Nano and Biological Technology Panel:

Quantum Information Science

Professor Andrew Dzurak

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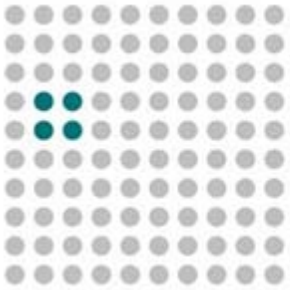
NSW Director, Australian National Fabrication Facility

School of Electrical Engineering & Telecommunications

The University of New South Wales



CENTRE FOR
QUANTUM COMPUTER
TECHNOLOGY

AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

ANFF

Report Documentation Page

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Quantum Information Science

Data Security

National Security
Financial Services
e-Commerce

Decryption

National Security
Intelligence

Killer Apps

Supercomputers

Database Searching
Bioinformatics
Modeling & Design

Semiconductors

Integrated Circuits
Sensors
Nano-structuring

Outline

- Quantum Computing & Communications

  Science fiction becomes science fact ...

- Single Atom & Single Photon Nanotechnologies

  Plenty of room at the bottom ...

- Future *q*-IT Applications

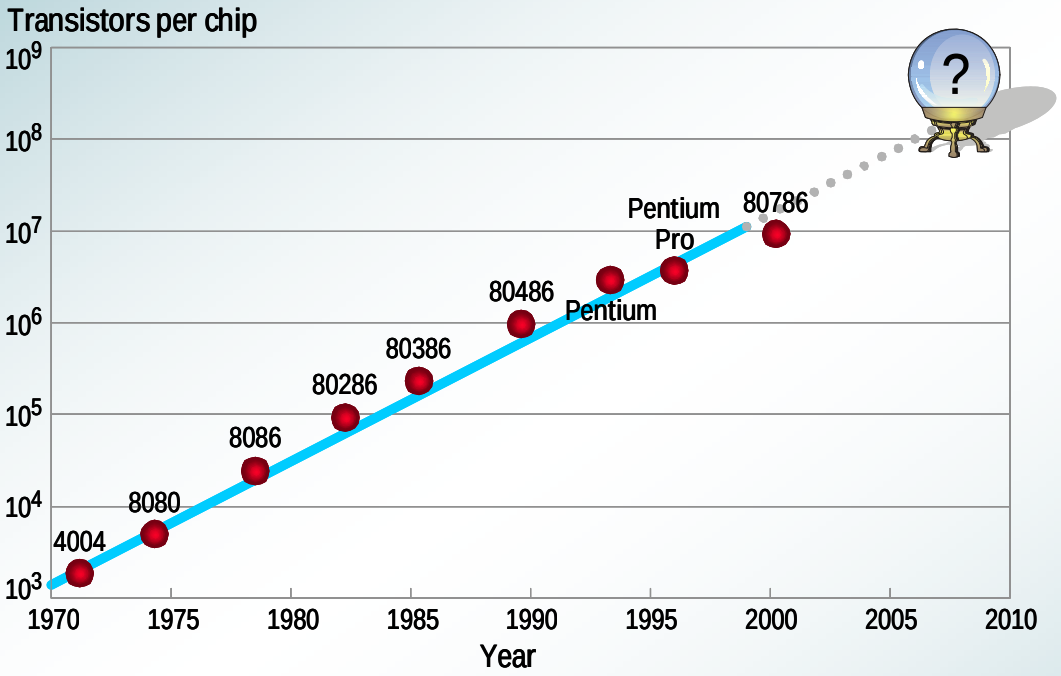
  What could be possible?

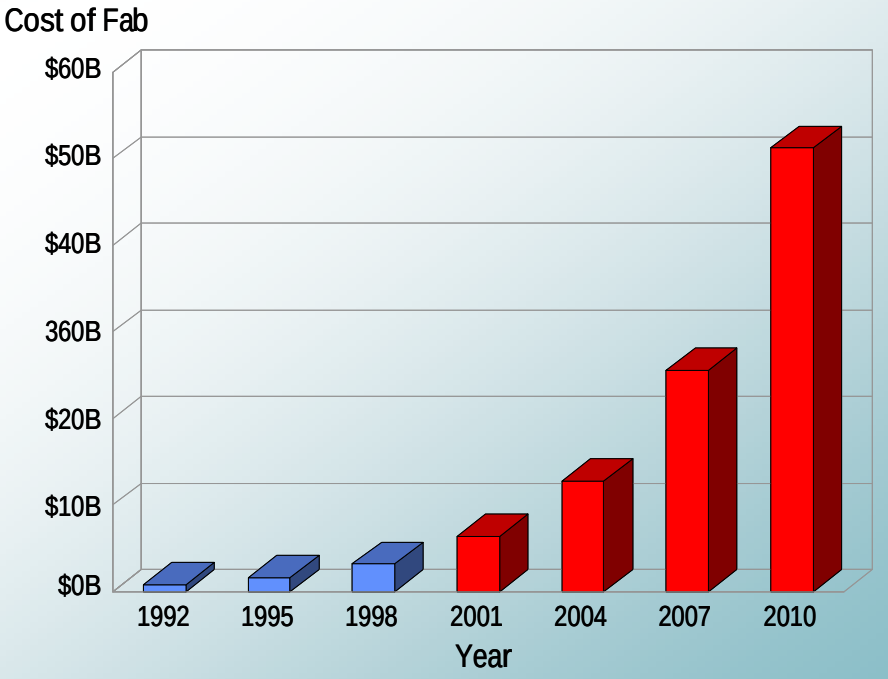
- Visualizing a Quantum Computer of the Future

  Computing at the atomic level ...

Conventional computing …

… must confront some serious issues

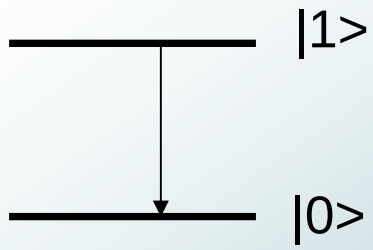


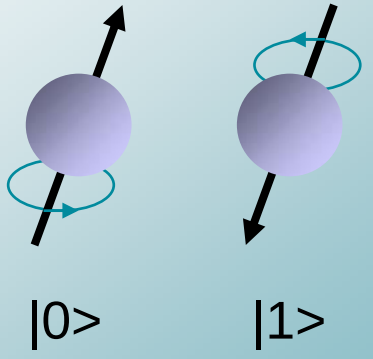


Quantum computing

... could well be the solution

Conventional Computer	Quantum Computer
0, 1	|0>, |1>
bits	**qubits** Quantum state of a two-level system



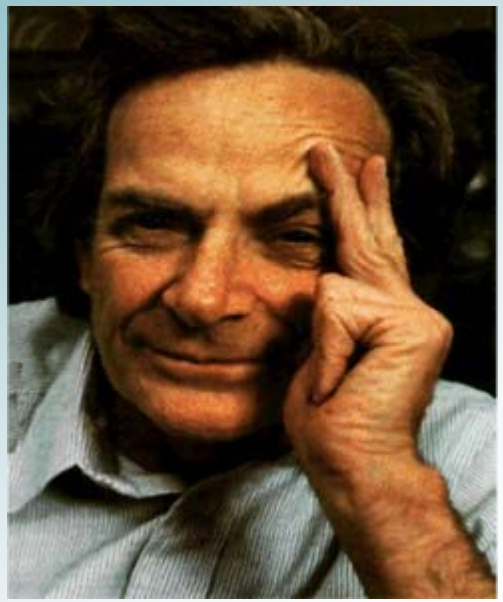


The power of quantum superposition …

Ever wished you could be in two places at the same time ?

- **Consider a 300 qubit byte of information**
- **$x = b_{300}b_{299} \ldots b_3b_2b_1$**
- **Example: x = 100110100……110011010**
- **Possible states = 2^{300} = Number of atoms in universe!!!**
- **A QC would compute with all of these in parallel**
- **Blue Gene: 10^{15} ops/sec would take 10^{78} years to look at each**

From basic science…



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

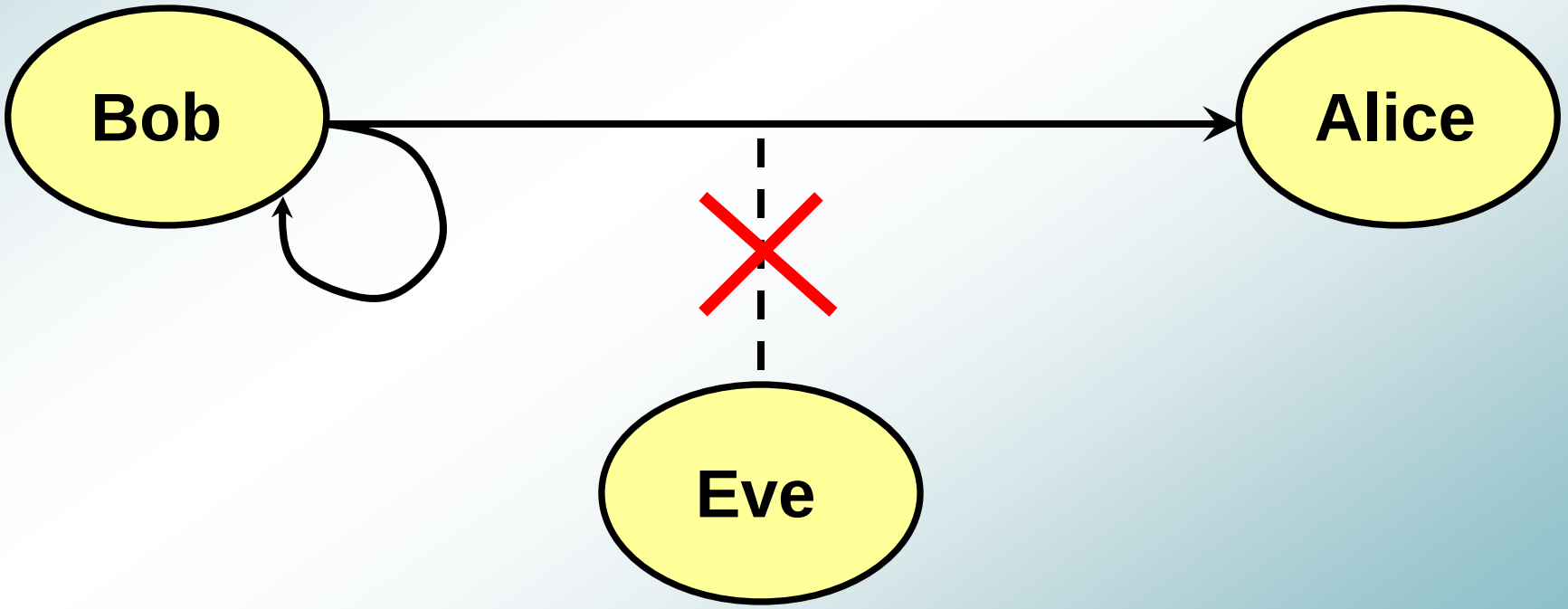
Algorithms for quantum computation:
discrete logarithms and factorings (1994)

…to new technologies….

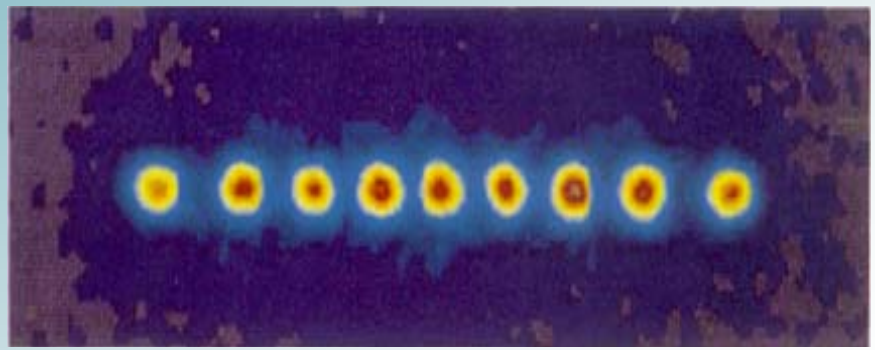
…quantum technologies

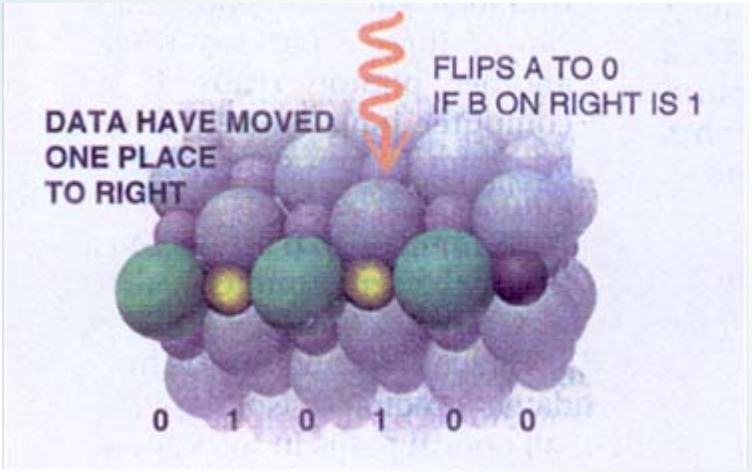
Quantum Communications

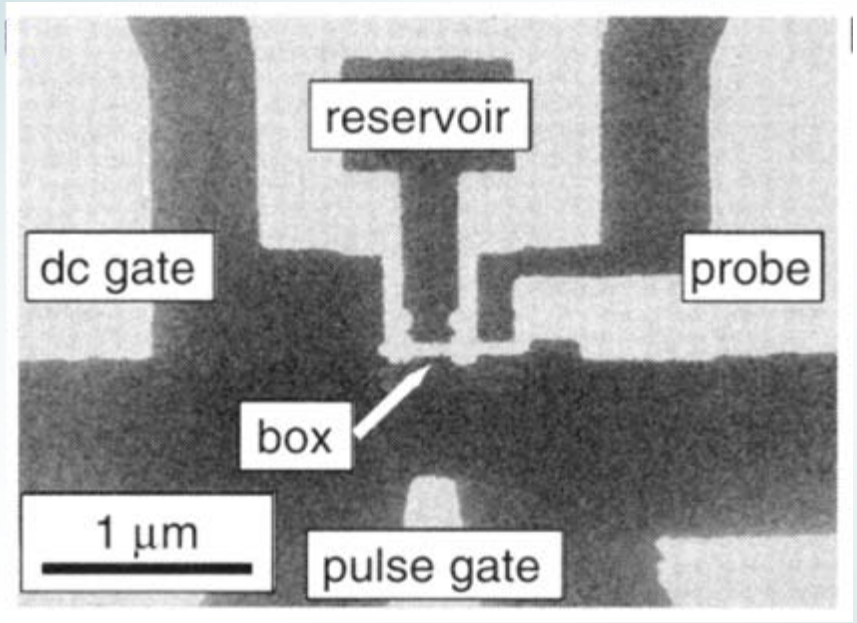
... when ***absolute*** security of information is vital...

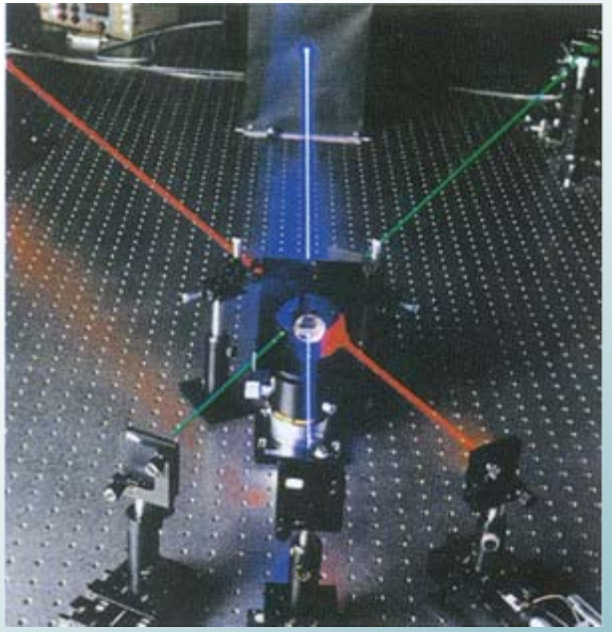


The first quantum computers …





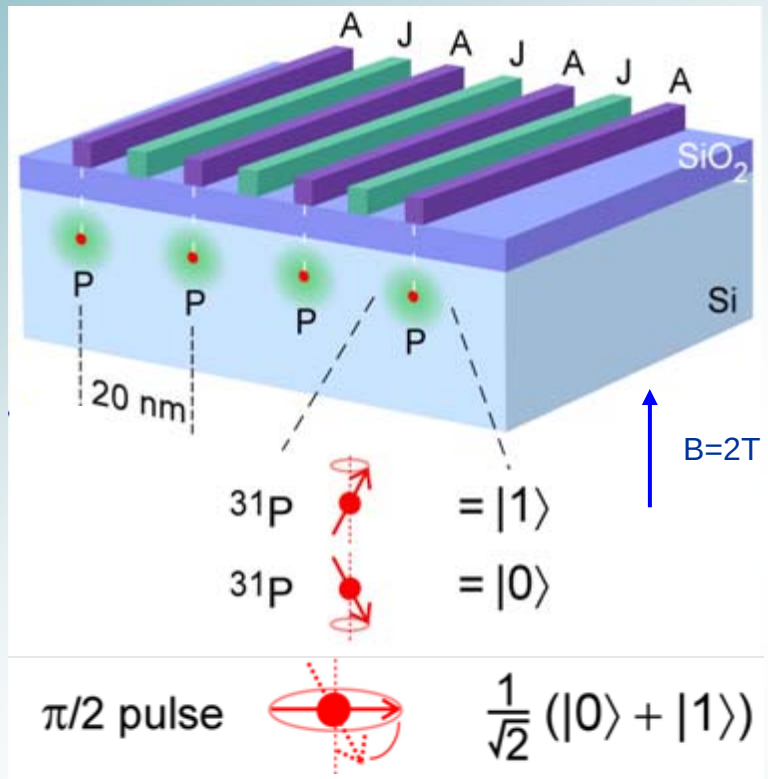




Australia-US Partnership in QC

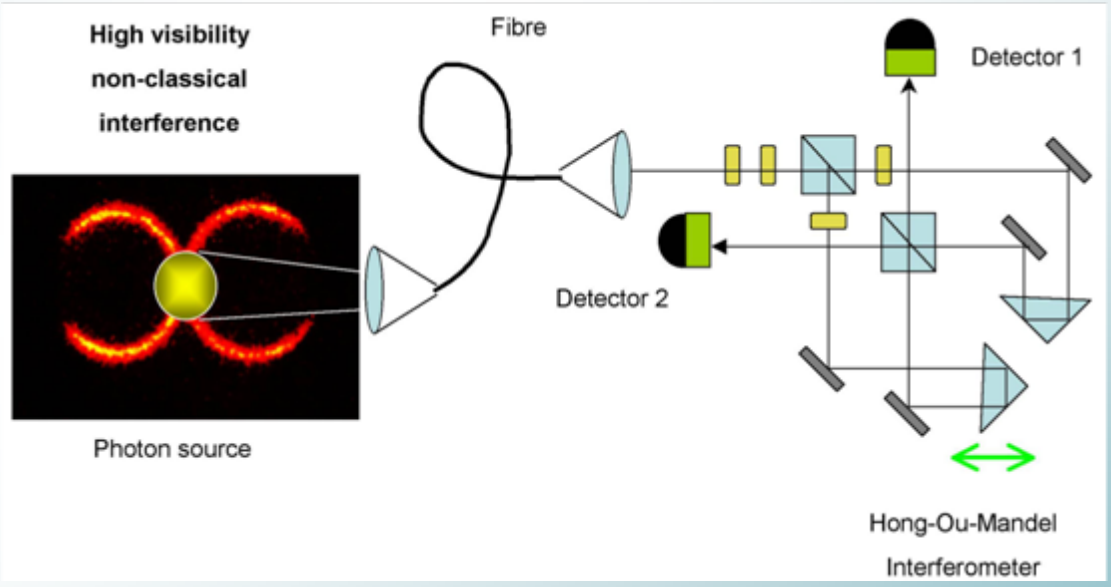
Silicon Solid State QC

Single Atom Nanoelectronics

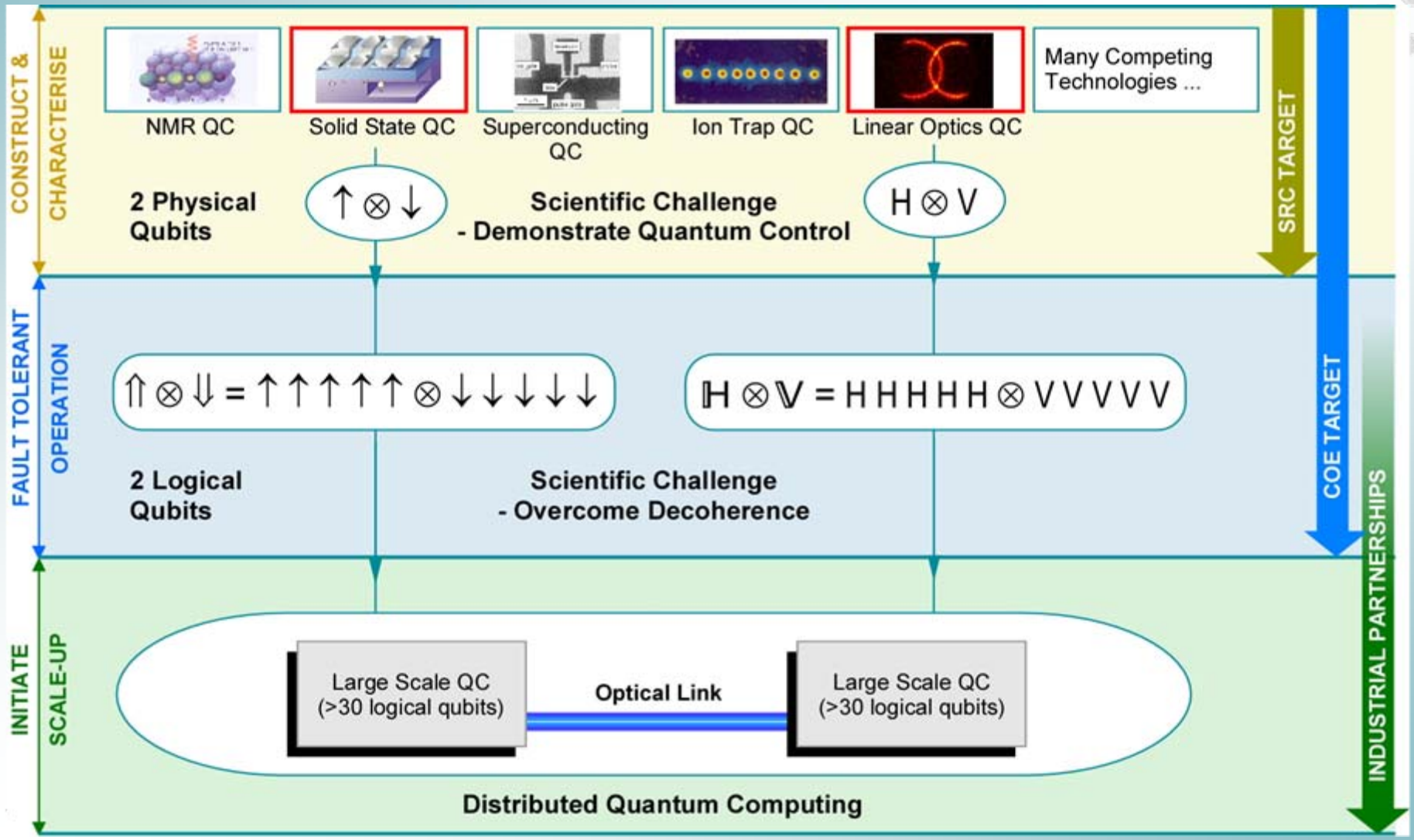


Linear Optics QC

Single Photon Photonics



Computing + Communications =



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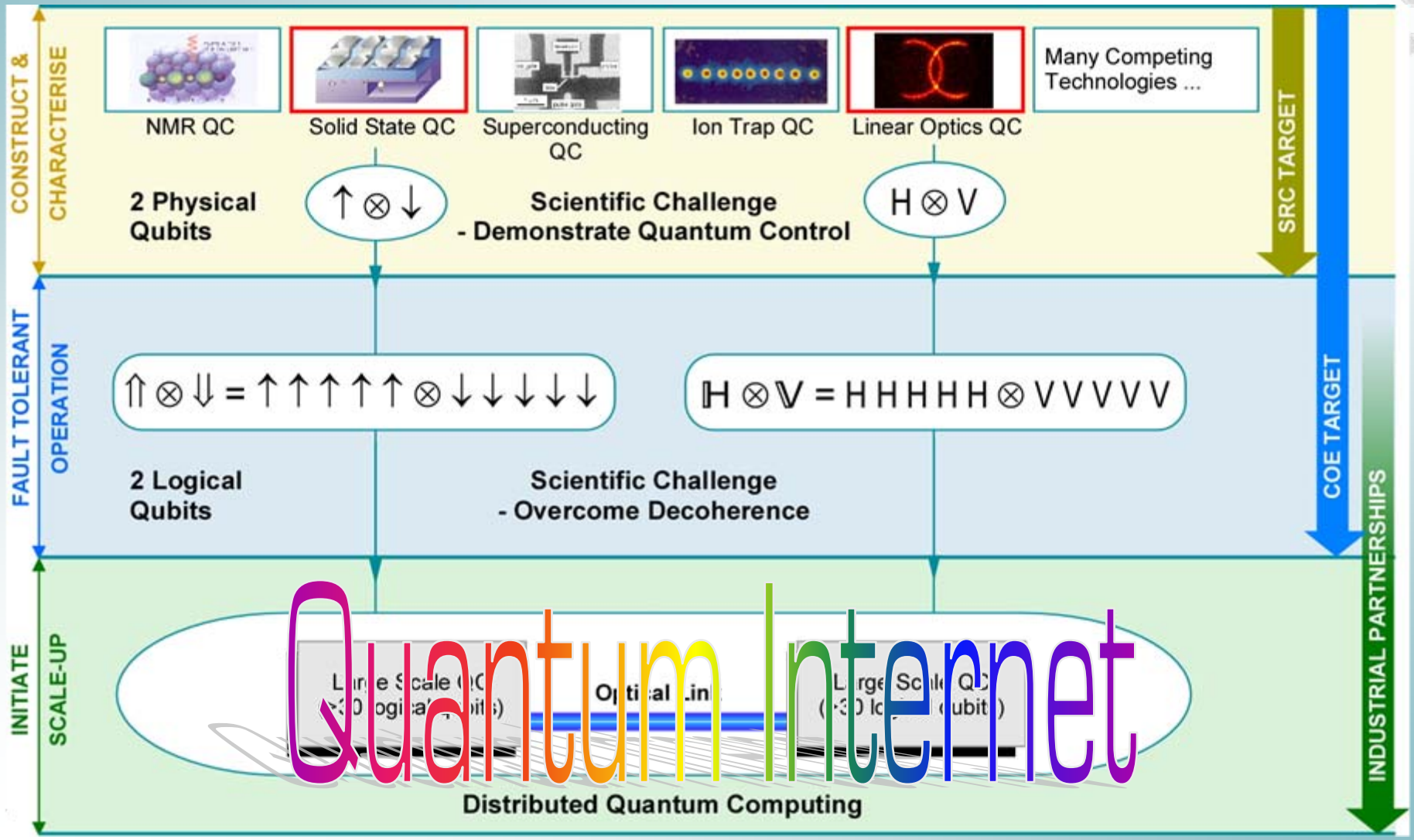
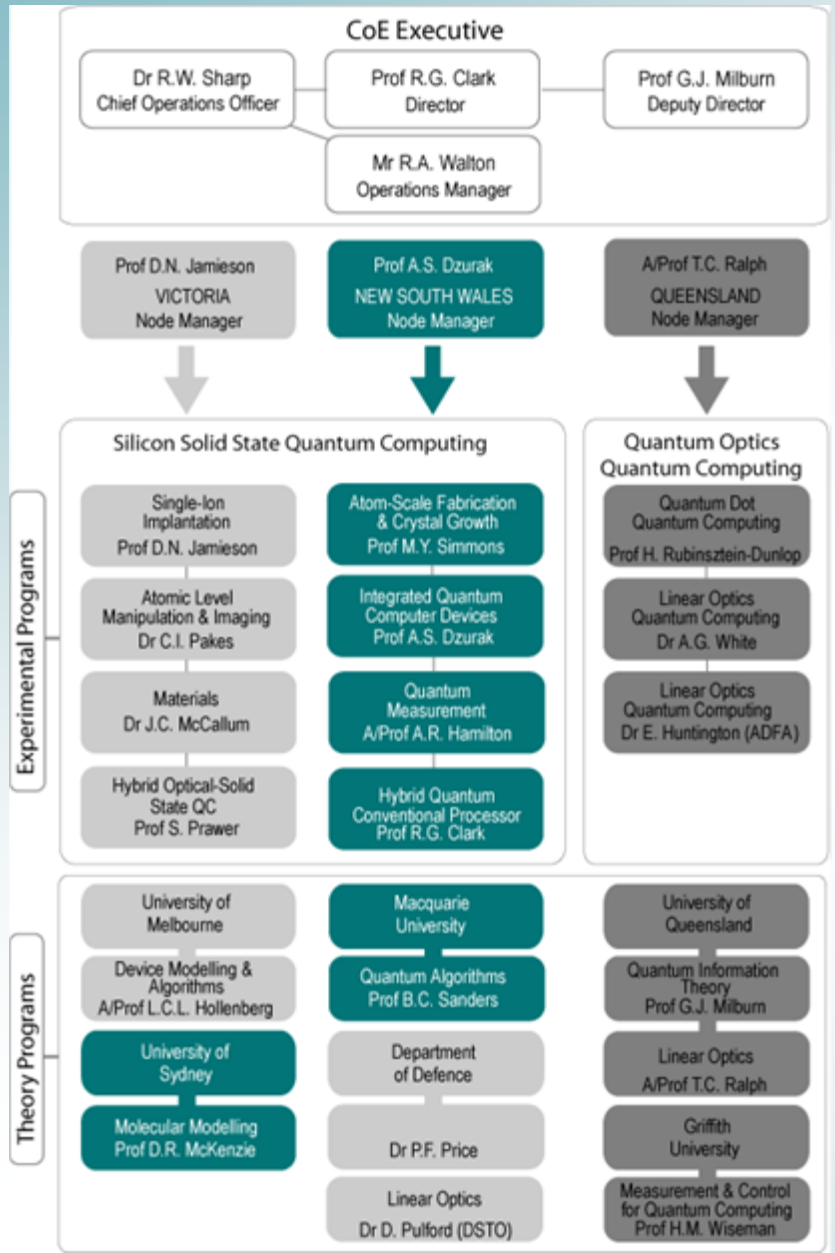
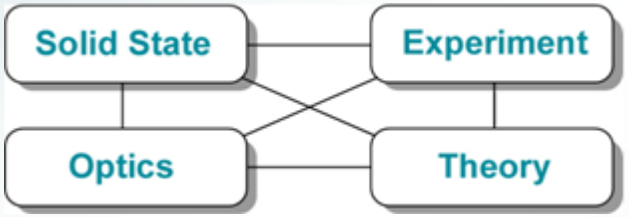
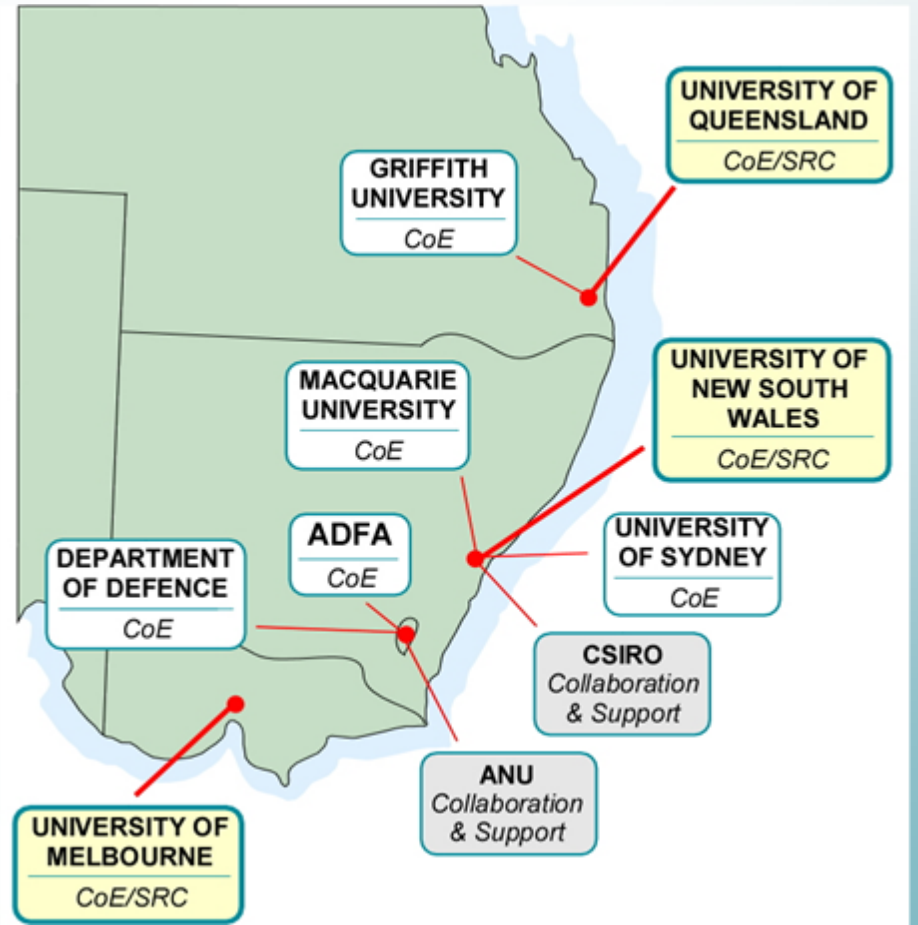


Australian Research Council Centre of Excellence for Quantum Computer Technology



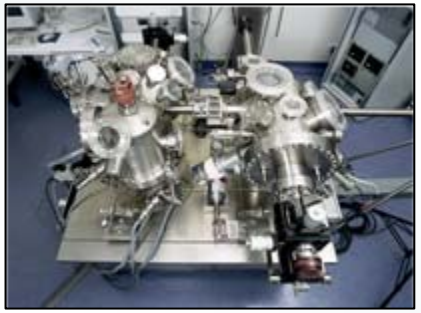


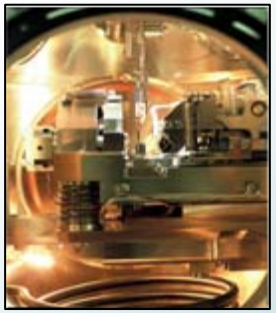
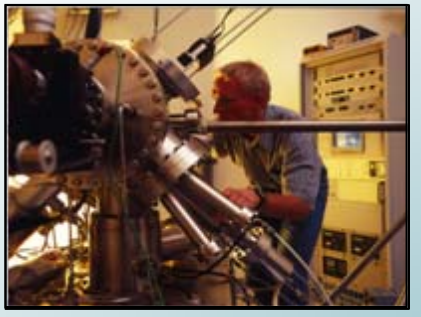


Underpinning Nanotechnologies

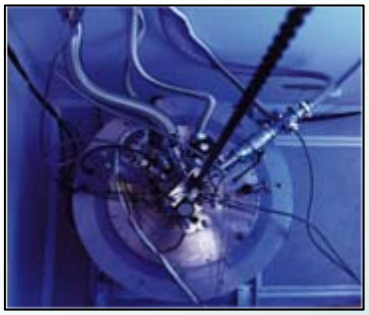
Nano-scale Fabrication

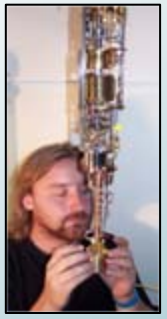
Atom-scale Fabrication



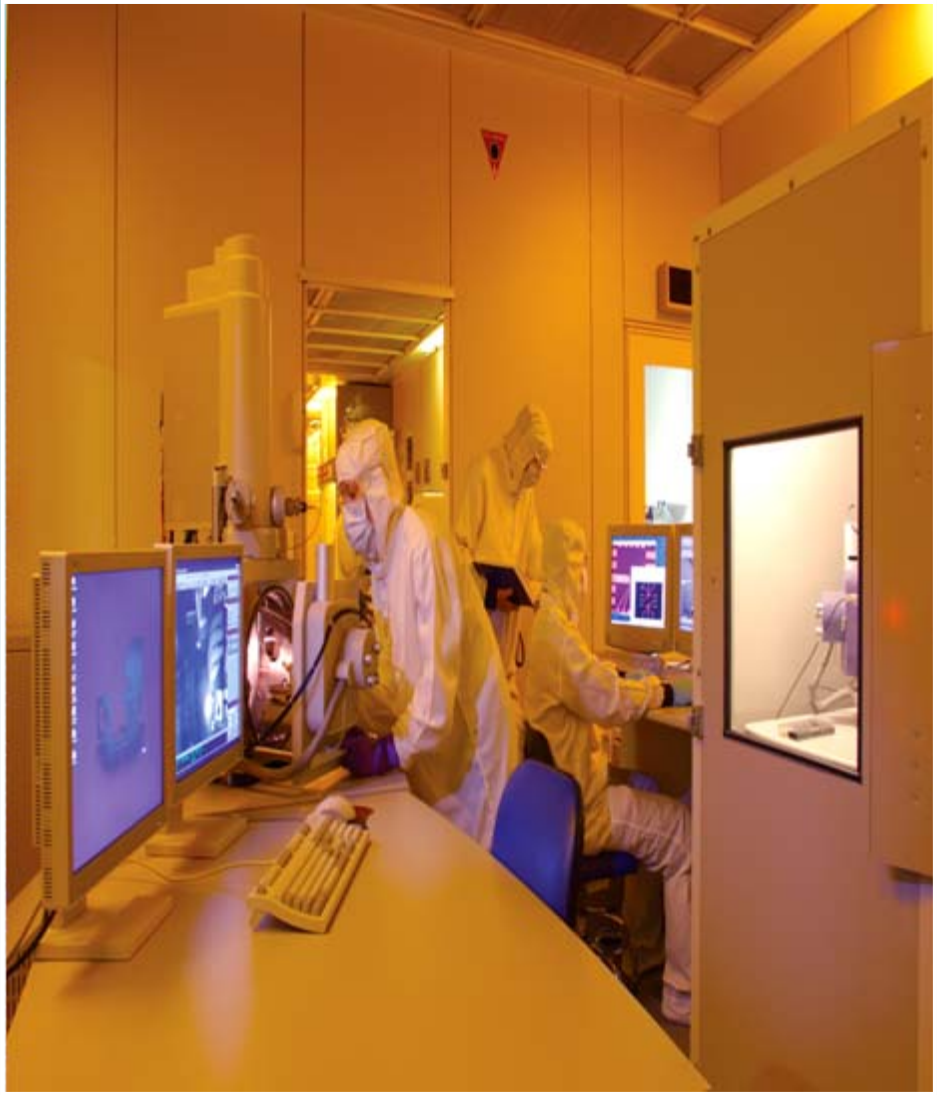



Quantum Measurement





Single Atom Nanoelectronics : Top Down

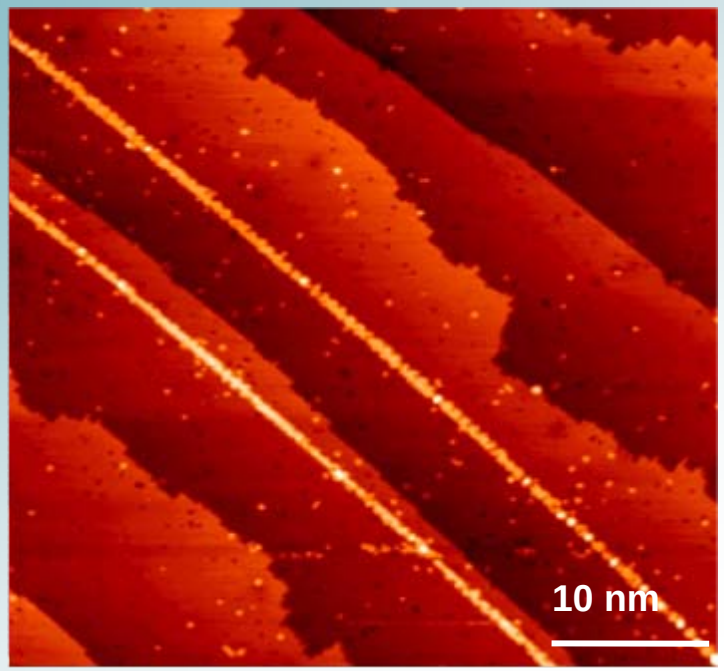


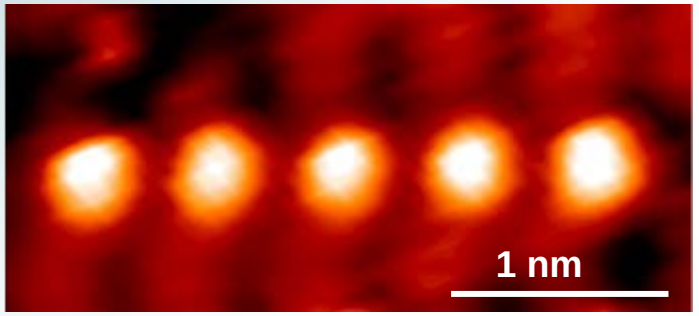
Sydney - UNSW

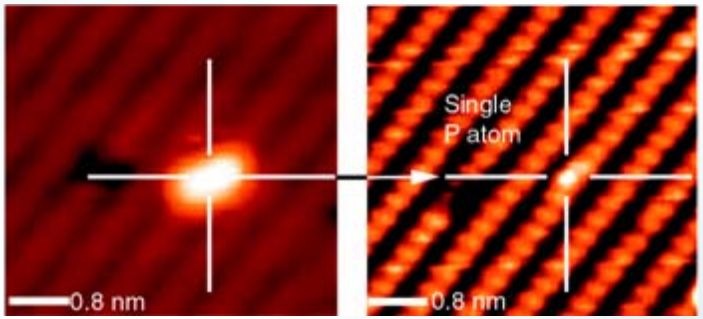
U Melbourne

D.N. Jamieson et al.

Single Atom Nanoelectronics : Bottom Up





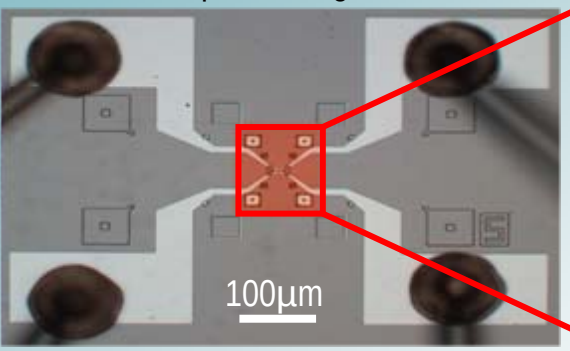


UNSW

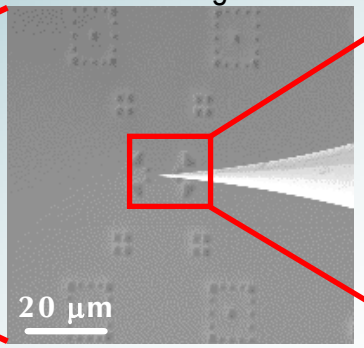
M.Y. Simmons et al.

Single Atom Nanoelectronics : Bottom Up

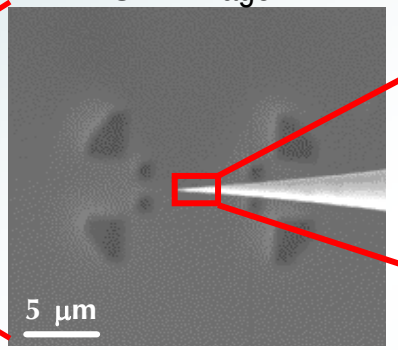
Optical Image



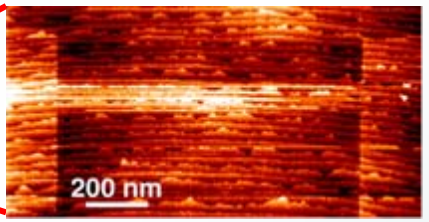
SEM Image



SEM Image



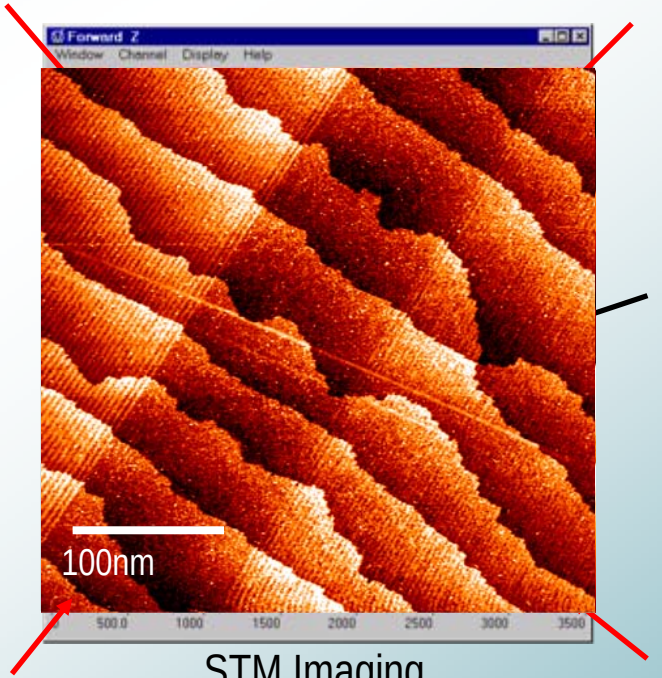
STM Image



90 x 900nm

SEM Imaging

22µm² scan area

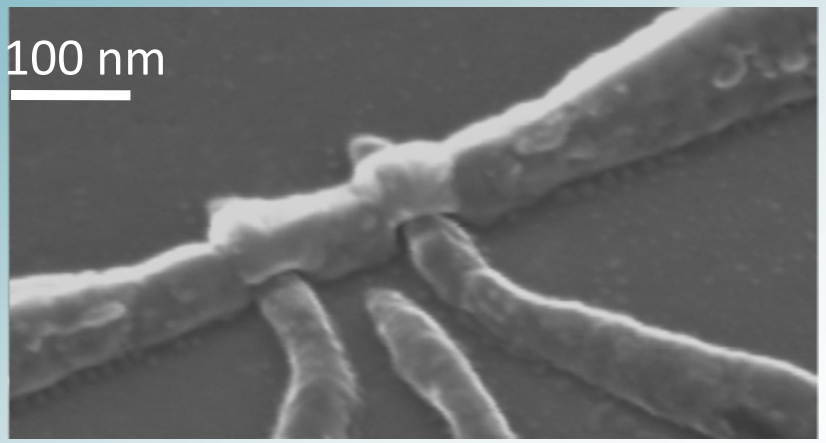


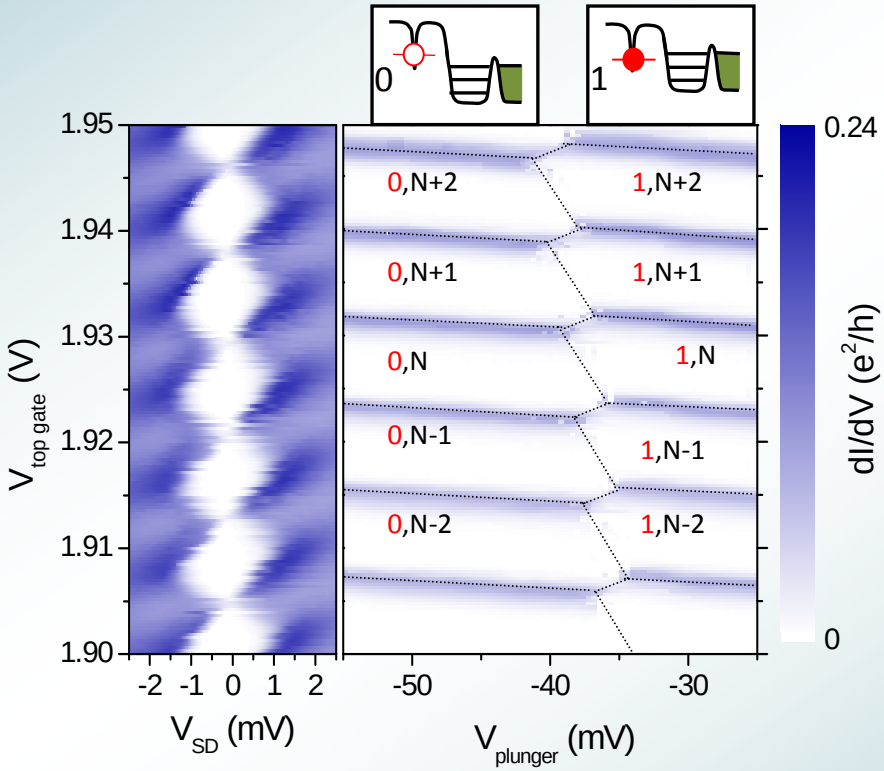
STM – Fabricated Device

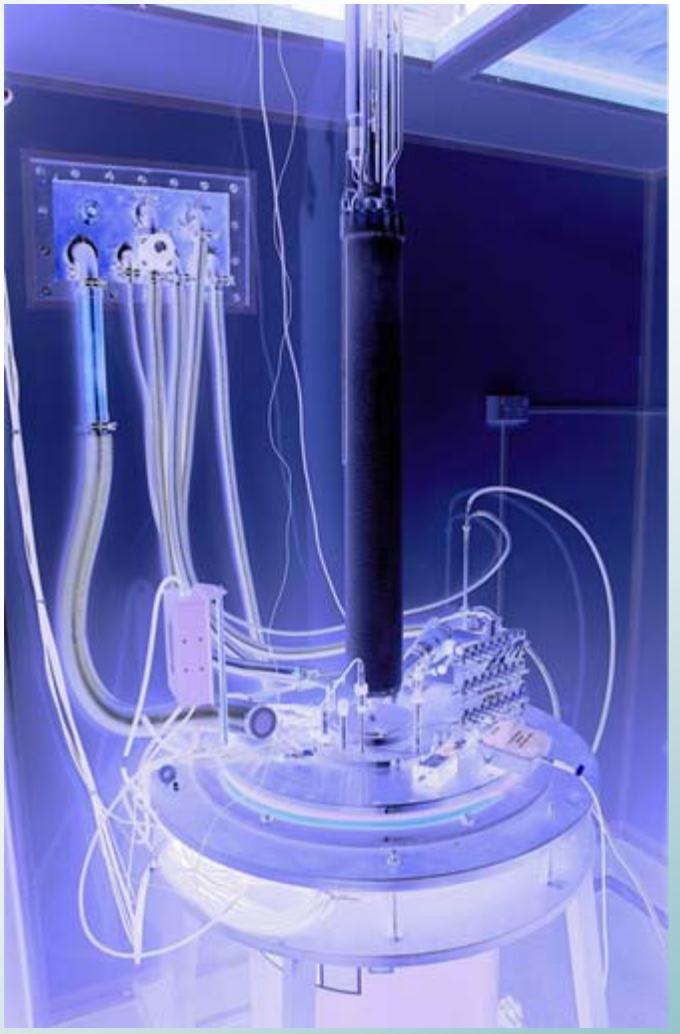
STM Imaging

50µm² scan area

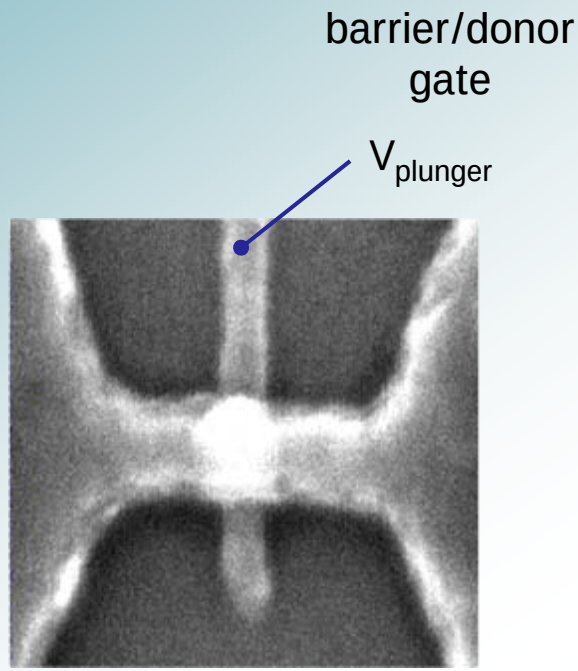
Single Electron Electronics

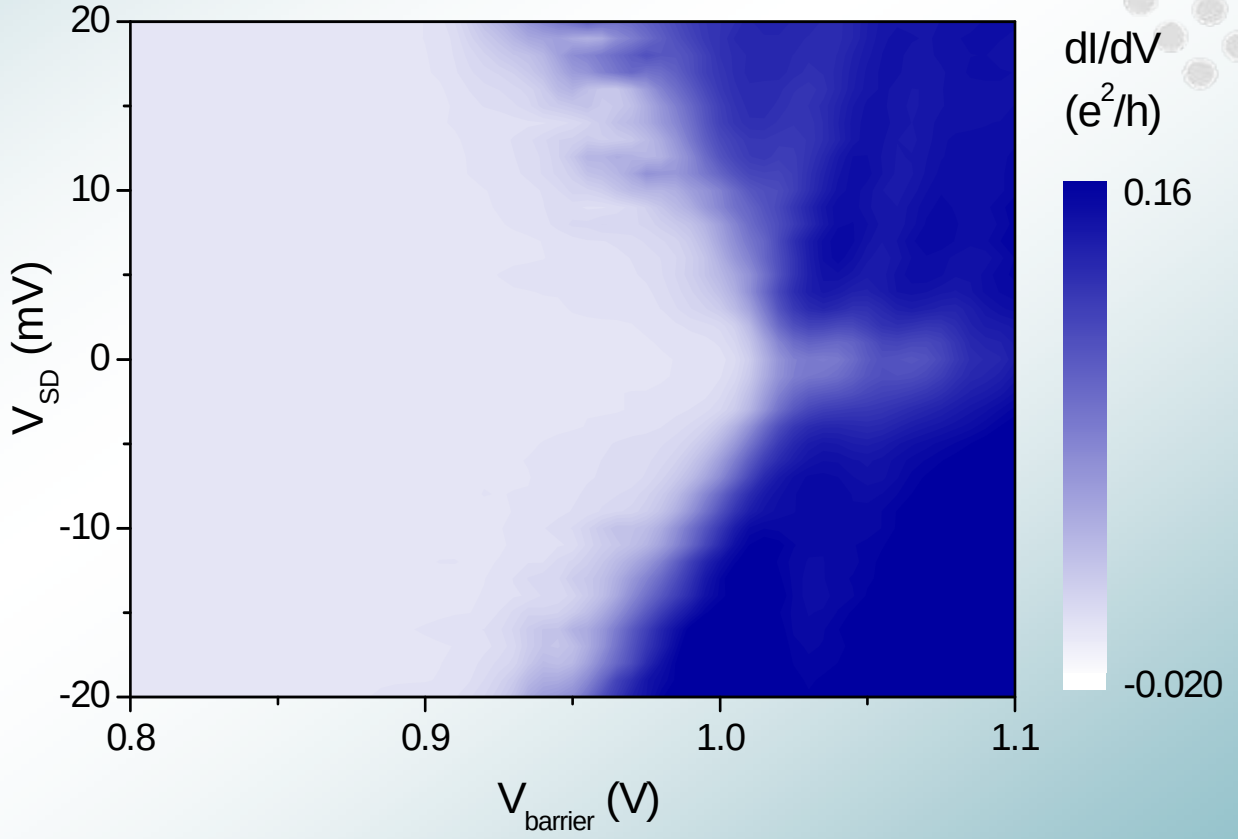






Single Atom Transistor: Control Device





no P-implant → no resonant tunneling features

A. Morello et al.

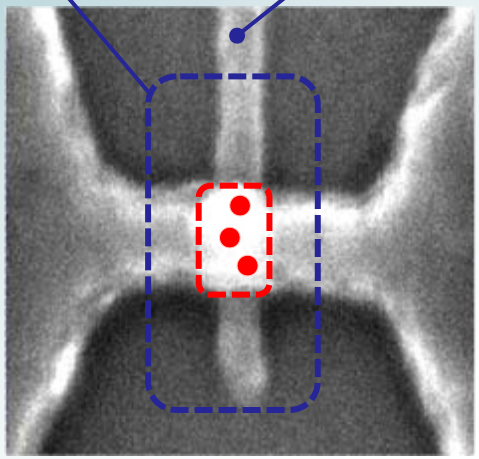
Single Atom Transistor: P Atom Implants

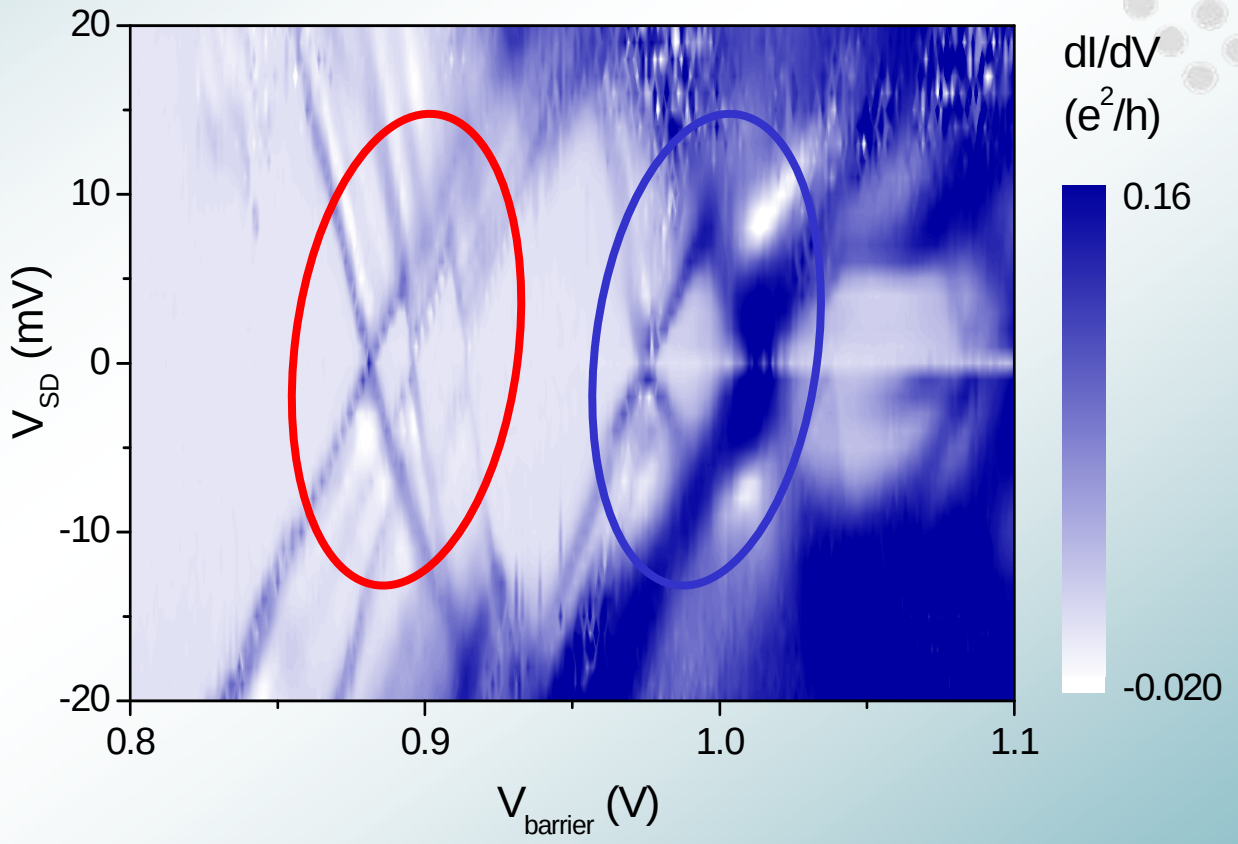
timed P-implant
<n> = 3
in 50×30 nm

barrier/donor gate

P-implant area

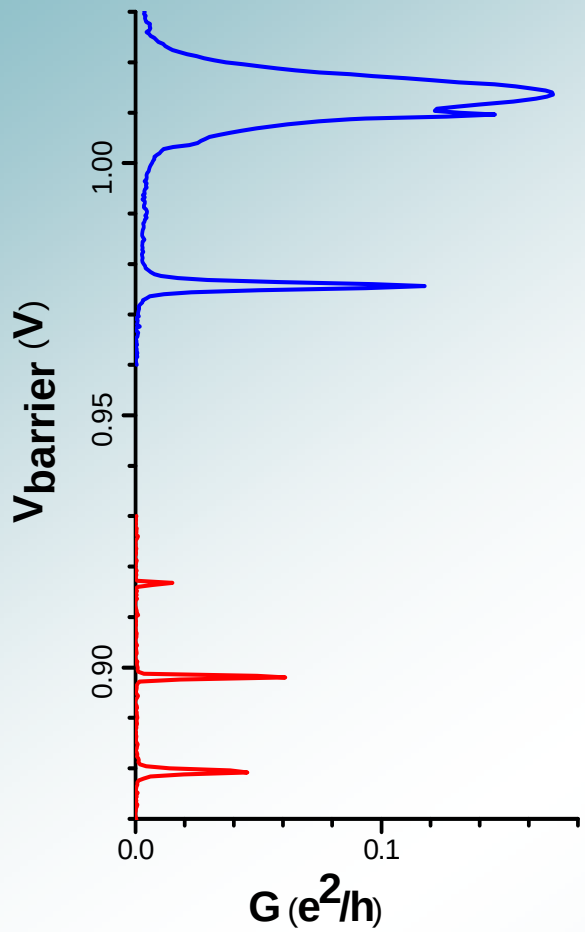
$V_{plunger}$

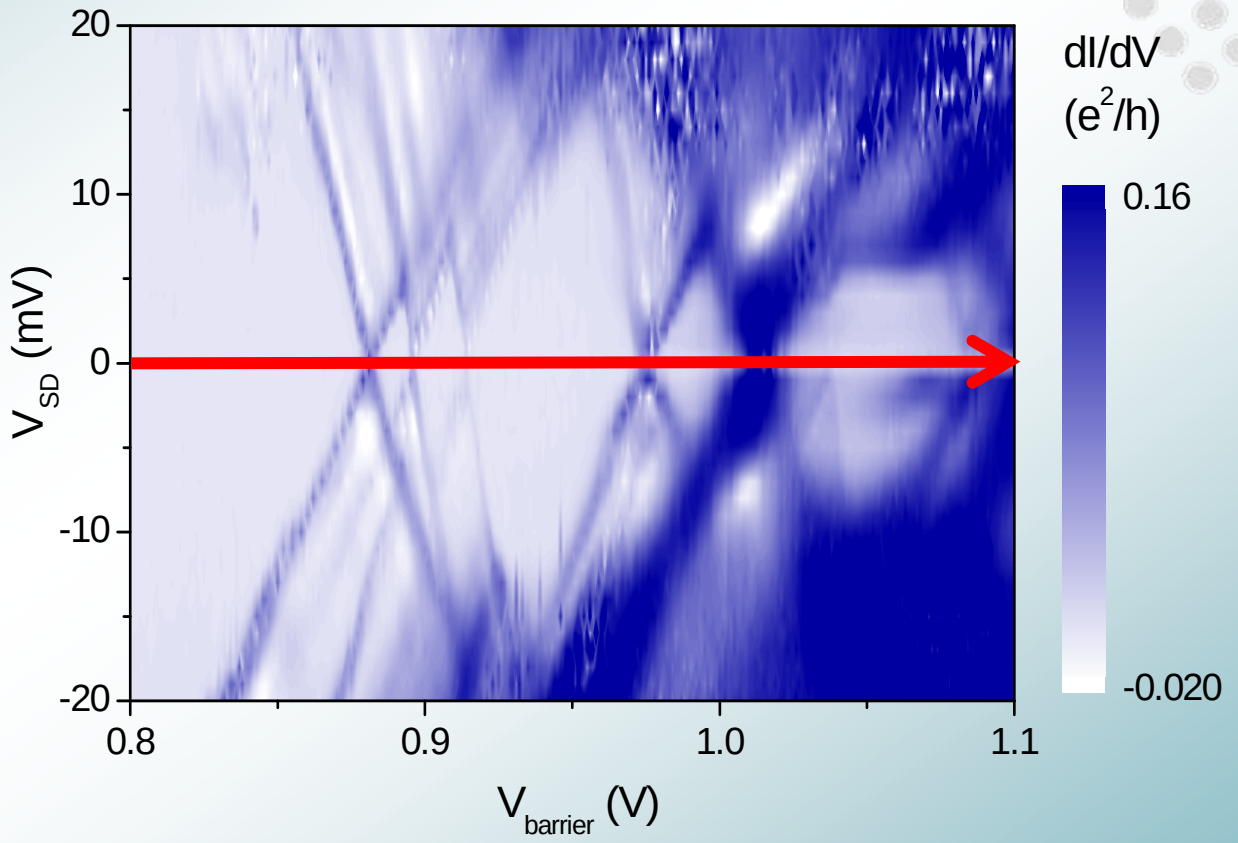




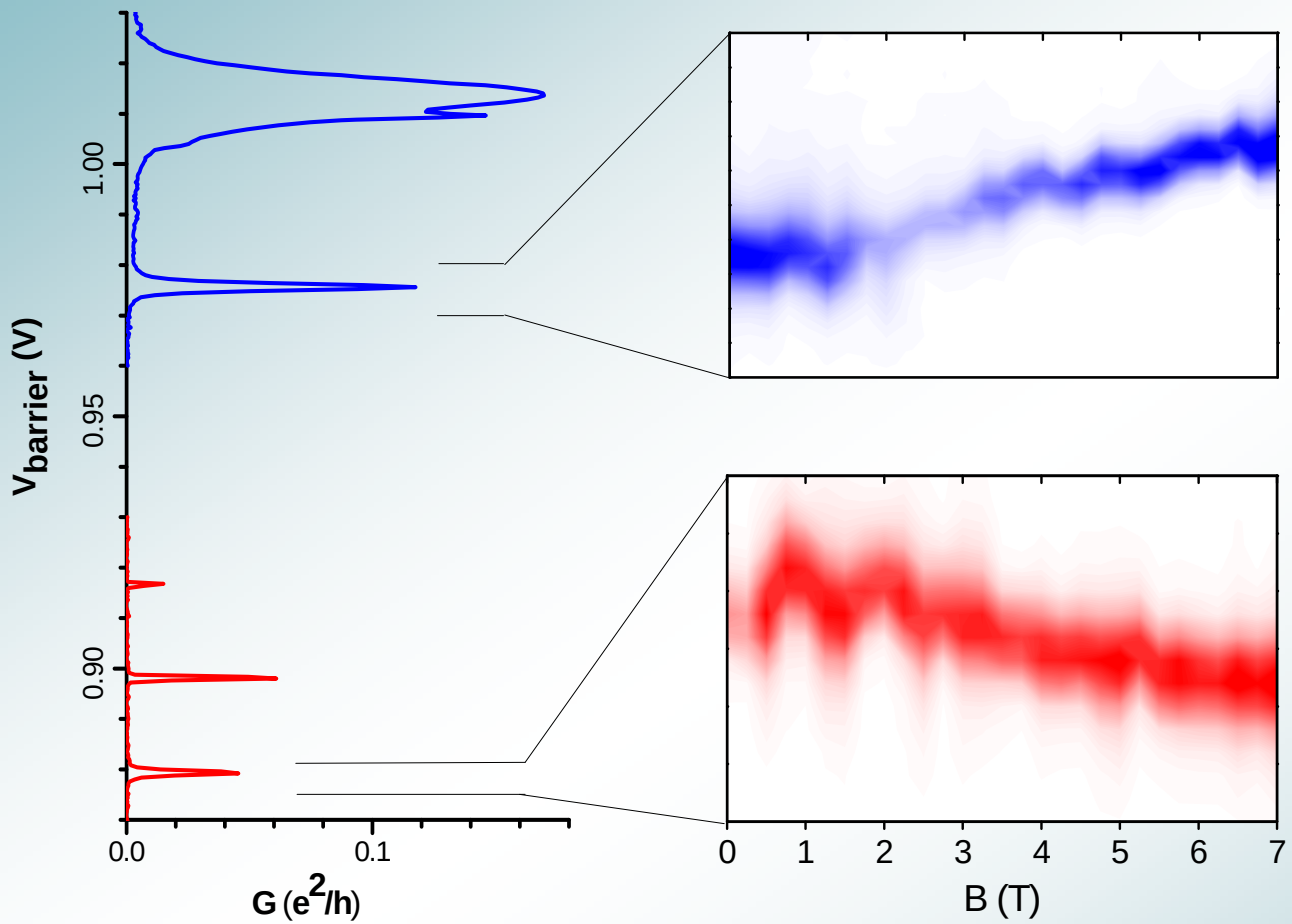
<n> = 3 atoms ↔ 3 pairs of sharp resonant tunneling features

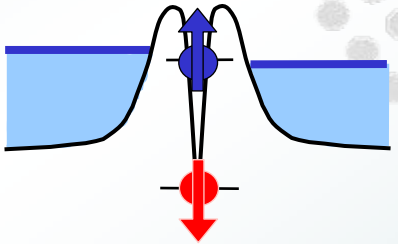
Single Atom Transistor: Tunneling Spectra



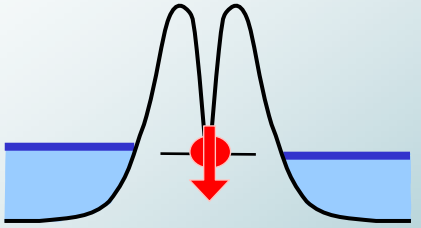


Zeeman Shift of P-Atom Electron States





Second electron on the donor
D^- state → spin-up



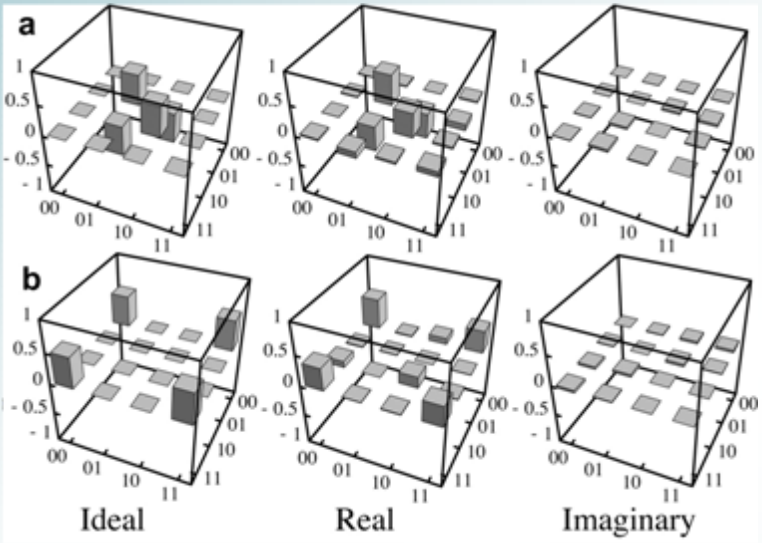
First electron on the donor
D^0 state → spin-down

Resolved the Zeeman shift on electron states of individual donors

Single Photon Photonics

Linear Optics Quantum Computing

Predicted Experiment



CNOT Gate

U Queensland

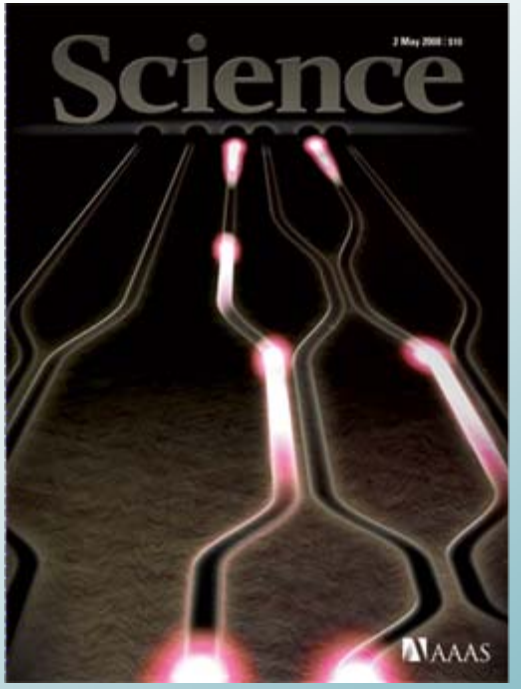
A.G. White et al.

Free Space & Fibre

Polarisation or Frequency Encoding

U Queensland &
Australian Defence Forces Academy

Integrated Optics



CNOT Gate

U Bristol

J.L O'Brien et al.

QIS – Key Application Areas

Data Security

National Security
Financial Services
e-Commerce

Decryption

National Security
Intelligence

Killer Apps

Supercomputers

Database Searching
Bioinformatics
Modeling & Design

Semiconductors

Integrated Circuits
Sensors
Nano-structuring

Secure Communications

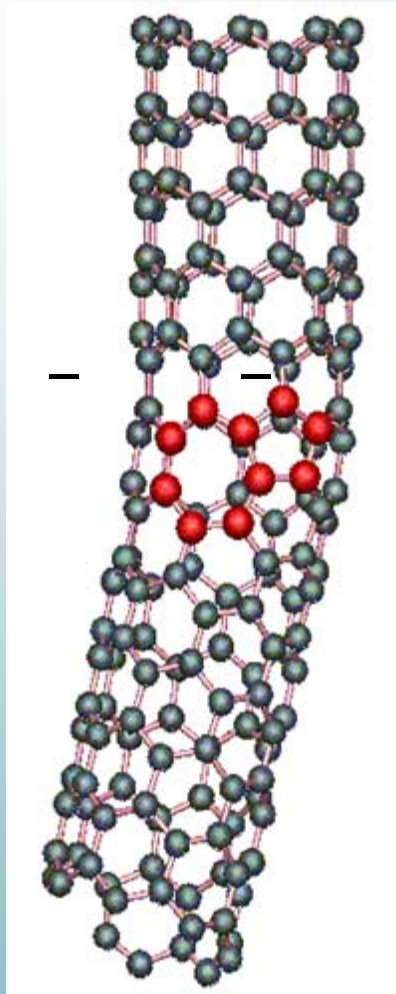
- Quantum communication systems can be made **perfectly** secure (existing protocol BB84)
- Key applications (near to medium term):
  - Military & Security Services Communications
  - Financial Services
  - e-Commerce
  - Corporate Communications (sensitive data)
- Current data encryption market = **$10 billion**
- Quantum LAN now available:
  - MagiQ (USA)
  - ID-Quantique (Switz)

Code Decryption

- Public key encryption (RSA-129) is (almost) uncrackable. Basis of public secure comms today
- A full-scale (few hundred qubits) quantum computer could crack RSA-129 in seconds (Peter Shor – 1994)
- Obvious applications in national and global security

High Performance Computing

- Simulation (modeling) & database searching
- Existing supercomputers now under strain
- Application areas:
  - Nuclear weapons simulation
  - Rapid data search – Security services
  - Biotechnology
    - modeling (new reagents & pharma)
    - searching (bioinformatics)
  - Advanced R&D
    - modeling (commercial, govt)
  - Internet Search Engines
    - *q*-Google ?
- Longer term prospect (15 – 30 years)



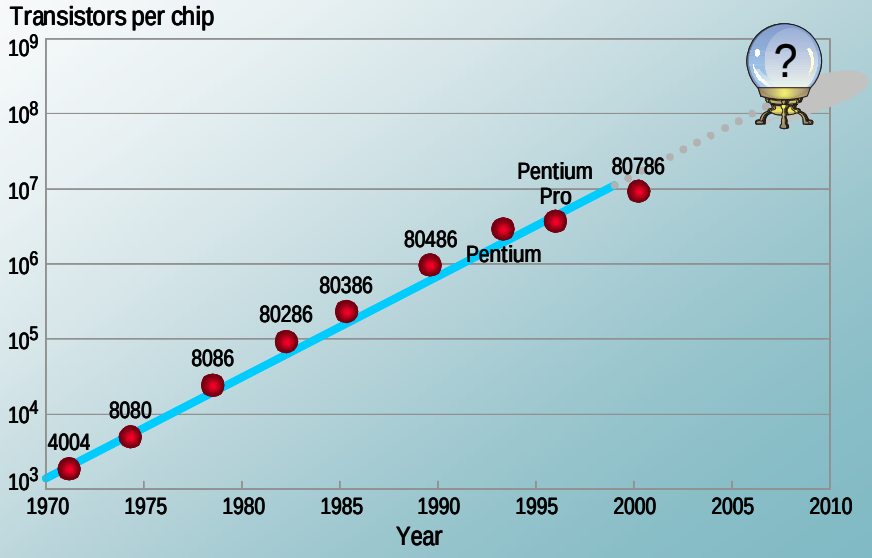
Next Generation Integrated Circuits

- Spin-off or pathway technologies potentially provide nearer term applications than QC per se
- Eg: Single atom nanotechnologies
- Possible applications:

  Next generation transistors

  - extending Moore's Law (to 2020)
  - single atom transistors

- Current world semiconductor market ⇒ **$200 billion**

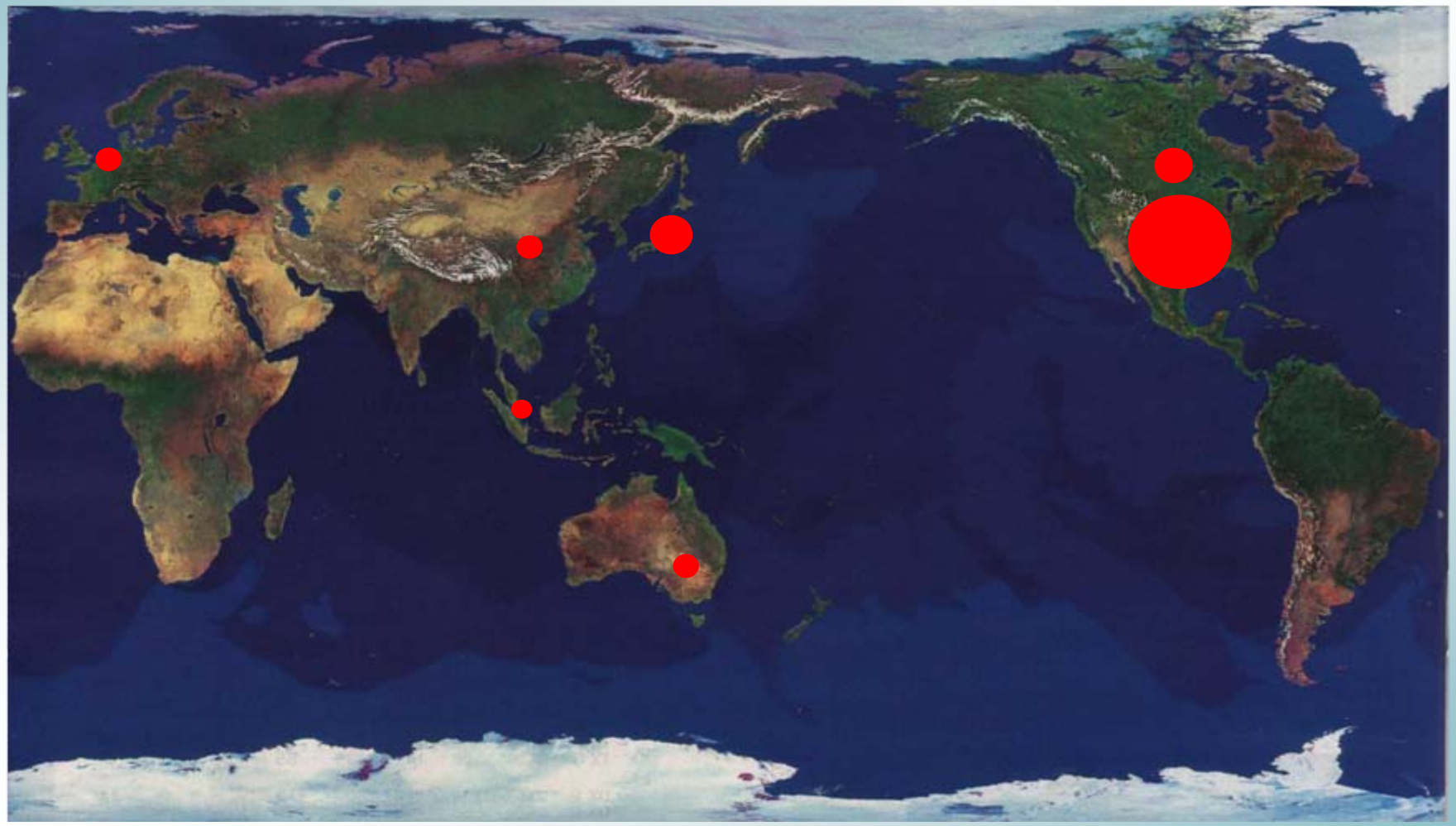


CQCT: Key International Collaborations

Major International QC Projects

QIS Investment Worldwide

World Total = US$180m p.a.*



* Source: 2004 - Oxford Business School

Summary – Quantum Information Science

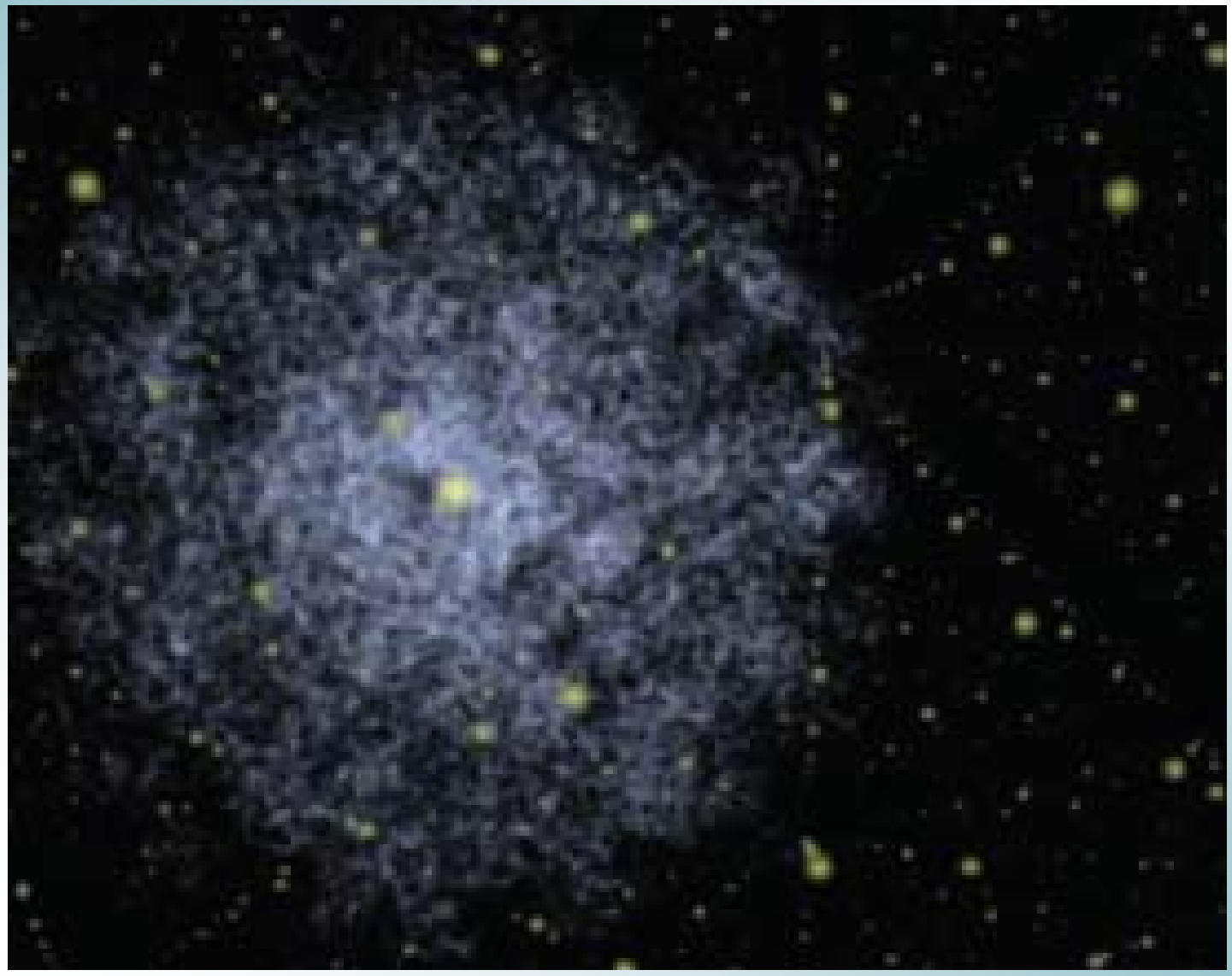
- Quantum information technologies now a reality
- First impacts will be secure communications:

  local area networks (0 – 5 years)

  q-Internet & satellite comms (5 – 15 years)
- Longer term (15 – 30 years) quantum computing:

  high-end computing (simulation, biotech)
- High risk, high pay-off technologies …

Visualizing a Silicon Quantum Computer



See: **Barry Sanders, Lloyd Hollenberg et al., in New Journal of Physics v10 (2008).**
Barry Sanders, in Physics World, December 2008.