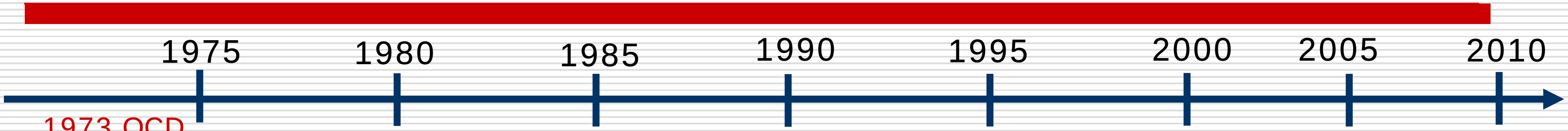
Seminar at ICRR
16 April 2010

Akira Ukawa
University of Tsukuba

Present and Future of Lattice QCD

Lattice QCD over the years...

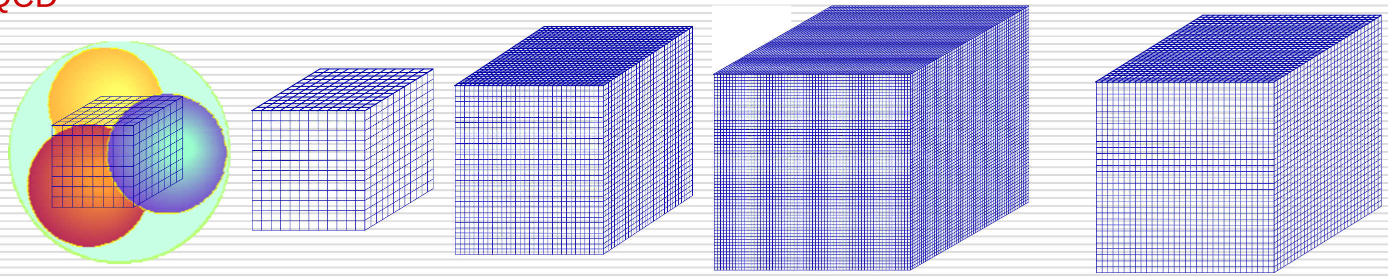


1973 QCD

1974 lattice QCD

Physics

1^{st} spec calculation
1981
Hamber-Parisi
Weingarten



Lattice size L

0.8fm 8^3x16

1.6fm 16^3x32

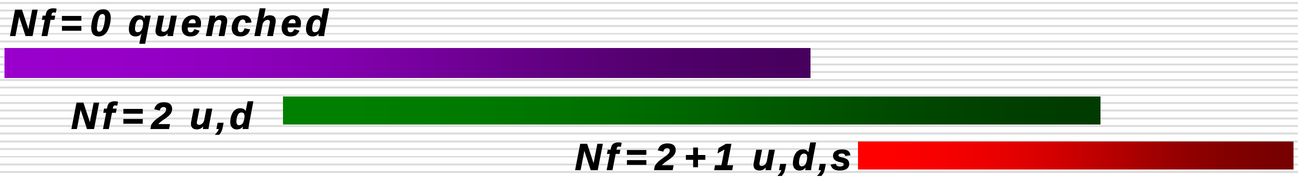
2.4fm 24^3x48

3.0fm 64^3x118

3.0fm 32^3x64

Algorithms

Nf =#sea quarks



Machines

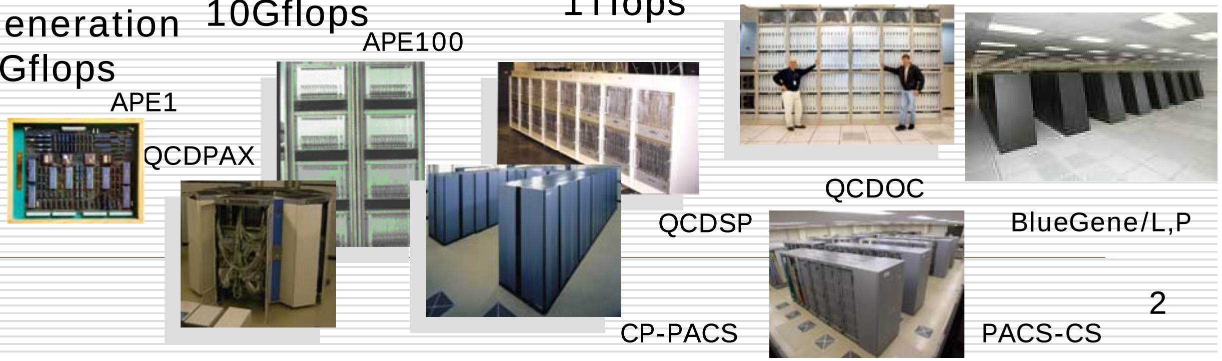
1st generation
1Gflops

2^{nd} generation
10Gflops

3^{rd} generation
1Tfops

4^{th} generation
10Tfops

100Tflops



My personal feeling

- Lattice QCD is finally turning a corner in the last couple of years.
- Previously, despite the premise, it remained an approximate method requiring extrapolations in a number of ways (quenching, unphysically heavy quark masses, etc).
- Progress over the years has been removing these restrictions, and it is now becoming a *real first principle method,* not only in principle but also *in practice*, for actually calculating physical quantities *at the physical point on physically large lattices, i.e., Nature*.

What I wish to do today

Review recent progress and try to share this feeling with you

- Algorithmic progress
- Flavor physics
- High temperature/density QCD
- No more nuclear physics?
- Computer trends -if time allows-
- Conclusions

Algorithmic progress

Quantum Chromodynamics

Gross-Wilczek-Politzer 1973

- Quantum field theory of quarks and gluons

$q_f(x)$ Quark field

$A_\mu(x)$ Gluon field

$\Big\}$ defined over 4-dim space time

$$L_{QCD} = \frac{1}{8\pi\alpha_s} Tr\left(F_{\mu\nu}F_{\mu\nu}\right) + \sum_f \bar{q}_f \left(\gamma_\mu \cdot \left(\partial_\mu - iA_\mu\right) + m_f\right) q_f$$

QCD lagrangian

$$\left\langle O\left(A, \bar{\psi}, \psi\right)\right\rangle = \frac{1}{Z} \int dA d\bar{q} dq O\left(A, \bar{q}, q\right) e^{-\int d^4x L_{QCD}}$$

Physical quantities by
Feynman path integral

- Knowing

1 coupling constant $\alpha_s = \frac{g_s^2}{4\pi}$
and
6 quark masses $m_u, m_d, m_s, m_c, m_b, m_t$

will allow full understanding of hadrons and their strong interactions

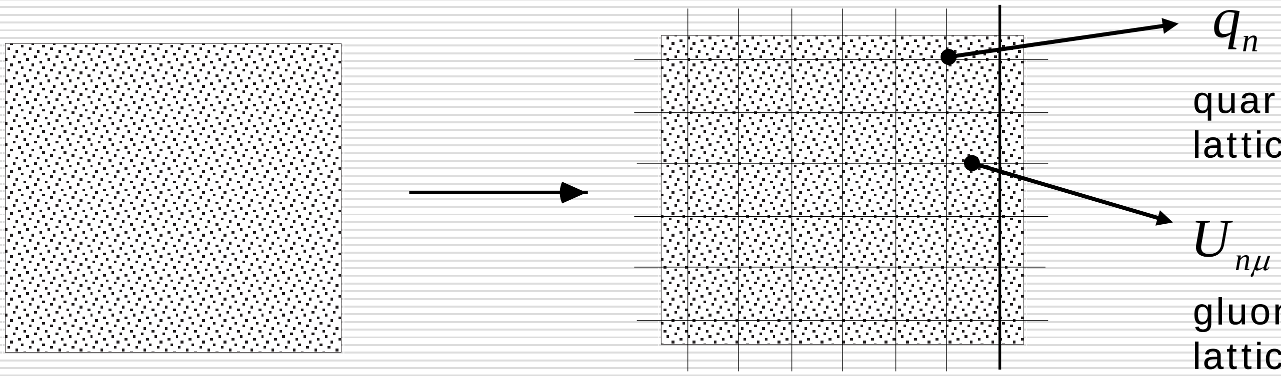
"fulfilling Yukawa's dream of 1934 in a refined way"

QCD on a space-time lattice

K. G. Wilson 1974

Space-time continuum

Space-time lattice



q_n

quark fields on lattice sites

$U_{n\mu}$

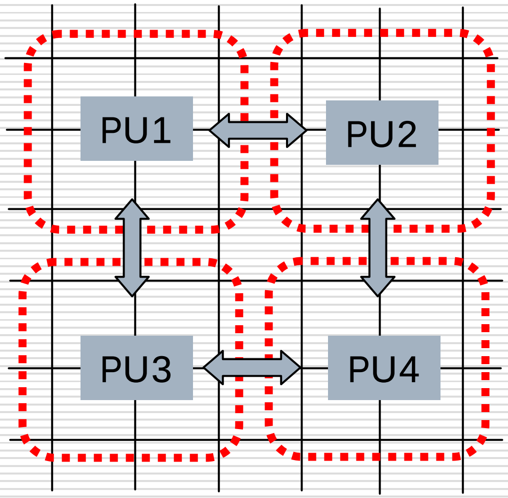
gluon fields on lattice links

- ☐ Feynman path integral
  - Action $S_{QCD} = \frac{1}{g_s^2}\sum_P tr(UUUU) + \sum_f \bar{q}_f (\gamma \cdot U + m_f) q_f$
  - Physical quantities as integral averages ⇨ Monte Carlo calculation of the integral average

$$\langle O(U,\bar{q},q)\rangle = \frac{1}{Z}\int \prod_{n\mu} dU_{n\mu} \prod_n d\bar{q}_n dq_n \; O(U,(U,\bar{q},q)) e^{-S_{QCD}}$$

Lattice QCD as computation(I)

- QCD is a local field theory; only nearest neighbor interactions
- Natural mapping of space-time lattice to processor array
  - Each compute node carries a sub-lattice
  - Only nearest neighbor communication needed



→ Highly parallelizable and scalable

Lattice QCD as computation(II)

- Quarks are fermions, so their field, being anti-commuting, needs a special trick

$$\underset{\text{Grassmann rep}}{\int \prod_n d\bar{q}_n dq_n \, e^{-\sum_{n,m} \bar{q}_n D_{nm}(U) q_m}} = \det D(U) = \underset{\text{Boson rep}}{\int \prod_n d\bar{\phi}_n d\phi_n \, e^{\boxed{-\sum_{n,m} \bar{\phi}_n \left(\frac{1}{D(U)}\right)_{nm} \phi_m}}}$$

- Need to invert the lattice Dirac operator D(U)
  - Sparse but large matrix
  - Large condition number ~ $1/m_q$ for quarks in nature

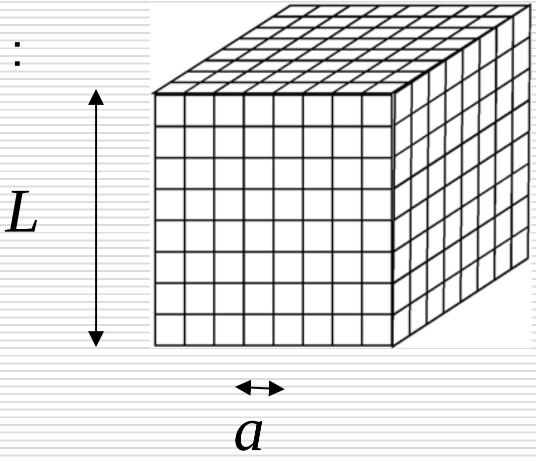
$$\sum_m D_{nm}(U) x_m = \phi_n \Rightarrow x_n = \left(\frac{1}{D(U)}\right)_{nm} \phi_m$$

Core calculation of QCD

⇨ Computationally very intensive

Difficulties with light quark masses

- Parameters of lattice QCD simulation:
  - Quark mass $m_q \text{ or } m_\pi \propto \sqrt{m_q}$
  - Lattice size $L\left(fm\right)$
  - Lattice spacing $a\left(fm\right)$



- #arithmetic ops of hybrid Monte Carlo (HMC) algorithm for Nf=2 flavor full QCD(2001)

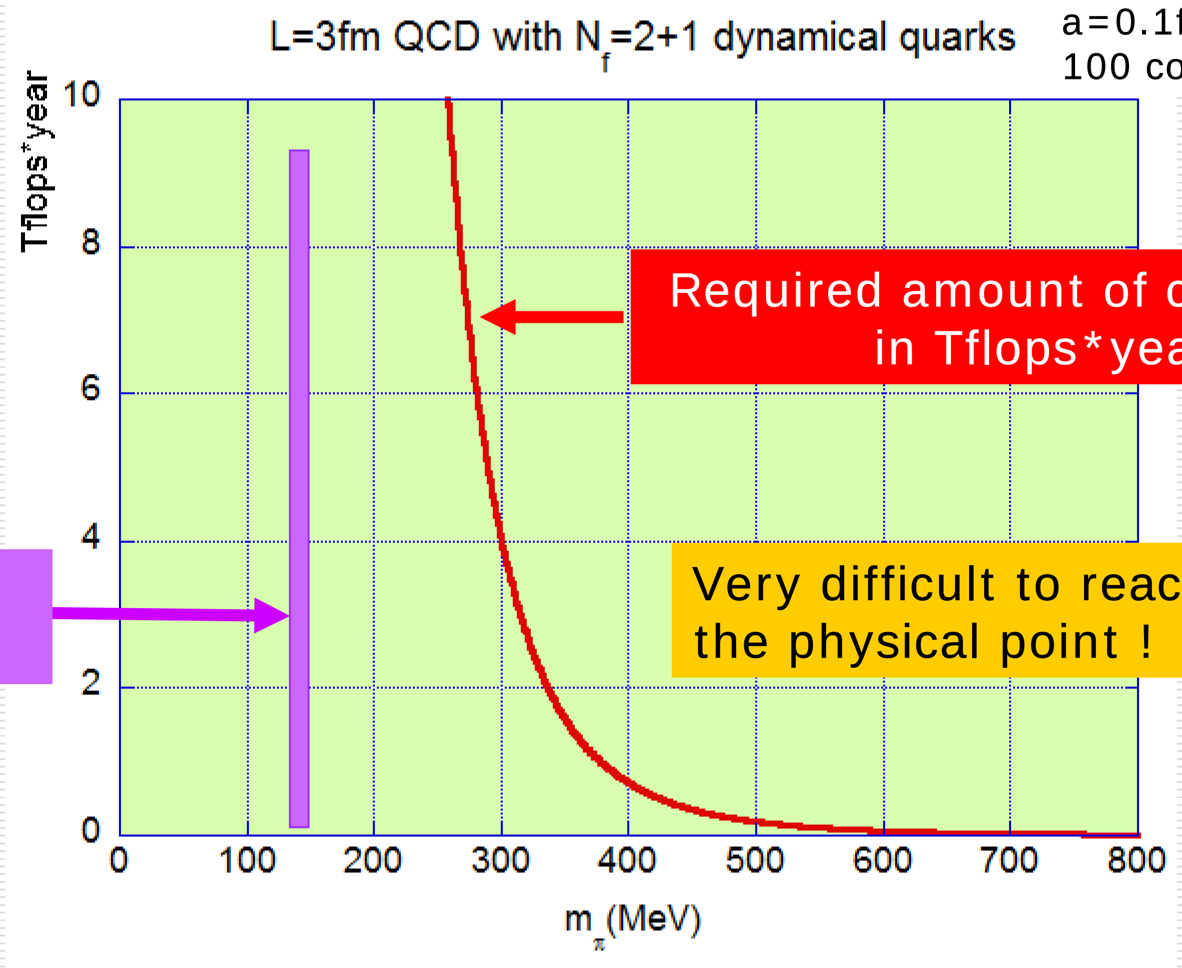
$$\#FLOP's \approx 1.9\left[\frac{\#conf}{1000}\right]\cdot\left[\frac{m_\pi}{500MeV}\right]^{-6}\cdot\left[\frac{L}{3\,fm}\right]^{5}\cdot\left[\frac{a}{0.1\,fm}\right]^{-7} Tflops\cdot year$$

  - Severe scaling toward small pion mass /large volume/small lattice spacing

“Berlin wall” at Lattice 2001@Berlin

A. Ukawa for CP-PACS and JLQCD

a=0.1fm
100 configurations

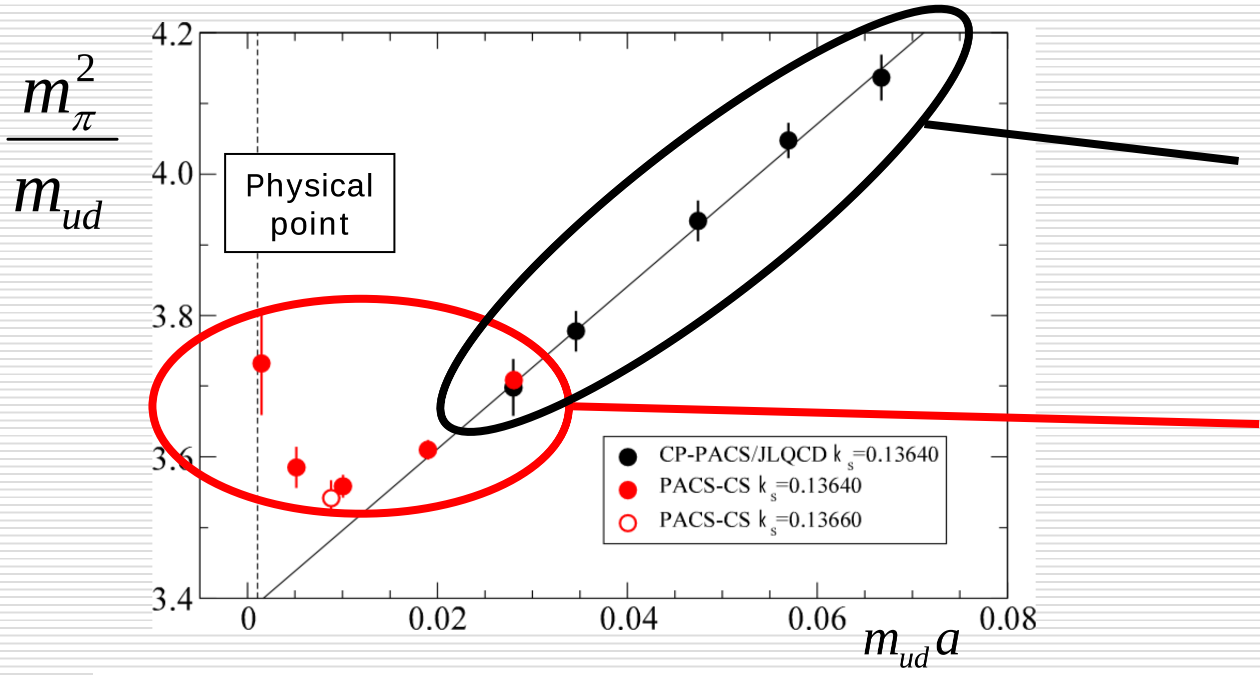


Required amount of computing in Tflops*year

Physical point
i.e., m_π=135MeV

Very difficult to reach the physical point !

Why so important to go physical?



Previous calculation with CP-PACS/Earth Simulator (2001～2005)

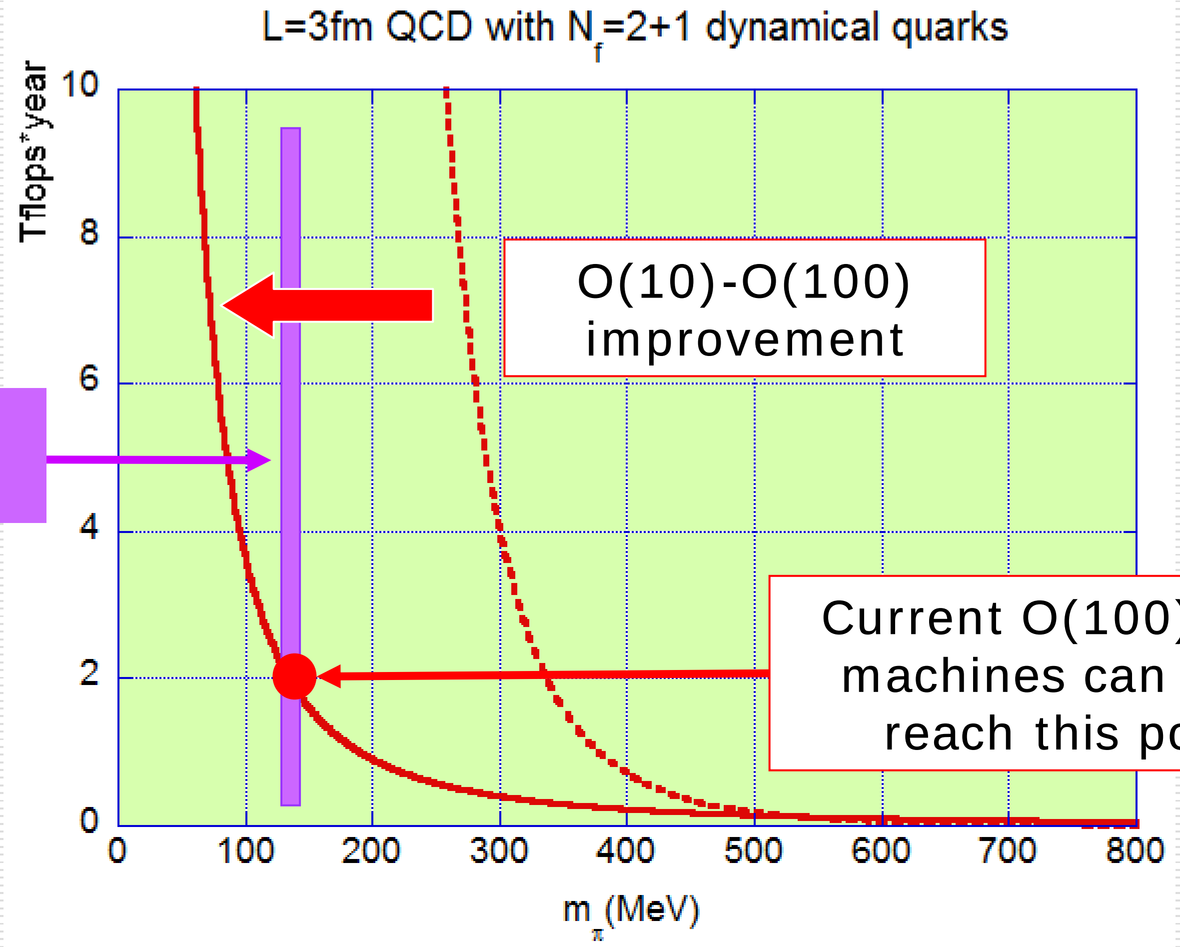
Recent calculation with PACS-CS (2006～2008)

- Anticipated effect of *chiral logarithm* at zero quark mass

$$\frac{m_\pi^2}{m_{ud}} \propto 1 + \frac{2Bm_{ud}}{(4\pi f)^2} \log \frac{2Bm_{ud}}{\mu^2} + \cdots$$

- However, extrapolation difficult to control since
  - Convergence radius a priori not known
  - Have to determine a number of unknown constants

Improved HMC algorithm



O(10)-O(100) improvement

Physical point i.e., m_π=135MeV

Current O(100)Tflops machines can easily reach this point!

Physical point simulation has become reality

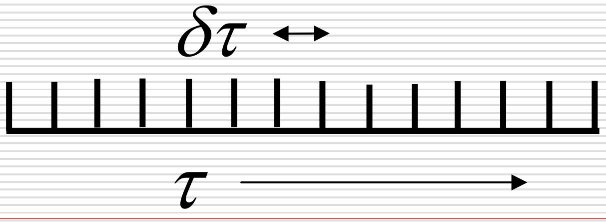
How that progress came about?

- Molecular dynamics equation of hybrid Monte Carlo algorithm

$$\frac{d}{d\tau}U_{n\mu} = -iU_{n\mu}P_{n\mu}$$

$$\frac{d}{d\tau}P_{n\mu} = F_{n\mu} = \overset{\text{gluon force}}{\frac{1}{g^2}\left(UUUU\right)_{n\mu}} + \underset{\text{Most time-consuming part of computation}}{\overset{\text{quark force}}{\bar{\phi}\left(\frac{1}{D(U)}\right)\frac{\partial D(U)}{\partial U_{n\mu}}\left(\frac{1}{D(U)}\right)\phi}}$$

- Molecular dynamics equation is integrated in discrete steps, so a larger time step is better!

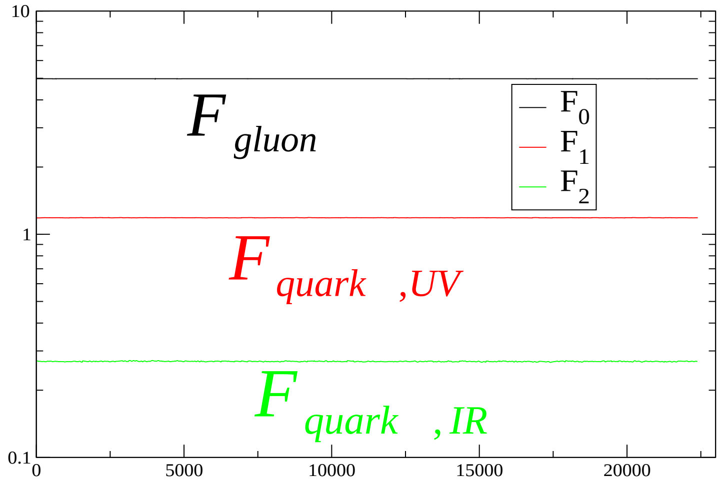


Key observation

M. Luescher (2005)

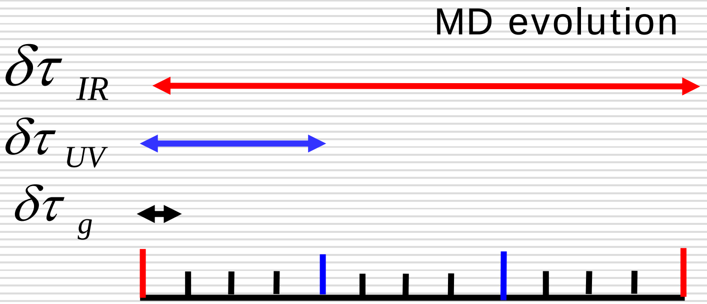
- ☐ Strategy :
  - ■ Separate UV and IR modes of quark fluctuations
  - ■ Use separate time step to UV and IR modes
- ☐ Numerically found:

$$F_{gluon} >> F_{quark,UV} >> F_{quark,I}$$



so take

$$\delta\tau_{gluon} << \delta\tau_{quark,UV} << \delta\tau_{quark,IR}$$



i.e., one can enlarge the time step for the most compute intensive IR quark force, leading to large acceleration of the algorithm.

This is physics.

Recent large-scale Nf=2+1 calculations

- Features
  - Fully incorporates dynamical effects of up, down, strange sea quarks, hence called "Nf=2+1"
  - Pion mass reaching down to $m_\pi \approx 200-300 MeV$

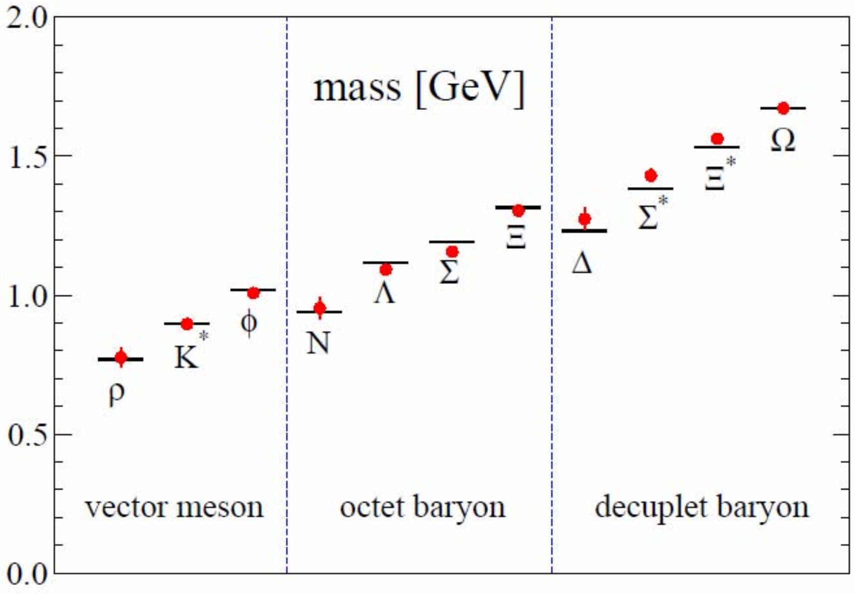
    even attempting the physical point $m_\pi \approx 140 MeV$
  - Lattice size to avoid finite size effects $m_\pi L \approx 3-4$

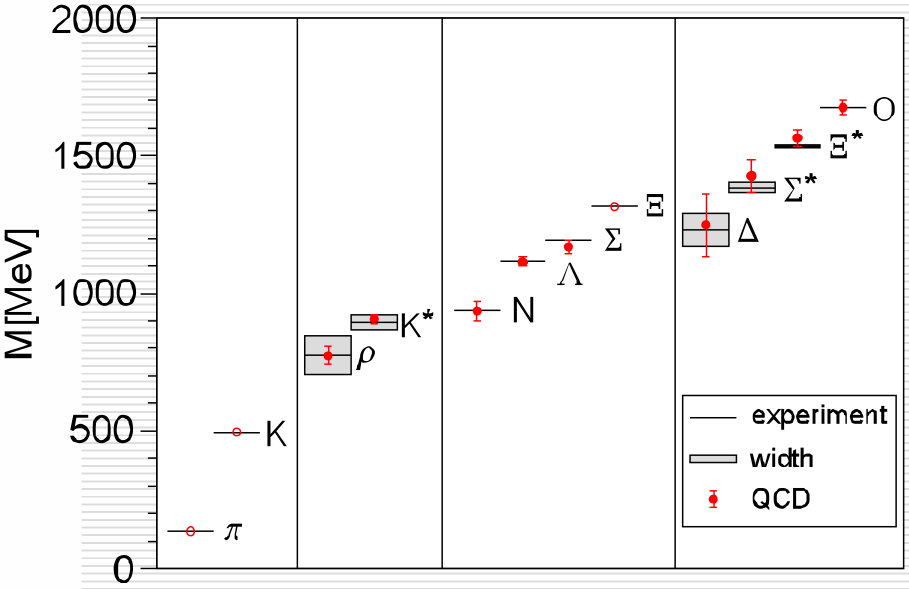
Collaborations	action	a (fm)	L (fm)	m_π (MeV)
MILC	staggered	0.06	4.0	180
PACS-CS	wilson-clover	0.09	2.3	155
BMW	wilson-clover	0.09	4.0	190
RBC-UKQCD	domain-wall	0.09	4.0	290
JLQCD	overlap	0.11	2.8	320
ETMC(Nf=2)	twisted mass	0.07	3.0	250

Hadron spectrum 2008

PACS-CS Collaboration
(Tsukuba, Japan)
Phys. Rev. D79 034504 (2008)

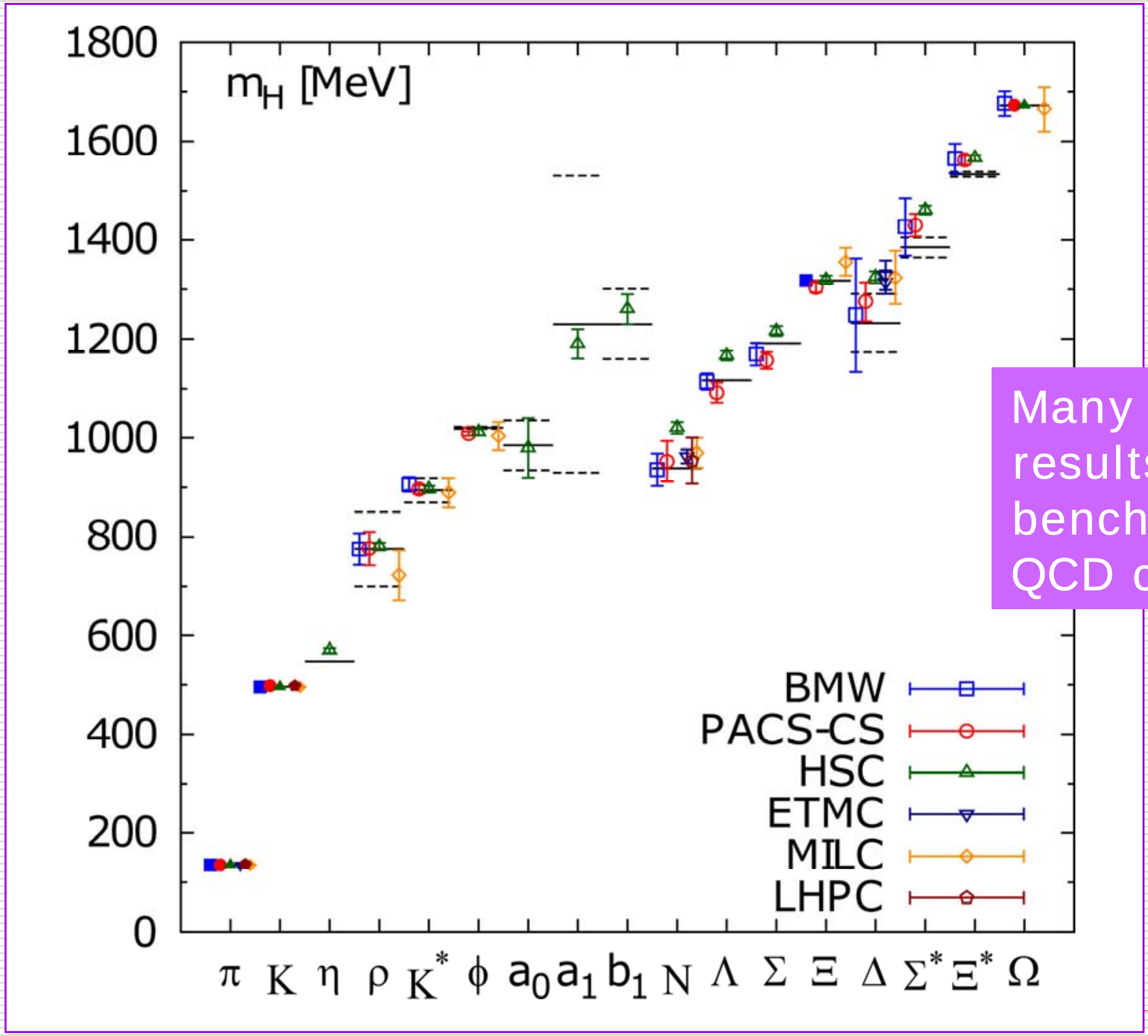
BMW Collaboration
(Butapest-Marseille-Wuppertal)
Science 322(2008) 1224
Continuum extrapolated





Hadron spectrum 2009

From E. Scholz@Lattice 2009



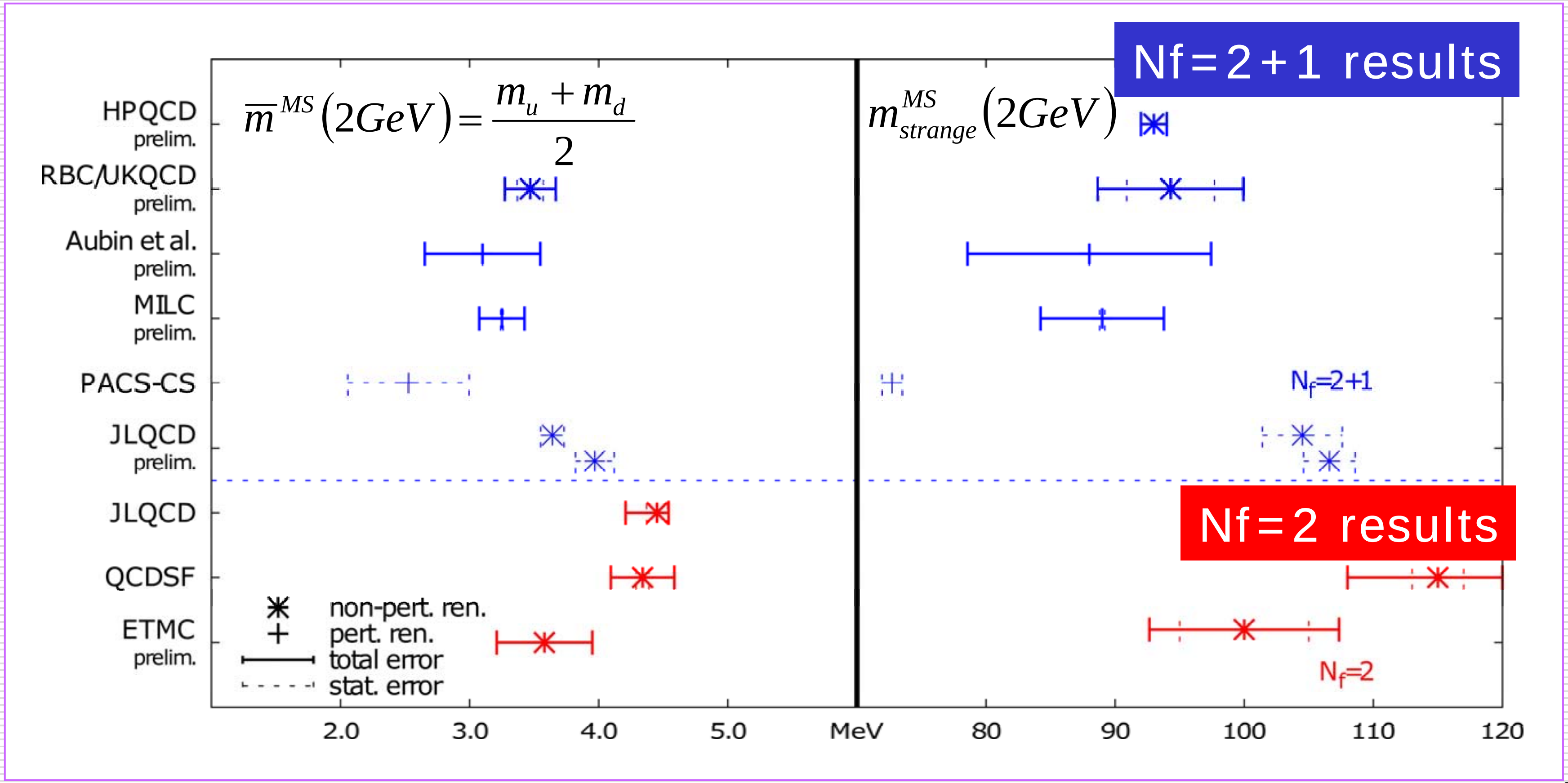
Many more Nf=2+1 flavor results; becoming a basic benchmark of any lattice QCD calculations

Light quark masses – status –

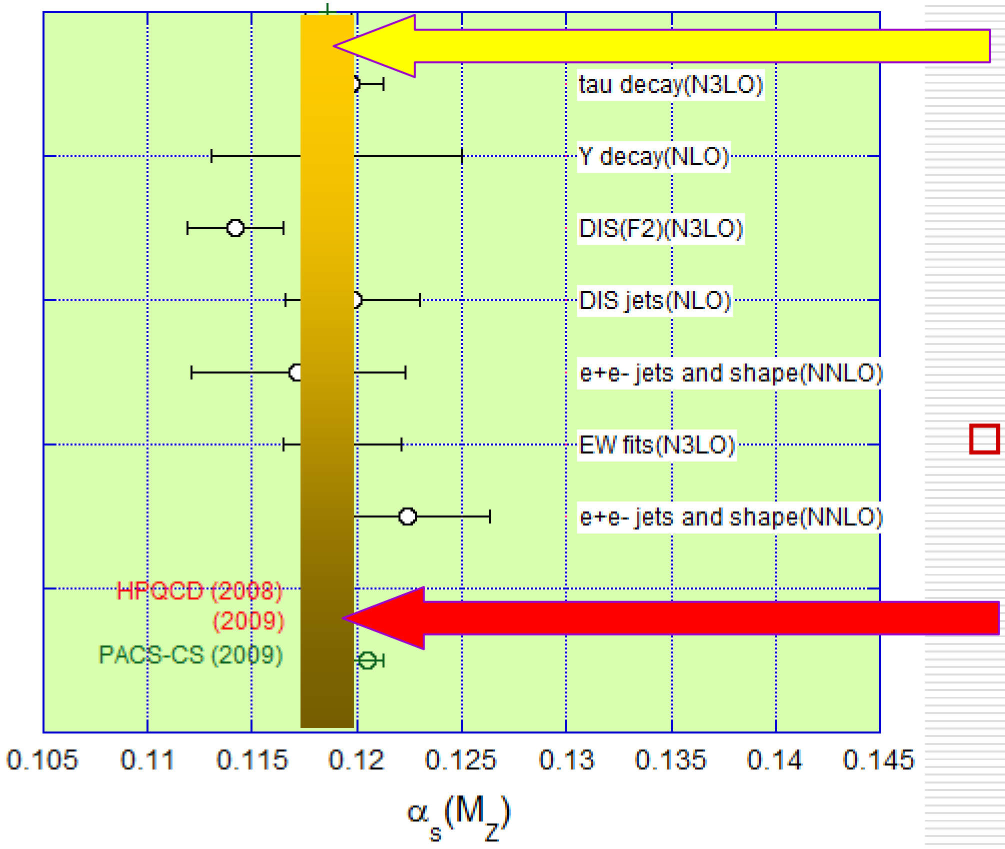
From E. Scholz@Lattice 2009

- Nf=2+1 continuum estimation indicates

$$\overline{m}^{MS}(2GeV) \approx 3MeV, \quad m_s^{MS}(2GeV) \approx 90MeV$$



Strong coupling constant – status -



- ☐ Experimental average

$$\alpha_s^{MS}(M_Z) = 0.1186 \pm 0.0011$$

S. Bethke, ArXiv.0908.1135

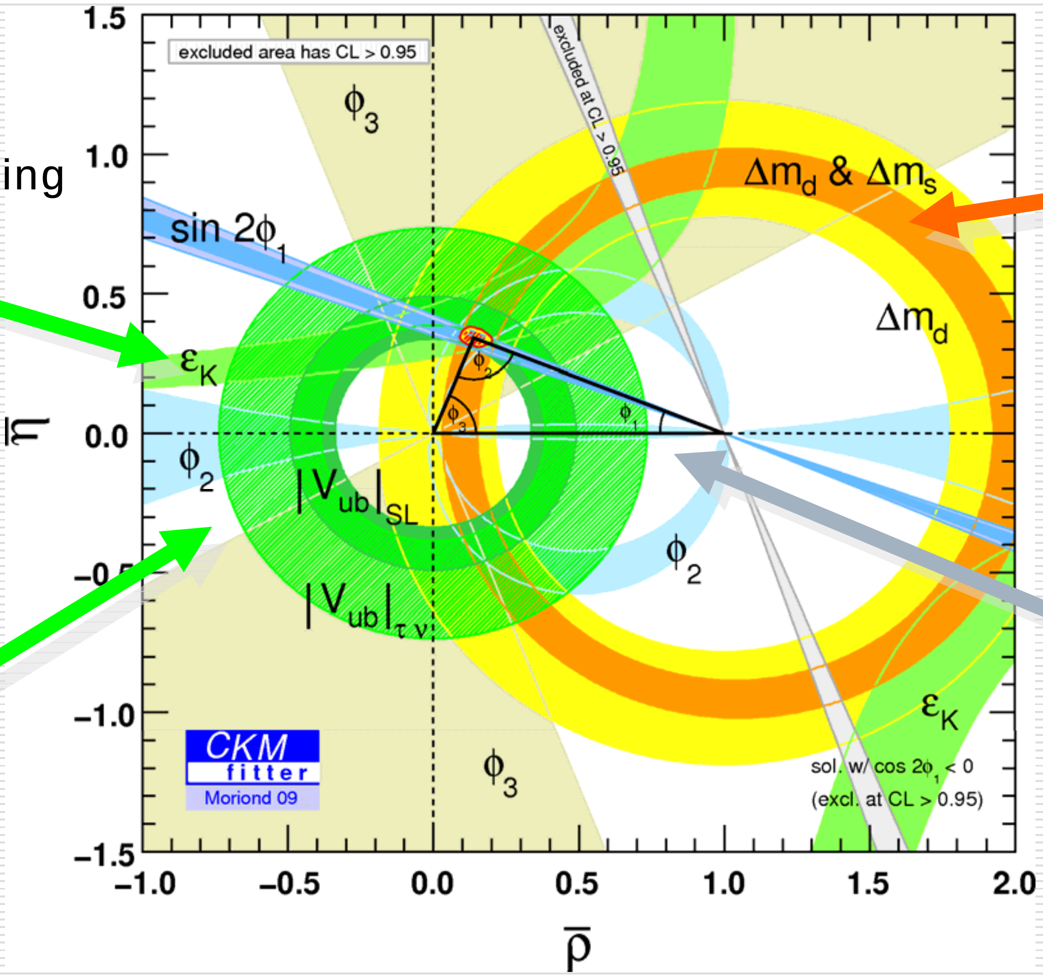
- ☐ Nf=2+1 Lattice QCD

$$\alpha_s^{MS}(M_Z) = 0.1184 \pm 0.0004$$

HPQCD 2009 update
(private communication from C. Davies)

Flavor physics

CKM matrix and lattice QCD



Neutral Kaon mixing

B_K

B-meson decays

$f_+\left(q^2\right)$

B-meson mixings

f_B, B_B

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

B->D* decays

$F(1), G(1)$

Inputs from lattice QCD 2009

Van de Water@Lattice 2009

Quantity	*Value*	*Error*
$\hat{B}_K$	0.725 ± 0.028	4%
ξ	1.243 ± 0.028	2%
$\lvert V_{ub} \rvert_{excl.}$	$3.42 \pm 0.37 \times 10^{-3}$	11%
$\lvert V_{cb} \rvert_{excl.}$	$38.6 \pm 1.2 \times 10^{-3}$	3%
f_K	$155.8 \pm 1.7 MeV$	1%

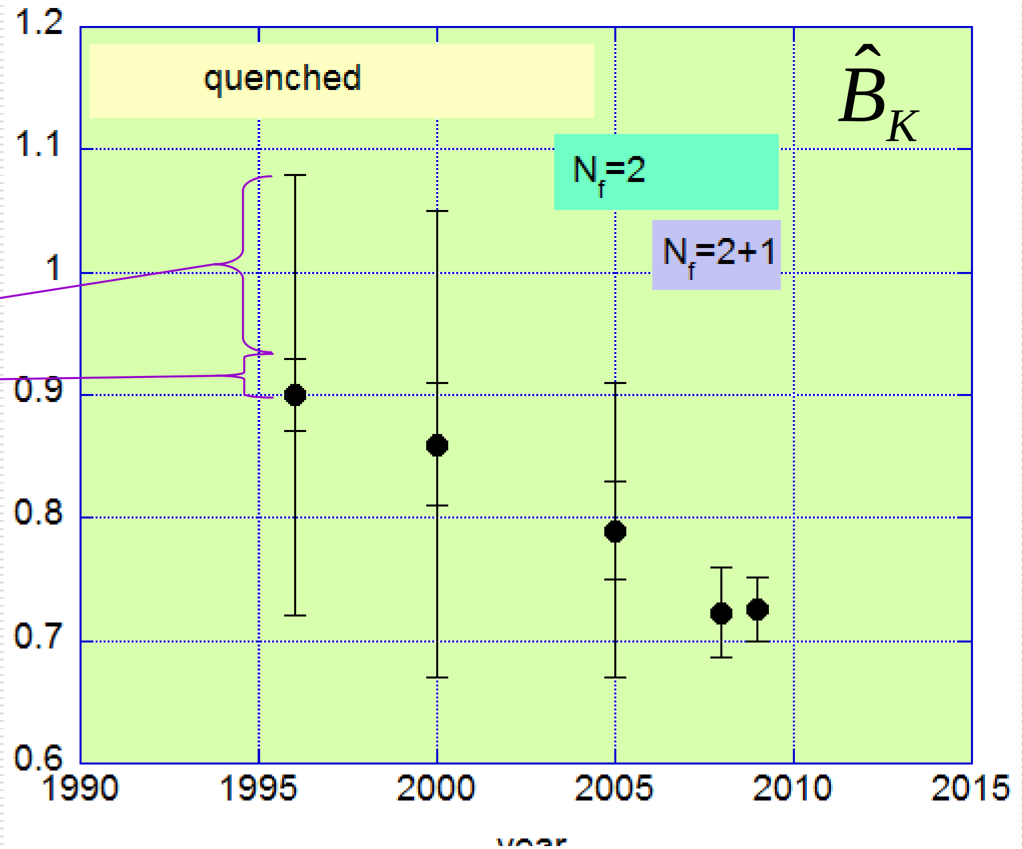
All values

- From Nf=2+1 simulations
- All errors calculated/estimated

  Statistical/Chiral extrapolation/Finite volume/Continuum extrapolation

B_K over the years

- 1996: JLQCD
  - Quenched
  - Continuum extrapolated
- 2008:RBC/UKQCD
  ArXiv 0710.5136
  - Nf=2+1
  - Chiral action
    DWF on DWF sea
  - one lattice spacing
- 2009:Aubin-Laiho-Van de Water
  ArXiv 0905.3947
  - Nf=2+1
  - Chiral action
    Overlap on staggered sea
  - Two lattice spacing and Continuum extrapolated



4% error of B_K is now smaller than 10% error due to $|V_{cb}|^4$ in ε_K

CKM status with lattice inputs 2009

From R. Van de Water @ Lattice2009

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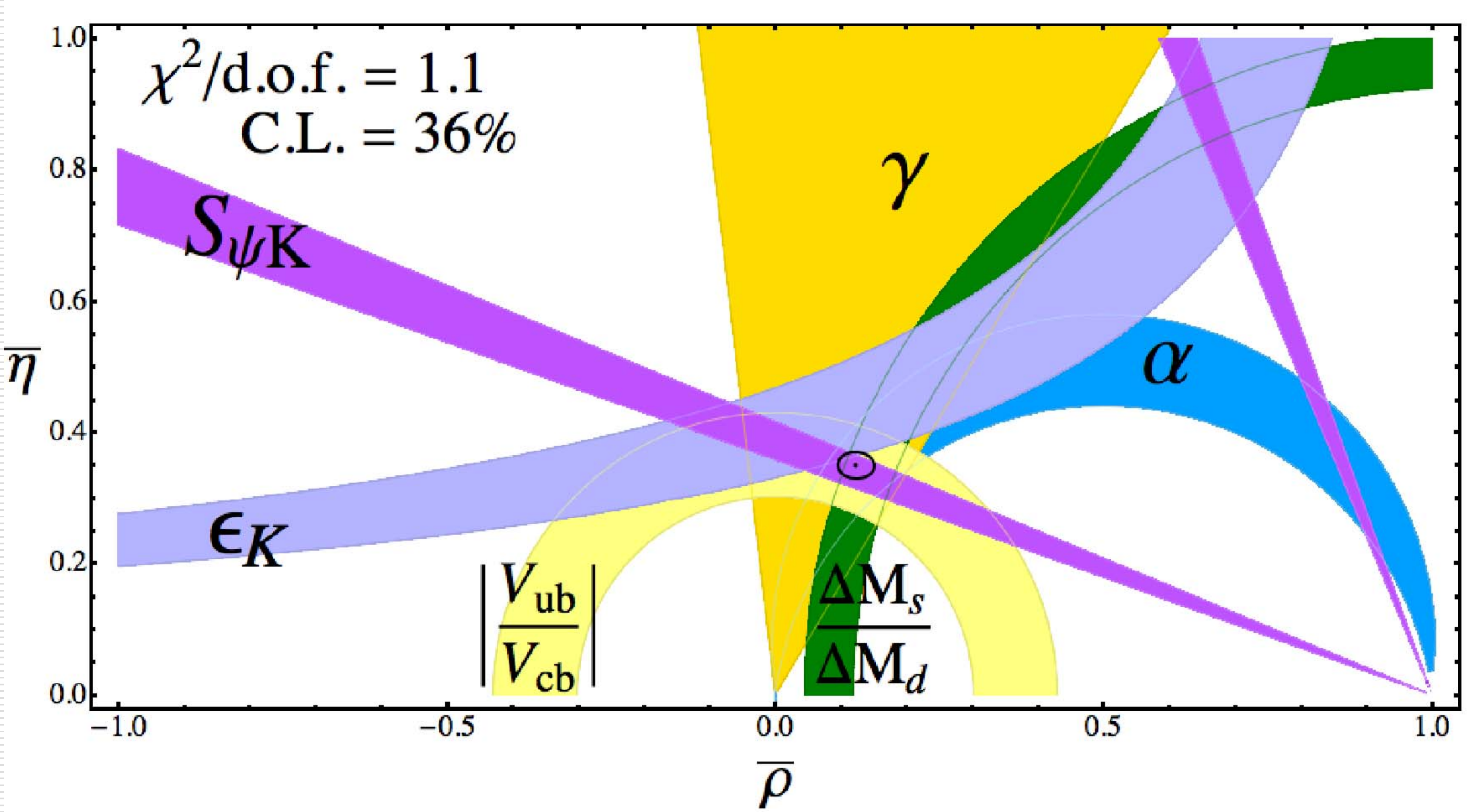


CKM unitarity with lattice inputs 2009

- *First row unitarity* holds to 0.1% accuracy

V_{ud}	V_{us}	V_{ub}	$\sum \lvert V_{ij} \rvert^2 - 1$
0.97425	0.2246	0.00342	-0.0004
± 0.00022	± 0.0012	± 0.00037	± 0.0013
Nuclear transitions Hardy-Towner ArXiv 0812.12.02	K-> pi FlaviA Net + Nf=2+1 lattice QCD RBC/UKQCD Lattice'09	B->pi HFAG + Nf=2+1 lattice QCD FNAL/MILC, HPQCD Lattice'08	

- *Second row unitarity* requires much improvement

V_{cd}	V_{cs}	V_{cb}	$\sum \lvert V_{ij} \rvert^2 - 1$
0.239	0.969	0.039	-0.002
± 0.032	± 0.105	± 0.001	± 0.110
		B->D,D* HFAV + Nf=2+1 lattice QCD FNAL/MILC, Lattice'08	

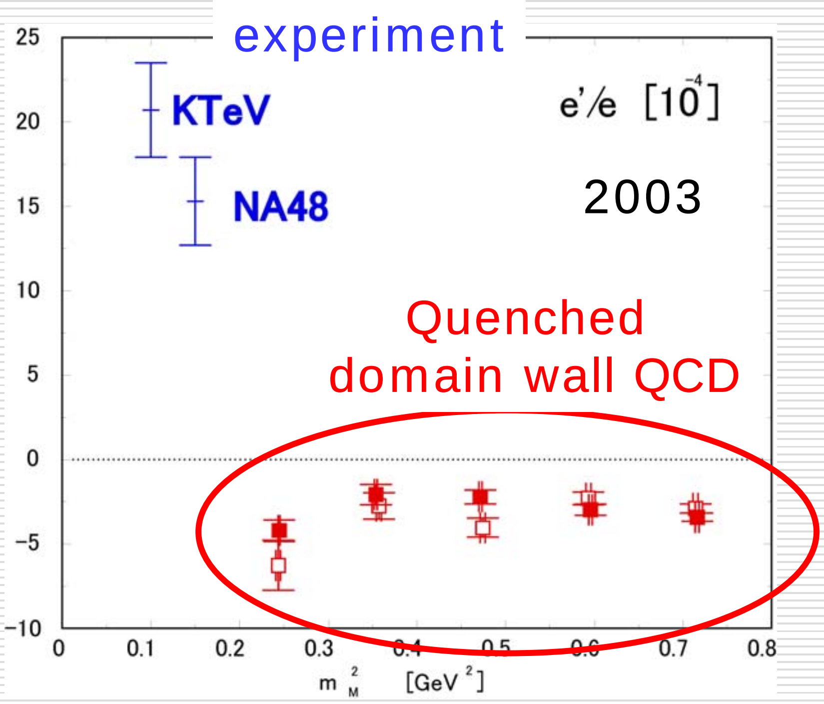
2004 number from FNAL/MILC/HPQCD
2005 number no better Vcs=1.015+-0.107

Charm physics on the lattice has to improve!

Comment on Re(ε '/ ε)

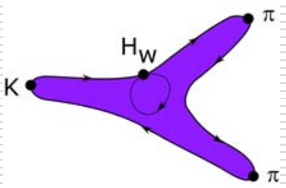
- Failure of the previous lattice calculation (2003) indicates
  - Inadequacies of Quenched approximation
  - Failure of SU(3) chiral perturbation thoery
- Steady progress since then

$$\frac{\varepsilon'}{\varepsilon} = \frac{\omega}{\sqrt{2}|\varepsilon|}\left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right]$$



Finite volume framework for K→π π amplitude

C. Lellouche and M. Luescher (2001)



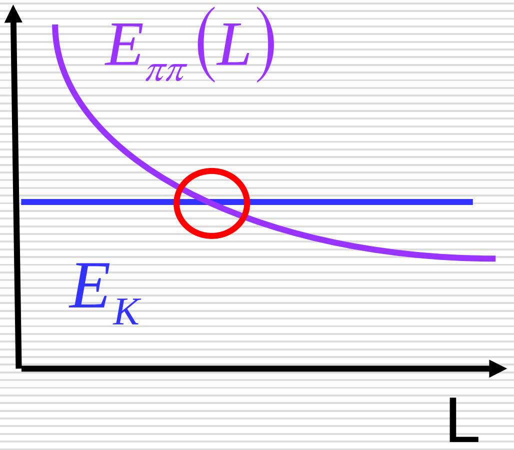
- Finite-size formula for direct K→π π amplitude

$$\underbrace{\left|A_{physical}(K\to\pi\pi)\right|}_{\text{Physical amplitude}}{}^{2}=8\pi\left(\frac{E_{\pi\pi}}{p}\right)^{3}\left\{p\frac{\partial\delta(p)}{\partial p}+q\frac{\partial\phi(q)}{\partial q}\right\}\underbrace{\left|\langle K|H_W|\pi\pi\rangle_{lattice}\right|^{2}}_{\text{Finite volume lattice amplitude}}$$

$$p^2=E_{\pi\pi}^2/4-m_\pi^2,\quad q^2=(pL/2\pi)^2$$

$$\tan\phi(q)=-\frac{q\pi^{3/2}}{Z_{00}(1;q^2)},\quad Z_{00}(1;q^2)=\frac{1}{\sqrt{4\pi}}\sum_{\vec{n}\in Z^3}\frac{1}{\vec{n}^2-q^2}$$

$$\delta(p)=n\pi-\phi(q)$$ Phase shift



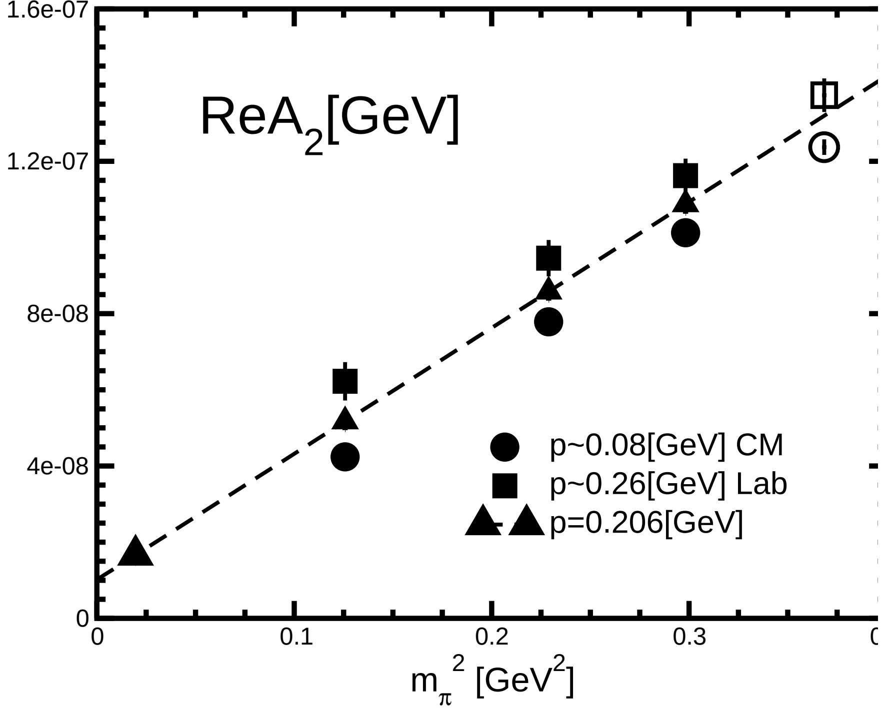
Requires $E_K=E_{\pi\pi}(L)$

Application for I=2 channel with domain wall QCD

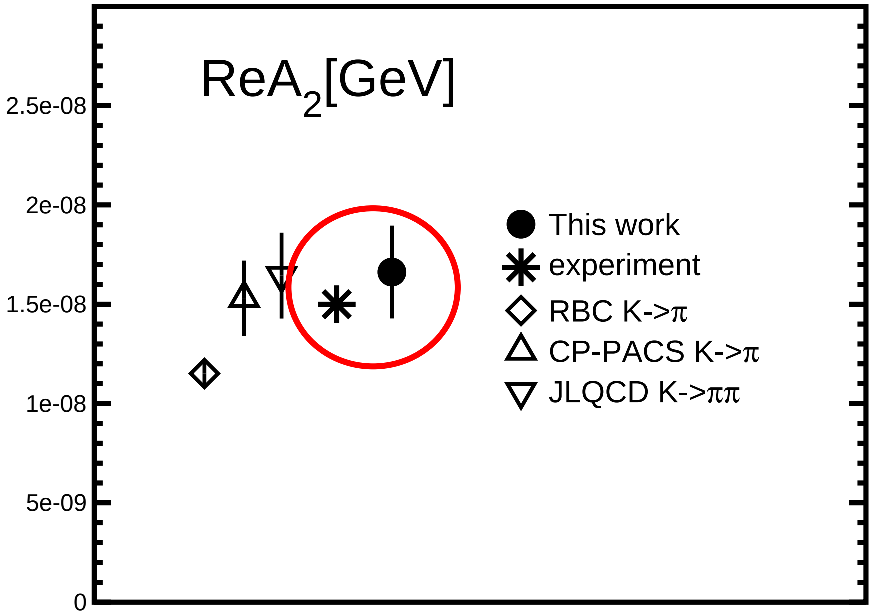
T. Yamazaki et al, Archive 0807.3130 (2008)

- Only I=2 channel at present, for which previous attempts yielded reasonable results
- But an encouraging start toward a direct K→π π calculation in Nf=2+1 full QCD; expect such a calculation in a few year's

Pion mass dependence

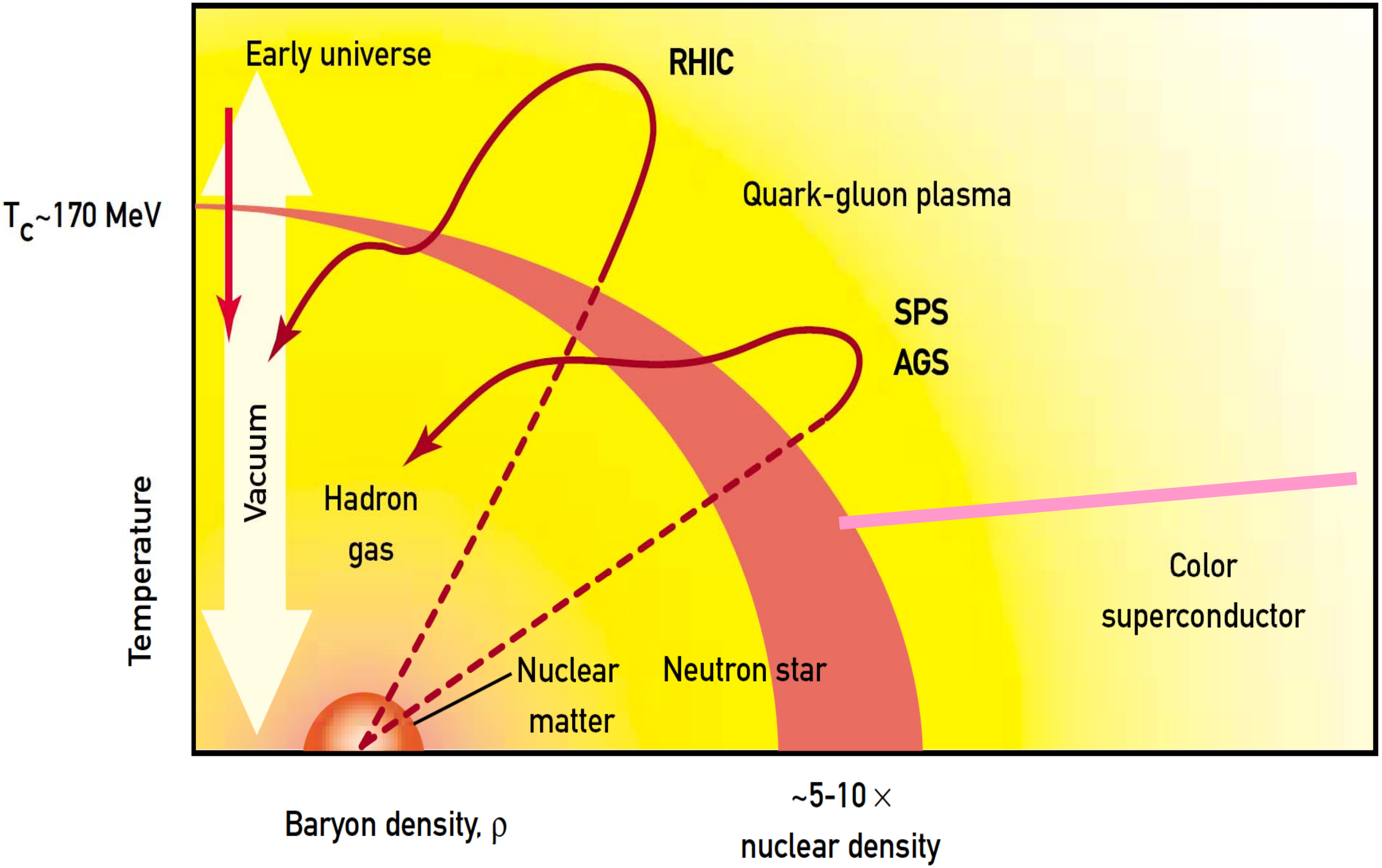


Result for I=2



Hot/Dense QCD

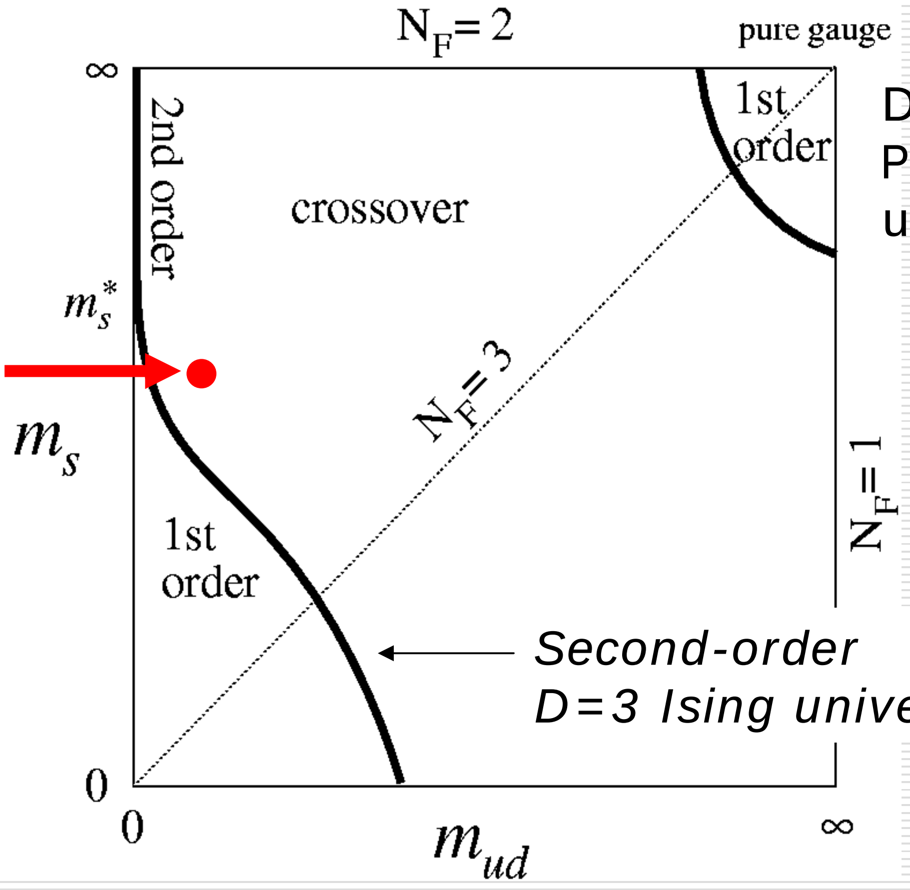
Schematic QCD phase diagram



Nf=2+1 Phase diagram at zero density

QGP transition at the physical point is a *crossover* according to staggered action (2006)

Wuppertal Group, Y. Aoki et al,
Nature 443 (2006) 675
Bielefeld-RBC-BNL Collaboration,
M. Cheng et al
HotQCD Collaboration



D=3 Z(3) Potts universality

Second-order D=3 Ising universality

Transition temperature

$$T_c \approx 150 - 170 MeV$$

- depends on the physical quantity
- still some debate on the value (Wuppertal vs Hot QCD)

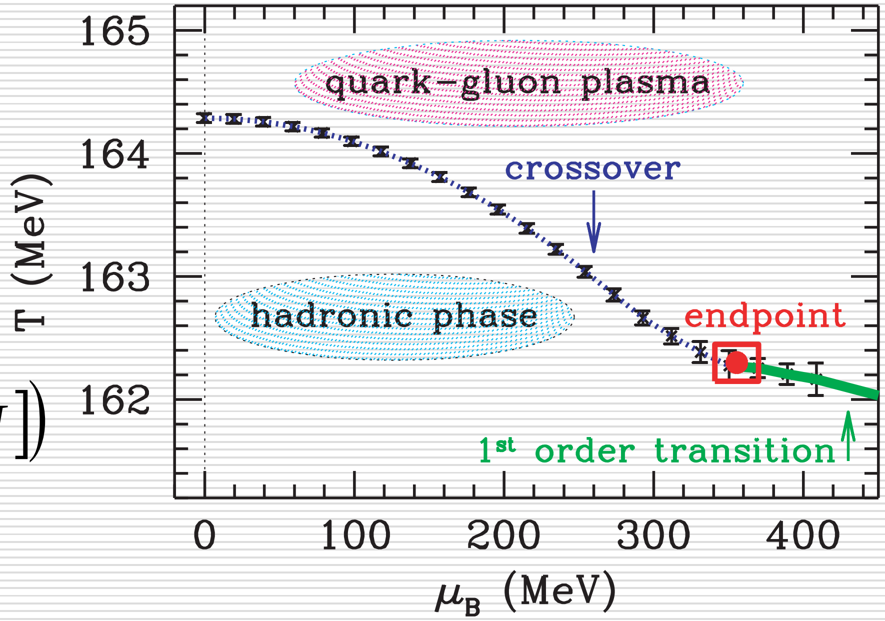
No major change since 2006

Status of finite-density QCD

- The *“sign problem”,* i.e., large phase fluctuation of the quark determinant detD for non-zero chemical potential

$$Z_{QCD} = \int \prod dU_{n\mu} \boxed{\det D[U]} \exp\left(-S_{gluon}[U]\right)$$

- Slow but steady progress over the years for *not too large baryon density:*
  - Estimate of the end point of the 1st order line on the T-μ plane



2-parameter reweigting method:
Z. Fodor, S. Katz, JHEP 0404 (2004) 050
Nf=2+1, Nt=4

$$(T_E, \mu_E) = (162 \pm 2, 360 \pm 40) MeV$$

Taylor expansion method:
C. Allton etal, Phys.Rev. D71 (2005) 054508
Nf=2, Lt=4

Canonical ensemble simulation ?

$$Z_{grand\ canonical}(T, m_q, \mu_B) = \sum e^{n_B \mu_B / T} Z_{canonical}(T, m_q, n_B)$$

$$Z_{canonical}(n_B, T, m_q) = \int [dU] \underbrace{\left[\frac{n_B}{2\pi} \int_0^{2\pi} d\varphi\, e^{-i3n_B\varphi} \det D(U, m_q, \mu = i\varphi T) \right]} e^{-S_{gluon}(U)}$$

Projects out the states with baryon number n_B

- ☐ Vital to accurately estimate the projection of the quark determinant
- ☐ Some previous attempts:
  - Exact evaluation of the projection; computationally expensive for large lattices
  - Saddle point approximation; controlling the approximation is not easy

Forcrand-Kratochvila
hep-lat/0602024

S. Ejiri
ArXiv 0804.3227

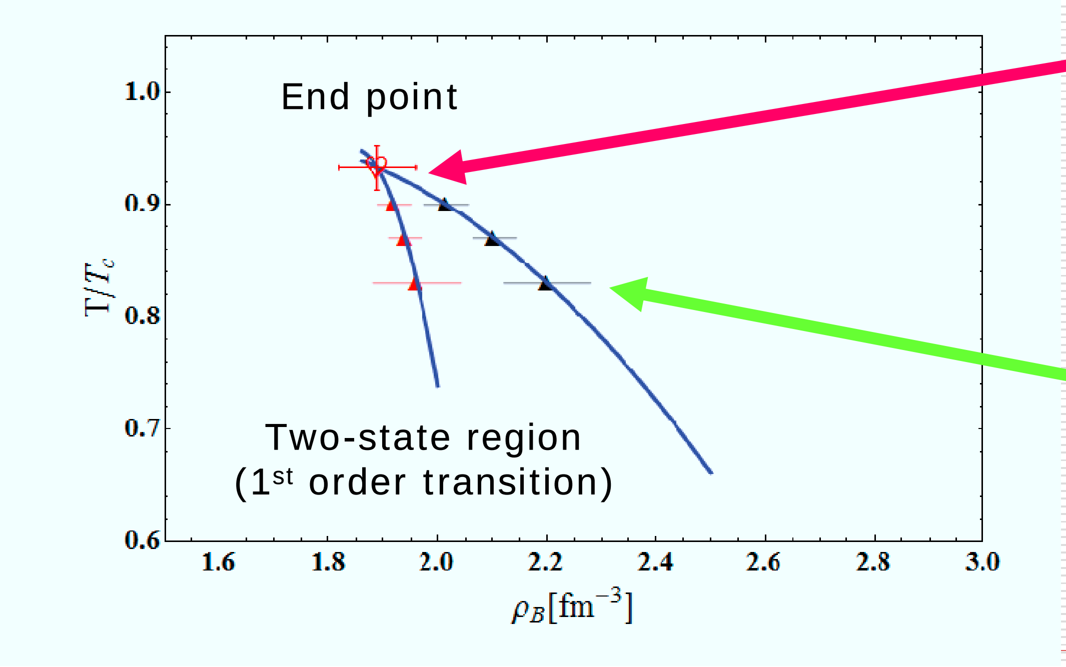
This year's attempt

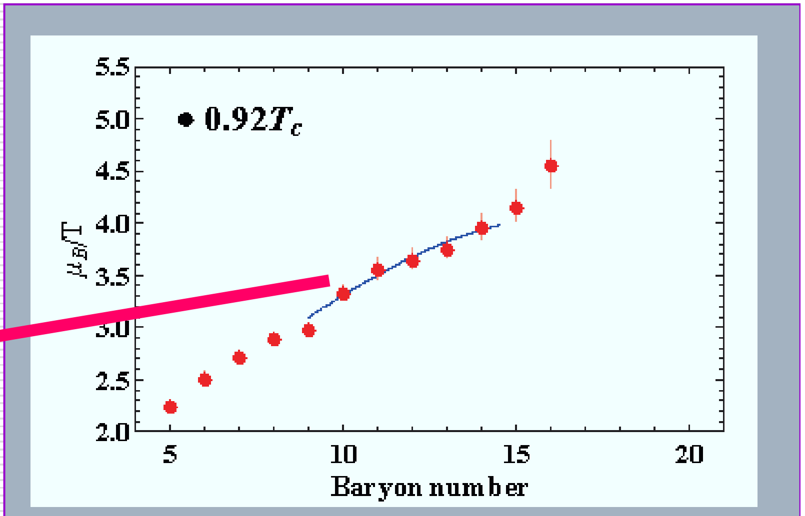
Anyi Li et al @Lattice 2009

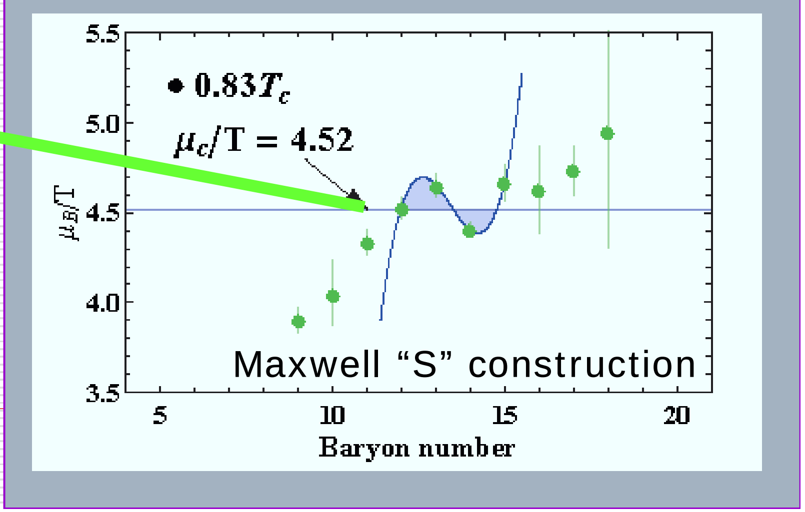
- ☐ Expand logdetD since detD is an extensive quantity

$$\ln\det D(U,m_q,\mu)=\sum_{n_B} e^{n_B\mu_B/T} A(U,m_q,n_B)$$

phase diagram for $N_f = 3\ m_\pi \approx 700MeV\ 6^3\times 4$







Nuclear physics

Two avenues from quarks to nuclei

- Effective theory approach
  - Extract nucleon two-body, three-body, ..., potentials via lattice QCD simulations
  - Use the potentials in conventional nuclear physics calculational schemes
    - S. Aoki, T. Hatsuda, N. Ishii (2007) based on the method developed by N. Ishizuka et al (2005)

- Direct approach
  - Calculate multi-quark Green's functions and directly extract the properties of nuclei, e.g., binding energies etc
    - Y. Kuramashi, M. Fukugita, A. Ukawa et al for nucleon-nucleon scattering lengths (1993)
    - T. Yamazaki, Y. Kuramashi, A. Ukawa for He4, He3 (2009)

Nuclear force from lattice QCD(2007)

N. Ishii, S. Aoki, T. Hatsuda, PRL 99, 022001 (2007)

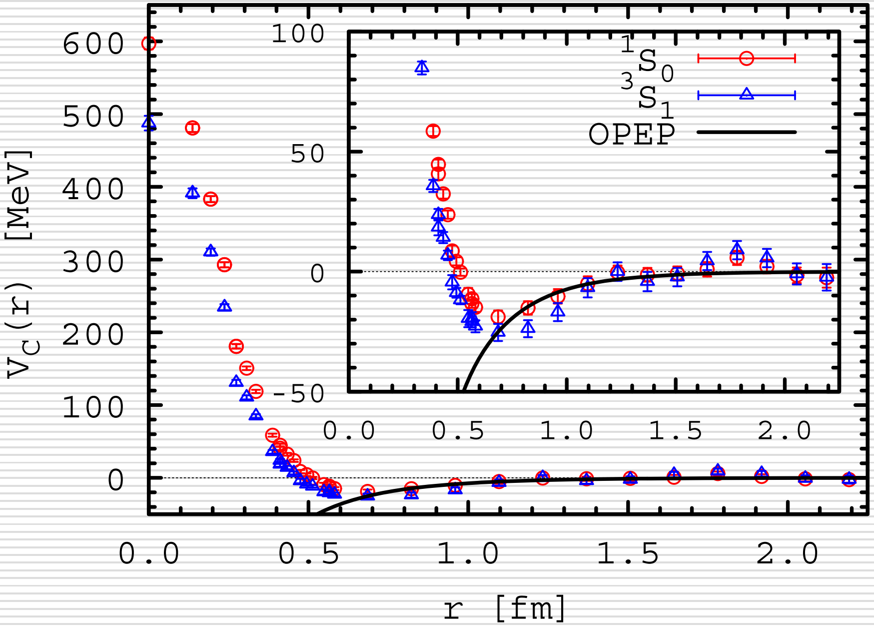
- 2-nucleon BS amplitude from lattice QCD

$$\phi(r) = \frac{1}{L^3} \sum_{\vec{x} \in L^3} \langle 0 | N(\vec{x}+r) N(\vec{x}) | NN \rangle$$

- Extraction of potential from an effective Schrodinger eq.

$$V(r) = E + \frac{1}{2\mu} \frac{\nabla^2 \phi(r)}{\phi(r)}$$

- Impact and prospects
  - Derivation of the hard core
  - Extension to hyperon-nucleon potential etc



Quenched QCD 32^4 lattice

$$m_\pi / m_\rho = 0.595$$

He nuclei directly from lattice QCD

T. Yamazaki, Y. Kuramashi, A. Ukawa, arXiv:0912.1383 (2009)

- Methodology
  - Define He operator in terms of quark fields

$$p(x)=\varepsilon^{abc}\left(u^a(x)C\gamma_5 d^b(x)\right)u^c(x)$$

$$n(x)=\varepsilon^{abc}\left(d^a(x)C\gamma_5 u^b(x)\right)d^c(x)$$

$$He^4(x)=\text{spin projection}\left(p(x)p(x)n(x)n(x)\right)$$

J. E. Beam,
Phys. Rev. 158, 907 (1968)

  - Calculate He Green's function to extract the binding energy

$$G_{He^4}(t)=\frac{\langle 0|He^4(t)He^4(0)|0\rangle}{\langle 0|p(t)p(0)|0\rangle^2\langle 0|n(t)n(0)|0\rangle^2}$$

$$\xrightarrow{t\to\infty} Z\exp\left(-\underbrace{\left(M_{He^4}-2m_p-2m_n\right)}_{-B_{He^4}}t\right)$$

Binding energy of He4 nuclei

Three difficulties

- Statistical error

$$\frac{noise}{signal} \propto \frac{1}{\sqrt{N_{meas}}} \exp\left(4\left(m_N - \frac{3}{2} m_\pi\right)t\right)$$

Use heavy pion and large statistics in quenched QCD

- Factorially large number of Wick contractions of quark operators

$$He^4 = p^2 n^2 = (udu)^2 (dud)^2 = u^6 d^6$$

$$N_u! \times N_d! = (2N_p + N_d)! \times (N_p + 2N_d)!$$

He3 5!x4!=2880
He4 6!x6!=518400

Use symmetries to remove identical contractions

- Identification of bound states

Bound state or scattering state?

Use a set of spatial sizes

Comments on Wick contractions

- Symmetries

  p⇔p, n⇔n in He operator

  Isospin all p ⇔all n

- Simultaneous calculation of two contractions

  u⇔u in p or d⇔d in n

Result of reduction:

- He

$$\frac{518400}{2_{ISO}\cdot 2^2_{u\leftrightarrow u}\cdot 2^2_{d\leftrightarrow d}\cdot\left(2_{p\leftrightarrow p}\cdot 2_{n\leftrightarrow n}\right)^2_{src,\sin k}}\xrightarrow[\text{w/o double count}]{}1107$$

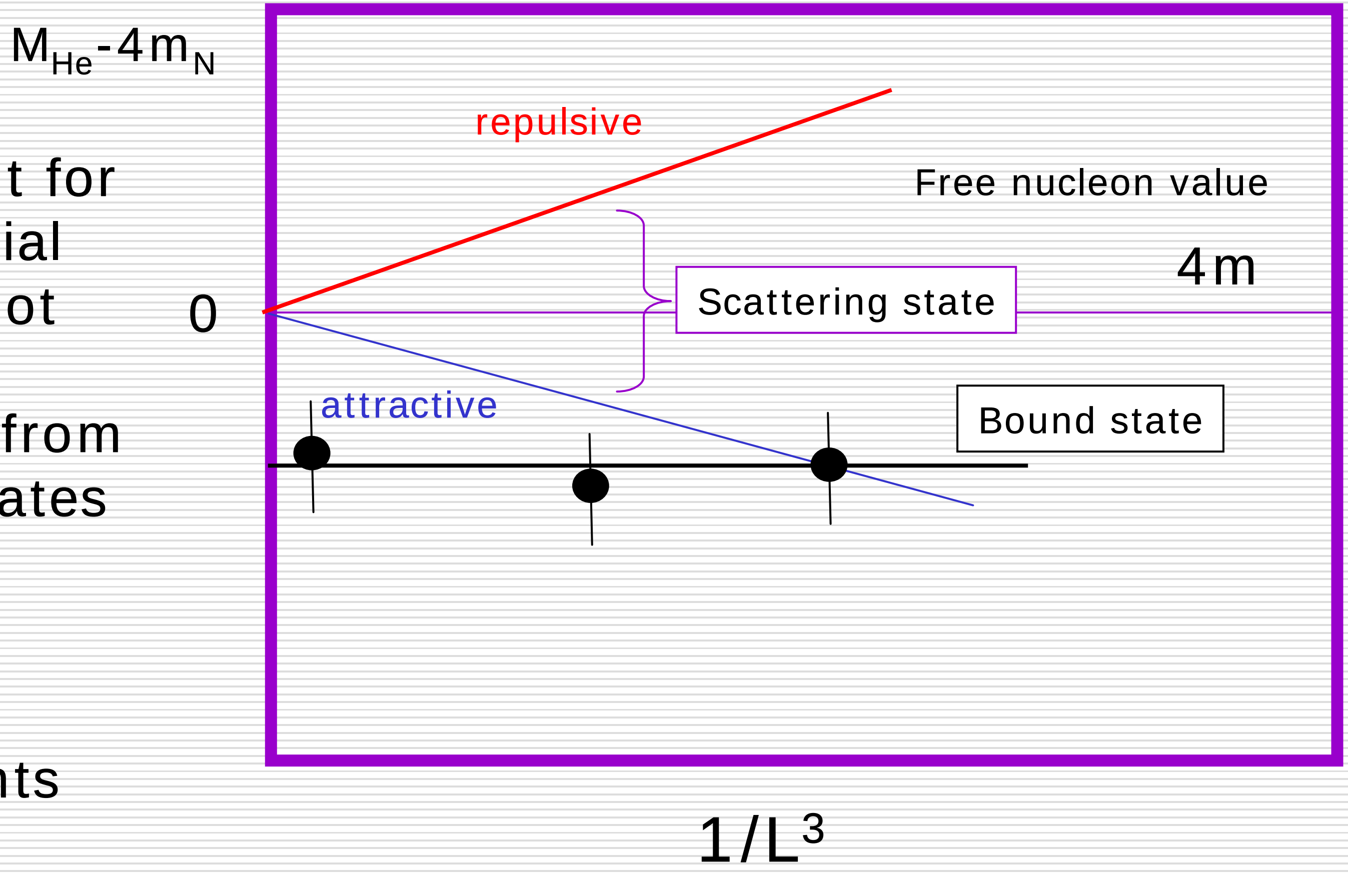
- He3

$$\frac{2880}{2^2_{u\leftrightarrow u}\cdot 2_{d\leftrightarrow d}\cdot\left(2_{p\leftrightarrow p}\right)^2_{src,\sin k}}\xrightarrow[\text{w/o double count}]{}93$$

Bound state or scattering state?

- Measurement for a single spatial volume cannot distinguish a bound state from scattering states

- Use multiple volumes for measurements



simulation

- Quenched calculation
  - Iwasaki gauge action $\beta=2.416$ $1/a=1.54$GeV
  - Tadpole-improved Wilson quark action

    $m_\pi=0.8$GeV, $m_N=1.62$GeV
- Lattice sizes and #measurements

L	L(fm)	#conf	#meas
24	3.1	2500	2
48	6.1	400	12
96	12.3	200	12

- Source smearing

$$q(\vec{x}) = A\exp\left(-B|\vec{x}|\right)$$

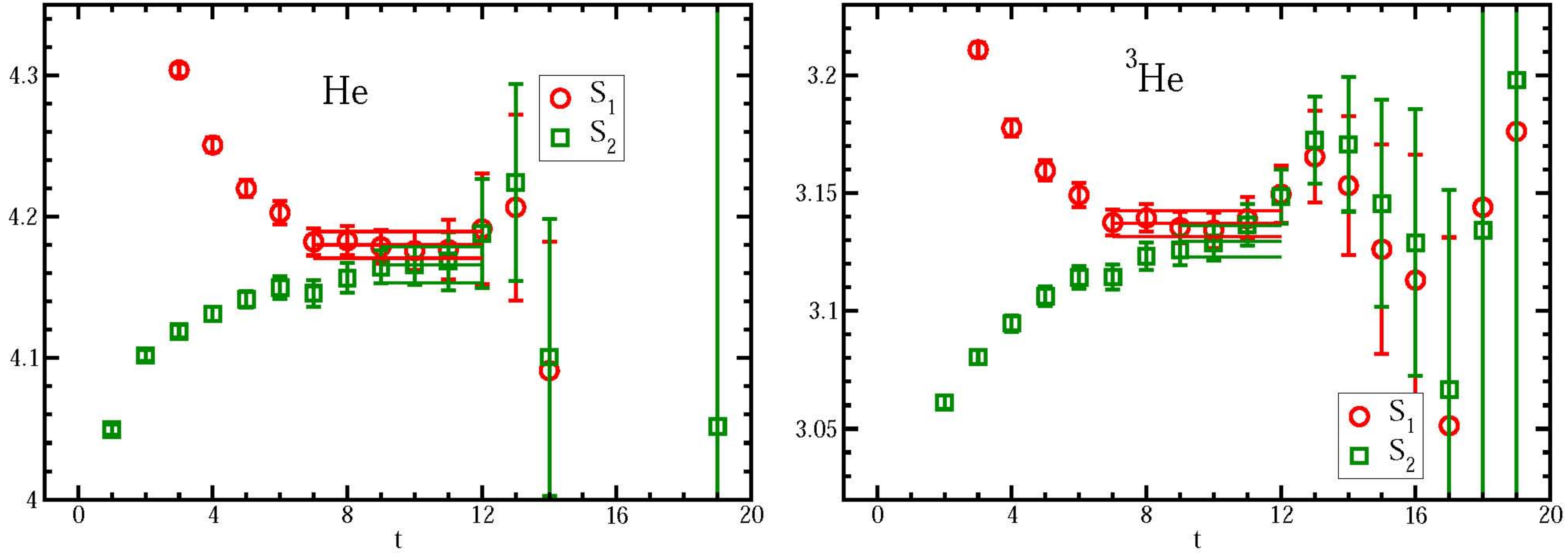
(A, B)=(0.5, 0.5), (0.5, 1.0) for L=24

(0.5, 0.5), (1.0, 0.4) for L=48, 96

S_1 S_2

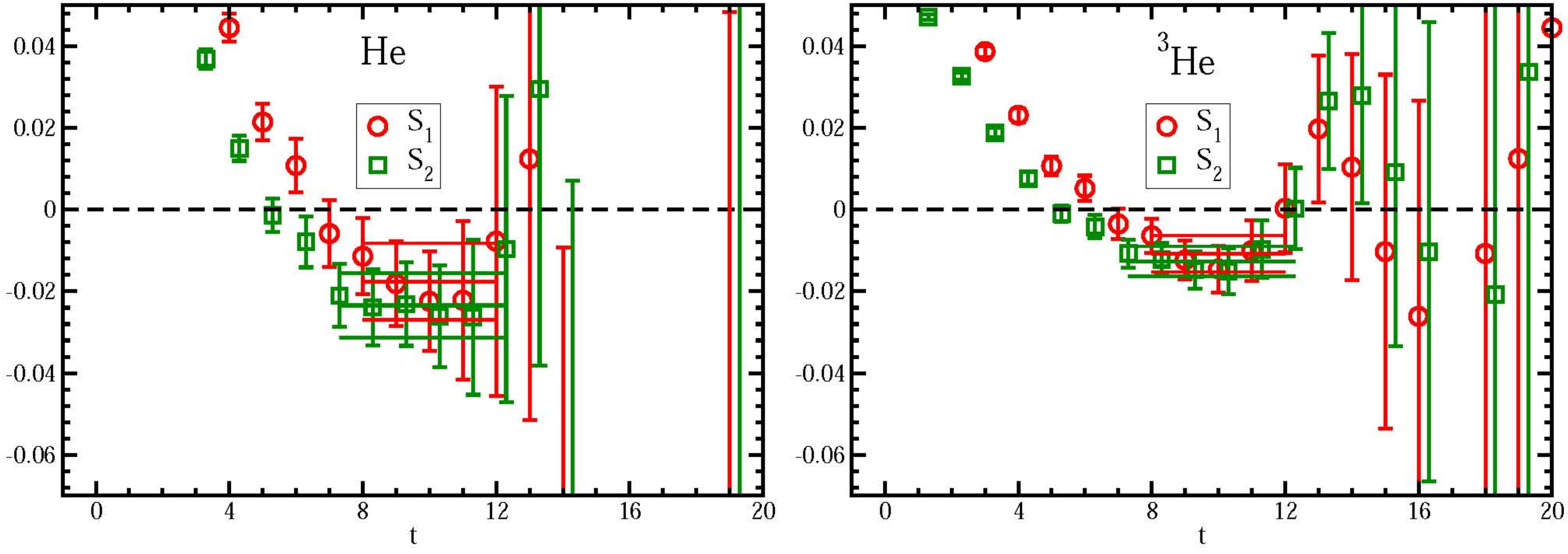
Results for effective mass L=48

$$m_{eff}(t) = \log \frac{C(t)}{C(t+1)} \xrightarrow{t\to\infty} m$$



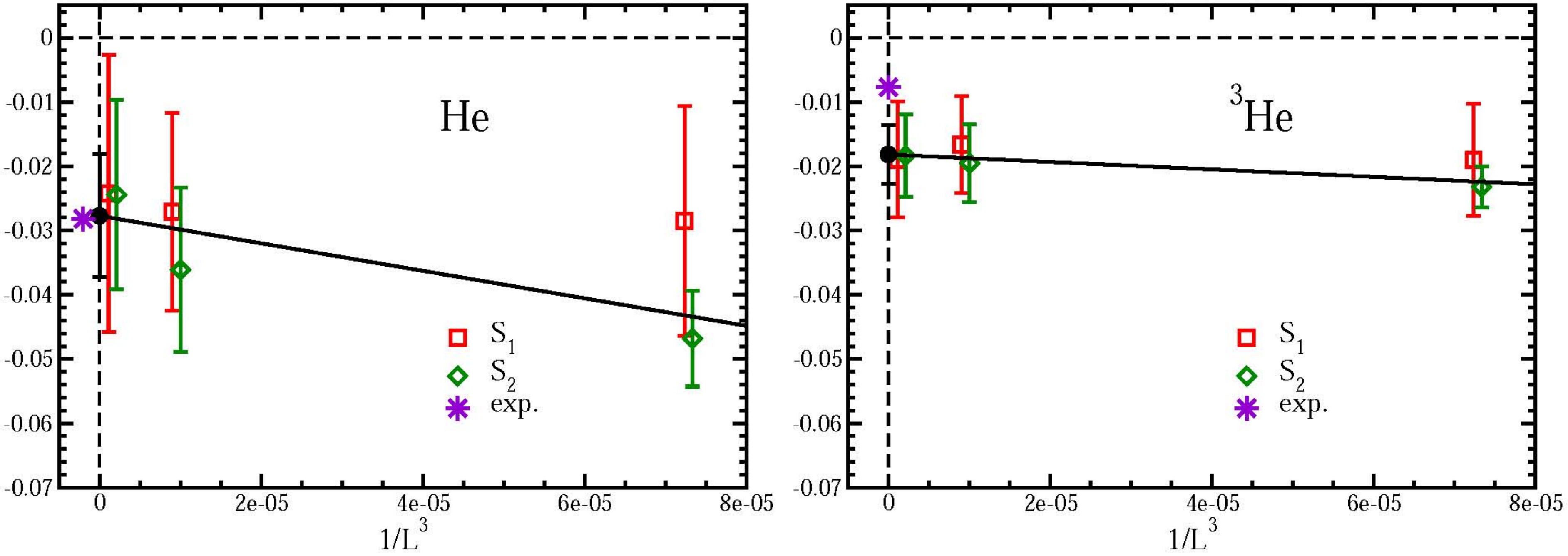
Results for effective energy shift L=48

$$B_{eff}(t) = \log \frac{G_{He}(t)}{G_{he}(t+1)} \xrightarrow{t\to\infty} -B_{He}$$



Results for size dependence

- Small volume dependence
- Non-zero value(!) in the infinite volume limit

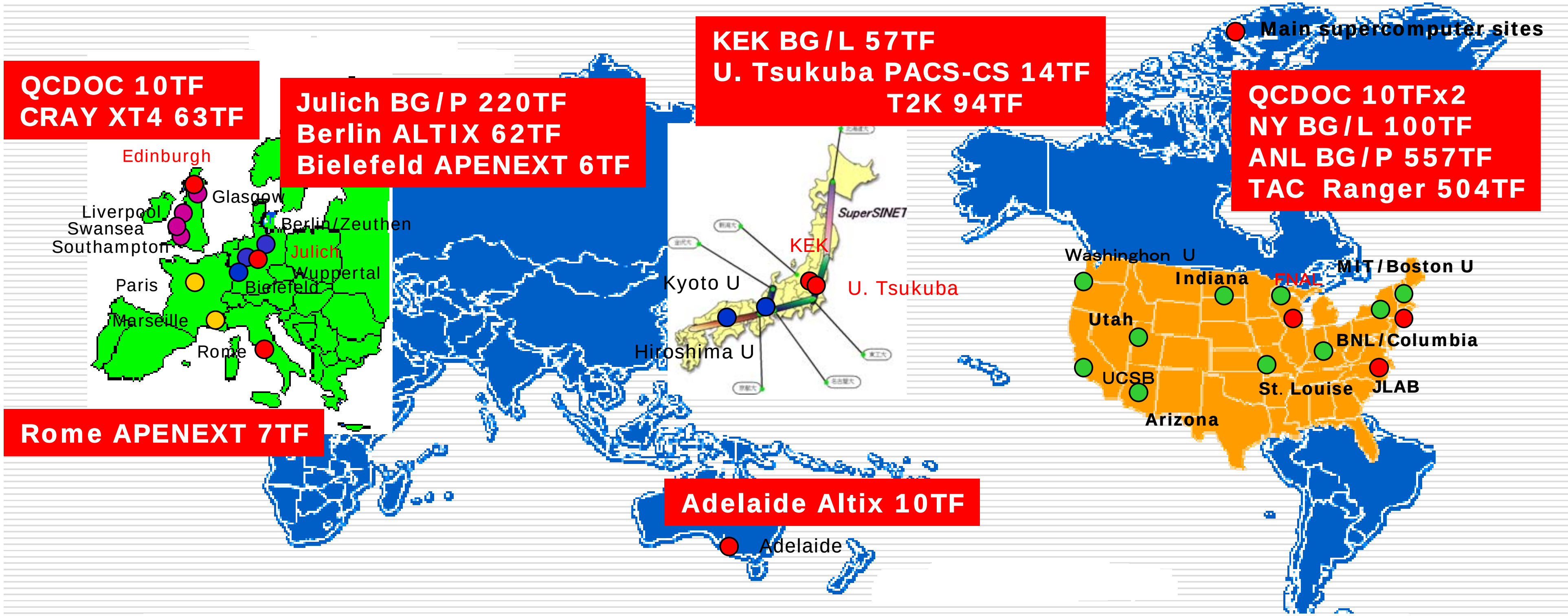


$\Delta E_{\rm He} = 27.7(7.8)(5.5)$ MeV

$\Delta E_{^3{\rm He}} = 18.2(3.5)(2.9)$ MeV

Computer trends and ILDG

Current computing resources for lattice QCD in the World



QCDOC 10TF
CRAY XT4 63TF

Julich BG/P 220TF
Berlin ALTIX 62TF
Bielefeld APENEXT 6TF

KEK BG/L 57TF
U. Tsukuba PACS-CS 14TF
T2K 94TF

QCDOC 10TFx2
NY BG/L 100TF
ANL BG/P 557TF
TAC Ranger 504TF

Rome APENEXT 7TF

Adelaide Altix 10TF

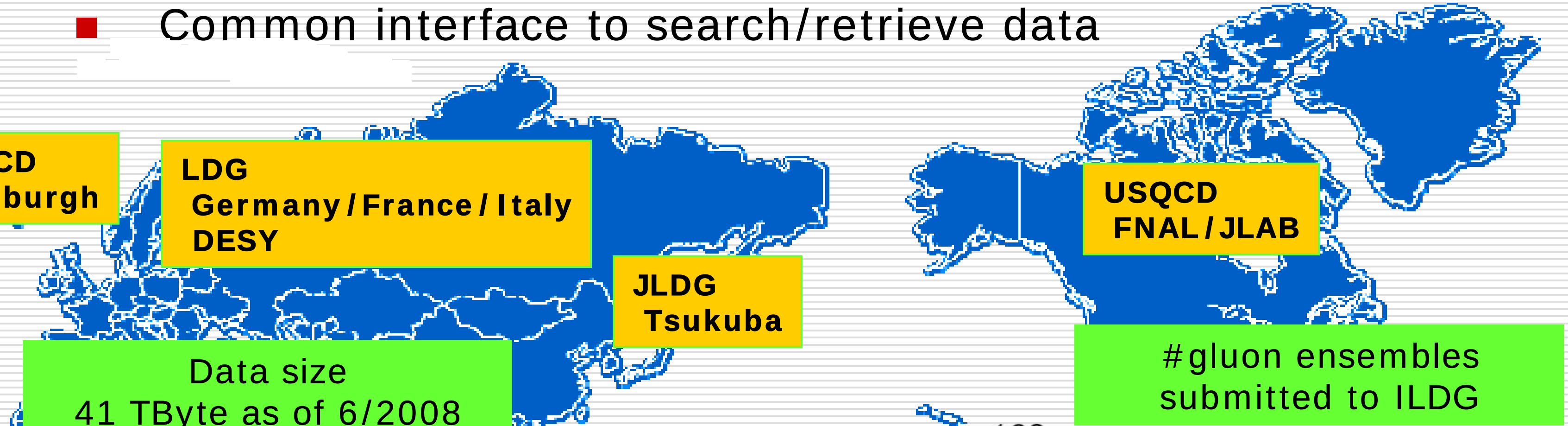
- About a dozen major cites scattered in USA, EU(UK, Germany, Italy etc), Japan
- In total 500～600Tflops in peak speed (US300Tf、EU150Tf、Japan100Tf); about 3% of World HPC resources

International Lattice Data Grid

In preparation since 2002 / in operation since 2006

- World-wide sharing of gluon configurations
- Grid of regional grids
  - Standardized xml to describe data
  - Common interface to search/retrieve data

http://ildg.sasr.edu.au/Plone



UKQCD
Edinburgh

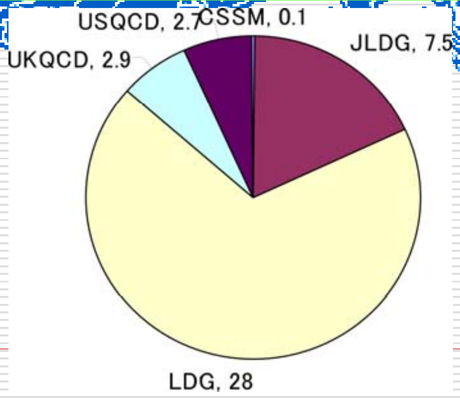
LDG
Germany/France/Italy
DESY

JLDG
Tsukuba

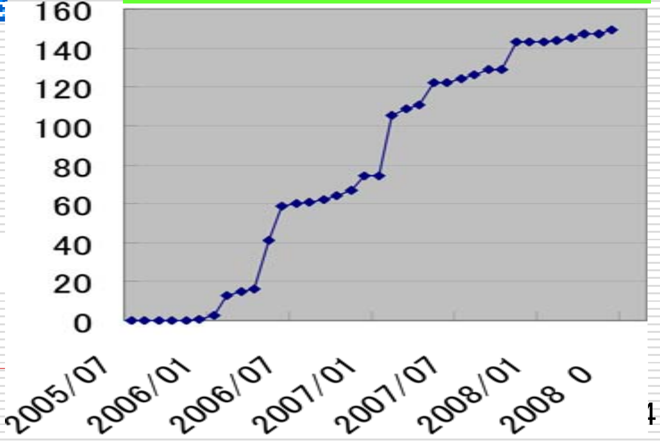
USQCD
FNAL/JLAB

CSSM
Adelaide

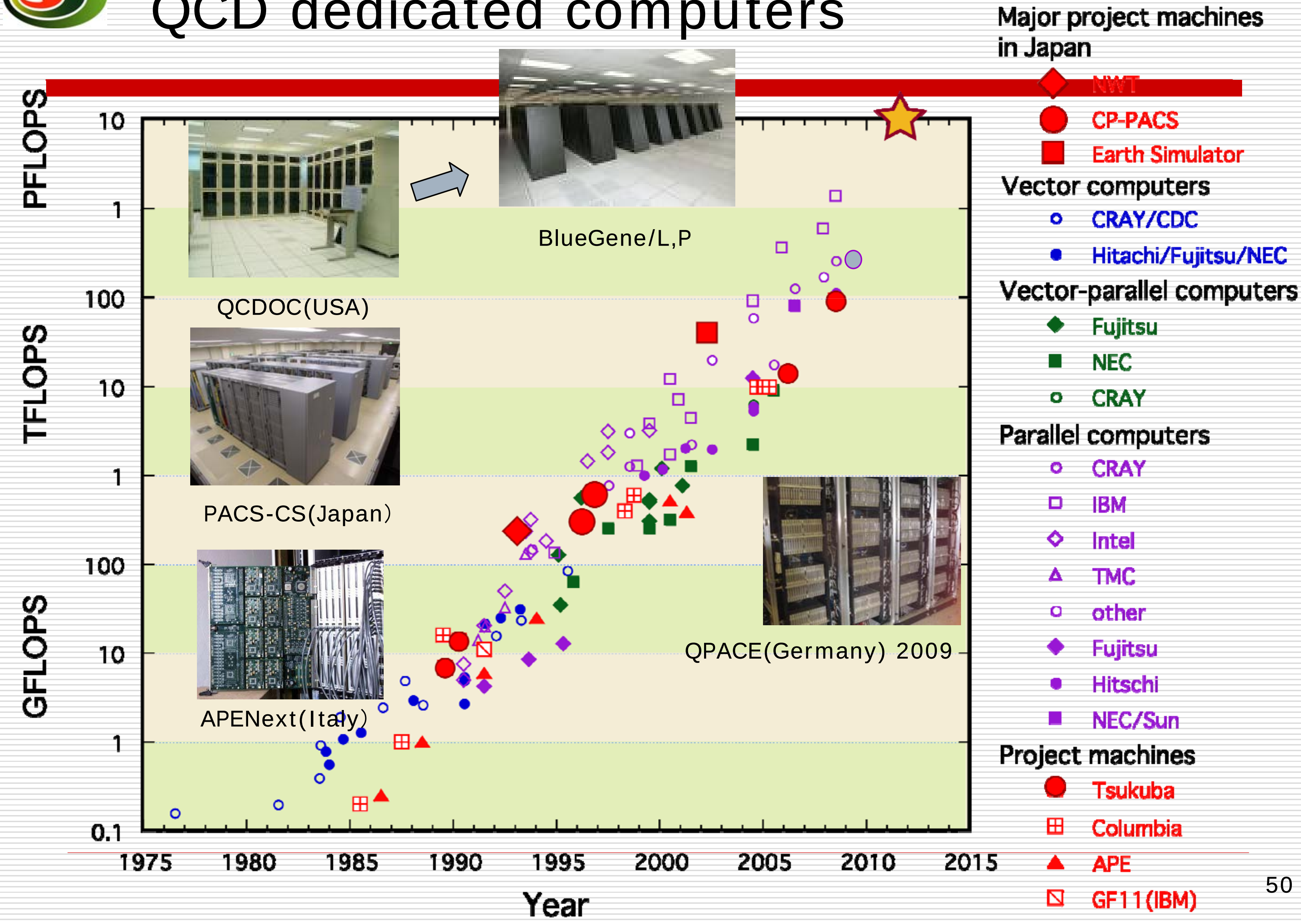
Data size
41 TByte as of 6/2008



#gluon ensembles
submitted to ILDG



Development of supercomputers and QCD dedicated computers



Future:petascale computing (2010-2015)

- Peta-scale computing is around the corner
  - “National” projects
    - USA: Bluewater,BlueGene/Q, ...
    - Japanese Petaflops Project
  - clusters based on commercial multi-core CPU(Intel, AMD)
- New projects for lattice QCD
  - QPACE Project (QCD Parallel Computing on the CELL)
    - CELL-based cluster/200Tflops in 2009
  - GPGPU?
    - Many-core high speed graphic cards/software development

O(10-100) enhancement will allow physical point simulation on larger volumes (L=3fm->6fm)/ smaller lattice spacings (a=0.1fm->0.05fm)

Status of the Japanese Next Generation Supercomputer Project

Political turmoil last year

16 September:

Hatoyama Cabinet took office (first real change of power since 1951)

18 September:

“Government Revitalization Unit (GRU) ” is set up; starts reexamination of F2010 budget

13 November:

GRU Working Group, after an 1-hour public hearing, recommends suspension of the Supercomputer Project ; many science & technology budget also recommended cut.

Late November :

appeals by many academic societies and universities against the cut

8 December:

Science and Technology Council recommends continuation of the Project

16 December:

Government decides to proceed with the Project

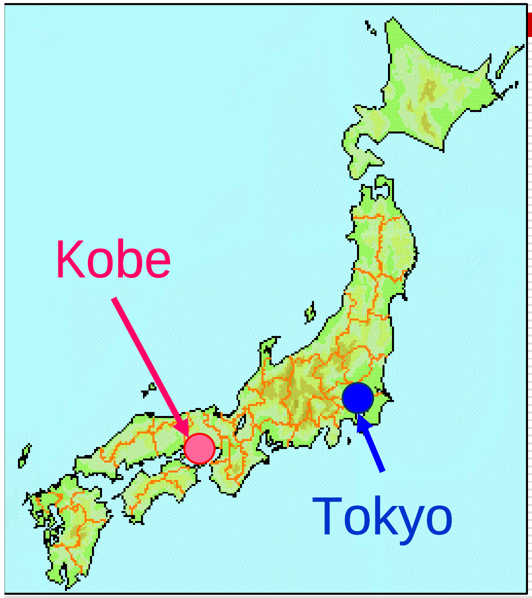
Modification of the project

- Machine R&D schedule
  - Original target date: November 2011
  - New target date: June 2012

- New target of the project

  “High Performance Computing Infrastructure (HPCI) Project”
  - Buildup of HPCI in Japan by connecting the next-generation supercomputer and other supercomputers in Japan
  - Buildup of “Consortium” for the best effective use of HPCI resources in Japan

Cite for the Next Generation Supercomputer



450km (280miles)
west from Tokyo

Building construction


2008.11.12

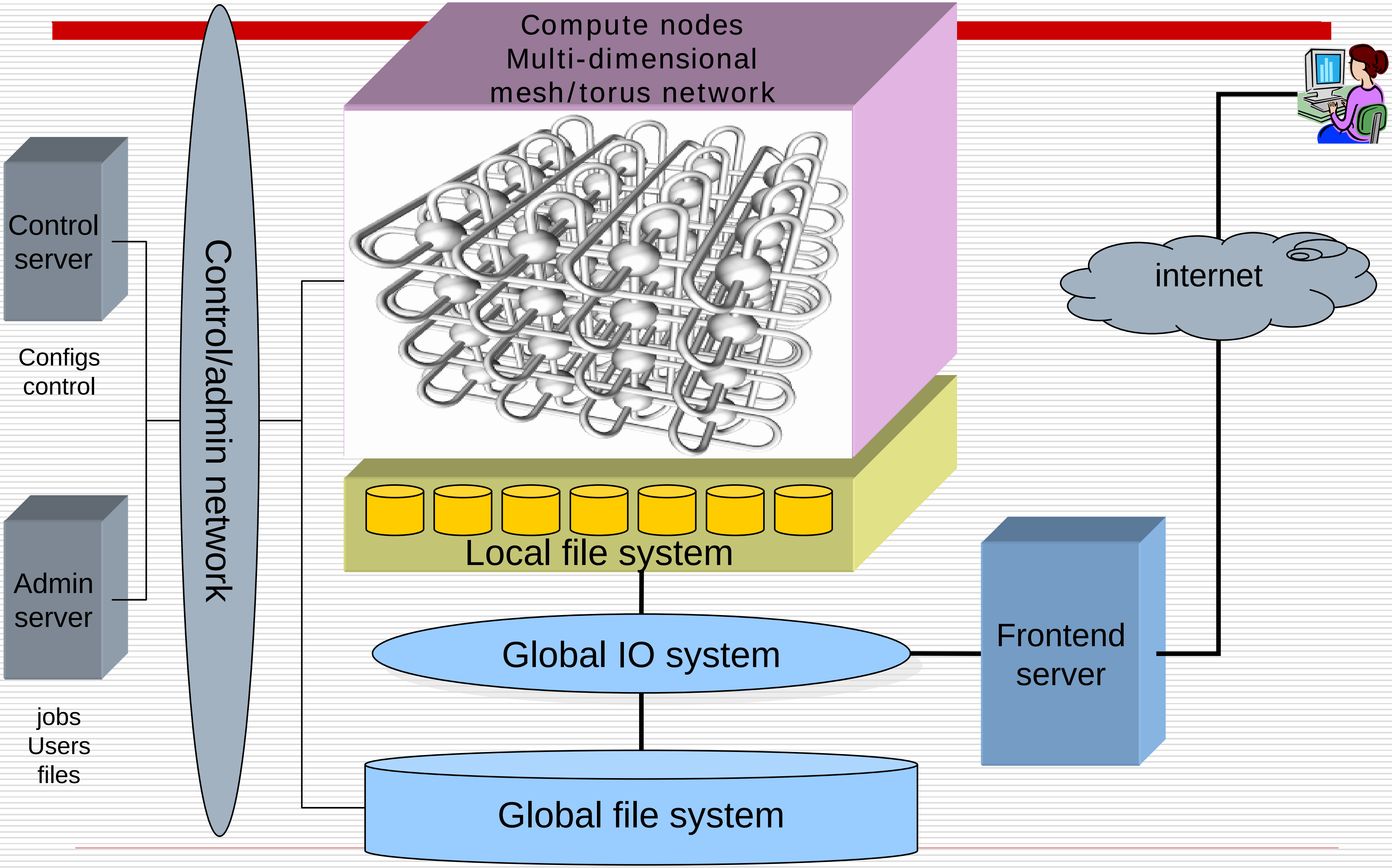

2009.3.26


2009.7.22


2009.9.1

To be completed
in May 2010

System overview



Compute nodes
Multi-dimensional
mesh/torus network

Control server

Configs
control

Admin server

jobs
Users
files

Control/admin network

Local file system

Global IO system

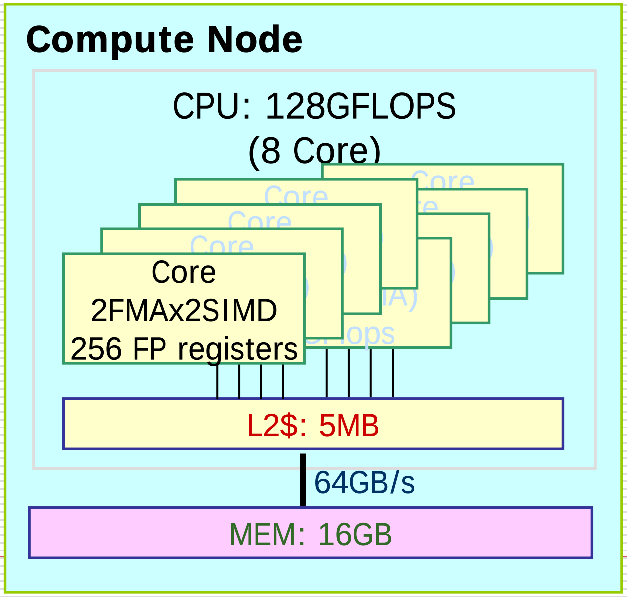
Global file system

Frontend server

internet

Compute node

- ☐ CPU:SPARC64^{TM} VIIIfx
  - 8 core 128Gflops
  - DDR3 Memory 64GB/sec
  - Power consumption 58W (water cooled at 30℃)
  - 45nm CMOS



Compute Node

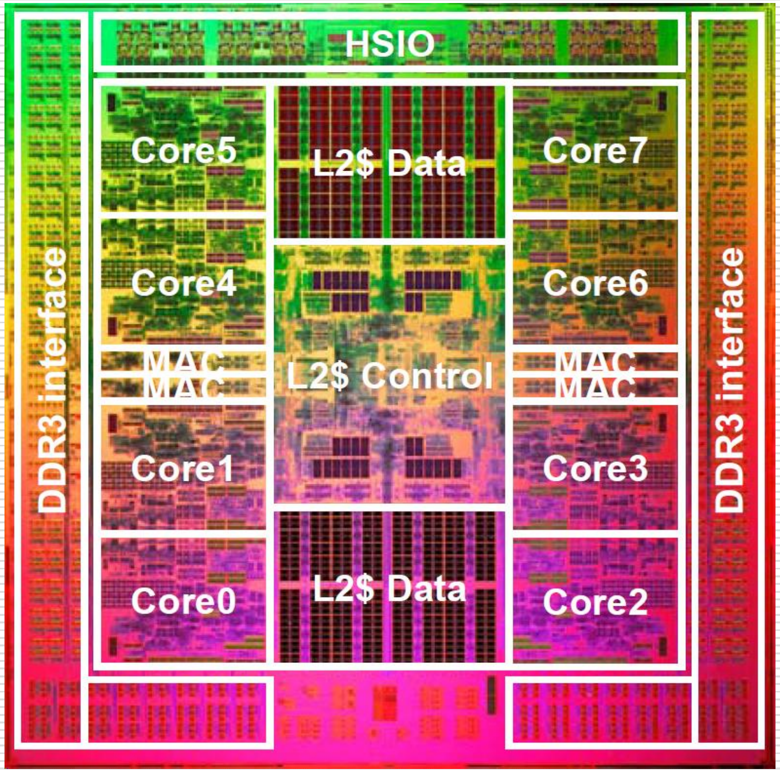
CPU: 128GFLOPS
(8 Core)

Core
2FMAx2SIMD
256 FP registers

L2$: 5MB

64GB/s

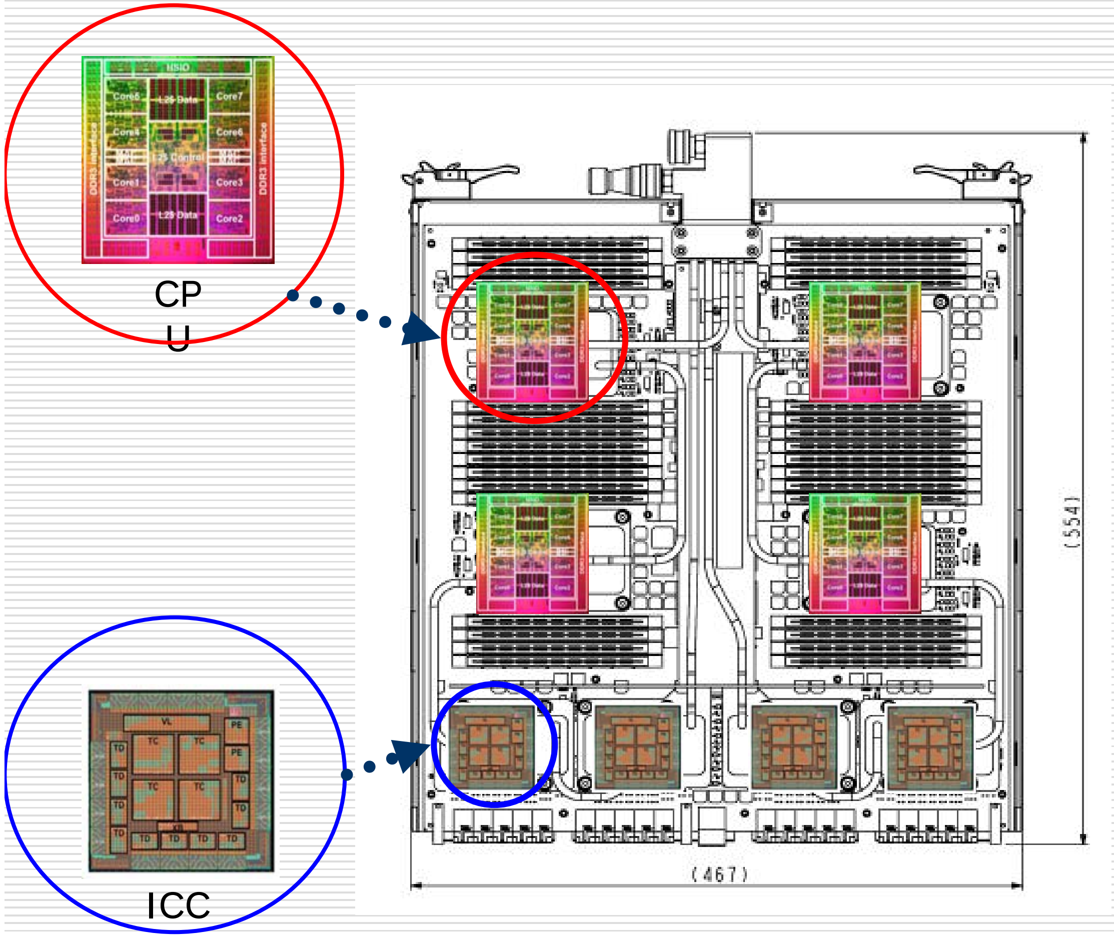
MEM: 16GB

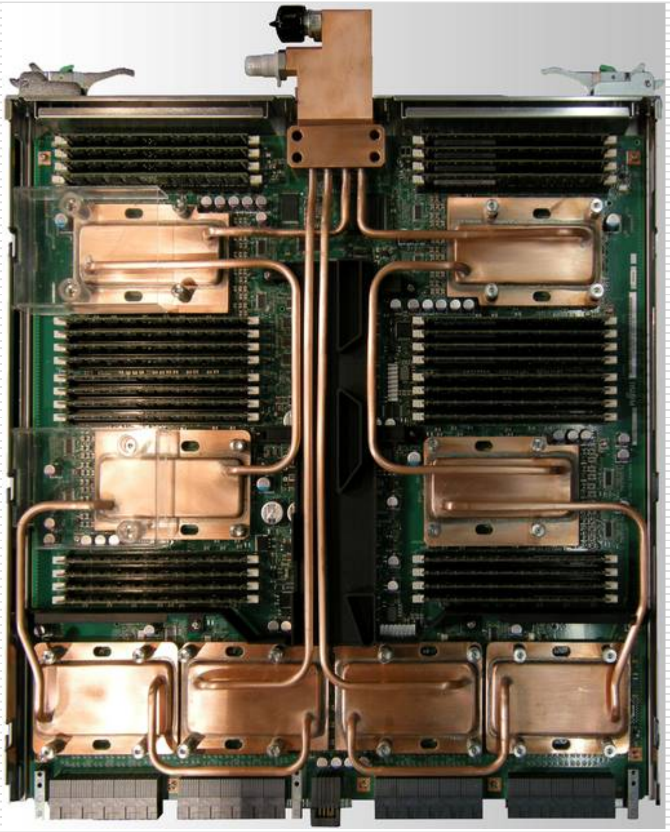


22.7mm x 22.6mm
760 M transistors

Photo courtesy FUJITSU Limited

System board



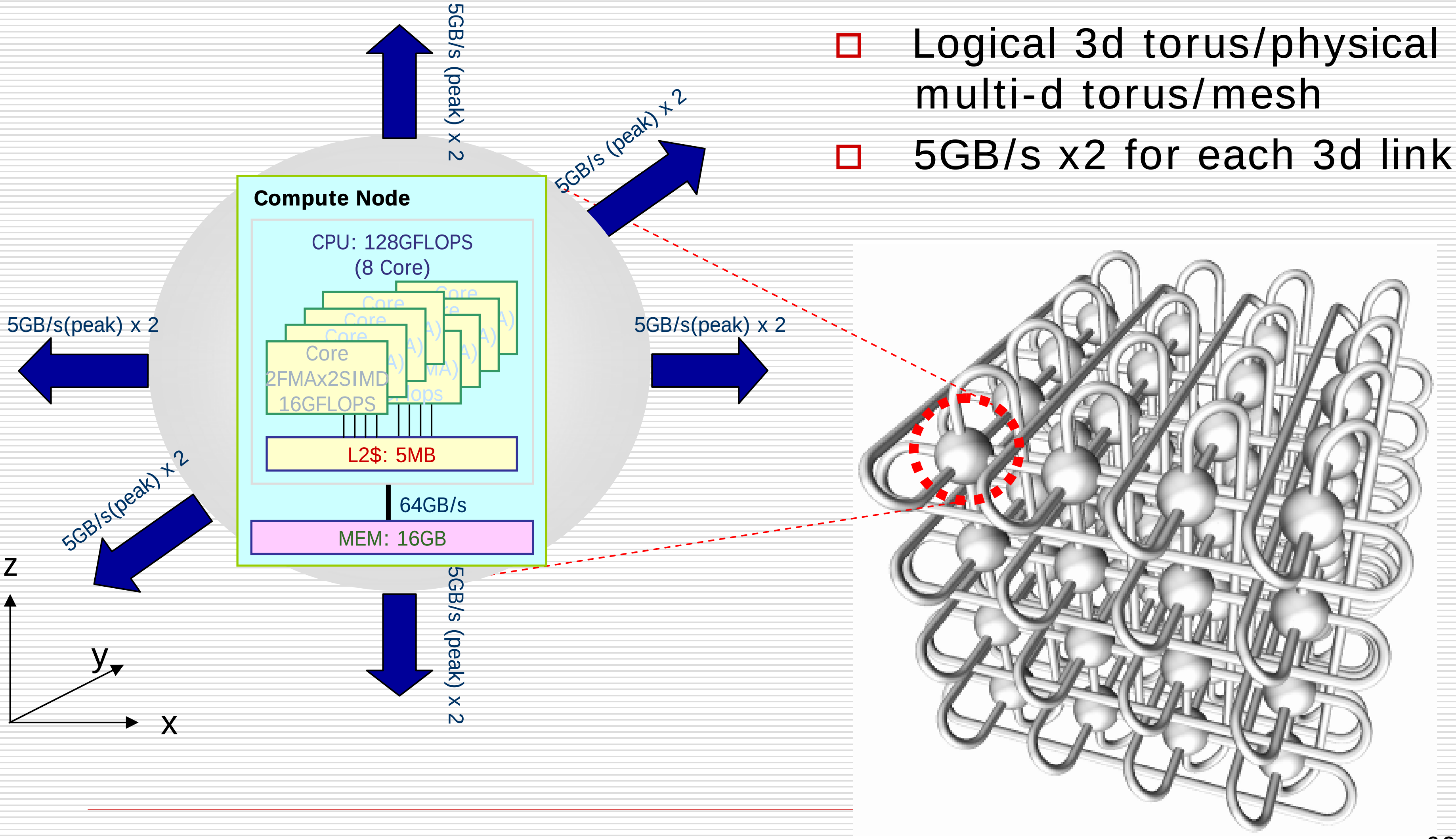


4 CPU and Network Interface/board

Photo courtesy FUJITSU Limited

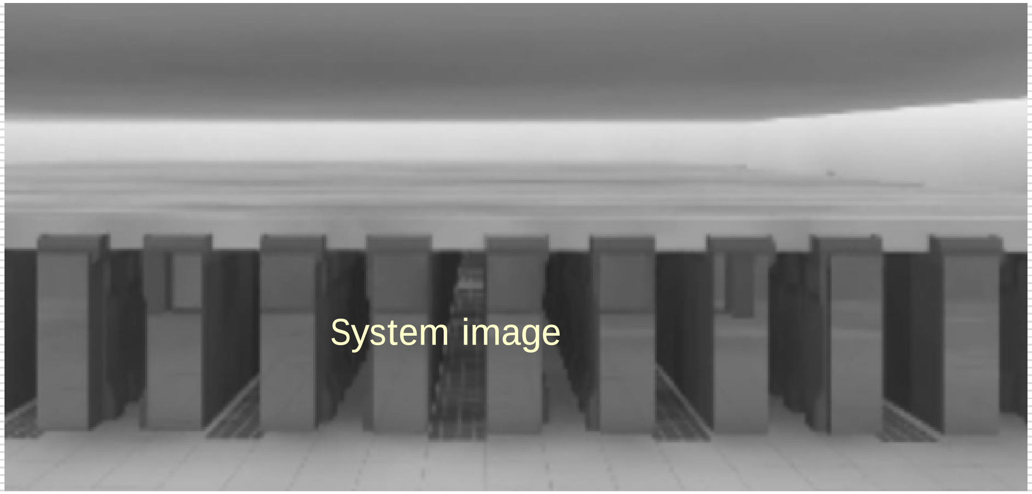
Network configuration

- Logical 3d torus/physical multi-d torus/mesh
- 5GB/s x2 for each 3d link



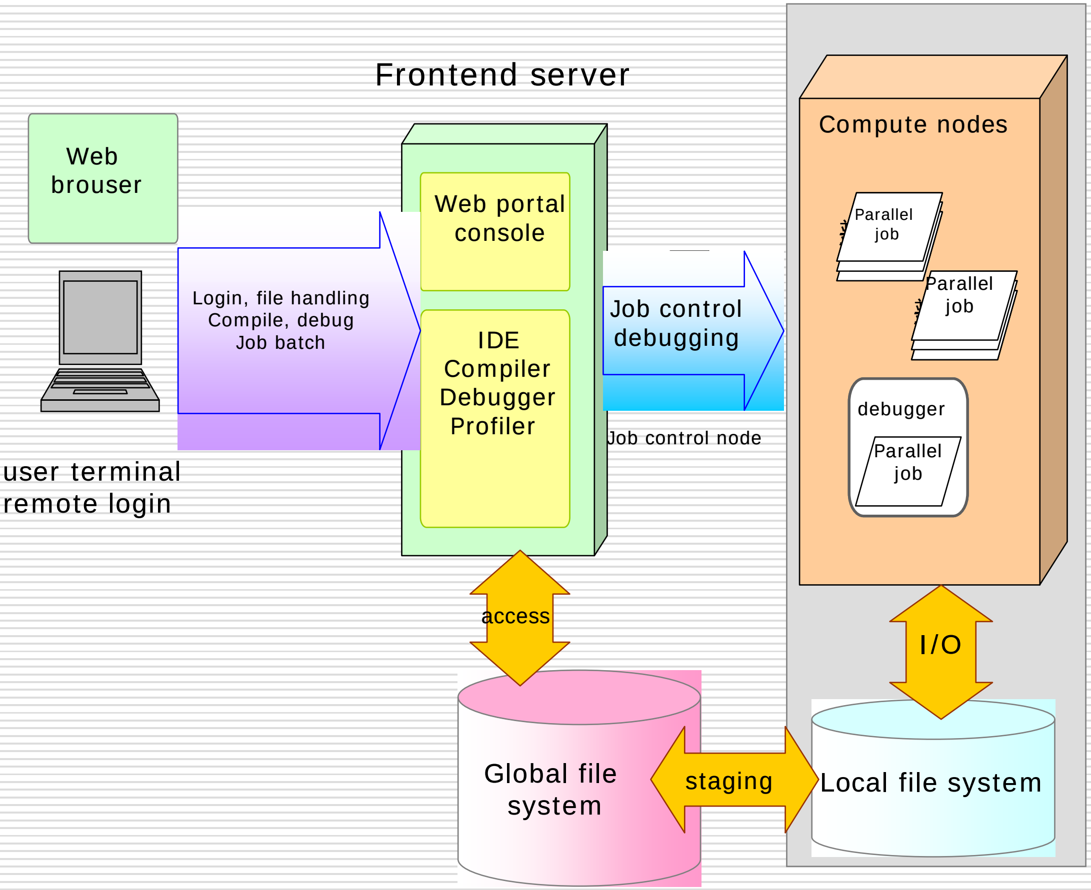
Rack prototype

- 96 nodes (24 system boards) and system disk
- 796mm×750mm×2060mm


System image

Software and job environment

- System software
  - OS: Linux
  - Programming
    - Fortran, C, C++
    - MPI library for communication
- Distributed file system
  - Stage in/out to/from local disk
  - File sharing
- Batch-based job execution
  - Interactive debugger (planned)



Research system of the Project

MEXT

Japanese Government

Strategy Committee

- 5 strategic areas have priority of use

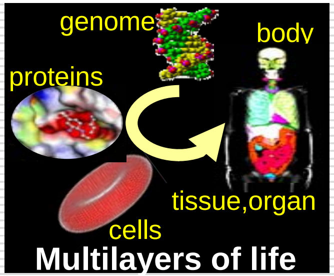
Life Science & Medicine

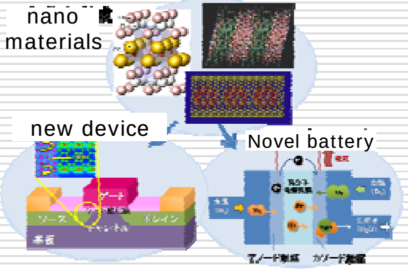
New materials & Energy

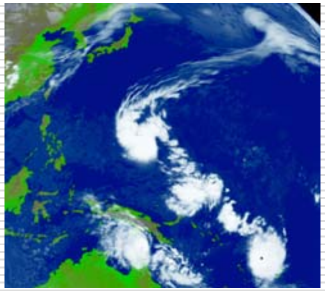
Global change prediction

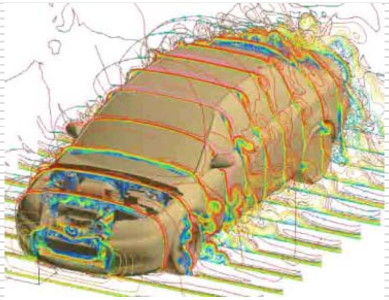
Next generation Engineering

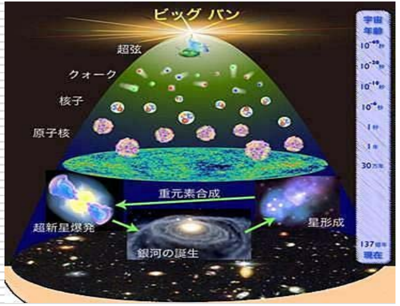
Matter & Universe

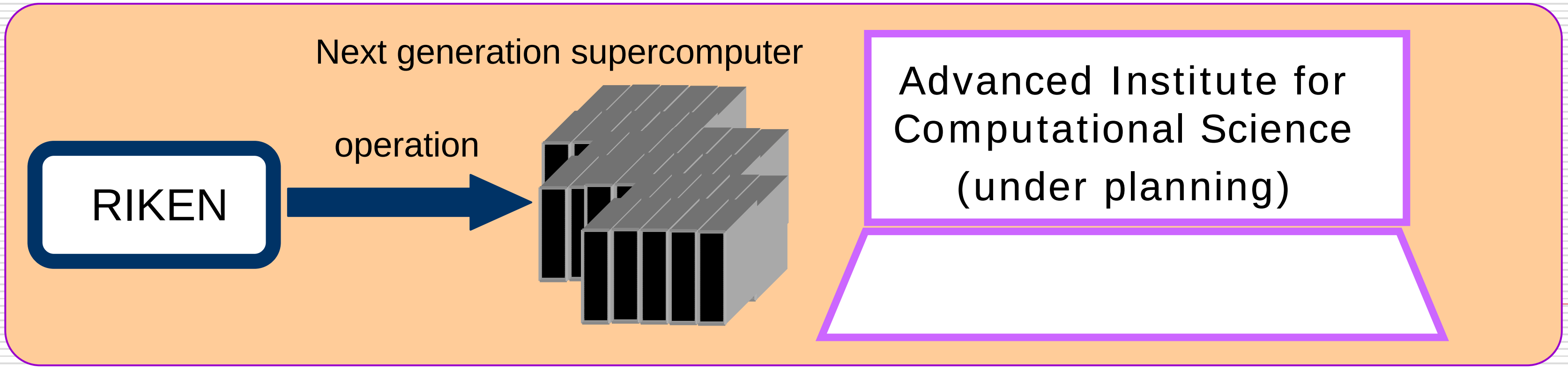












Next generation supercomputer

RIKEN

operation

Advanced Institute for Computational Science (under planning)

Conclusions

Where we stand now

- *Realistic calculation directly at the physical point is finally reality*
  - Fruit of continuous effort over 25 years toward:

    Better physics understanding

    Better algorithms

    More powerful machines

- *Change of philosophy from “simulation” to “calculation”*

  If lattice spacing sufficiently small,

  - No more approximations/extrapolations
  - Gluon configuration produced is Nature itself

Where do we go

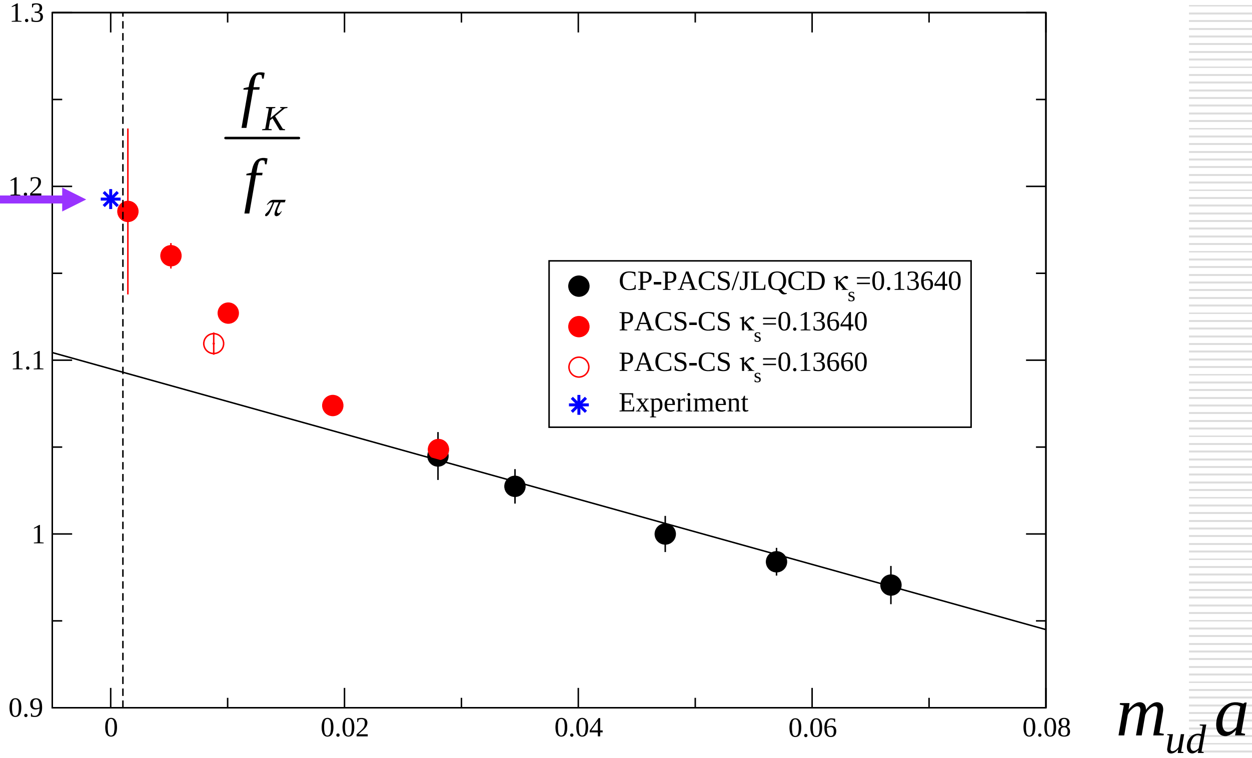
- *Expect that the fundamental issues of lattice QCD as particle theory makes major progress over the next five year range*
  - Single hadron properties and fundamental constants
  - Precision flavor physics (<1%) and old issues such as K→$\pi\pi$ decays
  - Hot/dense QCD with chiral lattice action on large lattices
- *Vast area of multi-hadron systems/atomic nuclei lies in wait for nuclear physics colleagues to explore*
  - Nuclear force from lattice QCD
  - Exotic nuclei with unusual n/p ratios/strangeness etc
  - Even direct computation bypassing nuclear theory!

Supplementary slides

Another example

Decay constant of K and π

experiment



$$\frac{f_K}{f_\pi} \propto 1 + \frac{5}{4}\frac{2Bm_{ud}}{(4\pi f)^2}\log\frac{2Bm_{ud}}{\mu^2} + \cdots$$

u/d quark mass difference

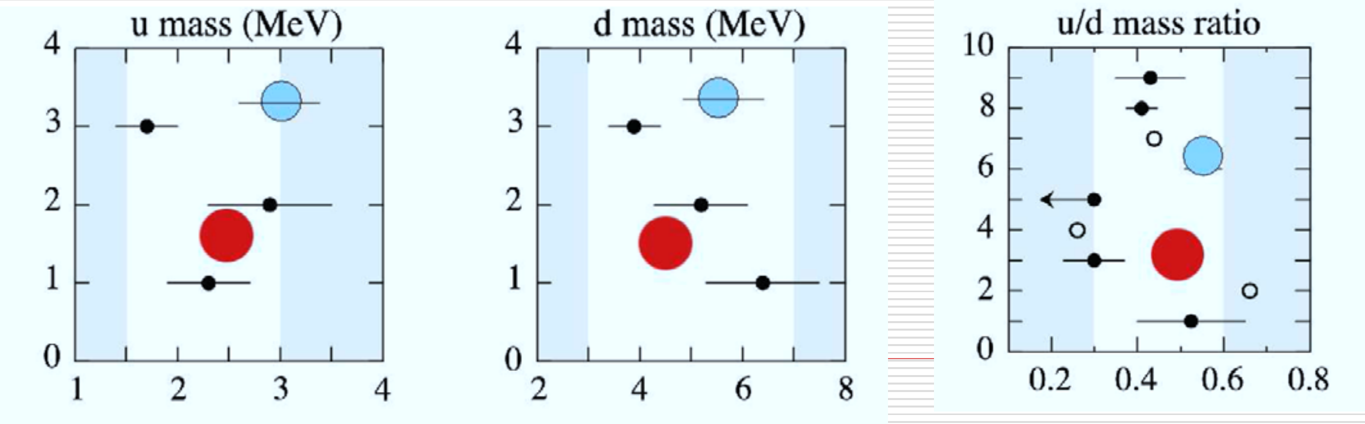
Handling of EM effects is the issue

- Use Dashen's theorem to estimate the EM effects, and obtain m_u/m_d from K^0, K^+ masses

Lattice09	$m_u (MeV)$	$m_d (MeV)$	m_u / m_d
MILC	1.96 ± 0.17	4.53 ± 0.27	0.432 ± 0.040
Aubin et al	1.7 ± 0.3	4.4 ± 0.5	0.39 ± 0.5

- Calculate EM effects by coupling (quenched)QED

  RBC/UKQCD@Lattice 2009 "study of isospin breaking effects"



Blue: Nf=2

Red: Nf=2+1

(non-Lattice) comment on ε_K

Buras-Guadagnoli ArXiv 0805.3887

$$\varepsilon_K = e^{i\phi_\varepsilon}\sin\phi_\varepsilon\left(\frac{\mathrm{Im}\,M_{12}^K}{\Delta M_K}+\boxed{\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}}\right)=\kappa_\varepsilon\frac{\mathrm{Im}\,M_{12}^K}{\Delta M_K}$$

- Usually neglected since small. However, with improved estimates of B_K and V_{cb}, this correction is significant
- Estimate by Buras-Guadagnoli

$$\kappa_\varepsilon \approx \sqrt{2}\sin\phi_\varepsilon\left(1-\frac{1}{\omega}\mathrm{Re}\left(\frac{\varepsilon'_K}{\varepsilon_K}\right)+\frac{1}{\sqrt{2}\left|\varepsilon_K\right|}\boxed{\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2}}\right)$$

$$= \boxed{0.92\pm0.02}$$

- Using quenched lattice QCD estimate for $\mathrm{Im}A_2$ (RBC, PACS-CS etc) yields the same value

Van de Water @ Lattice2009

$$-6.4\pm6.4\times10^{-5}$$

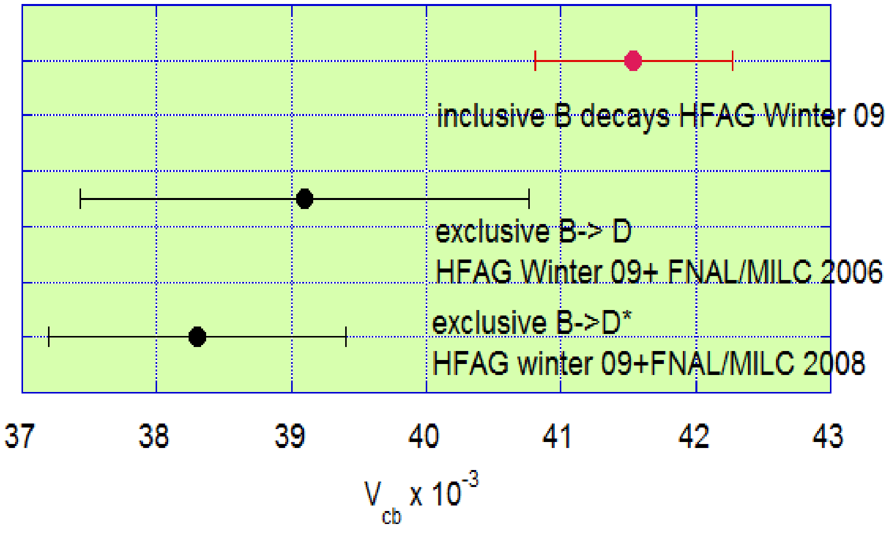
Quenched lattice QCD estimate; assign 100% error

⇒ ε_K band might move up

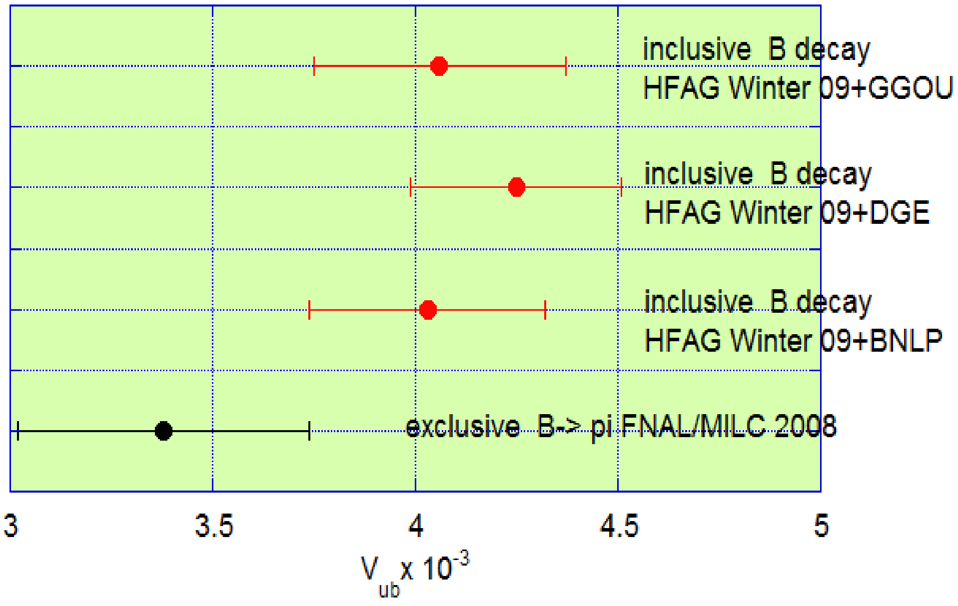
Inclusive vs exclusive determination of Vcb, Vub

- No change of lattice numbers since 2008
- Inclusive (exp + non-lattice theory) values still differ from exclusive (exp + lattice) vakues at 2 sigma level

V_{cb}



V_{ub}



Status of D decay constants

- Experiment 2009

  CLEO ArXiv 0901.1216

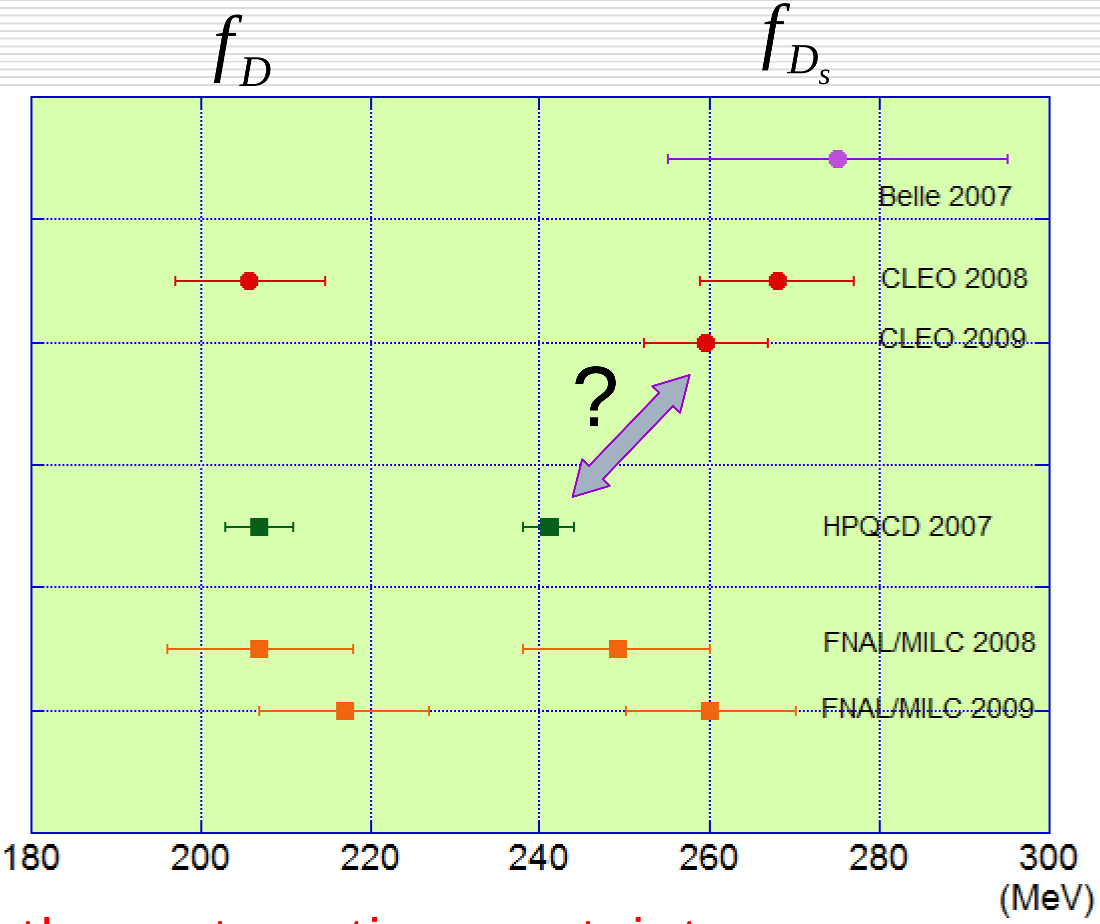
  $$f_D = 205.8 \pm 8.9 MeV$$

  $$f_{D_s} = 259.5 \pm 7.3 MeV$$

- Lattice QCD
  - HPQCD

    no change since the 2007 value
  - FNAL/MILC

    moved up, but large error



Lattice QCD has to resolve the systematic uncertainty:
- HISQ action for HPQCD
- Clover action for FNAL/MILC