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Going Beyond Moore's Law to Address Supercomputing Applications

With implications to embedded systems

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Sandia National Laboratories

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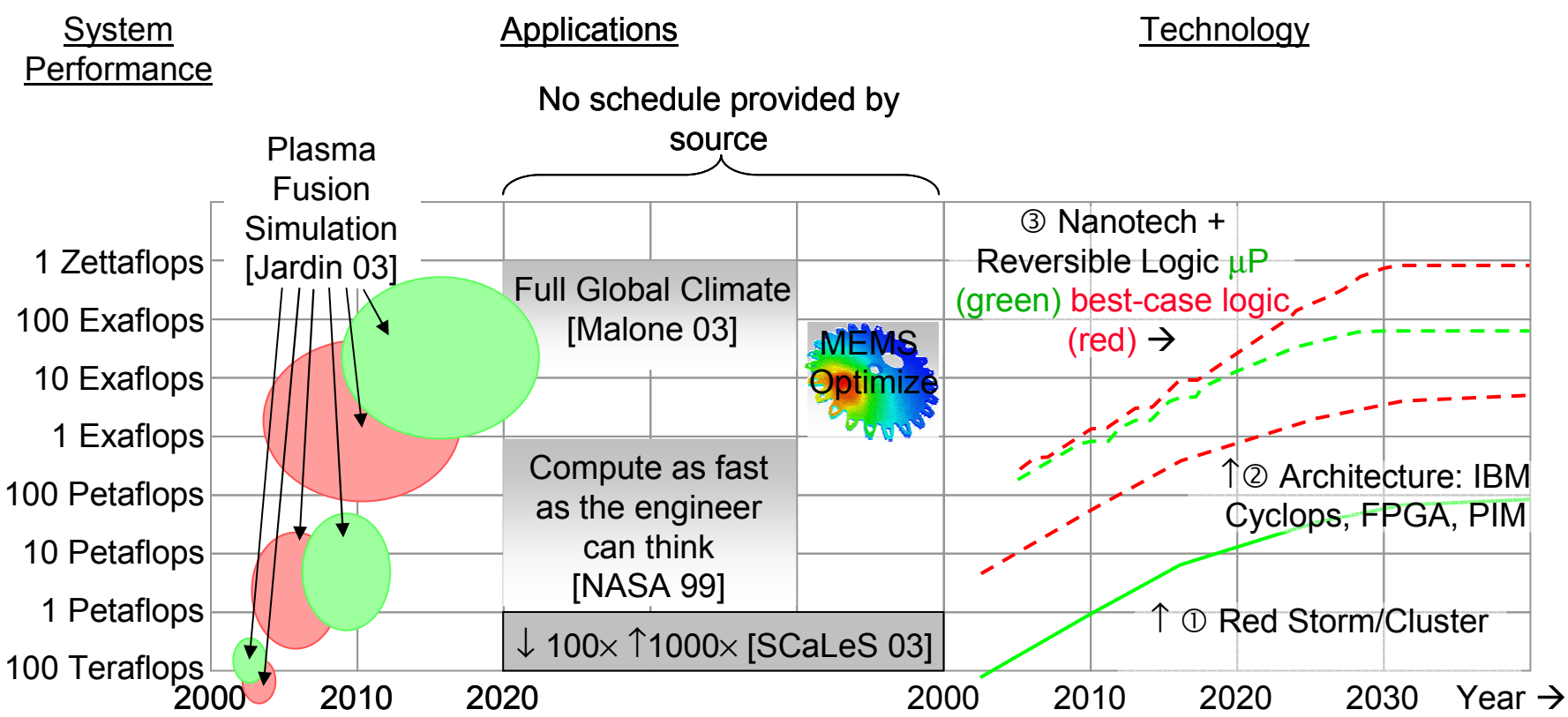
Applications and $100M Supercomputers



[Jardin 03] S.C. Jardin, "Plasma Science Contribution to the SCaLeS Report," Princeton Plasma Physics Laboratory, PPPL-3879 UC-70, available on Internet.
[Malone 03] Robert C. Malone, John B. Drake, Philip W. Jones, Douglas A. Rotman, "High-End Computing in Climate Modeling," contribution to SCaLeS report.
[NASA 99] R. T. Biedron, P. Mehrotra, M. L. Nelson, F. S. Preston, J. J. Rehder, J. L. Rogers, D. H. Rudy, J. Sobieski, and O. O. Storaasli, "Compute as Fast as the Engineers Can Think!" NASA/TM-1999-209715, available on Internet.
[SCaLeS 03] Workshop on the Science Case for Large-scale Simulation, June 24-25, proceedings on Internet a http://www.pnl.gov/scales/.
[DeBenedictis 04], Erik P. DeBenedictis, "Matching Supercomputing to Progress in Science," July 2004. Presentation at Lawrence Berkeley National Laboratory, also published as Sandia National Laboratories SAND report SAND2004-3333P. Sandia technical reports are available by going to http://www.sandia.gov and accessing the technical library.

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Outline

- An Exemplary Zettaflops Problem
- The Limits of Moore's Law
- Beyond Moore's Law
  - Industry's Plans
  - Nanotech and Reversible Logic
  - Quantum Computing
- Conclusions

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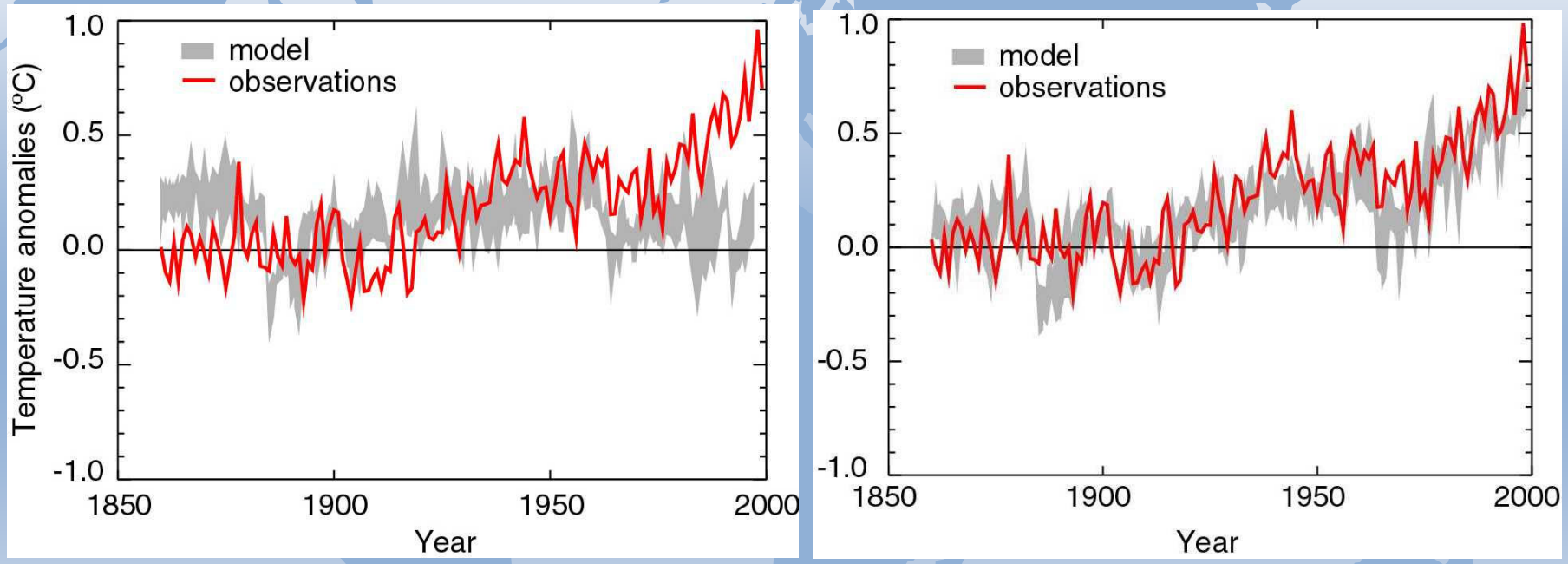
Simulation of Global Climate



Stott et al, Science 2000

"Simulations of the response to natural forcings alone … do not explain the warming in the second half of the century"

"..model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this*period" - IPCC 2001

Office of Science U.S. DEPARTMENT OF ENERGY

SciDAC Scientific Discovery through Advanced Computing

The World's Greatest Science Protecting America

Los Alamos NATIONAL LABORATORY EST.1943

FLOPS Increases for Global Climate

	Issue	Scaling
1 Zettaflops	Ensembles, scenarios 10×	Embarrassingly Parallel
100 Exaflops	Run length 100×	Longer Running Time
1 Exaflops	New parameterizations 100×	More Complex Physics
10 Petaflops	Model Completeness 100×	More Complex Physics
100 Teraflops	Spatial Resolution $10^4\times$ ($10^3\times$-$10^5\times$)	Resolution
10 Gigaflops	Clusters Now In Use (100 nodes, 5% efficient)	

Ref. "High-End Computing in Climate Modeling," Robert C. Malone, LANL, John B. Drake, ORNL, Philip W. Jones, LANL, and Douglas A. Rotman, LLNL (2004)

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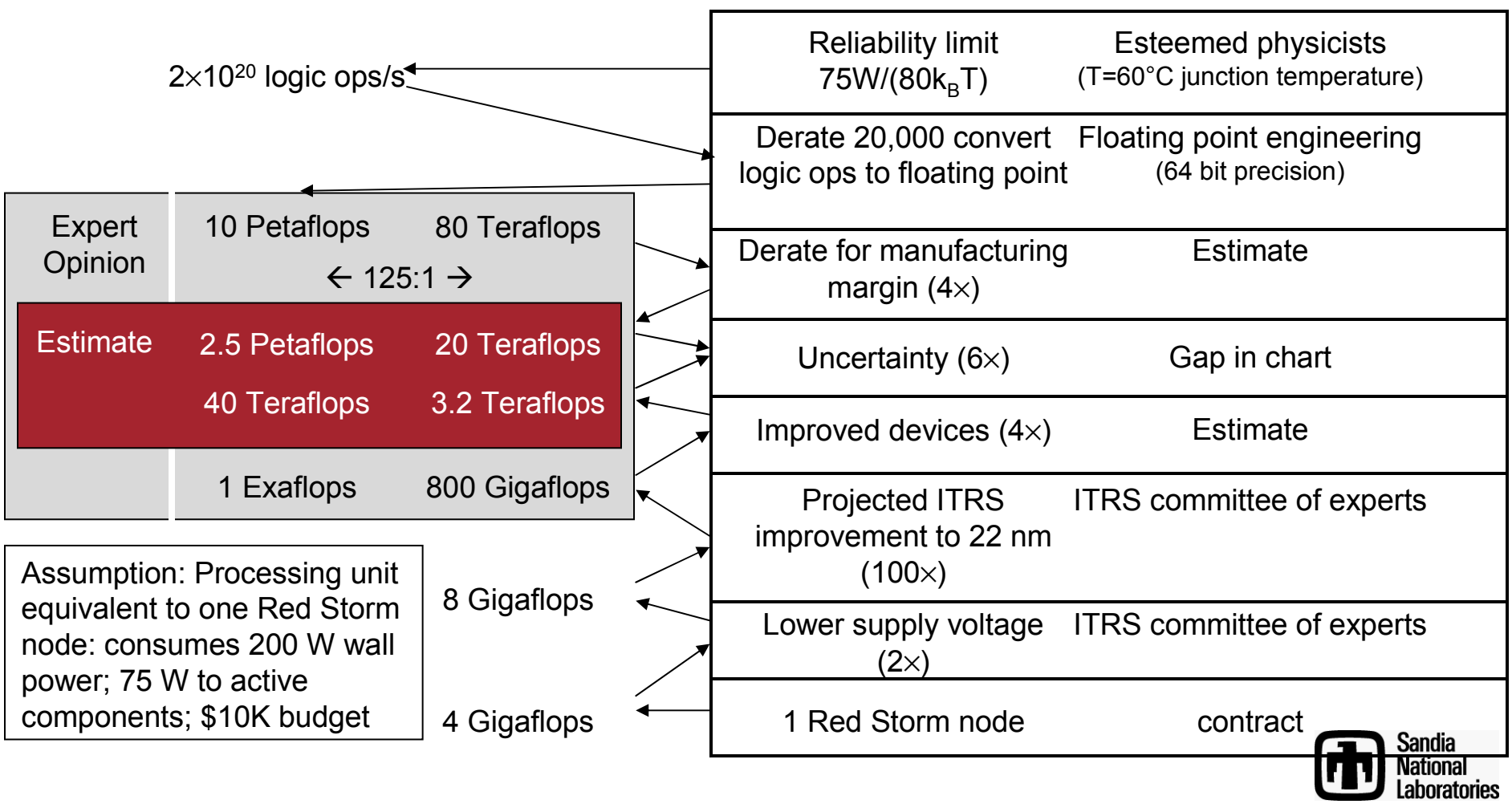
*** This is a Preview ***



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Metaphor: FM Radio on Trip to New York

- You drive to New York listening to FM radio
- Music clear for a while, but noise creeps in and then overtakes music
- Analogy: You live out the next dozen years buying PCs every couple years
- PCs keep getting faster
  - clock rate increases
  - fan gets bigger
  - won't go on forever
- Why…see next slide

Details: Erik DeBenedictis, "Taking ASCI Supercomputing to the End Game," SAND2004-0959

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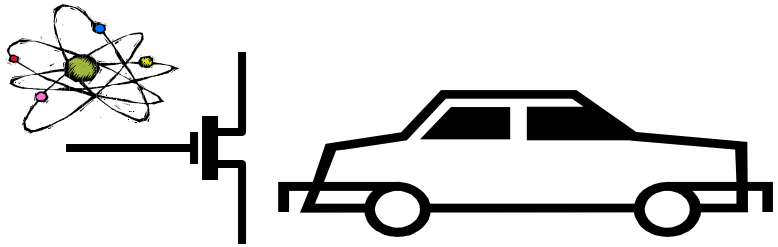
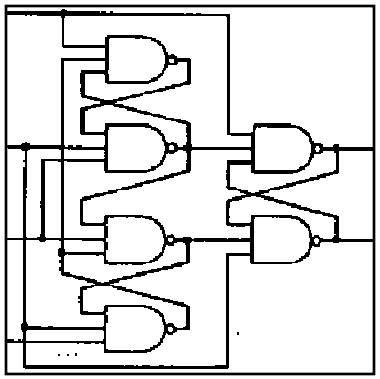
FM Radio and End of Moore's Law

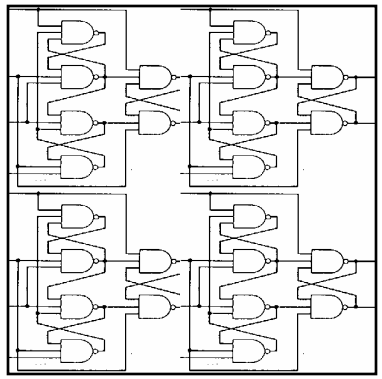
Distance



Driving away from FM transmitter→less signal
Noise from electrons → no change



Shrink



Increasing numbers of gates→less signal power
Noise from electrons → no change

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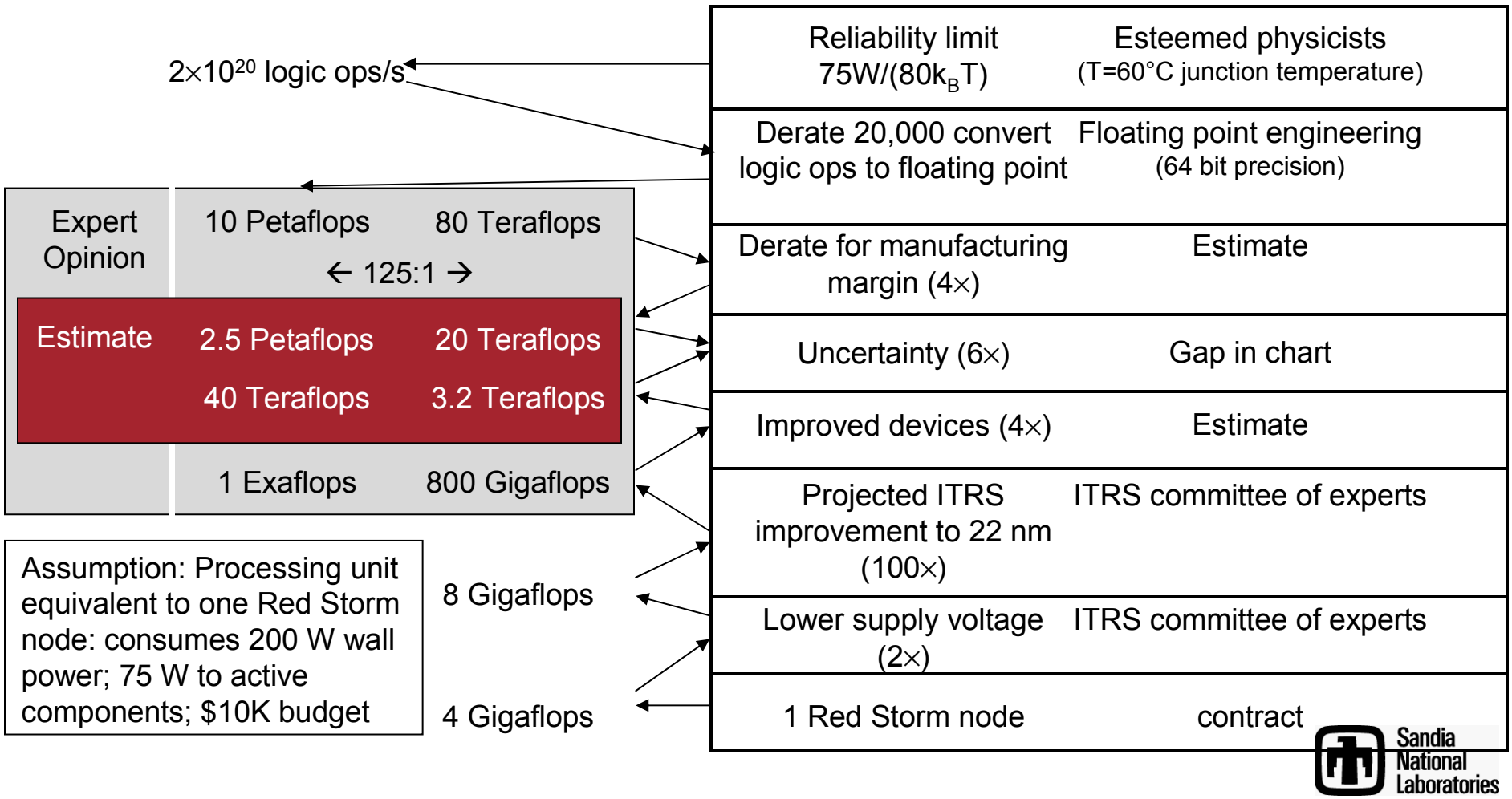
Limits for 75W Power Budget



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Proceeding

- So industry has plans to extend Moore's Law, right?
  - Next slide shows ITRS Emerging Research Devices (ERD), the devices under consideration by industry
  - All are either hotter, bigger, or slower
  - Erik is now on ITRS ERD committee
- What is scientifically feasible for Gov't funding?
  - Nanotechnology
    - Efforts all over
  - Reversible logic
    - Odd name for a method of cutting power below k_BT
    - Not currently embraced by industry

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ITRS Device Review 2016

Technology	Speed (min-max)	Dimension (min-max)	Energy per gate-op	Comparison
CMOS	30 ps-1 μs	8 nm-5 μm	4 aJ	
RSFQ	1 ps-50 ps	300 nm- 1μm	2 aJ	Larger
Molecular	10 ns-1 ms	1 nm- 5 nm	10 zJ	Slower
Plastic	100 μs-1 ms	100 μm-1 mm	4 aJ	Larger+Slower
Optical	100 as-1 ps	200 nm-2 μm	1 pJ	Larger+Hotter
NEMS	100 ns-1 ms	10-100 nm	1 zJ	Slower+Larger
Biological	100 fs-100 μs	6-50 μm	.3 yJ	Slower+Larger
Quantum	100 as-1 fs	10-100 nm	1 zJ	Larger

Data from ITRS ERD Section.

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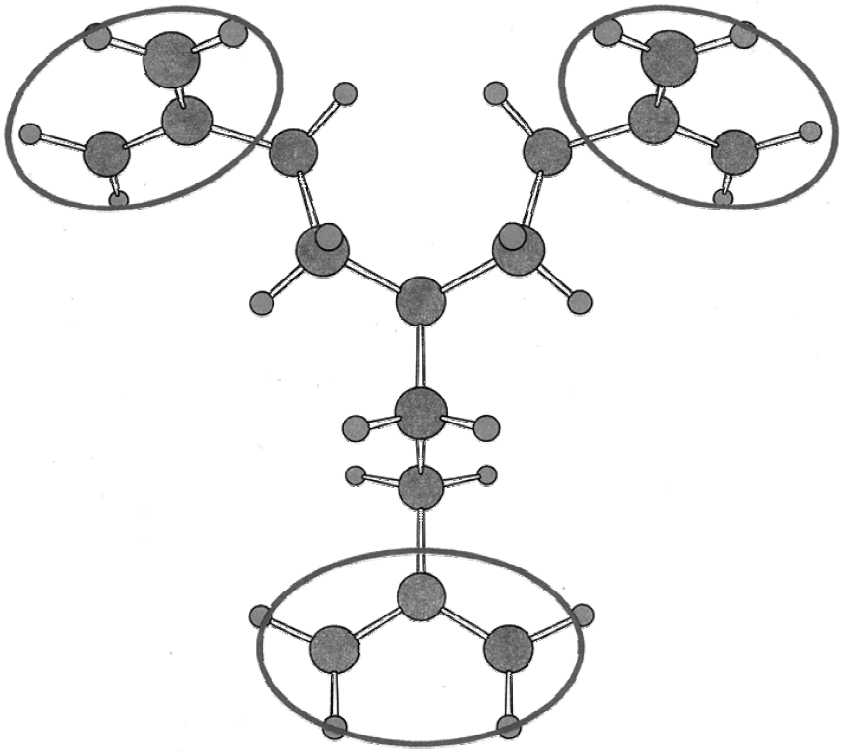
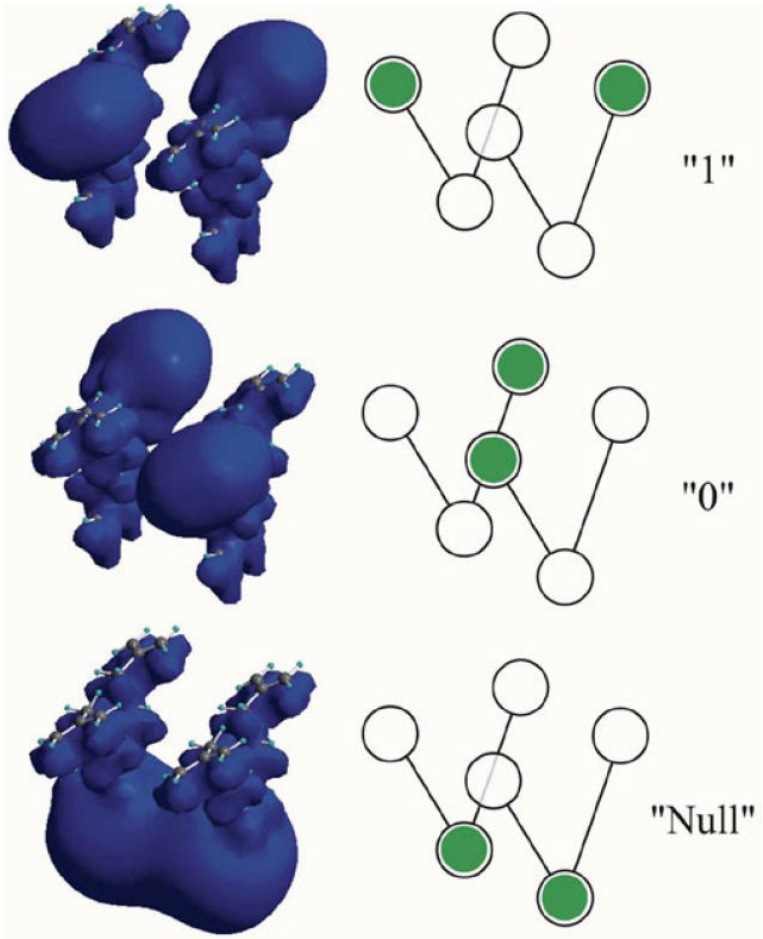
An Exemplary Device: Quantum Dots

- **Pairs of molecules create a memory cell or a logic gate**





Ref. "Clocked Molecular Quantum-Dot Cellular Automata," Craig S. Lent and Beth Isaksen
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 9, SEPTEMBER 2003

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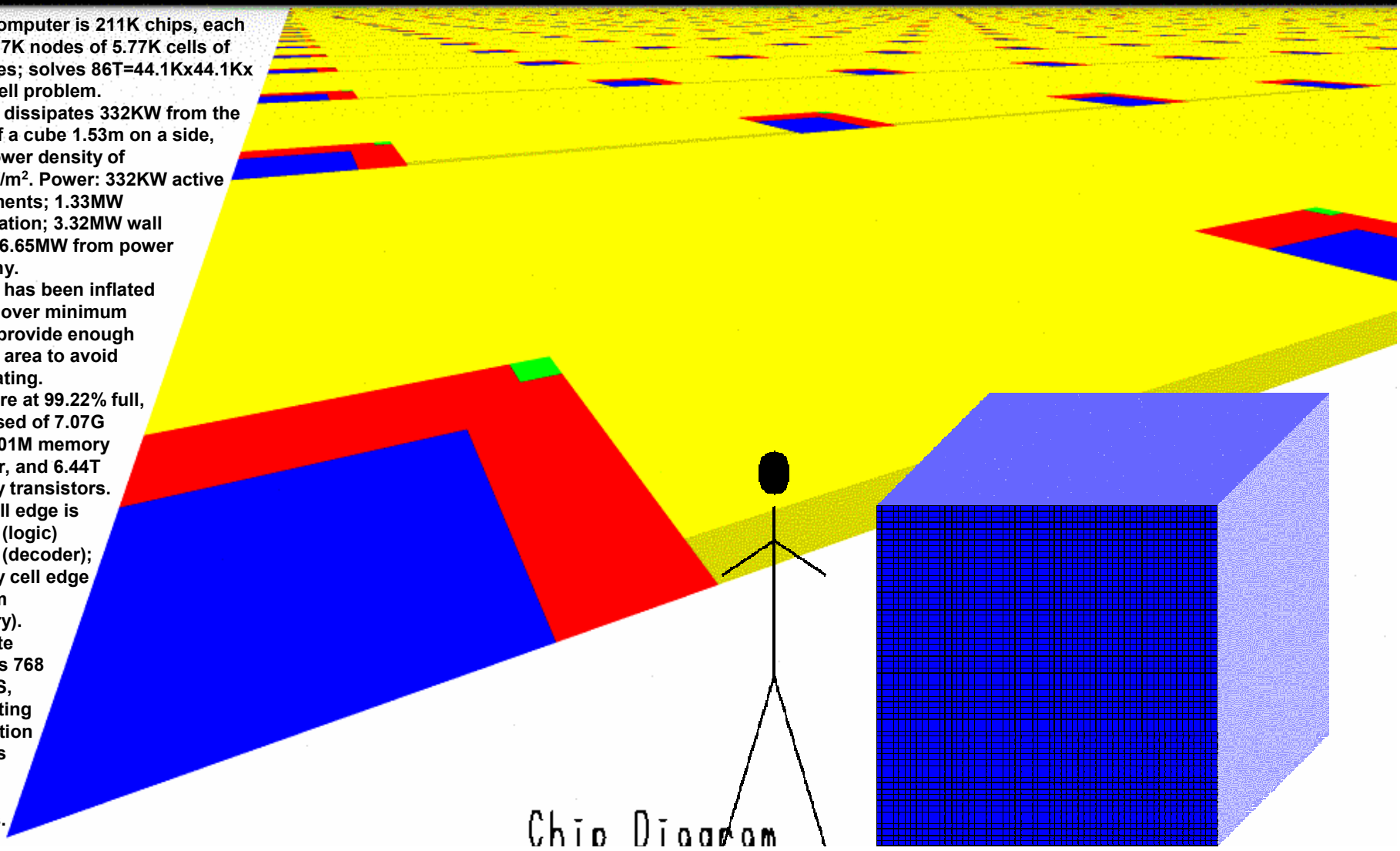
Atmosphere Simulation at a Zettaflops

Supercomputer is 211K chips, each with 70.7K nodes of 5.77K cells of 240 bytes; solves 86T=44.1Kx44.1Kx 44.1K cell problem.
System dissipates 332KW from the faces of a cube 1.53m on a side, for a power density of 47.3KW/m^2. Power: 332KW active components; 1.33MW refrigeration; 3.32MW wall power; 6.65MW from power company.
System has been inflated by 2.57 over minimum size to provide enough surface area to avoid overheating.
Chips are at 99.22% full, comprised of 7.07G logic, 101M memory decoder, and 6.44T memory transistors.
Gate cell edge is 34.4nm (logic) 34.4nm (decoder); memory cell edge is 4.5nm (memory).
Compute power is 768 EFLOPS, completing an iteration in 224µs and a run in 9.88s.



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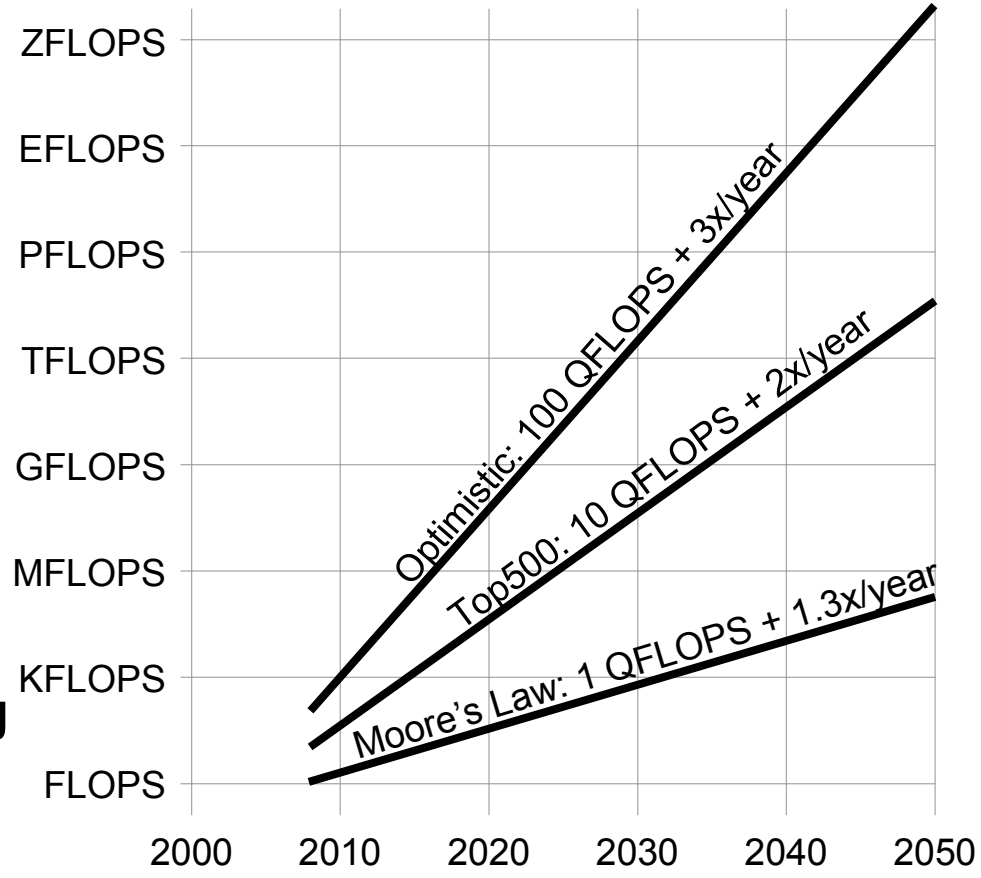
Quantum with No Speedup

- **There appears to be an engineering case for quantum computers of 1-100 Q-FLOPS**
- **One would expect an exponential growth rate for quantum computers similar to Moore's Law, but the rate constant is impossible to predict**
- **The story is not exciting so far**



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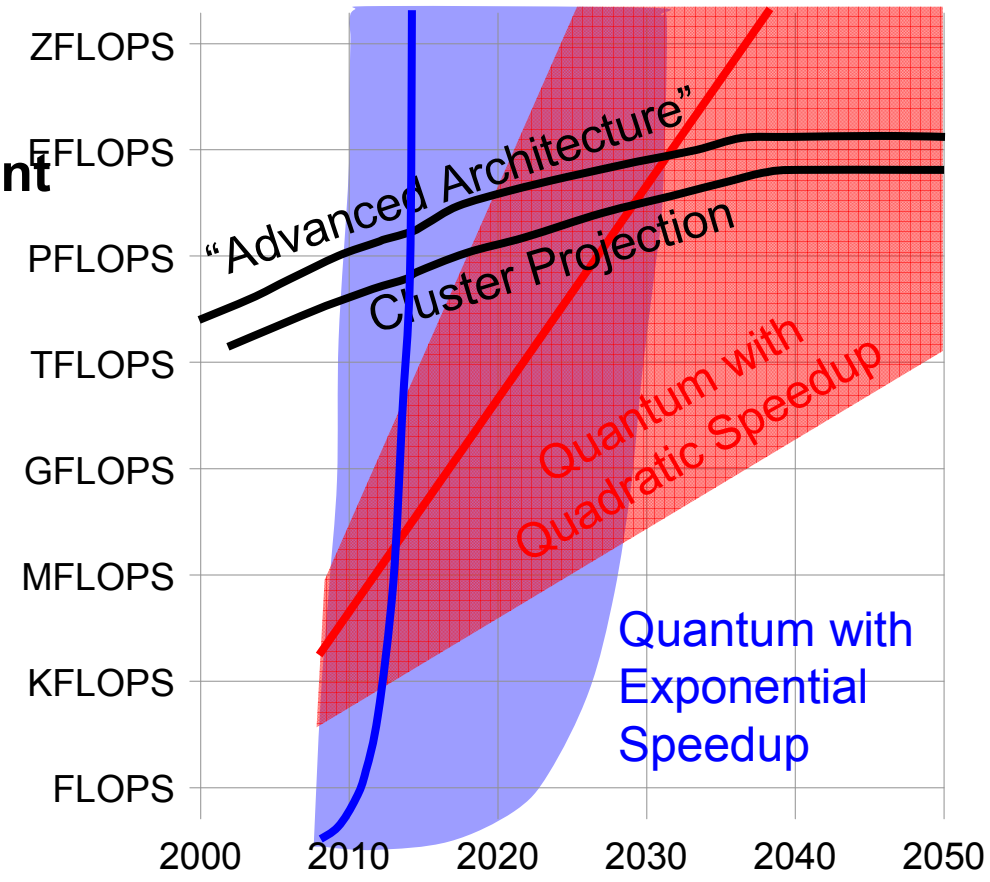
Rescaled Graph with Quantum Computing

- **Black curves from first slide**
- **Colored curves represent 2×/year growth**
  - **Shaded areas represent range of uncertainty**
- **Nominally**
  - **Blue represents crypto algorithms**
  - **Red represents continuous algorithms**



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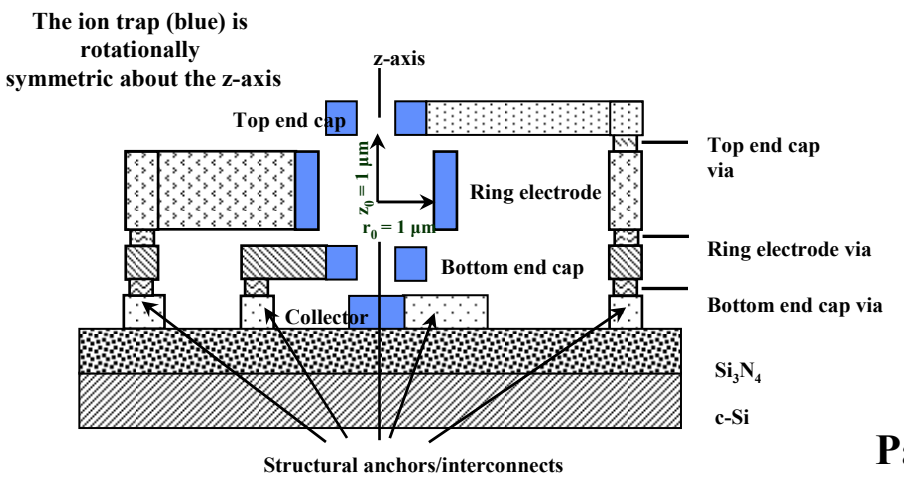
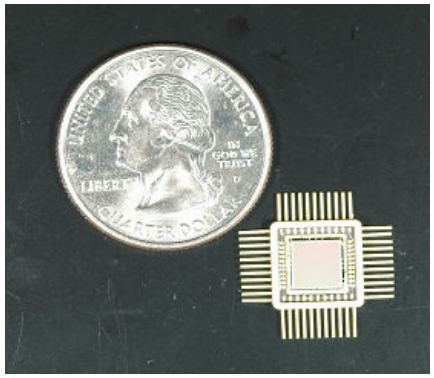
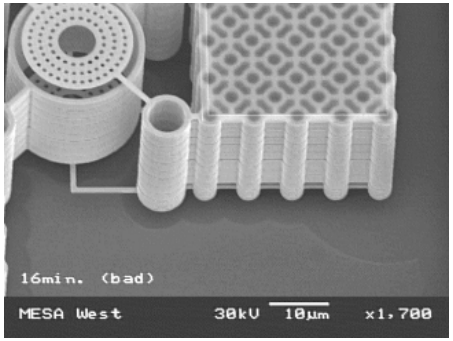
Sandia Microfabricated Ion Trap Arrays

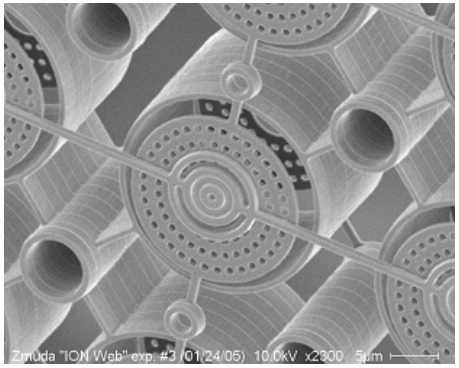


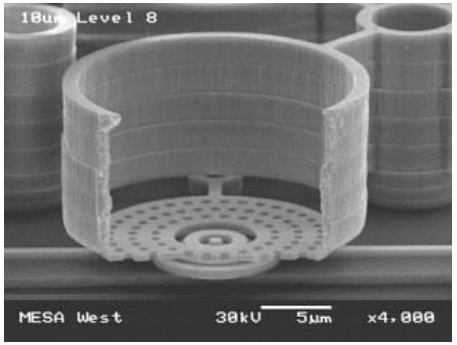


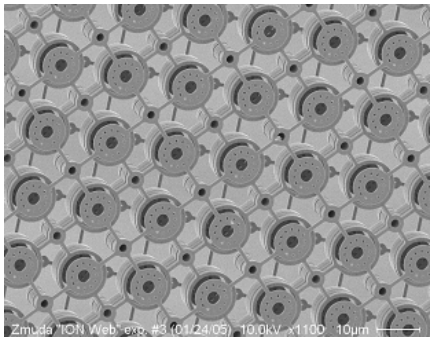
Packaged Array of 10^6 Microfabricated Traps



Microfabricated Trap Arrays







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Conclusions

- Sandia has mission need for computing up to Zettaflops for supercomputing and equally high ops/watt in other applications
- Meeting mission need will require reaching the limits of "Moore's Law," and possibly exceeding them
- Sandia has science and technology efforts to explore device technology
  - CINT, MESA, research divisions
- Sandia has computer systems efforts to explore architecture, software, and applications
- There is also activity in quantum computing

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