Q-EYES 2025

*Multimessenger Astronomy Beyond the Standard Model and Quantum Sensing*

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# Light dark-matter search with nitrogen-vacancy centres in diamond

David Herbschleb

So Chigusa, Masashi Hazumi, Riku Kawase, Hiroyuki Kawashima, Yuichiro Matsuzaki, Norikazu Mizuochi, Kazunori Nakayama

ICR Institute for Chemical Research

Kyoto University

# Light dark matter

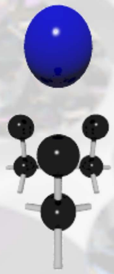
- Ultralight axion dark matter $m_a \ll 1\,eV$
- Classical field $a(t,\vec{x}) = a_0 \sin(m_a t + m_a \vec{v}_a \cdot \vec{x} + \phi)$
- Interaction with fermions $\mathcal{L}_{int} = \sum_\chi \frac{C_\chi}{2f_a} (\partial_\mu a)\bar{\chi}\gamma^\mu\gamma_5\chi$
- Interaction Hamiltonian

$$H_{int} = \frac{g_{a\chi\chi}}{m_\chi} \vec{\nabla} a \cdot \vec{S}_\chi = \sum_\chi \frac{g_{a\chi\chi}}{m_\chi} \sqrt{2\rho_a}\, \vec{v}_a \cos(m_a t + \phi) \cdot \vec{S}_\chi \qquad g_{a\chi\chi} = \frac{C_\chi m_\chi}{f_a}$$

$$\rho_a \approx 0.4\,\mathrm{GeV/cm^3}$$

$$v_a \approx 10^{-3} c$$

# Nitrogen-vacancy centre



- Diamond
- Nitrogen-vacancy (NV) centre
  - Prof Mizuochi
  - Sensitive sensor
  - Ambient/extreme conditions, inert, atomic size, long coherence times, ...
- Why NV for dark matter search?

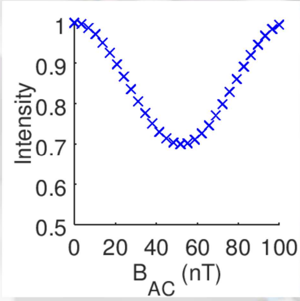


# Outline

- Introduction
- NV centre DM detection: method 1
- NV centre DM detection: method 2
- NV centre DM detection: method 3
- Summary

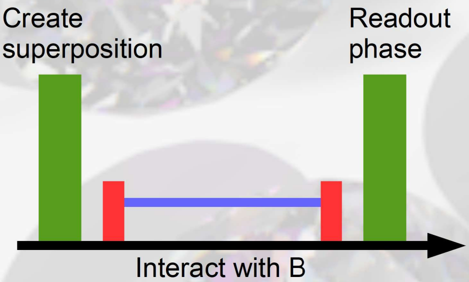
# 1 – Magnetic field sensing

- NV centre: electron spin




- Interaction Hamiltonian

$$H_{\text{int}} = \gamma_e \vec{B}(t) \cdot \vec{S}_e$$



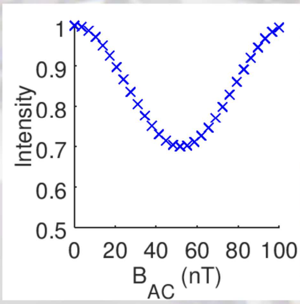

$$\psi = |0\rangle$$
$$\psi = 1/\sqrt{2}(|0\rangle + |1\rangle)$$
$$\psi = 1/\sqrt{2}(|0\rangle + e^{i\phi}|1\rangle)$$
$$\psi = 1/2((1 - i e^{i\phi})|0\rangle + (e^{i\phi} - i)|1\rangle)$$



# 1 – Magnetic field sensitivity

- Sensitivity $\eta = \sigma_B \sqrt{T_{\text{meas}}} = \frac{\sigma_{\text{signal}}}{\text{gradient}} \sqrt{T_{\text{meas}}}$
- Dependence

$$\eta \propto \frac{1/\sqrt{N_{\text{NV}}}}{C \gamma_e T_{\text{coh}}} \sqrt{T_{\text{coh}}} = \frac{1}{C \gamma_e \sqrt{N_{\text{NV}} T_{\text{coh}}}}$$




- High sensitivity to magnetic fields
  - Longest coherence time at room temperature of solid state spin
  - High density ensemble samples

# 1 – Axion field sensing?

- Interaction Hamiltonian for electron spin

$$H_{\mathrm{int}} = \frac{g_{\mathrm{aee}}}{m_{\mathrm{e}}} \sqrt{2\rho_{\mathrm{a}}}\, \vec{v}_{\mathrm{a}} \cos(m_{\mathrm{a}} t + \phi) \cdot \vec{S}_{\mathrm{e}}$$

- Rewrite $H_{\mathrm{int}} = \gamma_{\mathrm{e}} \vec{B}_{\mathrm{eff}}(t) \cdot \vec{S}_{\mathrm{e}}$

- Effective (not real) magnetic field $B_{\mathrm{eff}} \sim 4\,\mathrm{aT} \times \left( \frac{g_{\mathrm{aee}}}{10^{-10}} \right)$

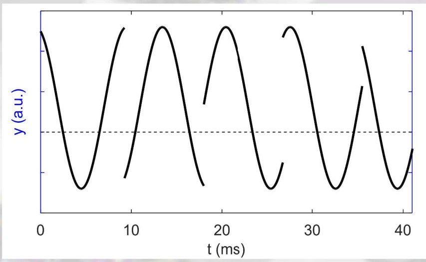
$$\vec{B}_{\mathrm{eff}} = \frac{g_{\mathrm{aee}}}{\gamma_{\mathrm{e}} m_{\mathrm{e}}} \sqrt{2\rho_{\mathrm{a}}}\, \vec{v}_{\mathrm{a}} \cos(m_{\mathrm{a}} t + \phi)$$



# 1 – Effective magnetic field

- NV centres for sensing

- Additional challenges
  - Signal to detect very small
  - Coherence time of axion field




$$\tau_{\mathrm{a}} = \frac{1}{m_{\mathrm{a}} v_{\mathrm{a}}^2} \approx 6.6\,\mathrm{s} \text{ for } m_{\mathrm{a}} = 0.1\ \mathrm{neV}$$

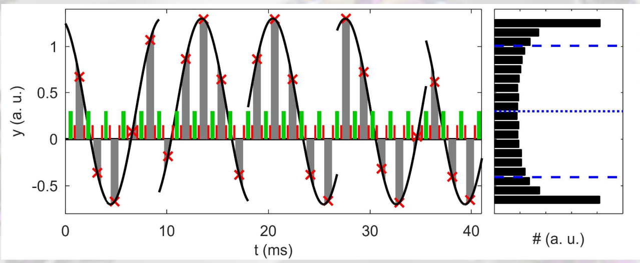
# 1 – Analysis methods

- Std method
  - Straightforward to understand
  - For optimal sensitivity, each mass needs separate analysis
- Power spectrum
  - Less straightforward
  - Single analysis suffices



# 1 – Std method

- Measure the standard deviation

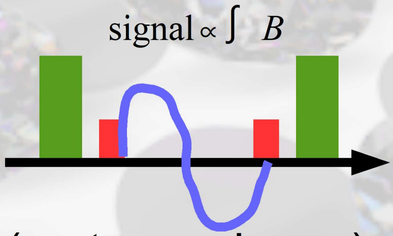


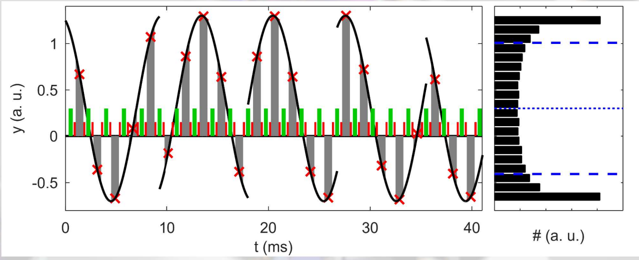

$$VAR = \sigma_y^2 = \frac{1}{N-1}\sum_{k=0}^{N-1}(y_i-\mu)^2 \approx \frac{1}{\tau}\int_0^{\tau}(A\sin(2\pi f t+\theta)+C-C)^2\,dt =$$

$$A^2 f\int_0^{1/f}\sin^2(2\pi f t+\theta)\,dt = \frac{A^2 f}{2}\int_0^{1/f} 1-\cos(4\pi f t+\theta)\,dt = \frac{A^2}{2}$$

# 1 – Std method

- Non-zero (average is zero)
  - Random direction $1/\sqrt{3}$
- Independent of phase
  - No synchronisation
- Independent of frequency (up to maximum)
  - Broadband

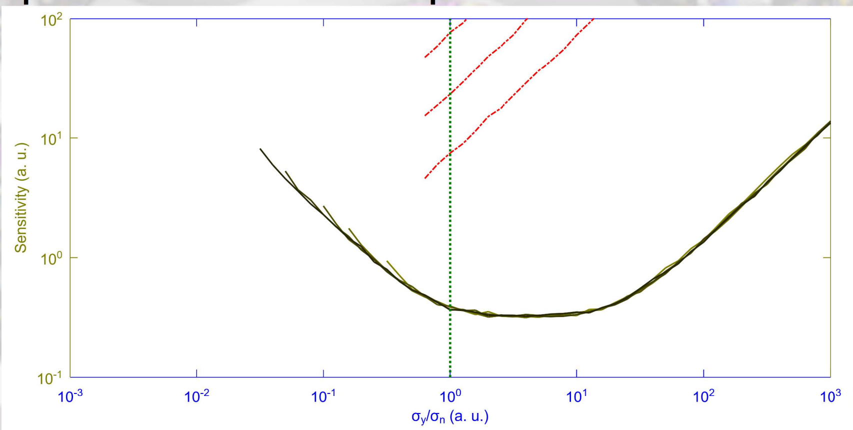




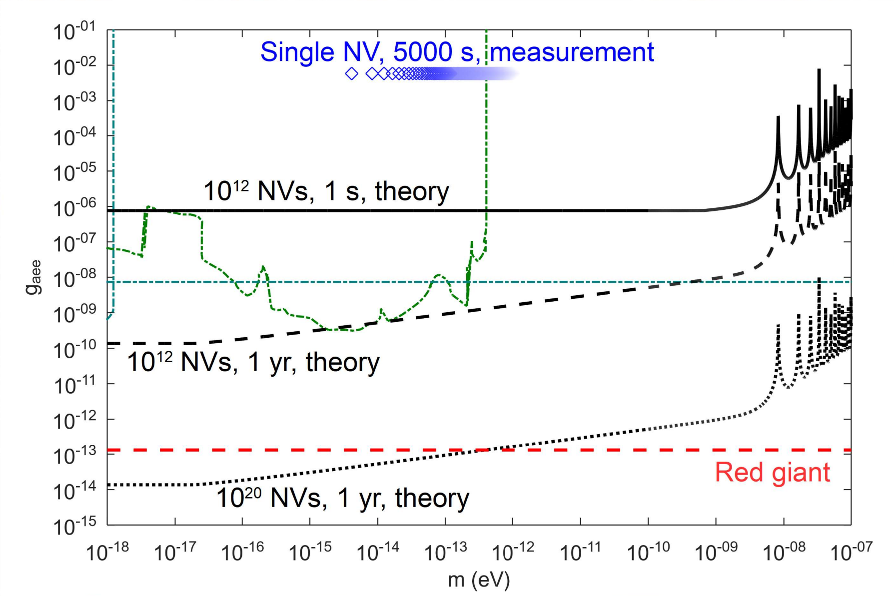

# 1 – Std method sensitivity

- Depends on noise amplitude




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

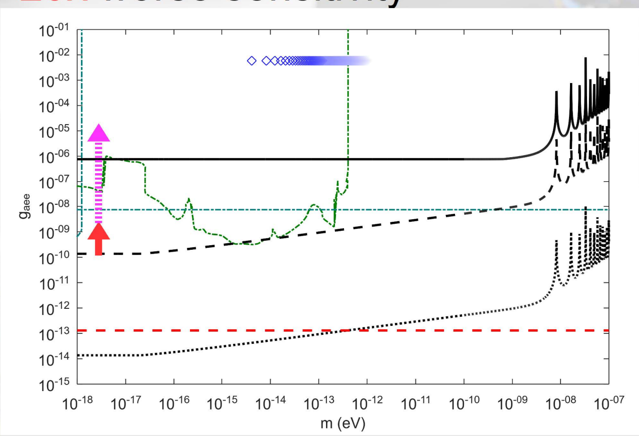
# 1 – Potential bounds






# 1 – Challenges

- Theory: spin-projection noise limited
- Experiment: shot-noise limited
  - Will get closer over time
  - At the moment: ~20x worse sensitivity
- $10^{18}$ NVs is a lot
- Noise



# Outline

S. Chigusa, M. Hazumi, E. D. Herbschleb, N. Mizuochi, K. Nakayama, JHEP 03, 083 (2025).

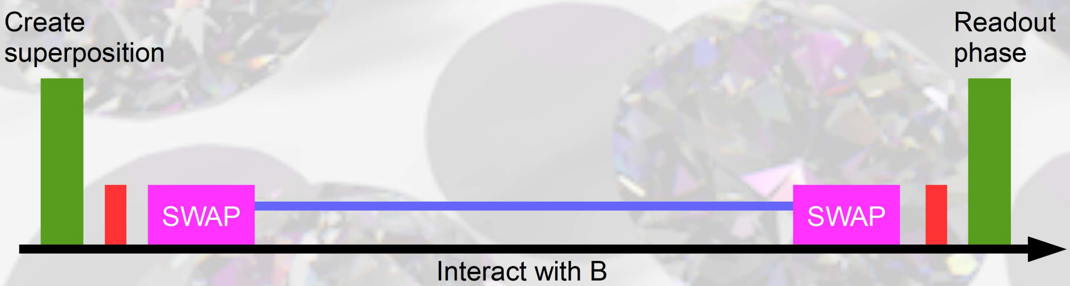
- Introduction
- 1: DM detection with electron spin
- NV centre DM detection: method 2
- NV centre DM detection: method 3
- Summary



# 2 – Magnetic field sensing

- NV centre: nitrogen atom
  Nuclear spin
- Interaction Hamiltonian

$$H_{\text{int}} = \gamma_{\text{N}} \vec{B}(t) \cdot \vec{I}_{\text{N}}$$



# 2 – Magnetic field sensitivity

- Sensitivity $\eta=\sigma_B\sqrt{T_{\text{meas}}}=\frac{\sigma_{\text{signal}}}{\text{gradient}}\sqrt{T_{\text{meas}}}$
- Dependence

$$\eta\propto\frac{1}{C\gamma_N\sqrt{N_N T_{\text{coh, N}}}}$$

- Low sensitivity to magnetic fields
  - Gyromagnetic ratio much smaller
  - Coherence time much longer
  - Overall worse sensitivity $\frac{1}{1/10^4\sqrt{10^4}}=100$

$\gamma_e=28\ \text{GHz/T}$
$\gamma_{14N}=3.1\ \text{MHz/T}$

$T_{\text{coh, e}}=1\ \mu\text{s}$
$T_{\text{coh, 14N}}=7\ \text{ms}$



# 2 – Axion field sensing?

- Interaction Hamiltonian for nitrogen nuclear spin

$$H_{\text{int}}=\frac{g_{\text{aNN}}}{m_N}\sqrt{2\rho_a}\vec{v}_a\cos(m_a t+\phi)\cdot\vec{I}_N$$

- Rewrite $H_{\text{int}}=\gamma_N\vec{B}_{\text{eff}}(t)\cdot\vec{I}_N$

$\frac{\gamma_e}{\gamma_N}$

- Effective magnetic field

$$B_{\text{eff}}\sim10^4\times4\,\text{aT}\times\left(\frac{g_{\text{aNN}}}{10^{-10}}\right)$$

$$\vec{B}_{\text{eff}}=\frac{g_{\text{aNN}}}{\gamma_N m_N}\sqrt{2\rho_a}\vec{v}_a\cos(m_a t+\phi)$$

Still longer coherence time → improved DM sensitivity

# 2 – Large effective magnetic field

- Nitrogen in NV centres for sensing
  - Long coherence time
- Additional challenges
  - Extra gates (SWAP)
  - Novel



# 2 – Nitrogen-14

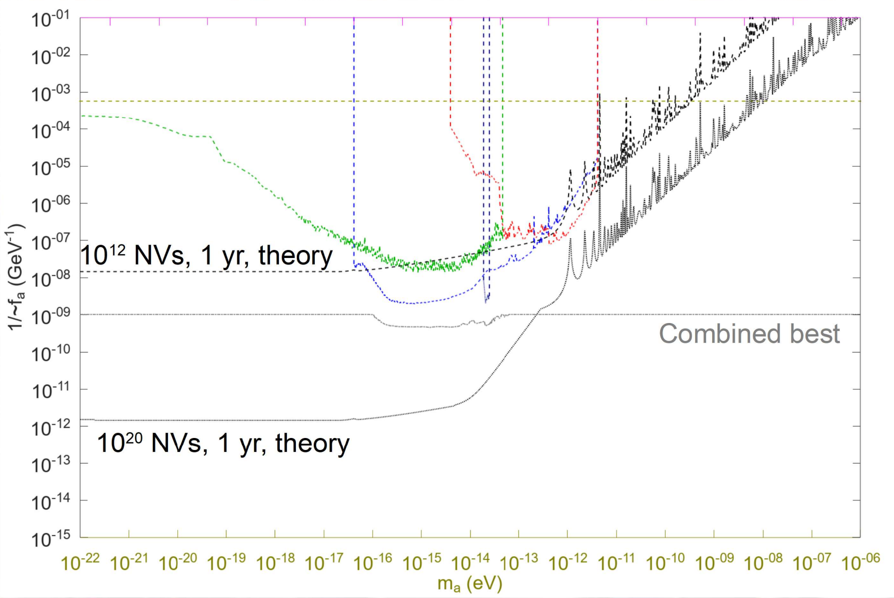
- Rare stable odd-odd nucleus
- Take into account for the coupling

$$g_{\mathrm{a}\chi\chi} = \frac{C_\chi m_\chi}{f_\mathrm{a}}$$

$$\frac{g_{\mathrm{aNN}}}{m_\mathrm{N}} \equiv -\frac{1}{6}\left(\frac{g_{\mathrm{app}}}{m_\mathrm{p}} + \frac{g_{\mathrm{ann}}}{m_\mathrm{n}}\right)$$

$$\tilde{f}_\mathrm{a}^{-1} = \left|\frac{1}{2}\frac{g_{\mathrm{app}}}{m_\mathrm{p}} + \frac{1}{2}\frac{g_{\mathrm{ann}}}{m_\mathrm{n}}\right|$$

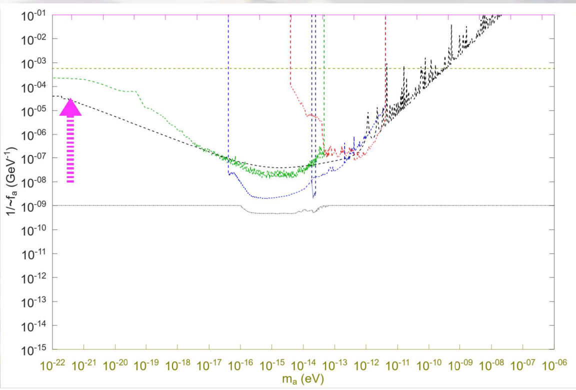
# 2 – Potential bounds






# 2 – Challenge status

- Shot-noise limit?
  - Nuclear spin: single-shot readout
  - Close to spin-projection noise limit
  - Factor ~2-3 (instead of 20)
- $10^{18} \rightarrow 10^{14}$
  - Is more reasonable
- Noise
  - Not resolved



# Outline

- Introduction
- 1: DM detection with electron spin
- 2: DM detection with nuclear spin
- NV centre DM detection: method 3
- Summary

S. Chigusa, M. Hazumi, E. D. Herbschleb, N. Mizuochi, K. Nakayama, JHEP 03, 083 (2025).

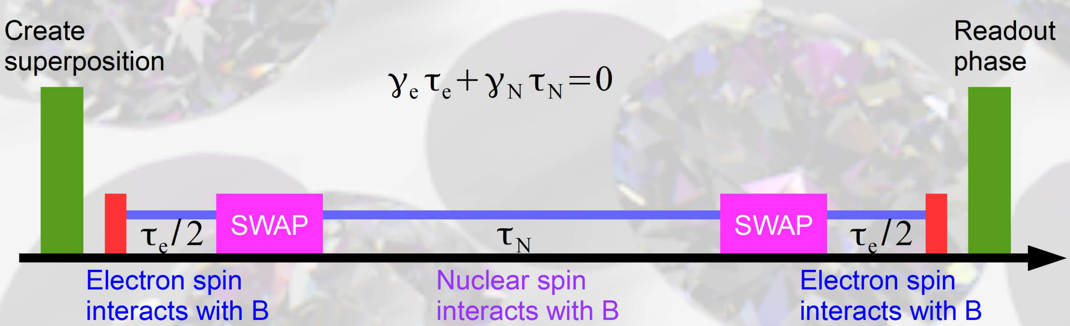
S. Chigusa, M. Hazumi, E. D. Herbschleb, Y. Matsuzaki, N. Mizuochi, K. Nakayama, PRD 111, 075028 (2025).



# 3 – Magnetic field sensing

- NV centre: electron spin & nitrogen atom with nuclear spin
- Interaction Hamiltonian

$$H_{\mathrm{int}} = \gamma_e \vec{B}(t) \cdot \vec{S}_e \qquad H_{\mathrm{int}} = \gamma_N \vec{B}(t) \cdot \vec{I}_N$$



# 3 – Magnetic field sensitivity

- Sensitivity $\eta = \sigma_B \sqrt{T_{\text{meas}}} = \frac{\sigma_{\text{signal}}}{\text{gradient}} \sqrt{T_{\text{meas}}}$
- Effect on electron spin cancels effect on nuclear spin $\gamma_e \tau_e + \gamma_N \tau_N = 0$
- Not sensitive to DC magnetic fields
  - Also not sensitive to "linear" magnetic fields
  - Low sensitivity to low-frequency AC fields



# 3 – Axion field sensing?

- Interaction Hamiltonian for spin

$$H_{\text{int}} = \frac{g_{a\chi\chi}}{m_\chi} \sqrt{2\rho_a} \vec{v}_a \cos(m_a t + \phi) \cdot \vec{S}_\chi$$

- Rewrite $H_{\text{int}} = \gamma_\chi \vec{B}_{\text{eff}}(t) \cdot \vec{S}_\chi$

$$B_{\text{eff, e}} \sim 4\,\text{aT} \times \left( \frac{g_{\text{aee}}}{10^{-10}} \right)$$

$$B_{\text{eff, N}} \sim 10^4 \times 4\,\text{aT} \times \left( \frac{g_{\text{aNN}}}{10^{-10}} \right)$$

- Effective magnetic field is **not** cancelled
- Effect of electron spin negligible $\tilde{f}_a$

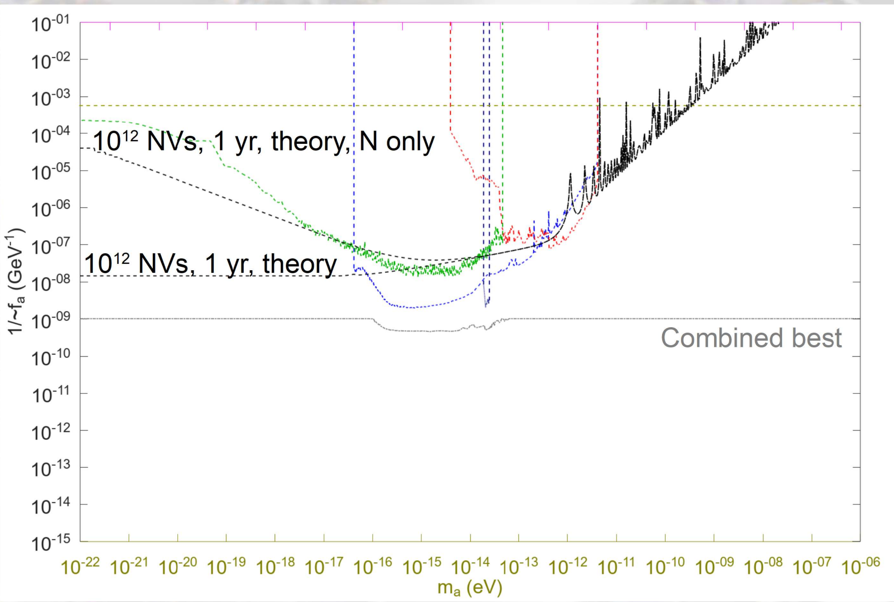
# 3 – Large effective magnetic field

- Hybrid spins in NV centres for sensing
- Magnetic noise cancelled

- Additional challenges (same as for just nuclear spin)
  - Extra gates (SWAP)
  - Even more novel



# 3 – Potential bounds

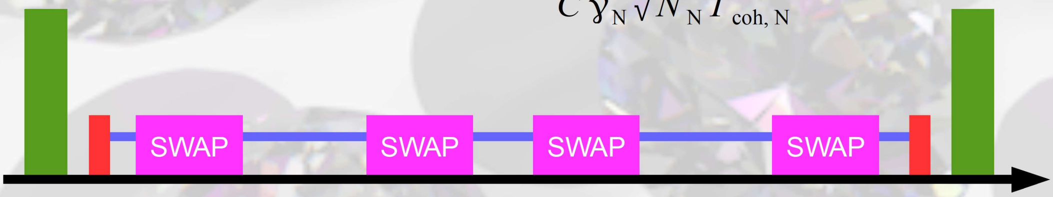


# 3 – Enhance sensitivity

- Repeat the sequence

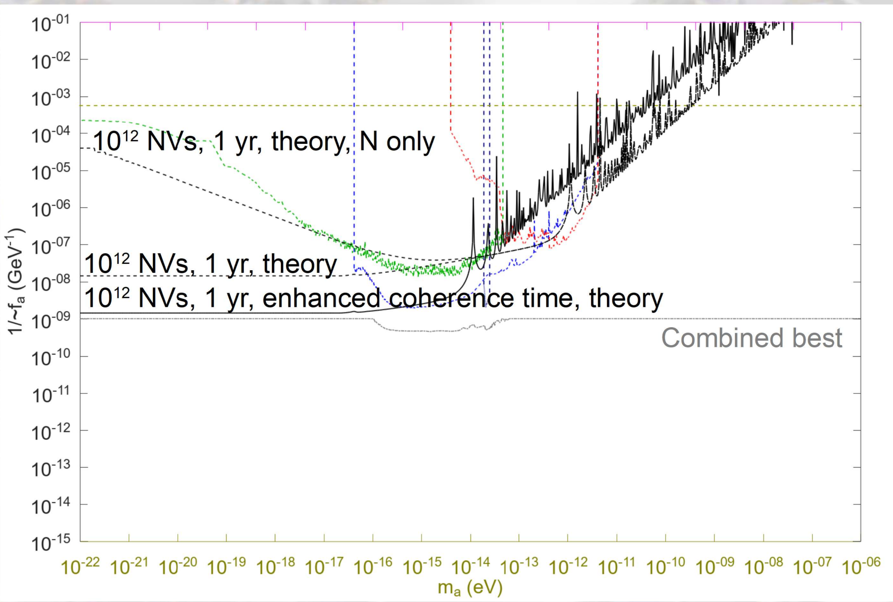
- Works as decoupling sequence for the noise
- But as DC sensing sequence for axion field

$$T_{\mathrm{coh}} \rightarrow T_1 \qquad \eta \propto \frac{1}{C\,\gamma_{\mathrm{N}}\sqrt{N_{\mathrm{N}} T_{\mathrm{coh,\,N}}}}$$






# 3 – Potential bounds – B



# 3 – Challenge status

- Shot-noise limit?
  - Nuclear spin: single-shot readout
  - Close to spin-projection noise limit
  - Factor ~2-3 (instead of 20)
- $10^{18} \rightarrow 10^{14} \rightarrow 10^{12}$
- Noise resilient



# Outline – Summary

- Introduction
- 1: DM detection with electron spin
- 2: DM detection with nuclear spin
- 3: DM detection with hybrid spin
- Summary

S. Chigusa, M. Hazumi, E. D. Herbschleb, N. Mizuochi, K. Nakayama, JHEP 03, 083 (2025).

S. Chigusa, M. Hazumi, E. D. Herbschleb, Y. Matsuzaki, N. Mizuochi, K. Nakayama, PRD 111, 075028 (2025).

Hybrid-spin decoupling protocol

S. Chigusa, M. Hazumi, E. D. Herbschleb, Y. Matsuzaki, N. Mizuochi, K. Nakayama, arXiv:2511.16732 (2025).

# "Summary"

- Other nuclear spins
  - $^{15}N$ (odd-even), $^{13}C$ (even-odd)
- Lower temperature
  - Increase $T_1$
- Further improvements
  - Xiaolin Ma
  - ...
- One eye for multimessenger astronomy