

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.

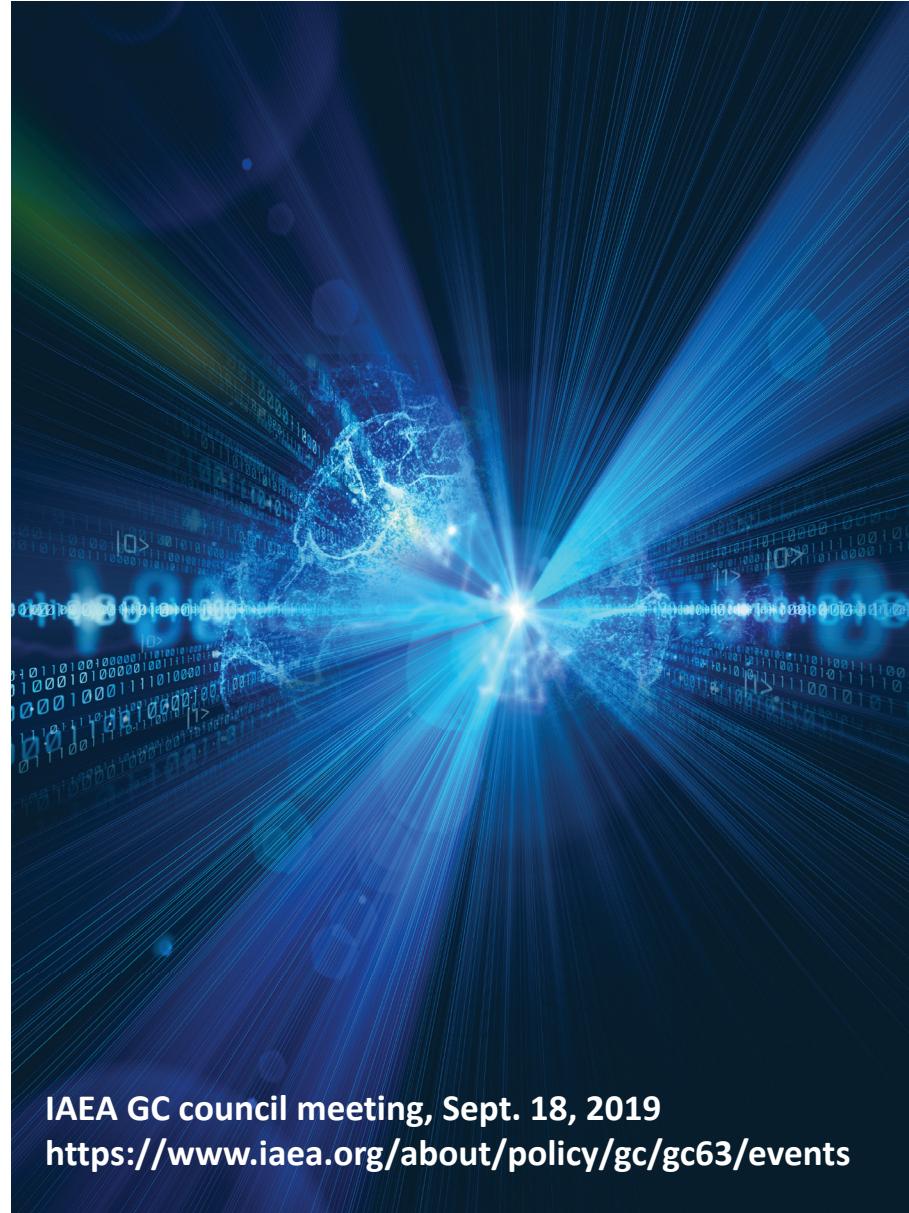


ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION **ATAP**



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>

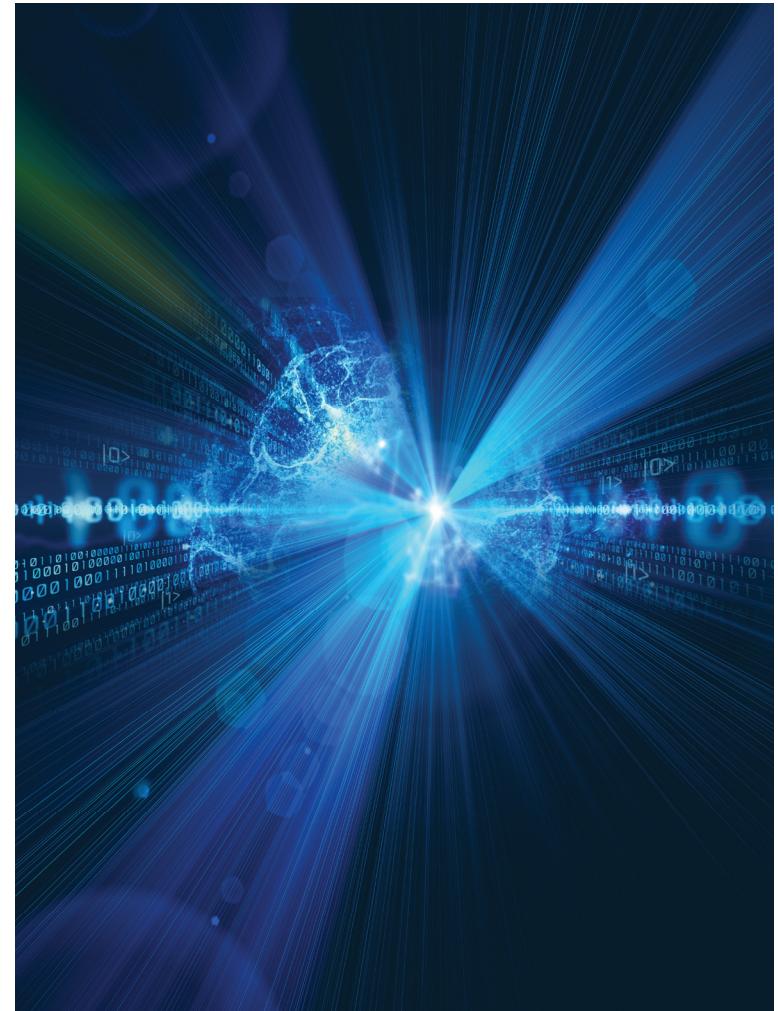
Outline

1.Qubits

2. Beams

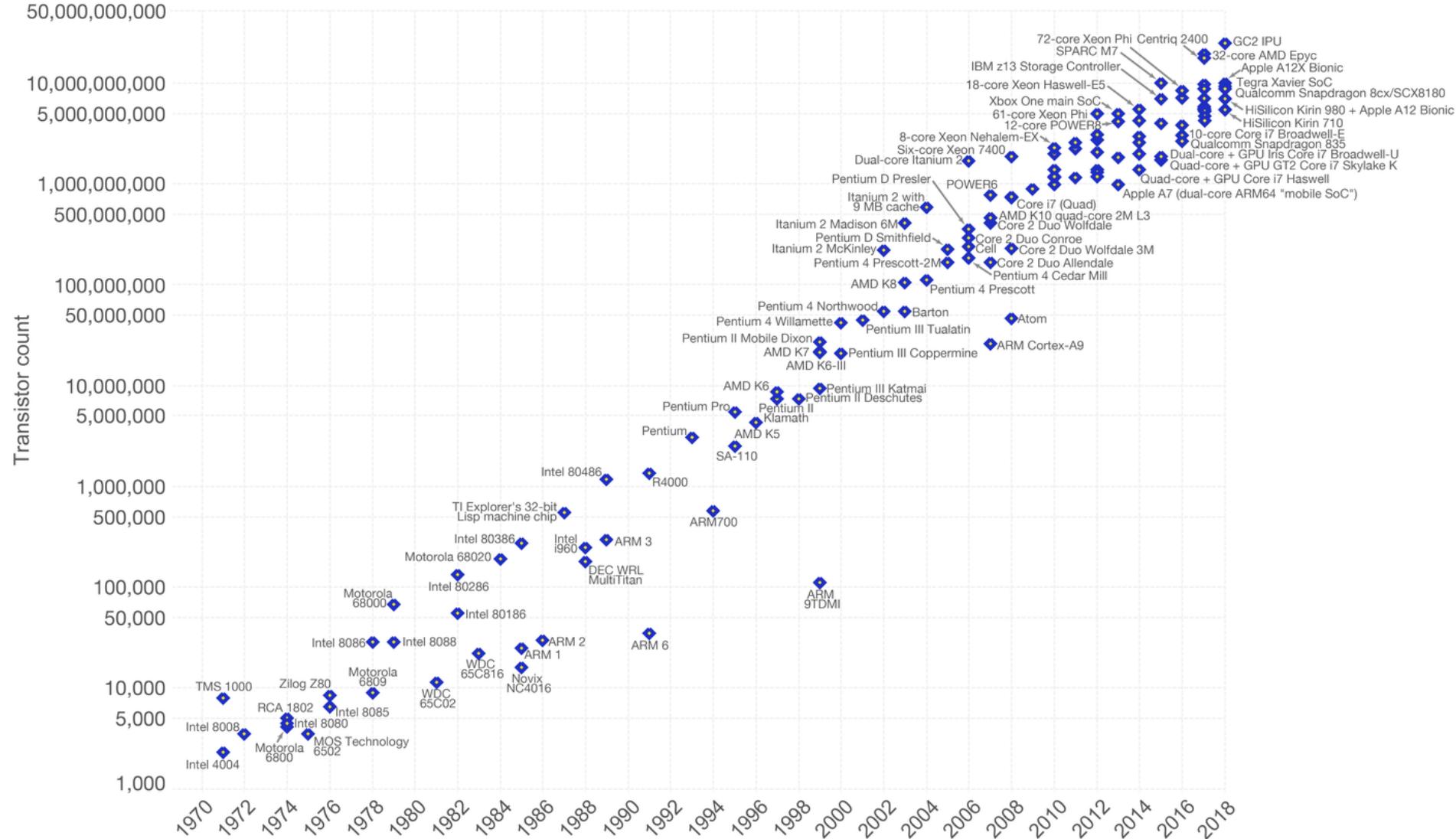
3. Fusion

4. Outlook

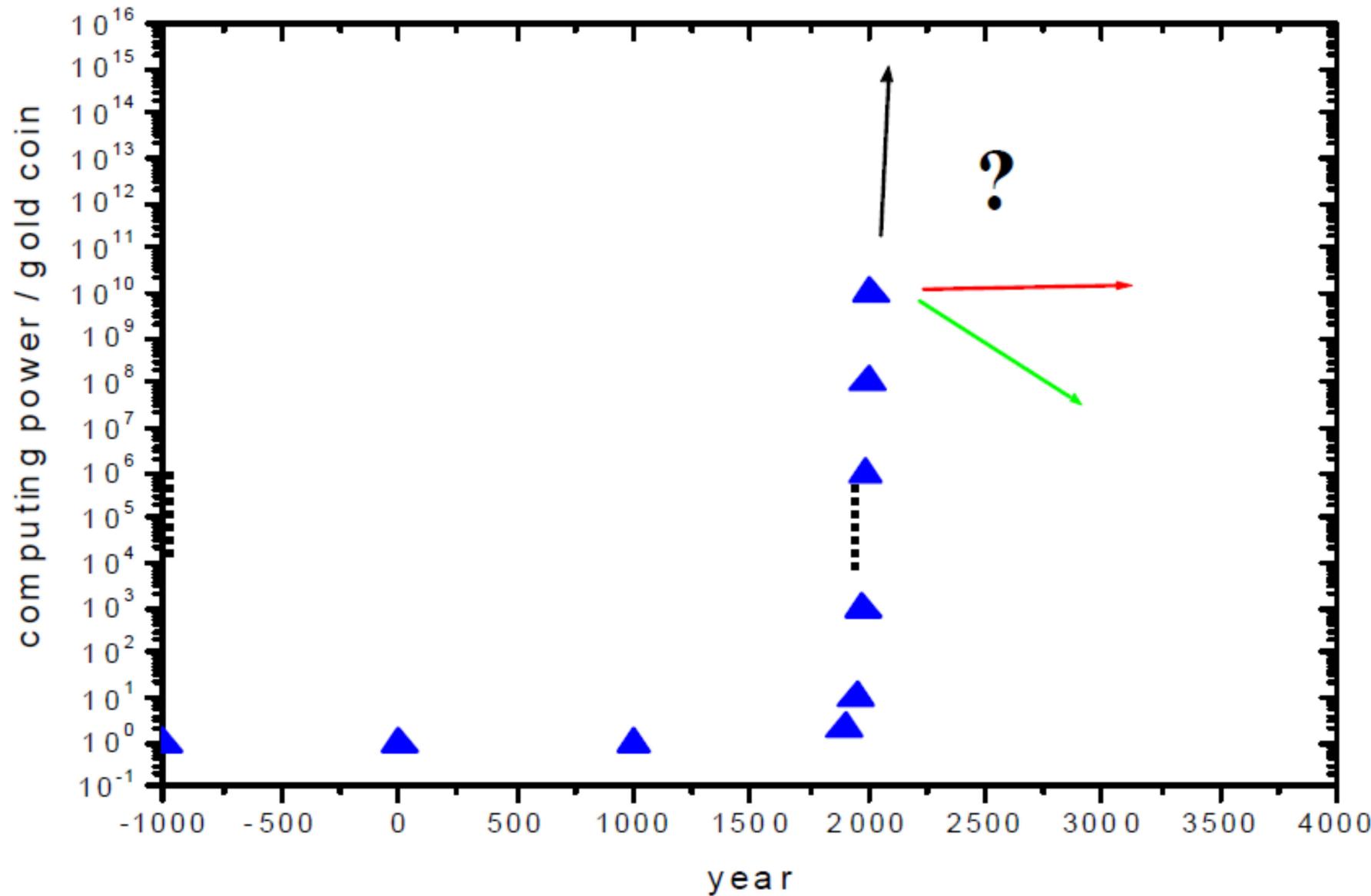


Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

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.



Evolution of computational power



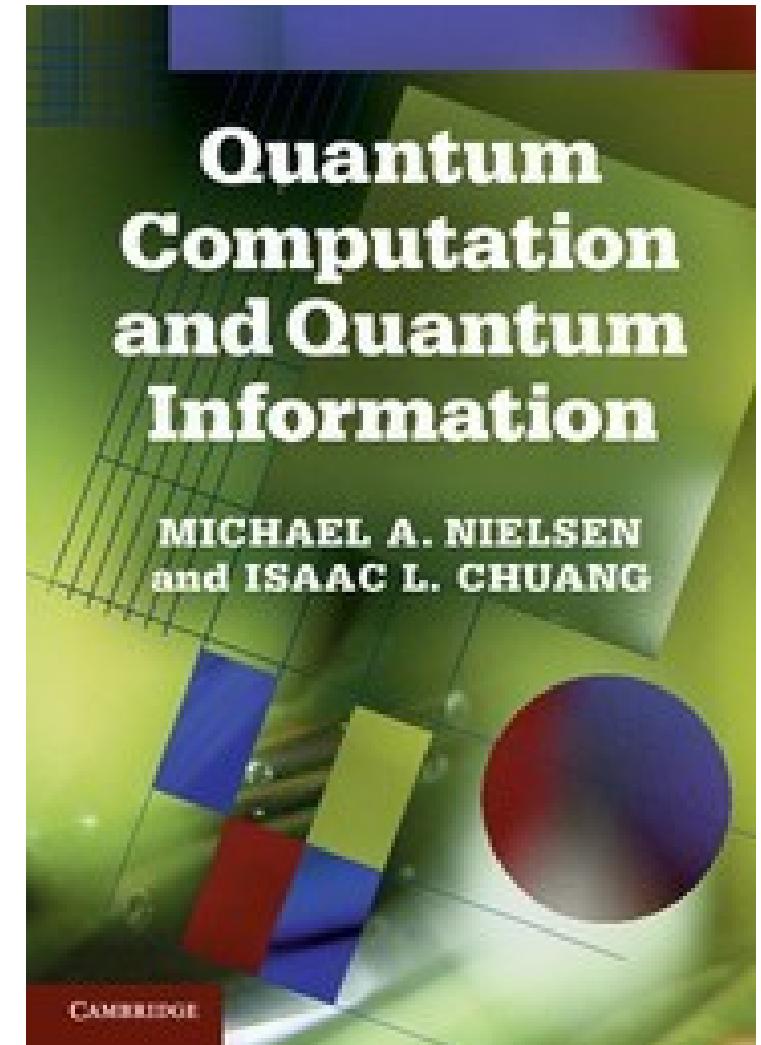
Quantum Information Science

Quantum –

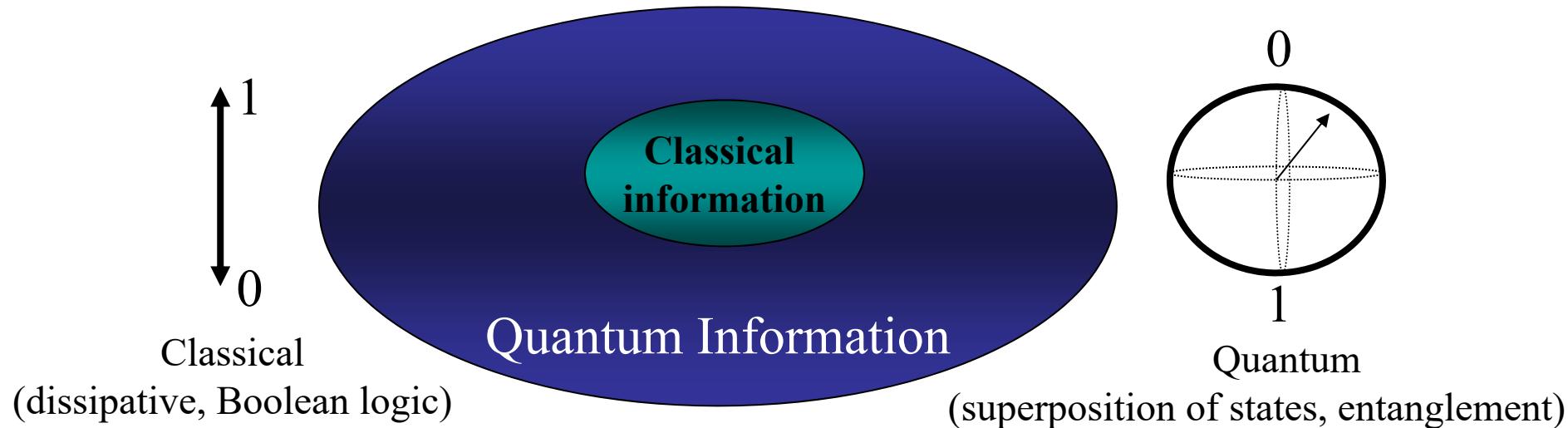
Communication

Sensing

Simulations / Computing



Quantum Information Science

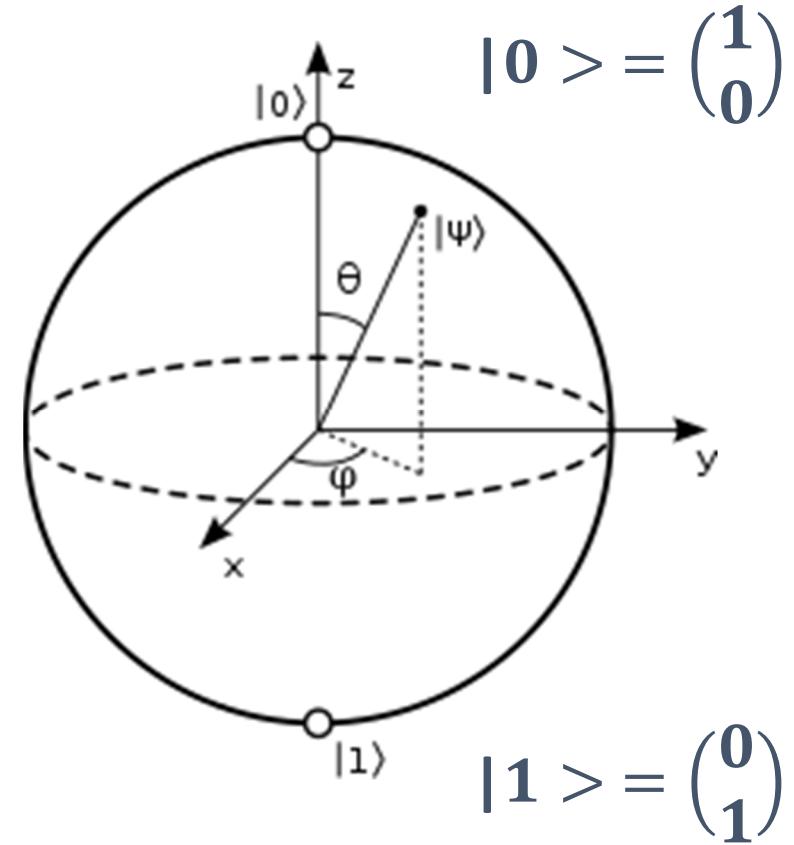


- “Information is a physical entity”, R. Landauer, 1999
- Flavors of quantum computing approaches¹
 - Quantum circuit model
 - Measurement based quantum computing
 - Adiabatic quantum computing
 - Topological quantum computing
 - ...

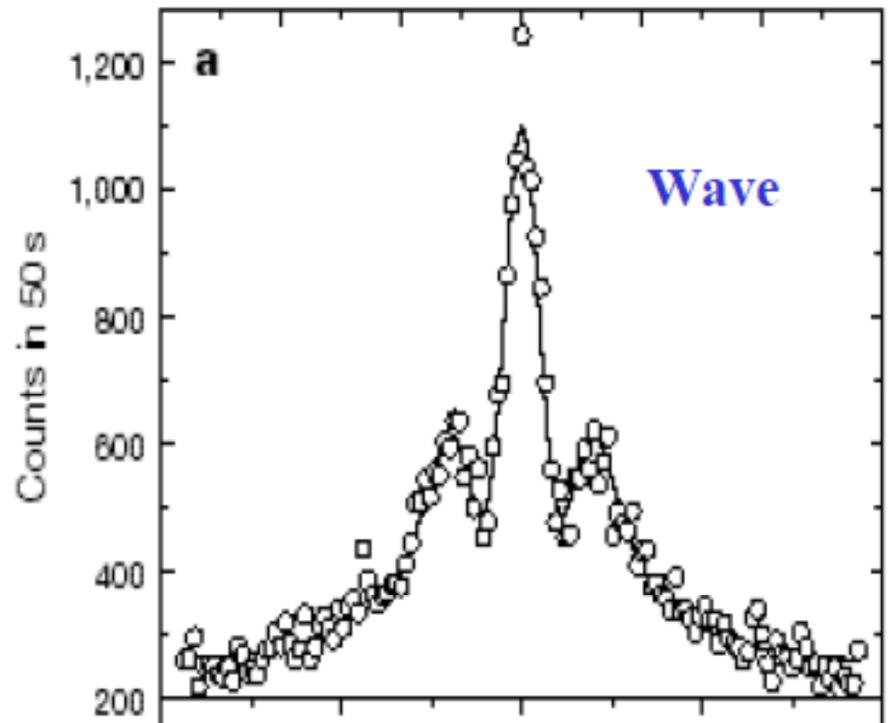
¹see e. g. “Quantum computers: Definition and implementations”, C. A. Perez-Delgado and P. Kok, Phys. Rev. A 83, 012303 (2011)

Qubits

- Quantum bits
 - Capacity scales as 2^N
 - Bloch sphere representation
 - Superposition of states
 - Multi-qubit entanglement
- Classical bits
 - Capacity scales as N
 - Boolean logic, and/or/not
 - Digital, 0 or 1



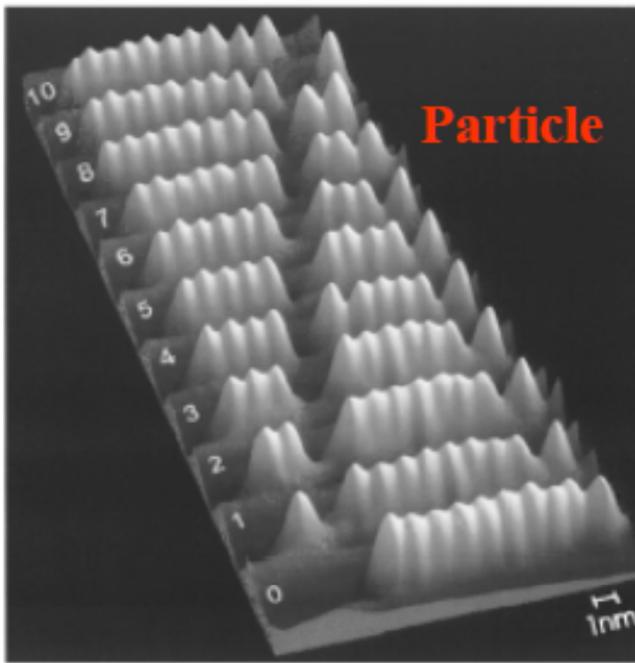
Wave-particle duality of C₆₀ molecules



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 C₆₀ molecules at Cu steps:
Operation of a molecular counting device

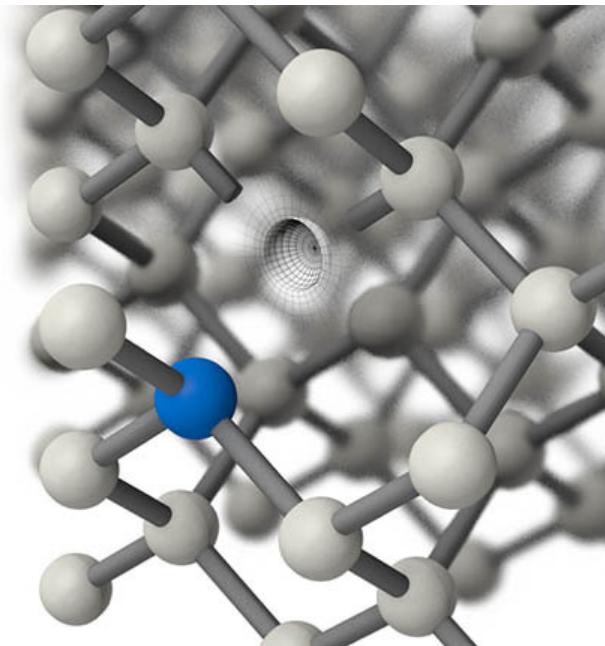
M. T. Cuberes,¹⁾ R. R. Schittler, and J. K. Gimzewski
IBM Research Division, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

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

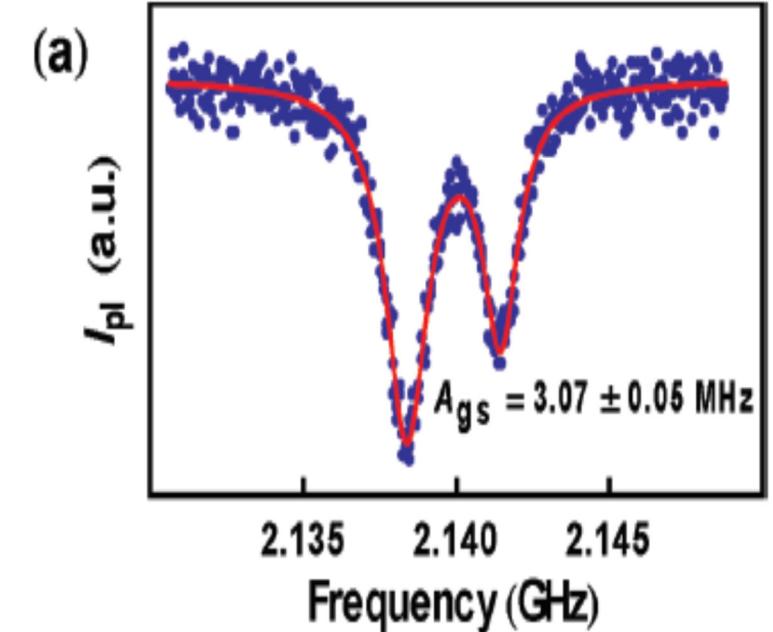
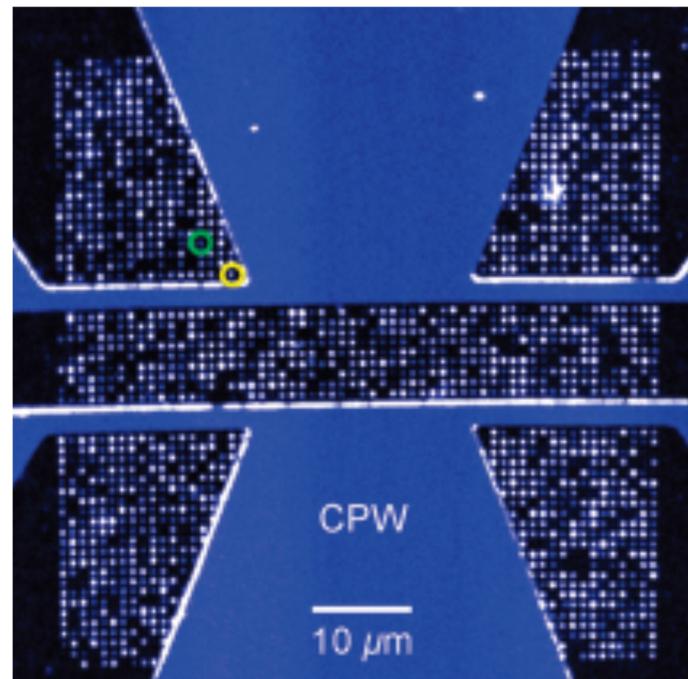
- Wave - superposition of “which path” states in double slits leads to interference
- Particle - interaction of molecules with environment destroys interference, de-coherence, and “classical” behavior
- Quantum info processing requires the coherent superposition of N qubits while gates are applied until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

Quantum sensing

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



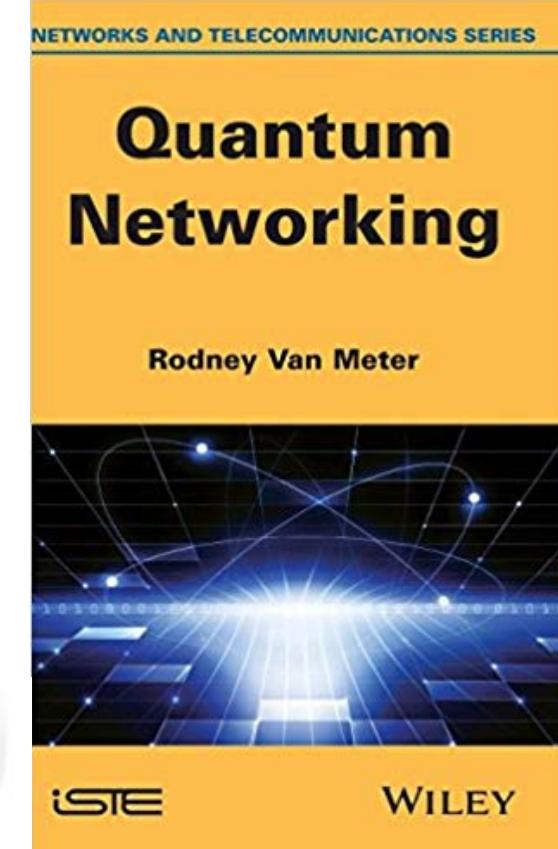
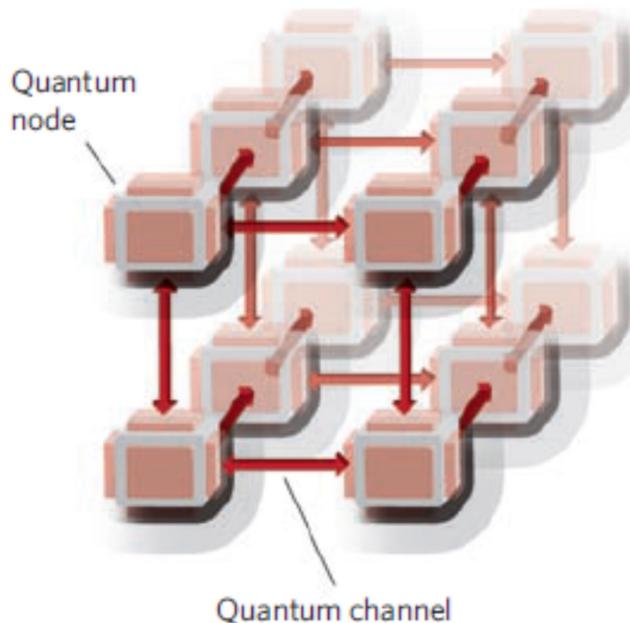
Physics Today June 2018



- 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)

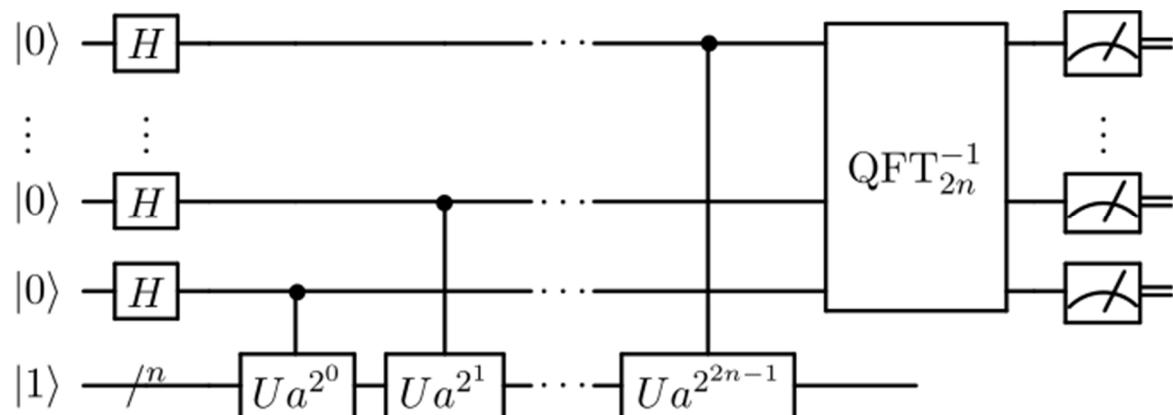
Quantum communication

- 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
 - $\text{Sqrt}(N)$ 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

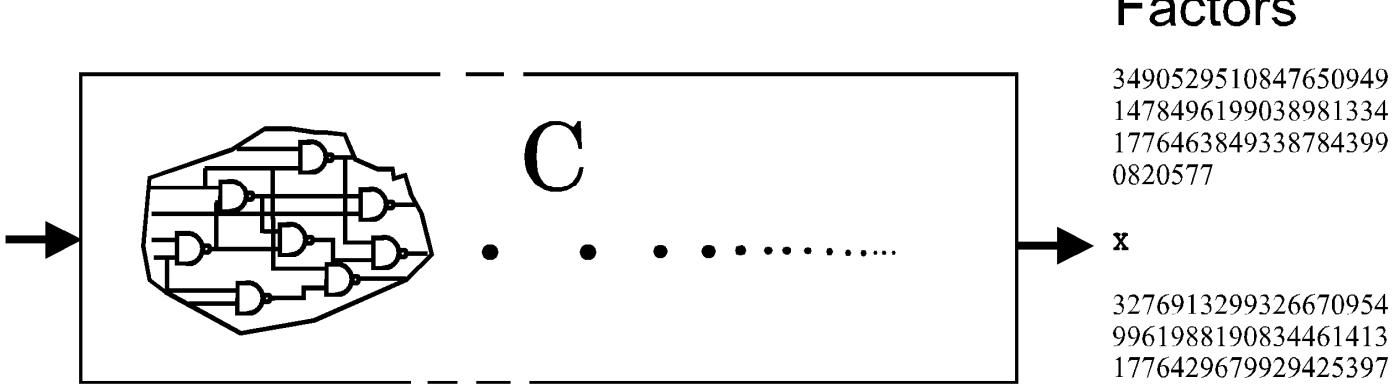


Fast Quantum Computation

Classical factoring problem required 8 months on hundreds of computers

RSA 129

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



Factors

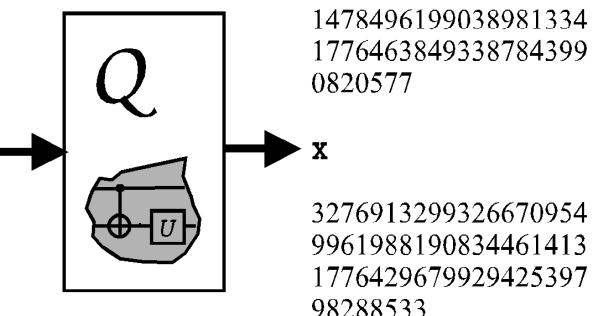
3490529510847650949
1478496199038981334
1776463849338784399
0820577

x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

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

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541

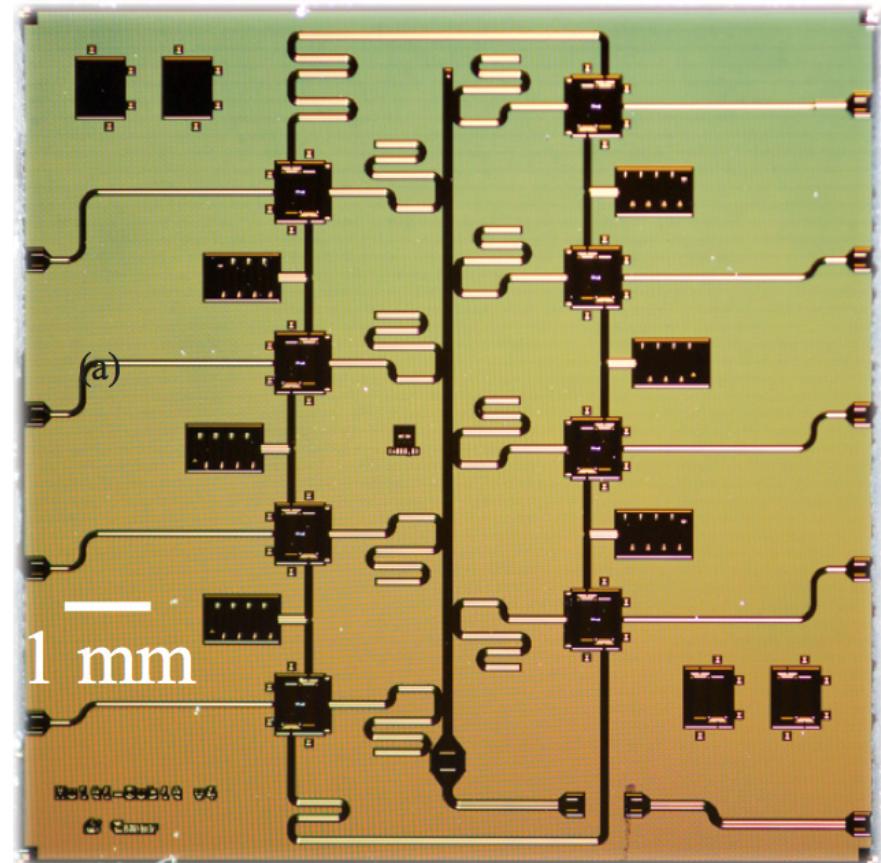


Exponential speedup
for Factoring

Quadratic speedup
for Search

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>

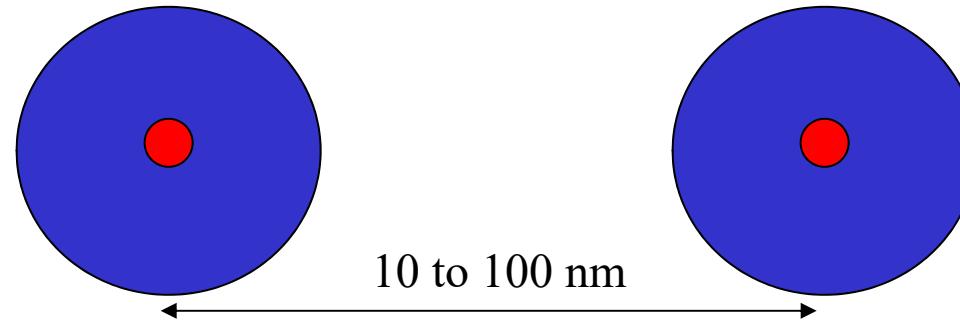
“Quantum Computing in the NISQ era and beyond”

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.

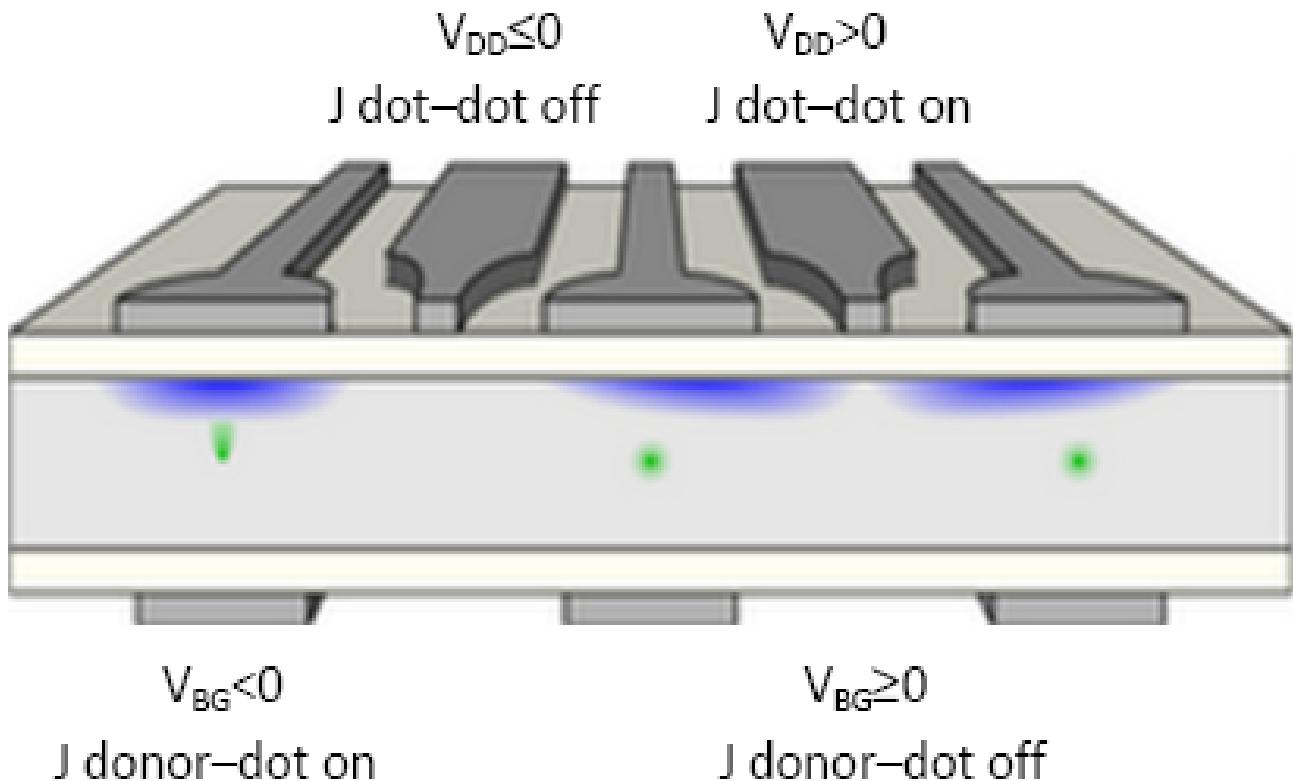
Criteria for physical implementation of a quantum computer (D. DiVincenzo)

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

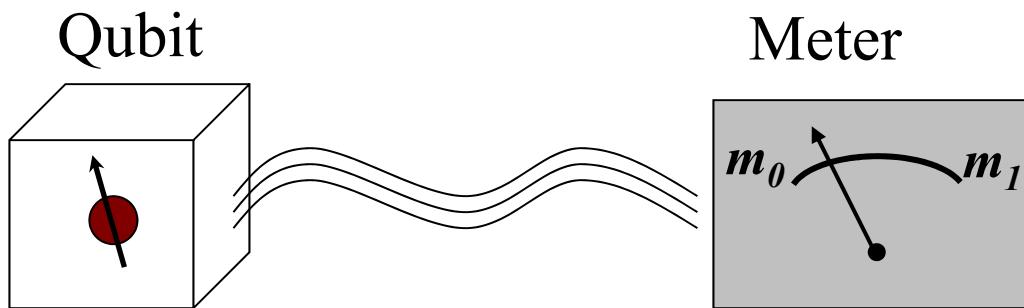
Spins of electrons and nuclei are promising qubit candidates



- 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)

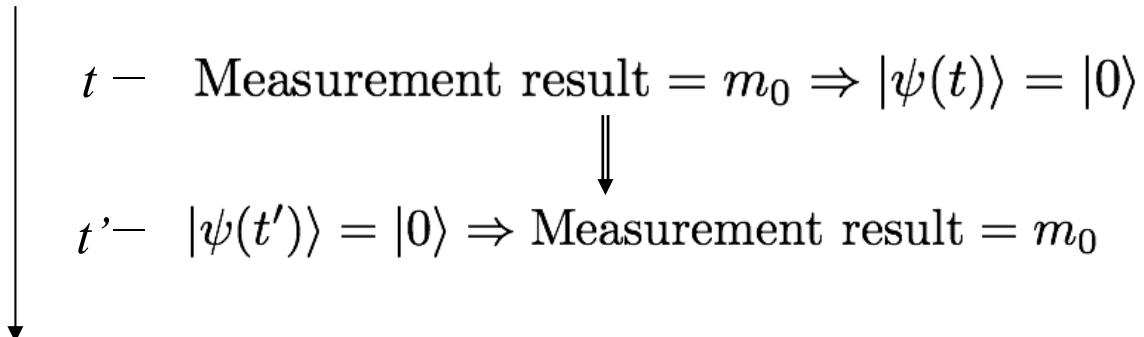
Quantum state measurement



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

$$\begin{aligned}\Pr\{m_0\} &= |\alpha|^2 \\ \Pr\{m_1\} &= |\beta|^2\end{aligned}$$

QND (quantum non-demolition) measurement



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

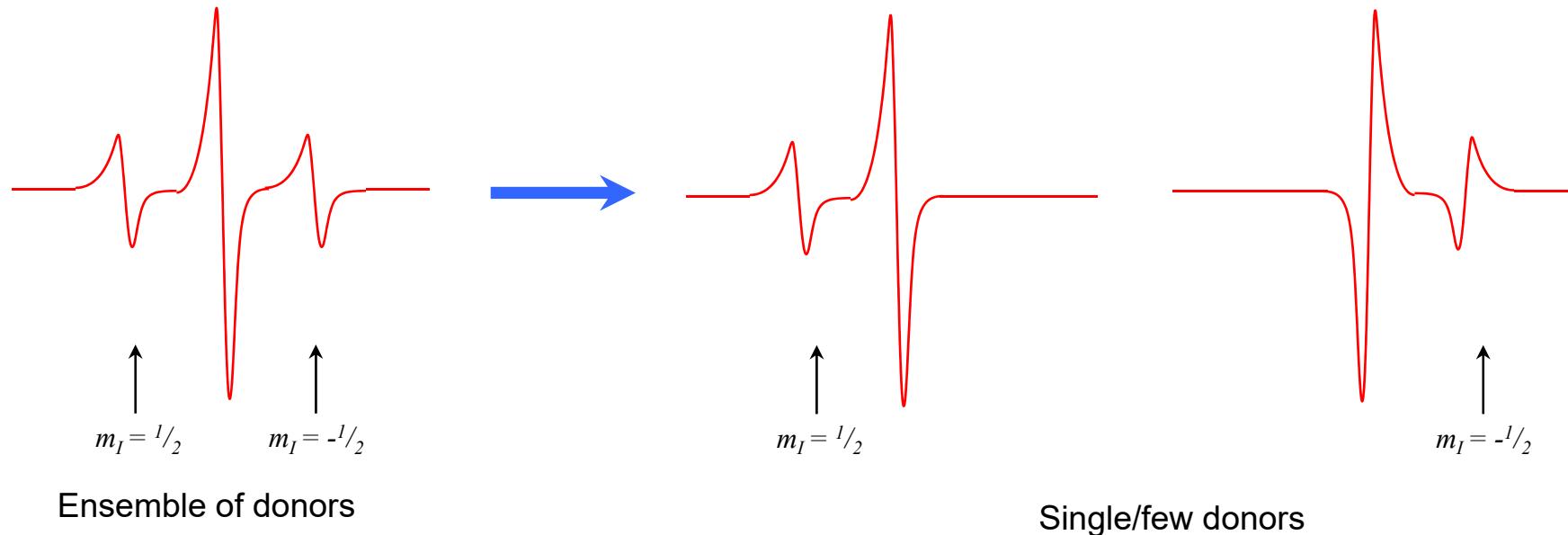
$$|\psi_i\rangle = \alpha|0\rangle + \beta|1\rangle$$

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

Readout of a single nuclear spin

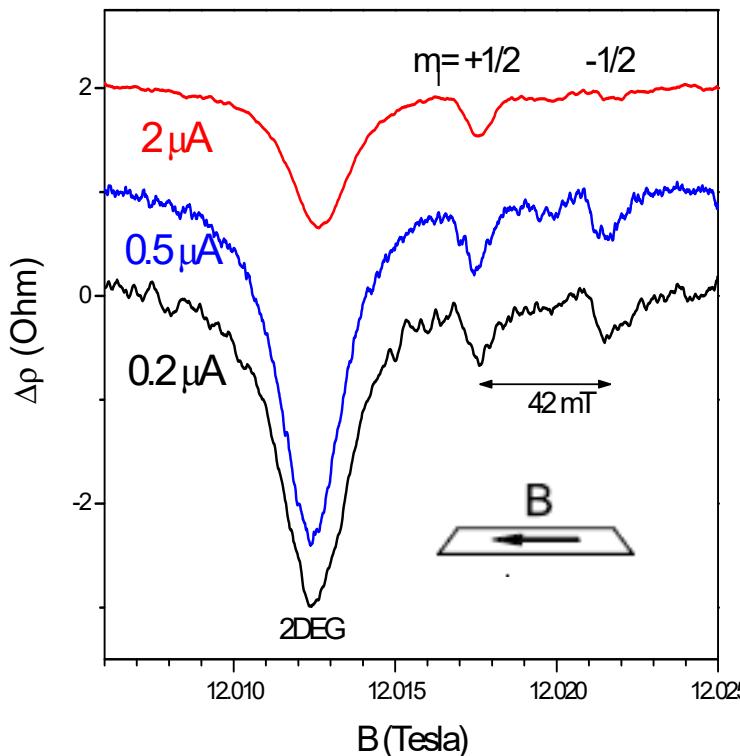
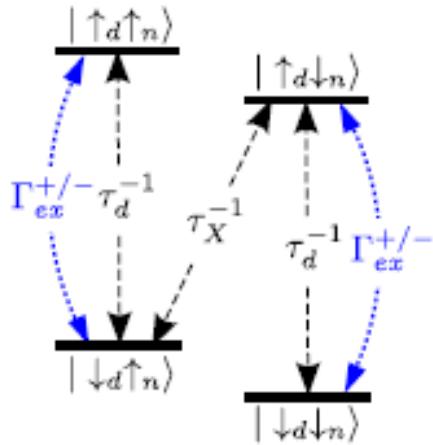
- Donor nuclear spin population measured by presence/absence of spin resonance lines
- Need to measure before nuclear spin flips, i.e., within T_1 of nucleus
- Repeat entire procedure → values of α and β for electron spin qubit

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



- 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 ^{29}Si 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

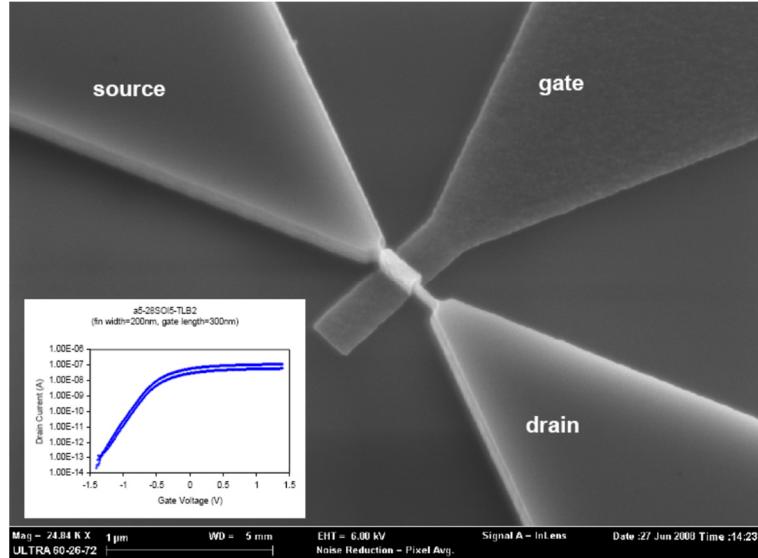
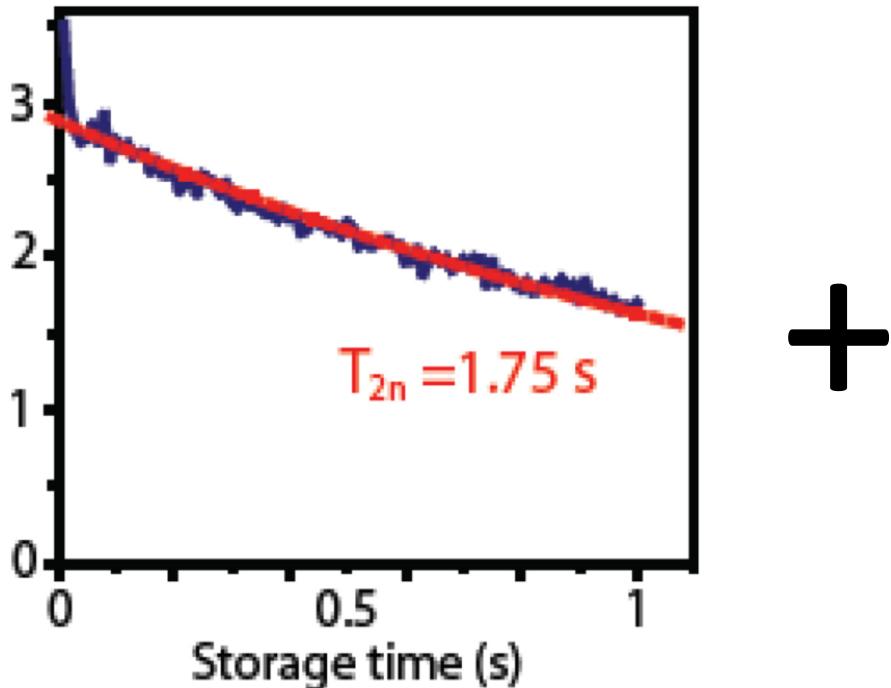
A: hyperfine coupling strength

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)

Long coherence times of donor spins in silicon devices



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

- 100 nm scale FinFet spin readout transistor formed in isotopically purified silicon on insulator (²⁸SOI) and implanted with ¹²¹Sb. 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)

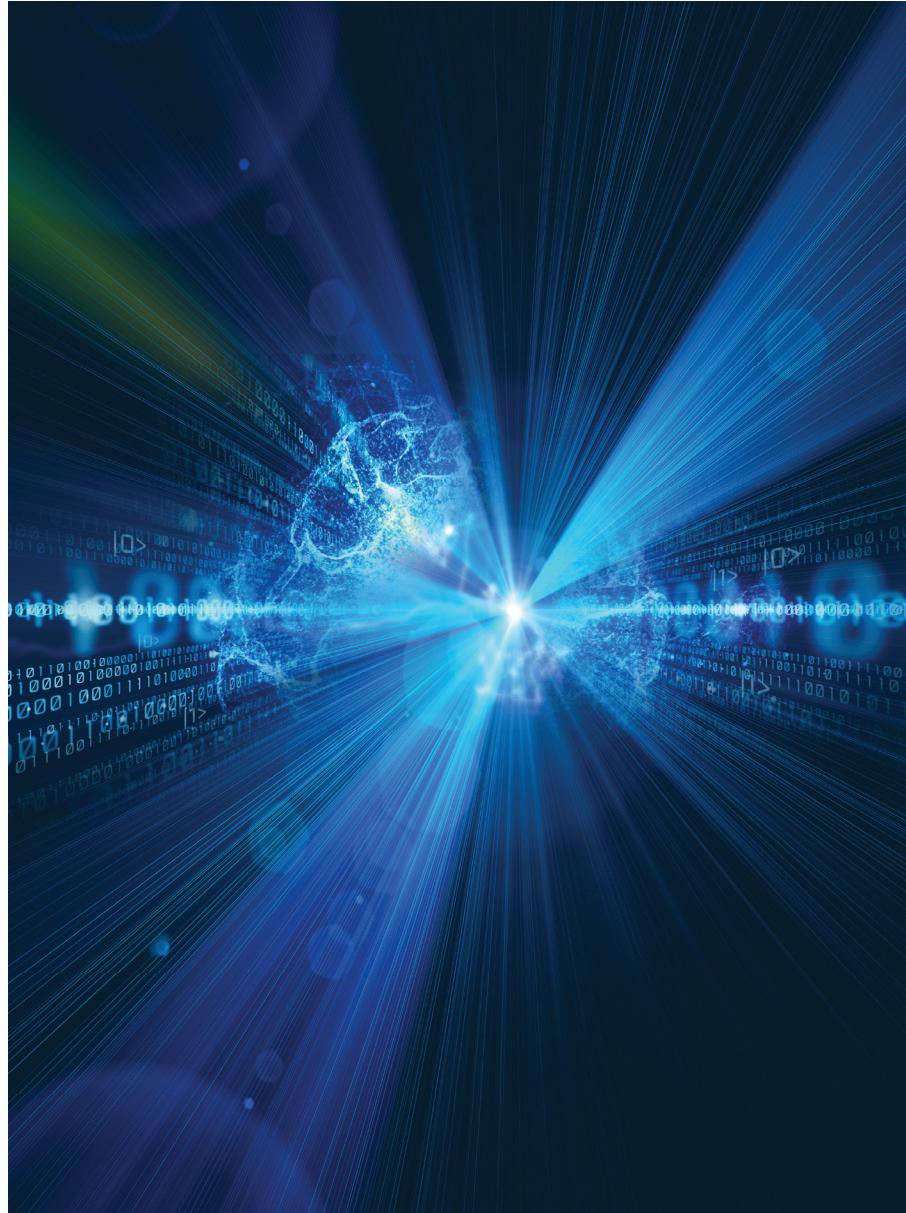
Outline

1. Qubits

2. Beams

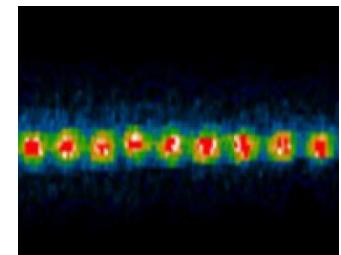
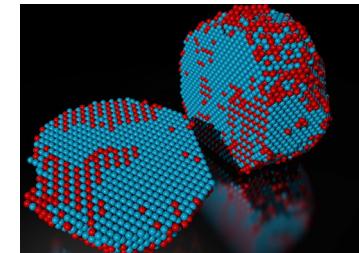
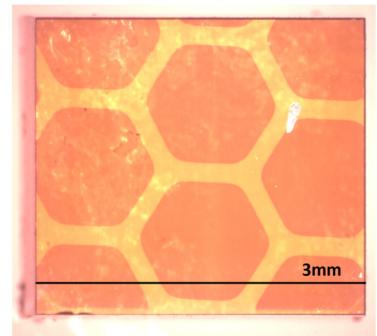
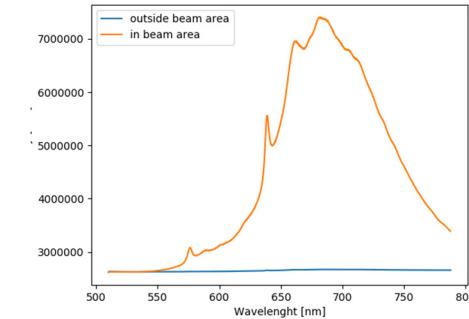
3. Fusion

4. Outlook

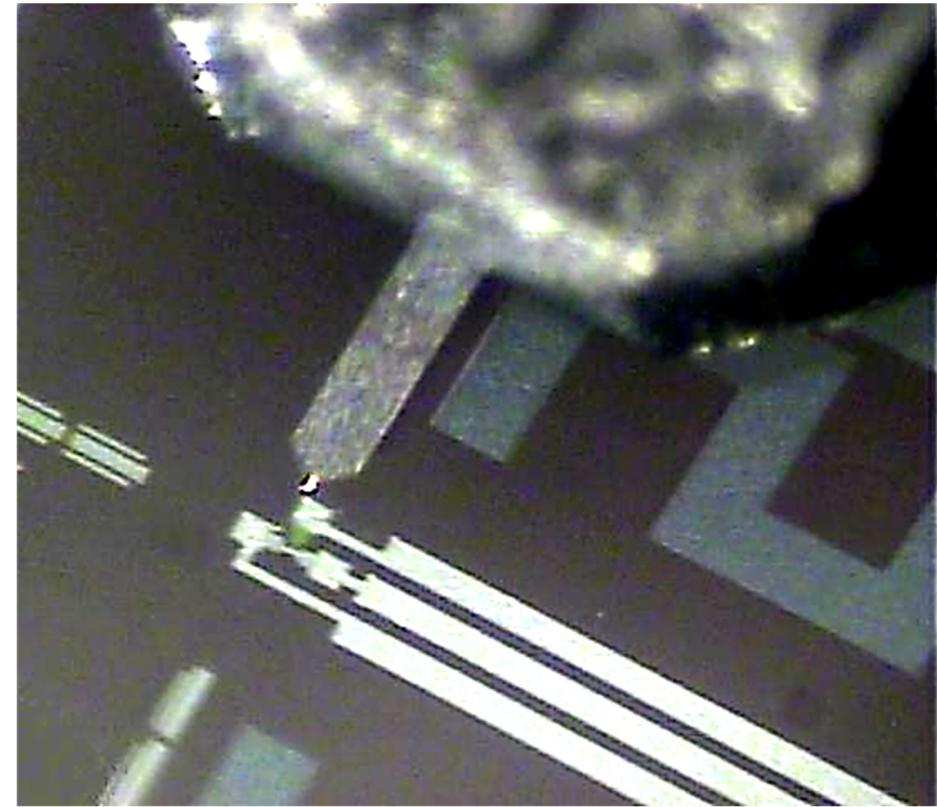
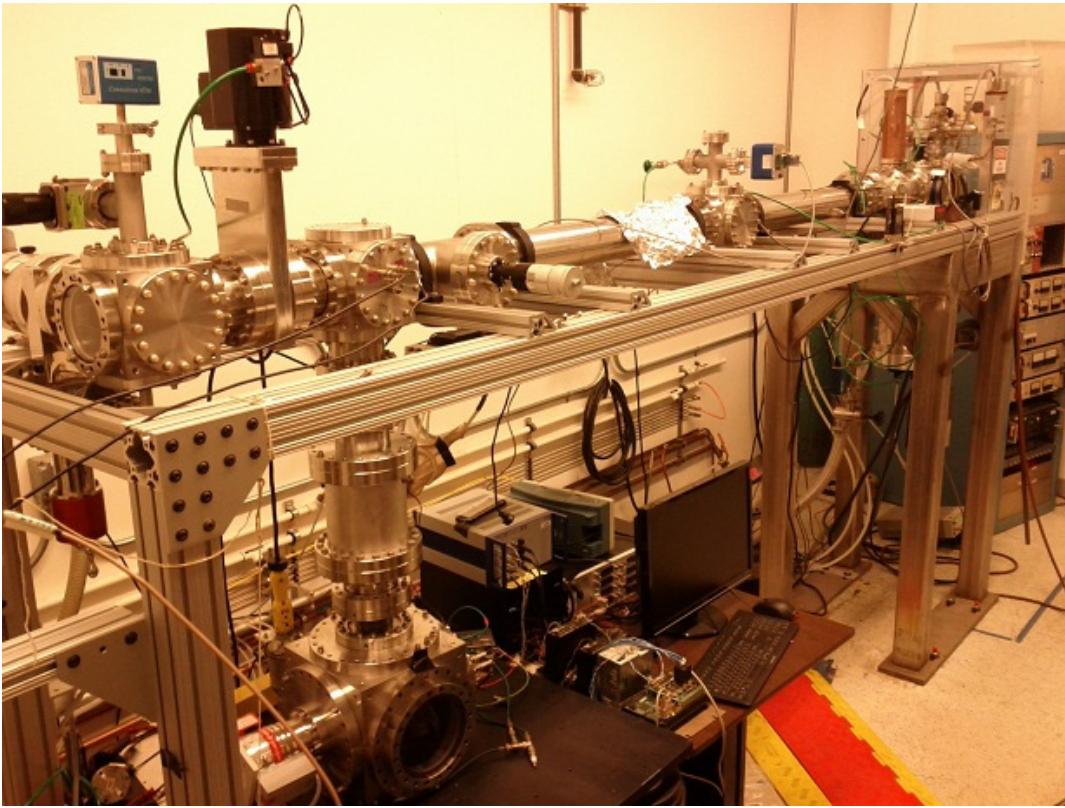


Beams and qubits

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

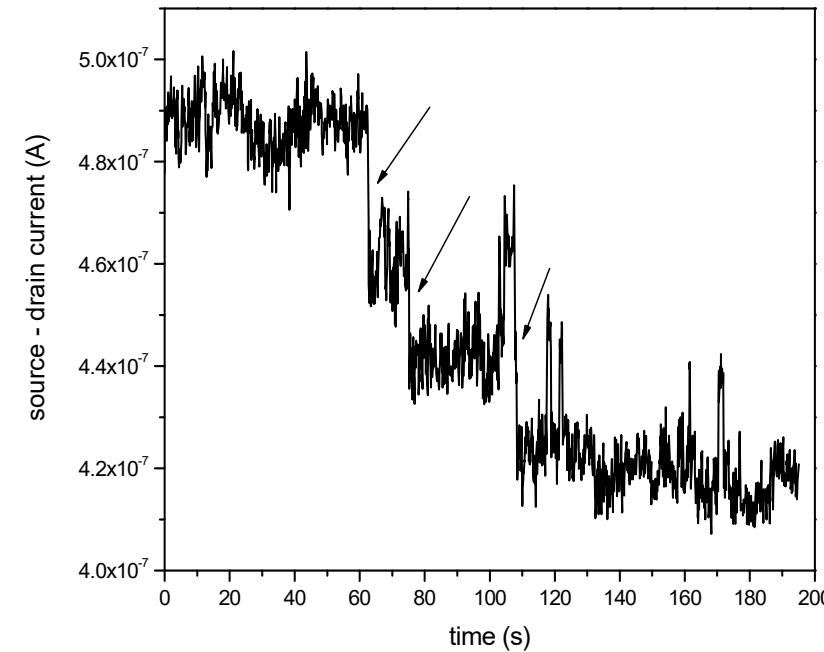
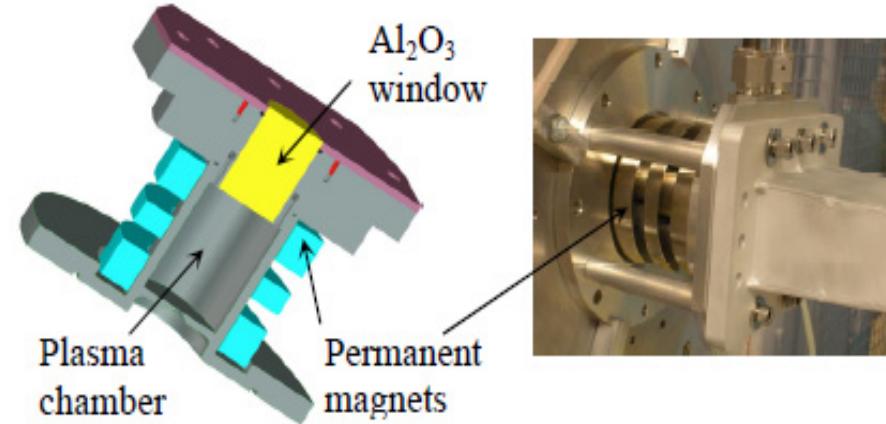
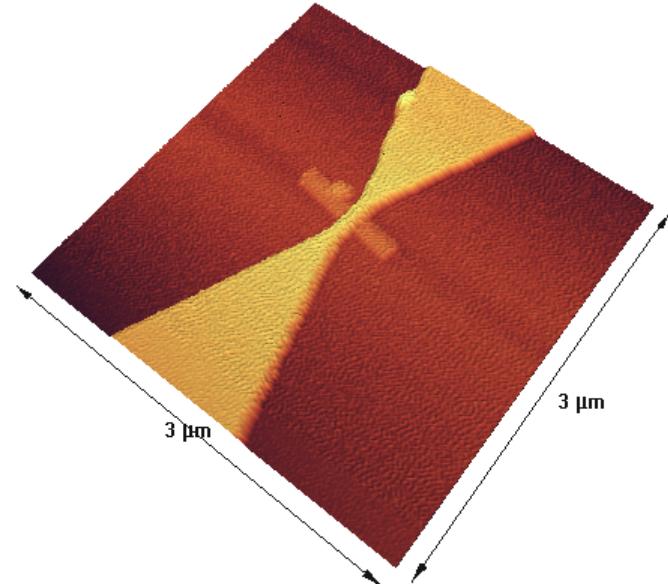
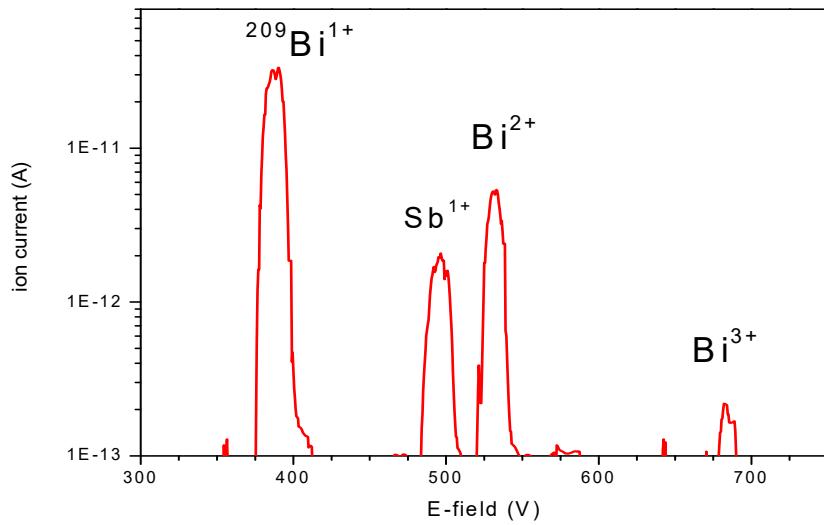


Qubit array formation - Single Ion Implantation with Scanning Probe Alignment



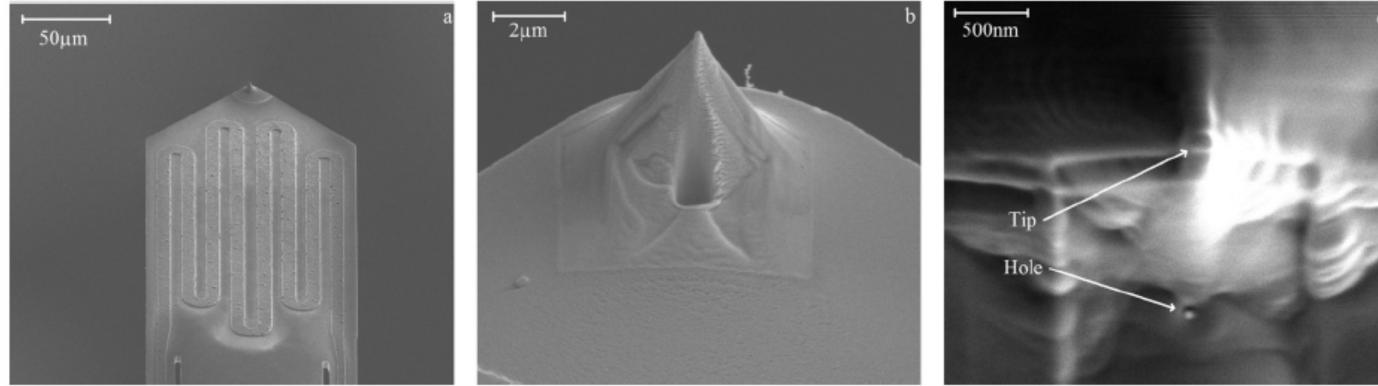
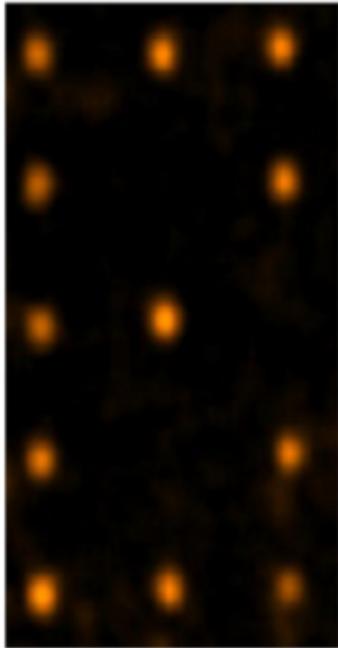
<https://www.youtube.com/watch?v=zTbBa5pvNdU>

Deterministic implantation of single bismuth ions



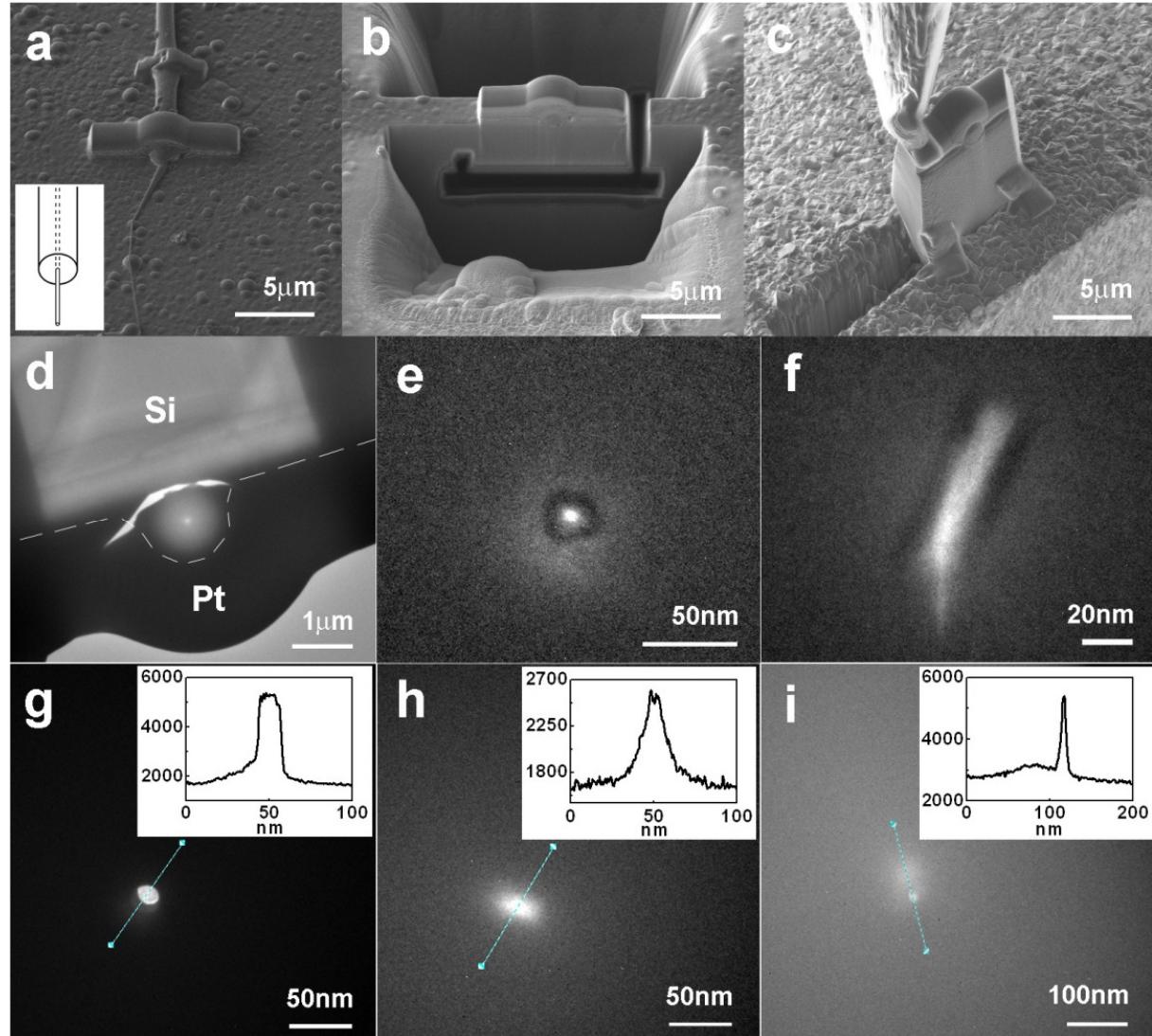
- Bi^+ , 10keV, 80x4000 nm device, $\Delta I/I \sim 5\%$

Single Ion Implantation with Scanning Probe Alignment



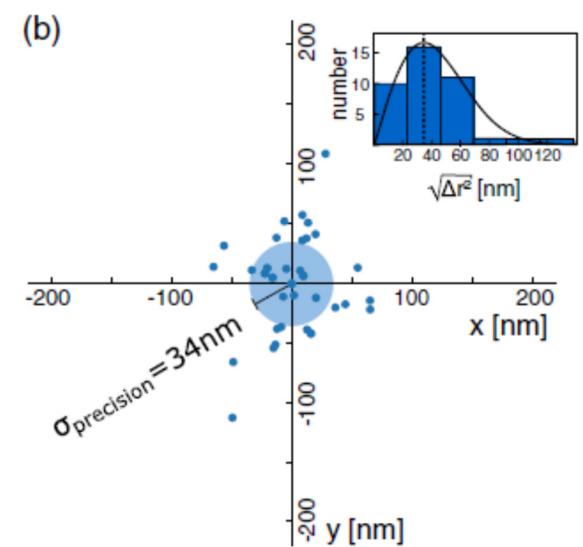
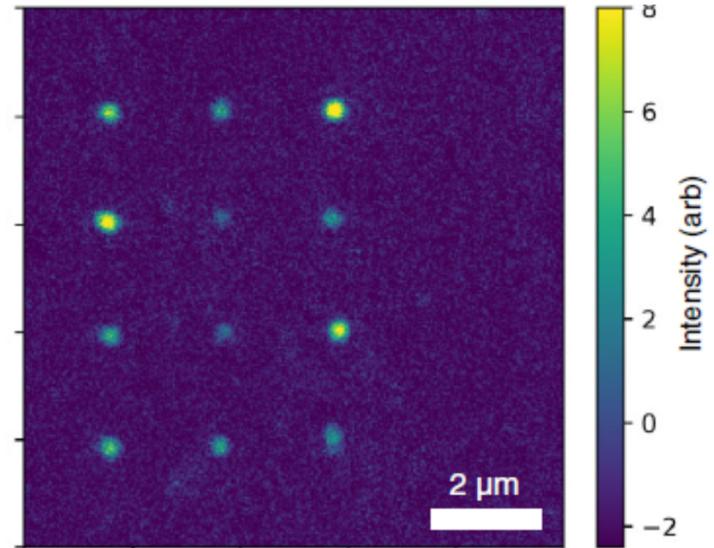
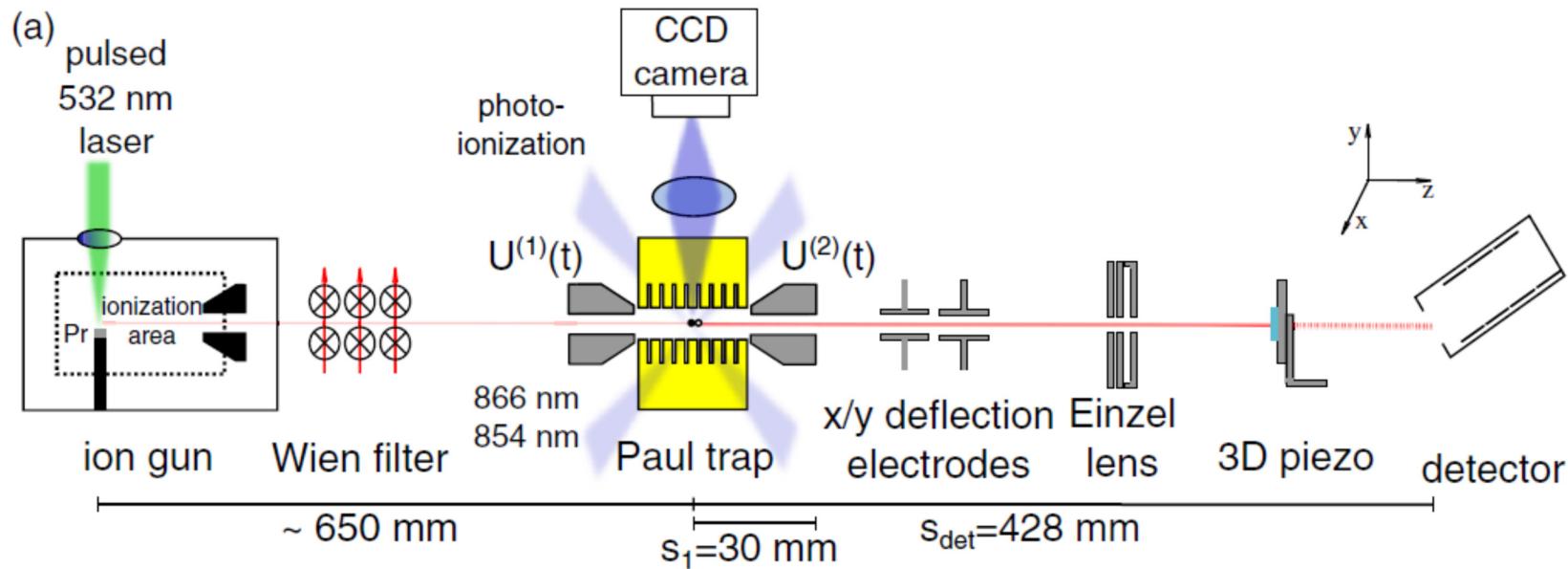
- NV-center array formation with dynamic shadow mask
- best spatial resolution achieved: 50 nm, smallest hole: 5 nm

Ultimate limit in dopant placement by implantation ?



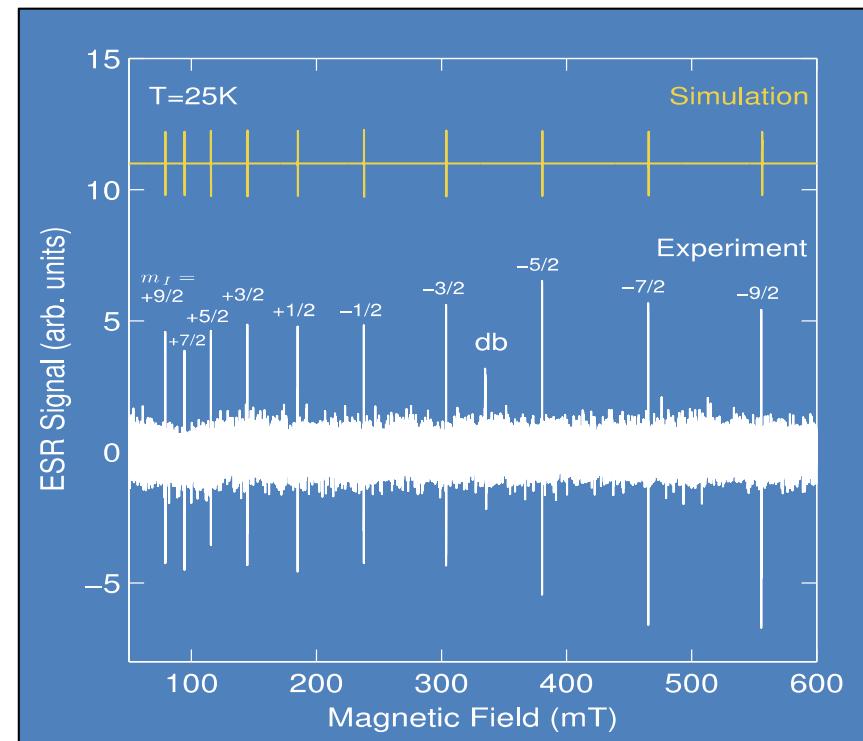
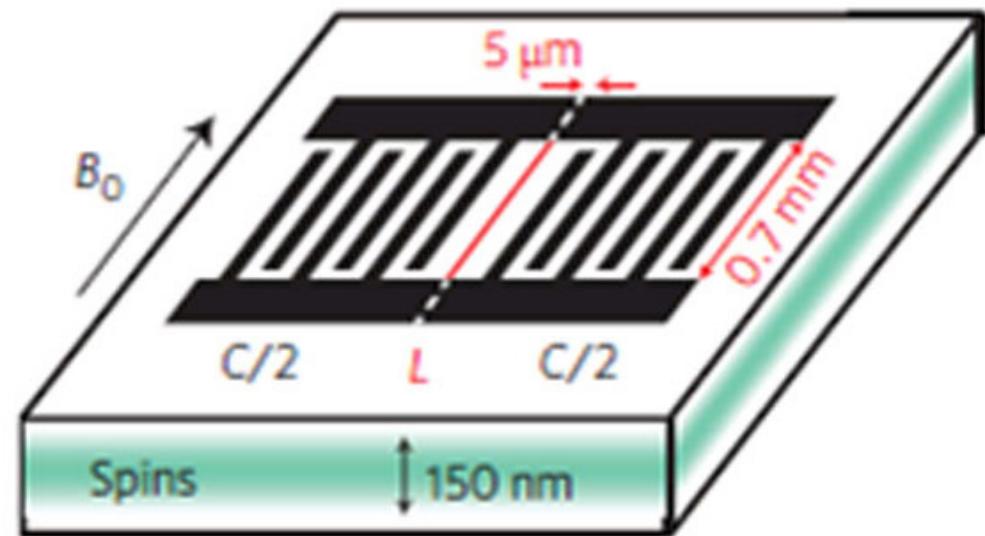
- We demonstrated transport of 200 keV electrons through a carbon nanotube over a length of several microns
 - The nanotube can act as a collimator for low energy ions with an aperture of 1 to 10 nm
 - Straggling can be minimized with low energy and high Z ions to <5 nm
 - Diffusion / segregation: some dopants stay put
- few nm ion placement accuracy seems possible

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)

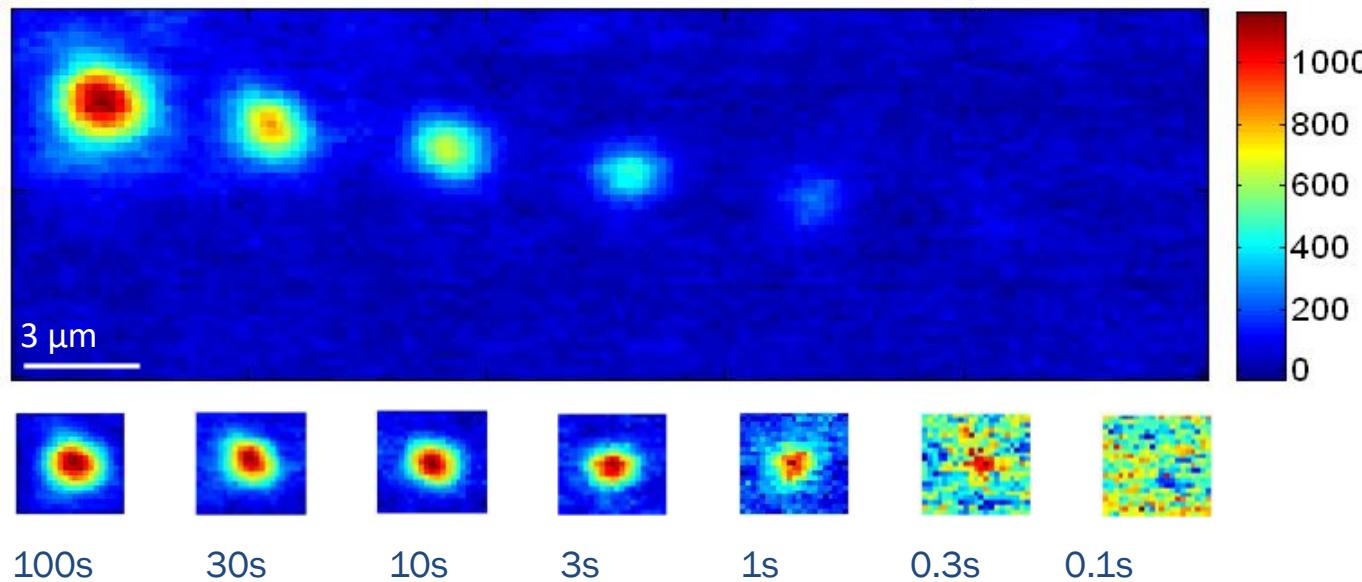
Can we extend the parameter space for qubit synthesis with intense beams ?



- 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

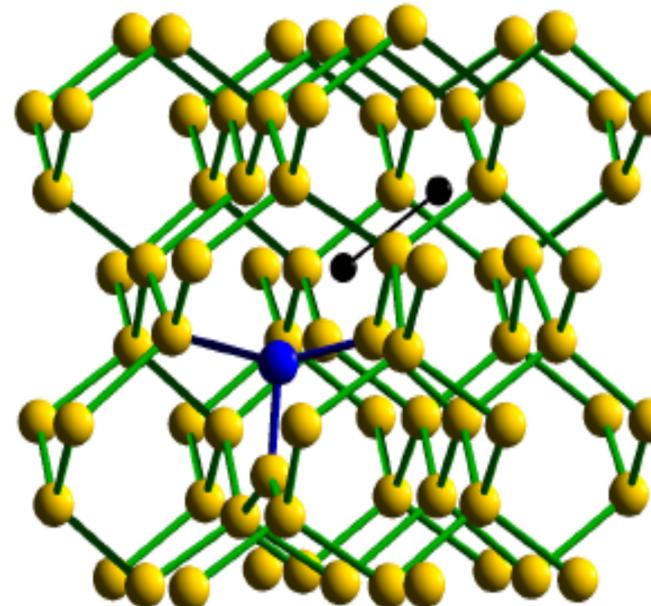


- confocal PL image of NV⁻ centers (635–642 nm) at room temperature, recorded following exposure of 1 μm squares to a 9 pA, 2 keV electron beam. Insets show locally auto-scaled spots.
- local activation enables iterative formation of NV⁻ in arrays
- can we form color centers with tailored properties ?
- Note: activation of NV⁰ centers in diamond by low energy electrons and high energy ions was reported already in the 70s and 80s (see A. M. Zaitsev, 2001)

How do NV-centers form in diamond?

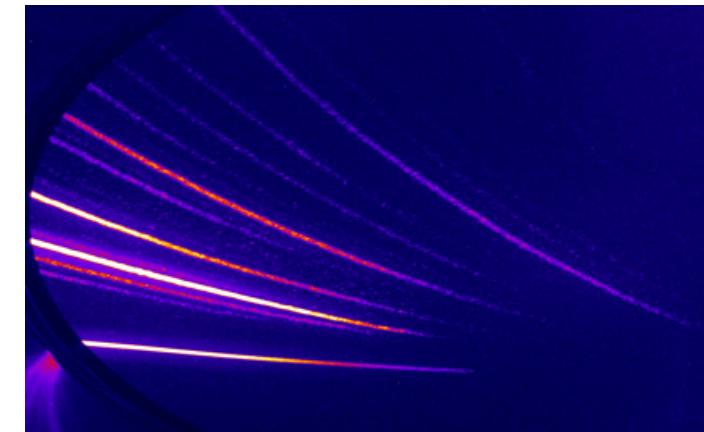
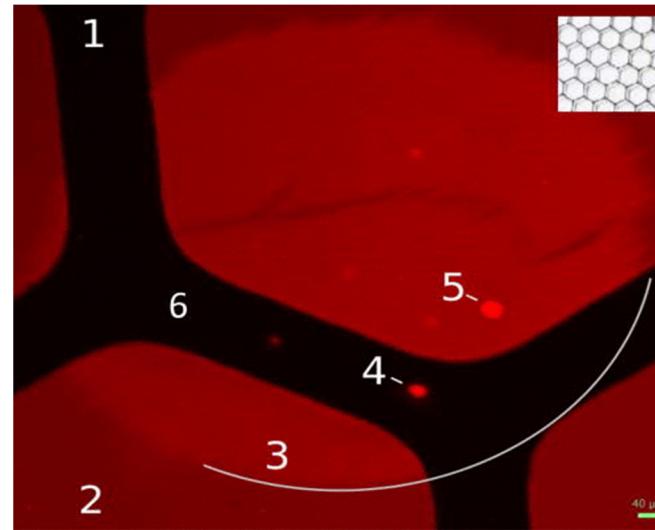
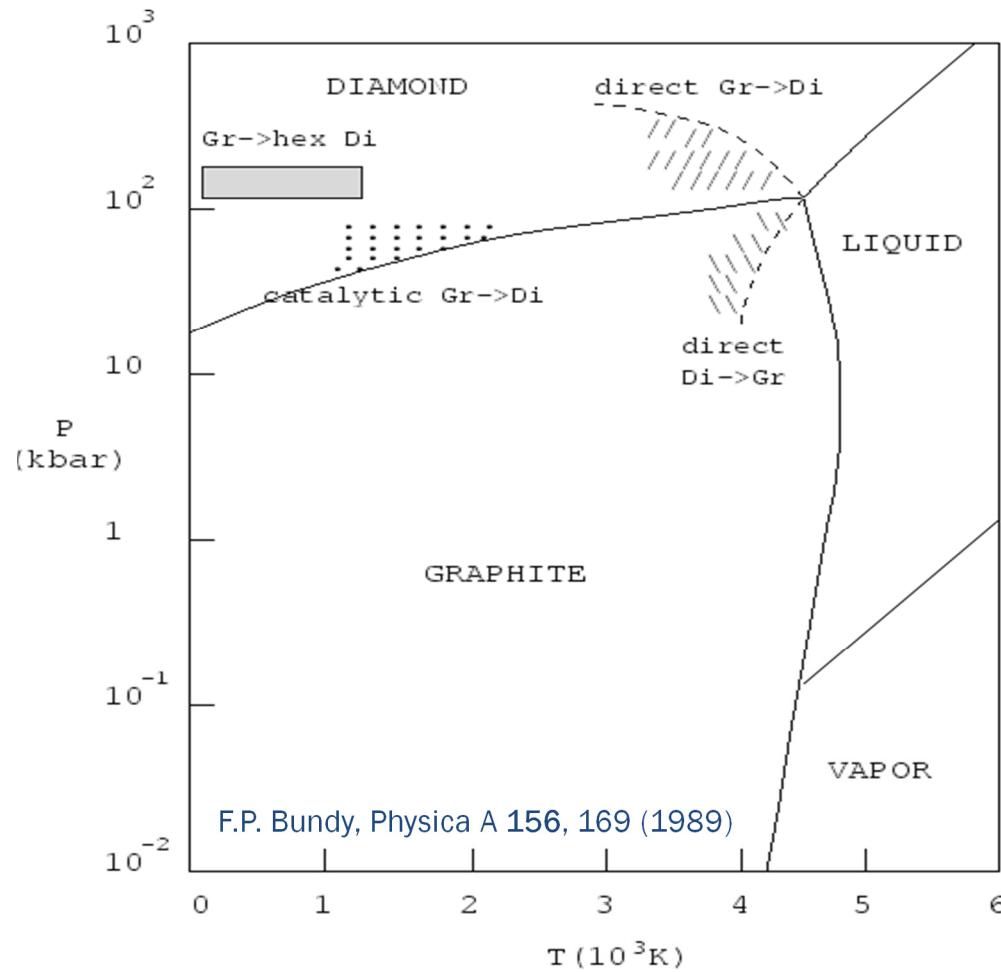


vs.



- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at $>300^\circ\text{C}$
- 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

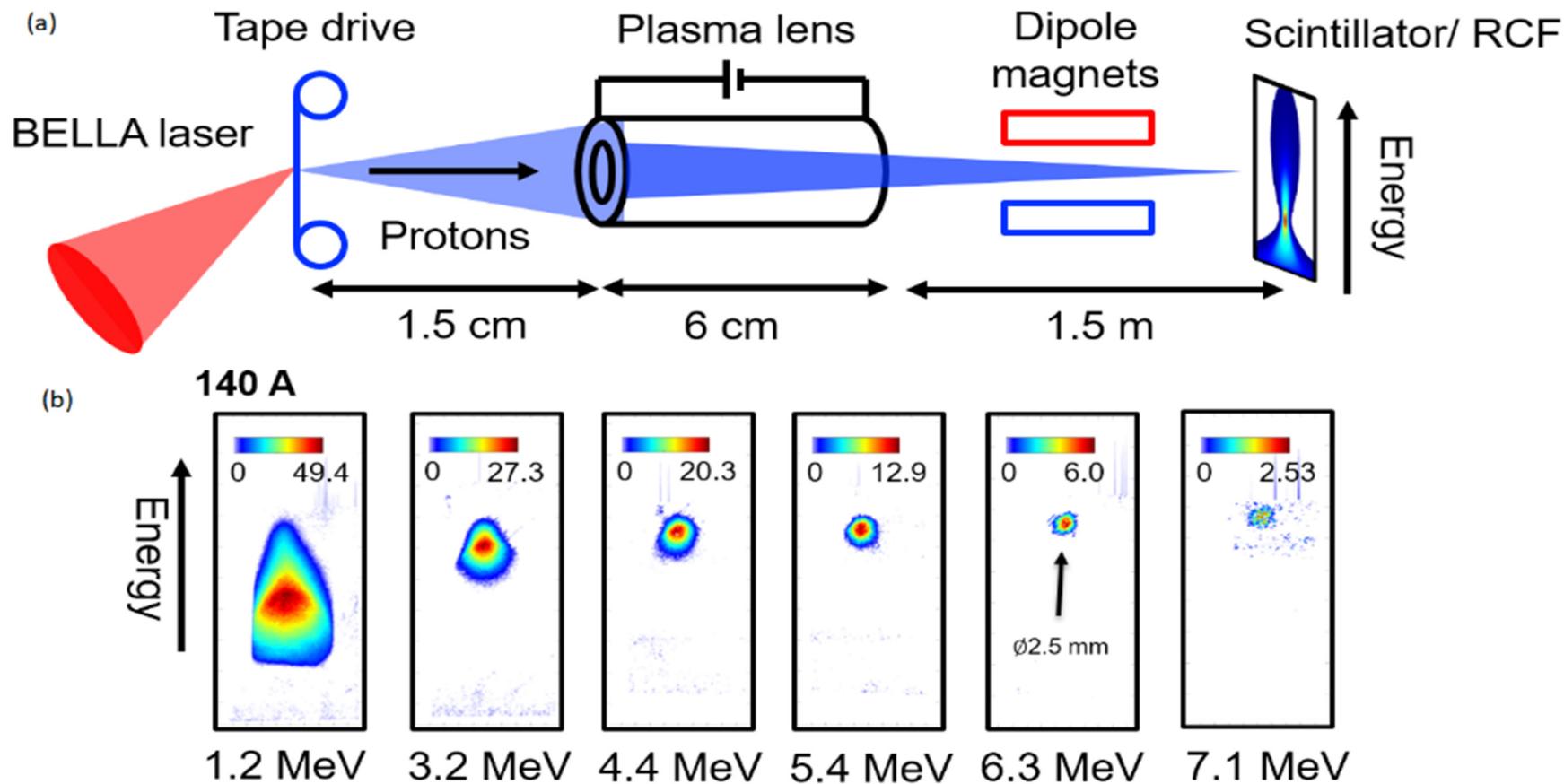
Qubit synthesis with intense beams



- 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

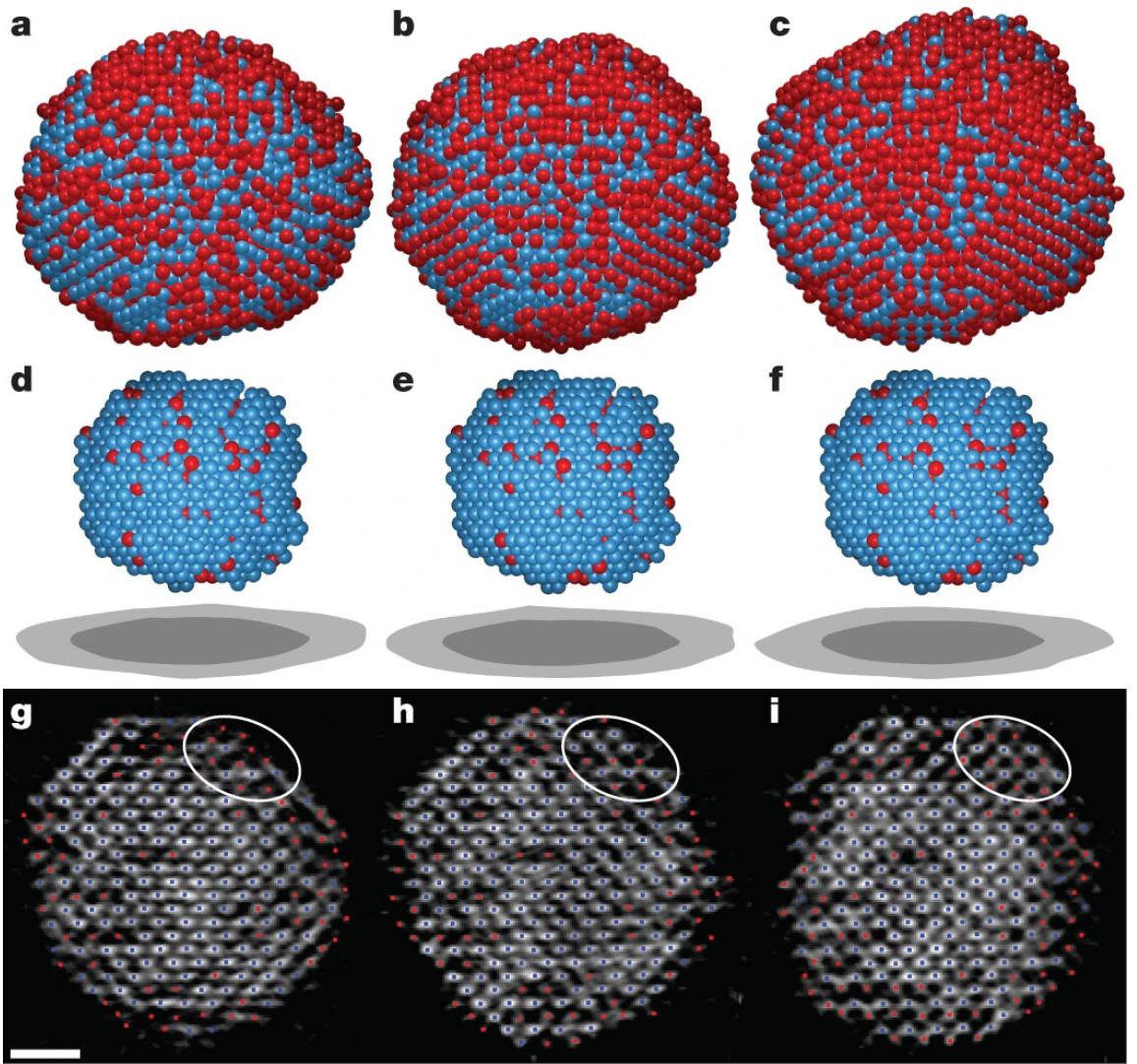
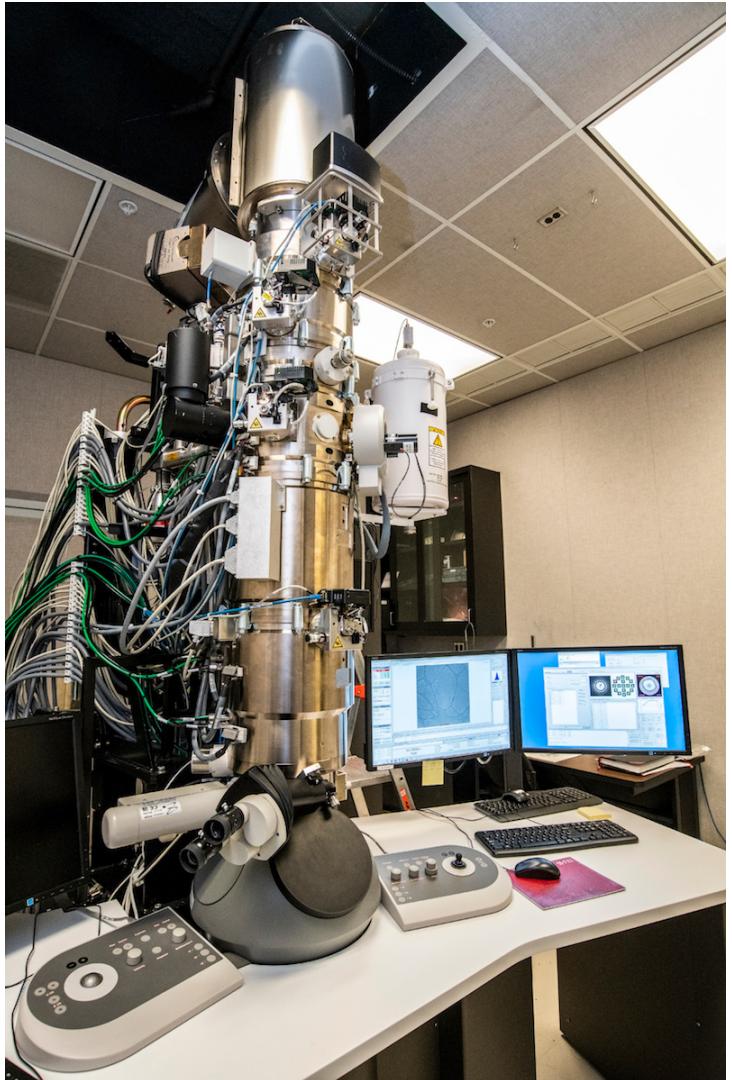
J. Schwartz, et al., JAP (2014)
J. H. Bin et al., RSI (2019)

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/>

Beams and qubits – electron microscopy from structure to coherence

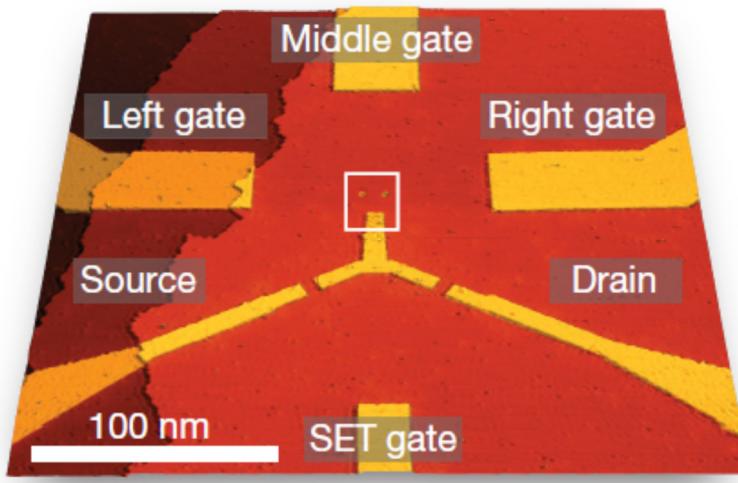


<https://newscenter.lbl.gov/2018/06/07/theres-a-new-microscope-in-town-themis-anyone/>

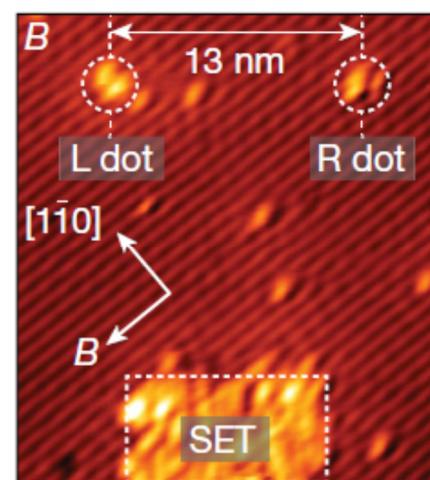
J. Zhou, et al., “Observing crystal nucleation in four dimensions using atomic electron tomography”, *Nature* **570**, 500 (2019)

Towards qubit integration with atomic precision

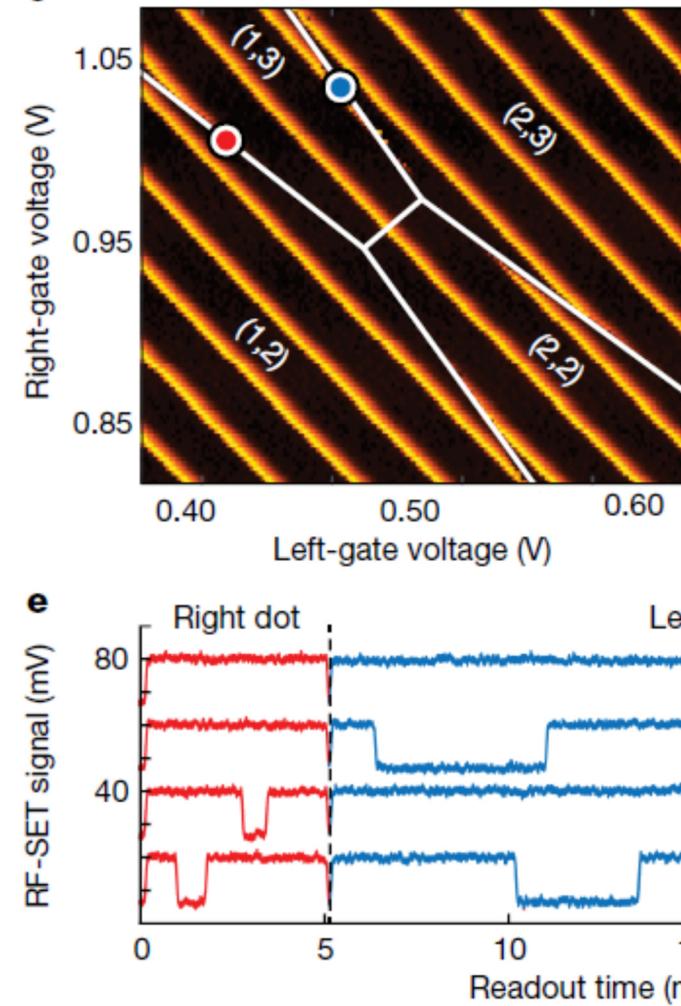
a



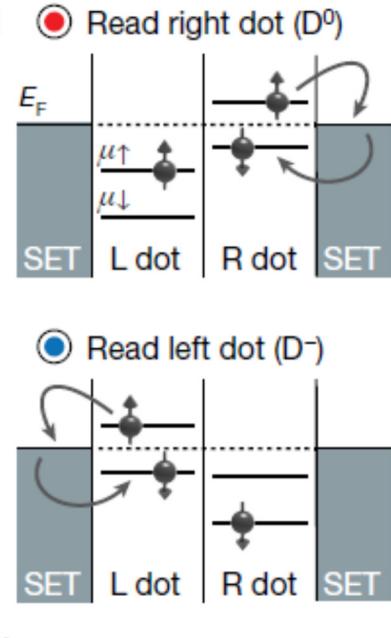
b



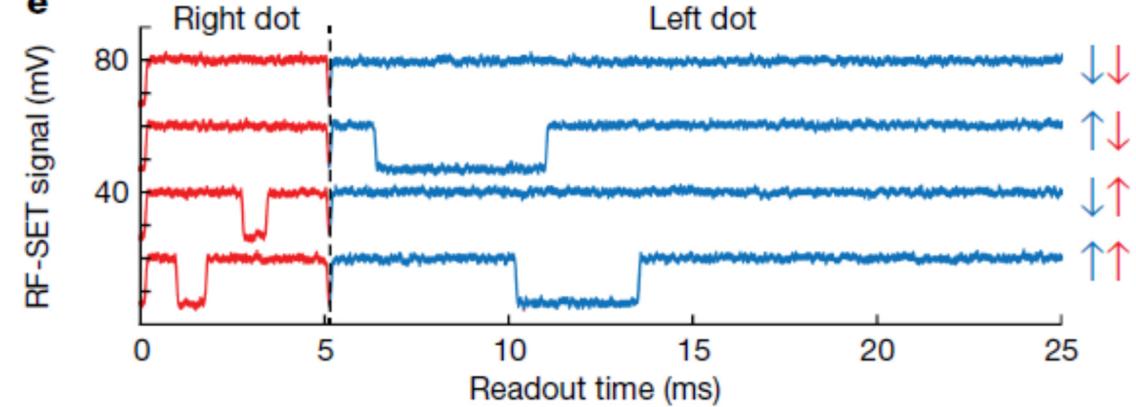
c



d

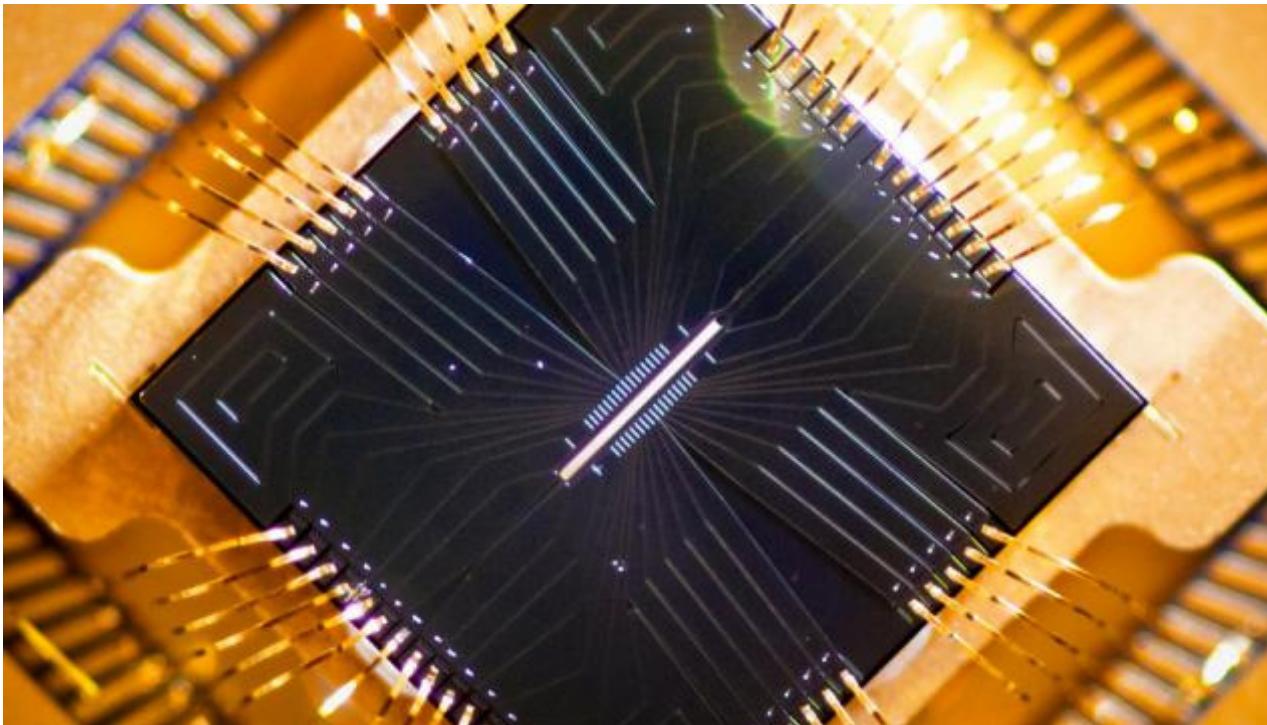
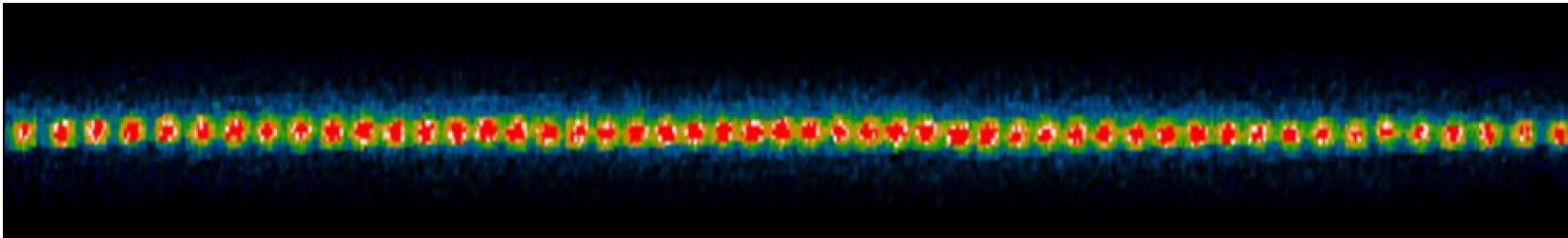


e



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)

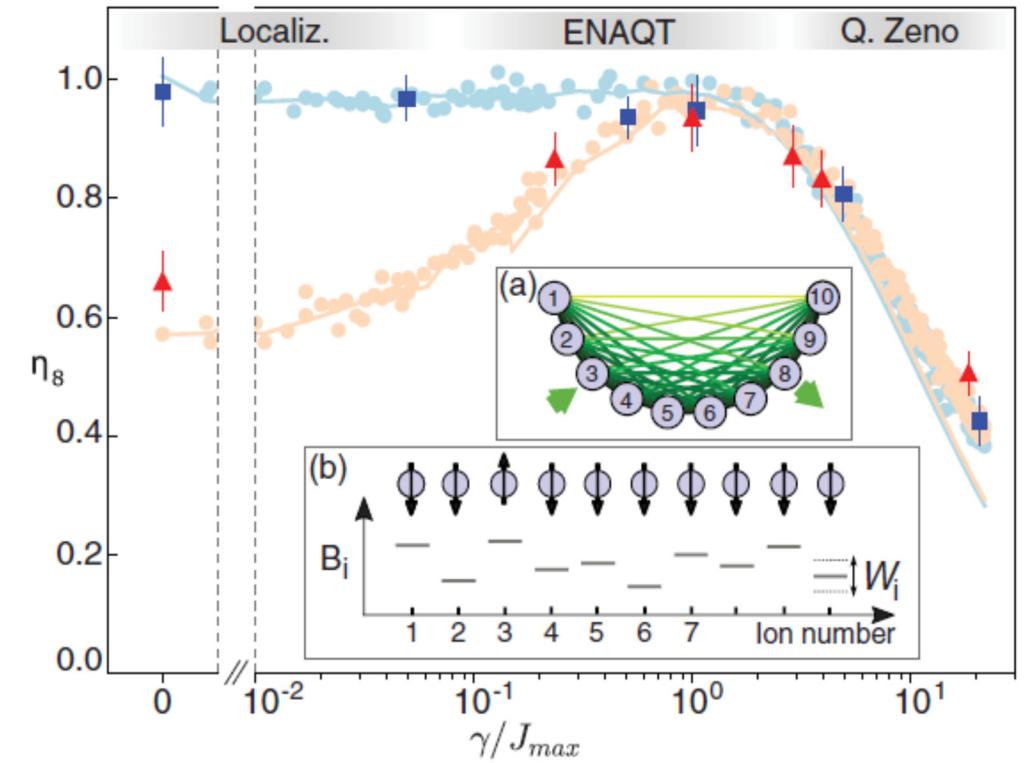
Qubits and beams – trapped ions



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

Noise and coherence

- “One scientist’s 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



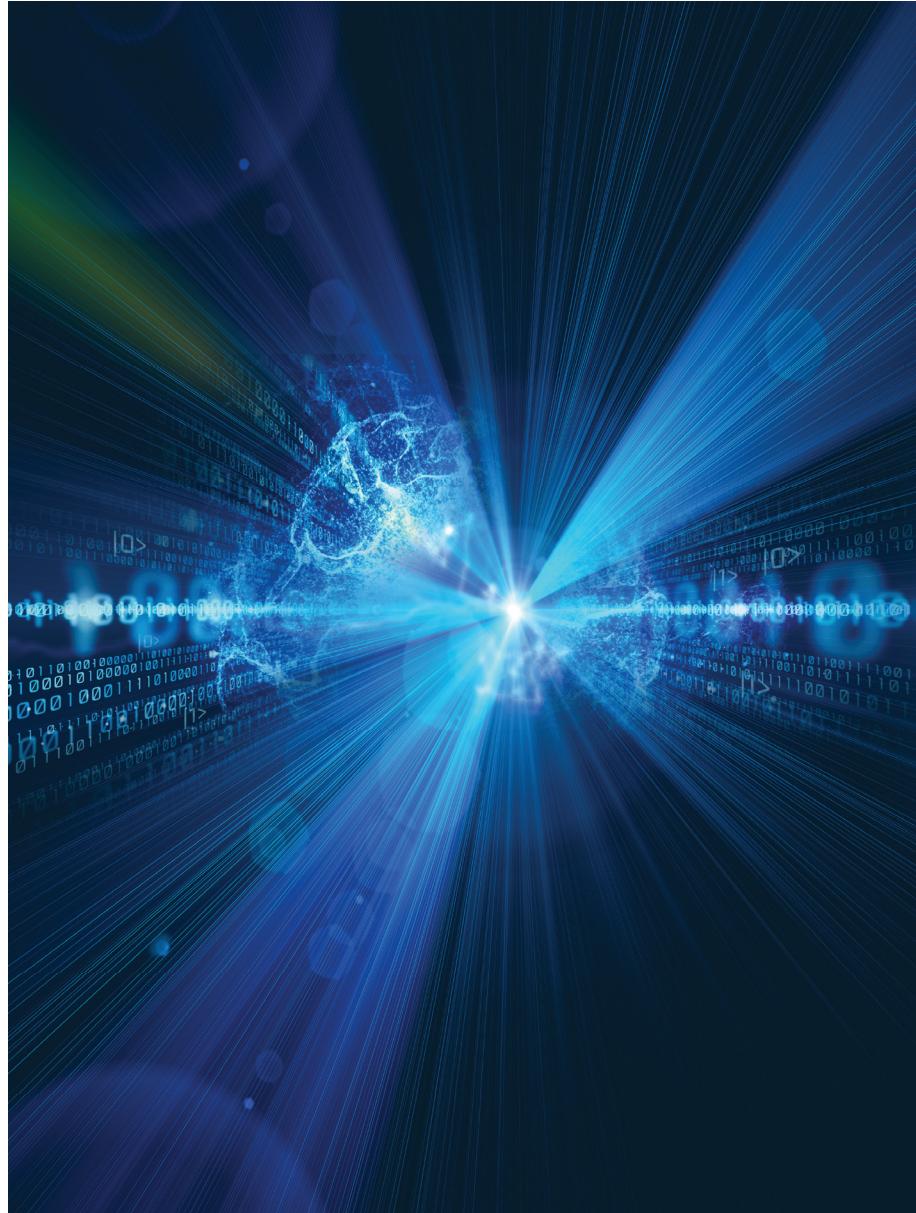
Environment-Assisted Quantum Transport in a 10-qubit Network,
C. Meier, et al., PRL 122, 050501 (2019)

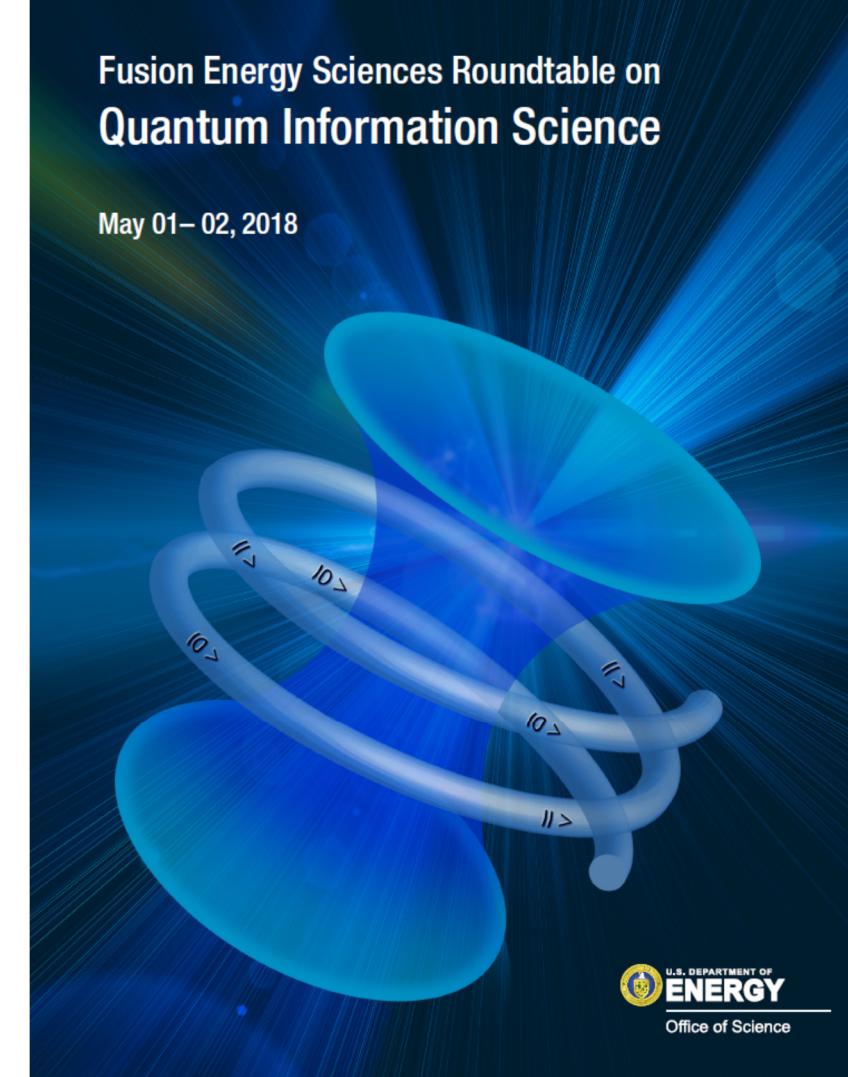
Beams and qubits

- 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)

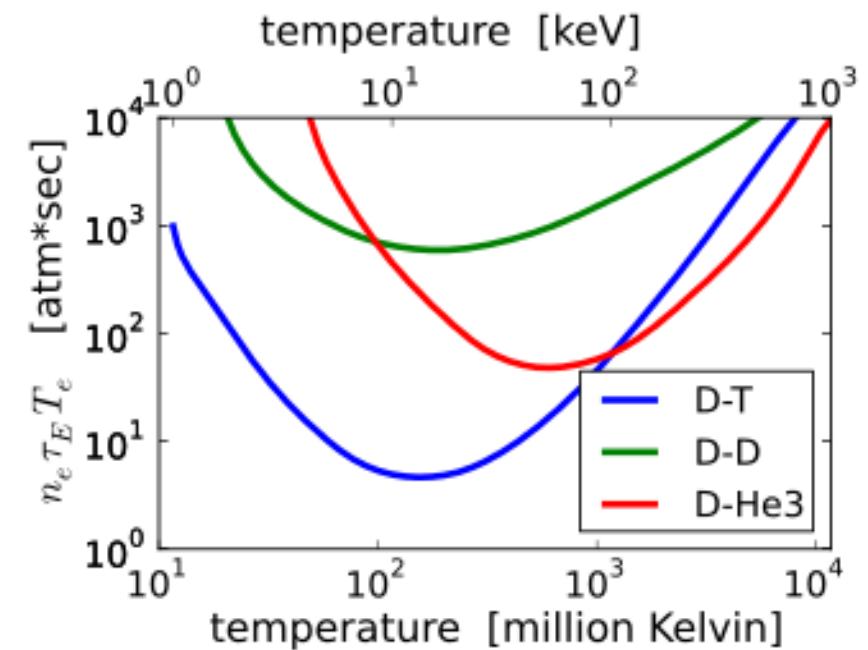
PRO 4: High energy density laboratory plasmas science for novel quantum materials

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

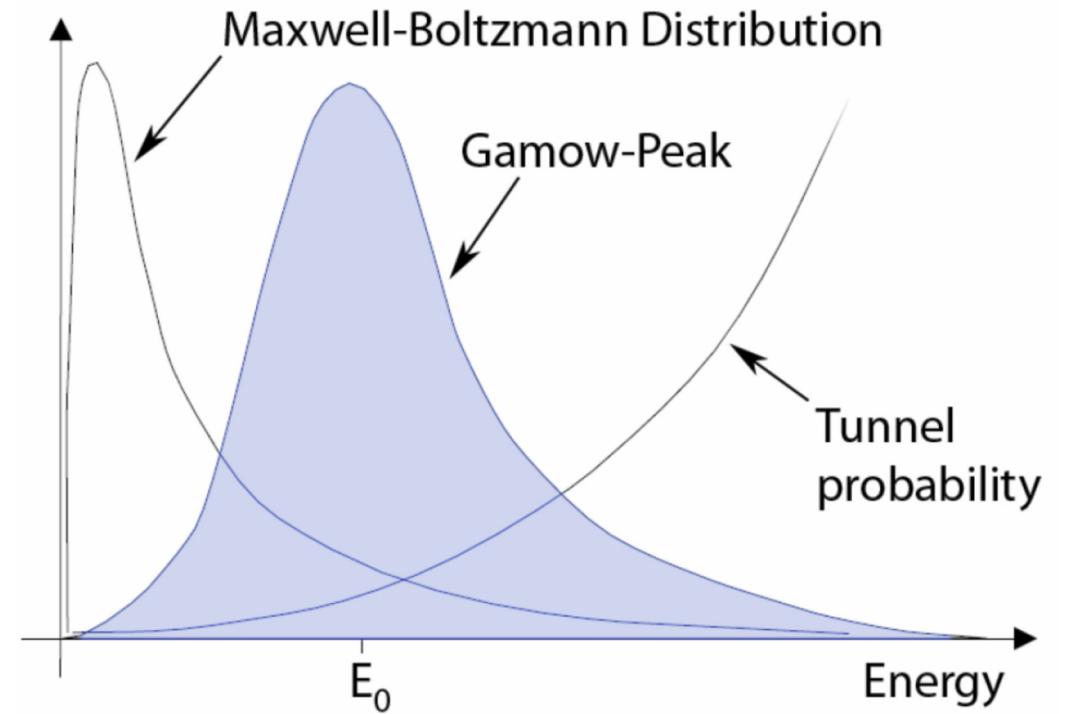
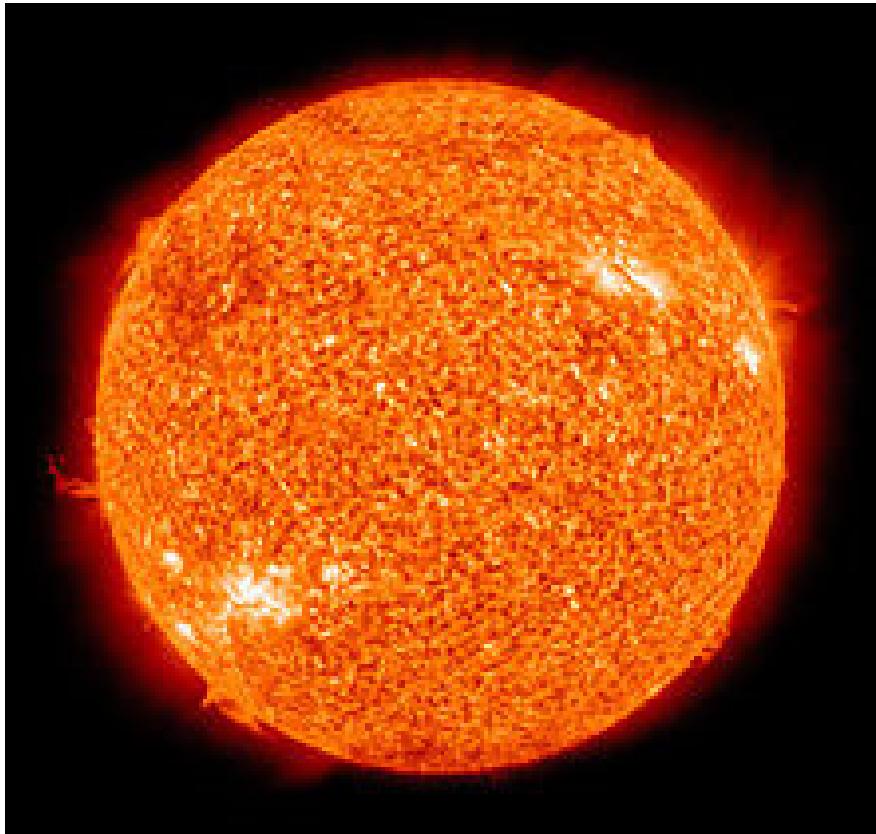
PRO 6: Plasma science tools for simulation and control of quantum systems

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>



Fusion in the sun



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

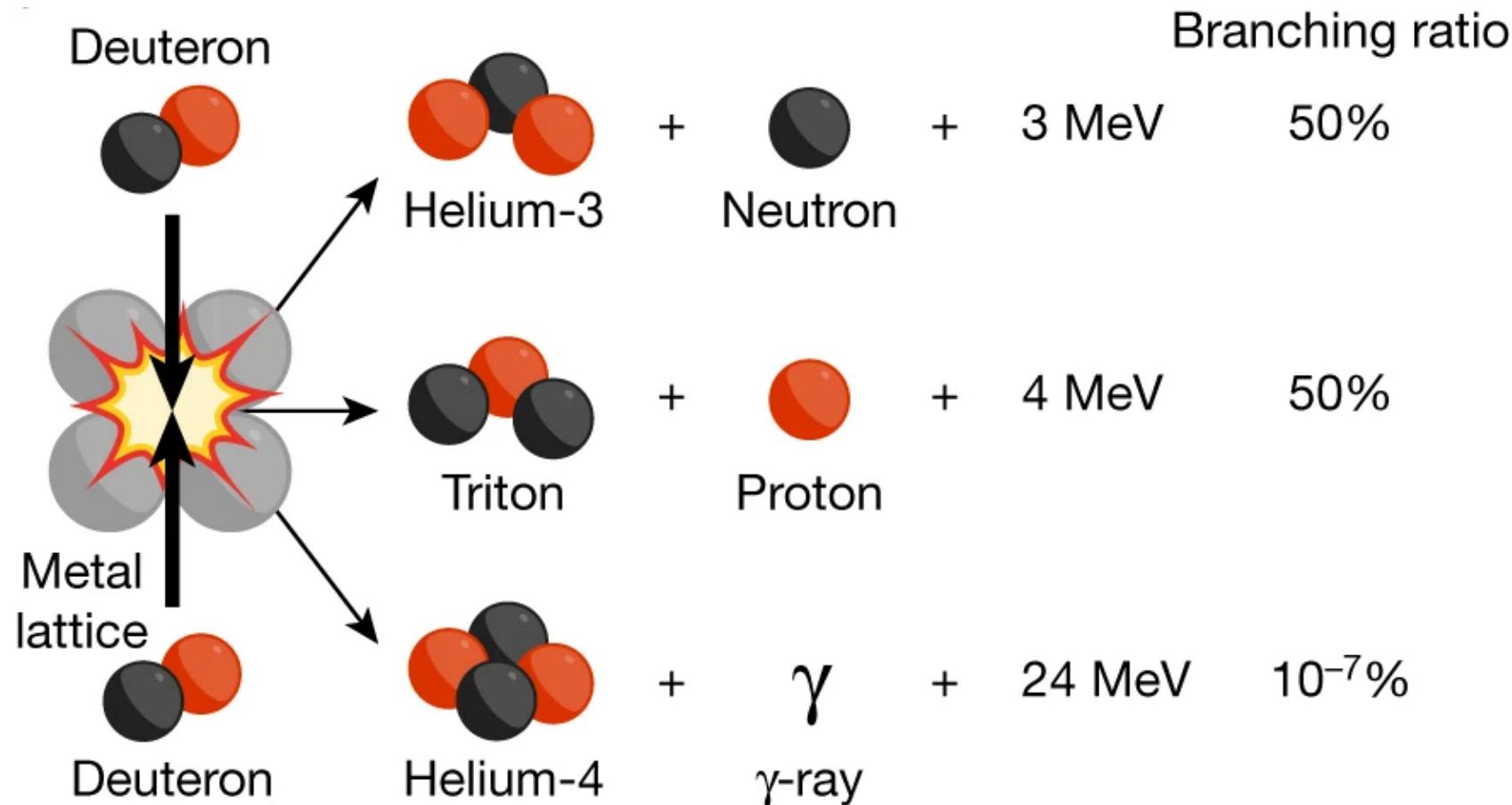
Maximum Gamow-Peak	= 7.8 keV
Effective width	= 7.5 keV
Energy window ($E_0 \pm \Delta/2$)	= 4.0 - 11.5 keV

<https://en.wikipedia.org/wiki/Sun>

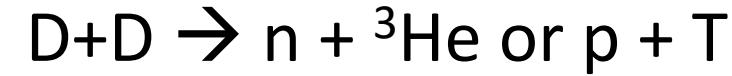
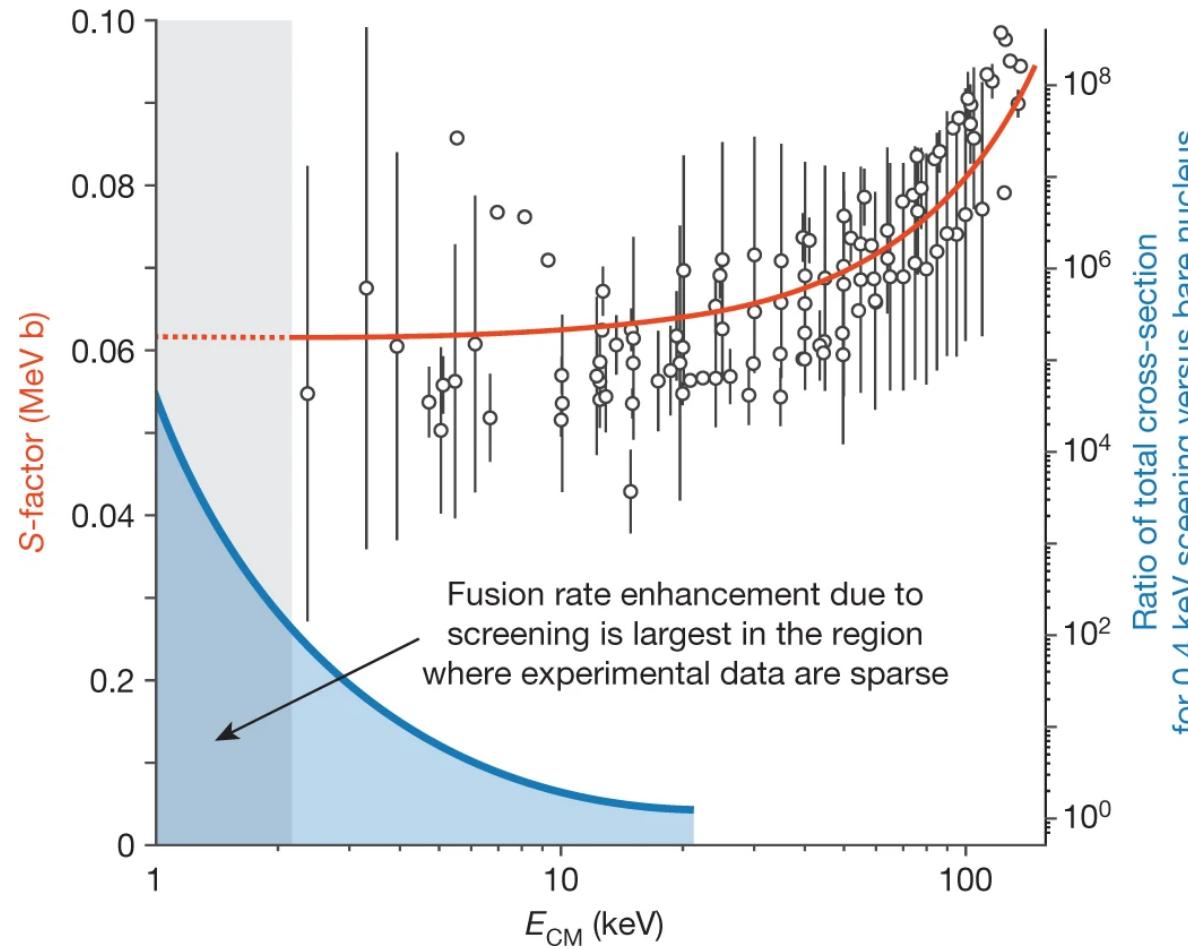
<http://www.kadonis.org/pprocess/gamow.php?tele=H&ta=2&pele=H&pa=2&t6=16>

<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

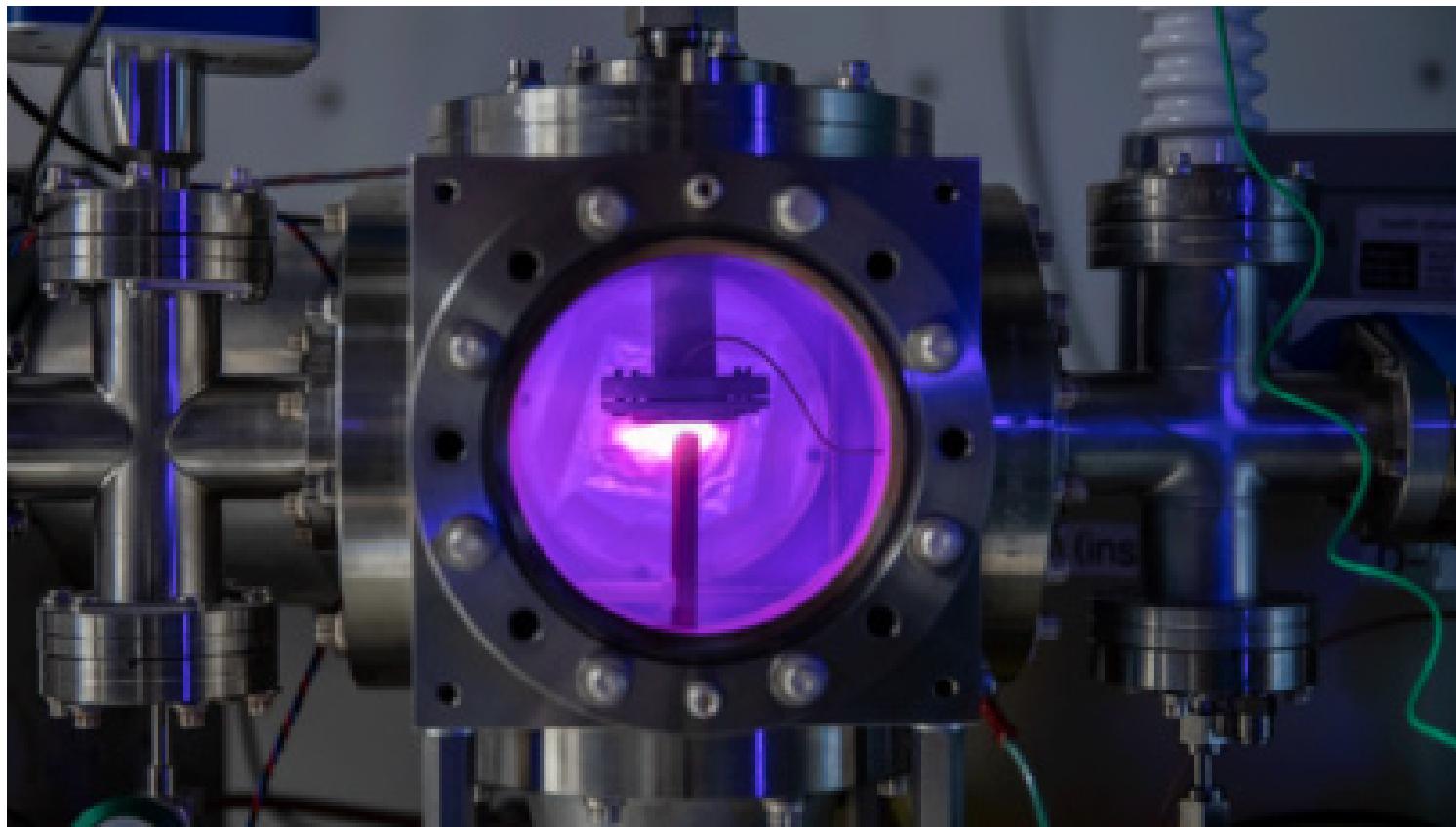


Electron screening affects low-energy fusion cross sections, especially in solids

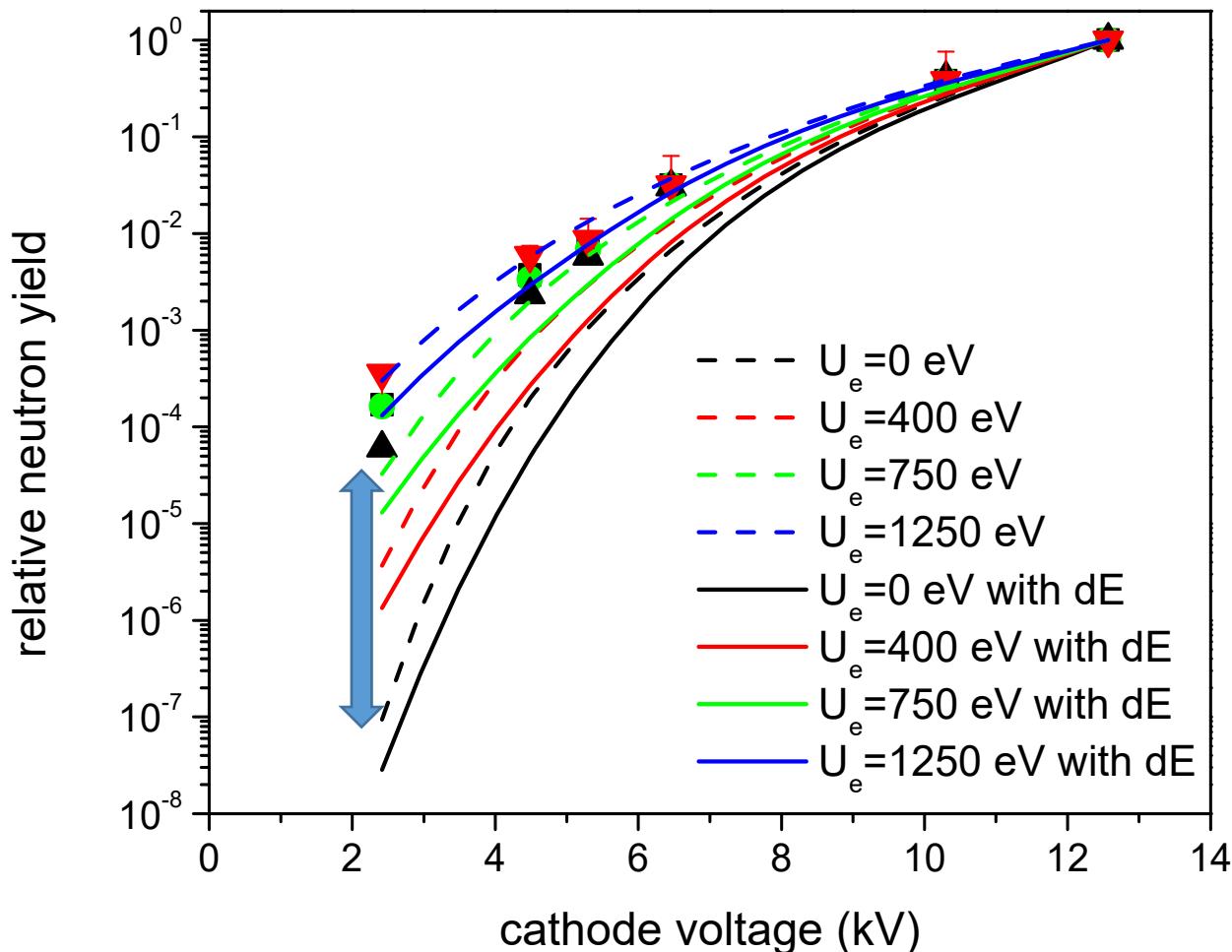


$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E + U_e)}} e^{-\sqrt{E_g/(E + U_e)}} S(E)$$

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).



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



Letter | Published: 06 July 1989

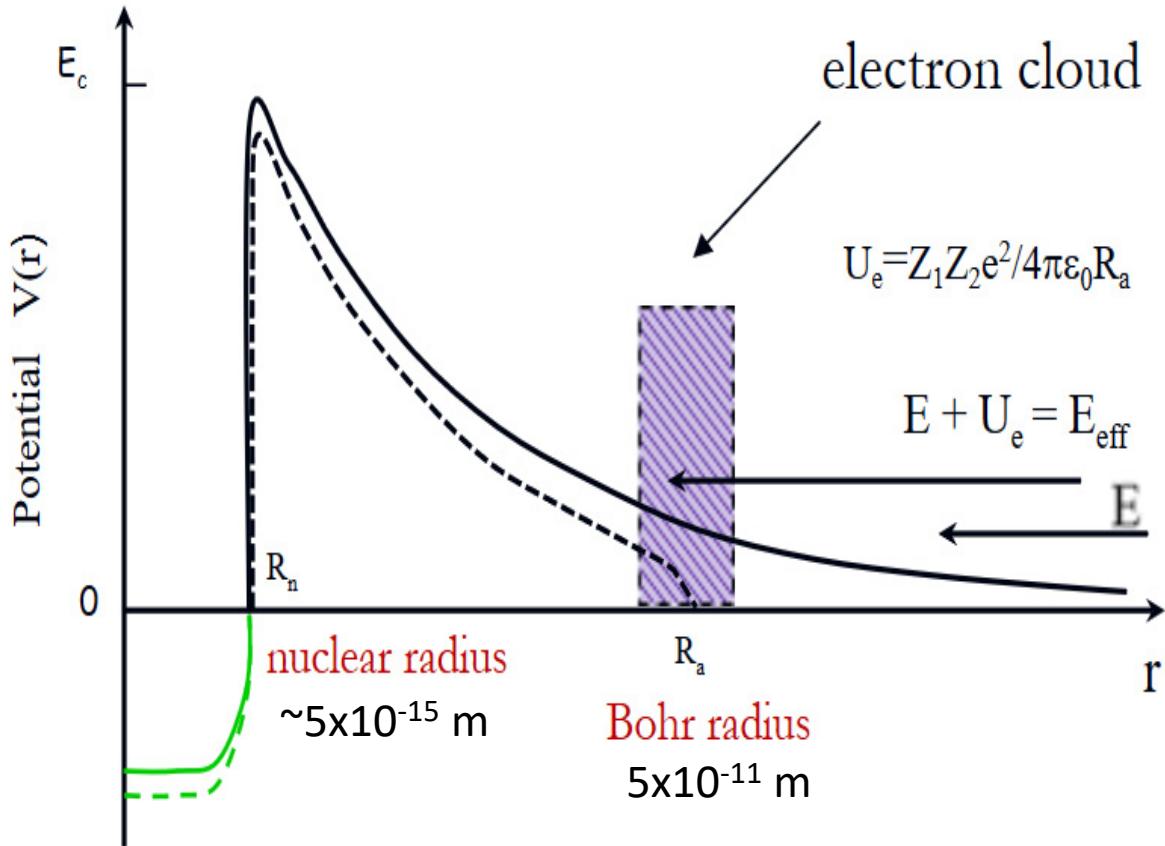
Can solid-state effects enhance the cold-fusion rate?

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 ?

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

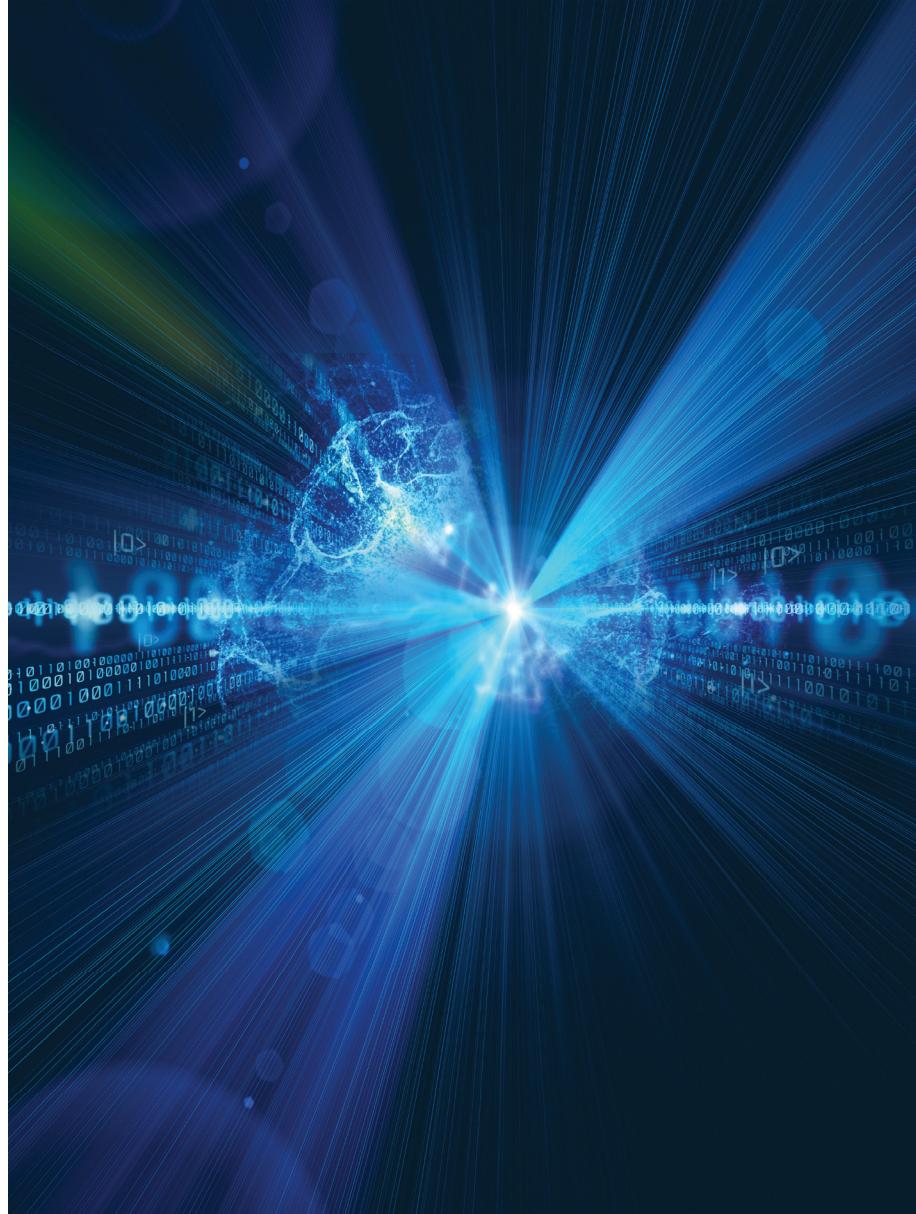


R. Babush et al., “Low-Depth Quantum Simulation of Materials,” Phys. Rev. X 8, 011044 (2018)

“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.”

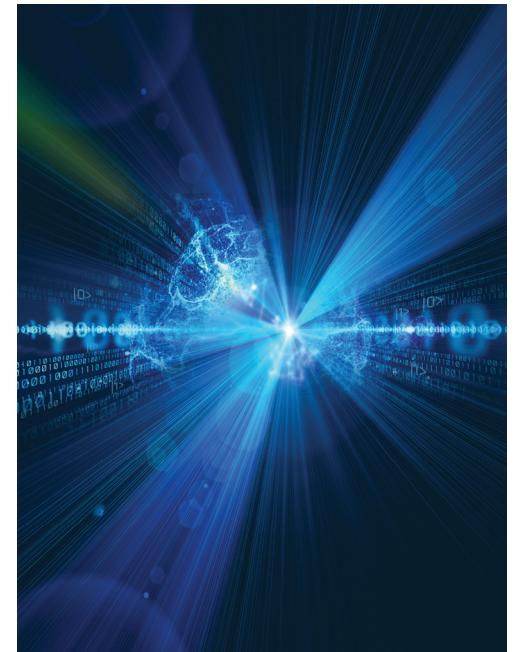
Outline

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?
 - ...



Accelerator and Beam Physics Grand Challenges and a National Roadmap Update

S. Nagaitsev[#](Fermilab/UChicago), J. Power (ANL), L. Spentzouris (IIT), J.-L. Vay (LBNL), P. Piot (NIU), Z. Huang (SLAC/Stanford), and J. Rosenzweig (UCLA)
 (Your comments can shape this roadmap! Please email to nsergei@fnal.gov)

ABSTRACT
 The Accelerator and Beam Physics (ABP) thrust is part of the DOE HEP-funded research portfolio of General Accelerator R&D. It focuses on the science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged-particle beams. We are now collecting input to the national community-driven research roadmap to address these challenges.

INTRODUCTION
 The Accelerator and Beam Physics (ABP) thrust is part of the DOE HEP-funded research portfolio, focused on General Accelerator R&D (GARD).

ABP Thrust Definition
 Accelerator and beam physics is the science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged-particle beams.
 The Accelerator and Beam Physics (ABP) thrust focuses on fundamental long-term accelerator and beam physics research and development.

ABP Vision Statement
 The ABP thrust explores and develops the science of accelerators and beams to make future accelerators better, cheaper, safer, and more reliable. Particle accelerators can be used to better understand our universe and to help solve societal challenges.

ABP Missions
 The primary scientific mission of the ABP thrust is to address and resolve the Accelerator and Beam Physics Grand Challenges, outlined below. Other equally important ABP missions are associated with the overall DOE HEP missions:

- Advance the physics of accelerators and beams to enable future accelerators.
- Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms in coordination with other GARD thrusts.
- Guide and help to fully exploit science at the HEP GARD beam facilities and operational accelerators.
- Educate and train future accelerator physicists.

GRAND CHALLENGES

Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

Summary:
 Beam intensities in existing accelerators are limited by collective effects and particle losses. A complete and robust understanding of these effects could help overcome the limits and increase beam intensities by orders of magnitude.

Description (deliverables):
 Future demands for beams will exceed present capabilities by at least an order of magnitude in several parameter regimes such as the average beam power and the peak beam intensity. Ultimately, the beam intensities in present accelerators are limited by collective effects and particle losses from various sources, e.g. space-charge forces between beam particles and beam impinging losses. How do we overcome the subtle differences in the ways that different beam properties lead to beam losses? A complete and robust understanding of these effects in real accelerators does not yet exist. Additionally, theoretical, computational and instrumentation tools to address this challenge are not yet fully developed at the precision level required by modern beam applications (see GC #3 and #4).

Promised dividends:

- Deliver an order of magnitude increase or more in secondary particle fluxes from proton and heavy-ion driver applications;
- Enable beam driven wakefield accelerators and ultrashort electron bunches for collider applications;
- Enable 1st generation of accelerator-driven energy systems;
- Inform challenges associated with beam quality, control and prediction.

Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?

Summary:
 Some applications of accelerators depend critically on the beam intensity and directionality, in order to yield new capabilities or to optimize the signal to noise ratio. Addressing this grand challenge will enable unprecedented beam qualities that can revolutionize applications of particle accelerators.

GRAND CHALLENGES (CONT'D)

Grand challenge #2 (beam quality)
Description (deliverables):
 The beam phase-space density is a determining factor for the luminosity of high-energy colliders, for the brightness of photon sources based on storage rings or free-electron lasers (FELs), and on emerging instruments using electrons directly for imaging — ultra-sensitive electron diffraction and microscopy. Pushing beam phase-space density beyond the current state-of-the-art has tremendous payoff towards discovery sciences driven by accelerators, particularly those with new capabilities: femto-second resolution electron imaging, and new tools for future collider development through source and wakefield accelerator research. Research topics span frontier schemes for generating of high-brightness electron and proton beams, control of space charge and coherent radiation effects and other collective instabilities, preservation of beam cooling, brightness during beam acceleration, compression and manipulation, and novel techniques for beam cooling.

Promised dividends:

- Create new paths for dramatically increasing in collider luminosity;
- Enable small-size wakefield-based colliders;
- Significantly enhance the brightness and wavelength reach of modern X-ray sources; Enable schemes for compact FELs;
- Create beam-based tools with unprecedented temporal and spatial resolution.

Grand challenge #3 (beam control): How do we control the beam distribution down to the level of individual particles?

Summary: A given accelerator application benefits most when the beam distribution is specifically matched to the application. This challenge aims to replace traditional methods that use beams of limited shapes with tailored beams.

Description (deliverables): A given accelerator application is best served by a beam with a specific distribution matched to the application. The goal of creating specific beam distributions represents a paradigm shift from traditional approaches based on rms beam properties. This new approach presents significant challenges in beam dynamics and diagnostics as well as accelerator design and operation. This challenge seeks to develop methods for beam diagnostics, and beam collimation methods capable of controlling the beam distribution down to the level of individual particles. This challenge also needs the associated theory and modeling tools that scale to the ultimate goal of controlling the complete 6-D phase space distribution at the individual particle level. In addition, given the complexity of these 6-D distributions and the associated collective effects, the use of artificial intelligence to control the beam distribution (in simulations or during accelerator operation) should be explored. Once this is accomplished, accelerator science will open the door to fundamentally new discoveries.

Promised dividends:

- Substantially increase luminosity in future colliders;
- Mitigate and control beam losses;
- Improve the performance of future advanced collider concepts;
- Enable table-top coherent light sources.

Grand Challenge #4 (beam prediction): How do we develop predictive “virtual particle accelerators”?

Summary: Developing “virtual particle accelerators” will provide predictive tools that enable fast computer modeling of particle beams and accelerators at unprecedented levels of accuracy and completeness. These tools will enable or speed up the realization of beams at extreme intensity and quality, as well as control of the beam distribution, reaching down to the level of individual particles.

Description (deliverables):
 The importance of particle accelerators to society, with their increasing complexity and the high cost of new accelerator facilities, demands that the most advanced computing tools be brought to bear on R&D activities. This has been achieved since the 1990s. Pushing the limits in beam intensity, quality, and control demands more accurate, more complete and faster predictive tools, with an ultimate goal of virtual accelerators. The development of such tools requires continuous advances in fundamental beams theory and applied mathematics, improvements in mathematical formulations and algorithms, and their optimized implementation on the latest computer architectures. The modeling of beams at extreme intensities and levels of quality, and design of accelerators that deliver them, also call for integrated predictive tools that can take advantage of the largest supercomputers.

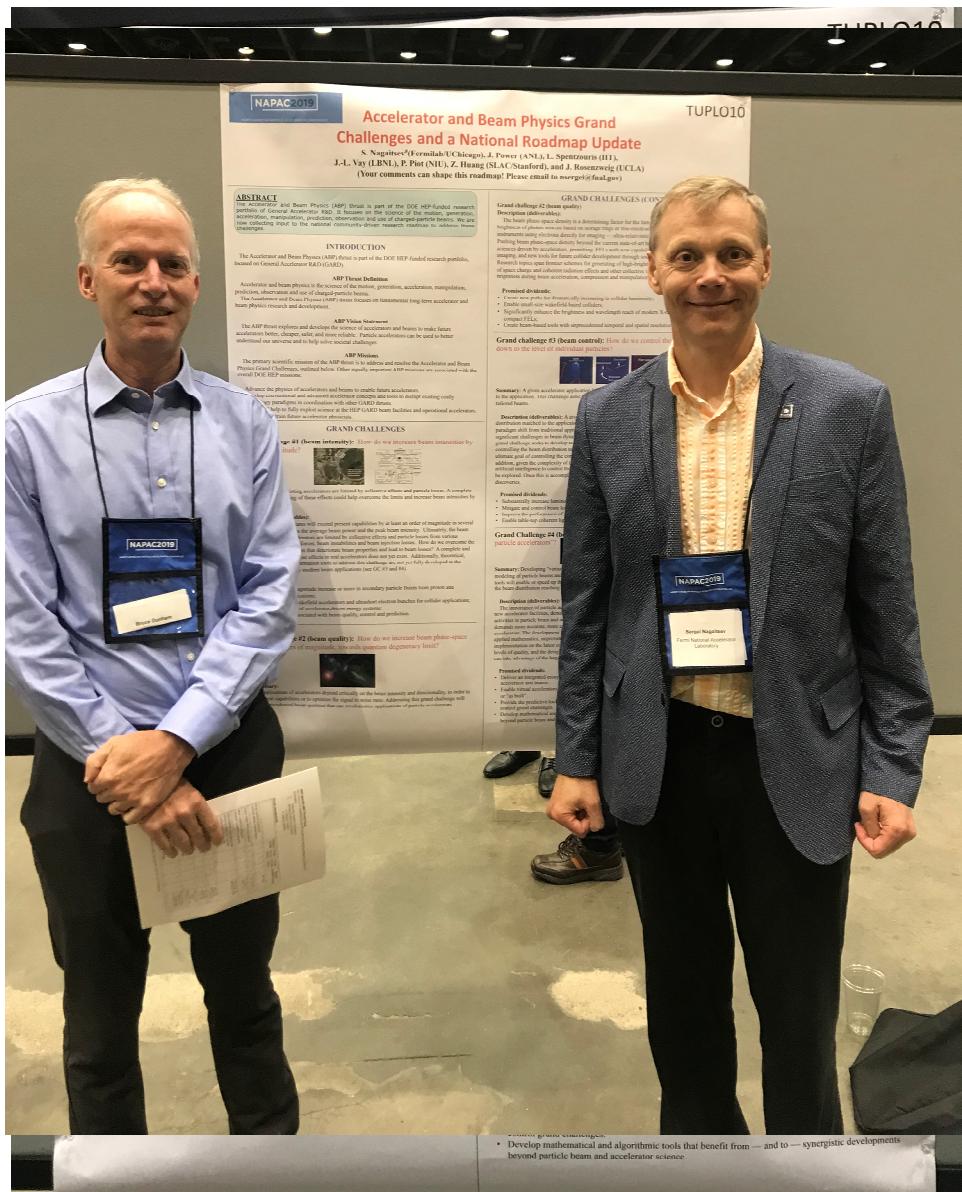
Promised dividends:

- Deliver an integrated ecosystem of predictive tools for accurate, complete and fast modeling of particle accelerators and beams;
- Enable virtual accelerators that can predict the behavior of particle beams in accelerators “as designed”, or “as built”;
- Provide the predictive tools that will enable or speed up the realization of the beam intensity, quality, and control grand challenges;
- Develop mathematical and algorithmic tools that benefit from — and to — synergistic developments beyond particle beam and accelerator science.

Accelerator and Beam Physics Grand Challenges and a National Roadmap Update

S. Nagaitsev[#](Fermilab/UChicago), J. Power (ANL), L. Spentzouris (IIT), J.-L. Vay (LBNL), P. Piot (NIU), Z. Huang (SLAC/Stanford), and J. Rosenzweig (UCLA)
 (Your comments can shape this roadmap! Please email to nsergei@fnal.gov)

- 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



Accelerator and Beam Physics Grand Challenges and a National Roadmap Update

S. Nagaitsev[#](Fermilab/UChicago), J. Power (ANL), L. Spentzouris (IIT), J.-L. Vay (LBNL), P. Piot (NIU), Z. Huang (SLAC/Stanford), and J. Rosenzweig (UCLA)

(Your comments can shape this roadmap! Please email to nsergei@fnal.gov)

- 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