What do we know about the viscosity of QCD matter?

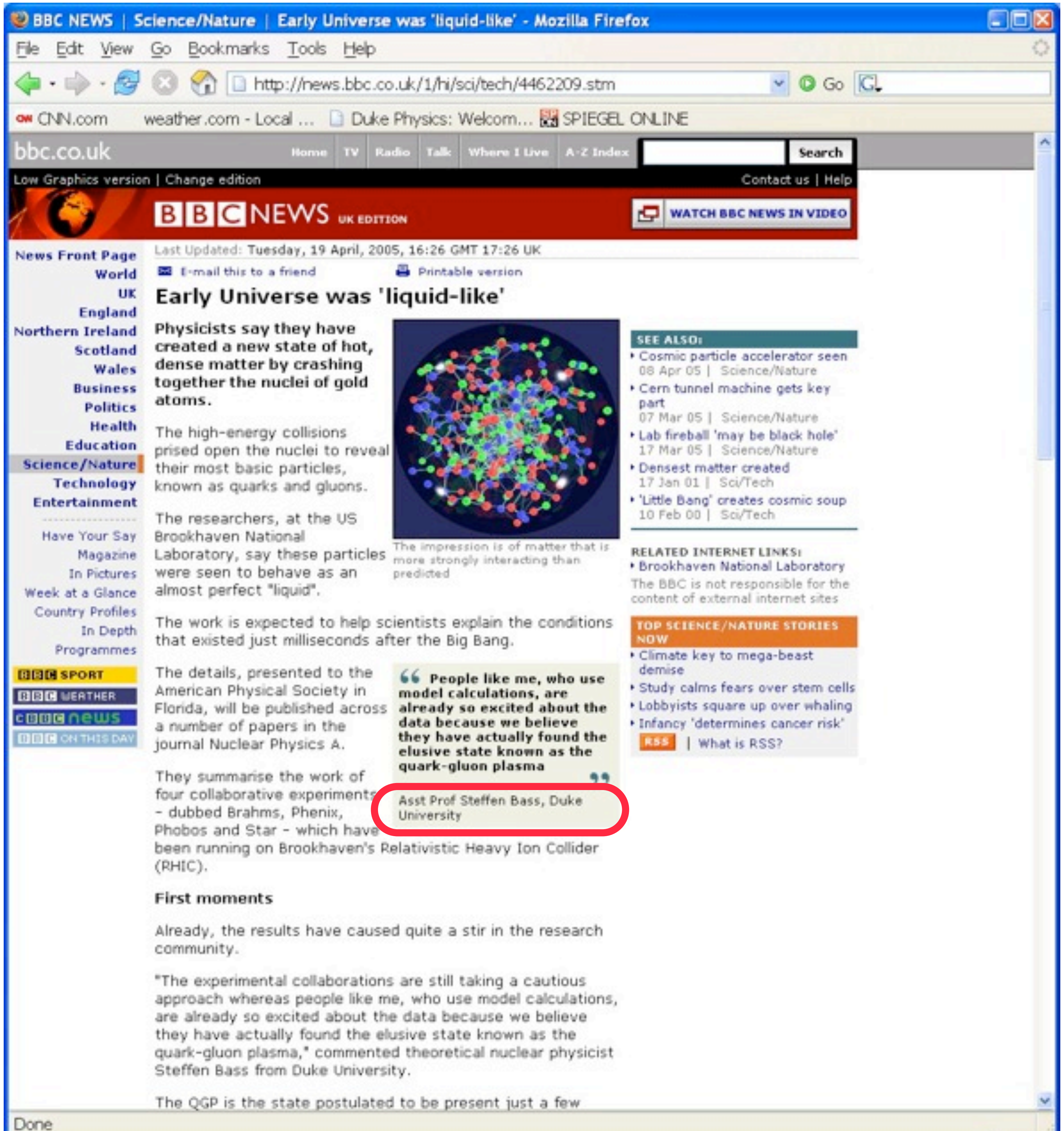
Steffen A. Bass
Duke University

- Near-Ideal Fluids & Elliptic Flow
- Shear-Viscosity of QCD Matter
- η/s of a Hadron Gas
- Improved Constraints on η/s

work supported through grants by

Near-Ideal Fluids & Elliptic Flow

RHIC in the press: Perfect Liquid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Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The impression is of matter that is more strongly interacting than predicted

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

"People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma"

Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's Relativistic Heavy Ion Collider (RHIC).

First moments

Already, the results have caused quite a stir in the research community.

"The experimental collaborations are still taking a cautious approach whereas people like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma," commented theoretical nuclear physicist Steffen Bass from Duke University.

The QGP is the state postulated to be present just a few

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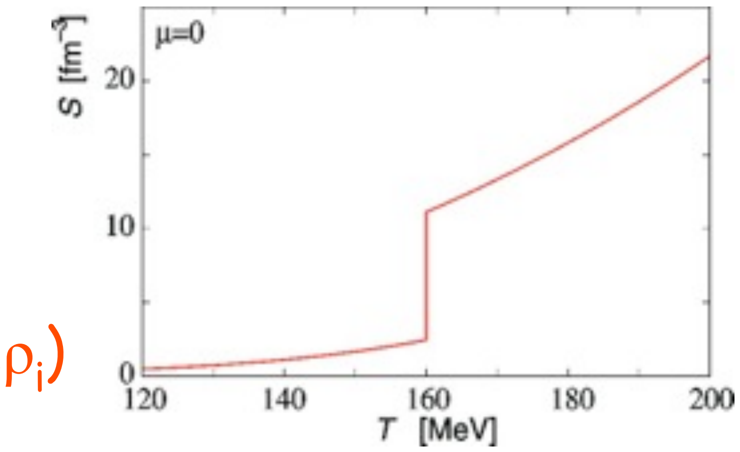
Done

- on April 18th, 2005, BNL announced in a press release that RHIC had created a new state of hot and dense matter which behaves like a nearly perfect liquid.
- how does one measure/ calculate the properties of a near ideal liquid?
- are there any other near ideal liquid systems found in nature?

Relativistic Fluid Dynamics (RFD)

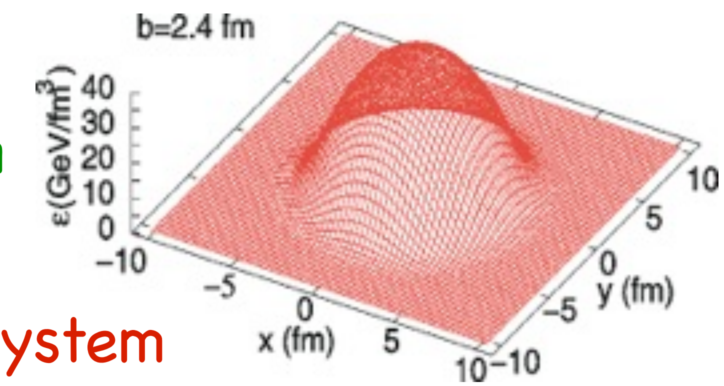
- transport of macroscopic degrees of freedom
- based on conservation laws: $\partial_\mu T^{\mu\nu}=0$ $\partial_\mu j^\mu=0$
- for ideal fluid: $T^{\mu\nu}= (\varepsilon+p)\, u^\mu\, u^\nu - p\, g^{\mu\nu}$ and $j_i^\mu = \rho_i\, u^\mu$
- **Equation of State** needed to close system of PDE's: $p=p(T,\rho_i)$

➤ connection to Lattice QCD calculation of EoS



- initial conditions (i.e. thermalized QGP) required for calculation
- assumes local thermal equilibrium, vanishing viscosity

➤ applicability of hydro is a strong signature for a thermalized system



Viscosity:

- shear and bulk viscosity are defined as the coefficients in the expansion of the stress tensor in terms of the velocity fields:

$$T_{ik} = \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) - \eta\left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik}\nabla\cdot u\right) + \varsigma\, \delta_{ik}\nabla\cdot u$$

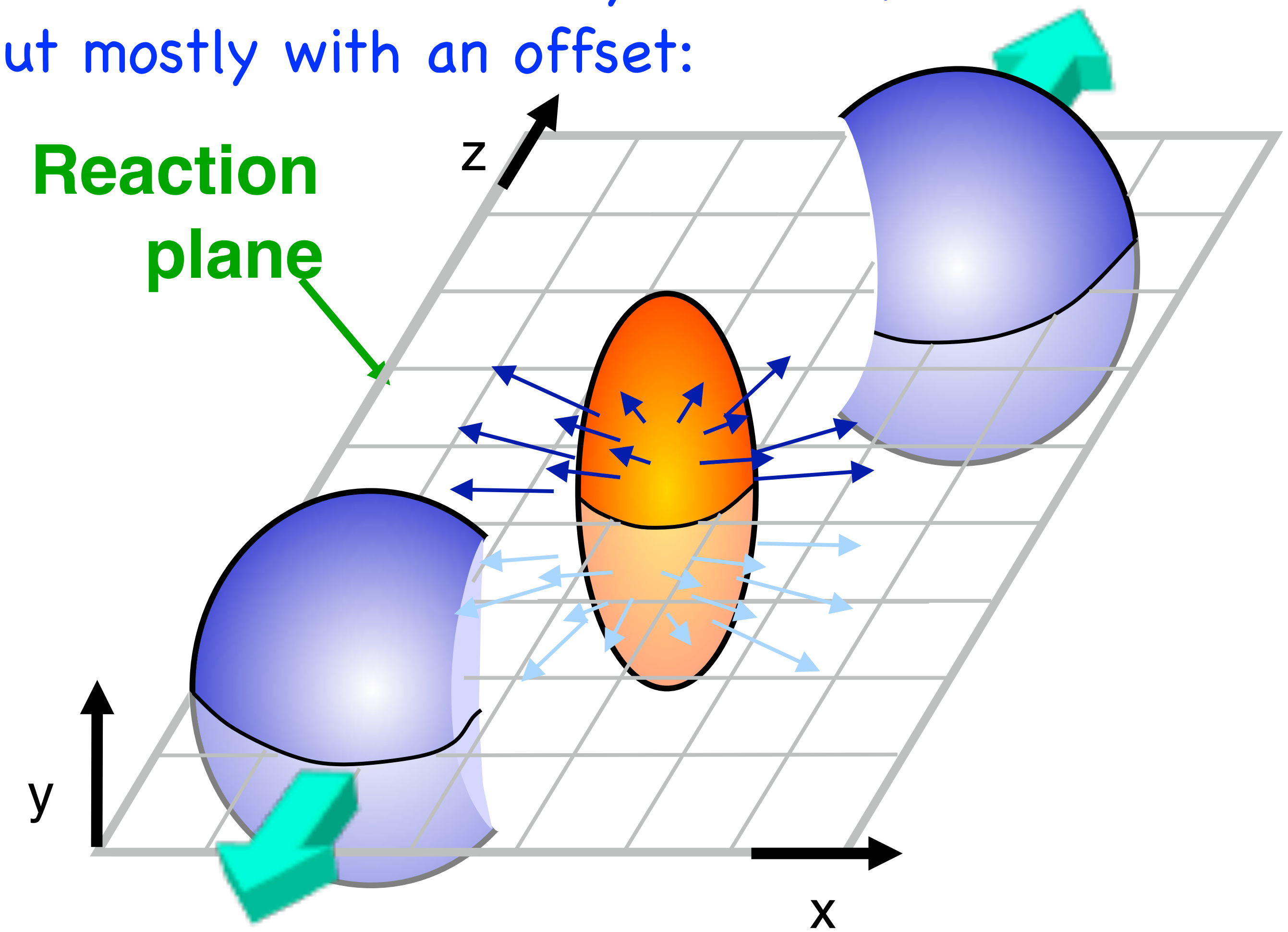
- viscous RFD requires solving an additional 9 eqns. for the dissipative flows

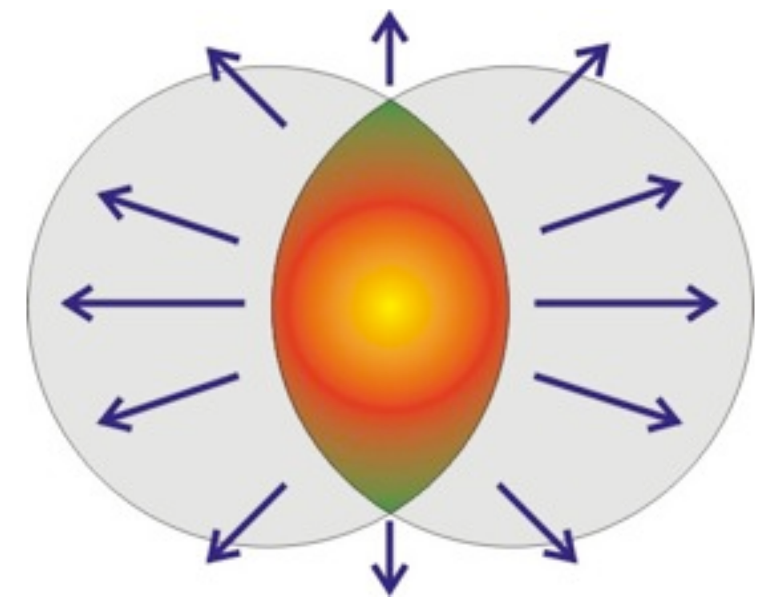
Note:

- for quasi-particulate matter, viscosity decreases with increasing cross section
- for viscous RFD, the microscopic origin of viscosity is not relevant!

Collision Geometry: Elliptic Flow

- two nuclei collide rarely head-on, but mostly with an offset:



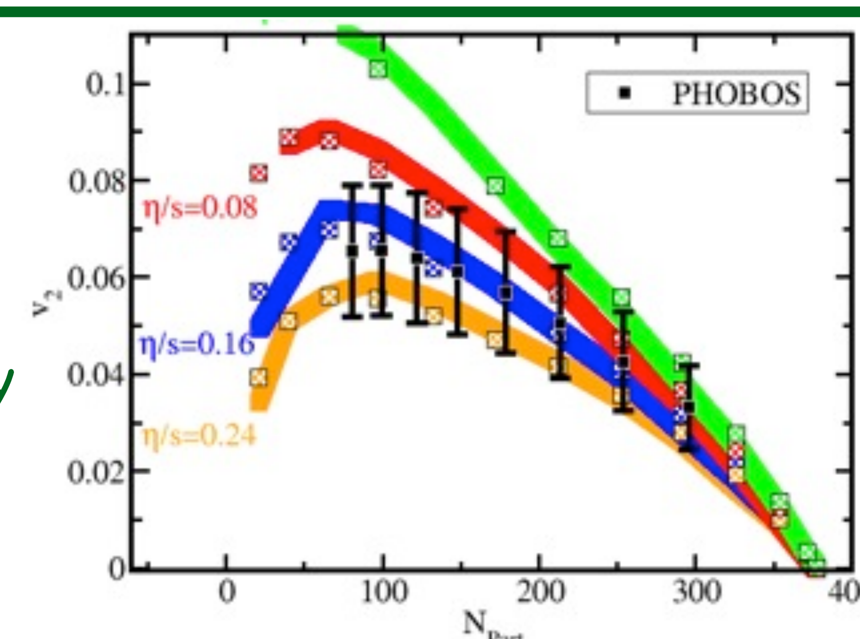


only matter in the overlap area gets compressed and heated up

elliptic flow (v_2):

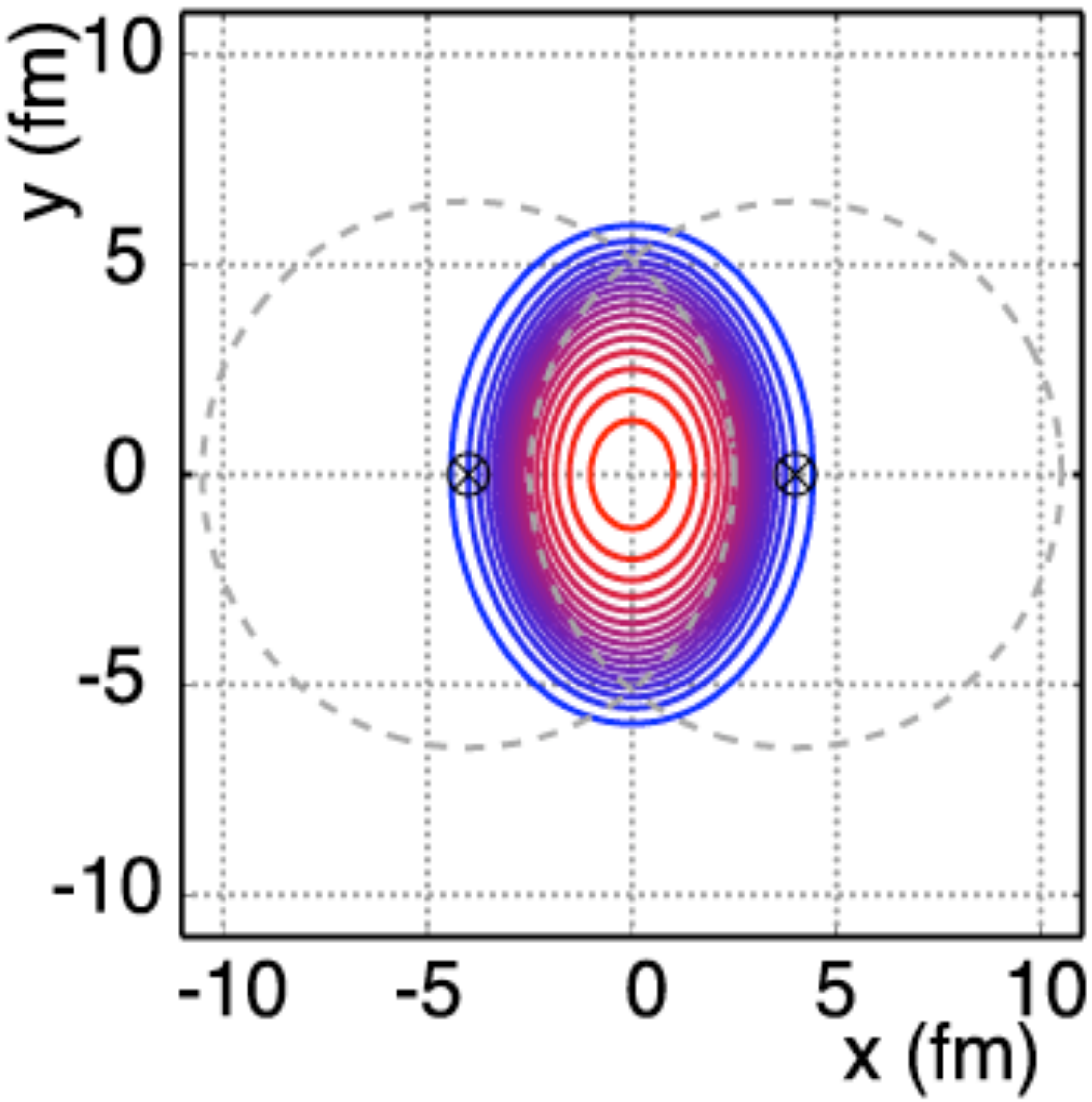
- gradients of almond-shape surface will lead to preferential emission in the reaction plane
- asymmetry out- vs. in-plane emission is quantified by 2nd Fourier coefficient of angular distribution: v_2

➢ vRFD: good agreement with data for very small η/s



Elliptic flow: early creation

initial energy density distribution:

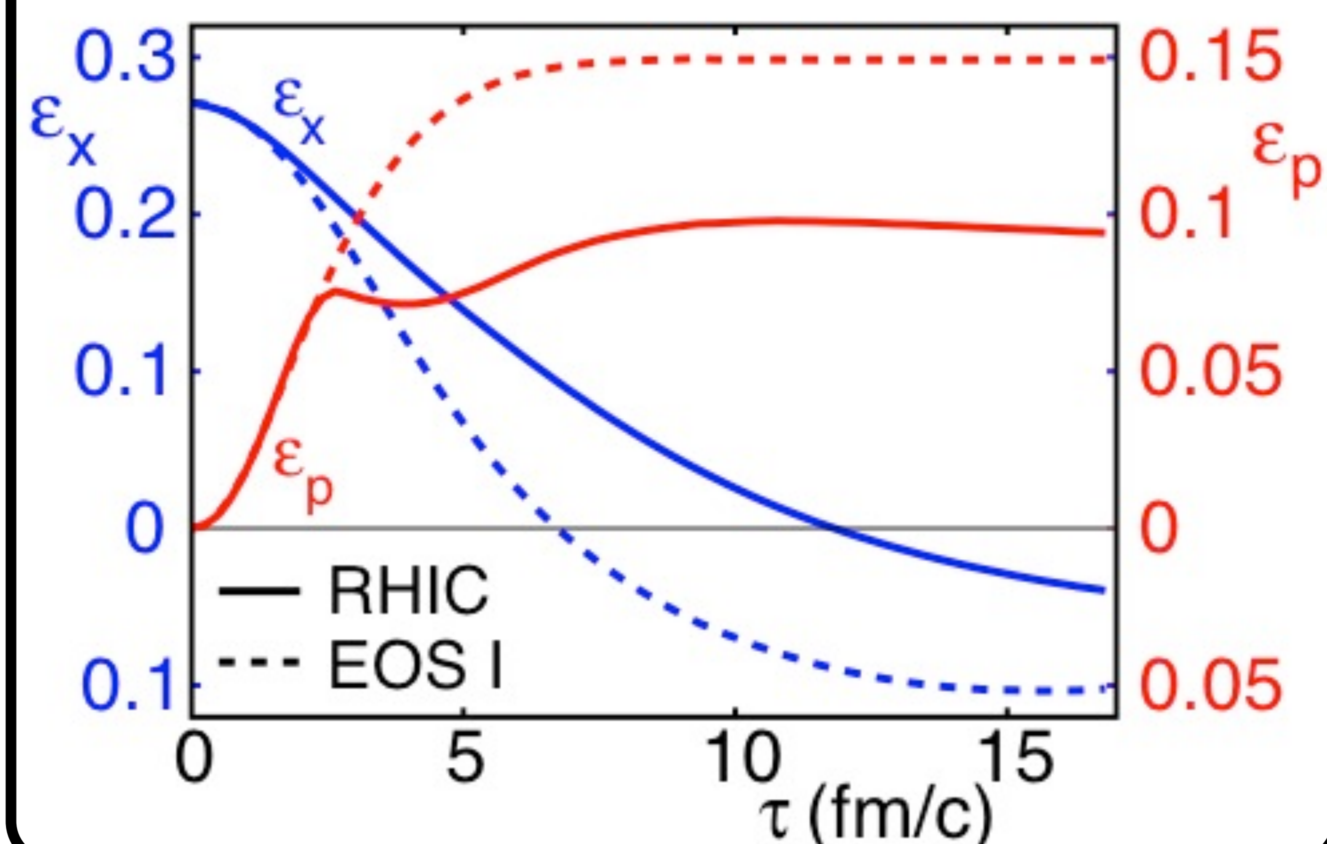


spatial eccentricity

$$\epsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momentum anisotropy

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



Most model calculations suggest that flow anisotropies are generated at the earliest stages of the expansion, on a **timescale of ~ 5 fm/c** if a QGP EoS is assumed.

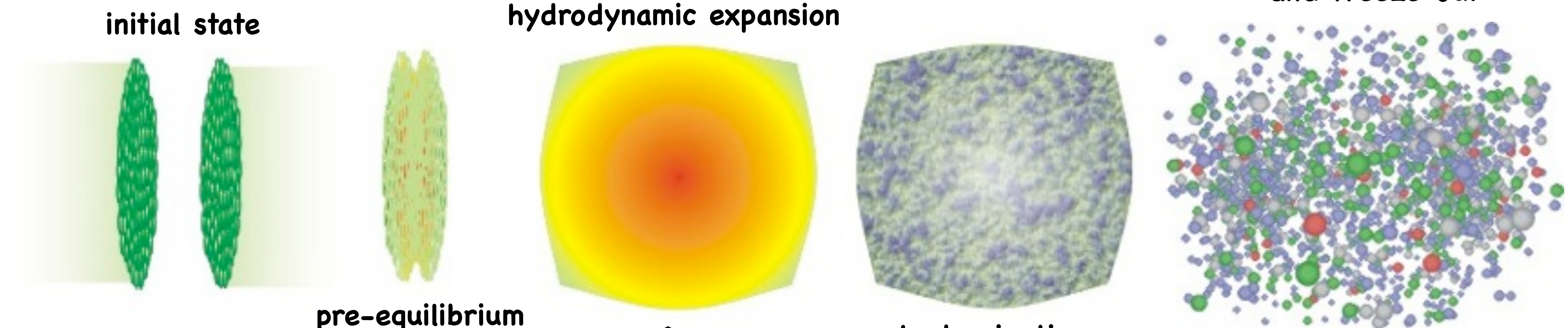
P. Kolb, J. Sollfrank and U.Heinz, PRC 62 (2000) 054909

shear-viscosity of QCD matter

M. Asakawa, S.A. Bass & B. Mueller: Phys. Rev. Lett. **96** (2006) 252301

M. Asakawa, S.A. Bass & B. Mueller: Prog. Theo. Phys. **116** (2006) 725

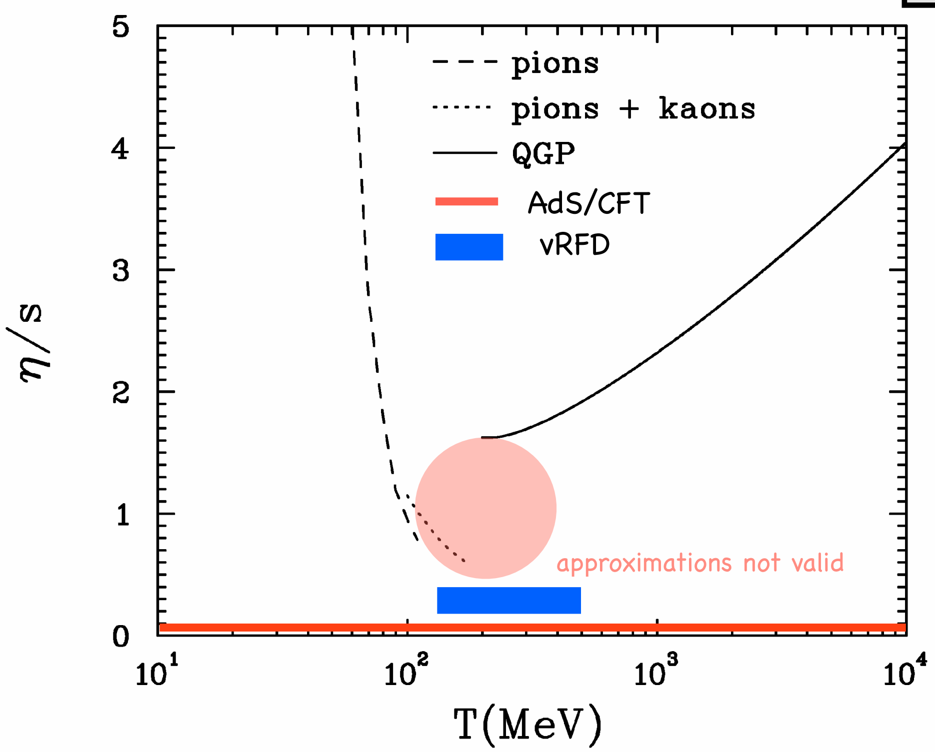
Viscosity at RHIC



large elliptic flow: near ideal fluid w/ small viscosity

parton recombination: quasi-particle d.o.f.

expanding hadron gas w/ increasing m.f.p.: large viscosity



- viscosity of QCD matter @ RHIC changes strongly with temperature & phase
- how can we quantify the viscosity of QCD matter?

L.P. Csernai, J.I. Kapusta & L. McLerran: Phys. Rev. Lett. **97**: 152303 (2006)
M. Prakash, M. Prakash, R. Venugopalan & G. Welke: Phys. Rept. **227**, 321 (1993)
P. Arnold, G.D. Moore & L.D. Yaffe: JHEP **05**: 051 (2003)

η/s from Lattice QCD

The confines of the Euklidian Formulation:

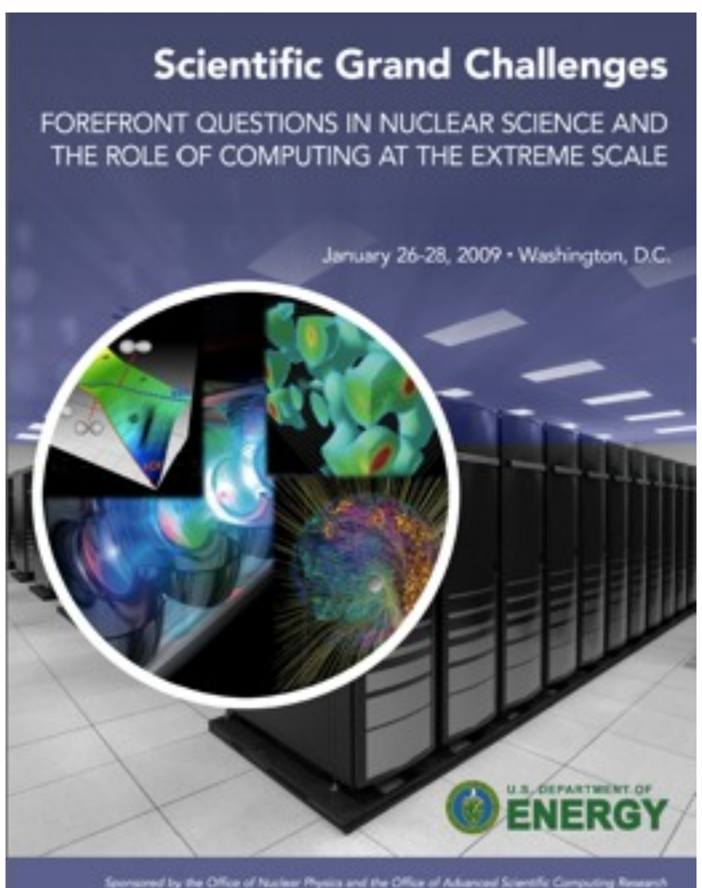
- extracting η/s formally requires taking the zero momentum limit in an infinite spatial volume, which is numerically not possible...

preliminary estimates:

caution:

systematic errors are O(1)!

T	1.58 T_C	2.32 T_C
η/s	0.2	0.26



- calculating QCD transport coefficients on the Lattice has been identified as a Priority Research Direction by the DOE Office of Nuclear Physics and the Office of Advanced Scientific Computing Research (ASCR) in their report on Extreme-Scale Computing

Harvey B. Meyer: Phys.Rev.**D79**: 011502, 2009

Harvey B. Meyer: **arXiv:0809.5202** [hep-lat]

AdS/CFT correspondence

- calculating viscosity and viscosity/entropy ratio too difficult in full QCD
- quantities are calculable in a related theory using string theory methods

model for QCD:

N = 4 Super-Yang-Mills theory	⟷	a string theory in 5d AdS
finite temperature	⟷	black hole in AdS_5
large N_C and strong coupling limit	⟷	classical gravity limit

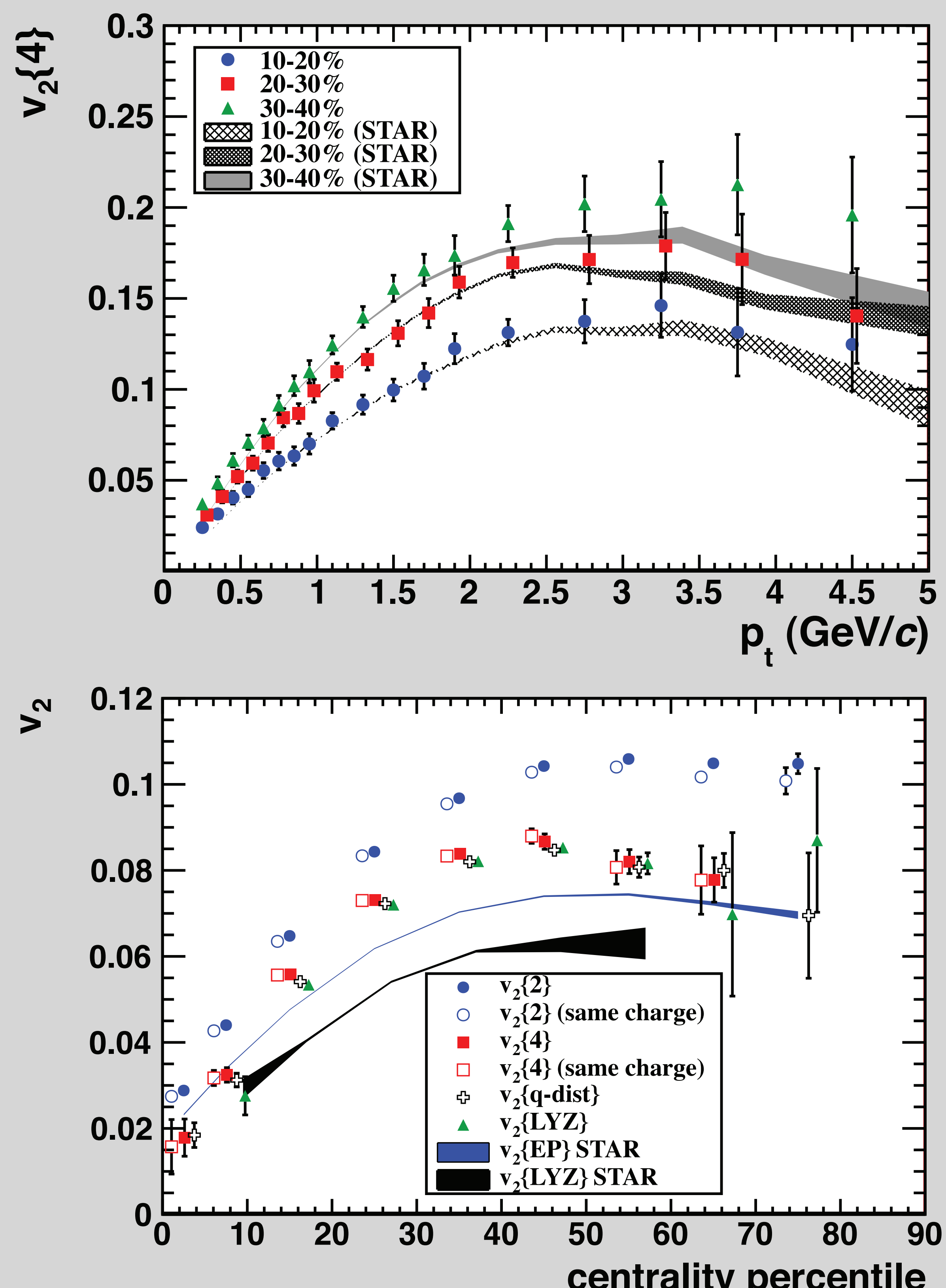
- YM observables at infinite N_C and infinite coupling can be computed using classical gravity
- technique can be applied to dynamical and thermodynamic observables
- in all theories with gravity-duals one finds: $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ (very small number!)

Caution:

- N=4 SUSY YM is not QCD!
- no information on how low η/s is microscopically generated

J. Maldacena: Adv. Theor. Math. Phys. 2 (1998) 231
E. Witten: Adv. Theor. Math. Phys. 2 (1998) 505
S.S. Gubser, I.R. Klebanov & M. Polyakov: Nucl.Phys. B636 (2002)

Elliptic Flow at the LHC



first data by the ALICE Collaboration:

- v_2 vs. p_T virtually identical to RHIC data
- rise in integrated v_2 vs. centrality due to increase in radial flow
- charged particle multiplicity suggests a rise in temperature by 30% compared to RHIC (or a factor of approx. 2.9 in energy-density)

The ALICE Collaboration: arXiv:1011.3914 [nucl-ex]

Implications for η/s:

- despite rise in temperature, η/s has to remain small, on the same level as observed at RHIC!
- can low value of η/s be reconciled with its known temperature dependence in the HTL calculations?
  - T-dependence is logarithmic; lack of sensitivity for a 30% rise?
  - physics beyond the HTL limit: color fields?

The sQGP Challenge: do quasi-particles drive η/s?

- the success of near ideal hydrodynamics has led the community to equate low viscosity with a vanishing mean free path and thus large parton cross sections: **strongly interacting QGP (sQGP)**

- does a small viscosity have to imply that matter is strongly interacting?
- consider effects of (turbulent) color fields?

Anomalous Viscosity: (see e.g. in Plasma-, Astro-, Biophysics)

- any contribution to the shear viscosity not explicitly resulting from momentum transport via a transport cross section

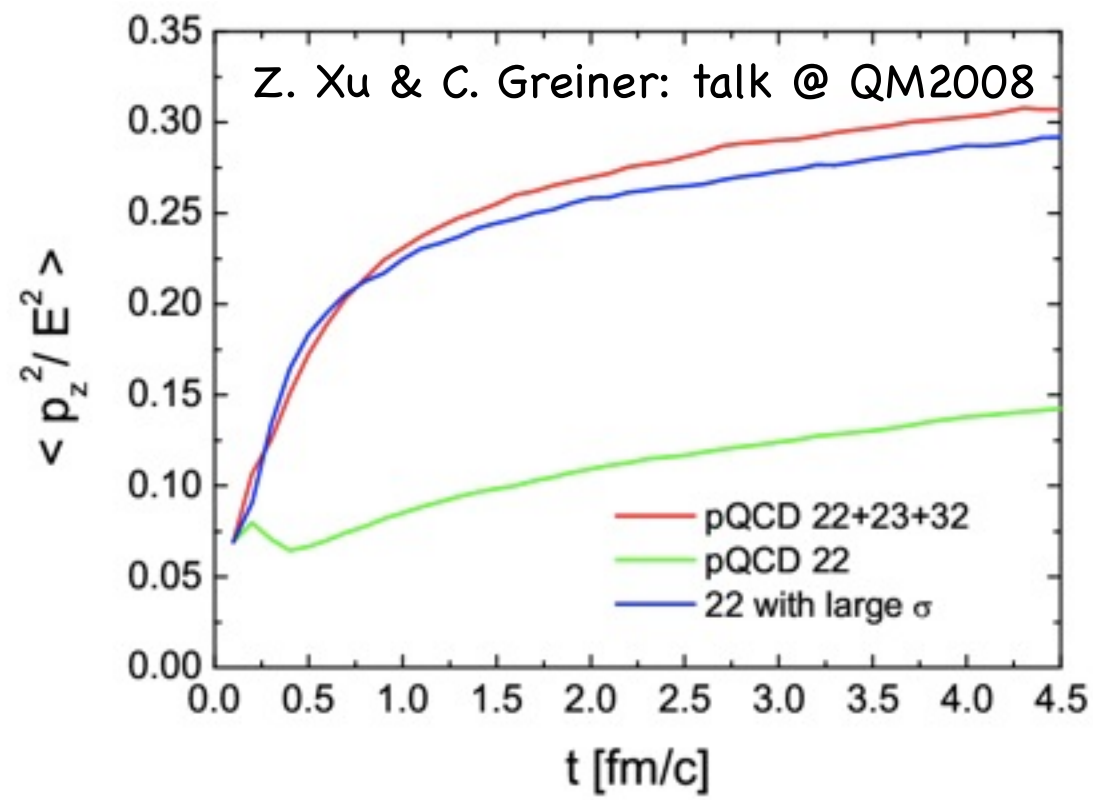
- can the QGP viscosity be anomalous?
  - soft, turbulent color fields generate anomalous transport coefficients, which may give the medium the character of a nearly perfect fluid even at moderately weak coupling.

microscopic kinetic theory:

η is given by the rate of momentum transport:

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f = \frac{\bar{p}}{3\sigma_{\mathrm{tr}}}$$

- microscopic transport with parton d.o.f. requires either unphysically large cross sections or a very specific implementation of the LPM effect to thermalize & create elliptic flow



Anomalous vs. Collisional Viscosity

collisional viscosity:

- derived in HTL weak coupling limit

$$\frac{\eta_C}{s} \approx \frac{5}{g^4 \ln g^{-1}}$$

anomalous viscosity:

- induced by turbulent color fields, due to momentum-space anisotropy

$$\frac{\eta_A}{s} = \mathcal{O}(1) \frac{(N_c^2 - 1)}{N_c} \frac{T^6}{g^2 \langle \mathcal{B}^2 \rangle \, \tau_{\mathrm{m}}} \quad \Rightarrow \quad \frac{\eta_A}{s} \sim \frac{1}{\langle B^2 \rangle}$$

- with ansatz for fields:

$$\frac{\eta_A}{s} = \bar{c}_0 \left(\frac{T}{g^2 |\nabla u|} \right)^{3/5}$$

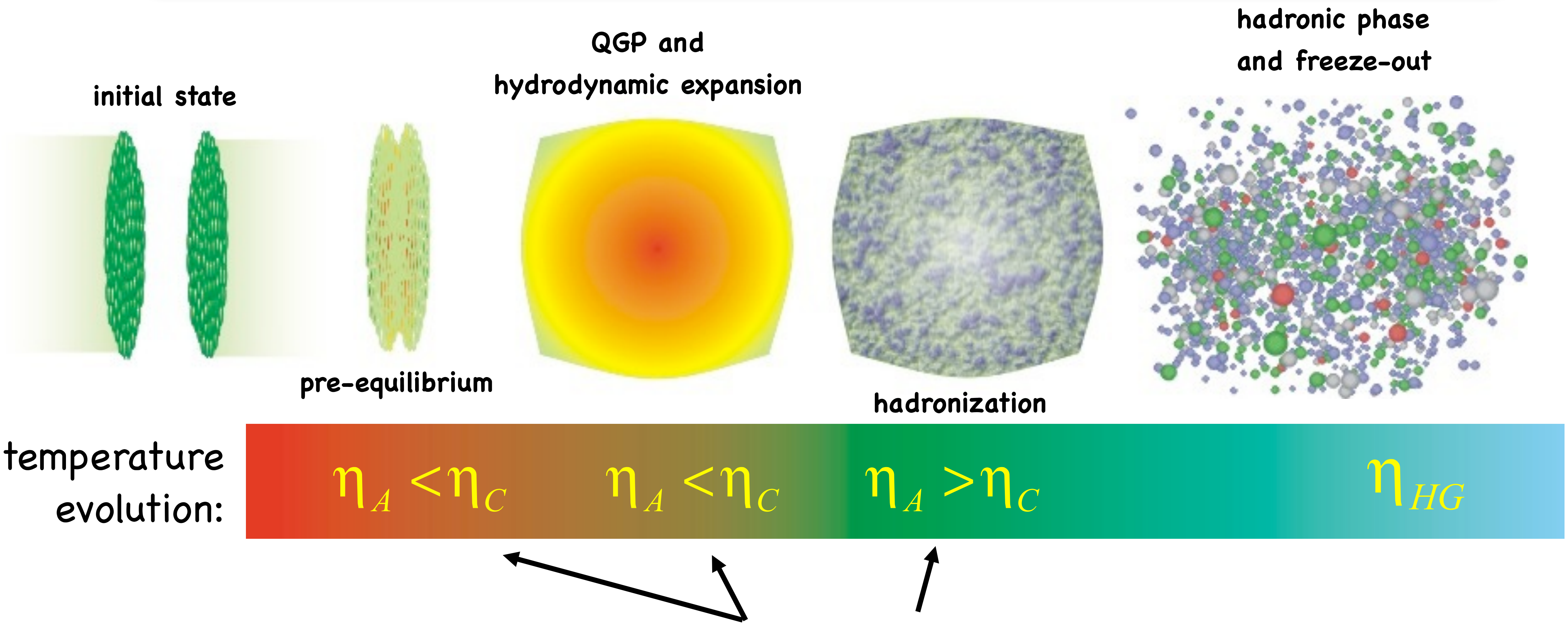
- for reasonable values of g: $\eta_A < \eta_C$

- sum-rule for system w/ 2 viscosities: (derived from variational principle)

$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

- total viscosity dominated by η_A

Collisional vs. Anomalous Viscosity



$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

- smaller viscosity dominates in system w/ 2 viscosities!

- anomalous viscosity dominates total shear viscosity during early QGP evolution
- a small viscosity does not necessarily imply strongly interacting matter!

η/s of a Hadron Gas

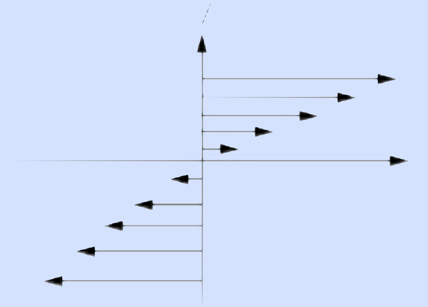
N. Demir & S.A. Bass: Phys. Rev. Lett. **102**, 172302 (2009)

Shear Viscosity: Linear Transport Equation & Green - Kubo Formalism

Mechanical definition of shear viscosity:

- application of a shear force to a system gives rise to a non-zero value of the xy-component of the pressure tensor P_{xy}. P_{xy} is then related to the velocity flow field via the shear viscosity coefficient η:

$$P_{xy} = -\eta \frac{\partial v_x}{\partial y}$$



- a similar linear transport equation can be defined for other transport coefficients: thermal conductivity, diffusion …

- using linear-response theory, the **Green-Kubo relations** for the shear viscosity can be derived, expressing η as an integral of an near-equilibrium time correlation function of the stress-energy tensor:

$$\eta = \frac{1}{T} \int d^3r \int_0^\infty dt \left\langle \pi^{xy}(\vec{0},0)\, \pi^{xy}(\vec{r},t) \right\rangle_{\text{equil}}$$

with the stress-energy tensor: $\pi^{\mu\nu}(\vec{r},t) = \int d^3p \frac{p^\mu p^\nu}{p^0} f(x,p)$

Microscopic Transport: η/s of a Hadron Gas

- for particles in a fixed volume, the stress energy tensor discretizes

$$\pi^{xy} = \frac{1}{V} \sum_{j=1}^{N_{\rm part}} \frac{p^x(j) p^y(j)}{p^0(j)}$$

- and the Green-Kubo formula reads:

$$\eta = \frac{V}{T} \int_0^\infty dt \, \langle \pi^{xy}(0)\, \pi^{xy}(t) \rangle$$

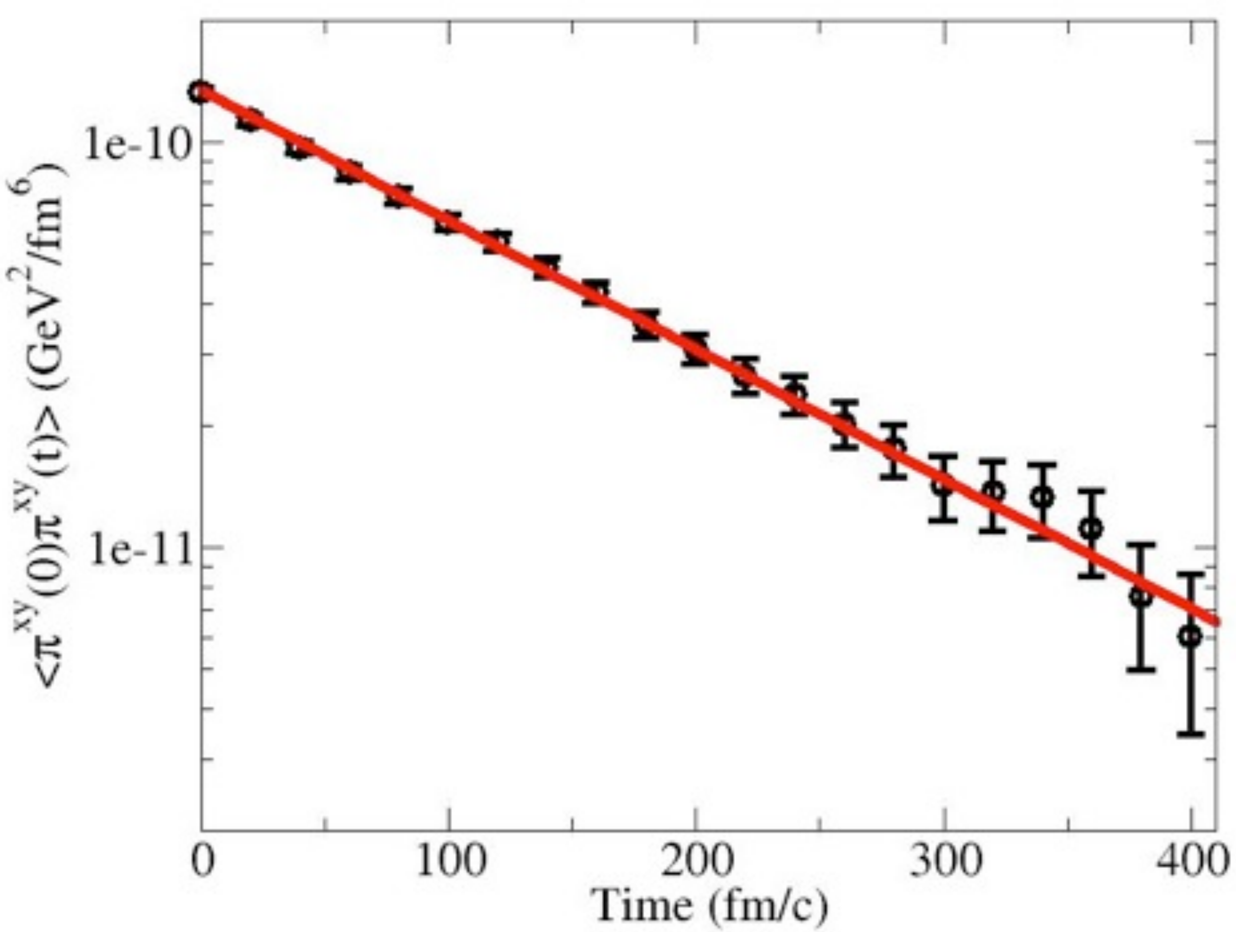
Entropy:

- extract thermodynamic quantities via:

$$P = \frac{1}{3V} \sum_{j=1}^{N_{\rm part}} \frac{|\vec{p}|^2(j)}{p^0(j)} \qquad \epsilon = \frac{1}{V} \sum_{j=1}^{N_{\rm part}} p^0(j)$$

- use Gibbs relation (with chem. pot. extratced via SM)

$$s_{\rm Gibbs} = \left(\frac{\epsilon + P - \mu_i \rho_i}{T} \right)$$



- evaluating the correlator numerically, e.g. in UrQMD, one empirically finds an exponential decay as function of time
- using the following ansatz, one can extract the relaxation time τ_π:

$$\langle \pi^{xy}(0)\, \pi^{xy}(t) \rangle \propto \exp\left(-\frac{t}{\tau_\pi} \right)$$

- the shear viscosity then can be calculated from known/extracted quantities:

$$\eta = \tau_\pi \frac{V}{T} \left\langle \pi^{xy}(0)^2 \right\rangle$$

A. Muronga: Phys. Rev. **C69**: 044901, 2004

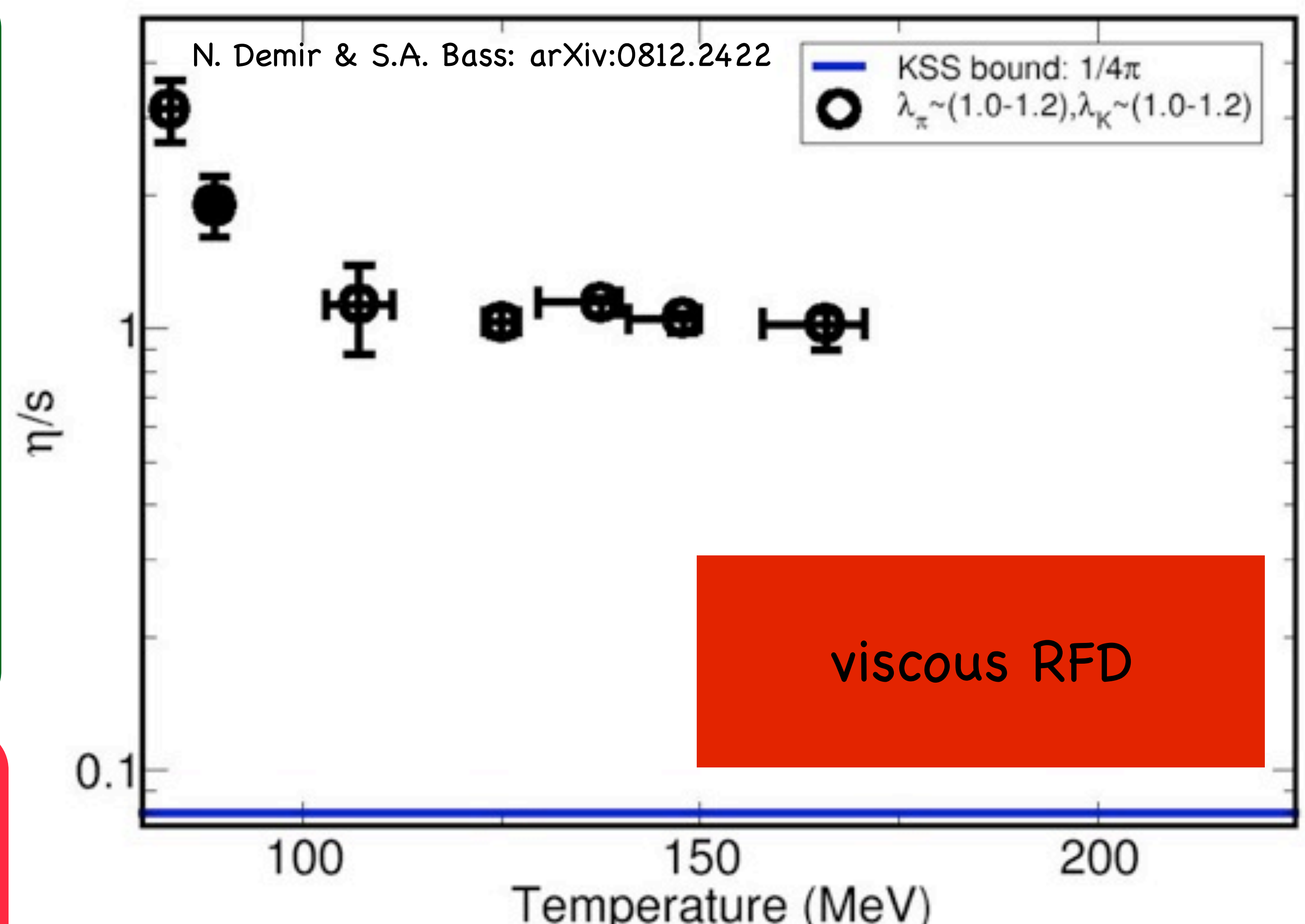
η/s of a Hadron Gas in & out of Equilibrium

first reliable calculation of of η/s for a full hadron gas including baryons and anti-baryons:

- breakdown of vRFD in the hadronic phase?
- what are the consequences for η/s in the deconfined phase?

- RFD freeze-out temperature to reproduce spectral shapes: ~110 MeV
- Statistical Model temperature fits to hadron yields/ratios: ~160 MeV
  - separation of chemical and kinetic freeze-out in the hadronic phase!
  - confirmed by hybrid models
  - implies non-unit species-dependent fugacities in RFD

- non-unit fugacities reduce η/s by a factor of two to η/s≈0.5
  - **improved constraint:** η/s needs to be significantly lower in deconfined phase for vRFD to reproduce elliptic flow!

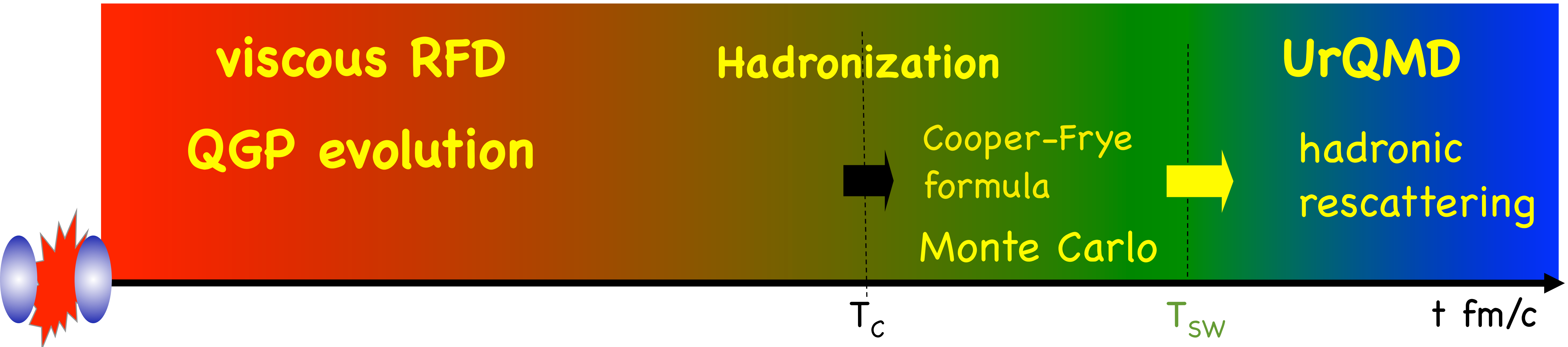


T. Hirano & K. Tsuda: Nucl. Phys. **A715**, 821 (2003)
P.F. Kolb & R. Rapp: Phys. Rev. **C67**, 044903 (2003)

Improved Constraints on η/s

Song, Bass, Heinz, Hirano & Shen: Phys. Rev. Lett. 106 (2011) 192301

Viscous Hydro + Micro Model



viscous RFD

- **ideally suited for dense systems**
  - model early QGP reaction stage
- **well defined Equation of State**
- **parameters:**
  - initial conditions
  - Equation of State including PCE for HG
  - viscosity over entropy-density ratio

\+

micro. transport (UrQMD)

- **no equilibrium assumptions**
  - model break-up stage
  - calculate freeze-out
  - includes viscosity in hadronic phase
- **parameters:**
  - (total/partial) cross sections

matching condition:

- use same set of hadronic states for EoS as in UrQMD
- generate hadrons in each cell using local T and μ_B
- take off-equilibrium distribution functions into account

S.A. Bass & A. Dumitru, Phys. Rev **C61** (2000) 064909
D. Teaney et al, nucl-th/0110037
T. Hirano et al. Phys. Lett. **B636** (2006) 299
C. Nonaka & S.A. Bass, Phys. Rev. **C75** (2006) 014902
H. Song, S.A. Bass, U.W. Heinz, T. Hirano & C. Shen, arXiv: 1011.2783 [nucl-th]

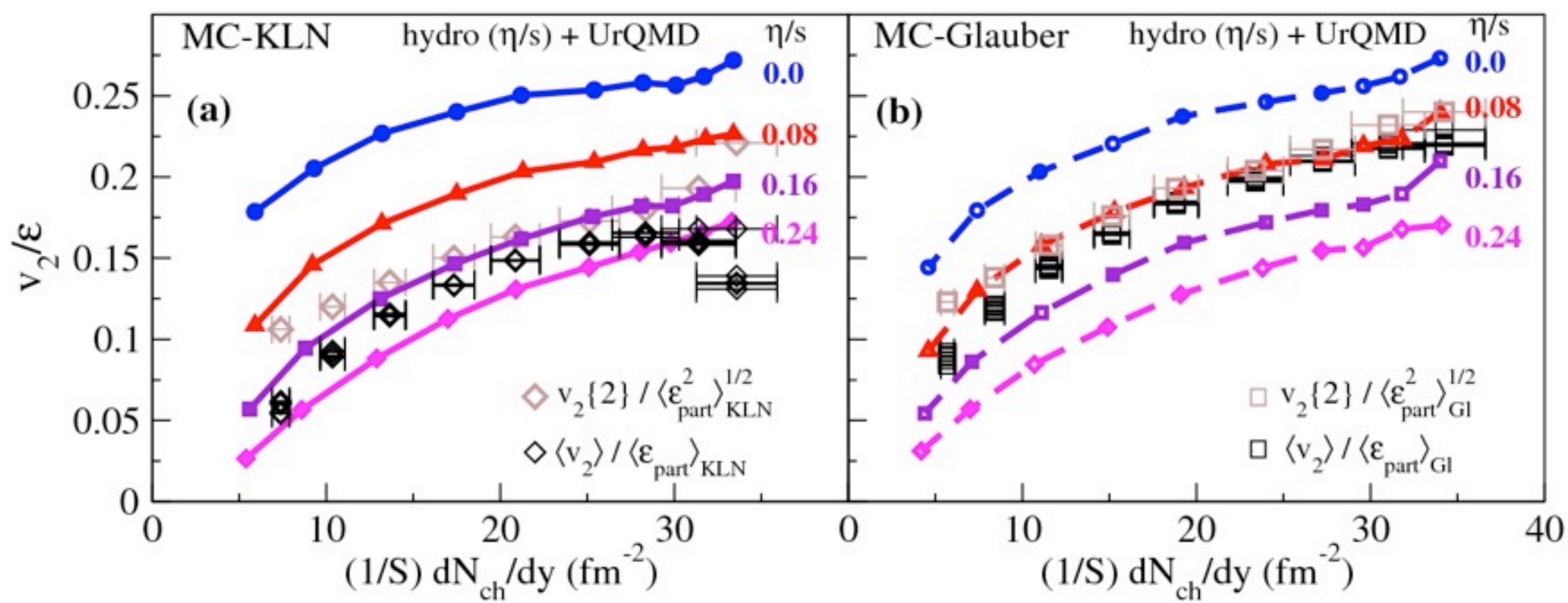
Improved Extraction of η/s

Viscous RFD Improvements:

- use fluctuating initial conditions
- state-of-the-art Lattice EoS, including PCE in hadronic phase prior to T_{sw}
- constrain τ_0 and s with fit to data for dN/dy and spectra

Milestones:

- eccentricity scaling yields same centrality dependence for MC-KLN & MC-Glauber
- centrality dependence agrees with data
- realistic treatment of hadronic phase, including viscosity and freeze-out



- slope of v_2/ε cannot distinguish between KLN and Glauber initial conditions
- QGP viscosity: $1/(4\pi) < \eta/s < 2/(4\pi)$ [Glauber] & $2/(4\pi) < \eta/s < 3/(4\pi)$ [KLN]

Conclusion & Outlook

Heavy-Ion collisions at RHIC have produced a state of matter which can be called the **Quark-Gluon-Plasma:**

- the properties of the QGP can be characterized by its transport coefficients, such as η/s and q-hat
  - near ideal fluidity: the smallest value of η/s observed in nature
  - η/s may strongly depend on temperature and phase of QCD matter

Transition from Discovery Phase to Exploratory Phase and onwards to Precision Spectroscopy of the QGP:

- improved constraints via hybrid viscous RFD + UrQMD calculation, that fully accounts for large viscosity of hadronic phase
- largest uncertainty currently due to lack of knowledge on the structure of the initial conditions
- need to establish the physics driving the small value of η/s (e.g. particles vs. fields) in the QGP phase


Thank you!
Any questions?

The End

Hard Thermal Loops: Instabilities

Nonabelian Vlasov equations describe interaction of "hard" (i.e. particle) and "soft" color field modes and generate the "hard-thermal loop" effective theory:

$$\frac{dp^\mu}{d\tau} = gQ^a\, F^{a\mu\nu}\, u_\nu \qquad \frac{dQ^a}{d\tau} = g f_{abc} A^{b\nu}\, u_\nu\, Q^c \qquad D_\mu F^{\mu\nu} = gJ^\nu$$

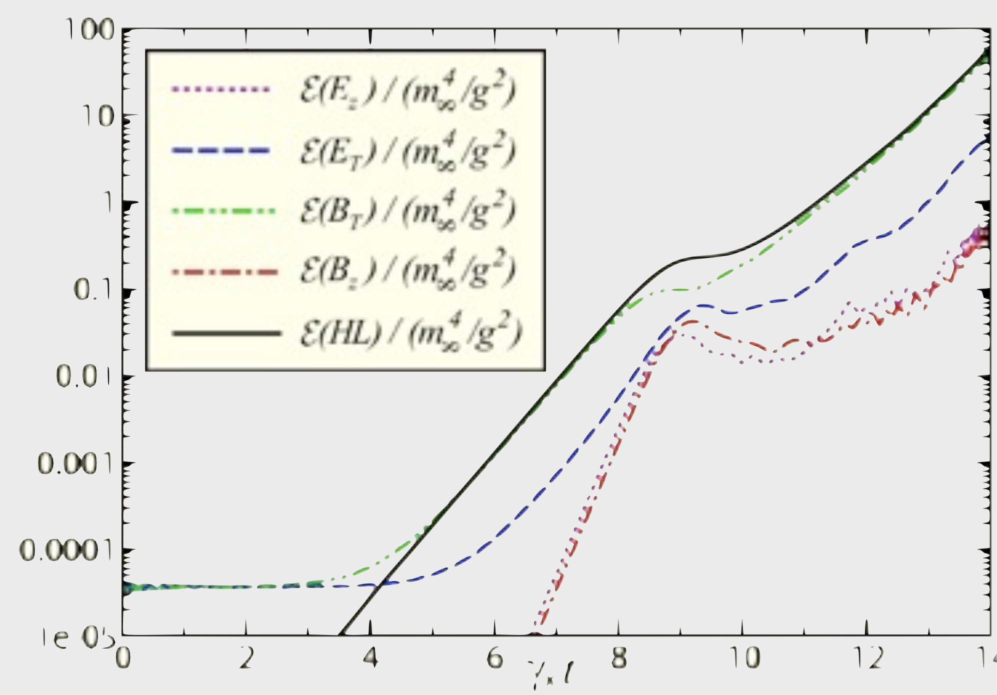
with $J^\nu(x) = \sum_i \int d\tau\, Q_i(\tau)\, u_i^\nu(\tau)\, \delta\left(x - x_i(\tau)\right)$

Effective HTL theory permits systematic study of instabilities of "soft" color fields

find HTL modes for anisotropic distribution:

$$f(\vec{p},\vec{r}) \approx \left(e^{\beta u\cdot p - f_1(\vec{p},\vec{r})} \mp 1\right)^{-1}$$

- for most $f_1 \neq 0$ there exist unstable modes
- energy-density and growth rate of unstable modes can be calculated:



P. Romatschke & M. Strickland, PRD **68**: 036004 (2003)
P. Arnold, J. Lenaghan & G.D. Moore, JHEP **0308**, 002 (2003)
S. Mrowczynski, PLB **314**, 118 (1993)

Anomalous Viscosity Derivation: Sketch

- linear Response: connect η with momentum anisotropy Δ:

$$\eta = -\frac{1}{15T}\int \frac{d^3p}{(2\pi)^3}\frac{\vec{p}^4}{E_P^2}\bar{\Delta}(p)\frac{\partial f_0}{\partial E_p}$$

with $f(\vec{p},\vec{r}) \approx \left(e^{\beta u\cdot p - f_1(\vec{p},\vec{r})} \mp 1\right)^{-1}$

and $f_1(\vec{p},\vec{r}) = -\frac{\bar{\Delta}(p)}{E_p T^2} p_i p_j (\nabla u)_{ij}$

- use color Vlasov-Boltzmann Eqn. to solve for f and Δ:

$$v^\mu \frac{\partial}{\partial x^\mu} f(\vec{r},\vec{p},t) + g\mathbf{F}^a \cdot \nabla_p f^a(\vec{r},\vec{p},t) + C[f] = 0$$

with

$$\mathbf{F}^a = \mathcal{E}^a + \mathbf{v}\times\mathcal{B}^a$$

- turbulent color field assumption:
  - ensemble average over fields:

$$\langle \mathcal{B}_i^a(x) U_{ab}(x,x')\mathcal{B}_j^b(x')\rangle = \langle \mathcal{B}_i^a \mathcal{B}_j^a\rangle\, \Phi_\tau^{(\mathrm{mag})}(|t-t'|)\, \tilde{\Phi}_\sigma^{(\mathrm{mag})}(|\mathbf{x}-\mathbf{x}'|)$$

  ➢ diffusive Vlasov-Boltzmann Eqn: $v^\mu \frac{\partial}{\partial x^\mu}\bar{f} - \nabla_p \cdot D \cdot \nabla_p \bar{f} + C[\bar{f}] = 0$

- example: anomalous viscosity in case of transverse magnetic fields

$$\eta_A^{(g)} = \frac{16\zeta(6)(N_c^2-1)^2}{\pi^2 N_c}\frac{T^6}{g^2\langle\mathcal{B}^2\rangle\,\tau_{\mathrm{m}}^{\mathrm{mag}}} \qquad \eta_A^{(q)} = \frac{62\zeta(6)N_c^2 N_f}{\pi^2}\frac{T^6}{g^2\langle\mathcal{B}^2\rangle\,\tau_{\mathrm{m}}^{\mathrm{mag}}}$$