QUISM

Multi-qubit enhanced sensing and metrology

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Multi-qubit enhanced sensing and metrology

Kick-off meeting

- Program goals
- Team expertise
- Preliminary results

Promise of qt. metrology

- Improved sensitivity
  - Entangled states
  - Feedback, adaptive methods
- Nano-scale probes
  - Proximity to target, nano-materials or biology applications
- Robust metrology
  - Clocks, based on fundamental physics laws

Challenges in qt. metrology

- Fragility of entangled states
  - Improved sensitivity implies higher sensitivity to external noise
- Complexity of control for multi-qubit systems
  - Qubit addressability, control robustness and fidelity
- Unavailable or inefficient quantum readout
  - Many-body observables, imperfect readouts

Goals of MURI-QUISM

- We will overcome these fundamental challenges by developing novel paradigms for:

1) Entangled States:

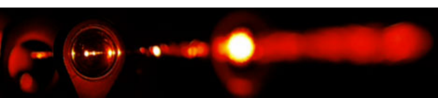
- We will explore novel classes of entangled states, more easily created and robust against decoherence, and novel experimental methods to create known entangled states such as N00N states.

2) Quantum control during signal acquisition

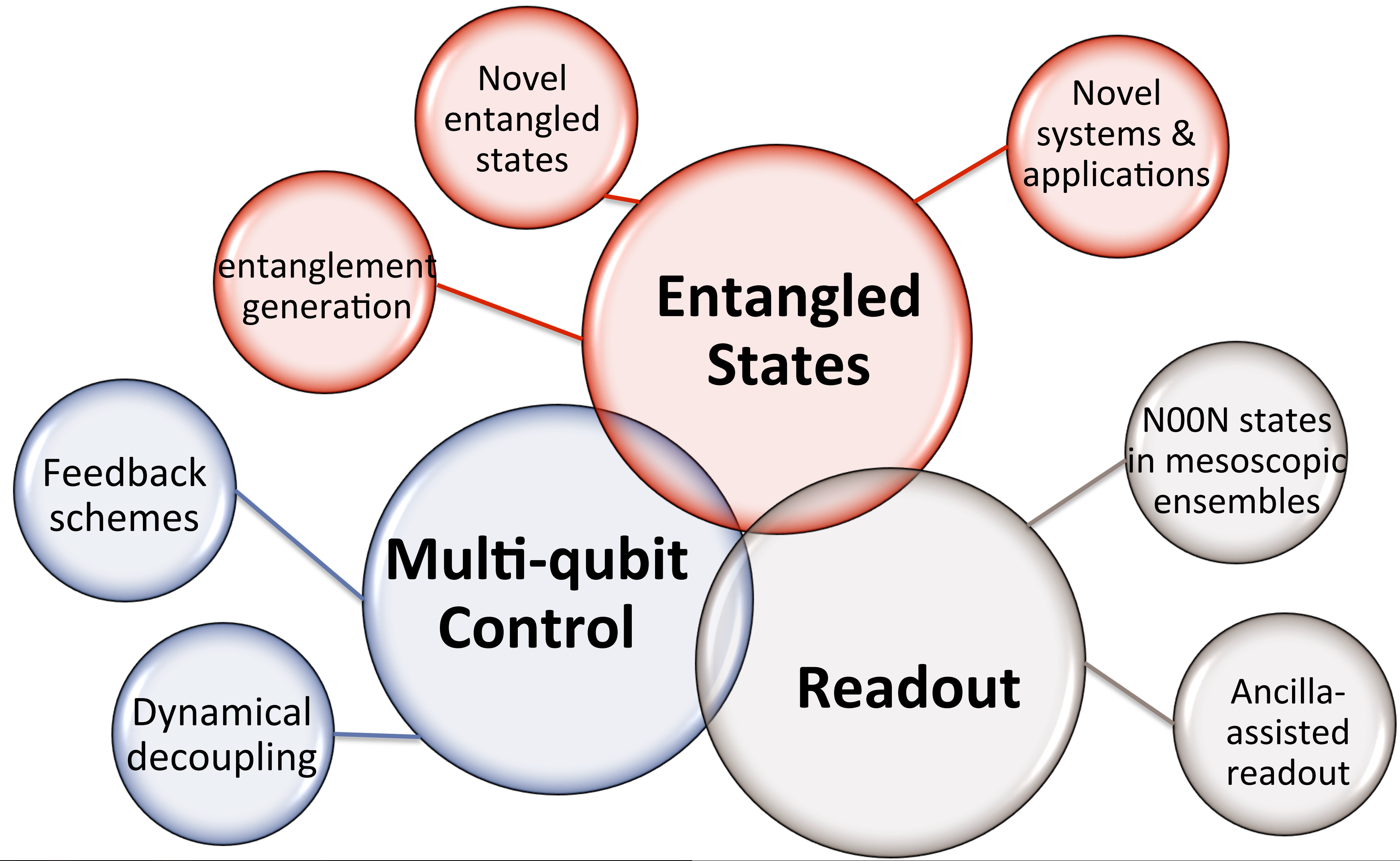
- We will develop quantum control and feedback methods to enhance device sensitivity to the signal, attain spectral signal resolution, and achieve increased noise immunity of the sensor.

3) Quantum-Enhanced Readout:

- We will investigate multi-qubit enhanced readout techniques to increase measurement efficiency and resolution, and measurement schemes to reach sensor performance near the Heisenberg limit.

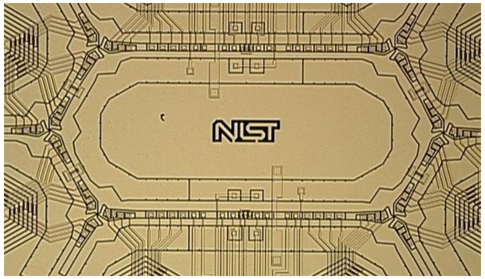


Program Themes

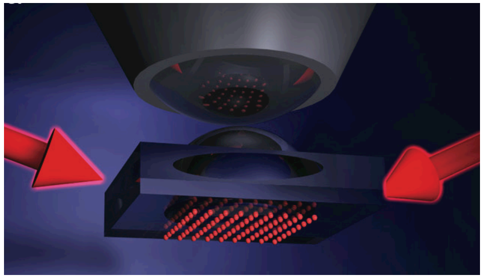


Experimental Platforms

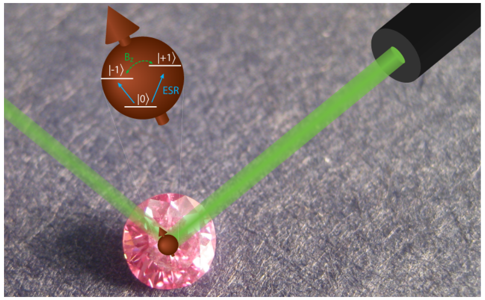
- Three complementary experimental platforms
  - Ions cooled and trapped by RF and Penning traps



  - Neutral atoms in cavity and ultracold atoms



  - Solid-state qubits, electronic spins (NV center)

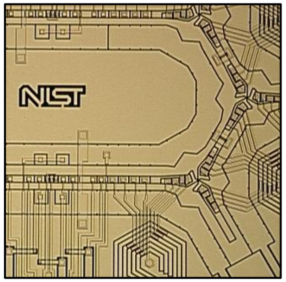


Experimental Platforms

	Entangled States	Control	Readout
NV	Environment enhanced metrology, squeezing, Scanning tip	Spectroscopy via dynamical decoupling	Repeated QND readouts, Spin to charge conversion
Atoms	N00N states in cavity	Single atom transistor	Metrology with quantum gas microscope and ensemble-cavity interaction
Ions	Optimal clock states, Coupled ion spectroscopy	Control in Penning traps	QND readout of multiple ions

Team members

Paola Cappellaro
MIT



John Bollinger
NIST

Eugene Demler
Harvard

Markus Greiner
Harvard

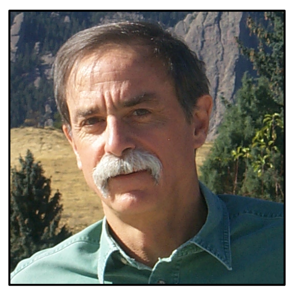
Seth Lloyd
MIT

Misha Lukin
Harvard

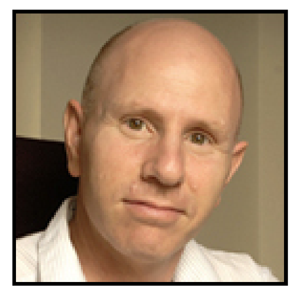
Vladan Vuletic
MIT

Ron Walsworth
Harvard

Dave Wineland
NIST



Amir Yacoby
Harvard



Susanne Yelin
U-Conn

Program Themes

Themes		Tasks	Team
Entangled States	Novel forms of entangled states	Optimal states for clock accuracy	SL,DW,JB, VV
		Environment enhanced metrology	PC, ML
	Novel schemes for entanglement generation	Spin squeezing in solid-state systems	PC, ML
		Generation of entangled states through microwave magnetic field gradients	JB, DW
	Extension to novel systems and applications	Coupled ion trap spectroscopy	JB, DW
		Scanning NV-magnetometer	AY
		Spin-labels for ancilla-enhanced spectroscopy	ML, RW
Multi-Qubit Control	Dynamical-decoupling for metrology tasks	Spectroscopy via dynamical decoupling	RW, PC, SL
		Control of qubit ensembles and of the environment	PC, RW, ED
		Entanglement and control w/ many ions in Penning traps	JB, DW
	Feedback schemes	Coherent ensemble-and measurement-based sensitive diamond magnetometer	SY, ML
Readout	Ancilla-assisted readouts	QND readout of multiple trapped ions	DW, JB
		Ancilla readout in NV centers	ML, RW
		Spin to charge conversion and readout of NV spin	AY
	N00N states in mesoscopic ensembles	Heisenberg limited metrology in quantum gas microscope	MG
		Quantum metrology with N00N states enabled by ensemble-cavity interaction	VV

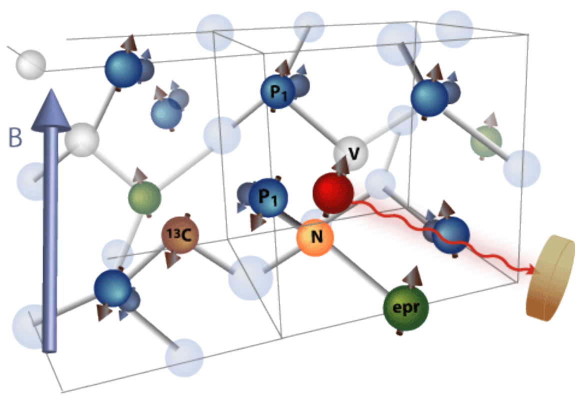
Some Preliminary Results

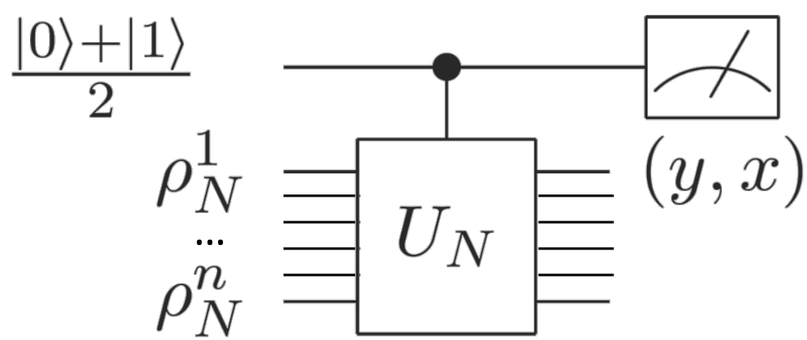
New entangled states

- Harness the bath of *"dark"* nitrogen spins

$$\mathcal{H} = \gamma B \Sigma_i I_z^i + S_z \Sigma_i \lambda_i I_z^i$$

  – B-field is sensed by *dark* spins, in turns detected by the *bright* NV center spin





- Parameter estimation via ancillary qubits

  – Effective evolution: $U_N = \exp(-iBt\,\Sigma_k I_z^k)$

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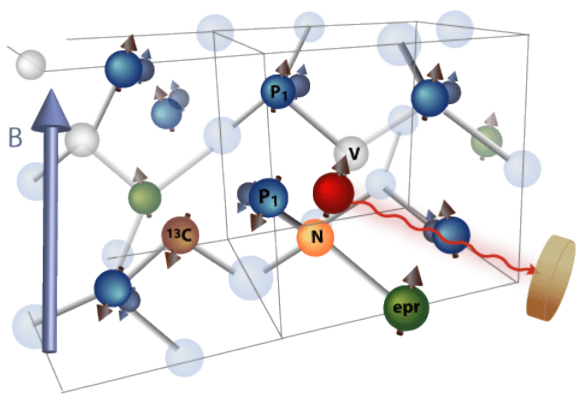

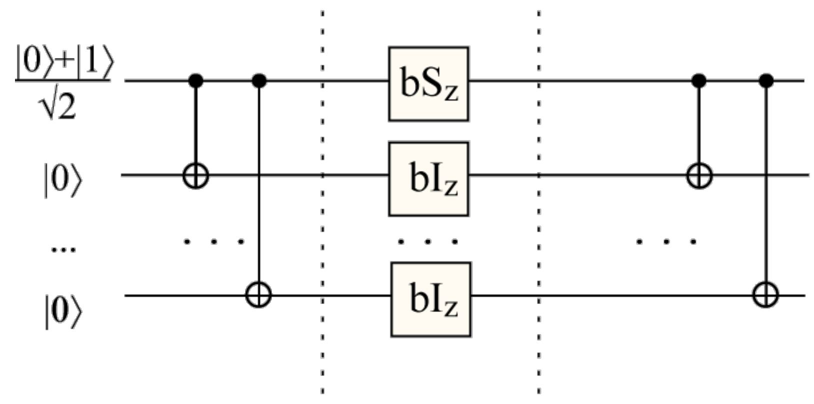

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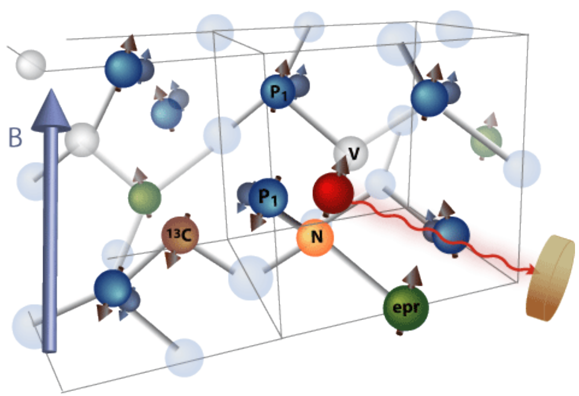

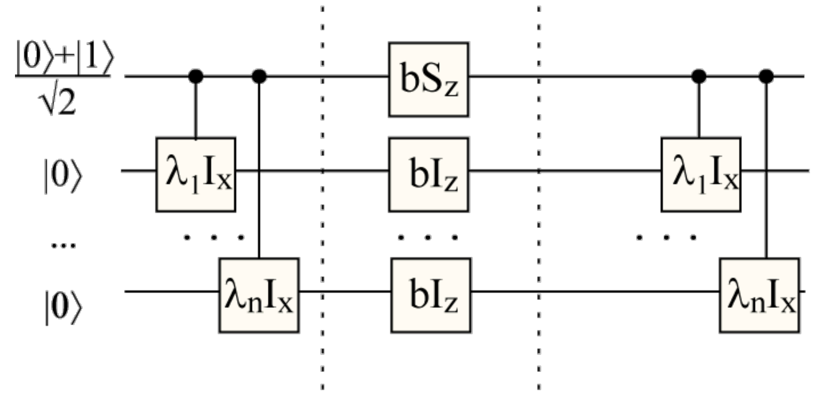

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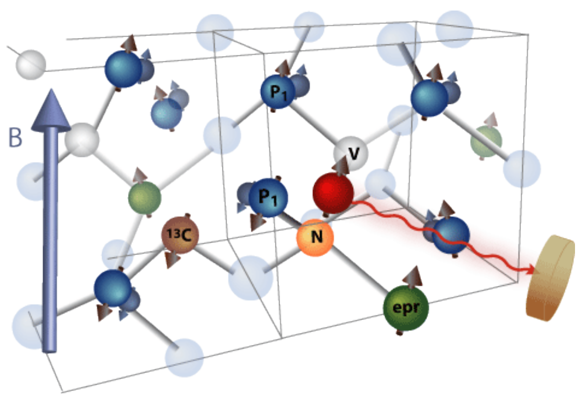

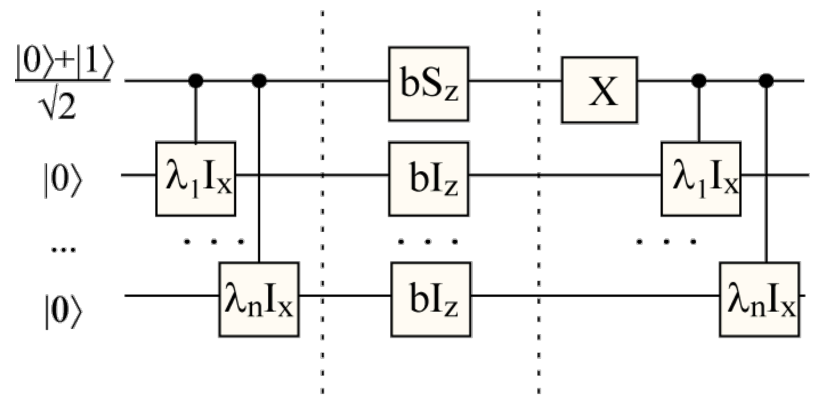

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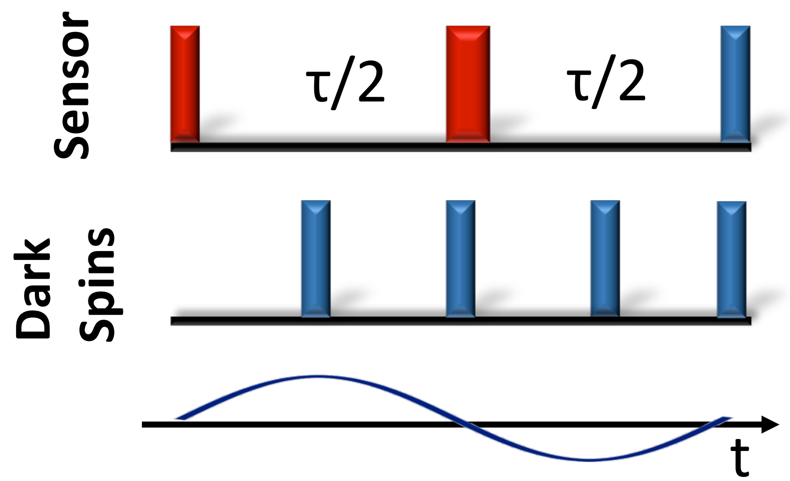
Dark Spins

- Sensitivity enhancement is possible even with random couplings
  - Control embedded in spin echo



- Sensitivity

$$\delta B \sim \frac{\hbar}{g\mu_B} \frac{4}{\sqrt{\tau}\Sigma_i \vartheta_i}$$

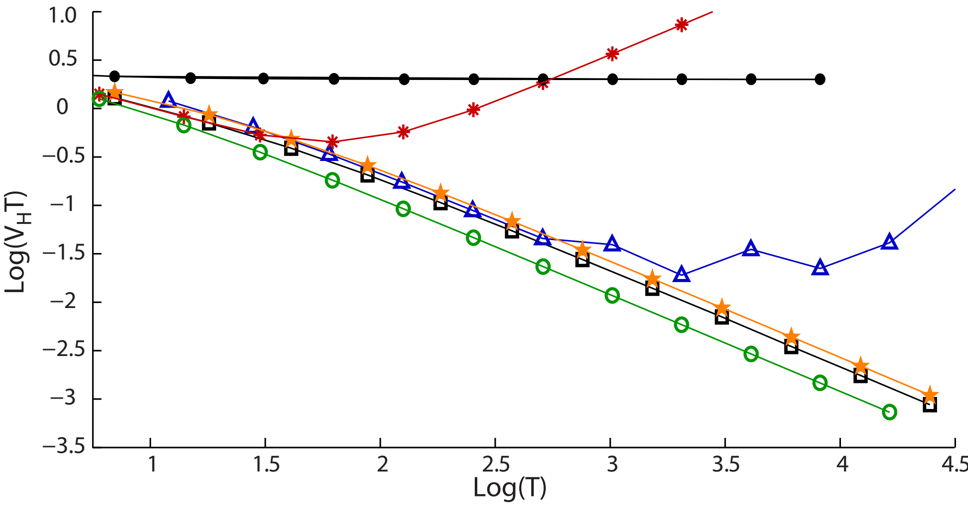
For strongly coupled spins $\lambda_i \tau \gtrsim \pi$

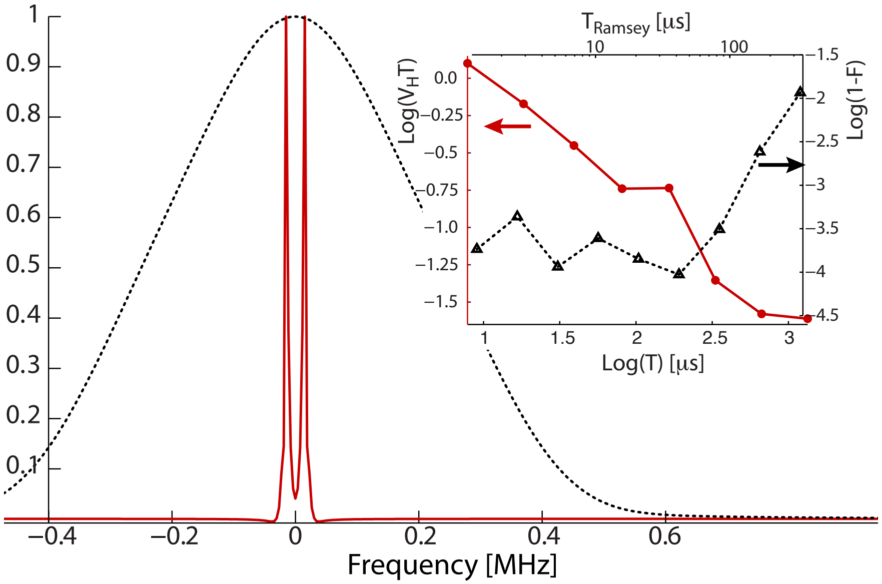
- We achieve the Heisenberg limit,

since $\Sigma_i \vartheta_i = \Sigma_i [1 - \cos(\lambda_i \tau / 2)] \approx N_{sc}$

Readout: Adaptive Methods

- Adaptive readout schemes can achieve Heisenberg limit with no entanglement

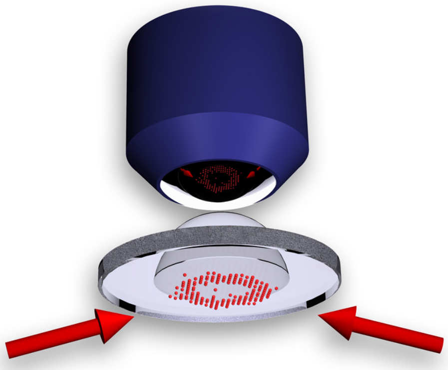


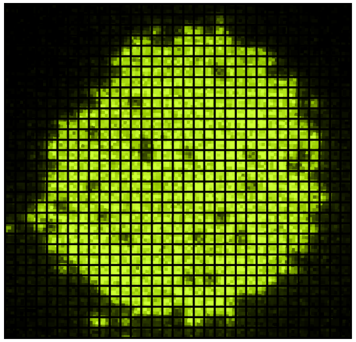


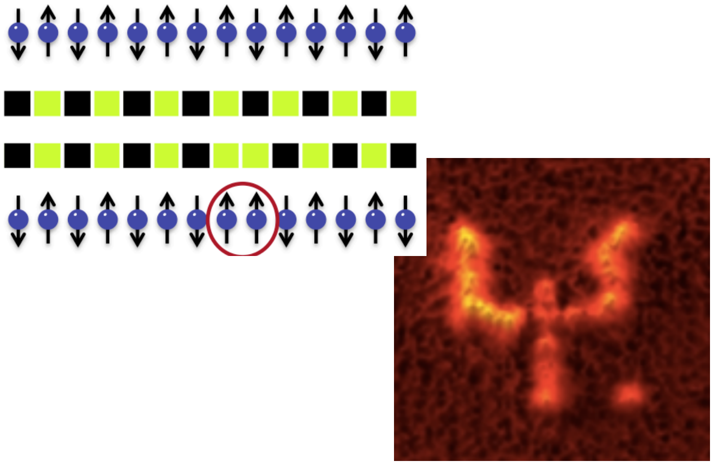
Given single-shot readout of a central spin, the adaptive method can narrow the spin bath distribution

Quantum gas microscope

Achieving ultimate quantum control



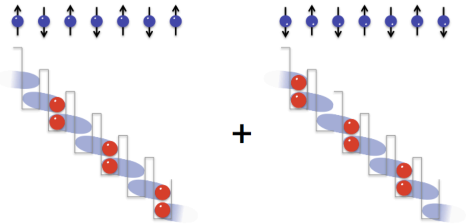




High fidelity single site - **single atom detection** in an optical lattice

Single spin **detection** and **manipulation**

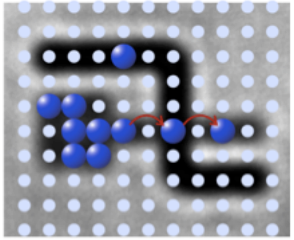
Strong interaction:
non-classical and
highly entangled states

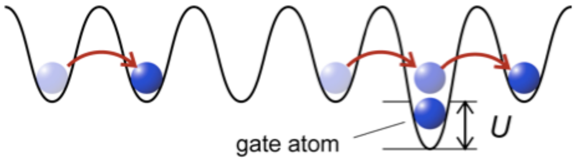


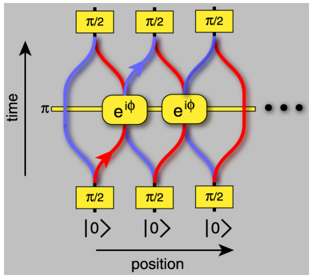
New platform for metrology

Heisenberg limited metrology with quantum gas microscope

- Create entangled states (e.g. N00N states) of large number of particles via cold collisions. Approaches: single atom transistor, Mott state in electric field, spin dependent potential



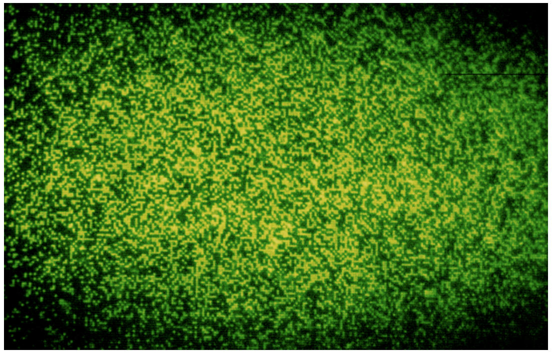




Single atom transistor

State dependent lattices

- Ultra-high fidelity single particle readout enables Heisenberg limited measurement. B-fields, E-fields, Van-der-Waal's forces…



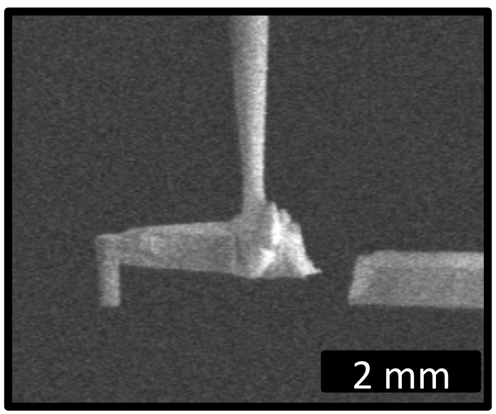
- High resolution (.5 micron) detection enables spatially resolved metrology

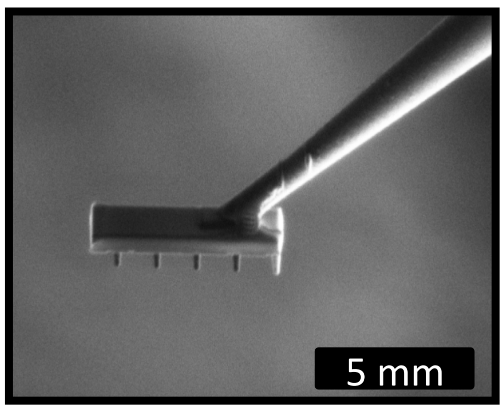
Scanning magnetometer

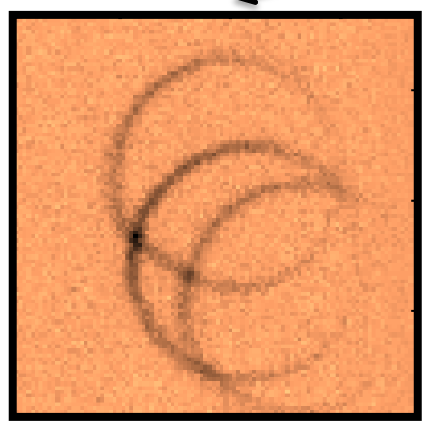
- Experiments by: Mike Grinolds, Sungkun Hong, Patrick Maletinsky (A. Yacoby's group)
- Collaboration with the groups of : Loncar, Lukin, Walsworth

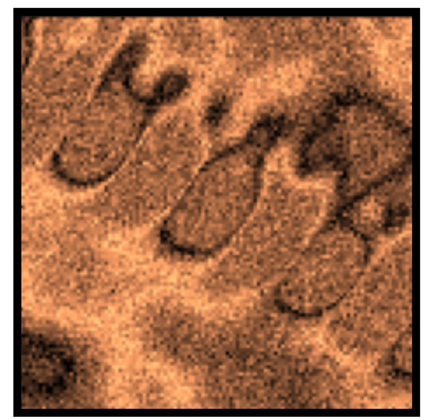
Nano-meter resolution of individual spins using magnetic field gradients

Monolithic diamond tips for nm magnetic field sensing









Imaging magnetic domains (hard drive)

DARPA, NIST, MURI. Nature Physics 7, 687-692 (2011)

Meeting Agenda

Metrology using few electron spins. **Amir Yacoby**, Harvard

Quantum techniques for precision measurements with NV-diamond
Ronald L. Walsworth, Harvard

Quantum optical control of atom-like systems for sensing and metrology
Mikhail D. Lukin, Harvard

Discussion and Poster Session

Proof of the Heisenberg limit for phase estimation. **Seth Lloyd**, MIT

Towards Quantum metrology with N00N states enabled by ensemble-cavity interaction. **Vladan Vuletic**, MIT

Trapped-ion metrology experiments at NIST. **John J. Bollinger**, NIST

THANK YOU!