New condensed matter probes with diamond quantum sensors

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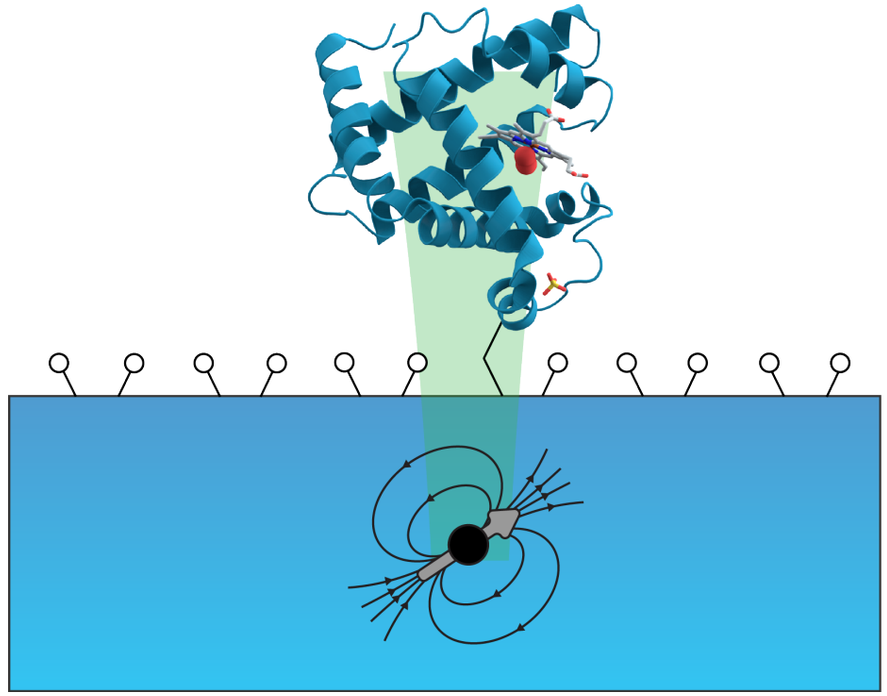
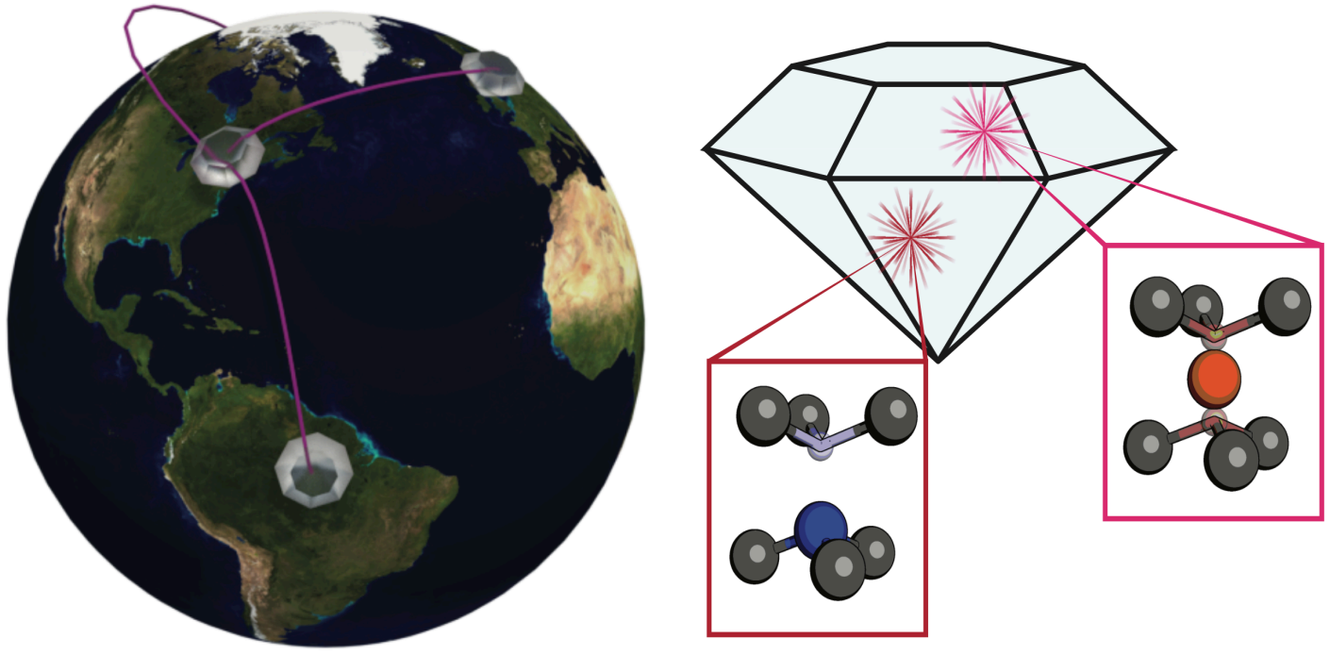
SPICE Quantum Spinoptics workshop
June 14, 2023

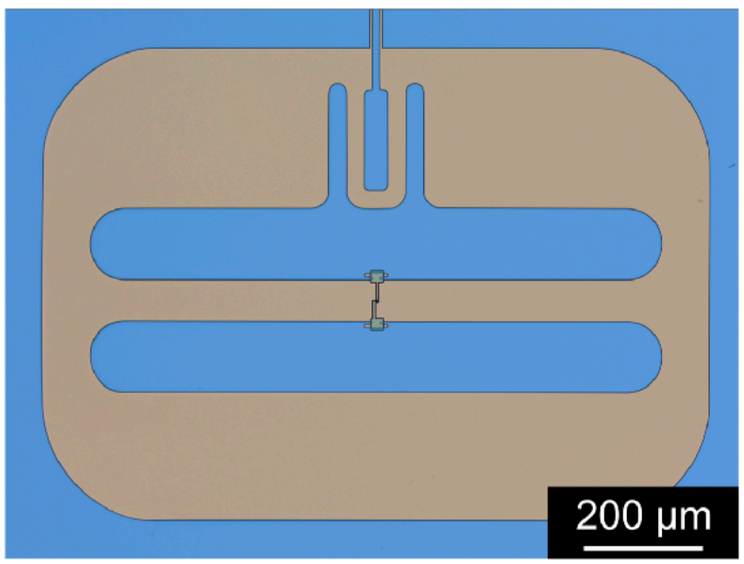
Nanoscale quantum sensing



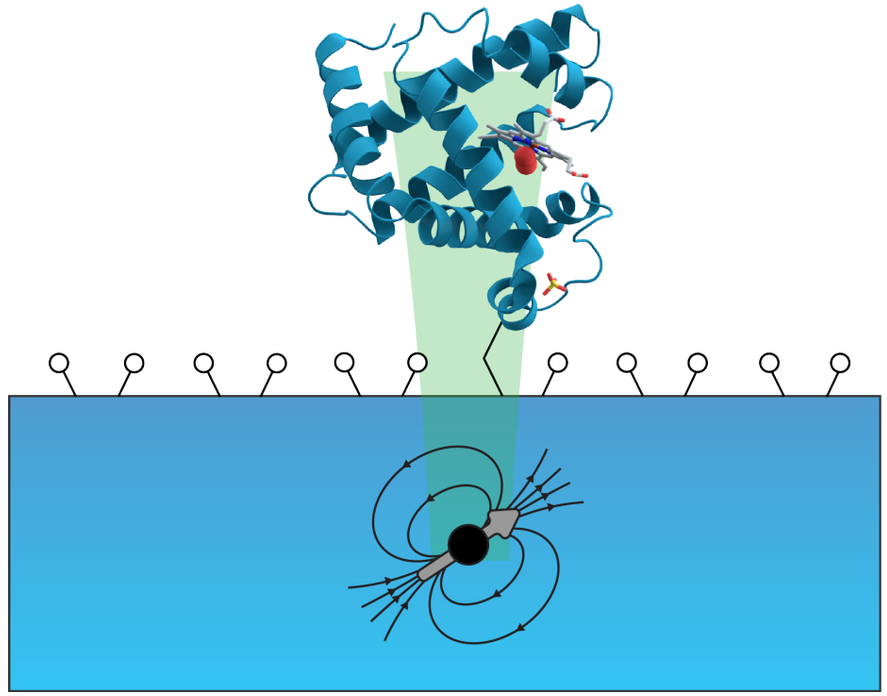


New solid state defects for quantum networks

New material systems for quantum computing



Nanoscale quantum sensing

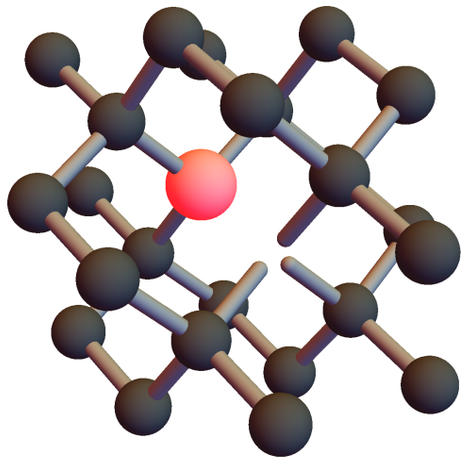


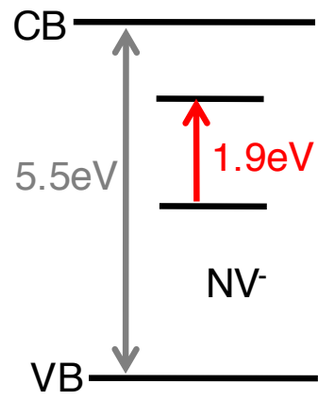
New solid state defects for quantum networks

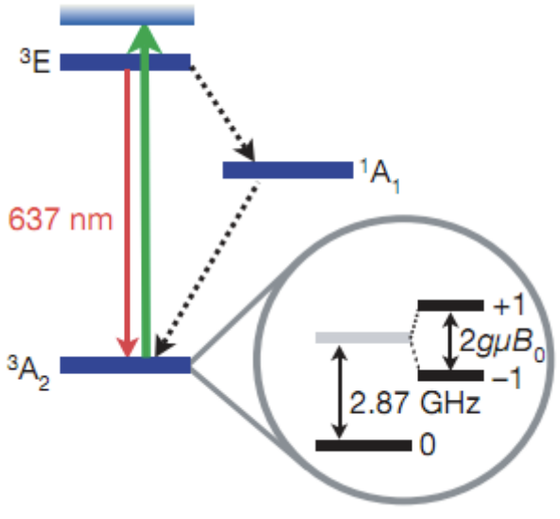
New material systems for quantum computing

Nitrogen vacancy centers

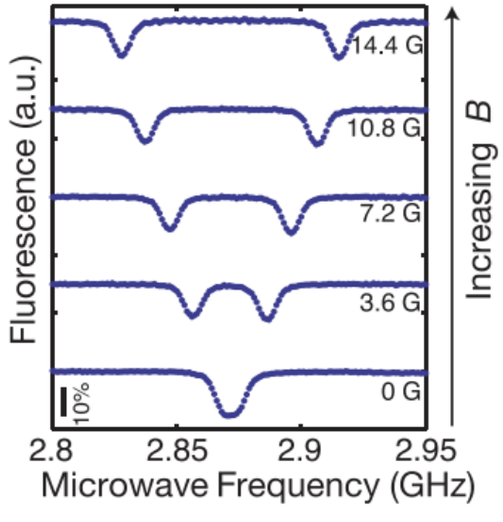
- ground state electronic spin with long coherence time
- can optically manipulate and measure spin (at room temp)
- single center imaging



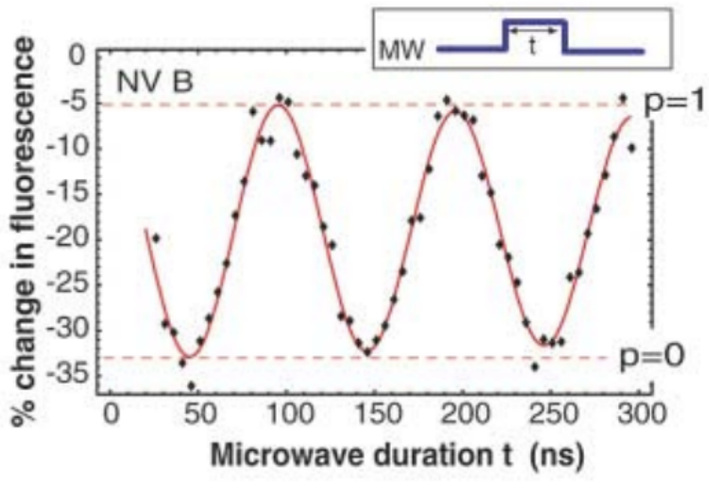




Maze *Nature* 2008

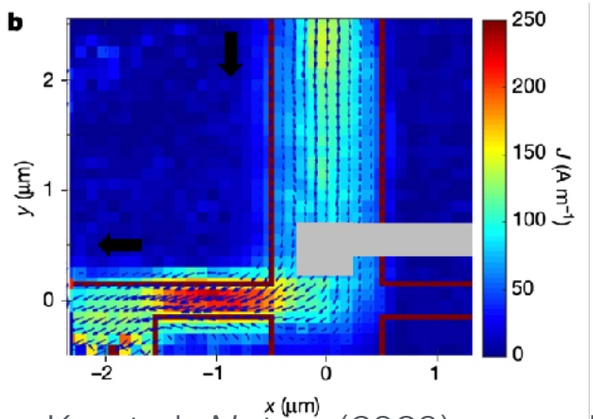


Hong *MRS Bull.* 2013

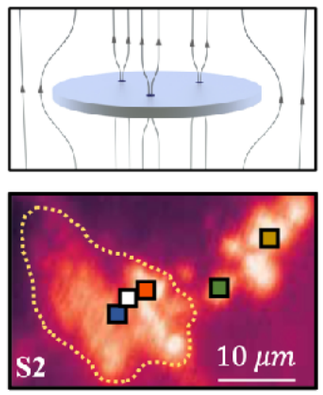


Childress *Science* 2005

Probing condensed matter phenomena

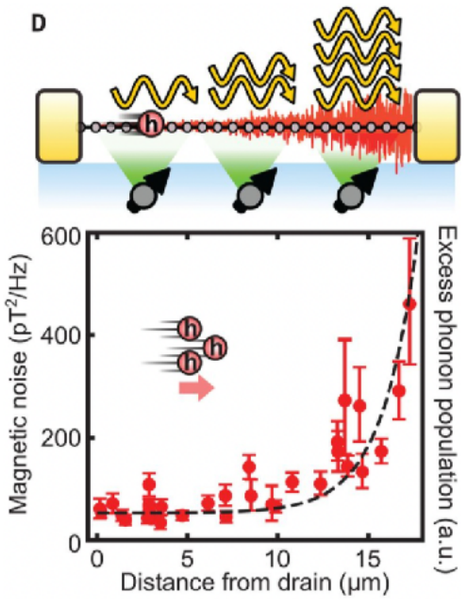


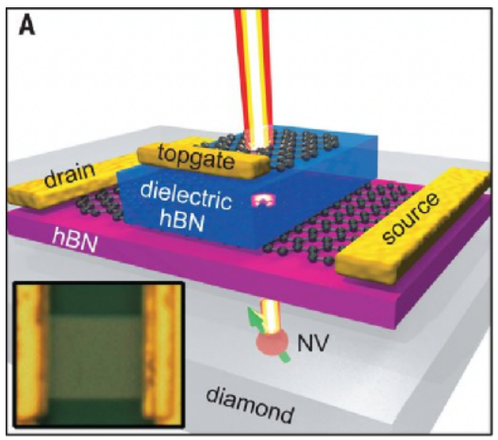
Ku et al, *Nature* (2020)



Bhattacharyya et al, *arXiv:2306.03122v1*

magnetic field





Anderson et al, *Science* (2019)

noise

susceptibility and ordering

dispersion

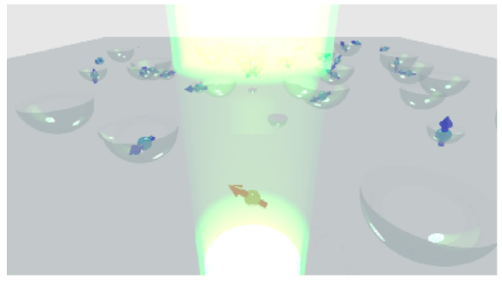
transport

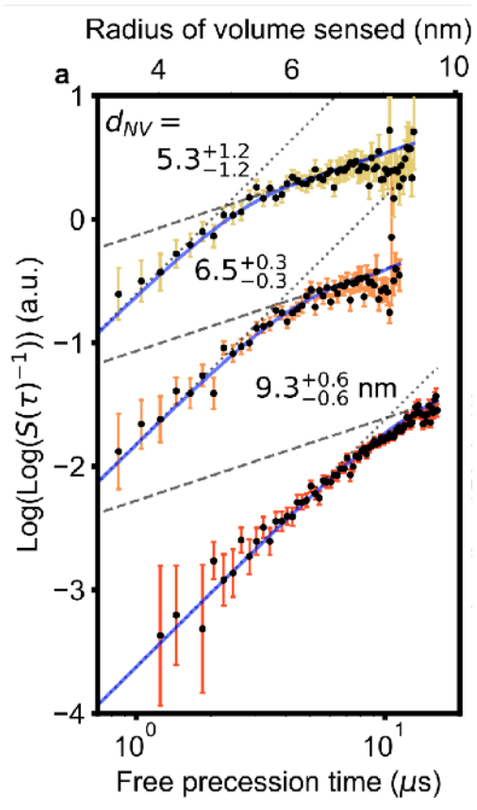
correlations

order parameters

Using shallow NV centers

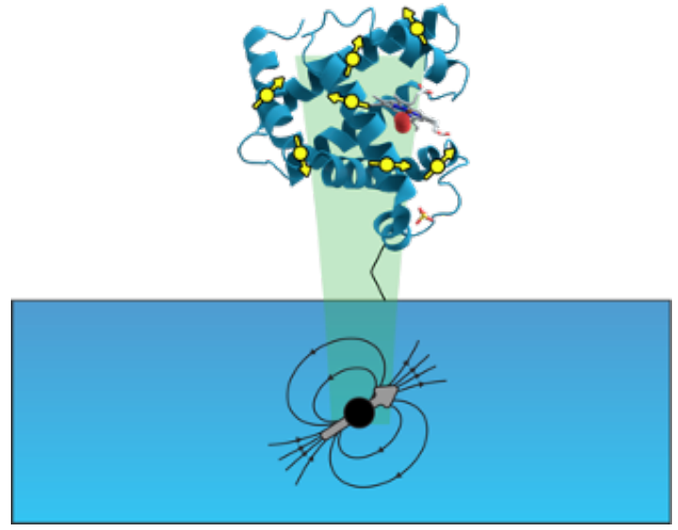
spin dynamics

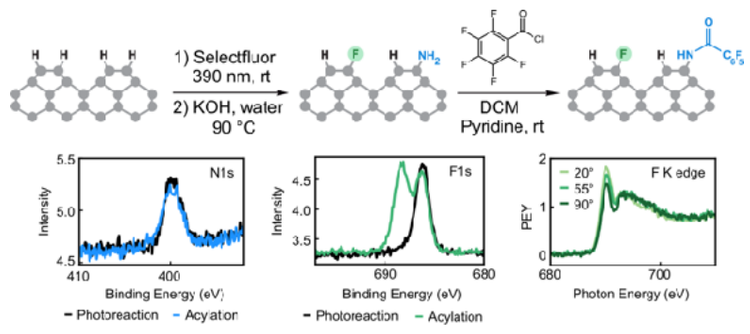




Dwyer, Rodgers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum* 2022

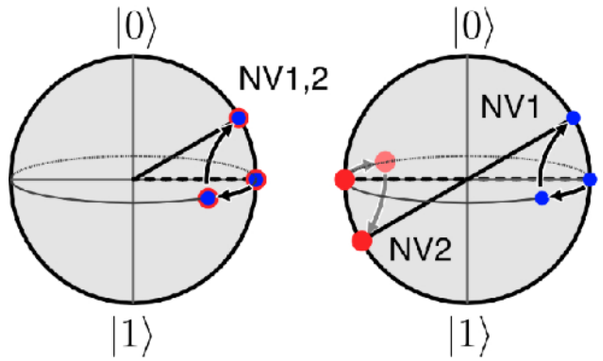
nanoscale NMR

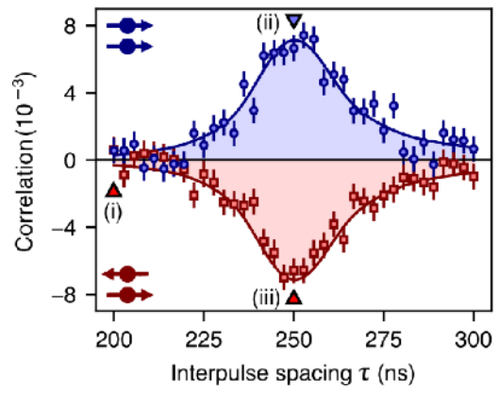


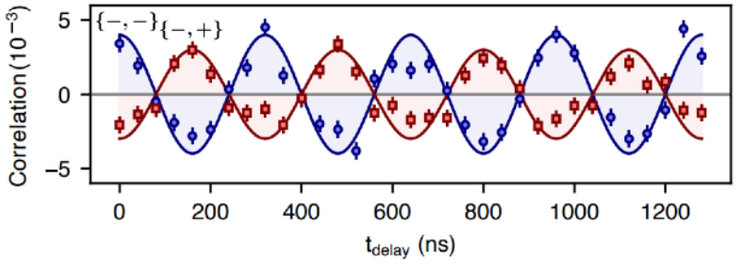


Rodgers, Nguyen, Knowles, NdL et al, *in preparation*

nanoscale covariance magnetometry



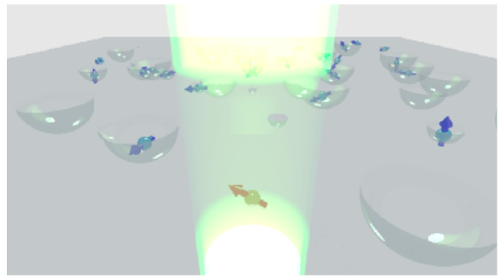


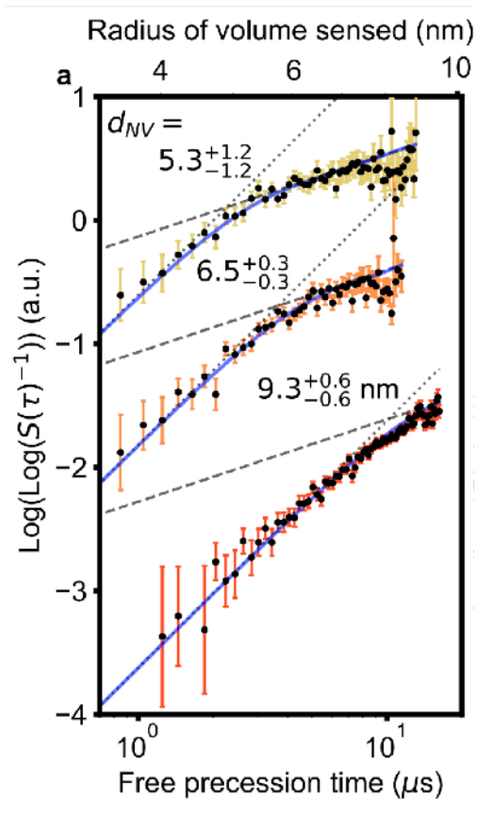


Rovny, NdL et al, *Science* 2022

Using shallow NV centers

spin dynamics





Dwyer, Rodgers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum* 2022

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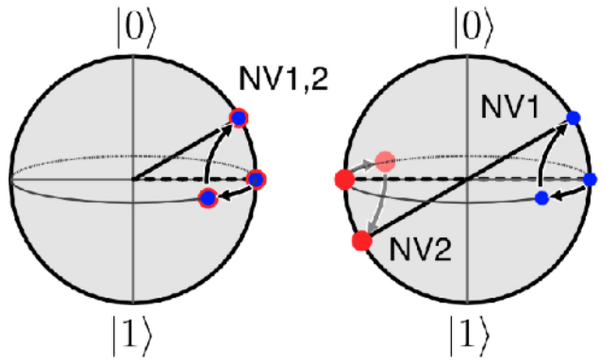
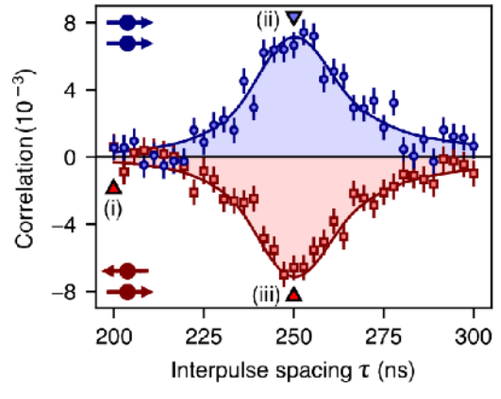
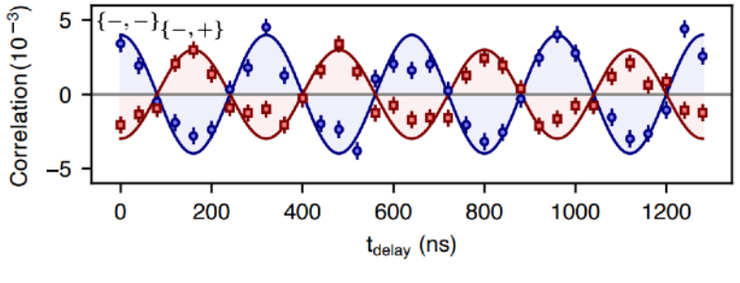
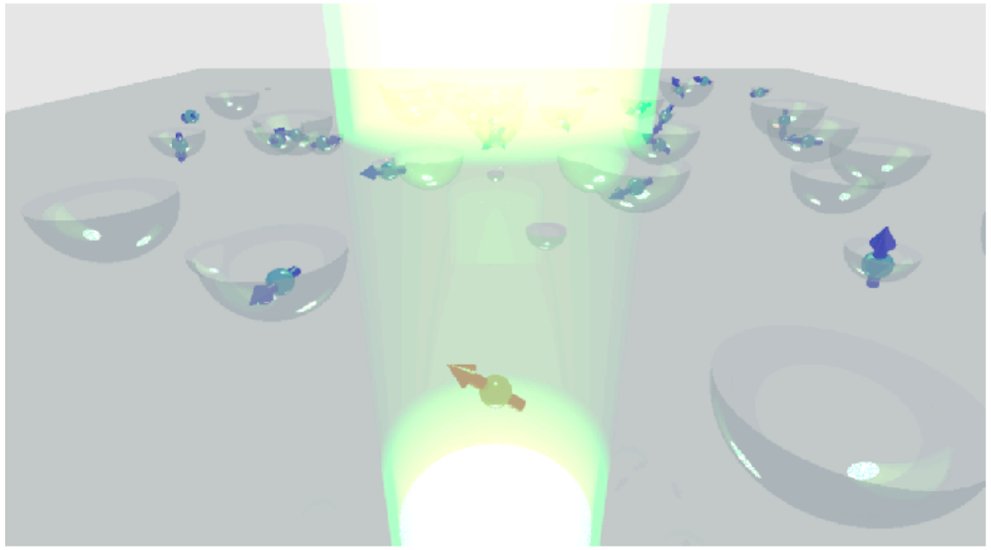


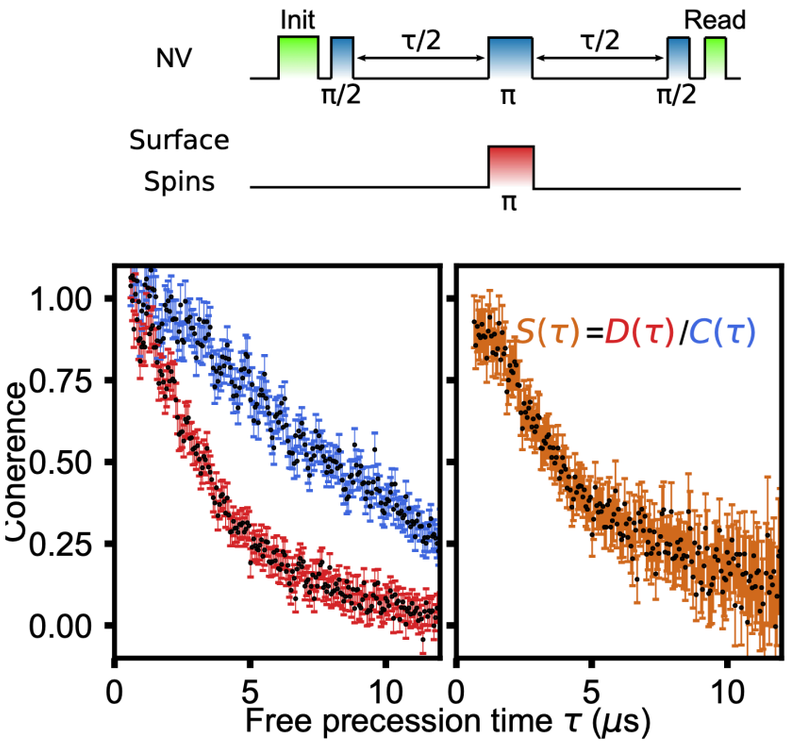


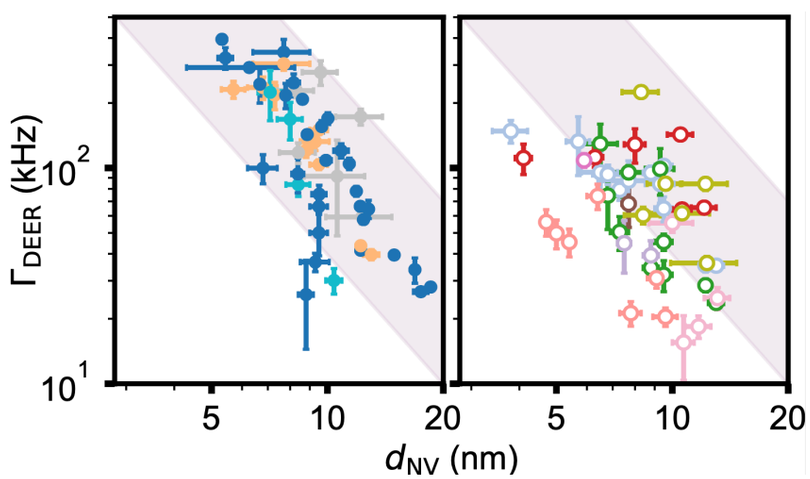


Rovny, NdL et al, *Science* 2022

Nanoscale spectroscopy of surface spins



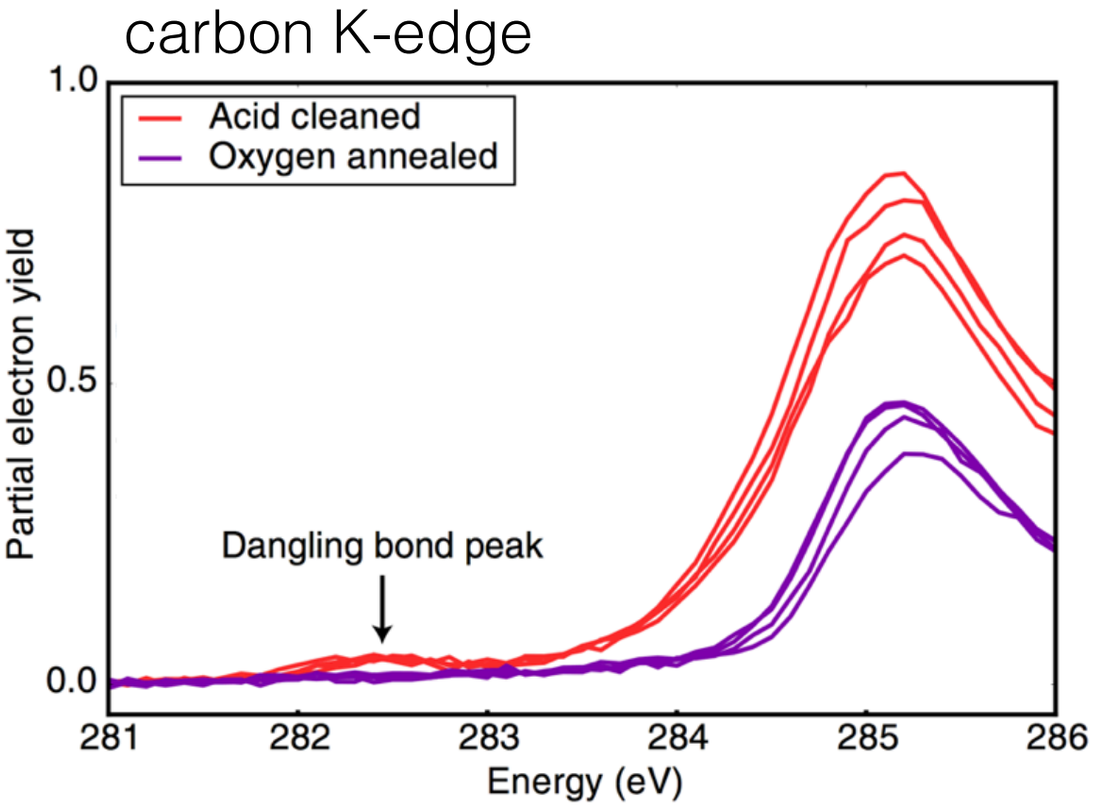


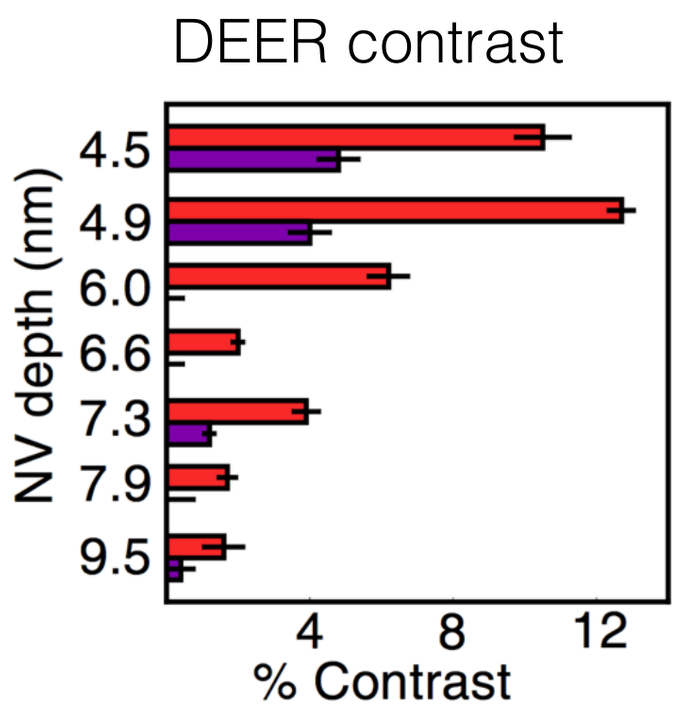


- Double electron-electron resonance (DEER) measurements => FID of surface spins
- Coupling decreases with depth

Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Surface spins correlate with dangling bond peak in NEXAFS

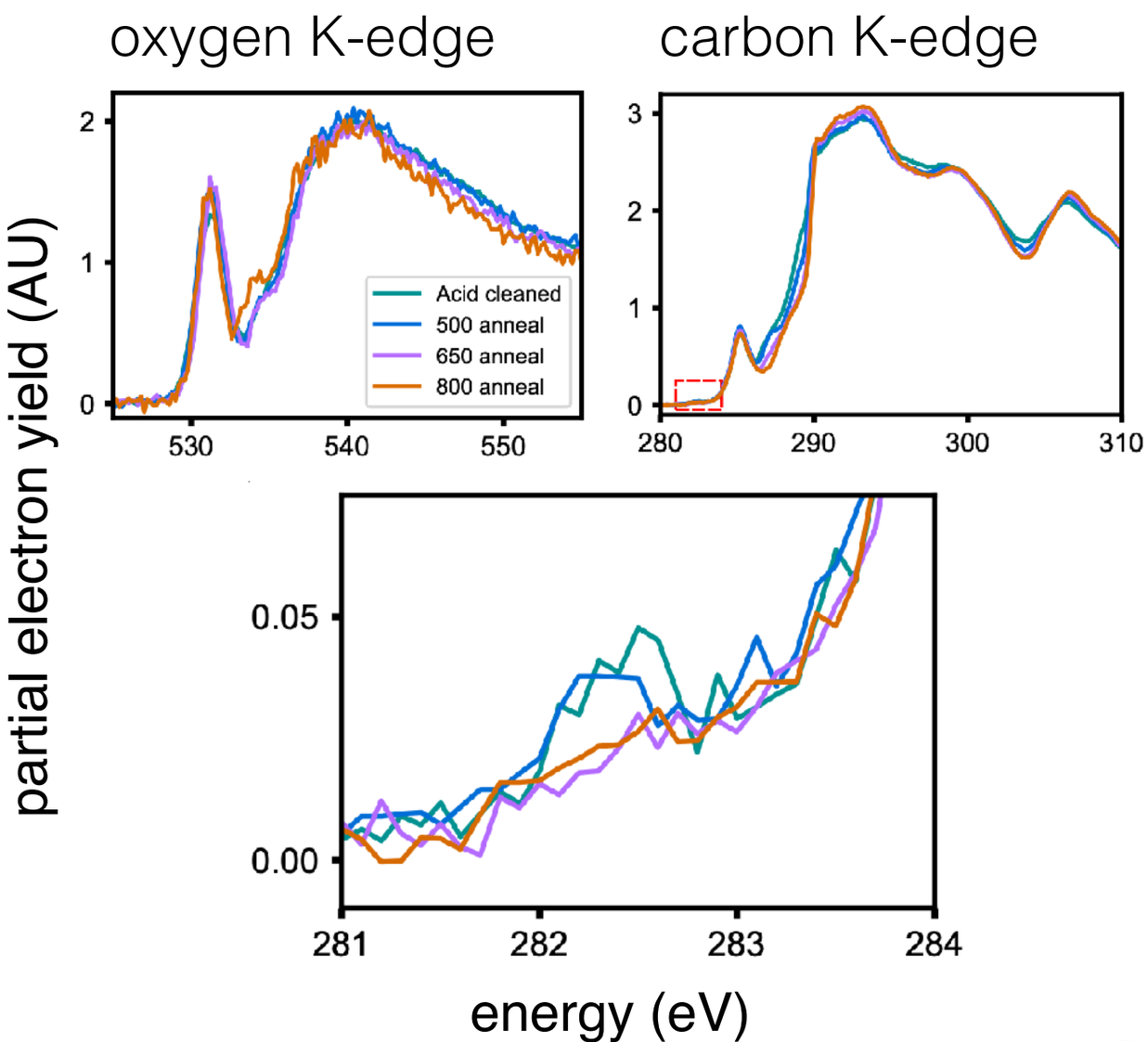




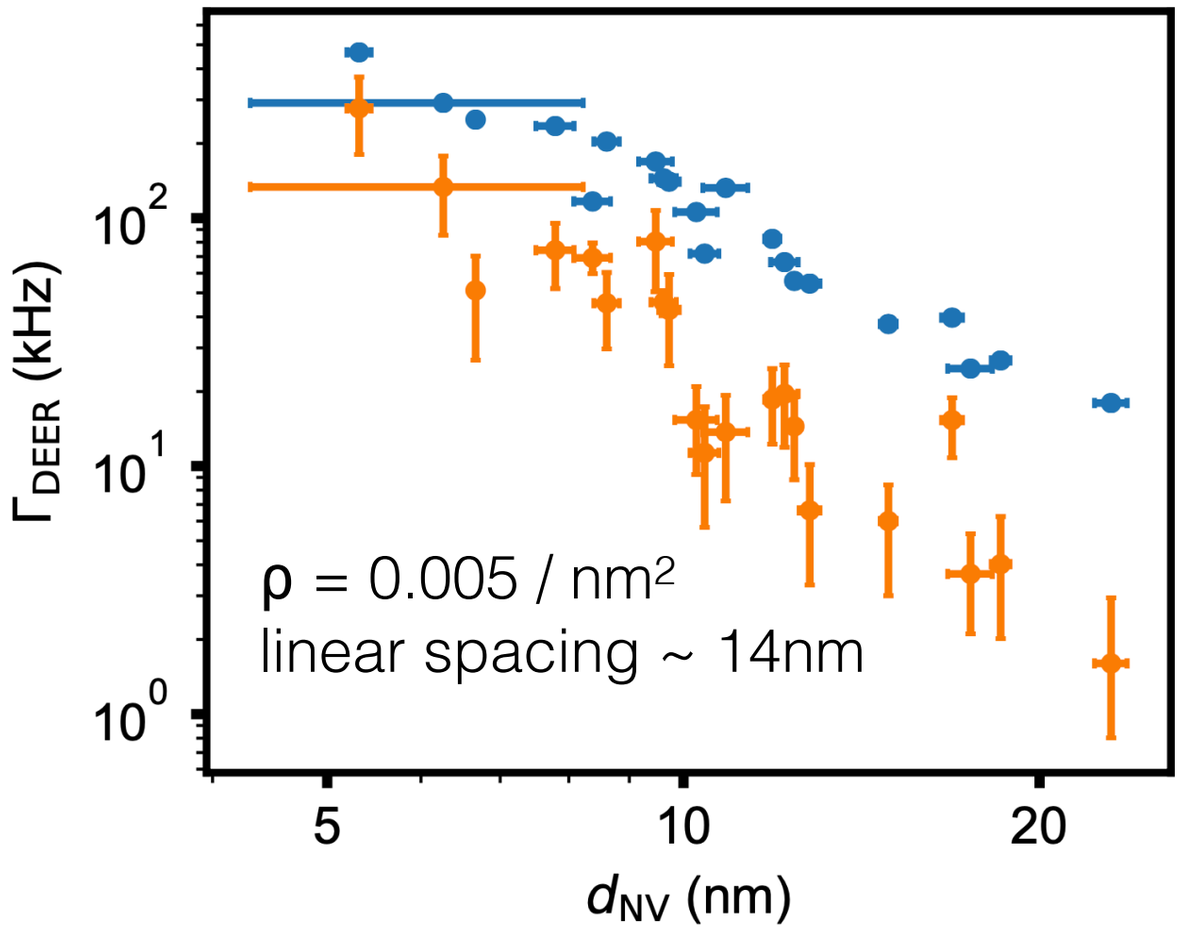
Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Selective annealing to tune surface spin density

in situ annealing sequence:

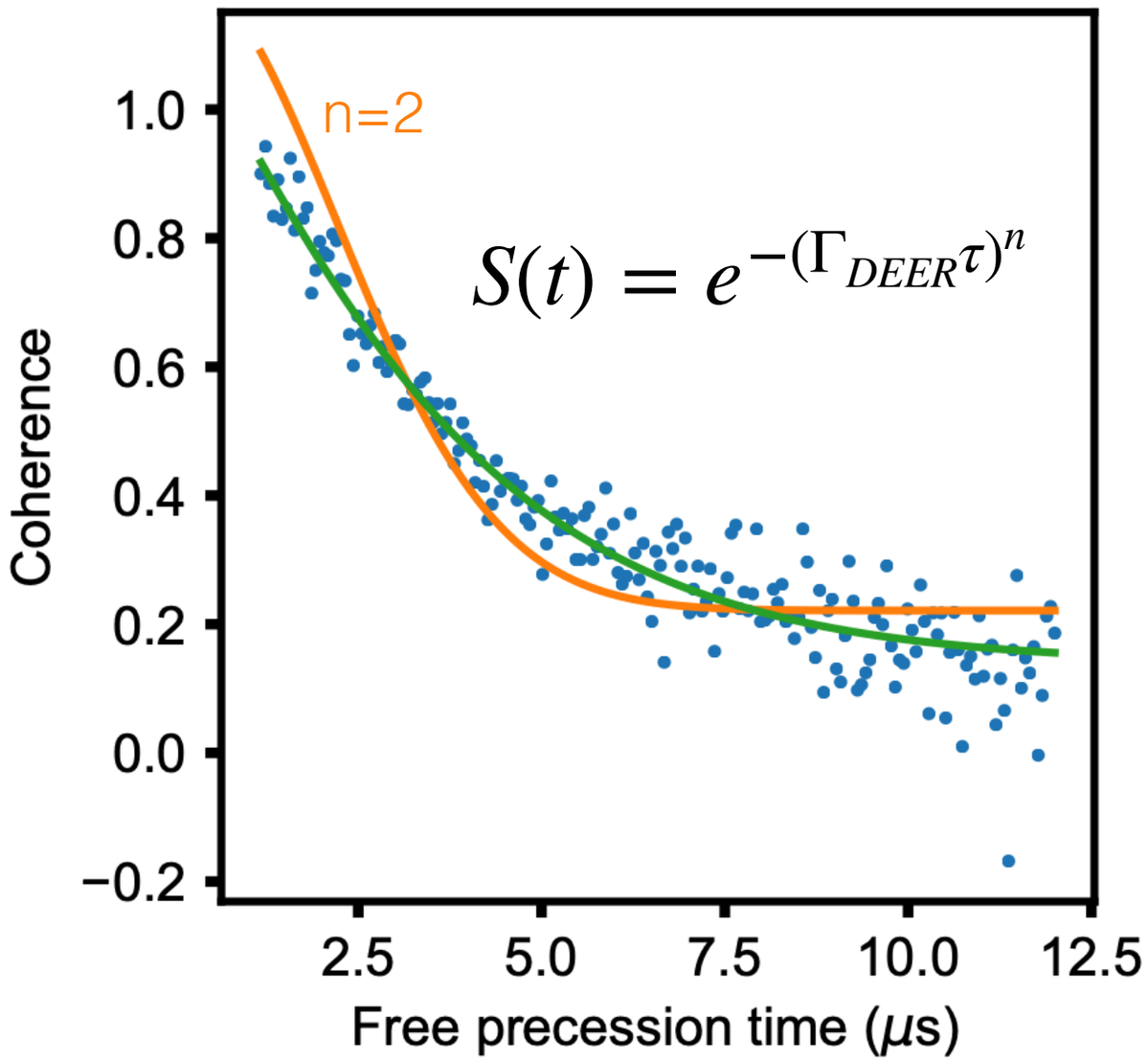


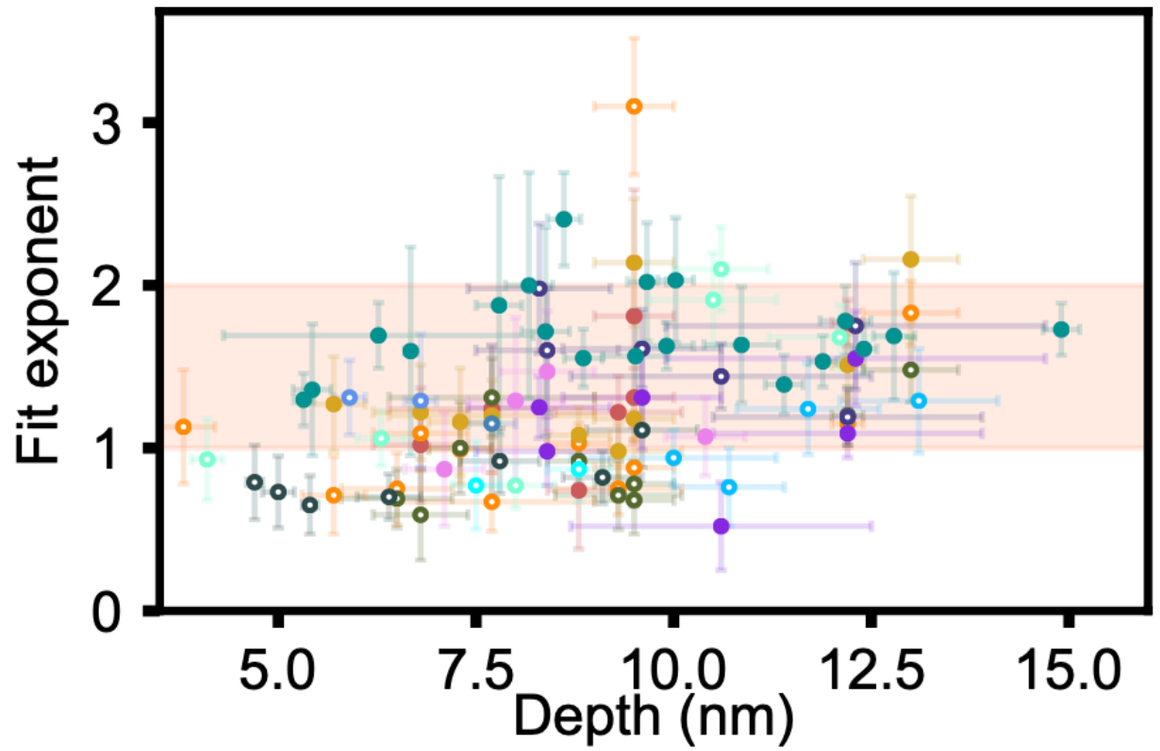
DEER coupling before and after 650 °C vacuum annealing:



Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Stretched exponential coherence decay at low density

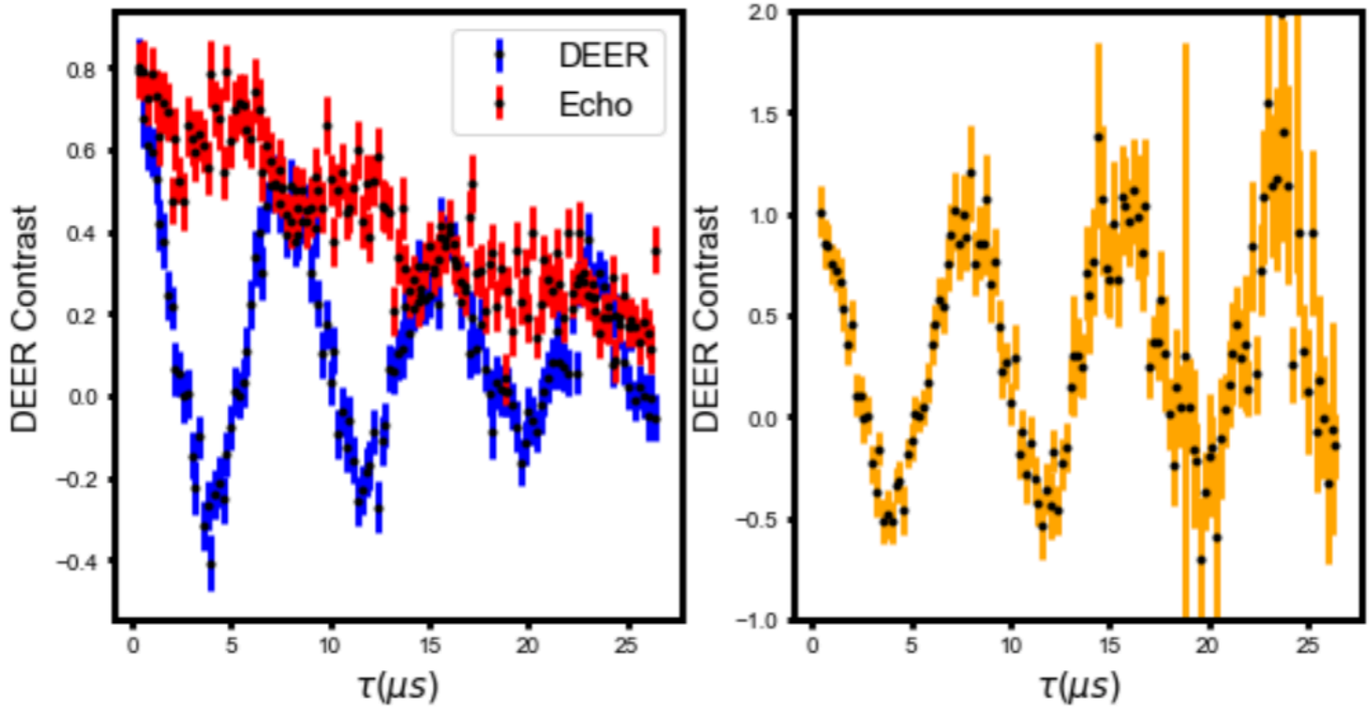




- should get n=2 in quasistatic limit
- standard theory only predicts 1<n<2 (for well-behaved, monotonically decreasing noise)

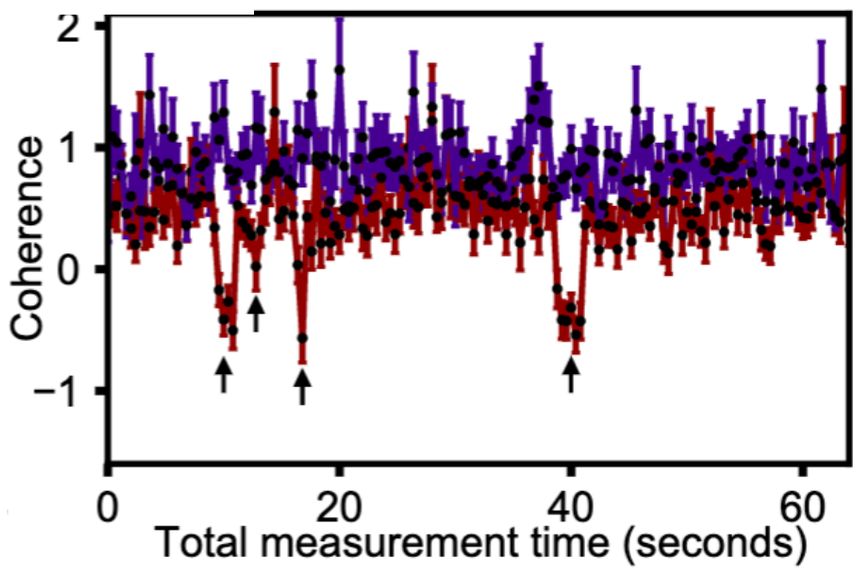
Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Coherent coupling is rare



observe coherent coupling in ~2% of NV centers

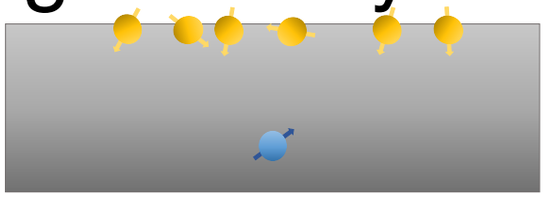
sometimes see coherently coupled signal blink on and off!

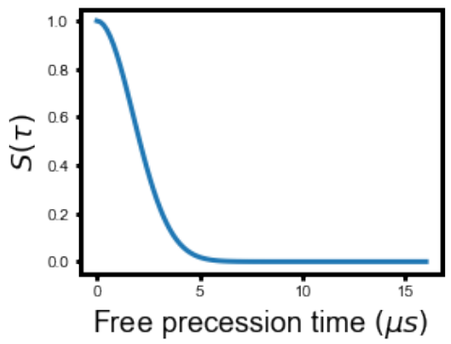


Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Stretched exponential decay

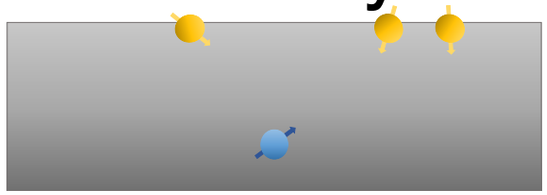
High density bath

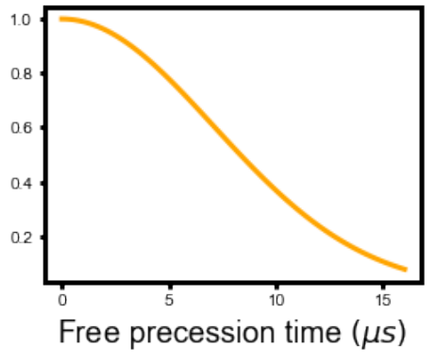




n = 2

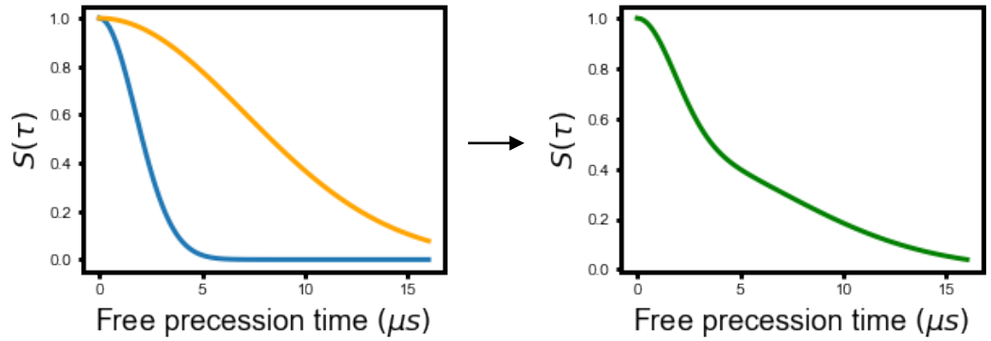
Low density bath

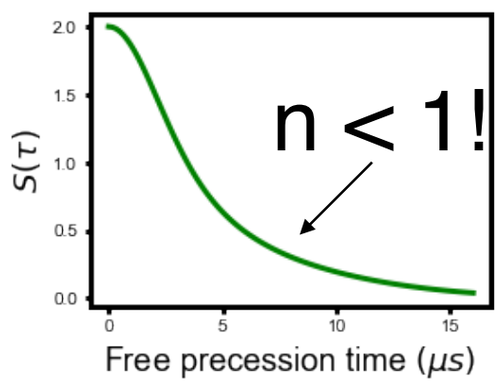




n = 2

Take average

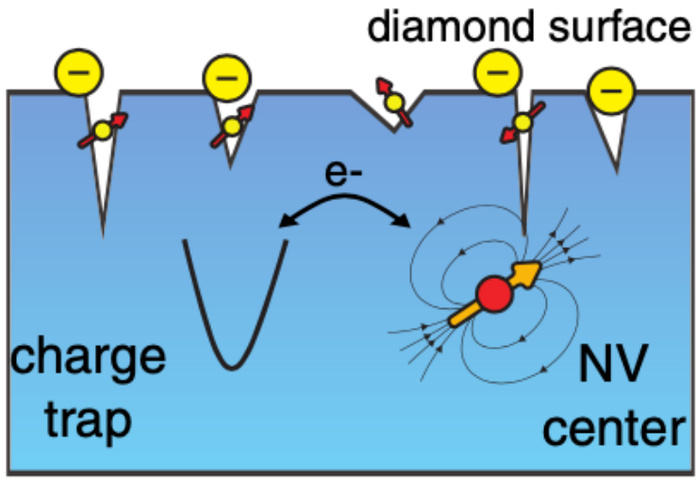


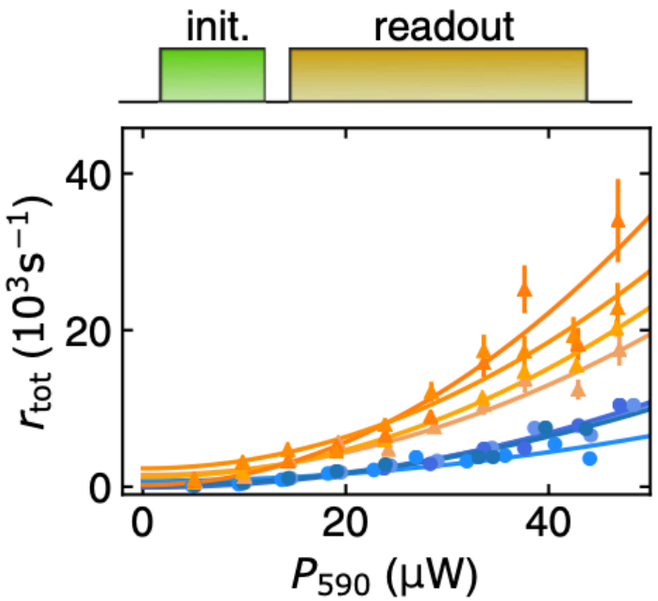


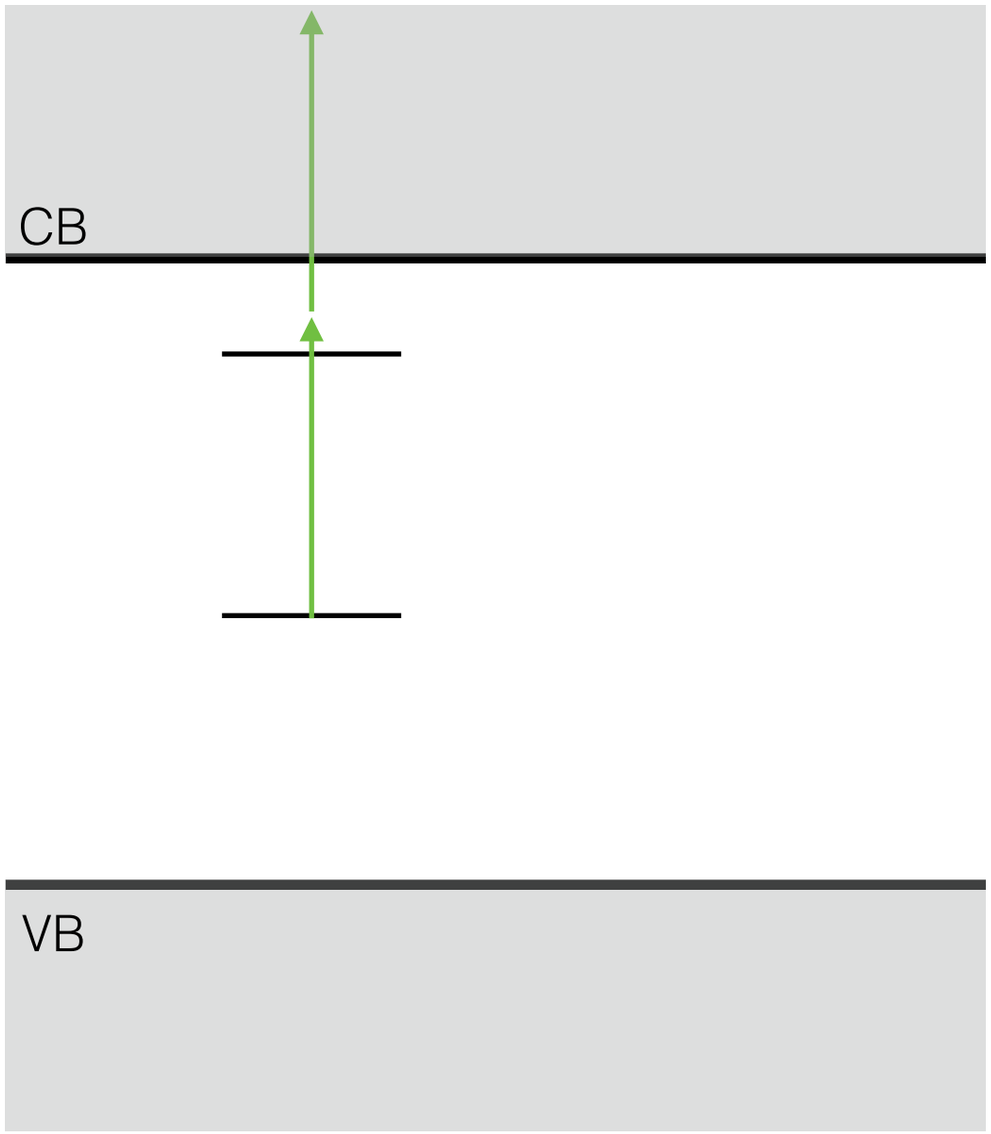
Averaging these configurations leads to n < 1.

Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Photoionization of defects in diamond

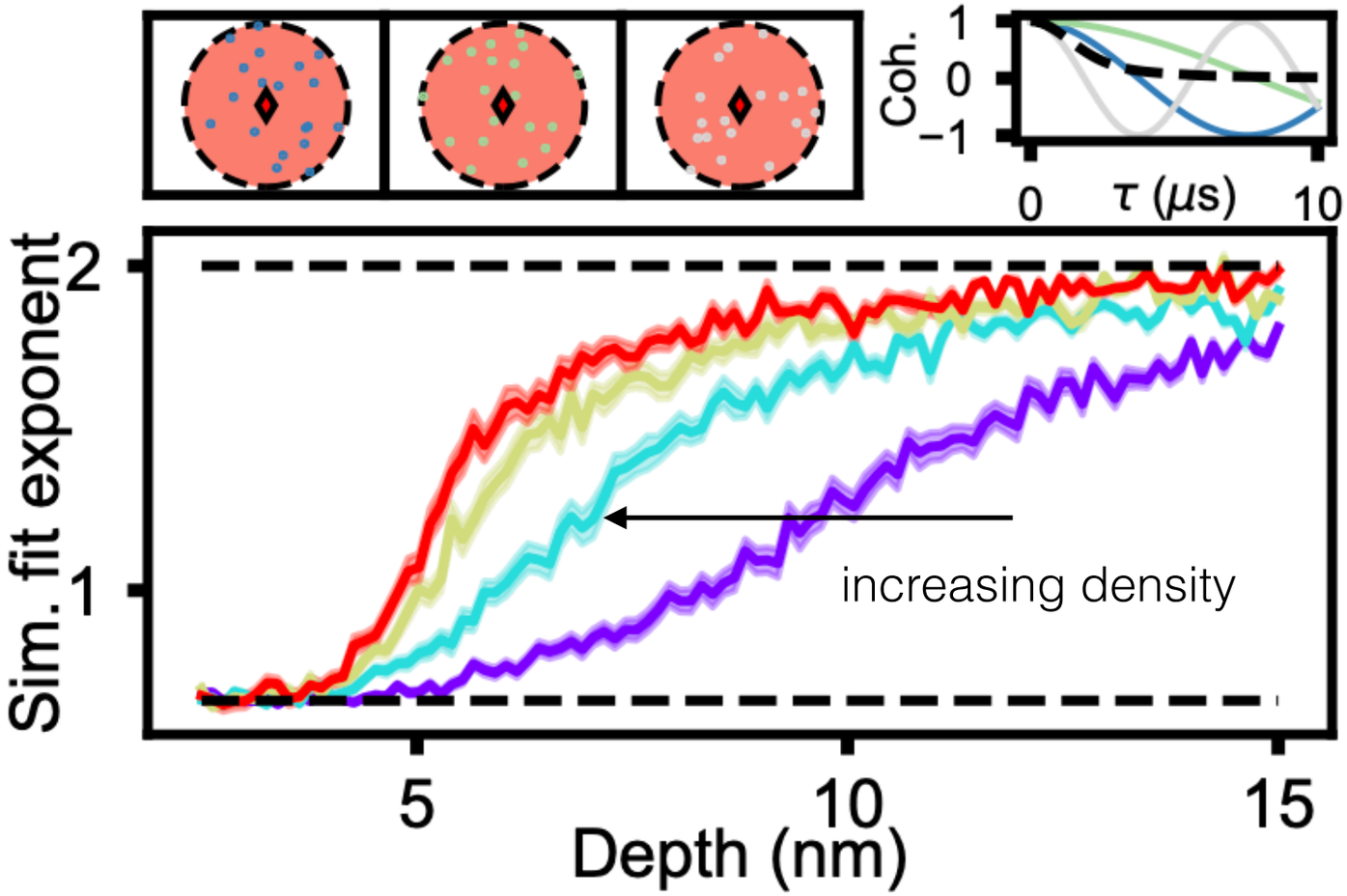






Yuan, Fitzpatrick, NdL et al, Phys Rev Research 2020

Numerical model: spins hop in 2D

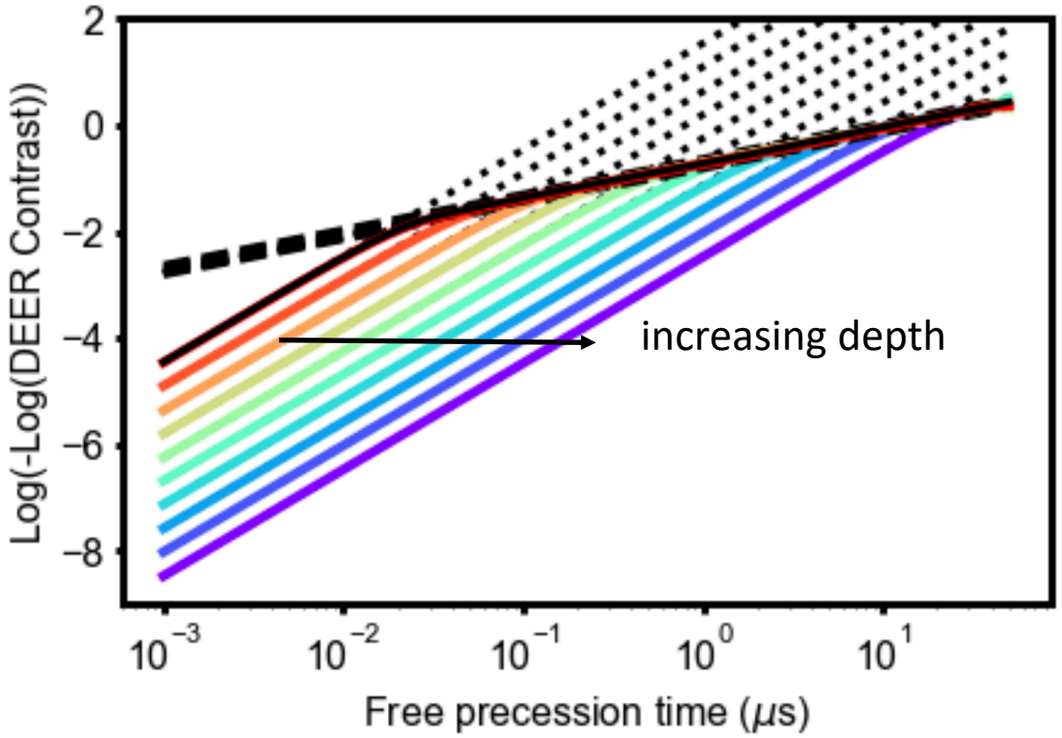


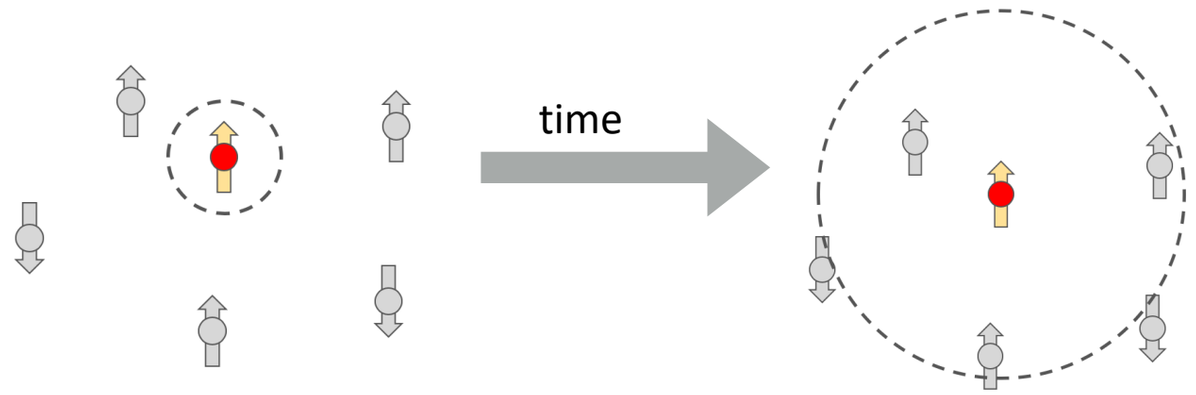
configurational averaging over many decoherence curves

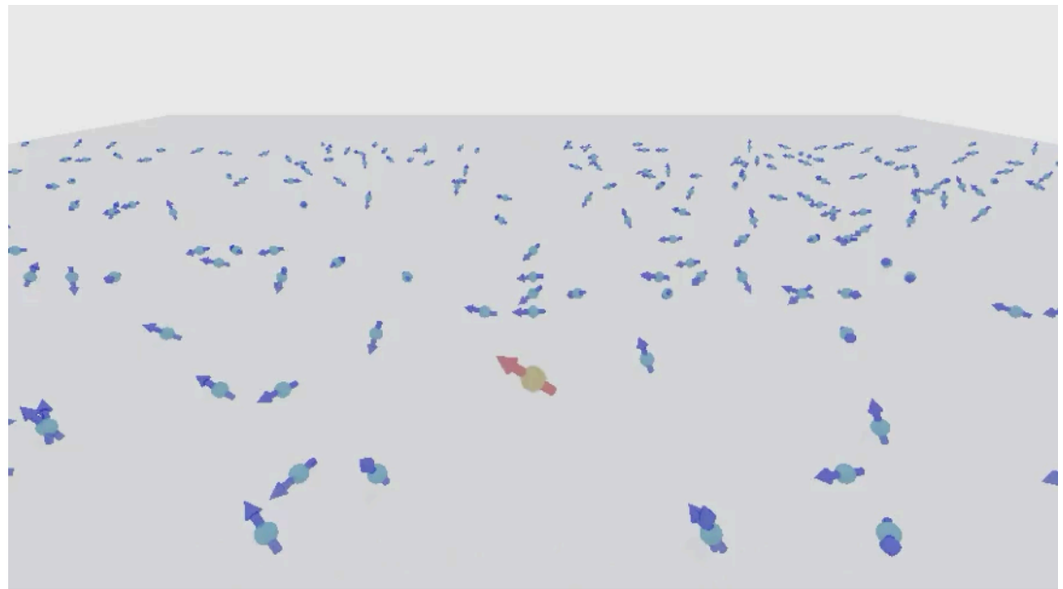
shallow NV sees 2D bath: n=2/3
deeper NV sees Gaussian noise bath: n=2

Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Analytical model: critical crossover time







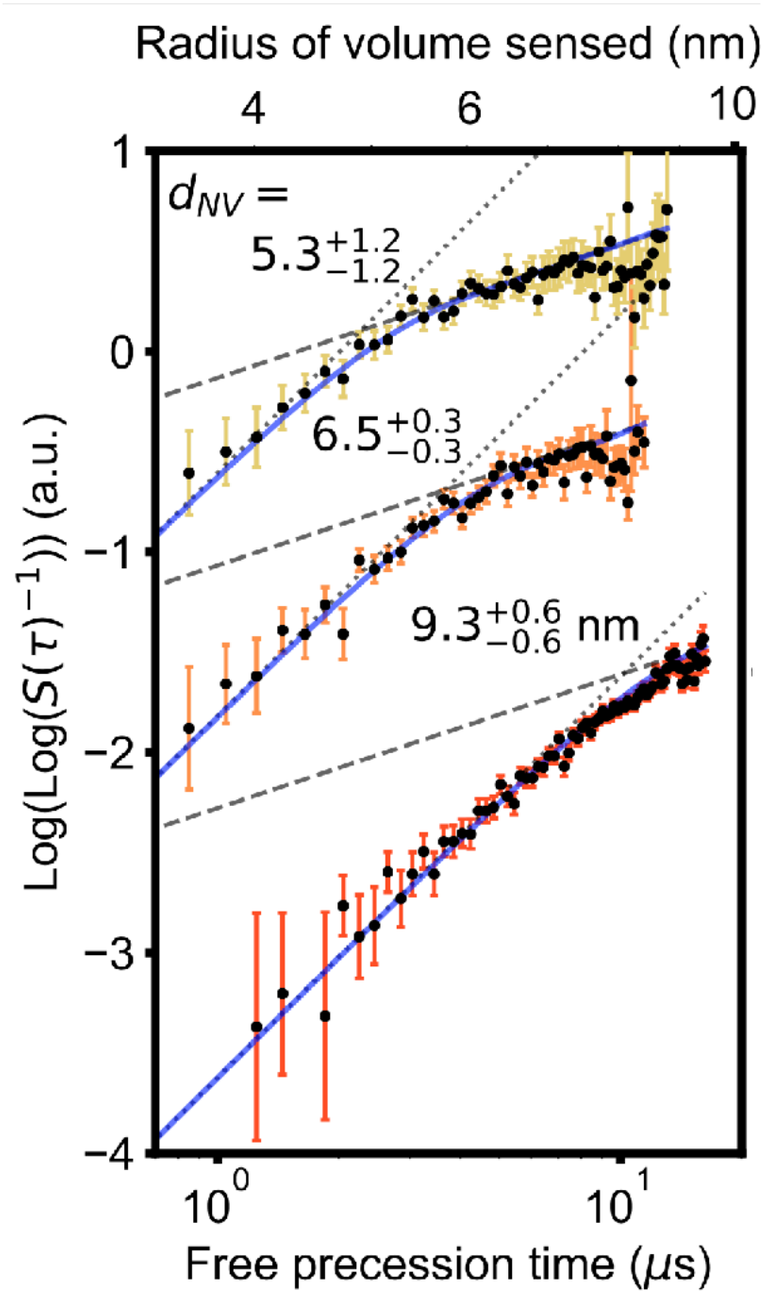
short times: $S(\tau) = e^{-(\Gamma_{\mathrm{DEER}}\tau)^2}$

long times: $\langle S(\tau)\rangle_c = \exp[-\frac{9\sqrt{\pi}\Gamma(\frac{11}{6})\rho}{5}(\frac{\mu_0\gamma^2\hbar\tau}{8\pi})^{2/3}]$

exponent = d/α

Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Experimental observation of crossover time



crossover time is observable because the NV center is a *separable probe*. Can set distance (=> timescale) arbitrarily.

Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

Summary: probing dynamics and dimensionality

- Careful measurements of shape of coherence decay gives *local* probe of dimensionality and dynamics

- surface spins are hopping around (implications for sensing)

- ability to choose the distance is key! (-> scanning NV measurements)

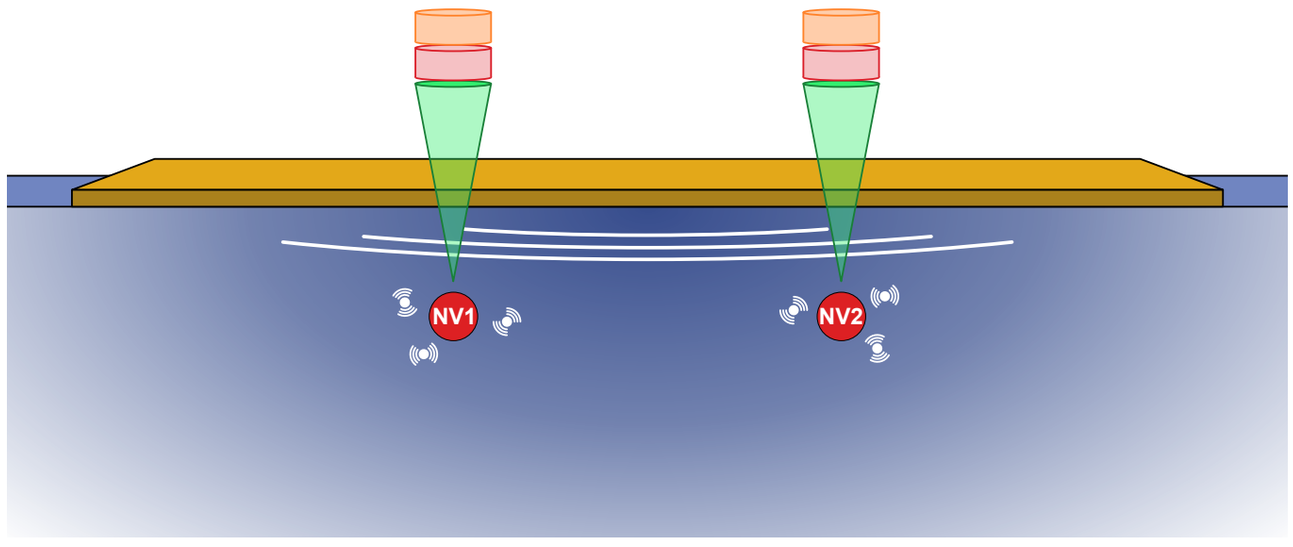
Dwyer, Rogers, Urbach, Dobrovitski, Lukin, NdL et al, *PRX Quantum 2022*

see also related work:
Davis, Jayich, Yao, *Nature Phys 2023*

Covariance magnetometry

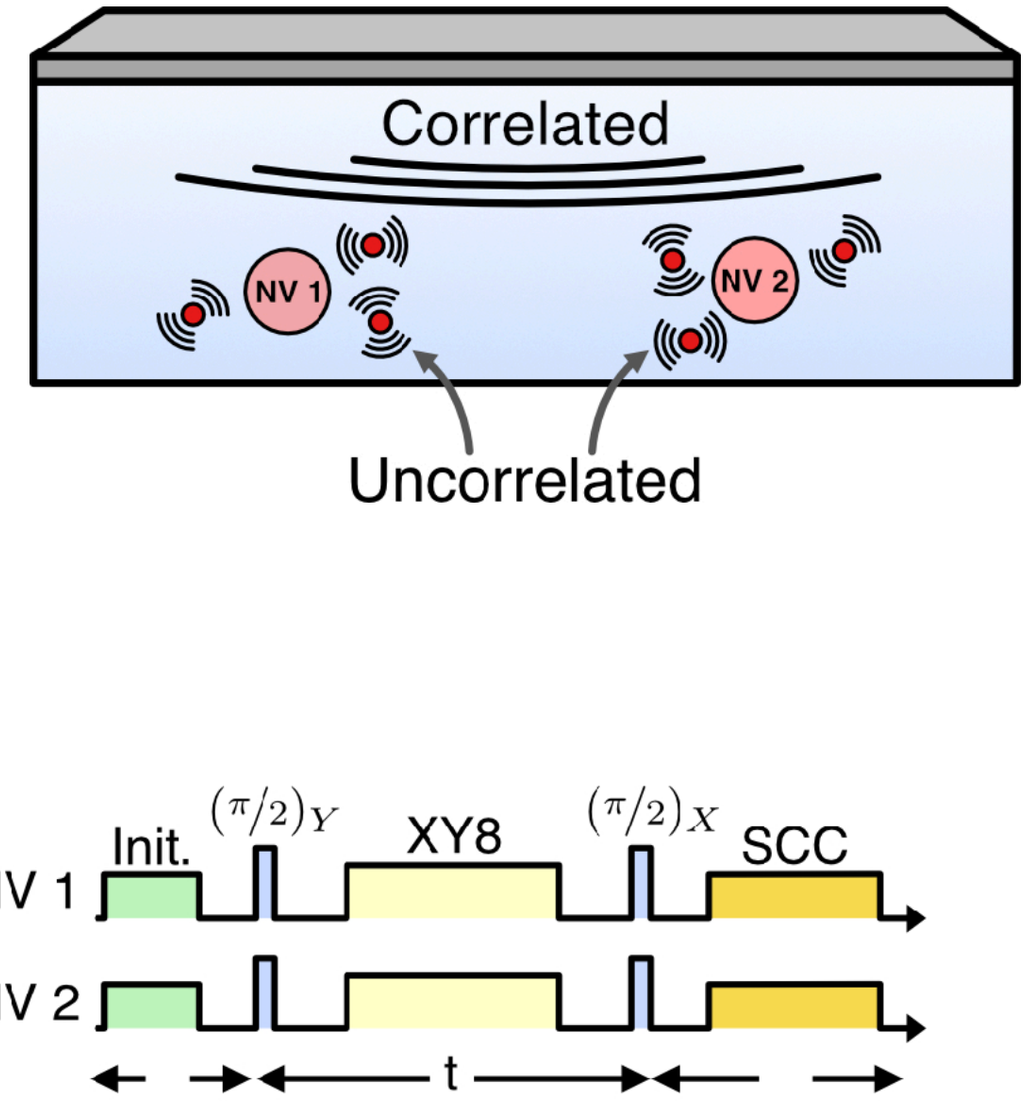
Jared Rovny

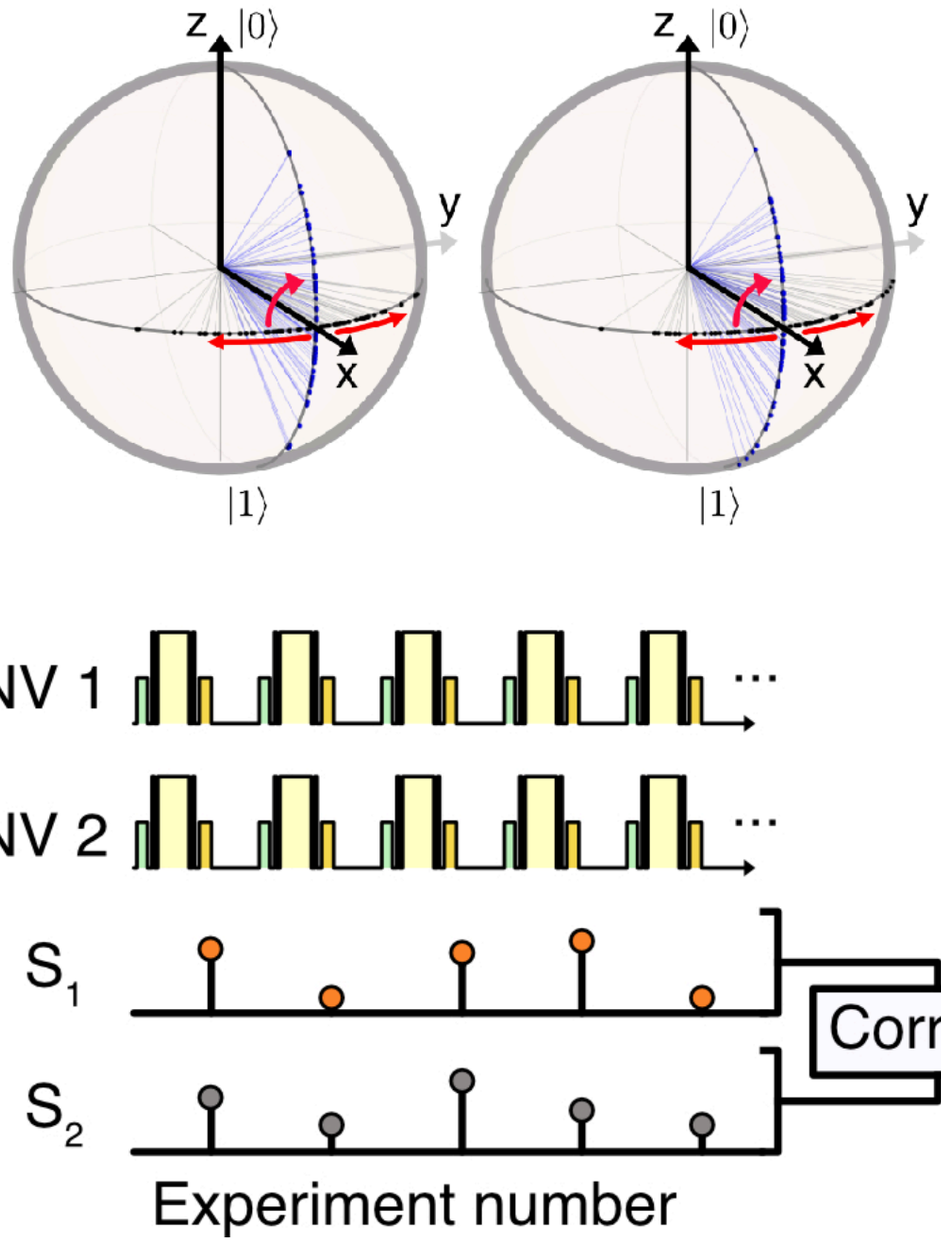
use 2 NV centers to look for spatiotemporal correlations:



collaboration with Kolkowitz group

Correlation measurements





collaboration with Kolkowitz group

Rovny, NdL et al, *Science* 2022

Increasing readout fidelity

$$p(S_1, S_2|\phi_1, \phi_2) = P(S_1, S_2|m_s^x, m_s^y)P(m_s^x, m_s^y|\phi_1, \phi_2)p(\phi_1, \phi_2)$$

readout quantum projection phase distribution

collaboration with Kolkowitz group

Rovny, NdL et al, *Science* 2022

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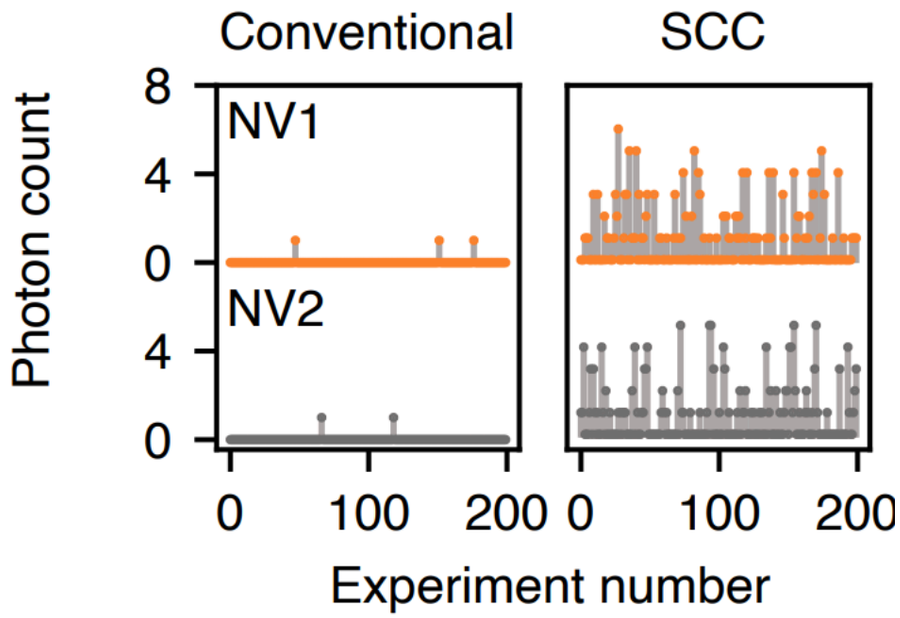
readout quantum projection phase distribution



collaboration with Kolkowitz group

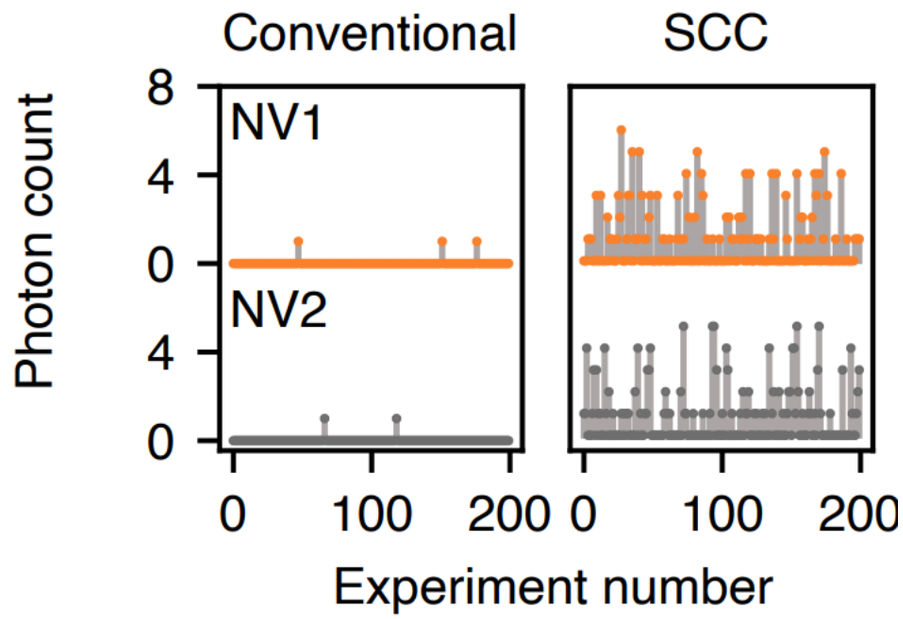
Rovny, NdL et al, *Science* 2022

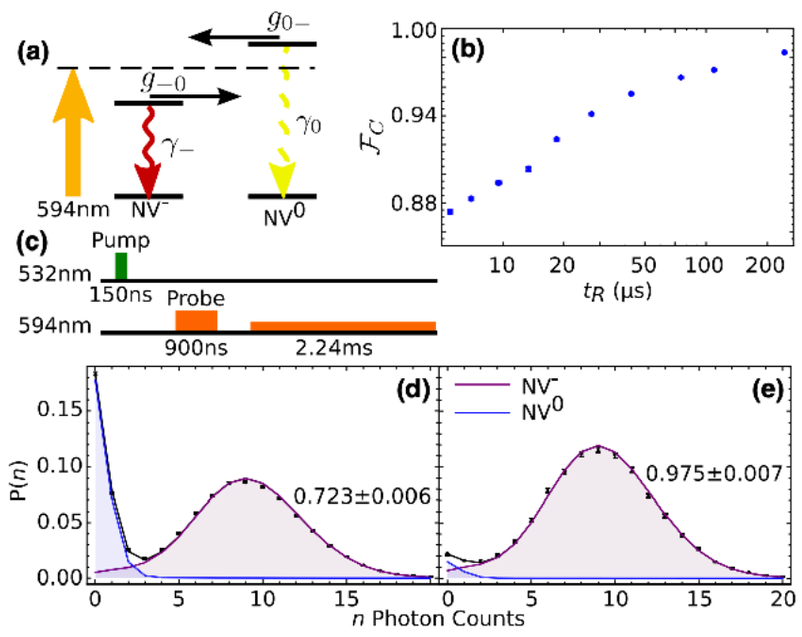
Increasing readout fidelity

$$p(S_1, S_2|\phi_1, \phi_2) = P(S_1, S_2|m_s^x, m_s^y) P(m_s^x, m_s^y|\phi_1, \phi_2) p(\phi_1, \phi_2)$$

readout quantum projection phase distribution

improved readout fidelity with spin-to-charge conversion





Shields et al, *PRL* 2015

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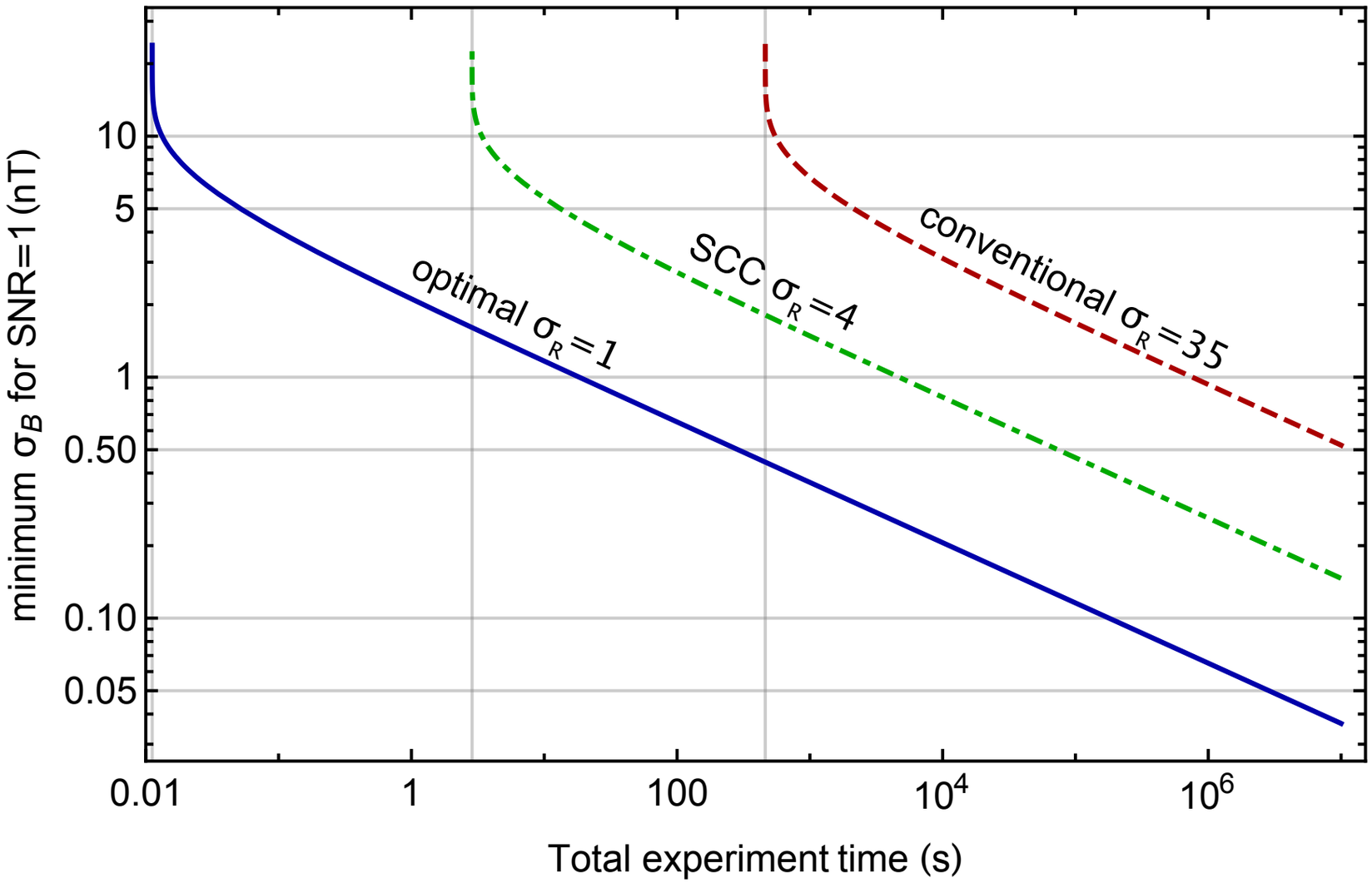
Rovny, NdL et al, *Science* 2022

Minimum detectable signal



maximum observable correlation is $1/\sigma_R^2$

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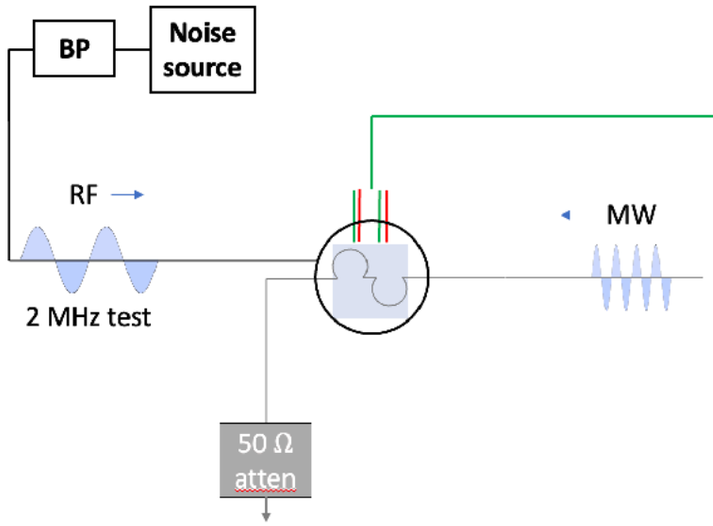
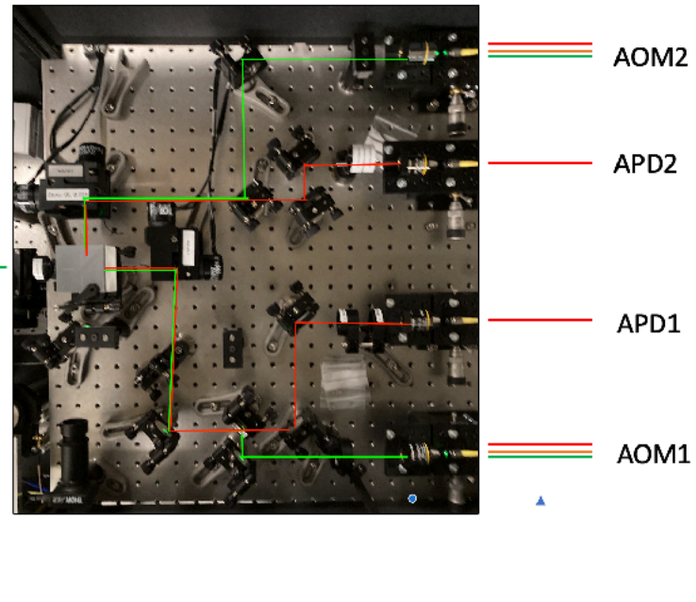
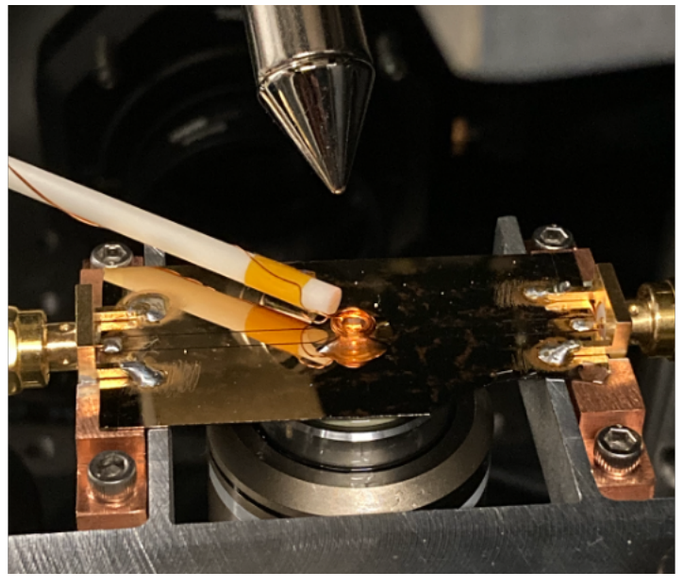
Experimental implementation

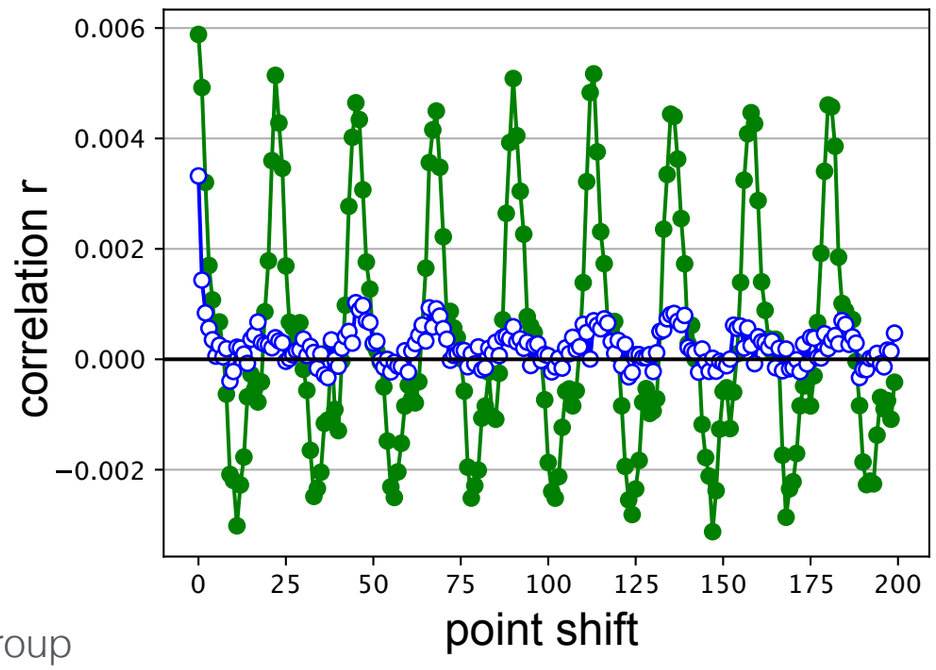


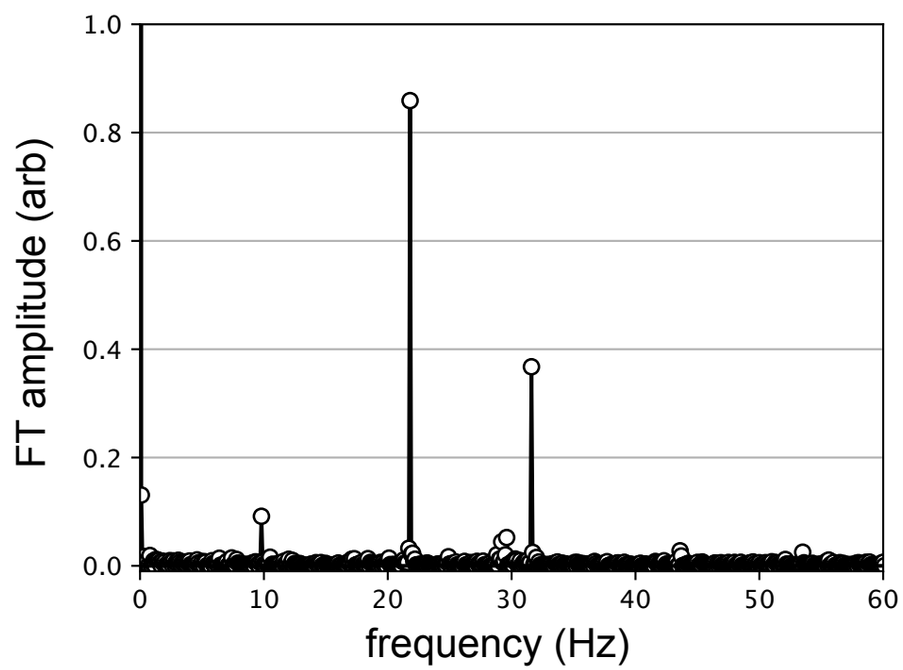


spin-to-charge readout



lots of trivial correlations





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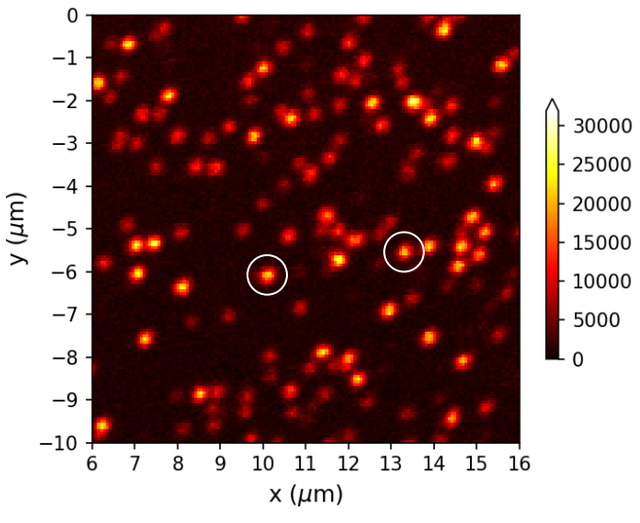
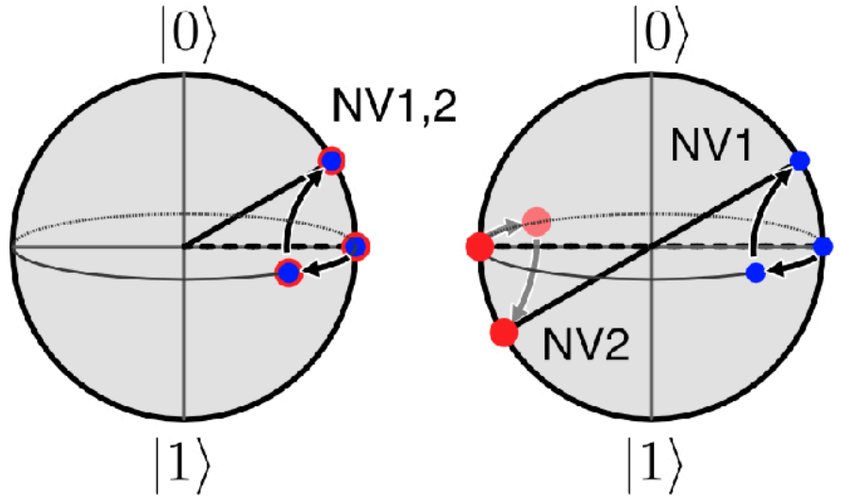
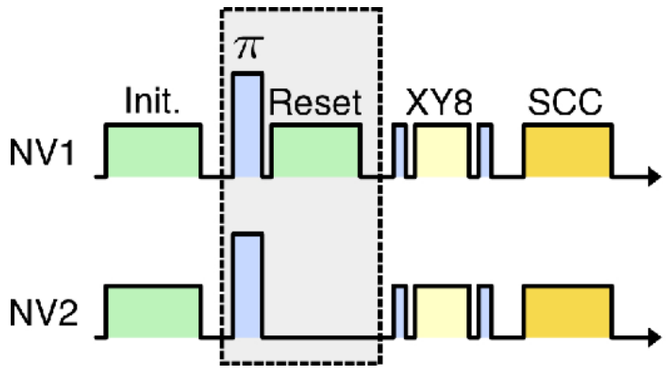
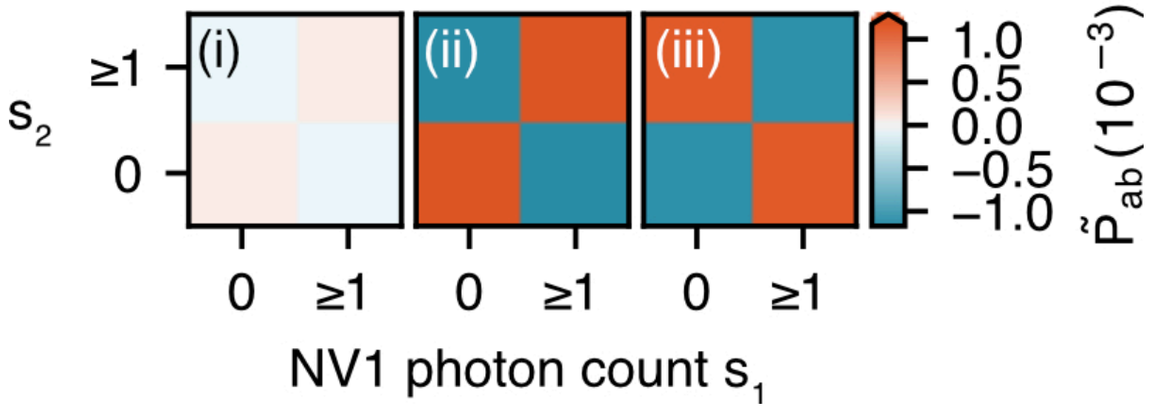
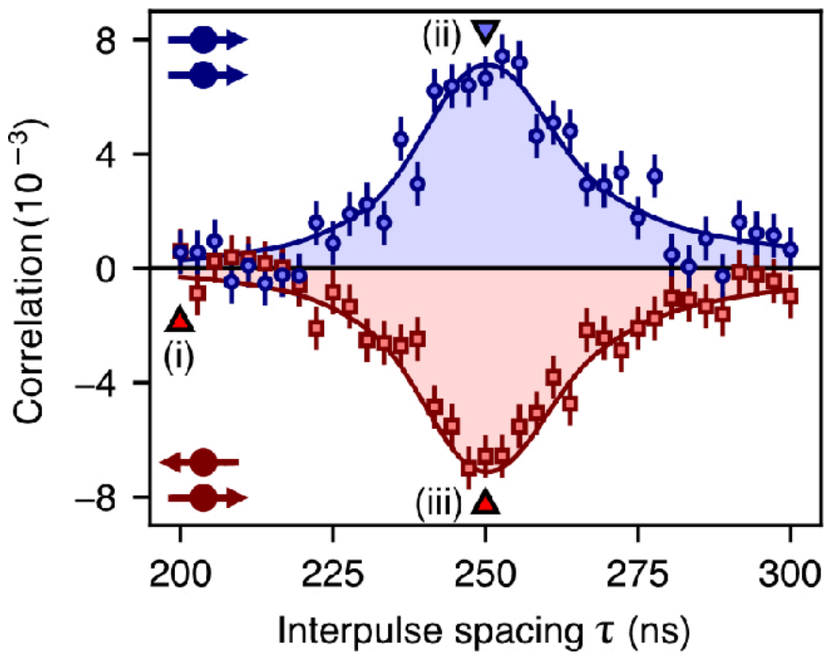
Detecting correlated noise









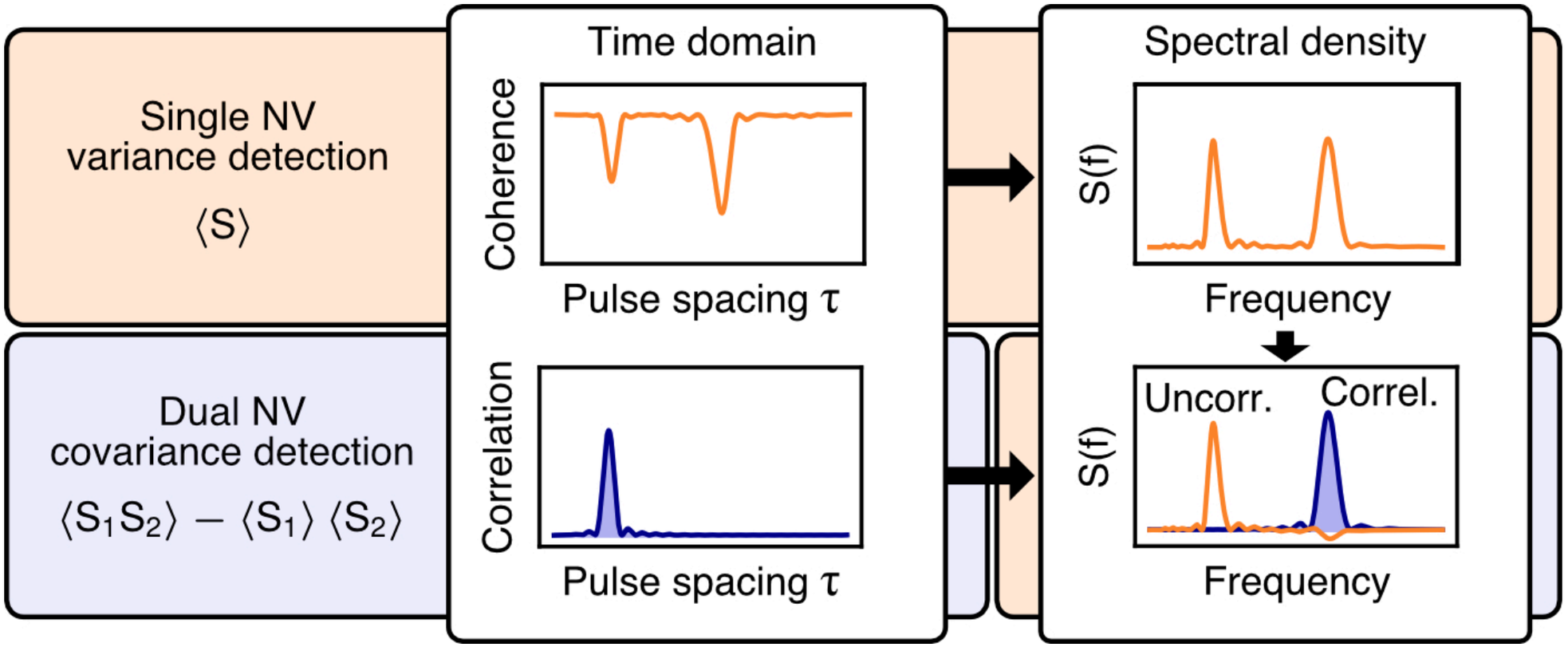


sense global 2 MHz signal

collaboration with Kolkowitz group

Rovny, NdL et al, *Science* 2022

Disentangling sources of noise



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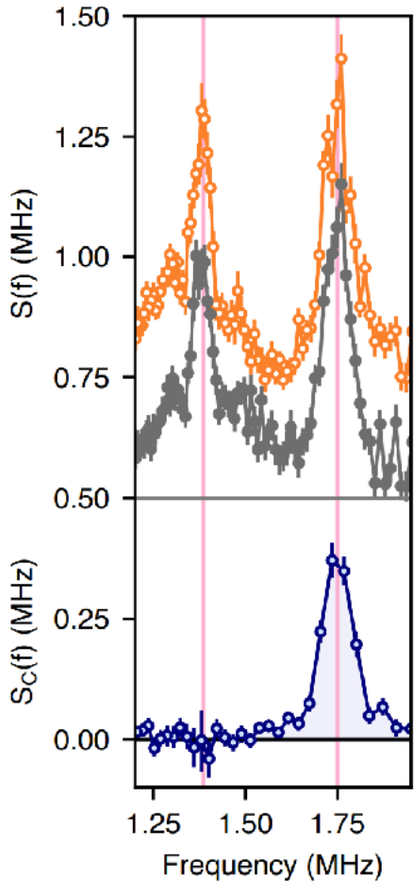
Rovny, NdL et al, *Science* 2022

Separating correlated from uncorrelated noise

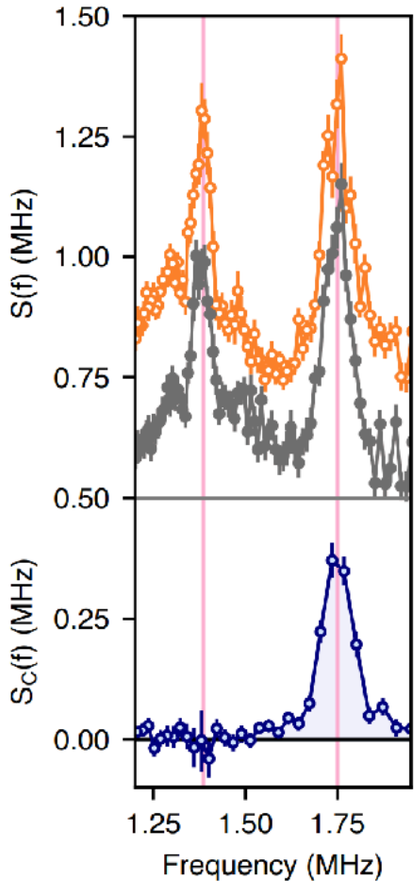


two narrowband noise sources

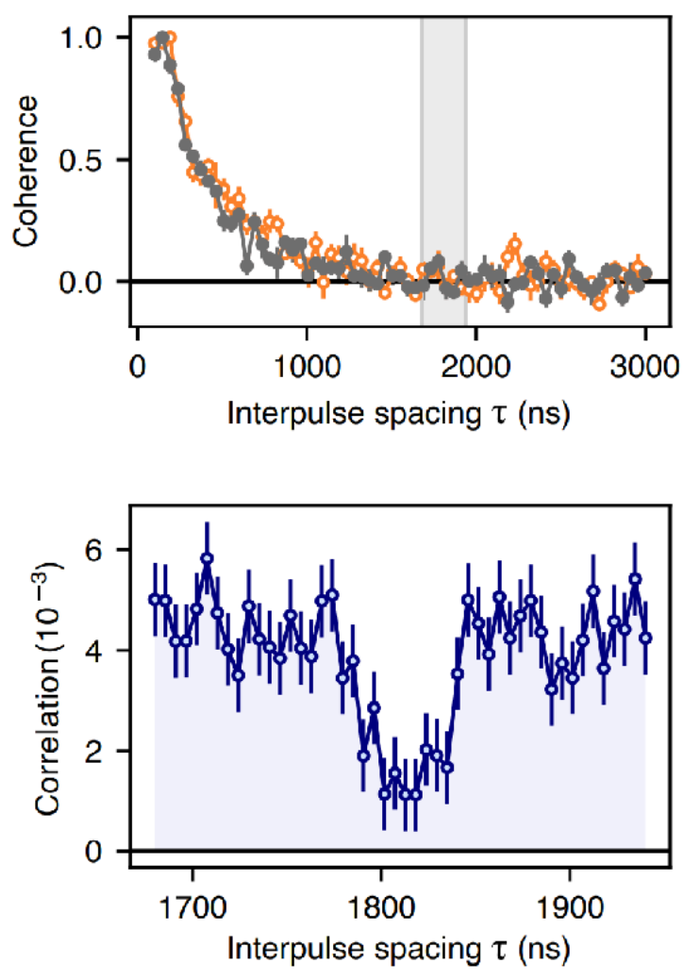
collaboration with Kolkowitz group

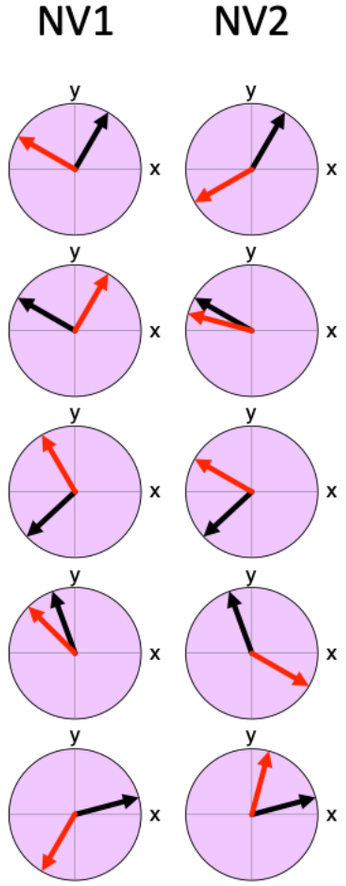
Rovny, NdL et al, *Science* 2022

Separating correlated from uncorrelated noise



two narrowband noise sources





correlated white noise + uncorrelated local noise

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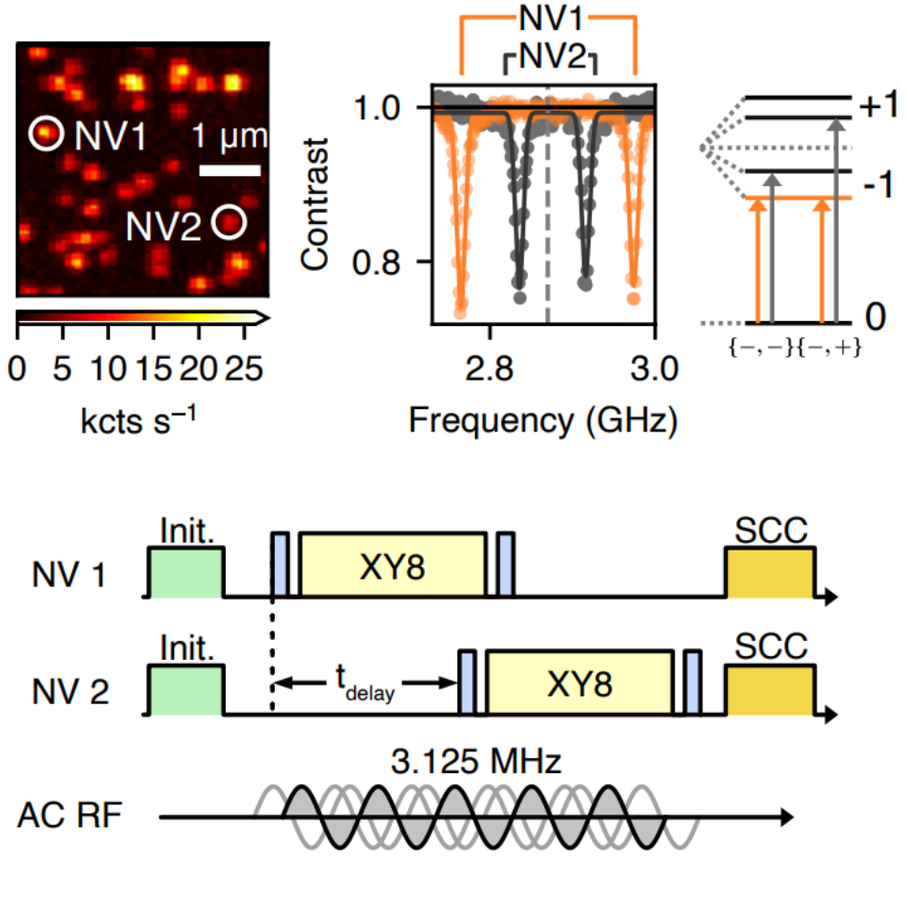
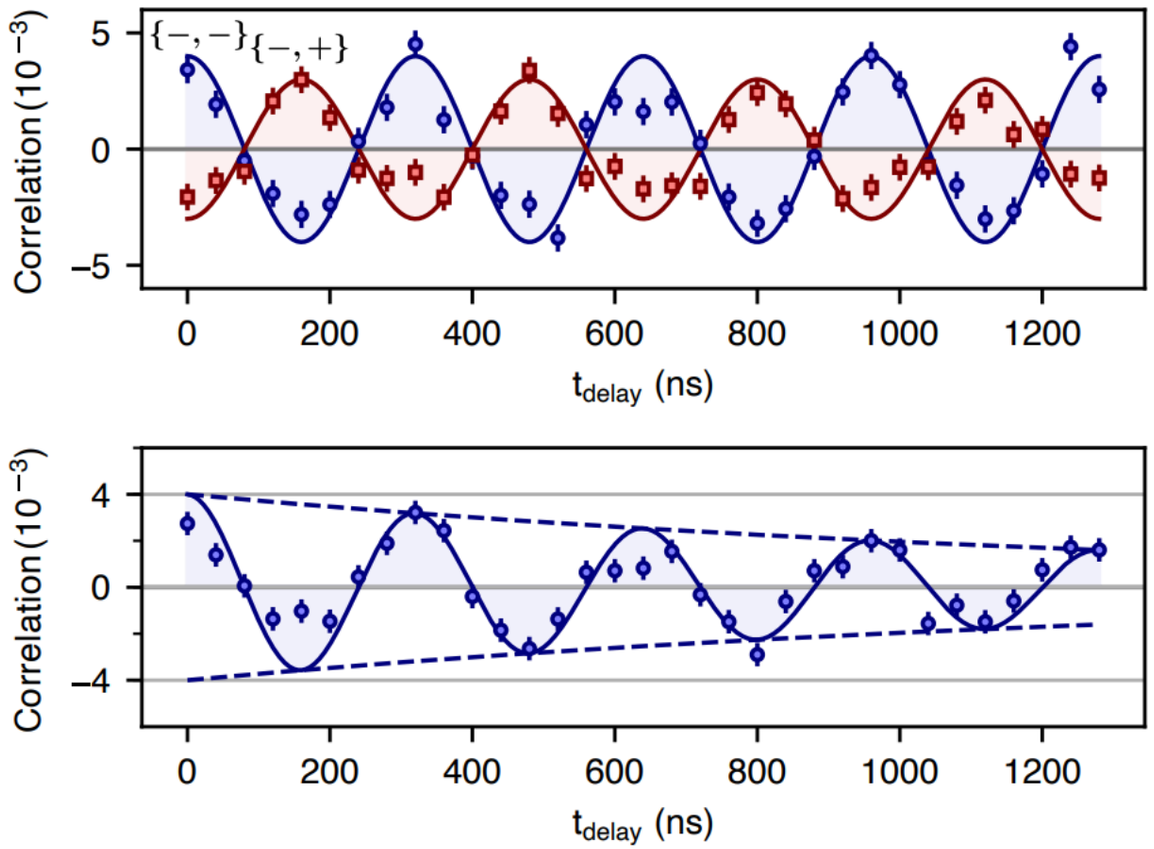
Temporal structure





probe of dynamics at ns timescales

collaboration with Kolkowitz group

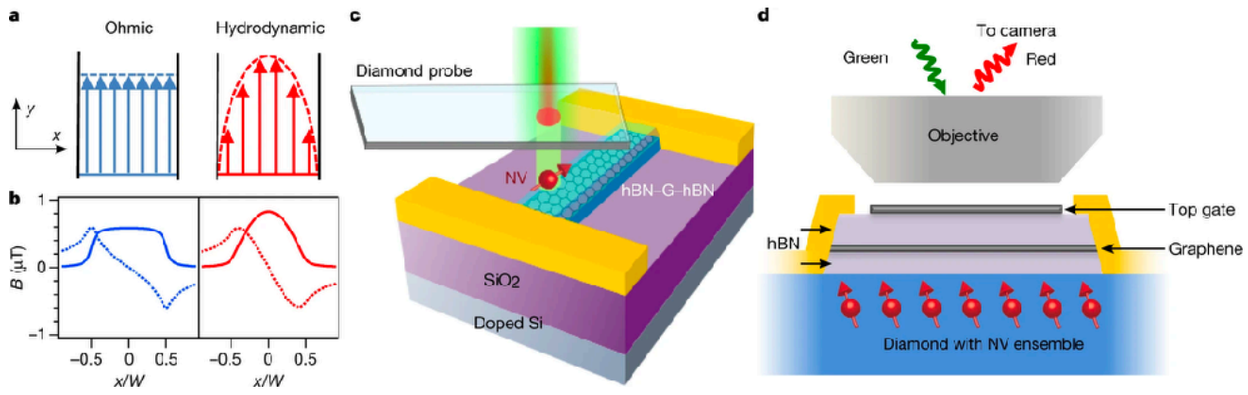
Rovny, NdL et al, *Science* 2022

conclusions

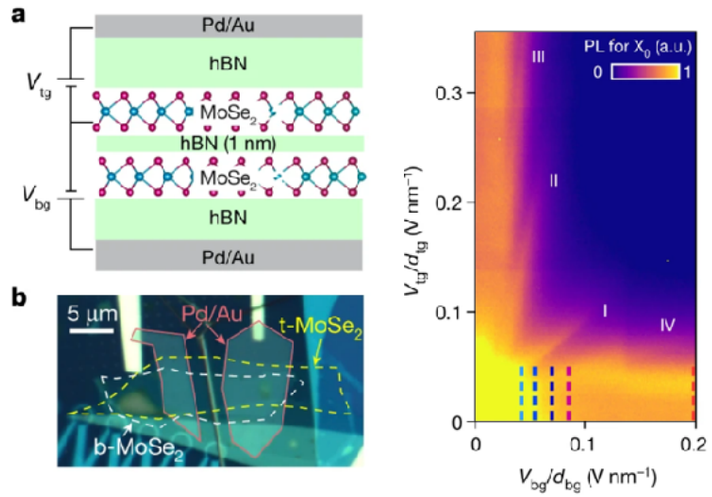
- method for measuring <B(r_1,t_1),B(r_2,t_2)> at 100nm - 100um scales
  - not physically accessible with any other technique!

- study magnetic and spin dynamics

- transport, structure factor, far-from-equilibrium dynamics



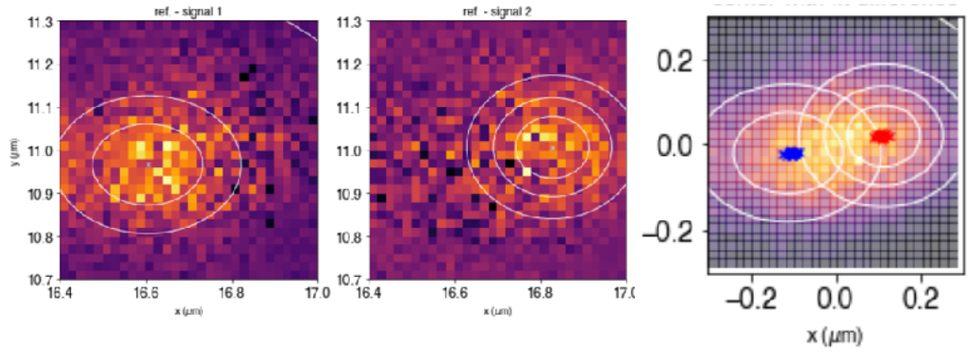
Ku, Kim, Yacoby, Walsworth, *Nature* 2020



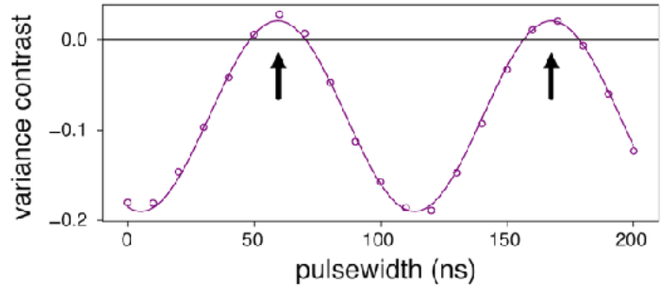
Zhou, Lukin, Kim, Demler, Park, *Nature* 2021

next steps: building a platform for condensed matter

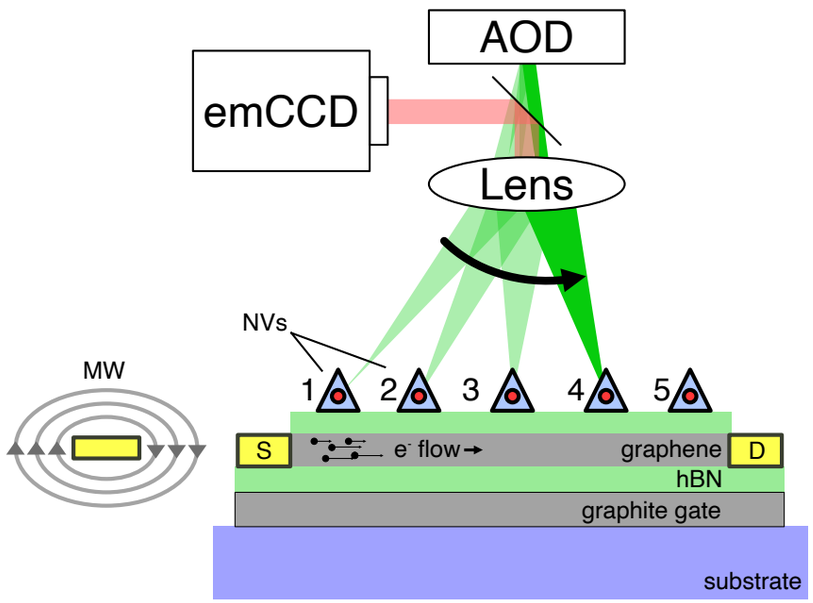
- covariance magnetometry below the diffraction limit

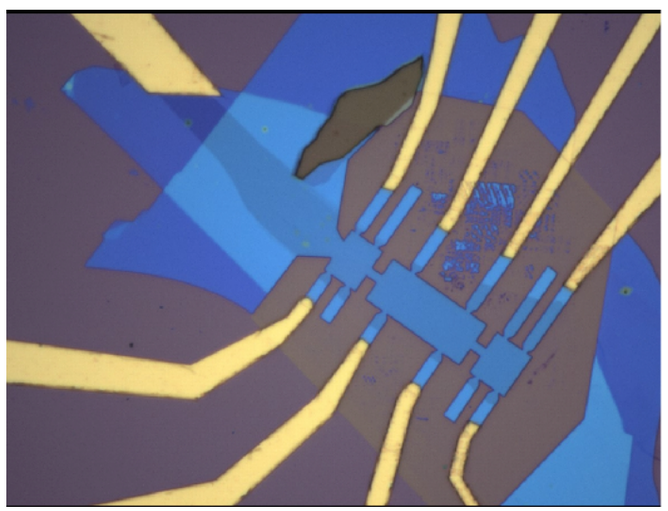


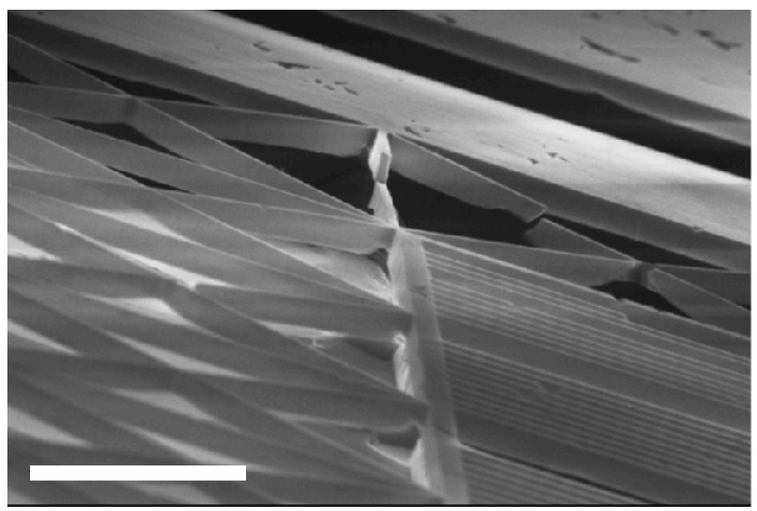
- massively mutliplexed measurements



- devices for integration with different materials





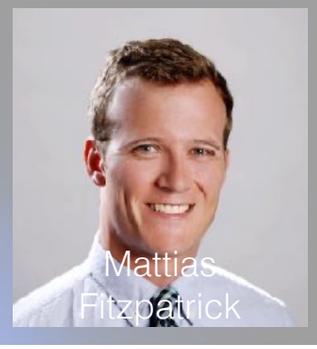


Acknowledgements


Jared Rovny


Zhiyang Yuan


Ahmed Abdalla


Mattias Fitzpatrick


Laura Futamura

Nanoscale covariance magnetometry with diamond quantum sensors

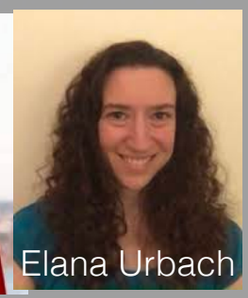
Jared Rovny[1], Zhiyang Yuan[1], Mattias Fitzpatrick[1]†, Ahmed I. Abdalla[1]‡, Laura Futamura[1]§, Carter Fox[2], Matthew Carl Cambria[2], Shimon Kolkowitz[2], Nathalie P. de Leon[1]*

Probing Spin Dynamics on Diamond Surfaces Using a Single Quantum Sensor

Bo L. Dwyer,[1,†] Lila V.H. Rodgers,[2,†] Elana K. Urbach,[1,†] Dolev Bluvstein,[1] Sorawis Sangtawesin,[3] Hengyun Zhou,[1] Yahia Nassab,[2,‡] Mattias Fitzpatrick,[2] Zhiyang Yuan,[2] Kristiaan De Greve,[1,§] Eric L. Peterson,[1] Helena Knowles,[1,¶] Tamara Sumarac,[1] Jyh-Pin Chou,[4] Adam Gali,[5,6] V.V. Dobrovitski,[7] Mikhail D. Lukin,[1] and Nathalie P. de Leon[2,*]


Lila Rodgers


Bo Dwyer


Elana Urbach

Jared Rovny, Zhiyang Yuan, Kai-Hung Cheng, Yizhou Xin, Alex Pakpour-Tabrizi

Frank Zhang, Rhine Samajdar, Sarang Gopalakrishnan
Minhao He, Ali Yazdani

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