Hot QCD: exploring the hot and dense strongly interacting matter

BROOKHAVEN
NATIONAL LABORATORY

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NY Center for Computational Science

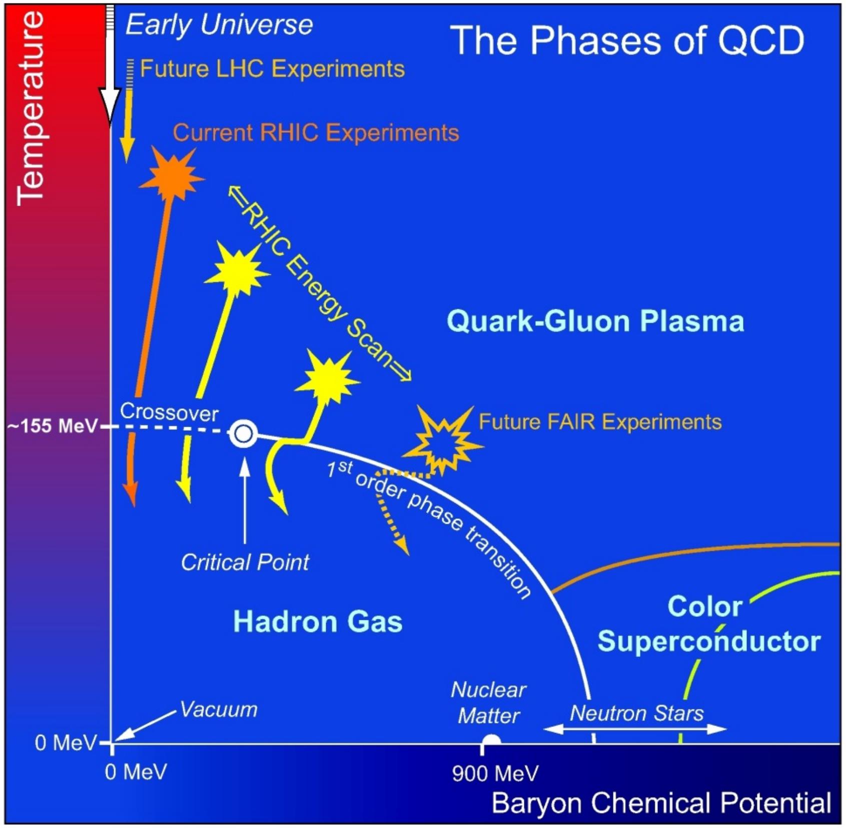
Computational Nuclear Physics, Washington D.C., SURA Headquarters, July 23-24, 2012

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 ?”



one of the major accomplishments since 2007: first reliable quantitative prediction for the phase diagram for small μ_B

Other questions raised by experimental results from RHIC according to 2012 NAS report “Exploring the Heart of Matter”:

How and at what time scale equilibration happens in heavy ion collisions ? => real time simulation of classical gauge fields

What is the viscosity of the matter produced at RHIC ? => relativistic 3+1 d hydro simulations coupled to realistic pre-equilibrium dynamics

Accomplishments since 2007 and future challenges

1) Detailed understanding of the chiral and deconfining aspects of QCD transition, and determination of the chiral transition temperature in the continuum limit for $\mu_B=0$.
Verify these results with chiral quarks, extend the study of the phase diagram to $\mu_B>0$. Locate critical end point (CEP) or rule out its existence.

2) Study of EoS at several lattice spacings.
Extend current studies to finer lattices perform continuum extrapolation.

3) Detailed study of fluctuations of conserved charges, exploratory study of the transition temperature as function of the quark mass.
Calculate fluctuation of conserved charges in the continuum limit.

4) Exploratory studies of quarkonium spectral functions and transport coefficients in quenched QCD.
Extend these studies to QCD with light dynamical quarks.

5) 3+1 dimensional relativistic viscous hydrodynamics with realistic initial conditions has been developed (NSAC milestone met).
Quantitative extraction of η/s from experimental data on flow.

NAS report 2012: “Exploring the Heart of Matter”, section “Exploring Quark Gluon Plasma”

1) The near perfect liquid QGP discovered at RHIC and now produced also at the LHC must have a particulate description if looked at with a good enough microscope; how, and at what short length scales, can its individual quark and gluon constituents be resolved? And, how does a strongly coupled liquid emerge from constituents that at short length scales are coupled only weakly?

What are the dof at high temperature ?

2) Experiments at RHIC indicate that the quark-gluon plasma liquid forms and reaches local equilibrium remarkably quickly, in about the time it takes light to travel across one proton. How does this happen? How does the system go from the strong gluon fields hypothesized to occur inside large nuclei to the flowing QGP liquid?

How does the equilibration in RHIC happens ?

3) Does the quark-gluon plasma liquid produced at RHIC and the LHC dissolve even the very small particles formed from heavy quarks and their anti-particles? Does the quark-gluon plasma prevent a heavy quark and antiquark from binding to each other only when they are farther apart than some “screening length”? How close together do they have to be for them to feel the same attraction that they

What happens to heavy quark bound states in QGP ?

extracting η/s from RHIC, LQCD calculation of critical point, fluctuations of conserved charges, quarkonium spectral functions, transport coefficients

Finite Temperature QCD and its Lattice Formulation

$$\langle O\rangle = \mathrm{Tr}\, O e^{-\beta H-\mu N} \qquad \beta = 1/T$$

$$\Downarrow$$

$$\langle O\rangle = \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi}\, O e^{-\int_0^\beta d\tau d^3x \mathcal{L}_{QCD}}$$

$$A_\mu(0,\mathbf{x}) = A_\mu(\beta,\mathbf{x}) \quad \psi(0,\mathbf{x}) = -\psi(\beta,\mathbf{x})$$

$\Downarrow$ Lattice

integral with very large dimensions

$$\langle O\rangle = \int \prod_x dU_\mu(x) O(det D_q[U,m,\mu]) e^{-\sum_x S_G[U(x)]}, U_\mu(x) = e^{igaA_\mu(x)}$$

$\mu = 0$ → Monte-Carlo Methods

challenge : cost ~ $1/a^7$

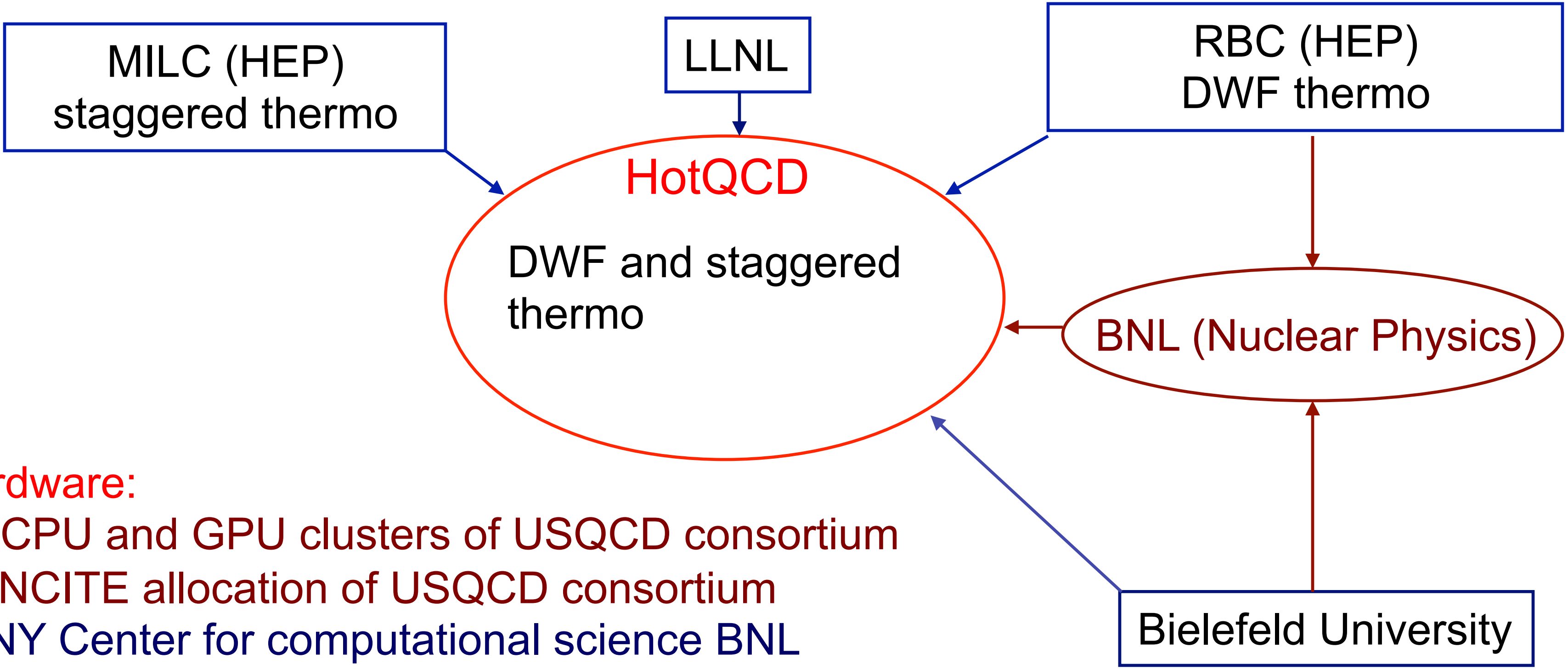
$\mu \neq 0$: $det D_q(U,m,\mu)$ complex → sign problem → Taylor expansion for not too large μ

- Improved staggered discretization : p4, asqtad, HISQ : relatively inexpensive numerical but does not preserve all the symmetries of QCD

- Domain Wall Fermion (DWF) formulation: preserves all the symmetries but *costs ~ 100x of staggered formulation*

HotQCD: a collaborative effort

Hot and dense QCD is a part of larger USQCD activity and benefit from international collaboration (Germany)



MILC (HEP)
staggered thermo

LLNL

RBC (HEP)
DWF thermo

HotQCD

DWF and staggered thermo

BNL (Nuclear Physics)

Bielefeld University

Hardware:

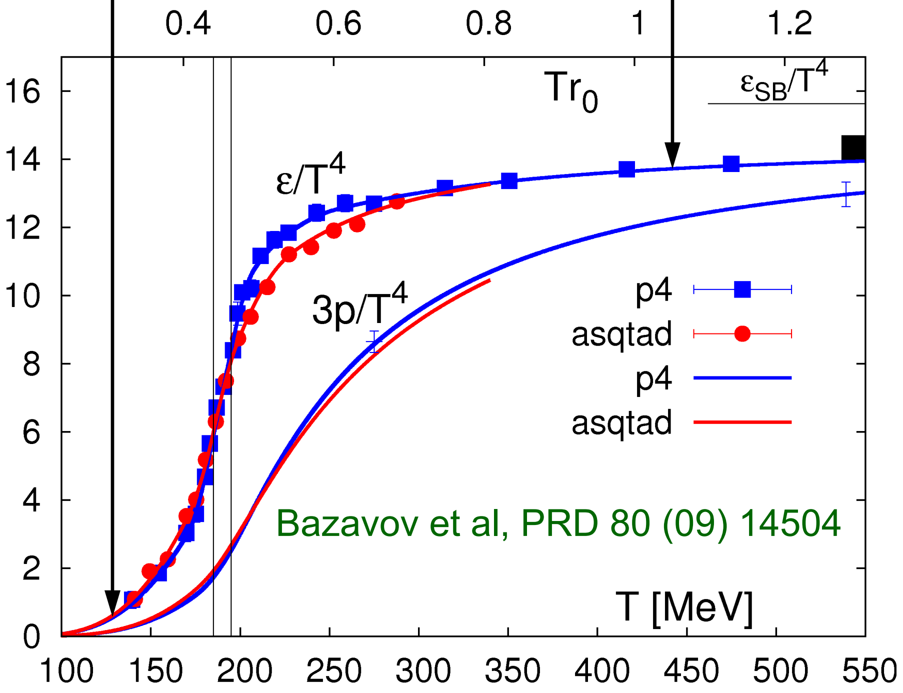
1) CPU and GPU clusters of USQCD consortium
2) INCITE allocation of USQCD consortium
3) NY Center for computational science BNL
   BG/L => 1 rack BG/Q
4) BG/L @ LLNL => BG/Q Sequoia (?)
5) GPU cluster at LLNL and Bielefeld University
6) BG/Q @ Juelich FZ
7) NERSC allocation (Franklin and Hopper)

Software : USQCD SciDAC project

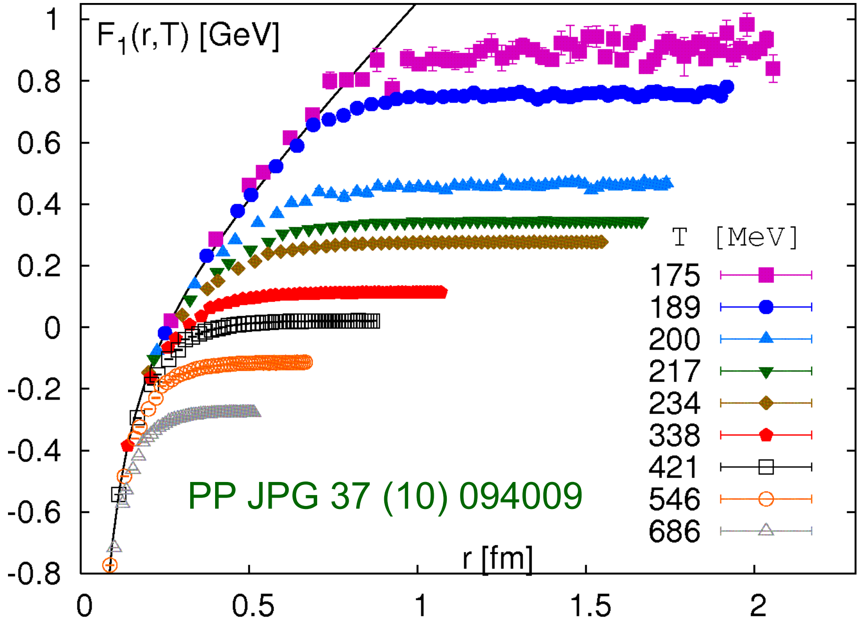
Deconfinement : pressure, energy density and color screening

meson gas = 3 light d.o.f.

free gas of quarks and gluons = 18 quark+18 anti-quarks +16 gluons =52 mass-less d.o.f



Bazavov et al, PRD 80 (09) 14504



PP JPG 37 (10) 094009

- rapid change in the number of degrees of freedom at *T=160-200*MeV: deconfinement

- deviation from ideal gas limit is about 10% at high *T* consistent with the perturbative result

free energy of static quark anti-quark pair shows Debye screening => quarkonium suppression @RHIC

- continuum limit ?

QCD thermodynamics at non-zero chemical potential

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

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

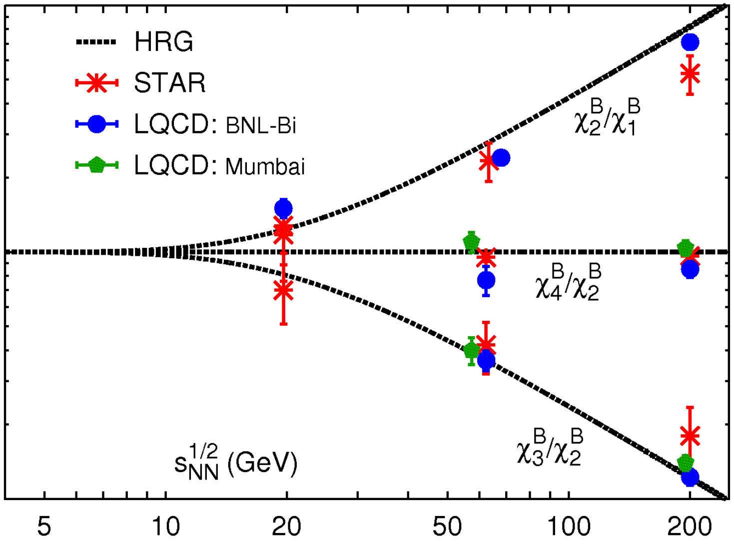
$$\chi_2^X=\frac{1}{VT^3}\langle(\delta N_X)^2\rangle \qquad \sigma_X=\langle(\delta N_X)^2\rangle$$
variance

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



Volume independent combinations:

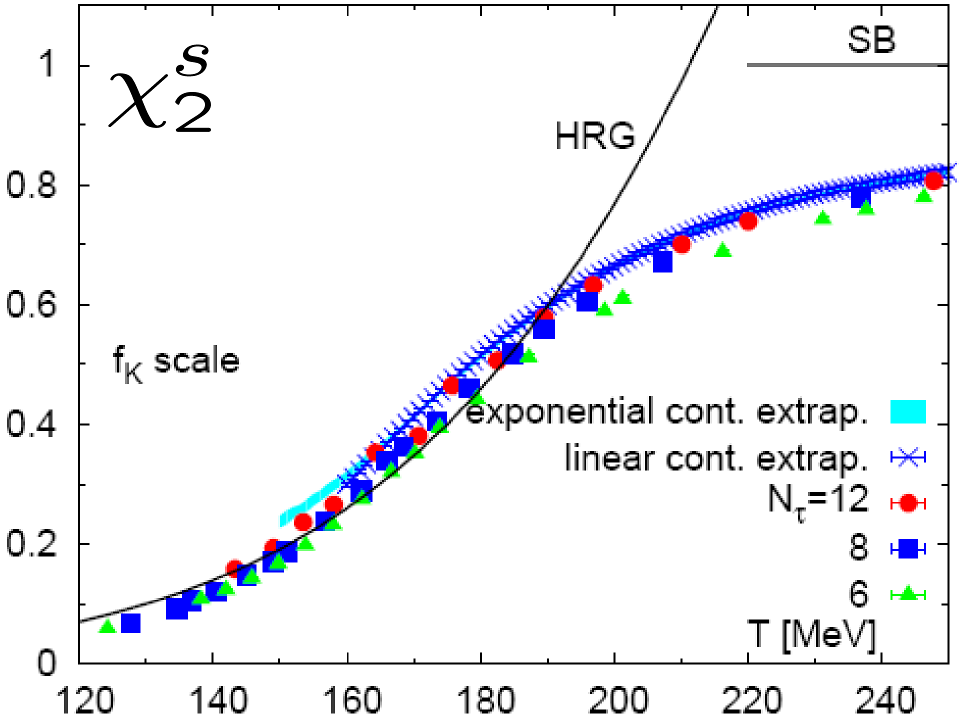
$$M_X/\sigma_X=\chi_1^X/\chi_2^X$$

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

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

Fluctuations at low temperatures

HotQCD, arXiv:1204.0784



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

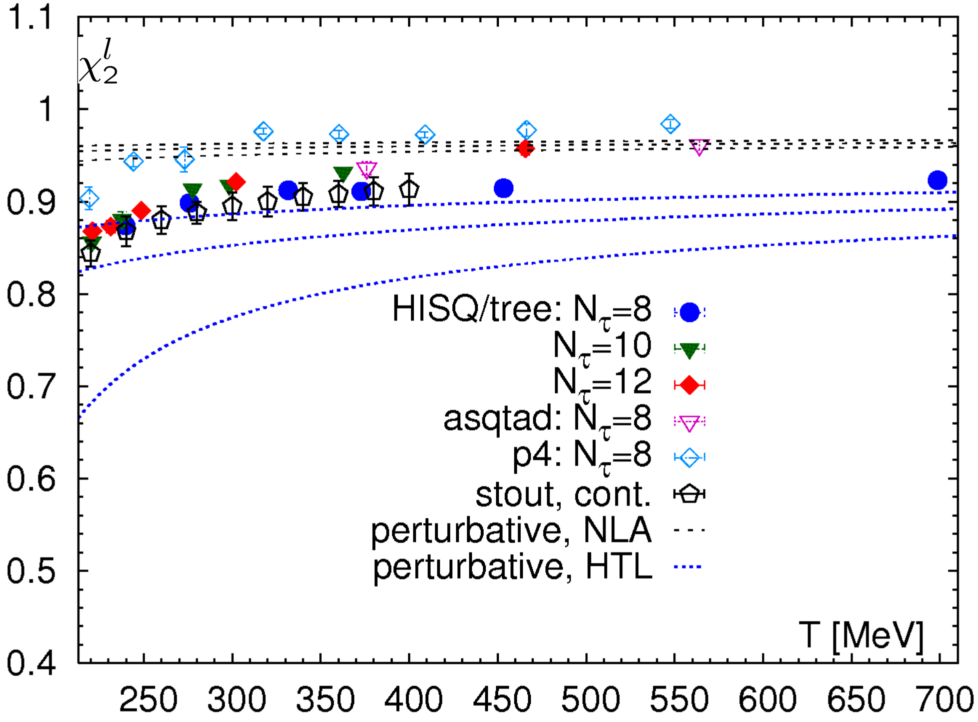
Reasonable agreement between lattice results and HRG. Can the remaining discrepancies be understood by missing hadronic states ? (search @ JLab)

Workshop on Excited Hadronic States
and the Deconfinement Transition
February 23-25, 2011
http://www.jlab.org/conferences/hadronic/

Deconfinement : increase in strange quark number fluctuations which approach the quark gas value at high *T*

Fluctuations at high temperatures

Ding (BNL)



NAS report 2012: “Exploring the Heart of Matter”, section “Exploring Quark Gluon Plasma” Question #1

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 => quark dof

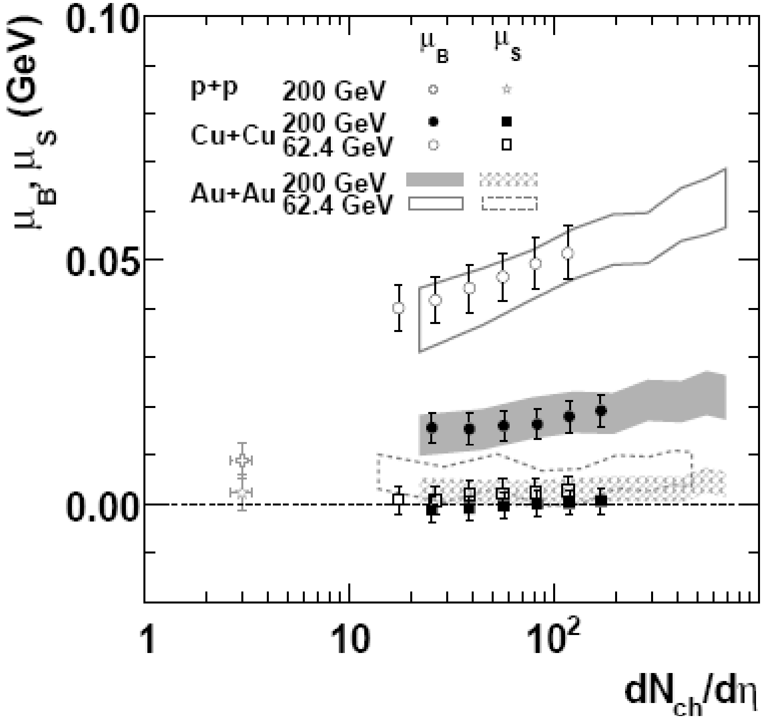
Determination of the freeze out conditions from LQCD

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

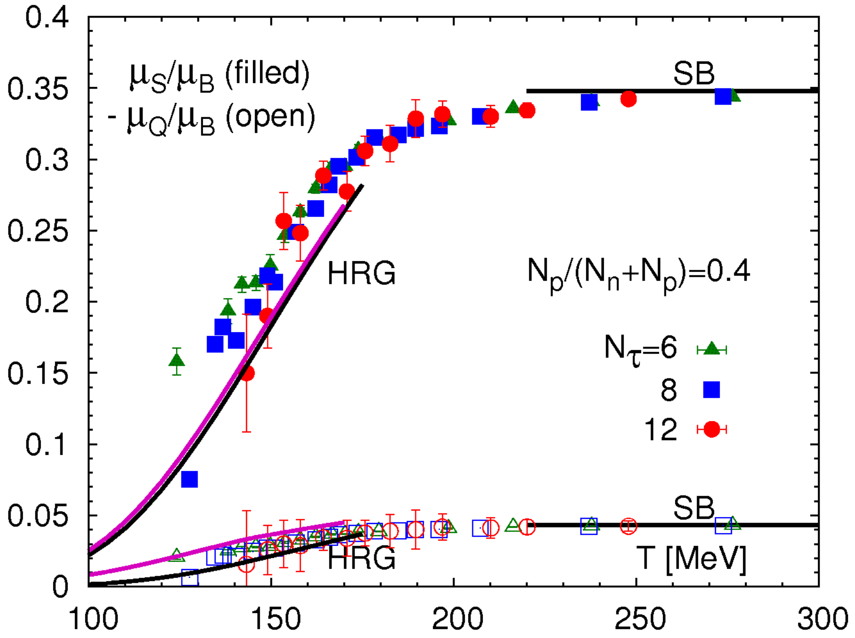
In the past the freezeout conditions in RHIC have been determined using HRG model $\Rightarrow T_f \sim 160$ MeV

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

STAR Phys.Rev. C83 (2011) 034910



ongoing BNL project on GPU



Chiral symmetry of QCD in the vacuum and for *T>0*

Nobel Prize 2008

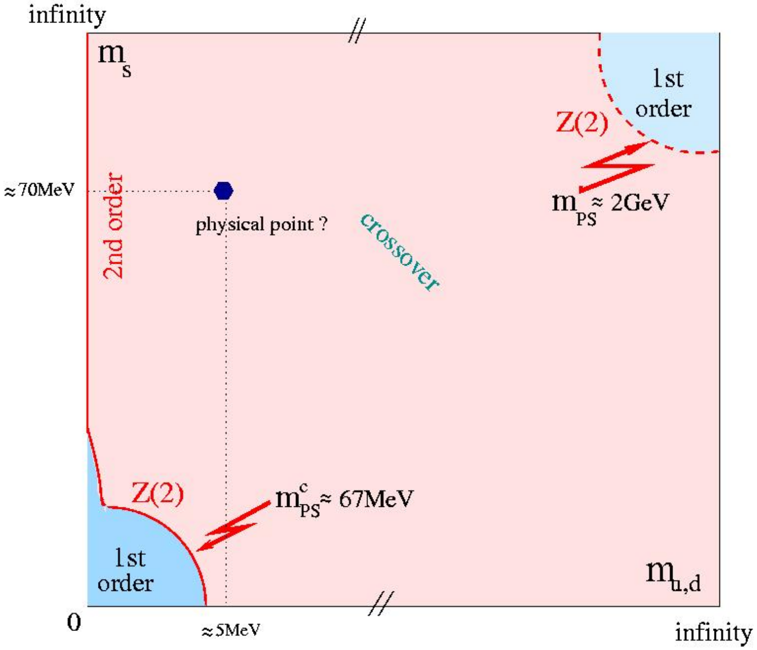
- Chiral symmetry : For light quarks $m_{u,d} << \Lambda_{QCD}$ QCD Lagrangian has

$SU_A(2)$ symmetry $\psi \rightarrow e^{i\phi^a T^a \gamma_5}\psi$ $\qquad \psi_{L,R} \rightarrow e^{i\phi^a_{L,R} T^a}\psi_{L,R}$

The vacuum breaks the symmetry $\langle\bar{\psi}\psi\rangle = \langle\bar{\psi}_L\psi_R\rangle + \langle\bar{\psi}_R\psi_L\rangle \neq 0$

$U_A(1)$ symmetry $\psi \rightarrow e^{i\phi\gamma_5}\psi$ is broken by anomaly (ABJ) : $\langle\partial^\mu j^a_\mu\rangle = -\frac{\alpha_s}{4\pi}\langle\epsilon^{\alpha\beta\gamma\delta}F^a_{\alpha\beta}F^a_{\gamma\delta}\rangle$

Pisarski, Wilczek, PD29 (1984) 338



$T \gg \Lambda_{QCD}$: $\langle\bar{\psi}\psi\rangle \simeq 0$, $U_A(1)$ symmetry ?

- Restoration of the $U_A(1)$ may effect the chiral transition

- LQCD calculations with staggered quarks suggest crossover, e.g. Aoki et al, Nature 443 (2006) 675

Evidence for 2nd order transition in the chiral limit
=> universal properties of QCD transition:

$SU_A(2) \sim O(4)$
relation to spin models

confirmed by calculations using DWF fermions

What is the transition temperature ?

To define the chiral transition temperature one needs to establish the connection to universal scaling

light quark mass m_l ↔ magnetic field H

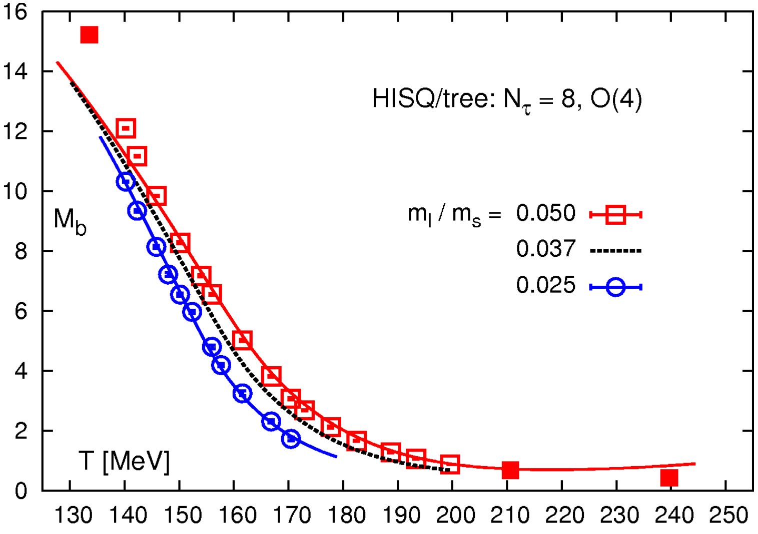
$$M_b = \frac{m_s \langle \bar\psi \psi \rangle_l}{T^4} = h^{1/\delta} f_G(t/h^{1/\beta\delta}) + f_{M,reg}(T,H)$$

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

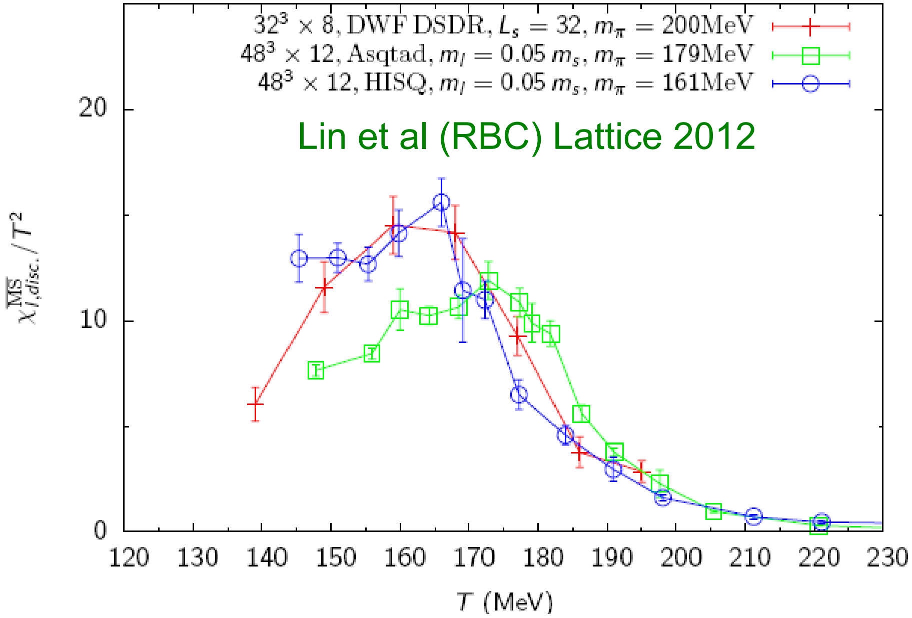
Bazavov et al (HotQCD), Phys. Rev. D85 (2012) 054503

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

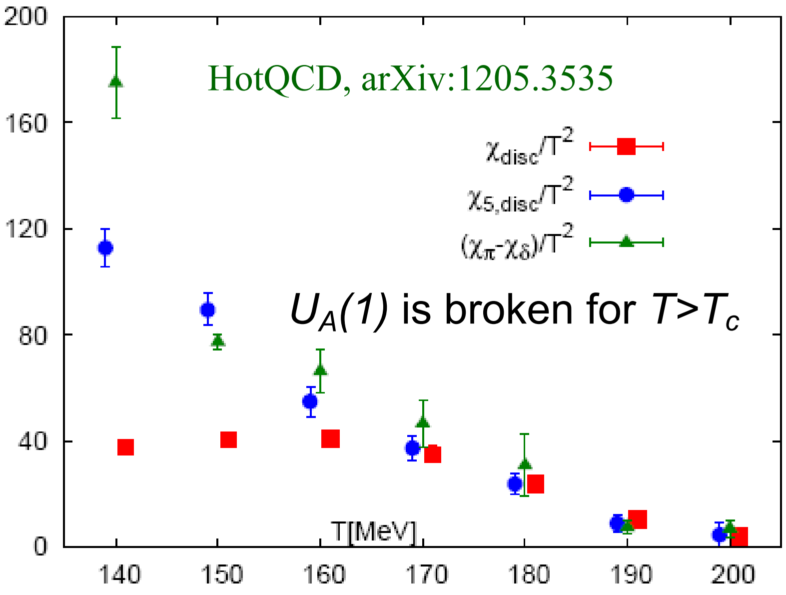
$$\epsilon(T_c) = 240 MeV/fm^3$$



Domain Wall Fermions



Lin et al (RBC) Lattice 2012



HotQCD, arXiv:1205.3535

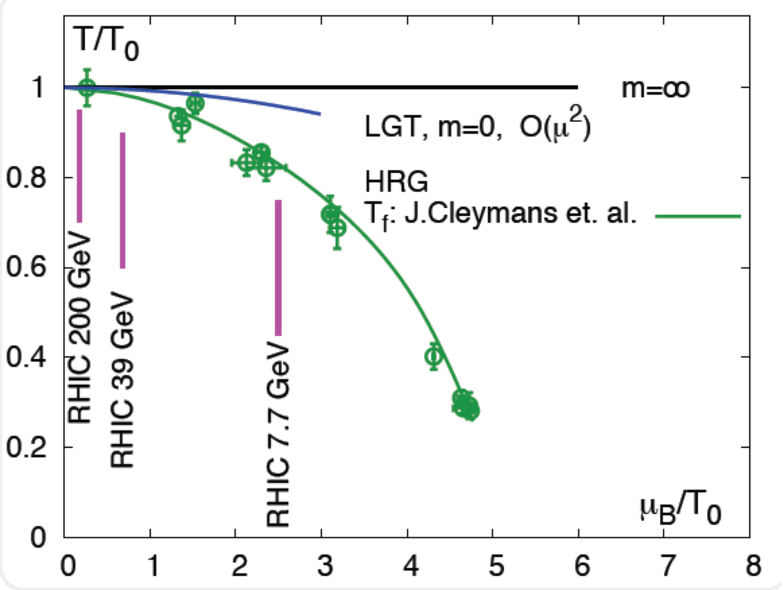
$U_A(1)$ is broken for $T>T_c$

Phase diagram and non-zero baryon density

How T_c depends on baryon density ?

$$\frac{T_c(\mu_B)}{T_c(0)} = 1 - 0.0066(5)\left(\frac{\mu_B}{T}\right)^2 + \mathcal{O}(\mu_B^4)$$

Kaczmarek et al, PRD83 (2011) 014504

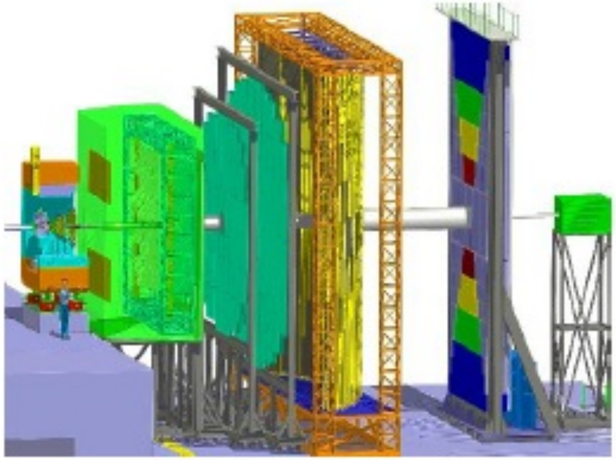


How close is the transition line to the freeze-out line ?

Is there a critical end-point (CEP) ?

relevance for RHIC energy scan and CBM@ FAIR

CBM@FAIR



Radius of convergence of Taylor expansion and CEP :

$$\rho_n = \sqrt{\chi_{n+2}/\chi_n},\ \mu_B^{\mathrm{CEP}} = \rho_n, n \to \infty$$

Spectral functions at *T>0* and physical observables

$$G(\tau,T)=\int_0^\infty d\omega\,\sigma(\omega,T)\,\frac{\cosh(\omega(\tau-1/(2T)))}{\sinh(\omega/(2T))}$$

Heavy meson spectral functions:

$$J_H=\bar{\psi}\,\Gamma_H\,\psi$$

⇨

quarkonia properties at $T>0$
heavy quark diffusion in QGP: D

Heavy flavor probes at RHIC

Discovery:
'Perfect' Liquid Hot Enough to be Quark Soup
February 15, 2010

Light vector meson spectral functions:

$$J_\mu=\bar{\psi}\,\gamma_\mu\,\psi$$

⇨

thermal dilepton production rate

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

thermal photon production rate :

$$p\frac{dW}{d^3p}=\frac{5\alpha_{em}}{9\pi}\frac{1}{e^{p/T}-1}\sigma_{\mu\mu}(\omega=p,p,T)$$

Thermal photons and dileptons provide information about the temperature of the

electric conductivity ζ :

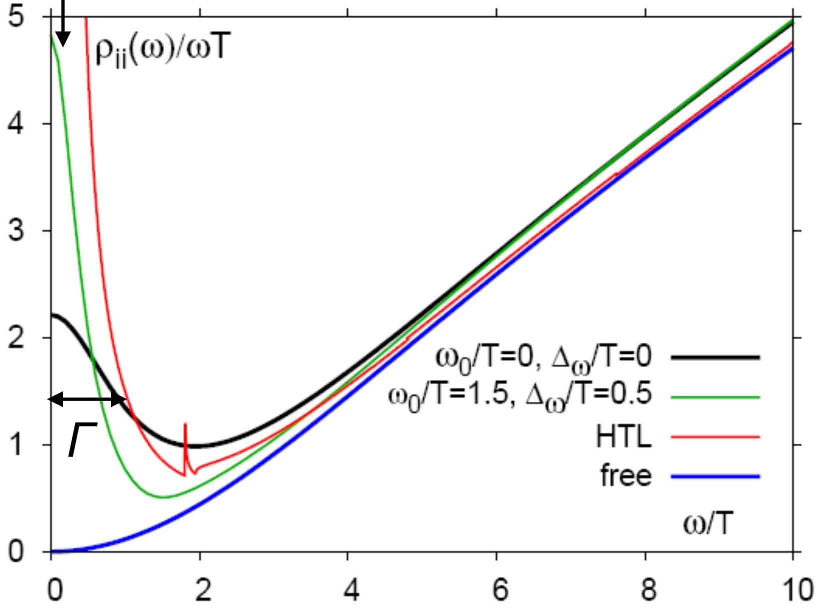
Lattice calculations of transport coefficients

Quenched QCD calculations, 128^3x32 lattice

Ding et al, PRD 83 (11) 034504

peak at *ω≈0* = transport peak

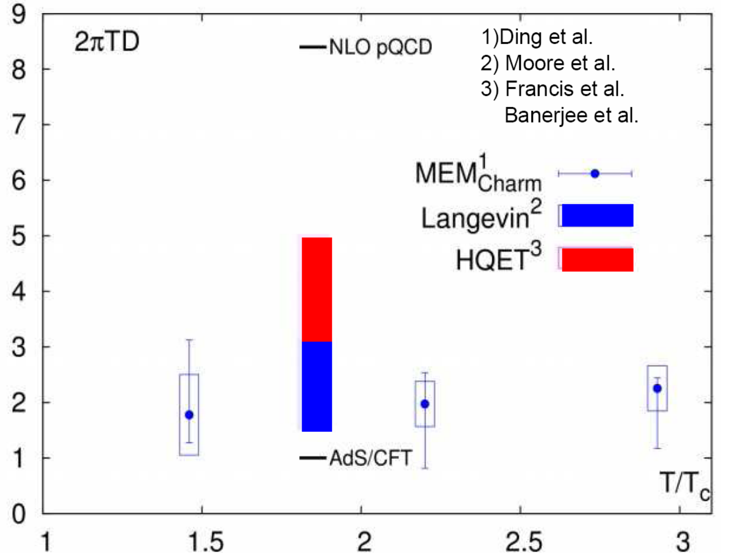
$$\Gamma \sim 1/\tau_{relax}, \;\; \sigma_{el} \sim \chi_Q/\Gamma$$

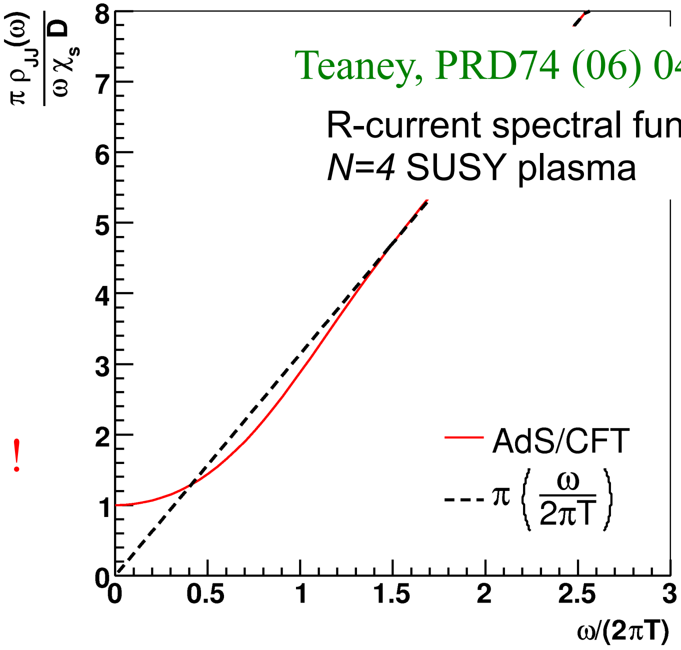


$$1/3 < \frac{1}{C_{em}} \frac{\sigma_{el}}{T} < 1, \;\; C_{em} = \sum_f Q_f^2$$

Perfect liquid: *η/s=1/(4 π)* ⇔ no transport peak !

Heavy quark diffusion constant, Ding et al





Teaney, PRD74 (06) 045025

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

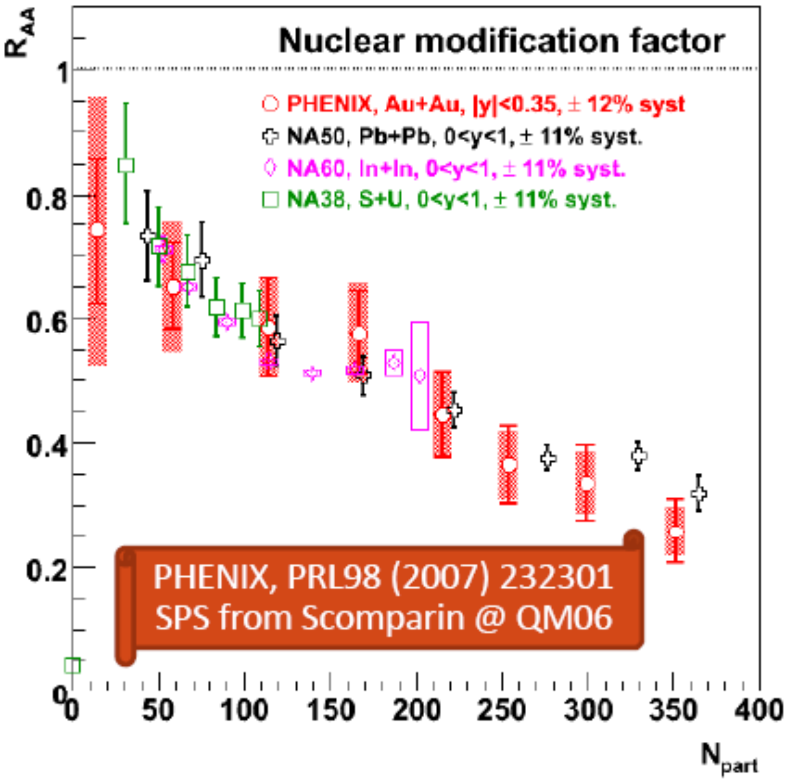
Charmonium spectral functions from MEM

NAS report 2012: section “Exploring QGP” Question #2:

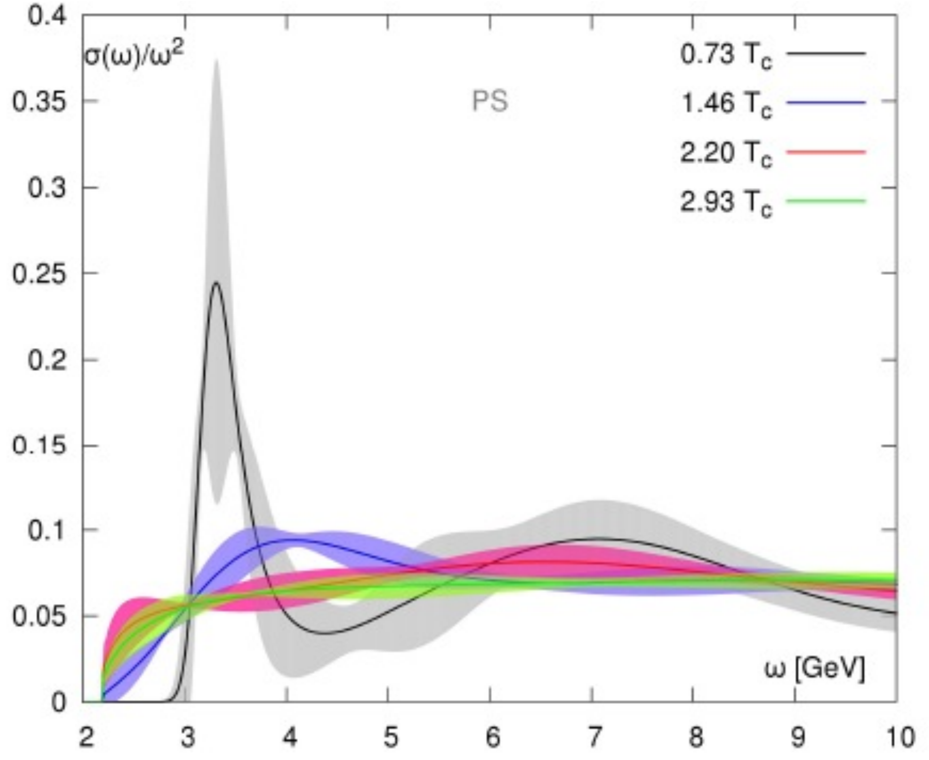
Charmonium spectral functions on isotropic lattice in quenched approximation with Wilson quarks:

H.-T. Ding et al, arXiv:1204.4945

$N_\tau=24\text{-}96,\ a^{-1}=18.97GeV$



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

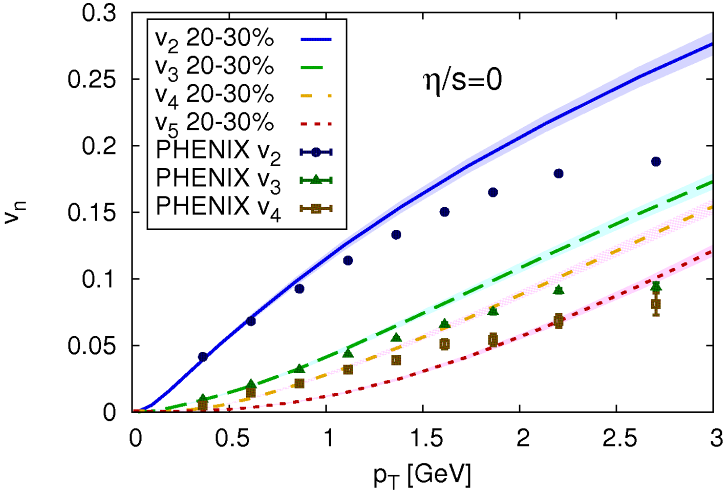


No clear evidence for charmonium bound state peaks above T_c in spectral functions !

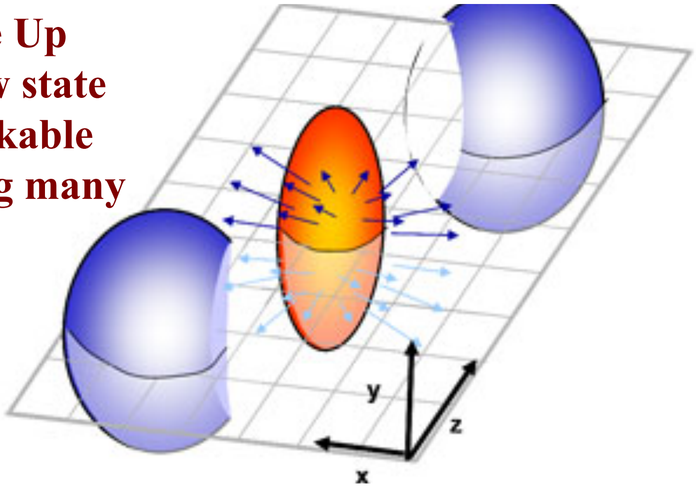
Viscous hydrodynamics and flow

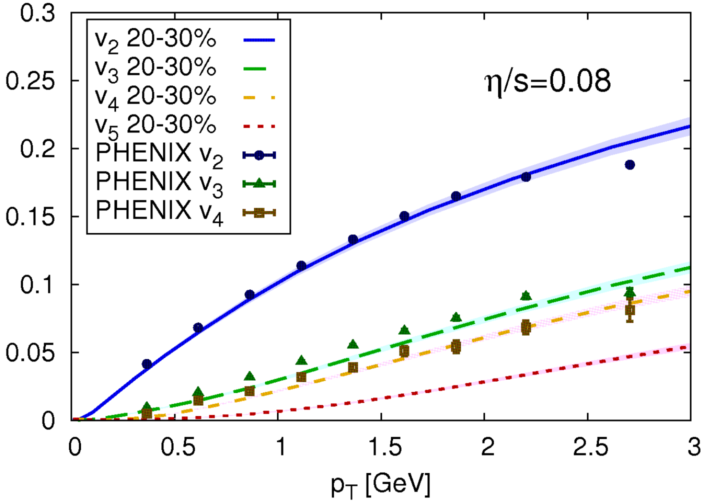
B. Schenke BNL

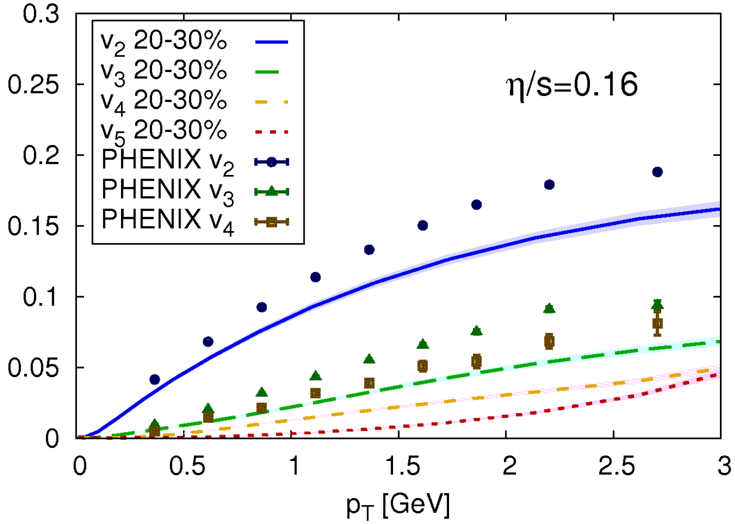
$$\frac{dN}{d\Phi} = v_0\,(1+2\,v_1\,\cos(\Phi)+2\,v_2\,\cos(2\Phi))$$



RHIC Scientists Serve Up "Perfect" Liquid, New state of matter more remarkable than predicted -raising many new questions
April 18, 2005



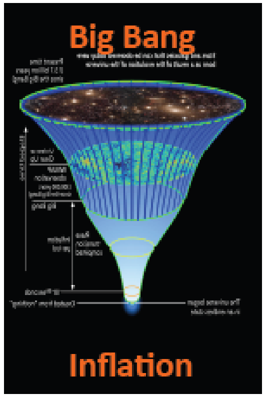




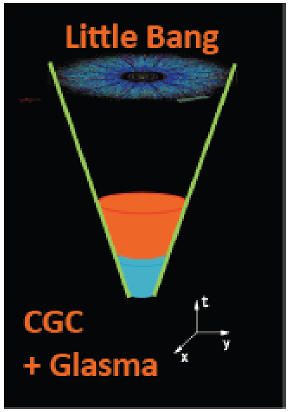
Needs EoS from lattice QCD (s95-p1 parametrization), however the biggest uncertainty comes from pre-equlibrium dynamics and initial fluctuations => numerical study of YM fields at early times (in progress), NAS report 2012: section “Exploring QGP” Question #2

How does Glasma thermalize to QGP ?

How does Glasma thermalize into QGP ?



Key role of spectrum of initial quantum fluctuations in both



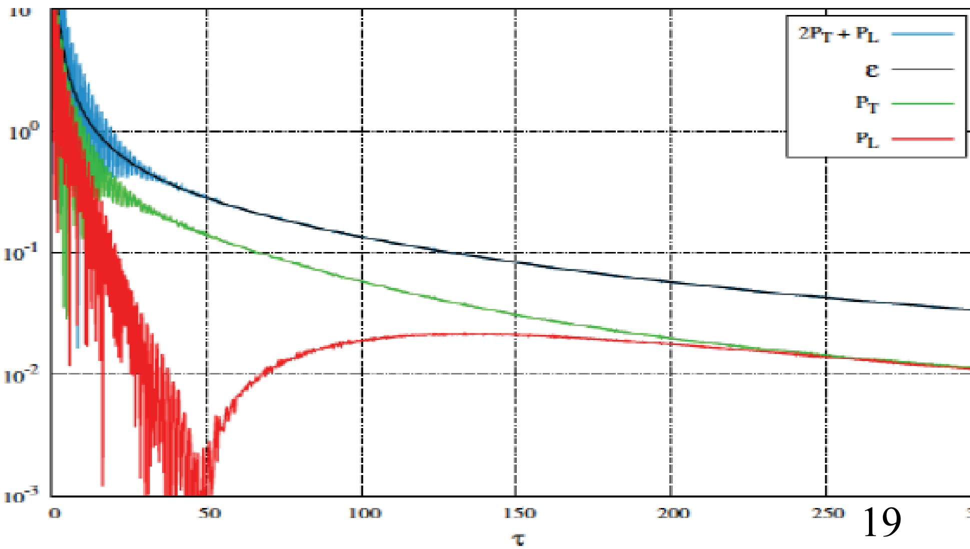
- **Ab initio formalism** *now available for detailed 3+1-D numerical event-by-event Yang-Mills simulations*

**DM8,
DM9,
DM12
DM13**

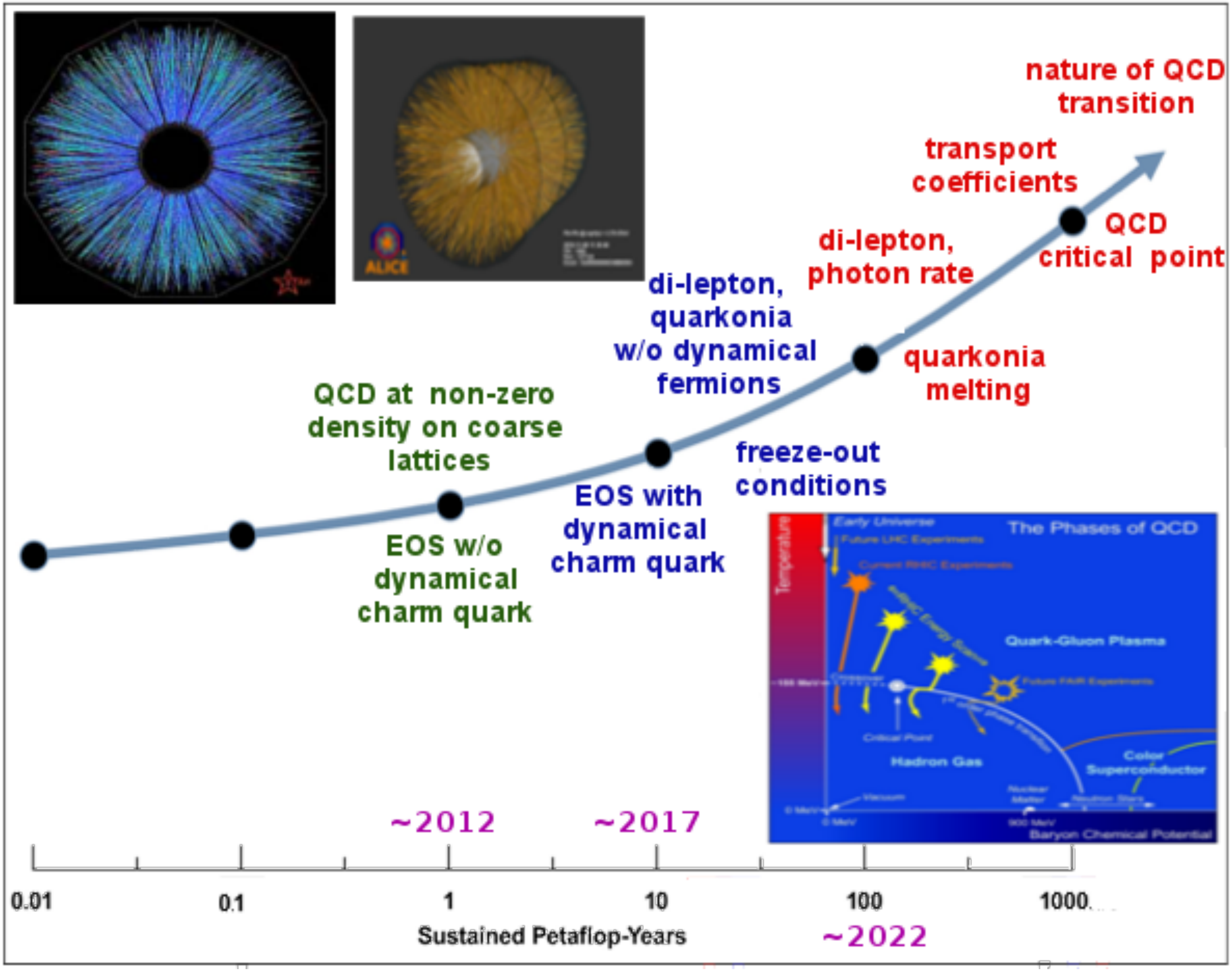
Proof of concept: isotropization of 3+1-D longitudinally expanding non-trivial scalar theory

Dusling,Epelbaum,Gelis,Venugopalan, arXiv:1206.3336, submitted to Nucl. Phys. A

Dusling,Gelis,Venugopalan, Nucl. Phys. A850 (2011) 69



Summary


nature of QCD transition
transport coefficients
QCD critical point
di-lepton, photon rate
quarkonia melting
di-lepton, quarkonia w/o dynamical fermions
freeze-out conditions
QCD at non-zero density on coarse lattices
EOS with dynamical charm quark
EOS w/o dynamical charm quark
ALICE
The Phases of QCD
Early Universe
Future LHC Experiments
Current RHIC Experiments
RHIC Energy Scan
Quark-Gluon Plasma
Future FAIR Experiments
Crossover
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
900 MeV
Temperature
Baryon Chemical Potential
~2012
~2017
~2022
0.01
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1
10
100
1000
Sustained Petaflop-Years

National Nuclear Physics Summer School

Organized by Stony Brook University and Brookhaven National Laboratory

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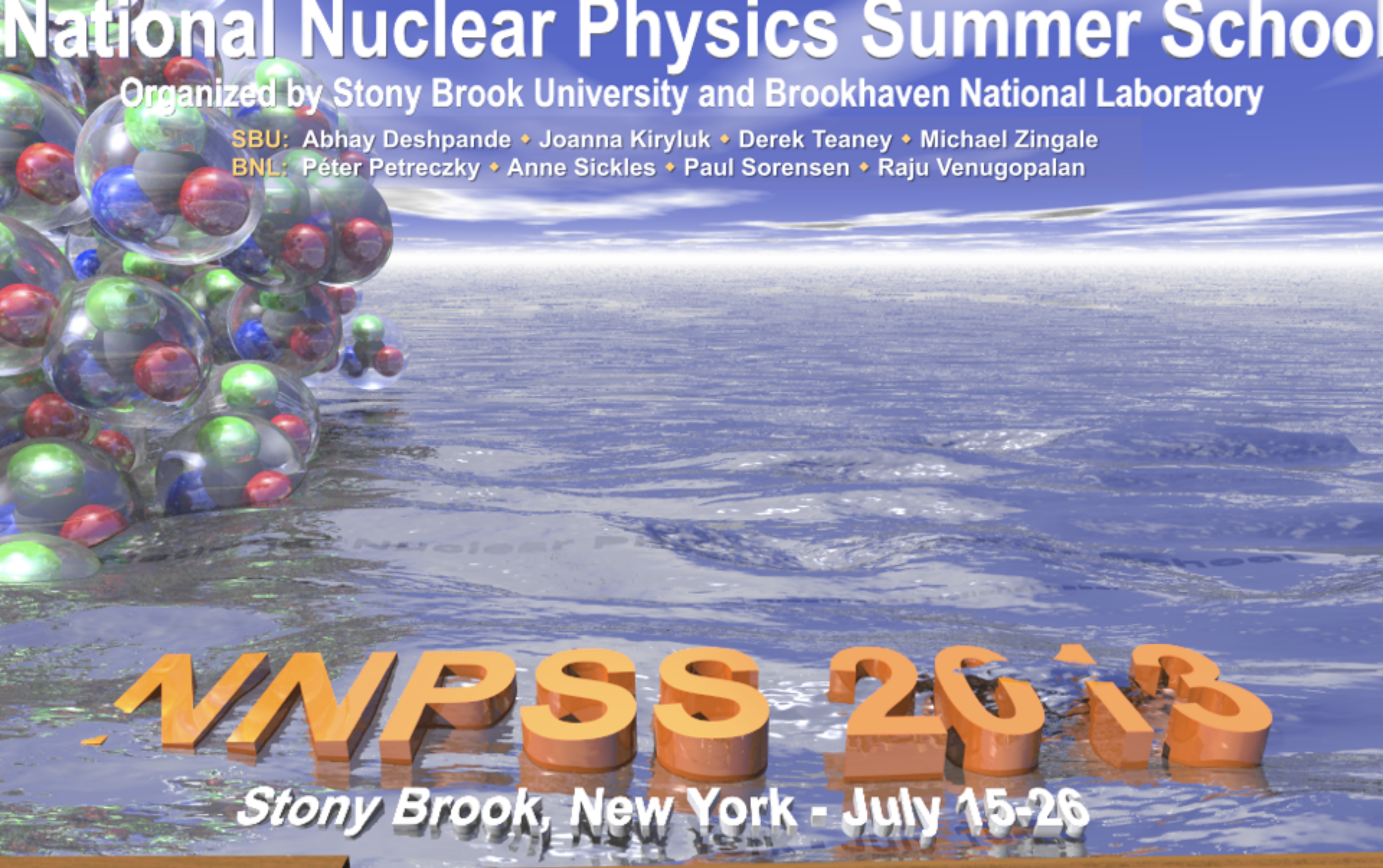

Stony Brook, New York - July 15-26

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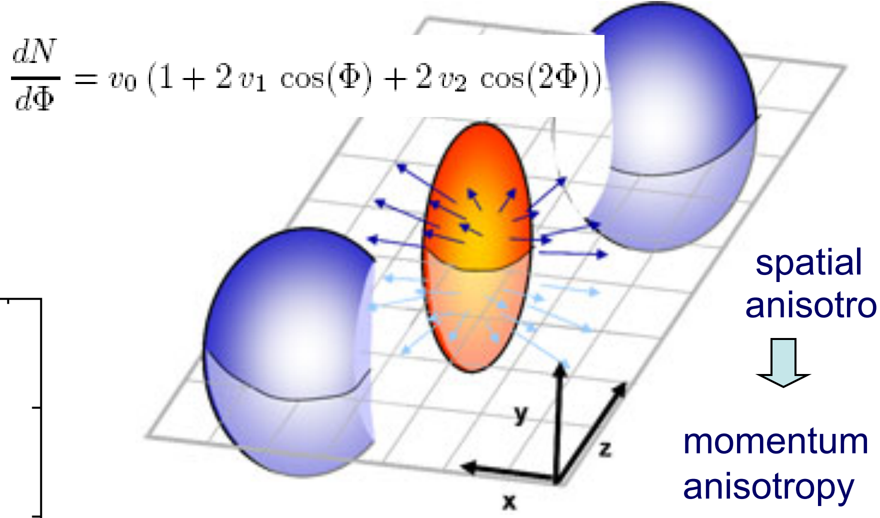
Back-up : Status of the EoS calculations

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

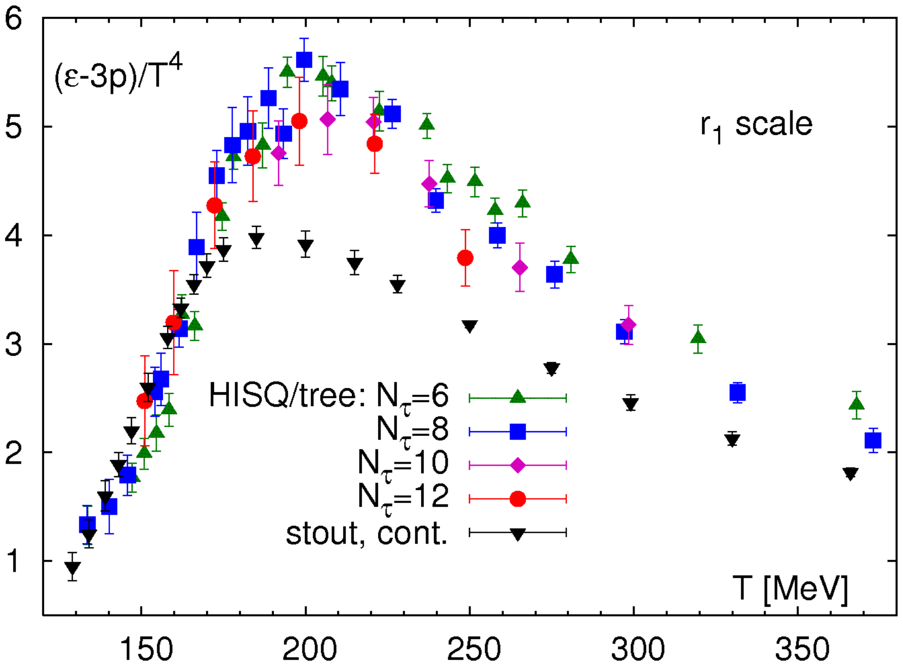
⇩

momentum space anisotropy

pressure gradients create anisotropic flow

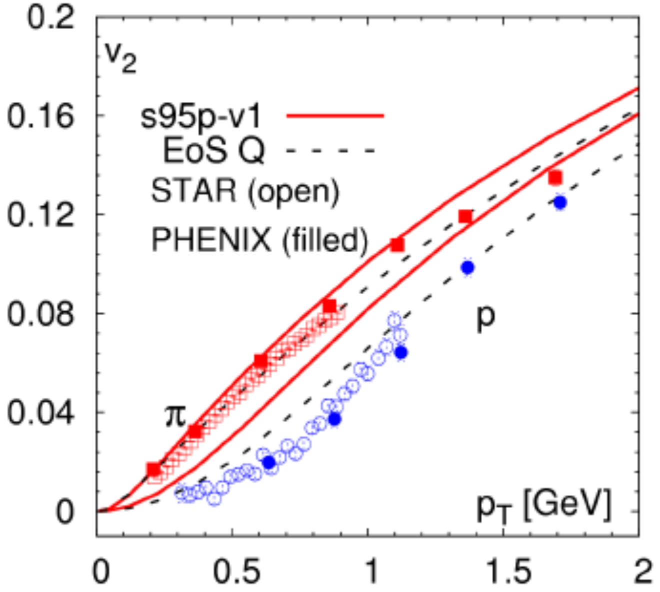
EoS is calculated from *ε-3p* using the intergral method

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



need *N_τ=12* to get cutoff effects under control

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

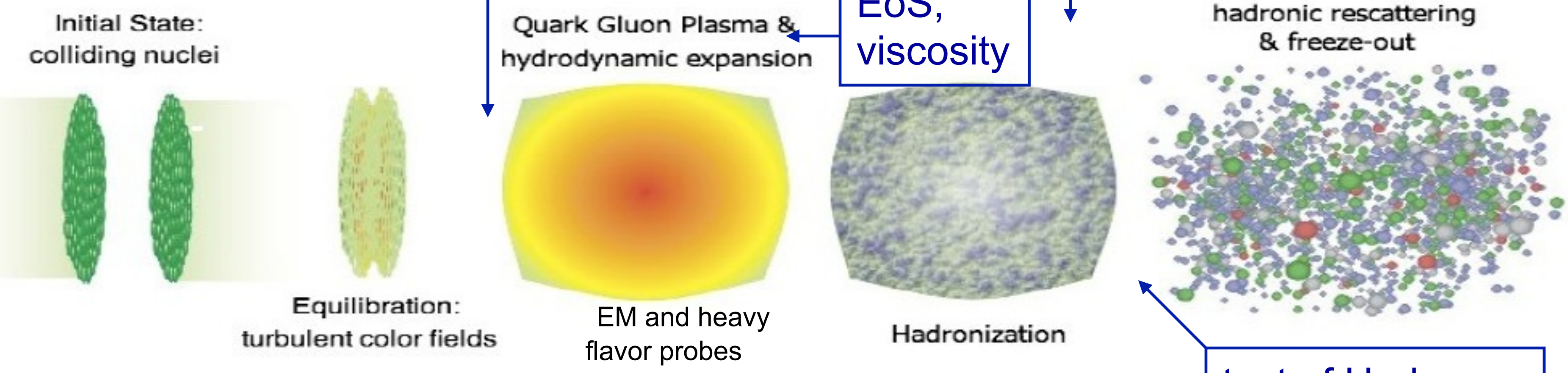


Back-up: Physics of heavy ion collisions and LQCD

high temperature QCD
weak coupling ?

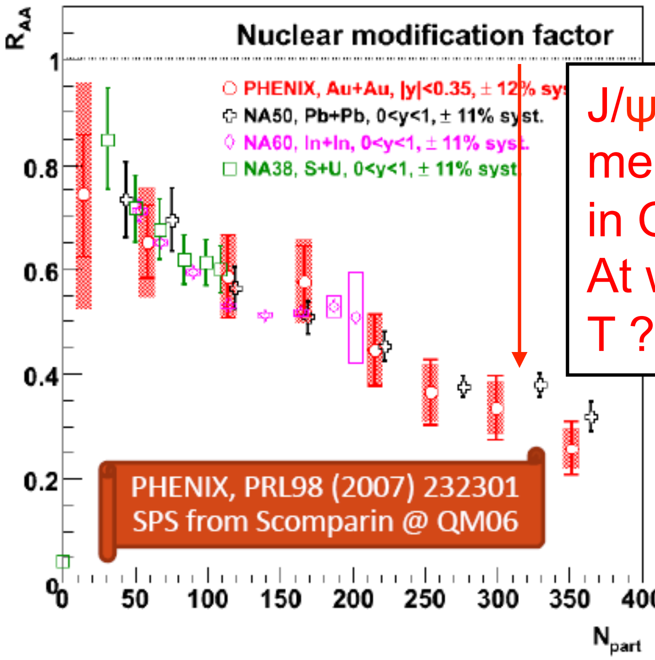
Chiral transition, T_c, fluctuations of conserved charges

EoS,
viscosity

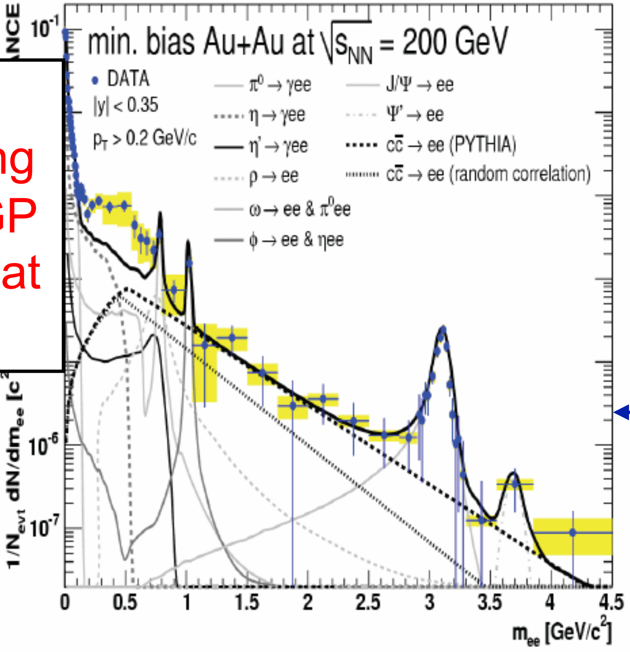


EM and heavy
flavor probes

test of Hadron
Resonance Gas
(HRG)
using LQCD



J/ψ
melting
in QGP
At what
T ?



quarkonium spectral
functions,
heavy quark diffusion,
thermal dileptons