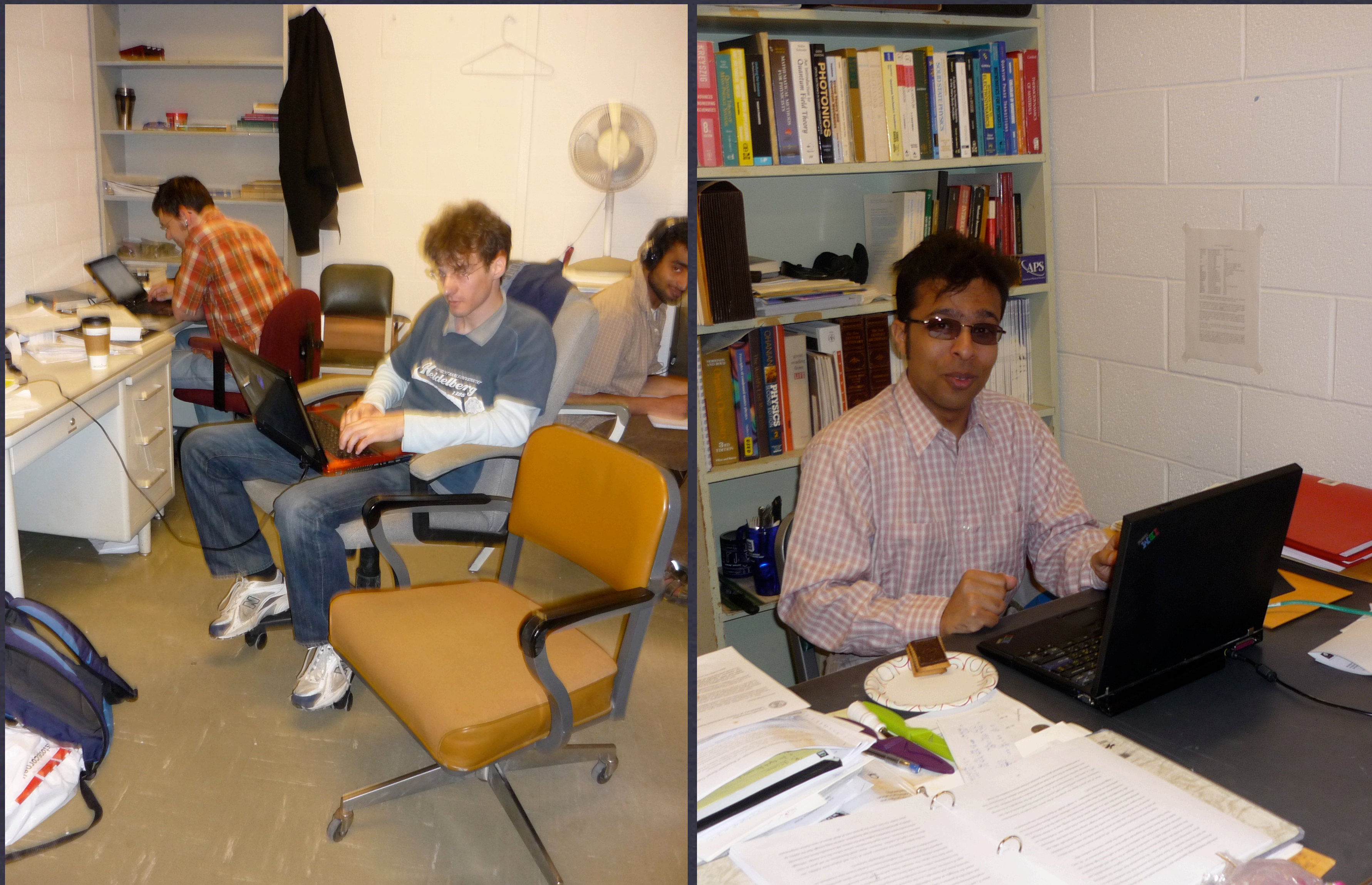
DARPA OLE

Phase 1A

Rice Collaboration

Data Analysis



Cornell Theory Team

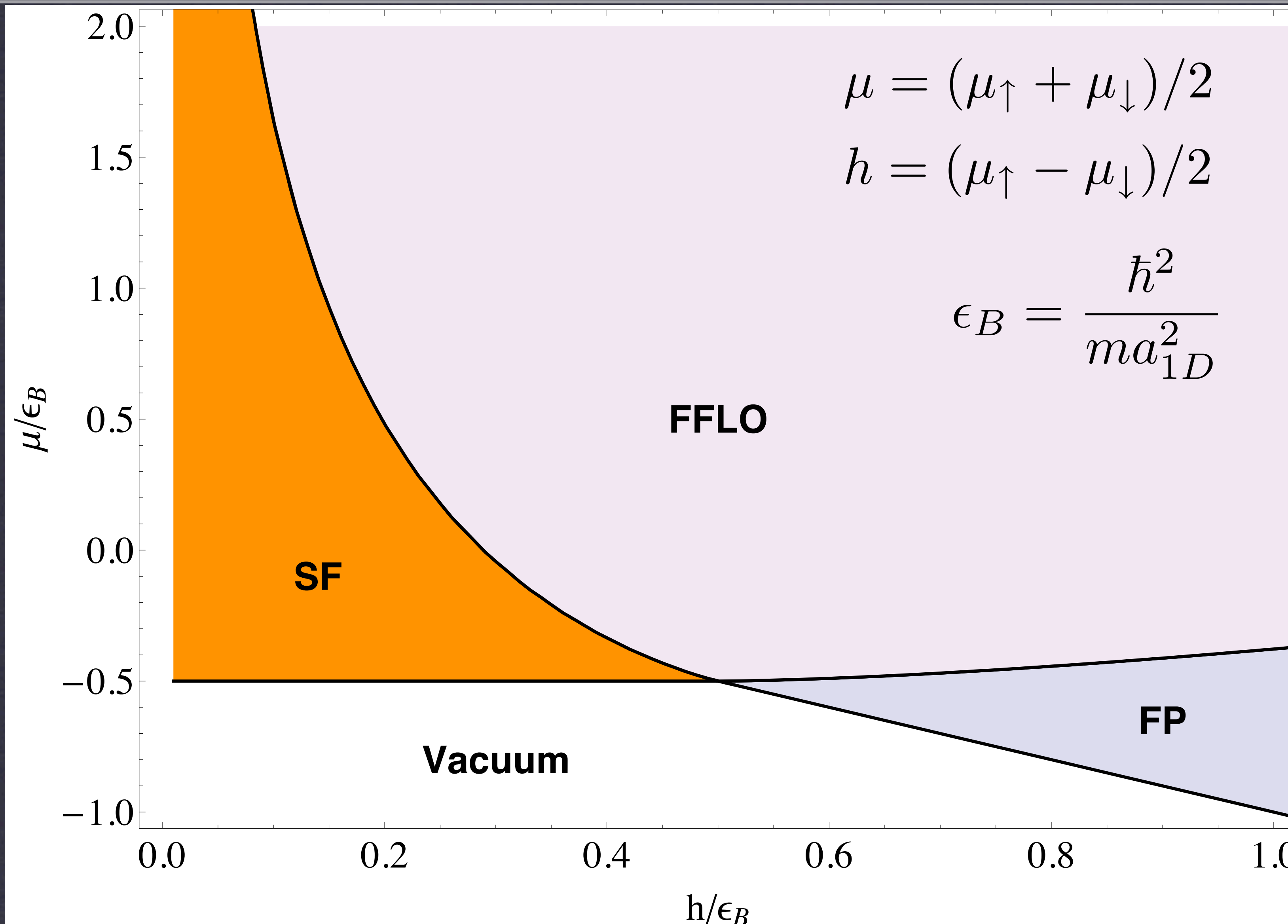
Stefan Baur, Kaden Hazzard, Sourish Basu, (not shown -- Stefan Natu)

Goals

1. Describe Phase Diagram
2. Describe Data
3. Explain how we analyze data (and why)
4. Discuss Accuracy

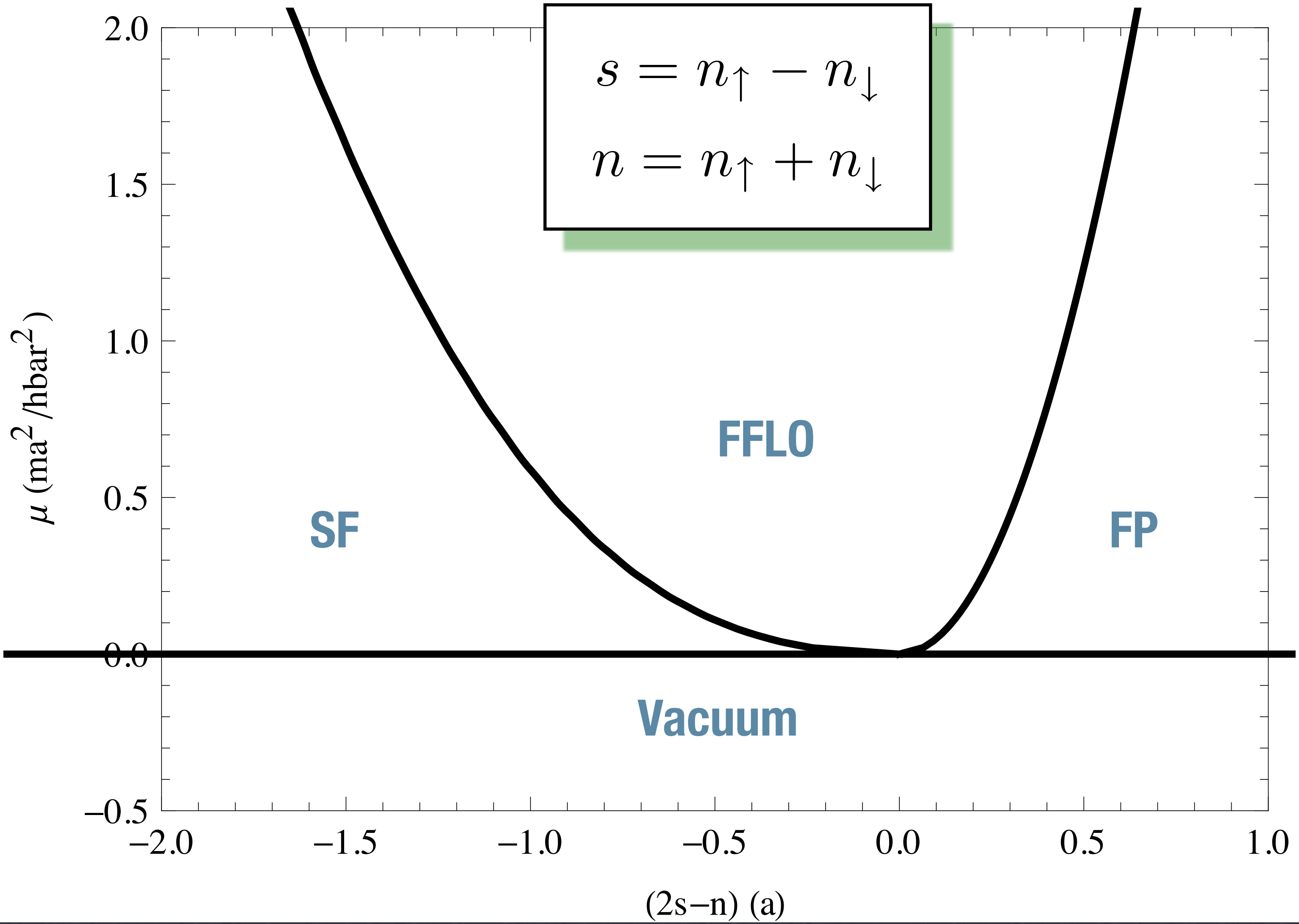
Take home message:

Many of our observations impact other OLE projects



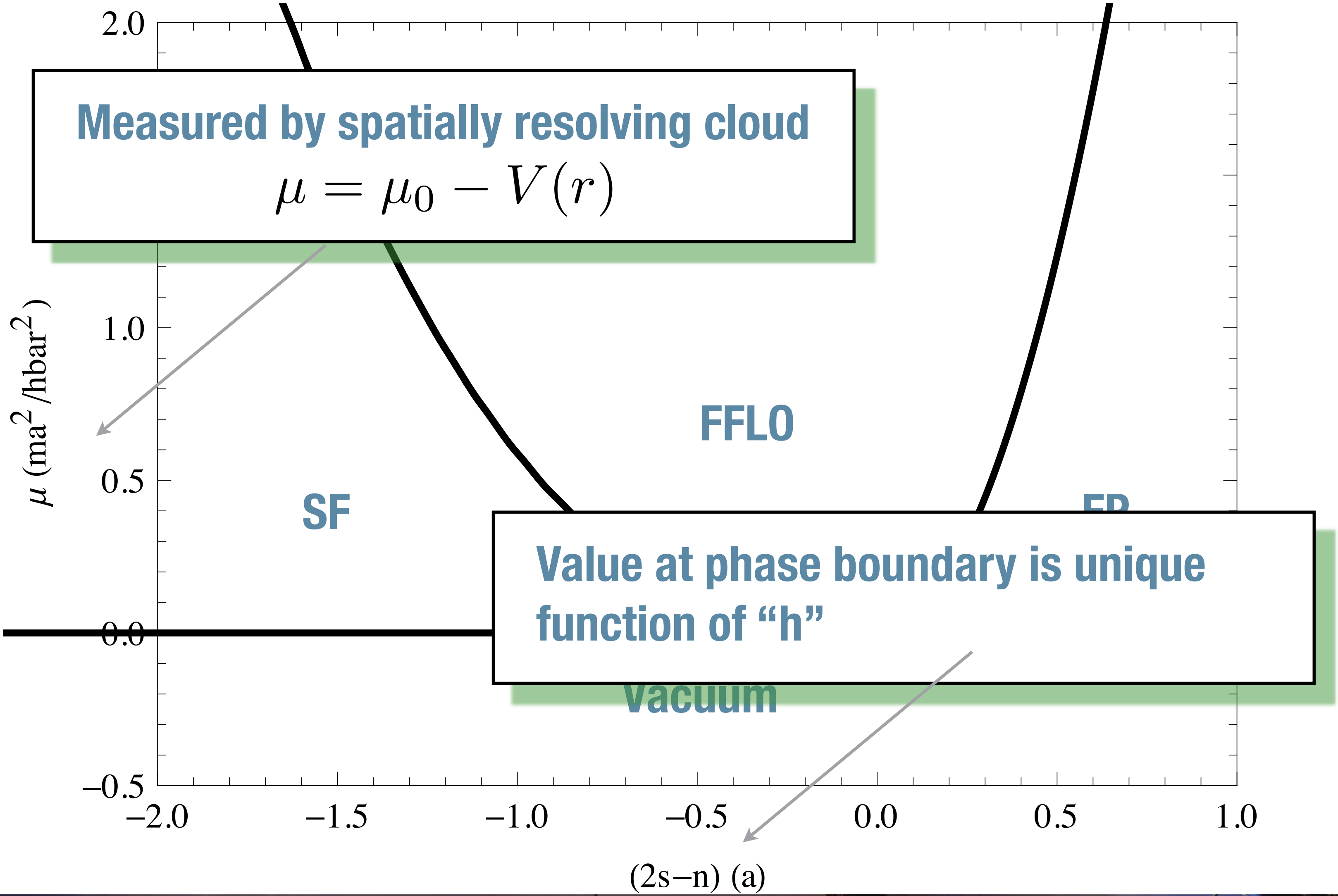
Phase Diagram

Exact: 1D fermions with attractive point interactions



Alternative variables

Shown at Initial DARPA Meeting -- Also discussed by Bolech at last meeting



Alternative variables

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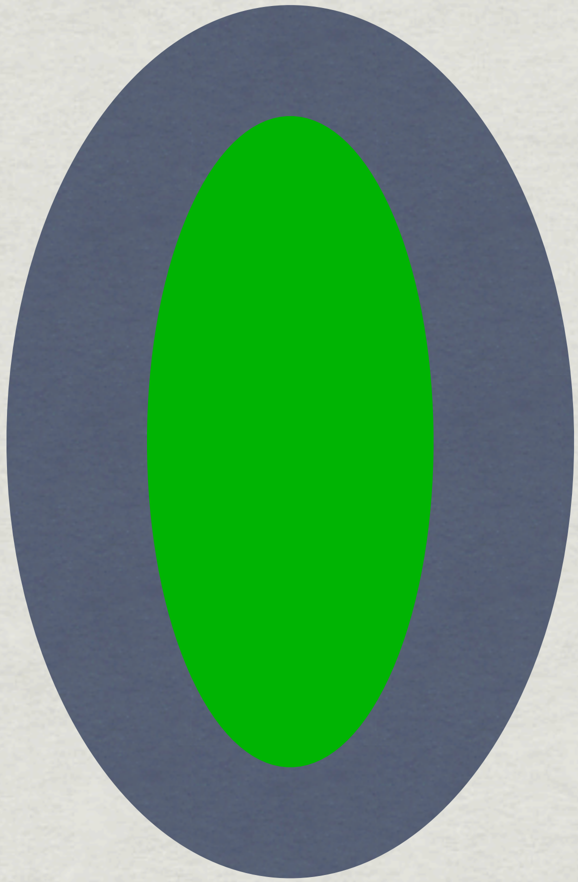
Extracting Phase Diagram

- Basic Idea:
    - Spatially resolve phase boundary
    - Measure relevant variables on boundary



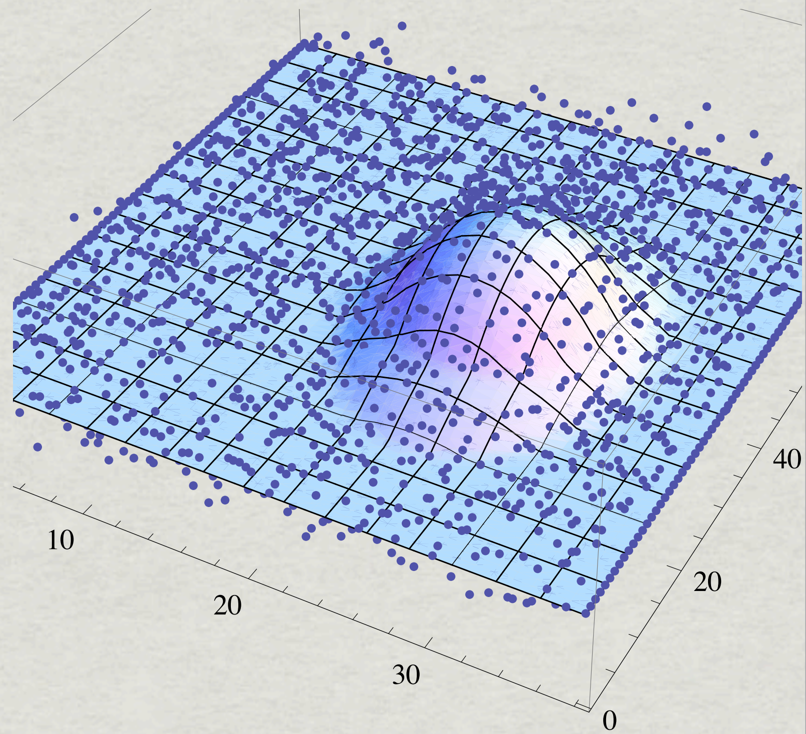
Extracting 3D densities

- Empirical Fit to 2D data

$$n_\downarrow = a - br^2 - cz^2$$

$$n_\uparrow - n_\downarrow = a' - b'r^2 - c'z^2$$

- Inverse Abel transform fit

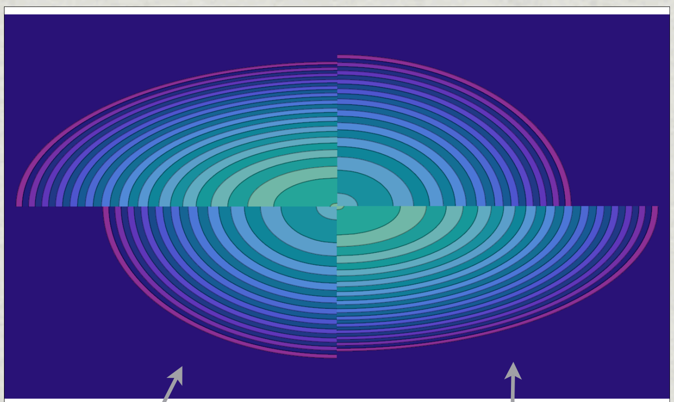


Observations

1. Non-equilibrium distribution between tubes
   - Explored as function of lattice turn-on
   - Important for ALL OLE projects
   - Makes finding phase diagram harder
2. Equilibrium distribution in each tube
3. Ratios of compressibilities matches theory
4. Generated Phase Diagram
5. Unresolved factor of 2.5

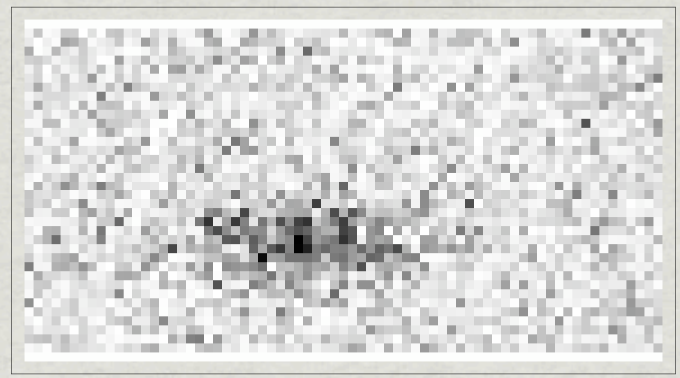
Non-equilibrium

Column Density



$n_\downarrow$ $n_\uparrow - n_\downarrow$

$n_\uparrow - n_\downarrow$

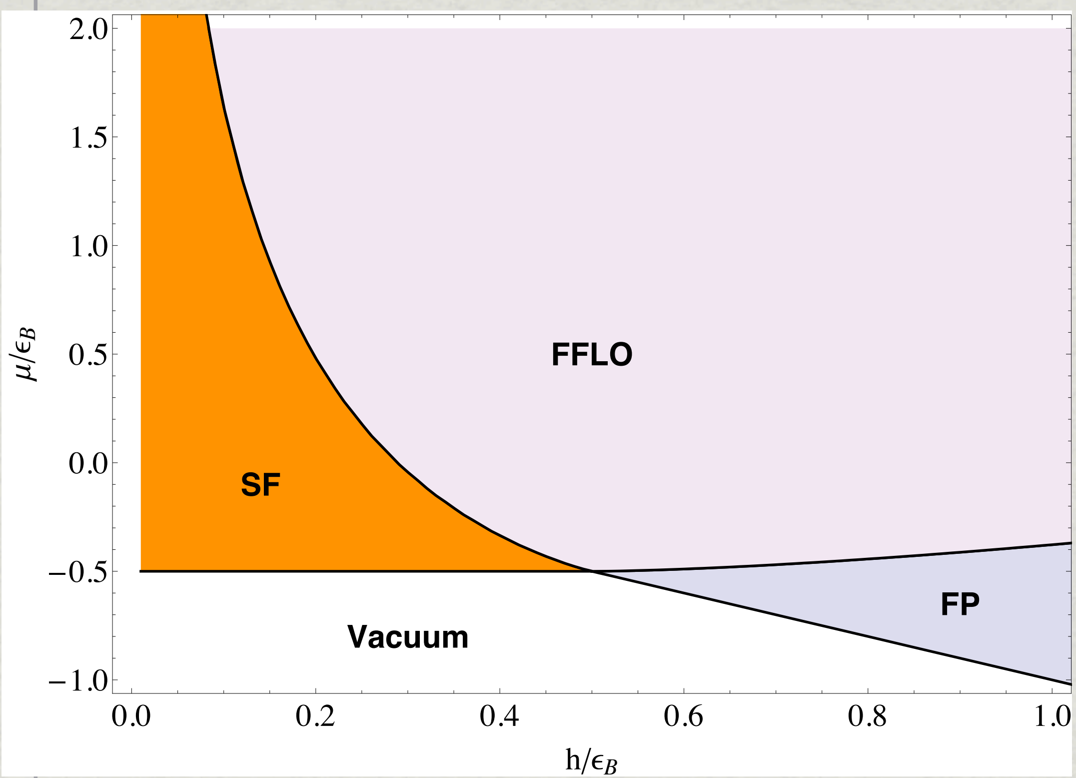


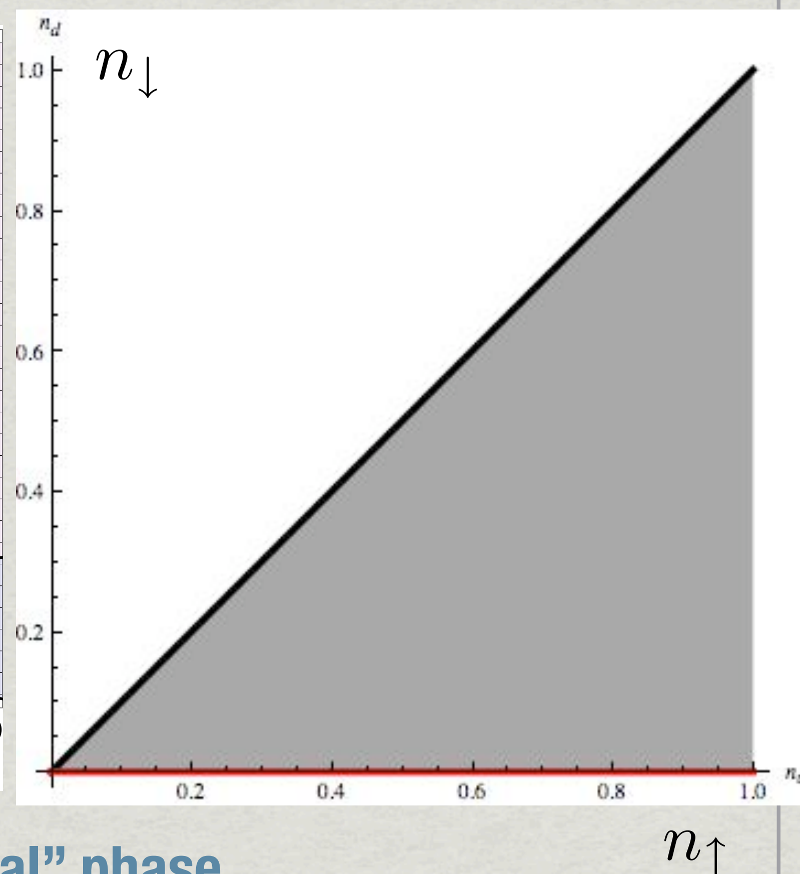
$n_\downarrow$

Boundary is nontrivial

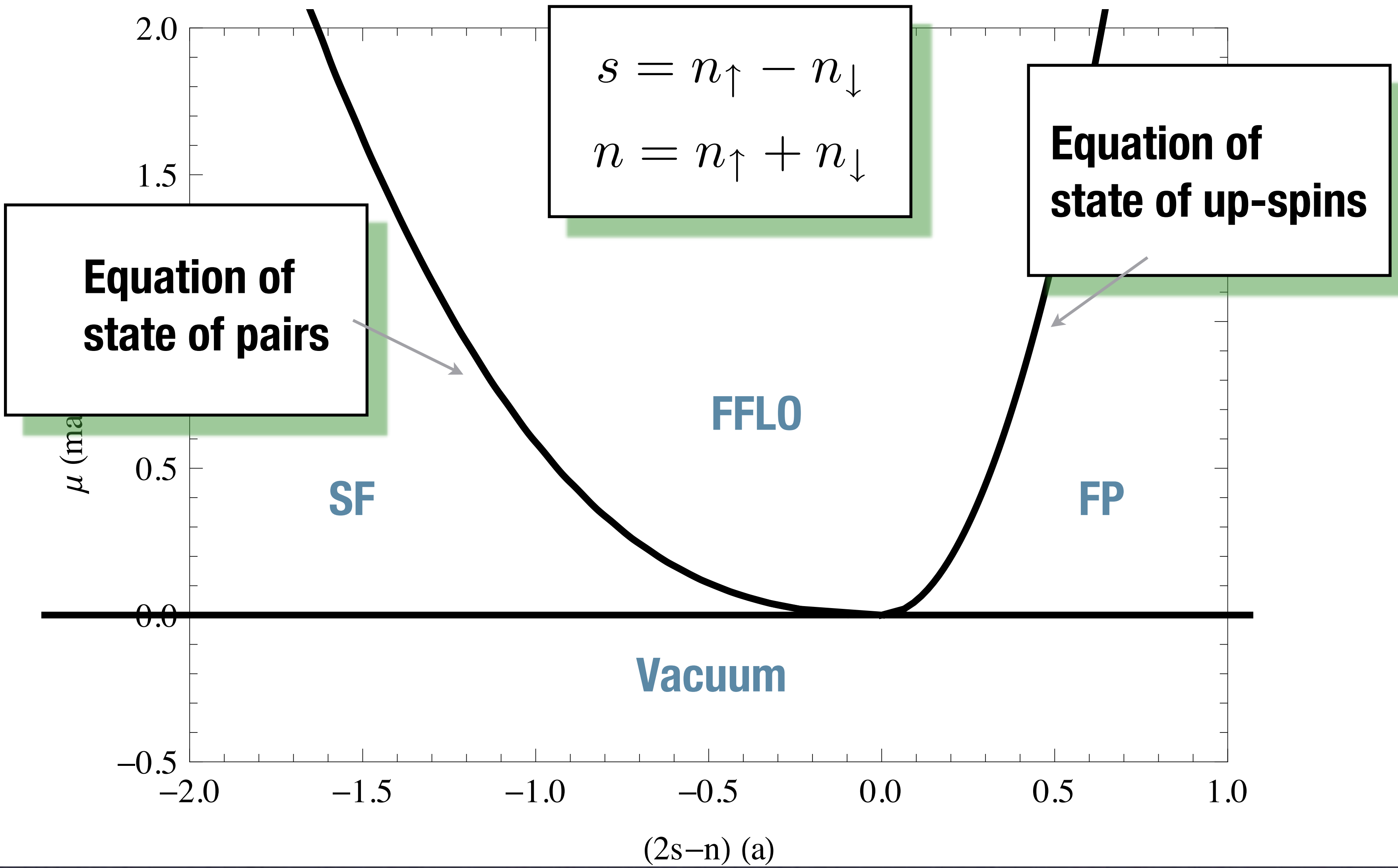
Extra Trick (Boosts signal-to-noise)

Two of our three phases are "trivial"





Phase boundary: equation of state of "trivial" phase



Alternative variables

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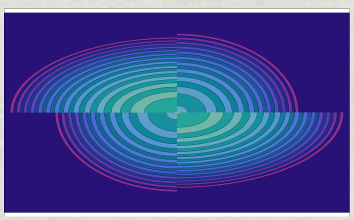
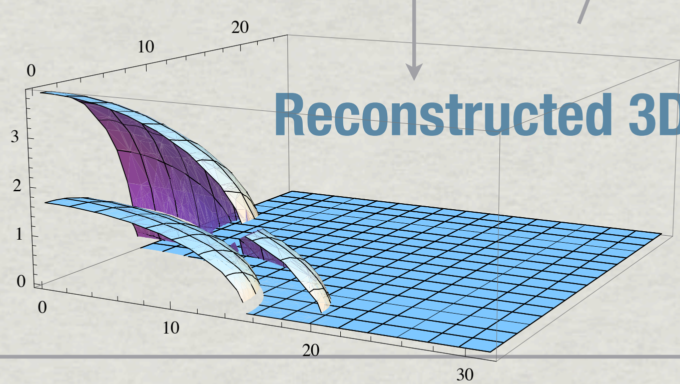
Approach

2D Densities

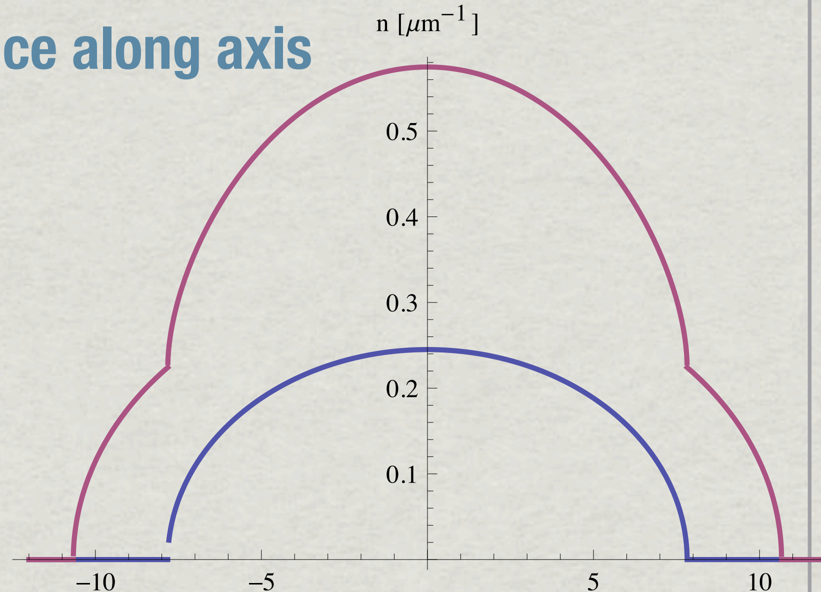
2D model





Reconstructed 3D density

Take Slice along axis



Plot

$$\mu = m\omega_z^2(z^2 - z_{\mathrm{edge}}^2)/2$$

vs density

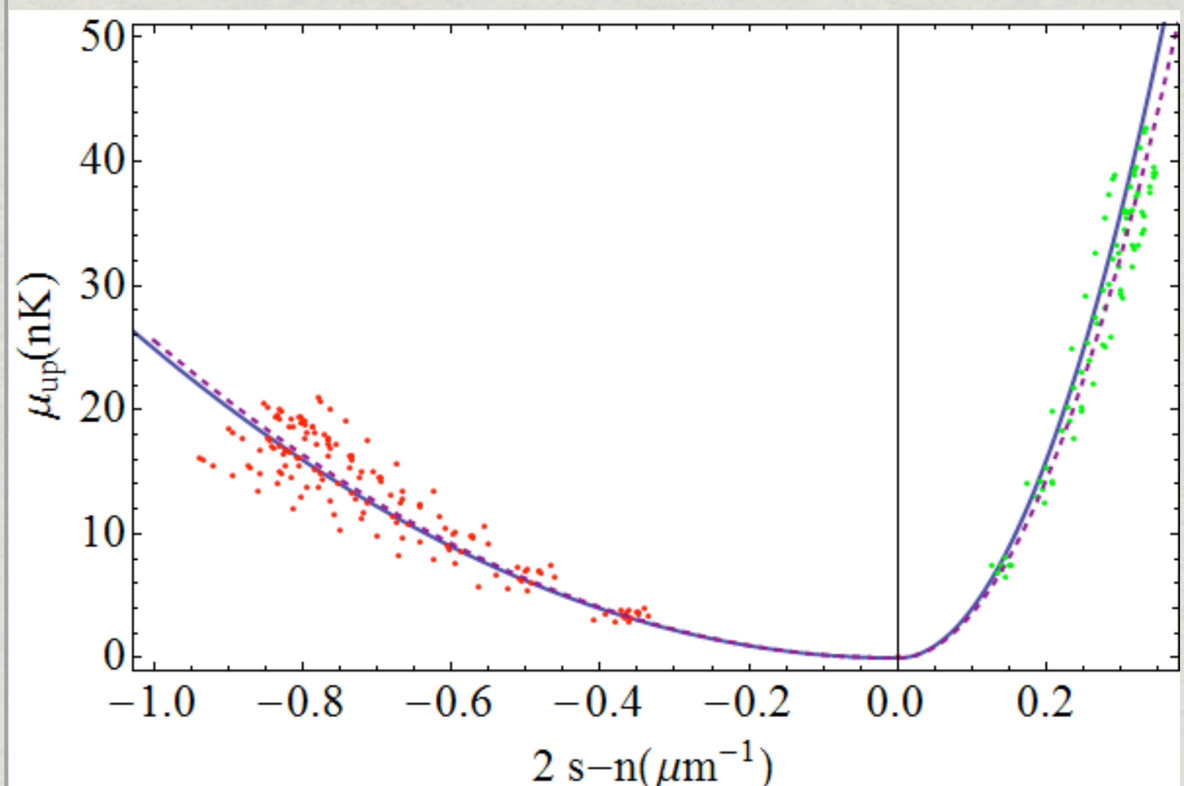
Result

Assumes $\nu_z = 42Hz$

Actual $\nu_z = 241Hz$

Fit works best away from critical polarization: throw away medium polarization data

Factor of 2.5 discrepancy in cloud size!!!



Ratio of compressibilities of paired and polarized states matches theory

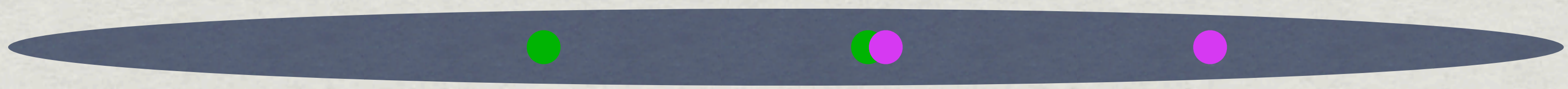
Sources of Errors

Major focus of theoretical efforts

- Temperature
- Inter-tube coupling
- 3D nature of bound state
- Non-equilibrium distribution
- Finite size effects

All should be below the 10% threshold

3D bound states



If bound state smaller than channel size:
not describable in terms of 1D fermions

Non-problem:

At unitarity, bound state is large

Strong coupling theory is same

Strong-coupling theory

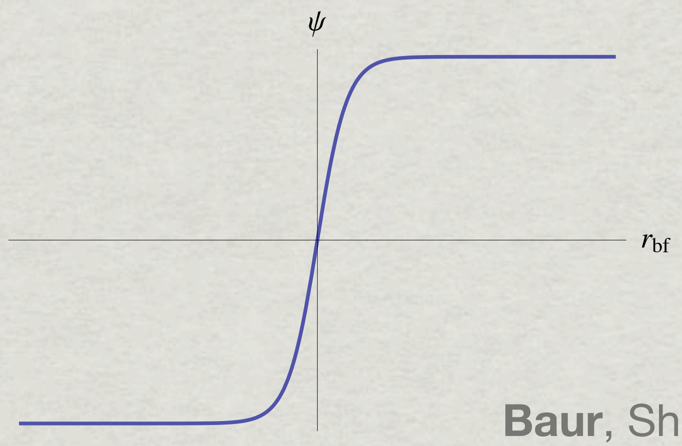
$$\mathcal{E} = \frac{\hbar^2\pi^2}{12m} n_\downarrow^3 + \frac{\hbar^2\pi^2}{6m}(n_\uparrow - n_\downarrow)^3$$

Tonks gas of Bosons (pairs)

Ideal fermi gas
(excess up-spins)

Bose-Fermi interactions

Perfect transmission: but phase shift of π



Finite T theory is trivial

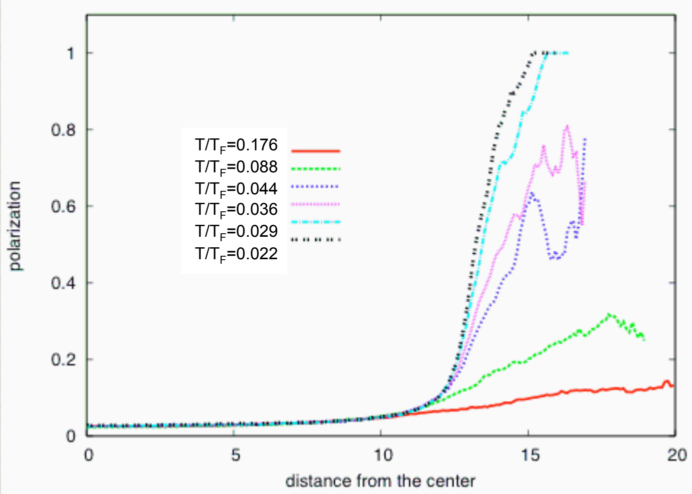
correlation functions: Jordan-Wigner

Baur, Shumway, Mueller, arXiv:0902.4653

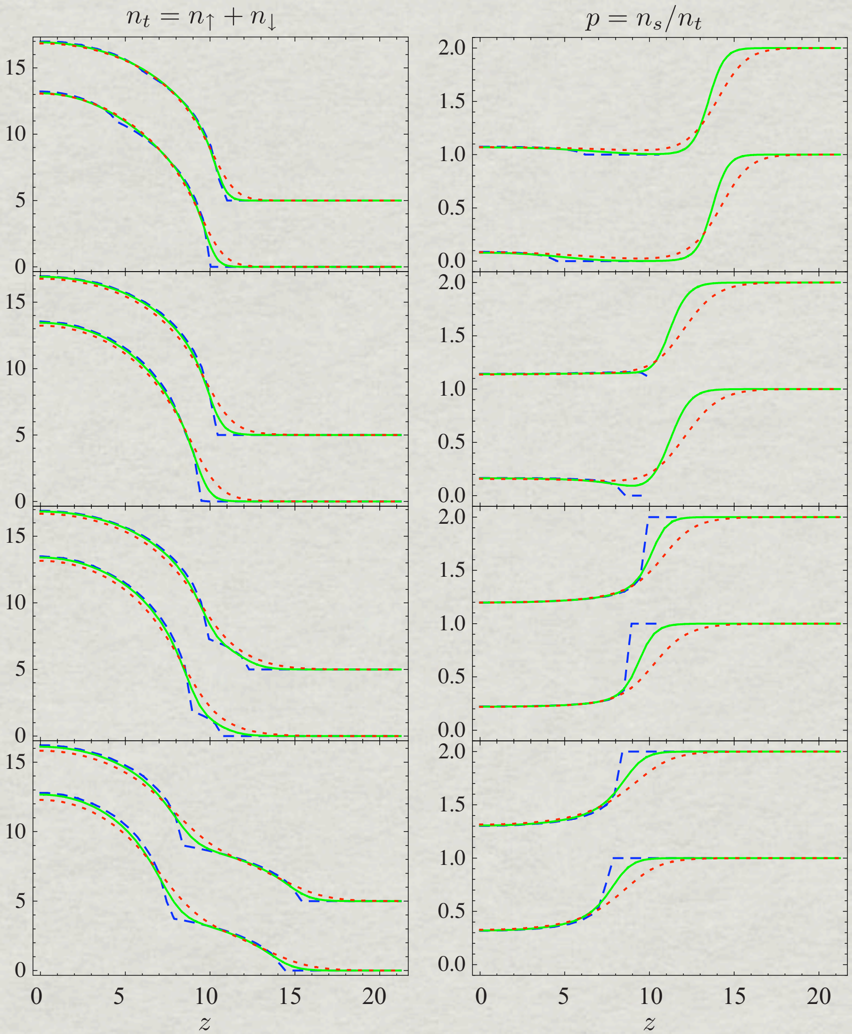
Zhao, Guan, Liu, Batchelor, Oshikawa

Finite T

Temp not problem if T<0.05 Tf

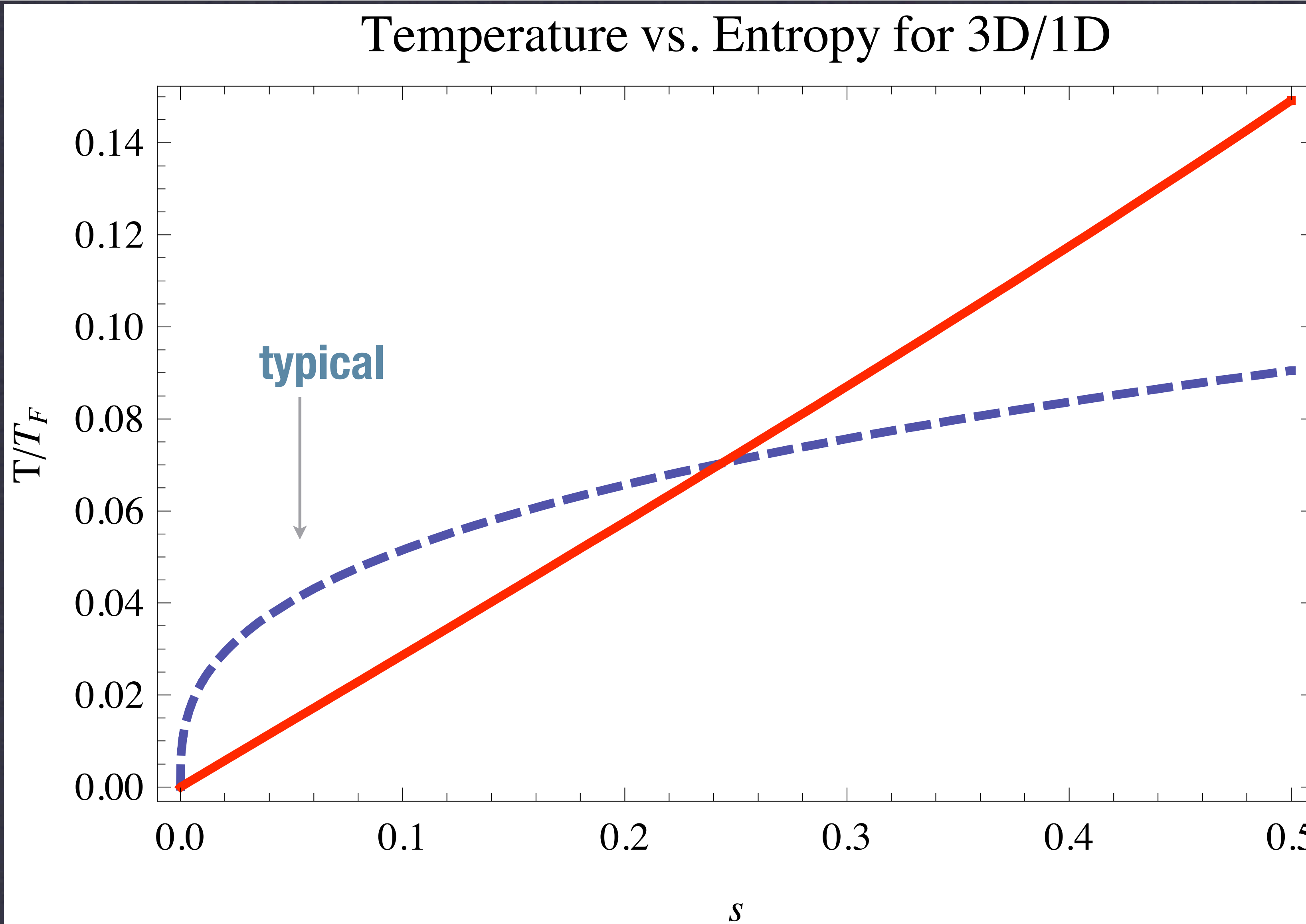


Casula, Ceperley, Mueller,
Phys. Rev. A 78, 033607 (2008)



Kakashvili, Bolech,
Phys. Rev. A 79, 041603 (2009)

Analytic strong-coupling theory agrees with this

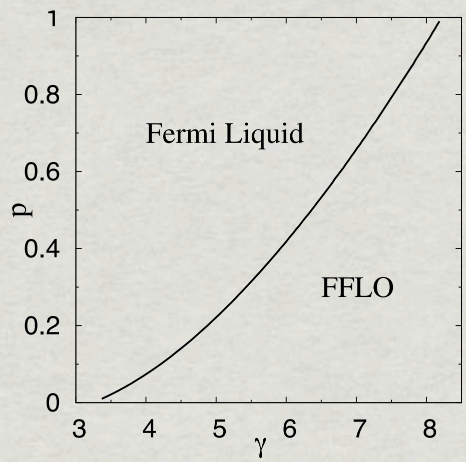


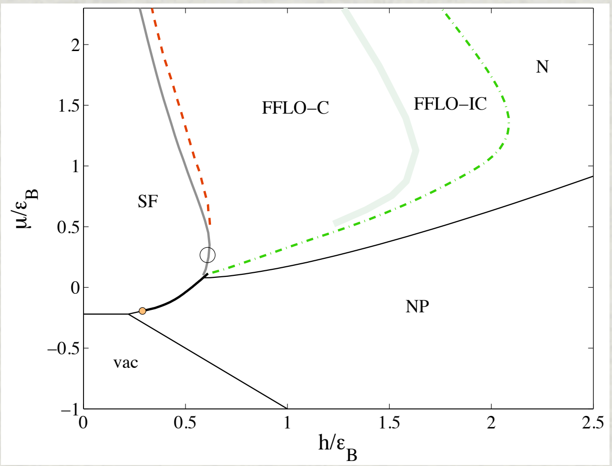
Adiabatic Cooling/Heating

Start cold enough, get cooling

Baur

Inter-tube coupling



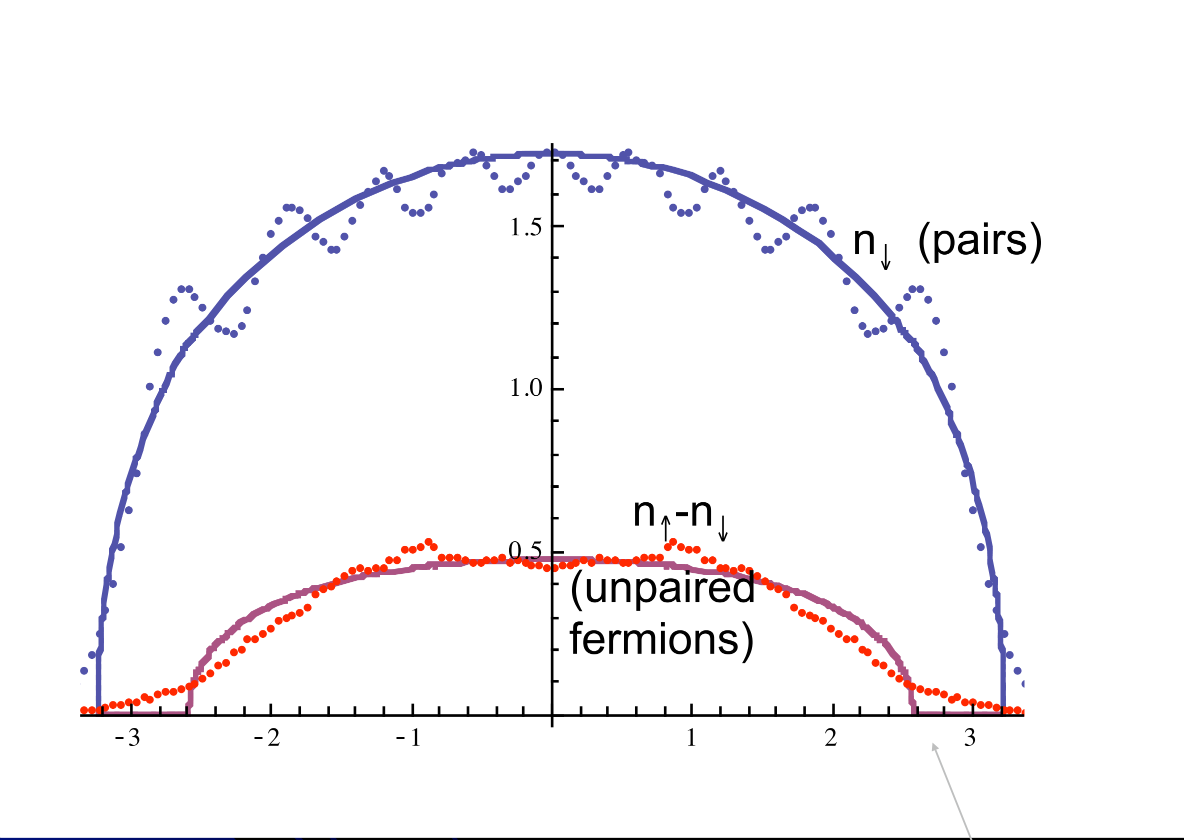


Zhao and Liu,
Phys. Rev. A 78, 063605 (2008)

Parish, Baur, Mueller, Huse
Phys. Rev. Lett. 99, 250403 (2007)

Finite coupling continuously connected to decoupled limit

Finite Size Effects



20 particles

g=2 d/a = 20

(very strong interactions)

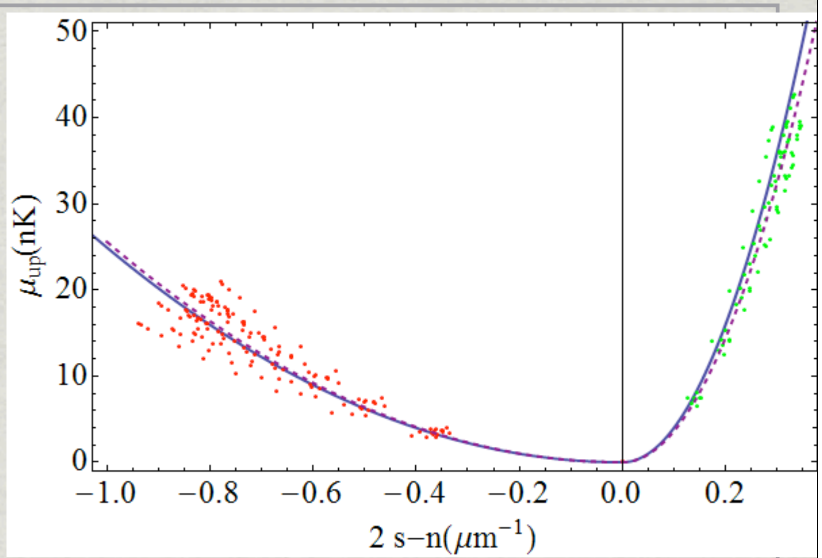
9 pairs
2 unpaired fermions

Dots: Monte-Carlo

Lines: TF

Smeared out by interparticle spacing

Outlook



- Find scale factor
- investigate dimensional crossover
- systematically study non-adiabaticity
- BCS-BEC Crossover
  - (another phase diagram without an exact solution)