# Quantum Spintronics Design
## (NV centers in diamond)

**Eisuke Abe**

*RIKEN Center for Emergent Matter Science*

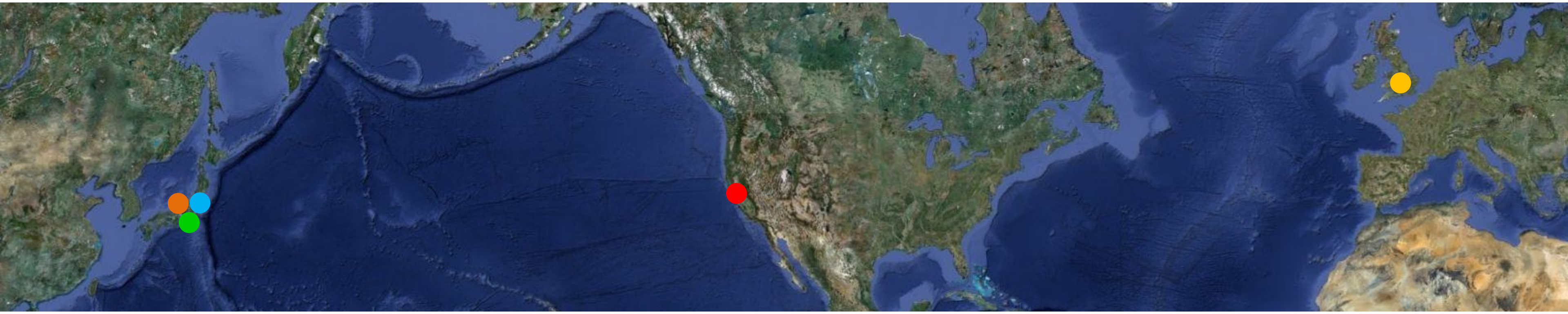
2020.02.19

CMD Spintronics Design Course

@Osaka University

RIKEN

# Short CV



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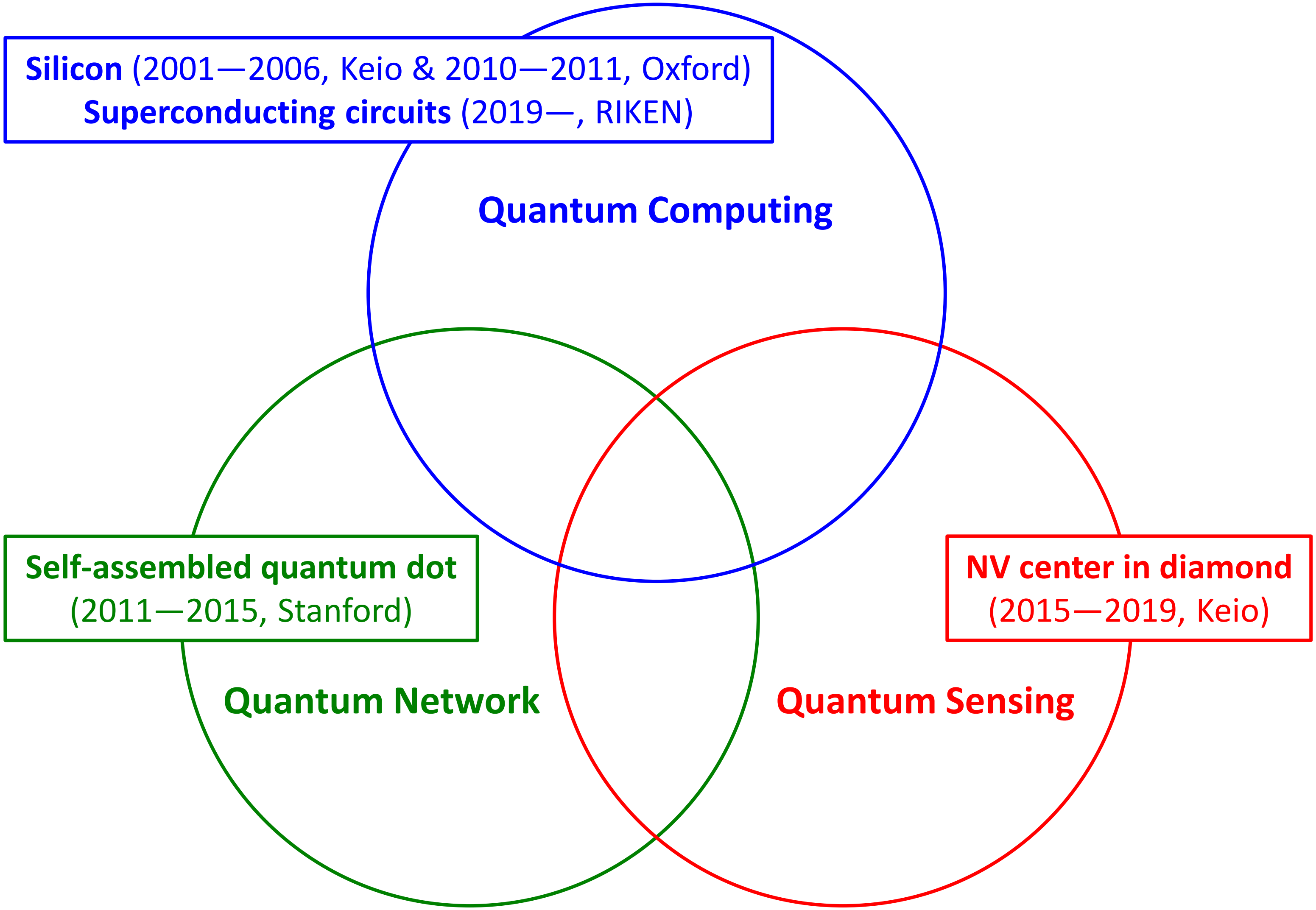
- ● **2001.4 – 2006.3 (Keio)** → Quantum computing (silicon)
- ● **2006.4 – 2009.12 (ISSP, UT)** → Quantum transport (GaAs QDs, Josephson)
- ● **2010.1 – 2011.6 (Oxford)** → Hybrid system (spin–cavity coupling)
- ● **2011.7 – 2015.3 (Stanford/RIKEN)** → Quantum network (InAs QDs)
- ● **2015.4 – 2019.1 (Keio)** → Quantum sensing (diamond)
- ● **2019.2 – Present (RIKEN)** → Quantum computing (Josephson)

# Quantum technologies



**Silicon** (2001—2006, Keio & 2010—2011, Oxford)
**Superconducting circuits** (2019—, RIKEN)

**Quantum Computing**

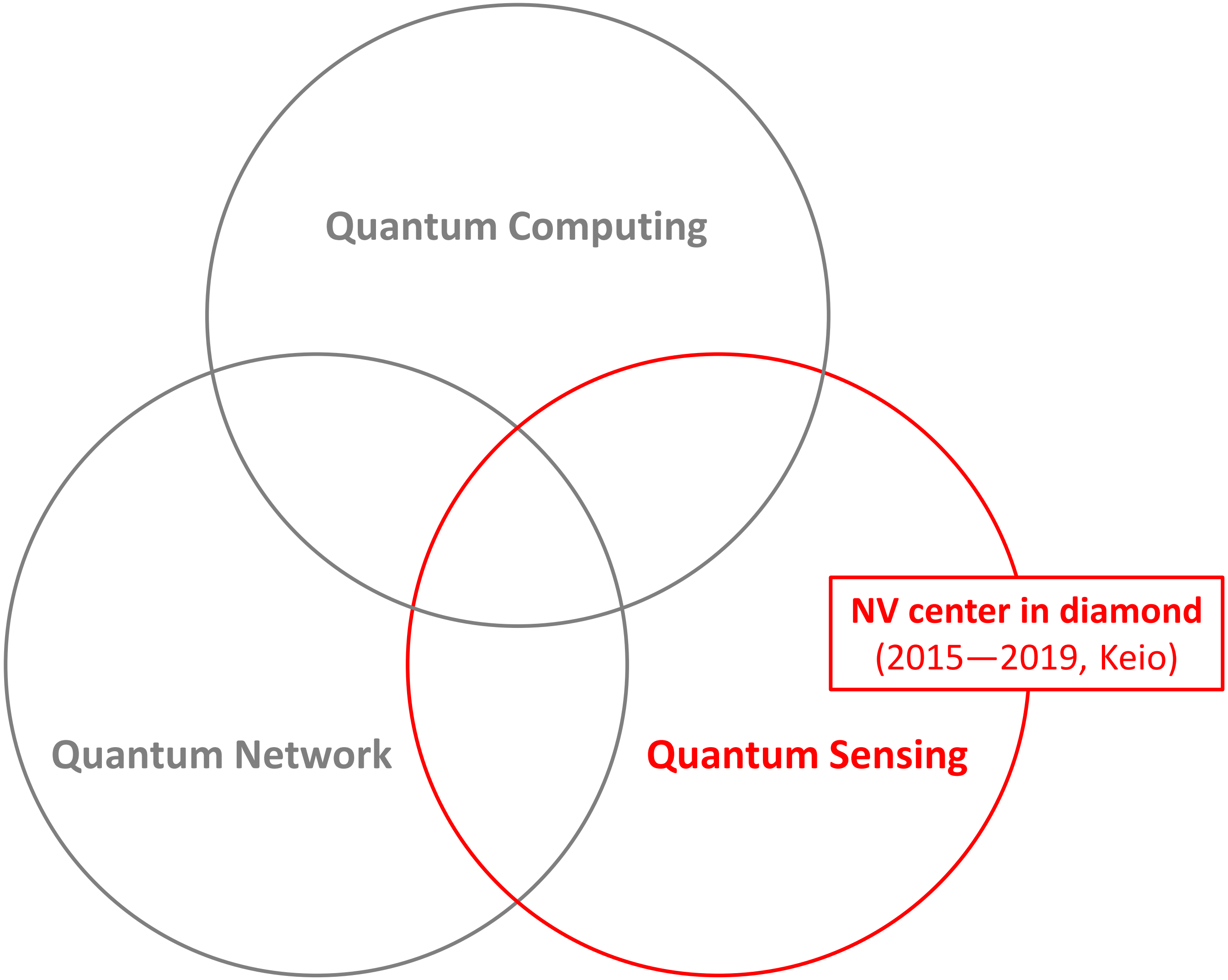
**Self-assembled quantum dot**
(2011—2015, Stanford)

**NV center in diamond**
(2015—2019, Keio)

**Quantum Network**

**Quantum Sensing**

# Quantum technologies



Quantum Computing

Quantum Network

Quantum Sensing

**NV center in diamond**
(2015—2019, Keio)

# Outline

- **Basics of NV centers in diamond**
  - Structure
  - Optical properties
  - Spin properties and control

- **Quantum sensing**
  - Principle of AC magnetometry
  - Detection of proton spin ensemble
  - Detection and localization of a single $^{13}C$ nuclear spin
  - Ultrahigh resolution sensing

# Outline

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# Diamond envy

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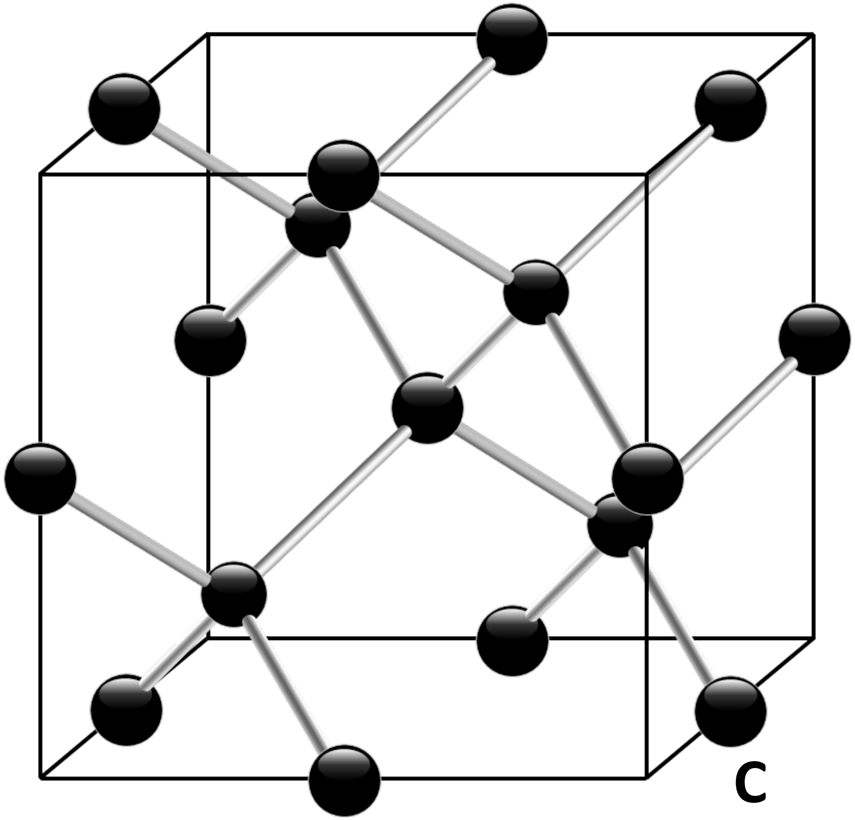
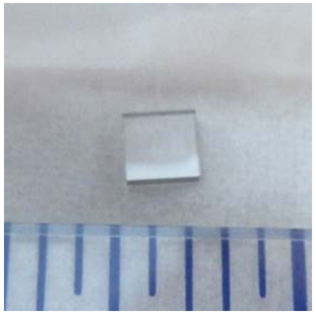


$\rho_N = 1.77 \times 10^{23}\ \mathrm{cm}^{-3}$

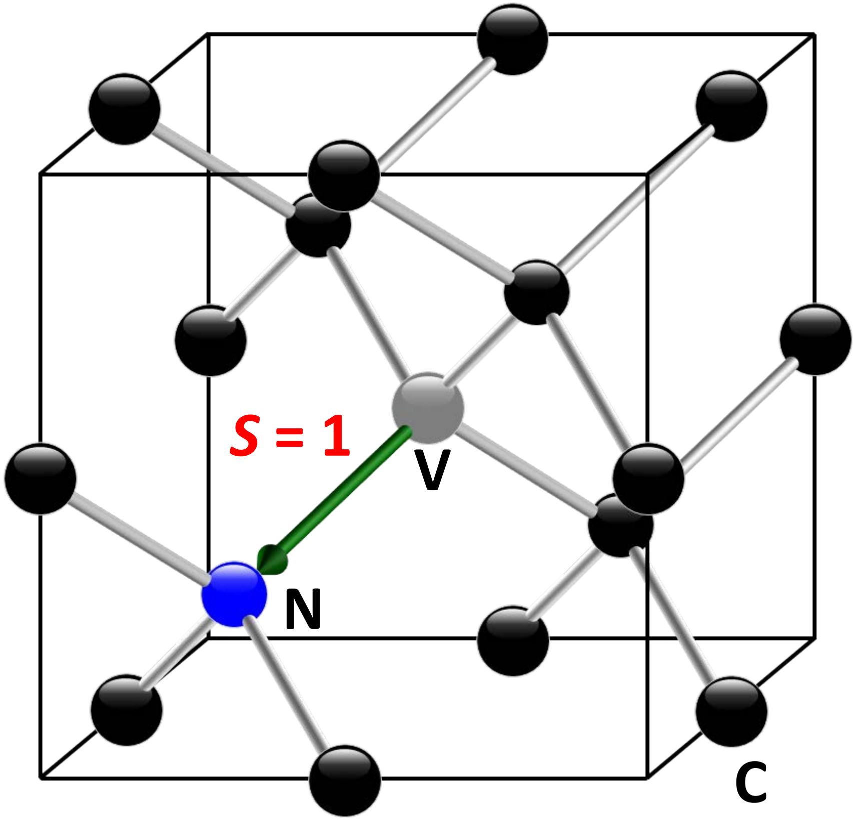
# Diamond NV

**Synthetic (CVD) diamond**
$2^2$ x 0.5 $mm^3$, \$700 (E6)
[N] < 5 ppb, [NV] < 0.03 ppb



***Not like…***

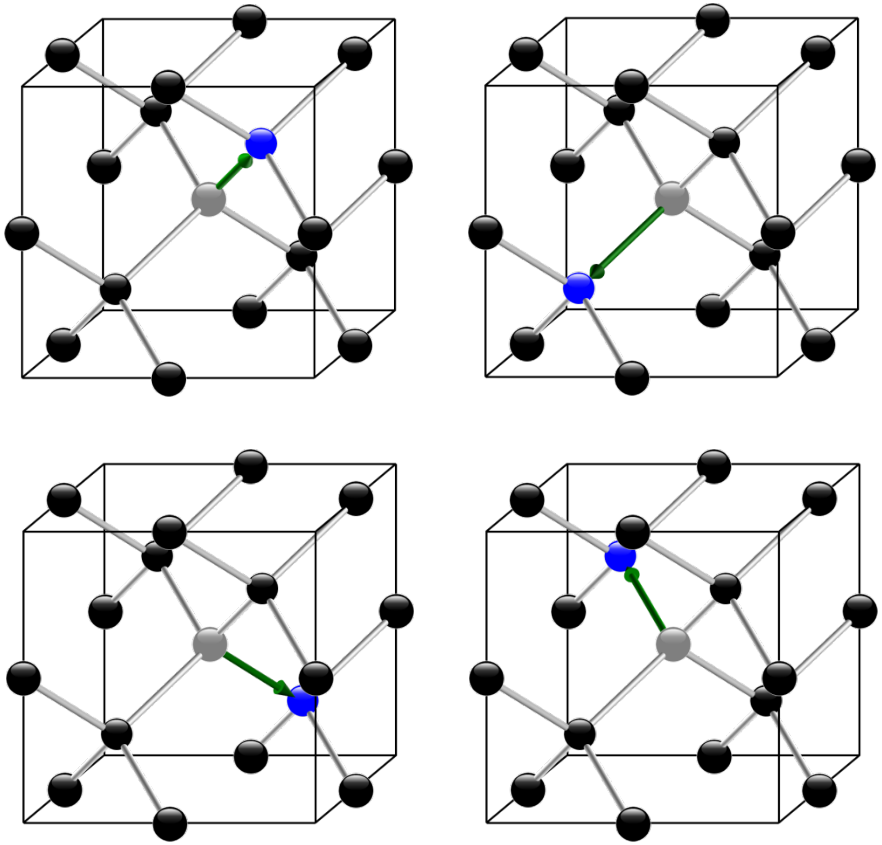
©GIA



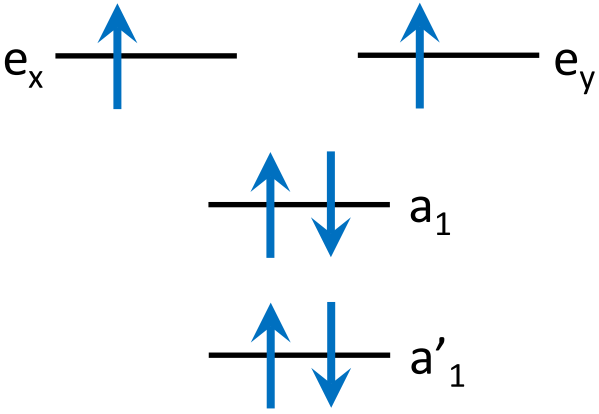
$\rho_N = 1.77 \times 10^{23}\ cm^{-3}$

# Crystal & energy level structures

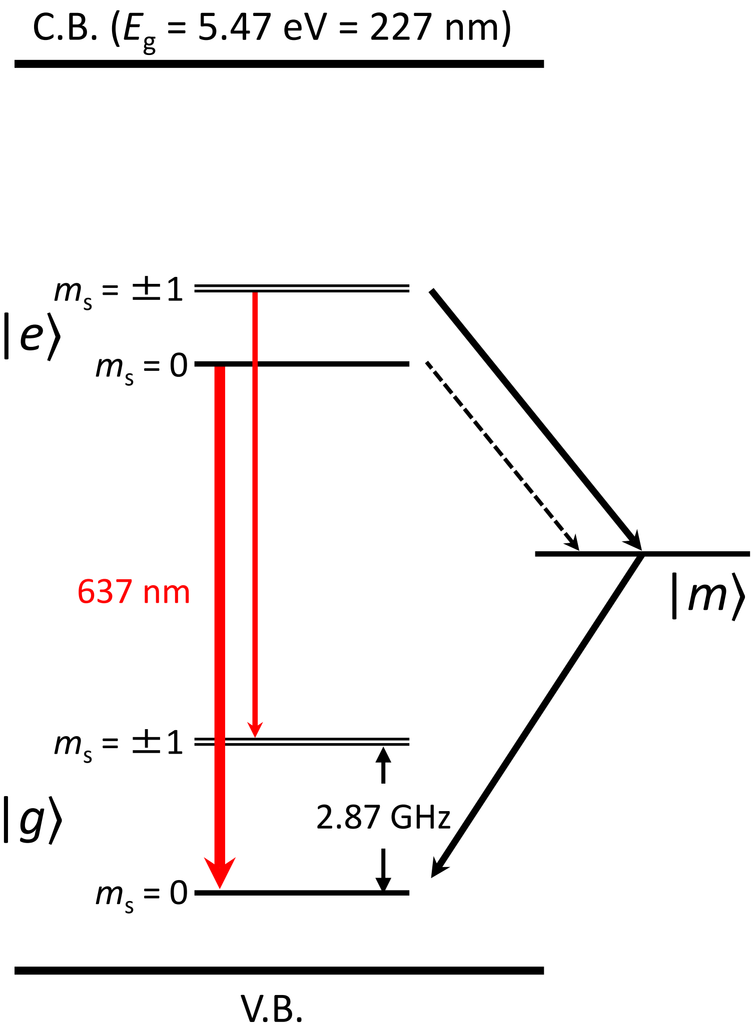
- Negatively-charged ($NV^-$)
- 4 $sp^3$ orbitals, 6 $e^-$ (5 from the defect, 1 captured)
- $C_{3v}$ (symmetry axis = quantization axis)



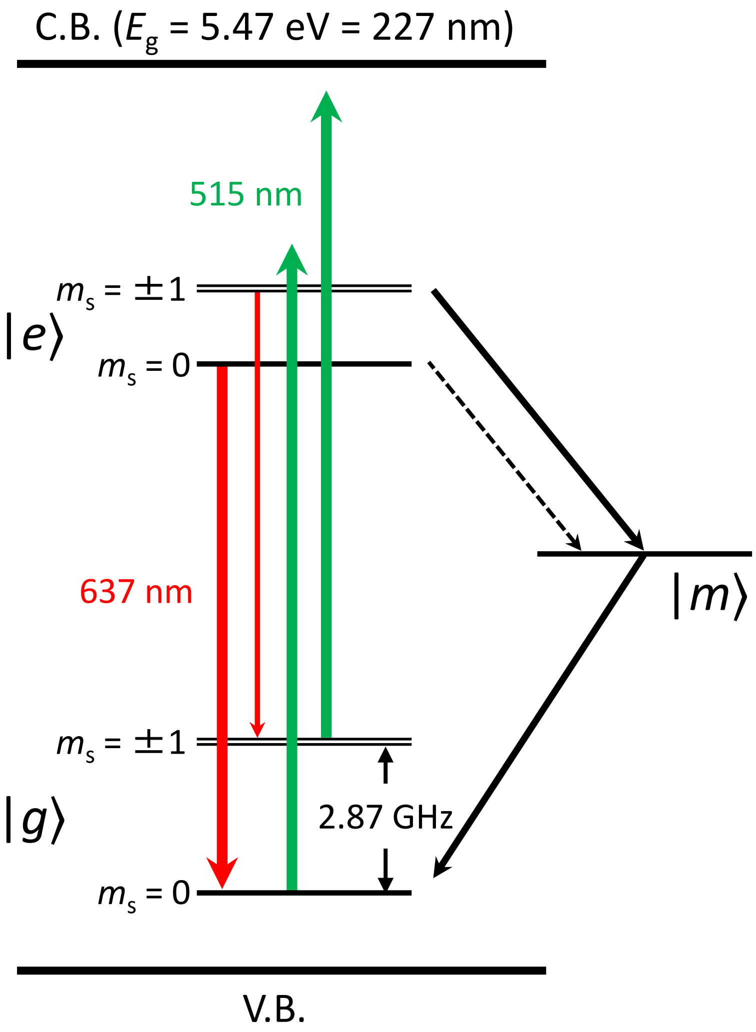
Effective spin-1 system
($e^2$-hole spin-triplet)

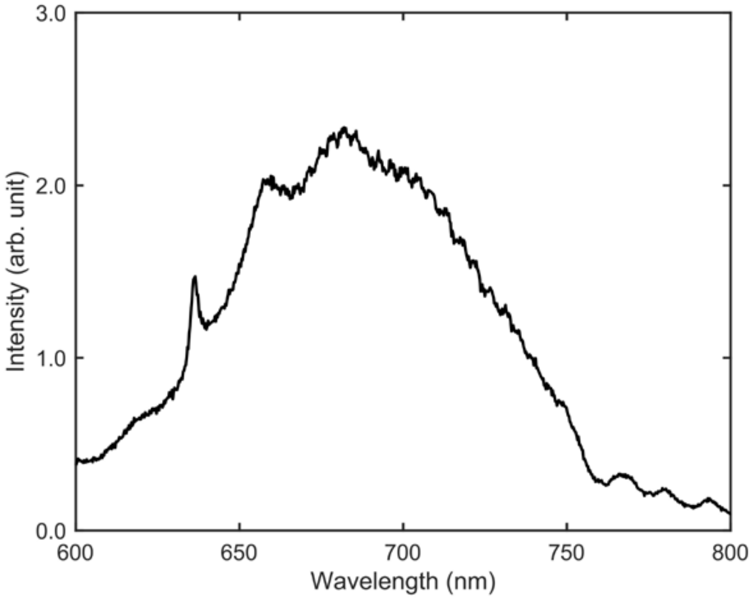


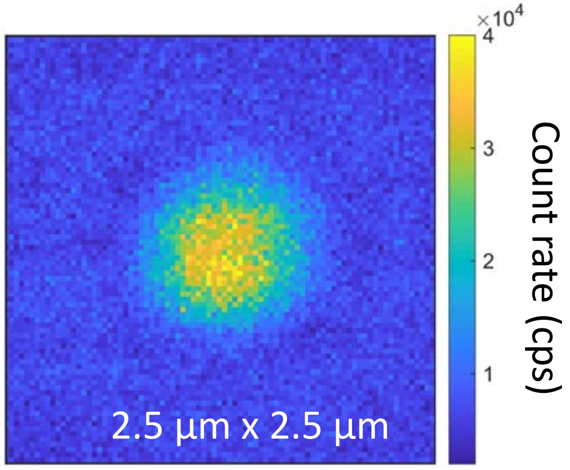
# Energy levels



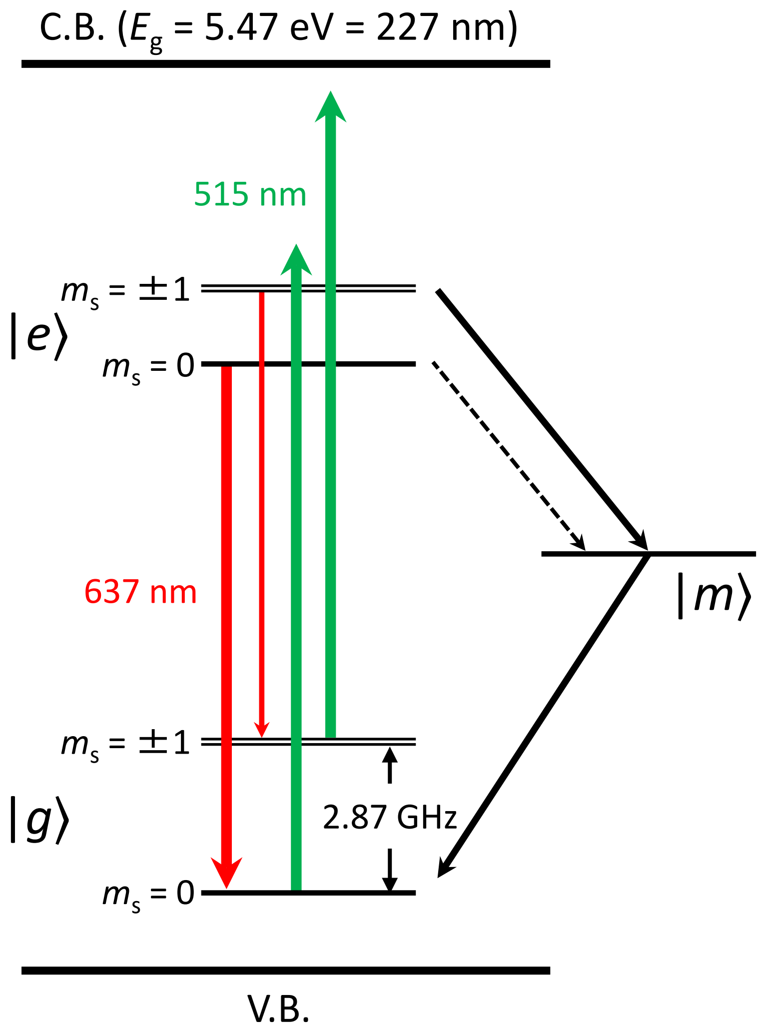
# PL spectroscopy & imaging



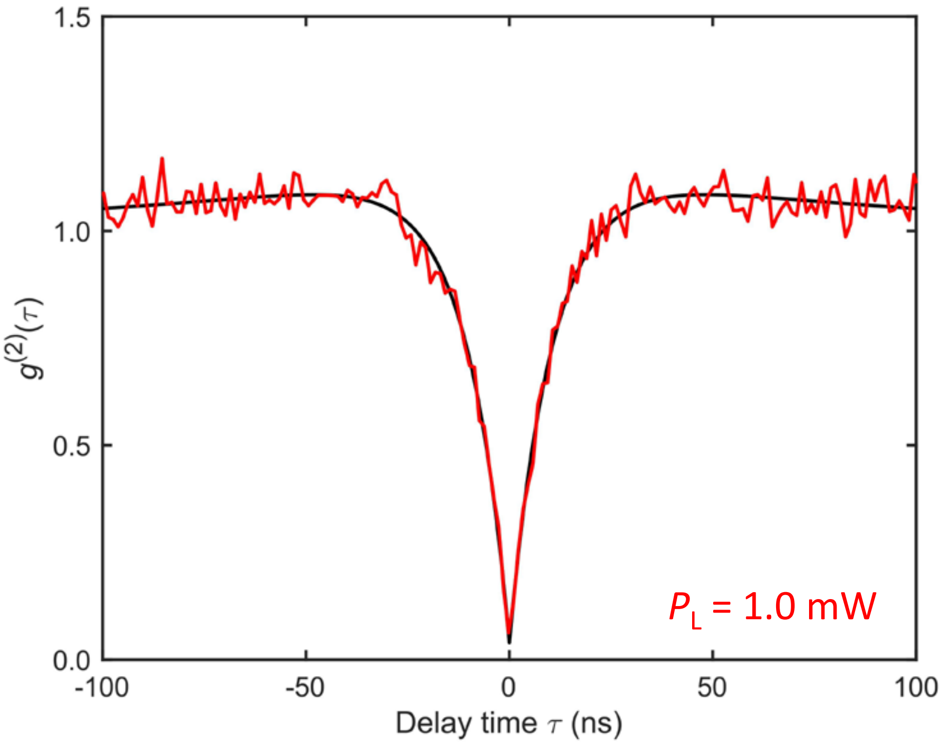




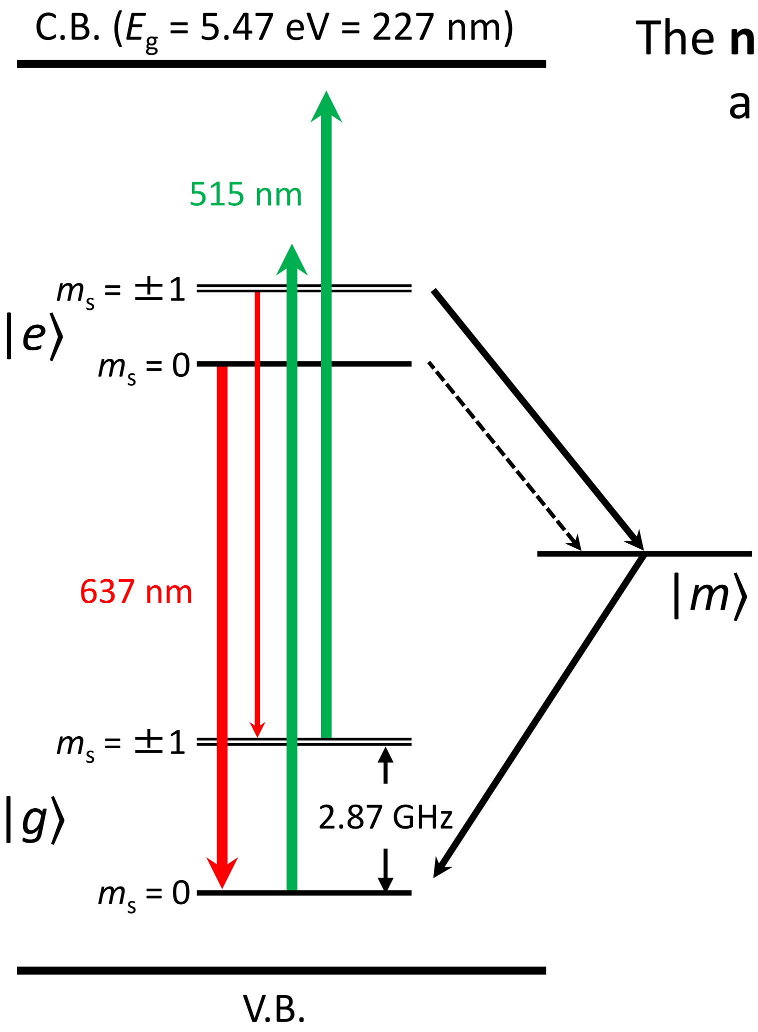
# Photon statistics



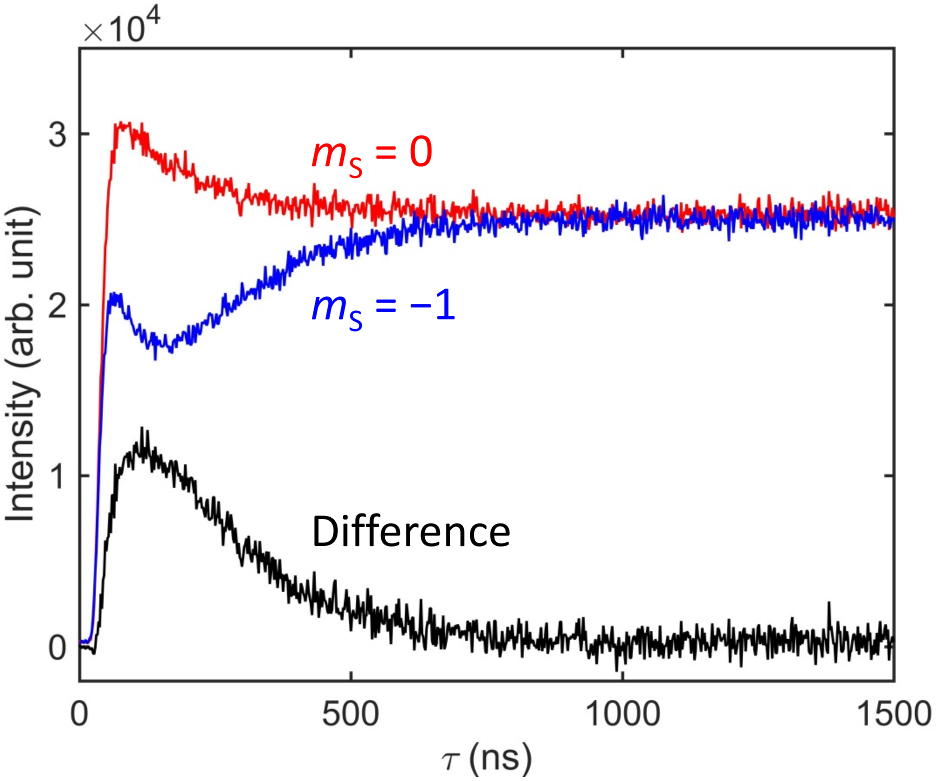
One photon at a time



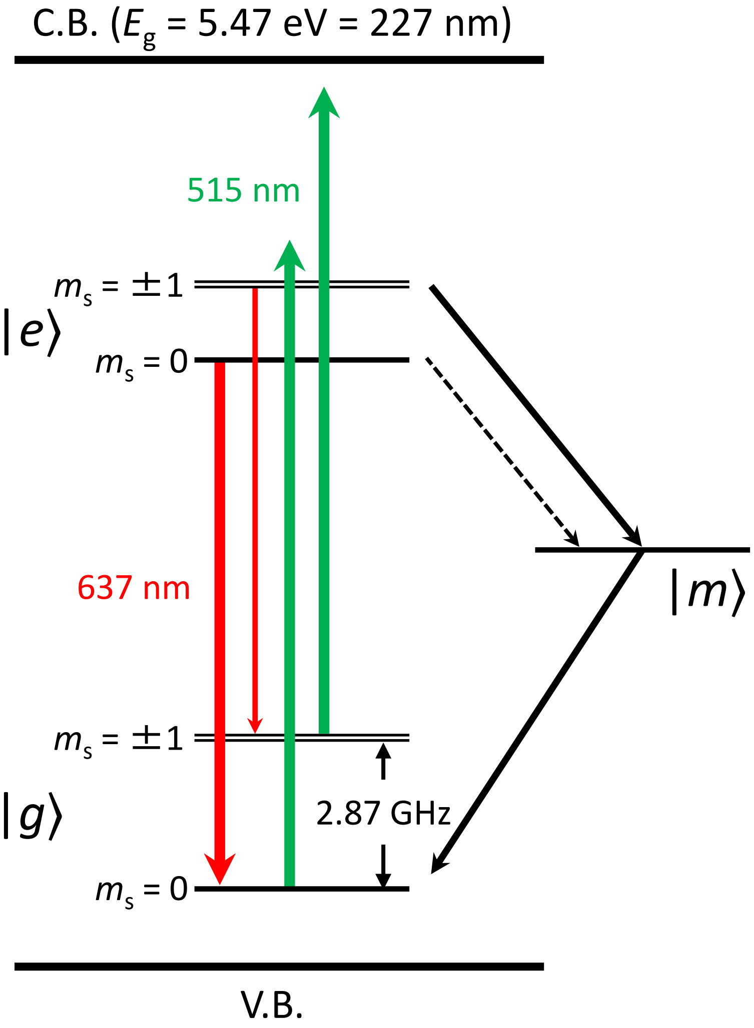
# Time-resolved fluorescence



The **non-radiative** & **spin-selective** channel provides a means to **read out** & **initialize** the NV spin

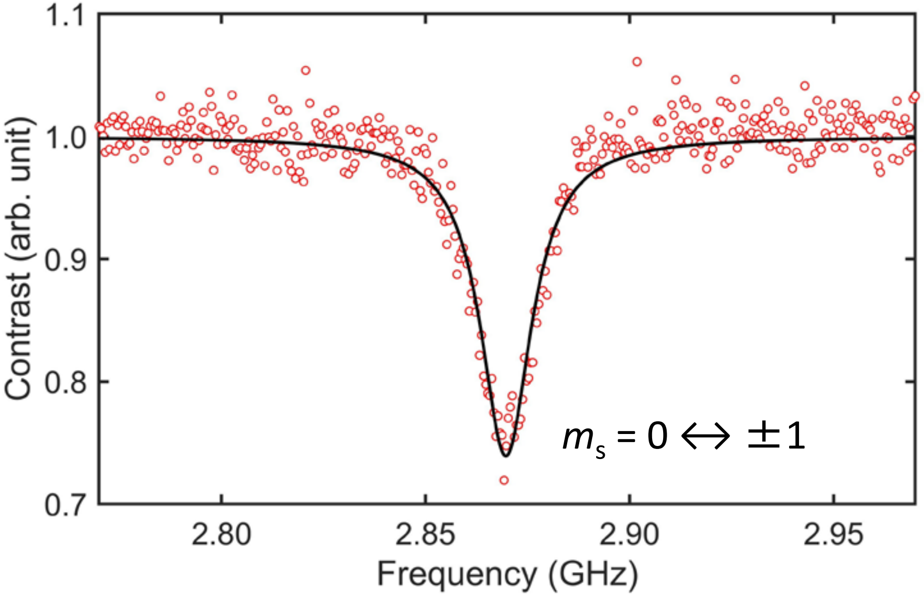


# CW ODMR at $B_0 = 0$

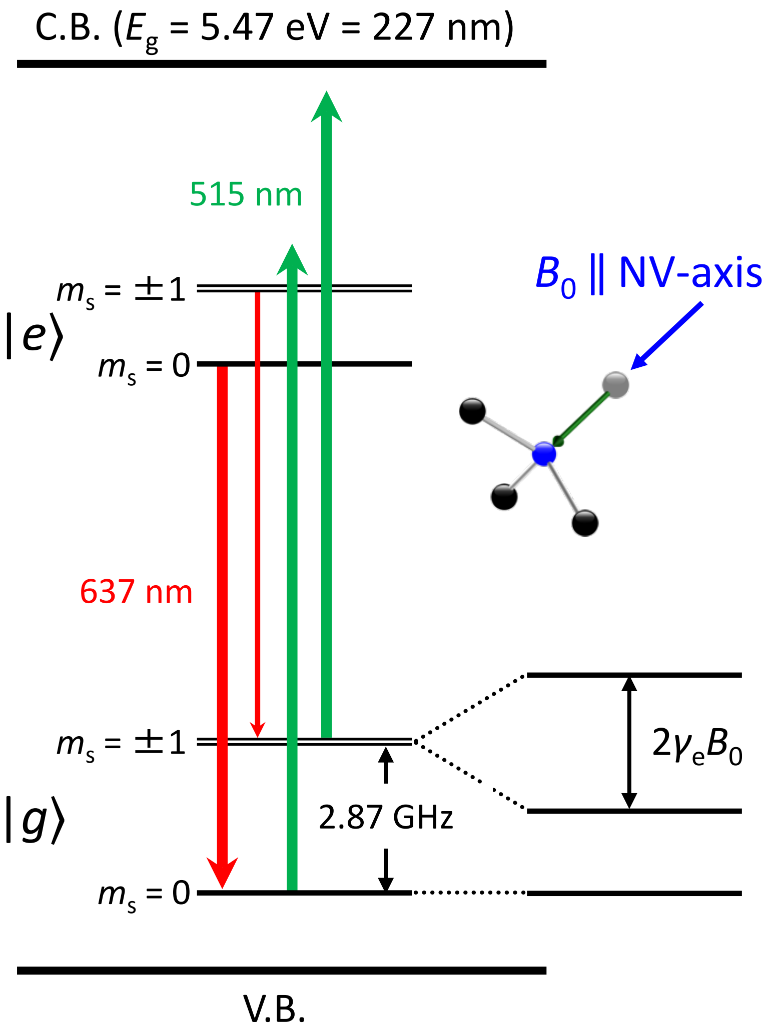


**Zero-field splitting** $H = DS_z^2$

$D$ = 2.87 GHz

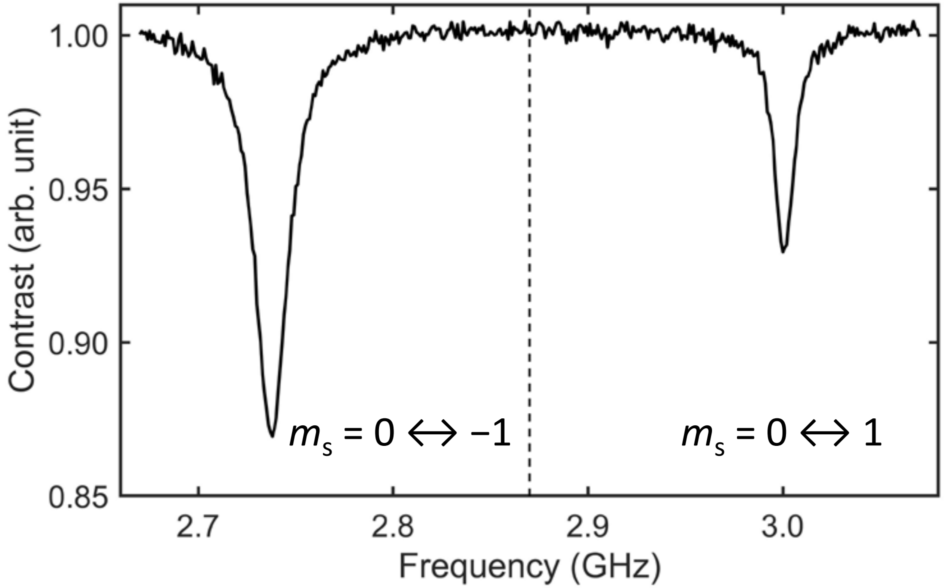


# CW ODMR at $B_0 > 0$



**Zeeman** $H = DS_z^2 + \gamma_e B_0 S_z$

$\gamma_e$ = 28 MHz/mT



$B_0$ = 4.7 mT (2.87±0.132 GHz)

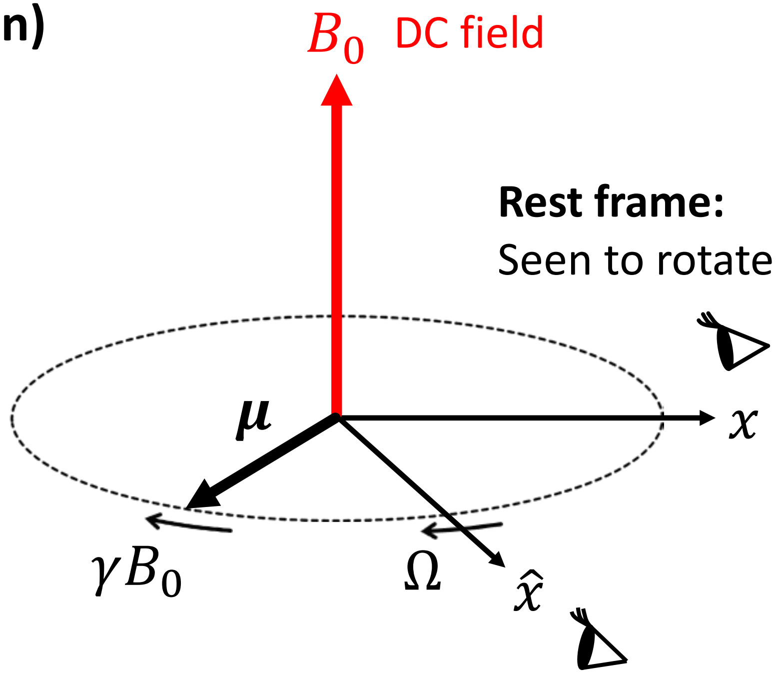
# Magnetic resonance

**Torque equation (Larmor precession)**

$$\frac{d\boldsymbol{\mu}}{dt} = \boldsymbol{\mu} \times \gamma \boldsymbol{B}_0$$

Gyromagnetic ratio

Magnetic moment: $\boldsymbol{\mu} = \gamma \boldsymbol{J}$

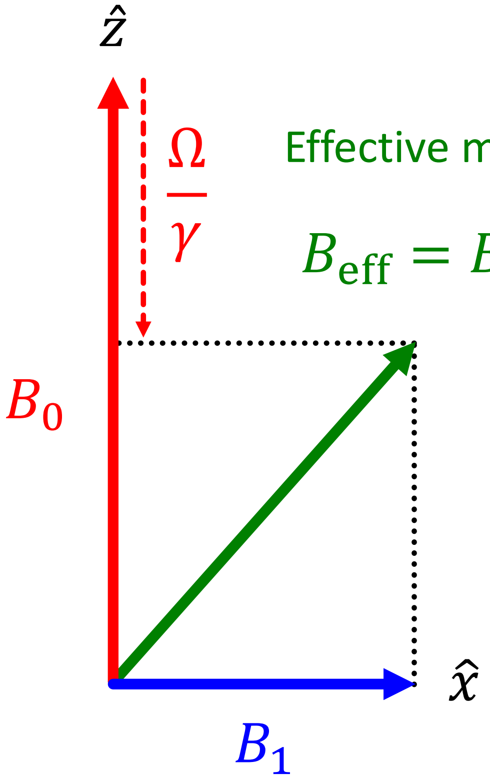


**Rest frame:**
Seen to rotate at $\gamma B_0$

**Frame rotating at angular velocity $\boldsymbol{\Omega}$:**
Rotate slower…why?

DC field along the $z$ direction becomes weaker

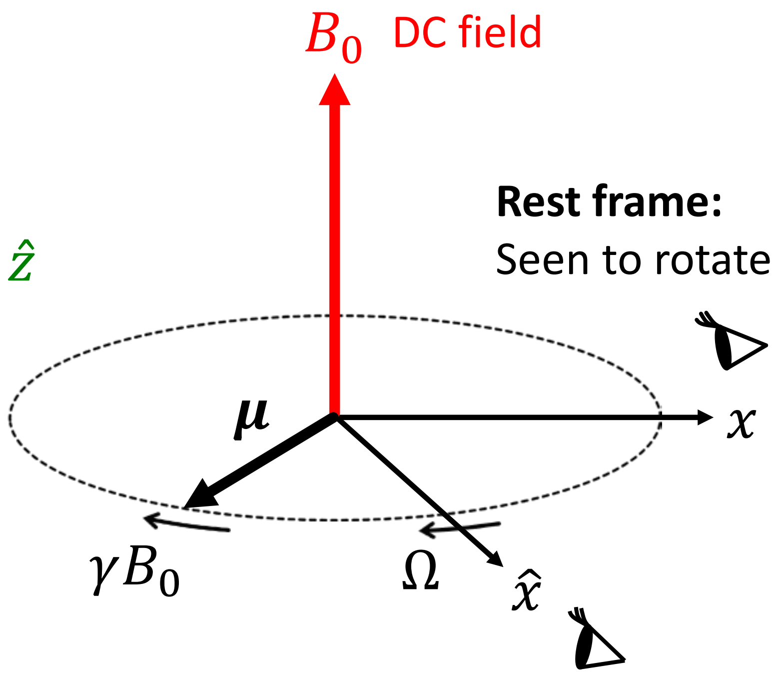
# Magnetic resonance



Effective magnetic field

$$B_{\text{eff}} = B_1\hat{x} + \left(B_0 - \frac{\Omega}{\gamma}\right)\hat{z}$$

AC field rotating in the $xy$ plane at $\Omega$



**Rest frame:**
Seen to rotate at $\gamma B_0$

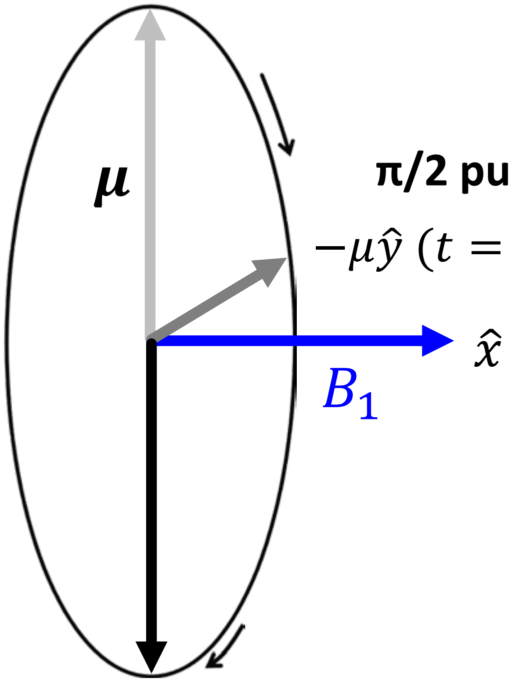
**Frame rotating at angular velocity $\Omega$:**
Rotate slower…why?

⇩

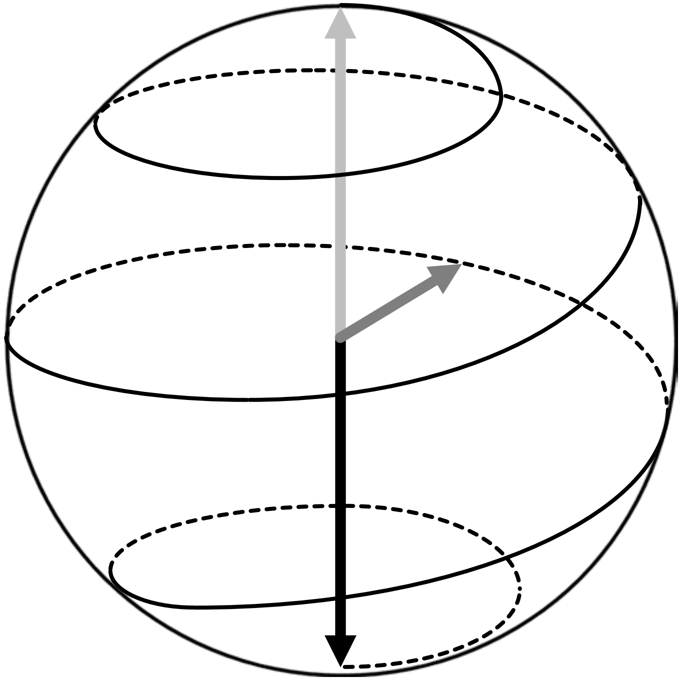
DC field along the $z$ direction becomes weaker

# Magnetic resonance

**Frame rotating at $\Omega = \gamma B_0$**



**Rest (non-resonant) frame**



- Rotations about the $\pm\hat{x}, \pm\hat{y}$ axes are realized by adjusting the microwave phases
- Rotation about the $\hat{z}$ axis is superposed when observed from the rest (non-resonant) frame

# Quantum bit

**Qubit, spin-1/2 (NV is spin-1!)**

$$\begin{cases} |\text{"0"}\rangle \equiv |m_s = 0\rangle \\ |\text{"1"}\rangle \equiv |m_s = -1\rangle \end{cases}$$

**Superposition state**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

⇩

$$|\psi\rangle = \underline{e^{i\gamma}}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle\right)$$

Global phase

$$0 \le \theta \le \pi$$

$$0 \le \gamma, \phi < 2\pi$$

⇩

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

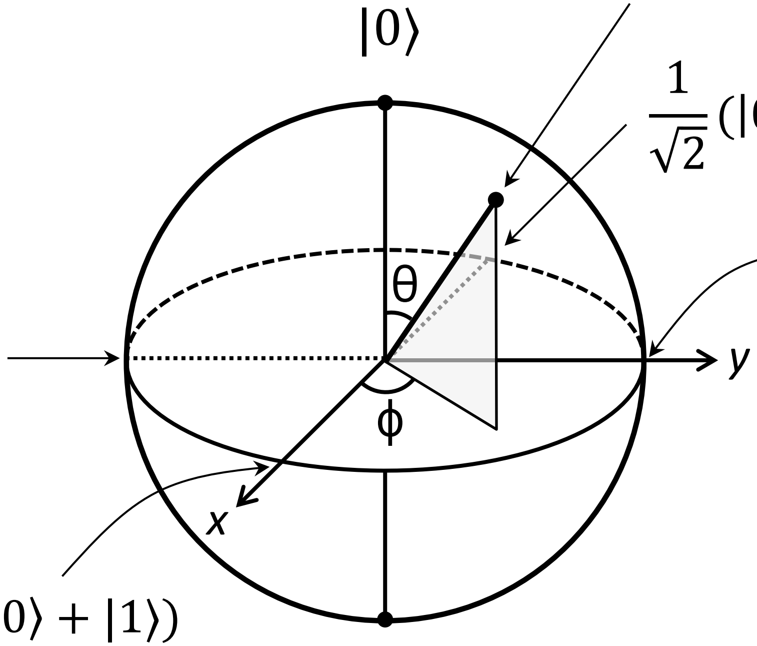
$$0 \le \theta \le \pi$$

$$0 \le \phi < 2\pi$$

# Bloch sphere

**Qubit, spin-1/2 (NV is spin-1!)**

$$\begin{cases} |"0"\rangle \equiv |m_s = 0\rangle \\ |"1"\rangle \equiv |m_s = -1\rangle \end{cases}$$



$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

$|0\rangle$

$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$

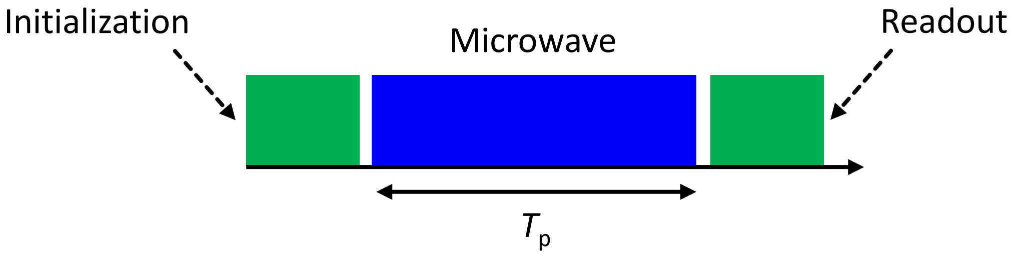
$\frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$

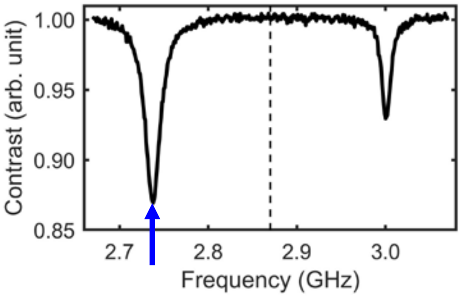
$\frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$

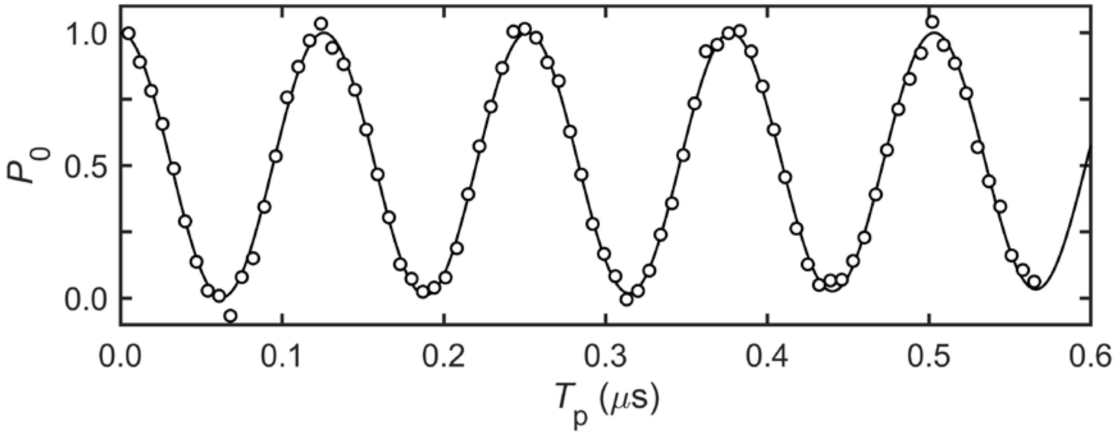
$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

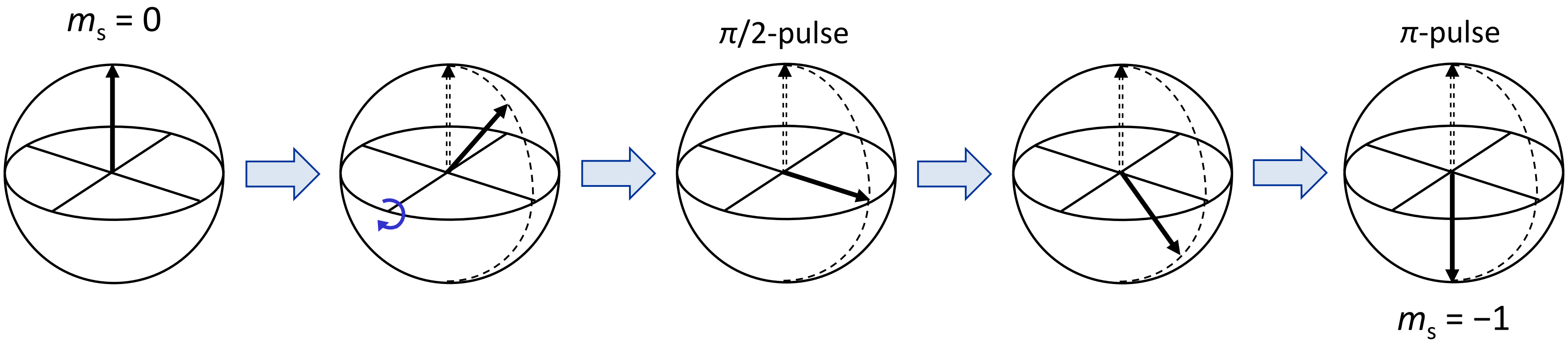
$|1\rangle$

# Rabi oscillation

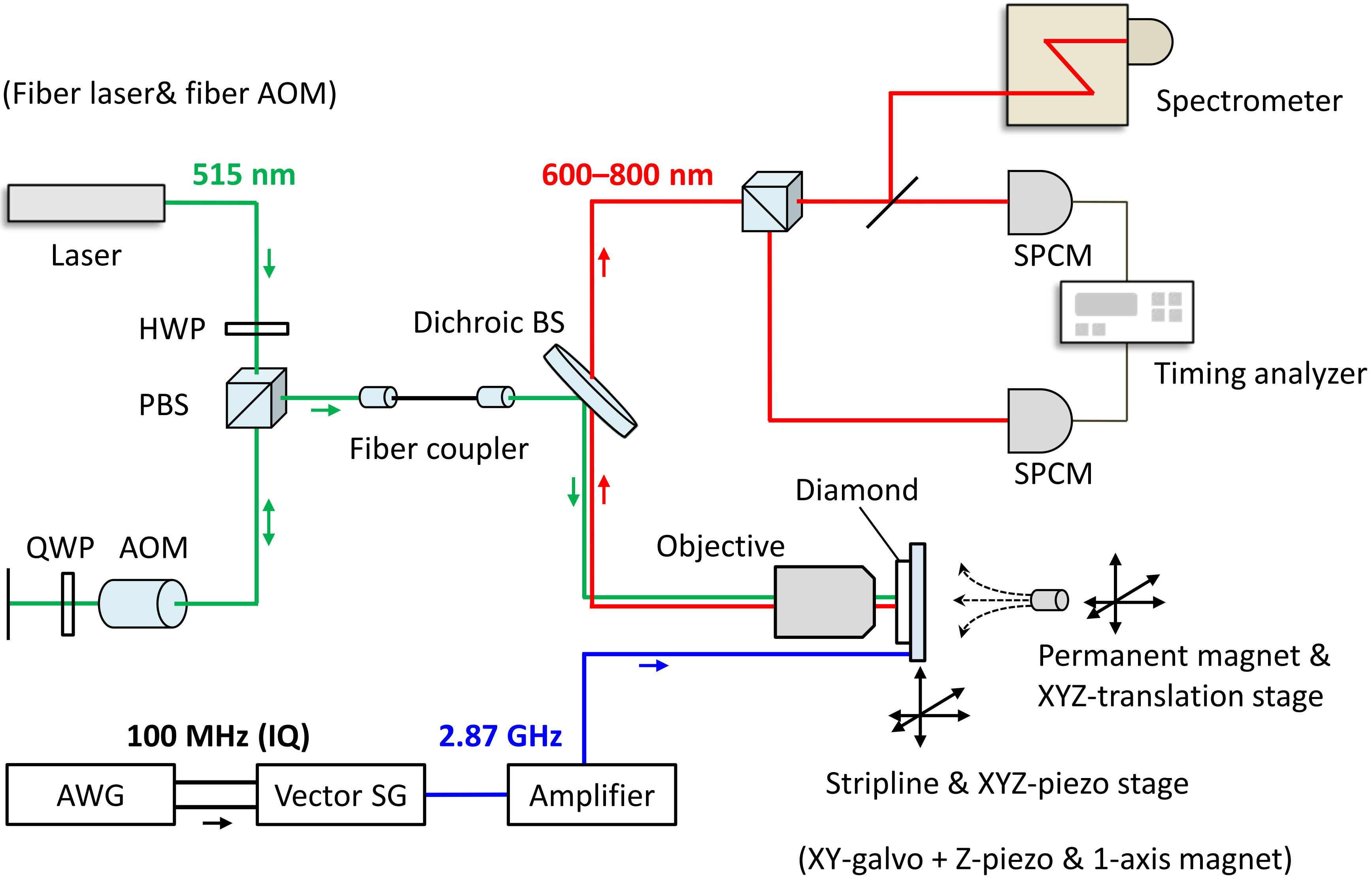








# Experimental setup



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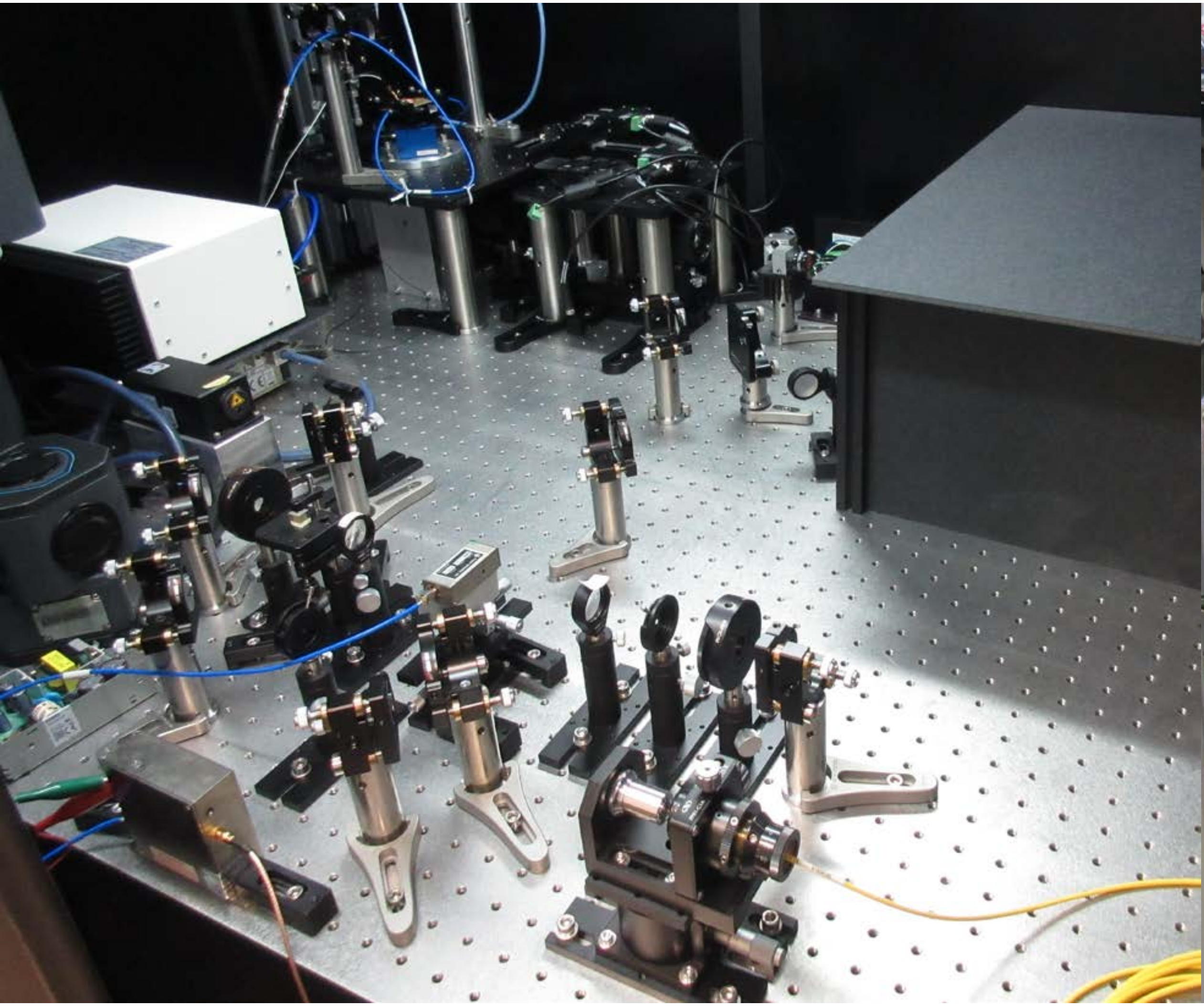

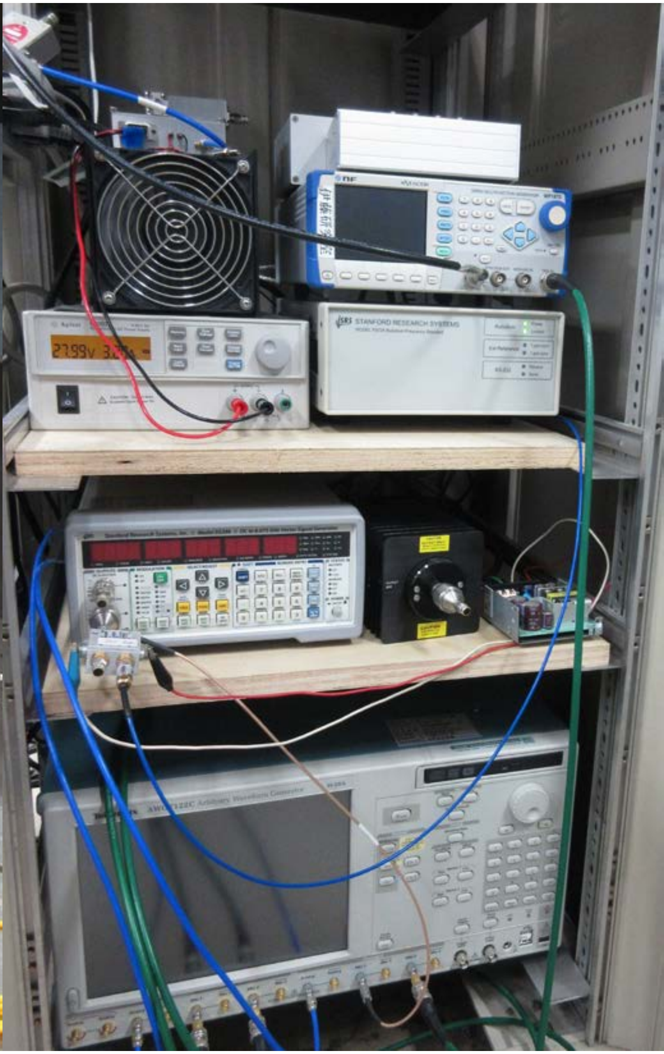

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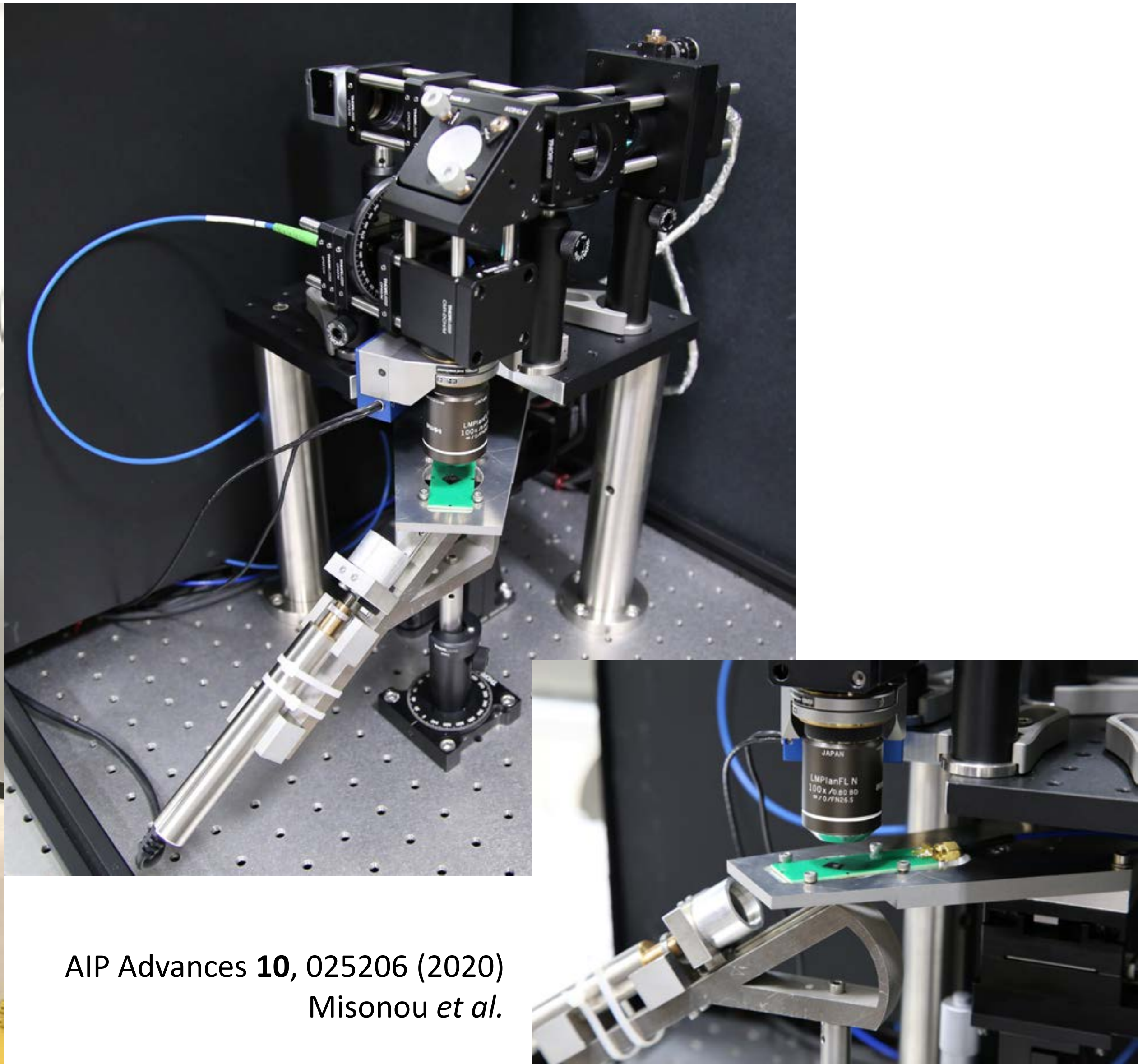


AIP Advances **10**, 025206 (2020)
Misonou *et al.*

# Outline

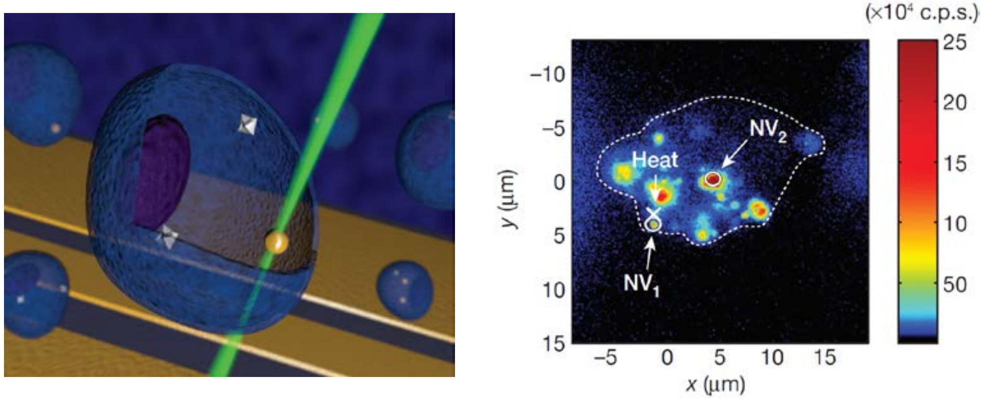
- **Basics of NV centers in diamond**
  - Structure
  - Optical properties
  - Spin properties and control

- **Quantum sensing**
  - Principle of AC magnetometry
  - Detection of proton spin ensemble
  - Detection and localization of a single $^{13}$C nuclear spin
  - Ultrahigh resolution sensing

# Quantum sensing with NV centers

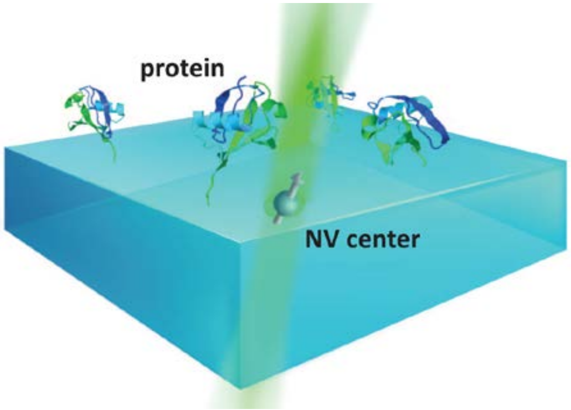
- *B*, *E*, *T*, *S*...
- DC & AC modes
- Wide temperature range
- Nondestructive
- High spatial resolution
- Various modalities

**Nanodiamond & biology**



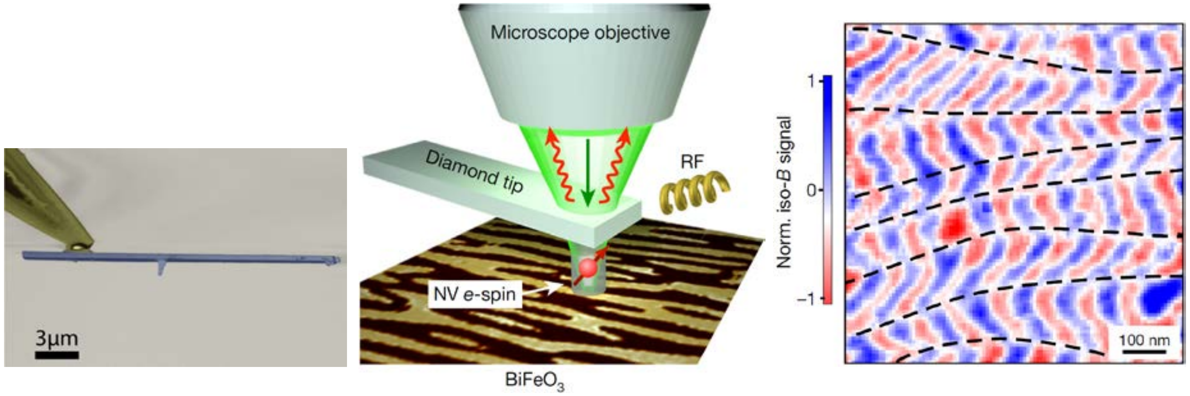
Nature **500**, 54 (2013)

**Near-surface NV center & NMR**



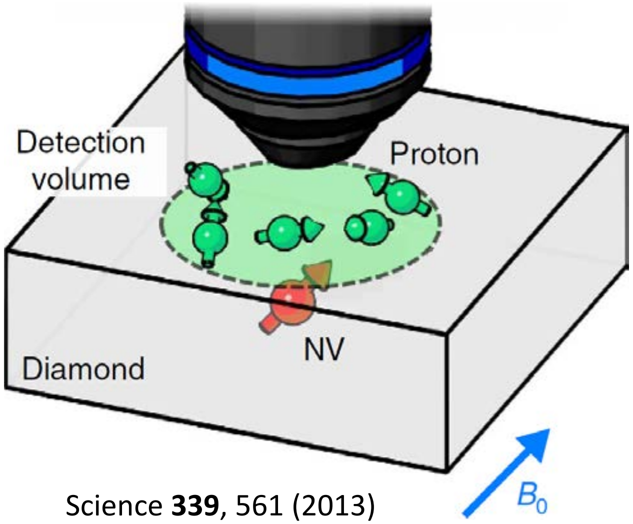
Science **351**, 836 (2016)

**Scanning probe & condensed matter**

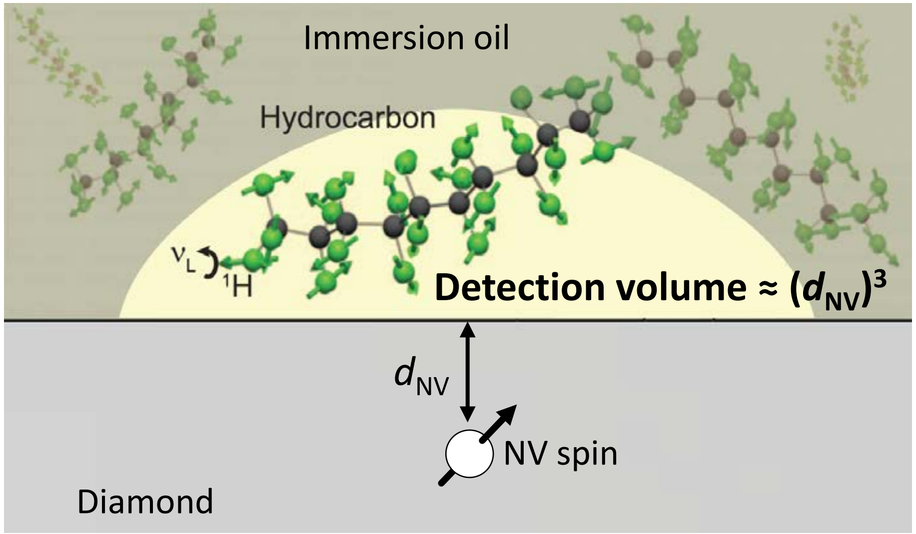


Rev. Sci. Instrum. **87**, 063703 (2016); Nature **549**, 252 (2017)

# Nuclear spin sensing



Science **339**, 561 (2013)



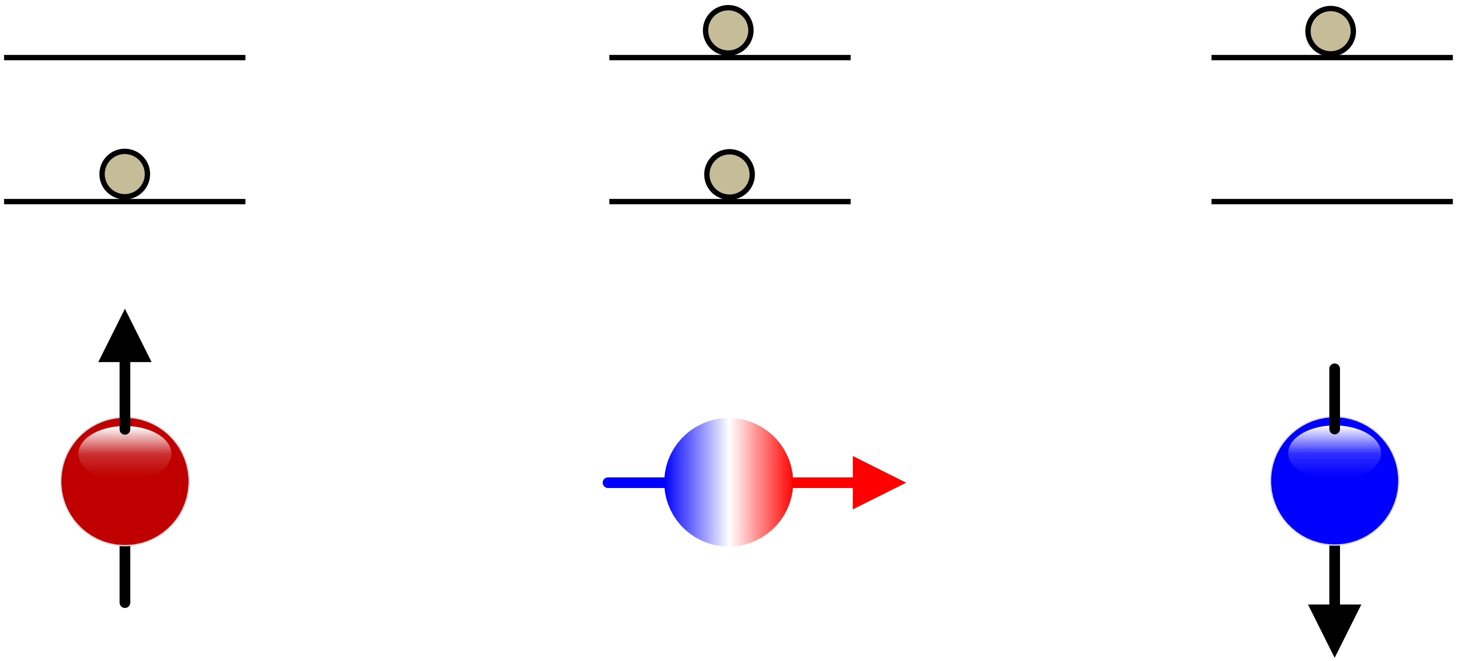
Nature Commun. **6**, 8527 (2015)

Nuclear spins **precess** at $f_{ac}$ = a few kHz–MHz under $B_0$

⇨ **Weak AC magnetic field** on the NV spin

⇨ Detect using **quantum coherence**

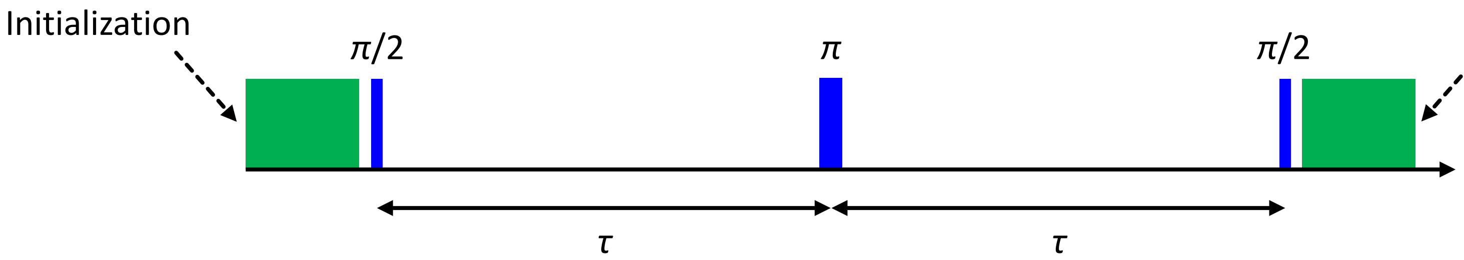
# Quantum coherence



$|0\rangle \equiv |m_s = 0\rangle$ $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$ $|1\rangle \equiv |m_s = -1\rangle$

**$T_2$: measure of how long a superposition state is preserved**

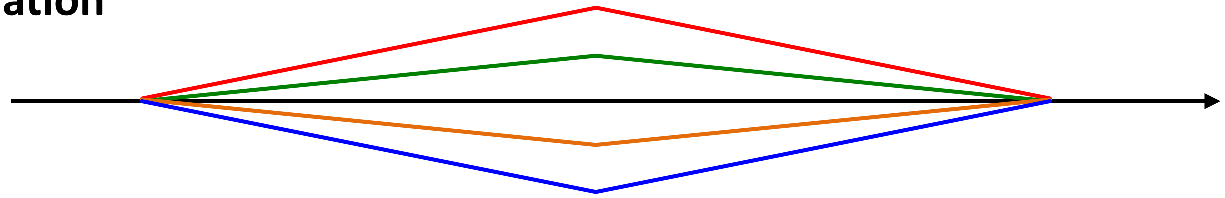
# Spin echo

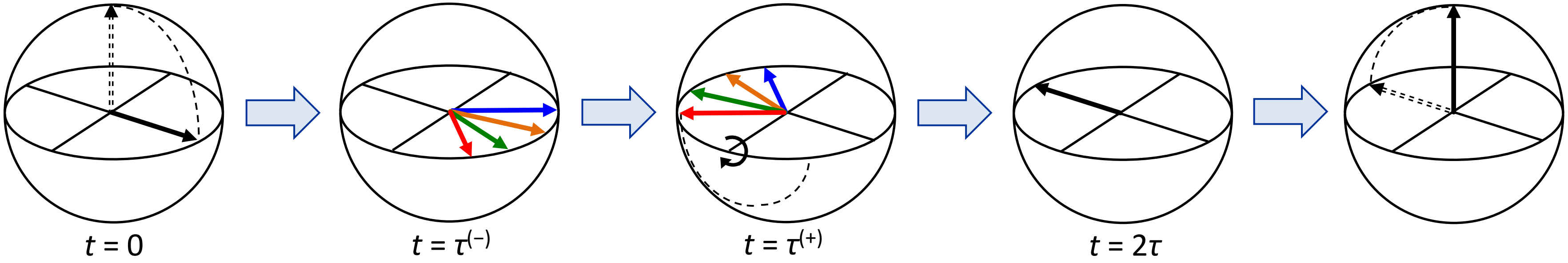


**Modulation function**

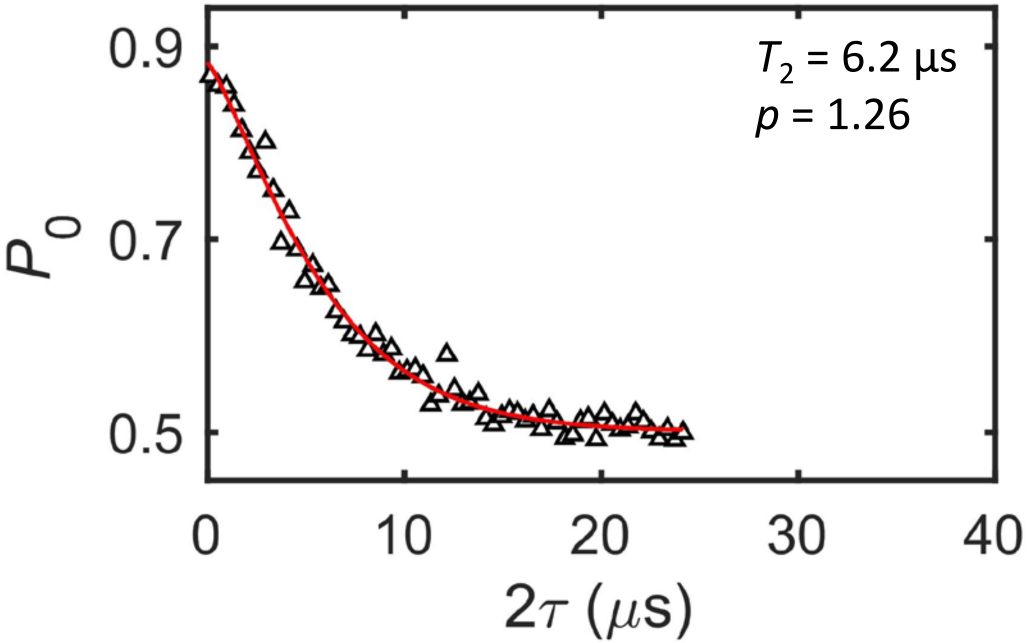
***Sign of phase accumulation***

**Phase accumulation by DC field**





# Coherence time



**Stretched exponential decay**

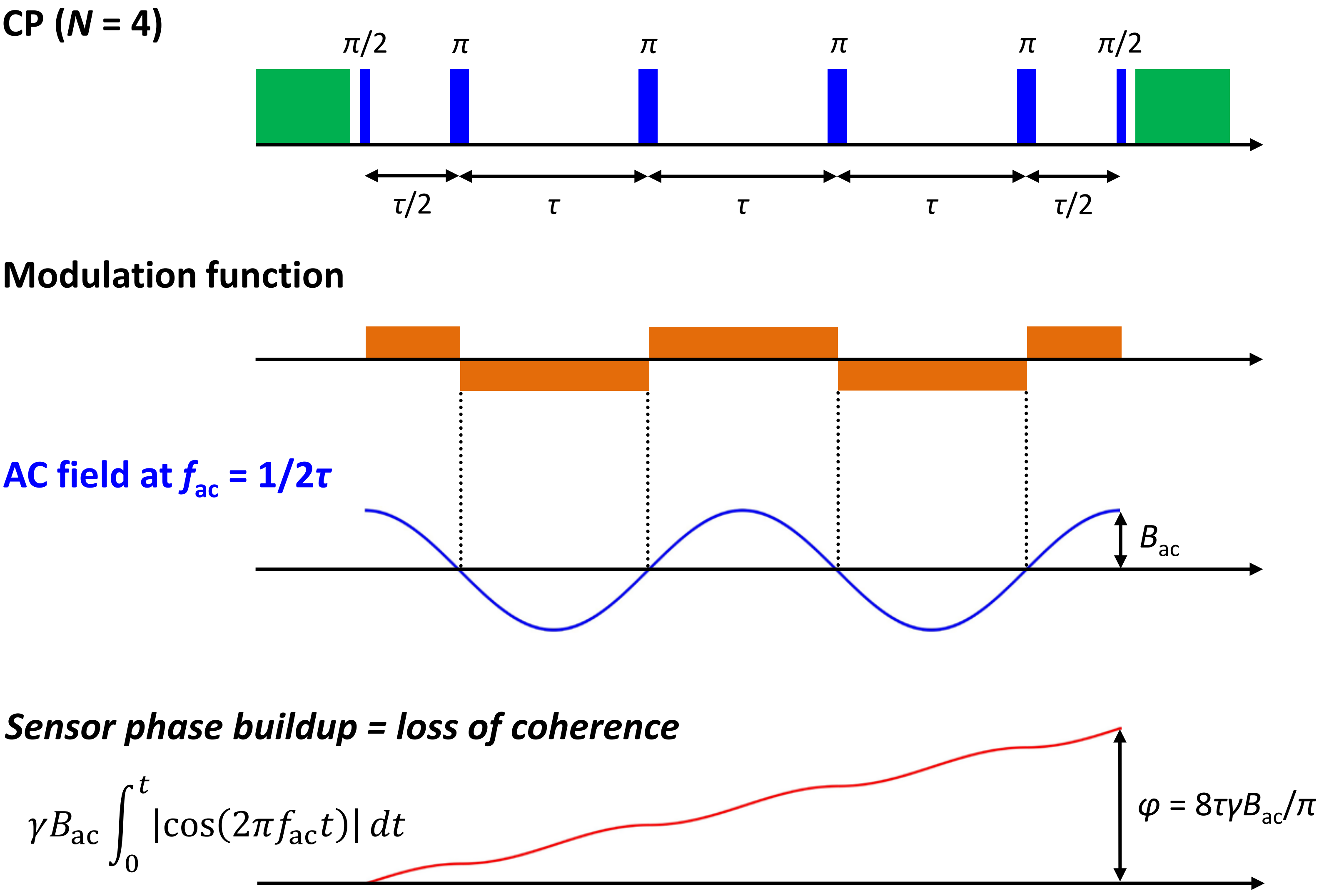
$$\exp\left[-\left(\frac{2\tau}{T_2}\right)^p\right]$$

**Near-surface NV center**

- $N^+$ implantation into $^{12}C$ ($I$ = 0) layer
- $d_{NV}$ = 6.26 nm
- $B_0$ = 23.5 mT

AIP Advances **10**, 025206 (2020) Misonou *et al.*

# AC magnetometry



**CP ($N$ = 4)**

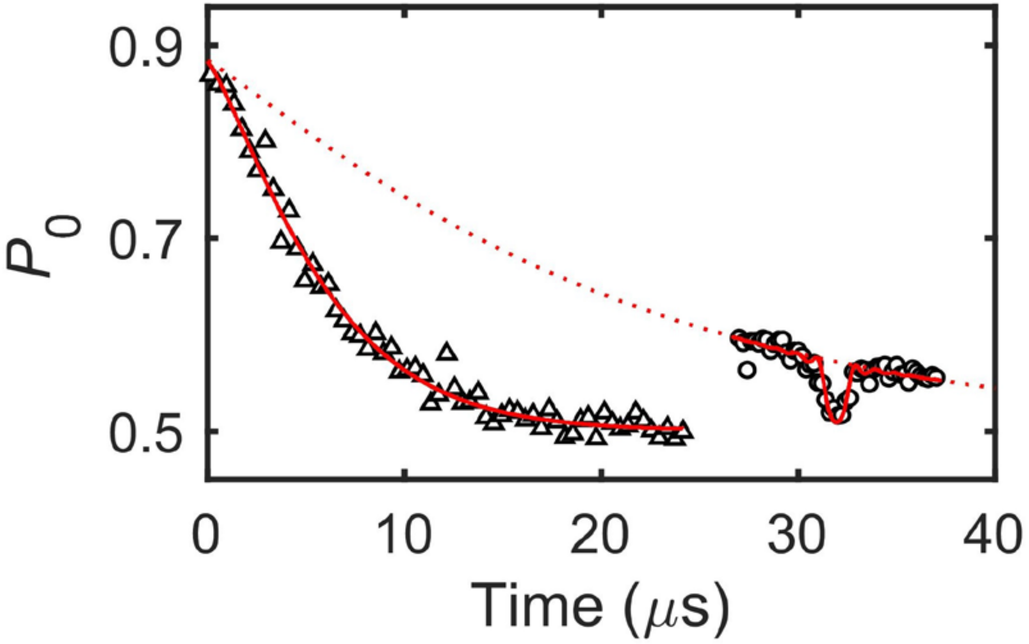
**Modulation function**

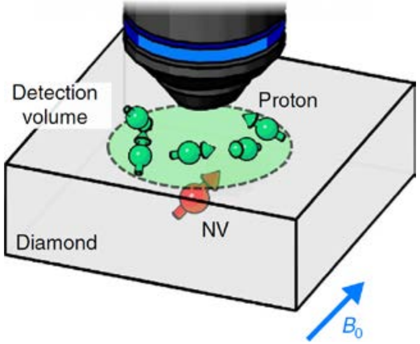
**AC field at $f_{ac} = 1/2\tau$**

***Sensor phase buildup = loss of coherence***

$$\gamma B_{\mathrm{ac}} \int_0^t |\cos(2\pi f_{\mathrm{ac}} t)|\, dt$$

# Nuclear spin sensing



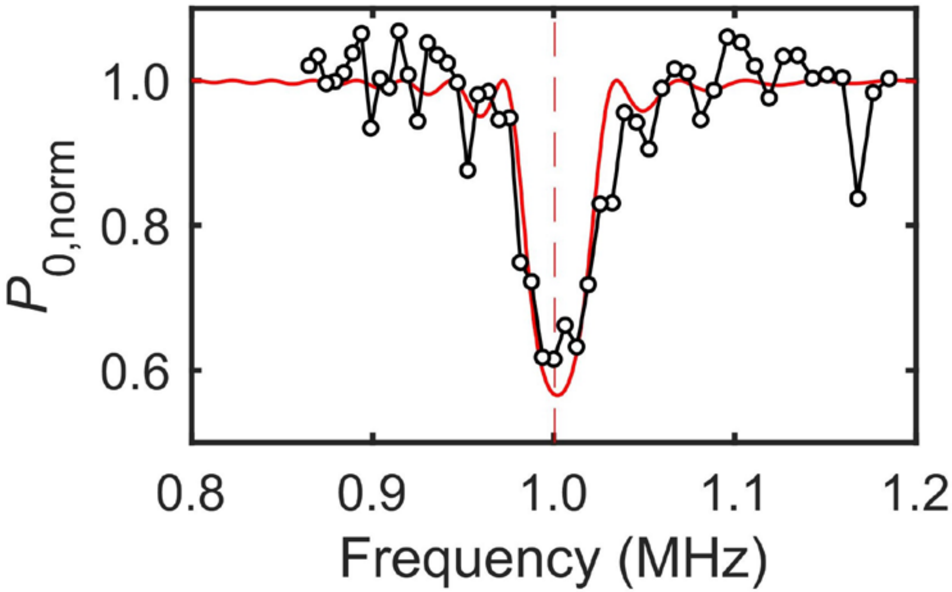


- $T_2$ = 6.2 μs @$B_0$ = 23.5 mT
- $N$ = 64 (XY16)
- $(2\tau)^{-1}$ = 64/(2 x 32 μs) = 1 μs

  → $\gamma_H B_0$ = (42.577 kHz/mT) x $B_0$ = 1.00 MHz

AIP Advances **10**, 025206 (2020) Misonou *et al.*

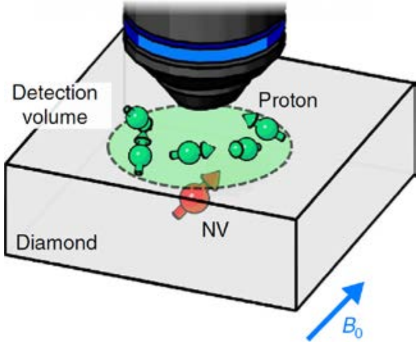
# Nuclear spin sensing



$$C(\tau) = f(B_{\mathrm{rms}})$$

$$B_{\mathrm{rms}} = \frac{\mu_0}{4\pi} h\gamma_{\mathrm{H}} \sqrt{\frac{5\pi\rho}{96 d_{\mathrm{NV}}^3}}$$

Phys. Rev. B **93**, 045425 (2016)

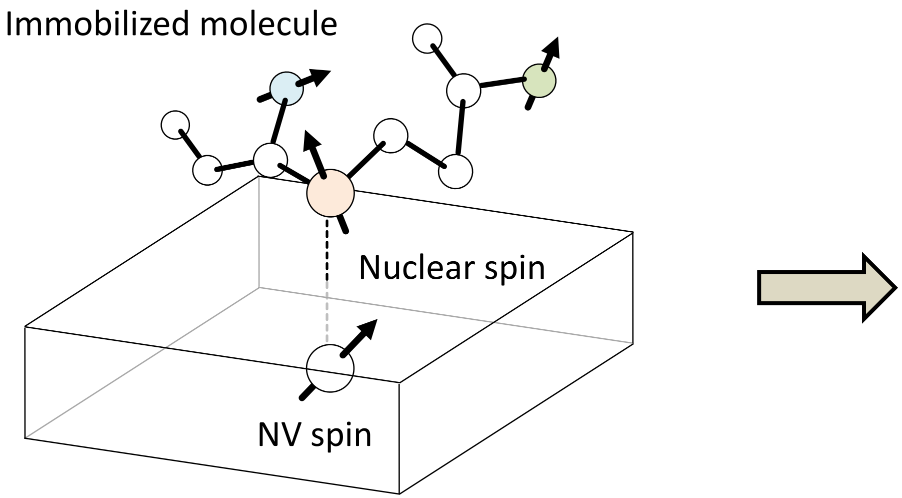


- Proton density $\rho = 6 \times 10^{28}$ m$^{-3}$ (known)
- $d_{\mathrm{NV}} = 6.26$ nm
- $B_{\mathrm{rms}} \approx 560$ nT
- Detection volume $(d_{\mathrm{NV}})^3 \approx 0.25$ zL (zepto = $10^{-21}$)
- # of proton $\rho(d_{\mathrm{NV}})^3 \approx 1500$
- Thermal pol. ($10^{-7}$) vs. statistical pol. $(1500)^{0.5} \approx 39$

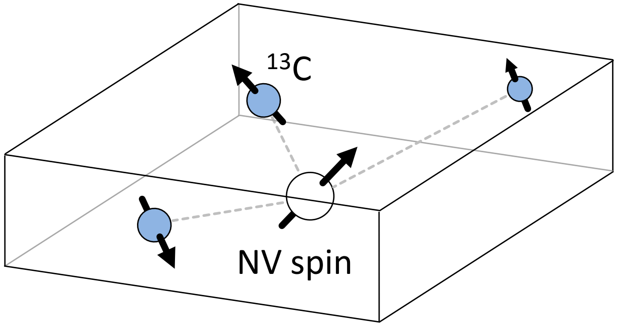
AIP Advances **10**, 025206 (2020) Misonou *et al.*

# Toward single-molecular imaging

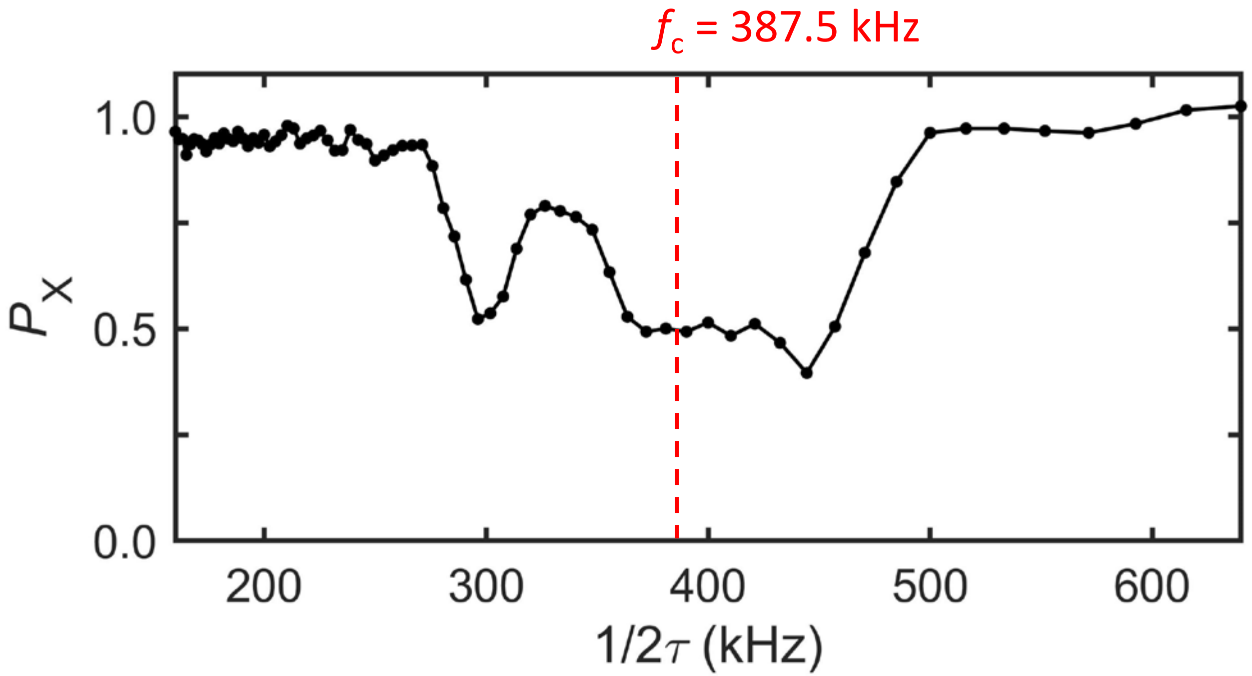
- **Strategy**
  - → Detect **individual nuclear spins** contained in a single molecule
  - → Determine their **nuclear species (& chemical shifts)** and **positions**
- **Practical issues**
  - → Preparation of high-quality near-surface NV centers
  - → Accurate positioning of single molecules/proteins near the sensor



Use $^{13}$C (1.1%) in diamond as a testbed



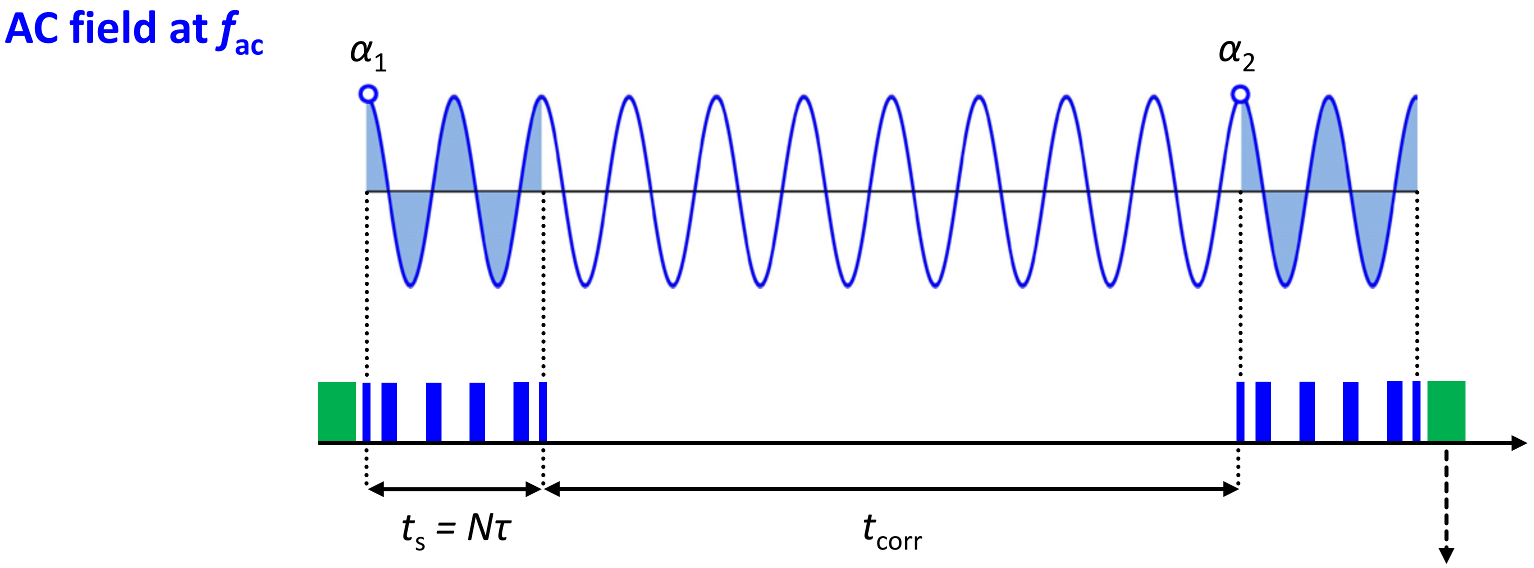
# Nuclear spin sensing



- Single NV in bulk ([$^{13}$C] = 1.1%, $d_{NV} \approx 50$ µm)
- $N = 16$
- $f_c = \gamma_C B_0 = 10.705$ kHz/mT x 36.2 mT

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Correlation spectroscopy

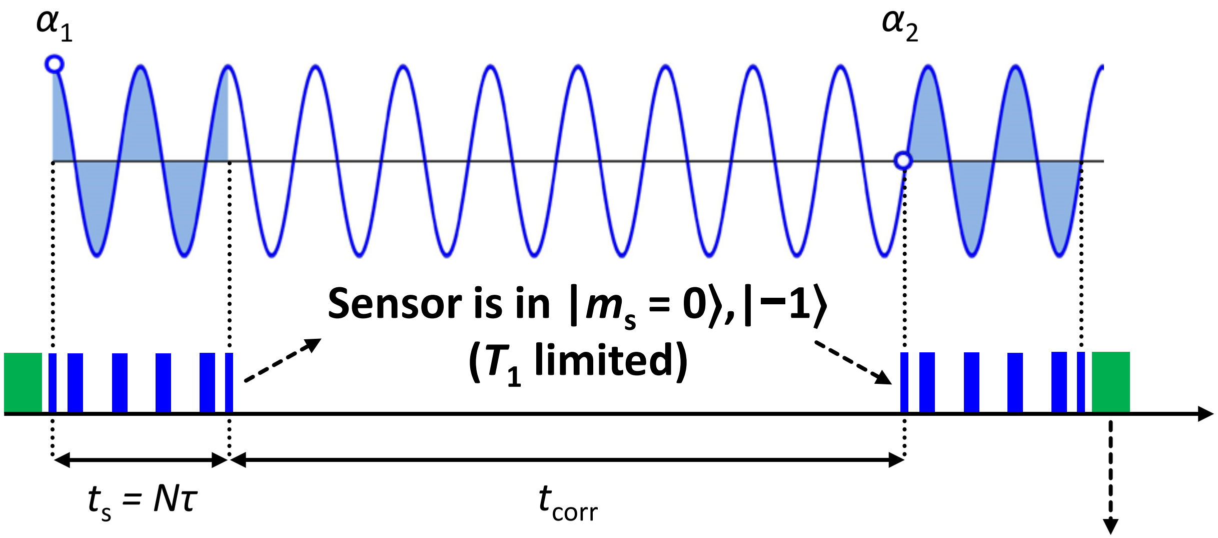


**Accumulate more phase if $t_{corr} = m/f_{ac}$**

Nature Commun. **4**, 1651 (2013) Laraoui *et al.*
Phys. Rev. Appl. **4**, 024004 (2015) Kong *et al.*
Nature Commun. **6**, 8527 (2015) Staudacher *et al.*
Phys. Rev. Lett. **116**, 197601 (2016) Boss *et al.*

# Correlation spectroscopy

**AC field at $f_{ac}$**



**Sensor is in $|m_s = 0\rangle, |-1\rangle$**
**($T_1$ limited)**

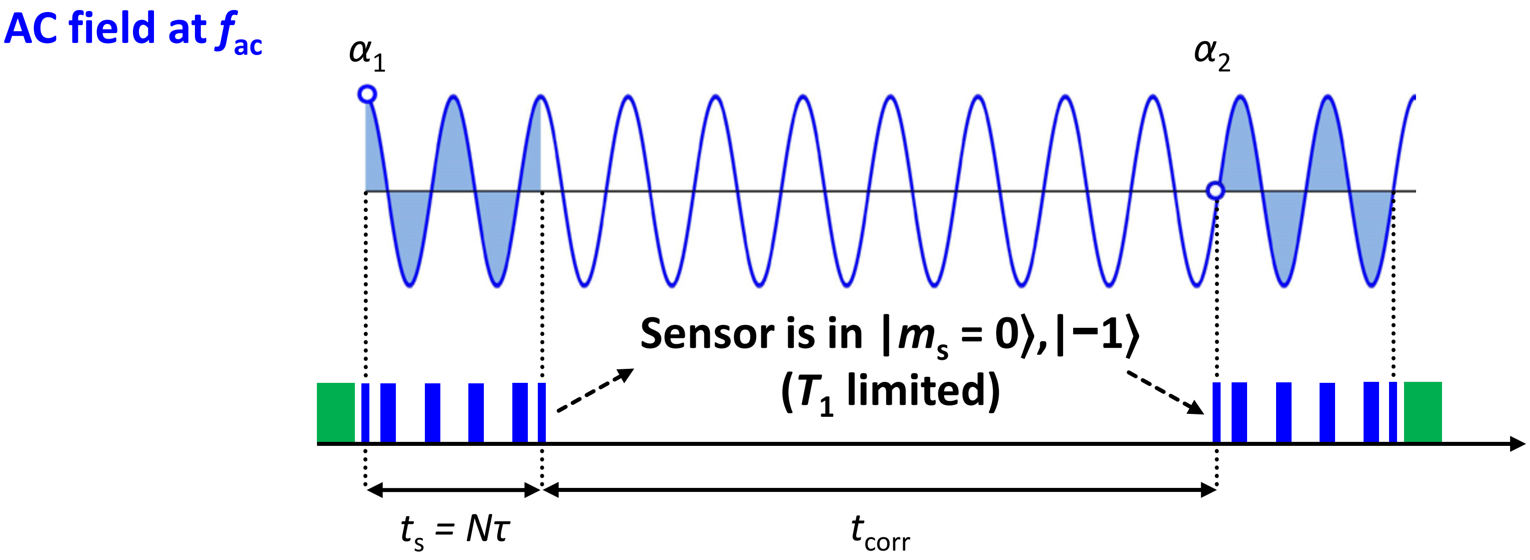
**No gain of the phase if**
**$t_{corr} = (m+1/4)/f_{ac}$**

**The transition probability for random phases**

$$p(t_1) \approx \frac{1}{2}\left\{1 - \frac{1}{2}\left(\frac{\gamma B_{ac} t_s}{\pi}\right)^2 \cos(2\pi f_{ac} t_{corr})\right\}$$

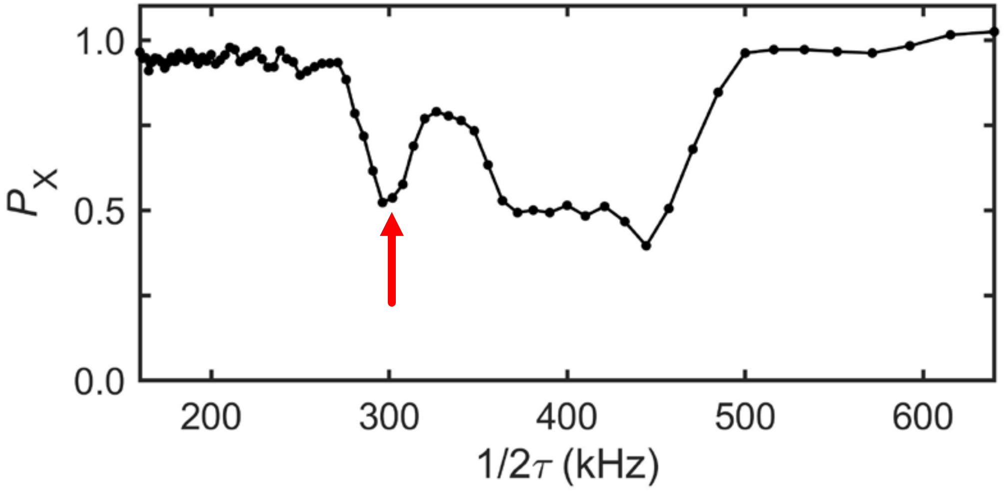
Nature Commun. **4**, 1651 (2013) Laraoui *et al.*
Phys. Rev. Appl. **4**, 024004 (2015) Kong *et al.*
Nature Commun. **6**, 8527 (2015) Staudacher *et al.*
Phys. Rev. Lett. **116**, 197601 (2016) Boss *et al.*

# Correlation spectroscopy



**AC field at $f_{ac}$**

**Sensor is in $|m_s = 0\rangle, |-1\rangle$ ($T_1$ limited)**

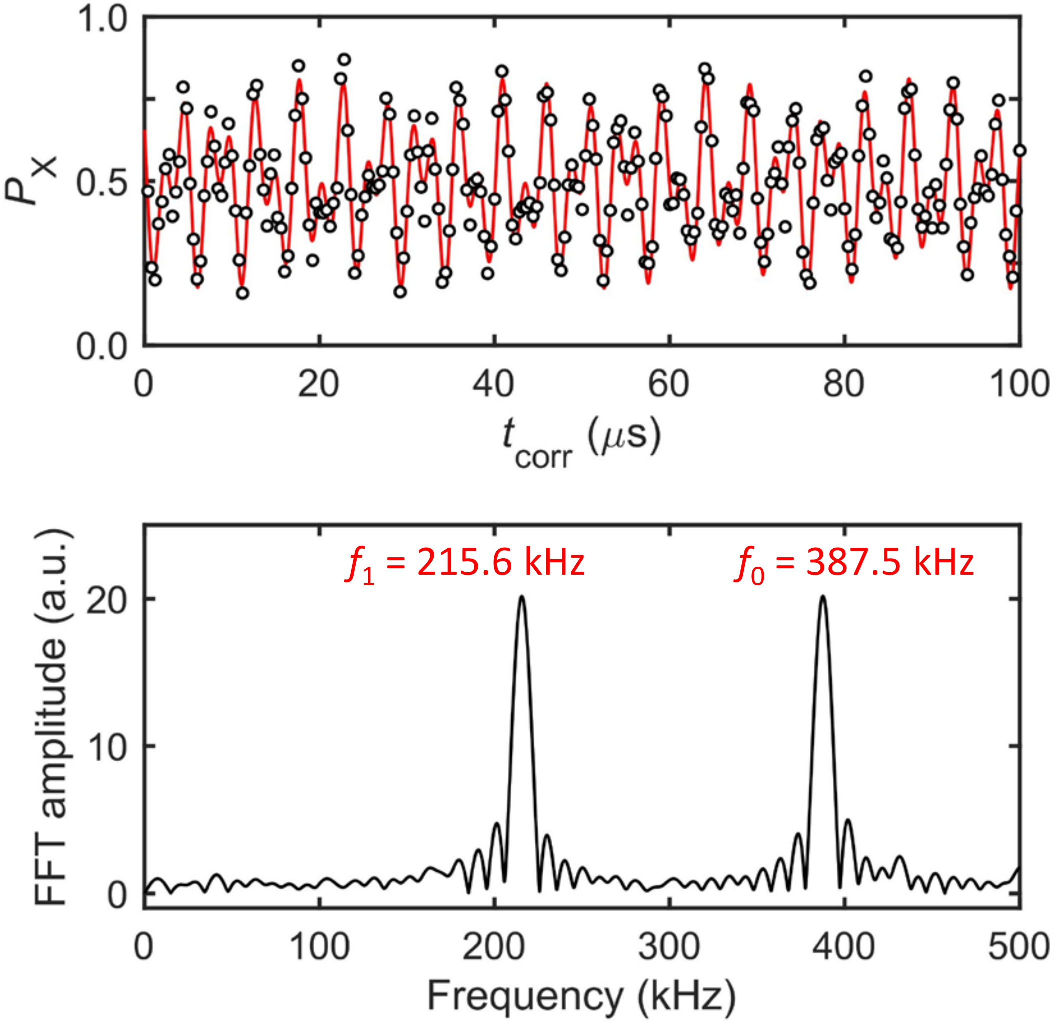


**Where to look at?**

- $f_t = 1/2\tau = 301.6$ kHz
- $\tau = 1.7875$ µs

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

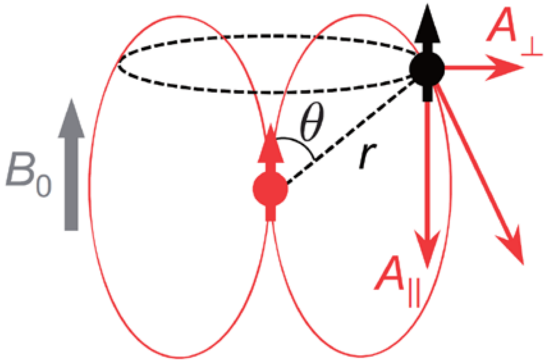
# Correlation spectroscopy of a nucleus



**No decay**

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

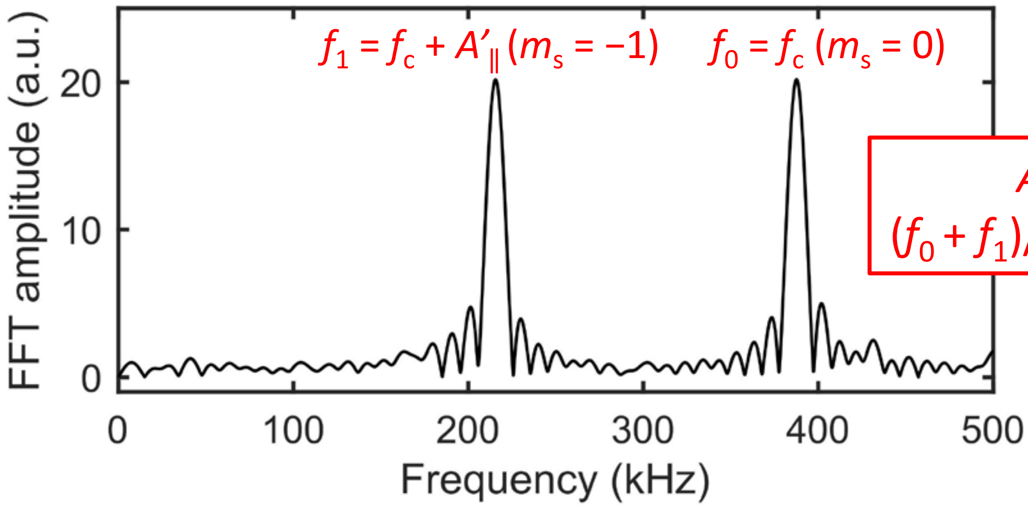
# Correlation spectroscopy of a nucleus



**Hamiltonian of NV–$^{13}$C coupled system**

$$H = f_c I_z + |m_s = -1\rangle\langle -1|(A_\parallel I_z + A_\perp I_x)$$

**→ No hyperfine field when $|m_s = 0\rangle$**

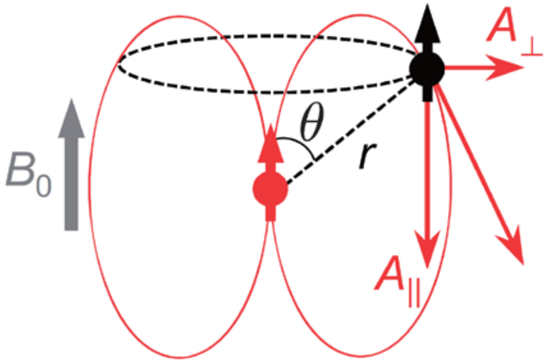


$A'_\parallel = -171.9$ kHz

$(f_0 + f_1)/2 = 301.55$ kHz → dip

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

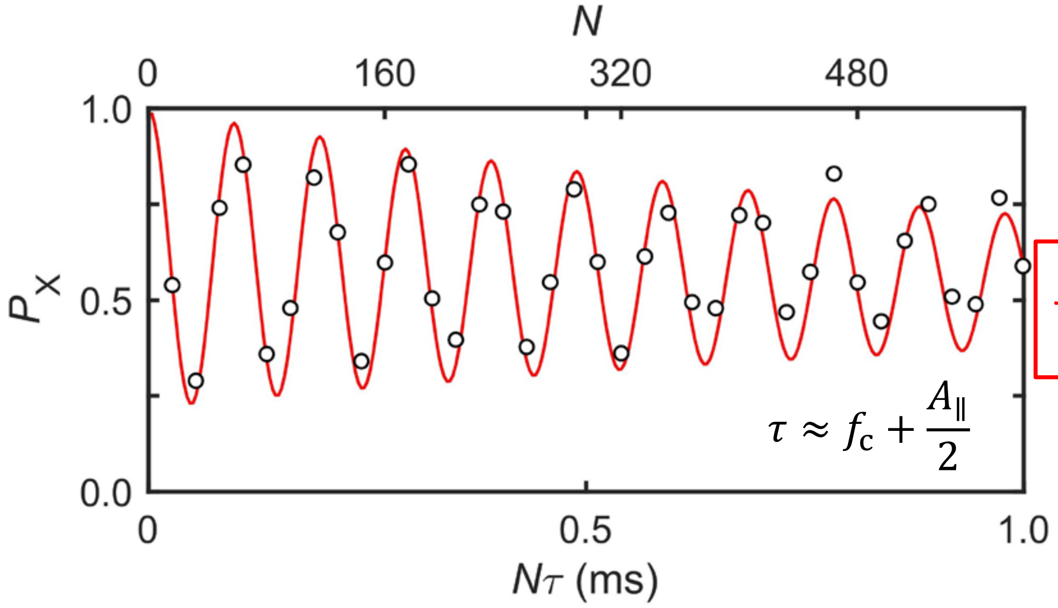
# Coherent control of a nuclear spin



**Hamiltonian of NV–$^{13}$C coupled system**

$$H = f_c I_z + |m_s = -1\rangle\langle -1|(A_\parallel I_z + A_\perp I_x)$$

**→ The single $^{13}$C *n*-spin rotates about the $A_\perp$ axis**

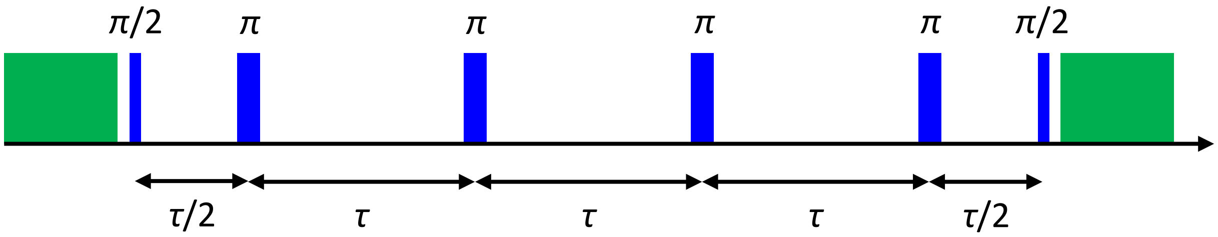


$f_{osc}$ = 10.2 kHz ≈ $A'_\perp/2$
$P_X < 0.5$ → single

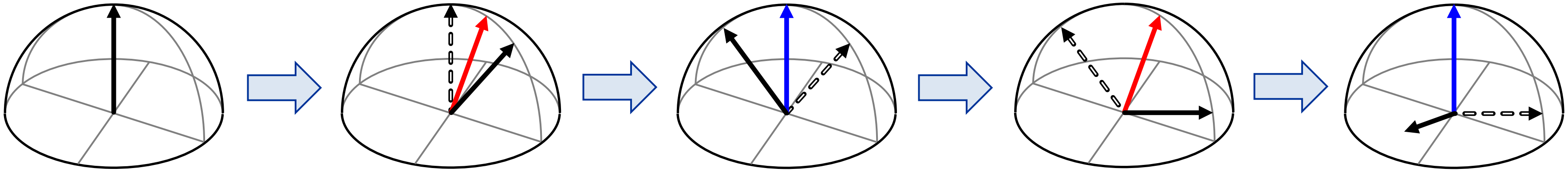
Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

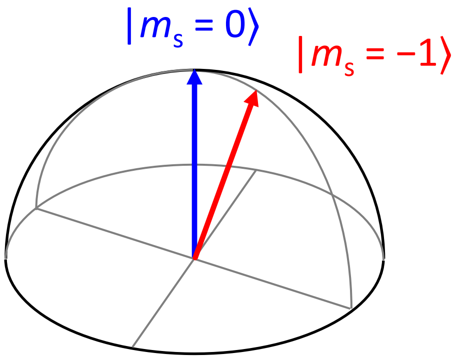
# Conditional rotation of a nuclear spin

**CP ($N$ = 4)**



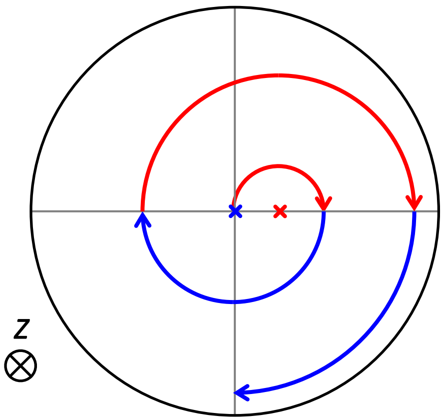
**Evolution of $n$-spin vector**



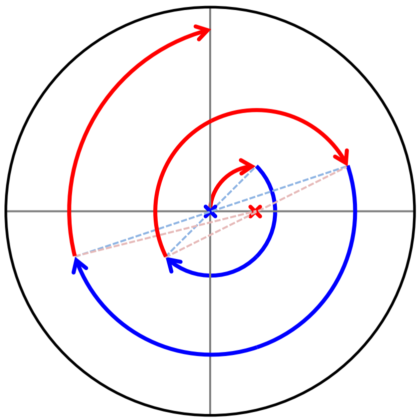


Q-axis of $n$-spin

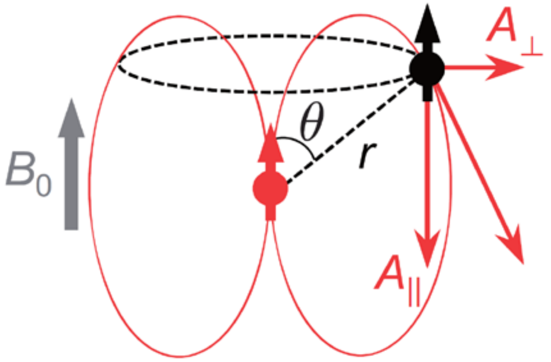
***Start from $|m_s = 0\rangle$***



***Start from $|m_s = -1\rangle$***



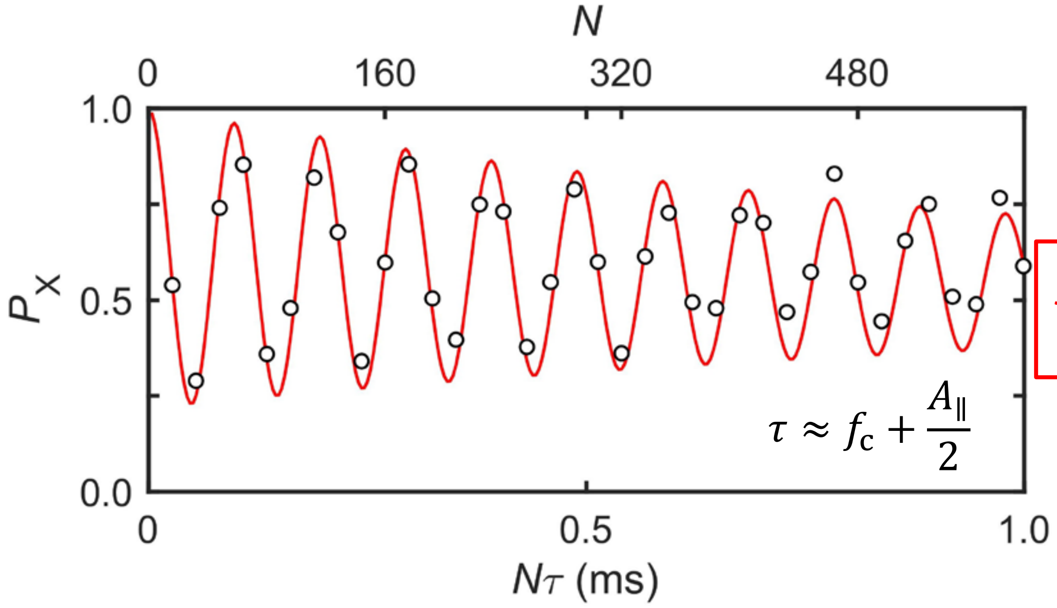
# Coherent control of a nuclear spin



**Transition probability of the NV spin**

$$P_\mathrm{X} = 1 - \frac{1}{2}(1 - \underbrace{\boldsymbol{n}_0 \cdot \boldsymbol{n}_{-1}}_{-1}) \sin^2 \frac{N\phi_\mathrm{cp}}{2}$$

Phys. Rev. Lett. **109**, 137602 (2012) Taminiau *et al.*

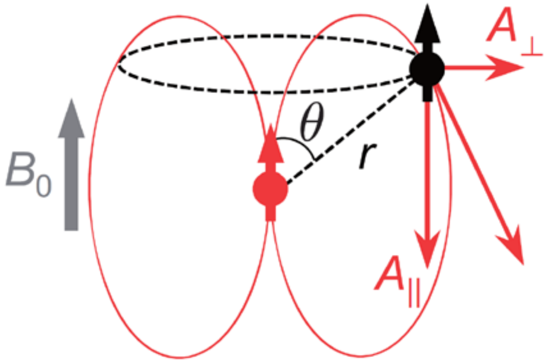


$$\tau \approx f_\mathrm{c} + \frac{A_\parallel}{2}$$

$f_\mathrm{osc}$ = 10.2 kHz ≈ $A'_\perp/2$
$P_\mathrm{X} < 0.5$ → single

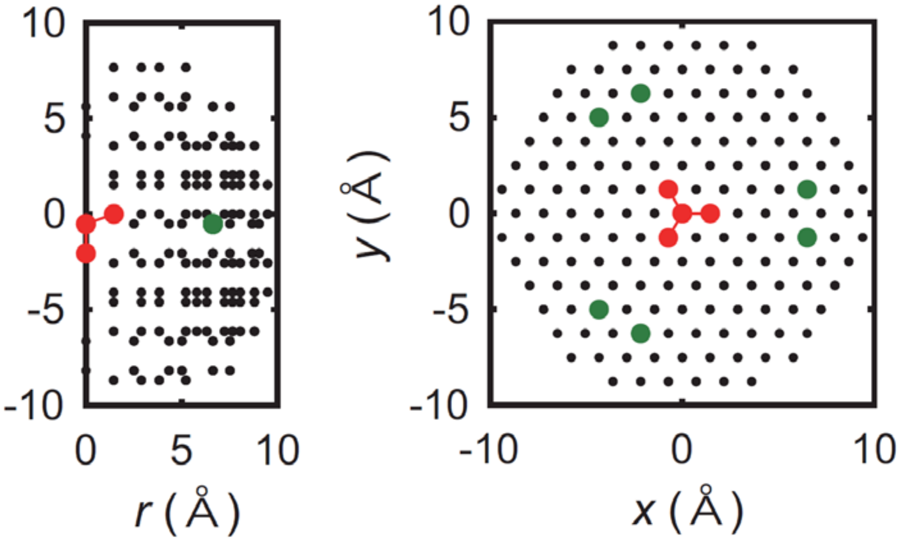
Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Determination of hf constants



**Magnetic dipole int. + contact hf int.**

$$A_\parallel \propto \frac{3\cos^2\theta - 1}{r^3} \qquad A_\perp \propto \frac{3\cos\theta\sin\theta}{r^3}$$



$(r, \theta)$ = (6.84 Å, 94.8°)

$A_\parallel = -173.1$ kHz
$A_\perp = 22.3$ kHz

⇕

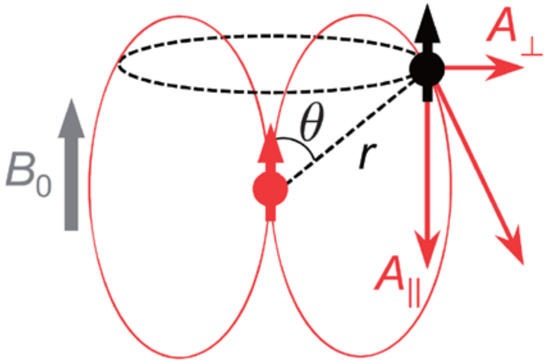
$A_\parallel = -175.1 \pm 2.1$kHz
$A_\perp = 21.9 \pm 0.2$ kHz

**DFT**: New J. Phys. **20**, 023022 (2018)
Nizovtsev *et al.*

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# How to determine $\phi$?

(azimuthal angle)

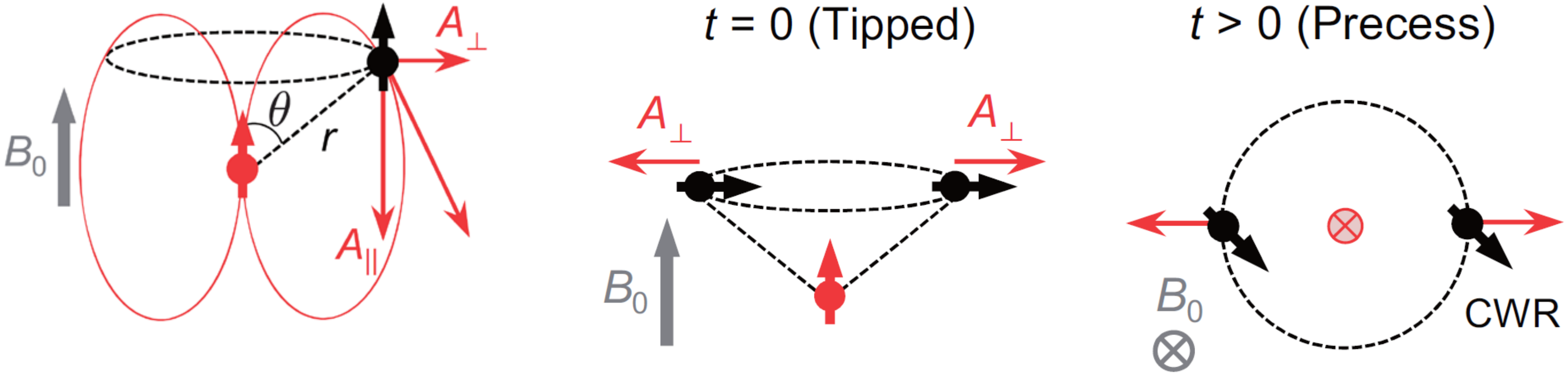


**Magnetic dipole int.**

$$A_\parallel \propto \frac{3\cos^2\theta - 1}{r^3} \qquad A_\perp \propto \frac{3\cos\theta\sin\theta}{r^3}$$

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# How to determine $\phi$?



**Transition probability of the NV spin after the detection of a single nuclear spin**

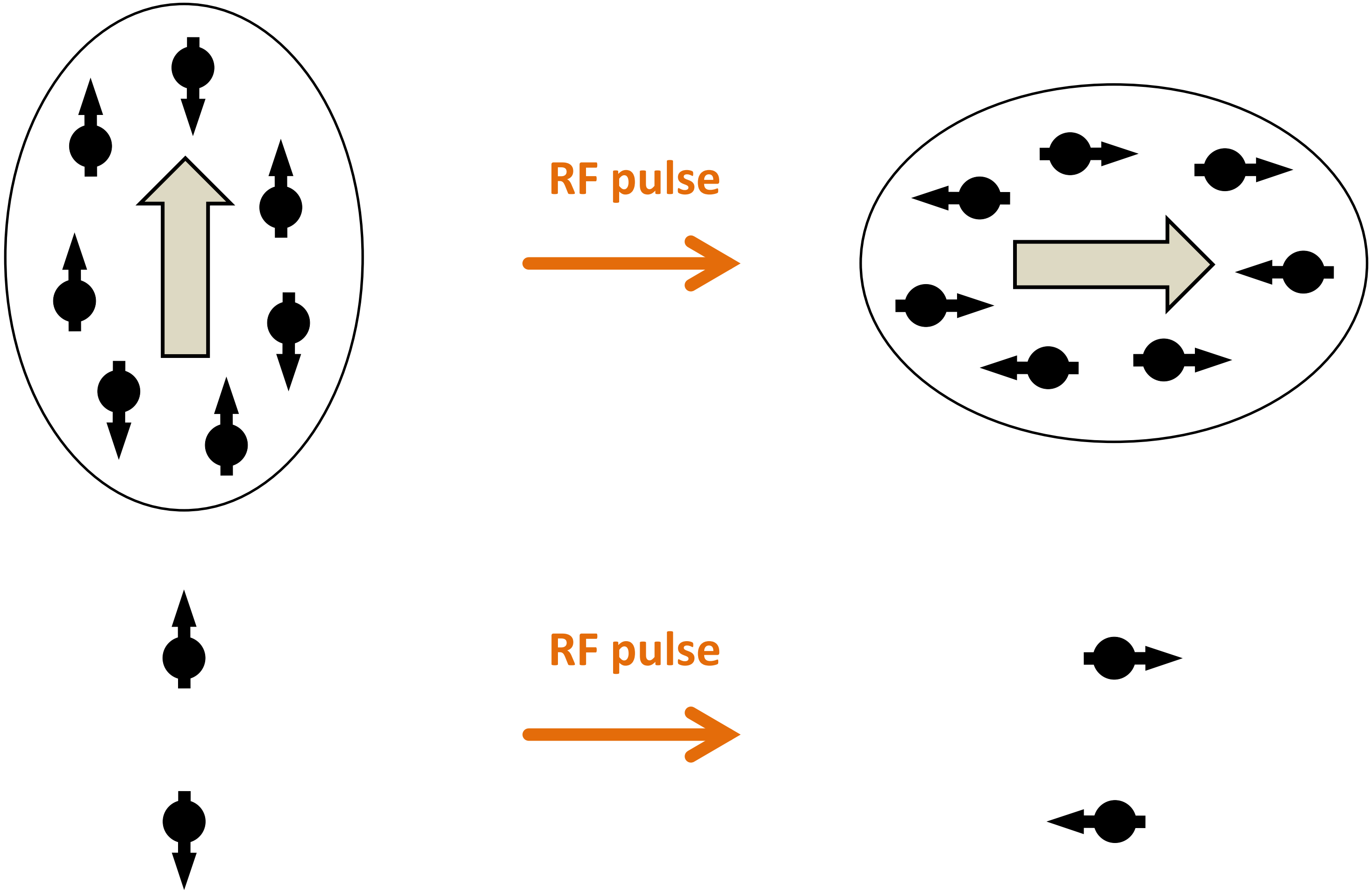
$$P_\mathrm{Y} = \frac{1}{2} - \frac{1}{2}\cos(\phi - \phi_\mathrm{n}) \sin N\phi_\mathrm{cp}$$

↓

Azimuthal angle of the nuclear Bloch vector: $2\pi f_\mathrm{p} t + \phi_\mathrm{n}(0)$

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Ensemble vs. single



RF pulse

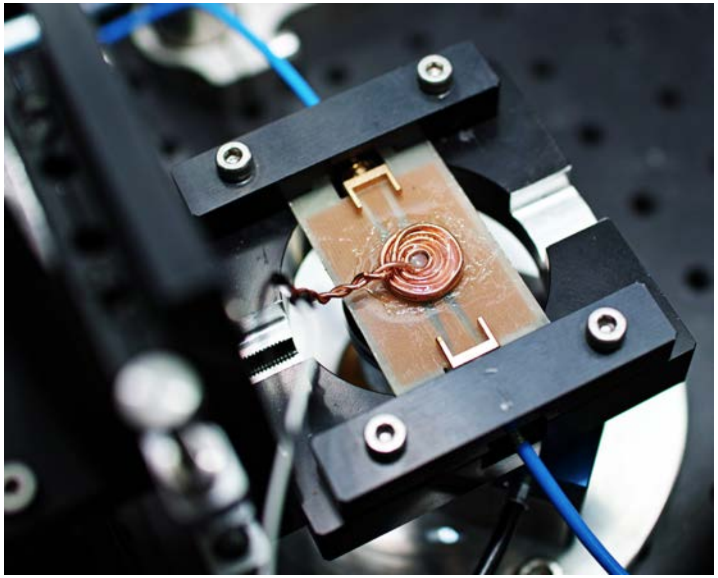
RF pulse

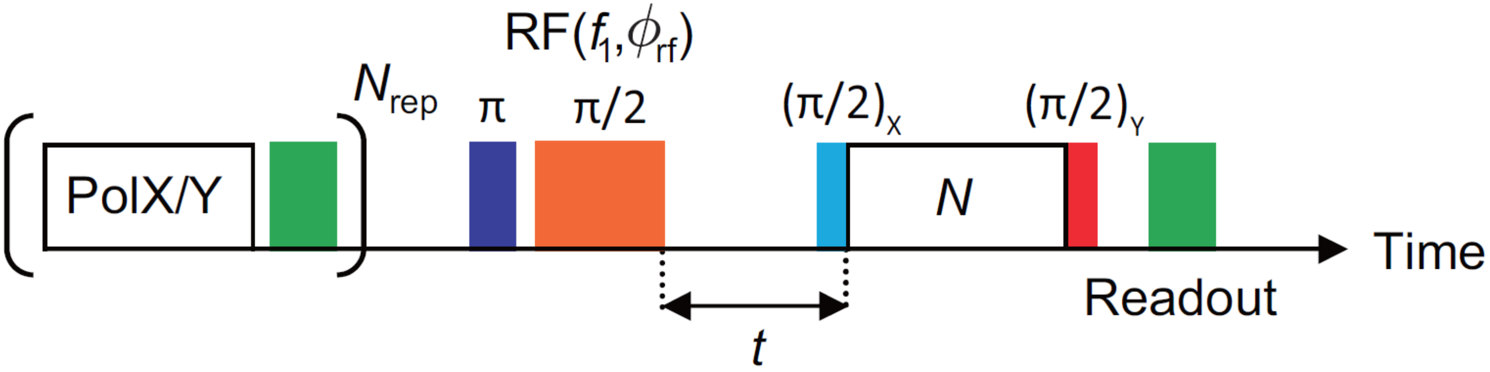
**The initial state matters**

→ Dynamic nuclear polarization (DNP)

# Determination of $\phi$ of a $^{13}$C *n*-spin

1. **DNP (PulsePol)**
2. **RF pulse@$m_s$ = −1**
3. **Wait *t* (*n*-spin precesses)**
4. **AC sensing**





Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Determination of $\phi$ of a $^{13}$C *n*-spin

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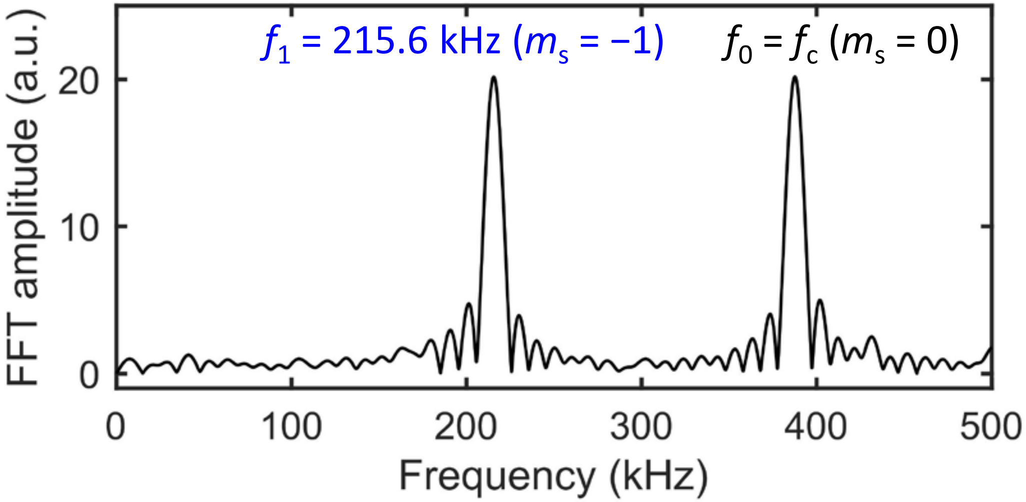
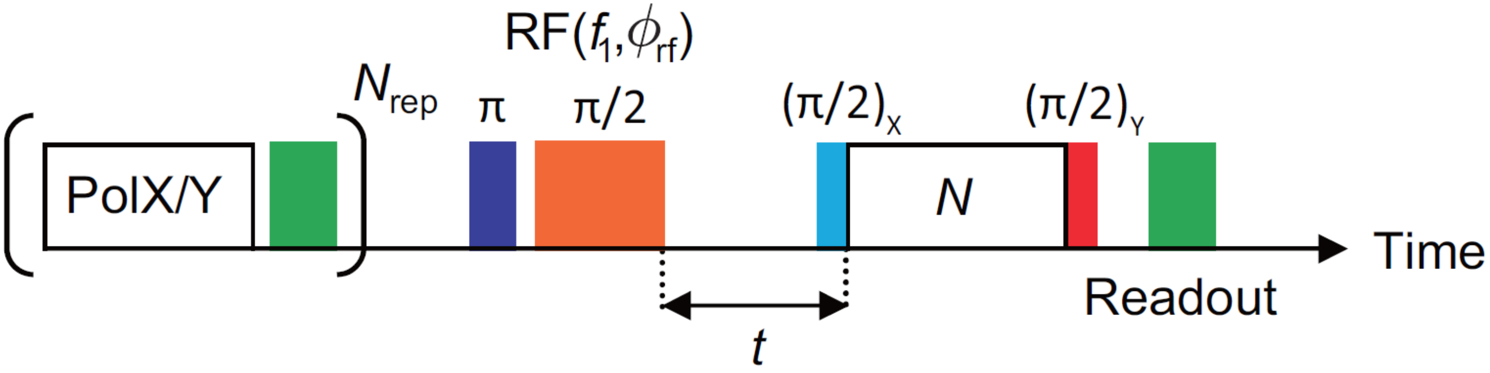


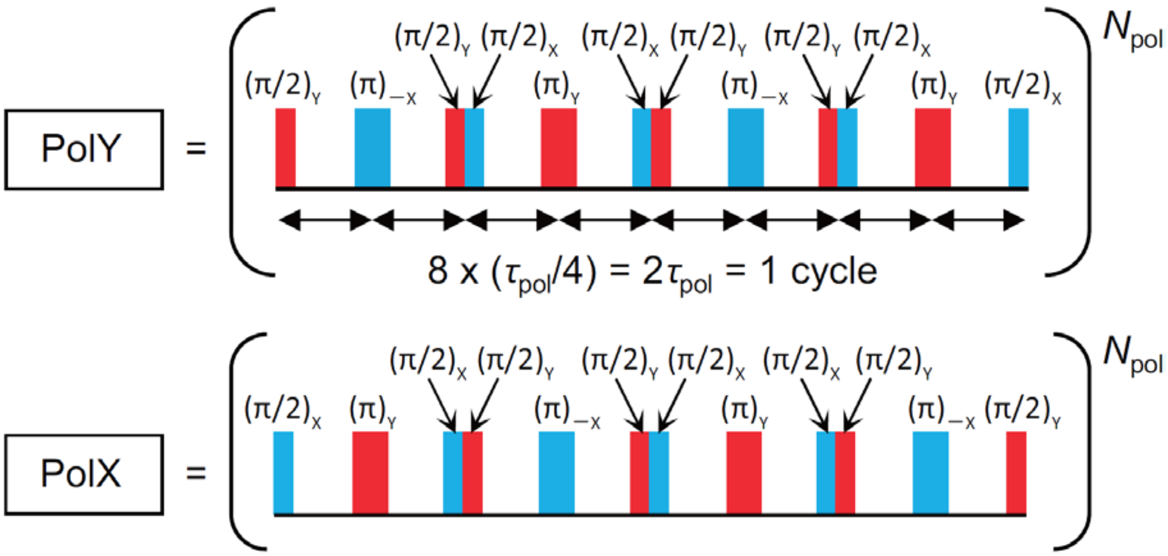


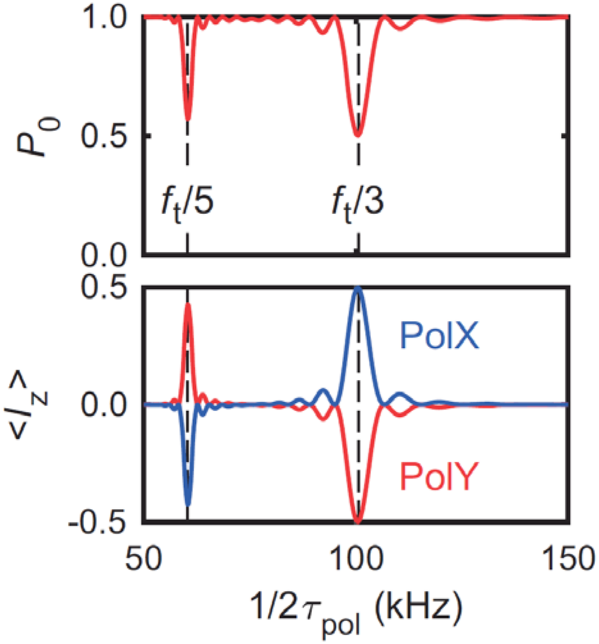
Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# PulsePol

**Hamiltonian engineering**

- Average Hamiltonian ∝ $S_{+}I_{-} + S_{-}I_{+}$, ∝ $S_{+}I_{+} + S_{-}I_{-}$
- DNP condition: $1/(2\tau_{\mathrm{pol}}) = f_{\mathrm{n}}/k$ ($f_{\mathrm{n}}$: $n$-precession frequency, $k$: odd)

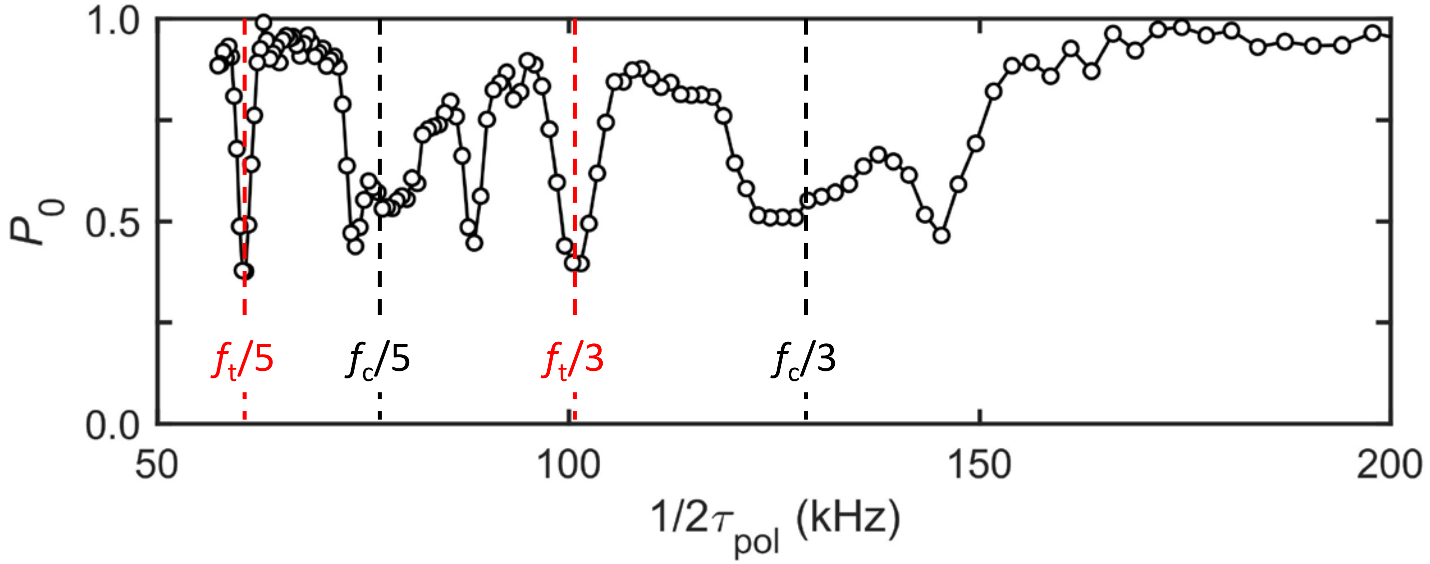


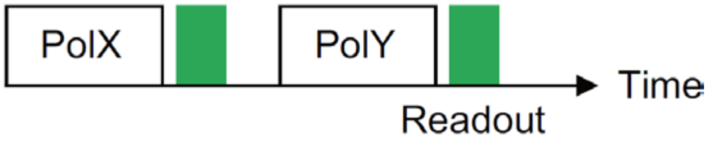


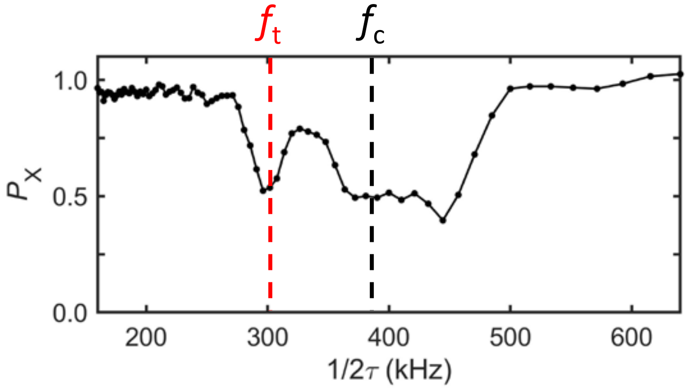
Sci. Adv. **4**, eaat8978 (2018) Schwartz *et al.*

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# PulsePol

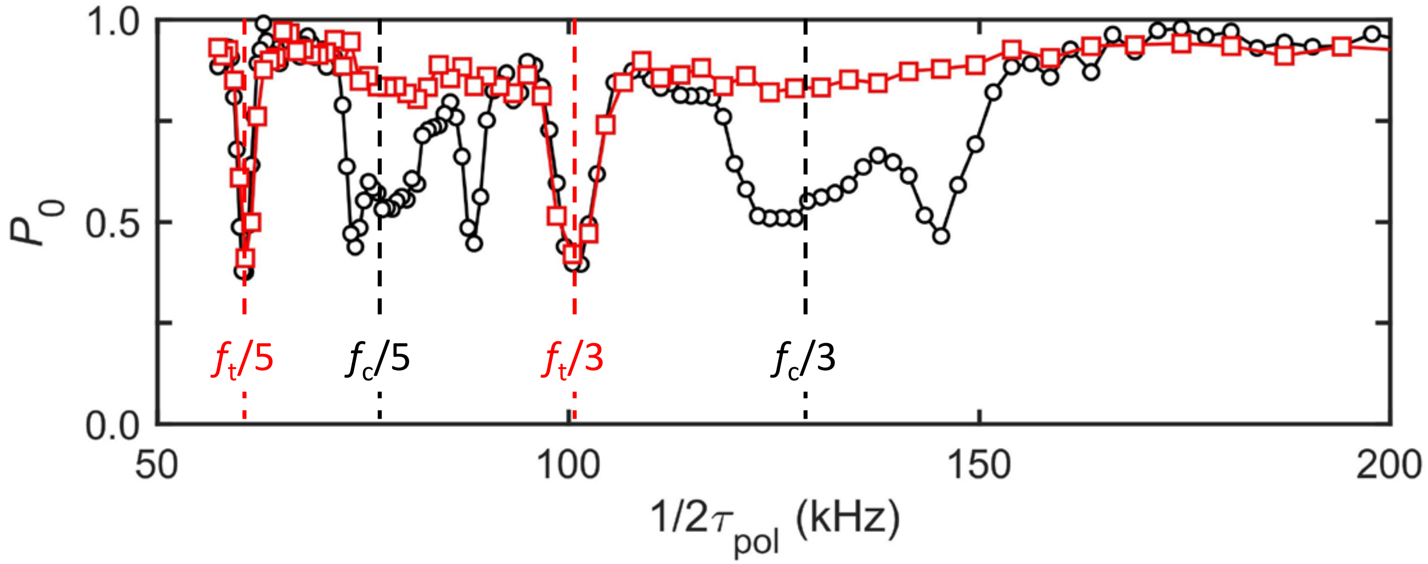


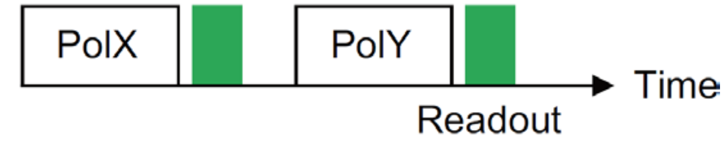


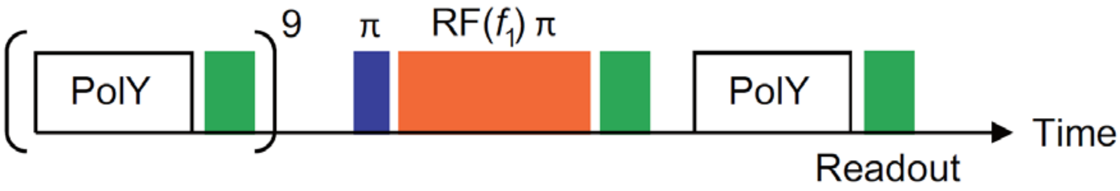


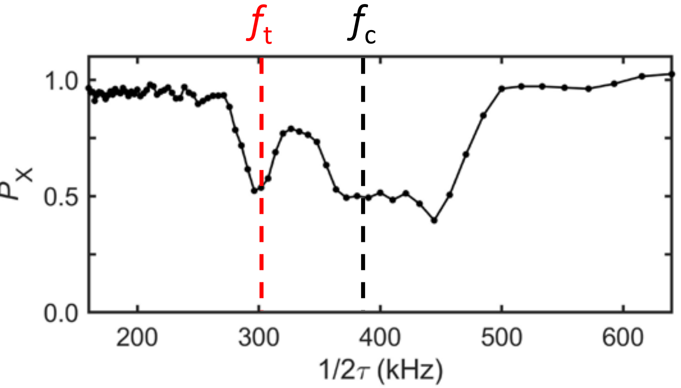
Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# PulsePol



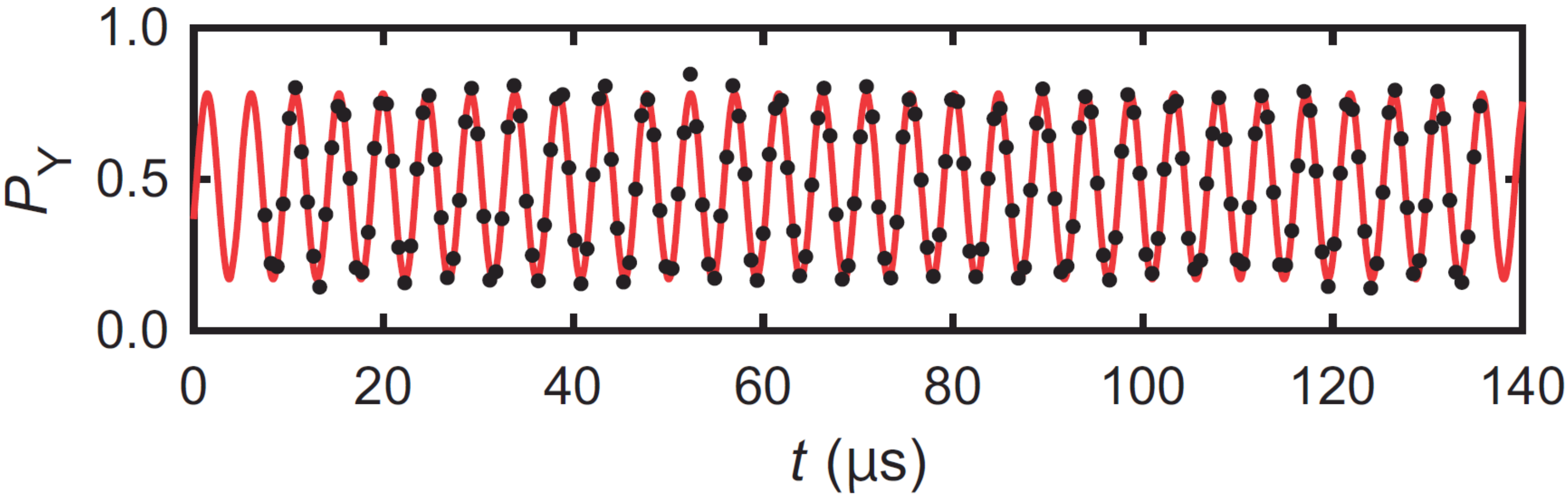


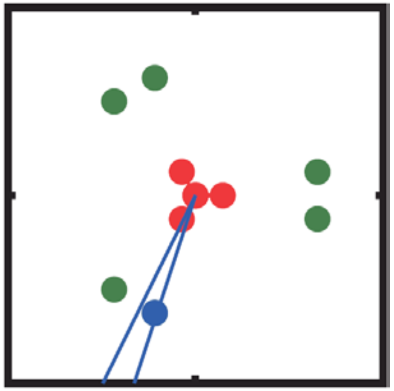




Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Determination of $\phi$ of a $^{13}$C *n*-spin





- ✓ $t \rightarrow 1$ ms (undersampling)
- ✓ $f_p = 215.79$ kHz $\approx f_1 = 215.6$ kHz
- ✓ $\phi - \phi_n(0) = 334.0^\circ$
- ✓ $\phi_n(0) = 89.2^\circ$ (Real-space *n*-spin trajectory)

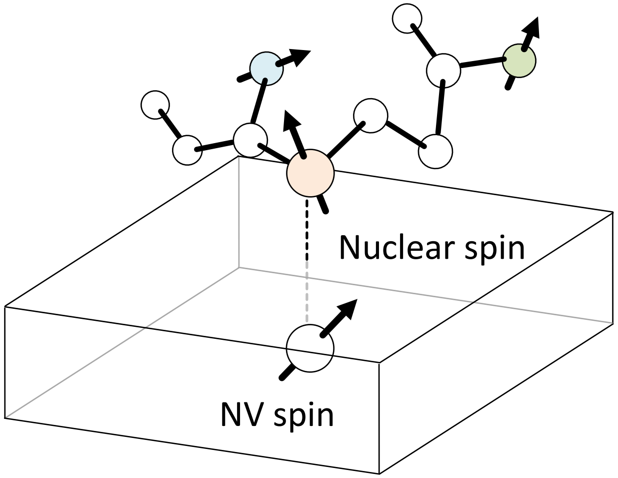
→ $\phi = 247.8 \pm 4.1^\circ$

Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.*

# Toward single-molecular imaging

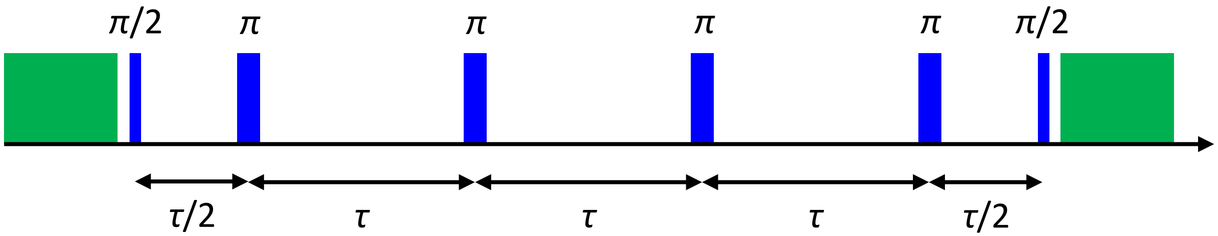
- **Information of the positions of the individual nuclei**
  - → Accurate measurement of *e*–*n* int. const's ($A_\parallel$, $A_\perp$) ≈ ($r$, $\theta$)
  - → Lack of information on the azimuthal angle $\phi$

- **Spectral resolution**
  - → Easy to resolve isotopes
  - → Need to measure *J*-couplings & chemical shifts (ppm!)
  - → Limited by sensor/memory lifetimes ($T_{2e/n}$, $T_{1e/n}$)



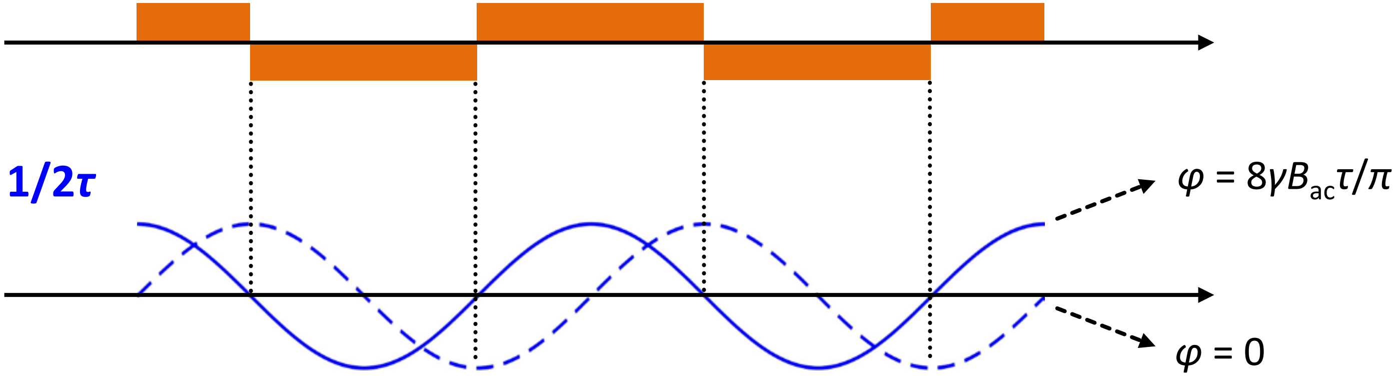
# AC magnetometry

**CP (*N* = 4)**



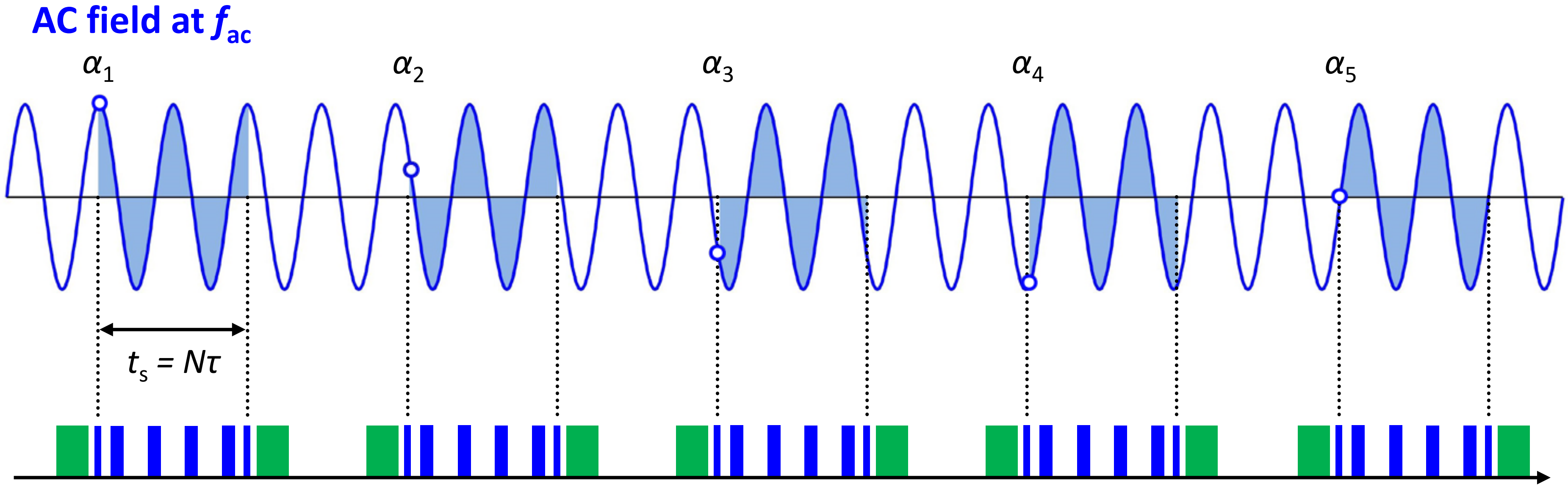
**Modulation function**

**AC field at $f_{ac} = 1/2\tau$**



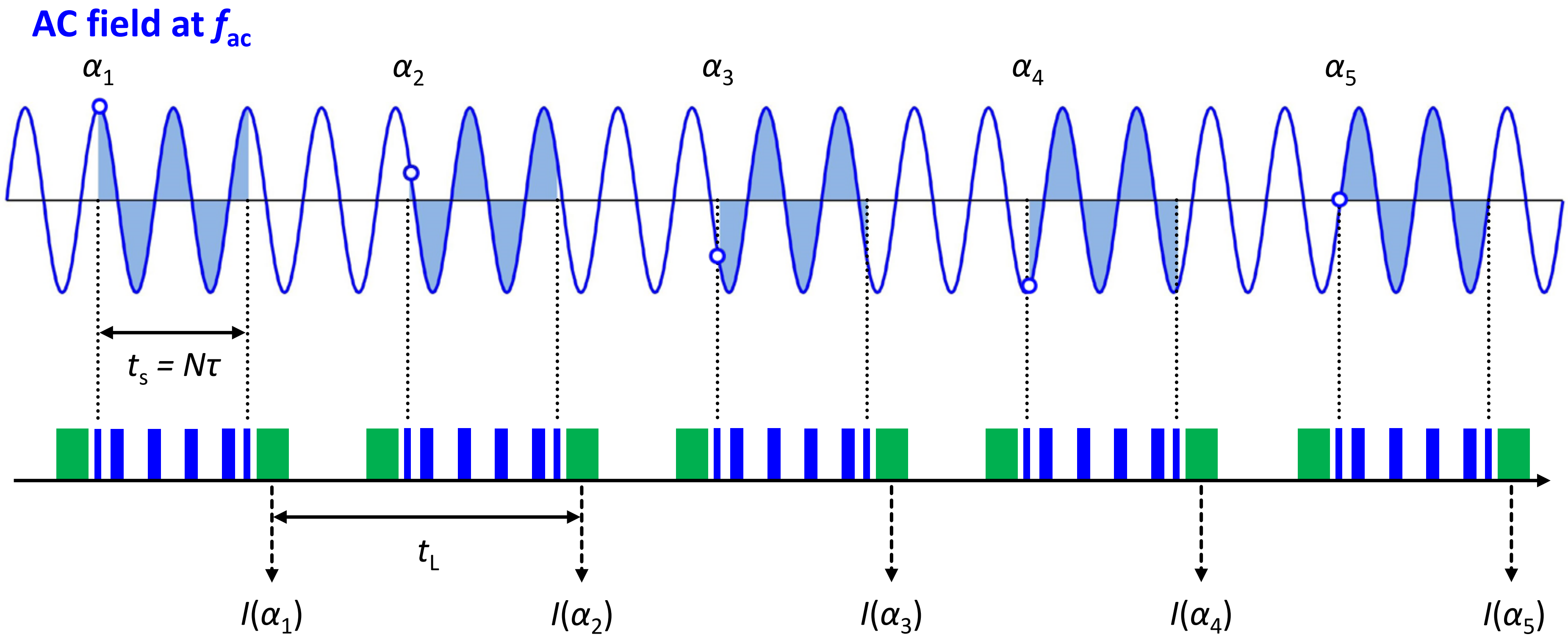
- $\varphi$ depends on the **initial phase $\alpha$ of the AC field** ($\varphi \propto \cos\alpha$)

# AC magnetometry



- $\varphi$ depends on the **initial phase** $\boldsymbol{\alpha}$ **of the AC field** ($\varphi \propto \cos\alpha$)
- Average over **random** $\boldsymbol{\alpha}$

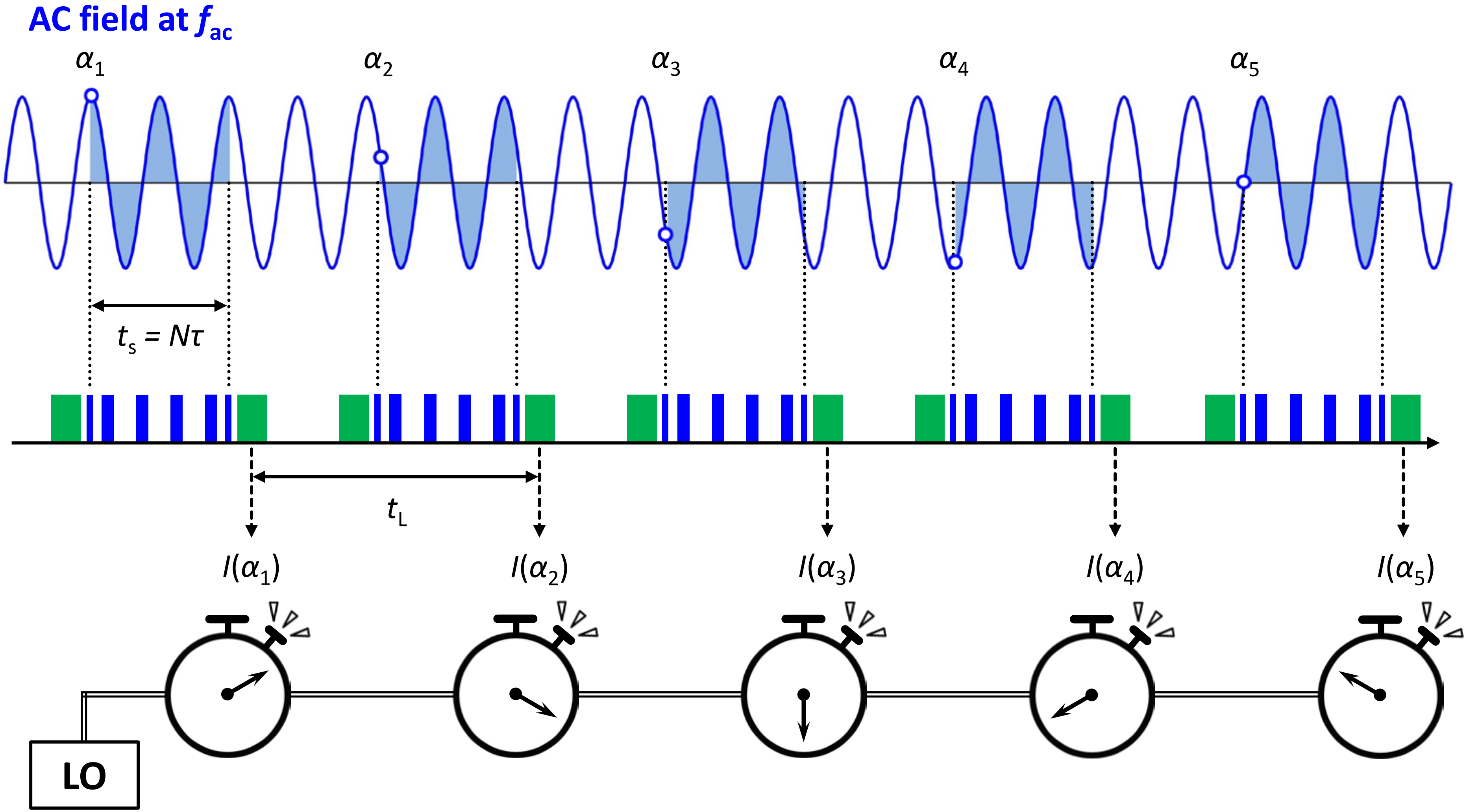
# Ultrahigh resolution sensing



- $\varphi$ depends on the **initial phase $\boldsymbol{\alpha}$ of the AC field** ($\varphi \propto \cos \alpha$)
- Average over **random $\boldsymbol{\alpha}$**
- **If the data acq. is periodic,** adjacent $\alpha$'s are related by $\alpha_{k+1} = 2\pi f_{ac} t_L + \alpha_k$

Science **356**, 832 (2017) Schmitt *et al.*; Science **356**, 837 (2017) Boss *et al.*; Nature **555**, 351 (2018) Glenn *et al.*

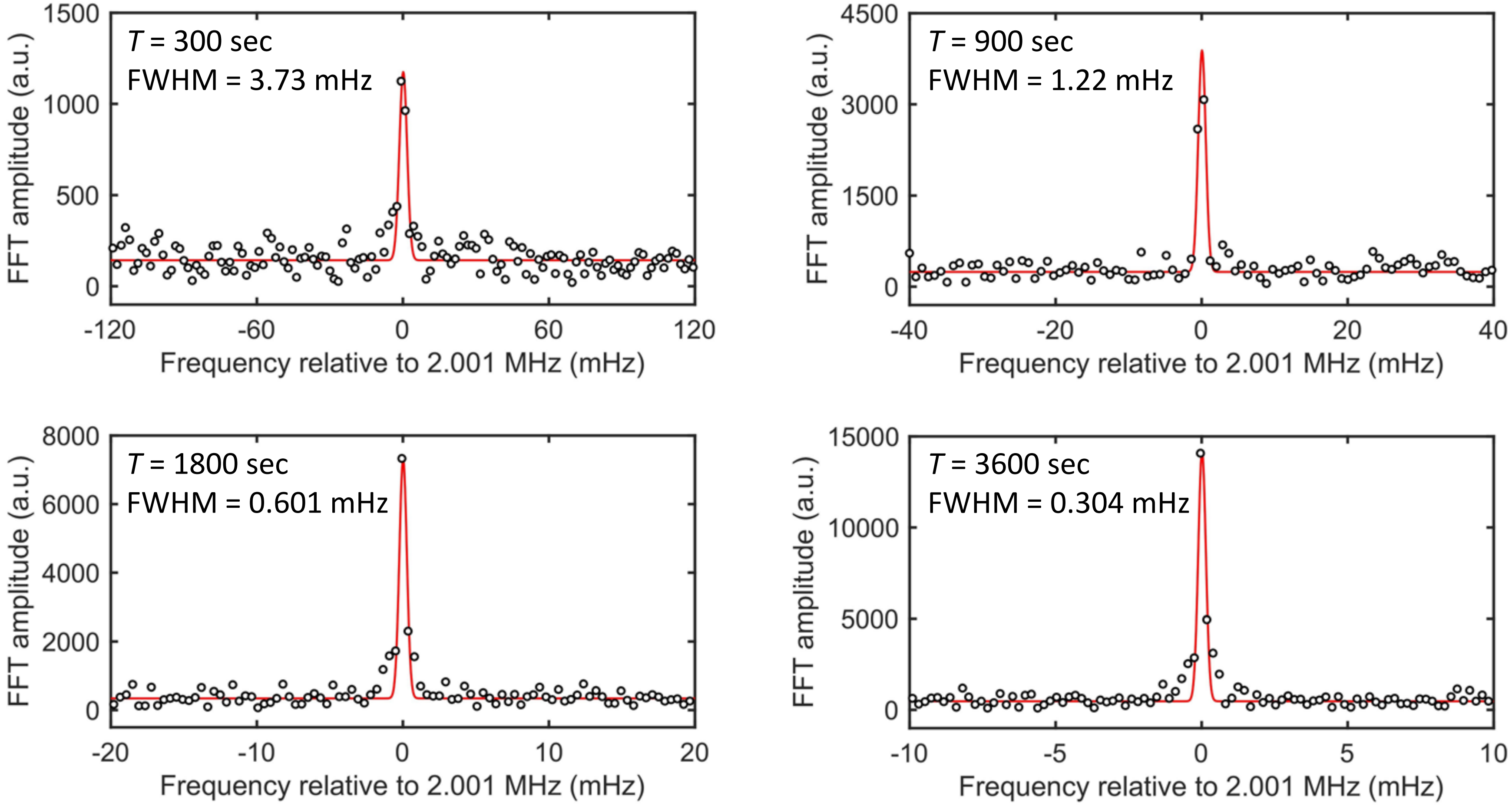
# Ultrahigh resolution sensing



Science **356**, 832 (2017) Schmitt *et al.*; Science **356**, 837 (2017) Boss *et al.*; Nature **555**, 351 (2018) Glenn *et al.*

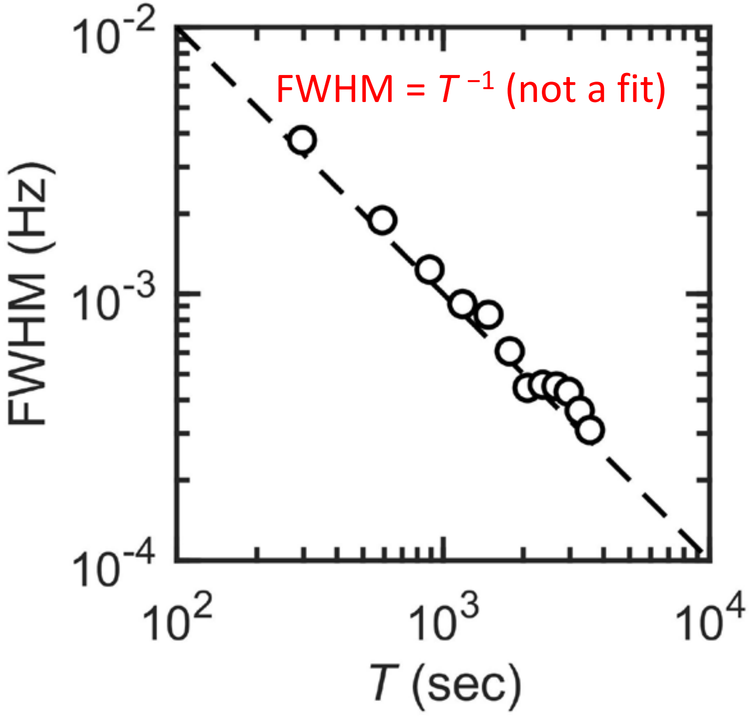
# Ultrahigh resolution sensing

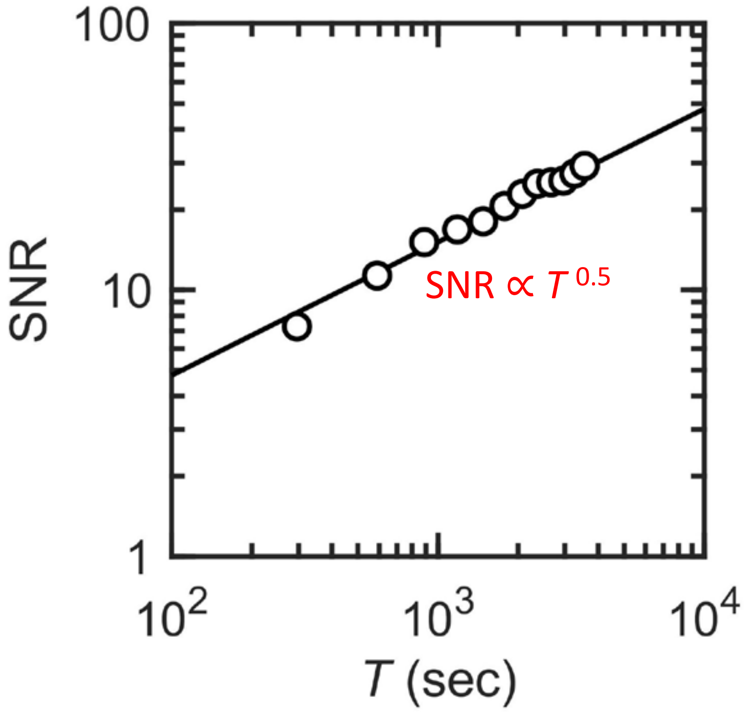
**$B_{ac}$ = 96.5 nT & $f_{ac}$ = 2.001 MHz applied from a coil, detected by a single NV center**



J. Appl. Phys. **123**, 161101 (2018) Abe & Sasaki

# Ultrahigh resolution sensing



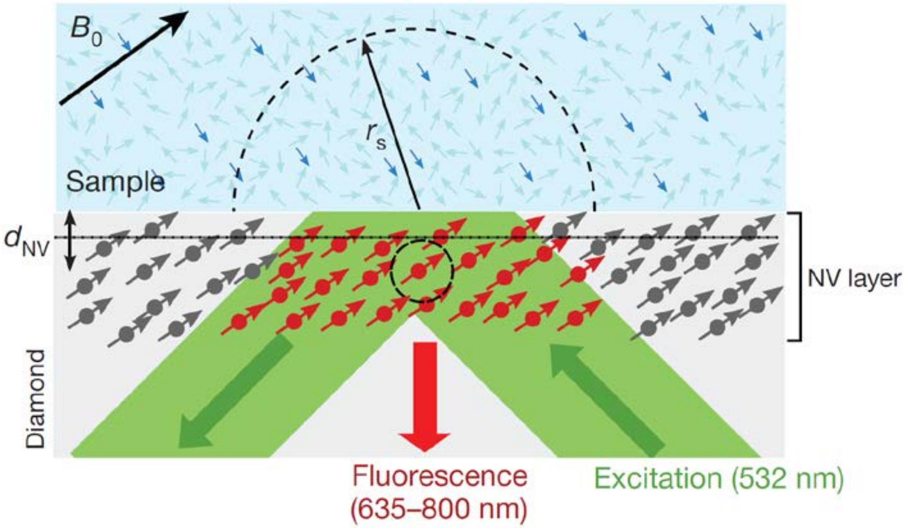


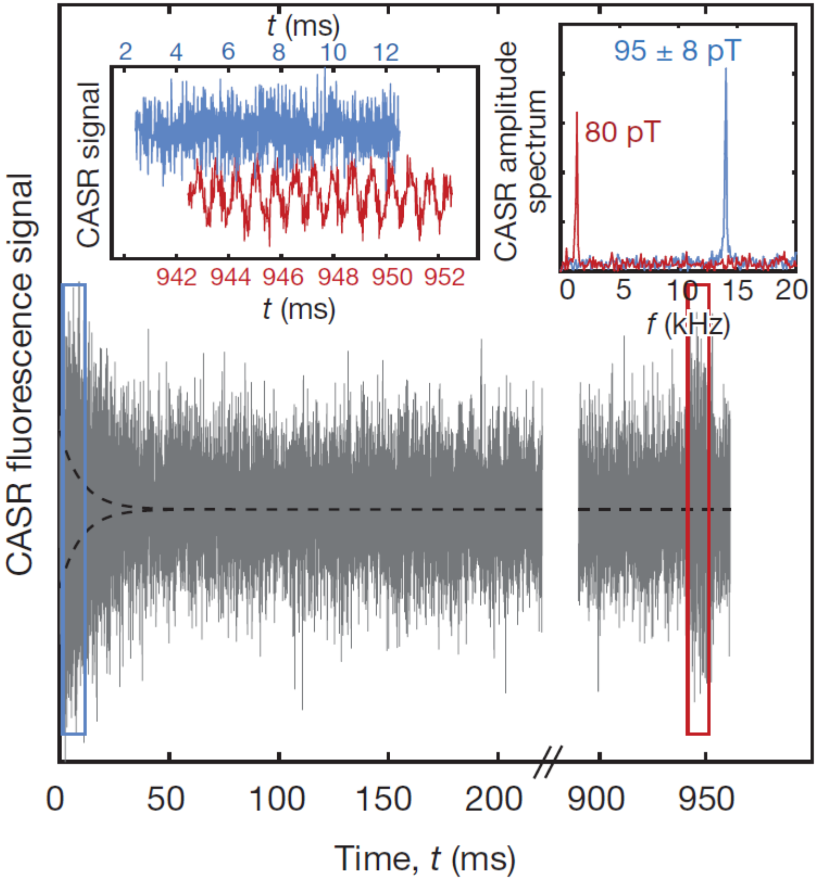
- Spectral resolution not limited by sensor/memory lifetimes ($T_{2e/n}$, $T_{1e/n}$)
- Only limited by the stability of LO (essentially infinite)
- Resolution = $T^{-1}$ & SNR ∝ $T^{0.5}$ → Precision ∝ $T^{-1.5}$

J. Appl. Phys. **123**, 161101 (2018) Abe & Sasaki

# NMR spectroscopy

Data from Harvard: Nature **555**, 351 (2018) Glenn *et al.*



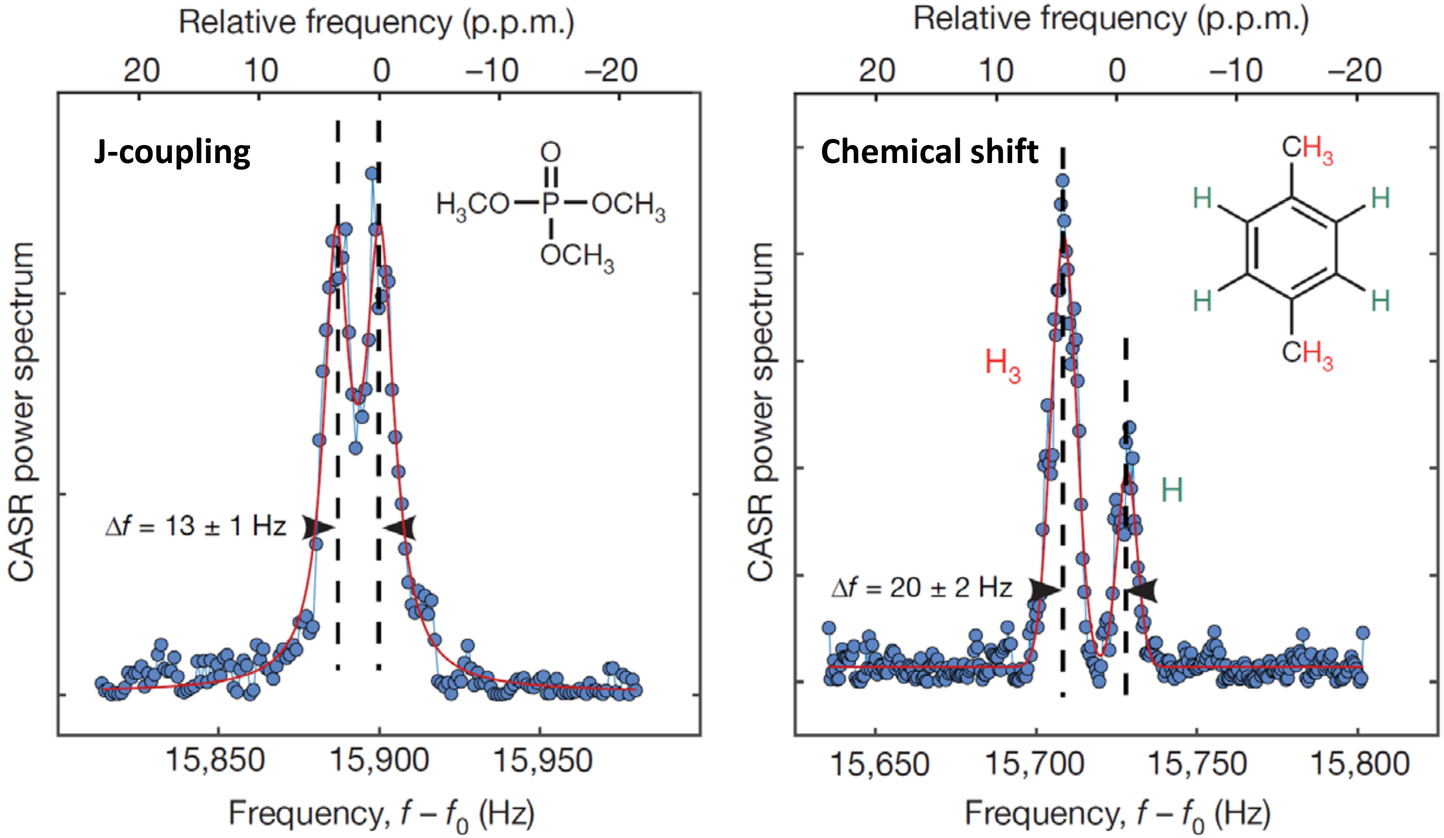


- $[NV] \approx 3 \times 10^{17}$ cm$^{-3}$
- # of NV ≈ $5 \times 10^9$
- $V_{detect} \approx 25$ pL
- # of protons ≈ $2.5 \times 10^{15}$
- RF pulse → FID

See also: Science **357**, 67 (2017) Aslam *et al.* (Wrachtrup, Stuttgart)
[$B_0 = 3$ T, $f_e = 87$ GHz, $T_{1n} = 260$ s]

# NMR spectroscopy

Data from Harvard: Nature **555**, 351 (2018) Glenn *et al.*



See also: Science **357**, 67 (2017) Aslam *et al.* (Wrachtrup, Stuttgart)
[$B_0$ = 3 T, $f_e$ = 87 GHz, $T_{1n}$ = 260 s]

# Summary

- **Tools for single-molecule imaging/structural analysis are being developed**
  - → Determination of the position of individual *n*-spins[1,2,3]
  - → Ultrahigh resolution sensing[4,5,6], resolving chemical shifts[6,7] & suppression of backaction from *n*-spins[8,9]

[1] Phys. Rev. B **98**, 121405 (2018) Sasaki *et al.* (Keio)
[2] Phys. Rev. Lett. **121**, 170801 (2018) Zopes *et al.* (ETH)
[3] Nature **576**, 411 (2019) Abobeih *et al.* (Delft)
[4] Science **356**, 832 (2017) Schmitt *et al.* (Ulm)
[5] Science **356**, 837 (2017) Boss *et al.* (ETH)
[6] Nature **555**, 351 (2018) Glenn *et al.* (Harvard)
[7] Science **357**, 67 (2017) Aslam *et al.* (Stuttgart)
[8] Nature Commun. **10**, 594 (2019) Pfender *et al.* (Stuttgart)
[9] Nature **571**, 230 (2019) Cujia *et al.* (ETH)