September 12-13 (2013) 新学術領域「中性子星核物質」 公募研究交流会(東北大学）

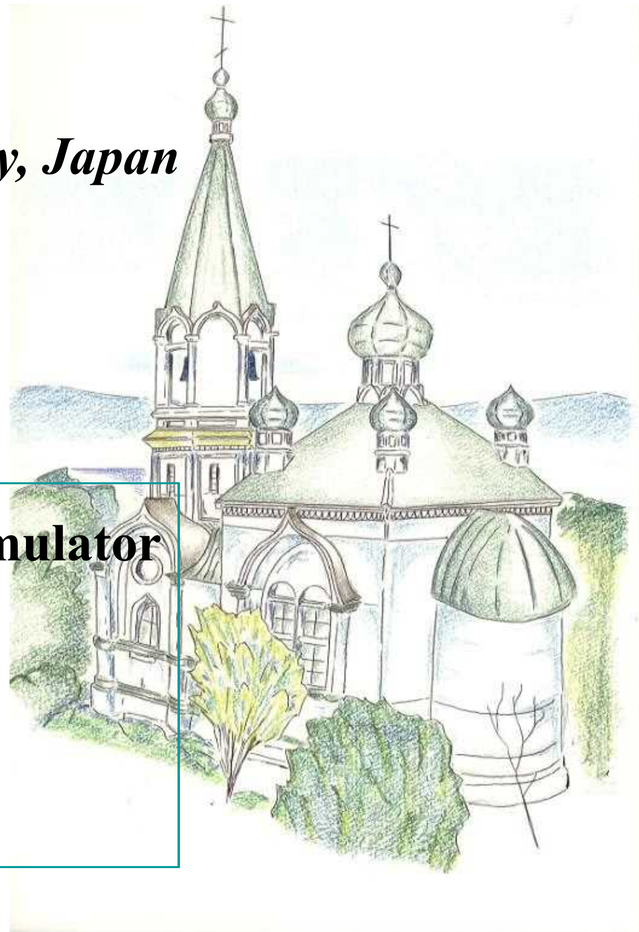
BCS-BECクロスオーバー領域におけるフェルミ超流体の熱力学と超流動物性

(公募研究　D01：2013～2014）

Yoji Ohashi

Department of Physics, Keio University, Japan

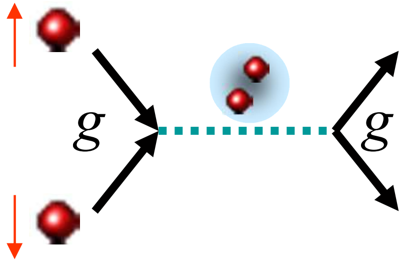
Collaborators:
R. Hanai (PhD)
H. Tajima (M2)



- **Introduction: cold Fermi atom gas as a quantum simulator**
- **Our Theoretical framework and previous results**
- **Some preliminary results**
- **summary**

Cold Fermi atom gas system as a useful ***Quantum Simulator***

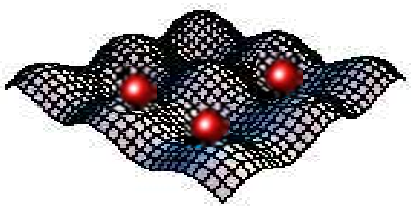
ultracold Fermi atom gas



Feshbach resonance

tunable interaction

- BCS-BEC crossover
- p-wave pairing
- hetero pairing
- resonance superfluid



band effect

- Hubbard model

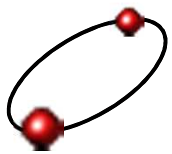
$$\frac{(\mathbf{p}-\alpha\mathbf{A})^2}{2m}$$

synthetic gauge field

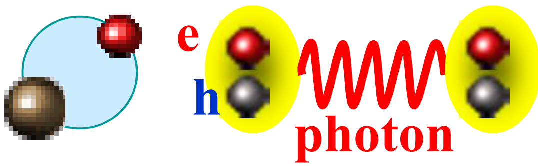
asymmetric LS coupling

- non-centro-symmetric state

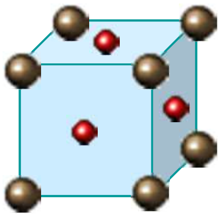
Fermi superfluid physics



exciton-polariton condensate

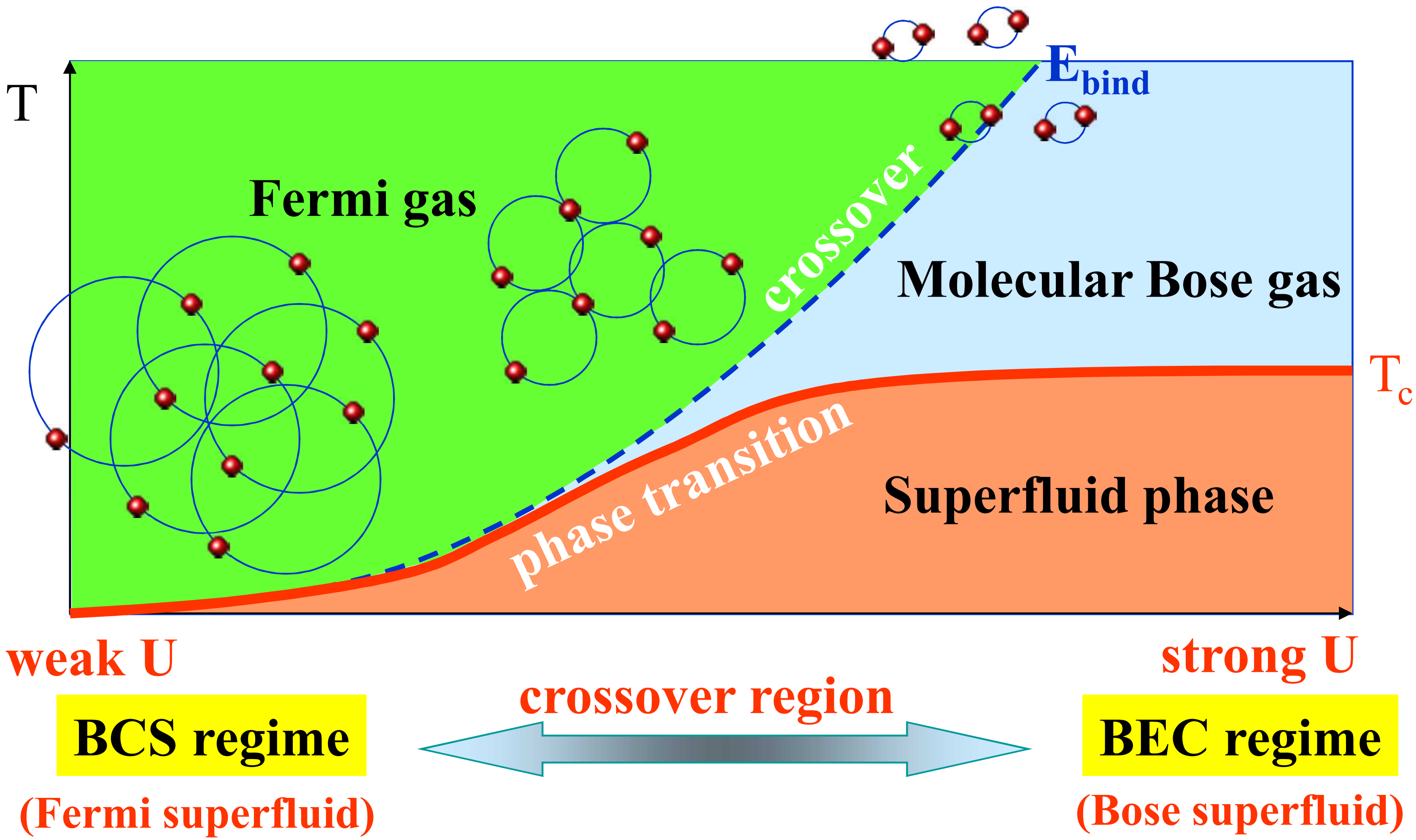


material science



BCS-BEC crossover

In this phenomenon, superfluid properties continuously changes from the weak-coupling BCS-type to a BEC of tightly bound molecules, with increasing the strength of a pairing interaction.

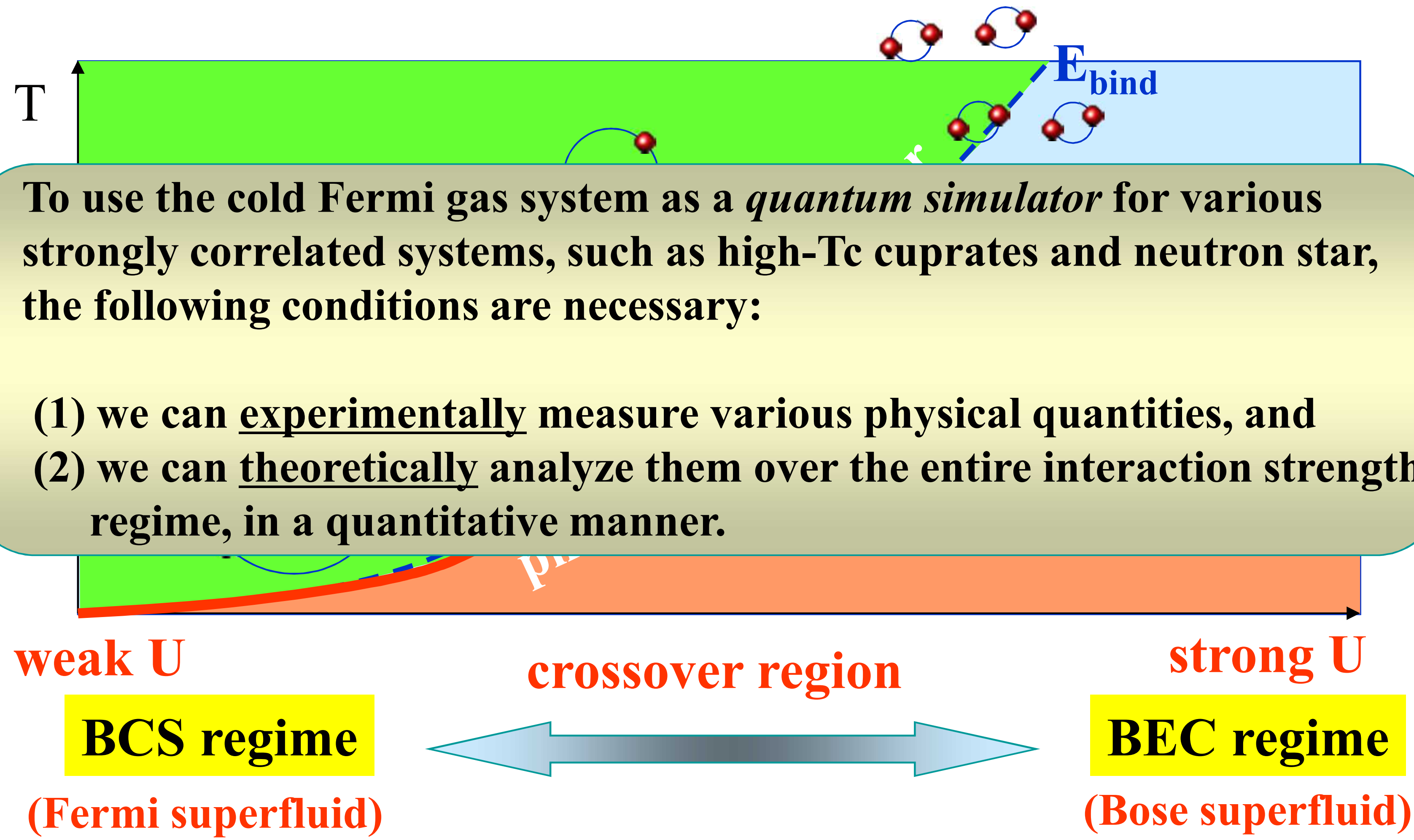


Quantum simulator ?

In this phenomenon, superfluid properties continuously changes from the weak-coupling BCS-type to a BEC of tightly bound molecules, with increasing the strength of a pairing interaction.

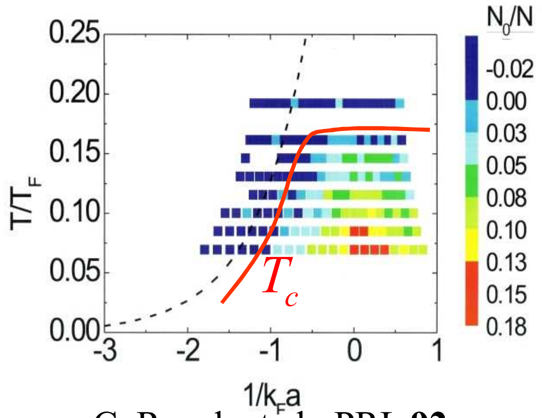
To use the cold Fermi gas system as a *quantum simulator* for various strongly correlated systems, such as high-Tc cuprates and neutron star, the following conditions are necessary:

(1) we can <u>experimentally</u> measure various physical quantities, and
(2) we can <u>theoretically</u> analyze them over the entire interaction strength regime, in a quantitative manner.



Current experimental situation: Very good!

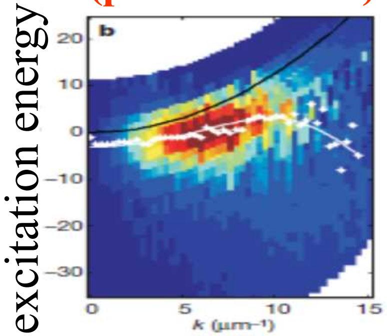
superfluid phase transition temperature Tc



C. Regal, et al. PRL **92** (2004) 040403.

single-particle excitations

(photoemission)

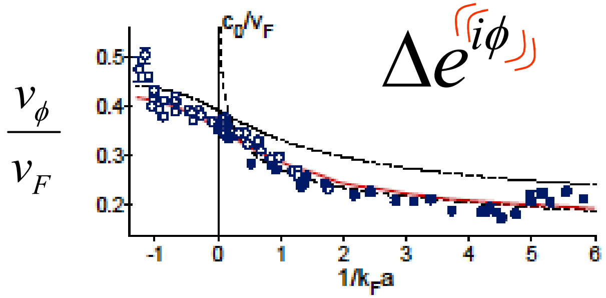


JILA, Nature **454** (2008) 744

collective excitations (Goldstone mode)

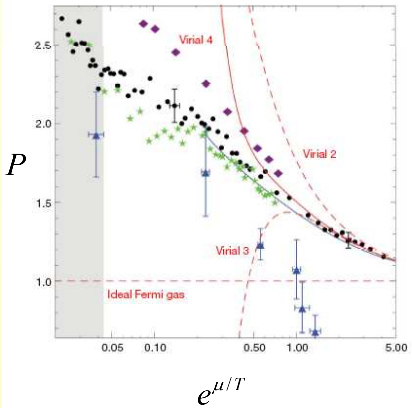
$$\boxed{\omega = v_\phi q}$$

$$\Delta e^{i\phi}$$



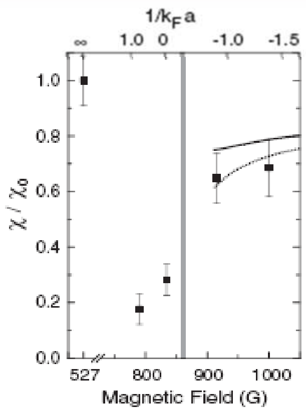
Thomas et al., PRL **98** (2007) 170401

local pressure



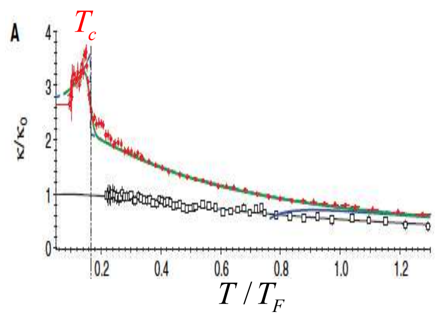
Salomon et al., Nature **463** (2010) 1057

spin susceptibility

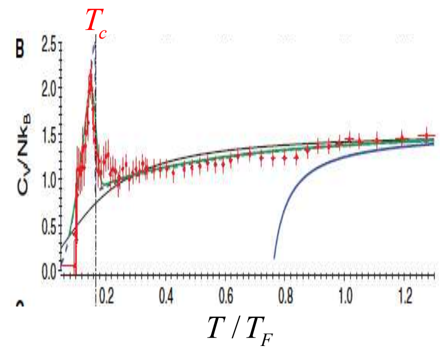


Ketterle et al., PRL **106** (2011) 010402

compressibility



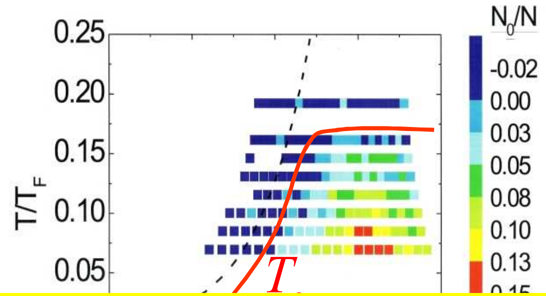
specific heat



Zwierlein et al., Science **335** (2012) 563

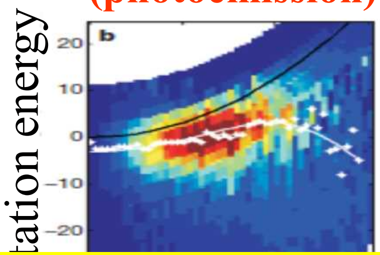
Current experimental situation: Very good!

superfluid phase transition temperature Tc



single-particle excitations

(photoemission)



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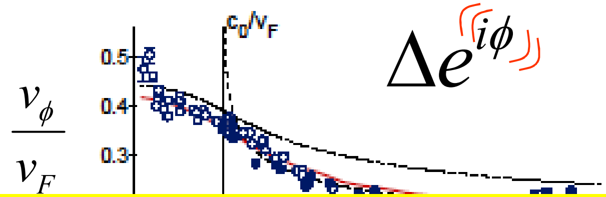
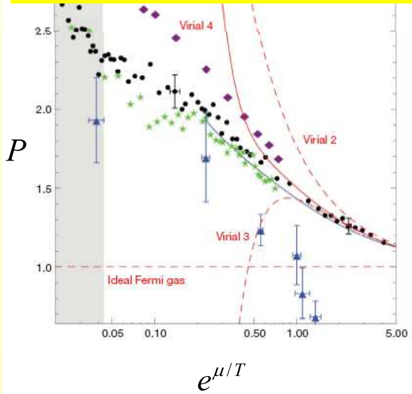
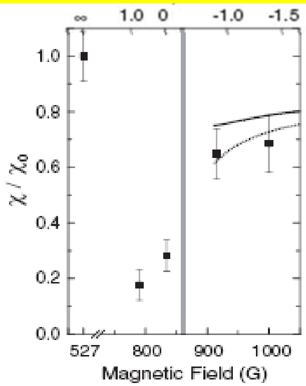


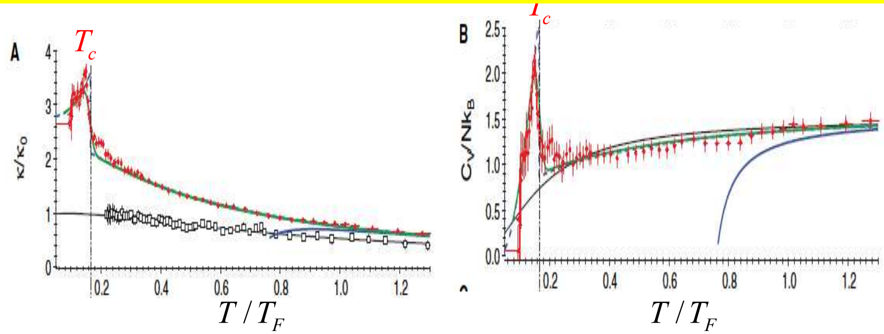
Toward the realization of "*Fermi gas quantum simulator*", in this 「公募研究」, we try to construct a <u>reliable theoretical framework</u> which enables us to analyze various observable physical quantities in the BCS-BEC crossover region in a unified manner.



Salomon et al., Nature **463** (2010) 1057



Ketterle et al., PRL **106** (2011) 010402



Zwierlein et al., Science **335** (2012) 563

Formulation (*broad* Feshbach resonance: ^{40}K, ^{6}Li)

$$H=\sum_{\mathbf{p},\sigma}(\varepsilon_p-\mu)c^\dagger_{\mathbf{p}\sigma}c_{\mathbf{p}\sigma}-U\sum_{\mathbf{p},\mathbf{q}}c^\dagger_{\mathbf{p}+\mathbf{q}\uparrow}c^\dagger_{\mathbf{p}'-\mathbf{q}\downarrow}c_{\mathbf{p}'\downarrow}c_{\mathbf{p}\uparrow}$$

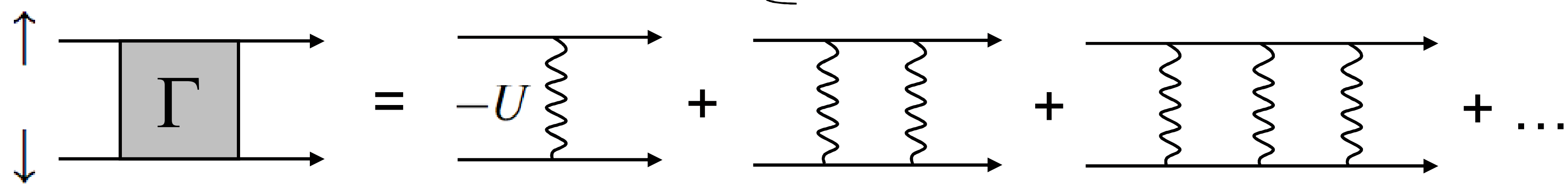
σ : two atomic hyperfine states $=\uparrow\downarrow$

U : tunable pairing interaction

- **BCS-BEC crossover**

  We include effects of strong pairing fluctuations at T>0 beyond the mean-field BCS theory.

  ➡ **Strong-coupling effects**
  - **Gaussian fluctuation theory**
  - **T-matrix theory**
  - **Extended T-matrix theory**
  - **Self-consistent T-matrix theory**

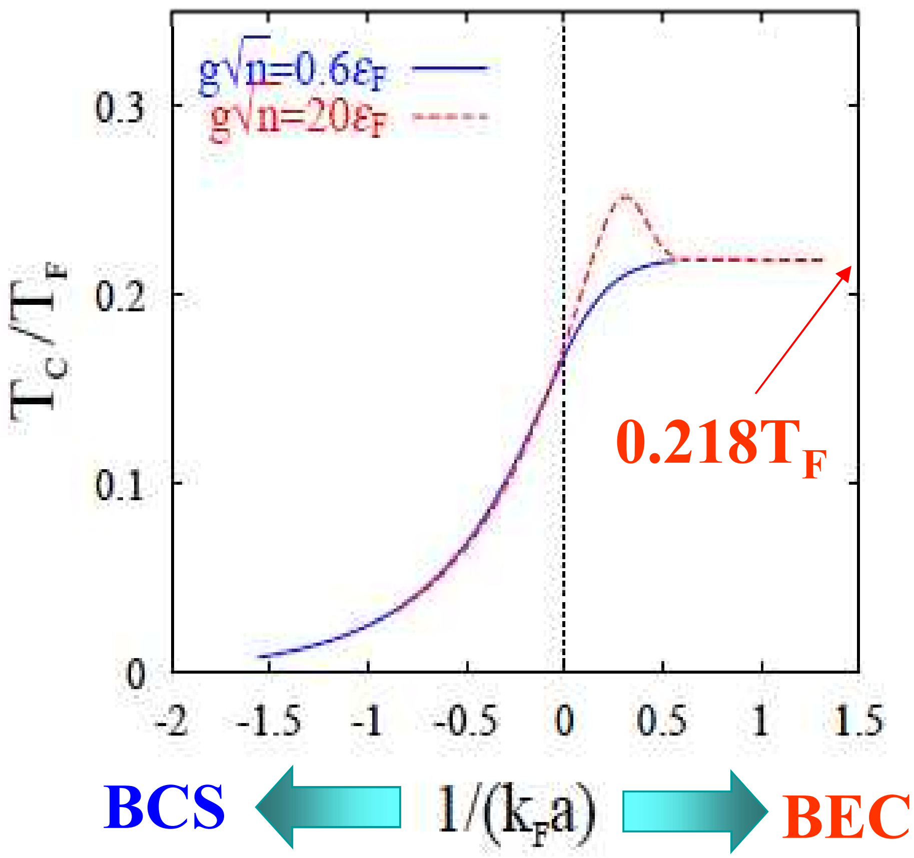


- **Fermi gases are always trapped in a harmonic potential.**

  ➡ **Spatial inhomogeneity** ⟶ **Local density approximation (LDA)**

Superfluid phase transition temperature T_c

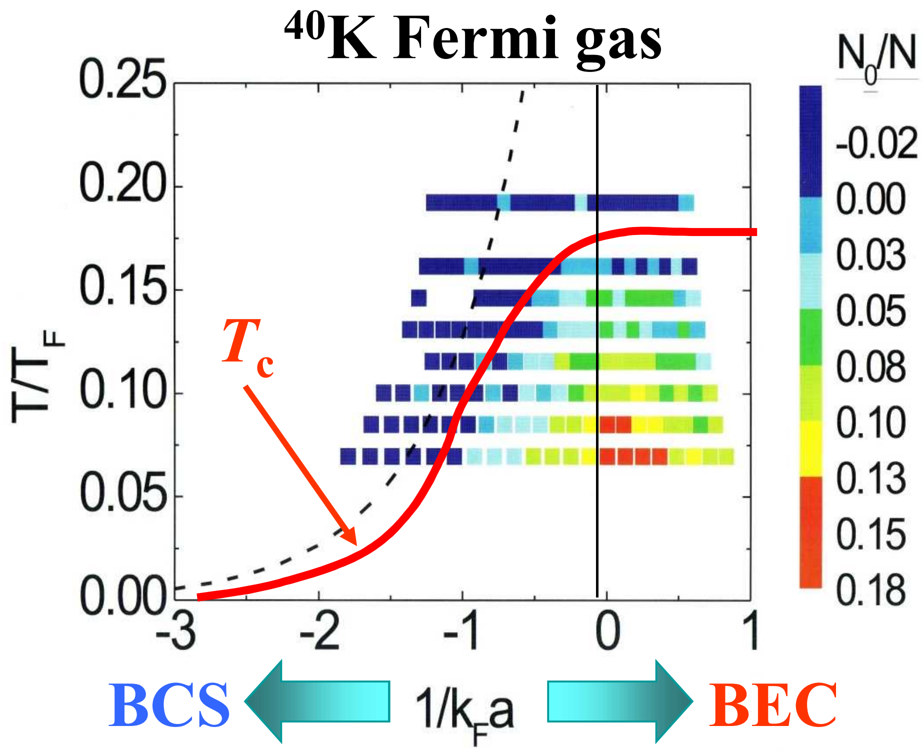
Our prediction (2002)



Ohashi, Griffin PRL 89 (2004) 130402

(Gaussian fluctuation theory)

Experiment (2004)

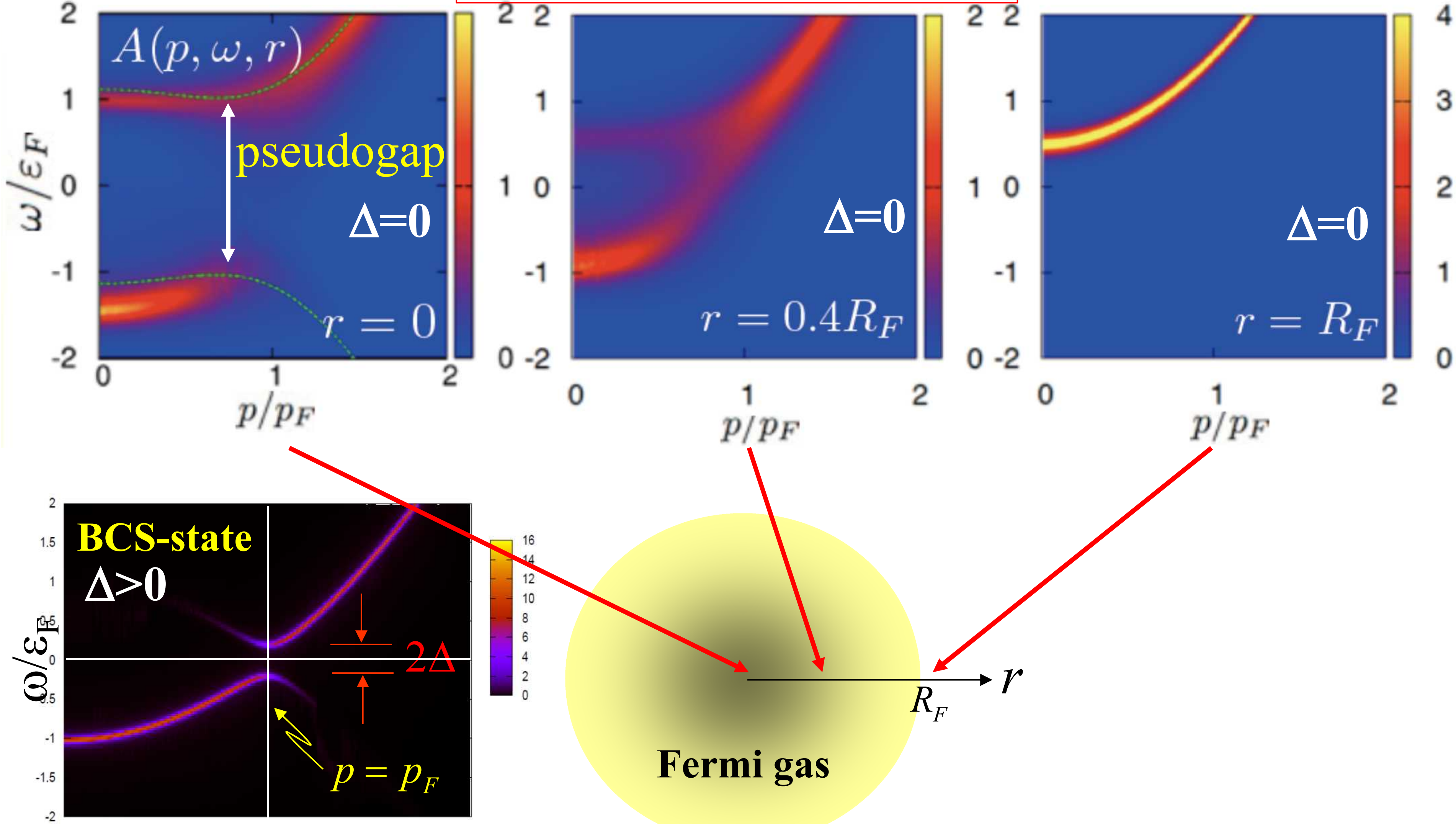


Regal, et al. PRL 92 (2004) 040403.

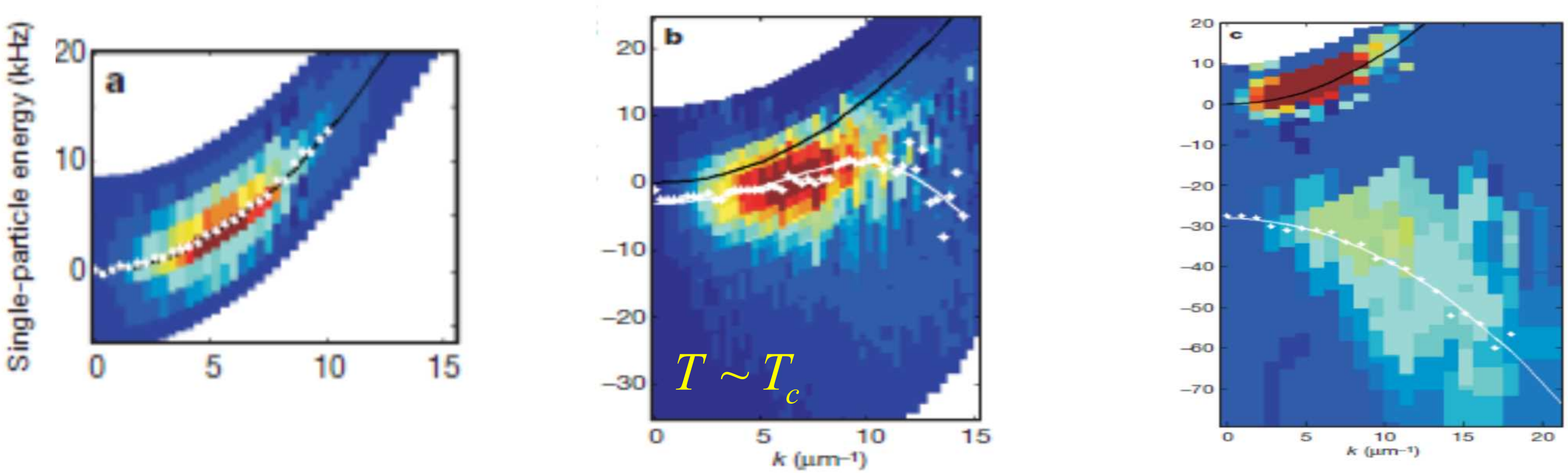
Pseudogap phenomenon at T_c (unitarity limit)

The superfluid order parameter Δ vanishes at Tc. However, one still sees a gap-like structure in the single-particle excitations (pseudogap).

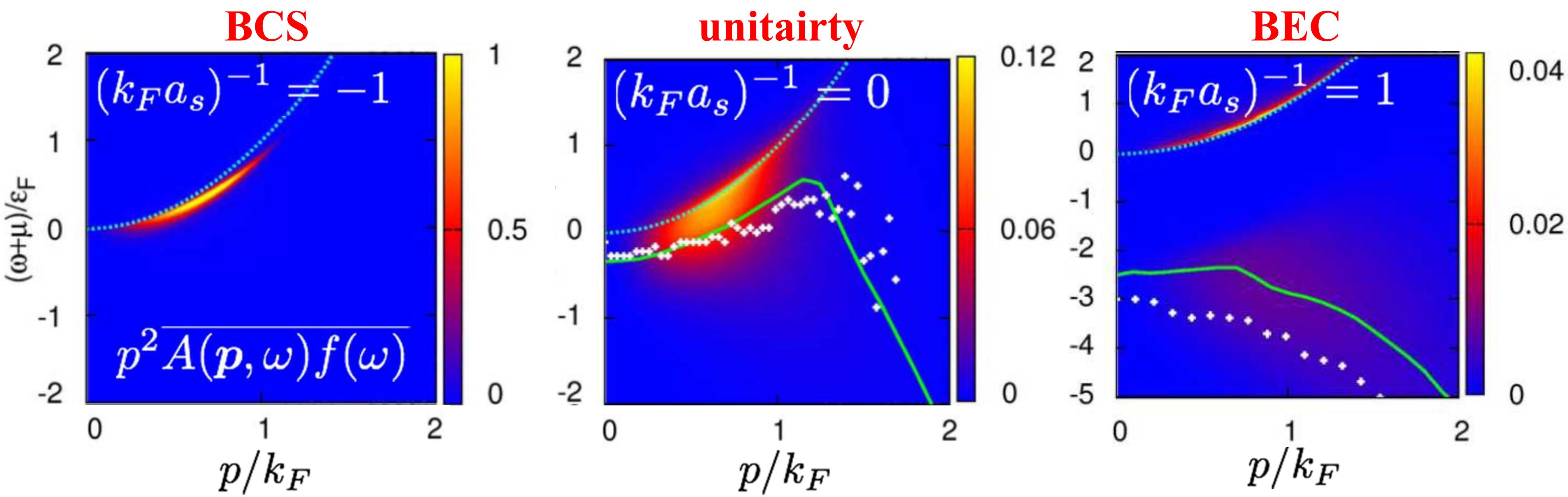
Single-particle spectral weight



Photoemission spectrum at T_c (T-matrix theory)



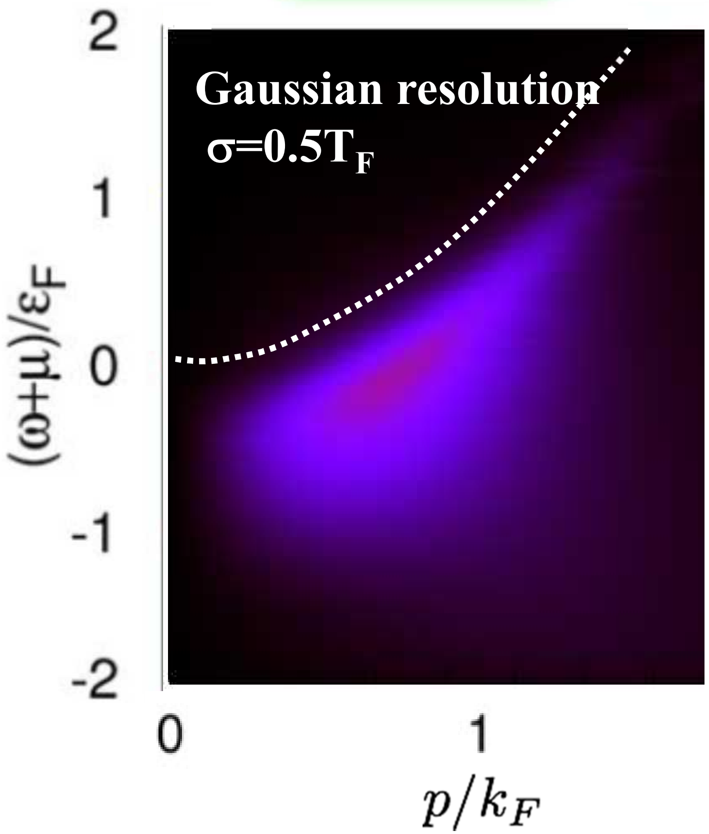
Experiment on ^{40}K: Stewart, Gaebler, Jin, Nature **454** (2008) 744



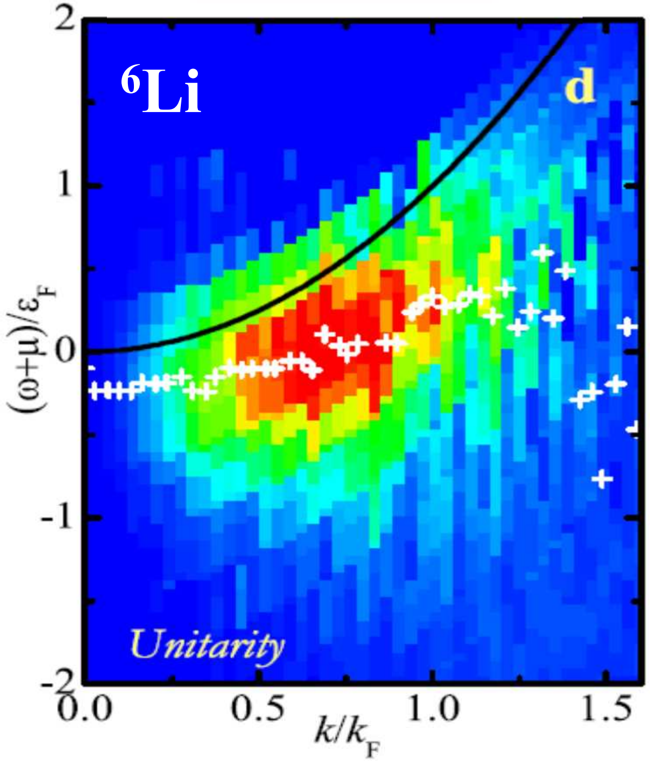
Theory: Tsuchiya, Watanabe, Ohashi, PRA 82 (2010) 033629

Photoemission spectra in the unitarity limit at T_c

our result



experiment

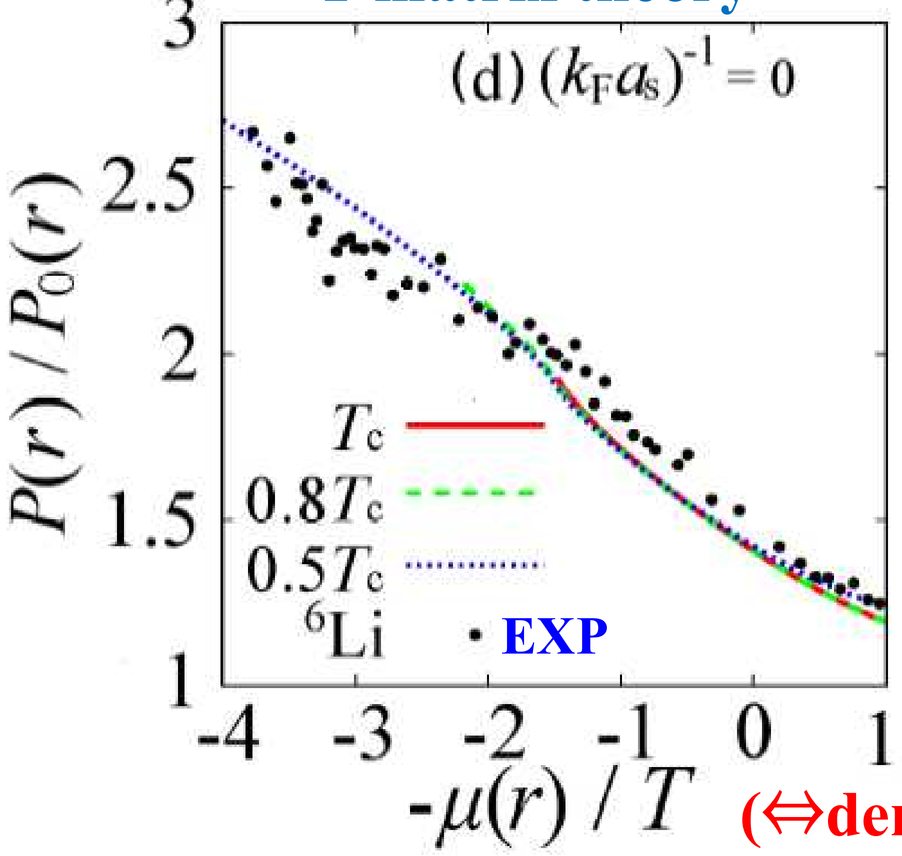


Data mapping: Hu et al., PRL 104 (2010) 240407

Tsuchiya, Watanabe, Ohashi,
PRA 82 (2010) 033629

Local pressure in the unitarity limit

T-matrix theory



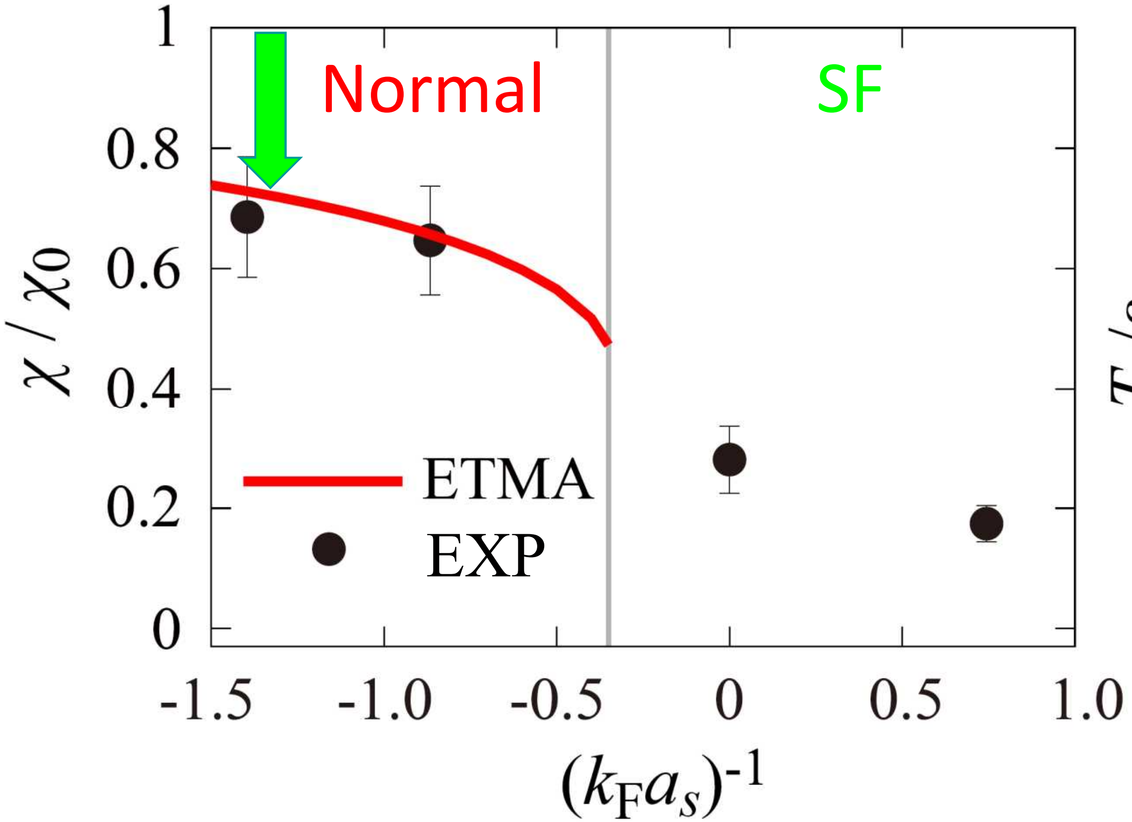
(⇔density) ⇨ **EOS**

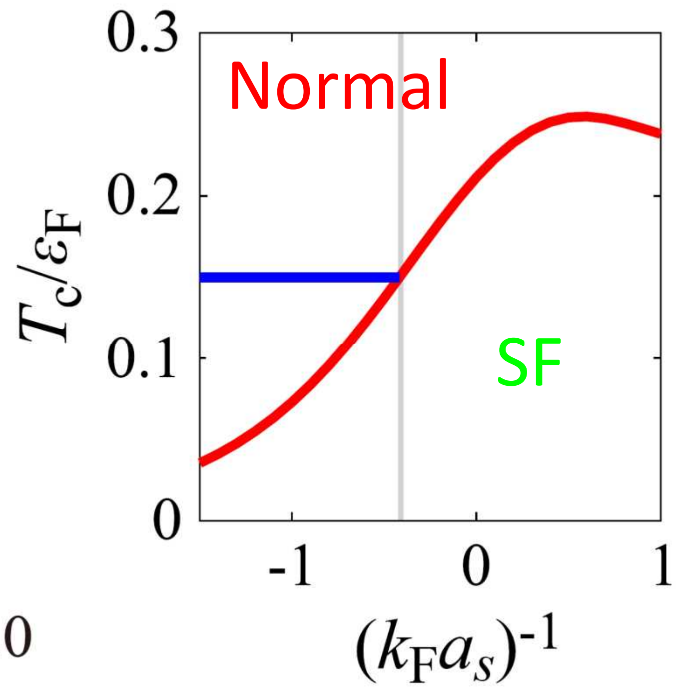
"Universal thermodynamics"

Theory: Watanabe, Ohashi, et al., PRA 86 (2012) 063603.

Experimental data: S. Nascimbene, *et al*, NJP **12** (2010), 103026

spin susceptibility in the normal state (extended T-matrix approximation: ETMA)

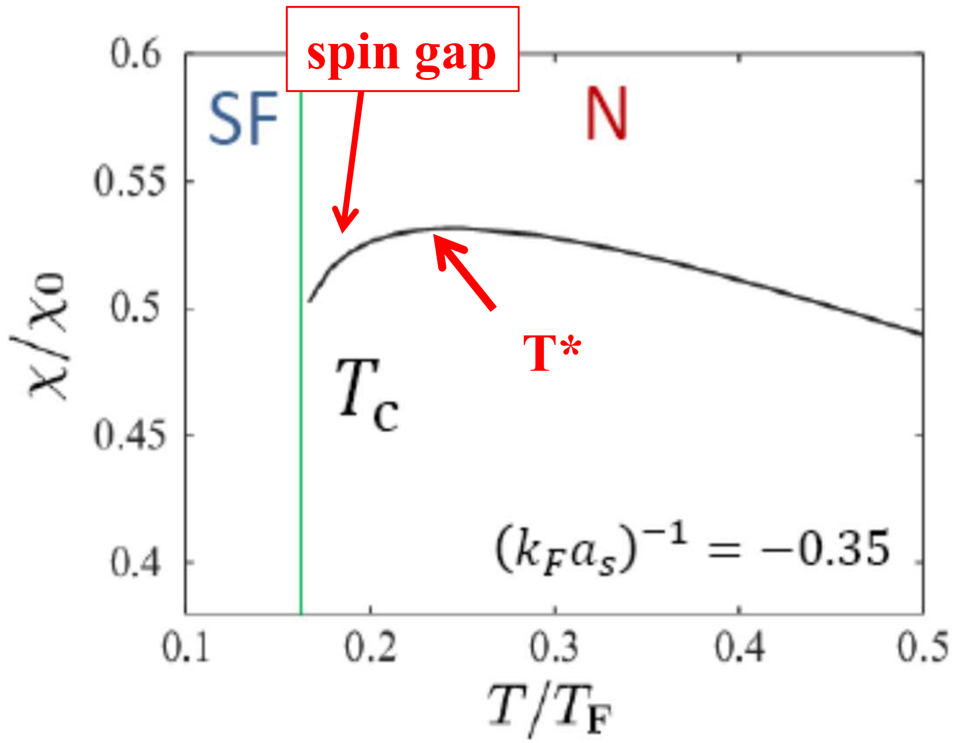




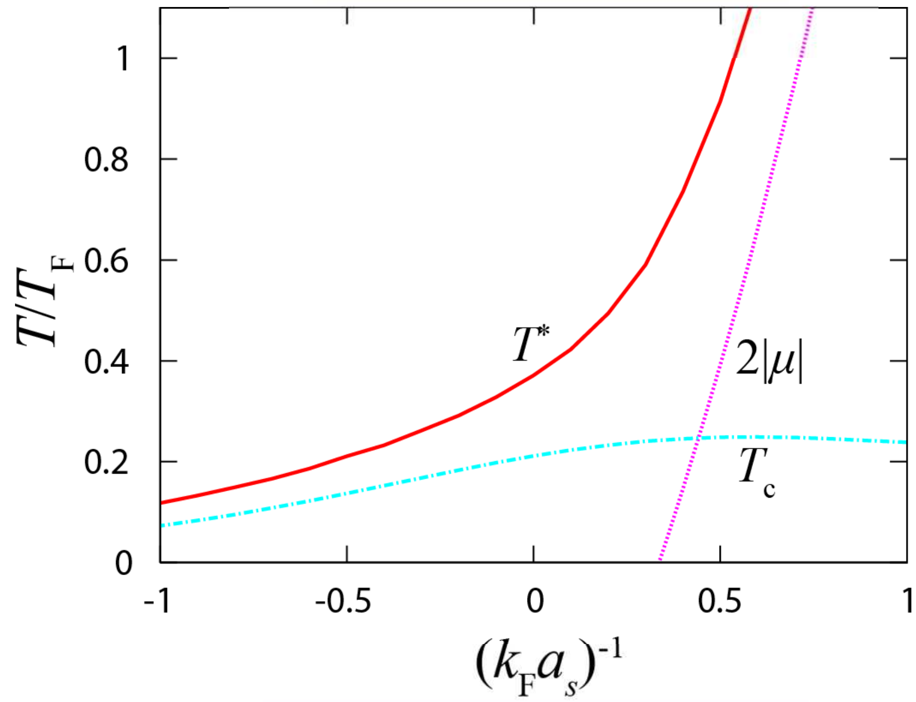
Theory: Kashimura, Ohashi et al., PRA 86 (2012) 043622

experimental data: MIT, PRL 106 (2011) 010402

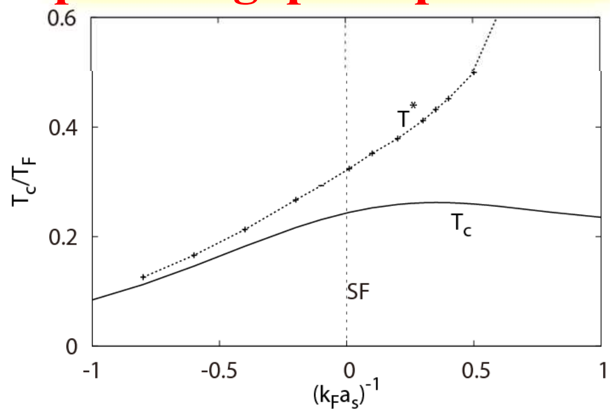
Spin gap phenomenon (ETMA)



T* Spin gap temperature

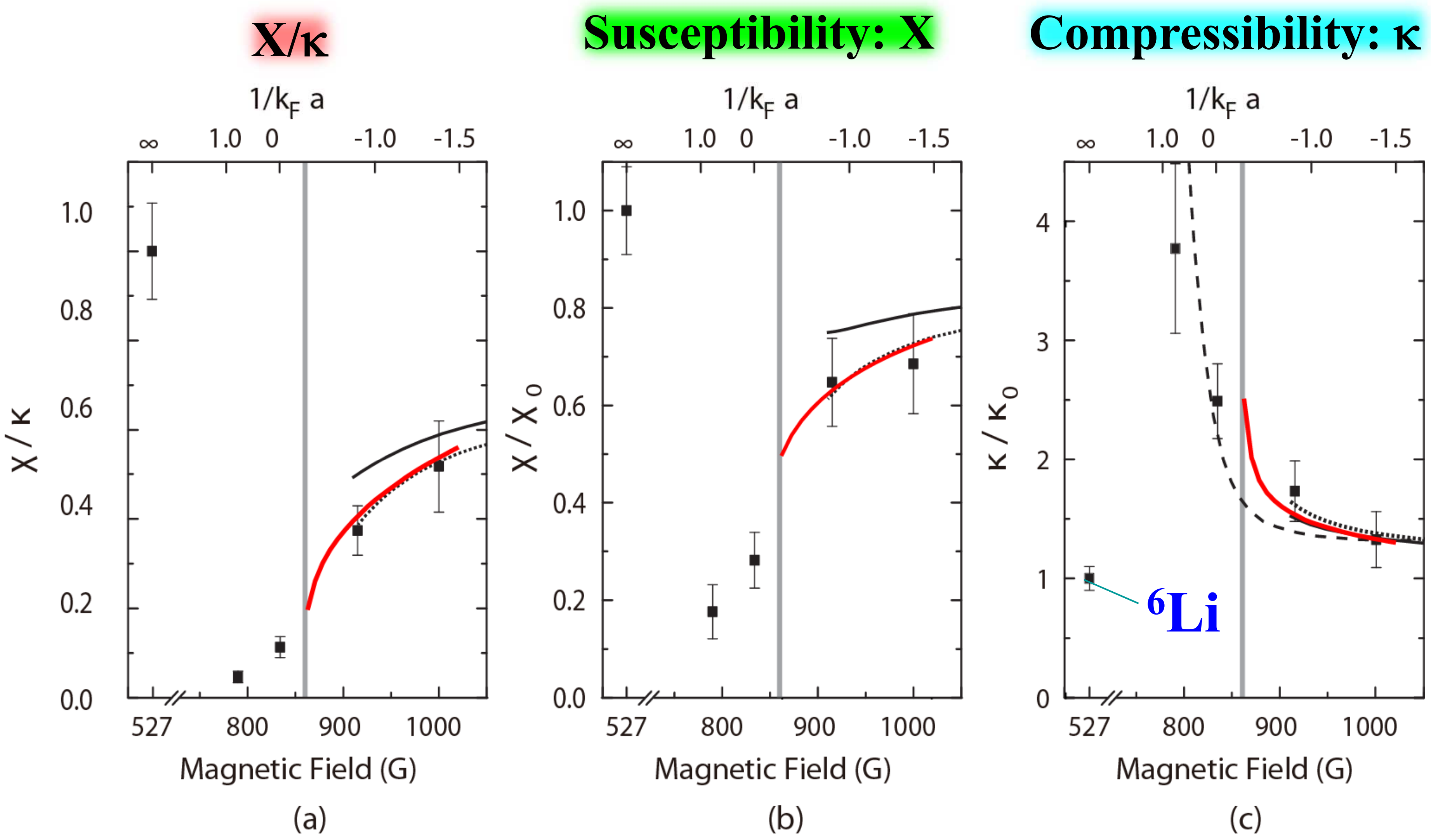


pseudo-gap temperature



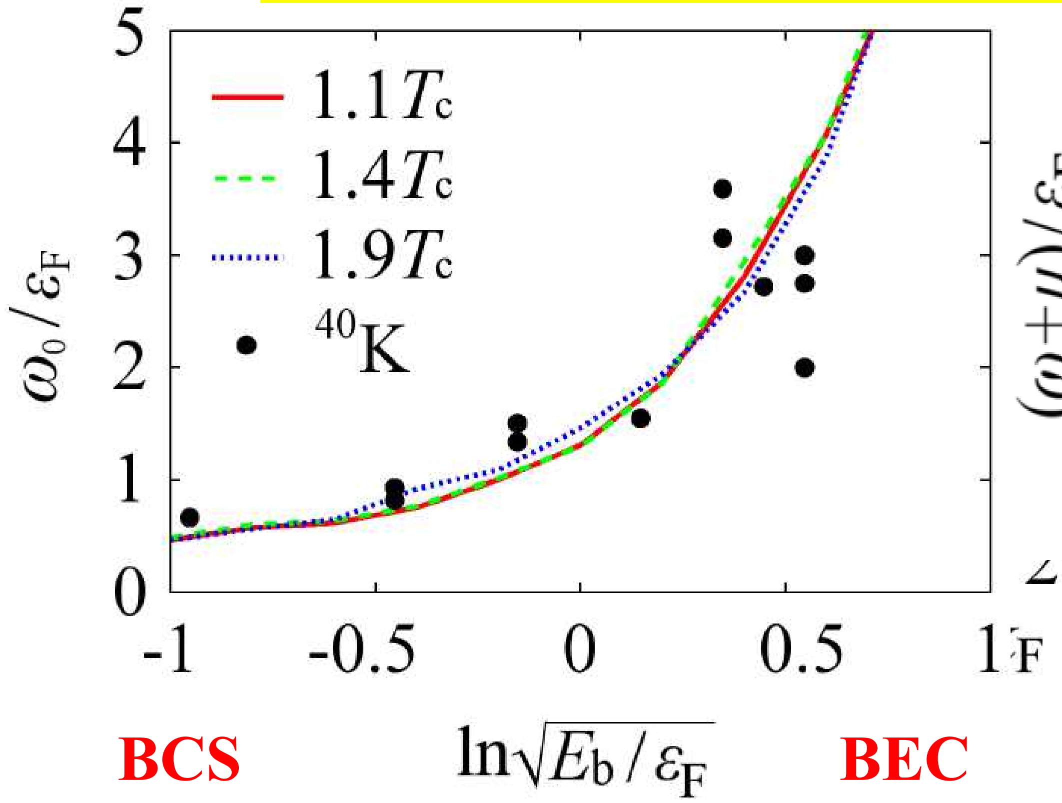
Tajima, Hanai, Ohashi, in preparation (2013)

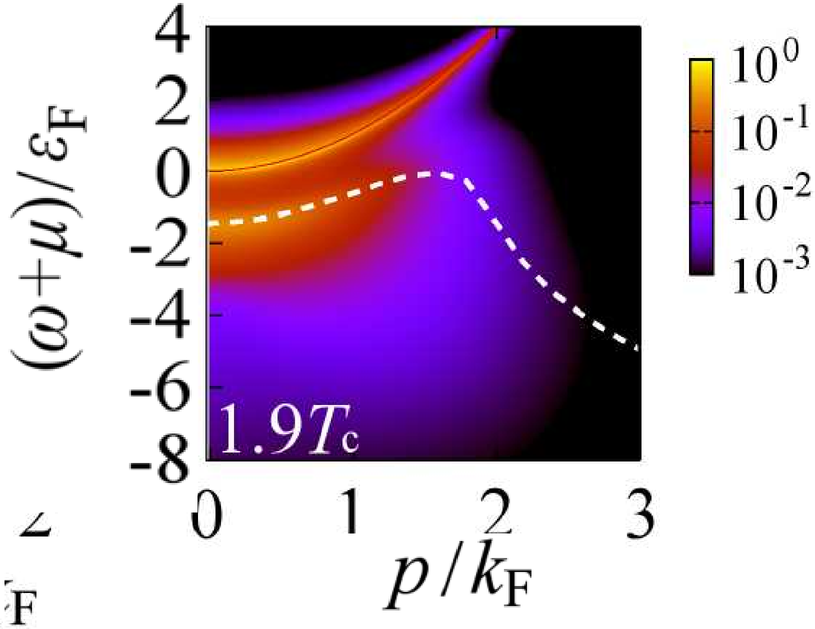
Compressibility in the crossover region (ETMA)



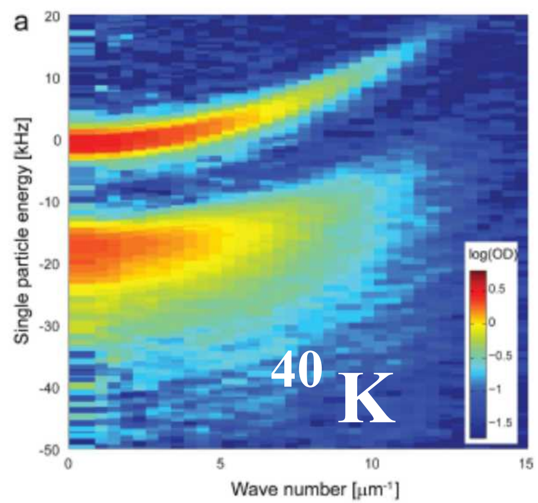
Tajima, Hanai, Ohashi, in preparation (2013)

Pseudogap size in a trapped 2D Fermi gas





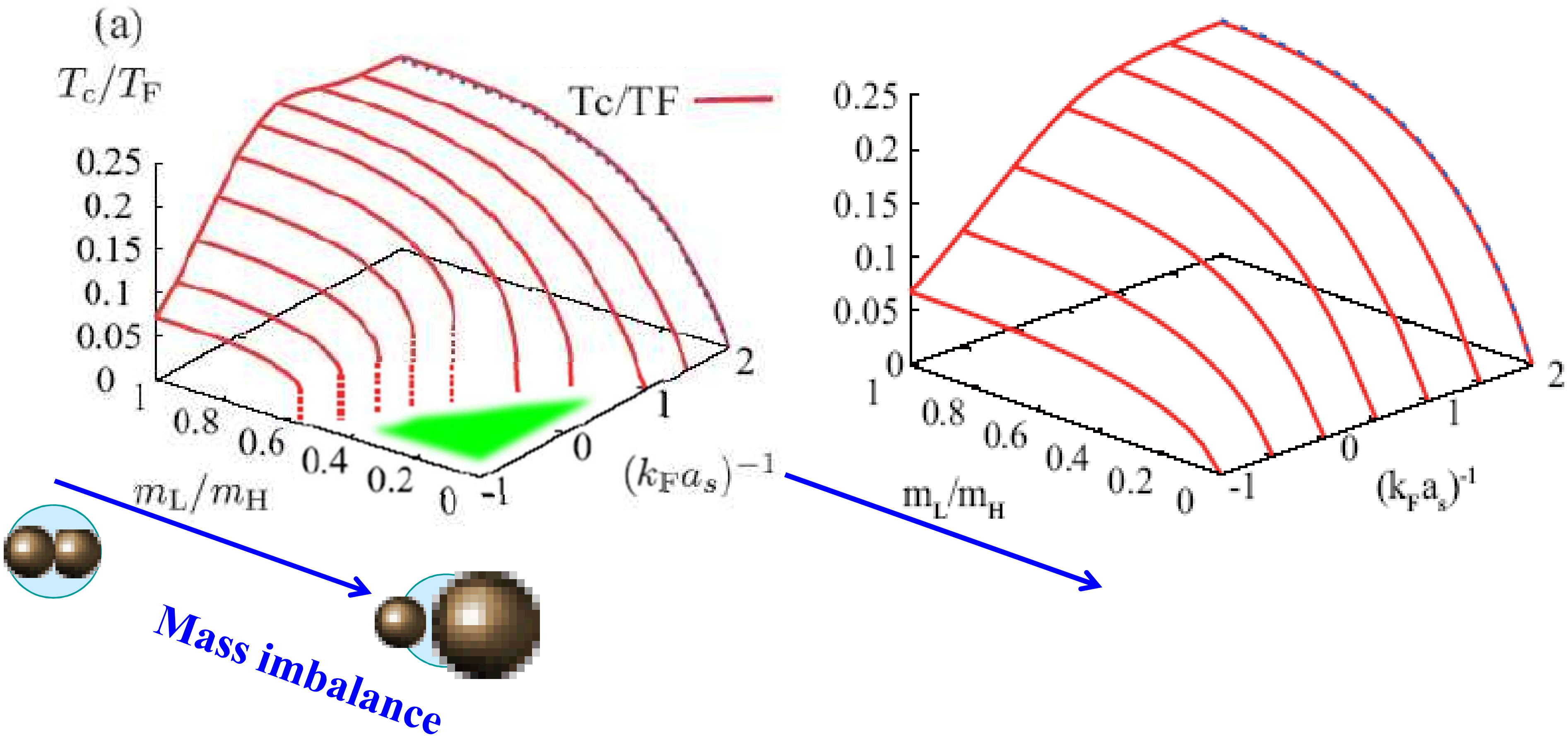
Watanabe, Tsuchiya, Ohashi,
PRA 88 (2013) 013637



Feld, *et al*. Nature 480. 75 (2011).

Mass-imbalanced Fermi gas: From the extended T-matrix approximation to self-consistent T-matrix theory (SCTMA)

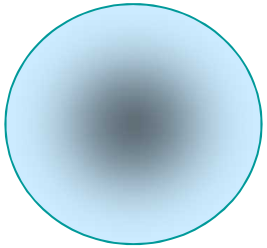
Extended T-matrix theory | **Self-consistent T-matrix theory**



Hanai, Ohashi, in preparation (2013)

Summary

BCS-BECクロスオーバー領域におけるフェルミ超流体の熱力学と超流動物性



Fermi gas

quantum simulator

- neutron star
- superconductivity
- exciton-polariton
- strongly-correlated system
- ……

experiment

- Tc
- single-particle excitations
- local pressure
- spin susceptibility
- compressibility
- specific heat

theory

$T \geq T_c$