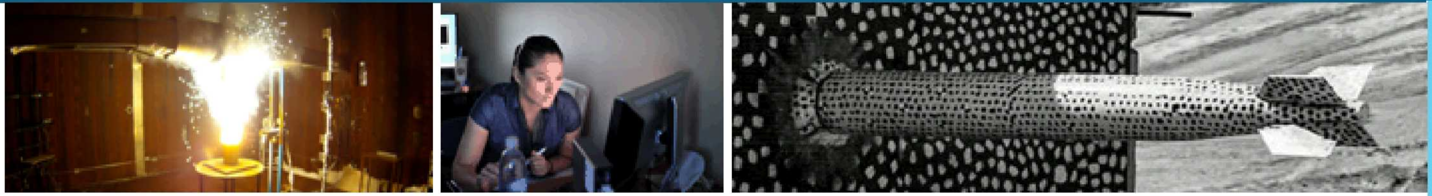
SAND2020-2846PE

Experimental quantum technologies at Sandia National Laboratories



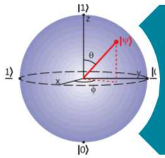
PRESENTED BY

Hayden McGuinness

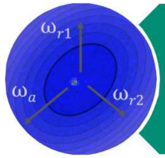
Photonic Microsystems Technologies

Outline

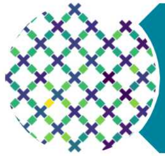
History of Sandia, quantum technology capabilities



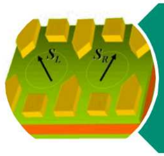
Intro to quantum information science (QIS)



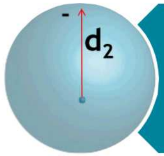
Ions: QSCOUT + TICTOC



Superconductors: Transmons + transduction



Semiconductors: donors + spins

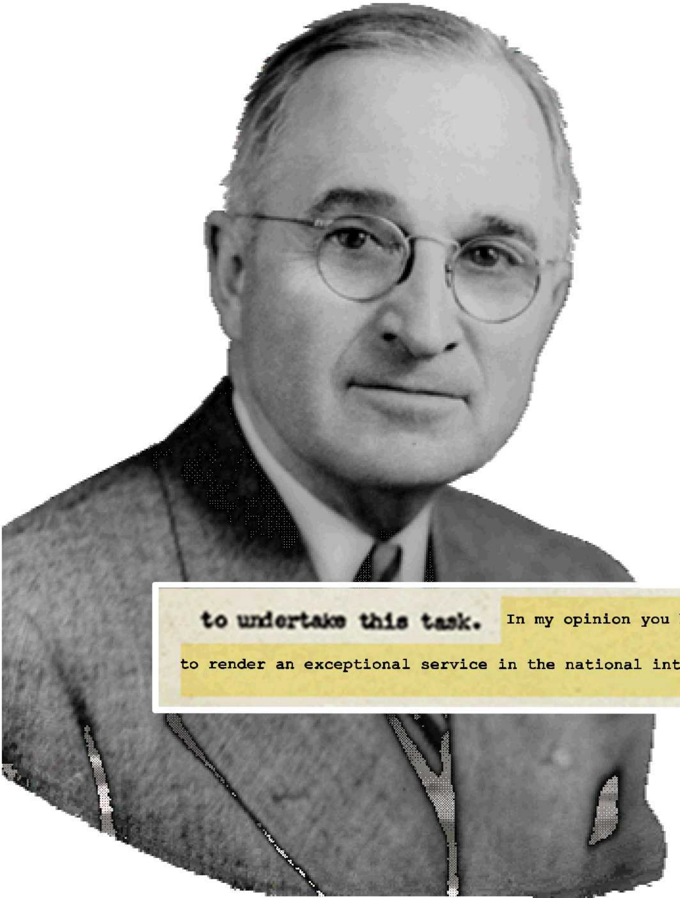


Neutrals: Rydberg + SIGMA + OPM MEG

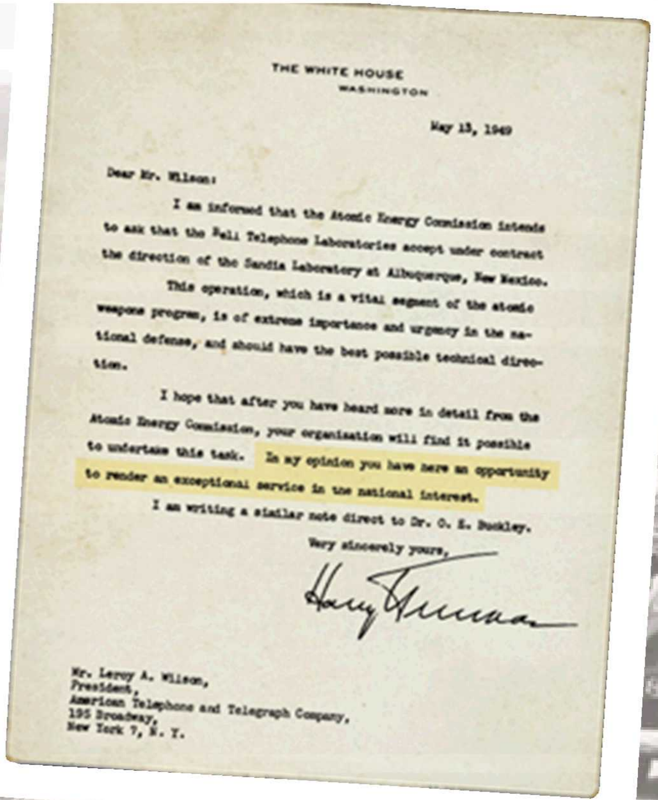
Sandia National Laboratories

Exceptional service in the national interest

- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established
- Mission broadened to National Security



to undertake this task. In my opinion you have here an opportunity
to render an exceptional service in the national interest.



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

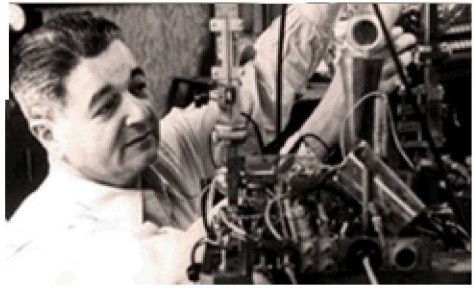
I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

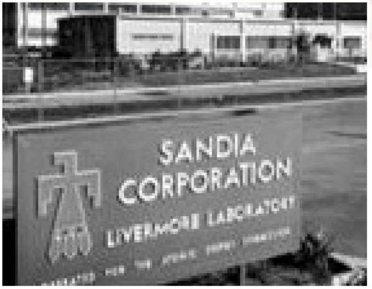
I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

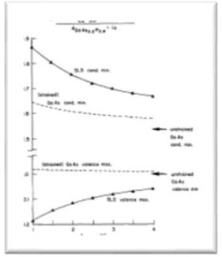
Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.



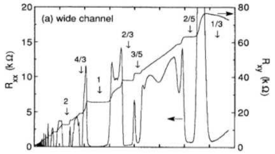


Quantum R&D at Sandia

Strained-layer superlattices from lattice mismatched materials, *Journal of Applied Physics* 53, 1586 (1982)

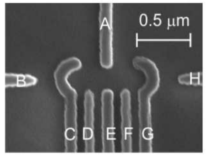


Fractional quantum Hall effect, J.A. Simmons, *et al.*, *Phys Rev B* 44 (1991).



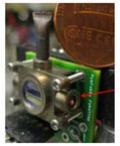
Functional single electron transistor, J.A. Simmons, T. Eiles (1997/98)

16th Electronic Properties of 2D Electronic Systems in Albuquerque (2005)

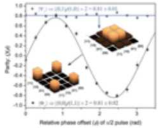


QIST Grand Challenge LDRD: Si quantum bits & logical qubits (2008-10)

DARPA IMPACT: Ion microwave atomic clock (2009-14)



AQUARIUS GC LDRD: Adiabatic QC (2011-13)



IBM Quantum Experience: 1st public access to QC (2016)

SECANT GC LDRD: QKD (2016-18)

DOE/SC Quantum Science Open User Testbed (QSCOUT) (2018-22)

1980s **1990s** **2000s** **2010s**

Simulating physics with computers, R.P. Feynman, *Int J Theo Phys* 21 (1982)

Simulating Physics with Computers

Richard P. Feynman

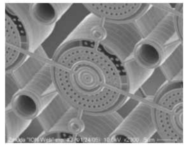
Quantum error correction, P.W. Shor, *Phys Rev A* 52

$$|0\rangle \to \frac{1}{2\sqrt{2}}(|000\rangle+|111\rangle)(|000\rangle+|111\rangle)(|000\rangle+|111\rangle),$$

$$|1\rangle \to \frac{1}{2\sqrt{2}}(|000\rangle-|111\rangle)(|000\rangle-|111\rangle)(|000\rangle-|111\rangle). \qquad (3.1)$$

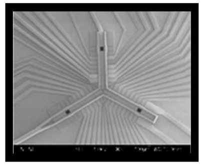
LDRD: "Quantum Computing Accelerator I/O," C.P. Tigges, N. Modine (2003)

1st QIS presentation by Sandia: Microfabricated ion traps for QC architectures, M. Blain, *et al*. (2004)

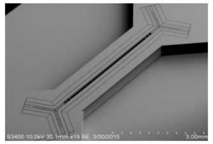


1st external QIS funding at Sandia: Trap foundry, M. Blain, *et al*. (2005); LDRD: Traps for QC & Qsim (2005)

3 LDRD: Ion qubits; Si qubits; QC architecture (2007)

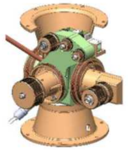


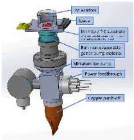
IARPA MQCO: Microfabricated surface traps for multiple qubits (2010-2015)



IARPA LOGIQ: Microfabricated traps for a logical qubit (2016-2021)

SIGMA GC LDRD: AI for inertial guidance (2018-20)





DARPA TICTOC: Ion optical clock (2019-21)

Aggressive LDRD investment built QIS at Sandia

~$100M LDRD investment anchored by ~$55M for the 4 Grand Challenge Projects:

QISI
Quantum Informa

- Sandia has won ~$50M in DOE/DARPA projects recently
  - QOALAS – algorithms for approximate optimization and learning
  - QSCOUT – a testbed to implement and explore NISQ hardware
  - QPERFORMANCE – benchmarking effort to assess the performance of NISQ processors
  - OVER-QC – capabilities for validating, assessing, and optimizing quantum circuits
  - TICTOC – manufacturable, miniature, high performance optical atomic clock.

AQUA
Adiabatic quantum architectures in ult

SECANT QKD

development

Strategic Inertial Guidance
ΣΙΓΜΑ
with MAtterwaves

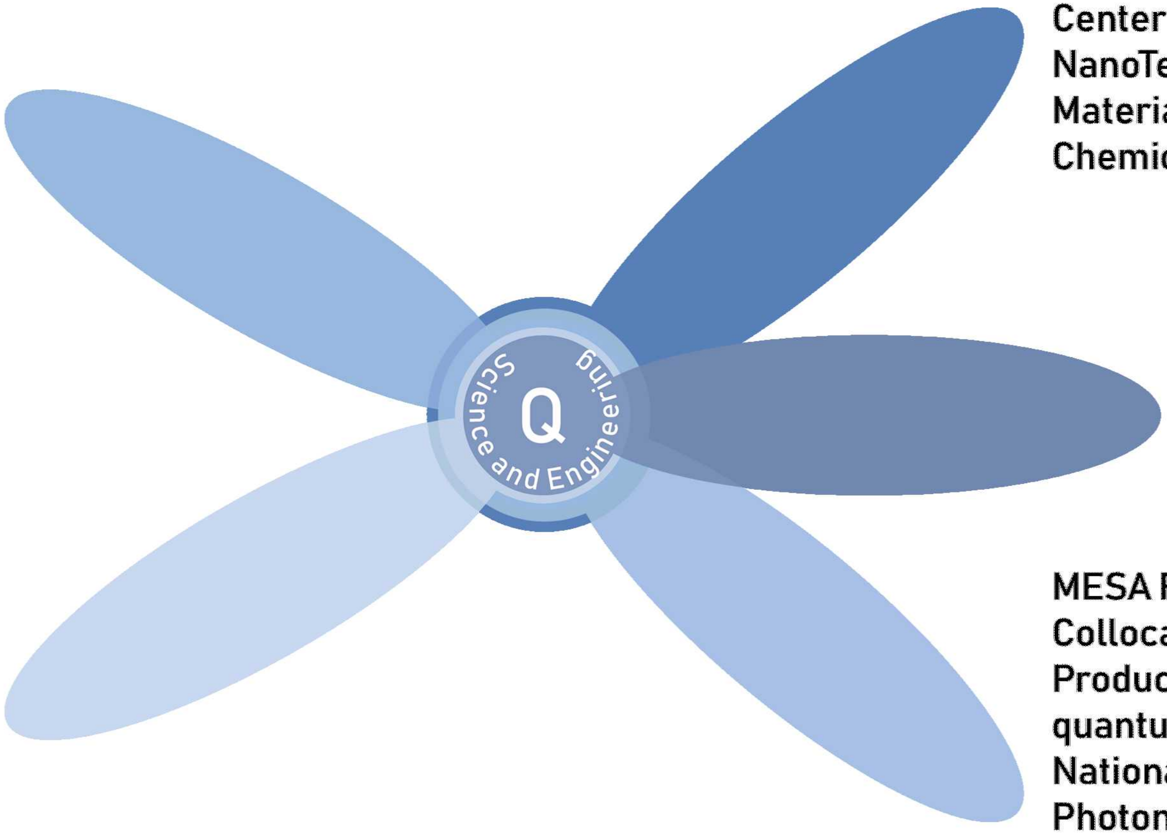
FY18-FY20
Atom Interferometer

- Develop deployable quantum devices
- Quantum sensing based location determination

Sandia Quantum Information Science Organization Chart

QIS work at Sandia draws on skills and resources from across the Labs

- QIS is an exciting opportunity for Sandia's engineers and scientists
- QIS benefits from decades of collective experience in all relevant domains at Sandia
- Examples: QSCOUT, SIGMA, TICTOC



Center for Computing Research: Quantum CS, Algorithms, QCVV

Center for Integrated NanoTechnologies (CINT), Material, Physical, & Chemical Sciences

MESA R&D: Quantum Experiments

RF & Electronic Systems, Optical Engineering, Mechanical Design

MESA Fab: Collocated Production + R&D of quantum devices. National Security Photonics Center (NSPC)

Center for Integrated NanoTechnologies (CINT)

DOE funded nano-science

- **Free** access to staff expertise and e
science
- Two proposal calls per year - short-t
accepted continuously

CINT Research Areas

In-situ characterization & na

- Dynamic response of materials a
mechanical, electrical, or other s

Nanophotonics & optical nan

- Synthesis, excitation, and energy t
active nanomaterials and electrom

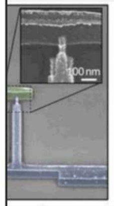
Soft, biological & composite na

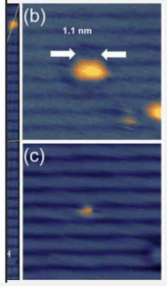
- Synthesis, assembly, and characteriz
and composite nanomaterials that dis

Quantum material systems

- Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

ails:





Materials synthesis

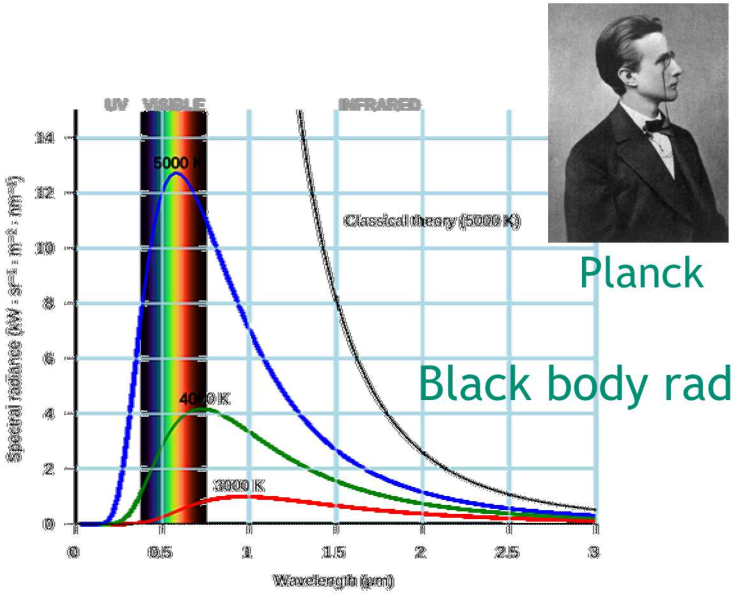
- Ultra-high mobility MBE
- Complex oxide PLD
- CVD nanowire growth

Correlated systems

- Mean-field modeling for quantum materials
- Many-body approaches

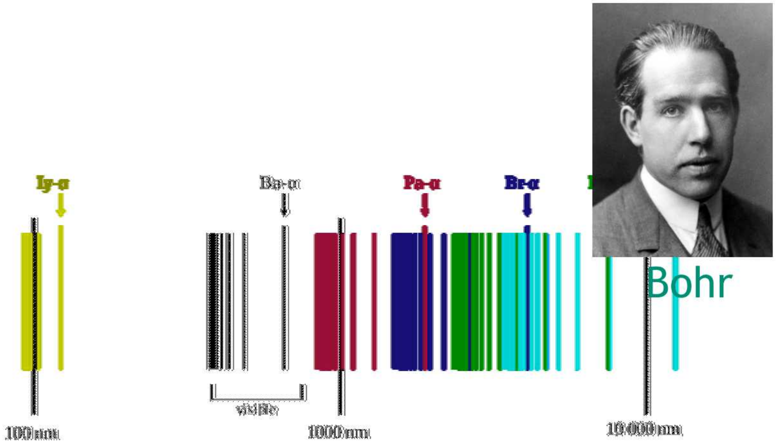
Quantum mechanics governs the physics of the small

- Physics that governs the small: atoms, molecules, small devices
- Dramatically different behavior from large-scale effects



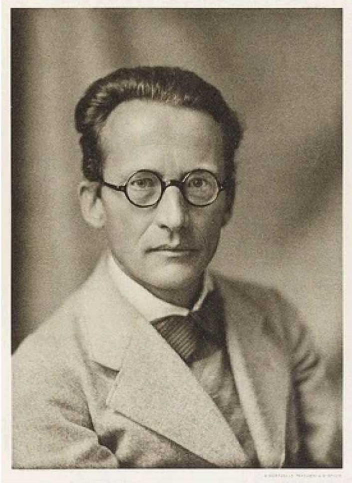
Planck

Black body radiation



Bohr

Hydrogen emissions wavelengths



Erwin Schrodinger

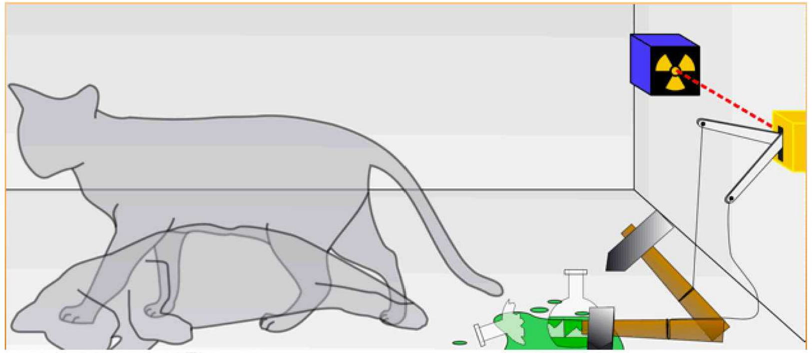
Werner Heisenberg

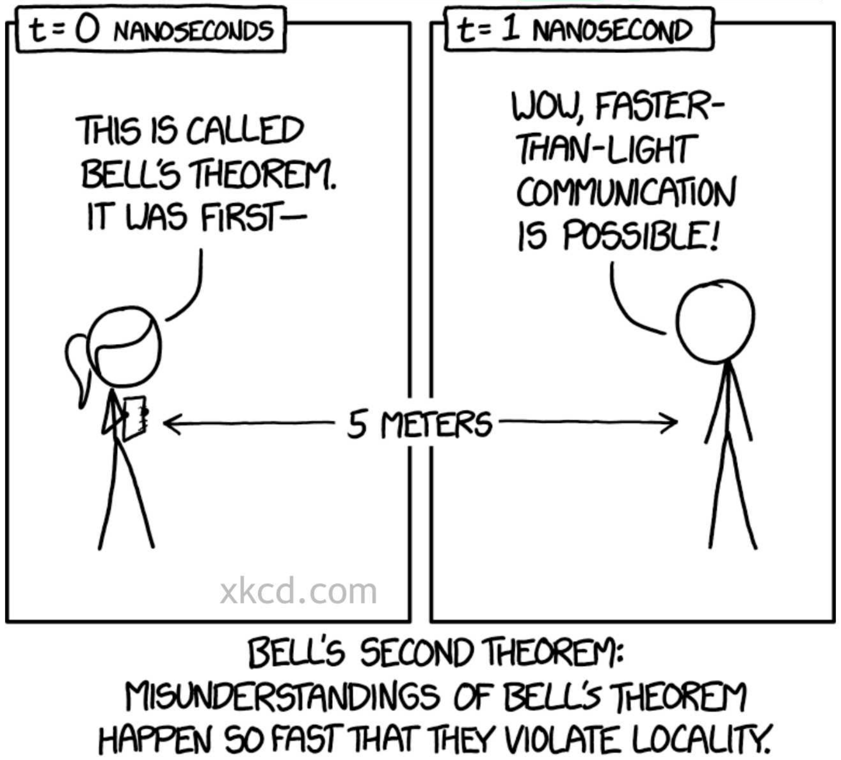
- A single theory resolved a number of conundrums and led to transistors, lasers, medical imaging, superconductors, …

Quantum weirdness has real implications

- Quantum has some celebrated oddities that aren't intuitive:
  - Schrodinger's Cat is a thought experiment demonstrating quantum superpositions: that a particle could be in multiple states at once.
  - Bell's Theorem considers the implications of quantum entanglement.

- What is surprising is that superpositions and entanglement have important implications when you combine them with information theory.





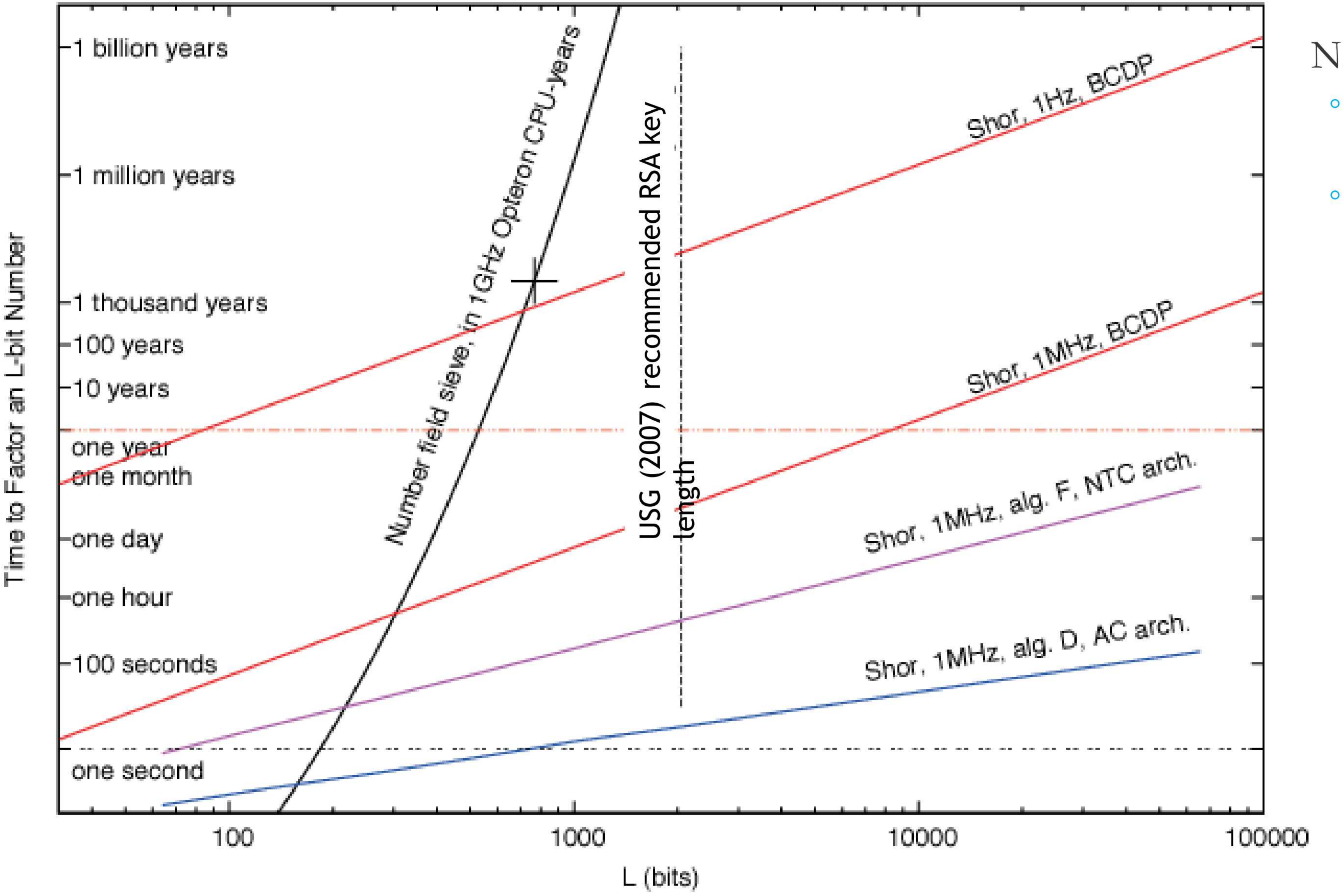
Quantum science impacts US national security

- "Unbreakable" cryptography based on the presumed difficulty of certain math problems could be readily cracked using a sufficiently large quantum computer
- "Unsolvable" problems in pharmaceuticals and energy science could be solved using a sufficiently large quantum computer
- Networked quantum communications are plausible in the near-term, and could be provably secure
- Quantum sensing and detection devices could improve sensitivity by 10-1000
- We still don't know the full landscape of applications

"The United States' large stake in all these potential applications warrants a cohesive national effort to achieve and maintain leadership in the rapidly emerging field of quantum information science."
-Dr. Jack Marburger, former DOSTP, 1/2009

From A Federal Vision for Quantum Information Science.

Quantum shakes the foundations of cryptanalysis



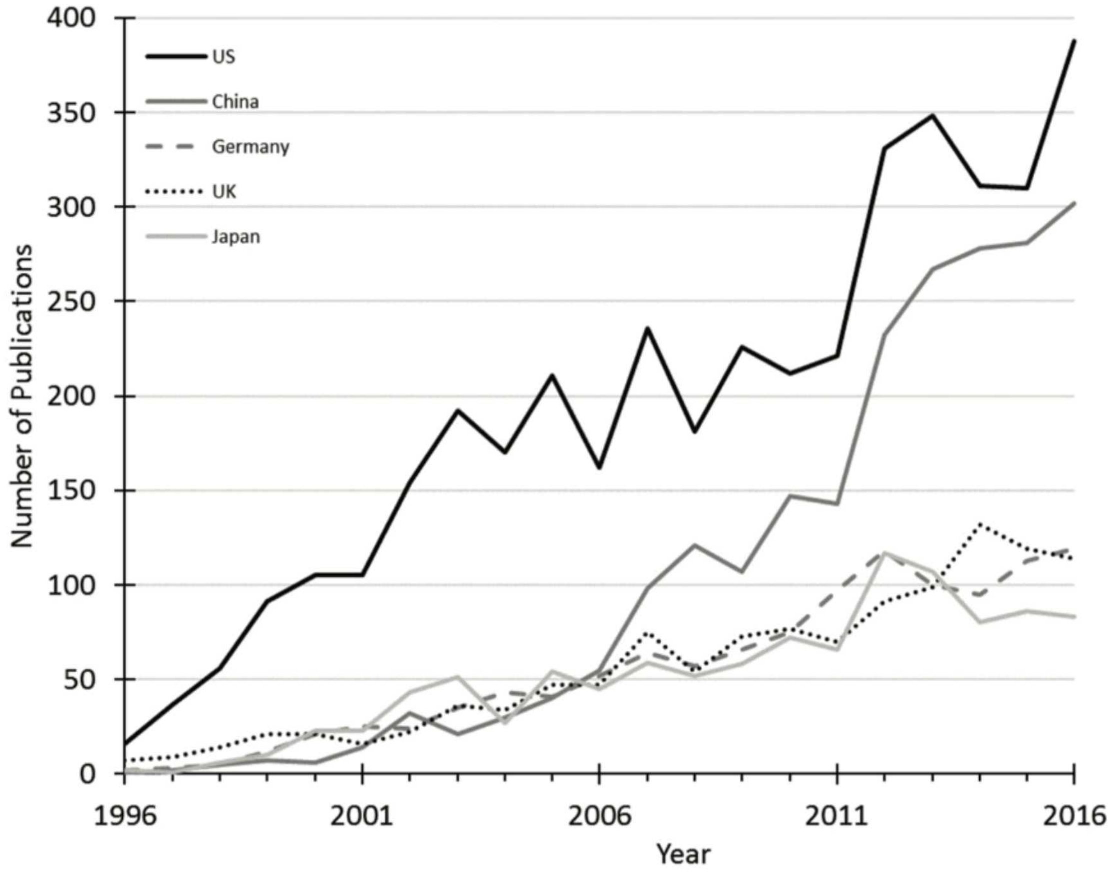
NIST recommended RSA key length:

- Classical (black): Requires trillions of years on a classical computer
- Quantum (red-purple): Could be solved in seconds-days on a quantum computer.

A blueprint for building a quantum computer, R. van Meter & C. Horsman, *Comm. ACM*, (2013) doi:10.1145/2494568

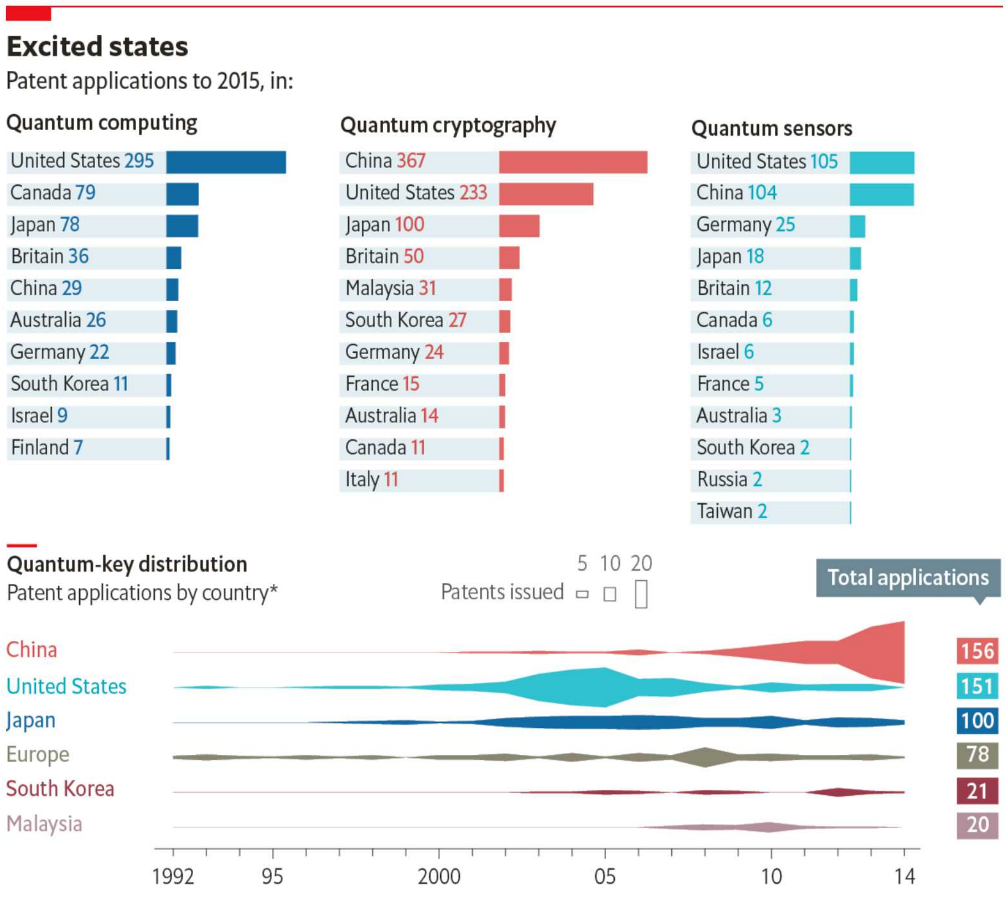
Quantum is growing worldwide

Publications



Quantum Computing: Progress and Prospects. *National Academy of Sciences*, 2019

Patent Applications



Sources: UK Intellectual Property Office; European Commission

*By location of corporate headquarters

Quantum Technology is Beginning to Come Into Its Own. *Economist*, 2017

Quantum shakes the foundation of chemistry

- The Haber process converts nitrogen into ammonia, and consumes roughly 2% of the world's energy supply.

$$\underbrace{N_2 + 3\,H_2}_{\Delta H^\circ=0\,\mathrm{kJ}} \longrightarrow \underbrace{2\,NH_3}_{\Delta H^\circ=-91.8\,\mathrm{kJ\cdot mol^{-1}}}$$

- The Haber process requires large factories with high temperatures and pressures, but plants perform nitrogen fixation every day.

- With technology that could be developed in the next 20 years, a quantum computer could unravel biological nitrogen fixation.

Fritz Haber

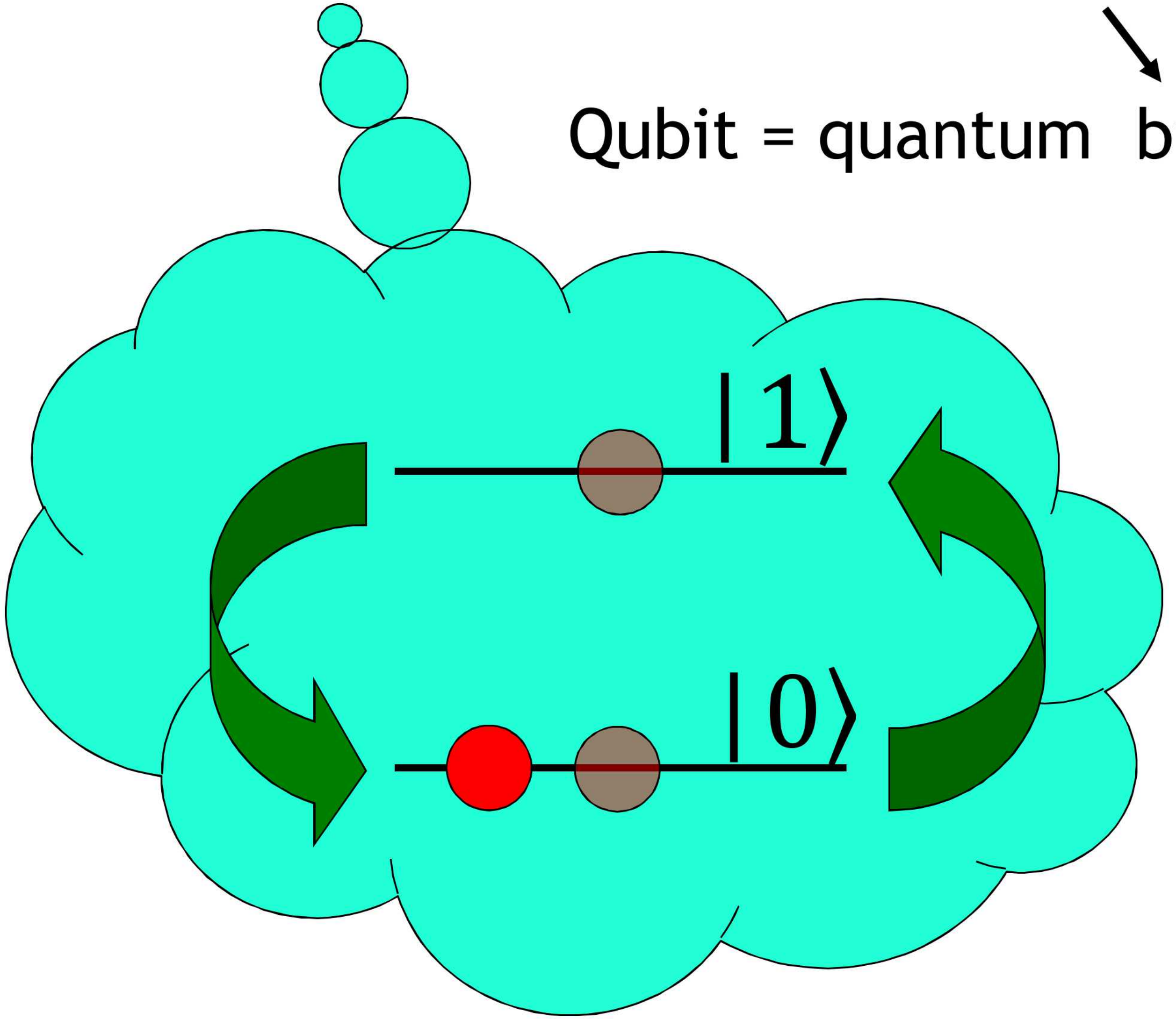
Elucidating Reaction Mechamisms on a Quantum Computer. Reiher et al., PNAS (2017)

What is a qubit?

01110001011
01010100010

Qubit = quantum bit

- stable
- controllable (coherent)
- *quasi* two-level quantum system…



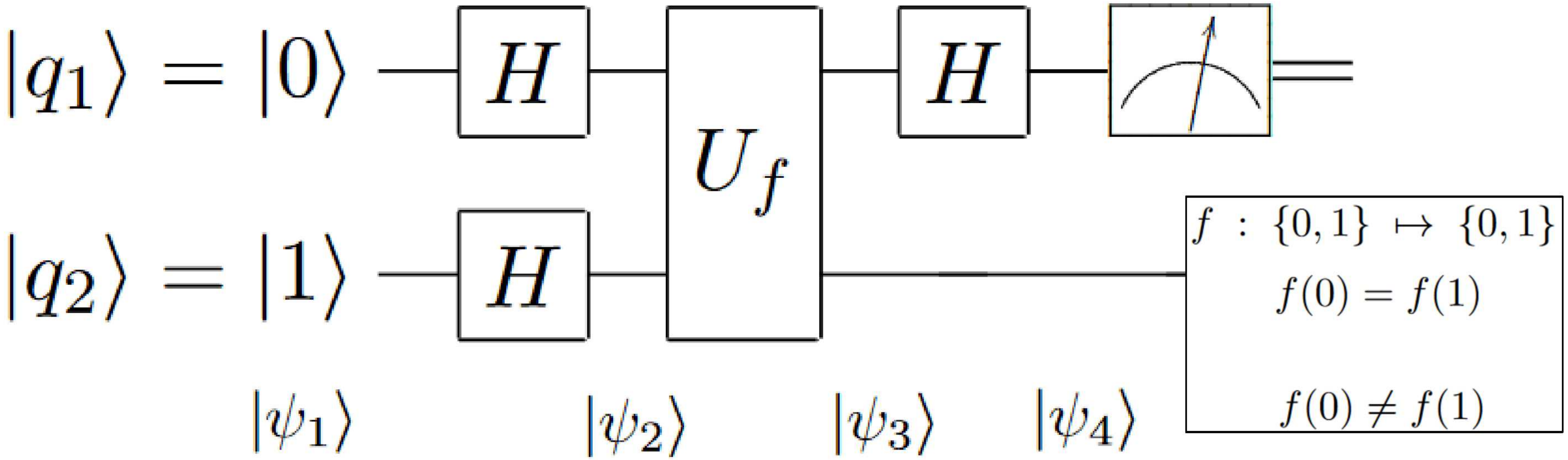
Superposition + Entanglement

$$|0\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle$$

$$(|\alpha|^2+|\beta|^2 = 1)$$

$$|0,0\rangle \rightarrow \alpha|0,1\rangle + \beta|1,0\rangle$$

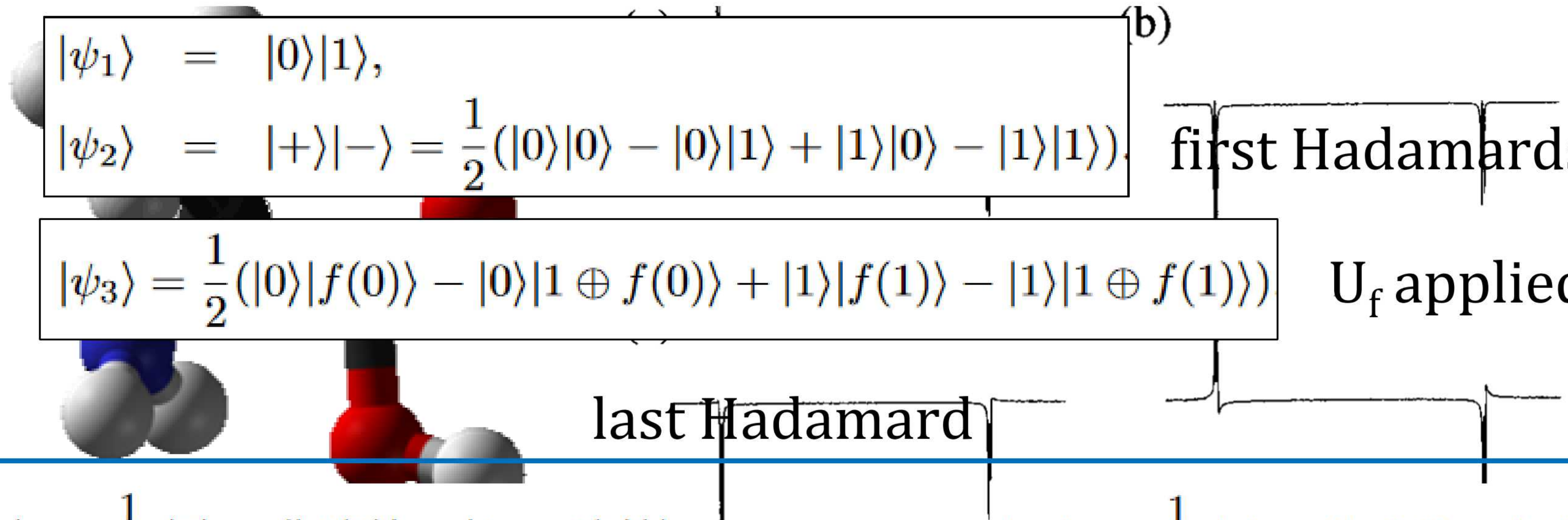
What's the big deal about entanglement? Deutsch's algorithm



$f : \{0,1\} \mapsto \{0,1\}$

$f(0) = f(1)$

$f(0) \neq f(1)$



$$\begin{aligned} |\psi_1\rangle &= |0\rangle|1\rangle, \\ |\psi_2\rangle &= |+\rangle|-\rangle = \frac{1}{2}(|0\rangle|0\rangle - |0\rangle|1\rangle + |1\rangle|0\rangle - |1\rangle|1\rangle). \end{aligned}$$

first Hadamards

$$|\psi_3\rangle = \frac{1}{2}(|0\rangle|f(0)\rangle - |0\rangle|1 \oplus f(0)\rangle + |1\rangle|f(1)\rangle - |1\rangle|1 \oplus f(1)\rangle)$$

U_f applied

last Hadamard

$$|\psi_4\rangle = \frac{1}{\sqrt{2}}|0\rangle \otimes (|f(0)\rangle - |1 \oplus f(0)\rangle)$$

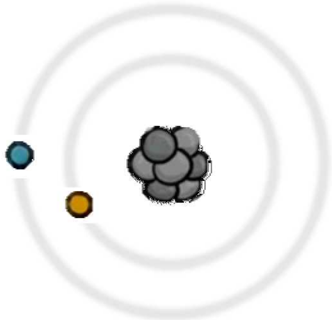
or

$$|\psi_4\rangle = \frac{1}{\sqrt{2}}|1\rangle \otimes (|f(0)\rangle - |f(1)\rangle).$$

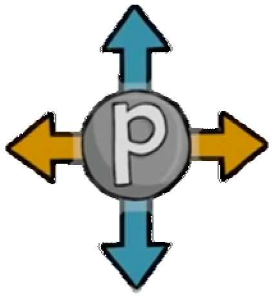
Requirements for building a quantum computer

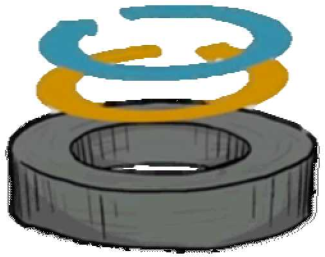
The DiVincenzo criteria (simplified)

1. A scalable, high-fidelity qubit processing technology
2. A computer architecture for organizing the components
3. Methods for suppressing runtime errors


Atomic state


Electron spin


Photon polarization


Superconducting current


Tiny part that goes to the moon.

Most of the rocket just fights Earth's gravity.

The vast majority of what a quantum computer will do is correct its own errors.

Sensing

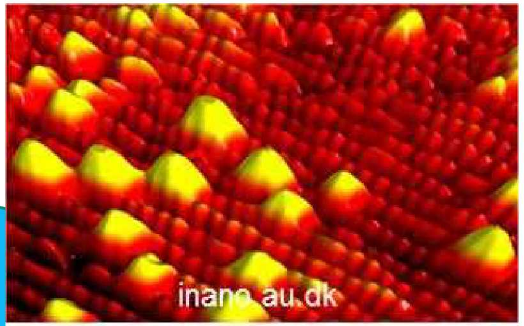
Timing


www.wall321.com

Non Destructive Evaluation


dwfritz.com

Surface Science


inano.au.dk

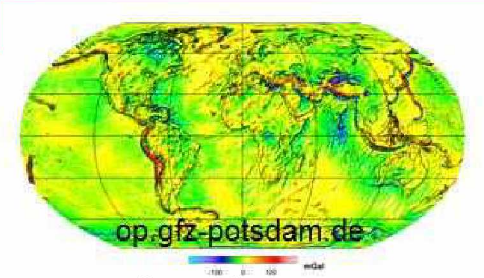

www.zeroonezero.com

Medical Imaging

QUANTUM SENSORS


blog.techimpact.org

Navigation


op.gfz-potsdam.de

Gravimetry

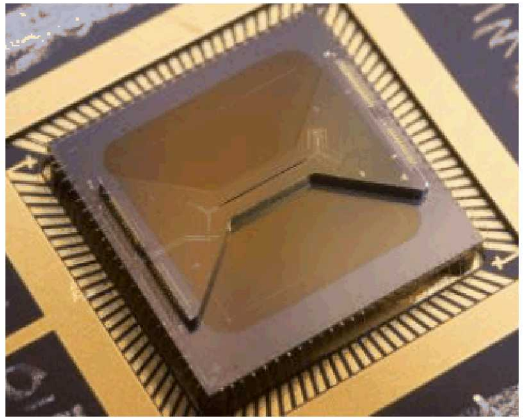
Trace Chemical Detection

Examples of qubits

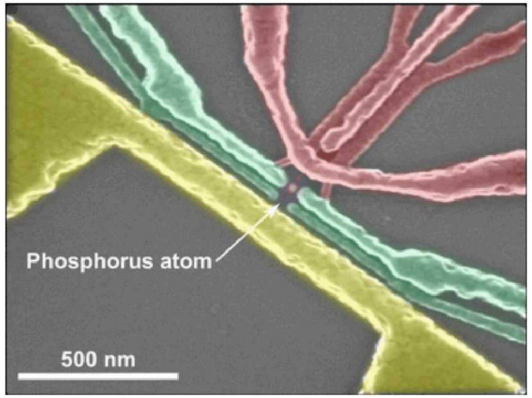
Today

Tomorrow

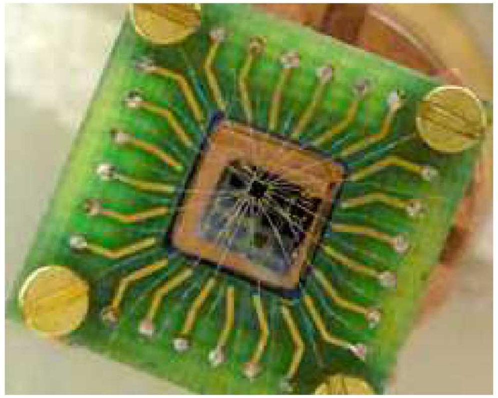
Future



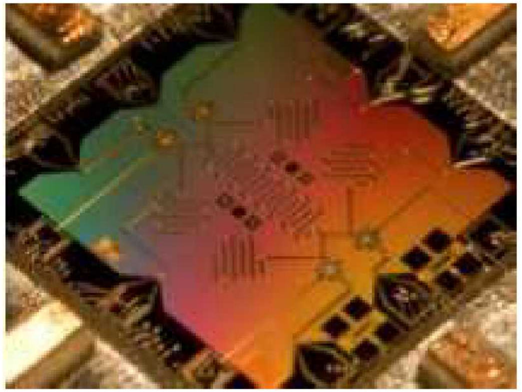
Trapped ions



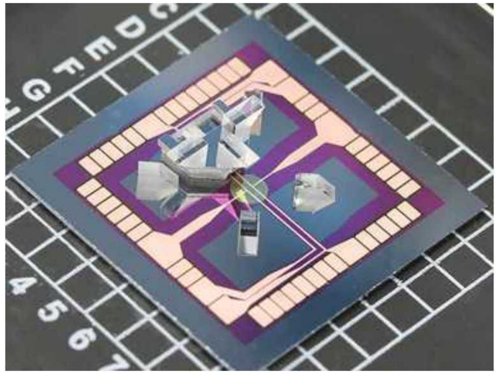
Semiconducting



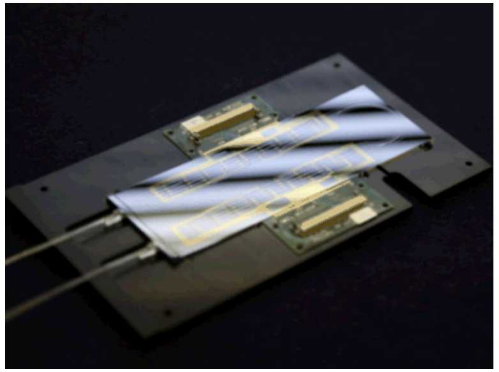
Topological



Superconducting

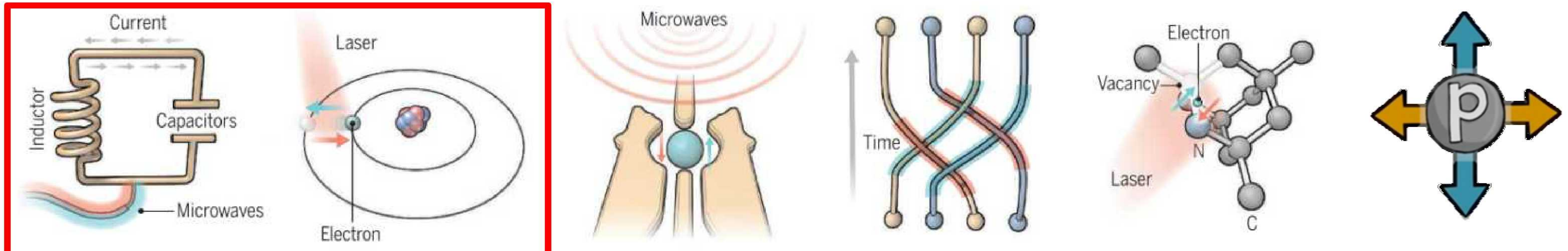


Trapped atoms



Photonic

Qubit comparison



	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**	**Photons**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.	Single photons are most commonly entangled through polarization or path variables. Principally controller with waveguides, mirrors, and beamsplitters.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10	<0.001
Logic success rate	~~99.4%~~ 99.5%	~~99.9%~~ >99.9 %	~99%	N/A	99.2%	~98%
Number entangled	High*	High	Low	N/A	Low	Medium
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies	PsiQ
Pros	Solid state Fast working. Build on existing semiconductor industry.	can room temp/connects Very stable. Highest achieved gate fidelities.	Very fast, solid state Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.	Room temperature, manufacturable
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.	Generation/extraction, lifetimes, fidelity

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

* Usually nearest-neighbor connectivity

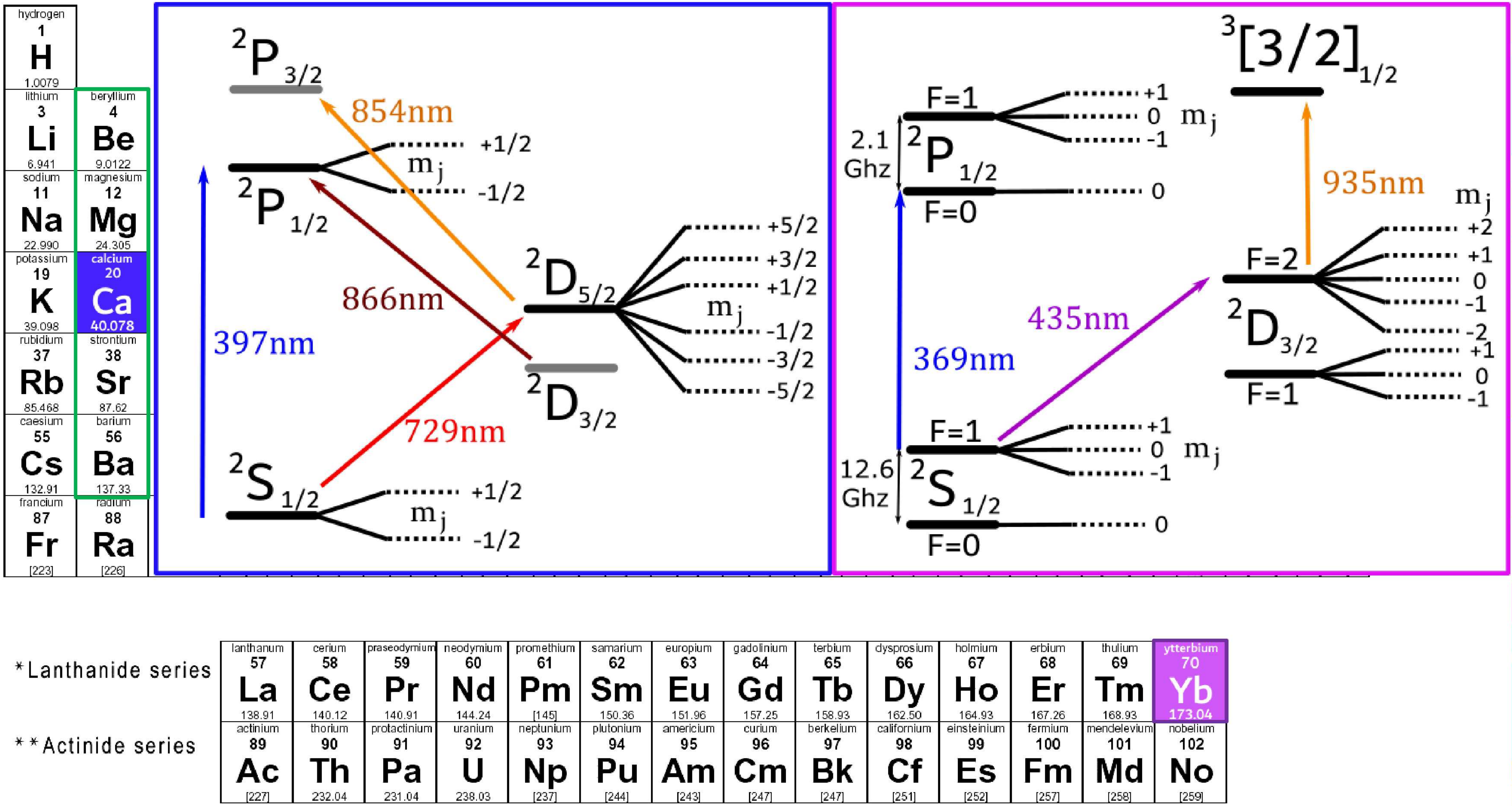
Science magazine, *A bit of the action*, Dec. 1 2016

ions

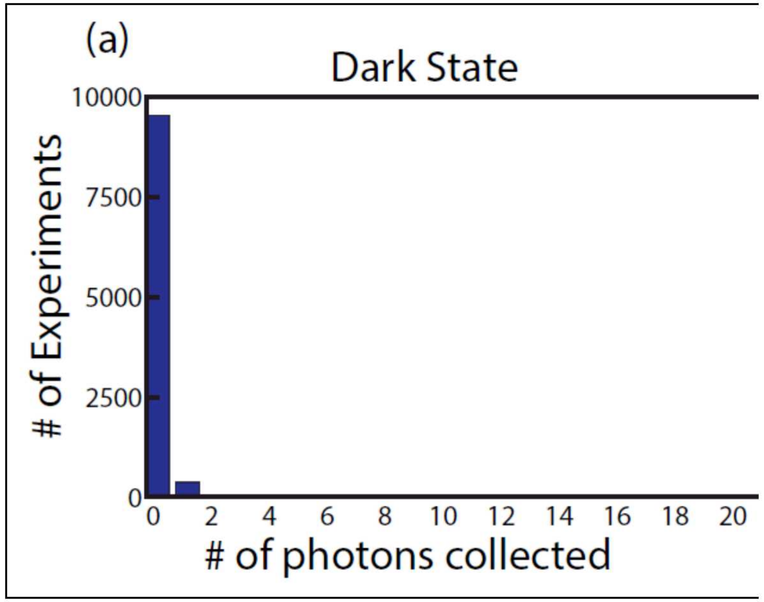
QSCOUT

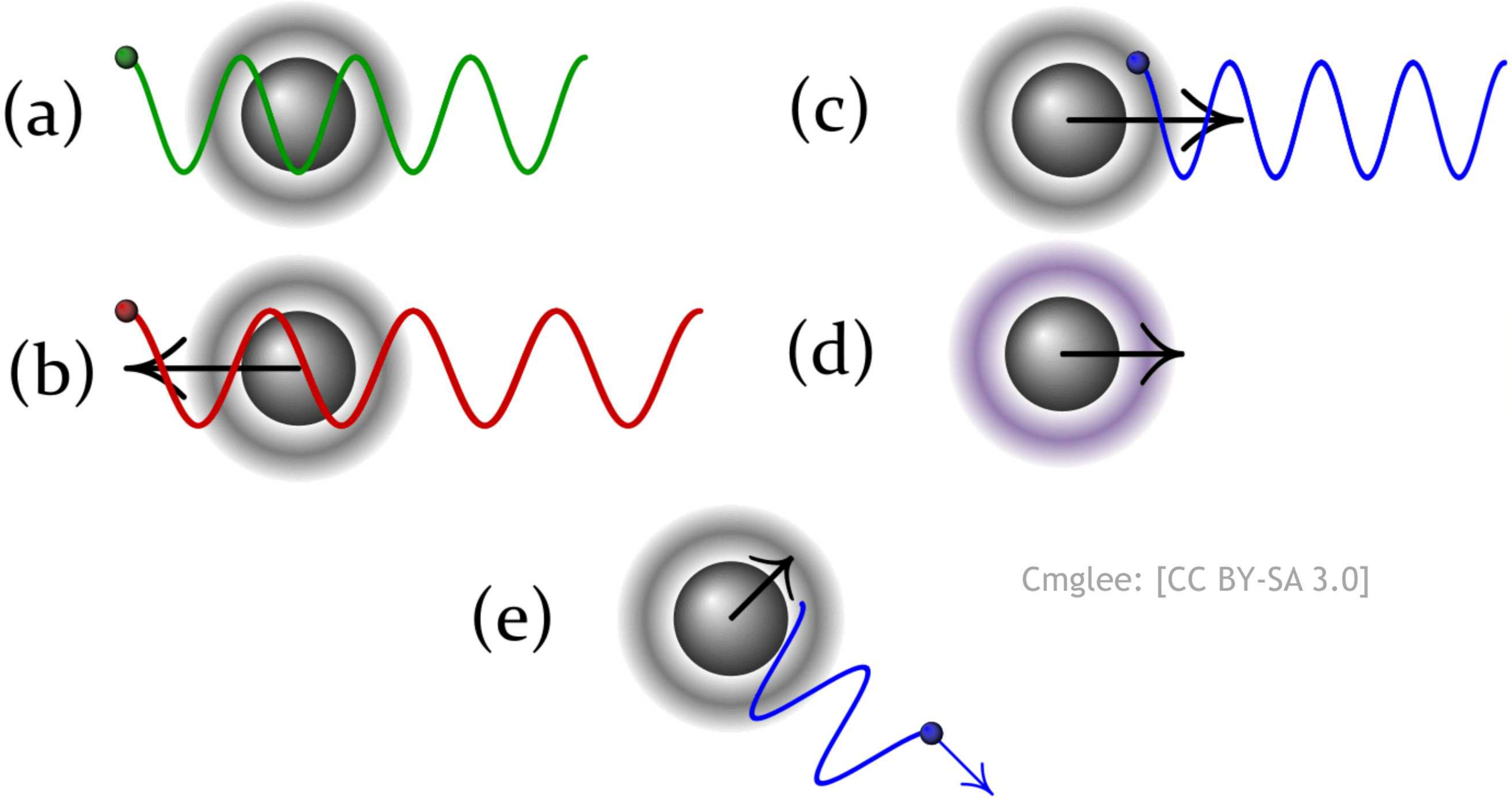
TicToc

Two common ion species: $^{171}Yb^{+}$ and $^{40}Ca^{+}$



Cooling, Prepping, Detection





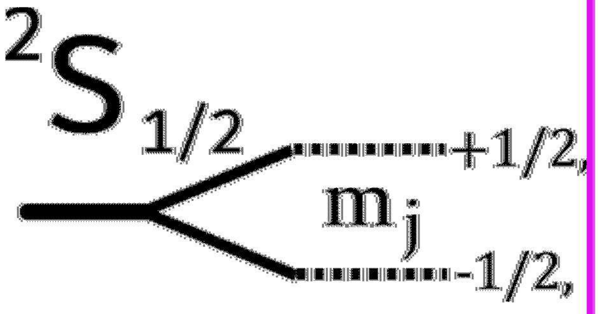
Cmglee: [CC BY-SA 3.0]

Mizrahi, J. (2013). *ULTRAFAST CONTROL OF SPIN AND MOTION IN TRAPPED IONS*. Ph.D. University of Maryland Department.

Types of ionic qubits

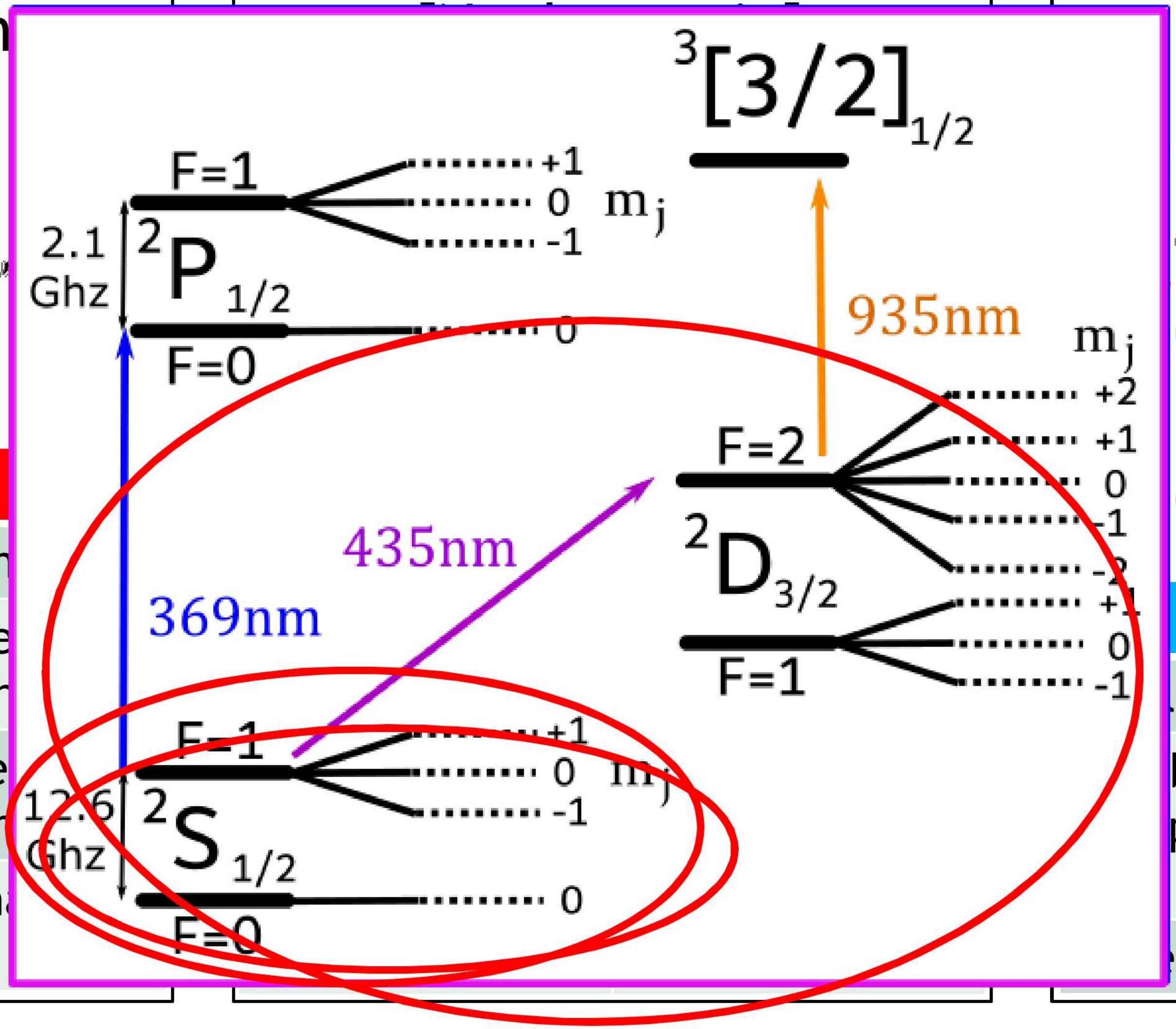
Zeeman

[No Nuclear spin



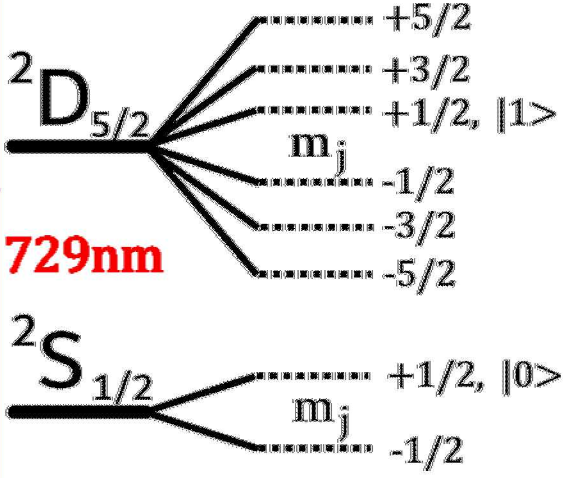
Pros	Cons
RF Transition	Detection
“Infinite” lifetimes	Level ene dependen
	No mome photon tr
	Off reson scatter

Hyperfine



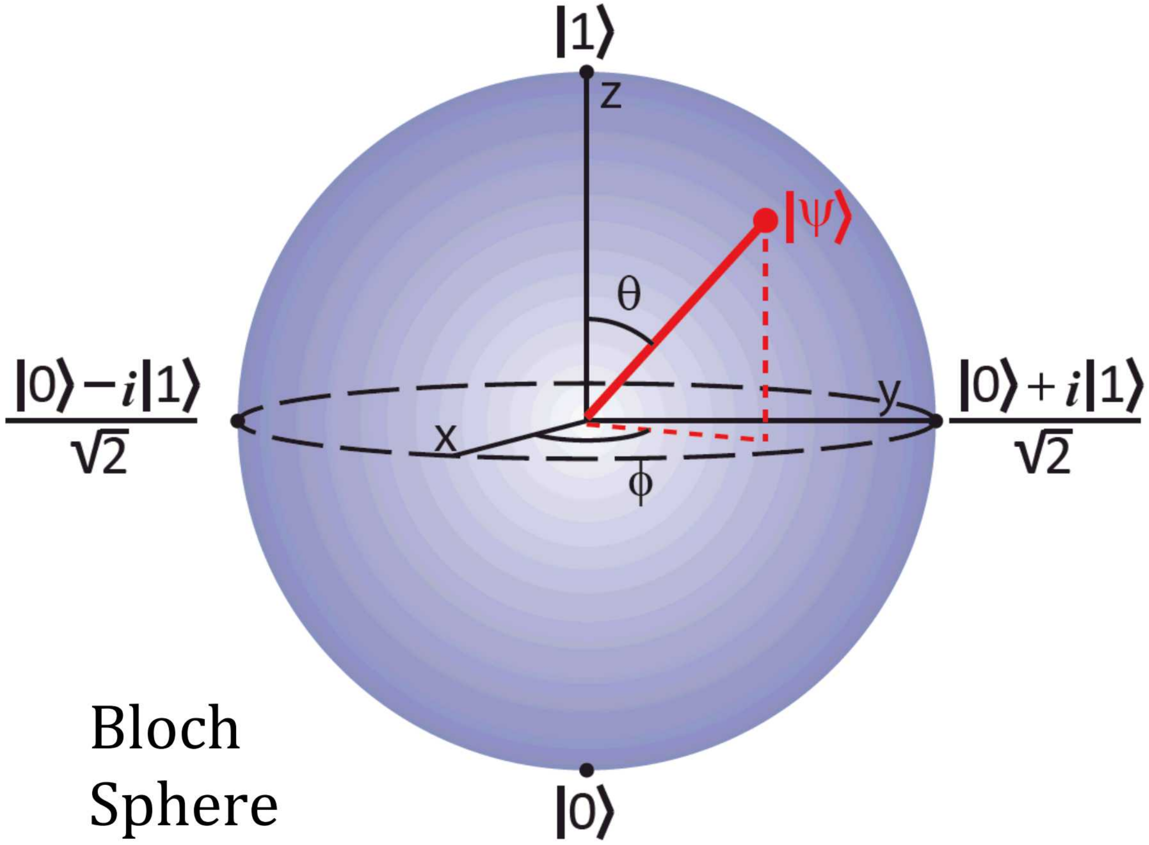
Optical

[between orbitals]



	Cons
e optical	Lifetimes ~ 1s
be B-field pendent	Coherence dependent on laser linewidth
ection	

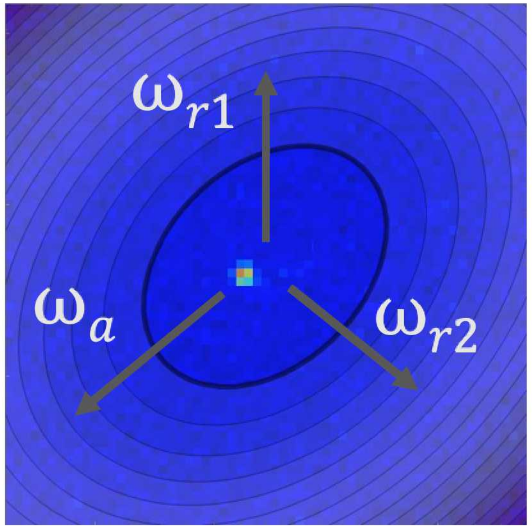
Single qubit operations, internal/external DoF

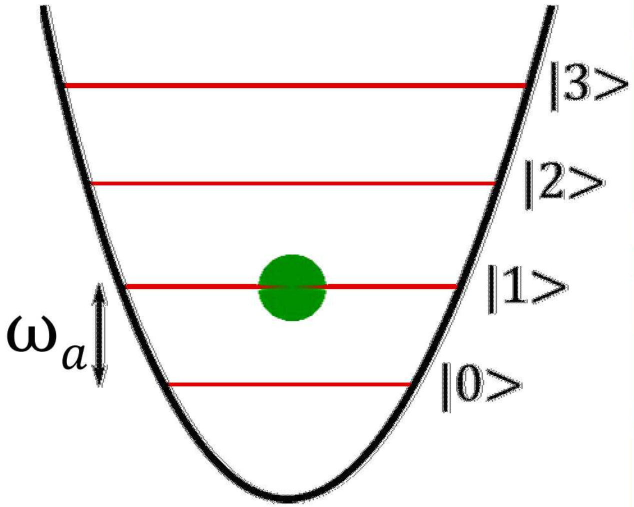


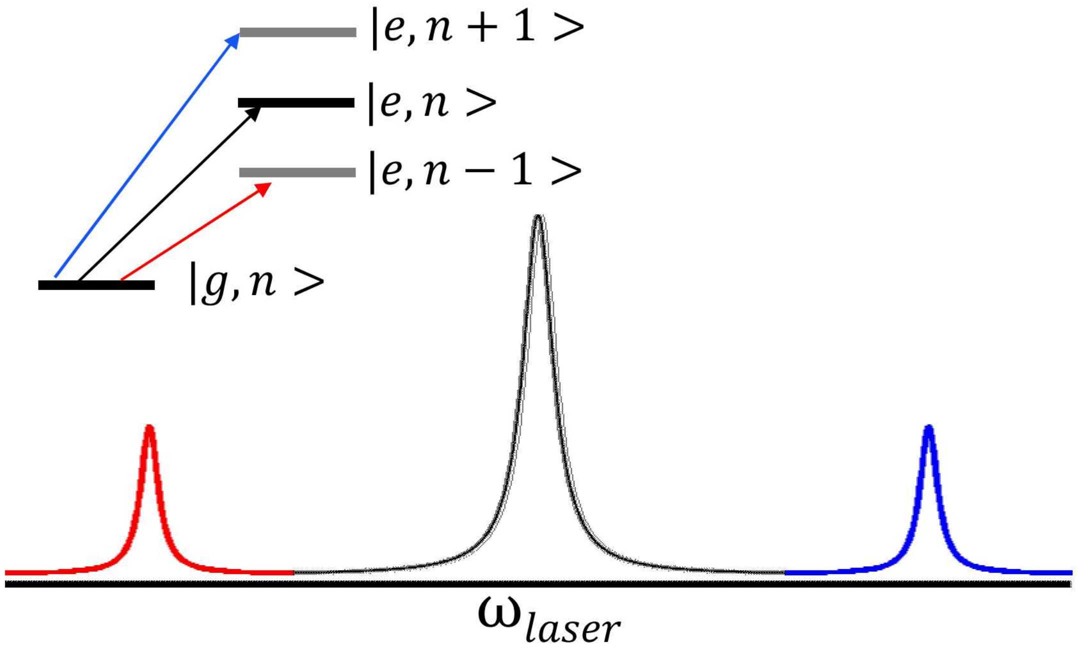
Bloch Sphere

$$|\Psi > = \sin\left(\frac{\theta}{2}\right) |0 > +e^{i\phi} \cos\left(\frac{\theta}{2}\right) |1 >$$

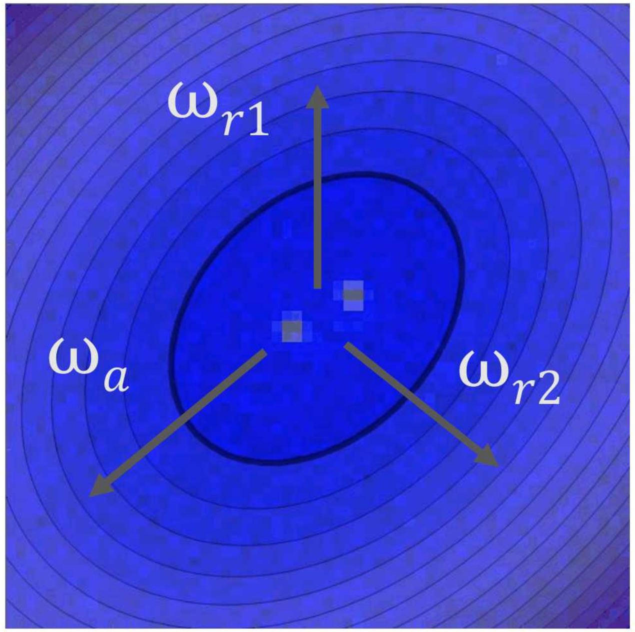
Mizrahi, J. (2013). *[Previous reference]*

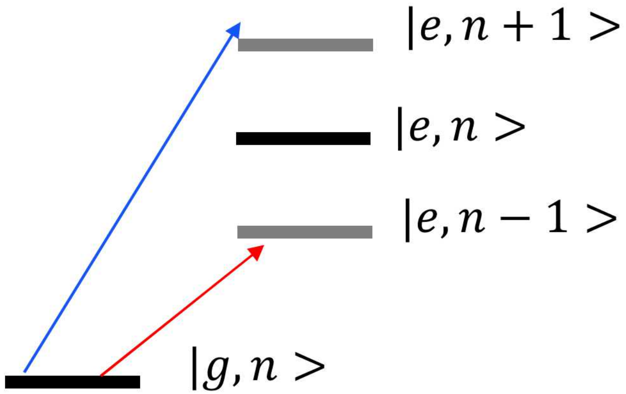




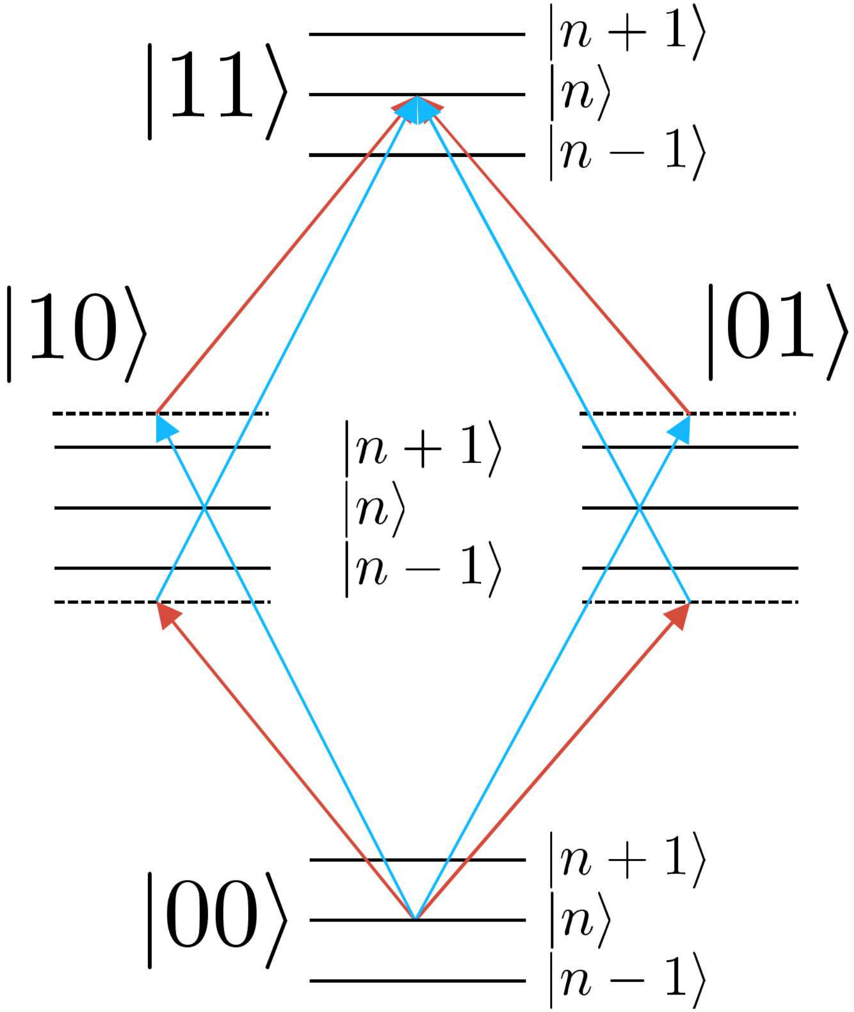


The Mølmer–Sørensen two-qubit gate

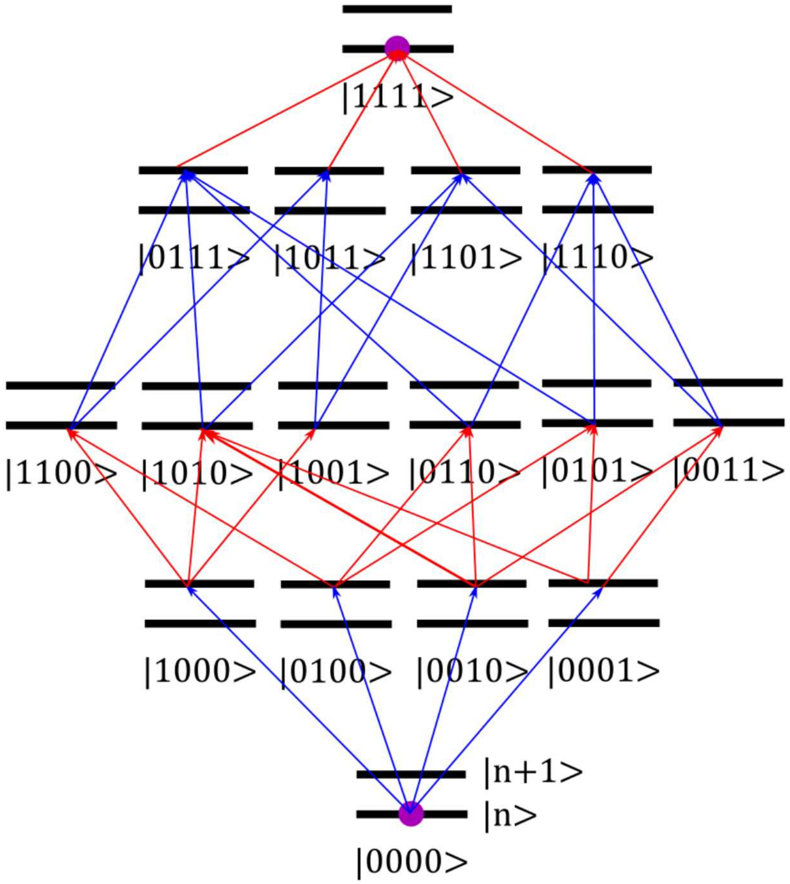




$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$



$$|0000\rangle \rightarrow |0000\rangle + |1111\rangle$$



Roos, C., **Quantum information processing with trapped ions.** ETH Zürich, 23.11. 2009

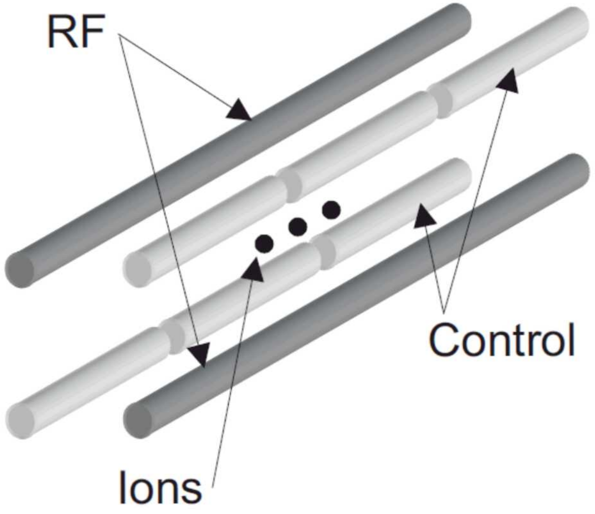
Trapology: 3D vs Surface traps

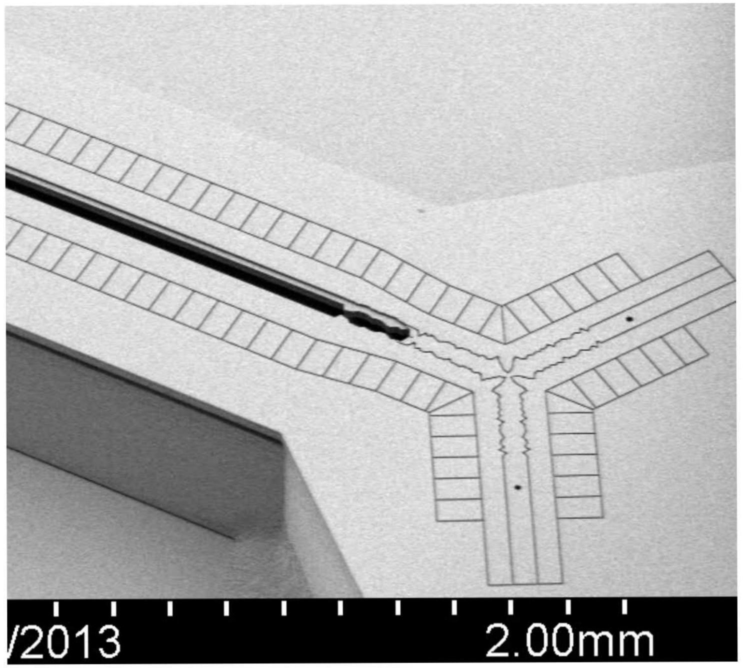
Advantages

- More manufacturable ("scalable")
- Consistent geometry = consistent behavior
- Greater field control (more electrodes)
- 2D geometry
- Integration of other technologies (waveguides, detectors, filters…)
- Laser access

Challenges

- Low depth (ion lifetime), anharmonicities in potential
- Proximity to surface (charging, heating)
- Delicate (dust, voltage)
- Capacitance





Surface trap capabilities and requirements

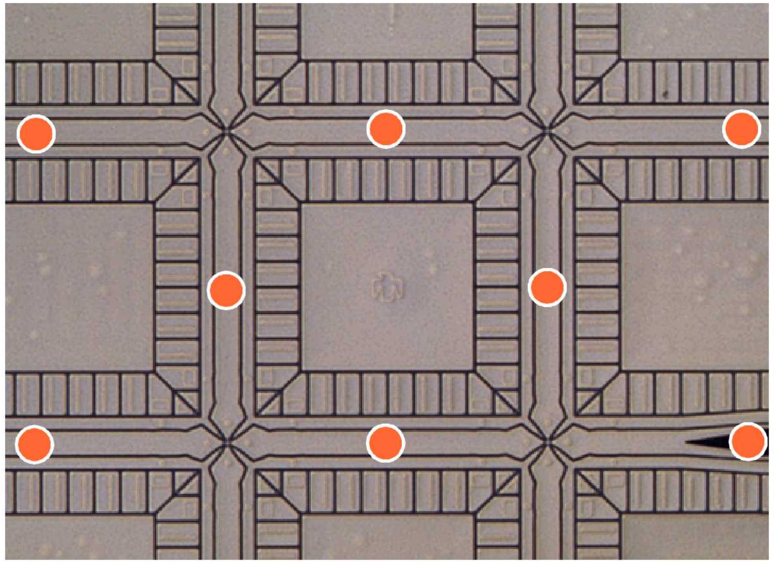
Essential capabilities

- Store ions for long periods of time (hours)
- Move ions to achieve 2D connectivity
- Support high fidelity operations
- Uniform performance

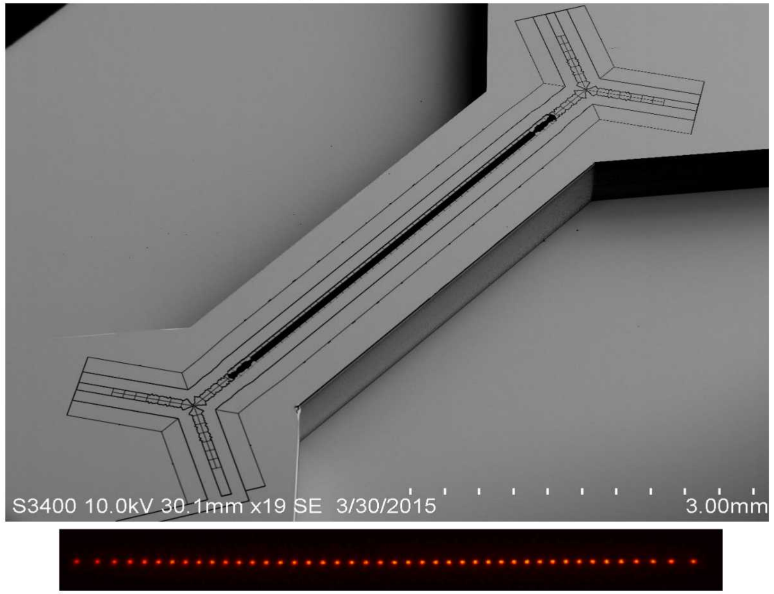
Derived requirements

- Voltage breakdown >300 V @ ~50 MHz
- Backside loading hole
- Multi-level lead routing for accessing interior electrodes
- Standardization [lithographically defined electrodes]
- Overhung electrodes
- High optical access [high NA delivery and collection optics]

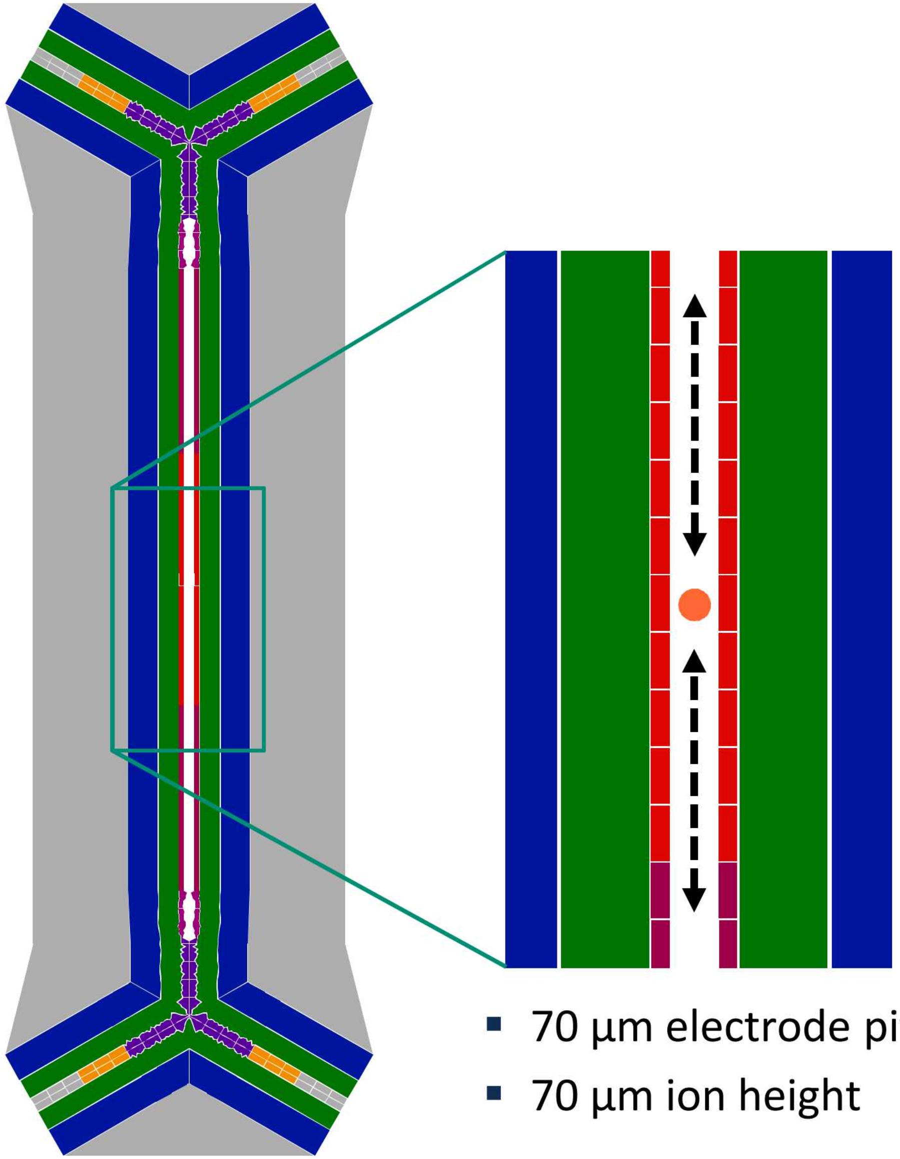
Quantum CCD



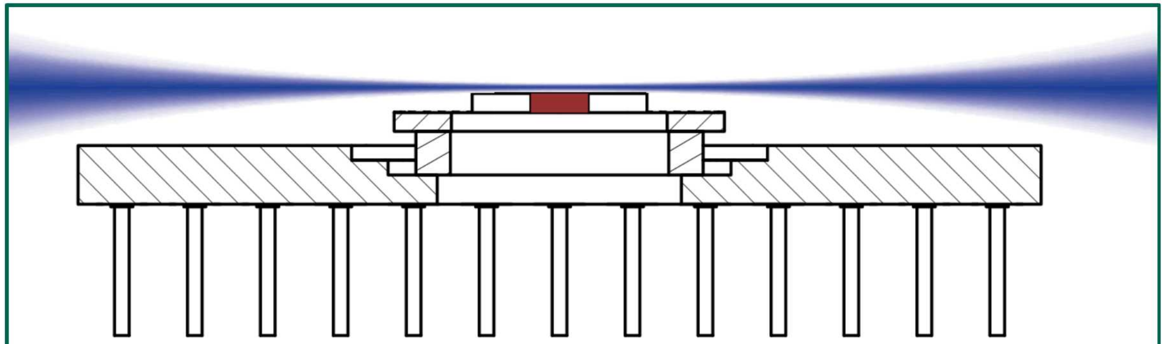
MUSIQC architecture



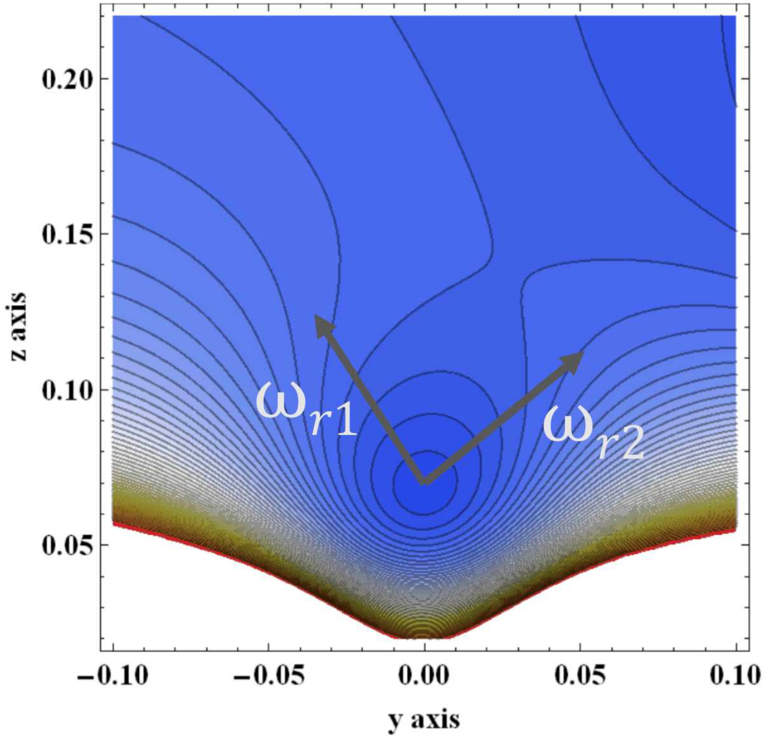
High optical access 2 (HOA2)



- 70 µm electrode pitch
- 70 µm ion height

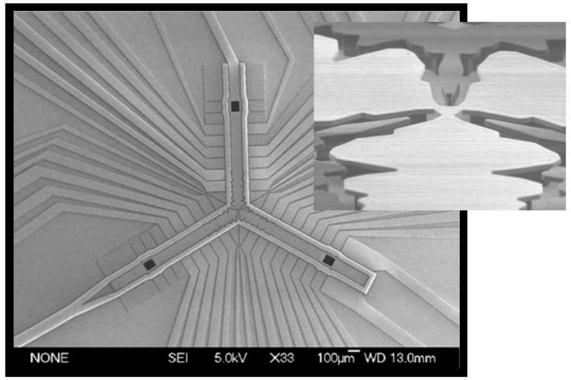


Can accommodate 4/2 um beam waist (369 nm)

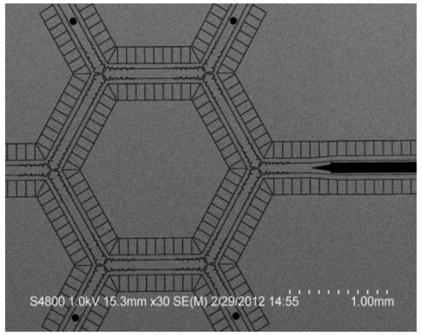


Some of Sandia's Traps

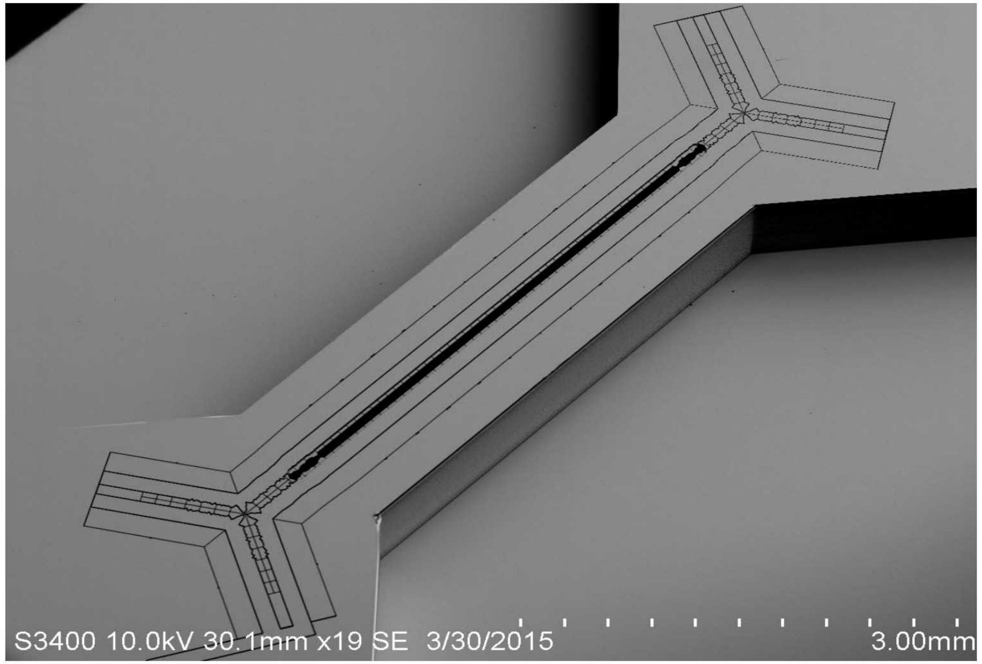
Y-junction traps



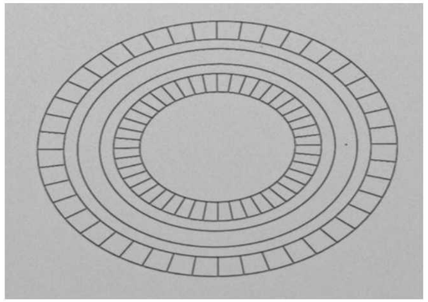
Circulator trap

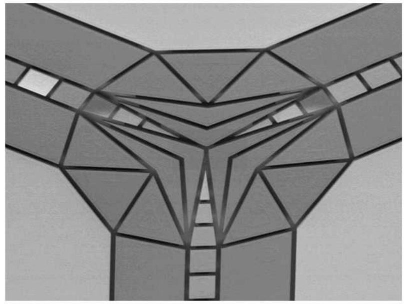


High Optical Access (HOA) trap



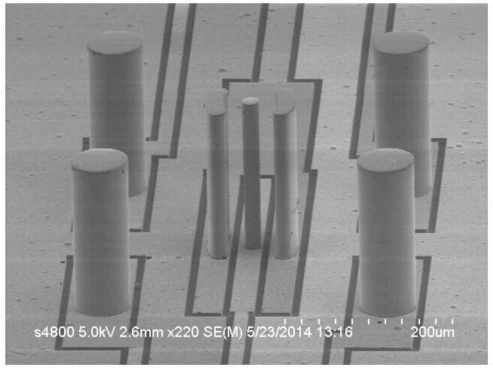
Ring trap:



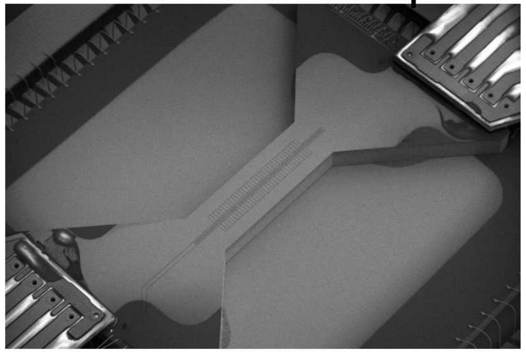


Switchable RF trap

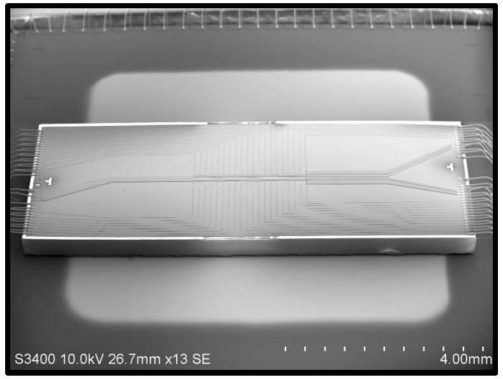
Stylus trap



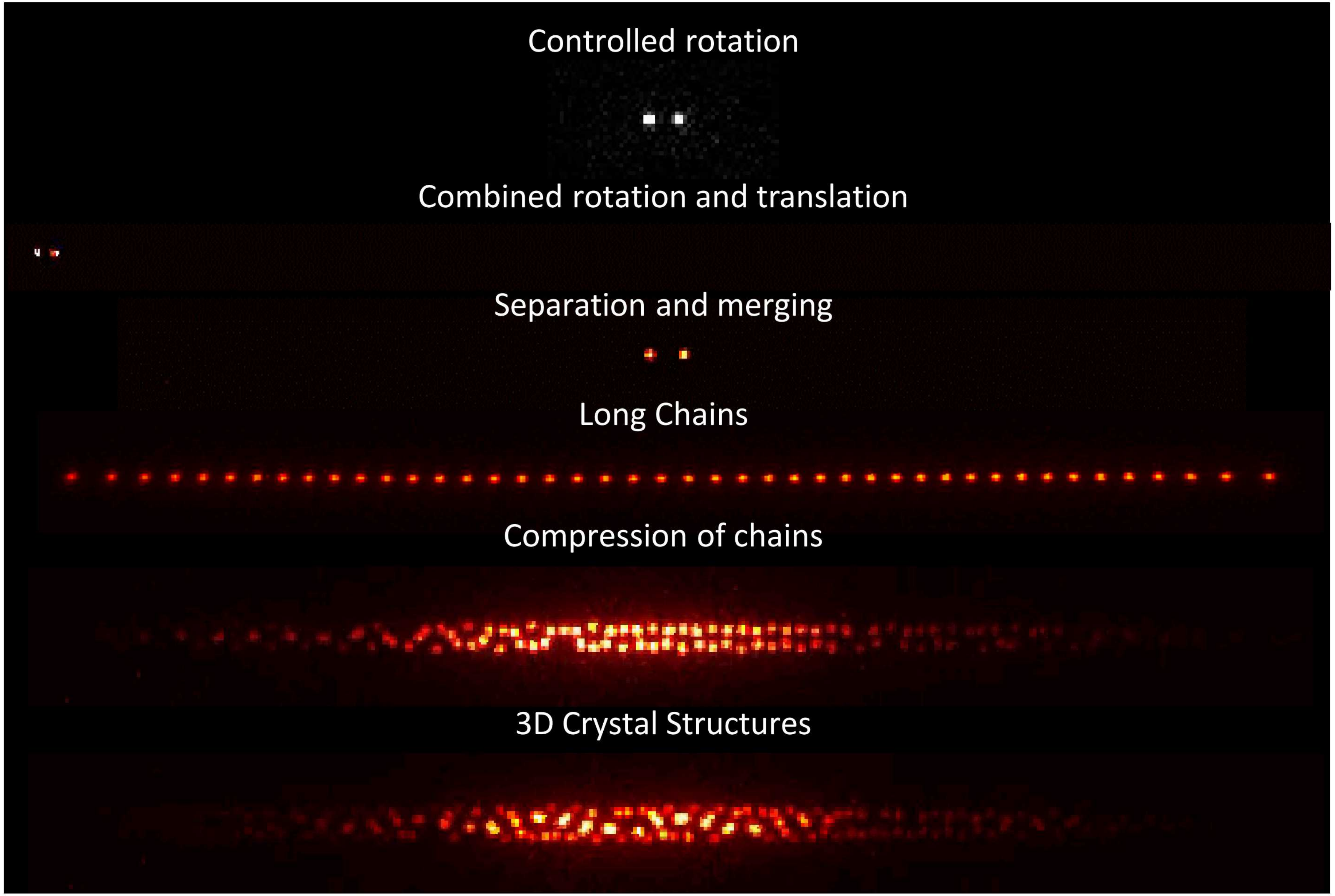
Microwave trap



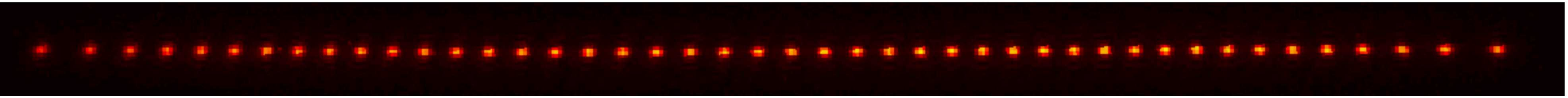
EPICS trap



Ion configurations



QSCOUT DOE Quantum Testbed Laboratory



Testbed systems designed for open access to support scientific applications

- High-fidelity operations
- Gate-level access
- Open system with fully specified operations and hardware
- Low-level access for optimal control down to gate pulses
- Open for comparison and characterization of gate pulses
- Open for vertical integration by users

$$\#gates \propto (\#qubits)^2$$

https://qscout.us
https://qscout.sandia.gov

Duke UNIVERSITY

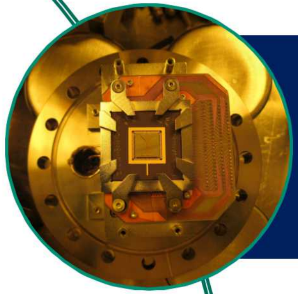
Ken Brown et al.

Tufts UNIVERSITY

Peter Love et al.

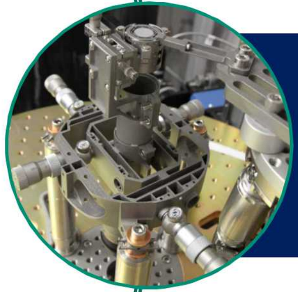
QSCOUT

QSCOUT Systems engineering



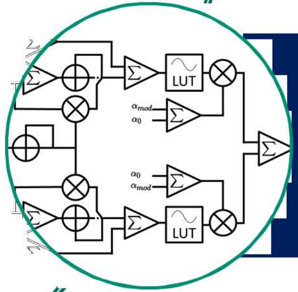
Reducing background collisions

Vacuum technology



Individual addressing

Optical and mechanical engineering



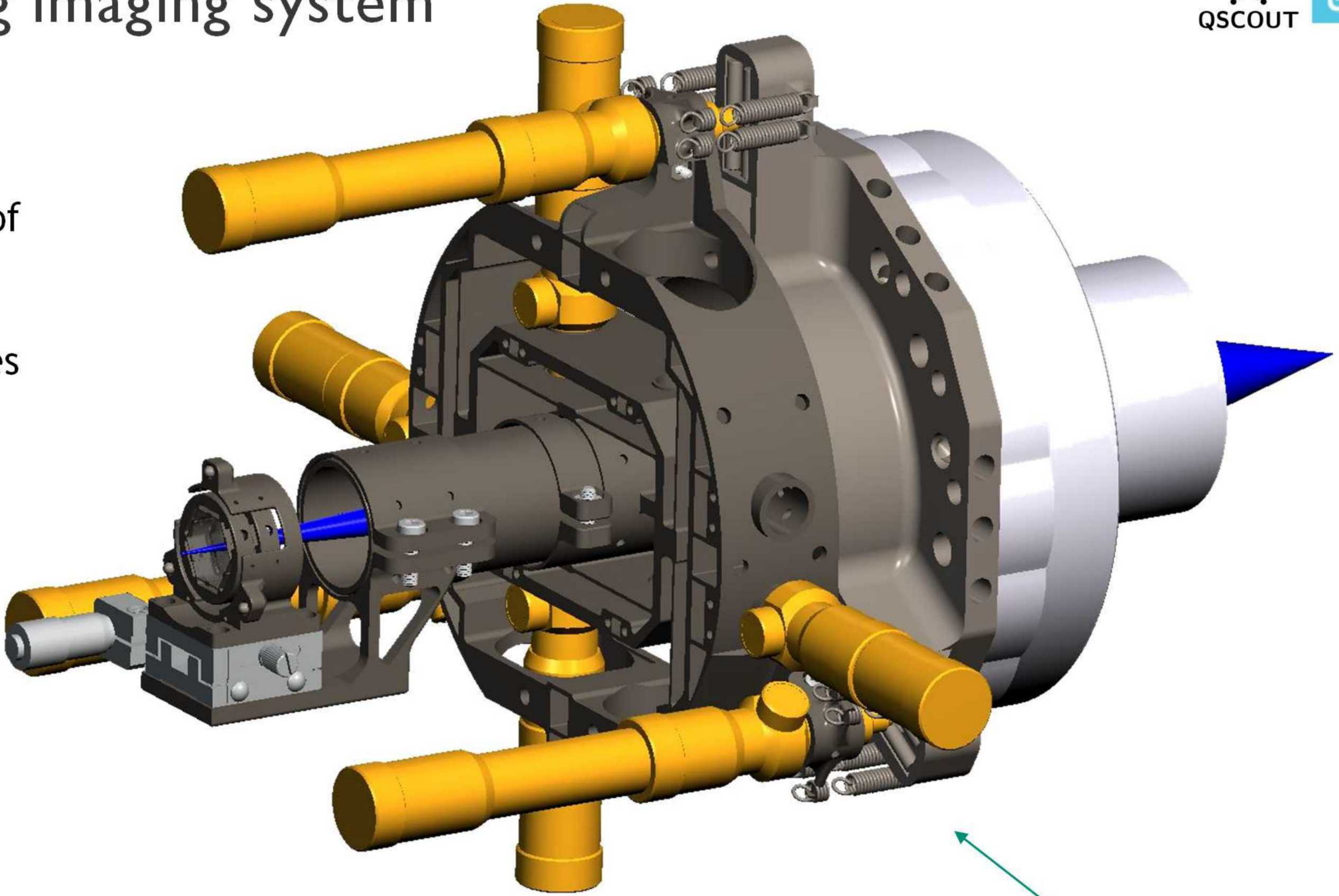
Coherent Pulse control

Electrical engineering

Individual addressing imaging system

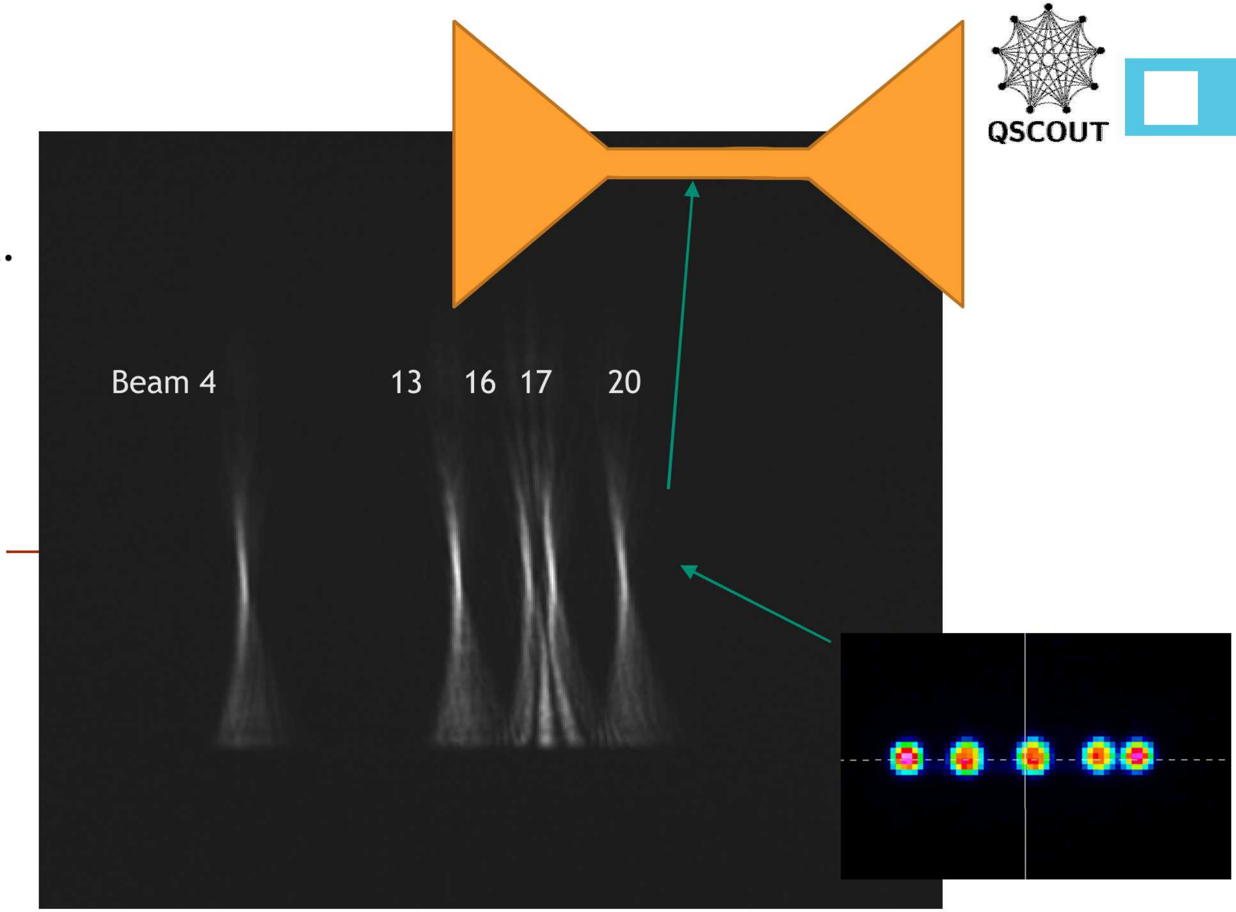
Custom design to

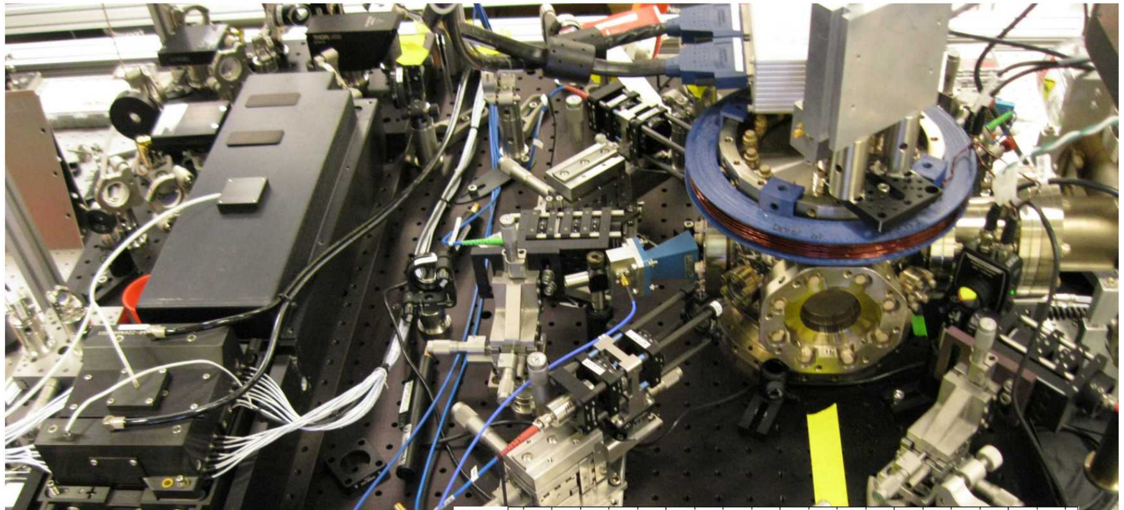
- Accommodate needed degrees of freedom in very cramped space
- Resilient to temperature changes
- Provide the needed stability

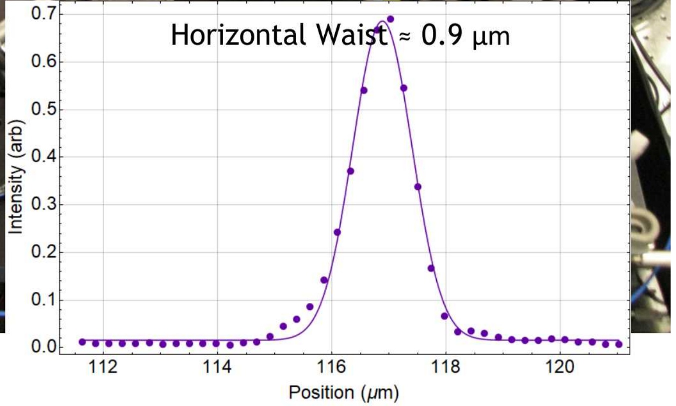


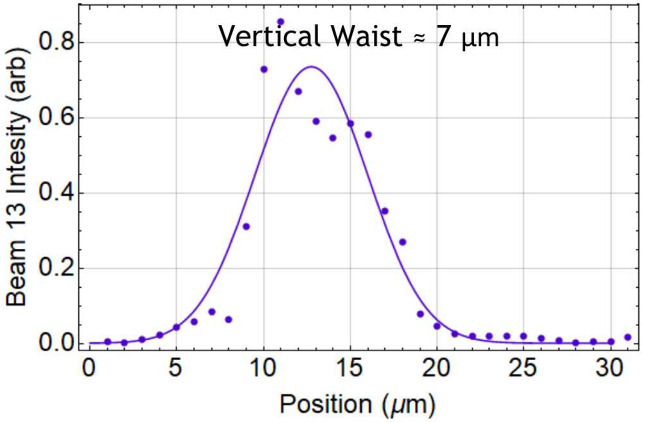
Qubit Laser – Apparatus Test

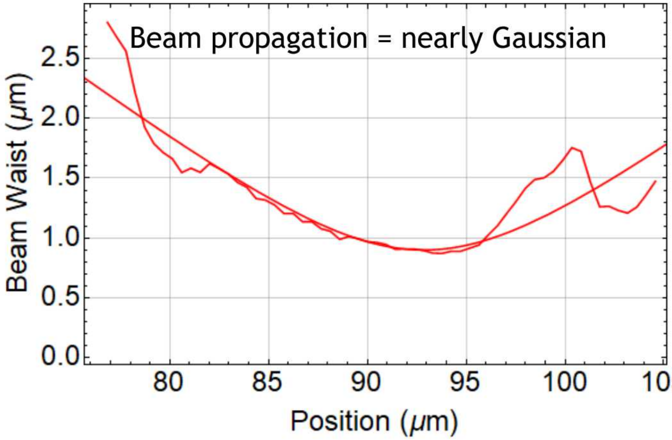
- Adjacent beams are clearly separated, and about 5 μm apart.
- The beam waists are nearly the designed values.
- Up to 32 channels/ions for individual addressing.



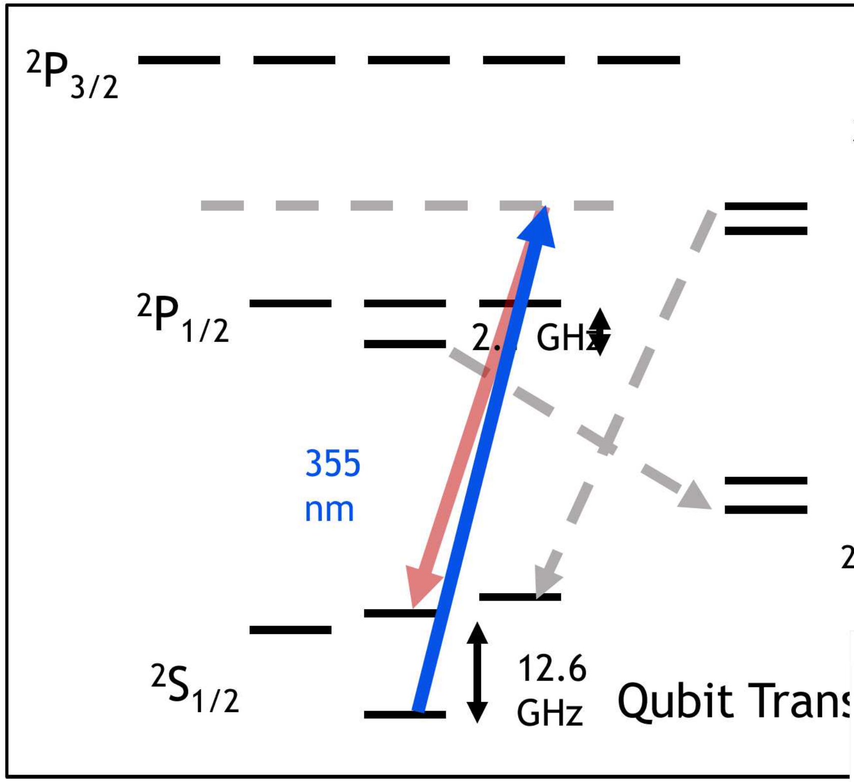


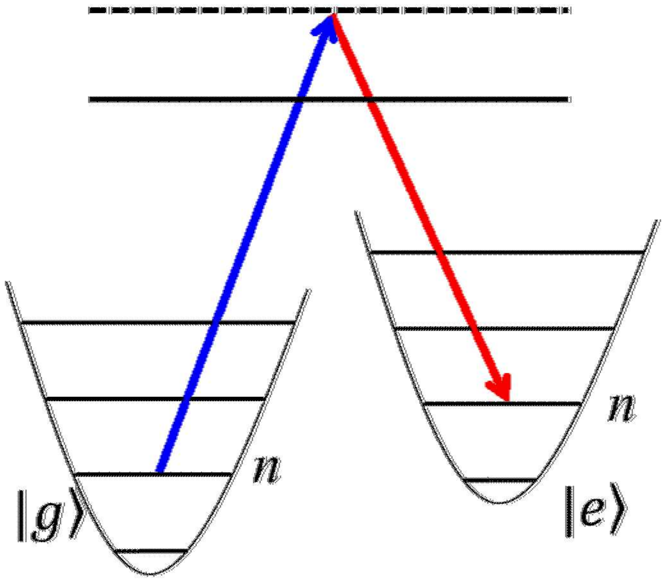




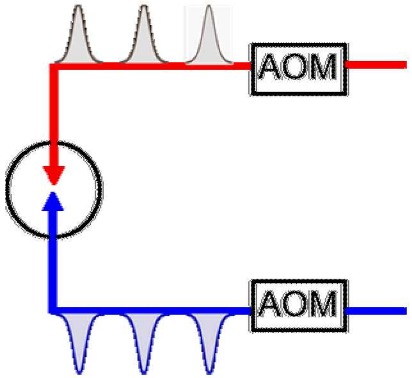


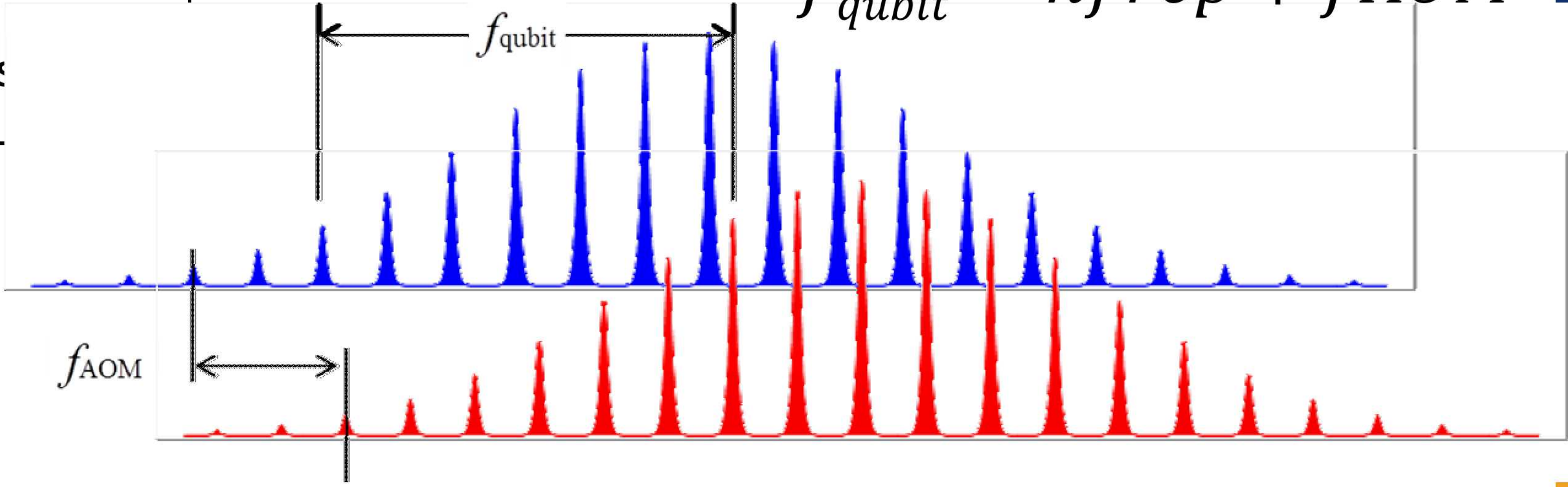
Raman transitions



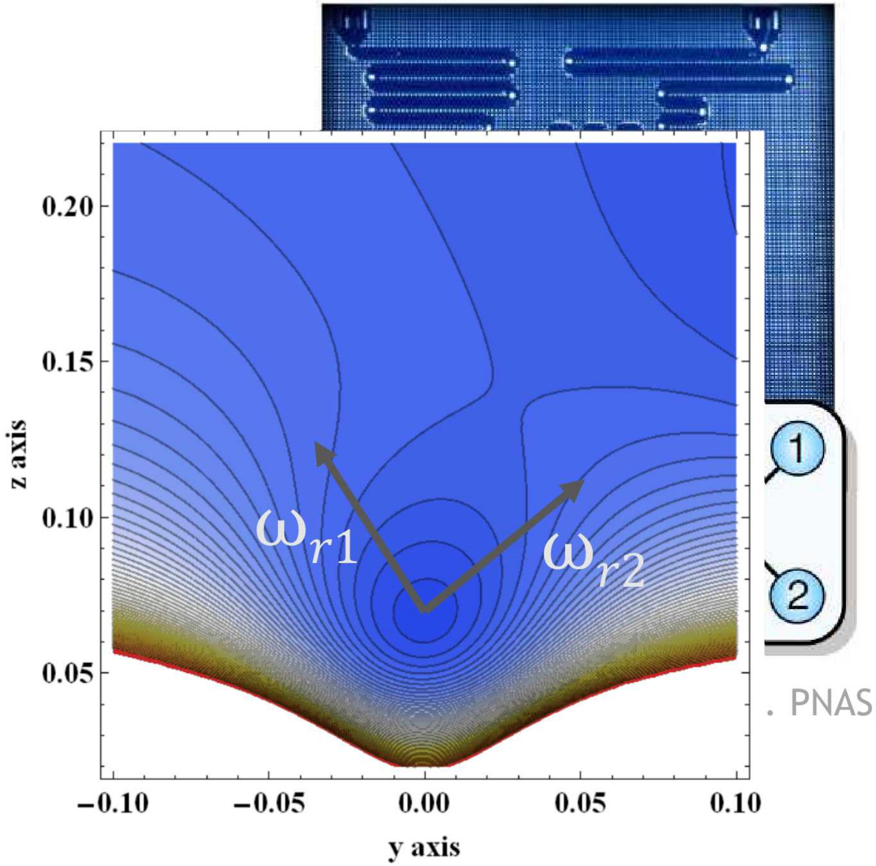


$$f_{qubit} = nfrep + fAOM$$

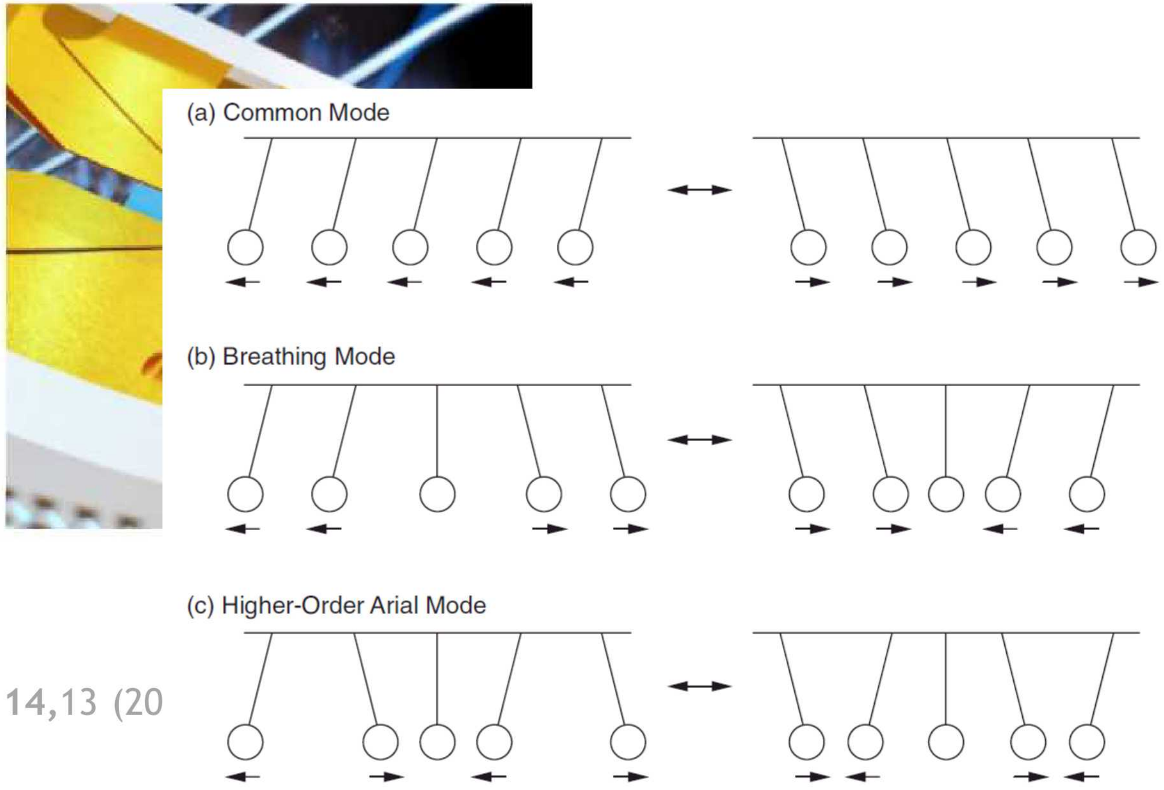




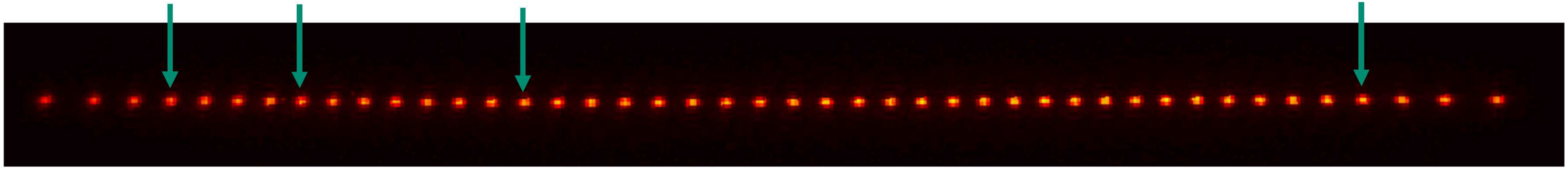
Full connectivity



. PNAS, **114**,13 (20



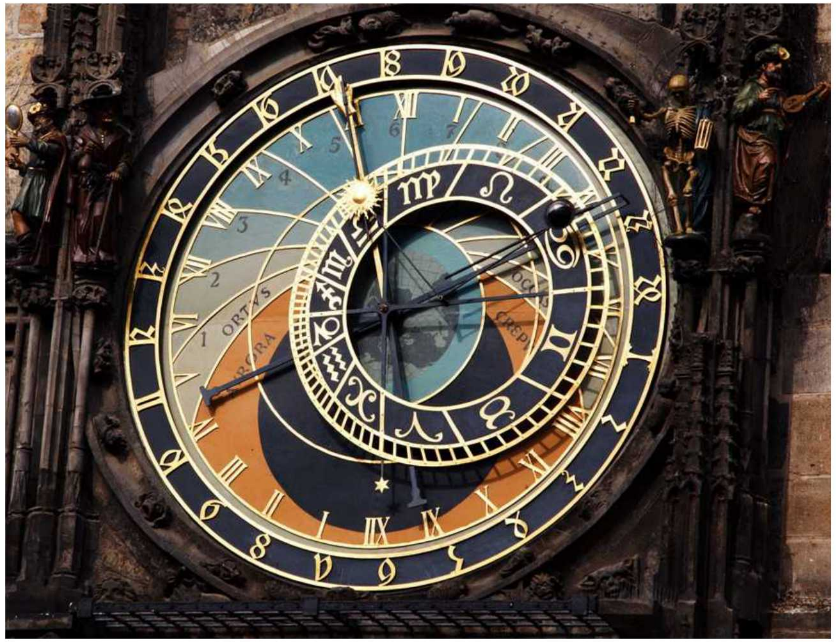
M. Holzscheiter, Los Alamos Science, **27** (2002)



Clocks

Oscillator + Counter = Clock

Image : amazon.com, GOGO



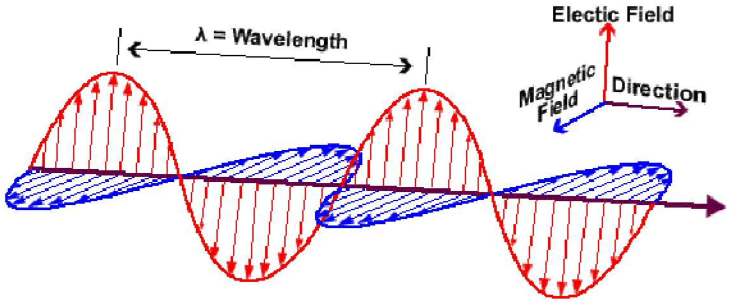


Image: NOAA

oomlout [CC BY-SA]

Atomic microwave clocks

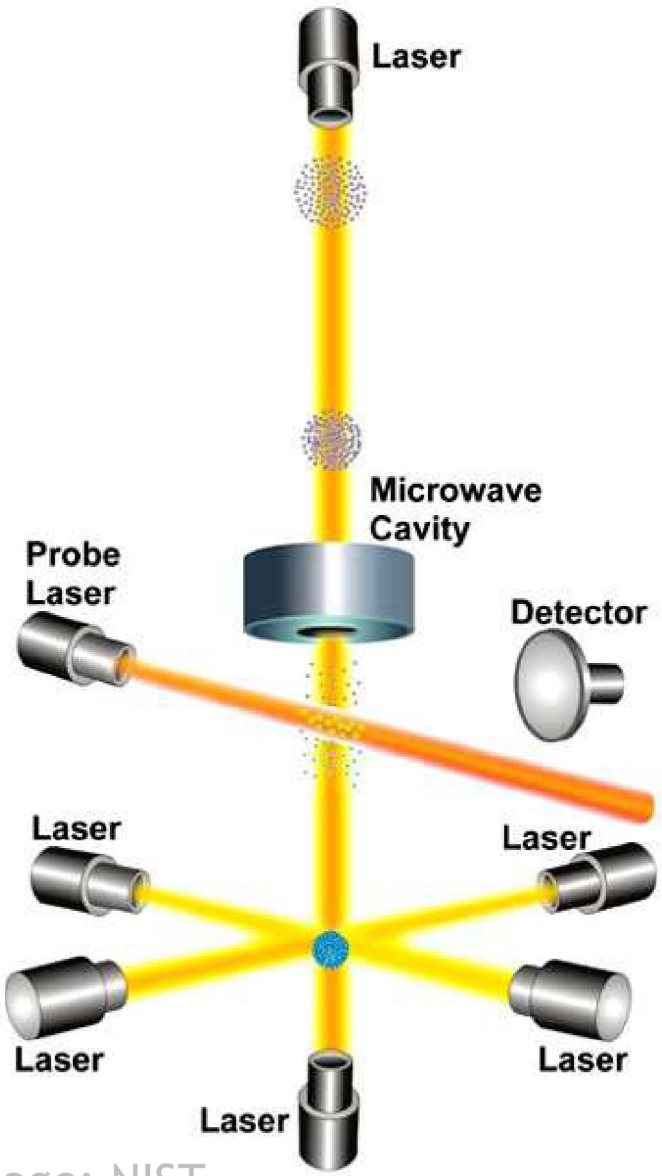
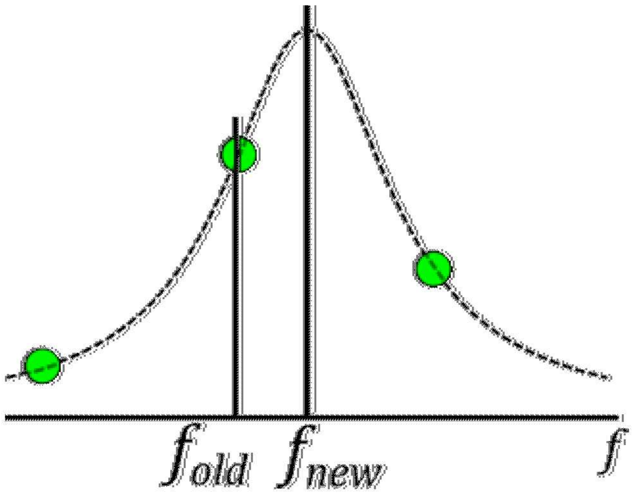
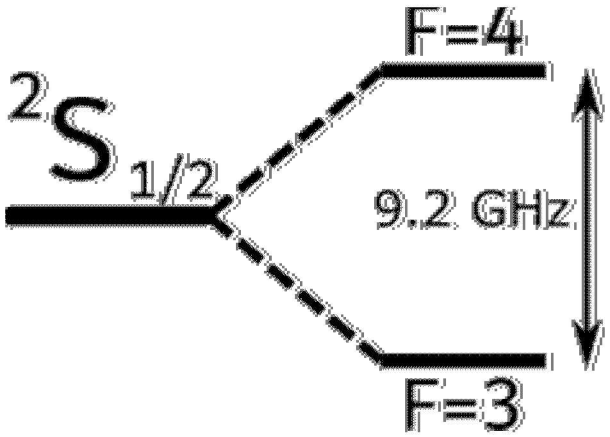


Image: NIST

1. Trap numerous atoms
2. Prepare atoms in F=3
3. Launch atoms vertically
4. 50% Microwave transition to F=4
5. Atoms peak, fall, interrogated again
6. Probe laser detects population in F=4

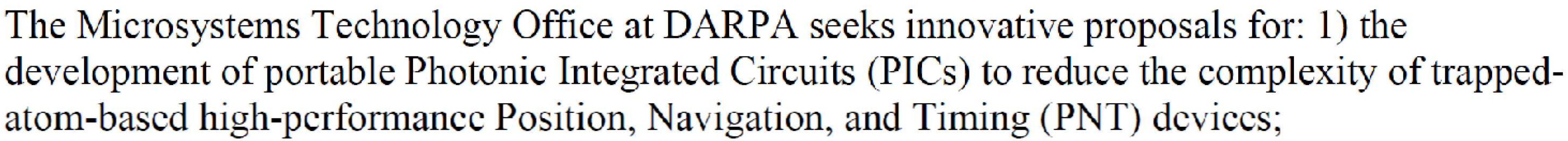




TICTOC (Trapped Ion Clock with photonic Technologies On Chip)

- Microwave clocks are now a relatively mature technology
  - → The next step is to use optical frequencies
  - → ~ 10 GHZ (microwave) vs. ~ 10,000 GHz (optical) means better resolution

DARPA

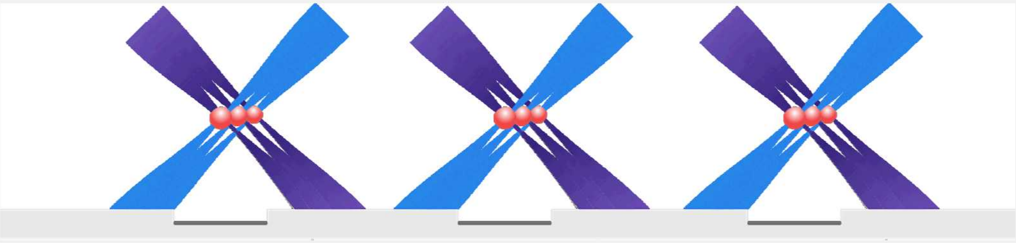

The Microsystems Technology Office at DARPA seeks innovative proposals for: 1) the development of portable Photonic Integrated Circuits (PICs) to reduce the complexity of trapped-atom-based high-performance Position, Navigation, and Timing (PNT) devices;

TicToc

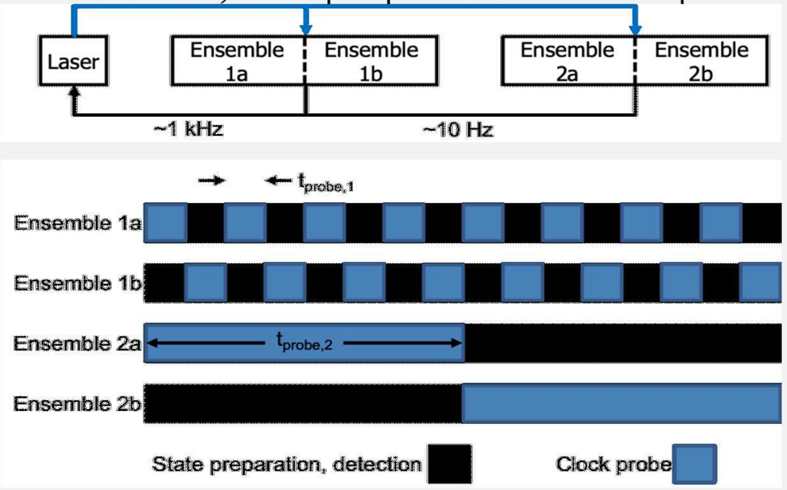
Sandia National Laboratories	Prime. Ion traps, waveguides, detectors, integration
NIST	Multi-ensemble design, protocols, reference standards, demonstration
OEwaves	High spectral purity LO development and integration
PURDUE UNIVERSITY	Micro-frequency comb
Yale University	Doubling resonator

TICTOC components

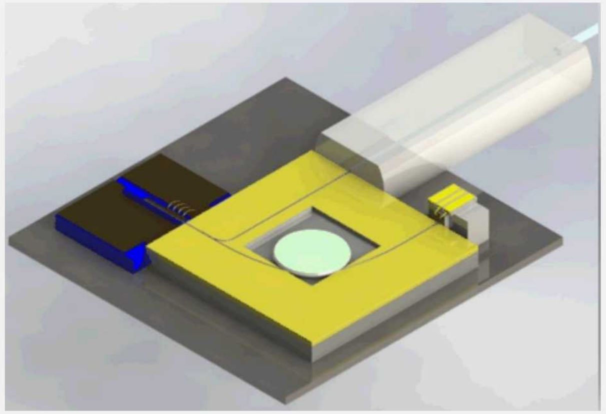
- Optical clock using micro-fabricated $^{171}Yb^+$ **ion traps** with monolithically integrated **waveguides**, and **detectors**



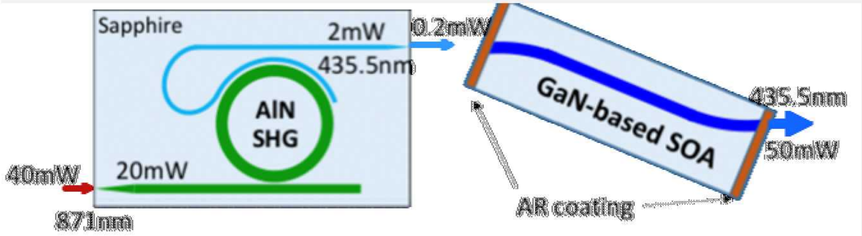
- **Multi-ensemble interrogation**. Staggered interrogations to eliminate dead time; multiple probe times to improve stability



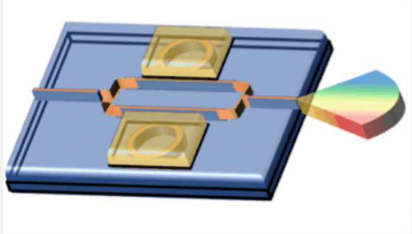
- High spectral purity semiconductor laser
- Self-injection locked via Rayleigh scattering from high-Q monolithic MgF_2 WGM microcavity



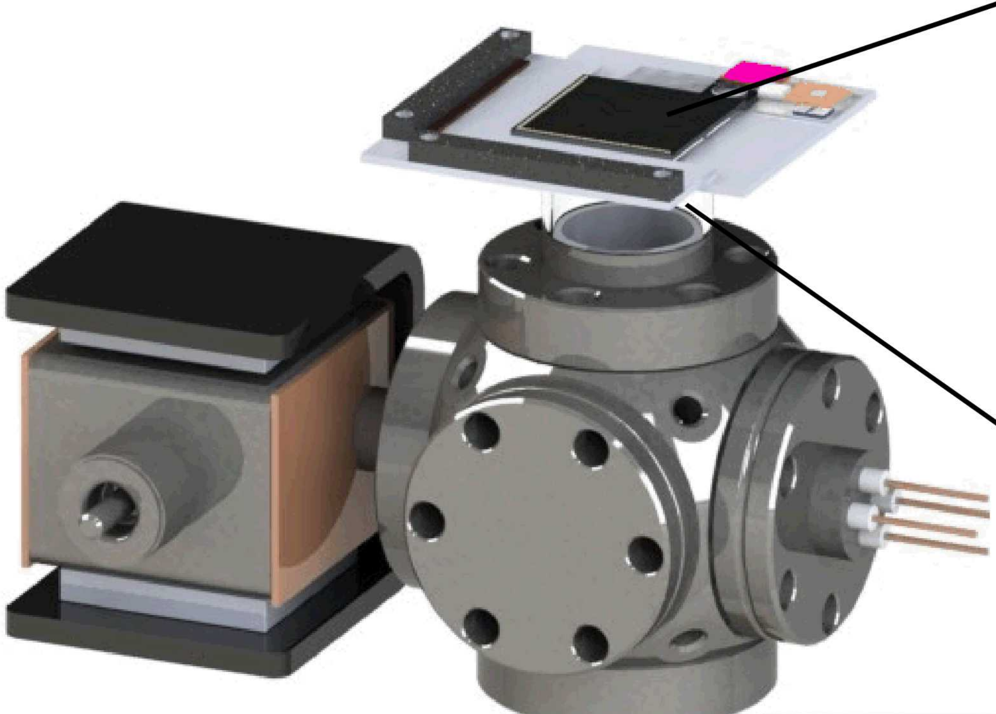
- High efficiency doubler converts 871 nm LO to 435.5 nm to interrogate $^{171}Yb^+$ clock transition. 500%/W

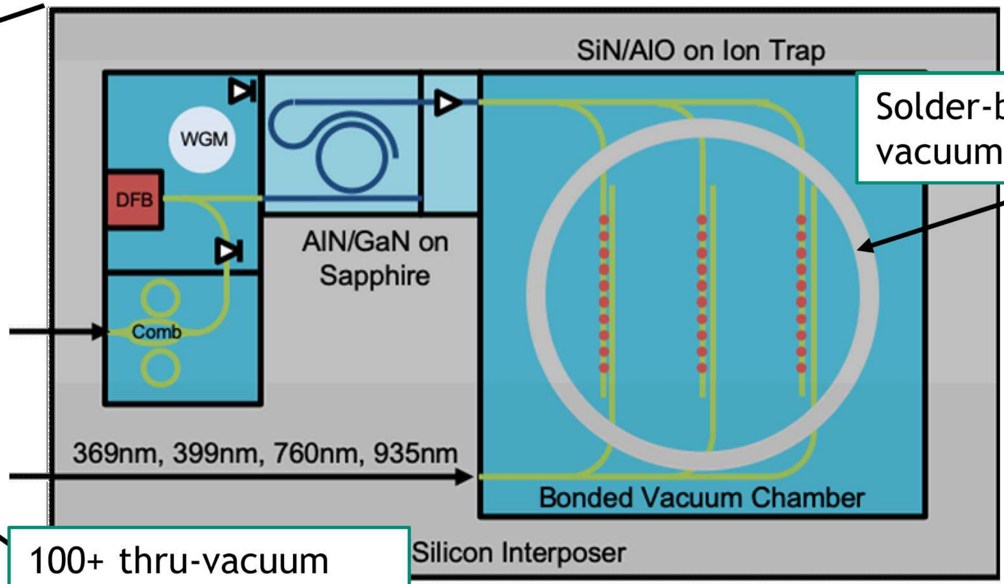


- Micro frequency comb transfer optical frequency to microwave domain
- Large FSR Dual Kerr combs with single pump laser



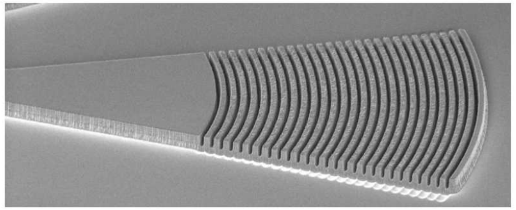
Technical approach





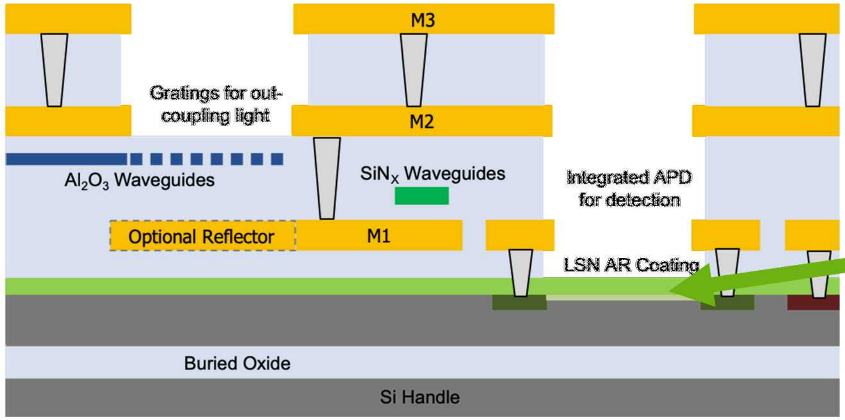
Solder-bonding vacuum cell

100+ thru-vacuum electrical and optical I/O delivered via PIC

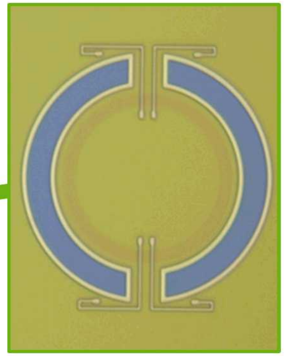


Light delivery with waveguides and grating couplers

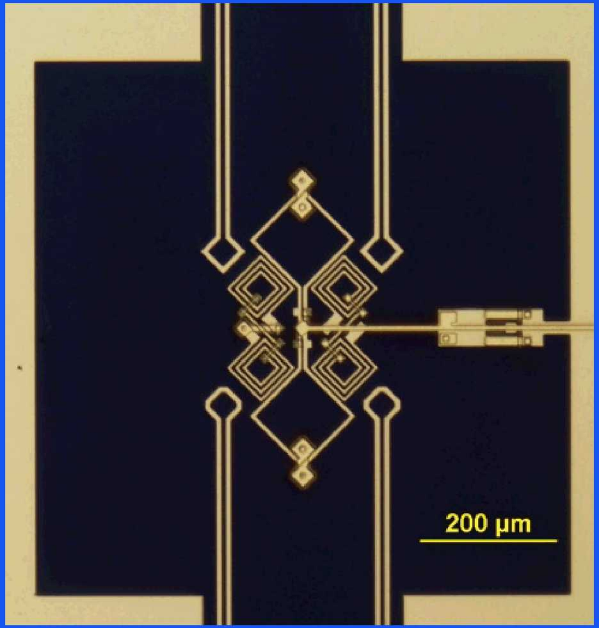
Cross section of Ion trap



Detection with avalanche photodiodes



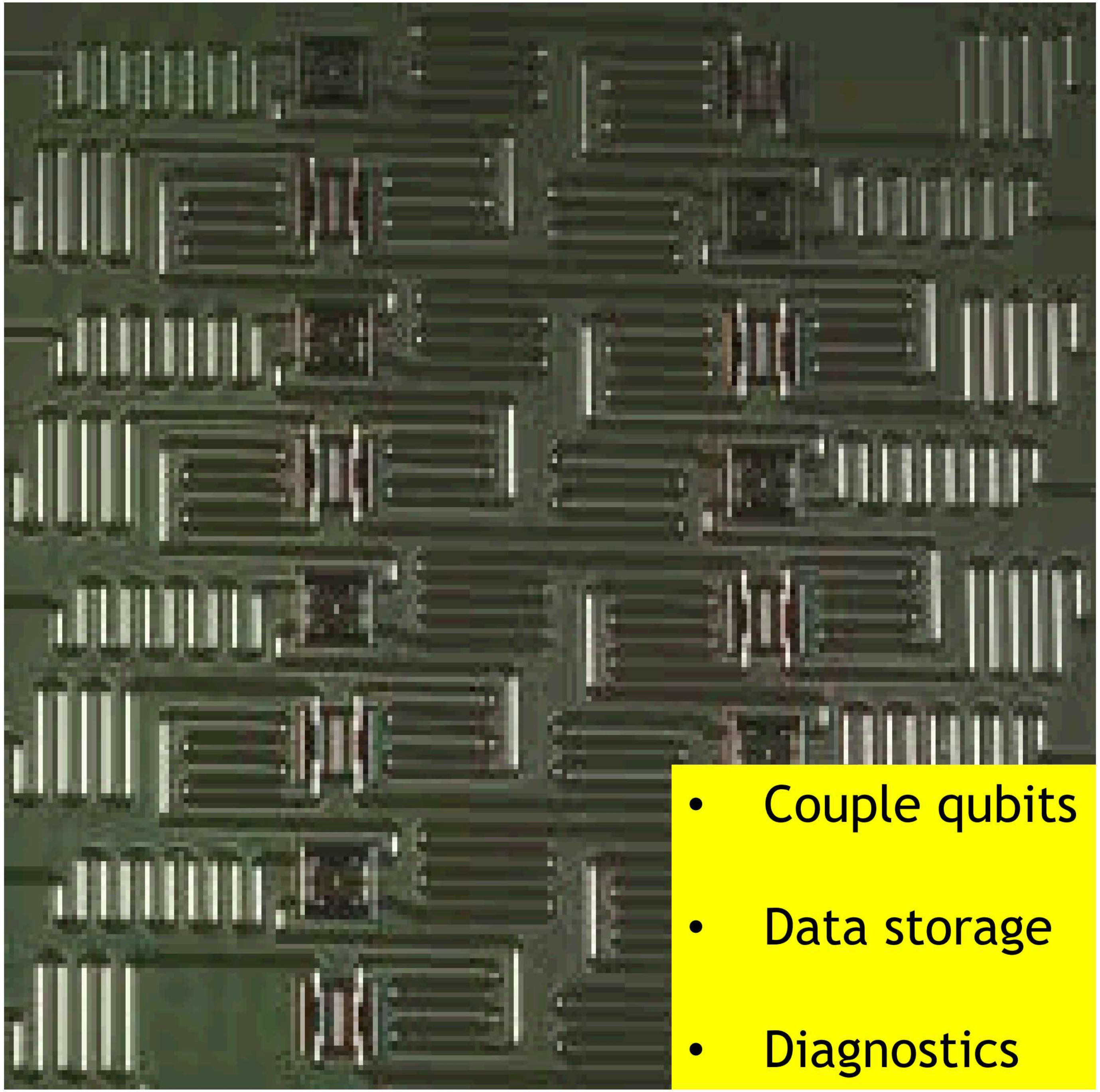
superconductors



Forest Stearns

Superconductors

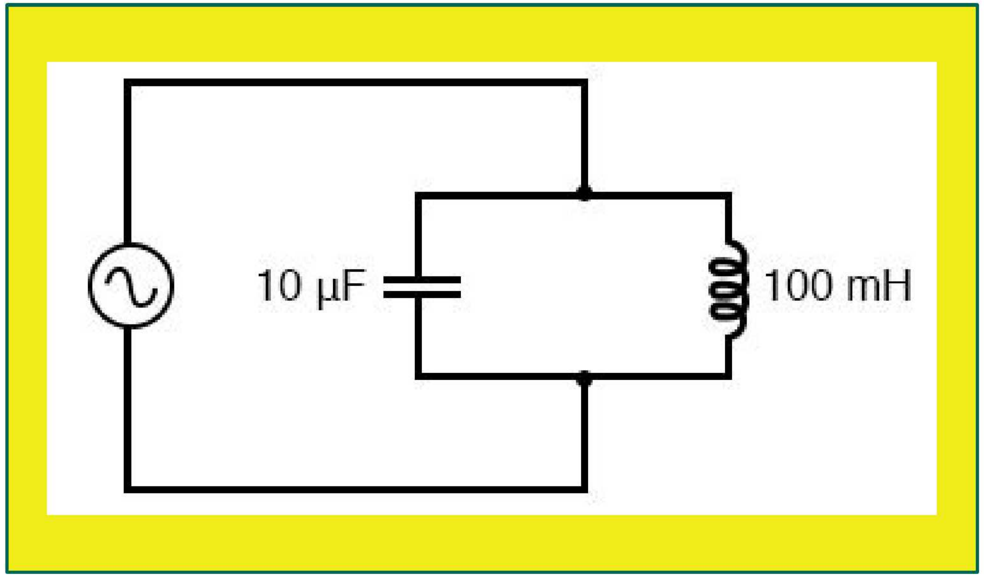
- Resonators & Qubits
- What can go wrong
- Testers/Diagnostics
- Notes and Conclusions

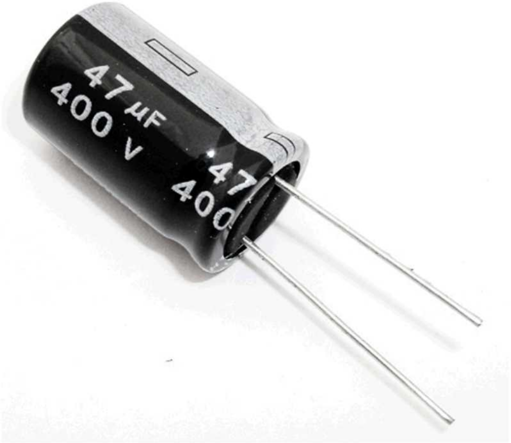


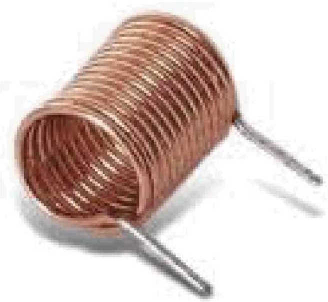
- Couple qubits
- Data storage
- Diagnostics

IBM’s 16 qubit chip

Question: What is a superconducting qubit?







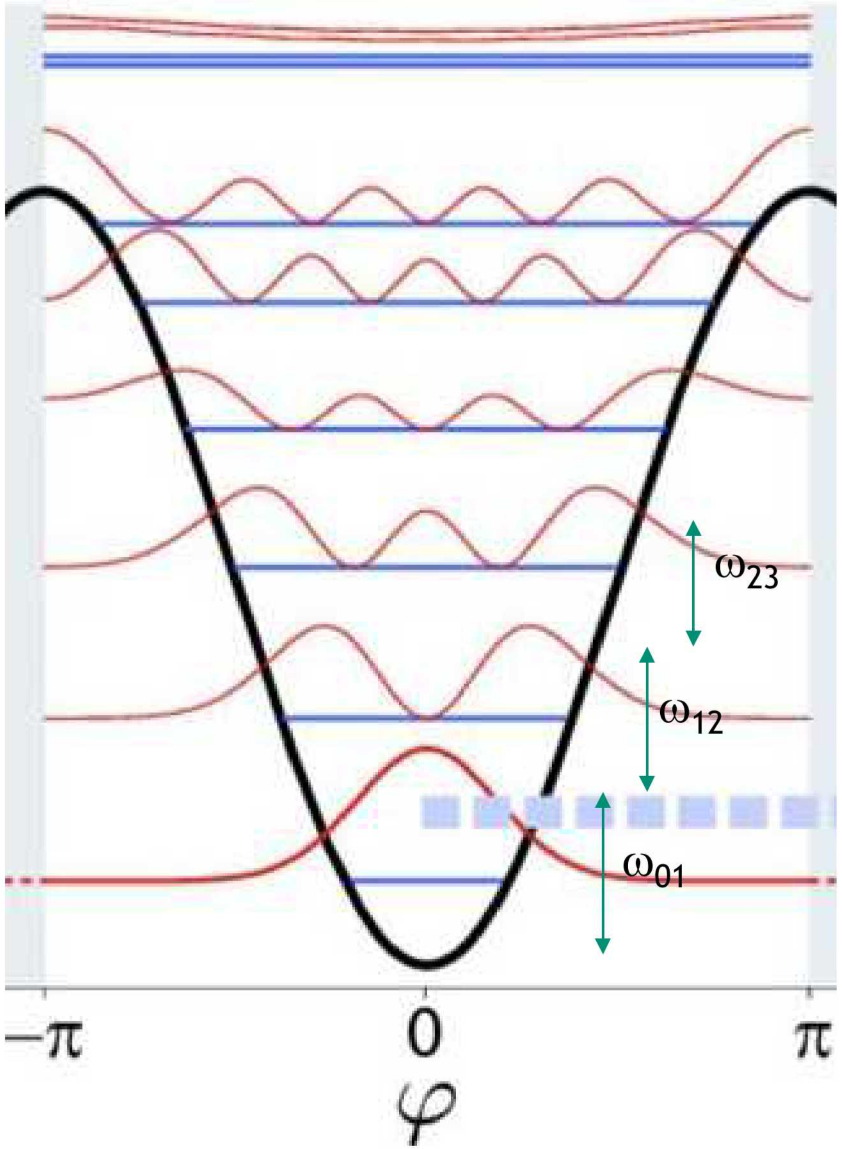
$$\omega_{01} = {}^{1}\!/_{\sqrt{LC}}$$

But Q $>10^6$

1 Photon

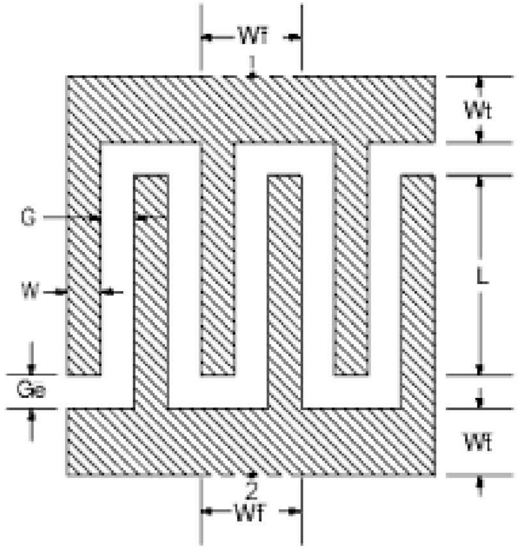
Answer: Non-linear superconducting resonator

Superconducting qubits require nonlinearity

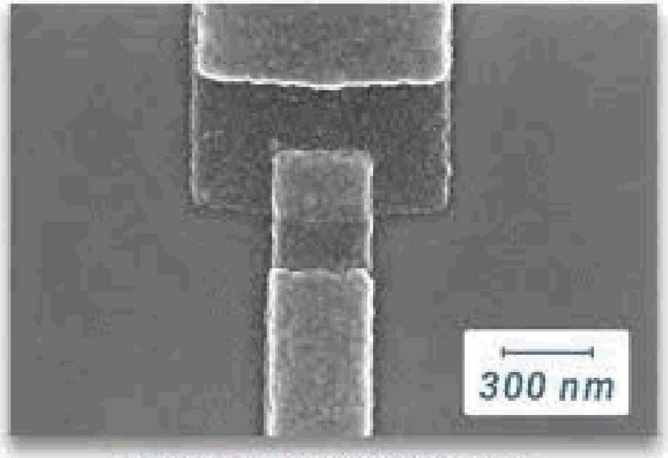


$$\omega_{01} \neq \omega_{12} \neq \omega_{23}$$

IDC



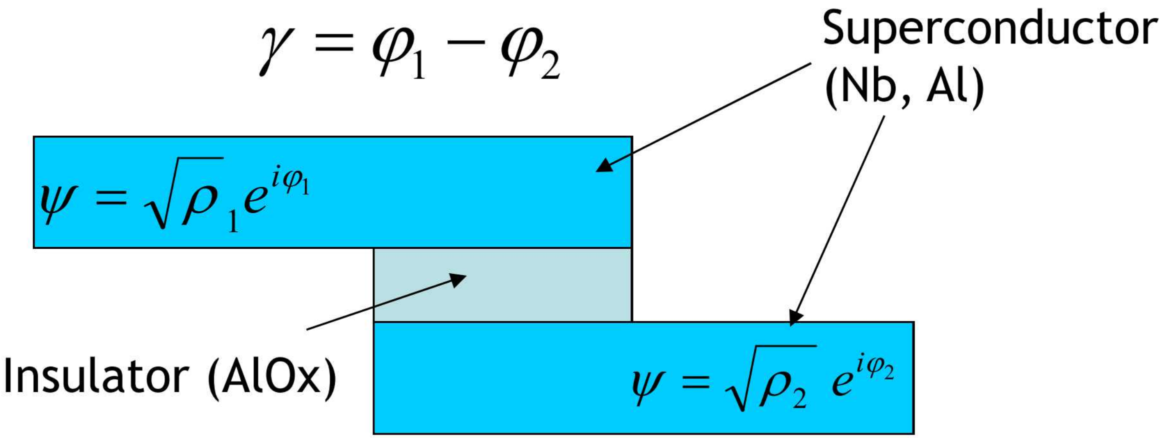
Josephson Junction



SEM image courtesy of the Institute for Quantum Computing (IQC) at the University of Waterloo

Josephson Junctions Provide Nonlinearity for Qubits

$$\gamma = \varphi_1 - \varphi_2$$

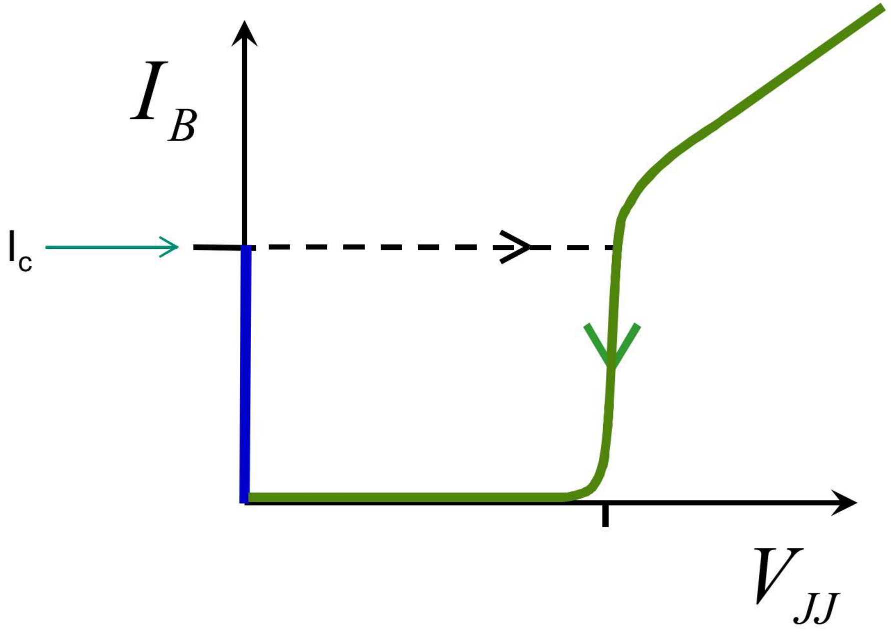


Superconductor (Nb, Al)

Insulator (AlOx)

$$\psi = \sqrt{\rho}_1 e^{i\varphi_1}$$

$$\psi = \sqrt{\rho_2}\ e^{i\varphi_2}$$



<u>Josephson equations:</u>

$$I = I_c \sin\gamma$$

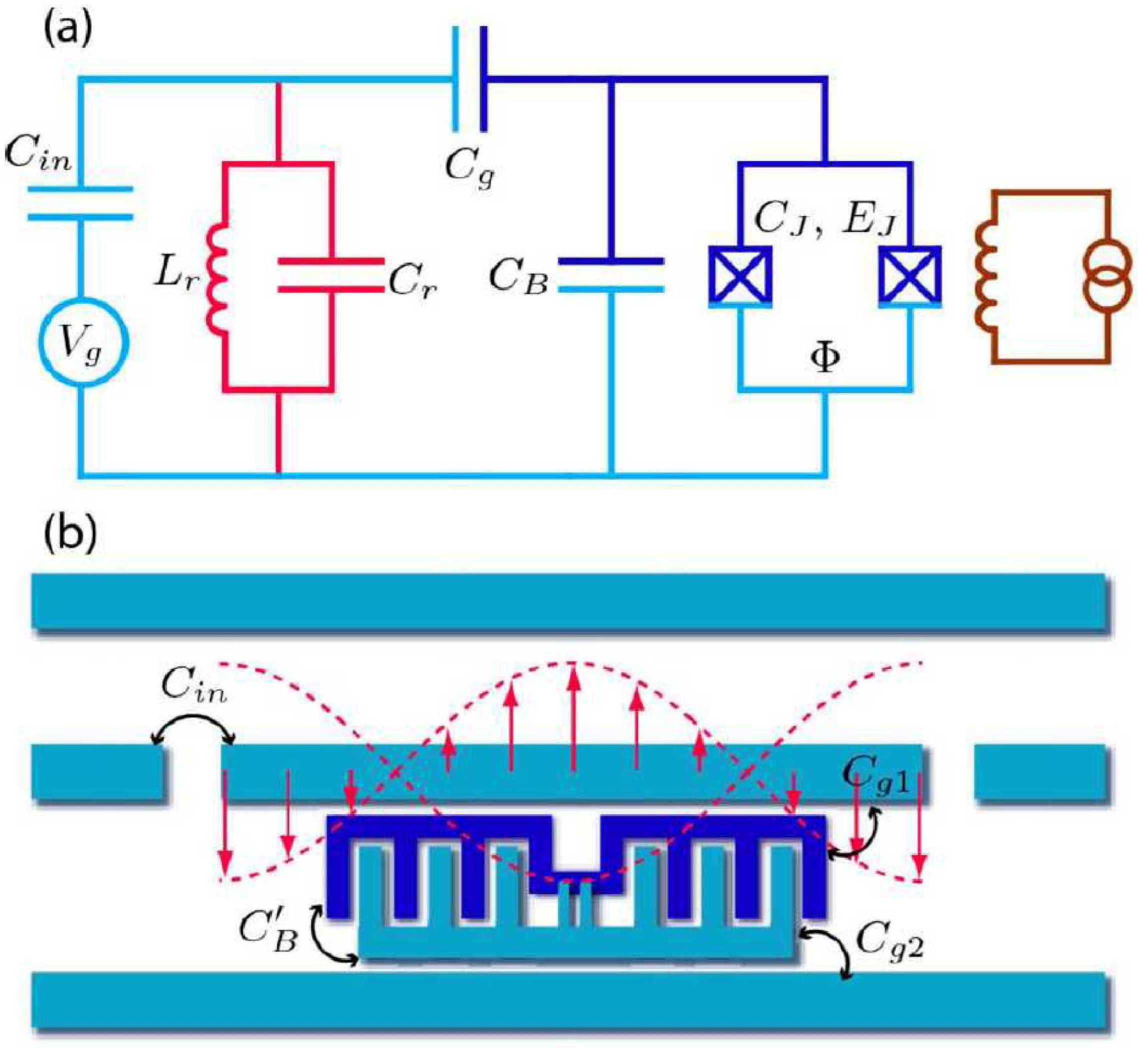
$$V = \frac{\Phi_0}{2\pi}\frac{d\gamma}{dt}$$

$$\gamma = \varphi_1 - \varphi_2$$

$$C_j = \frac{\varepsilon A}{d}$$

$$L_j = \frac{\Phi_0}{2\pi\, I_c}\frac{1}{\sqrt{1-\left(\frac{I_b}{I_c}\right)^2}}$$

Overview of transmonic qubit



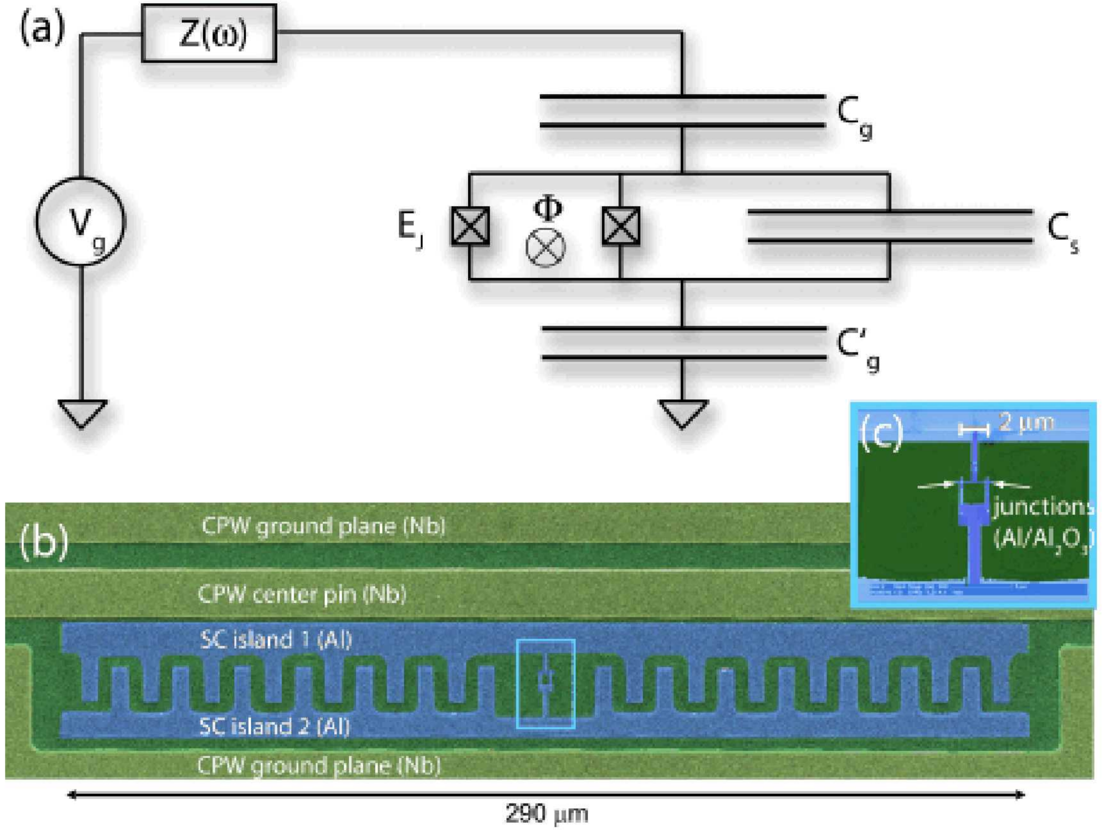
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}.$$

Jaynes-Cummings Hamiltonian

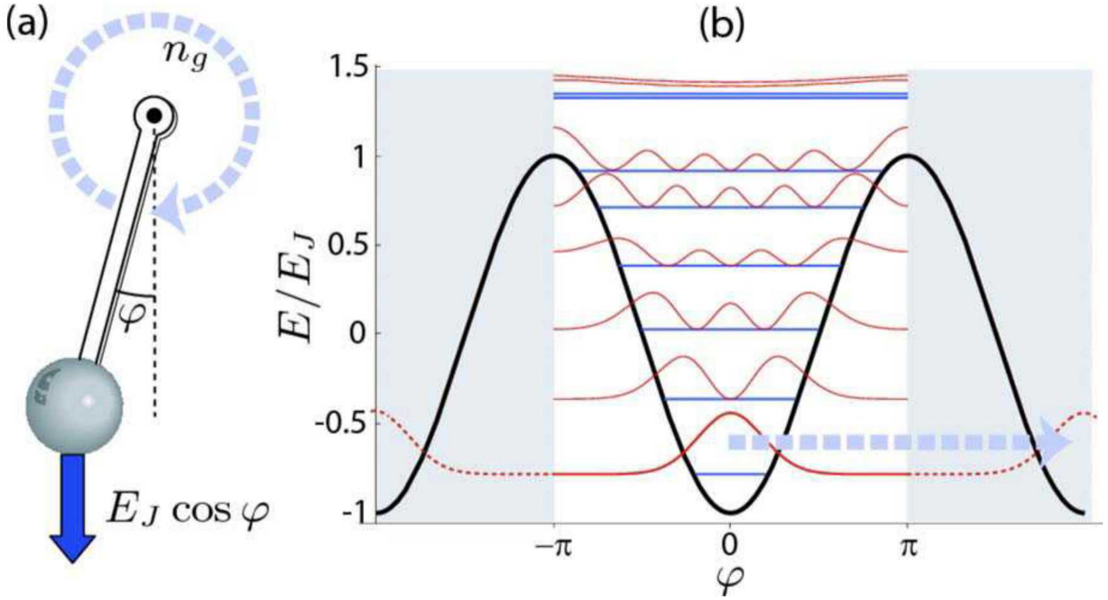
$$\mathcal{H} = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma_z - \hbar g \left(a^\dagger \sigma^- + a\sigma^+\right)$$

J. Koch *et al.*, PRA, 76, 042319 (2007)

One view of a transmon

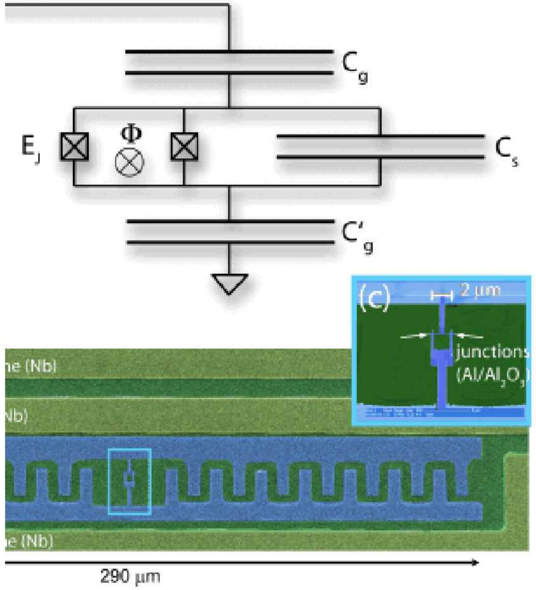


A. Hauck *et al.,* Quant. Inf. Proc. 8, 105 (2009)

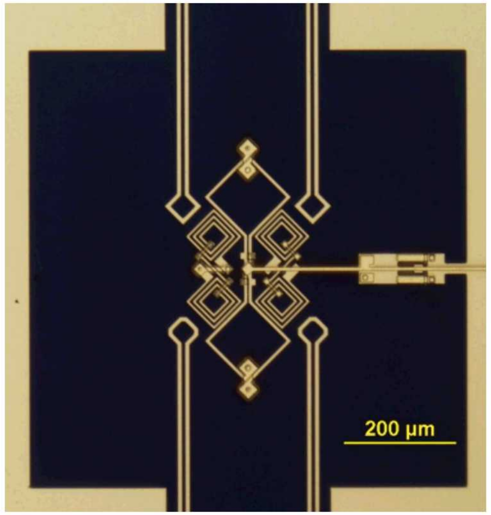


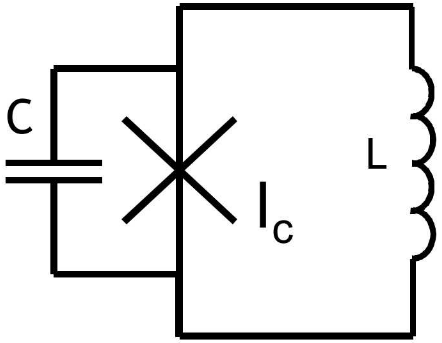
J. Koch *et al.*, PRA, 76, 042319 (2007)

Quick overview of other types of qubits

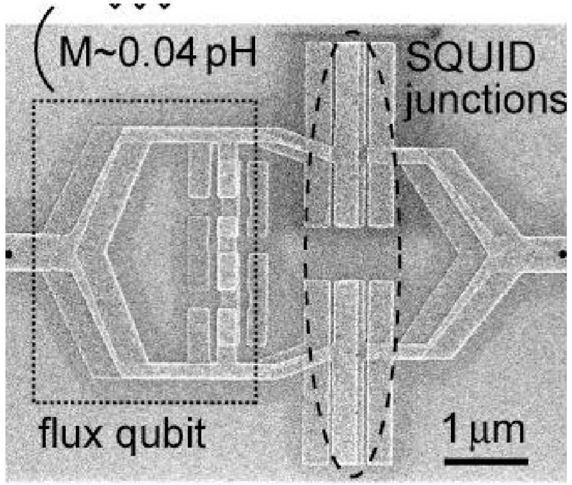


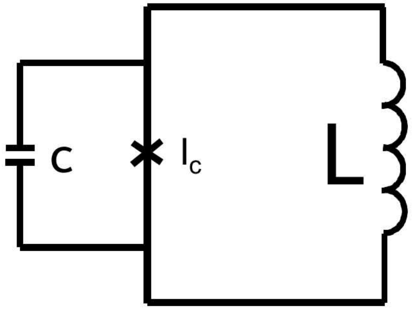
Phase qubit



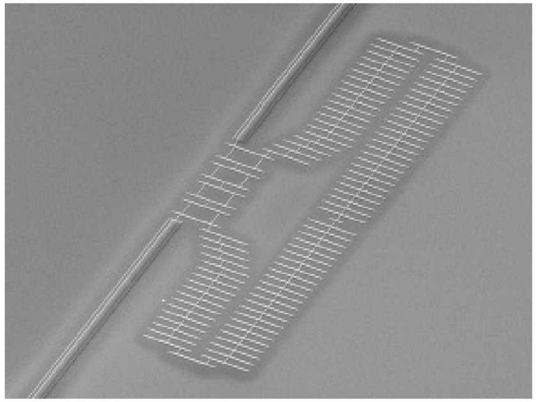


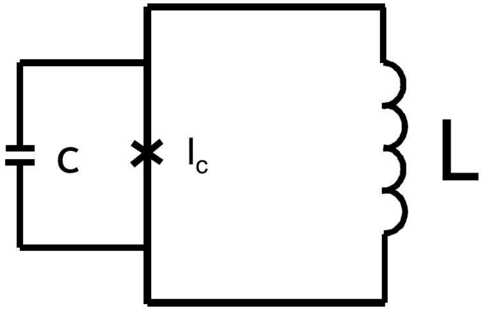
Flux qubit





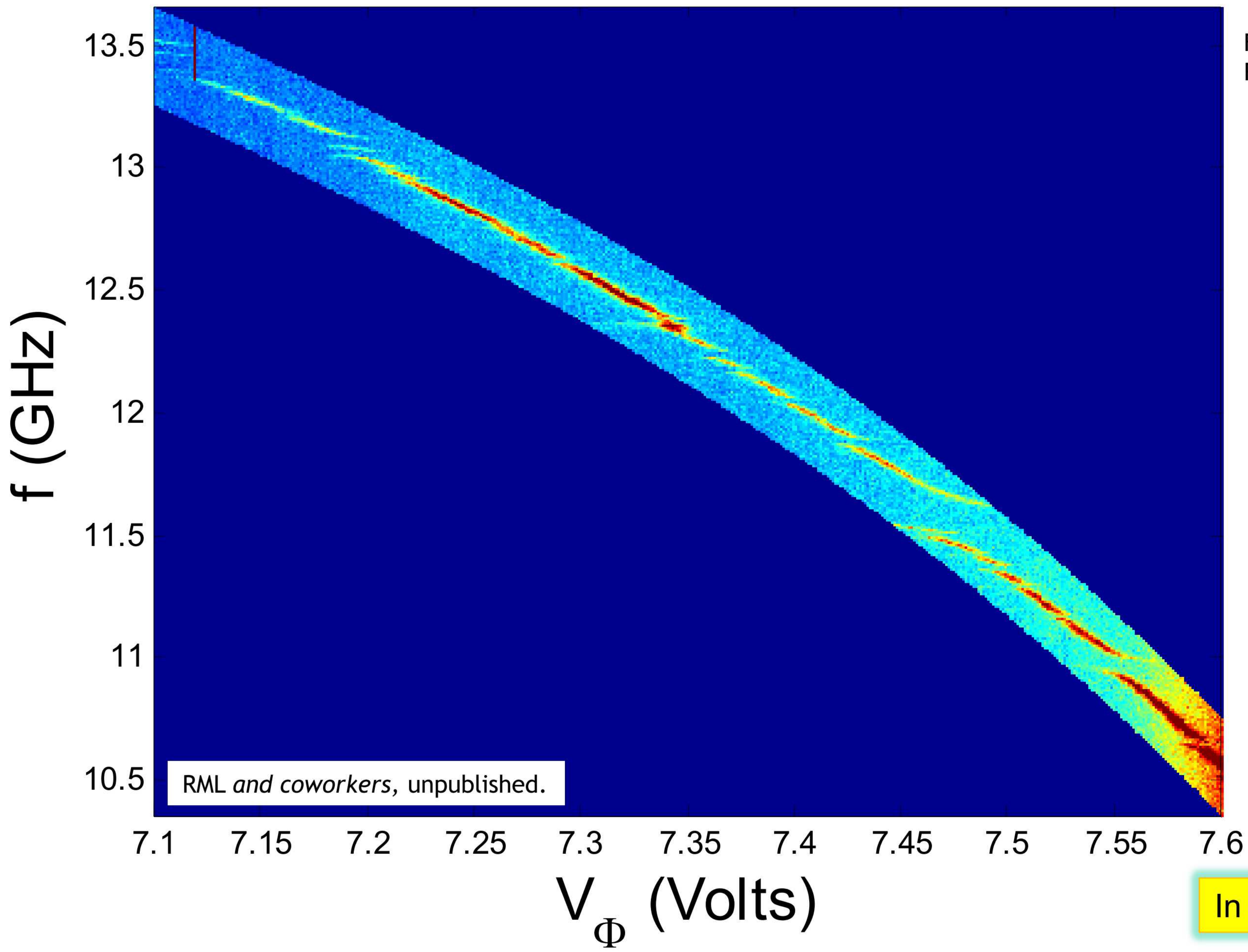
Fluxonium
Yale group





All have inductance and capacitance… & hence rf losses.

Problem: two-level fluctuators in oxides & on surfaces



RML *and coworkers*, unpublished.

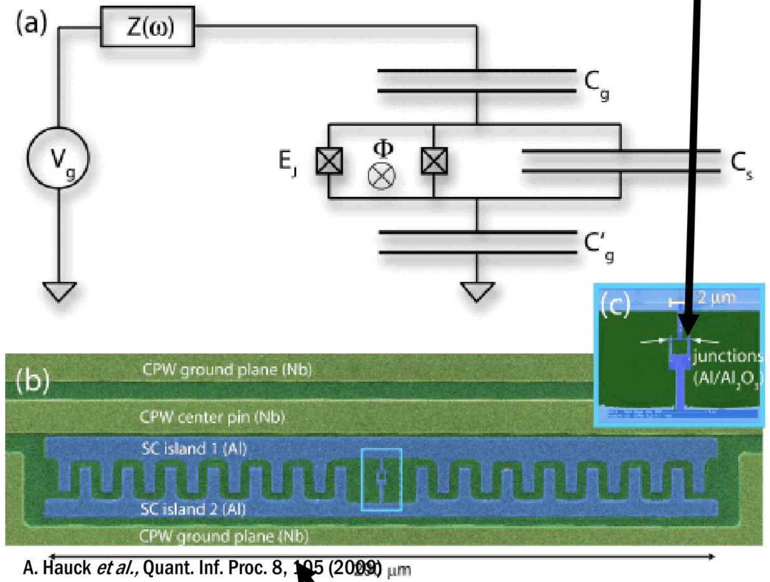
First reported by:
R.W. Simmonds *et al*. Phys. Rev. Lett. **93**, 077003 (2004).

In general: ~0.7 TLS/GHz μm^2

What are the paths to decoherence

- Defects in SC
- Interface dirt
- Environment
- Trapped flux
- also, stray light

Josephson junctions

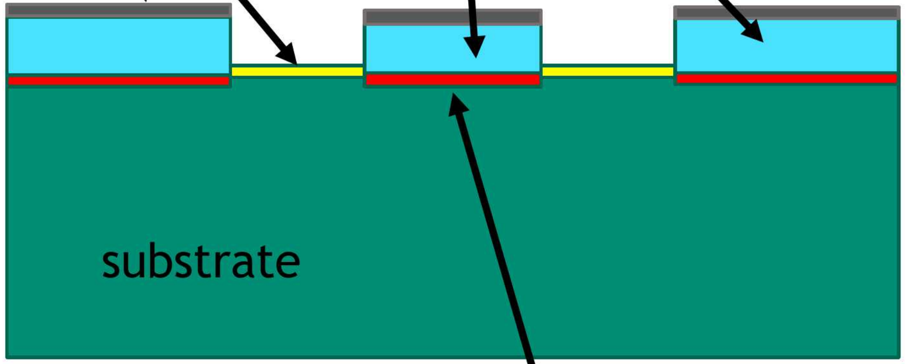


A. Hauck *et al.*, Quant. Inf. Proc. 8, 105 (2009)

Interdigital capacitor

Aluminum film

Surface oxides

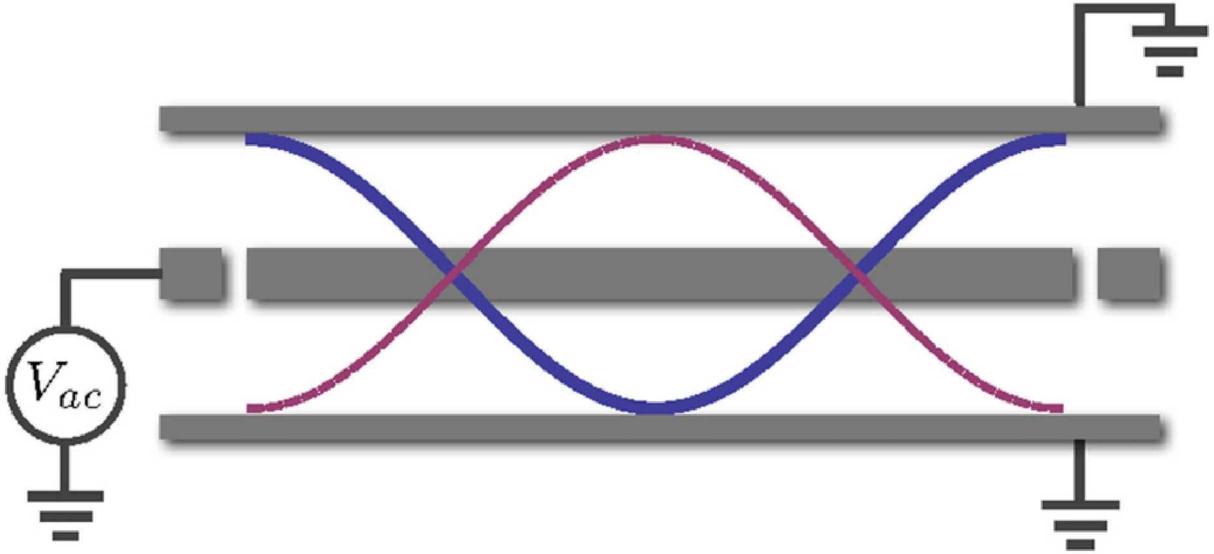


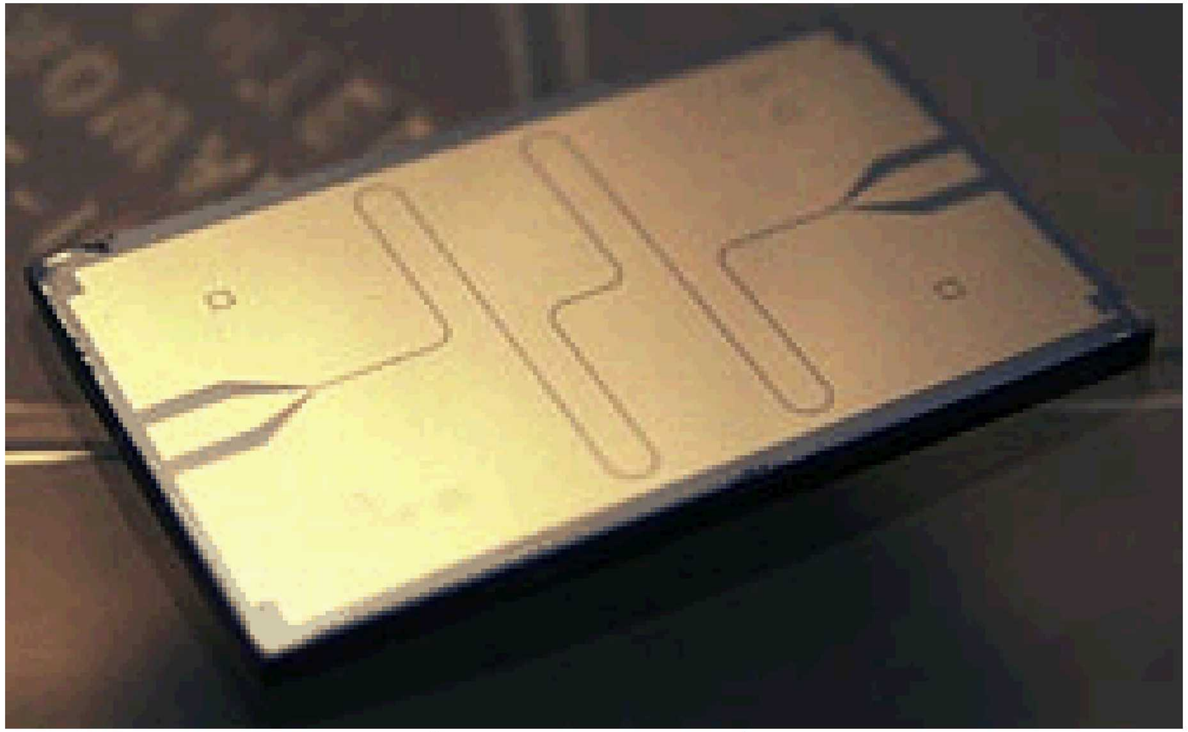
Dirt at interfaces

Hence qubit fab is:

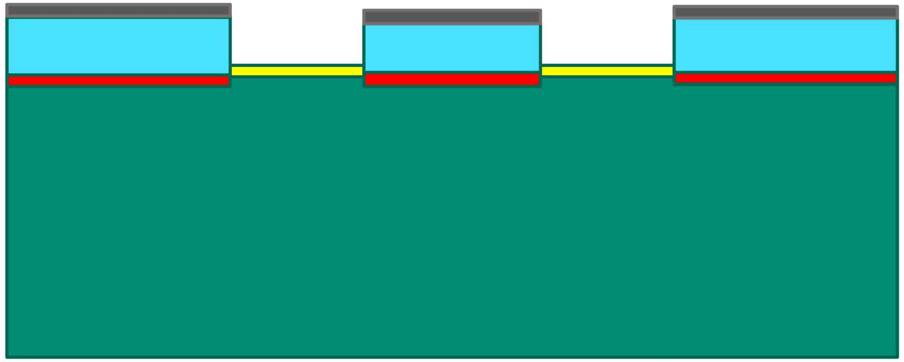
Single layer of metal + stitching
On low loss substrates
No interlayer dielectrics!

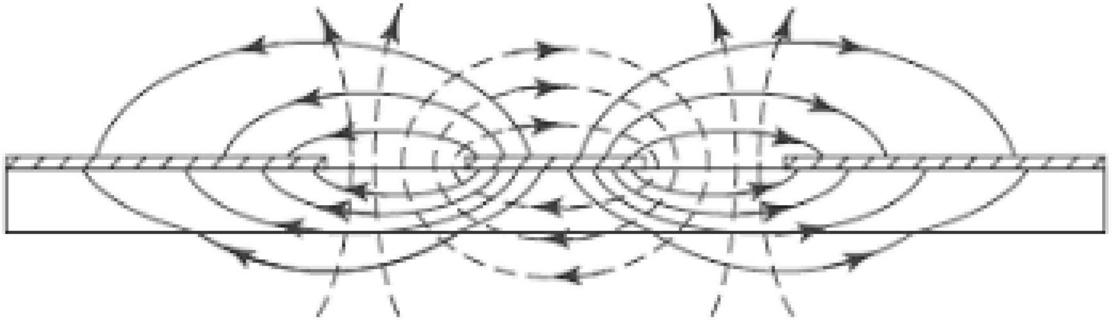
Superconducting Resonators have many of the same features as qubits





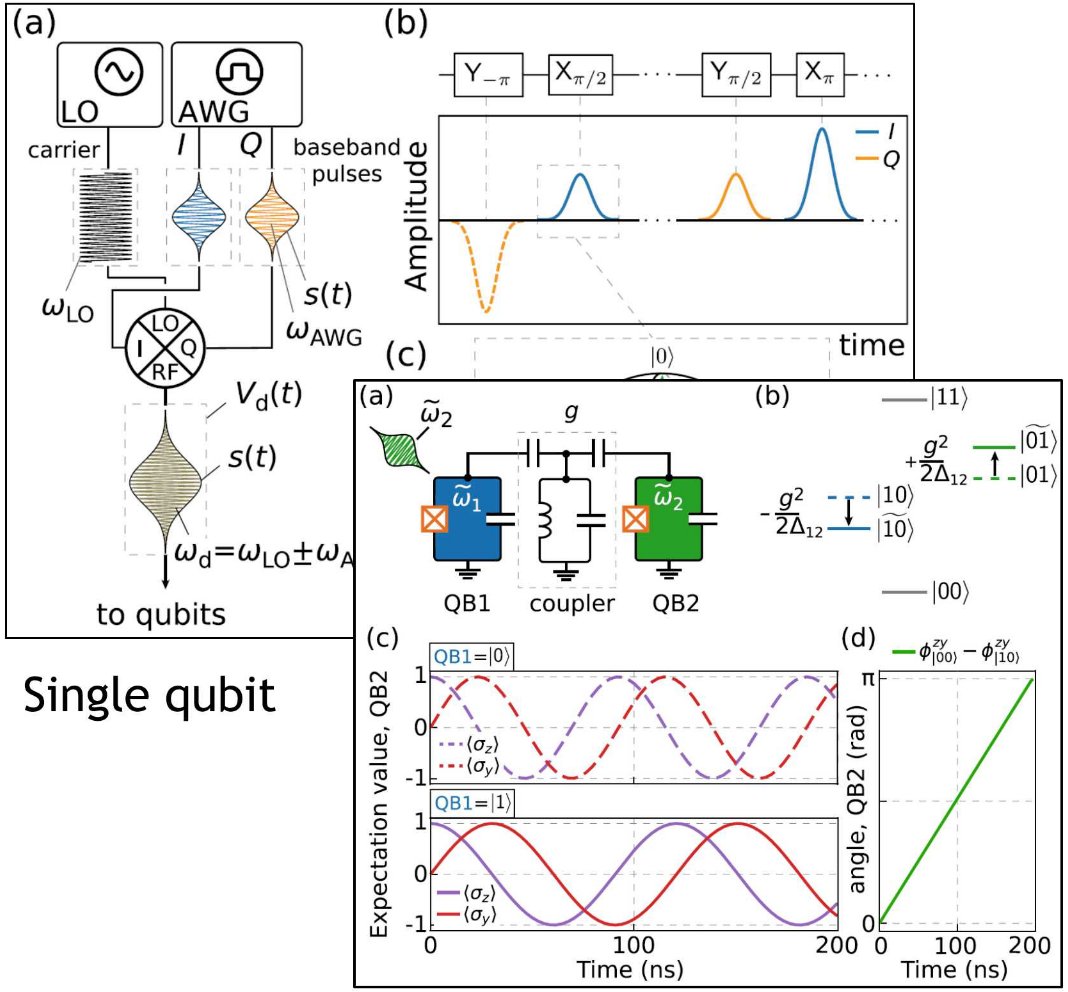
cross-section view





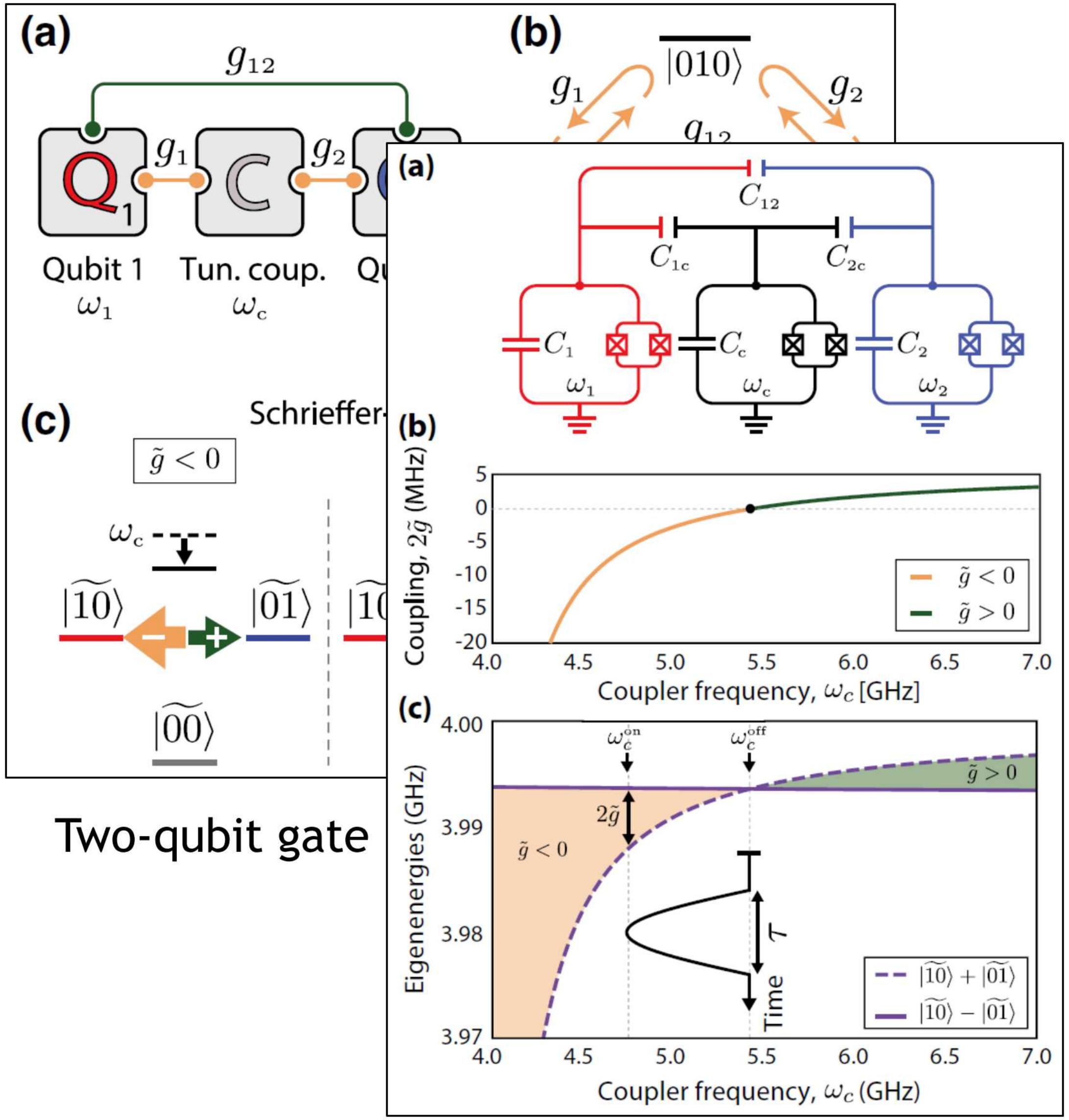
But simpler to measure

Superconducting gates



Single qubit

Two-qubit gate

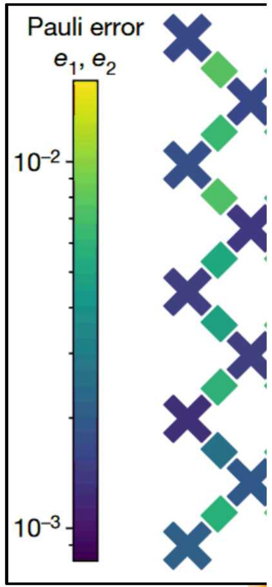


Two-qubit gate

P. Krantz *et al.*, Appl. Phys. Rev. **6**, 021318 (2019);

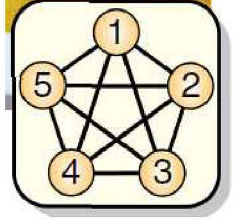
F. Yan *et al.*, Phys. Rev. Applied, **10**, 054062 (2018)

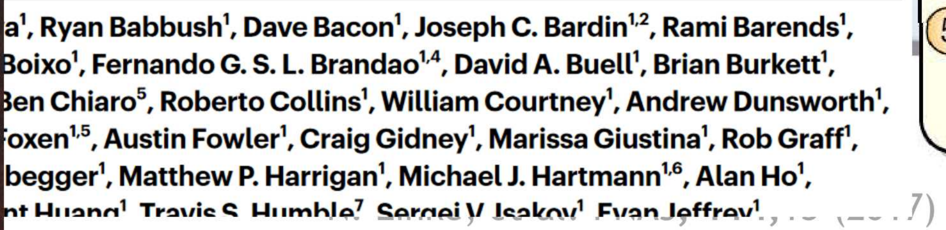
Google's Quantum Supremacy



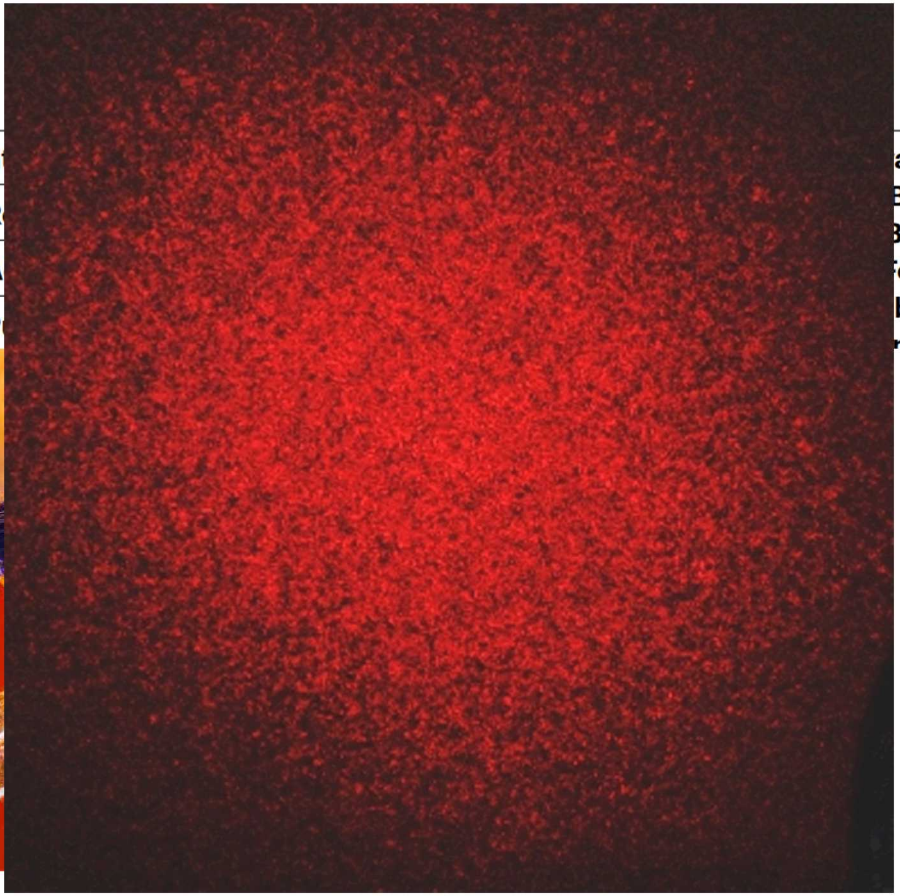
Article

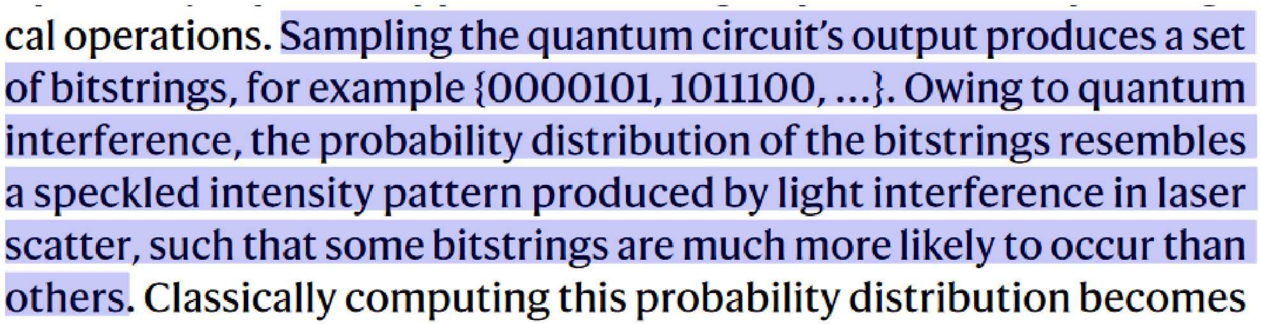
Quantum supremacy using a programmable superconducting processor





a[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1],
Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1],
Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1],
Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1],
begger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1],
nt Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1],





cal operations. Sampling the quantum circuit's output produces a set of bitstrings, for example {0000101, 1011100, …}. Owing to quantum interference, the probability distribution of the bitstrings resembles a speckled intensity pattern produced by light interference in laser scatter, such that some bitstrings are much more likely to occur than others. Classically computing this probability distribution becomes

F. Arute *et al.*, Nature, **574**, 24 (2019)

Google's random circuit in more detail

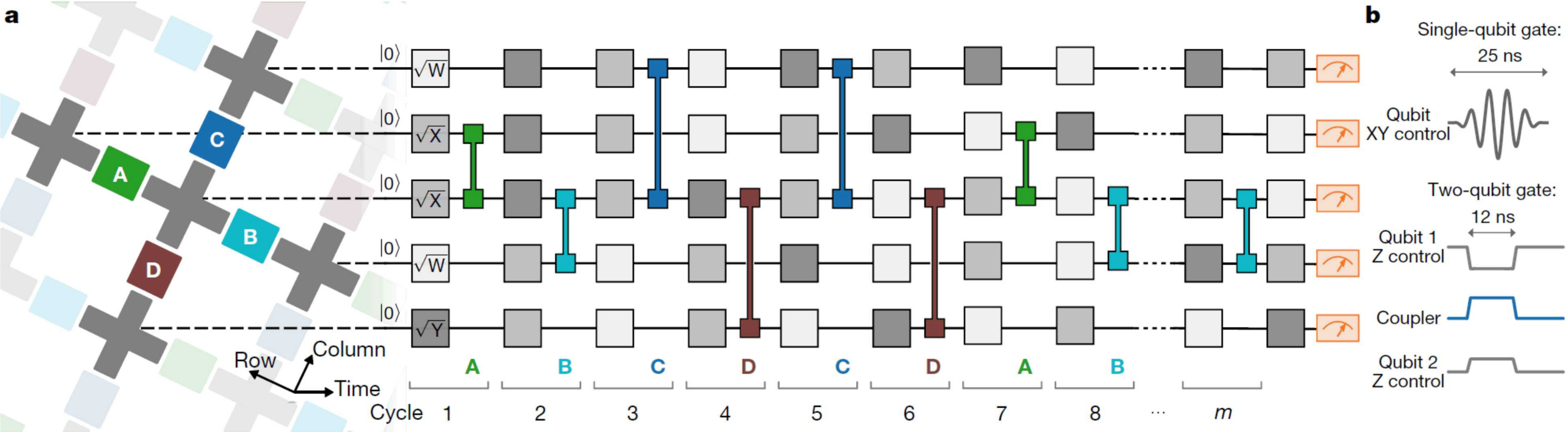
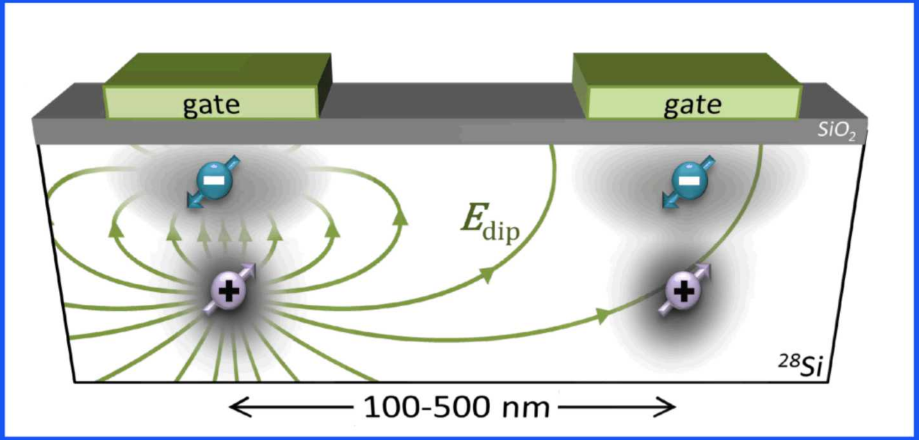
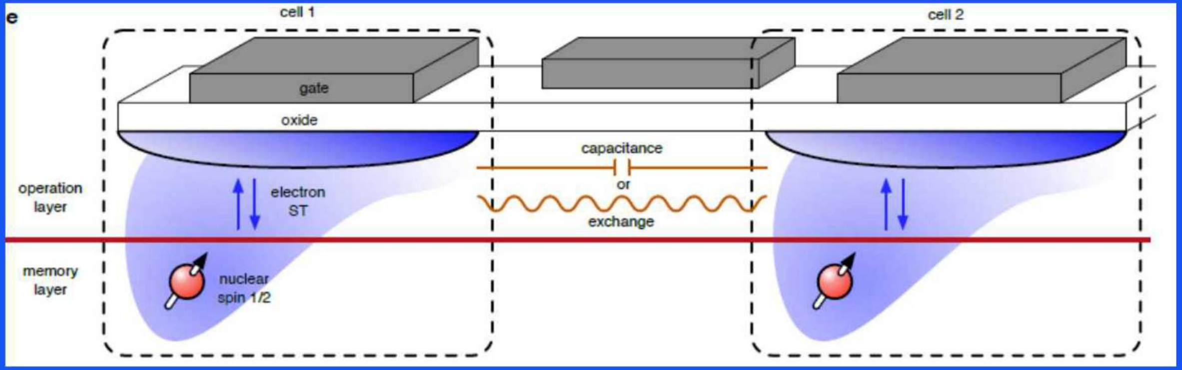


Fig. 3 | Control operations for the quantum supremacy circuits. a, Example quantum circuit instance used in our experiment. Every cycle includes a layer each of single- and two-qubit gates. The single-qubit gates are chosen randomly from $\{\sqrt{X}, \sqrt{Y}, \sqrt{W}\}$, where $W = (X + Y)/\sqrt{2}$ and gates do not repeat sequentially. The sequence of two-qubit gates is chosen according to a tiling pattern, coupling each qubit sequentially to its four nearest-neighbour qubits. The couplers are divided into four subsets (ABCD), each of which is executed simultaneously across the entire array corresponding to shaded colours. Here we show an intractable sequence (repeat ABCDCDAB); we also use different coupler subsets along with a simplifiable sequence (repeat EFGHEFGH, not shown) that can be simulated on a classical computer. **b**, Waveform of control signals for single- and two-qubit gates.

F. Arute *et al.*, Nature, **574**, 24 (2019)

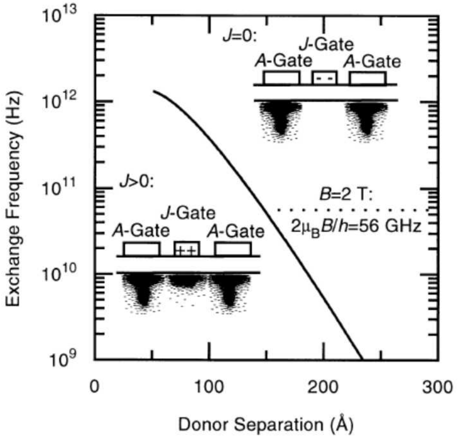
Semiconductors





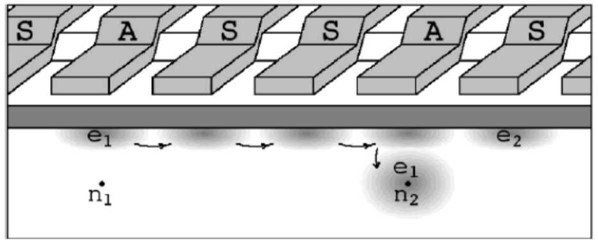
Donor architectures

Exchange btwn QDs



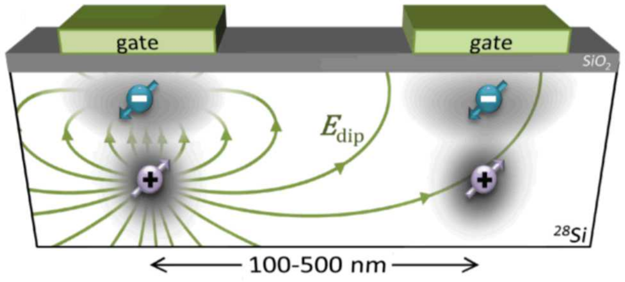
Kane (1998), Vrijen (2000)

Transport along QDs



Skinner & Kane (2003), Hollenberg (2007), Morton (2009), Witzel (2015), Pica (2015)

Dipole coupling



Tosi (2015), Hill (2015)

- Many donor qubit proposals driven by:
  - Nuclear & electron spin decoherence times and fidelities
  - On/off control of a naturally provided bulk potential
  - Temperature robustness

- Grand challenge: engineering deterministic coupling
  - Specialized fab using hydrogen lithography & STM
  - Counted implant
  - Success also achieved with timed implant

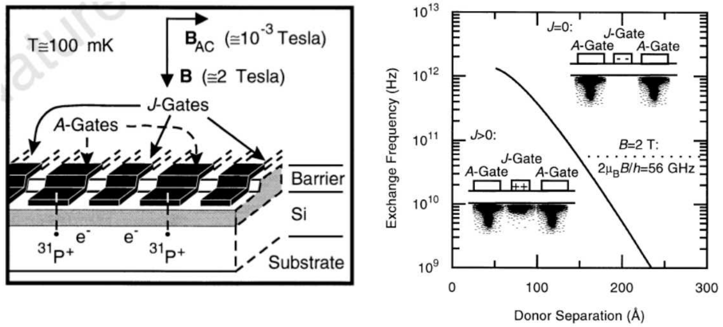
Ionized nuclear spin
CQC2T, Nat. Nano. 2014:
T_2^* = 600 ms
$T_{2,\ \mathrm{CPMG}}$ = 36.5 s
$F_{\mathrm{prep/readout}}$ = 99.995%

J. Phys.: Cond. Matter (2015):
Random benchmarking
F_{gate} = 99.95-99.99%

Donor qubits

- Donor nuclear spin qubits have exceptional fidelities
- Fabricating and controlling single atoms is hard
- Many proposals access donors through surface QDs
- This talk: first coherent coupling of MOS QD with donor qubit

Donor qubit architecture



Kane, Nature, 1998.

?

?

Ionized nuclear spin
CQC2T, Nat. Nano. 2014:
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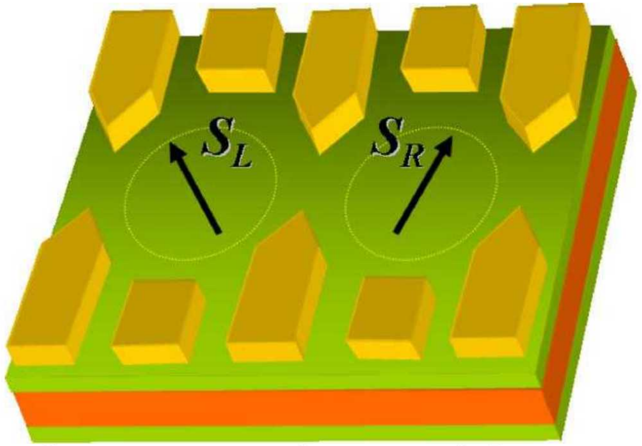
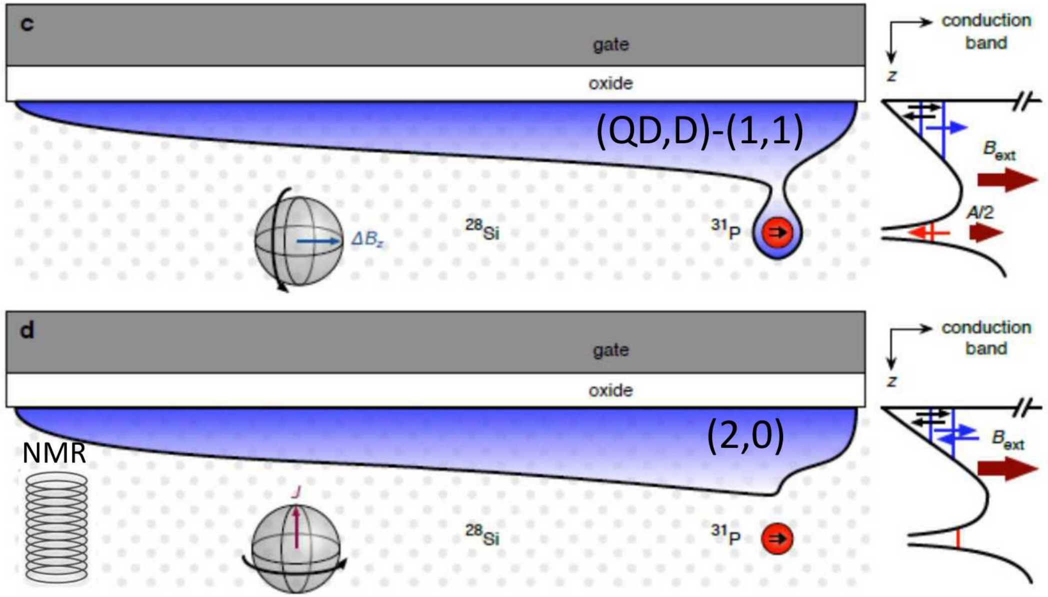


Quantum dot architecture

D. **Loss** and D. P. **DiVincenzo** Phys. Rev. A, 1998.

Notional approach

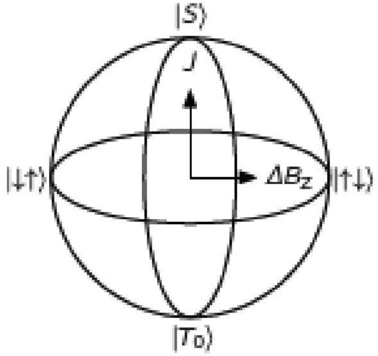


Hamiltonian

$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

$$\downarrow$$

$$\boxed{AI \cdot S}$$

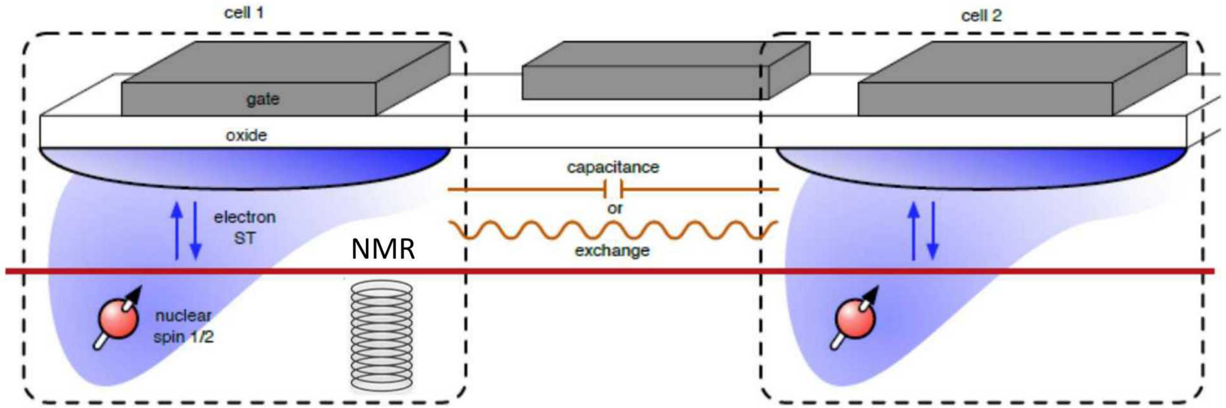


- Treat problem as hybridization of QD and donor qubits
- Voltage tune to resonance – nudge QD to one of many donors
- Encode as two electron singlet-triplet electron qubit
  - Nuclear spin qubit: spectator or 2nd qubit with hyperfine coupling
- Gradient field is supplied by nuclear spin of donor
  - 58 MHz (P) to greater than GHz (Sb or Te) might be possible
- Electrical control through voltage tuned exchange energy
- NMR to drive nuclear spin & several electrical readouts possible

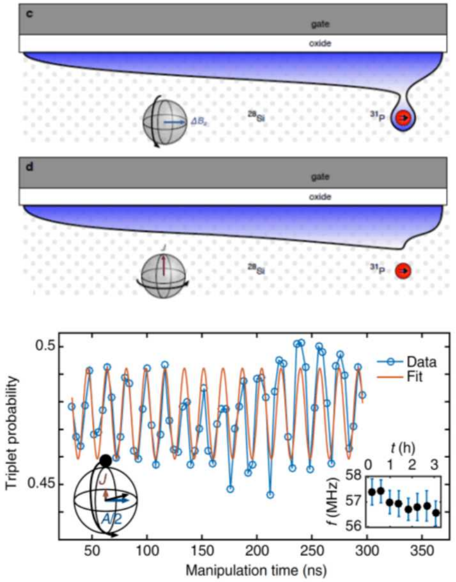
This is also a phase gate on the nuclear spin $\longrightarrow \boxed{AI \cdot S}$

Harvey-Collard Nature Comm. accepted (2015)
Rudolph IEDM & arXiv 1705.05857 (2016)
Harvey-Collard arXiv 1703.02651 (2017)

Realizing the donor qubit device architecture

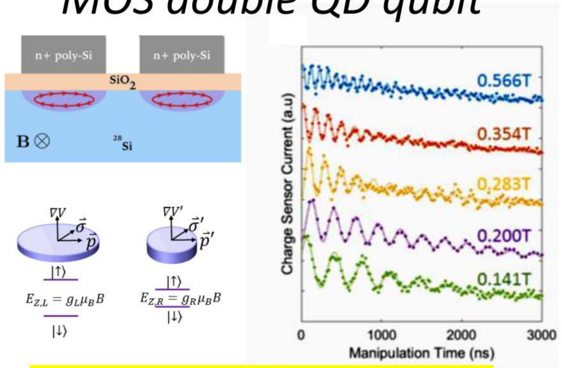


Donor coupling to QD



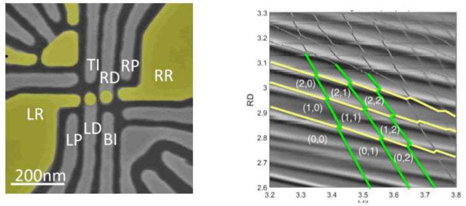
Harvey-Collard Nat. Comm. 2017

MOS double QD qubit

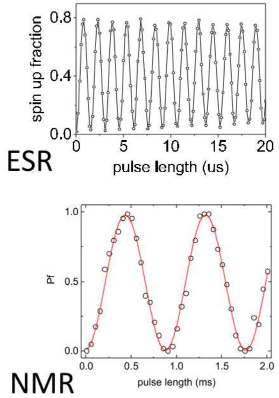


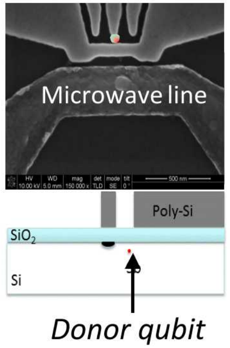
Jock et al, Nat. Comm. 2018

Lithographic double QD



ESR/NMR

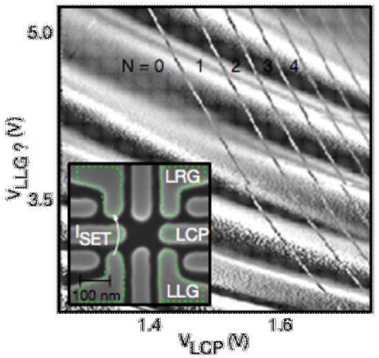




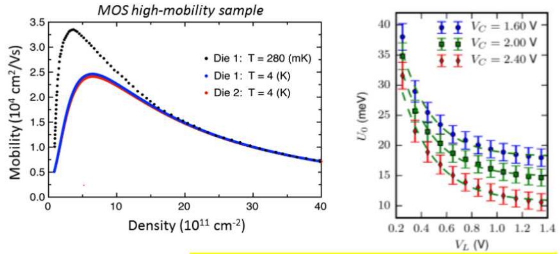
Tracy et al. APL 2016

- Key pieces for realizing this device architecture
- Three Si qubit systems demonstrated

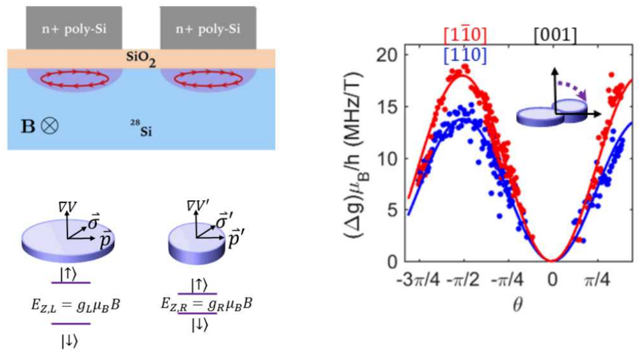
Summary



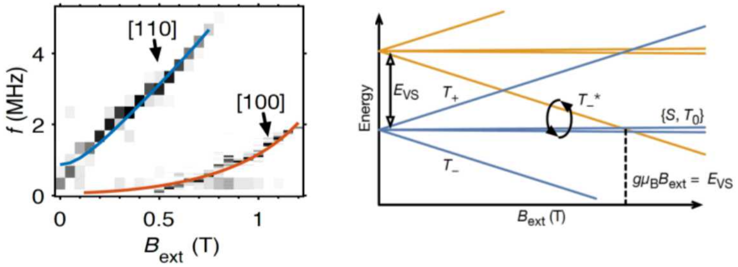
Rudolph et al., IEDM (2016)
Rochette et al., arXiv 1707.03895

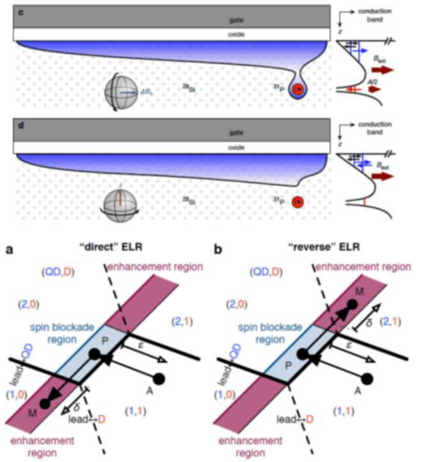


Shirkhorshidian arXiv 1705.01183

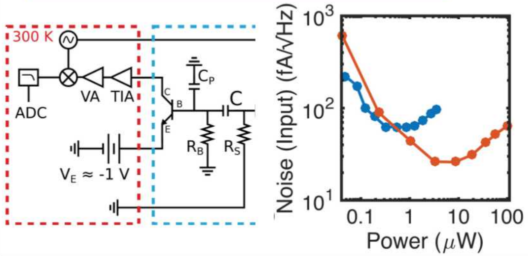


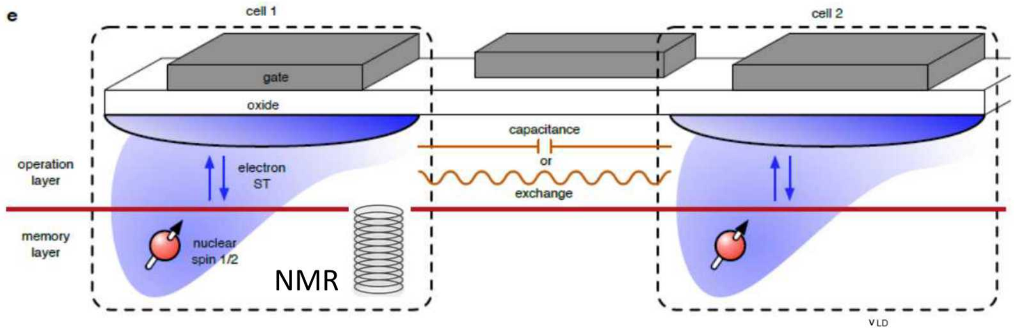
Jock Nat. Comm. 2018

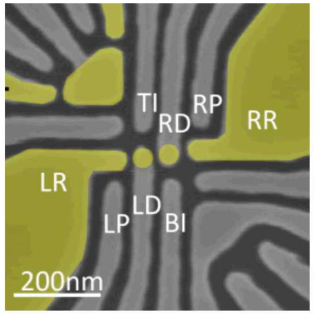


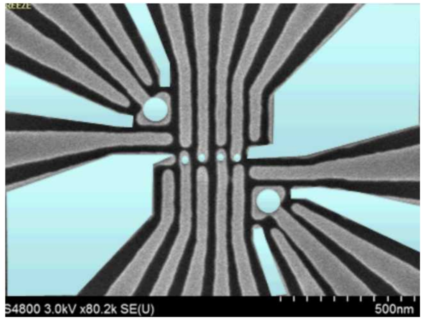


Harvey-Collard PRX 2018





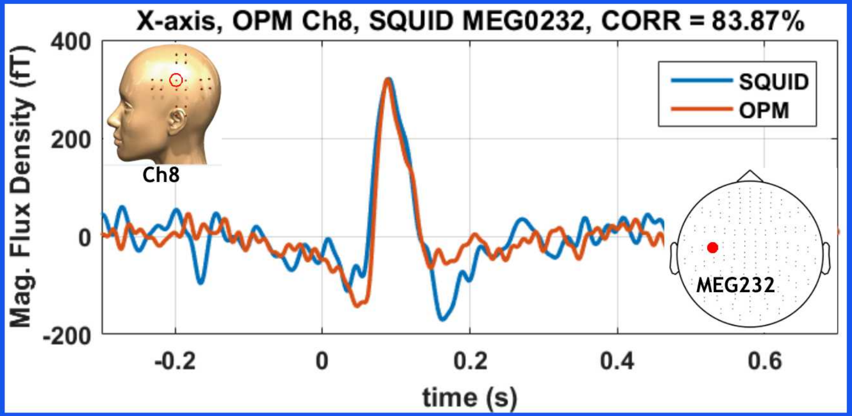




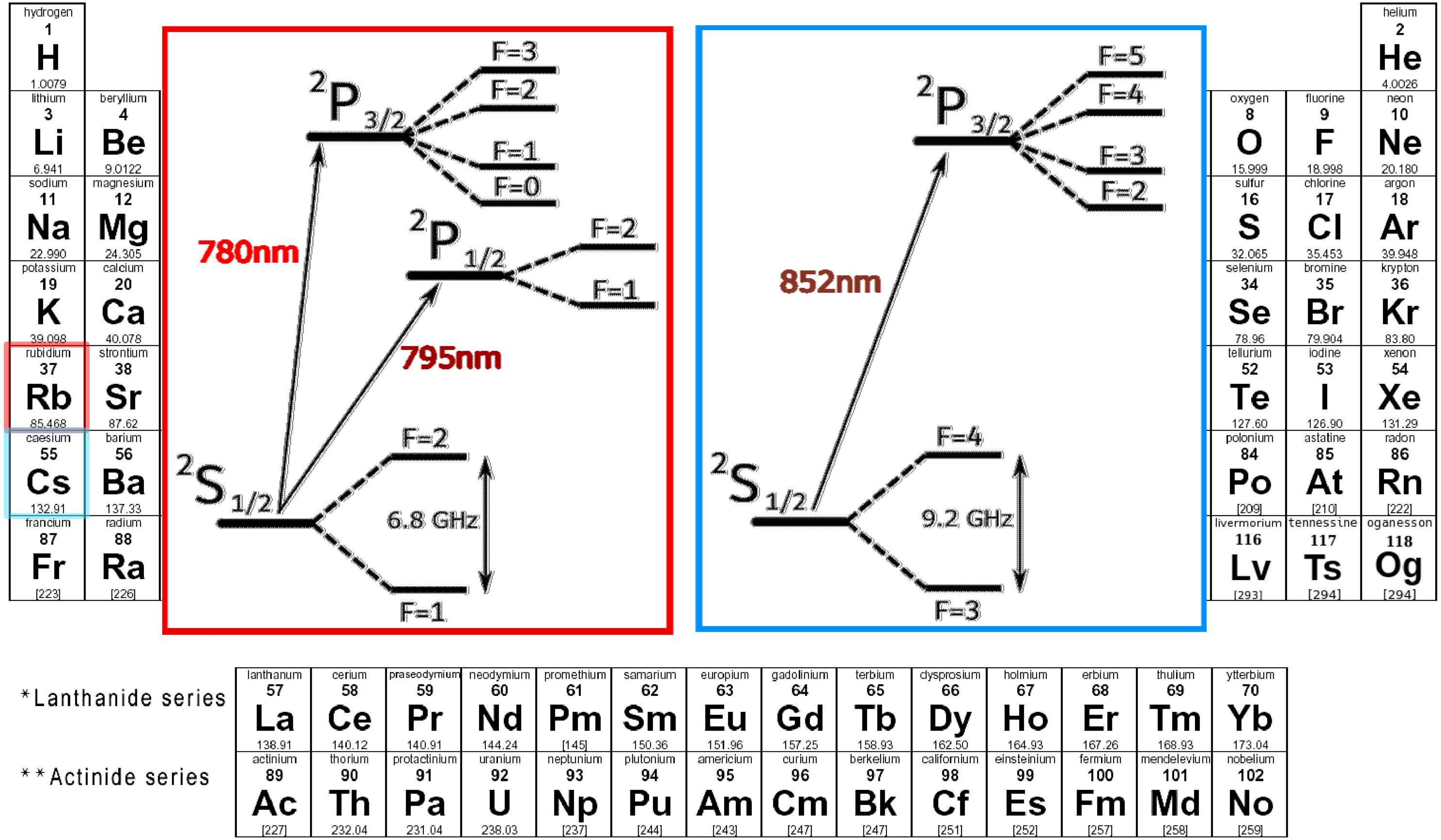
neutrals

ΣΙΓΜΑ

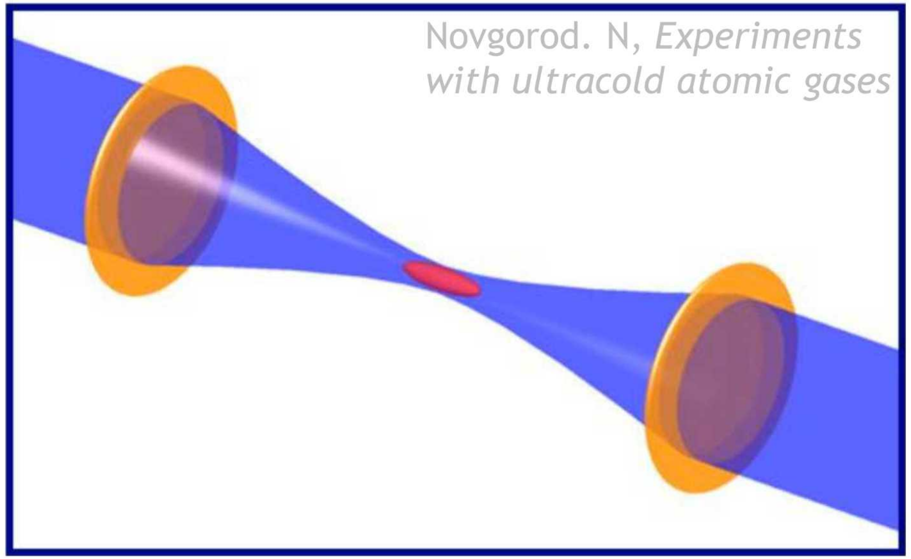
Strategic Inertial Guidance with MAtterwaves



Two neutral atoms: ^{87}Rb and ^{133}Cs

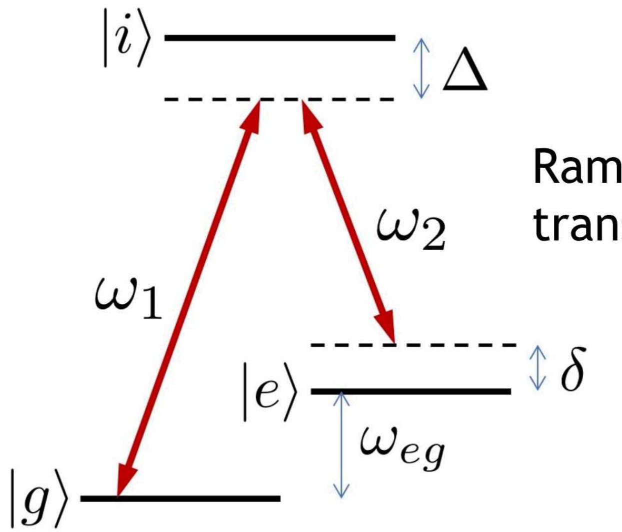


Dipole trap and setup

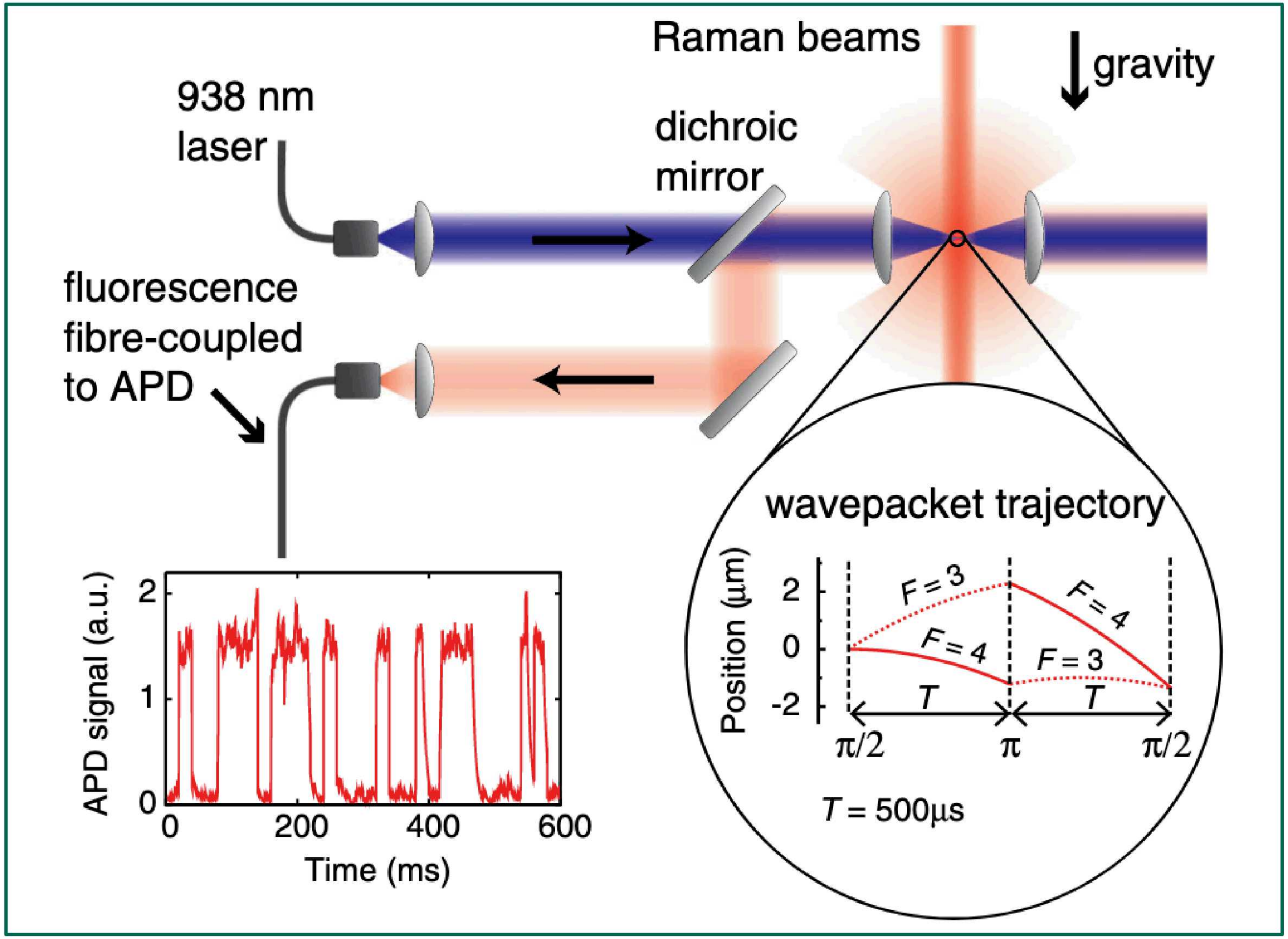


Novgorod. N, *Experiments with ultracold atomic gases*

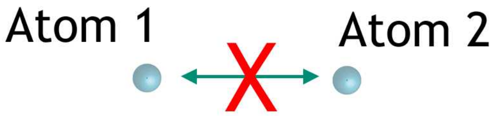
Laser produces conservative force



Raman transition

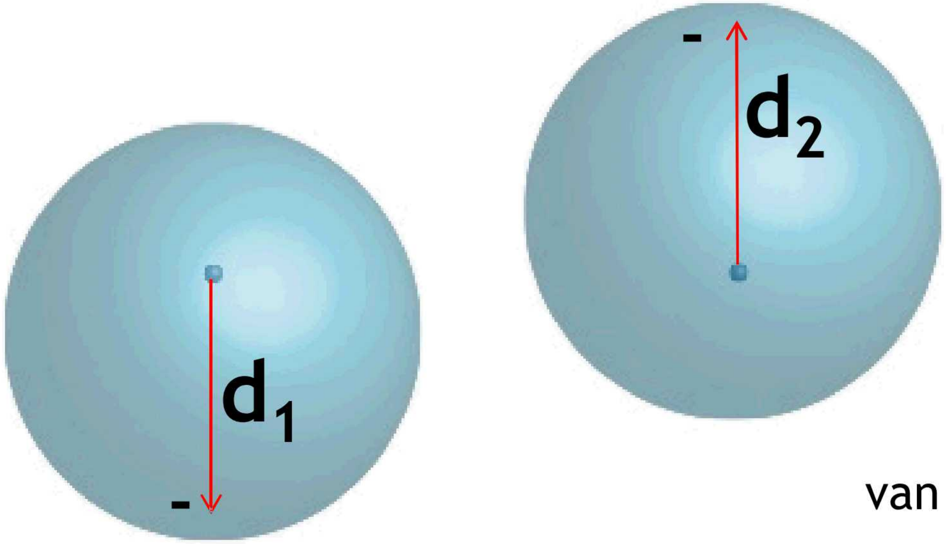


Making neutrals interact



- Interaction between ground state atoms is small ~100 Hz

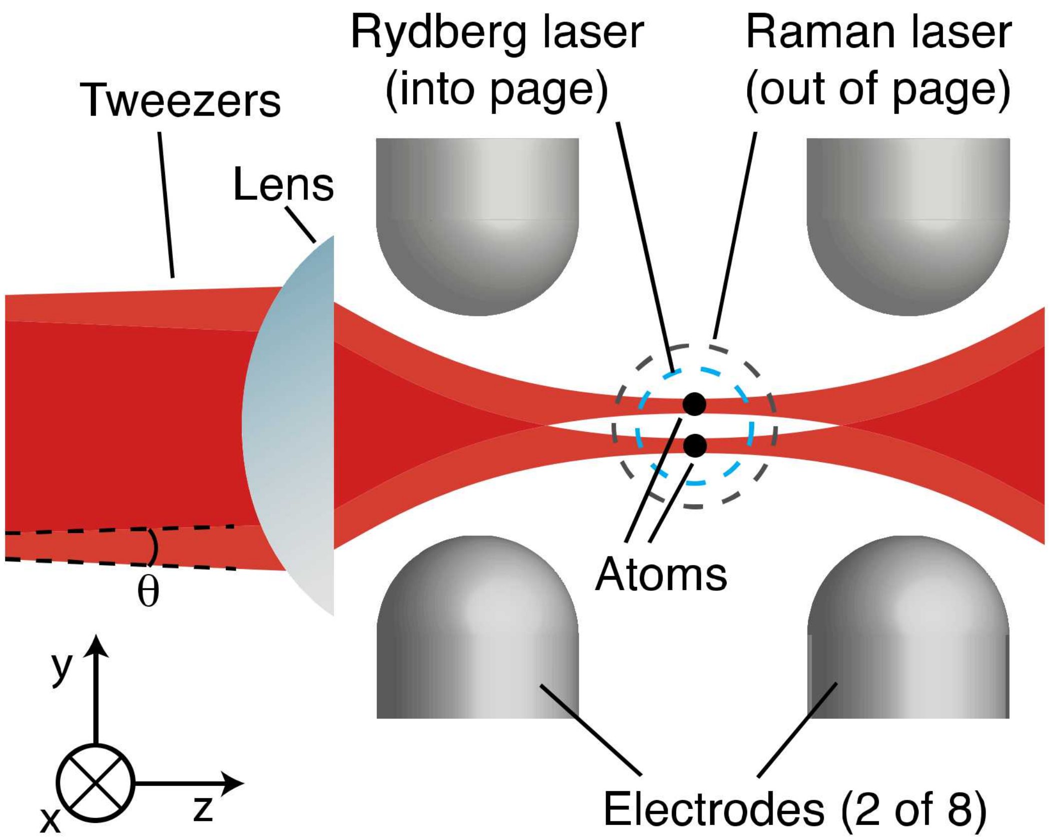
One solution: use Rydberg states

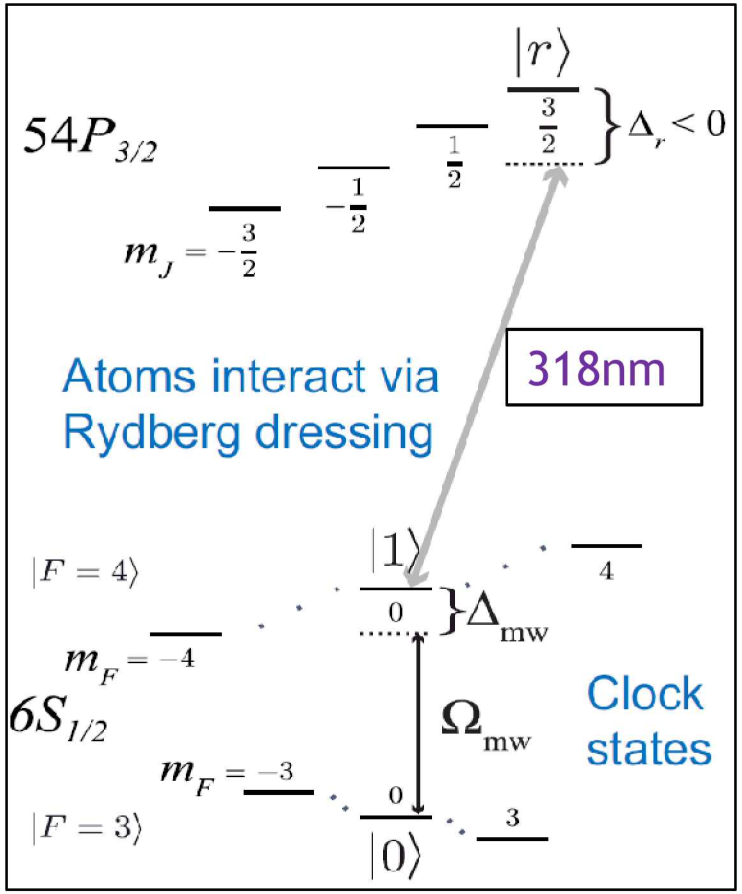


van der Waals interaction

- Even the presence of another atom can cause a massive response >> 10 MHz
- Induced Electric Dipole-Dipole Interaction

Entangling neutrals



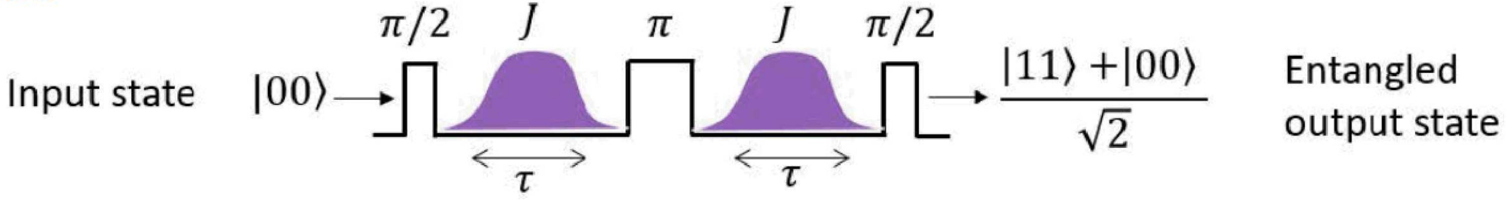


Atoms interact via Rydberg dressing

318nm

Clock states

Pulse sequence



Atom interferometers and SIGMA

Atom interferometry applications

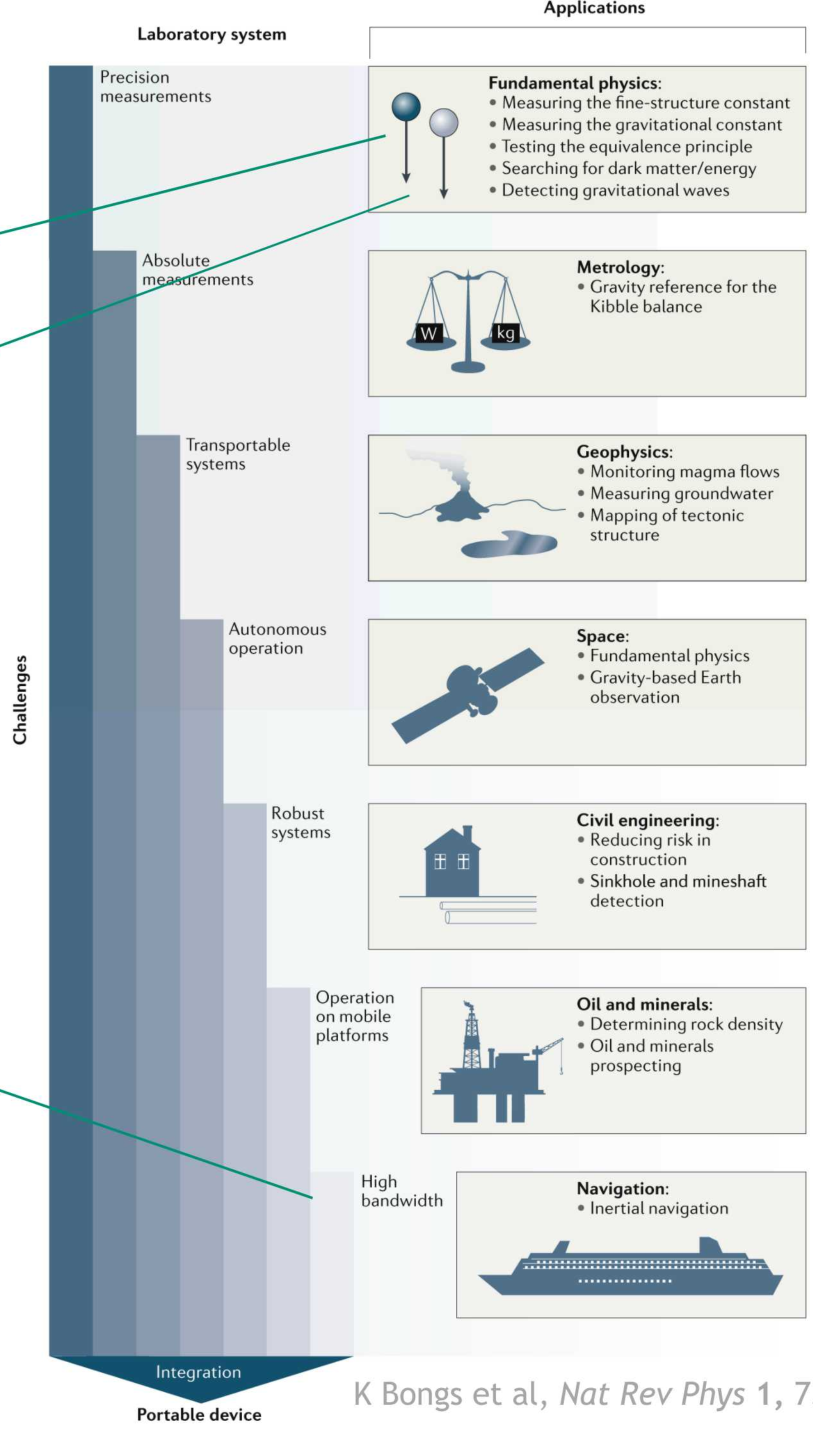
- Most accurate measurement of the fine structure constant, α=1/137.035999046(27)
- Low frequency (0.1-10 Hz) gravitational-wave measurements

Inertial Navigation

- Matterwave interferometers respond to
    - Force (acceleration)
    - Rotation
    - Force gradients

SIGMA (Strategic Inertial Guidance with Matterwaves)

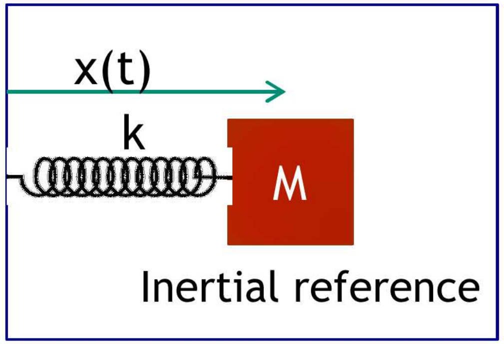
- high accuracy, real-time, non-aided navigation
- World’s first truly portable, compact atom interferometer inertial sensor.



K Bongs et al, *Nat Rev Phys* **1**, 731–739 (2019)

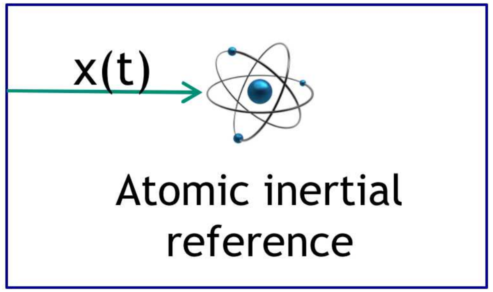
Classical and quantum inertial sensors

Classical accelerometer

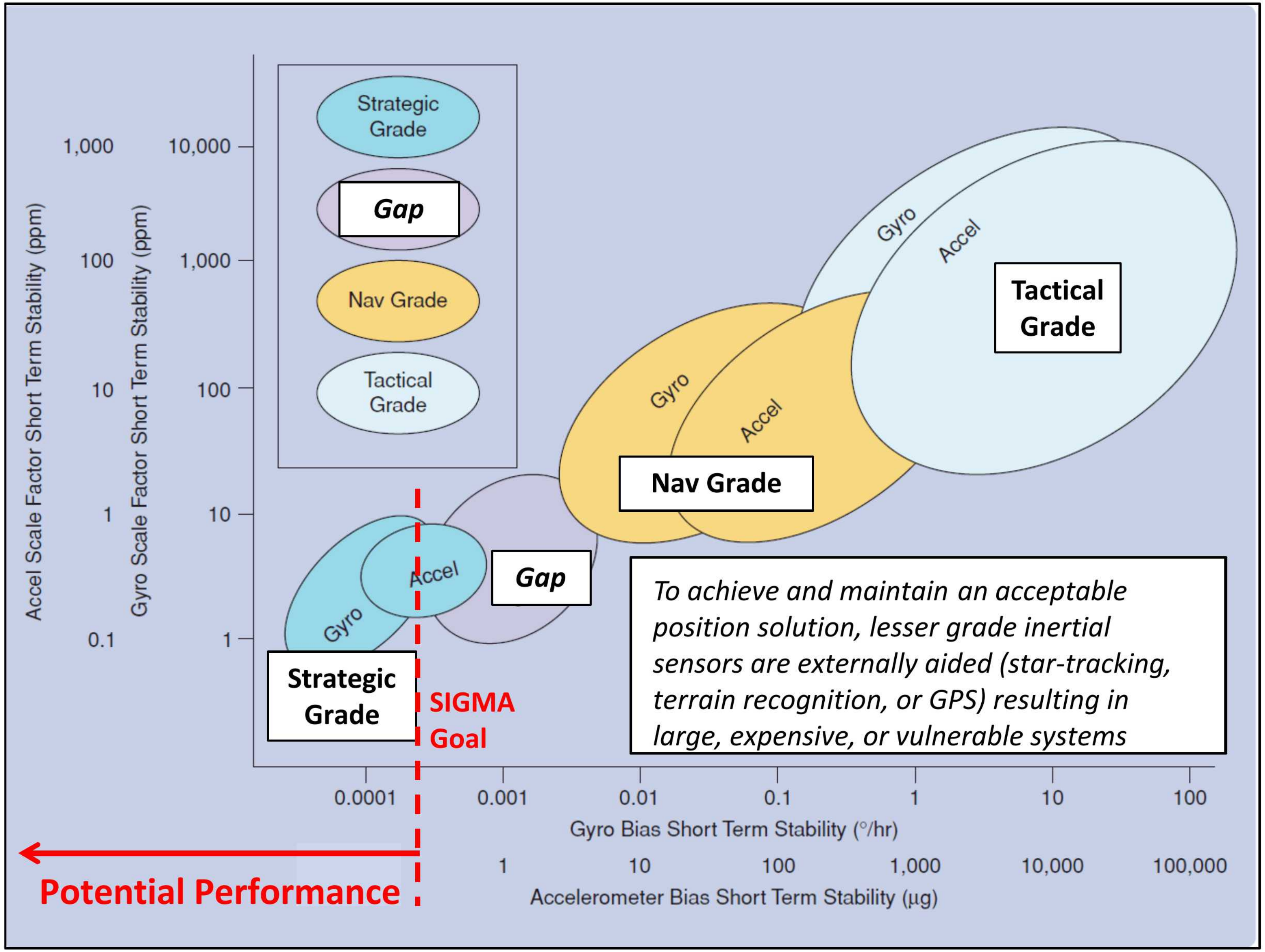


Problem: Eventually falls out of calibration/drifts

Free-fall accelerometer

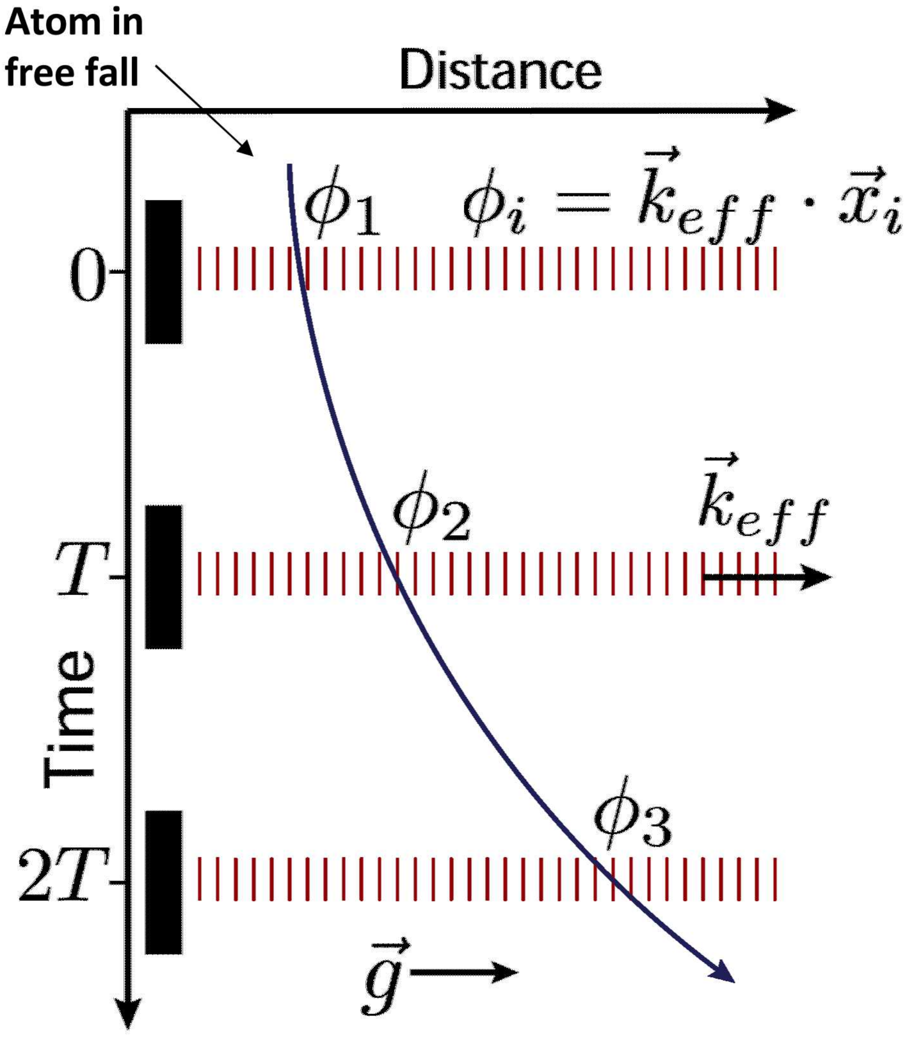


Atoms inherently "calibrated"



To achieve and maintain an acceptable position solution, lesser grade inertial sensors are externally aided (star-tracking, terrain recognition, or GPS) resulting in large, expensive, or vulnerable systems

Laser/atom system as ruler



"Laser ranging"

$$\vec{k}_{eff} \approx 1.6 \times 10^7 \mathrm{rad/m}$$

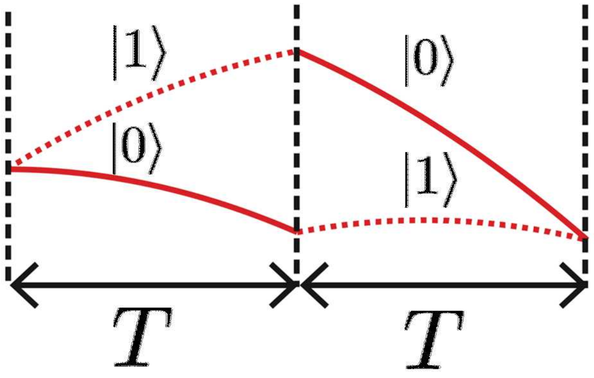
Finite difference formula for curvature

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$$

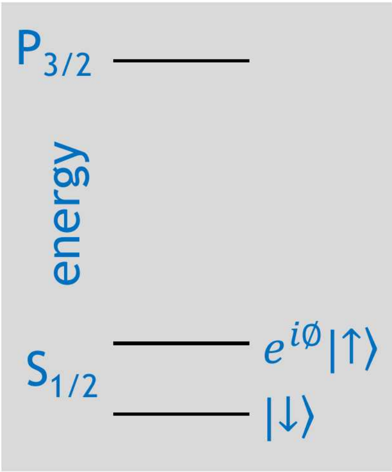
$$\Delta\phi = \vec{k}_{eff} \cdot \vec{g}\, T^2$$

$$P_{|1\rangle} = \frac{1}{2}(1 - \cos(\Delta\phi + \phi_0))$$

Why is it an interferometer?

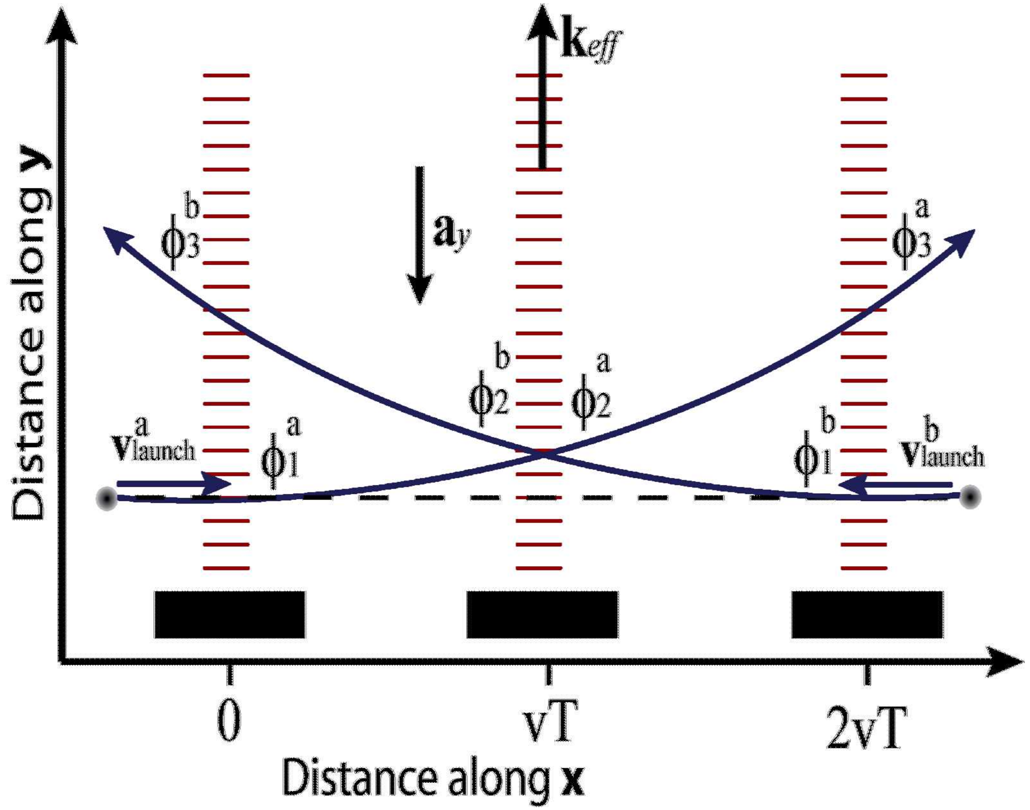


Single atom trajectory

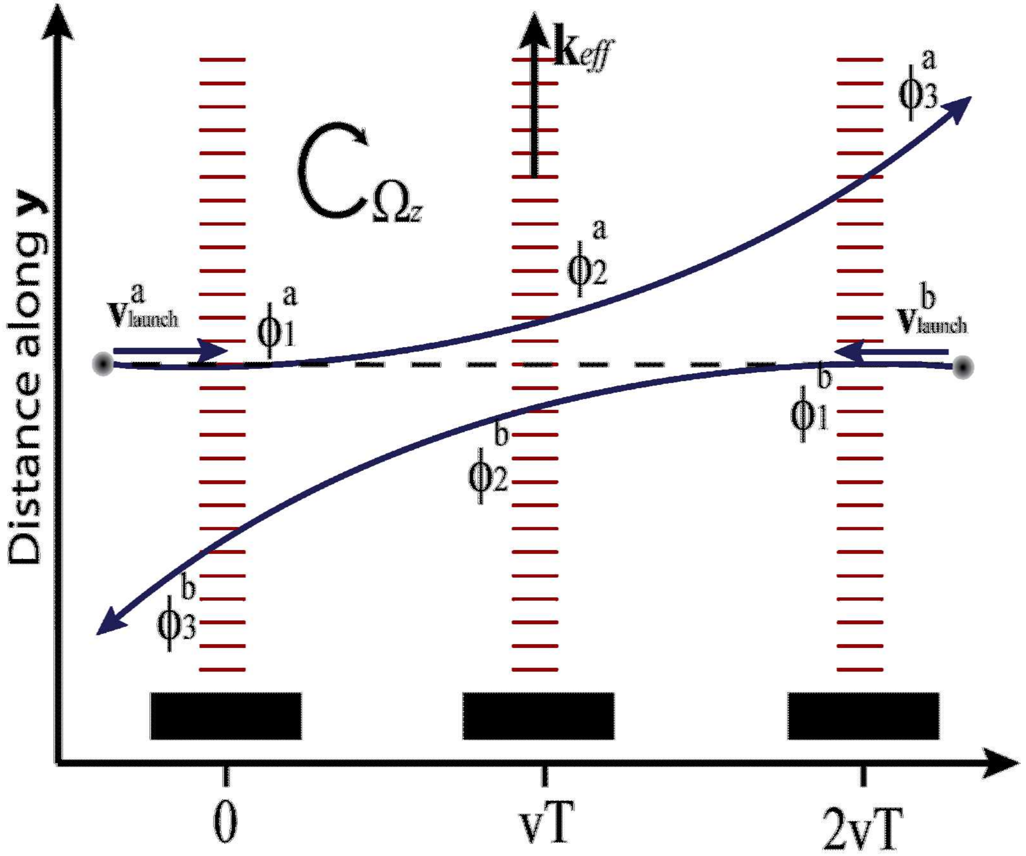


Kasevich, and Chu, Phys. Rev. Lett. 67, 181–184 (1991)

Simultaneous measurements of acceleration and rotation



Platform acceleration

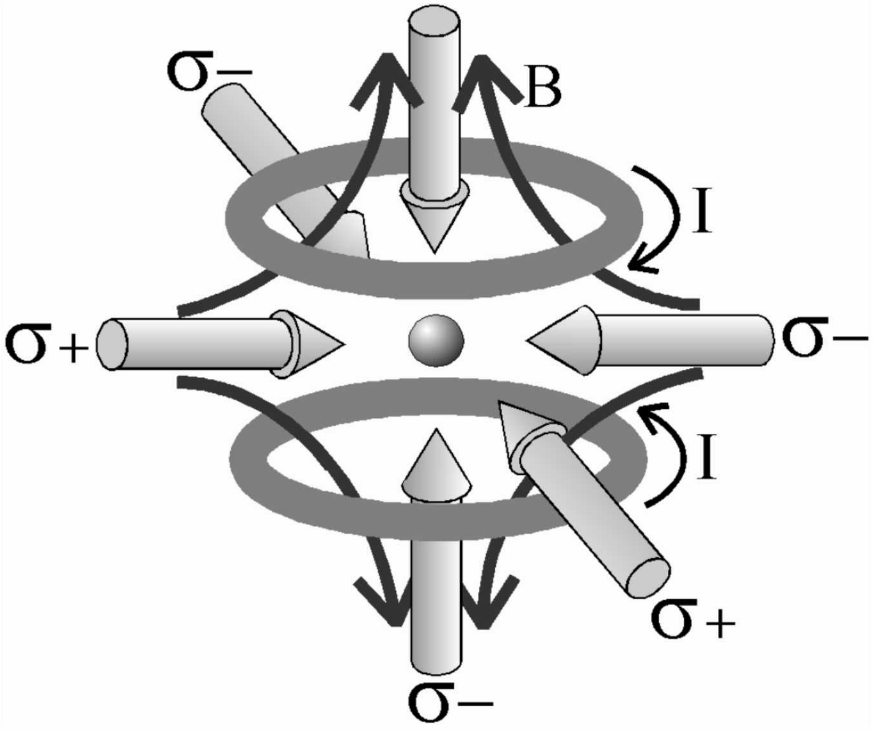


Platform rotation

$$\boxed{\Delta\phi = \vec{k}_{eff}\cdot(\vec{a}T^2 - 2(\vec{v}\times\vec{\Omega})T^2)}$$

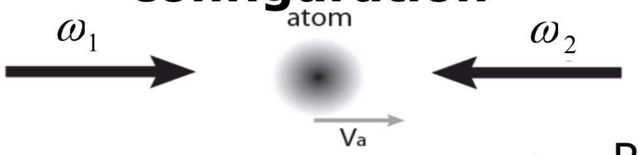
How is the phase actually measured

Magneto-Optical Trap (MOT)

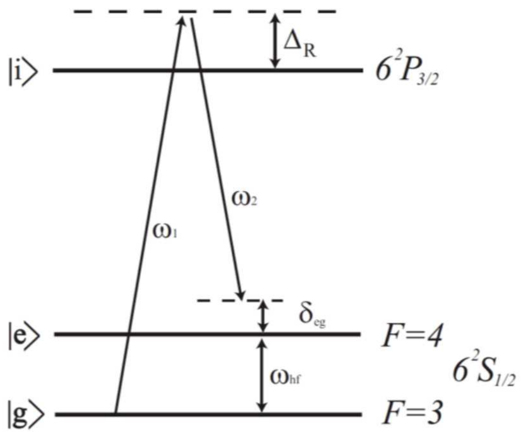


Rakholi, A.(2015) *High Data-Rate Atom Interferometry for Measuring Dynamic Inertial Conditions* Ph.D. University of New Mexico.

Laser configuration



Relevant energy diagram (Cs)



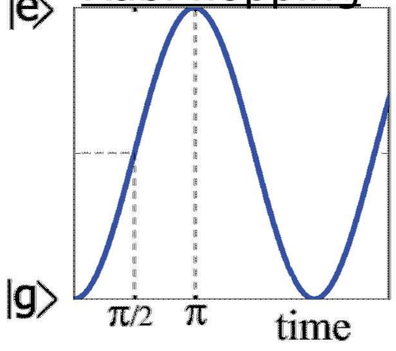
Effective 2-level system

$$H'_{\text{int}} = -\vec{\mu}_{eff}\cdot\vec{E}_{eff}e^{i(\vec{k}_{eff}\cdot\vec{x}-\omega_{hf}t)}$$

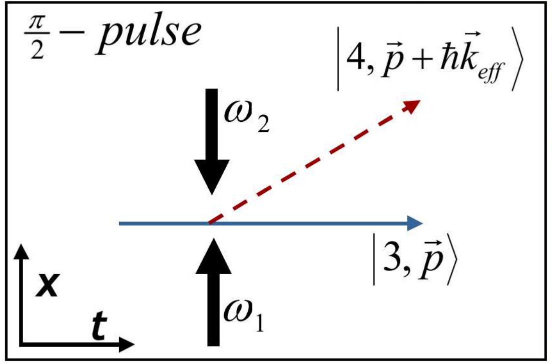
$$\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2 \approx 2\vec{k}_1$$

Valid for $\Omega_{eff} << \Delta$

Rabi flopping

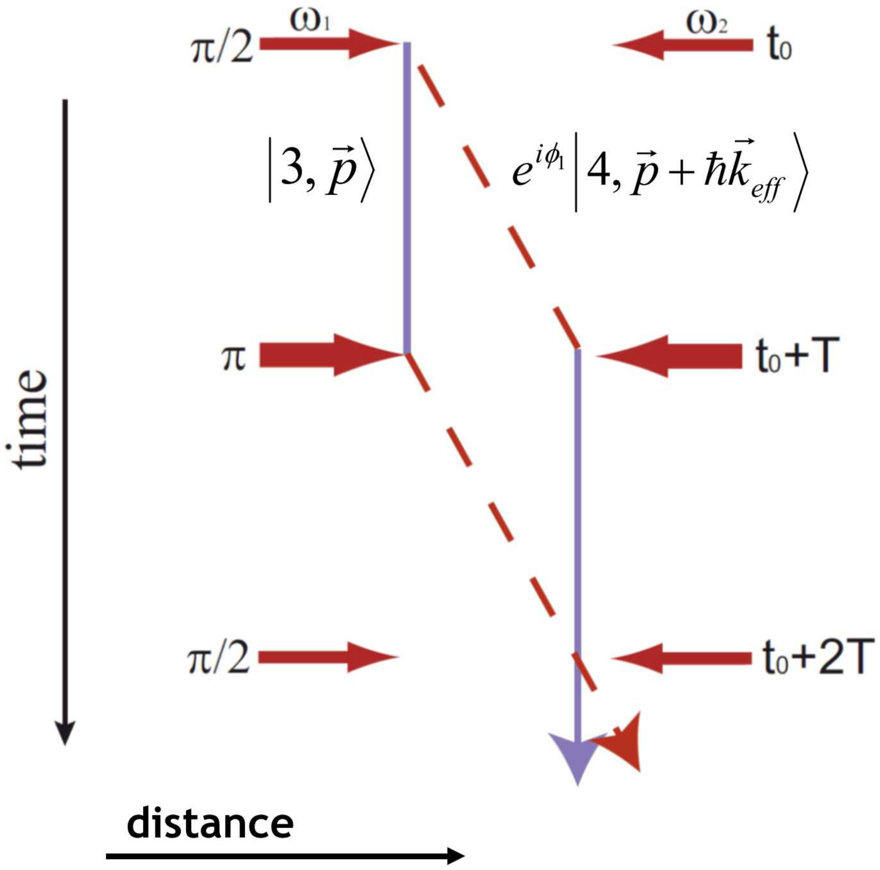


Atom optics beamsplitter



Area enclosed by wavepackets

Interferometer Recoil diagram



Transition rules

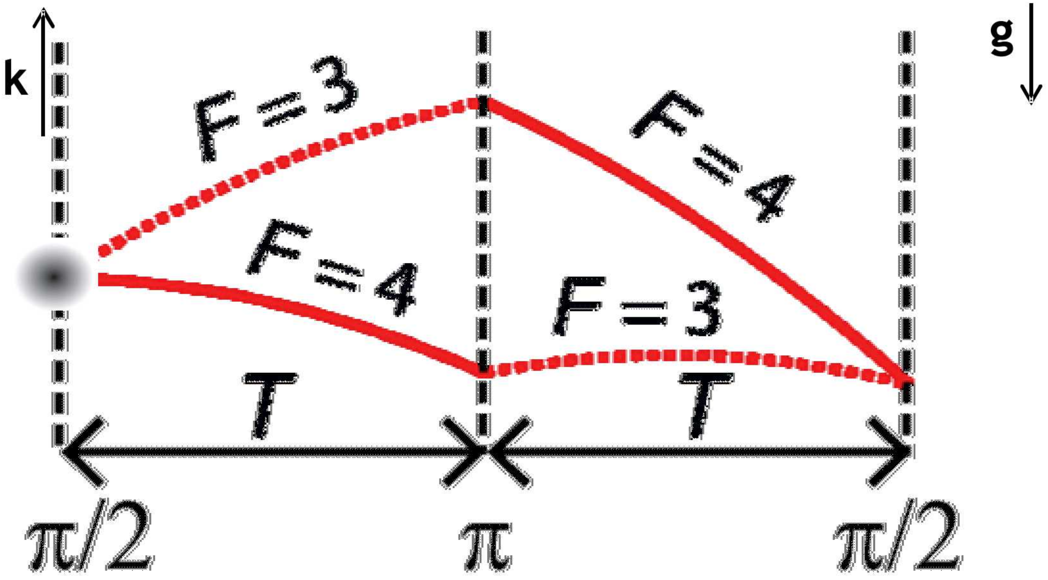
$$\left.\begin{array}{c}\left|3,\vec{p}\right\rangle \rightarrow e^{i\phi}\left|4,\vec{p}+\hbar\vec{k}_{eff}\right\rangle \\ \left|4,\vec{p}+\hbar\vec{k}_{eff}\right\rangle \rightarrow e^{-i\phi}\left|3,\vec{p}\right\rangle \\ \phi=\vec{k}_{eff}\cdot\vec{x}\end{array}\right\}\begin{aligned}\Delta\phi &= \phi_1-2\phi_2+\phi_3 \\ &= \vec{k}_{eff}\cdot(\vec{a}T^2-2(\vec{v}\times\vec{\Omega})T^2)\end{aligned}$$

Interferometer transition probability

$$\left|\left\langle 4\middle|\Psi\right\rangle\right|^2 = \tfrac{1}{2}\left(1-\cos\Delta\phi\right)$$

Under gravity

wavepacket trajectory



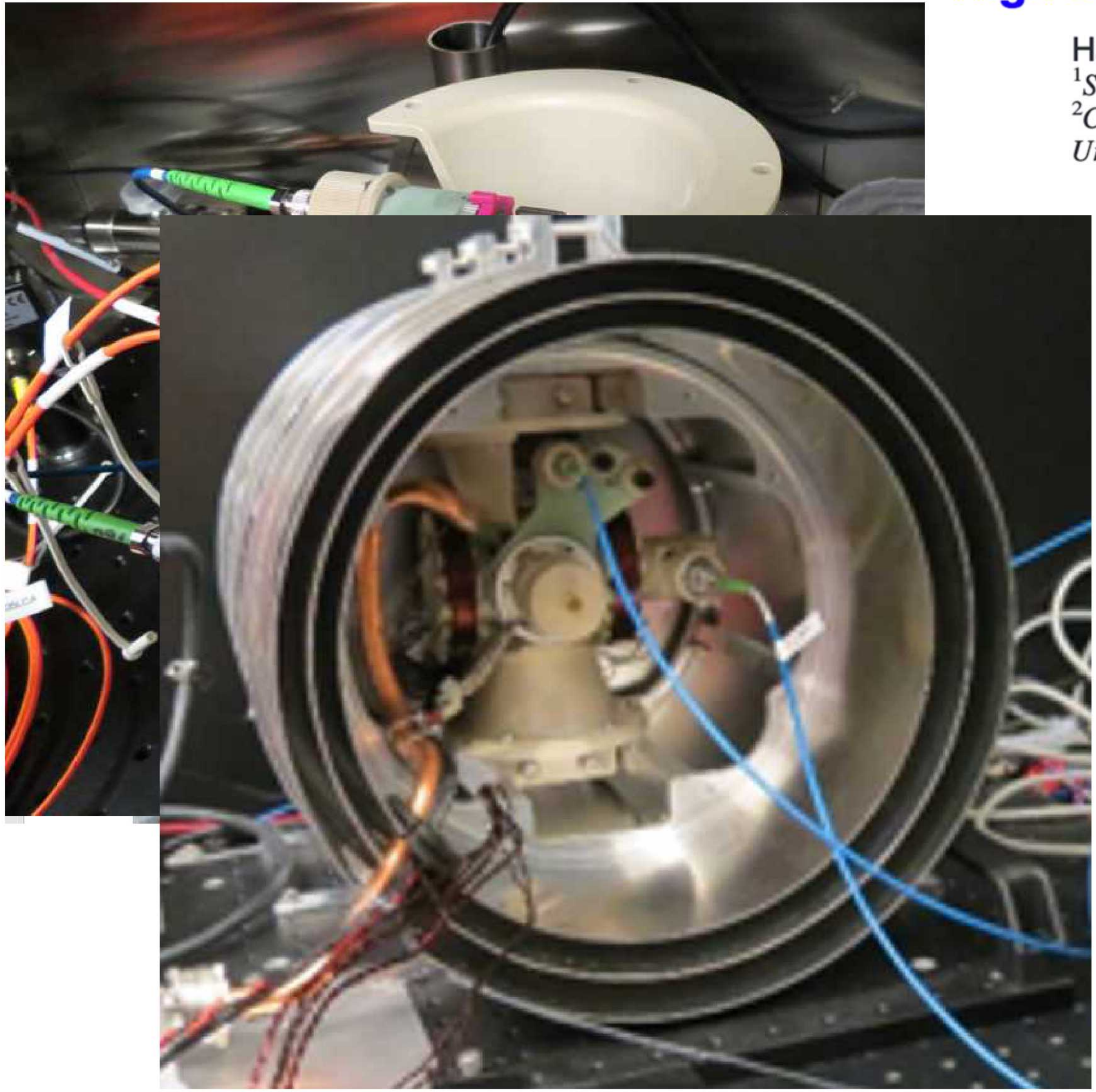
$$\Delta\phi_{tot} = \Delta\phi_{light} + \Delta\phi_{path} + \Delta\phi_{separation}$$

Light interaction imprints phase

Feynman path integral

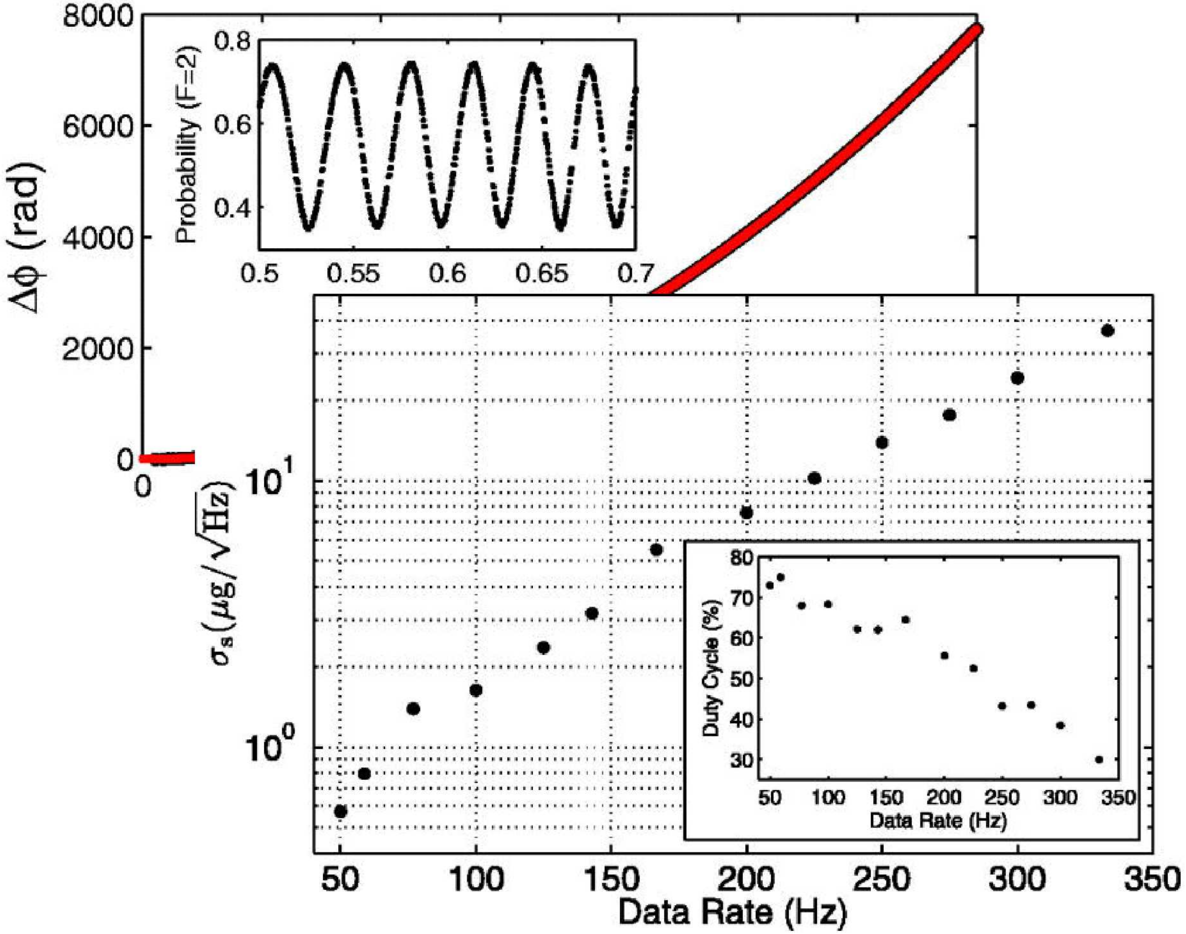
Wavepacket overlap

Atom interferometer results

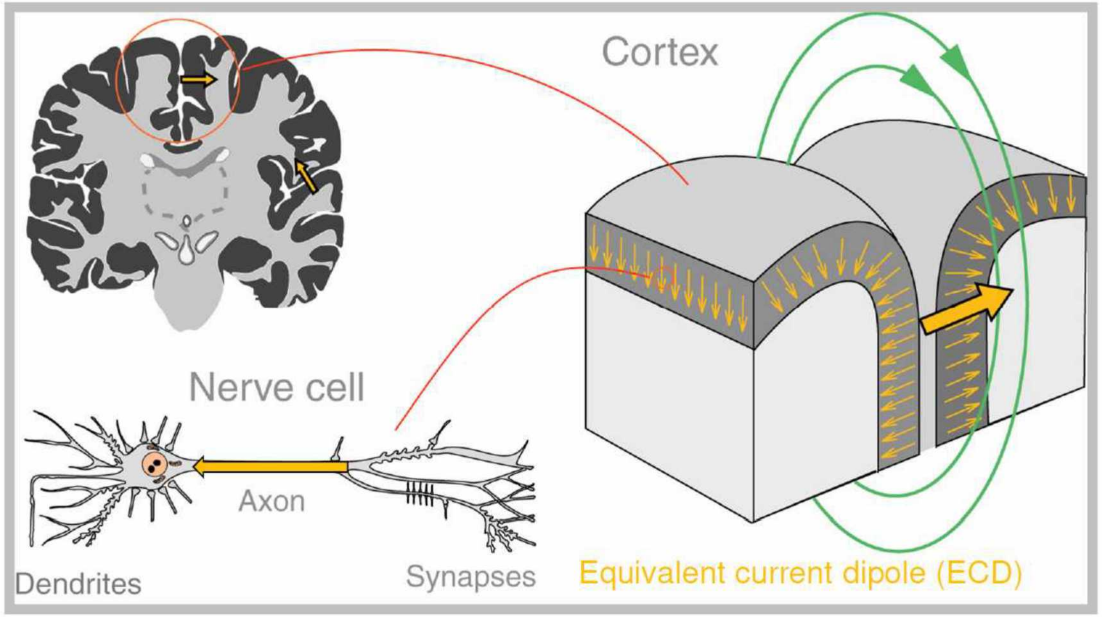


High data-rate atom interferometer for measuring acceleration

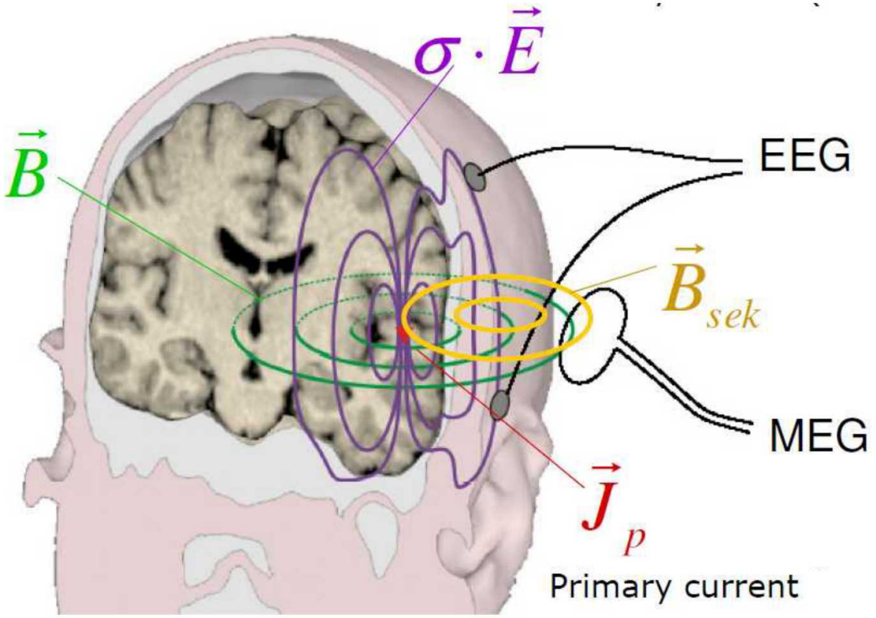
Hayden J. McGuinness,[1,a)] Akash V. Rakholia,[1,2] and Grant W. Biedermann[1,2]
[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*Center for Quantum Information and Control (CQuIC), Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, 87131, USA*



Magnetoencephalography using optically pumped magnetometers



B. Maess, MPI for Human Cognitive and Brain Sciences



Lauri Parkkonen (Aalto University)

- SQUID require dewar and a rigid helmet due to liquid He (~ 4 °k).
- SQUID's helmet manufactured to fit 95% adult male subject's head size.
- Large sensor-source distance diminishes the magnetic field and high frequency spatial components are affected more severely.
- Optically Pumped Magnetometers (OPMs) enable on-scalp Magnetoencephalography enhancing spatial resolution of magnetoencephalography.
- Applications:
    - Brain Computer Interface (BCI)
    - Clinical, e.g. epilepsy

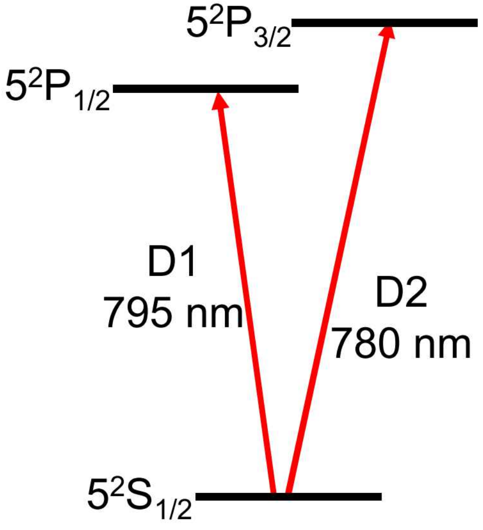
How the field is measured

Two optical resonances in Rubidium (fine structure)

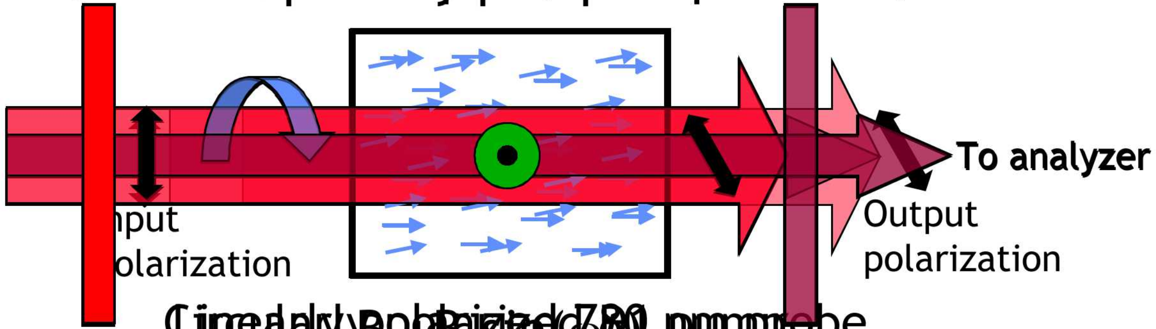
- Use D1 for optical pumping and D2 for probing

Based on: V. Shah and M. V. Romalis, PRA 80, 013416 (2009)

^{87}Rb Fine Structure



Field modulation/phase sensitive detection required to extract dispersive lineshape



Oriented spins rotate the polarization

Signals to detect

Spin Polarization Bloch Equation

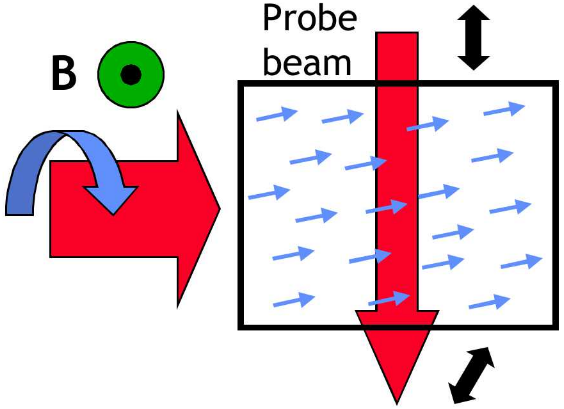
$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \gamma \mathbf{S} \times \mathbf{B} + R(S_0\hat{z} - \mathbf{S}) - \frac{\mathbf{S}}{T_2}$$

Steady State Solution

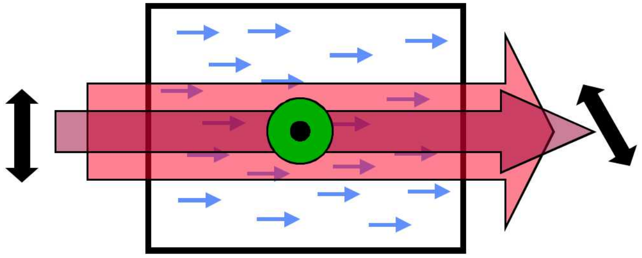
$$S_x = S_0 \frac{-\beta_y + \beta_x \beta_z}{1 + (\beta_x^2 + \beta_y^2 + \beta_z^2)} \qquad S_z = S_0 \frac{1 + \beta_z^2}{1 + (\beta_x^2 + \beta_y^2 + \beta_z^2)}$$

$$\boldsymbol{\beta} = \gamma \mathbf{B}/(R + T_2^{-1})$$

Transverse Pump

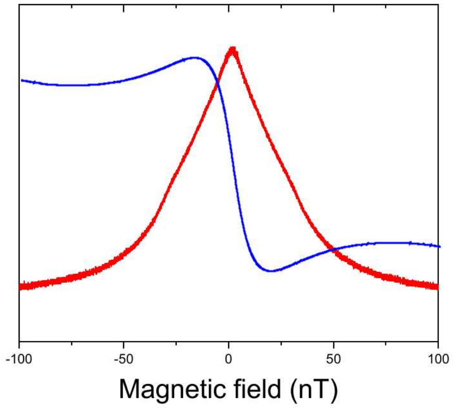


Detect the Pump
or a Collinear Probe

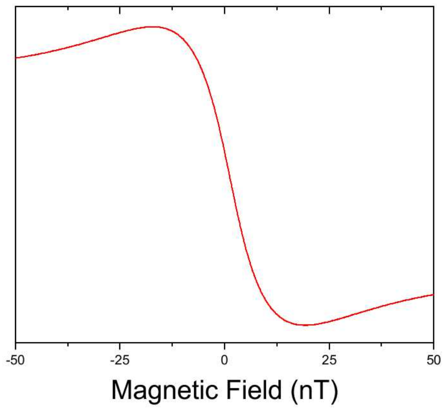


B_0+B_1sin(ωt)

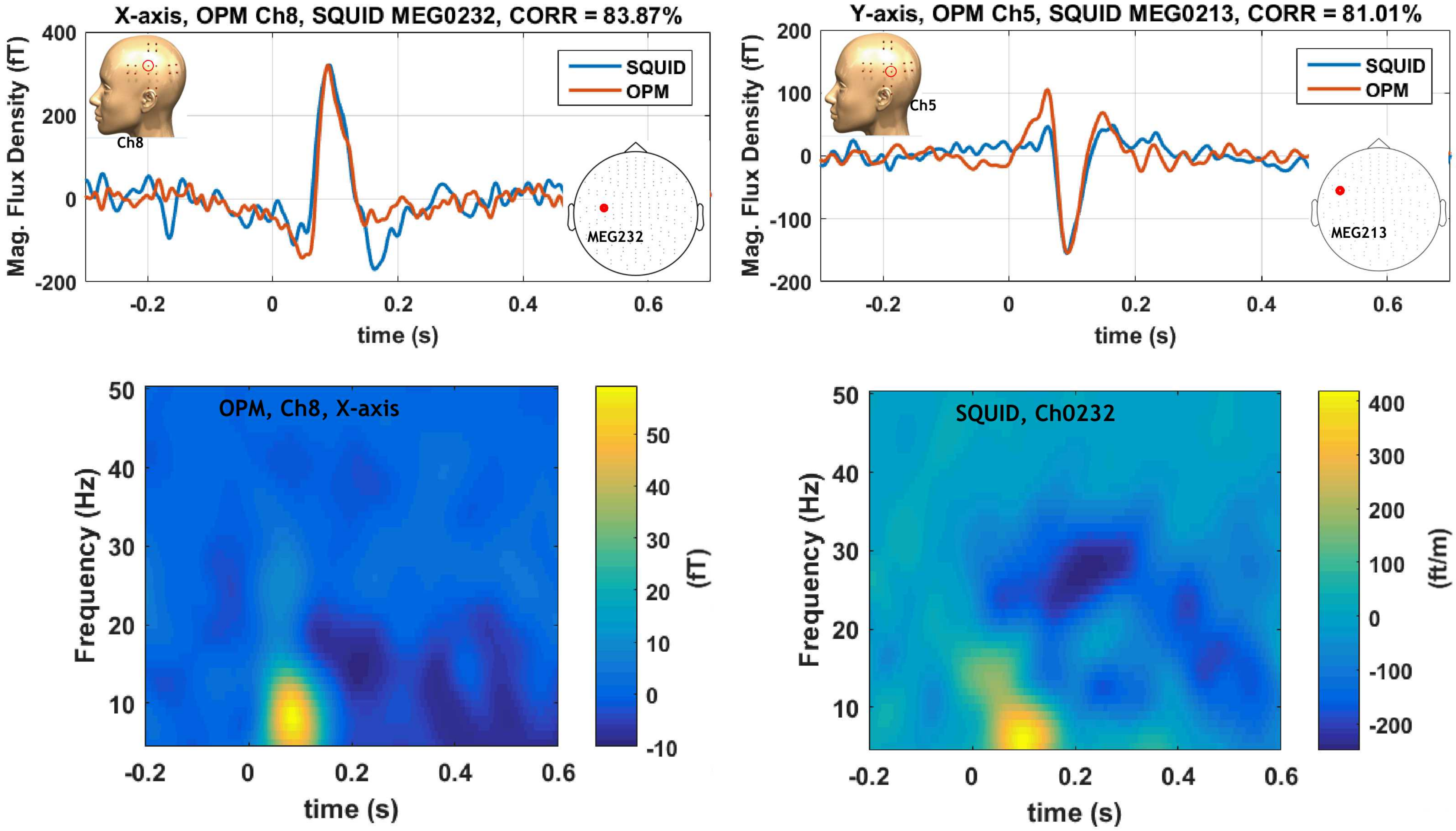
Atomic Polarization, S_z
Pump Transmission,
or Angle of Light Polarization



Atomic Polarization, S_x
or Angle of Light Polarization



Head-to-head SQUID vs. OPM



- More than 80% correlation for both x and y component

Thanks!

LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

DARPA

MGMT + Development

- Mike Descour
- Rick Muller
- Jake Douglass

Technical Staff

- Dan Stick
- Rupert Lewis
- Ryan Jock
- Peter Schwindt
- Brandon Ruzic
- Matt Eichenfield
- Paul Parazzoli

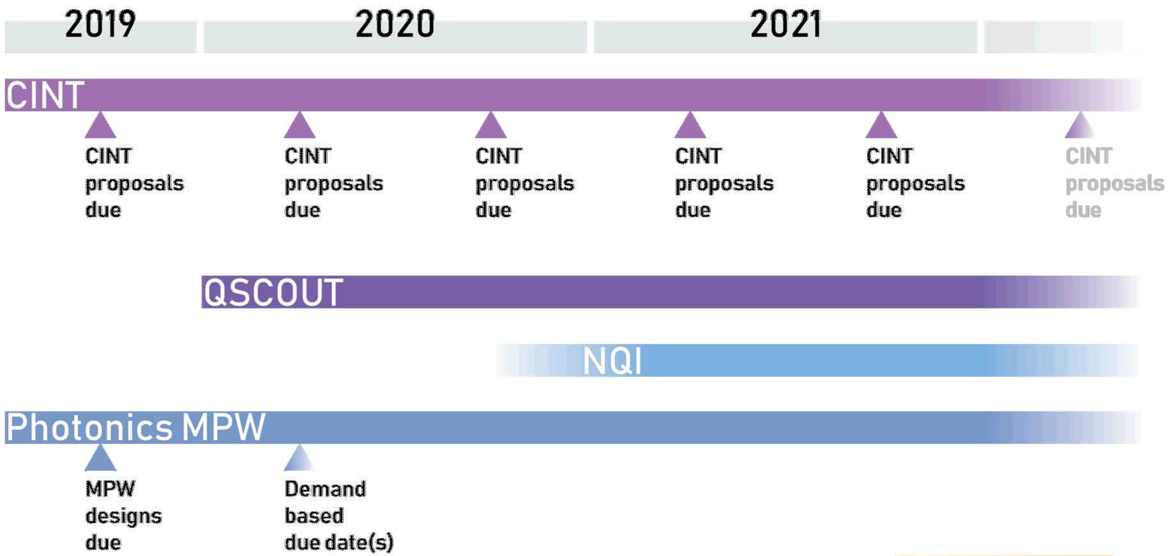
NMSU

- Phillip DeLeon
- Many more

How to partner with Sandia

Numerous technical **partnerships** in place today:

- Academic institutions, industry, & Government
- **CINT**: semi-annual proposals cadence: `cint.lanl.gov`
- **QSCOUT**: coming later in 2020
- **NQI**: in progress
- Contact `quantum@sandia.gov`
- **National Security Photonics Center**: `sandia.gov/mesa/nspc`
- Contact `photonics@sandia.gov`



2019 2020 2021

CINT

CINT proposals due

CINT proposals due

CINT proposals due

CINT proposals due

CINT proposals due

CINT proposals due

QSCOUT

NQI

Photonics MPW

MPW designs due

Demand based due date(s)

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ARL

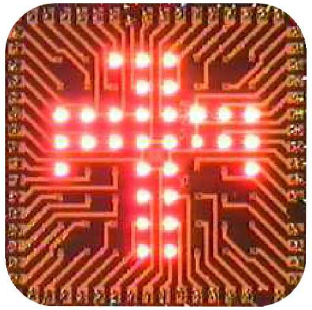
Backup Slides

1960s Microelectronics and Microsystems *Present*

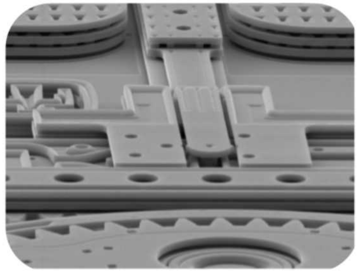
Laminar Flow Clean Room

Design/Build Galileo ICs

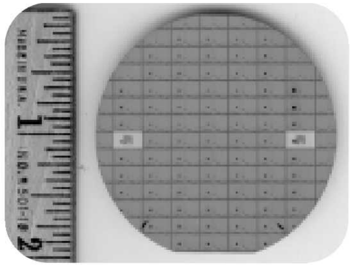
High Efficiency VCSEL



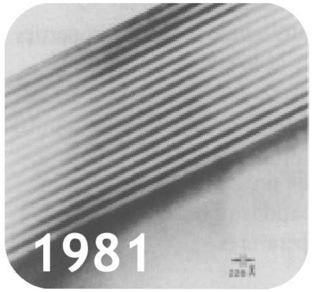
5-Level Surface Micromachining



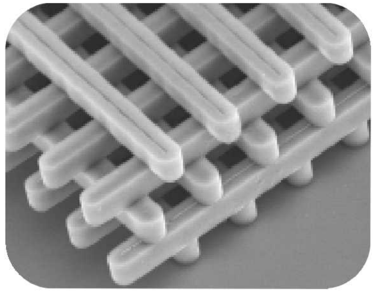
Microsystems-Enabled Photovoltaics



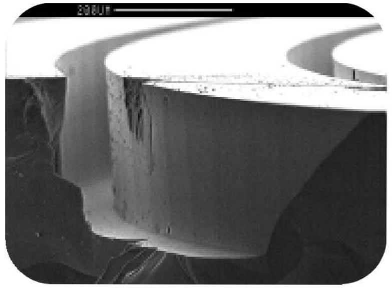
Radiation-Hardened CMOS



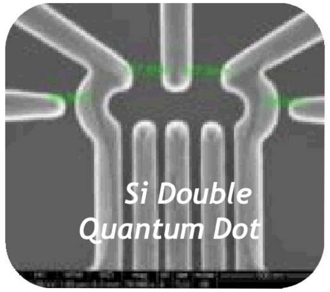
Strained-layer Superlattices



Photonic Lattice



MicroChemLab



Quantum Computing

1980s Quantum Engineering *Present*

QSCOUT details

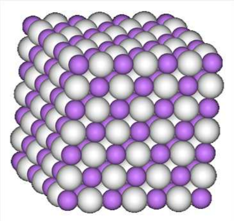
DOE/SC Advanced Scientific Computing Research (ASCR) **QSCOUT** (PI: P. Maunz)

- Quantum processor with **5-15 trapped-ion qubits**
- Goal: **Available to the DOE/SC computing community** in 2020
  - Access to quantum processor with high-fidelity operations
  - Low-level access to gate & quantum circuit implementations
  - Full information on implementation of quantum operations
  - Ability to run any testing circuits

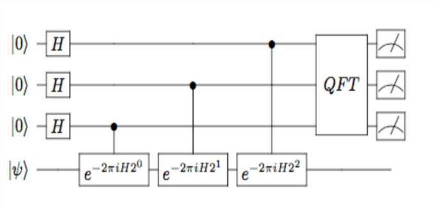
Design approach

- Build on established qubits ($^{171}Yb^{+}$)
- Use Sandia microfabricated traps
- Use established qubit manipulation tools (e.g. pulsed laser as demonstrated at UMD, Duke, Sandia)

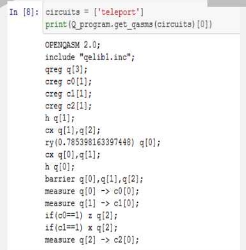
Example QSCOUT workflow:



Lithium hydride example



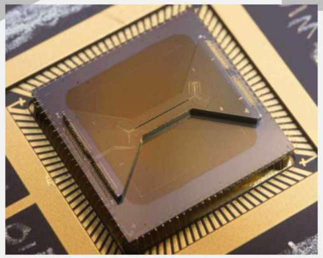
Textbook digital quantum simulation circuit



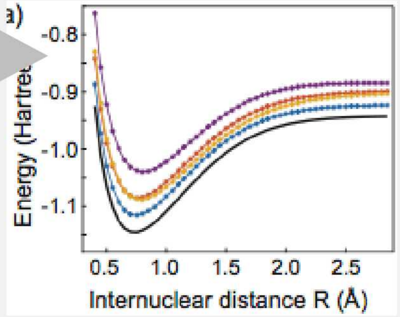
```
In [8]: circuits = ['teleport']
        print(Q_program.get_qasms(circuits)[0])

        OPENQASM 2.0;
        include "qelib1.inc";
        qreg q[3];
        creg c0[1];
        creg c1[1];
        creg c2[1];
        h q[1];
        cx q[1],q[2];
        ry(0.785398163397448) q[0];
        cx q[0],q[1];
        h q[0];
        barrier q[0],q[1],q[2];
        measure q[0] -> c0[0];
        measure q[1] -> c1[0];
        if(c0==1) z q[2];
        if(c1==1) x q[2];
        measure q[2] -> c2[0];
```

QSCOUT code/ microcode



Implement on hard-ware/trapped ions



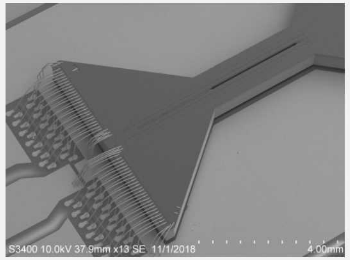
Results

QSCOUT's **main interdisciplinary tasks**

Qubit hardware	Gate modeling	QCVV
Hardware controllers	Software stack	Exemplar apps

QSCOUT **collaborations**

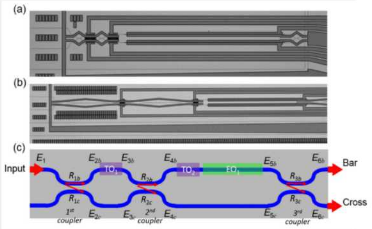
- Duke University (K. Brown)
- Tufts University (P. Love)
- LBNL
- Open to others…

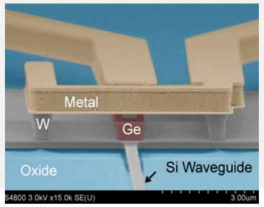


The National Security Photonics Center

Integrated photonics for quantum communications

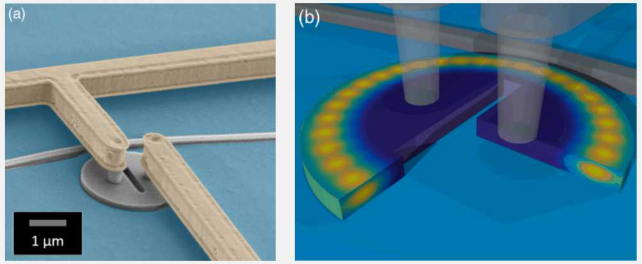
Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms: compact microsystems for telecom and visible wavelengths





Cryogenic optical interconnects

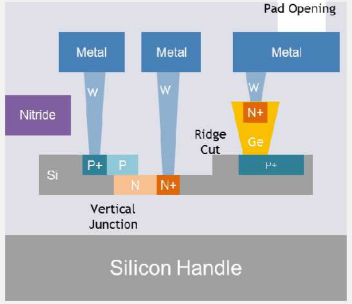
High-speed low-power resonant modulator operating at cryogenic temperatures (≤ 4 K)



Optica **4,** 374-382 (2017)

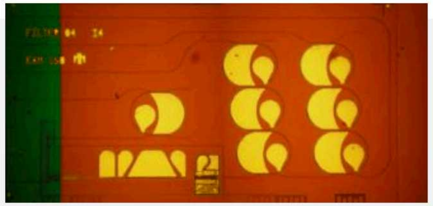
Silicon photonics integrated circuits

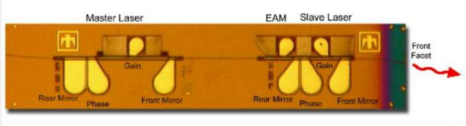
- Leverage CMOS (200 mm SOI)
- 22 passive devices, 20 active devices, design guide and library
- **MPW runs available**, up to passive+active+Ge devices



III-V photonic integrated circuits (PICs)

- InP, GaAs, GaN
- Elements: Waveguides, lasers, amplifiers, modulators, detectors, phase shifters
- **MPW runs available**





More information on photonics MPW opportunities:

- National Security Photonics Center: `sandia.gov/mesa/nspc`
- Contact `photonics@sandia.gov`