# Searching for exotic spin dependent interactions by NV centers

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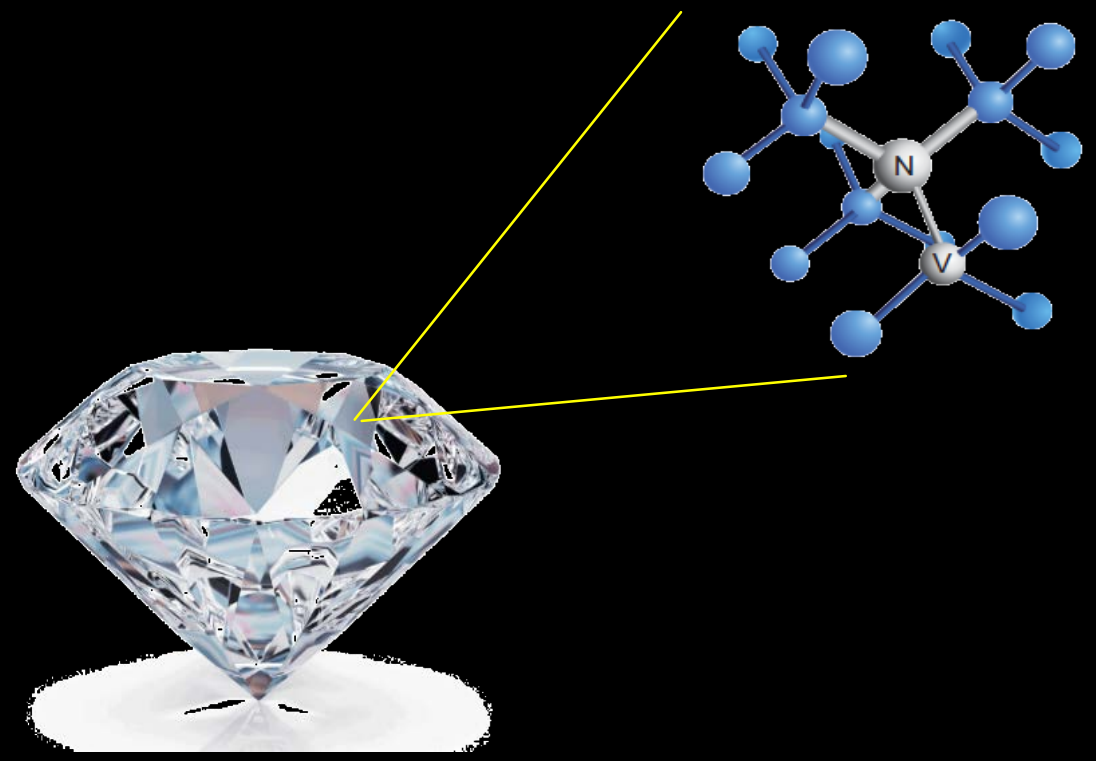
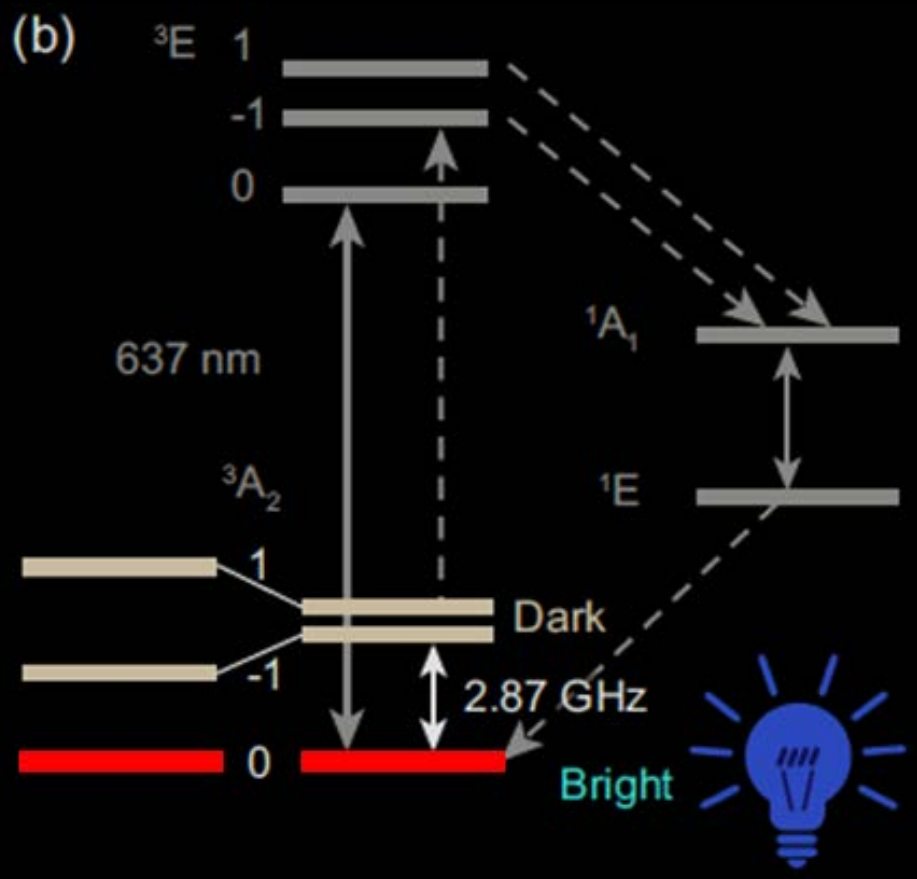
# Outlines

- Brief introduction about the NV centers
- Experiments on searching for exotic spin dependent interactions

# NITROGEN-VACANCY (NV) CENTERS



# NV CENTERS AS QUANTUM SENSORS

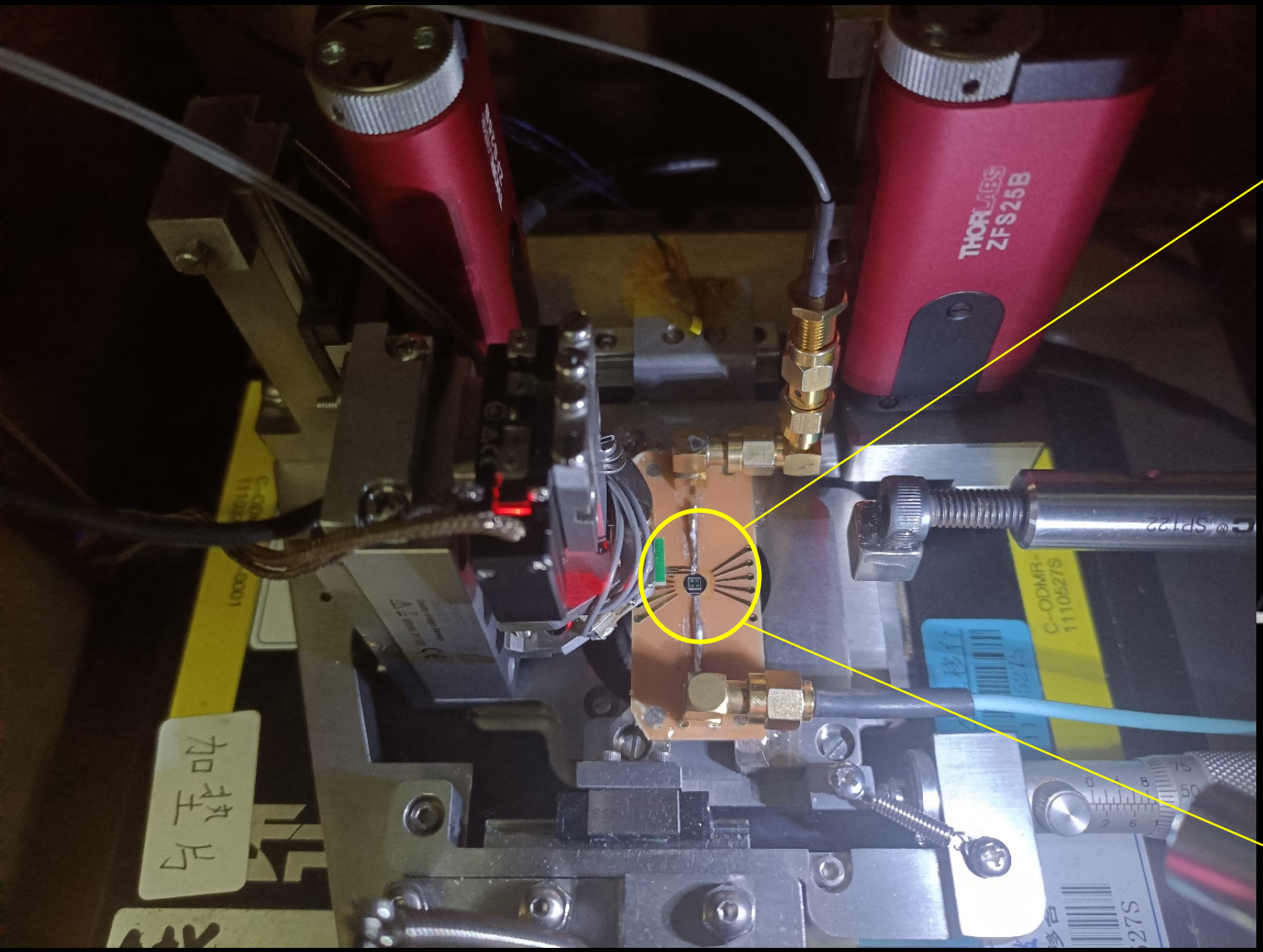
$$\mathrm{H} = D \cdot S_Z^2 + E \cdot (S_x^2 - S_y^2) - \gamma_e B \cdot S + S \cdot \sum_i A_i \cdot I_i$$

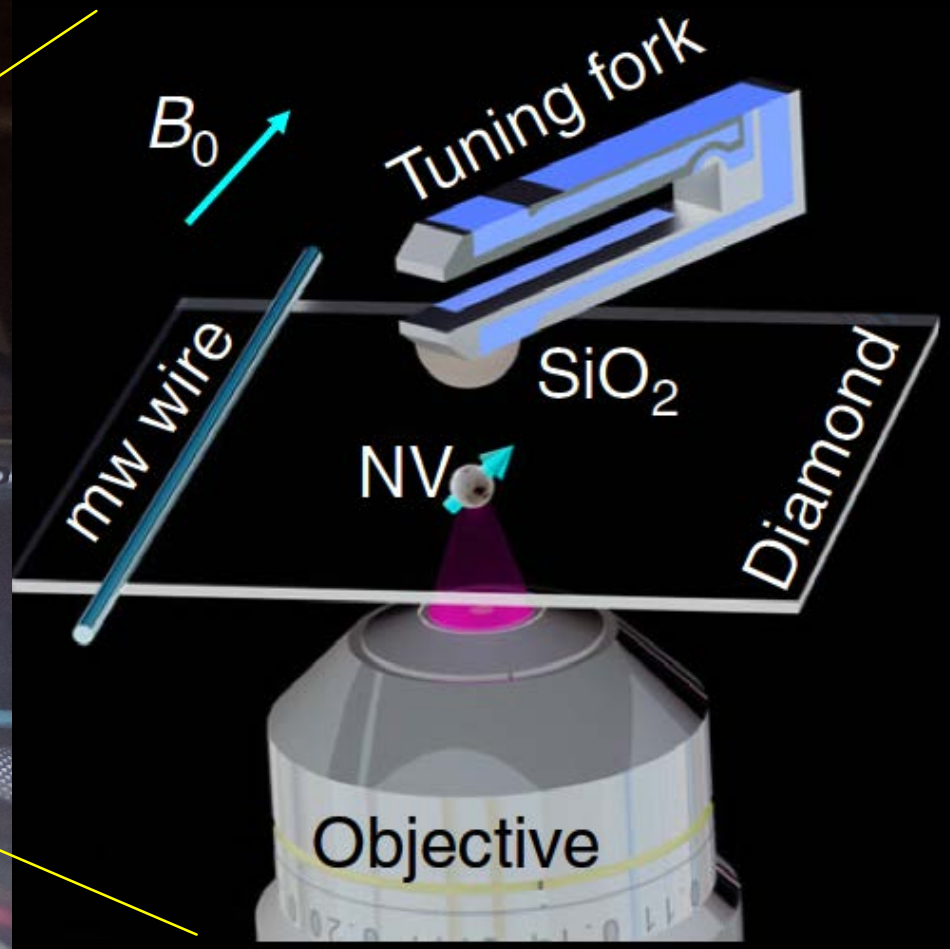
- Temperature
- Electric-field stress detection
- Magnetic field
- Spin-coupling Spin-sensing

# SEARCHING FOR EXOTIC SPIN INTERACTIONS BEYOND THE STANDARD MODEL

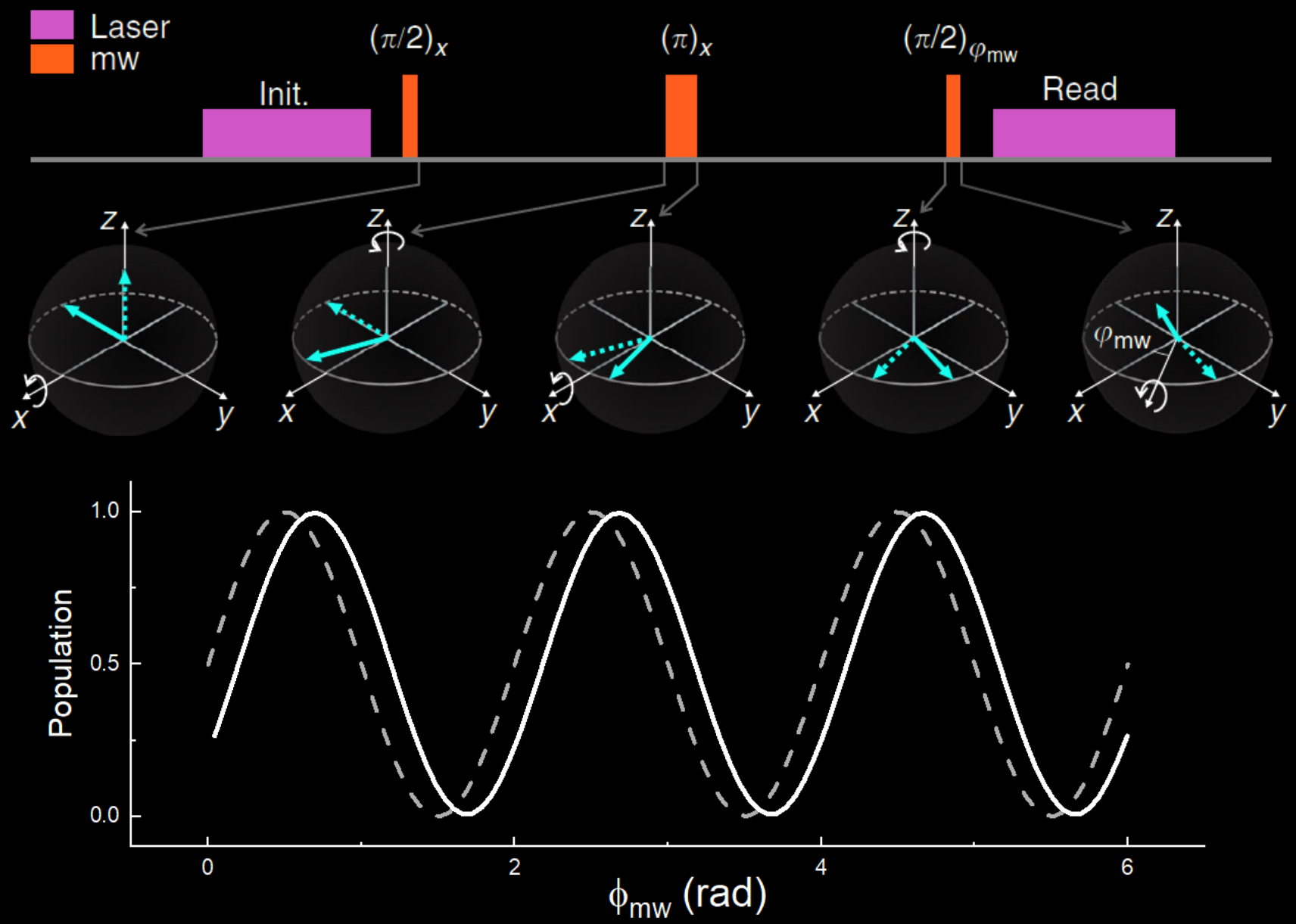
- electron-nucleon monopole-dipole interaction
  - Nature Communications 9, 739 (2018)
- parity-odd spin- and velocity- dependent interaction
  - arXiv:2009.09257 (2020)
- parity-even spin- and velocity- dependent interaction
  - arXiv:2010.15667 (2020)

# Experimental Setup

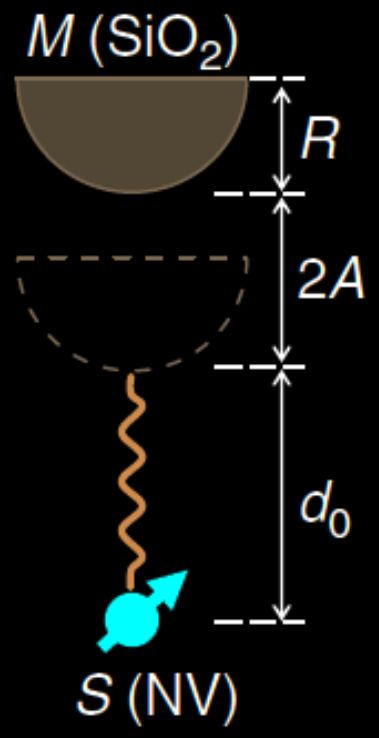


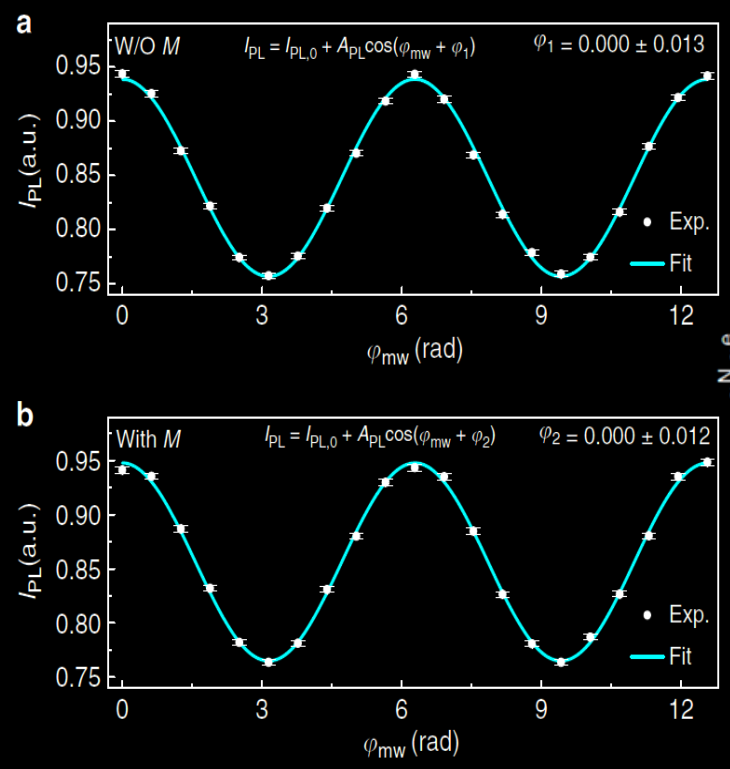



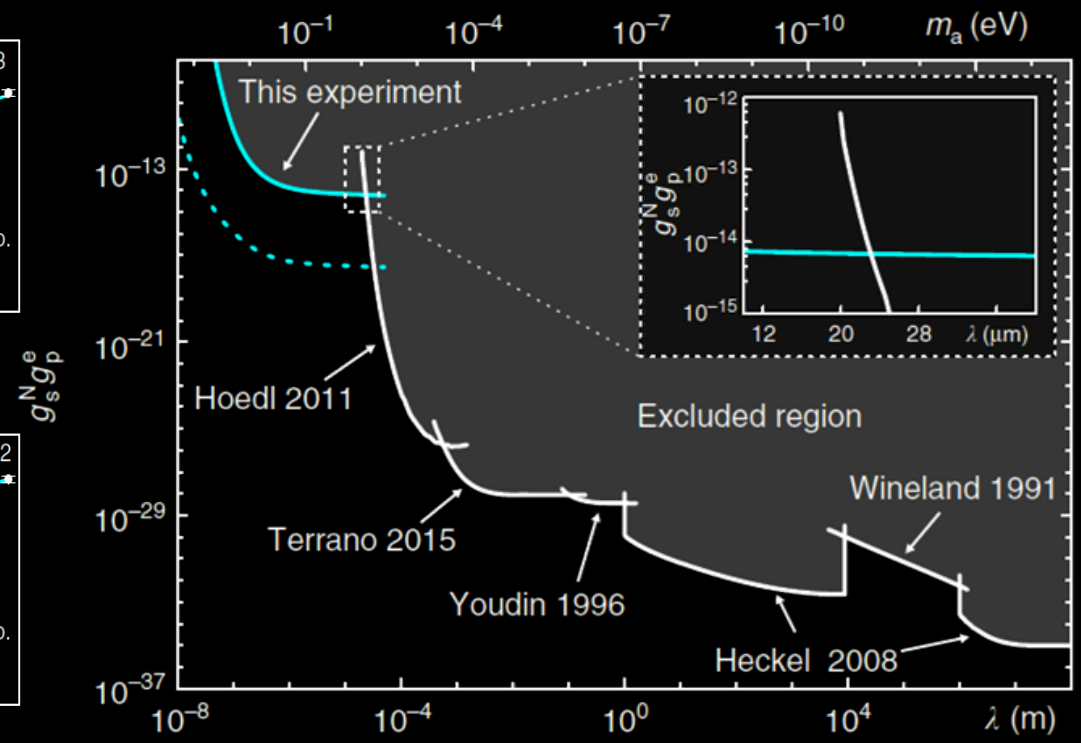
# Quantum interferometer based on NV center



# Searching for Electron-Nucleon Monopole-Dipole Interaction



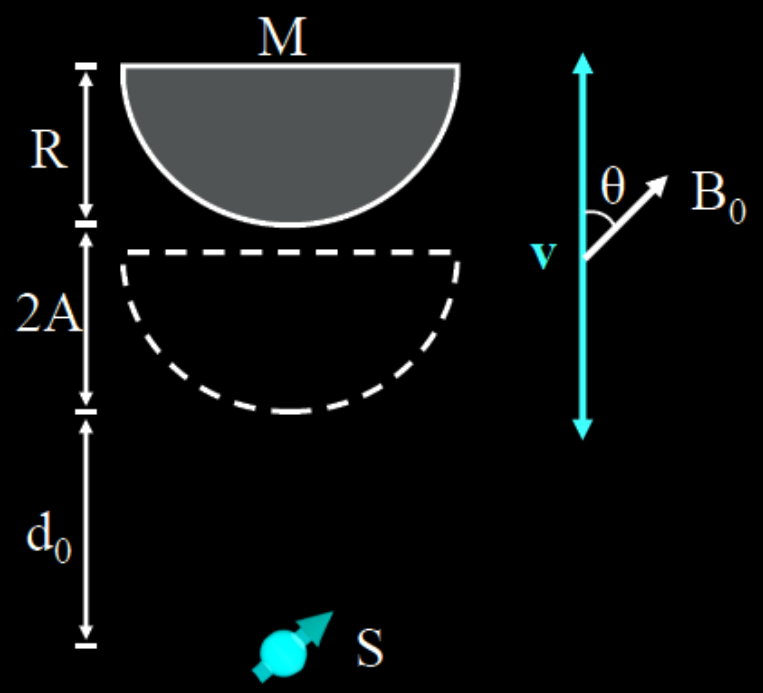

$$V_{sp}(\mathbf{r}) = \frac{\hbar^2 g_s^N g_p^e}{8\pi m}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda}} \boldsymbol{\sigma} \cdot \mathbf{e}_r$$

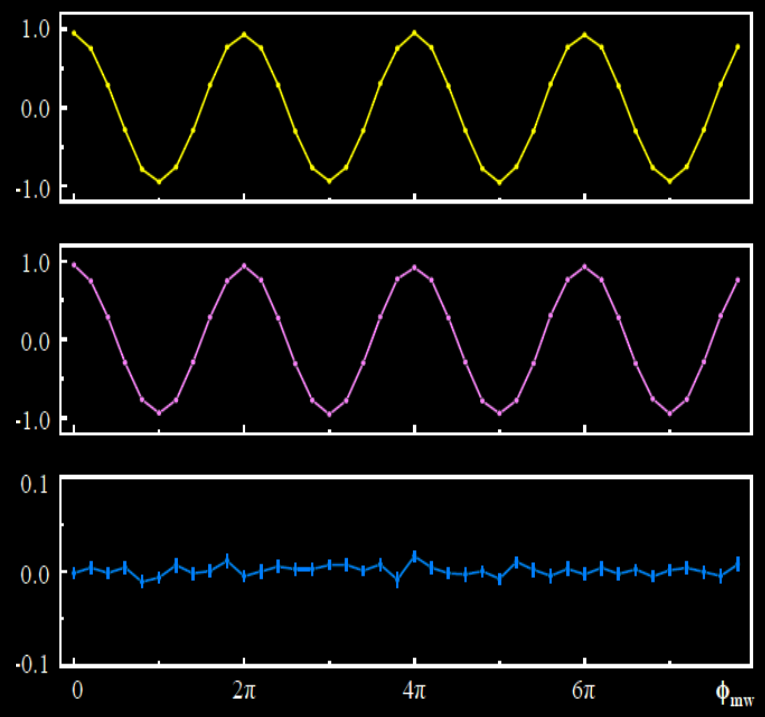
No signal

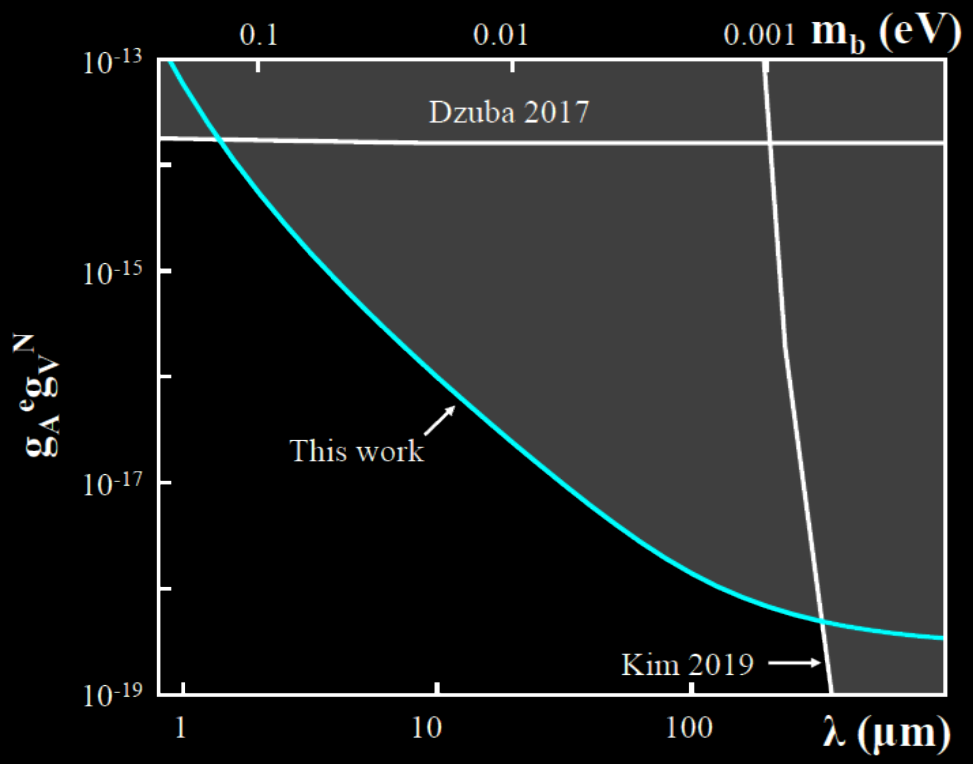
Constraint has been set

Nature Communications 9, 739 (2018)

# Searching for Parity-Odd Spin- and Velocity-Dependent Interaction



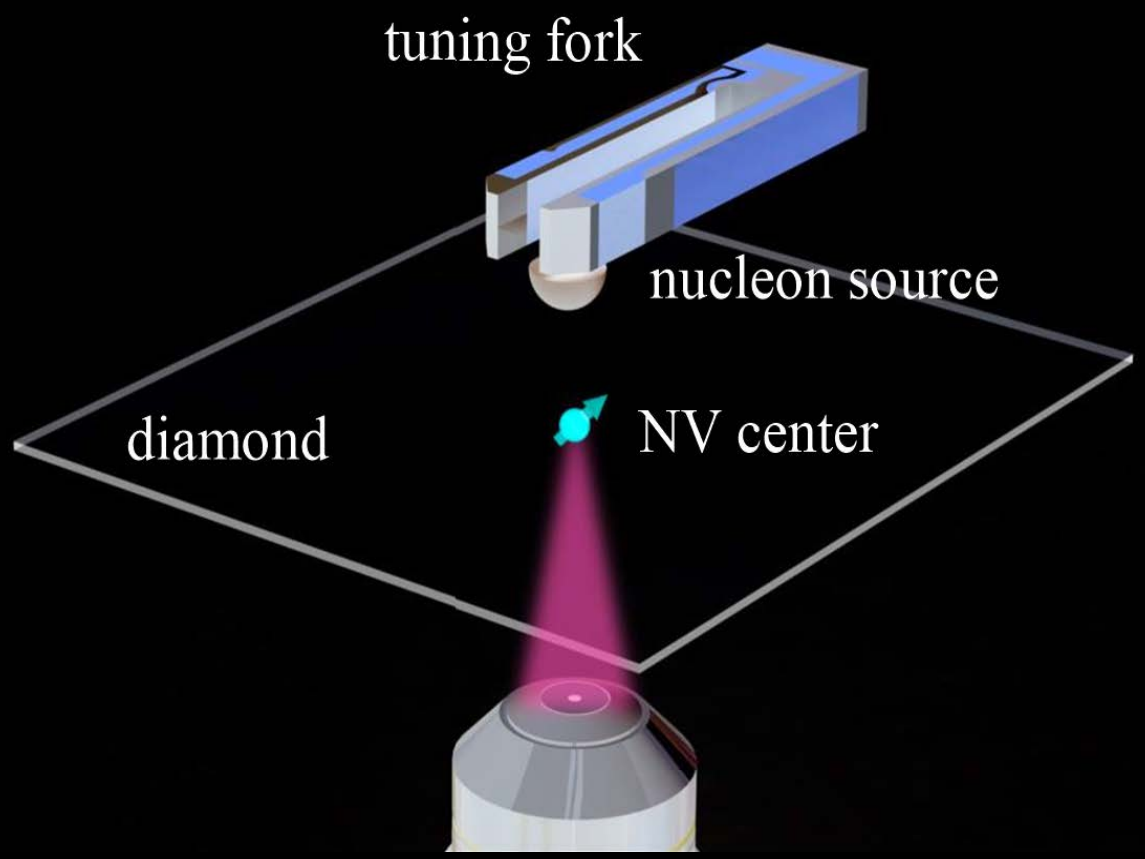

$$V = g_A^e g_V^N \frac{\hbar}{4\pi}(\boldsymbol{\sigma}\cdot\boldsymbol{v})\left(\frac{e^{-\frac{r}{\lambda}}}{r}\right)$$

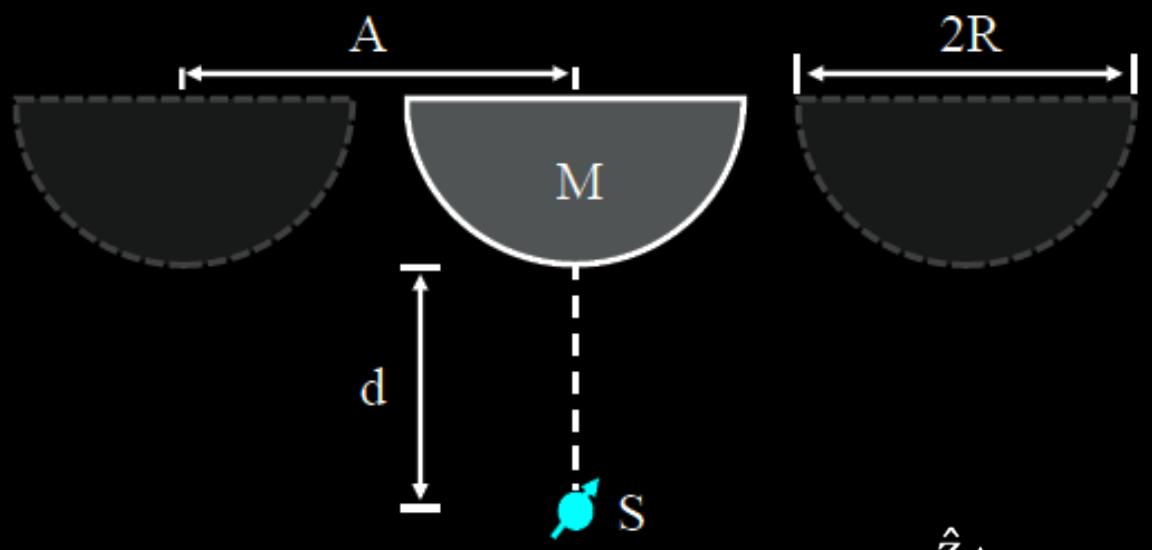
No signal

Constraint has been set

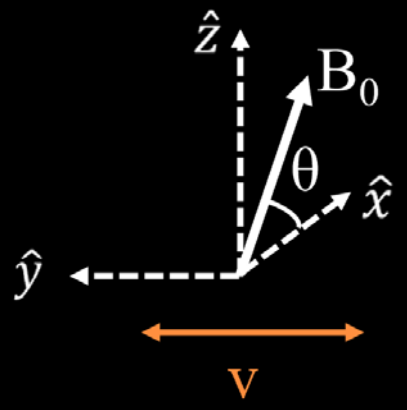
arXiv:2009.09257 (2020)

# Searching for
# Parity-Even Spin- and Velocity-Dependent Interaction



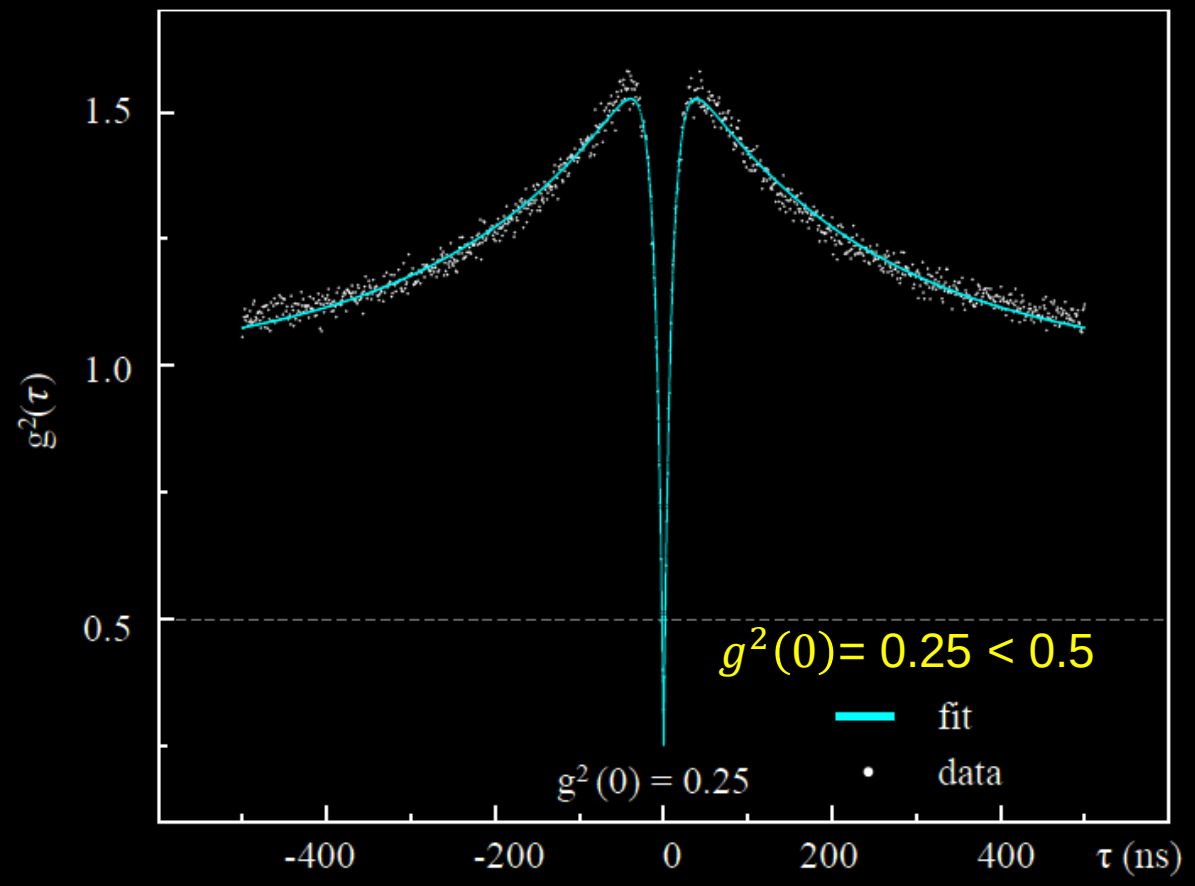



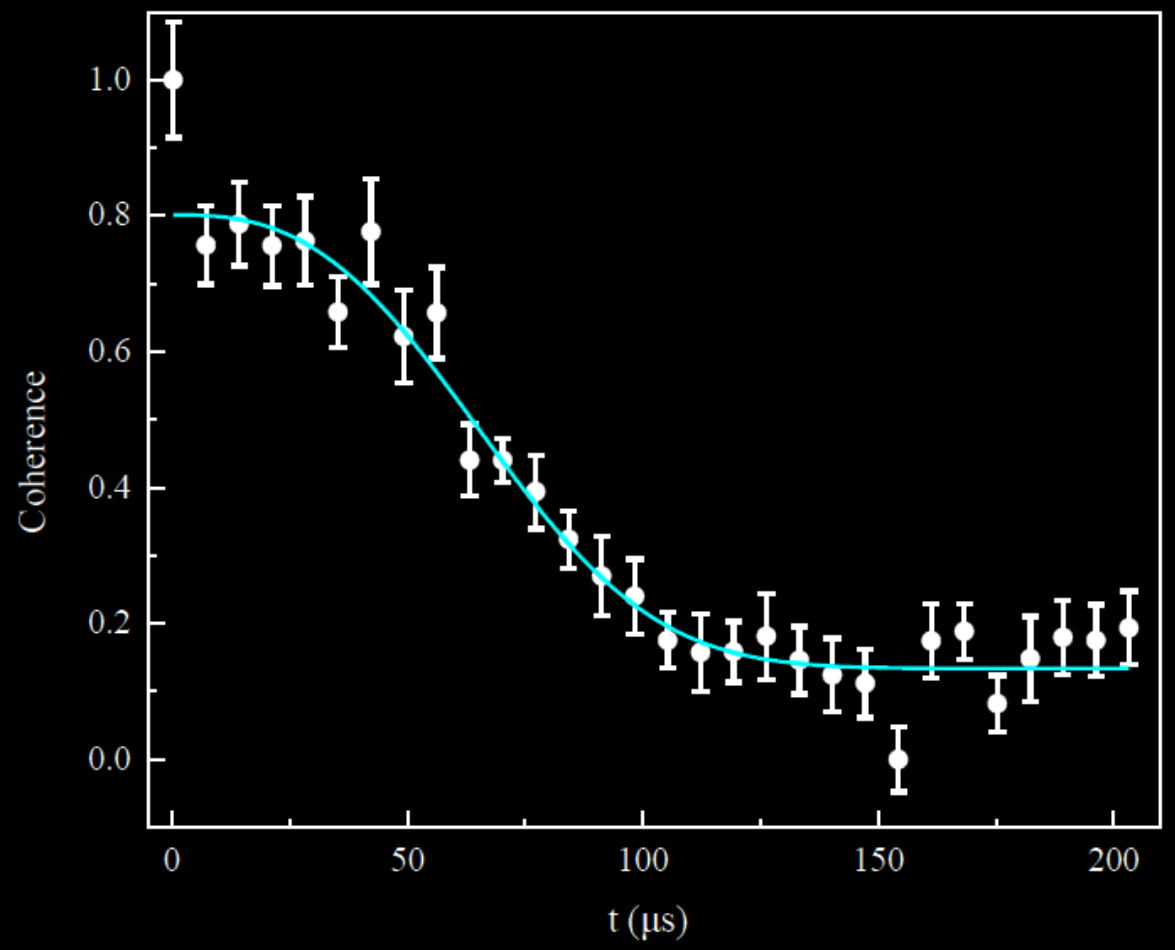

$f = 70.47$ kHz
$A = 120$ nm
$d : 1 \text{ -> } 12\ \mu m$




arXiv:2010.15667 (2020)

# PROPERTIES OF THE NV CENTER

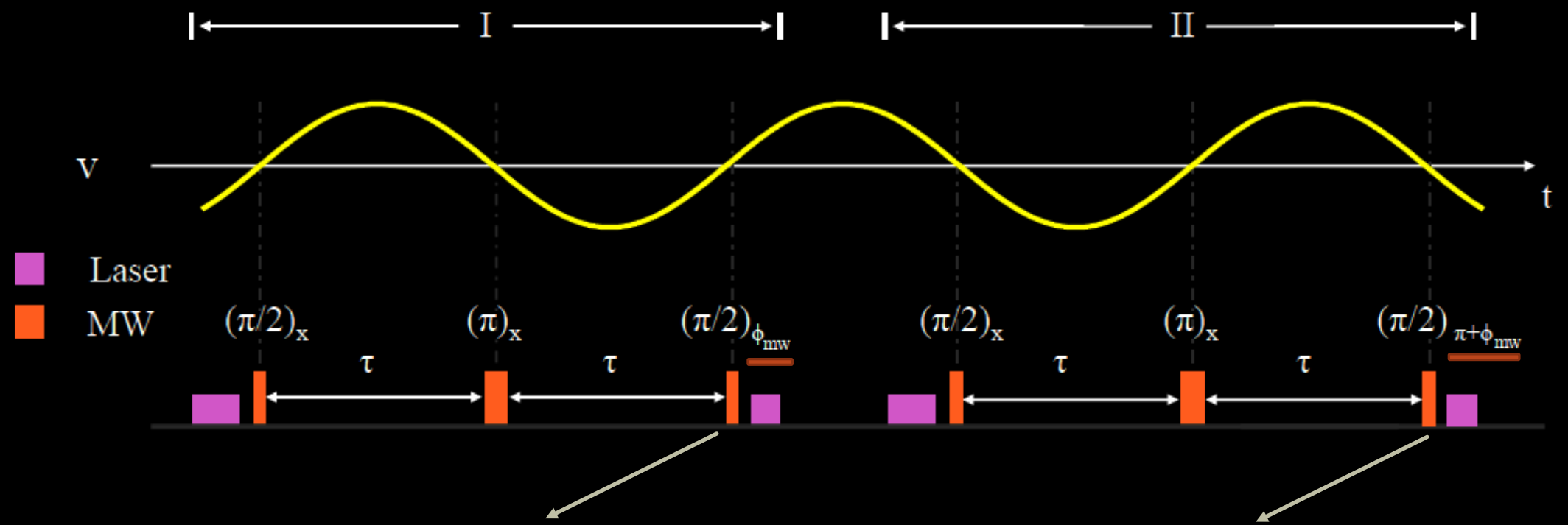



This is a single NV center close to the surface with depth less than 10 nm

$T_2$ = 77(3) μs

# EXPERIMENTAL PULSE SEQUENCE



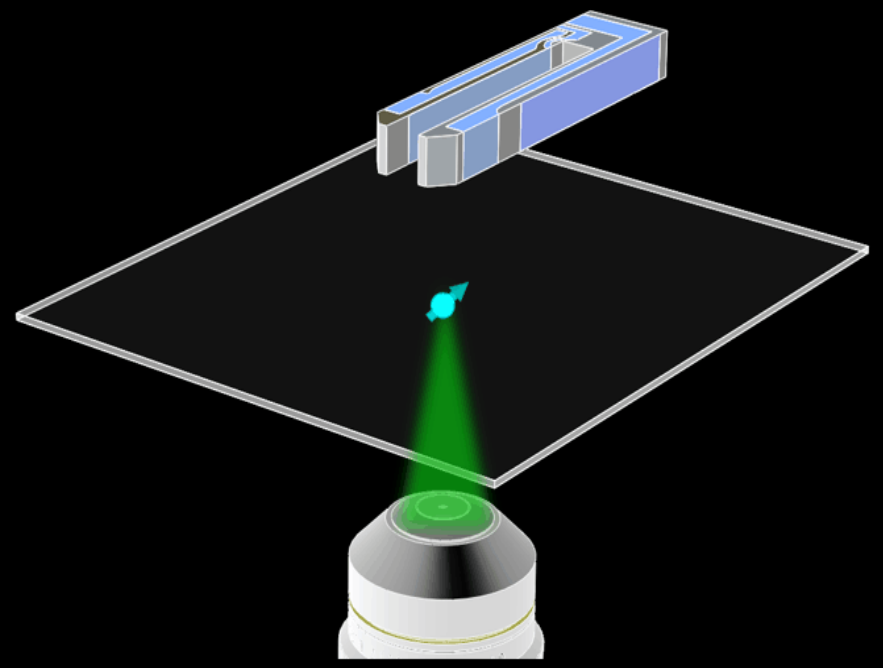

$$P_+ = [1+\cos(\phi_{mw}+\phi)]/2. \qquad P_- = [1+\cos(\phi_{mw}+\pi-\phi)]/2,$$

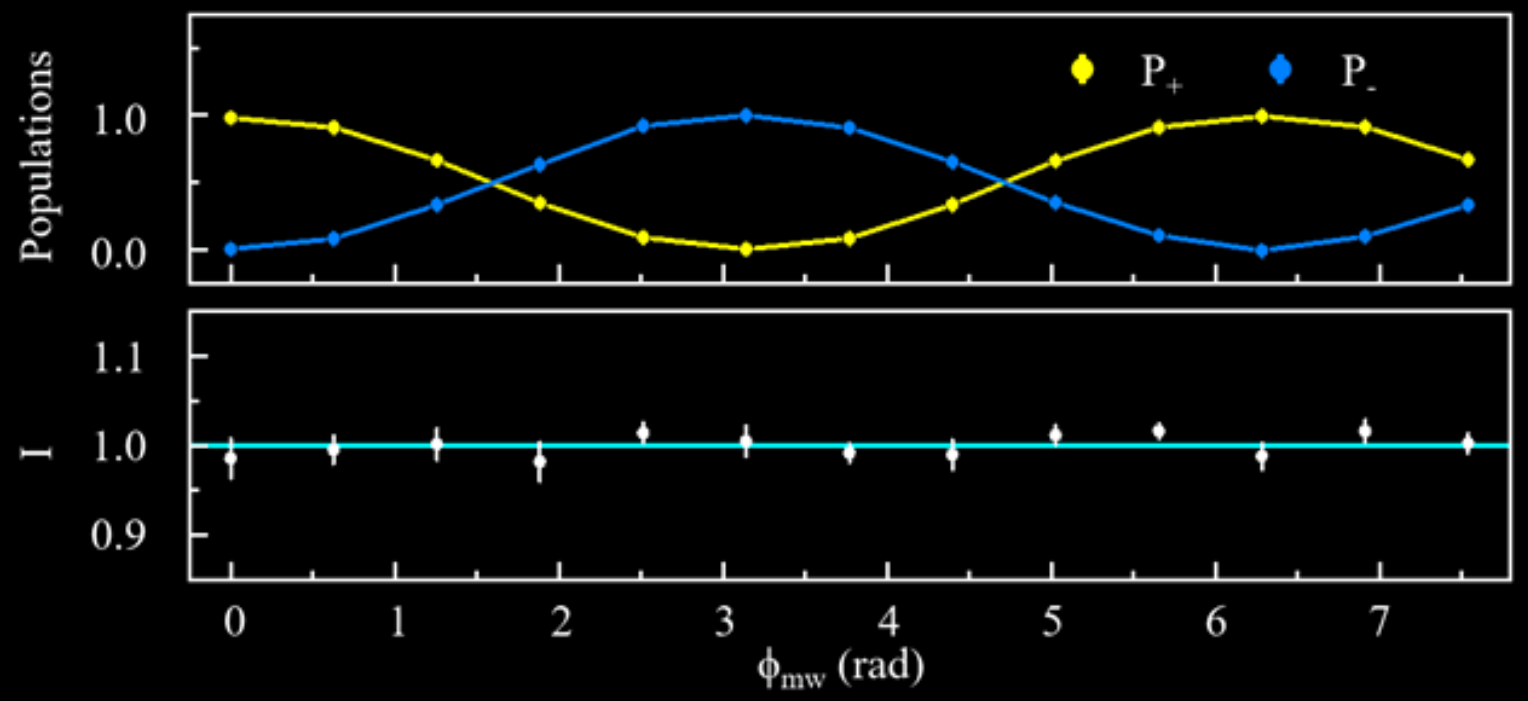
$$I = P_+ + P_- = 1 - \sin(\phi_{mw})\sin(\phi)$$

$\phi_{mw}$ Phase of the mw pulses

$\phi$ Phase shift due to the hypothetical interaction

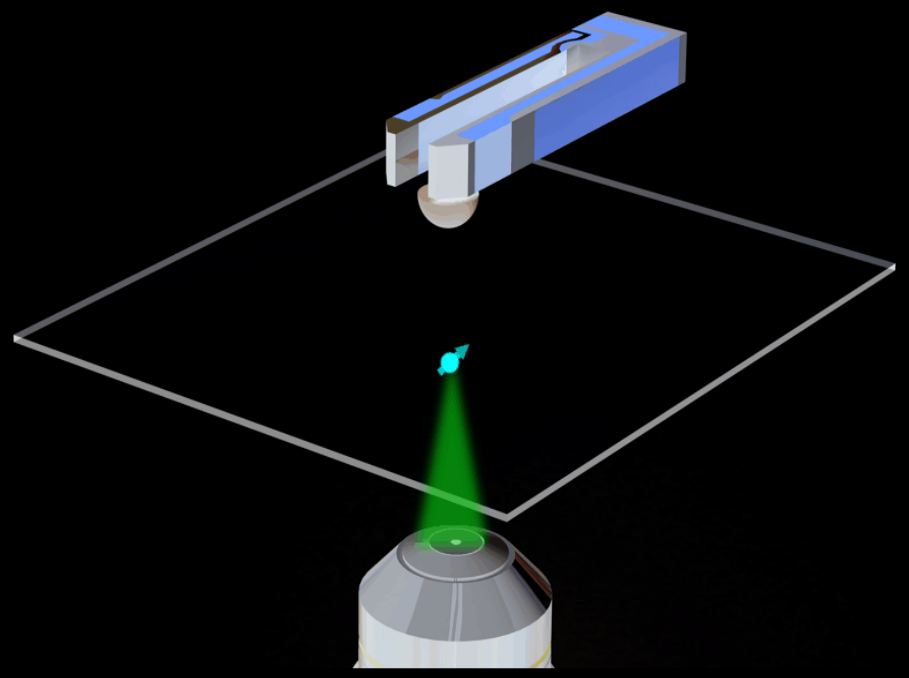
# EXPERIMENTAL RESULT WITHOUT THE NUCLEON SOURCE

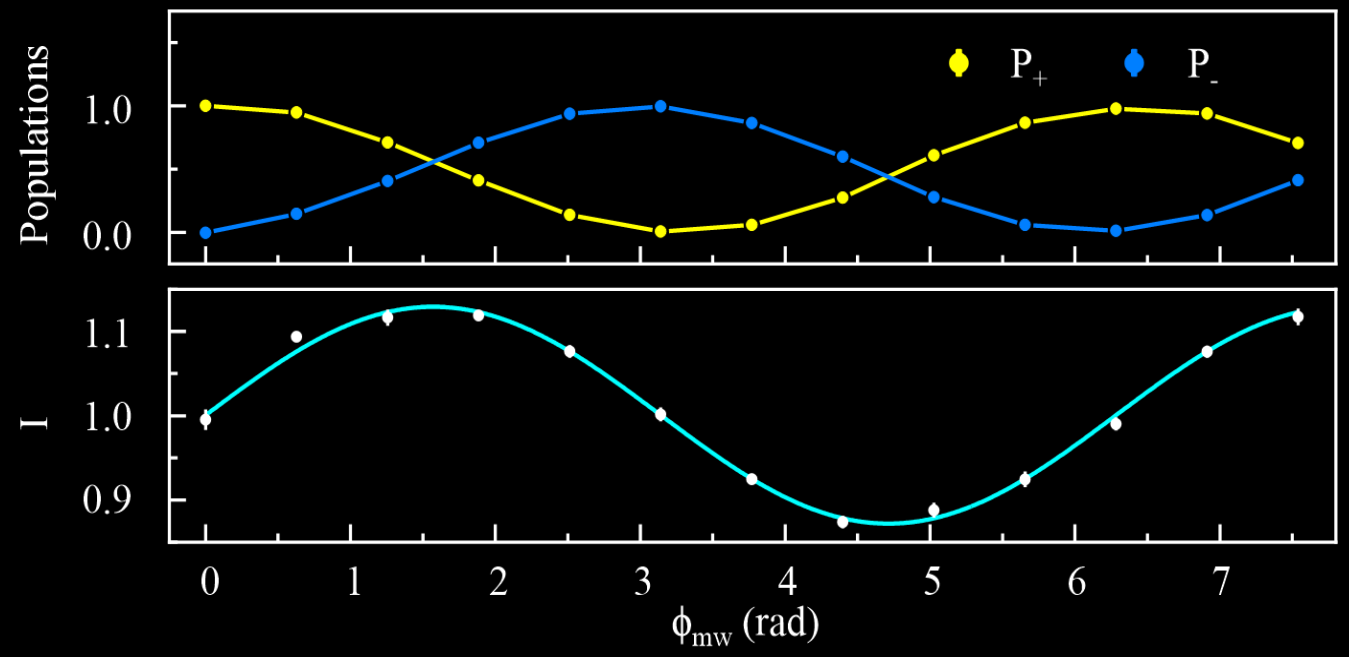





No signal has been observed.

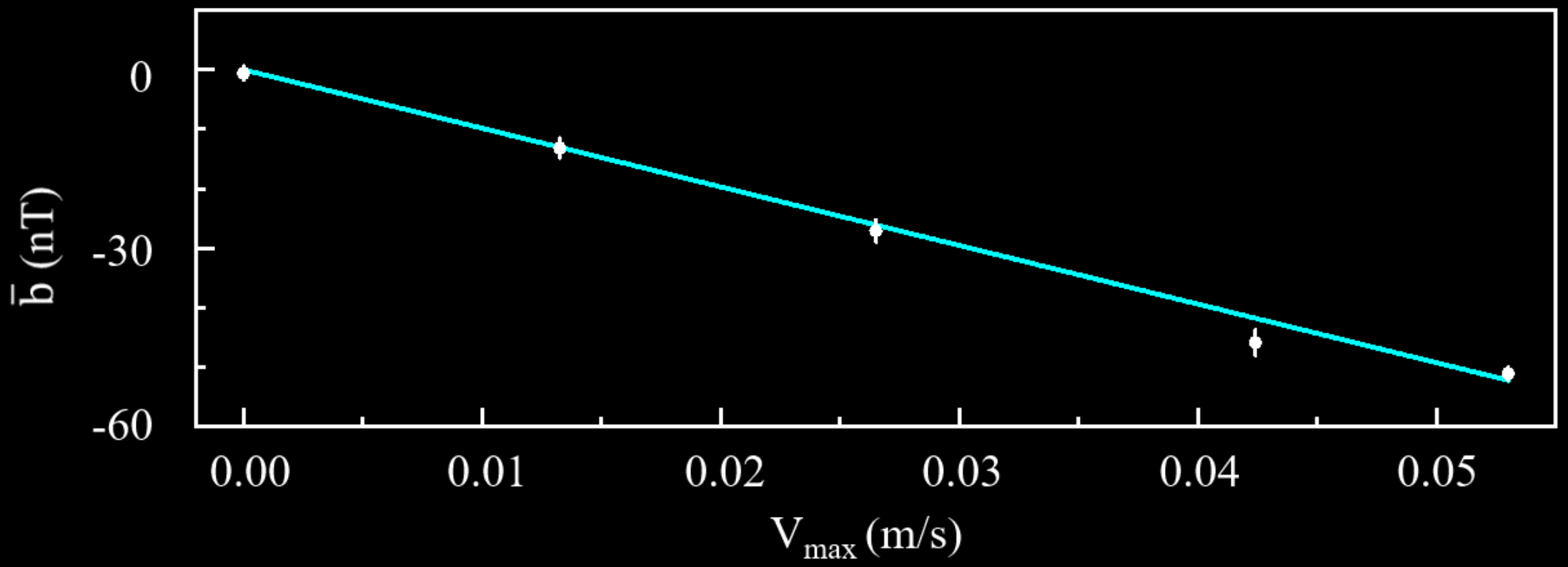
# EXPERIMENTAL RESULT WITH THE NUCLEON SOURCE





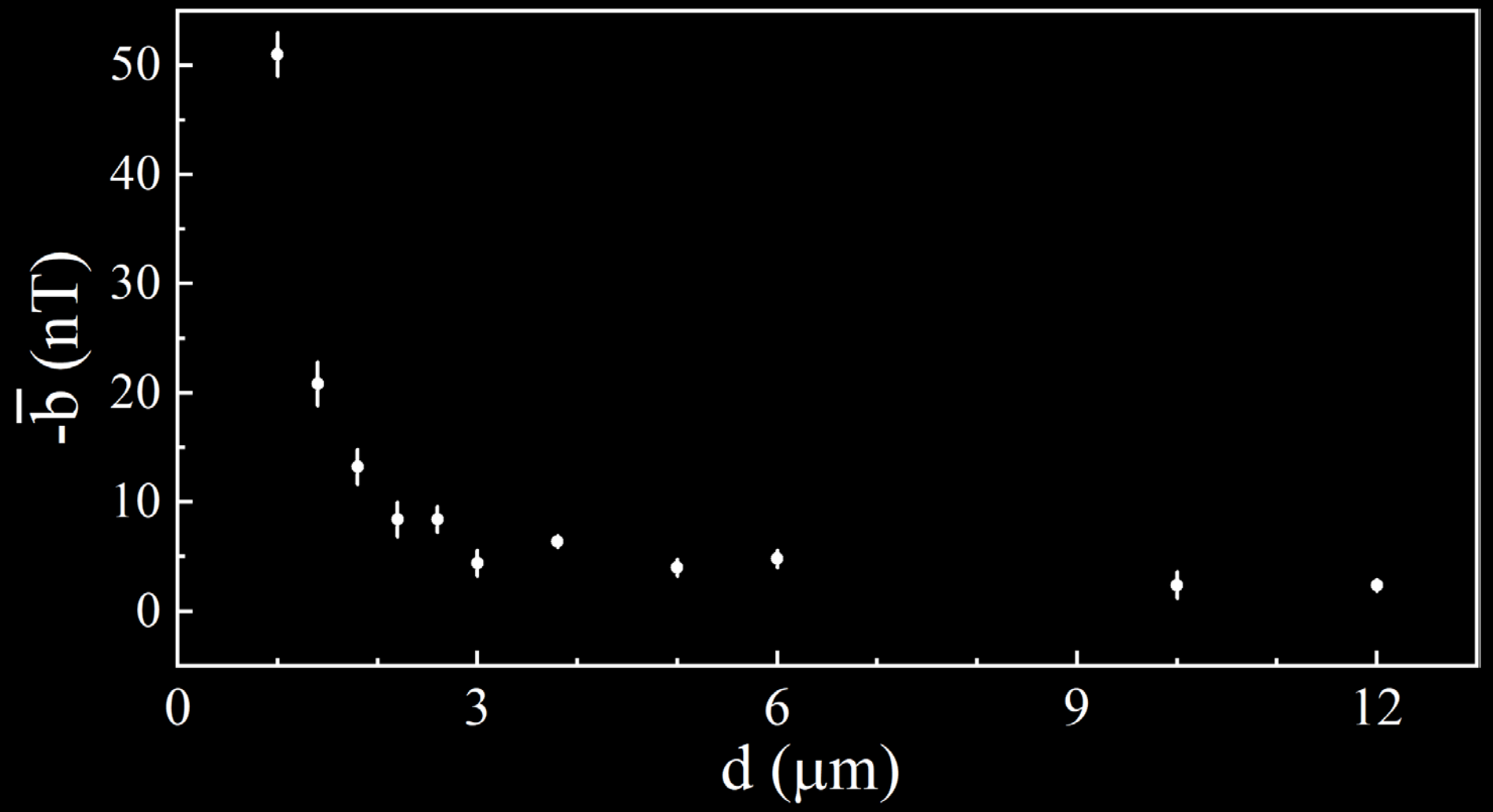

When d = 1 μm, Φ = 0.128(3) rad,
the corresponding averaging magnetic field is $\bar{b}$ = 51(1) nT.

# The dependency of the magnetic field $\bar{b}$ on the velocity of the mass




This effect is velocity dependent.

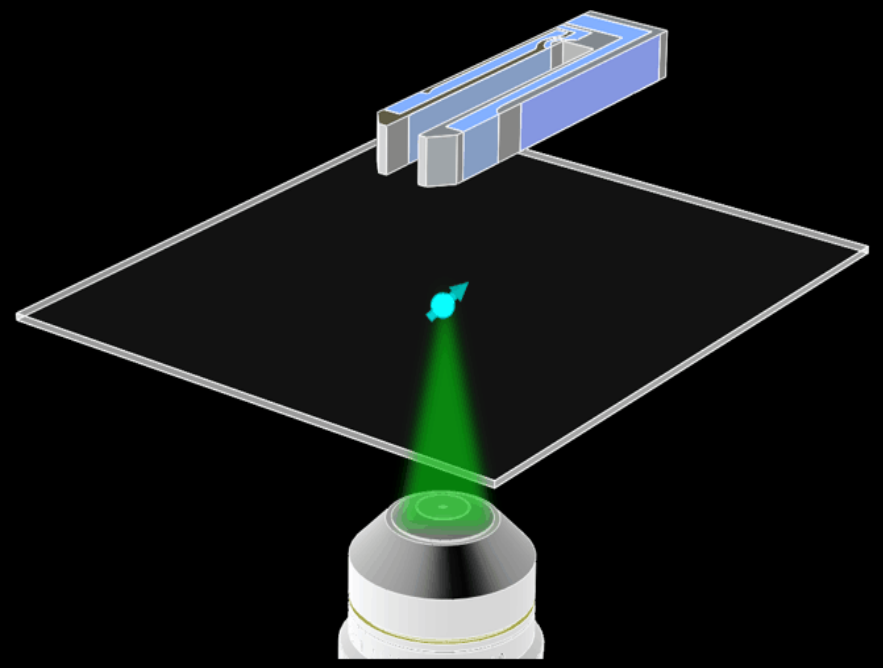
# The dependency of the magnetic field $\bar{b}$ on the distance d.

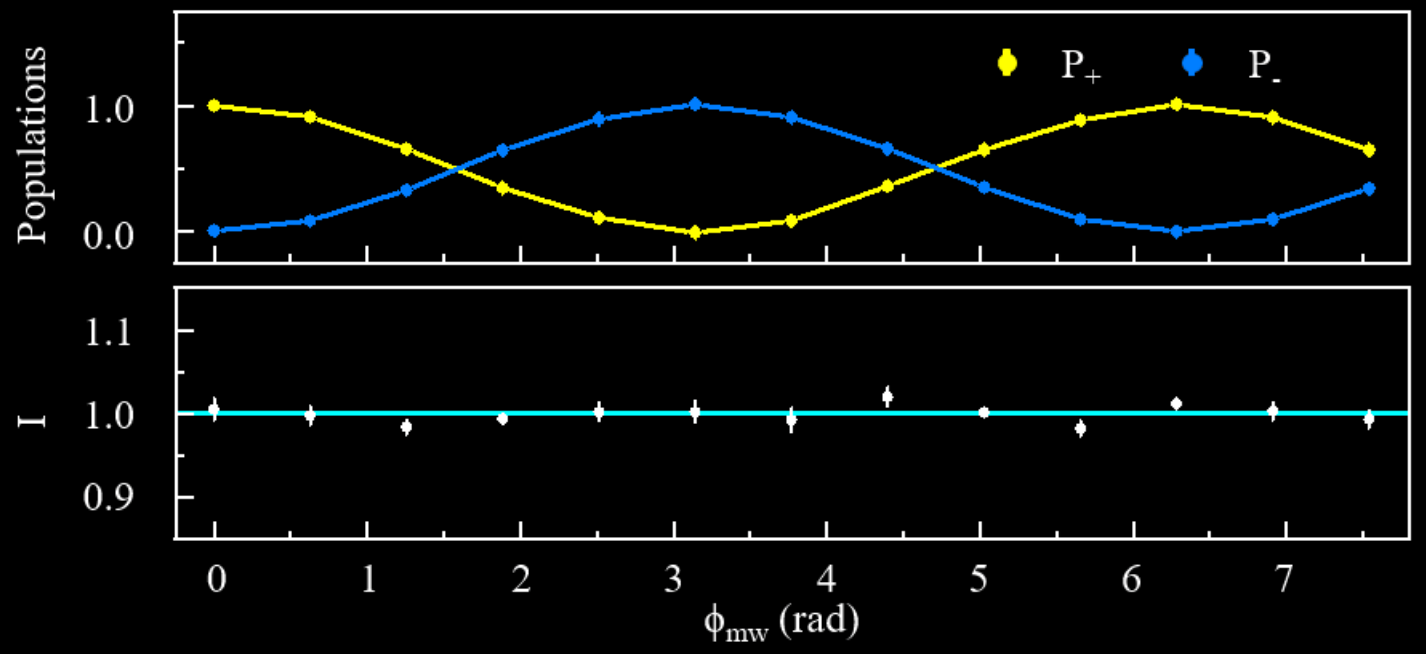


# ANALYSIS OF THE SOURCES OF THE MAGNETIC SIGNAL

- Tuning fork?
- Spins in the moving mass ?
- Diamagnetism of the moving mass?
- Electric charge on the moving mass?
- …

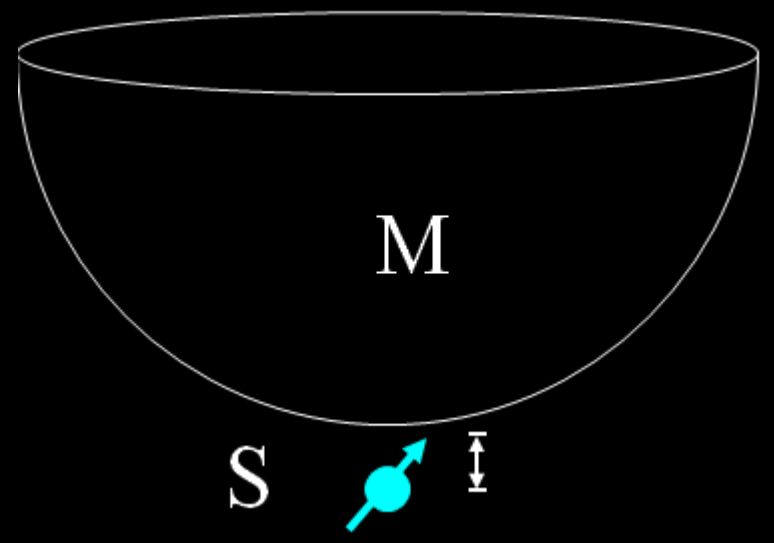
# TUNING FORK?






NO!

# SPINS IN THE MOVING MASS?

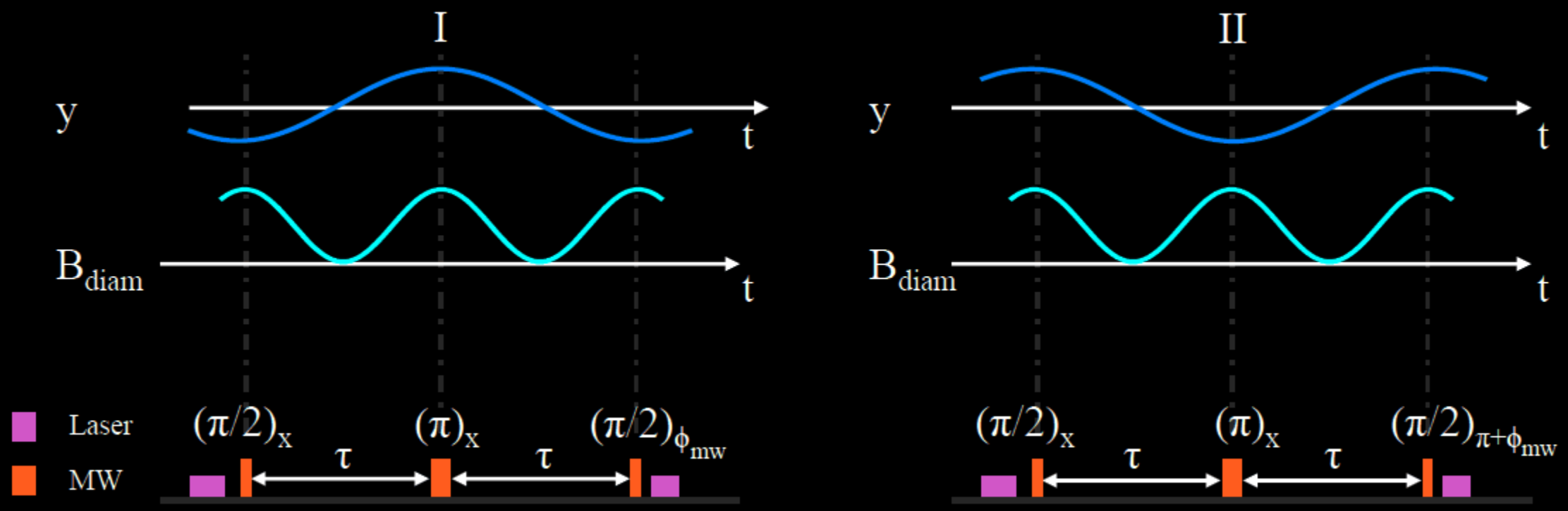



| Fused Silica ($SiO_2$) [ from Edmund Optics ] | |
|---|---|
| Impurities ($^{1}H$) | <0.1% |
| $^{29}Si$ | 4.7 % |
| $^{17}O$ | 0.04 % |

Under ambient condition, B = 473 Gauss,
Polarization of $^{1}H$ ~ 3E10-4
Polarization of $^{29}Si$ ~ 6.5E-5

Effect due to the spins in the moving mass is negligible.

# DIAMAGNETISM OF THE MOVING MASS?




The effect of the diamagnetism of the moving mass can be canceled by the spin echo sequence.

Considering the imperfection of the synchronization of the Hahn-echo sequence (less than 40 ns), the magnetic signal is less than 2.3E-7 nT, when d = 1 μm.

# ELECTRIC CHARGE ON THE MOVING MASS?

Biot-savart law

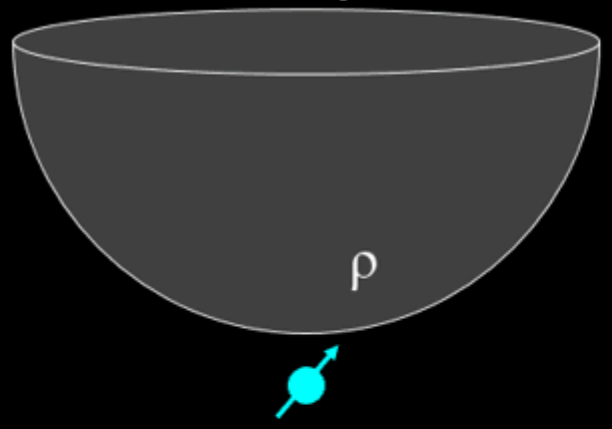
$$\vec{B} = \frac{\mu}{4\pi} q \frac{\vec{v} \times \vec{r}}{r^3}$$

The electric charge on the moving mass will generate magnetic field on the NV center!

# IF THE MAGNETIC SIGNAL IS FROM THE ELECTRIC CHARGE ON THE MOVING MASS, THEN

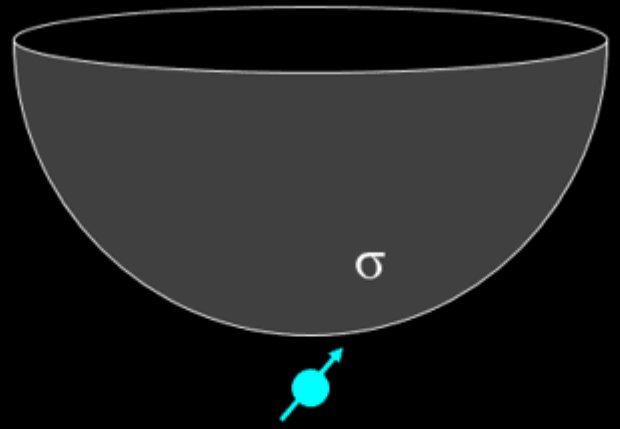
Case 1

$$Q = \rho V$$



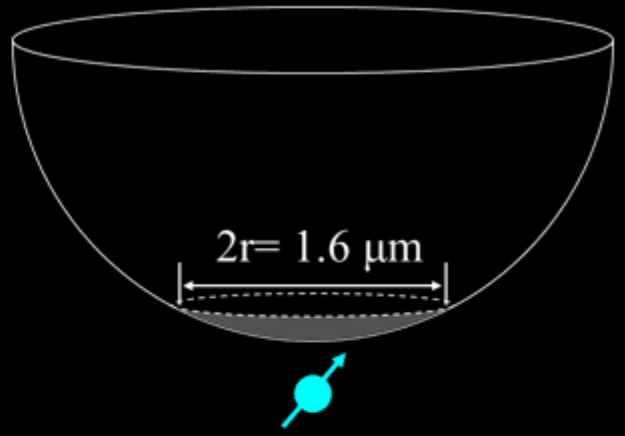

Case 2

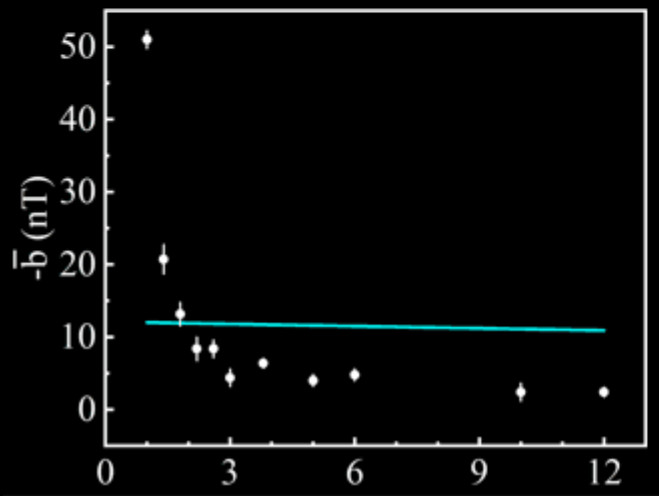
$$Q = \sigma S$$

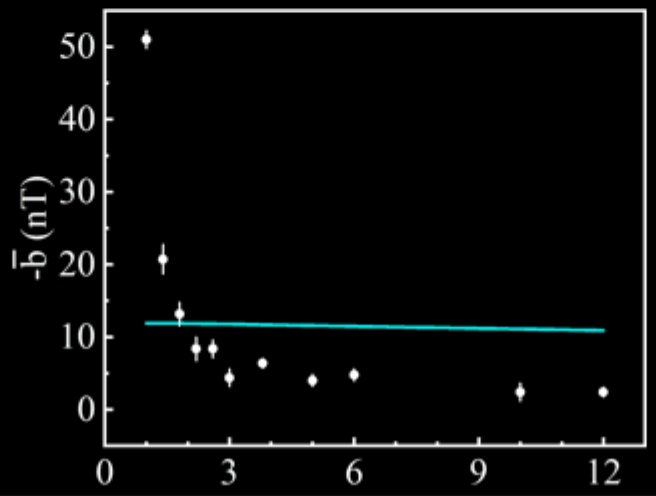


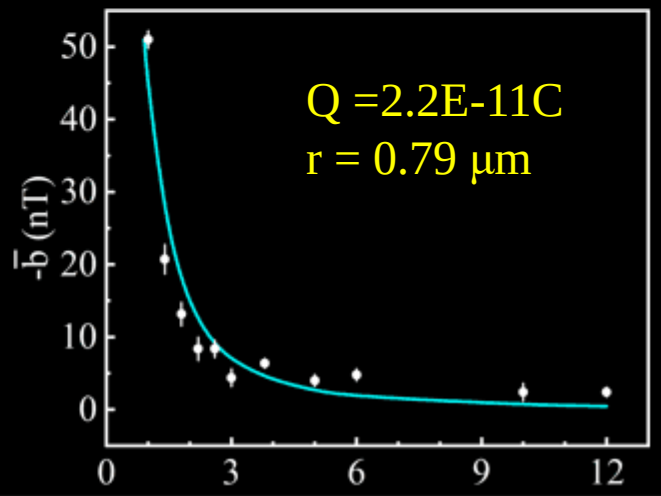

Case 3

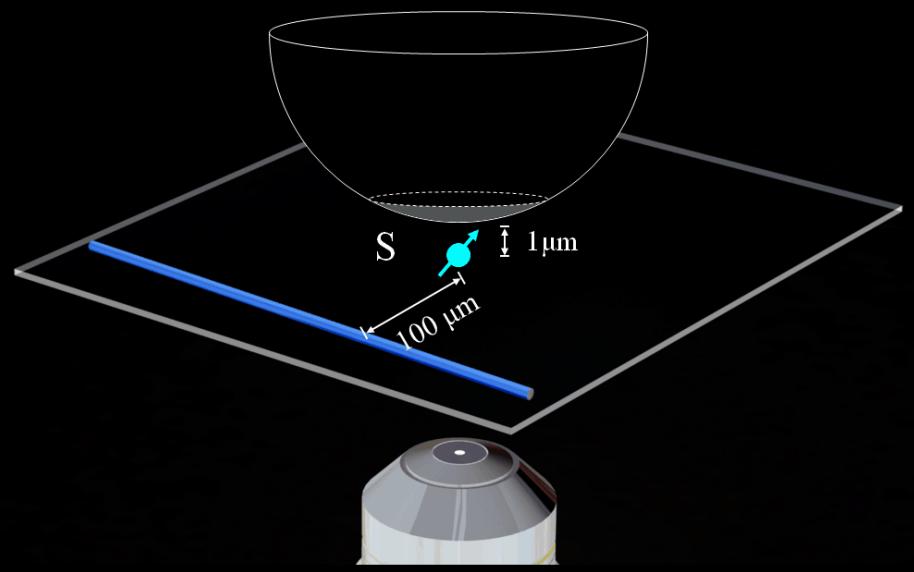
$$Q = \sigma' S'$$

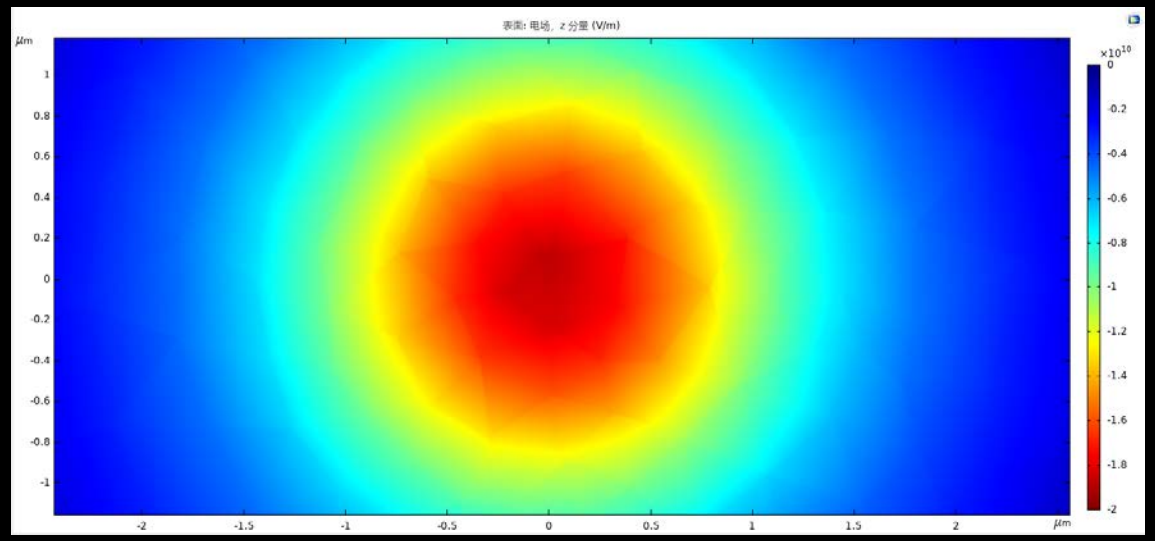




Simulation by COMSOL

$E_z = 120\ MV/cm$
$E_\perp = 160\ MV/cm$

$E_z$ : electric field along NV axis
$E_\perp$: electric field perpendicular to NV axis

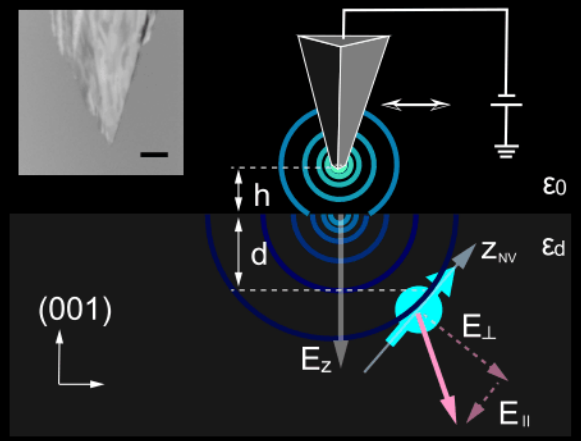
Electrical breakdown occurs in the air when the dielectric strength of the air is exceeded.
E=30kV/cm in the air at ambient condition will lead to break down. We have not observed such effect.

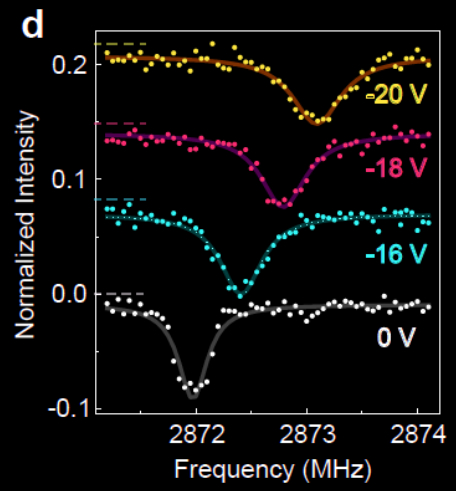
We have to discuss the effect of such strong eclectic field on the NV center.

$$H_0 = \gamma \vec{B} \cdot \vec{S} + (D + d_{||} E_z) S_z^2 - d_\perp E_x (S_x^2 - S_y^2) + d_\perp E_y (S_x S_y + S_y S_x)$$

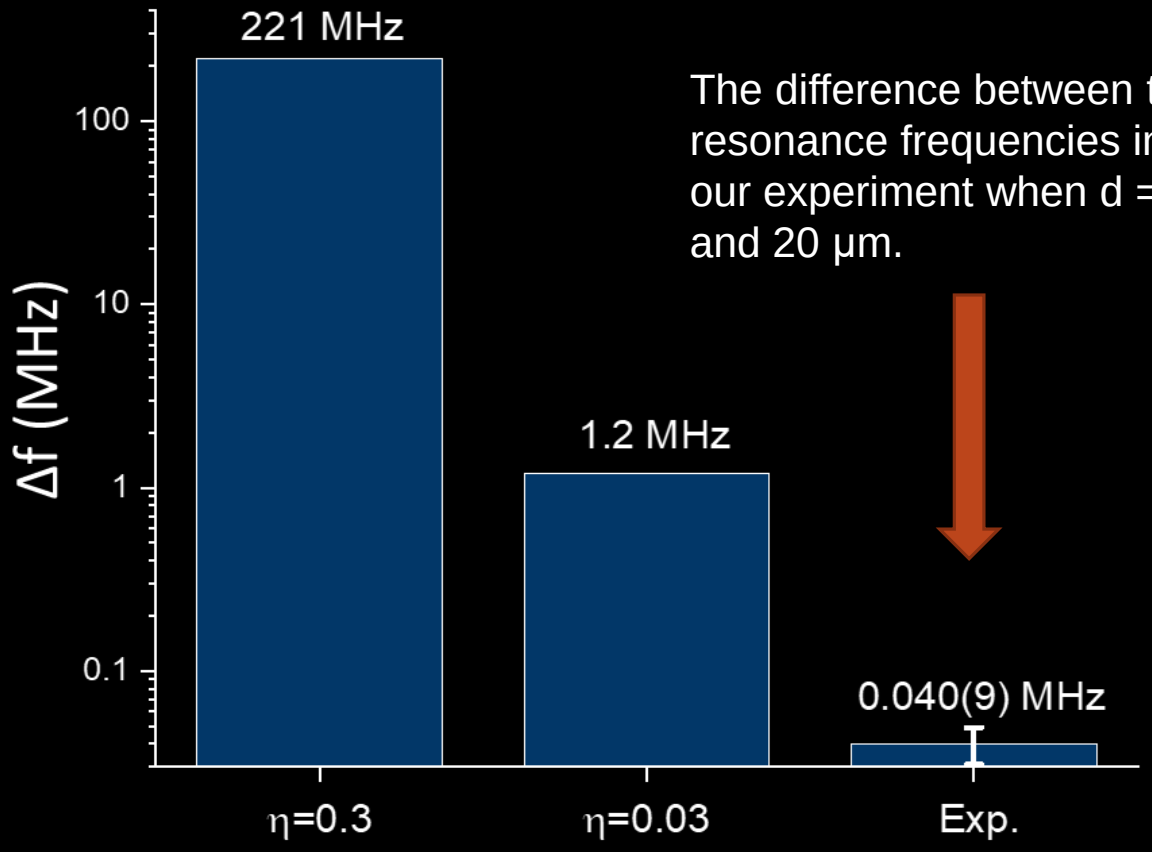
$d_{//}$ = 0.35 (2) Hz cm / V  $d_\perp$ = 17 (3) Hz cm / V  Chem. Phys. Lett. 168, 529 (1990)

The screening effect, according to recent experimental data [1], the screening effect is about $\eta \sim 0.3$



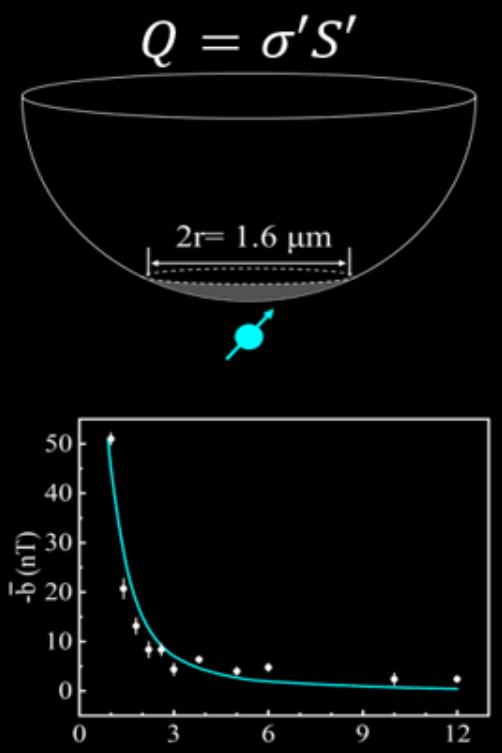




[1] K. Bian, et al, arXiv: 2011.04473(2020)




The difference between the resonance frequencies in our experiment when d = 1 and 20 μm.

# Electric charge on the moving mass?




If we use the charge on the moving mass to explain the dependency of the magnetic signal on the distance, the corresponding electric field is too strong.

- Electrical breakdown has not been observed.
- Resonance frequency shift due to such strong electric field has not been observed.

Thus we can exclude the electric charge on the moving mass as the source of the magnetic signal.

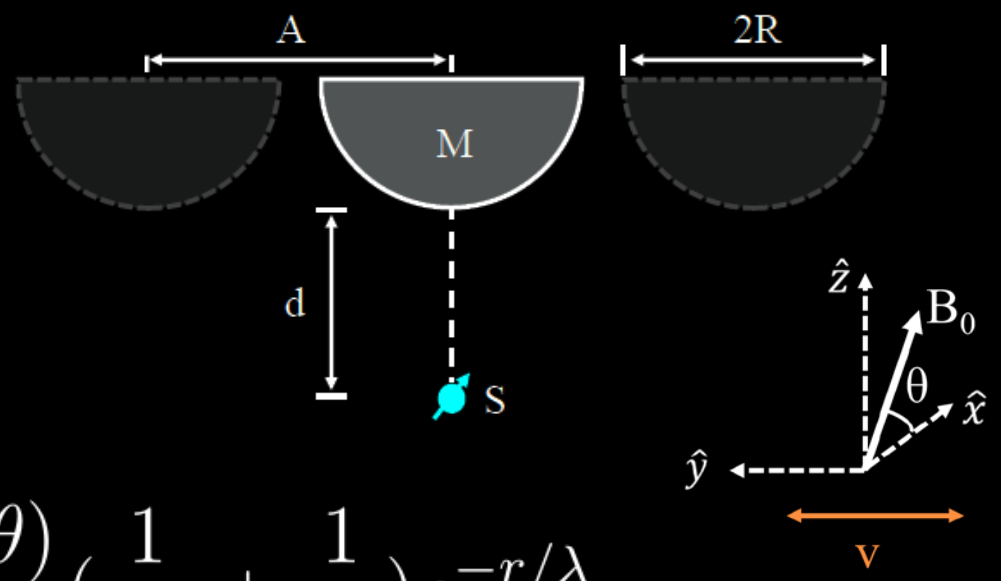
# ANALYSIS OF THE SOURCES OF THE MAGNETIC SIGNAL

- Tuning fork? NO
- Spins in the moving mass ? NO
- Diamagnetism of the moving mass? NO
- Electric charge on the moving mass? NO

- Exotic spin dependent interaction?

# parity-even spin- and velocity- dependent interaction

$$V = f^{\perp}\frac{\hbar^2}{8\pi m_e c}\boldsymbol{\sigma}\cdot\boldsymbol{v}\times\hat{r}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}$$

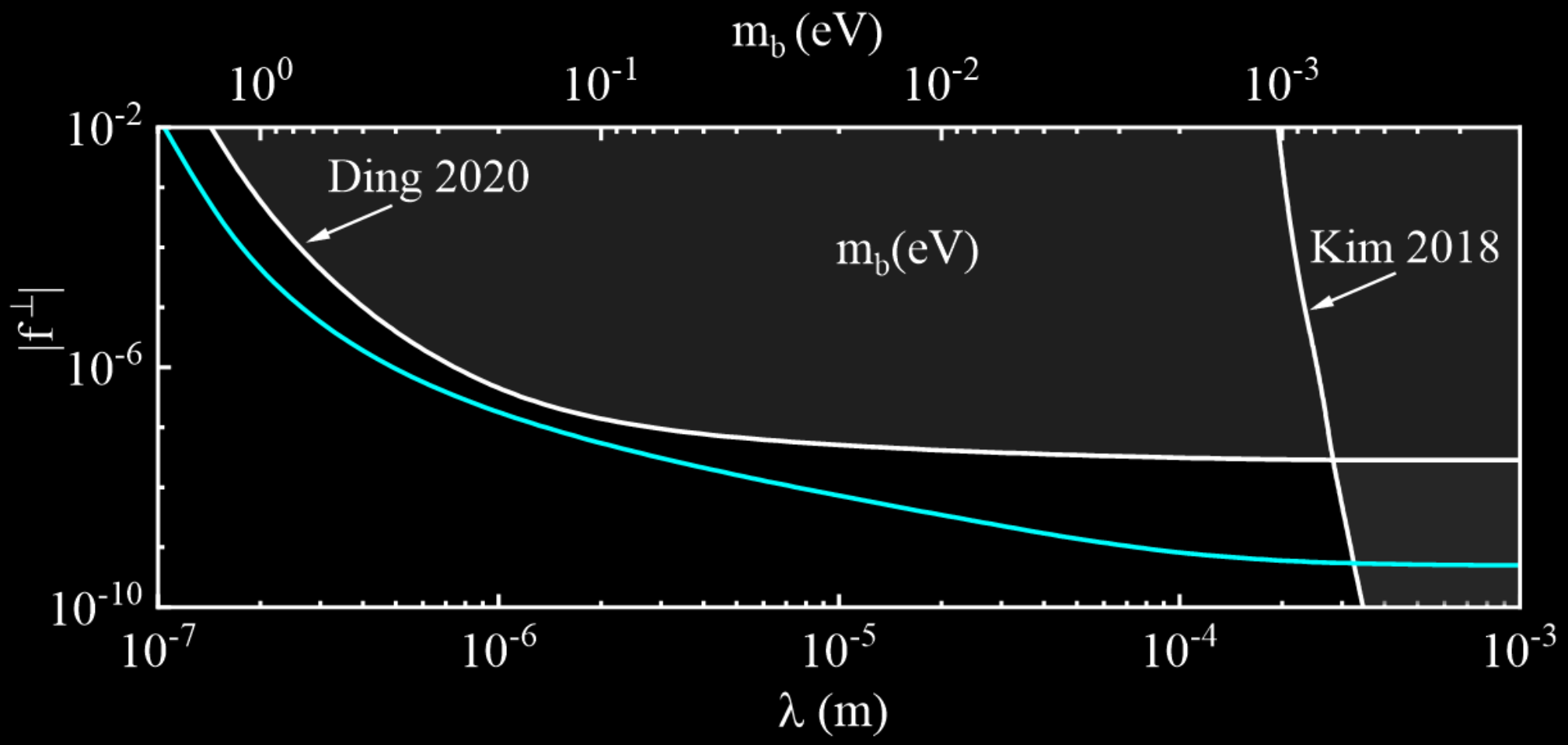


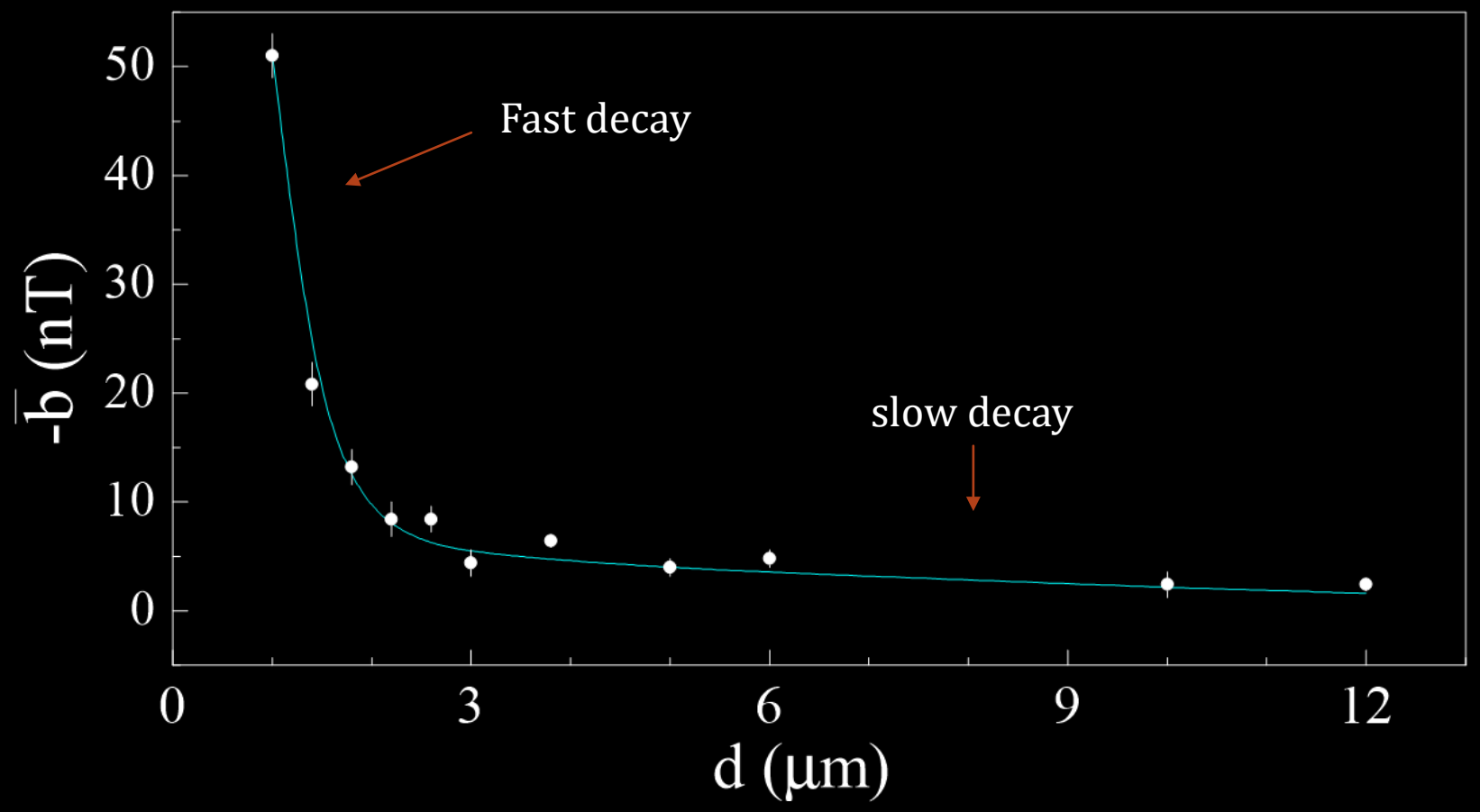

$$B(r) = f^{\perp}\frac{\hbar}{4\pi m_e c\gamma_e}v_y\frac{(-r_x\sin\theta + r_z\cos\theta)}{r}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$\mathbf{B}_{\text{eff}} = \int_V \rho\mathbf{B}(r)dV$$

Dobrescu, B. A. & Mocioiu, I. Spin-dependent macroscopic forces from new particle exchange. J. High Energy Phys. 11, 005 (2006).

# PRECISION OF OUR EXPERIMENT



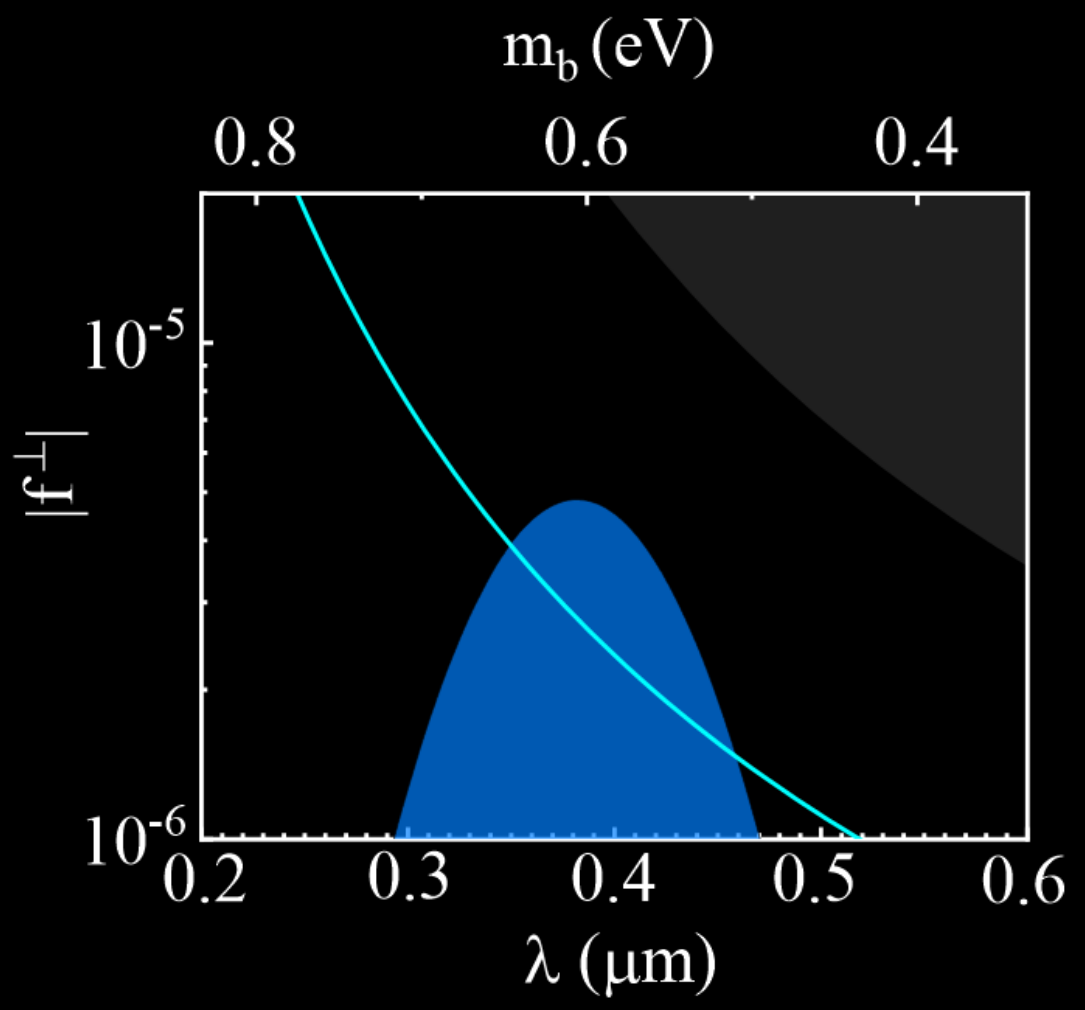


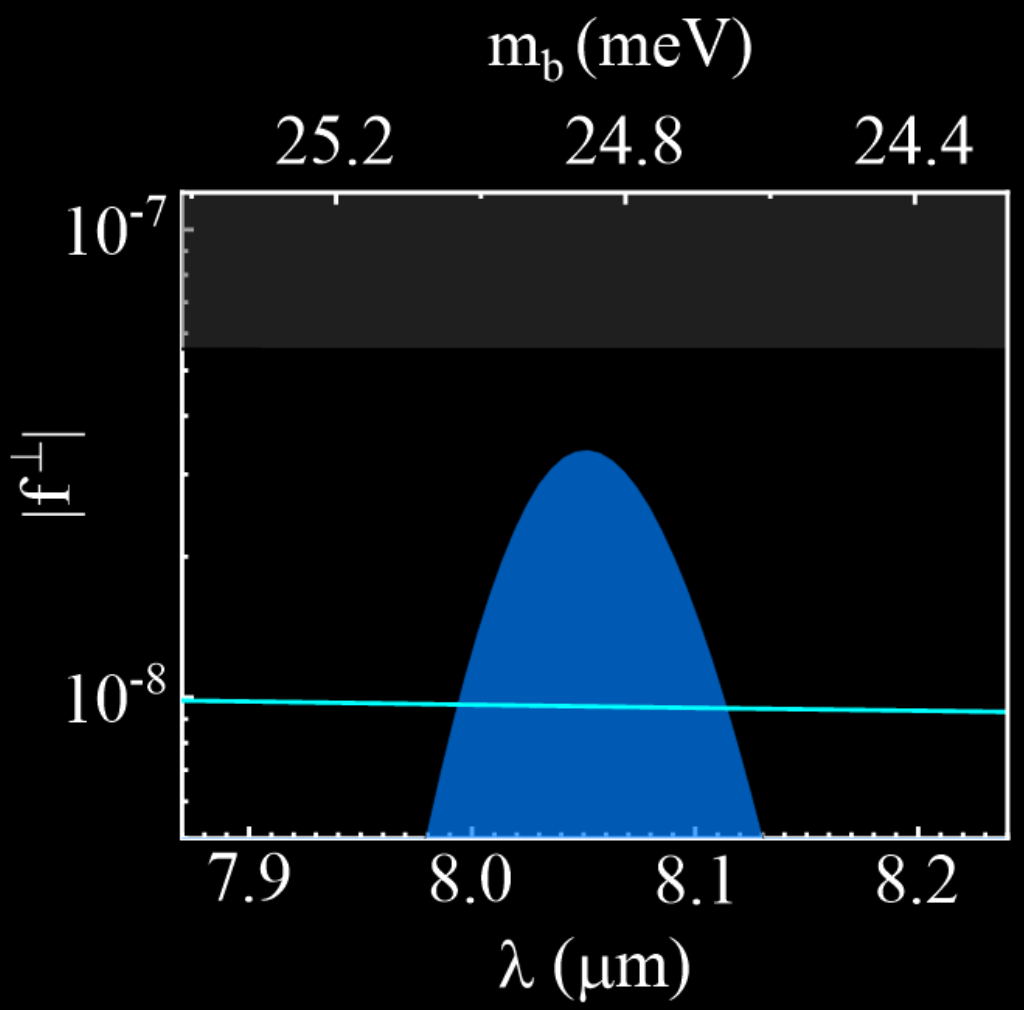

$$\bar{b} = \frac{1}{\tau}\int_0^{\tau}\left(\sum_{i=1}^{N} B_{eff}\left(\lambda_i, f^{\perp}(\lambda_i), t\right)\right) dt,$$

$$f(\lambda) = f_1^{\perp} g(\lambda, \lambda_1, \Gamma_1) + f_2^{\perp} g(\lambda, \lambda_2, \Gamma_2),$$

$$g(\lambda, \lambda_c, \Gamma) = \exp\left[-(\lambda - \lambda_c)^2/2\Gamma^2\right]$$

# SPECTRUM OF THE NEW BOSONS



# Summary

- NV centers can be a powerful platform for investigating new physics.
- Non-zero magnetic signal has been observed on the NV center with a moving mass.
- Possible sources of this signal have been carefully analyzed.
- A possible explanation of such magnetic signal could be a type of parity-even spin- and velocity- dependent interaction.

# Acknowledgements

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