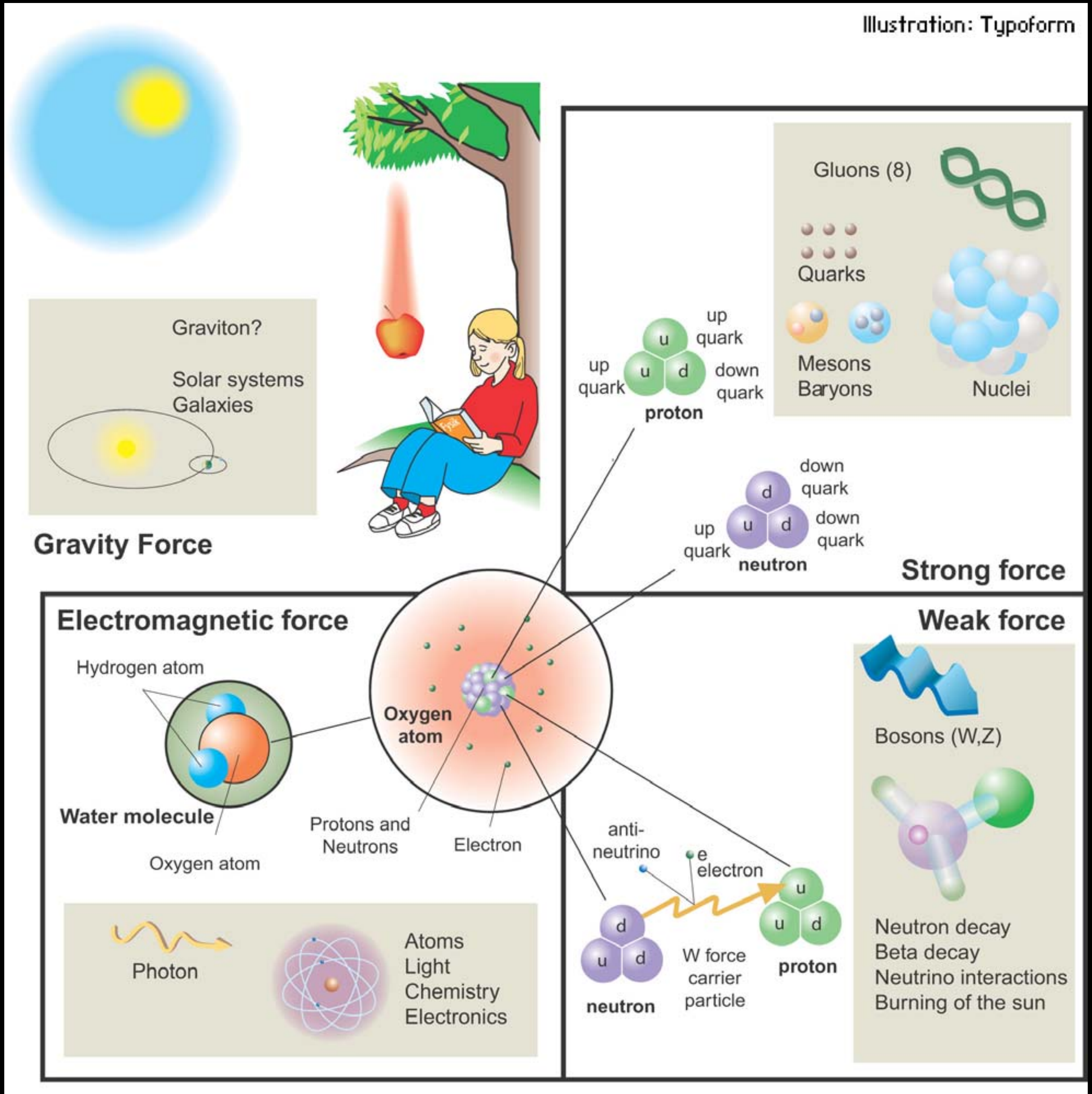
What is QCD?

- Quantum ChromoDynamics is the theory of the strong force
  - the strong force describes the binding of quarks by gluons to make particles such as neutrons and protons
- The strong force is one of the four fundamental forces in the Standard Model of Physics– the others are:
  - Gravity
  - Electromagnetism
  - The Weak force
- The 2004 Physics Nobel prize was awarded to David J. Gross, H. David Politzer, and Frank Wilczek for their work leading to QCD

The Four Fundamental Forces



Quarks and Gluons in QCD

The QCD quark action expresses the strong interaction between quarks and gluons:

$$S_{Dirac} = \overline{\psi}(\not{D} + m)\psi$$

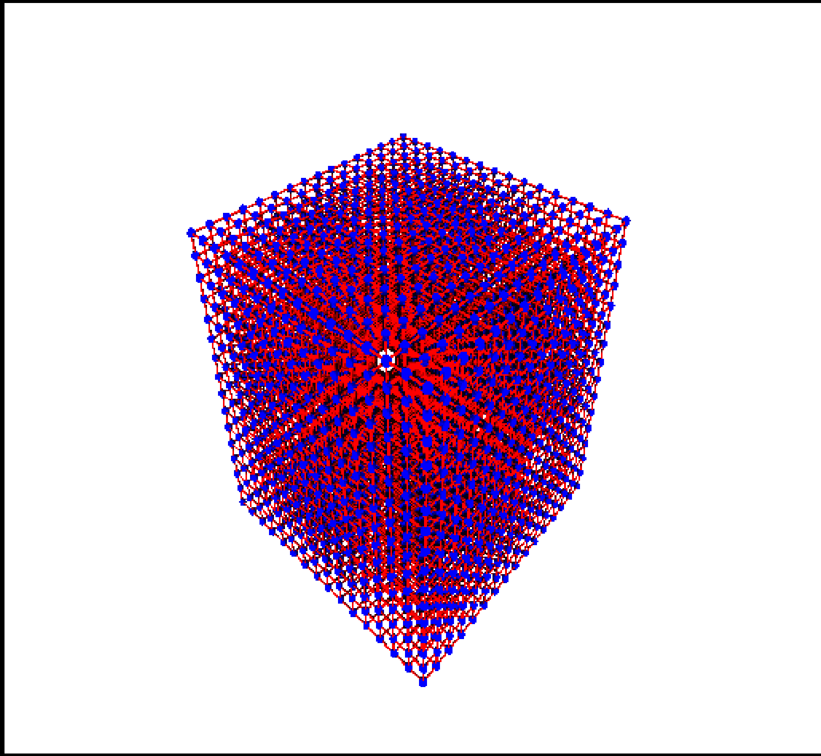
where the Dirac "dslash" operator,

$$\not{D}\psi = \sum_{\mu} \gamma_{\mu}(\partial_{\mu} + igA_{\mu}(x))\psi(x)$$

depends on the gluons, $A_{\mu}(x)$ as well as the quarks $\psi(x)$.

Lattice QCD – Numerical Simulation of QCD

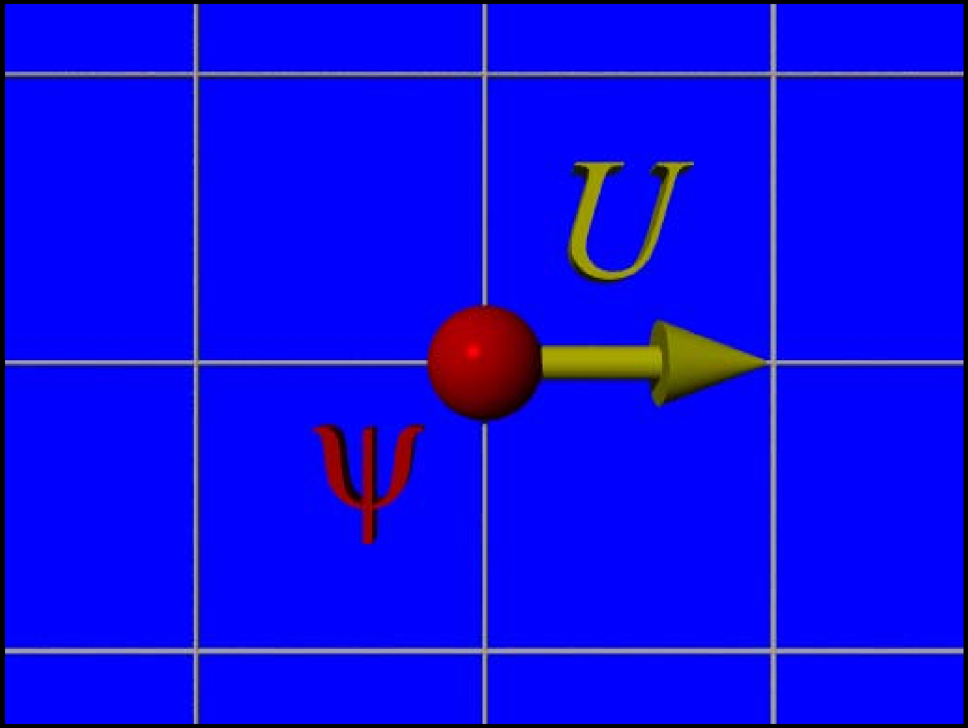
- Space and time are discretized on a four dimensional lattice.
- On a parallel computer, the lattice is divided among all the nodes.



An illustration of how a 16^3 space lattice is partitioned into 8 sub-lattices.

Quarks and Gluons in lattice QCD

- Complex 3x1 quarks vectors, $\psi(x)$, are defined at lattice sites.
- Complex 3x3 gluon matrices, $U_\mu(x)$, are defined on each lattice link.



Quark and Gluon Interactions

A simple discretized form of the Dirac operator is

$$\not{D}\psi(x) = \frac{1}{2a}\sum_{\mu}\gamma_{\mu}[U_{\mu}(x)\psi(x+a\hat{\mu}) - U_{\mu}^{\dagger}(x-a\hat{\mu})\psi(x-a\hat{\mu})]$$

Quark and gluon interactions are represented by the algebra of complex 3x3 (gluon) matrices and 3x1 (quark) vectors at adjacent sites.

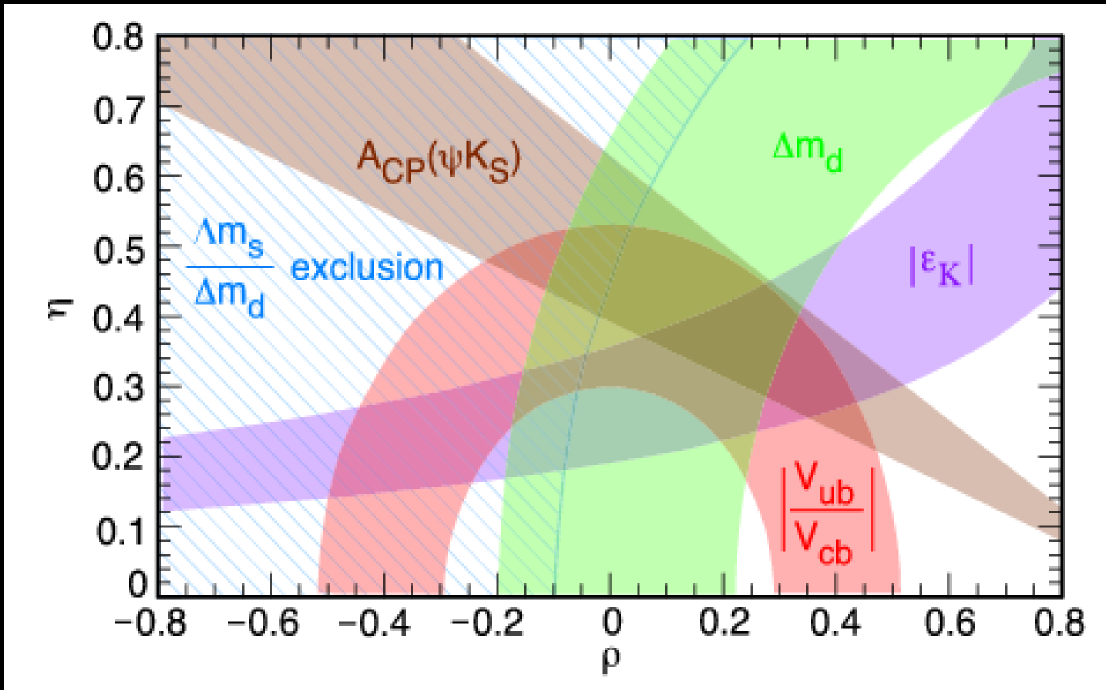
The dominant computation is repeated inversion of the (sparse matrix) Dirac operator via the Conjugate Gradient method.

Why do Lattice QCD?

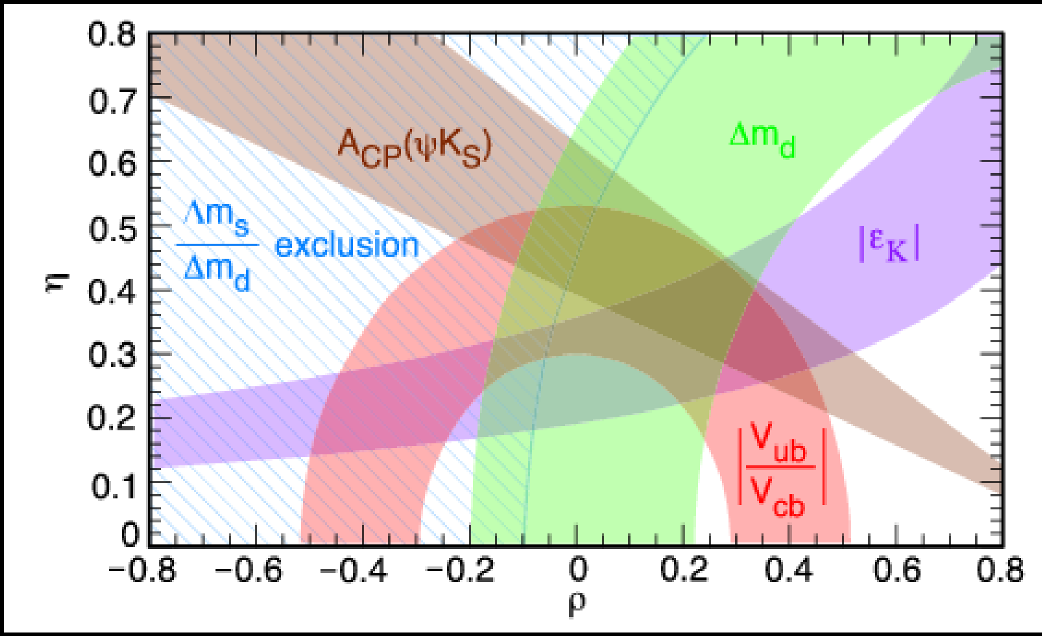
- Many QCD problems can only be simulated numerically, using Lattice QCD
- To test the Standard Model, physicists take experimental data and compare to the theoretical predictions of QCD
  - Differences may indicate new physics, for example, explaining why the universe is dominated by matter and has so little anti-matter

Testing the Standard Model

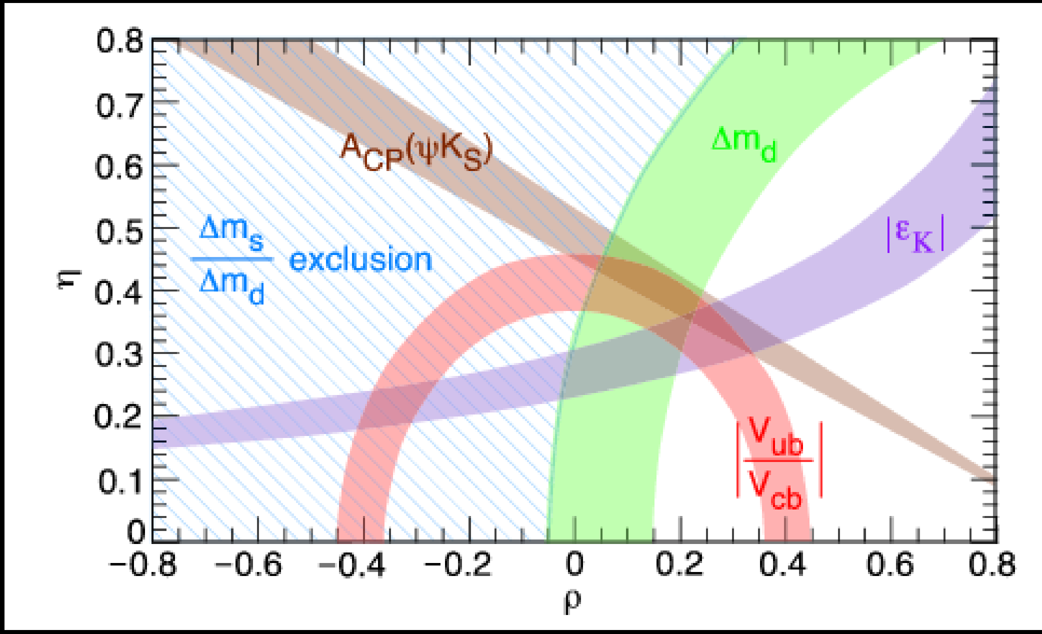
- Regions of different colors correspond to different constraints from theory and experiment
- The intersection of the colored regions is allowed by the Standard Model



Testing the Standard Model

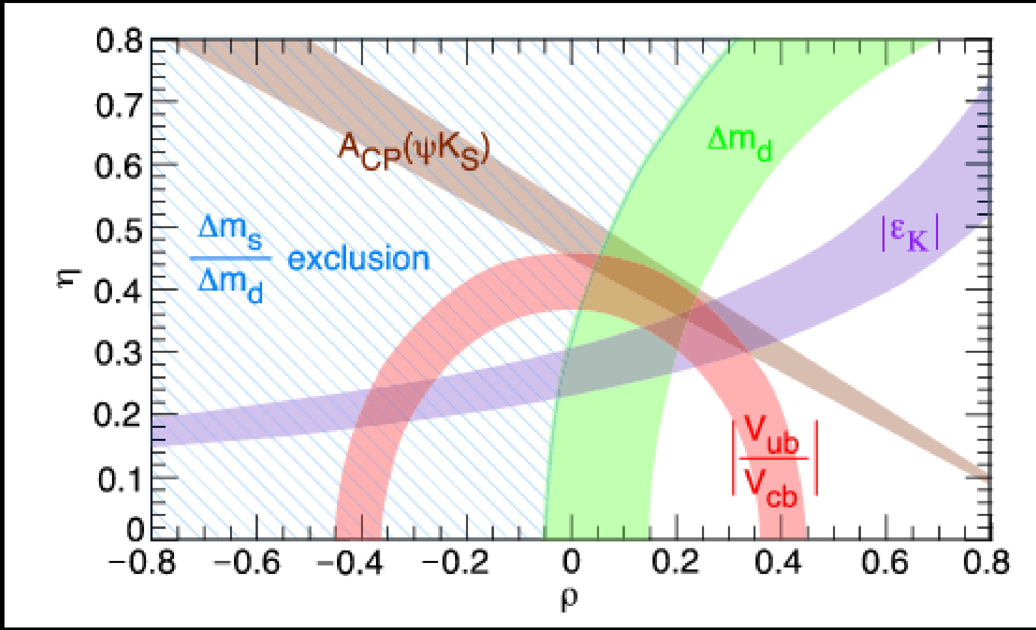


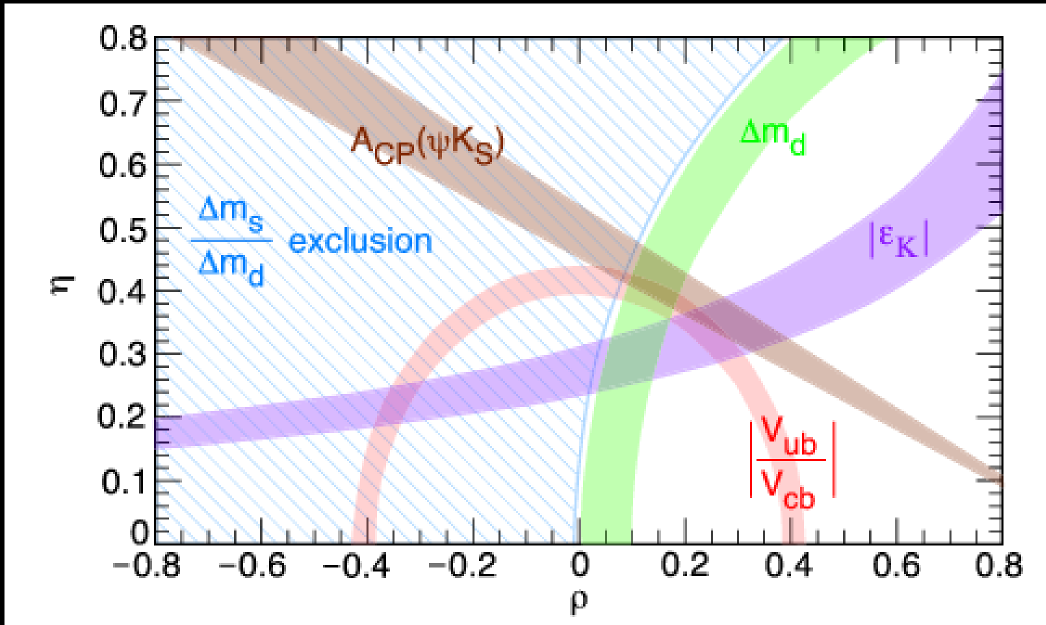
- New B-factory experiments, such as BaBar at SLAC and Belle at KEK, will reduce the experimental errors, shrinking the areas of each region



Testing the Standard Model

- Even tighter constraints will result from better theoretical calculations from Lattice QCD
- If the regions don't overlap, there must be new physics!

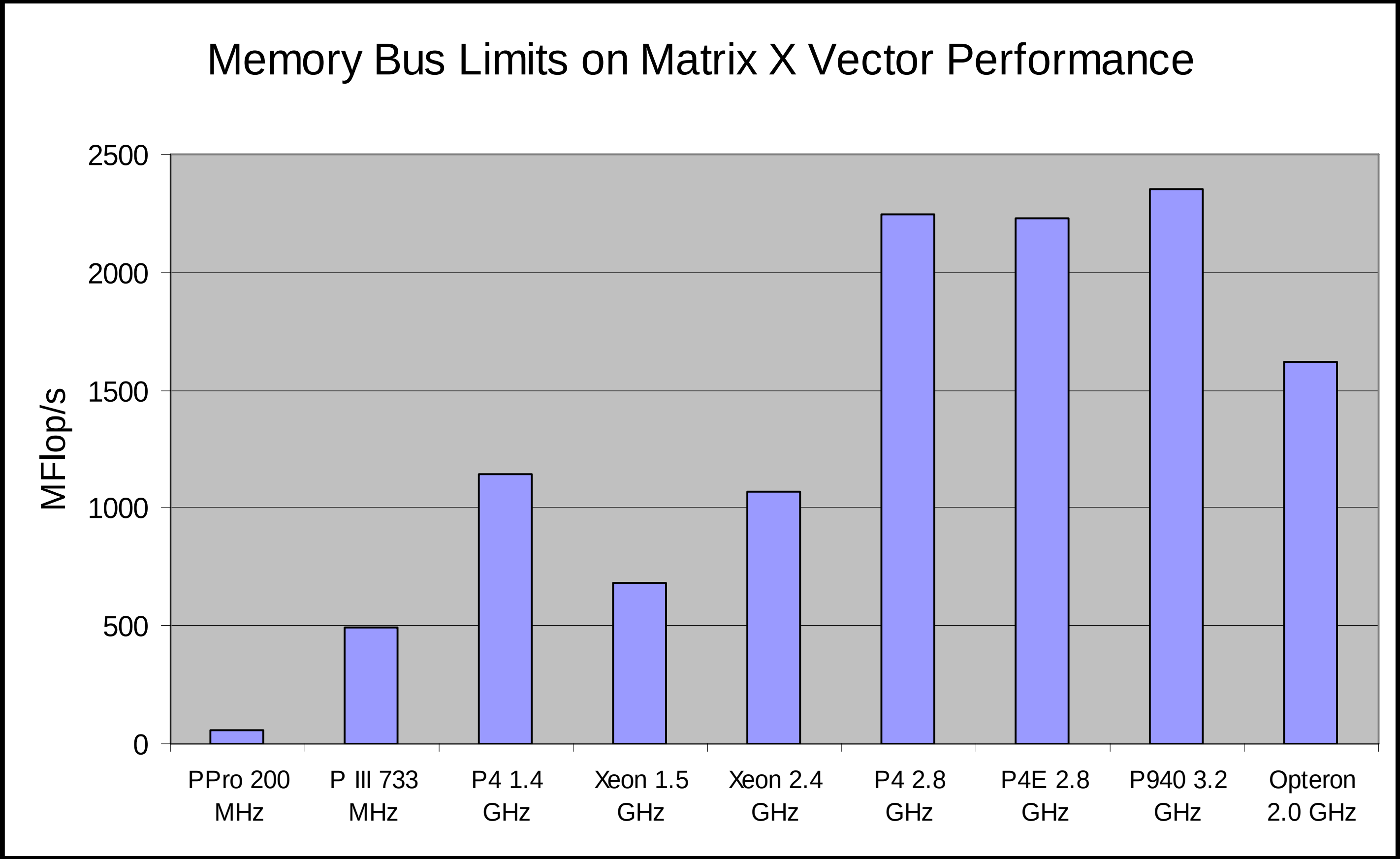




Machines for Lattice QCD

- Lattice QCD codes require:
  - excellent single and double precision floating point performance
    - majority of Flops are consumed by small complex matrix-vector multiplies (SU3 algebra)
  - high memory bandwidth (principal bottleneck)
  - low latency, high bandwidth communications
    - typically implemented with MPI or similar message passing APIs

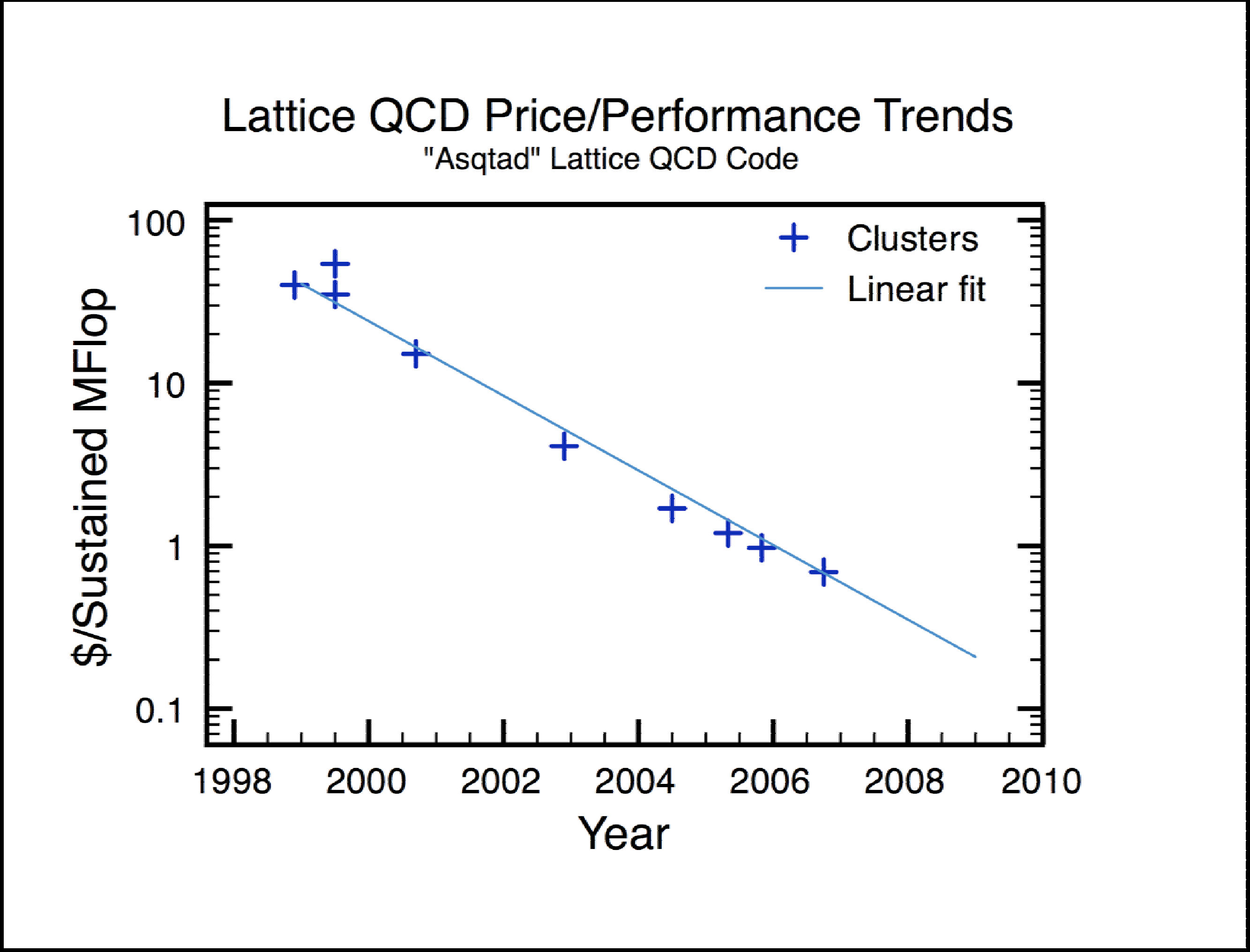
Memory Bandwidth Limits Performance



Lattice QCD Clusters at Fermilab

Cluster	QCD	Pion	Kaon
Nodes	128	520	600
Processor	2.8 GHz Pentium 4E	3.2 GHz Pentium 940	2.0 GHz Dual Opteron 270
Network	Myrinet 2000	Infiniband 4X (SDR)	Infiniband 4X (DDR)
Performance	0.14 Tflop/s	0.86 Tflop/s	2.6 Tflop/s

Performance Trends – Clusters



For More Information

- Fermilab lattice QCD portal:
  http://lqcd.fnal.gov/
- US lattice QCD portal:
  http://www.lqcd.org/