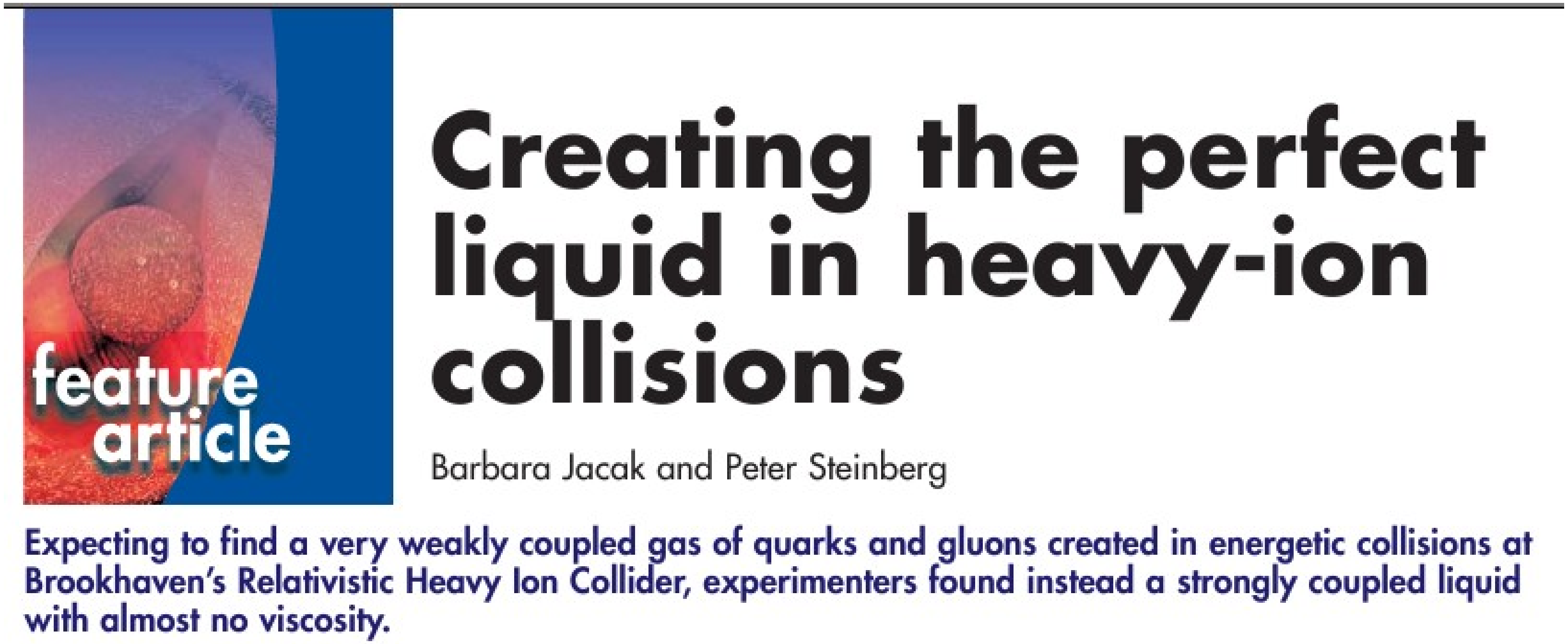
Facets of the QCD Phase Diagram

“Herr Koch, Intelligenz ist die geringste Voraussetzung für wissenschaftlichen Erfolg”
(U. Mosel, 1984)

(“Intelligence is the least prerequisite for scientific sucess”)

Big Scientific Success



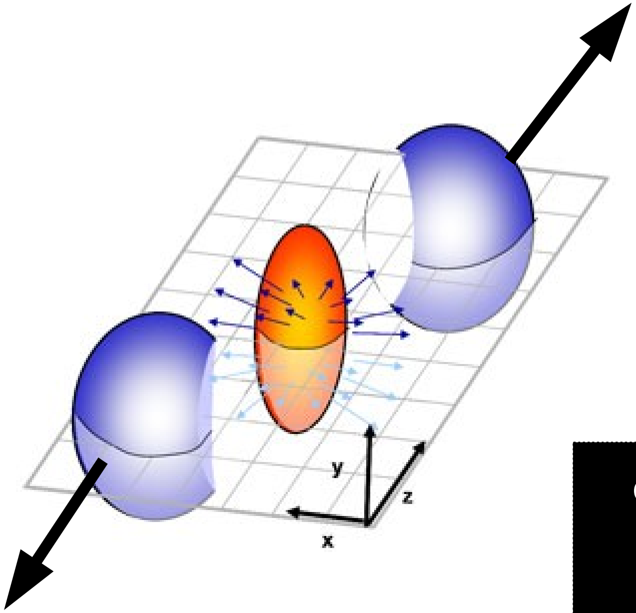
feature article

Creating the perfect liquid in heavy-ion collisions

Barbara Jacak and Peter Steinberg

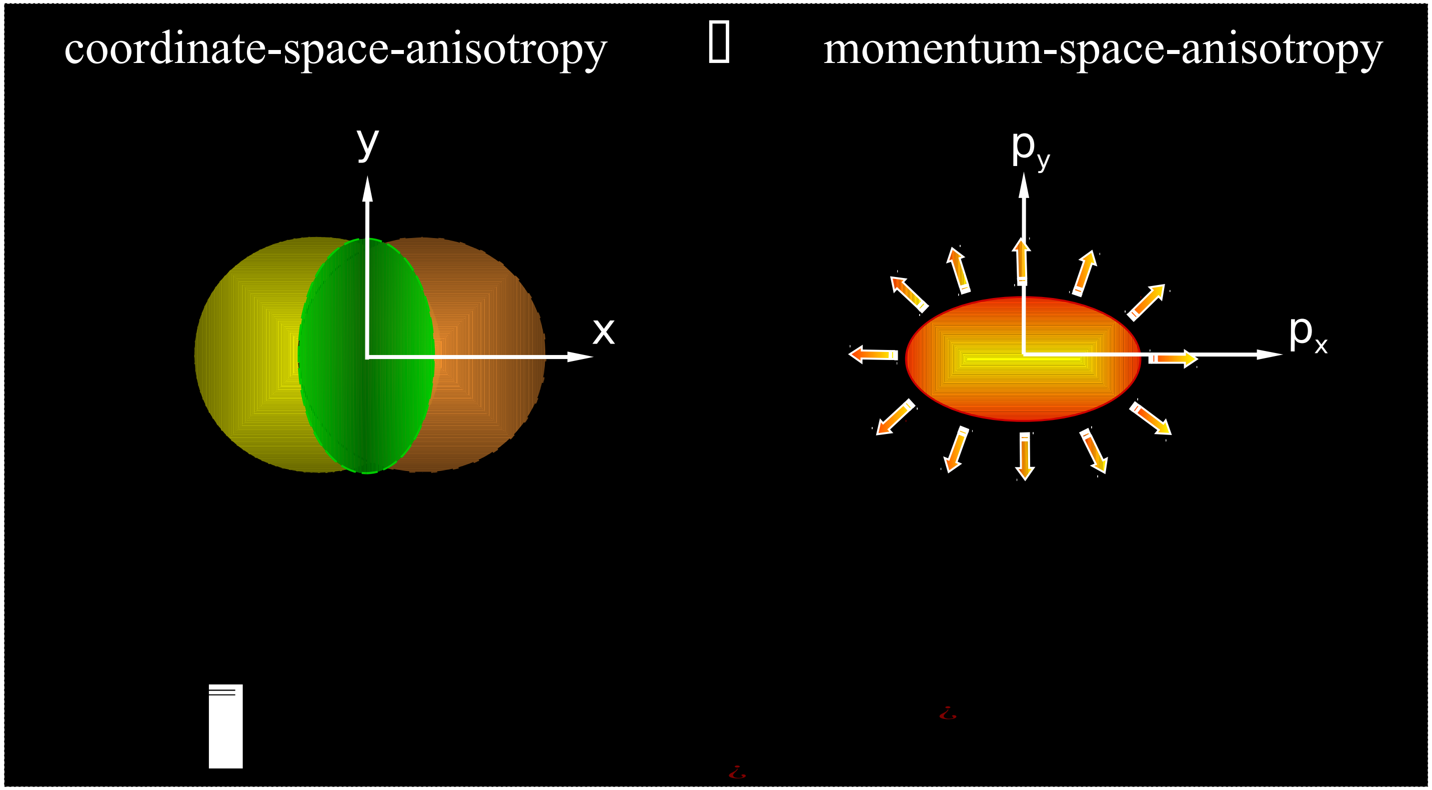
Expecting to find a very weakly coupled gas of quarks and gluons created in energetic collisions at Brookhaven's Relativistic Heavy Ion Collider, experimenters found instead a strongly coupled liquid with almost no viscosity.

Physics Today, May 2010



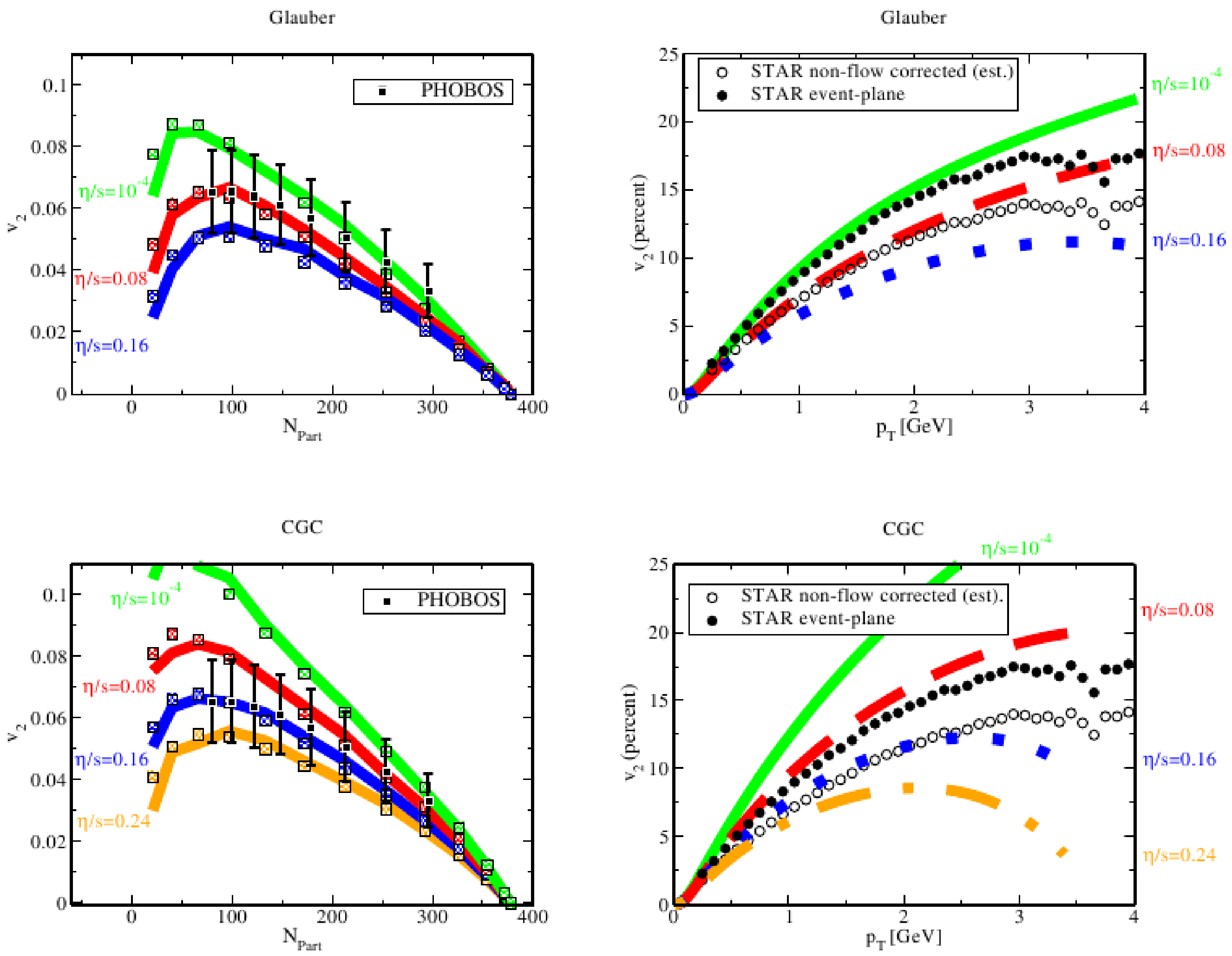
Elliptic Flow

$$\frac{dN}{d\phi\, dp_t} = \frac{dN}{d\, p_t}\left(1 + v_1(p_t)\cos(\phi) + 2\,\underline{v_2(p_t)}\cos(2\,\mathrm{phi}) + \ldots\right)$$



coordinate-space-anisotropy ▯ momentum-space-anisotropy

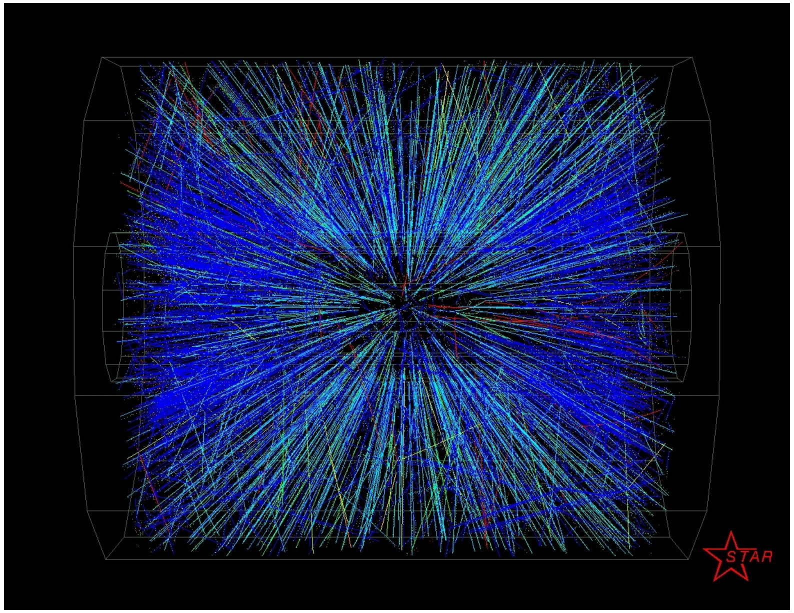
Viscous Hydrodynamics



Romatschke, Luzum, arXiv:0804.4015

The Perfect Liquid?

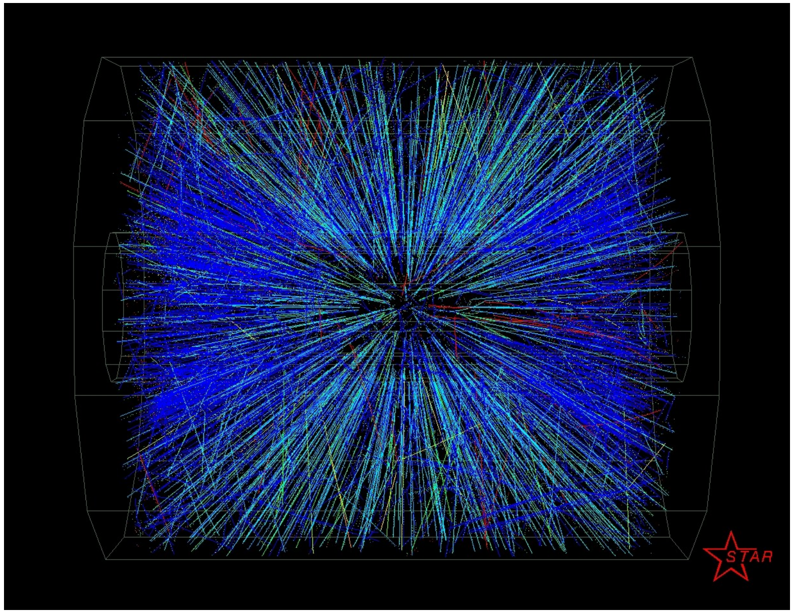
VS



J. Liao and V.K, arXiv:0909.3105,
Phys.Rev.C80:034904,2009.

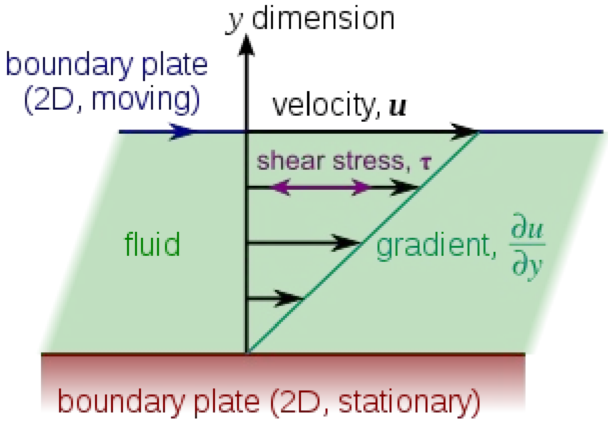
The Perfect Liquid?

VS



J. Liao and V.K, arXiv:0909.3105,
Phys.Rev.C80:034904,2009.

Viscosity

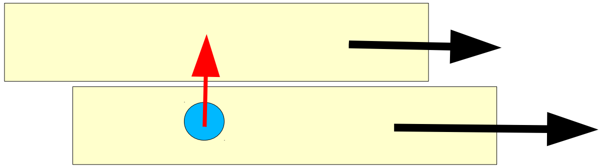


Correction to ideal fluid dynamics

Shear tensor: $\sigma_{i,j}=\eta\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\delta_{i,j}\frac{\partial v_i}{\partial x_i}\right)$

$\eta = shear\ viscosity$

Kinetic theory (dilute gases): Momentum exchange by particle transport



$$\eta \sim n\,\bar{v}\,m\,\lambda$$

$n = density$
$\bar{v} = thermal\ velocity$
$\lambda = mean\ free\ path$

Viscosity ~ mean free path!

Viscosity

Navier Stokes Equation: $\rho\left[\frac{\partial\vec{v}}{\partial t}+(\vec{v}\vec{\nabla})\vec{v}\right]= -\vec{\nabla}p + \eta\nabla^2\vec{v}+\ldots$

"Inertia" "Force" "Friction"

	Viscosity [kg/m s]	Kinematic Viscosity $\nu=\frac{\eta}{\rho}$ [m^2 / s]
Water	0.001	0.10
Air	0.000018	1.5

The kinematic viscosity (friction/inertia) controls how good a fluid is

Minimum viscosity

AdS/CFT correspondence:

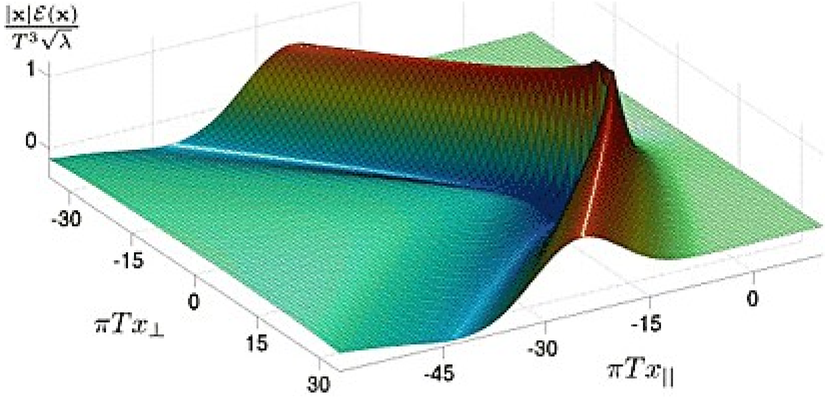
Maldacena et al, hep-th/9905111v3
Kovtun, Son, hep-th/0405231v2

$$\frac{\eta}{s} \geqslant \frac{1}{4\pi}$$

$\eta = shear\ viscosity$

$s = entropy\ density$

Holds for a large class of strongly coupled gauge theories



Kovtun, arXiv:0706.0368

Kinetic theory + waving hands:

$$\eta \sim n \bar{v} m \lambda$$

$$\bar{v} m = p\ , \quad p\lambda > \hbar\ , \quad n \sim s$$

$$\frac{\eta}{n} \sim \frac{\eta}{s} \geqslant 1$$

Quantum bound

More detailed derivation: Danielewcz and Gyulassy (85)

The perfect fluid?

- Is there a quantum bound on eta/s?
- Does the quantum bound provide a limit on fluidity?
- Has RHIC produced such a system? I assume so
- How about other substances
    - Water, Bio Vital, liquid Helium, cold quantum gases???

- How does one define fluidity?
- How do I compare systems on the atomic/molecular scale with those at quark/gluon scale?

Defining Fluidity

Hydrodynamics works for a big variety of systems:

- Liquids (Water)
- Gases (Air, sound)
- Interstellar Dust (Star formation)
- QGP ?

Problem: How to compare substances at vastly different length scales?

- Interstellar Dust: $n^{-1/3} \sim 10^{-4}$ m
- Water: $n^{-1/3} \sim 3\ 10^{-10}$ m
- Air : $n^{-1/3} \sim 3\ 10^{-9}$ m
- QGP : $n^{-1/3} < 10^{-15}$ m

Typical criterion for applicability of fluid dynamics:

Kinetic theory???

Knudsen Number : $$\frac{\textit{Mean Free Path}}{\textit{typical lengthscale of variation}}$$

Different length-scales???

Obviously not what we need

Defining Fluidity

1) Extract “effective mean free path” solely from fluid-dynamics
2) Calibrate with “inter-particle” distance

Effective mean free path:

Analyze sound modes and determine minimum wavelength

$$\omega = c_s k + \frac{i}{2} k^2 \frac{\frac{4}{3}\eta}{w/c^2}$$

Damping ~ k^2:
Hydro always works
in long wavelength limit

Enthalpy density:

$$w = \epsilon + p = Ts + \mu n \approx Ts + m n$$

$w \rightarrow m n$ Non-relativistic limit: **mass** density controls inertia

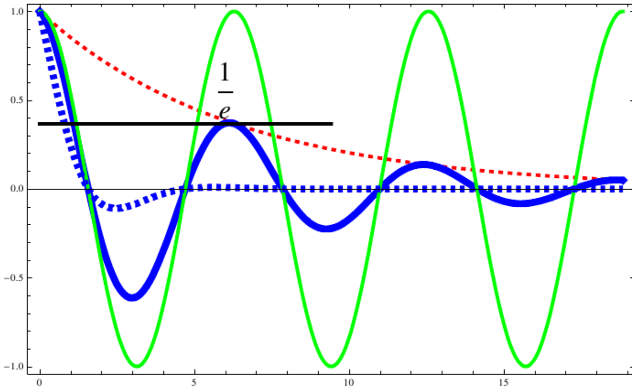
$w \rightarrow Ts$ Relativistic limit: entropy density controls inertia

$\frac{\eta}{s}$ cannot be a universal quality measure

Fluidity measure

Effective mean free path: Analyze sound modes

$$\omega = c_s k + \frac{i}{2} k^2 \frac{\frac{4}{3}\eta}{w/c^2}$$



Require: $$\frac{|\Im(\omega)|}{|\Re(\omega)|} \equiv \frac{L_\eta}{\Lambda} \ll 1$$

Provides a minimal wavelength $\Lambda = L_\eta$

Dilute (kinetic limit): $L_\eta \to \lambda_{mfp}$

Enthalpy density

$$\boxed{L_\eta = \frac{\eta}{w\, c_s}}$$

$$w = \epsilon + p = Ts + \mu n \approx Ts + m n$$

Fluidity measure

$$\boxed{L_\eta = \frac{\eta}{w\, c_s}}$$

Calibrate with “inter-particle distance” d:

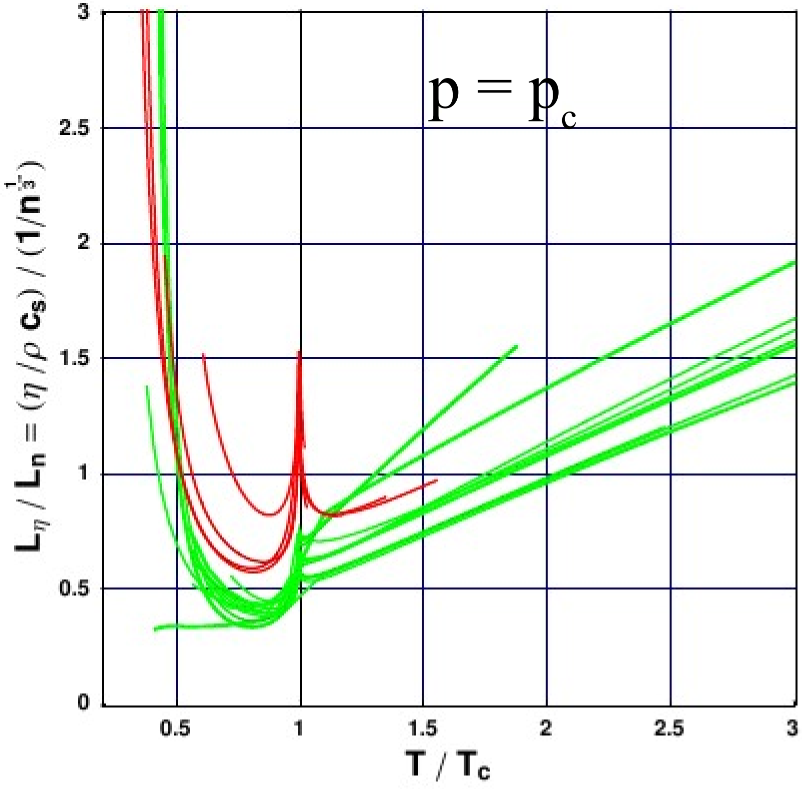
$d \Leftrightarrow \langle \epsilon(x) \epsilon(0) \rangle$ Non-relativistc systems $d = n^{(-1/3)}$

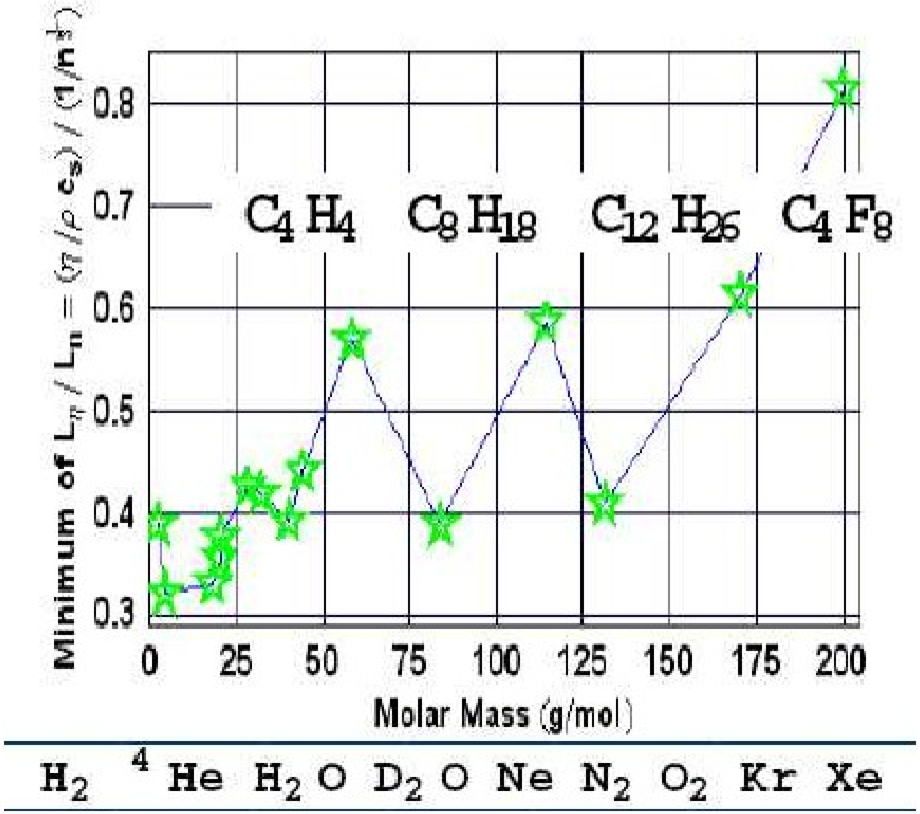
Fluidity measure: $\boxed{F = \frac{L_\eta}{d} = \frac{\eta}{w\, c_s} \frac{1}{d} = \frac{\eta}{w\, c_s} n^{1/3}}$

Depends only on *intrinsic* properties of substance
Well defined: NO kinetic theory needed!

Fluidity measure

16 substances with M_{mol}, T_c, p_c spanning 2 Orders of Magnitude

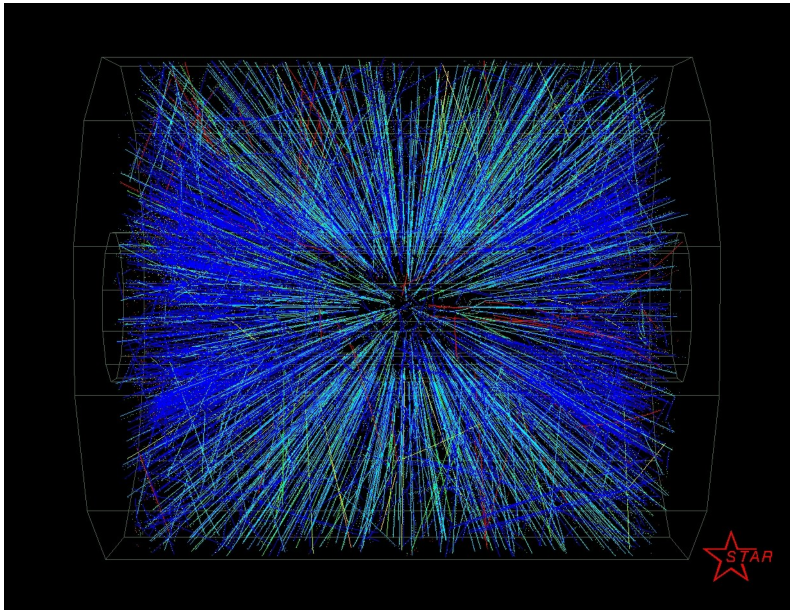




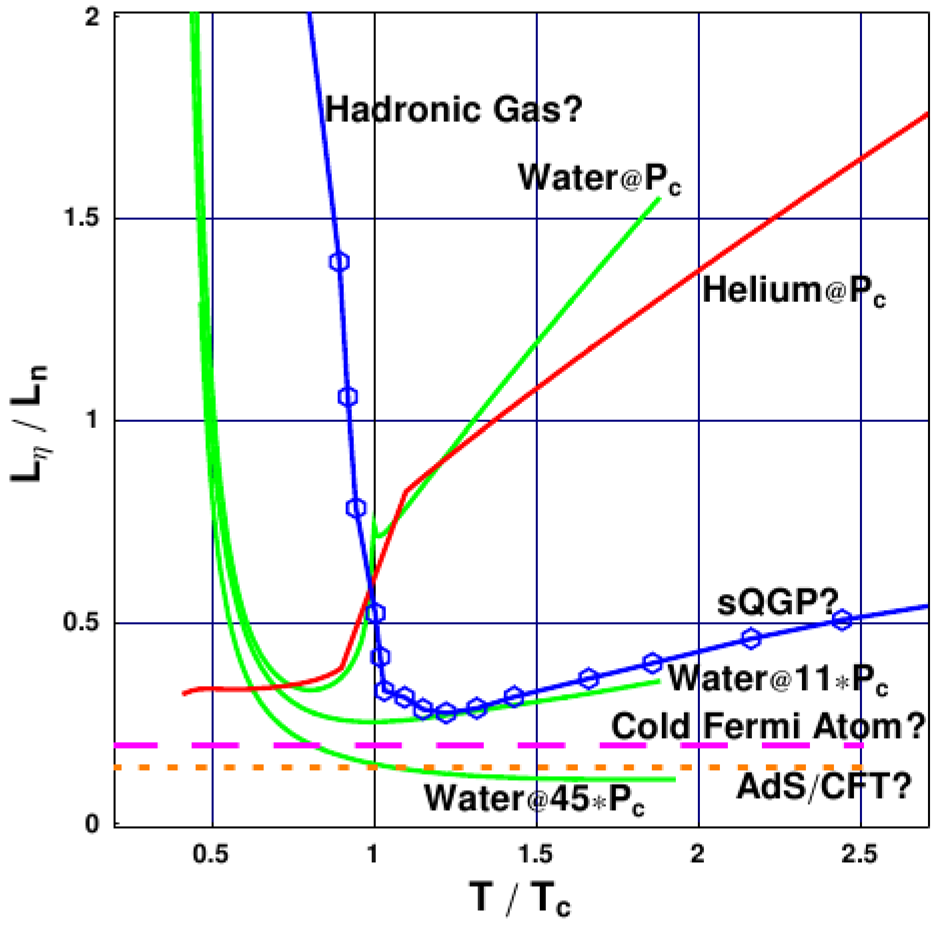
A good fluid is a good fluid!!!!!

So who is the winner?

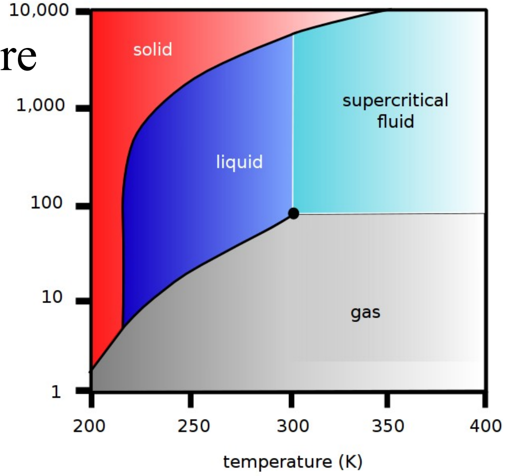
VS



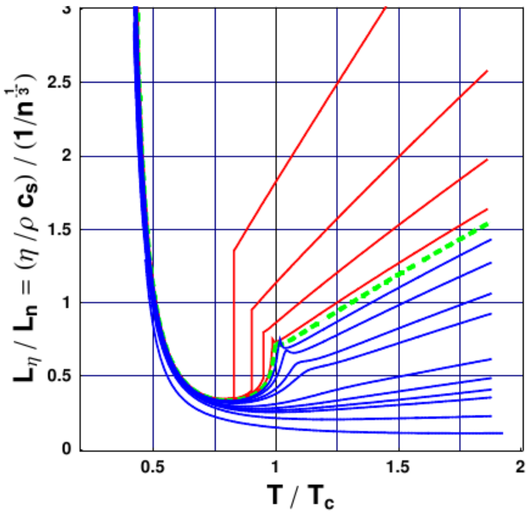
None of the above
Super-critical fluids!!!



pressure



CO_2



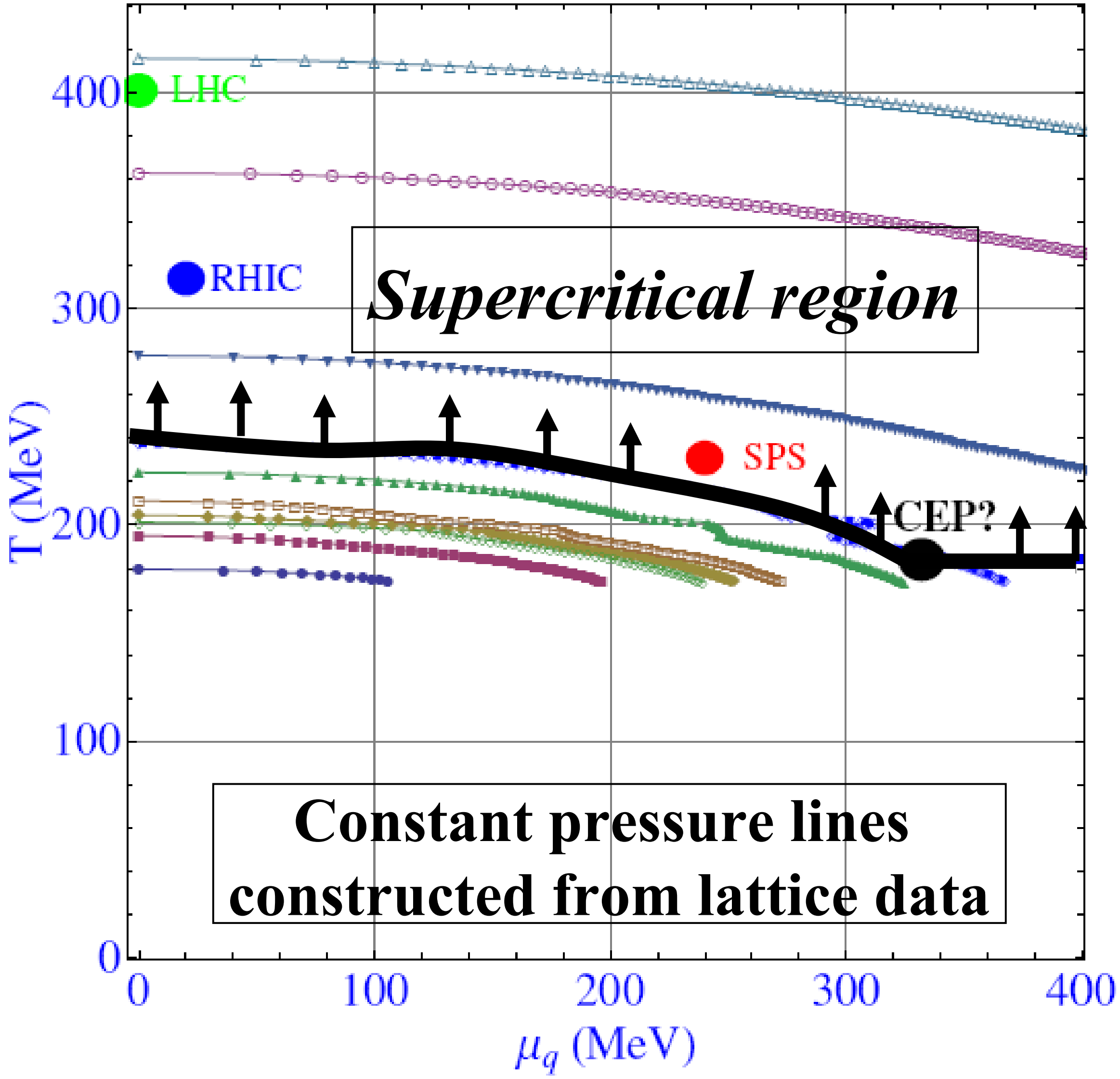
Water

Used in dry cleaning, decaffeinating coffee, ...

An the winner is...

Consequences for the QGP????

RHIC and the Dry-Cleaner



If there is a QCD critical point RHIC-QGP would be in Super critical region

Predict: even better hydro behavior at LHC....

Viscosity comparison

Air:	2×10^{-5} Pa s
Water:	1×10^{-3} Pa s
Tar Pitch:	2×10^{8} Pa s
QGP:	2×10^{9} Pa s

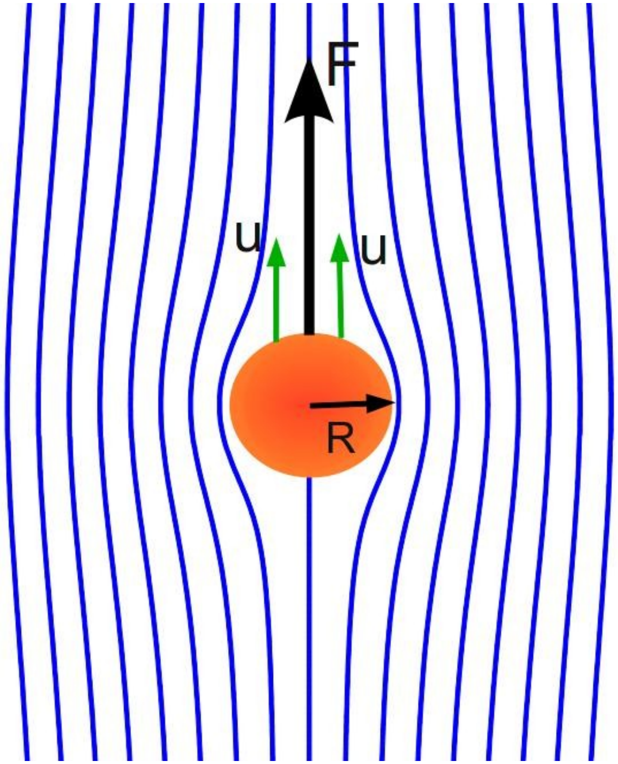
Ig-Nobel, 2005

$$\eta_{\mathrm{QGP}} \simeq 10^{12}\, \eta_{\mathrm{Water}}$$

Stirring the QGP

Stokes' Formula

$$F = 6\pi R u \,\eta$$



$$\eta_{QGP} \simeq 10^{12}\,\eta_{Water}$$

Rescale the sphere (spoon)

$$R_{QGP} \simeq 10^{-6} R_{Water}$$

$$F_{QGP} \simeq 10^{6} F_{Water}$$

What have learned so far

- Universal Fluidity Measure $F = \frac{\eta}{w\, c_s} \frac{1}{d}$
- A good fluid is a good fluid
  - Gives F=0 for super-fluid component of ^{4}He !
  - Works also for academic cases a la Cohen et al.
- QGP nothing special
  - However, very sticky when stirred
- eta/s dimensionless and meaningless
- Supercritical fluids win the race
- QGP may be a supercritical fluid
  - Predict better hydro description at LHC

And what does Lattice QCD say?

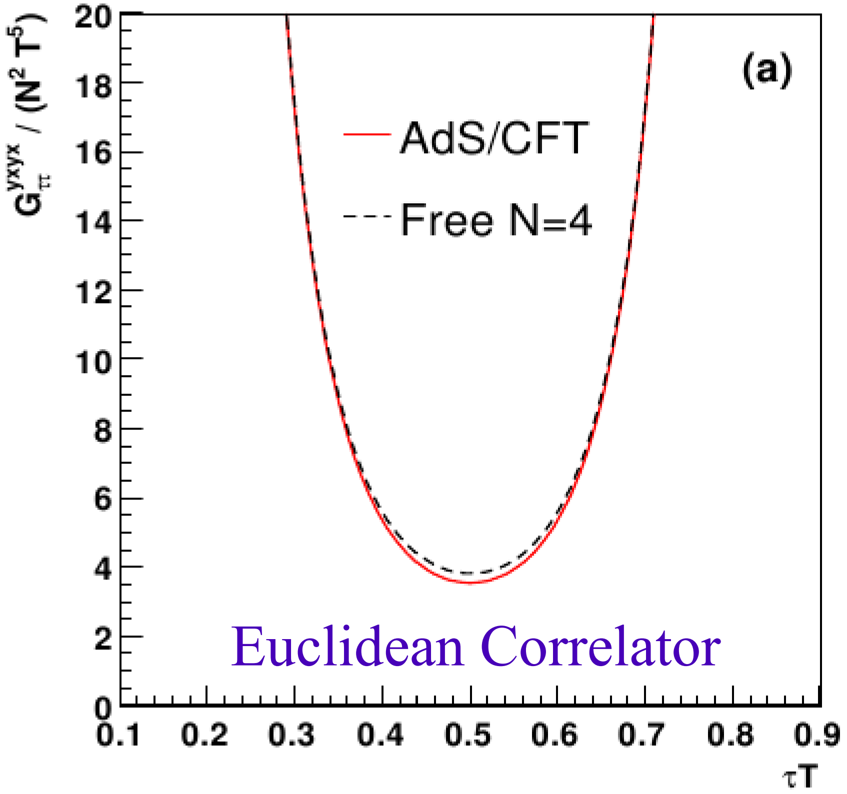
- Mixed message
  - Shear viscosity difficult to extract (time like)
    - Requires analytic continuation to real time...
  - No or very weak correlations among quarks above T_c (weak coupling ?)
  - Some indications for liquid behavior in pure glue

Euclidean Space Correlator

$$\eta = -\frac{d}{d\omega} Im\Pi^R|_{\omega=0^+} \qquad \Pi^R \sim \int e^{-i\omega t}\langle[T_{xy}(t), T_{xy}(0)]\rangle$$

Viscosity results from <u>time-like</u> correlator

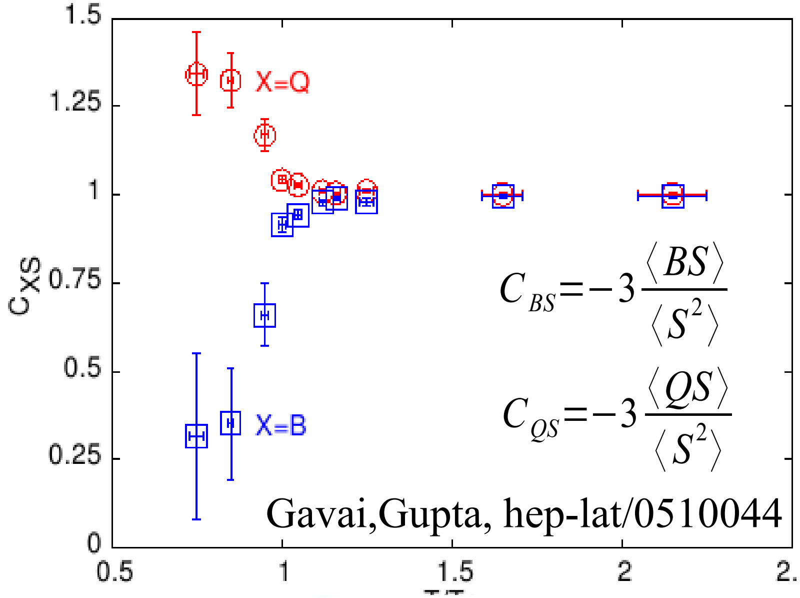
$$\langle T_{xy}(\tau) T_{xy}(0)\rangle$$



D. Teaney
Phys.Rev.D74:045025,2006.
hep-ph/0602044

Difficult to distinguish between FREE and Strongly interacting in <u>Euclidean</u> Space

Evidence for uncorrelated flavor (quarks)

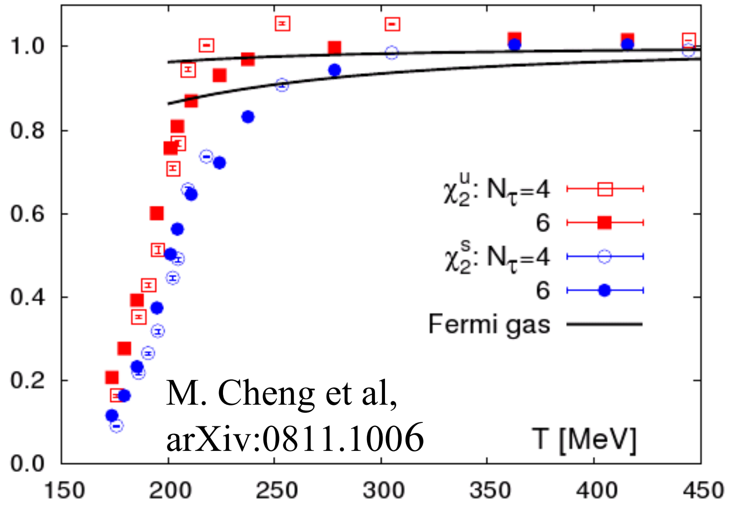


$$C_{BS}=-3\frac{\langle BS\rangle}{\langle S^2\rangle}$$

$$C_{QS}=-3\frac{\langle QS\rangle}{\langle S^2\rangle}$$

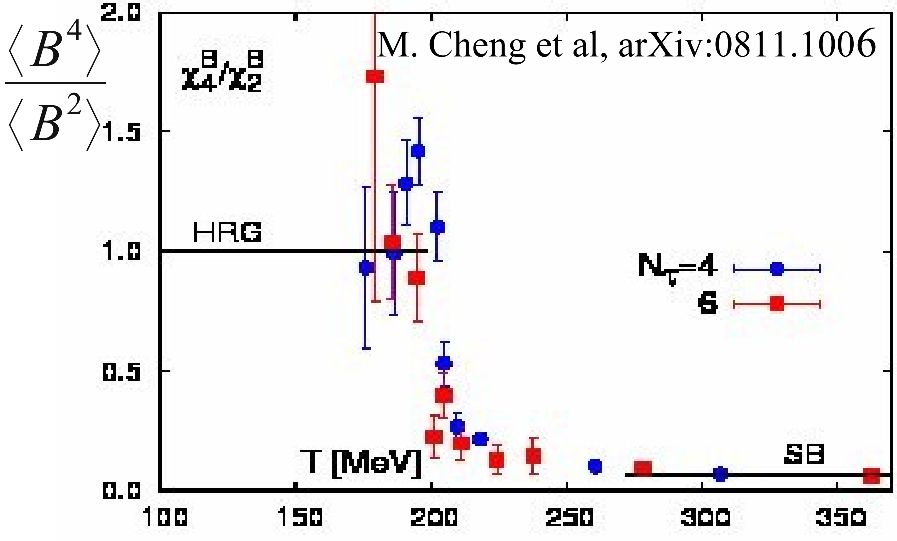
Gavai,Gupta, hep-lat/0510044

Quark Number susceptibility



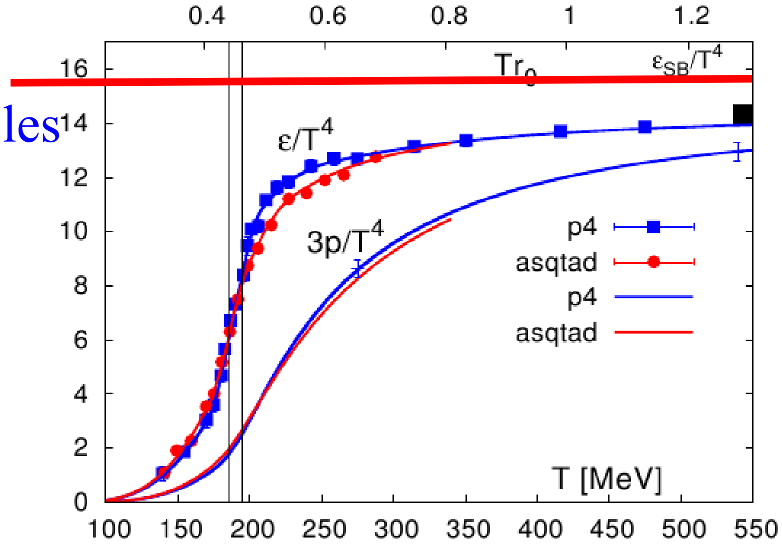
M. Cheng et al, arXiv:0811.1006

Free particles



M. Cheng et al, arXiv:0811.1006

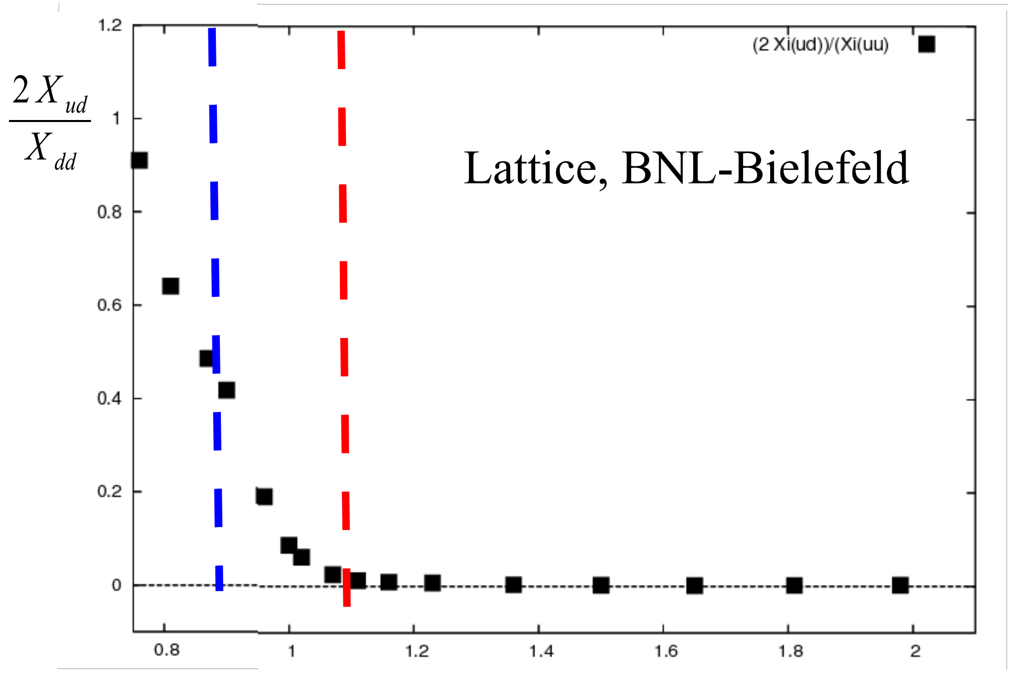
Free particles



Correlations

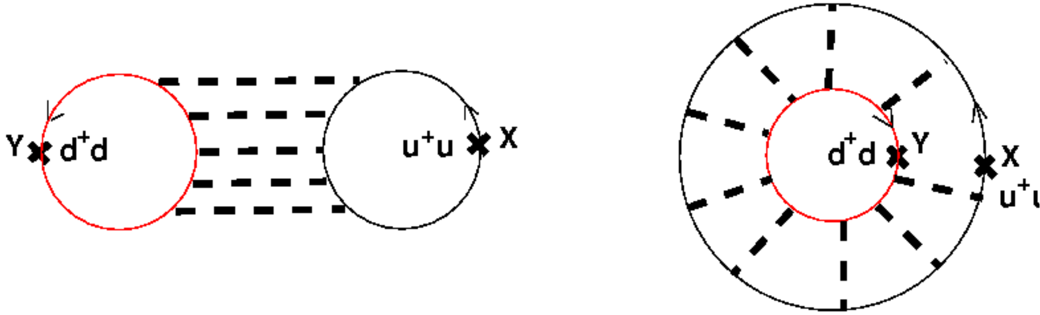
off-diagonal
Susceptibilities

$$\chi_{ud} = \langle (\delta u)(\delta d) \rangle = T^2 \frac{\partial^2}{\partial \mu_u \partial \mu_d} \log(Z) = -T \frac{\partial^2}{\partial \mu_u \partial \mu_d} F$$



Lattice, BNL-Bielefeld

1.1 T_c



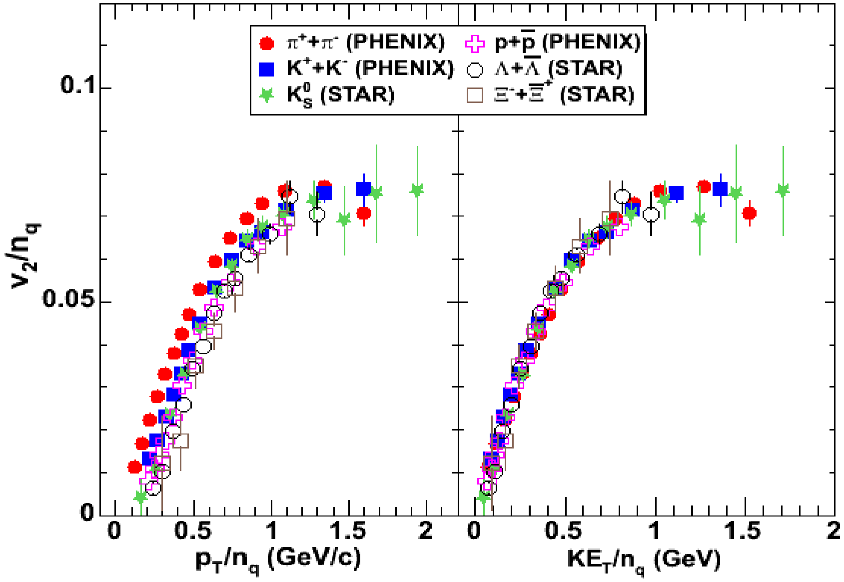
Weak Correlations above 1.1 T_c

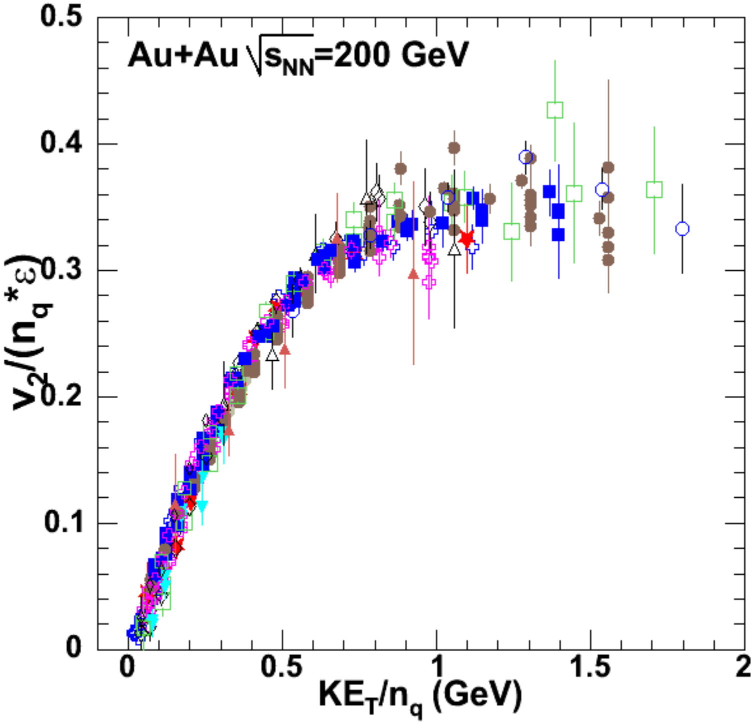
Consistent with hadron gas for T<0.9 T_c

Consistent with quark number scaling of elliptic flow v_2

Elliptic Flow
(quark number scaling)

works even
for the pions???





Coalescence (recombination): $\frac{dN}{d\phi}(\bar{q}\,q) = \frac{dN}{d\phi}(\bar{q})\frac{dN}{d\phi}(q) \sim (1+2v_2\cos(\phi))(1+2v_2\cos(\phi))$

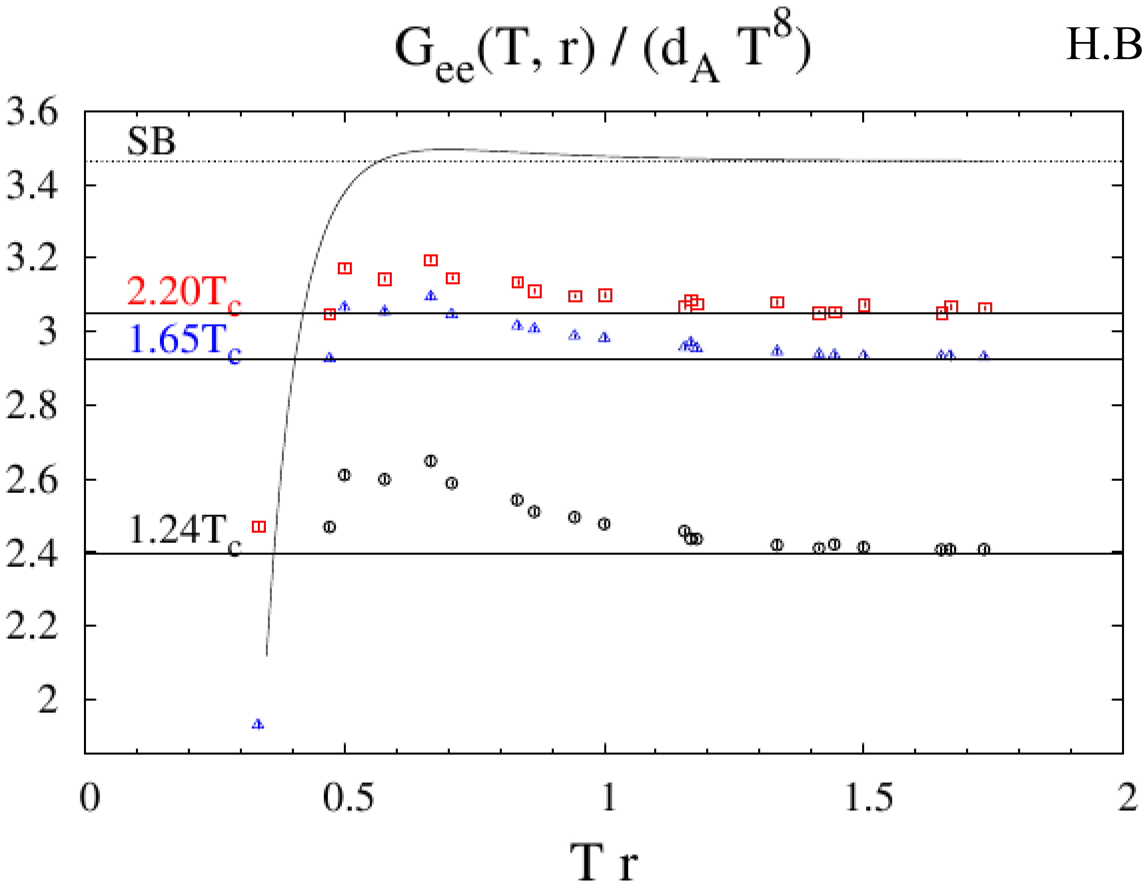
$$\sim(1+4v_2\cos(\phi))$$

$$\underline{\rightarrow v_2(\bar{q}\,q)=2v_2}$$

$v_2 = n_q\, v_2{}^0$
quark number scaling

Density-Density correlator in pure Glue

H.B. Meyer, arXiv:0808.1950

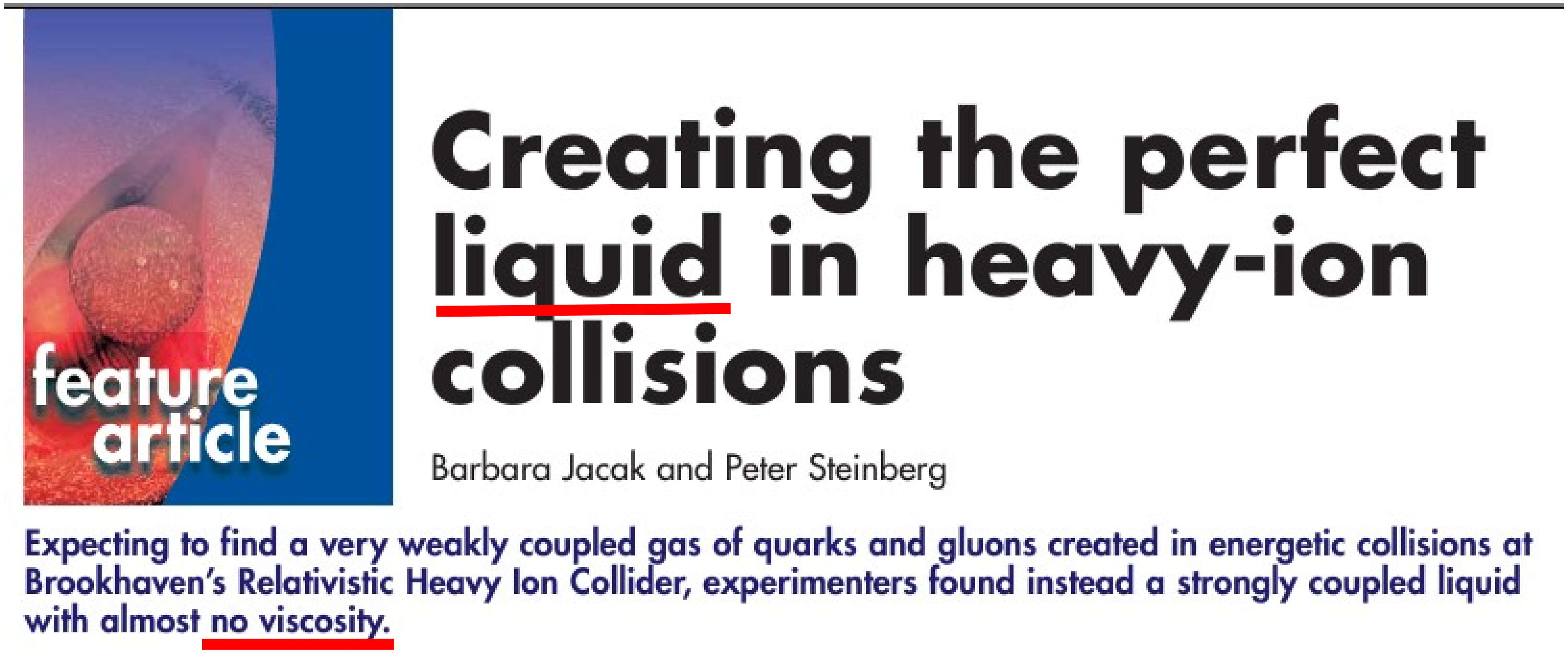


Not inconsistent with liquid like behaviour...

Summary

- The RHIC fluid
    - Fluidity of the RHIC “fluid” is nothing special
        - However very sticky when stirred
    - A good fluid is a good fluid
    - Is RHIC fluid in the super-critical regime?
        - If so, hydro should work even better at LHC
    - QGP has HUGE viscosity

    - Lattice input
        - Very weak flavor correlations just above T_c .
            - Strong coupling???
        - Difficult to extract viscosity
        - Density-Density correlator for pure glue show some structure

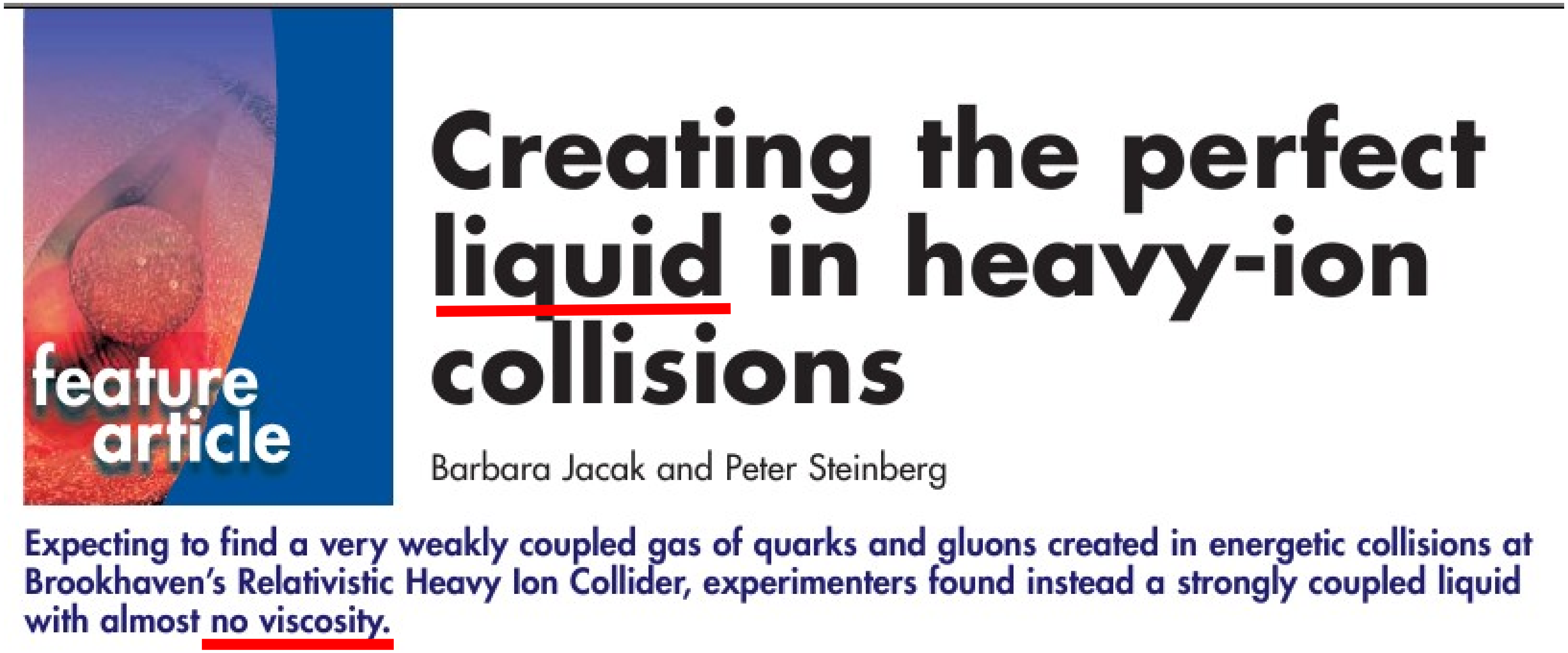


Creating the perfect liquid in heavy-ion collisions

Barbara Jacak and Peter Steinberg

Expecting to find a very weakly coupled gas of quarks and gluons created in energetic collisions at Brookhaven's Relativistic Heavy Ion Collider, experimenters found instead a strongly coupled liquid with almost no viscosity.

Physics Today, May 2010



feature article

Creating the perfect liquid in heavy-ion collisions

Barbara Jacak and Peter Steinberg

Expecting to find a very weakly coupled gas of quarks and gluons created in energetic collisions at Brookhaven's Relativistic Heavy Ion Collider, experimenters found instead a strongly coupled liquid with almost no viscosity.

Ulrich's advise was not so bad!

Live long and prosper!

The End