Quantum Nature Based Detection of Signals Free of Classical Noise

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Outline

- Exotic interaction beyond standard model

- The Nitrogen-Vacancy (NV) Center in Diamond

- Quantum Nature Based Detection-Quantum Correlation

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- Exotic interaction beyond standard model

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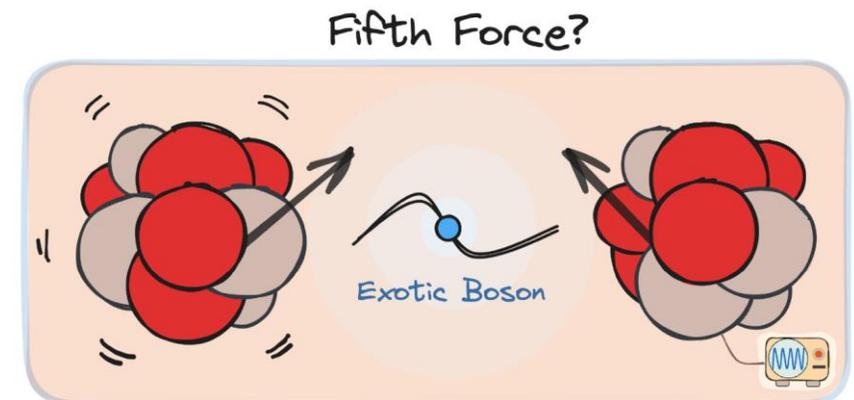- Quantum Nature Based Detection-Quantum Correlation

Exotic Interactions

- **Motivation: Beyond the Standard Model**
  - The Standard Model is highly successful but incomplete (e.g., Dark Matter, Dark Energy, Strong CP problem).
  - The "Dark Things": New physics may be hidden in light, weakly coupled particles (e.g., Axions, ALPs, Dark Photons, Exotic Bosons).

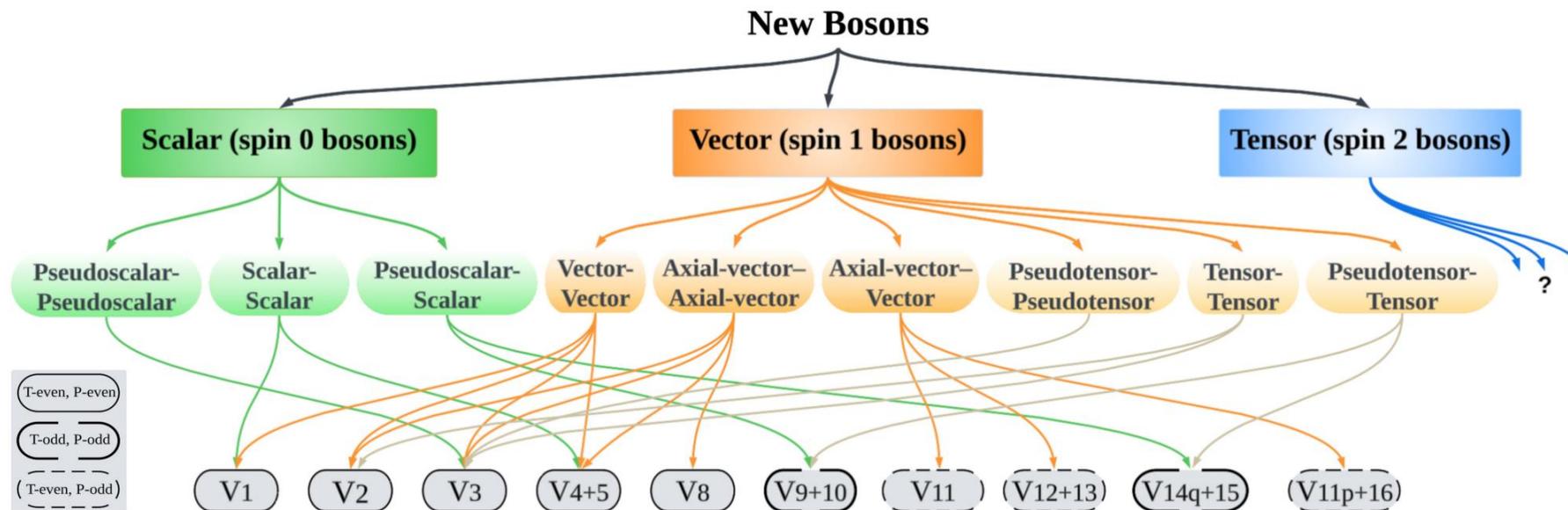- **The "Fifth Force" Hypothesis**
  - Exchange of these new bosons induces exotic spin-dependent interactions between fermions.
  - Manifests as a short-range correction to gravity or electromagnetism.

Fifth Force?

Exotic Boson

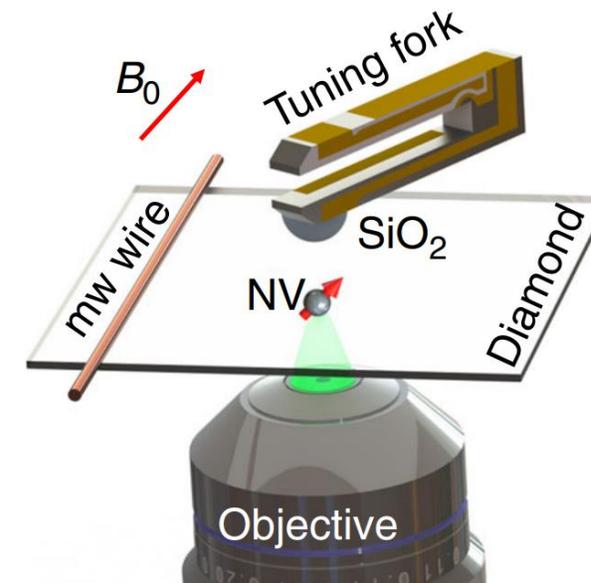Cong et al., (2025). Spin-dependent exotic interactions. *Rev. Mod. Phys., 97, 025005.*

Exotic interactions

- 16 independent potentials ($V_1 \cdots V_{16}$) derived from symmetry principles (Dobrescu & Mocioiu)

- Many potentials (e.g., V_{4+5}, monopole-dipole) are strictly constrained at macro-scales but poorly explored at the micro-scale.

Cong et al., (2025). Spin-dependent exotic interactions. *Rev. Mod. Phys., 97, 025005.*

Exotic interactions

- **The Challenge: Short-Range & Complex Couplings**
  - Short-Range: Existing constraints are weak at the submillimeter scale.
  - Complex Couplings: Target interactions involve spin and relative velocity terms.

- **The Solution: Table-top System**
  - Single NV Center: Acts as a localized quantum spin sensor

Rong *et al.,* Searching for an exotic spin-dependent interaction with a single electron-spin quantum sensor. *Nat Commun* **9**, 739 (2018)

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The NV Center in Diamond

NV:

- point defect in diamond

Composition:

- 1 vacancy + 1 substitutional nitrogen
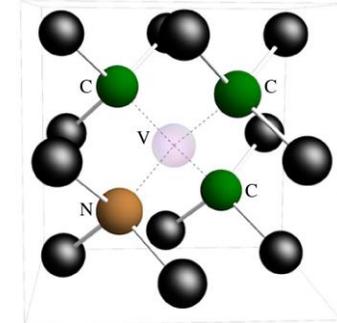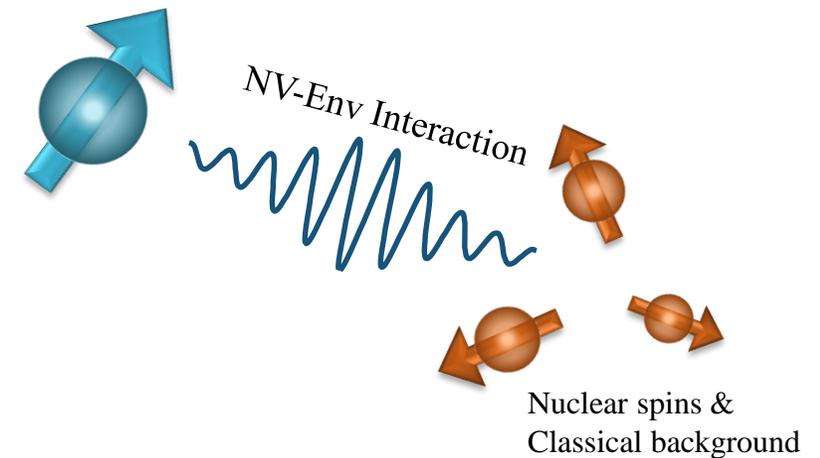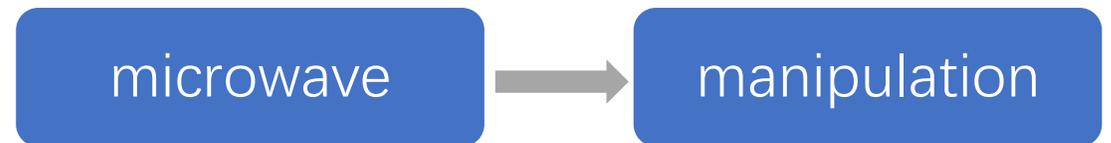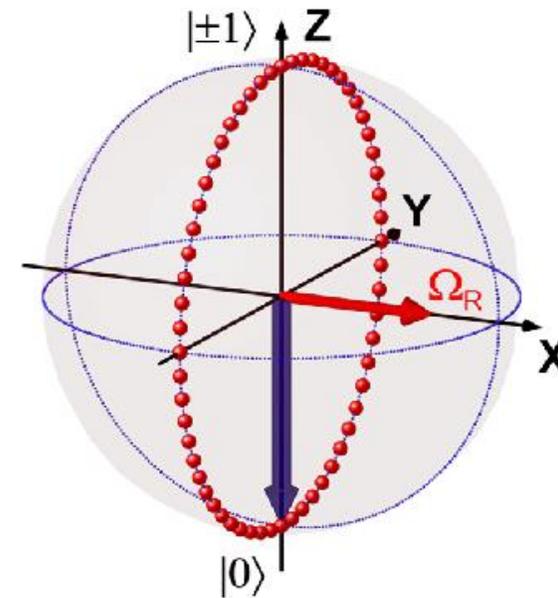
Spin-1 system:
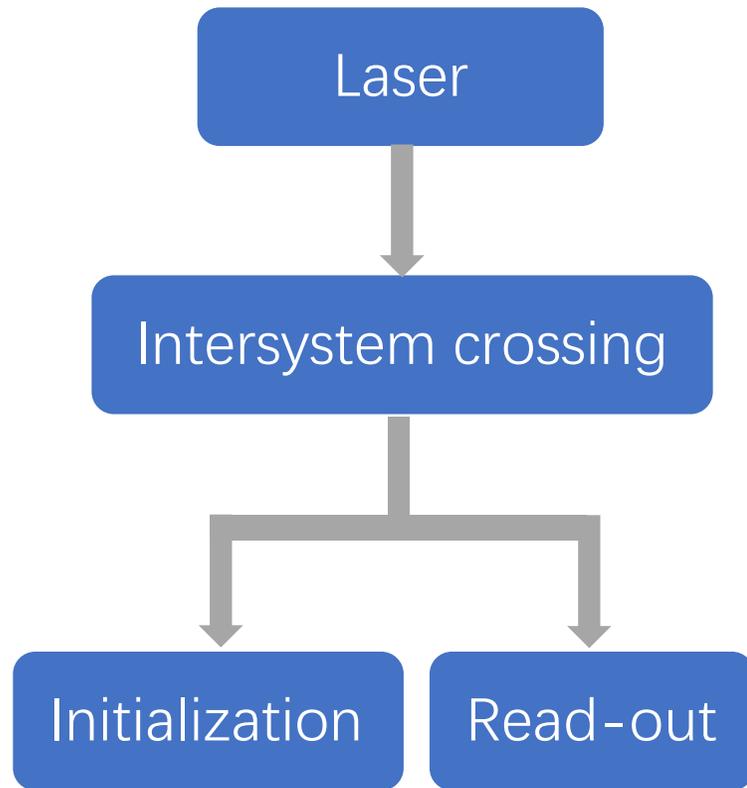
- extra electron -> NV$^-$ -> S = 1

Figure from Doherty M W, Manson N B, Delaney P, et al. The nitrogen-vacancy colour centre in diamond[J]. Physics Reports, 2013, 528(1): 1-45.
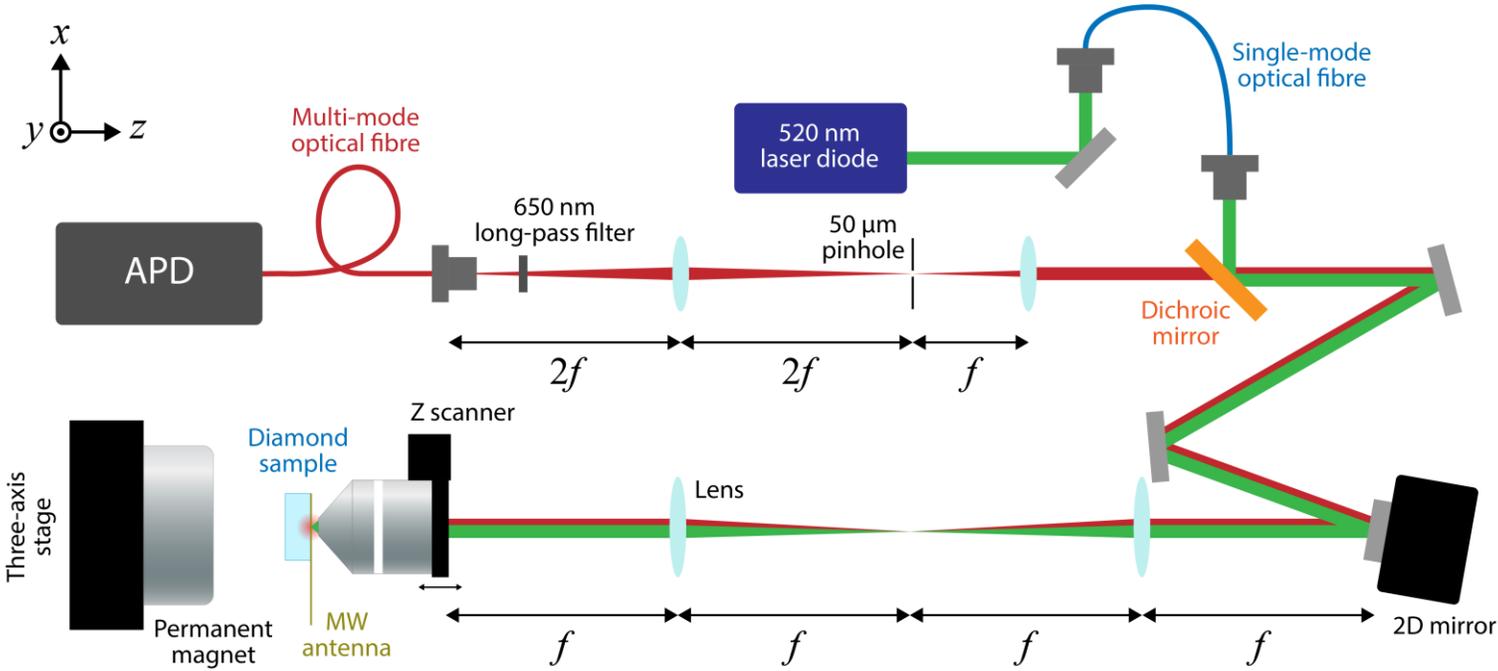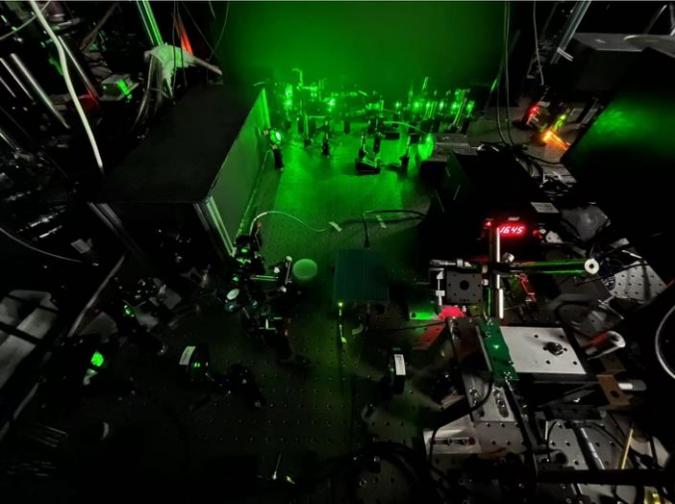

NV center

NV-Env Interaction

Nuclear spins & Classical background

The NV Center in Diamond

Laser

↓

Intersystem crossing

↓

Initialization   Read-out

microwave → manipulation

The NV Center in Diamond

Experiment Setup

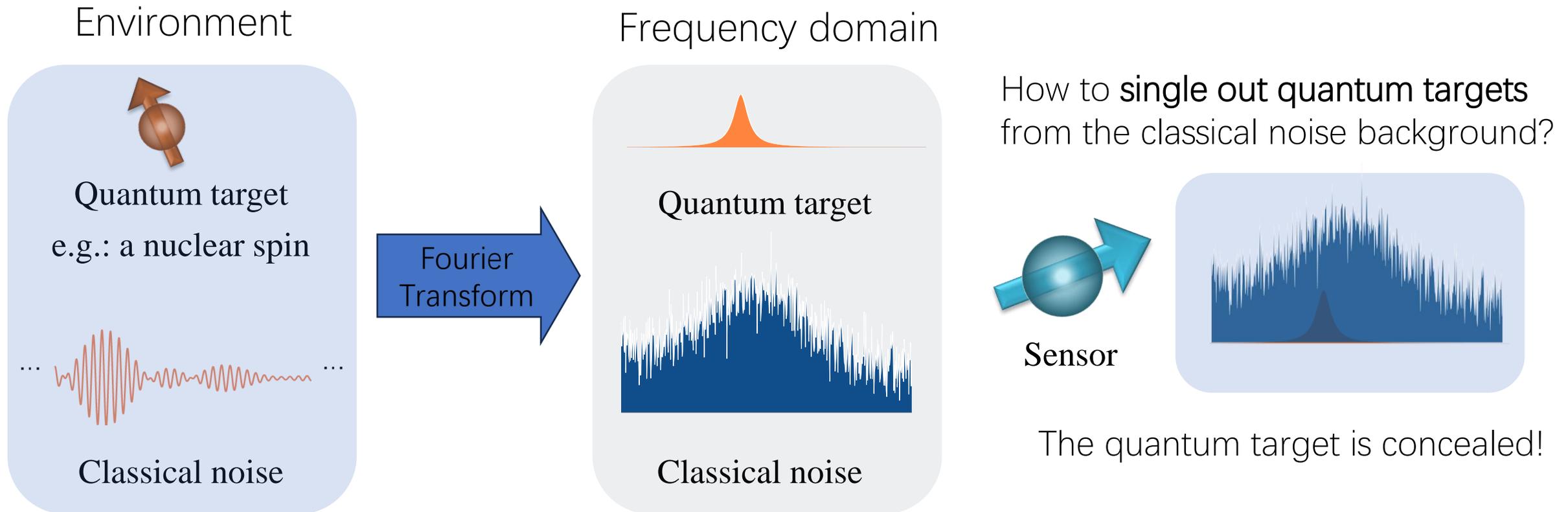- Room temperature
- Ambient pressure

Outline

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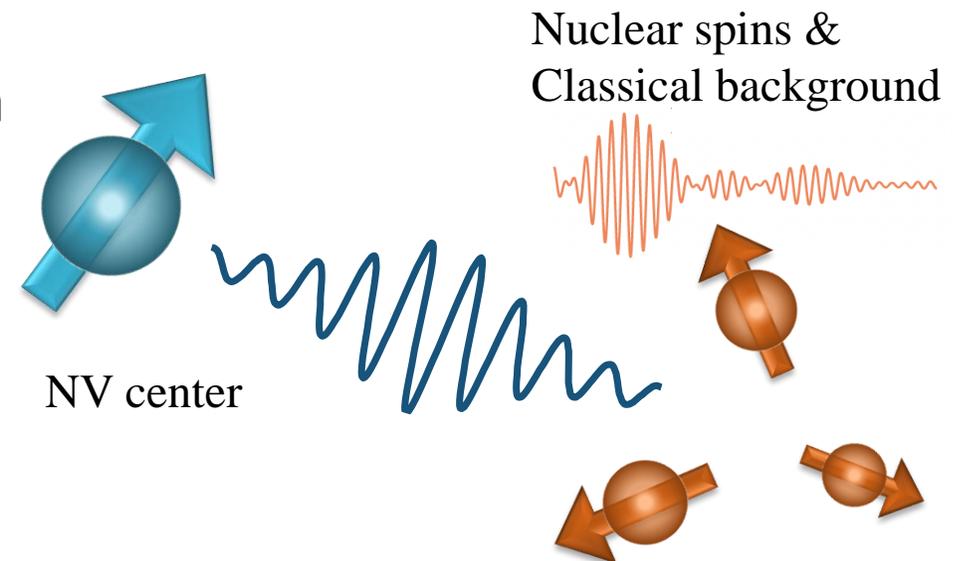- Quantum Nature Based Detection-Quantum Correlation

Quantum Signal Distillation

- Why we need Quantum Signal Distillation?

Environment

Quantum target
e.g.: a nuclear spin

Classical noise

Fourier
Transform

Frequency domain

Quantum target

Classical noise

How to **single out quantum targets** from the classical noise background?

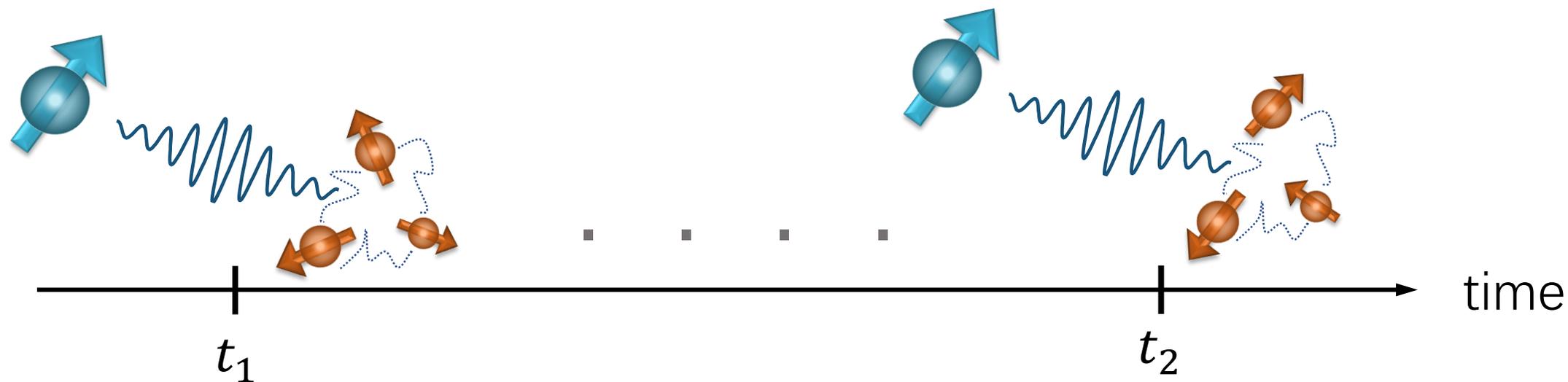Sensor

The quantum target is concealed!

Quantum Signal Distillation, how?

- **Add a quantum dimension to the sensing technology**
  - Single out quantum signals from a classical background

- **Based on Correlation**
  - Extend resolution from T2 to T1 limitation
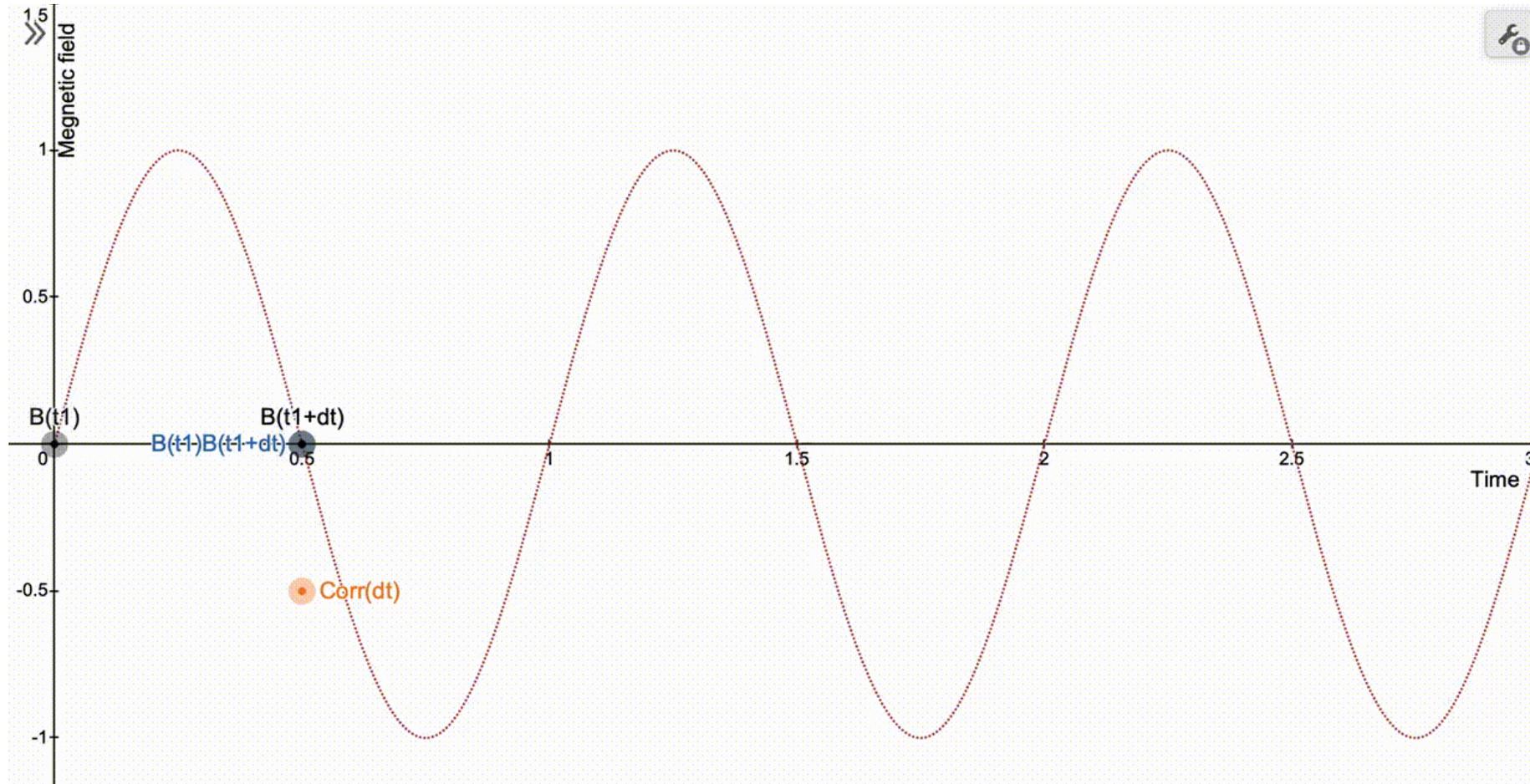 - Read out nuclear spins simultaneously

Nuclear spins &
Classical background

NV center

2nd-order classical Correlation
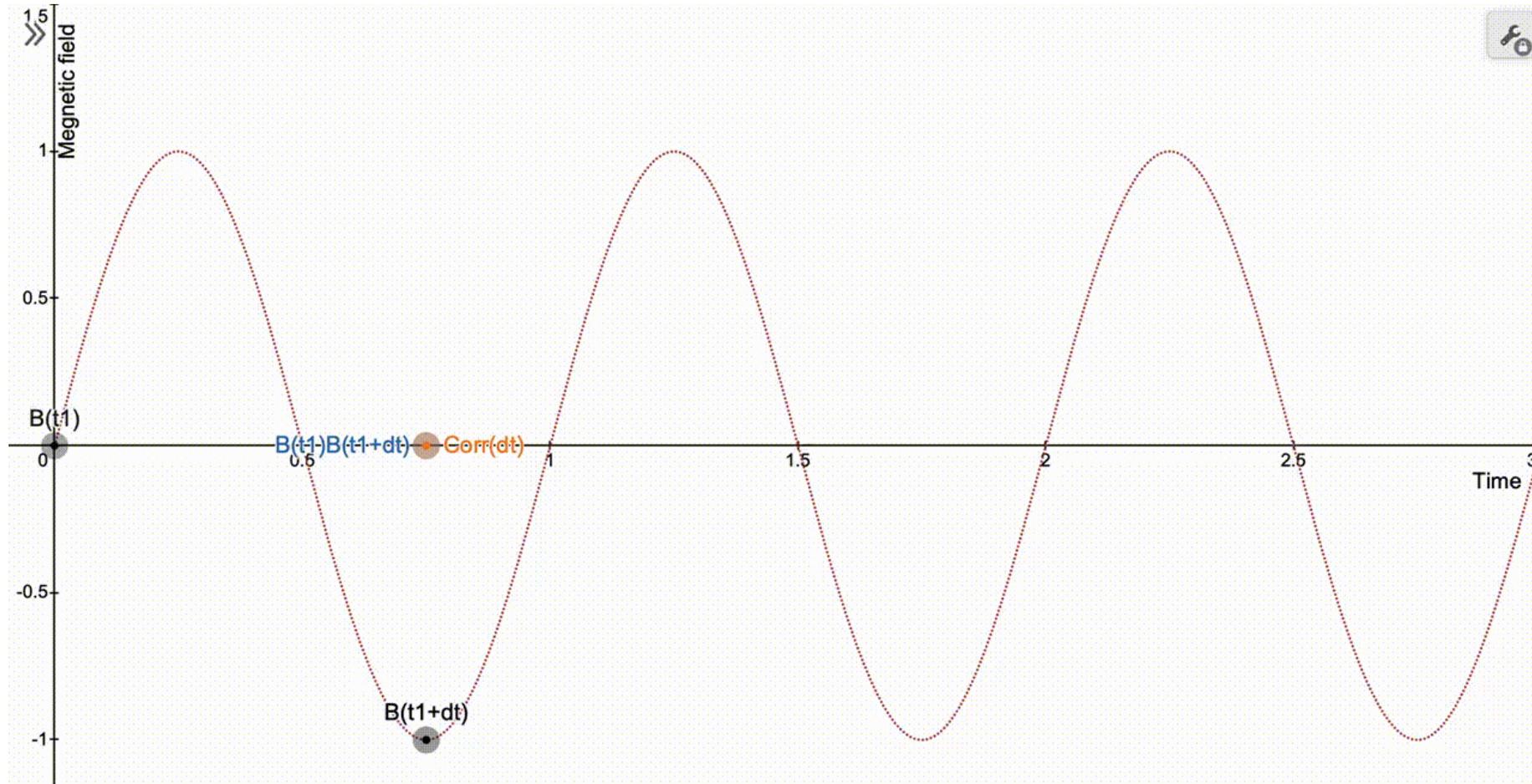
Second-order Correlation (autocorrelation):

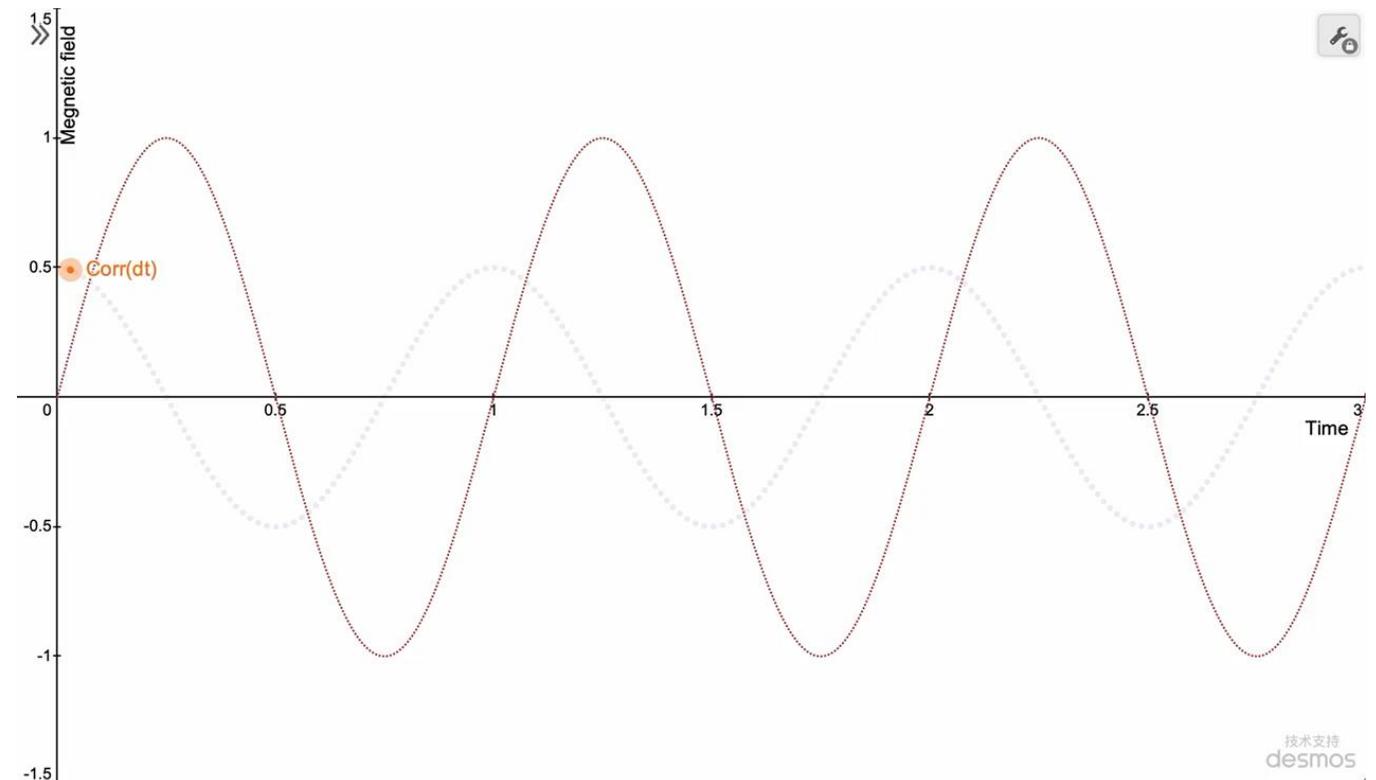$$S(dt) =: \langle B_z(t_2)B_z(t_1) \rangle_{t_1} ; \quad dt = t_2 - t_1$$

Shen et al. *Phys. Rev. Lett., 130, 070802.*

The Correlation Signal : dt = 0.5T

The Correlation Signal : dt = 0.75T

Properties of the classical Correlation

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▶1. The correlation is a function of the time interval.

▶2. The correlation of a periodic function is, itself, periodic with the same period.

▶3. The correlation of multiple signals can be added up linearly, for e.g. several ^{13}C spins with different frequencies.

Noise operator instead of classical signals

time

t_1 t_2

Second-order Correlation:

$$S(dt) =: \langle \widehat{\boldsymbol{B}}_z(t_2) \widehat{\boldsymbol{B}}_z(t_1) \rangle_{t_1} ; \quad dt = t_2 - t_1$$
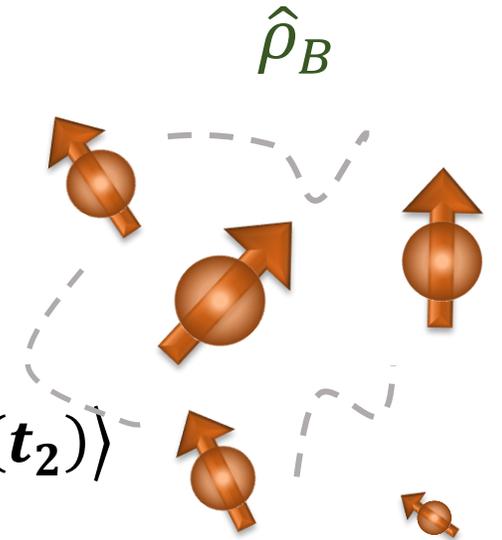
Scalar -> Operator

Adding a quantum dimension

Separate $\langle \hat{B}_z(t_2)\hat{B}_z(t_1) \rangle$ into two parts

- One is classical correspondence

$$S_c(t_2, t_1) = \frac{1}{2}\langle \{\hat{B}_z(t_2), \hat{B}_z(t_1)\} \rangle =: \frac{1}{2}\langle \hat{B}_z(t_2)\hat{B}_z(t_1) + \hat{B}_z(t_1)\hat{B}_z(t_2) \rangle$$

$\hat{\rho}_B$

- One is purely quantum

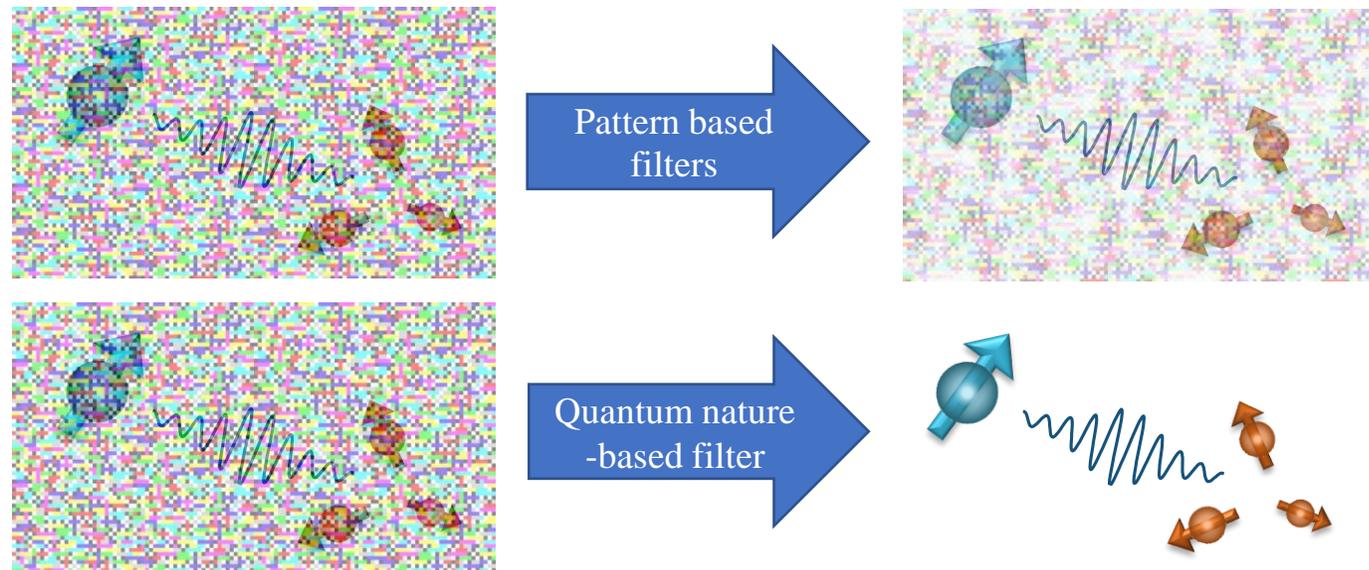$$S_Q(t_2, t_1) = \frac{1}{2i}\langle [\hat{B}_z(t_2), \hat{B}_z(t_1)] \rangle =: \frac{1}{2i}\langle \hat{B}_z(t_2)\hat{B}_z(t_1) - \hat{B}_z(t_1)\hat{B}_z(t_2) \rangle$$

Quantum Signal Distillation

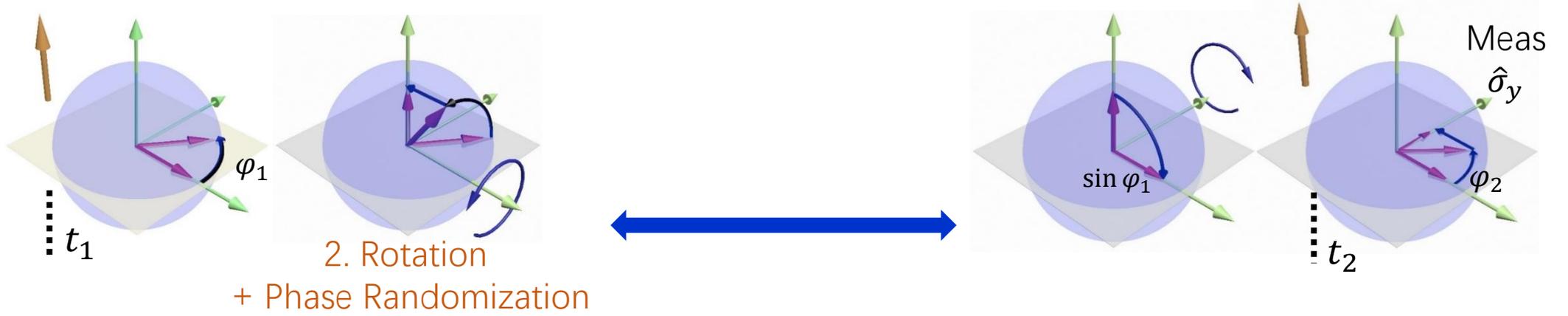$S_Q(t_2, t_1) = \frac{1}{2i}\langle[\hat{B}_z(t_2), \hat{B}_z(t_1)]\rangle$ vanishes when,

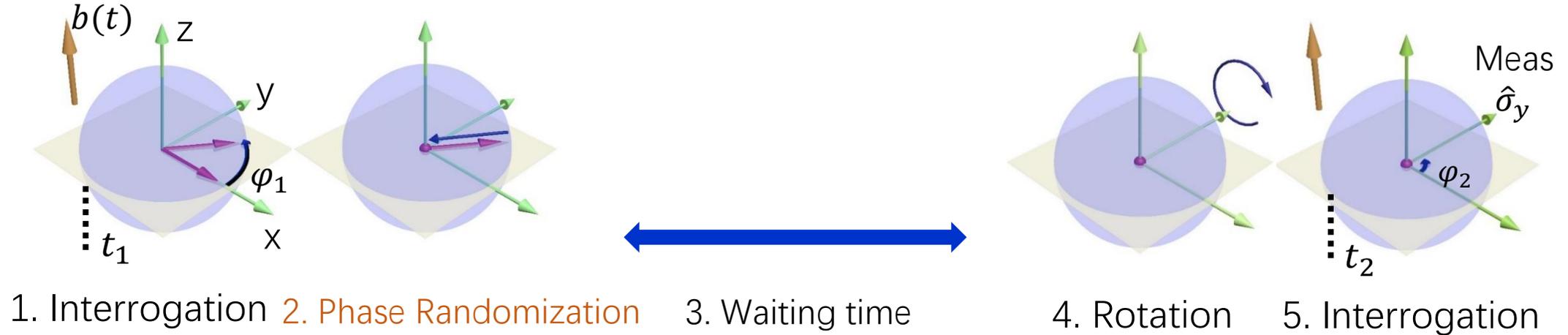$\hat{B}_z(t)$ **commutes with itself** at any time

Pattern based filters

Quantum nature -based filter

Quantum Correlation

1. Interrogation 2. Phase Randomization 3. Waiting time 4. Rotation 5. Interrogation

Classical Correlation

2. Rotation
+ Phase Randomization

The quantum correlation signal from quantum theory

Quantum Correlation

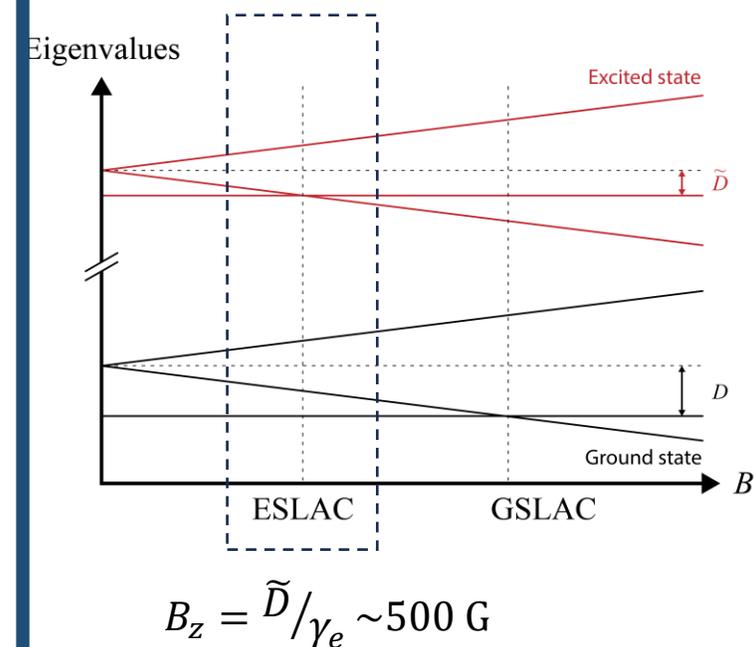1. Interrogation   2. Phase Randomization   3. Waiting time   4. Rotation   5. Interrogation
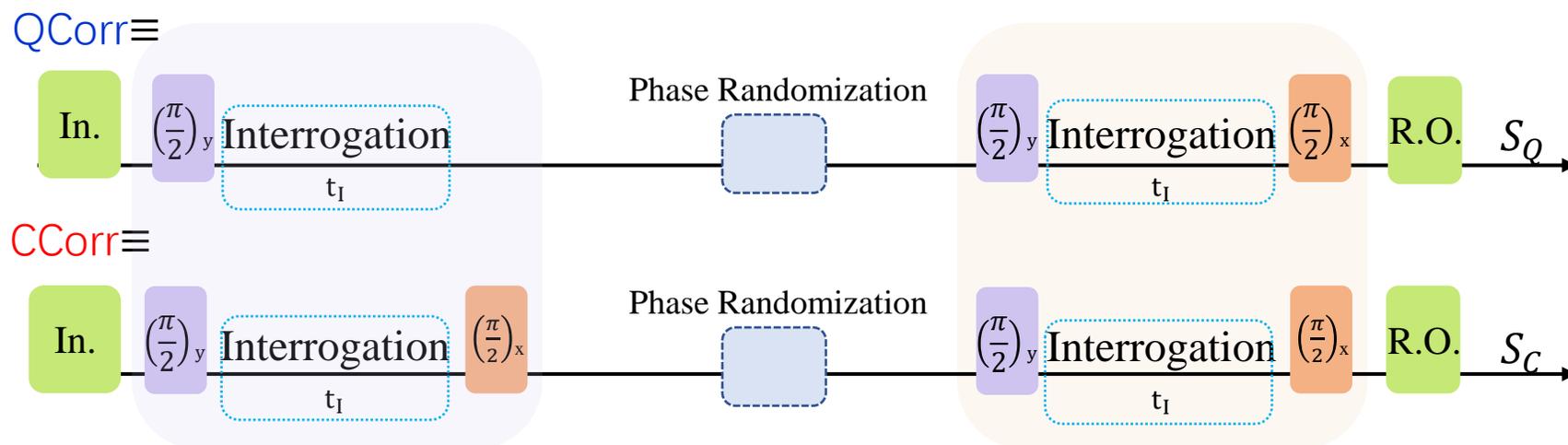
The entanglement between the sensor and the bath leads to the result:

$$S_Q \approx -i\langle[\hat{\varphi}_2, \hat{\varphi}_1]\rangle/2$$

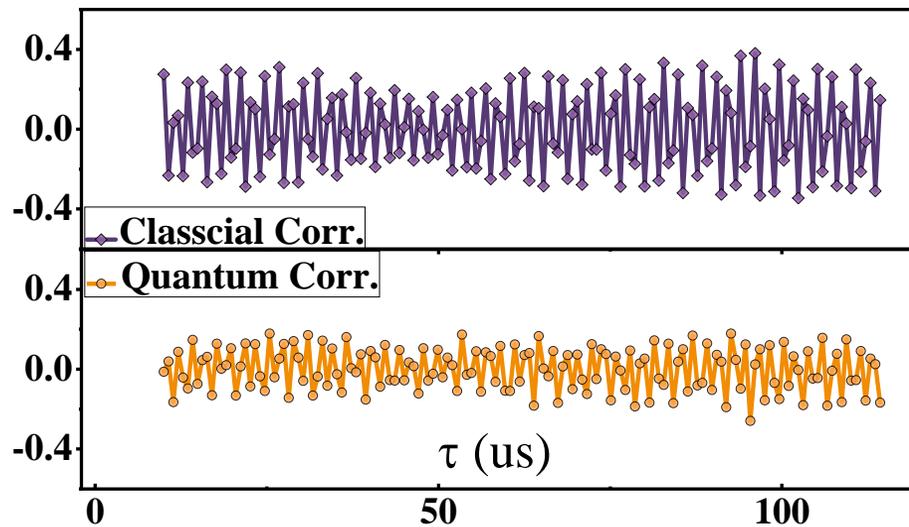For a single nuclear spin, S_Q is proportional to its polarization

$$S_Q \sim P_z$$

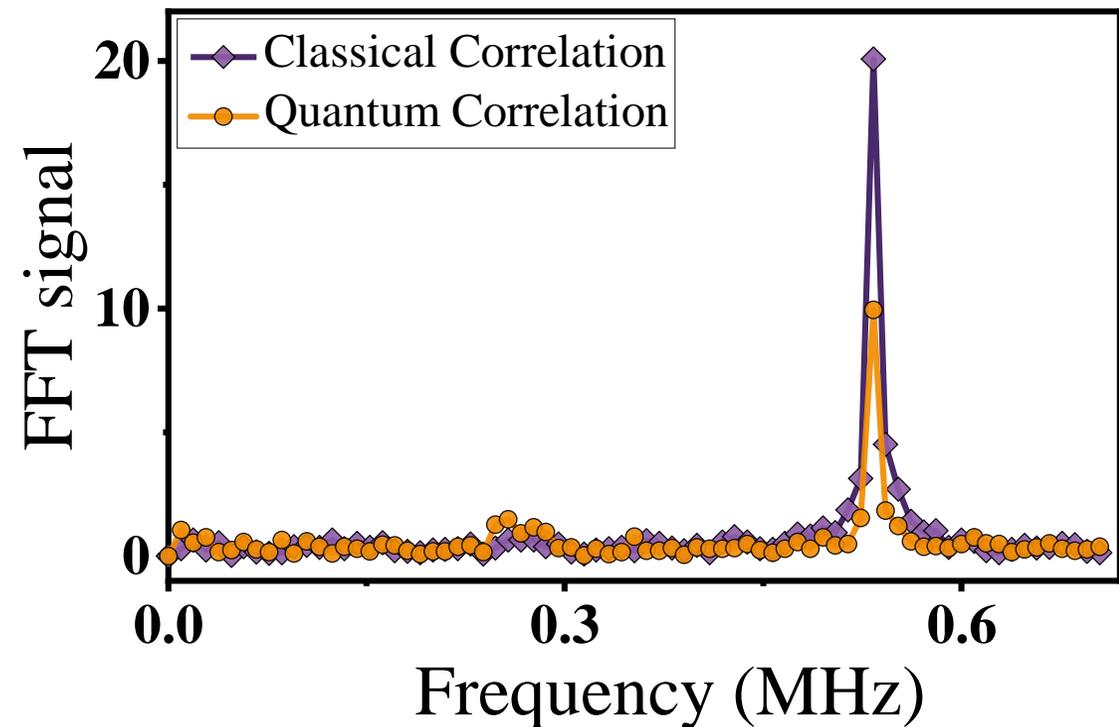# Measurement of the Correlation signals

QCorr ≡

CCorr ≡

$$B_z = \widetilde{D}/\gamma_e \sim 500 \text{ G}$$

Correlation signals of a single nuclear spin

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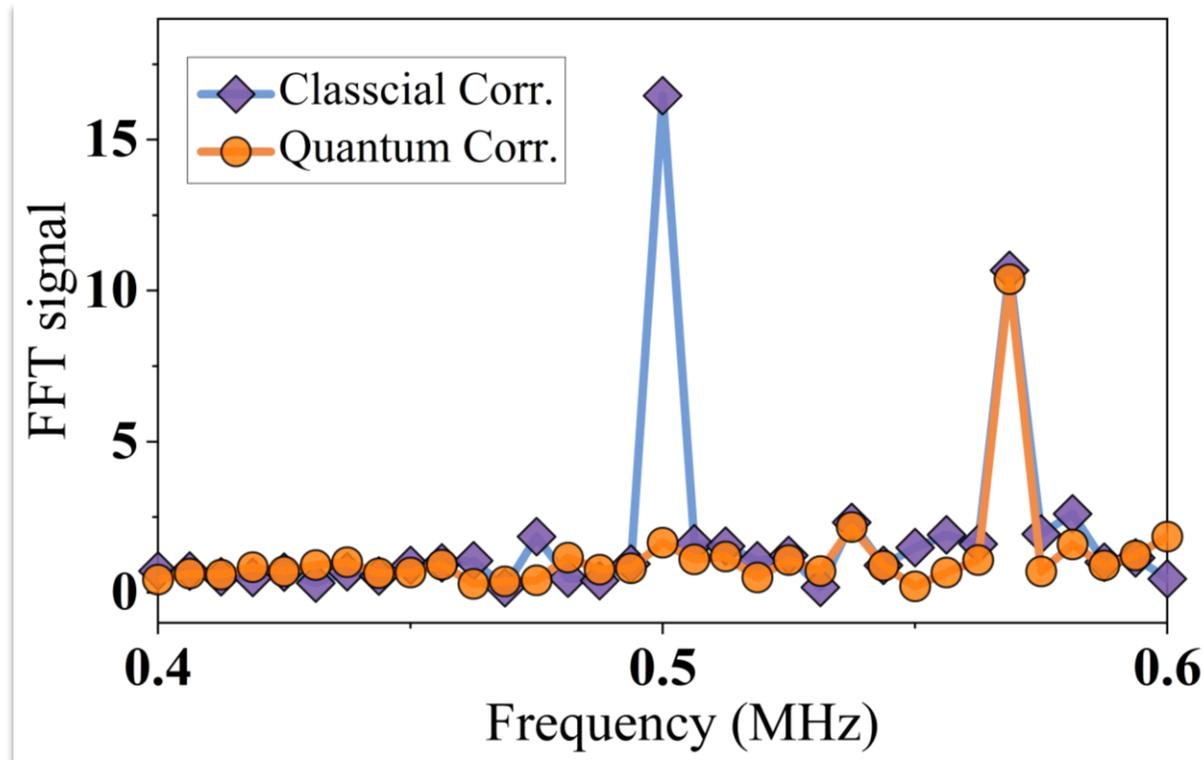UNIVERSITY OF SCIENCE
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Correlation signals in time domain

Correlation spectrums after Fourier Transform

Correlation Spectrums of a single nuclear spin together with a 0.5 MHz microwave
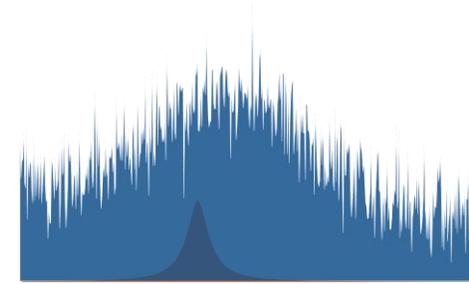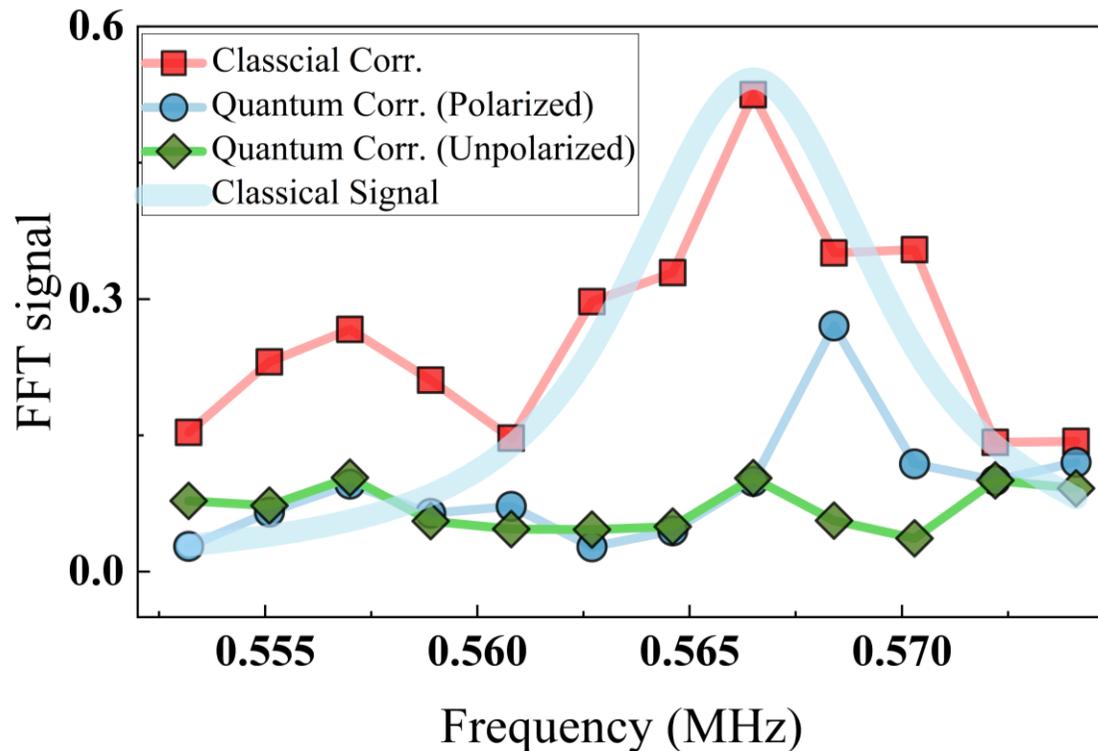
▶Classical correlation:

Both the target ^{13}C nuclear spin signal and the classical background occur

▶Quantum correlation:

Only the ^{13}C nuclear spin signal exists

Quantum Signal Distillation

▶Classical correlation:

The classical noise conceals the target ^{13}C nuclear spin signal.

▶Quantum correlation:

The ^{13}C nuclear spin signal can still be detected if it is polarized.

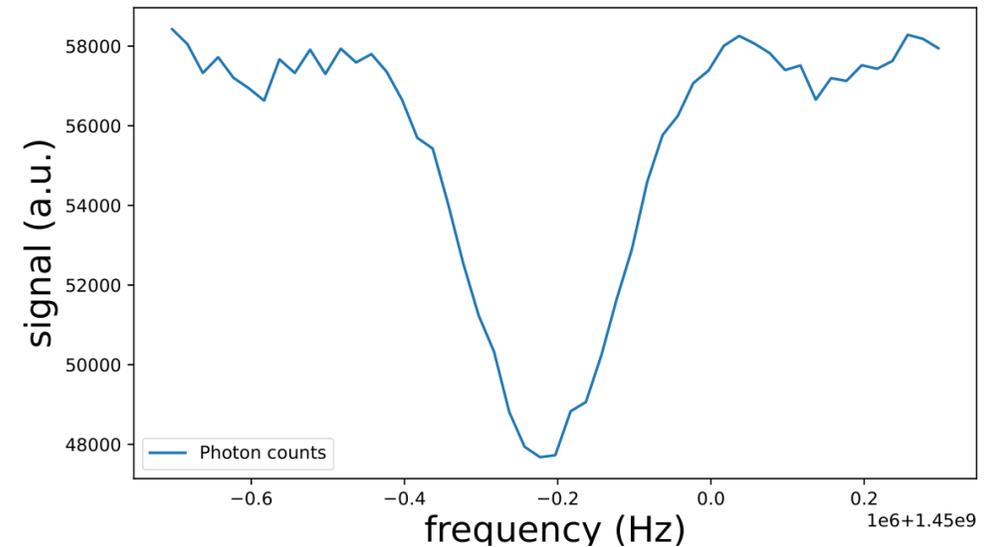# Acknowledgements

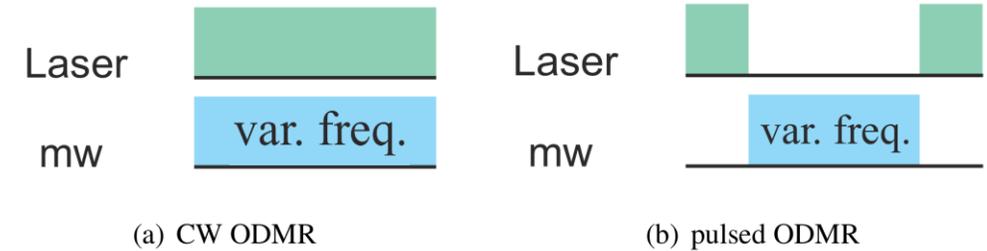- Thank you all!

杨森教授课题组（港科大）

王评教授（北师大珠海校区）

The NV Center in Diamond

Manipulations of NV as a qubit

- Optically Detected Magnetic Resonance(ODMR)

    - To determine the transition frequency between its spin-up and down states

(a) CW ODMR   (b) pulsed ODMR

The NV Center in Diamond

Manipulations of NV as a qubit

- Rabi Oscillation

  - To implement rotation gates on the NV qubit

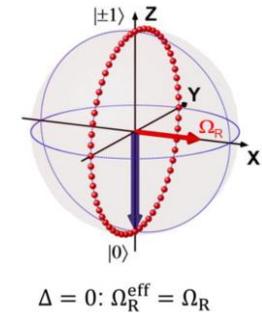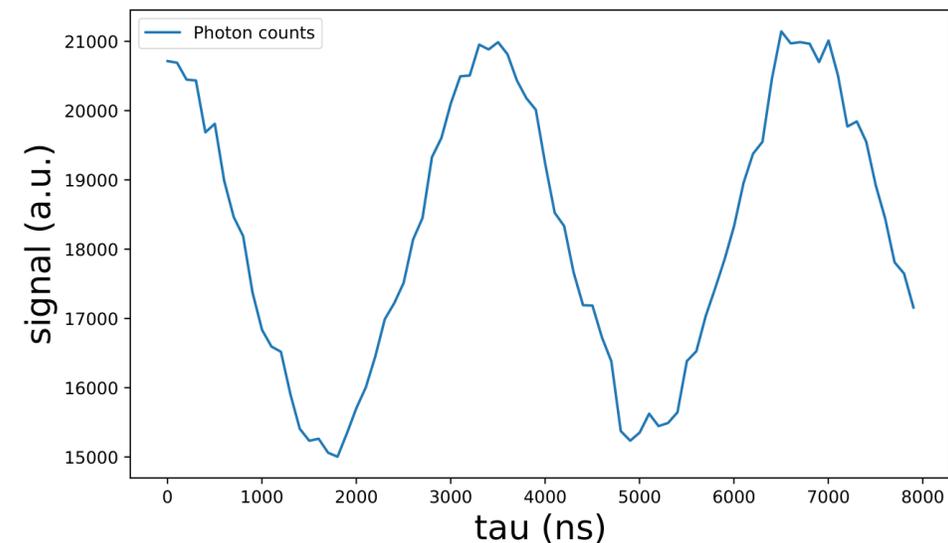$$\Delta = 0: \Omega_R^{eff} = \Omega_R$$

Figure from Yang Y, Vallabhapurapu H H, Sewani V K, et al. Observing hyperfine interactions of NV− centers in diamond in an advanced quantum teaching lab[J]. American Journal of Physics, 2022, 90(7): 550-560.
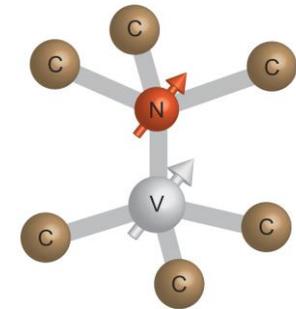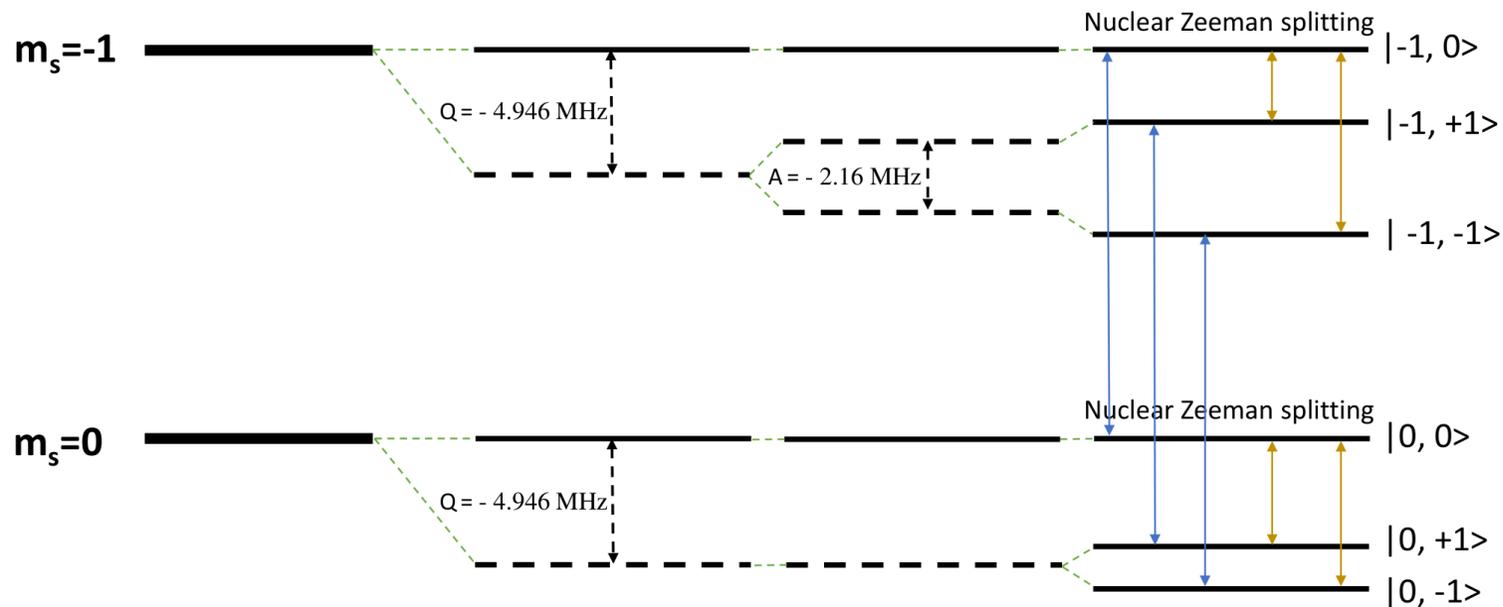
Multi-qubits with Nitrogen spin

$$\hat{H}_{NV-Nuclear} = \hat{S} \cdot \mathrm{A} \cdot \hat{I}$$

$$\hat{H} = D_{gs}\hat{S}_z^2 + \frac{\gamma_e}{2\pi}\vec{B} \cdot \vec{S} + \sum_i \hat{H}_{NV-Nuclear_i} + \sum_i \hat{H}_{Nuclear_i}$$
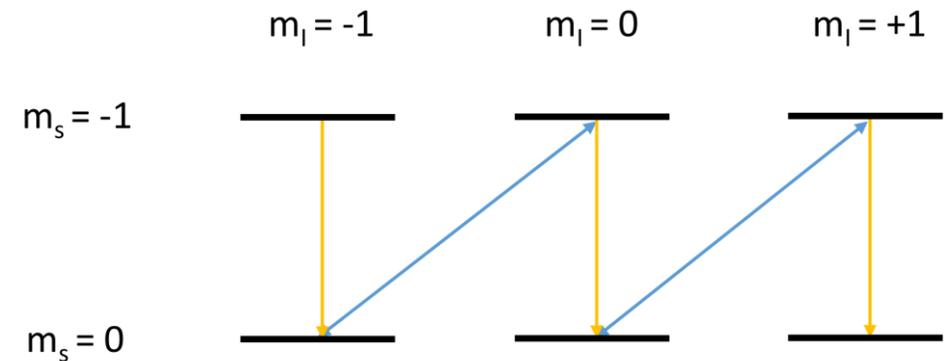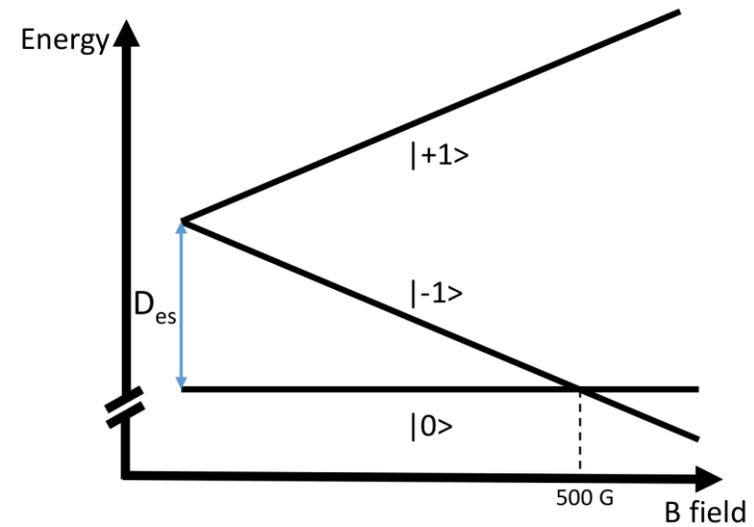
$$\hat{H}_{nuclear} = Q\hat{I}_z^2 - \frac{\gamma_N}{2\pi}B_z\hat{I}_z$$

$m_s=-1$

Nuclear Zeeman splitting

$|-1, 0\rangle$

$Q = - 4.946$ MHz

$A = - 2.16$ MHz

$|-1, +1\rangle$

$| -1, -1\rangle$

$m_s=0$

Nuclear Zeeman splitting

$|0, 0\rangle$

$Q = - 4.946$ MHz

$|0, +1\rangle$

$|0, -1\rangle$

30

The NV Center in Diamond

Multi-qubits with Nitrogen spin

Excited state level anticrossing (esLAC)

Initialization

Read-out

The NV Center in Diamond

Manipulations of the 2-qubit system

- Nuclear Magnetic Resonance (NMR)

  - To determine the transition frequency between the nitrogen nuclear's spin-up and down states

- Nuclear Rabi Oscillation

  - To implement rotation gates on the Nitrogen spin qubit