Status of CASPEr-~~wind~~ *gradient* and study of its quantum sensitivity limits

Yuzhe Zhang and Dr. Hendrik Bekker
for the CASPEr collaboration

1. Introduction
2. Nuclear magnetic resonance
3. Hyperpolarized ^{129}Xe
4. Reaching the quantum projection noise limit
5. Conclusions and outlook

HIM
Helmholtz-Institut Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Axions and axion-like particles (ALPs)

Coupling to	Operator	Experiment
Photon	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$	ABRACADABRA, ADMX, ALPS, CAST, HAYSTAC…
Gluon	$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$	CASPEr-electric ->Dr. Deniz Aybas, today 16:10 **“Searching for axion-like dark matter with CASPEr-electric”**
Fermion	$\frac{\partial_\mu a}{f_a} \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$	QUAX, ARIADNE, GNOME -> Hector M. Roig, today 14:15 **“Search for Axion domain walls using the Global Network of Optical Magnetometers for Exotic physics (GNOME)”** CASPEr-gradient

a axion field

$F_{\mu\nu}$ field strength of electromagnetism

$G_{\mu\nu}$ field strength of QCD

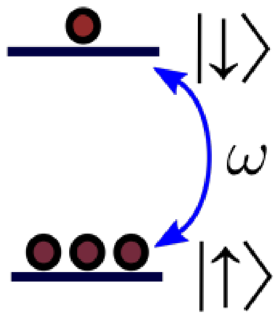
Ψ_f standard model fermion

*Operators from Graham, P. W. and S. Rajendran, Phys. Rev. D 88, 035023 (2013)

Motivation: search for ALPs with nuclear magnetic resonance (NMR)

Magnetic field

$$H = \gamma \vec{B} \cdot \vec{\sigma}$$



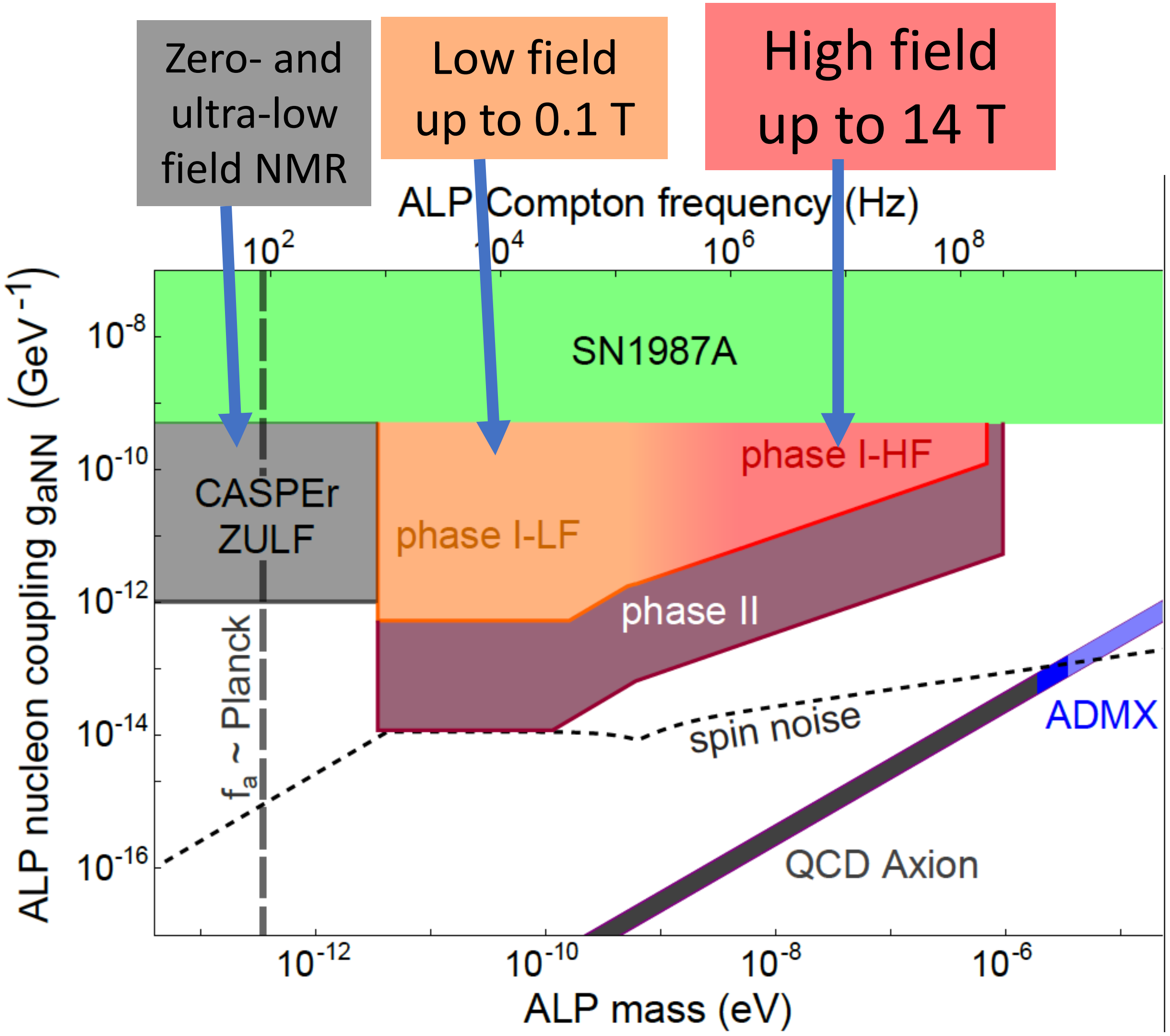
$$\omega = 2\pi\gamma B$$

ALP field

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \Rightarrow H = g_{aNN} \underline{\vec{\nabla} a} \cdot \vec{\sigma}$$

pseudomagnetic field

H	Hamiltonian
γ	gyromagnetic ratio
$\vec{B}$	magnetic field
$\vec{\sigma}$	nuclear spin
ω	Larmor frequency
g_{aNN}	coupling constant
a	axion or ALP field



Pulsed NMR scheme

duration set by ALP coherence time

Dr. Arne Wickenbrock, tomorrow at 15:45
“The spectral lineshape of gradient-coupled bosonic dark matter in our galaxy”

ALP field

$$H = g_{aNN} \vec{\nabla} a \cdot \vec{\sigma}$$

Field in pick-up coil

Sample magnetization vector

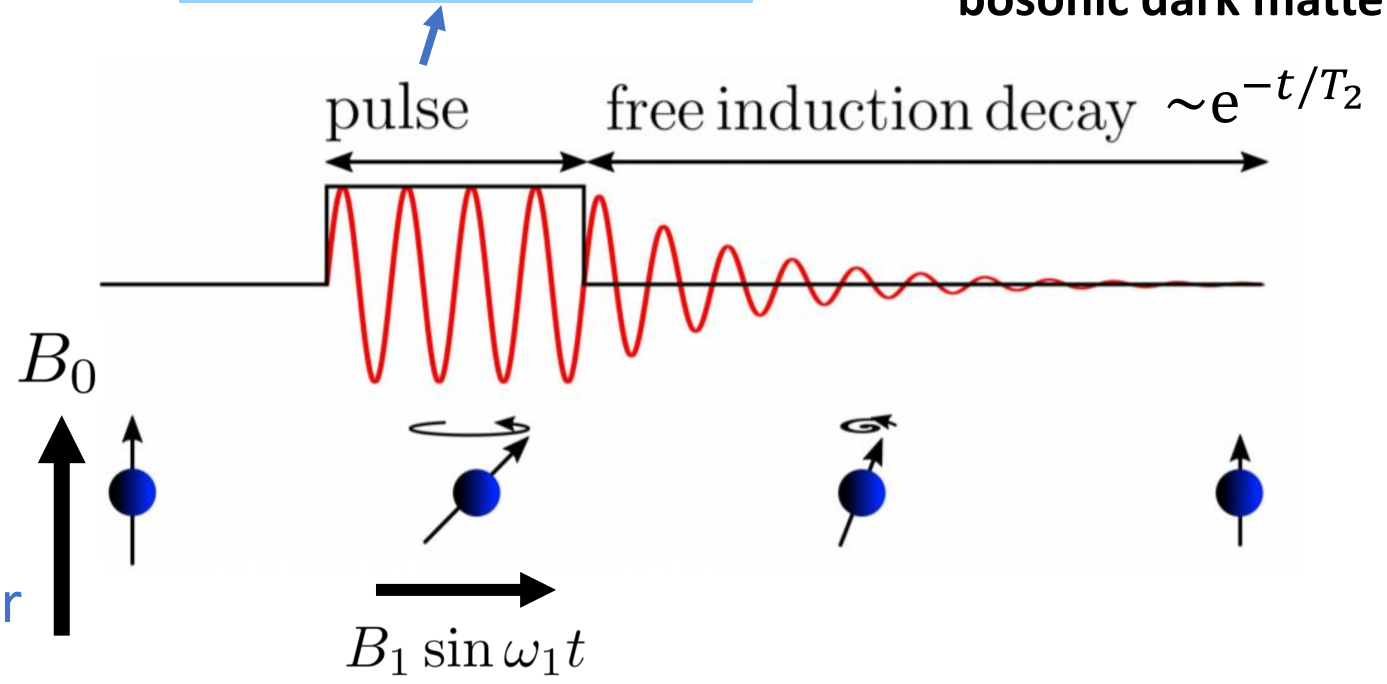
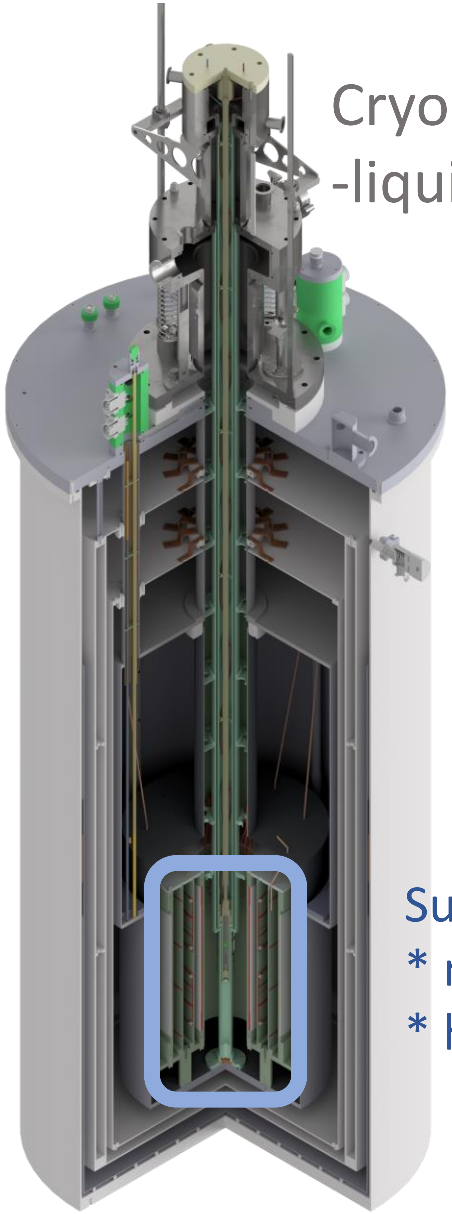


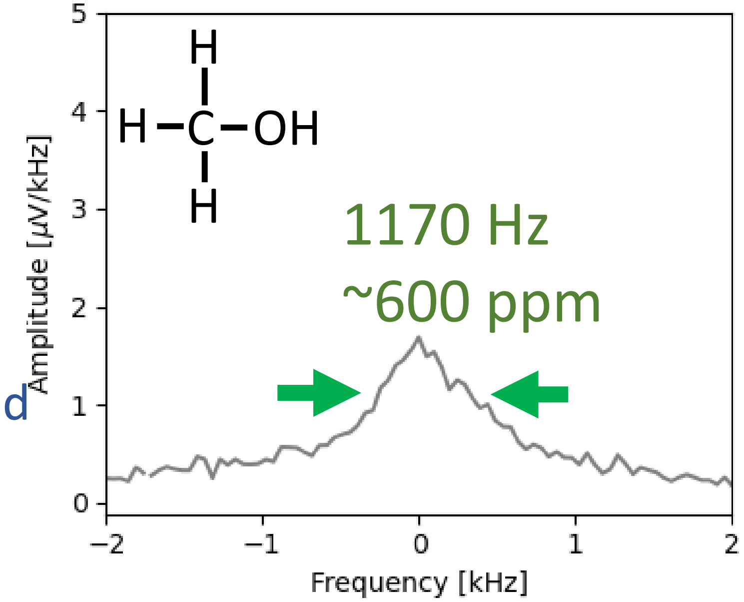
*Figure from D. Aybas *et al*, Search for axion-like dark matter using solid-state nuclear magnetic resonance, Phys. Rev. Lett. 126 (14), 141802

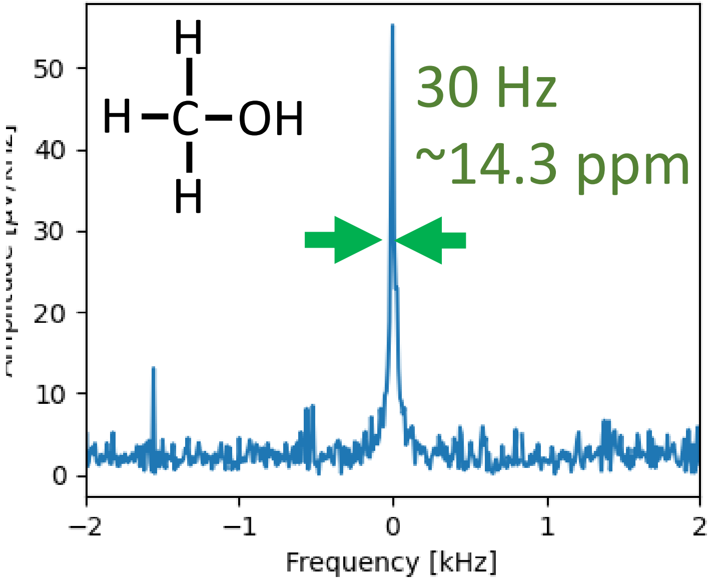
Methanol H–C(H)(H)–OH (proton) NMR experiment



Cryostat
-liquid He (~4 K)

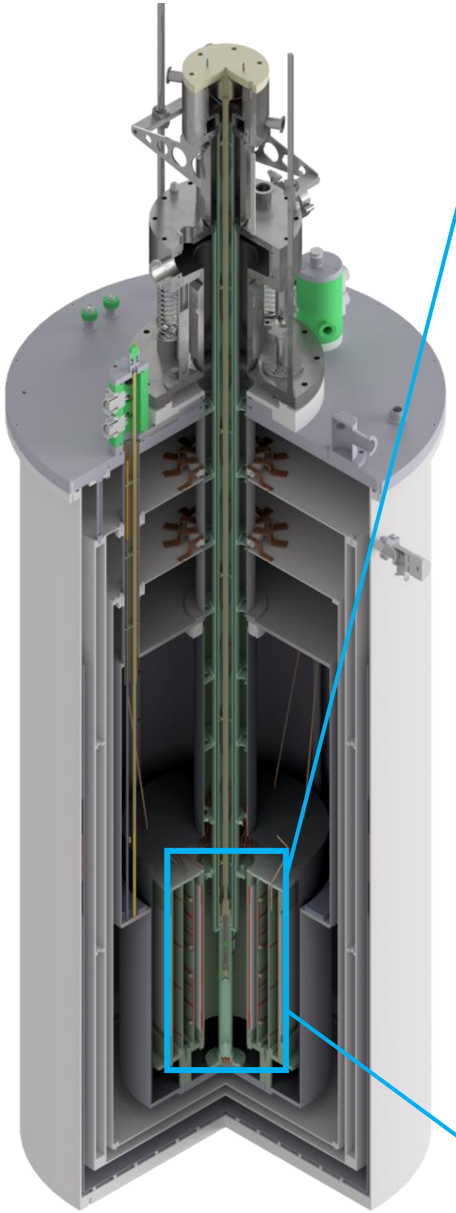
Superconducting coil
* magnetically shielded
* homogeneity 2 ppm





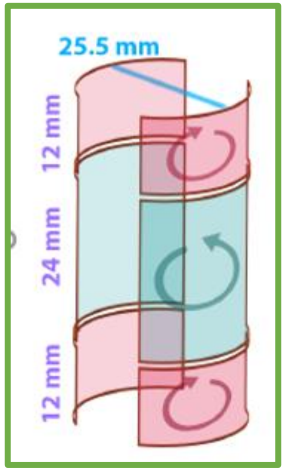
^{1}H NMR signals at ~2 MHz

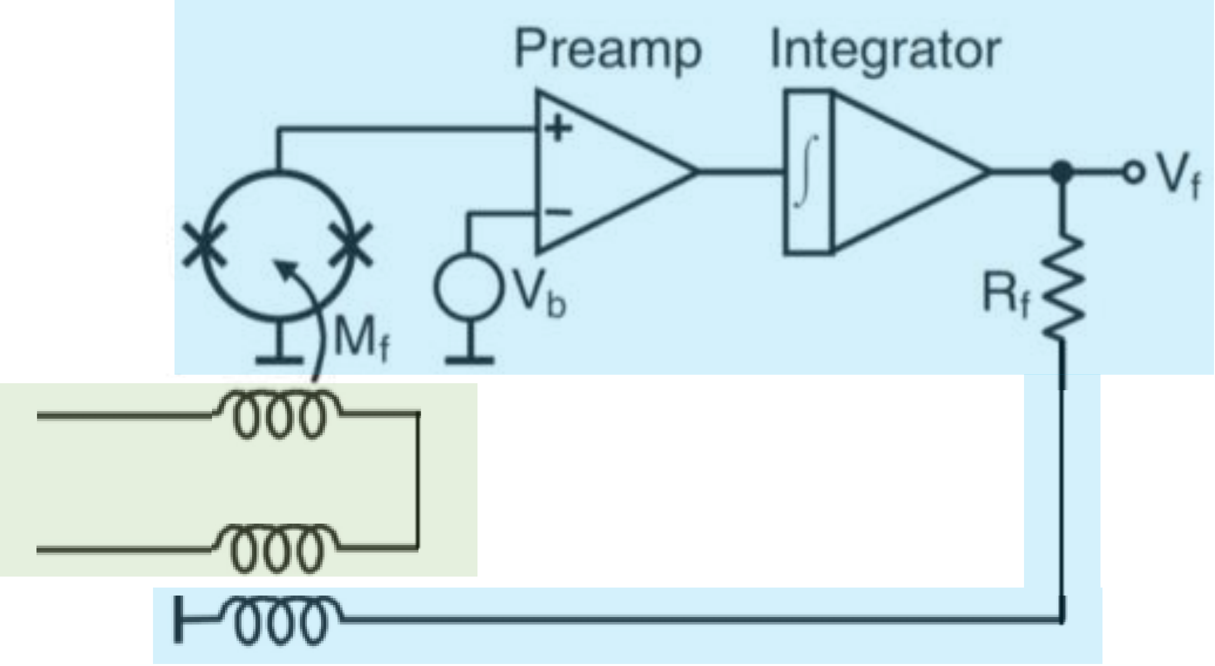
Superconducting quantum interference devices (SQUIDs)



SQUIDs

gradiometer

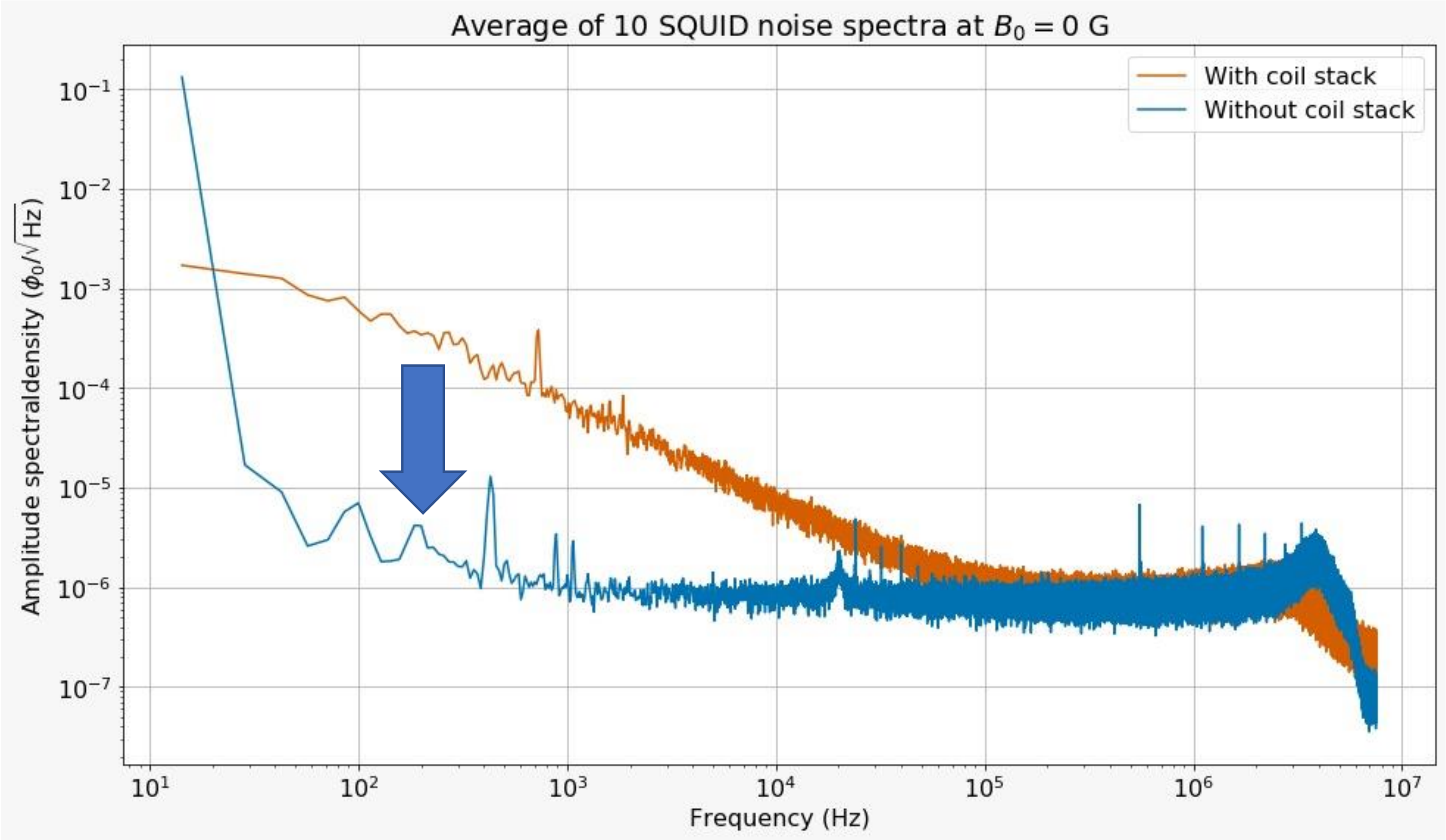




*Scheme of SQUID https://commons.wikimedia.org/wiki/File:SQUID_IV.jpg

**Gradiometer coil illustration made by Nataniel Figueroa Leigh

Noise limit of the SQUIDs



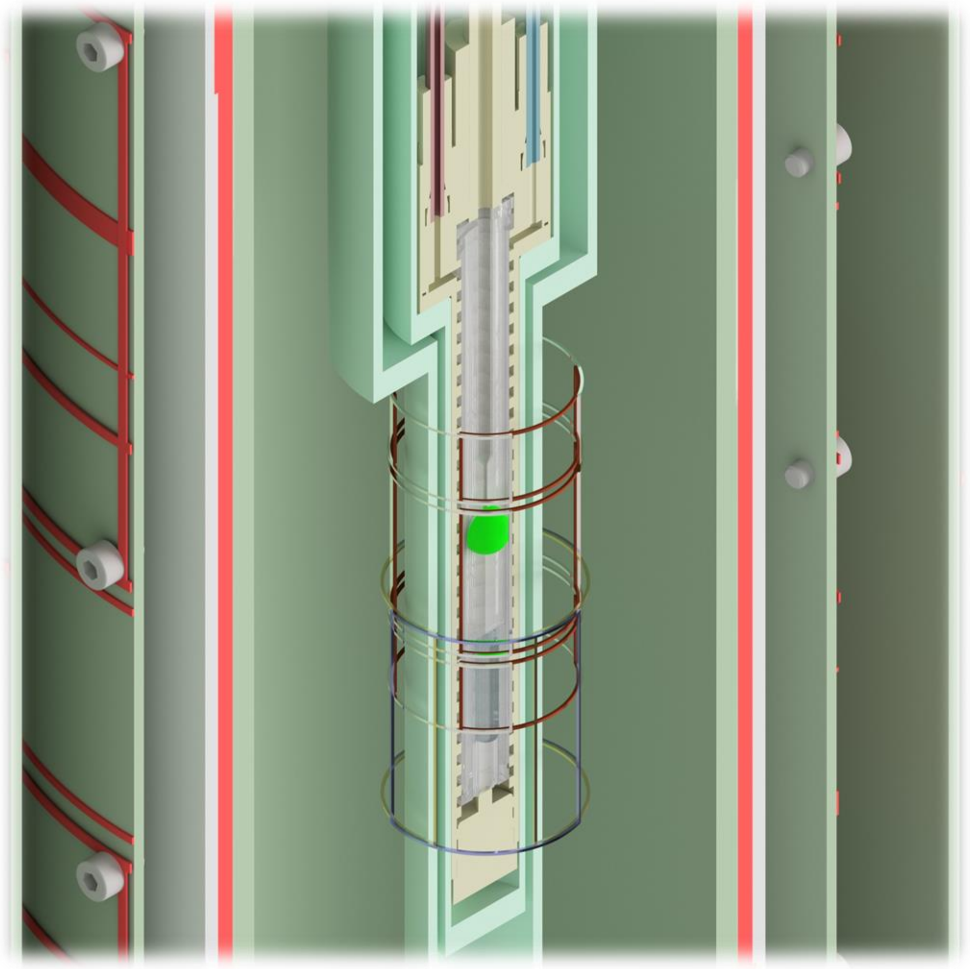
Introduces Johnson noise!

$$\sqrt{\frac{q k_B T R}{\pi N^2 A^2 \nu^2}} \propto \nu^{-1}$$

q (geometric) filling factor
k_B Boltzmann constant
T temperature of the copper coil

R resistance of the copper coil
N number of turns
A area of the coil
ν frequency

Hyperpolarized ^{129}Xe sample



Romalis, M. V., and M. P. Ledbetter. "Transverse Spin Relaxation in Liquid ^{129}Xe in the Presence of Large Dipolar Fields." *Phys. Rev. Letters* 87, no. 6 (2001): 067601
Limes, M. E., Z. L. Ma, E. G. Sorte, and B. Saam. "Robust Solid ^{129}Xe Longitudinal Relaxation Times." *Phys. Rev. B* 94, no. 9 (2016): 094309

Sensitivity of NMR to perturbing field determined by population imbalance, polarization

$$Pol = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

In thermal equilibrium, typically

$$Pol \approx 10^{-6}$$

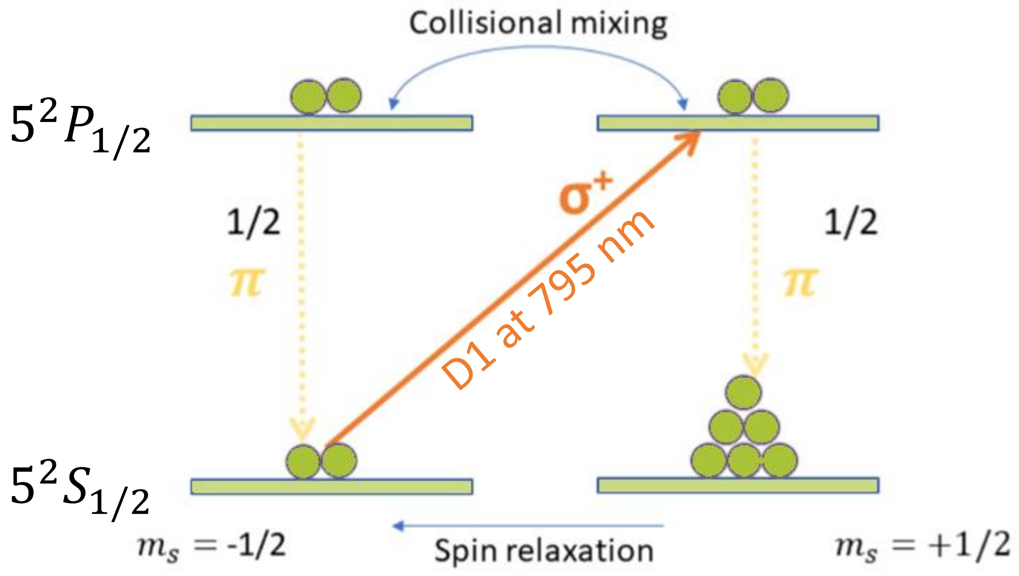
Hyperpolarized ^{129}Xe, several labs demonstrated

$$Pol > 0.5$$

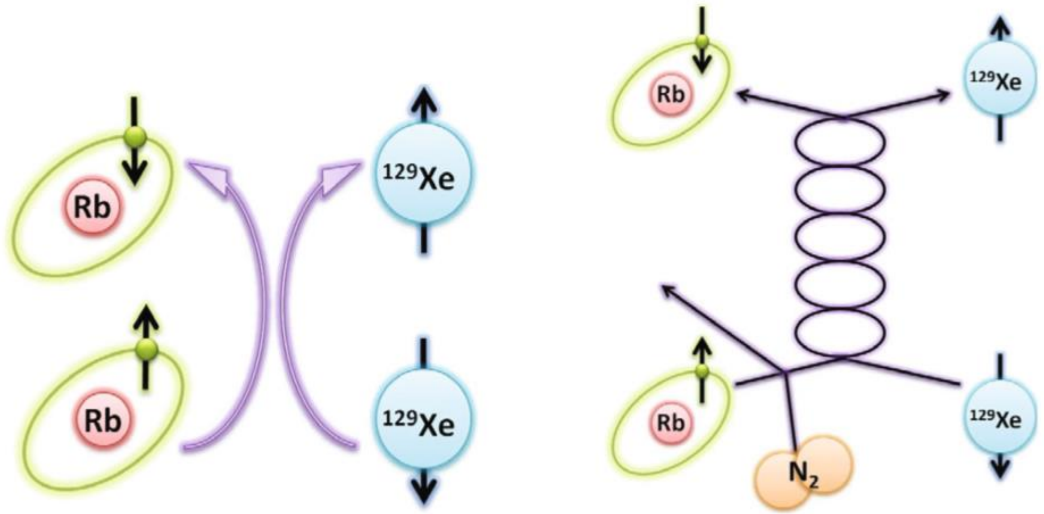
Property	Value
Liquid temp. range	$161 - 165$ K
Spin density	$1.3 \cdot 10^{22}\,\mathrm{cm}^{-3}$
Volume	0.25 mL
Transverse spin relaxation T_2	≈ 1300 s
Longitudinal relaxation T_1	≈ 1500 s

Spin exchange optical pumping (SEOP)

Polarize Rb electron shell

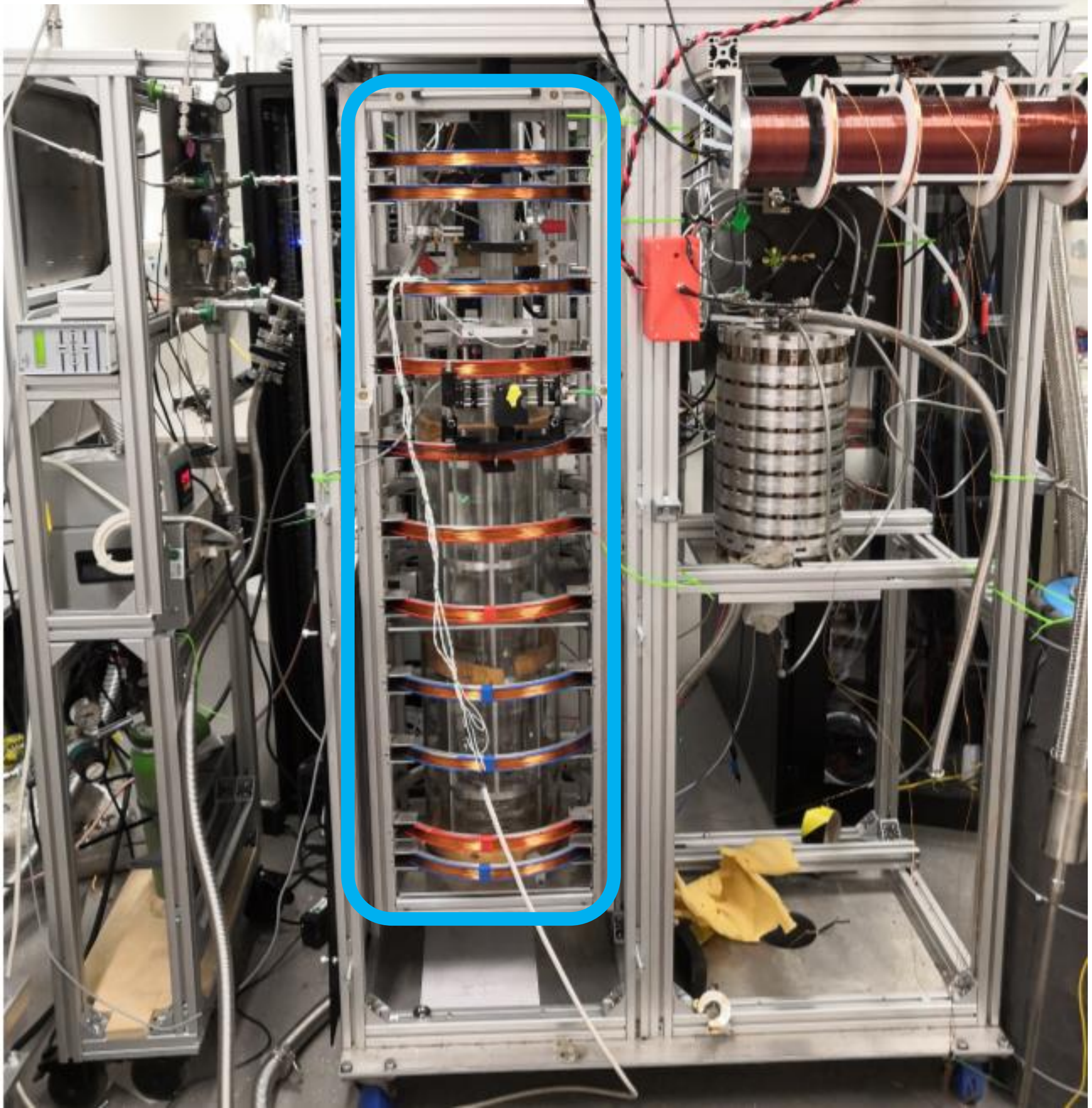


Transfer spin to ^{129}Xe nucleus



M. G. Sendra, "Characterization and preparation of hyperpolarized xenon for the Cosmic Axion Spin Precession Experiment", MSc thesis JG University Mainz (2017)
Imai *et al*, "Continuous Flow Production of Concentrated Hyperpolarized Xenon Gas from a Dilute Xenon Gas Mixture by Buffer Gas Condensation." *Scientific Reports* 7, no. 1 (2017): 7352
Kavtanyuk *et al*, "Production of Hyperpolarized ^{129}Xe Using Spin Exchange Optical Pumping." *Journal of the Korean Phys. Soc.* 73, no. 10 (2018): 1458–65
Hersman *et al,* "Large Production System for Hyperpolarized 129Xe for Human Lung Imaging Studies." *Academic Radiology* 15, no. 6 (2008): 683–92

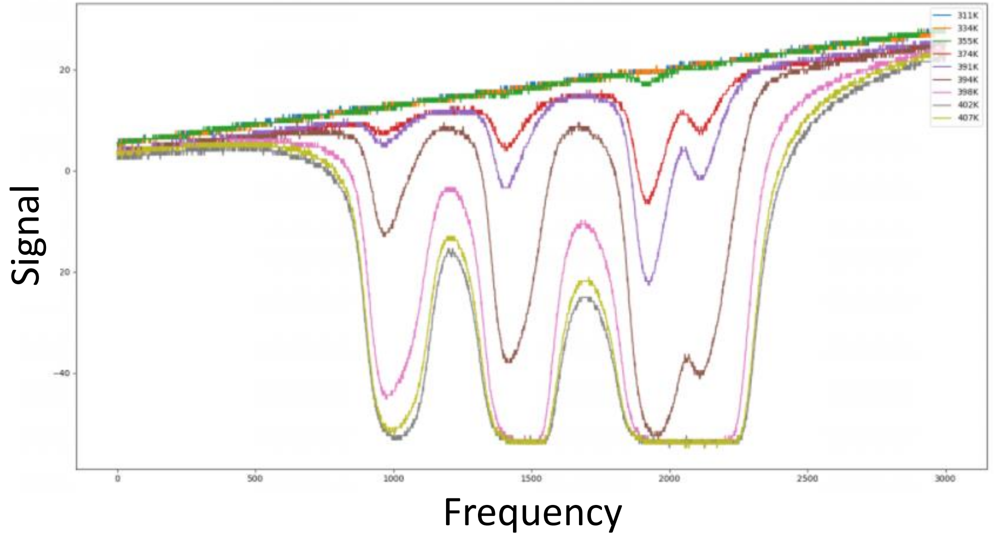
The SEOP setup



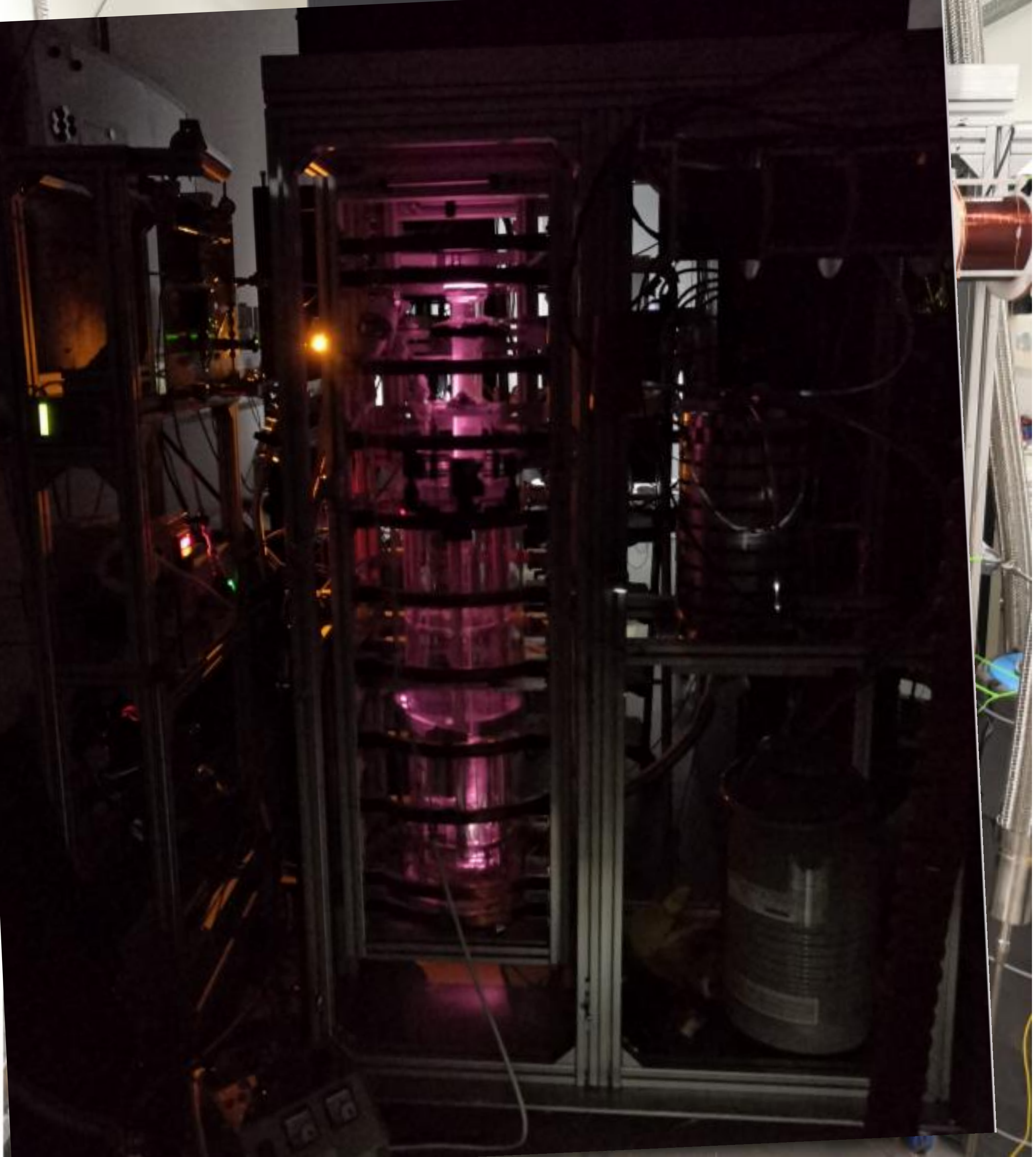
SEOP cell

- Xe, N_2, and He mixed with Rb vapor
- Interaction region for 795 nm laser light at D1 line
- Spin exchange between Rb and ^{129}Xe

Light absorption of Rb D2 at various vapor densities

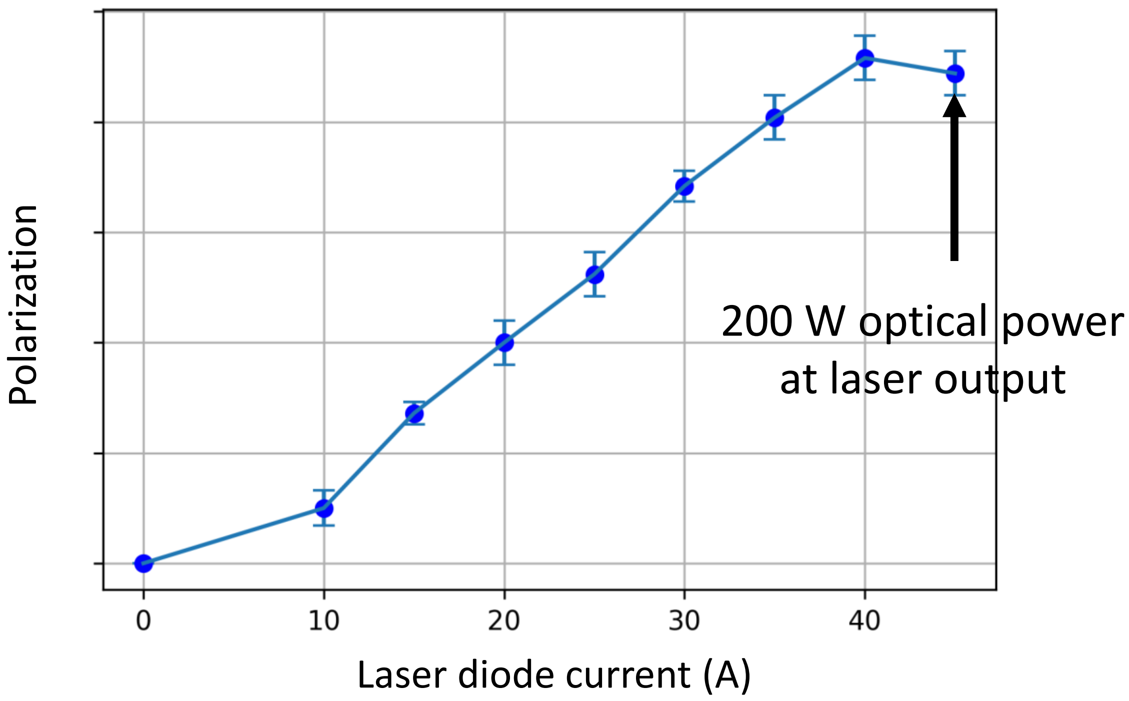


Measurements by Gary Centers and Arian Dogan

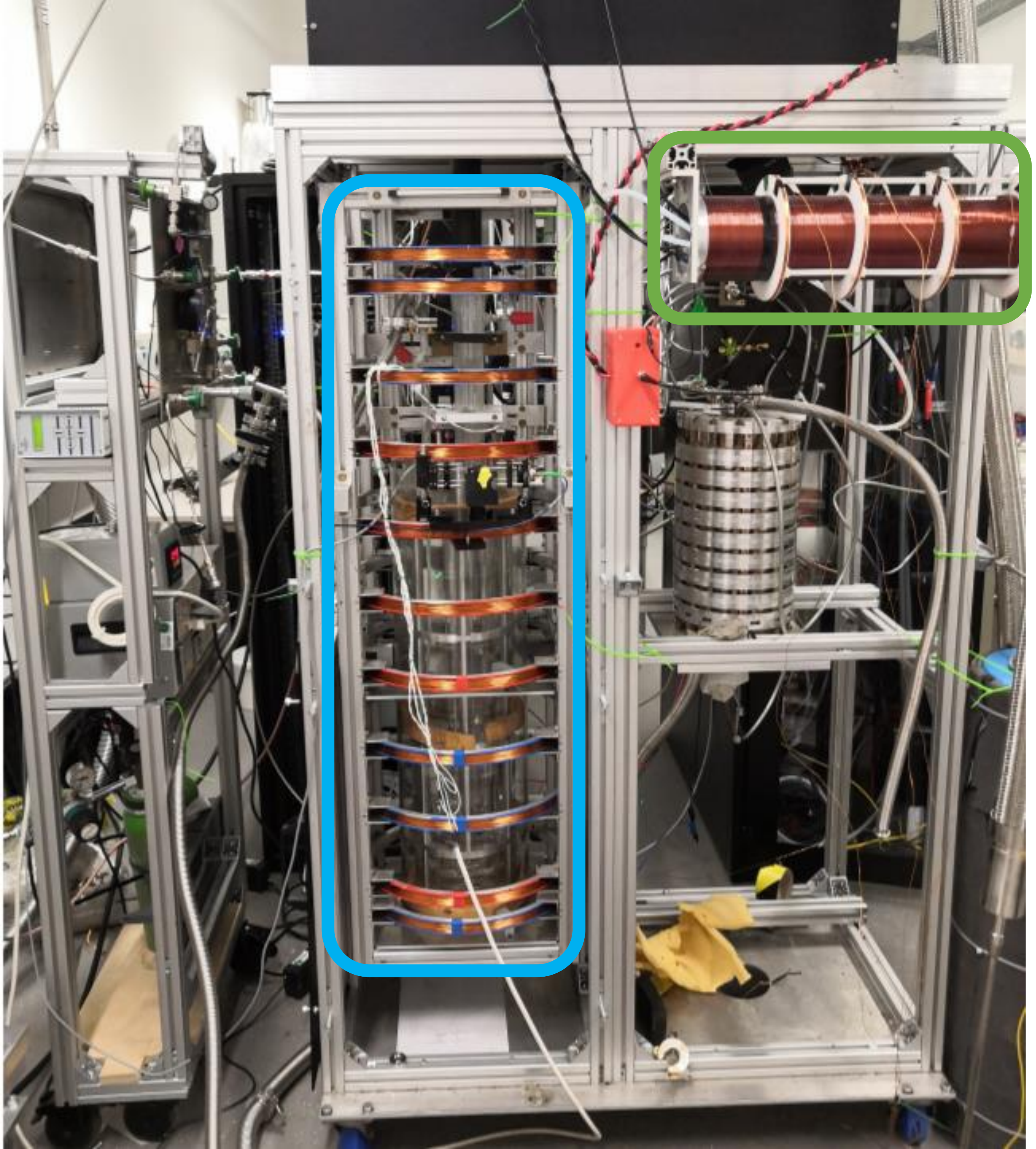


SEOP cell

- Xe, N_2, and He mixed with Rb vapor
- Interaction region for 795 nm laser light at D1 line
- Spin exchange between Rb and ^{129}Xe



Measurements by Gary Centers and Arian Dogan

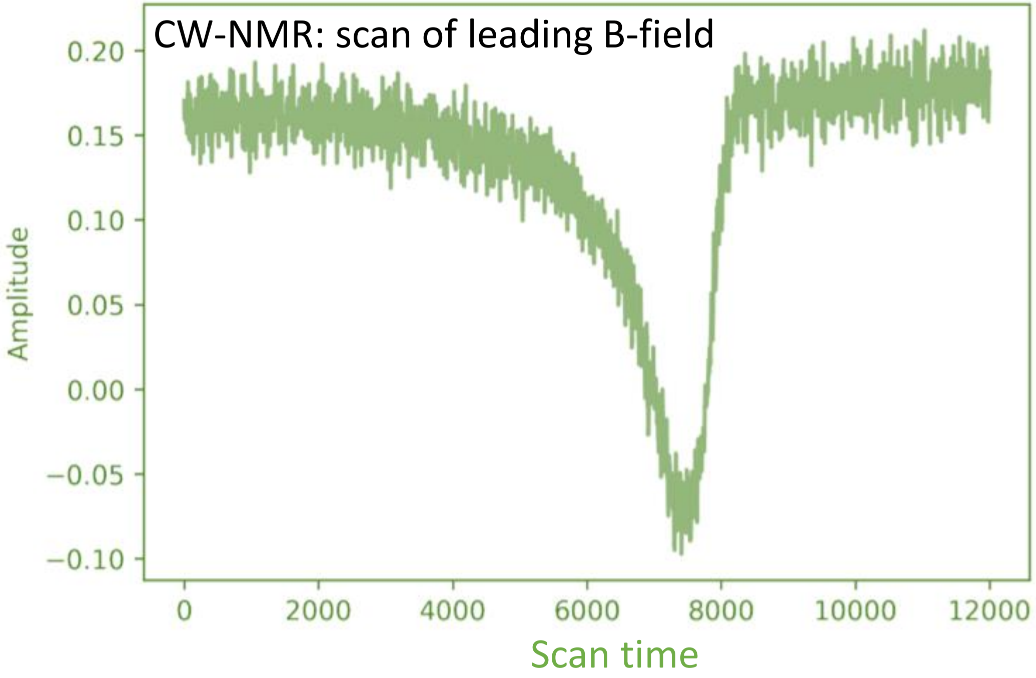


SEOP cell

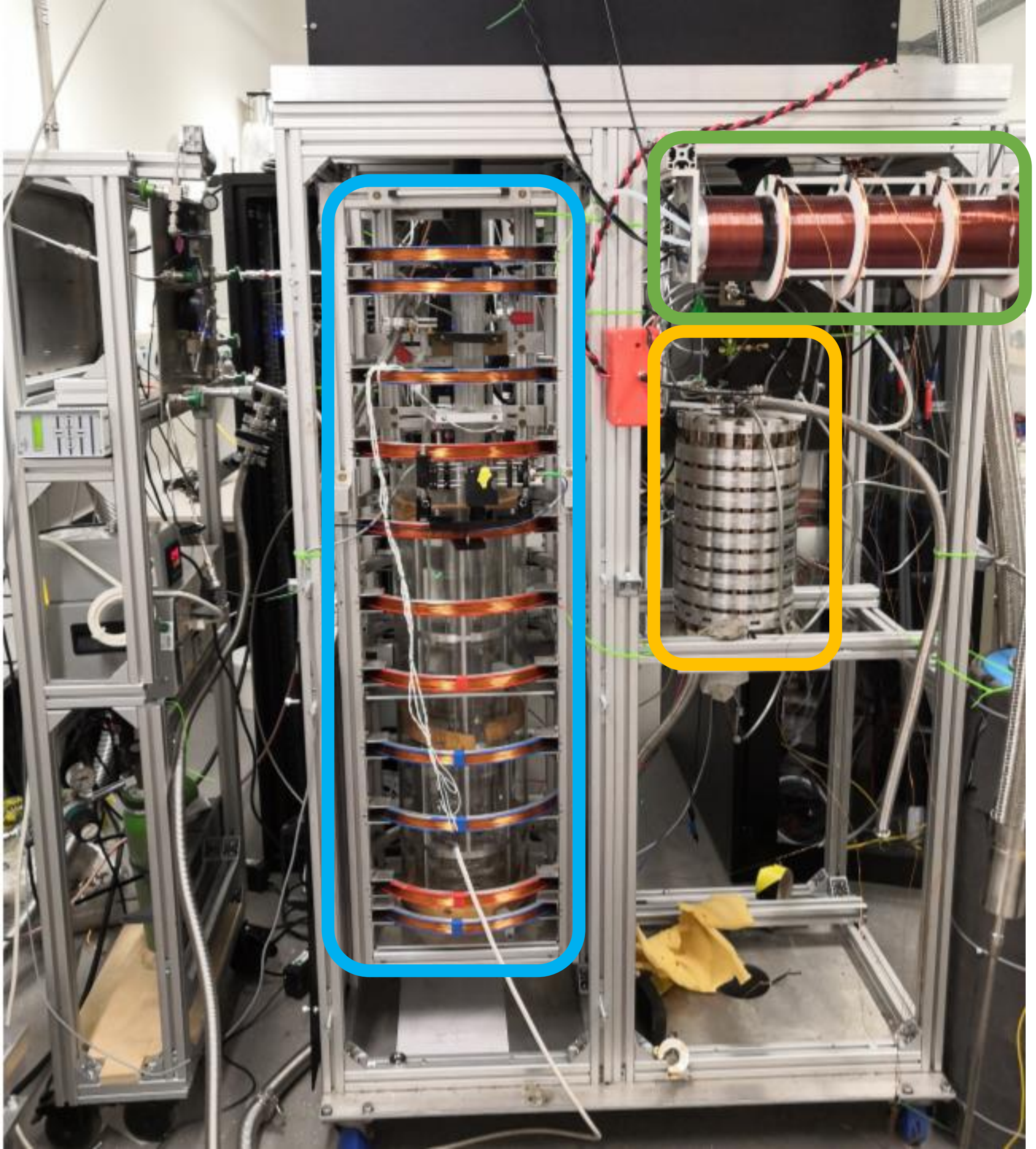
- Xe, N_2, and He mixed with Rb vapor
- Interaction region for 795 nm laser light at D1 line
- Spin exchange between Rb and ^{129}Xe

NMR diagnostic

- Polarization, $P = 11(3)$ % achieved, further optimization underway



Measurements by Gary Centers and Arian Dogan



SEOP cell

- Xe, N_2, and He mixed with Rb vapor
- Interaction region for 795 nm laser light at D1 line
- Spin exchange between Rb and ^{129}Xe

NMR diagnostic

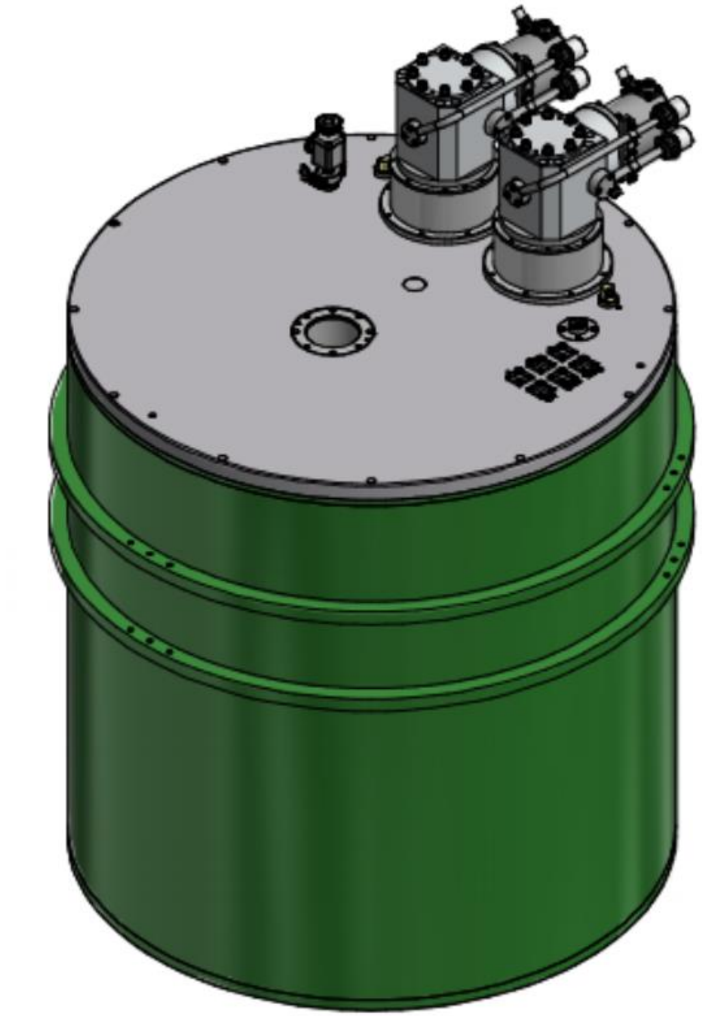
- Polarization, $P = 11(3)$ % achieved, further optimization underway

Cryoseparator

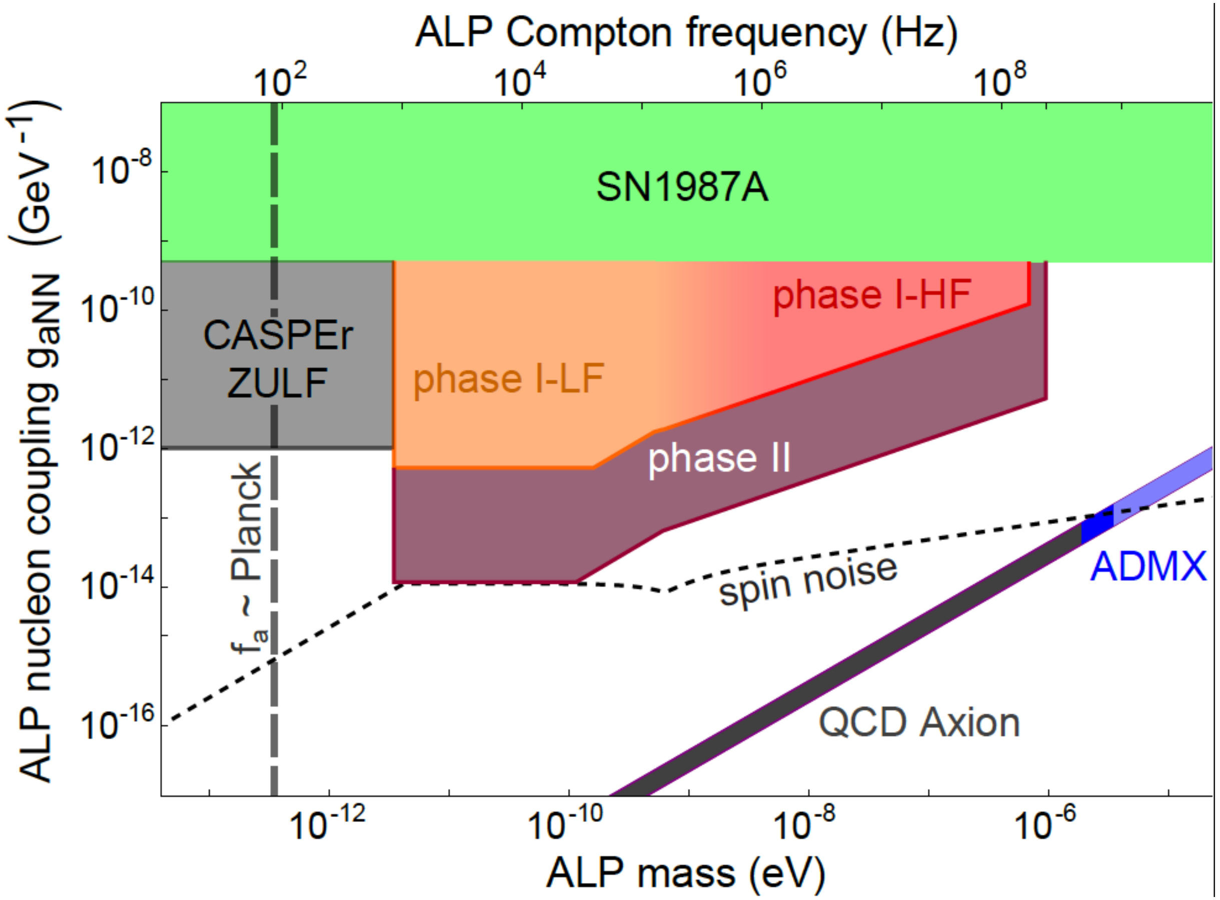
- Freeze out Xe
- Store until needed
- Conserve polarization in 0.2 T field ($T_1 > 1$ h)

Measurements by Gary Centers and Arian Dogan

CASPEr-gradient high field



- Magnet and cryostat in production
  - 0 - 14.1 T
  - Actively shielded
  - Warm bore
- Classical NMR probe to be designed

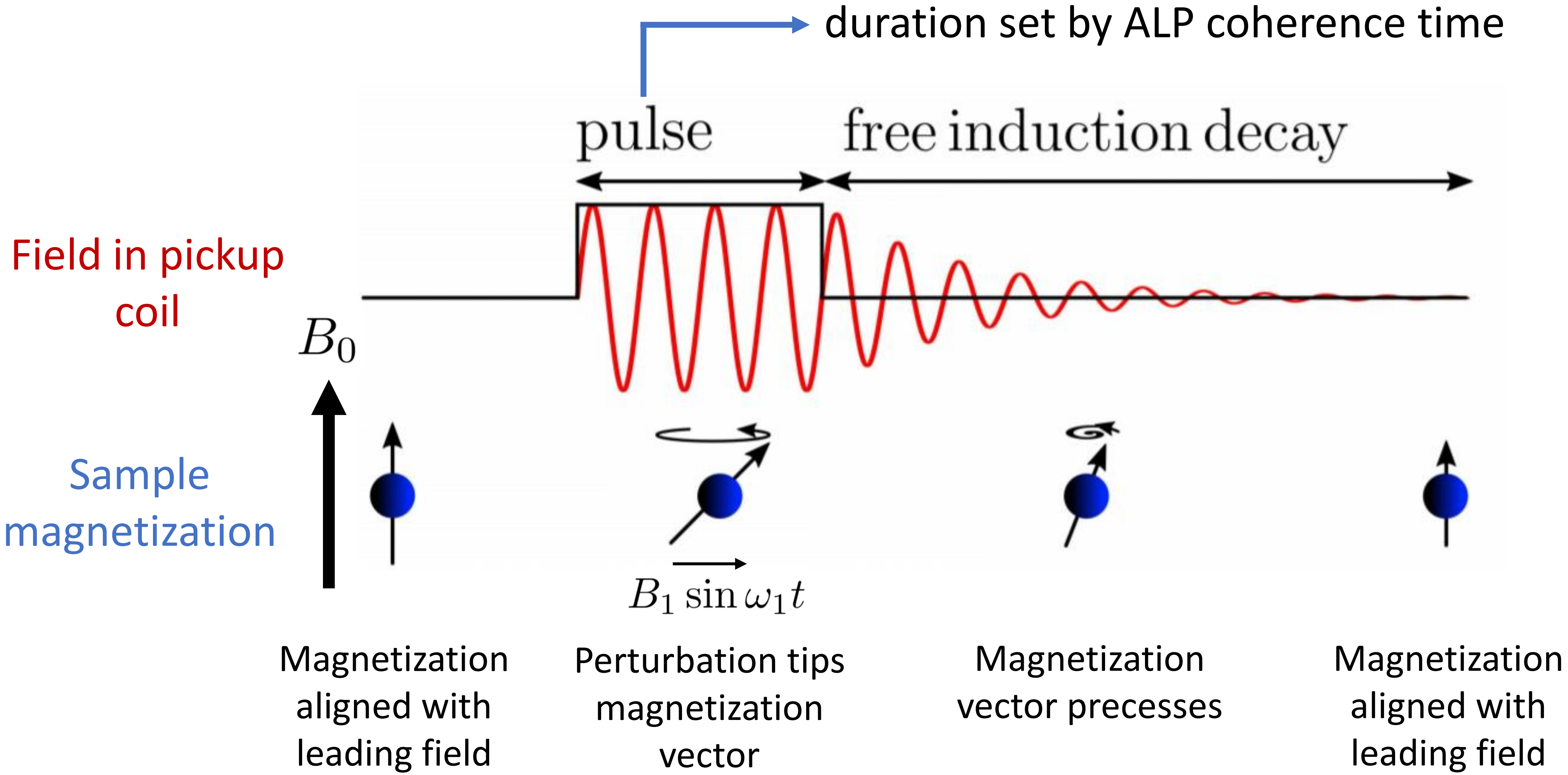


Conclusions so far

- CASPEr-gradient low field
  - Probe g_{aNN} in mass range $5 \cdot 10^{-12} - 5 \cdot 10^{-9}$ eV
  - First test measurements on thermal proton spins underway
  - Polarization of 11(3) % achieved for ^{129}Xe
  - Connection of ^{129}Xe to cryostat under construction

- CASPEr-gradient high field
  - Probe g_{aNN} in mass range $10^{-9} - 10^{-6}$ eV
  - Magnet expected Christmas 2021
  - NMR probe to be designed

Fundamental noise limit of NMR

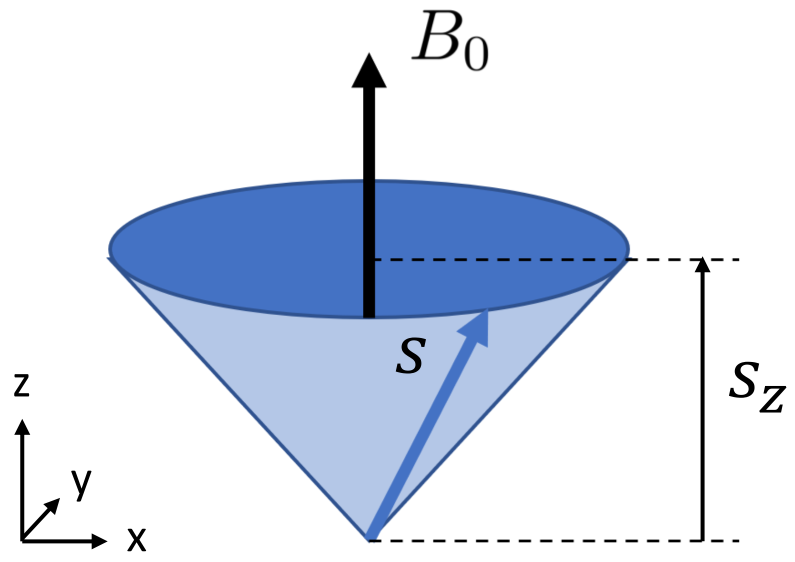


D. Aybas *et al*, Search for axion-like dark matter using solid-state nuclear magnetic resonance, Phys. Rev. Lett. 126 (14), 141802

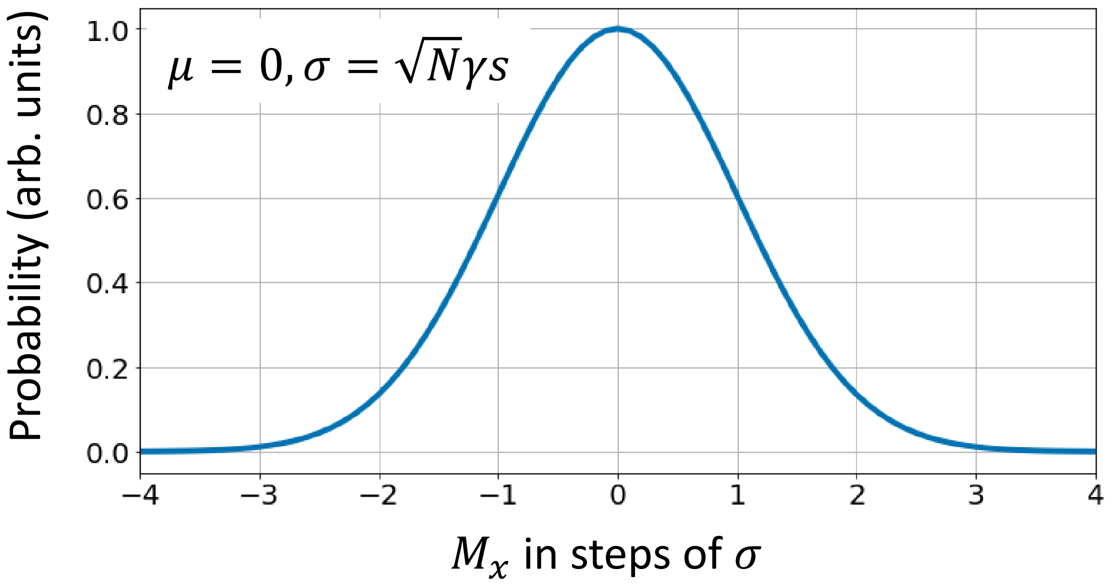
Spin projection noise 1, Heisenberg

$$[s^2, s_z] = [s^2, s_z] = [s^2, s_z] = 0$$
$$[s_x, s_z] = i\hbar s_y$$
$$[s_y, s_z] = i\hbar s_x$$

Measurement of s_x of a spin in the state $\{s, s_z\}$ will yield $s_x = \pm|m_s|$ with 50 % probability each



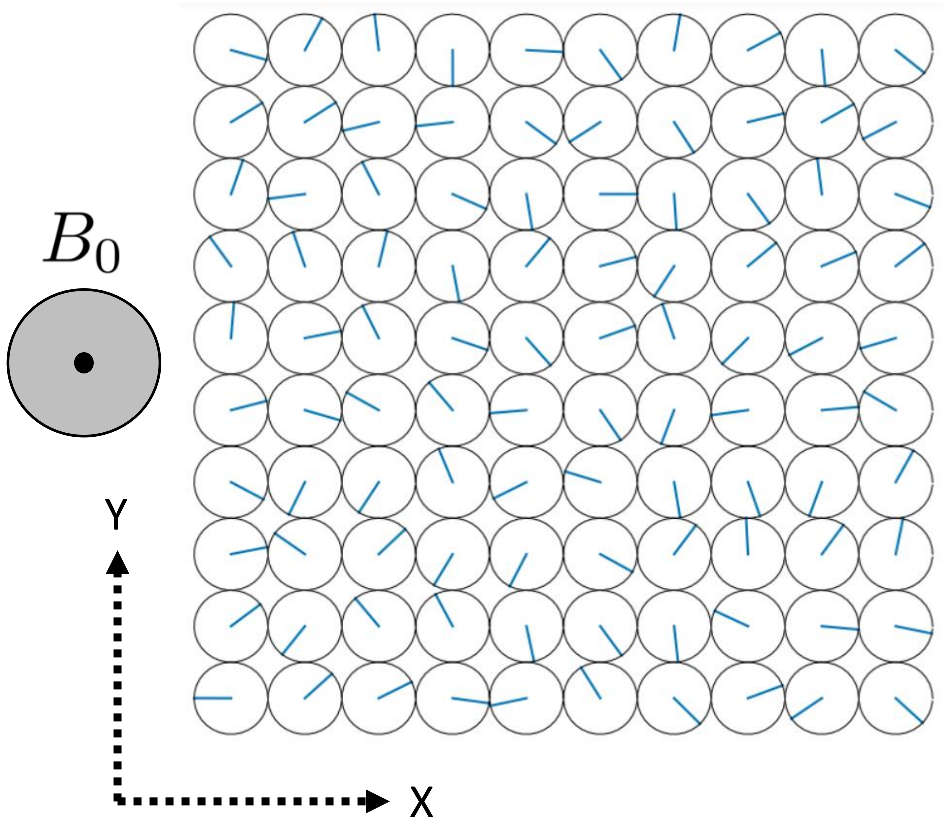
Central limit theorem: for N independent spins the magnetization $M_x \propto \sum_N m_s$ follows the normal distribution

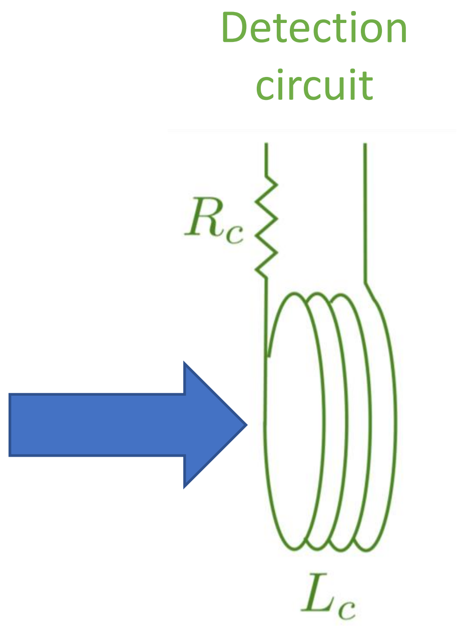


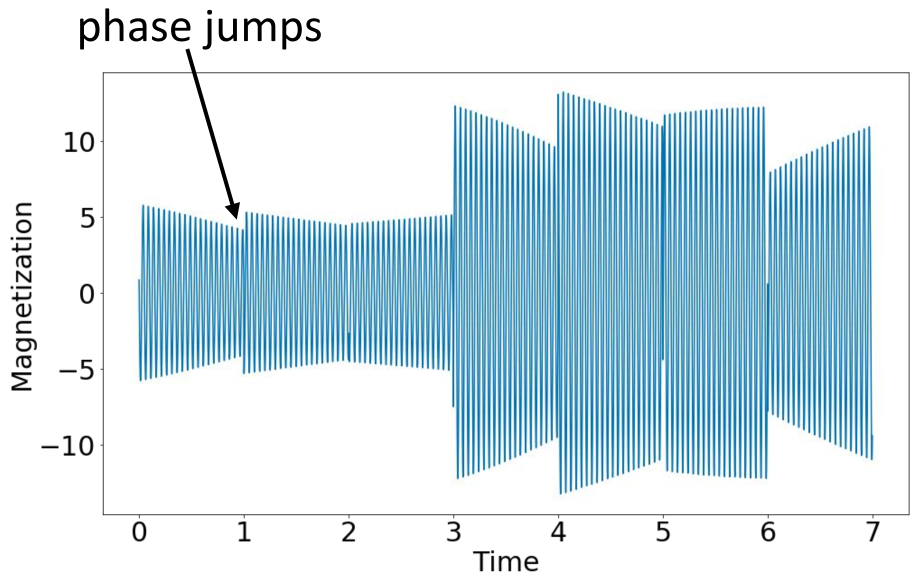
Spin projection noise 2, Bloch

"Even in the absence of any orientation by an external magnetic field one can expect in a sample with N nuclei of magnetic moment μ_N to find a resultant moment of the order $\sqrt{N}\mu_N$ because of statistically incomplete cancellation."

100 precessing spins with random phases





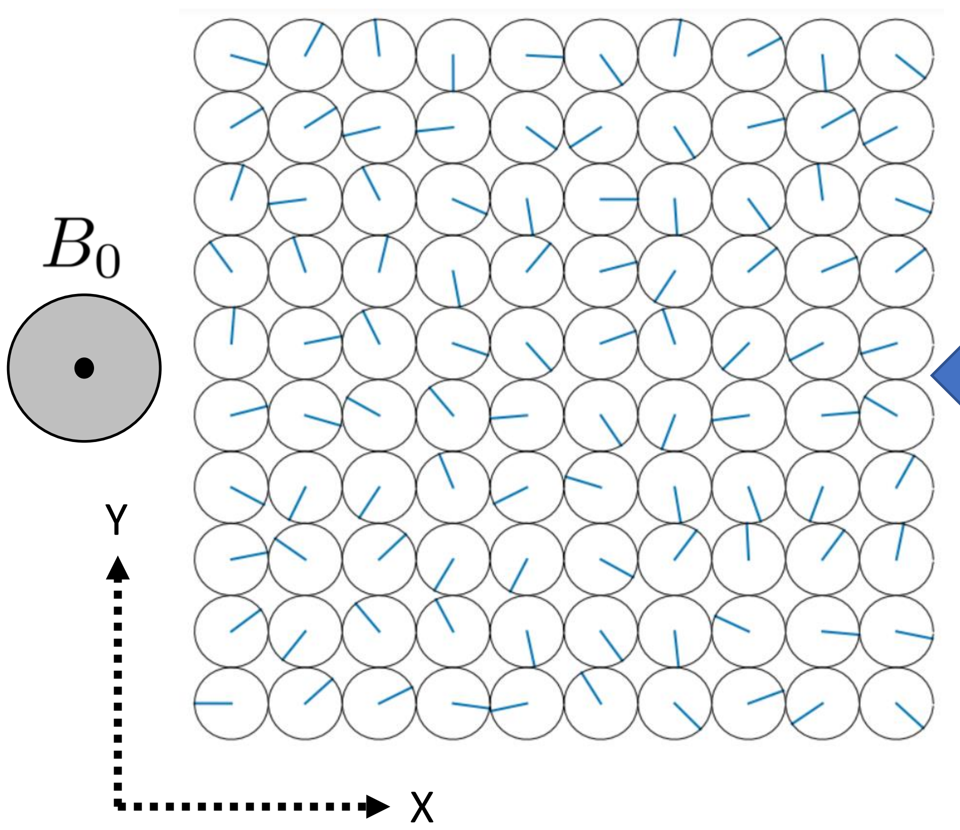


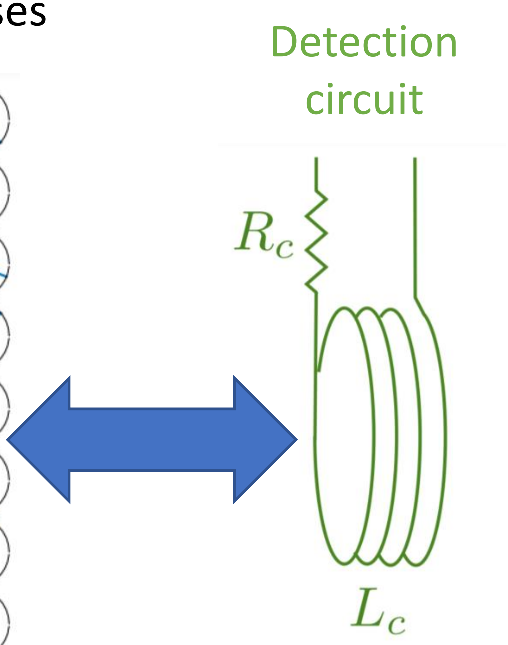
$$\frac{M_x^{\frac{\pi}{2}\text{pulse}}}{M_x^{\text{noise}}} \approx \frac{N \cdot Pol}{\sqrt{N}} = \frac{10^{22} \cdot 10^{-6}}{\sqrt{10^{22}}} = 10^5$$

F. Bloch, "Nuclear Induction." *Phys.Rev.* 70, no. 7–8 (October 1, 1946): 460–74

Spin projection noise 2, Bloch

100 precessing spins with random phases





Two contributions to NMR spin noise

1. Spin projection noise
2. Back action (absorbed circuit noise, Jerschow *et al*)
    - Historically called "radiation damping" in the NMR community
    - Described by relaxation mechanism with characteristic time T_r -> line broadening

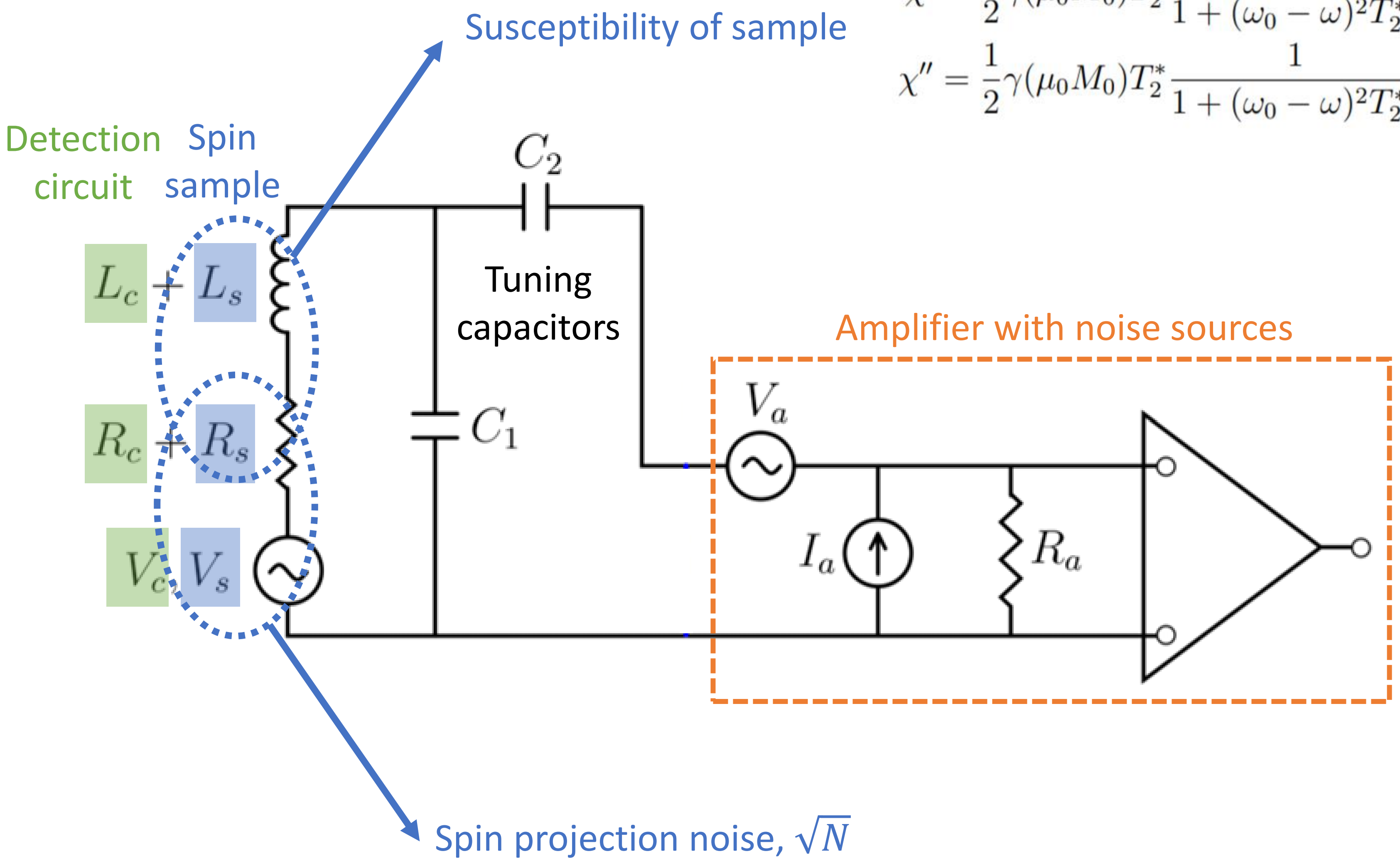
$$\frac{1}{T_r} = \frac{1}{2} q Q_c \gamma \mu_0 M_0$$

q filling factor
Q_c coil Q-value
γ spin gyromagnetic ratio
μ_0 permeability of free space
M_0 sample magnetization

N. Mueller, A. Jerschow, and J. Schlagnitweit, Nuclear Spin Noise, eMagRes. Vol. 2. 2. Chichester, UK: John Wiley & Sons, Ltd, 2013, pp. 237–243

Equivalent network

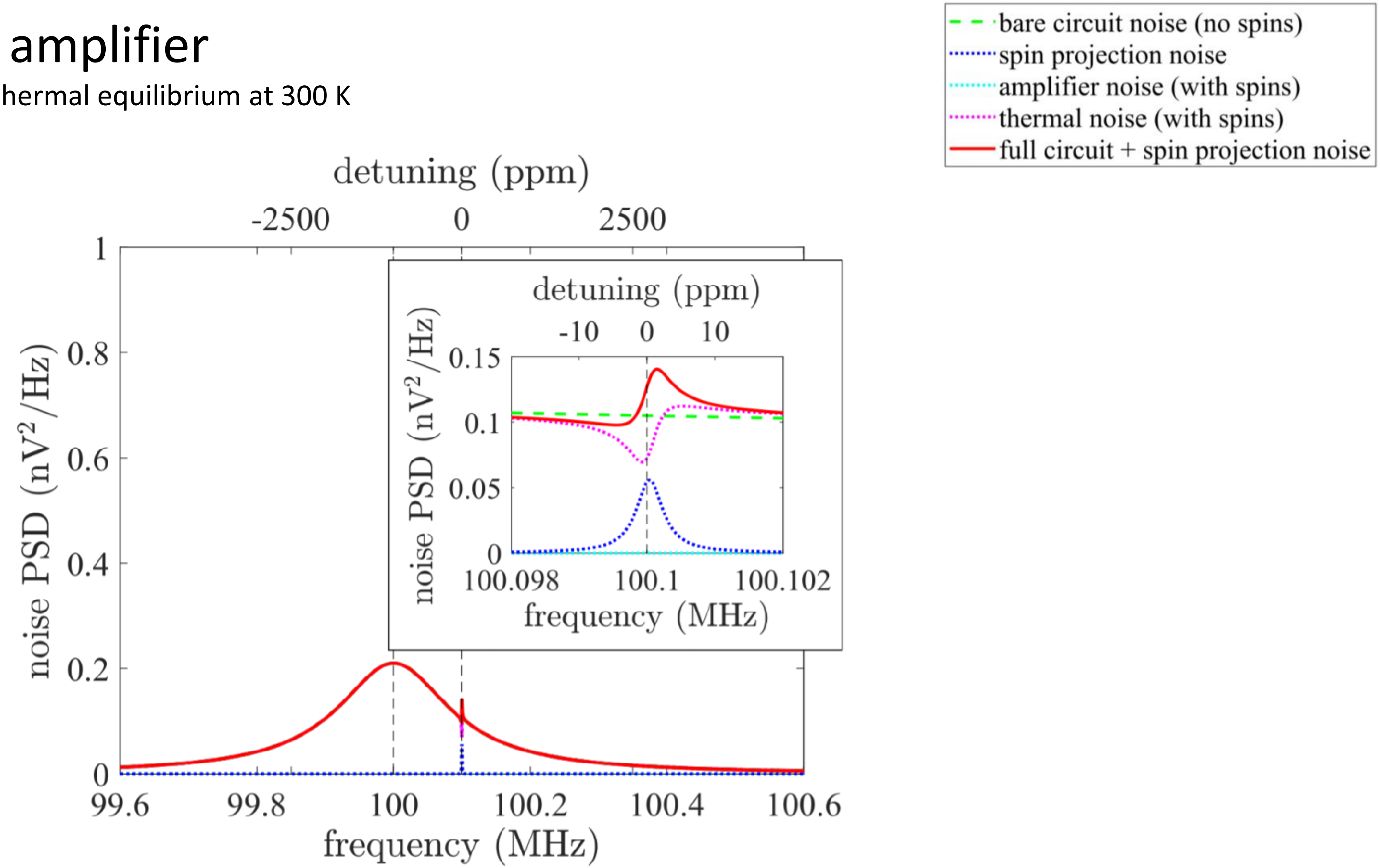
$$\chi' = \frac{1}{2}\gamma(\mu_0 M_0)T_2^* \frac{(\omega_0 - \omega)T_2^*}{1 + (\omega_0 - \omega)^2 T_2^{*2}},$$
$$\chi'' = \frac{1}{2}\gamma(\mu_0 M_0)T_2^* \frac{1}{1 + (\omega_0 - \omega)^2 T_2^{*2}}.$$



D. Aybas *et al*, Quantum sensitivity limits of nuclear magnetic resonance experiments searching for new fundamental physics, Quantum Science and Technology, Focus on Quantum Sensors for New-Physics Discoveries (2021)

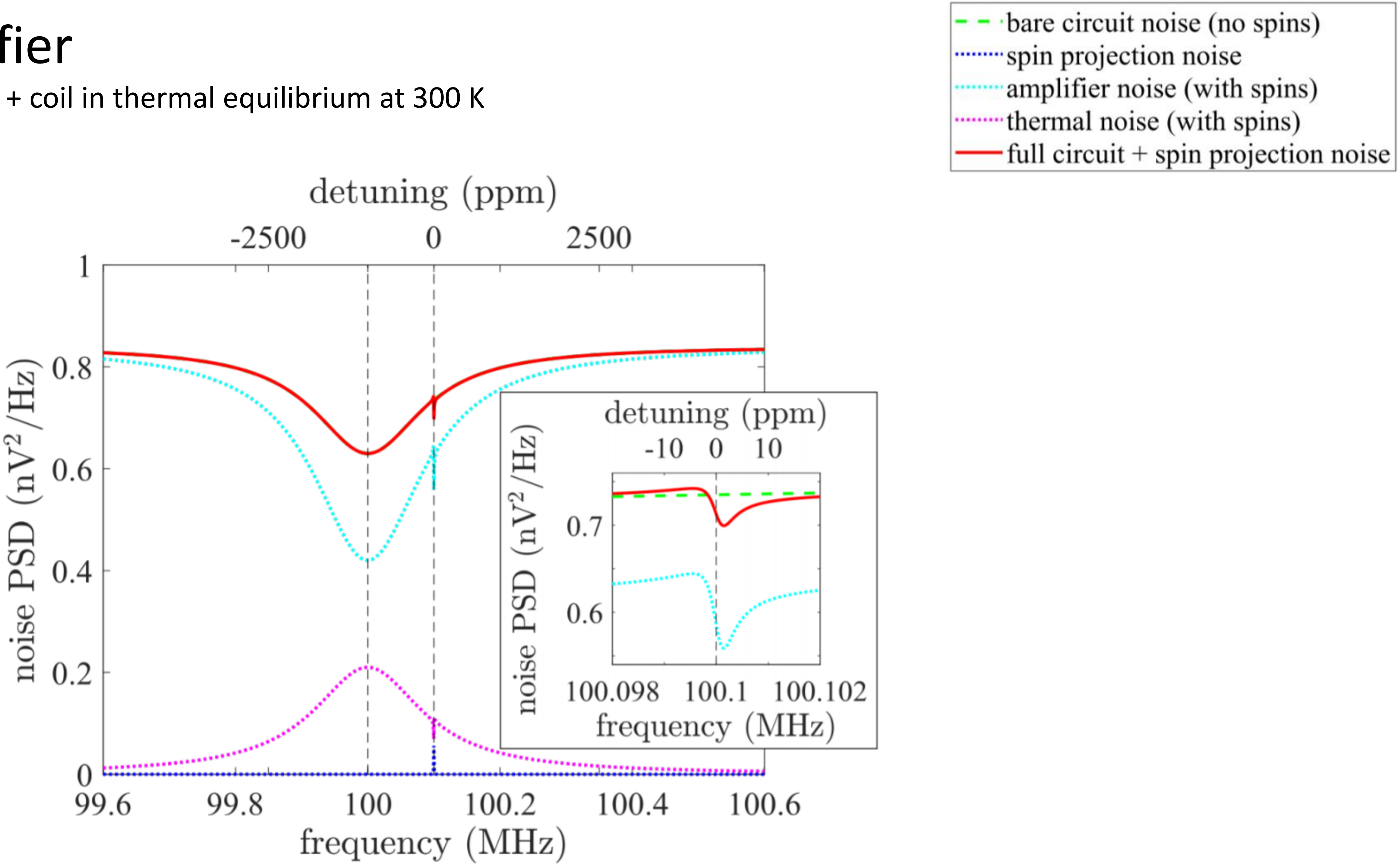
Noiseless amplifier

Sample + coil in thermal equilibrium at 300 K



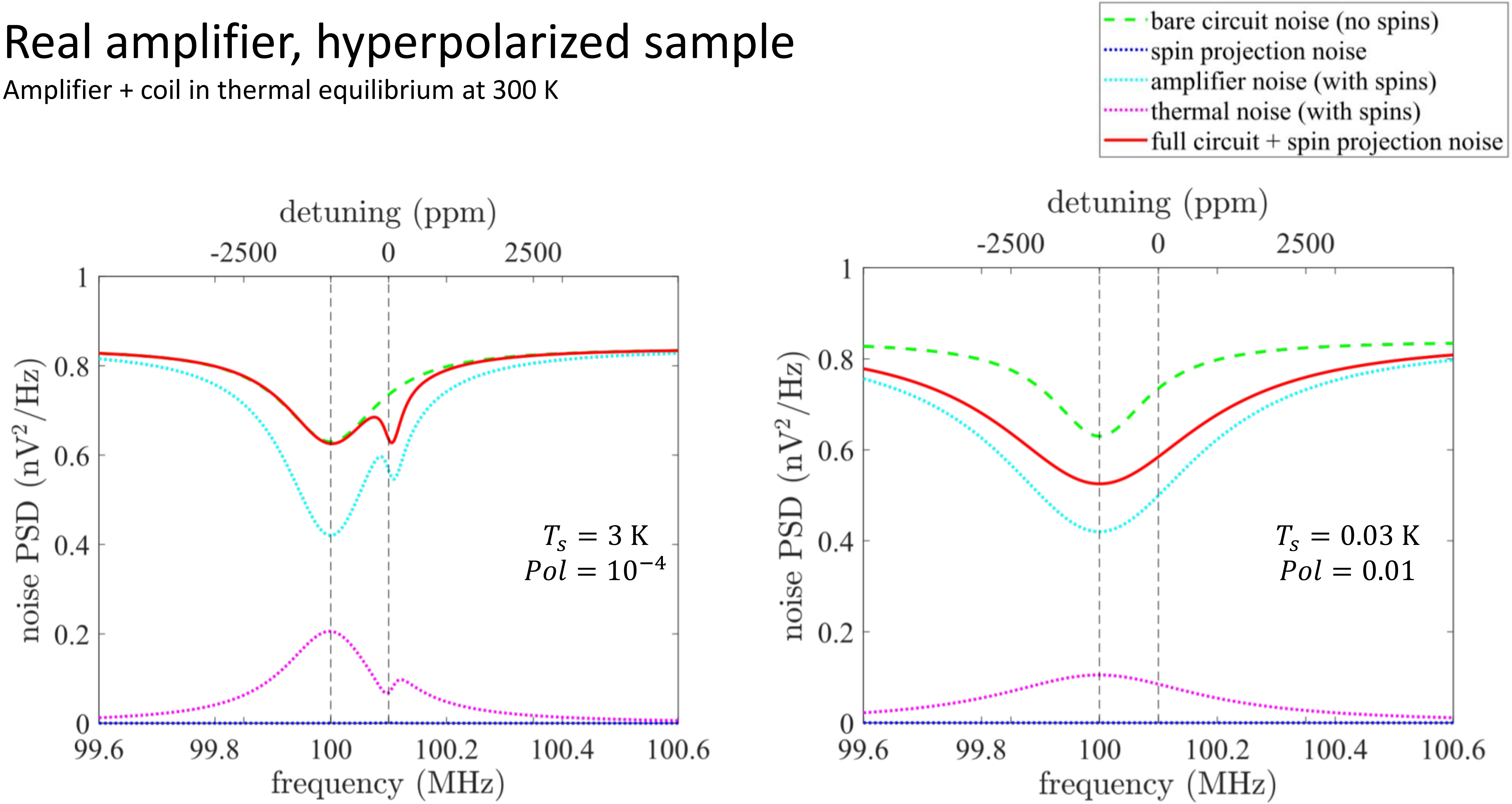
Real amplifier

Amplifier + sample + coil in thermal equilibrium at 300 K

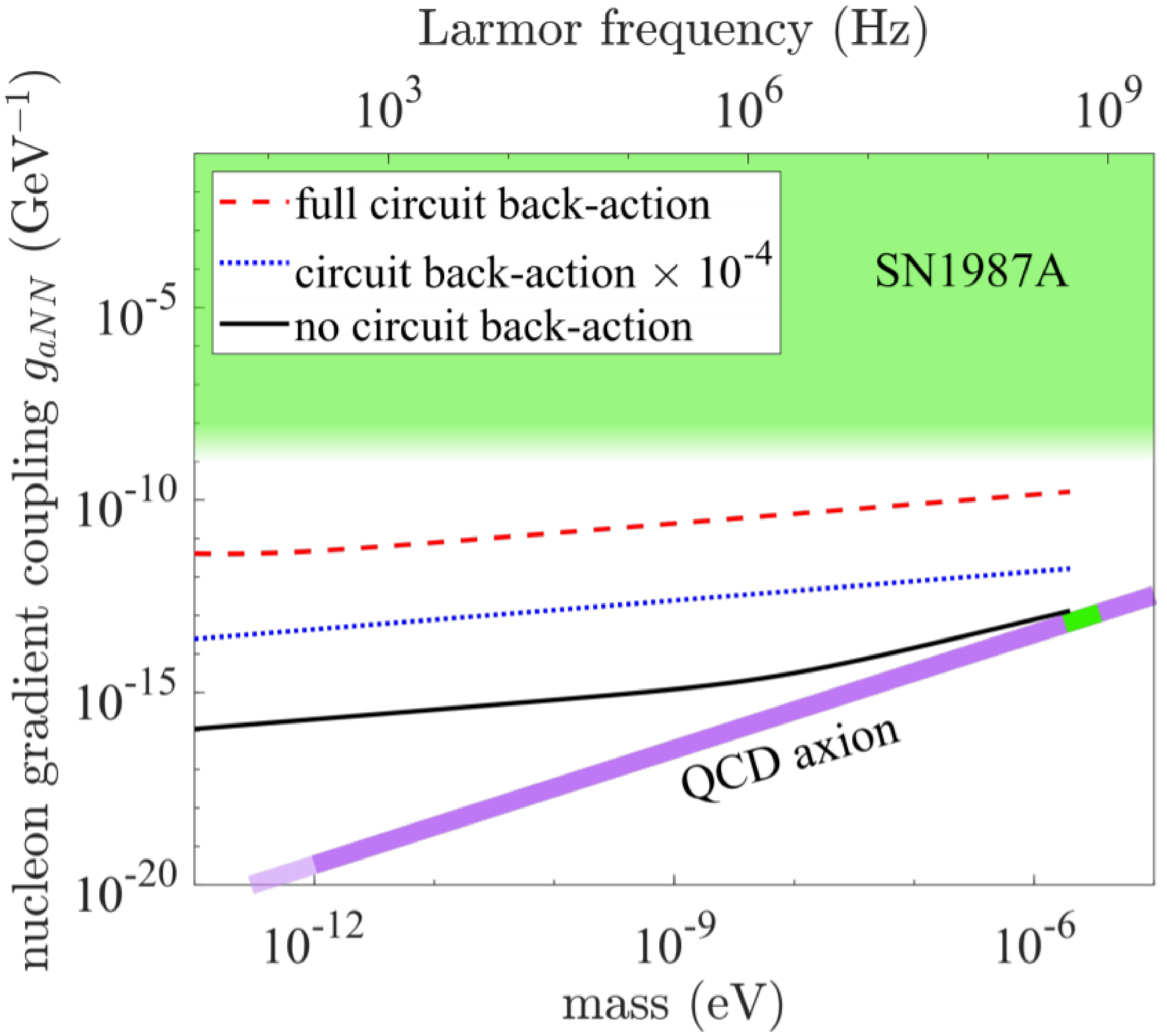


Real amplifier, hyperpolarized sample

Amplifier + coil in thermal equilibrium at 300 K



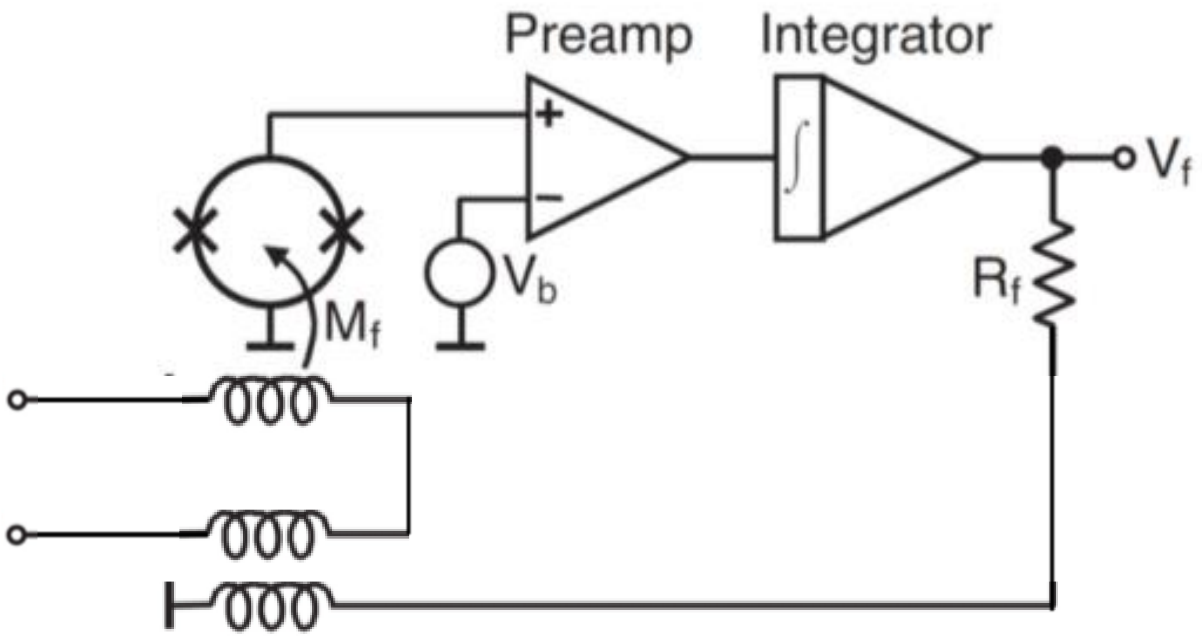
Noise limit including back action



$2 \cdot 10^{26}$ spins, $Q_C = 10^3$

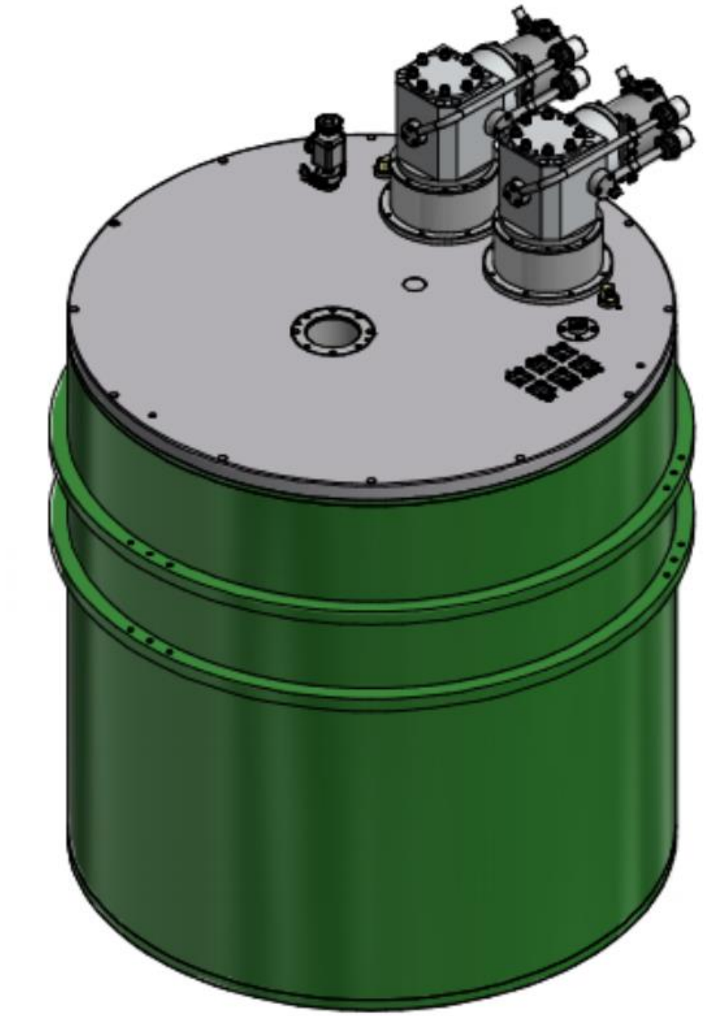
Back-action evasion in SQUIDs

Flux-locked loop network
compensates flux in SQUID



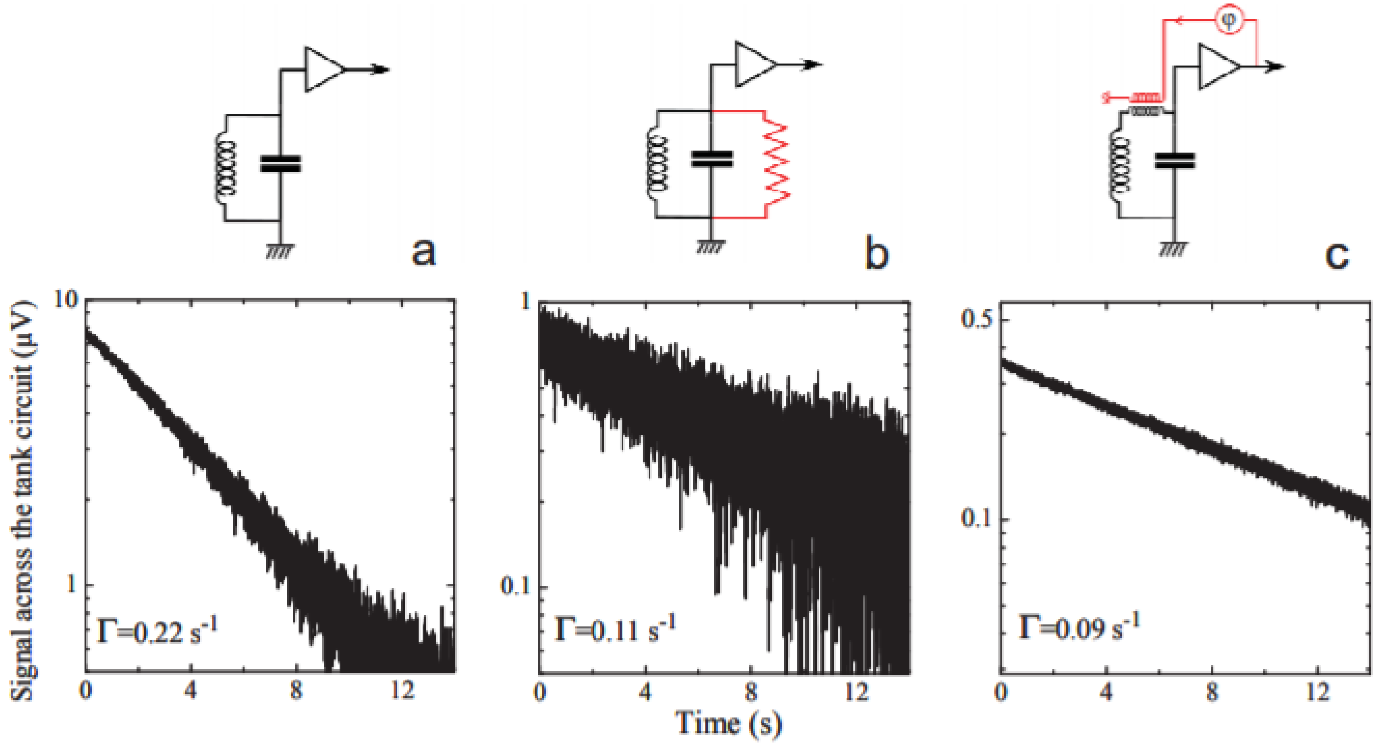
Gradiometer

CASPEr-gradient high field



- Magnet and cryostat in production
  - 0 - 14.1 T
  - Actively shielded
  - Warm bore
- Classical NMR probe to be designed
  - Optimized for DM search
  - Q-switching?
  - Active feedback?

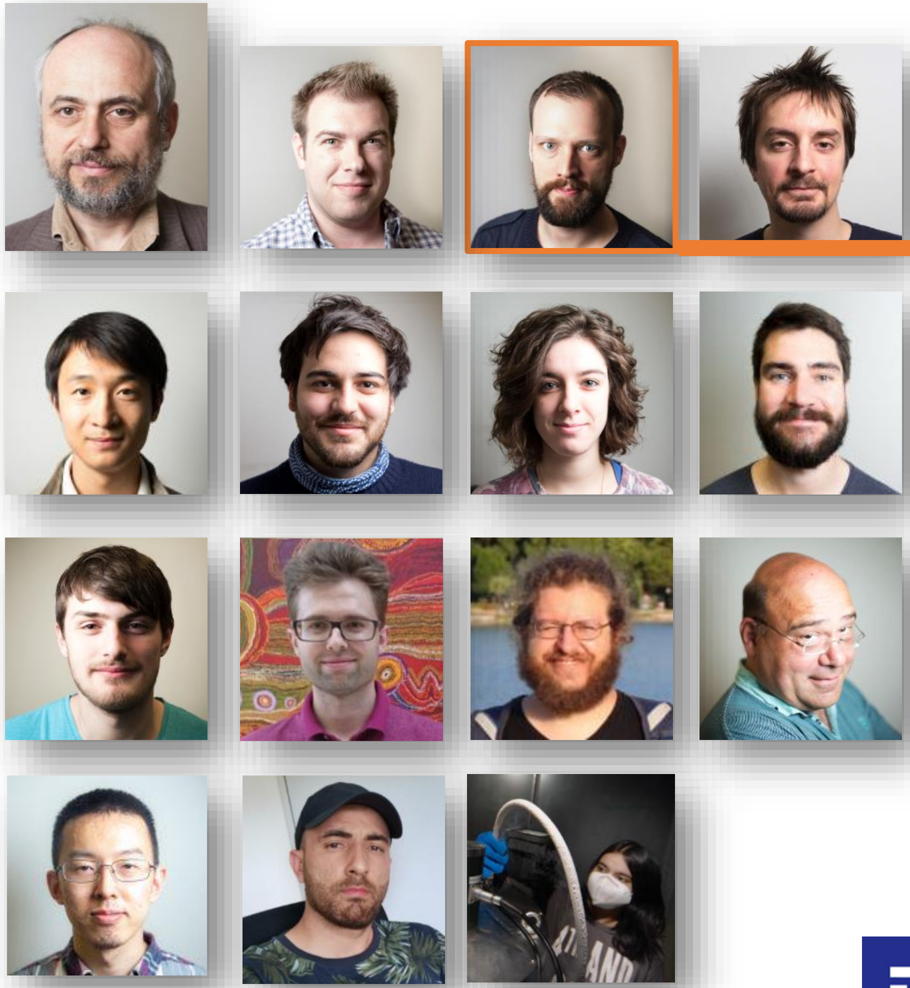
$$\frac{1}{T_r} = \frac{1}{2} q Q_c \gamma \mu_0 M_0$$



E Baudin *et al*, An active feedback scheme for low field NMR experiments, 2011 *J. Phys.: Conf. Ser.* **294** 012009

Acknowledgements

HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz
GSI
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Stockholm University



Dr. Arne Wickenbrock
Tomorrow at 15:45
“The spectral lineshape of gradient-coupled bosonic dark matter in our galaxy”

Dr. Deniz Aybas today at 16:10
“Searching for axion-like dark matter with CASPEr-electric”

Collaborators

DFG
erc
HEISING - SIMONS FOUNDATION
SIMONS FOUNDATION

Conclusions and outlook

- CASPEr-gradient low field
  - Probe g_{aNN} in mass range $5 \cdot 10^{-12} \; - \; 5 \cdot 10^{-9}$ eV
  - First test measurements on thermal proton spins underway
  - Polarization of 11(3) % achieved for ^{129}Xe
  - Connection of ^{129}Xe to cryostat under construction

- CASPEr-gradient high field
  - Probe g_{aNN} in mass range $10^{-9} - 10^{-6}$ eV
  - Magnet expected Christmas 2021

- Probe design considerations
  - Goal: reach spin projection noise limit
  - Suppress backaction!

D. Aybas *et al*, Quantum sensitivity limits of nuclear magnetic resonance experiments searching for new fundamental physics, Quantum Science and Technology, Focus on Quantum Sensors for New-Physics Discoveries (2021)