Spring 3-5-2018

NV Center Detection of Electric Fields and Low-Intensity Light

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NV Center Detection of Electric Fields and Low-Intensity Light

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APS March Meeting Los Angeles
Session 26: Sensing with Defects
Monday March 5, 2018, 2:03 pm

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This work was supported by the DARPA program DETECT

DARPA

Motivation

- NV centers in diamond have been shown to be sensitive electric field sensors

Dolde *et al*. Nat. Phys. **7**, 459 (2011)

Dolde *et al*. Phys. Rev. Lett. **112**, 097603 (2014)

B26.00002 High precision electric field sensing with spin ensembles in diamond. J. Steiner et al.

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Motivation

- Can electric field detection be parlayed into single/few photon detection?

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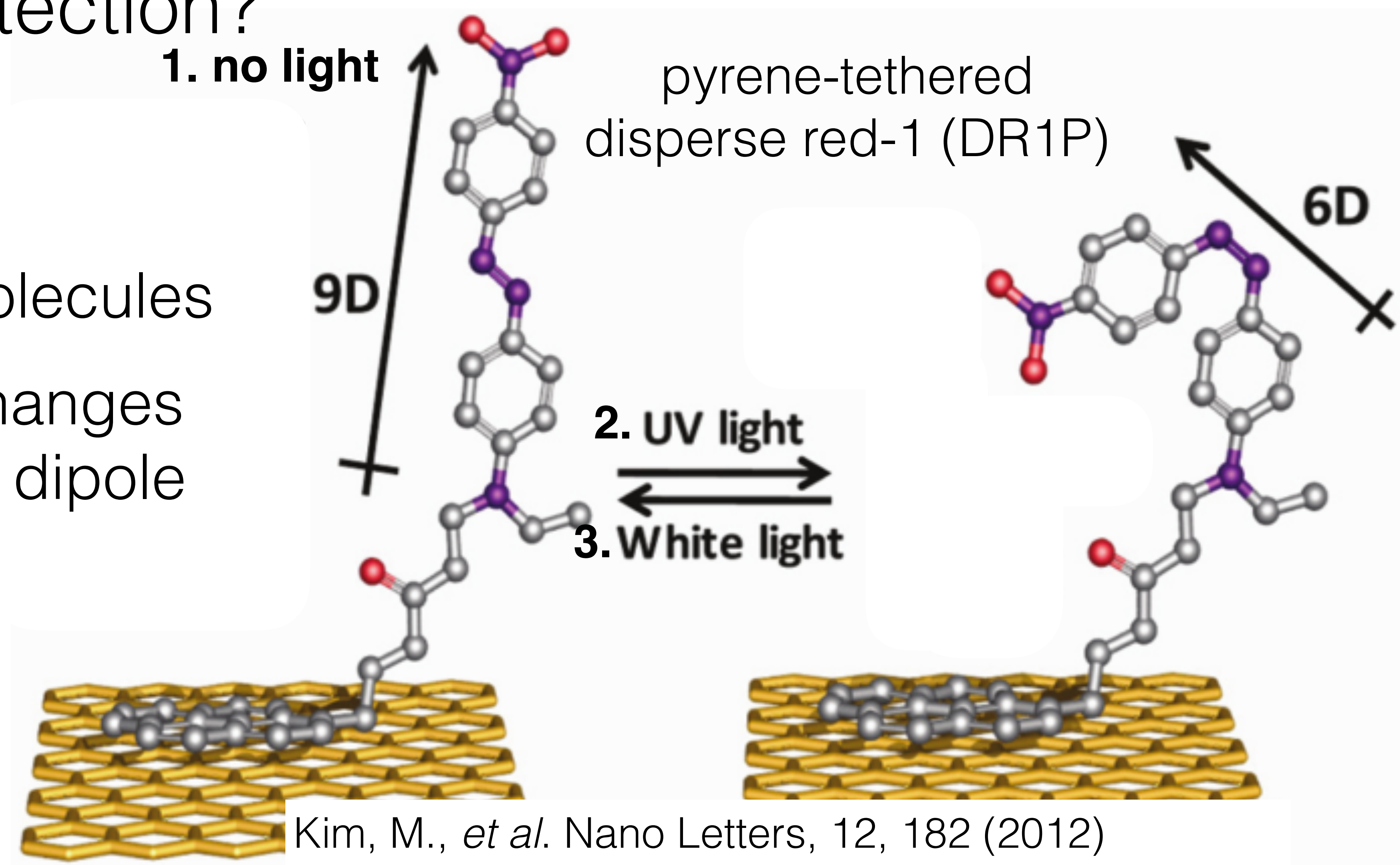

Kim, M., *et al*. Nano Letters, 12, 182 (2012)

- photosensitive molecules
- conformational changes lead to change in dipole moment

- light sensor based on electric field of dipole
  - transport in graphene, carbon nanotubes modulated by the electric field after absorption

Young, Sarovar, Léonard, arXiv:1710.09512 (2017)

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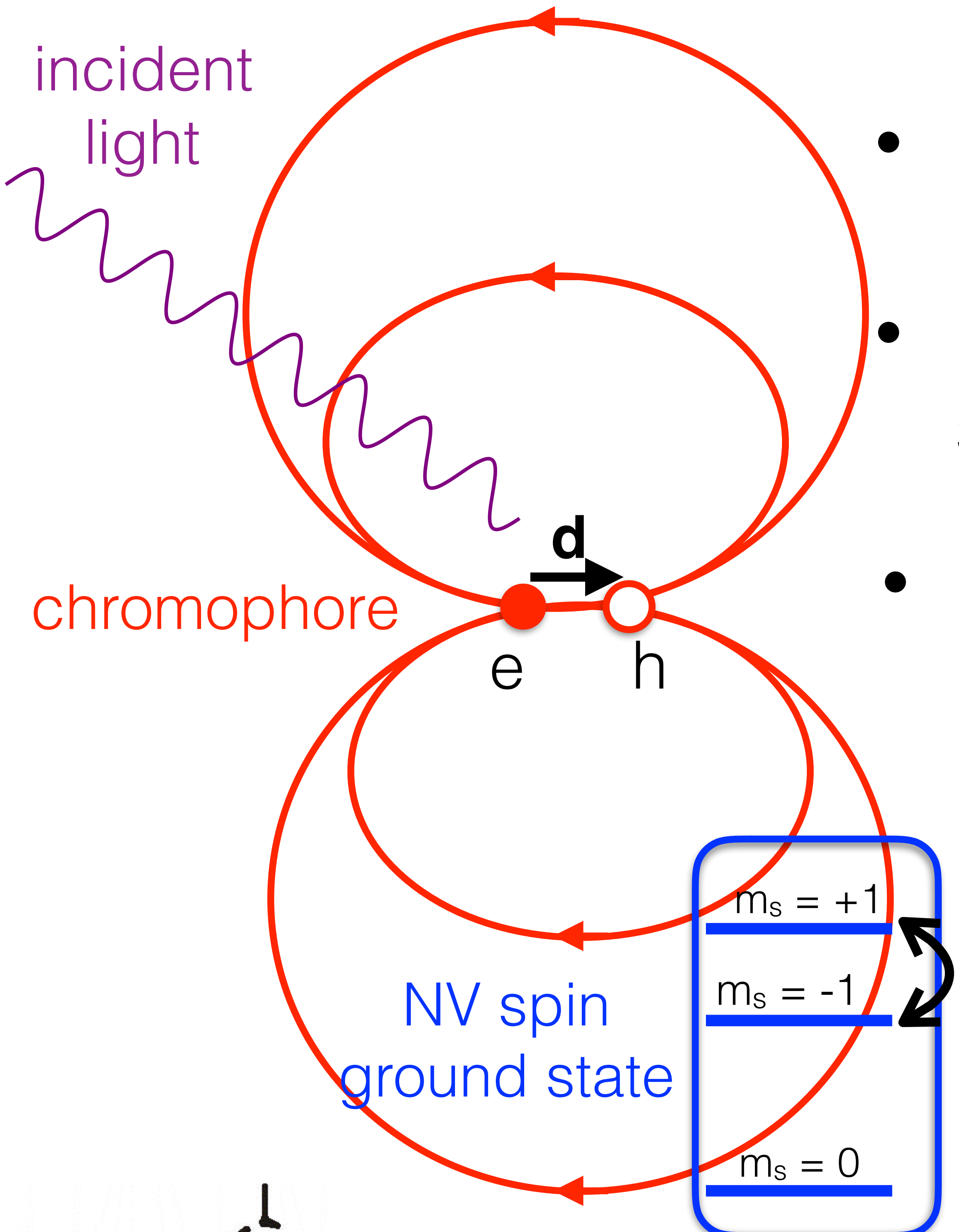
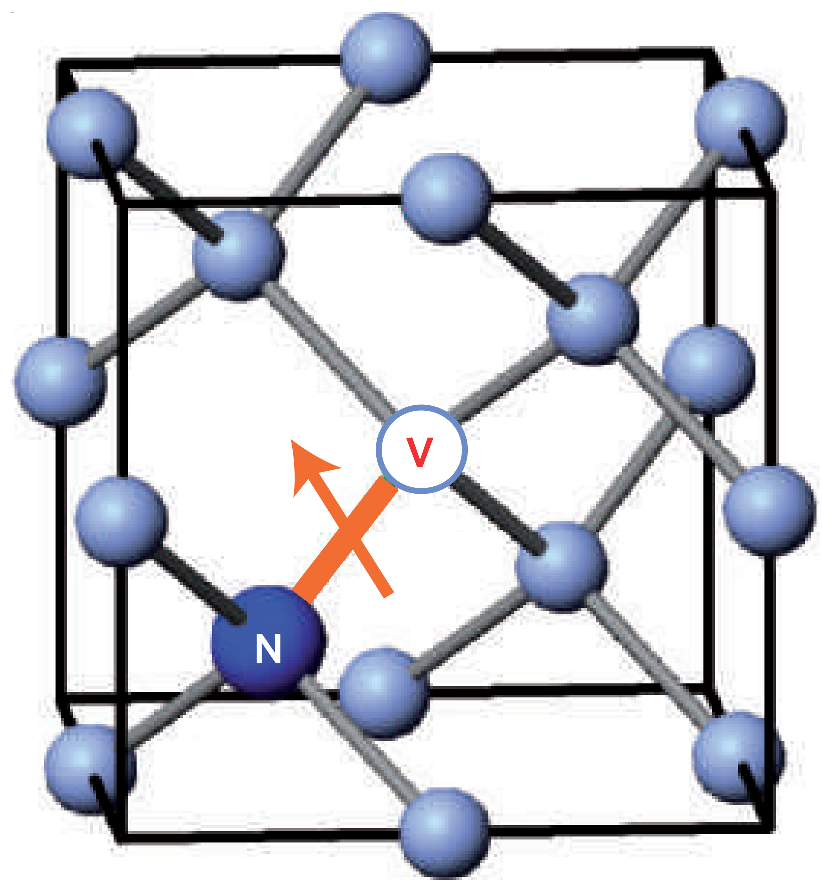
Diamond NV Center as Sensor



- Position chromophore near diamond
- Electric dipole field interacts with NV spin
- Chromophore electric field ~10^6 V/m at few nm below diamond surface



Flatté and Koenraad, Nat. Mat. **10** 91, (2011)

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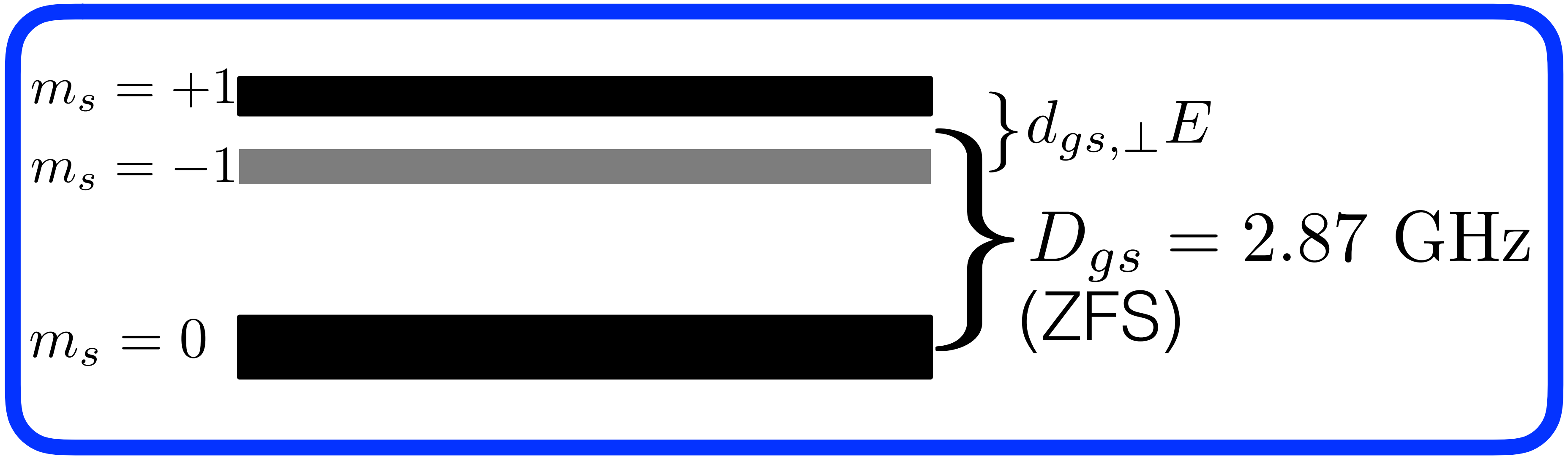
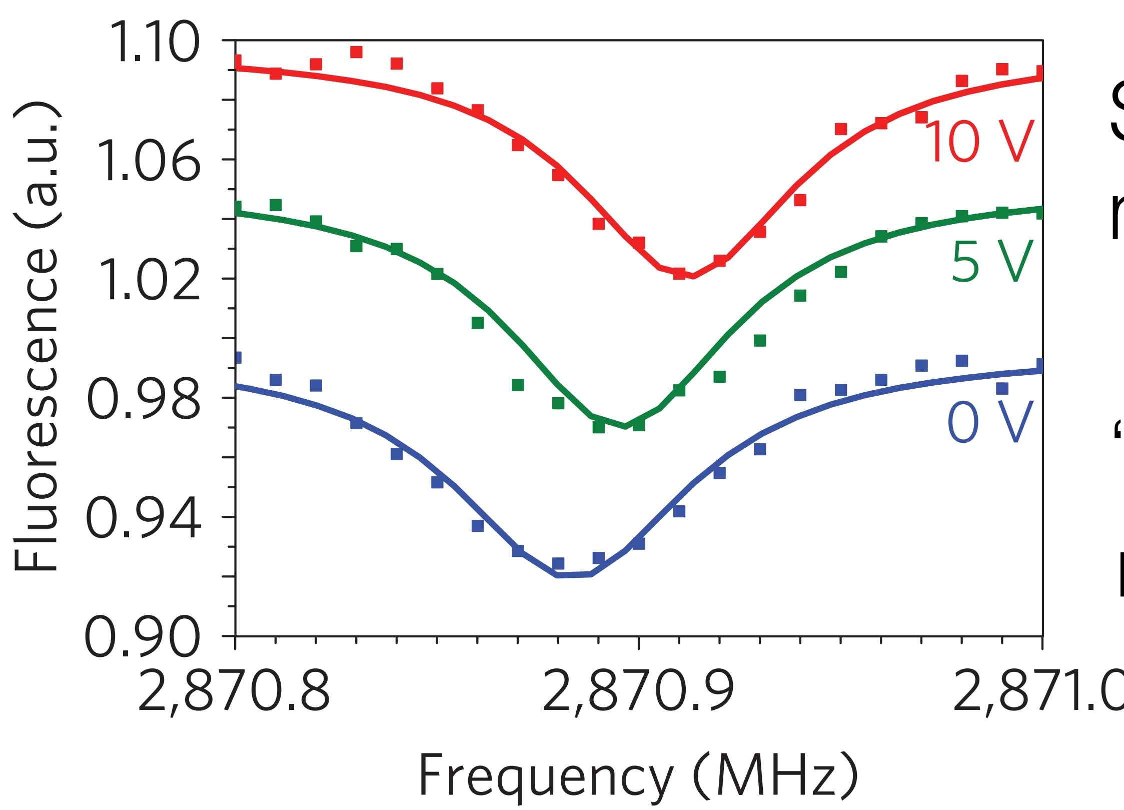
NV Ground State

Electric field splits m_s =+/-1 states

$$\mathscr{H}_{gs} = (2\pi\hbar D_{gs} + d_{gs,||}E_z)S_z^2 + d_{gs,\perp}\left[E_x(S_x^2 - S_y^2) + E_y(S_xS_y + S_yS_x)\right]$$





Stark shift observed in magnetic resonance

"parameter estimation"

Dolde *et al*. Nat. Phys. **7**, 459 (2011)

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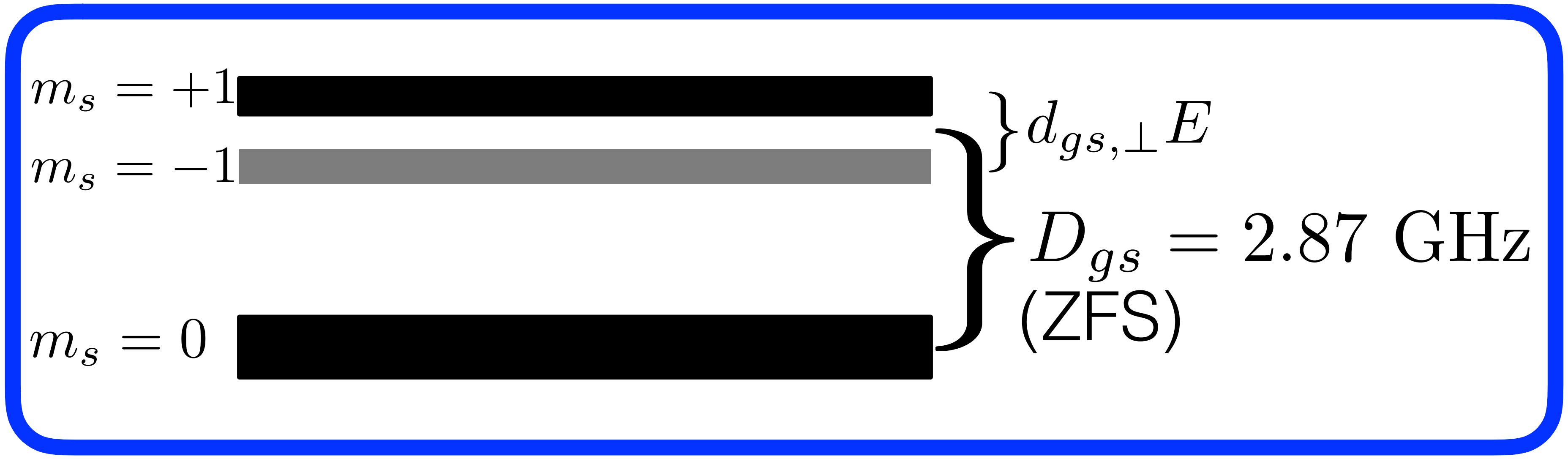
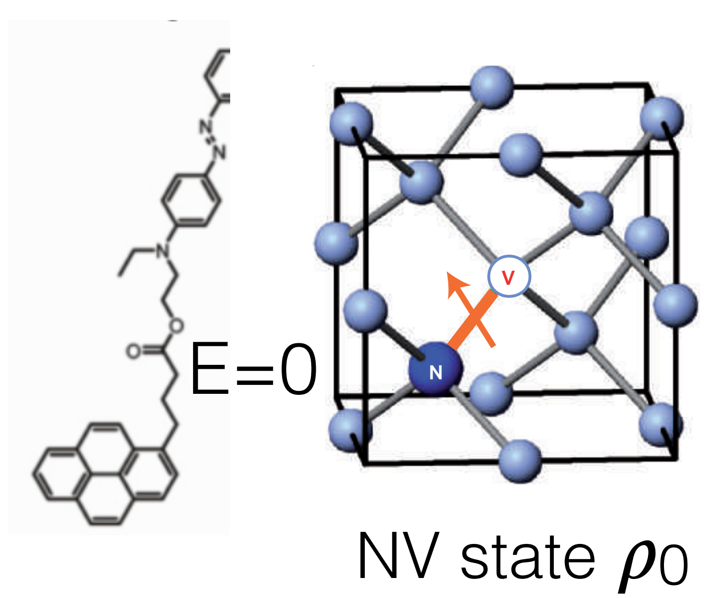
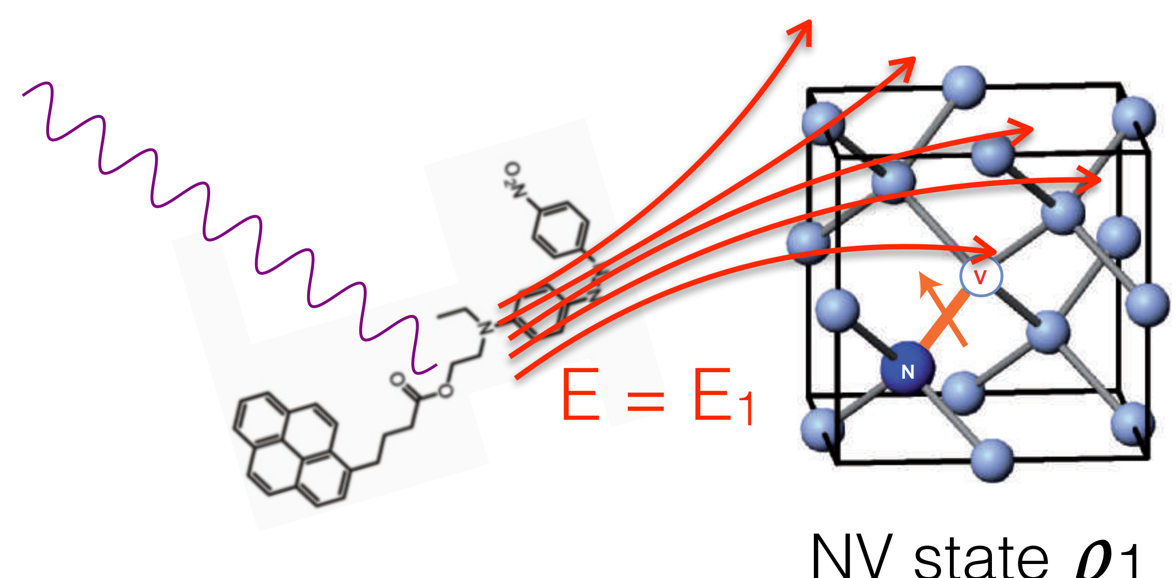


<u>no light absorbed</u>



<u>light absorbed</u>



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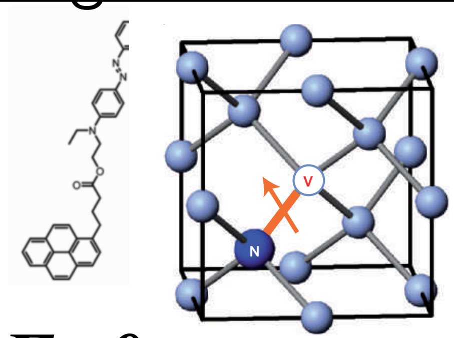
initiate spin as $|1\rangle$

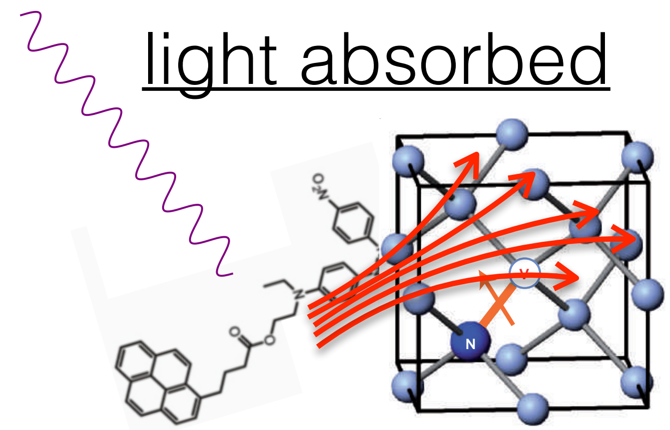
<u>no light absorbed</u>



$\boldsymbol{E=0}$

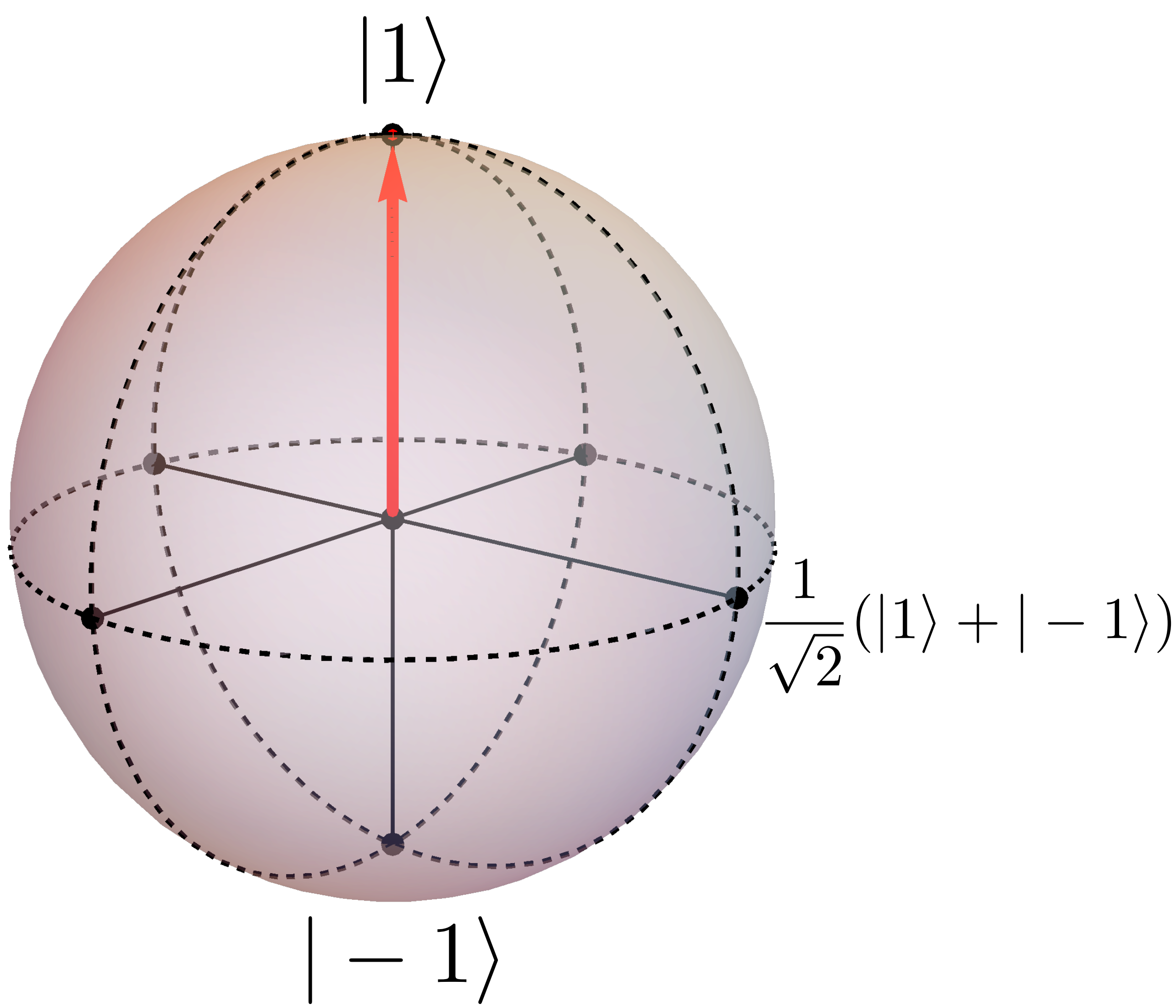
NV state |1>

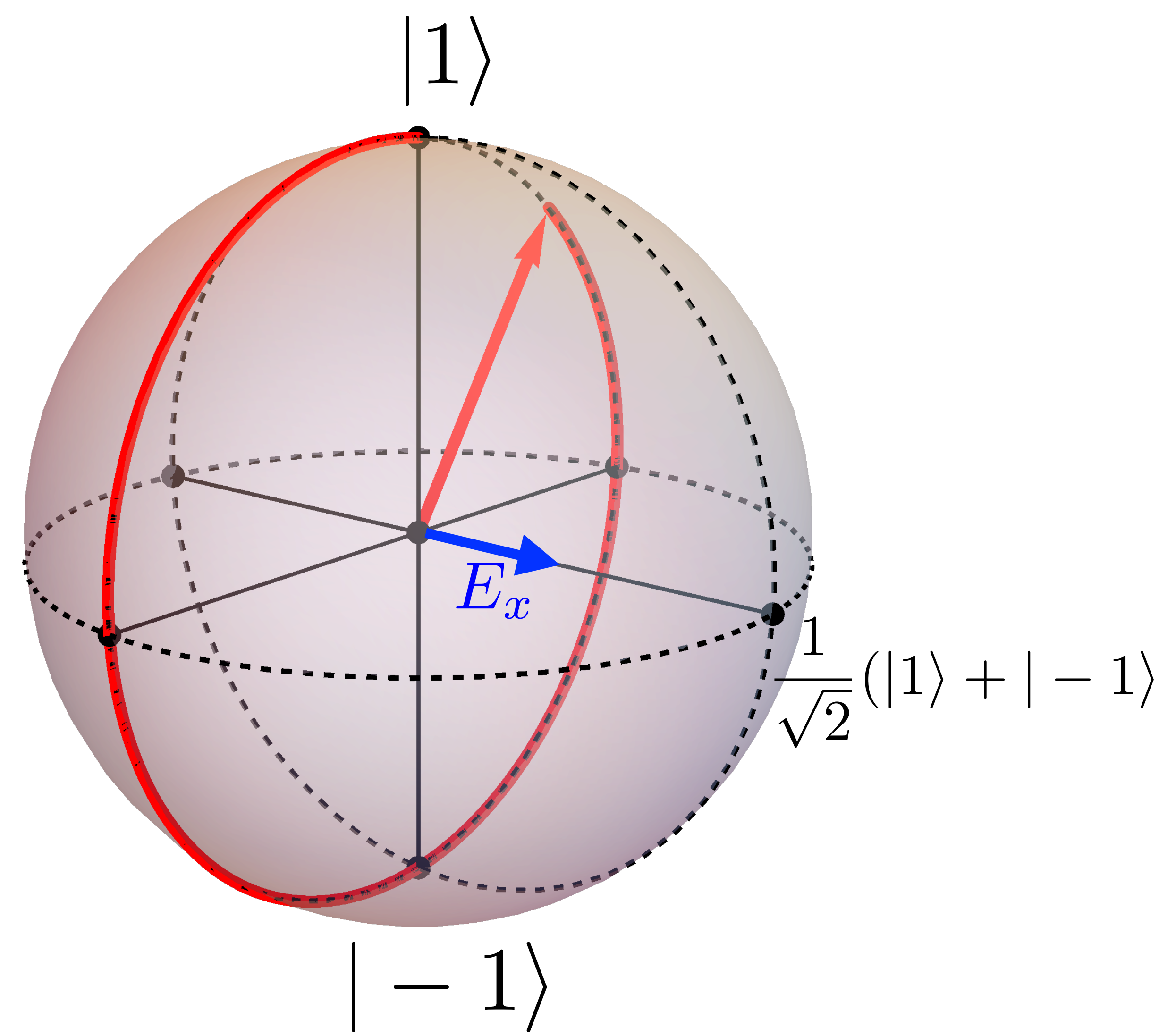
<u>light absorbed</u>



$\boldsymbol{E = E_x}$

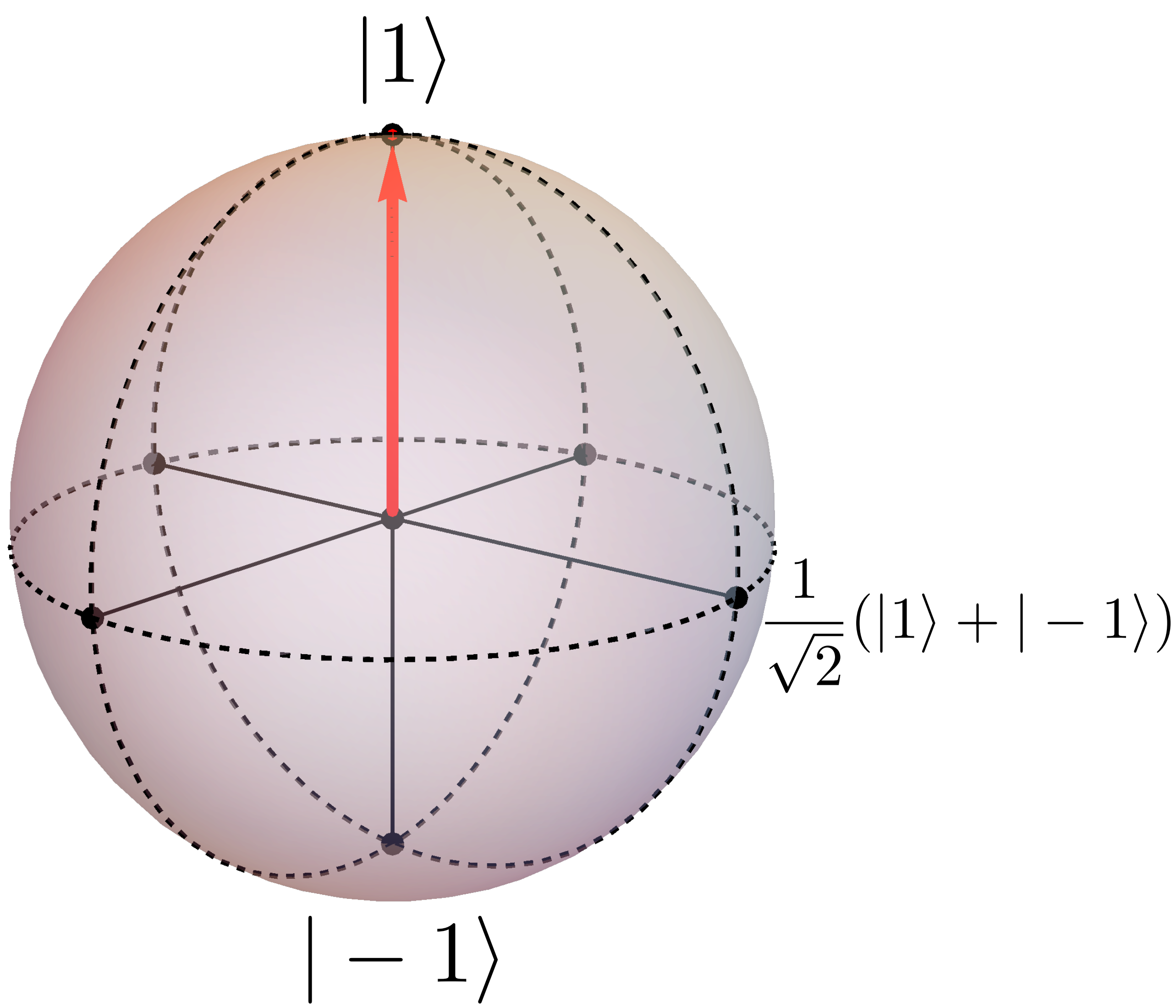
NV state a|1> + b|-1>

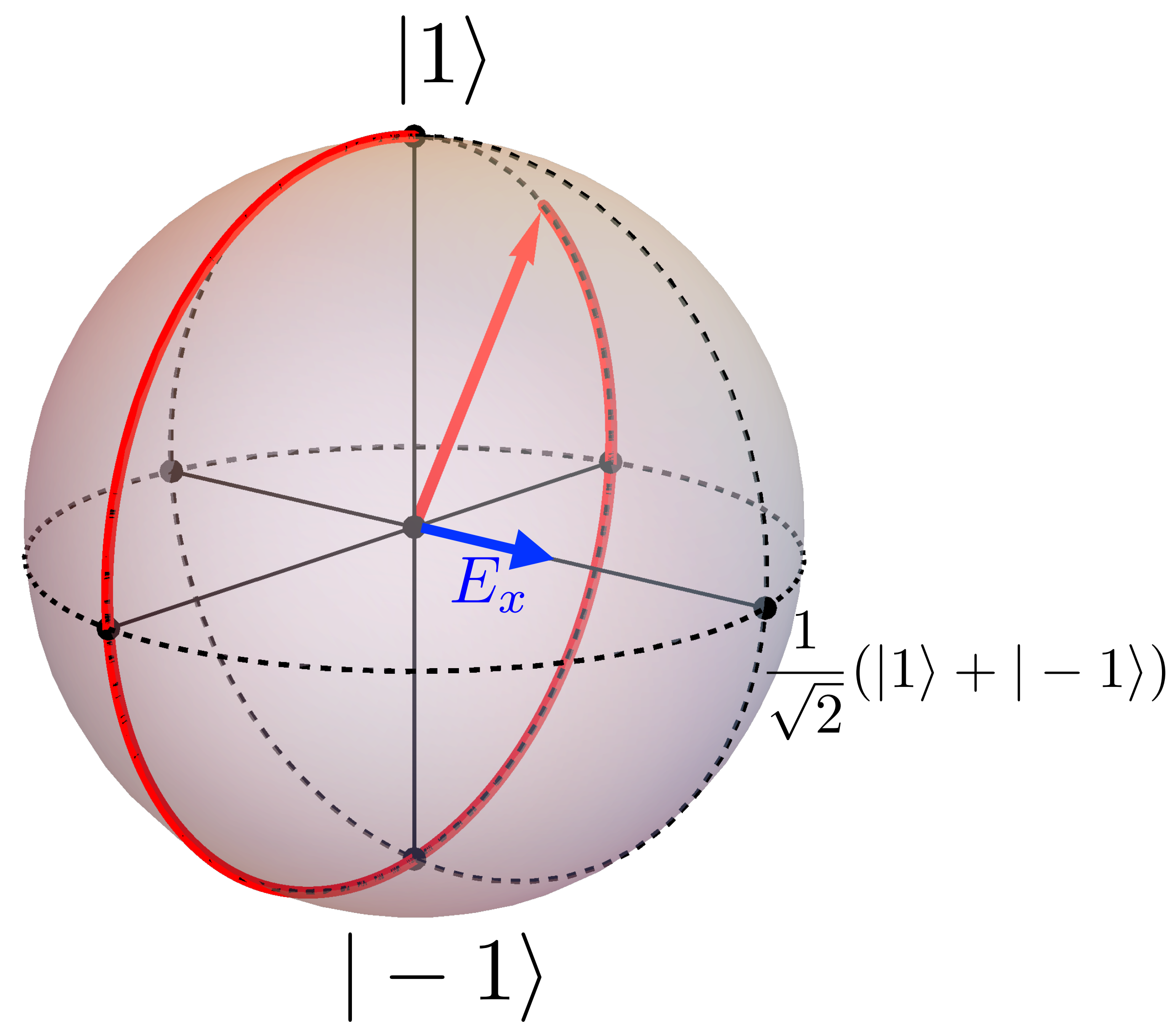




Quantum Discrimination

- Measuring |-1⟩ ➪ electric field ➪ photon absorption
- Distinguishing between non-orthogonal states is not possible with certainty (what to conclude if |1⟩ is measured?)





Quantum Discrimination

- Quantum discrimination theory determines which operators will minimize the error [positive operator valued measurements (POVMs)]

  C. W. Helstrom, Quantum Detection and Estimation Theory (Academic, New York, 1976)

- $|\pm 1\rangle$ is not best measurement basis

- Optimal measurement operators (i.e. minimize error)

$\hat{\Pi}_0 = |\phi_0\rangle\langle\phi_0|$ where $|\phi_k\rangle$ are eigenvectors of

$\hat{\Pi}_1 = |\phi_1\rangle\langle\phi_1|$

$$\Lambda = P_1\rho_1 - P_0\rho_0$$

ρ_0 density matrix for E = 0

ρ_1 density matrix for E ≠ 0

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AZ Chaudhry. Phys. Rev. A **91**, 062111 (2015)

Quantum Discrimination

- Find minimal error probability
- Density matrices without electric field (ρ_0) and with electric field (ρ_1) are determined from Liouville-Lindblad equation

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}\underbrace{[\mathscr{H}_{gs}, \rho]}_{\text{coherent}} + \hat{L}_d \rho \underbrace{\hat{L}_d^T - \frac{1}{2}\{\hat{L}_d^T}_{\text{decoherence}} \hat{L}_d, \rho\}$$

$$\mathscr{H}_{gs} = (2\pi\hbar D_{gs} + d_{gs,||} E_z) S_z^2 + d_{gs,\perp}\left[E_x(S_x^2 - S_y^2) + E_y(S_x S_y + S_y S_x)\right]$$

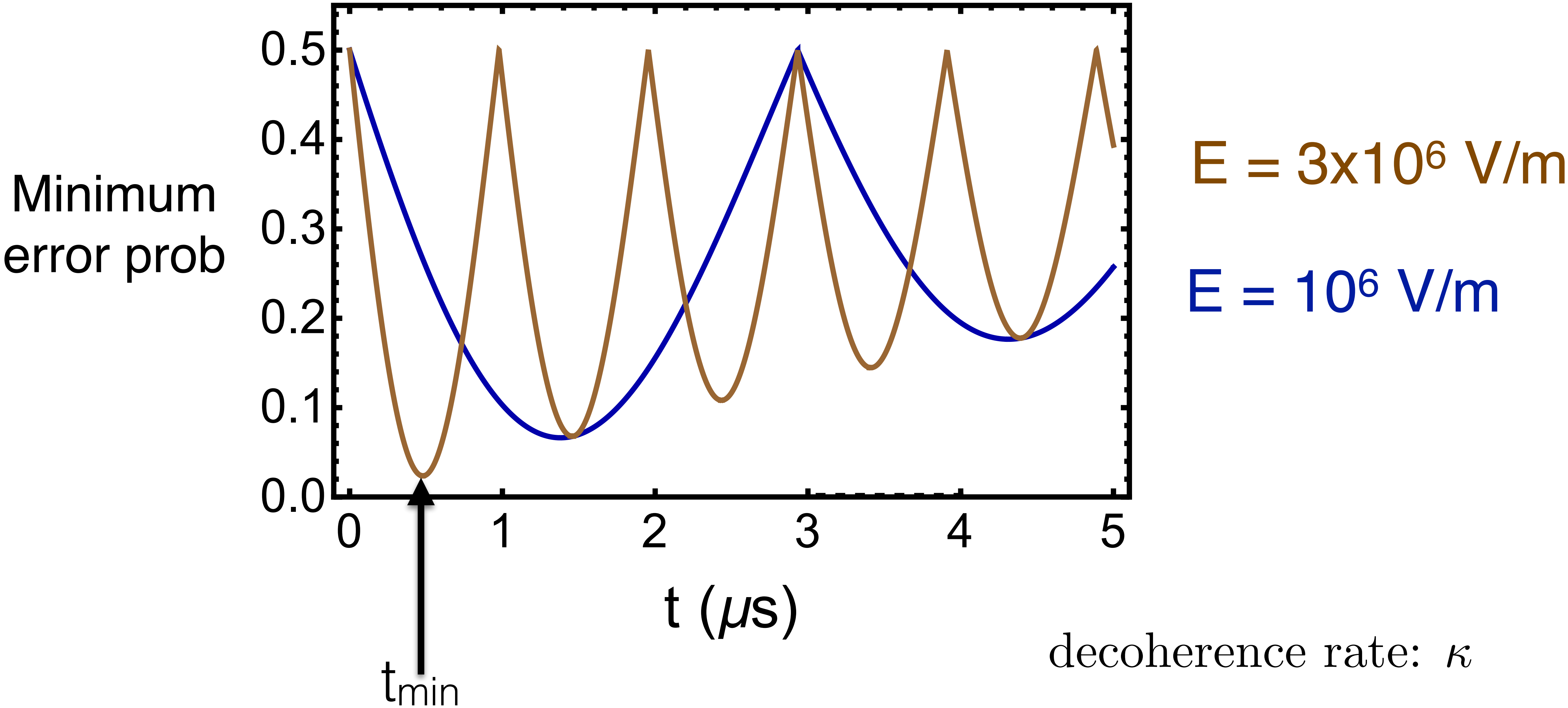
$$\Lambda = P_1 \rho_1 - P_0 \rho_0$$

Minimum error prob $= P_0 \mathrm{Tr}(\hat{\Pi}_1 \rho_0) + P_1 \mathrm{Tr}(\hat{\Pi}_0 \rho_1)$

$$U^\dagger \rho_i U$$

Results

Minimum error probability = $\frac{1}{2}(1 - e^{-\kappa t}|\sin(\frac{Et}{\hbar})|)$

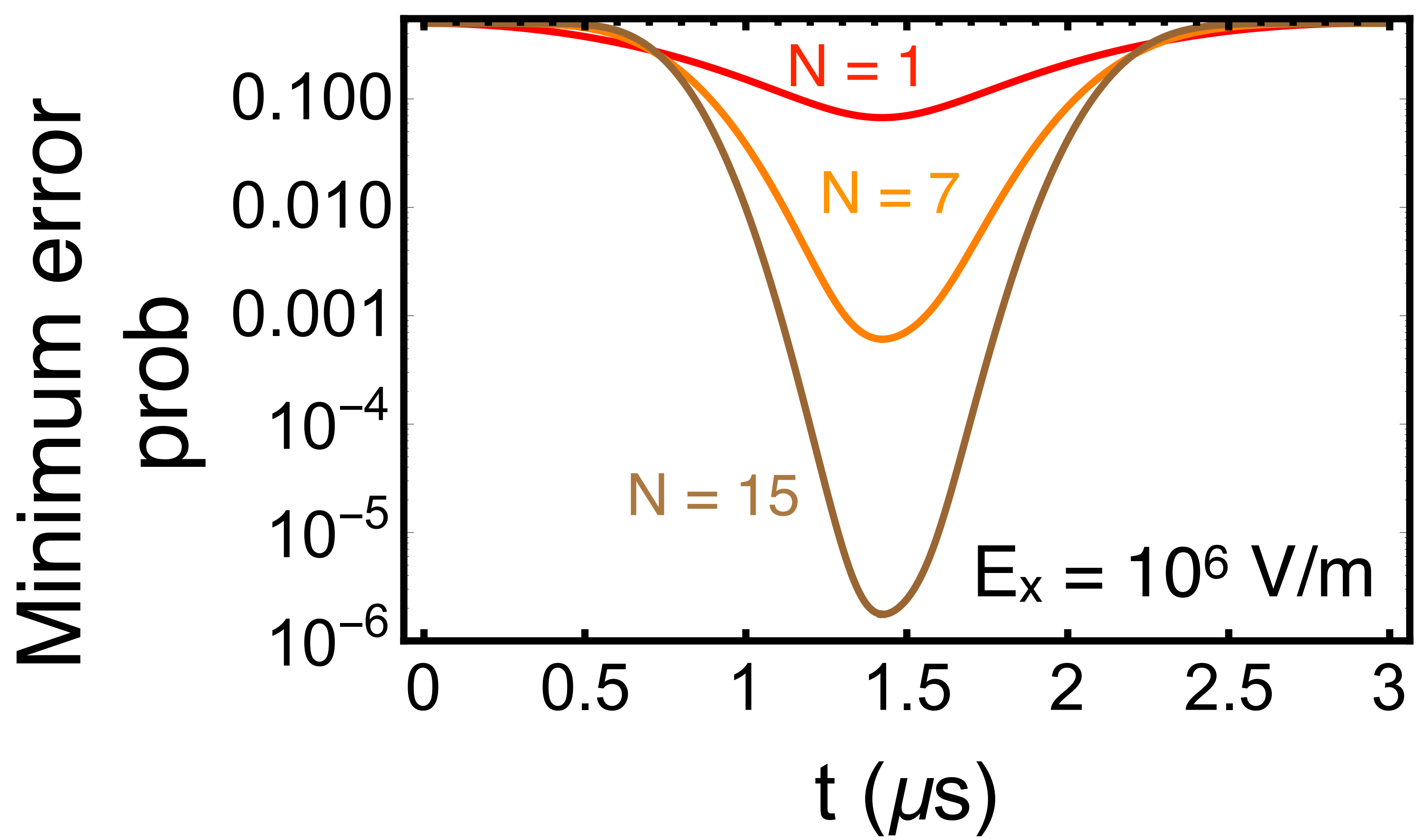


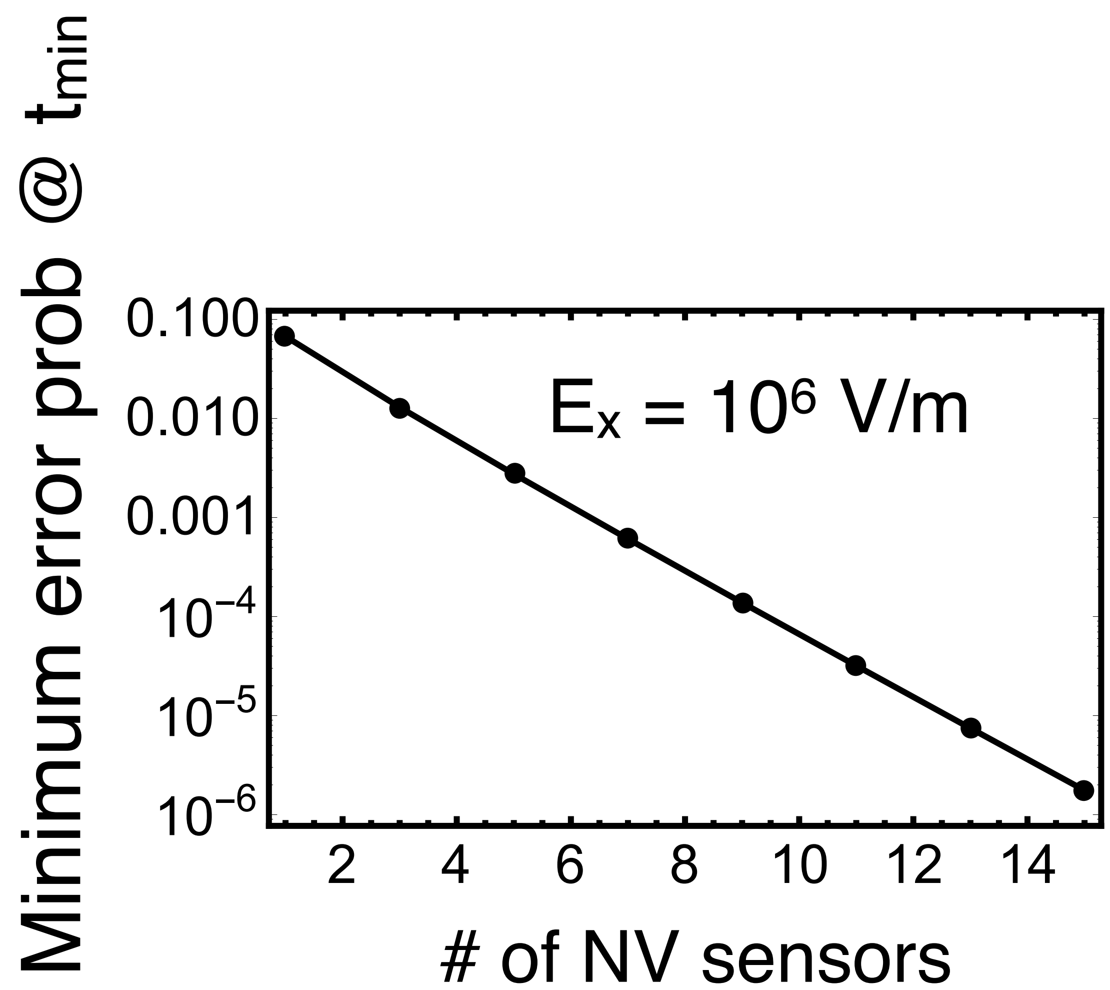
decoherence rate: κ

- Measurement should take place when error smallest @ t_{min}
- Larger electric fields, more accuracy and faster determination

Results

- Exponentially reduce minimum error probability by adding multiple independent sensors





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Minimum error prob @ t_{min}

$$= P_0 \sum_{n=0}^{\lfloor N/2 \rfloor} \binom{N}{n} (1 - \mathrm{Tr}(\rho_0 \Pi_1))^n \mathrm{Tr}(\rho_0 \Pi_1)^{N-n} + P_1 \sum_{n=0}^{\lfloor N/2 \rfloor} \binom{N}{n} (1 - \mathrm{Tr}(\rho_1 \Pi_0))^n \mathrm{Tr}(\rho_1 \Pi_0)^{N-n}.$$

Conclusions

- NV spin + chromophore as single shot (i.e. fast) electric field/photon quantum detector
- Errors are competitive with superconducting nanowire single photon detectors
    - multiple NV sensors allows for dramatic error reduction
- Photon arrival/field-turn-on times can be determined

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