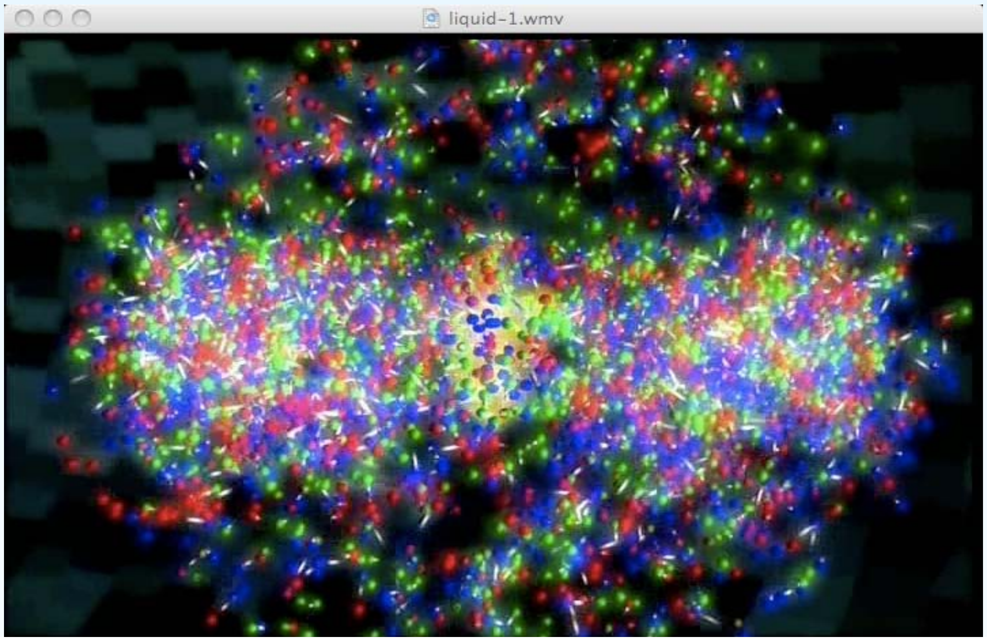
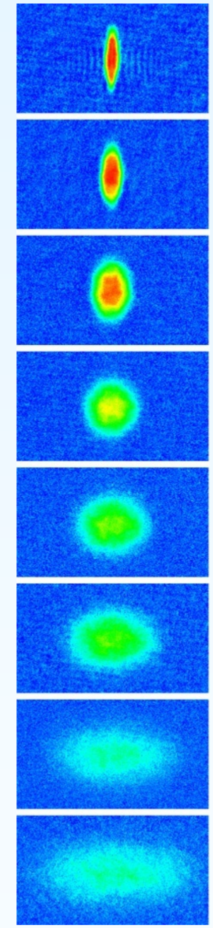
From Strongly-Interacting Fermi Gases to Nuclear Matter

John E. Thomas



Quark-gluon plasma T = 10^{12} K BIG BANG

Computer simulation of RHIC collision



Ultracold atomic gas

T = 10^{-7} K

JETLab Group

PHYSICS

Students:

Yingyi Zhang
Ethan Elliot
Willie Ong
Chinyun Cheng
Arun Jaganathan
Nithya Arunkumar

Post Docs:

Haibin Wu
Ilya Arakelian
James Joseph

J. E. Thomas

Support:

ARO
NSF
DOE
AFOSR

Former Members:

Ken O'Hara*
Mike Gehm*
Stephen Granade*
Staci Hemmer*
Joe Kinast*
Bason Clancy*
Le Luo*
Andrey Turlapov*
Xu Du*
Jessie Petricka*
Chenglin Cao*

Outline

PHYSICS

- *Introduction: Optically trapped Fermi gases:*
  – Universal behavior

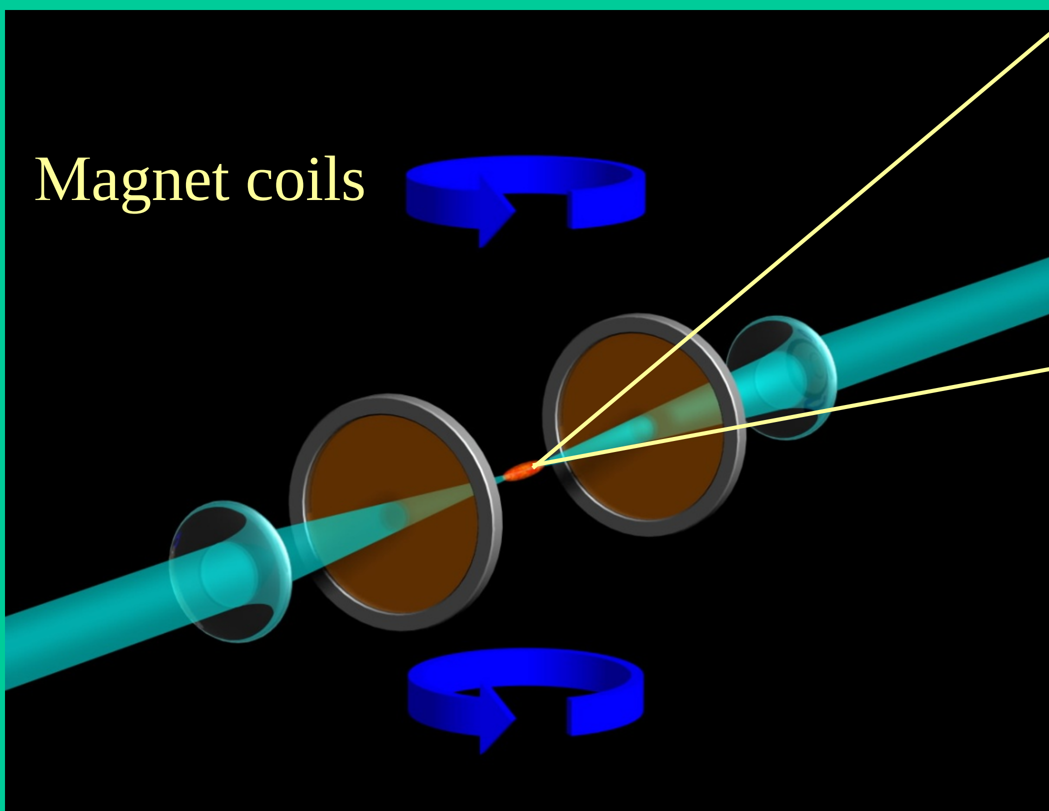
- *Thermodynamics of strongly-interacting Fermi gases:*
  – Global entropy and energy
  – Temperature calibration

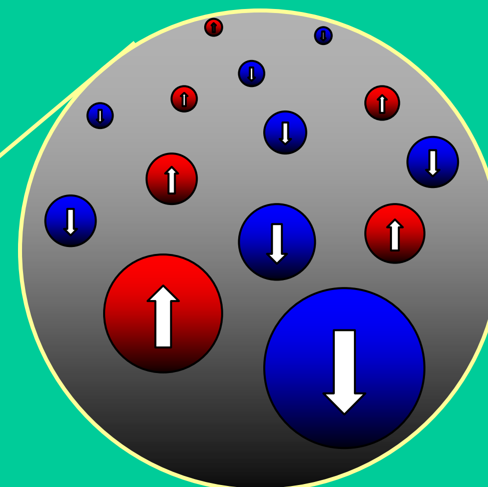
- *Quantum viscosity in strongly-interacting Fermi gases:*
  – Shear forces and heating in collective modes and expanding gases
  – Comparison to the minimum viscosity conjecture
  – Vanishing *Bulk* viscosity

- *Strongly-interacting Fermi gases in two dimensions*
  – Dimers and polarons in radio-frequency spectra

Optically Trapped Fermi Gas

Our atom: Fermionic ^{6}Li





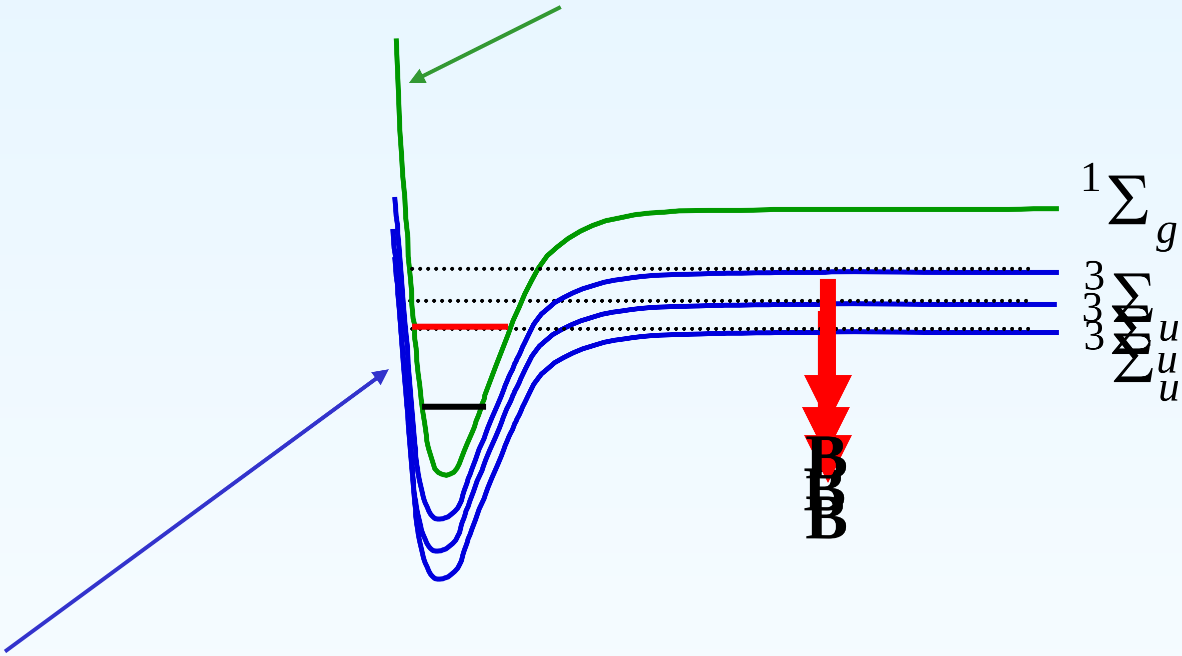
$$|\uparrow\rangle = \left|-\frac{1}{2},1\right\rangle \qquad |\downarrow\rangle = \left|-\frac{1}{2},0\right\rangle$$

$$\left|\textbf{electron } S_z, \textbf{nuclear } I_z\right\rangle$$

Feshbach Resonance

Resonant Coupling between Colliding Atom Pair – Bound Molecular State

Singlet Diatomic Potential: Electron Spins Anti-Parallel

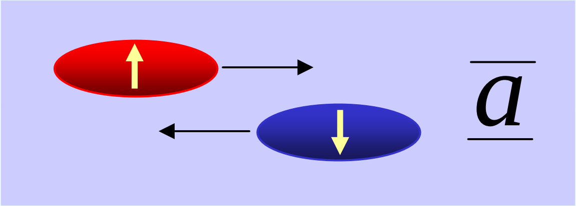


Triplet Diatomic Potential: Electron Spins Parallel

Zero Energy Scattering Length $a_s \rightarrow \pm\infty$

Feshbach Resonance: Tunable Interactions

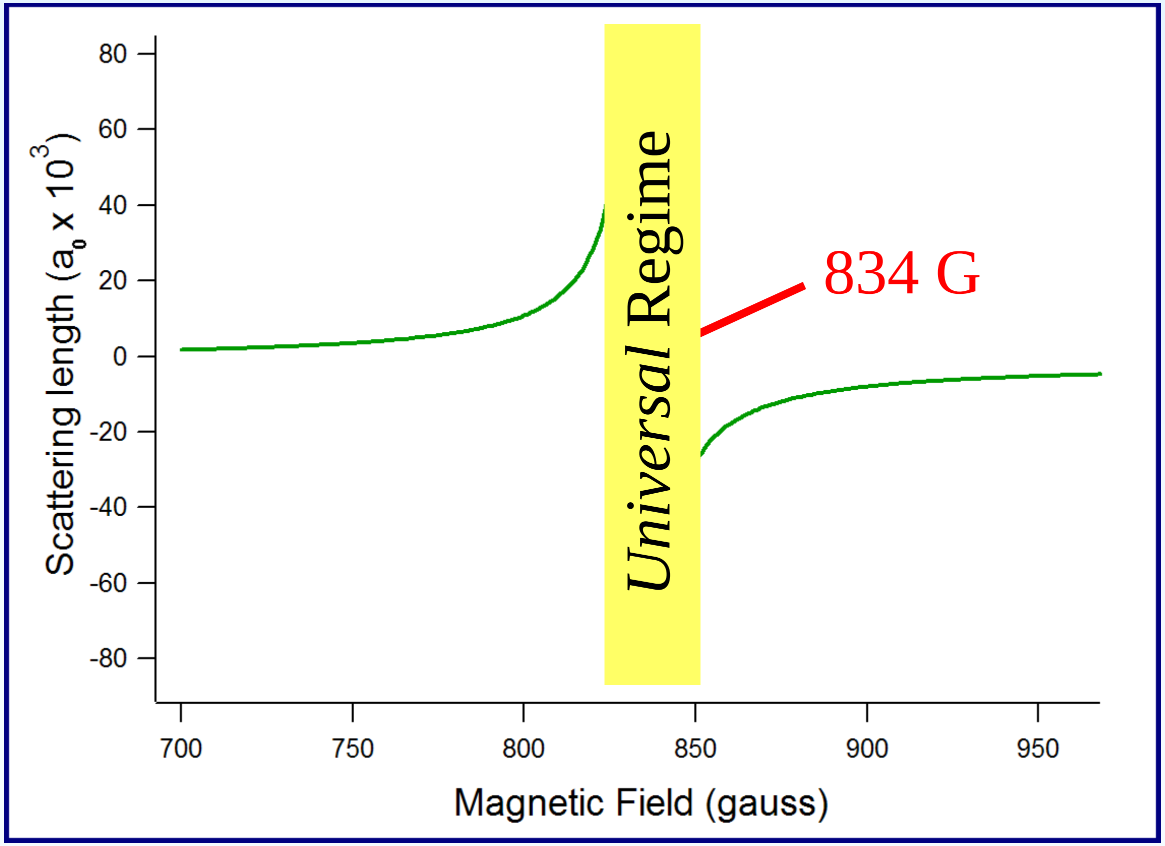
PHYSICS NC



S-wave scattering length

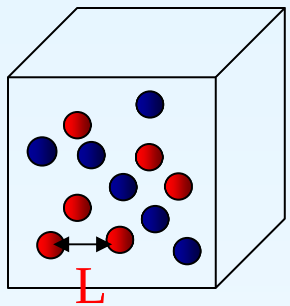
Interparticle Spacing :

$L \approx 2000\, a_0$



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

The *Universal* Regime: *Natural Units*

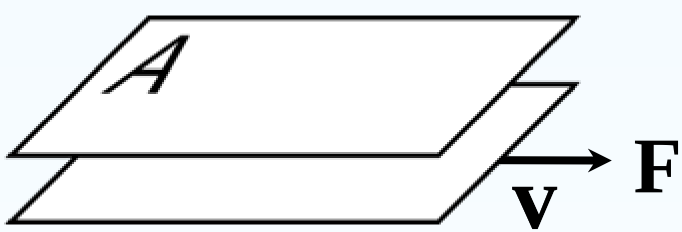


T=0: Atom spacing L
is the *only* length scale.

Consequences of the *Heisenberg Uncertainty Principle:*

- Energy and Temperature have *Natural Units* determined by L $\dfrac{\hbar^2}{2mL^2}$

  - Viscosity—stickiness?

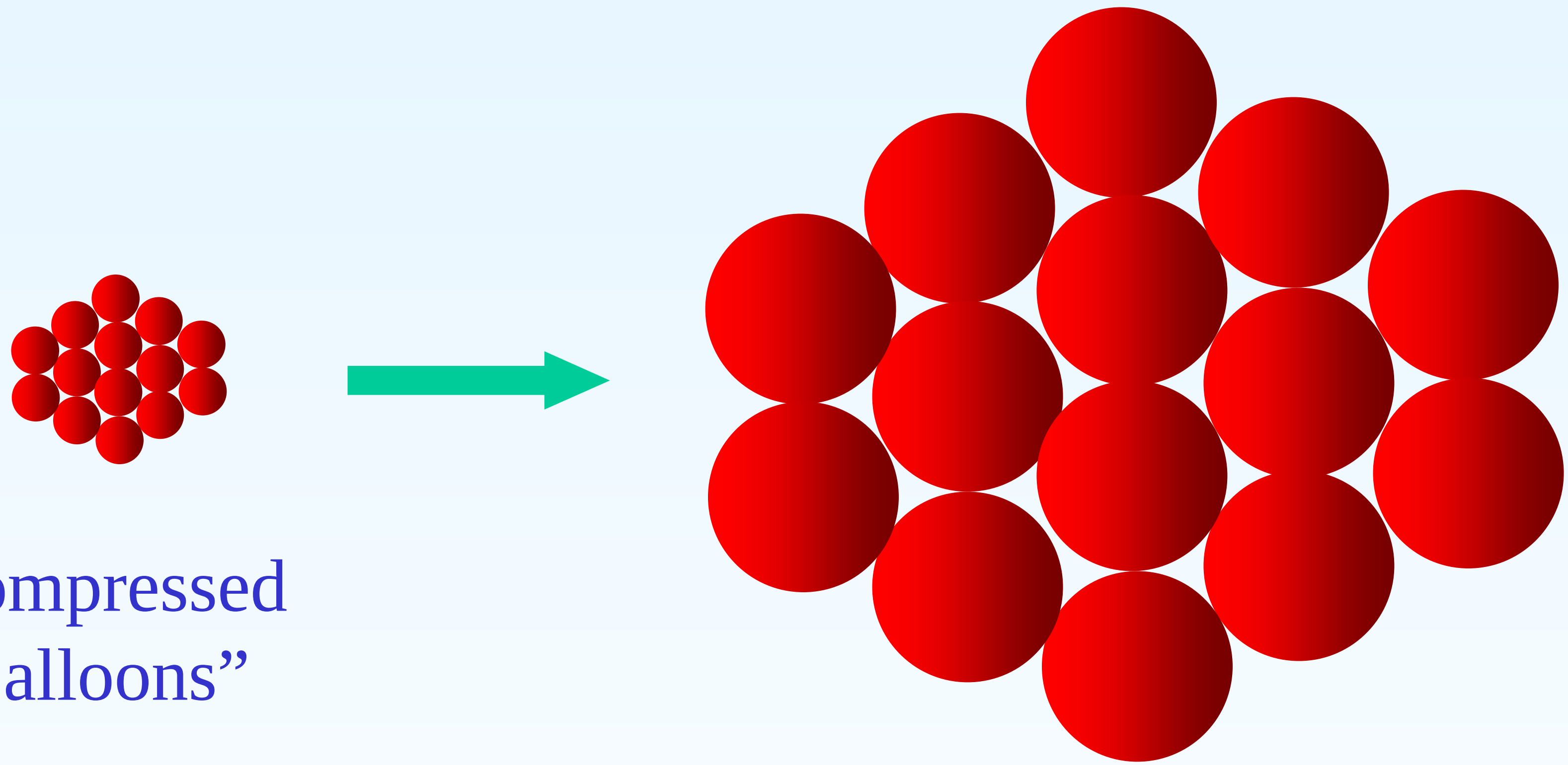


Viscosity: Momentum/Area

$$\frac{\hbar}{L^3}$$

Magic of a *Universal* Strongly Interacting Fermi Gas

PHYSICS NC

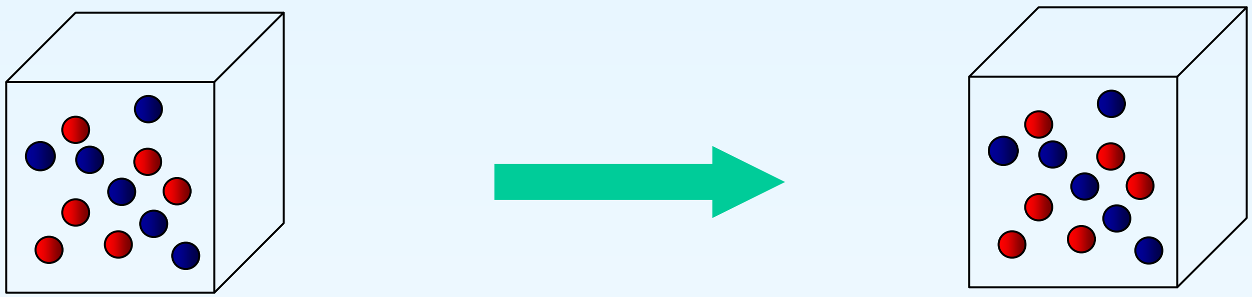


Compressed “Balloons”

Expanded “Balloons”

Universal Ground State Energy

Ideal Fermi Gas | **Strongly Interacting Fermi Gas**



B = 527.5 G

$a = 0$

$E_{\text{ideal}} = \text{Fermi energy}$

B = 834G

$a >> L$

$$\boxed{\mathrm{E}_{\text{gnd}} = (1+\beta)\,E_{\text{ideal}}}$$

Bertsch 1998, Baker 1999, Heiselberg 2001

Theory: Carlson (2008) $\beta = -0.60(1)$

Experiment: Duke (2008) $\beta = -0.61(2)$

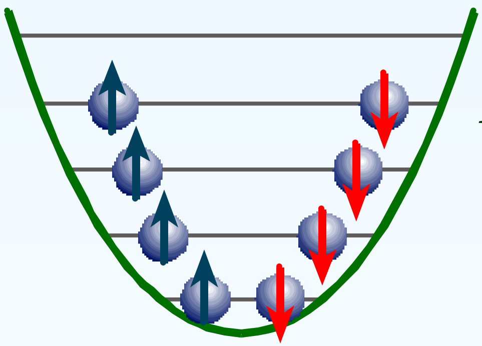
Experiment: MIT (2011) $\beta = -0.624(5)$

Quantum Degeneracy in Fermi Gases

$$|\uparrow\rangle = \left|-\frac{1}{2},1\right\rangle \quad |\downarrow\rangle = \left|-\frac{1}{2},0\right\rangle$$

Harmonic Potential:

$$\varepsilon = (n_x + n_y + n_z)h\nu$$



$$E_F = k_B T_F$$

Zero Temperature

Trap Fermi Temperature Scale:

$$\boxed{E_F = k_B T_F = h\nu(3N)^{1/3}}$$

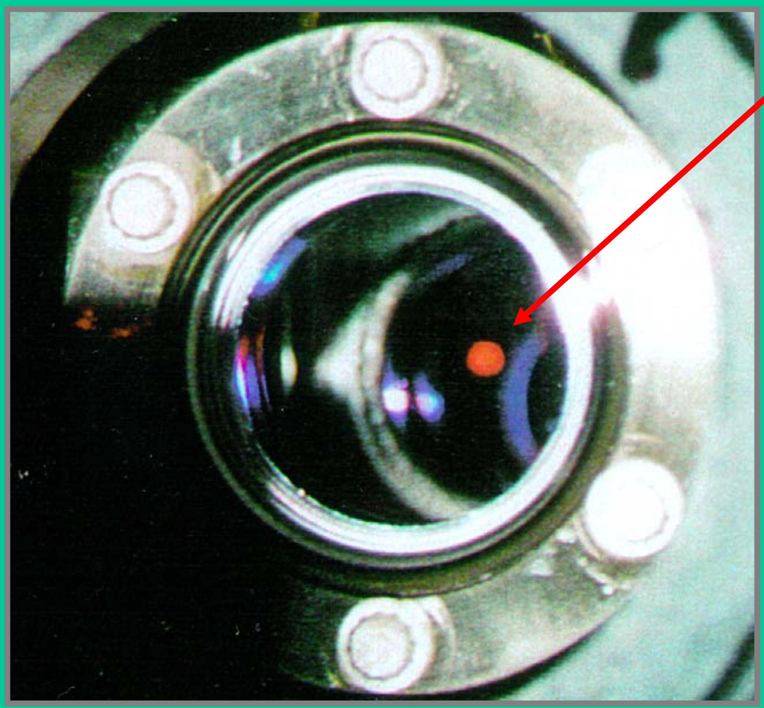
Optical Trap Parameters:

$$\nu = (\nu_x \nu_y \nu_z)^{1/3} = 600\ \text{Hz}$$

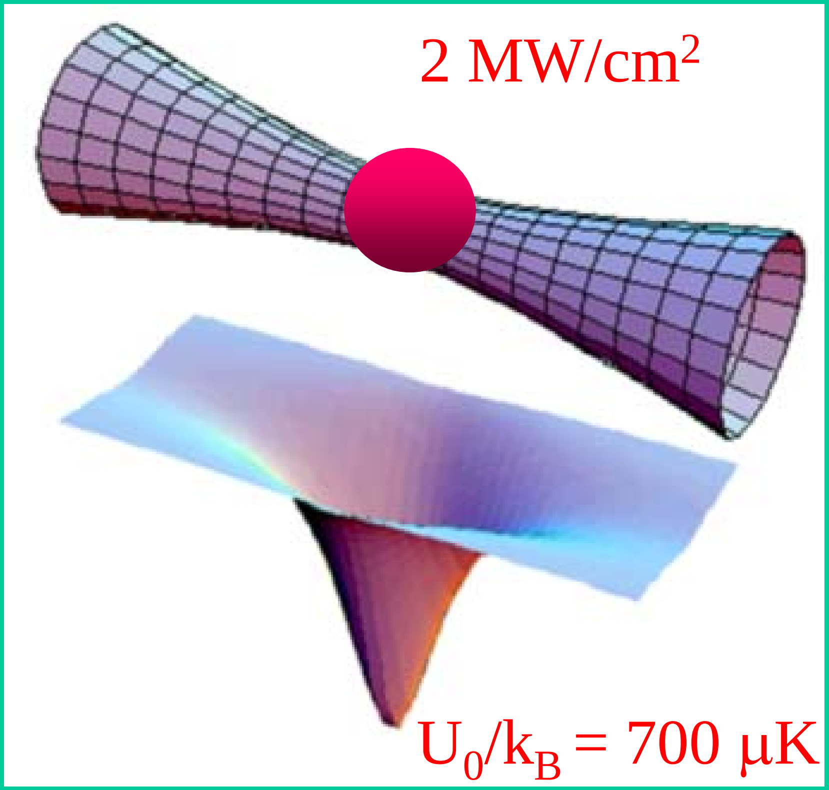
$$N = 2\times 10^5$$

$T_F = 2.4\ \mu\text{K}$

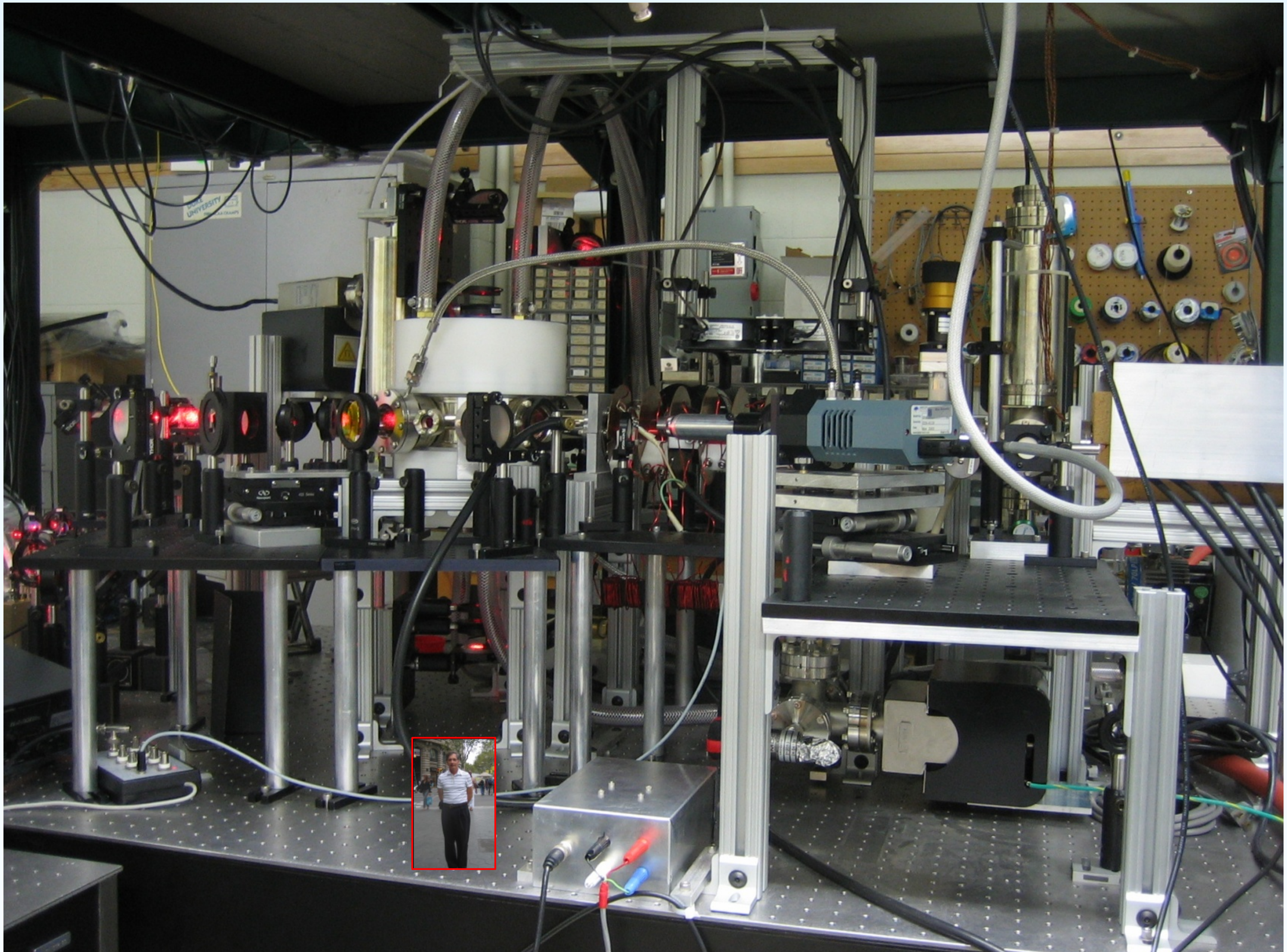
Preparation of Degenerate ^{6}Li gas



Atoms precooled
in a magneto-optical trap
to 150 μK

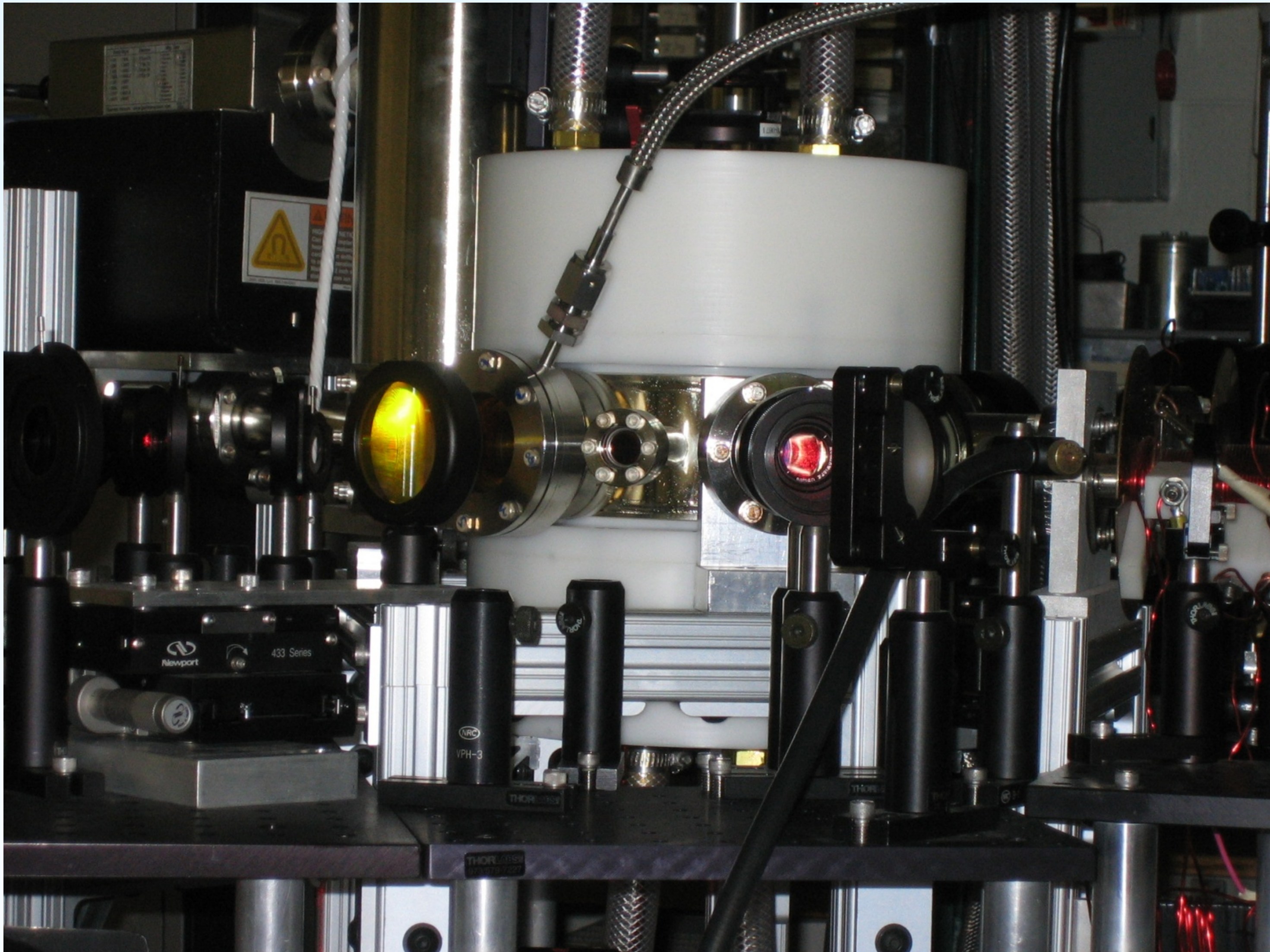


Experimental Apparatus



Experimental Apparatus

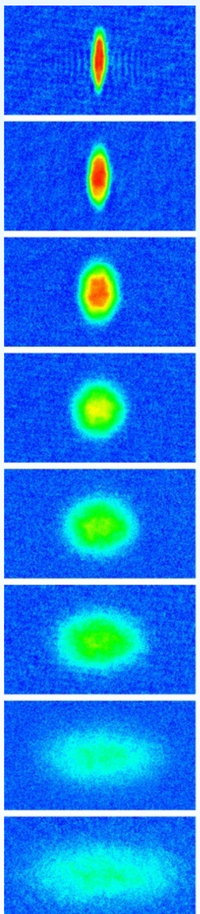
PHYSICS



Strongly Interacting Fermi Systems in Nature

PHYSICS NC

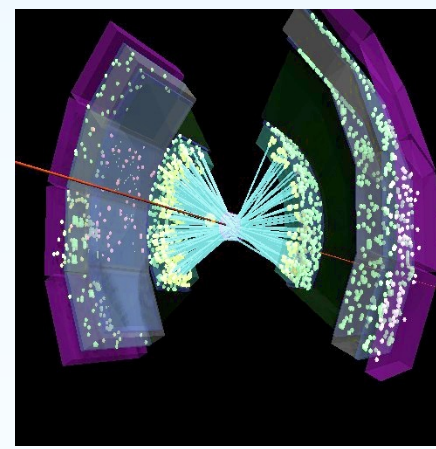
- Ultracold Atomic Fermi Gases
- Quark-Gluon Plasma
- Neutron Matter
- High-Temperature Superconductors
- Black Holes in String Theory



Strongly Interacting Degenerate
^{6}Li gas T = 10^{-7} K

Duke, Science (2002) O'Hara et al.

Similar "Elliptic" Flow



Quark-gluon plasma

T = 10^{12} K

The Minimum Viscosity Conjecture—String Theory

PHY$^{N}_{C}$S ICS

Viscosity—Hydrodynamics

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

Kovtun et al., PRL 2005

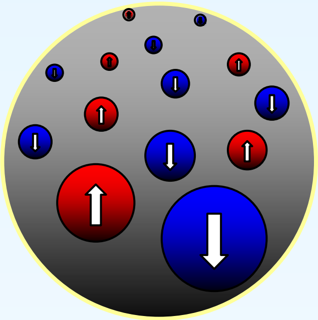
Entropy density—Thermodynamics

Minimum defines a *Perfect* normal fluid

In a ^{6}Li gas we can *measure* η and s.

Thermodynamics of Strongly Interacting Fermi gases

PHYSICS



- Ground State Energy
- Finite temperature: Energy and Entropy
- *Temperature calibration*

"Universal" – independent of the microscopic interactions

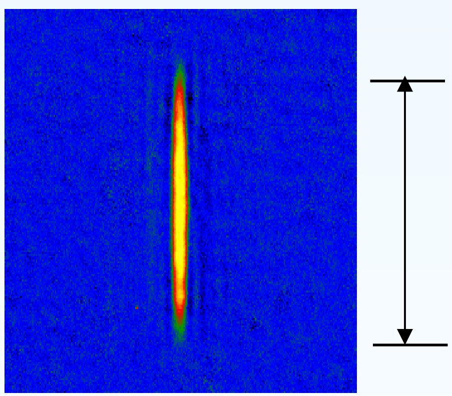
Global energy E measurement

Universal Gas obeys the Virial Theorem

Thomas (2005)
Castin (2004)
Werner and Castin (2006)
Son (2007)

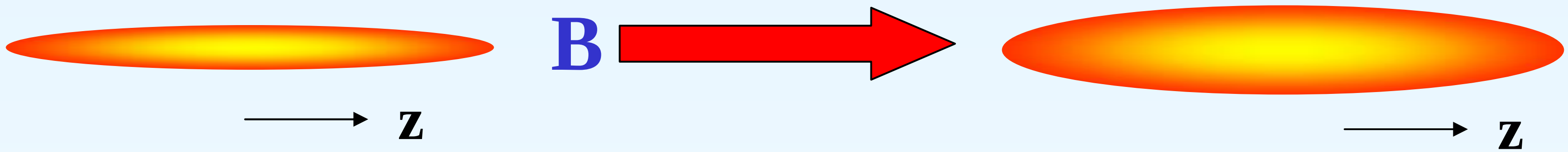
In a HO potential: $E = 2\langle U \rangle$

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



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

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



Start 834 G **End 1200 G**

Strongly interacting at 834 G:
Energy **E_S known from cloud size**
— Universal Fermi gas

Weakly interacting at 1200 G:
Entropy **S_W known from cloud size**
— Weakly Interacting Fermi gas

Energy Measurement:

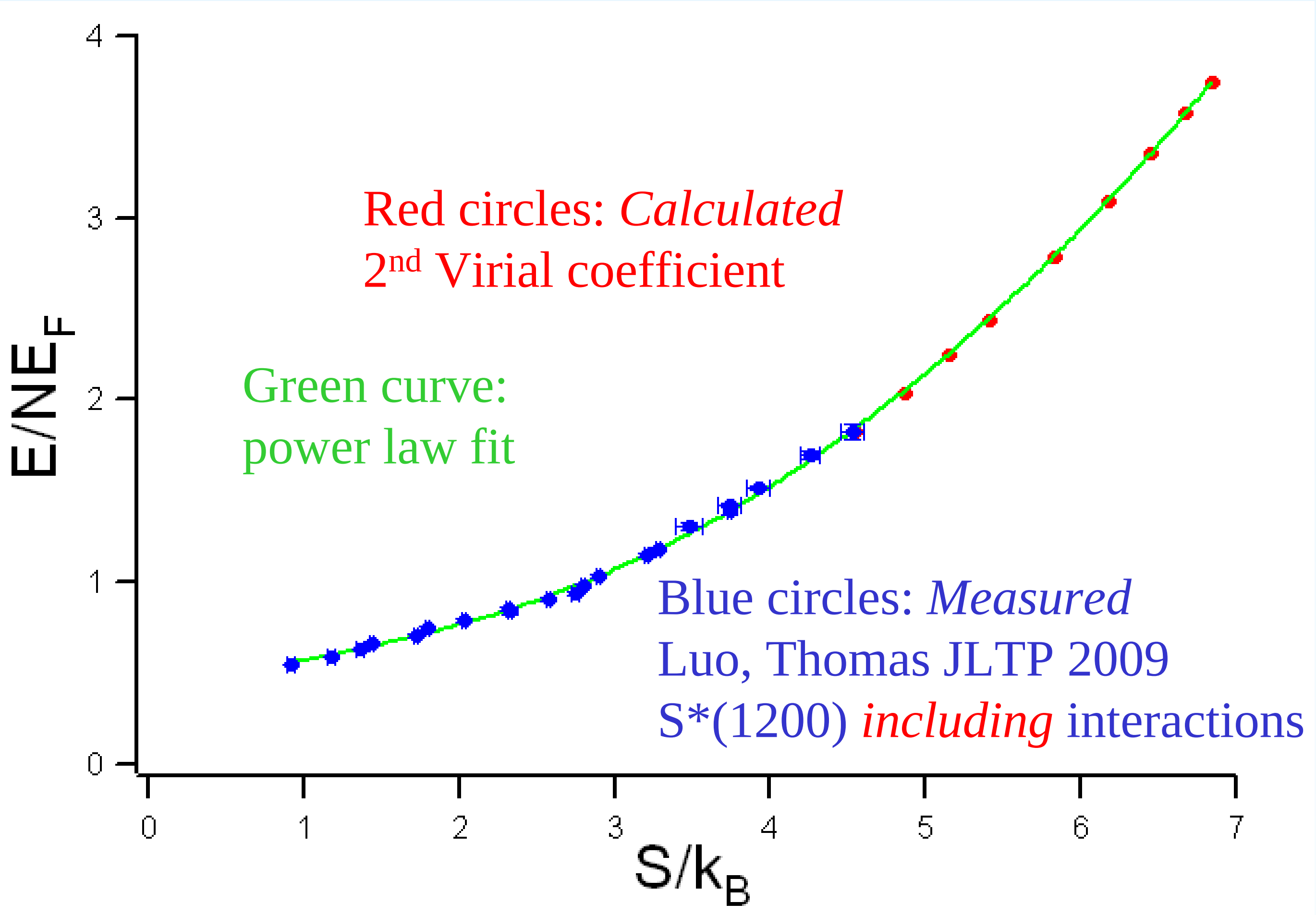
$$E_S = 3m\omega_z^2 \langle z^2 \rangle_{834G}$$

Adiabatic:

$$S_S = S_W$$

Energy per particle versus Entropy per Particle

PHYSICS (NC)



Temperature Calibration

PHYSICS NC

Power law fit to global E versus S data:

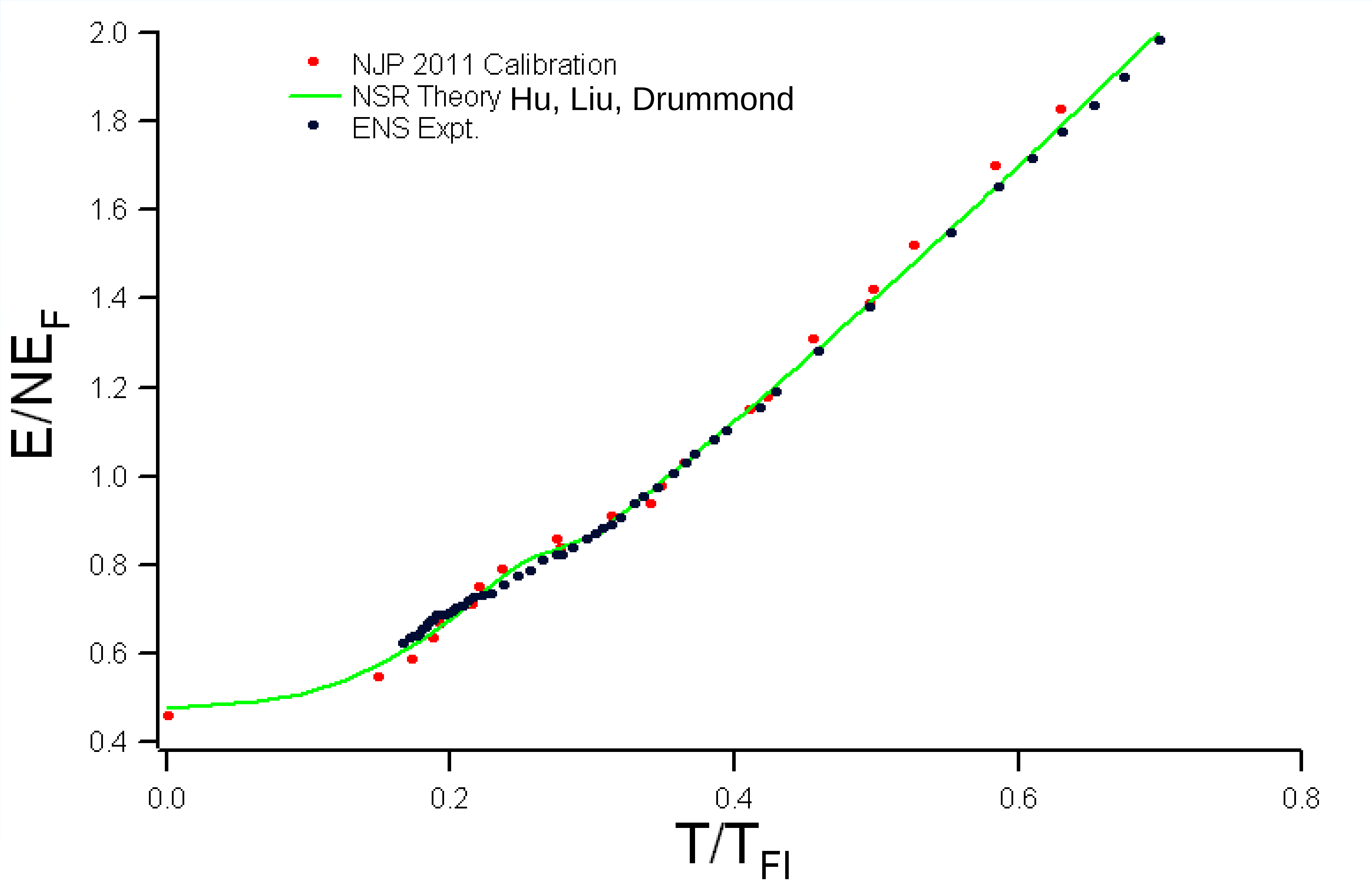
$$E_<(S) = E_0 + aS^b; \quad 0 \le S \le S_c$$

$$E_>(S) = E_1 + cS^d; \quad S \ge S_c$$

Temperature from: $T = \dfrac{\partial E}{\partial S}$

Energy versus Temperature

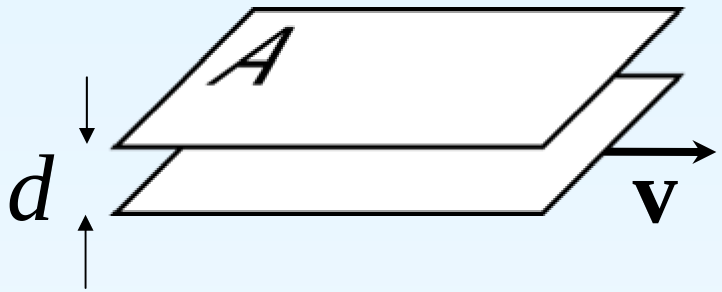
PHYSICS NC



“Quantum” Viscosity Hydrodynamics

Quantum Viscosity

Shear forces



$$\mathbf{F} = \eta \frac{A}{d} \mathbf{v}$$

Viscosity scale:

$$\eta = \frac{p}{\sigma}$$

$$p = \hbar k$$

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

$$\boxed{\eta \propto \hbar k^3}$$

Quantum scale—requires Planck's constant!

Quantum Viscosity at Low and High Temperature

PHYSICS NCS

$$\eta \propto \hbar k^3$$

<u>Low Temperature</u>

$$T \leq T_{\mathrm{F}}$$

$$k \approx k_{\mathrm{F}} \approx 1/L$$

$$\boxed{\eta \approx \hbar n}$$

<u>High Temperature</u>

$$T \geq T_{\mathrm{F}}$$

$$k \approx k_{\mathrm{Thermal}} \approx \sqrt{2mk_{\mathrm{B}}T}/\hbar$$

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

Entropy density scale: $s \approx n k_{\mathrm{B}}$

Low temperature: $\boxed{\eta / s \approx \hbar / k_{\mathrm{B}}}$ ➡ String theory limit

Universal Shear Viscosity

PHY$\overset{N}{\underset{C}{S}}$ICS

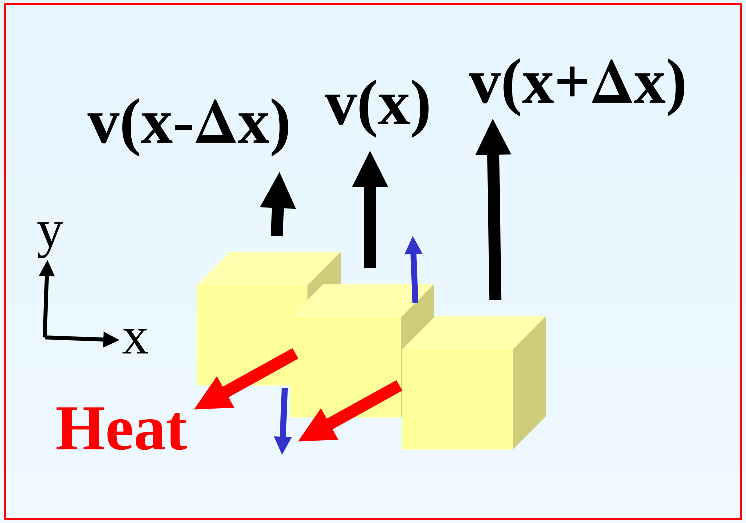
$$\boxed{\eta(\mathbf{x},t) = \alpha(\theta)\hbar n(\mathbf{x},t)} \qquad \theta = \frac{T}{T_F(n)}$$

Measuring Universal Shear Viscosity
at Low and at High Temperature:

Breathing Mode and Elliptic Flow

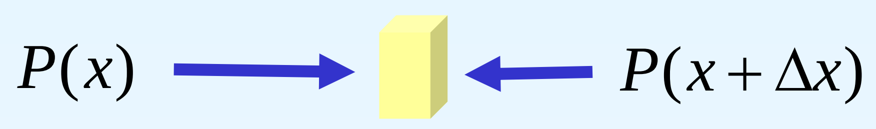
Viscous Hydrodynamics

PHYSICS



- **Shear force at *each* surface** $\eta \frac{\partial v_y}{\partial x}$
- ***Net* shear force on *volume element*** $\frac{\partial}{\partial x}\left(\eta \frac{\partial v_y}{\partial x}\right)$
- **Friction *heating* at each surface** $\dot{q} = \frac{\eta}{2}\left(\frac{\partial v_y}{\partial x}\right)^2$

Pressure Forces with Heating

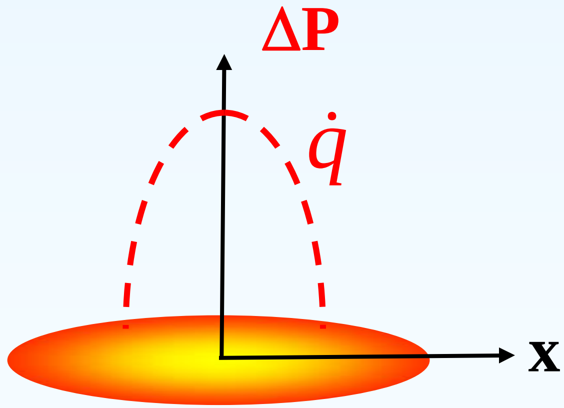


Scalar pressure gradient: *Outward* force—expands after release.

Friction force: Inward—*slows* the flow

Friction *Heating:*

$$\dot{q} = \frac{\eta}{2}\left(\frac{\partial v_y}{\partial x}\right)^2$$



The viscosity must ***vanish***
at the cloud edges

Heating *gradient*: *Outward* pressure force that *speeds* the flow!

Hydrodynamic *Forces*

PHYSICS NC

- **Net Force with Friction:**

$$\boxed{m\left(\partial_t + \mathbf{v}\cdot\nabla\right)\mathrm{v}_i = f_i - \partial_i U_{trap} + \sum_j \frac{\partial_j\left(\eta\sigma_{ij} + \varsigma\sigma'_{ij}\right)}{n}}$$

Force arising from scalar pressure: $f_i = -\dfrac{\partial_i P}{n}$

Shear viscosity: η $\quad \sigma_{ij} = \partial_j \mathrm{v}_i + \partial_i \mathrm{v}_j - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{v}$

Bulk viscosity: ς $\quad \sigma'_{ij} = \delta_{ij}\nabla\cdot\mathbf{v}$

- **Initial Condition:** $f_i(t=0) = \partial_i U_{Trap}\left(\mathbf{x}\right) = m\omega_i^2 x_i$

Universal Pressure with Heating

PHYSICS (NC)

- **Friction Heating rate per unit volume**

$$\dot{q} = \frac{1}{2}\eta\sum_{ij}\sigma_{ij}^2 + \varsigma(\nabla\cdot\mathbf{v})^2$$

- **Energy conservation:** $\left(\partial_t + \mathbf{v}\cdot\nabla + \frac{5}{3}\nabla\cdot\mathbf{v}\right)\mathcal{E} = \dot{q}$

- **Universal Pressure:** $P = \frac{2}{3}\mathcal{E}$ Ho, PRL 2004

$$\boxed{\left(\partial_t + \mathbf{v}\cdot\nabla + \frac{5}{3}\nabla\cdot\mathbf{v}\right)P = \frac{2}{3}\dot{q}}$$

Cao, Elliot,Wu, Joseph, Petricka, Schaefer, and Thomas
Science **331**, 58 (2011)

Universal Viscous Hydrodynamics

Equation for $f_i = -\dfrac{\partial_i P}{n}$

$$\left(\partial_t + \mathbf{v}\cdot\nabla + \tfrac{2}{3}\nabla\cdot\mathbf{v}\right) f_i + \sum_j (\partial_i \mathrm{v}_j) f_j - \tfrac{5}{3}\overbrace{(\partial_i \nabla\cdot\mathbf{v})}^{0}\frac{P}{n} = -\tfrac{2}{3}\frac{\partial_i \dot{q}}{n}$$

Scale transformation: $n(x,y,z,t) = \dfrac{n\left(\frac{x}{b_x},\frac{y}{b_y},\frac{z}{b_z}\right)}{b_x(t)b_y(t)b_z(t)}$

$$\mathrm{v}_i = x_i\frac{\dot{b}_i}{b_i} \qquad f_i = a_i(t)\, m\,\omega_i^2 x_i$$

$$b_i(0) = 1; \quad \dot{b}_i(0) = 0; \quad a_i(0) = 1$$

Extracting the *Shear* Viscosity

PHYSICS NC

$$\boxed{\eta(\mathbf{x},t) = \alpha(\theta)\hbar n(\mathbf{x},t)} \qquad \theta = \frac{T}{T_F(n)}$$

$$\dot{a}_i + 2\frac{\dot{b}_i}{b_i}a_i + \frac{2}{3}\sum_j \frac{\dot{b}_j}{b_j}a_i = \frac{\hbar\overline{\alpha}}{3m\omega_i^2\left\langle x_i^2\right\rangle_0 b_i^2(t)}\sum_{ij}\sigma_{ij}^2$$

$$\frac{\ddot{b}_i}{b_i} = (a_i - 1_{trap})\,\omega_i^2 - \frac{\hbar\overline{\alpha}}{m\left\langle x_i^2\right\rangle_0 b_i^2(t)}\sigma_{ii} \qquad \partial_j \mathrm{v}_i = \delta_{ij}\frac{\dot{b}_i}{b_i}$$

$$b_i(0) = 1; \quad \dot{b}_i(0) = 0; \quad a_i(0) = 1$$

<u>Trap-averaged Viscosity coefficient</u>

$$\boxed{\overline{\alpha} \equiv \frac{1}{N\hbar}\int d^3\mathbf{x}\,\eta(\mathbf{x},t) = \frac{1}{N}\int d^3\mathbf{x}\,n(\mathbf{x},t)\alpha(\theta)}$$

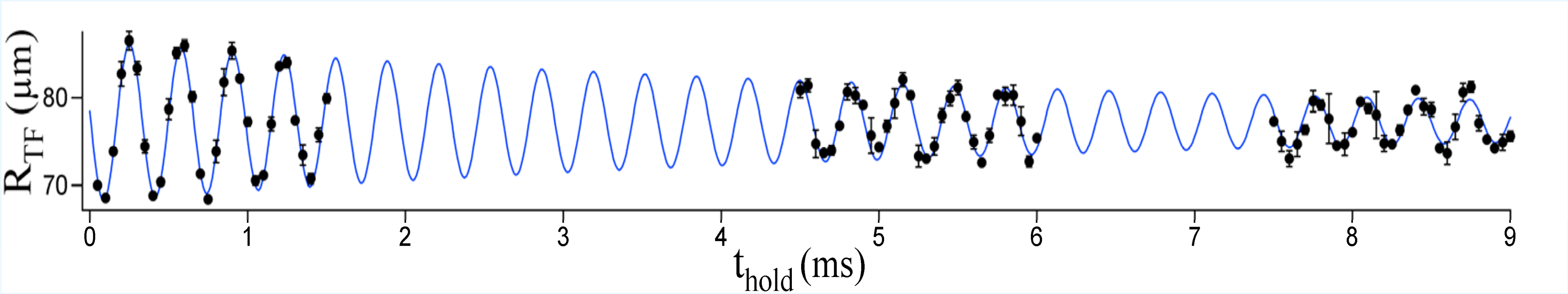
Adiabatic invariant: Time independent!

Precision Measurement of Viscosity at *Low* Temperature: Breathing Mode

Quantum Viscosity

PHYSICS (NC)

- Low Temperature: Damping of the Breathing Mode



For viscous damping: $\boxed{\eta = \alpha \hbar n}$

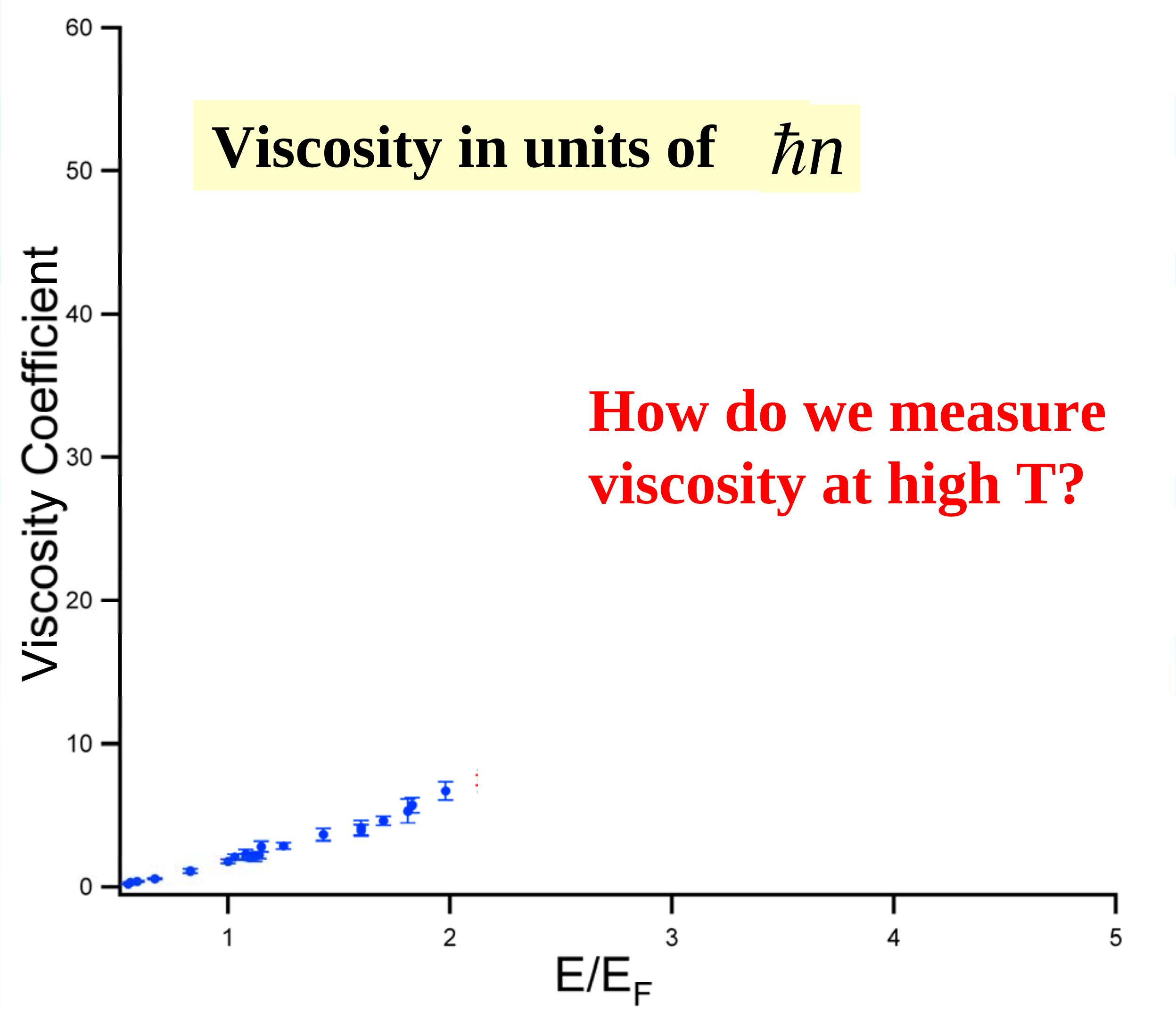
Damping rate: $$\boxed{\frac{1}{\tau} = \frac{\hbar \bar{\alpha}}{3m\langle x^2 \rangle_0}}$$

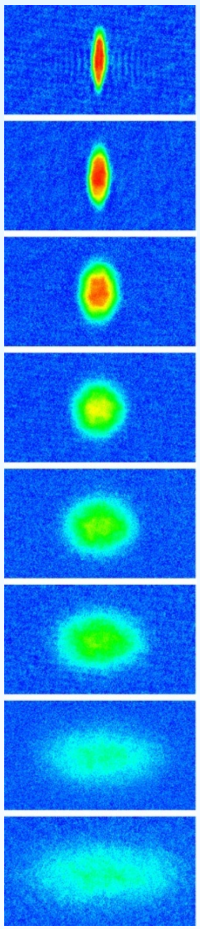
- Heating is negligible

- Measure trap-averaged *viscosity coefficient* $\bar{\alpha}$

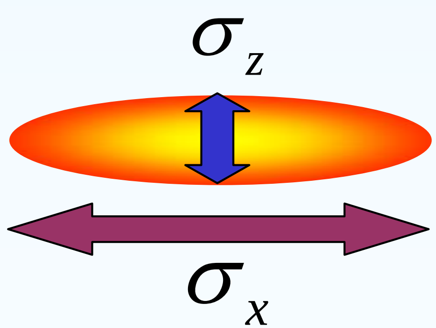
Viscosity Coefficient: Low Temperature

PHYSICS





High Temperature Quantum Viscosity in Elliptic Flow



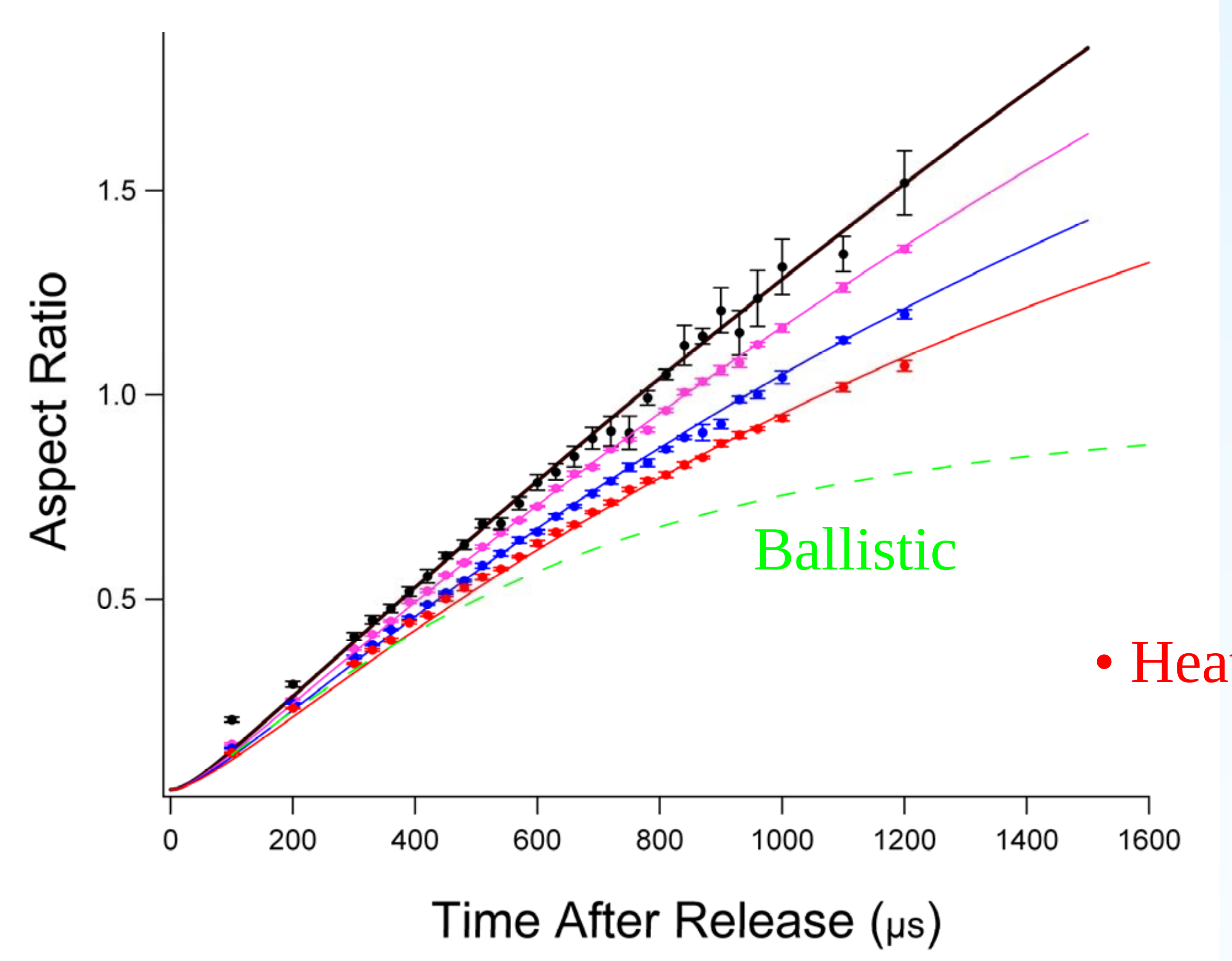
- **Measure *Aspect Ratio*:**

$$\boxed{\frac{\sigma_x}{\sigma_z}}$$

Quantum Viscosity

PHYSICS (NC)

• High Temperature: Expansion Dynamics—Elliptic Flow



$\frac{E}{E_F}$

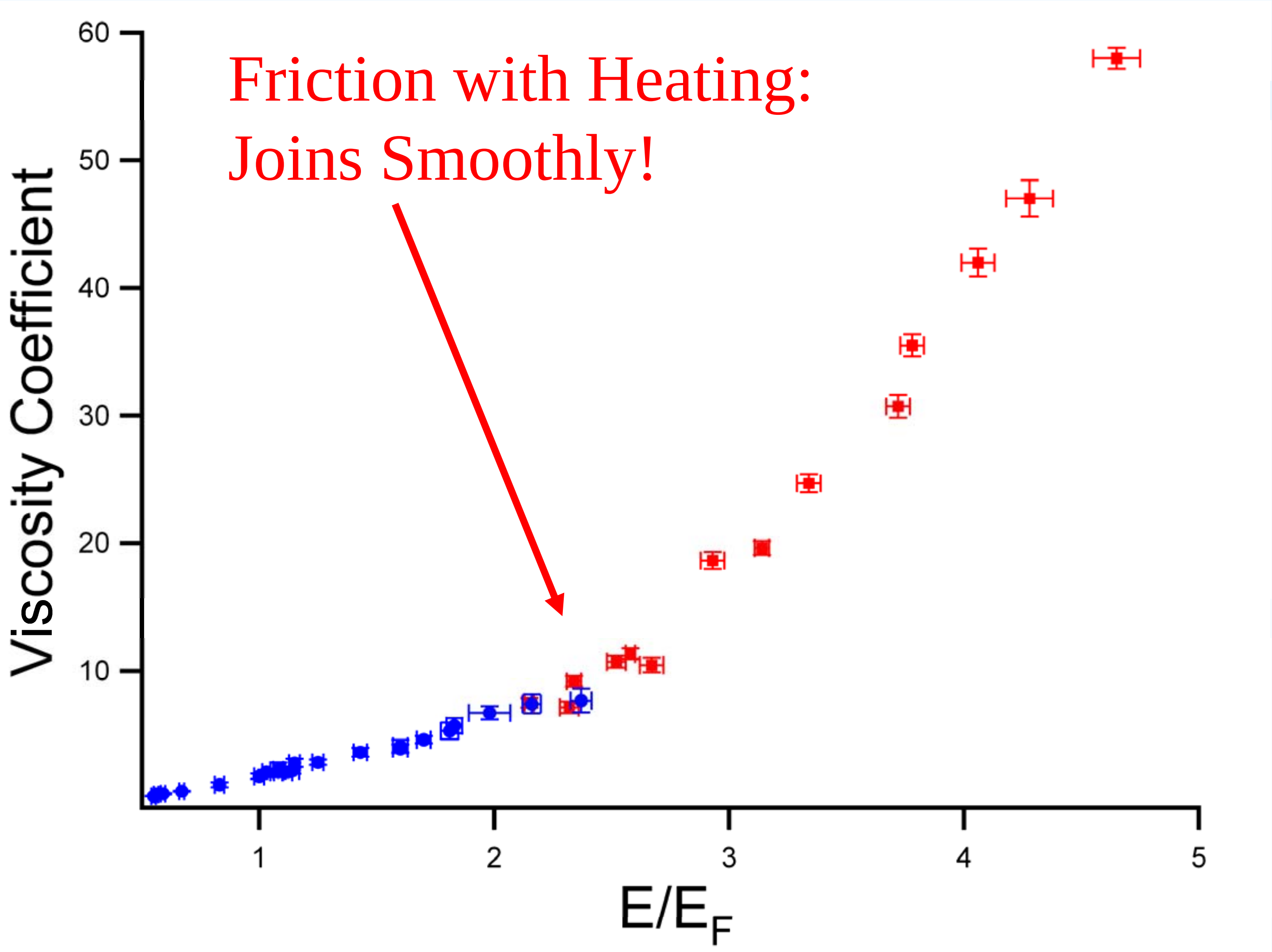
0.6
2.3
3.3
4.6

• Heating is important!

High and Low Temperature Data

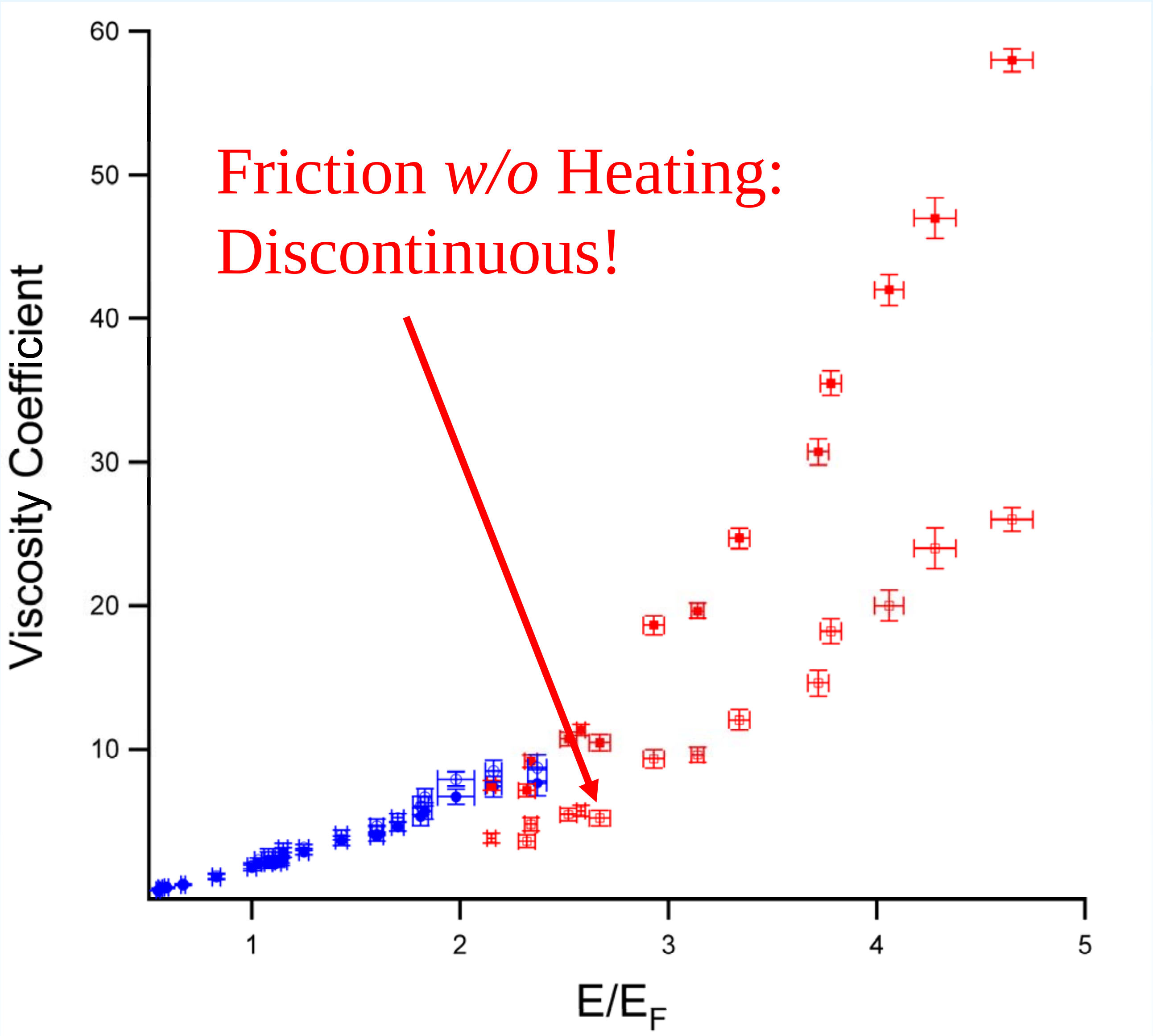
PHYSICS NC

Viscosity in units of $\hbar n$



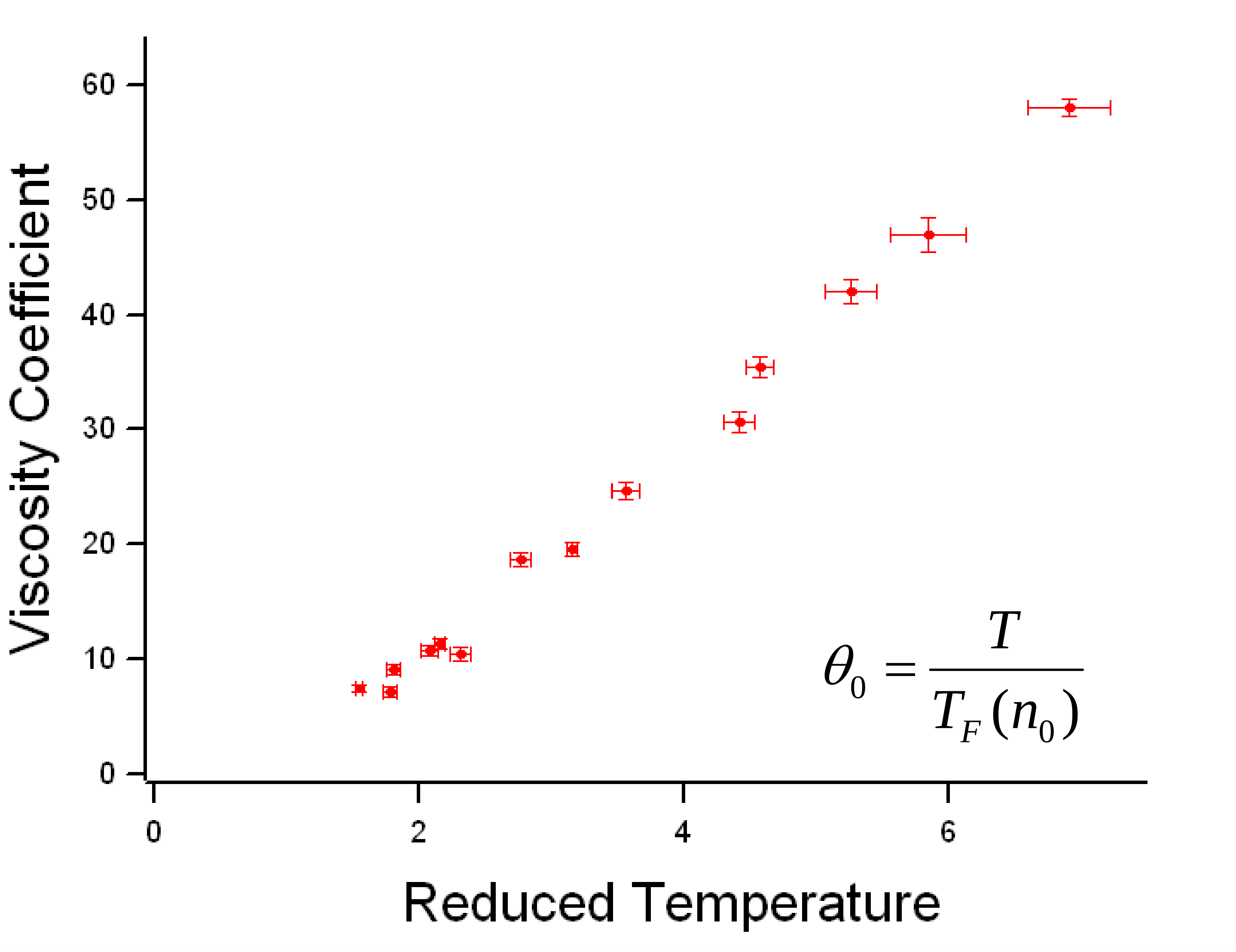
Effect of the *Heating* Rate

PHYSICS



Universal High Temperature Scaling

PHYSICS



Ratio of the Shear Viscosity to the Entropy Density

PHYSICS NC

$$\frac{\eta}{s} = \frac{\alpha \hbar n}{s} = \frac{\alpha \hbar}{\frac{s}{n}}$$

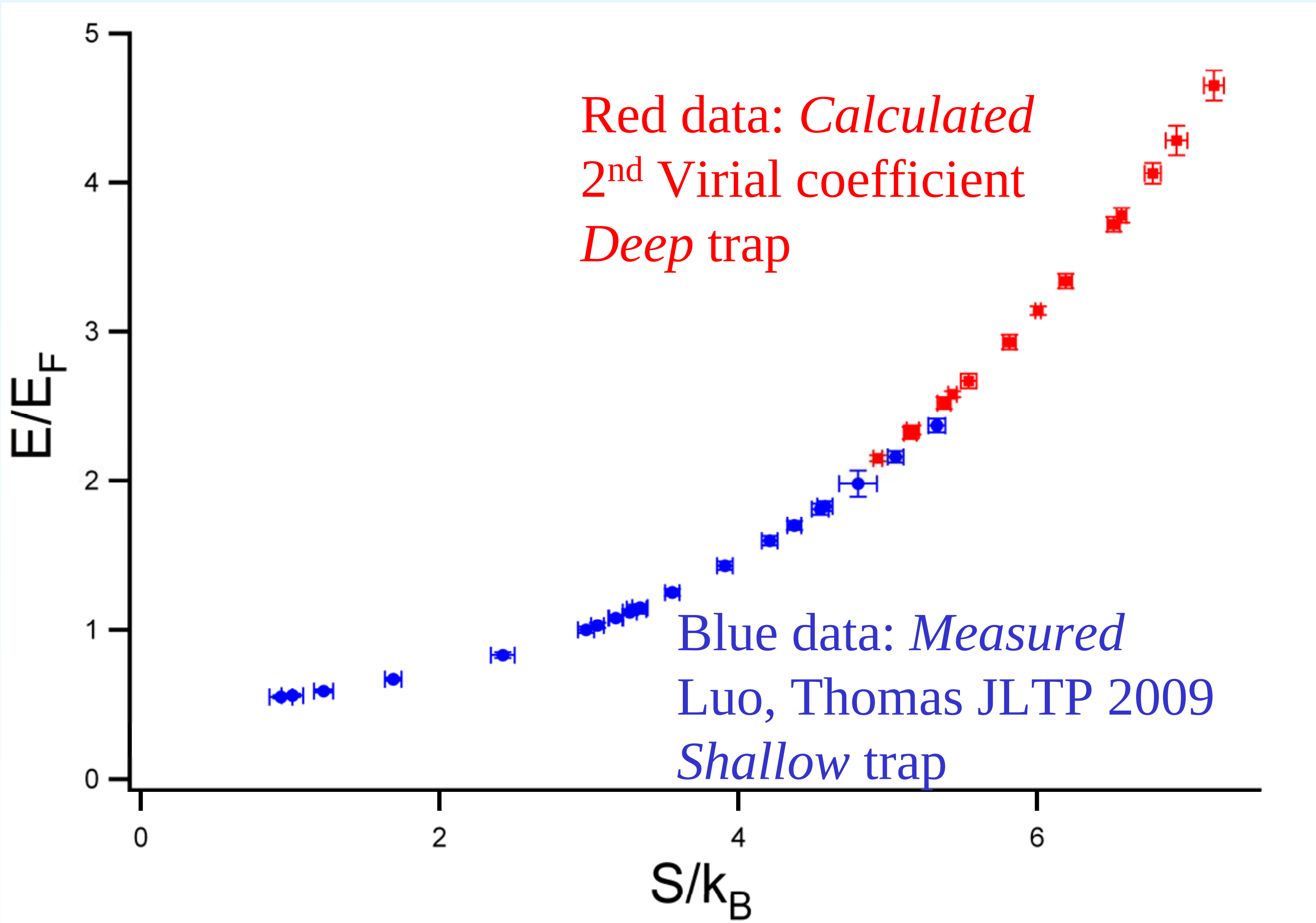
$$\boxed{\frac{\eta}{s} = \frac{\hbar}{k_B} \frac{\langle \alpha \rangle}{S/k_B}}$$

Trap averaged viscosity coefficient

Average entropy per particle

Schaefer, PRA **76**, 063618 (2007)
Turlapov, et al., JLTP **150**, 567 (2008)

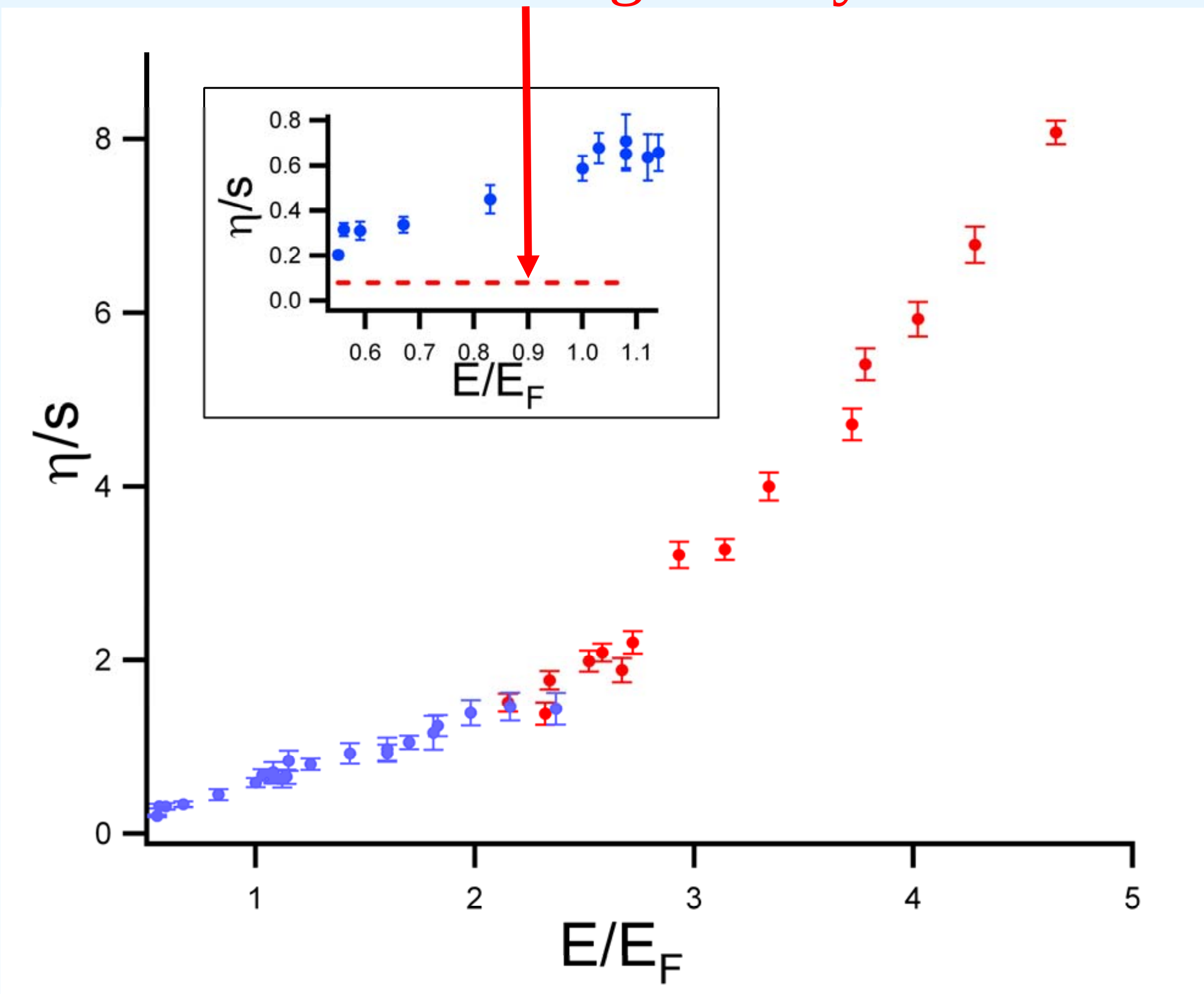
Energy per particle versus Entropy per Particle



Ratio of the Viscosity to the Entropy

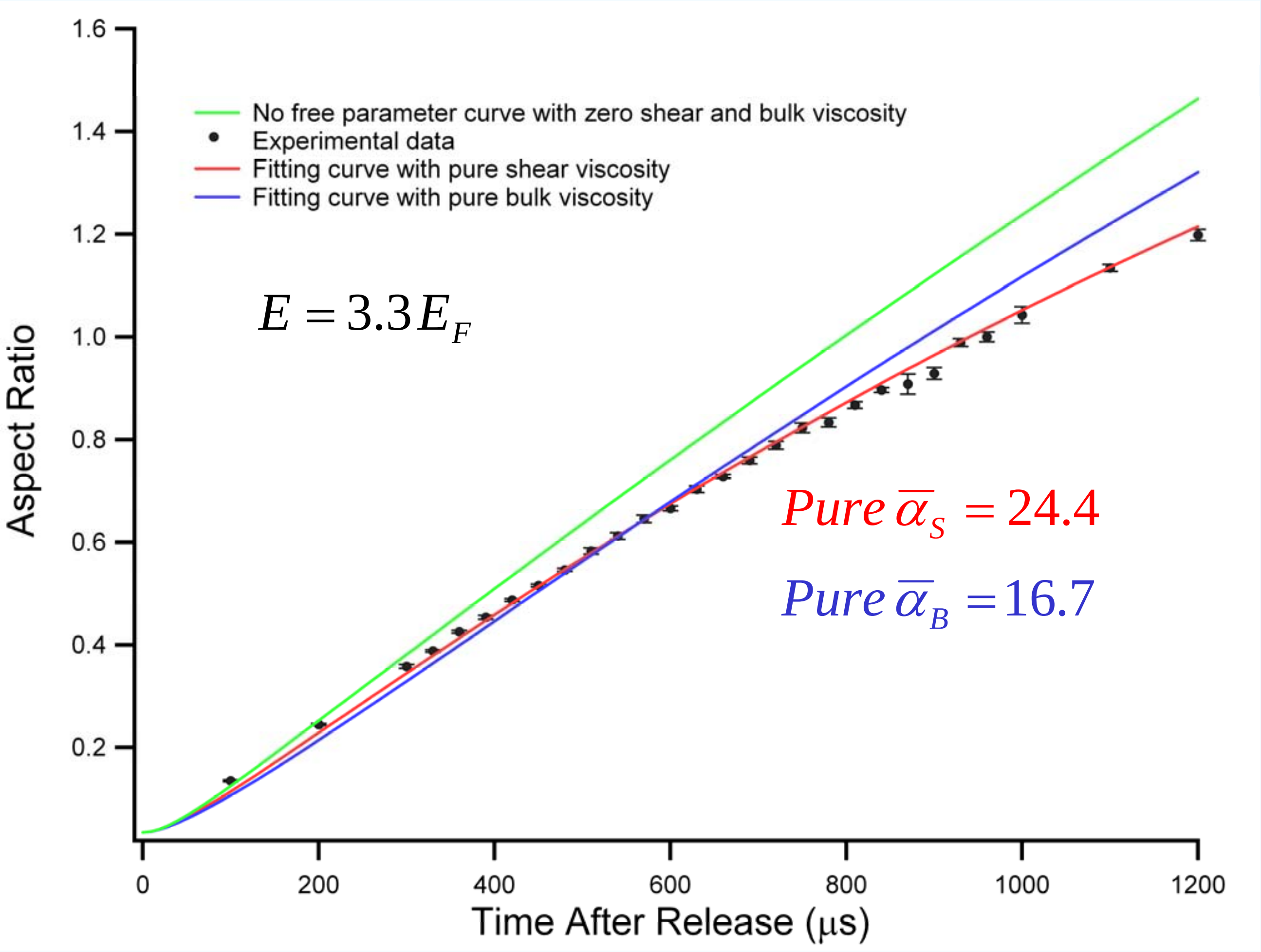
PHYSICS NC

String Theory Limit



What about *Bulk* Viscosity?

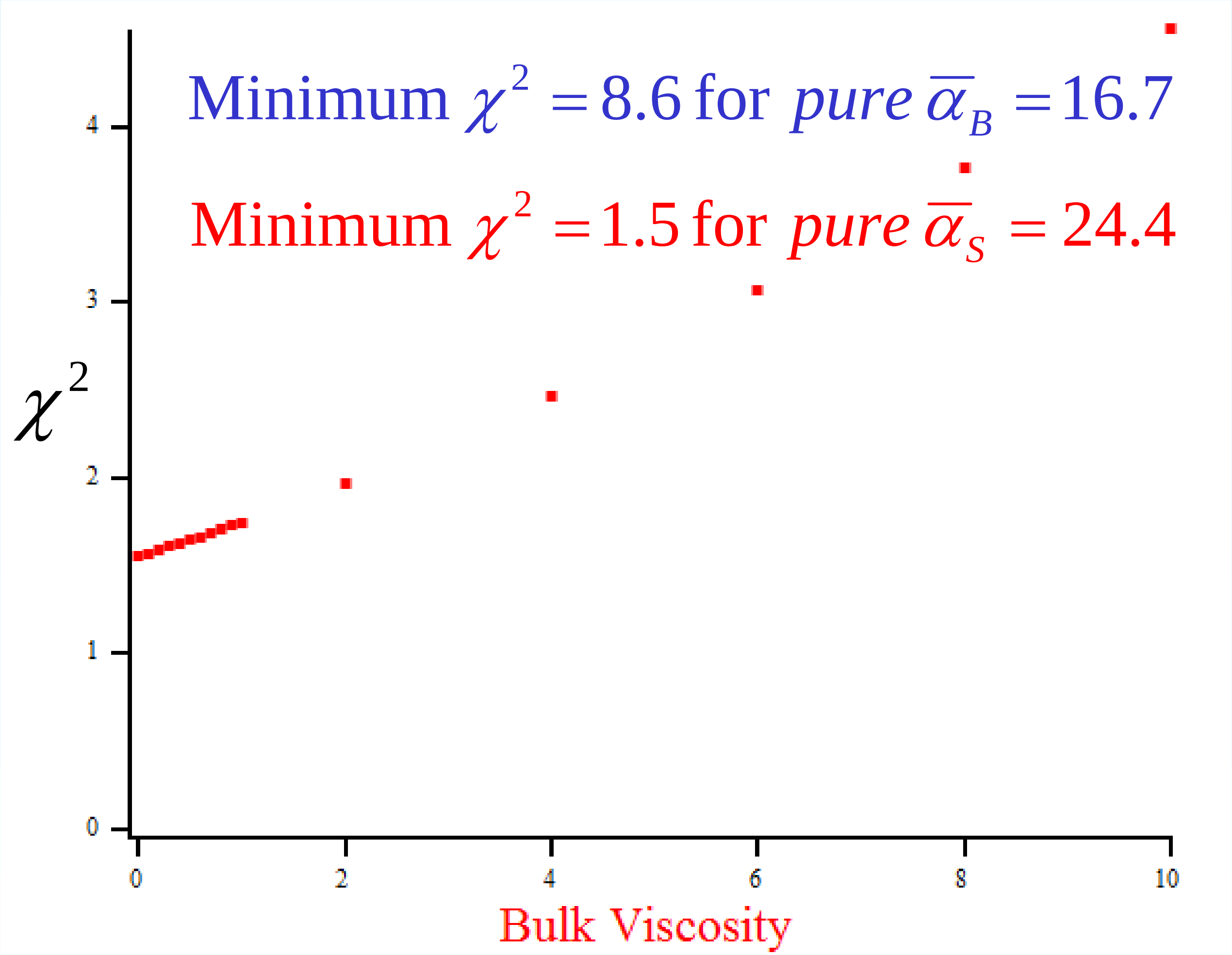
PHYSICS



Vanishing Bulk Viscosity

PHYSICS (NC)

- *Two* parameter fit, *optimum* shear viscosity for each bulk viscosity

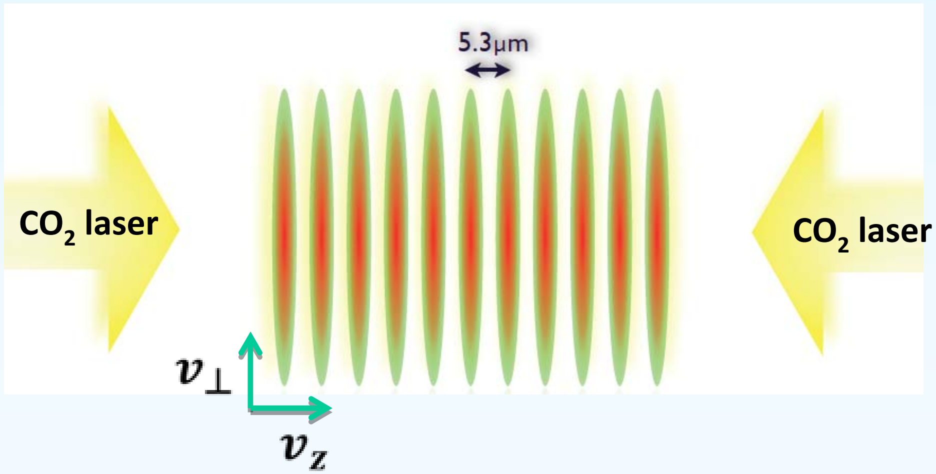


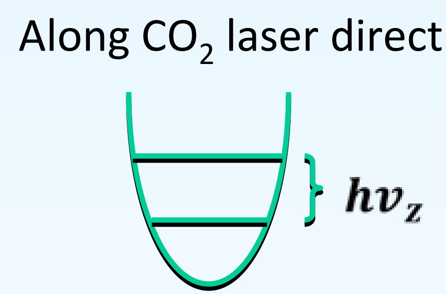
Radio-frequency spectra of a quasi-two-dimensional Fermi gas:

Quasi-Two-Dimensional Fermi gas

PHYSICS

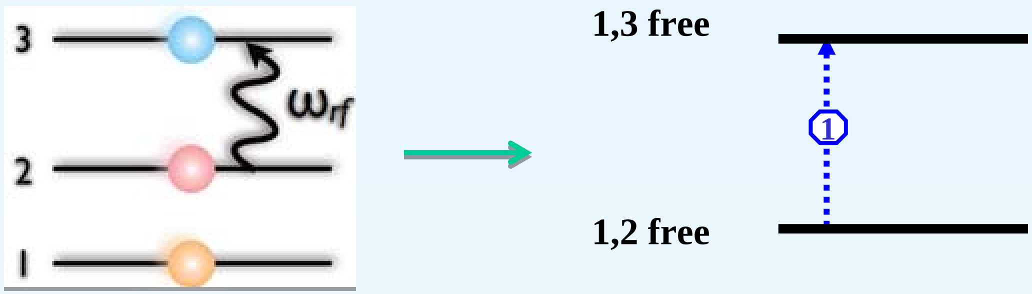
- We study confinement-induced dimers and many-body effects in a quasi-2D system.

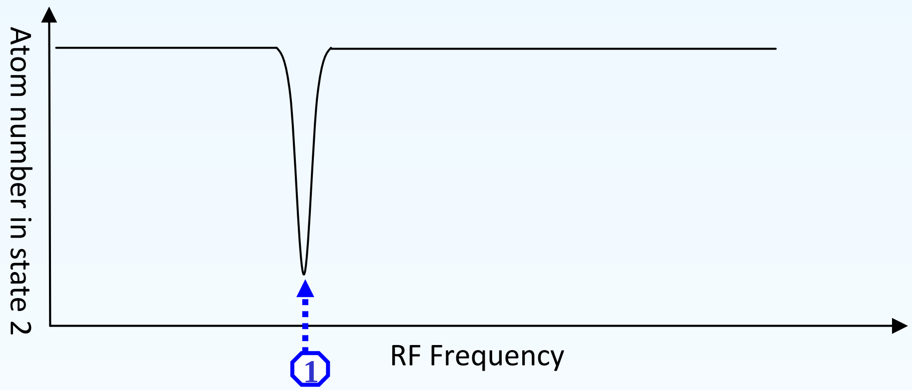




- 50-50 mixture of ^{6}Li $|1\rangle$ and $|2\rangle$
- Atom number per pancake ~ 1000
- $\nu_\perp/\nu_z$ =1/25
- $E_{F\perp}$~ 1.5 $h\nu_z$ (ν_z: 25kHz-180kHz; $E_{F\perp}$: 2μK-12μK)

RF transitions: Bare atom

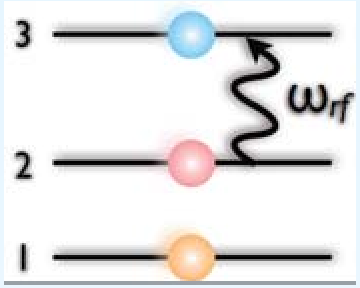


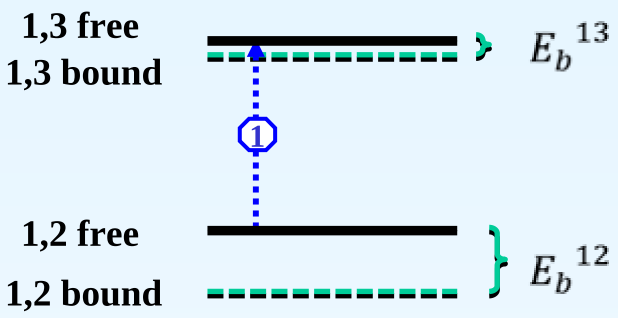


Bare atomic transition

RF transitions: dimer-to-dimer

PHYSICS NC





Confinement-induced dimer binding energy for 3D harmonic trap: $E_b \equiv \varepsilon_b h\upsilon_z$

Magnetic field dependent S-wave scattering length with pseudopotential: $a[B]$

$$V(\mathbf{r}) = \frac{4\pi\hbar^2 a}{m}\delta(\mathbf{r})\partial_r[r\ldots]$$

$$\boxed{\frac{l_z}{a} = \int_0^\infty \frac{du}{\sqrt{4\pi u^3}}\left\{1-\prod_j\left(\frac{2\beta_j u}{1-e^{-2\beta_j u}}\right)^{1/2} e^{-\varepsilon_b u}\right\}}$$

$$l_z \equiv \sqrt{\hbar/(m\omega_z)} \qquad \beta_j \equiv \upsilon_j/\upsilon_z$$

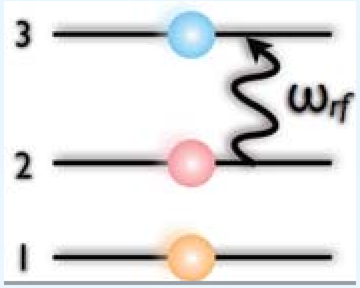
$$a \to \infty$$

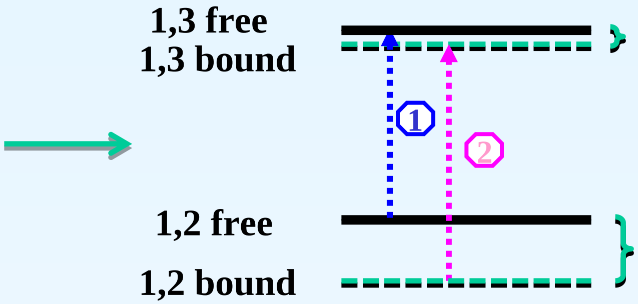
$$E_b \equiv 0.245\, h\upsilon_z \qquad E_b \equiv 0.290\, h\upsilon_z$$

$$\beta_\perp \equiv \upsilon_\perp/\upsilon_z = 0 \qquad \beta_\perp \equiv \upsilon_\perp/\upsilon_z = 1/25$$

RF transitions: dimer-to-dimer

PHYSICS





$$\psi_{E_b}(z,\rho) \cong \phi_0(z)\frac{\kappa}{\sqrt{\pi}}K_0(\kappa\rho)$$

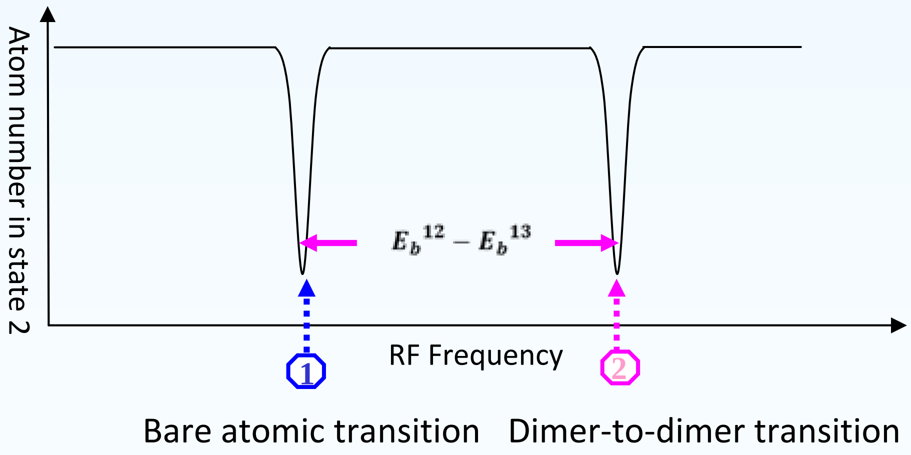
$$E_b = \frac{\hbar^2\kappa^2}{m}$$

2 **Bound-to-bound transition spectrum:**

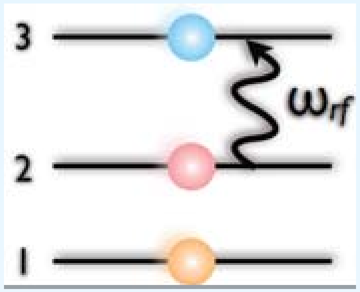
$$\boxed{I_{bb}(\nu) = \varepsilon_{bb}(q)\,\delta\left[\nu - \frac{E_b^{12} - E_b^{13}}{h}\right]}$$

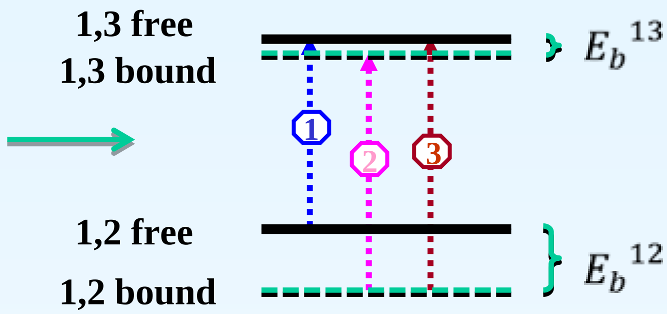
$$\int d\nu\, I_{bb}(\upsilon) \equiv \varepsilon_{bb}(q) = \frac{q^2}{4\sinh^2(q/2)}$$

$$q \equiv \ln\left(E_b^{13}/E_b^{12}\right)$$



RF transitions: dimer-to-unbound ("free")





① **Bare atom transition**

② **Bound-to-bound transition**

③ **Bound-to-free transition**

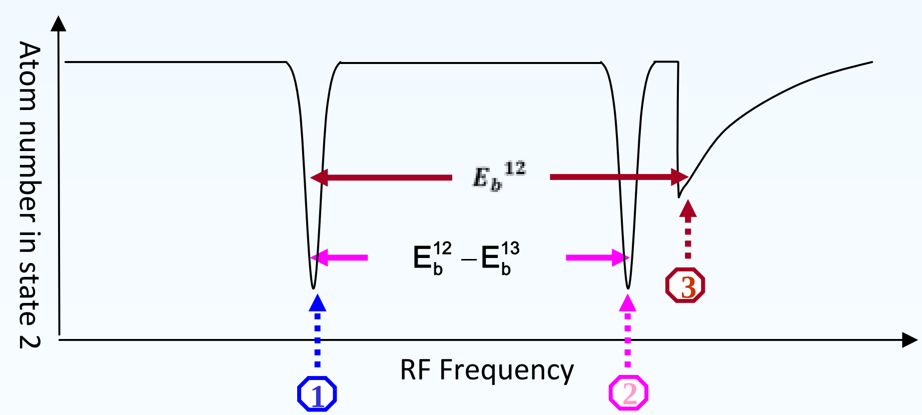
③ **"Free" wavefunction:** $\psi_{E_\perp}(z,\rho) \cong \phi_0(z)\frac{1}{\sqrt{A}}\left\{J_0(k_\perp\rho) - \frac{\pi i}{\ln(E_b/E_\perp)+\pi i}H_0(k_\perp\rho)\right\}$; $E_\perp = \frac{\hbar^2 k_\perp^2}{m}$

Bound-to-free transition spectrum:

$$I_{bf}(\upsilon) = \frac{E_b^{12}}{h\nu^2}\theta\left(\upsilon - \frac{E_b^{12}}{h}\right)\frac{q^2}{\left[q - \ln\left(\frac{h\upsilon}{E_b^{12}} - 1\right)\right]^2 + \pi^2}$$

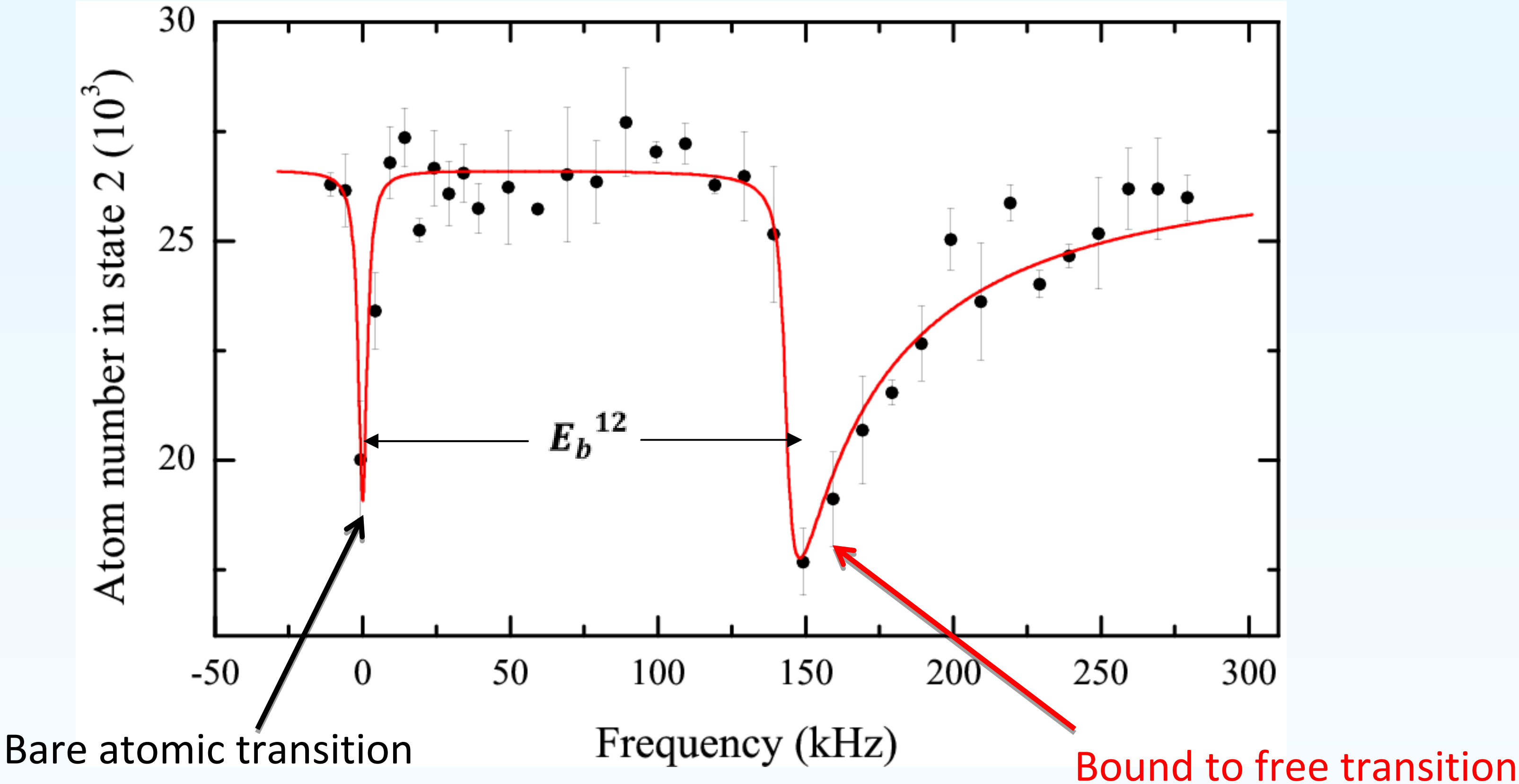
$$q \equiv \ln\left(E_b^{13}/E_b^{12}\right)$$

$$\int d\upsilon I_{bf}(\upsilon) = 1 - \varepsilon_{bb}(q)$$



RF 12-to-13 spectrum at 720 G

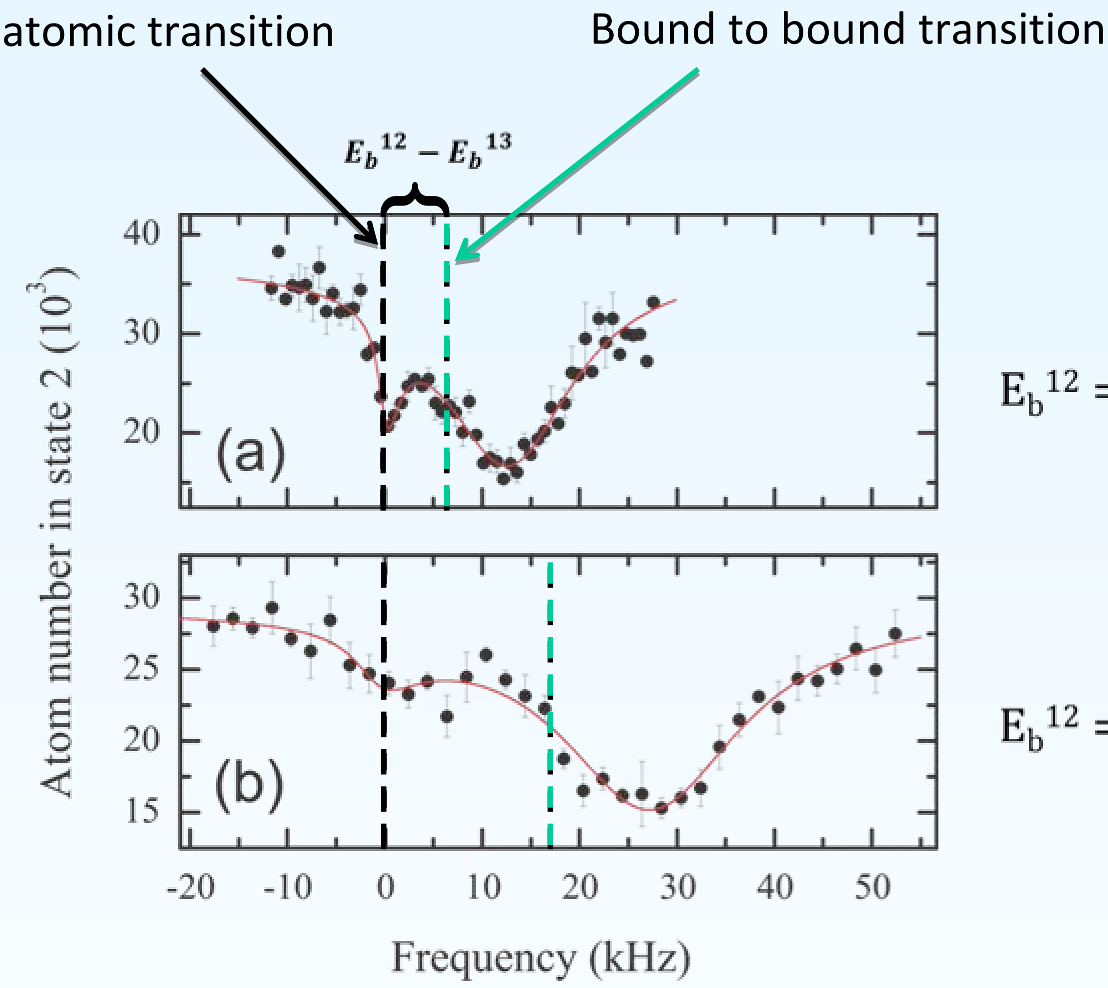
PHYSICS



$\epsilon_{bb} = 0.27, \mathrm{E_b}^{12} = 145\ \mathrm{kHz}, \mathrm{E_b}^{13} = 2.9\ \mathrm{kHz}$

RF 12-to-13 spectrum at 832G

PHYSICS NC



$\upsilon_z = 24.5\ \text{kHz}$

$\epsilon_{bb} = 0.66,$
$E_b^{12} = 7.25\ \text{kHz}, E_b^{13} = 0.81\ \text{kHz}$

$\upsilon_z = 82.0\ \text{kHz}$

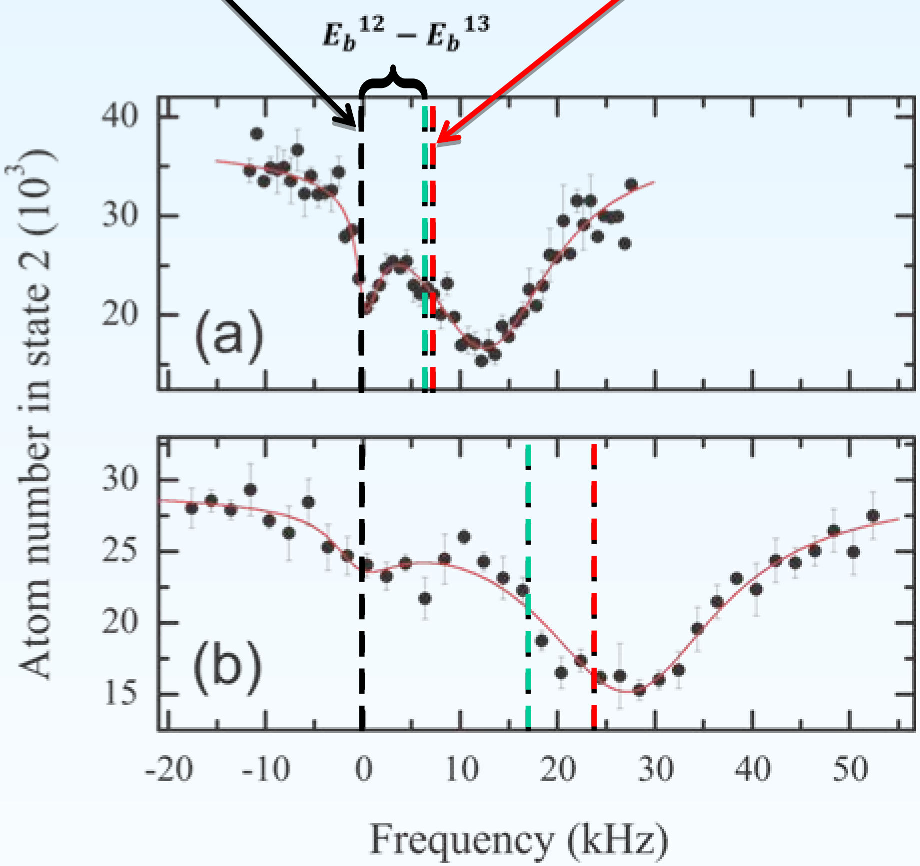
$\epsilon_{bb} = 0.83,$
$E_b^{12} = 23.9\ \text{kHz}, E_b^{13} = 5.79\ \text{kHz}$

RF spectrum at 832G

PHYSICS

Bare atomic transition

Bound to free transition



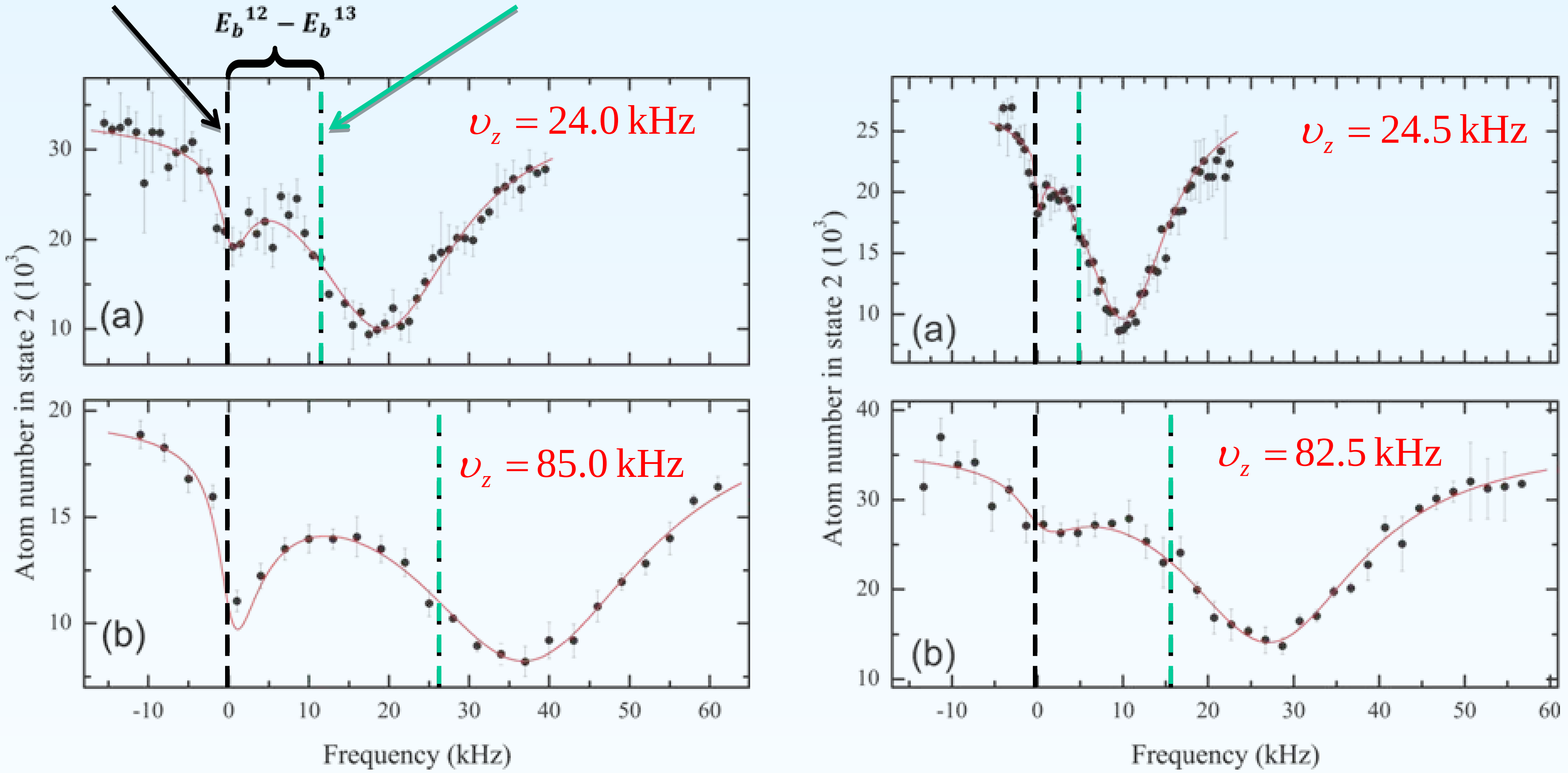
$\epsilon_{bb} = 0.66$,
$E_b{}^{12} = 7.25$ kHz, $E_b{}^{13} = 0.81$ kHz

$\epsilon_{bb} = 0.83$,
$E_b{}^{12} = 23.9$ kHz, $E_b{}^{13} = 5.79$ kHz

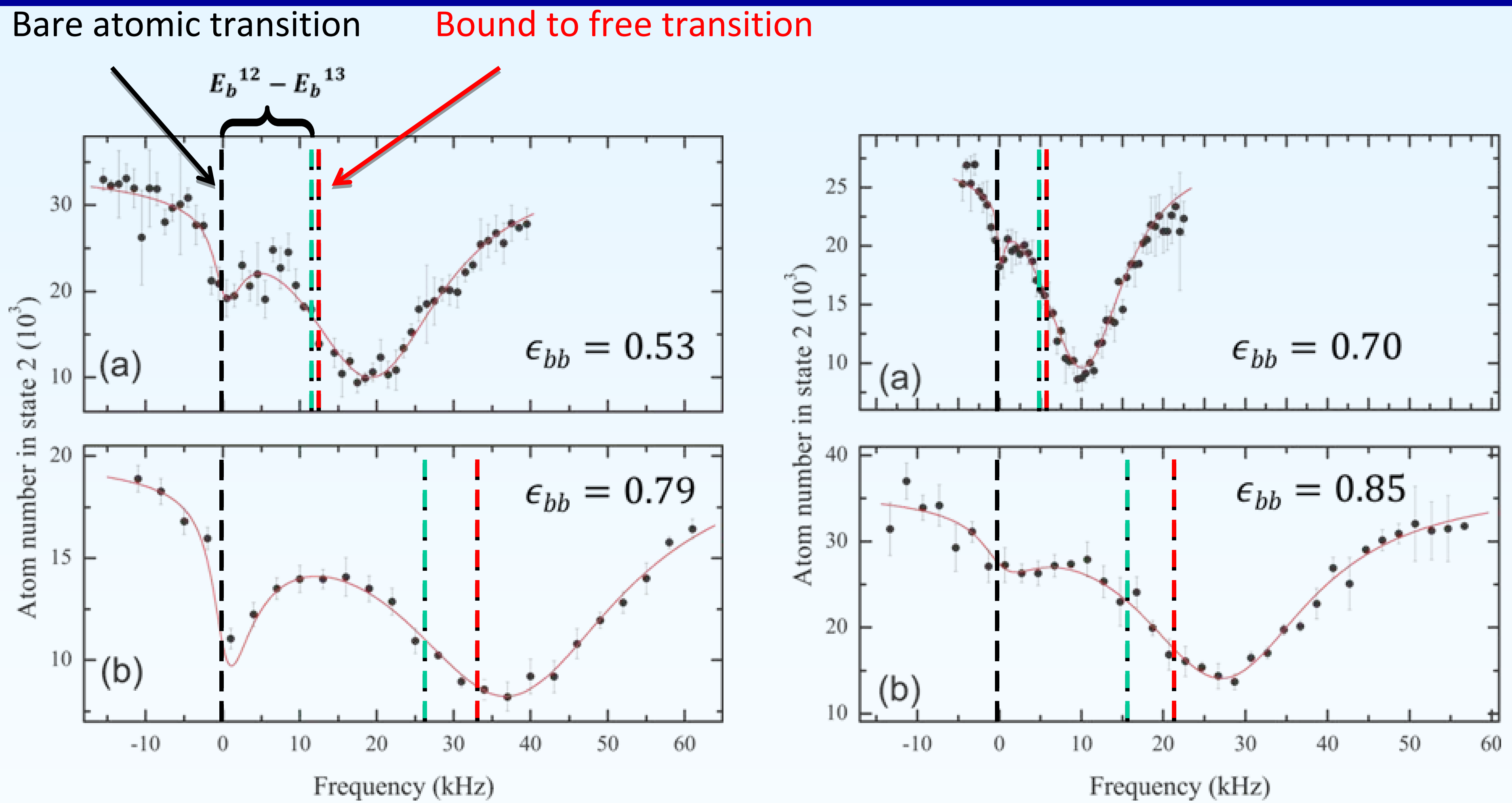
RF 12-to-13 spectra at 811G & 842G

Bare atomic transition

Bound to bound transition



RF spectra at 811G (left) & 842G (right)



- Spectra in *disagreement* with dimer theory!

BCS Theory—Many-body effects?

PHYSICS

RF spectrum *non-interacting* final state:

$$\boxed{I_{BCS}(\upsilon) \propto \frac{1}{\upsilon^2}\int_0^\infty d^2\mathbf{x}_\perp |\Delta|^2 \theta\left[h\upsilon + \mu - \sqrt{\mu^2 + |\Delta|^2}\right]}$$

<u>Randeria PRL 1989:</u> T = 0 Gap equation in 2D: $E_b = \sqrt{\mu^2 + |\Delta|^2} - \mu$

$$T_{2B}(k_{\perp 0}) = \frac{\hbar^2}{m}\frac{4\pi}{\pi i + \ln[\varepsilon_b/(2\varepsilon_{\mathbf{k}\perp 0})]} \Rightarrow \boxed{h\nu_{\text{threshold}} = E_b}$$

Threshold *exactly* at the dimer binding energy!

Observed by Sommer et al, PRL 2012.

Polarons in 2D?

PHYSICS

For 2-3 transition, state 3 initially empty:
3-impurity in Fermi sea of atoms in state 1—Polaron?

Chevy's ansatz for the zero-momentum polaron PRA 2006:

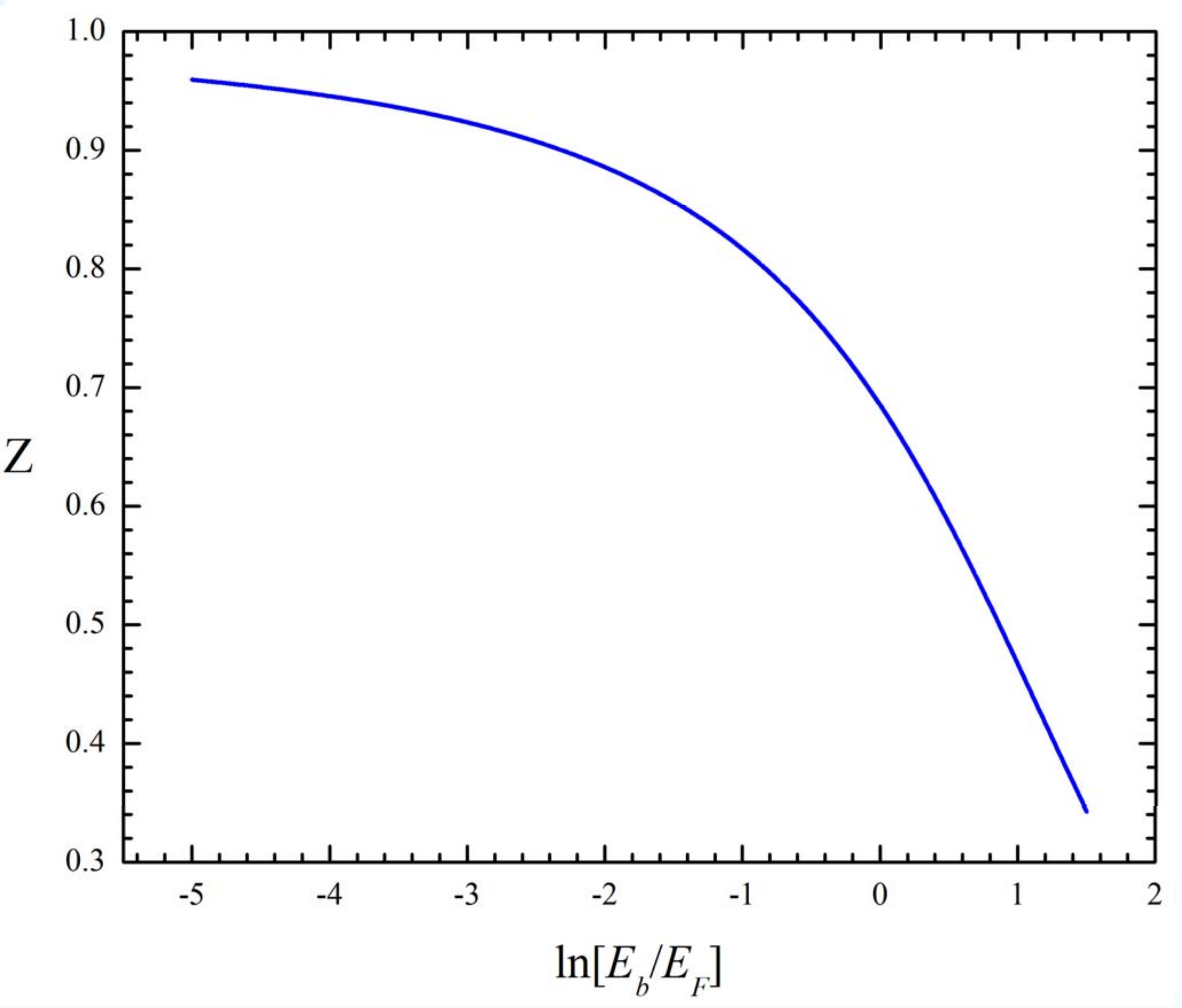
$$\boxed{\left|E_{pi}\right\rangle = \varphi_{0i}\left|\mathbf{k}=0\right\rangle_i \left|FS\right\rangle_1 + \sum_{q<k_F<k} \varphi_{\mathbf{kq}i}\left|\mathbf{q}-\mathbf{k}\right\rangle_i c^+_{\mathbf{k}1} c_{\mathbf{q}1}\left|FS\right\rangle_1}$$

Follow Shirotzek et al., PRL 2009, but change 3D to 2D:

$$\varepsilon \equiv \frac{E_{pi}}{E_{F\perp}} \qquad \boxed{\varepsilon = \Sigma(\varepsilon)}$$

$$\Sigma(\varepsilon) = -2\int_0^1 \frac{du}{-\ln\left(\dfrac{E_b}{E_{F\perp}}\right) + \ln\left[\sqrt{(1-\varepsilon/2)^2 - u} + (1-\varepsilon/2-u/2)\right]}$$

Polaron Energy E_p and Weight Z

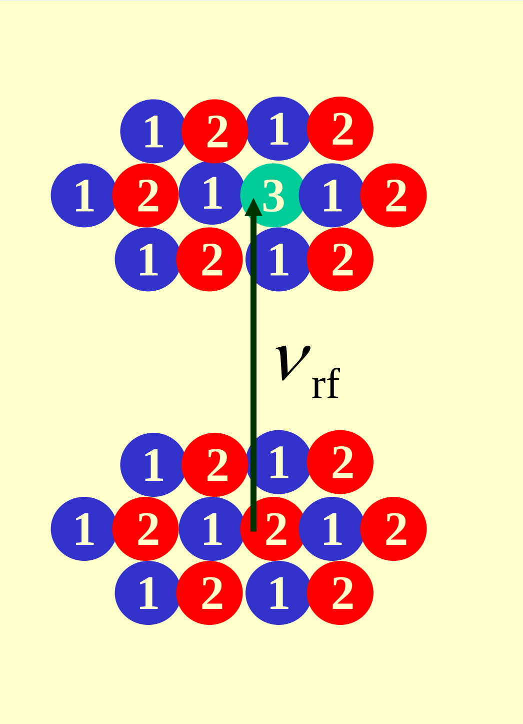


2-1 Polaron-to-3-1 Polaron Transition

PHYSICS NC

Problem: 3-1 Polaron energy is HUGE!

*Try 2-1 polaron-to-3-1 polaron transition!



*Following Zwierlein et al., PRL 2003 and Baym et al., PRL 2007, we assume that 2-3 interactions cause *no shifts* for 2-to-3 transitions.

Polaron-to-polaron transitions

PHYSICS

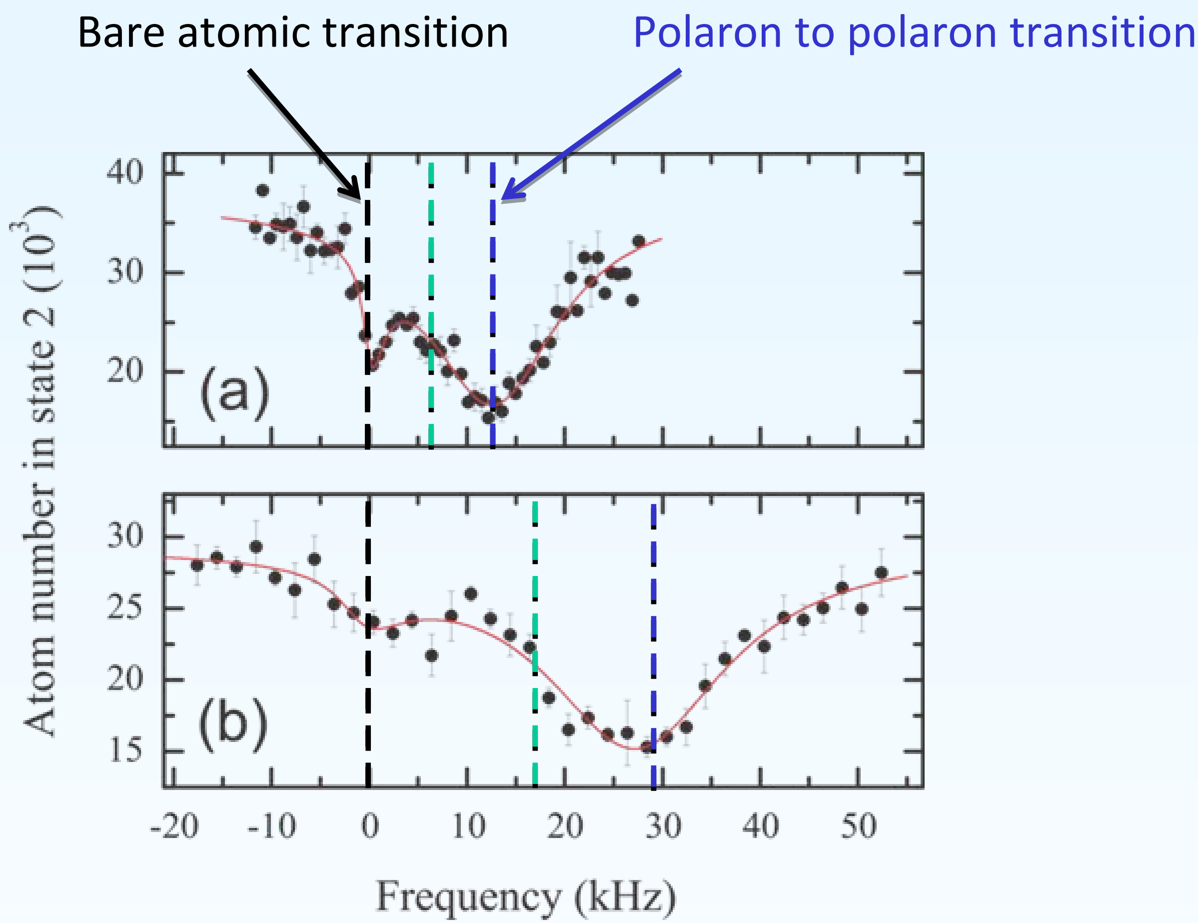
- Polaron: an impurity atom in $|2\rangle$ or $|3\rangle$ immersed in a bath of $|1\rangle$ atoms.

$$h\Delta v_{\mathbf{polaron}} = E_b(2,1) - E_b(3,1)$$

$$E_{F\ local} = \lambda_1 E_{F\perp} \qquad \lambda_1 = 0.67$$

$\boldsymbol{B}\ (\boldsymbol{G})$	$v_z\ (\boldsymbol{kHz})$	$\Delta v_{measure}\ (\boldsymbol{kHz})$	$\Delta v_{\mathbf{polaron}}\ (\boldsymbol{kHz})$
809	24	18.7	18.3
810	85	37.1	37.0
842	24.5	10.1	9.7
842	82.5	27.2	26.7
832	24.5	12.3	11.6
832	82	28.3	29.1

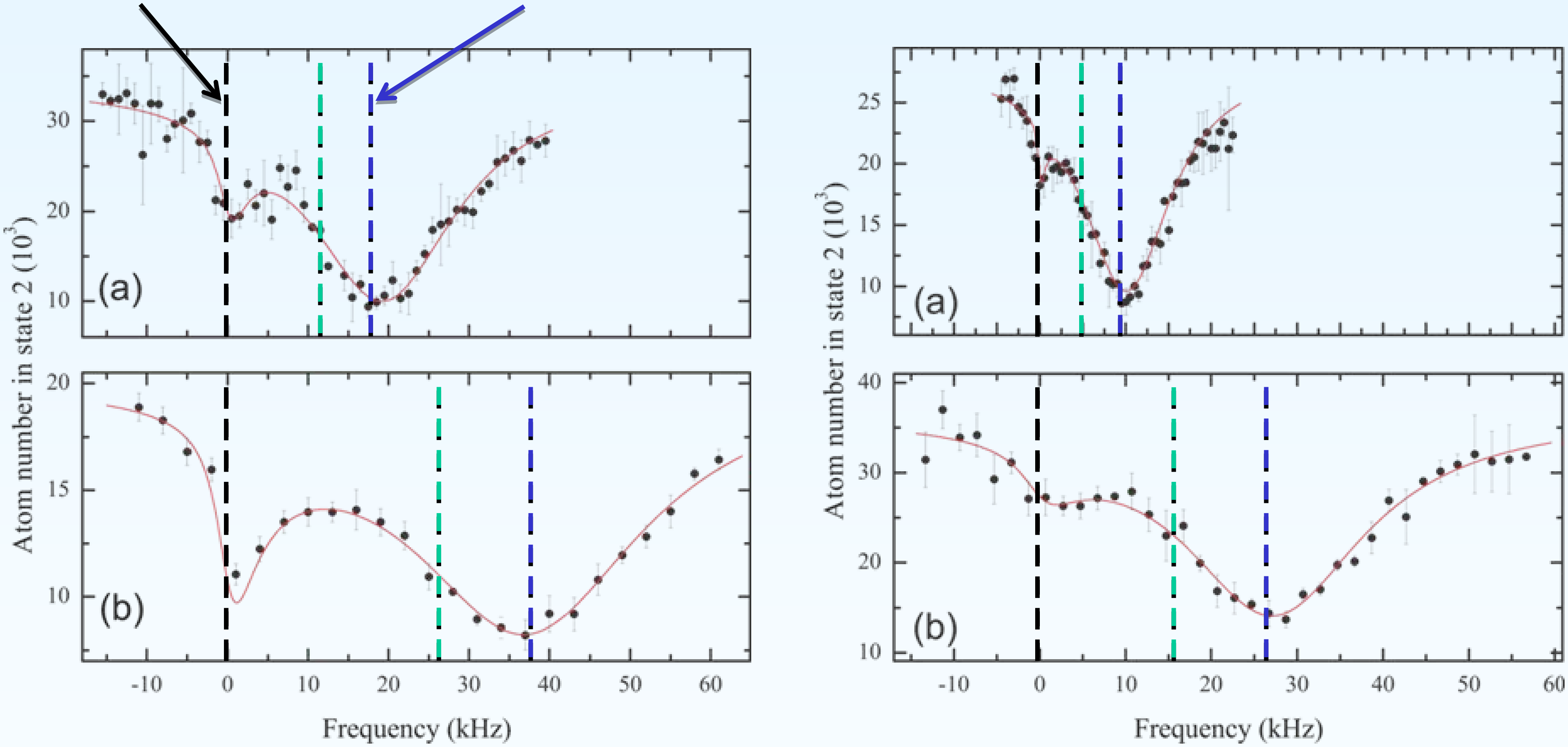
RF 12-to-13 spectrum at 832G



RF 12-to-13 spectra at 811G & 842G

Bare atomic transition

Polaron to polaron transition



Summary

PHYSICS

- Thermodynamics of strongly-interacting Fermi gases:
  - Tests of non-perturbative many-body theory/Temperature
- Transport: Minimum viscosity hydrodynamics:
  - Shear viscosity versus reduced temperature
  - Bulk viscosity vanishes for high temperature expansion
  - Minimum η/s 5 times the minimum viscosity conjecture
- Quasi-2D Fermi gas
  - Many-body physics — dimers versus polarons
- Future
  - Dependence of shear and bulk viscosity on interaction strength
  - Nonlinear hydrodynamics and shock waves
  - Optical control of interactions and dispersion

JETLAB Team 2012

PHYSICS NC