Axion with NV diamond

Atsuhiro Umemoto
QUP Postdoc
in Quantum Detector group

QUP workshop at KEK 8th April 2025

Dark matter search with diamond NV center

- a main project of QUP quantum cluster group

⇒ using a magnetic sensing with quantum sensors (NV center) to detect light bosonic dark matter

- a highly sensitive dark matter search with a unique experimental setup realizable only at QUP

Member for NV center experiment

Quantum Detector

Masaya Hasegawa

QUP Principal Investigator

Associate Professor

KEK, IPNS

e-mail masaya.hasegawa-at-kek.jp

more

Hideo Iizuka PI

QUP Principal Investigator

Senior fellow / Professor

Toyota Central R&D Labs. / KEK

e-mail

hiizuka-at-mosk.tytlabs.co.jp

more

Tsutomu Mibe

QUP Senior Scientist

Professor

KEK, IPNS

e-mail mibe-at-post.kek.jp

more

Atsuhiro Umemoto

QUP Postdoctoral Fellow

more

Norikazu Mizuochi

QUP Affiliate member

Professor

Institute for Chemical Research (ICR), Kyoto University

e-mail

mizuochi-at-scl.kyoto-u.ac.jp

more

Kenichi Yatsugi

Toyota Central R&D Labs

Yoshinari Kondo

KEK Cryogenic Group

Member for NV center experiment

Quantum Detector

Masaya Hasegawa

- research facilities
- support for physics data analysis

Tsutomu Mibe

- research facilities
- support for physics data analysis

Hideo Iizuka PI

QUP Principal Investigator

Senior fellow / Professor

- MW antenna design

hiizuka-at-mosk.tytlabs.co.jp

more

Atsuhiro Umemoto

- Constructing the entire experimental setup
- Dark matter search

Norikazu Mizuochi

QUP Affiliate member

- Experimental expert in NV centers
- Technical support

more

Kenichi Yatsugi

Toyota Central R&D Labs

- MW antenna fabrication

Yoshinari Kondo

KEK Cryogenic Group

- Low temp experiment

Light bosonic dark matter search

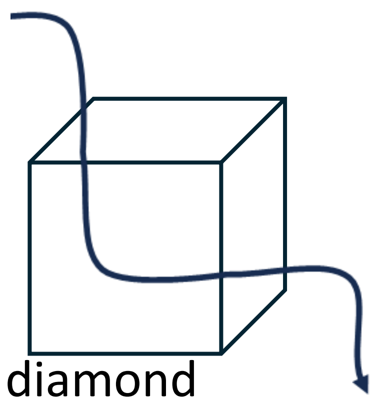
JHEP PUBLISHED FOR SISSA BY SPRINGER

Light dark matter search with nitrogen-vacancy centers in diamonds

So Chigusa[a,b] Masashi Hazumi[c,d,e,f,g] Ernst David Herbschleb[h]
Norikazu Mizuochi[h,i,c] and Kazunori Nakayama[j,c]

J. High Energ. Phys. 2025, 83

new approach for the detection of light dark matter, e.g. axion like particle (ALP)
→ ALP DM behaves like a classical field with respect to spin.



$$\mathcal{L} = -ig_{aee}a(x)\overline{\psi}\gamma_5\psi(x)$$ interaction with Spin 1/2 particle

$$i\hbar\frac{\partial\varphi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_{aee}\hbar}{2m}\vec{\sigma}\cdot\vec{\nabla}a\right]\varphi$$ non-relativistic approximation

$$-\frac{g_{aee}\hbar}{2m}\vec{\sigma}\cdot\vec{\nabla}a = -2\left(\frac{e\hbar}{2m}\right)\left(\frac{1}{2}\vec{\sigma}\right)\cdot\left(\frac{g_{aee}}{e}\vec{\nabla}a\right)$$

spin Axion Magnetic field

$$a(t,\vec{x}) = a_0 cos(m(t-\vec{v}\cdot\vec{x})+\delta)$$

The measurement based on magnetic sensing using NV centers is effective

Sensitivity estimation

* ALP DM search with Ideal setup

axion magnetic field

$$\vec{B}_{\rm eff} = \sqrt{2\rho_{\rm DM}} \times \frac{g_{aee}}{e} \vec{v}_{\rm DM}$$

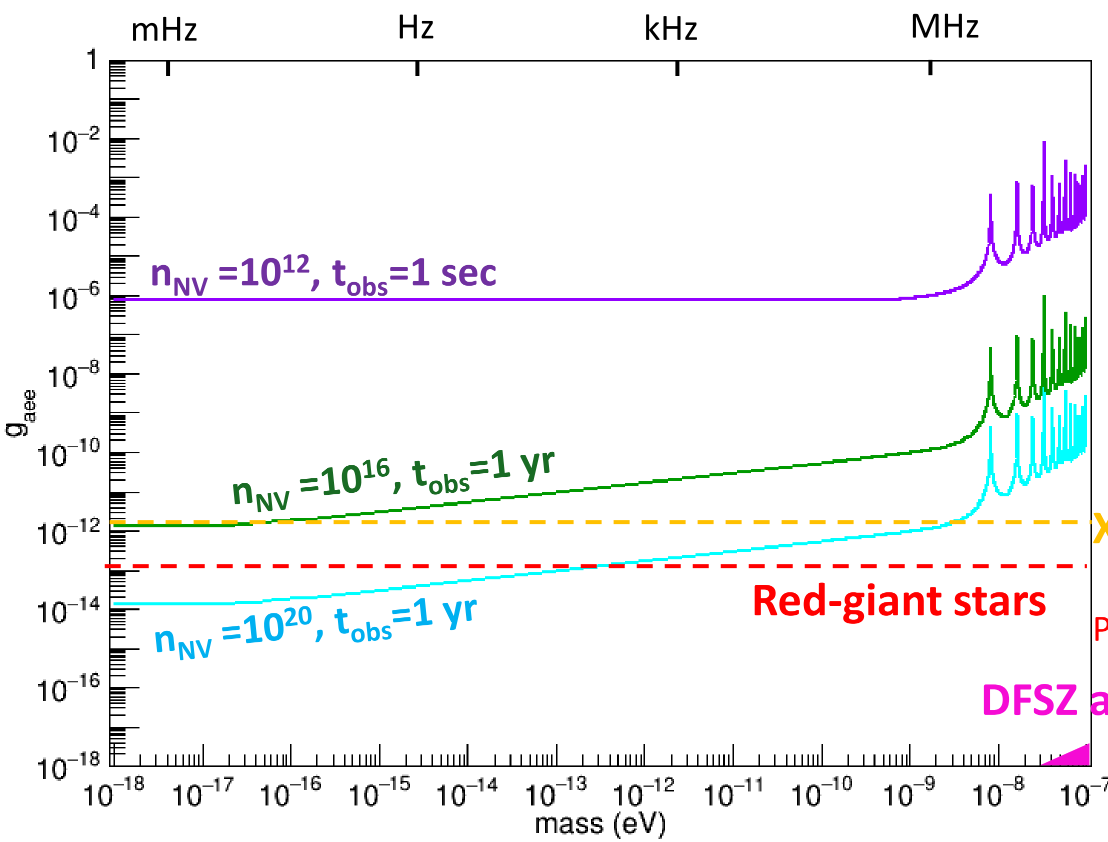
$$\sqrt{2\rho_{\rm DM}}\, v_{\rm DM} \simeq 1.3 \times 10^{-8}\,{\rm T}$$

Typical size of DM signal using NV

$$\sqrt{\langle S^2 \rangle} = \frac{\gamma_e B_z^{\rm eff}}{2m} \sqrt{1-\cos(m\tau)}.$$

DM coherence time

$$\tau_{\rm DM} \simeq (m v_{\rm DM}^2)^{-1} \simeq 6.6\,{\rm s}\,(m/10^{-10}\,{\rm eV})^{-1}$$



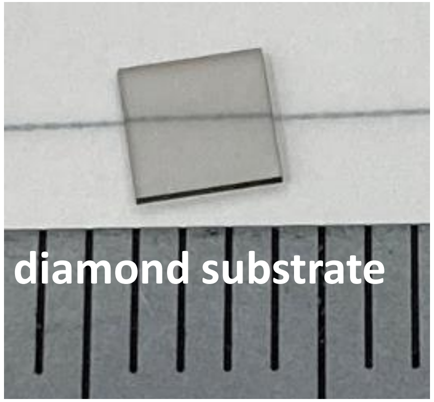
Phys. Rev. Lett. **129**, 161805 (2022)

Phys. Rev. D **102**, 083007 (2020),

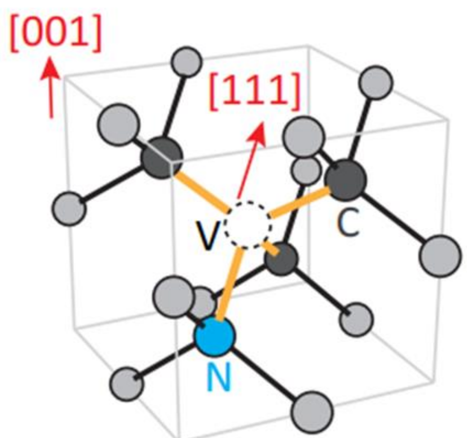
0.4 g diamond (NV 1 ppm ~1.6 × 10^{17}/cc) x 1yr achieves XENONnT (solar axion search, with 5.9 ton effective LXe detector) experiment.

⇒ aim to detect ALP DM with a sensitivity surpassing XENONnT experiment by 2030

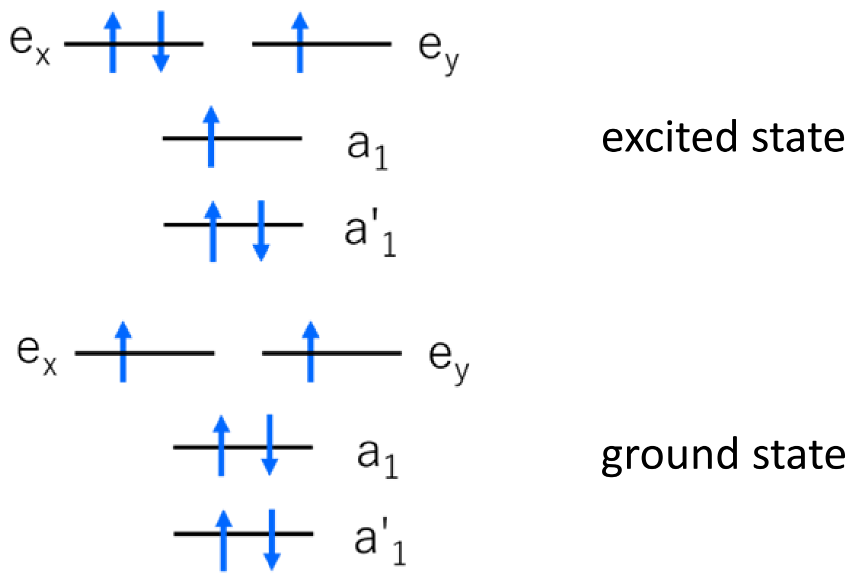
Diamond nitrogen vacancy (NV) center

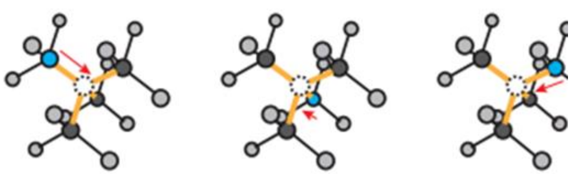


- defect with nitrogen (substituting for carbon) and vacancy
- generated by ion implantation or electron beam irradiation or formed naturally during the diamond growth process



spin-triplet S = 1





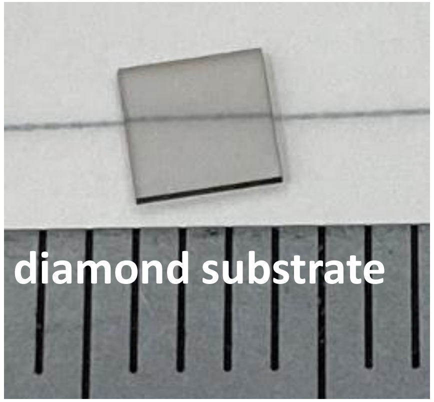
[$\bar{1}1\bar{1}$] [$\bar{1}\bar{1}1$] [$1\bar{1}\bar{1}$]

4 directions of NV center

Six electrons from surrounding carbon and nitrogen atoms make electron spin in a spin-triplet state

Sasaki, 20210603_natsugaku_text.pdf (2021)

Diamond nitrogen vacancy (NV) center



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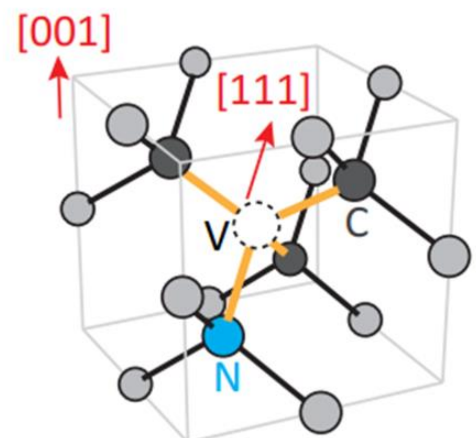
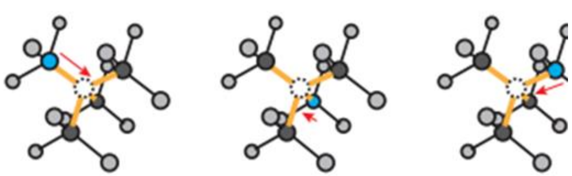
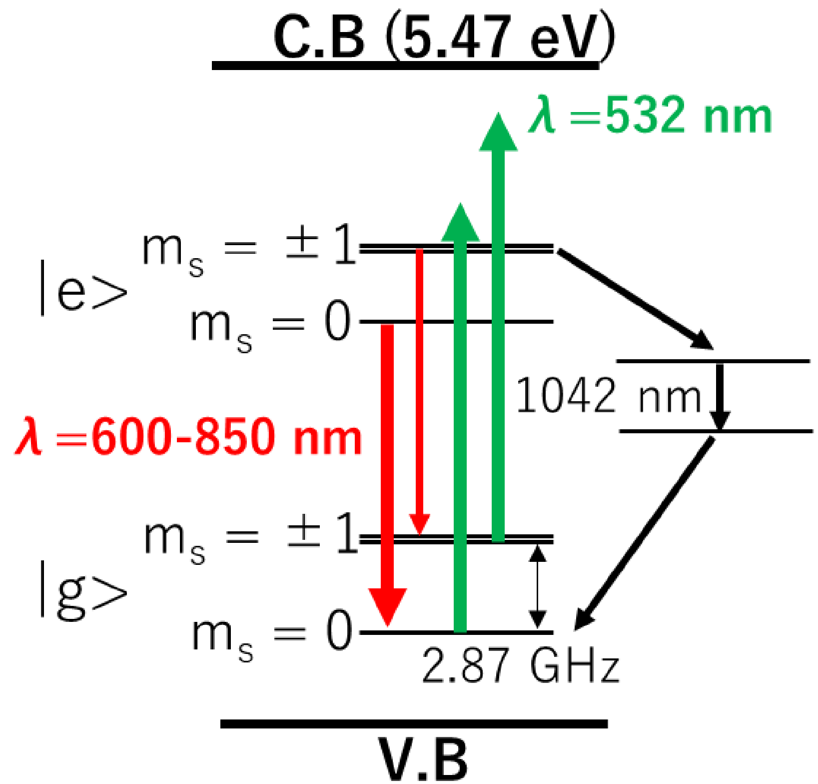






$[\bar{1}1\bar{1}]$ $[\bar{1}\bar{1}1]$ $[1\bar{1}\bar{1}]$

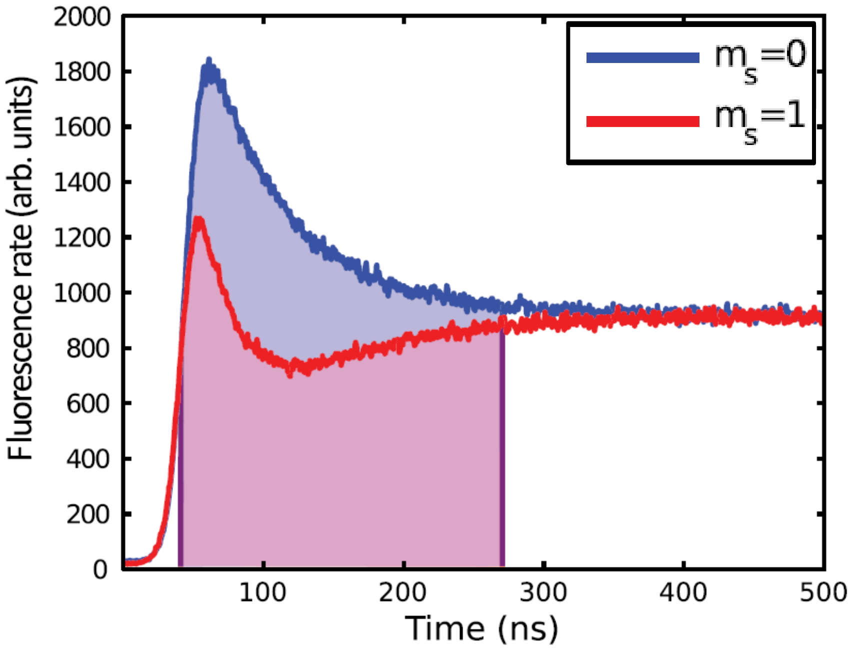
4 directions of NV center

- Optical pumping for spin initialize to $m_s = 0$
- Photoluminescence depended on spin state

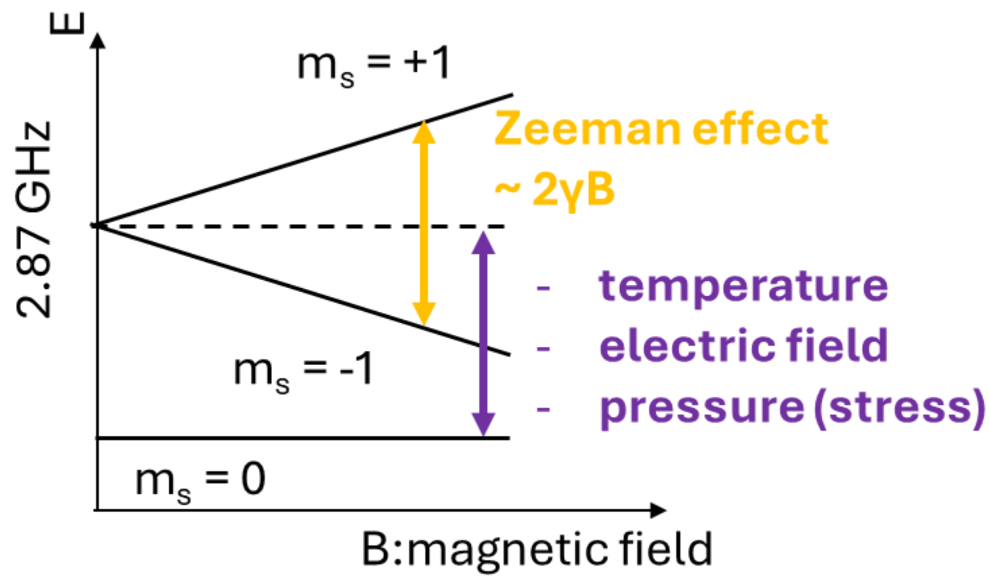
Sasaki, 20210603_natsugaku_text.pdf (2021)

Optical property and response to external field

Photo-luminescence contrast of NV center



response to external field



Spin state recognized from photoluminescence contrast

Works as various types of sensors

Rev. Mod. Phys., Vol. 92, No. 1 (2020)

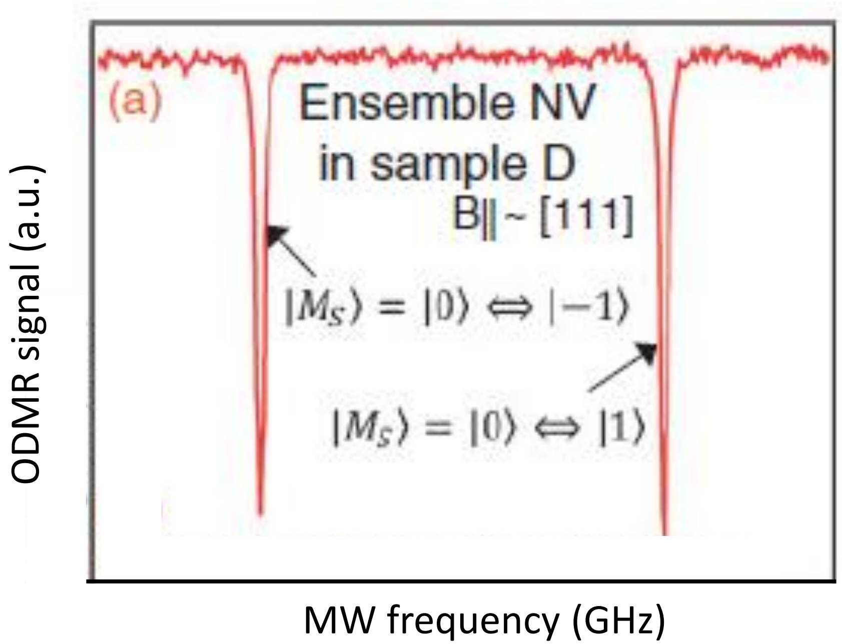
NV axis and Zeeman splitting

Mizuochi group

Applied Physics Express 7, 055201 (2014)
http://dx.doi.org/10.7567/APEX.7.055201

Perfect selective alignment of nitrogen-vacancy centers in diamond

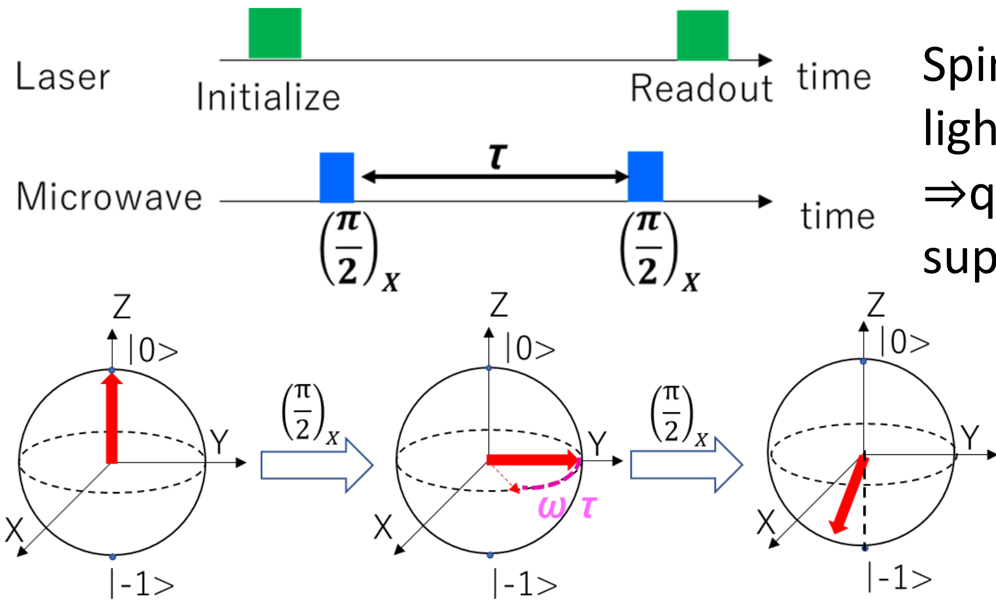
Takahiro Fukui[1], Yuki Doi[1], Takehide Miyazaki[2], Yoshiyuki Miyamoto[2], Hiromitsu Kato[3,4], Tsubasa Matsumoto[3,4], Toshiharu Makino[3,4], Satoshi Yamasaki[3,4], Ryusuke Morimoto[5], Norio Tokuda[5], Mutsuko Hatano[4,6], Yuki Sakagawa[1], Hiroki Morishita[1,4], Toshiyuki Tashima[1,4], Shinji Miwa[1,4], Yoshishige Suzuki[1,4], and Norikazu Mizuochi[1,4*]



more than 99% of the NVs can be aligned along the [111] axis in high-quality diamond
⇒ 4 times large number of sensors

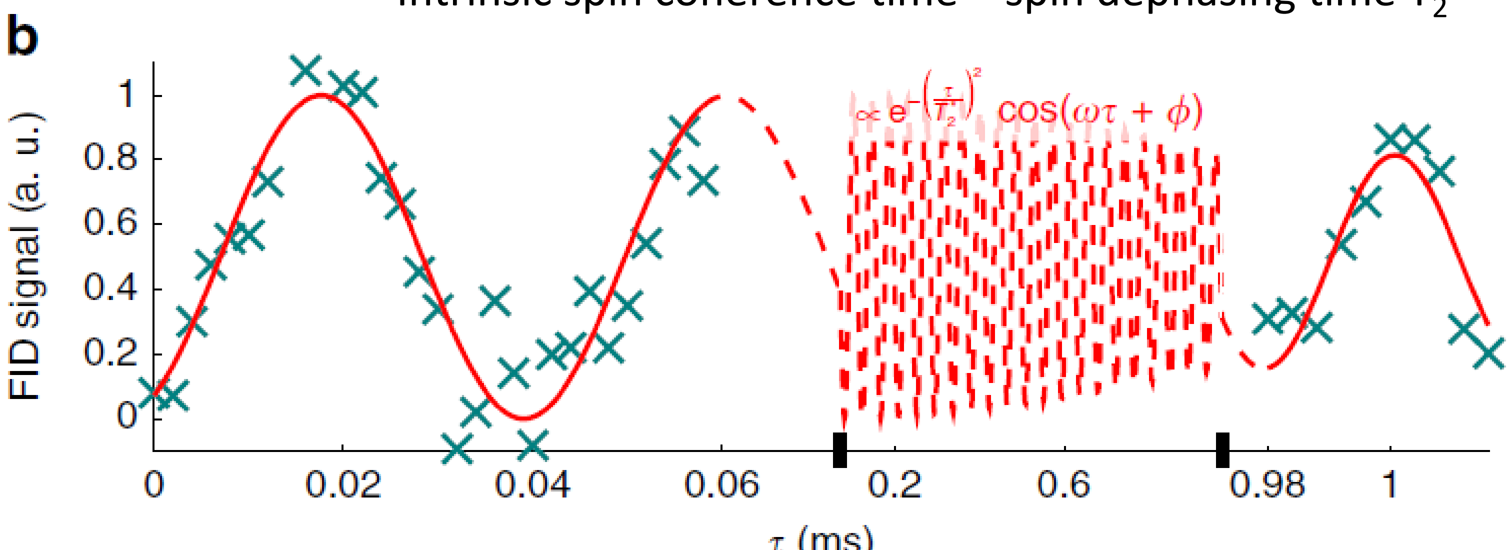
We will use this perfect aligned NV center diamond for DM search

two level system as a quantum sensor



Spin manipulation by green light laser and Microwave
⇒quantum sensing realized by super position of spin two level system

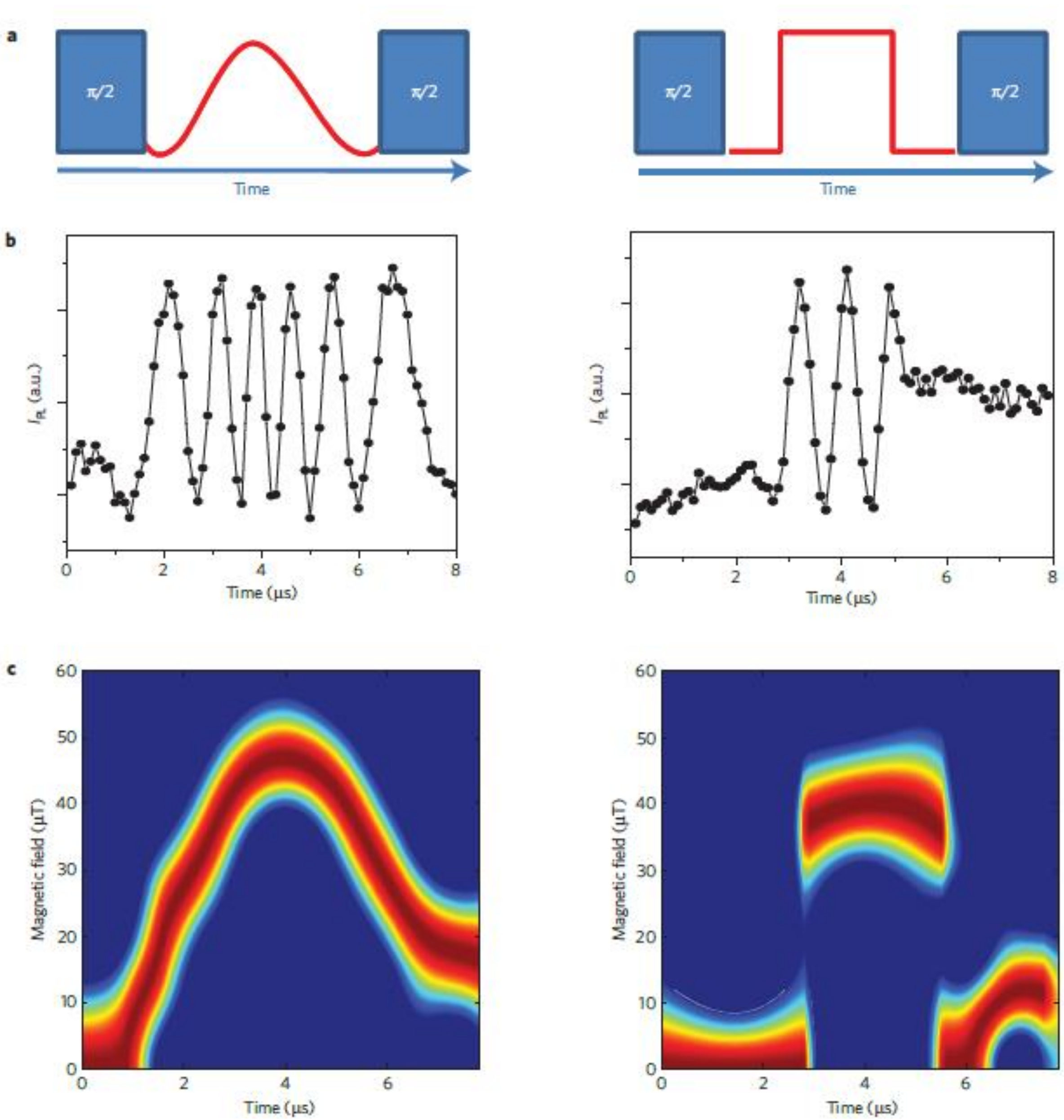
Intrinsic spin coherence time ~ spin dephasing time T_2^*



T_2^* = 1.54 ms

N. Mizuochi, et al., Nat Commun 10, 3766 (2019)

Magnetometry using NV center



Schematic image of input magnetic field

Experimental data

Reconstructed magnetic field

Nature Materials, 8, 383 (2009)

Benefit of low temperature

$$\eta \propto \frac{1}{\sqrt{n_{NV} T_2}}$$

ideally, determined by the number of NV (n_{NV}) and the spin coherence time (T_2).

NV	temperature	sensitivity	n_{NV}	T_2
Single	RT	9.1 nT/√Hz *1	1	2.4 ms*1
ensemble	RT	9 pT/√Hz*2	1.4×10^{11} / (8.5×10^{-4} mm^3)*2	40 μs*3
Single	77 K		1	0.6 s*4

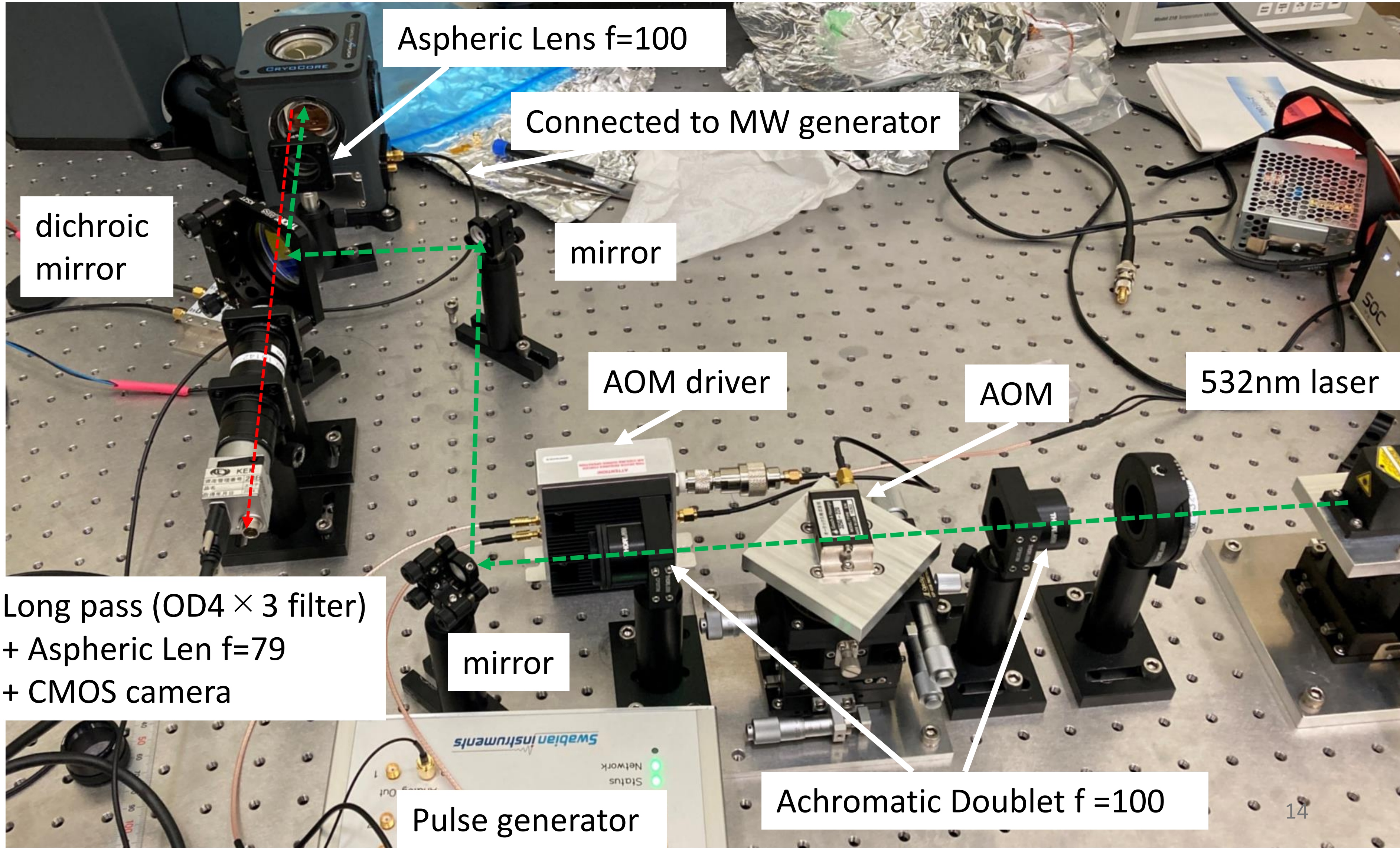
x250

*1 : Nat Commun 10, 3766 (2019), *2: Phys. Rev. X 5, 041001 (2015)
*3 : npj Quantum Inf 8, 95 (2022) ([P1] 5 ppm,NV ensemble, T_2 = 40 μs), *4 : Nat Commun 4, 1743 (2013)

magnetometry using ensemble NV at low temperature is promising
⇒ there are few experiment using ensemble NV at Low temp

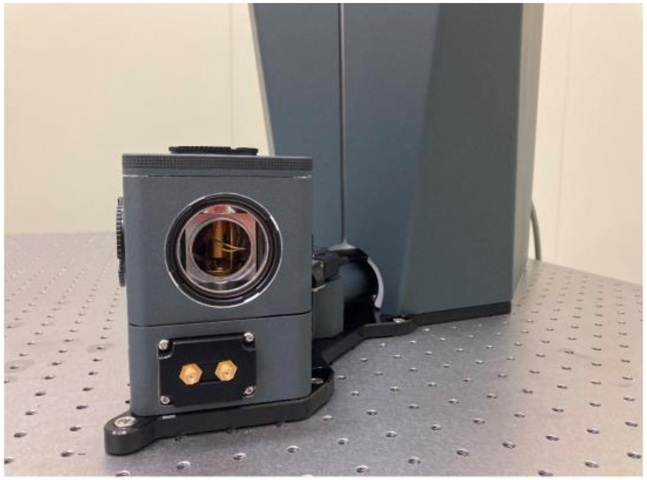
Current measurement setup

Diamond in cryochamber



Cryogenic chamber

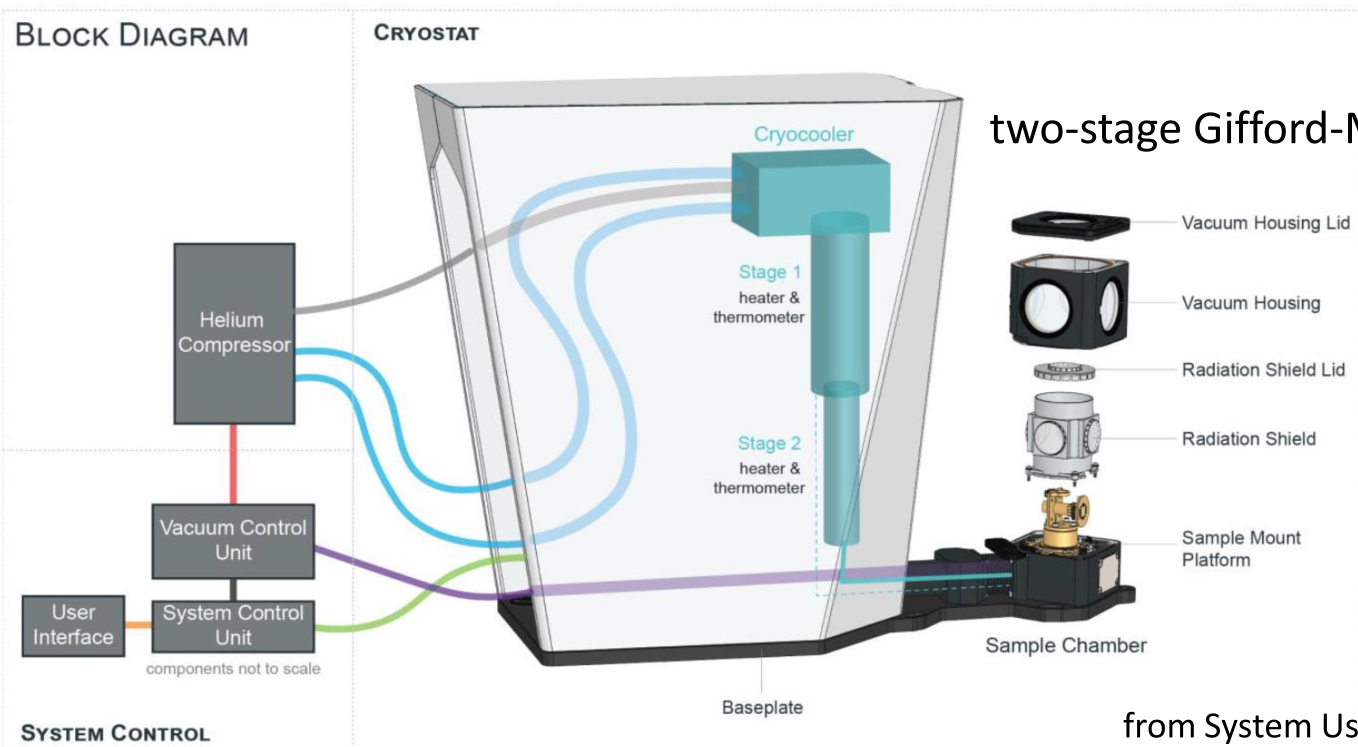
CryoCore (MONTANA INSTRUMENTS)



- Minimum temperature < 4 K
- 5 optical windows
- vibration of sample stage < 50 nm

Chamber : ϕ53 mm x 63 mm

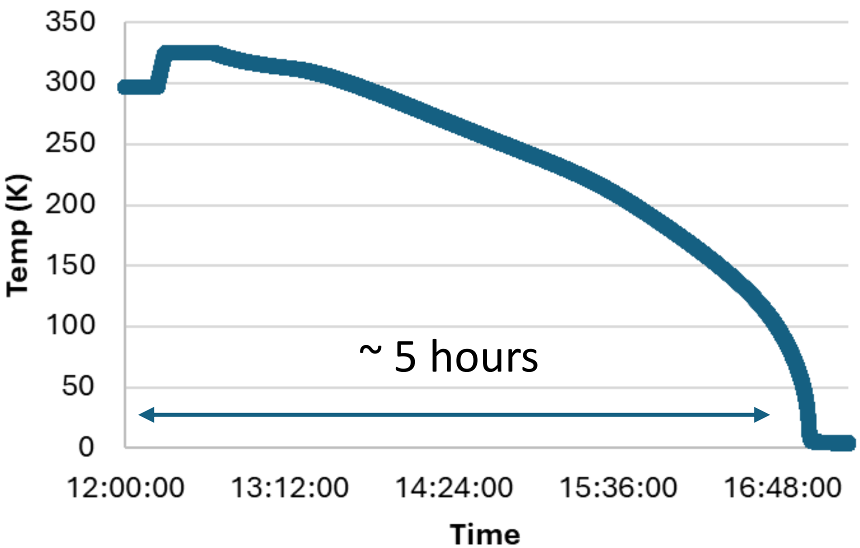
2 RF and 20 DC connectors

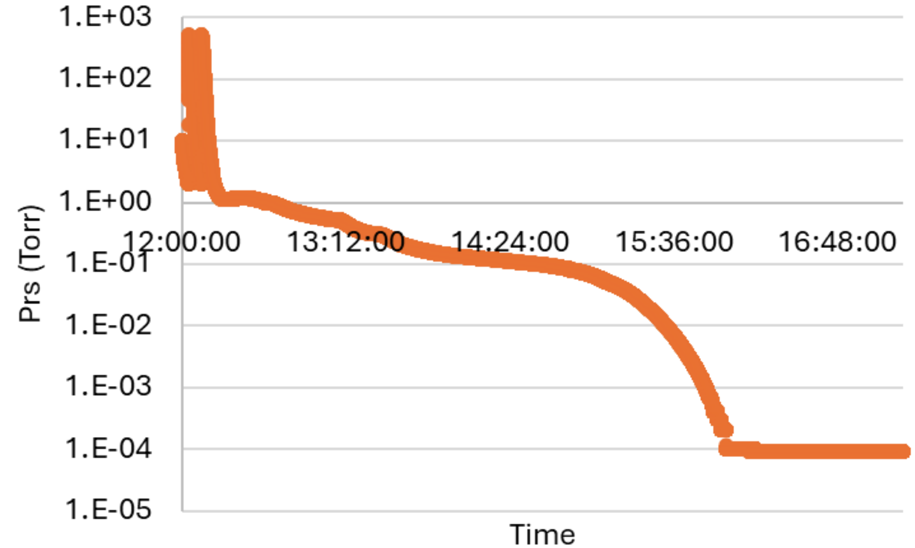


two-stage Gifford-McMahon cryocooler

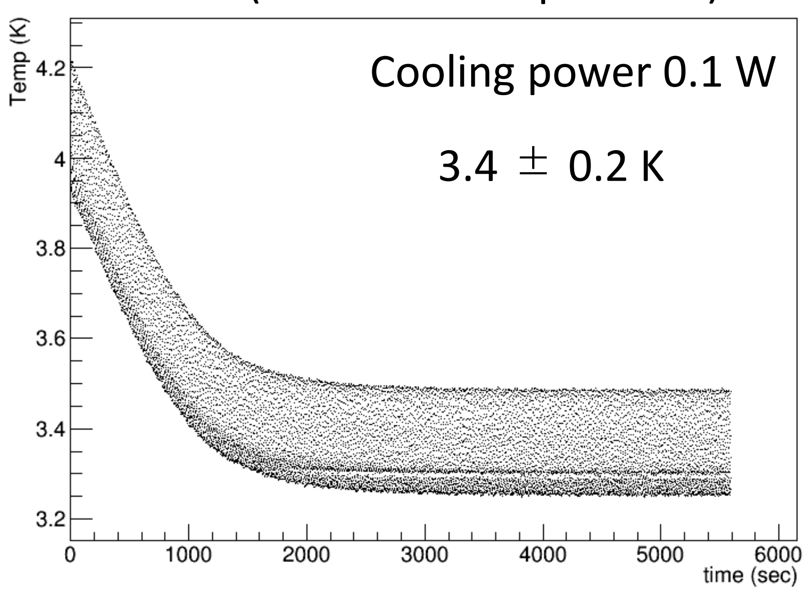
from System User Manual

Operation and cooling power

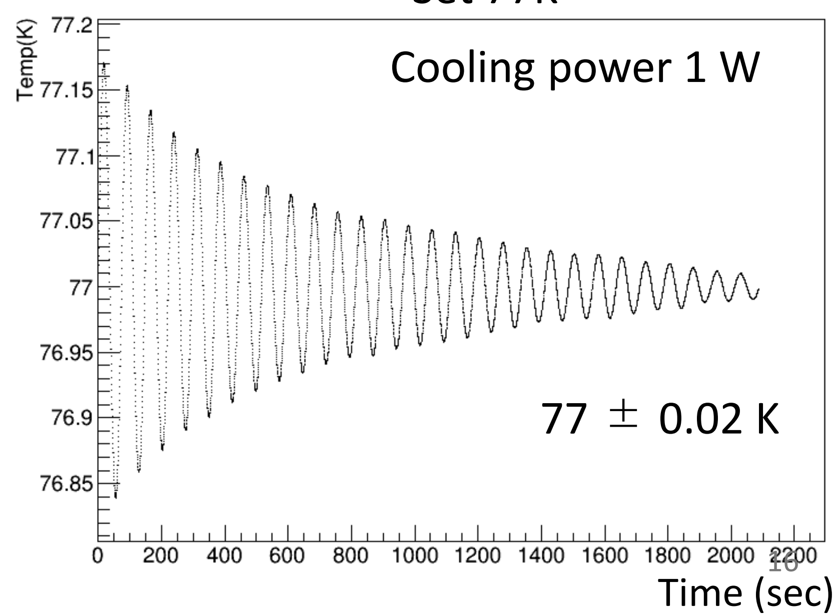




Set 0K (minimum temperature)



Set 77K

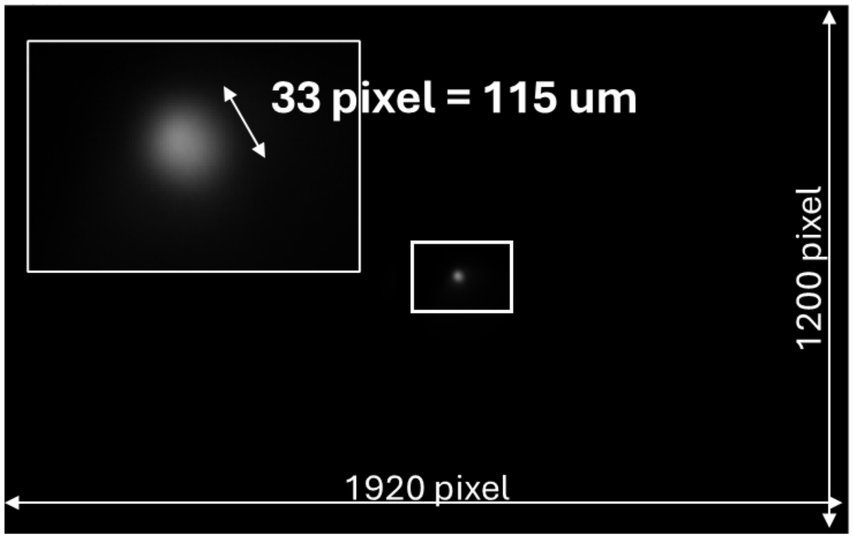


Demonstration result

Preliminary

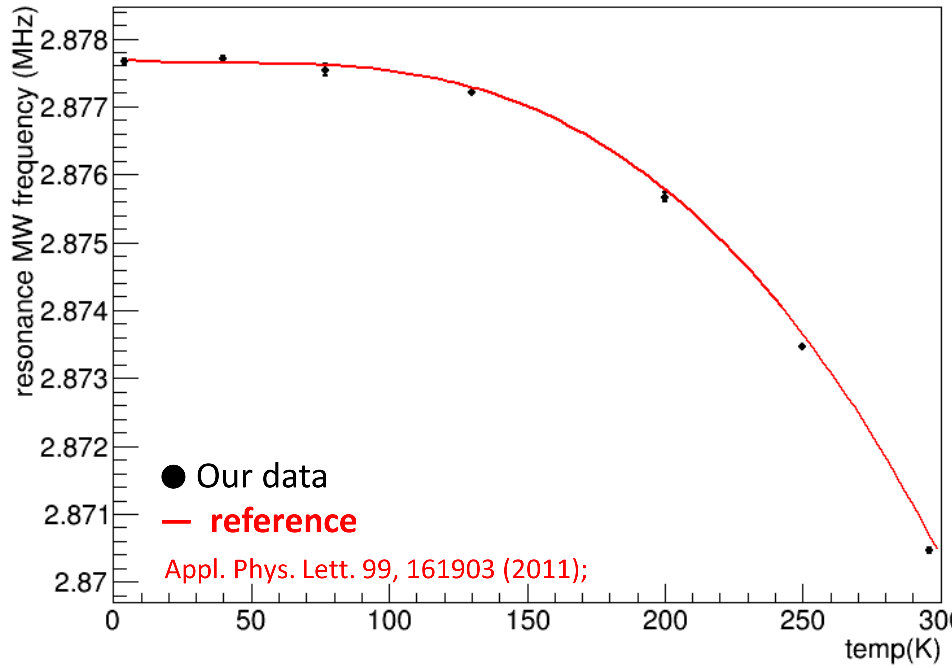
Diamond (commercially available)
- Size : 3x3x0.5 mm
- NV concentration : 4.5 ppm

Laser power set 0.2 W



luminescence detection by CMOS Camera

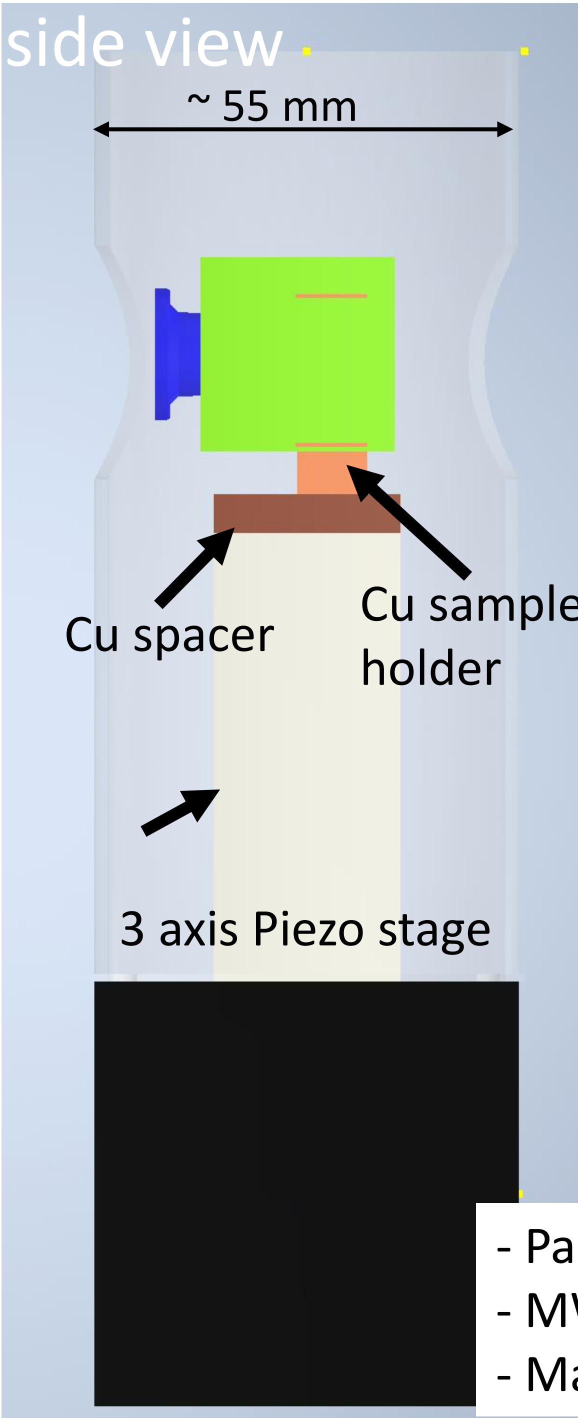
Temperature dependent

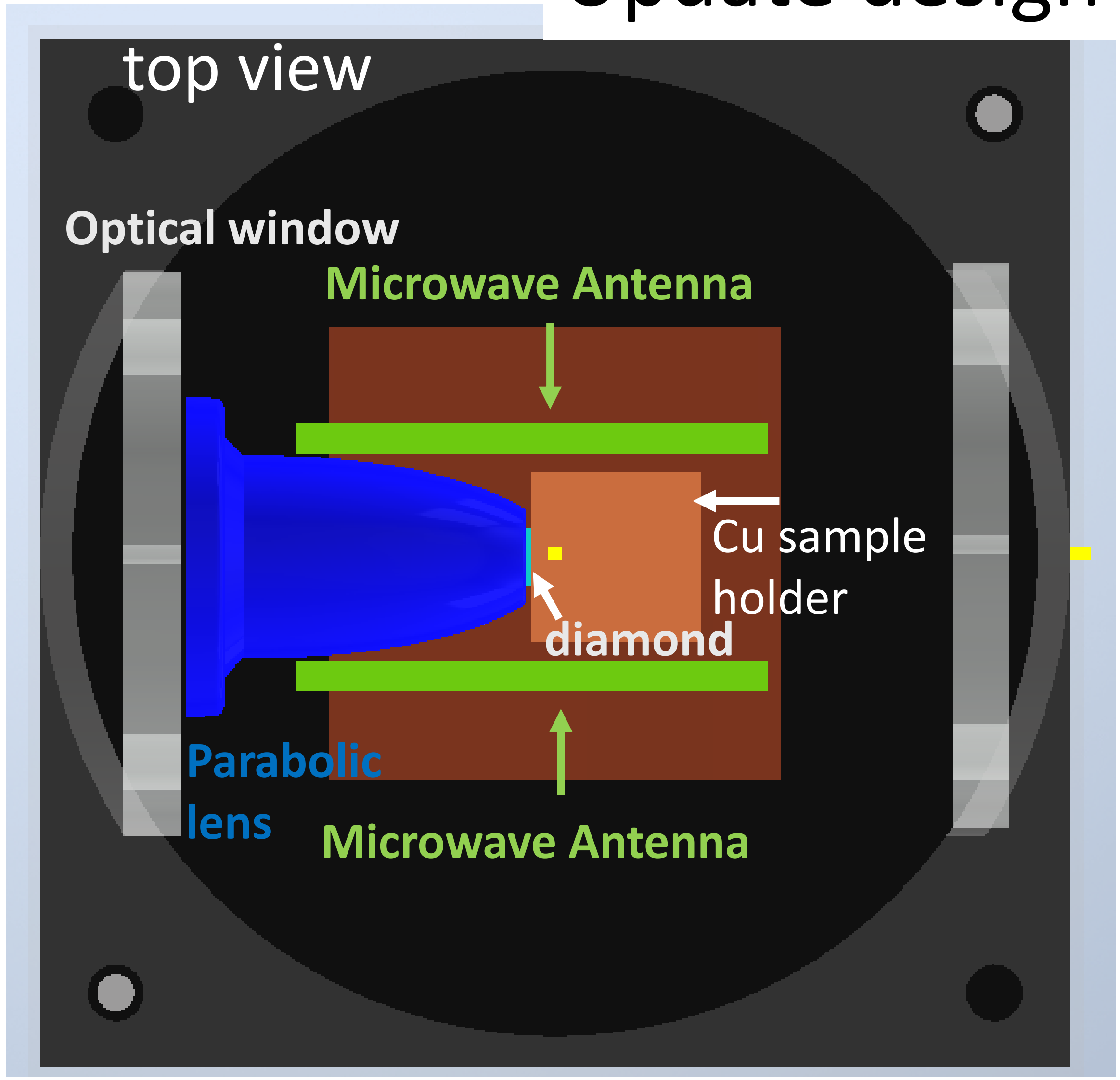


temperature dependence consistent with previous studies

low-temperature measurement system under construction

Update design





- Parabolic lens for improving light collection efficiency
- MW antenna to apply magnetic field in a single direction
- Magnet (or coil) outside of chamber for $NV_{//}$ magnetic field

Plan (schedule)

- FY 2025

\- magnetic field sensing

⇒ sensitivity evaluation using ensemble NV at low temperature

ALPs dark matter search (t_{obs} ~ 1 sec, $n_{NV} = 10^{12}$)

- FY 2026

\- magnetic noise reduction to improve sensitivity

\- analysis using directional information of dark matter

Plan (schedule)

- FY 2025

- magnetic field sensing

⇒ sensitivity evaluation using ensemble NV at low temperature

ALPs dark matter search (t_{obs} ~ 1 sec, $n_{NV} = 10^{12}$)

- FY 2026

- magnetic noise reduction to improve sensitivity
- analysis using directional information of dark matter

Our system is not only for dark matter search

Understanding the characteristics of NV center as quantum sensor
⇒ results of the T_1 and T_2 measurements should be worthy of a paper
(e.g. using perfect aligned NV axis diamond with cryogenic setup)

Summary

- We promoting Axion like particles dark matter search using NV center diamond as a main project of QUP cluster group
- Highly sensitive dark matter search will be realized by unique experimental setup realizable only at QUP