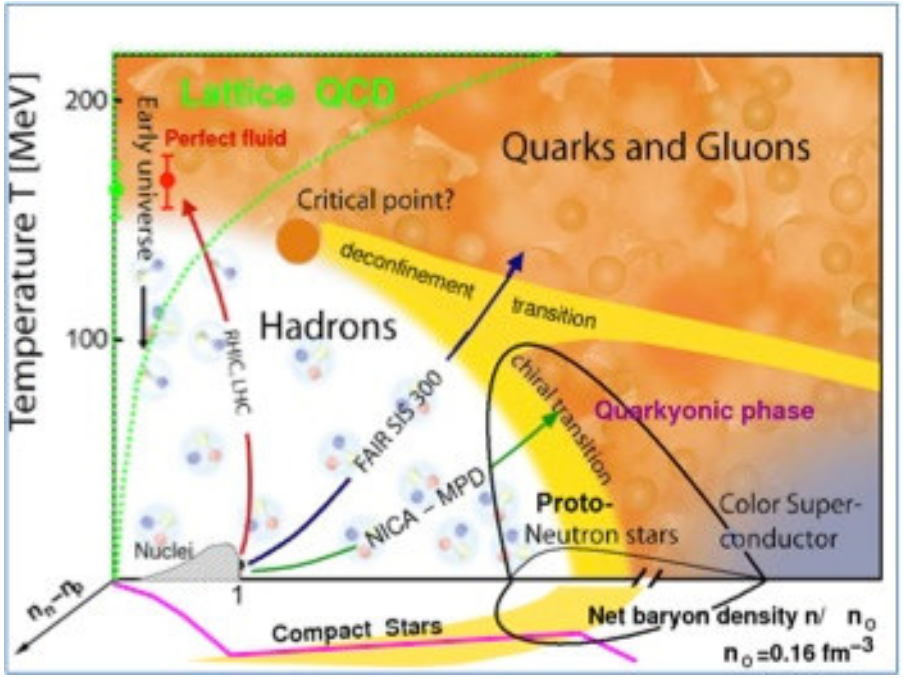
USQCD and thermodynamics:

where we are and where we are going ?

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) EFT
4) combination of the above

LQCD results → models of dynamical evolution → RHIC experiments

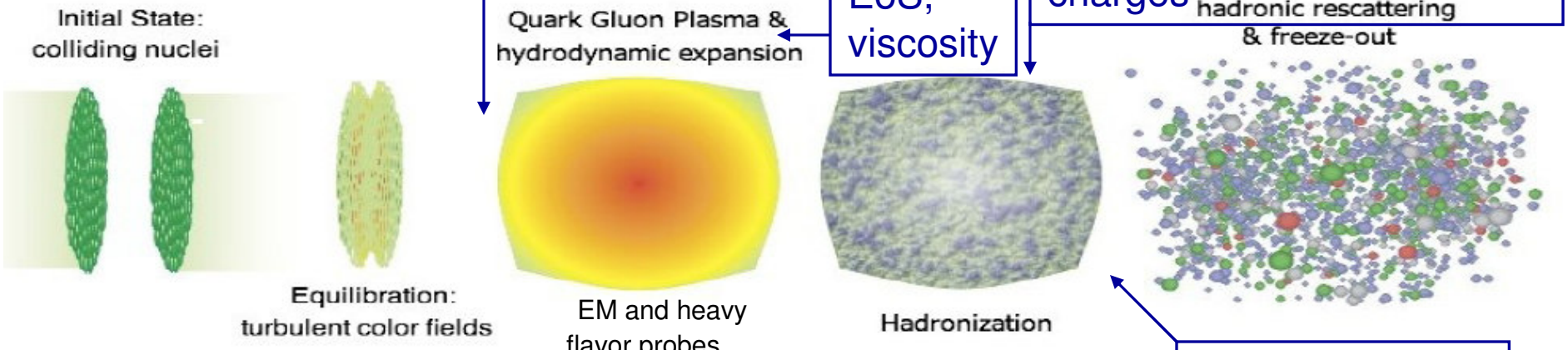
SciDAC-3: EoS, chiral aspects of the QCD transition (with HISQ/DWF), Taylor expansion, spectral functions

Physics of heavy ion collisions and LQCD

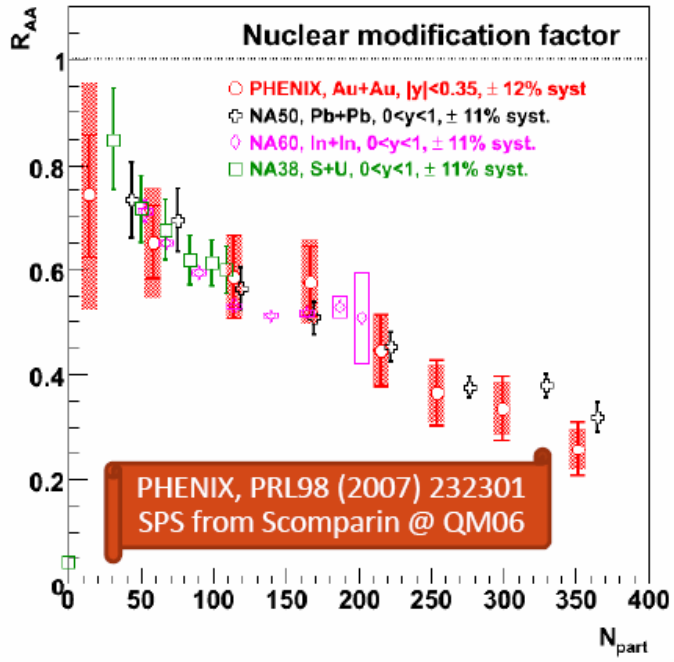
high temperature QCD
weak coupling ?

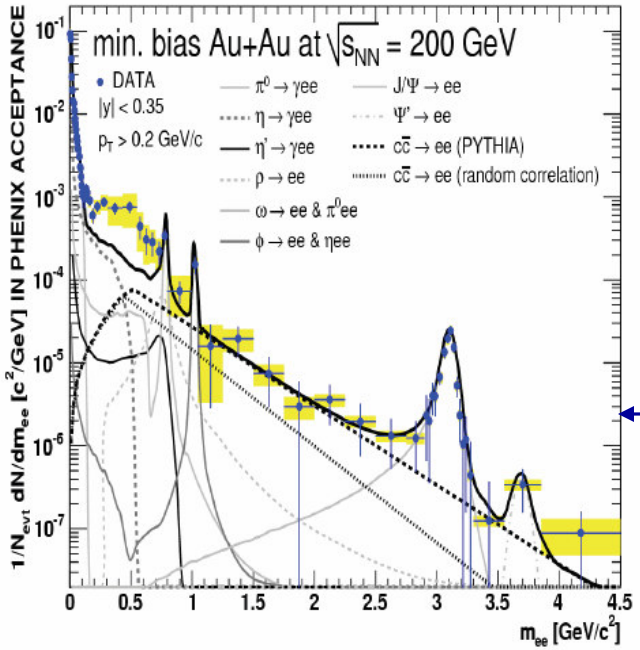
EoS,
viscosity

Chiral transition, T_c fluctu-
ations of conserved
charges



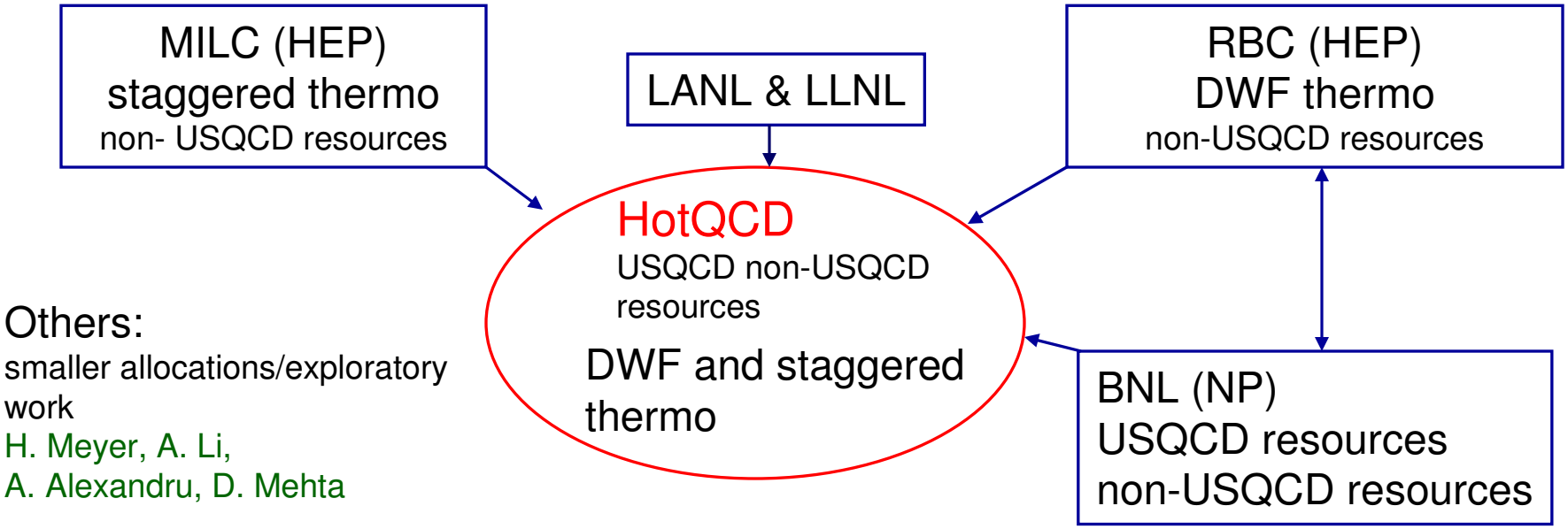
test of Hadron
Resonance Gas
(HRG)
using LQCD





quarkonium spectral
functions,
heavy quark diffusion,
thermal dileptons

Structure of thermo LQCD community and USQCD proposals



USQCD proposal 2011/2012 (time requested in M J/psi core h and GPU node h) :

HotQCD (PI A. Bazavov) EoS calculations : BG/P (INCITE), 17M, USQCD clusters, 15M

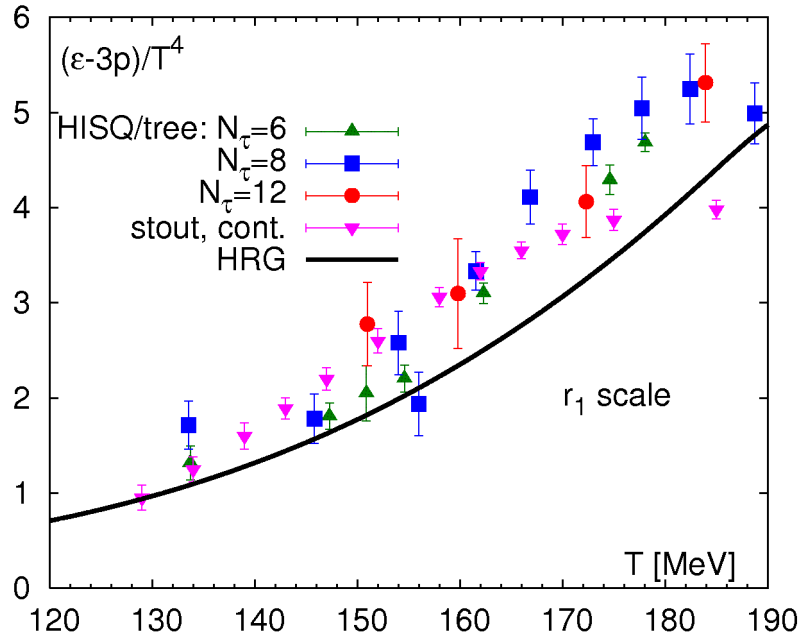
BNL (PI H.T. Ding) Universal Behavior of the chiral transition : USQCD clusters, 40M

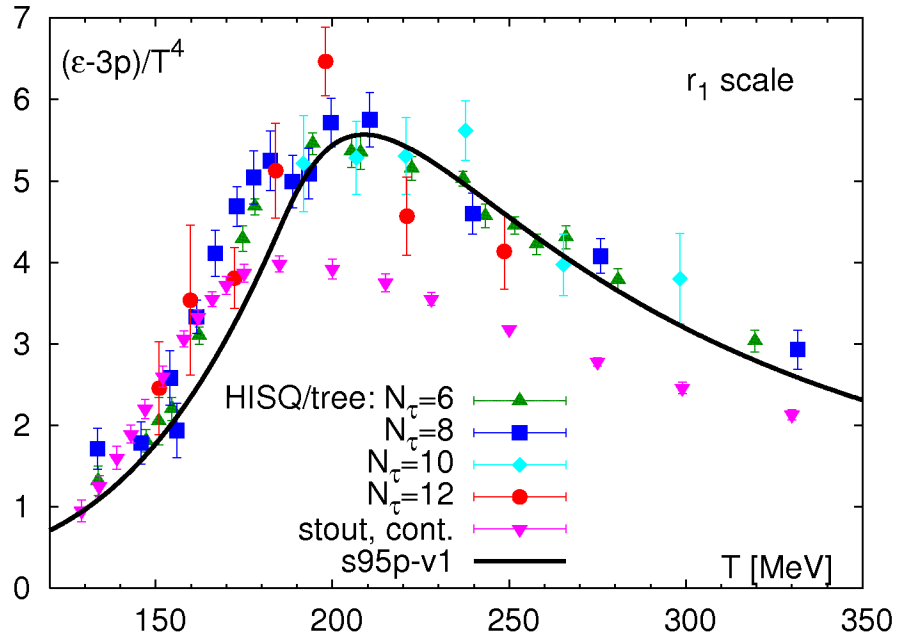
BNL (PI S. Mukherjee) Taylor Expansion : GPUs in JLab, 1400K

Y. Maezawa (type B proposal) Spatial meson correlators : USQCD clusters, 2.1M

D. Mehta (type B proposal) Shear viscosity in 2-flavor QCD : USQCD clusters, 2.5M

Status of the EoS calculations

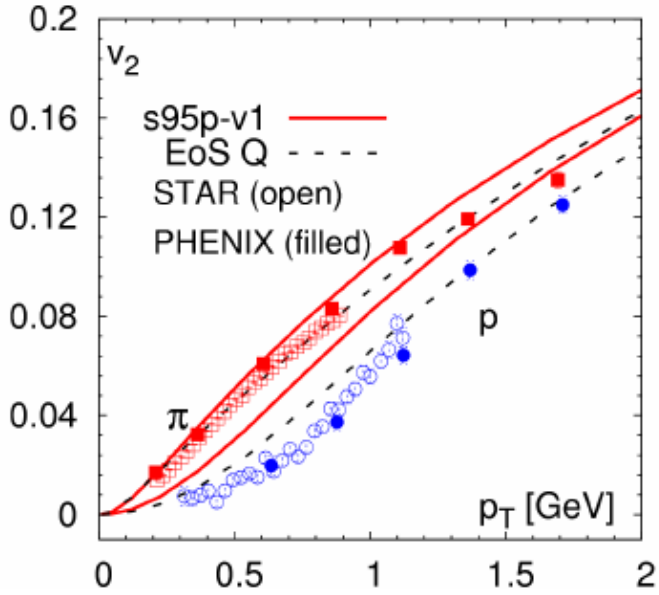




Ongoing project on INCITE resources (BG/P in ANL) and USQCD cluster in FNAL

LQCD based parametrization of the EoS used in most of hydro models for HIC

P. Huovinen, P. Petreczky,
NP A837, 26 (2010)



What is the transition temperature ?

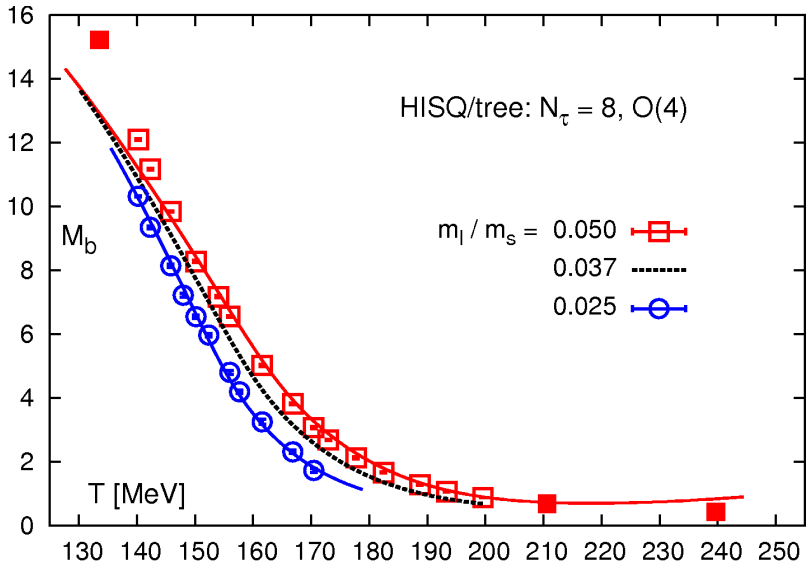
T_c determination requires the study of the chiral transition as function of the quark mass (now HISQ, later DWF):

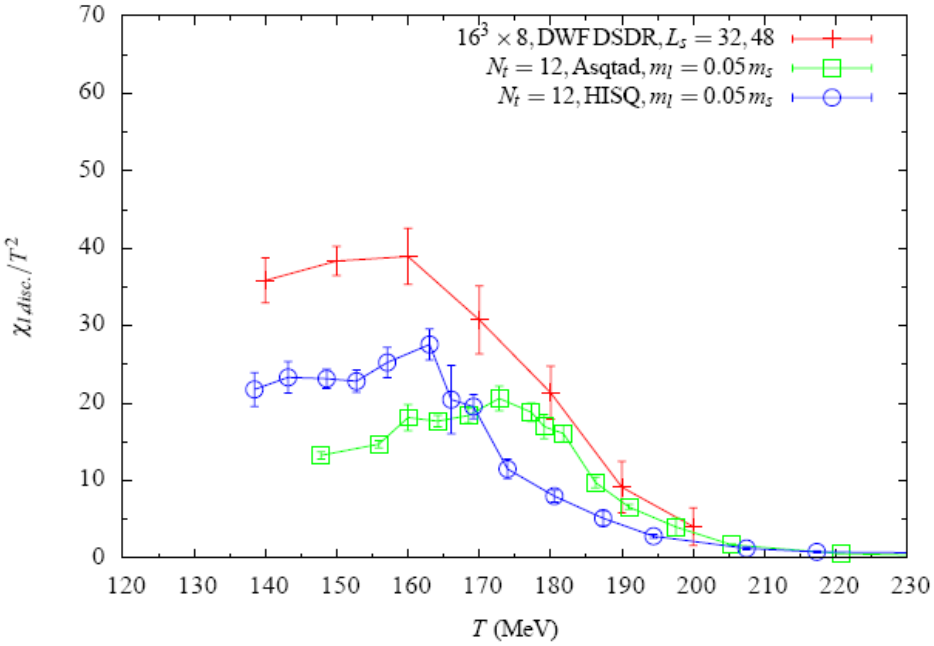
$$M_b = \frac{m_s \langle \bar{\psi}\psi \rangle_l}{T^4} = h^{1/\delta} f_G(t/h^{1/\beta\delta}) + f_{M,reg}(T,H)$$

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

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

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





How well is the regular part is under controll, need smaller m_l ?
USQCD Proposal by H.T. Ding:
down to $m_l = m_s/80$
⇒ crucial for understanding the transition at non-vanishing baryon density, $T_c(\mu)$

Can be staggered formulation be trusted ?
⇒ DWF on larger lattices in the future
proper treatment of axial anomaly

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

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

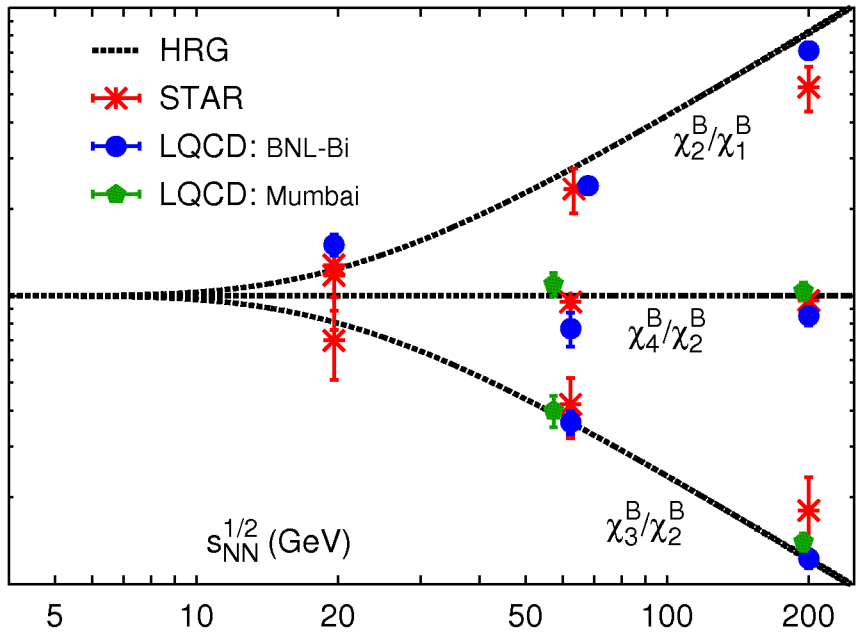
$$\frac{p(T,\mu_u,\mu_d,\mu_s)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{uds}_{ijk} \cdot \mu_u^i \cdot \mu_d^j \cdot \mu_s^k$$ quark

Taylor expansion coefficients give the fluctuations and correlations of conserved charges, e.g.

$$\frac{\chi_2^X}{T^2} = \frac{\chi_X}{T^2} = \frac{1}{VT^3}(\langle X^2\rangle - \langle X\rangle^2)$$

$$\frac{\chi_{11}^{XY}}{T^2} = \frac{1}{VT^3}(\langle XY\rangle - \langle X\rangle\langle Y\rangle)$$

BES @ RHIC



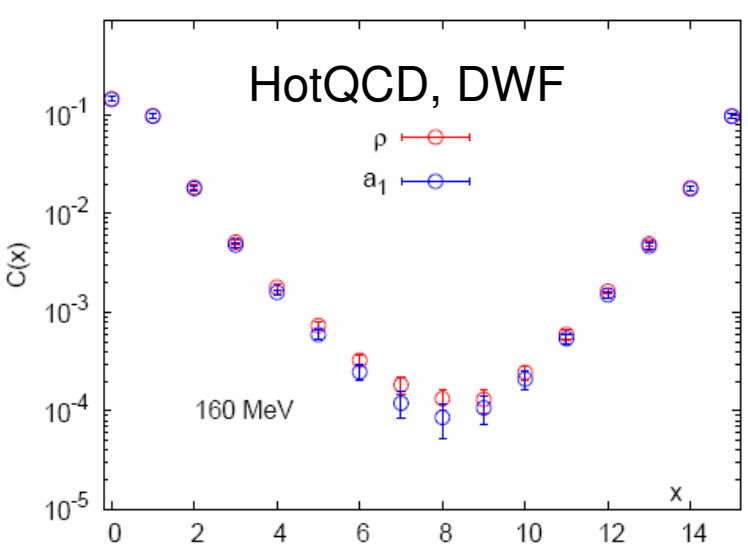
can be done very effectively on single GPUs (ongoing project by Mukherjee)

Spatial and temporal correlators

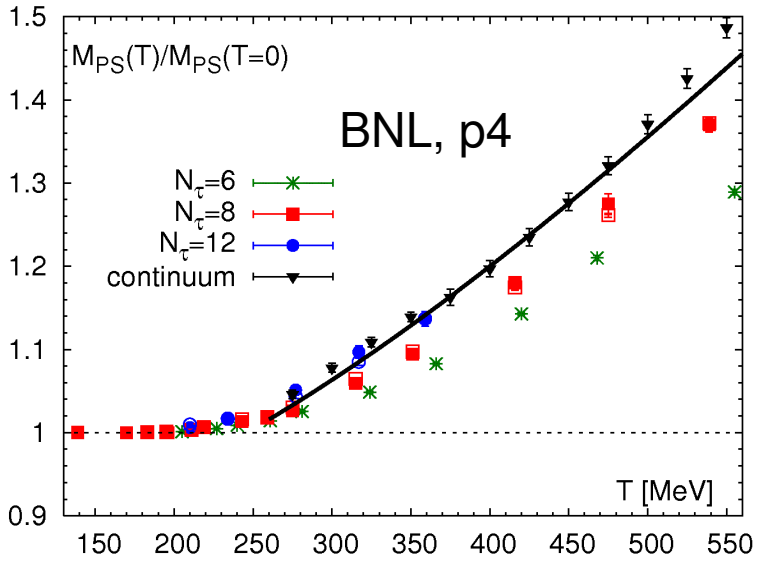
• Temporal and spatial correlation functions are related to meson properties and transport coefficients

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

Chiral symmetry:
low/intermediate mass dilepton rate



Onset of deconfinement:
charmonium melting



J/ψ melting at *T>300*MeV

near term future : more detail study using HISQ action (Y. Maezawa, type B proposal)

• quark contribution to the energy-momentum correlator => shear viscosity in QCD
(D. Mehta type-B proposal 2012)

Conclusions

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

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 ?

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 ?

Use improved staggered fermions to achieve sufficiently small lattice spacing and large N_T

Use chiral fermions to control the symmetries of QCD