MEASURING LOCAL SHEAR VISCOSITY IN FERMI GASES

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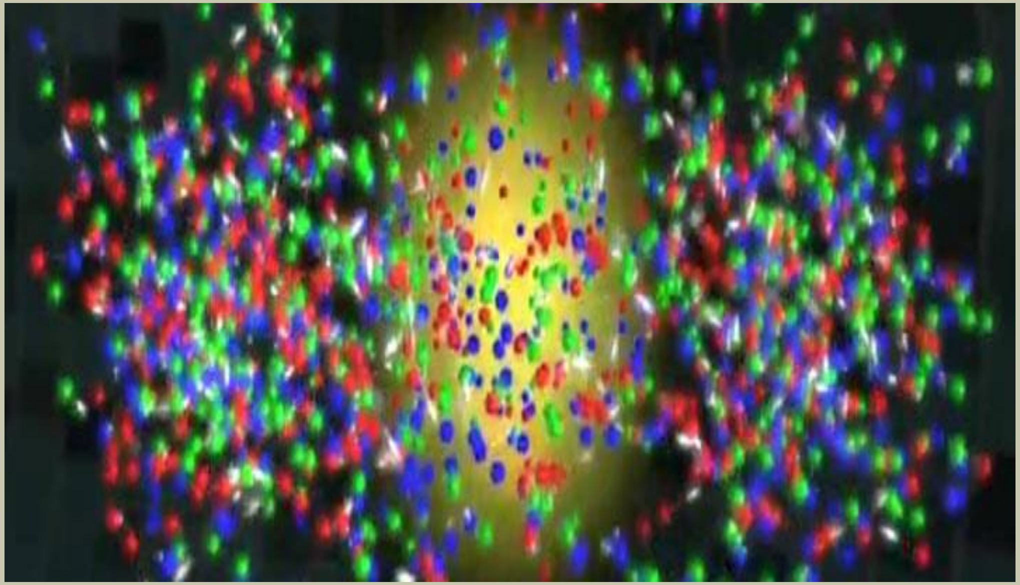
April 2, 2015

INT workshop
Frontiers in quantum simulation with cold atoms

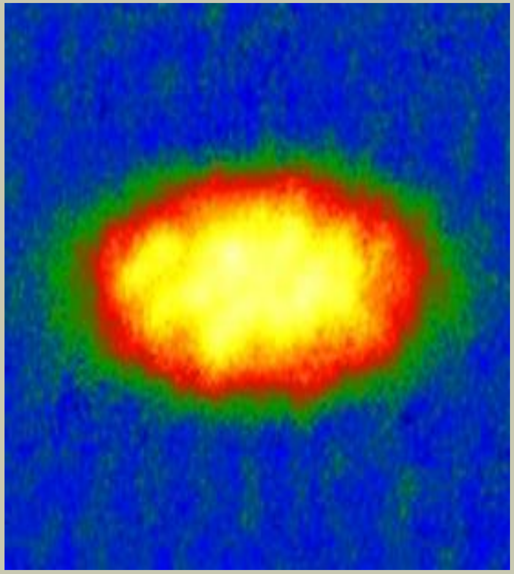
University of Washington

WHY STUDY SHEAR VISCOSITY IN FERMI GASES?

Strongly Interacting Hydrodynamic Systems



Quark Gluon Plasma



Ultra-Cold Fermi Gas

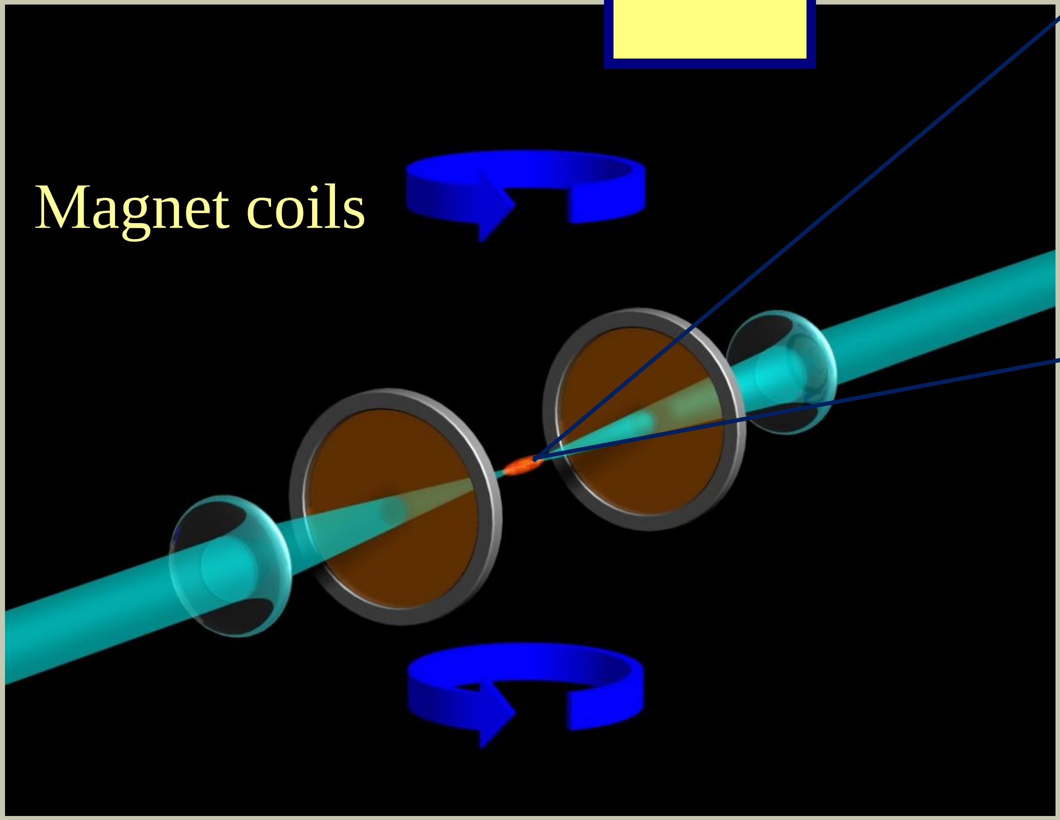
OUTLINE

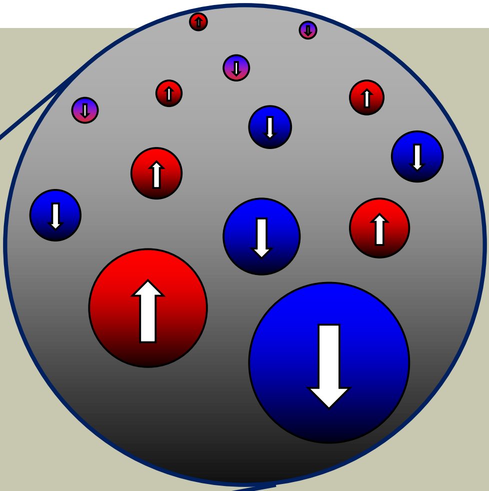
- Creating a fluid out of a gas
  - Optically trapped strongly interacting Fermi gas
- Transport Measurements
  - Measuring *cloud averaged* shear viscosity in expanding Fermi gases
  - Thermometry from the equation of state
- Iterative Matrix Inversion
  - Obtaining *local* shear viscosity from cloud averages using *image processing* methods
  - Discovering hidden features in the local shear viscosity and direct comparison to theory

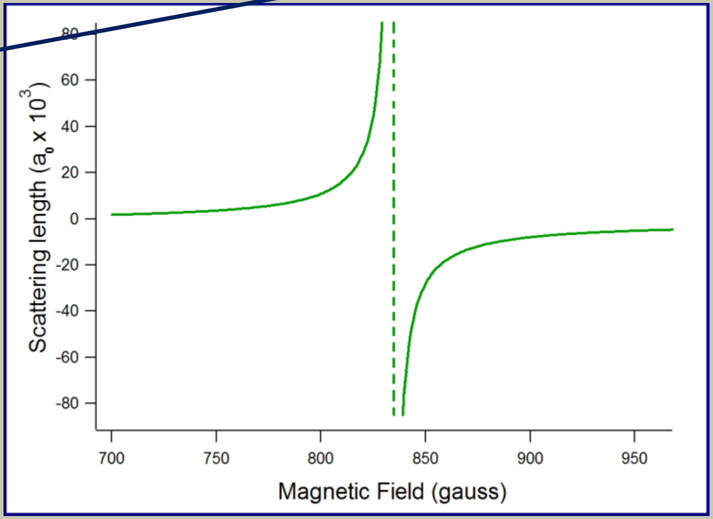
OPTICALLY TRAPPED FERMI GAS

Our atom: Fermionic

^{6}Li

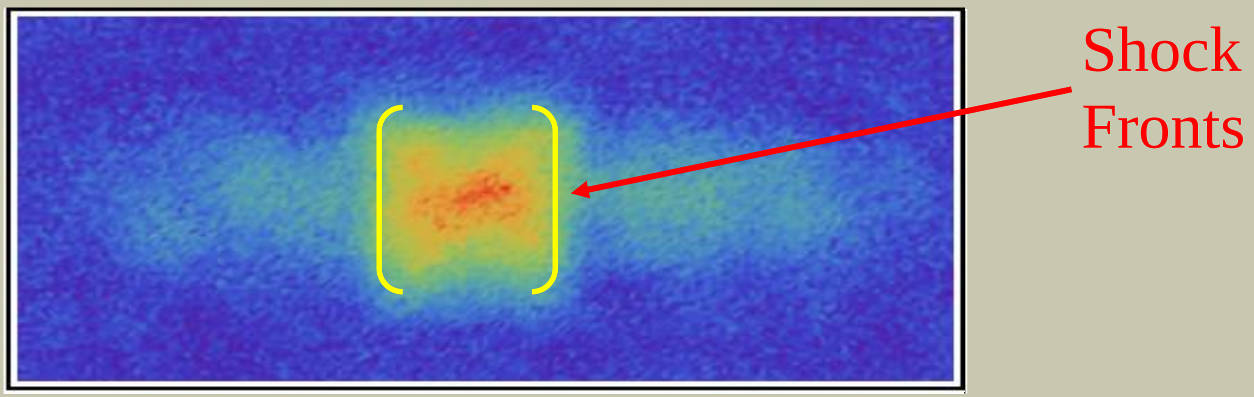






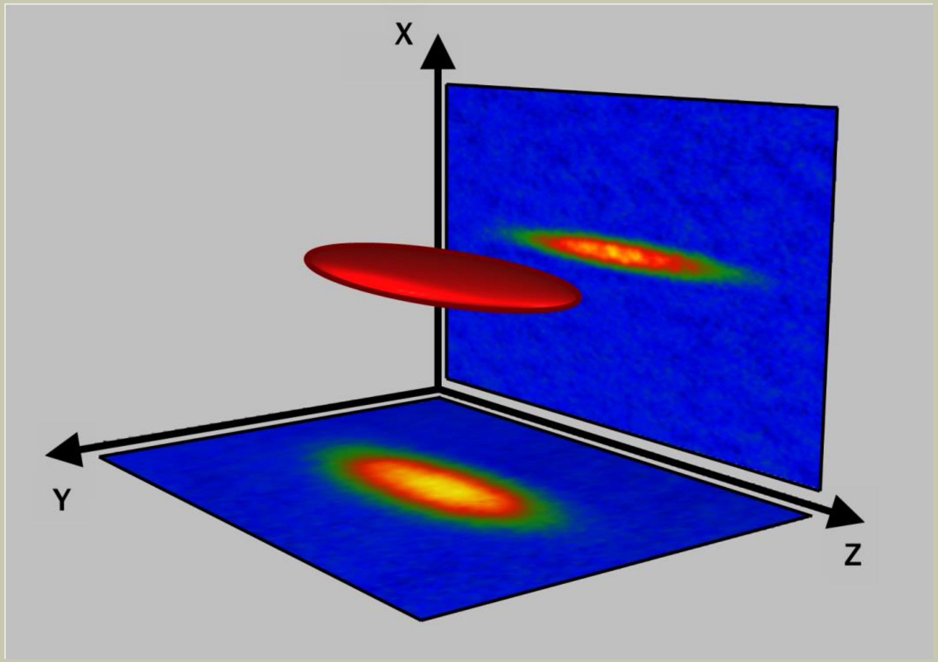
STRONG INTERACTIONS: SHOCK WAVES IN FERMI GASES

- Trapped gas is divided into two clouds with a repulsive optical potential.
- The repulsive potential is extinguished, the two clouds accelerate towards each other and collide.



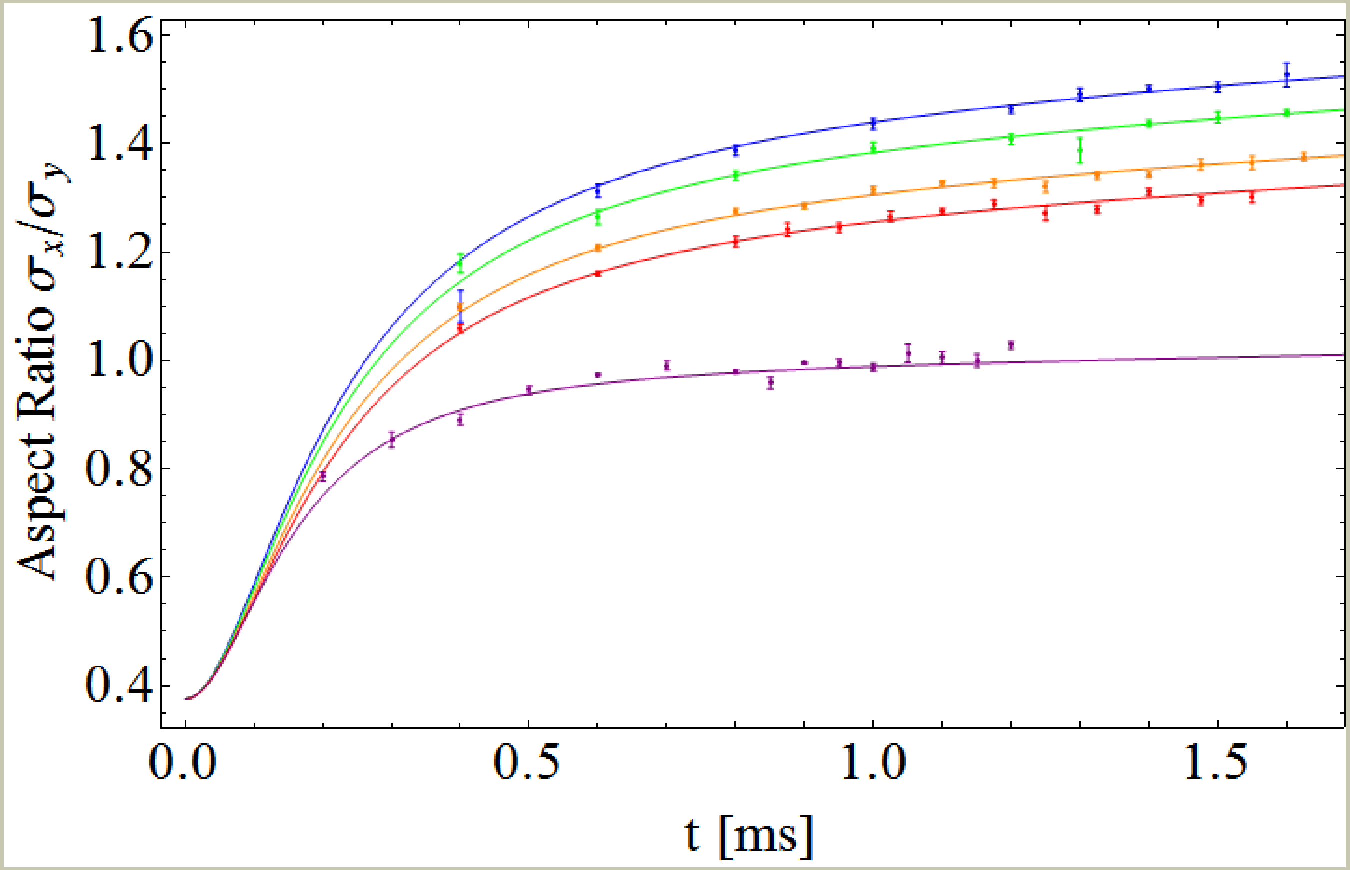
SHEAR VISCOSITY FROM EXPANSION

A gas trapped in a 3-wise (1:3:30) elliptical trap is allowed to expand. Absorption images are taken in two planes.



Trap averaged viscosity determined from XY aspect ratio.

ASPECT RATIO VS EXPANSION TIME



832 G

- E/E_F=0.52
- E/E_F=0.75
- E/E_F=1.22
- E/E_F=1.69

527.5 G

- **Ballistic**

SCALING APPROXIMATION FOR HYDRODYNAMIC EXPANSION

$$n(x,y,x,t) = \frac{n_0(x/b_x, y/b_y, z/b_z)}{\Gamma}$$

$$\Gamma = b_x b_y b_z$$

Volume scale factor

$$\ddot{b}_i = \frac{\overline{\omega_i^2}}{\Gamma^{2/3} b_i}\left[1 + C_Q(b_{ijk}, \langle \alpha_S \rangle)\right] - \frac{\hbar \langle \alpha_S \rangle \sigma_{ii}}{m \langle x_i^2 \rangle_0 b_i}$$

$$\sigma_{ii} = 2\frac{\dot{b}_i}{b_i} - \frac{2}{3}\frac{\dot{\Gamma}}{\Gamma}$$

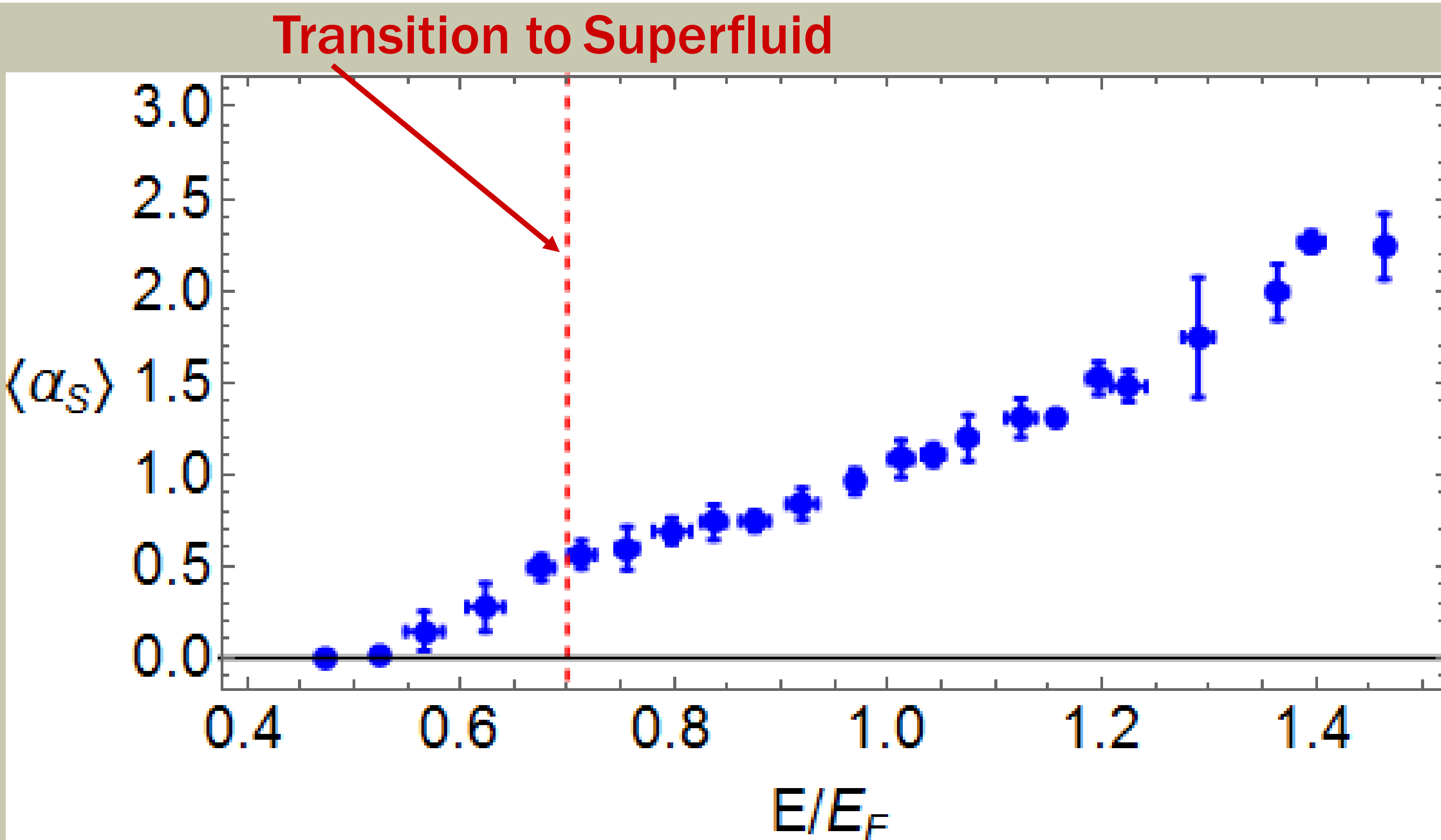
Viscous stress tensor

cloud-averaged shear viscosity coefficient

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

$$\langle \alpha_S \rangle = \frac{1}{N}\int d^3 r\, \alpha\, n$$

CLOUD AVERAGE SHEAR VISCOSITY VS ENERGY

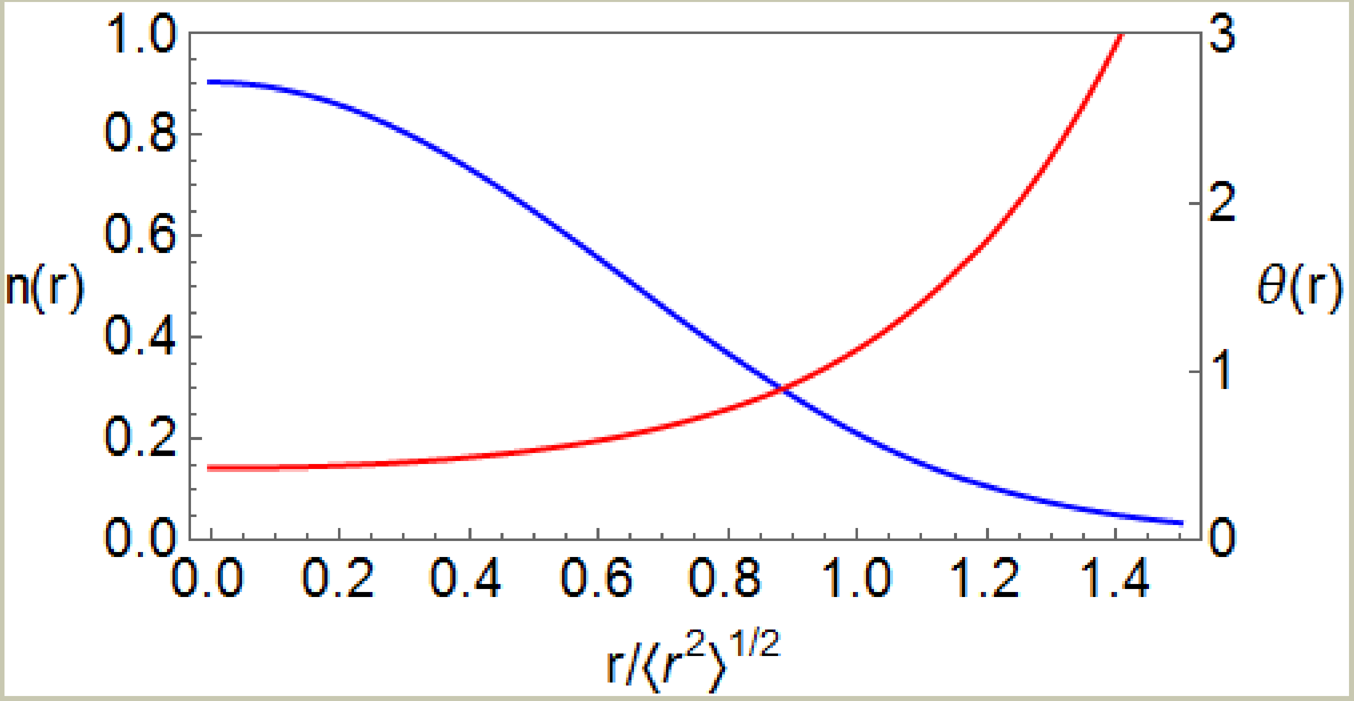


REDUCED TEMPERATURE

The trapping potential and the equation of state determine the density n(r) as a function of position at a given temperature, T.

$$U(r) = U_0\left[1 - \exp\frac{\left(-m\bar{\omega}^2 r^2\right)}{2U_0}\right]$$

*EoS from Ku et al., *Science*, 2012

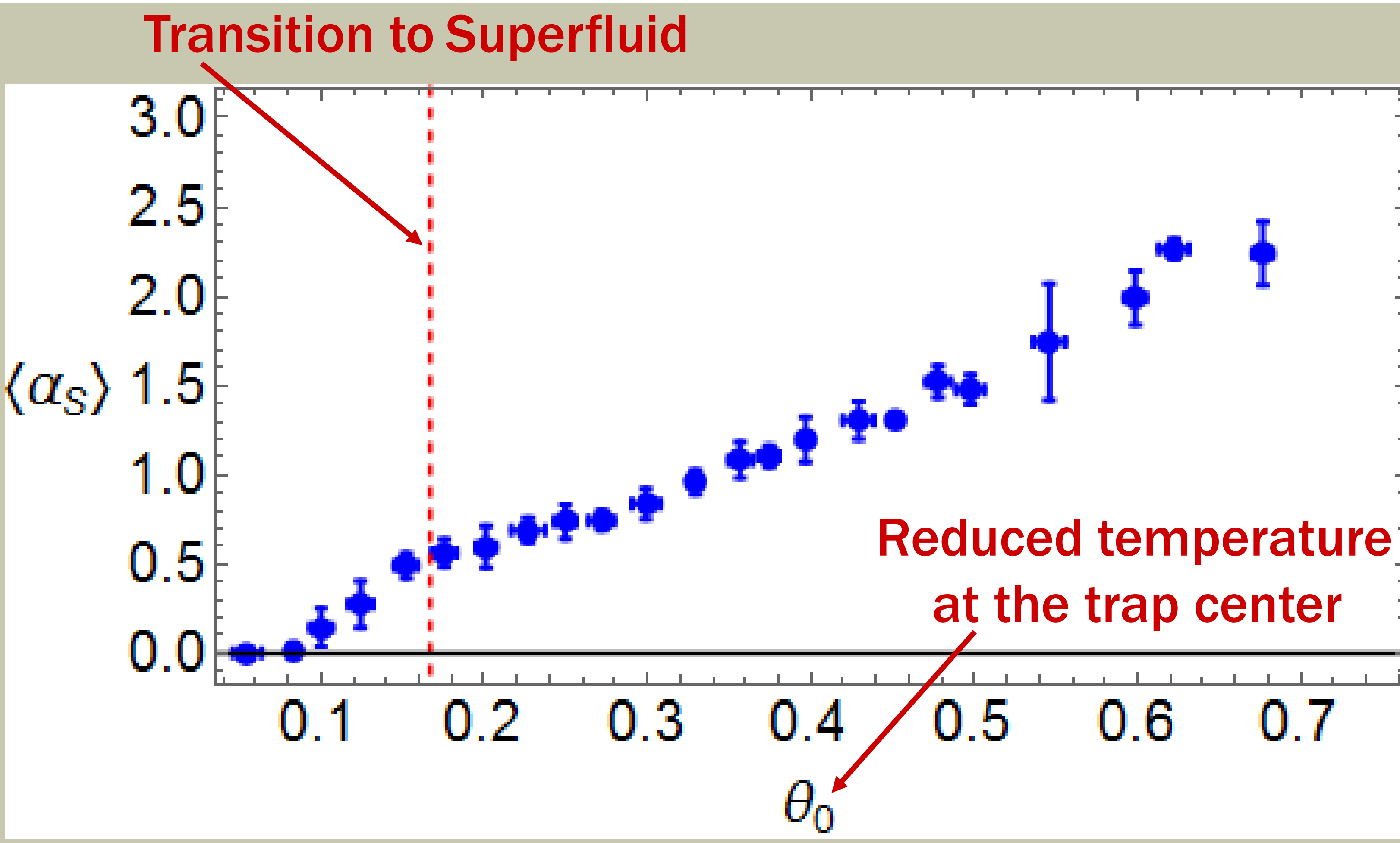


Reduced Temperature

$$\theta(\mathrm{r}) = \frac{\mathrm{T}}{\mathrm{T_F}(r)}$$

$$\mathrm{T_F}(r) \propto n(r)^{2/3}$$

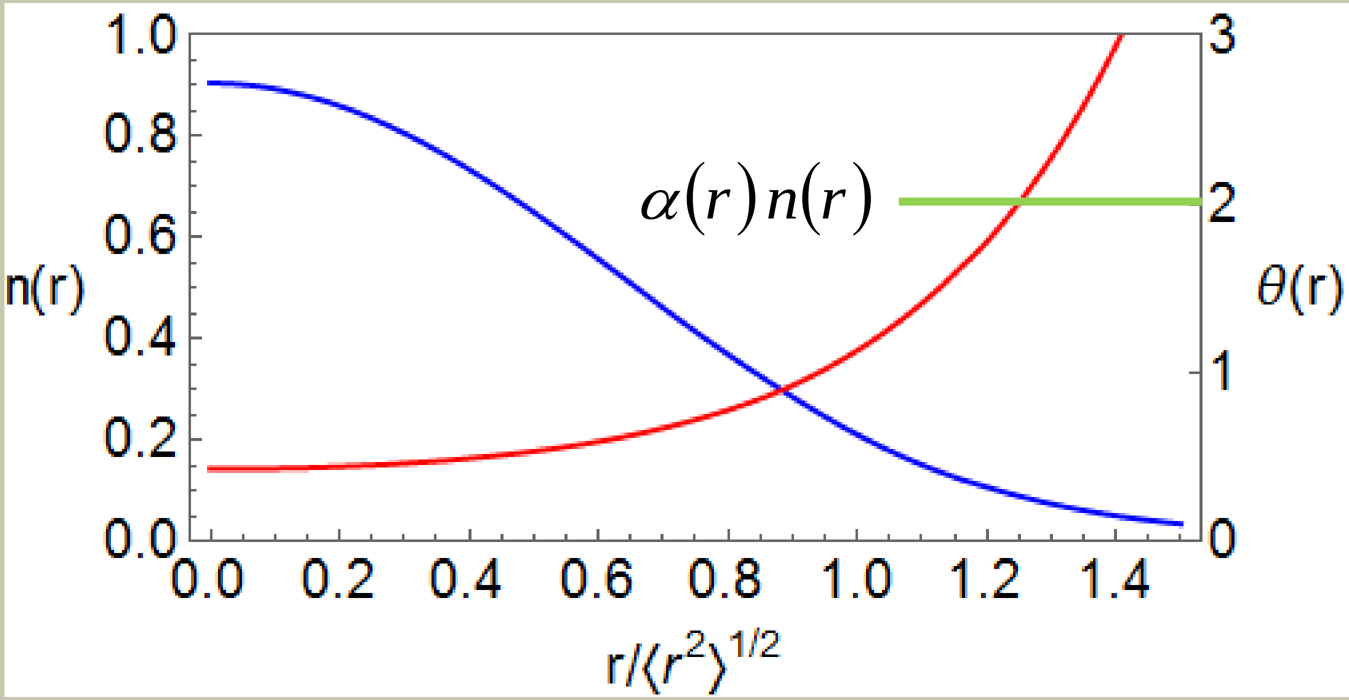
CLOUD AVERAGED SHEAR VISCOSITY VERSUS REDUCED TEMPERATURE



LOCAL VISCOSITY VS POSITION (HIGH TEMPERATURE LIMIT)

$$\langle \alpha_s \rangle = \frac{1}{N} \int_0^\infty d^3r \, n(r) \alpha(r)$$

$$\eta = \hbar \, n(r) \alpha(r)$$

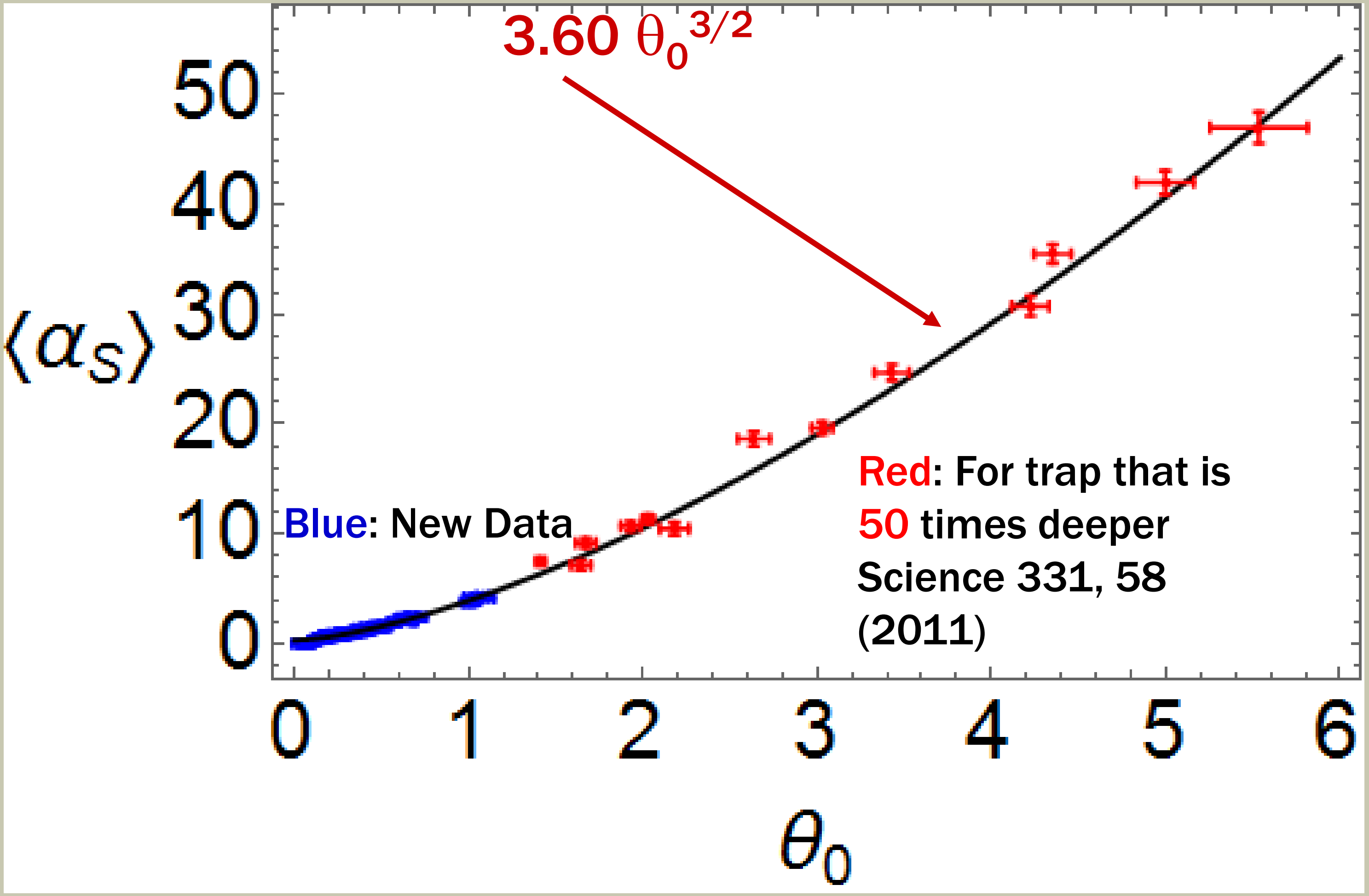


Constant in the trap

$$\eta \propto T^{3/2}$$

$$\alpha(\theta) = \alpha_{3/2} \theta^{3/2}$$

MEASURED CLOUD AVERAGED VISCOSITY (HIGH TEMPERATURE)



FINITE VOLUME INTEGRAL

$$\langle \alpha_S \rangle = \frac{1}{N} \int_0^{R_C} d^3r\, \alpha(r)\, n(r)$$

$$c_1 \theta_0^{3/2} = \frac{1}{N} \alpha_{3/2} \theta_0^{3/2} n_0 \frac{4\pi}{3} R_C^3$$

Volume

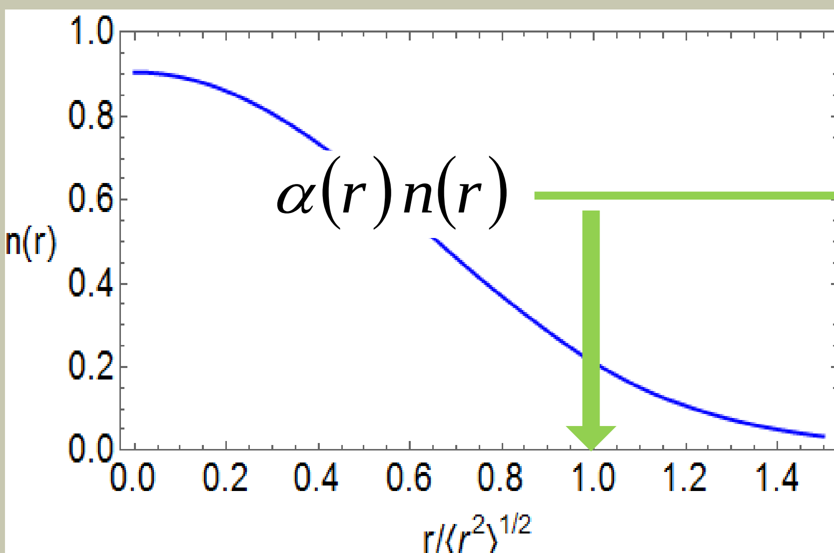
Fit from our data

c_1=3.60

from theory

$\alpha_{3/2}$=2.77

G. M. Bruun and H. Smith, Phys. Rev. A **75**, 043612 (2007).



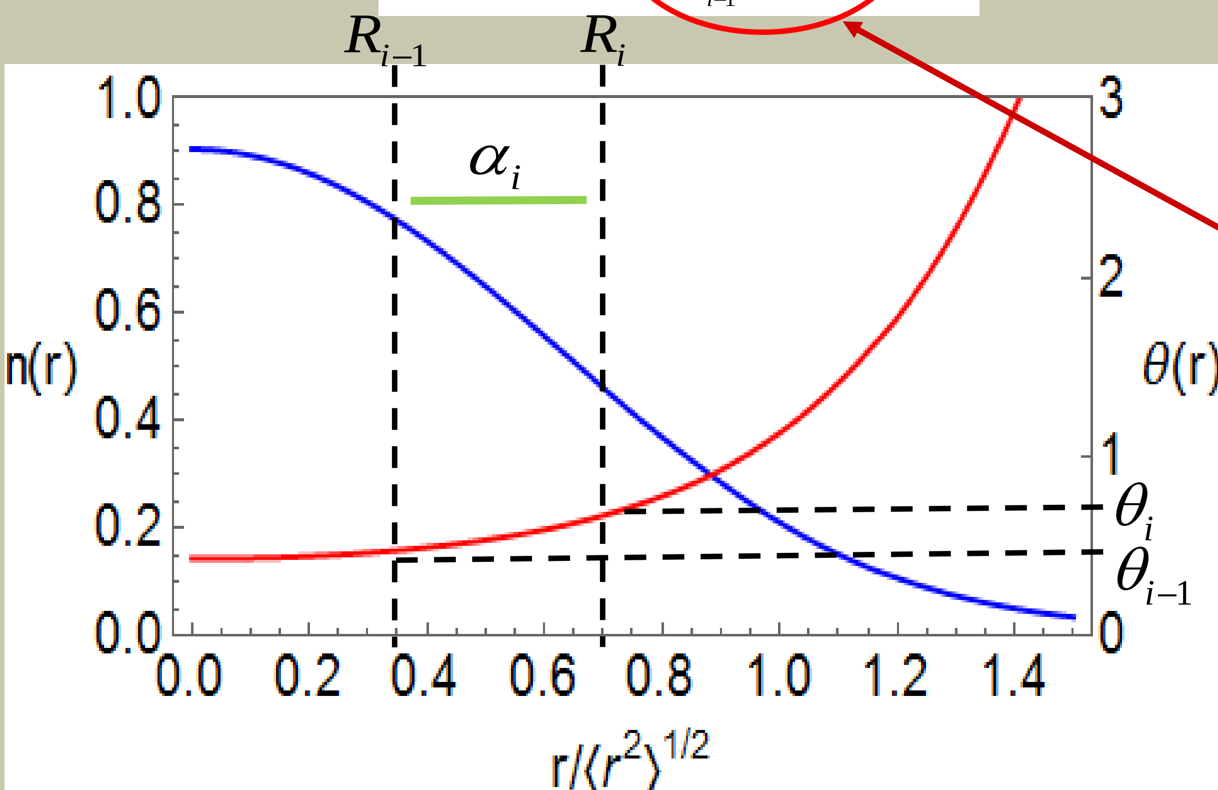
$$n_0 = N\left(\pi \frac{2}{3}\langle r^2 \rangle\right)^{-3/2}$$

For a Gaussian density

$$R_C = 0.98 \langle r^2 \rangle^{1/2}$$

LOCAL SHEAR VISCOSITY FROM TRAP AVERAGED MEASUREMENTS

$$\langle \alpha_S \rangle_j = \sum_i \frac{1}{N} \int_{R_{i-1}}^{R_i} d^3r\, n(r)\, \alpha_i$$



$$\alpha(\theta) = \begin{cases} \alpha_{\mathrm{i}} : \theta_{i-1} < \theta < \theta_i \\ \alpha_{\mathrm{i+1}} : \theta_i < \theta < \theta_{i+1} \\ \vdots \end{cases}$$

C_{ji}

$$\langle \boldsymbol{\alpha}_S \rangle = \mathbf{C}\boldsymbol{\alpha}$$

NOISY CLOUD-AVERAGED MEASUREMENTS (~200 POINTS)

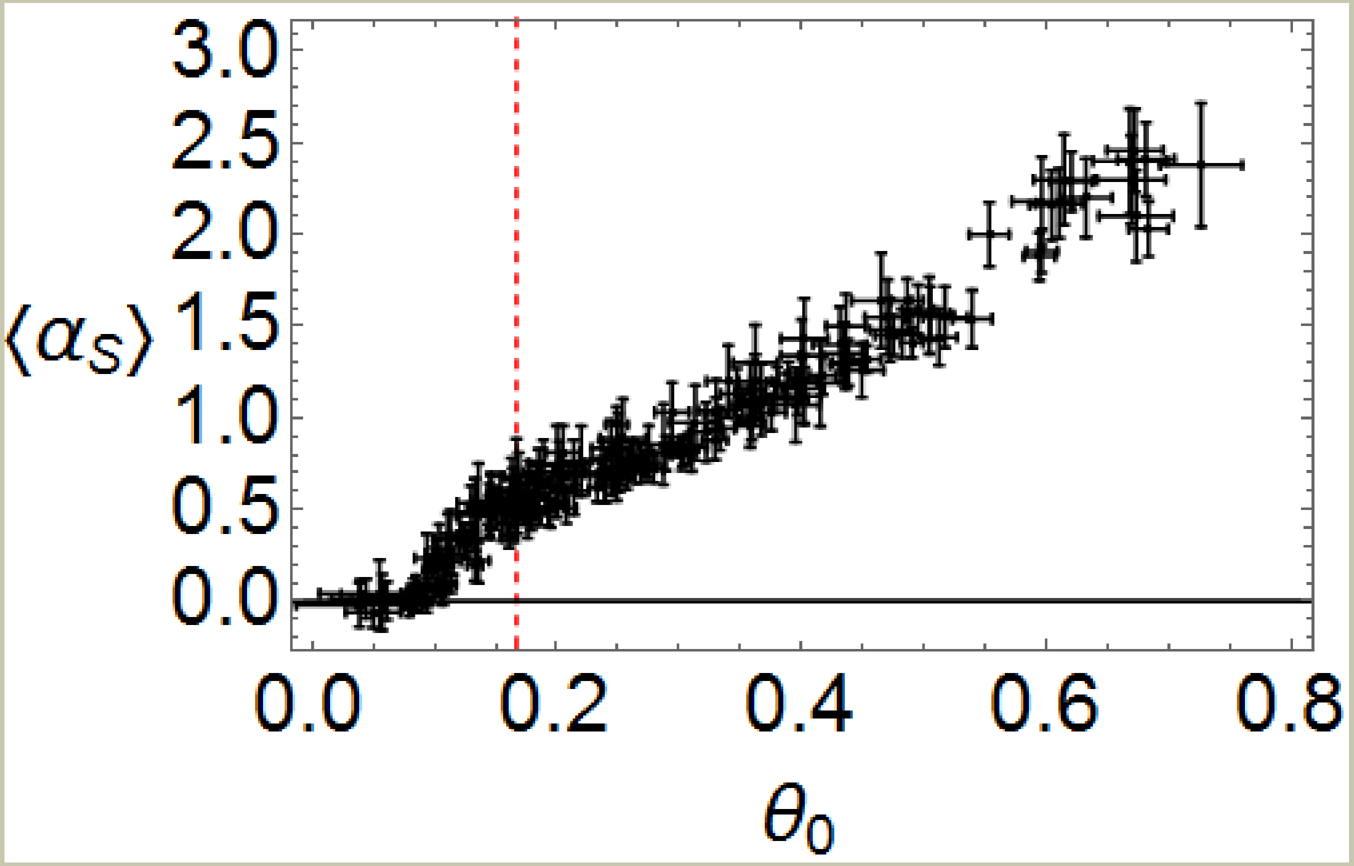
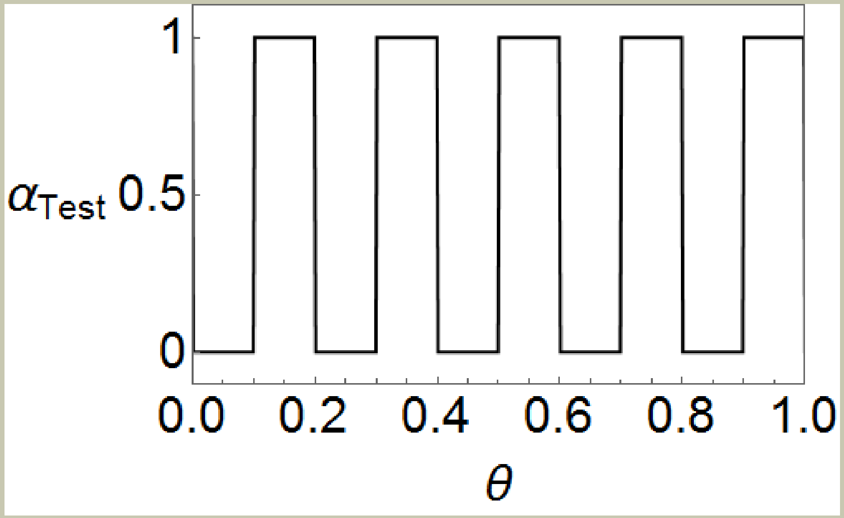
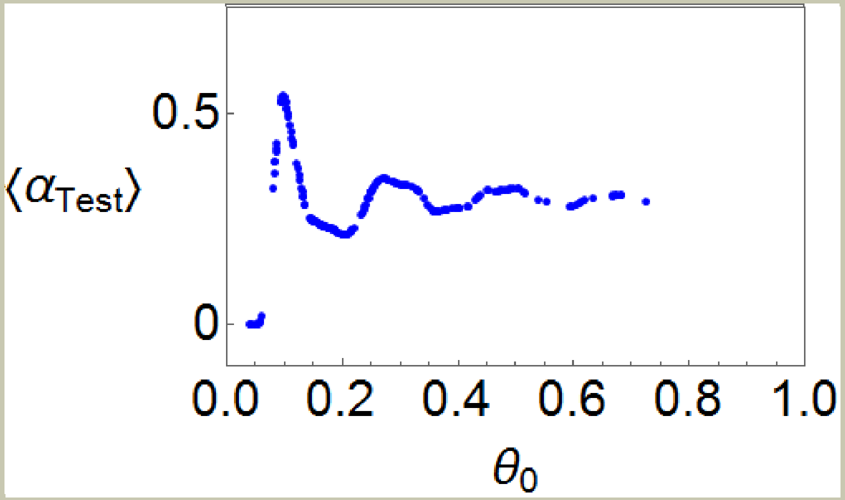


IMAGE PROCESSING TECHNIQUE
ITERATIVE MATRIX INVERSION

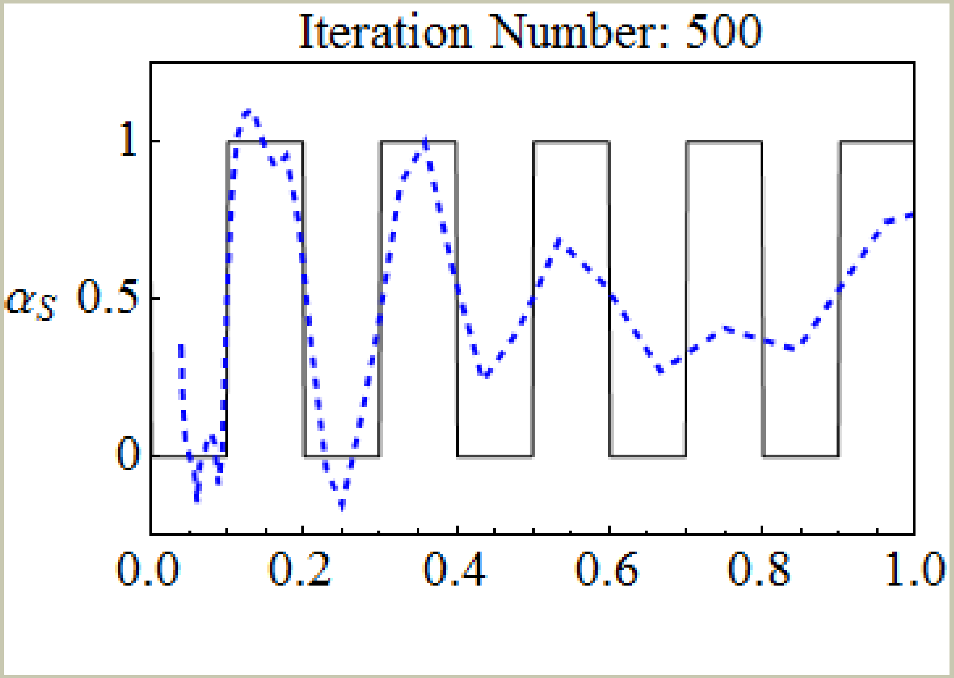
$$\boldsymbol{\alpha}_{m+1} = (1-\beta)\boldsymbol{\alpha}_m + \beta\,\Psi\left[\boldsymbol{\alpha}_m + \mathbf{C}^{\mathrm{T}}\left(\left\langle \boldsymbol{\alpha}_S \right\rangle - \mathbf{C}\bullet\boldsymbol{\alpha}_m\right)\right]$$





ITERATIVE SOLUTION TEST FUNCTION

$$\boldsymbol{\alpha}_{m+1} = (1-\beta)\boldsymbol{\alpha}_m + \beta\,\Psi\left[\boldsymbol{\alpha}_m + \mathbf{C}^{\mathrm{T}}\left(\langle\boldsymbol{\alpha}_S\rangle - \mathbf{C}\bullet\boldsymbol{\alpha}_m\right)\right]$$



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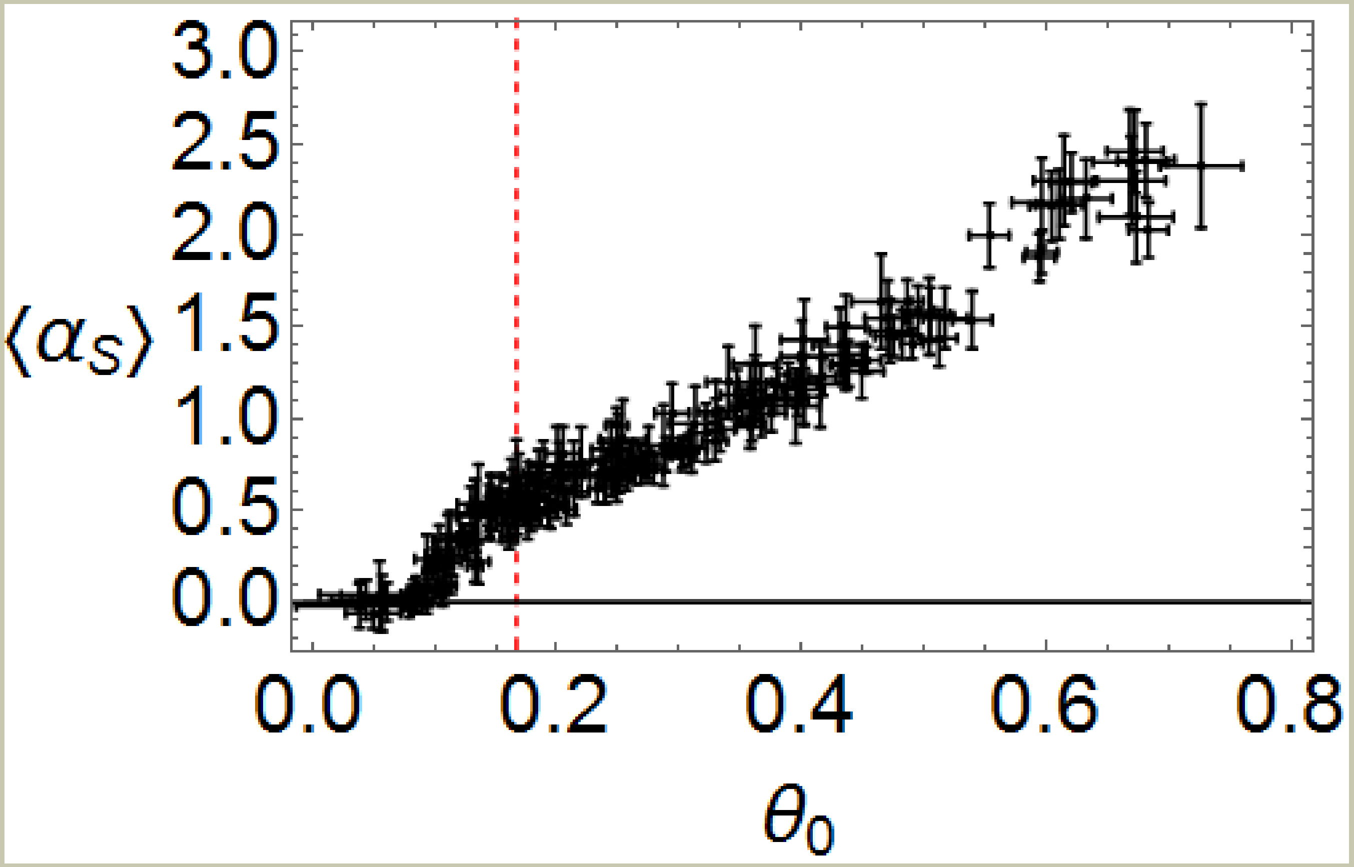
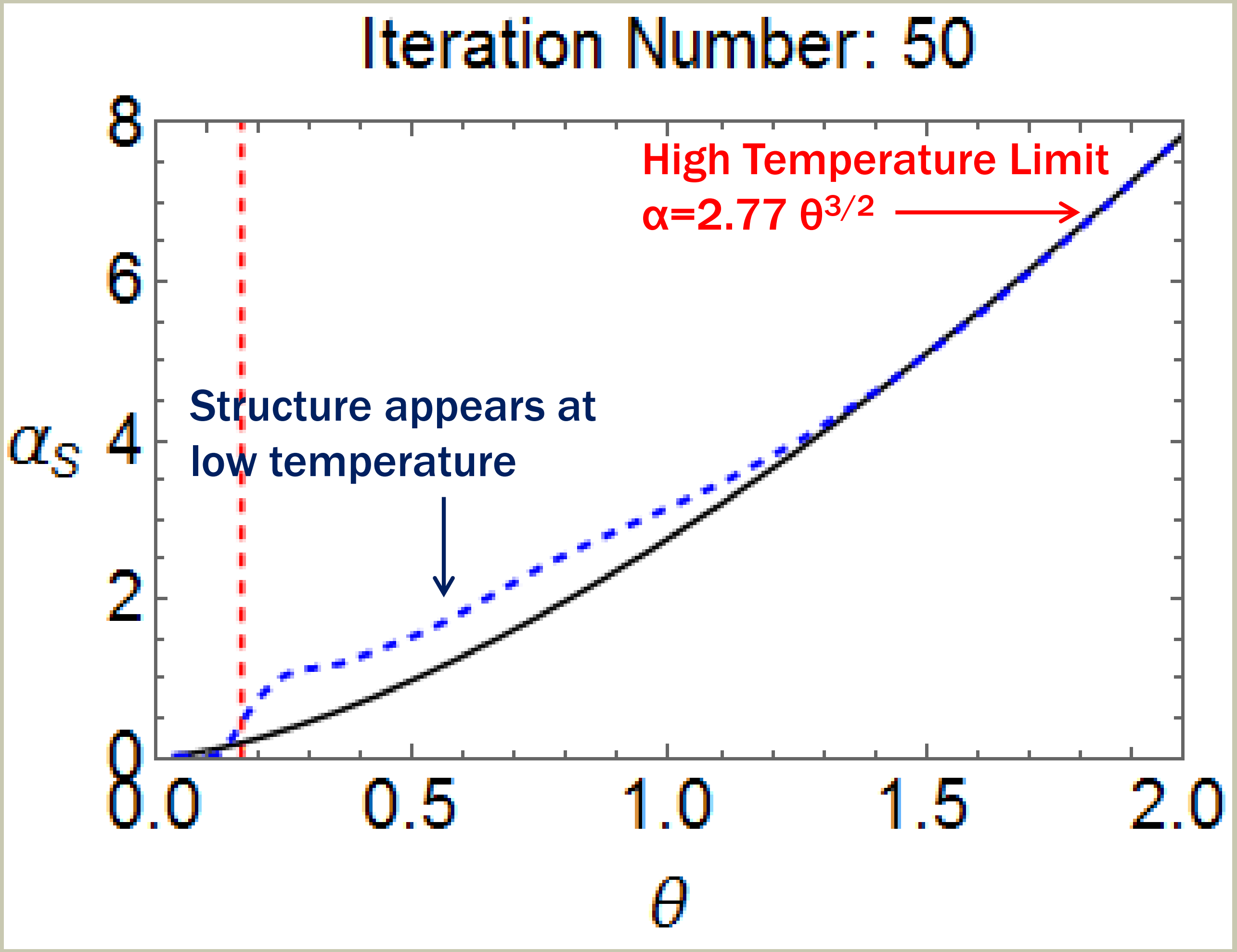
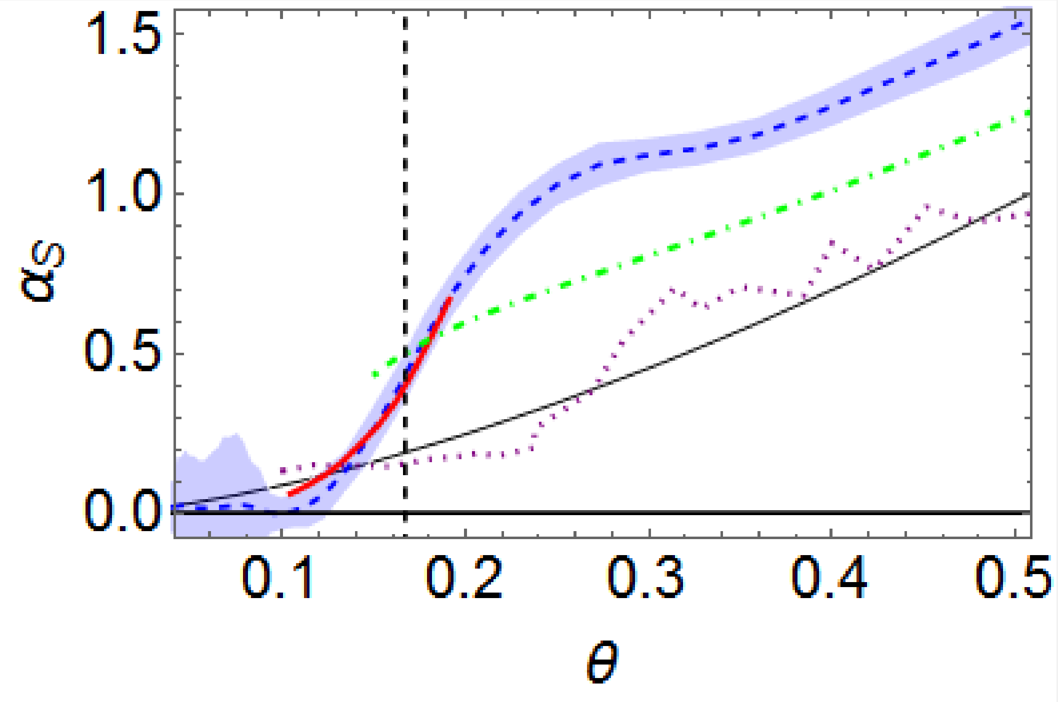


LOCAL SHEAR VISCOSITY VERSUS TEMPERATURE



LOCAL SHEAR VISCOSITY (COMPARISON TO THEORY)



measured

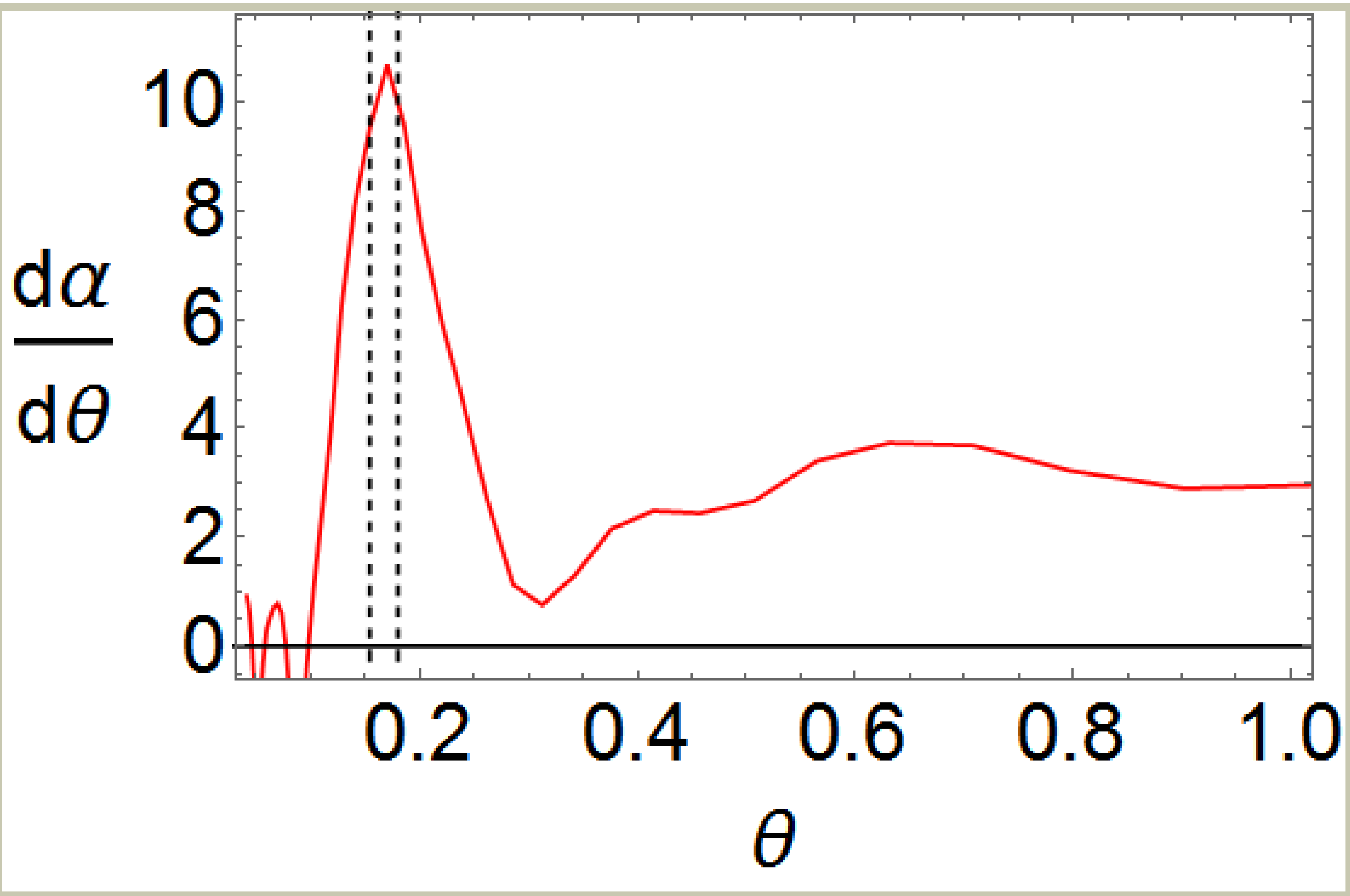
kinetic theory
$\alpha = 2.77\ \theta^{3/2}$

Guo et al., PRL 2011
(absent bosonic modes)

Enss et al., Annals 2011
(Diagrammatic Kubo formula)

Wlazłowski et al., PRL 2012 (Monte Carlo)

DERIVATIVE OF LOCAL SHEAR VISCOSITY VERSUS TEMPERATURE



SUMMARY

- Hydrodynamic Strongly Interacting Fermi Gas
- Measuring Cloud Averaged Shear
  - Scaling approximation used to measure energy per particle and cloud averaged shear viscosity self consistently
- Determining Local Shear Viscosity
  - From image processing techniques
  - Comparison to theory

THANK YOU

Graduate Student:

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PI:

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Support:

ARO

NSF

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