Quantum Computing & Applications for Engineering

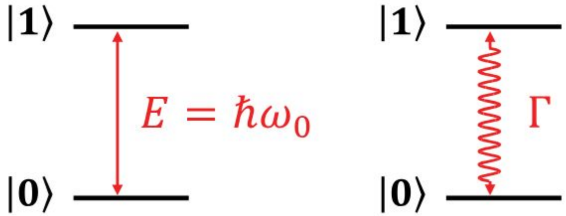
10/22/2024

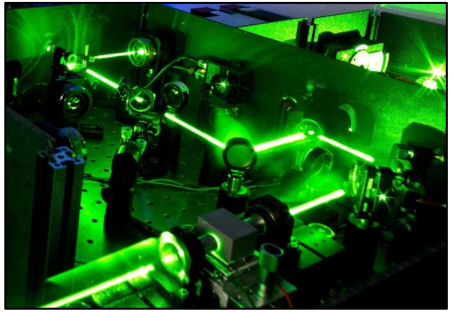
Announcements

- Project 2 proposals due w/ HW 4
- Guest Speakers
  - 10/28 - Haimeng Zhang (IBM)
  - 11/5 - Abhishek Chopra (BosonQPsi)
  - 11/12 - TBA
  - 11/19 - TBA
- Weekly bonus submissions on LMS

Quantum Sensing

Quantum Sensing

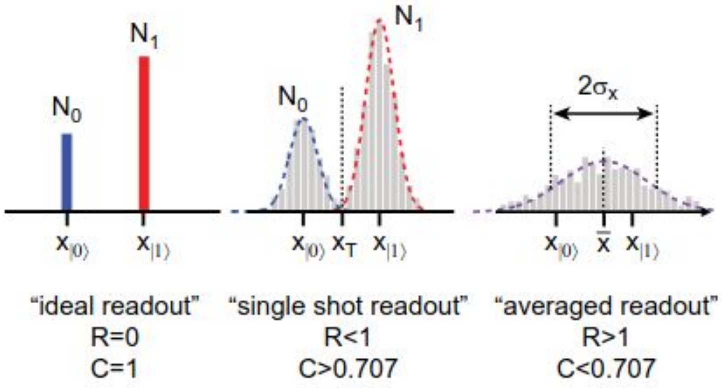


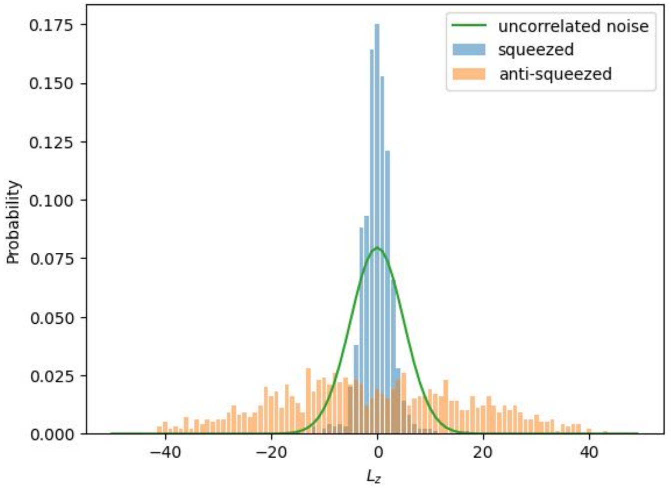


- If qubits are so sensitive to the environment, then they ought to make great sensors.
- Individual qubits or quantum systems can be very small.
    - SWaP-C: size, weight, power and cost.
    - Sizes are typically <1 mm
- We can definitely make noisy qubits!
- In many cases, we don’t need to perform “gates” at all.
    - Optics and photonic elements
    - Simple signals

Quantum Sensing

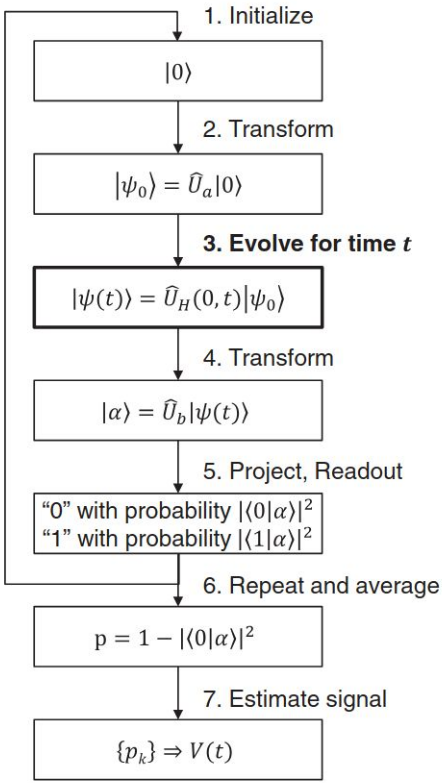
- Control over may long-running operations is much less important.
  - You can prepare and read out the state many times.
  - Get a statistical distribution of the field over many repeated measurements.
- Entanglement lets you scale better than the “shot noise” limit.
  - Uncertainty decreases linearly with N.
  - Classical only goes as √N.
- “Squeezing” lets you arbitrarily increase the sensitivity of one signal at the expense of another.





The Quantum Sensing Protocol

- Start with a qubit (or entangled set) in superposition.
- Let it sit there for one coherence time.
    - The environment does “the computation”.
    - Shorter times reduce the ability of the signal to couple.
    - Longer times result in decoherence and collapse to classical states.
- Read it out.
- Repeat.



Sensitivity

- The sensitivity of a quantum sensor is proportional to the coherence time and coupling constant.
- The ideal measuring time is equal to T_1 or T_2, depending on the measurement.
- The minimum detectable signal is defined by the signal that equals the noise floor.

$$v_{min} = \frac{\sqrt{2e}}{\gamma C \sqrt{T_\chi}}$$

$e = 2.718\ldots$

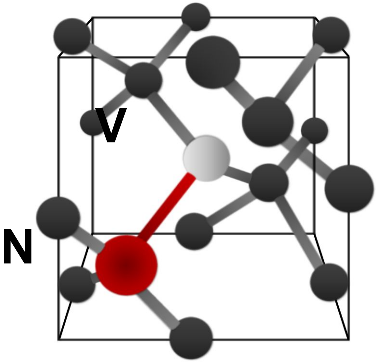
$\gamma \rightarrow$ coupling constant

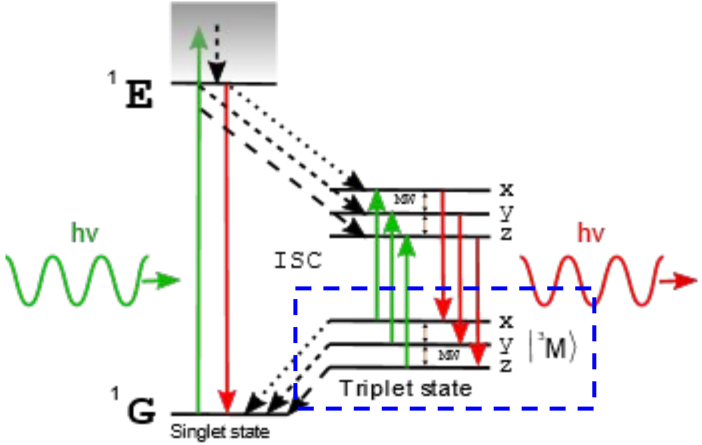
$C \rightarrow$ Efficiency

$T_\chi \rightarrow$ Coherence time

Example - NV Center Magnetometry

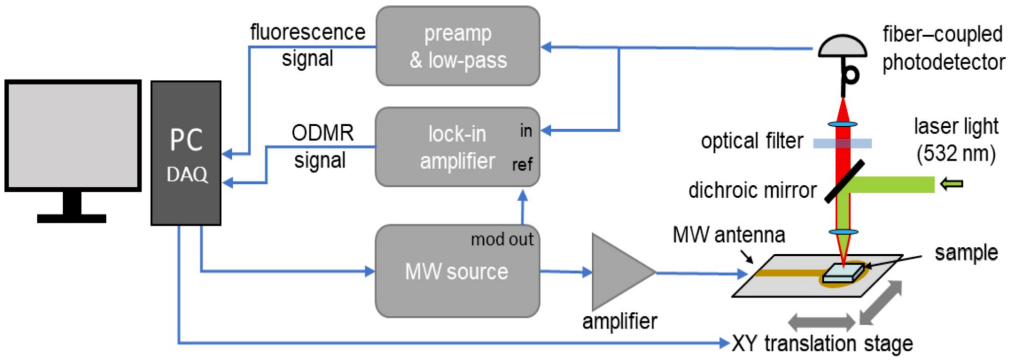
- A substitutional nitrogen next to a vacancy in diamond acts as a qubit.
  - Negatively charged → NV^-
  - Has its own energy and spin level structure.
- NV sensors use the +1, -1 and 0 spin states.
- Temperature, pressure and magnetic field change the location and frequency of the spin states.

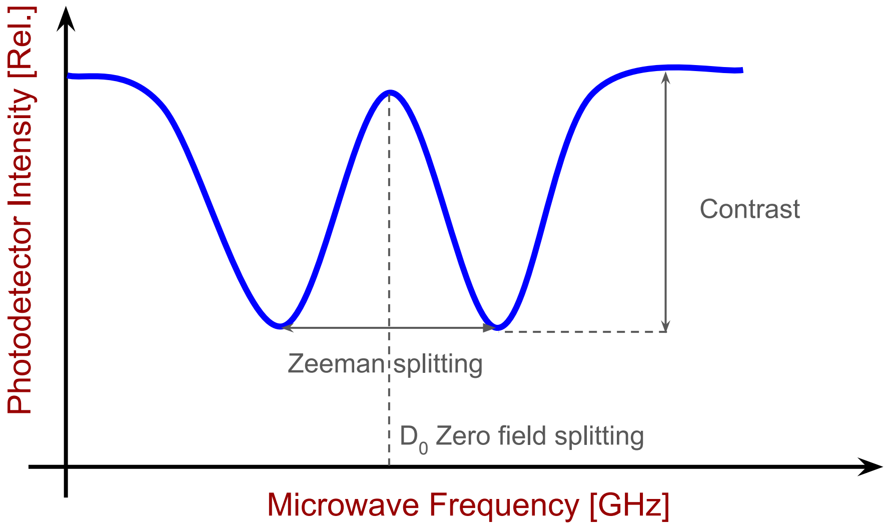




NV Centers

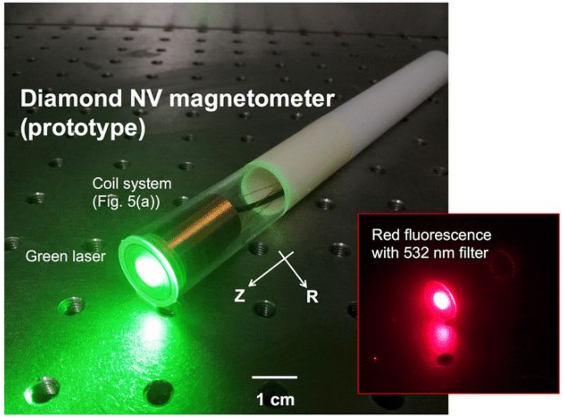
- NV sensors use a technique called *optically-detected magnetic resonance* (ODMR).
  - Similar to MRI
- Use microwave signals to put the NV centers in superposition.
- Use laser pulses to read out the state.
- Record emitted photons

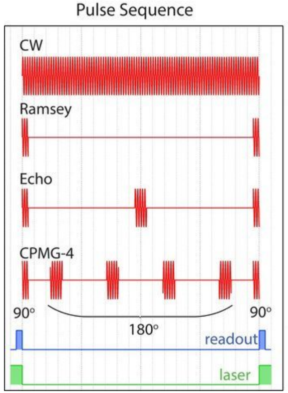




ODMR Measurements with NV Centers

- Start with the NV center in the 0 state.
- Tune a microwave signal to ~2.8 GHz.
  - Slightly higher than a microwave oven or WiFi radio.
  - ~0.1-100 mW (-20–20 dBm)
- Let the spins evolve under a pulse sequence.
- Illuminate with green light. (~520-532nm)
  - Laser, LED, or even filtered sunlight will do.
- NV center emits a red (637nm) photon if spin is 0, stays dark if it's +/- 1.
- Repeat for several frequencies

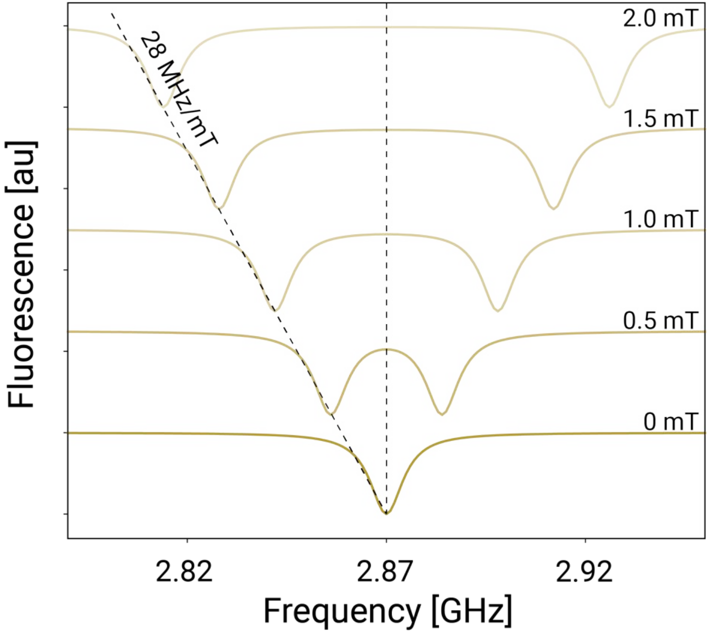




Limitations/Challenges	Information Extracted
T_2^* limited	Spectral shifts due to temperature, or DC magnetic, electric or strain fields.
T_2^* limited, microwave amplification and timing control	DC spectral shifts
T_2 limited, microwave amplification and timing control	Higher resolution DC spectral shifts without inhomogeneous field broadening
Dipole-dipole limited, complex phase and timing control	AC magnetic fields, long qubit coherence times, manipulation of ^{13}C neighboring nuclear spins

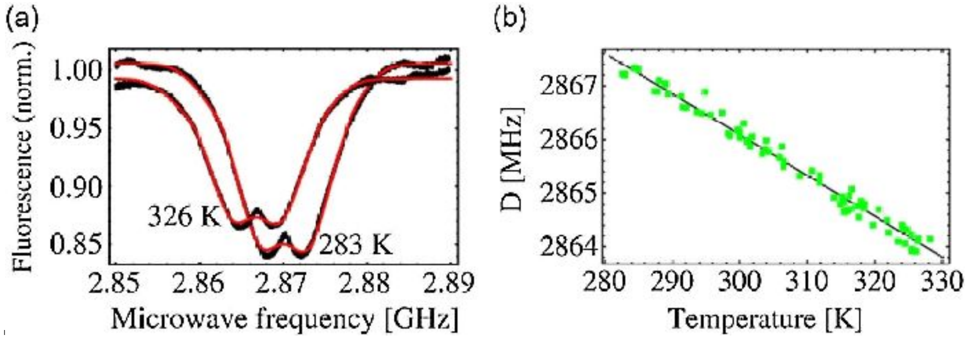
Magnetic Field

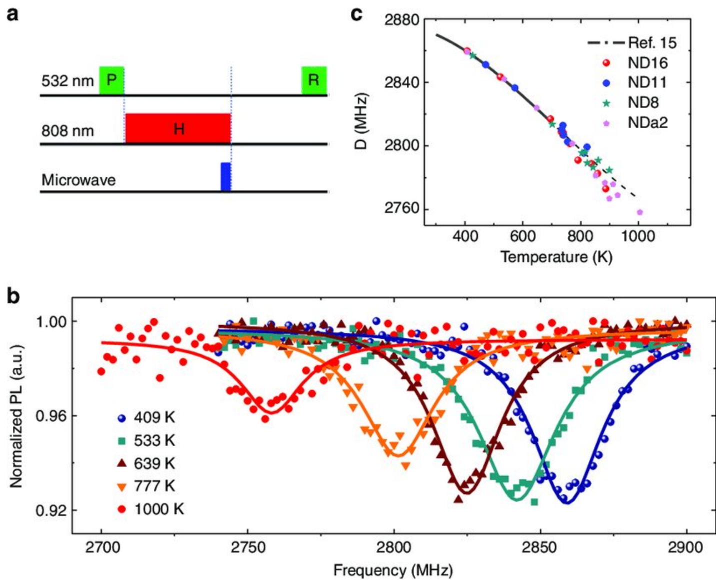
- To measure the magnetic field, we look at the spacing between the ODMR peaks.
- Stronger magnetic fields increase the spacing between the peaks.
- We can also get the field orientation.
    - 4 possible NV directions in the crystal.
    - 8 Possible peaks in the spectrum
- Sensitivities can be in the pT range.



Temperature & Pressure

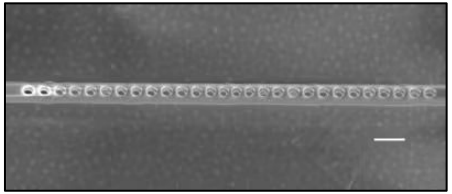
- The centerline of the spectrum is proportional to the diamond's temperature and local crystal strain.
  - Zero-field splitting
  - Frequency decreases as temperature and strain increase.
- ~0.1 - 10 mK sensitivities
- NV centers work reliably up to 1000K!

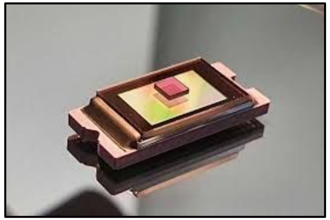


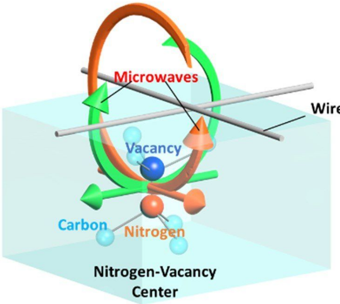


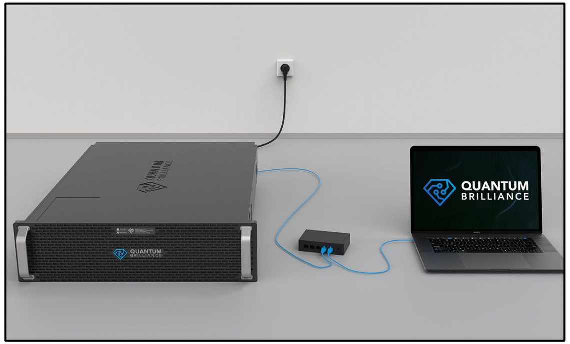
NV Centers for Quantum Computing?

- If we're doing computing, we pick one spin peak and make that the |1> state.
    - Tune the frequency/phase to apply gates
    - Apply signals to two to entangle
- Laser does initialization and readout.
    - Record a 0 if we get a photon
    - Record a 1 if we don't
- Practical challenges in manufacturing and addressing.
    - Need to create individual defects deterministically.
    - Need them close enough to address and communicate.
    - Need them far enough apart to avoid interference.



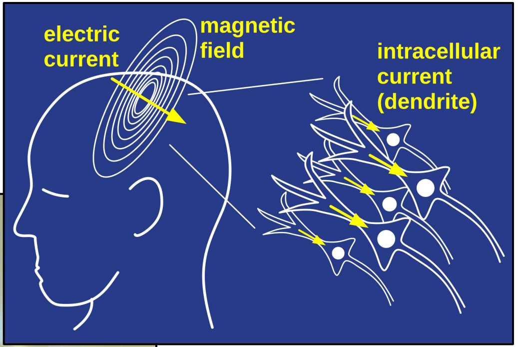


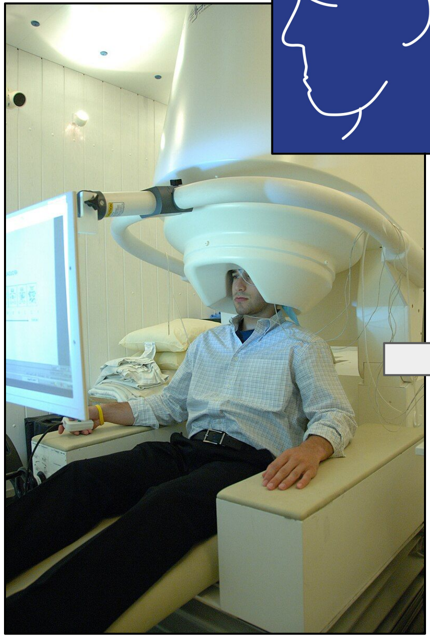




Example - Quantum Magnetoencephelography (MEG)

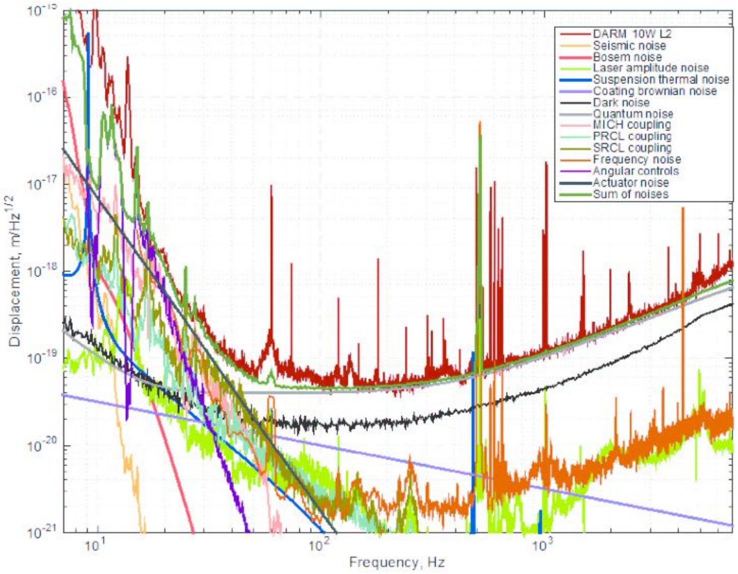
- Magnetoencephelography (MEG) is a brain-imaging technique.
  - Measures the magnetic signatures of electrical activity in real-time
- Current systems are technologically demanding.
  - Large cryogenic tanks and shielded rooms.
  - Only 100 systems in the world.
- Quantum versions in development.
  - Optically-pumped magnetometers.
  - Bike-helmet sized.
  - 100x improvement in signal and spatial resolution.





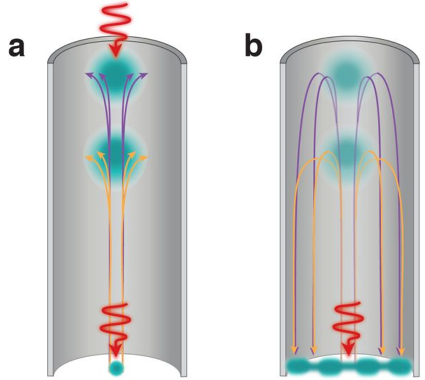
Example - Photon Interferometry at LIGO

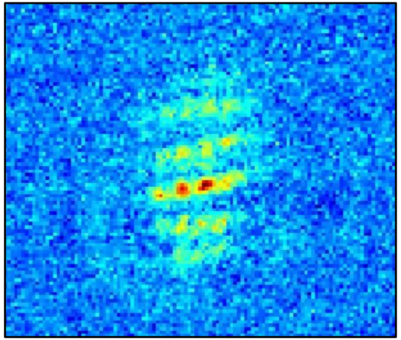
- Laser-Interferometer Gravitational Wave Observatory
  - Detects displacements ~10^{-19} m
  - 0.0001 the diameter of a proton
- Early observations failed due to a high noise floor.
- Quantum squeezing enabled improvements in sensitivity and positive results.



Example - Gravity Interferometers

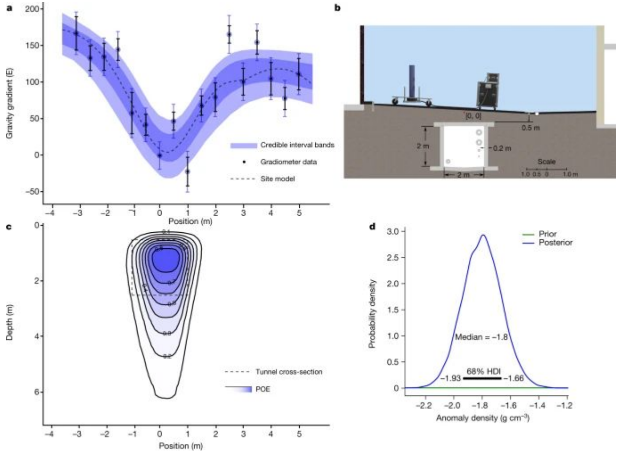
- Very cold atoms enter a quantum phase of matter - Bose Einstein Condensate.
- Atoms are launched up a fountain (30cm - 10m) high.
- The atoms’ wave functions create an interference pattern as they fall back to a screen.
- The spacing of the interference fringes is proportional to the acceleration.
- Sensitivities of 10^{-9} g →About the same as a person standing 1m away.

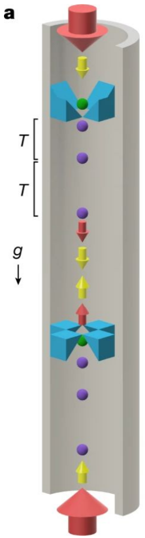




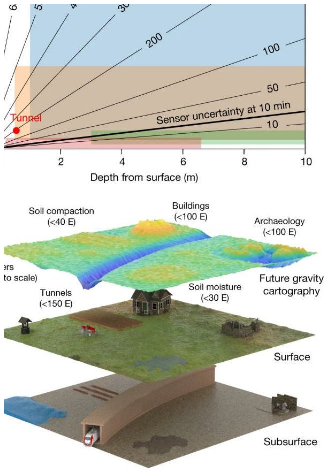
Gravity Interferometers - Mapping

- The Earth's gravity field is not uniform.
  - Lots of clumps and voids.
  - Mountains, caves, etc.
- Classical gravimeters are common in geology.
  - Mining & prospecting
  - Aquifer depletion
- Quantum gravimeters offer higher resolution.
  - Civil engineering - Mapping "lost" infrastructure.
  - Navigation - Use gravity anomalies as waypoints.



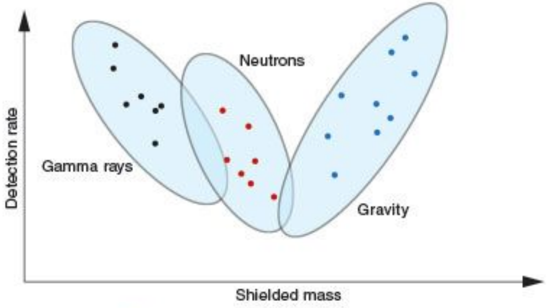


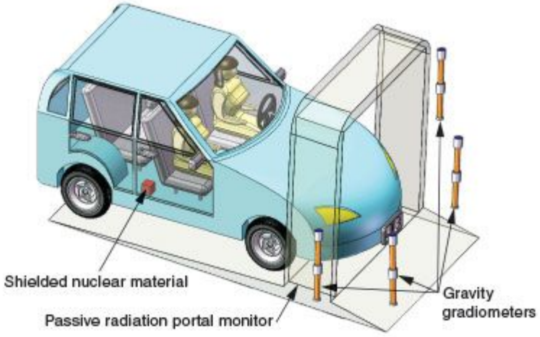
Stray, B., Lamb, A., Kaushik, A. *et al.* Quantum sensing for gravity cartography. *Nature* **602**, 590–594 (2022). https://doi.org/10.1038/s41586-021-04315-3



Gravity Interferometers - Security

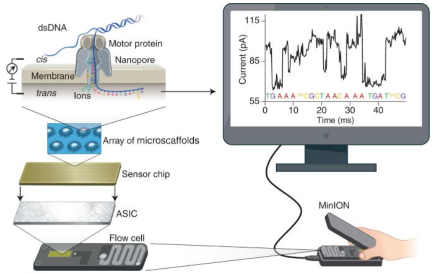
- In 2011, LLNL and AOSense tested an interferometer in a nuclear security application.
  - Portal monitors at ports-of-entry.
  - Reduce false positives.
- Uranium & plutonium are easy to hide.
  - Low kg-quantities are significant.
  - Radiation is easily shielded.
  - Very dense (~20g/cm^3).
- Gravitational anomalies, plus gamma/neutron measurements, improve reliability.

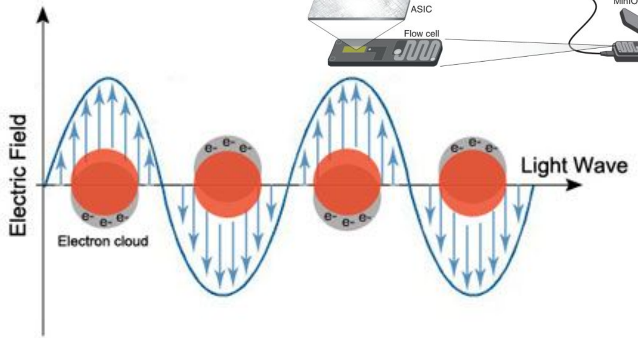


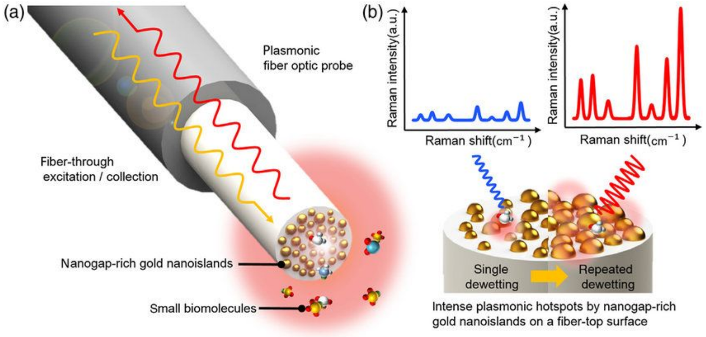


Plasmonic Sensors - Rare Earth Materials

- Electrons in a metal oscillate like a wave.
    - Frequence is the plasma frequency.
    - A single wave is a *plasmon*
- Light at certain wavelengths will couple to the surface electrons of a metal.
- The presence of nearby materials affects the resonant frequency.
    - Rare earth metals
    - DNA bases
    - Trace chemicals

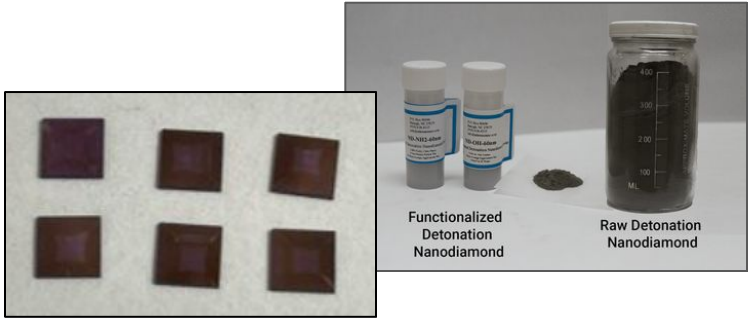




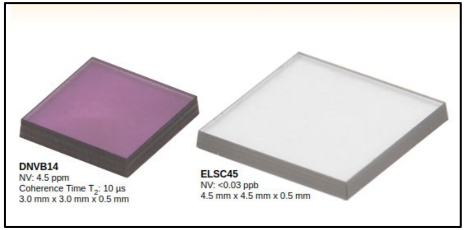


DIY Quantum Sensors?

- Costs of components are coming down:
  - NV-doped diamonds: $180 - $500
  - Laser module: ~$20
  - Photodetector: ~$20
  - Signal generator: ~$50
  - Computer (Raspberry Pi Pico): $5
- It’s totally conceivable that a person or group here could build one!



Adamas Nanotechnologies
https://www.adamasnano.com/



Thorlabs/Element6
https://www.thorlabs.com/

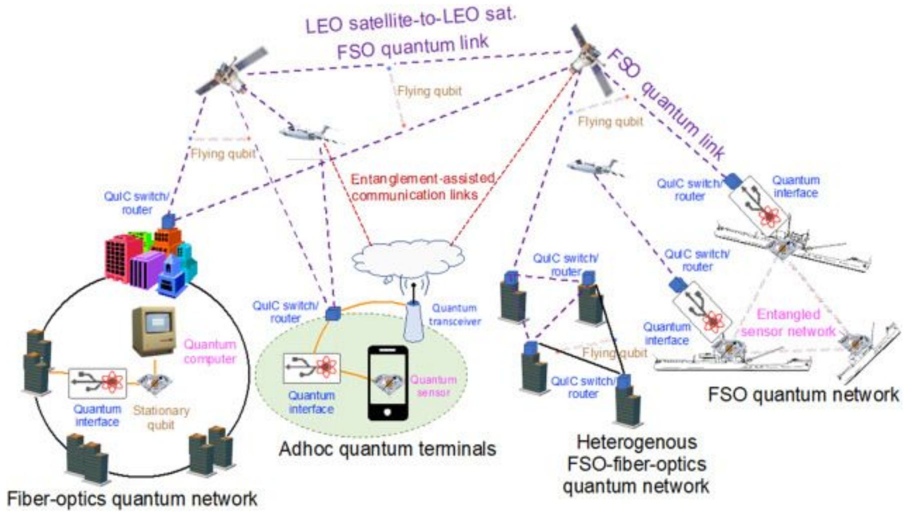
Demo

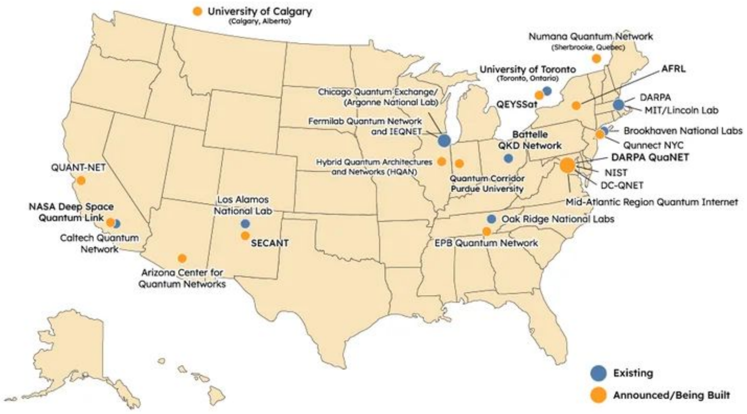
Break

Quantum Networking

Quantum Networking

- Computers are way more useful when we can link them together.
  - Internet
  - Parallel computing
  - Secure communications
- We can send coherent quantum information between two quantum devices.
- Typically requires optical photons.



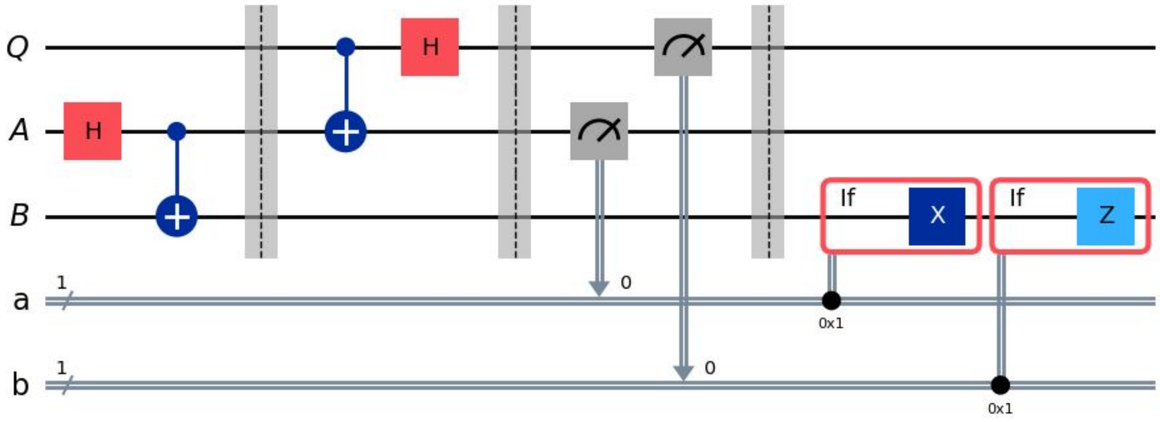


Teleportation

- Teleportation is the main method used to send quantum information over arbitrary distances.
- Quantum information can only be moved, not copied.
- Every qubit sent also requires communicating two classical bits to define the measurement basis.

Teleportation

- Alice and Bob have an entangled qubit pair.
- Bob goes away somewhere.
- Some time later, Alice has another qubit she wants to send to Bob.
- She entangles it with her half of the first pair, and measures the results.
- She classically communicates with Bob the results of her measurements.
- Bob applies X and or Z gates depending on Alice’s results to recover the communicated information.

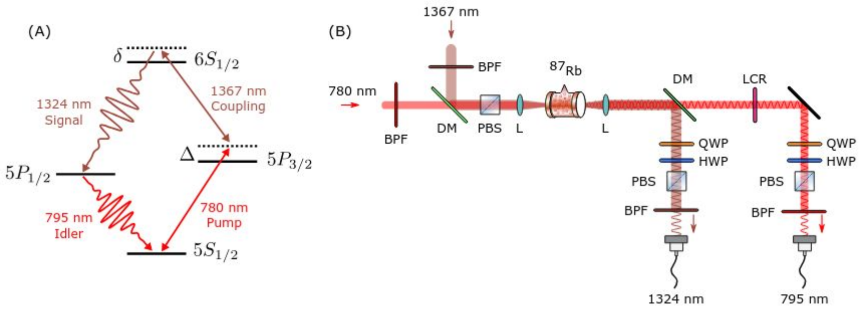


Teleportation

- Current distance records:
  - 143 km (89 mi) through air
  - 102 km (63 mi) through fiber optics
  - 21 m (69 ft) through solids
- Further distances require quantum repeaters.
  - Qubit data is encoded into a quantum memory.
  - Memory is re-entangled and re-transmitted.
- Classical communication is still required.
  - Bob needs Alice’s result in order to apply the right gates and recover the qubit.
  - Teleportation does not enable faster than light travel.

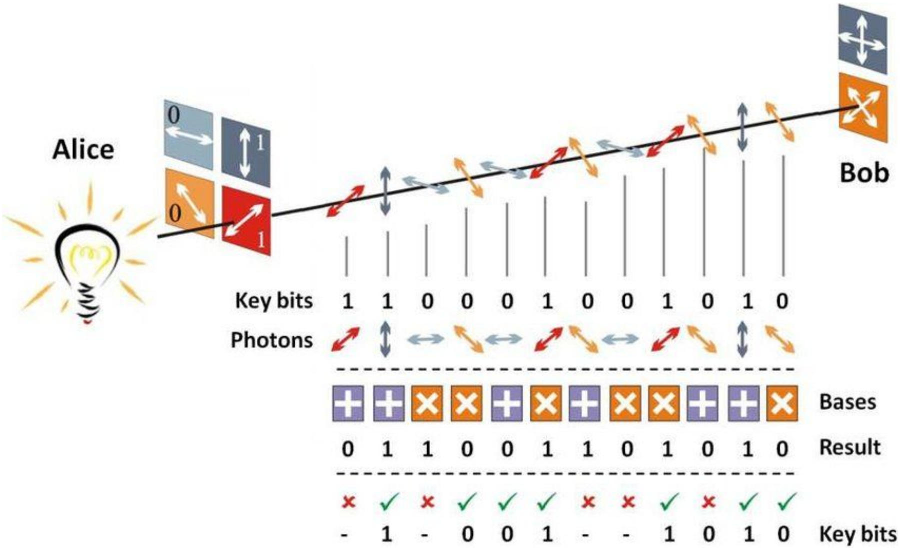
Quantum Networking

- Two companies in the US making quantum networking equipment.
  - Qunnect (NYC)
  - Qubitekk (Chattanooga, TN)
- Create entangled pairs:
  - Nonlinear crystals
  - Rubidium vapor cells
- Send one over the network.
- Receive by collecting the photon in a new vapor cell/crystal in a magnetic field. Storage time ~100μs
- Retransmit the exiting photon



Quantum Key Distribution

- QKD is a simpler form of quantum networking for sending cryptographic keys.
- Entanglement is not required.
    - Simplest protocol uses superposition only.
    - BB84 Protocol
- Perfectly secure in principal.
    - The presence of an eavesdropper can be detected by the statistics of the measurement.
- Practical debates over true security.



Quantum Key Distribution

- NSA and NIST have taken a stance opposing QKD. (Link)
    - Prohibited for securing sensitive government networks and defense systems.
    - Discouraged for non-sensitive applications.
    - Post-quantum cryptography is more cost-effective.
- Calls out 5 limitations:
    - No authentication of users
    - Supply chain security
    - Denial-of-service attacks
    - Incomplete physical validation
    - Physical hardware security
- Others disagree.
    - Some US government agencies
    - Private Companies
    - Many countries' programs