Spookytechnology and Society

Thoughts on the status and implications of quantum information science and technology

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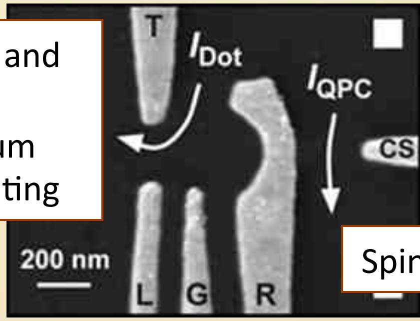
May 21, 2008

Who is this guy?

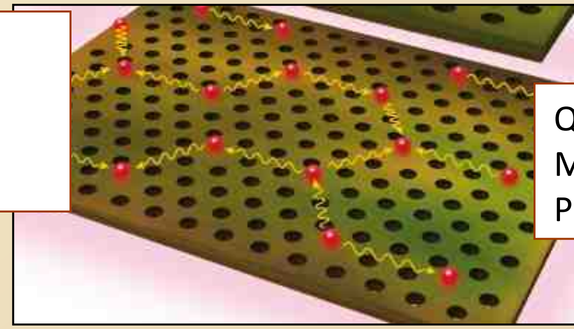
Condensed matter physicist

Silicon and GaAs quantum computing



Spintronics

Quantum photonics: systems and devices



Quantum Many-Body Physics

BS, Physics and Comp. Sci. '00
PhD, U. Wisconsin-Madison '05

NSF Distinguished International Postdoctoral Research Fellow
'05-'07 (Cambridge University-UK, U. Melbourne-AU, U. Tokyo-JP)

As of Oct 07

Technical consultant to DARPA on quantum information S&T programs

Employee of S&T consulting division of Booz Allen Hamilton

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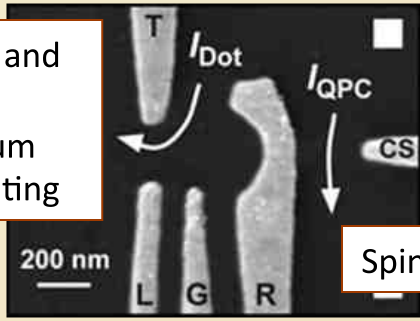

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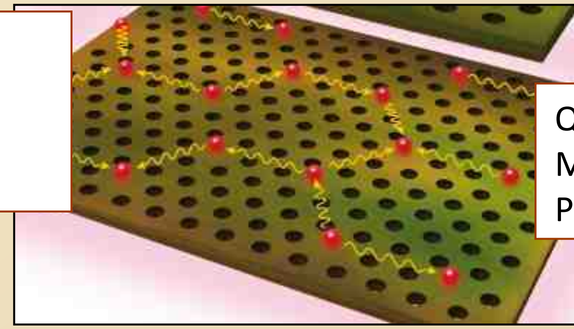

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The opinions I share today are completely my own and in no way represent the views of my employer or clients.

Not a talk about quantum computers

Quantum Overview

Technology
Quantum Information
Devices

"Nanotechnology and Society"

Where I'm coming from
Science and Tech Studies
Defining "nano"
Sociology, Government, Historical Context

Physics

Quantum Devices
Cond-mat
Q.Info

Context

What I was working on
Intro to Quantum Information

Preparing for the future

Wrap-up
Creating it
Competition
6 months on

Examples

Silicon Quantum Computing
Quantum Metrology
Solid Light

Spookytech

My proposal
Motivation and Justification
Reaction
Alternatives
Discussion

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A few words about DARPA and what I do...

"DARPA's original mission, established in 1958, was to prevent technological surprise like the launch of Sputnik."

- Project-based (3-5 years), program manager driven
  - ~140 technical program managers (3-5 year terms)
  - ~20 senior managers
  - ~120 support staff
  - the rest contractors (**technical**, programmatic, support)
- High tech - but no operational or political roles
- Long, cool history (check it out)
- "DARPA hard"

- I won't talk about anything going on at DARPA

Revolutions

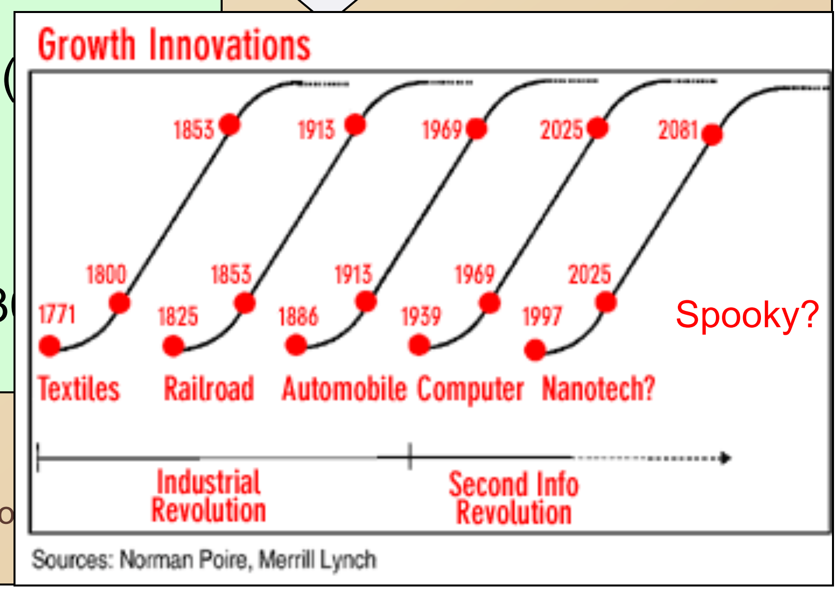
~5,000 - 3,000 BC - First great technological revolutiong
- the “irrigation society” -Drucker

~1750 AD - Second great tech revolution

<u>Major Revolutions after 1750 (start date)</u>

the industrial revolution (1771)
the age of steam and railways (1829)
the age of steel, electricity and heavy engineering (1875)
the age of oil, the automobile and mass production (1908)
the first quantum revolution (1945)
the age of information and telecommunications (
the age of bio-engineering (1980)?
the second industrial revolution - nano (2005)?
the second quantum revolution (2015)?
the age of machine-phase nanotechnology (203

Increasing rate of innovation



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The new quantum story

1. Recent ability to trap/create/control single quanta of nature (electrons, photons, atoms, plasmons, magnons,…)
   - Verify our interpretation of QM
   - Technology
2. Re-visiting less-understood and largely ignored aspects of quantum theory
   - New approach to many problems
   - Non-locality, superposition, measurement
   - Physical foundation for information theory and computation
3. “Spookytechnology” as a unifying term
4. What I’m interested in today: how this revolution unfolds, how we define it, how we guide it to the public and policy makers, how we prepare for it

National Nanotechnology Initiative and Society

- This year research on the societal implications of nanotechnology accounts for nearly 10% of direct federal funding on nanotechnology in the United States: 80% of that on environmental and toxicological effects and the remaining on broader sociological studies. (Mihail Roco, 2003)
- Purpose?
  - GMO, education, clever
- "Nanotechnology and Society" as keyword

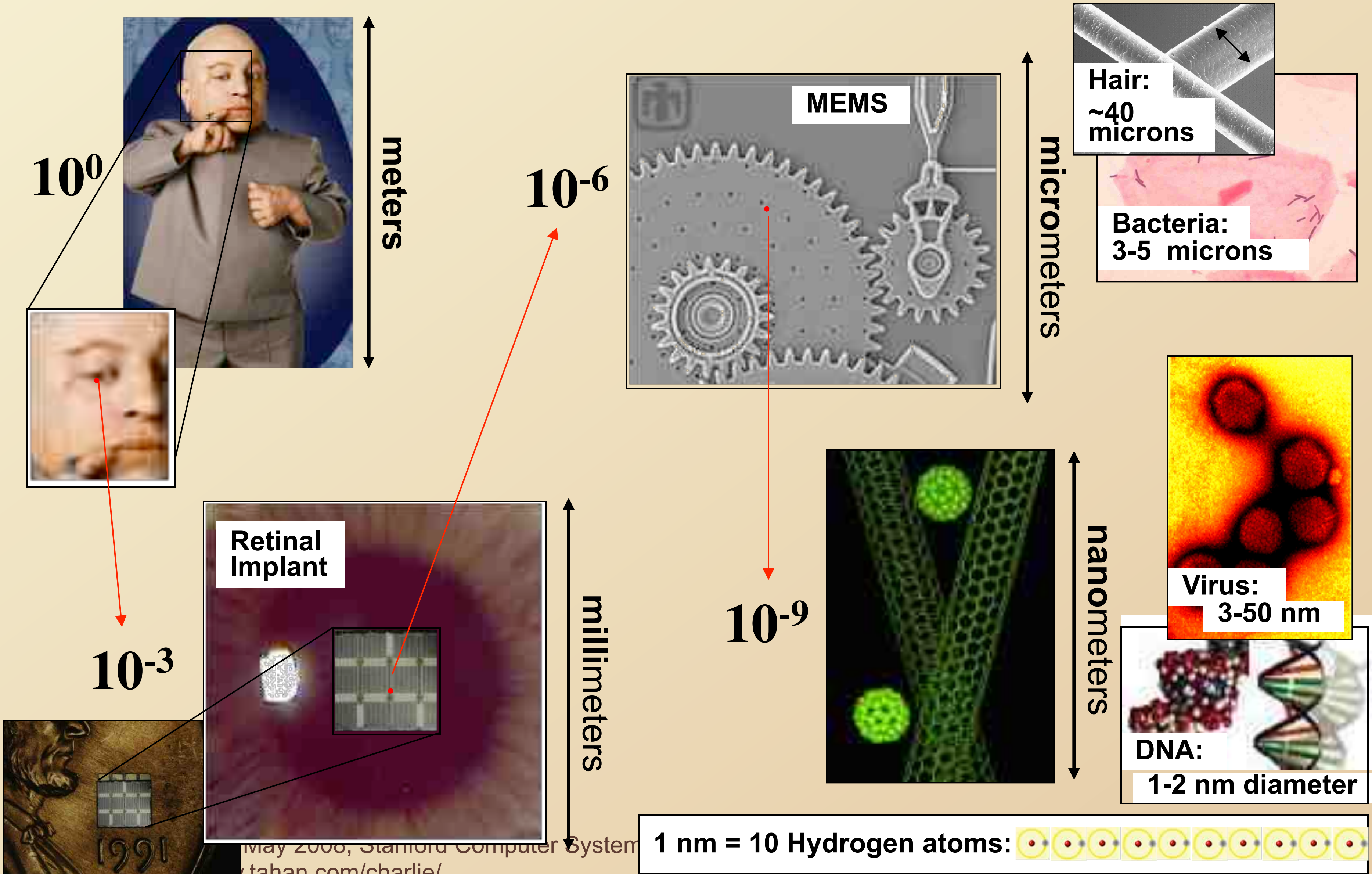
Nanotechnology and Society

- *2005:* Opportunity to teach my own class on "nanotechnology and society" as a 5th-year grad student
  - Course development with profs from Sociology, Public Affairs, History of Science, Engineering
  - Negatives: this helps your science career how?
  - Advantages - totally different community, nanoethics, nanotechnology task force in UK

C. TAHAN, R. LEUNG, G.M. ZENNER, K.D. ELLISON, W.C. CRONE, and C.A. MILLER, "**Nanotechnology and Society: A discussion-based undergraduate course**," Am.J. Phys. 74, 443 (April 2006)

- First question: **What is nanotechnology?**
  - Totally ambiguous

Size and Scale: Factors of 1000



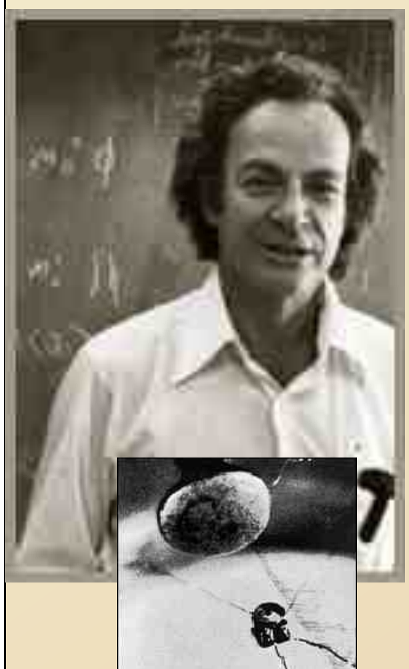
May 2008, Stanford Computer System
.tahan.com/charlie/

Defining Nanotechnology

NSF/NNI's def:

Nanotechnology is the creation of functional materials, devices, and systems through control of matter on the nanometer length scale, exploiting novel phenomena and properties (physical, chemical, biological) present only at that length scale (Roco).

History



c. 1960

<u>Feynman:</u>

- **miniaturization**
- **info. storage**
- **precision chemistry**
- **tiny machines making tinier machines**

c. 1974

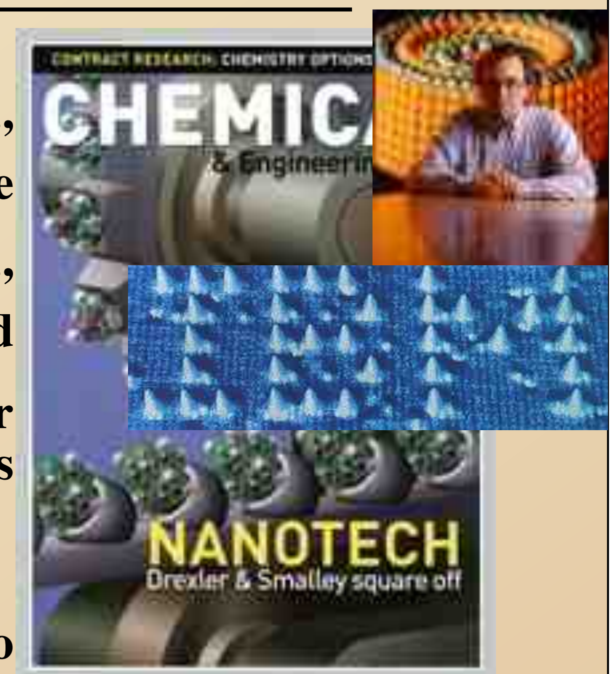
- **"nanotechnology" coined for first time**

c. 1987

- **"nanotech" popularized**
- **idea of molecular self-assemblars**

c. 1990

- **S&T started to catch up**



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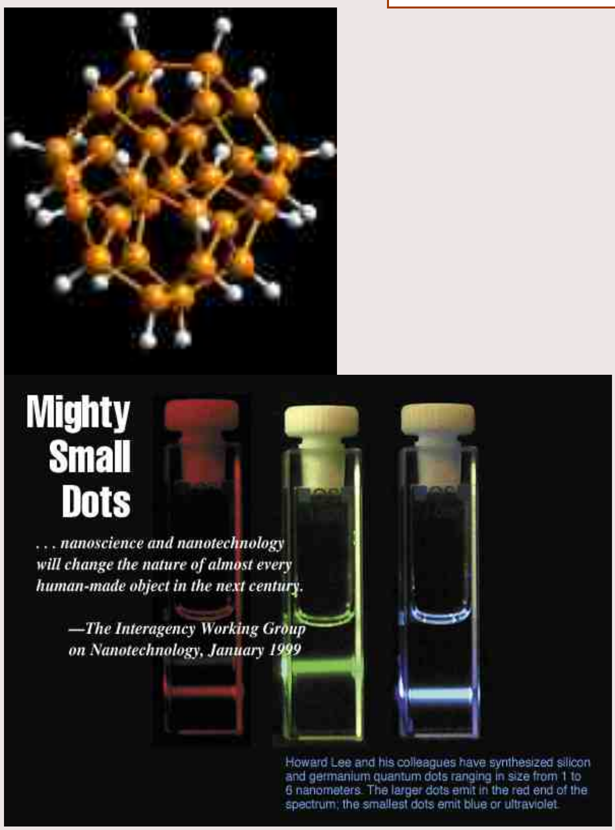
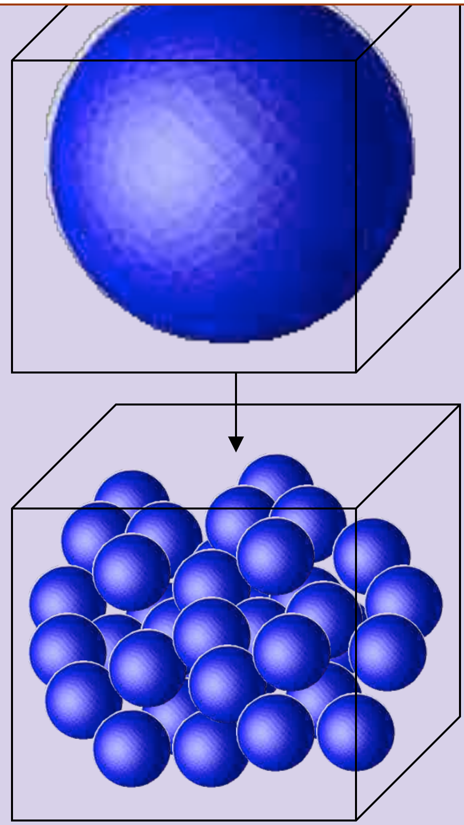
New properties at nanoscale

Nanoparticles create real toxicological concerns.



Completely different physical behavior than bulk.

Quantum (as in quantized, not q.info)



More surface area per volume. More reactive.

Chemical

Nanoparticles can cross the blood brain barrier. Microparticles can't

Biological

Nanotech: Vision vs. Reality

My bipolar view of the term "nanotechnology"

- Umbrella term
    - Advanced materials
    - GMR/CMR
    - Bio
- Truth: Length scale effects
- New space race - funding

- Molecular nano-machines
- Self-assembly, self-replication
- "Machine-phase nanotechnology
- Grey goo

C. TAHAN, "**Identifying Nanotechnology in Society**," Chapter in Advances in Computers, edited by Marvin Zelkowitz (Elsevier, 2007). arxiv.org/abs/physics/0612080

C. TAHAN, "**The Nanotechnology R(evolution)**," Chapter in Nanoethics: Examining the Societal Impact of Nanotechnology, edited by Fritz Allhoff, Patrick Lin, James Moor, and John Weckert (John Wiley & Sons, 2007), arxiv.org/physics/0612080

My definition for nano (focus on risk)

Nanotechnology, at present, is nanoparticles and nanomaterials that contain nanoparticles. Nanoparticles are defined as objects or devices with at least two dimensions in the nanoscale regime (typically under 10 nm) that exhibit new properties, physical, chemical, or biological, or change the properties of a bulk material, due to their size. Nanotechnology of the future will include atom-by-atom or molecule-by-molecule built active devices.

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Nanotechnology in whole

- Great uniting force for physical sciences at a practical level
- But threats too

- Nanotechnology has become a marketing term to encompass and drive the belief that more funding is needed in the physical sciences to maintain economic, scientific, and military advantage over international competition.

- What makes nano exciting to a STS person?
  - Sociology of the mess
  - The actual science, compartmentalized
  - Risk dealt with
  - Other than that?

Not a talk about quantum computers

Quantum Overview

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Quantum Information
Devices

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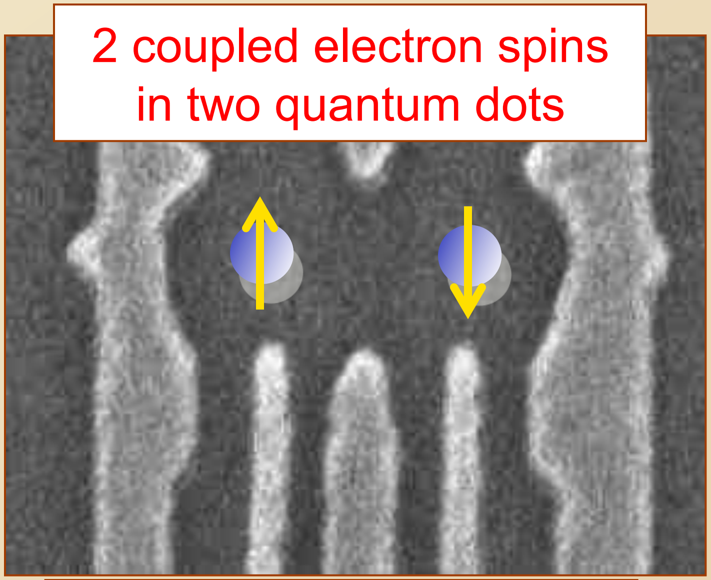
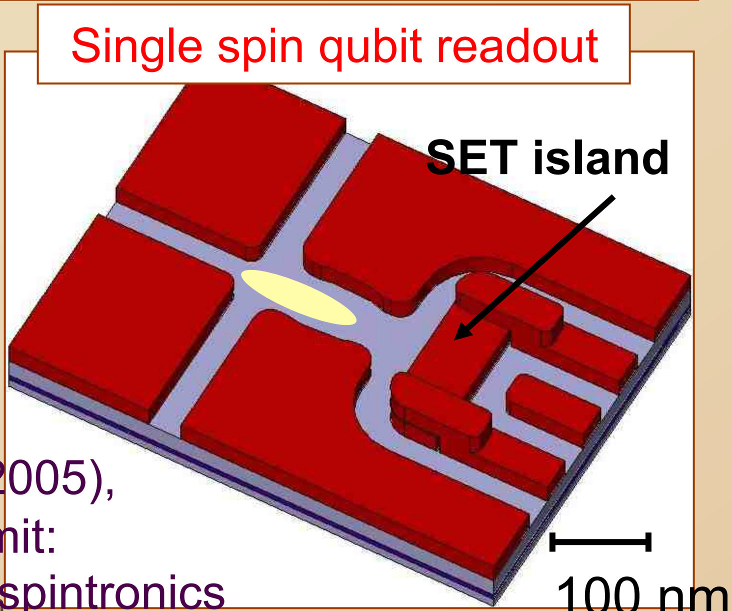
What I was working on…

- Silicon nanodevices for quantum computing and spintronics
- Quantum information, a real revolution
  - Thinking, language, as well as application
- These nano STS people are really missing the boat!





C. TAHAN, PhD Thesis (2005), "Silicon in the quantum limit: Quantum computing and spintronics in silicon heterostructures"

Quantum Computers, the extreme "advanced quantum technology"

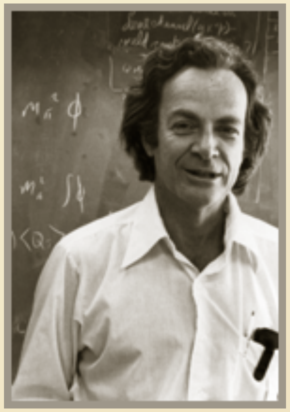
By 1925 there was a solidified interpretation of quantum mechanics that lead people to connect the mathematics to experience.

- **1st generation quantum technologies**
  - Quantum physics circa 1925
  - **Dual wave-particle like nature of matter - interference**
  - Quantization of particles (**photons**!)
  - Electron waves in a semiconductor crystal
  - Bulk systems
- **Quantum-designed technologies: 1940s**
  - **Atom bomb**
  - **Transistor**
  - **Laser**
  - **Nuclear magnetic resonance (MRI)**

- "New" quantum
  - Superposition
  - Entanglement
  - Coherence/Decoherence
  - Measurement
  - Quantum many-body effects
- **2nd generation quantum technologies**
  - **Quantum communication** (quantum key distribution to quantum repeaters)
  - **Quantum metrology**, lithography, imaging – using entanglement for sub-wavelength resolution imaging/writing
  - **Specialized devices**, based on, eg, EIT, slow light, BEC, etc.
  - **Quantum simulators** (materials, drugs, …)
  - **Quantum computers** (specialized to universal)

Dowling and Milburn got here first, Proc. Royal Society

QC as intro to Quantum Information



R. Feynman

Charles Bennett

David Deutsch

Peter Shor

1982

- Simulate a quantum system with another quantum system?

1993/1992

- First quantum algorithm
- Quantum teleportation

1994-5

"ok to get a phd in this stuff"

- **Code breaking Q.algorithm**
- **Quantum Error Correction possible**

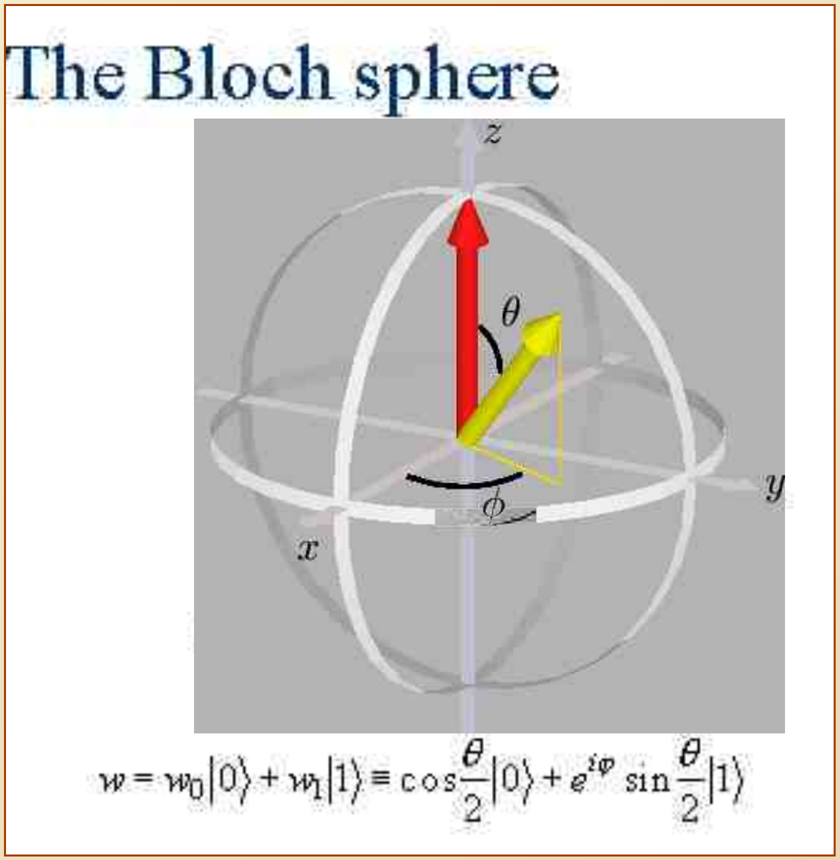
Quantum Superposition and Formalism

Qubit: $|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ $|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$

Quantum superposition

$$\longrightarrow \quad |\pm\rangle = \frac{|0\rangle \pm |1\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\\pm 1\end{pmatrix}$$

"off AND on"



Multiple qubits:

$|0\rangle \otimes |1\rangle \otimes |0\rangle =$ 3 qubits

$$\begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} =$$

2^n Hilbert space for *n* qubits

$$\begin{pmatrix}1\begin{pmatrix}0\\1\end{pmatrix}\\0\begin{pmatrix}0\\1\end{pmatrix}\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = [8\times 1]$$

dimensional Hilbert space

Quantum measurement

qubit: two level quantum system

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

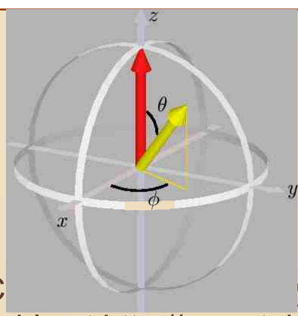
"off" **"on"**

1 classical bit:

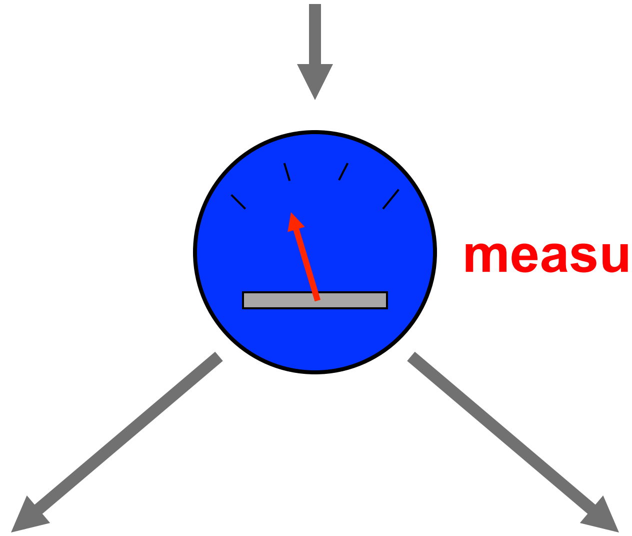
b = 0 or 1

1 qubit:

$|b\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$



$|R\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$



measurement

$|0\rangle$ (probability $|\alpha_0|^2$)

$|1\rangle$ (probability $|\alpha_1|^2$)

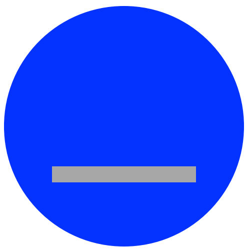
Not like watching an apple fall!

Quantum Entanglement

"Spooky action at a distance"

Unentangled

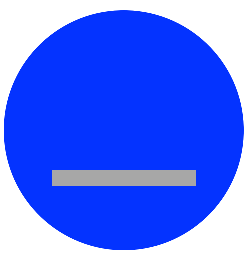
$$(|0\rangle + |1\rangle)\times(|0\rangle + |1\rangle)$$



qubit 1

$|0\rangle\times(|0\rangle + |1\rangle)$ (prob. 0.5)

$|1\rangle\times(|0\rangle + |1\rangle)$ (prob. 0.5)

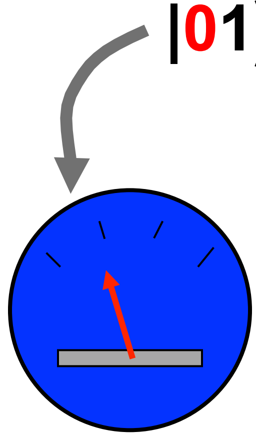


qubit 2

$|00\rangle$ (pr. 0.25)
$|01\rangle$ (pr. 0.25)
$|10\rangle$ (pr. 0.25)
$|11\rangle$ (pr. 0.25)

Entangled

$$|01\rangle + |10\rangle$$

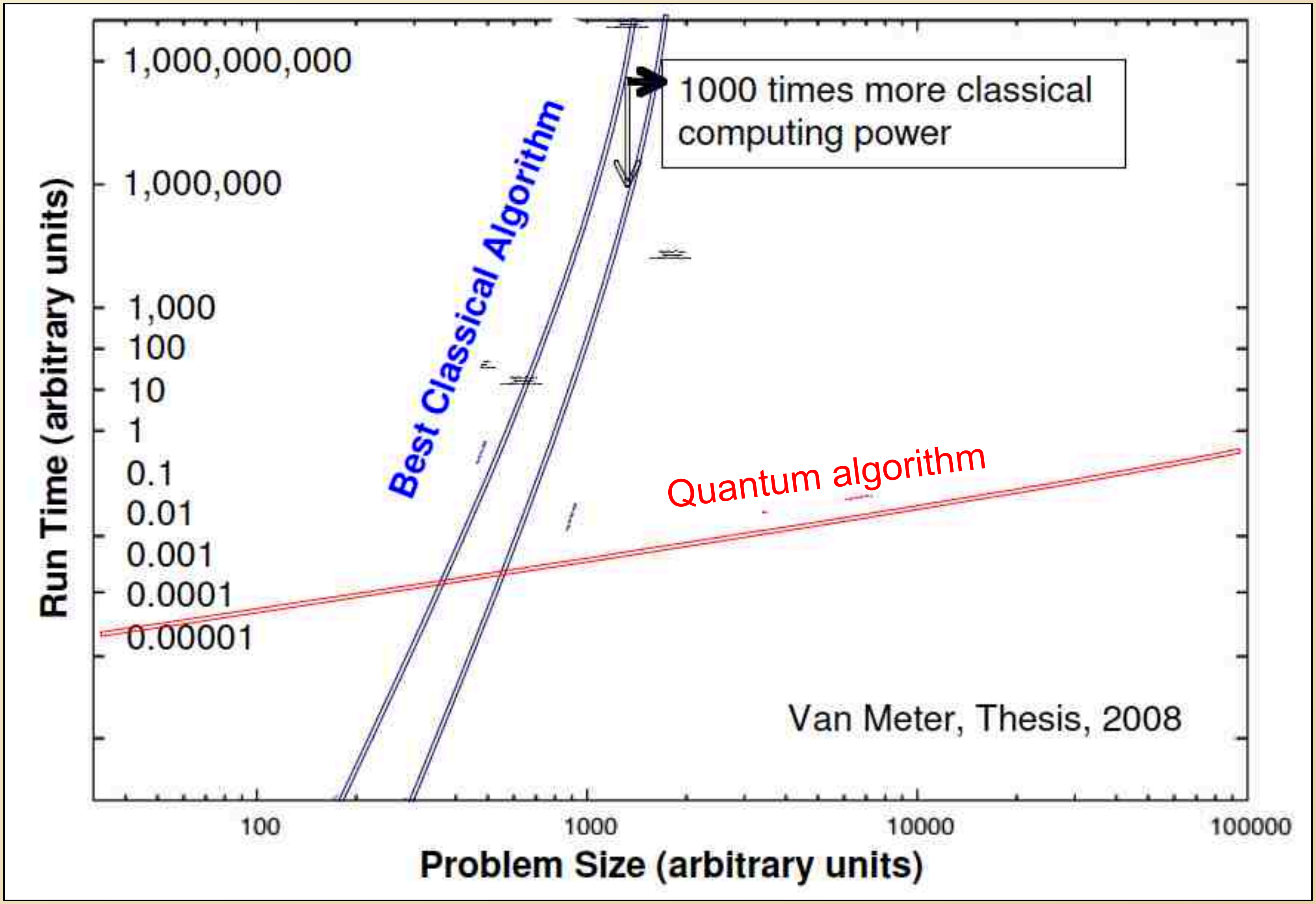


qubit 1

$|01\rangle$ (pr. 0.5)
$|10\rangle$ (pr. 0.5)

Measurement of qubit 1 fixes state of qubit 2.

The graph that says it all re: QC



Unifying Language

- Inside Physics
  - Condensed Matter
  - AMO
  - Information Theory
  - High Energy Physics?
- Physics and Computer Science
  - Information theory
- Mathematics
- Engineering

Quantum mechanics courses that haven't changed really since the 1920s are being rewritten.

Introducing Spookytech

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MY PROPOSAL

- Fall 2008: “Spookytechnology and Society”
- My Goals:
  - Use the history of nanotech as a guide
  - Start discussion on educational and societal issues in physics community
  - Bridge the gap with science and tech studies community
  - Propose new terminology and definition
    - Controversial
    - Broader definition than just QC or QI
    - “Quantum” overused
    - Avoid ambiguous definition of field by outside (scifi, pop-sci)
  - Cocktail party cool: *Spookytechnology is technology based on the spooky properties of quantum physics*

On being selectively ridiculous

My name and definition

spookytechnology encompasses all functional devices, systems, and materials whose utility relies in whole or in part on higher order quantum properties of matter and energy that have no counterpart in the classical world. These purely quantum traits may include superposition, entanglement, decoherence (along with the quantum aspects of measurement and error correction) or new behavior that emerges in engineered many-body systems.

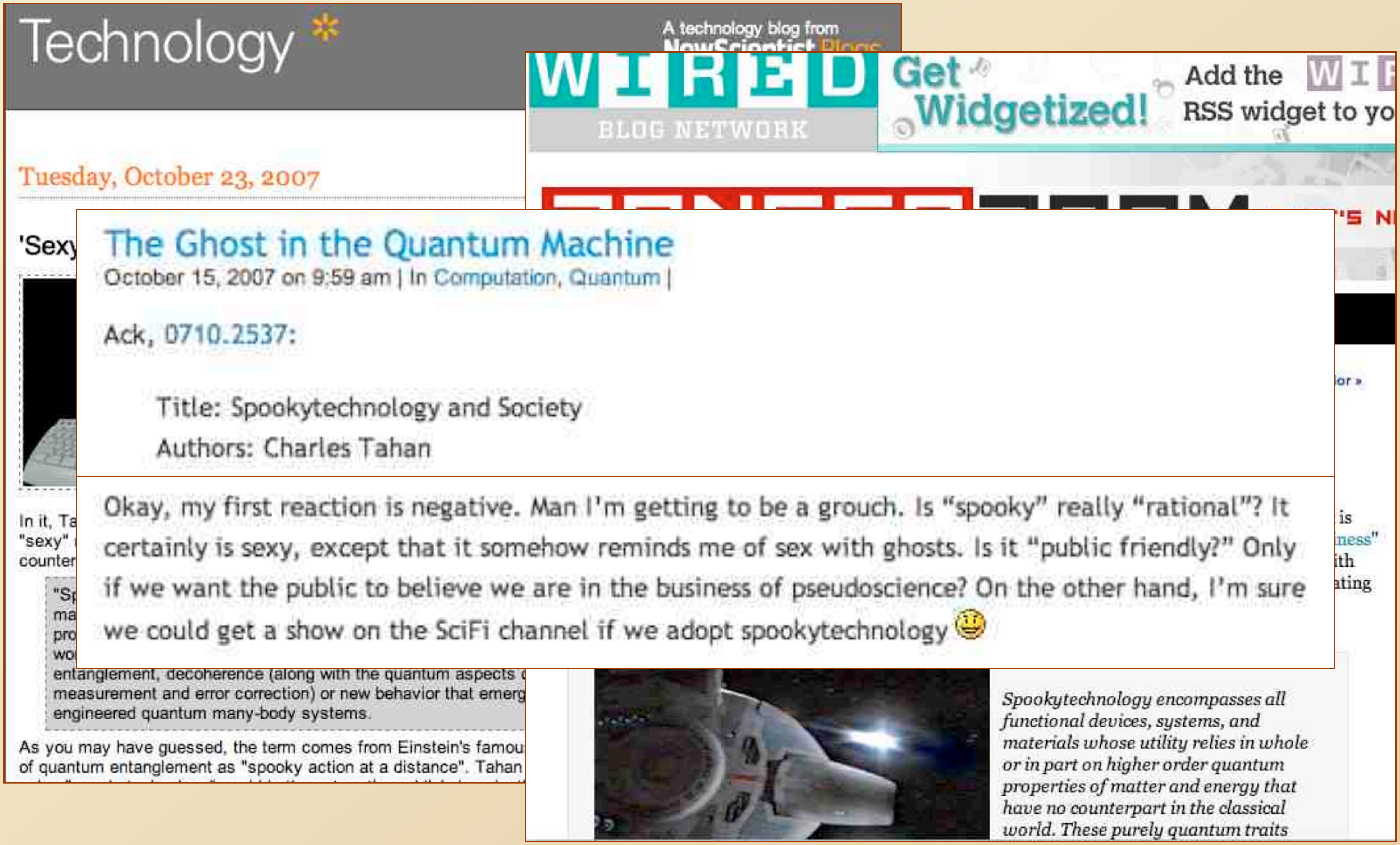
C. TAHAN, "Spookytechnology and Society," (12 October 2007), http://arxiv.org/abs/0710.2537

"spukhafte Fernwirkung"

Nano vs. Spooky

- Spookytech still in inception phase - has not entered public conciousness
- No environmental implication
- Spookytech is really a new paradigm shift, whereas nano is more a loose confederation - or a practical paradigm
- Spookytech has a language founded on quantum optics (discrete QM) and information theory

Immediate community reaction



Immediate community reaction

1. **Reminds me of casper the ghost.**
2. **"Not rational"**
3. **"We don't want to scare people/ pseudoscience."**
4. **"quantum" is still sexy**
5. **"Too anthropomorphic" David Deutsch, *Oxford Press***
6. **Sounds like "pooh"**
7. **Physicists don't like "cute words." - P.Ball, Nature**

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Rational? Why not “meter-technology”?

Makes about as much sense as nano-technology when you think about it.

But making sense is not the point of most terms.

“It’s scary/it will lead to pseudo-science”

Alternatives

- Quantum Technology
- 2nd Generation Quantum Technology
- Quantum Information Technology
  - Quinfotechnology
  - QIT
- Quantum coherent technology
- Quantum entanglement-based technology
- Quantronics

Still sexy after all these years

My name and definition

Quantum … technology [cut off by the overlay box] compasses all functional devices, systems, and materials whose utility relies in whole or in part on higher order quantum properties of matter and energy that have no counterpart in the classical world. These purely quantum traits may include superposition, entanglement, decoherence (along with the quantum aspects of measurement and error correction) or new behavior that emerges in engineered many-body systems.

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"spukhafte Fernwirkung"

Examples of spookytech

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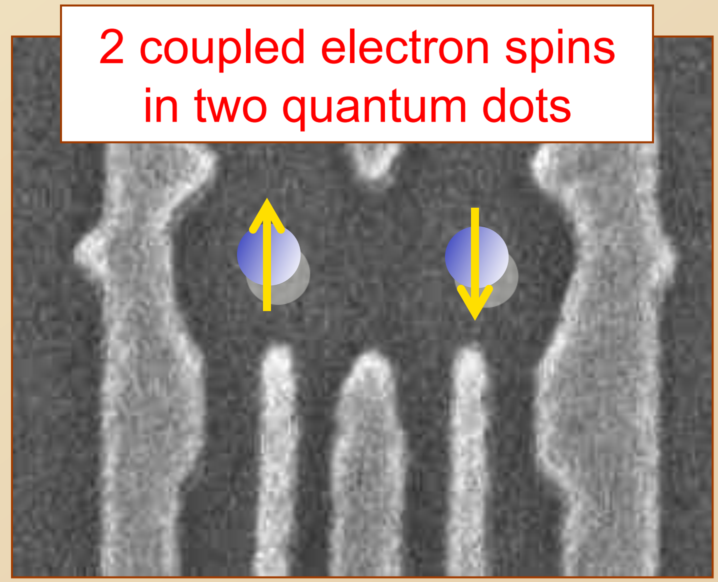
Example: A Quantum Computer

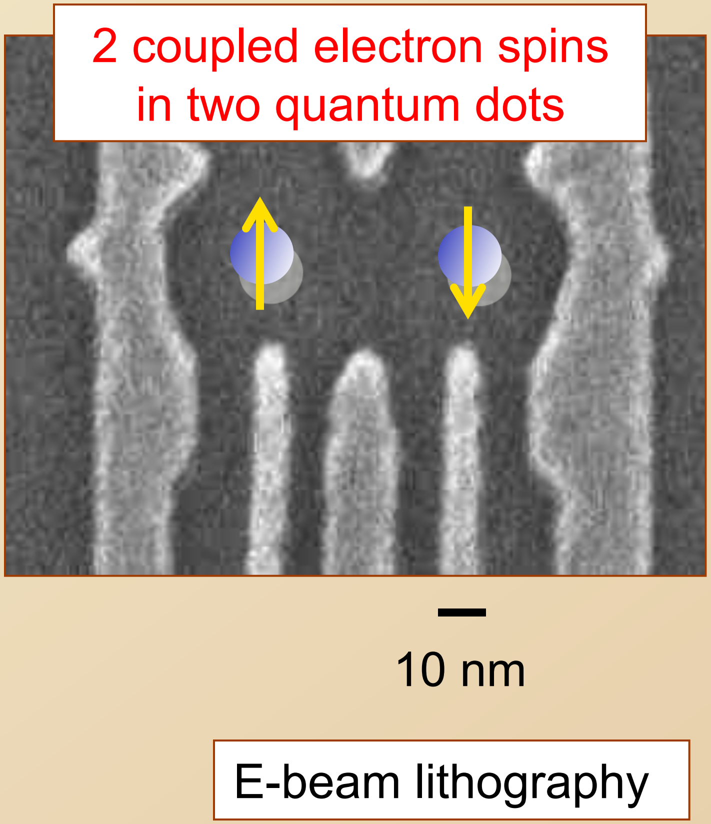
Quantum Algorithms / Computer Science, Math

- **What we need:**
  - **Universal set of gates**
  - **Good, scalable qubit**
  - Fast readout (measurement) of qubit
  - Fast initialization / source of new qubits
  - Quantum Error Correction
  - Flying qubits

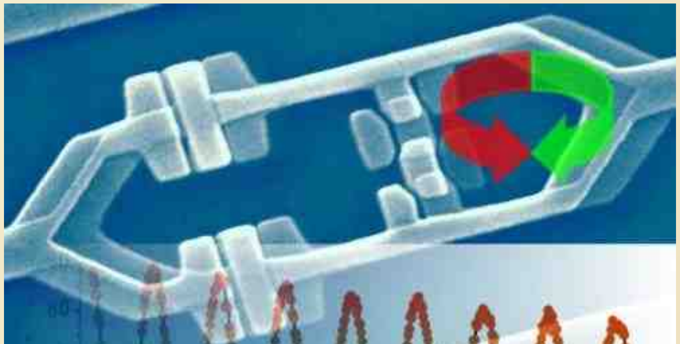


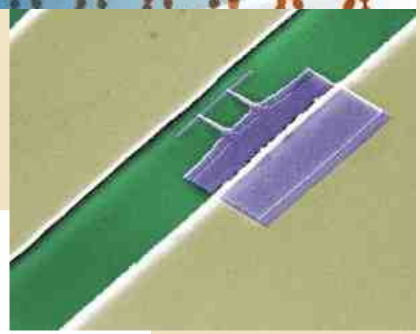
Silicon towards quantum

- Silicon may be most studied material in history (but largely from an engineering perspective)
- Currently at 45 nm node
- Two ways to get to quantum: cold vs. small
- Quantum at room temperature
- Quantum at 10 milli-Kelvin



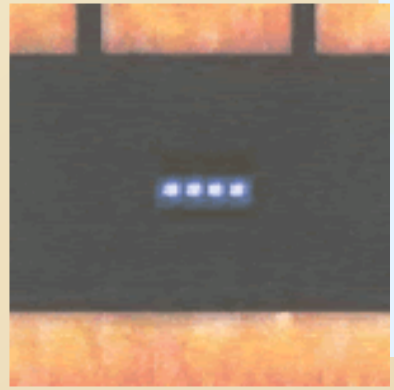
Other promising quantum computing architectures

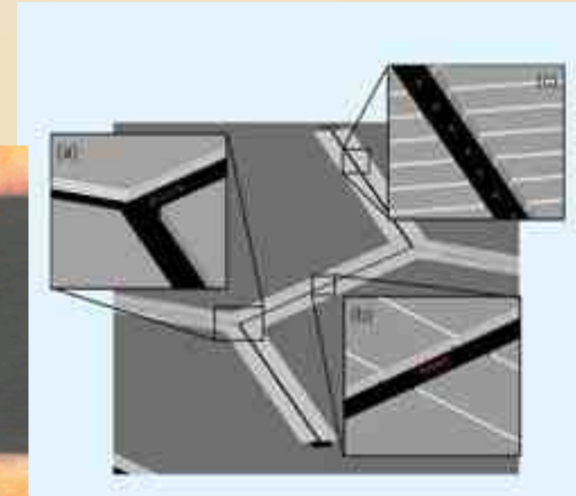


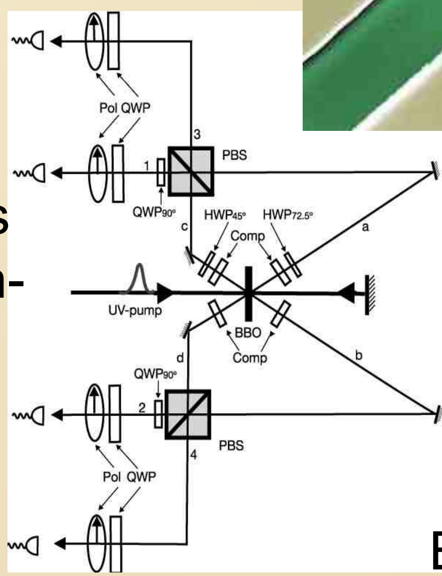


Superconducting qubits

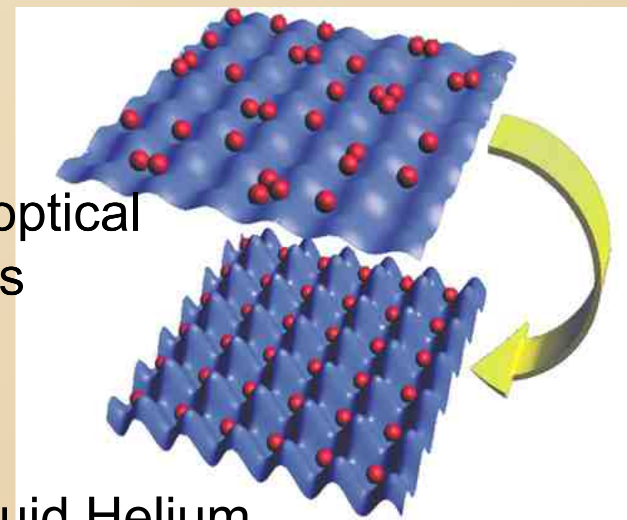
Ion traps







Photons and non-linear optics

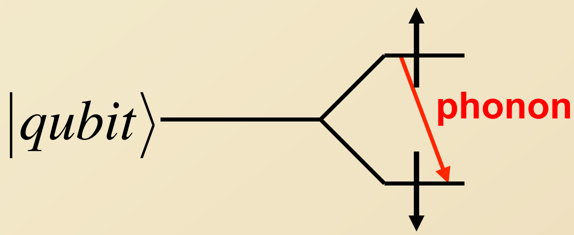


Cold atom optical lattices

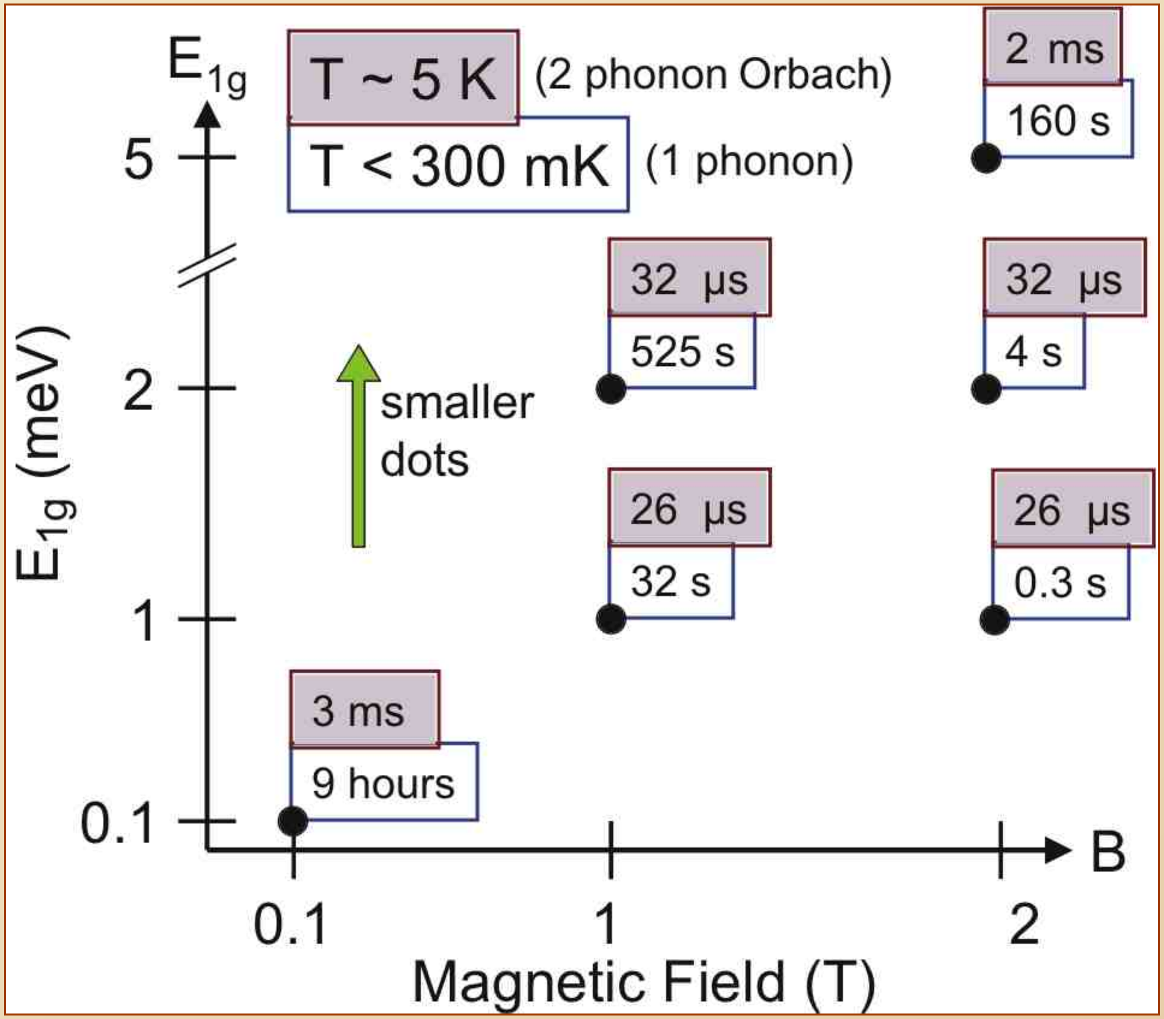
Electrons floating on liquid Helium

Spin relaxation times of electron spin in silicon

The longer the coherence time of a qubit, the less quantum error correction you need.



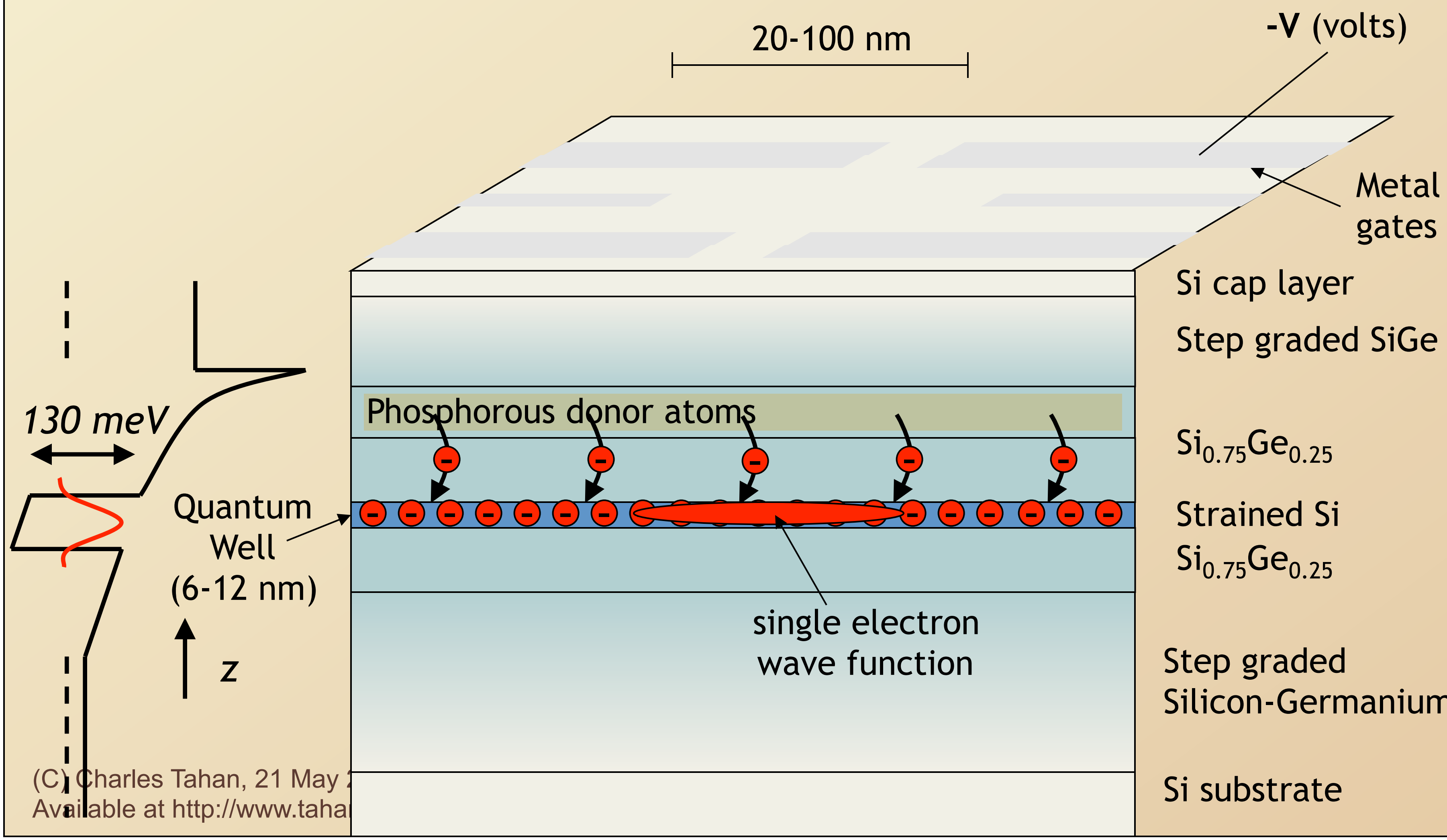
Spins in silicon have extraordinary coherence properties for solid-state quantum systems while being compatible with CMOS.



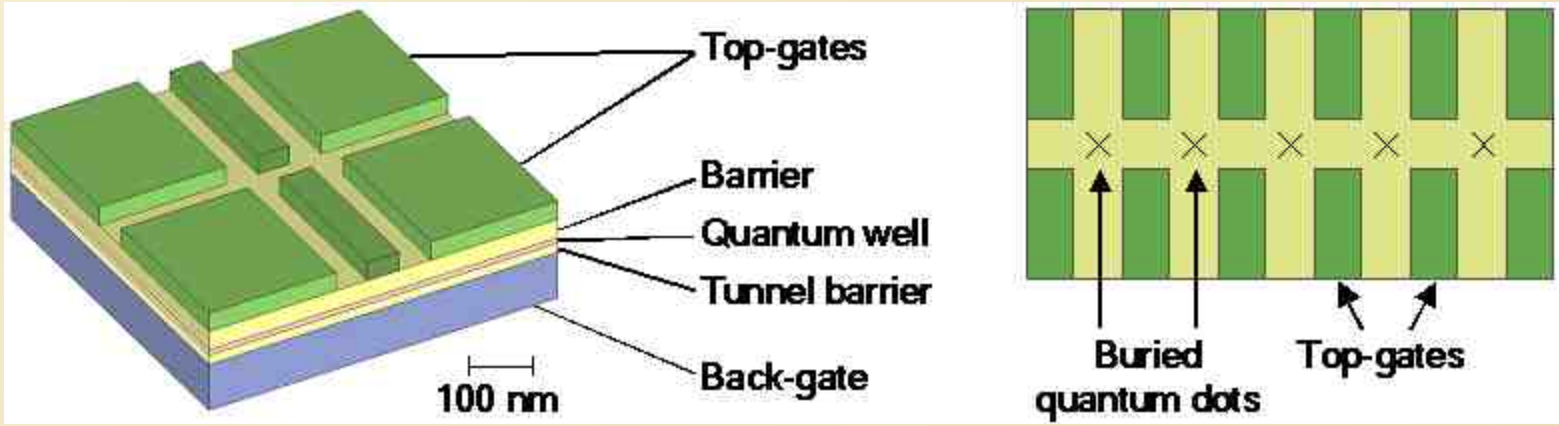
C. Tahan et al.

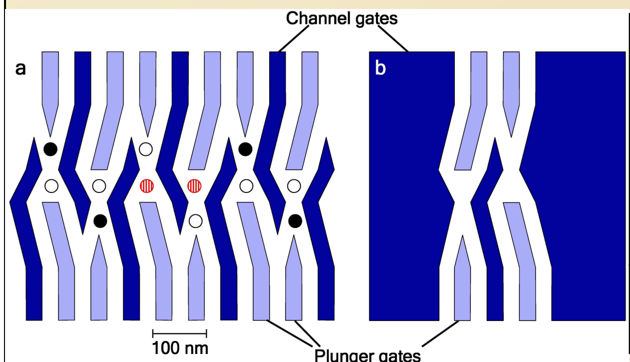
A quantum well quantum dot

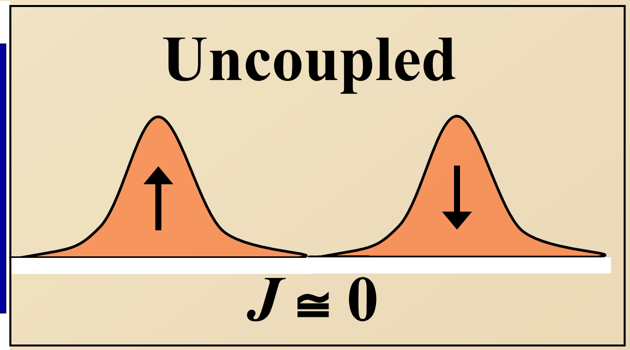
Goal: **a single electron tunably confined vertically and horizontally in a semiconductor nanostructure**

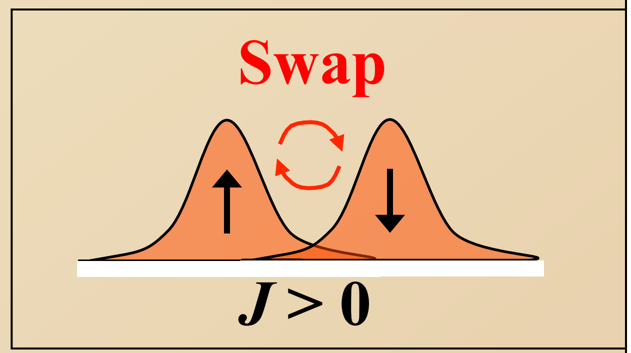


2, we need a way to make a CNOT 2-qubit gate









$H_{2\text{ quantum dots}} \rightarrow H_{eff} = J\, \mathbf{s}_1 \cdot \mathbf{s}_2$

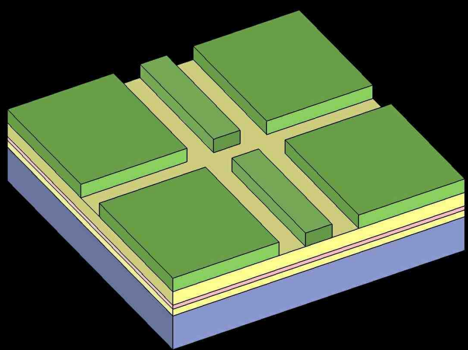
SWAP doesn't entangle but Sqrt[SWAP] does.

SWAP: $\text{Int}[J(t)\, dt] = \pi\hbar$

=> CNOT

Simulation

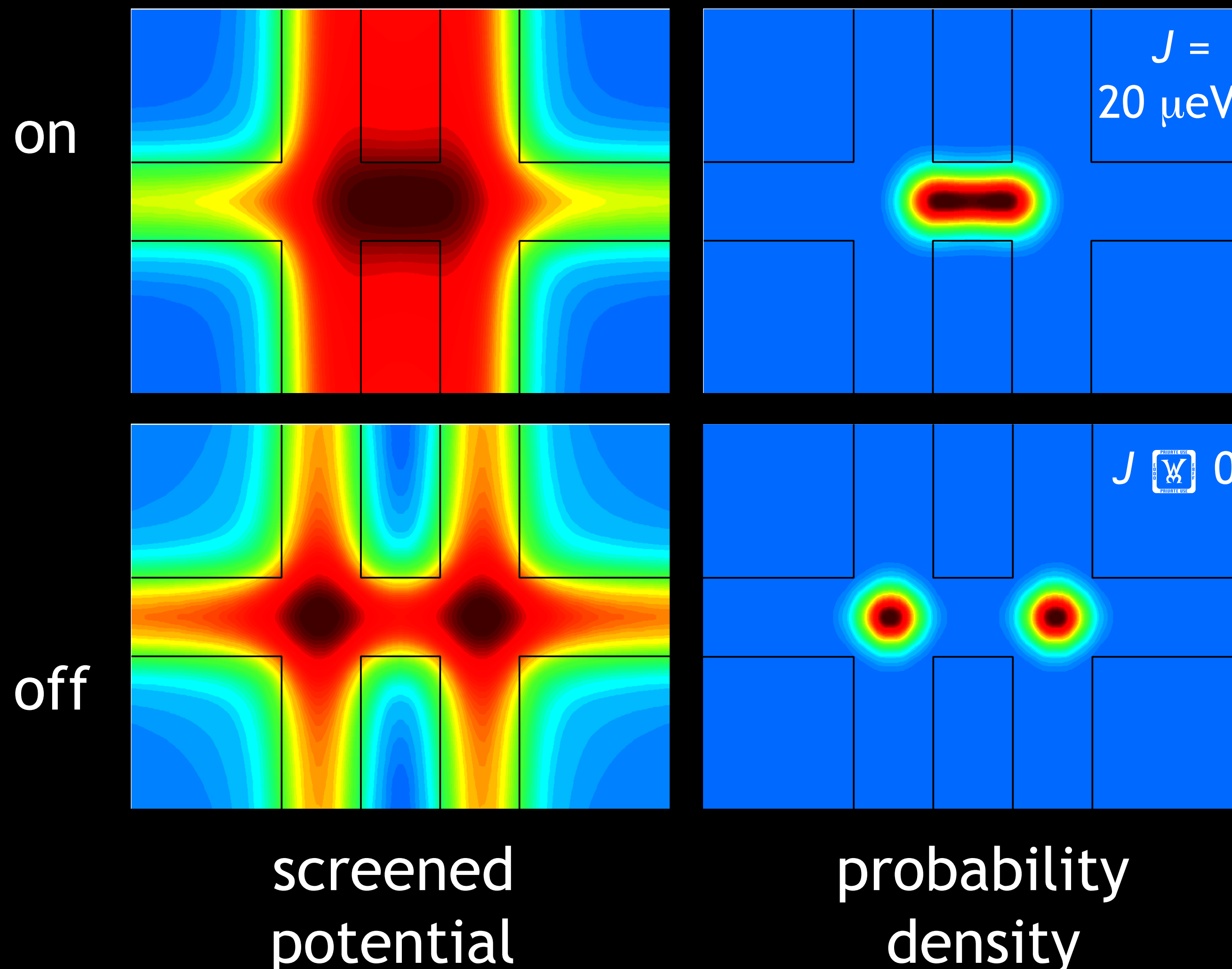
(Friesen, Rugheimer, Savage, et al., ’03)



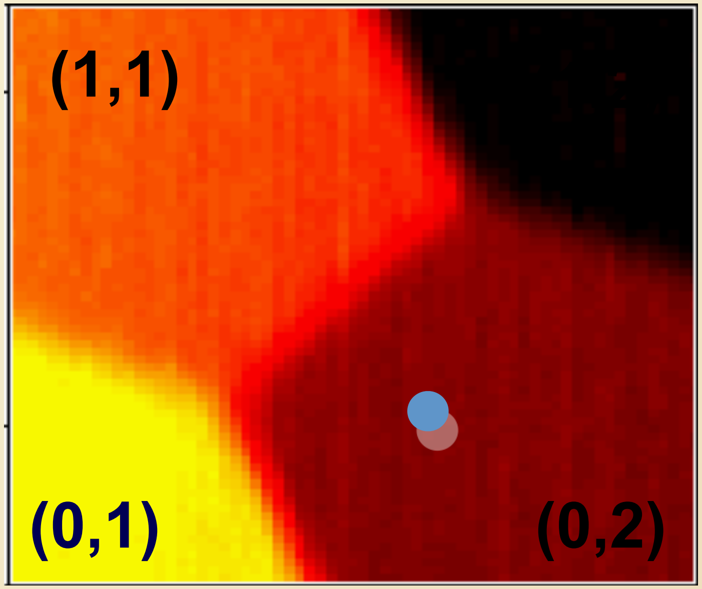
$$|S\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$

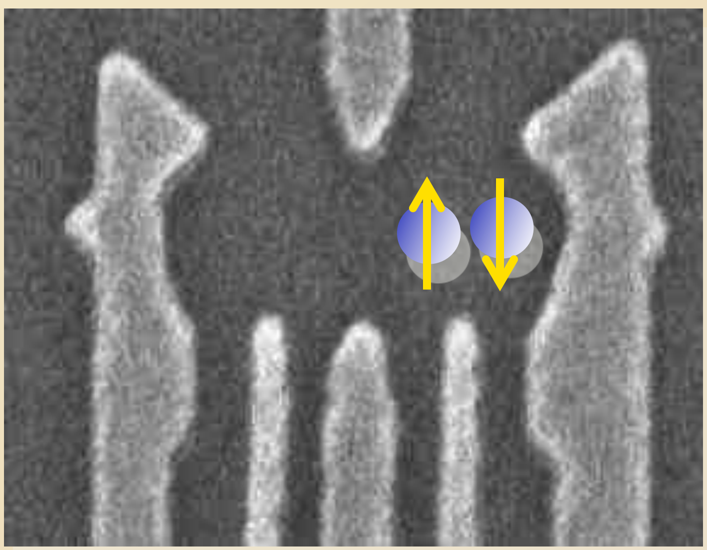
$$|T\rangle = \begin{cases} |\uparrow\uparrow\rangle \\ \dfrac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}} \\ |\downarrow\downarrow\rangle \end{cases}$$

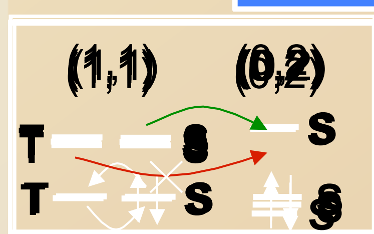
$$J = E_S - E_T$$

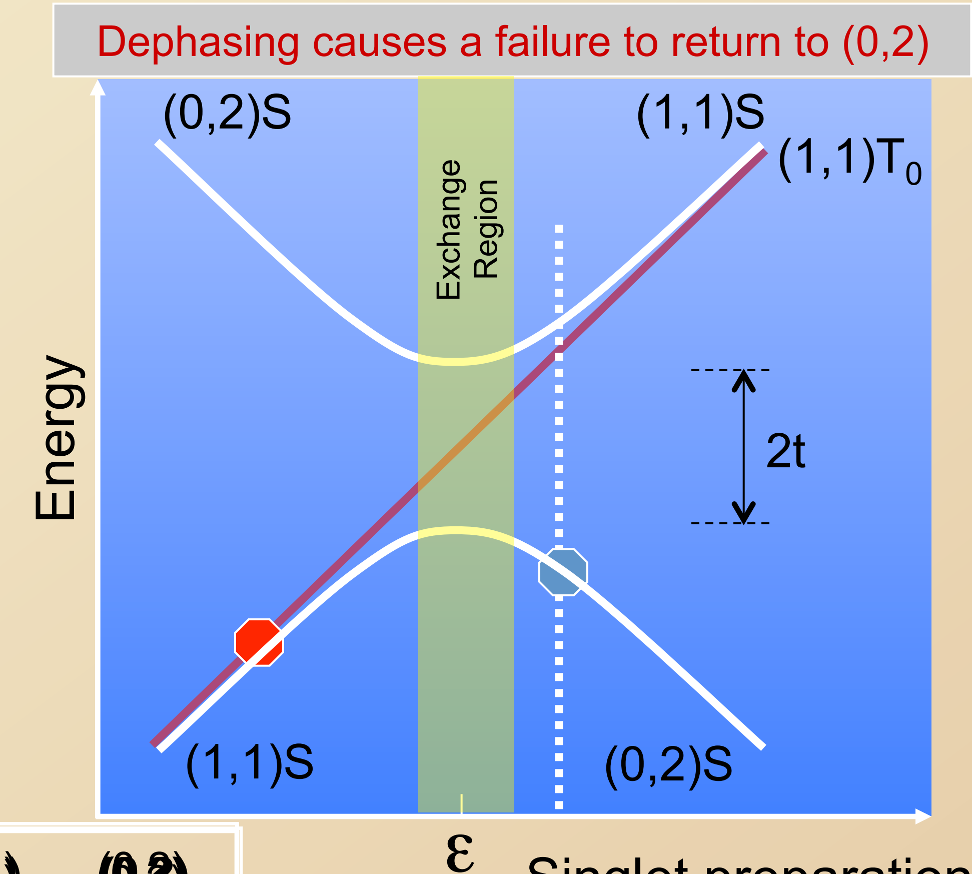


GaAs DQD Spin Qubits
Harvard – *Science* **309**, 2180 (2005)









- Singlet preparation
- Singlet separation
- Evolution
- Projection
- Reset

Slide courtesy M. Biercuk

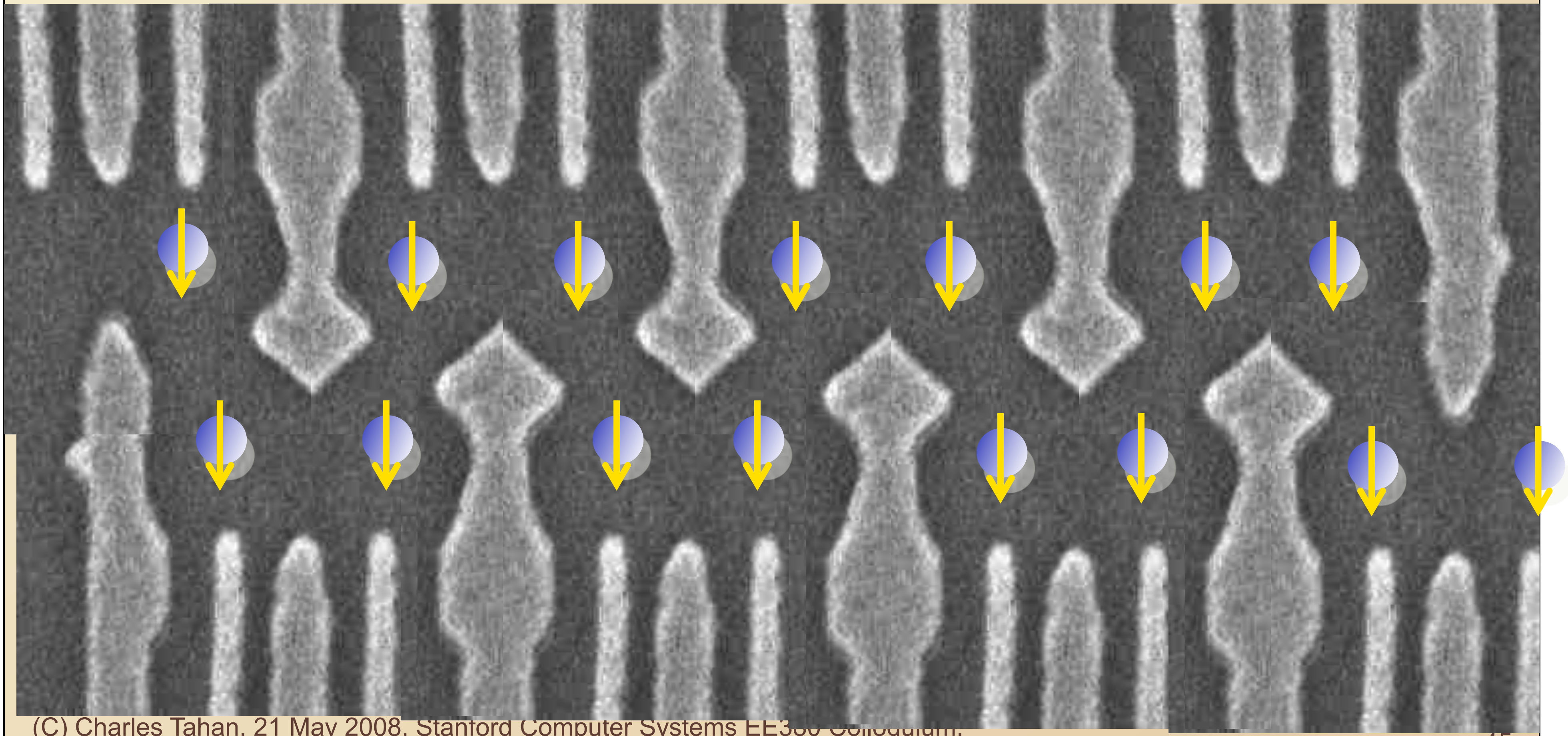
Petta *et al.*, *Science* **309**, 2180 (2005).

(C) Charles Tahan, 21 May 2008, Stanford Computer Systems EE380 Colloquium, Available at http://www.tahan.com/charlie/

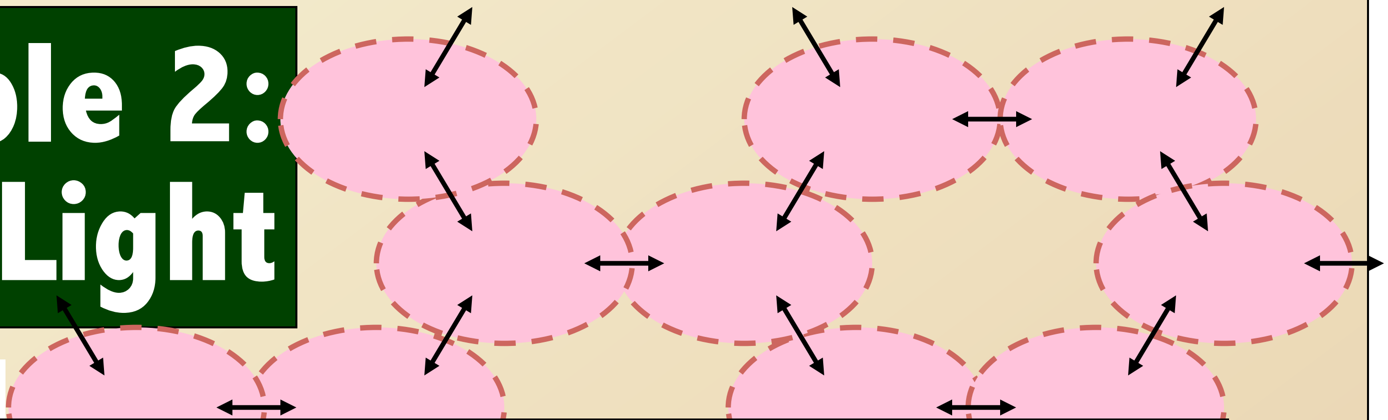
Powerpoint is great isn't it?

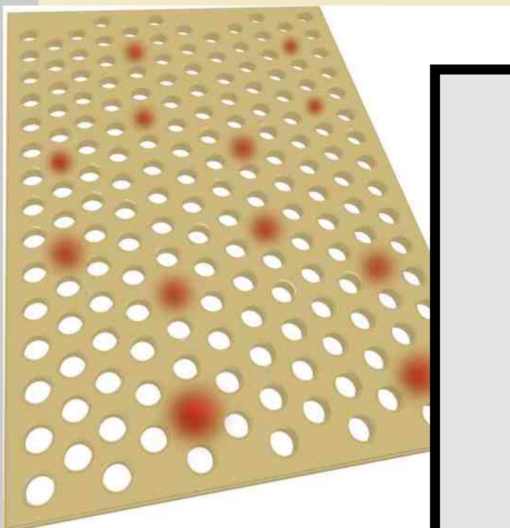
- Quantum dot quantum computer

The glory of being a theorist.



Example 2: Solid Light





Engineer **a system where photons will interact strongly and exhibit quantum many-body dynamics in an interesting and perhaps useful way.**

icle

1. Array o
2. Each c
3. Couple
4. Photon interaction mediated by 2LS nonlinearity

With Andy Greentree et al., University of Melbourne (Nature Physics '06)

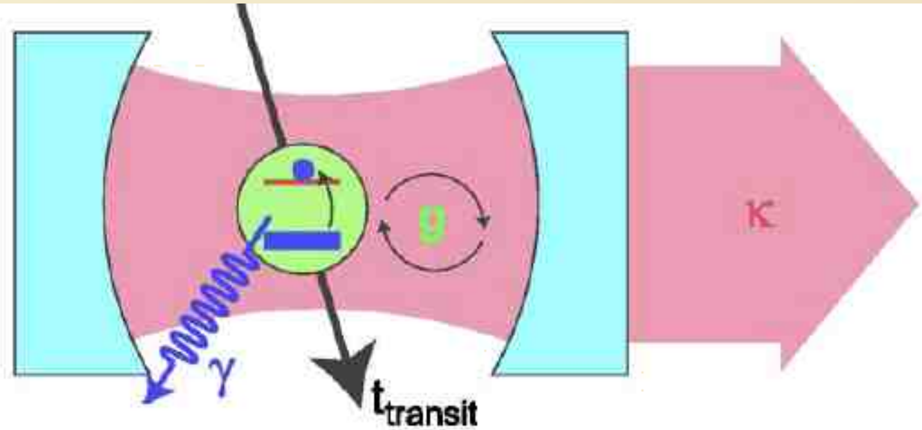
The New Idea

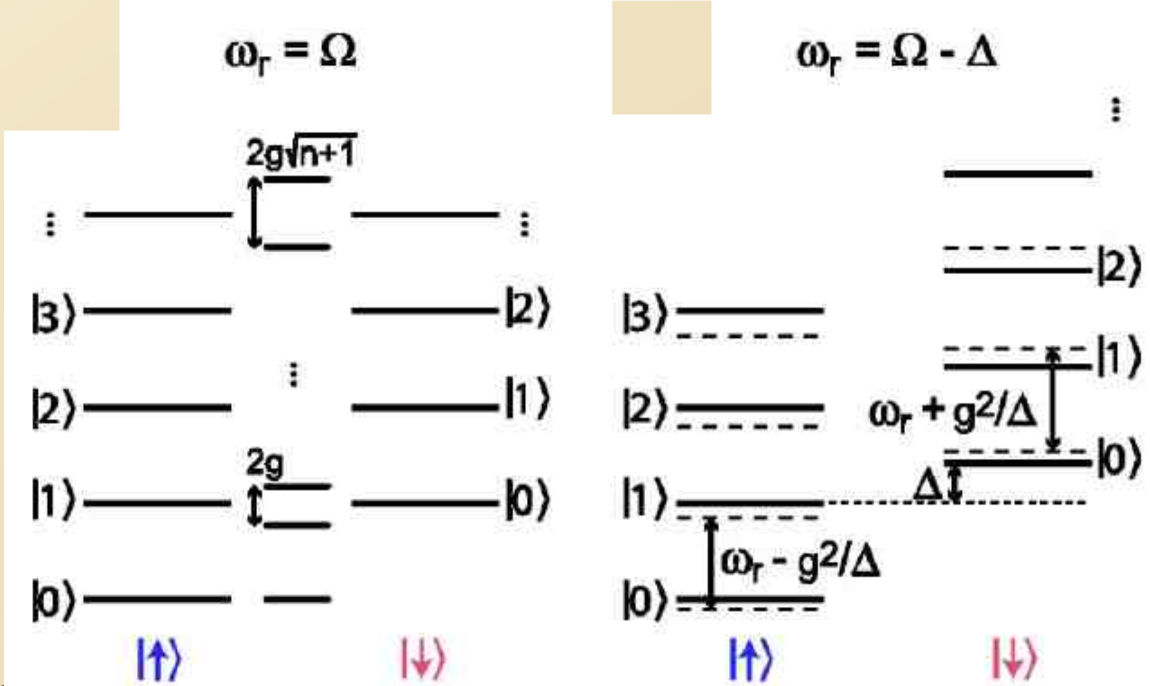
Photons…

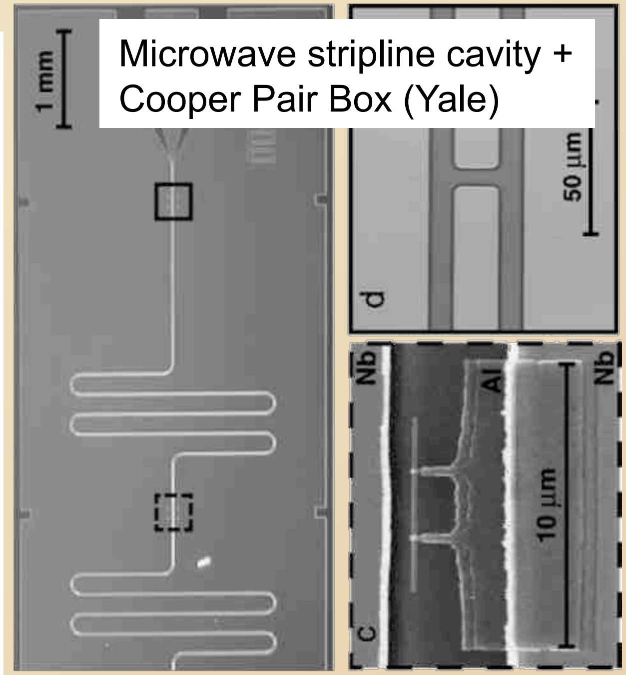
1. Don't interact with each other much
2. Great for communication, not for computation
3. Aren't conserved (created or destroyed at will)
4. Can be made coherent easily (lasers) - unlike matter
5. Can't exhibit the behavior that "strongly interacting" particles like electrons do

How can we make photons exhibit quantum many body behavior?

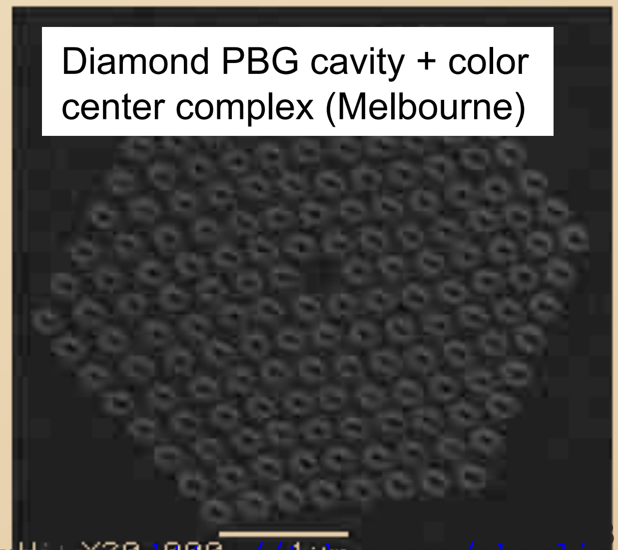
Cavity-QED: From atomic to solid-state







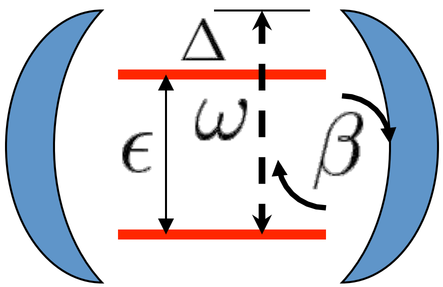
Microwave stripline cavity + Cooper Pair Box (Yale)



Diamond PBG cavity + color center complex (Melbourne)

Background

Cavity-QED: From atomic to solid-state

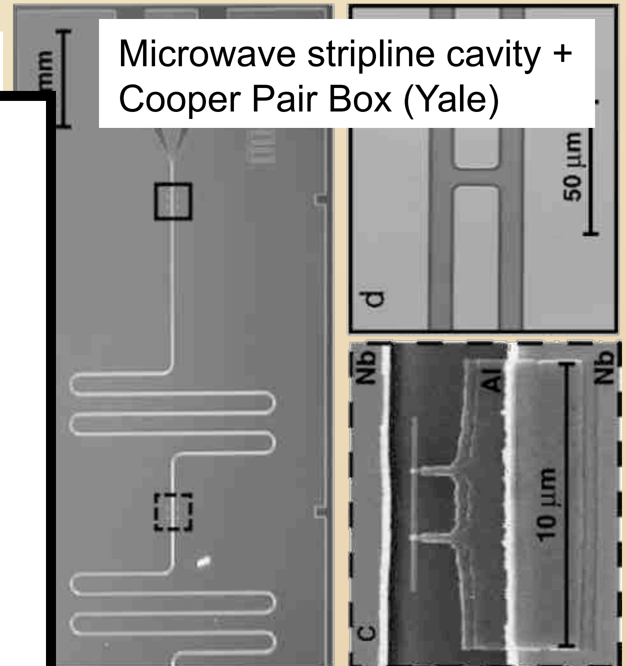


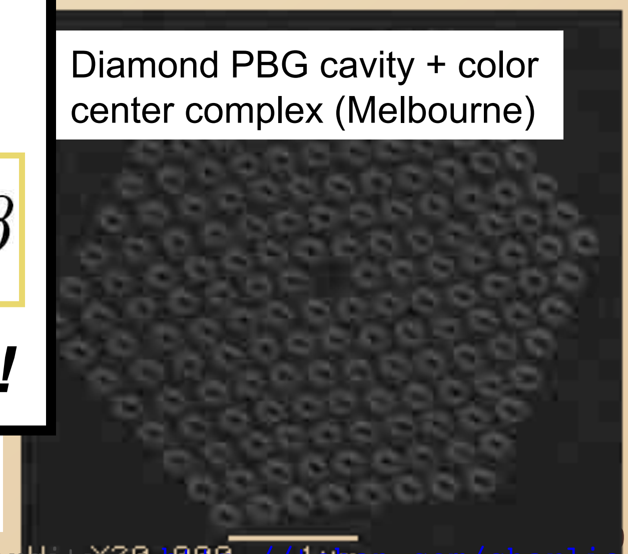
Matter-induced photon-photon nonlinearity

On-site repulsion, U:

$$U(n, \Delta = 0) = \left(\sqrt{n+1} - \sqrt{n}\right)\beta$$

photon blockade!

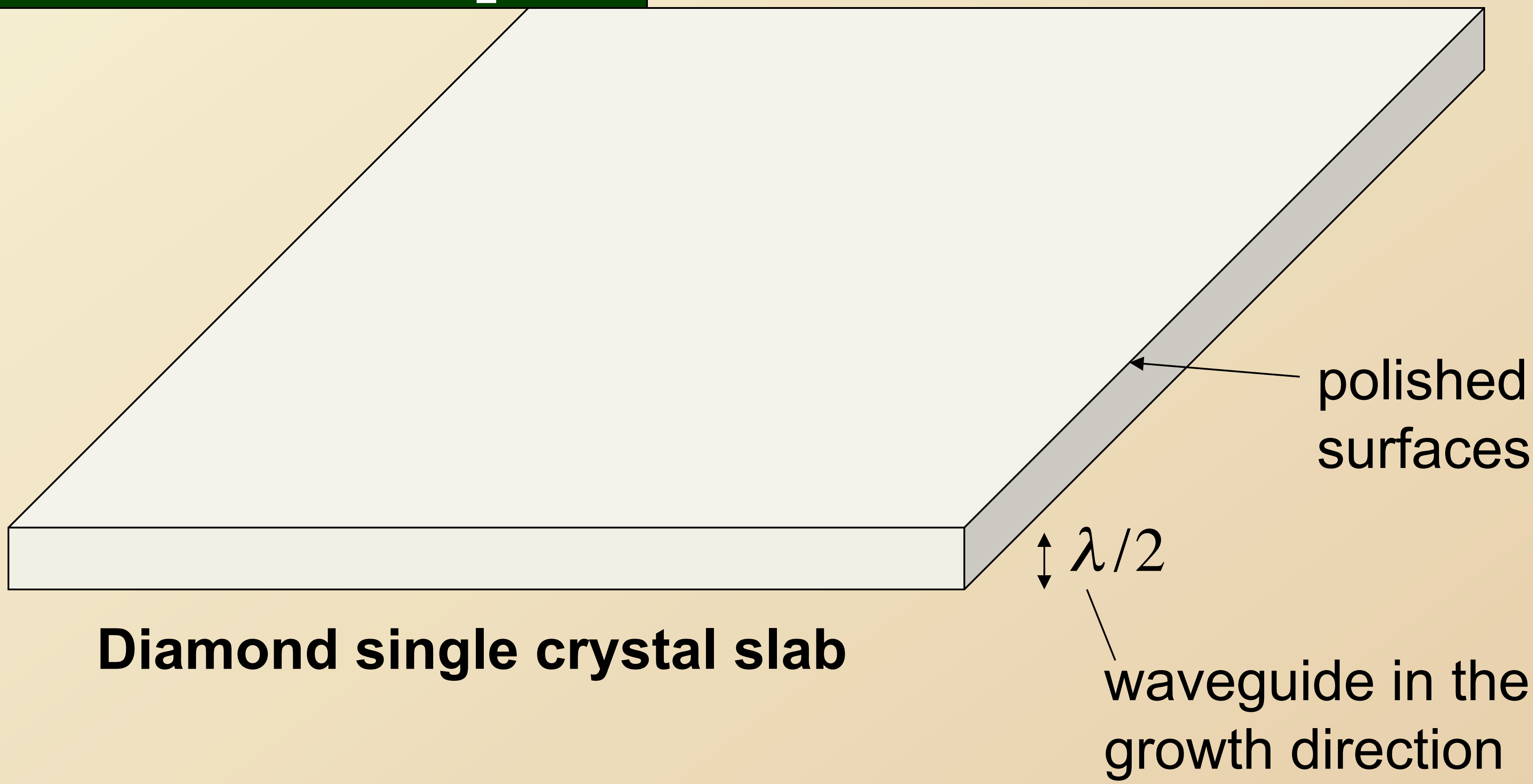




Background

Step 1

Photonic superlattice in a NV/Diamond photonic bandgap architecture



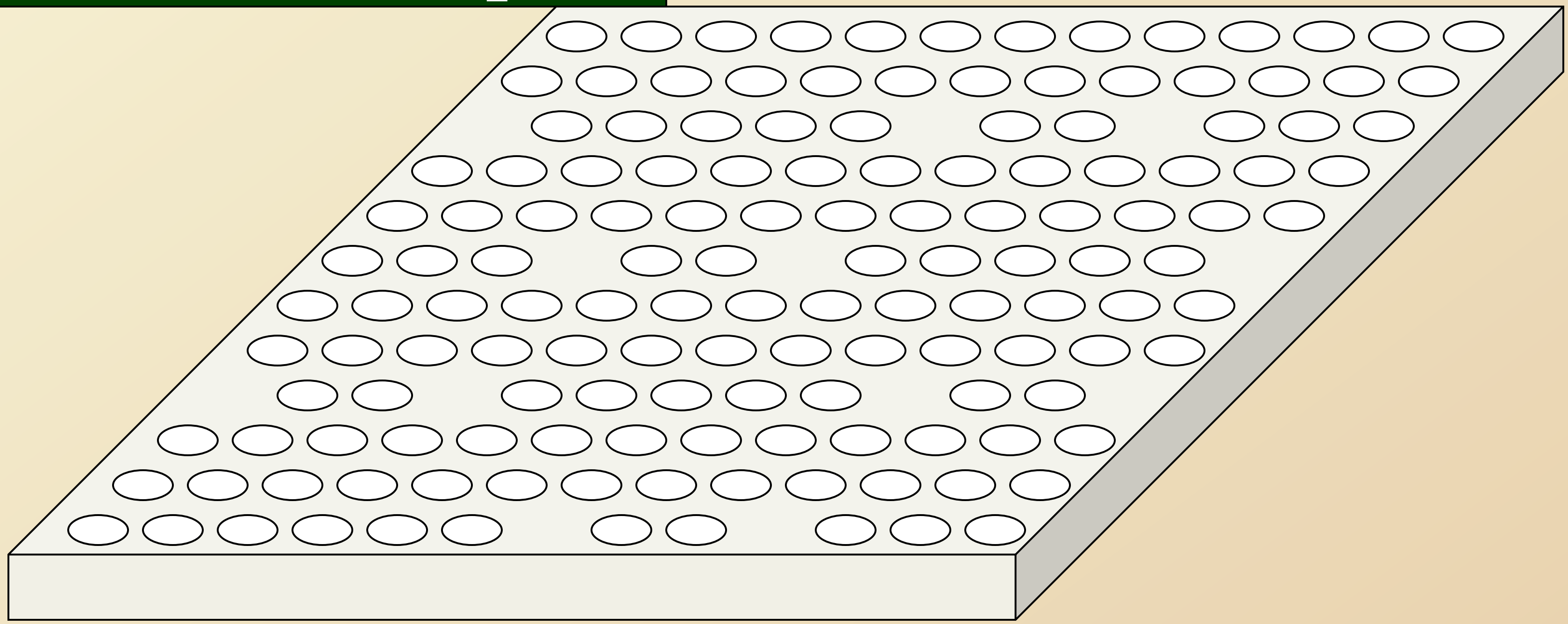
Diamond single crystal slab

An Implementation

An Implementation

Step 2

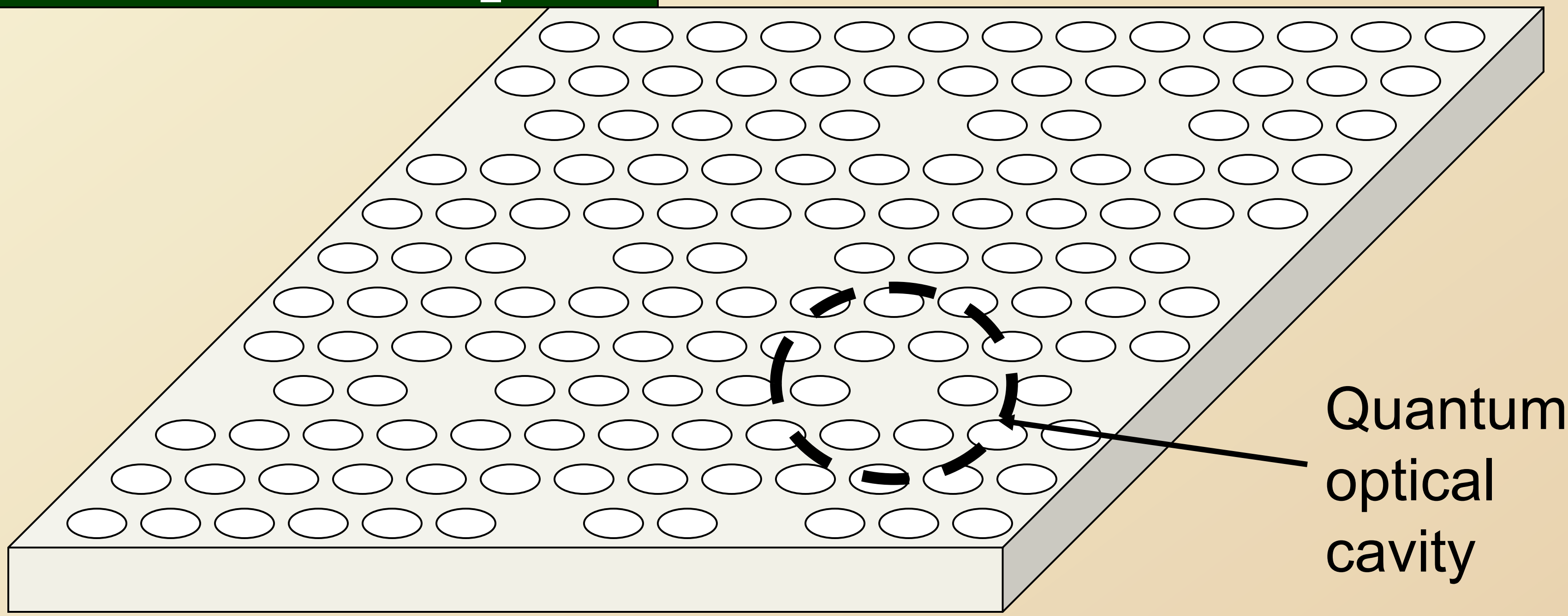
Photonic superlattice in a NV/Diamond photonic bandgap architecture



Drill holes selectively to create superlattice of defect-cavities (aka quantum optical cavities)

Step 2

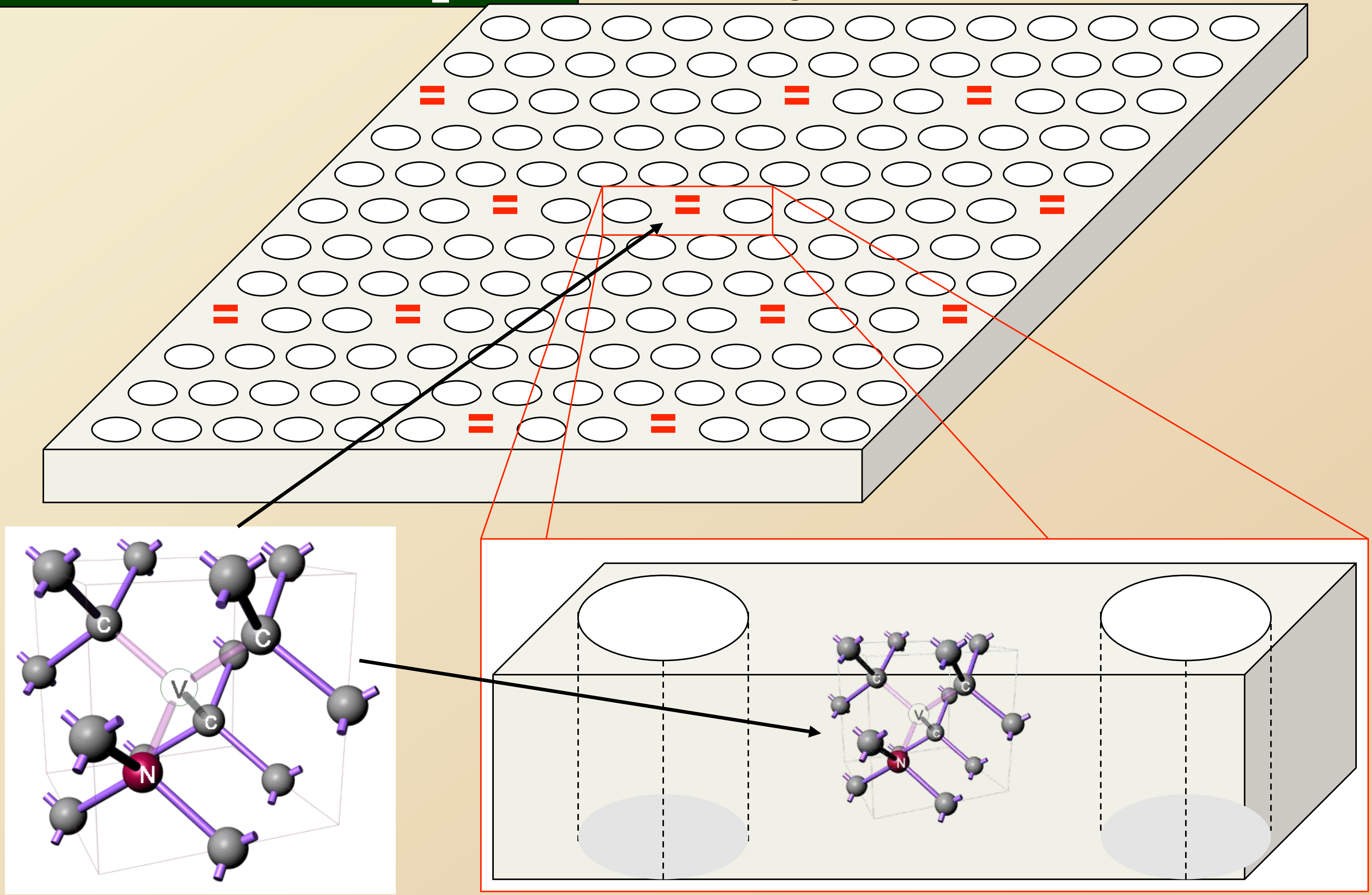
Photonic superlattice in a NV/Diamond photonic bandgap architecture



Drill holes selectively to create superlattice of defect-cavities (aka quantum cavities)

Step 3

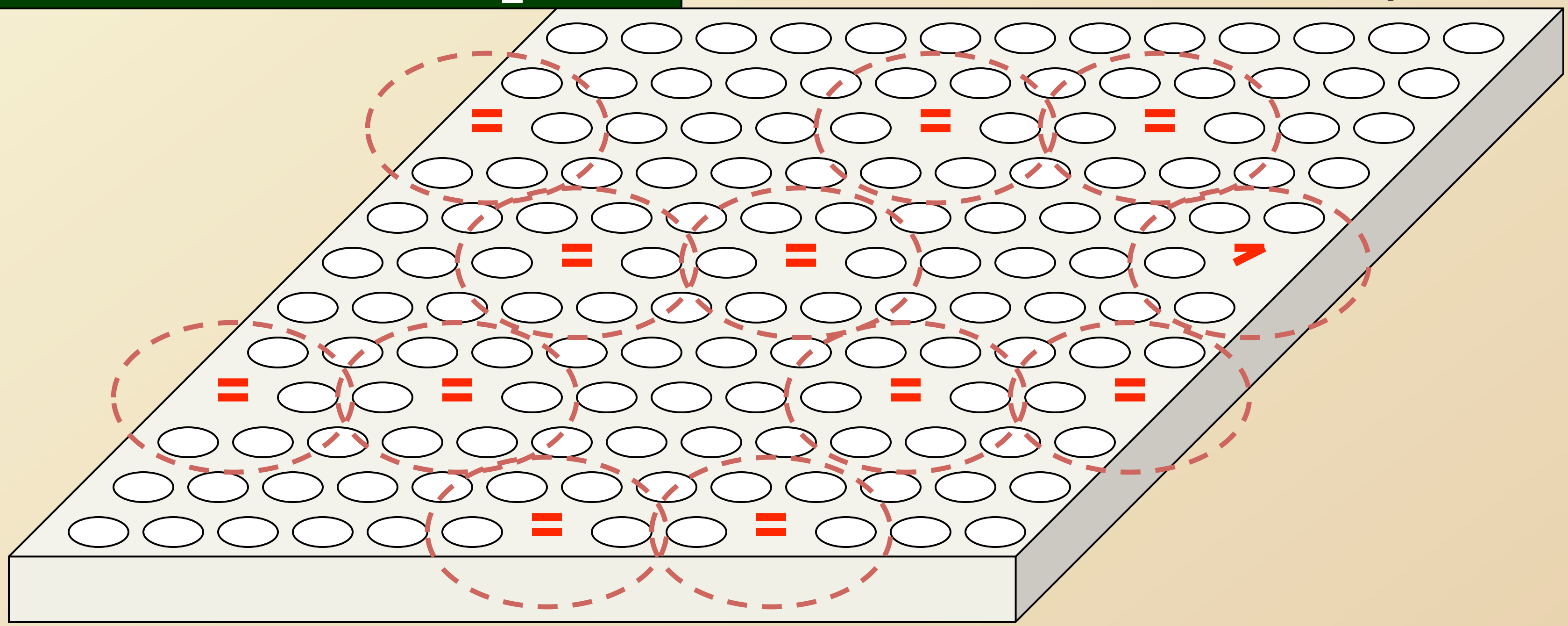
Create NV$^-$ complex in each cavity

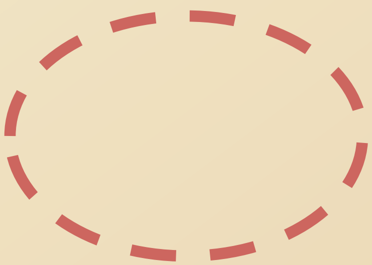


An Implementation

Step 4

Add photons (say with a coherent laser pulse)



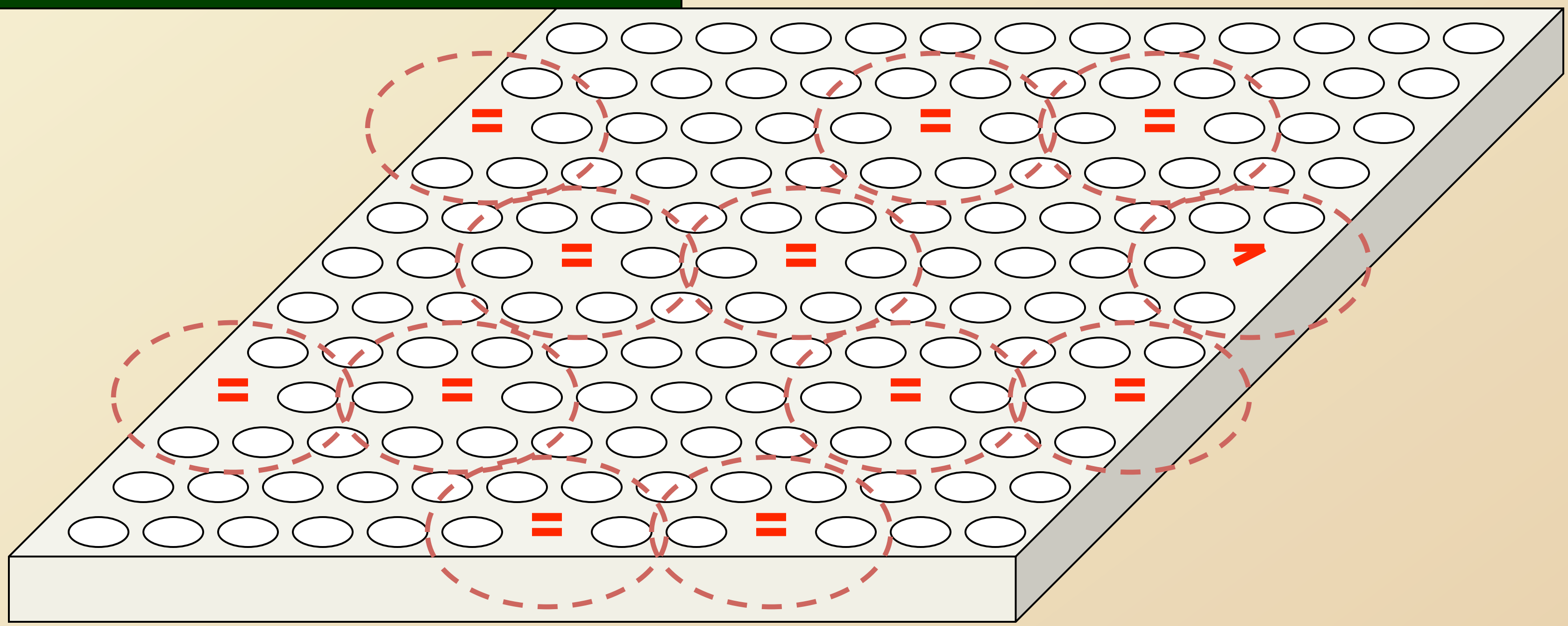


= Extent of dressed-atom photon trapped in each cavity.

Hopping is allowed to nearest neighbor cavities via evanescent coupling.

An Implementation

Hamiltonian



$$H = \sum_i H_i^{JC} + \sum_{\langle i,j\rangle} \kappa \left(a_i^\dagger a_j + a_j^\dagger a_i \right) - \sum_i \mu_i N_{\text{exc}}$$

photon hopping

conserved
tions

$$\mathcal{H}^{JC} = \underbrace{\epsilon \sigma_+ \sigma_-} + \underbrace{\omega a^\dagger a} + \underbrace{\beta \left(\sigma_+ a + \sigma_- a^\dagger \right)}$$

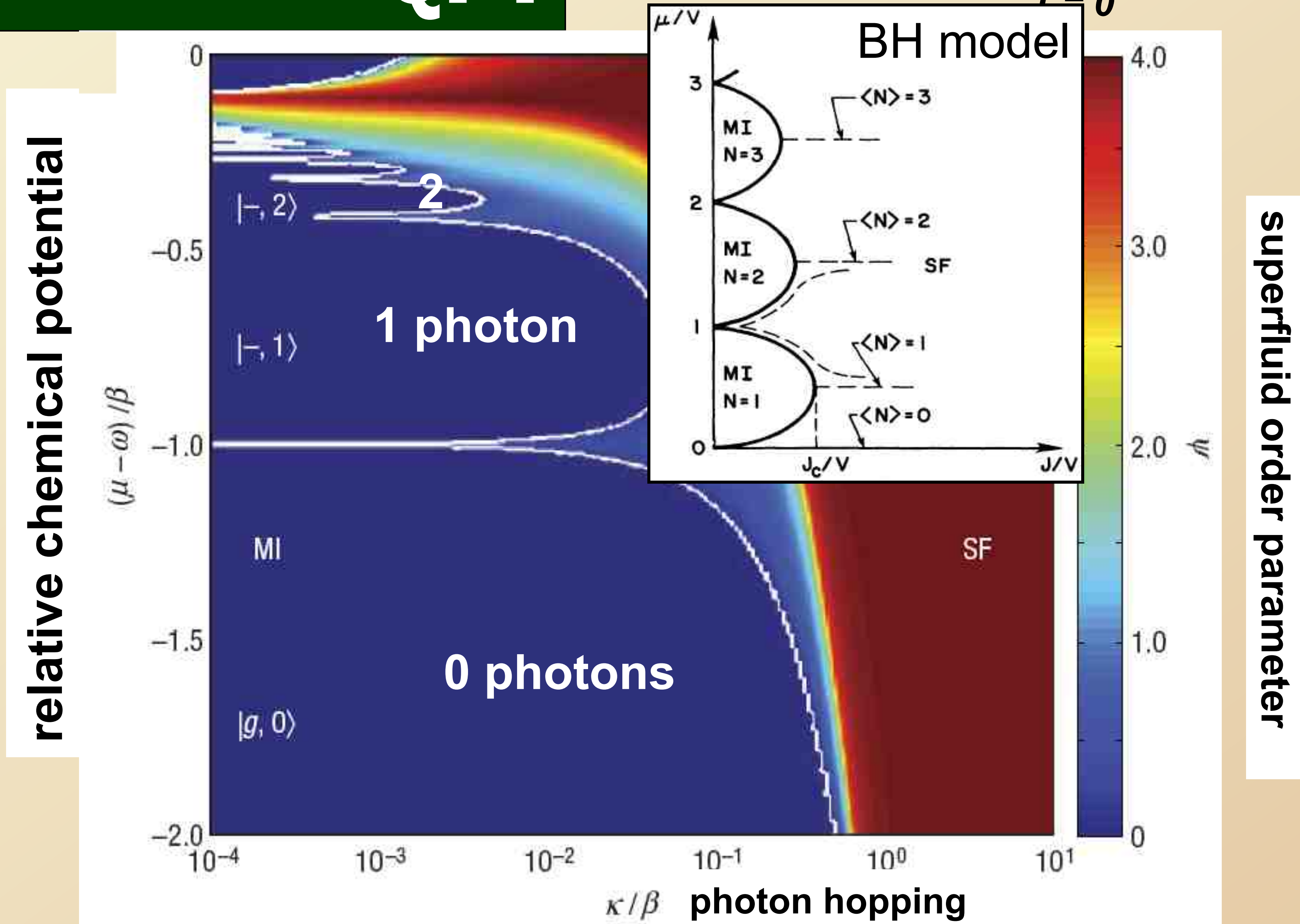
Jaynes-Cummings **two-level system** **photons** **atom-light coupling**

Physical Model

QPT

Theoretical Analysis

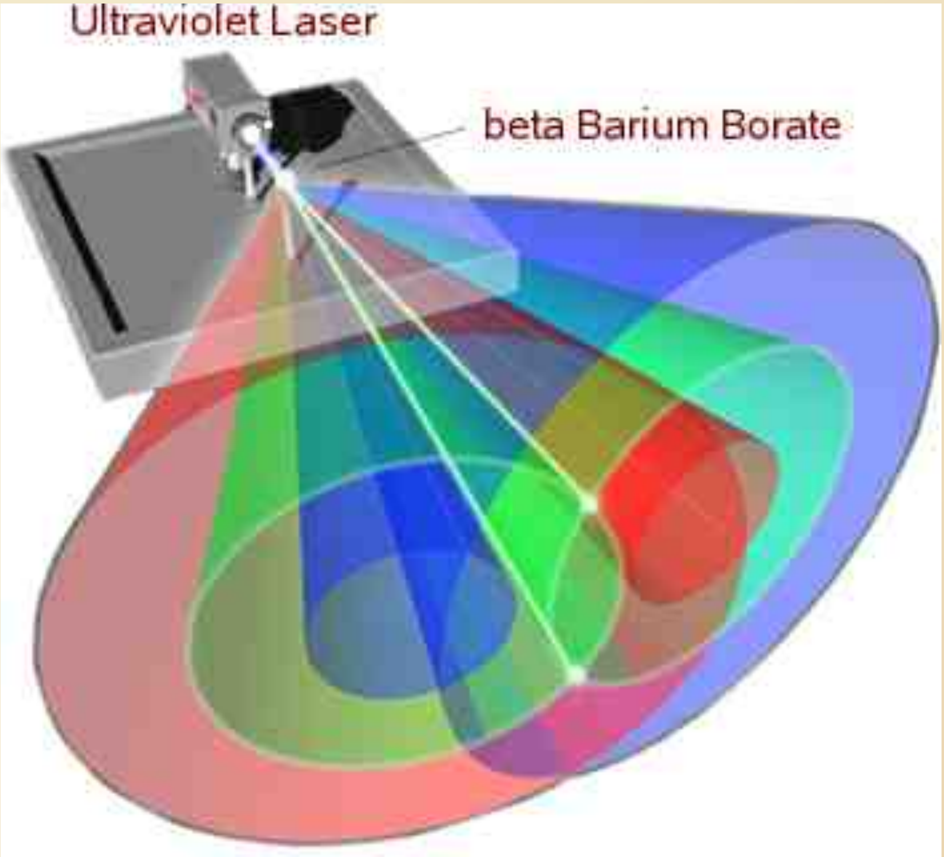
0 detuning
No disorder
T = 0



Impact

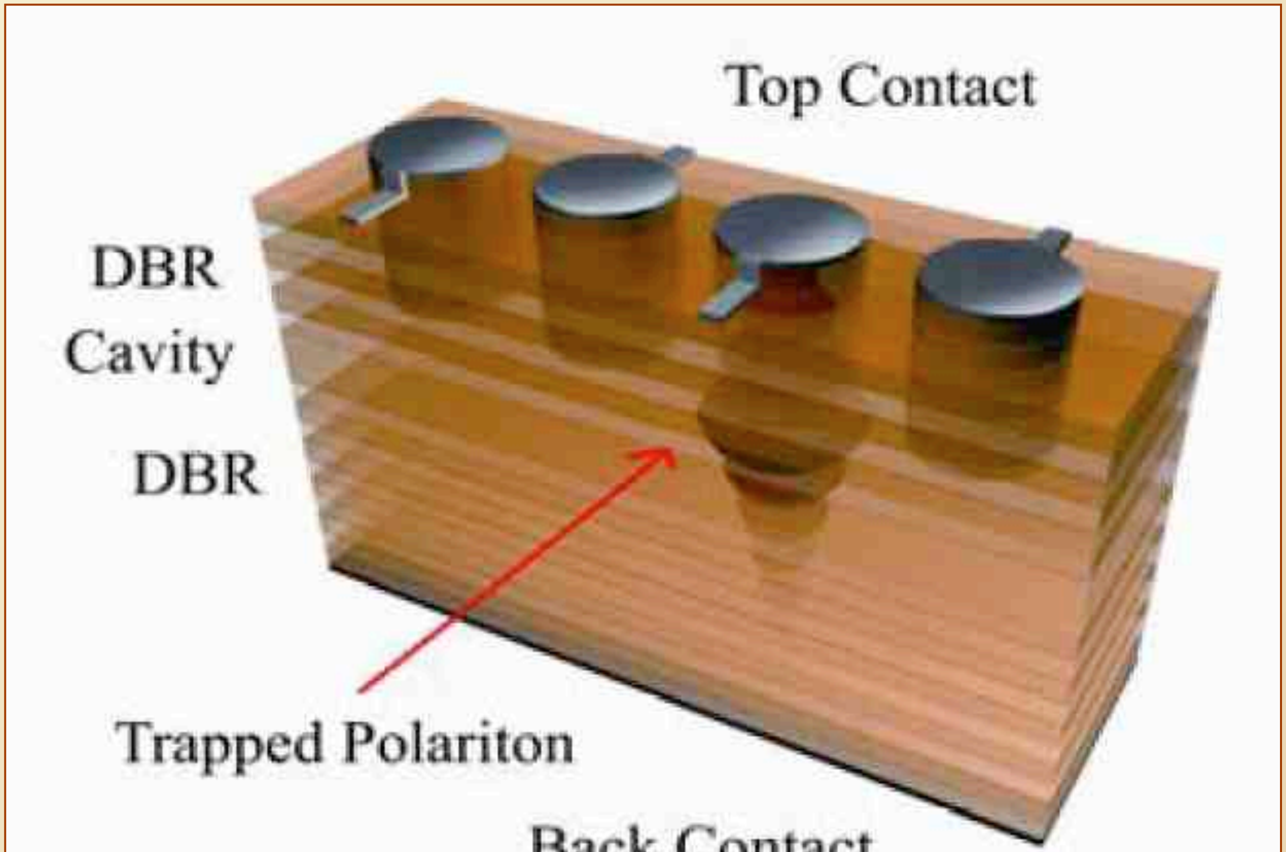
- "Engineered" quantum many-body interaction of photons (dressed)
- Predict gapped **Mott insulator phase (exactly *n* photons per site)** to superfluid transition
- Each site directly accessible (cavity volume comparable to wavelength of light) - optical fiber probe?
- **Possible uses: quantum simulator (very tunable); loading of many single photon sources; ?**
- IMPLEMENTATIONS: InAs QDs in PBGs, microwave strip-line cQED arrays, Rb atom arrays in high-Q superconducting cavities; NV/diamond, microcavities

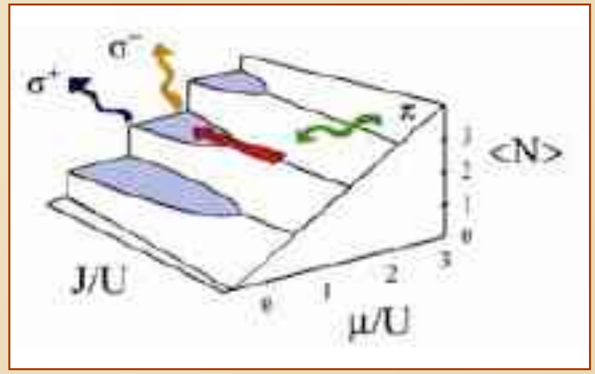
Generating entangled photons



1. An ultraviolet laser sends a single photon through Beta Barium Borate.
2. As the photon travels through the crystal, there is a chance it will split.
3. If it splits, the photon will exit from the Beta Barium Borate as two photons.
4. The resulting photon pair are entangled.

“Entangled-Pair Shotgun”



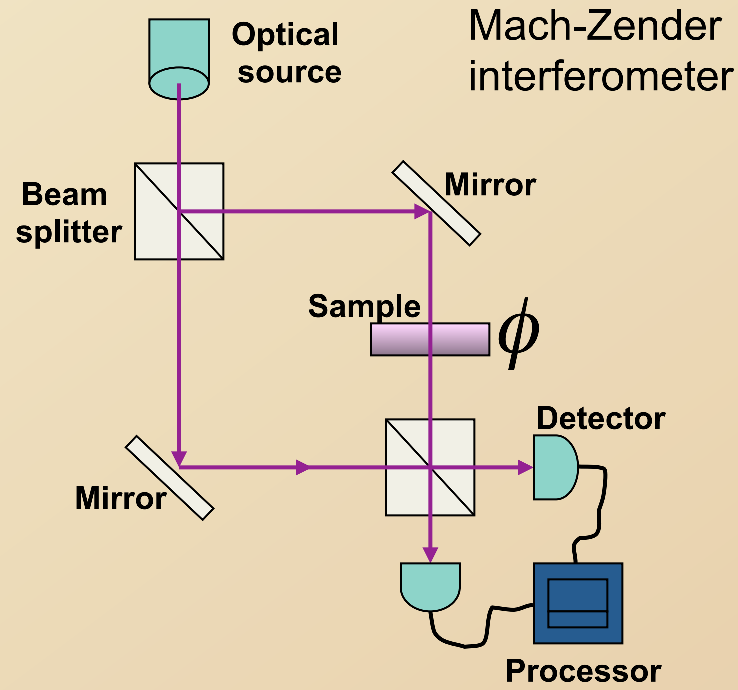


Neil Na and Yoshi Yamamoto, *Stanford*

FIG. 5. Phase diagram of the Bose-Hubbard model (not to scale). The system is first pumped by a linearly-polarized (π) external laser, and then followed by a δ switching indicated by the red arrow. Subsequent dual electric field control triggers polarization-entangled photon-pairs that are circularly-polarized (σ).

Example 3: Phase estimation

- **Precision measurement of length, displacement, speed, optical properties, etc.**
- **Primitive or subroutine for quantum algorithms (like Shor's)**
- **Using phase for communication, etc.**



Quantum tricks can reduce the number of photons needed by SQRT(N)

Source:
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Almost done

Quantum Overview
Technology
Quantum Information
Devices

"Nanotechnology and Society"
Where I'm coming from
Science and Tech Studies
Defining "nano"
Sociology, Government, Historical Context

Context
What I was working on
Intro to Quantum Information

Physics
Quantum Devices
Cond-mat
Q.Info

Preparing for the future
Wrap-up
Creating it
Competition
6 months on

Spookytech
My proposal
Motivation and Justification
Reaction
Alternatives
Discussion

Examples
Silicon Quantum Computing
Quantum Metrology
Solid Light

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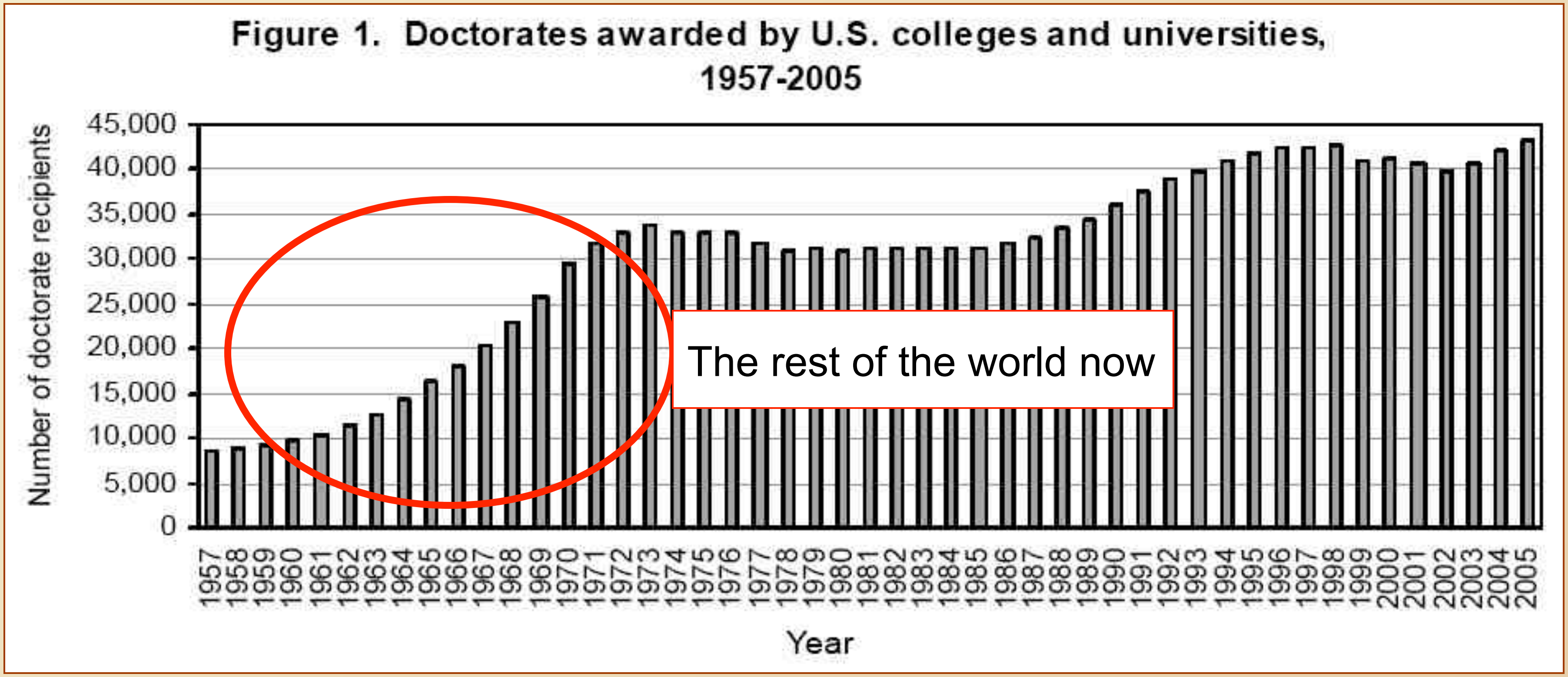
The US then, the world now



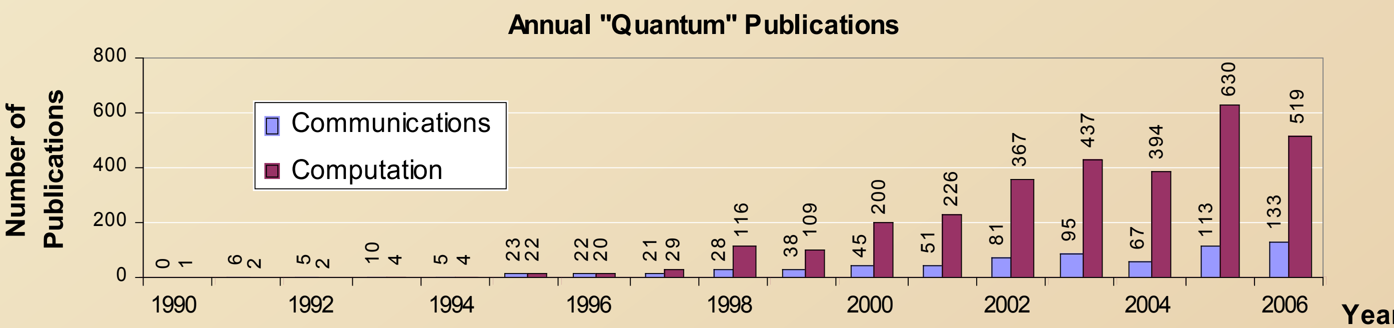
Quantum Information Activity Worldwide

Published References by Region
<u>Quantum Communications</u>

N. America	Europe	Asia
199	390	189

Published References by Region
<u>Quantum Computation</u>

N. America	Europe	Asia
1051	1256	555



Results based on ISI Web of Science search for publications containing the phrases “quantum computat*,” “quantum bit,” “qubit,” or “quantum informat*,” from 1990-2006.

Results based on ISI Web of Science search for publications containing the phrases “quantum cryptography,” “quantum key,” “QKD,” or “quantum communicat*,” from 1990-2006.

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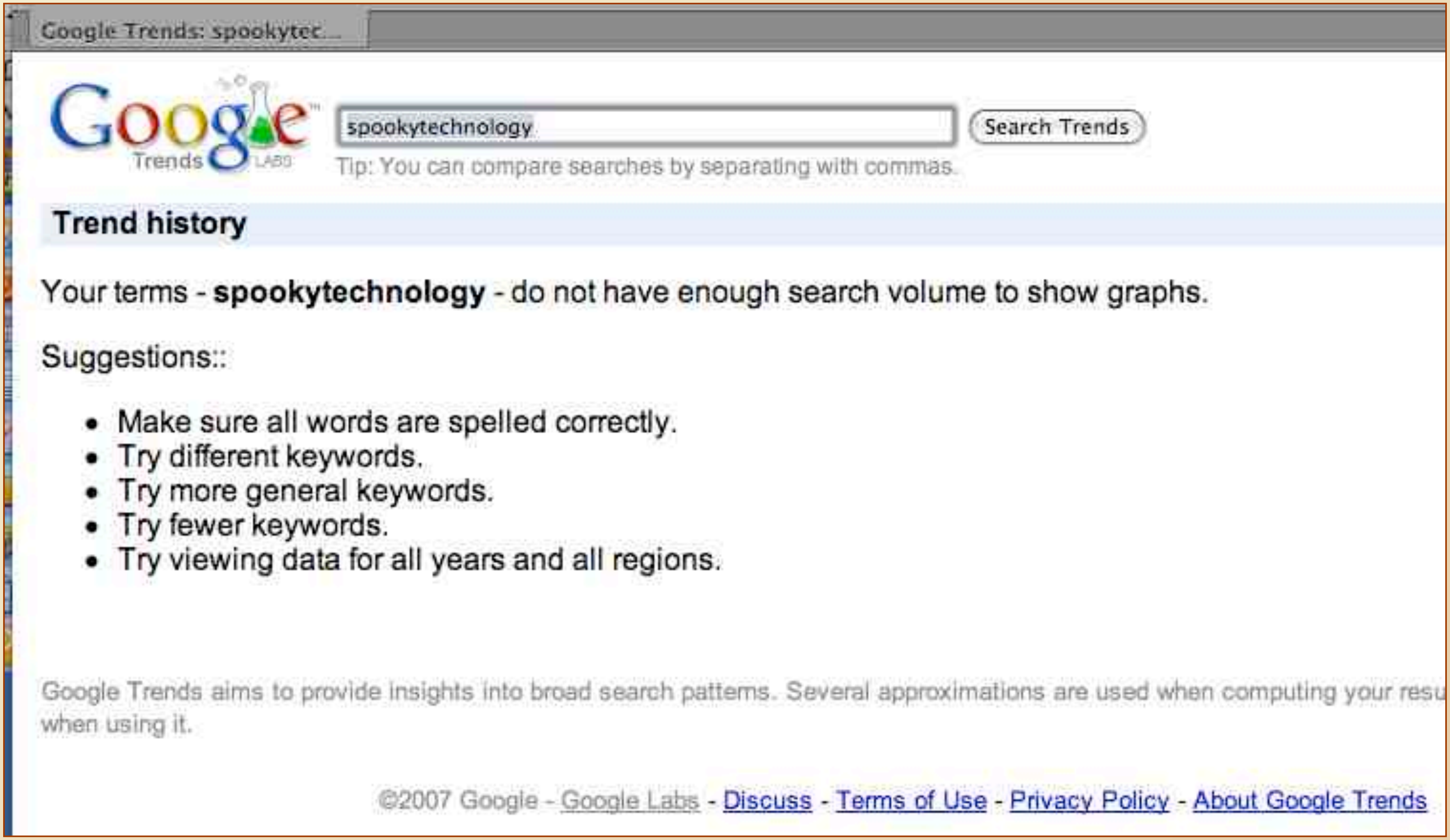
6 months later: the sound of crickets chirping on the internet



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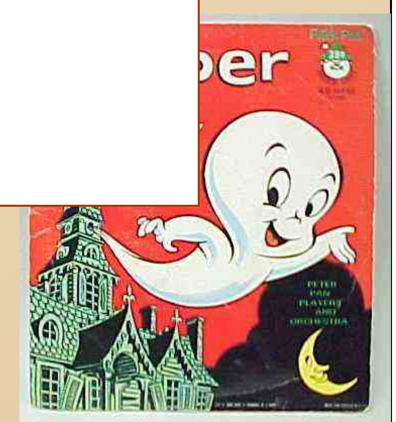
The end

- More information:
  - http://www.tahan.com/charlie/

It is not only the speed of technological change that creates a "revolution," it is its scope as well. Above all, today, as seven thousand years ago, technological developments from a great many areas are growing together to create a new human environment. (Drucker, 1965)



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