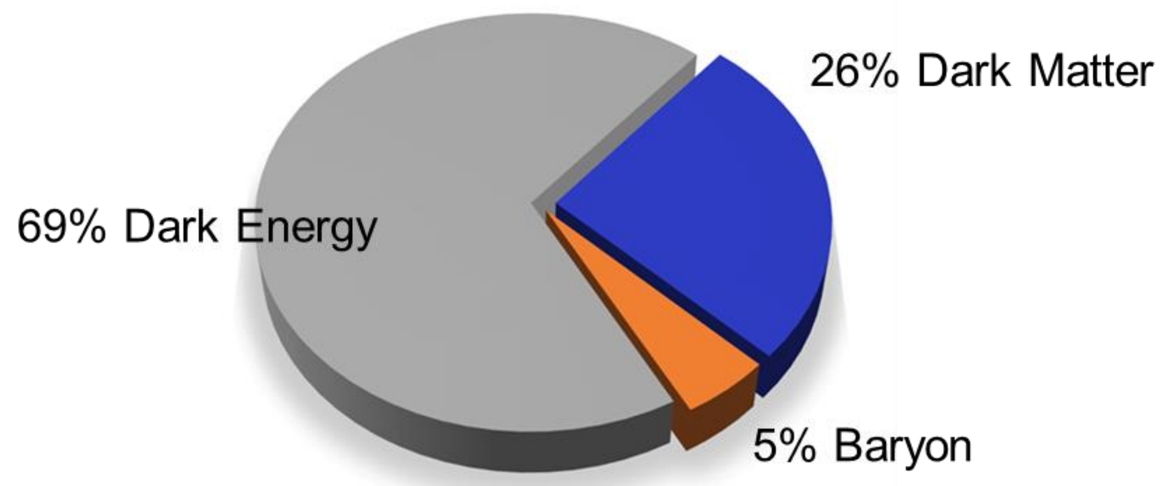
Dark matter search using diamond NV centers at QUP

Atsuhiro UMEMOTO
KEK QUP Postdoc
On behalf of Quantum Detector Cluster Group in QUP

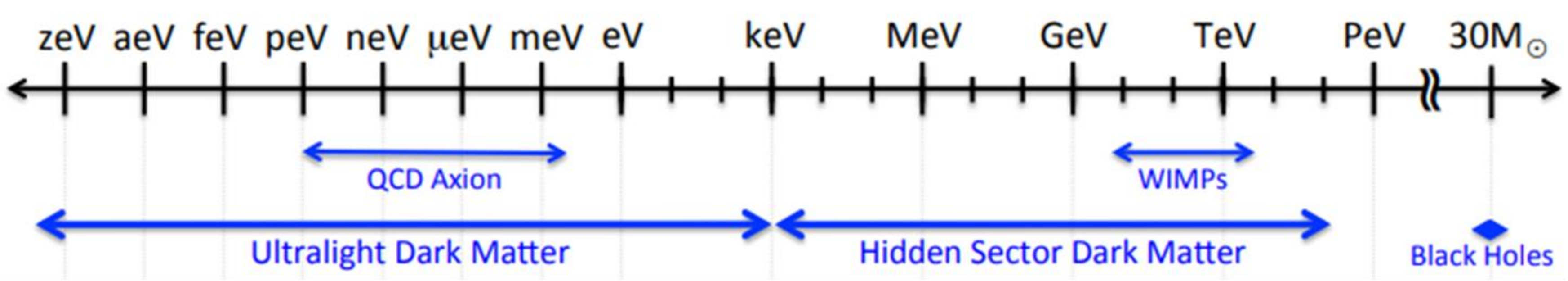
Dark Matter

Pie chart of the universe



2018 Planck Results

Candidates for dark matter (huge discovery space)



・・・・and there are many candidates (theoretical models)

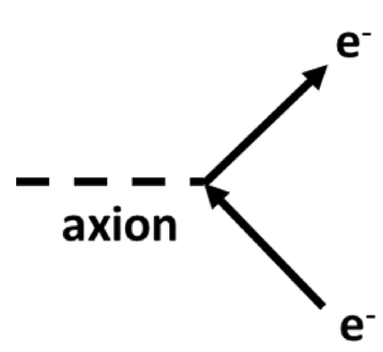
US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

The particle characteristics

- longer decay life-time than the age of universe
- non-zero mass
- no electromagnetic charge
- and etc..

Beyond the standard model

In the case of ultralight dark matter (e.g. axion like particles)



$\mathcal{L} = -ig_{aee}a(x)\bar{\psi}\gamma_5\psi(x)$ 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

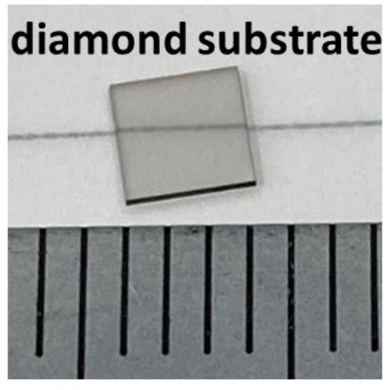
$-\frac{g_{aee}\hbar}{2m}\vec{\sigma}\cdot\vec{\nabla}a = -2\left(\frac{e\hbar}{2m}\right)\left(\frac{1}{2}\vec{\sigma}\right)\cdot\left(\frac{g_{aee}}{e}\vec{\nabla}a\right)$ g_{aee} : axion electron coupling

spin Axion field (like an effective magnetic field)

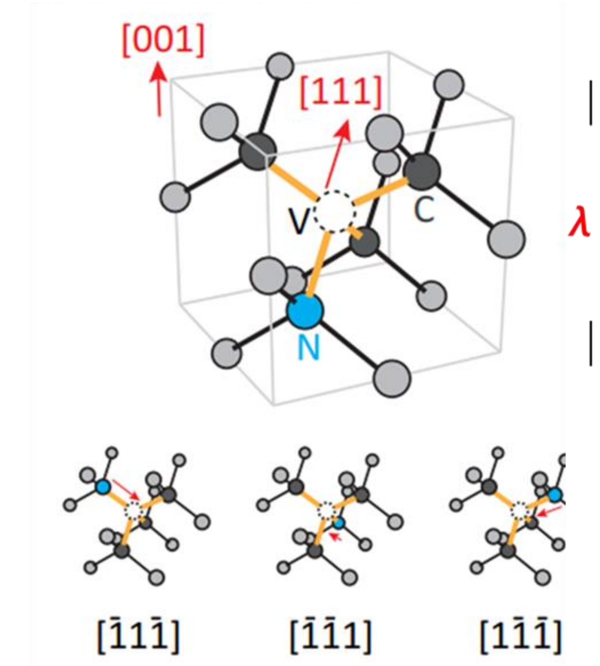
detectable through a magnetic sensing via spins

Diamond nitrogen vacancy (NV) center

- Characteristics

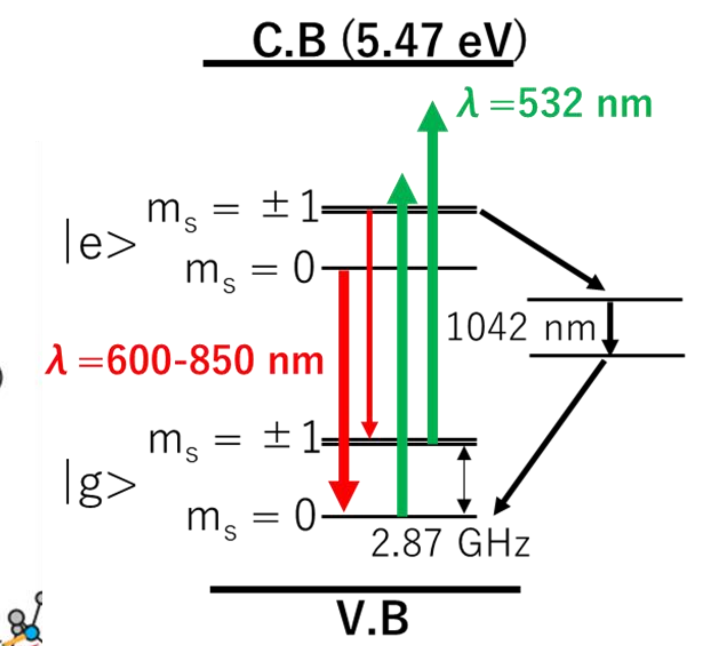


- Defect with nitrogen (substituting for carbon) and vacancy
- Quantum sensor with excellent spin coherence property

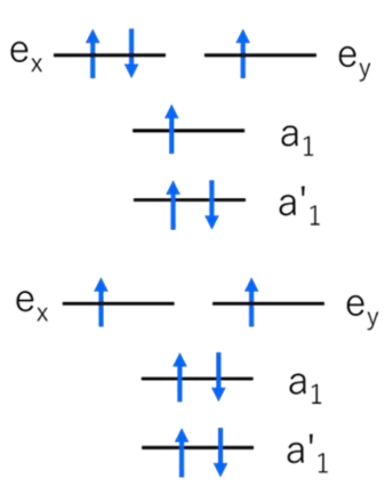


4 directions of NV center

Sasaki, 20210603_natsugaku_text.pdf (2021)



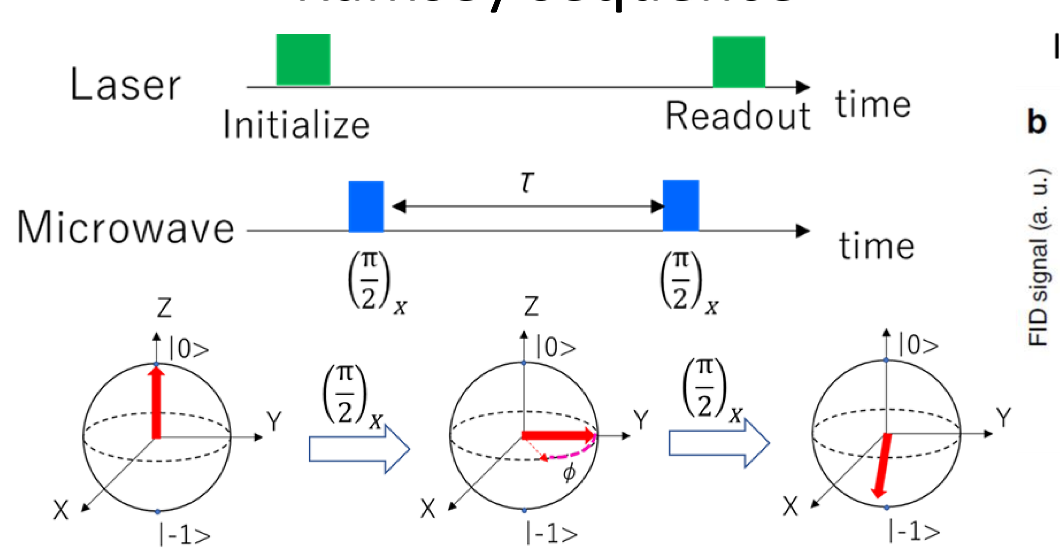
Energy level diagram NV

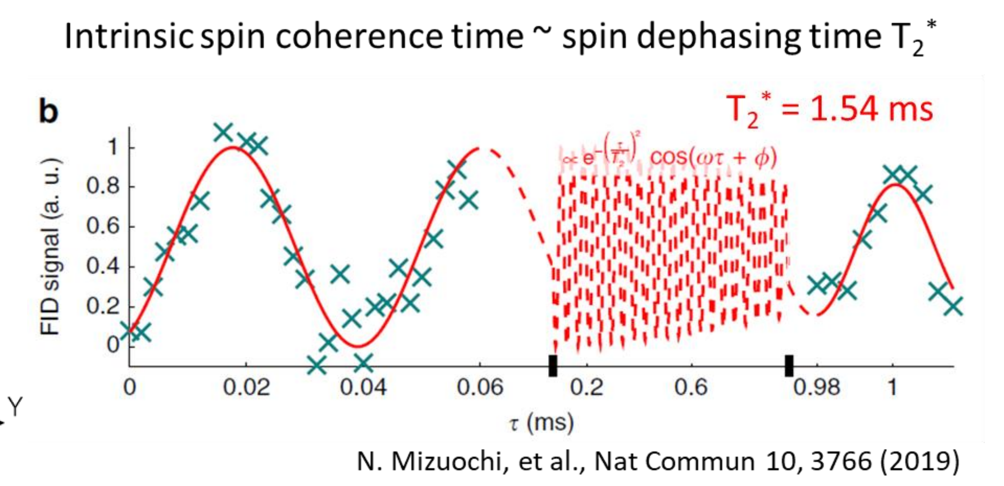


- **Optical pumping for spin initialize to $m_s = 0$**
- **Photoluminescence depended on spin state**

- Two level system and spin manipulation

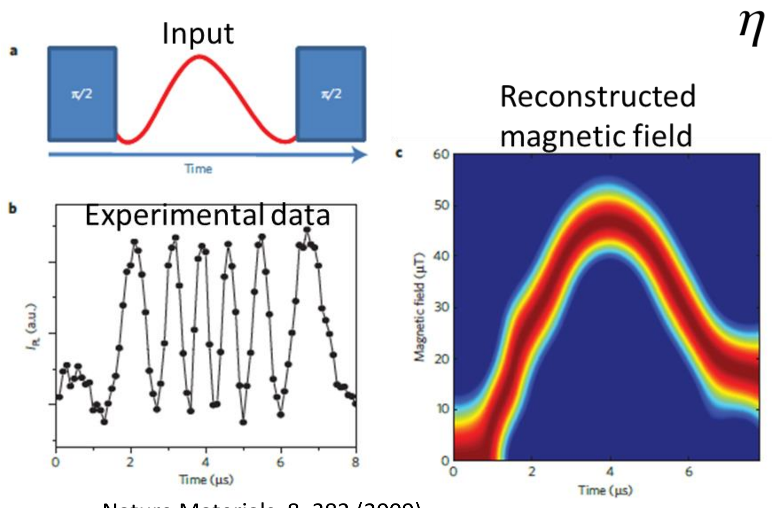
Ramsey sequence





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

- Magnetic field sensing



Nature Materials, 8, 383 (2009)

$\eta \propto \frac{1}{\sqrt{n_{NV}T_2}}$ larger n_{NV} and T_2 for improved sensitivity

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	$1.4 \times 10^{11} / (8.5 \times 10^{-4}\ mm^3)$*2	40 μs*3
Single	77 K		1	0.6 s*4

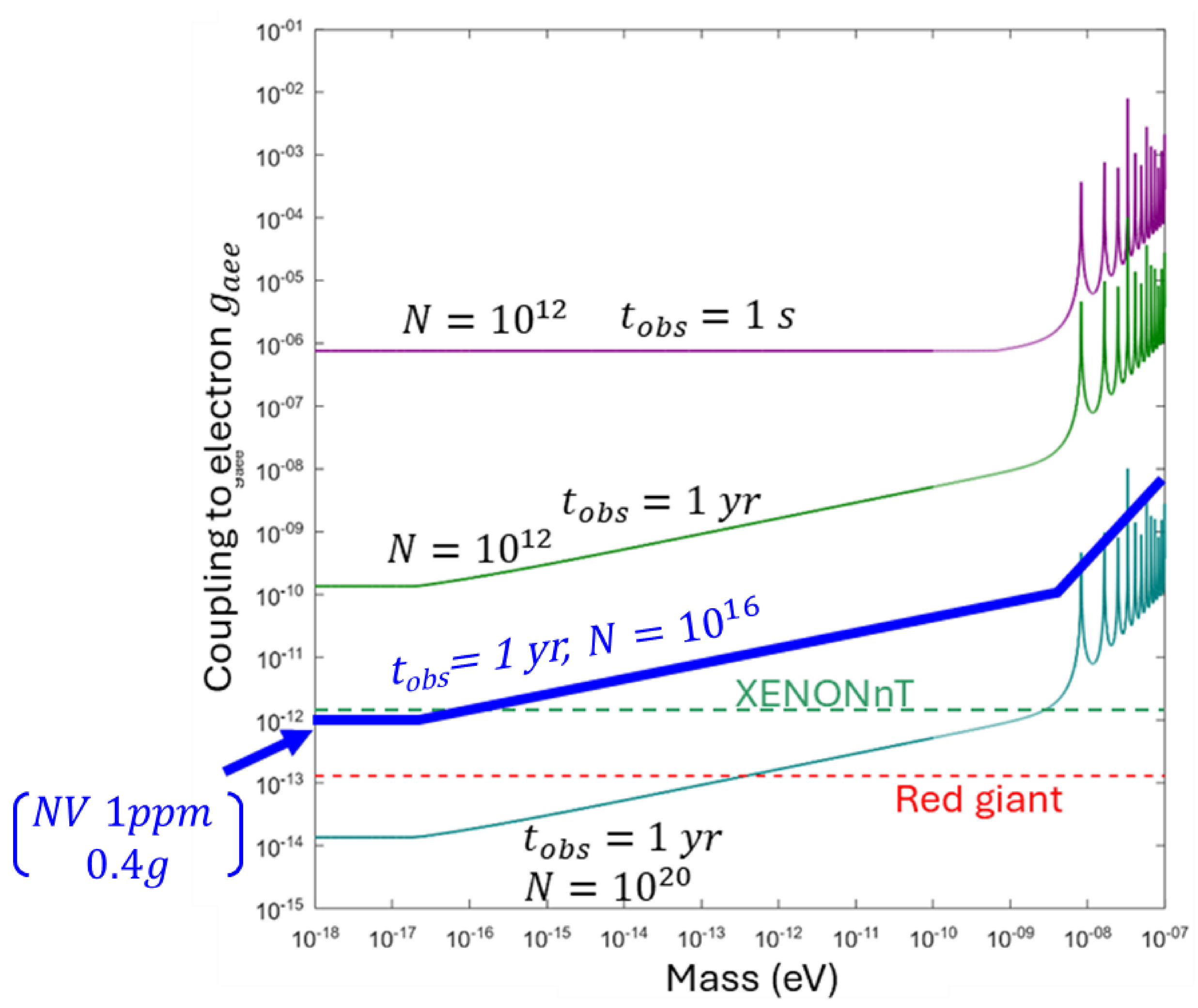
x250

*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)

ensemble with low temp measurement is promising

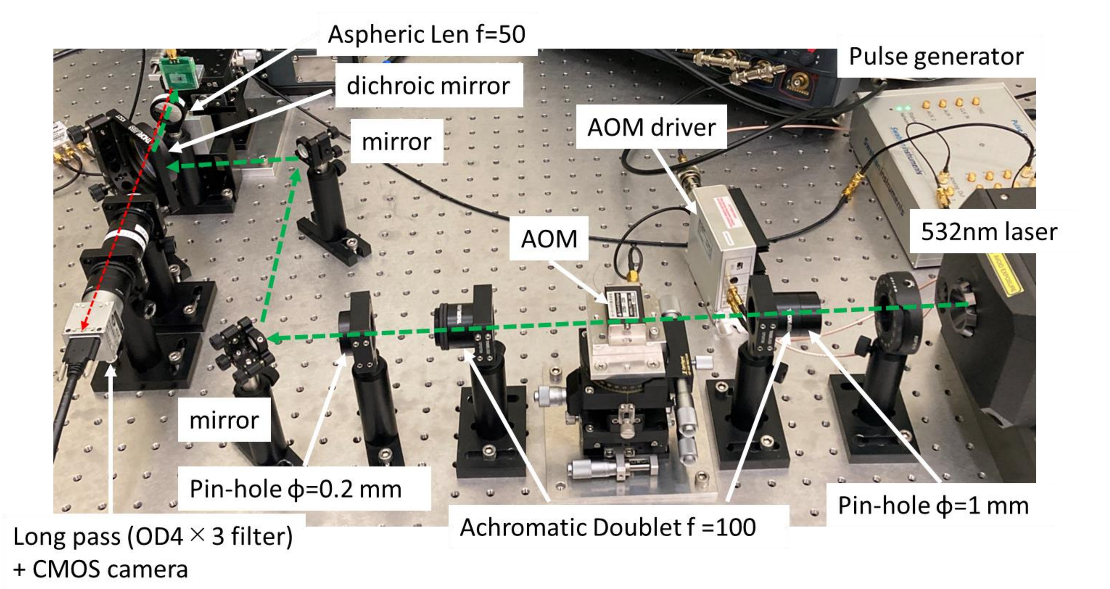
Experiment : strategy and schedules

Ideal sensitivity for axion like particles search

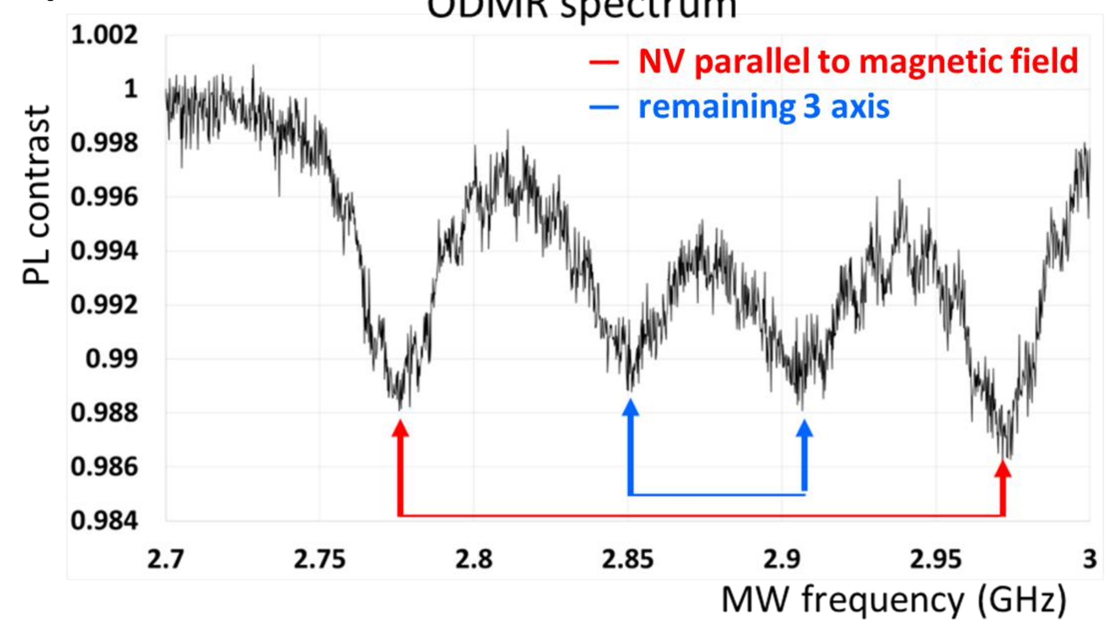


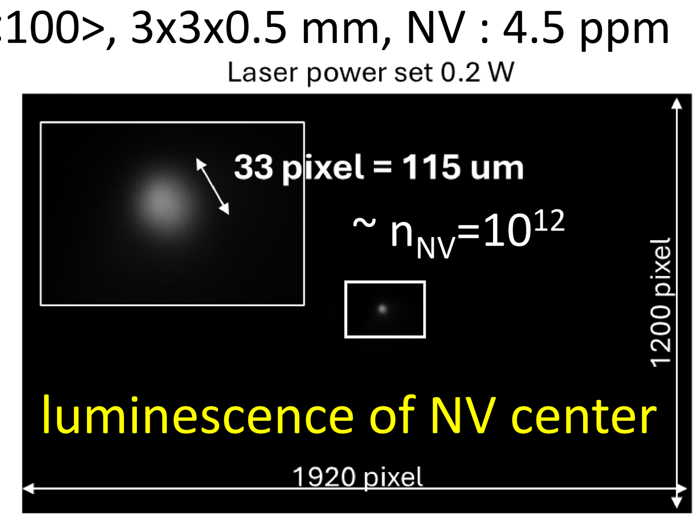
Measurement using 0.4 g diamond detector
(NV 1 ppm ~1.6 × 10^{17}/cc) x 1yr achieves
XENONnT (solar axion search, with 5.9 ton LXe)
first physics goal :
axion like DM search with a sensitivity surpassing
XENONnT by 2030

FY2024 : demonstration at room temp.



diamond substrate <100>, 3x3x0.5 mm, NV : 4.5 ppm





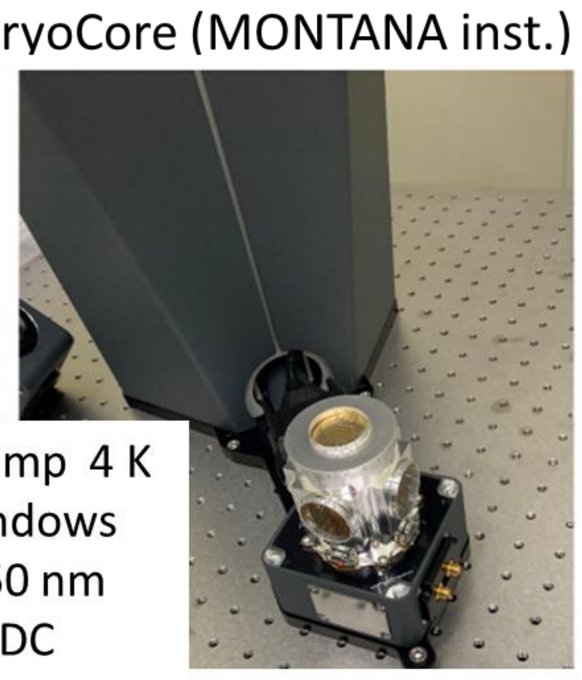
- luminescence dependent on the NV spin state

But the laser malfunctioned.
- introduce a new 10W laser in next Spring
- conduct measurements using a temporary one

FY2025 : low temp experiment to improve n_{NV} and T_2

table-top cryo-station was installed.

CryoCore (MONTANA inst.)



- Minimum temp 4 K
- 5 optical windows
- vibration < 50 nm
- 2 RF and 20 DC

Chamber : ϕ53 mm x 63 mm

Optical system will be constructed to perform the magnetic sensitivity for dark matter search