Spin-imbalanced quasi-2D Fermi gases

Ilya Arakelyan
JETLab
NC State University

JETLab Group

PI: J. E. Thomas

Graduate Students:

Willie Ong

Chingyun Cheng

Jayampathi Kangara

Graduated Student:

Yingyi Zhang

Support:

ARO

DOE

NSF

AFOSR

Outline

Introduction

- *Creating layered quasi-two dimensional Fermi gases:*
  – Meaning of quasi-2D?

Experiments

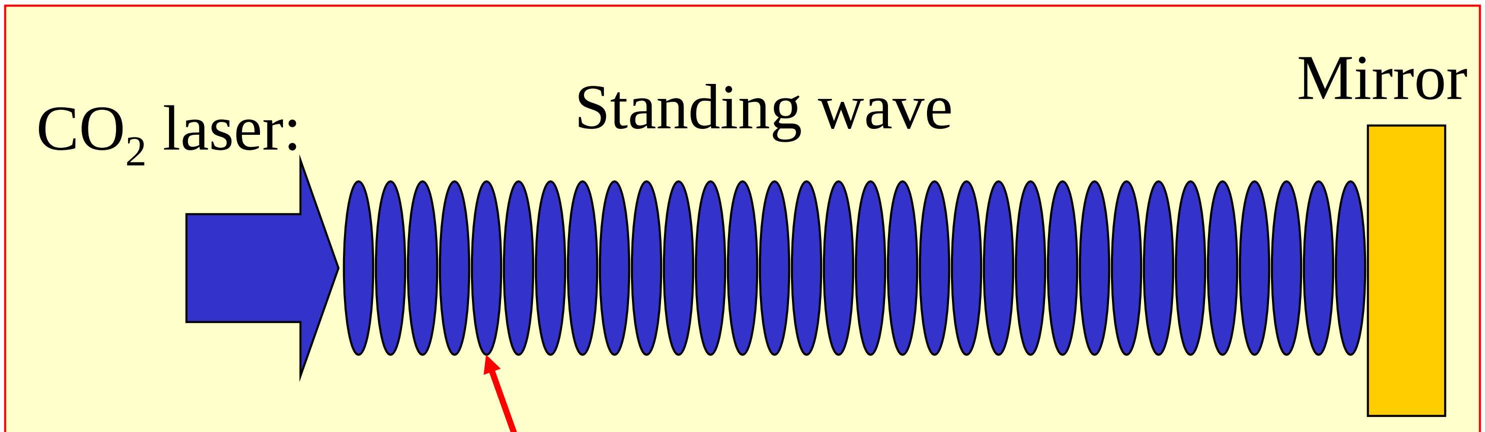
- *Radio-frequency spectroscopy of quasi-2D Fermi gases:*

– Failure of dimer and 2D-BCS theories
– 2D Fermi-polaron model

- *Thermodynamics of quasi-2D Fermi gases:*

– Density, pressure, and temperature in spin-imbalanced mixtures
– Phase transition of spin-imbalanced mixtures to a balanced core

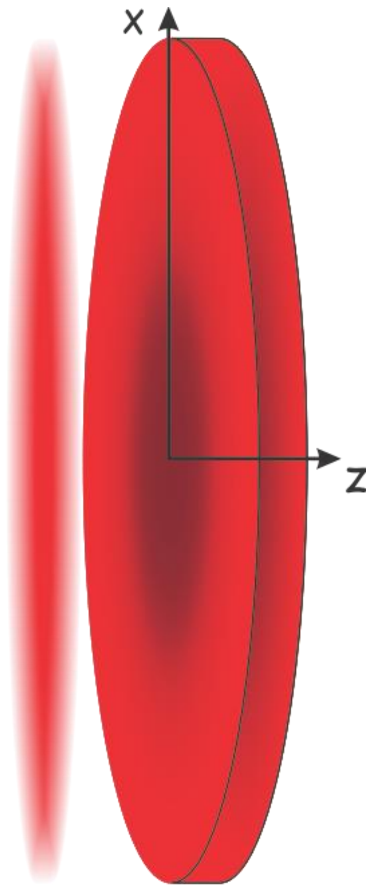
Creating a Quasi-2D Fermi Gas

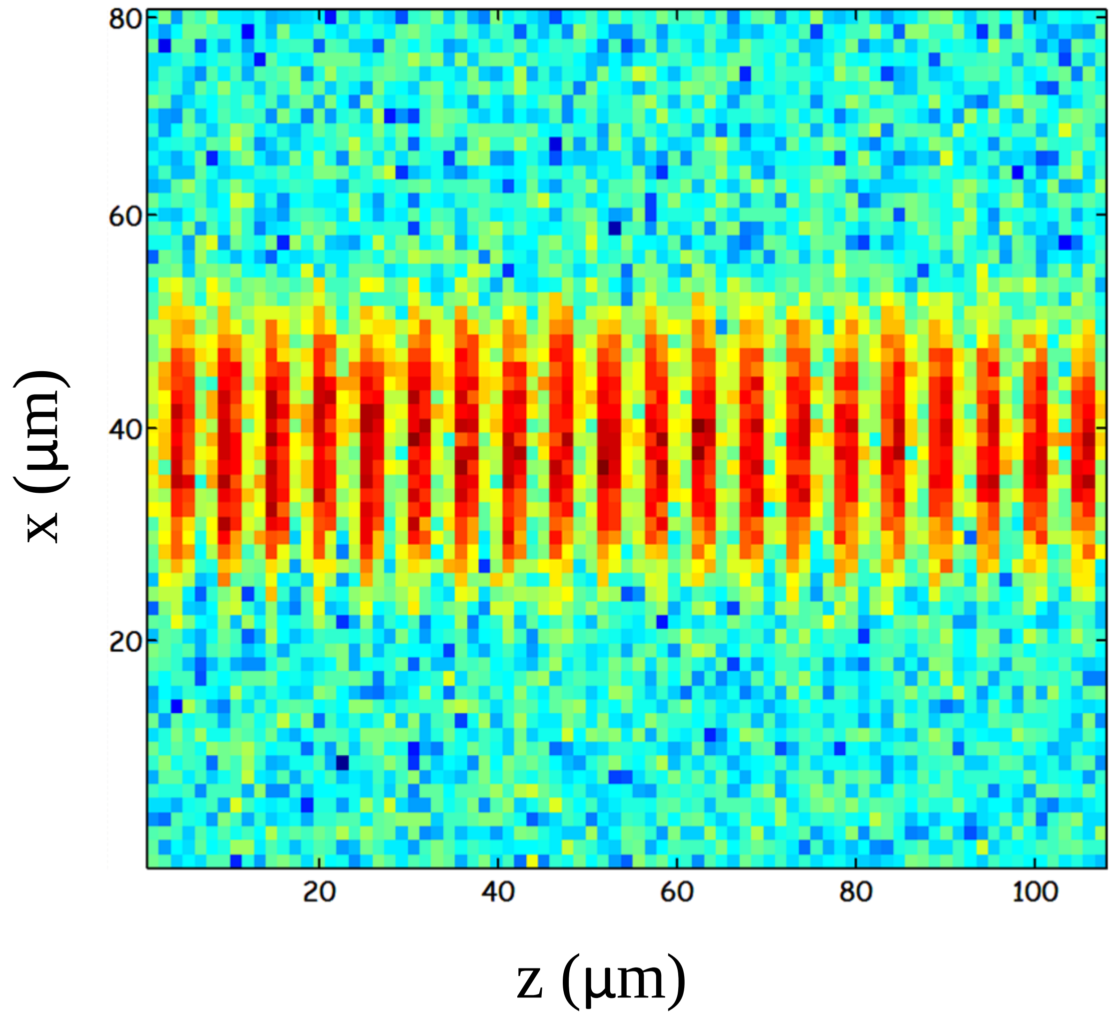


~1000 atoms/site, 5.3 μm spacing

Individual optical imaging

Atoms in Standing Wave Trap

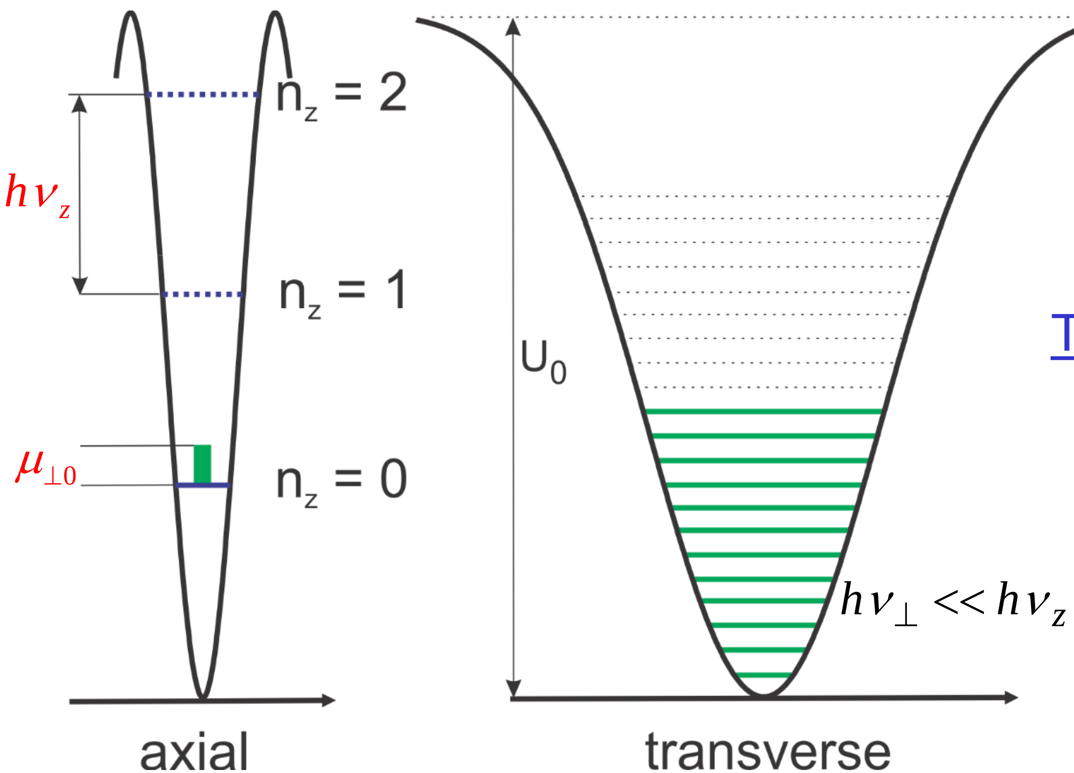




Two-Dimensional Gas

$$\sin^2\left(\frac{2\pi z}{\lambda}\right)$$

$$1-e^{-\frac{m\omega_\perp^2\rho^2}{2U_0}}$$



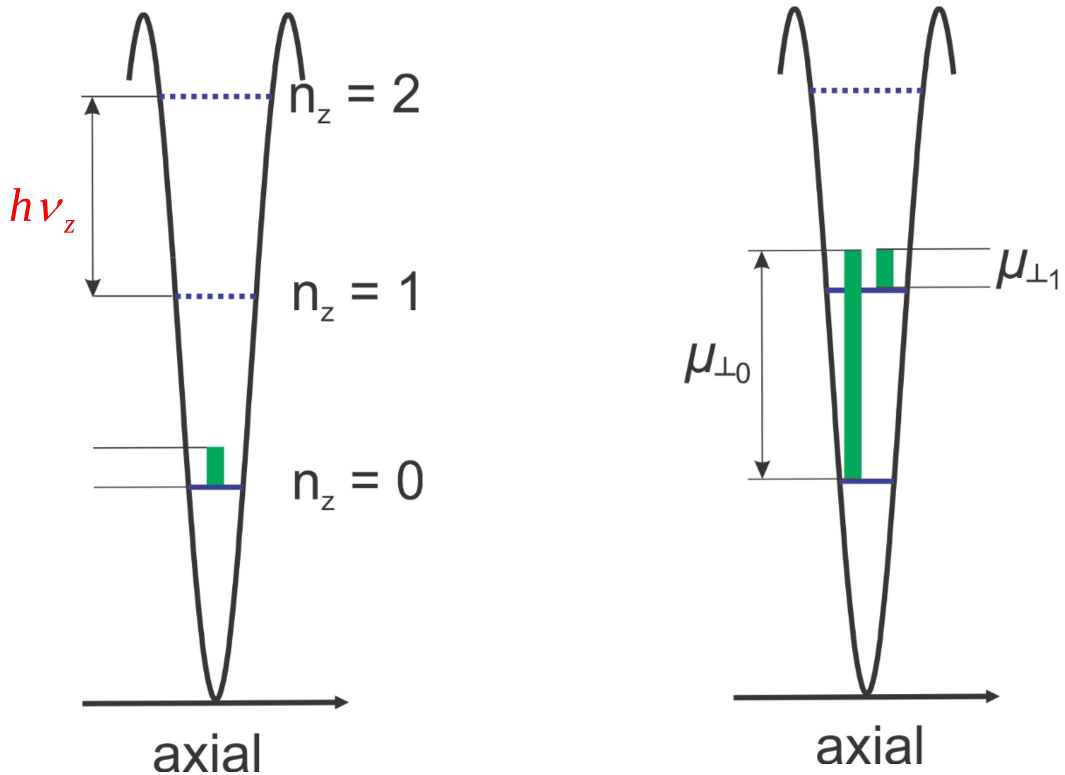
2D Transverse
Fermi Energy

$$\mu_{\perp 0} = E_F \equiv h\upsilon_\perp \sqrt{2N_0}$$

True 2D if: $\mu_{\perp 0} = E_F << h\upsilon_z$

3D if: $\mu_{\perp 0} = E_F >> h\upsilon_z$

Quasi-Two-Dimensional Gas



True 2D if:

$$\mu_{\perp 0} = E_F << h\upsilon_z$$

Quasi-2D if:

$$E_F \approx h\upsilon_z$$

Quasi-2D Fermi Gases

Search for high temperature superconductivity in layered materials:

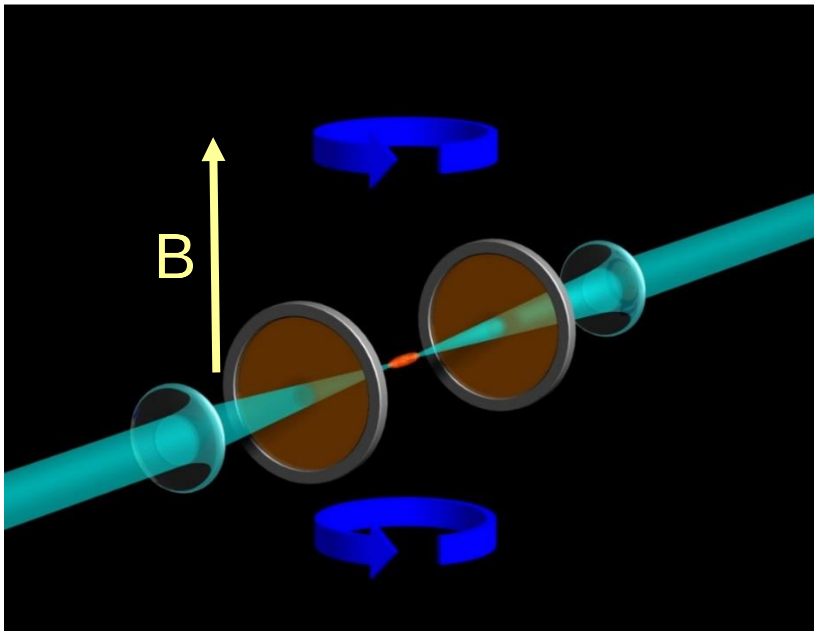
- In copper oxide and organic films, electrons are confined in a quasi-two-dimensional geometry
- Complex, strongly interacting many-body systems
- Phase diagrams are not well understood
- Exotic superfluids in spin-imbalanced systems

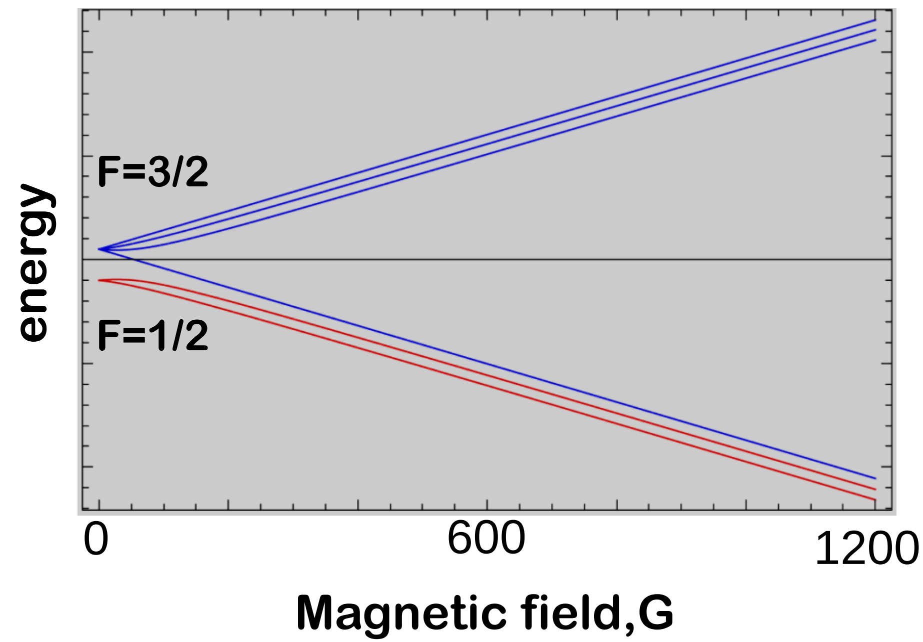
Enhancement of the superfluid transition temperature compared to true 2D materials:

- Heterostructures and inverse layers
- Quasi-2D organic superconductors
- Intercalated structures and films of transition metals

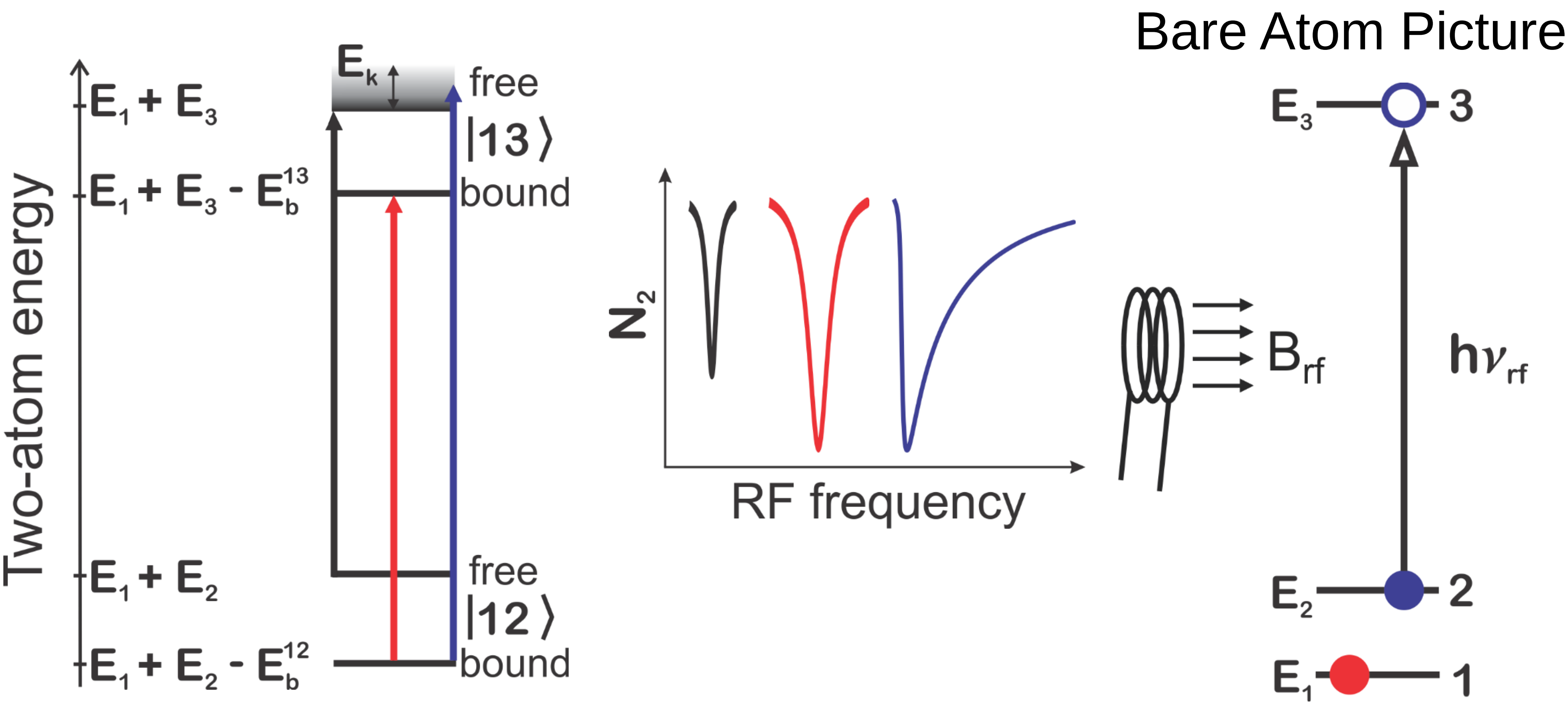
Optically-Trapped ^{6}Li Atoms

^{6}Li Fermi Gas



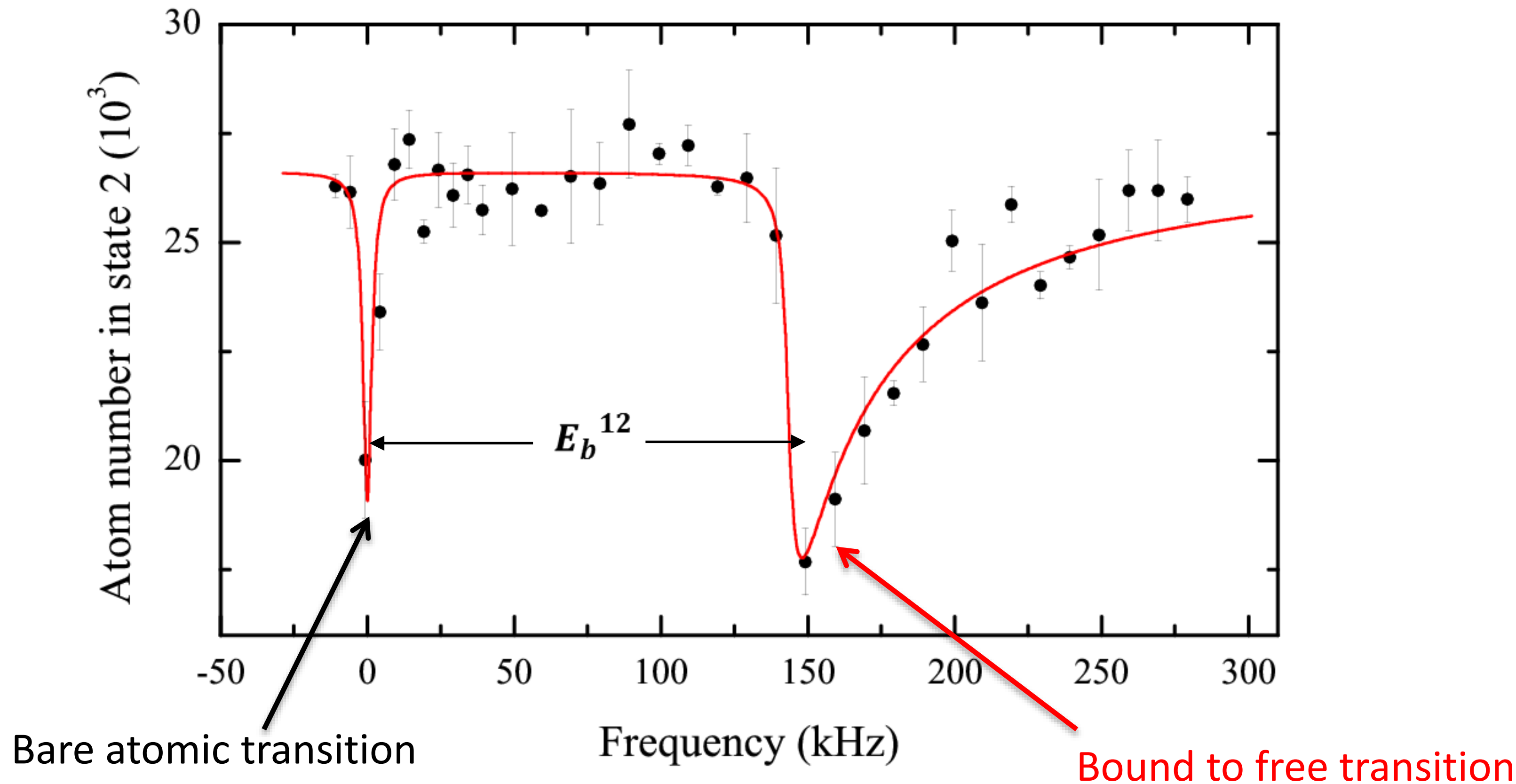


Radio Frequency Spectroscopy



$E_b(a_s, \nu_{trap})$ - dimer binding energy

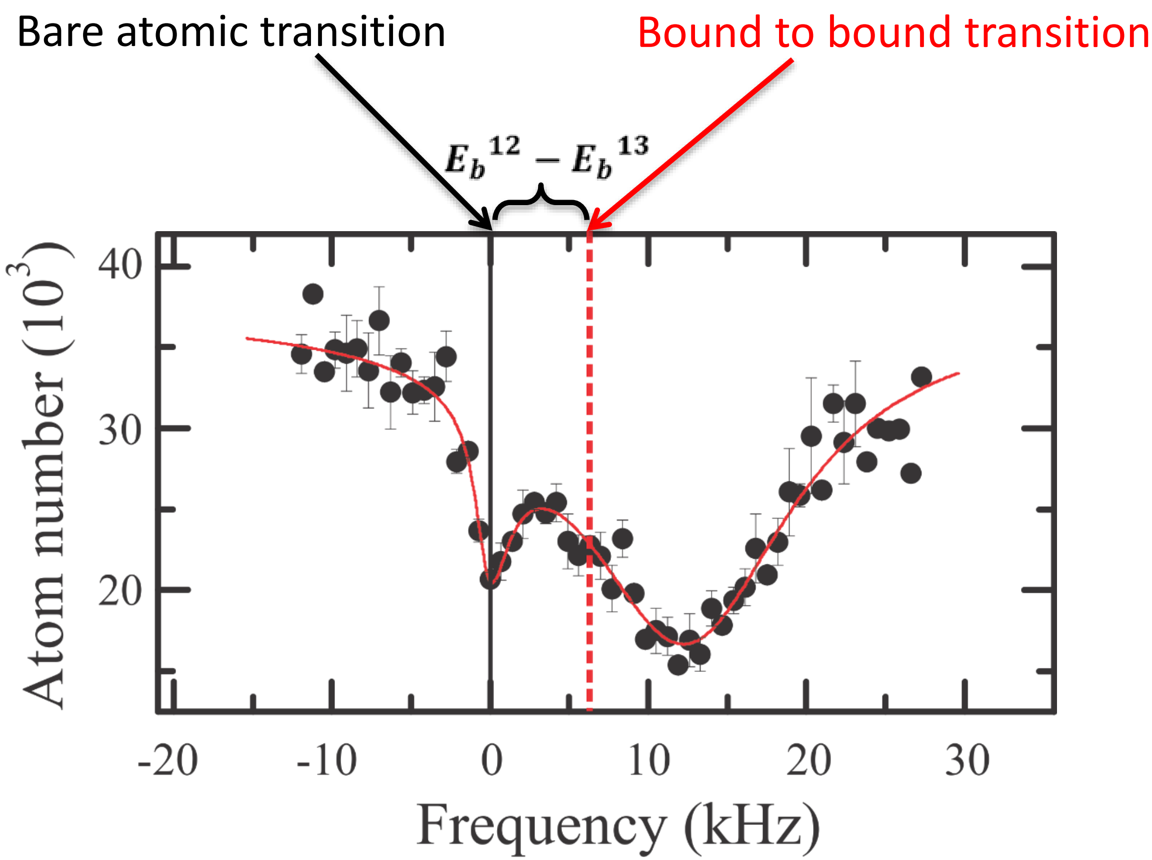
RF 12-to-13 spectrum at 720 G



Calculated dimer binding energies:

$$E_b^{12} = 145\,\text{kHz}$$
$$E_b^{13} = 2.9\,\text{kHz}$$

RF 12-to-13 spectrum at 832 G



$$E_b^{12} = 7.25\ \text{kHz}$$

$$E_b^{13} = 0.81\ \text{kHz}$$

Dimer theory fails!

Many-body physics?
BCS Theory in Two Dimensions

BCS-*Two* dimensions: (Randeria 1989)

Predicts radio-frequency transition with frequency ω:

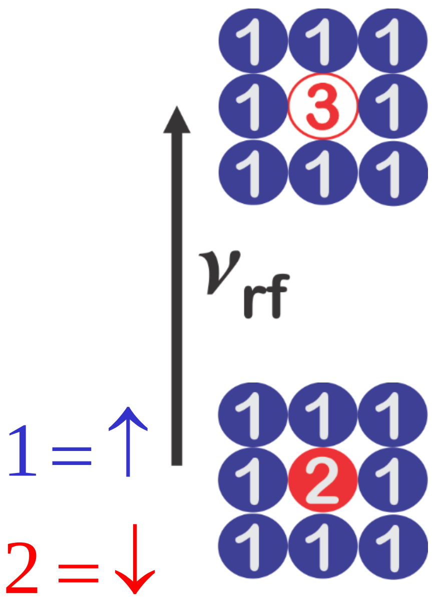
$$\hbar\omega = \sqrt{\mu_\perp^2 + \Delta^2} - \mu_\perp$$

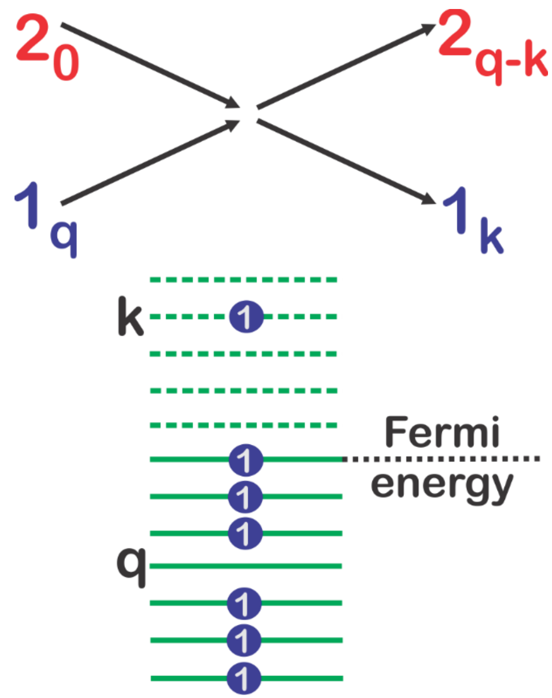
Gap equation: $$E_b = \sqrt{\mu_\perp^2 + \Delta^2} - \mu_\perp$$

$$h\omega = E_b$$ Dimer Spectrum!

No many-body effects on the spectrum!

Fermi-Polaron Gas (Chevy)





$$\left|\psi\right\rangle_{\text{polaron}} = \phi_0 \left|\downarrow, \mathbf{p}=0\right\rangle \left|FS\uparrow\right\rangle + \sum_{\mathbf{kq}} \phi_{\mathbf{kq}} \left|\downarrow, \mathbf{q}-\mathbf{k}\right\rangle \left|FS\uparrow; 1_{\mathbf{k}\uparrow} 0_{\mathbf{q}\uparrow}\right\rangle$$

single spin down

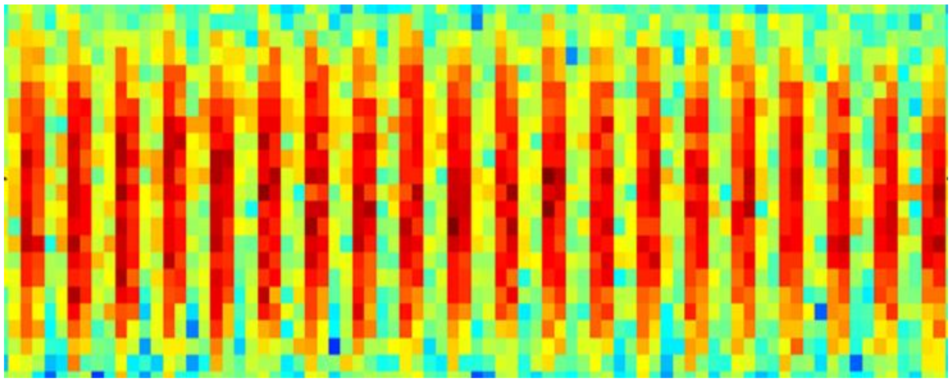
cloud of particle-hole pairs

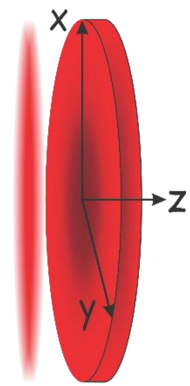
Comparison of Polaron Model with Measurements

$$h\Delta\upsilon_{\mathrm{dimer}} = E_{b12} - E_{b13} \qquad h\Delta\upsilon_{\mathrm{polaron}} = E_{p12} - E_{p13}$$

$\boldsymbol{B(G)}$	ν_z (kHz)	$\Delta\nu_{meas}$ (kHz)	$\Delta\nu_{dimer}$ (kHz)	$\Delta\nu_{polaron}$ (kHz)
832	24.5	12.3	6.6	11.6
832	82.0	28.3	18.3	29.1
832	135	38.8	26.9	42.8
831	179	44.5	33.2	48.3

Thermodynamics—Spin Imbalance





Measure Column Density:

$$n_c(x) = \int_{-\infty}^{\infty} dy\, n_{2D}(\sqrt{x^2 + y^2})$$

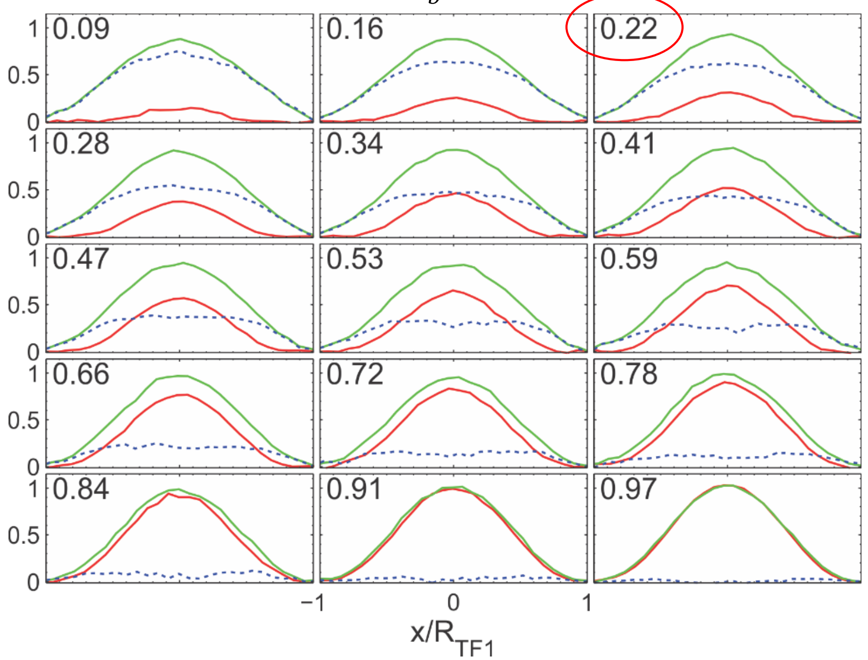
Transverse Density Profiles: $n_{2D}(\rho)$

Column Densities versus N_2/N_1

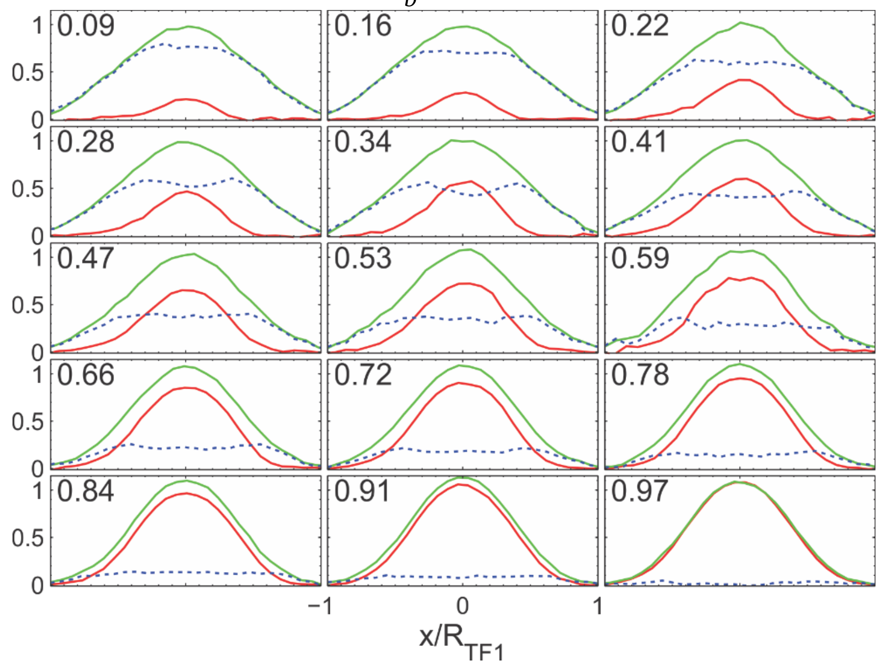
Majority state: $N_1 \simeq 800$ per site Minority state: $N_2 \leq N_1$

E_b = 2D dimer binding energy E_F = 2D ideal gas Fermi energy

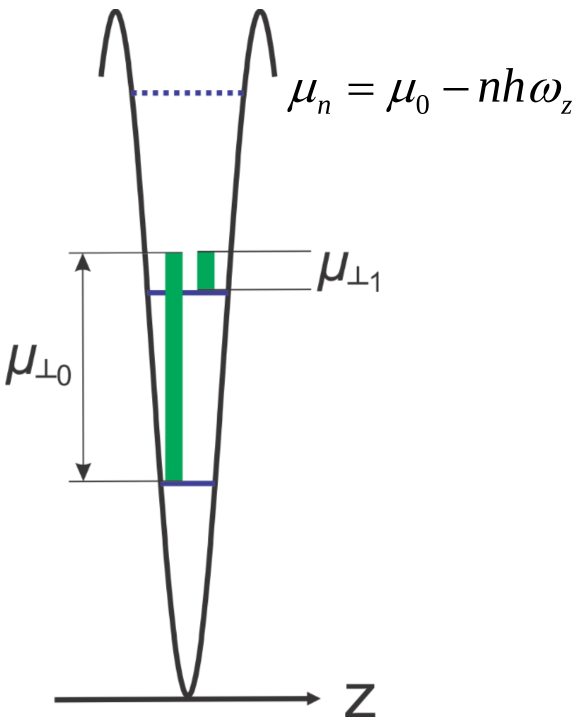
- 832 G $\frac{E_F}{E_b} = 6.6$



- 775 G $\frac{E_F}{E_b} = 0.75$



Quasi- 2D Fermi Gas Temperature



$$n_{2D}^{(n)}(\rho) = \frac{2N}{\pi R^2}\tilde{T}\ln\left[\frac{1+e^{[\tilde{\mu}_n - \tilde{U}(\rho)]/\tilde{T}}}{1+e^{[\tilde{\mu}_n - \tilde{U}_0]/\tilde{T}}}\right]$$

Total 2D-Density

$$n(\rho) = \sum_n n_{2D}^{(n)}(\rho)$$

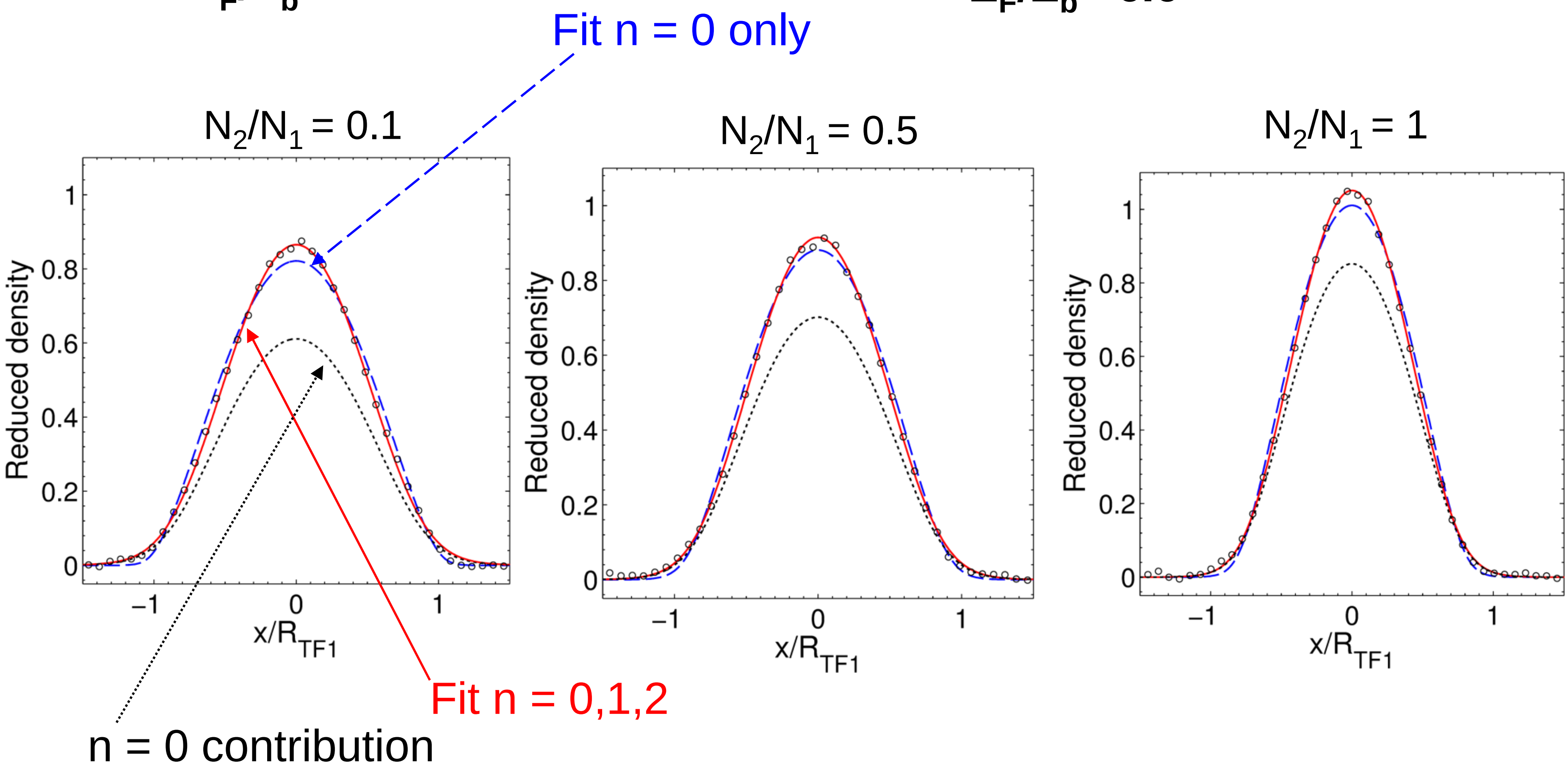
Normalization determines μ_0

Fit Column Density:

$$n_c(x) = \int_{-\infty}^{\infty} dy\, n(\sqrt{x^2 + y^2})$$

Quasi-2D Fermi Gas Spatial Profiles

E_F/E_b= 2.1 **E_F/E_b= 6.6**



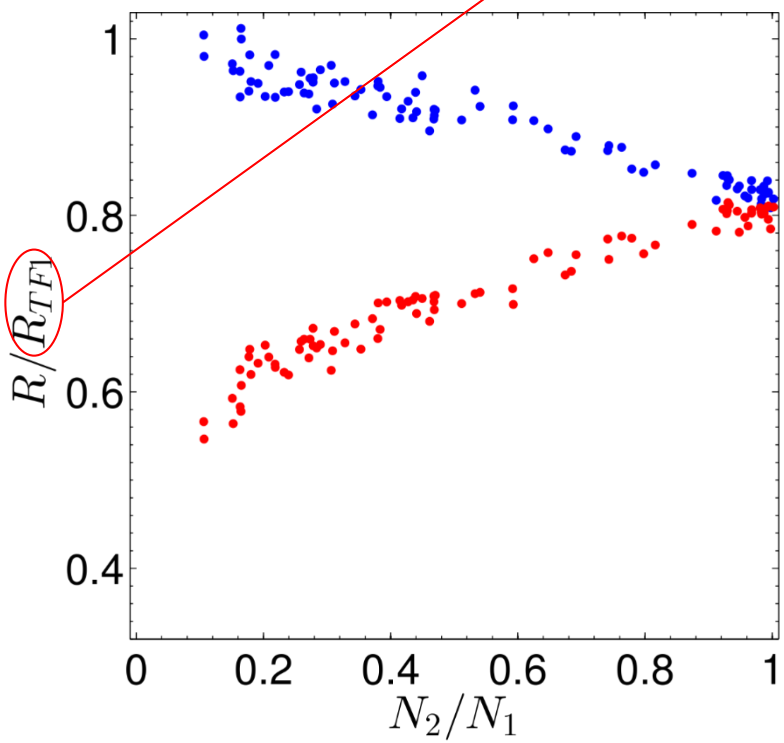
$T/T_F = 0.21$ $T/T_F = 0.18$ $T/T_F = 0.14$

Majority and Minority Radii

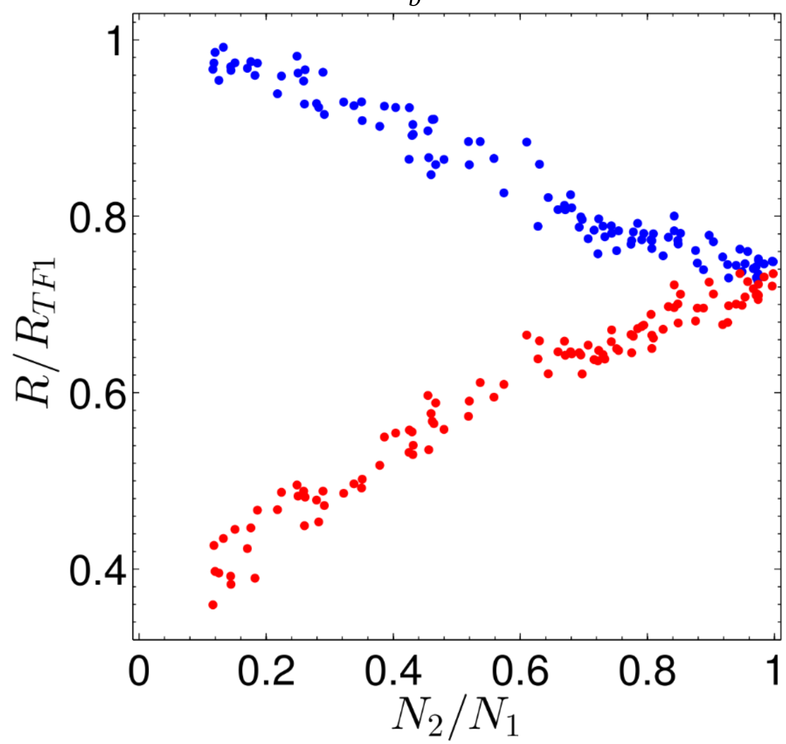
E_b = 2D dimer binding energy E_F = 2D ideal gas Fermi energy

Ideal gas Thomas-Fermi radius - Majority

$$\frac{E_F}{E_b} = 6.6$$



$$\frac{E_F}{E_b} = 0.75$$

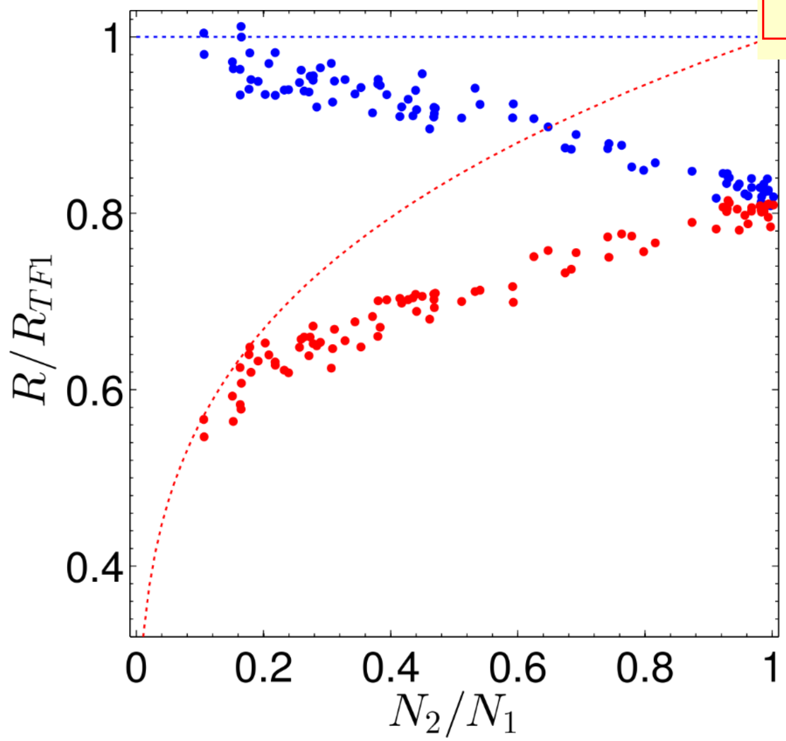


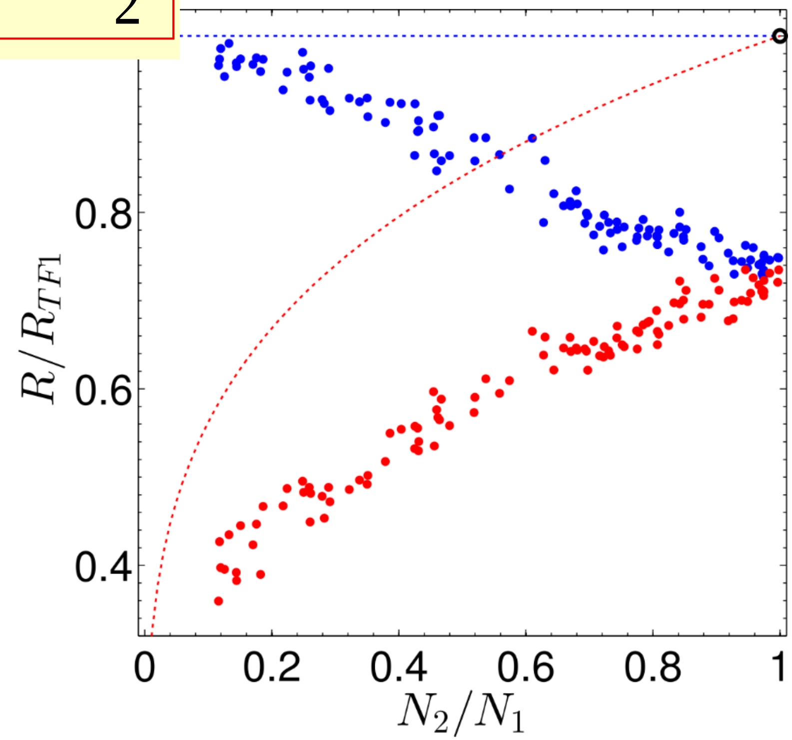
Majority and Minority Radii

$$\frac{E_F}{E_b} = 6.6$$

$$\varepsilon_F = \mu + \frac{E_b}{2}$$

$$\frac{E_F}{E_b} = 0.75$$





Ideal gas

○ 2D-BCS—balanced

2D-Polaron Thermodynamics

Free energy density of imbalanced gas: $f = \frac{1}{2} n_1 \varepsilon_{F1} + \frac{1}{2} n_2 \varepsilon_{F2} + n_2 E_p(2)$

Ideal Fermi gas

Minority Polaron Energy

Polaron energy: $E_p(2) = y_m(q_1)\,\varepsilon_{F1}$

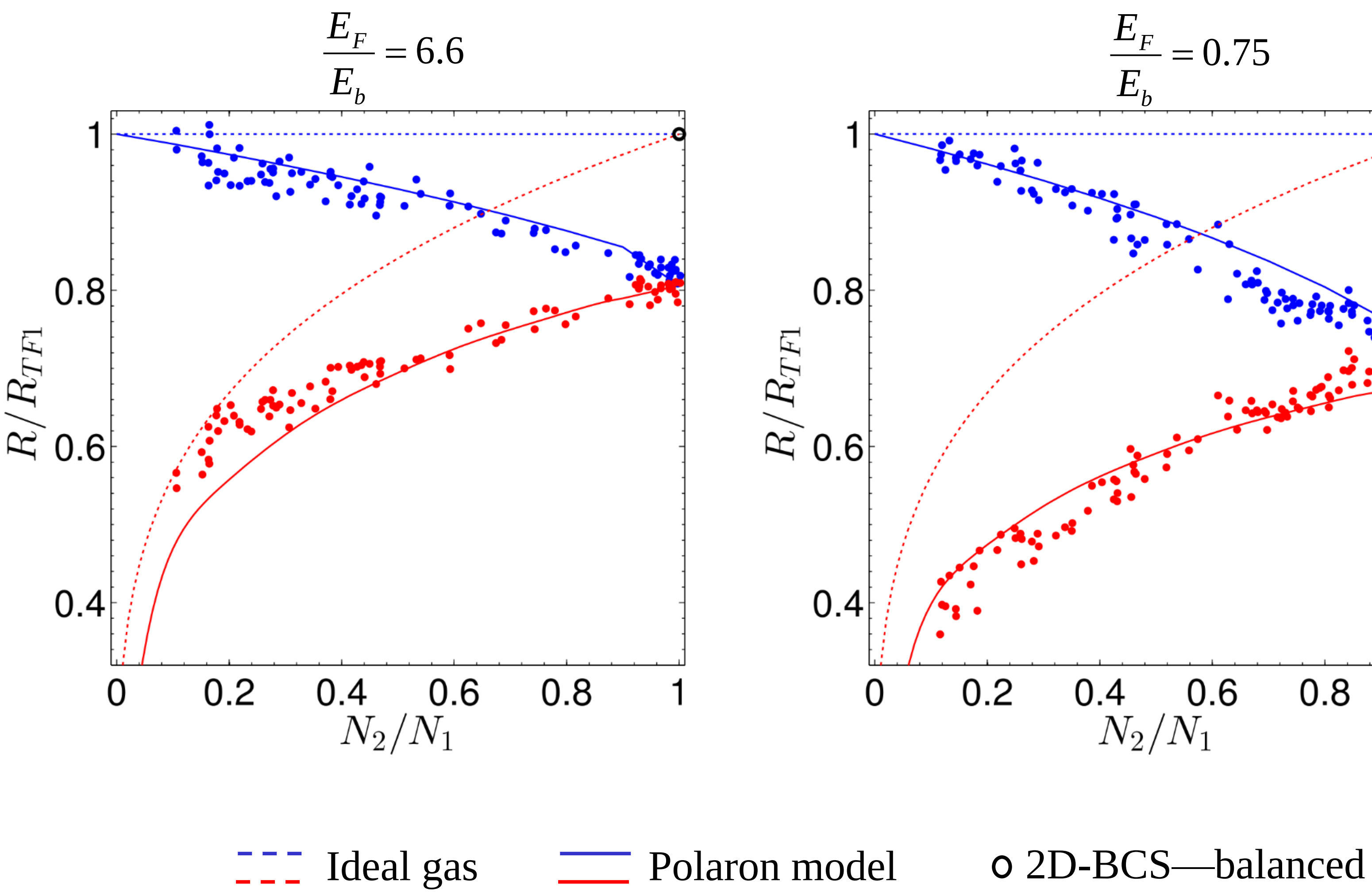
$\varepsilon_{F1} = \frac{2\pi h^2}{m} n_1$ $\quad q_1 \equiv \frac{\varepsilon_{F1}}{E_b}$ $\quad y_m(q_1) = \frac{-2}{\log(1+2q_1)}$

Klawunn and Recati 2011

Chemical potentials: $\frac{\partial f}{\partial n_1} = \mu_1 = \mu_{10} - U(\rho), \quad \frac{\partial f}{\partial n_2} = \mu_2 = \mu_{20} - U(\rho)$

Pressure: $p = n_1\mu_1 + n_2\mu_2 - f$

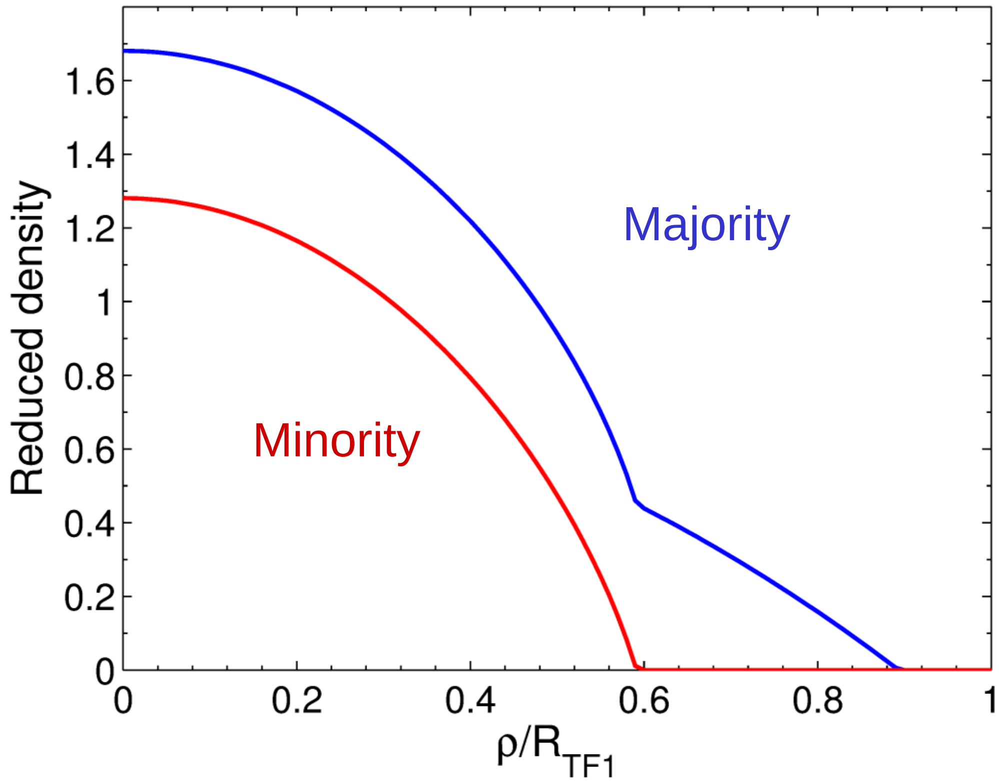
Majority and Minority Radii



Predicted Density Profiles

$E_F/E_b = 0.75$ $N_2/N_1 = 0.5$

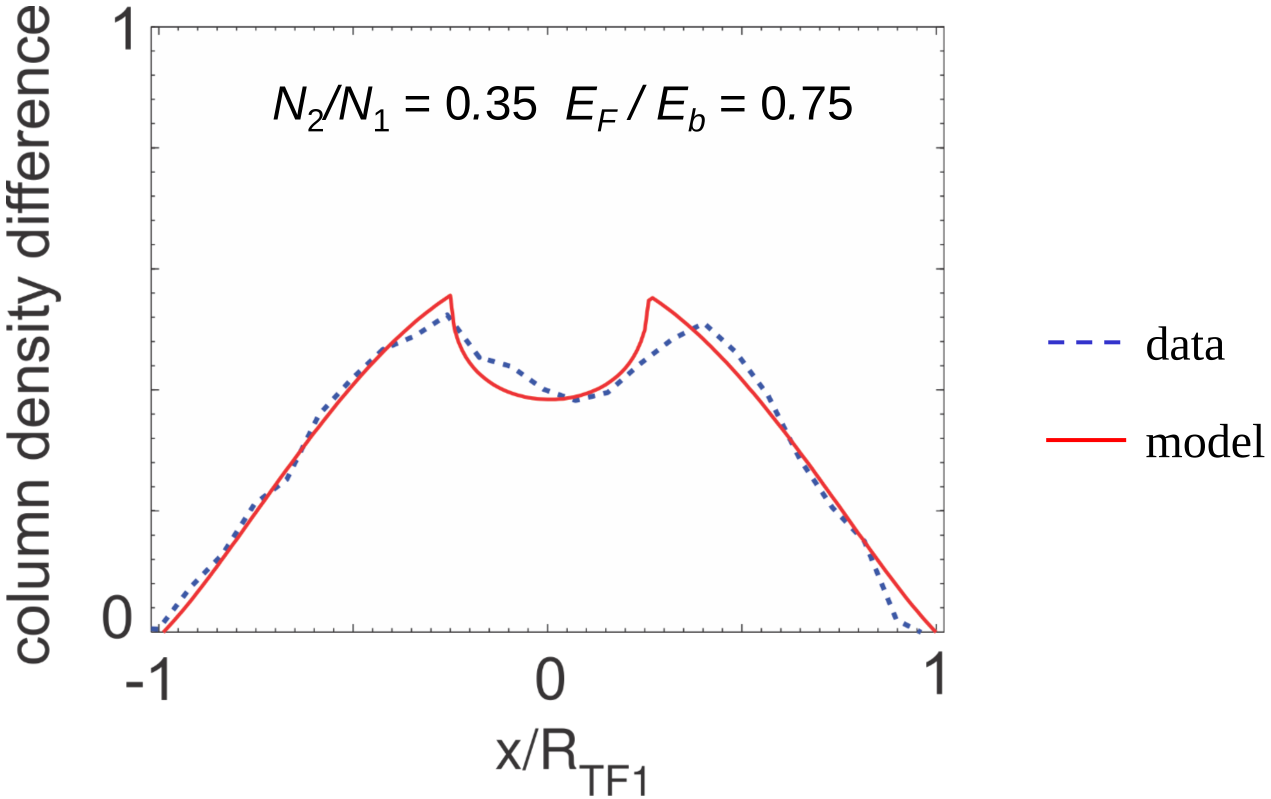
$$\frac{n_{2D}}{n_{\rm ideal}}$$



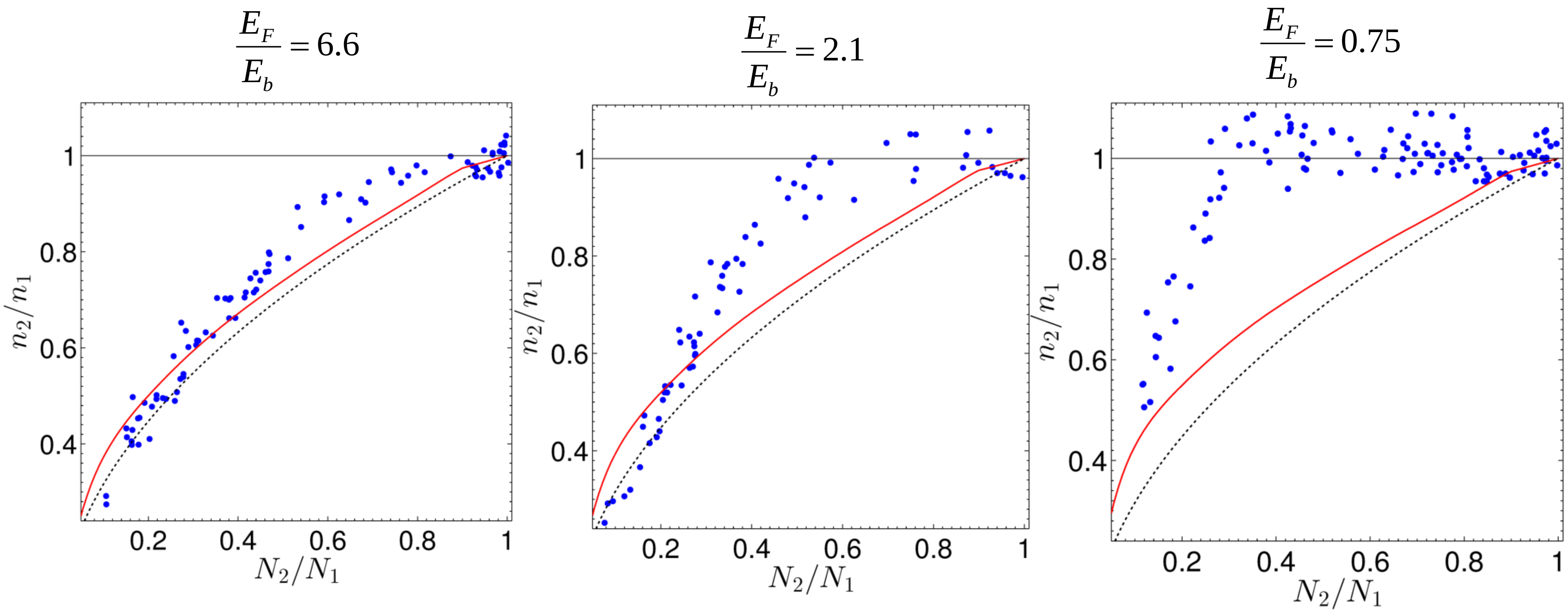
Transition to a Balanced Core?

Balanced Core 2D-Profile: $\Delta n_{2D}(\rho) = A\Theta[\rho - R]\Theta[R_1 - \rho](1-\rho^2/R_1^2)$

balanced core $\rho < R$



2D-Central Density Ratio



Polaron model

Ideal gas

- Transition to balanced core:
- Not predicted!

Summary

- BCS theory for a true 2D system
  fails in the quasi-2D regime.

- 2D polaron model explains several features of the
  density profiles in the quasi-2D regime.

- 2D polaron model with the analytic approximation is
  too crude to predict the transition to a balanced core.

- Measurements with imbalanced mixtures provide
  the first benchmarks for predictions of the
  phase diagram for quasi-2D Fermi gases.