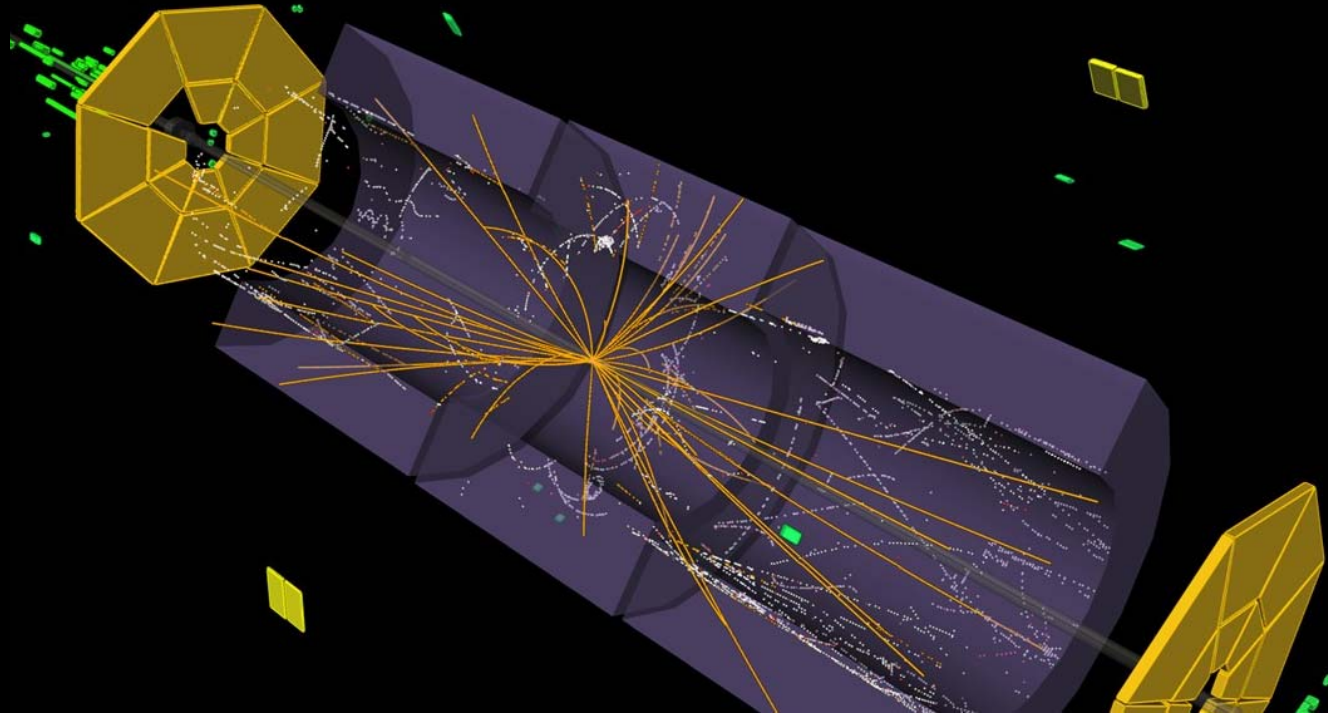


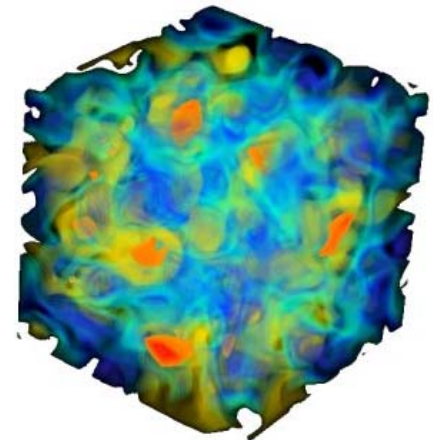
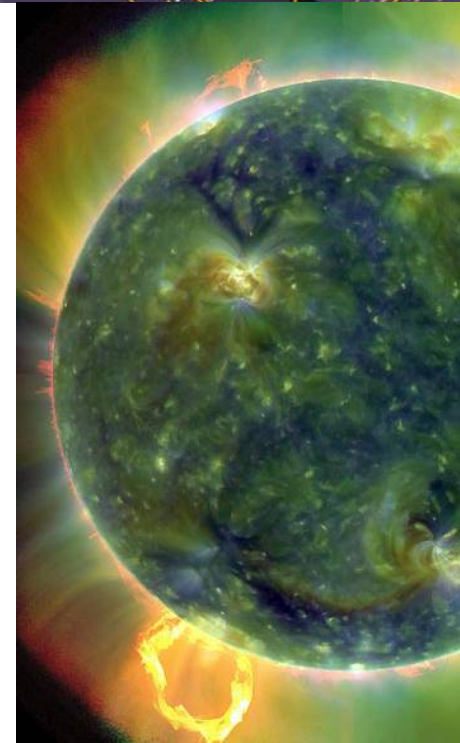
Solving the Mysteries of Quarks

Richard Kenway
University of Edinburgh



Quantum Chromodynamics (QCD)

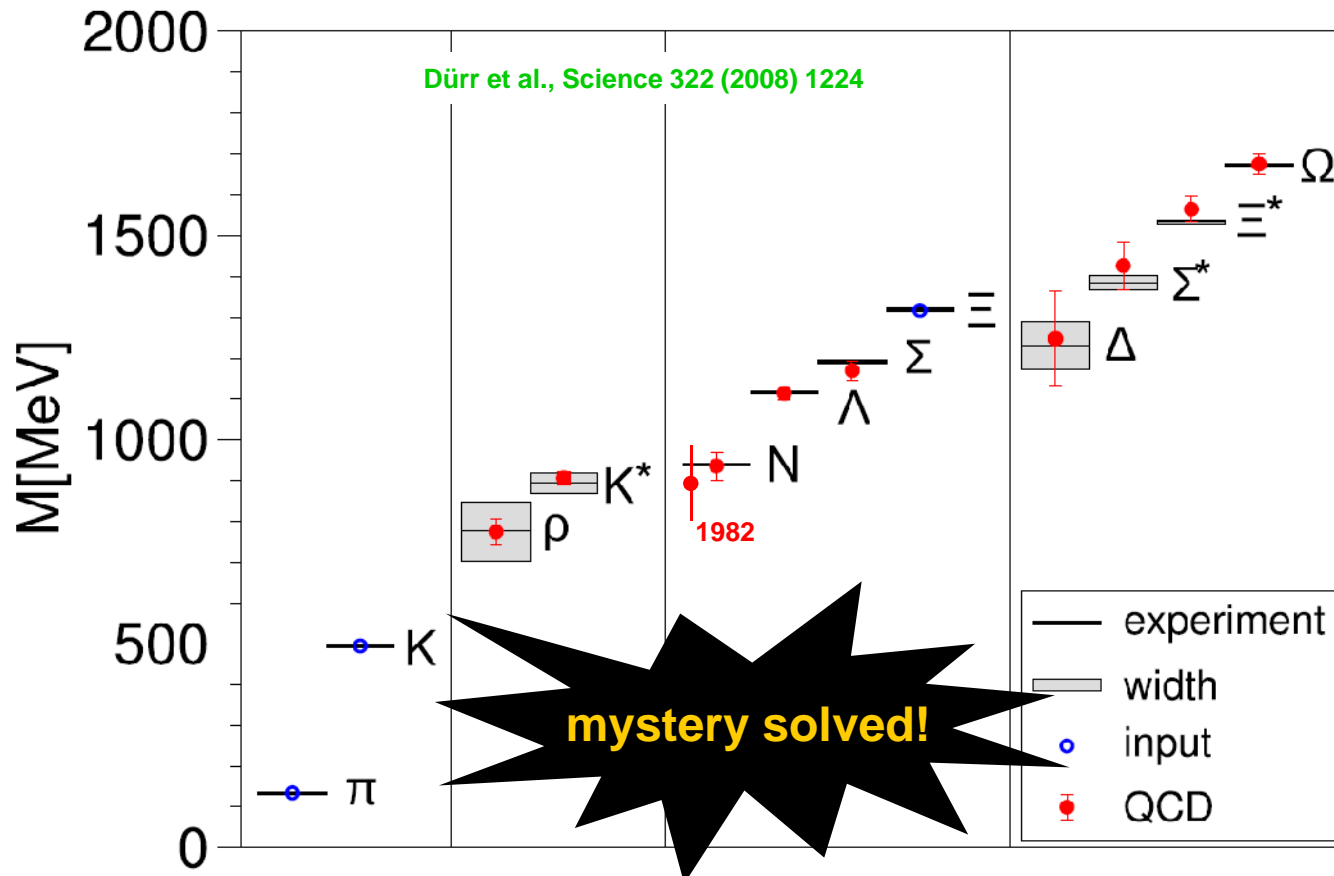
- quantum field theory of the strong interaction
 - a gauge theory like quantum electrodynamics
 - binds quarks and gluons into hadrons
- Euclidean spacetime lattice \rightarrow 4D statistical mechanics
 - Monte Carlo works at zero chemical potential
- continuum limit at the critical point $g^* = 0$
(asymptotic freedom)
 - physical correlation lengths diverge on the scale of the lattice spacing
 - continuum symmetries restored in QCD universality class
- only inputs are the quark masses and the unit of length
 - truly *ab initio* simulations
 - rigorous demands on computers, software and algorithms



What is mass?

- 99% of the observable (bright) mass in the Universe comes from QCD
- explains why the proton mass is far below the Planck scale / gravity is weak

$$\frac{\text{gravitational force}}{\text{electrostatic force}} \approx 137 \frac{M_{\text{proton}}^2}{M_{\text{Planck}}^2} \approx 10^{-36} \quad M_i = c_i \Lambda_{\text{QCD}} = c_i \frac{1}{a} \exp\left(-\frac{1}{2\beta_0 g(a)^2}\right) \approx c_i M_{\text{Planck}} \exp\left(-\frac{1}{2\beta_0 g(M_{\text{Planck}}^{-1})^2}\right)$$

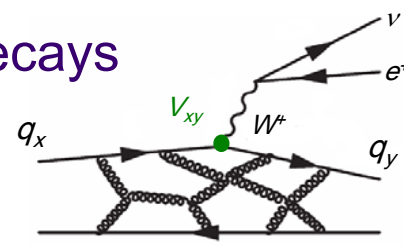


quark masses
encrypted in
hadron masses

u and d masses
are smaller than
symbols

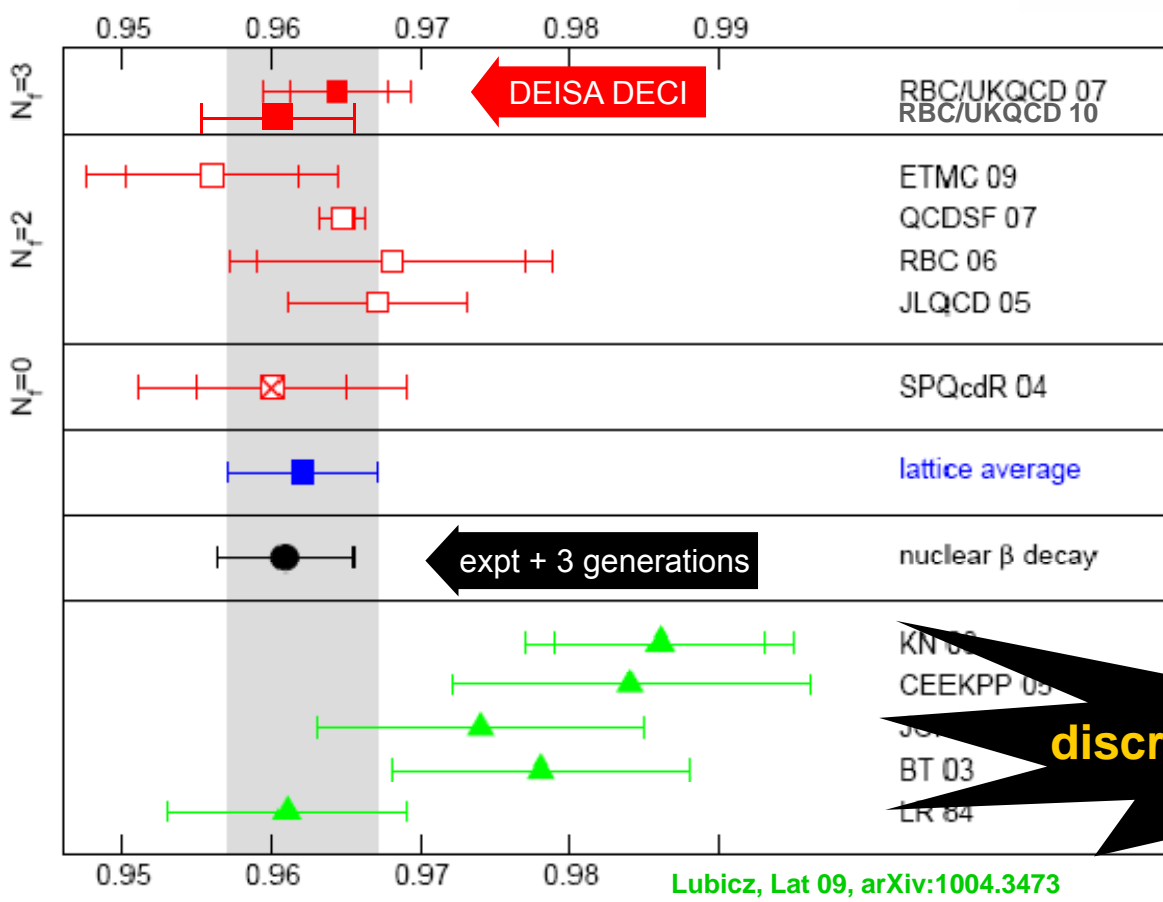
Why are there 3 generations?

- needed for matter-antimatter asymmetry
- consistent with experiment, eg $K \rightarrow \pi \ell \nu$ decays



Leptons	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
	e electron	μ muon	τ tau
	I II III The Generations of Matter		

Quarks	u up	c charm	t top
	d down	s strange	b bottom



- determines a fundamental parameter of the Standard Model

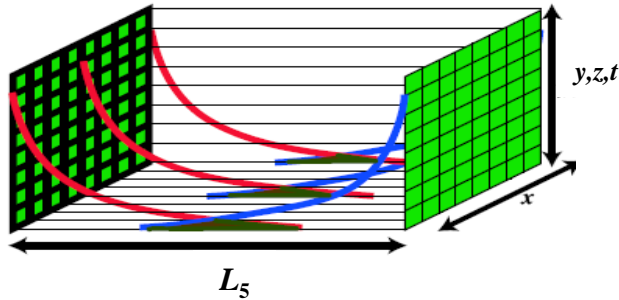
$$|V_{us}| = 0.2252(13)$$



Why are the quark masses so different?

- Why are some quarks light?

- massless fermions are trapped naturally on 4D walls in 5D spacetime



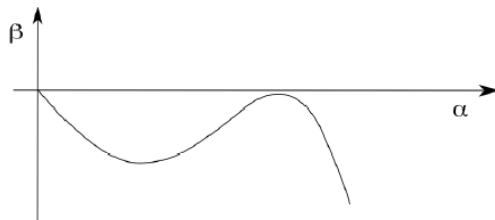
$$m_q \approx \frac{e^{-\alpha L_5/a_5}}{L_5} + \frac{\rho(0)}{L_5} \xrightarrow{a_5 \rightarrow 0} \frac{\rho(0)}{L_5} \xrightarrow{a \rightarrow 0} 0$$

4D extended states don't leak into 5D
density of localised 4D zero modes vanishes

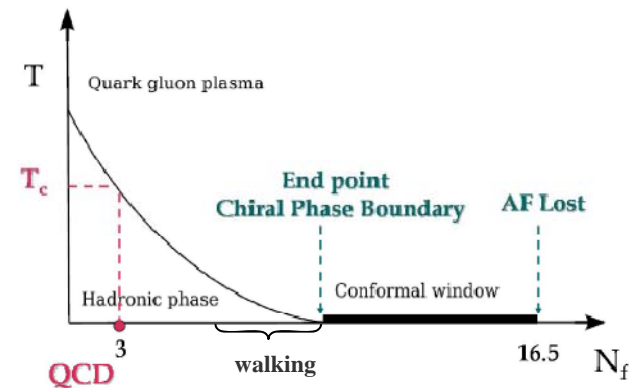
→ 5D simulations

- Why are some quarks heavy?

- electroweak symmetry is broken dynamically by technicolor
- multi-GeV quark masses (*c*, *b* and *t*) + experimental limits (FCNC) demand new strong dynamics, eg walking



→ simulation is essential



Extreme computing

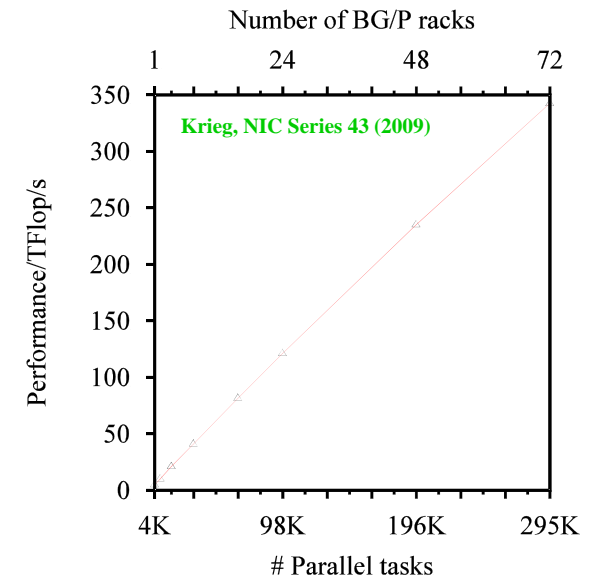
QCD as a co-design vehicle

- Computational challenges
 - seek discrepancies between Standard Model and experiment to discover new physics
 - explore new strong dynamics
 - complexity grows faster than computational volume
- Path to exascale
 - performance gap is 10,000 ×
 - weak scaling should provide 10-100
 - strong scaling must provide 10-100
- Priority software challenges
 - uncertainty quantification and fault tolerant algorithms
 - high speed complex linear algebra for multi-core nodes to efficiently exploit memory bandwidth, eg using mixed precision
- Other key developments
 - high speed inter-node communications and global operations
 - high bandwidth parallel I/O
 - multi-scale algorithms
 - world-wide data sharing (ILDG)

INTERNATIONAL
EXASCALE
SOFTWARE PROJECT



Jack Dongarra	Alok Choudhary	Yutaka Ishikawa	Paul Messina	John Shalf	Aad van der Steen
Peta Beckman	Sudip Dossanjh	Fred Johnson	Bernd Mohr	David Skinner	Fred Stretz
Terry Moore	Al Geist	Sanjay Kale	Matthias Mueller	Thomas Sterling	Bob Sugar
Jean-Claude Andre	Bill Gropp	Richard Kenway	Wolfgang Nagel	Rick Stevens	Shinji Sumimoto
Jean-Yves Berthou	Robert Harrison	Bill Kramer	Hiroshi Nakashima	William Tang	Jeffrey Vetter
Taisuke Boku	Mark Herold	Jesus Labarta	Michael E. Papka	John Taylor	Robert Wisniewski
Franck Cappello	Michael Heroux	Bob Lucas	Dan Reed	Rajeev Thakur	Robert Wisniewski
Barbara Chapman	Adolfo Hoisie	Barney Maccabe	Mitsuhsa Sato	Anne Trefethen	Kathy Yelick
Xuebin Chi	Koh Hotta	Satoshi Matsuoka	Ed Seidel	Marc Snir	



- QCD is the correct low-energy theory of the strong force
 - lattice QCD is now an integral part of experimental data analysis
- There is physics beyond the Standard Model
 - neutrino masses, dark matter, dark energy, ...
- LHC era mysteries
 - either the Higgs boson is elementary → supersymmetry
 - or, it is composite → new strong dynamics
- Exascale era computational challenges
 - lattice QCD analysis package: data grid + petascale servers
 - many theories of new strong dynamics to explore through simulation
 - QCD has a successful track record of co-design