QCD Thermodynamics at High Temperature

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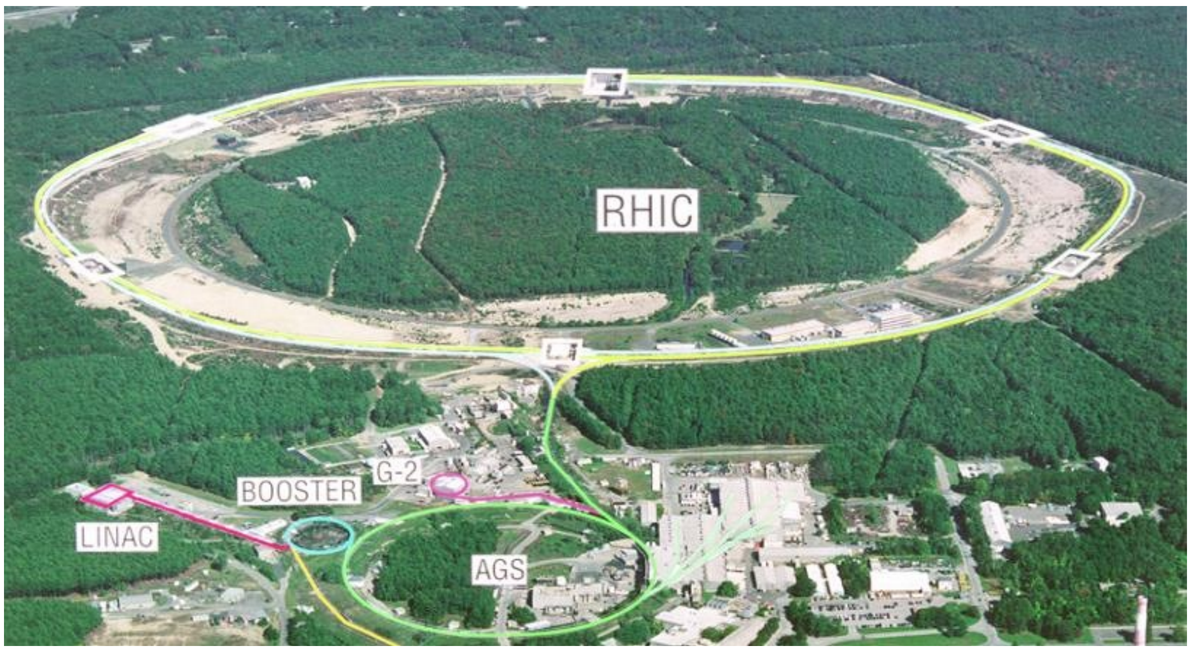


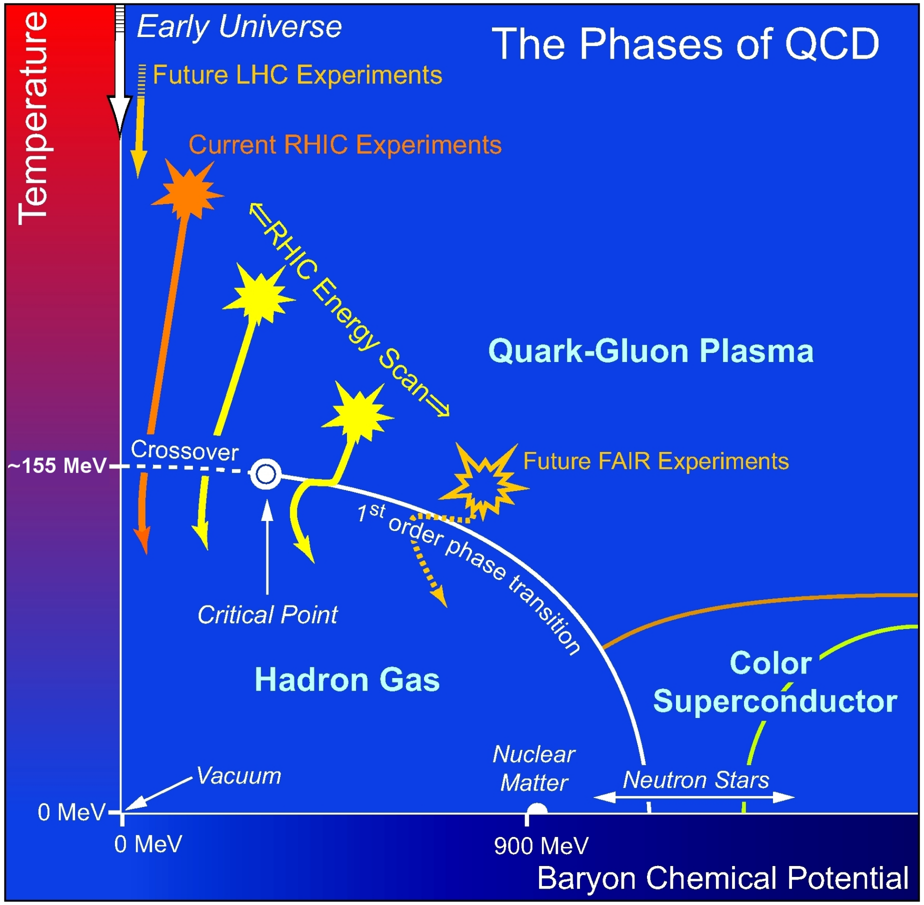
NY Center for Computational Science

Large Scale Computing and Storage Requirements for Nuclear Physics (NP).
Bethesda MD, April 29-30, 2014

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 ?"



Challenges for LQCD:

1) **Equation of state**

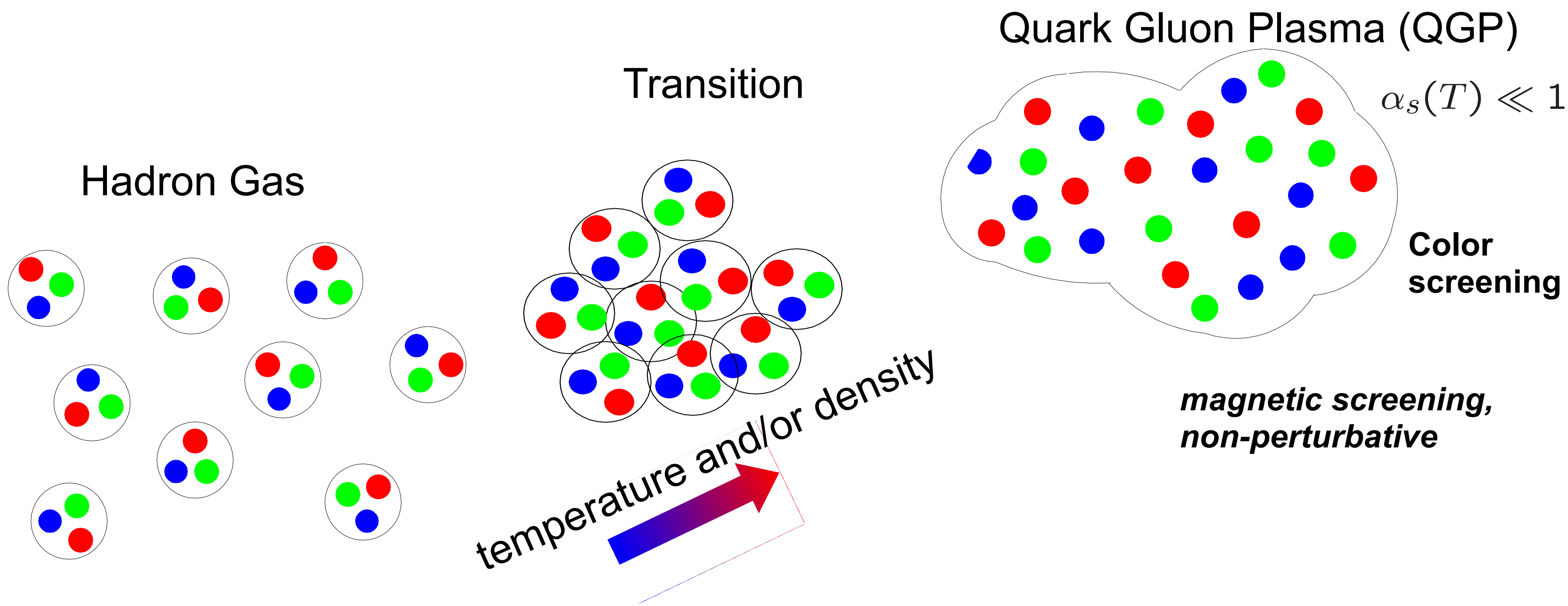
2) **Phase diagram and the transition temperature**

3) **Fluctuations of conserved charges**

4) **In-medium hadron spectral functions**

5) **Transport coefficients**

Deconfinement at high temperature and density

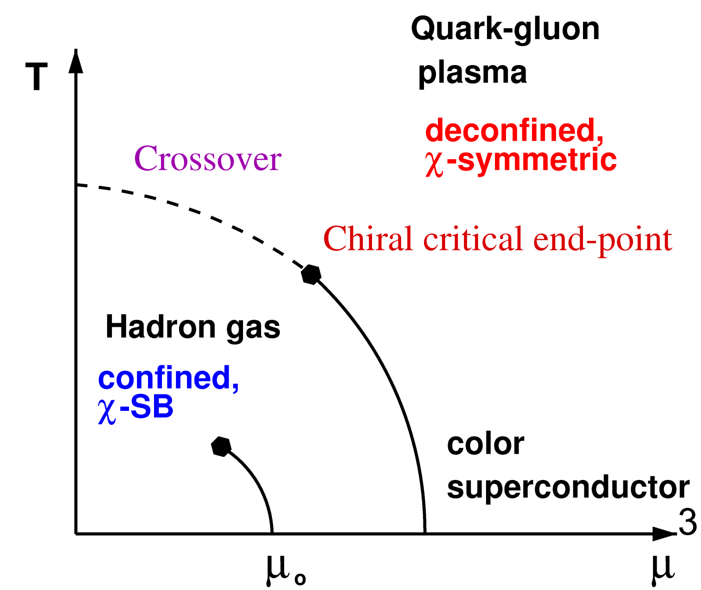


$$\mathbf{T_c = (154 \pm 9)}\ \mathrm{MeV}$$

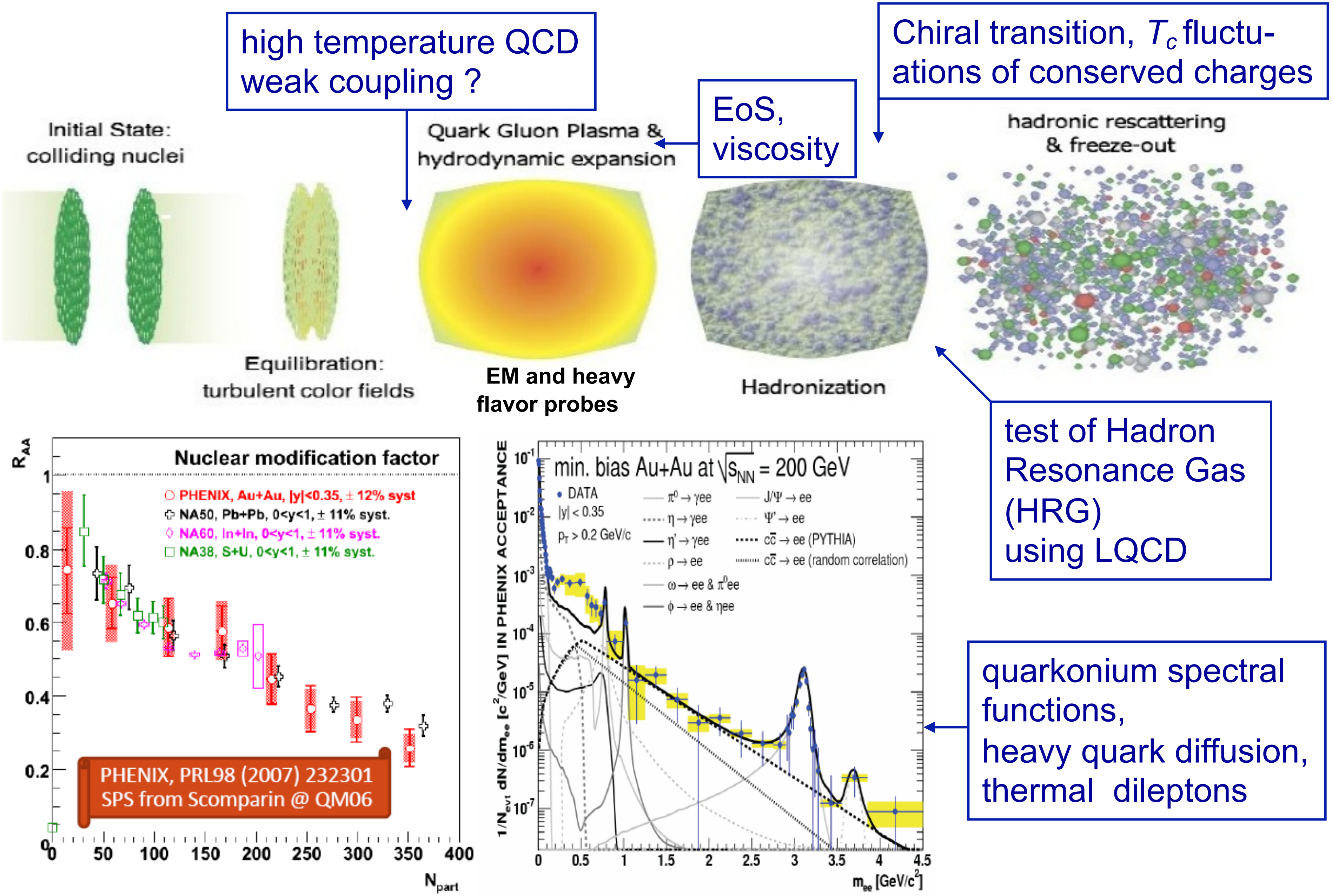
Chiral symmetry is broken in the low temperature (hadronic) "phase"

but is restored at high T

QCD analog of
feromagnet-paramagnet transition



Physics of heavy ion collisions and LQCD



Finite Temperature QCD and its Lattice Formulation

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

$$\Downarrow$$

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

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

Lattice

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

Generation of gauge configuration (Markov chain) $\mu = 0$ ➡ Hybrid Monte-Carlo

Most of cycles : $D_q^{-1} A$

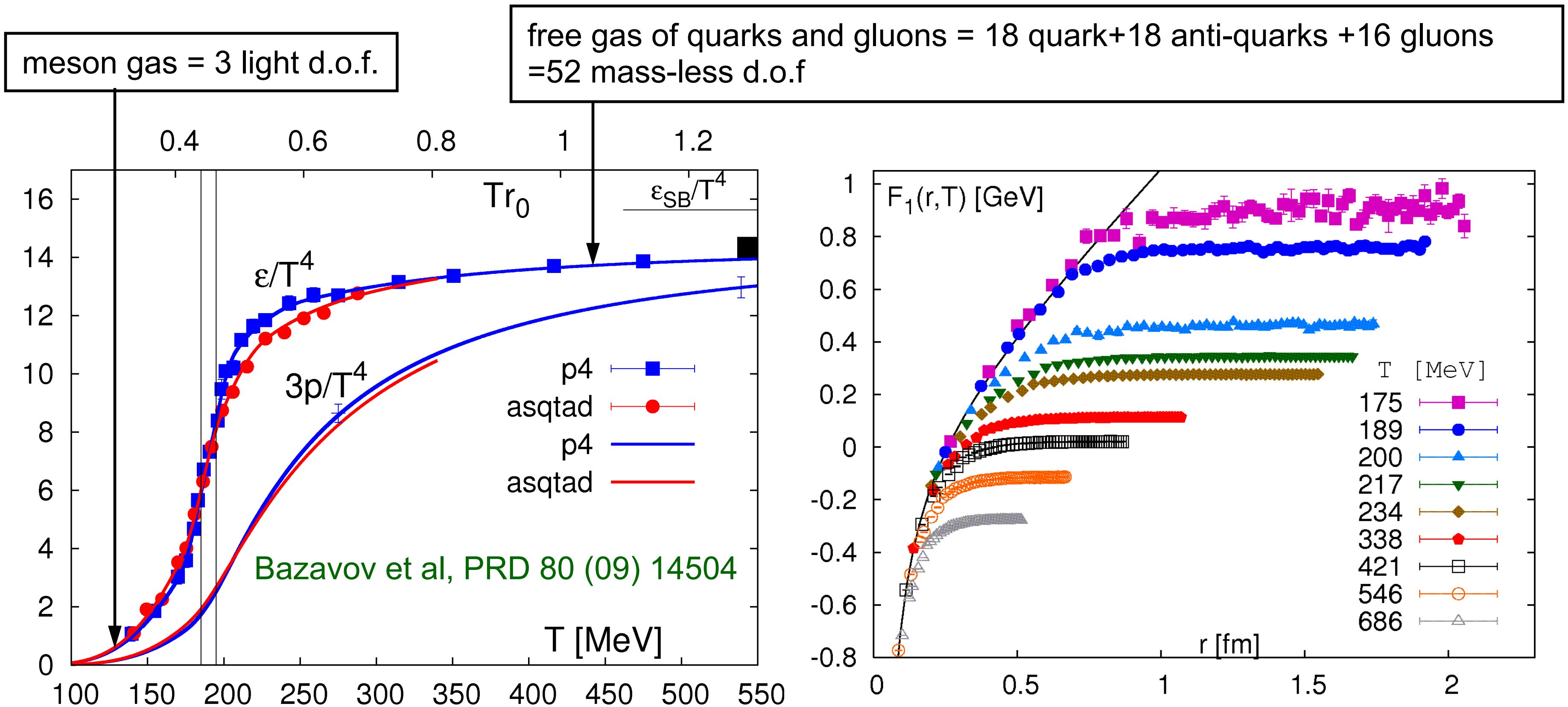
$\mu \neq 0$: $det D_q(U,m,\mu)$ complex ➡ sign problem ➡ Taylor expansion for not too large μ

Most of cycles : $D_q^{-1} A$

- Highly Improved Staggered Quark (HISQ) relatively inexpensive numerical but does not preserve all the symmetries of QCD (except for zero *a*)
- Domain Wall Fermion (DWF) formulation: preserves all the symmetries but *costs ~ 100x of staggered formulation*

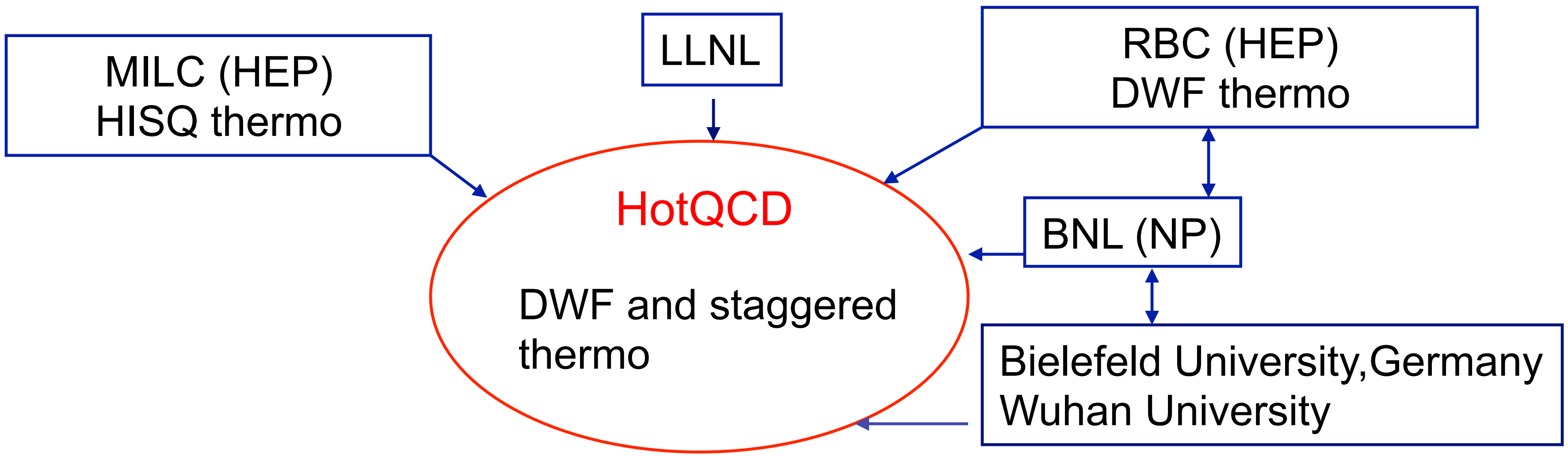
Need to take the limit of zero *a* : cost ~ $1/a^7$, $T=1/(a N_\tau)$

Deconfinement : pressure, energy density and color screening



- rapid change in the number of degrees of freedom at T=160-200MeV: deconfinement
- deviation from ideal gas limit is about 10% at high T consistent with the weakly coupled quark gluon gas
- free energy of static quark anti-quark pair shows Debye screening => quarkonium suppression @RHIC

HotQCD : a collaborative effort



Software (USQCD):

MILC code (MIMD C code + platform dependent optimization at t lower level) a lso for GPU (CUDA)

Columbia Physics System, CPS (C++, optimized for BG/Q, DWF only)

Optimized CUDA GPU code from Bielefeld U.

Resource in 2013-2014 (in core h):

1) CPU clusters of USQCD: 40M
2) GPU clusters of USQCD: 2.5 M
3) INCITE allocation of USQCD: 120M (Mira)
   44M (Titan, projected)
4) BNL, BG/Q: 18M, BG/L: 50M,
5) GPU cluster at LLNL and Bielefeld U.: 3.1M
6) BG/Q in Europe: 15M
7) NERSC allocation (PI Bazavov): 10M
8) BG/Q (LLNL) : 100 M (DWF thermo only)

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!l!} \chi_{ijk}^{BQS} \cdot \left(\frac{\mu_B}{T}\right)^i \cdot \left(\frac{\mu_Q}{T}\right)^j \cdot \left(\frac{\mu_Q}{T}\right)^k$$

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

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

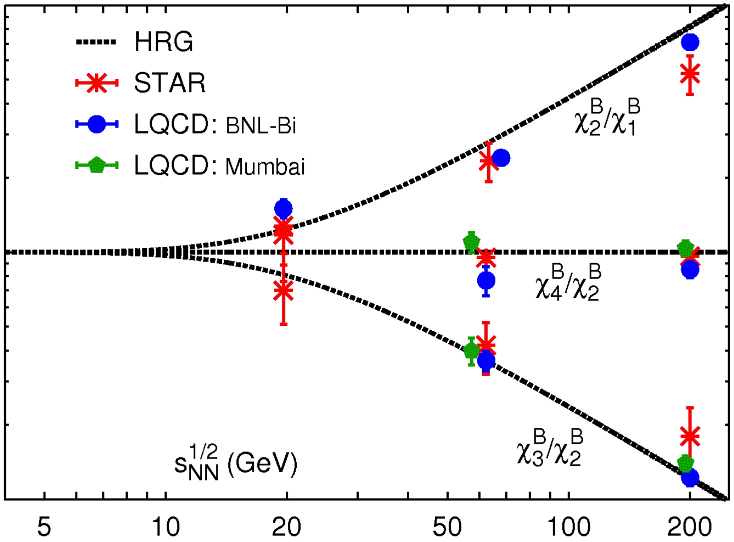
Skewness

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

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:

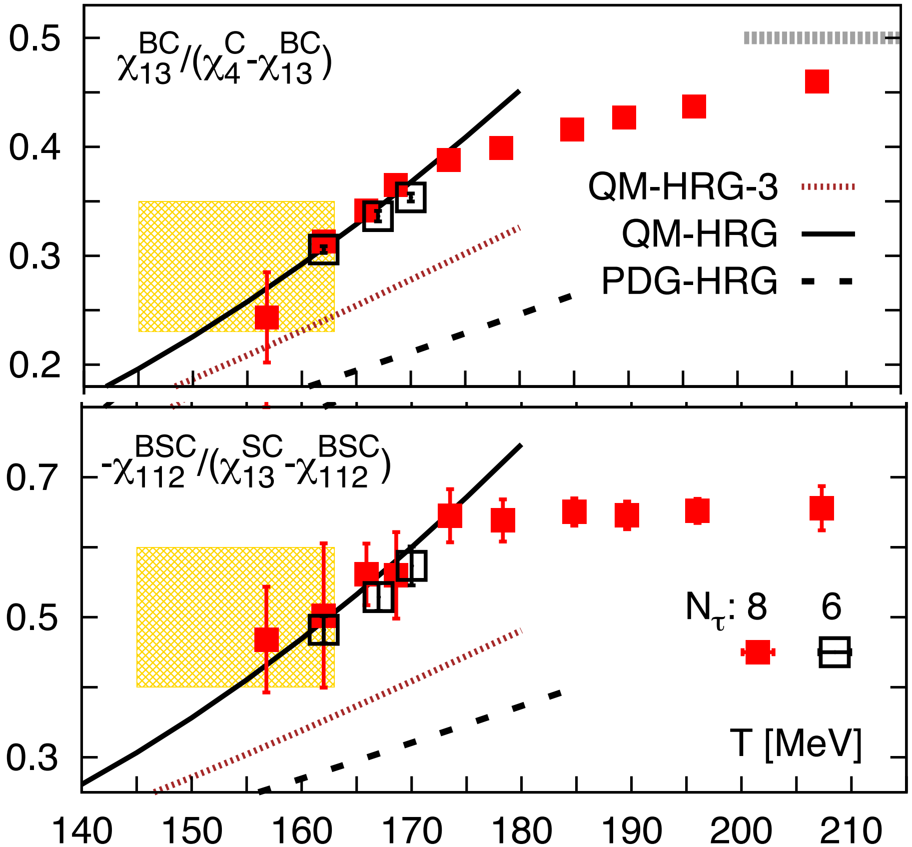
$$M_X/\sigma_X = \chi_1^X/\chi_2^X$$

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

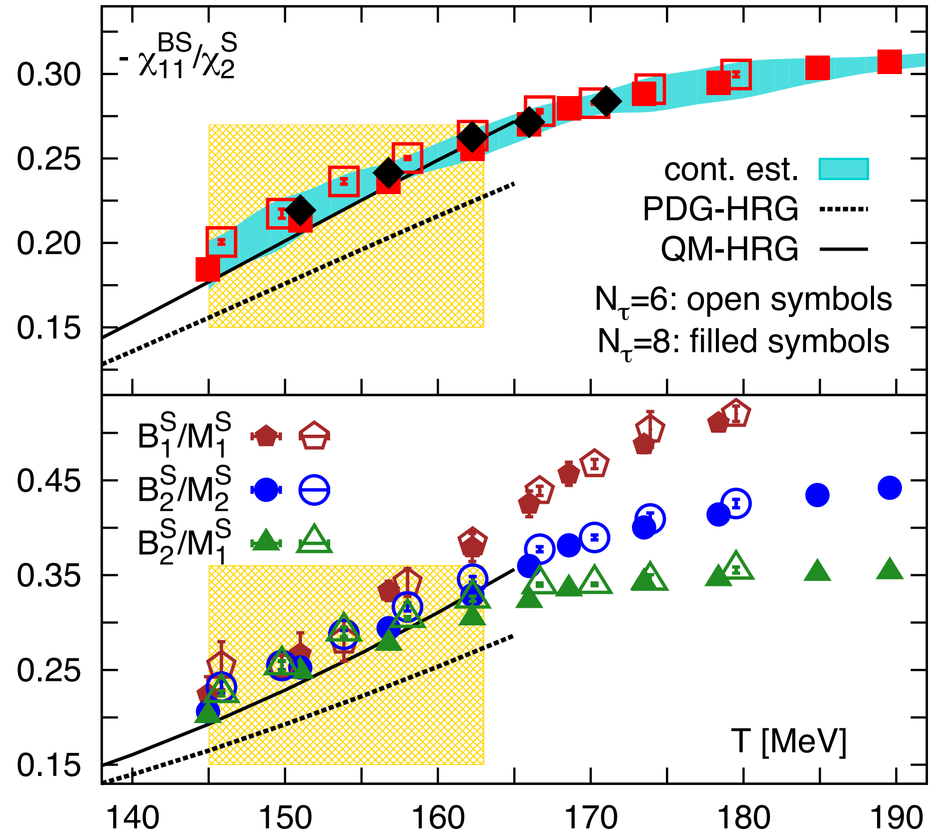
$$K_X \cdot \sigma_X^2 = \chi_4^X/\chi_2^X$$

Charge and strangeness fluctuations and missing hadrons

Bazavov et al, arXiv:1404.4043v1



Bazavov et al, arXiv:1404.6511

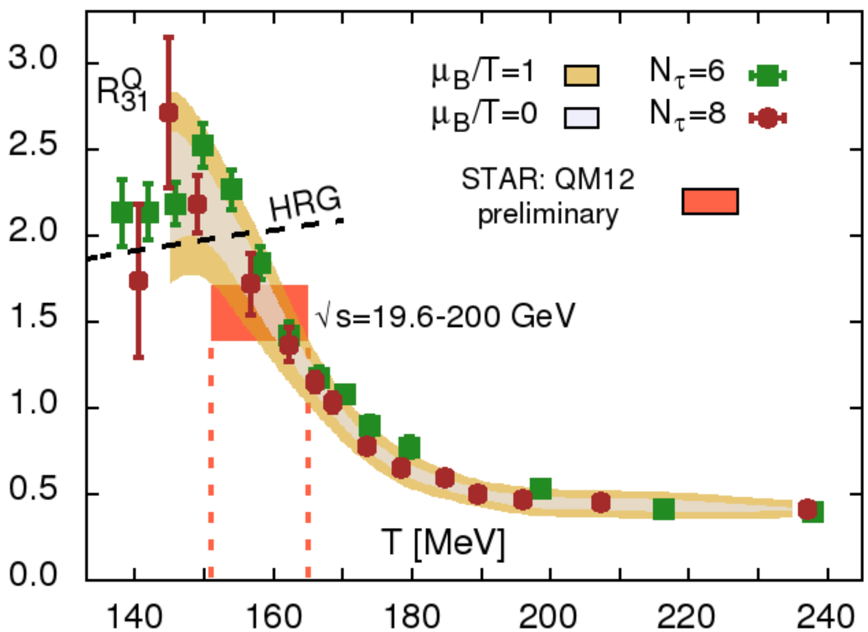


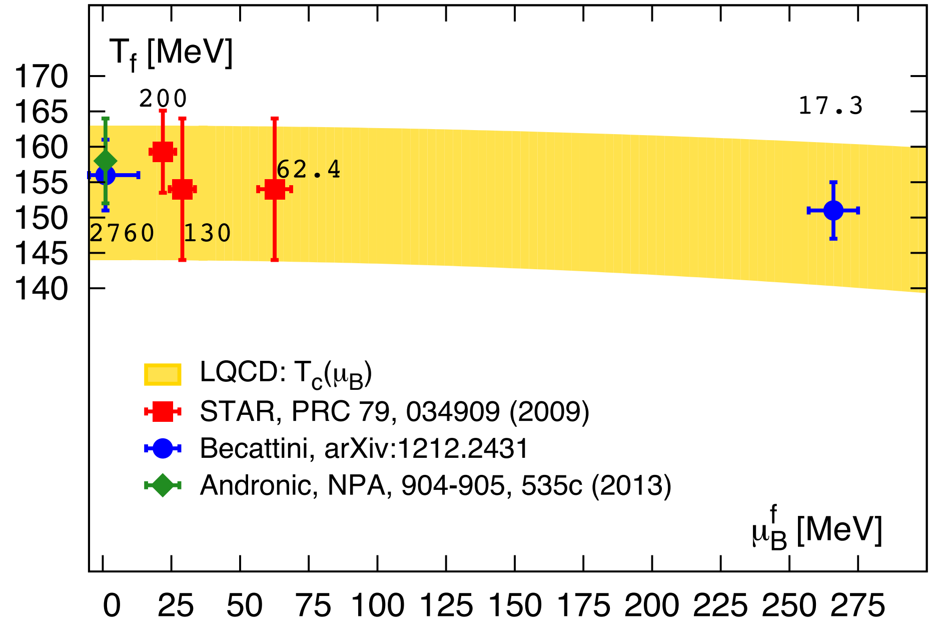
Experimental knowledge of strange and charm hadron spectrum is rather incomplete
Future experiments @ Jlab and FAIR (Germany) will address this problem

HRG that includes hadron states predicted by by quark model (also LQCD) agrees better with lattice results that HRG with PDG states only !

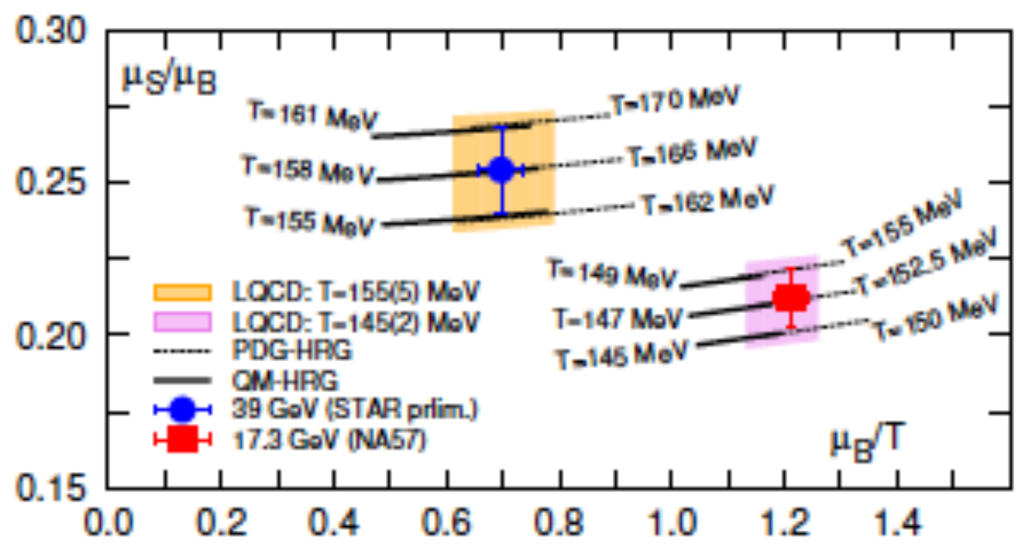
QCD thermodynamics at non-zero chemical potential

Bazavov et al, PRL109 (2012) 192302, Mukherjee, Wagner, arXiv:1307.6255





For consistent description of
The freeze-out of strange hadrons
Need to include the contribution of
“missing states”
Bazavov et al, arXiv:1404.6511



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:

$$\boxed{J_H=\overline{\psi}\,\Gamma_H\,\psi}$$

Heavy flavor probes at RHIC

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

Light vector meson spectral functions:

$$\boxed{J_\mu=\overline{\psi}\,\gamma_\mu\,\psi}$$

Thermal photons and dileptons provide information about the temperature of the

thermal dilepton production rate

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

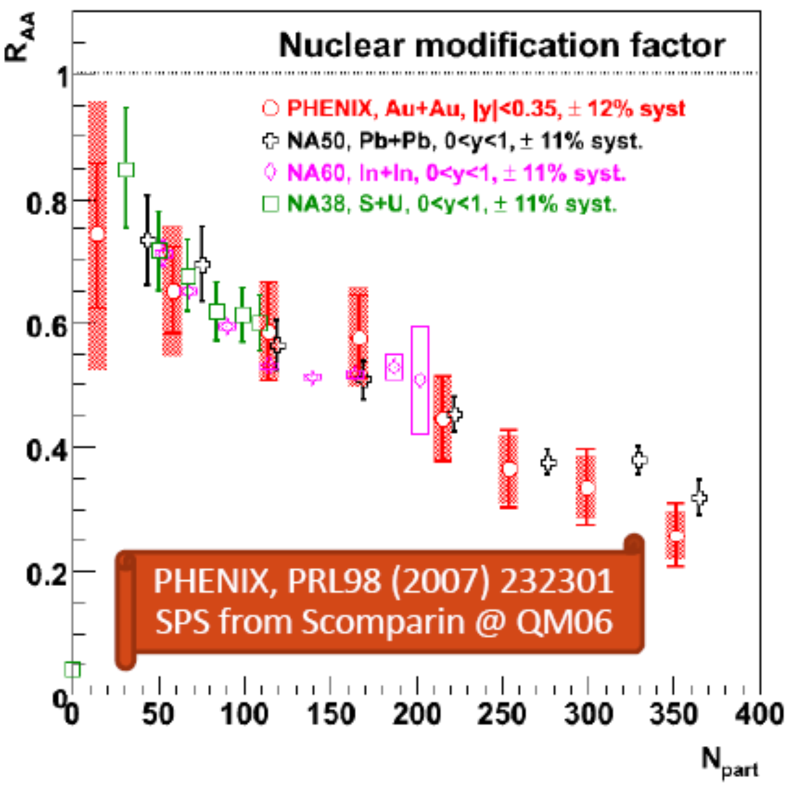
thermal photon production rate :

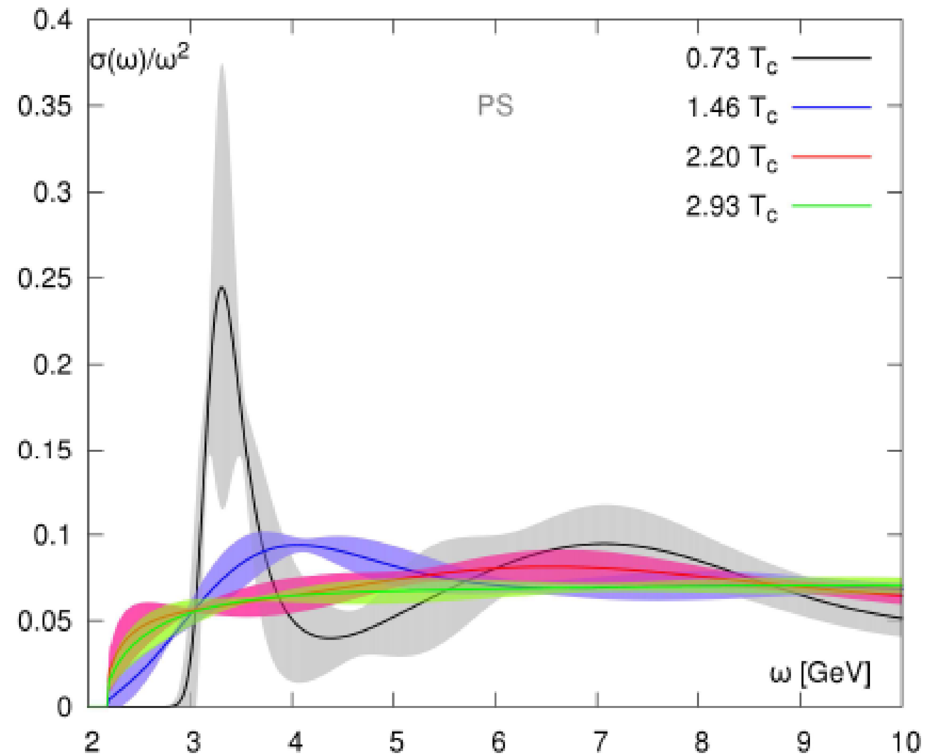
$$p\frac{dW}{d^3p}=\frac{5\alpha_{em}}{9\pi}\frac{1}{e^{p/T}-1}\sigma_{\mu\mu}(\omega=p,p,T)$$

electric conductivity ζ :

Quarkonium spectral spectral functions

Charmonium spectral functions on isotropic lattice in quenched approximation with Wilson quarks:
H.-T. Ding et al, arXiv:1204.4945
$N_\tau=24\text{-}96,\ a^{-1}=18.97GeV$





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

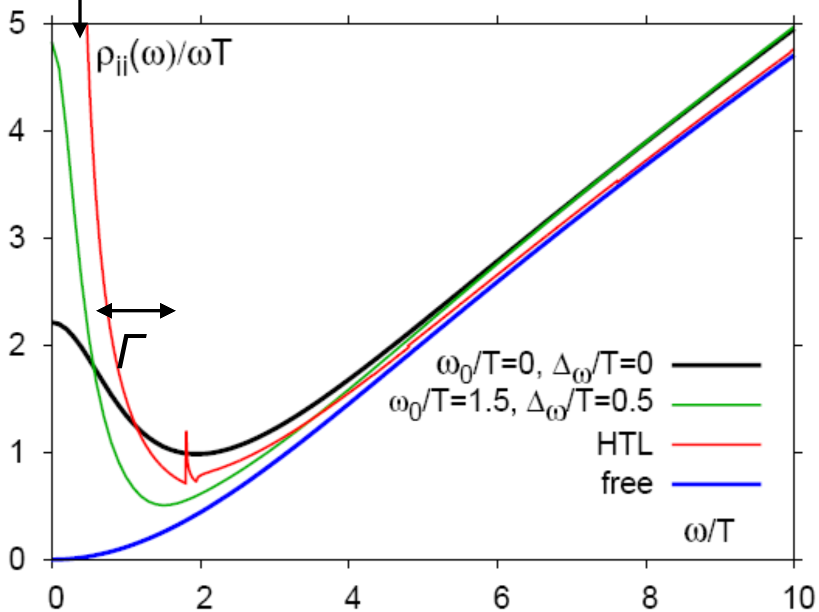
Lattice calculations of transport coefficients

Electric condictivity:

Ding et al, PRD 83 (11) 034504

peak at $\omega \approx 0$ = transport peak

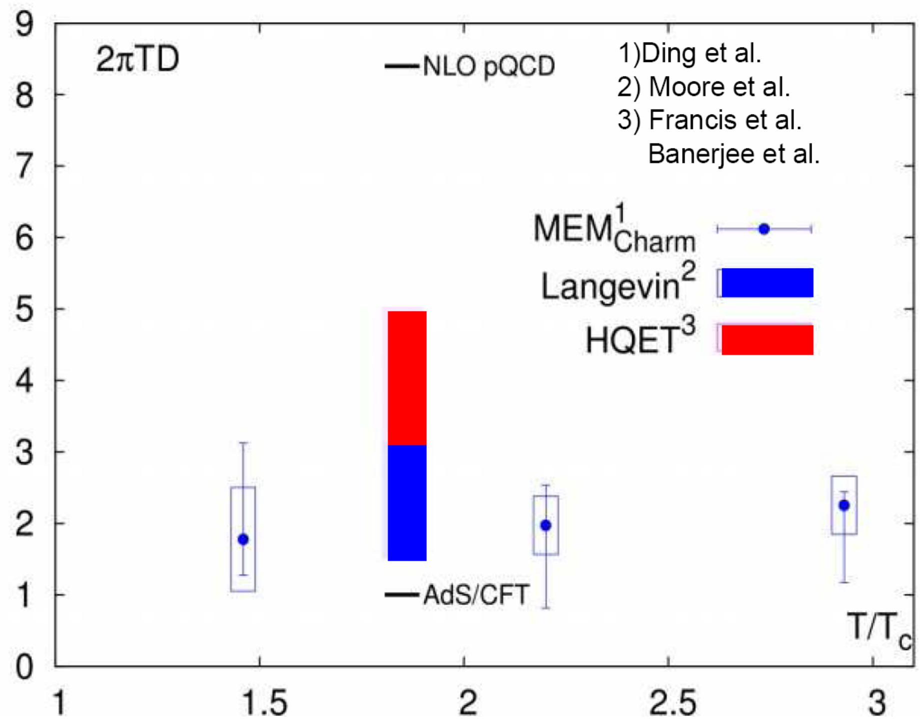
$$\Gamma \sim 1/\tau_{relax},\ \ \sigma_{el} \sim \chi_Q/\Gamma$$



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

Heavy quark diffusion constant:

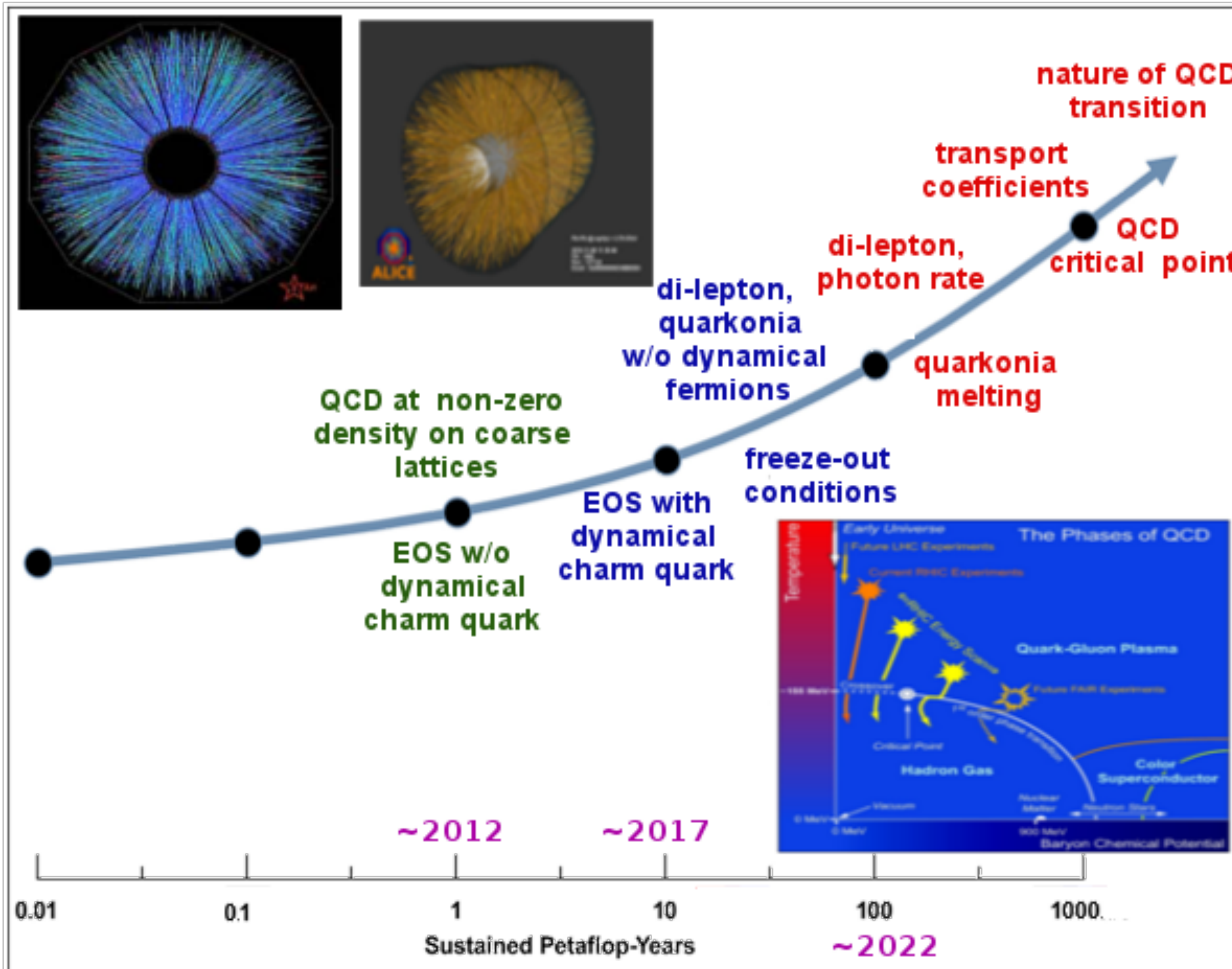
Ding et al, arXiv:1204:4954
Banarjee et al, arXiv:1109.5738
Kaczmarek et al, arXiv:1109:3941



Quenched QCD calculations up to 128^3x32 lattice

Perfect liquid: $\eta/s=1/(4\pi)$ ⇔ no transport peak !

Summary



ALICE
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
The Phases of QCD
Early Universe
Future LHC Experiments
Current RHIC Experiments
Temperature
Quark-Gluon Plasma
Future FAIR Experiments
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
Baryon Chemical Potential
~2012
~2017
~2022
0.01
0.1
1
10
100
1000.
Sustained Petaflop-Years

Back-up slide