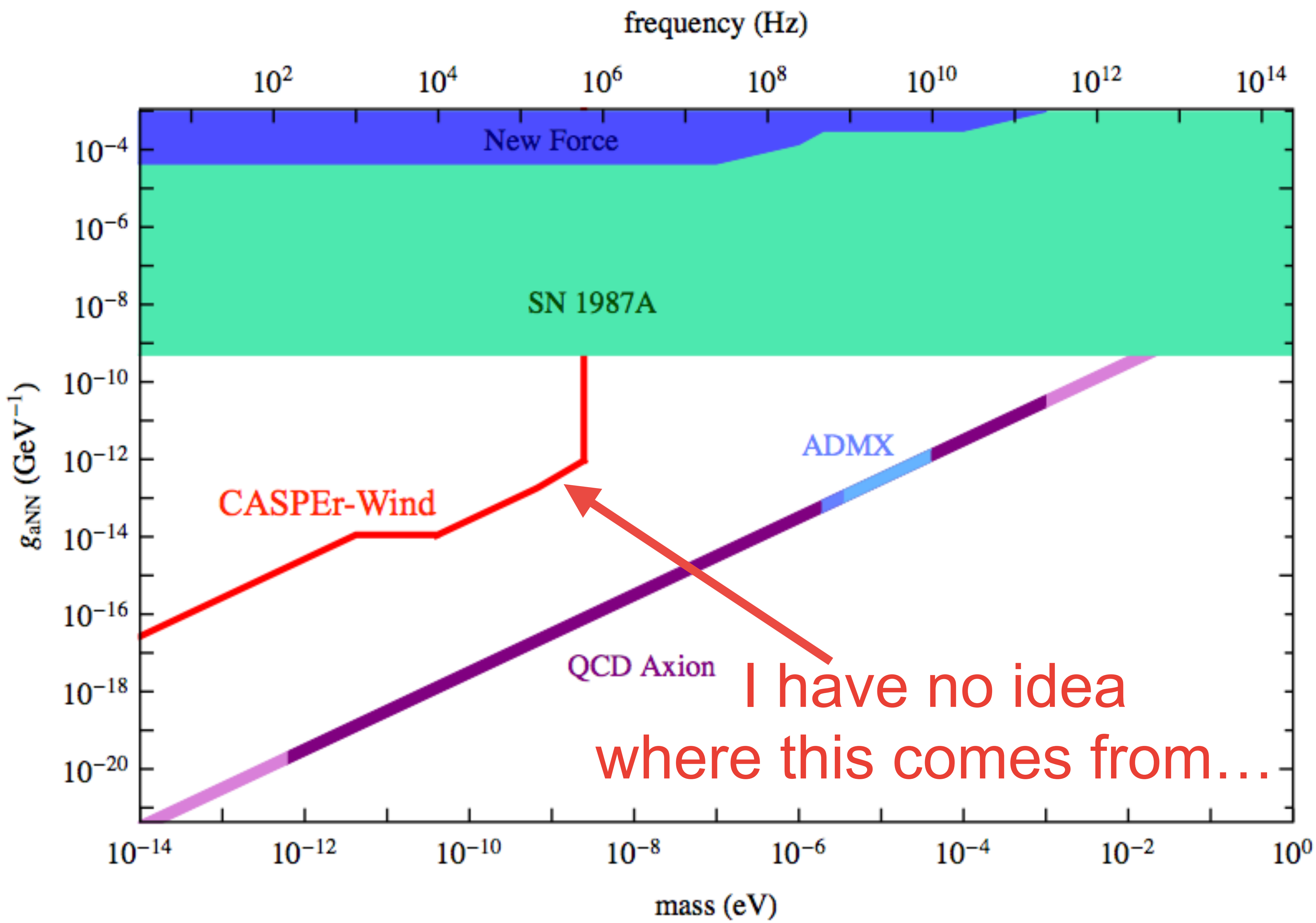
High-Field CASPEr-Wind



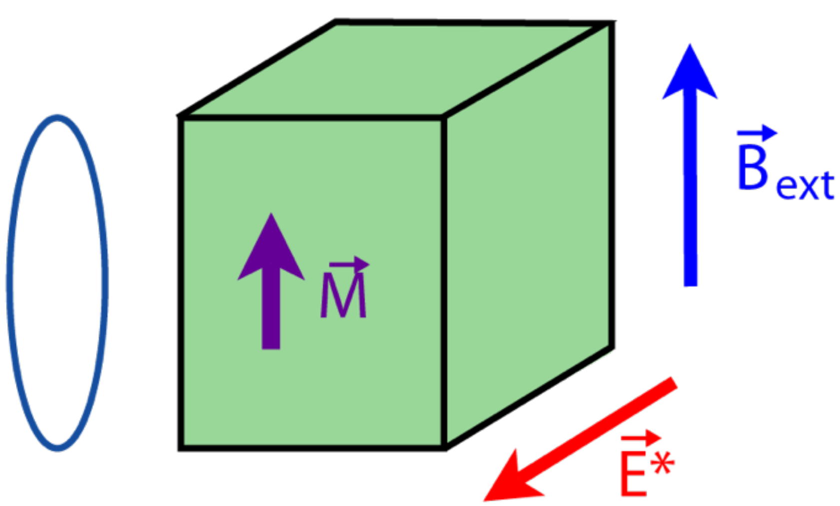
- Commercially available
- Highest detector sensitivity
- Expensive

CASPEr-Wind



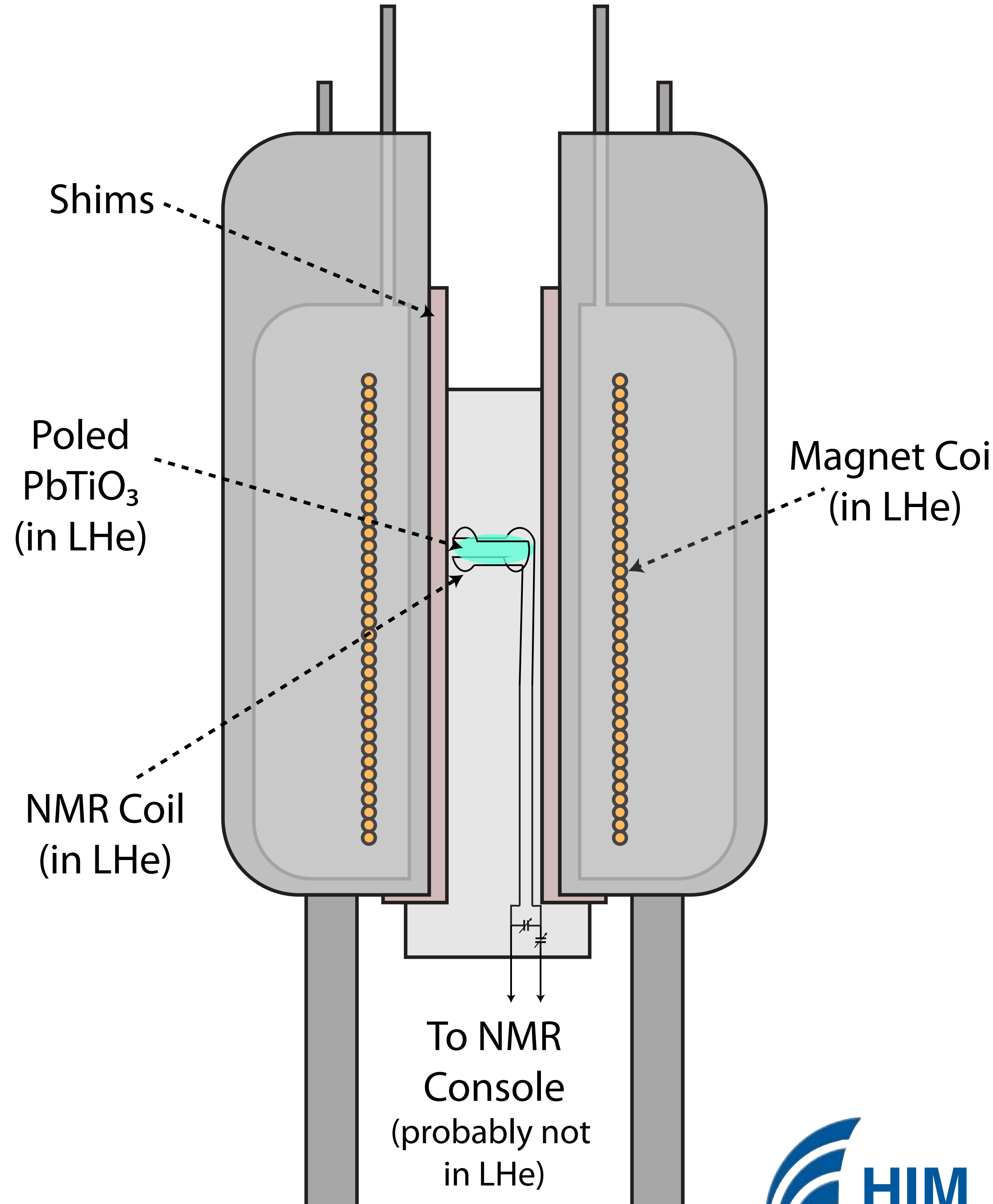
frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
New Force
SN 1987A
ADMX
CASPEr-Wind
QCD Axion
g_{aNN} (GeV^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
mass (eV)
I have no idea
where this comes from…

High-Field CASPEr-Electric



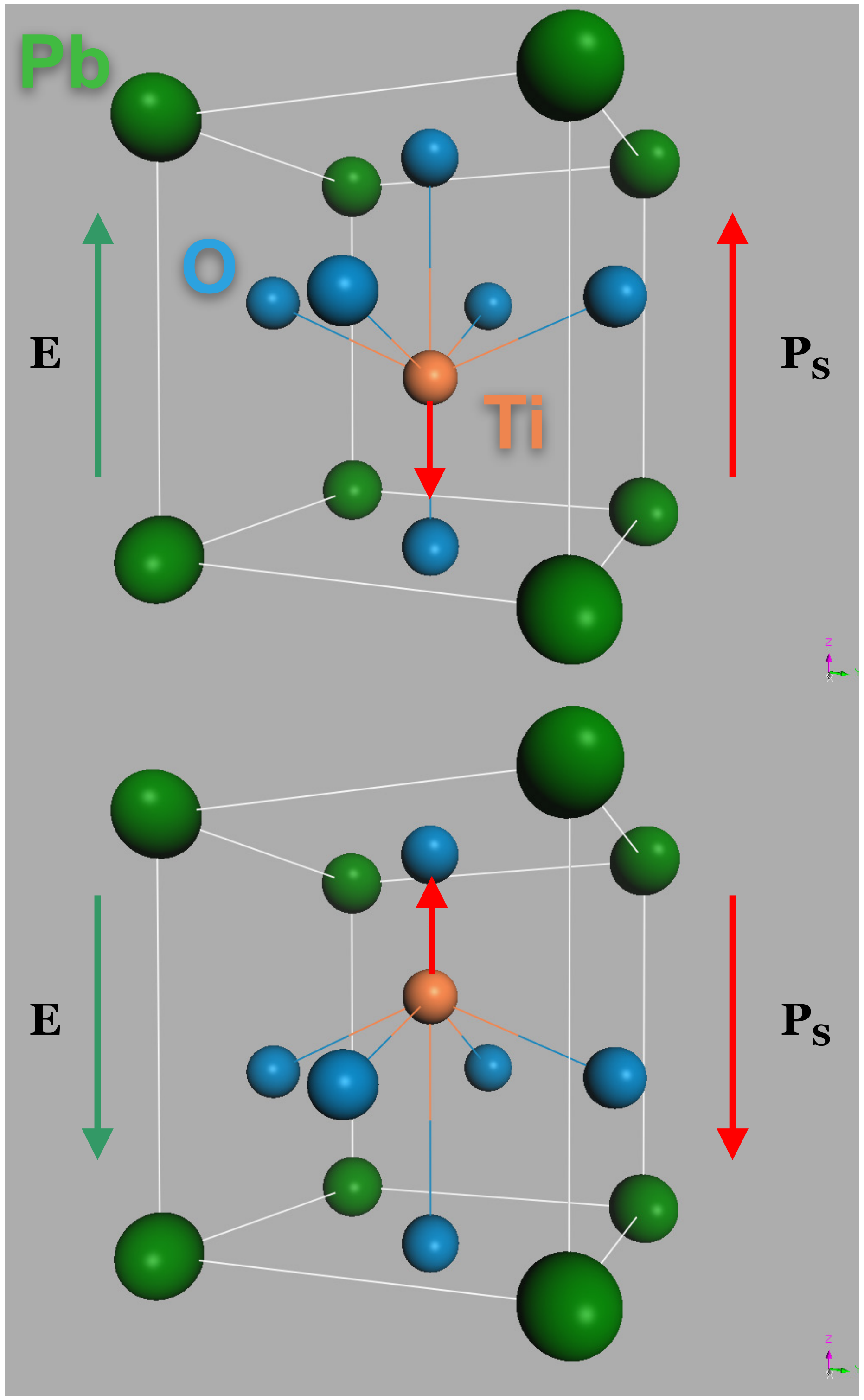
- Just add electric field! (basically the same experiment)

- Primary challenge: ***find an appropriate sample***



^{207}Pb in Ferroelectrics

- Huge effective electric field ($\sim 3 \times 10^{8}$ V/cm)
- ^{207}Pb
  - 22.6% natural abundance
  - $\gamma_{Pb}/\gamma_{H} \approx 1/5$ (104.6 MHz at 11.74 T)
- But T_1 is long, and T_2 is short
- And then there's the linewidth…



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^{207}Pb in Ferroelectrics

PHYSICAL REVIEW B, VOLUME 63, 024104

^{207}Pb NMR study of the relaxor behavior in $PbMg_{1/3}Nb_{2/3}O_3$

R. Blinc, A. Gregorovič, B. Zalar, and R. Pirc
Jožef Stefan Institute, P.O. Box 3000, 1001 Ljubljana, Slovenia

V. V. Laguta and M. D. Glinchuk
Institute for Material Sciences, Ukrainian Academy of Sciences, 03142 Kiev, Ukraine

)N

Solid State Communications 115 (2000) 95–98

www.elsevier.c

Variable temperature ^{207}Pb NMR of $PbTiO_3$

D.A. Bussian, G.S. Harbison*

Department of Chemistry, University of Nebraska-Lincoln, 508 Hamilton Hall, Lincoln, NE 68588-0304, USA

SUPER BROAD RESONANCES

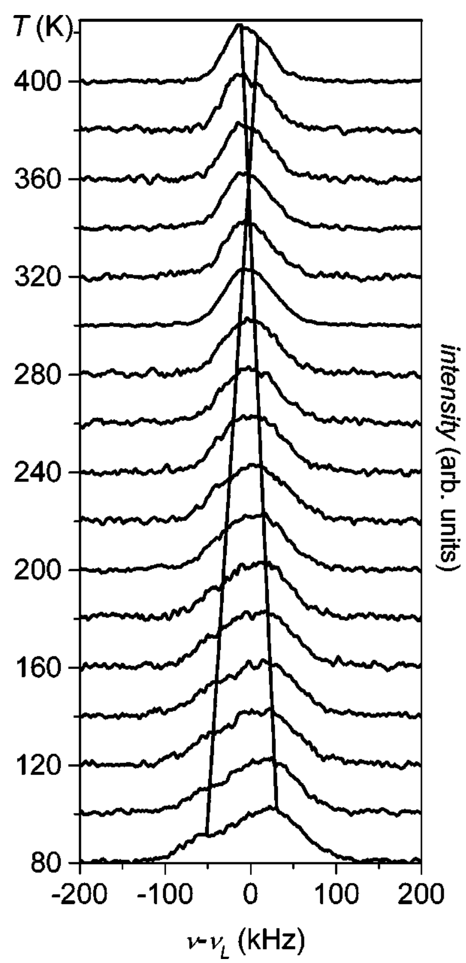

FIG. 3. Temperature dependence of ^{207}Pb NMR lineshape in PMN for the orientation $[001]\|\vec{B}_0$.

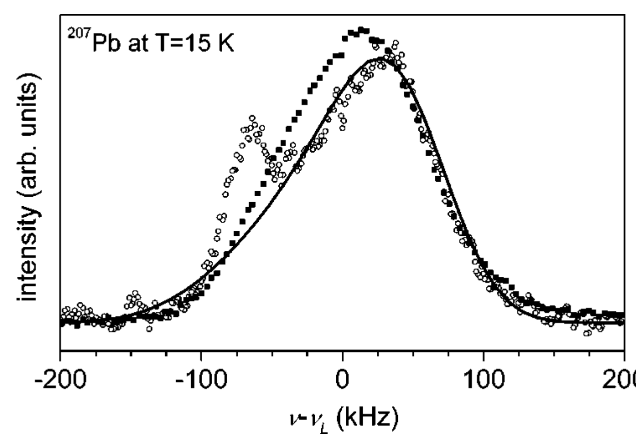

FIG. 5. NMR ^{207}Pb line shape at the orientations $[001]||B_0$ (open circles) and $[011]||B_0$ (solid squares) at the temperature 15 K.

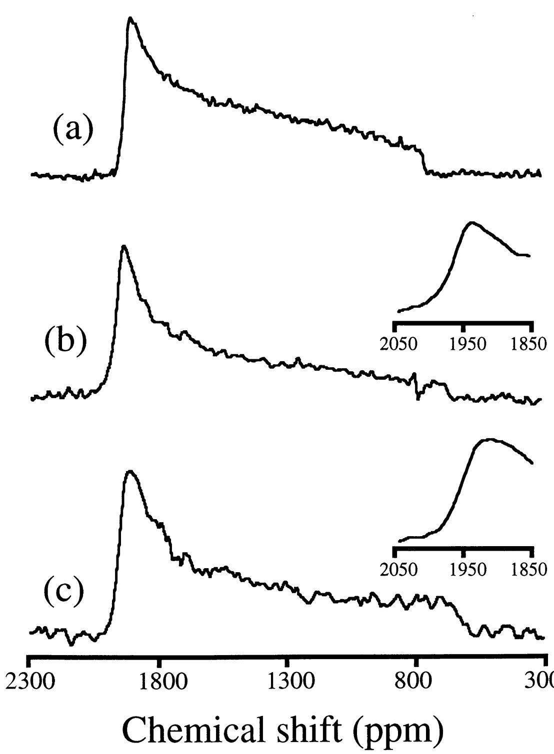

Fig. 1. ^{207}Pb NMR powder spectra of $PbTiO_3$: (a) at 25°C; (b) at −100°C; (c) at −150°C. An expanded view of the perpendicular edges of the two lower temperature spectra are shown in the inset.

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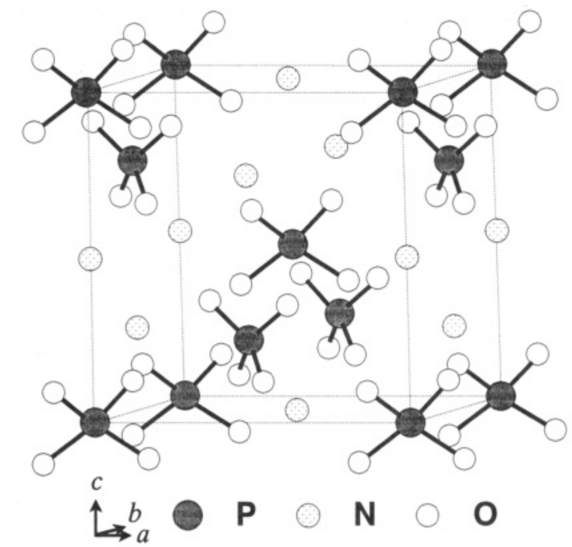
Single Crystal vs. Sintered Powder

3108 J. Phys. Chem. 1994, 98, 3108–3113

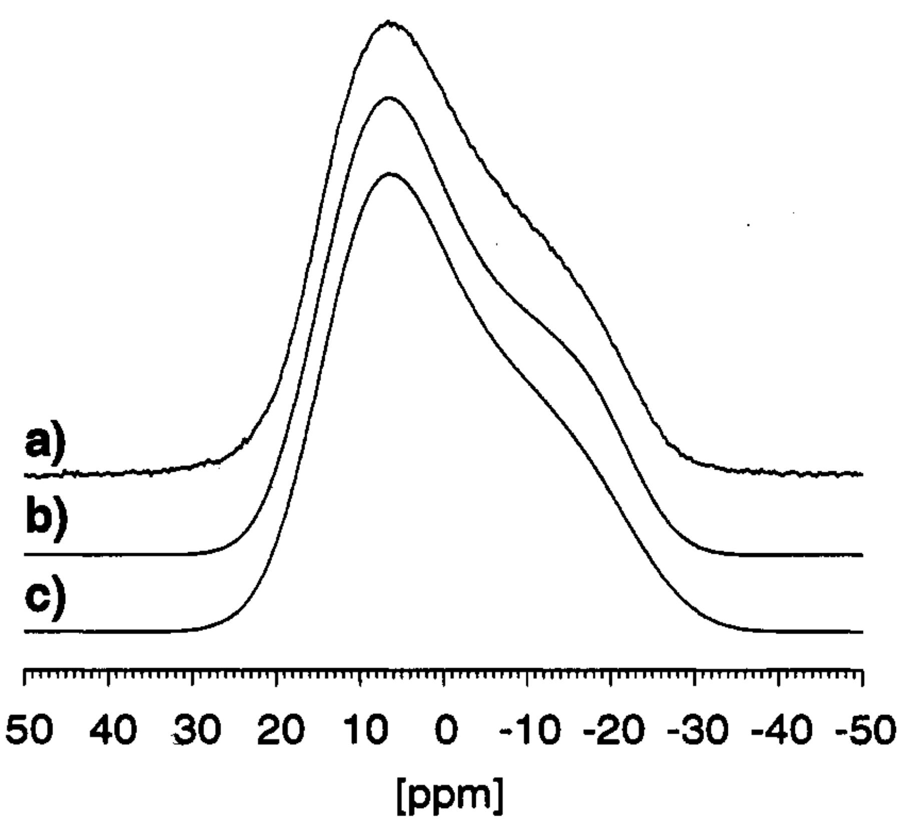
^{31}P NMR Study of Powder and Single-Crystal Samples of Ammonium Dihydrogen Phosphate: Effect of Homonuclear Dipolar Coupling

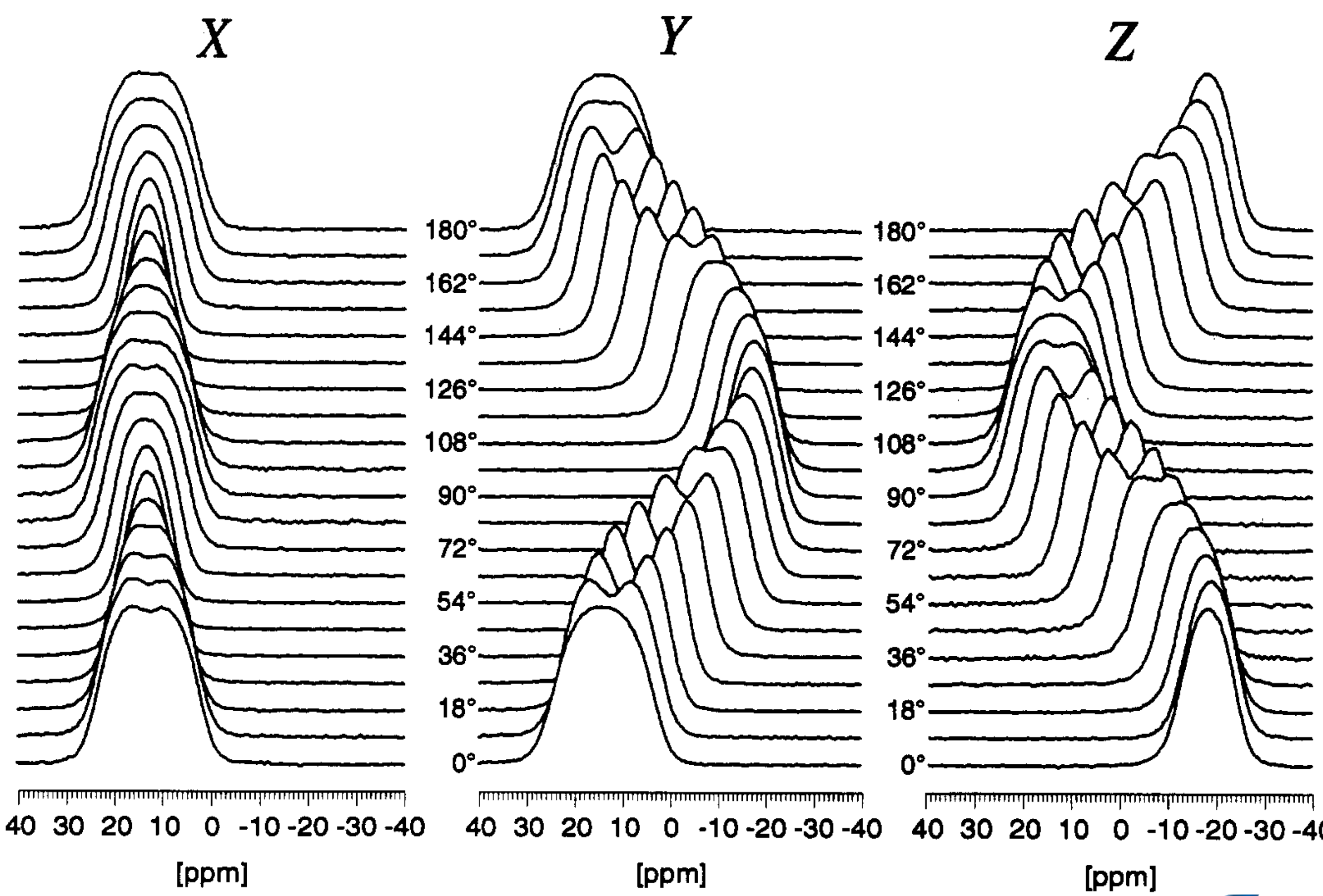
Klaus Eichele and Roderick E. Wasylishen*
Department of Chemistry, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J3



Single Crystal

Powder





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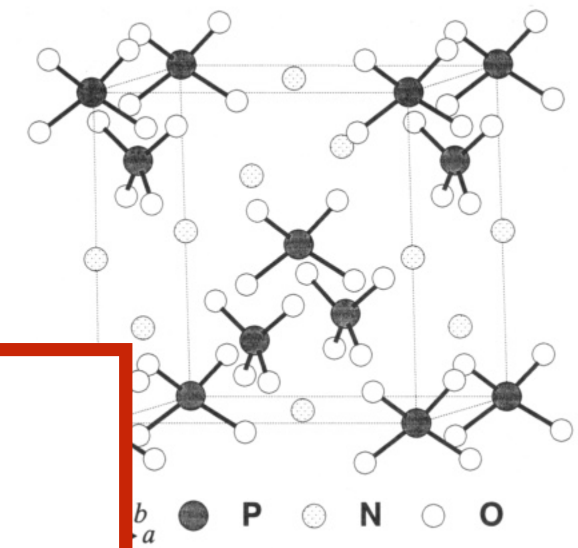
Single Crystal vs. Sintered Powder

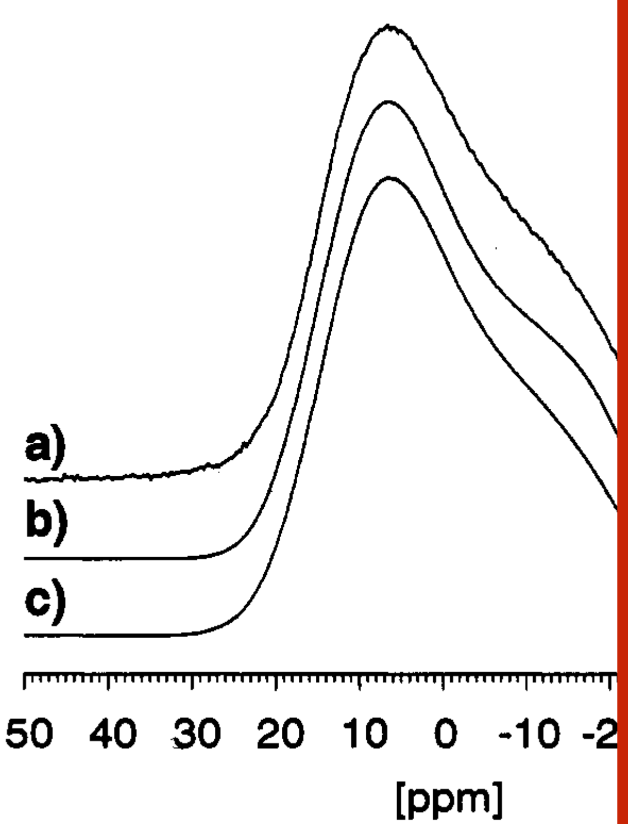
3108 *J. Phys. Chem.* **1994,** *98,* 3108–3113

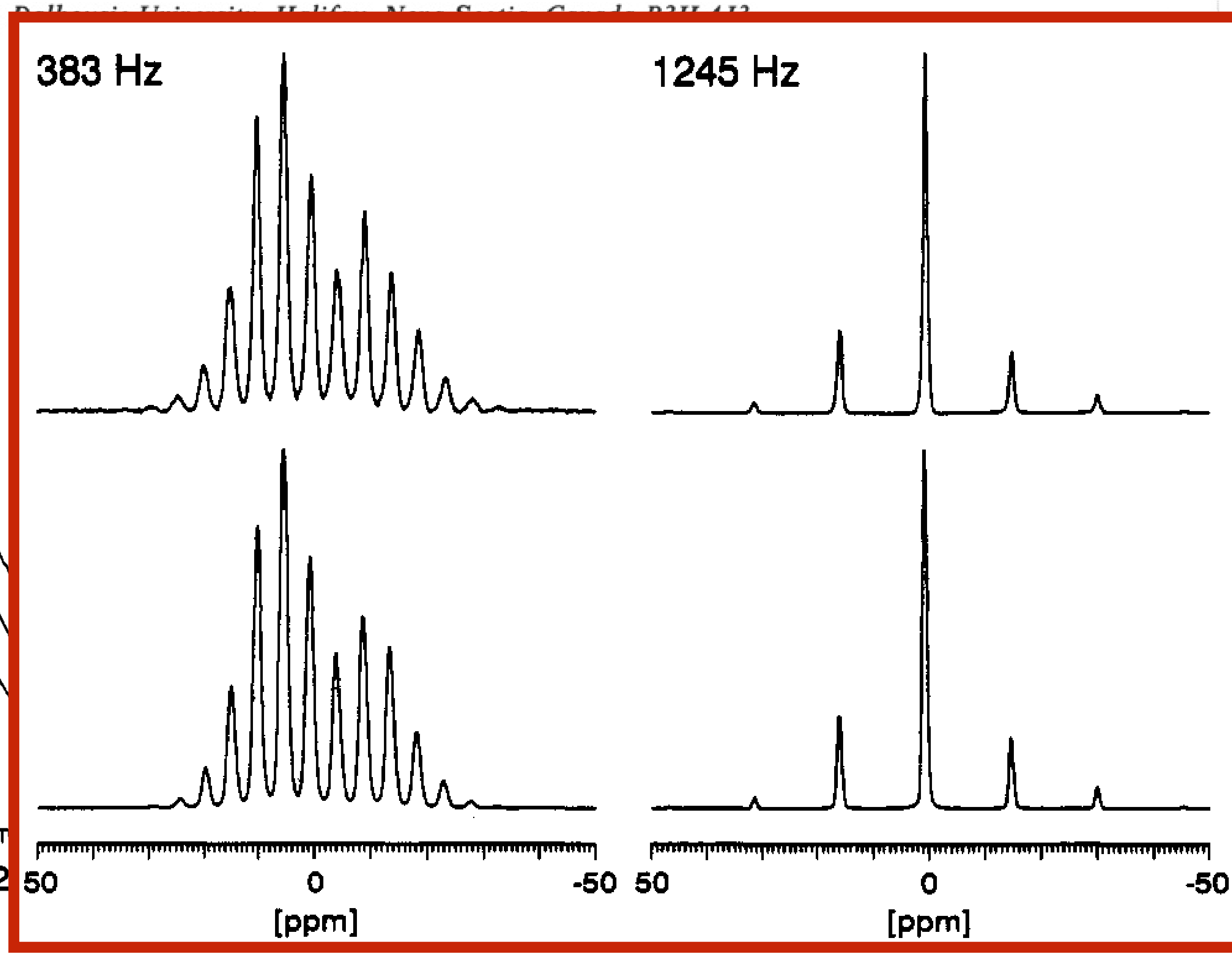
^{31}P NMR Study of Powder and Single-Crystal Samples of Ammonium Dihydrogen Phosphate: Effect of Homonuclear Dipolar Coupling

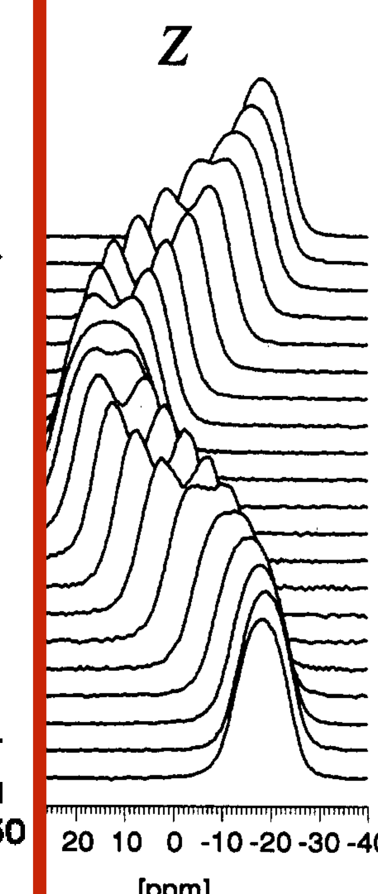
Klaus Eichele and Roderick E. Wasylishen*

Department of Chemistry,









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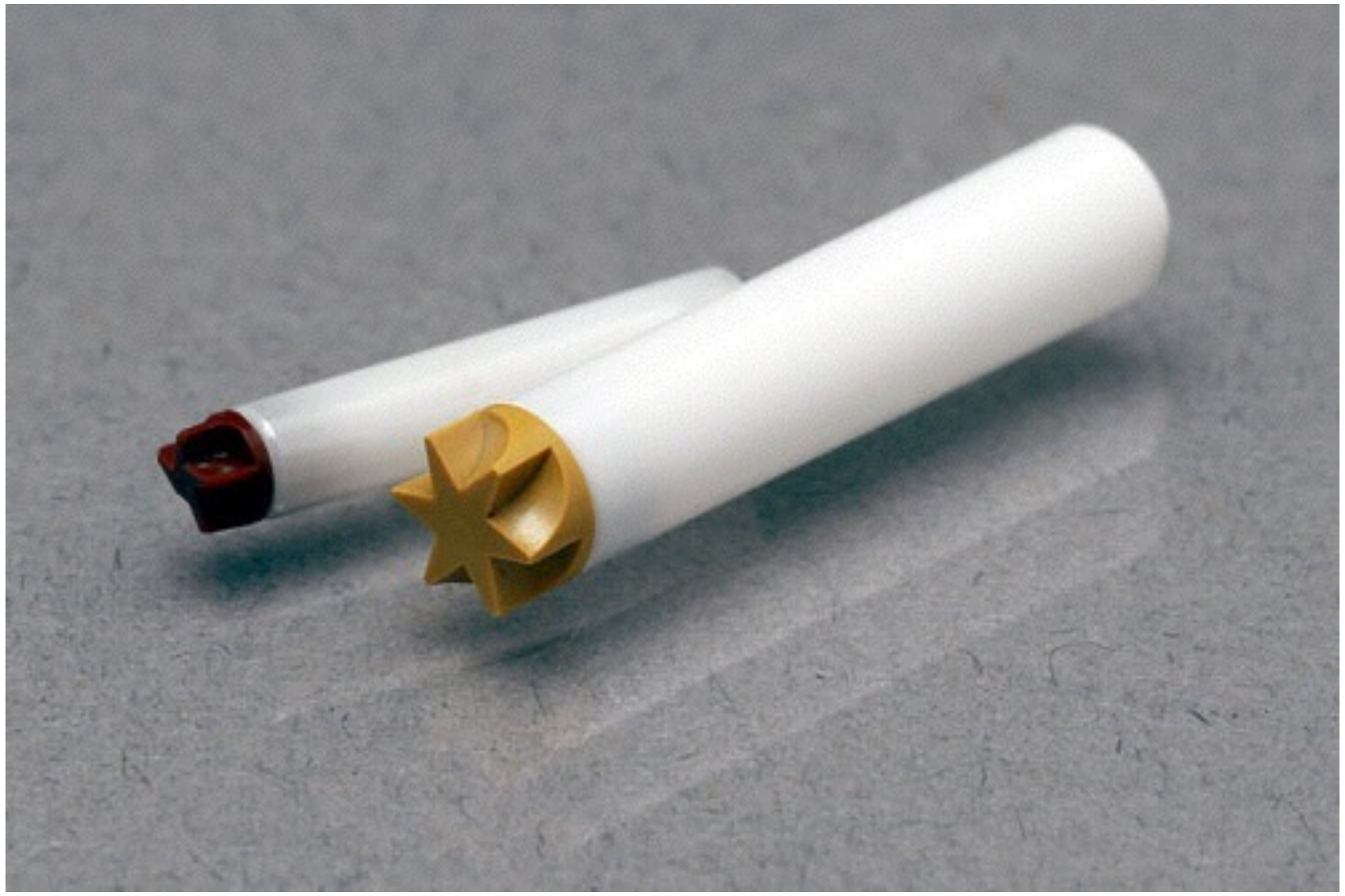
Machine a Ferroelectric Rotor?

- ✦ Maximum filling factor
- ✦ MAS = narrow lines
  - Decouple D-D coupling
  - Average out CSA



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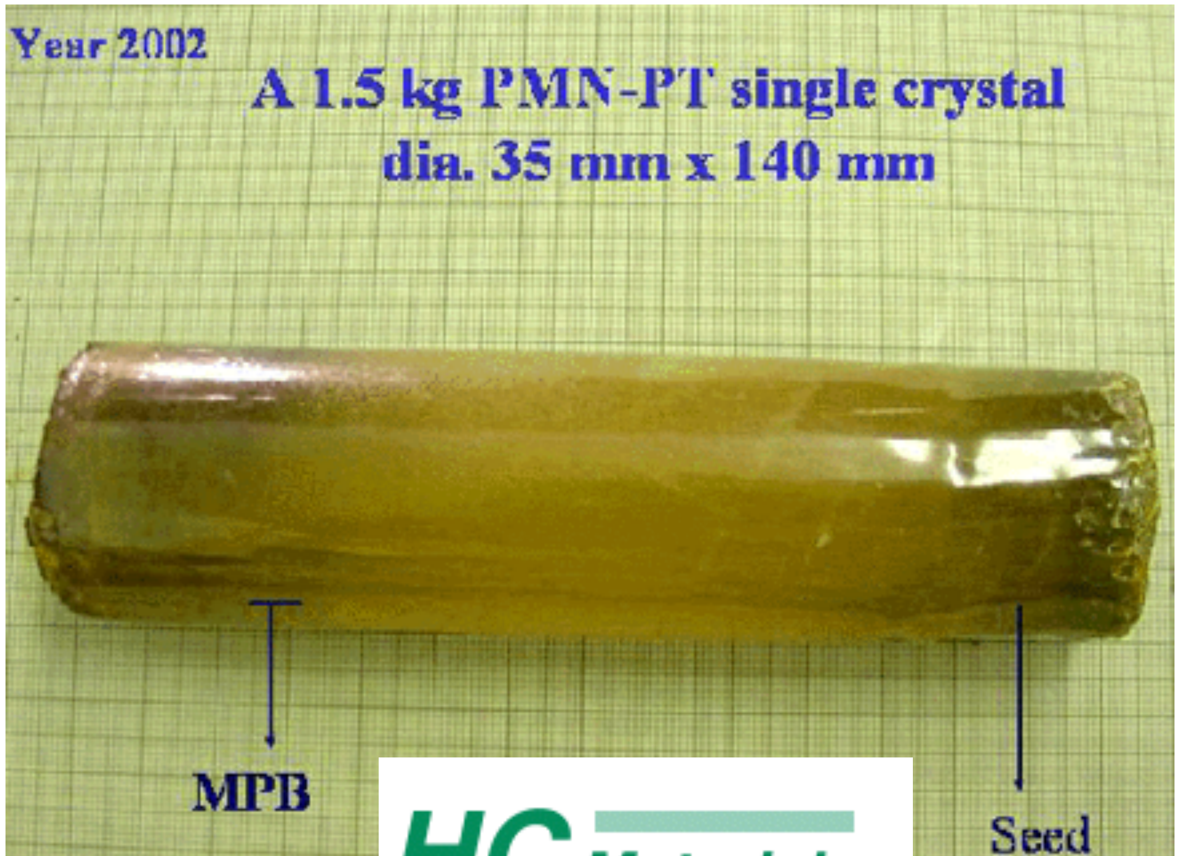
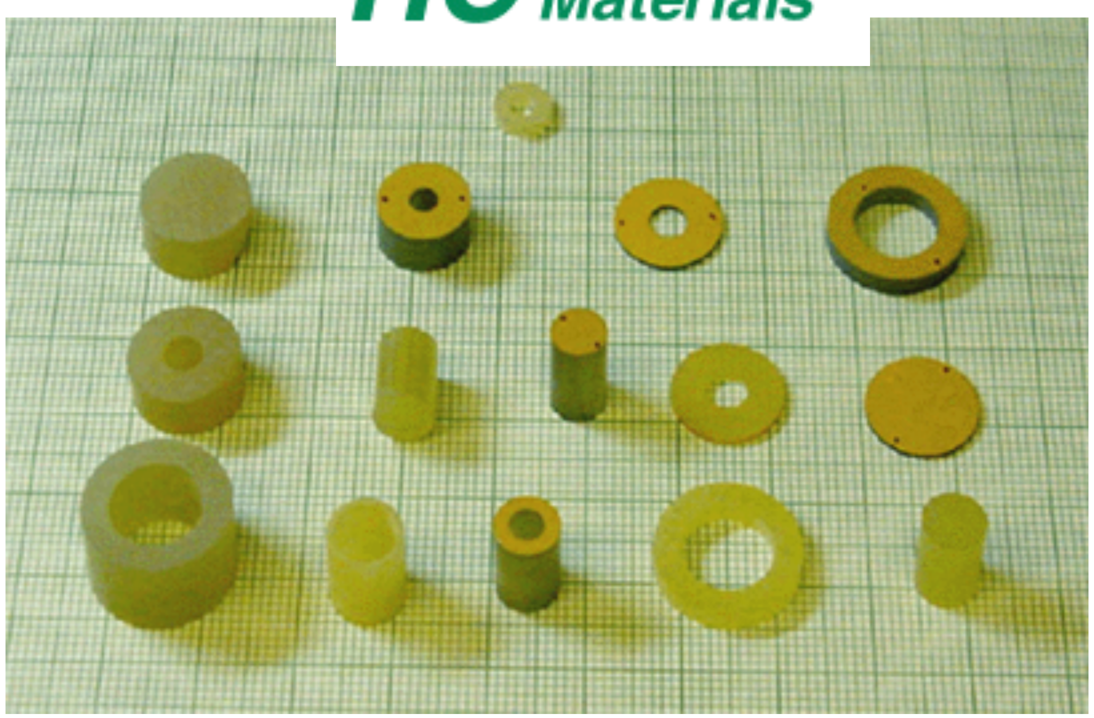
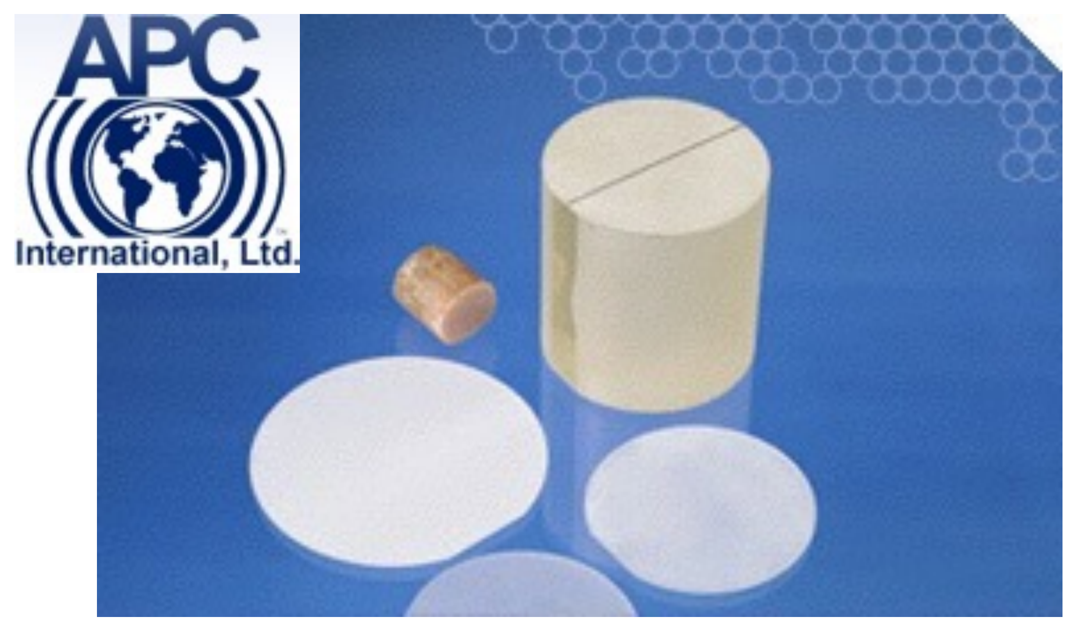
Single Crystal Suppliers



HC Materials



MICROFINE
MATERIALS TECHNOLOGIES PTE LTD



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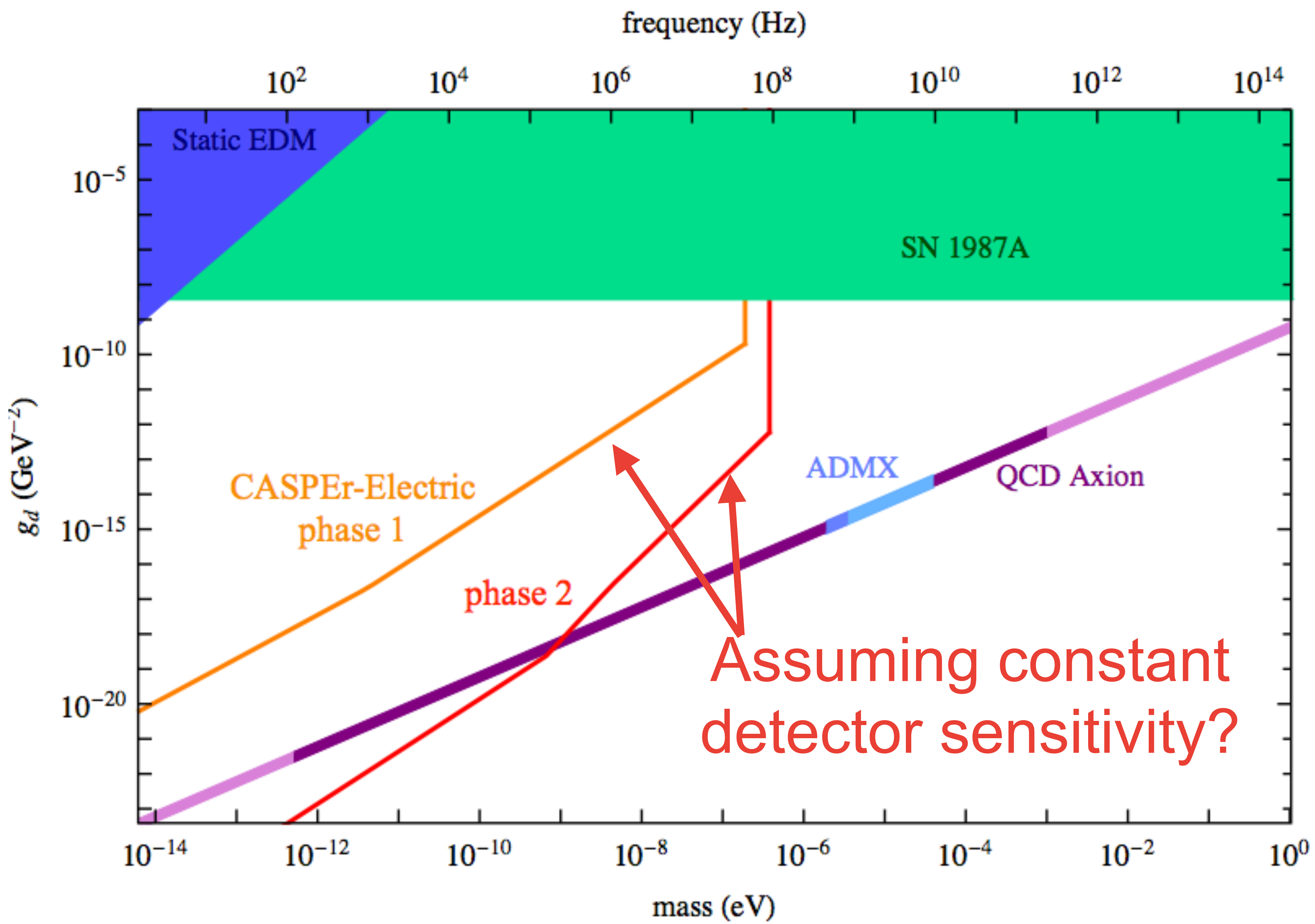
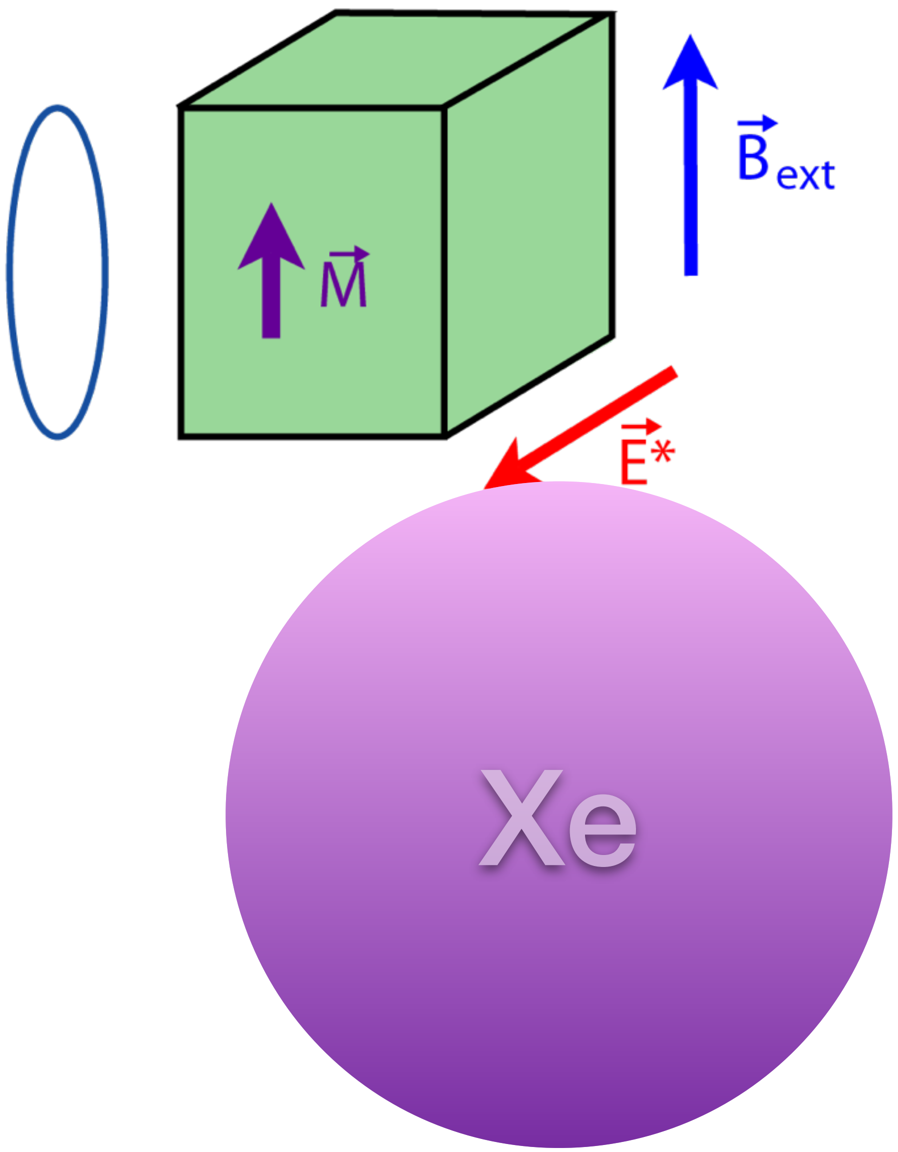
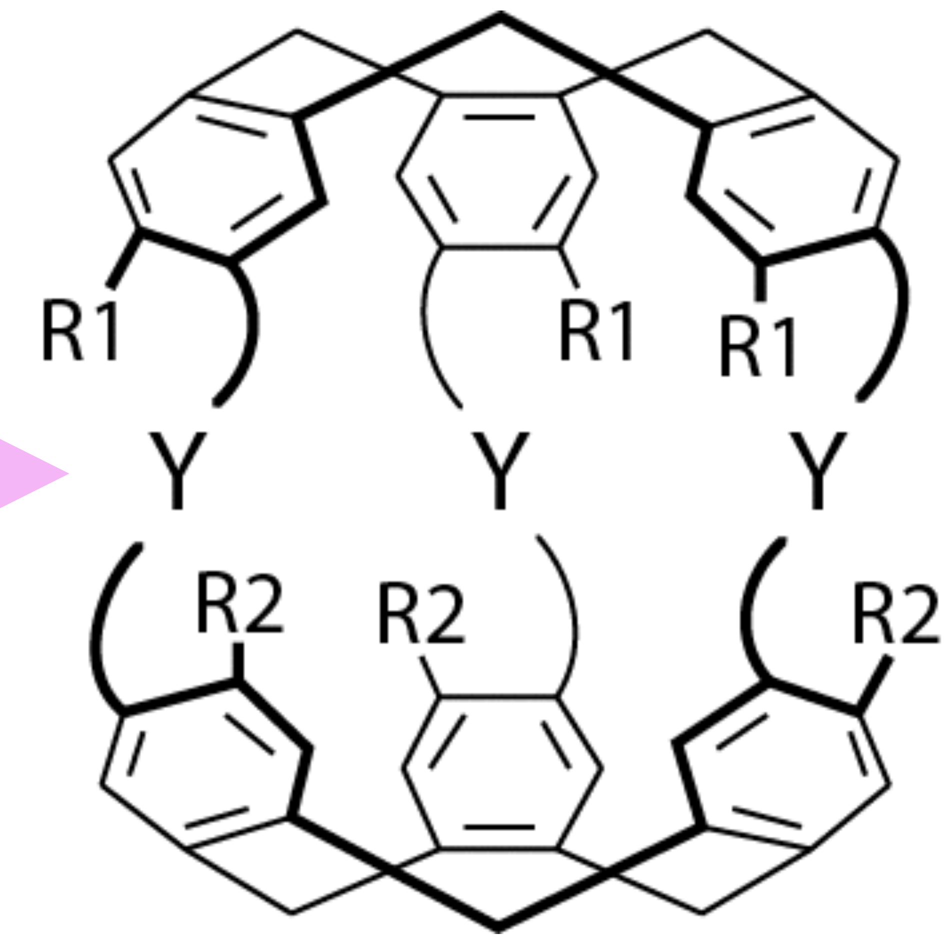
CASPEr-Electric



^{129}Xe in Polar Cages



But what about E Field?



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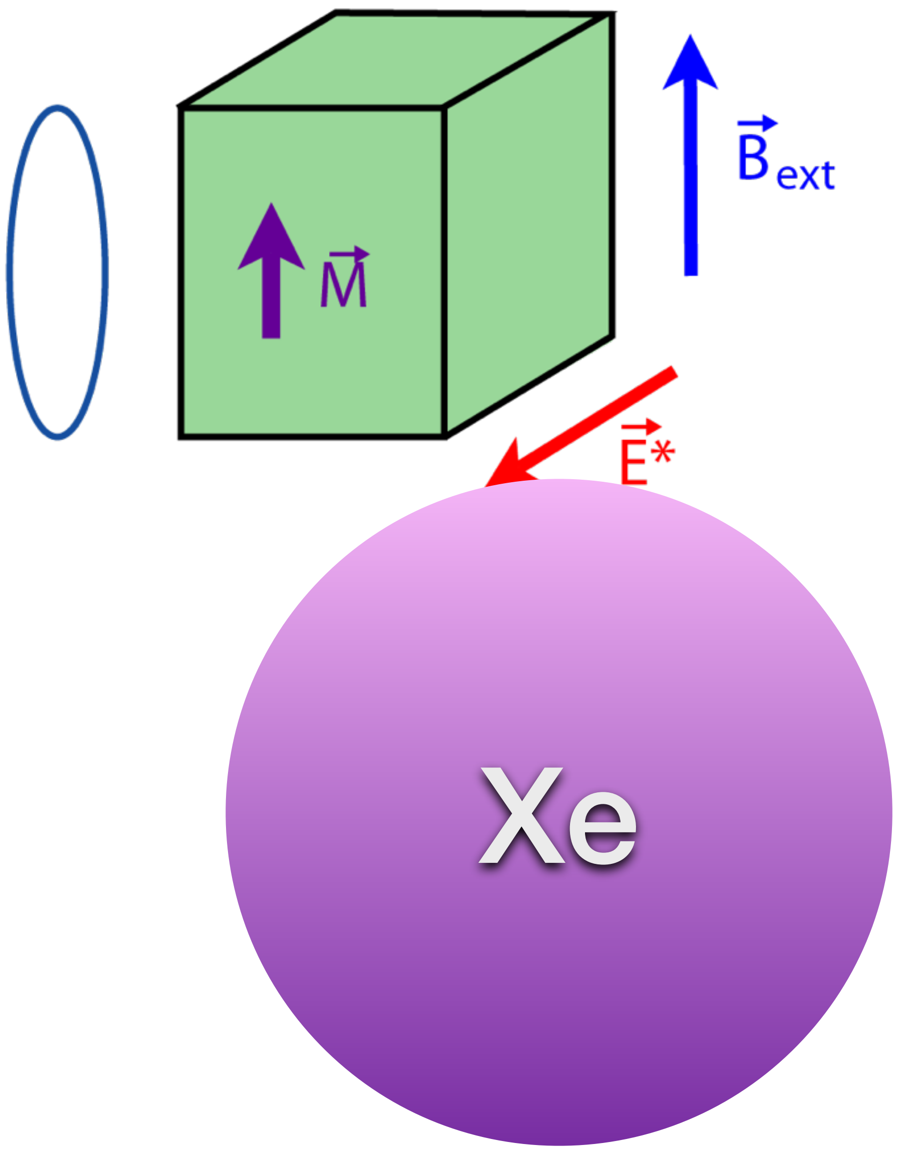

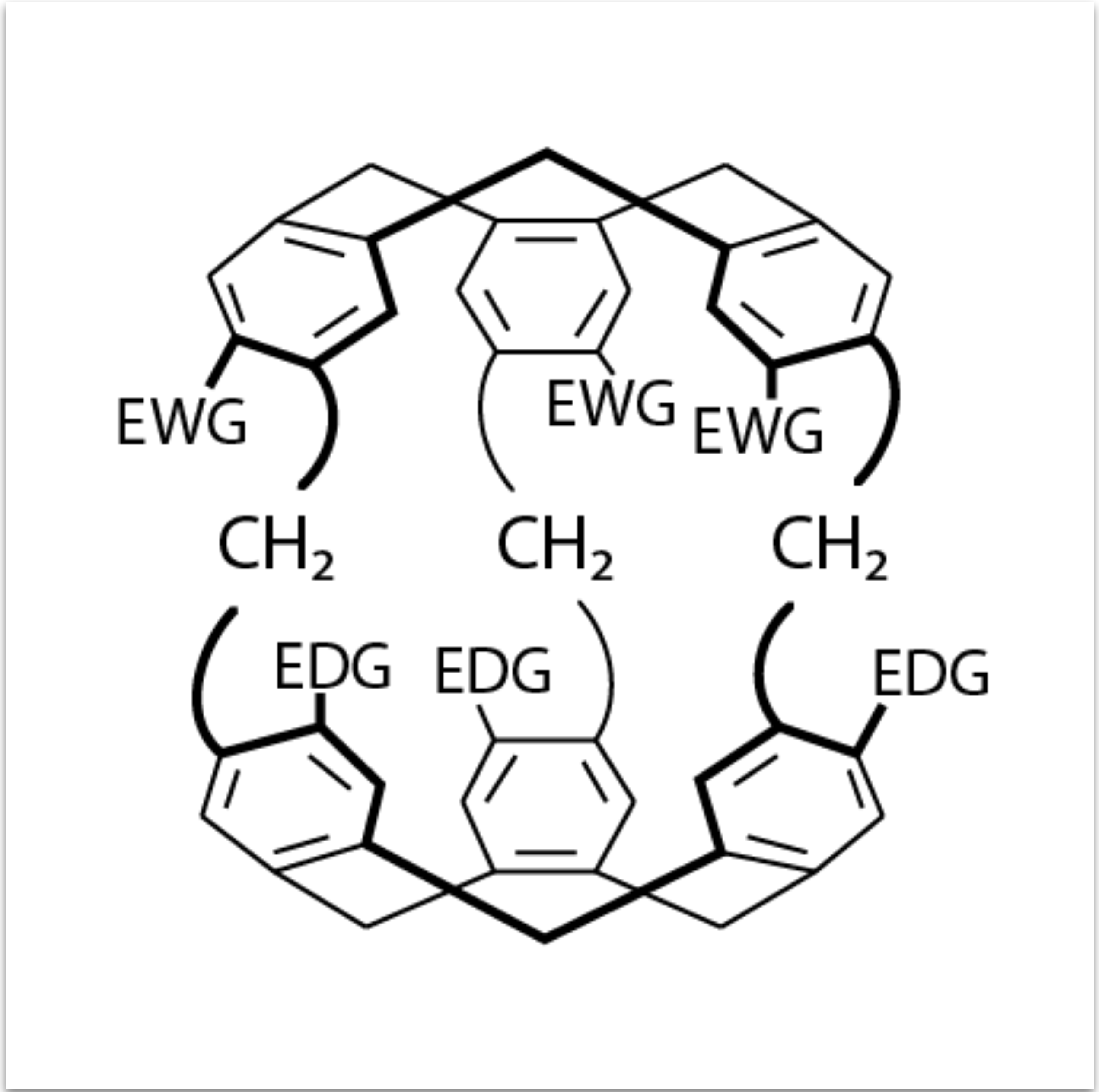

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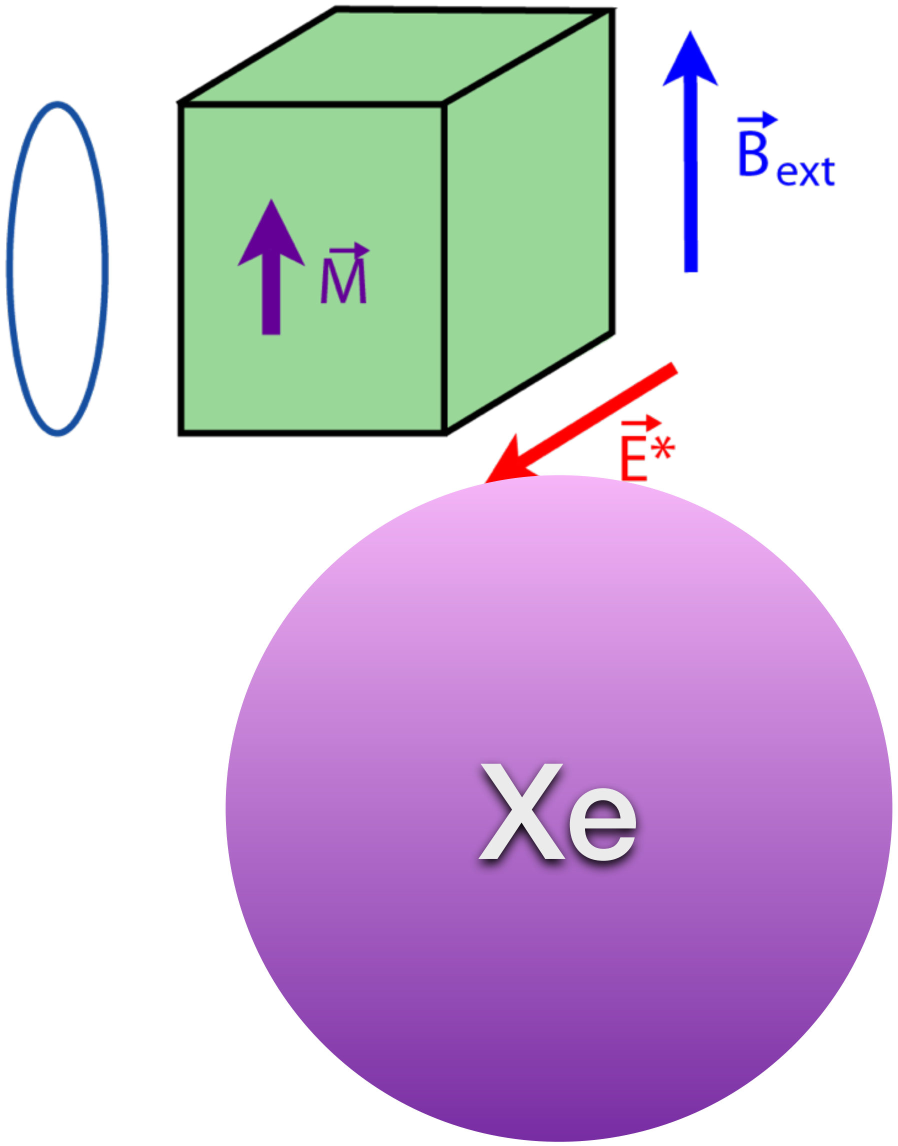

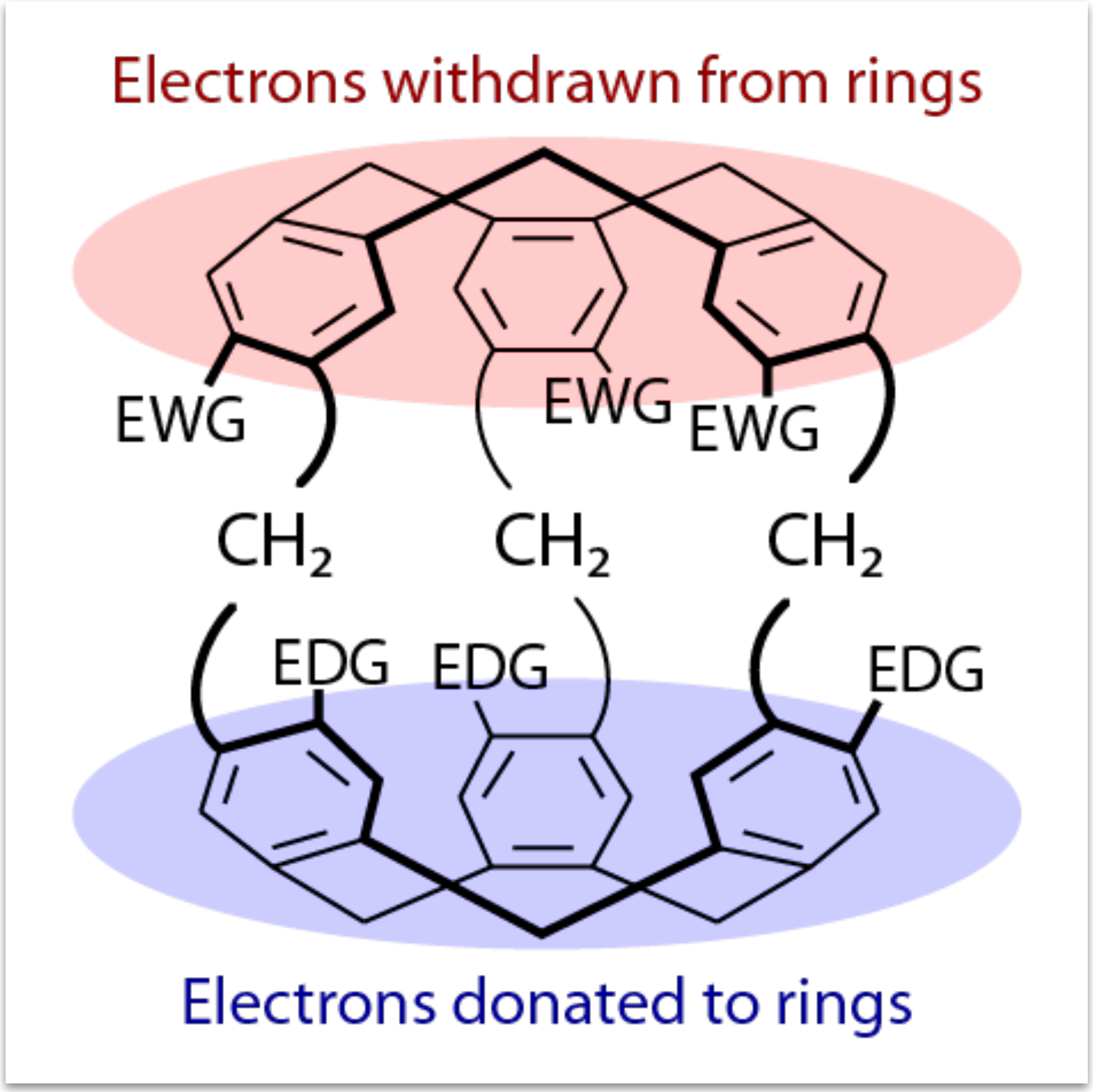

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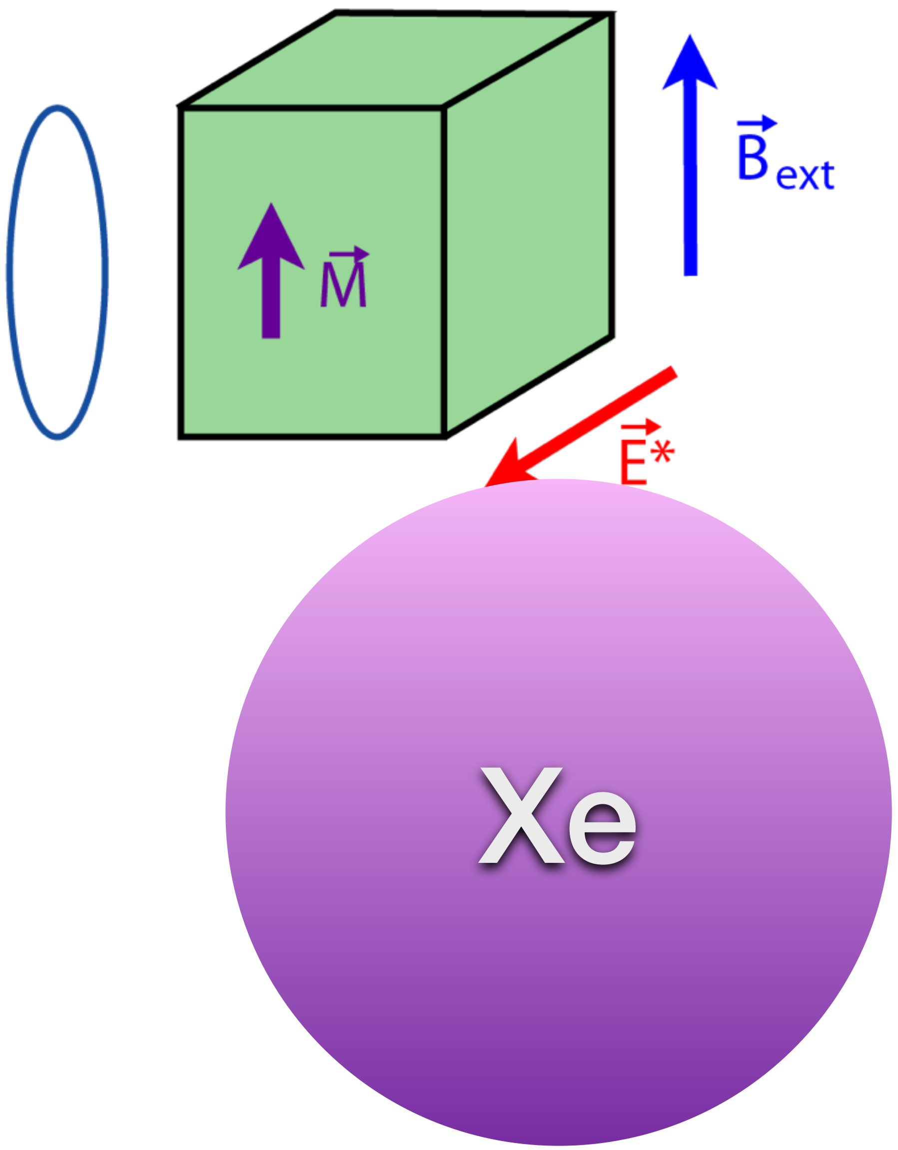
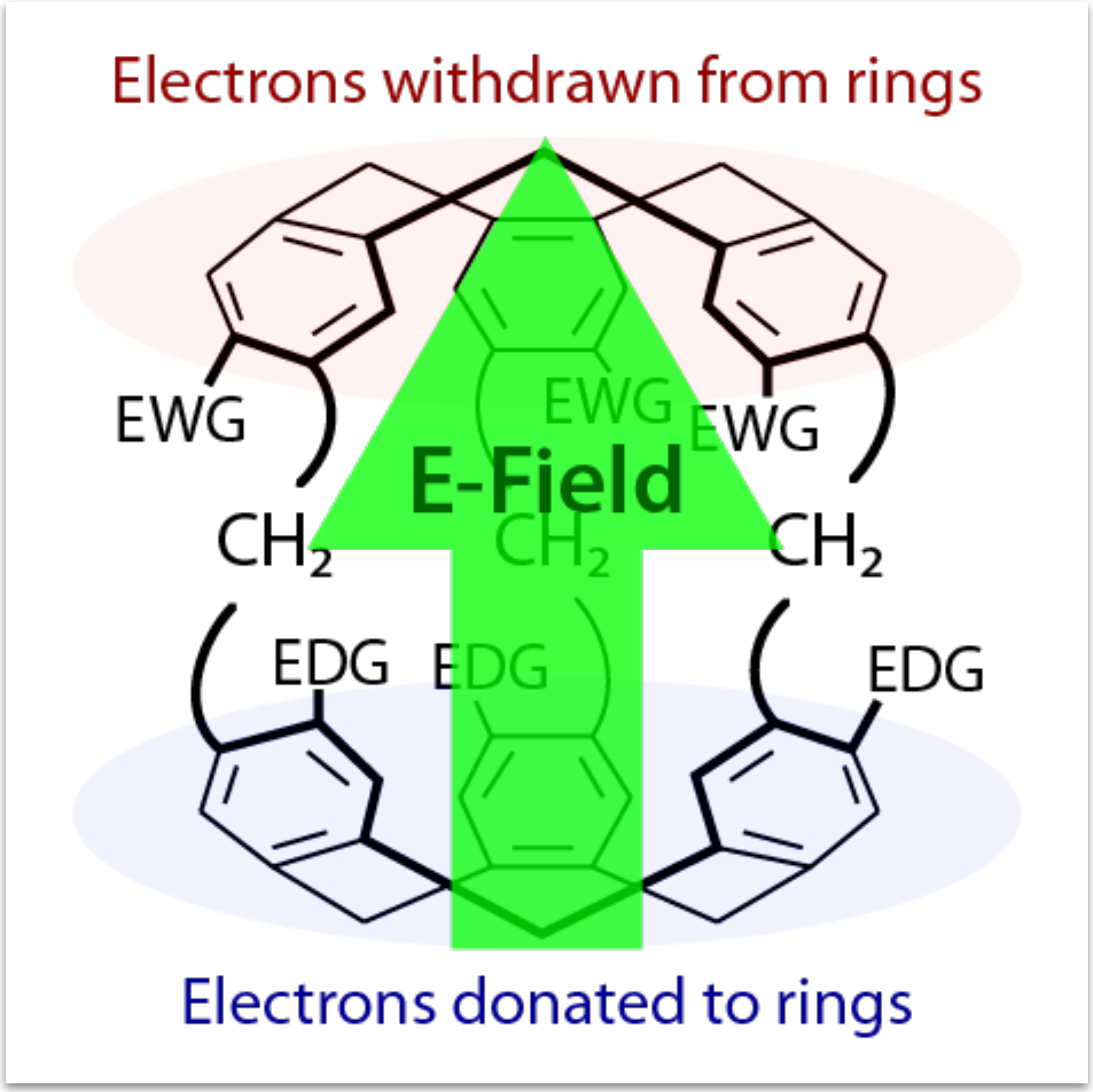
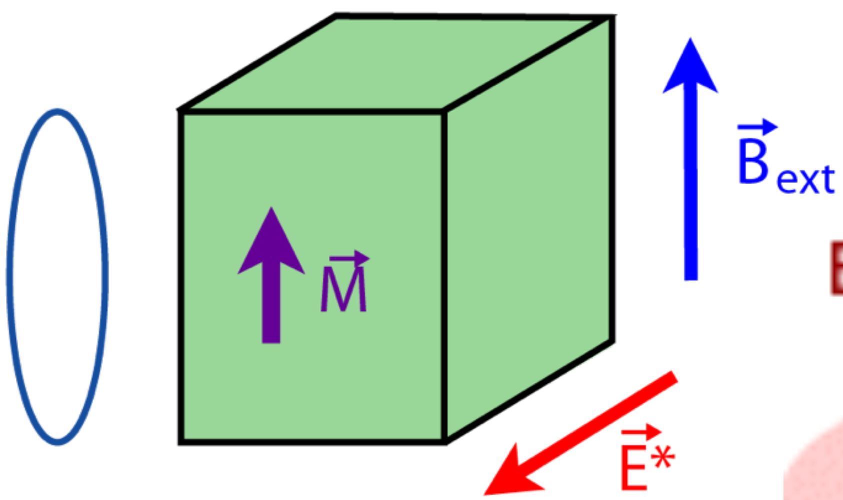
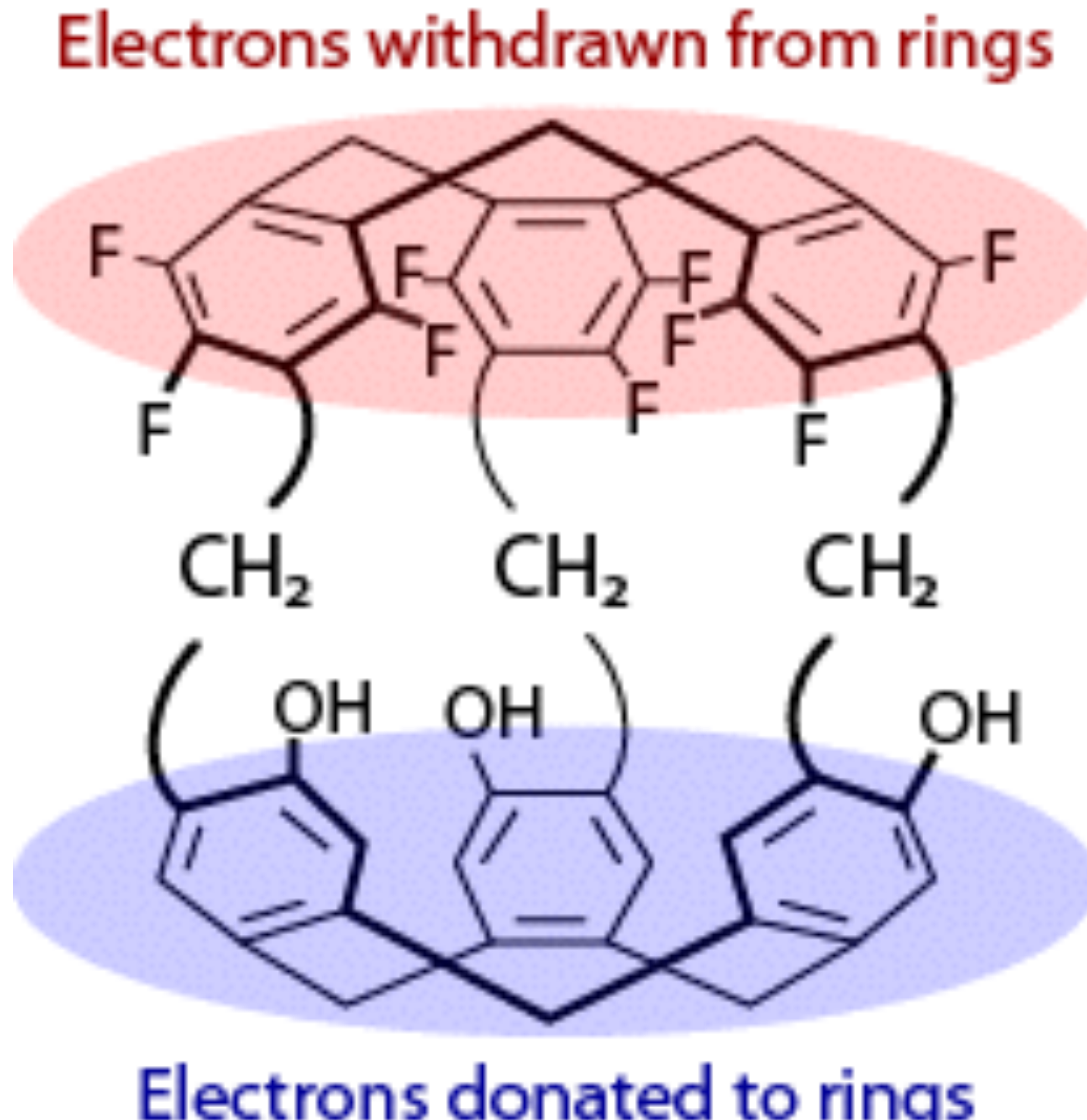


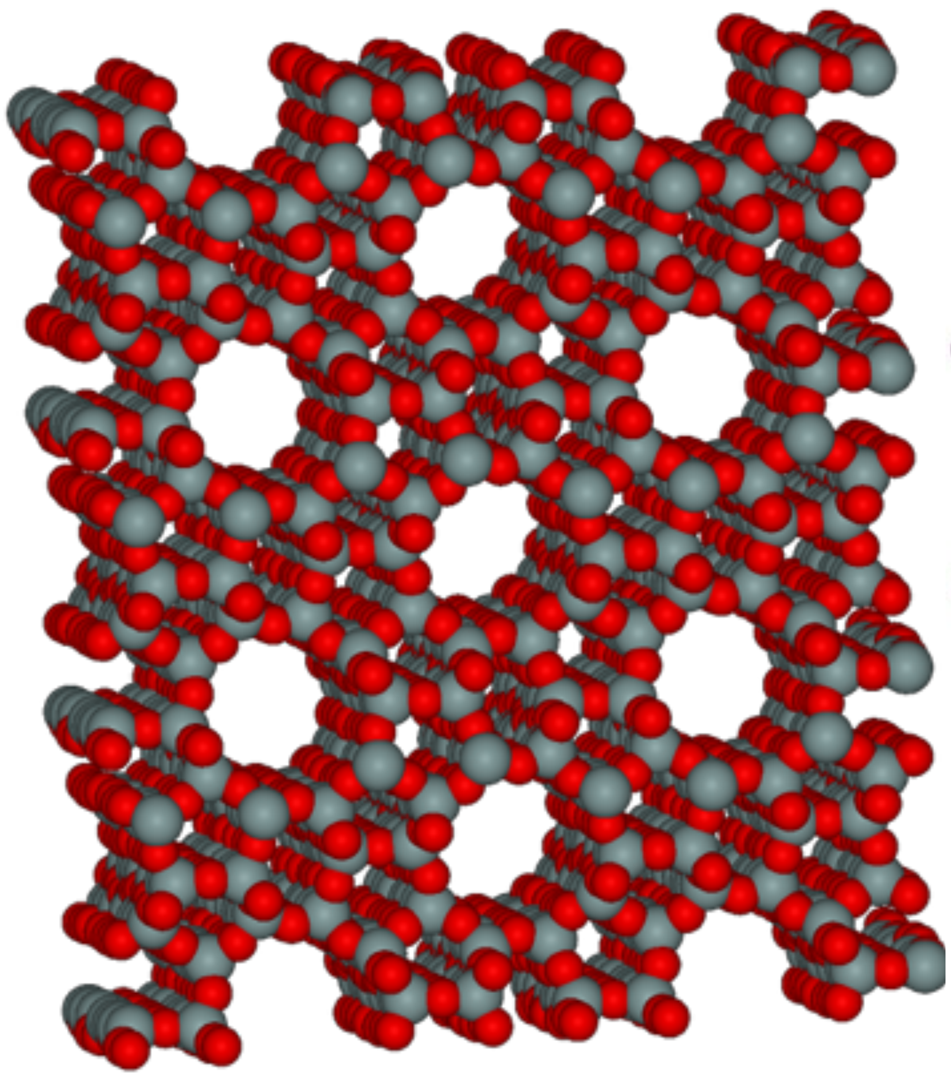


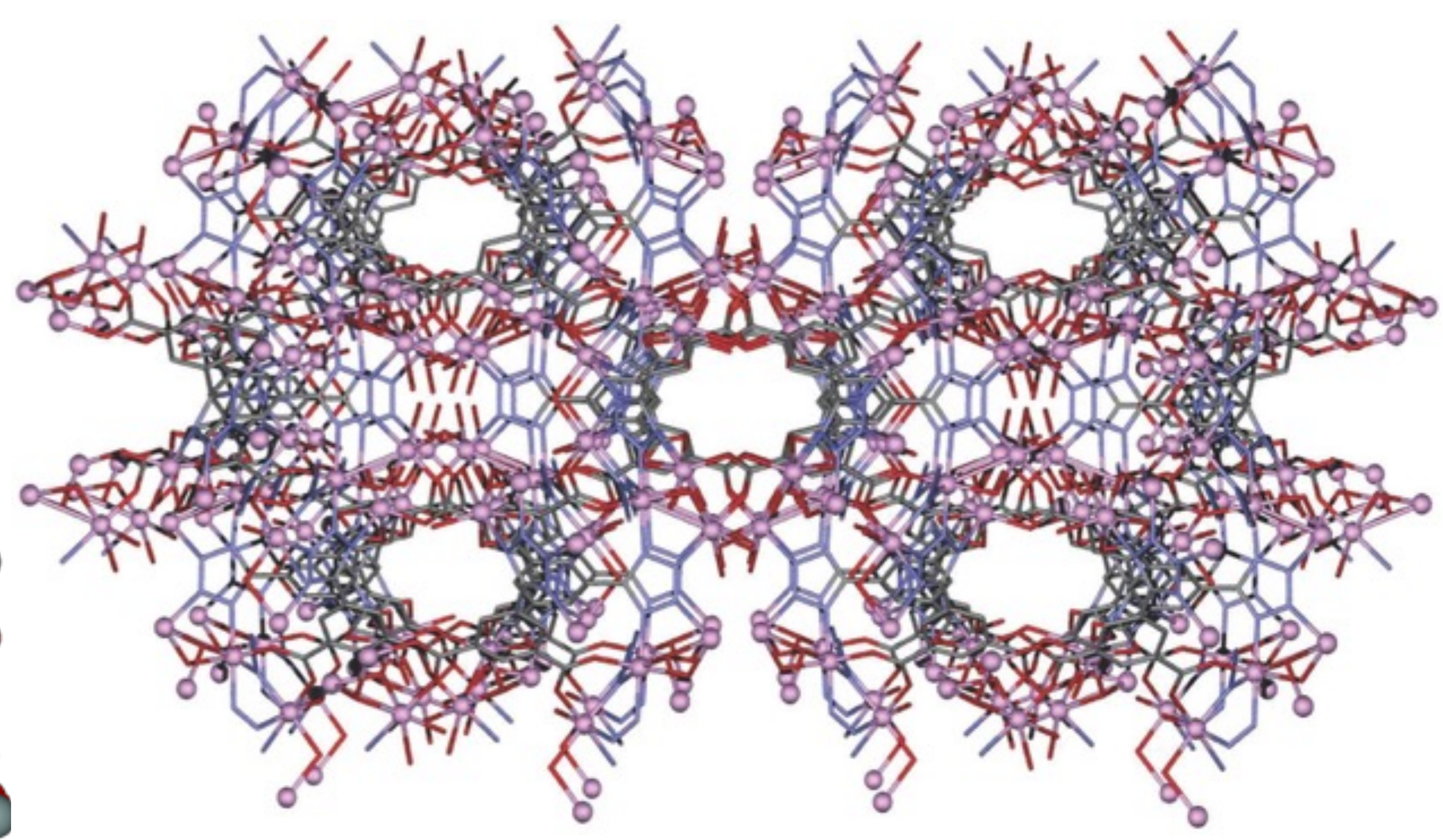
Toward Bulk Synthesis of Polar Cages

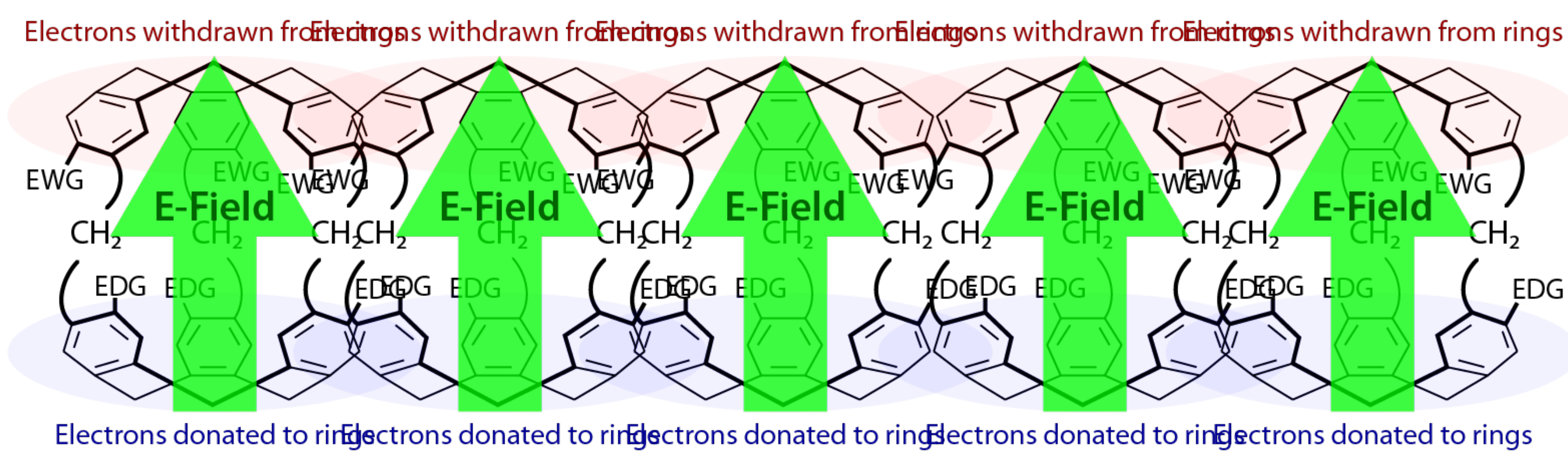




Combination: Para/ferroelectric Zeolite?



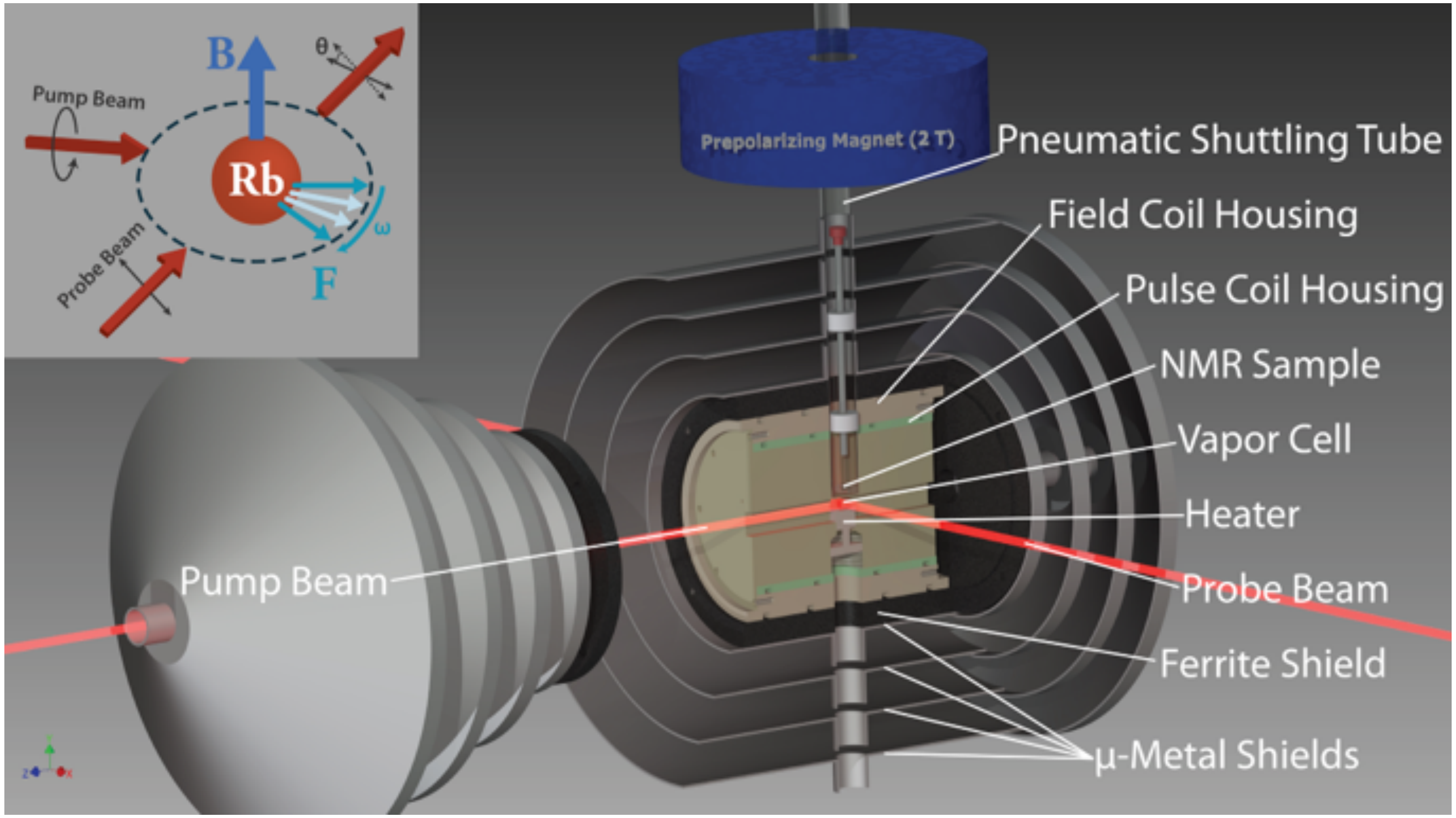


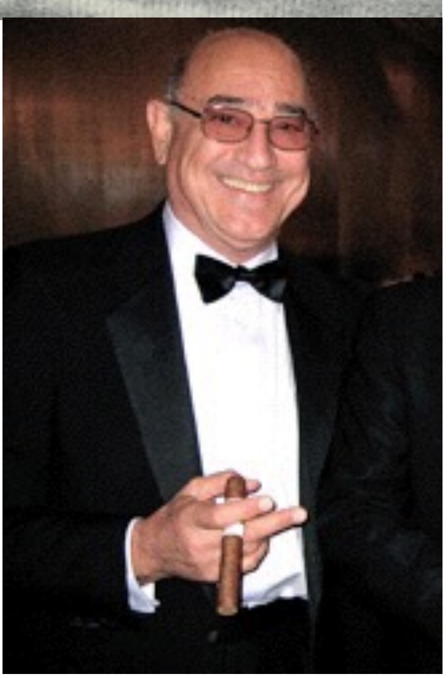


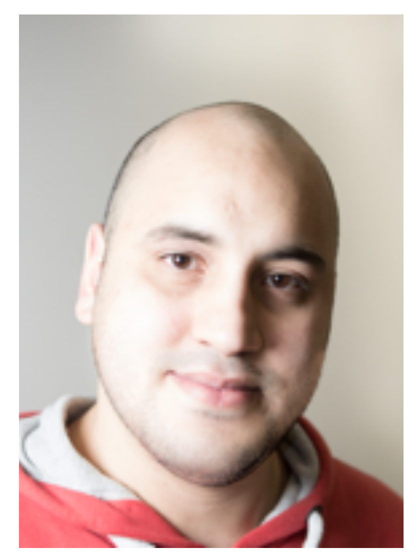
Conclusions

- CASPEr $\Longrightarrow$ NMR, and NMR is a mature field
- Nuclear spin antenna:
  - ALPs interact with nuclei
  - Nuclear magnetization measured by pickup loop(s)
- All that remains is to produce samples, stick them in magnets, and start measuring

ALSO: ZULF-NMR







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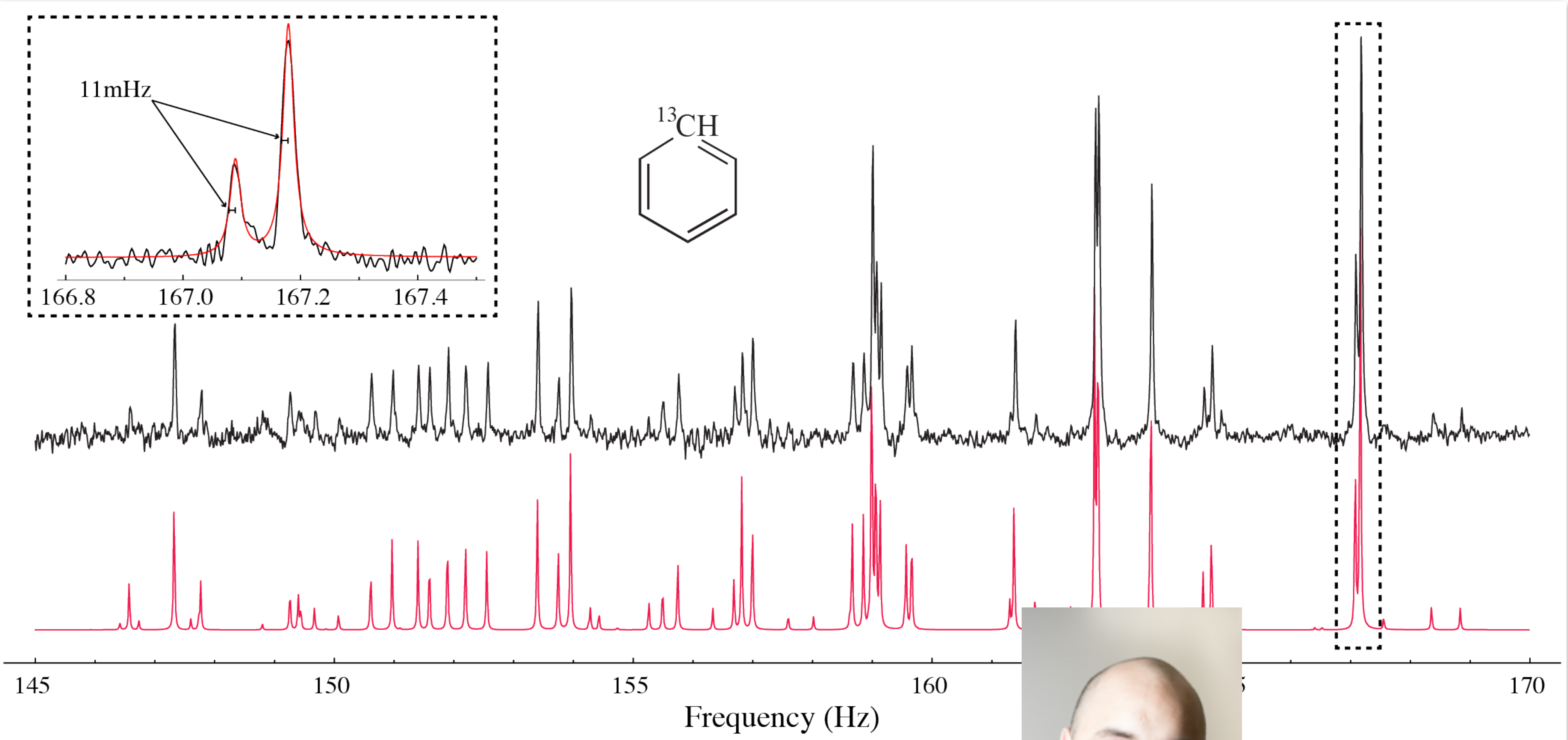

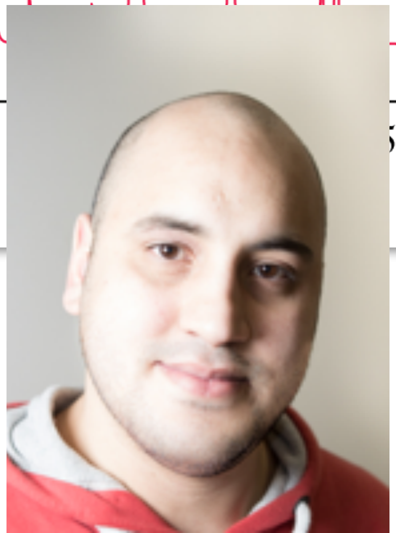

Proper fitting underway!

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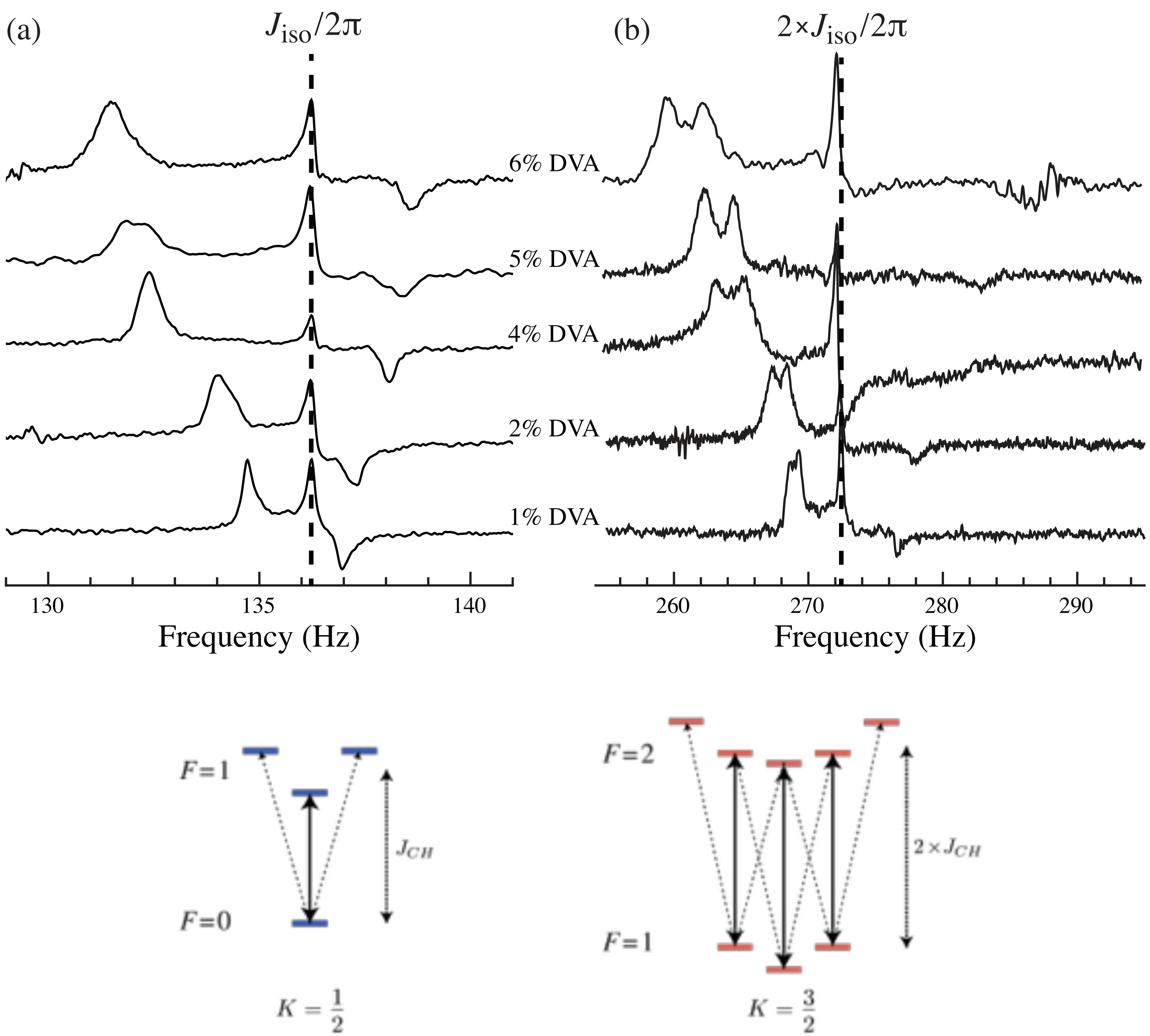
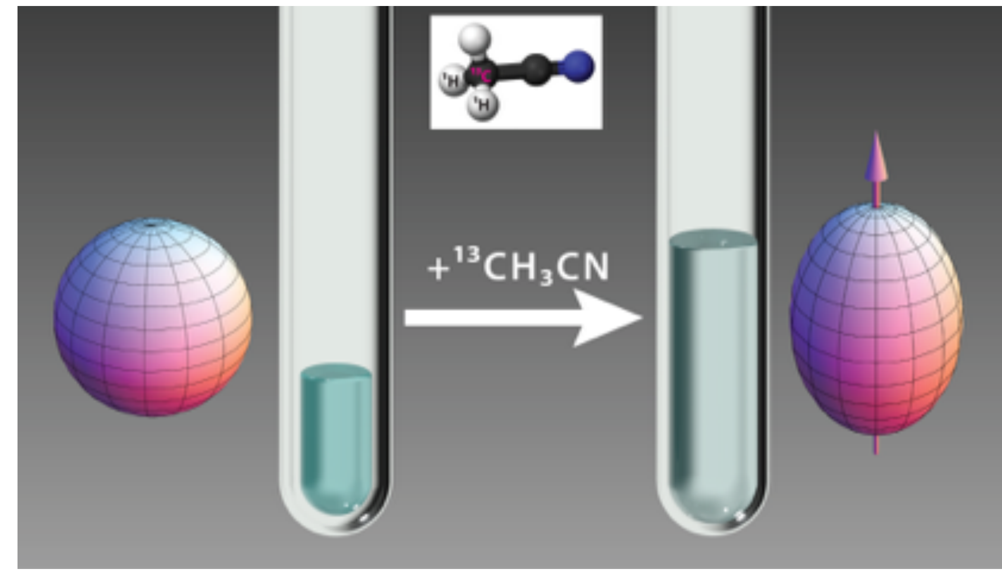
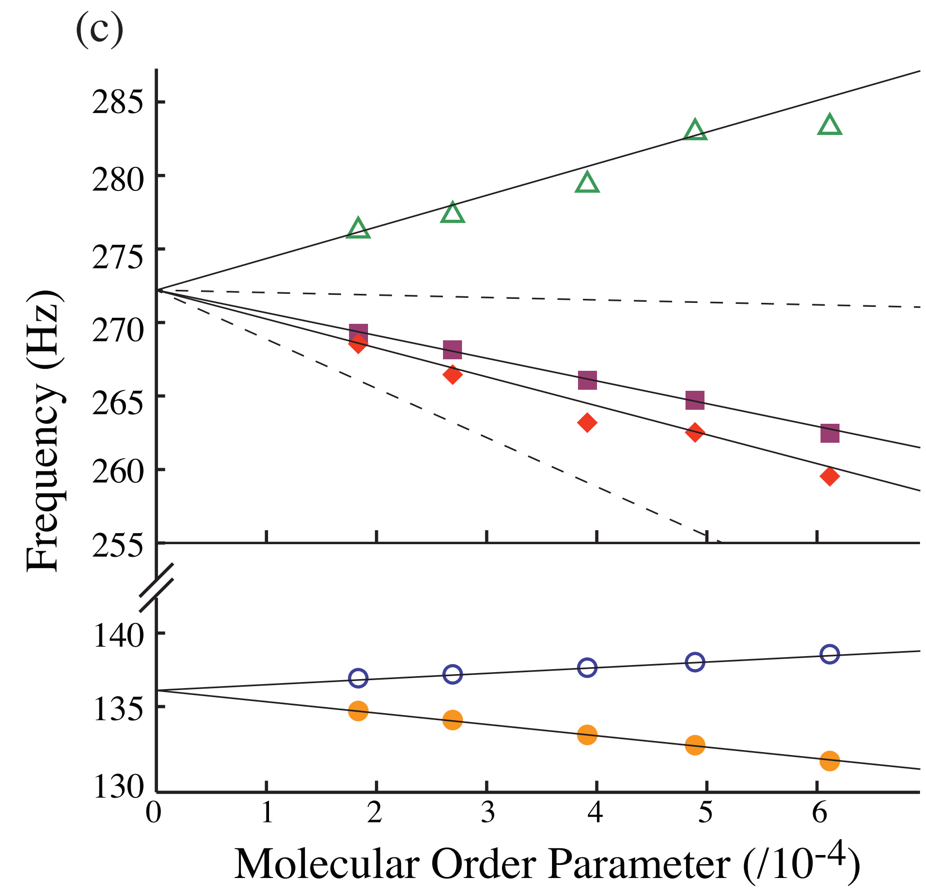
ALSO: ZULF-NMR







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