USQCD thermodynamics

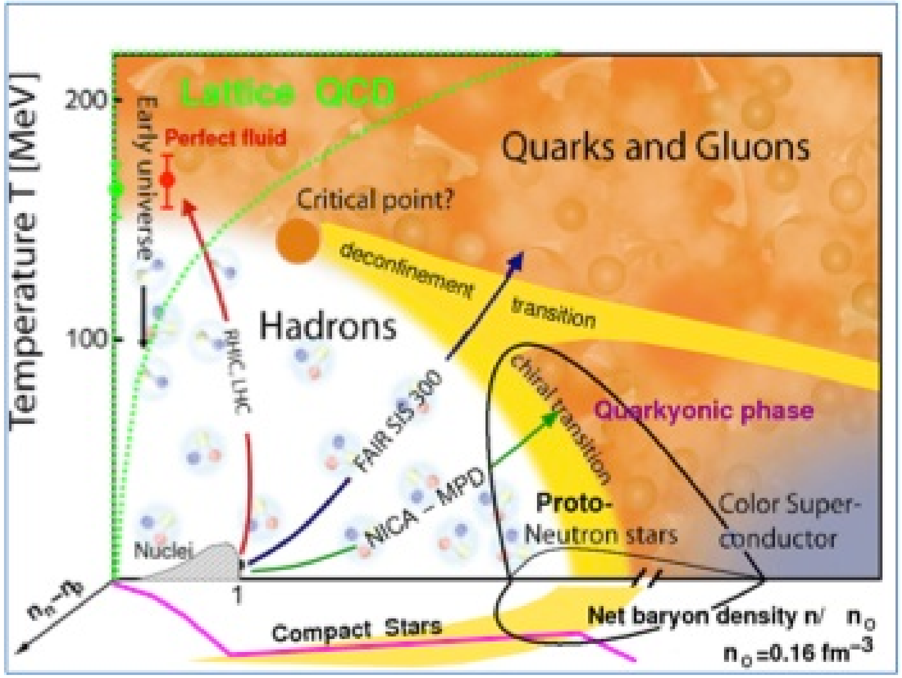
Peter Petreczky, BNL

Defining questions of nuclear physics research in US:

Nuclear Science Advisory Committee (NSAC) “The Frontiers of Nuclear Science”, 2007 Long Range Plan

“What are the phases of strongly interacting matter and what roles do they play in the cosmos ?”

“What does QCD predict for the properties of strongly interaction matter ?”



Tools :

1) LQCD
2) Heavy ion experiments
   +phenomenology
3) combination of the above

LQCD results → models of dynamical evolution → RHIC experiments

USQCD SciDAC-3: EoS, chiral aspects of the QCD transition (with HISQ/DWF), Taylor expansion, spectral functions

Ongoing calculations:

- The chiral transition and T_c
- Lattice calculations of the EoS
- Fluctuations of conserved charges
- Quarkonium correlators

Large scale calculations with
Highly Improved Staggered Quark (HISQ)
action

Exploratory calculations using
Domain Wall Fermions (DWF)

Calculations on the next-genaration hardware:

- QCD transition with chiral action
- Quarkonium spectral functions and thermal dilepton rate
- Electric conductivity and heavy quark diffusion constant

Large scale calculations using
Domain Wall Fermions (DWF)

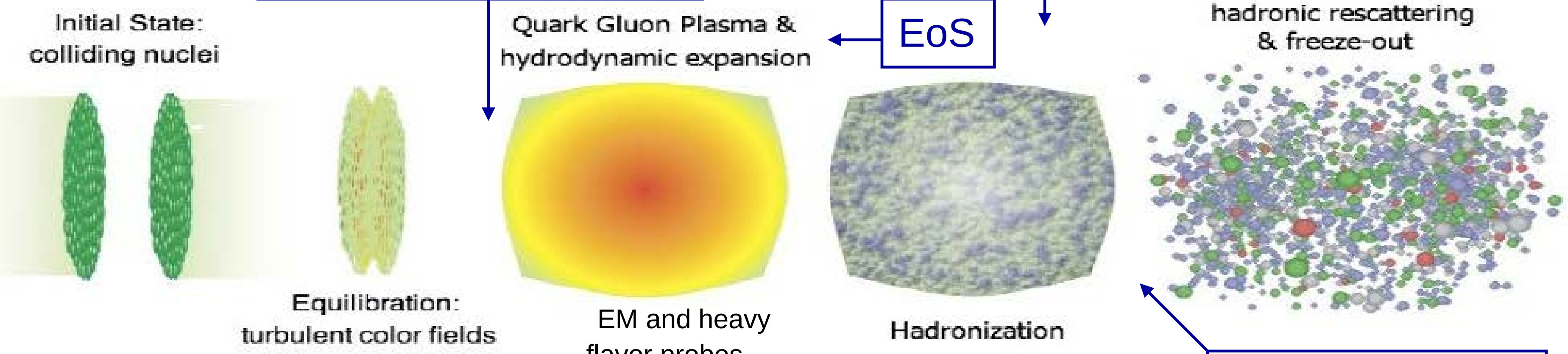
Extremely large scale calculations with
Highly Improved Staggered Quark (HISQ)
action

Physics of heavy ion collisions and LQCD

high temperature QCD
weak coupling ?

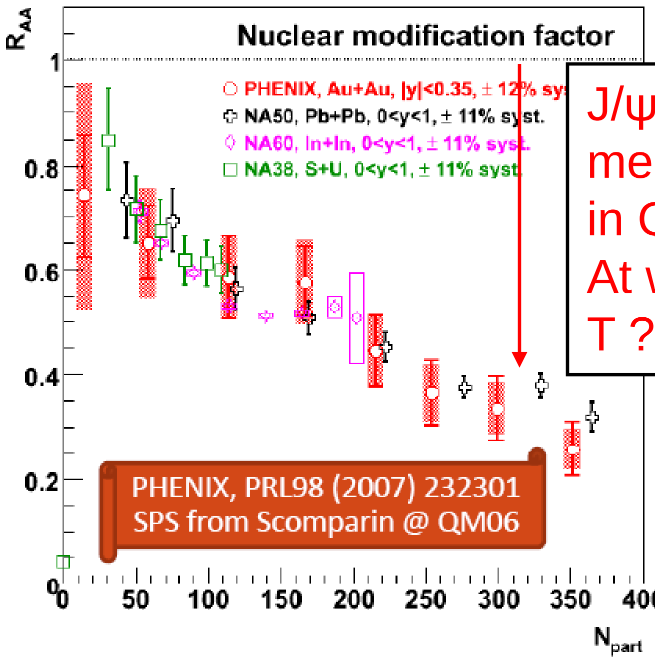
Chiral transition, T_c fluctuations of conserved charges

EoS



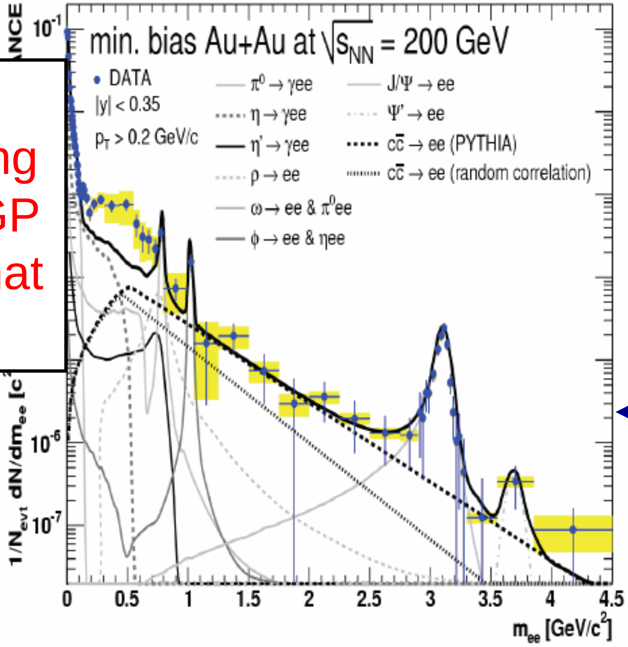
EM and heavy
flavor probes

test of Hadron
Resonance Gas
(HRG)
using LQCD



PHENIX, PRL98 (2007) 232301
SPS from Scomparin @ QM06

J/ψ
melting
in QGP
At what
T ?



quarkonium spectral
functions,
heavy quark diffusion,
thermal dileptons

Impact of the US lattice thermo calculations

of citations during the past year of the most cited HotQCD/BNL paper (SPIRES)

1) Bazavov et al, Equation of state and QCD transition at finite temperature,
Phys. Rev. D80 (2009) 014504
80 times (286 in all years)

2) Cheng et al, The QCD equation of state with almost physical quark masses,
Phys. Rev. D77 (2008) 014511
41 times (336 in all years)

3) Bazavov et al, The chiral and deconfinement aspects of the QCD transition,
Phys. Rev. D85 (2012) 054503
36 times

4) Cheng et al, Baryon Number, Strangeness and Electric Charge Fluctuations in QCD at High Temperature
Phys. Rev. D79 (2009) 074505
29 times(103 in all years)

5) Kaczmarek et al, Phase boundary for the chiral transition in (2+1) -flavor QCD at small values of the chemical potential
Phys. Rev. D83 (2011) 014504
28 times (36 total in all years)

Different Hardware for thermo computations

EoS calculations need large $T=0$ lattices, e.g. 48^3x64 :
INCITE allocation on leadership machines

Moderate size ($T>0$) lattices, e.g. 48^3x12 or smaller :
USQCD clusters in JLab and FNAL

Taylor expansion coefficients/fluctuation of conserved charges are very efficiently calculated on GPU cluster in JLab

USQCD proposal 2011/2012 (in M J/psi core h) :

HotQCD (PI A. Bazavov) EoS calculations : Clusters (15M), BG/P (16M, INCITE)

BNL (PI H.T. Ding) Universal Behavior of the chiral transition : Clusters (39M)

BNL (PI S. Mukherjee) Taylor Expansion : GPUs in JLab (1.4M node h)

Y. Maezawa (BNL) Spatial meson correlators : Clusters (2.1M)

D. Mehta (Syracuse U) Shear viscosity in 2-flavor QCD : Clusters (2.5M)
(INCITE is 21% of all CPU resources for thermo, ~10% of total resources with GPUs)

What is the transition temperature ?

The notion of the transition temperature is only useful if it can be related to the critical temperature in the chiral limit !

Study the temperature and quark mass dependence of the chiral condensate and describe it by the universal scaling form

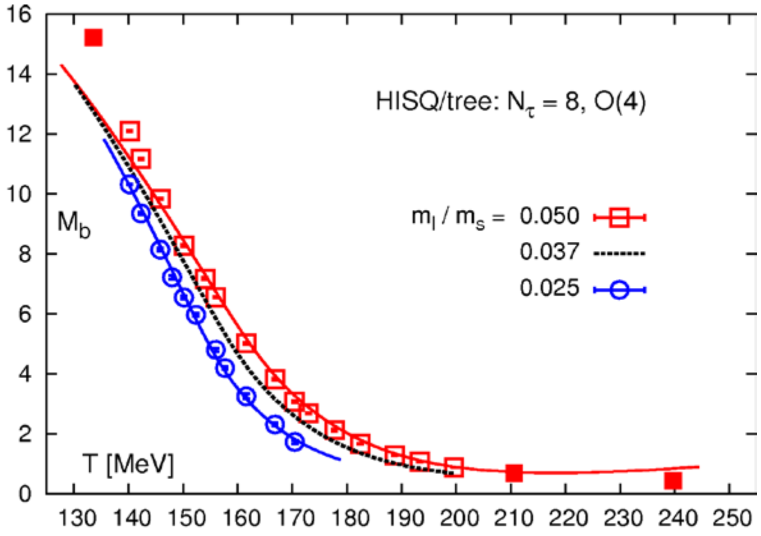
light quark mass m_l ↔ magnetic field H

$$M_b = \frac{m_s \langle \bar{\psi}\psi \rangle_l}{T^4} = h^{1/\delta} f_G(t/h^{1/\beta\delta}) + f_{M,reg}(T,H)$$

$$H = m_l/m_s, \quad h = H/h_0, t = (T - T_c^0)/(T_c^0 t_0)$$

Bazavov et al, Phys. Rev. D85 (2012) 054503

$$T_c = (154 \pm 8 \pm 1(scale))\text{MeV}$$



Can hadronic transport models be trusted if $T_c \sim 150$ MeV ?

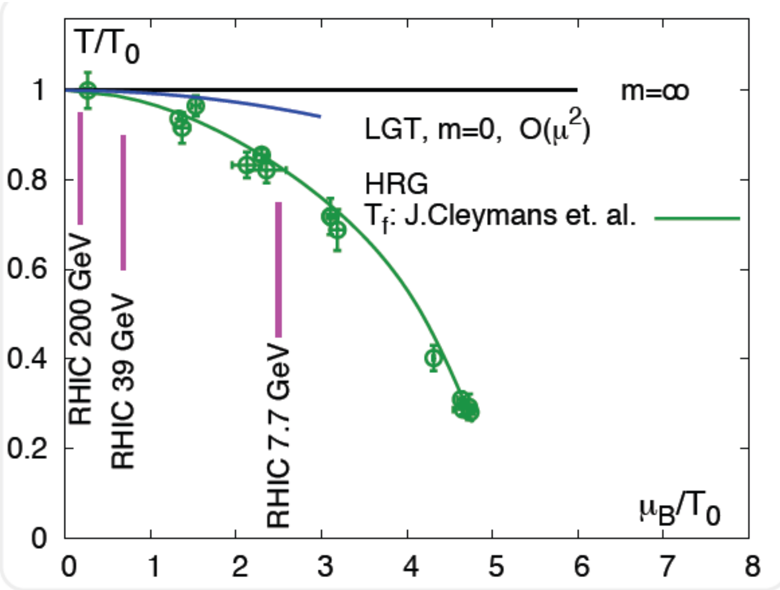
How close is the transition line to the freeze-out line ?

How well is the regular part is under control ?

How T_c depends on baryon density ?

Need smaller m_l !

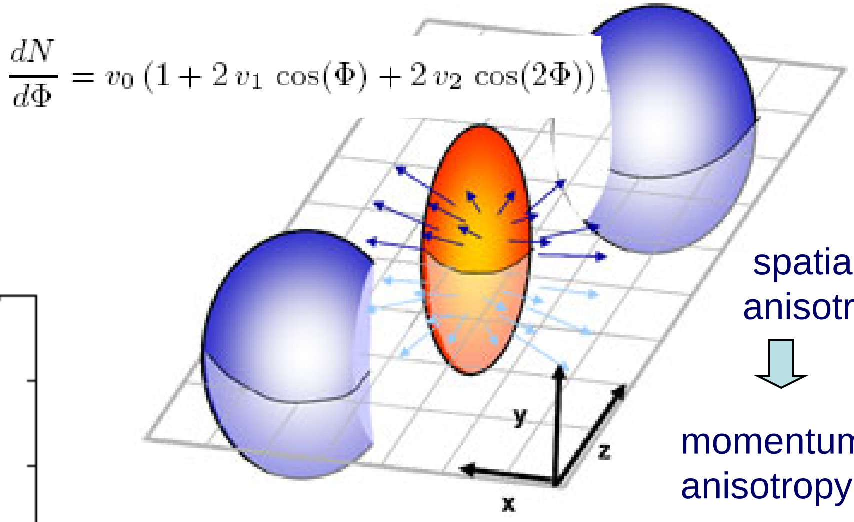
USQCD Proposal by H.T. Ding: down to $m_l = m_s/80$



Status of the EoS calculations

T_c and EoS → hydro model → v_2 and particle spectra → comparison with experiment

particle spectra and elliptic flow parameter v_2



$$\frac{dN}{d\Phi} = v_0\,(1 + 2\,v_1\,\cos(\Phi) + 2\,v_2\,\cos(2\Phi))$$

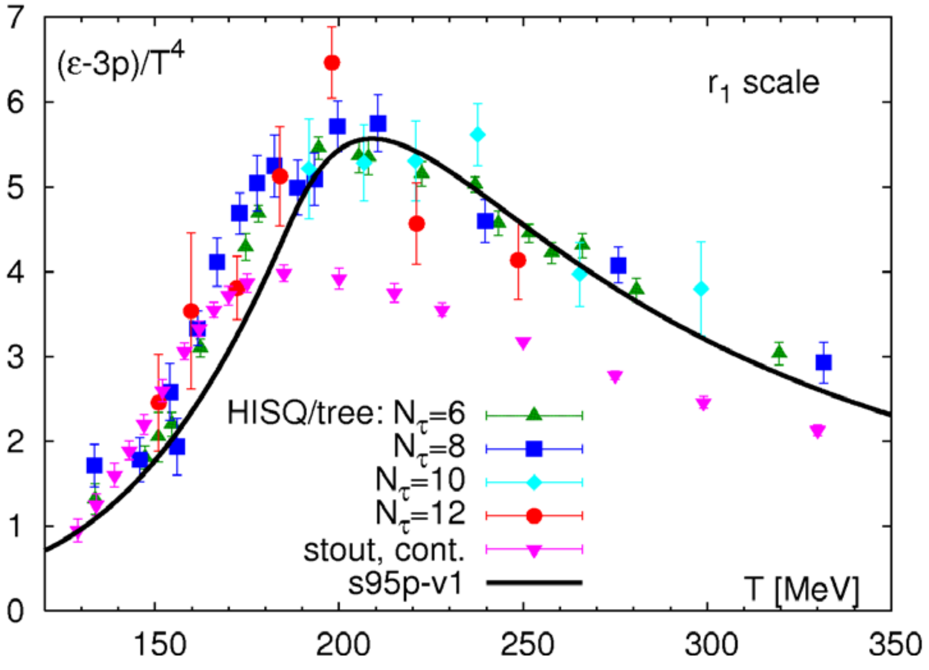
spatial anisotropy

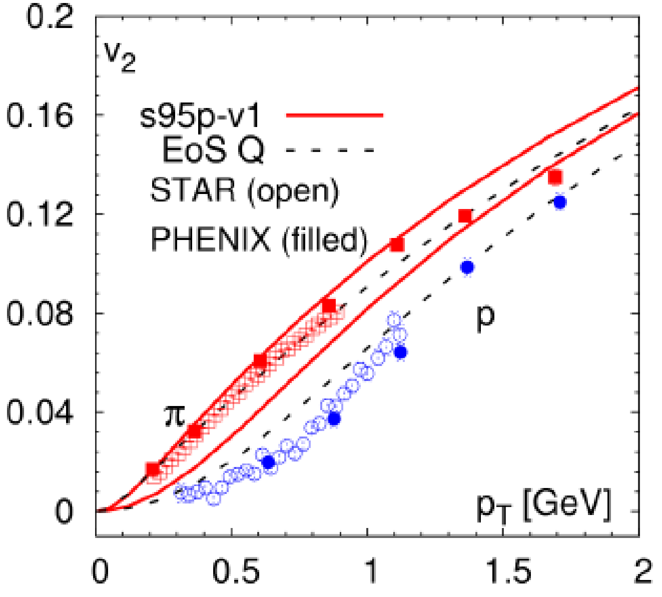
momentum space anisotropy

pressure gradients create anisotropic flow

EoS is calculated from *ε-3p* using the intergral method

Summary of the lattice results on *ε-3p :*





need $N_\tau=12$ to get cutoff effects under control

Ongoing project on INCITE resources (BG/P in ANL) and USQCD cluster in FNAL

QCD thermodynamics at non-zero chemical potential

Taylor expansion : $$\frac{p(T,\mu_B,\mu_S,\mu_Q)}{T^4} = \sum_{i,j,k}\frac{1}{i!j!k!}\chi^{BSQ}_{ijk}\cdot\mu_B^i\cdot\mu_S^j\cdot\mu_Q^k$$ hadronic

$$\frac{p(T,\mu_u,\mu_d,\mu_s)}{T^4} = \sum_{i,j,k}\frac{1}{i!j!k!}\chi^{uds}_{ijk}\cdot\mu_u^i\cdot\mu_d^j\cdot\mu_s^k$$ quark

LQCD : Taylor expansion coefficients ⇨ fluctuations of conserved charges: *X*= *B, S, Q* ⇨ Beam energy scan @ RHIC → parameters of the distribution

$$\chi_1^X = \frac{1}{VT^3}\langle N_X\rangle \qquad M_X = \langle N_X\rangle$$ mean

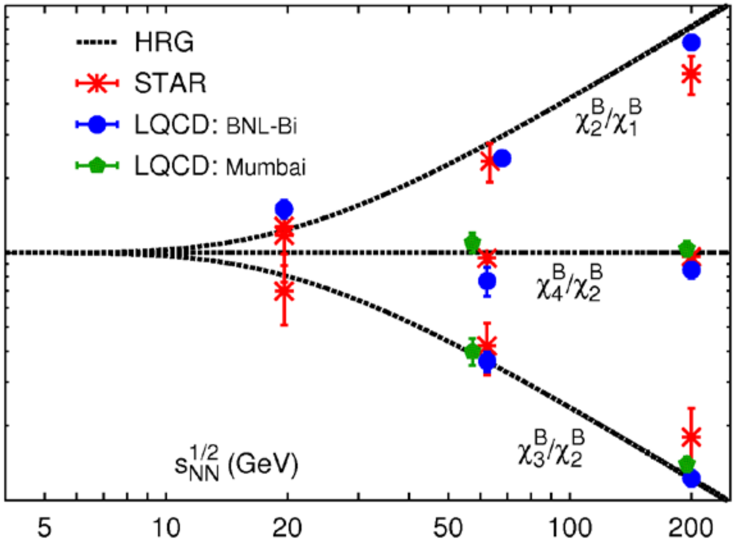
$$\chi_2^X = \frac{1}{VT^3}\langle(\delta N_X)^2\rangle \qquad \sigma_X = \langle(\delta N_X)^2\rangle$$ variance

$$\chi_3^X = \frac{1}{VT^3}\langle(\delta N_X)^3\rangle \qquad S_X = \langle(\delta N_X)^3\rangle/\sigma_X^3$$ Skewness

$$\chi_4^X = \frac{1}{VT^3}[\langle(\delta N_X)^4\rangle - 3\langle(\delta N_X)^2\rangle^2] \qquad K_X = \langle(\delta N_X)^4\rangle/\sigma_X^4 - 3$$ Kurtosis

$$N_X = X - \bar{X}, \quad \delta N_X = N_X - \langle N_X\rangle$$

can calculated very effectively on single GPUs (ongoing BNL project, PI S. Mukherjee)



Volume independent combinations:

$$M_X/\sigma_X = \chi_1^X/\chi_2^X$$

$$S_X\cdot\sigma_X = \chi_3^X/\chi_2^X$$

$$K_X\cdot\sigma_X^2 = \chi_4^X/\chi_2^X$$

Determination of the freeze out conditions from LQCD

Chemical freeze out : formation of hadrons after cooling of the plasma, particle abundances don’t change for $T<T_f$

In the past the freezeout conditions in RHIC have been determined using HRG model

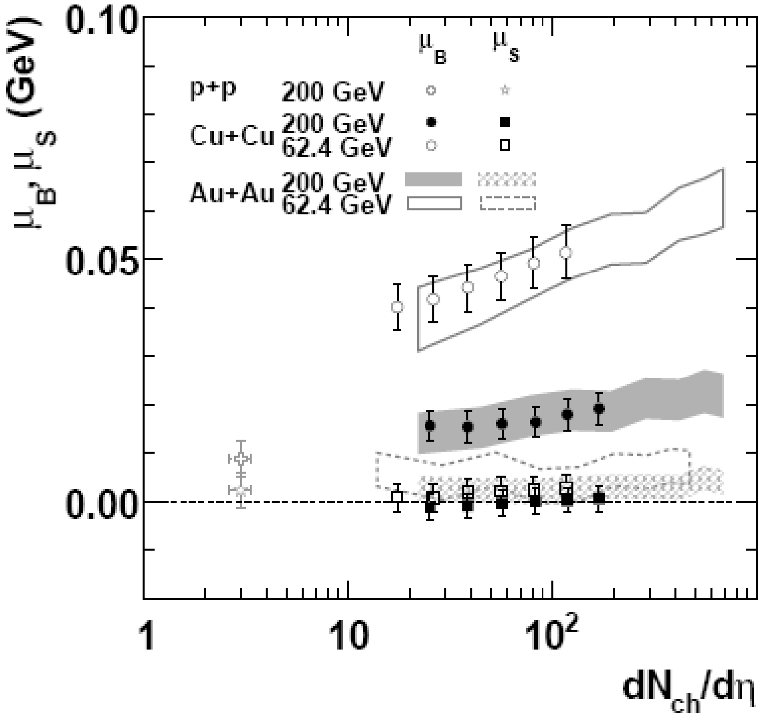
$\Rightarrow T_f \sim 160$ MeV

$\Rightarrow$ validity of HRG ?

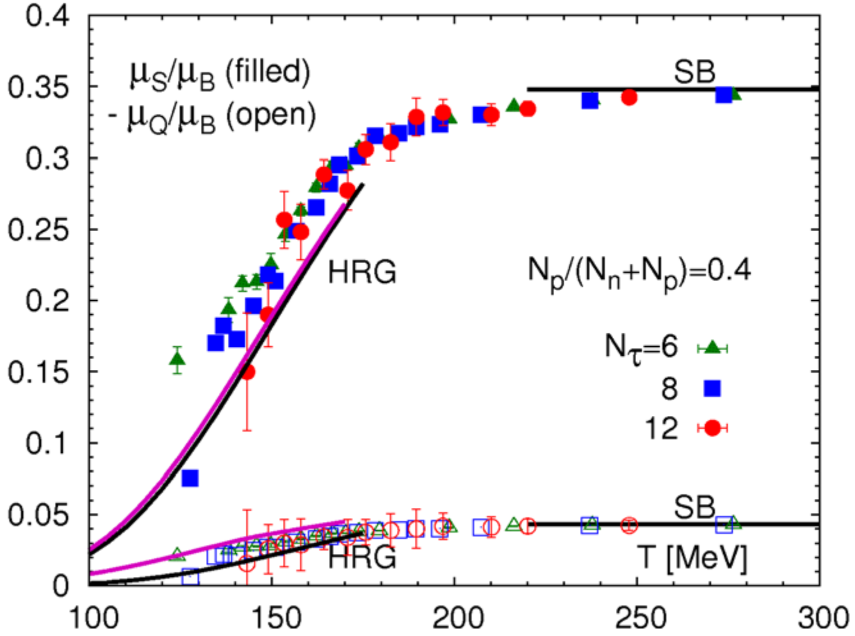
$\Rightarrow$ to locate the critical end-point the freeze-out line should close to $T_c(\mu)$

$\Rightarrow$ freeze-out conditions can be determined using LQCD results on Taylor expansion coefficients and comparing them experimental results on event-by-event fluctuations

STAR Phys.Rev. C83 (2011) 034910

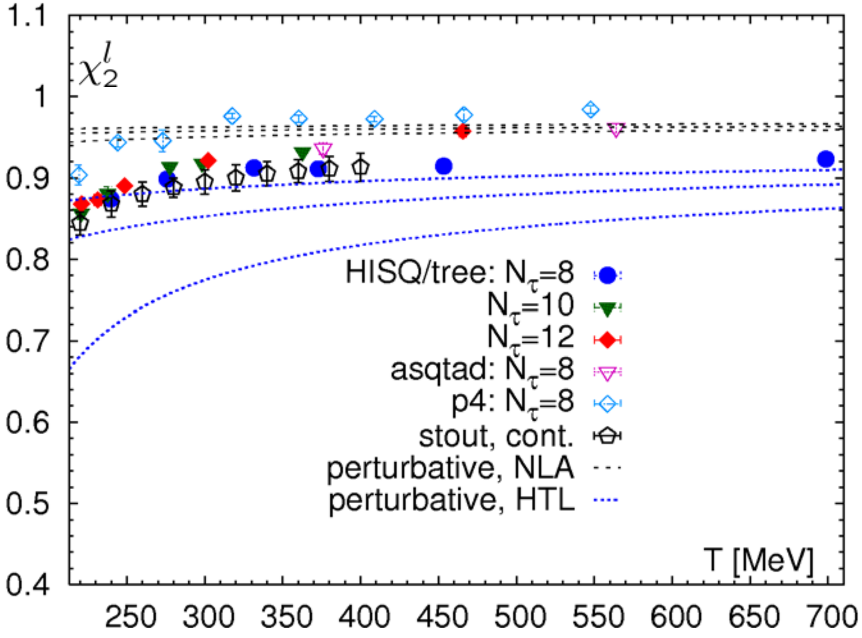


ongoing BNL project on GPU

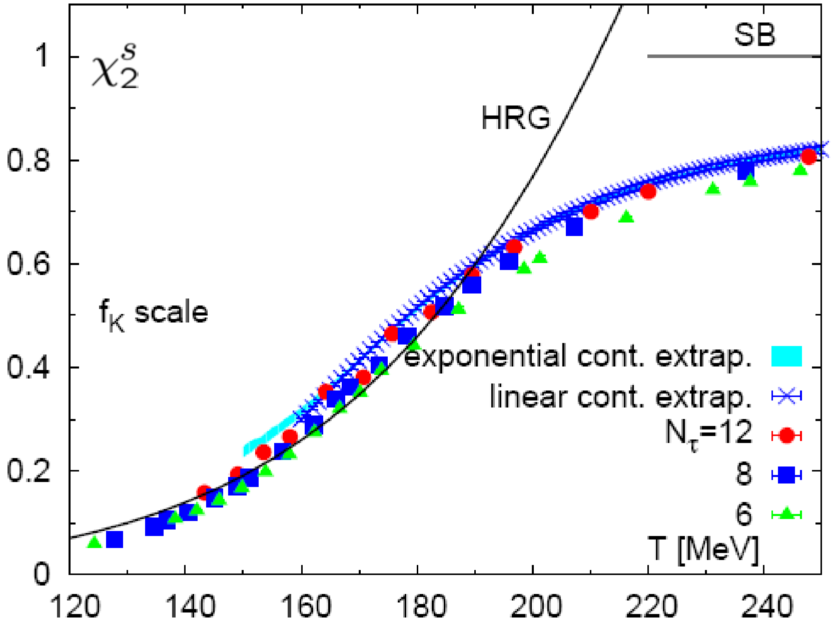


Fluctuations at low and high temperatures

H.-T.Ding (2011-2012)



HotQCD, USQCD clusters



At sufficiently high *T* fluctuations can be described by perturnation theory because of asymptotic freedom

The quark number susceptibilities for *T>300*MeV agree with resummed petrurbative predictions
A. Rebhan, arXiv:hep-ph/0301130
Blaizot et al, PLB 523 (01) 143

Hadrons are the relevant d.o.f. at low *T*
$\Rightarrow$ hadron gas + interactions
(approximated by s-channel resonances)
$\Rightarrow$ non-interacting hadron resonance gas (HRG)

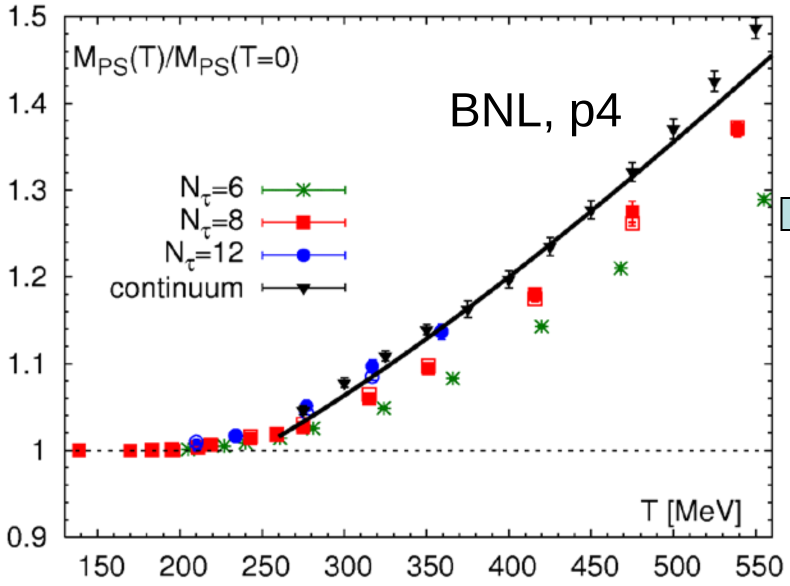
Reasonable agreement between lattice results and HRG the remaining discrepancies are due to the lack of continuum extrapolation

Spatial and temporal correlators

- Temporal and spatial correlation functions are related to meson properties and transport coefficients

$$G(\tau) = \int_0^\infty d\omega \rho(\omega, T) \frac{\cosh(\omega \cdot (\tau - \frac{1}{2T}))}{\sinh(\omega/(2T))} \qquad G(z,T) = \int_{-\infty}^{\infty} e^{ipz} \int_0^\infty d\omega \frac{\rho(\omega, p, T)}{\omega}$$

The study of temporal correlators requires $N_\tau \geq 16$ and very high statistics ($\tau<1/T$)
(available so far only in quenched QCD)
1st step toward dynamical QCD : explore the spatial correlators $G(z) \sim \exp(-M z)$



⇨ *1S charmonium* melting at *T>300*MeV ⇨ suppression of the *J/ψ* nuclear modification factor R_{AA} measured @ RHIC

near term future : more detail study using HISQ action (Y. Maezawa, BNL, 2012)

- Quark contribution to the energy-momentum correlator **=>** shear viscosity in QCD (D. Mehta, Syracuse U, 2012)

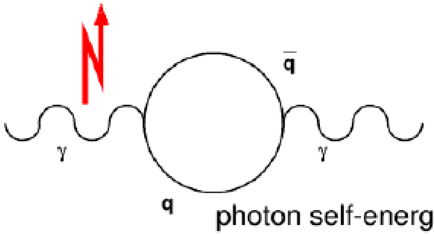
Calculations of the vector spectral functions and dilepton rate

Differential yield of dileptons (Exp.)

Vector spectral function (LQCD)

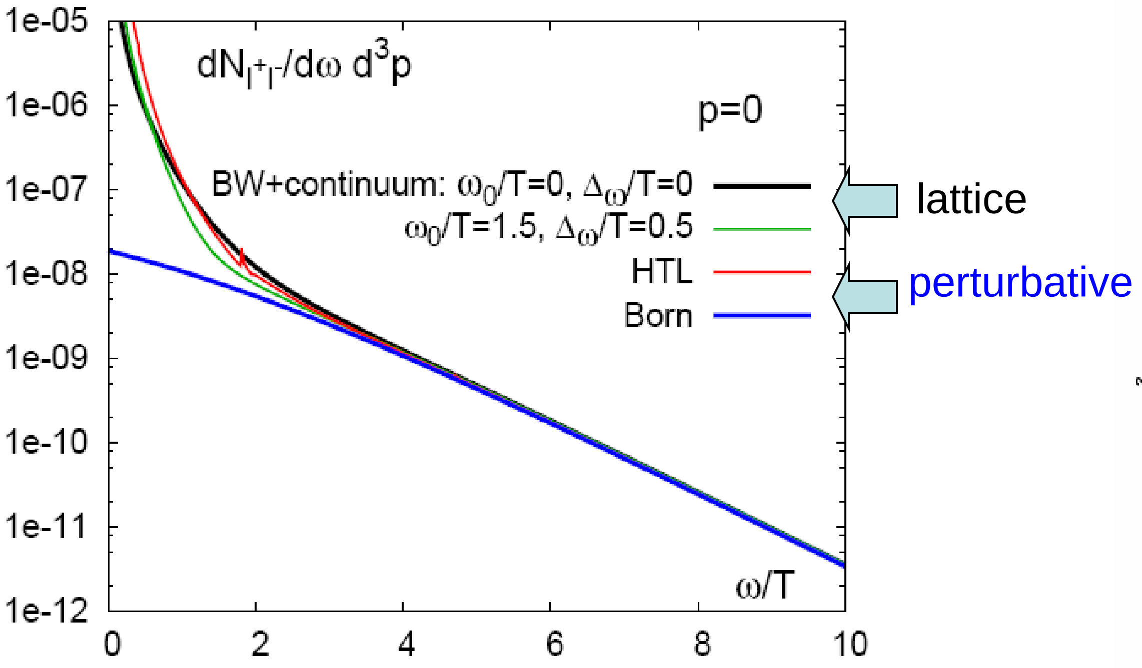
$$\frac{dW}{d\omega d^3p} = \frac{5\alpha_{em}^2}{27\pi^2} \frac{1}{e^{\omega/T}-1} \frac{\rho_{ii}(\omega,p,T)}{\omega^2-p^2}$$

rate $\sim |q\bar{q} \to \gamma^*|^2 \cdot |l^+l^- \to \gamma^*|^2$

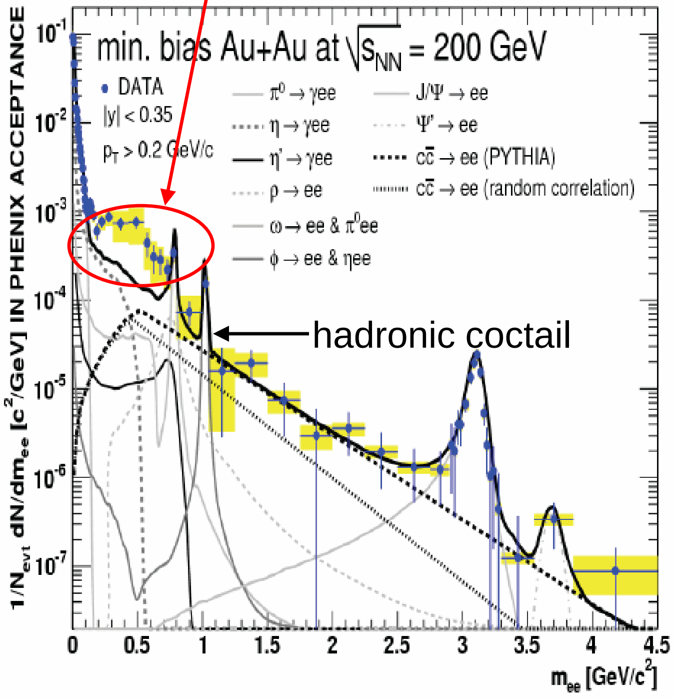


Quenched calculations, *128^{3}x32 lattice*

Ding et al, PRD 83 (11) 034504



*PHENIX :*Excess due to thermal emission



hadronic coctail

unquenched results could be compared with excess in the low mass dilepton rate @RHIC will require calculations on BG/Q

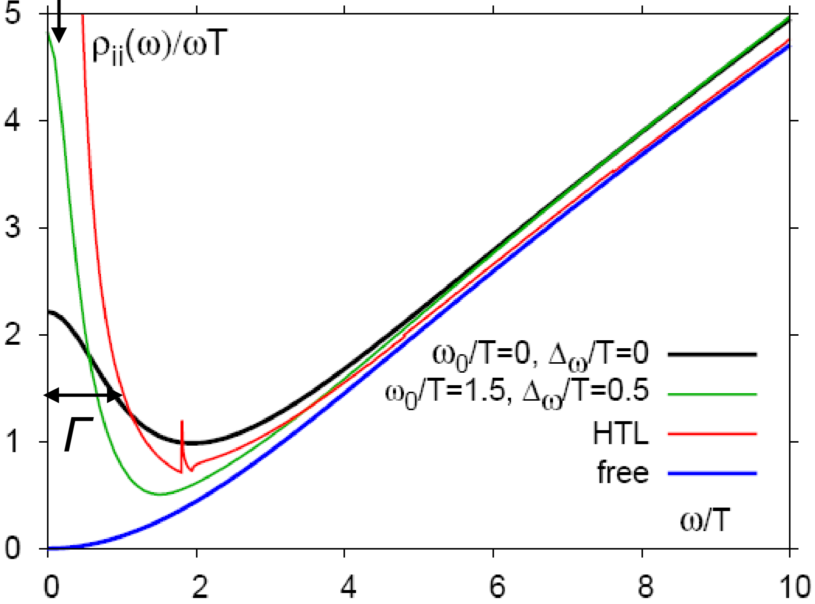
Lattice calculations of the vector spectral functions

Quenched QCD calculations, 128^3x32 lattice

Ding et al, PRD 83 (11) 034504

peak at *ω≈0* = transport peak

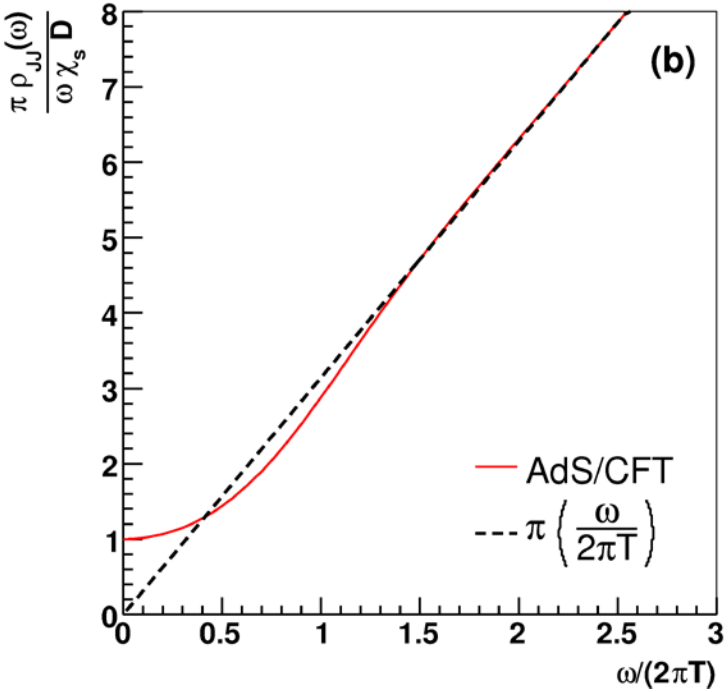
$\Gamma \sim 1/\tau_{relax},\ \sigma_{el} \sim \chi_Q/\Gamma$



$$1/3 < \frac{1}{C_{em}}\frac{\sigma_{el}}{T} < 1,\ C_{em} = \sum_f Q_f^2$$

R-current spectral function in *N=4* SUSY plasma

Teaney, PRD74 (06) 045025

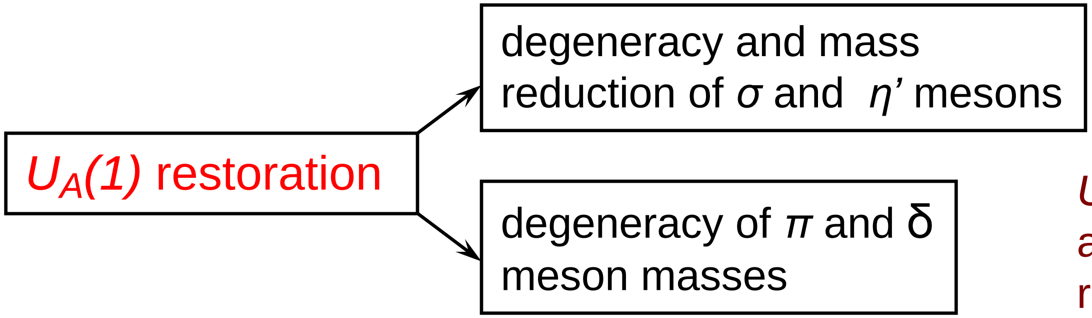


Perfect liquid: *η/s=1/(4 π)* ⬄ no transport peak !
The vector spectral function from LQCD is different from strongly coupled (super-symmetric) plasma with no transport peak

Thermodynamics with Domain Wall Fermions

Symmetries of continuum QCD, proper treatment of axial symmetry that could effect the properties of the chiral transition (change the order of the transition)

exact chiral symmetry on the lattice **=>** Domain Wall Fermions (DMF)



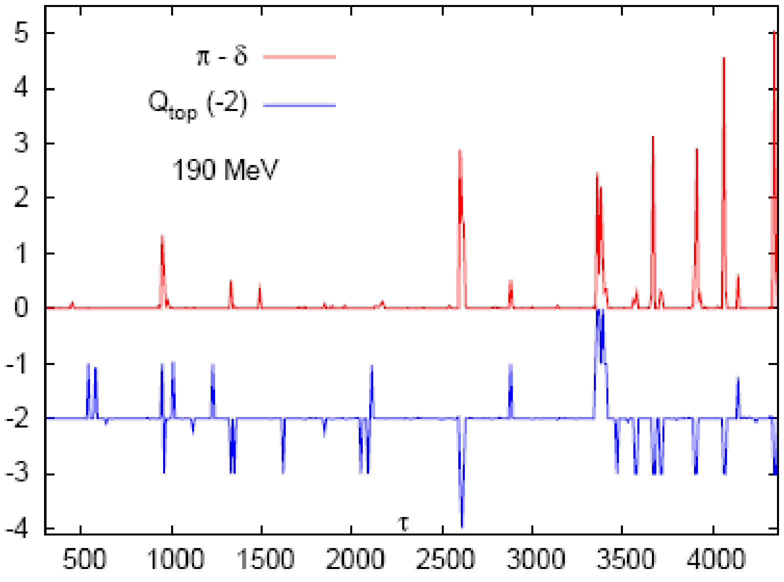
$U_A(1)$ restoration

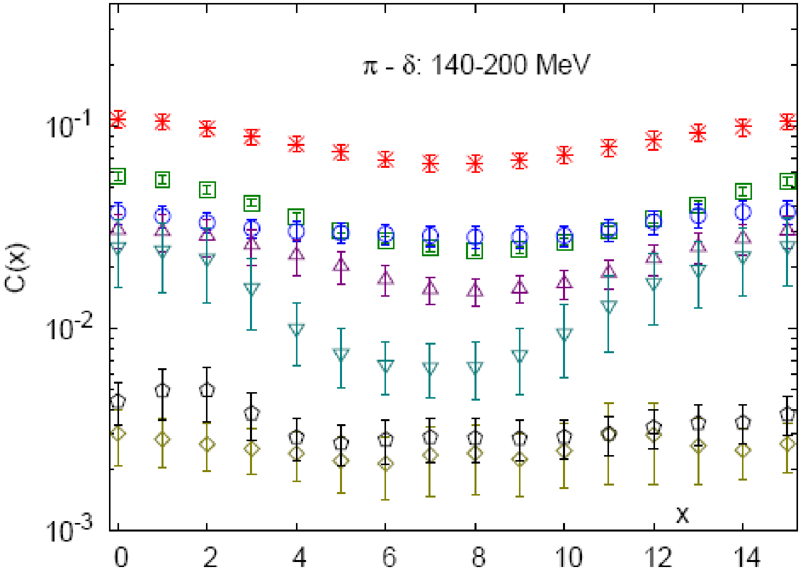
degeneracy and mass reduction of *σ* and *η'* mesons

degeneracy of *π* and δ meson masses

possible η' mass reduction at RHIC
Csorgo et al, PRL 105 (2010) 182301

$U_A(1)$ restoration is restored above the chiral transition, the residual *$U_A(1)$* breaking is controlled by configurations with non-trivial topology





need to increase the volume *16^3x8* → *32^3x8* **=>** calculations on BG/Q

Summary

Lattice QCD starts to provide quantitative results that provide important input for interpreting the experimental results from RHIC

T_c, EoS, fluctuation of conserved charges, spectral functions

How sensitive is the QCD transition at physical quark masses to the universal properties in the chiral limit ? How the transition is modified by baryon chemical potential ?

- Now : HISQ action, exploratory DWF calculations
- >5years : large scale DWF calculations

How the hadronic spectral functions are modified when T is increased ?
Are the transport coefficients of QCD are closer to the weakly or strongly interacting picture ?

- Now exploratory calculations
- >5 years : extremely large scale HISQ calculations

OUR APPROACH:
- Use improved staggered fermions to achieve sufficiently small lattice spacing and large N_T
- Use chiral fermions to control the symmetries of QCD