Nearly Perfect Fluidity: From Cold Atoms to Hot Quarks

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RHIC serves the perfect fluid

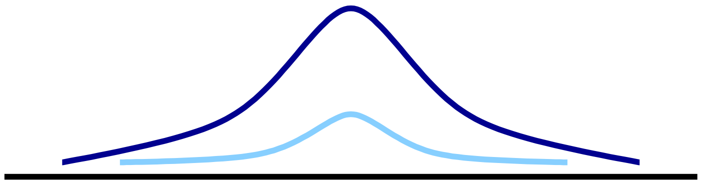
Experiments at RHIC are consistent with the idea that a thermalized plasma is produced, and that the equation of state is that of a weakly coupled gas of quarks and gluons.

But: Transport properties of the system (primarily viscosity and energy loss) are in dramatic disagreement with expectations for a weakly coupled QGP. The plasma must be very strongly coupled.

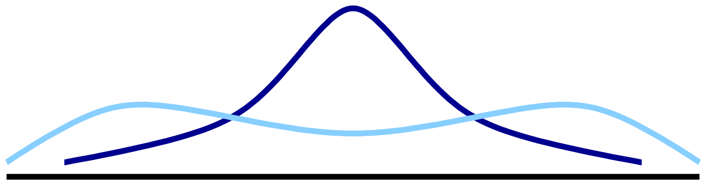
In this talk I will try to explain this statement, review the current evidence (including data from the LHC), and put the results in a broader perspective (by comparing with another strongly coupled fluid, the dilute atomic Fermi gas at "unitarity").

Fluids: Gases, liquids, plasmas, . . .

Hydrodynamics: Long-wavelength, low-frequency dynamics of conserved charges (or spontaneously broken symmetry fields).



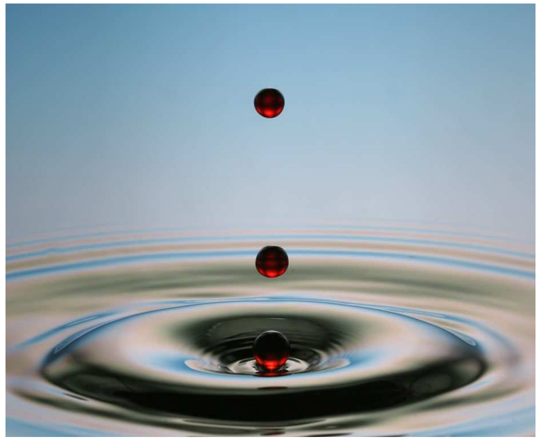
$\tau \sim \tau_{micro}$



$\tau \sim \lambda$

Historically: Water

$(\rho, \epsilon, \vec{\pi})$



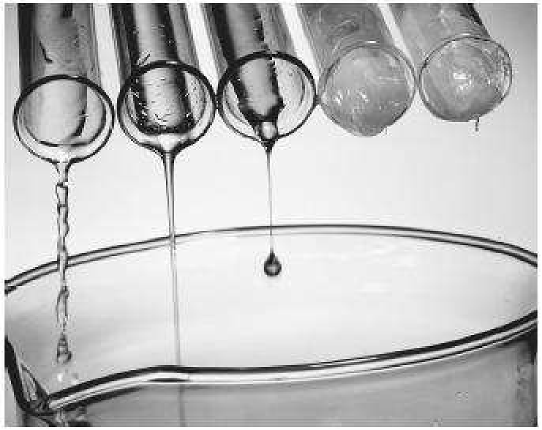
Simple non-relativistic fluid

Simple fluid: Conservation laws for mass, energy, momentum

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0$$

$$\frac{\partial \epsilon}{\partial t} + \vec{\nabla} \vec{j}^{\epsilon} = 0$$

$$\frac{\partial}{\partial t}(\rho v_i) + \nabla_j \Pi_{ij} = 0$$



Constitutive relations: Stress tensor

$$\Pi_{ij} = P\delta_{ij} + \rho v_i v_j + \eta \left(\nabla_i v_j + \nabla_j v_i - \frac{2}{3}\delta_{ij} \nabla_k v_k \right) + O(\nabla^2)$$

reactive dissipative 2nd order

Expansion $\Pi^0_{ij} \gg \delta\Pi^1_{ij} \gg \delta\Pi^2_{ij}$

Regime of applicability

Expansion parameter $Re^{-1} = \frac{\eta(\partial v)}{\rho v^2} = \frac{\eta}{\rho L v} \ll 1$

$$\frac{1}{Re} = \underbrace{\frac{\eta}{\hbar n}}_{\substack{\text{fluid}\\ \text{property}}} \times \underbrace{\frac{\hbar}{mvL}}_{\substack{\text{flow}\\ \text{property}}}$$

$$\begin{array}{lll} \text{Bath tub}: & mvL \gg \hbar & \text{hydro reliable} \\ \text{Heavy ions}: & mvL \sim \hbar & \text{need } \ \eta < \hbar n \end{array}$$

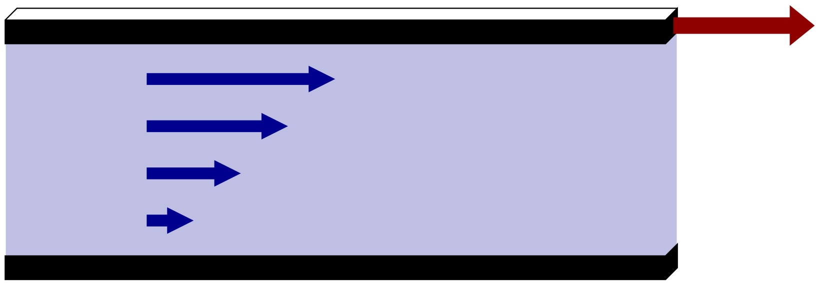
Shear viscosity and friction

Momentum conservation at $O(\nabla v)$

$$\rho\left(\frac{\partial}{\partial t}\vec{v} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right) = -\vec{\nabla}P + \eta\nabla^2\vec{v}$$

Navier-Stokes equation

Viscosity determines shear stress ("friction") in fluid flow



$$F = A\,\eta\,\frac{\partial v_x}{\partial y}$$

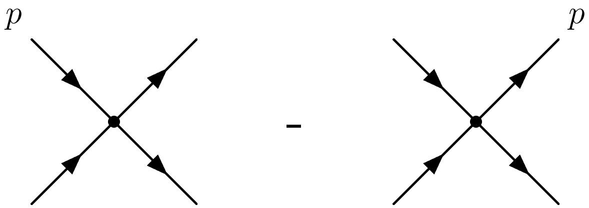
Kinetic theory

Kinetic theory: conserved quantities carried by quasi-particles.

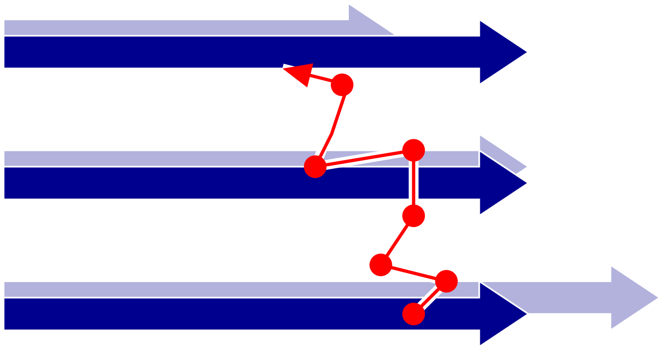
Quasi-particles described by distribution functions $f(x, p, t)$.

$$\frac{\partial f_p}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f_p + \vec{F} \cdot \vec{\nabla}_p f_p = -C[f_p]$$

$$C[f_p] \;=$$



Shear viscosity corresponds to momentum diffusion



$$\eta \sim \frac{1}{3} n \, \bar{p} \, l_{mfp}$$

Shear viscosity: Additional properties

Weakly interacting gas, $l_{mfp} \sim \frac{1}{n\sigma}$:

$$\boxed{\eta \sim \frac{1}{3}\frac{\bar{p}}{\sigma}}$$

shear viscosity independent of density

Non-interacting gas $(\sigma \to 0)$:

$$\boxed{\eta \to \infty}$$

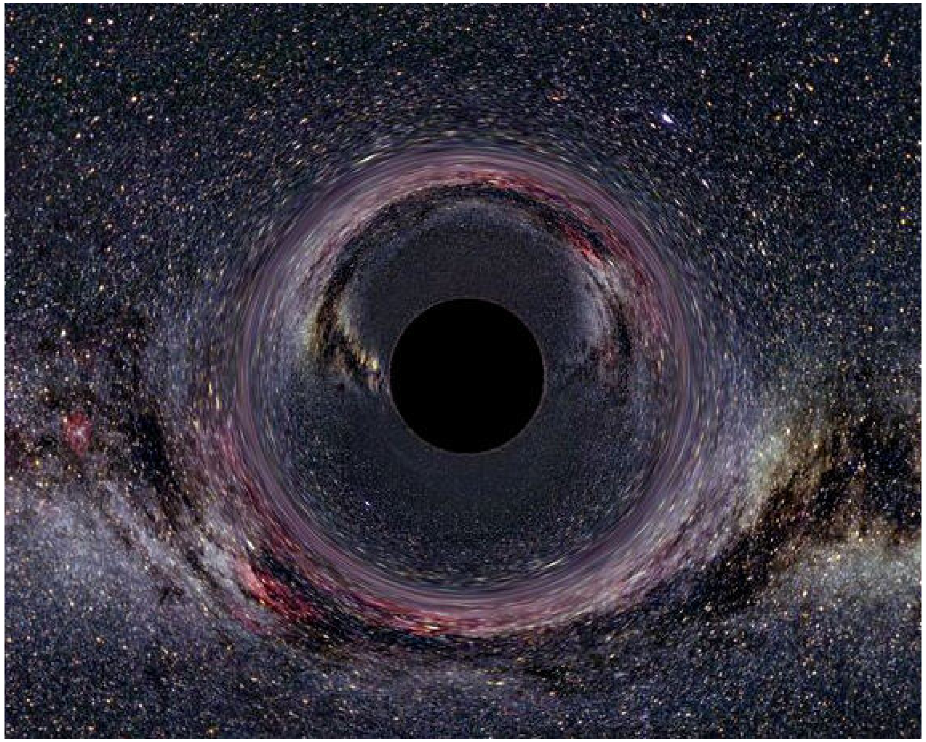
non-interacting and hydro limit $(T \to \infty)$ limit do not commute

strongly interacting gas:

$$\boxed{\frac{\eta}{n} \sim \bar{p} l_{mfp} \geq \hbar}$$

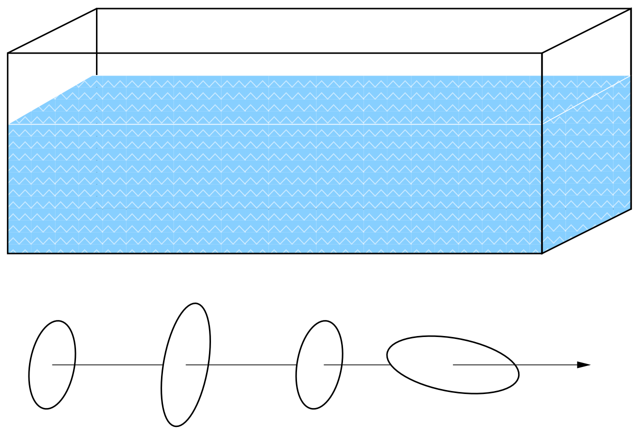
but: kinetic theory not reliable!

And now for something completely different . . .

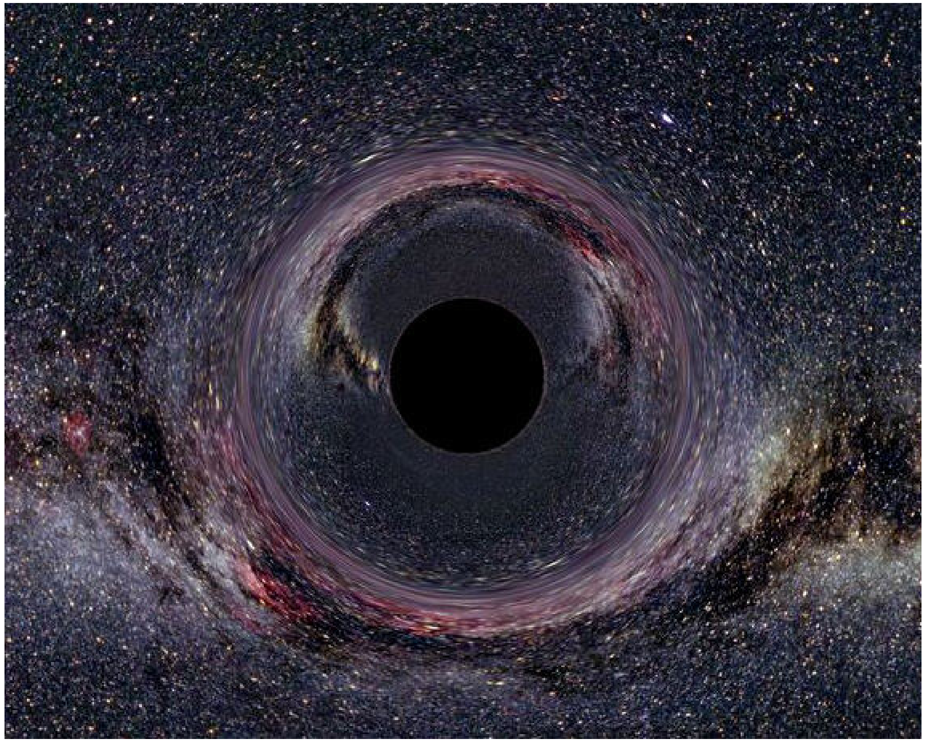


This is an irreversible process, $\Delta S > 0$.

And now for something completely different . . .

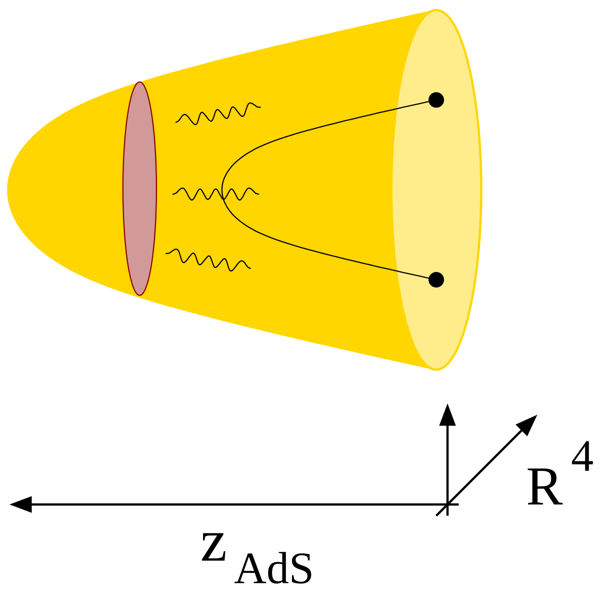


gravitational wave shears fluid



Idea can be made precise using the "AdS/CFT correspondence"

Strongly coupled thermal field theory on R^4	$\Leftrightarrow$	Weakly coupled string theory on AdS_5 black hole
CFT temperature	$\Leftrightarrow$	Hawking temperature of black hole
CFT entropy	$\Leftrightarrow$	Hawking-Bekenstein entropy $\sim$ area of event horizon



Holographic duals: Transport properties

Thermal (conformal) field theory $\equiv$ AdS_5 black hole

CFT entropy $\Leftrightarrow$ Hawking-Bekenstein entropy

$\sim$ area of event horizon

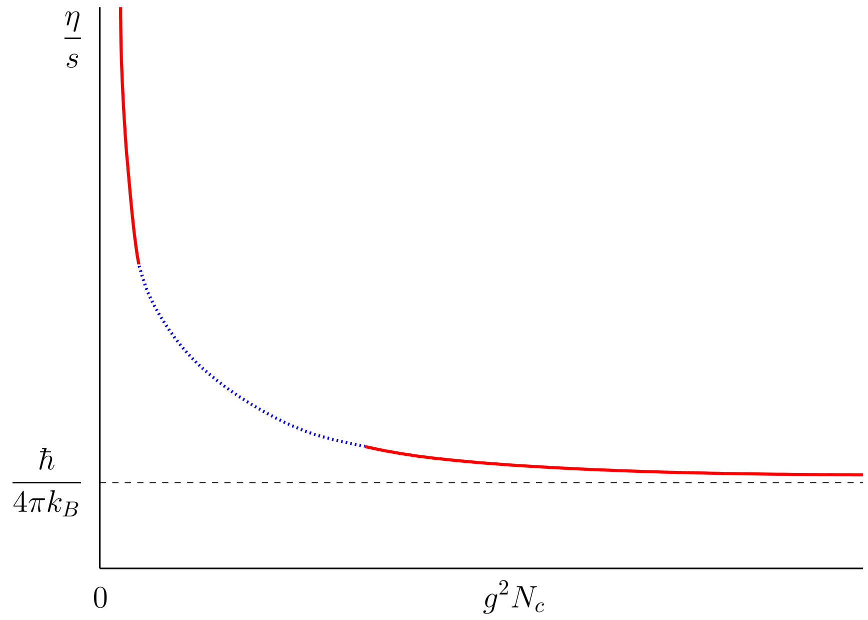
shear viscosity $\Leftrightarrow$ Graviton absorption cross section

$\sim$ area of event horizon

Strong coupling limit

$$\boxed{\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}}$$

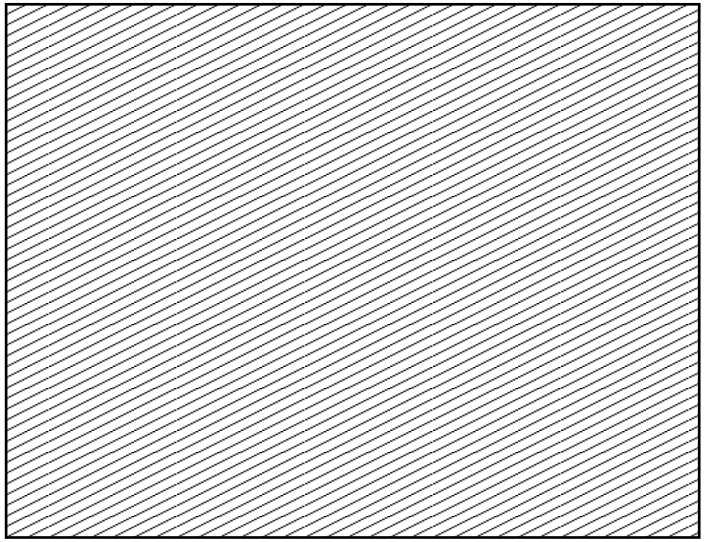
Son and Starinets (2001)

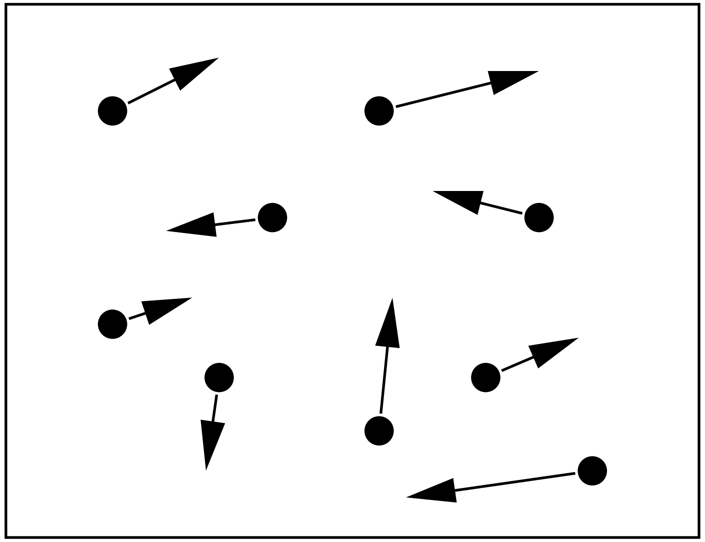


Strong coupling limit universal? Provides lower bound for all theories?

Answer appears to be no; e.g. theories with higher derivative gravity duals.

Kinetics vs no-kinetics





low viscosity goo

gravity dual

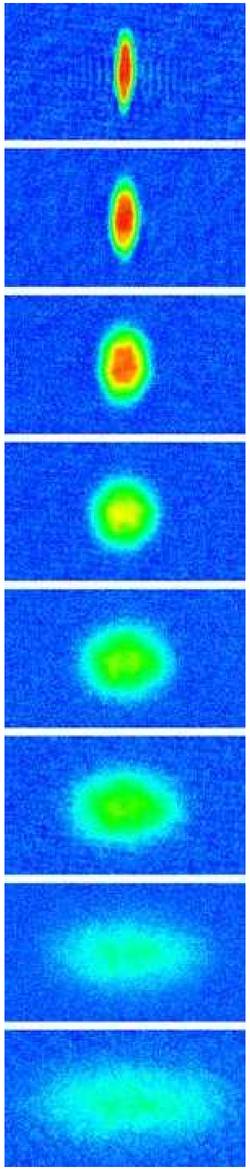
$\eta/s \simeq 1/(4\pi)$

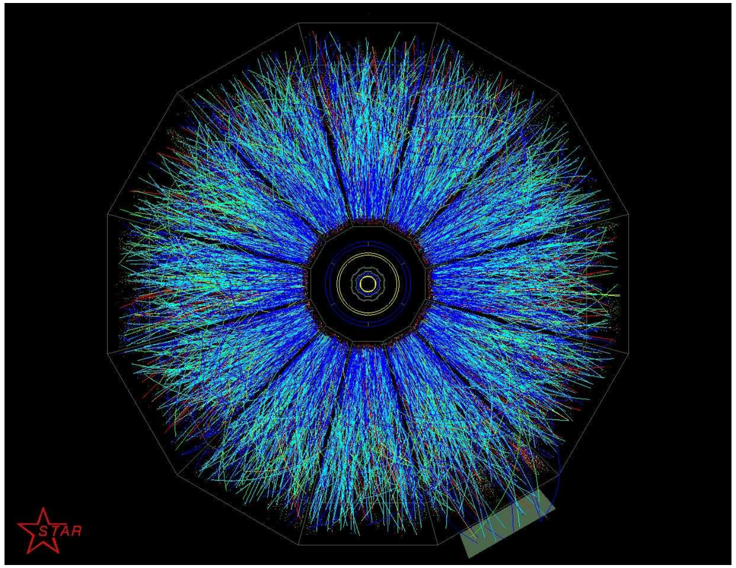
pQCD plasma

quasi-particles

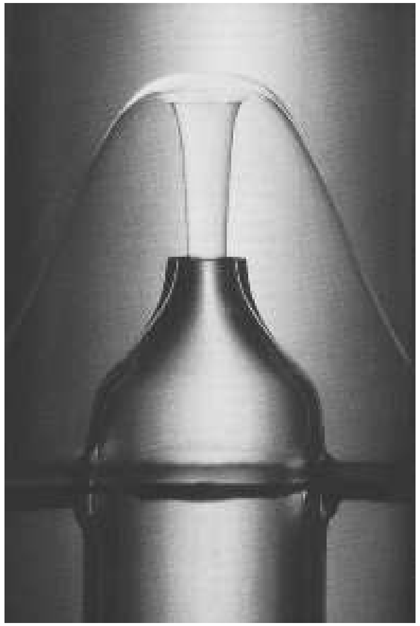
$\eta/s \sim 1/\alpha_s^2 \gg 1$

Perfect Fluids: The contenders





QGP (T=180 MeV)



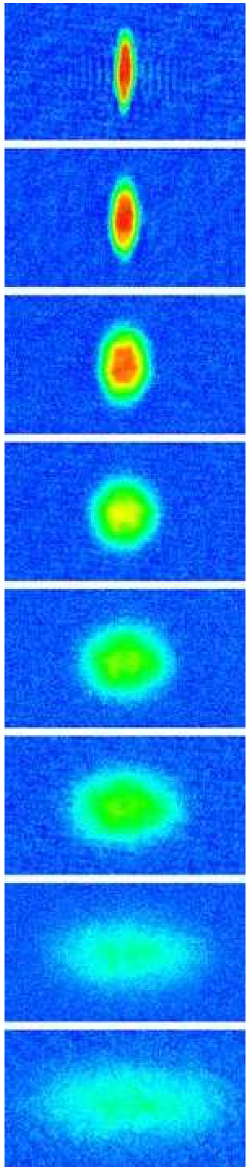
Liquid Helium

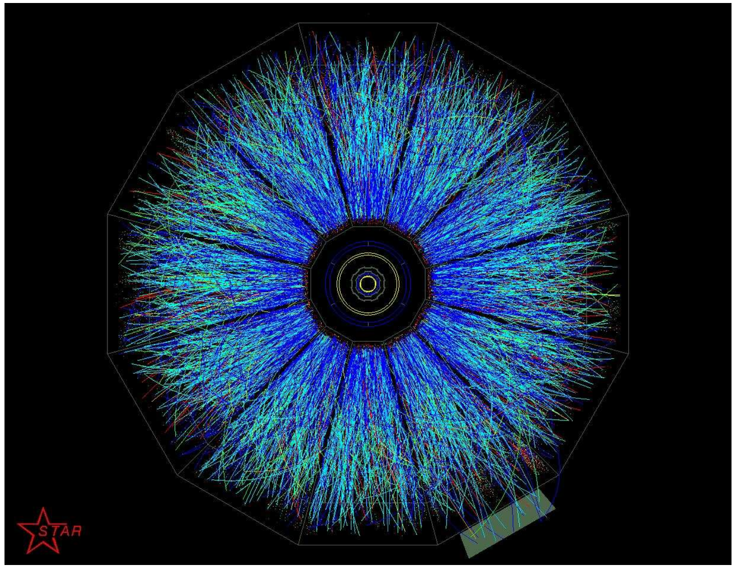
(T=0.1 meV)

Trapped Atoms

(T=0.1 neV)

Perfect Fluids: The contenders

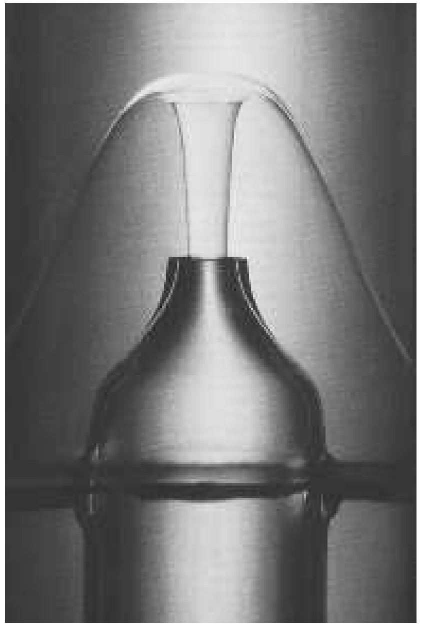




QGP $\eta = 5 \cdot 10^{11} Pa \cdot s$

Trapped Atoms

$\eta = 1.7 \cdot 10^{-15} Pa \cdot s$



Liquid Helium

$\eta = 1.7 \cdot 10^{-6} Pa \cdot s$

Consider ratios

η / s

Perfect Fluids: Not a contender

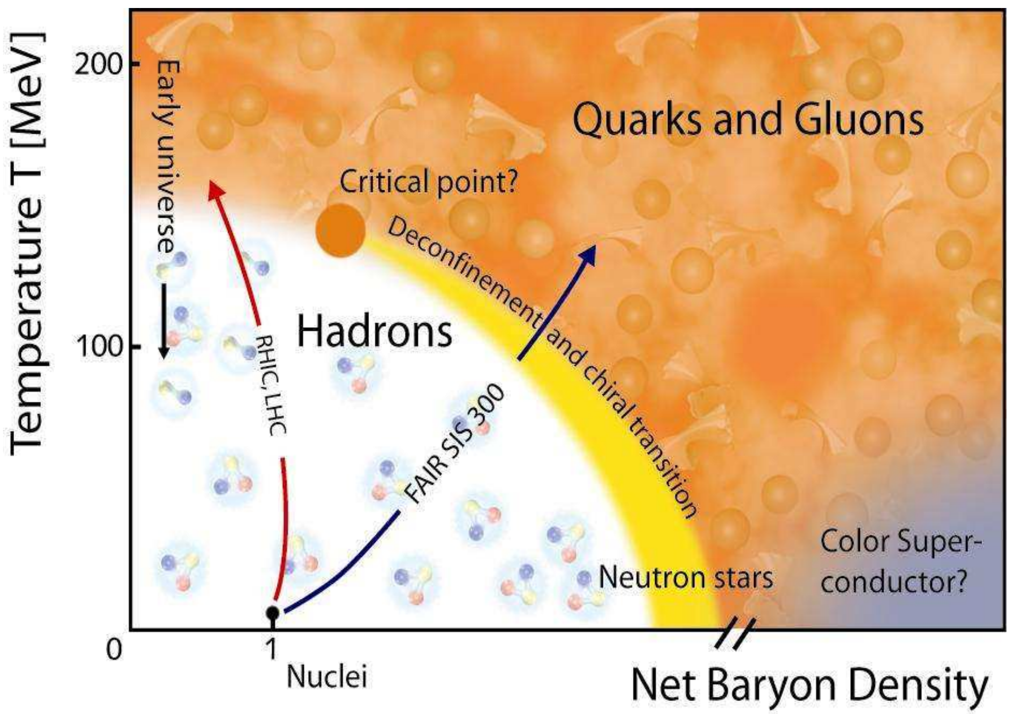
Queensland pitch-drop experiment

1927-2011 (8 drops)

$$\eta = (2.3 \pm 0.5) \cdot 10^8 \; Pa\, s$$

I. QCD and the Quark Gluon Plasma

$$\boxed{\mathcal{L} = \bar{q}_f(i\not{D} - m_f)q_f - \frac{1}{4g^2}G^a_{\mu\nu}G^a_{\mu\nu}}$$



Quantumchromodynamics (QCD)

Elementary fields: **Quarks** **Gluons**

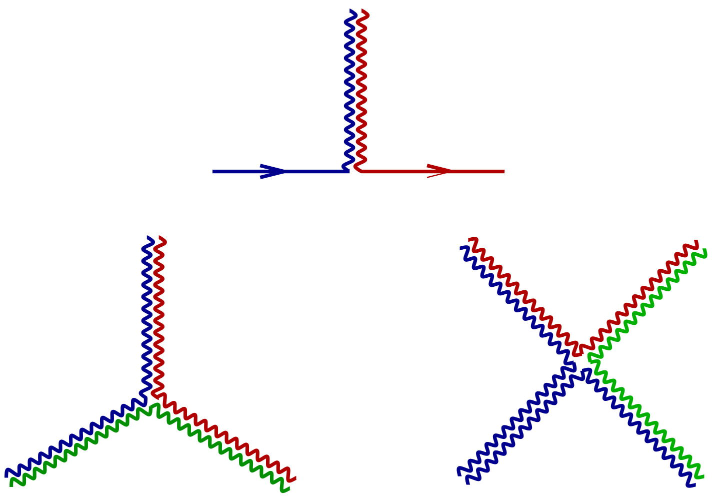
$$(q_\alpha)^a_f \begin{cases} \text{color} & a = 1, \ldots, 3 \\ \text{spin} & \alpha = 1, 2 \\ \text{flavor} & f = u, d, s, c, b, t \end{cases} \qquad A^a_\mu \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}$$

Dynamics: Generalized Maxwell (Yang-Mills) + Dirac theory

$$\boxed{\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

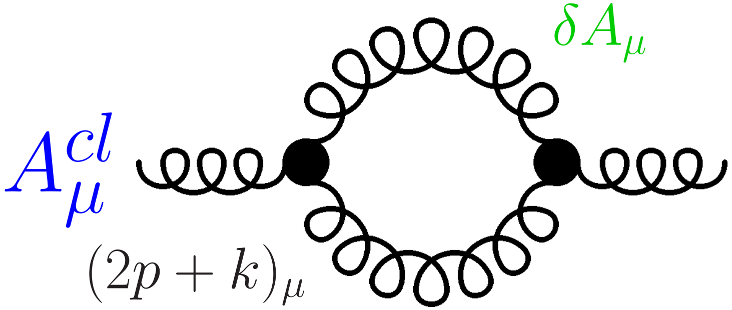
$$i\not{D} q = \gamma^\mu \left(i\partial_\mu + g A^a_\mu t^a \right) q$$



Asymptotic freedom

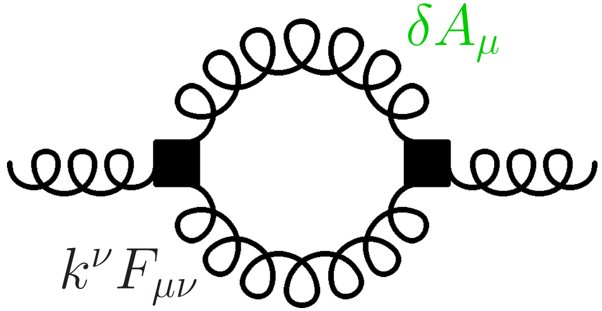
Modification of Coulomb interaction due to quantum fluctuations

electric gluons



dielectric $\epsilon > 1$

magnetic gluons



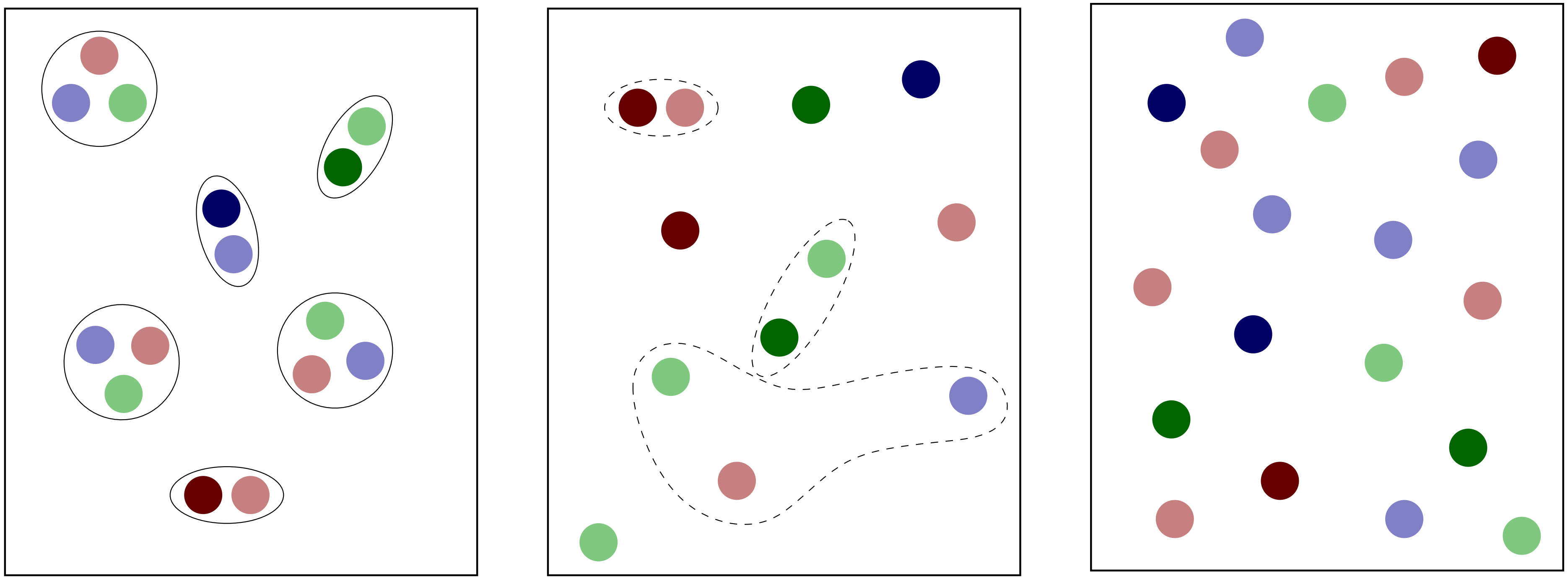
para-magnetic $\mu > 1$

vacuum: $\mu\epsilon = 1$

anti-screening $\epsilon < 1$

$$\beta(g) = -\frac{\partial g}{\partial \log(r)} = \frac{g^3}{(4\pi)^2}\left\{\frac{1}{3} - 4\right\} N_c < 0$$

From hadrons to quarks



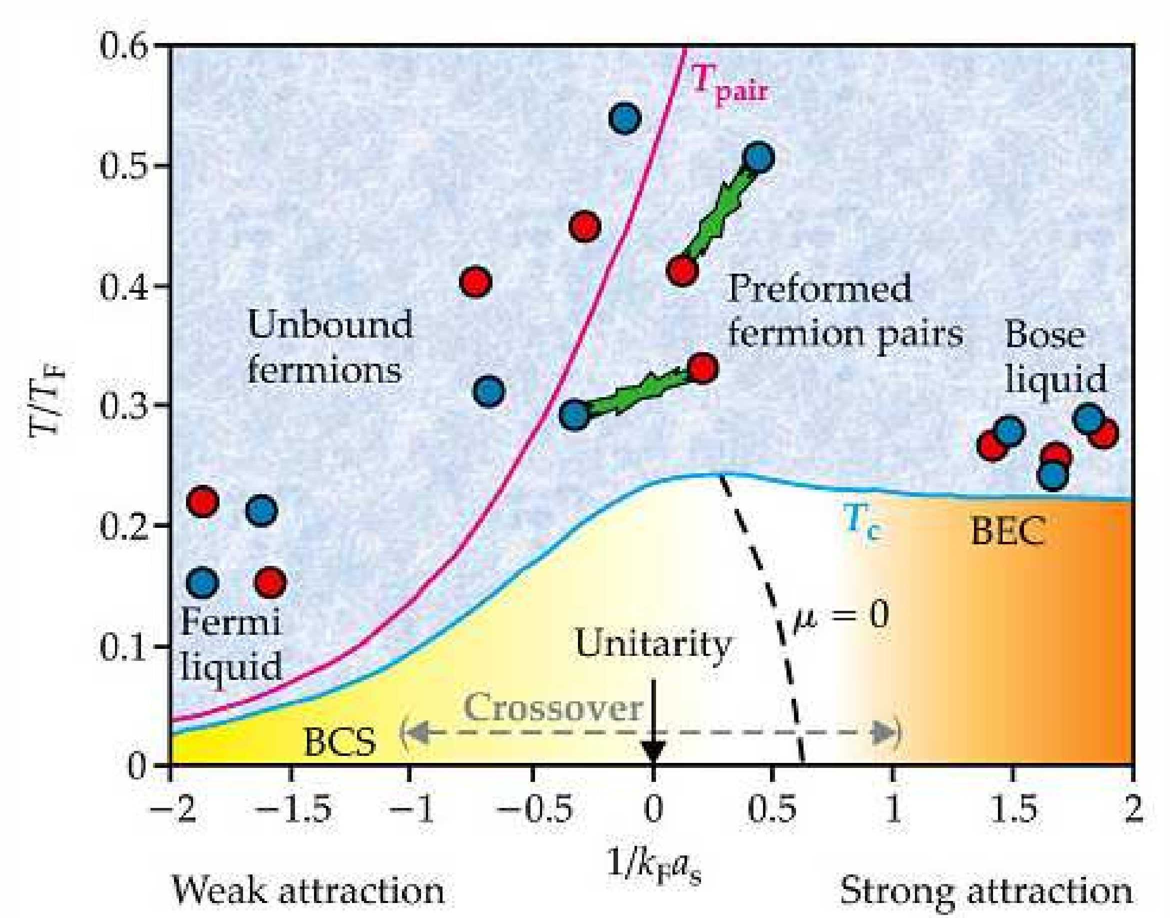
weakly coupled
hadron gas

strongly correlated
fluid

weakly coupled
quark gluon plasma

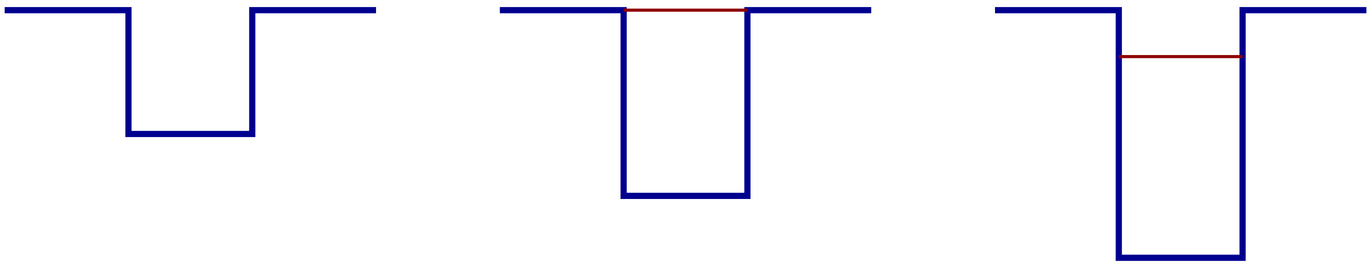
II. Dilute Fermi gas: BCS-BEC crossover

$$\boxed{\mathcal{L}_{\text{eff}} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2M} \right) \psi - \frac{C_0}{2} (\psi^\dagger \psi)^2}$$



Unitarity limit

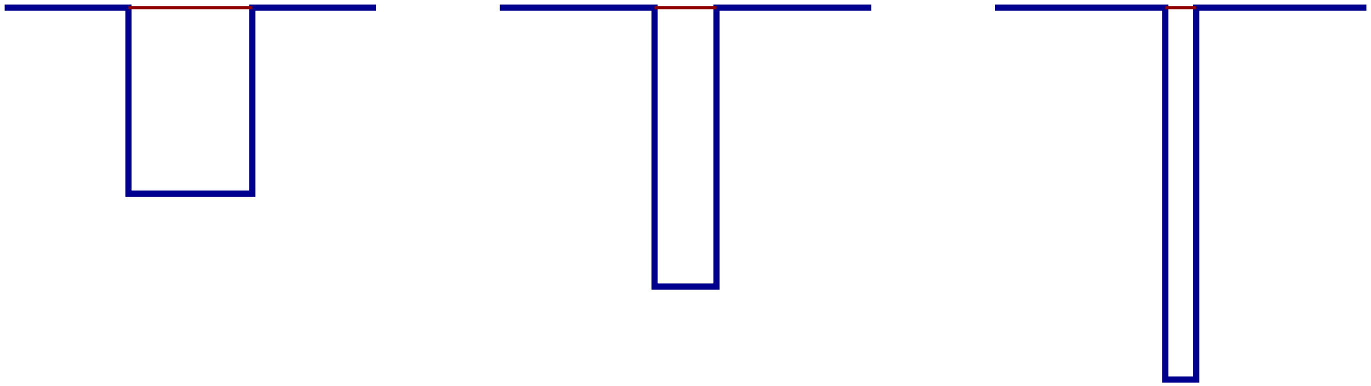
Consider simple square well potential



$a < 0$ $\quad$ $a = \infty,\ \epsilon_B = 0$ $\quad$ $a > 0,\ \epsilon_B > 0$

Unitarity limit

Now take the range to zero, keeping $\epsilon_B \simeq 0$

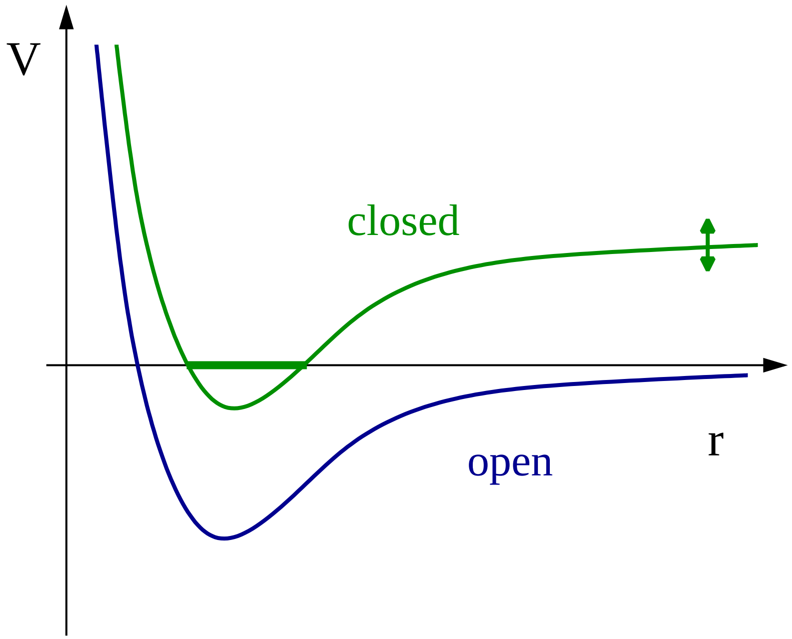


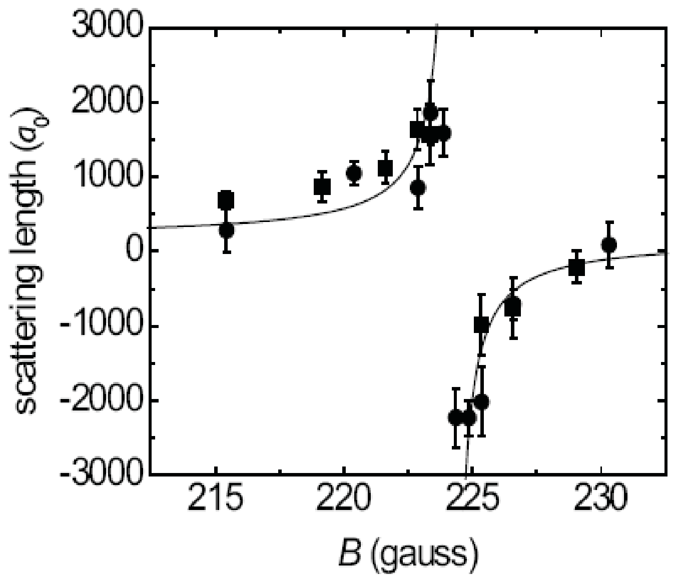
Universal relations

$$\mathcal{T} = \frac{1}{ik + 1/a} \qquad \epsilon_B = \frac{1}{2ma^2} \qquad \psi_B \sim \frac{1}{\sqrt{a}r}\exp(-r/a)$$

Feshbach resonances

Atomic gas with two spin states: "$\uparrow$" and "$\downarrow$"

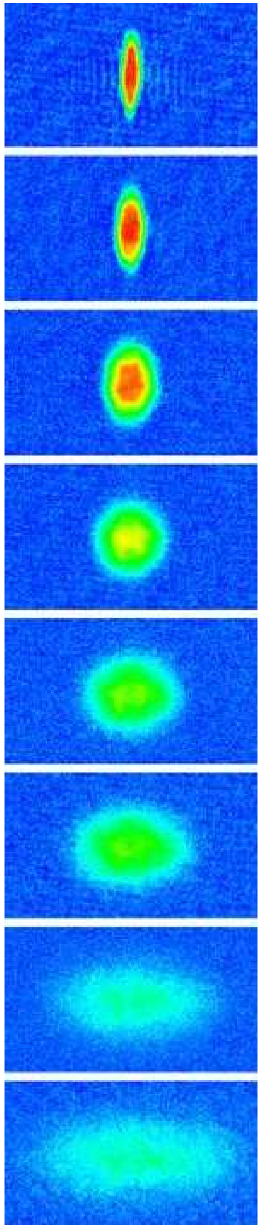




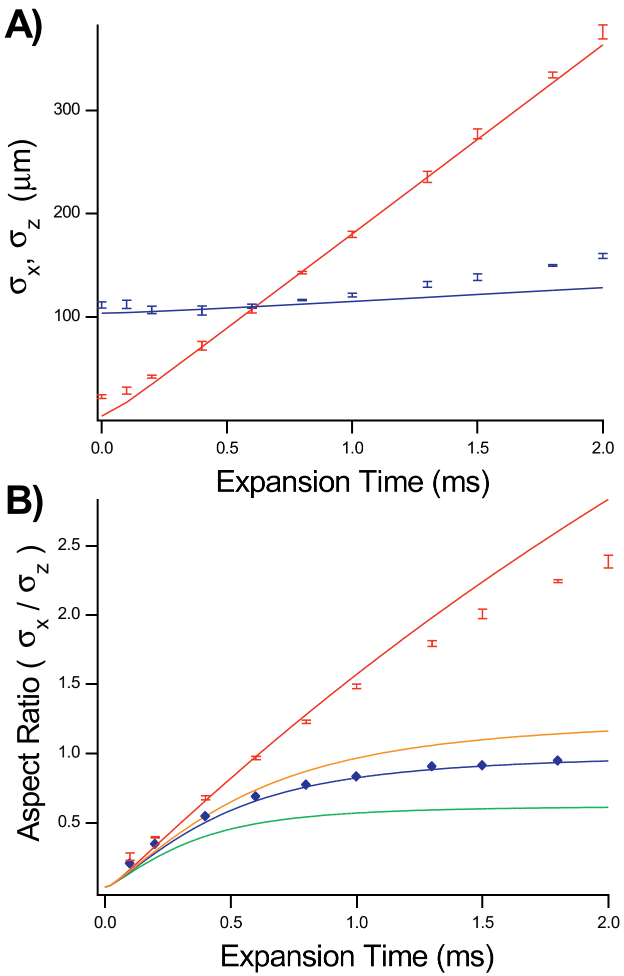
Feshbach resonance

$$a(B) = a_0\left(1 + \frac{\Delta}{B - B_0}\right)$$

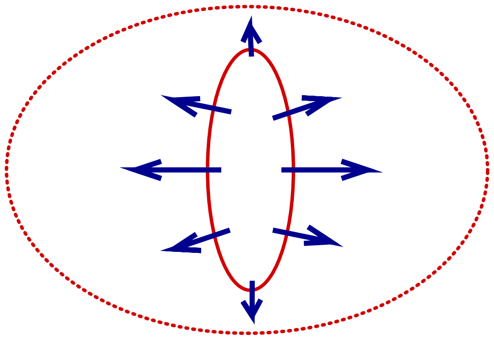
III. Almost ideal fluid dynamics (cold Fermi gas)



O'Hara et al. (2002)

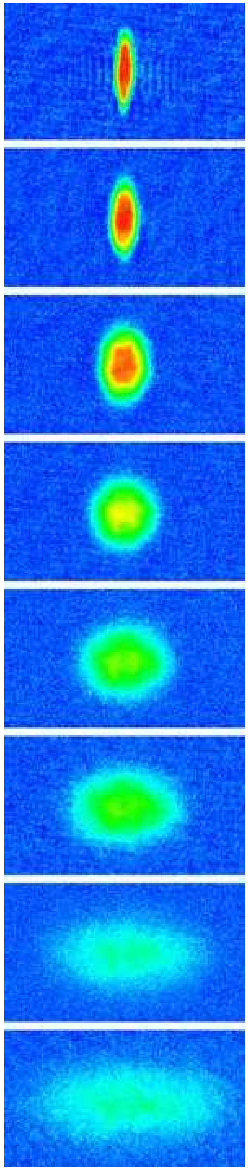


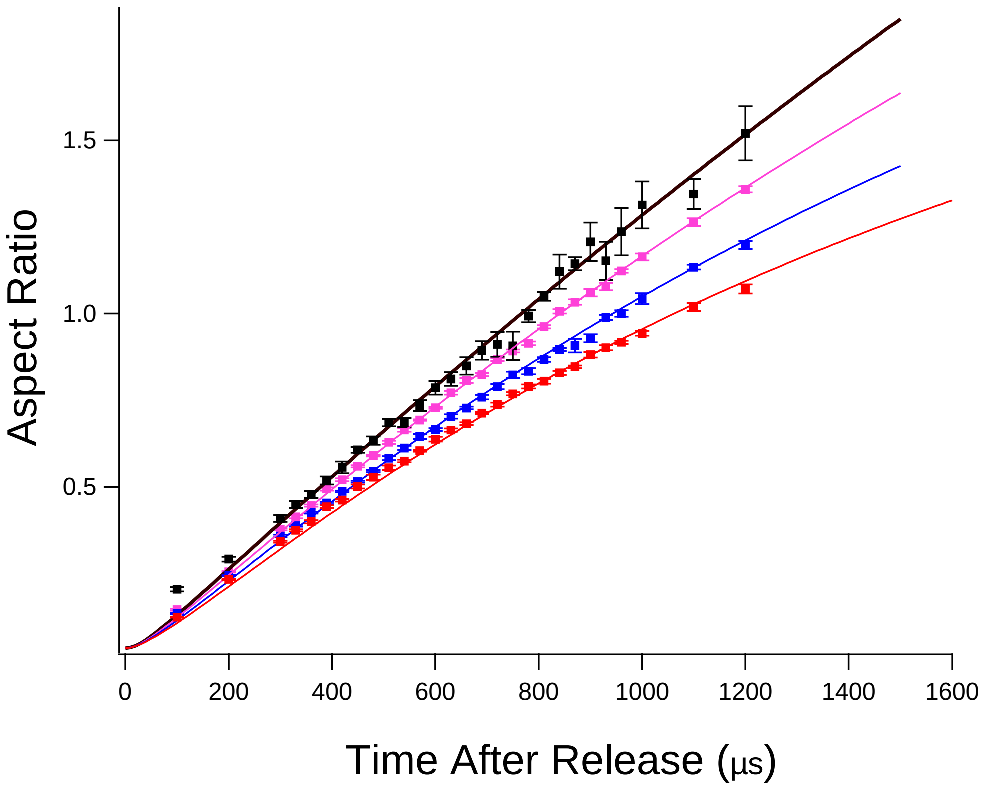
Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy



Elliptic flow: High T limit

Quantum viscosity $\eta = \eta_0 \frac{(mT)^{3/2}}{\hbar^2}$





$\eta = \eta_0 (mT)^{3/2}$

$\tau_R = \eta / P$

Cao et al., Science (2010)

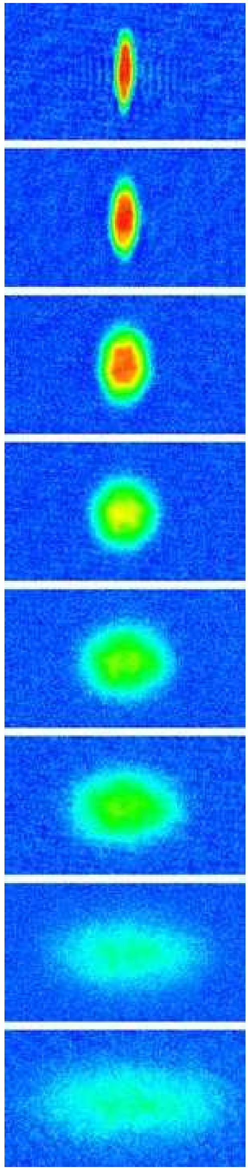
fit: $\eta_0 = 0.33 \pm 0.04$

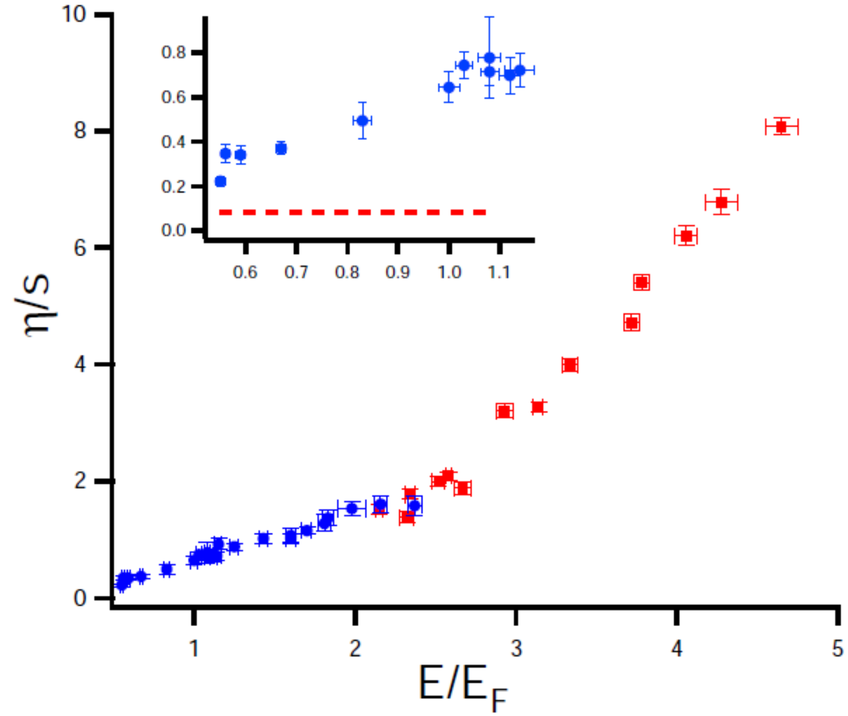
theory: $\eta_0 = \frac{15}{32\sqrt{\pi}} = 0.26$

Viscosity to entropy density ratio

consider both collective modes (low T)

and elliptic flow (high T)



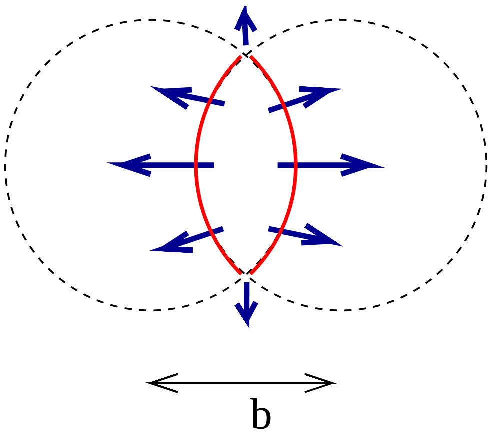


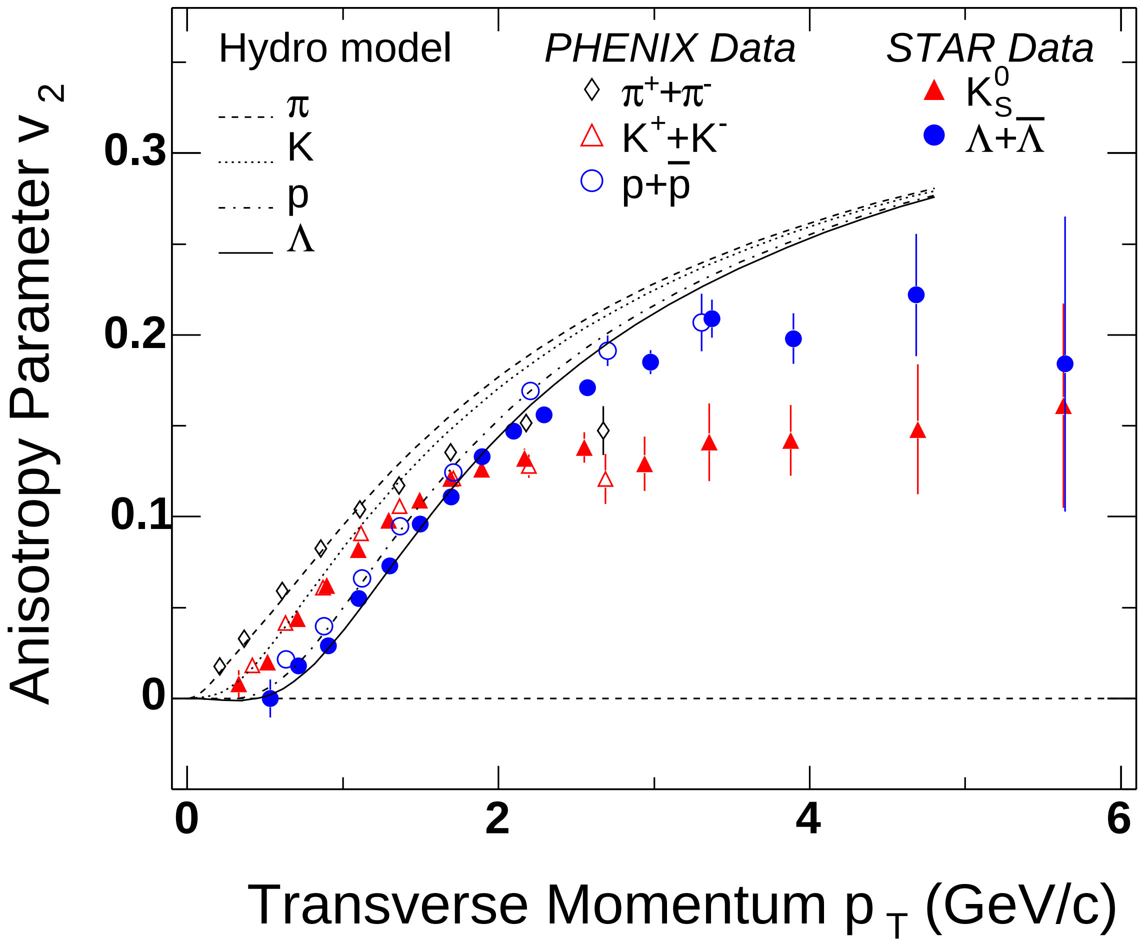
Cao et al., Science (2010)

$$\eta/s \leq 0.4$$

IV. Elliptic Flow (QGP)

Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy

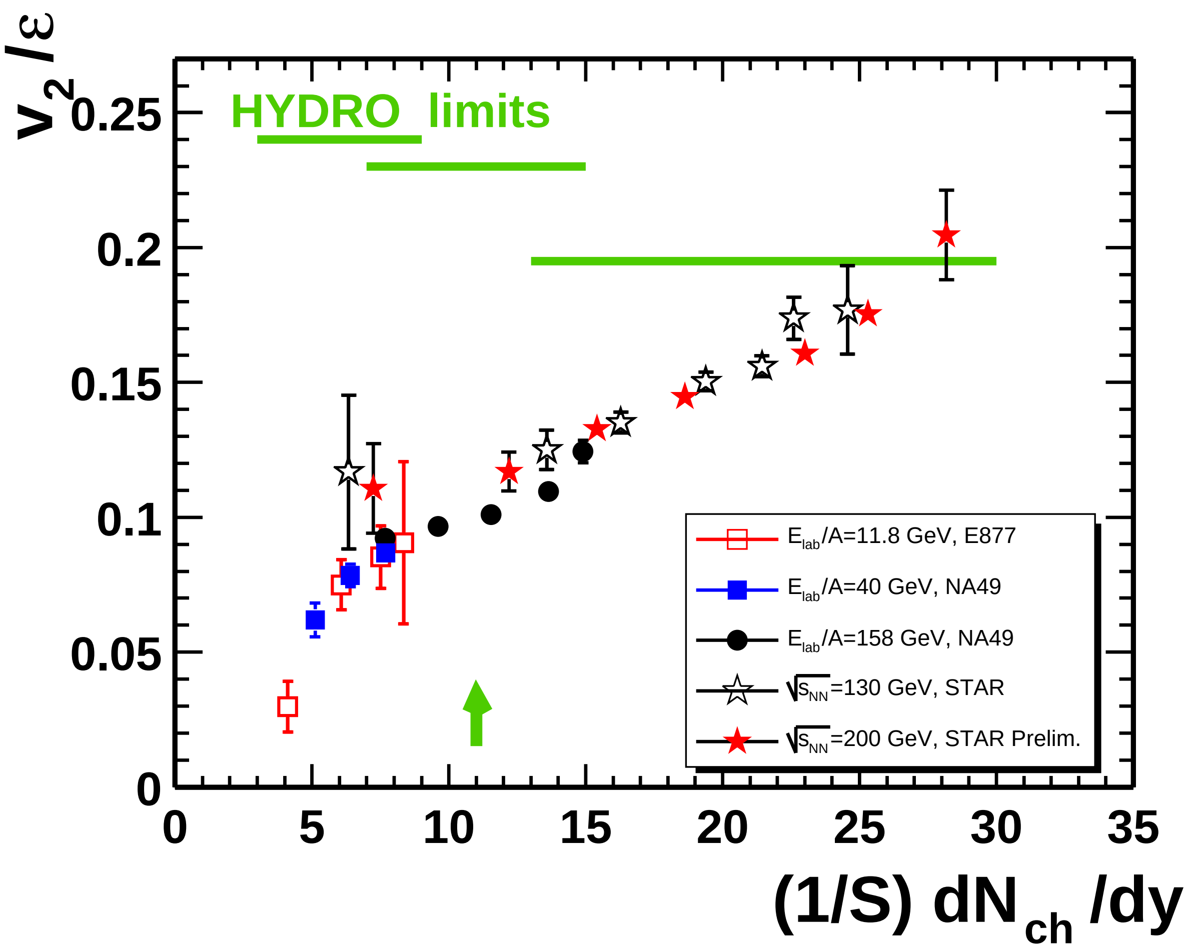




source: U. Heinz (2005)

$$p_0 \left. \frac{dN}{d^3p} \right|_{p_z=0} = v_0(p_\perp)\,(1 + 2v_2(p_\perp)\cos(2\phi) + \dots)$$

Elliptic flow: initial entropy scaling



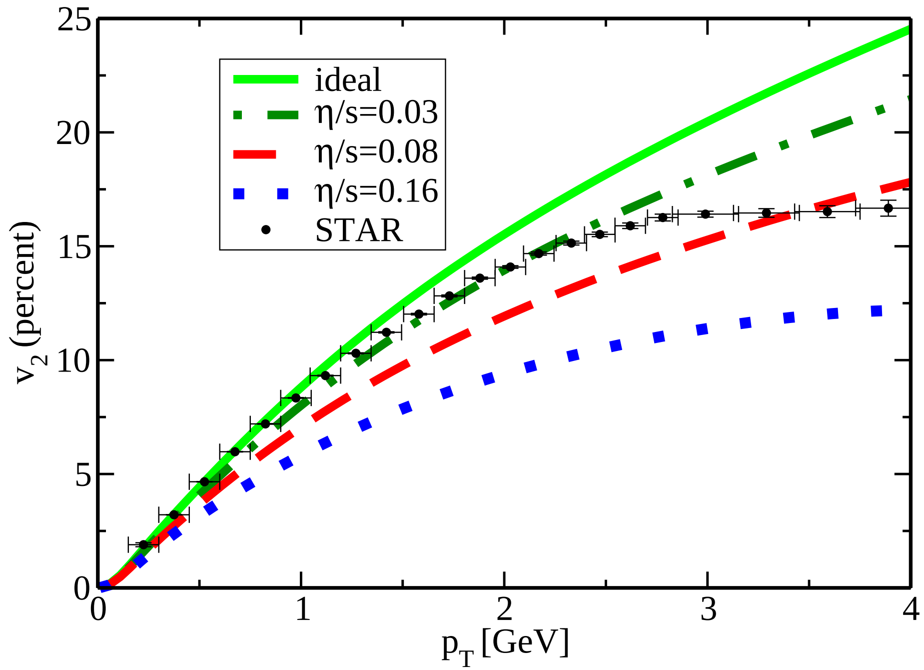
source: U. Heinz (2005)

Viscosity and Elliptic Flow

Viscous correction to v_2 (blast wave model)

$$\frac{\delta v_2}{v_2} = -\frac{1}{3}\frac{1}{\tau_f T_f}\left(\frac{\eta}{s}\right)\left(\frac{p_\perp}{T_f}\right)^2$$

Grows with $p_\perp$, decreases with system size



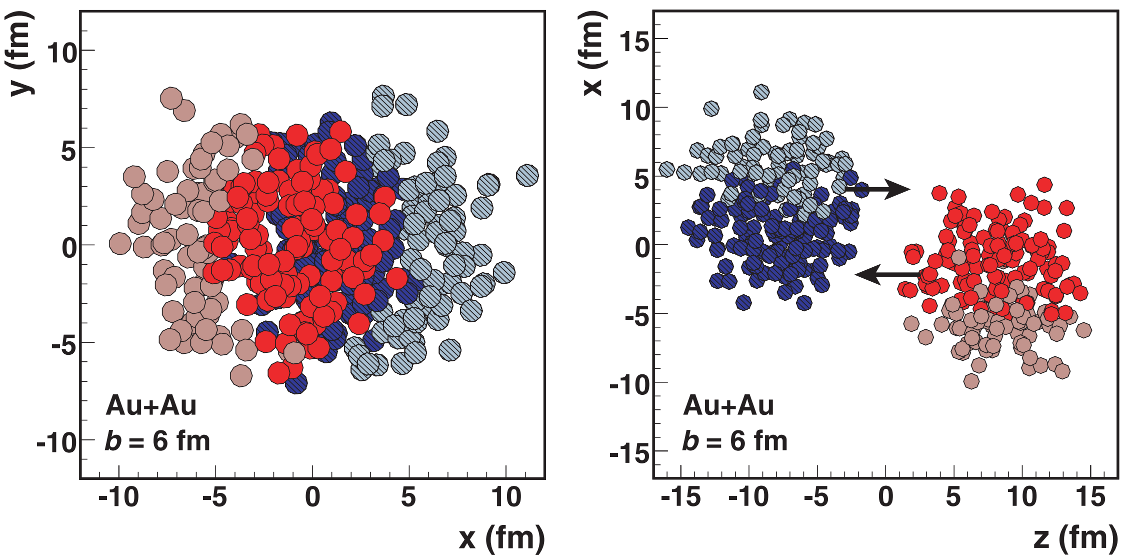
Romatschke (2007), Teaney (2003)

Many details: Dependence on initial conditions, freeze out, etc.

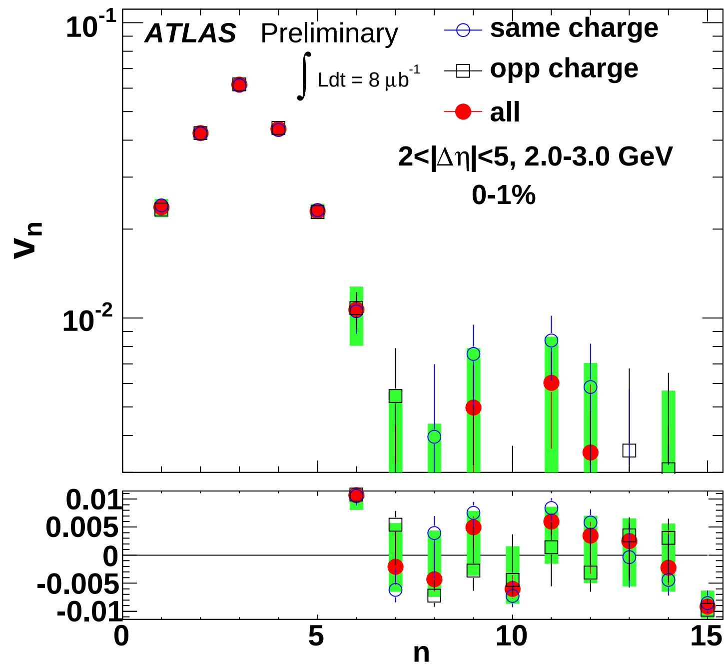
conservative bound $\boxed{\frac{\eta}{s} < 0.25}$

Higher moments of flow

Hydro converts moments of initial deformation to moments of flow



Glauber MC (P. Steinberg)

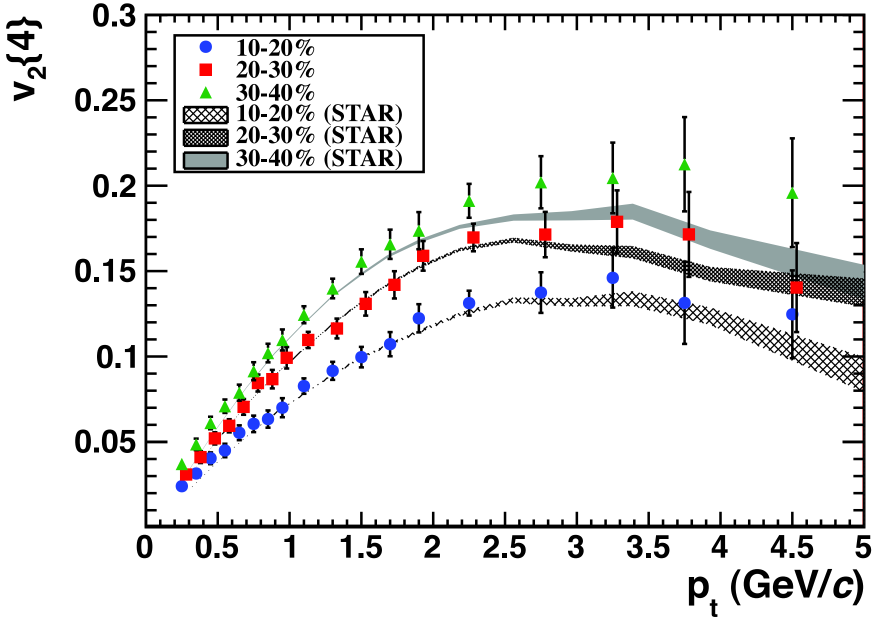


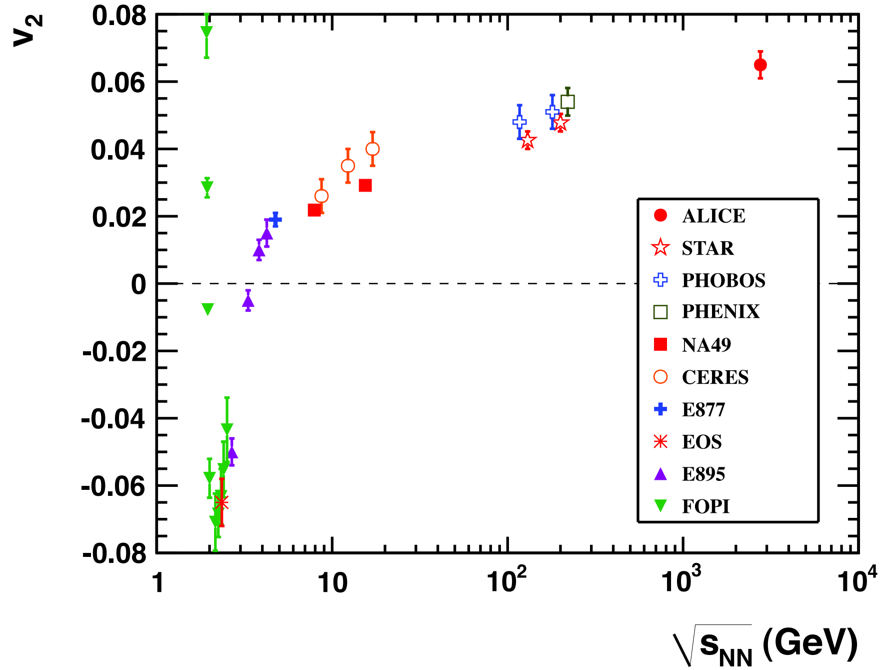
Atlas (J. Jia, QM 2011)

Glauber predicts flat initial spectrum $(n \geq 3)$. Observed flow spectrum consistent with sound attenuation

$$\delta T^{\mu\nu}(t) = \exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{T}\right)\delta T^{\mu\nu}(0)$$

Alice flow: Nearly perfect fluidity at the LHC?





Differential v_2 equal to RHIC

accidental cancellation? freezeout?

Integrated v_2 somewhat high

mean p_T increase? acceptance?

The bottom-line

Remarkably, the best fluids that have been observed are the *coldest* and the *hottest* fluid ever created in the laboratory, cold atomic gases (10^{-6}K) and the quark gluon plasma (10^{12}K) at RHIC.

Both of these fluids come close to a bound on the shear viscosity that was first proposed based on calculations in string theory, involving non-equilibrium evolution of back holes in 5 (and more) dimensions.