Towards the shear viscosity of a cold unitary fermi gas

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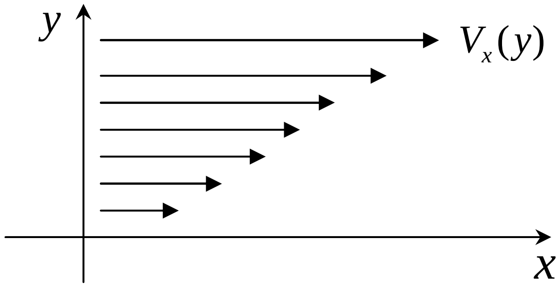
- Shear viscosity



Frictional force

$$T_{ij} = -\eta\left(\frac{\nabla_i V_j(x) + \nabla_j V_i(x)}{2} - \frac{1}{3}\delta_{ij}\nabla\cdot V(x)\right).$$

Shear viscosity measures
how “perfect” a fluid is!

Smaller shear viscosity implies
larger particle interaction!

- Kovtun, Son, and Starinets ('05)

  Conjecture: Shear viscosity / entropy density

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

- Motivated by AdS/CFT

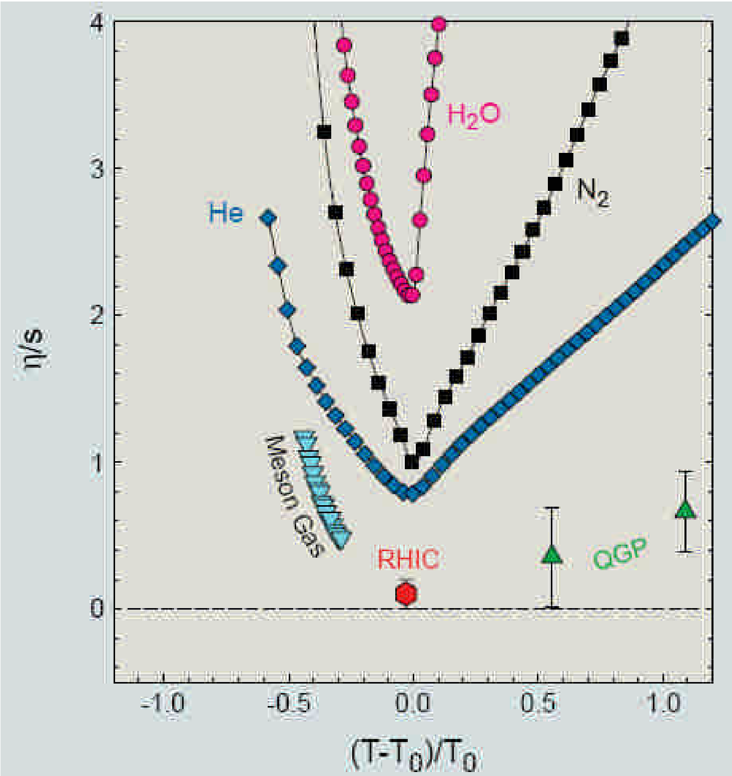
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

- "QGP" (quark gluon plasma) almost saturates the bound @ just above Tc (Teaney; Romatschke, Romatschke; Song, Heinz; Luzum…)
- LQCD, gluon pasma (Karsch, Wyld; Nakamura, Sakai; Meyer)

$\Rightarrow$ QGP near Tc, a perfect fluid, SQGP

η/s goes to a local minimum near a phase transition

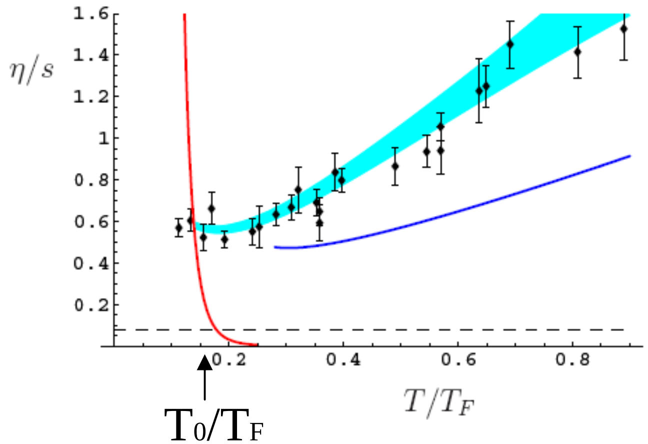
in more than 30 systems with no exception found so far.



Lacey et al., PRL 98:092301,2007; 2007 US Nuclear Science Long Range Plan

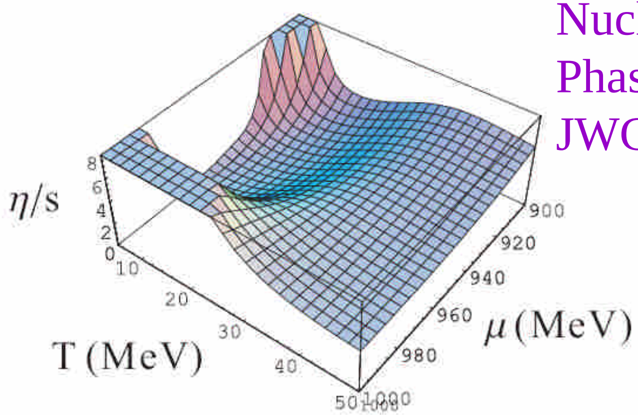
Cold Unitary Atoms

Rupak & Schafer 2007



Nuclear liquid-gas Phase transition

JWC et al. 2007



QCD Phase Diagram

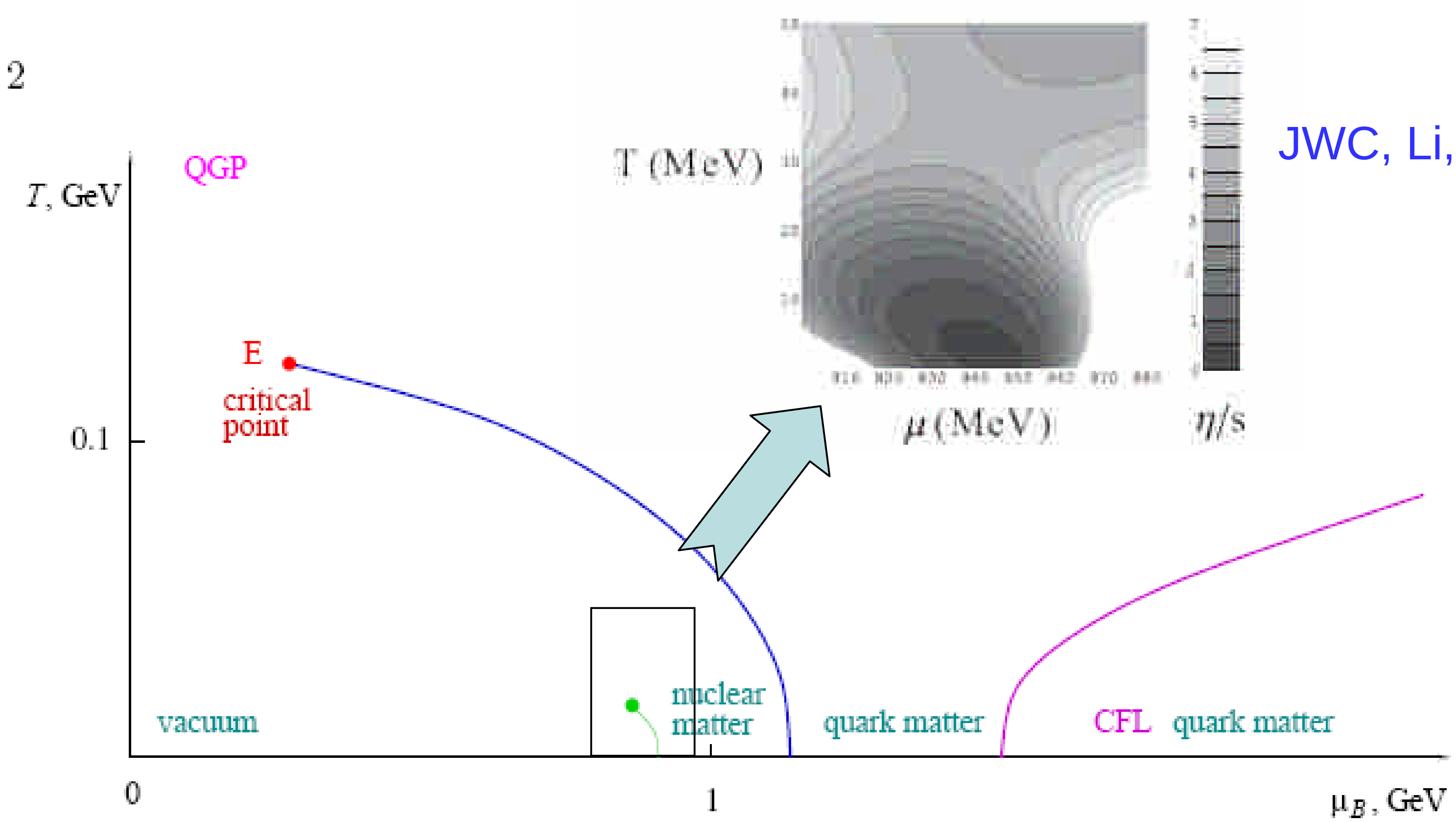
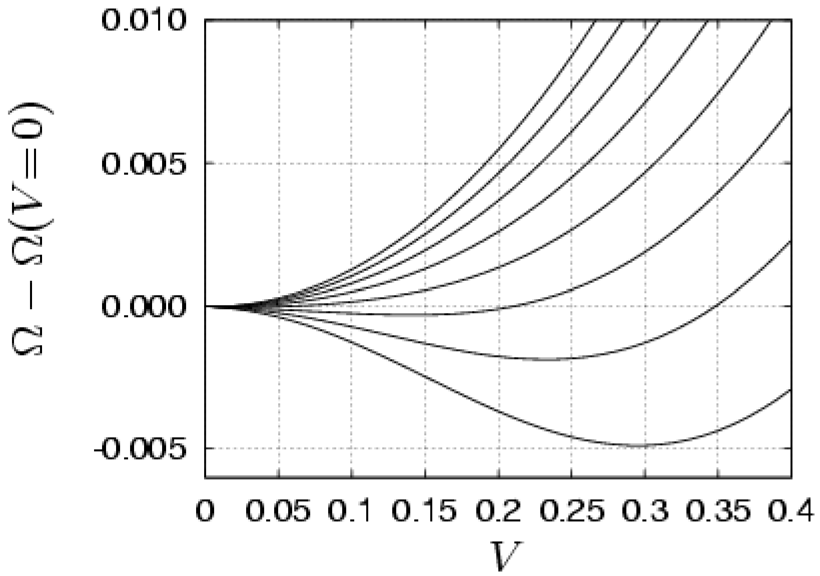


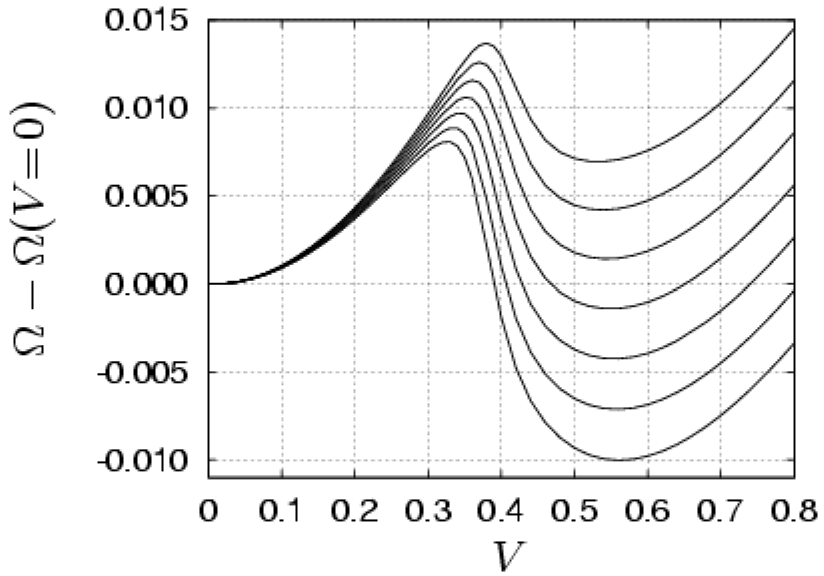
Fig. 1. QCD phase diagram

JWC, Li, Liu, Nakano

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}a\phi^2 - \frac{1}{4}b\phi^4 - \frac{1}{6}c\phi^6$$

(JWC, M. Huang, Y.H. Li, E. Nakana, D.L. Yang)

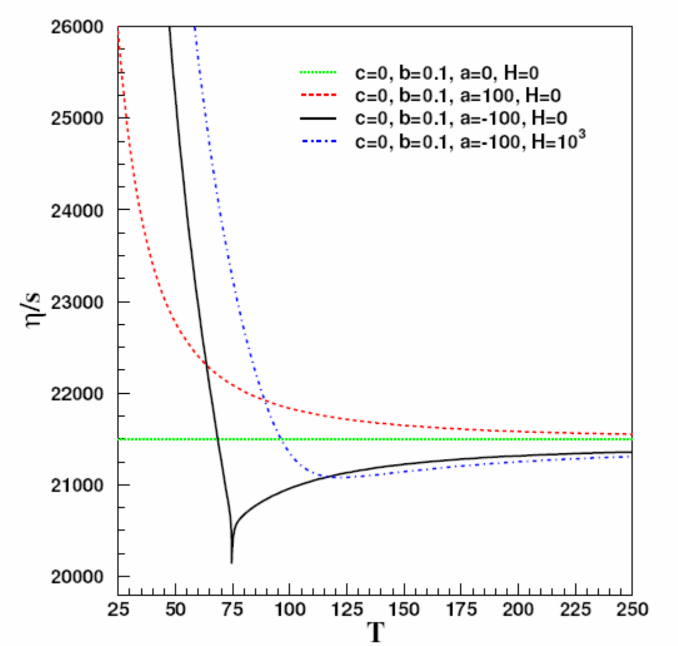


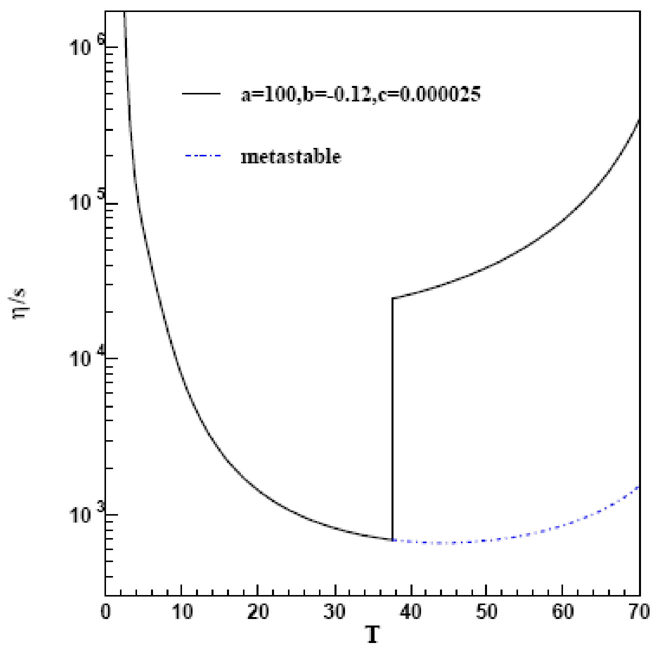


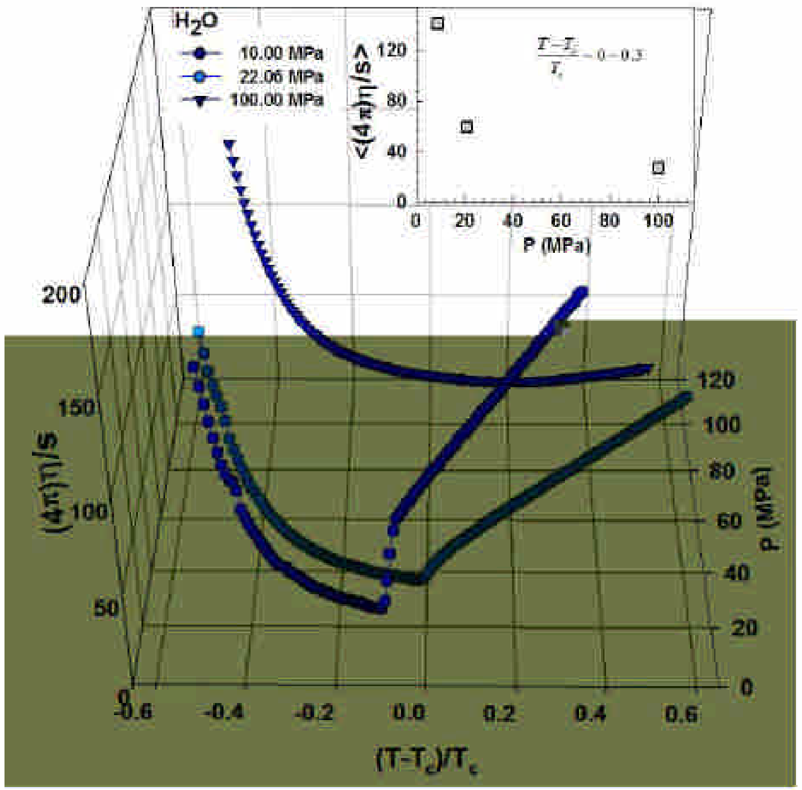
2nd-order p.t.:
a < 0, b > 0, c = 0
crossover: + $\delta\mathcal{L} = H\phi$
No p.t.: a > 0, b > 0, c = 0

1st-order phase transition
a > 0, b < 0, c > 0

η/s of Water



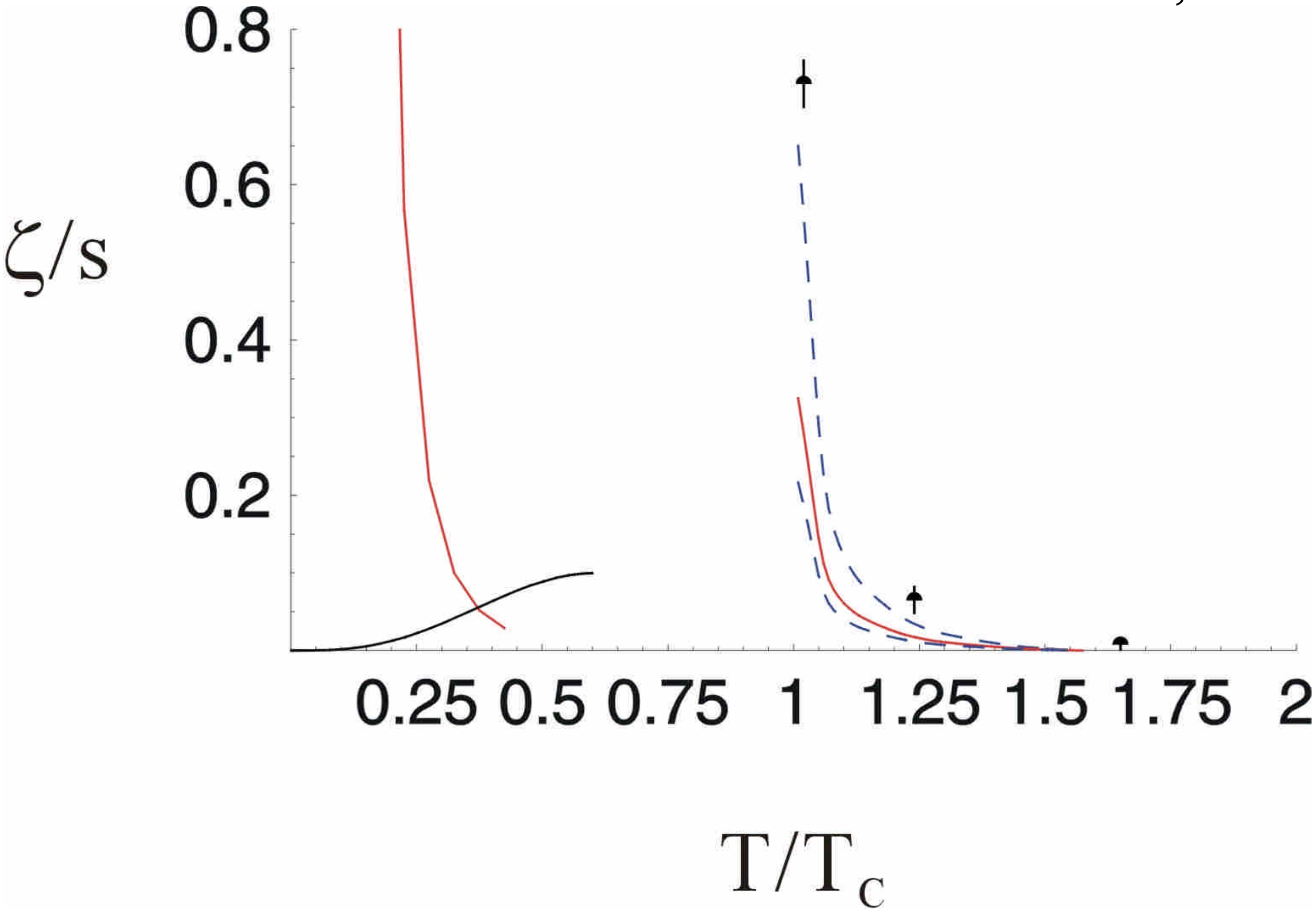




(Lacey et al.)

QCD Bulk Viscosity

Karsch, Kharzeev, Tuchin; Meyer; JWC, Wang; Fernandez-Fraile, Gomez Nicola

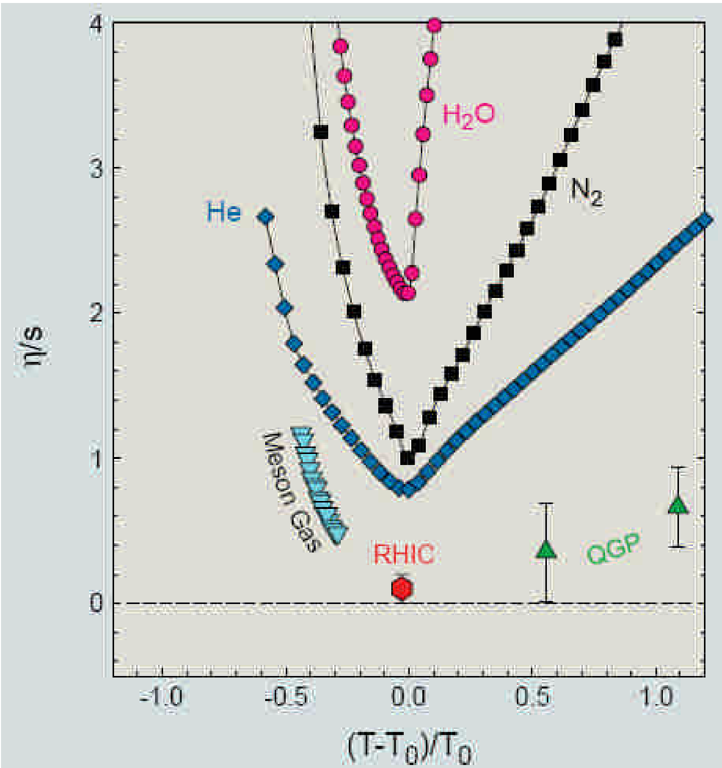


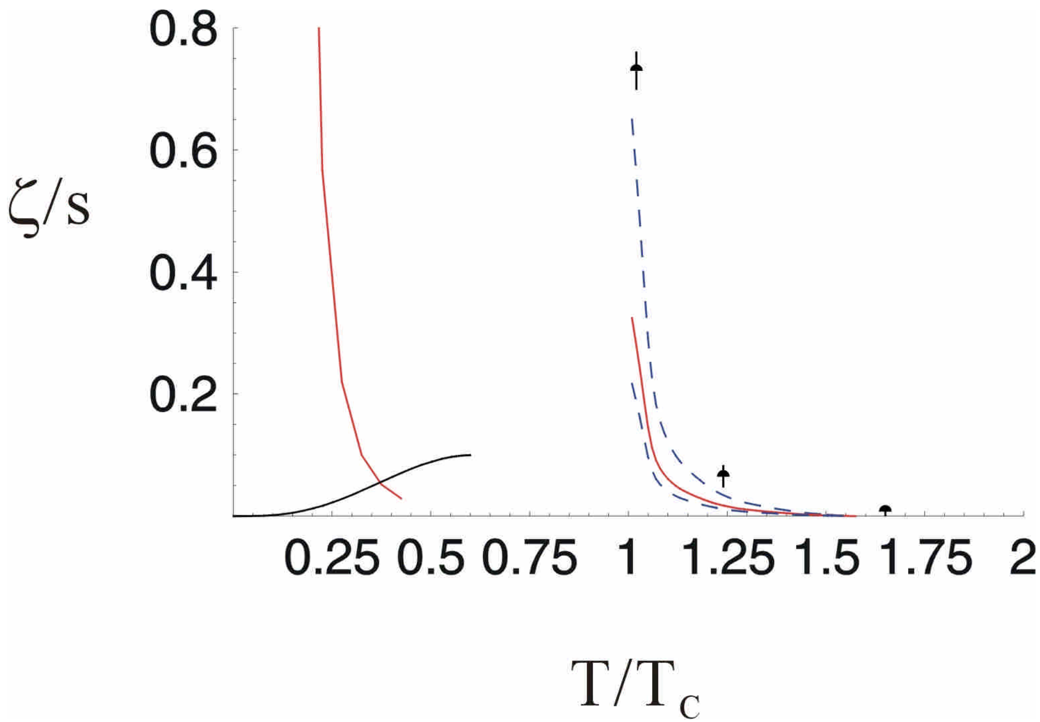
Universality?

Universal η/s and ζ/s behaviors?

(η/s reaches local minimum near p.t.

ζ/s reaches local maximum near p.t.)

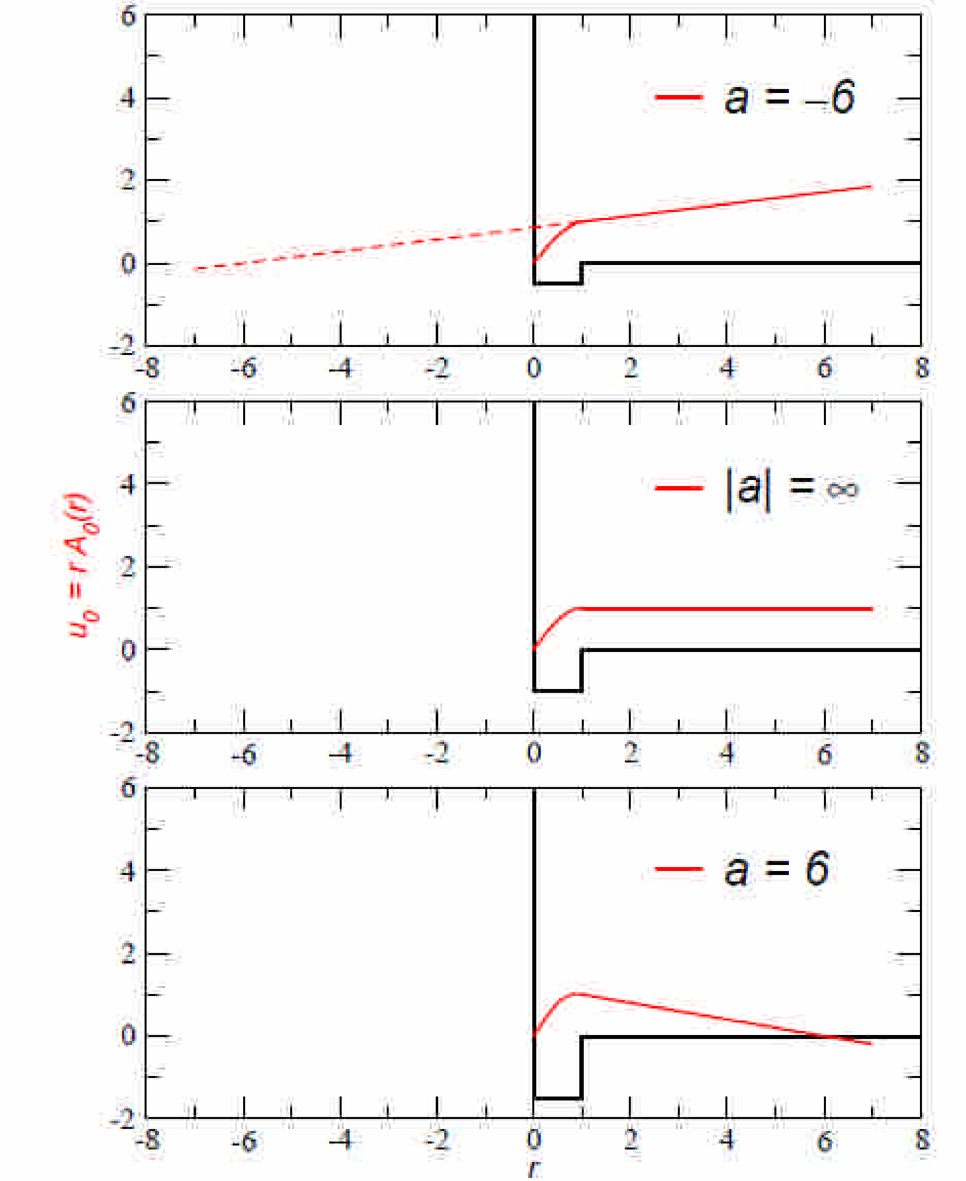


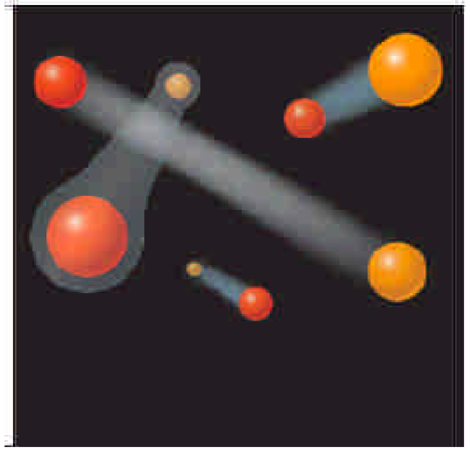


Cold Fermions

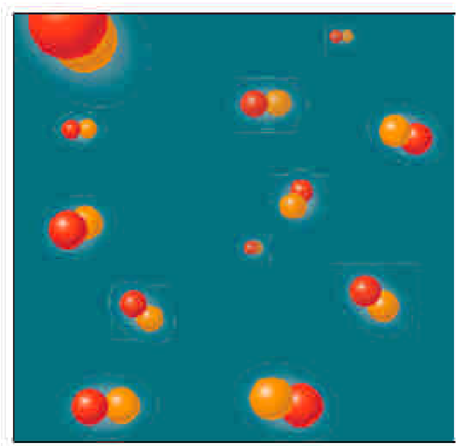
- S-wave, scattering length
- Feshbach resonance

Scattering Length (S-wave)

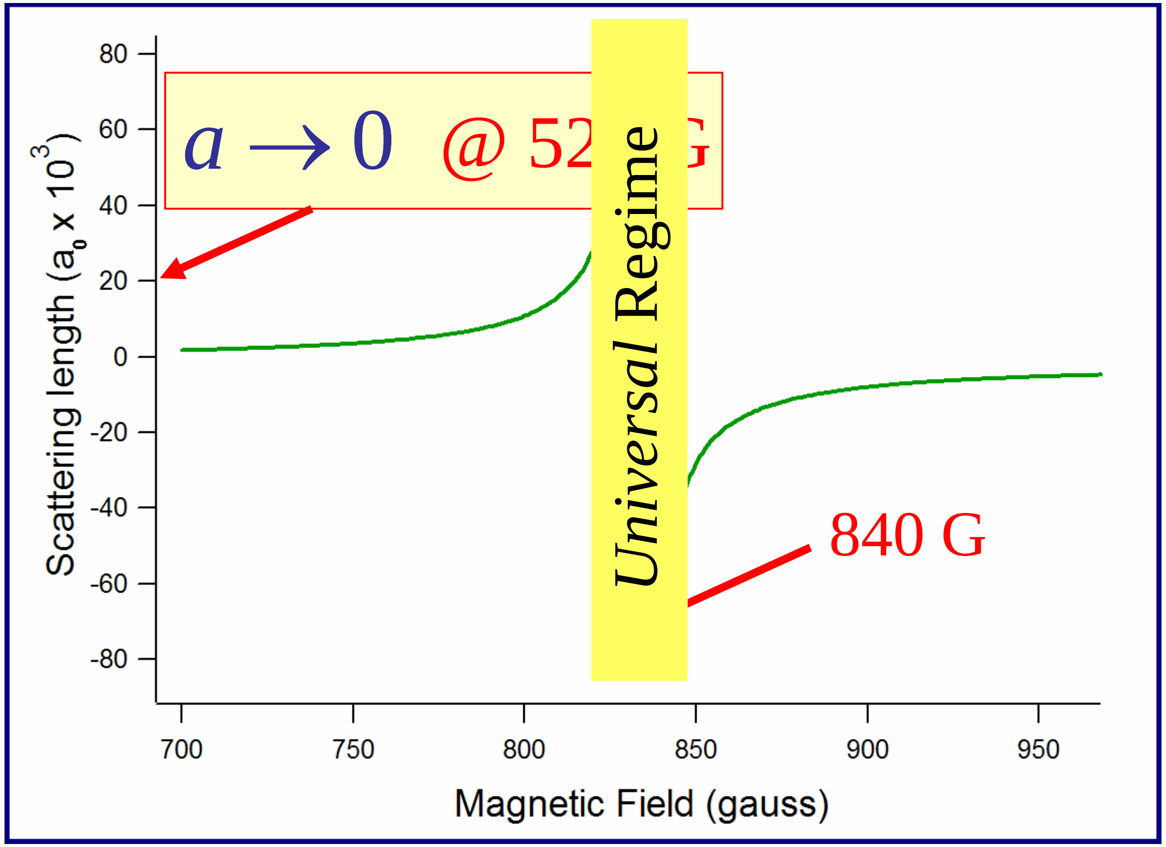




Unitarity limit



Tunable Interactions: Feshbach Resonance



*Generated using formula published in Bartenstein, et al, *PRL* **94** 103201 (2005)

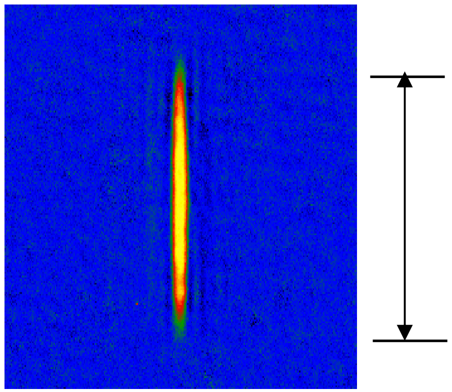
Source: J.E. Thomas

Energy E Measurement

Universal **Gas obeys the Virial Theorem** Duke, PRL (2005)

In a HO potential: $E = 2\langle U \rangle$

Energy per particle $E = 3m\omega_z^2 \langle z^2 \rangle$

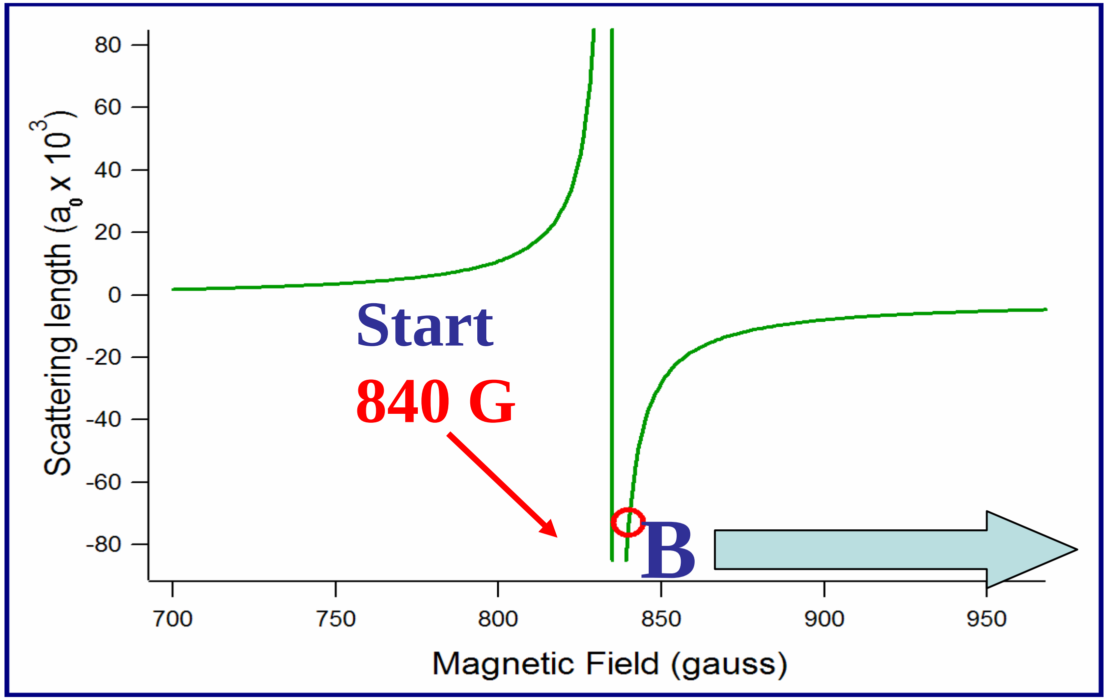


For a *universal* quantum gas, the energy E is determined by the *cloud size*

Source: J.E. Thomas

Entropy S Measurement by *Adiabatic* Sweep of Magnetic Field B

Duke Physics
Atom Cooling and Trapping



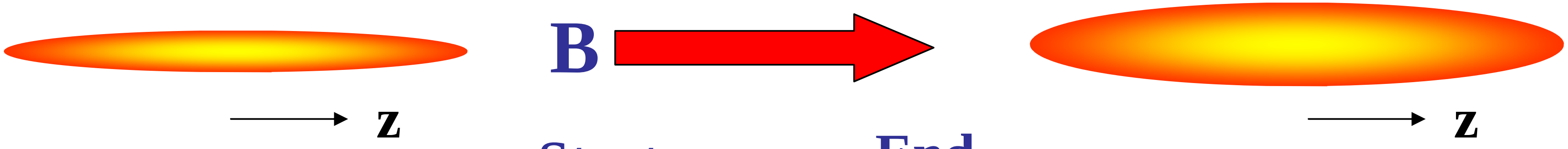
End
1200 G

Source: J.E. Thomas

Weakly interacting:
Entropy at 1200 G known from cloud size — Ideal Fermi gas

Measuring the Energy E versus Entropy S by Adiabatic Sweep of Magnetic Field B

Duke Physics
Atom Cooling and Trapping



Start
840 G

End
1200 G

Strongly interacting at 840 G:
Energy **E_S known from cloud size**
— Universal Fermi gas

Weakly interacting at 1200 G:
Entropy **S_W known from cloud size**
— Ideal Fermi gas (textbook)

Energy Measurement:

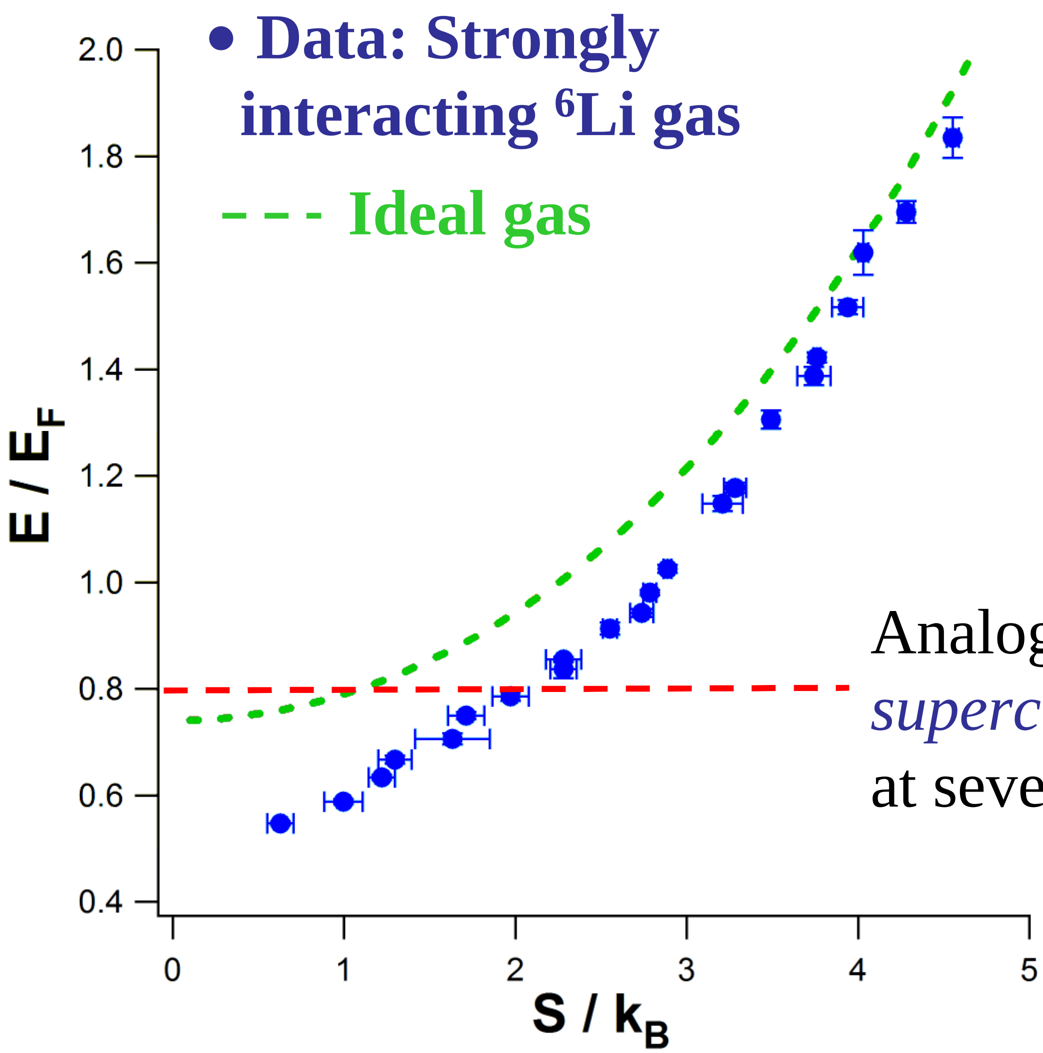
$$E_S = 3m\omega_z^2 \langle z^2 \rangle_{840G}$$

Adiabatic:

$$S_S = S_W$$

Source: J.E. Thomas

Energy versus Entropy



Critical temperature for the *superfluid transition*

$$T = \frac{\partial E}{\partial S}$$

$T_c = 0.20\ T_F$!!

Analog of a *super-high temperature superconductor* that would work at several *thousand* degrees!

Source: J.E. Thomas

Viscous Hydrodynamics

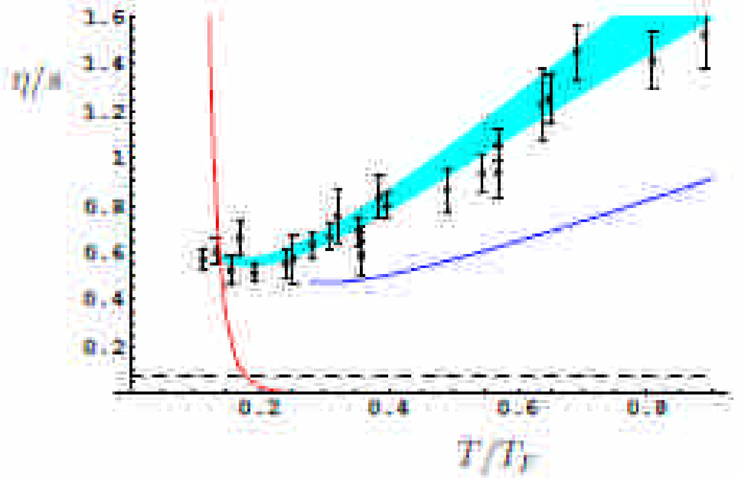
Energy dissipation (η, ζ, κ: shear, bulk viscosity, heat conductivity)

$$\dot{E} = -\frac{1}{2}\int d^3x\,\eta(x)\left(\partial_i v_j + \partial_j v_i - \frac{2}{3}\delta_{ij}\partial_k v_k\right)^2 - \int d^3x\,\zeta(x)\,(\partial_i v_i)^2 - \frac{1}{T}\int d^3x\,\kappa(x)\,(\partial_i T)^2$$

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

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

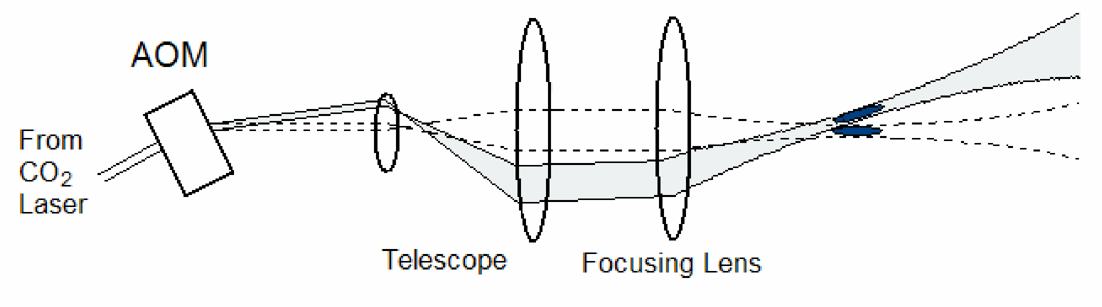
Schaefer (2007), see also Bruun, Smith

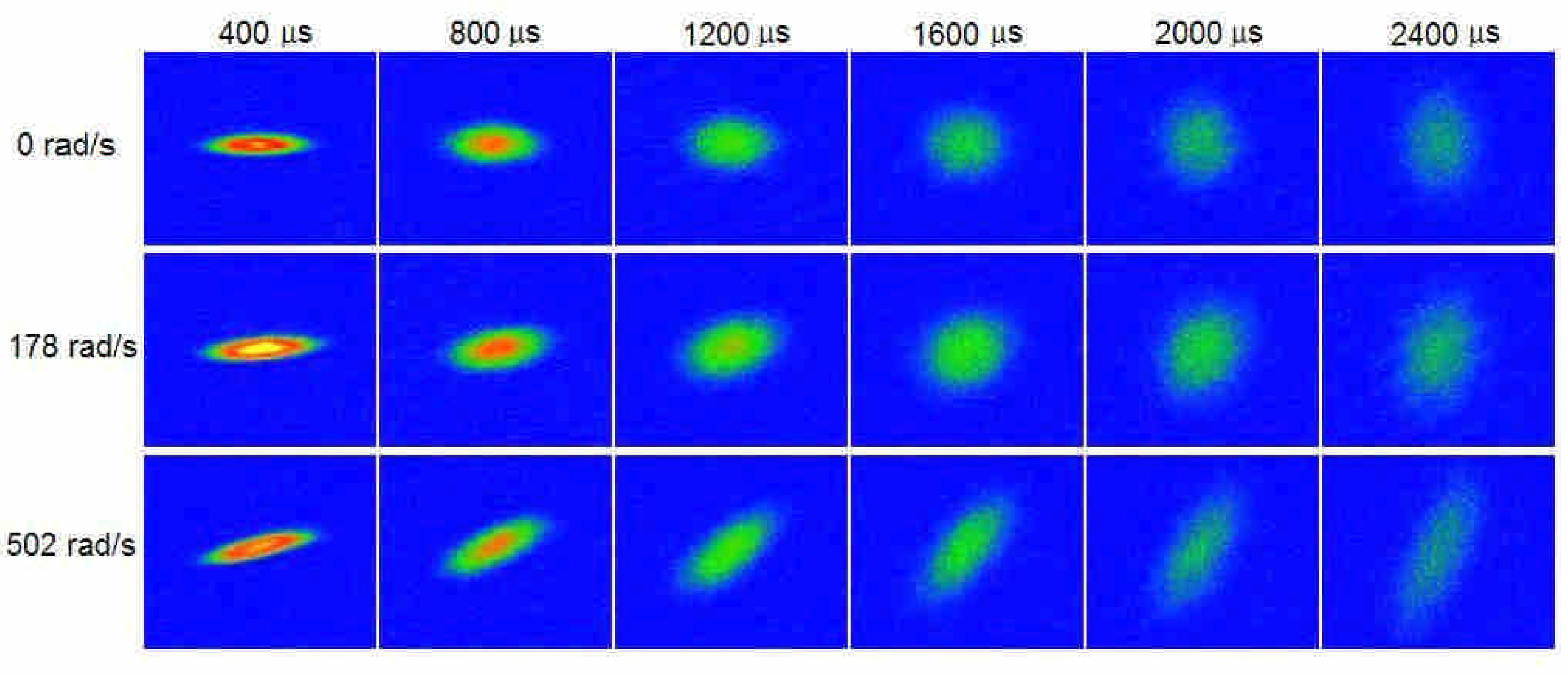


Source: T. Schafer

N dependence not seen!

Expansion of a rotating gas



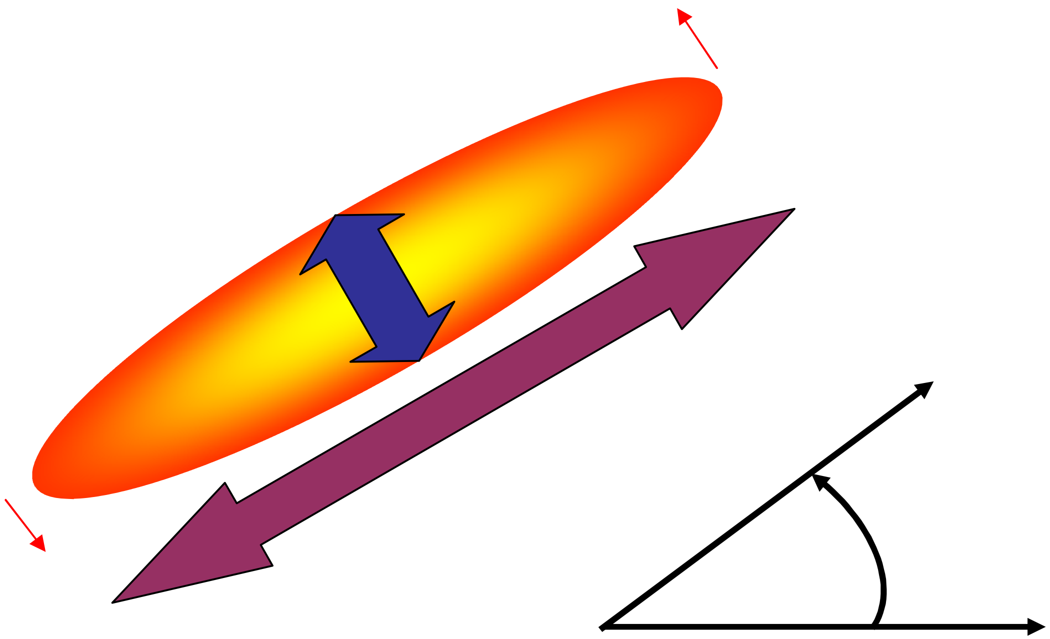


Source: J.E. Thomas

Measuring the *angle* of the cloud

Duke Physics

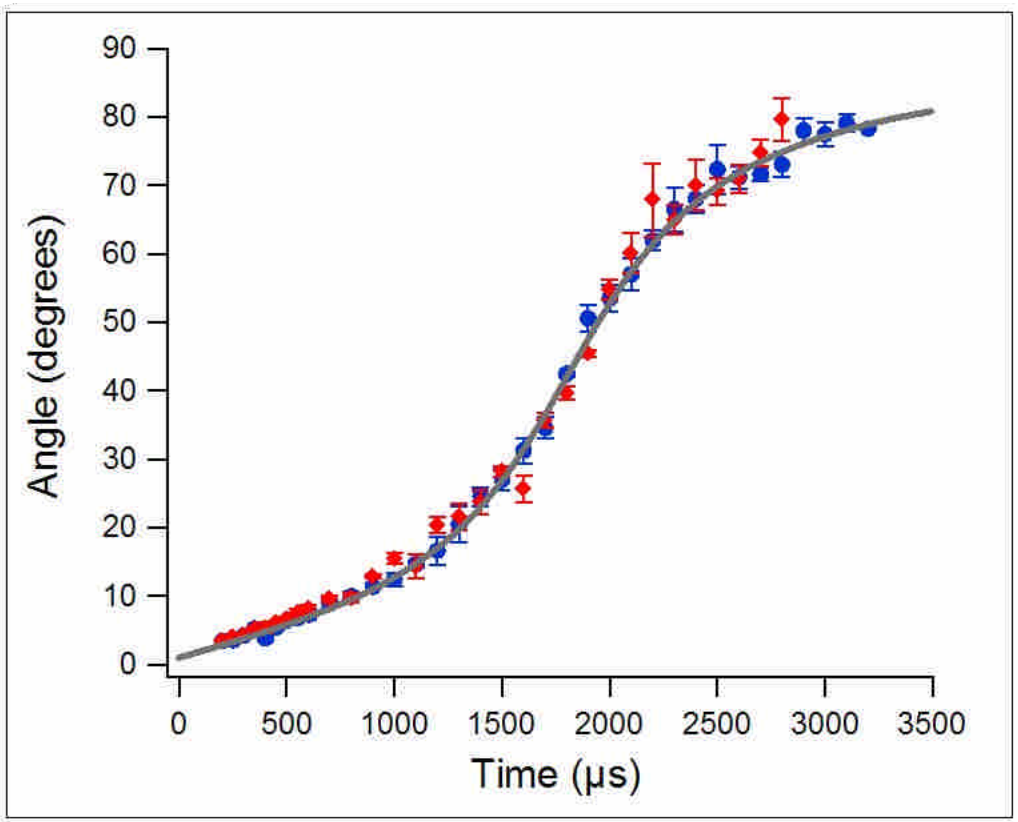
Atom Cooling and Trapping



Measure the *angle* of the *long* axis of the rotating cloud with respect to the laboratory axis

Source: J.E. Thomas

Measuring the *Angular Velocity*



Theory—superfluid flow

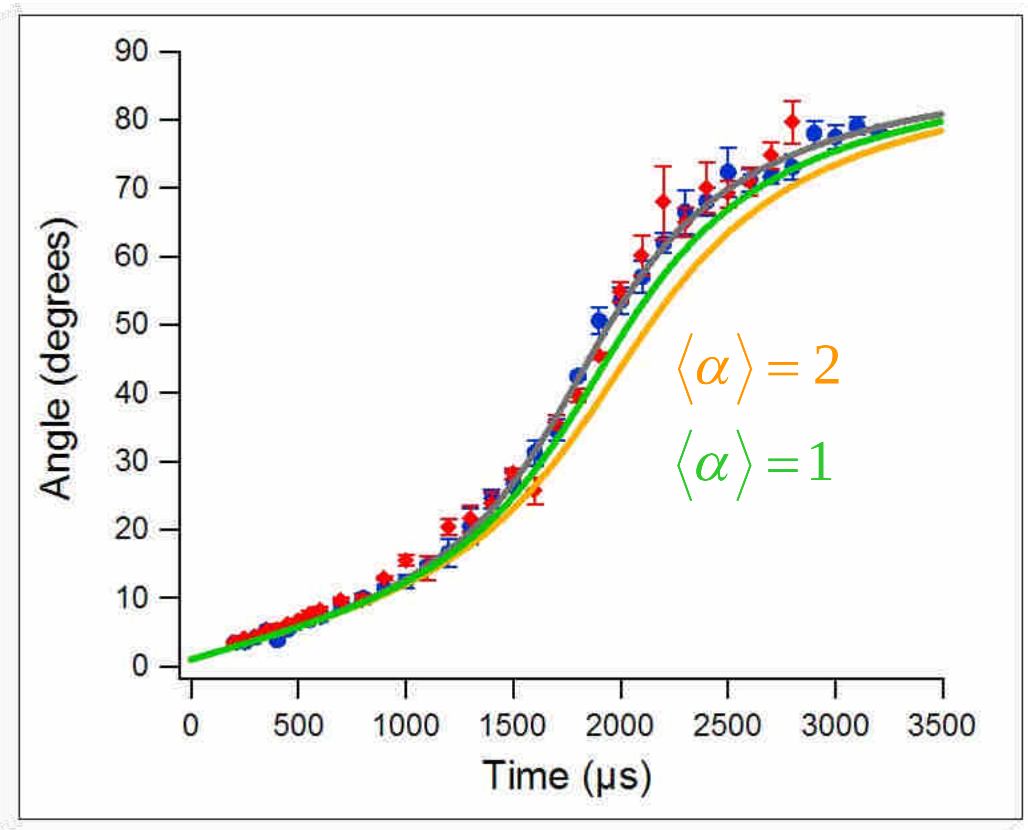
Rotates *faster* as it *expands*—*opposite* to the behavior of an ice-skater!

Source: J.E. Thomas

- Superfluid, Ω_0 = 178 rad/s
- Normal Fluid, Ω_0 = 178 rad/s

How low is the viscosity η?

$$\eta = \alpha \hbar n$$

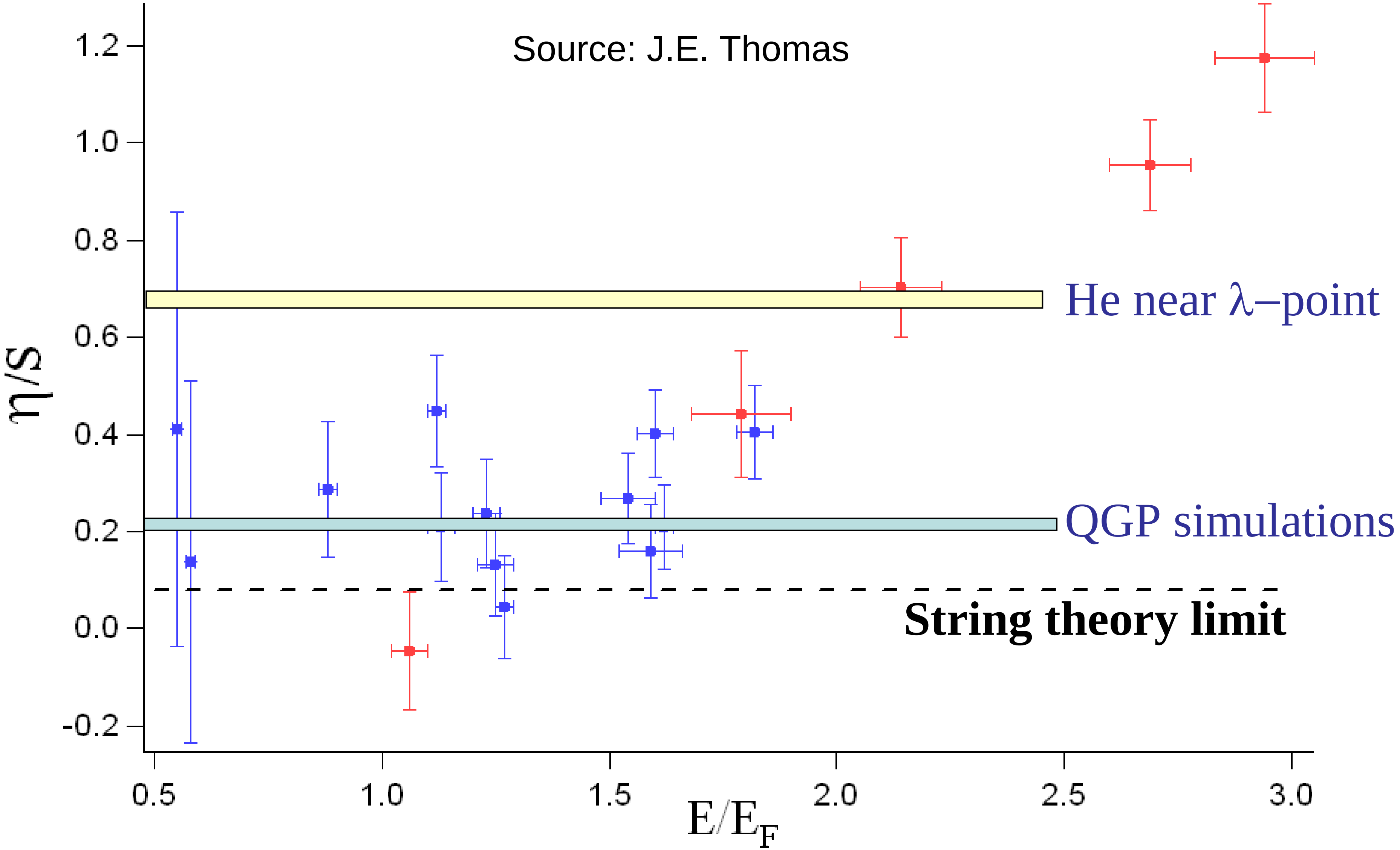


Source: J.E. Thomas

- Ω_0 = 178 rad/s ; Superfluid
- Ω_0 = 178 rad/s ; Normal Fluid

Viscosity/entropy density (units of $\hbar / k_B$)

Duke Physics
Atom Cooling and Trapping



Schafer & Chafin, 0912.4236; Normal fluid

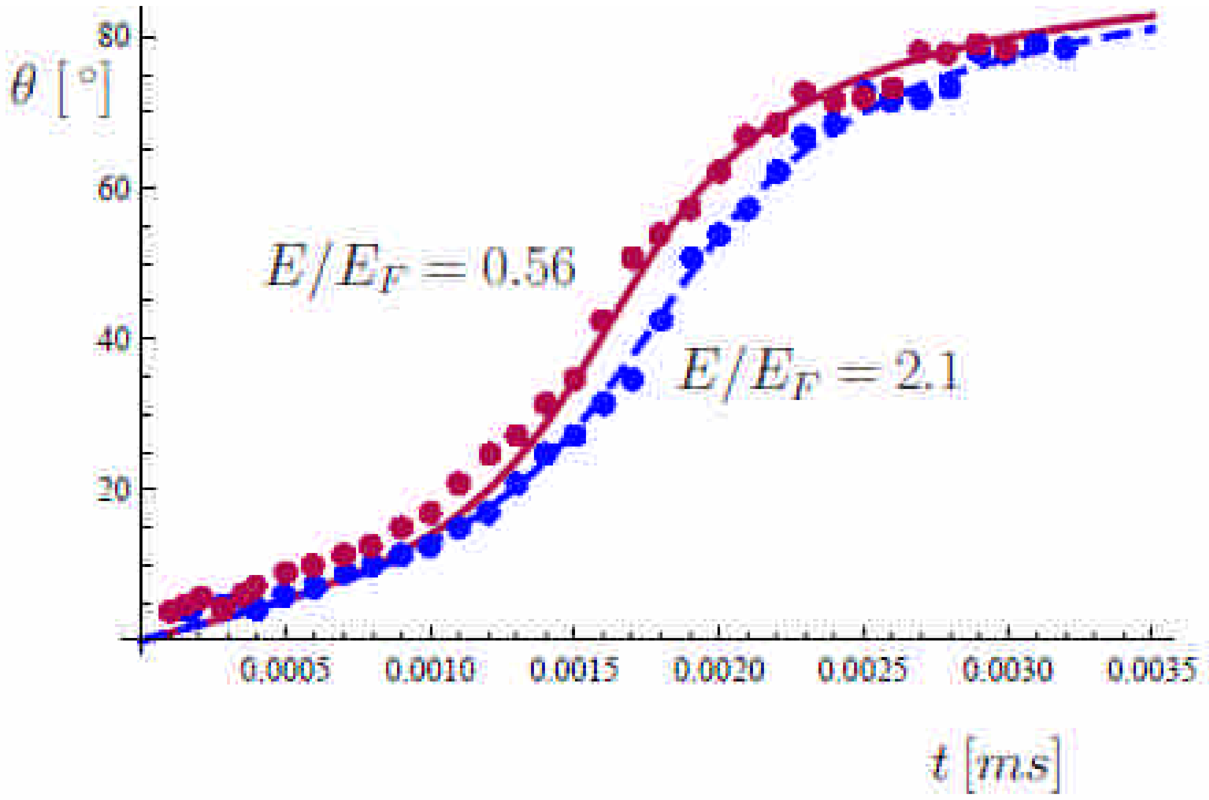
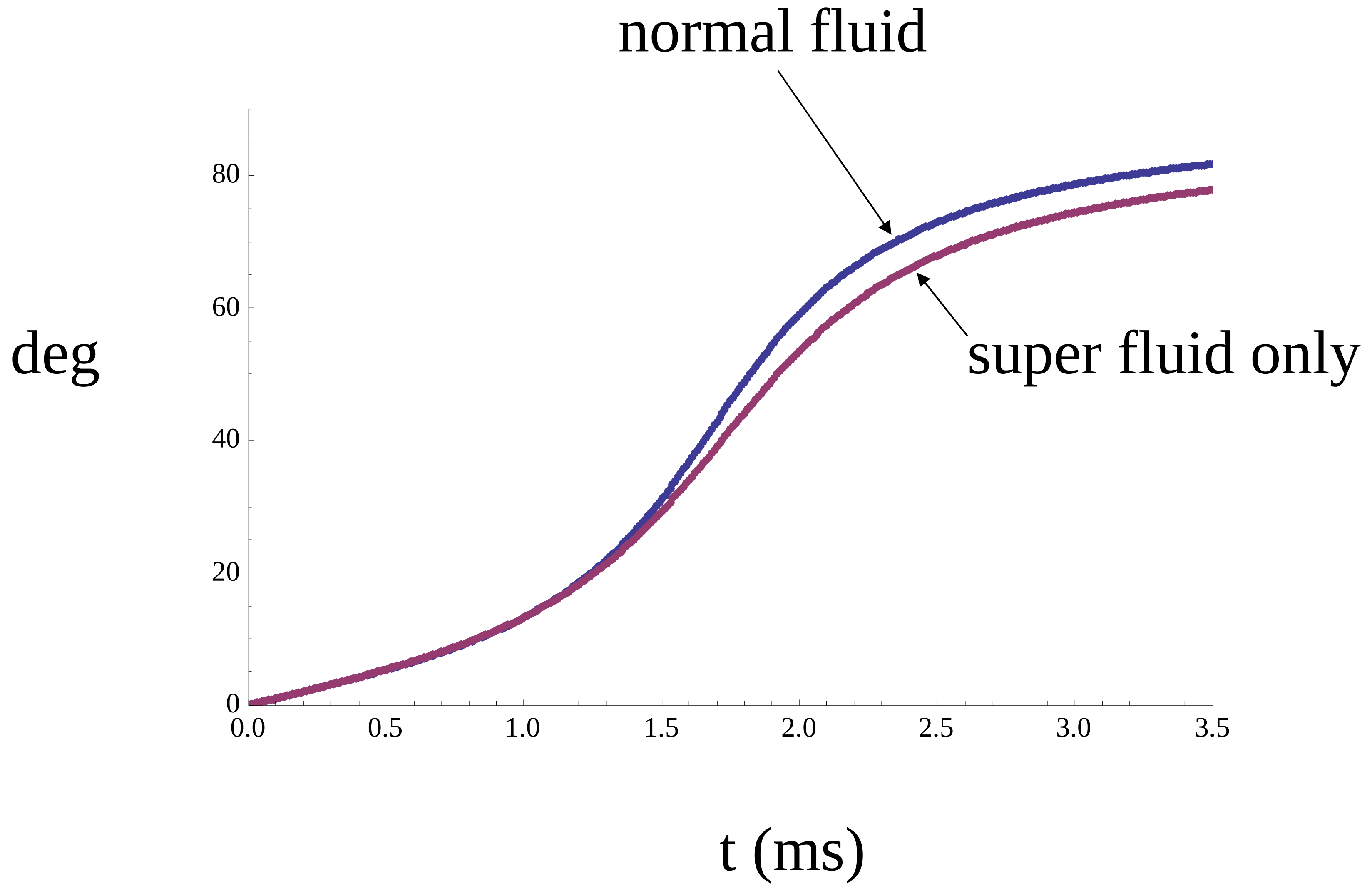


Fig. 5 Time evolution of the angle of the major axis of a rotating expanding cloud after release from the trapping potential. The data are taken from [14]. The two data sets were obtained with initial energies $E/E_F = 0.56$ and 2.1. The solid line shows the prediction of ideal fluid dynamics, and the dashed lines shows the solution of the Navier-Stokes equation for $\beta = 0.077$. Using an entropy per particle $S/N \simeq 4.8$ this value of β implies a shear viscosity to entropy density ratio $\langle \alpha_s \rangle = 0.76$



normal fluid
super fluid only
deg
t (ms)
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Outlook

- Is the two fluid model a good starting point?