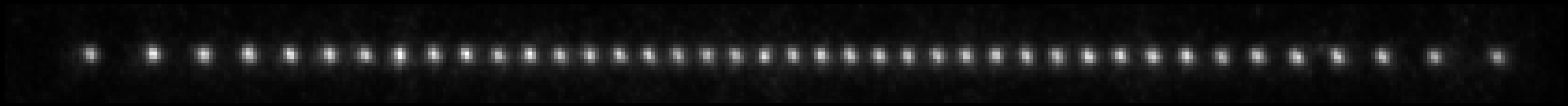
Future of ion trap quantum computing and prospects for a national user facility

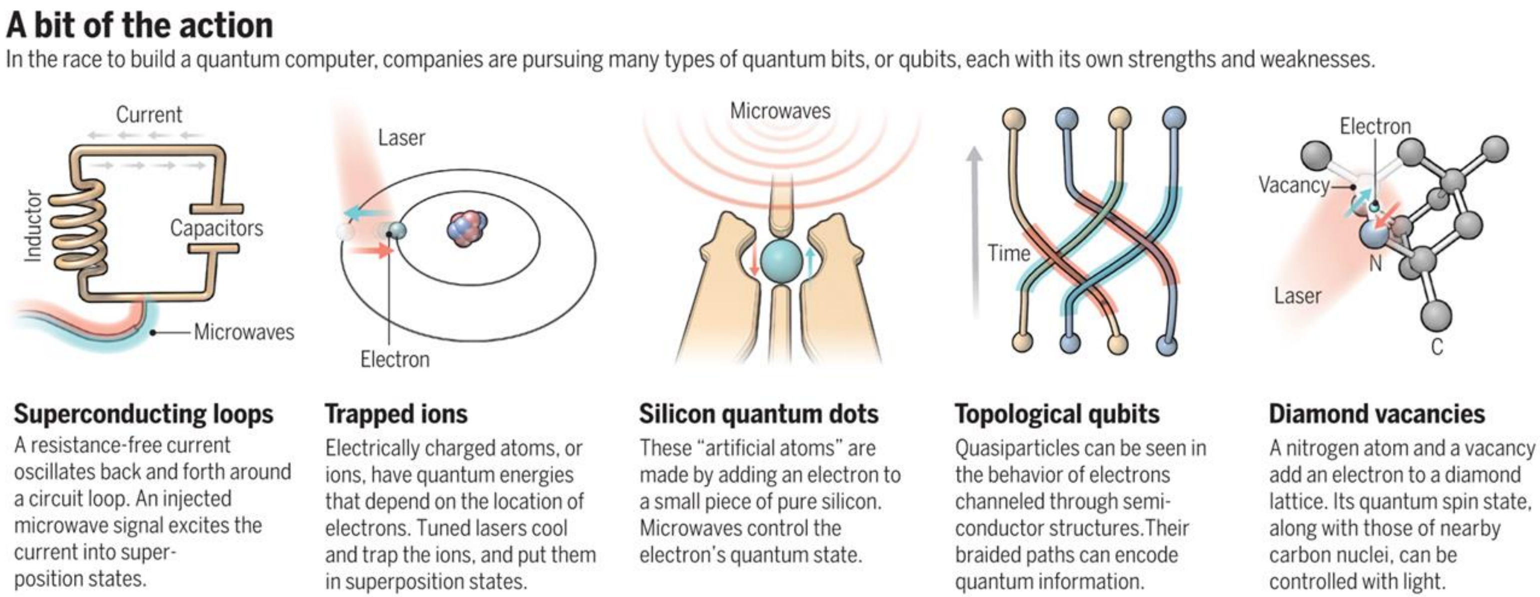
TRIUMF Science Week 2020 (Aug 2020)

Paul C Haljan

Simon Fraser University



Qubit technologies



Photons,
+ others …

Gabriel Popkin Science 2016;354:1090-1093

- Trapped ions are excellent hosts for quantum information –source of highly reproducible qubits with good coherence, good connectivity.
- Trapped ions have demonstrated all necessary operations on a few ions (DiVincenzo Criteria).
- NISQ processors of 10's of qubits in operation (IonQ, Honeywell, AQT, …)
- Scaling further is the task – lots of innovation achieved and further required.

Ion-trap QI companies (selection)

- **Honeywell (USA):**
  - Founded <2010?.
  - Employees >100.
  - Cloud-based access end 2019. Device size?

- **IonQ (USA):**
  - Founded 2015 by C. Monroe and J. Kim.
  - Employees >40.
  - Cloud-based access to 11-qubit system: fully connected, two qubit gates 99%.

- **Alpine Quantum Technologies (Austria):**
  - Founded ~2019 by R. Blatt, P. Zoller and T. Monz.
  - Cloud-based access to ion-trap quantum processor and devices for sale planned.

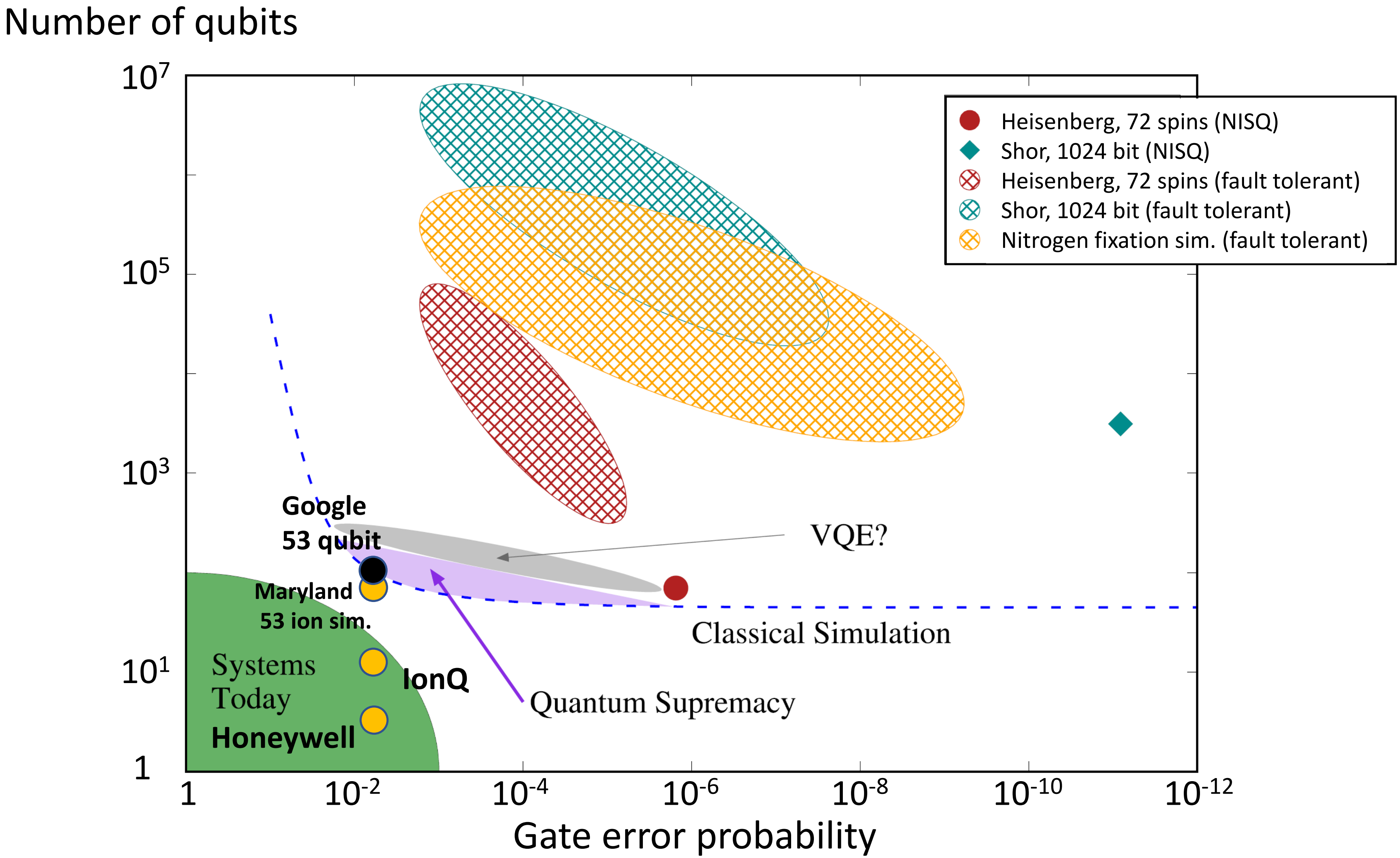
- **ColdQuanta (USA):**
  - Trap vacuum packaging and system integration
- ....

Also national lab initiatives (sample):

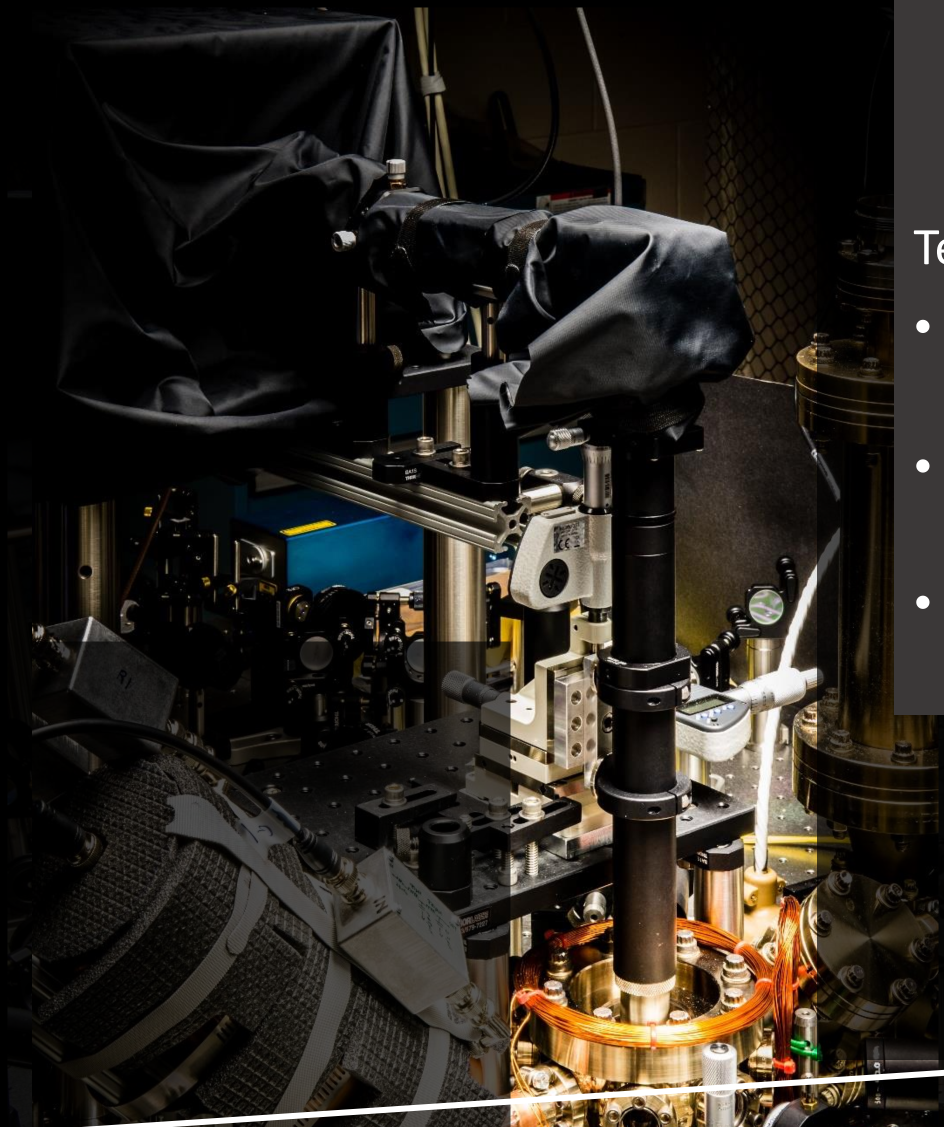
- **Sandia Labs:** Quantum Scientific Computing Open User Testbed (QSCOUT) ....

TRIUMF? – Build on Canadian QI expertise including ion trap QI (SFU, Waterloo, …)

Noisy intermediate state quantum (NISQ) Era … and beyond



Adapted from Maslov et al Proc. IEEE 107 (2019)

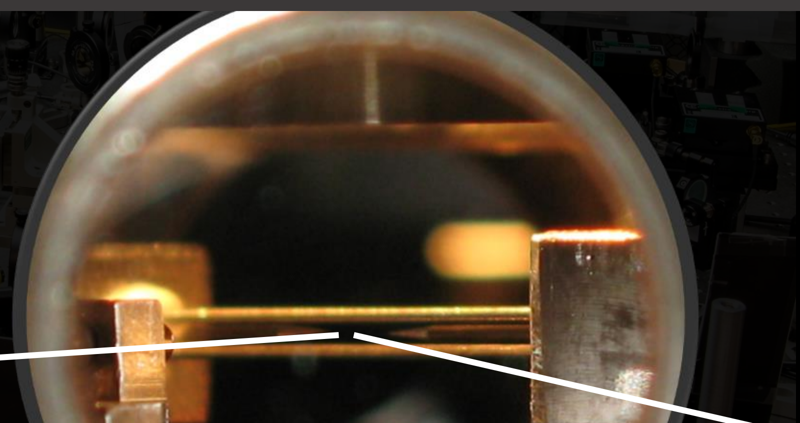


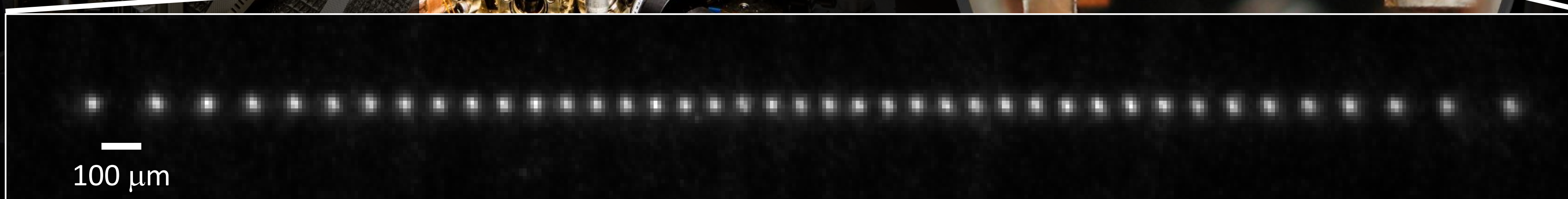
Ion trapping group

SFU

Technology based on Ytterbium Yb^{+}

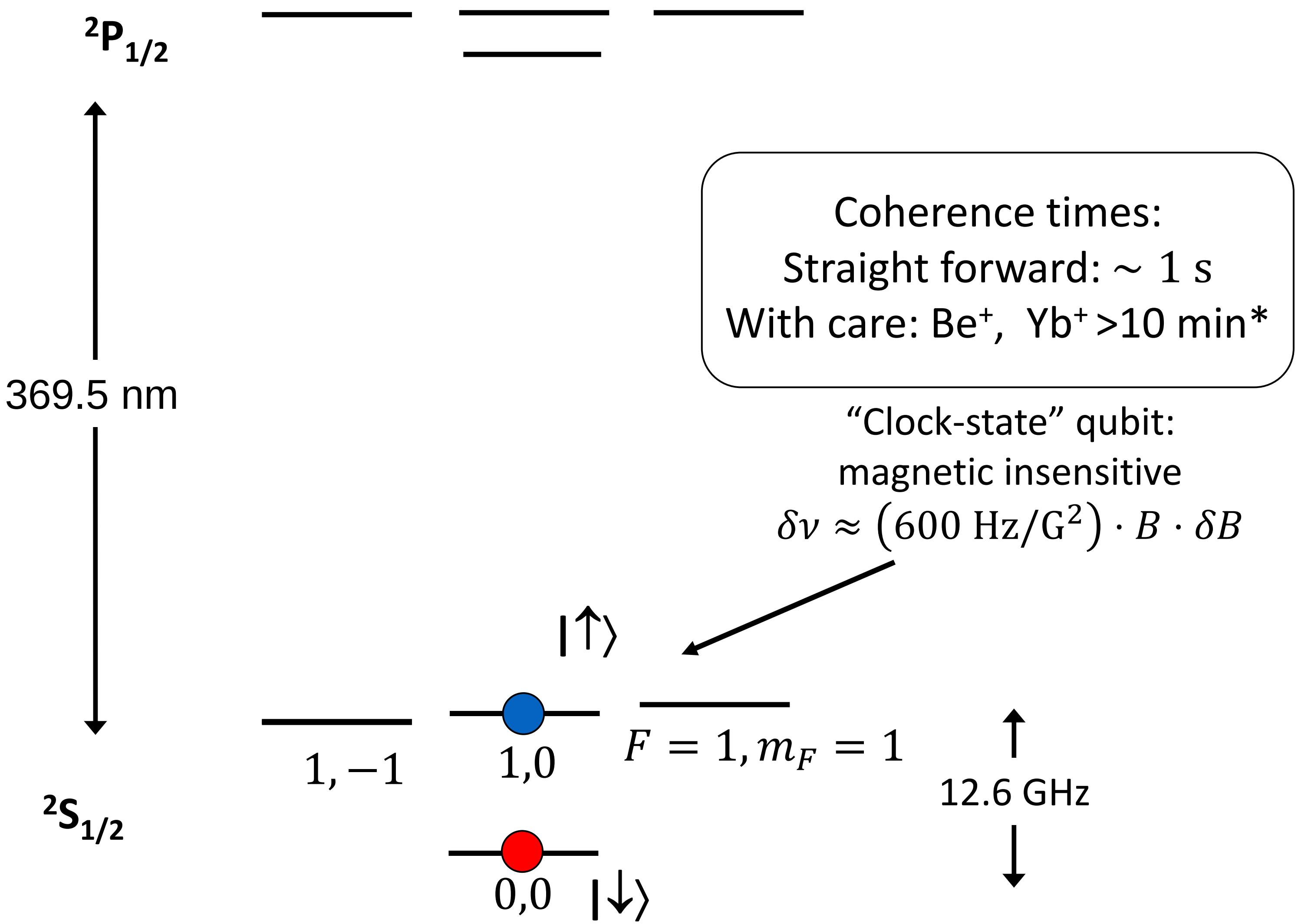
- R = 0.7 mm, ν_{rf} = 30 MHz, V_{rf} = 700 V, V_{dc} = 1-100 V
- Secular trap frequencies: ν_z = 0.01-0.5 MHz, ν_r = 0.9 MHz
- UHV 10^{-11} Torr, 300 K. Trap lifetime hours – days.





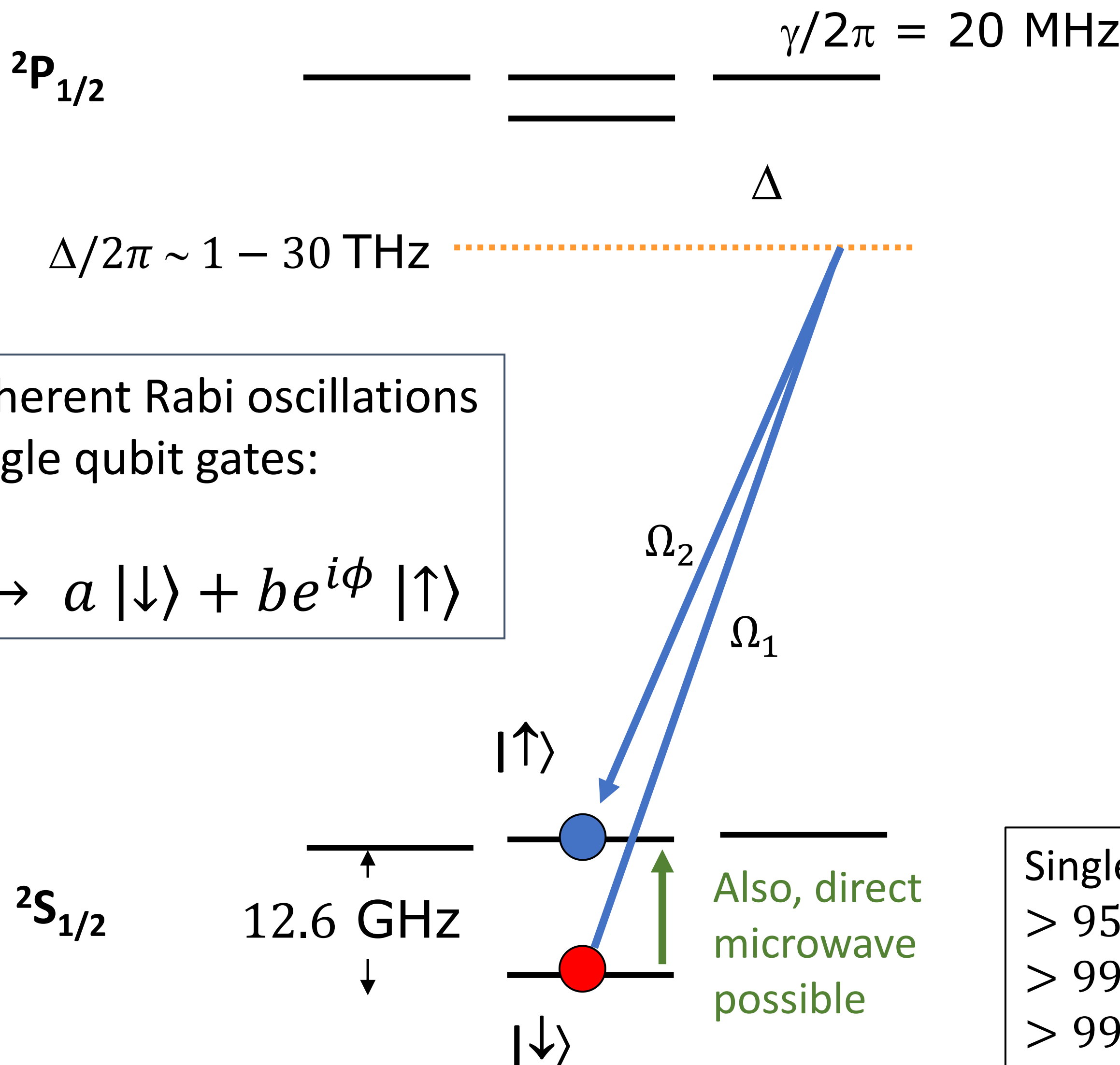
Hyperfine ion-qubits: excellent quantum memory

$^{171}Yb^{+}$ (I=1/2) atomic structure



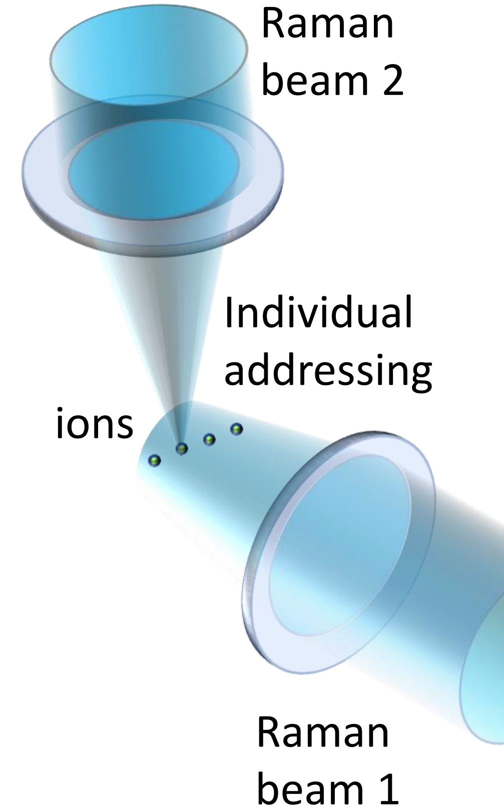
*J. Bollinger, et. al., IEEE Trans. Instrum. Meas. **40**, 126 (1991). Y.Wang et al., Nature Photonics 11, 646 (2017).

Stimulated optical Raman transitions: single qubit gates ('spin rotations')



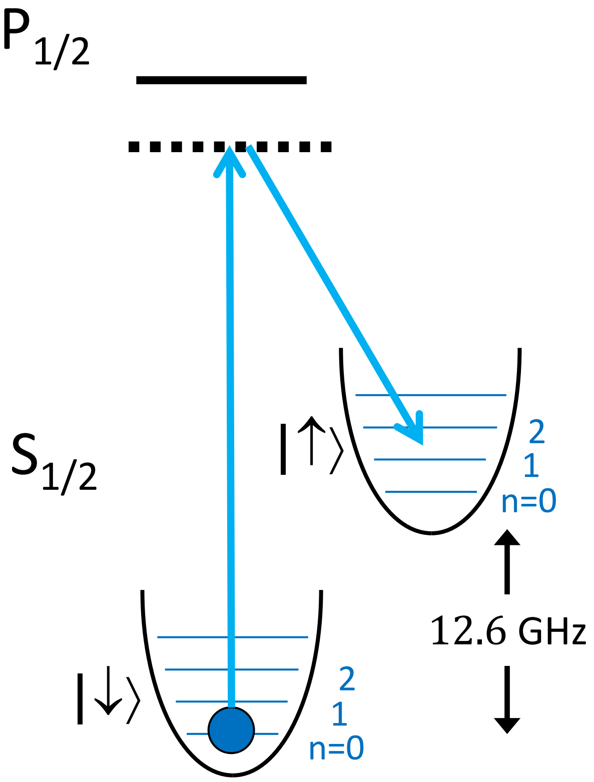
- Coherent Rabi oscillations
- Single qubit gates:

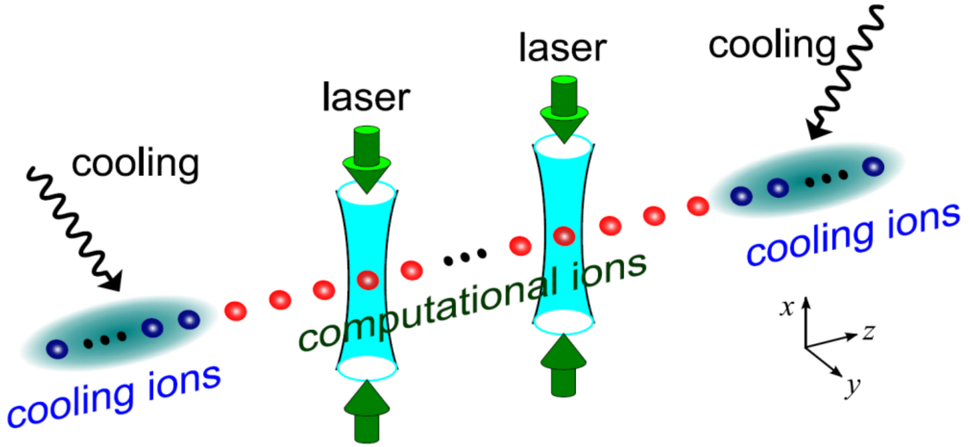
$$|\downarrow\rangle \rightarrow \ a\,|\downarrow\rangle + b e^{i\phi}\,|\uparrow\rangle$$



Single-qubit gate fidelities:
$>$ 95%, 10 μs (Yb^+, SFU)
$>$ 99.5% (Yb^+, JQI)
$>$ 99.99%, 1 – 10 μs
(Ca^+ Oxford, Be^+ NIST)

Laser-driven entangling gates





- **Motional quantum data bus:** collective vibrations of trapped ion crystal allow quantum information to be shared between ion-qubits.
- Lasers to engineer 2-qubit entangling gates:

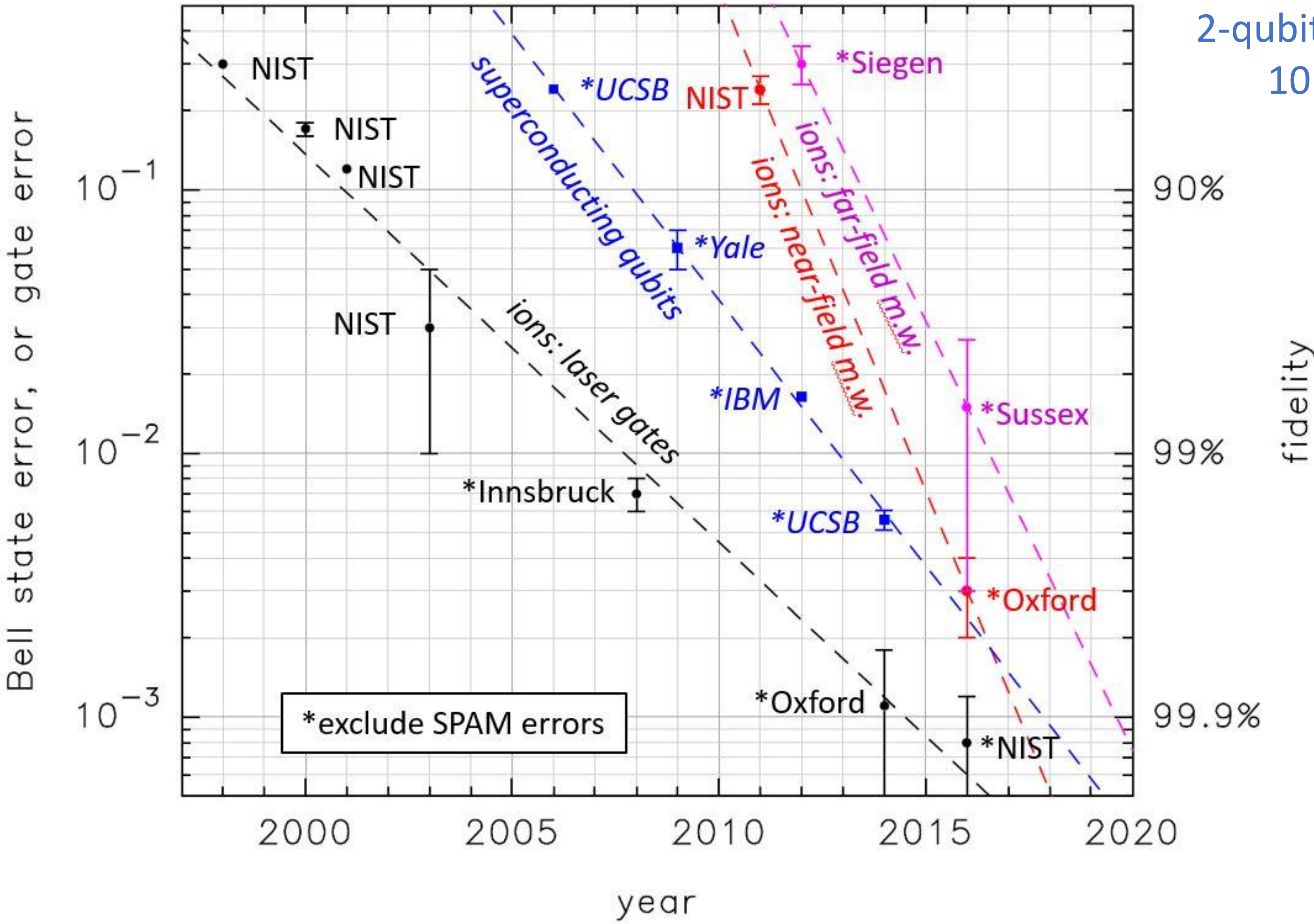
$$(|\downarrow\rangle + |\uparrow\rangle) \otimes |\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle$$

- Parallelized gates, multi-qubit gates possible, …

Theory: Milburn-Schneider-James, Molmer-Sorensen
S.-L. Zhu et al, EPL 73, 485 (2006)
P. H. Leung and K. R. Brown, PRA 98, 032318 (2018)

Two-qubit gate fidelities

https://nqit.ox.ac.uk/content/ion-traps

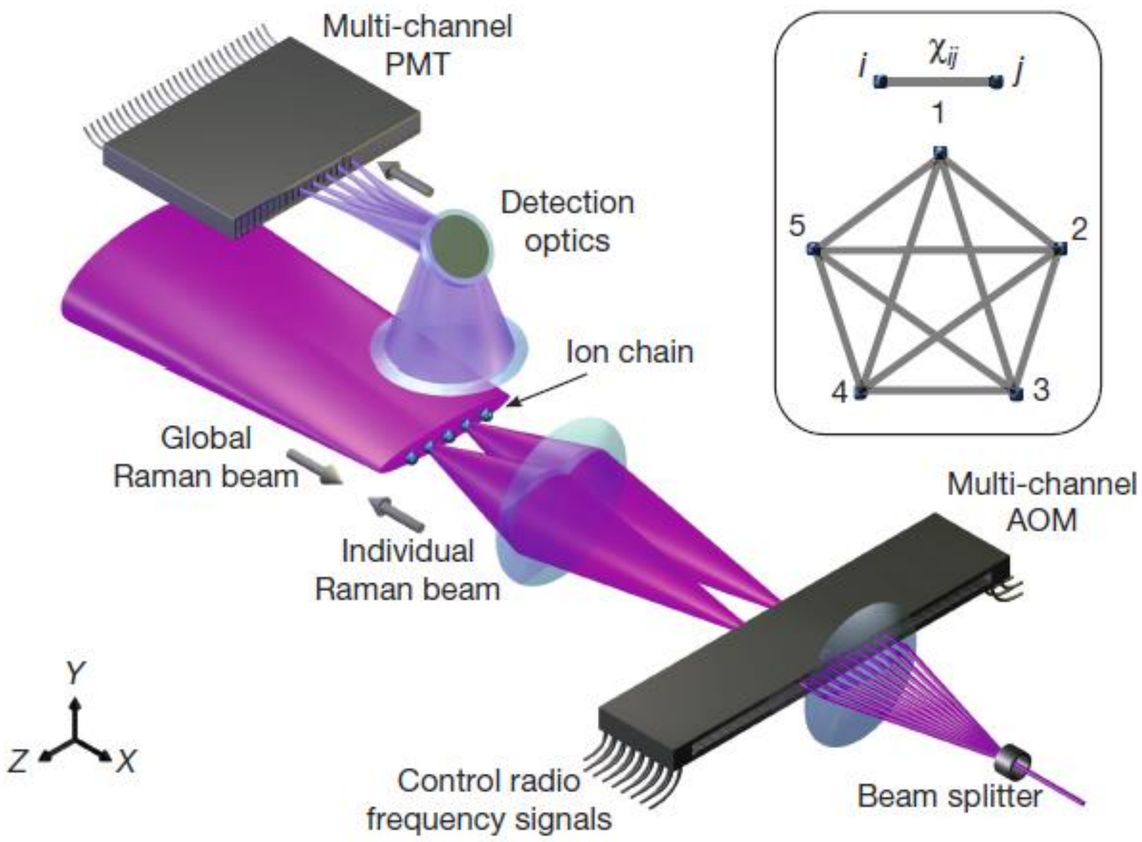


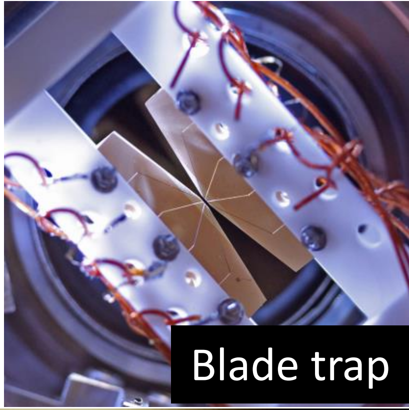
2-qubit gate speeds
10 – 100 μs

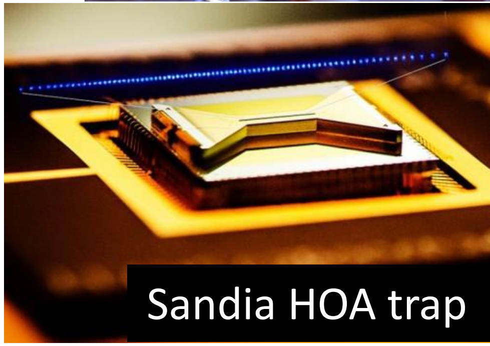
- Current gate fidelities a little lower for longer ion strings
  e.g. JQI/Maryland 17 ions: two-qubit gates fidelity 95-97% in 200 μs
  K. A. Landsman et al. PRA **100**, 022332 (2019)

Ion-trap NISQ processor – JQI/Maryland

Optical setup (JQI/Duke): multichannel AOM and multichannel PMT







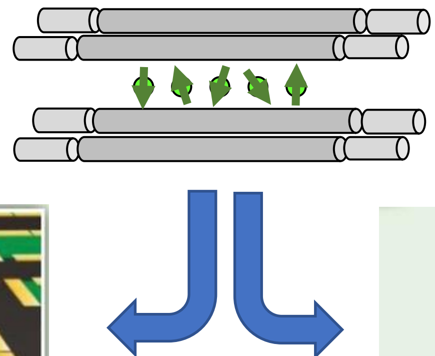
IonQ (publically released):

- Fully-connected qubits: **11**
- Addressable pairs: **55**
- One-qubit gate error: <0.03%
- Two-qubit gate error: <1.0%

Image: 5 ions Debnath et al, Nature 2016

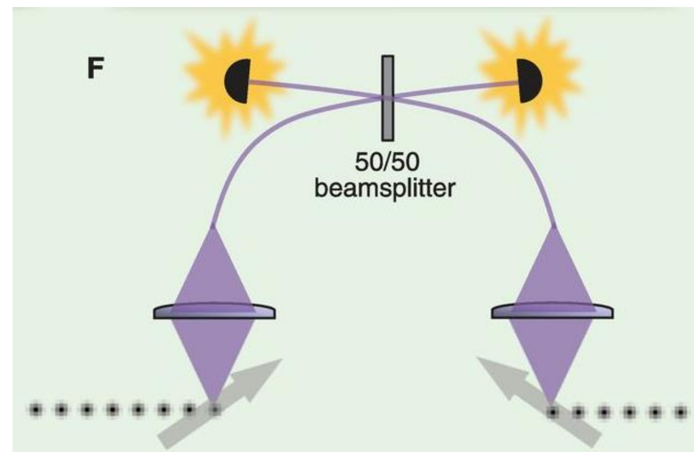
Scaling up the ion trap processor

- Limit to length of ion string register $N < 100$ (?): control of large number of motional vibrations during two-qubit gates becomes difficult for large N.
- Modular approach: larger system built up from interconnected ion traps.



Quantum CCD architecture

D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).

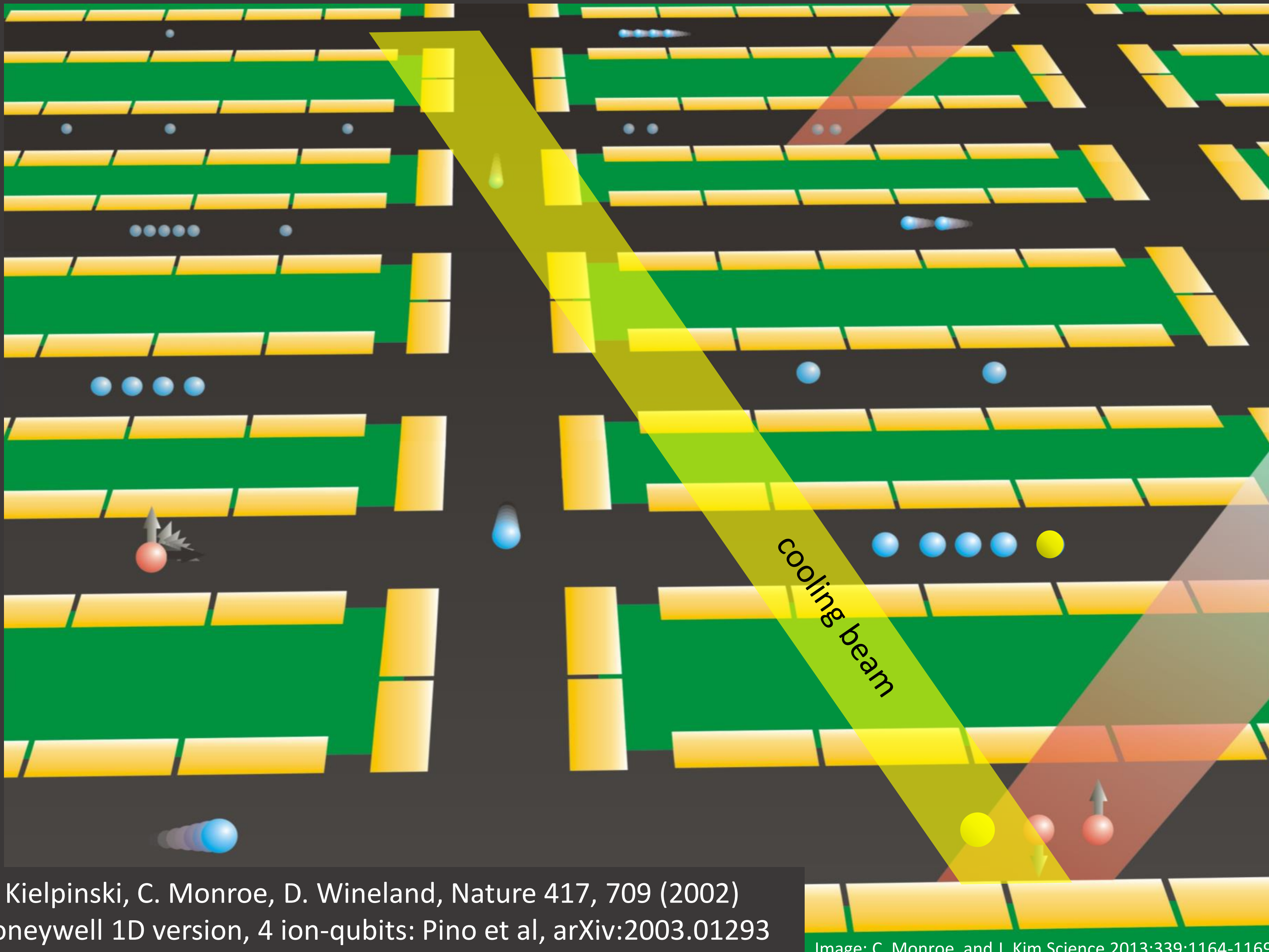


Quantum networks, MUSIQC architecture

Cirac et al PRL (1997)
Simon and Irvine PRL 91, 110405 (2003)
Duan et al QIC 4, 165 (2004)
C. Monroe, and J. Kim Science (2013)

Or hybrid …

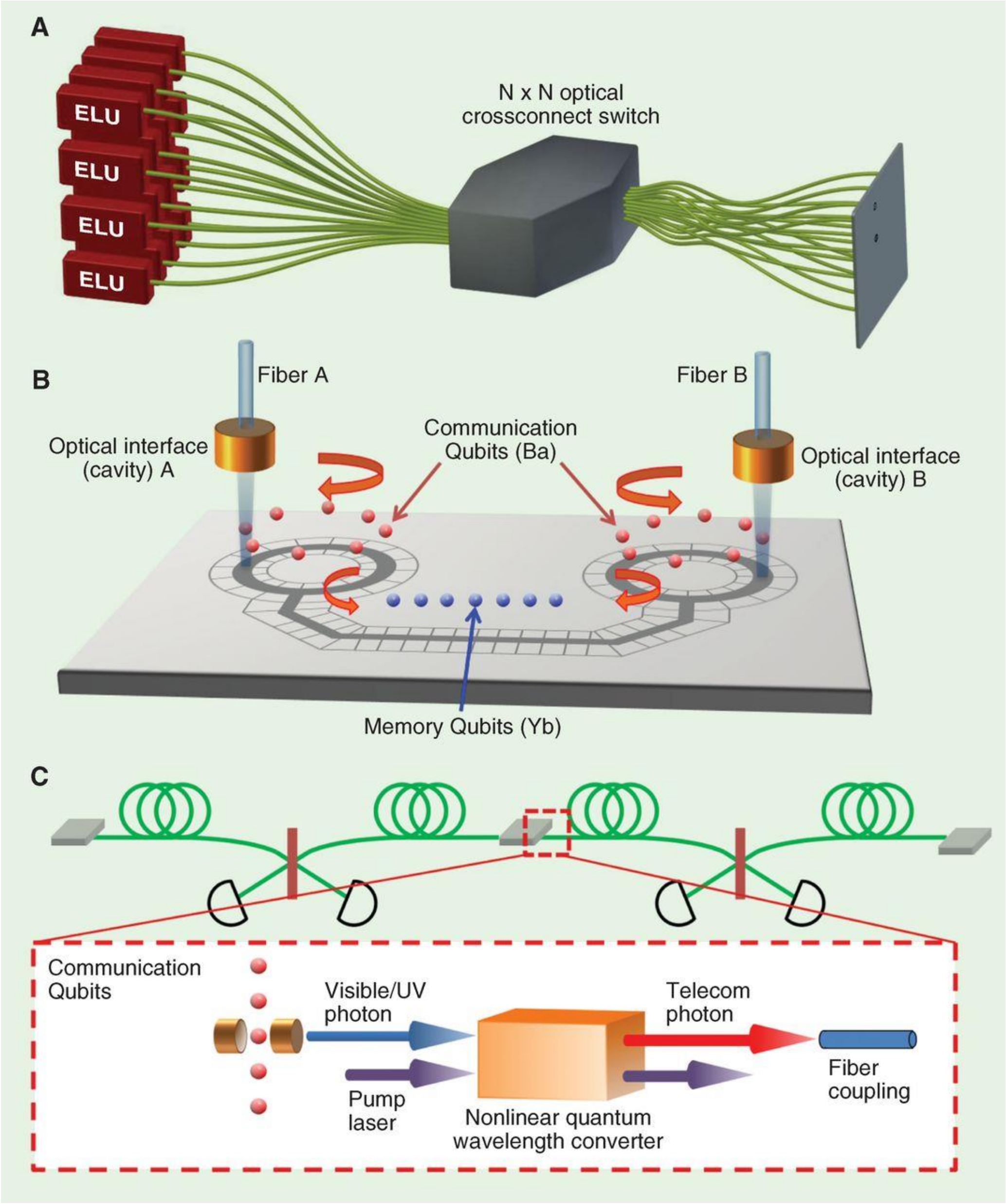
Quantum CCD architecture



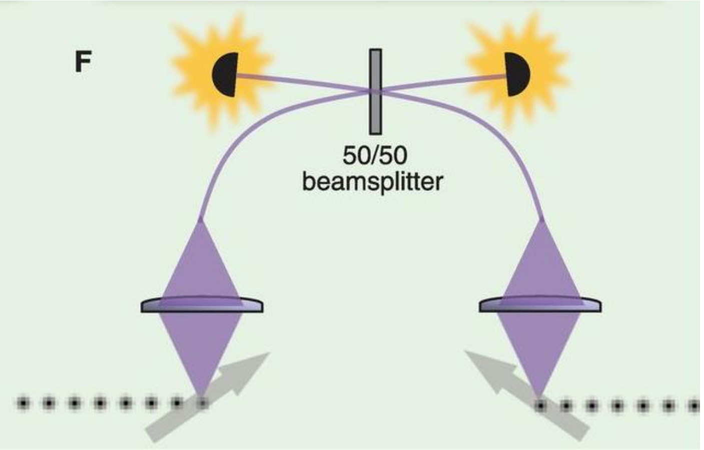
D. Kielpinski, C. Monroe, D. Wineland, Nature 417, 709 (2002)
Honeywell 1D version, 4 ion-qubits: Pino et al, arXiv:2003.01293

Image: C. Monroe, and J. Kim Science 2013;339:1164-1169

Scaling via quantum networking (long term vision)



C. Monroe, and J. Kim Science 2013;339:1164-1169



Remote ion entanglement via photons

D. Hucul, et al., Nature Phys. 11, 37 (2015)

Why a national ion quantum computing facility at TRIUMF?

1. **Good qubits!**
2. **The Canadian advantage**
   - Timely, hands-on access to gate-based quantum computing hardware in Canada, complementing other hardware platforms e.g. D-Wave, Xanadu.
   - Training in quantum hardware development.
3. **A network of hardware and software collaboration**
   - SFU (local ion trap hardware), BC Quantum Algorithms Institute, Quantum BC Network, national/international e.g. US-Canada NWQuantum network.
4. **The cost advantage**
   - Leverage local experimental expertise at SFU and TRIUMF.
   - Relatively modest initial investment compared to other technologies.
5. **The user facility**
   - Sustainable operation and innovation through TRIUMF and local user base.
   - Ion trap technology a natural fit for TRIUMF capabilities.
   - Overlap with other scientific goals of the TRIUMF community – atomic-physics based precision tests and spectroscopy, TRILIS…

Project stages

- Short term: ~10 ion-qubit processor - programmable, full connectivity, high fidelities
    - Extend existing SFU ion trap setup.
    - Components off the shelf (COTS).
    - Low ion-trap device complexity (no shuttling).
    - Implementation of test algorithms and benchmarking.

- Long term: 20+ ion-qubit system, cloud available.
    - Robustness and fidelity improvements.
    - Full-stack development – high-level software, optimized compiler implementation down to trap-level primitive operations.
    - Online control – intranet, cloud in future.

Quantum computing applications

- Initial applications: Hybrid quantum-classical algorithms.
  - *Optimization - VQE algorithm for ground state energy solutions*
    - Application to nuclear structure, chemistry, materials science.
    - Extensions of current work at TRIUMF - di Matteo et al. arXiv arXiv:2008.05012.
    - Reasonable resource requirements for NISQ processor.
  - *Machine Learning*
    - Motivations from big data, particle physics (Fedorko TRIUMF)
    - Quantum chemistry (e.g. Krems UBC - multichannel scattering).
    - Resource hungry, more speculative for NISQ devices, but prototype testing possible.

See talks this session.
Also previous sessions:
Kazuhiro Terao
Heather Gray, …

- Technical developments towards scaling:
  - *Leverage nuclear/particle design capabilities for ion trap quantum hardware*
    - FPGA-based arbitrary waveform generators.
    - Scalable control hardware, on-board decision making capabilities, cloud-based experiment monitoring and control.
    - Multichannel single-photon collection and detection hardware in near-UV.

Leveraging local capabilities

All the expertise needed to build an ion trap quantum computing user facility is available locally in British Columbia:

- Local ion-trap quantum technology group at SFU to seed the facility with Gen-1 setup.
- TRIUMF technical expertise in managing major user infrastructure.
- Local user community to anchor the facility (**Quantum BC** including SFU, TRIUMF, UBC and BC quantum technology industry).
- BC Quantum Algorithms Institute to provide co-design capabilities – benchmarking, resource estimation, compilation and architecture optimization.

Conclusions

- Trapped ions are excellent hosts for quantum information.
- <10-20 qubits demonstrated in NISQ devices.
- <100 ion-based NISQ processor is on 5-10 year horizon. Lots of innovation already realized and more required.
- Hands-on access to a wide range of quantum hardware is in Canada's interest for full participation in the "second quantum revolution."
- TRIUMF as a capable mobilizer of large science projects is an ideal host of a national ion trap quantum test bed facility.
- Leverages the local BC quantum tech ecosystem.