From bits to qubits: a quantum leap for computers

Susan Coppersmith

University of Wisconsin-Madison
Department of Physics

Susan Coppersmith career path: it felt like I was muddling along.

B.S. from MIT

Ph.D. from Cornell

→married in grad school
husband obtained MD-PhD, then did medical internship, residency, and fellowship

Postdocs at Brookhaven National Laboratory
and AT&T Bell Laboratories

Visiting lecturer at Princeton

Member of Technical Staff at AT&T Bell Laboratories

→husband finished training

Professor at University of Chicago

→daughter was born

Professor at University of Wisconsin-Madison

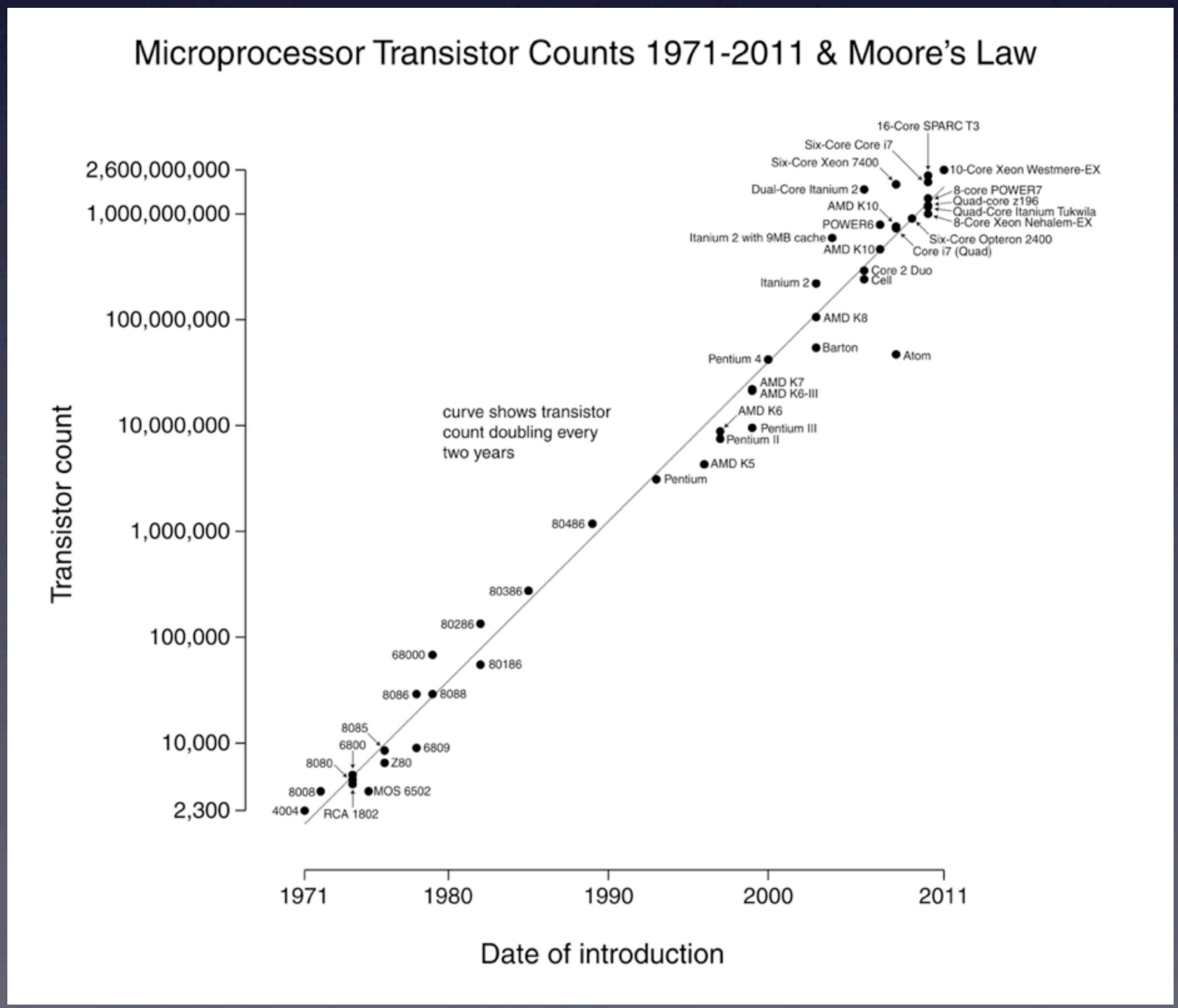
Exposure to a variety of environments has been a big plus. Coordination with family has been challenging but rewarding.

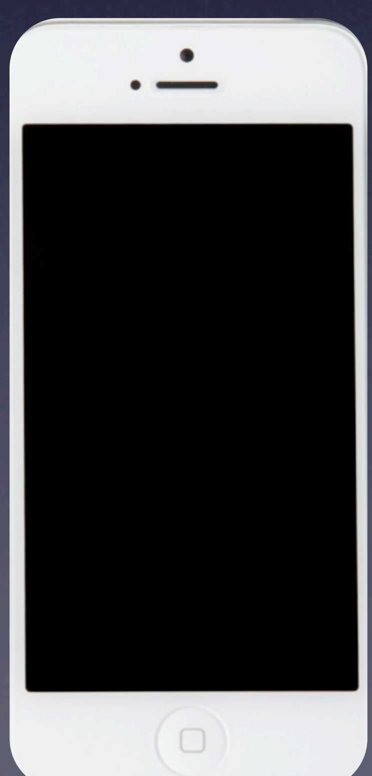
Main advice: work with people you like, on things that you find really interesting.

Since before 1960, the capabilities of digital electronic devices have grown exponentially

Regency TR-1 transistor radio (1954)
4 transistors
$49.95, equivalent to $427 today

from Wikipedia



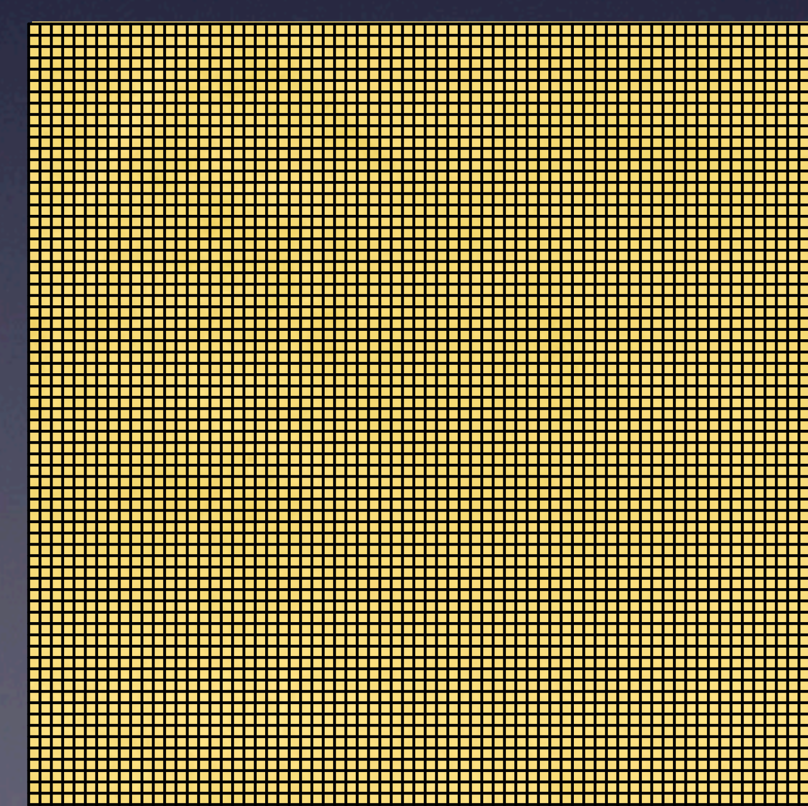


iPhone 5s
~100,000,000 transistors
$620 (unlocked)

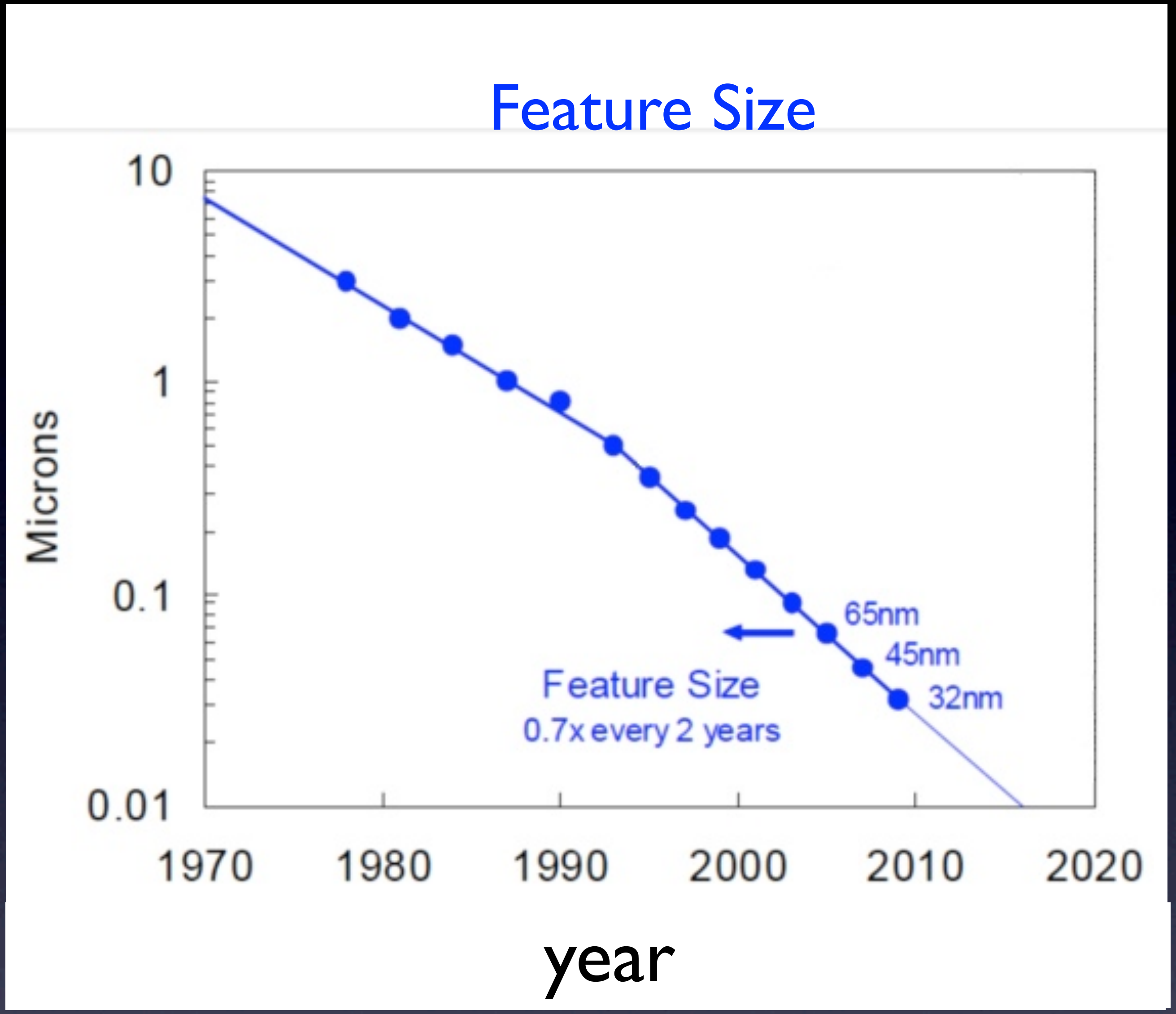
The numbers of transistors in a device has kept increasing because the area per transistor has been shrinking.

1970: ~200 transistors per square millimeter

2011: >1,000,000 transistors per square millimeter



Transistor sizes continue to shrink with time.

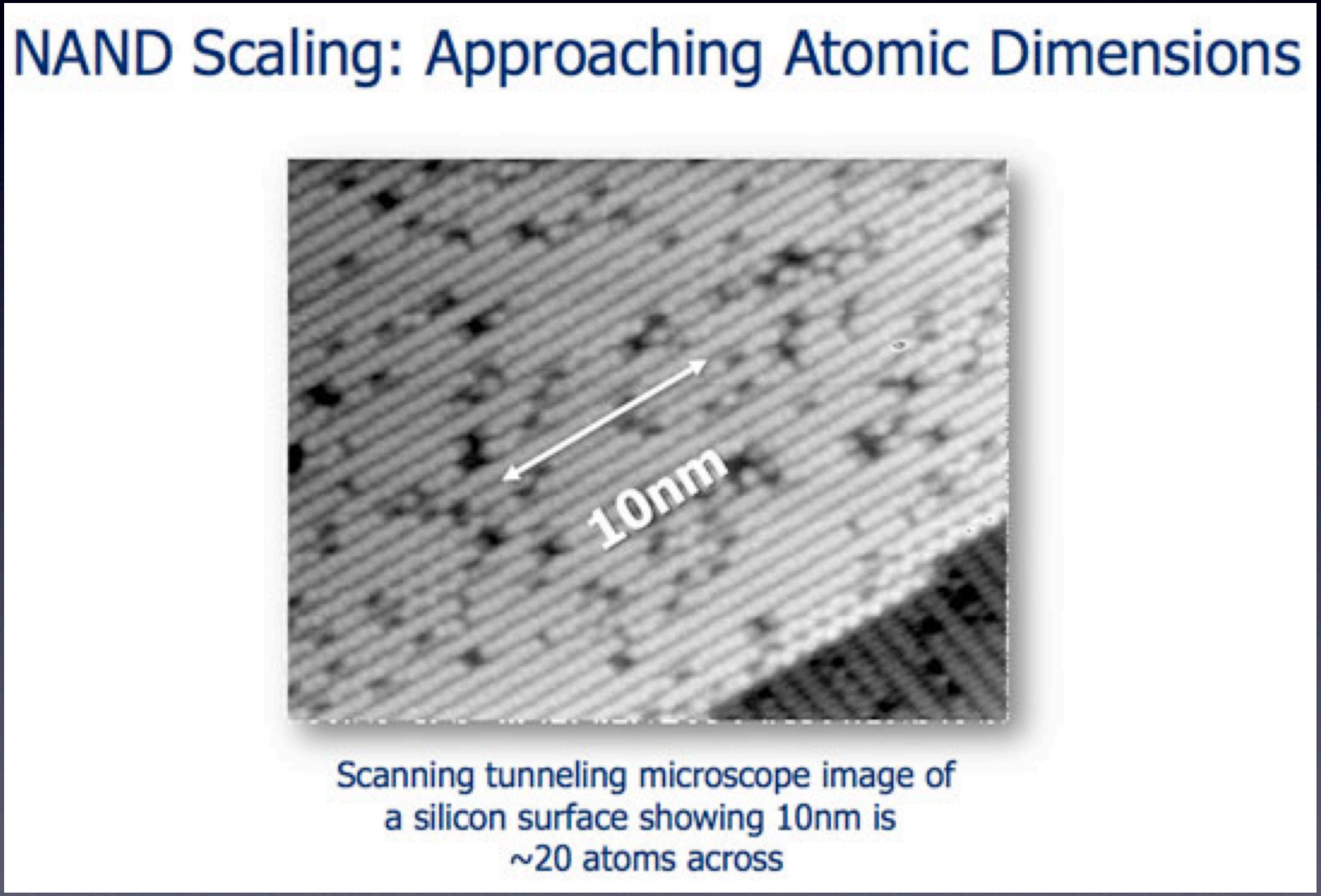


K. Kulin, Proceedings of IWCE '09.
13th International Workshop on
Computational Electronics, 2009

New Intel 2013 fab facility:
feature sizes of 14 nanometers

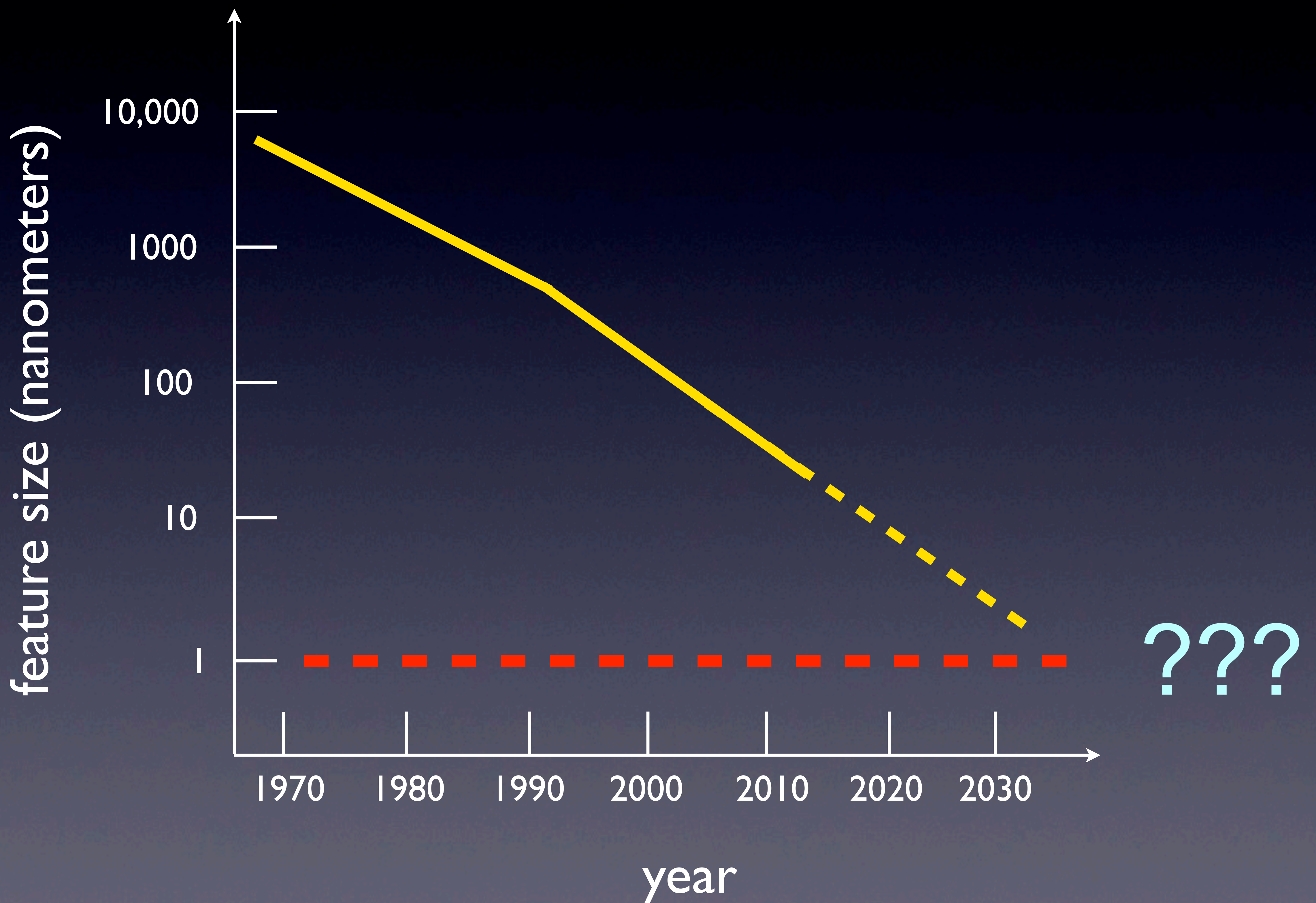
But transistors cannot shrink indefinitely!

Current transistor sizes are only a few times the size of atoms. It is impossible to shrink transistors to be smaller than the size of one silicon atom.



http://www.anandtech.com/show/2928

Feature sizes cannot shrink past one nanometer, the size of one silicon atom. What happens then?

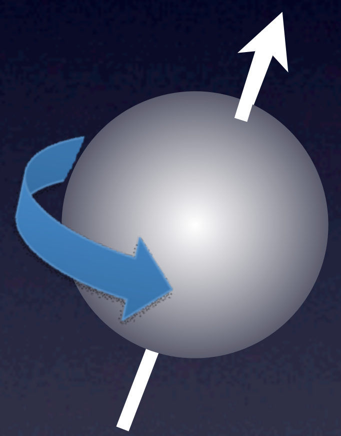


Eventually, it will not be feasible to make computers faster by shrinking the size of transistors.

But at the smallest sizes possible, it may be possible to make computers faster by exploiting the fundamental laws of physics.

Behavior on small length scales is governed by the laws of quantum mechanics, which are different from the laws of classical mechanics that govern objects in everyday life.

Example: a spin



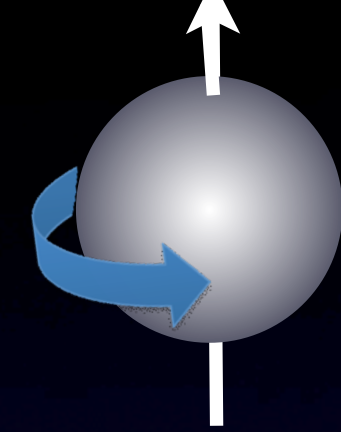
Classical mechanics: a measurement of the value of a component of spin can take any in a range of values.

Quantum mechanics: The results of possible measurements are quantized − they only take on one of a finite set of values.

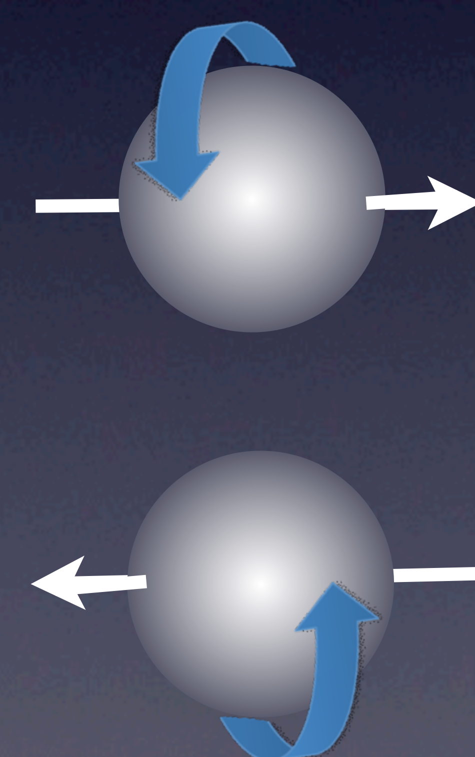
For an electron: each measurement of the spin yields one of only two values. We'll call them $\hbar/2$ and $-\hbar/2$.

Measurements of electron spins yield only two values, $\hbar/2$ and $-\hbar/2$.

An experimental procedure can prepare spins, each of which yields the result $\hbar/2$ for a measurement of spin along a certain axis ("the spin is along the z axis").



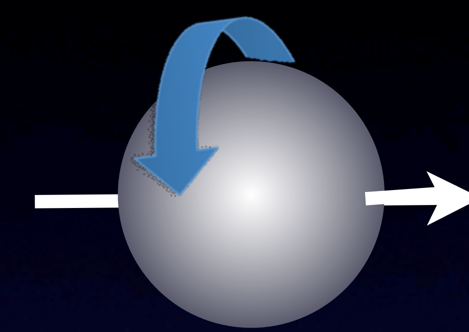
If you prepare the spins the same way and measure along a perpendicular axis, half the spins will yield the result $\hbar/2$ and half will yield the result $-\hbar/2$.



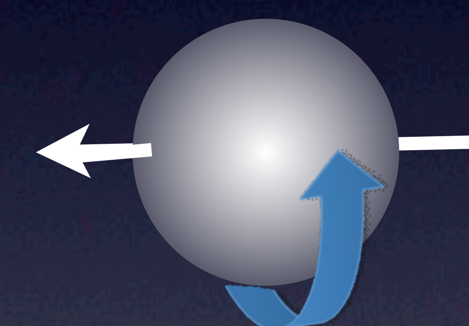
Stern-Gerlach experiment (1922)

In quantum mechanics, a measurement changes the quantum state ("the quantum state collapses")

If you prepare a population of electrons, all in a given spin state in which half the electrons, when measured along a certain axis, have spin ħ/2 and the other half have spin -ħ/2.



If you measure any of those electrons along that axis a second (or third, or fourth...) time, you will always get the same answer!

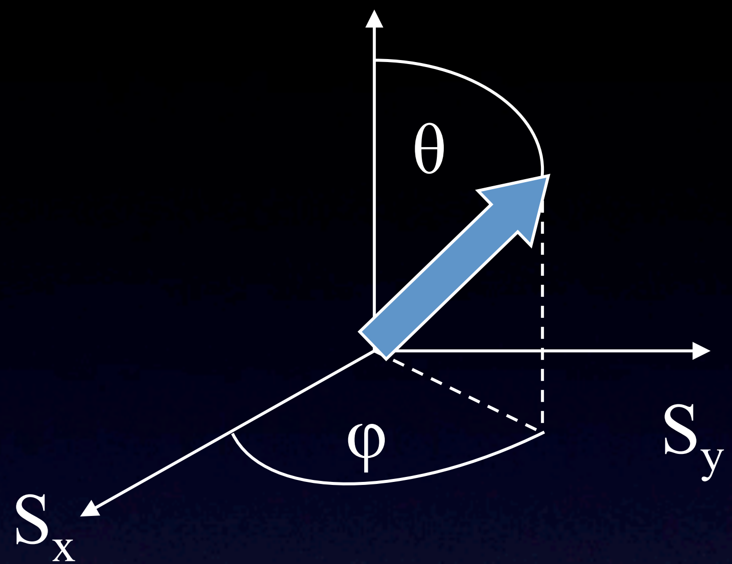


measurement #	electron 1	electron 2	electron 3	electron 4
1	+ ħ/2	- ħ/2	- ħ/2	+ ħ/2
2	+ ħ/2	- ħ/2	- ħ/2	+ ħ/2
3	+ ħ/2	- ħ/2	- ħ/2	+ ħ/2
4	+ ħ/2	- ħ/2	- ħ/2	+ ħ/2
5	+ ħ/2	- ħ/2	- ħ/2	+ ħ/2

Why care about the laws of quantum physics?

A quantum computer that exploits the laws of quantum physics could perform some calculations much faster than the classical computers that we have now.

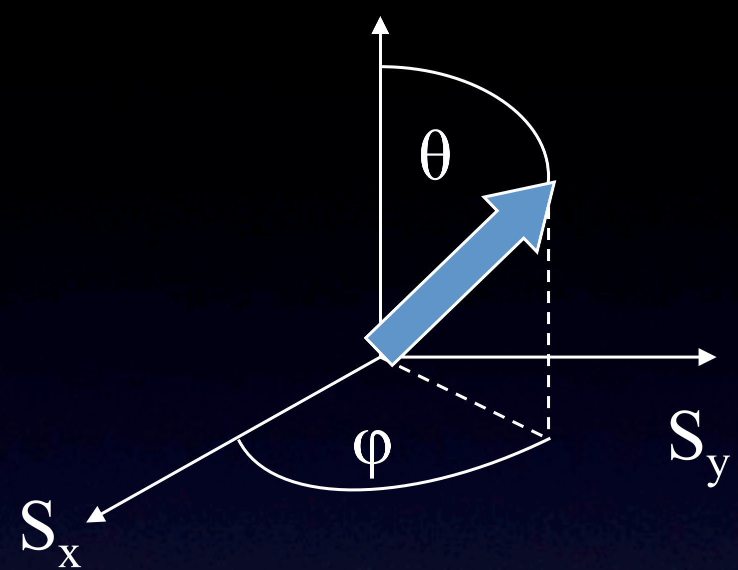
Bits versus qubits: classical versus quantum spins



$$\vec{S} = S_x\hat{i} + S_y\hat{j} + S_z\hat{k}$$

Classical spin: specified by 3 continuous variables. Can measure S_x, S_y, and S_z simultaneously. Each has a range of possible values.

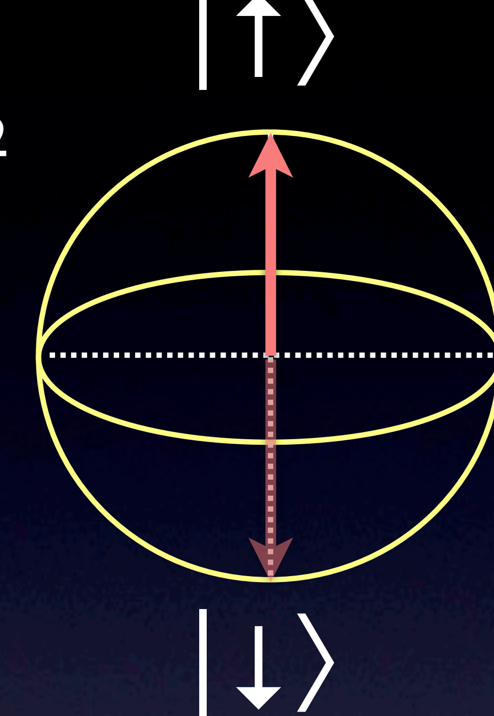
Bits versus qubits: classical versus quantum spins



$$\vec{S} = S_x\hat{i} + S_y\hat{j} + S_z\hat{k}$$

Quantum spin: can only simultaneously specify S^2 and (say) S_z.

Values are quantized.



Classical spin: specified by 3 continuous variables. Can measure S_x, S_y, and S_z simultaneously. Each has a range of possible values.

e.g., for $S^2 = \frac{3}{4}\hbar^2$,

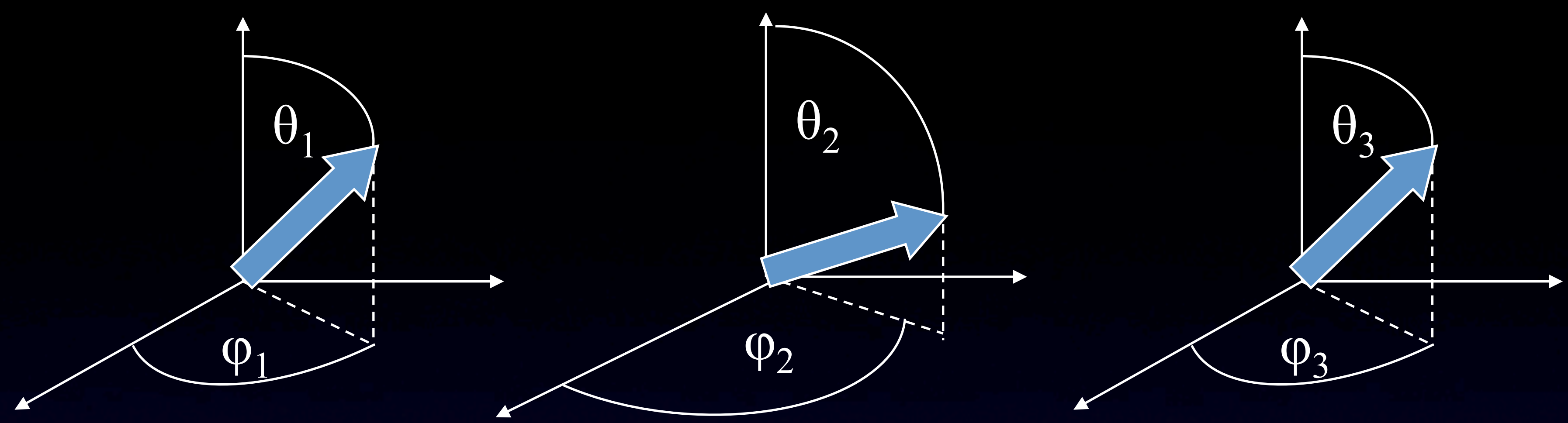
all measurements of S_x, S_y, and S_z yield either $\hbar/2$ or $-\hbar/2$.

Qubit:

$$|0\rangle \Leftrightarrow S_z = -\frac{\hbar}{2}$$

$$|1\rangle \Leftrightarrow S_z = \frac{\hbar}{2}$$

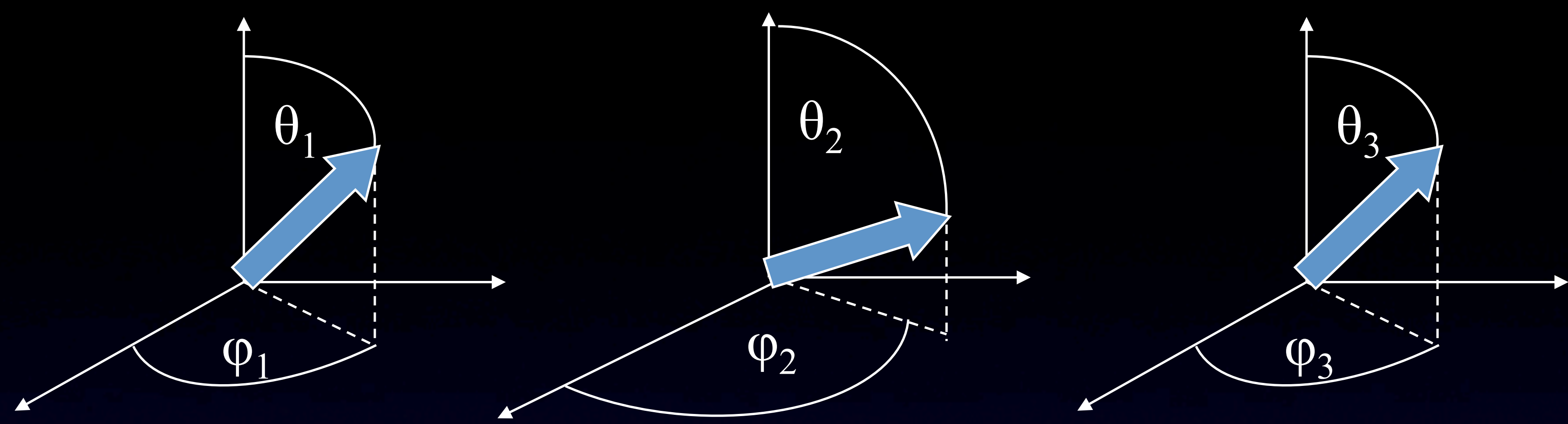
Specifying classical and quantum states of N spins



Classical:

2N numbers

Specifying classical and quantum states of N spins



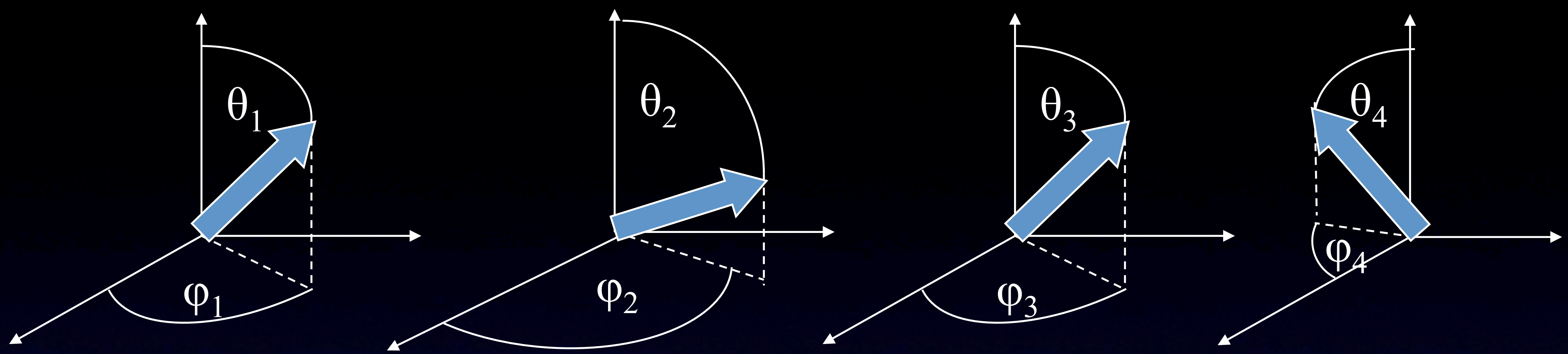
Classical:
2N numbers

$$
\begin{aligned}
|\psi\rangle = {} & A_{000}|0\rangle|0\rangle|0\rangle + A_{001}|0\rangle|0\rangle|1\rangle + A_{010}|0\rangle|1\rangle|0\rangle \\
& + A_{011}|0\rangle|1\rangle|1\rangle + A_{100}|1\rangle|0\rangle|0\rangle + A_{101}|1\rangle|0\rangle|1\rangle \\
& + A_{110}|1\rangle|1\rangle|0\rangle + A_{111}|1\rangle|1\rangle|1\rangle
\end{aligned}
$$

Quantum:
2^N numbers

Need exponentially more numbers to specify the quantum wavefunction than the classical state.

Specifying classical and quantum states of N spins



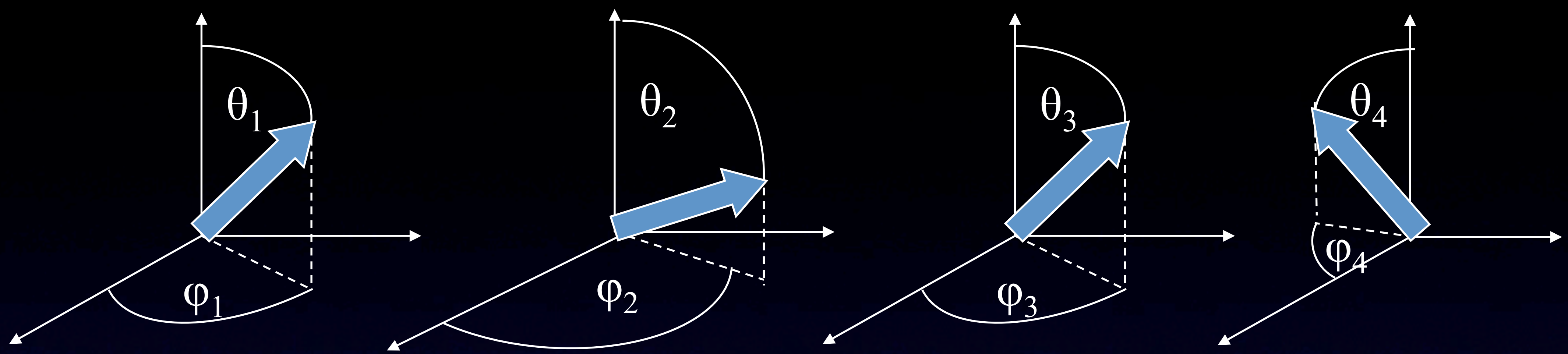
Classical:
2N numbers

$$
\begin{aligned}
|\psi\rangle = {} & A_{0000}|0\rangle|0\rangle|0\rangle|0\rangle + A_{0001}|0\rangle|0\rangle|0\rangle|1\rangle + A_{0010}|0\rangle|0\rangle|1\rangle|0\rangle + A_{0011}|0\rangle|0\rangle|1\rangle|1\rangle \\
& + A_{0100}|0\rangle|1\rangle|0\rangle|0\rangle + A_{0101}|0\rangle|1\rangle|0\rangle|1\rangle + A_{0110}|0\rangle|1\rangle|1\rangle|0\rangle + A_{0111}|0\rangle|1\rangle|1\rangle|1\rangle \\
& + A_{1000}|0\rangle|0\rangle|0\rangle|0\rangle + A_{1001}|0\rangle|0\rangle|0\rangle|1\rangle + A_{1010}|0\rangle|0\rangle|1\rangle|0\rangle + A_{1011}|0\rangle|0\rangle|1\rangle|1\rangle \\
& + A_{1100}|0\rangle|1\rangle|0\rangle|0\rangle + A_{1101}|0\rangle|1\rangle|0\rangle|1\rangle + A_{1110}|0\rangle|1\rangle|1\rangle|0\rangle + A_{1111}|0\rangle|1\rangle|1\rangle|1\rangle
\end{aligned}
$$

Quantum:
2^N numbers

Need exponentially more numbers to specify the quantum wavefunction than the classical state.

Specifying classical and quantum states of N spins



Classical:
2N numbers

$$
\begin{aligned}
|\psi\rangle = {} & A_{0000}|0\rangle|0\rangle|0\rangle|0\rangle + A_{0001}|0\rangle|0\rangle|0\rangle|1\rangle + A_{0010}|0\rangle|0\rangle|1\rangle|0\rangle + A_{0011}|0\rangle|0\rangle|1\rangle|1\rangle \\
& + A_{0100}|0\rangle|1\rangle|0\rangle|0\rangle + A_{0101}|0\rangle|1\rangle|0\rangle|1\rangle + A_{0110}|0\rangle|1\rangle|1\rangle|0\rangle + A_{0111}|0\rangle|1\rangle|1\rangle|1\rangle \\
& + A_{1000}|0\rangle|0\rangle|0\rangle|0\rangle + A_{1001}|0\rangle|0\rangle|0\rangle|1\rangle + A_{1010}|0\rangle|0\rangle|1\rangle|0\rangle + A_{1011}|0\rangle|0\rangle|1\rangle|1\rangle \\
& + A_{1100}|0\rangle|1\rangle|0\rangle|0\rangle + A_{1101}|0\rangle|1\rangle|0\rangle|1\rangle + A_{1110}|0\rangle|1\rangle|1\rangle|0\rangle + A_{1111}|0\rangle|1\rangle|1\rangle|1\rangle
\end{aligned}
$$

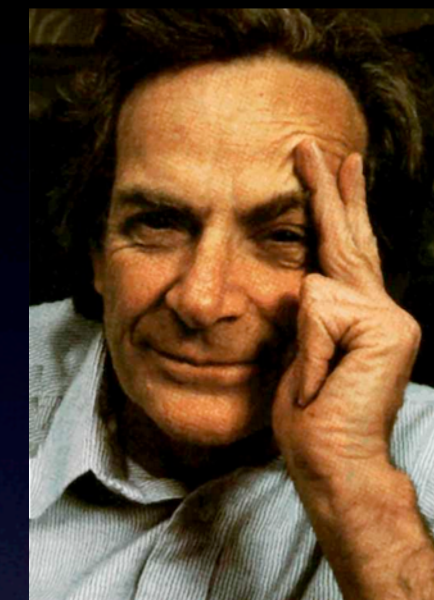
Quantum:
2^N numbers

Need exponentially more numbers to specify the quantum wavefunction than the classical state.

Complication: measurement "collapses" wavefunction

A computer that exploits the laws of quantum mechanics can solve some problems faster than one obeying laws of classical mechanics

- Quantum simulation (exponential (?))
  [Feynman 1982]



- Shor's factoring algorithm (exponential speedup (?))
  [Shor 1994]

- Grover's database search algorithm ($\sqrt{N}$ versus N)
  [Grover 1996]

To build a quantum computer, one needs to be able to perform all the necessary spin operations without measuring the spins unintentionally.

In other words, one must control the quantum evolution without destroying quantum coherence.

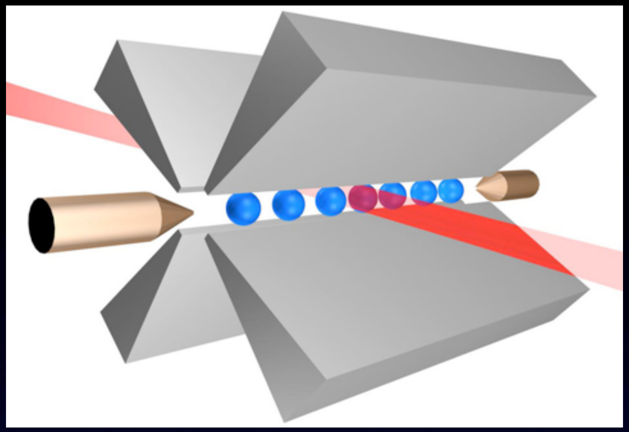
$$\text{Figure of merit: } \frac{\text{coherence time}}{\text{gate operation time}}$$

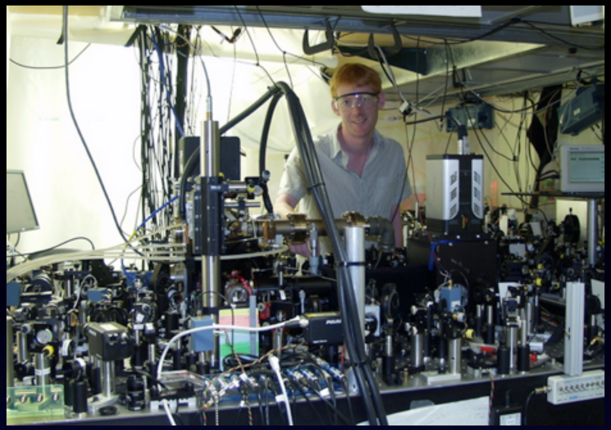
Need figure of merit $>10^4$ for scalable quantum computation.

$\Longrightarrow$ Need fast operations and long coherence times.

Several different schemes for quantum computing are being pursued. For example:

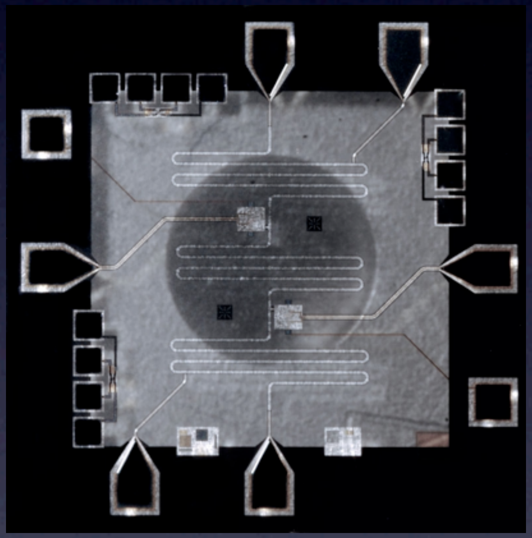
Trapped ions

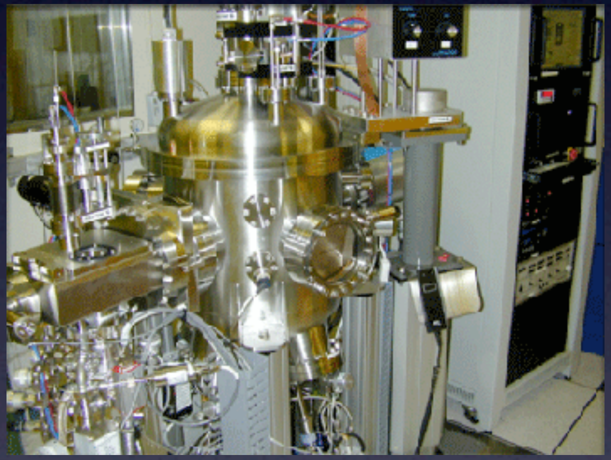




14 qubits

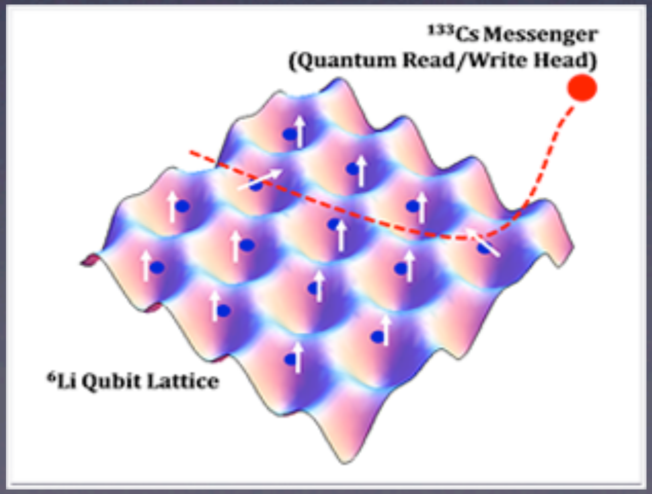
Superconductors

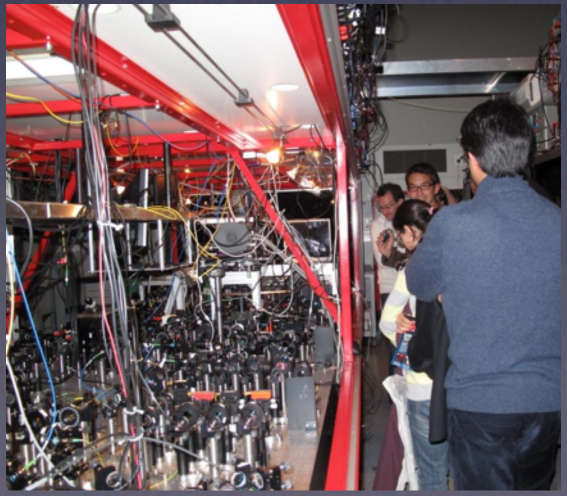




4 qubits

Neutral atoms





~6 qubits

Current status:

Many different groups are pursuing different physical implementations of quantum computation.

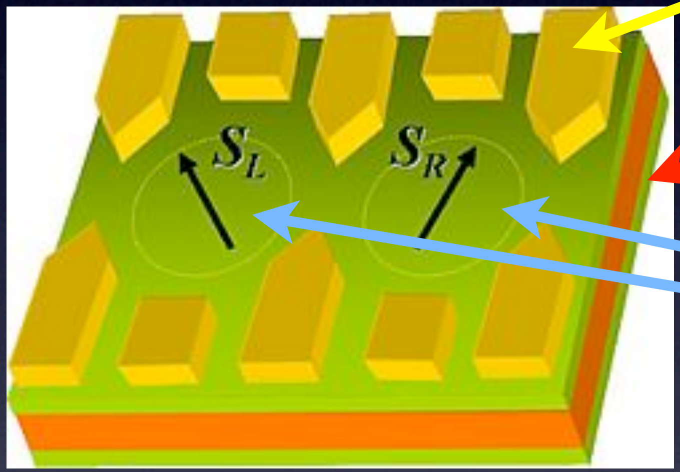
The largest coherent quantum computer that has been built so far has 14 qubits. (It can factor $21=3\times7$.) Need many more qubits to be more powerful than current classical computers.

Monz, T. *et al*. *Phys. Rev. Lett.* **106**, 130506 (2011).

UW Si/SiGe quantum dot quantum computer

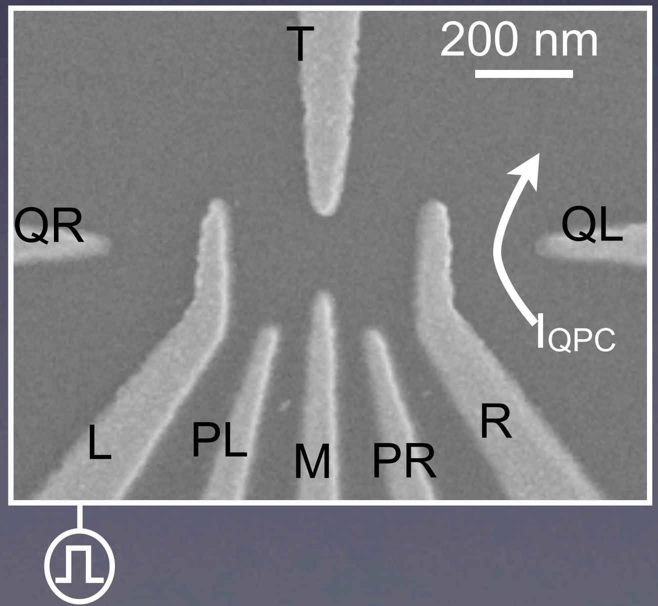
Overview of our approach: quantum dots in Si/SiGe heterostructures confined and controlled with voltages applied using top gates

metal gates to confine and control electrons



electrons are confined to thin silicon layer sandwiched between silicon-germanium

One electron per "quantum dot"



Voltages applied to top gates define electron potentials. Measure system by measuring current through quantum point contact (QPC), which depends on how many electrons are in each quantum dot.

UW-Madison Solid-State Quantum Computing Team

PI: Mark Eriksson

Zhan Shi, Christine Simmons, Dohun Kim, Jon Prance, Dan Ward, Xian Wu, Robert Mohr, Don Savage, Max Lagally, Robert Joynt

SNC theory collaborators:

Mark Friesen, John Gamble, Xuedong Hu, Teck Seng Koh

Sponsored in part by the Army Research Office, the National Science Foundation, and the United States Department of Defense.

Current status of Si/SiGe quantum dot quantum computer: we just got one qubit to work.

X. Shi et al., Nature Communications **5**, 3020 (2014);
D. Kim et al., arXiv:1401.xxxx

Why are we excited about just one qubit?

Our methods for fabricating our qubit is similar to those used for classical electronics. So if we can fabricate one high quality qubit, there is a good chance that we can scale up the process.

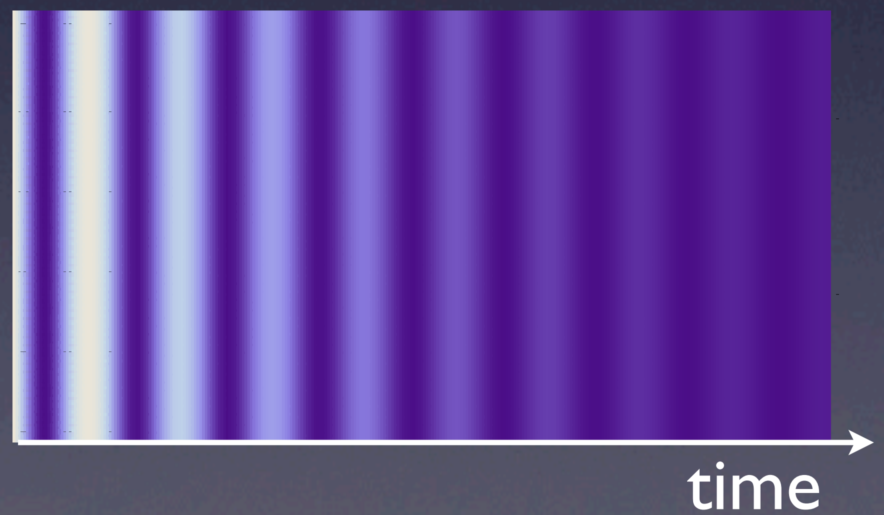
So we need to make the qubit very high quality.

Assessing qubit quality − look for long-lived quantum oscillations

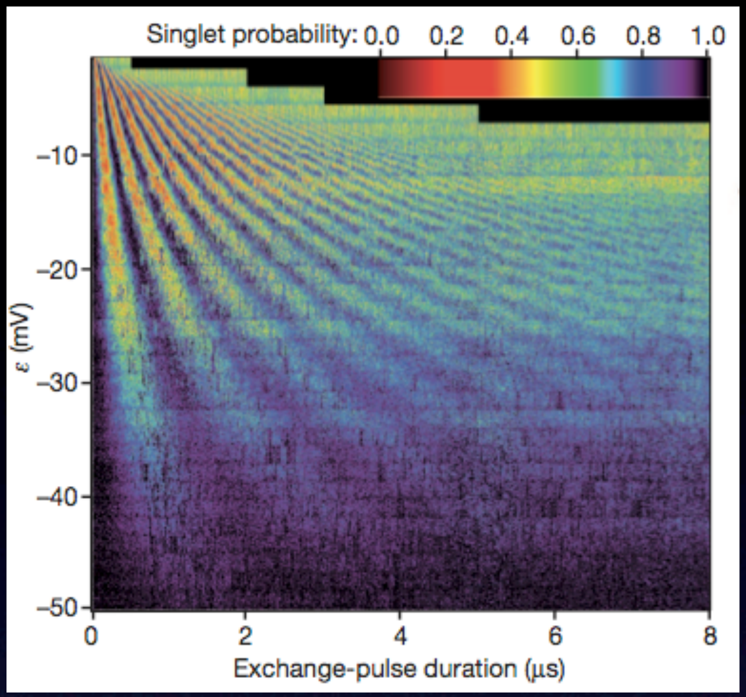
Prepare electron spins in a quantum state where, if it is not measured, it would oscillate between $|0\rangle$ and $|1\rangle$ (spin ħ/2 and spin -ħ/2).

Prepare lots of spins the same way, and measure their spin states at different times. The average of the spin state oscillates as a function of time, until it has been measured by its environment.

gray scale plot of spin value



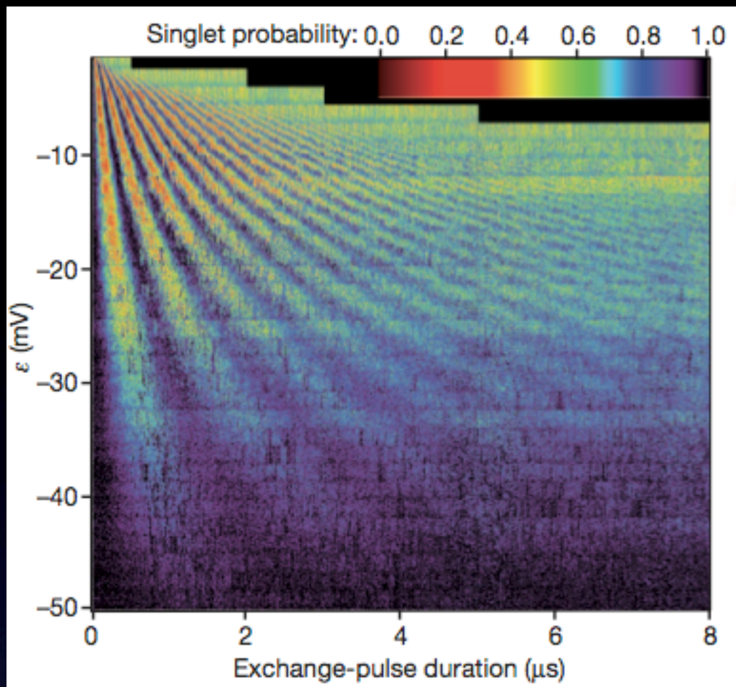
Need to get >1000 oscillations for a scalable qubit.



Previous work with highest figure of merit for a quantum dot qubit

~20 oscillations

B.M. Maune et al., Nature **481**, 344 (2012)

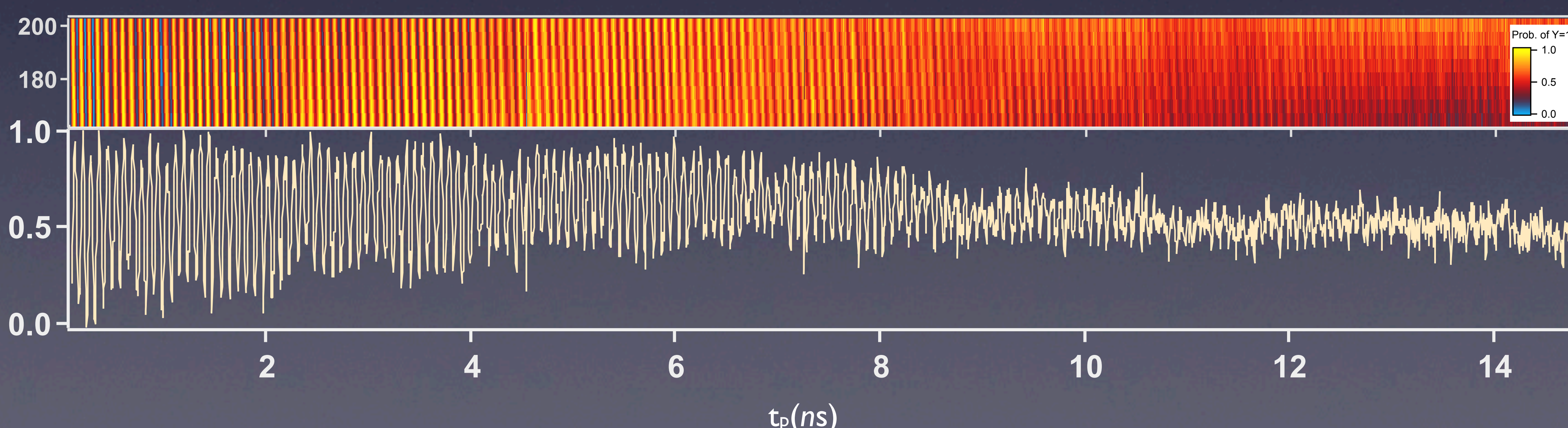


Previous work with highest figure of merit for a quantum dot qubit

~20 oscillations

B.M. Maune et al., Nature **481**, 344 (2012)

Our quantum dot qubit now has >100 oscillations (theory predicts that >1000 is achievable)



D. Kim et al., arXiv:1401.xxxx

Summary

Feature sizes in silicon electronics continue to shrink and in the foreseeable future will become comparable to the size of silicon atoms, where quantum effects become very important.

Quantum computers that exploit the laws of quantum physics could perform some calculations much faster than any classical computer.

A new "quantum dot hybrid qubit" that enables faster gating has been developed.

Initial experiments on hybrid quantum dot qubit are promising.

Thank you!

Thank you!

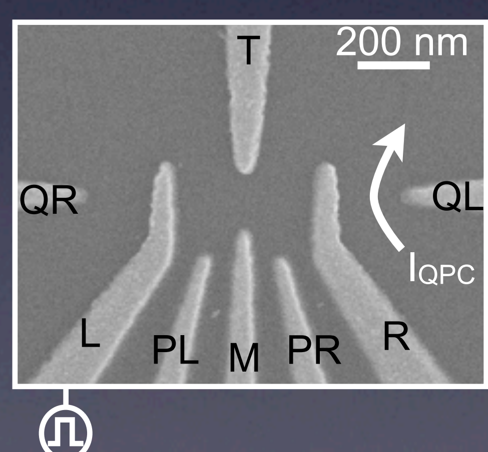
Questions?

Our new "hybrid quantum dot qubit" enables fast qubit operations in a relatively simple (and hence relatively easy-to-fabricate) architecture

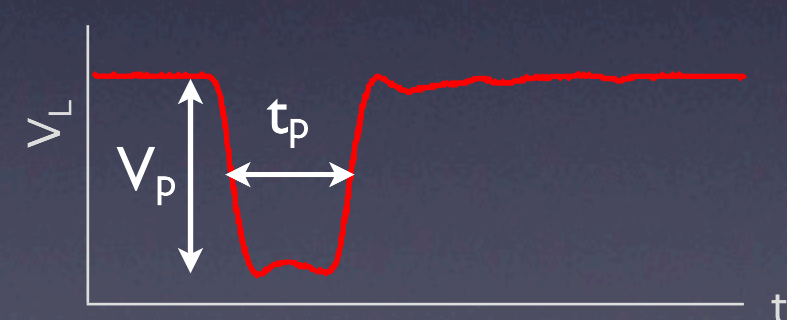
Z. Shi et. al, Phys. Rev. Lett. 108, 140503 (2012)

T.S. Koh et al., Phys. Rev. Lett. 109, 250503 (2012)

device (top view)



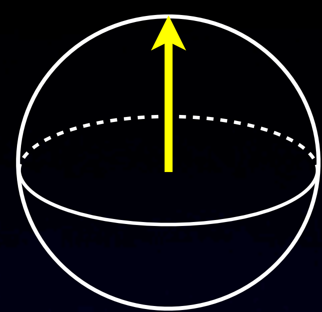
manipulation voltage pulse



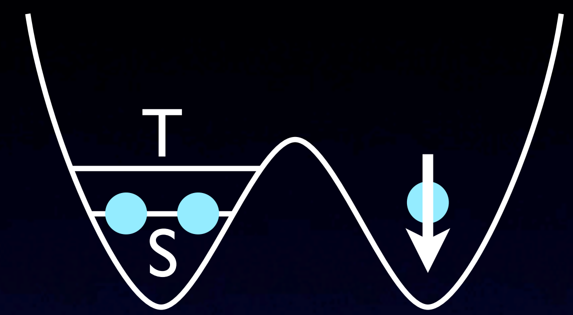
t_P ~ 100ps - 4 ns

A “hybrid” 3-electron qubit:

$$|0\rangle = |S\rangle|\downarrow\rangle$$

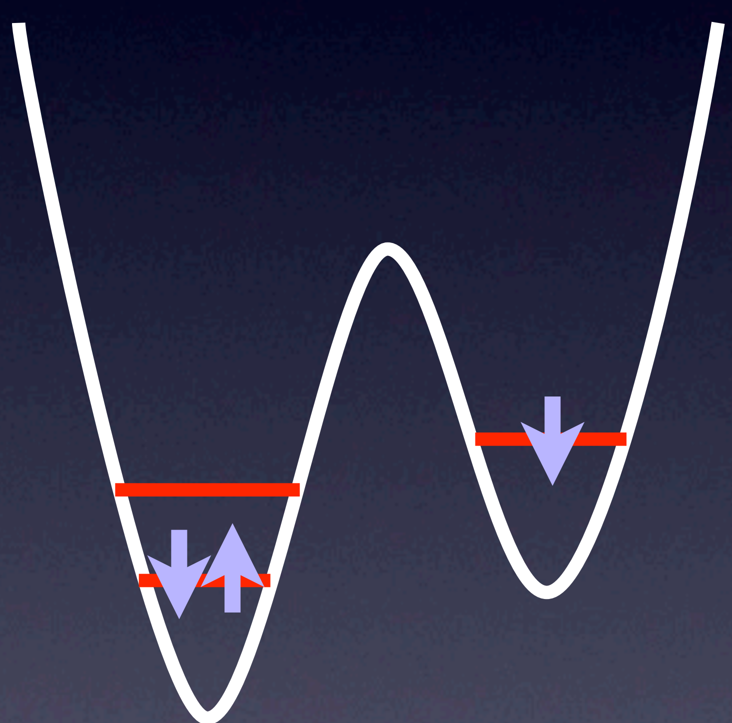


$$|1\rangle = \sqrt{\frac{1}{3}}|T_0\rangle|\downarrow\rangle - \sqrt{\frac{2}{3}}T_-|\uparrow\rangle)$$

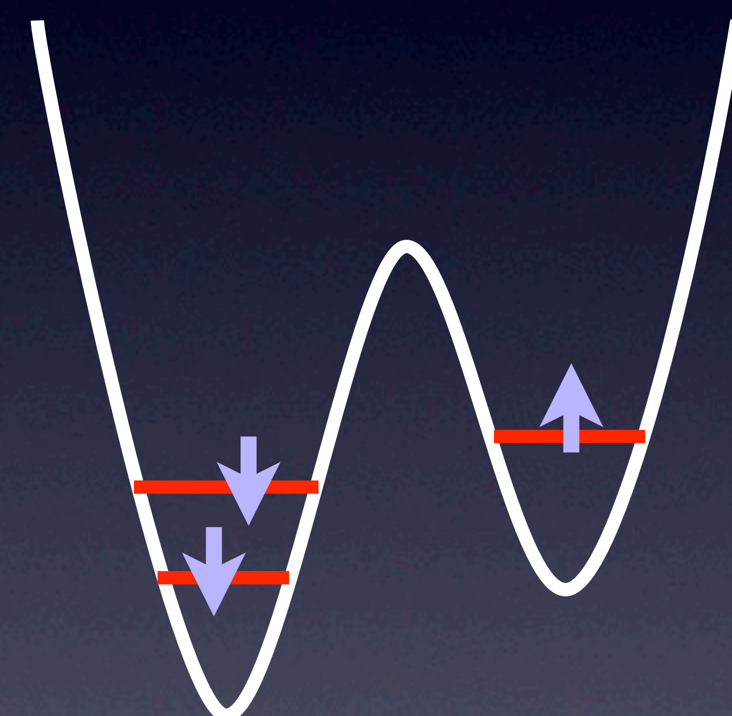


Z. Shi et. al, Phys. Rev. Lett. 108, 140503 (2012)
J. Gamble et al., Phys. Rev. B 86, 035302 (2012).

Gates for hybrid qubit are fast because all gate operations are controlled electrically

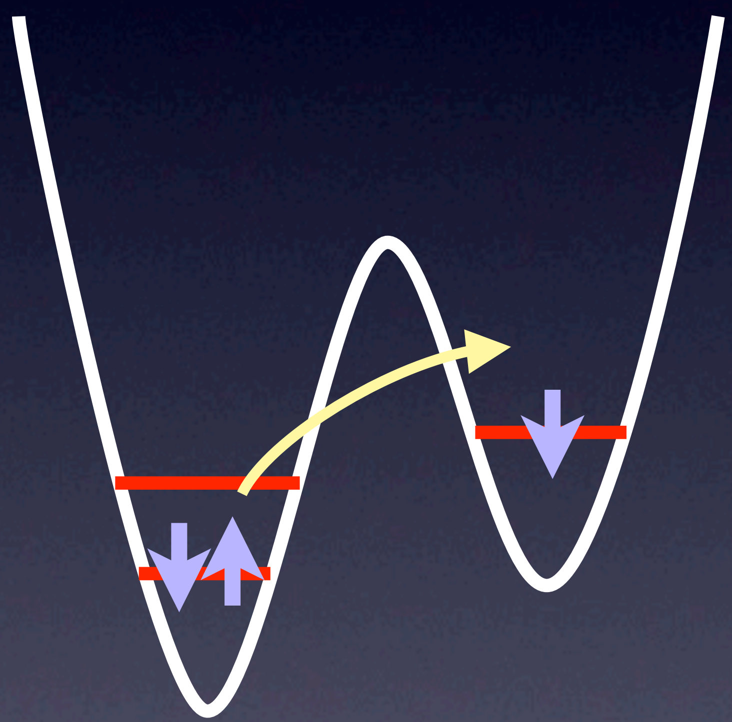


Singlet

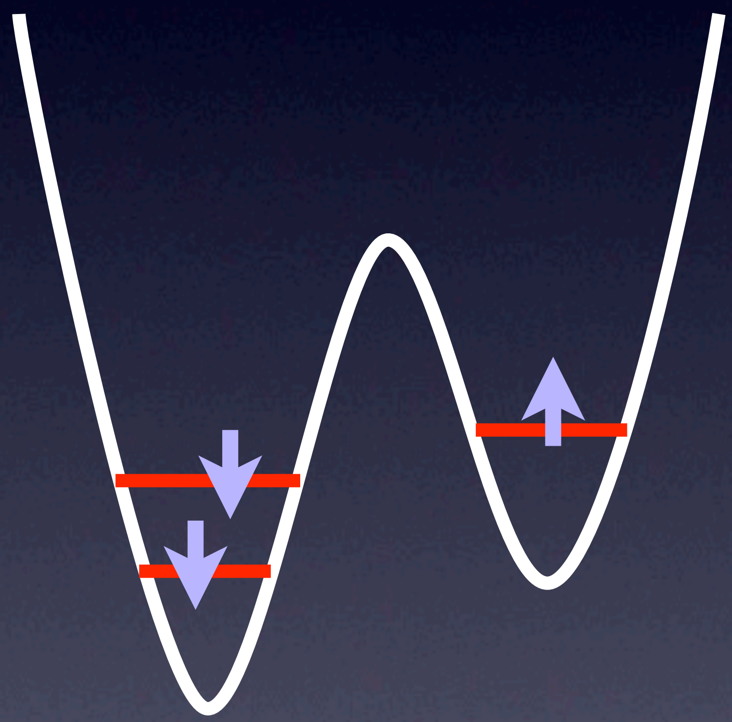


Triplet

Gates for hybrid qubit are fast because all gate operations are controlled electrically

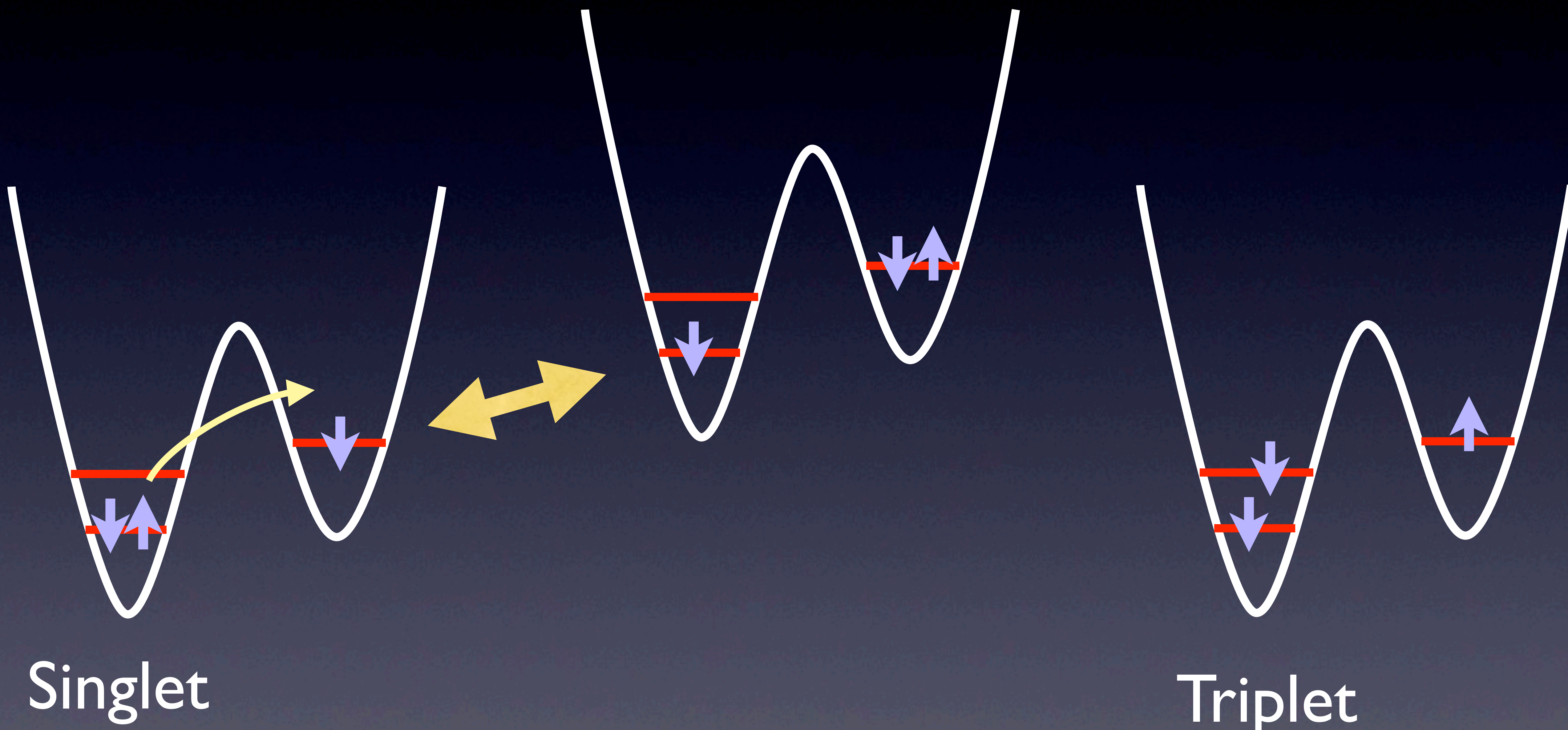


Singlet

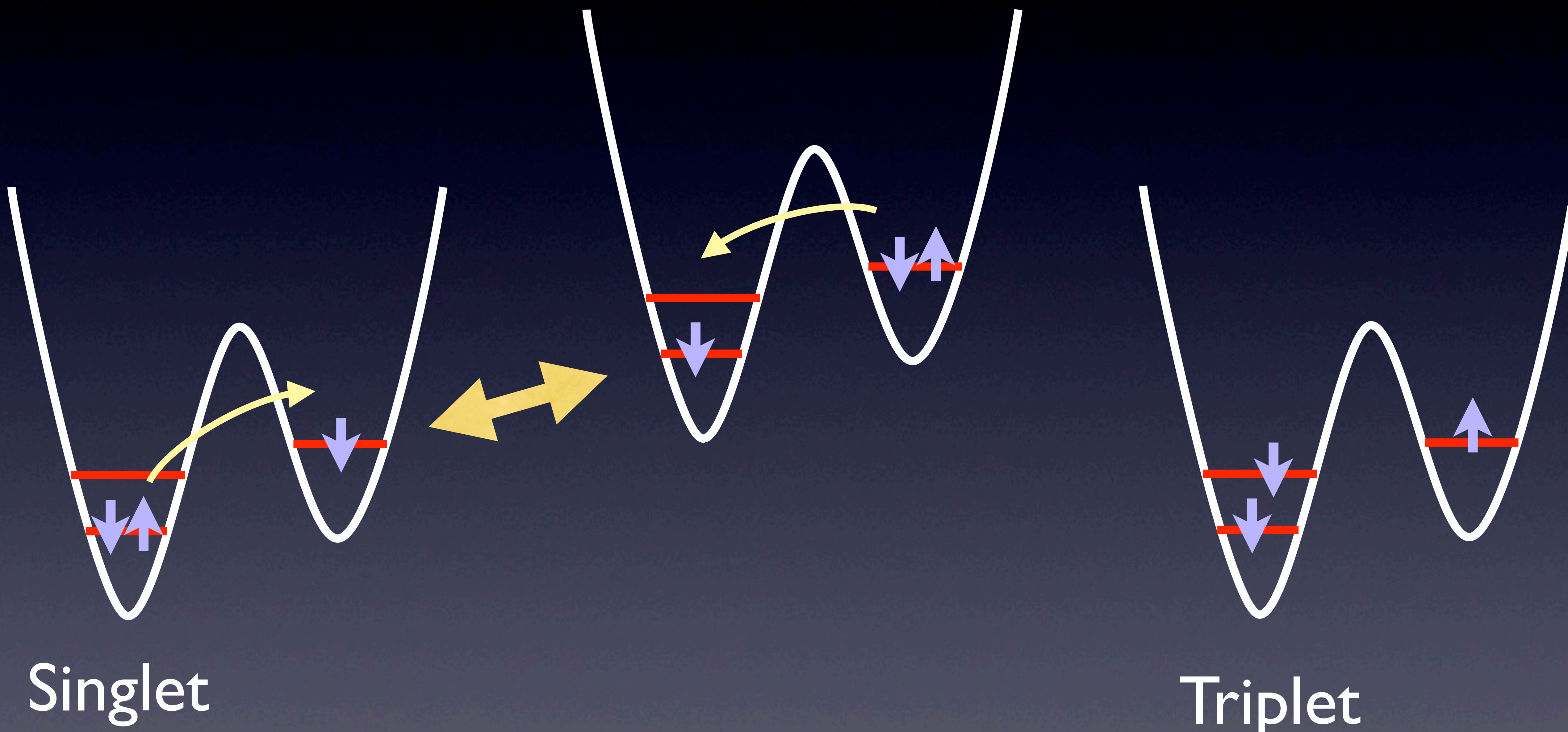


Triplet

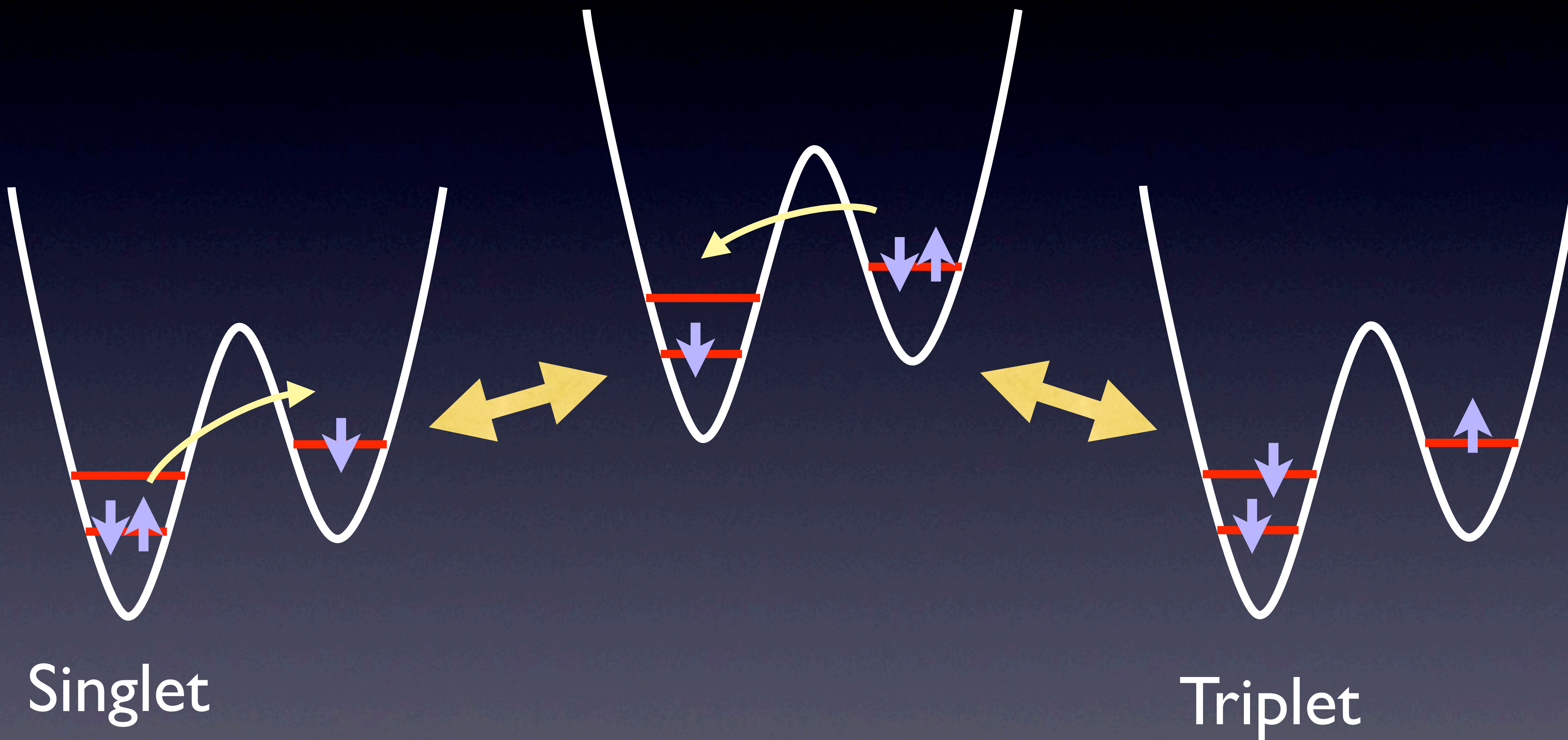
Gates for hybrid qubit are fast because all gate operations are controlled electrically



Gates for hybrid qubit are fast because all gate operations are controlled electrically



Gates for hybrid qubit are fast because all gate operations are controlled electrically



Charge transitions change the spin state in the left dot from singlet to triplet.

Our theoretical calculations yield a coherence time of hybrid qubit of ~1 μs in Si (versus < 1ns for charge qubit).

J. Gamble et al., Phys. Rev. B **86**, 035302 (2012)

Theory predicts that hybrid qubit gate operations can be performed at ~10 GHz

⇒ Figure of merit of 10^4 (if theory is correct).