

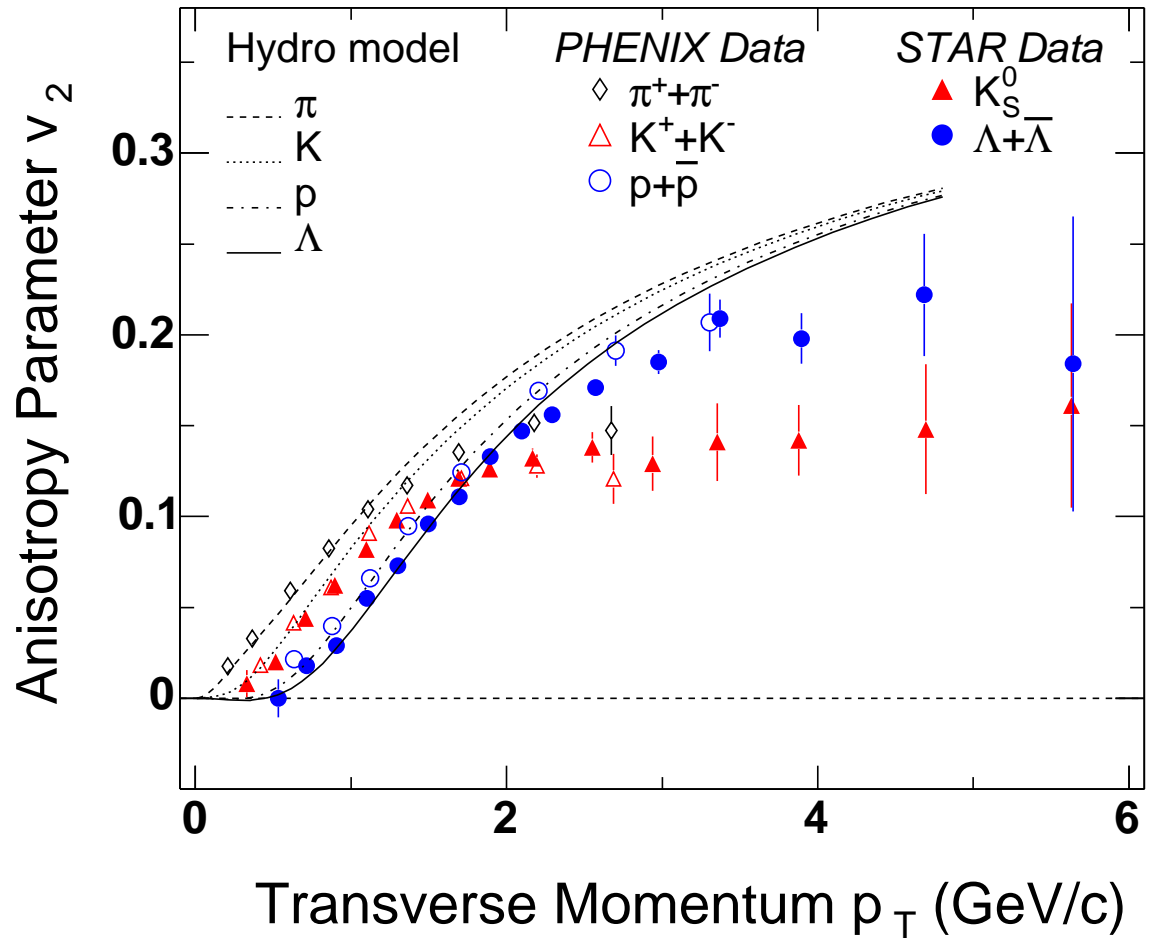
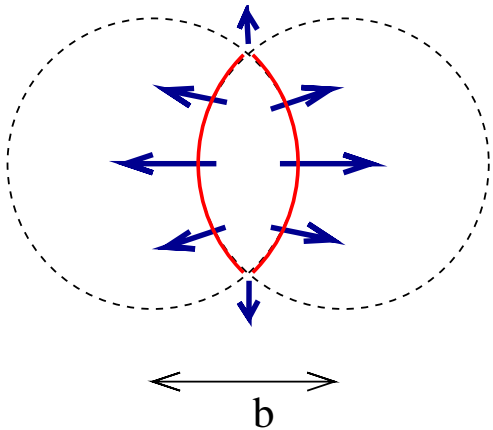
# Perfect Fluidity in Cold Atomic Gases?

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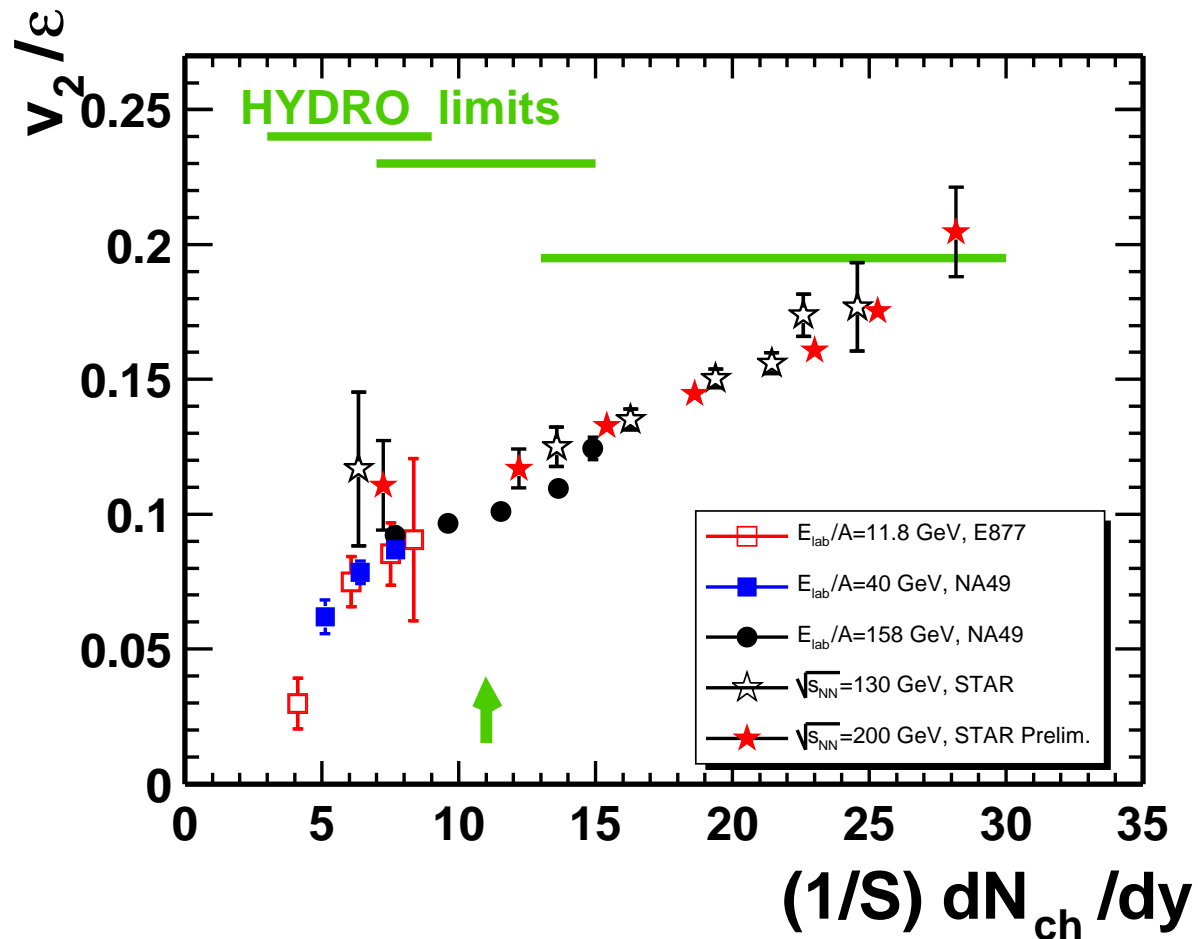
# Elliptic Flow

Hydrodynamic expansion converts  
coordinate space  
anisotropy  
to momentum space  
anisotropy



source: U. Heinz (2005)

# Elliptic Flow II



Requires “perfect” fluidity ( $\eta/s < 0.1$  ?)

(s)QGP saturates (conjectured) universal bound  $\eta/s = 1/(4\pi)$ ?

## Viscosity Bound: Rough Argument

Kinetic theory estimate of shear viscosity

$$\eta \sim \frac{1}{3} n \bar{v} m l = \frac{2}{3} n \left( \frac{1}{2} m \bar{v}^2 \right) \frac{l}{\bar{v}} = \frac{2}{3} n \epsilon \tau_{mft}$$

Entropy density:  $s \sim k_B n$ . Uncertainty relation implies

$$\frac{\eta}{s} \sim \frac{\epsilon \tau_{mft}}{k_B n} \sim \frac{E \tau_{mft}}{k_B} \leq \frac{\hbar}{k_B}$$

Validity of kinetic theory as  $E \tau \sim \hbar$ ?

Why  $\eta/s$ ? Why not  $\eta/n$ ?

# Holographic Duals at Finite Temperature

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

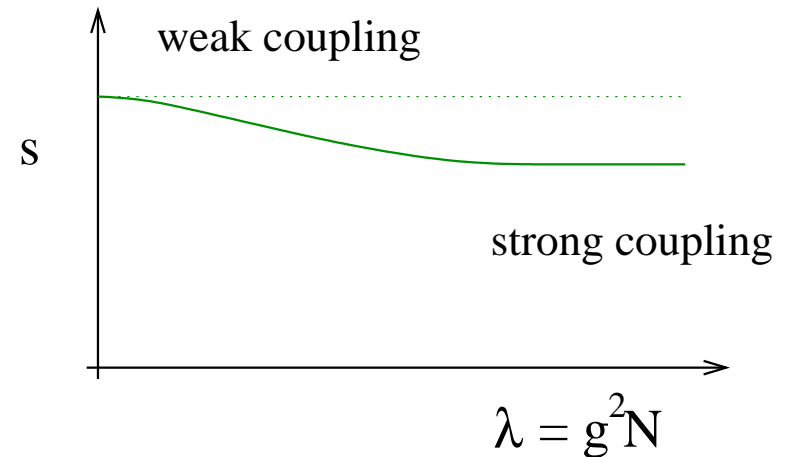
CFT temperature  $\Leftrightarrow$  Hawking temperature of  
black hole

CFT entropy  $\Leftrightarrow$  Hawking-Bekenstein entropy  
 $\sim$  area of event horizon

Strong coupling limit

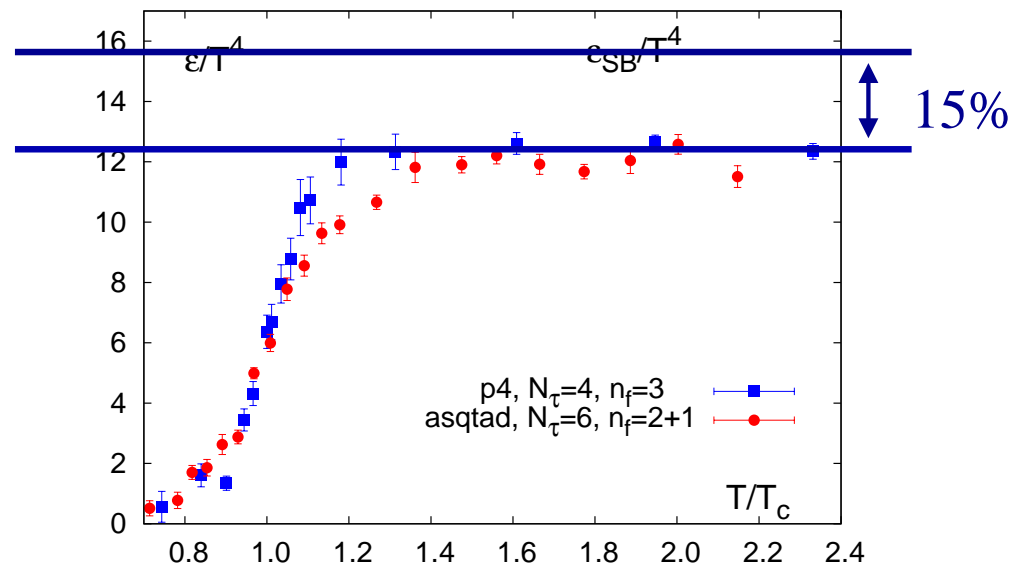
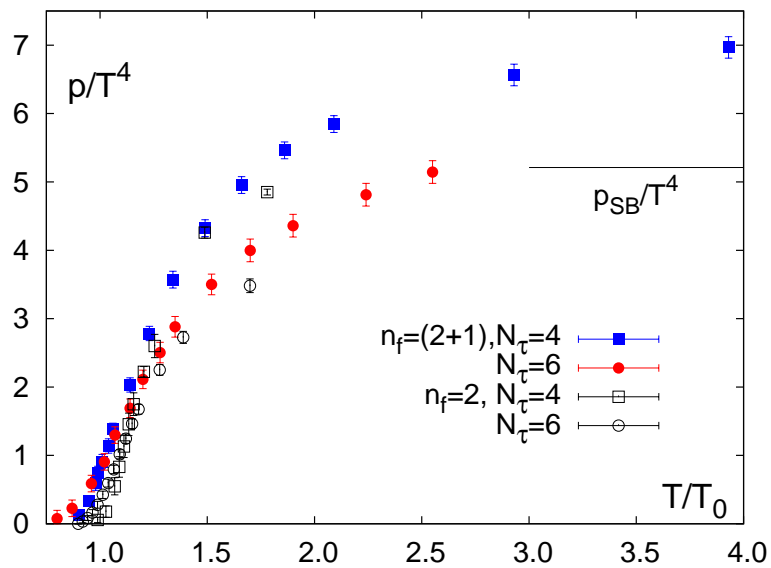
$$s = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4} s_0$$

Gubser and Klebanov



Extended to transport properties by Policastro, Son and Starinets

# Quark Gluon Plasma Equation of State (Lattice)



Compilation by F. Karsch (SciDAC)

# 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  $\Leftrightarrow$

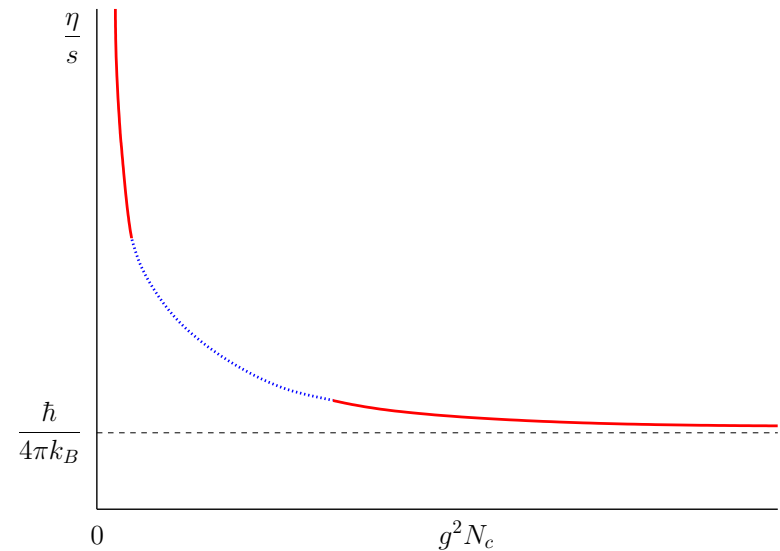
Graviton absorption cross section

$\sim$  area of event horizon

Strong coupling limit

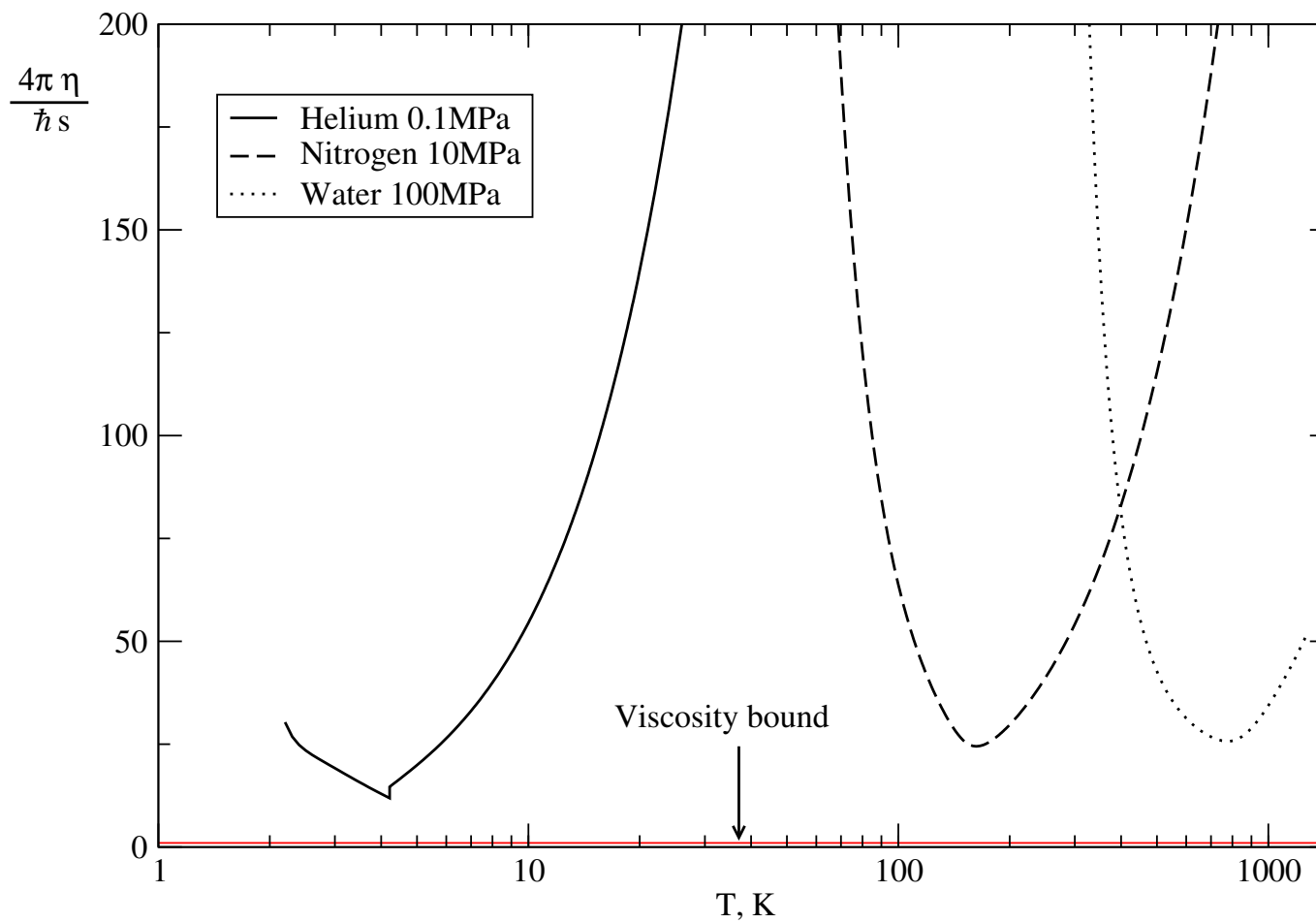
$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$$

Son and Starinets



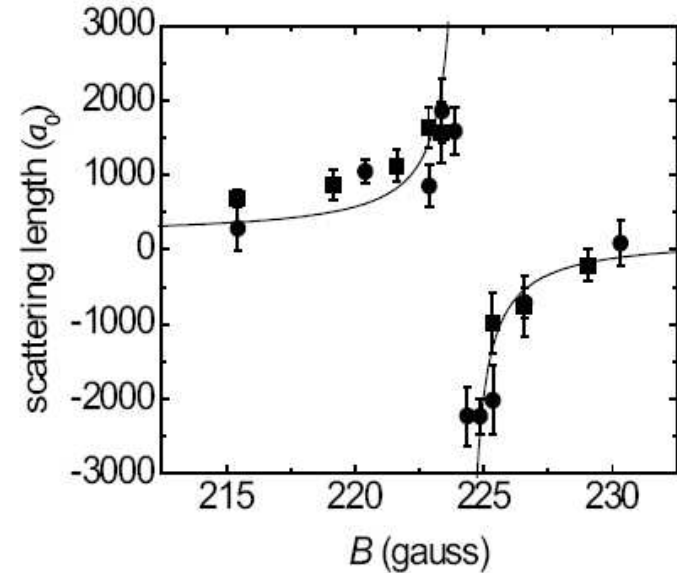
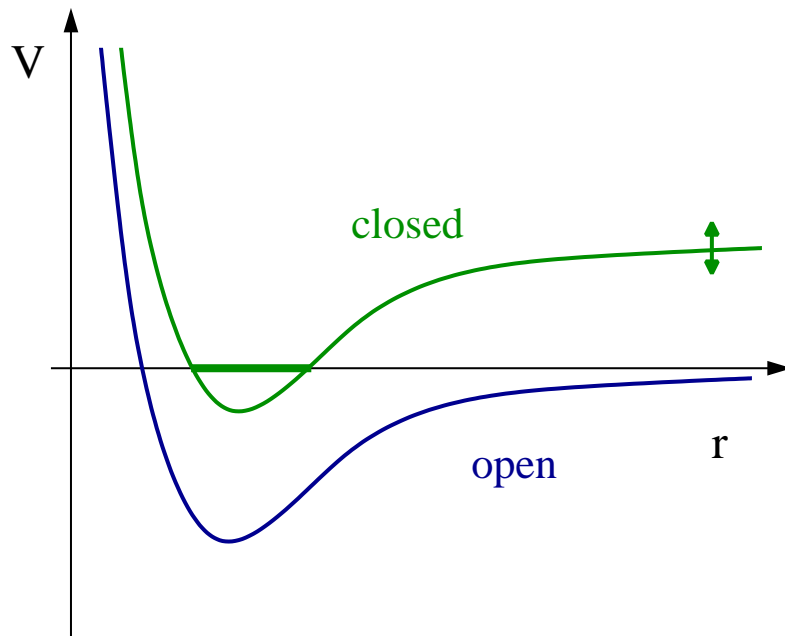
Strong coupling limit universal? Provides lower bound for all theories?

# Viscosity Bound: Common Fluids



# Designer Fluids

Atomic gas with two spin states: “↑” and “↓”



Feshbach resonance

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

“Unitarity” limit  $a \rightarrow \infty$

$$\sigma = \frac{4\pi}{k^2}$$

## Why are these systems interesting?

System is intrinsically quantum mechanical

cross section saturates unitarity bound

System is scale invariant at unitarity. Universal thermodynamics

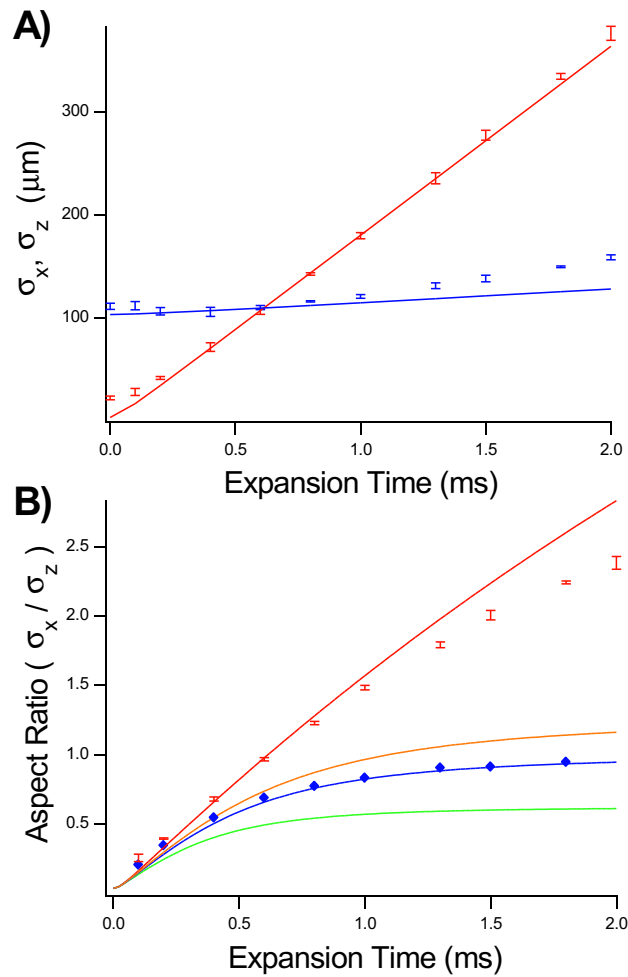
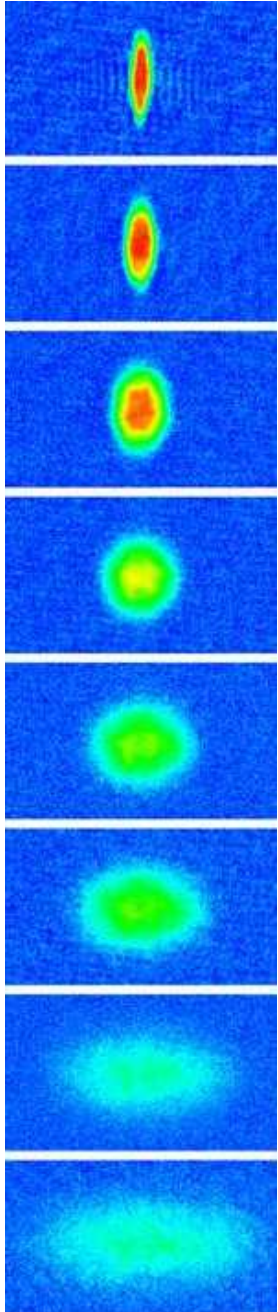
$$\frac{E}{A} = \xi \left( \frac{E}{A} \right)_0 = \xi \frac{3}{5} \left( \frac{k_F^2}{2M} \right)$$

System is strongly coupled but dilute

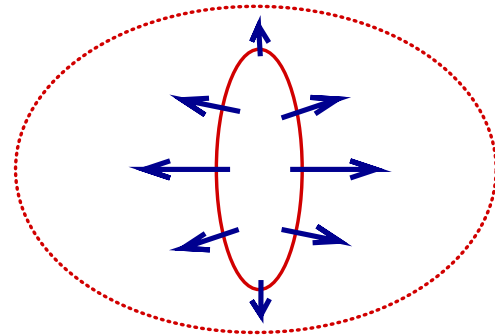
$$(k_F a) \rightarrow \infty \quad (k_F r) \rightarrow 0$$

Strong elliptic flow observed experimentally

# Elliptic Flow

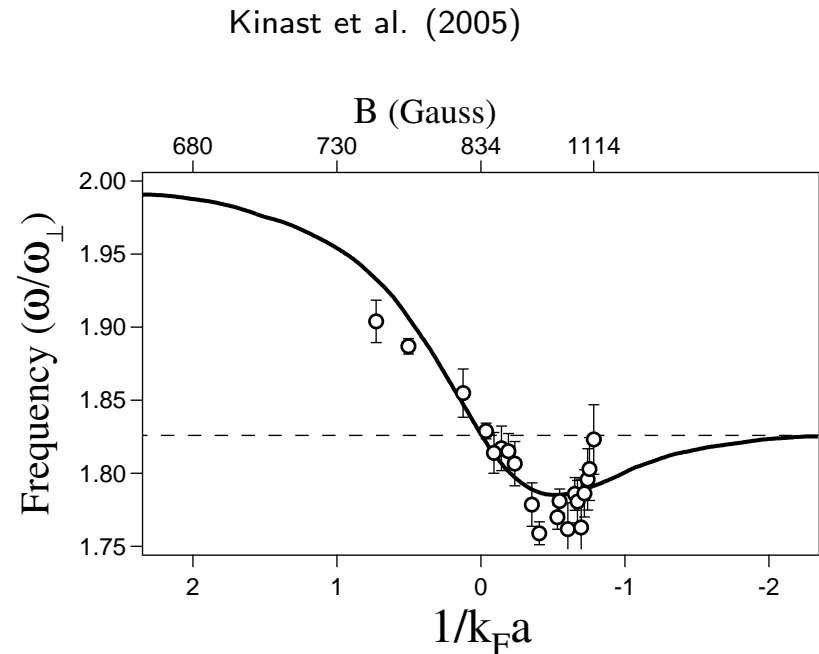
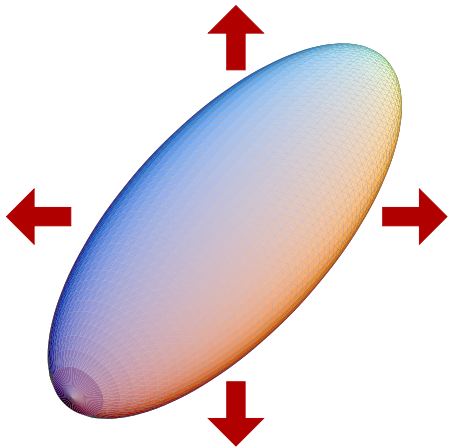


Hydrodynamic expansion converts  
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# Collective Modes

Radial breathing mode



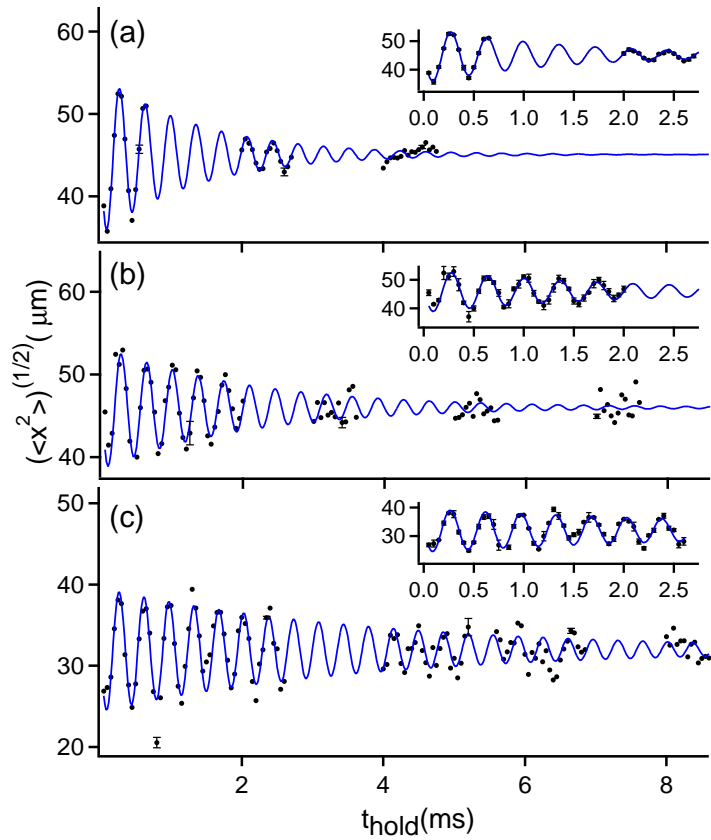
Ideal fluid hydrodynamics, equation of state  $P \sim n^{5/3}$

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

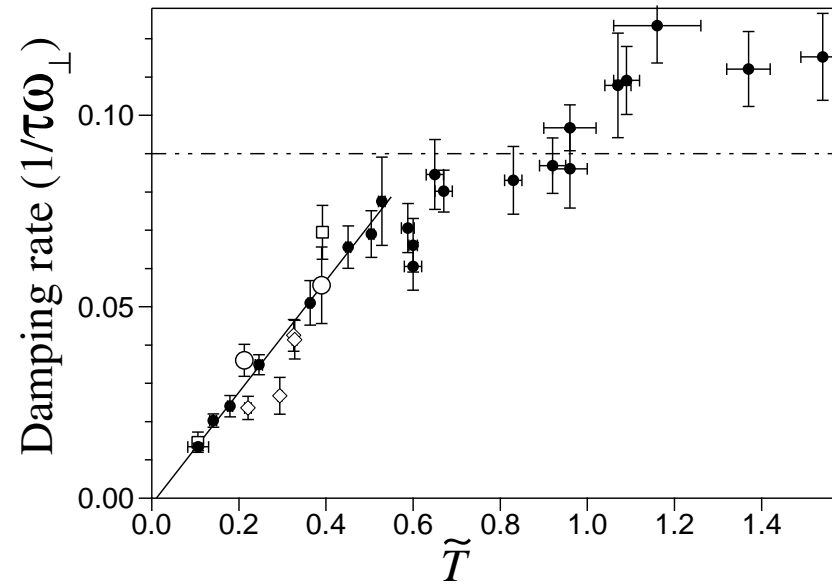
$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v} = -\frac{1}{mn} \vec{\nabla} P - \frac{1}{m} \vec{\nabla} V$$

$$\omega = \sqrt{\frac{10}{3}} \omega_{\perp}$$

# Damping of Collective Excitations



$$T/T_F = (0.5, 0.33, 0.17)$$



$\tau\omega$ : decay time  $\times$  trap frequency

Kinast et al. (2005)

# Viscous Hydrodynamics

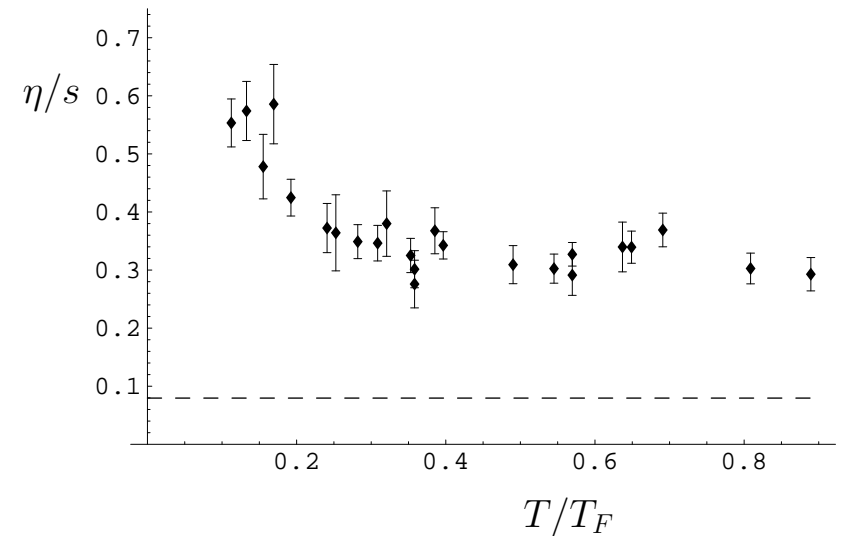
Energy dissipation ( $\eta, \zeta, \kappa$ : shear, bulk viscosity, heat conductivity)

$$\dot{E} = -\frac{\eta}{2} \int d^3x \left( \partial_i v_j + \partial_j v_i - \frac{2}{3} \delta_{ij} \partial_k v_k \right)^2 - \zeta \int d^3x (\partial_i v_i)^2 - \frac{\kappa}{2} \int d^3x (\partial_i T)^2$$

Shear viscosity to entropy ratio  
(assuming  $\zeta = \kappa = 0$ )

$$\frac{\eta}{s} = \frac{3}{4} \xi^{\frac{1}{2}} (3N)^{\frac{1}{3}} \frac{\Gamma}{\omega_{\perp}} \frac{\bar{\omega}}{\omega_{\perp}} \frac{N}{S}$$

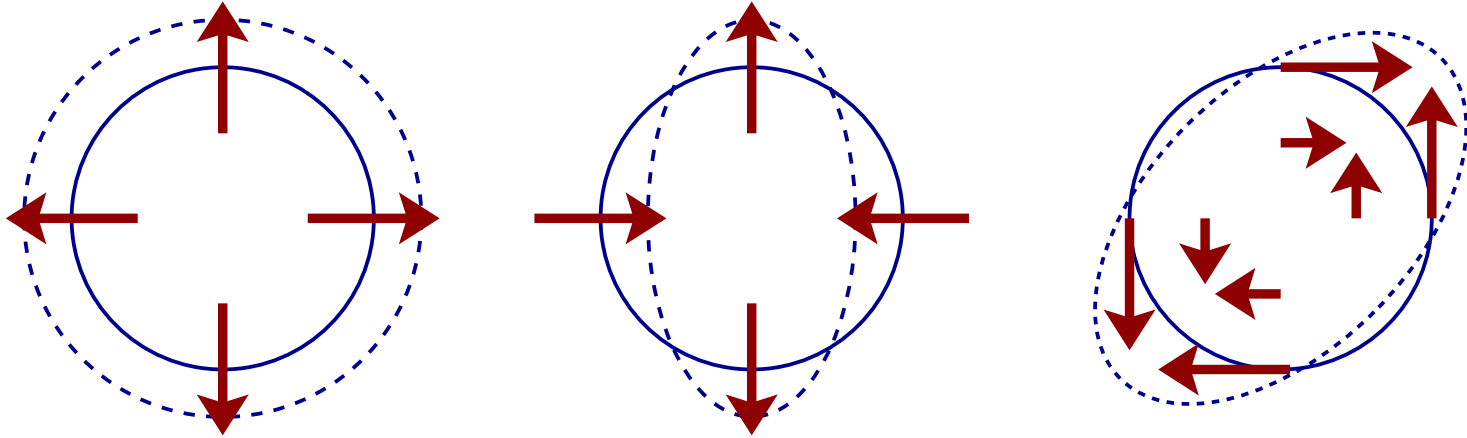
see also Bruun, Smith, Gelman et



al.

# Damping dominated by shear viscosity?

Study dependence on flow pattern



Study particle number scaling

viscous hydro:  $\Gamma \sim N^{-1/3}$

Boltzmann:  $\Gamma \sim N^{1/3}$

Role of thermal conductivity?

suppressed for scaling flows:  $\delta T \sim T(\delta n/n) \sim const$

## Final Thoughts

Cold atomic gases provide interesting, strongly coupled, model system in which to study sources of dissipation.

$$\eta/s \sim 1/3$$

Smaller than any other known liquid (except for QGP?). Since other sources of dissipation exist, this is really an upper bound.

Conjectured bound (if correct) should apply to non-relativistic systems, too. Note that the  $a \rightarrow \infty$  limit can also be realized in the QCD phase diagram (by tuning  $\mu, \mu_e$  and  $m_q$ ).

Purely field theoretic proofs?

$\mathcal{N} = 4$  SUSY YM is special because there is no phase transition. In real systems there is a phase transition as the coupling becomes large, and the new phase (confined in QCD, superfluid in the atomic system) has weakly coupled low energy excitations, and a large viscosity.

No quasi-particles in sQGP?