Qubits, beams and fusion

Thomas Schenkel

Accelerator Technology & Applied Physics Division

Lawrence Berkeley National Laboratory

THXBB1, NAPAC, Sept. 05, 2019

Work at Lawrence Berkeley National Laboratory was funded by the US Department of Energy, DOE, Office of Science Offices of High Energy Physics and Fusion Energy Sciences, by ArpaE, and in part by Google LLC under CRADA between LBNL and Google LLC.

LBNL operates under U.S. Department of Energy contract DE-AC02-05CH11231.

Outline

1. Qubits
2. Beams
3. Fusion
4. Outlook

IAEA GC council meeting, Sept. 18, 2019
https://www.iaea.org/about/policy/gc/gc63/events

Outline

1. Qubits

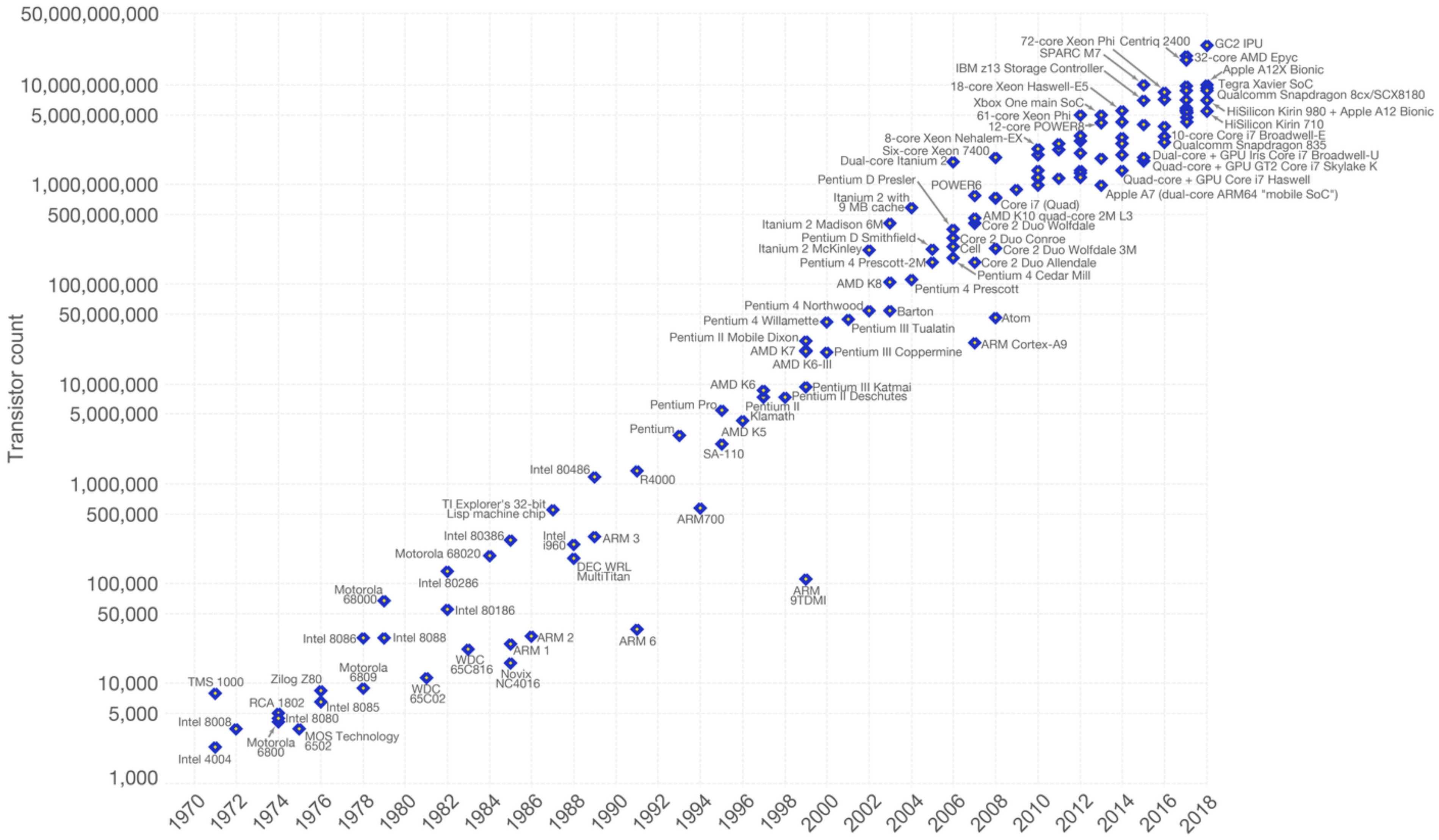
2. Beams

3. Fusion

4. Outlook

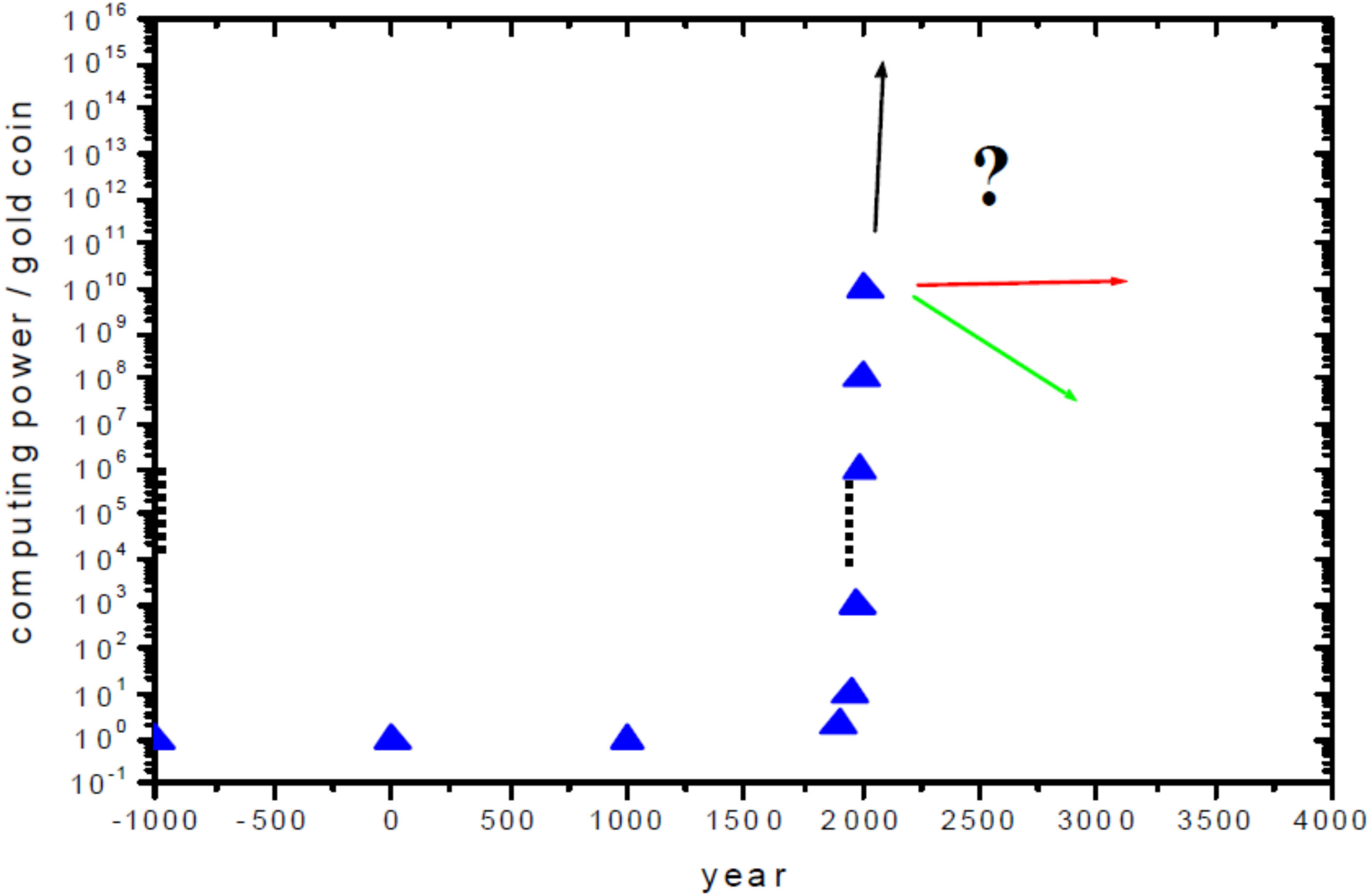
Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Evolution of computational power



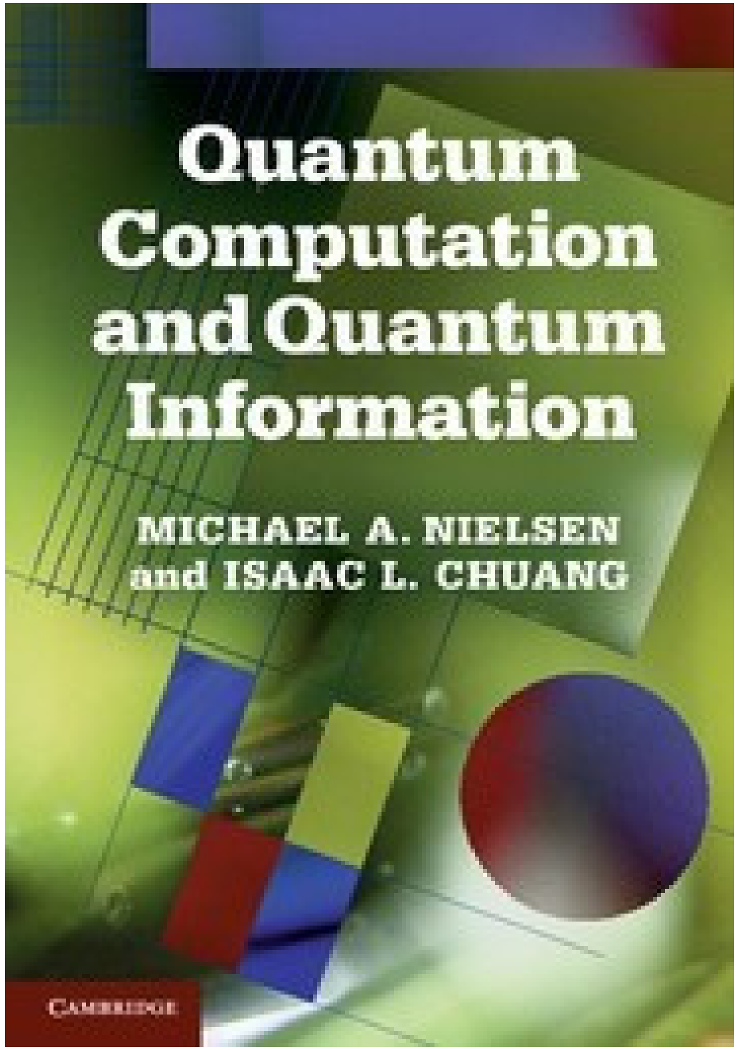
Quantum Information Science

Quantum –

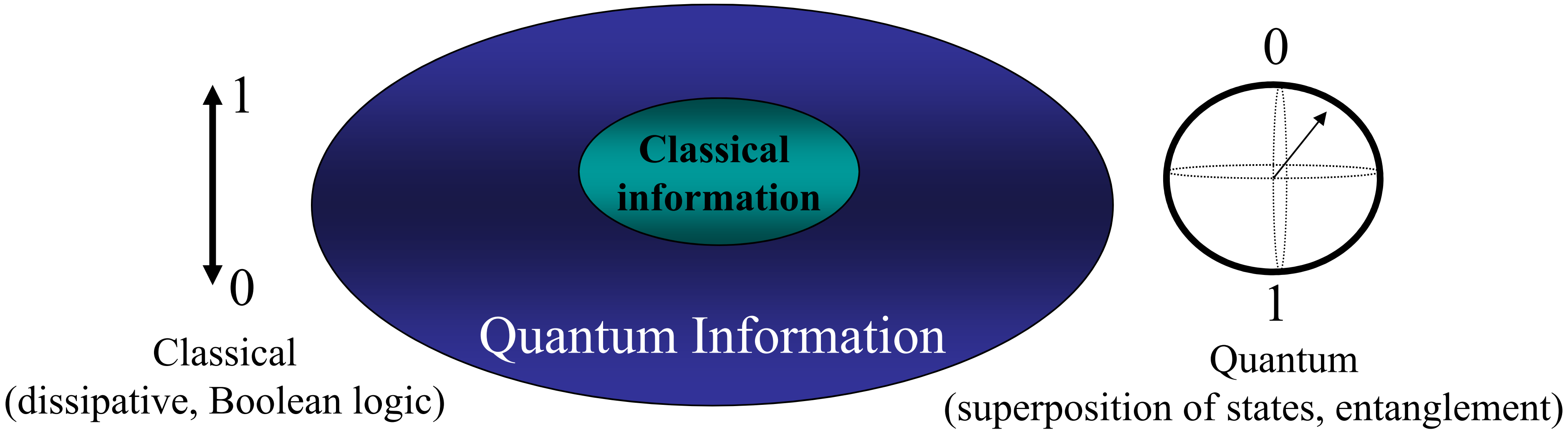
Communication

Sensing

Simulations / Computing



Quantum Information Science



- “Information is a physical entity”, R. Landauer, 1999
- Flavors of quantum computing approaches[1]
    - Quantum circuit model
    - Measurement based quantum computing
    - Adiabatic quantum computing
    - Topological quantum computing
    - …

[1]see e. g. “Quantum computers: Definition and implementations”, C. A. Perez-Delgado and P. Kok, Phys. Rev. A 83, 012303 (2011)

Qubits

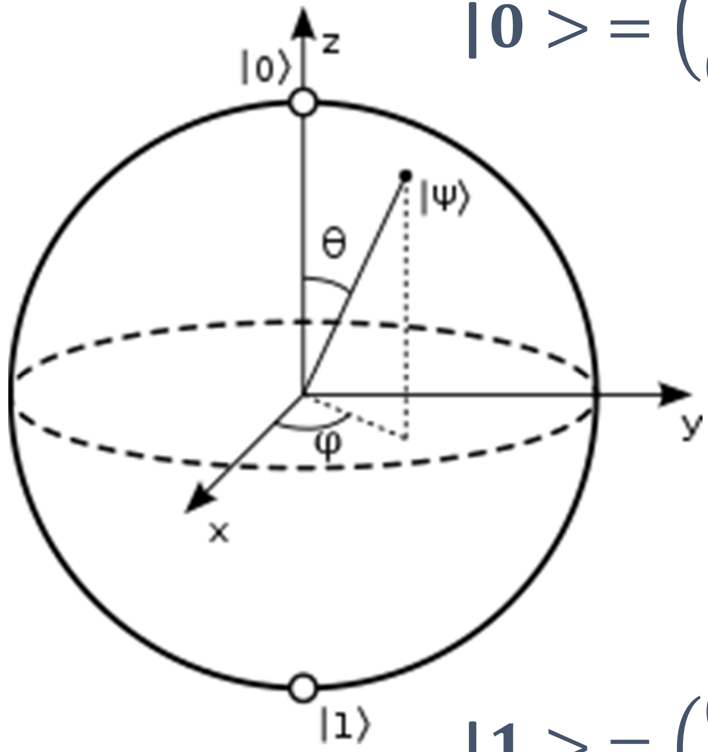
- Quantum bits
  - Capacity scales as 2^N
  - Bloch sphere representation
  - Superposition of states
  - Multi-qubit entanglement

$|\psi \geq = \alpha|0 > +|\beta >$

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

$\frac{1}{\sqrt{2}}(|00>+|11>$

- Classical bits
  - Capacity scales as N
  - Boolian logic, and/or/not
  - Digital, 0 or 1

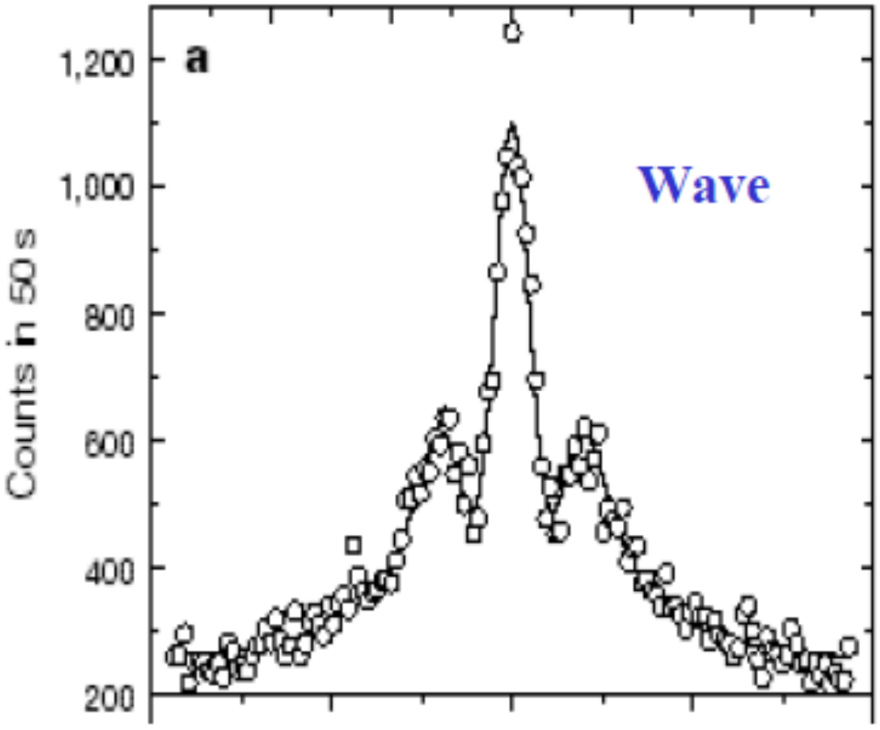


$|\mathbf{0}> = \begin{pmatrix} \mathbf{1} \\ \mathbf{0} \end{pmatrix}$

$|\mathbf{1}> = \begin{pmatrix} \mathbf{0} \\ \mathbf{1} \end{pmatrix}$

https://en.wikipedia.org/wiki/Qubit

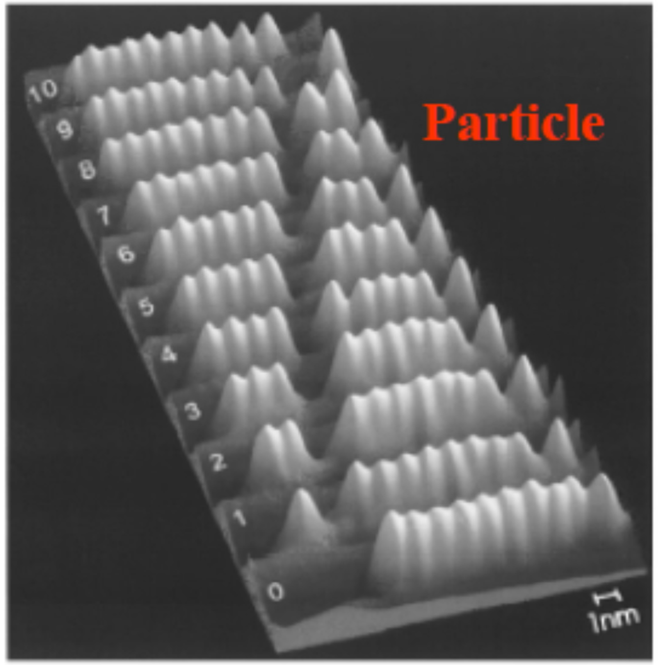
Wave-particle duality of C_{60} molecules



Markus Arndt, Olaf Nairz, Julian Vos-Andreae, Claudia Keller, Gerbrand van der Zouw & Anton Zeilinger

Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria

NATURE | VOL 401 | 14 OCTOBER 1999 |



Room-temperature repositioning of individual C_{60} molecules at Cu steps: Operation of a molecular counting device

M. T. Cuberes,[a] R. R. Schlittler, and J. K. Gimzewski

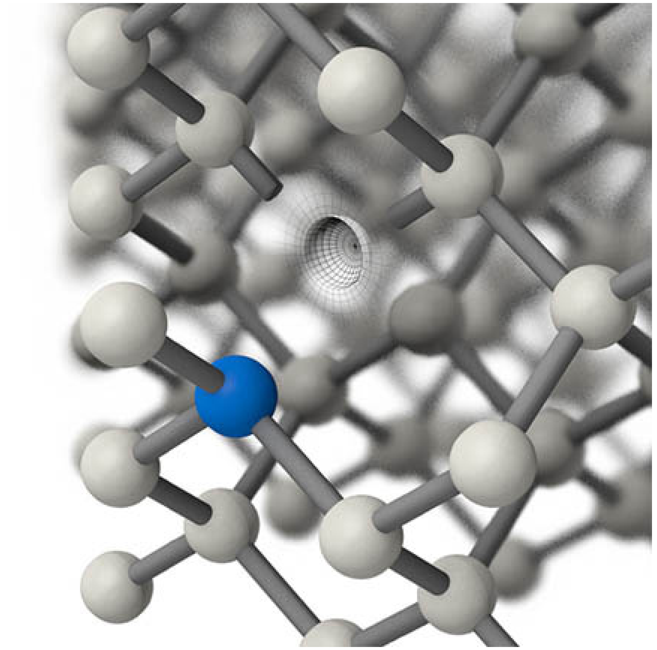
IBM Research Division, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

Appl. Phys. Lett. **69** (20), 11 November 1996

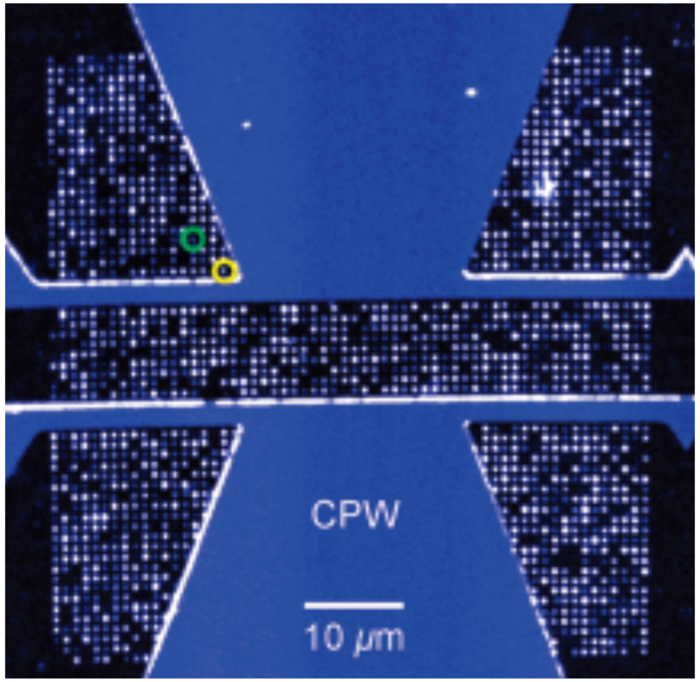
- Wave - superposition of "which path" states in double slits leads to interference
- Particle - interaction of molecules with environment destroys interference, de-coherence, and "classical" behavior
- Quantum info processing requires the coherent superposition of N qubits while gates are applied until a measurement is made

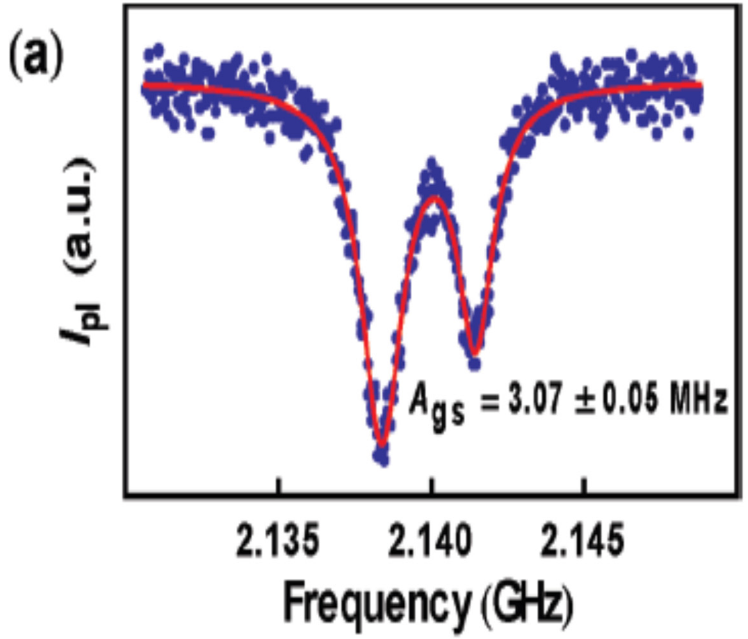
Quantum sensing

- Use a “quantum object”, track coherence and entanglement
- Example: Nitrogen-Vacancy centers in diamond



Physics Today June 2018



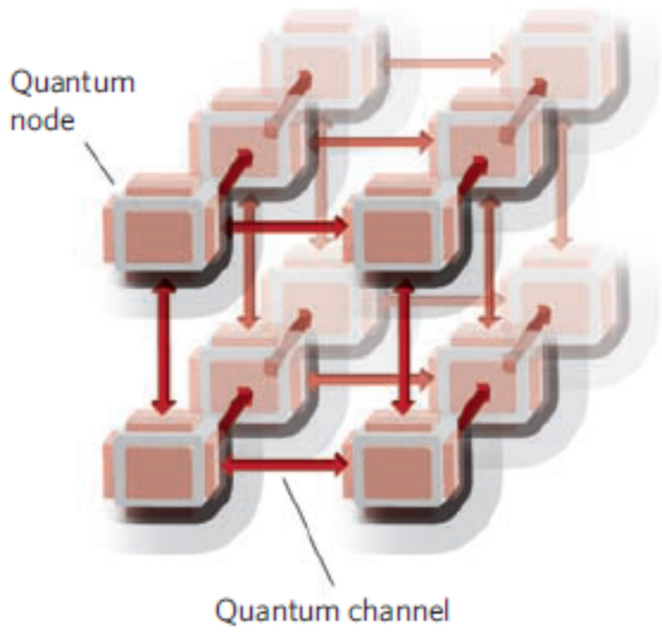


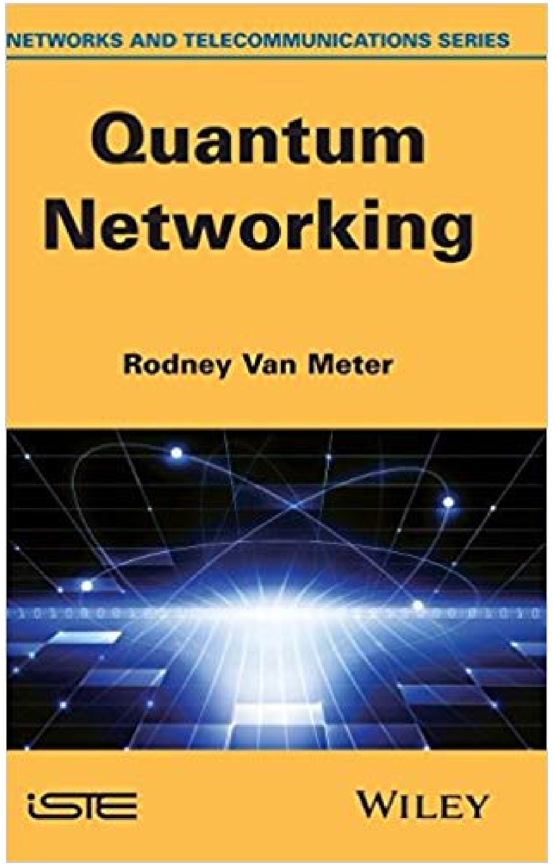
- C. L. Degen, F. Reinhard, P. Cappellaro, “Quantum Sensing”, Rev. Mod. Phys. 89, 035002 (2017)
- D. M. Toyli, C. D. Weis, G. D. Fuchs, T. Schenkel, D. D. Awschalom, NanoLett *10*, 3168 (2010)
- D. R. Glenn, et al., Nature 555, 351 (2018)

Quantum communication

- Quantum cryptography and quantum key distribution
- Information transfer with pairs of entangled photon
- Eavesdropping breaks interference and can be detected, hence info transfer is protected by physics
- Used commercially, but bit rates are low to date due to inefficient sources of single photons, entangled photons pairs, detectors
  - Free space vs fiber limits
  - Need for quantum repeaters
  - Need for transducers

- Paths to a "quantum internet" ?
  - H. J. Kimble, Nature 453, 1023 (2008)





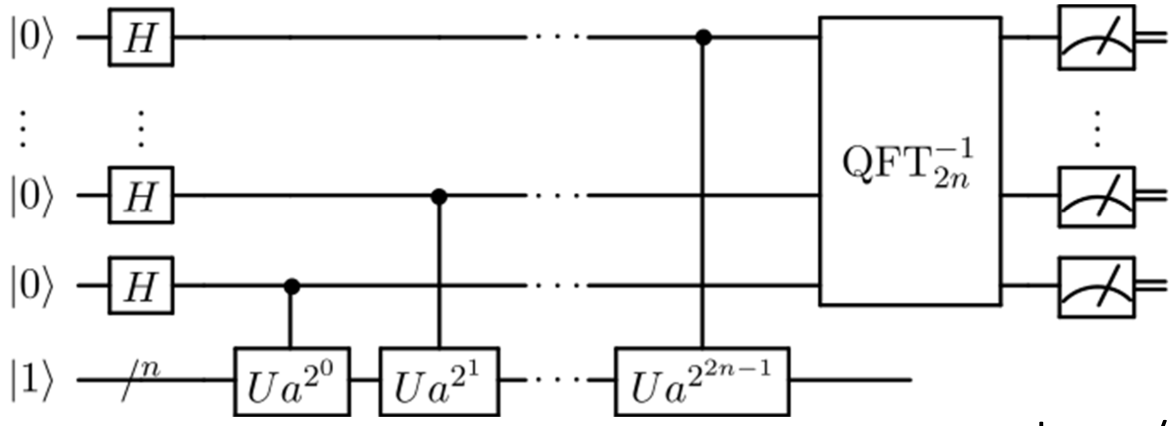
The promise of quantum computing

- Richard Feynman, “Simulating physics with computers”, 1981

- Peter Shor, "Algorithms for quantum computation: discrete logarithms and factoring“, 1994
  - Exponential speed-up in factoring of large numbers due to “quantum parallelism”

- Lov K. Grover, “A fast quantum mechanical algorithm for database search”, 1996
  - Sqrt (N) speedup in search (inverted function)

- Both Shor and Grover require error correction and thousands of logical qubits
- Quantum simulations can be conducted with a few qubits
- Intense race to achieve “quantum supremacy” for any problem



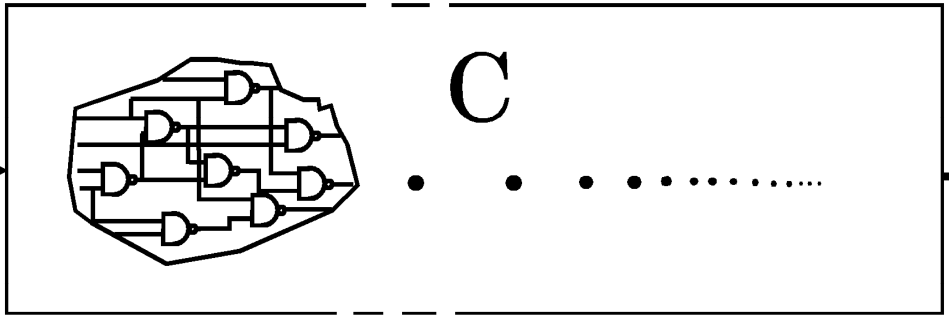
https://en.wikipedia.org/wiki/Shor%27s_algorithm

Fast Quantum Computation

Classical factoring problem required 8 months on hundreds of computers

RSA 129

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



Factors

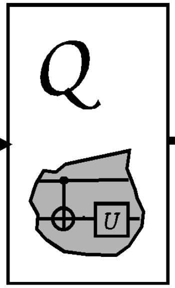
3490529510847650949
1478496199038981334
1776463849338784399
0820577

x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

Same Input and Output, but Quantum processing of intermediate data gives

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



3490529510847650949
1478496199038981334
1776463849338784399
0820577

x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

Exponential speedup
for Factoring

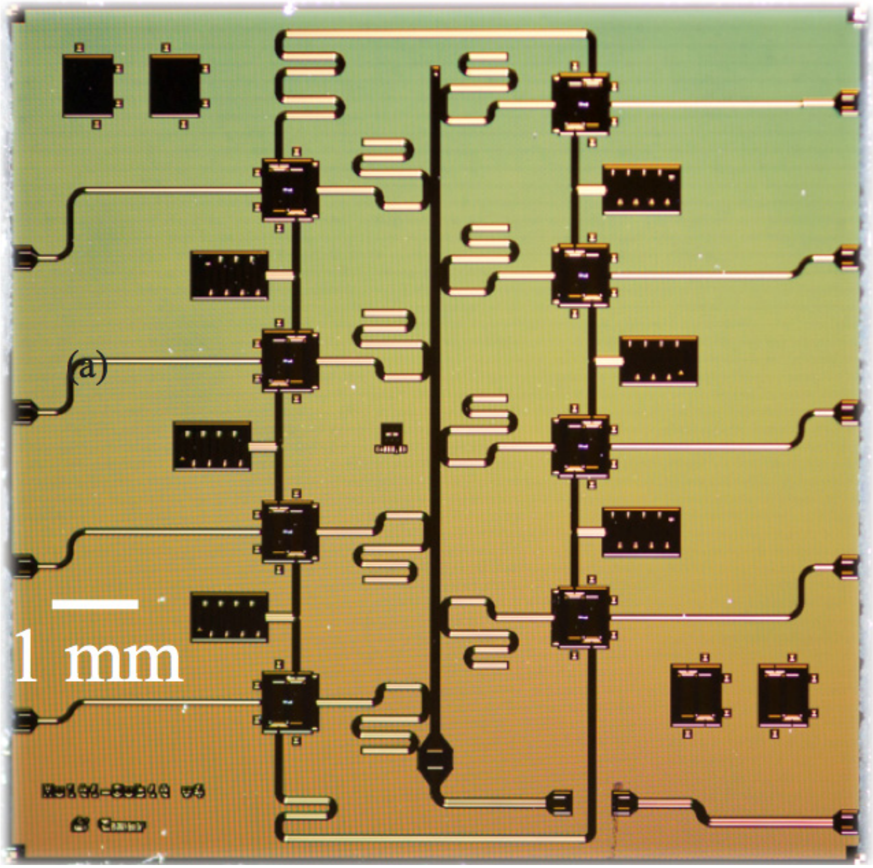
Quadratic speedup
for Search

Slide by David DiVincenzo

Quantum information processing in a nutshell

- entangle ensembles of qubits (control)
- prevent interaction with environment (max. coherence)
- run sequences of unitary operations on the qubits with single and two-qubit gates
- read-out the end result in a projective measurement

- but
  - quantum information can't be simply copied and refreshed (no cloning theorem)
  - error correction is required for runs longer than the coherence time
  - one logical qubit requires 100 to 1000 logical qubits for error corrections
  - quantum simulations without error correction might show speed-up over best classical for selected problems without error correction



Chip with eight superconducting circuit qubits, Irfan Siddiqi, https://berkeleyquantum.org

“Quantum Computing in the NISQ era and beyond”

John Preskill, Caltech

- **Noisy Intermediate-Scale Quantum (NISQ) technology**

- Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today’s classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably.

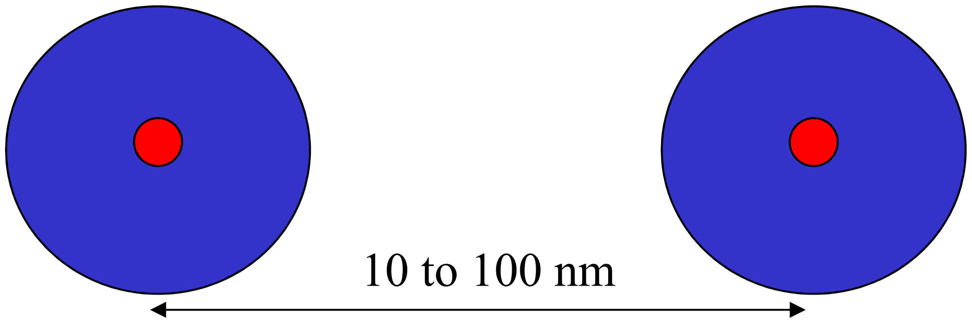
- NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future.

- Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

John Preskill, Quantum 2 (31 July 2018), p. 79; https://doi.org/10.22331/q-2018-08-06-79

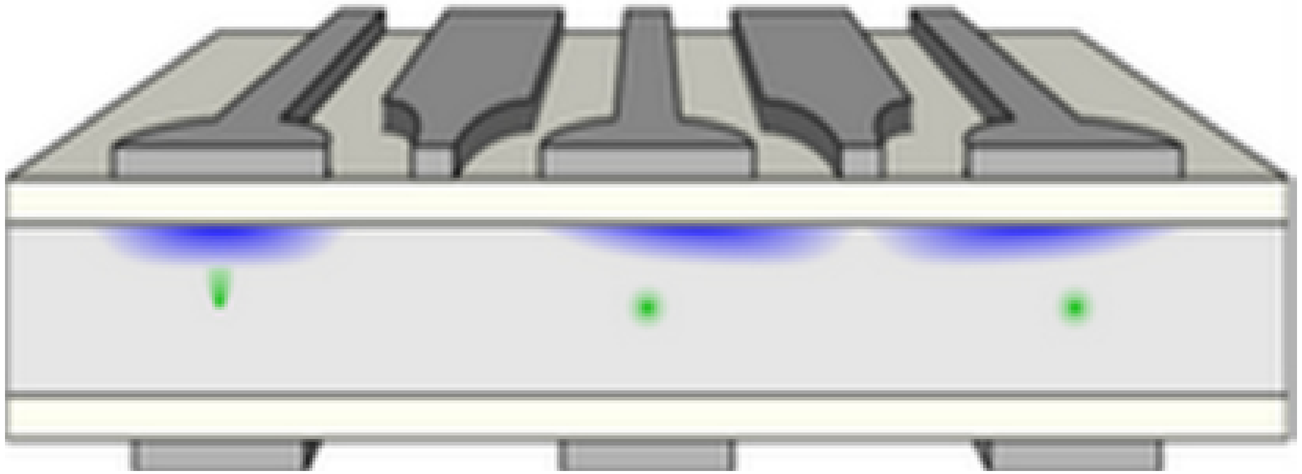
Criteria for physical implementation of a quantum computer **(D. DiVincenzo)**

1. Well defined extendible qubit array – stable memory
2. Initialization in the “000…” state
3. Long decoherence time (>10^4 operation time, to allow for error correction)
4. Universal set of gate operations (not, cnot)
5. Read-out: Single-quantum measurements (projective measurement)
6. Efficient quantum communication (form, transmit and convert “flying qubits”)



Nuclear and electron spins are promising qubit candidates

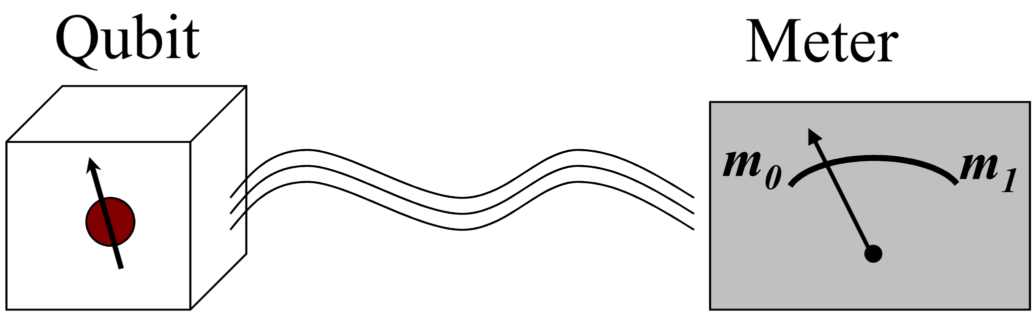
Spins of electrons and nuclei are promising qubit candidates



- Long coherence times, > 1 s
- Single shot single donor spin readout (A. Morello et al., Nature 467, 687, 2010)
- Fast single and two qubit gates (Y. He, et al., Nature 571, 371 (2019)
- Connectivity beyond nearest neighbor coupling not yet demonstrated
- Transducer to photons not demonstrated (early steps: C. M. Yin, et al., Nature 497, 91 (2013))
- Scaling has proven tricky to date

“Surface code architecture for donors and dots in silicon”, G. Pica, B. W. Lovett, R. N. Bhatt, T. Schenkel, and S. A. Lyon, Phys. Rev. B **93**, 035306 (2016)

Quantum state measurement



$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

$$\Pr\{m_0\} = |\alpha|^2$$
$$\Pr\{m_1\} = |\beta|^2$$

QND (quantum non-demolition) measurement

t – Measurement result $= m_0 \Rightarrow |\psi(t)\rangle = |0\rangle$

$\Downarrow$

t' – $|\psi(t')\rangle = |0\rangle \Rightarrow$ Measurement result $= m_0$

time

M. Sarovar, K. C. Young, T. Schenkel, K. B. Whaley, "Quantum-non demolition measurements of single spins in semiconductors", Phys. Rev. B 78, 245302 (2008)

Approach to measure the spin state of an electron

$$|\psi_i\rangle = \alpha|0\rangle + \beta|1\rangle$$

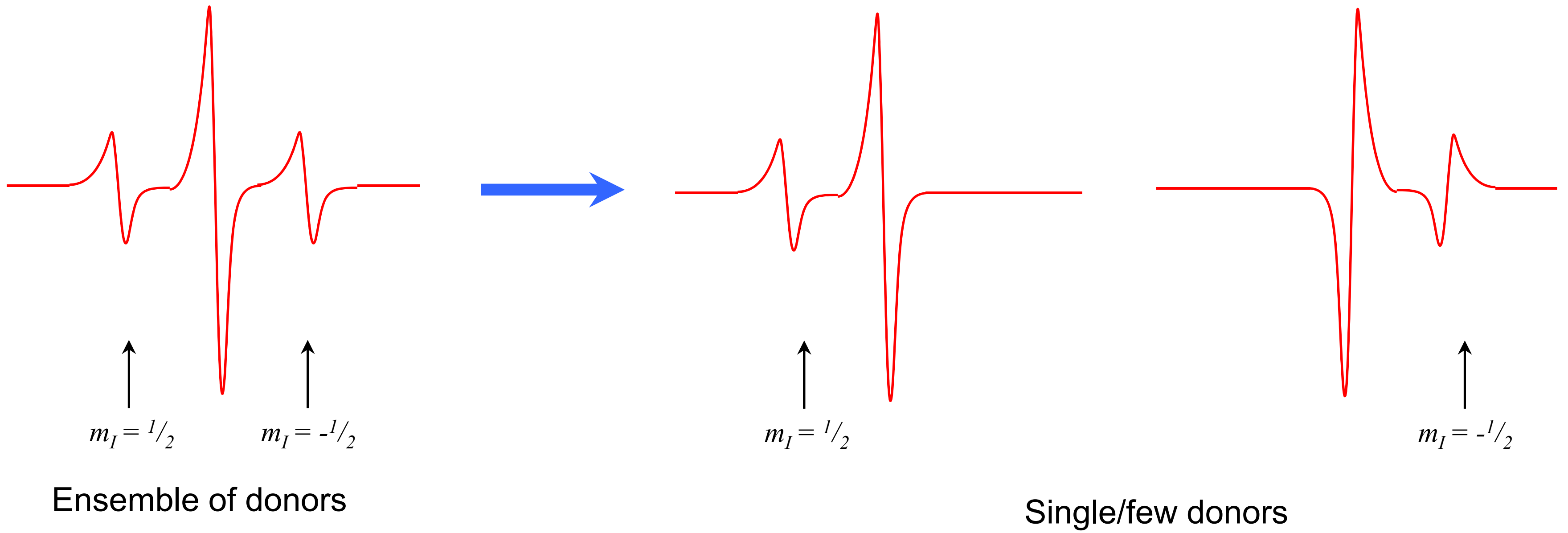
1. transfer electron spin state information α and β, onto nuclear spin populations
2. electrically detected magnetic resonance (EDMR) measures the nuclear spin state populations
3. measurement must be completed within T_1 of nucleus under conditions of driving electron spin on resonance

M. Sarovar, K. C. Young, T. Schenkel, K. B. Whaley, “Quantum-non demolition measurements of single spins in semiconductors”, Phys. Rev. B 78, 245302 (2008)

Readout of a single nuclear spin

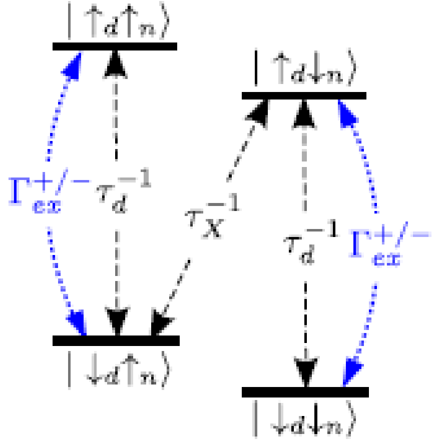
- Donor nuclear spin population measured by presence/absence of spin resonance lines
- Need to measure before nuclear spin flips, i.e., within T_1 of nucleus
- Repeat entire procedure → values of α and β for electron spin qubit

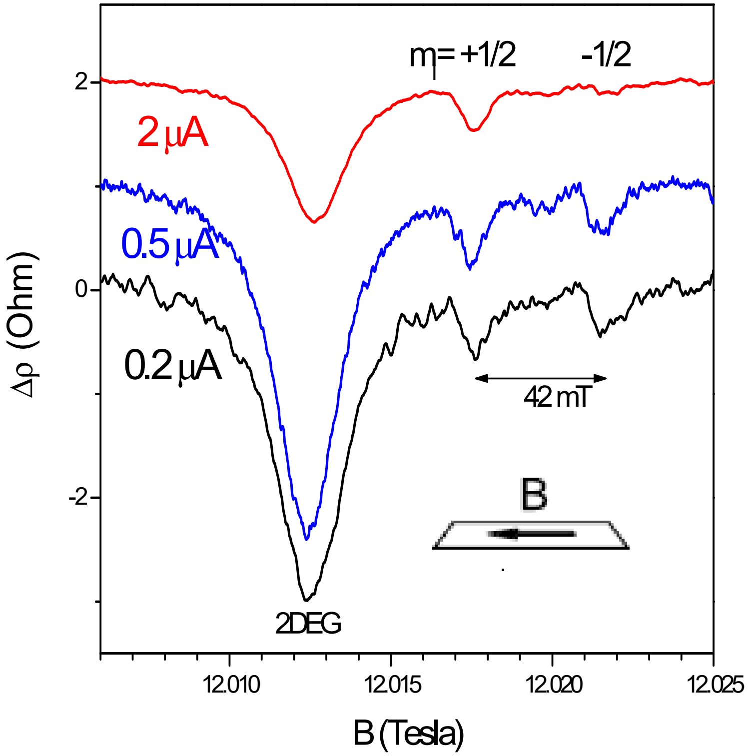
$$|\Psi_e\rangle = \alpha|\uparrow\rangle_e + \beta|\downarrow\rangle_e$$



- J. J. L. Morton, A. M. Tyryshkin, R. M. Brown, S. Shankar, B. W. Lovett, A. Ardavan, T. Schenkel, E. E. Haller, J. W. Ager, S. A. Lyon, "Solid state quantum memory using the ^{31}P nuclear spin", Nature 455, 1085 (2008)
- M. Sarovar, K. C. Young, T. Schenkel, K. B. Whaley, "Quantum-non demolition measurements of single spins in semiconductors", Phys. Rev. B 78, 245302 (2008)
- J. J. Pla, F. A. Mohiyaddin, K. Y. Tan, J. P. Dehollain, R. Rahman, G. Klimeck, D. N. Jamieson, A. S. Dzurak, A. Morello, "Coherent Control of a Single 29Si Nuclear Spin Qubit", Phys. Rev. Lett. 113, 246801 (2014); J. Pla et al., Nature 496, 334 (2013)

All-electrical nuclear spin polarization of donors





- "hot" 2DEG electrons from high source-drain bias fields, rapid exchange scattering leads to difference in spin and lattice (phonon) temperatures
- Nuclear polarization detected by EDMR
- 5K, 300GHz radiation and in-plane B-field (co. J. van Tol, NHMFL, Tallahassee)

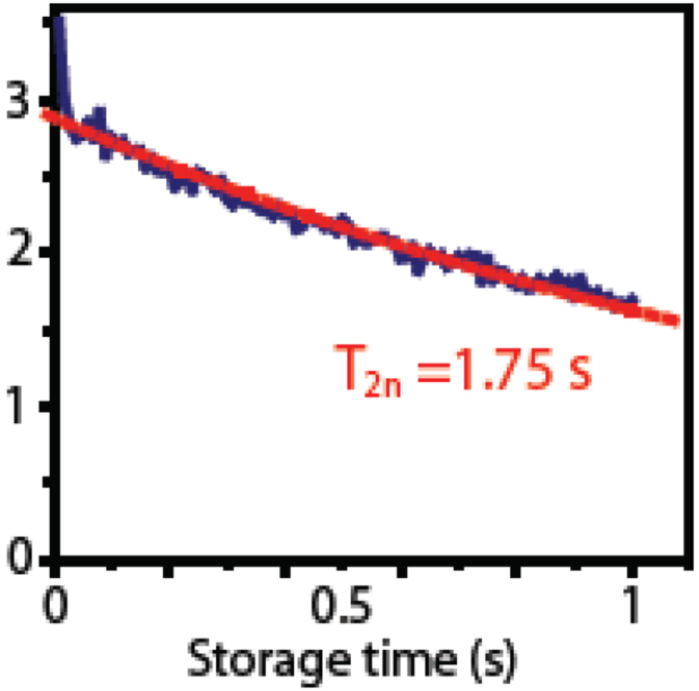
$$\tau_X \sim \frac{1}{B^2 T A^2 I}$$

- τ_X: electron-nuclear spin flip-flop rate scaling
  - B: external magnetic field
  - T: temperature
  - A: hyperfine coupling strength
  - I: nuclear spin
- $P_n = {}^{(Y\uparrow n - Y\downarrow n)}/_{(Y\uparrow n + Y\downarrow n)}$ =66% for Phosphorus at 12 T (I=1/2, A=0.1 GHz)

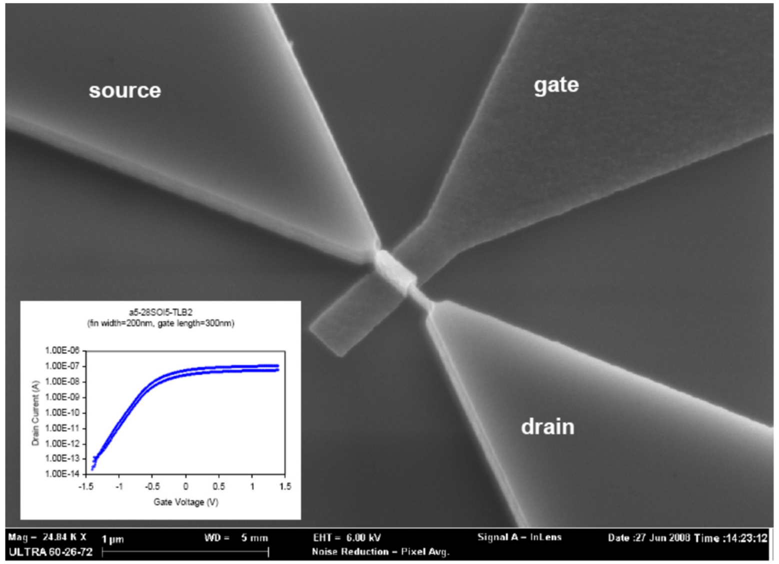
→ **Expect for Bismuth at 0.3 T (I=9/2, A=1.5 GHz)**

C. C. Lo, C. D. Weis, J. van Tol, J. Bokor, T. Schenkel, "All-Electrical Nuclear Spin Polarization of Donors in Silicon", Phys. Rev. Lett. 110, 057601 (2013)

Long coherence times of donor spins in silicon devices



- Recovered echo intensity vs. nuclear spin storage time showing a ^{31}P nuclear spin coherence time of 1.75 s in ^{28}Si.



- 100 nm scale FinFet spin readout transistor formed in isotopically purified silicon on insulator (^{28}SOI) and implanted with ^{121}Sb. I_{sd}-V_g curves in the insert.

J. Morton, A. Tyryshkin, R. Brown, S. Shamkar, B. Lovett, A. Ardavan, T. Schenkel, E. Haller, J. Ager, S. Lyon, Nature 455, 1085 (2008)

C. C. Lo, A. Persaud, T. Schenkel, J. Bokor, et al., Semicond. Sci. Tech 24, 10522 (2009)

Outline

1. Qubits

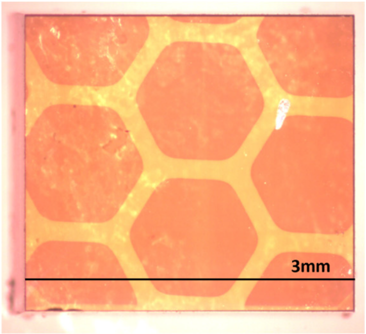
2. Beams

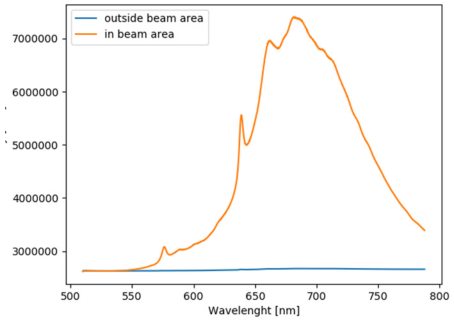
3. Fusion

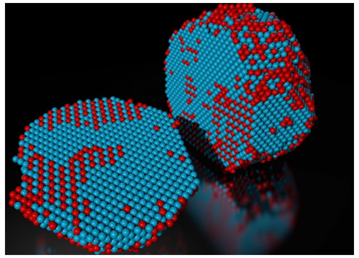
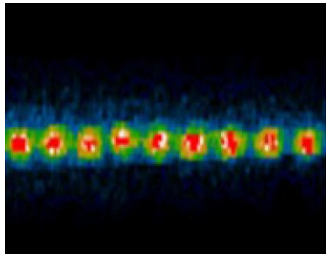
4. Outlook

Beams and qubits

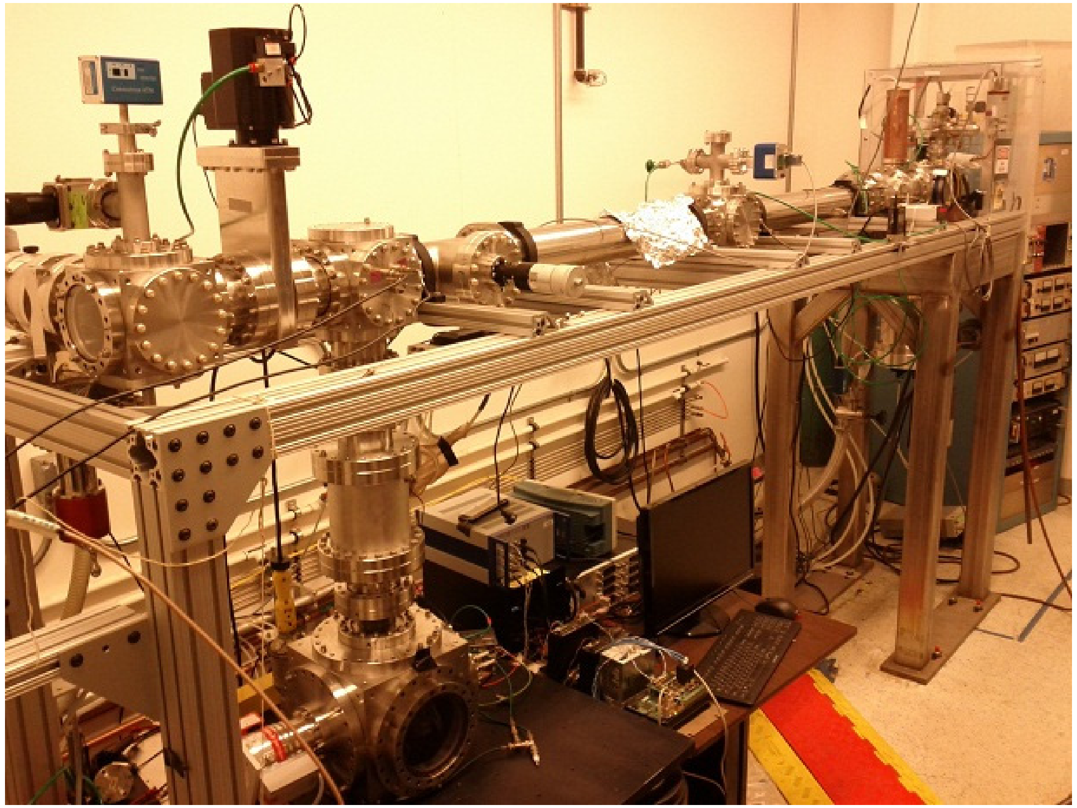
- Qubit array formation with ion beams
- Beam driven qubit synthesis
- Electron microscopy to image qubits
- Ion traps and “quantum beams”

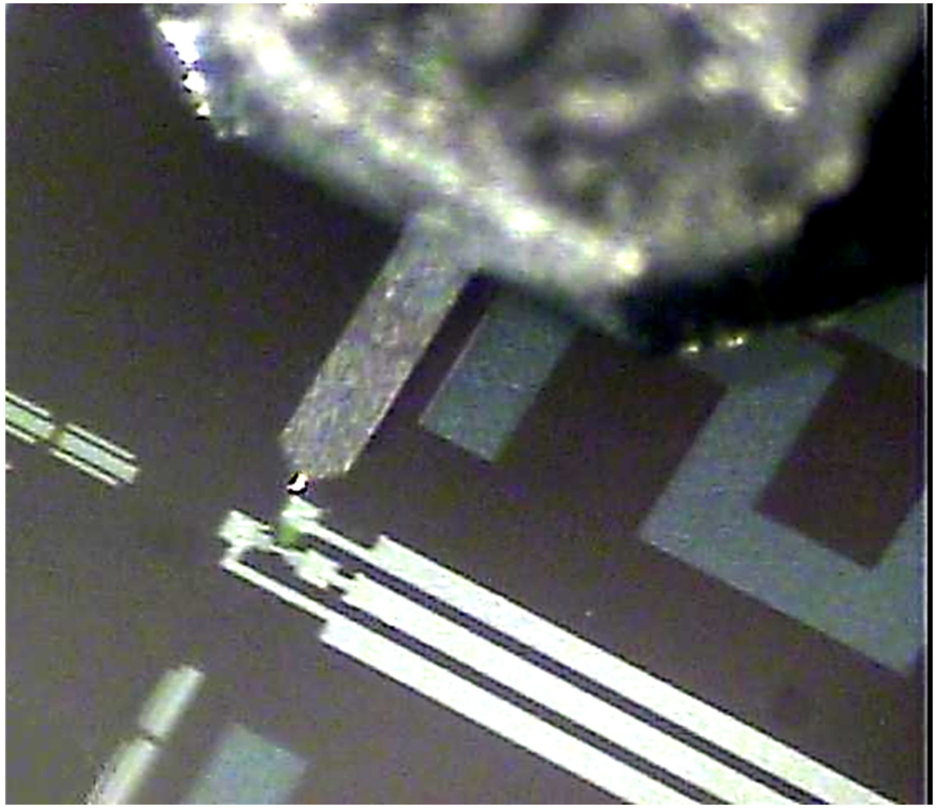




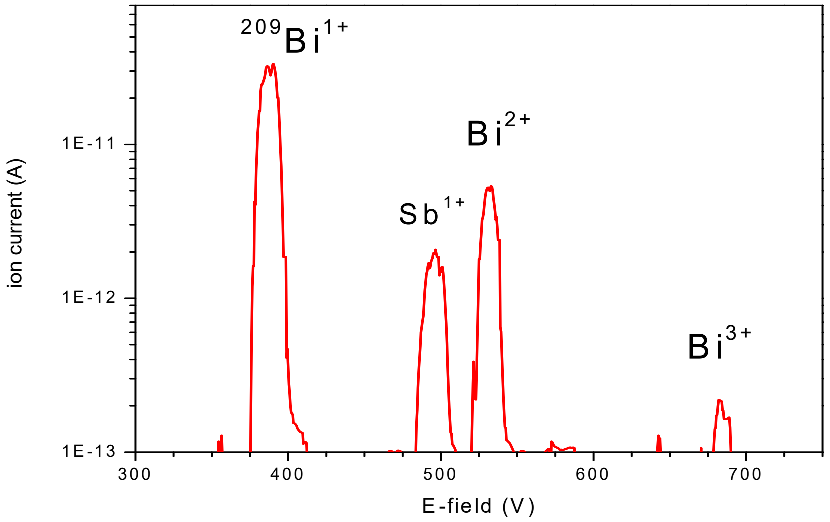
Qubit array formation -
Single Ion Implantation with Scanning Probe Alignment

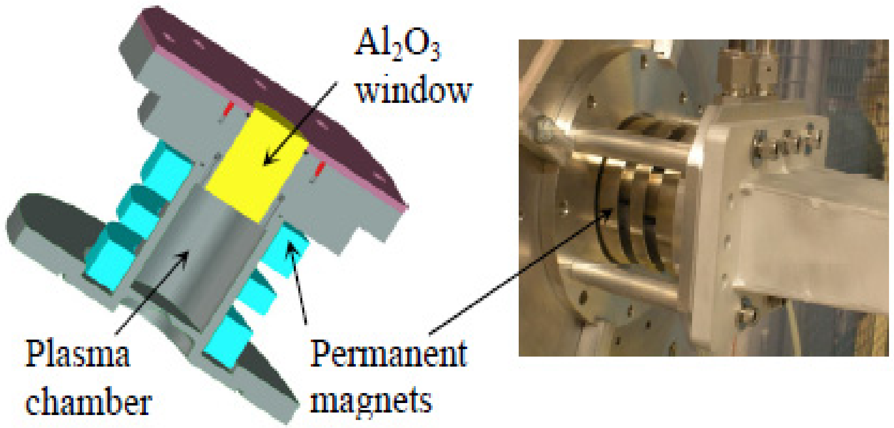


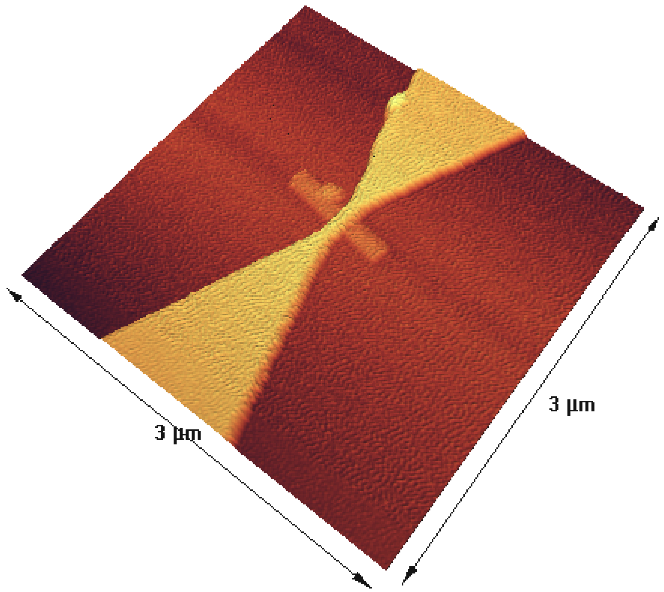


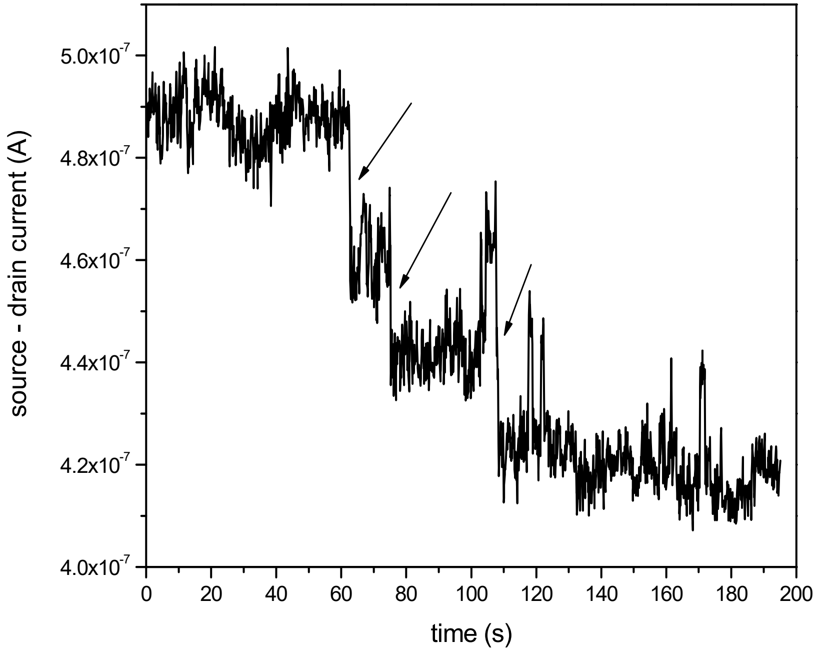
https://www.youtube.com/watch?v=zTbBa5pvNdU

Deterministic implantation of single bismuth ions



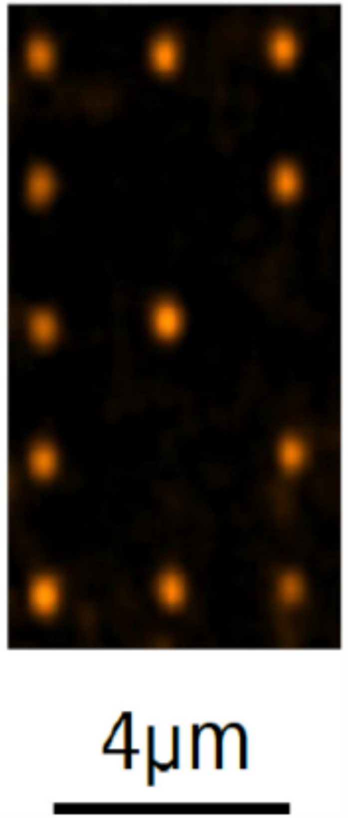


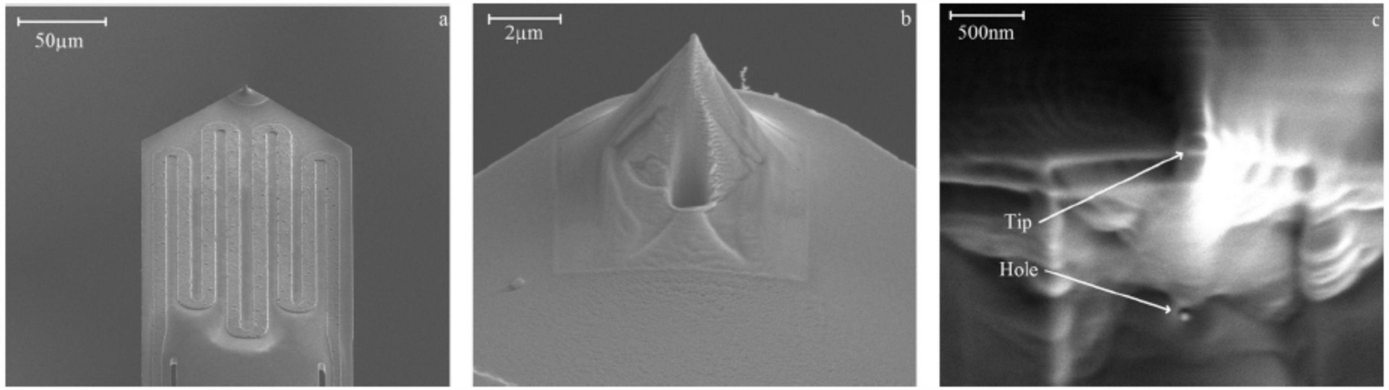




- Bi+, 10keV, 80x4000 nm device, ΔI/I ~5%

Single Ion Implantation with Scanning Probe Alignment

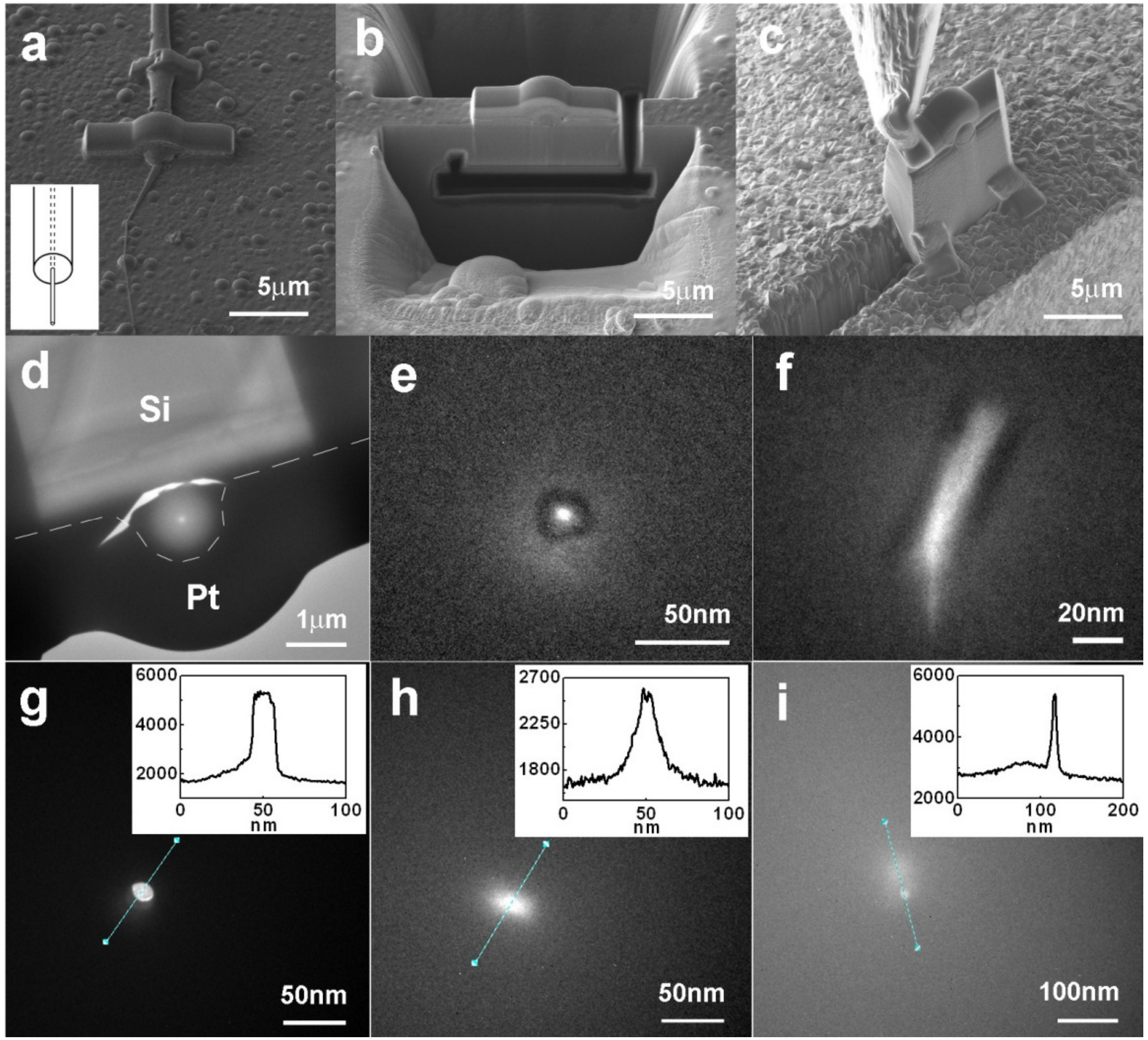




- NV-center array formation with dynamic shadow mask
- best spatial resolution achieved: 50 nm, smallest hole: 5 nm

M. Ilg, …, T. Schenkel, …, et al., J. Vac. Sci. Technol. B 30, 06FD04-1 (2012)

Ultimate limit in dopant placement by implantation ?



• We demonstrated transport of 200 keV electrons through a carbon nanotube over a length of several microns

•The nanotube can act as a collimator for low energy ions with an aperture of 1 to 10 nm

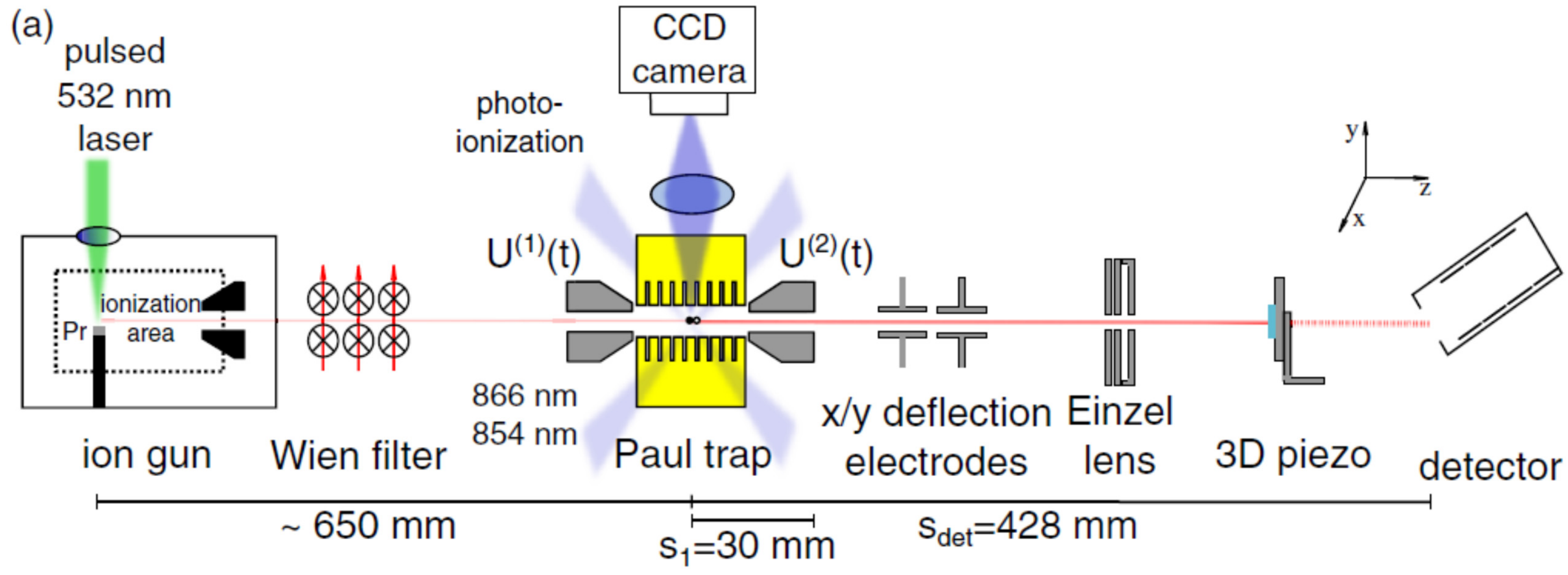
•Straggling can be minimized with low energy and high Z ions to <5 nm

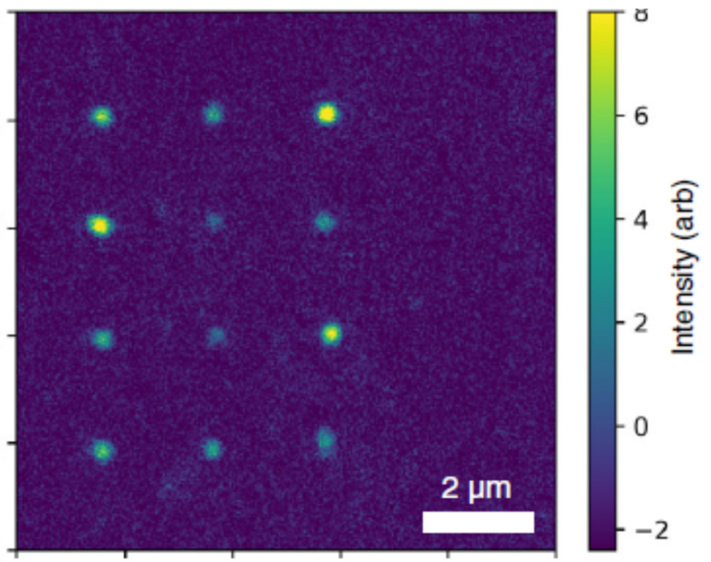
• Diffusion / segregation: some dopants stay put

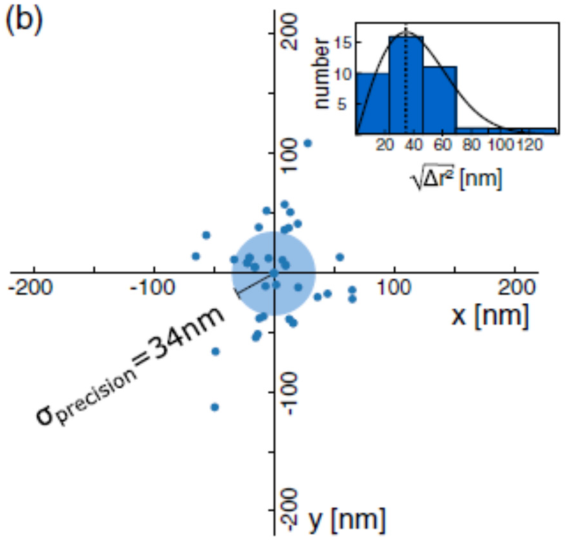
→**few nm ion placement accuracy seems possible**

G. Chai, H. Heinrich, L. Chow, and T. Schenkel, "Electron transport through single carbon nanotubes", Appl. Phys. Lett. 91, 103101 (2007)

Deterministic ion beams for qubit array formation

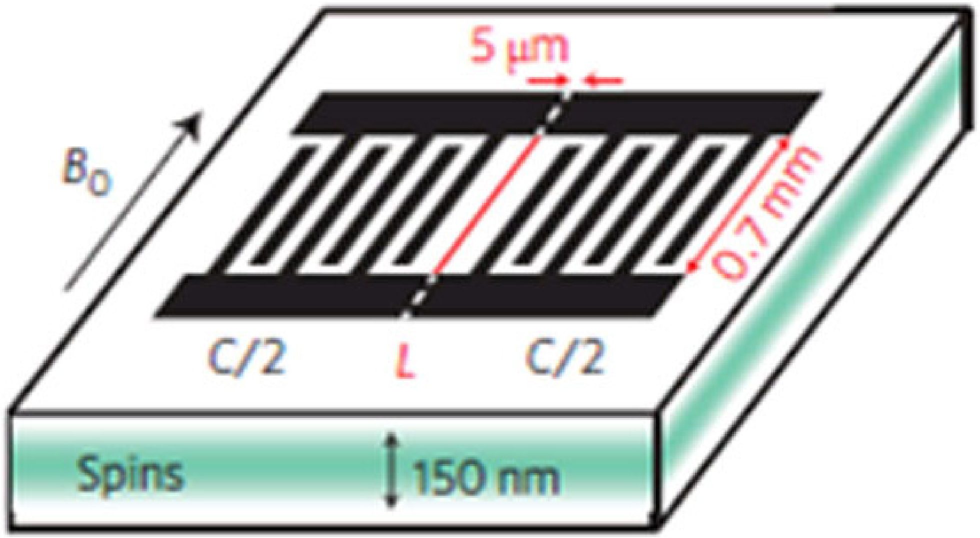


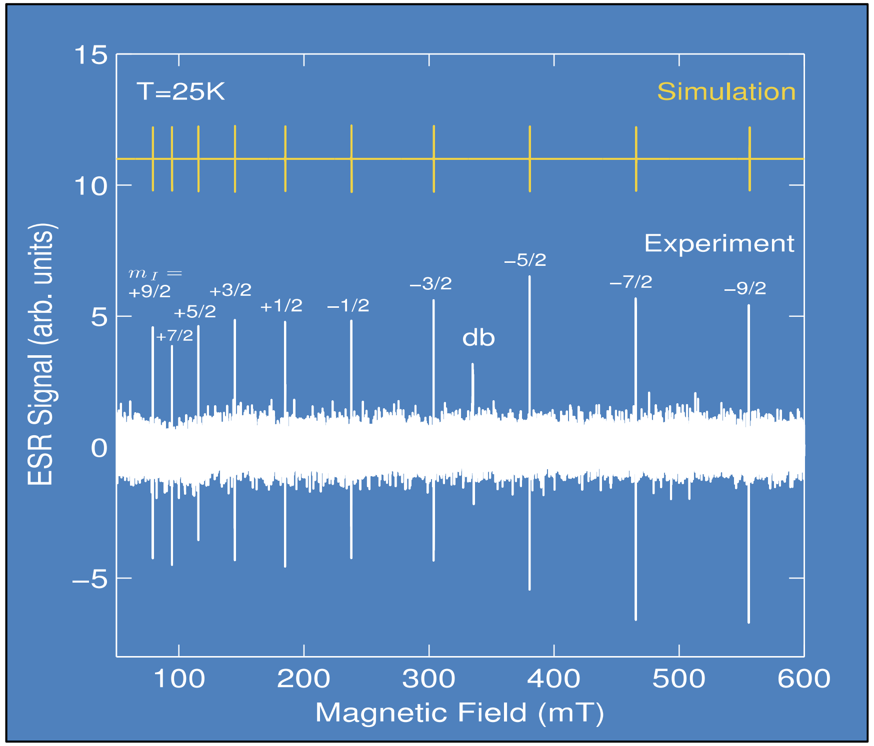




K. Groot-Berning, T. Kornher, G. Jacob, F. Stopp, S. T. Dawkins, R. Kolesov, J. Wrachtrup, K. Singer, F. Schmidt-Kaler, „Deterministic Single-Ion Implantation of Rare-Earth Ions for Nanometer-Resolution Color-Center Generation", Phys. Rev. Lett. 123, 106802 (2019)

Can we extend the parameter space for qubit synthesis with intense beams ?





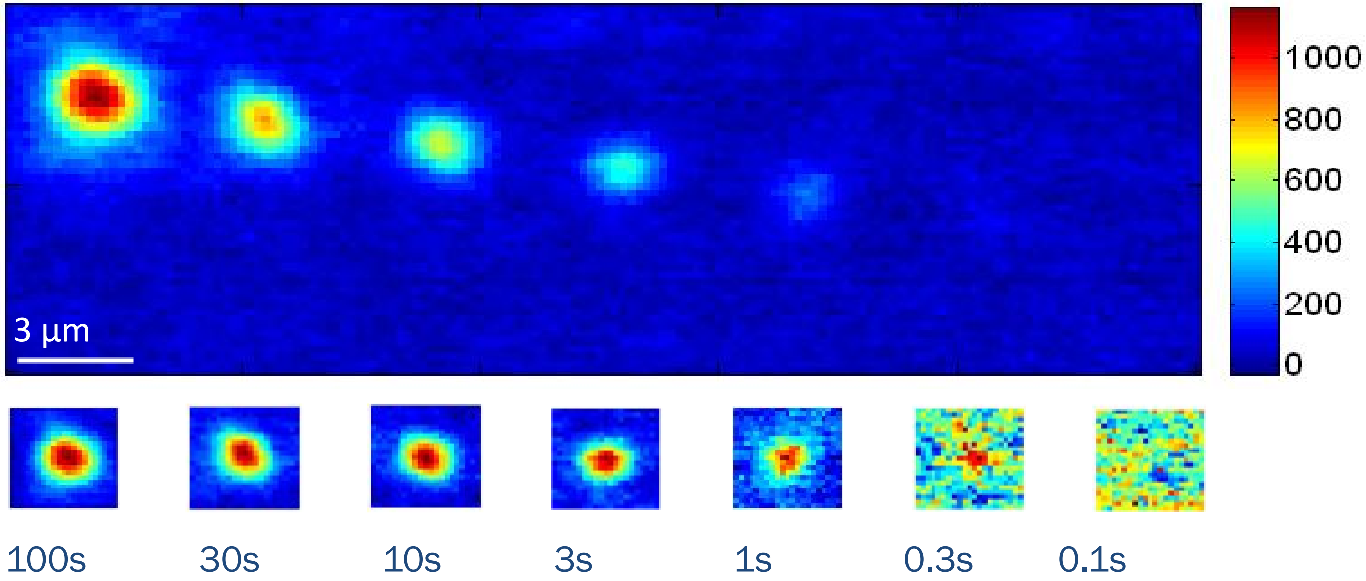
- Bismuth doped ^{28}Si enabled the demonstration of the Purcell effect with spins
- But only 60% of the bismuth atoms were electrically active

→ Opportunity to improve with processing under "extreme conditions"?

→ Opportunity for quantum sensing applications using spins

"Controlling spin relaxation with a cavity", A. Bienfait, J. Pla, Y. Kubo, X. Zhou, M. Stern, C. C. Lo, C. D. Weis, T. Schenkel, D. Vion, D. Esteve, J. J. L. Morton, P. Bertet, Nature 531, 74 (2016)

Beam driven formation of nitrogen-vacancy centers in diamond



- confocal PL image of NV^- centers (635–642 nm) at room temperature, recorded following exposure of 1 µm squares to a 9 pA, 2 keV electron beam. Insets show locally auto-scaled spots.

- **local activation enables iterative formation of NV^- in arrays**
- **can we form color centers with tailored properties ?**

- Note: activation of NV^0 centers in diamond by low energy electrons and high energy ions was reported already in the 70s and 80s (see A. M. Zaitsev, 2001)

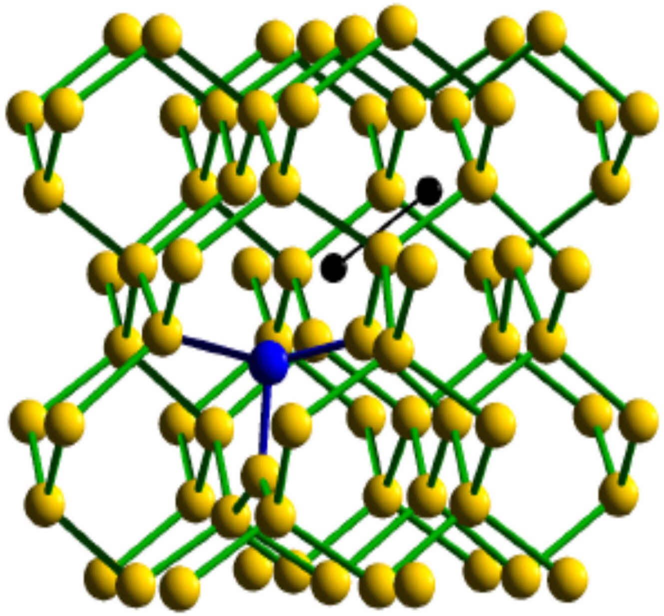
J. Schwartz, ..., T. Schenkel, et al., New J. Physics, 2012; J. Appl. Phys. 2014

How do NV-centers form in diamond?

$N_{substitutional} + V \rightarrow NV^{0,-}$

vs.

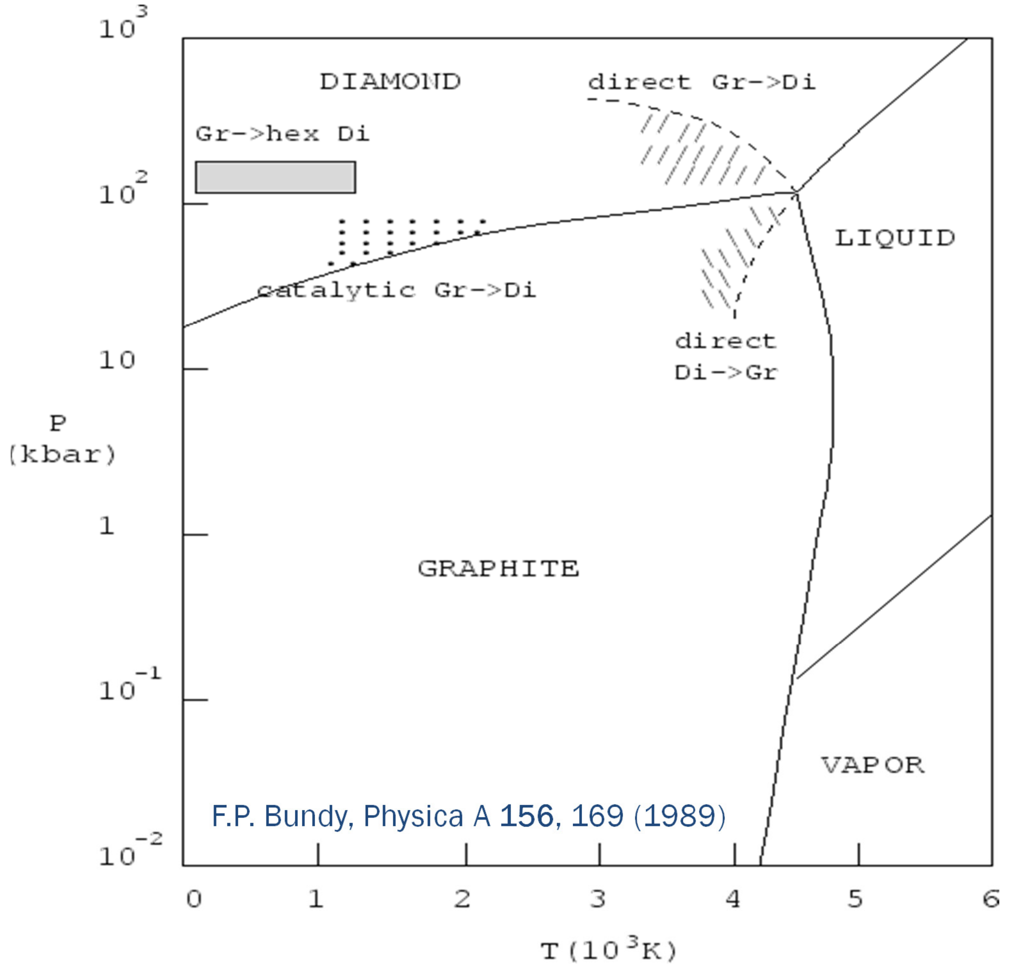
$N_{interstitial} + V_n \rightarrow NV^{0,-}$

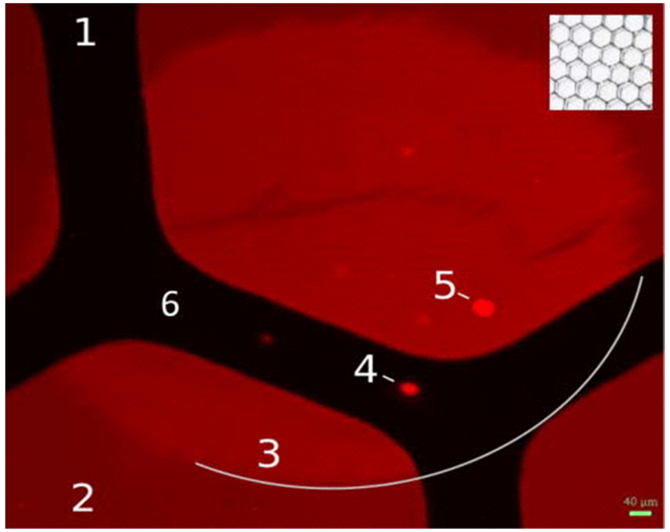


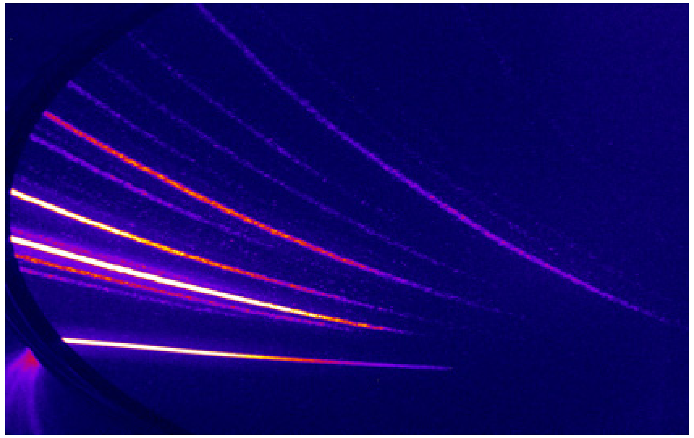
- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at >300°C
- J. Adler, R. Kalish, et al., J. of Physics, 2014
- P. Deak et al. PRB 2014: di-vacancy formation favored over NV formation during annealing of N rich diamond after vacancy producing irradiation

J. Schwartz, ..., T. Schenkel, ..., et al., NJP 2012, JAP 2014

Qubit synthesis with intense beams



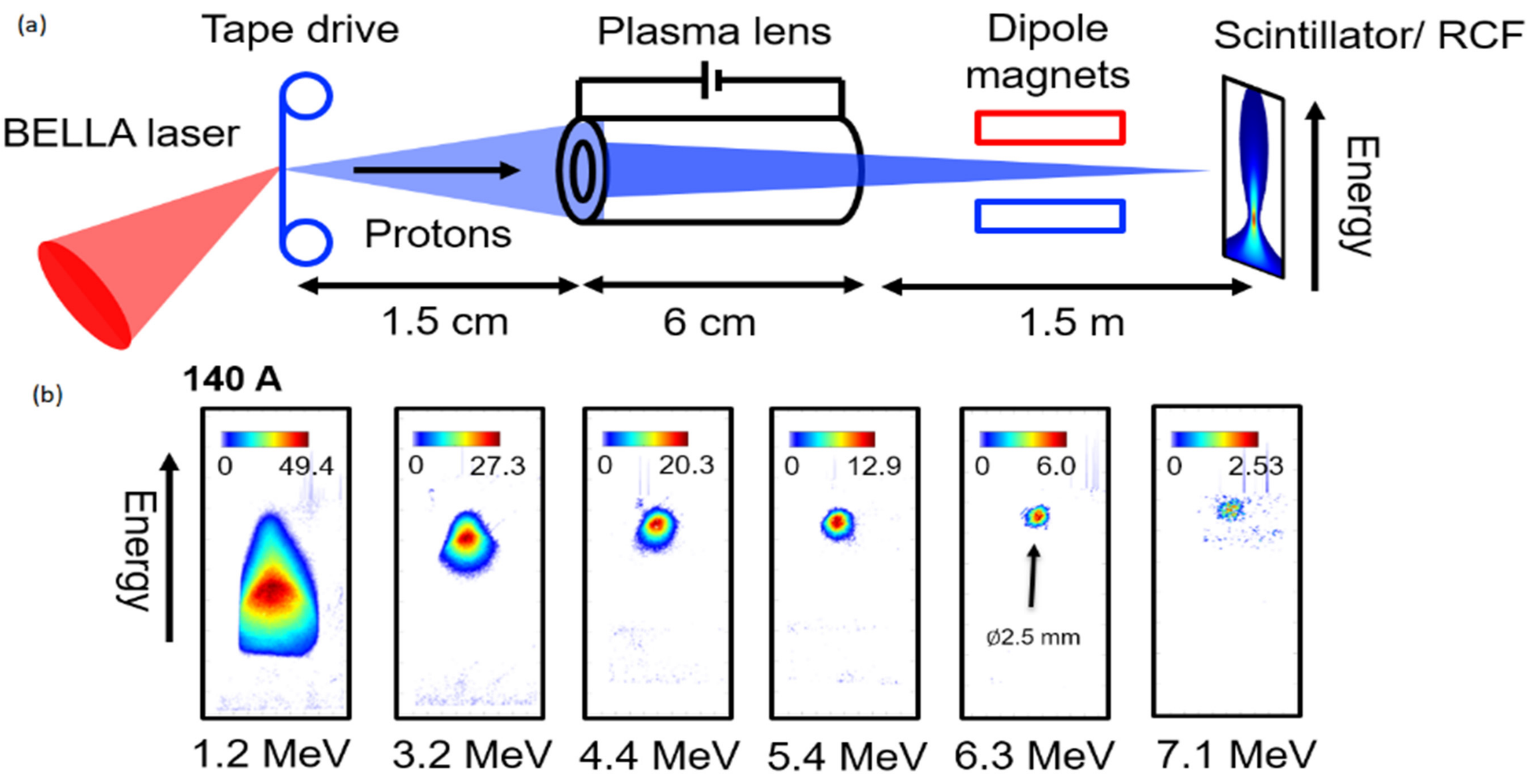




- NV-centers in diamond a great, but …
- Can we form color center qubits that emit light in the telecom bands ?
- Local melting, intense excitation, rapid re-crystallization

J. Schwartz, et al., JAP (2014)
J. H. Bin et al., RSI (2019)

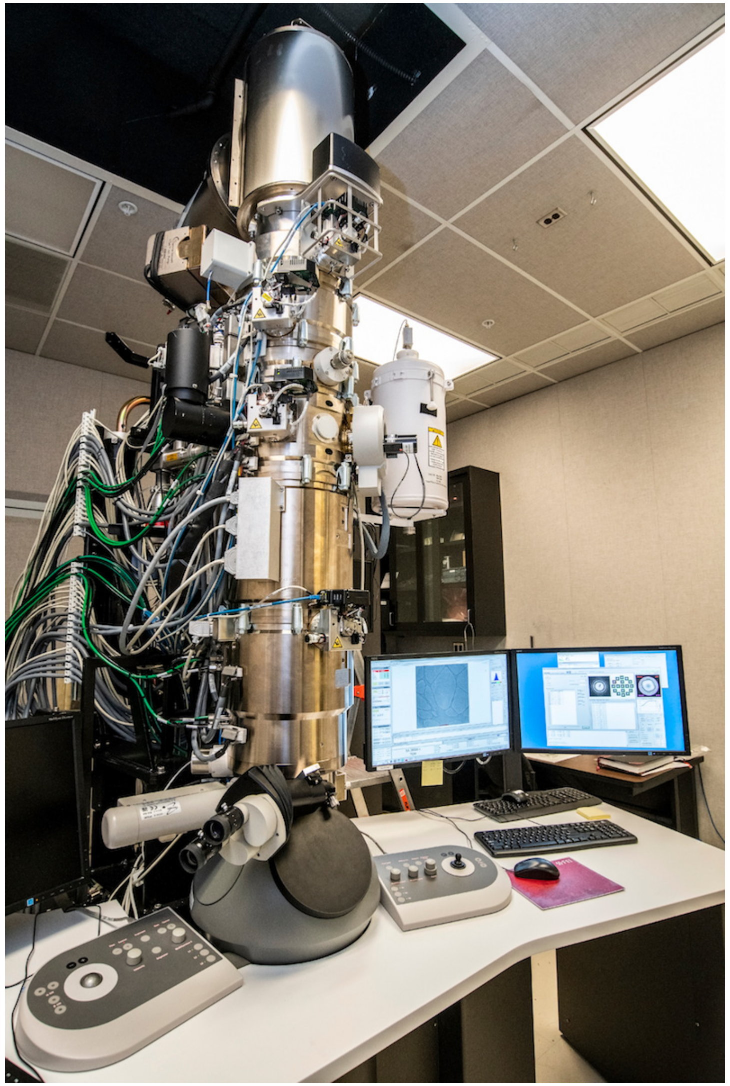
Intense ion pulses for synthesis of color centers



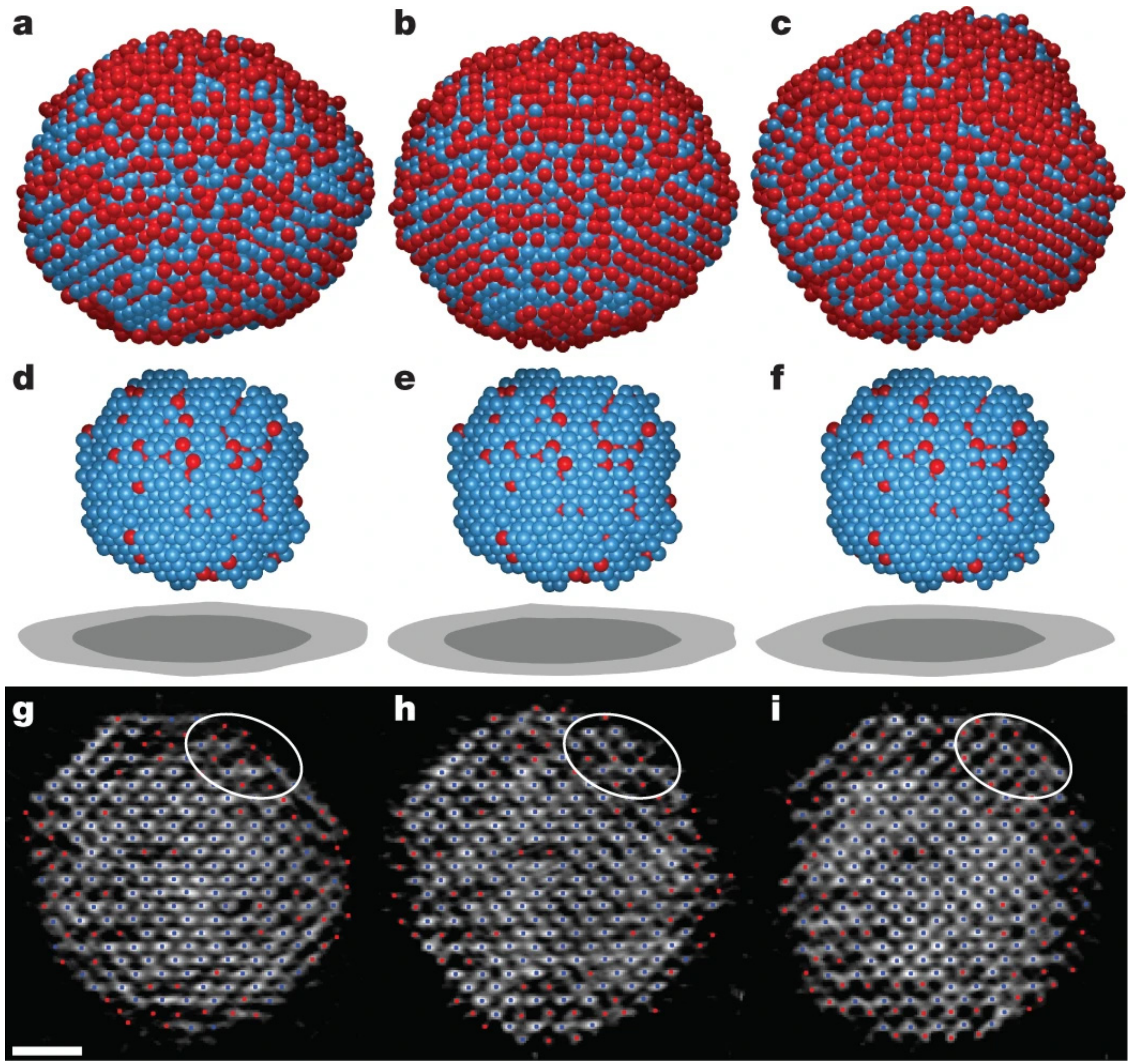
- Experiments with >1000 petawatt shots per day enable tuning, alignment, parametric studies
- The BELLA Center is part of LaserNetUS, https://www.lasernetus.org/

Sven Steinke, Jianhui Bin, et al., in preparation
J. H. Bin, Q. Ji, P. A. Seidl, D. Raftrey, S. Steinke, A. Persaud K. Nakamura, A. Gonsalves, W. P. Leemans, T. Schenkel, Rev. Sci. Instr. 90, 053301(2019)

Beams and qubits – electron microscopy from structure to coherence

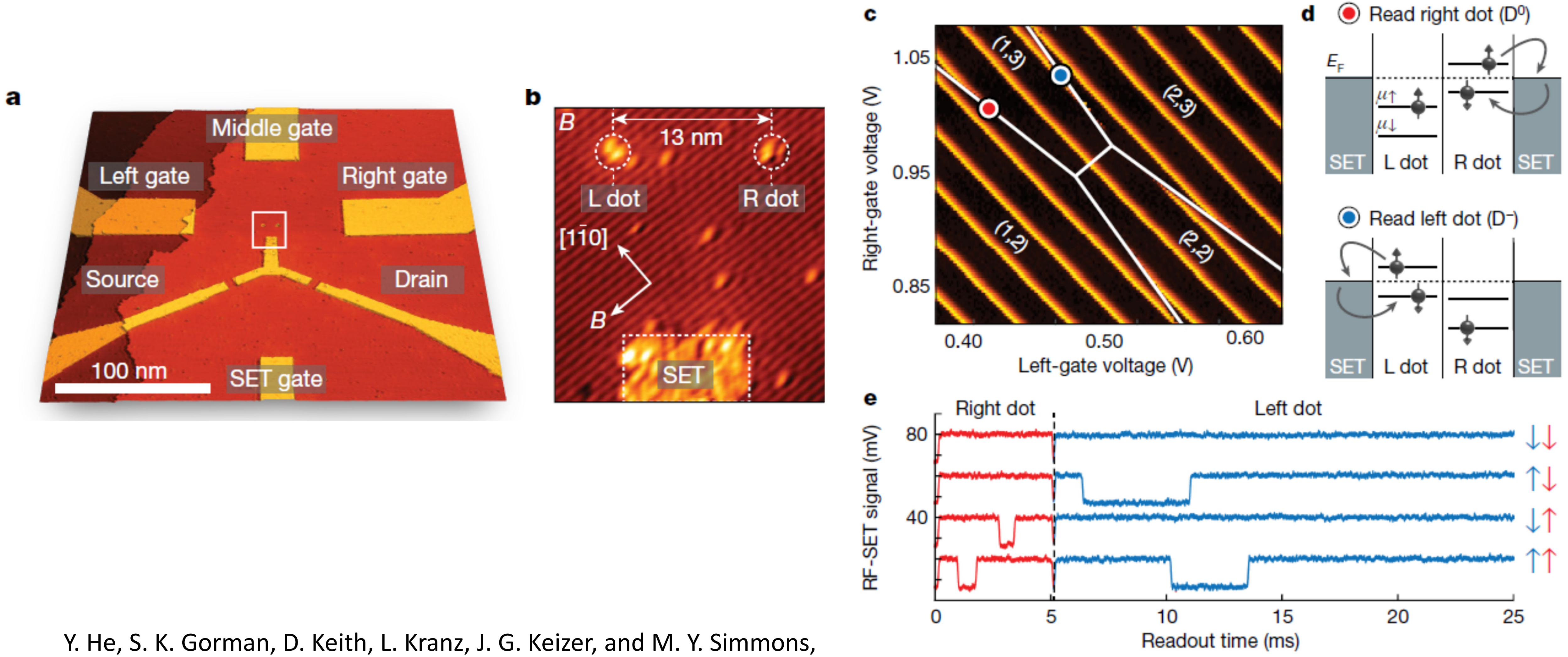


https://newscenter.lbl.gov/2018/06/07/theres-a-new-microscope-in-town-themis-anyone/



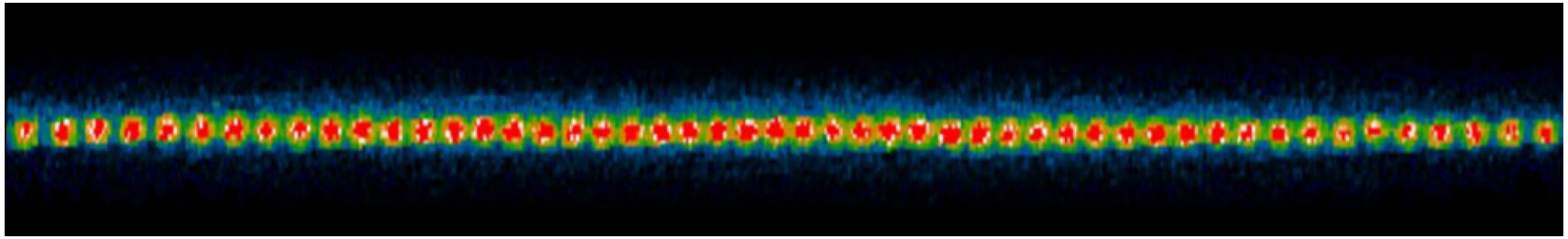
J. Zhou, et al., "Observing crystal nucleation in four dimensions using atomic electron tomography", Nature **570**, 500 (2019)

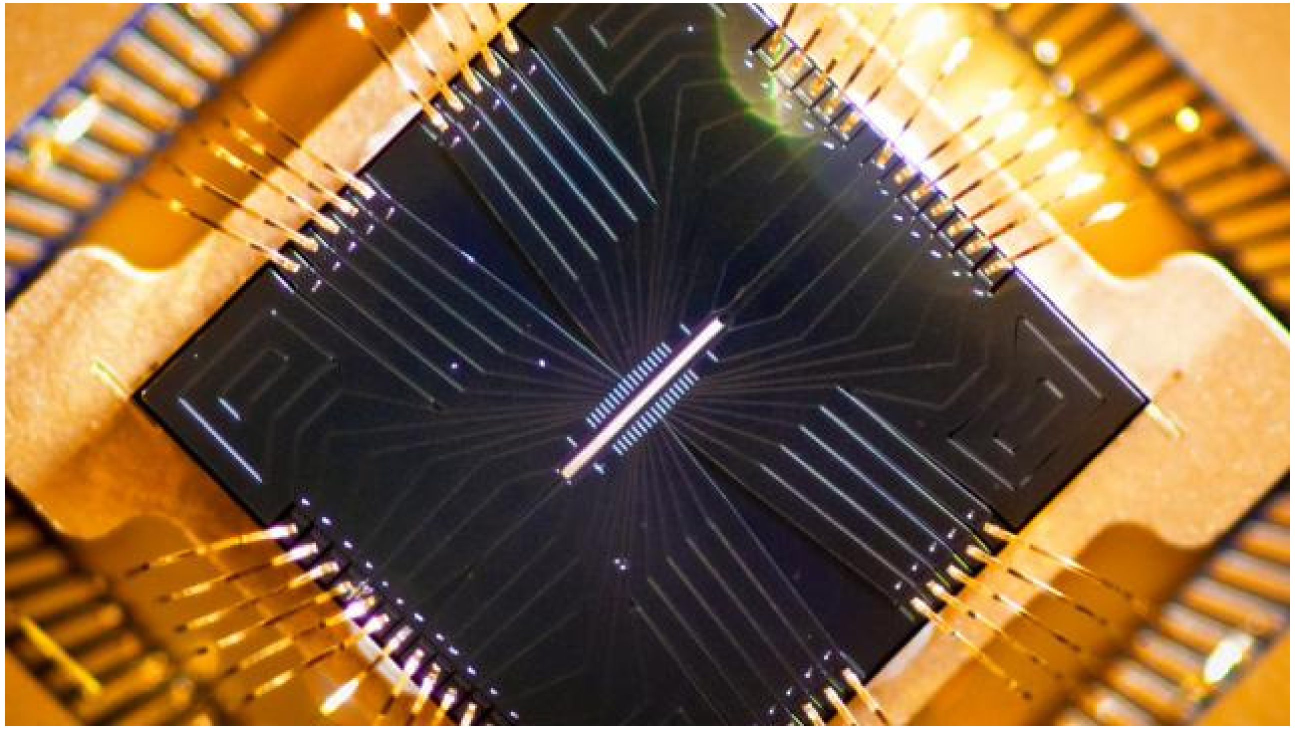
Towards qubit integration with atomic precision



Y. He, S. K. Gorman, D. Keith, L. Kranz, J. G. Keizer, and M. Y. Simmons, "A two-qubit gate between phosphorus donor electrons in silicon", Nature 571, 371 (2019)

Qubits and beams – trapped ions





Chris Monroe, http://iontrap.umd.edu/

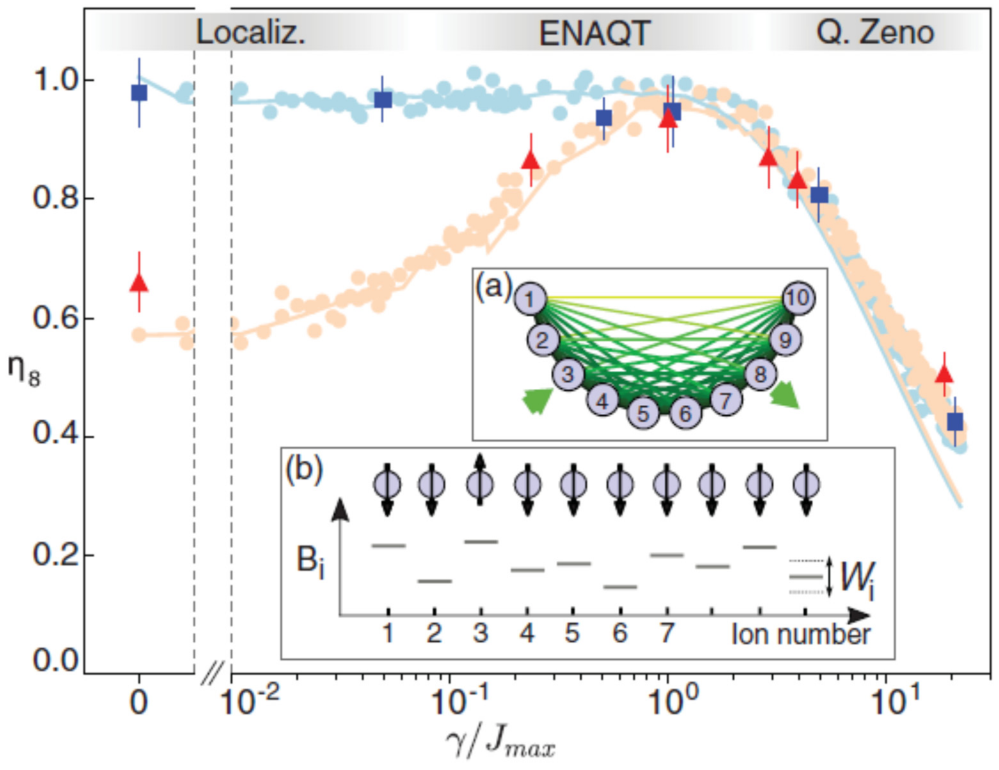
Noise and coherence

- “One scientists noise is another one’s qubit”*

- Markovian – no memory
- Non-Markovian – imprint in the environment, memory

- Beam cooling

- Beam and qubit themes connect in the quest for “ultimate beams”
  - Intensity, brightness, control and predictability



Environment-Assisted Quantum Transport in a 10-qubit Network, C. Meier, et al., PRL 122, 050501 (2019)

Beams and qubits

- Accelerator Science and Technology can advance Quantum Information Science
- QIS can advance Accelerator Science and Technology

- Accelerators for QIS
  - Qubit integration (spin qubits, trapped ions, cavities, …)
  - Microscopy of quantum materials – structure and coherence
  - Simulations of ion and atom qubits
  - Probing of space-time
  - …

- QIS for Accelerators
  - Cooling and quantum beams
  - Speed-up in simulations?
  - Noise – Markovian and non-Markovian
  - …

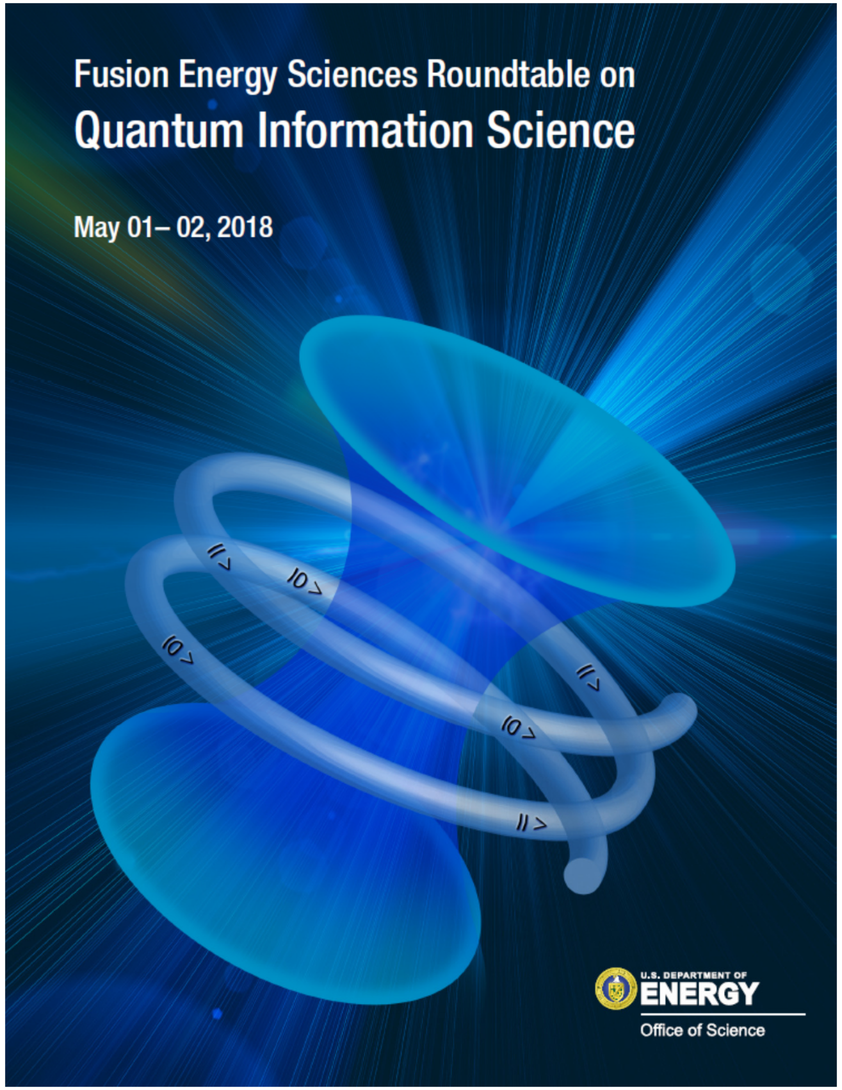
Outline

1. Qubits

2. Beams

3. Fusion

4. Outlook



https://science.osti.gov/fes/Community-Resources/Workshop-Reports
https://science.osti.gov/-/media/fes/pdf/workshop-reports/FES-QIS_report_final-2018-Sept14.pdf?la=en&hash=E4BDACCE1E6975AEE8D2B07778A42E8966048275

- **Can emerging Quantum Information Science advance Fusion Energy Sciences ?**
  - **Quantum for Fusion**

- **Can research in Fusion Energy Sciences advance Quantum Information Science ?**
  - **Fusion for Quantum**

Priority Research Opportunities for Quantum Information Sciences to advance Fusion Energy Sciences (Quantum for Fusion)

PRO 1: Reconceptualizing classical plasma physics problems for quantum computation

PRO 2: Quantum simulation for fusion problems (near term)

PRO 3: Quantum sensing for plasma diagnostics

Priority Research Opportunities for Fusion Energy Sciences to advance Quantum Information Science (Fusion for Quantum)

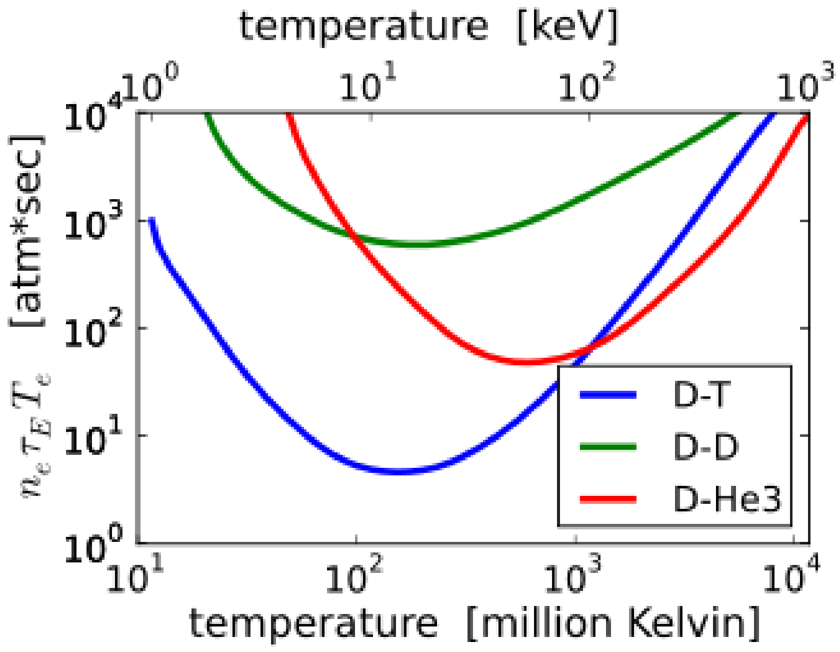
PRO 4: High energy density laboratory plasmas science for novel quantum materials

PRO 5: Relativistic plasma science for qubit control and quantum communication

PRO 6: Plasma science tools for simulation and control of quantum systems

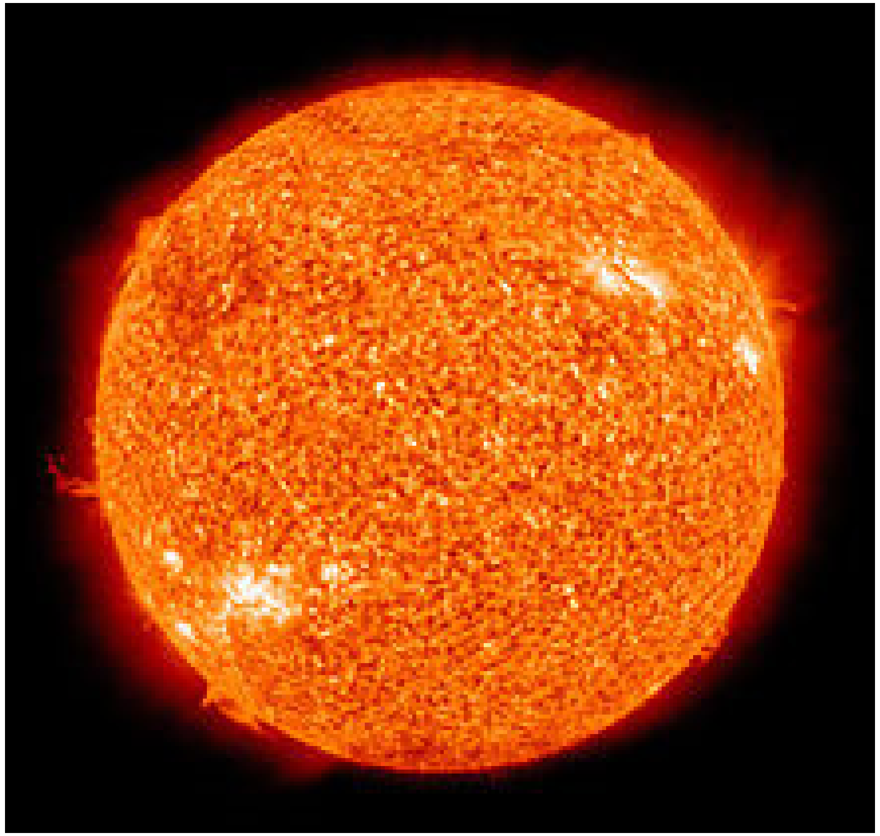
Grand challenge: Energy gain from fusion (Lawson criteria)

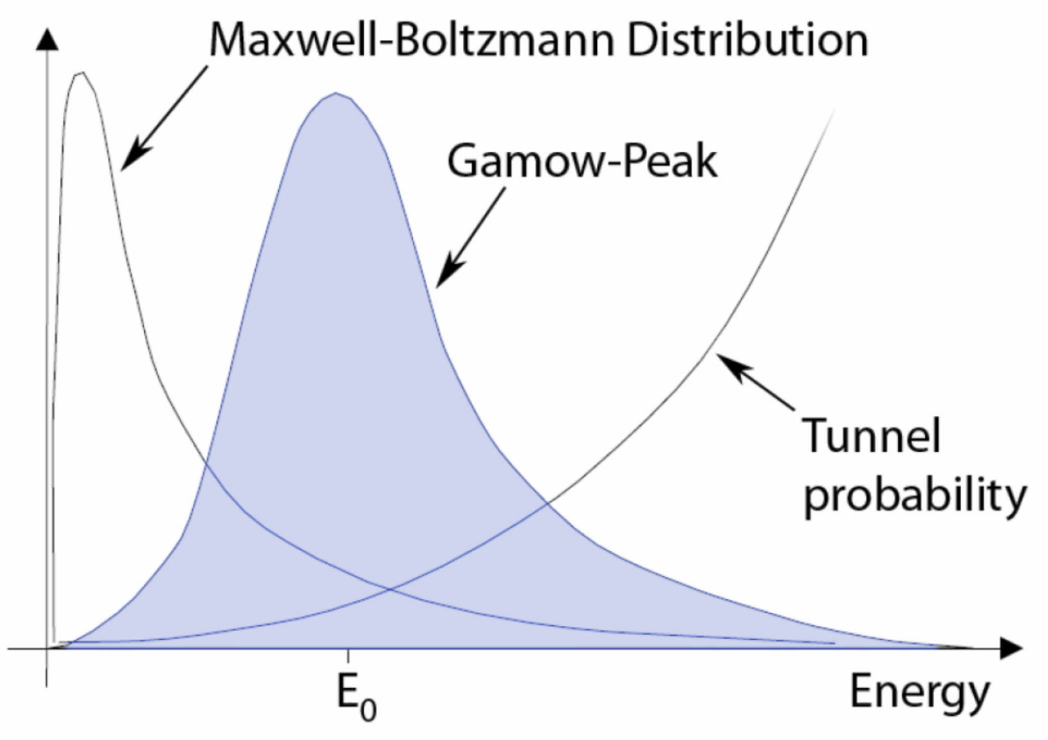
- **to achieve energy gain in a fusion reactor, the fuel has to be dense enough and hot enough for long enough**
- triple product of density, temperature and confinement time
- Sun – gravity
- Tokamak – magnetic confinement
- NIF, HIF – inertial confinement
- MIF – magneto-inertial confinement
- Steady progress internationally to reach the burning plasma era
- https://www.energy.gov/science/fes/burning-plasma-science-long-pulse-and-high-power



https://en.wikipedia.org/wiki/Lawson_criterion

Fusion in the sun



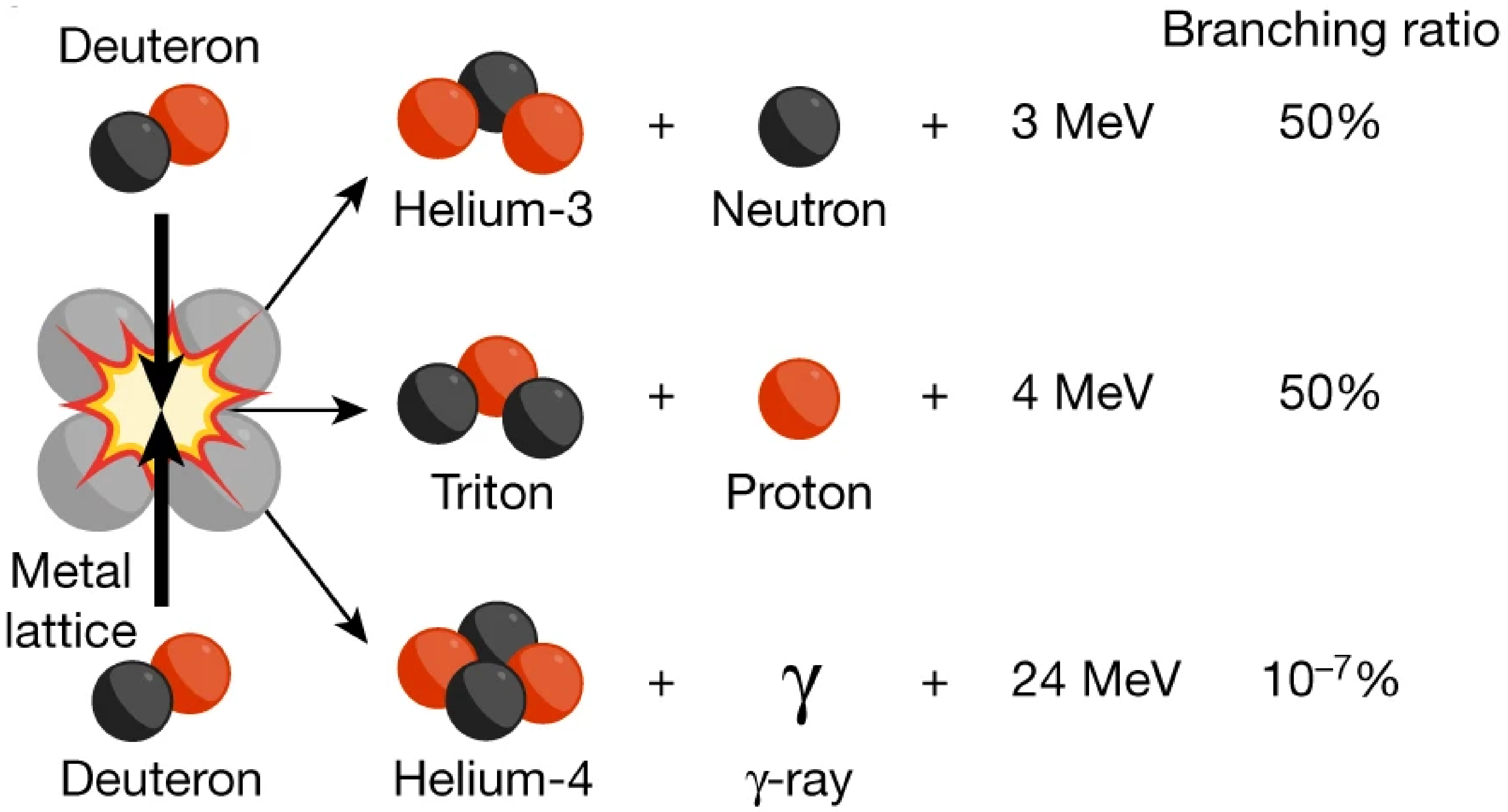


Gamow window for ^2H on ^2H at T=16 MK

Maximum Gamow-Peak	= 7.8 keV
Effective width	= 7.5 keV
Energy window ($E_0 \pm \Delta/2$)	= 4.0 - 11.5 keV

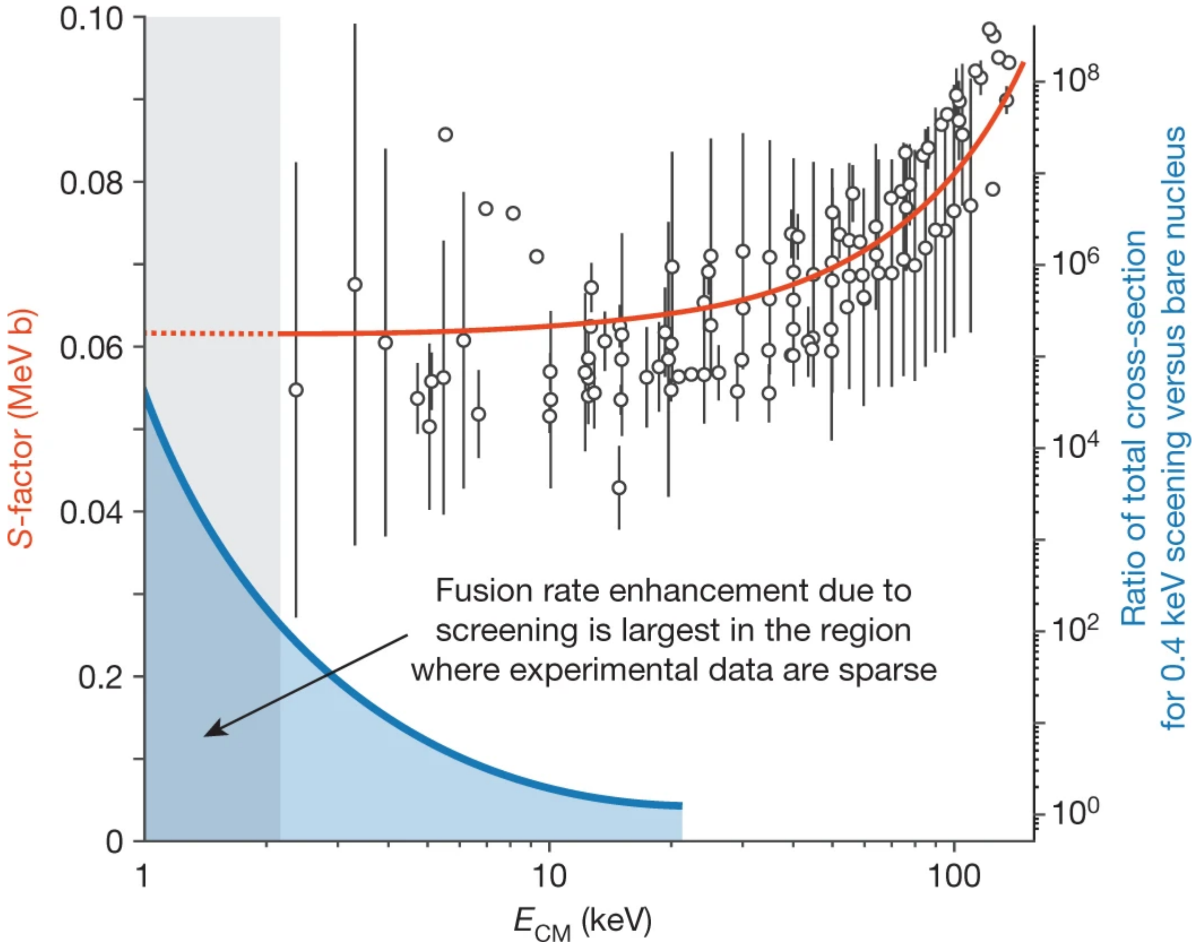
https://en.wikipedia.org/wiki/Sun
http://www.kadonis.org/pprocess/gamow.php?tele=H&ta=2&pele=H&pa=2&t6=16
http://indico.gsi.de/event/783/session/10/contribution/35/material/slides/0.pdf

We understand the deuterium – deuterium (D-D) fusion reaction very well in the gas phase and in low density plasmas



C. P. Berlinguette, et al., Nature (2019)

Electron screening affects low-energy fusion cross sections, especially in solids

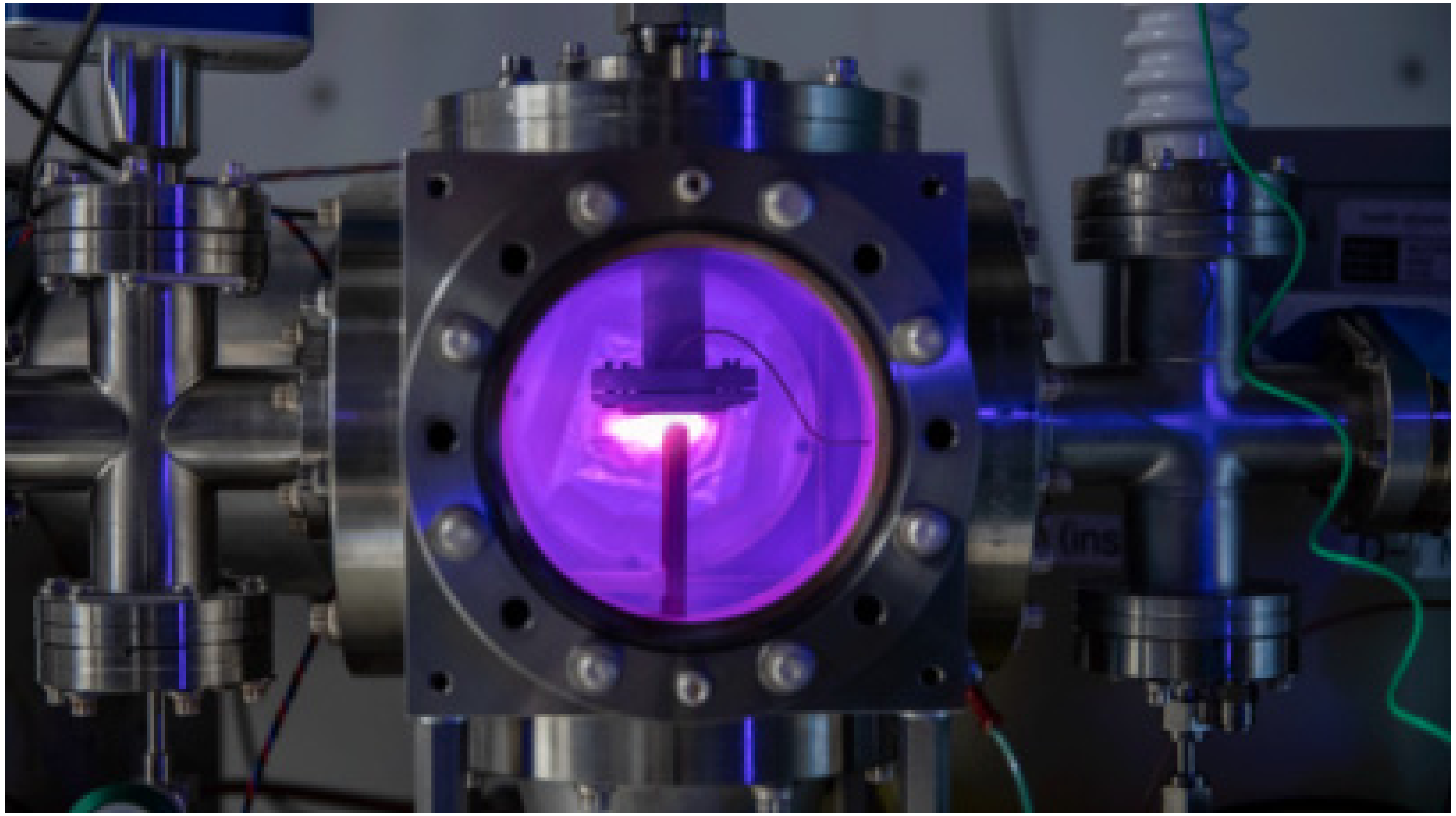


D+D → n + ^{3}He or p + T

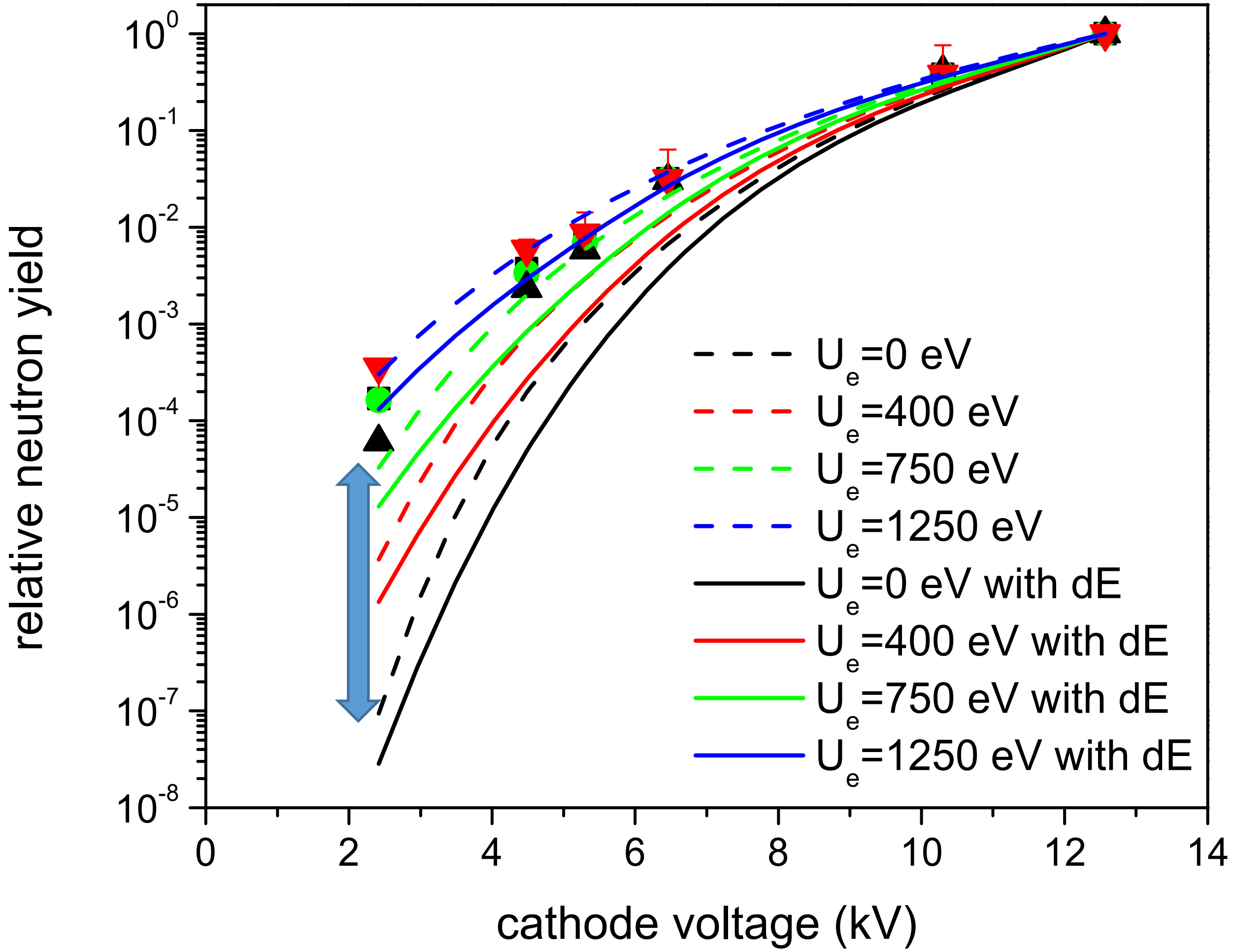
$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E+U_e)}} e^{-\sqrt{E_g/(E+U_e)}} S(E)$$

Plot adapted from D. T. Casey, et al. "Thermonuclear reactions probed at stellar-core conditions with laser-based inertial-confinement fusion", Nat. Phys. 13, 1227 (2017).

C. P. Berlinguette, Y.-M. Chiang, J. N. Munday, T. Schenkel, D. K. Fork, R. Koningstein, "Revisiting the cold case of cold fusion" , *Nature* **570**, 45–51 (2019)



We observe fusion rates that are > 100 times higher than expected for ion energies of below 5 keV



Letter | Published: 06 July 1989

Can solid-state effects enhance the cold-fusion rate?

A. J. Leggett & G. Baym

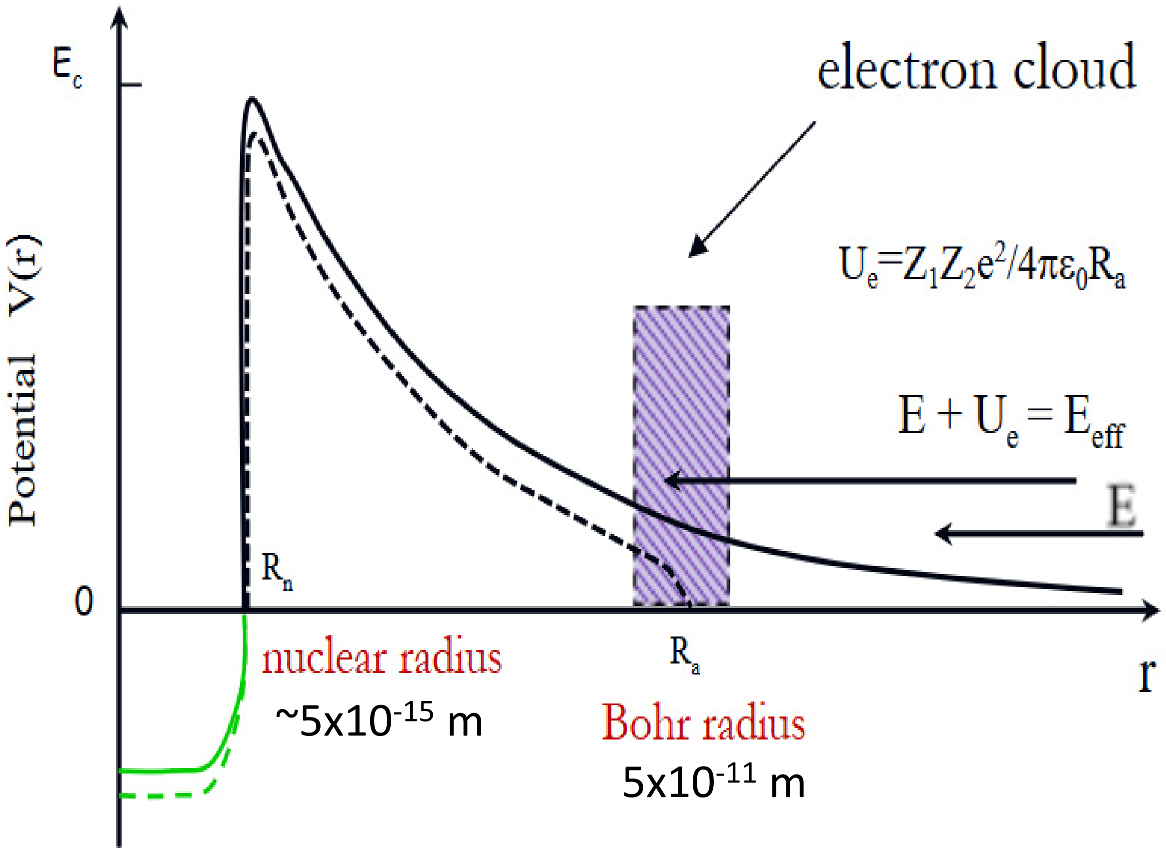
Nature **340**, 45–46 (1989) | D

- Solid-state effects strongly enhance D-D fusion rates at reaction energies below a few keV (center-of-mass)

- Can we learn how to control tunneling ?
- Opportunities for quantum simulations ?

T. Schenkel, et al., https://arxiv.org/abs/1905.03400

Electron screening affects low-energy fusion cross sections – can we simulate this with a quantum simulator ?



R. Babush et al., "Low-Depth Quantum Simulation of Materials," Phys. Rev. X 8, 011044 (2018)

"We conclude with a proposal to simulate the uniform electron gas (jellium) using a low-depth variational ansatz realizable on near-term quantum devices. From these results, we identify simulations of low-density jellium as a promising first setting to explore quantum supremacy in electronic structure."

H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. A **327** (1987) 461.

figure adapted from Matej Lipoglavšek, https://slideplayer.com/slide/10339372/

Outline

1. Qubits

2. Beams

3. Fusion

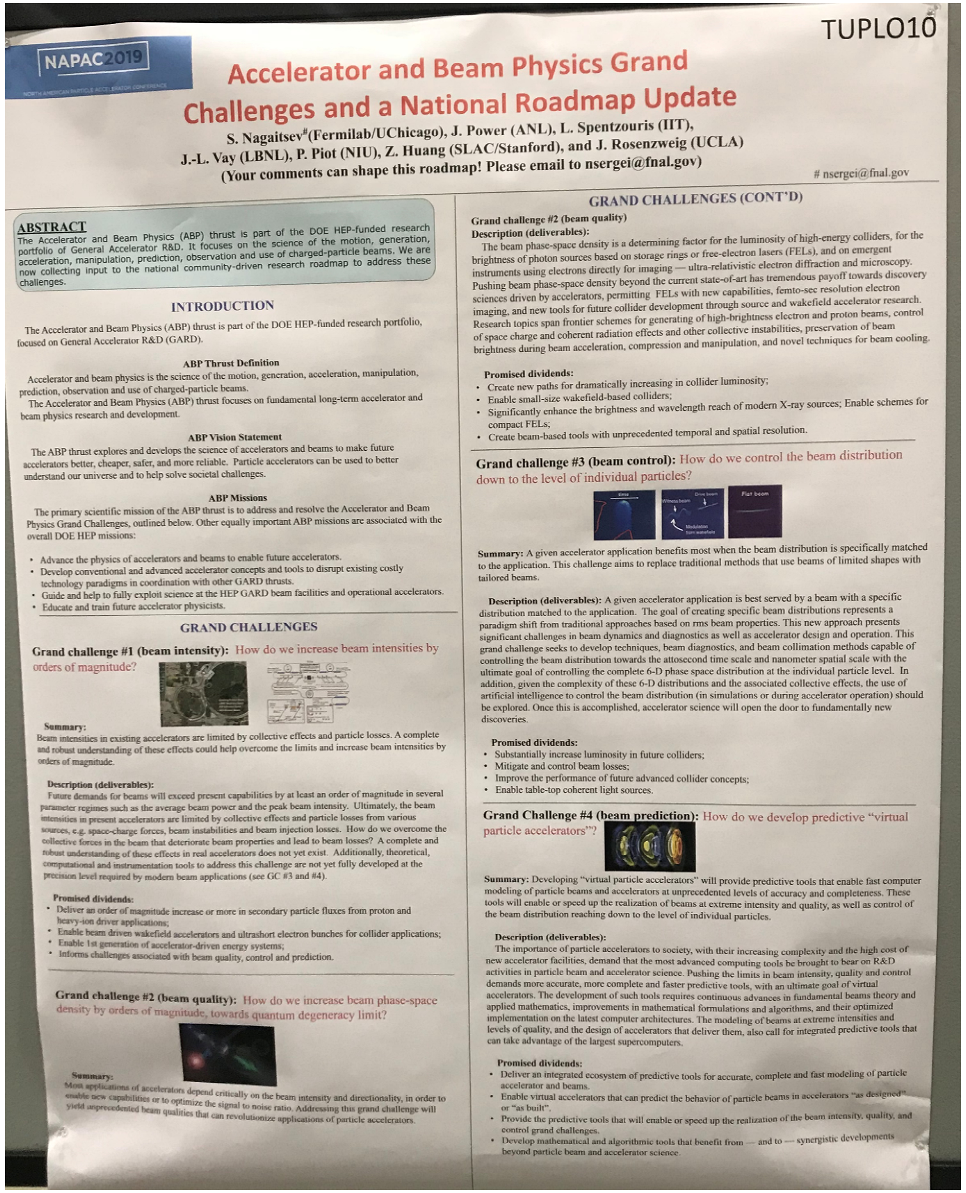
4. Outlook

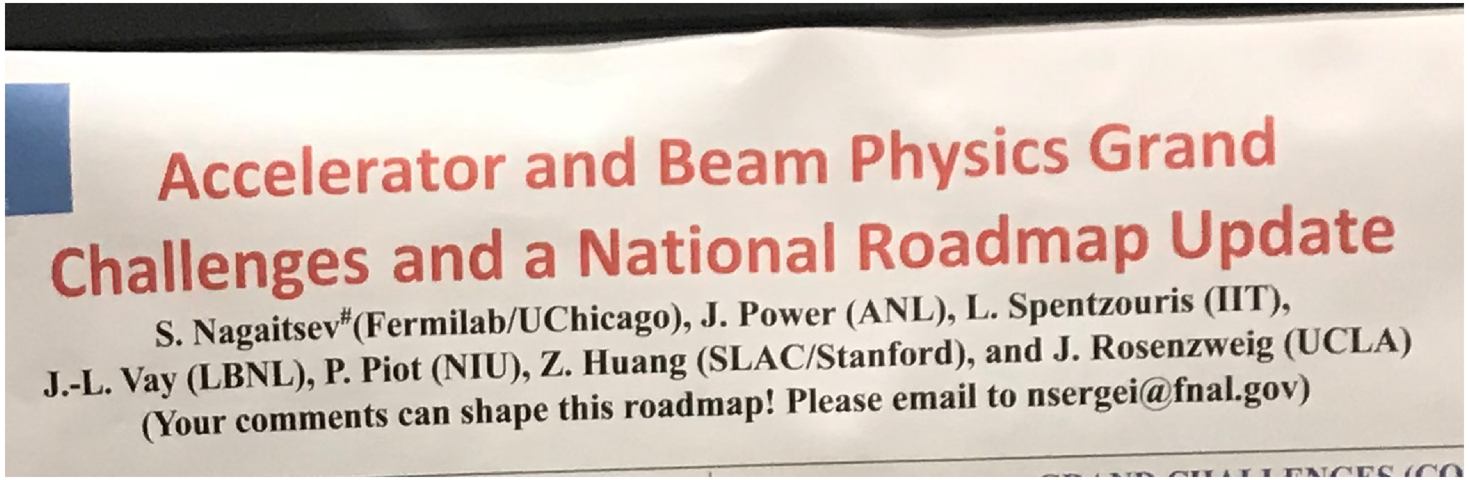
Outlook

- Quantum information science (QIS) promises to revolutionize information technology
  - Special purpose quantum simulations now, paths to quantum computing with error correction
  - Quantum sensing for enhanced precision and sensitivity, structure - coherence correlations
  - Quantum communication for new privacy and secure data transfer

- QIS momentum touches many areas of science and technology
  - Examples from Fusion Energy Sciences

- Accelerators for QIS
  - Qubit integration (spins, ions, cavities, …)
  - Microscopy of quantum materials
  - Simulations of ion and atom qubits
  - Probing of space-time
- QIS for Accelerators
  - Cooling and quantum beams
  - Speed-up in simulations?
  - …

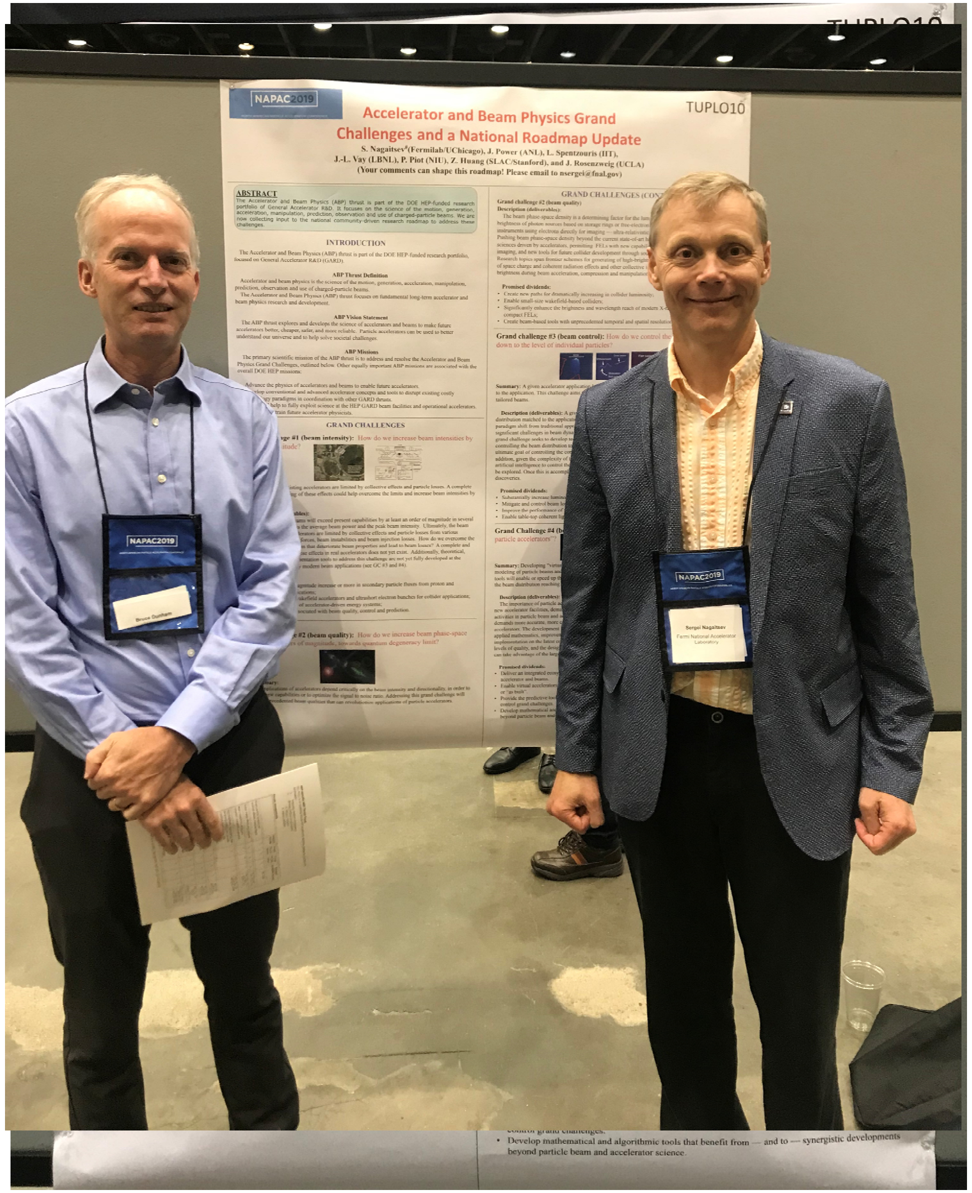


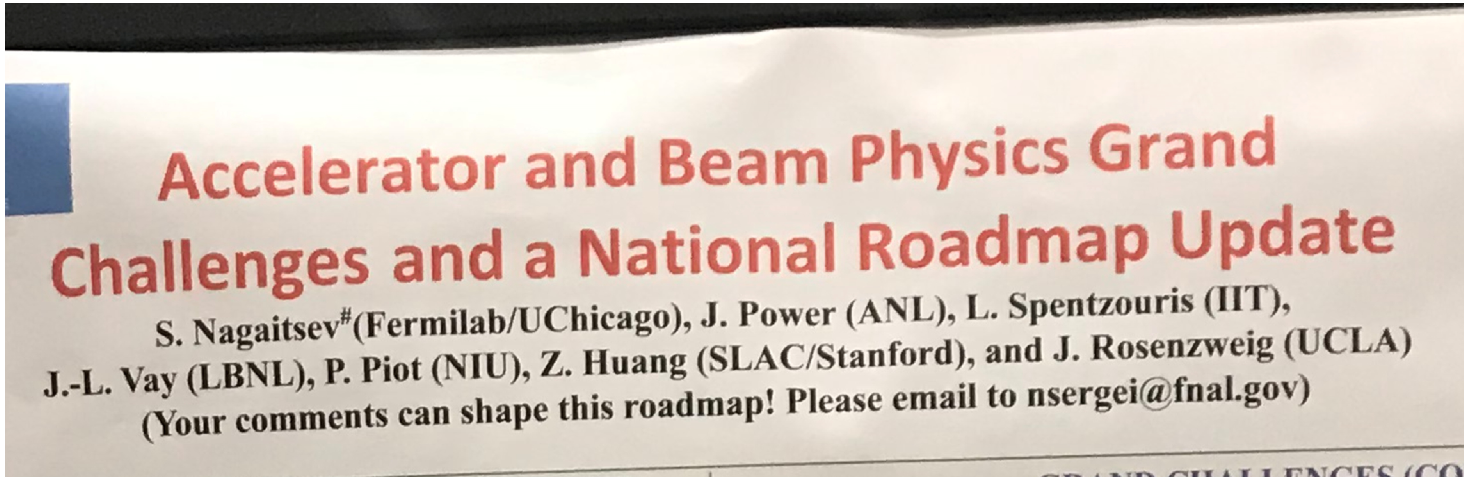


- Grant challenges in Accelerator and Beam Physics connect also with opportunities in Quantum Information Science

- Goal to gain fundamental understanding of the flow and direction of energy with particle accelerators
- Analogy to flow and direction of information in (quantum) computers
- Mastery enables discovery science and a wealth of applications

1. Beam intensity
2. Beam quality
3. Beam control
4. Beam prediction





- Grant challenges in Accelerator and Beam Physics connect also with opportunities in Quantum Information Science

- Goal to gain fundamental understanding of the flow and direction of energy with particle accelerators
- Analogy to flow and direction of information in (quantum) computers
- Mastery enables discovery science and a wealth of applications

1. Beam intensity
2. Beam quality
3. Beam control
4. Beam prediction