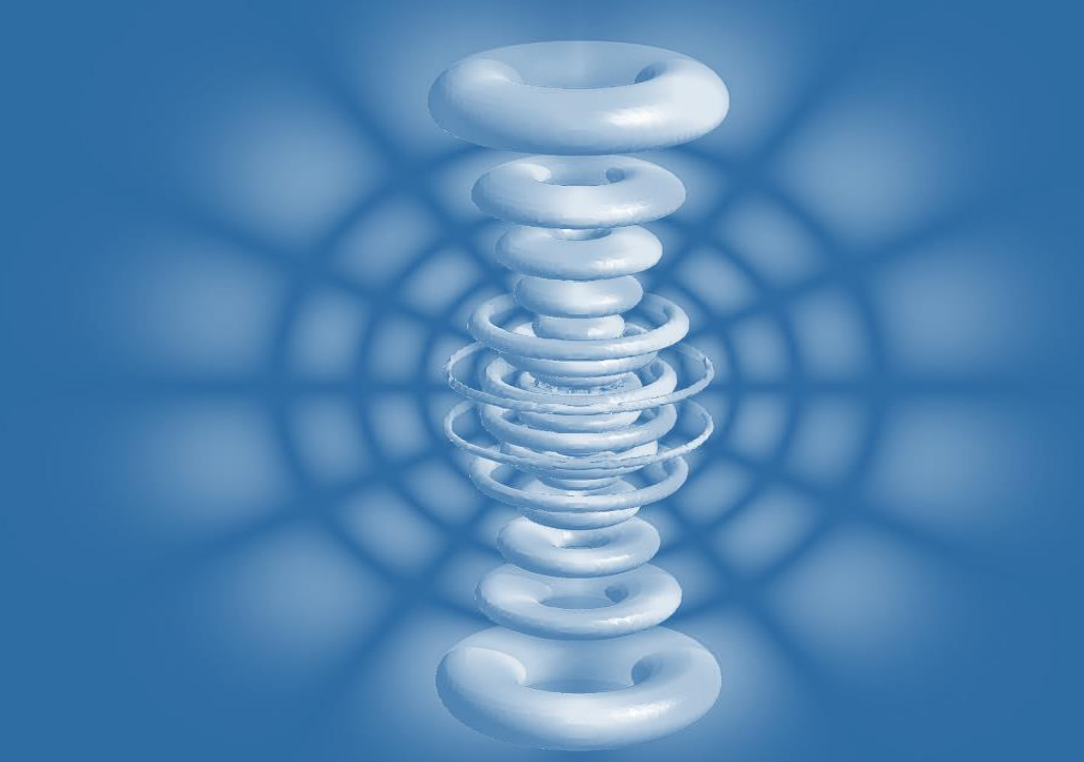
Quantum Sensing in Pittsburgh



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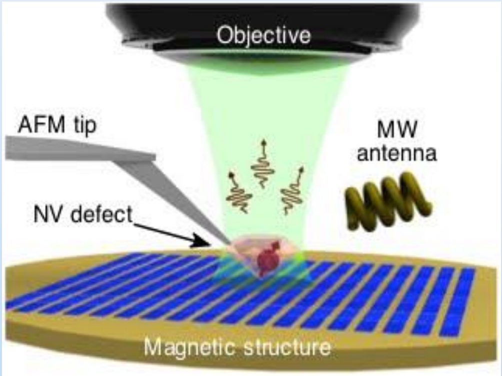
What is Quantum Sensing?

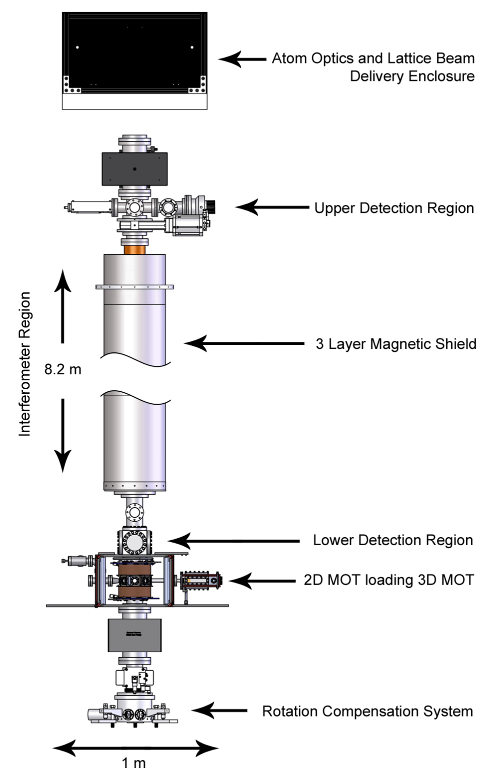
- Type 1: Use of a quantum object to measure physical (classical/quantum) property

NV center magnetic imaging



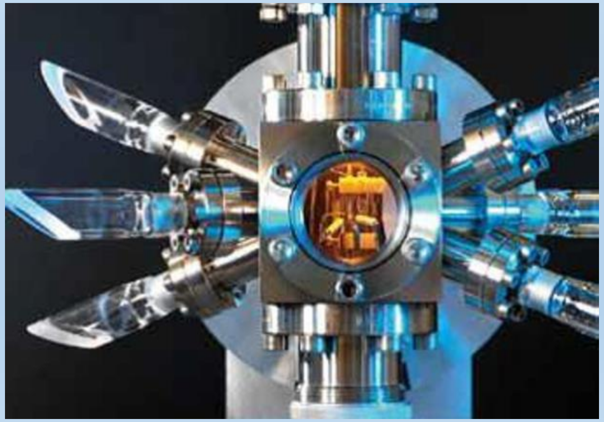
Type 2: Use of quantum coherence / interference to measure physical property

Atomic cloud gravimeter



Type 3: Use of quantum entanglement to improve performance of sensor beyond classical limits

Trapped ion clock



LIGO

Degen et al, RMP 89, 035002(2017)

"DiVincenzo" Criteria for Quantum Sensing

- Well-defined qubit with discrete, resolvable energy levels
- Qubit can be initialized into a well-known state and read-out
- Coherent manipulation, typically by time dependent fields
- Quantum system interacts with a relevant physical quantity V(t) with a strength $\gamma = \partial^q E / \partial V^q$; usually q = 1 or 2.

Degen et al, RMP 89, 035002(2017)

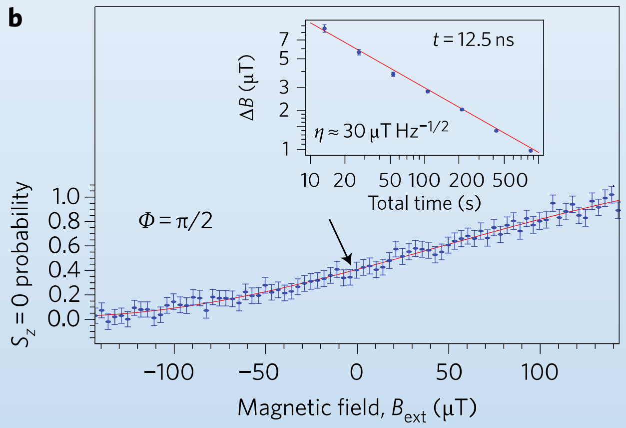
Key characteristics of quantum sensors

- Parameter being sensed (e.g. electric field, magnetic, currents, thermal etc)
- Intrinsic sensitivity $\eta \propto \frac{1}{\gamma\sqrt{T_x}}$

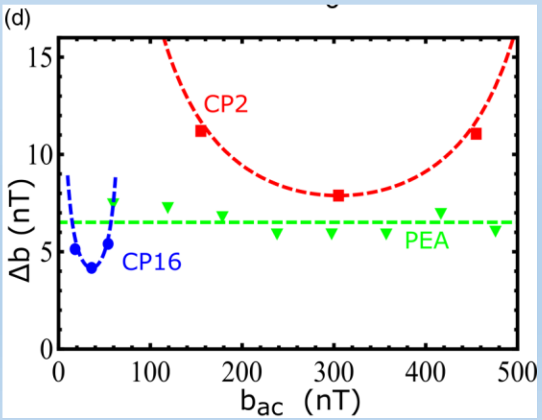
T_x ~ coherence time

But also: spatial resolution, dynamic range, linearity, bandwidth, robustness….

What do applications need?



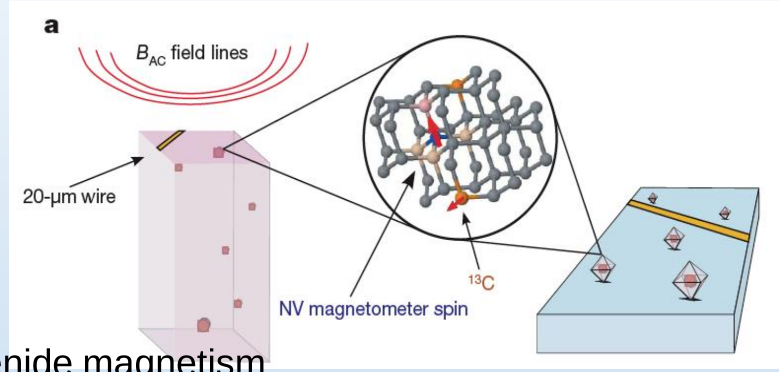
Nusran et al, Nat. Nanotech., 7, 109-113 (2012).



Nusran et al, PRB Rapid Comm 88, 220410 (2013).

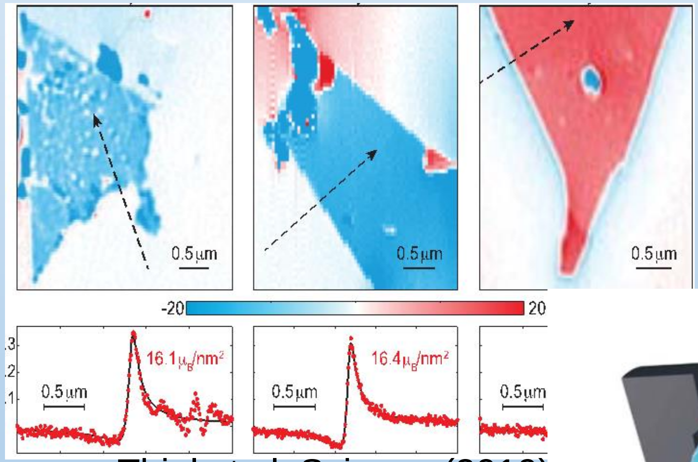
Nitrogen-Vacancy (NV) Centers in Diamond for Quantum Sensing

- Long-lived qubit in stable diamond host
- Optical and microwave fields for spin control and readout
- Sensitive to magnetic field, temperature, electric fields, pressure…
- Applications demonstrated in materials science, biophysics, geomagnetics, …

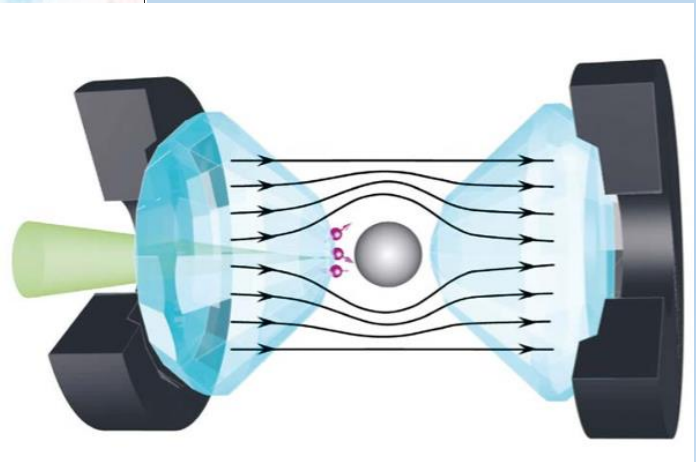


Maze et al, Nature (2008)

Transition metal chalcogenide magnetism



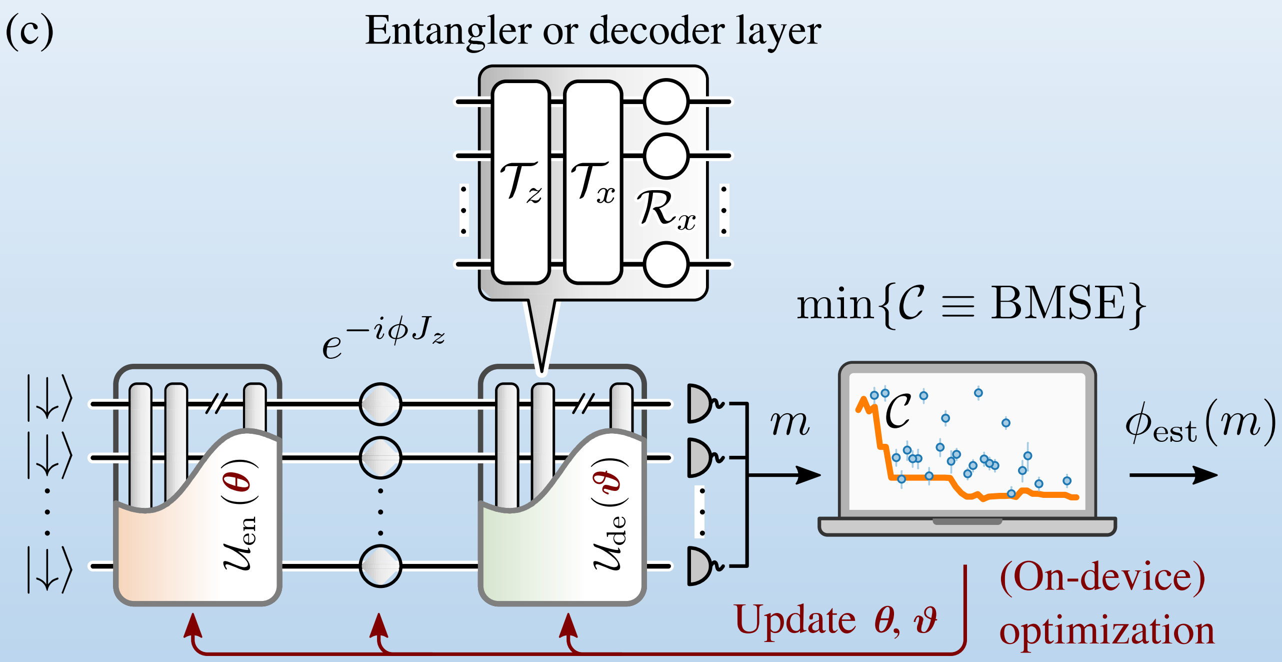
Thiel et al, Science (2019)



M. Lesik, et al., Science (2019).

Entanglement frontier for quantum sensing

- Recent work on variational algorithms for creating optimal entangled states for sensing
- What are the best algorithms? How to implement in realistic systems?
- How to take advantage of the intrinsic correlations and many-body nature of solid-state quantum sensors?

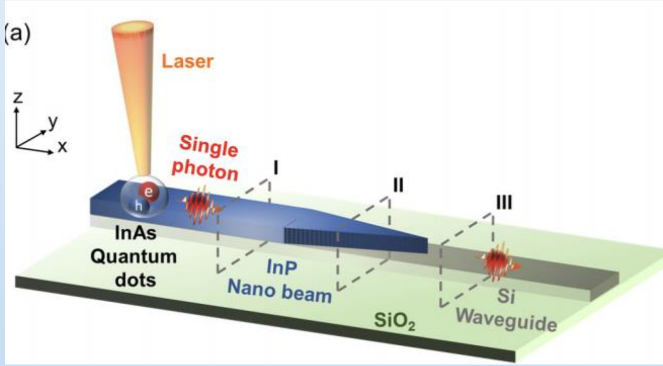


Kaubruegger et al, PRX 11, 041045 (2021)

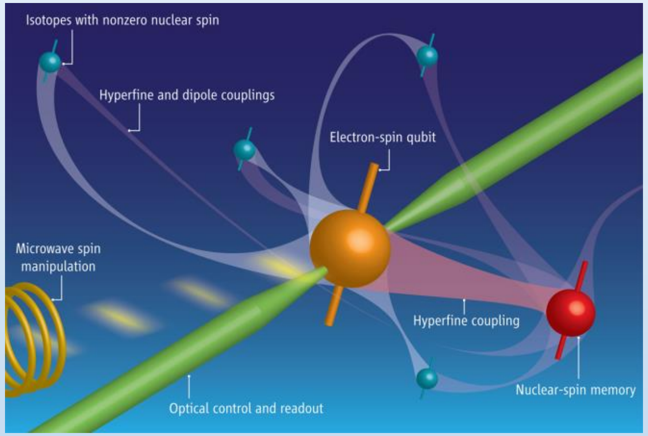
Backup slides

Quantum to Quantum Transduction for Quantum Networking & Interconnects

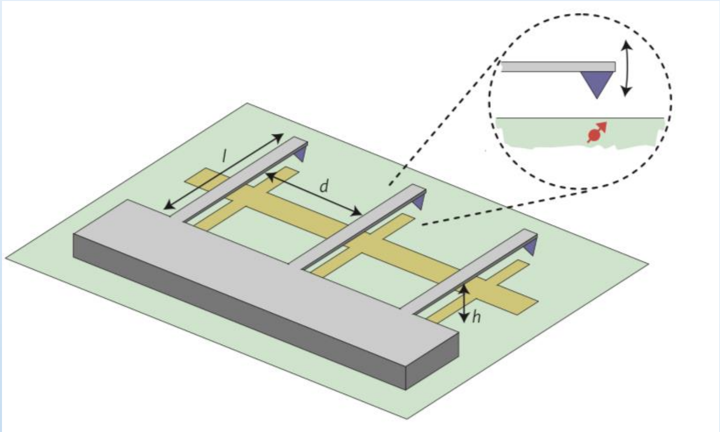
Quantum communication channel



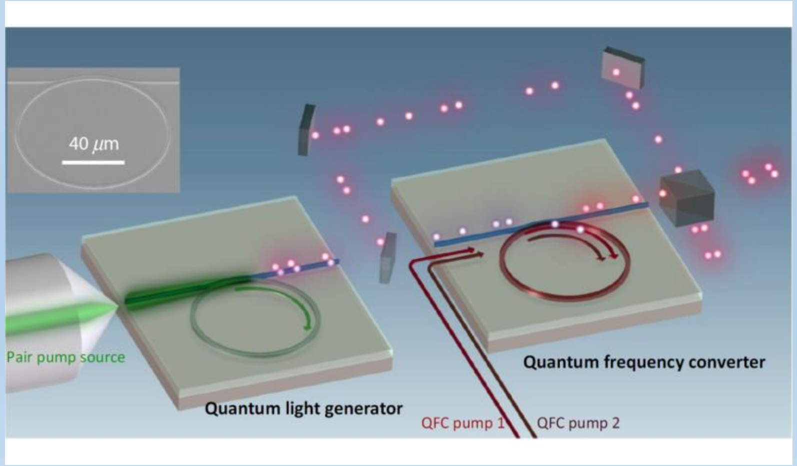
Quantum memory



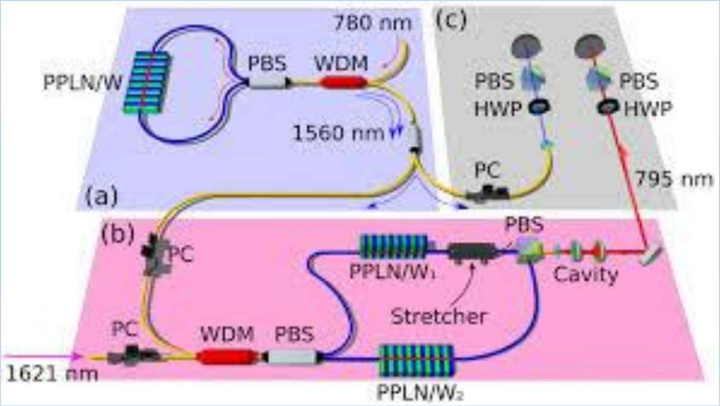
Quantum transducer



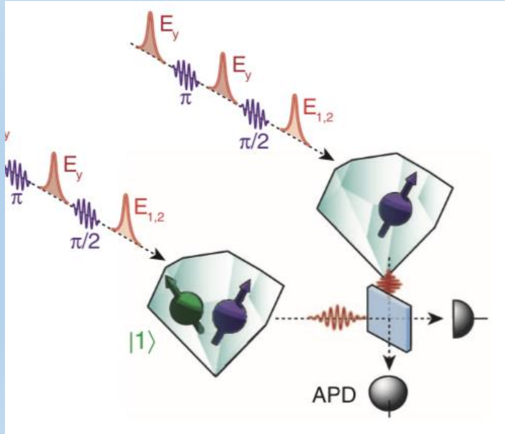
Quantum converter



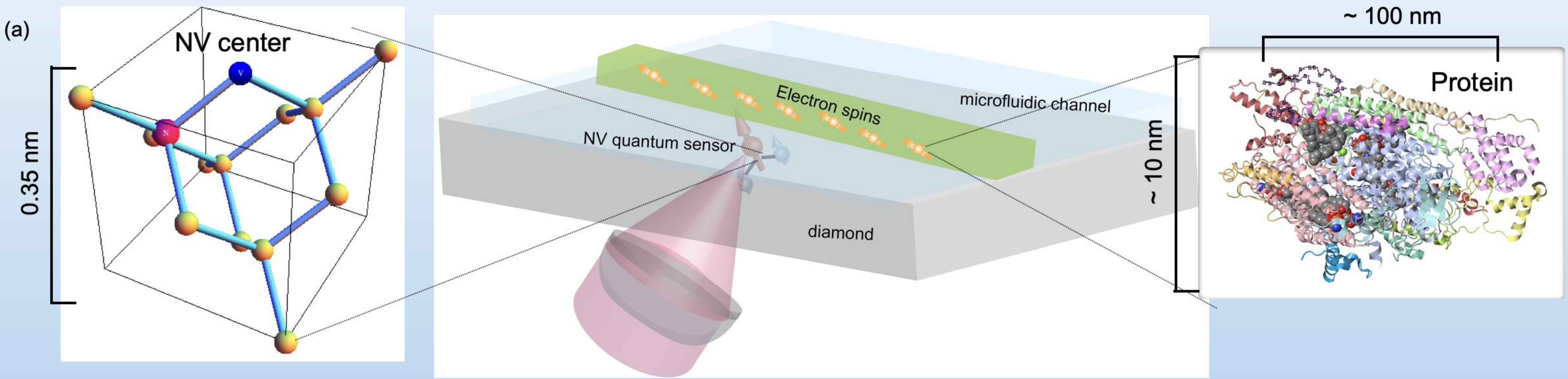
Quantum sources



Quantum repeater nodes



Quantum sensing and imaging for biochemistry & biophysics

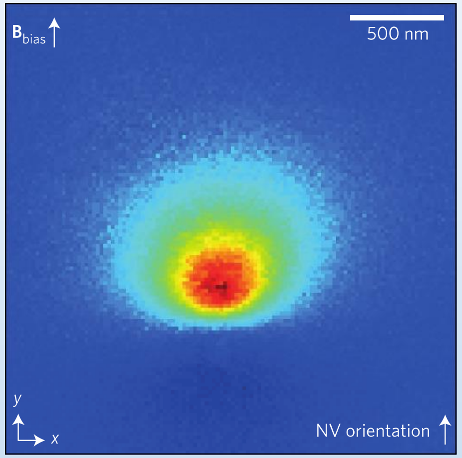


Challenges:

(a) Control of diamond surface termination and NV coherence properties
(b) Reducing diffusion and increasing integration times for best sensitivity
(c) Characterization over wide range of length scales, pH, temperatures, magnetic fields etc
(d) Different sensing modalities, increasing parallelization, reducing equipment complexity, and comparison to traditional EPR needed

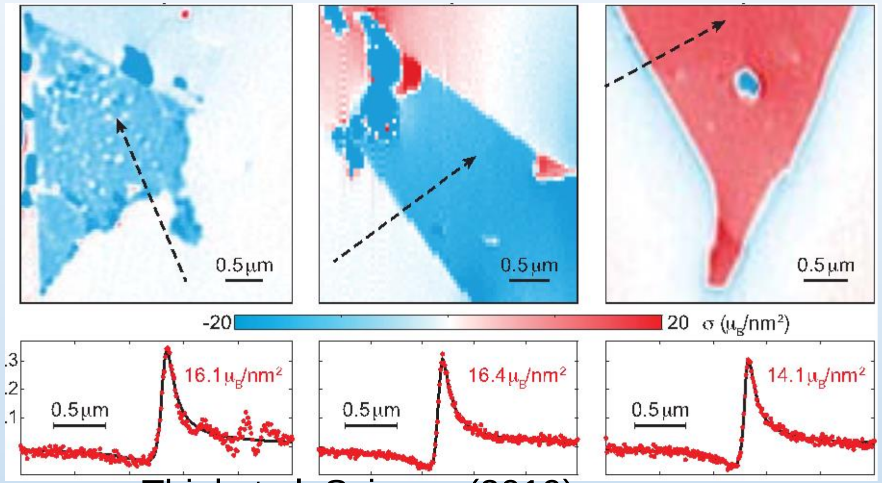
Materials Science Applications

Magnetic vortex imaging



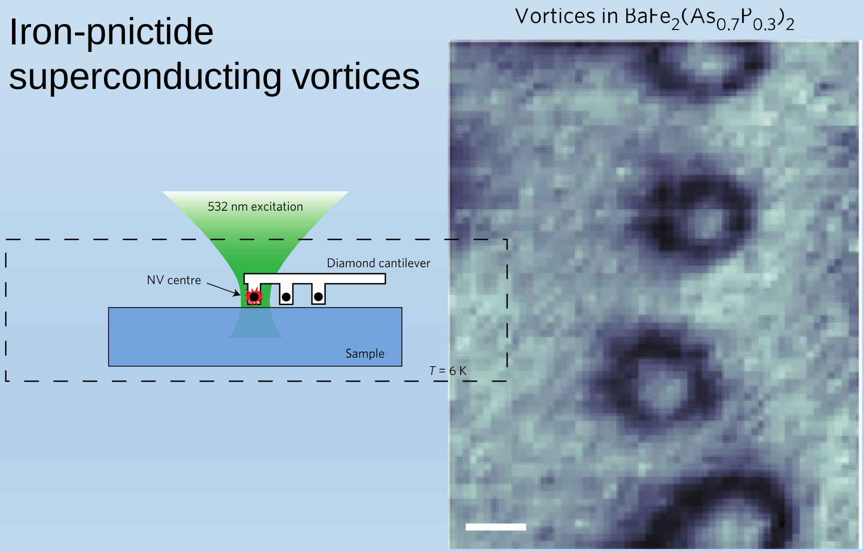
Thiel et al, Nat. Nano (2016)

Transition metal chalcogenide magnetism



Thiel et al, Science (2019)

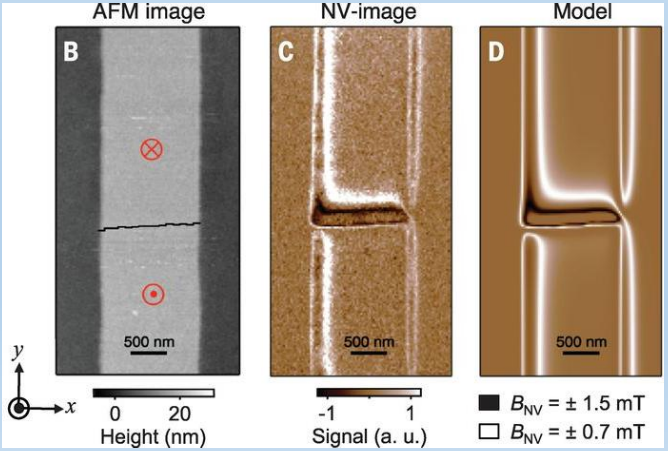
Iron-pnictide superconducting vortices



Pelliccione et al, Nat. Nano (2016)

Domain wall pinning

Tetienne et al, Science (2014)



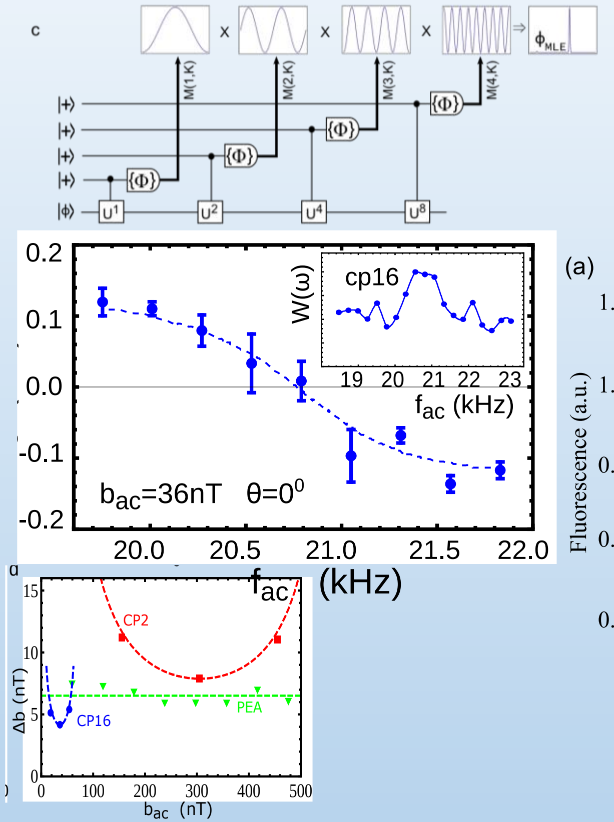
Quantum Sensors @ Pitt: Nanoscale spin physics

Gurudev Dutt, Dept. of Physics

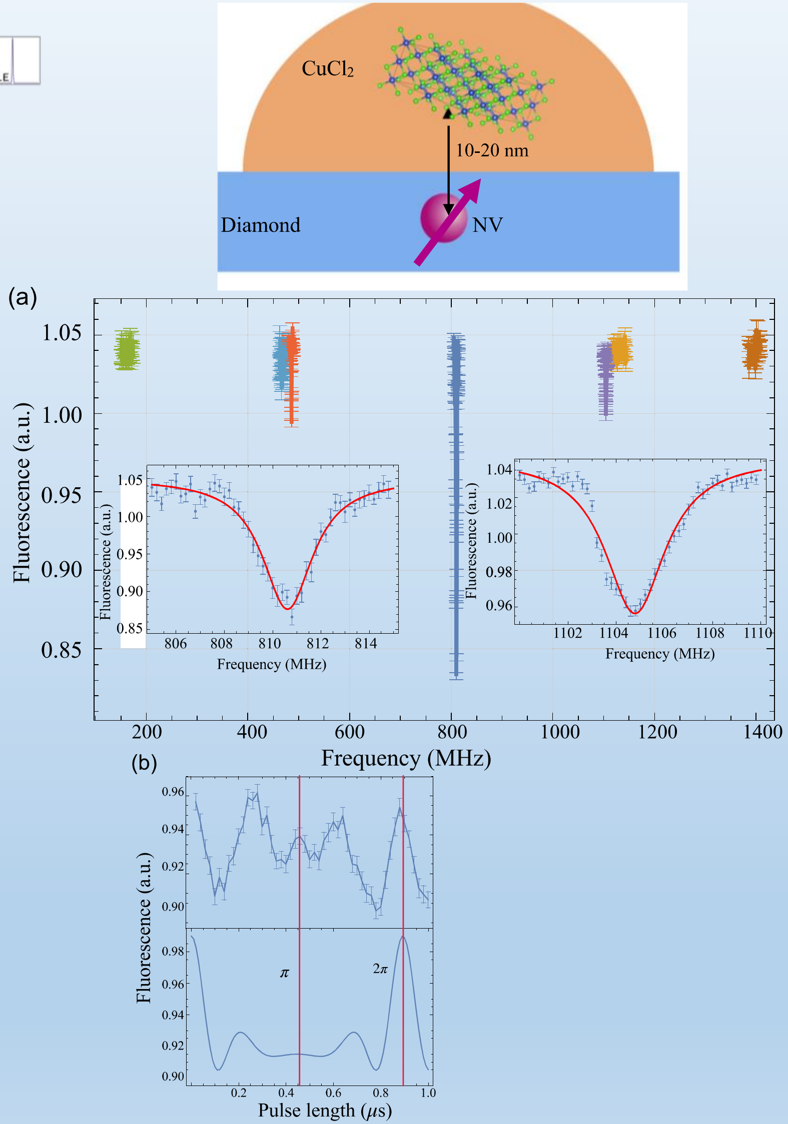
- ✓ Phase estimation algorithms[1]
- ✓ Sub-shot noise scaling of sensitivity[2]

- ✓ Single spin dual-channel lock-in magnetometer[3]
- ✓ Geometric phase measurement in single spin qubits[4]

- ✓ Nanoscale electron spin resonance of molecules[5]



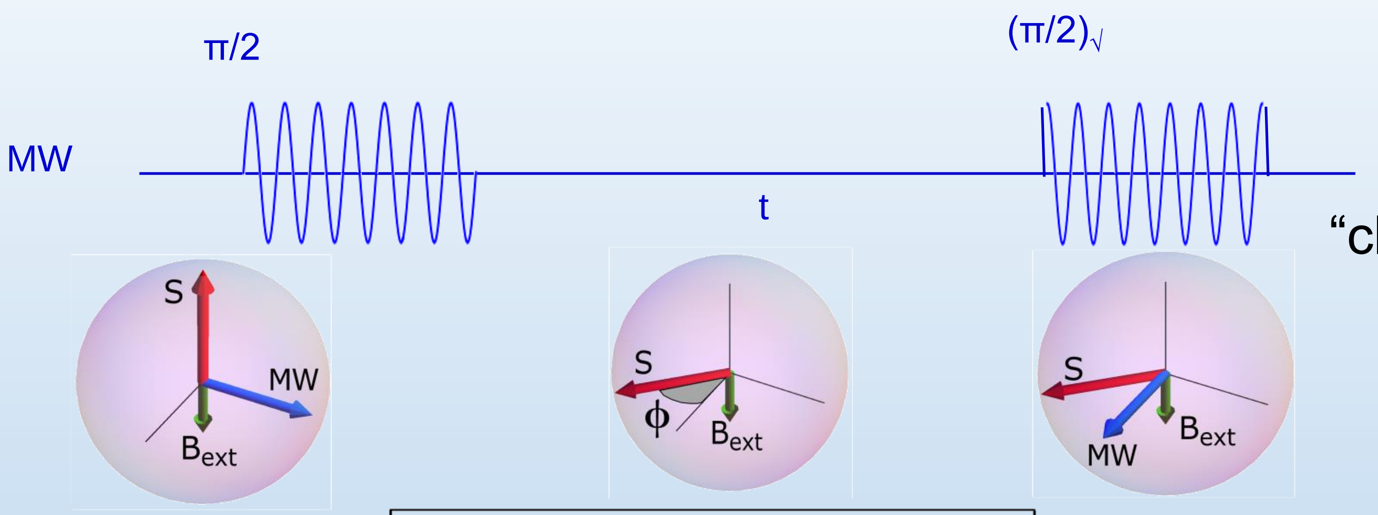
Phase estimation algorithms for increased sensitivity over wide dynamic range



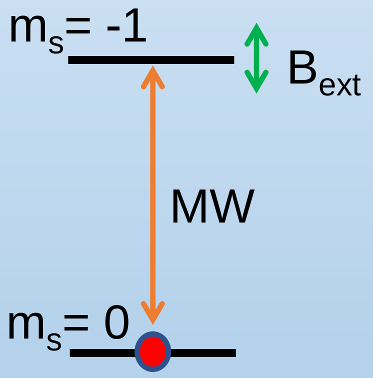
ESR of single Cu spins on diamond surface

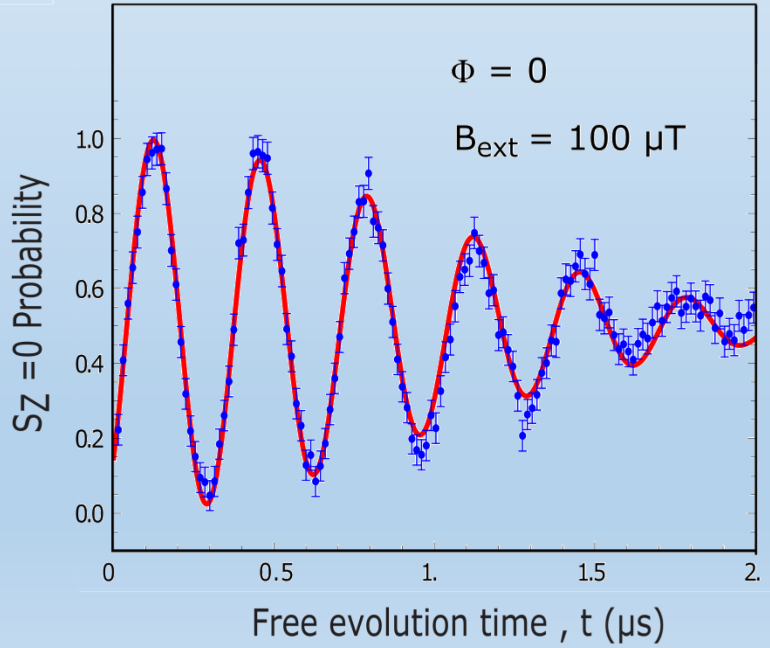
1. N. M. Nusran, GD, Phys. Rev. B. 90, 024422 (2014).
2. N. M. Nusran, M. U. Momeen, GD, Nature Nanotechnology 7, 109-113 (2012).
3. N. M. Nusran, GD, Phys. Rev.B (Rapid), 88, 220410R (2013)
4. K. Zhang, N. M. Nusran, B. Slezak,GD, New J. Phys. 18, 053029 (2016)
5. K. Zhang, S. Ghosh, S. Saxena, GD, PRB 102, 224412 (2021)

Example: DC Magnetometry with Ramsey Fringes



"clock" transition





$$\phi = \gamma B_{ext} t$$

$$\gamma = 27.99 GHz/T$$

$$P(0) = \frac{1 - e^{-t^2/T_2^{*2}} Cos(\phi - \Phi)}{2}$$

Φ = Control Phase

Nusran et al, Nat. Nanotech., 7, 109-113 (2012).