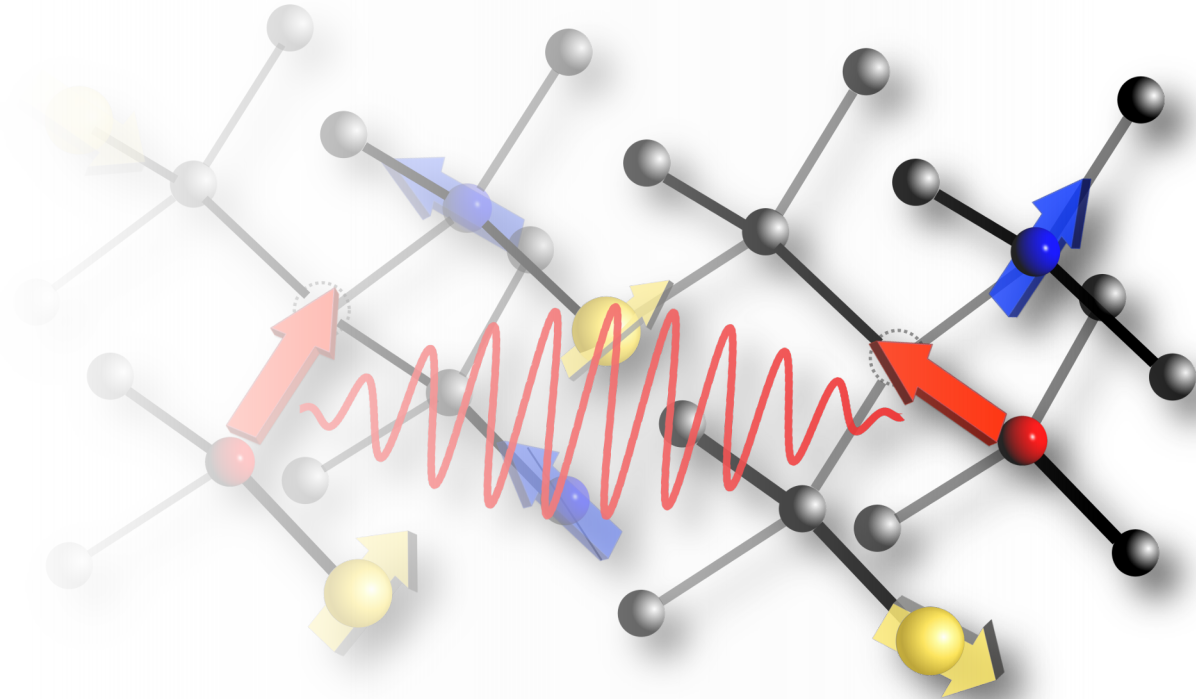


Solid-state defect-based quantum sensing : from basics to dark matter detection

Particle Physics, Quantum Information
and Machine Learning

Paul Junghyun Lee
Center for Quantum Technology
KIST



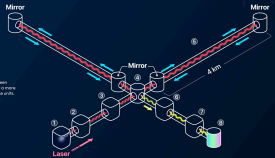
Technology utilizing quantum '**enhanced**' measurements beyond the classical limit using novel quantum mechanical nature..

(Quantum Superposition, Quantum Entanglement etc..)

Metrology

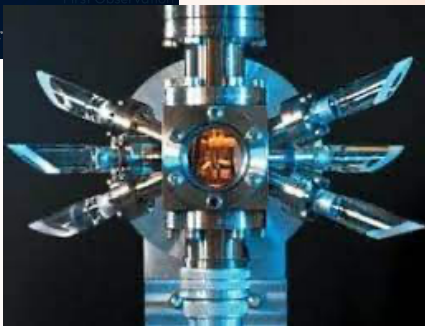
LIGO

Laser Interferometer
Gravitational-Wave
Observatory

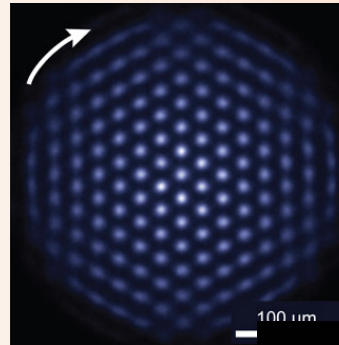


Gravitational
wave
observation,
LIGO

Precise
Atomic
clocks, NPL

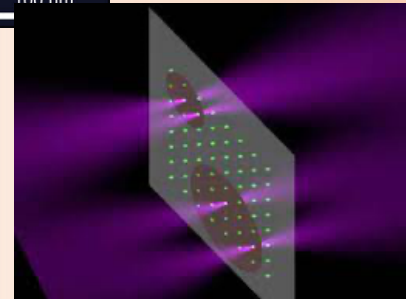


Quantum Simulation

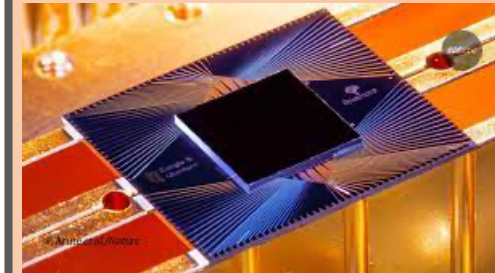


Trapped ions,
NIST

Neutral
atoms,
Harvard



Quantum Computing



Super
conducting
qubit,
Google

Photonic
qubit,
USTC





Seth Lloyd
MIT

“A classical (computation) is like a solo voice. A quantum (computation) is like a symphony — many lines of tones interfering with one another.”

Experimental realization of a quantum algorithm

Isaac L. Chuang¹, Lieven M.K. Vandersypen², Xinlan Zhou², Debbie W. Leung³, and Seth Lloyd⁴

¹ IBM Almaden Research Center K10/D1, San Jose, CA 95120, ² Solid State Electronics Laboratory, Stanford University, Stanford, CA 94305

³ Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 ⁴ MIT Dept. of Mechanical Engineering, Cambridge, Mass. 02139

submitted January 19, 1998; revised March 7, 1998, accepted March 18, 1998.

Quantum hype in NMR machines

those systems. On the other hand, because of their natural isolation from the environment, nuclear spins are particularly good ‘quantum bits’⁶, and their use for quantum computation is possible by applying nuclear magnetic resonance (NMR) techniques in an unconventional manner^{17–19}. Here, we report on the

However, limitations in scalability, slow gate operations..

I. Chuang *et. al.*, Nature **393**, 143–146 (1998)

Why Solid-State Defect for Quantum?

Naturally **trapped** atoms, from a **single** to **multiple spins** (qubit/qudit) in a **Solid-State** host material

Solid-state defect spin qubits (e.g. NV center in diamond) are promising..

- ▶ Long spin relaxation time T_1
(**ATM, RT operational, $T_1 \sim 5\text{ms}$ at RT**)
- ▶ Long spin dephasing times T_2^* , T_2
($T_2^* \sim 50\mu\text{s}$, $T_2 \sim 500\mu\text{s}$)
- ▶ Spin-to-Photon interconnection
- ▶ Can be combined with cutting-edge nano-fabrication technique

Atomic Defects in Solid-State matter

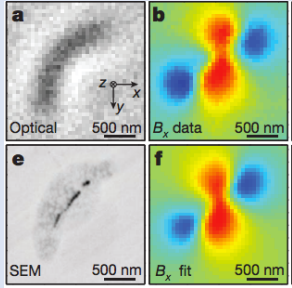
- ▶ Long spin relaxation time
(**ATM, RT operational, $T_1 \sim 5\text{ms}$ at RT**)
- ▶ Long spin dephasing time
($T_2^* \sim 50\mu\text{s}$, $T_2 \sim 500\mu\text{s}$)
- ▶ Spin-to-Photon interconnection
- ▶ Can be combined with cutting-edge nano-fabrication technique

Walsworth group, UMD

Solid-State Defect Spins for Quantum Technology

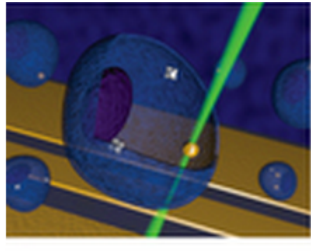
Diamond based point defects are promising qubit platform for quantum sensing to quantum information science

In vivo magnetic field sensing



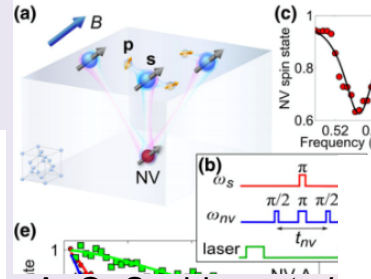
D. Le Sage *et al.*,
Nature (2013)

Cell thermometry with diamond



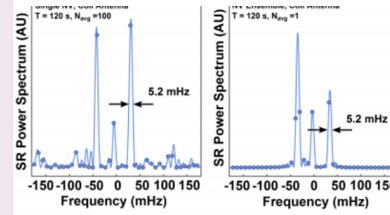
G. Kucsko *et al.*,
Science (2014)

Single proton B-field sensing



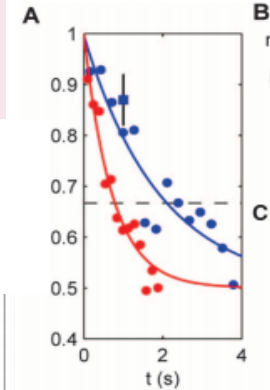
A. O. Sushkov *et al.*,
PRL (2014)^(b)

High spectral resolution nanoscale NMR



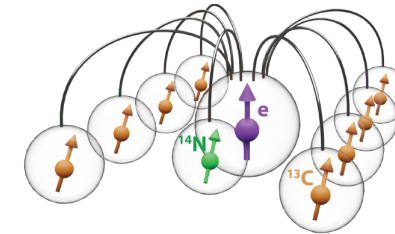
D. Glenn *et al.*,
Nature (2018)

Quantum memory 1sec



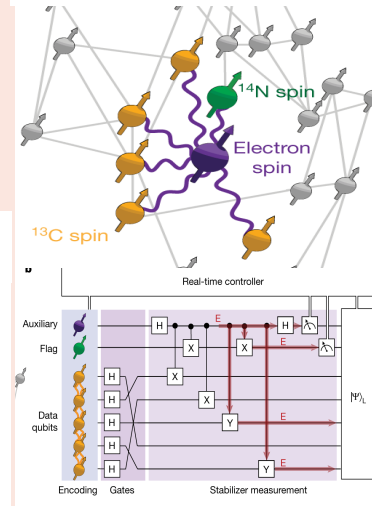
P. Maurer *et al.*,
Science (2012)

7 qubit GHZ state



C. E. Bradley *et al.*,
PRX (2019)

7 qubit FT Logical qubit



M. H. Abobeih *et al.*,
Nature (2022)

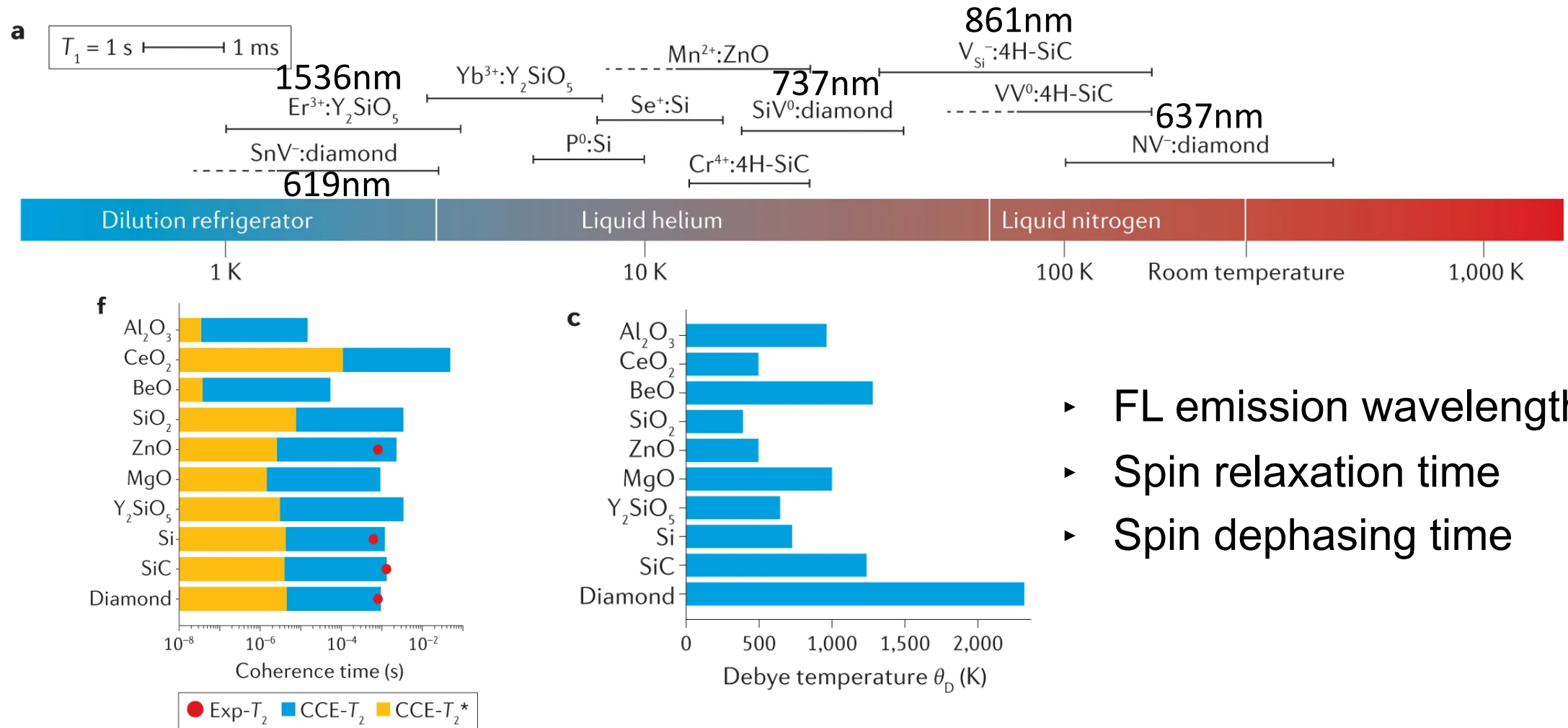
Quantum Sensing

Quantum Information

- ☐ **Introduction to Defect Qubits**
- ☐ **Building Blocks for Quantum Sensors**
- ☐ **Quantum Metrology with Defect Qubits**
- ☐ **Defect Qubits for Dark Matter Detection**

Wide Range of Spin Defects in Solid-State Matter

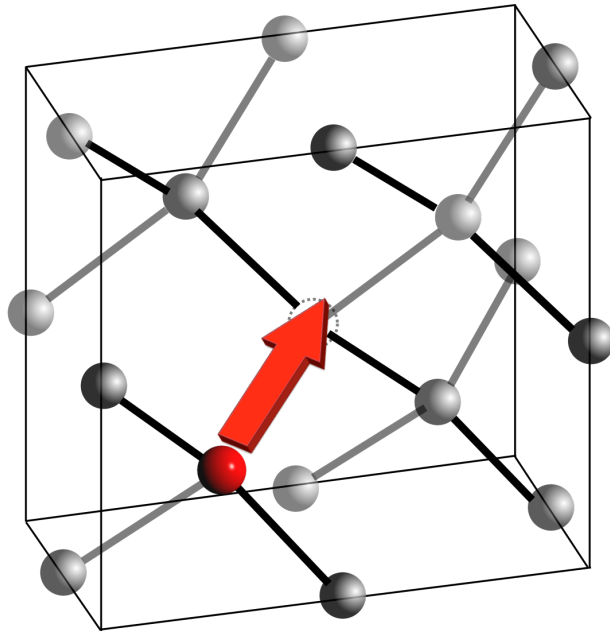
Different spin defects have different qubit performances



G. Wolfowicz *et. al.*, Nat. Rev. Mat. **6**, 906–925 (2021)

Diamond based point defects : NV, SiV, Ge-V, SnV etc..

Nitrogen Vacancy center

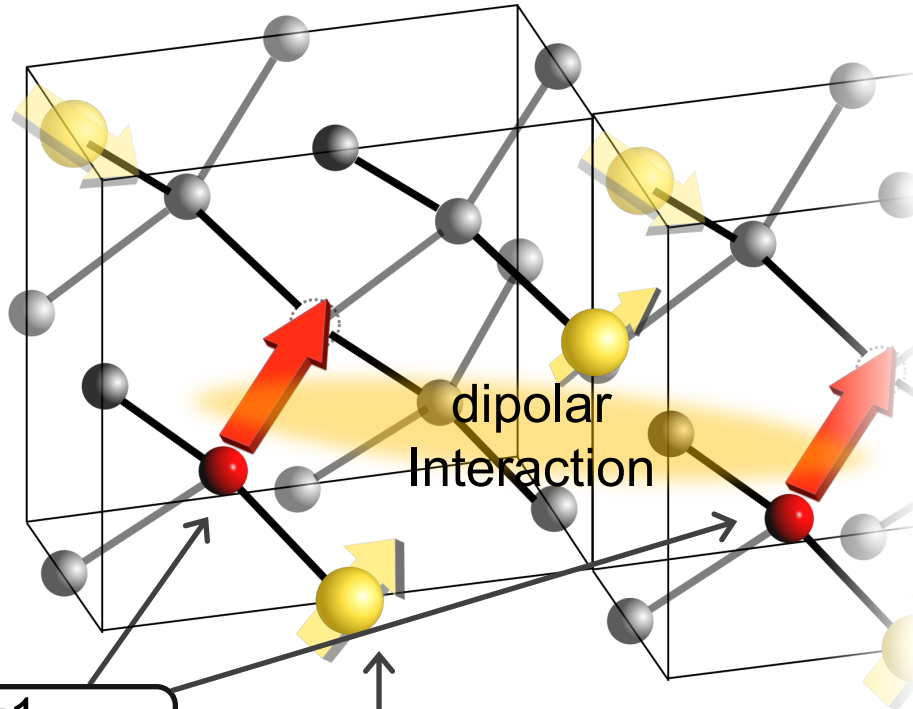


- ▶ Can be operated at RT, ATM
- ▶ Spin state initialization with 532nm laser
- ▶ Robust spin state control using microwave signal

- ❑ Introduction to Defect Qubits
- ❑ Building Blocks for Quantum Sensors
- ❑ Quantum Metrology with Defect Qubits
- ❑ Defect Qubits for Dark Matter Detection

Building Blocks for the Quantum Sensors

Mixed hybrid spin network
trapped in diamond



NV, $s=1$
Physical/
Ancilla qubit

$[^{13}\text{C}] = 1.1\%$, $I=1/2$
Physical/Memory qubit

$$\hat{H} = \sum_i (\vec{S}_i \cdot \mathbf{D}_i \cdot \vec{S}_i + \vec{S}_i \cdot g \cdot \vec{B})$$

$$+ \sum_{i,k} \vec{S}_i \cdot \mathbf{A}_{i,k} \cdot \vec{I}_k + \sum_{i,j} \vec{S}_i \cdot \mathbf{D}_{i,j} \cdot \vec{S}_j$$

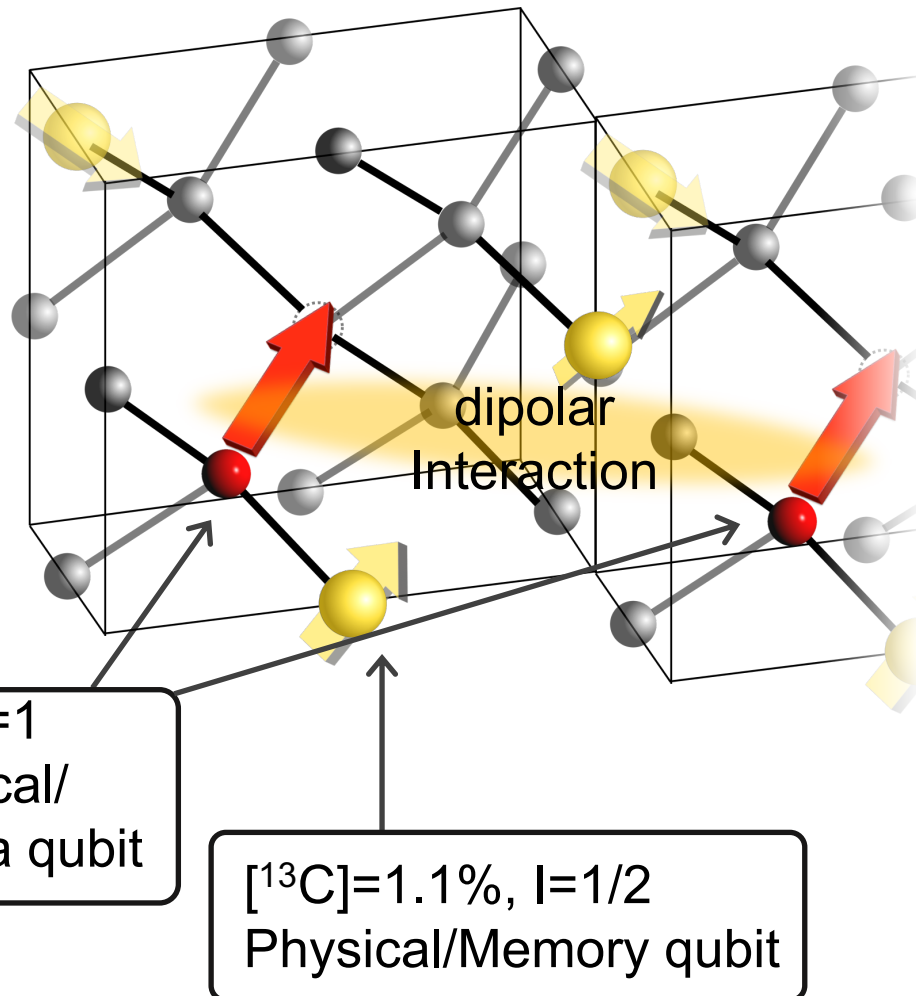
$$\hat{H}_{dip} = \frac{\mu_0 h^2 \gamma^2}{4\pi r^3} (\vec{S}_A \cdot \vec{S}_B - 3(\vec{S}_A \cdot \vec{r})(\vec{S}_B \cdot \vec{r}))$$

- For strong coupling, $|\mathbf{D}_{i,j}| > 1/T_{2,NV}$
(usually $r < 10$ nm)

$$|\mathbf{A}_{i,k}| \ll |\mathbf{D}_{i,j}|$$

- At long range, electronic spin coupling much stronger than nuclear spin coupling

Mixed hybrid spin network
trapped in diamond



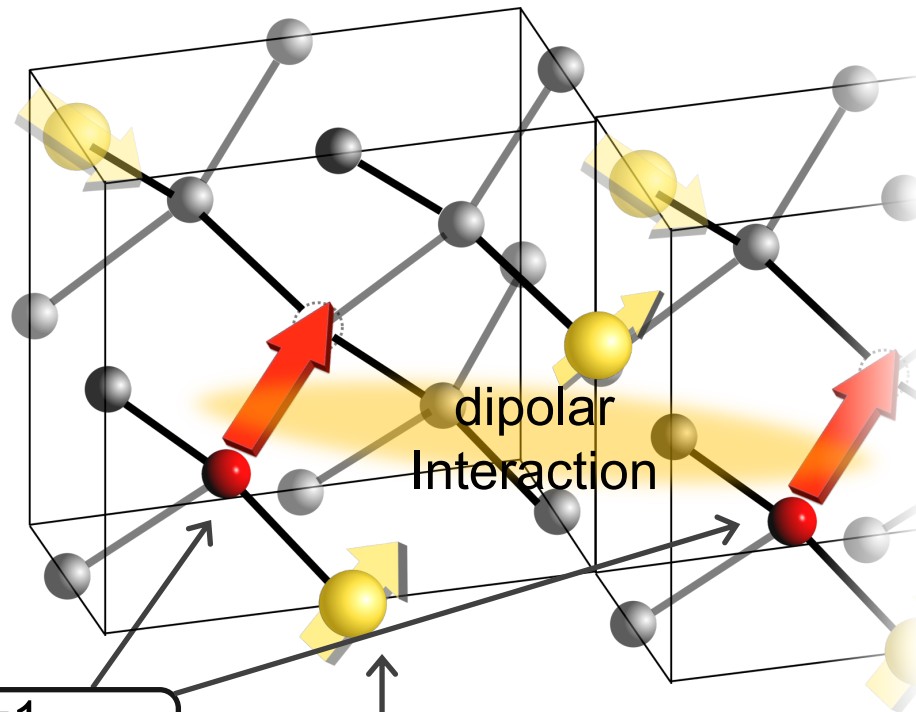
Electronic spins for scalable quantum channel

1. Fast single/two qubit gate
2. Realization of multi qubit spin register

Nuclear spins for physical/memory qubit

1. Long spin coherence time
2. Fine control via dynamical decoupling

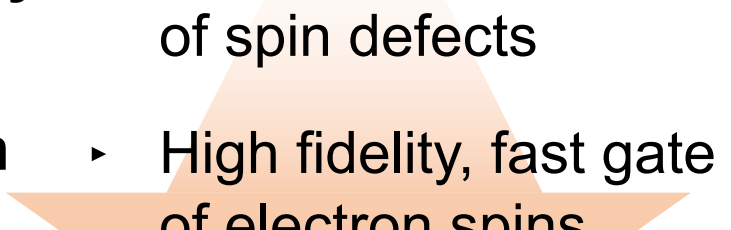
Mixed hybrid spin network trapped in diamond



NV, s=1
Physical/
Ancilla qubit

$[^{13}\text{C}] = 1.1\%$, $I = 1/2$
Physical/Memory qubit

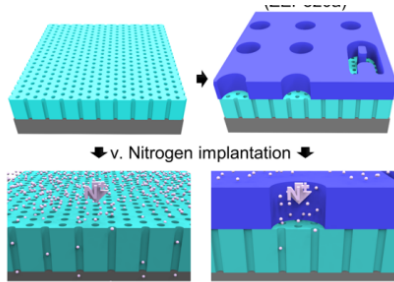
NMR based Quantum Machine



- Scalability** ▶ Deterministic generation of spin defects
- Quantum gates** ▶ High fidelity, fast gate control of electron spins
- Less error** ▶ High purity material engineering

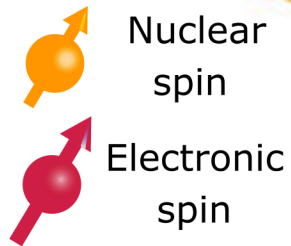
Spin defect-based Quantum Machine

Diamond-based Quantum Machine

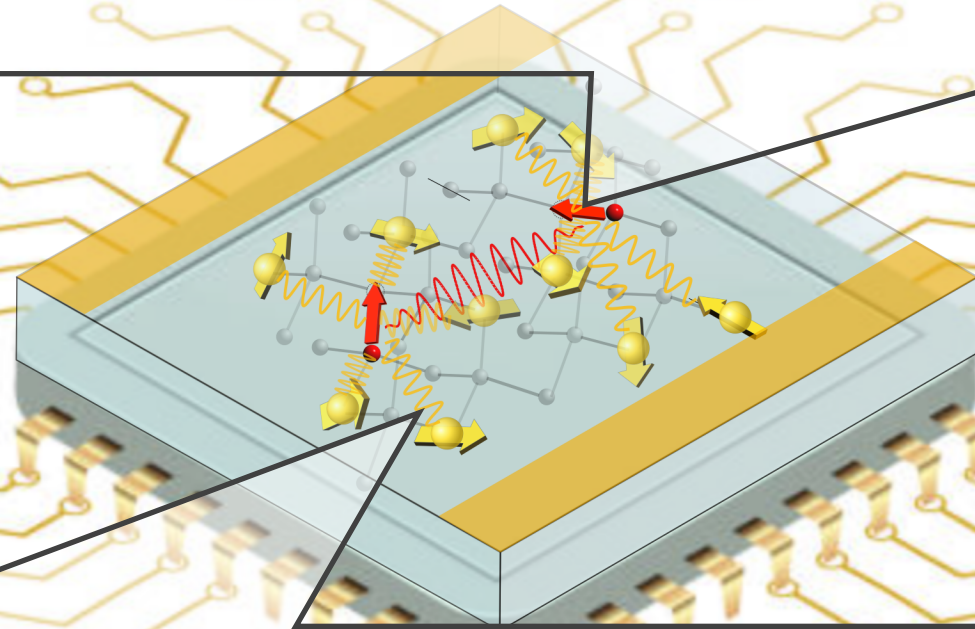


Mask ion implantation technique ($\Delta x \sim 5\text{nm}$) or
single ion implantation + AFM tip ($\Delta x \sim 5\text{nm}$)

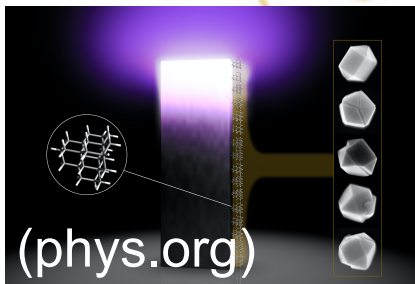
Physical qubit



Ancilla qubit



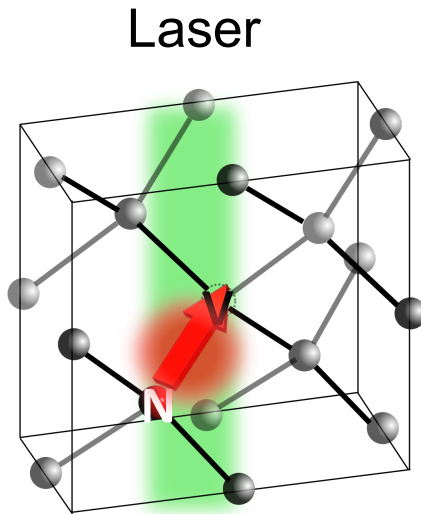
Single node
~ 50 qubits



CVD 1.1% natural ^{13}C (up to 50 qubits) or
 ^{13}C enriched diamond (up to 100 qubits)

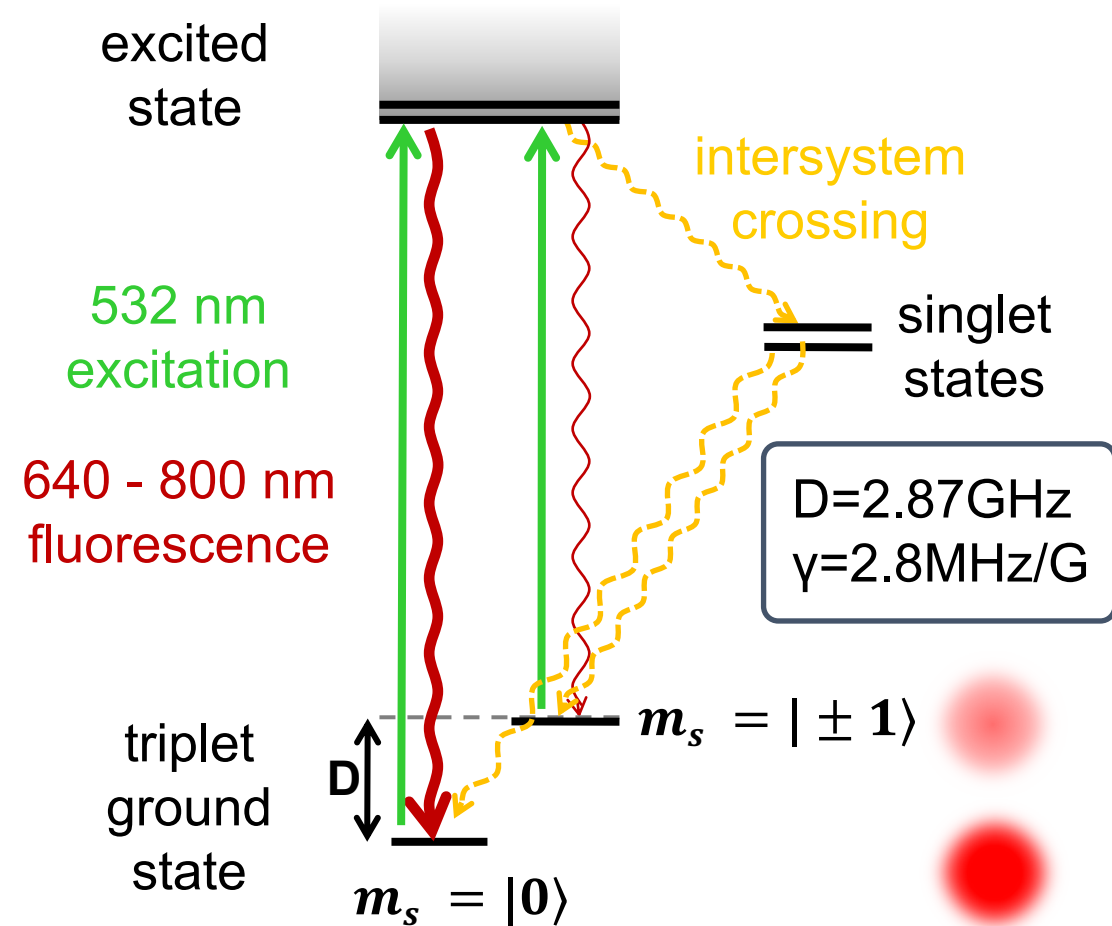
Optical Initialization and Readout

@ Room Temp, ATM



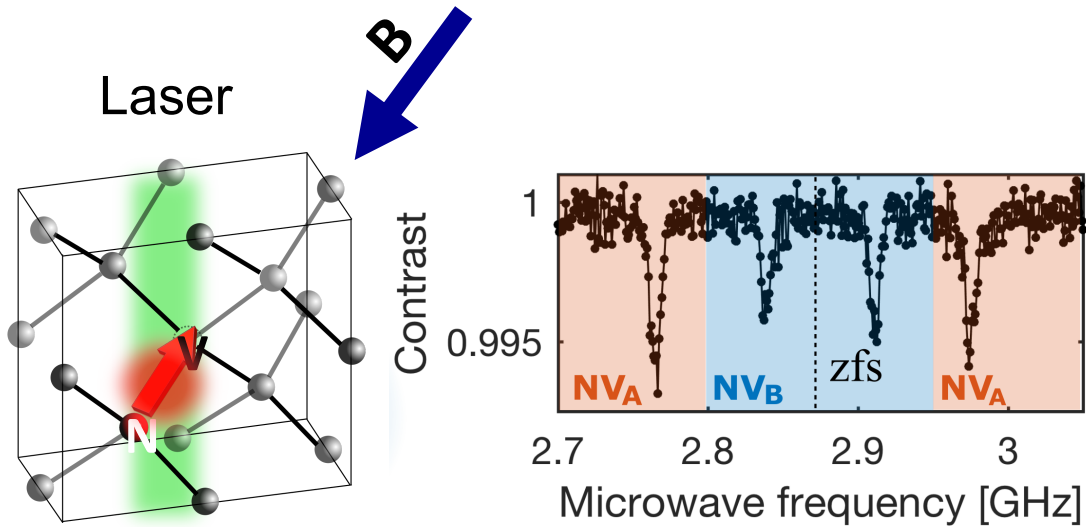
Spin triplet state ($S = 1$)

Zero-field splitting due to spin-spin interactions ($D=2.87\text{GHz}$)

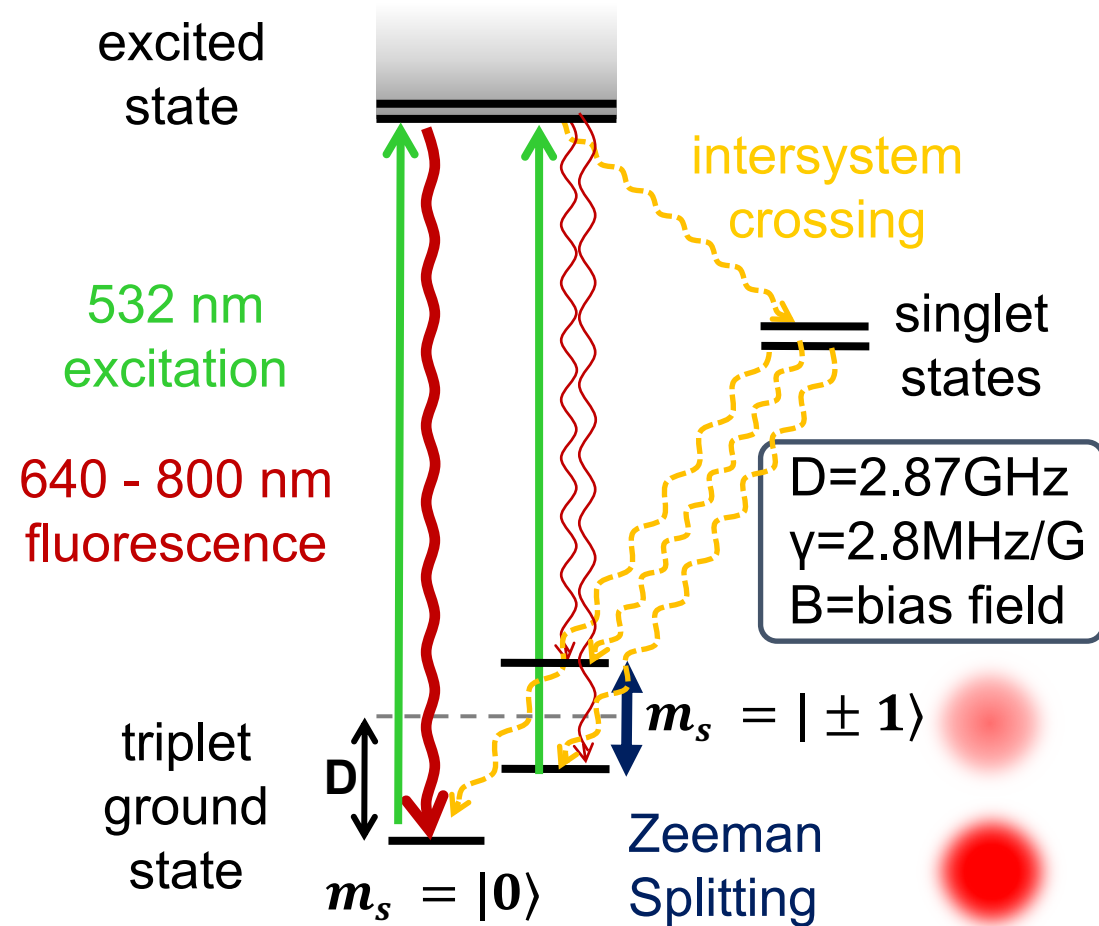


NV center under the Static B-field

@ Room Temp, ATM

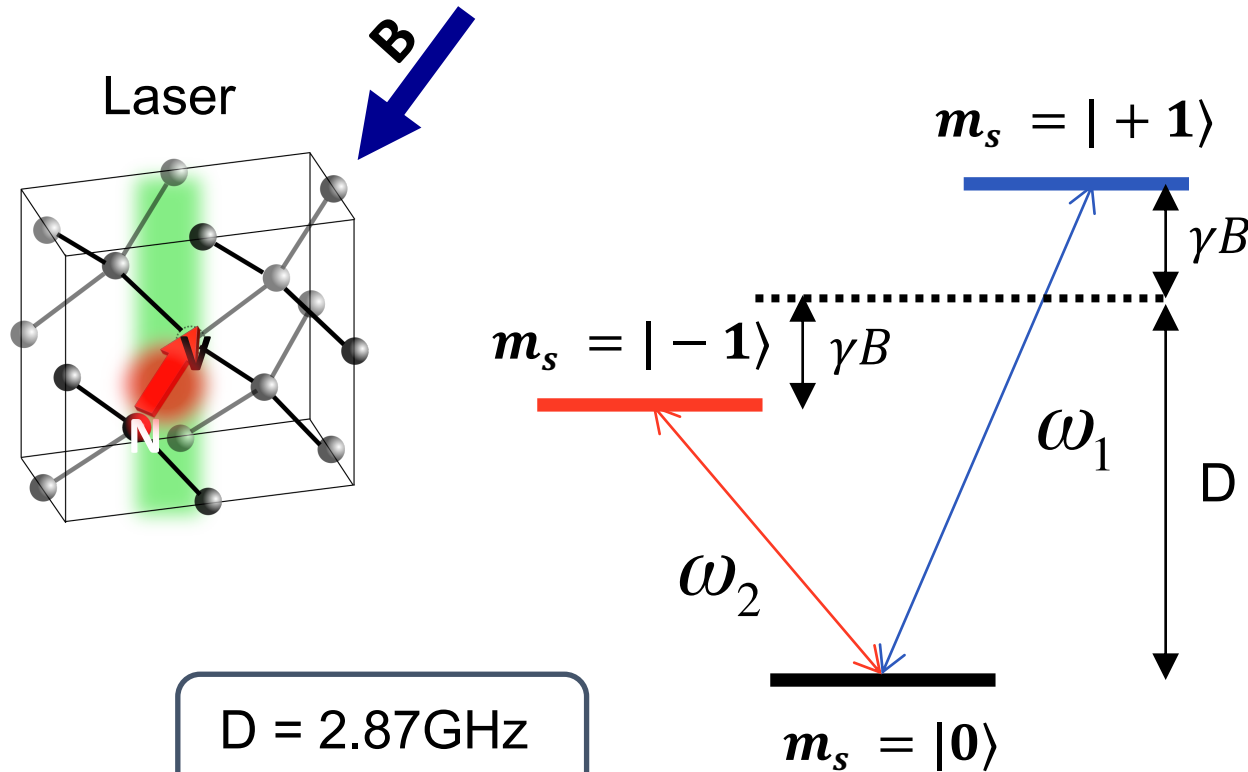


Optically-detected magnetic resonance (ODMR)



NV spin Qubit Control via MW

@ Room Temp, ATM



$D = 2.87\text{GHz}$
 $\gamma = 2.8\text{MHz/G}$
 $B = \text{bias field}$

Resonance frequencies

$$\omega_1 = D + \gamma B$$

$$\omega_2 = D - \gamma B$$

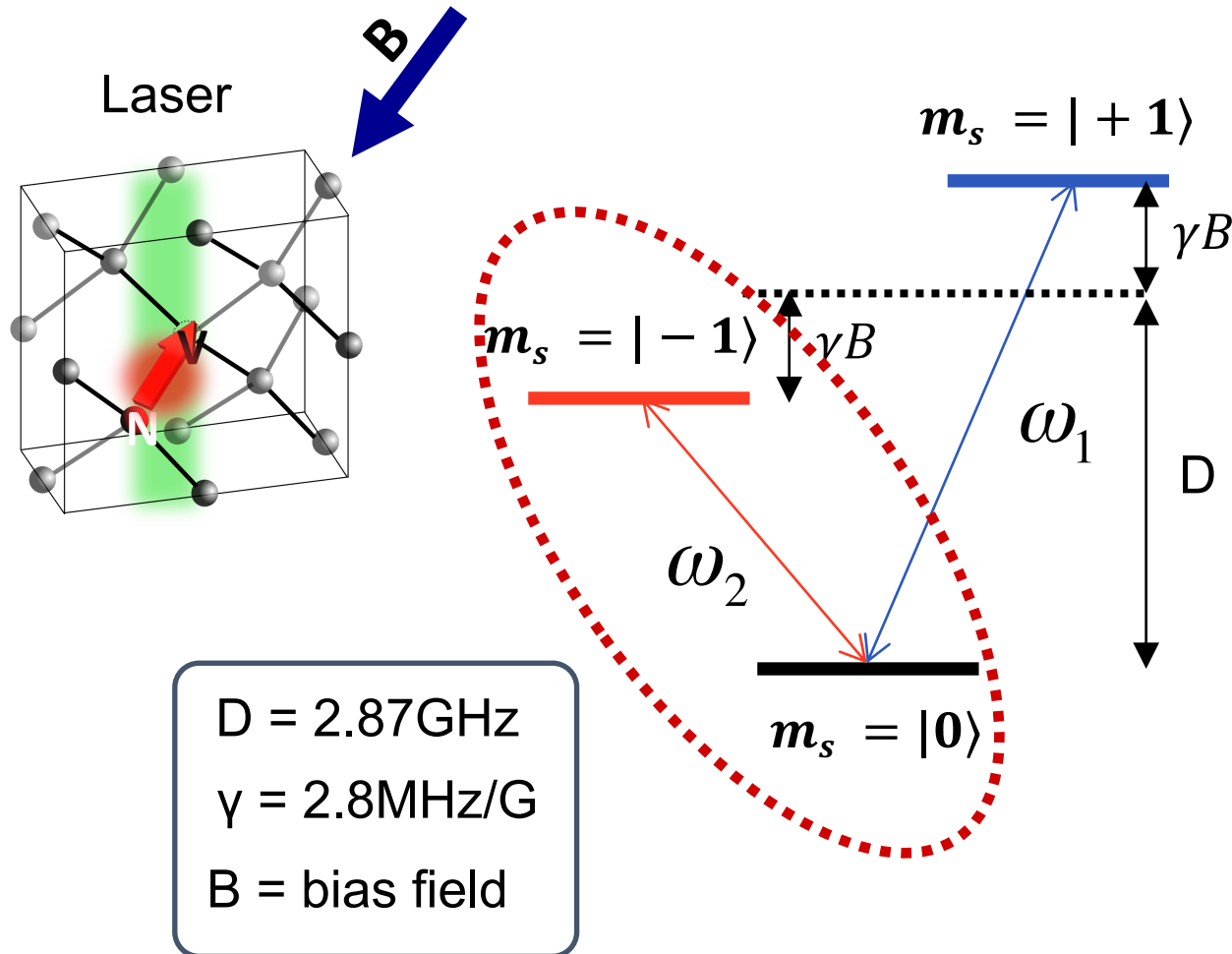
Hamiltonian

$$H = D(S_z)^2 + \gamma B S_z + \Omega_1 \cos(\omega_1 t) S_x + \Omega_2 \cos(\omega_2 t) S_x$$

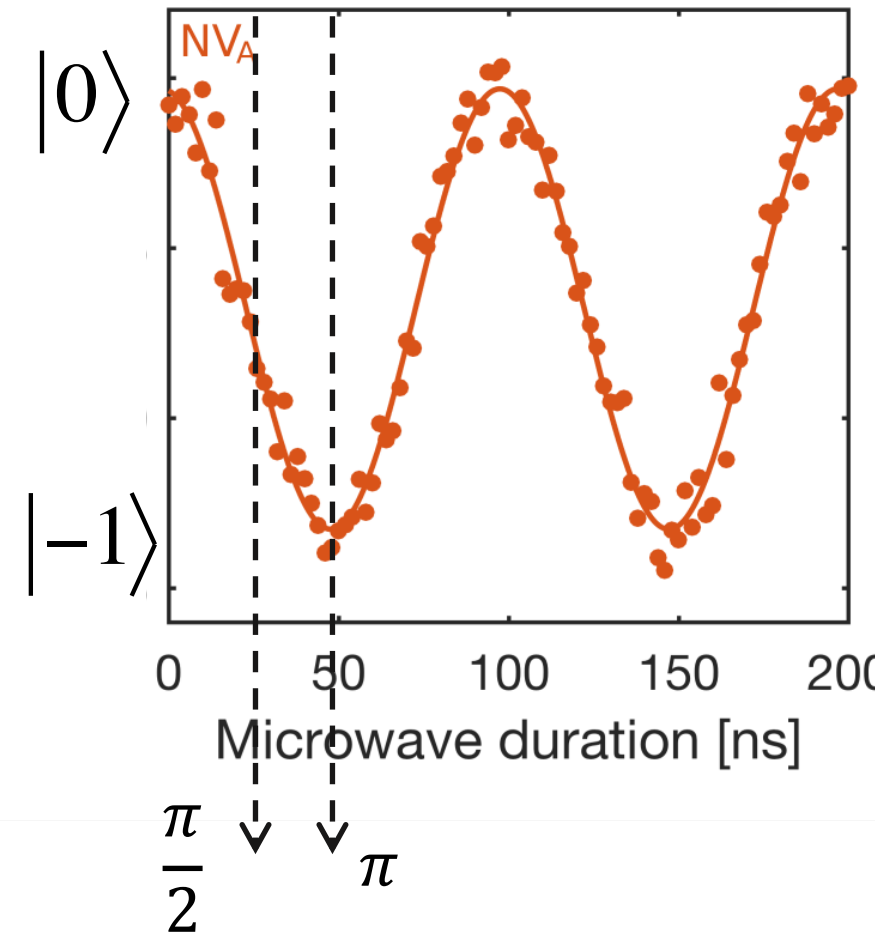
→ Can be used as a Qubit / Qutrit

NV spin Qubit Control via MW

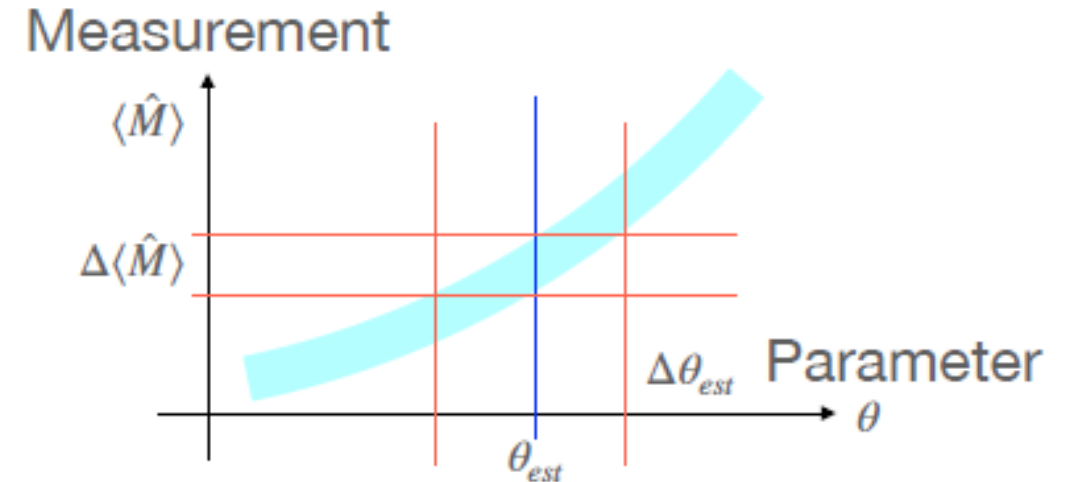
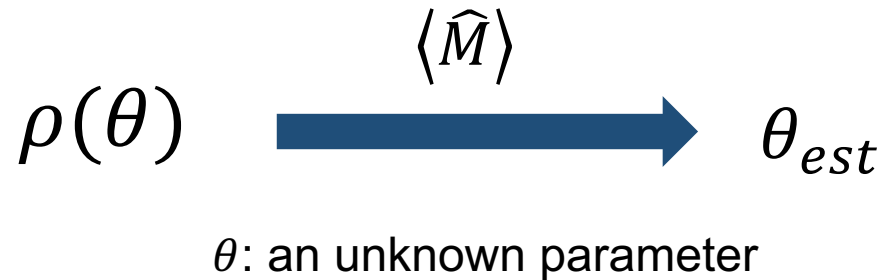
@ Room Temp, ATM



Rabi oscillation



- ☐ Introduction to Defect Qubits
- ☐ Building Blocks for Quantum Sensors
- ☐ Quantum Metrology with Defect Qubits
- ☐ Defect Qubits for Dark Matter Detection



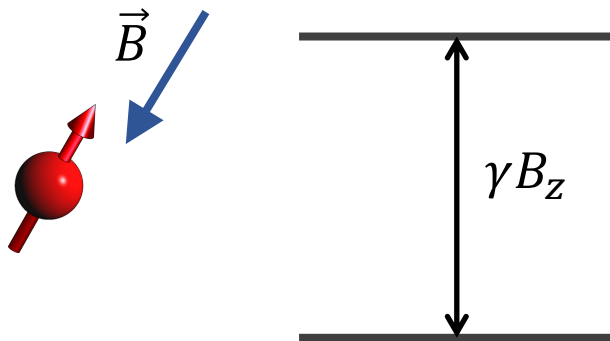
- ▶ What is the best possible precision allowed?
 - Classical Fisher information (CFI : F_c): It measures how sensitively the distribution changes with θ .
 - Quantum Fisher information (QFI : F_Q): the *ultimate* information about θ contained in the state.
 - **Quantum Cramér-Rao bound** for *unbiased* estimator $\hat{\theta}$, N independent measure:

$$\Delta \theta_{est} \geq \frac{1}{\sqrt{N F_c}} \geq \frac{1}{\sqrt{N F_Q}}$$

Three Steps in Quantum Sensing

◆ 1st step :

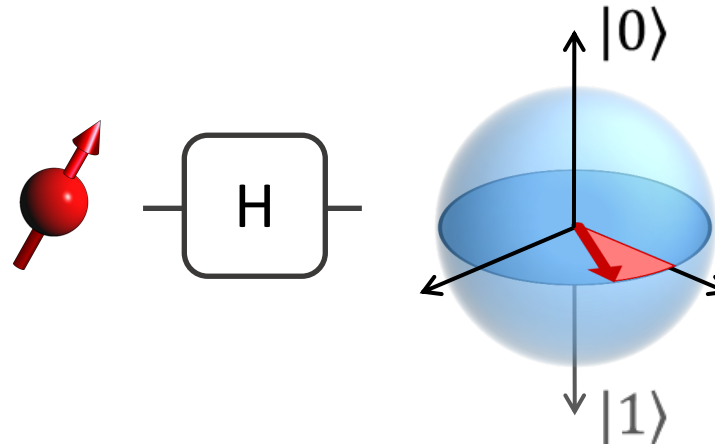
Using a quantum system
(Ex. Zeeman effect)



Single photon,
Single charge,
Single spin etc..

◆ 2nd step :

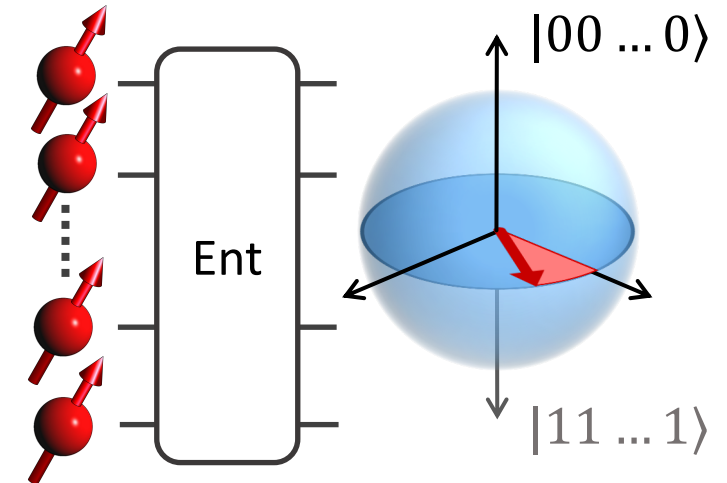
Using a quantum coherence
(Ex. Superposition)



Ramsey interferometry,
Mach-Zehnder,

◆ 3rd step :

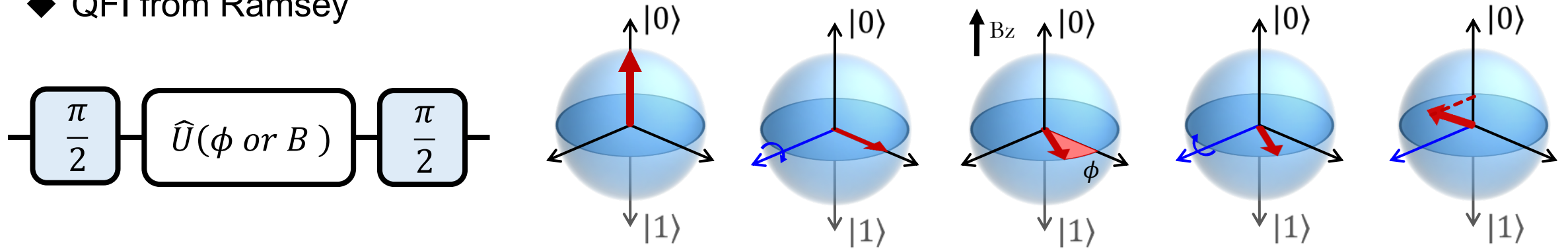
Using a quantum resources
(Ex. Entanglement)



Entangled state,
Squeezed state etc..

Example : Ramsey Interferometry

◆ QFI from Ramsey

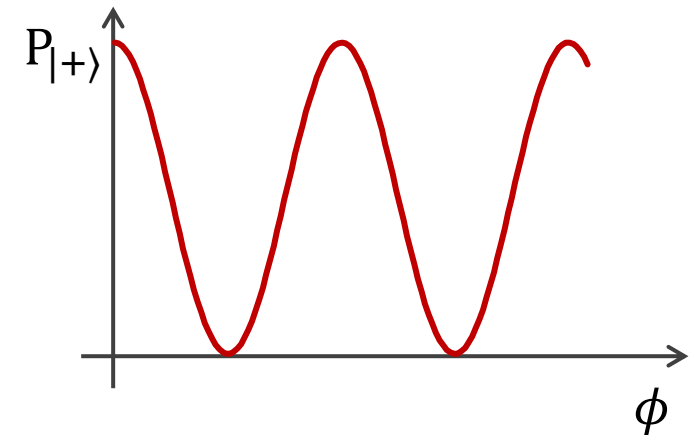


- Initialize $|\psi\rangle_i = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$
- Phase accumulation $|\psi\rangle_\phi = \frac{1}{\sqrt{2}}(|0\rangle + e^{-i\phi}|1\rangle)$
- Readout $|\psi\rangle_f = \frac{1 + e^{-i\phi}}{2}|0\rangle + \frac{1 - e^{-i\phi}}{2}|1\rangle$

$$F_Q = F_C = 1$$

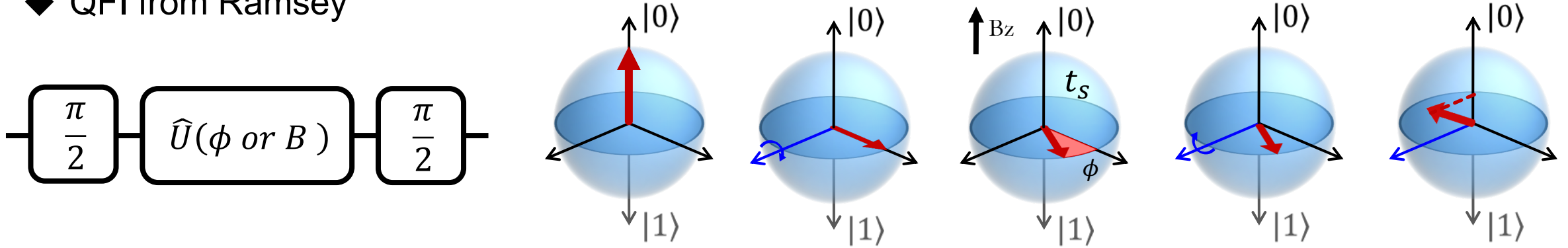
Optimal POVM = $\{|+\rangle\langle+|, |-\rangle\langle-|\}$

$$|+\rangle = 1/\sqrt{2}(|0\rangle + |1\rangle) \quad |-\rangle = 1/\sqrt{2}(|0\rangle - |1\rangle)$$

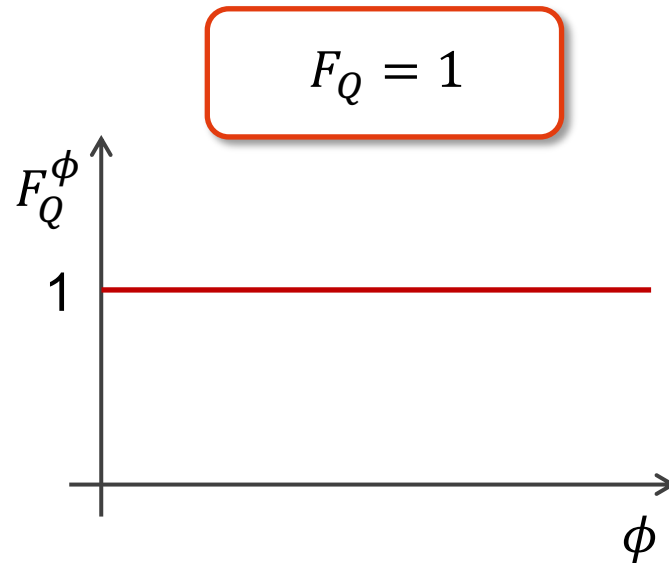


Different Perspectives in QFI parameter

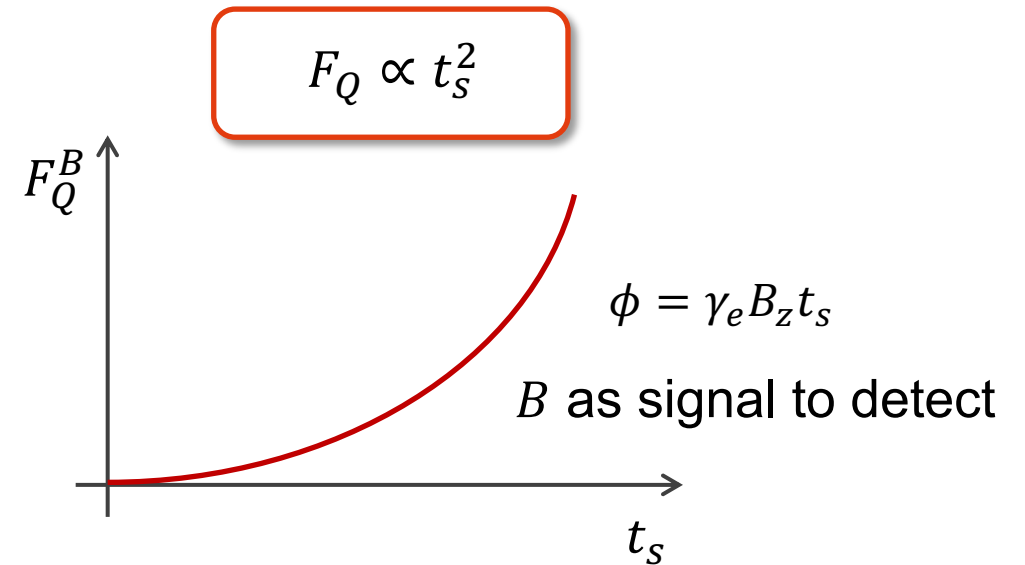
◆ QFI from Ramsey



▸ QFI with as phase parameter



▸ QFI with as signal parameter



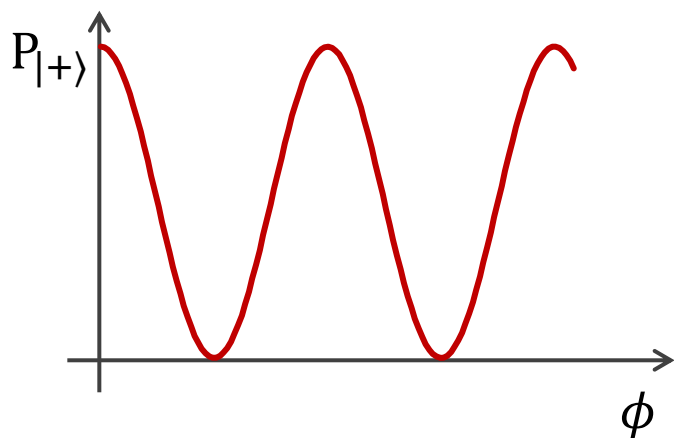
How to Further Enhance QFI?

◆ To beat the Standard Quantum Limit

→ Need to use non-classical states, ex) Entangled state, Squeezed state etc..

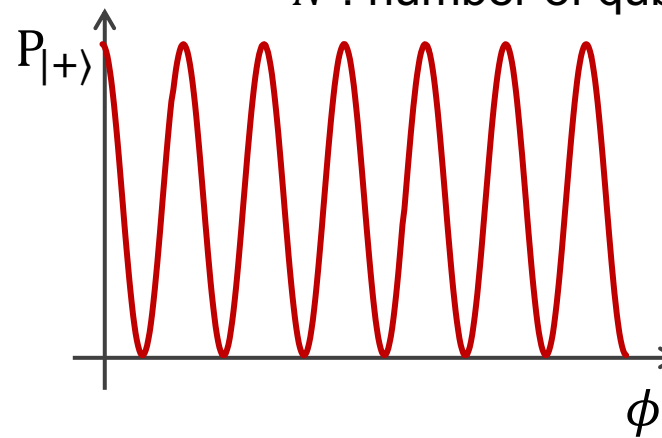
Ex) GHZ (Greenberger–Horne–Zeilinger) state

$$|\psi\rangle_\phi = \frac{1}{\sqrt{2}}(|0\rangle + e^{-i\phi}|1\rangle)$$



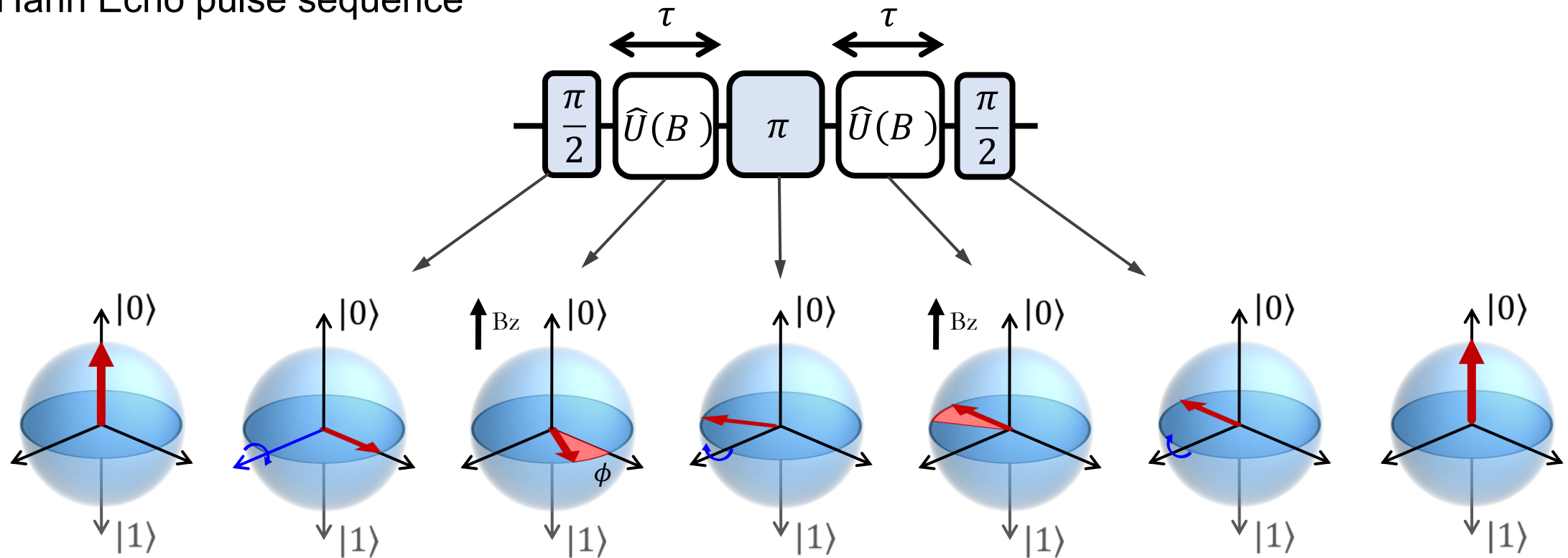
$$|\psi\rangle_\phi = \frac{1}{\sqrt{2}}(|00\dots 00\rangle + e^{-iN\phi}|11\dots 11\rangle)$$

N : number of qubits



$$F_Q \propto N^2$$

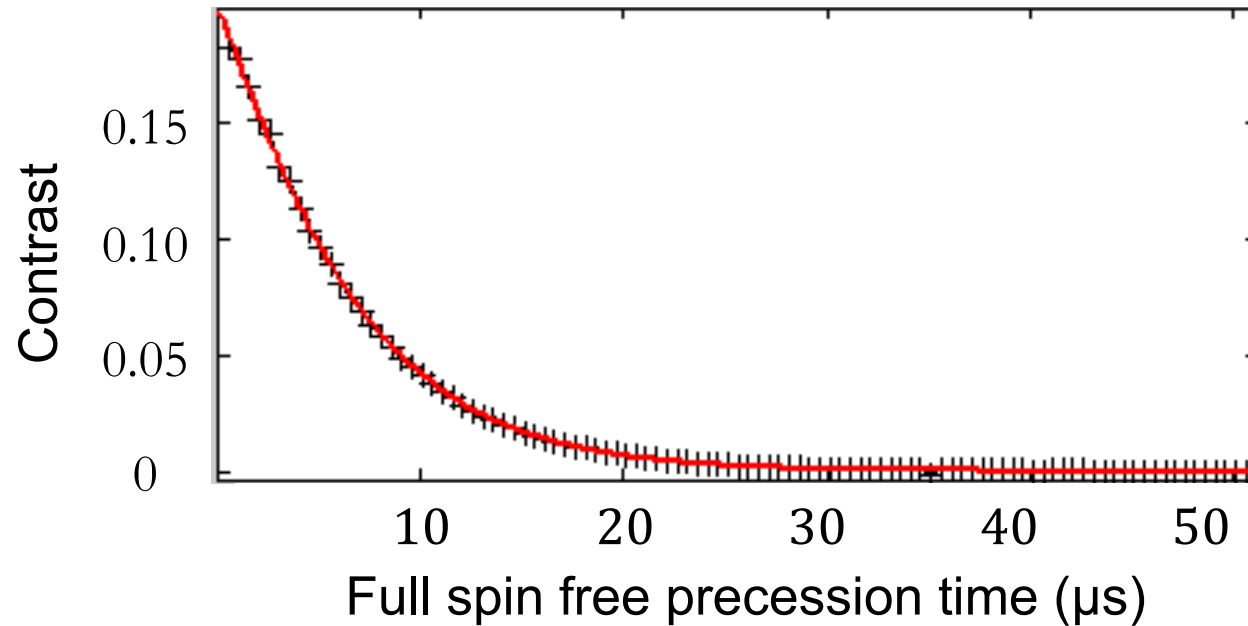
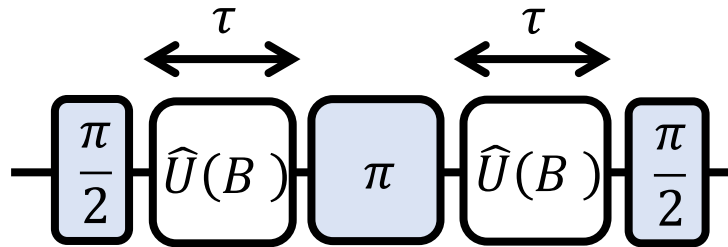
◆ Hahn Echo pulse sequence



π -refocusing pulse cancels out the phase accumulation by B_z

→ DC field noise can be suppressed, longer spin coherence time T_2

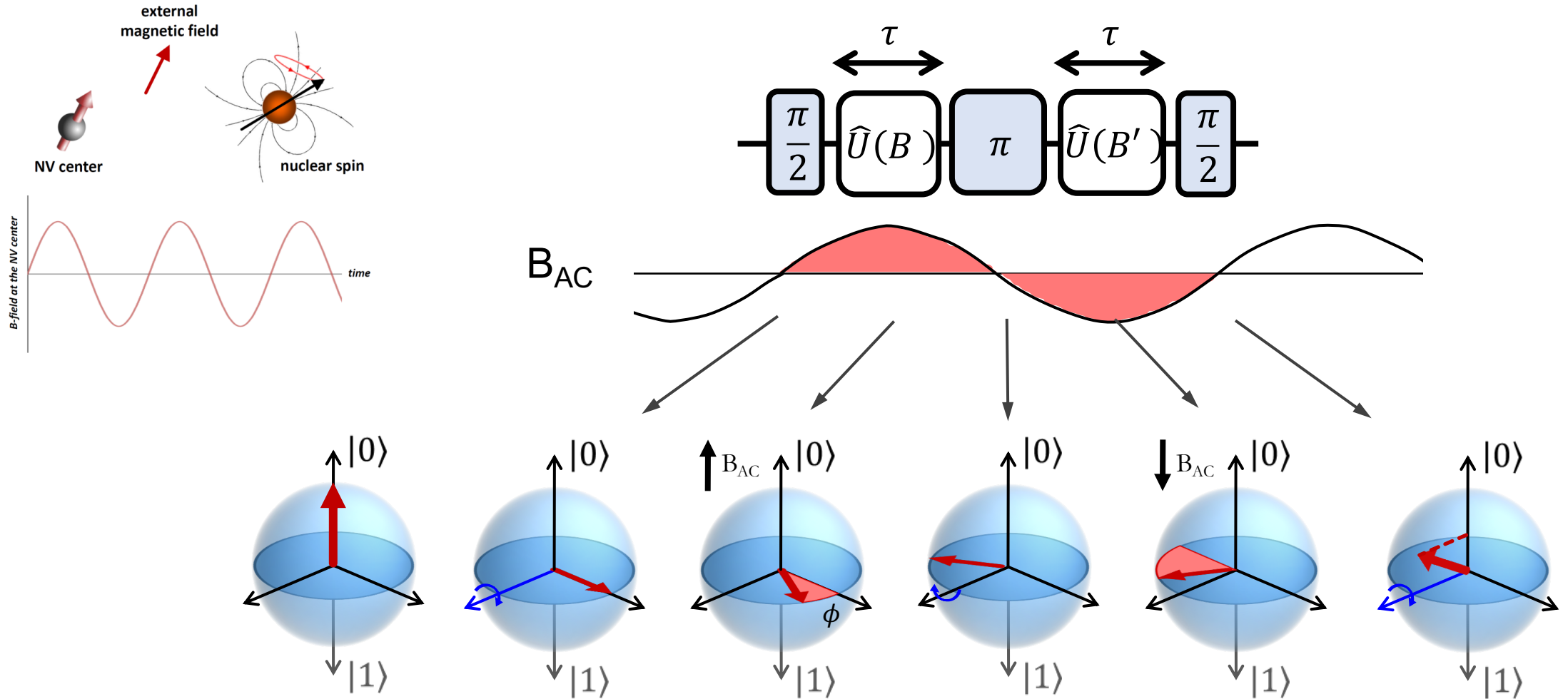
◆ Hahn Echo pulse sequence



- ▶ Limited spin coherence time T_2 due to the nearby magnetic fluctuation noise
- ▶ Refocusing π -pulse cancels DC noise, but susceptible to AC noise

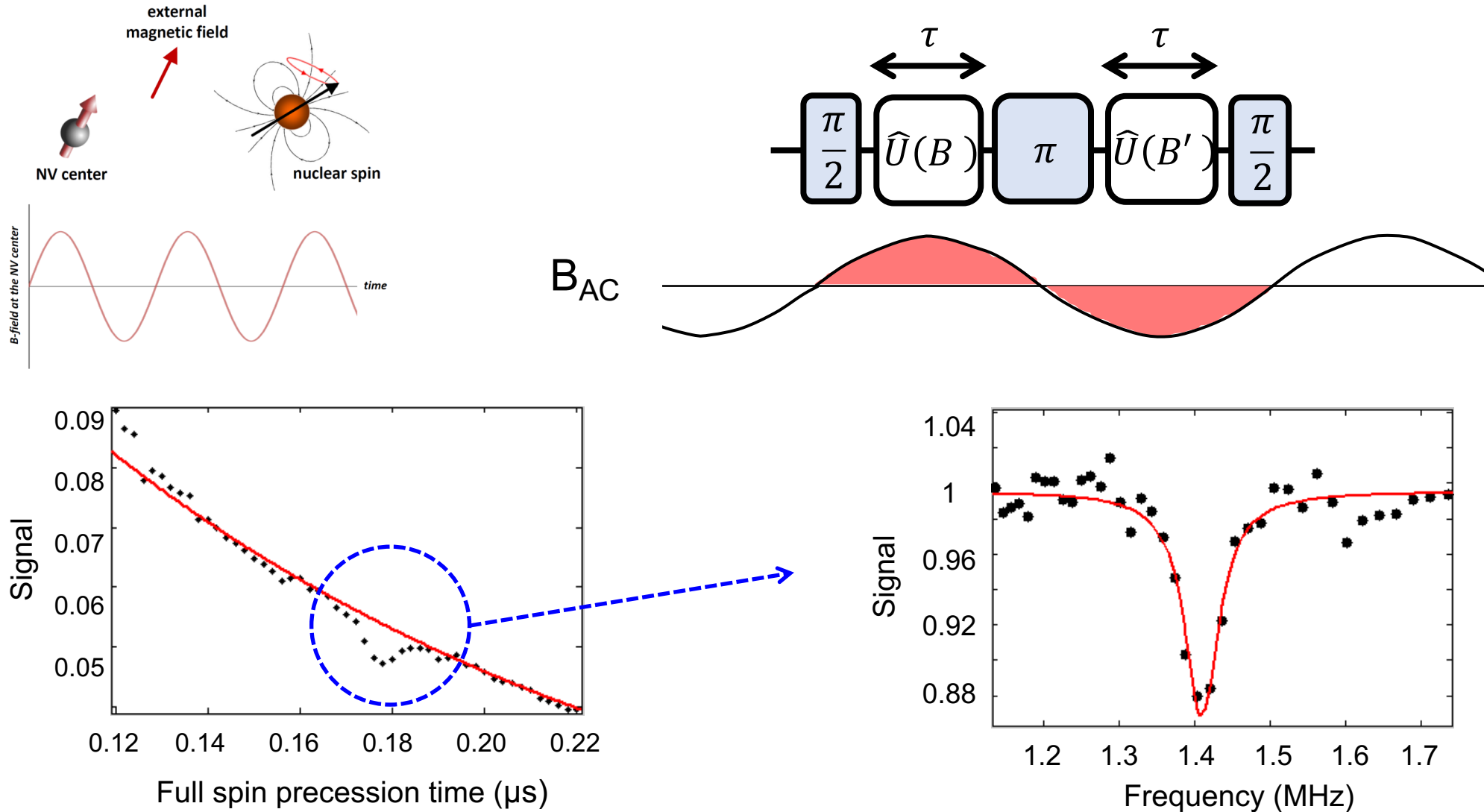
AC-field Sensing Protocol

◆ AC field sensing protocol

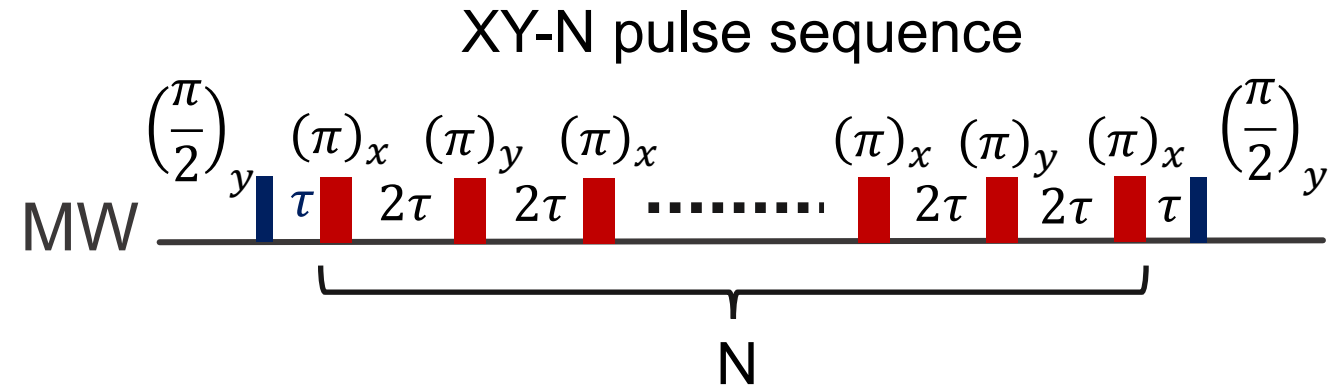
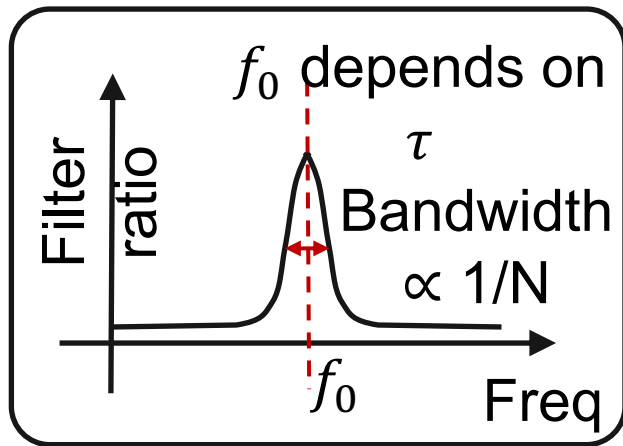
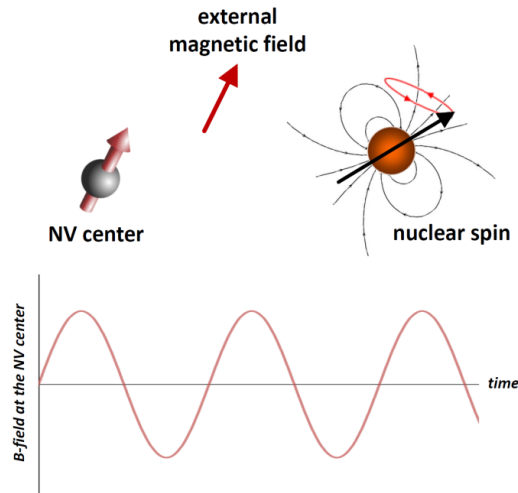


AC-field Sensing Protocol

◆ AC field sensing protocol



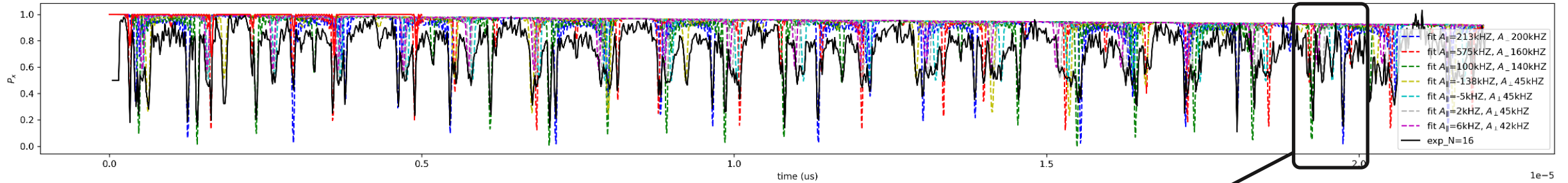
Enhanced AC-field Sensing Protocol



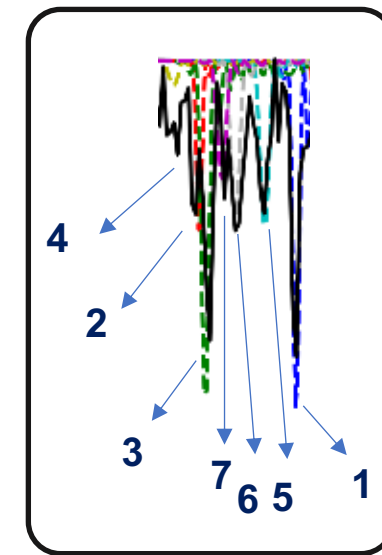
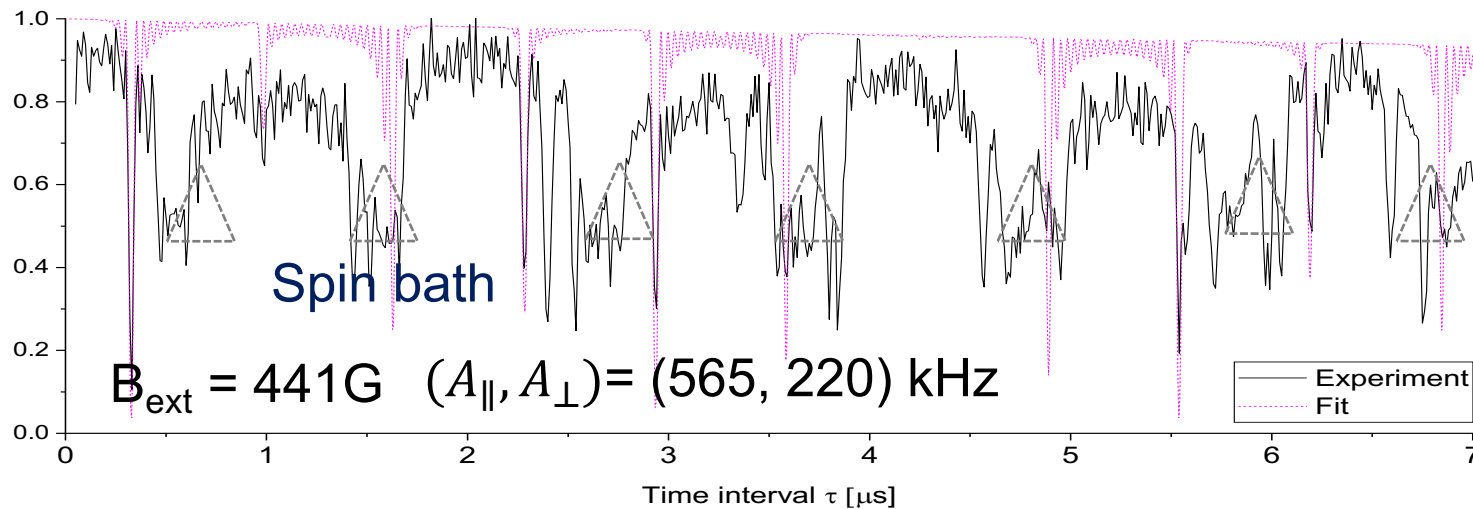
- ▶ Dynamical decoupling pulse allows longer coherence time $T_{2,N}$ suppressing nearby magnetic fluctuation noise
- ▶ By sweeping N and τ , we can engineer a filter function, and detect specific AC frequency signal
- ▶ Spectral resolution of the signal FFT depends on $T_{2,N}$

Example : Nuclear Spin Detection via NV Spin

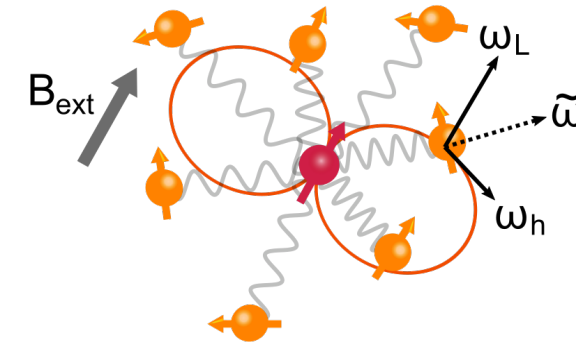
XY-8 pulse sequence measurement



System Hamiltonian is solved and fit to data

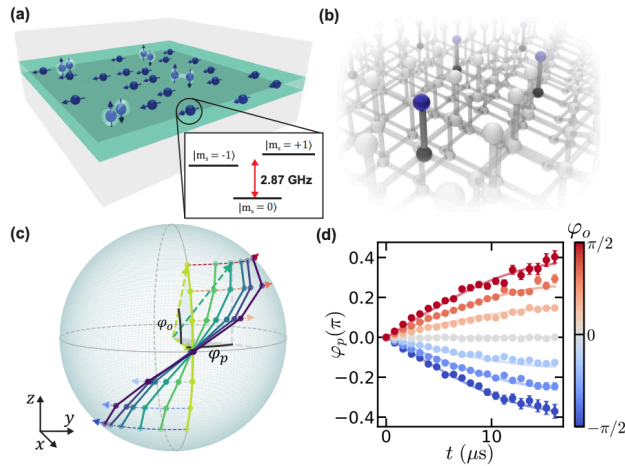


Detecting 7 different ^{13}C nuclear spins



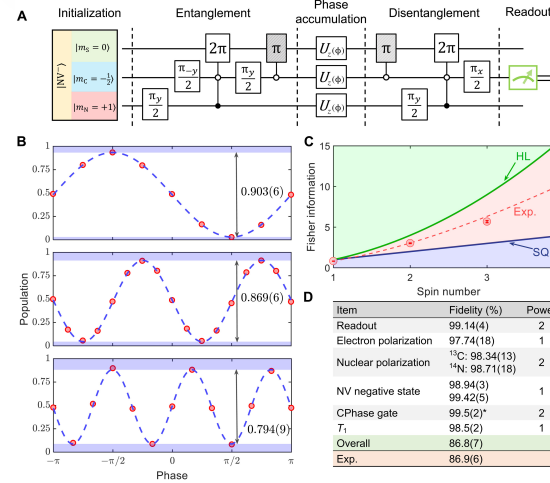
Optimal engineering of non-classical state is important

Spin squeezing with spin ensemble



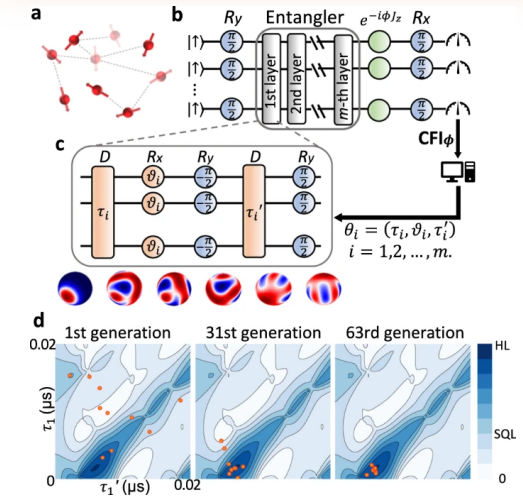
Nature **646**, 74-80 (2025)

NV-Nuclear spin entanglement



Sci. Adv. **7**, 32 (2021)

Electron spin entanglement



npj Quant. Info. **8**, 150 (2022)

- ▶ Generation of spin-squeezing with solid-state electronic spins via strong dipolar interaction.
- ▶ Small-scale local multi-qubit entanglement using hyperfine or dipolar interaction.

- ☐ Introduction to Defect Qubits
- ☐ Building Blocks for Quantum Sensors
- ☐ Quantum Metrology with Defect Qubits
- ☐ Defect Qubits for Dark Matter Detection

Directional recoil-track readout with quantum defects

Phys. Rev. D 96, 035009 (2017)
Quant. Sci. Tech. 6, 024011 (2021)
Phys. Rev. Appl. 17, 024041 (2022)

HEP detector instrumentation and radiation diagnostics

Nano Letters 23, 9811-9816 (2023)
J. Phys. Chem. C 129, 2739 (2025)
RSC Advances 15, 1011-1019 (2025)

Recoil-created color centers and defect channels

Phys. Lett. B 782, 242-250 (2018)
Phys. Rev. Appl. 16, 064060 (2021)
arXiv:2503.20732 (2025)

NV magnetometry and spin metrology for wavelike dark matter

JHEP 03, 083 (2025)
Phys. Rev. D 111, 075028 (2025)
Phys. Rev. A 113, L060802 (2026)



Defect Quantum Sensing for HEP

Directional recoil-track readout with quantum defects

Phys. Rev. D 96, 035009 (2017)
Quant. Sci. Tech. 6, 024011 (2021)
Phys. Rev. Appl. 17, 024041 (2022)

HEP detector instrumentation and radiation diagnostics

Nano Letters 23, 9811-9816 (2023)
J. Phys. Chem. C 129, 2739 (2025)
RSC Advances 15, 1011-1019 (2025)

Recoil-created color centers and defect channels

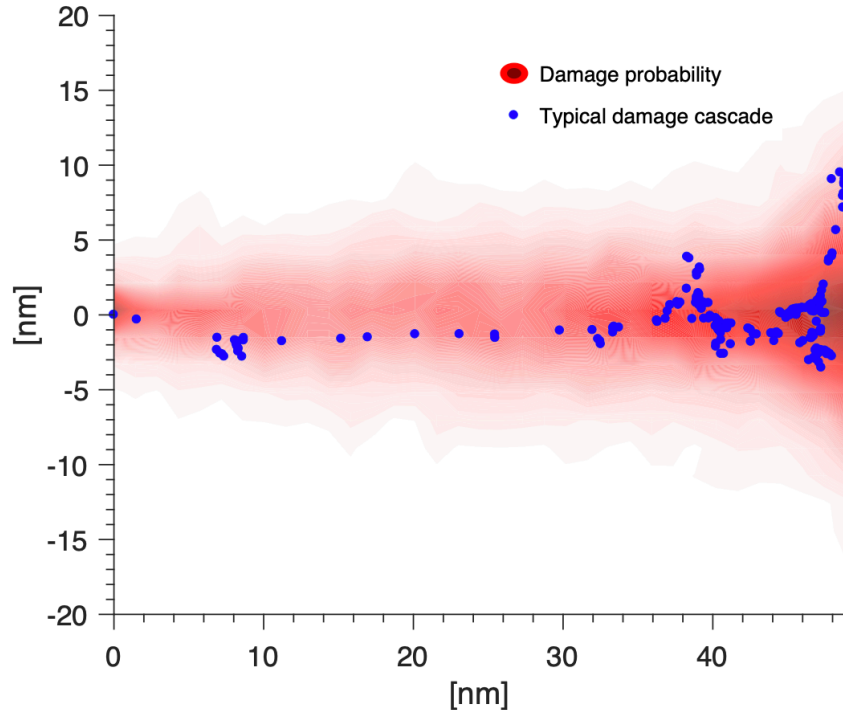
Phys. Lett. B 782, 242-250 (2018)
Phys. Rev. Appl. 16, 064060 (2021)
arXiv:2503.20732 (2025)

NV magnetometry and spin metrology for wavelike dark matter

JHEP 03, 083 (2025)
Phys. Rev. D 111, 075028 (2025)
Phys. Rev. A 113, L060802 (2026)



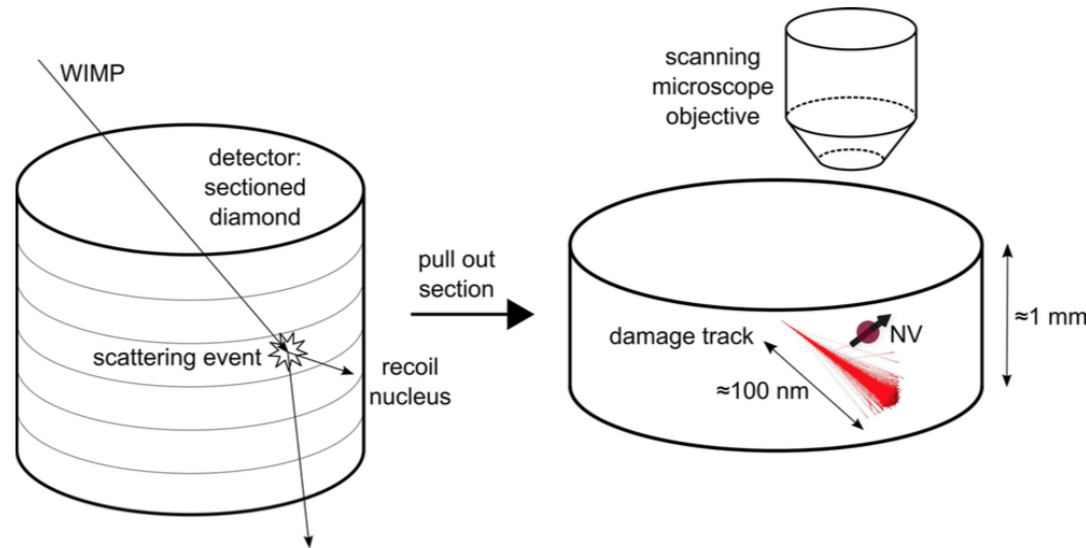
◆ Directional Detection of Weakly Interacting Massive Particles (WIMPs)



Damage cluster with 30keV ions

- ▶ WIMP scatters within a crystal
→ induces a nuclear recoil that creates a localized "damage cluster" approximately 50 nm in size
- ▶ Damage cluster induces local strain in the crystal lattice
→ shifts the energy levels of nearby quantum defects
- ▶ These shifts can be measured optically or through paramagnetic resonance

Directional Recoil-Track Readout Steps



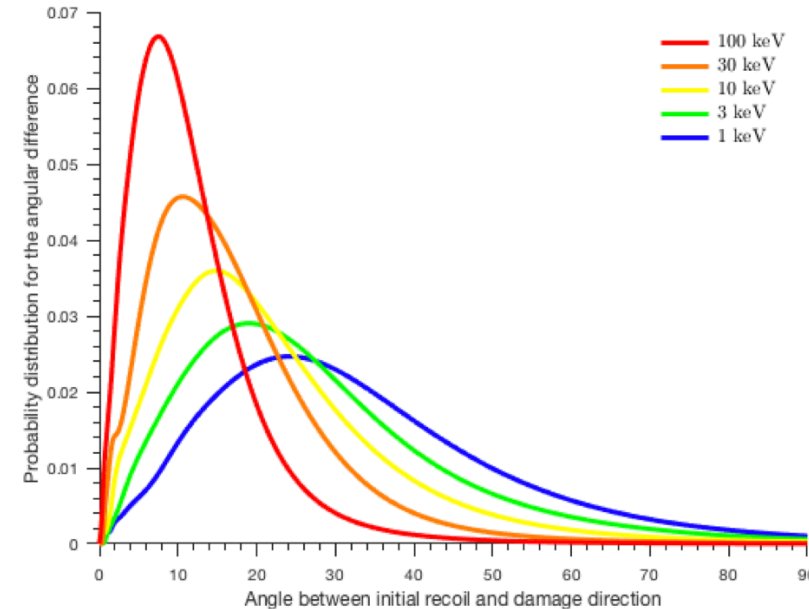
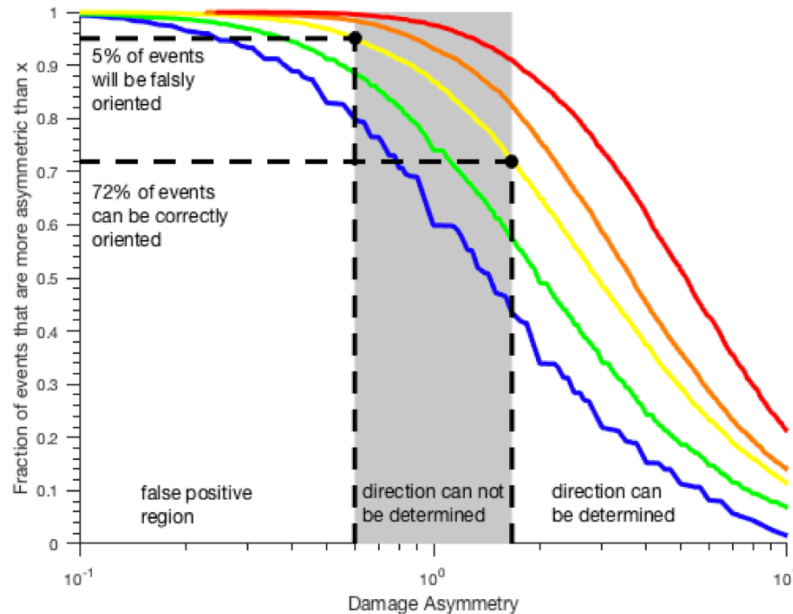
Walsworth group at UMD

- ▶ 1st step : Use **conventional detection techniques** (like collecting ionization or scintillation) to narrow down the recoil event to a millimeter-scale region
- ▶ 2nd step : Interrogate the **quantum defects** specifically in that vicinity to determine the high-resolution directional information

Why Directional Readout with Defects?

◆ Directional detection of particles

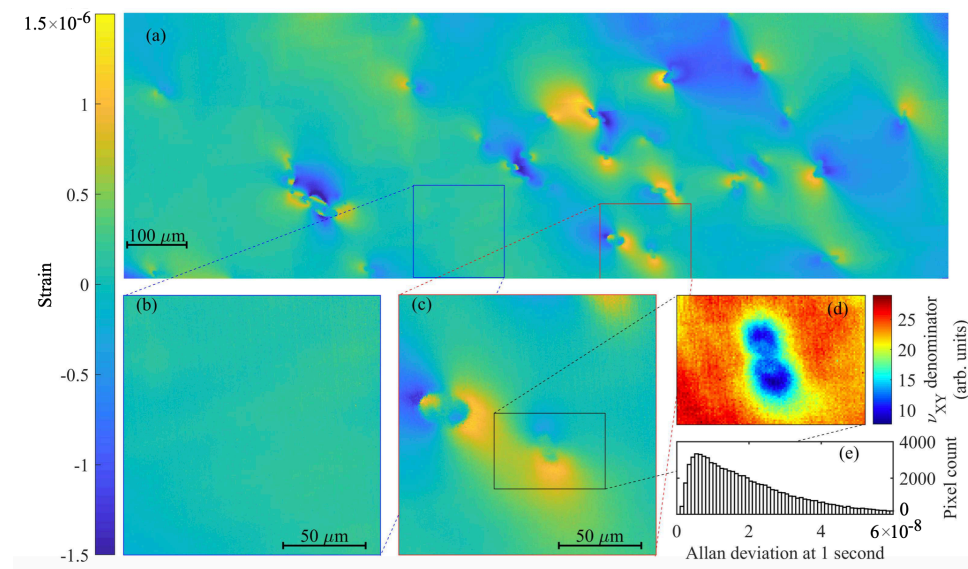
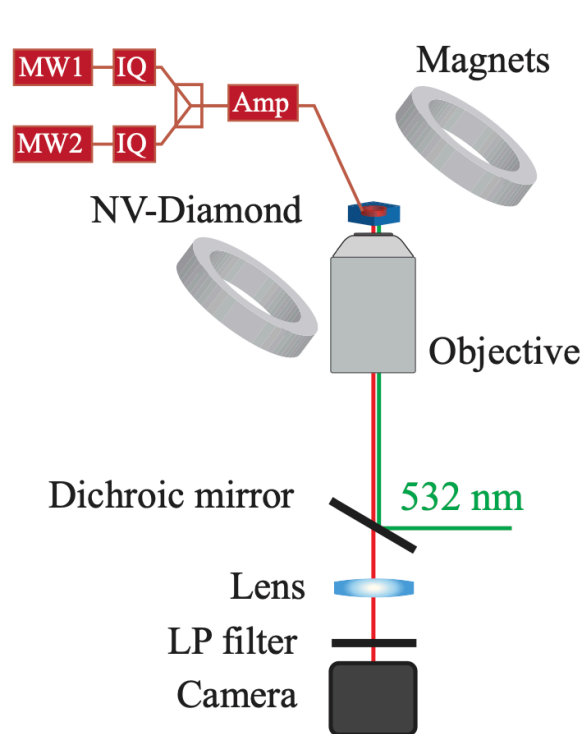
Phys. Rev. D 96, 035009 (2017)



- ▶ **Recoil direction** allows researchers to distinguish between WIMP and solar neutrinos
- ▶ **Solid-state densities**, much larger target mass (and thus a higher chance of a WIMP hit) can be packed into a smaller, more manageable detector volume ($\sim 1\text{m}^3$)
- ▶ **Efficiency greater than 70%** and a false positive rate of less than 5% for 10 keV recoil energies, representing a high level of precision for such low-energy events

Experimental Demonstration of NV Strain Sensing

◆ High sensitivity strain sensing with NV center



- ▶ **pulsed quantum interferometry** for strain sensing
- ▶ The protocol exceeds the sensitivity benchmarks required for the **directional detection of WIMP**
- ▶ Yet, the spatial resolution needs to be improved from μm to 50nm scale

◆ QUP at KEK



International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK



mini-workshop on quantum sensing with diamond NV center

Tuesday May 12, 2026, 2:00 PM → 5:00 PM Asia/Tokyo

2F meeting room (QUP bldg.)

Tsutomu MIBE (KEK IPNS)

Description This workshop aims to bring together researchers working in the fields of diamond NV center to discuss recent progress, share new ideas, and explore future directions. The program will consist of invited talks and discussions in an informal setting, encouraging active participation and collaboration. We warmly invite interested researchers and students to participate.

2:00 PM → 2:30 PM Tour of QUP facilities 30m

2:30 PM → 3:00 PM Coffee 30m

3:00 PM → 3:30 PM NV research at Aral-lab at Science Tokyo 30m

Speaker: Keigo Arai (Science Tokyo)

3:30 PM → 4:00 PM NV research at KIST and its application at xDots 30m

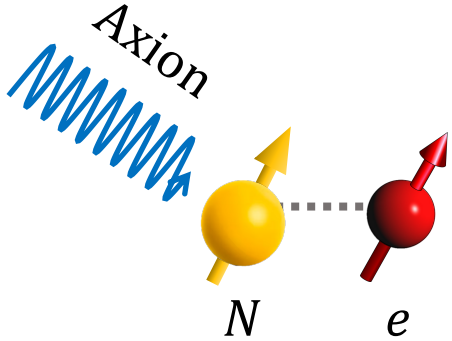
Speakers: Woodo Lee (xDots), Junghyun Lee (KIST)

4:00 PM → 4:30 PM Quantum sensing with NV at QUP 30m

Speaker: David Herbschleb (QUP)

- ▶ Launched initial collaboration with KEK QUP, for NV magnetometry for wavelike dark matter
- ▶ This requires high fidelity gate control of NV center and nuclear spins (from KIST)

◆ Axion-nuclear spin direct interaction



- ▶ Axion dark matter as a classical field with coherent oscillation, which interacts with fermion spins as an **effective magnetic field**
- ▶ Using **Axion-Nuclear spin (^{14}N) interaction** as Hamiltonian, determined by the axion interaction with neutron and proton spins, g_{ann} and g_{app}
- ▶ This changes the nuclear spin's accumulated phase, and can be readout via NV center through e-N two qubit gate

$$H_{\text{int}} = \gamma_N \vec{B}_N(t) \cdot \vec{I}, \quad (28)$$

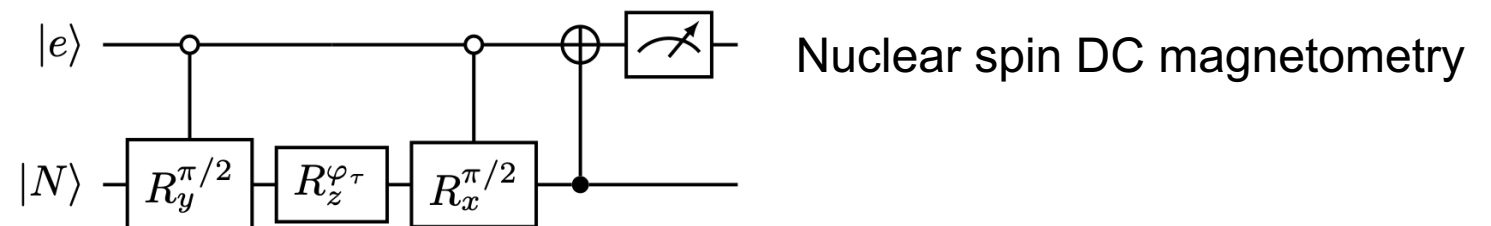
with the effective magnetic field defined as

$$\vec{B}_N(t) \equiv B_N \hat{v}_a \cos(m_a t + \phi), \quad (29)$$

$$\gamma_N B_N \simeq -\frac{1}{6} \left(\frac{g_{app}}{m_p} + \frac{g_{ann}}{m_n} \right) \sqrt{2\rho_a} v_a, \quad (30)$$

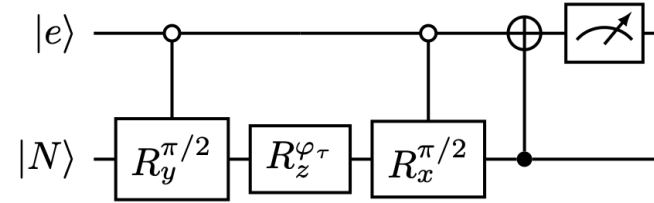
with $\hat{v}_a \equiv \vec{v}_a/v_a$. For convenience, we define

$$\tilde{f}_a \equiv \left| \frac{g_{app}}{2m_p} + \frac{g_{ann}}{2m_n} \right|^{-1}, \quad (31)$$

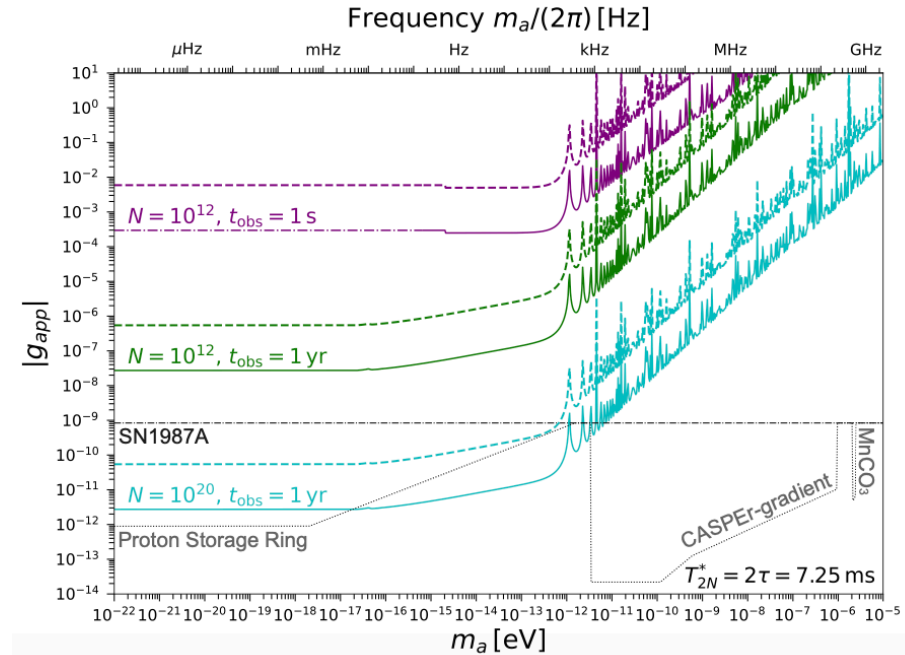
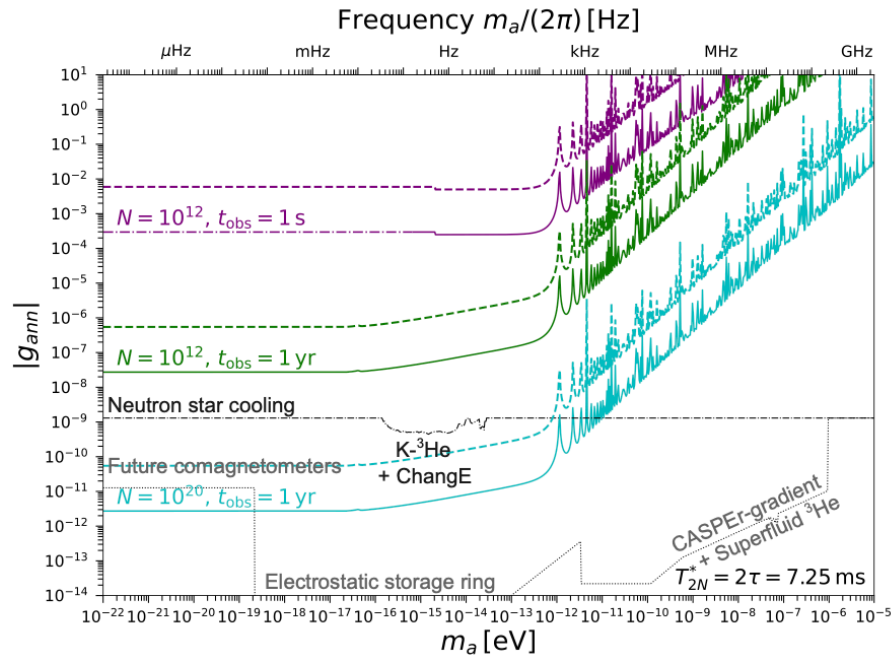


Nuclear Spin Ramsey for Wavelike Darkmatter

◆ Nuclear spin Ramsey interferometry



N : number of spins

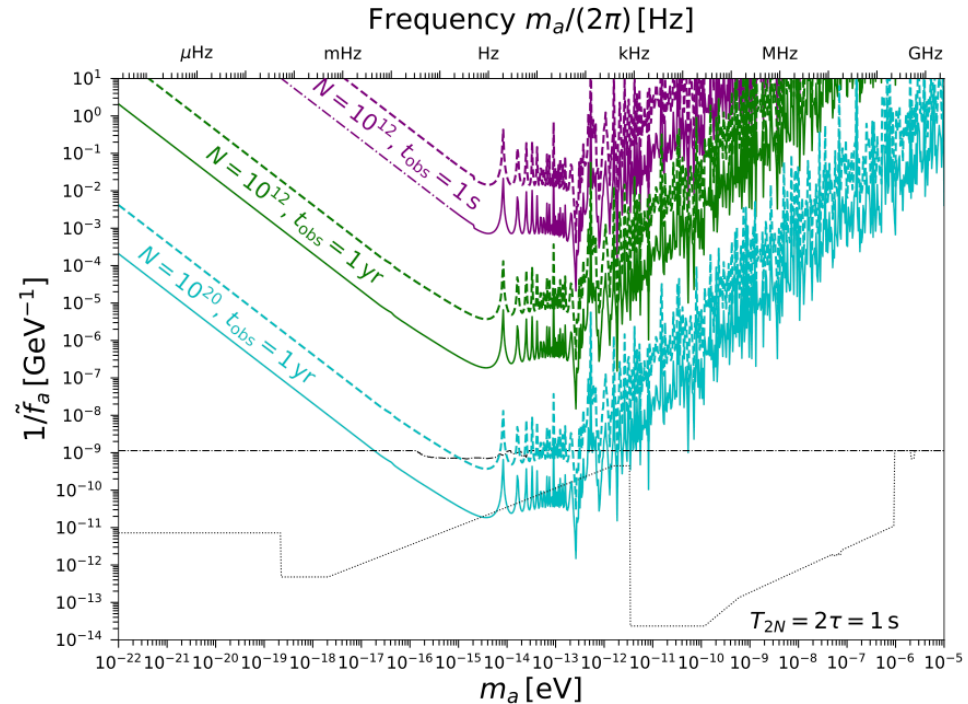
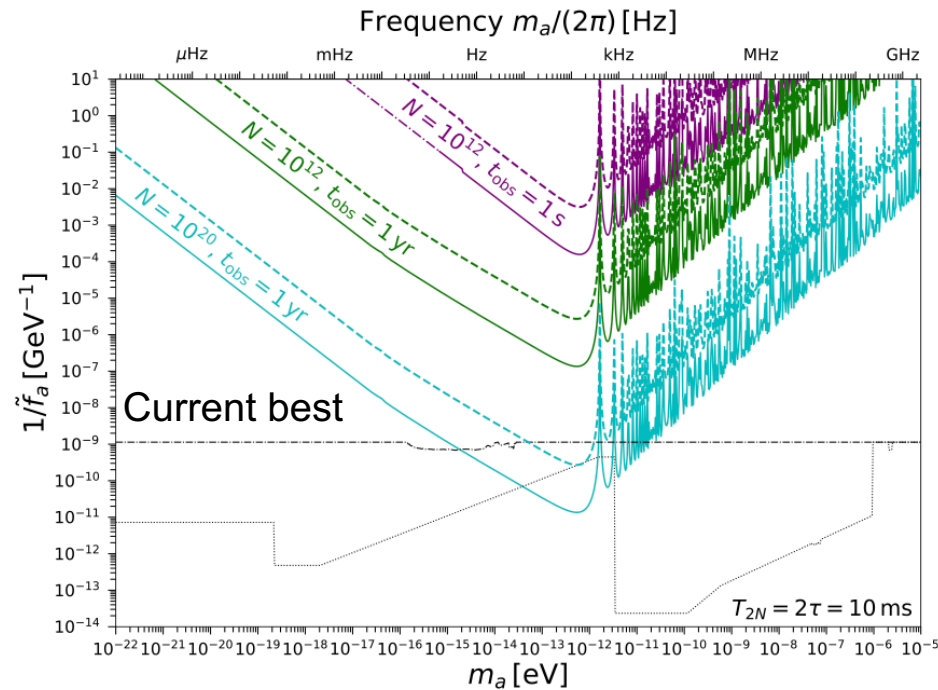
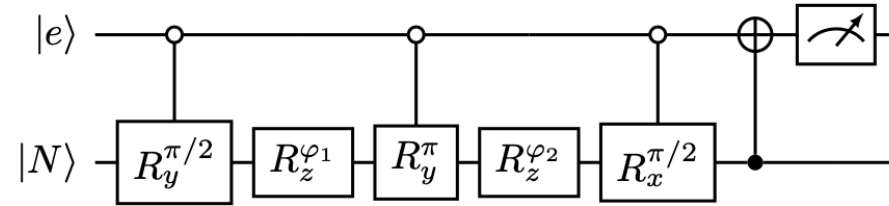


- ▶ The method is sensitive to a broad frequency range ($\lesssim 100$ Hz), corresponding to axion masses $m_a \lesssim 4 \times 10^{-13}$ eV

- ▶ Nuclear spins have long coherence times ($T_2^* \sim 7.25$ ms)

For Enhanced Sensitivity for Wavelike Darkmatter

◆ Nuclear spin multi-pulse interferometry

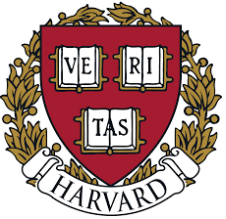


- ▶ Potentially extending to **100 seconds** in cryogenic environments will have more precise frequency resolution and higher sensitivity to weak signals

- Nitrogen Vacancy center in diamond (qutrit) is a promising quantum metrology platform for quantum enhanced sensing
- Basic quantum sensing protocols, Ramsey interferometry, Hahn-Echo, dynamical decoupling pulse sequences are discussed
- Defect spins in diamond started to be applied for the search of dark matter, imaging strain from the nuclear recoil
- Wavelike dark matter also can be theoretically detected via phase measurements

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Thanks for your attention