NewSpin2, College Station, 12/16/2011

Strongly Interacting Fermi Gases: Universal Thermodynamics, Spin Transport, and Dimensional Crossover

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Ultracold atomic Fermi Gases

Ideal test-bed for Many-Body physics

- Tunable, resonant interactions
- Fermi mixtures with controllable spin composition
- All relevant parameters precisely known

I. Realize idealized models of many-body physics

→ Benchmarking the many-body problem

Need high precision to discriminate between theories

- Equation of State of Unitary Fermi Gas

- Evolution from 3D to 2D

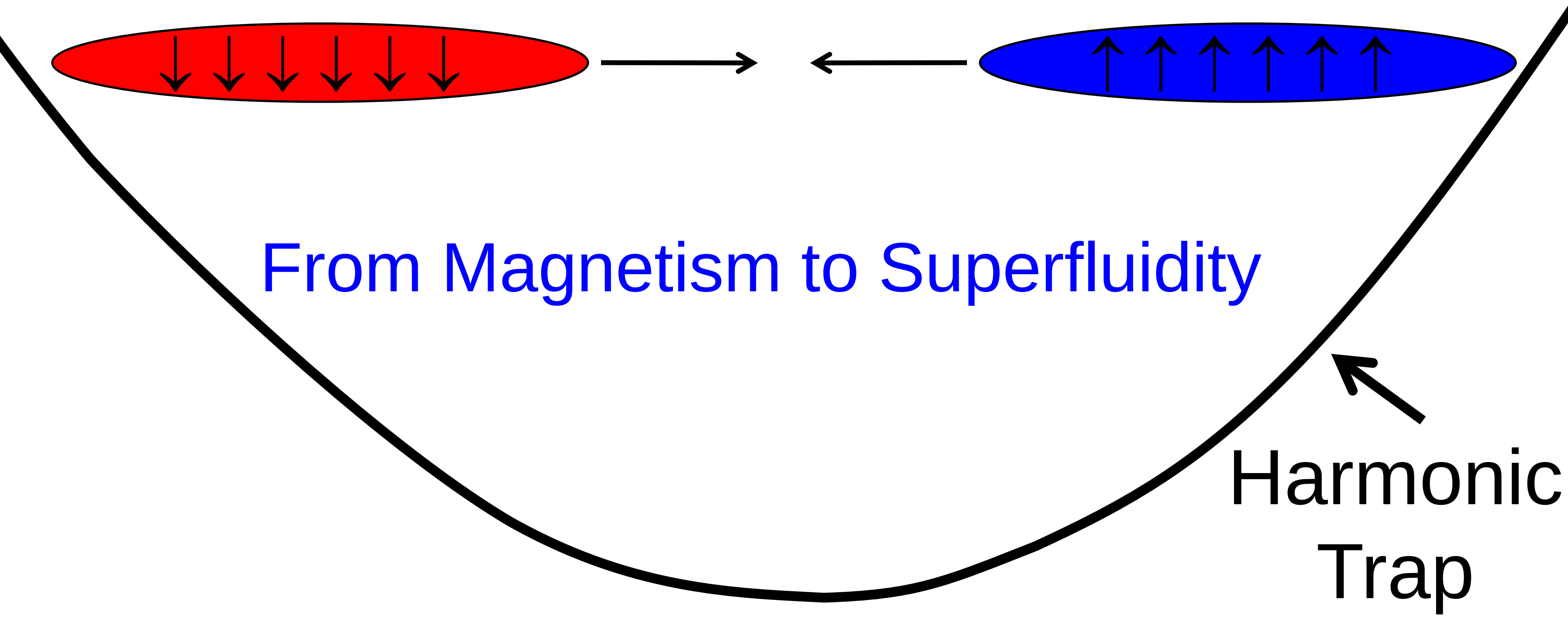
II. “Beyond the Standard Model”

Non-Equilibrium Physics, New States of Matter

- Spin Transport

Little Fermi Collider (LFC)

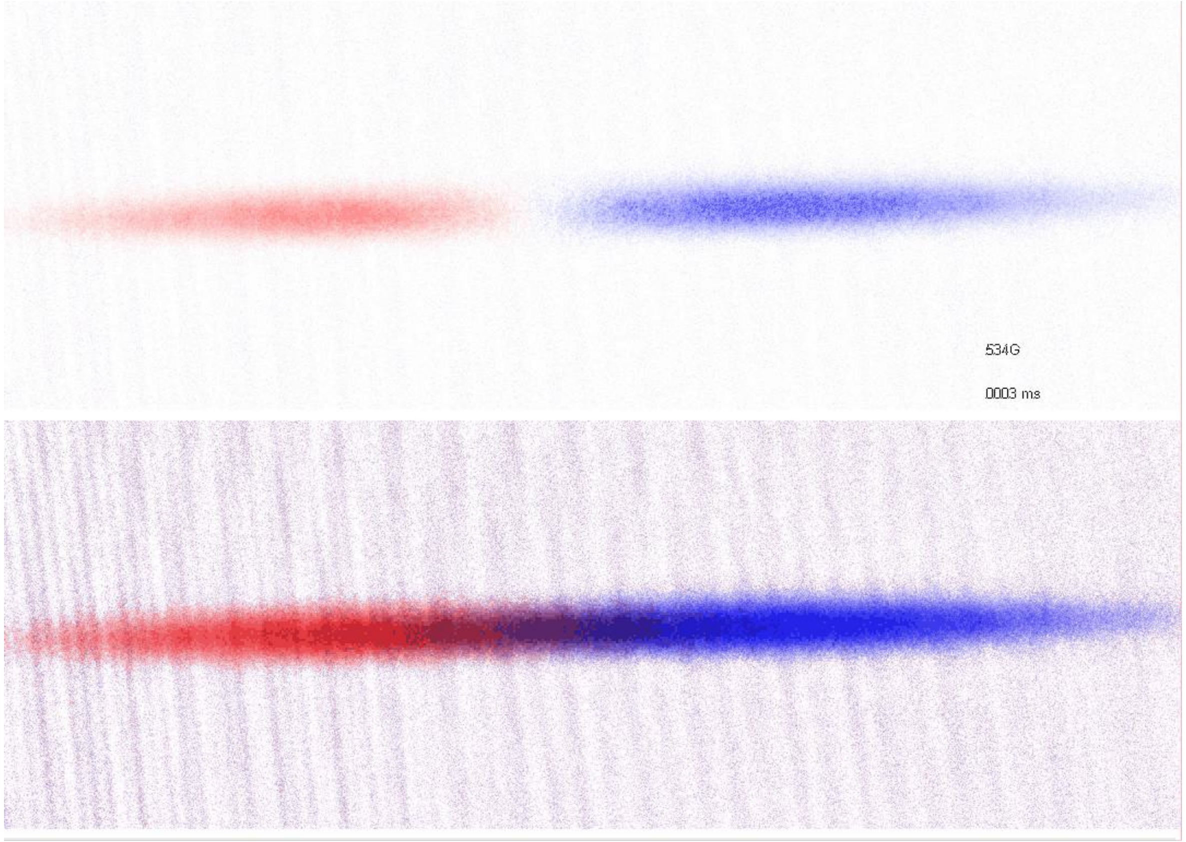
A $\downarrow$ Fermi gas collides with a $\uparrow$ cloud with resonant interactions



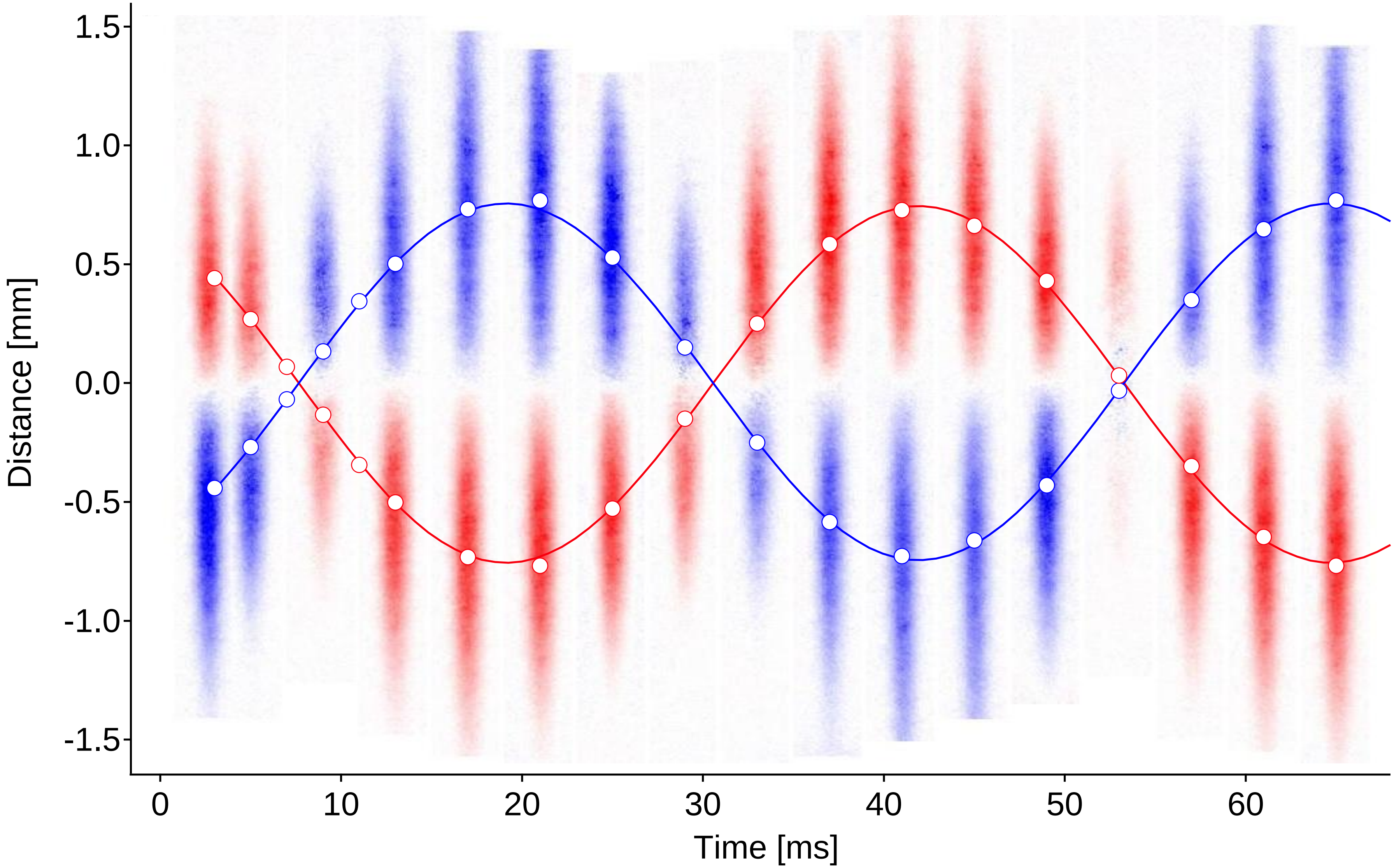
A. Sommer, M. Ku, G. Roati, MWZ, Nature **472**, 201 (2011)

Little Fermi Collider

No Interactions, a=0

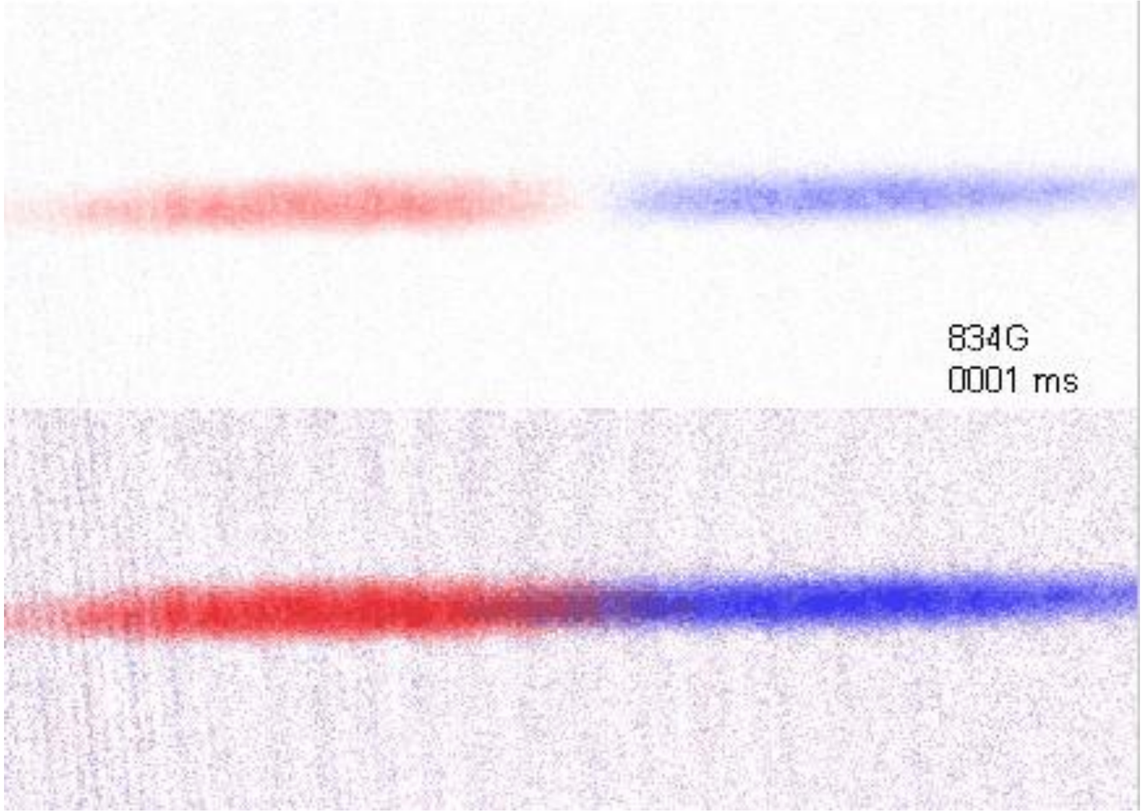


Evolution without interactions



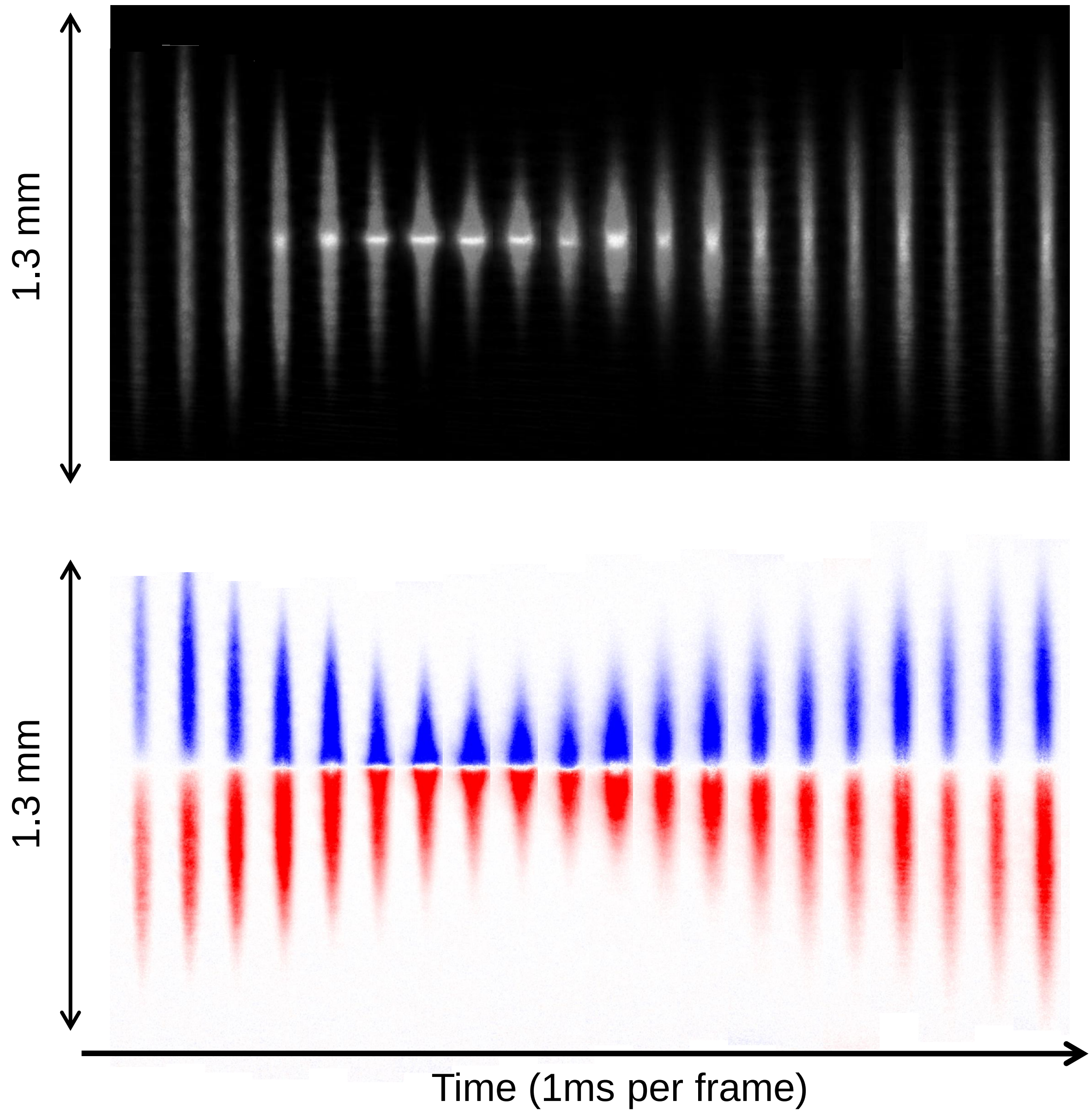
Little Fermi Collider

Unitary Interactions, 1/a=0

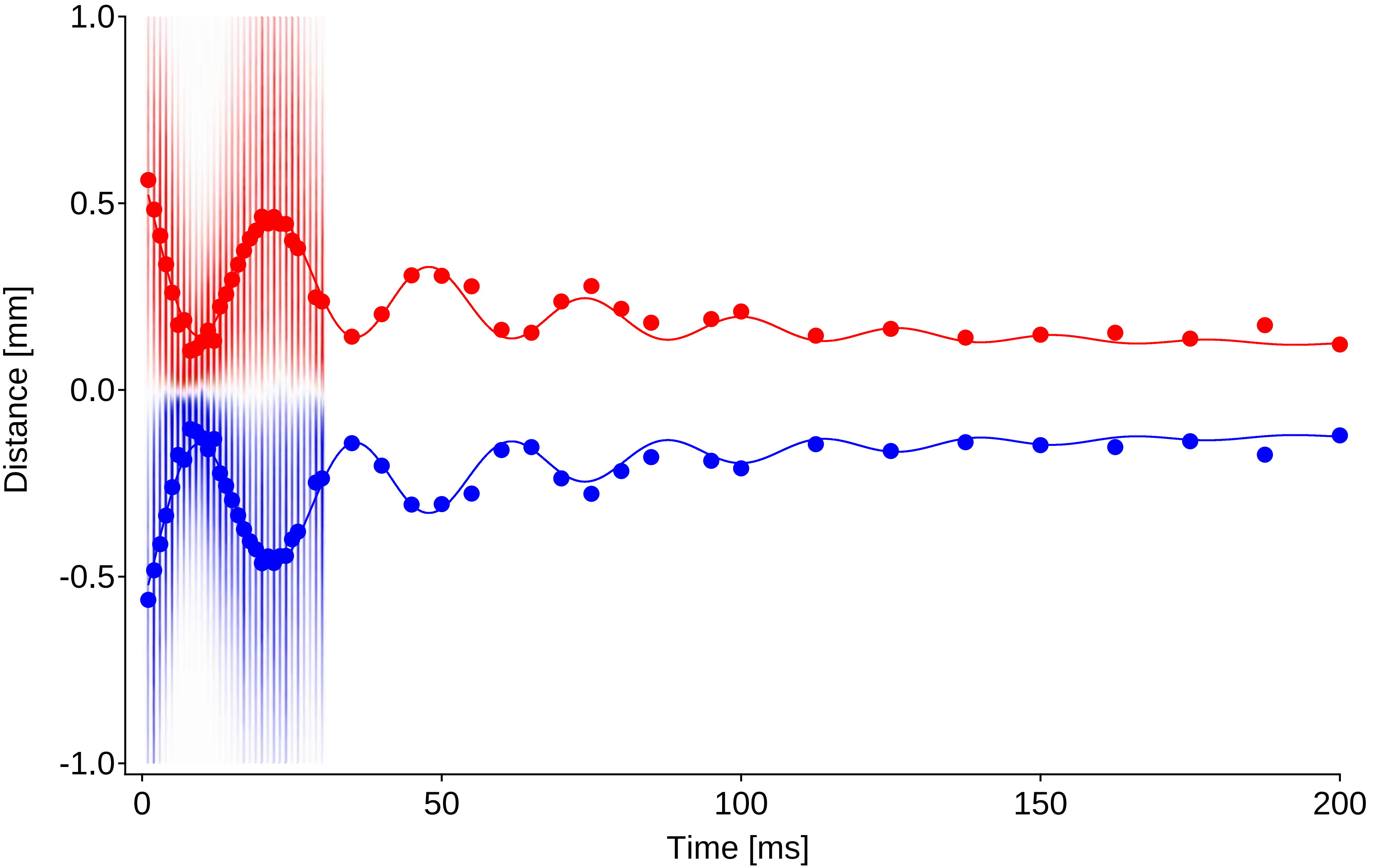


First collision

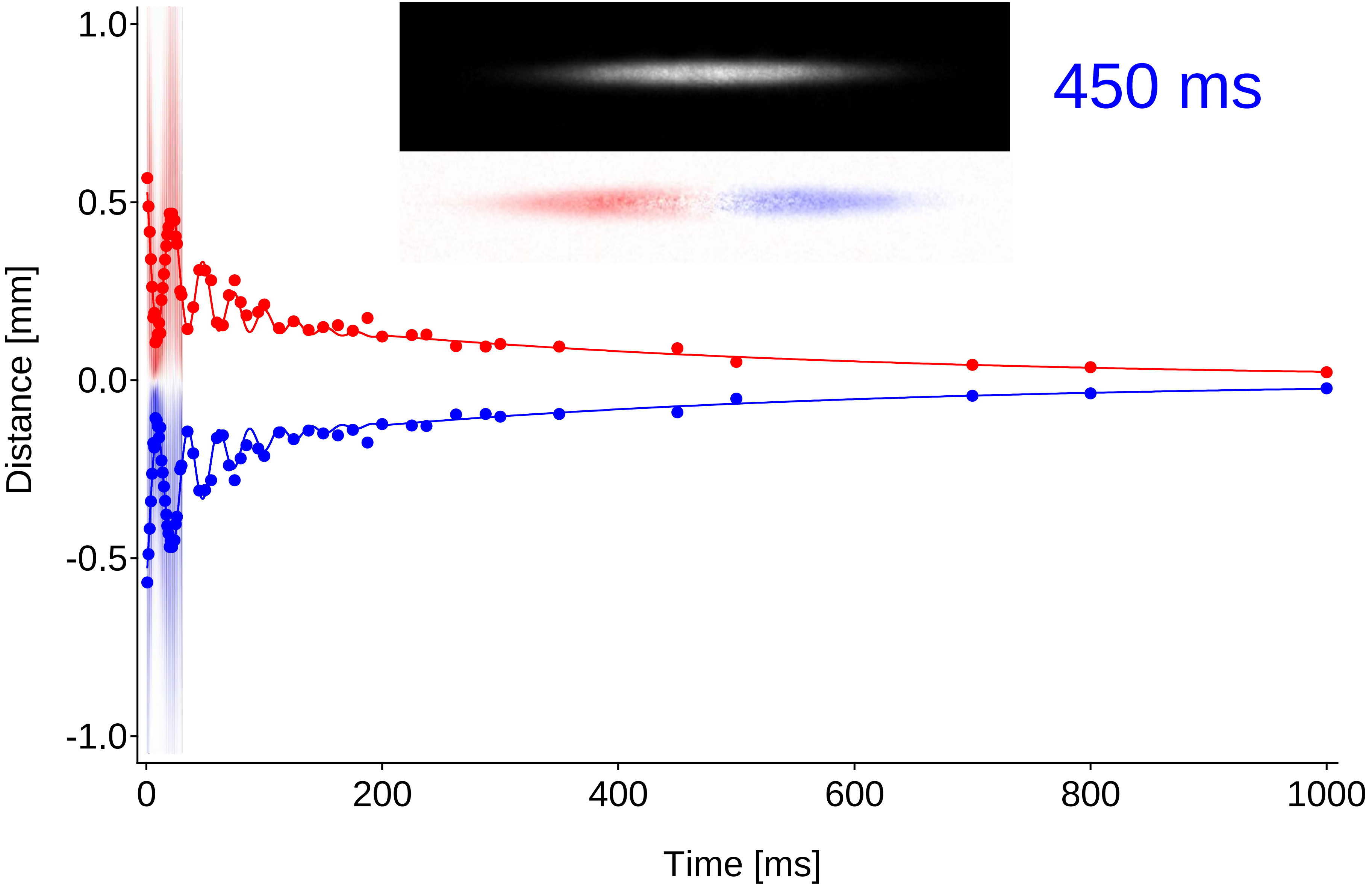
initial 20 ms



Later times



Much later times



Universal Spin Transport

Relaxation of spin current only due to $\downarrow\uparrow$ collisions

Resonant scattering cross section: $\sigma \sim \frac{1}{k_F^2}$

Mean free path: $l = \frac{1}{n\sigma} \sim \frac{1}{k_F}$ = interparticle spacing

"A perfect liquid"

Spin drag coefficient (∝ Collision rate) $\Gamma_{SD} \sim n\sigma v \sim \frac{\hbar}{m} k_F^2 \sim E_F / \hbar$

Diffusion constant: $D \sim \frac{(\text{mean free path})^2}{\text{collision time}} \sim \frac{\hbar}{m}$

$$\frac{\hbar}{m} = \frac{(100\ \mu\text{m})^2}{1\ \text{s}}$$

Universal Spin Transport

Relaxation of spin current only due to ↓↑ collisions

Resonant scattering cross section: $\sigma \sim \frac{1}{k_F^2}$

Mean free path: $l = \frac{1}{n\sigma} \sim \frac{1}{k_F}$ = interparticle spacing

"A perfect liquid"

Spin drag coefficient (∝ Collision rate) $\Gamma_{SD} \sim n\sigma v \sim \frac{\hbar}{m} k_F^2 \sim E_F / \hbar$

Diffusion constant: $D \sim \frac{(\text{mean free path})^2}{\text{collision time}} \sim \frac{\hbar}{m}$

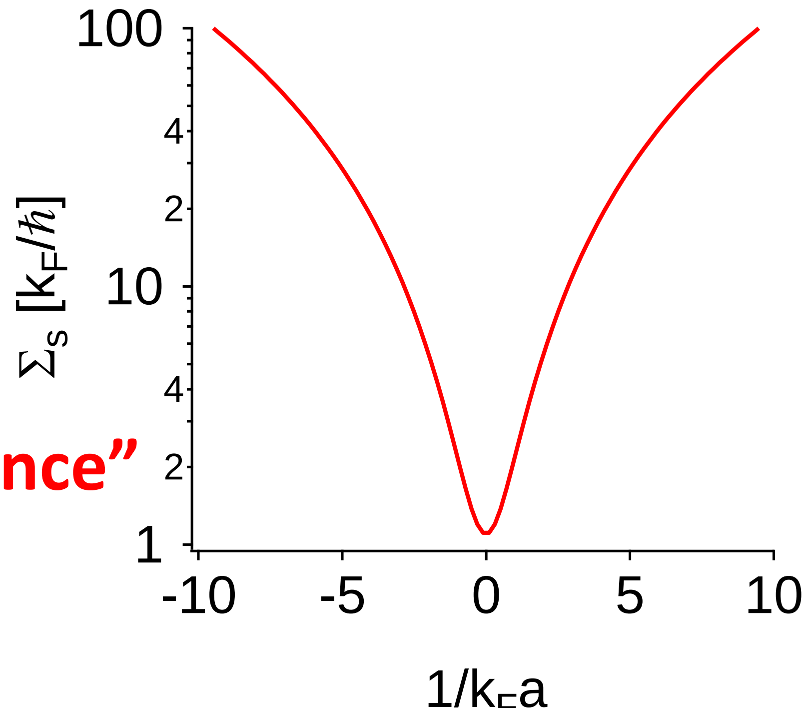
Spin conductivity: $\Sigma_s = \frac{n}{m\Gamma_{SD}} = \frac{1}{m\sigma v} \sim \boxed{\frac{k_F}{\hbar}}$

Tunable spin conductivity

- Spin conductivity in cold Fermi gases is tunable over a wide range

$$\Sigma_{spin} = \frac{n}{m}\frac{1}{\Gamma_{SD}} = \frac{1}{m\sigma v}$$

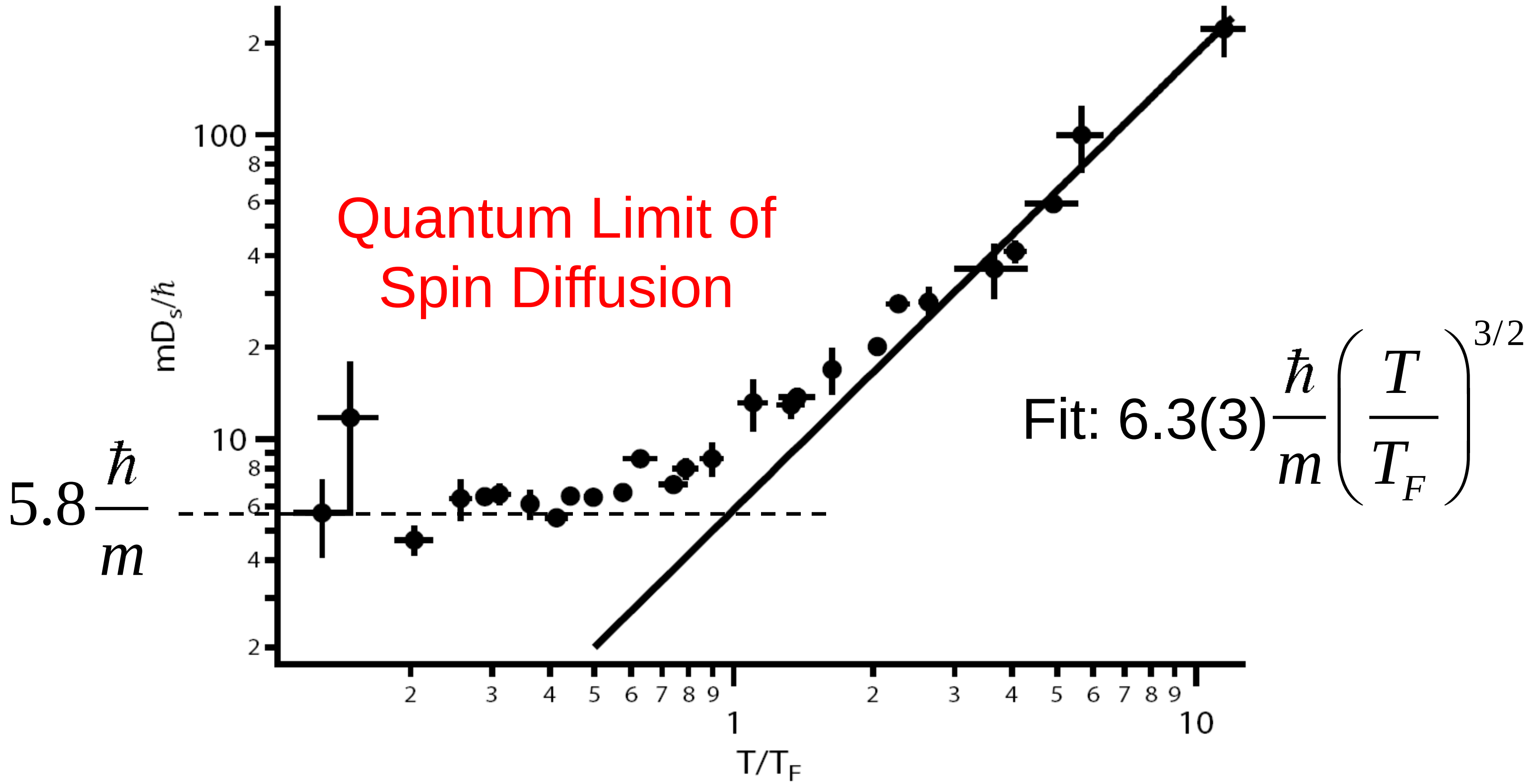
$$\Sigma_{spin} \underset{T\sim T_F}{\approx} \frac{k_F}{\hbar}\frac{1+ck_F^2a^2}{a^2}$$



"Giant Magneto Spin Resistance"

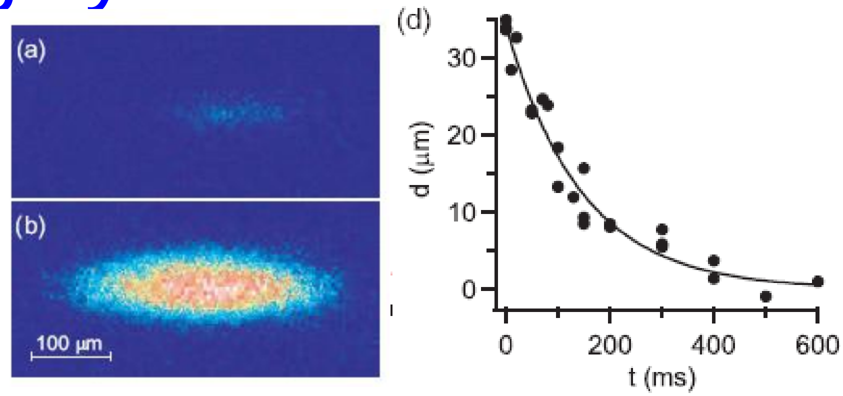
Spin Diffusion vs Temperature

$$j_s = n_{tot}\dot{d} = n_{tot}\Gamma_{sd}d = -D_s\left(\frac{dn_\uparrow}{dx} - \frac{dn_\downarrow}{dx}\right)$$



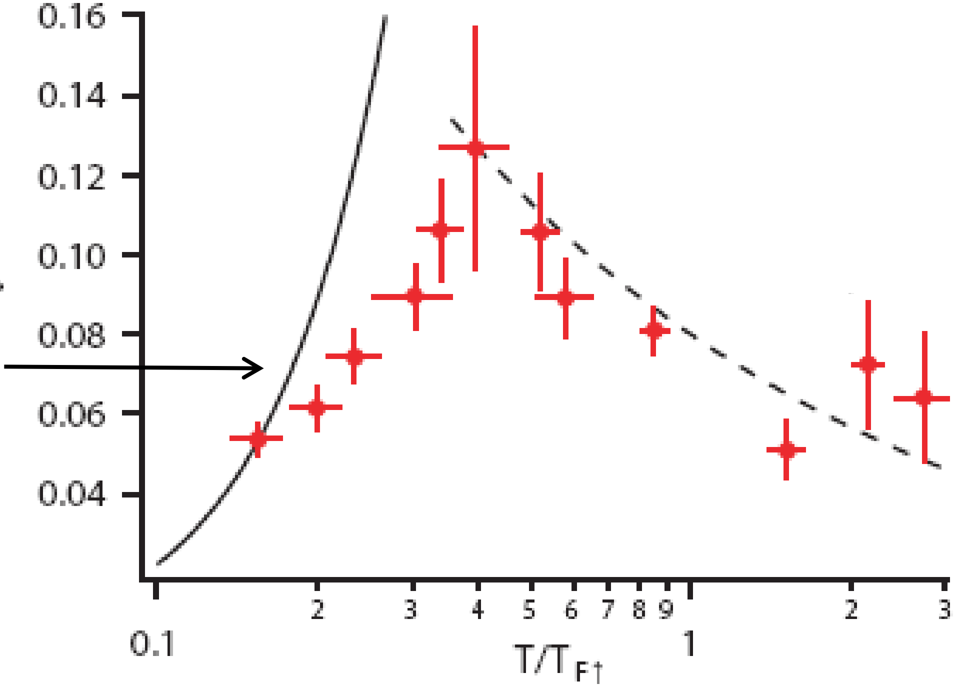
Spin Diffusion for imbalanced mixtures

- highly imbalanced mixture: Fermi liquid



Collision rate

Pauli blocking



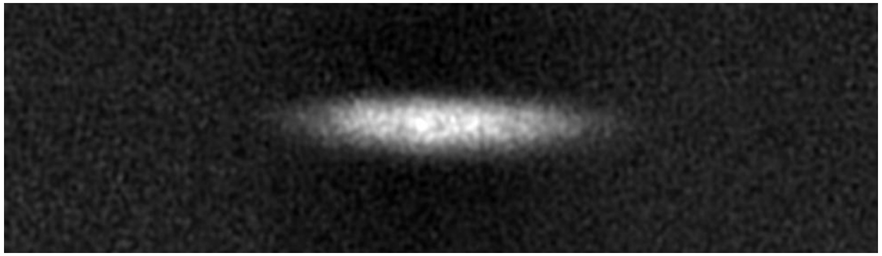
Classical Regime

Temperature

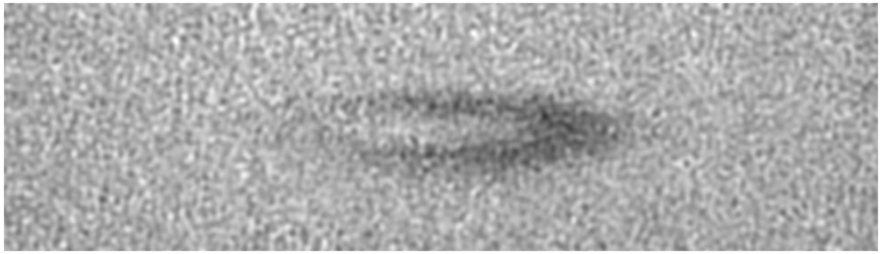
A. Sommer, M. Ku, MWZ, NJP 13, 055009 (2011)

Spin Diffusion in Presence of Superfluid

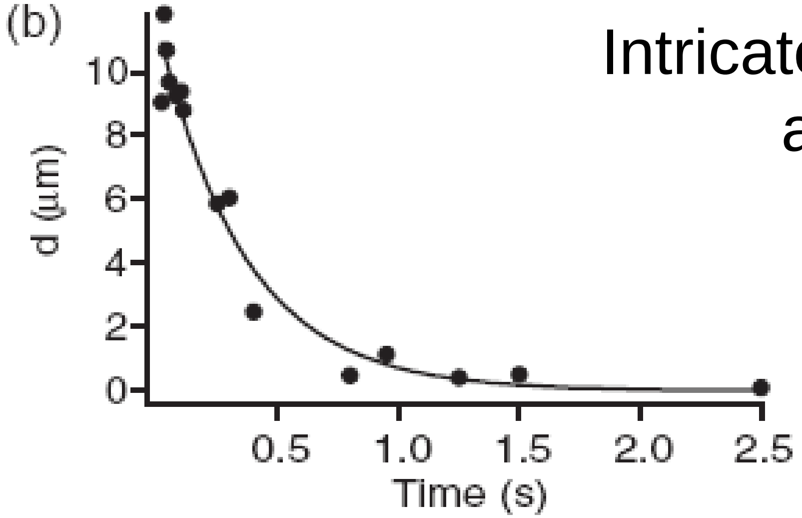
- Slight imbalance: Normal + Superfluid



Total density



Difference density



Intricate motion of normal unpaired atoms around(?) the superfluid core

Lot’s of Andreev reflections

A. Sommer, M. Ku, MWZ, NJP 13, 055009 (2011)

Thermodynamics

Equilibrium Thermodynamics
as baseline for non-equilibrium studies

→ Establish Equation of State

Classical gas $P = nk_B T$

Generally need $P(n,T)$

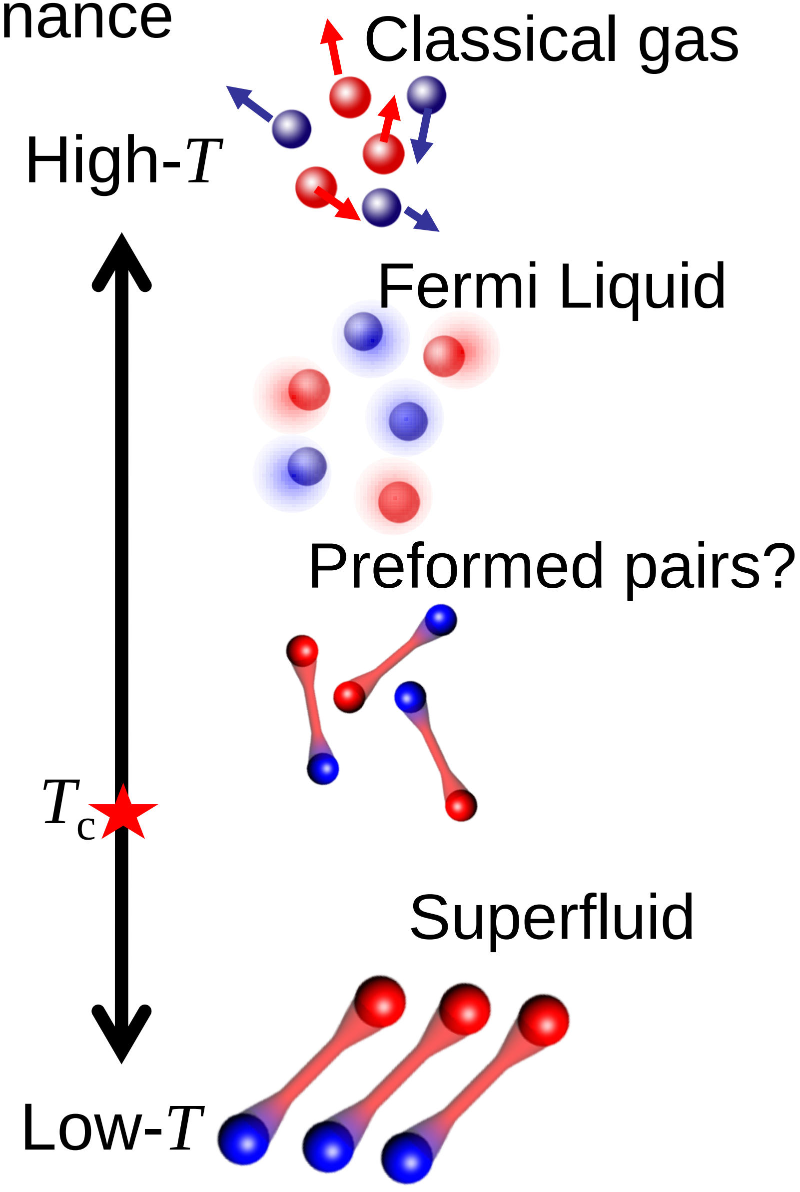
Or fixing chemical potential $P(\mu,T)$

Or replacing $n = \left.\dfrac{\partial P}{\partial \mu}\right|_{T,a,\ldots}$ $\boxed{n(\mu,T)}$

Thermodynamics of the Unitary Fermi Gas

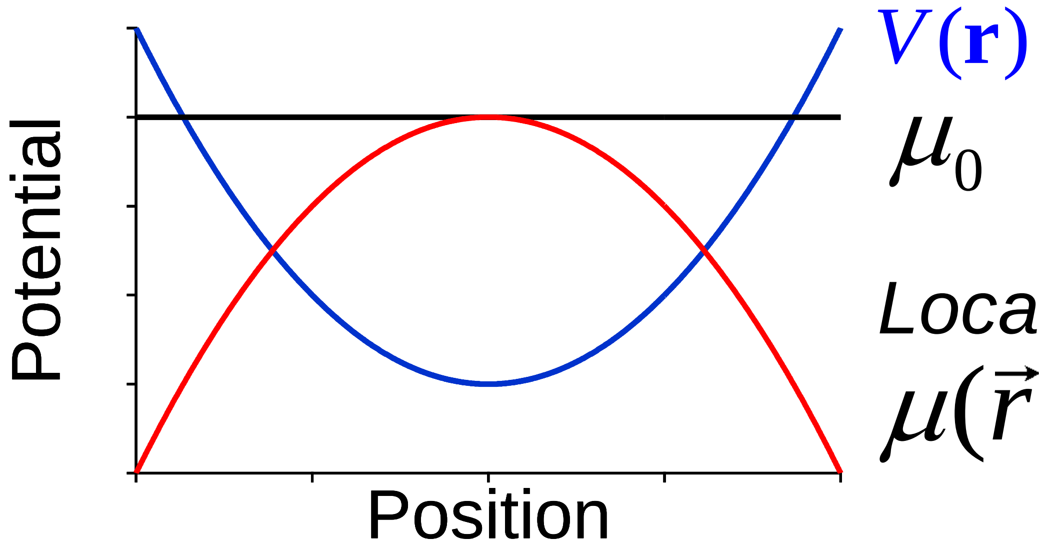
Spin ½ - Fermi gas at a Feshbach resonance

- *Normal state:*
  - Is it a Fermi liquid?
  - Are there preformed pairs (pseudogap regime)?
- *Superfluid properties*:
  - Transition temperature
  - Critical Entropy
  - Energy of the superfluid
  - …



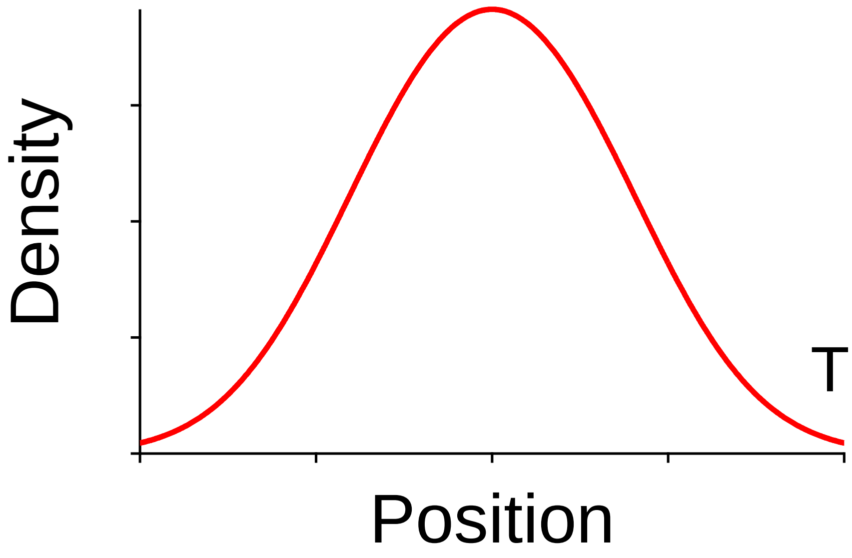
Equation of State

Equation of state from density distribution in a trap



Local chemical potential

$$\mu(\vec{r}) = \mu_0 - V(\vec{r})$$

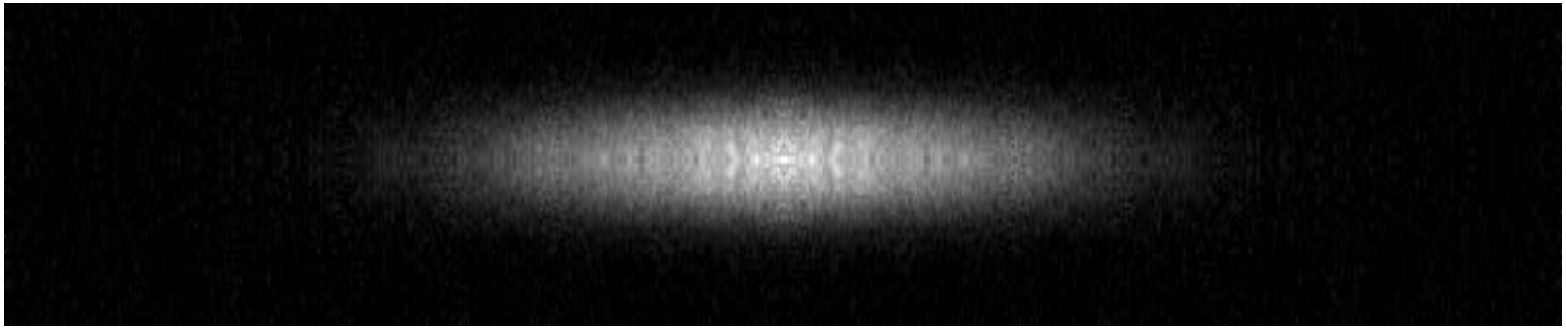


Local density

$$n(V) = n(\mu_0 - V, T)$$

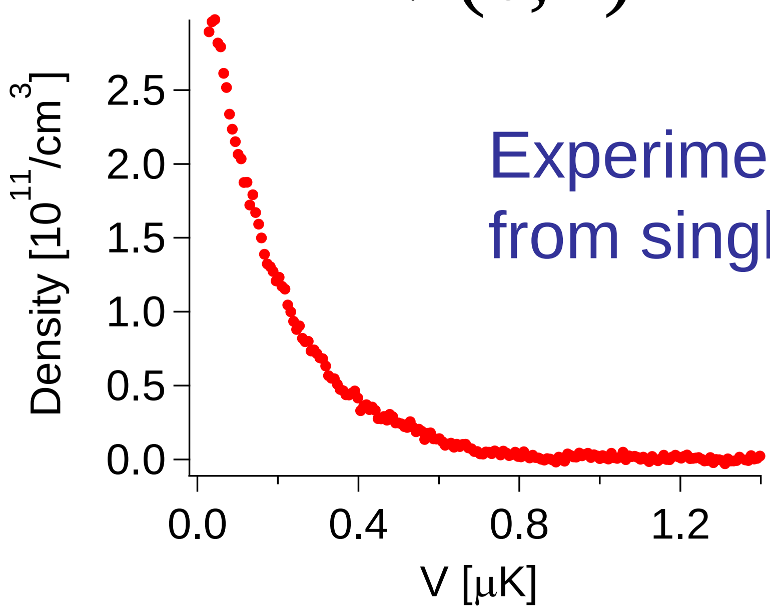
The density profile provides a scan through the equation of state

Measuring density



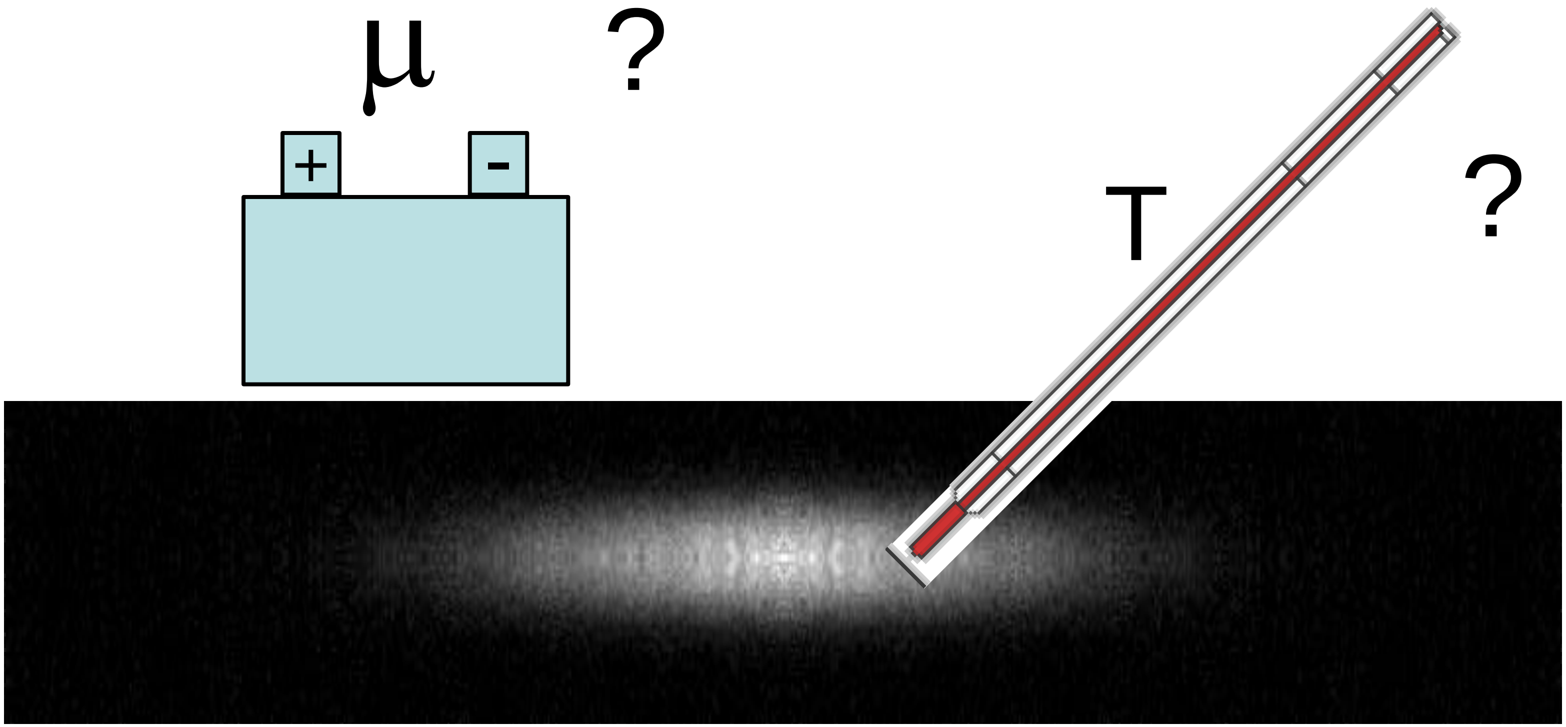
1. Cylindrical Symmetry: Inv. Abel
→ Get $n(\rho, z)$

2. Equidensity lines = Equipotential lines
→Get $V(\rho, z)$ as we know $V(0, z)$



Experimental $n(V)$
from single profile

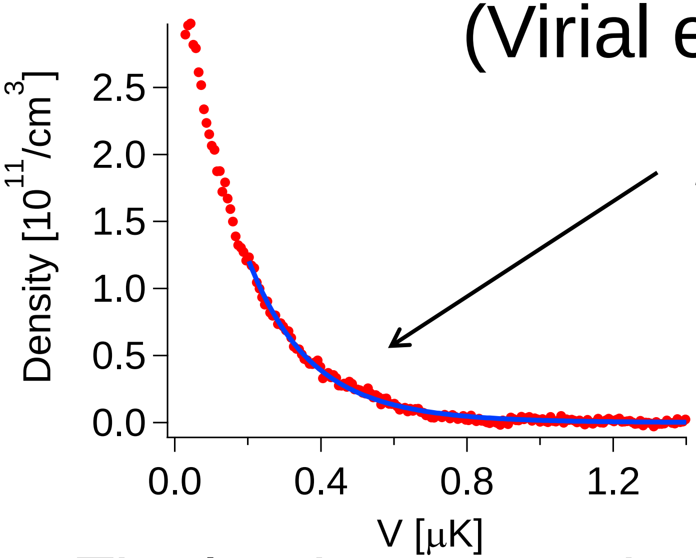
How to get μ and T?



How to get μ and T?

Solutions:

- Fit wings to high-temperature theory (Virial expansion, Hartree-Fock, etc…)



$$n\lambda^3 = 2\left(e^{\beta\mu} + 2b_2 e^{2\beta\mu} + 3b_3 e^{3\beta\mu} + \ldots\right)$$

$$b_2 = \frac{3\sqrt{2}}{8} \qquad b_3 = -0.29095295$$

b_2: Beth, Uhlenbeck (1937), Ho, Mueller (2004)
b_3: Liu, Hu, Drummond (2009), Blume et al. (2011)

That's what we all do.

3D Bose gas (see recent Cambridge expt.)

2D Bose Gas: Chicago, ENS, JILA

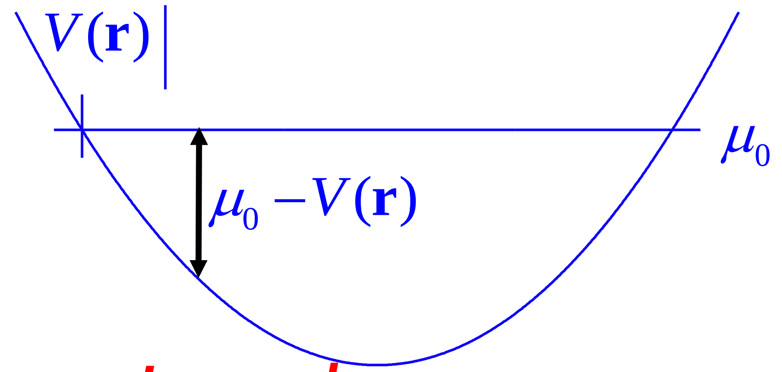
3D Unitary Fermi Gas: ENS (T fixed via ^{7}Li thermometer)

No-fit equation of state

We want: $n(\mu, T)$

We know $\mu = \mu_0$ - V

Thus $d\mu = - dV$



Local compressibility

$$\kappa = \frac{1}{n^2}\frac{\mathrm{d}n}{\mathrm{d}\mu} = -\frac{1}{n^2}\frac{\mathrm{d}n}{\mathrm{d}V}$$

Local pressure

$$P = \int_{-\infty}^{\mu} \mathrm{d}\mu\, n = \int_{V}^{\infty} \mathrm{d}V'\, n(V')$$

Compressibility Equation of State

$$\kappa(n, P)$$

No fit at all!

Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
arXiv:1110.3309 (2011)

No-fit Equation of State

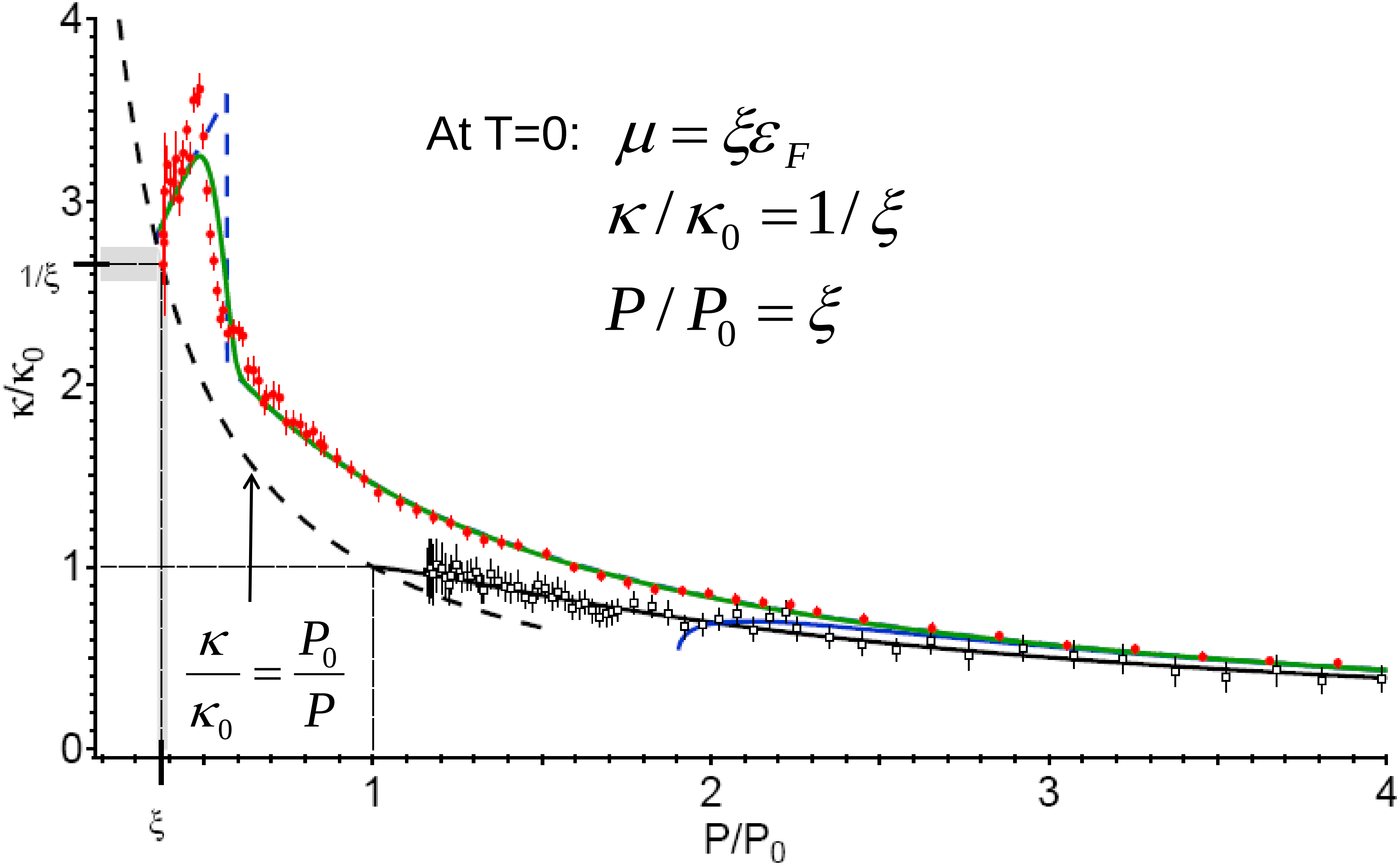
Normalize compressibility & pressure via known density:

$$\tilde{\kappa} = \frac{\kappa}{\kappa_0} = \frac{\mathrm{d}\varepsilon_F}{\mathrm{d}\mu} = -\frac{\mathrm{d}\varepsilon_F}{\mathrm{d}V} \qquad \tilde{P} = \frac{P}{P_0}$$

$$\kappa_0 = \frac{3}{2}\frac{1}{n\varepsilon_F} \qquad P_0 = \frac{2}{5}n\varepsilon_F$$

For a scale-invariant system $\boxed{\tilde{\kappa} = \tilde{\kappa}(\tilde{p})}$

Compressibility Equation of State



At T=0: $\mu = \xi \varepsilon_F$

$$\kappa / \kappa_0 = 1/\xi$$

$$P / P_0 = \xi$$

$$\frac{\kappa}{\kappa_0} = \frac{P_0}{P}$$

Compressibility Equation of State

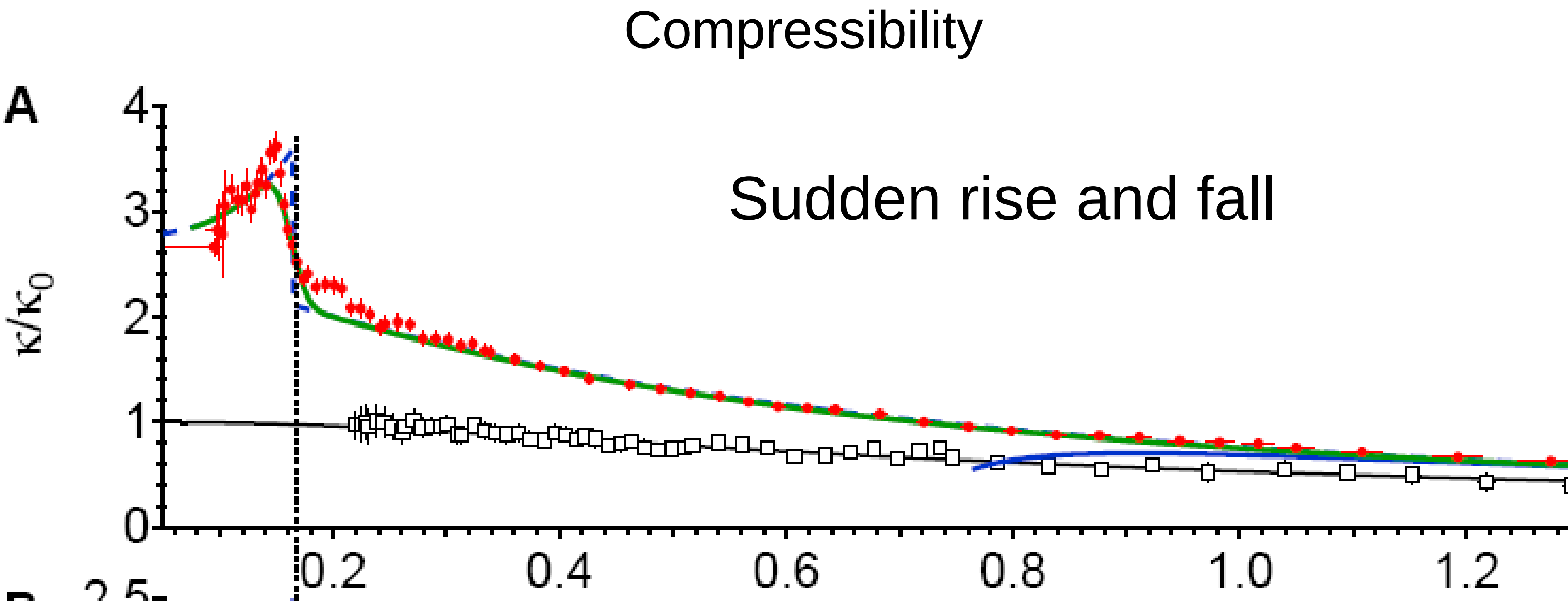
$$\kappa(n,P) \longrightarrow \kappa(n,T)$$

Getting the temperature scale:

$$\left.\frac{\mathrm{d}\left(P/P_0\right)}{\mathrm{d}\left(T/T_F\right)}\right|_T = \frac{5}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)$$

$$\frac{T}{T_F} = \frac{T_i}{T_F}\exp\left\{\frac{2}{5}\int_{\tilde{p}_i}^{\tilde{p}} d\tilde{p}\,\frac{1}{\tilde{p} - \frac{1}{\tilde{\kappa}}}\right\}$$

Compressibility Equation of State

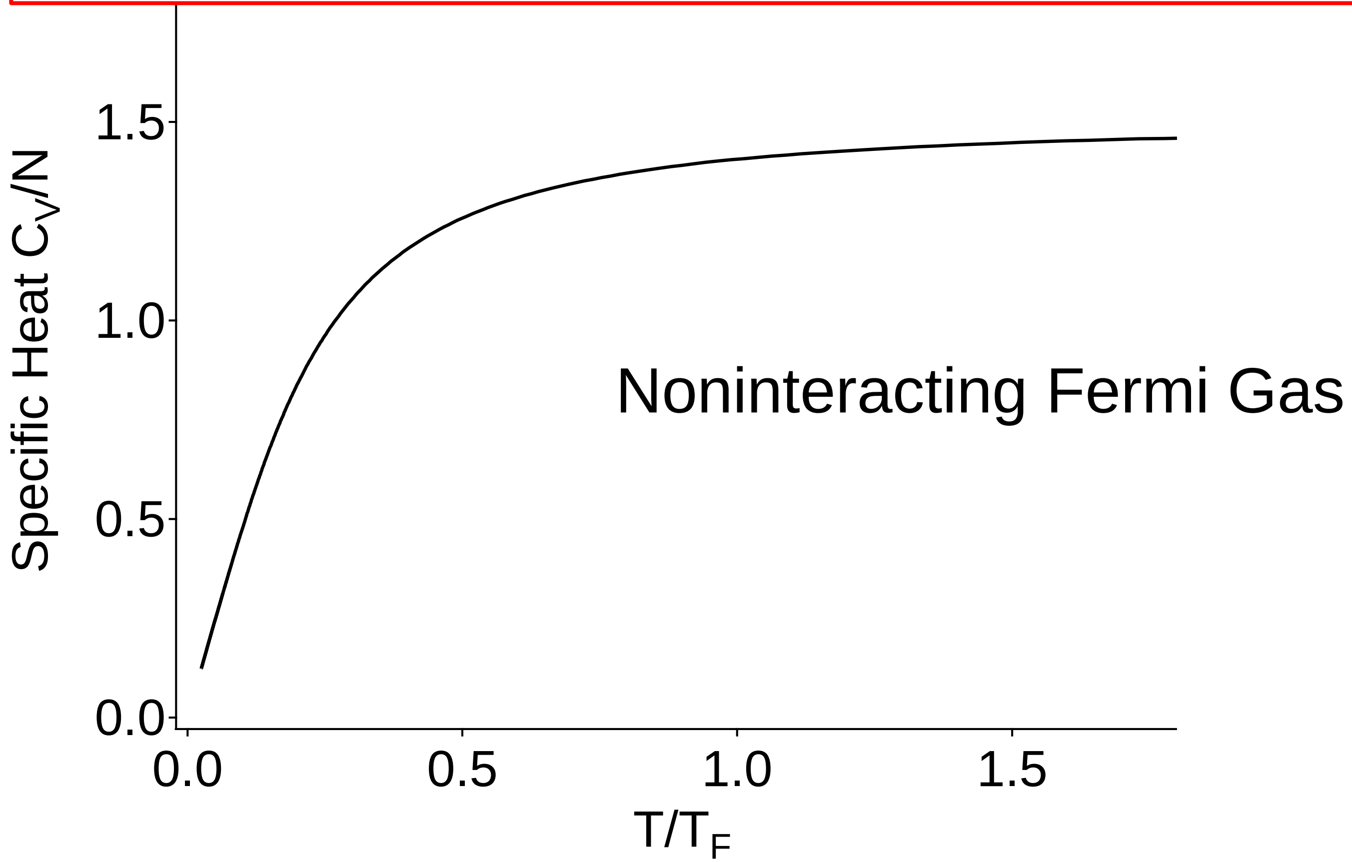


Heat capacity

At unitarity:

$$P = \frac{2}{3}\frac{E}{V}$$

$$\boxed{\frac{C_V}{Nk_B} = \frac{\mathrm{d}\left(E/Nk_B\right)}{\mathrm{d}T}\bigg|_{N,V} = \frac{\mathrm{d}\left(P/nE_F\right)}{\mathrm{d}(T/T_F)} = \frac{3}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)}$$



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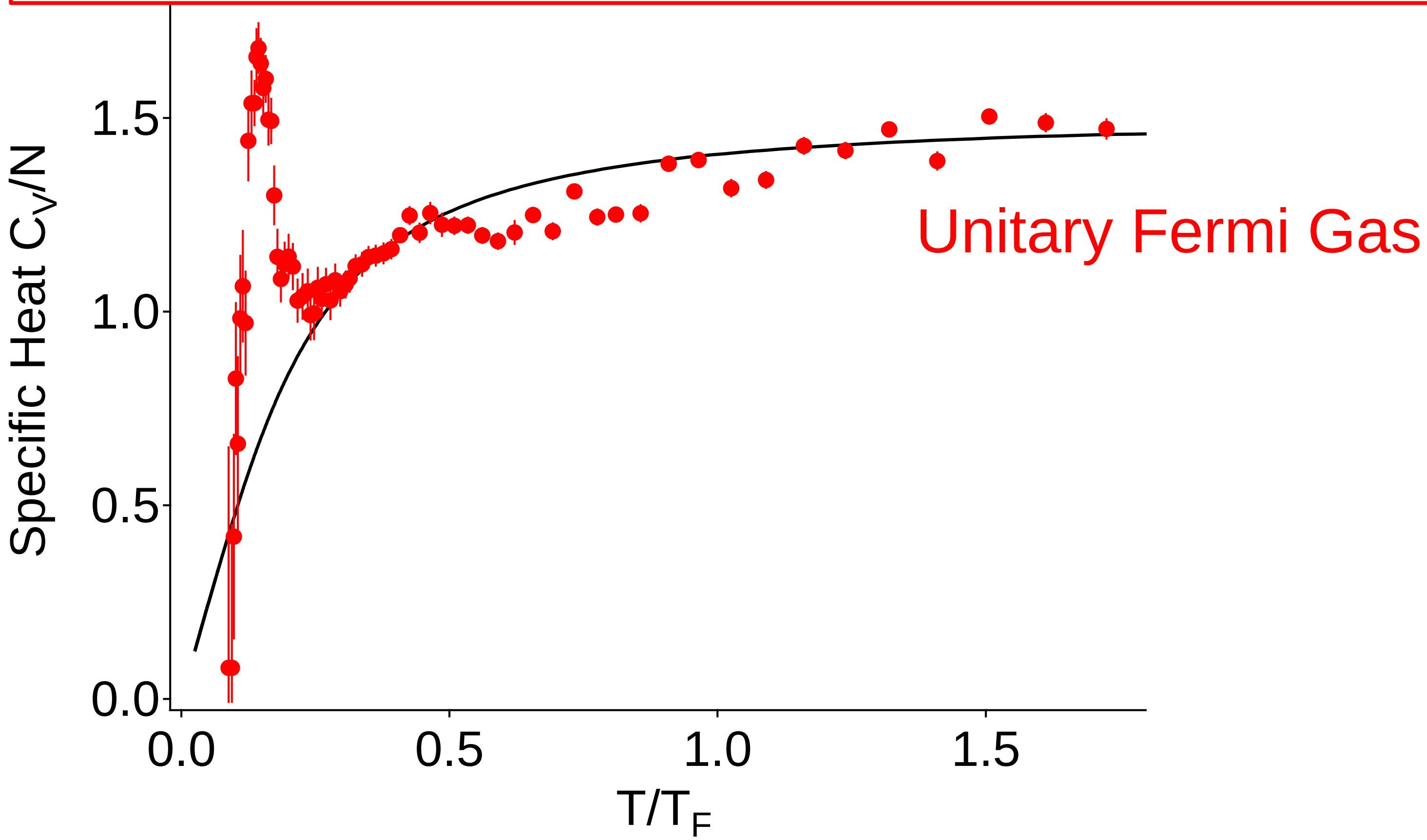

Heat capacity

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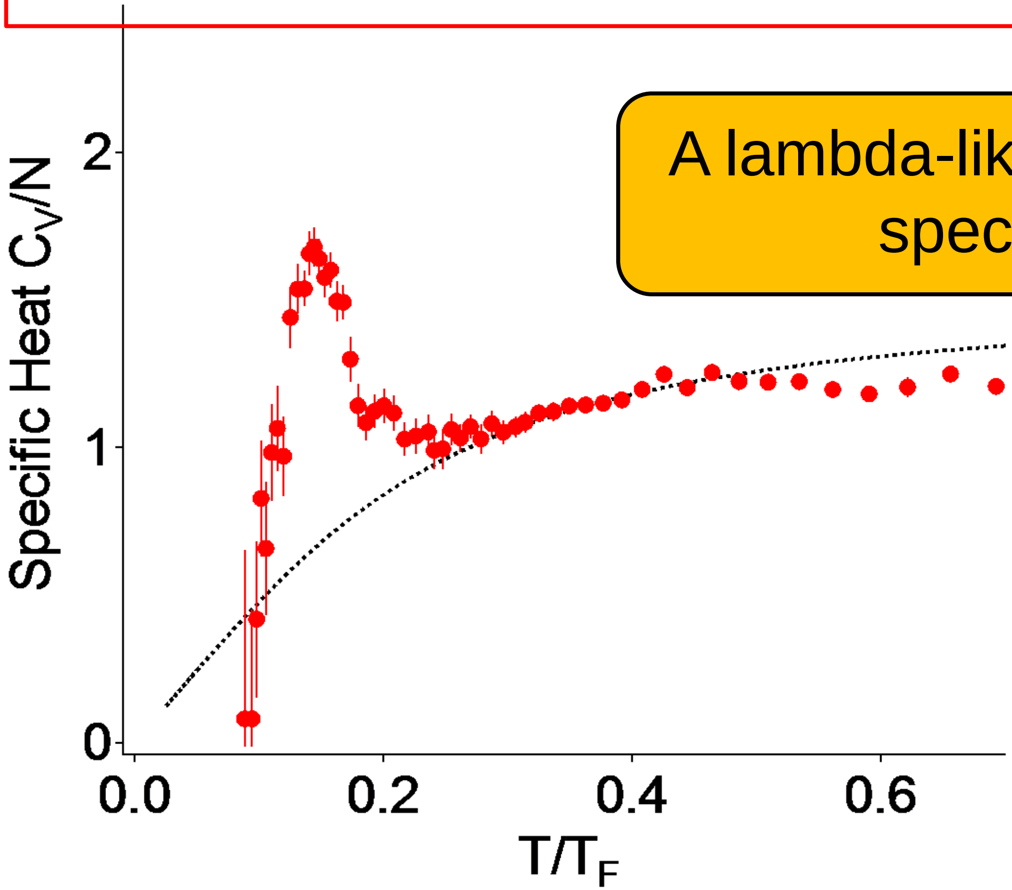
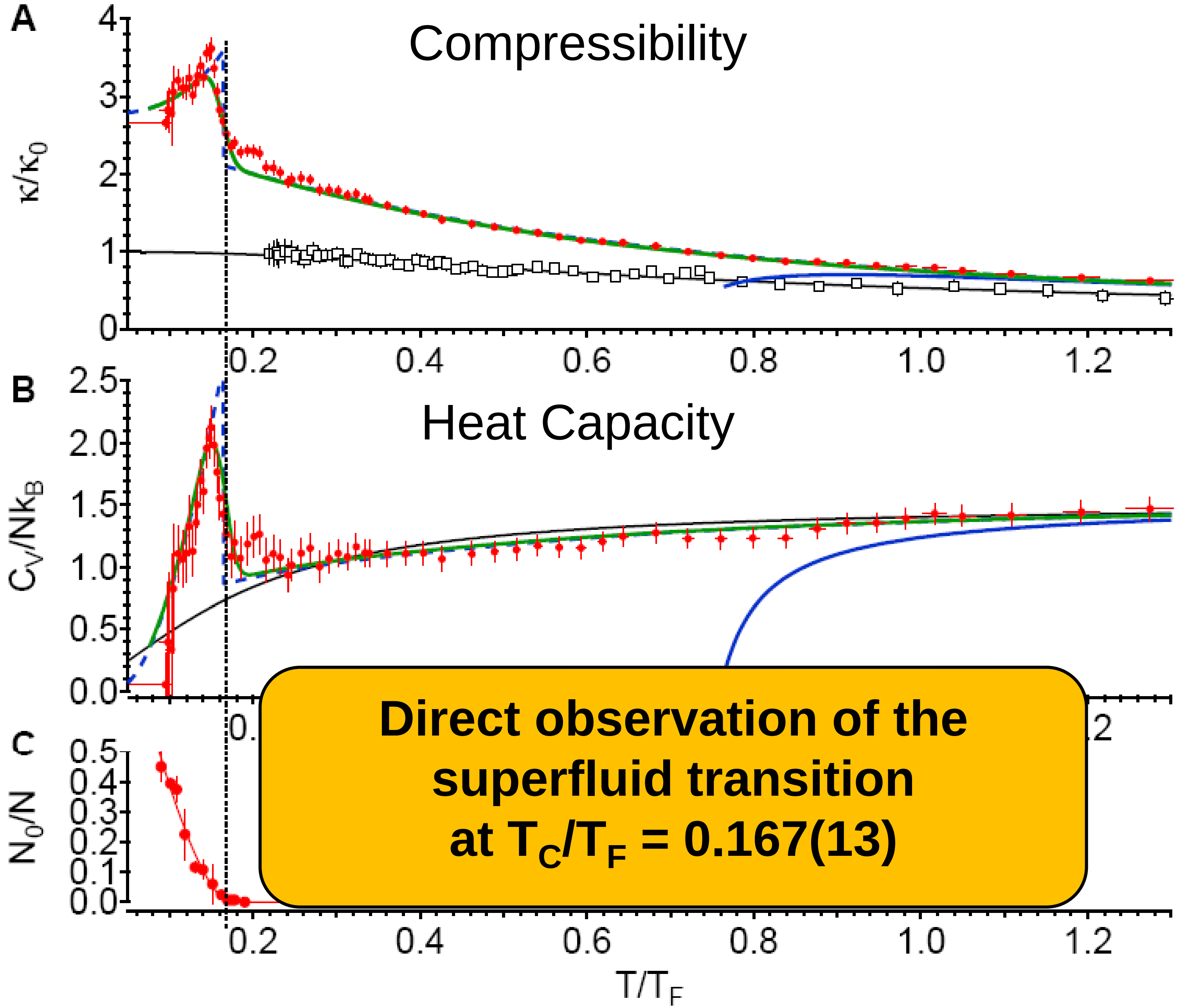


A lambda-like feature in the specific heat

Compressibility, Heat Capacity, Condensates



Compressibility Equation of State

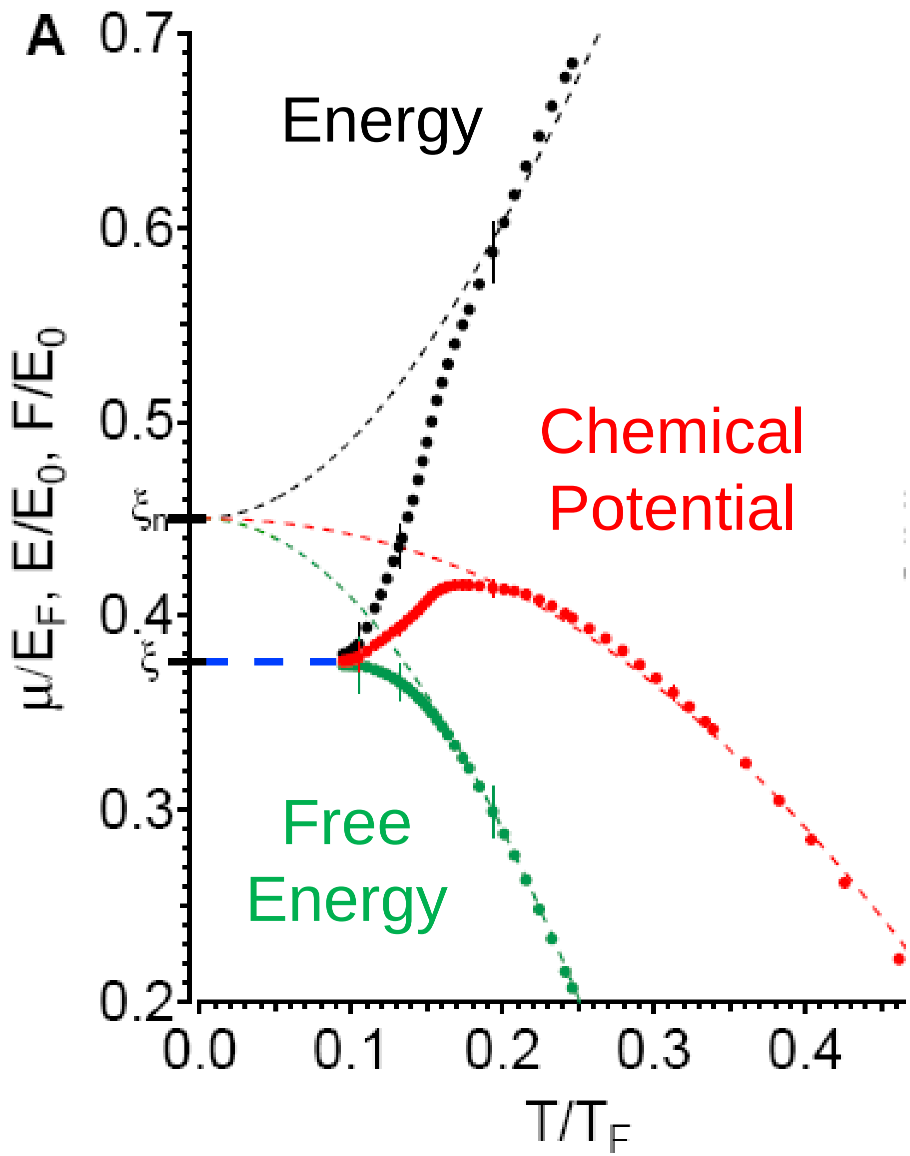
Going back to Density Equation of State

$$\tilde{\kappa} = \frac{\mathrm{d}\varepsilon_F}{\mathrm{d}\mu} = -\frac{T_F^2}{T^2}\frac{\mathrm{d}(T/T_F)}{\mathrm{d}(\beta\mu)}$$

$$\beta\mu = \beta\mu_i - \int_{T_i/T_F}^{T/T_F} d(T/T_F)\frac{T_F^2}{T^2}\frac{1}{\tilde{\kappa}}$$

with $\beta\mu_i$ and T_i known at high temperatures

Normalized Density Equation of State

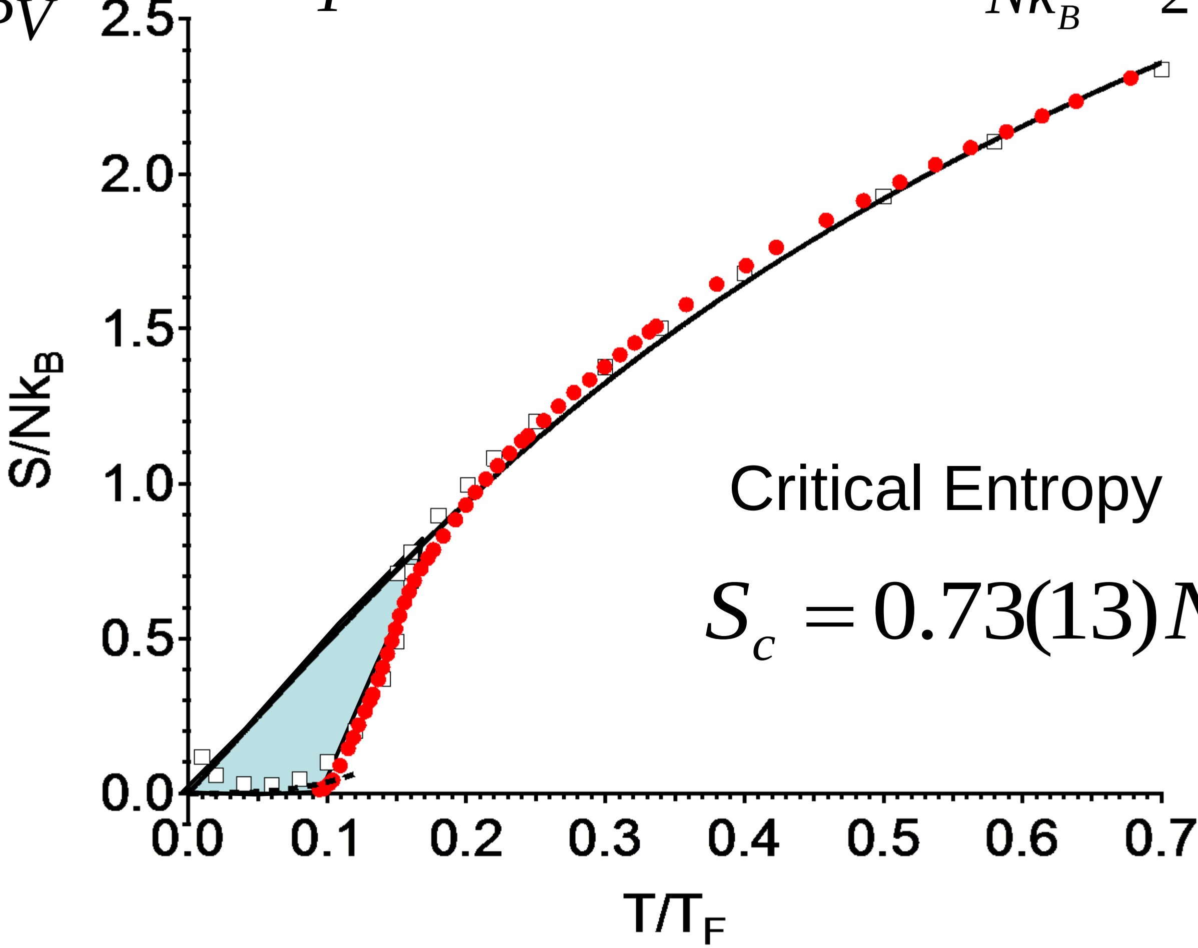


New value for ξ: $\xi = 0.376(5)[8]$

Entropy vs Temperature

On resonance: $S = \frac{1}{T}\left(E + PV - \mu N\right)$ $\qquad \frac{S}{Nk_B} = \frac{5}{2}\frac{P}{nk_B T} - \mu\beta$

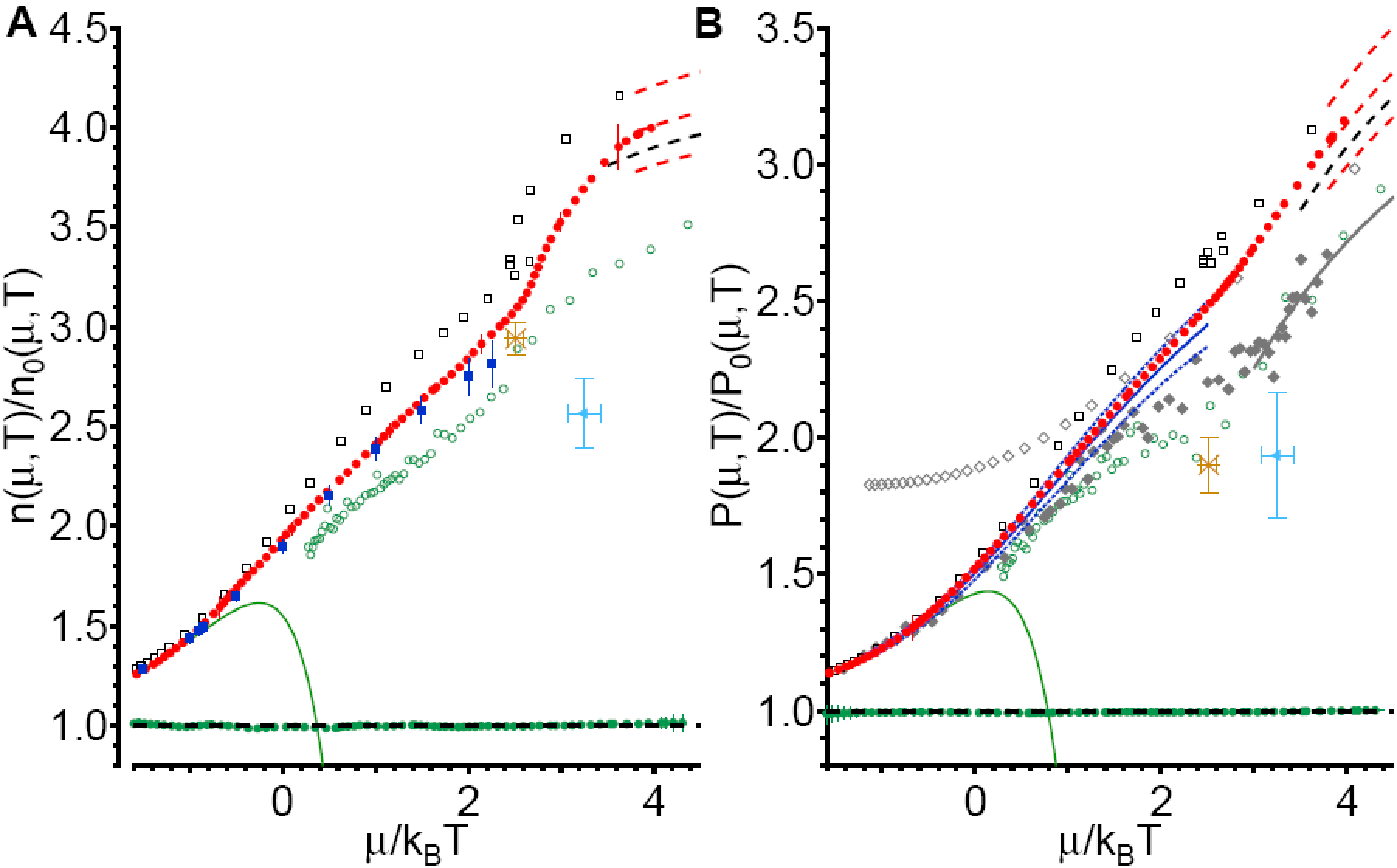
$E = \frac{3}{2}PV$



Critical Entropy

$$S_c = 0.73(13)\,Nk_B$$

Density and Pressure



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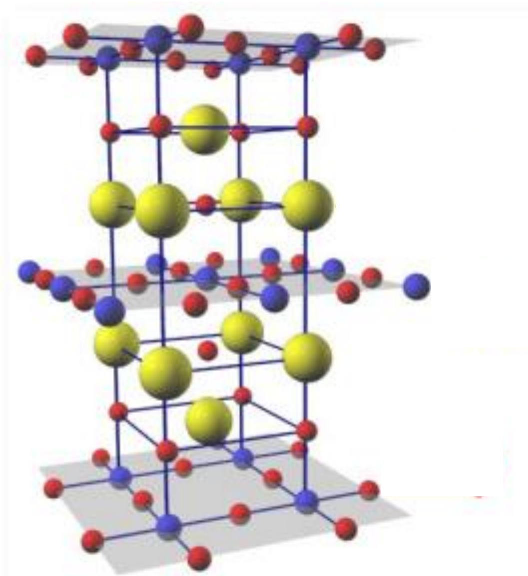
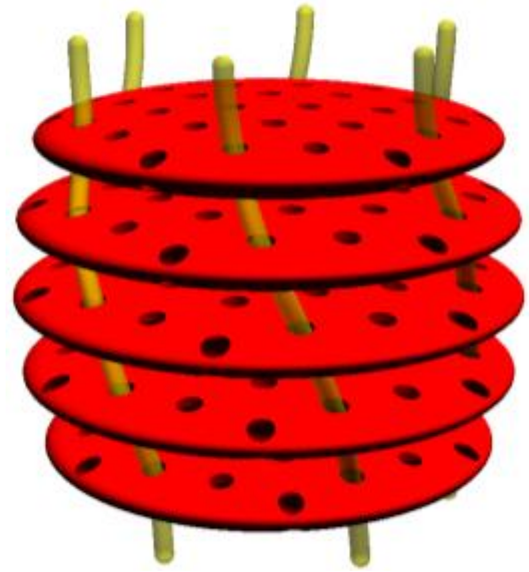
arXiv:1110.3309 (2011)

Strongly Interacting Fermi Gases in coupled quasi-2D layers



High-T_c Superconductor with stacks of CuO planes



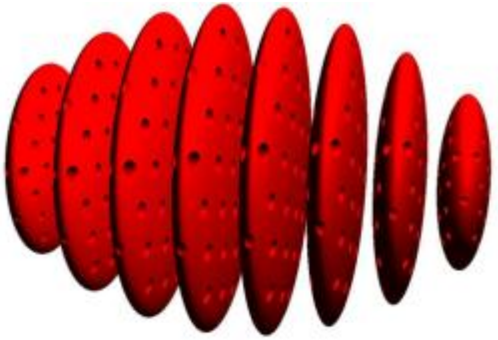
Stacks of 2D coupled fermionic superfluids

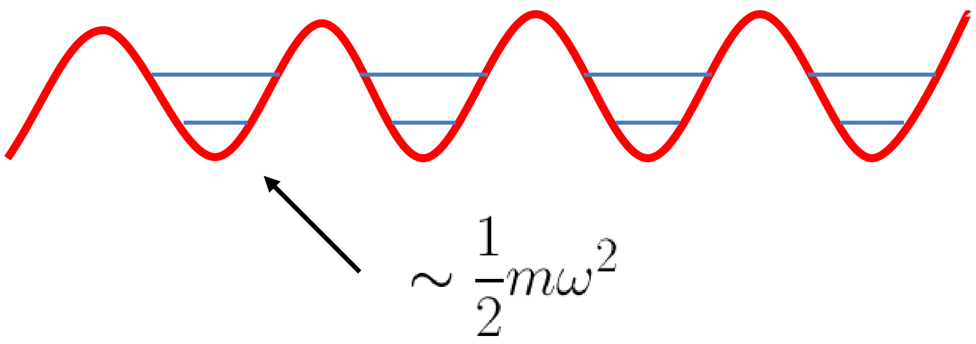
- Access physics of layered superconductors
- Evolution of Fermion Pairing from 3D to 2D
- Berezinskii-Kosterlitz-Thouless transition in deep 2D limit

A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein
PRL, to appear, arXiv:1110.3058 (2011)

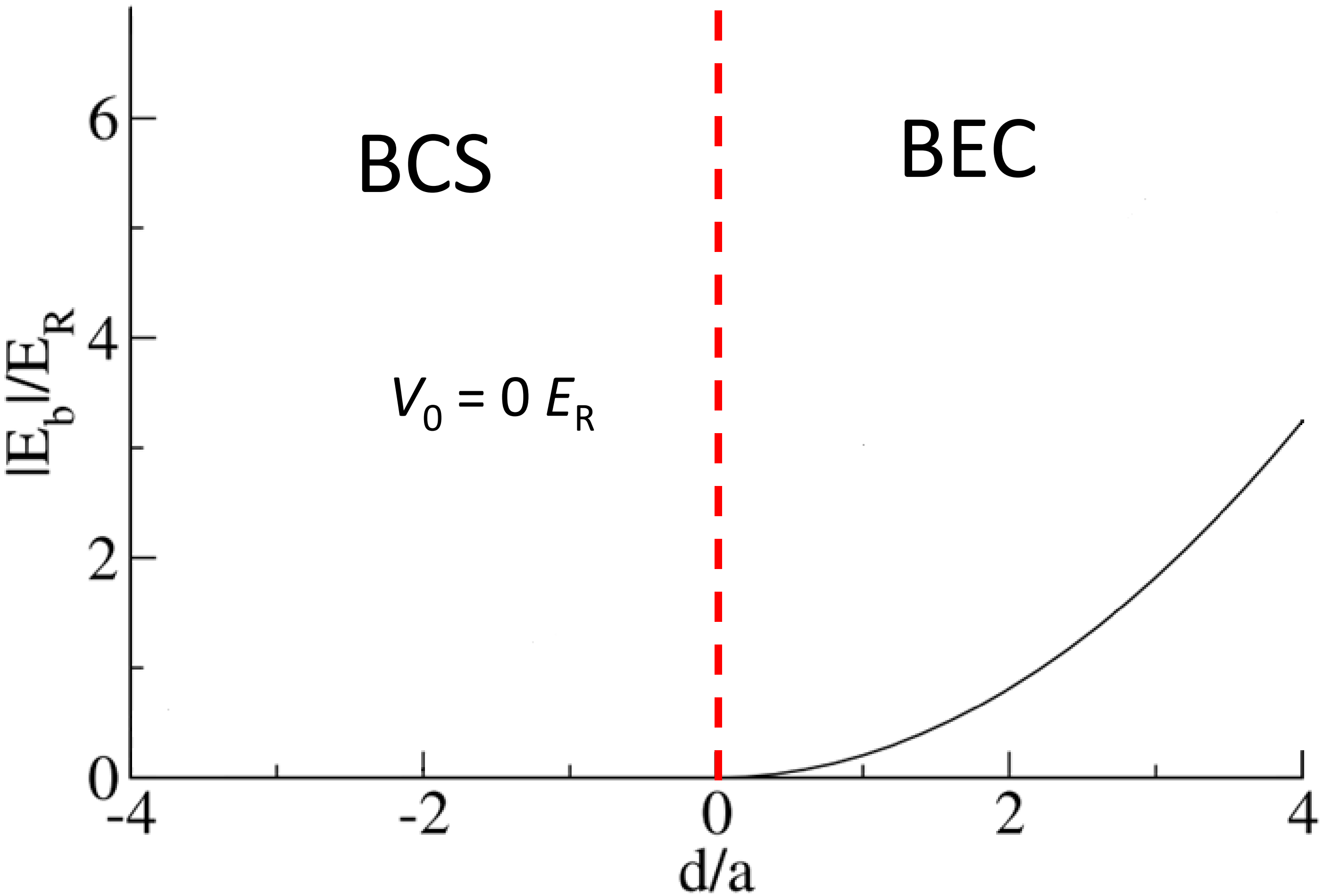
Making quasi-2D Fermi gases

- Confine tightly in 1 direction
- 1D lattice (retro-reflected 1064nm)
- Lattice depths up to 30 E_R
- 2D-ness tuned by lattice depth
- Deep lattice: $\frac{\varepsilon_F}{\hbar\omega} \sim 0.1$, aspect ratio of ~1:1000



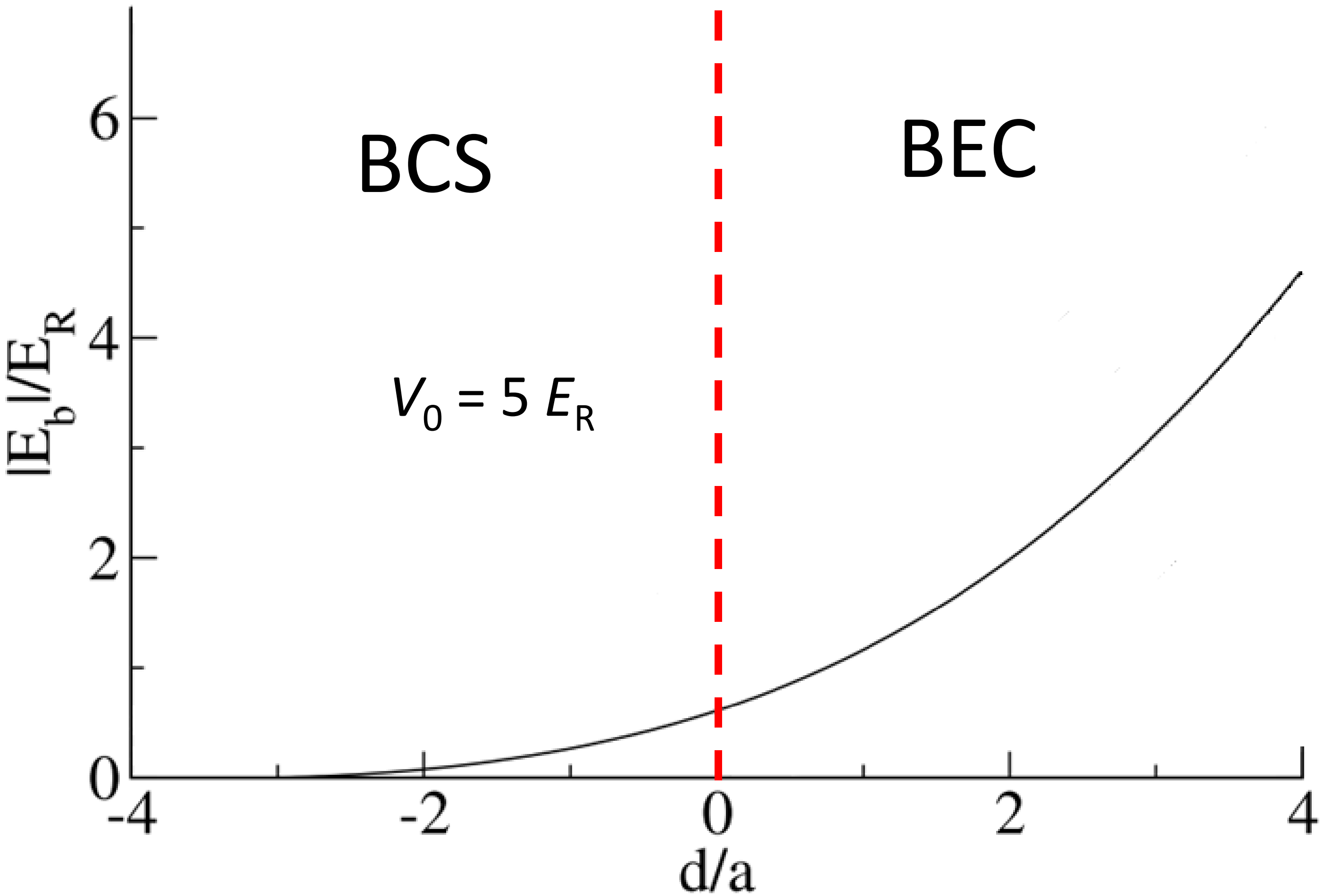


Binding Energy from 3D to 2D (1D lattice)



Orso & Wouters. PRL **95** 060402 (2005)

Binding Energy from 3D to 2D (1D lattice)



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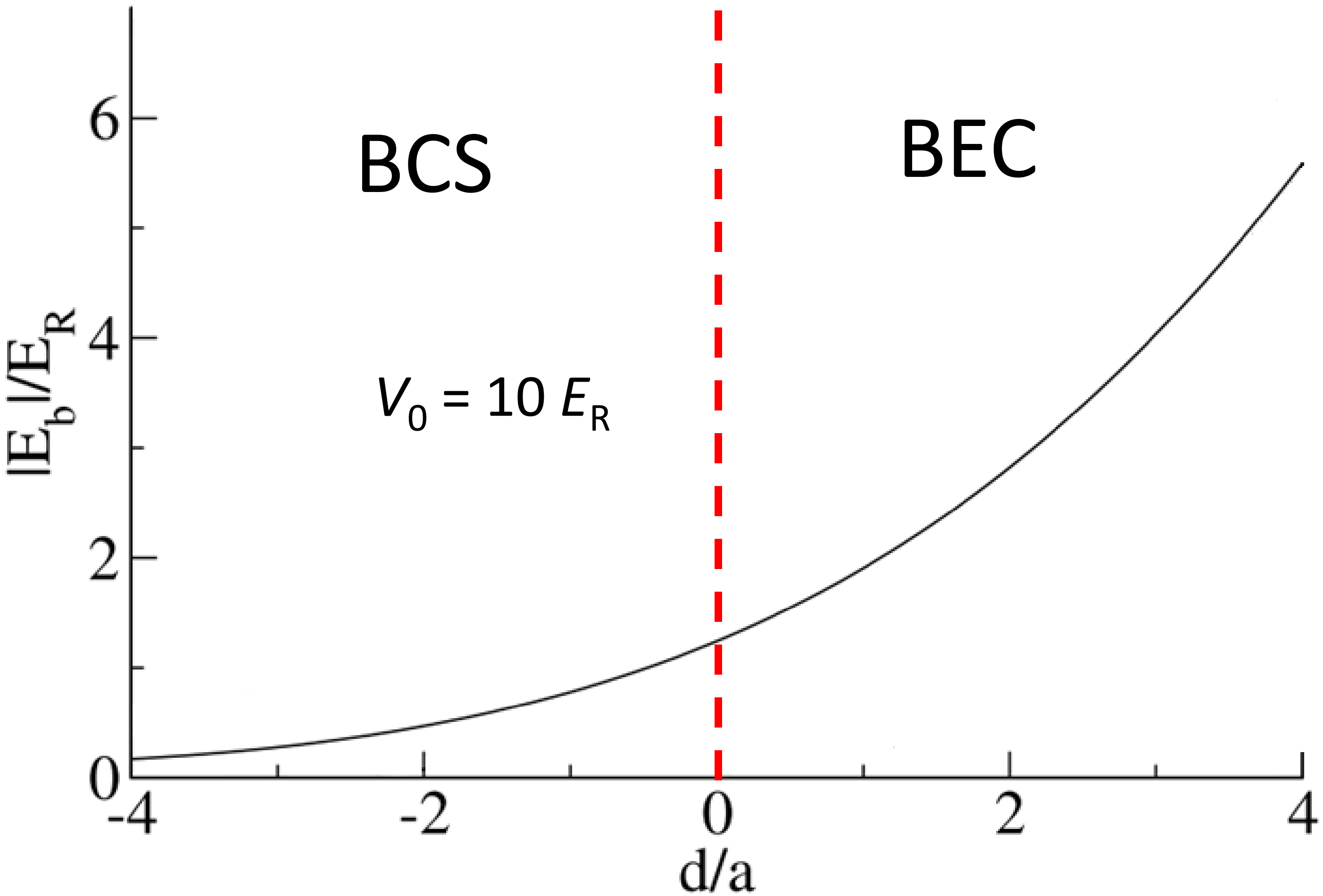

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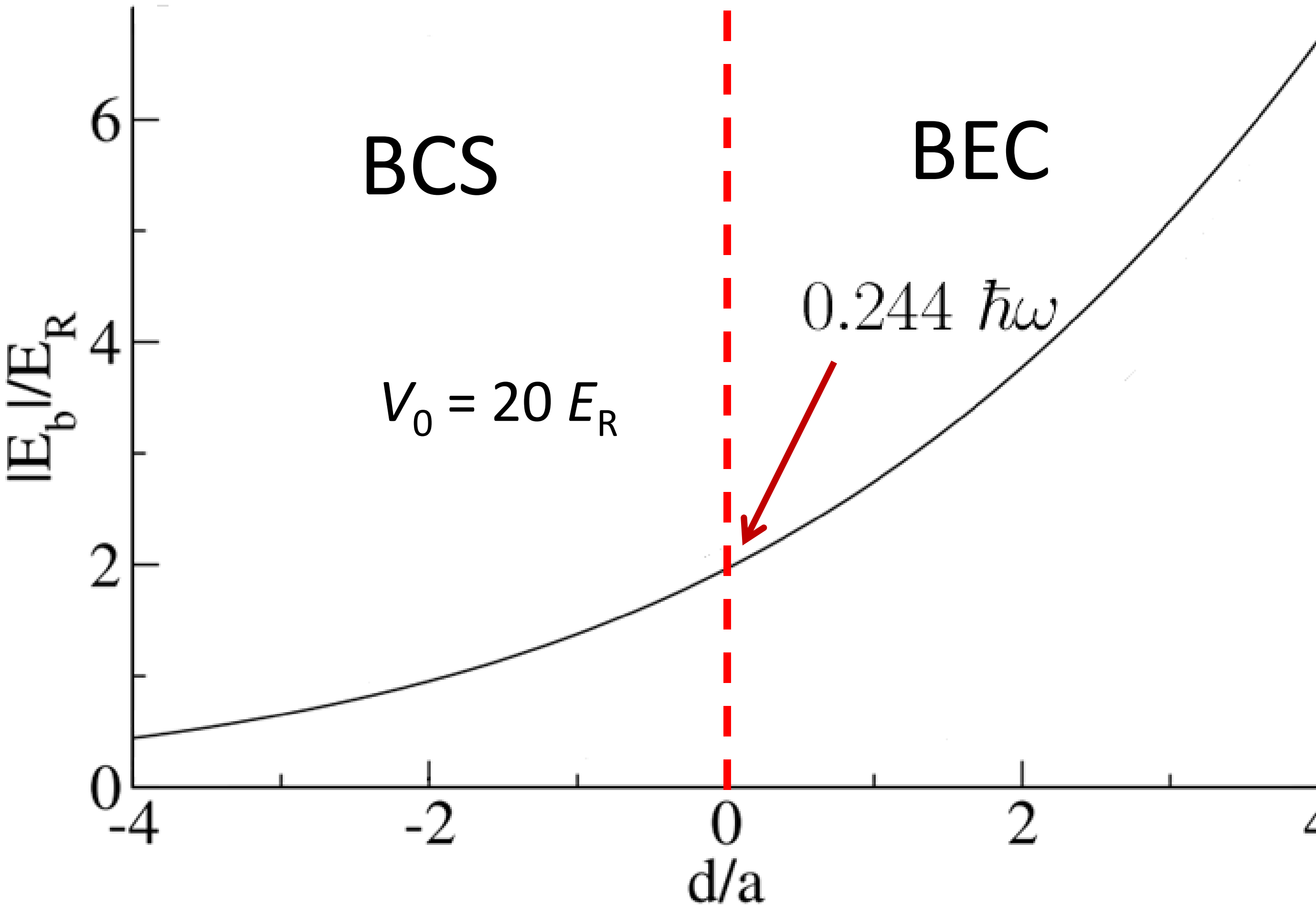


Orso & Wouters. PRL **95** 060402 (2005)

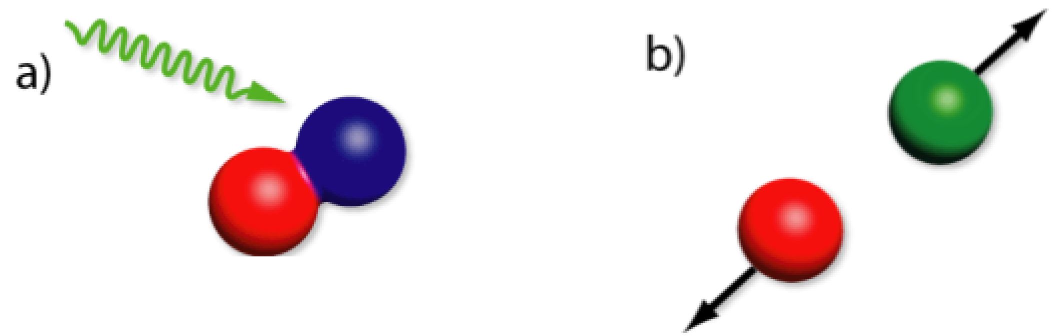
Evolution of Fermion Pairing from 3D to 2D

Density of States: 3D $\sim \sqrt{\varepsilon}$

2D $const.$

Direct consequence: Always a bound state in 2D

RF spectrum:



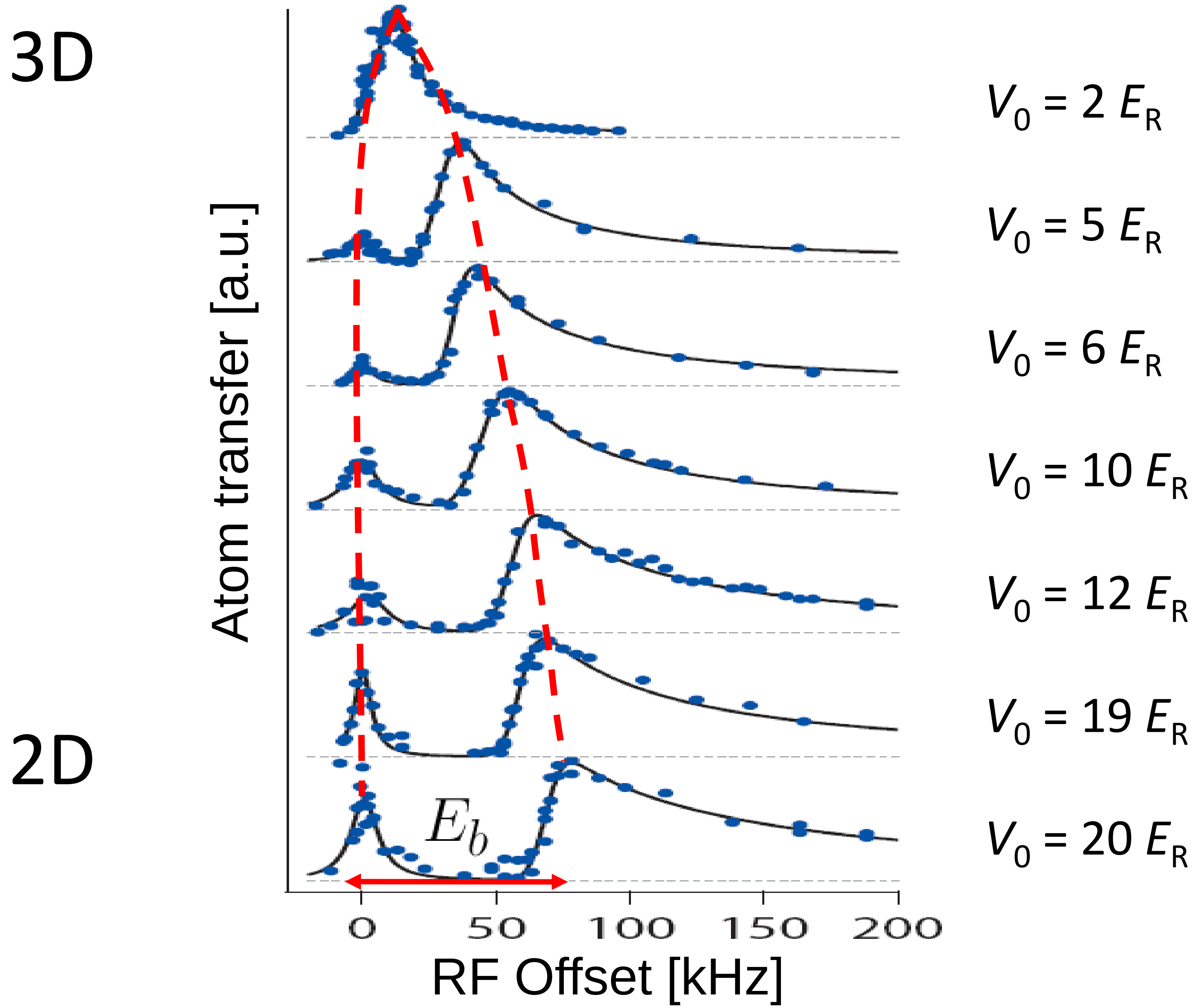
RF Spectrum: $I(\omega) \sim \rho(\varepsilon_k)\,|\psi(k)|^2|_{\varepsilon_k=\varepsilon(\omega)}$

3D: $I(\omega) \sim \dfrac{\sqrt{\omega-\omega_{th}}}{\omega^2}$

Interactions in final state:

2D: $I(\omega) \sim \dfrac{\theta(\omega-\omega_{th})}{\omega^2}$ $\dfrac{\ln^2(E_b^f/E_b)}{\ln^2((\omega-E_b)/E_b^f)+\pi^2}$

Evolution of Fermion Pairing from 3D to 2D



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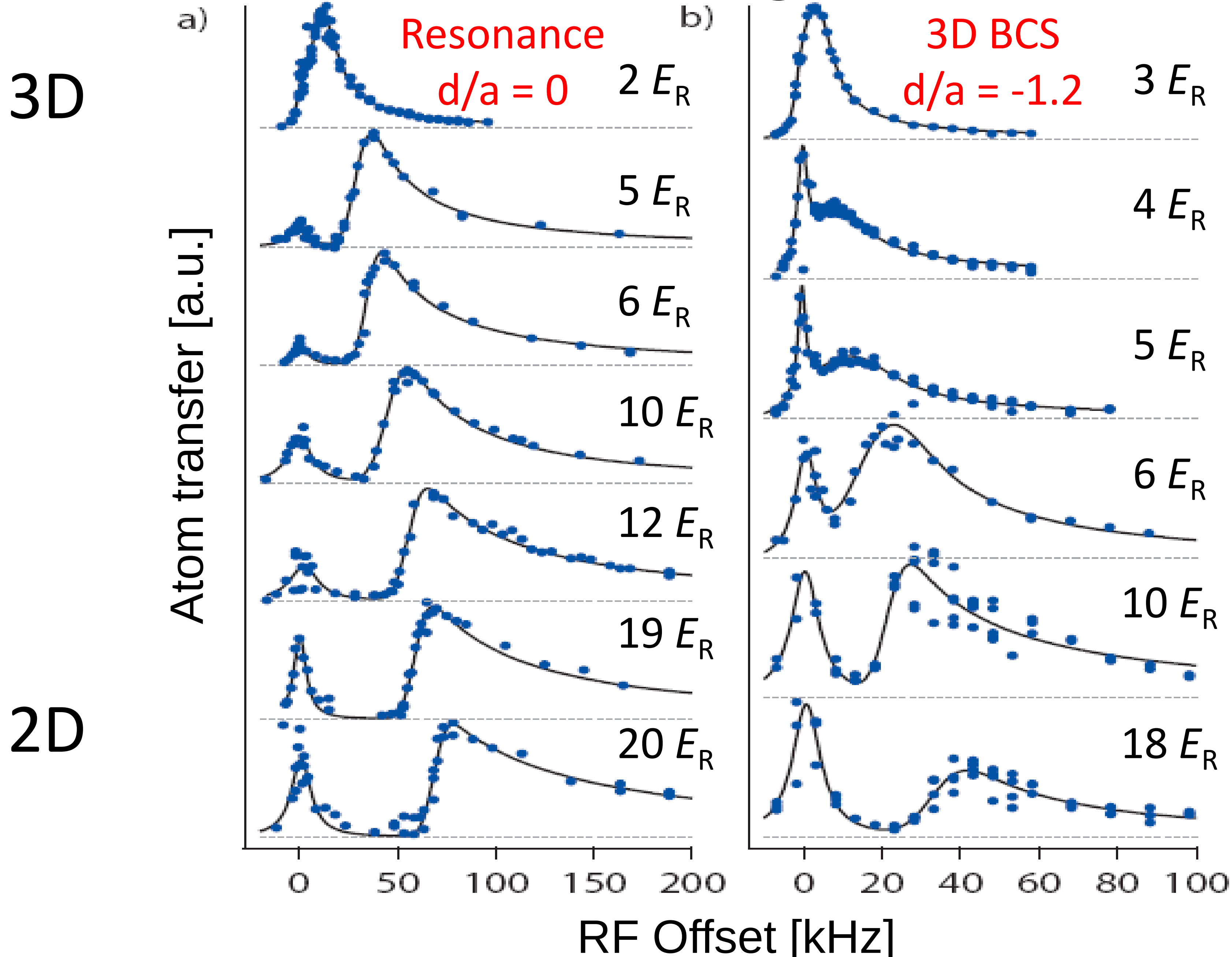
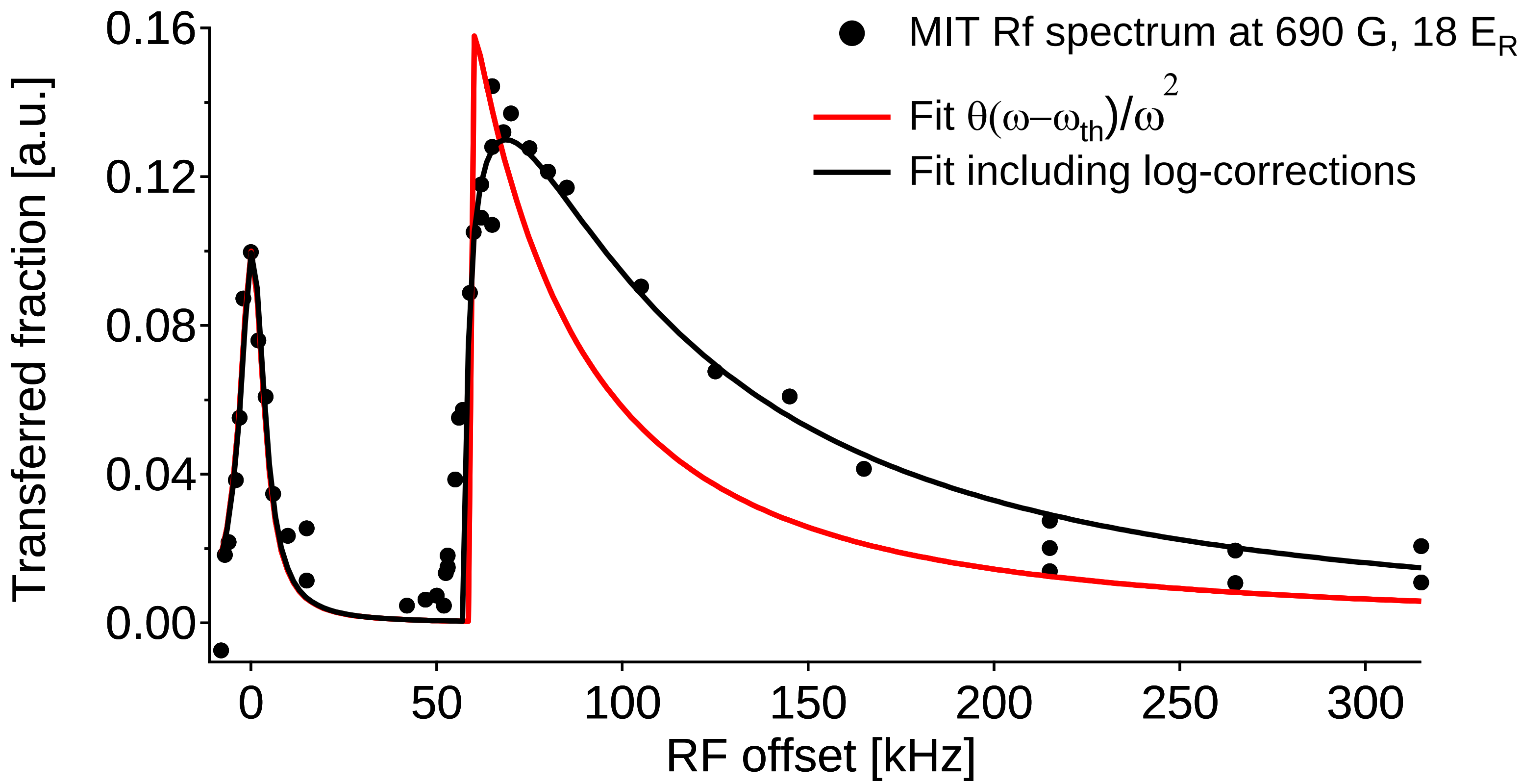


Logarithmic Corrections in Spectra in 2D

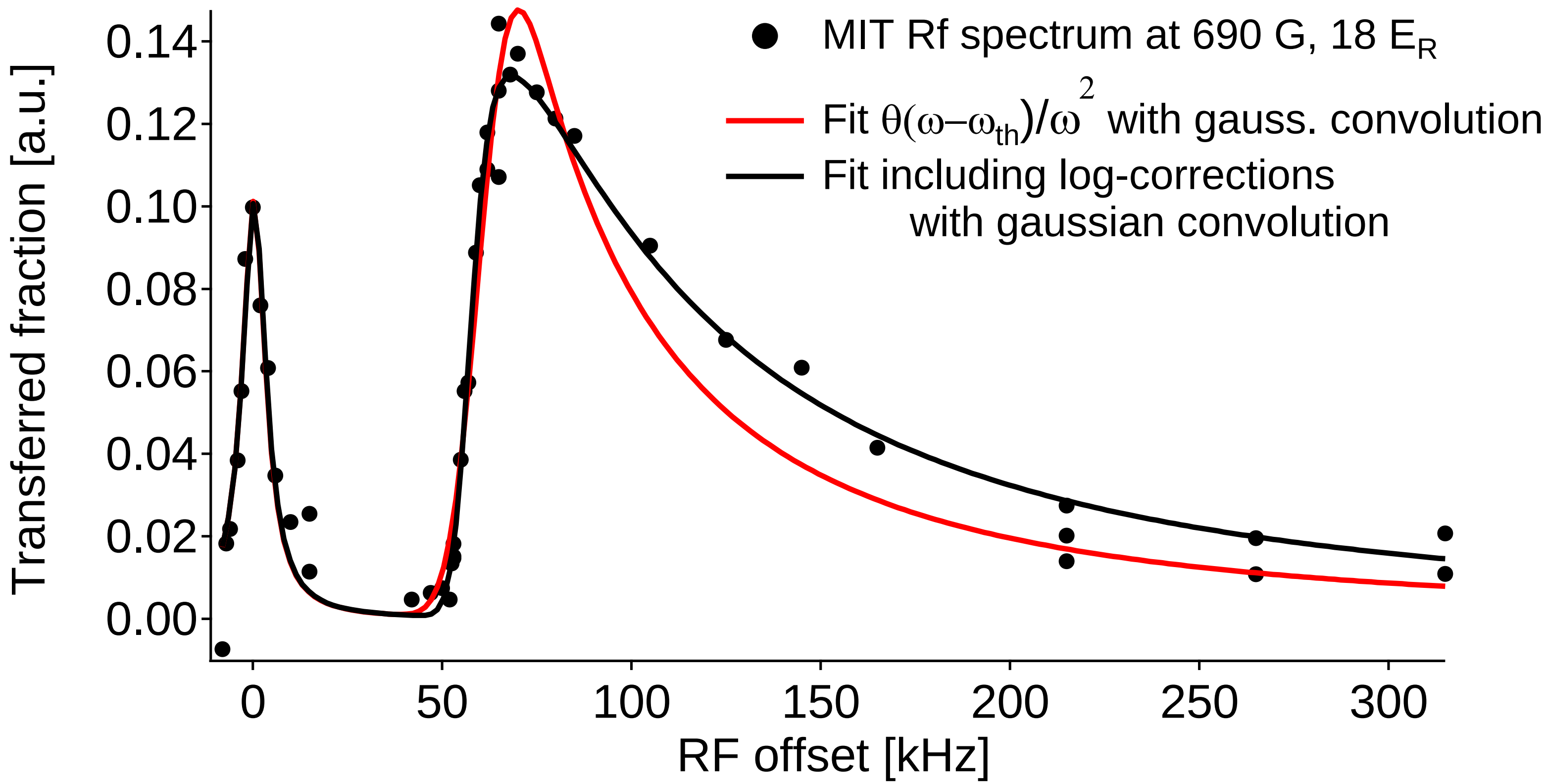
2D nature of interactions strongly influence “naïve” spectra



$$I_{Pair}(\omega) \sim \frac{\theta(\omega-\omega_{th})}{\omega^2} \frac{\ln^2(E_b^f / E_b)}{\ln^2((\omega-E_b)/E_b^f)+\pi^2}$$

Logarithmic Corrections in Spectra in 2D

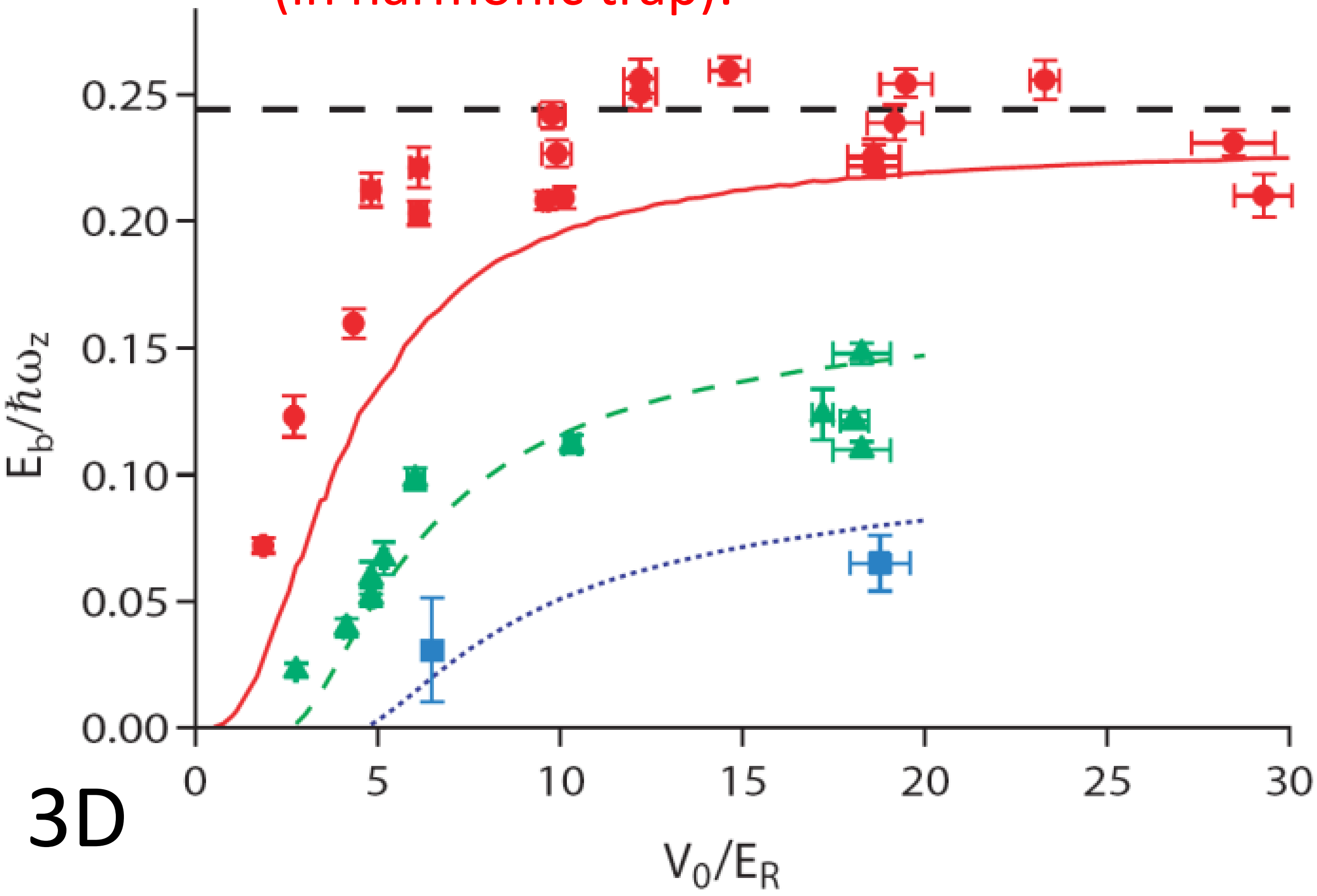
2D nature of interactions strongly influence “naïve” spectra



$$I_{Pair}(\omega) \sim \frac{\theta(\omega - \omega_{th})}{\omega^2} \, \frac{\ln^2(E_b^f / E_b)}{\ln^2((\omega - E_b)/E_b^f) + \pi^2}$$

Evolution of Fermion Pairing from 3D to 2D

On Resonance (in harmonic trap): $E_{B,th} = 0.244\hbar\omega_z$



3D

2D

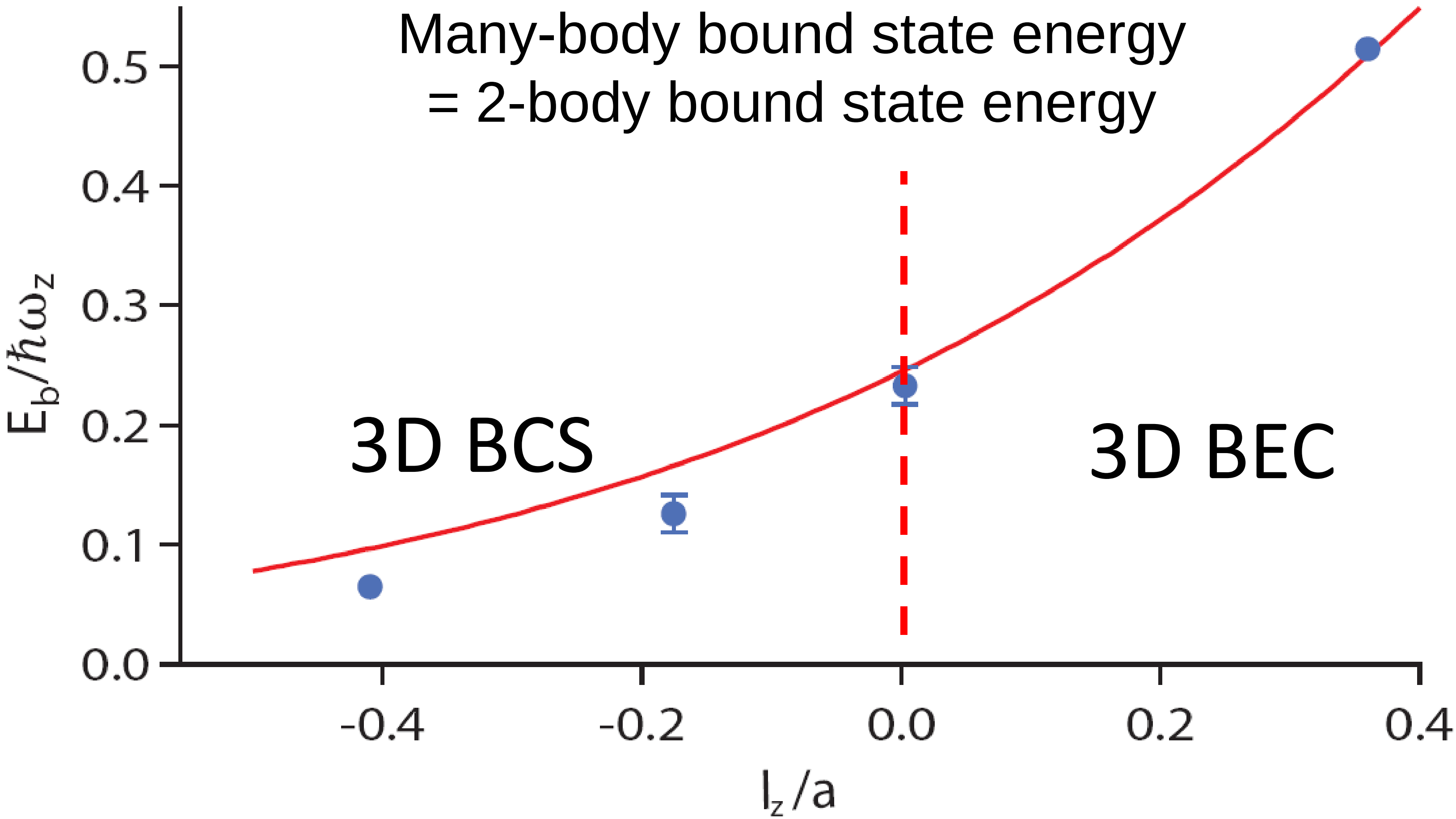
Resonance d/a = 0

3D BCS d/a = -1.2

3D BCS d/a = -2.7

A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein
PRL, to appear, arXiv:1110.3058 (2011)

Deep 2D regime
Comparison with mean-field BEC-BCS in 2D



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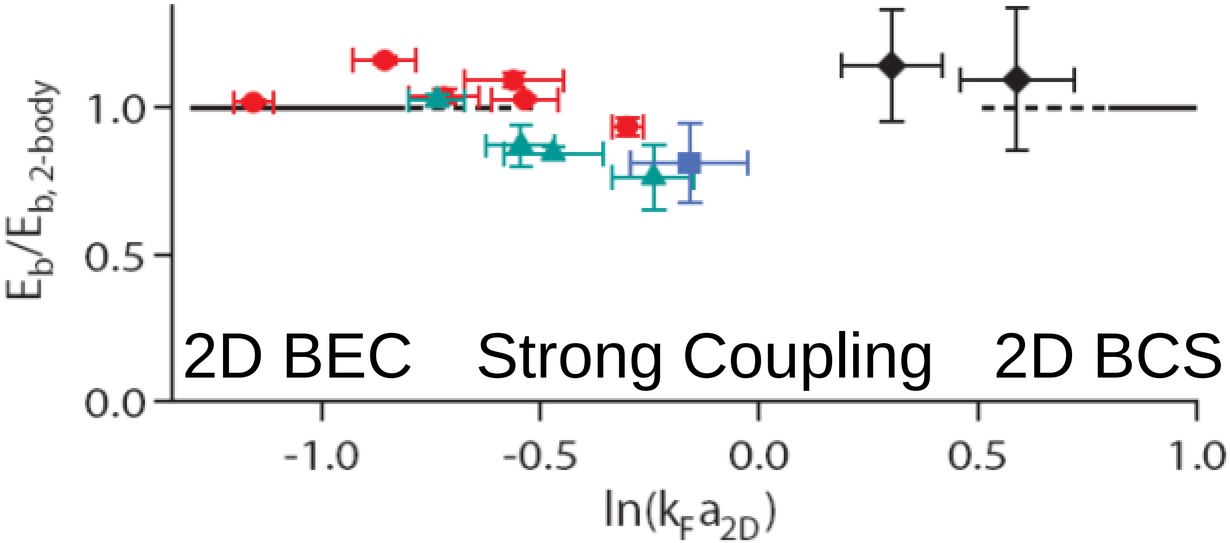
Deep 2D regime
Comparison with mean-field BEC-BCS in 2D

Prediction: Randeria et al. (1989)
Many-body bound state energy
= 2-body bound state energy



Only small deviation observed between
many-body and 2-body bound-state energy

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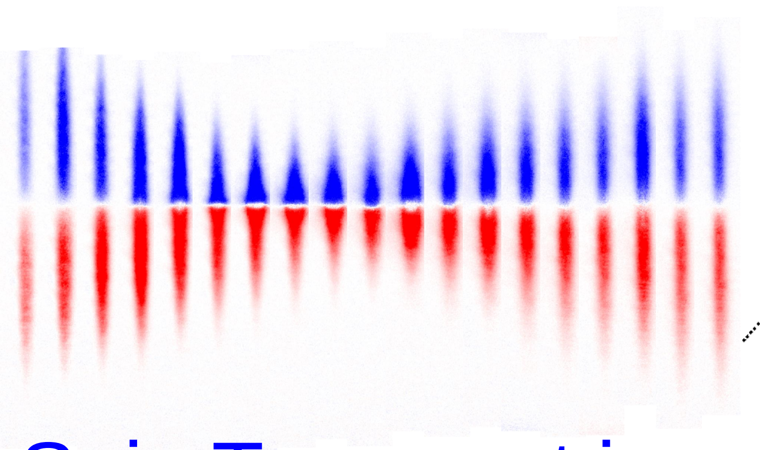
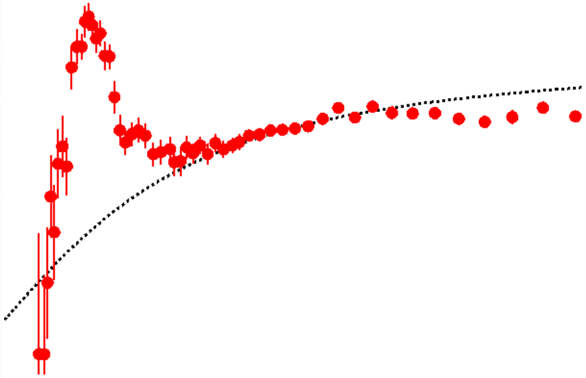
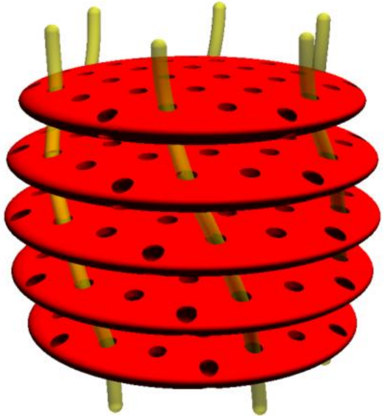
Conclusion & Outlook

Spin Transport in a Strongly Interacting Fermi Gas

- Quantum Limited Diffusion

Revealing the Superfluid Lambda Transition

- Compressibility, Density, Pressure → No-Fit EoS

→ Specific Heat, Chemical potential, Entropy, Energy etc.

→ Observe transition at T_c=0.167(13) T_F

Fermi gases in 2D

→ Are those pairs superfluid?

→ Study coherence, thermodynamics, rotation…

BEC I

BEC-BCS Crossover

2D Fermi Gases

Ariel Sommer
Mark Ku
Lawrence Cheuk
Dr. Waseem Bakr
Dr. Tarik Yefsah

Fermi I

LiNaK

Fermi-Fermi mixtures

Cheng-Hsun Wu
Ibon Santiago
Jee Woo Park
Dr. Peyman Ahmadi
Dr. Sebastian Will

Fermi II

Fermi Gas

Microscope

Thomas Gersdorf
Takuma Inoue
Melih Okan
Dr. Waseem Bakr