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Diamond quantum sensor and light dark matter search

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Collaborators and Acknowledgements

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MEXT-QLEAP

科研費 KAKENHI

JST CREST Core Research for Evolutional Science and Technology
Japan Science and Technology Agency

A-STEP

Light dark matter search with NV centers in diamonds

Effective dark matter electron interaction Hamiltonian

$$H_{\mathrm{eff}} = \gamma_e \vec{B}_{\mathrm{eff}} \cdot \vec{S}_e \cos(mt + \delta),$$

$$\vec{B}_{\mathrm{eff}} = \sqrt{2\rho_{\mathrm{DM}}} \times \begin{cases} \frac{g_{aee}}{e} \vec{v}_{\mathrm{DM}} & \text{for axion,} \\ \epsilon \left(\vec{v}_{\mathrm{DM}} \times \hat{H} \right) & \text{for dark photon,} \end{cases}$$

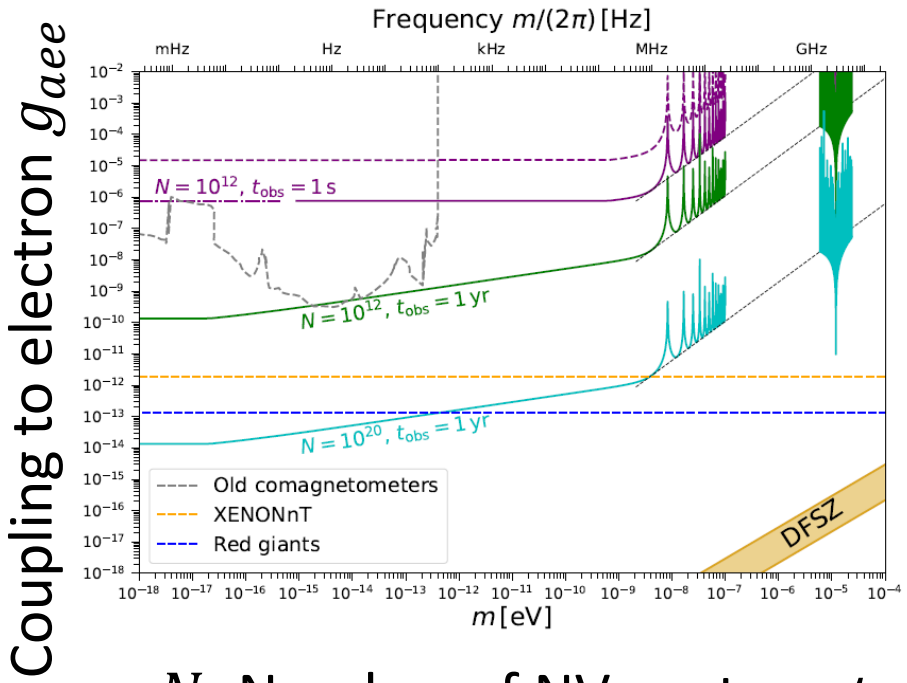
Effective magnetic field induced by axion or dark photon.

S. Chigusa, M Hazumi, E. D. Herbschleb, N. Mizuochi, and K. Nakayama, arXiv:2302.12756.

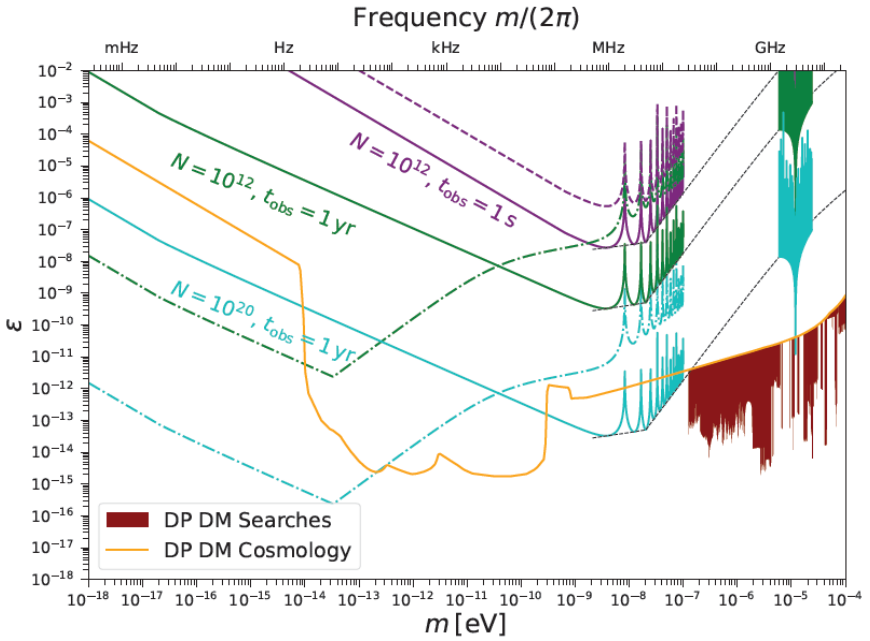
Light dark matter search with NV centers in diamonds

The reach of diamond NV-center magnetometry on dark matter models.

The case of axion dark matter coupling with electron.



The case of dark photon dark matter with kinetic mixing with the ordinary photon.

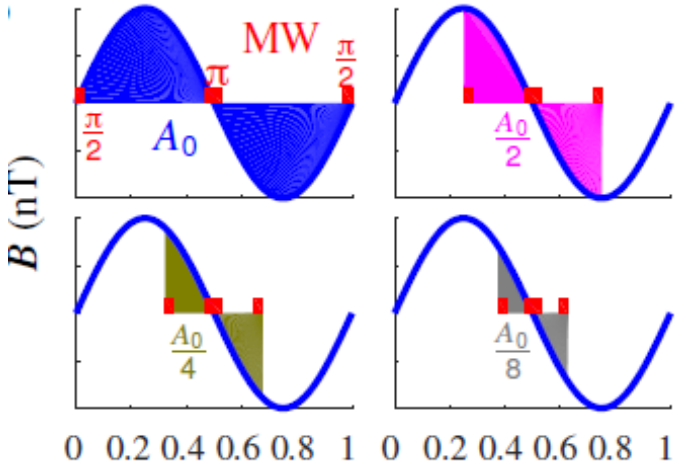


N: Number of NV centers, t_{obs}: Observation time

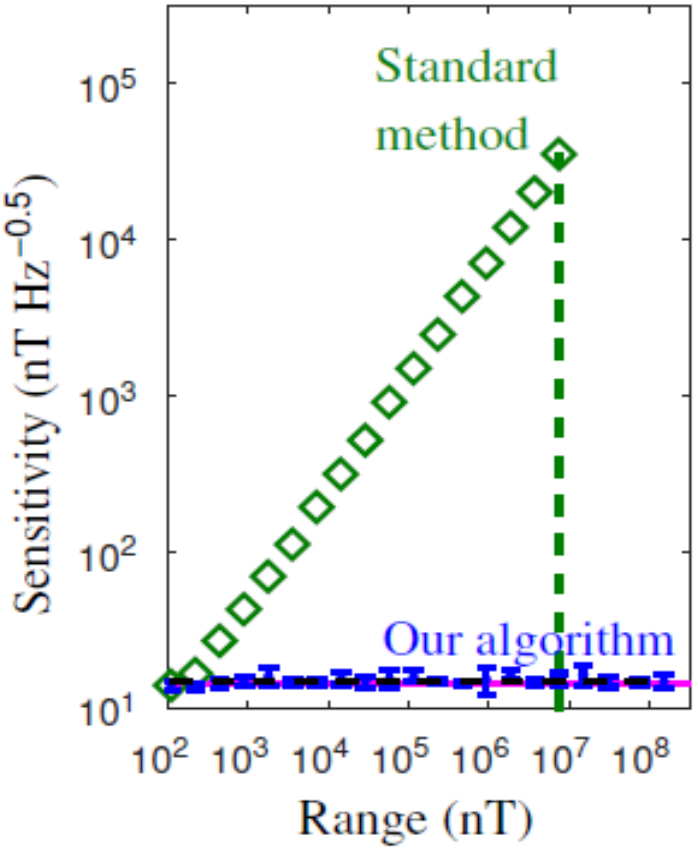
S. Chigusa, M Hazumi, E. D. Herbschleb, N. Mizuochi, and K. Nakayama, arXiv:2302.12756.

High dynamic range quantum measurements retaining its sensitivity

- Change of the pulse interval and combine different sequences of area (A_n).
- Calculation of the optimal sequence combination with an algorithm based on Bayes' theorem.



Sensitivities of standard method with ours.



Dynamic range of about 10^7 retaining high sensitivity.

E. D. Herbschleb, NM, et al., *Nature communications*, 12, 306 (2021).

Related research

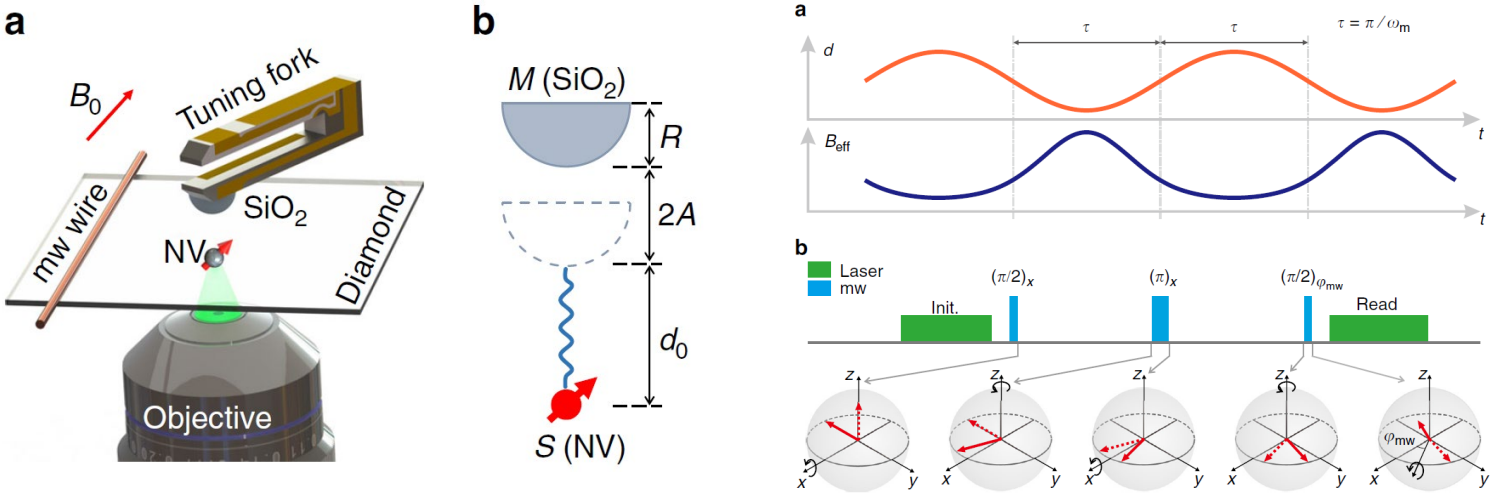
"Searching for an exotic spin-dependent interaction with a single electron-spin quantum sensor",
X. Rong, J. Du et al., *Nature Communications*, (2018) 9, 739.

The axion-mediated monopole–dipole interaction can be described as

$$V_{\mathrm{sp}}(\mathbf{r}) = \frac{\hbar^2 g_{\mathrm{s}}^{\mathrm{N}} g_{\mathrm{p}}^{\mathrm{e}}}{8\pi m}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\boldsymbol{\sigma}\cdot\mathbf{e}_r,$$

Such interaction is equivalent to the Hamiltonian of the electron spin in an effective magnetic field $\mathrm{B_{sp}(r)}$ arising from the nucleon,

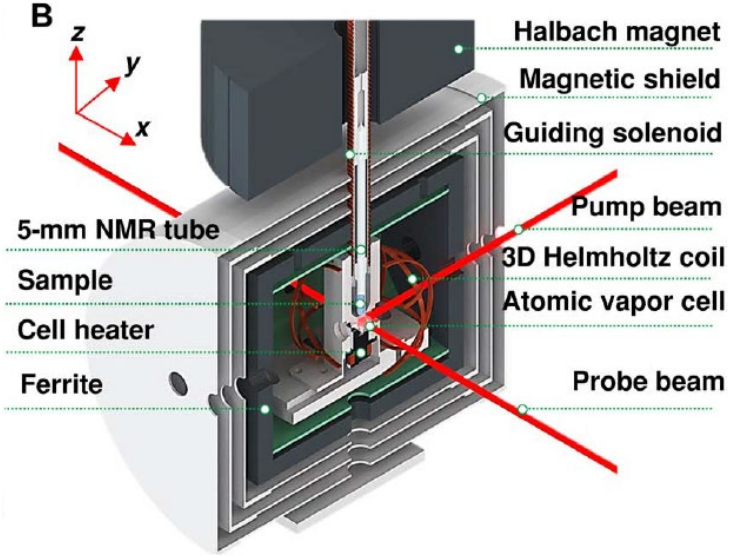
$$\mathbf{B}_{\mathrm{sp}}(\mathbf{r}) = \frac{\hbar g_{\mathrm{s}}^{\mathrm{N}} g_{\mathrm{p}}^{\mathrm{e}}}{4\pi m\gamma}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\mathbf{e}_r,$$

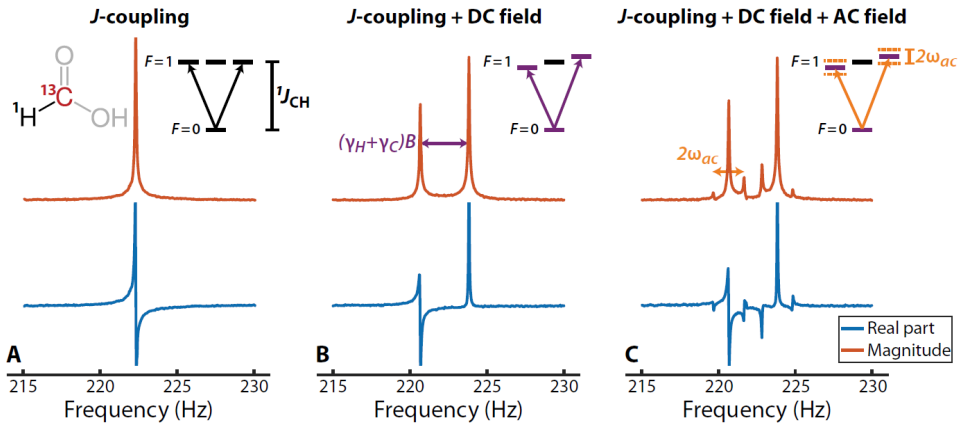


Related research

"Constraints on bosonic dark matter from ultralow-field nuclear magnetic resonance",
A. Garcon, D. Budker et al., *Science Advances* 2019, 5, eaax4539.

Detected from NMR through coupling of dark matter and nuclear spin





Sensitivity of the sensor: 10 fT/(Hz)$^{1/2}$. 50 microL.

No dark matter signal was detected above background, establishing new experimental bounds for dark matter bosons with masses ranging from 1.8×10^{-16} to 7.8×10^{-14} eV.

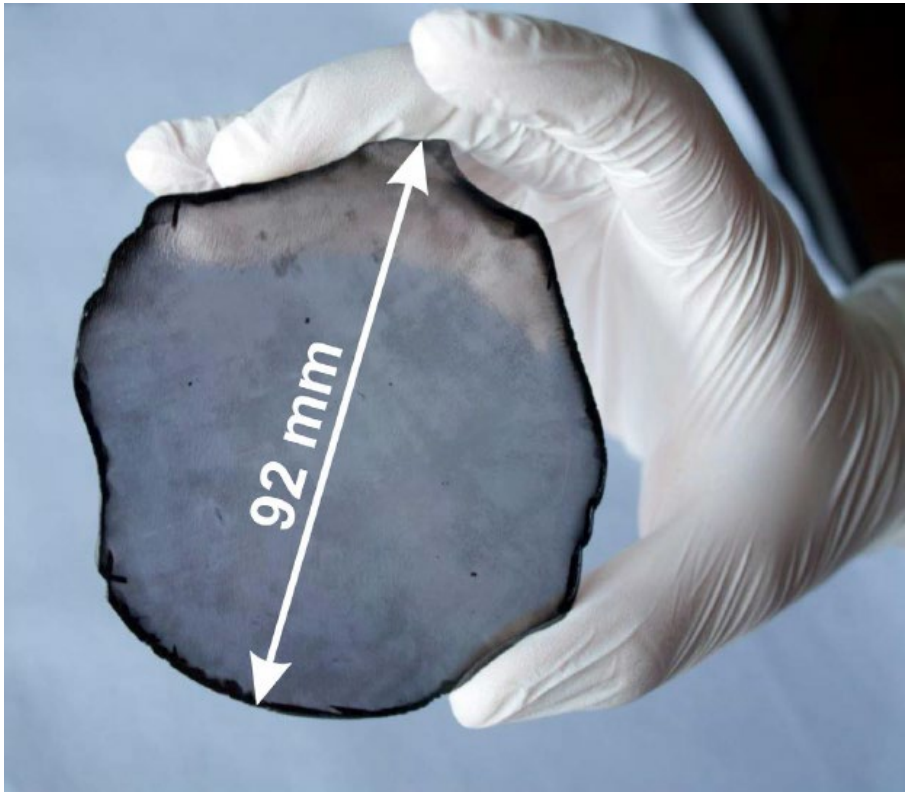
Content

1. Diamond and NV centers
2. Diamond quantum sensor

- How to measure the magnetic field.
- High sensitivity.
- Our recent researches.

Synthetic Diamond

Synthetic Diamond (CVD, HPHT) Commercially available http://www.e6.com/

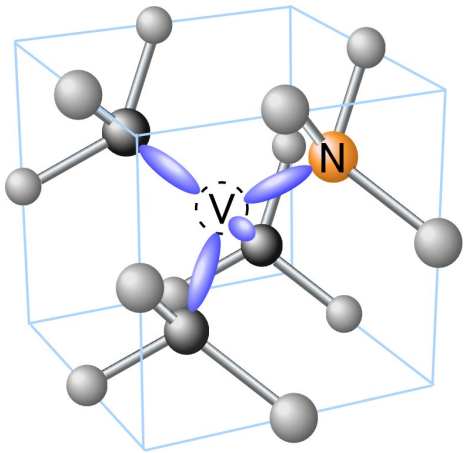


Hetero-epi, CVD, single crystal

Scientific reports 7:44462 (2017)
doi:10.1038/srep44462

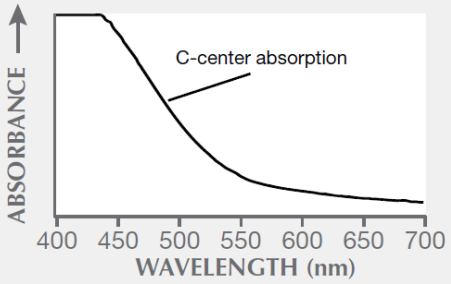
Colors and Impurities in diamond

Many colors:
Impurities and defects

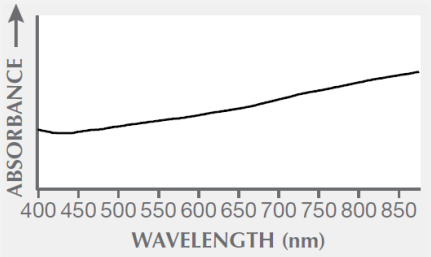


NV center

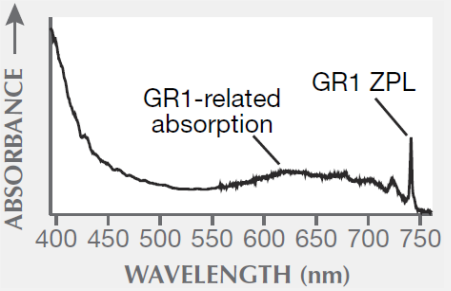
Nitrogen



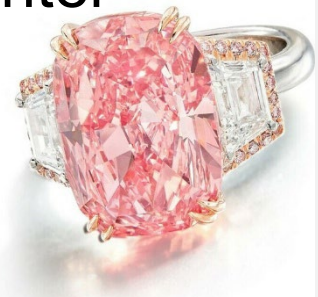
Boron

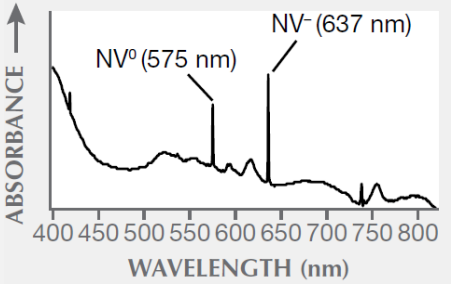


Vacancy



NV center

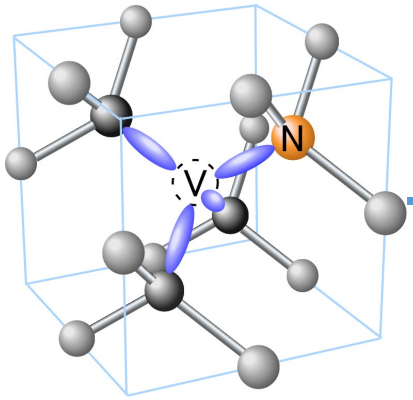


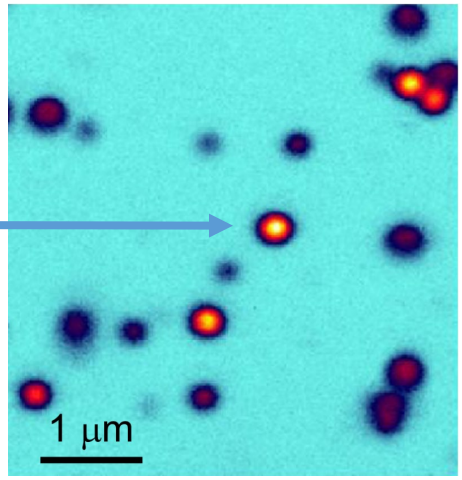


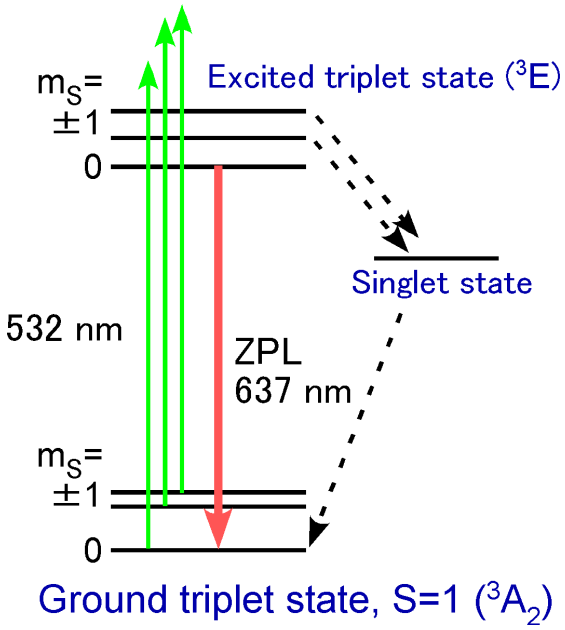
Gems & Gemology 56, 194 (2020)

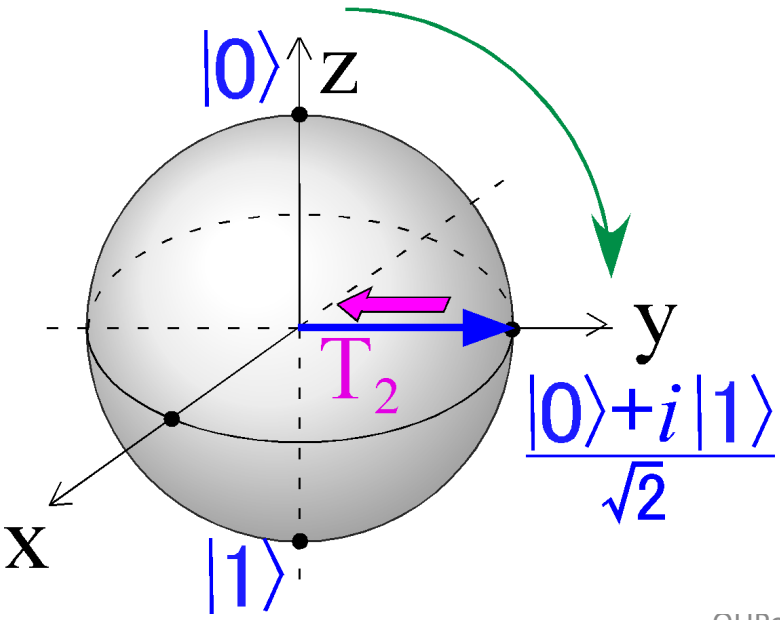
NV center in diamond

Confocal image at RT







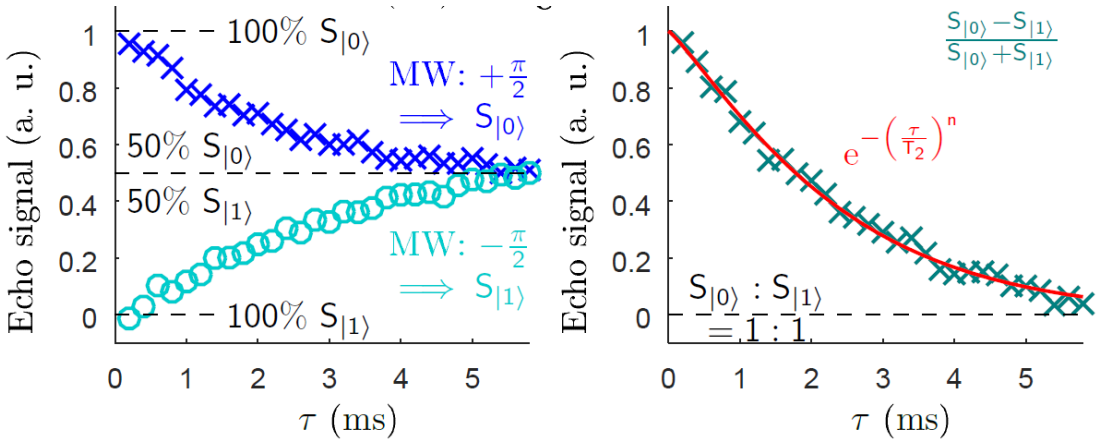


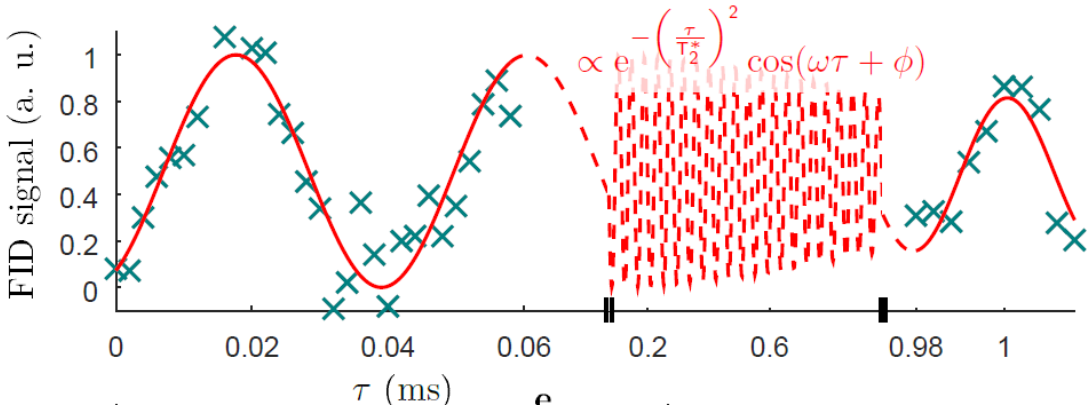
Coherent Control and detection of individual spin

Long coherence time : High sensitivity

Ultra-long coherence times among room-temperature solid-state spins

In Phosphorus doped n-type diamond (synthesized at AIST)





$T_2 \approx 2.4$ ms

Previous report: T_2=1.8ms:
Nature Material 2009

AC sensitivity : 9.1 nT/(Hz)$^{1/2}$

$T_2^* \approx 1.5$ ms

Previous report: T_2^*=0.47 ms
Science 2012

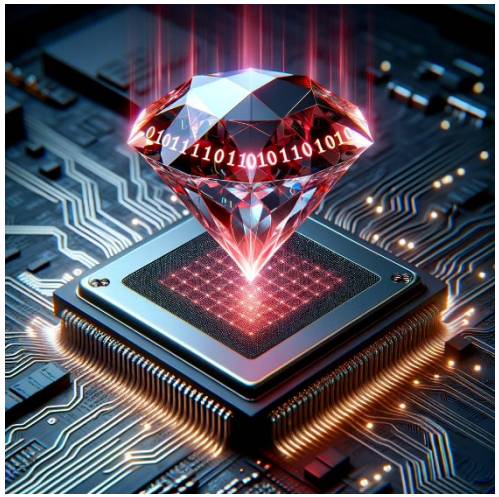
DC sensitivity : 10 nT/(Hz)$^{1/2}$

- Longest T_2 and T_2^* among solid-state electron spins at RT.
- The long T_2 and T_2^* and n-type semiconductor properties are compatible.

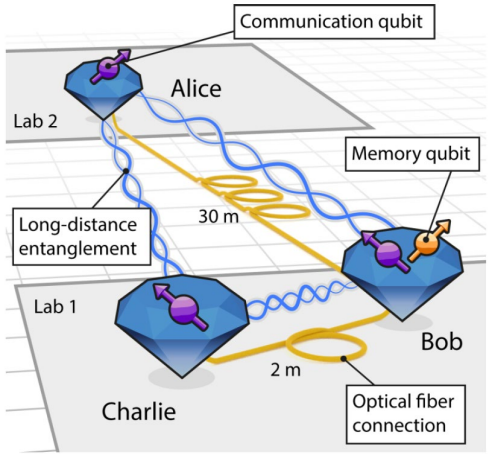
E. D. Herbschleb, NM, et al., *Nature Communications* 10, 3766 (2019).

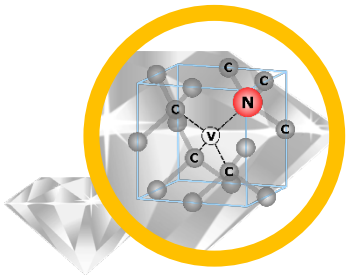
NV centers and Quantum application

Quantum computing

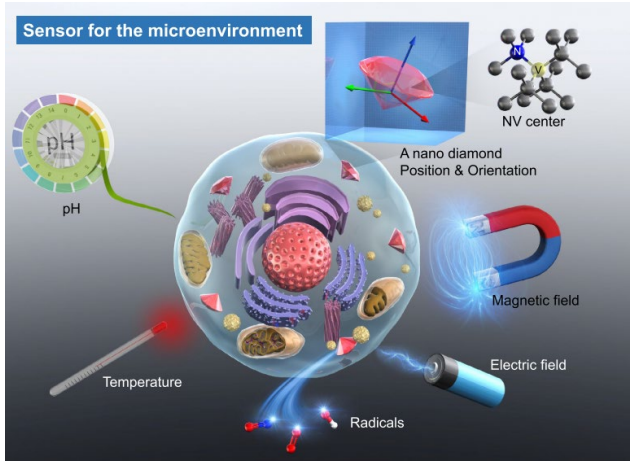


Quantum communication





Quantum sensing

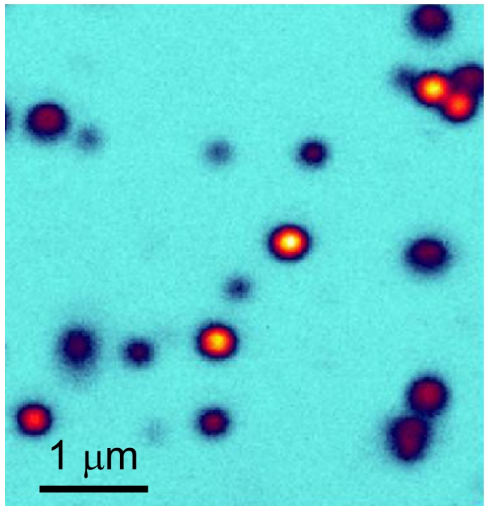


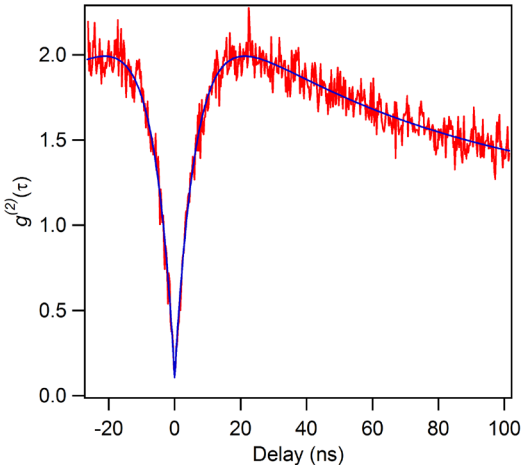
M. Ruf et al., *J. Appl. Phys.*, **130**, 080901 (2021)

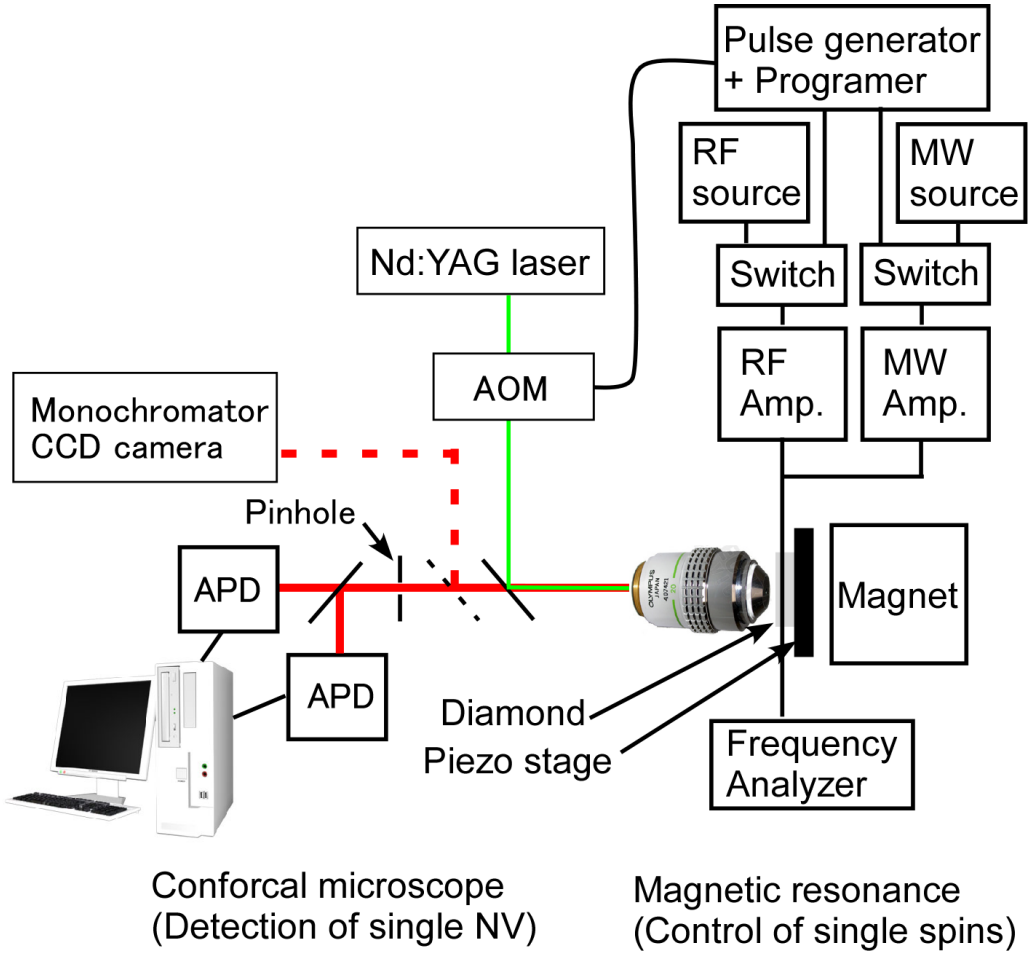
T. F. Segawa et al., *Prog. Nucl. Magn. Reson. Spectrosc.*, **134 – 135**, 20-38 (2023)

Measurement of individual centres and their spin

Confocal microscope with magnetic resonance system

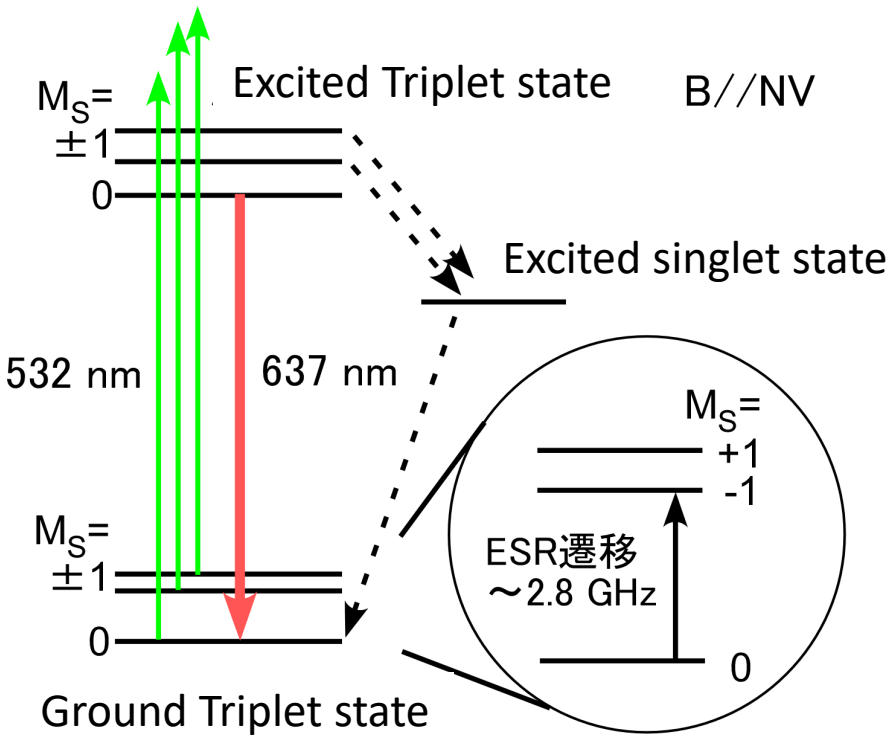


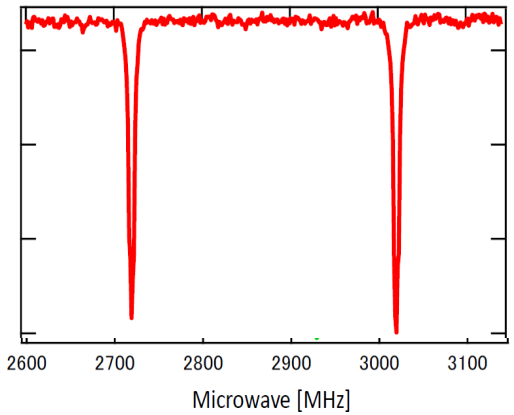




Measurement of single color center using a piezostage

Optically detected magnetic resonance (ODMR)





1: Initialization（To $M_S = 0$）: Laser excitation (532 nm) and spin selective deactivation due to SOC.

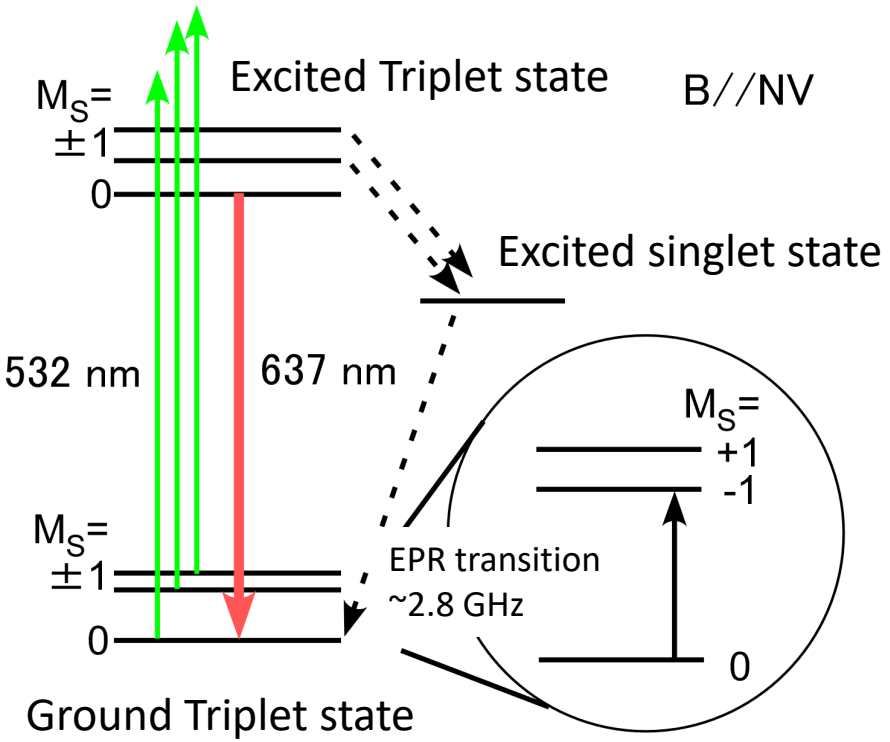
2: Magnetic resonance (To M_S=-1)

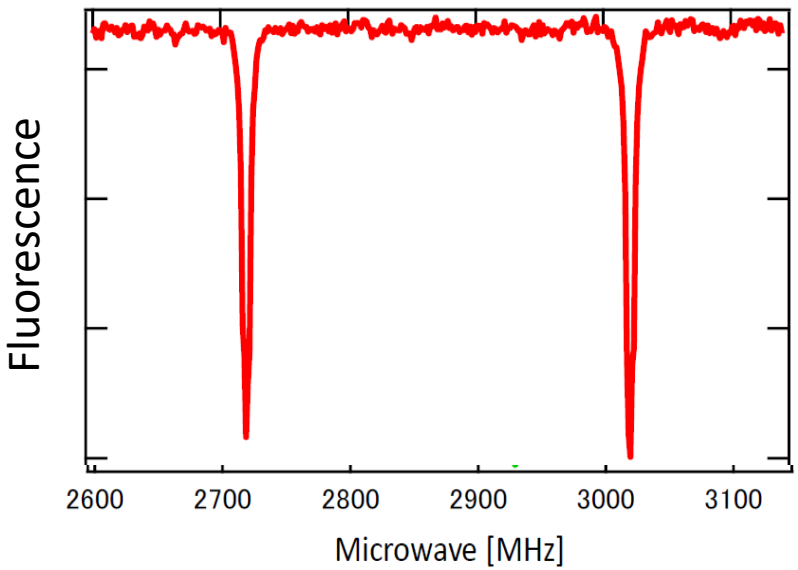
Microwave irradiation to Zero-field splitting (dipolar-dipolar interaction) = 2.87 GHz

3: Optical detection:

Laser excitation (532 nm) and detection of change of fluorescence.

How to sense the magnetic field?





ODMR spectrum of NV center

The resonance frequency of the ODMR signal shifts depending on B (magnetic field).

The narrower the line width, the smaller the shift can be detected. (The longer T_2, the narrower the line width!）

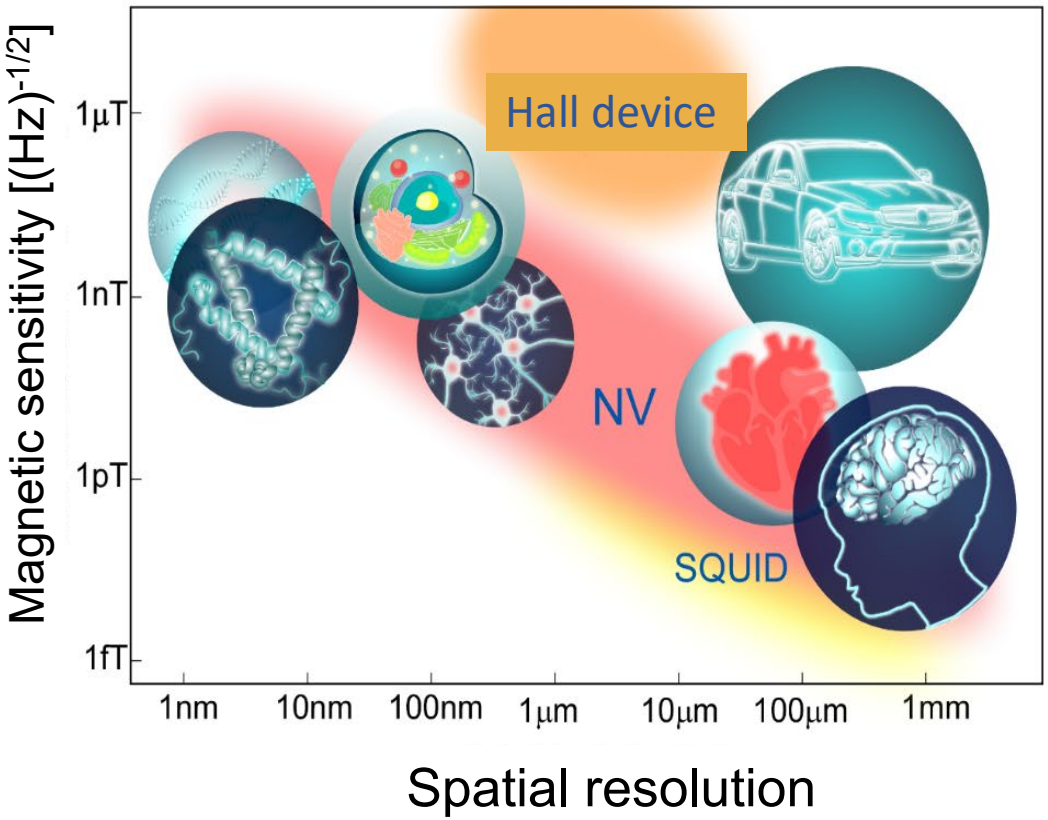
Why can we enhance sensitivity and spatial resolution?

Sensitivity（η）

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

n_{NV} ：Number of NV

Not only T_2 but also the number of NV contributes to the sensitivity.



Mizuochi, OYO BUTSURI, 87, 251-261(2018).

Sensors with many NV centers achieve high sensitivity.

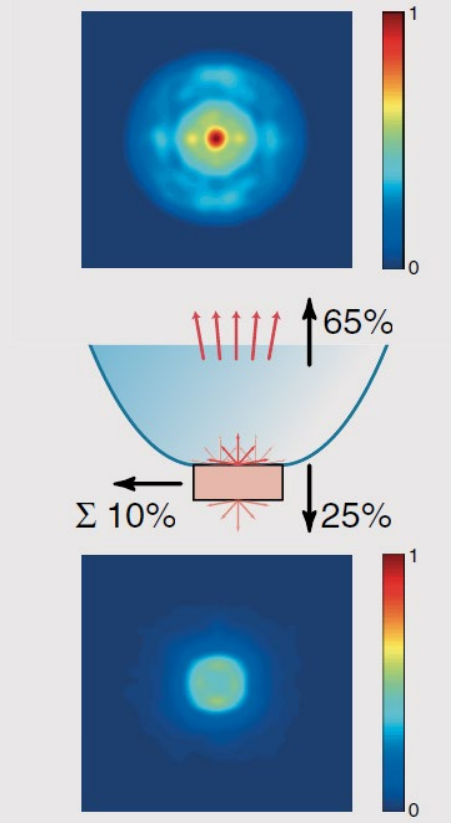
The trade-off relationship is that if the concentration of the NV center increases, T_2 becomes shorter.

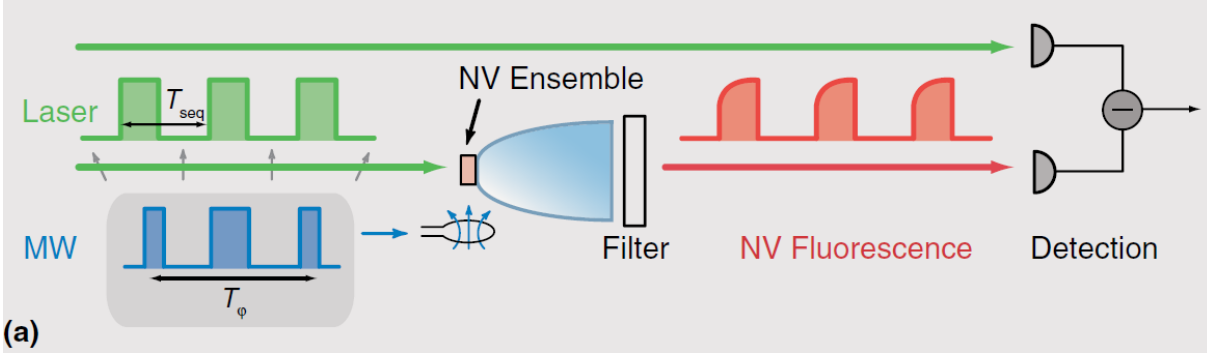
High-sensitive diamond quantum sensors

Subpicotesla Diamond Magnetometry

Thomas Wolf,[1,*] Philipp Neumann,[1,†] Kazuo Nakamura,[2] Hitoshi Sumiya,[3]
Takeshi Ohshima,[4] Junichi Isoya,[5] and Jörg Wrachtrup[1]

Phys. Rev. X 5, 041001 (2015).
Phys. Rev. X 13, 029903(E) (2023)





n_{NV} (number of NV center) = $10^{11}/cm^3$

Volume: 8.5×10^{-4} mm^3

(Diameter ~50 μm, Thickness : 0.5 mm)

Sensitivity: 9 $pT/(Hz)^{1/2}$

High-sensitive diamond quantum sensors

n_{NV}=1 AC sensitivity : 9.1 nT/(Hz)$^{1/2}$
DC sensitivity : 10 nT/(Hz)$^{1/2}$

E. D. Herbschleb, NM, et al., *Nature Communications* 10, 3766 (2019).

n_{NV} = 10^{11}/cm^3 with the above sensitivity

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

AC sensitivity : 29 fT/(Hz)$^{1/2}$
DC sensitivity : 32 fT/(Hz)$^{1/2}$

There is space to improve the sensitivity from engineering development.

High-sensitive diamond quantum sensors

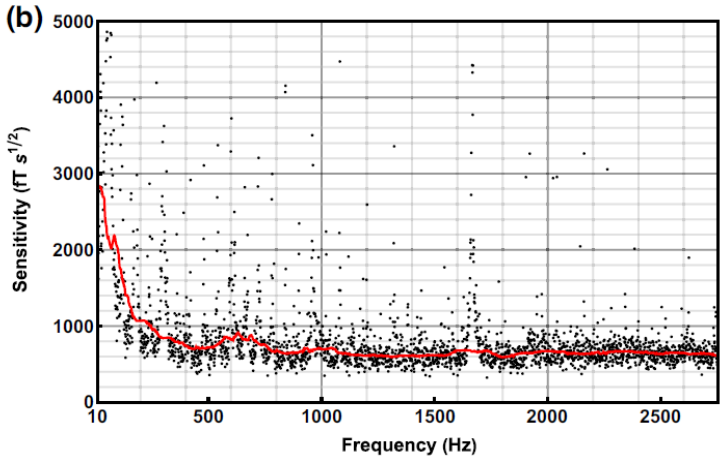
Sensitive ac and dc magnetometry with nitrogen-vacancy-center ensembles in diamond

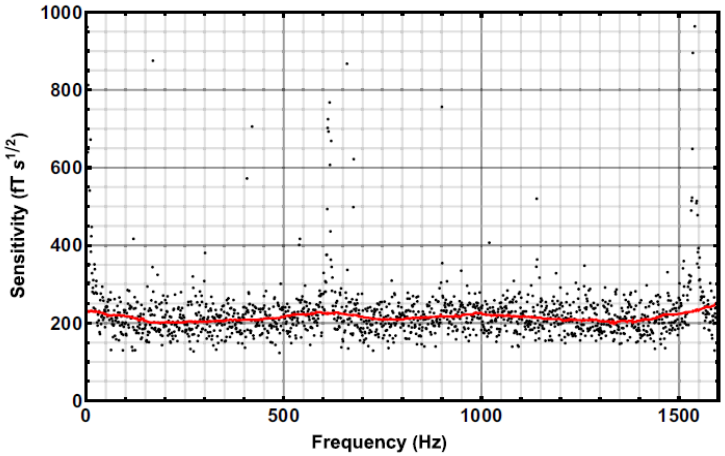
John F. Barry,[1,*] Matthew H. Steinecker,[1] Scott T. Alsid,[1,2] Jonah Majumder,[1] Linh M. Pham,[1] Michael F. O'Keeffe,[1] and Danielle A. Braje[1]

Phys. Rev. Appl. 22, 044069 (2024).

AC sensitivity: 210 fT/(Hz)$^{1/2}$

DC sensitivity: 460 fT/(Hz)$^{1/2}$





Measurement

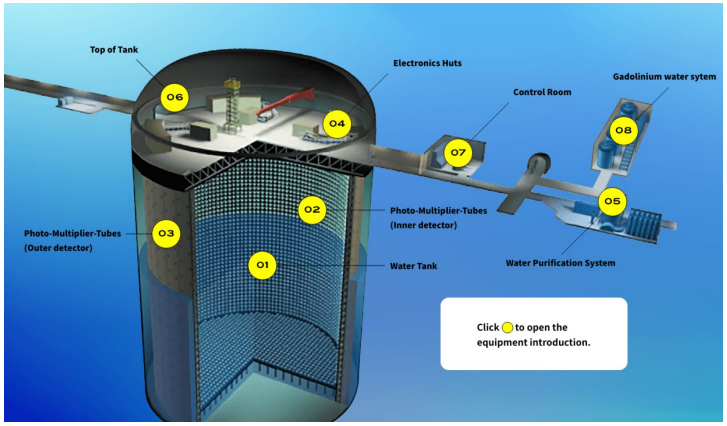
Obtaining $N=10^{20}$ requires volume of $\sim 10^3$ cm^3 for NV concentration of 1.6×10^{17}cm^{-3} with high sensitivity [1].

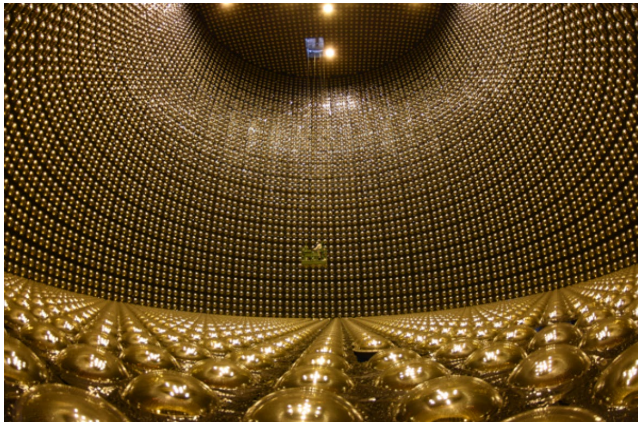
[1] Phys. Rev. X 5, 041001 (2015).

Alternatively, the same sensitivity can be obtained by combining many smaller individual sensors.

For example, Hyper-Kamiokande uses 40,000 of 50-cm PMTs (photomultiplier tube: photo-sensors).

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 958, 163033 (2020), 10.1016/j.nima.2019.163033.

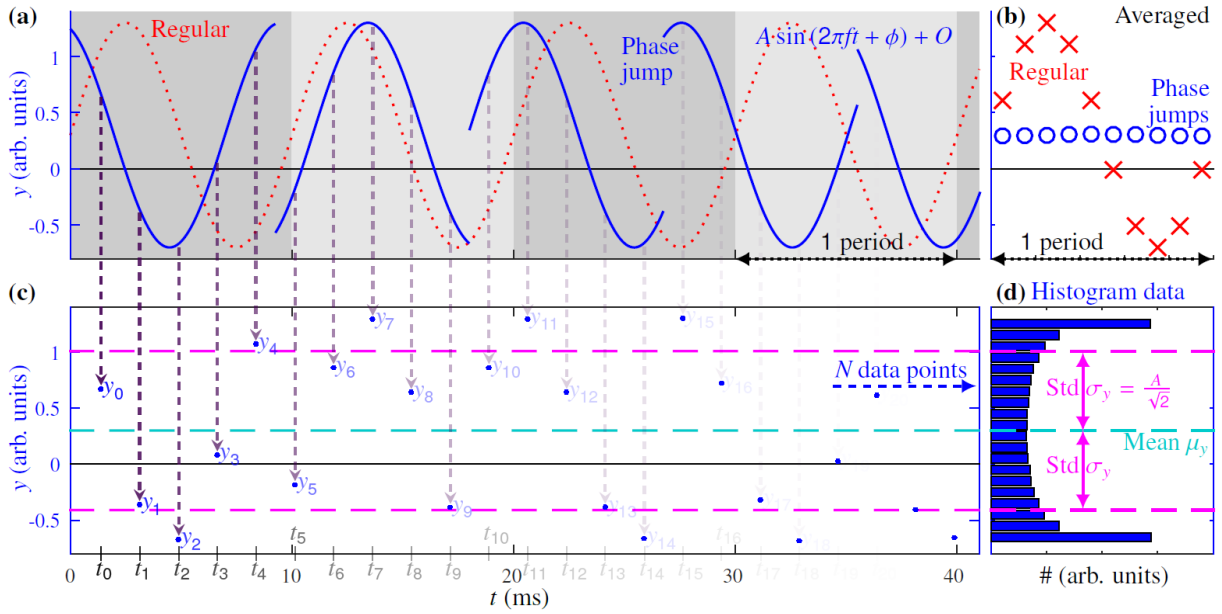




https://www-sk.icrr.u-tokyo.ac.jp/sk/

Quantum sensing technique

Standard deviation quantum sensing



Contributed Talks, Today 17:20-
"Robust quantum sensing with nitrogen-vacancy centres for light dark matter detection"
Speaker: David Herbschleb (Kyoto University)

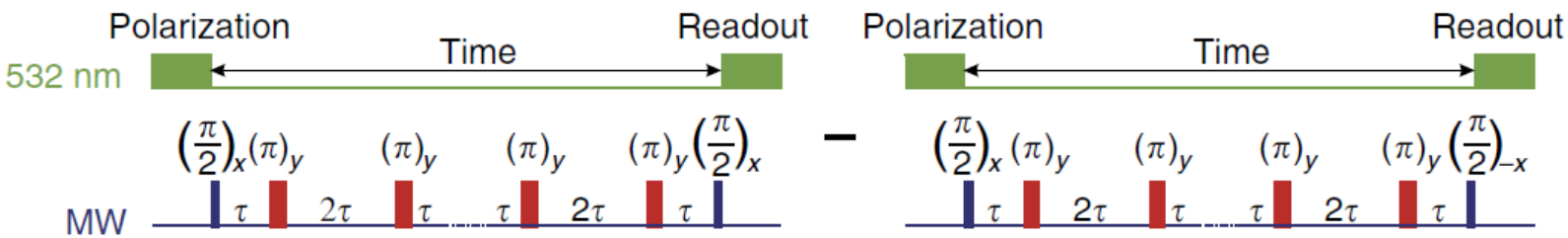
E. D. Herbschleb, S. Chigusa, R. Kawase, H. Kawashima, M. Hazumi, K. Nakayama, N. Mizuochi, *APL Quantum*, **1**, 046106 (2024).

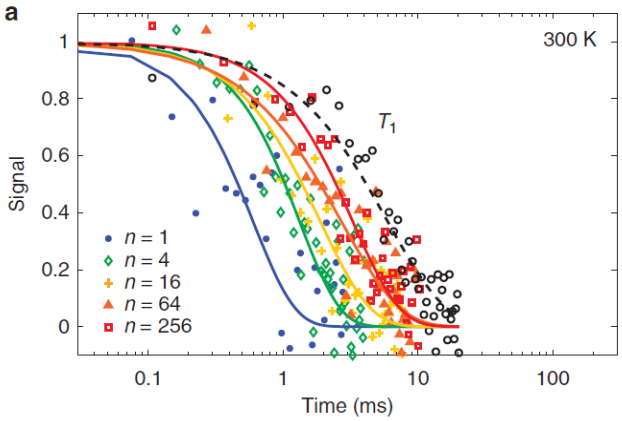
Measurement setup

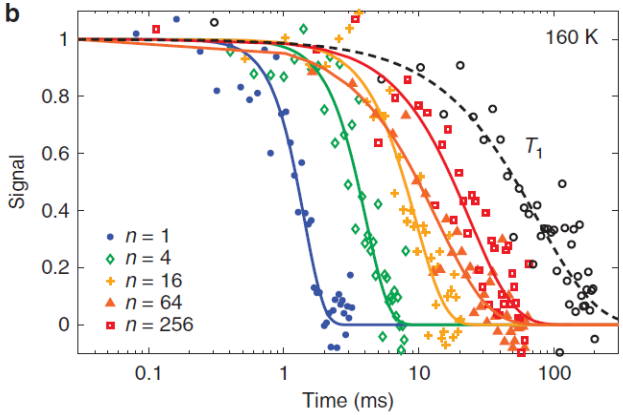
High sensitive sensing measurement at low temperature.

Poster, Today 18:30-
No. 4, Atsuhiro Umemoto, KEK QUP
“Dark matter search using diamond NV centers at QUP”

Extension of T_2 by dynamical decoupling



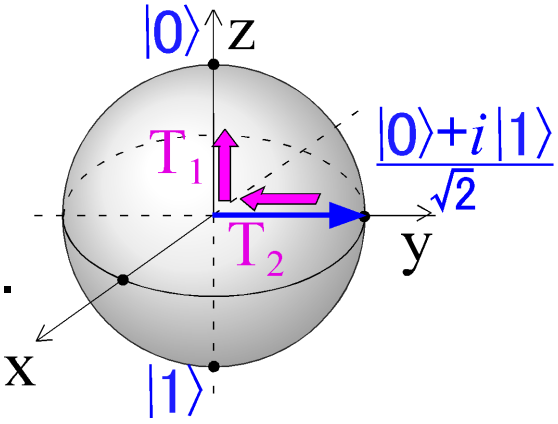




"Solid-state electronic spin coherence time approaching one second" *Nature communications* 4, 1743 (2013)

T_2 (dd) = 0.6 s at 77 K

T_2 can be extended to T_1 by dynamical decoupling technique.



Long longitudinal relaxation time (T_1)

Direct process (High temp. region)

Spin ↓ → Spin ↑ + Phonon (k)

$$\frac{1}{T_1} = \frac{54\pi\nu^2}{\hbar\rho v_0^5}\left(\frac{\mu_B^{\ 2}}{r_0^3}\right)^2 kT$$

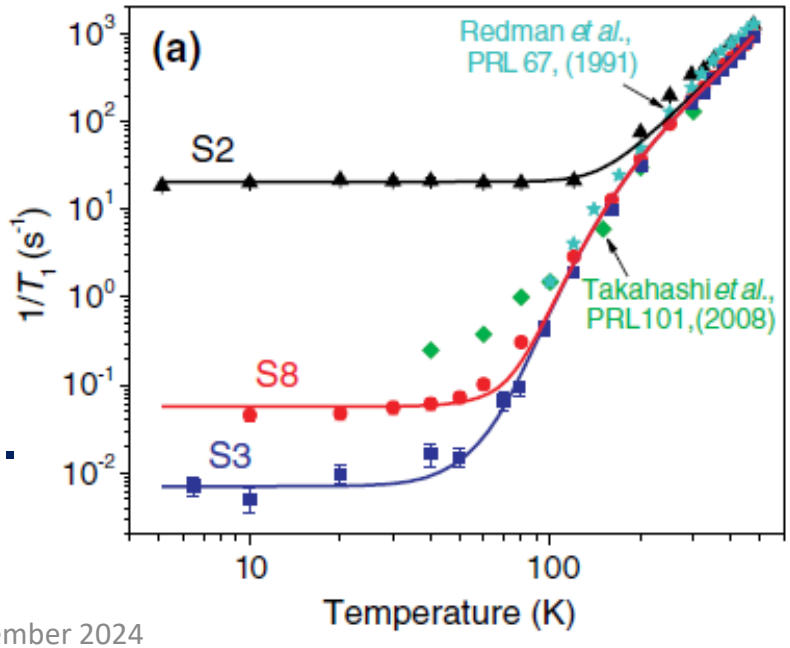
Raman process (low temp. region)

Phonon (k) + Spin ↓ → Spin ↑ + Phonon (k')

$$\frac{1}{T_1} = \frac{163\pi^2 6!}{\rho^2 v_0^{10}}\left(\frac{\mu_B^{\ 2}}{r_0^3}\right)^2\left(\frac{kT}{h}\right)^7$$

ρ : mass density,
ν : oscillator frequency
v_0 : velocity of sound
$v_0 = (M/\rho)^{1/2}$
r_0 : lattice separation of neighbours
μ_B : Bohr magneton

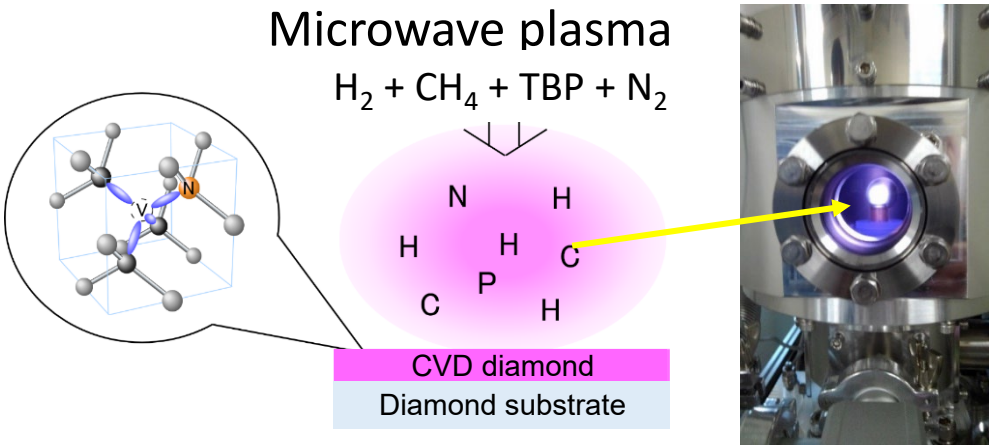
M: Elasticity: Resistance to deformation



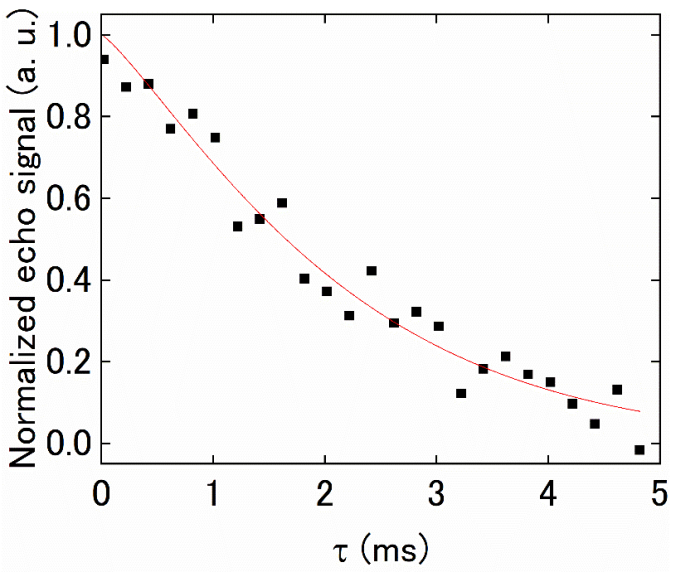
Several ms at RT.
More than 200 sec at low temp.

A. Jarmola, D. Budker, et al., *Phys. Rev. Lett.* **108**, 197601 (2012).

n-type diamond synthesized with TBP at Kyoto Univ.



Long T_2 and [N] dependence



T_2 : 2.23 ms

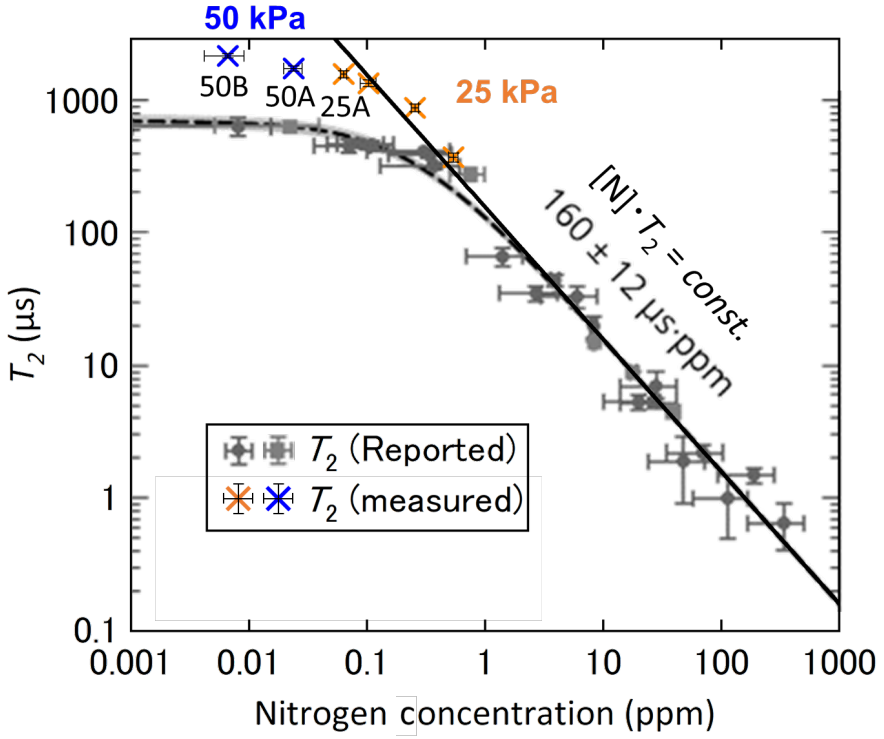
T_2^* : 820 μs

The coherence times have approached the longest ones.

Nitrogen is not the main source of decoherence in our diamond

[N] dependence on T_2

J. F. Barry, et al., *Rev. Mod. Phys.* **92**, 68 (2020).
R. Kawase, NM, et al., *submitted.*



Sample	Pressure (kPa)	CH_4/H_2 (%)
25A (previous)	25	0.25
50A	50	0.25
50B	50	1

Summary

1. Diamond and NV centers
2. Diamond quantum sensor

- How to measure the magnetic field.
- High sensitivity.
- Our recent researches.