Novel Quantum Phases in 2D ^{3}He on Graphite

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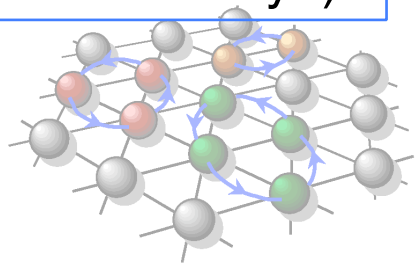
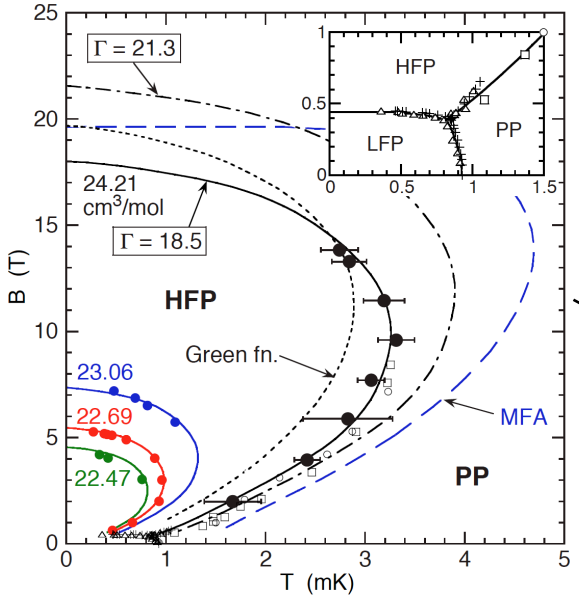
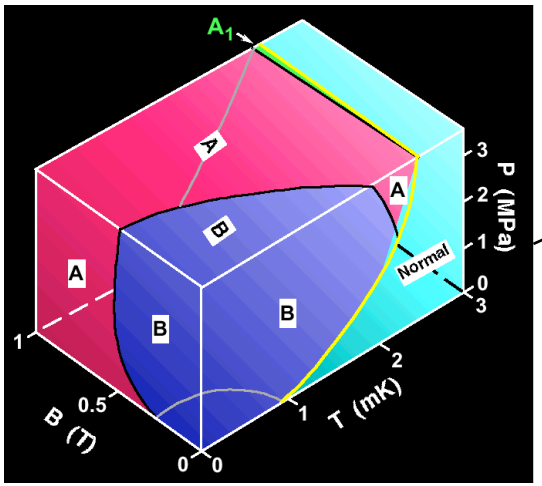
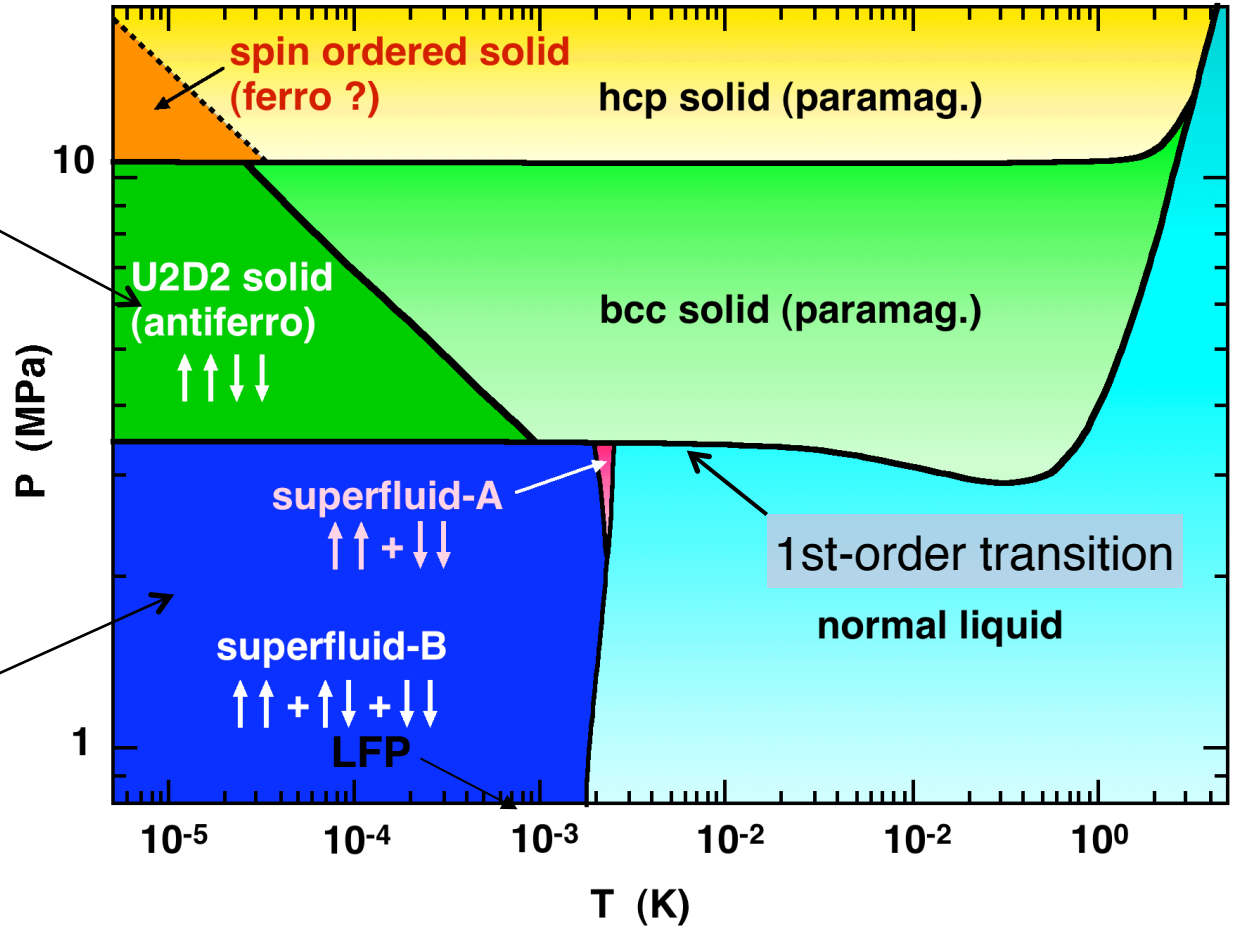
- Shintaro **Takayoshi** (ISSP Univ. of Tokyo)



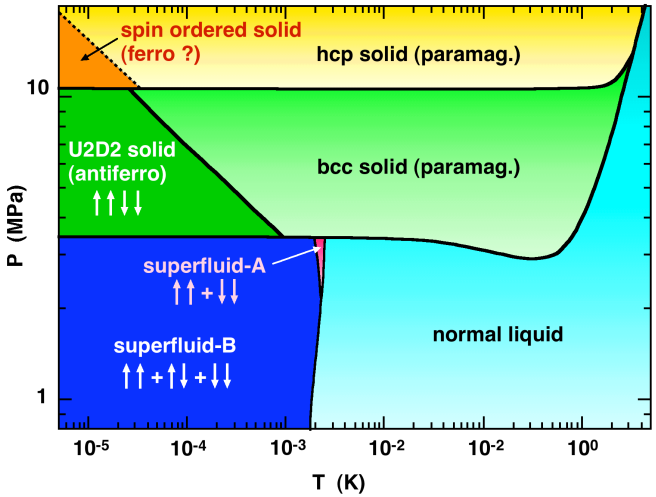
Rich phase diagram of 3D ^{3}He



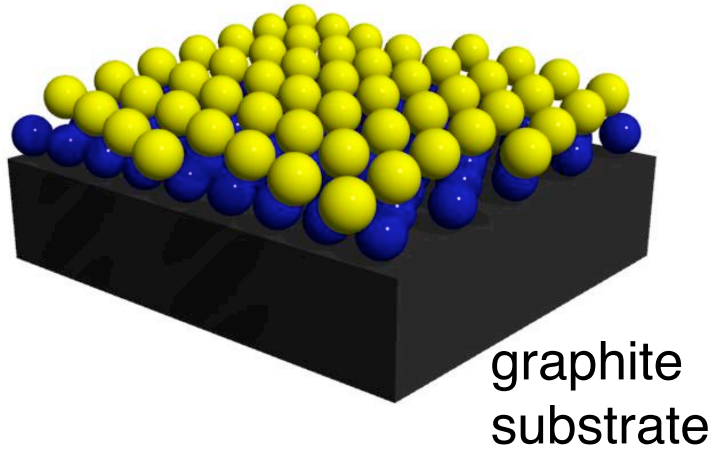




How rich is the phase diagram of 2D ^{3}He compared to 3D ?



3D ^{3}He



2D ^{3}He

expectation

Larger frustration

- exotic ground-state?
  (2D superfluid phase, spin liquid, …)
- quantum criticality?

concern

Substrate effects

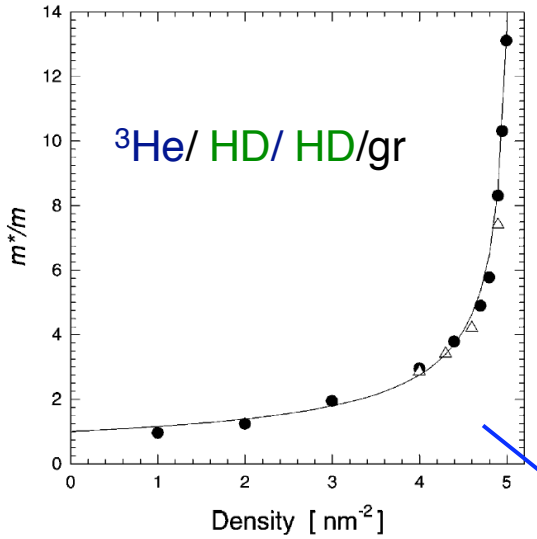
- irregularity?
- finite size effects?
- *quasi* two-dimensionality?

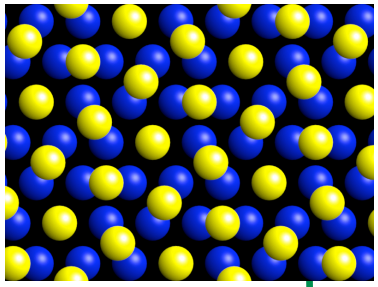
Previously known phase diagram of 2nd layer ^{3}He on graphite

Mott-Hubbard transition

A. Casey et al., PRL **90**, 115301 (2003)

Diverging m^* towards localization

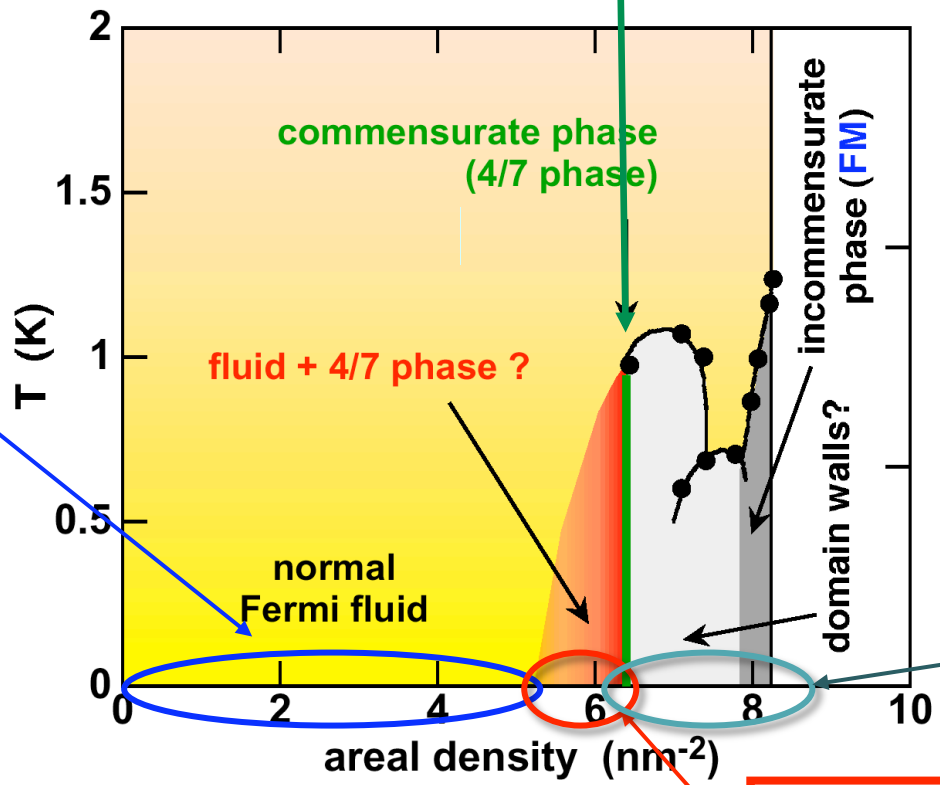


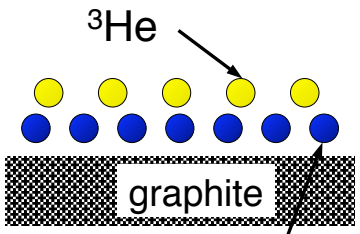


4/7 phase
(possible gapless QSL)

low-density quantum solid
with a triangular lattice

Elser, PRL **62**, 2405 (1989)
Piece&Manousakis, PRB **59**, 3802 (1999)





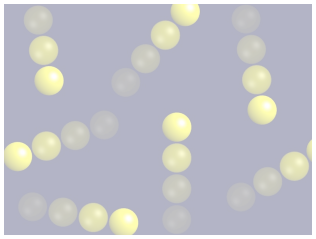
solid ^{3}He or ^{4}He

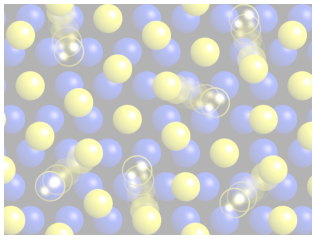
Detailed P.D.?

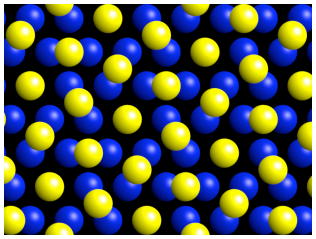
Really two-phase coexistence?
or quantum critical behavior?

D.S. Greywall, PRB **41**, 1842 (1990)

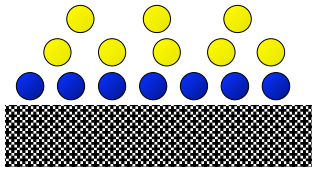
Phase diagram of 2D ^{3}He (2nd layer) at higher densities







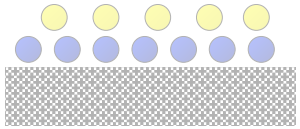
3-4-5 layers systems



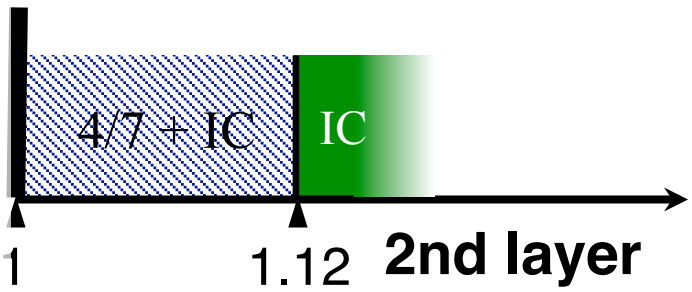
Fermi fluid

ZPV phase?

4/7 phase



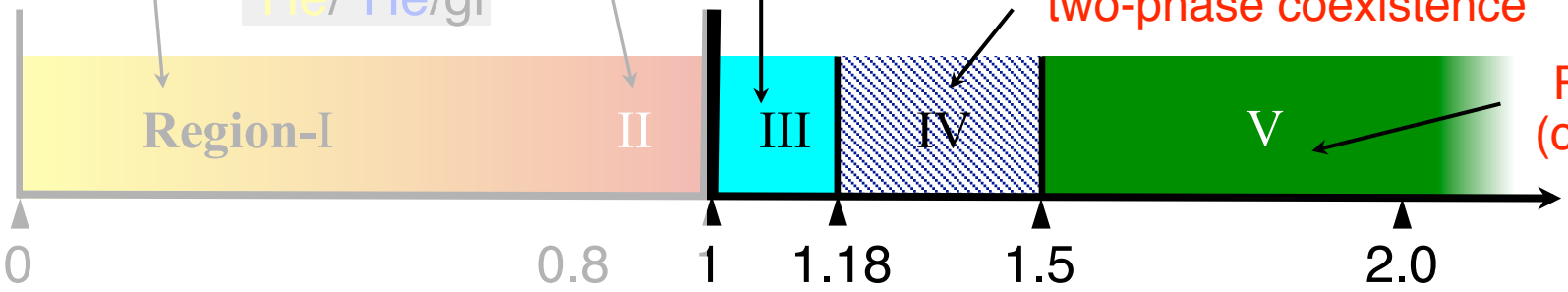
^{3}He/^{4}He/gr



3rd layer promotion

two-phase coexistence

FM IC-phase
(compressible)

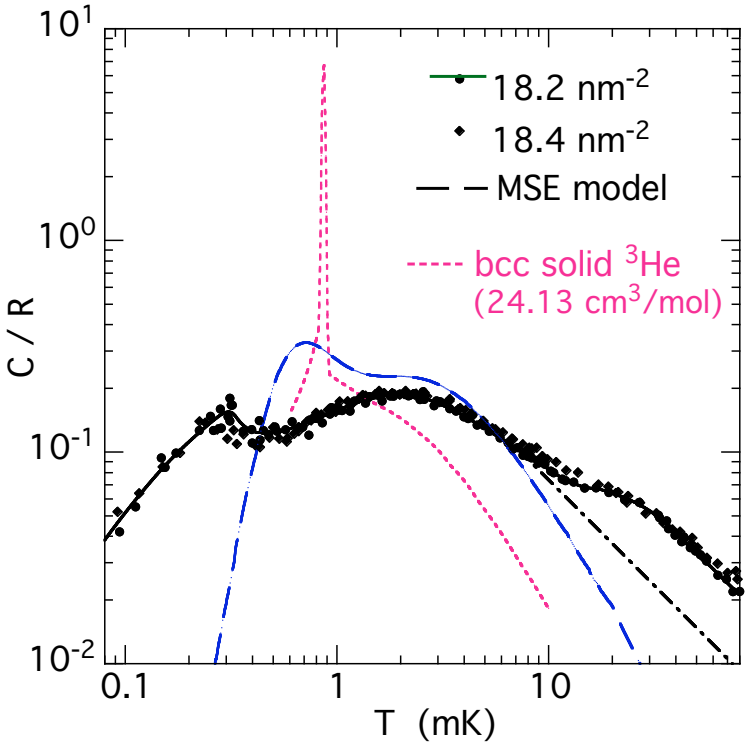


total ^{3}He density ($n \equiv \rho/\rho_{4/7}$)

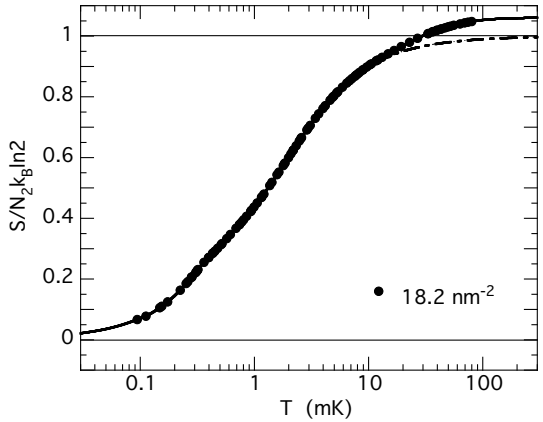
Gapless spin-liquid behavior in 4/7 phase

- Absence of finite-T phase transitions … truly 2D
  down to $T/J \approx 10^{-2}$-10^{-3} (J = 1-10 mK)
- Double peak in $C(T)$ … highly frustrated
- No exponential behaviour at $T << J$ … gapless excitation

Specific heat

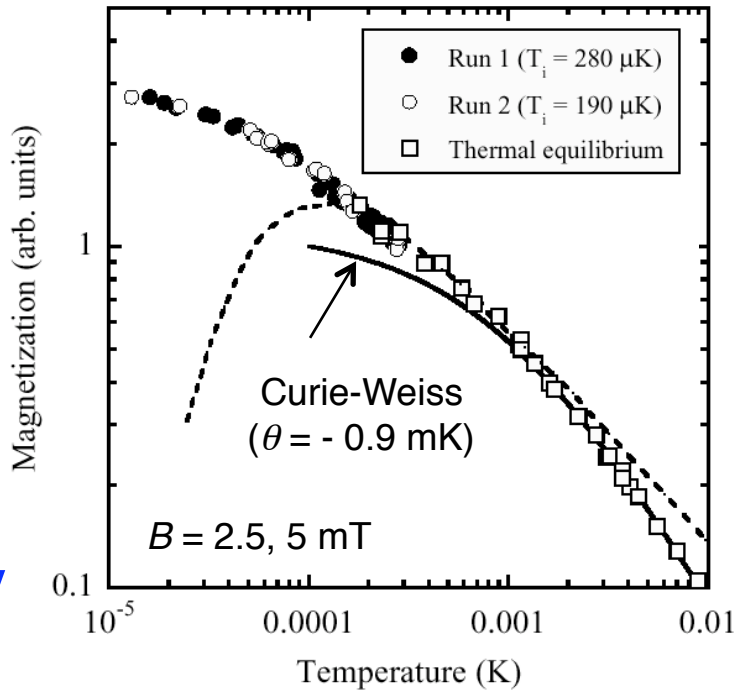


entropy



- $\Delta C(T) \approx N_2 k_B \ln 2$
  … no missing entropy

magnetization



K. Ishida et al., PRL **79**, 3451 (1997)

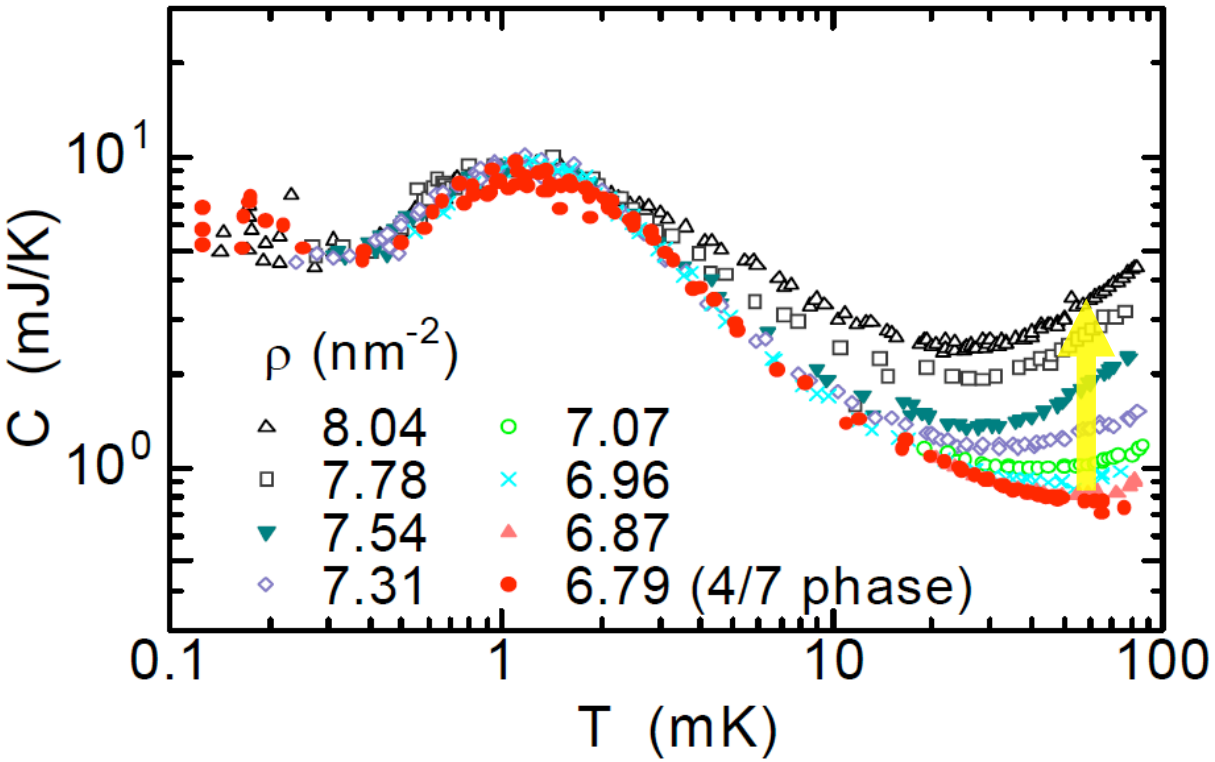
R. Masutomi, et al., PRL **92**, 025301 (2004)

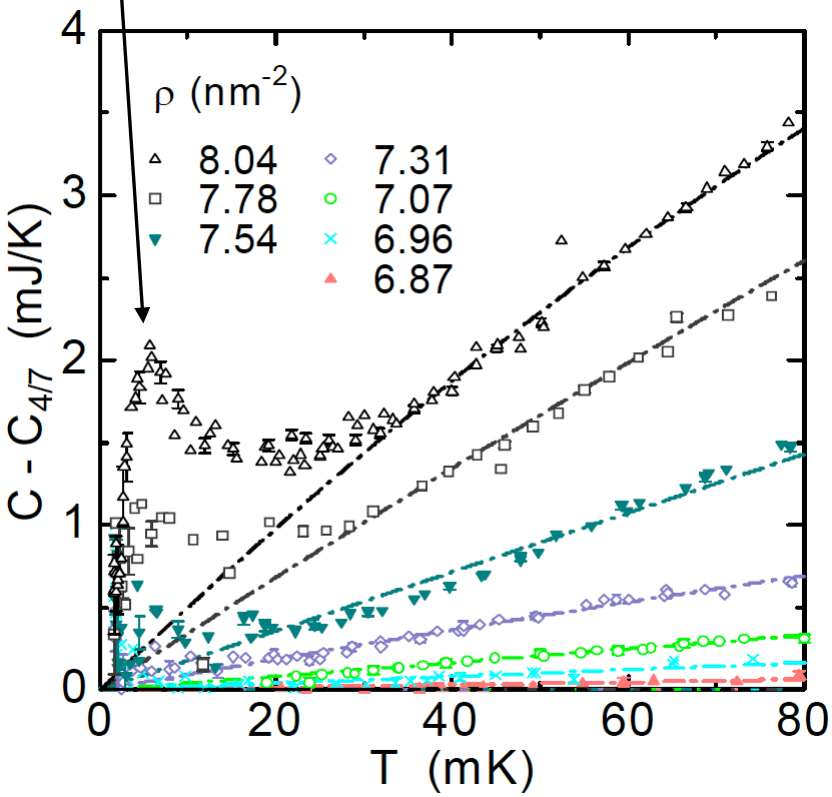
Excess heat capacities in Region III ($1 \le n \le 1.2$)

Excess heat capacities: $C_{ex} \equiv C(\rho) - C(\rho_{4/7})$

3rd-layer Fermi Liquid + ferromagnetic background

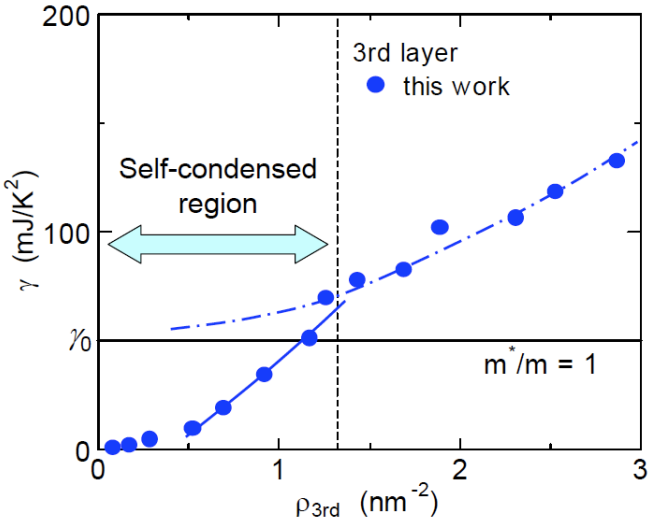
$$C(T) = \gamma T + \Gamma T^2$$

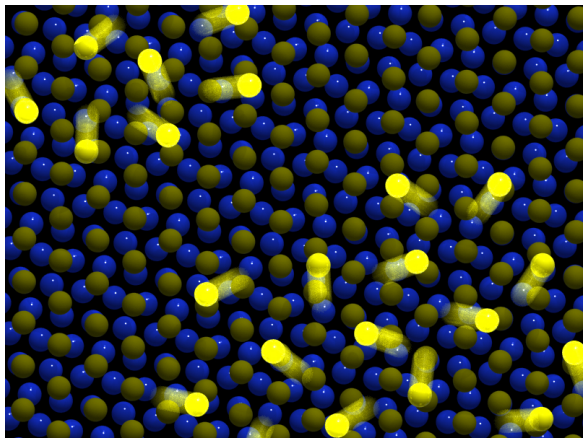




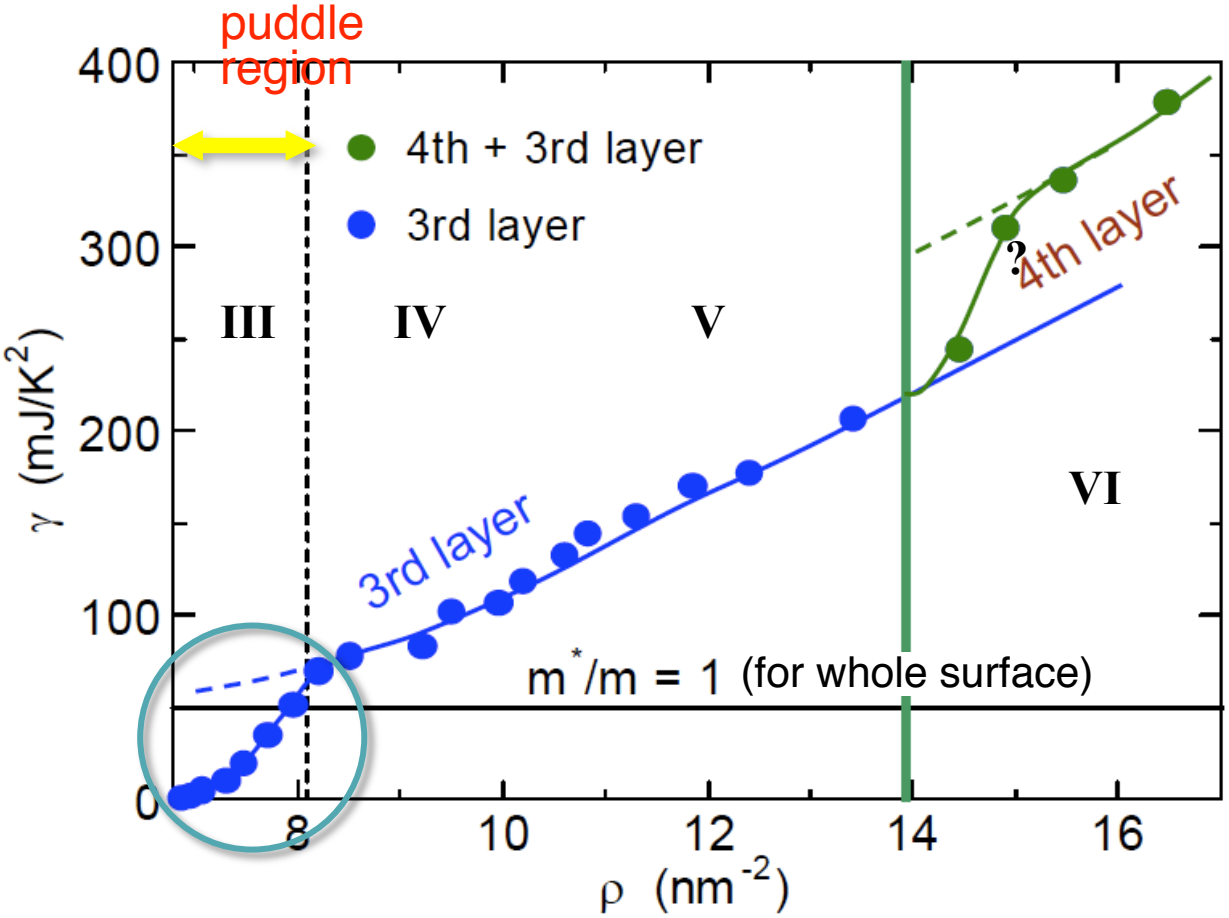
Degenerate Fermi-liquid puddles in the 3rd layer

^{3}He atoms in the 3rd layer form self-bound Fermi liquid puddles.



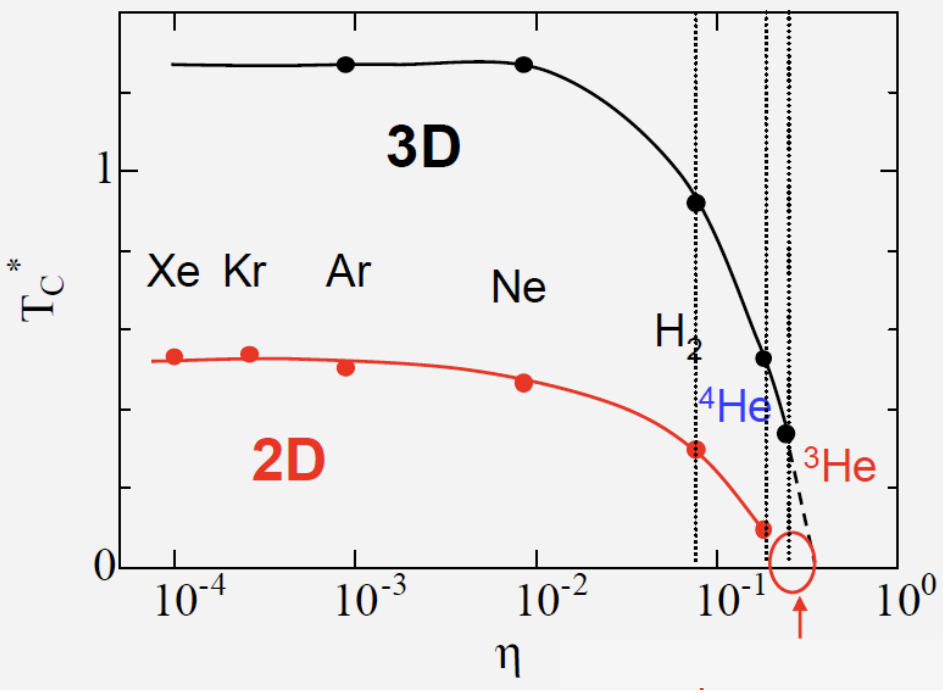


$\rho_{puddle} \approx 1.4\ nm^{-2}$



Puddle formation at layer higher than 3rd layer

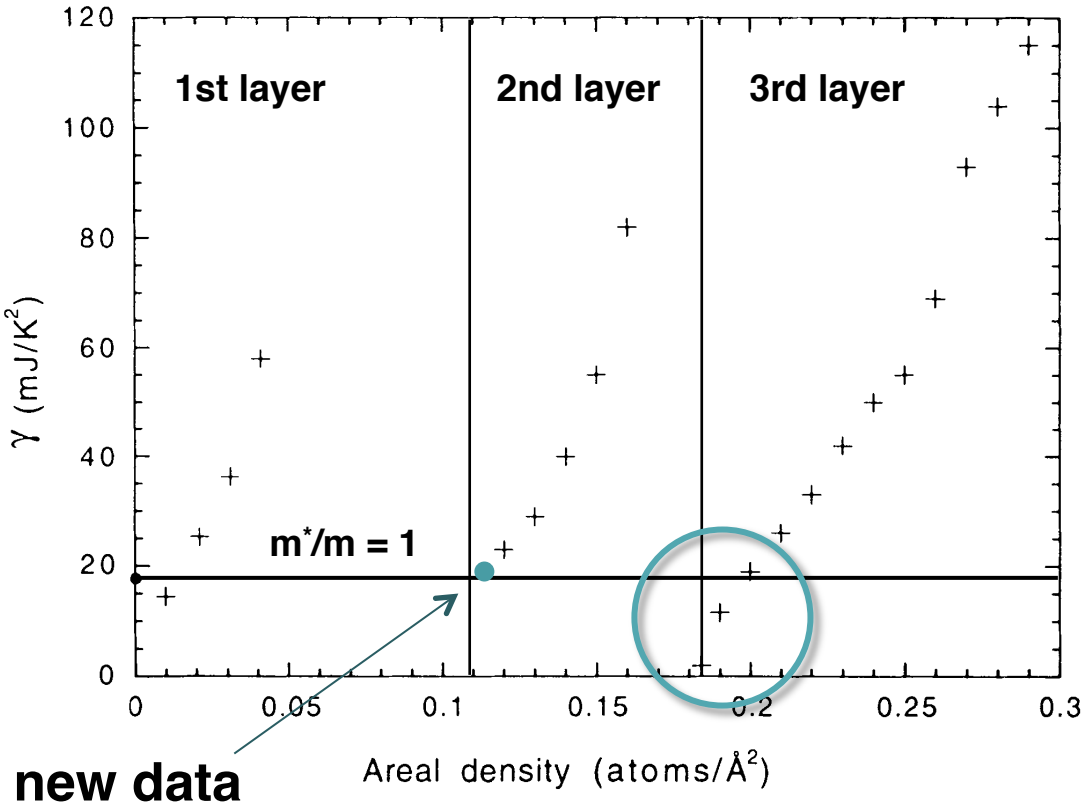
Reduced critical temperature (T_c*) of rare gases in 3D and 2D



quantum parameter:

$$\eta \equiv \frac{K}{U} = \frac{\hbar^2 / m\sigma^2}{\varepsilon}$$

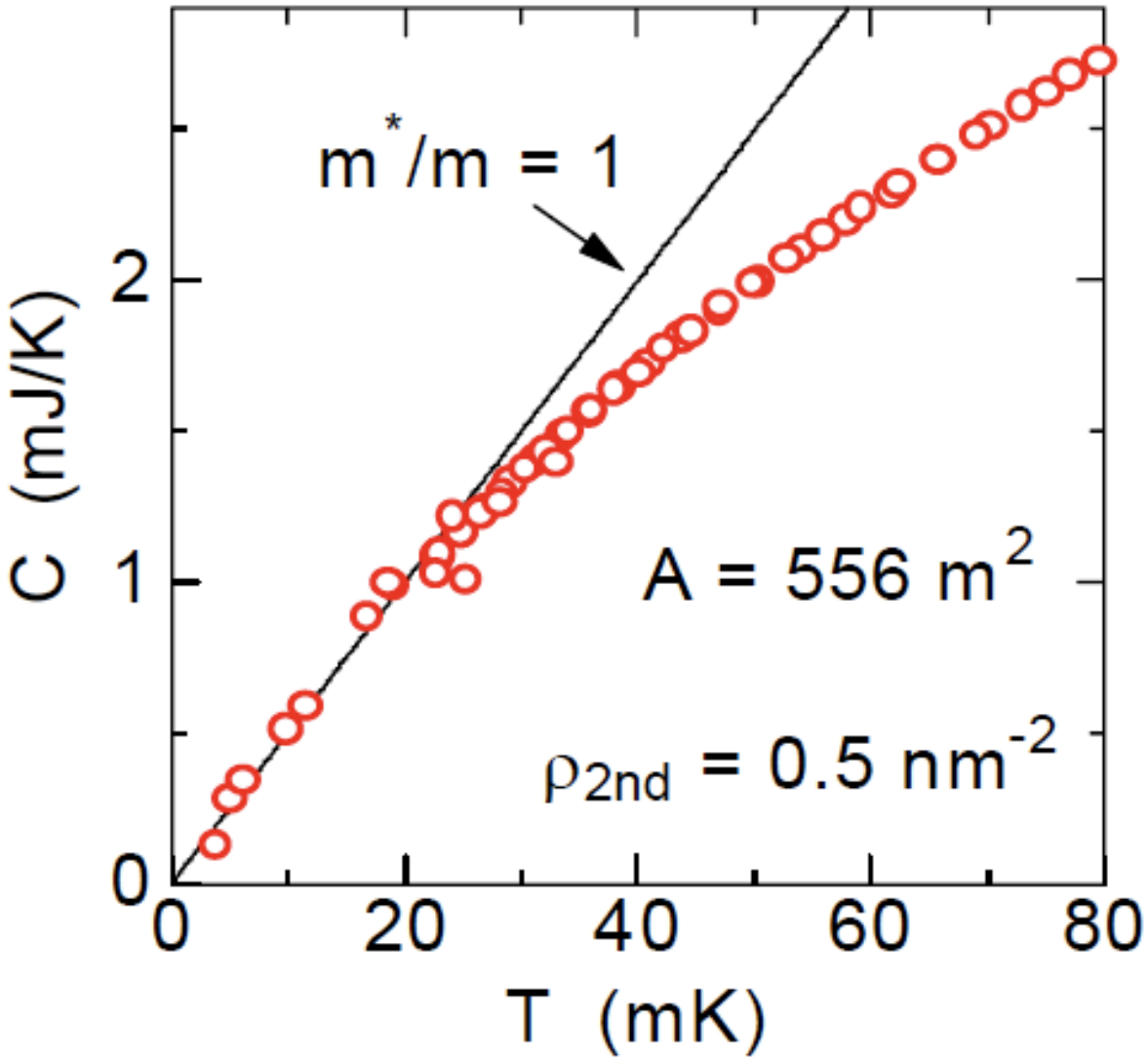
Less confinement to the 2D plane in 3rd layer allows the gas-liquid transition.



new data

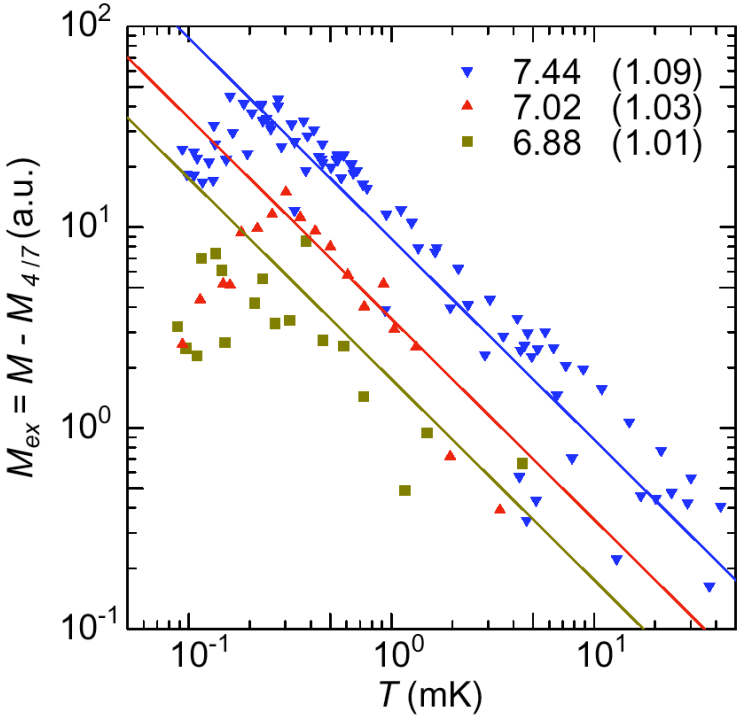
H. Godfrin et al., PRB **49**, 12377 (1994)

(exp. data from Greywall (1990))

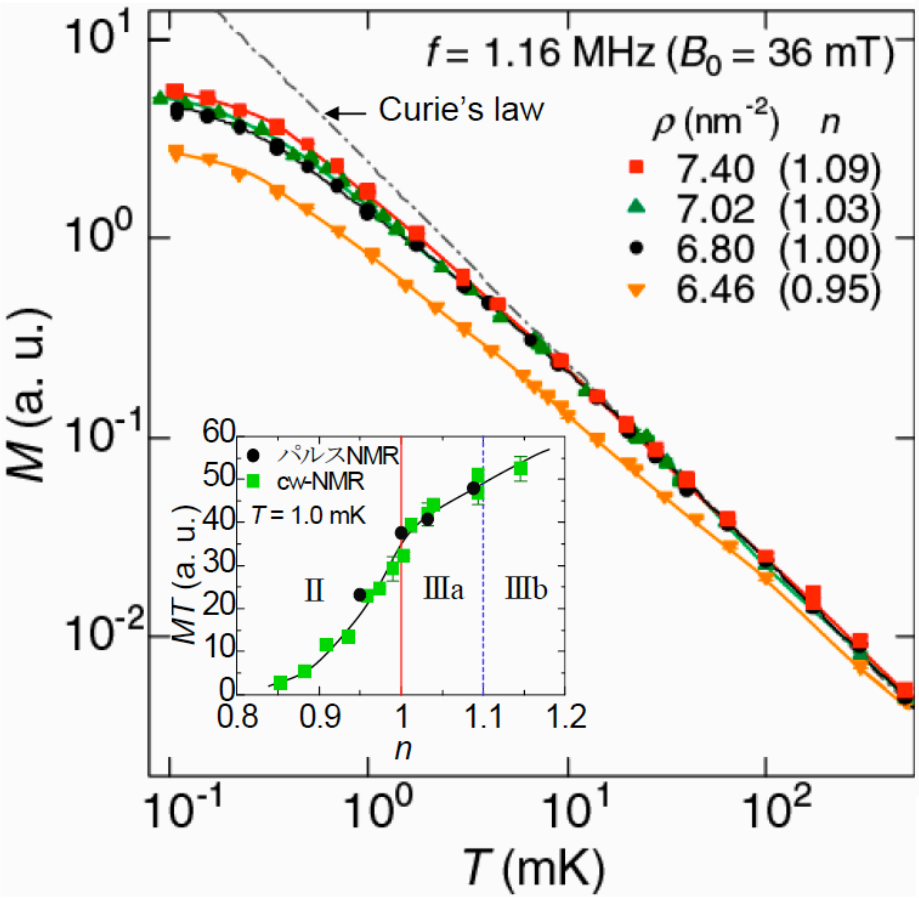

m*/m = 1
A = 556 m2
ρ2nd = 0.5 nm-2
C (mJ/K)
T (mK)
0
1
2
0
20
40
60
80

Excess magnetization in Region III ($1 \leq n \leq 1.2$)

Previous cw-NMR data show drops of excess magnetization below 0.3 mK.

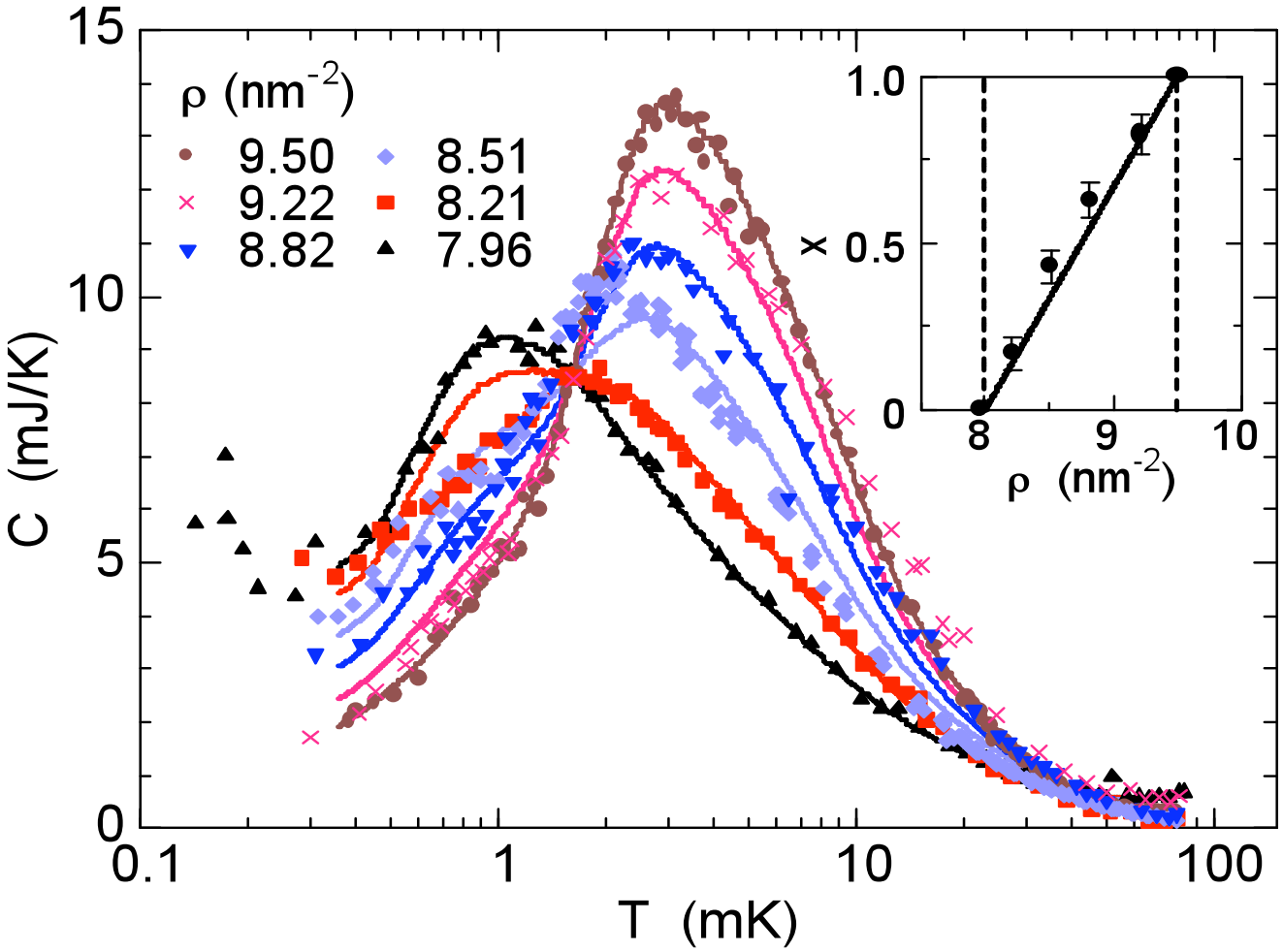


However,
new pulsed-NMR data show no anomalies.

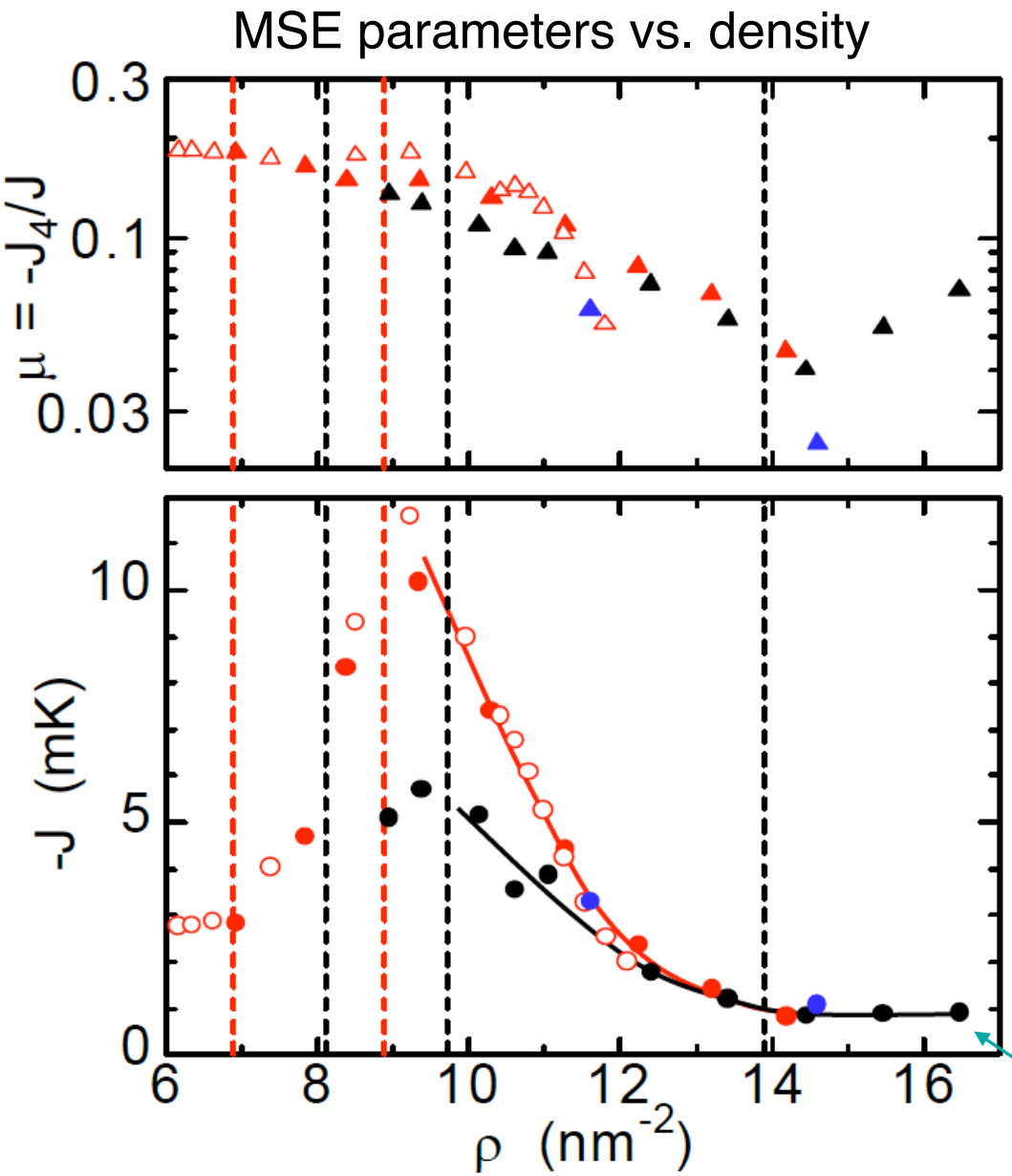


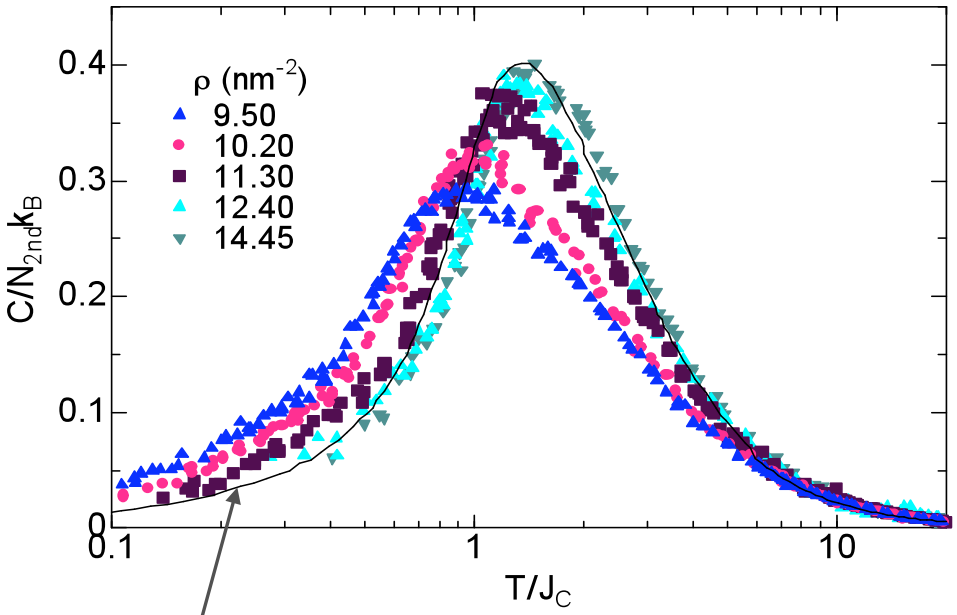
Heat capacities in Region IV ($8 \leq \rho \leq 10$ nm^{-2})

Simple **two-phase coexistence**
between 4/7 phase and IC phase



Frustration-tunable 2D ferromagnet



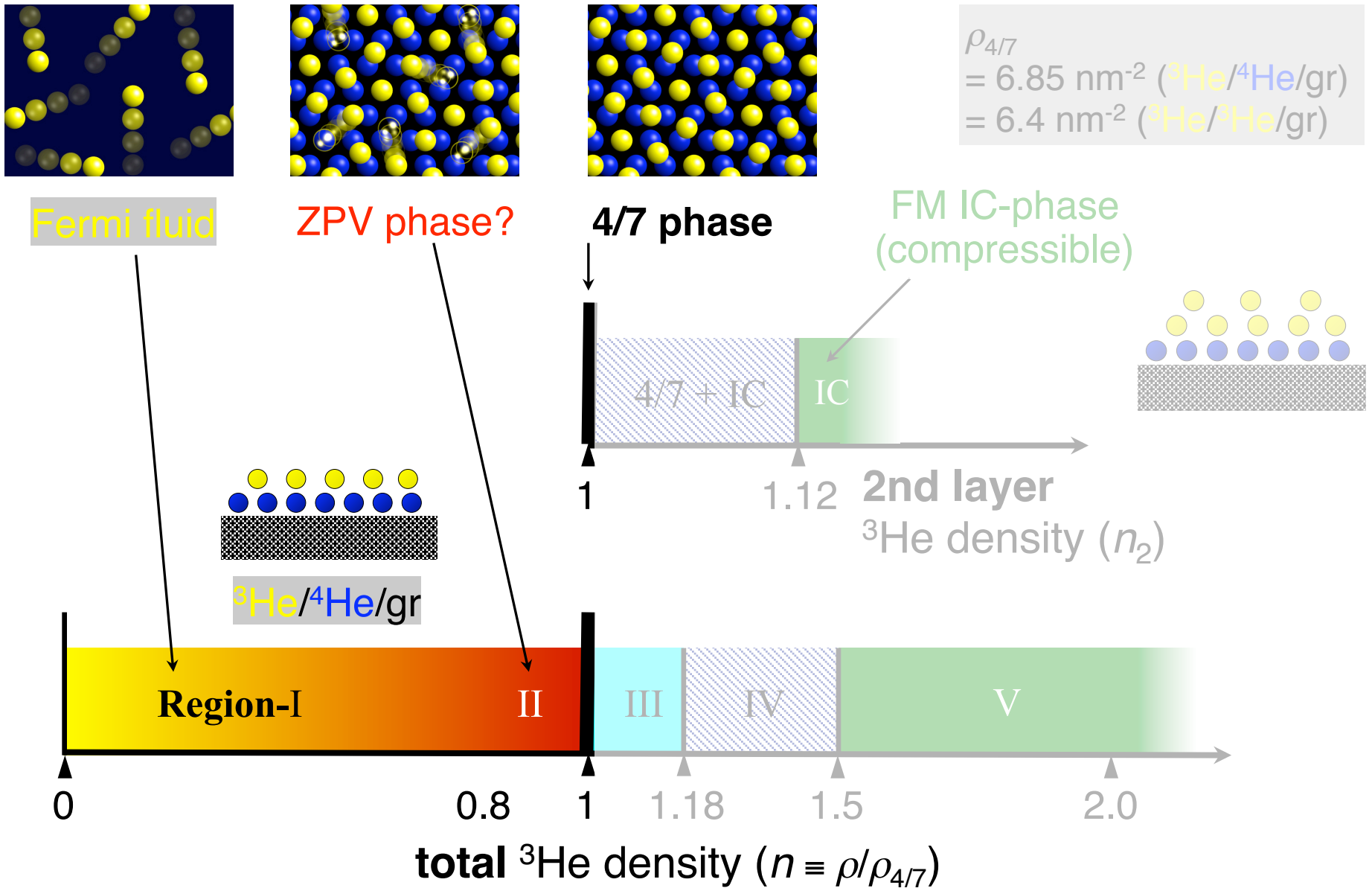


HFT model (S = 1/2 Heisenberg model on a triangular lattice)

B. Bernu and G. Misguich., PRB **63**, 134409 (2001)

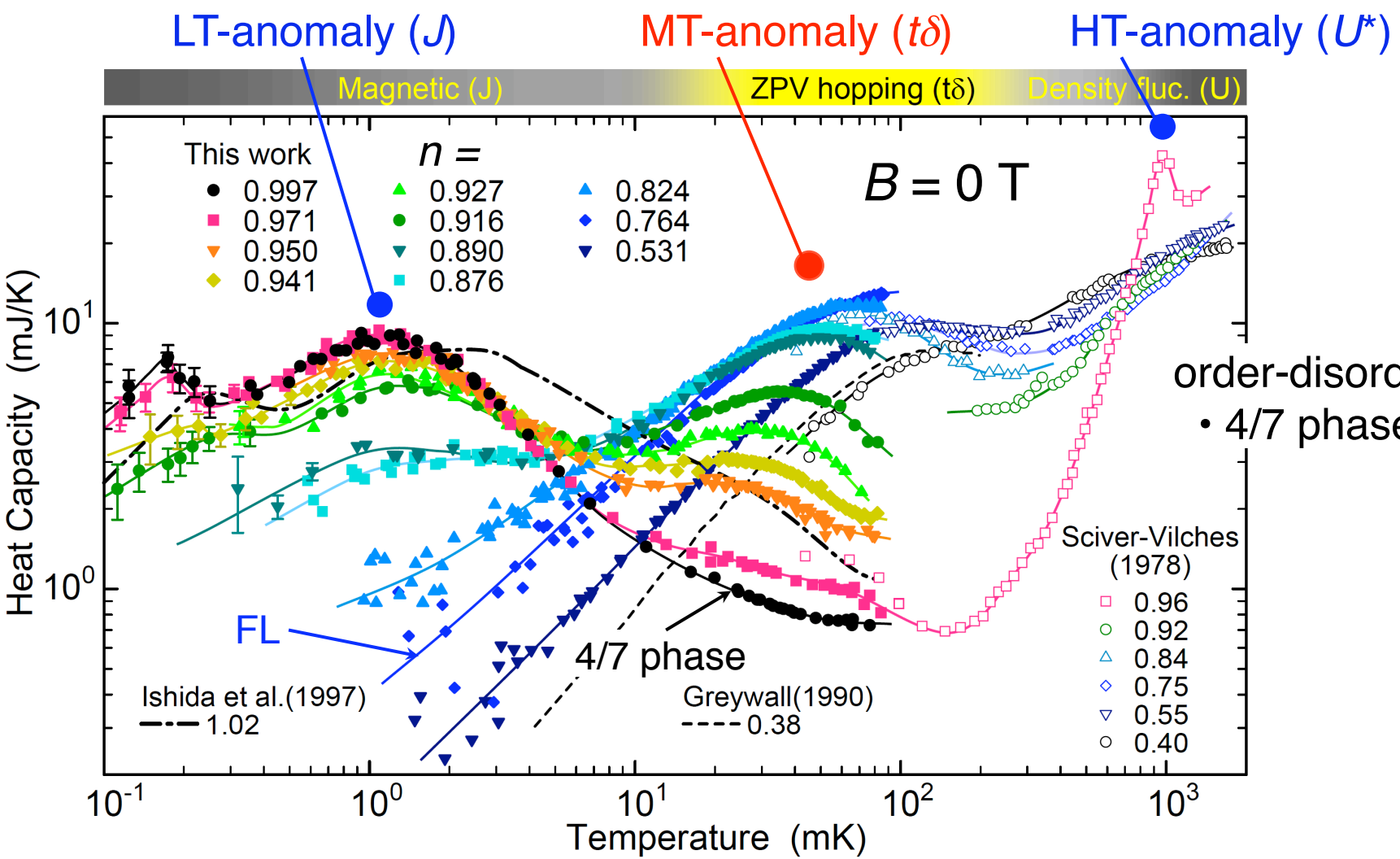
J_3 dominates at high densities.

Hole doping into 4/7 phase (Region-II)



Heat capacities in Region-II

Three distinct energy-scales over three orders of magnitude

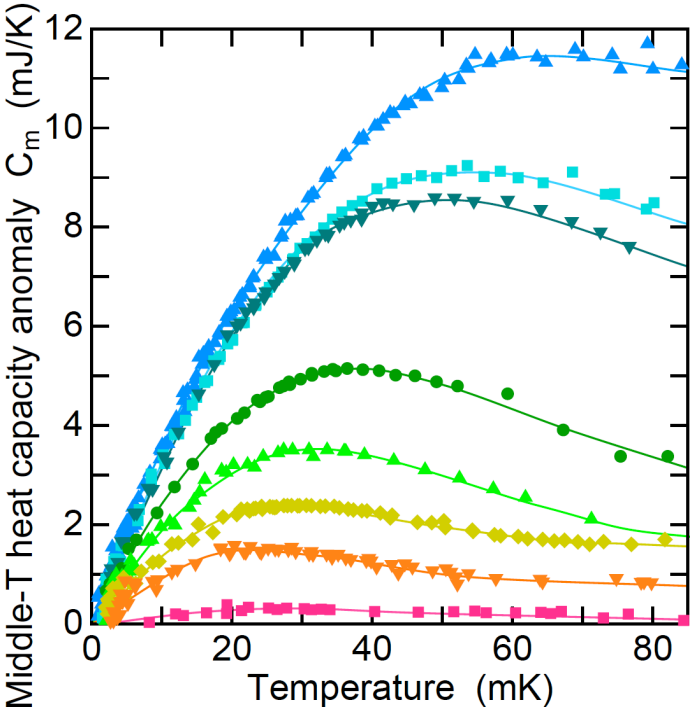


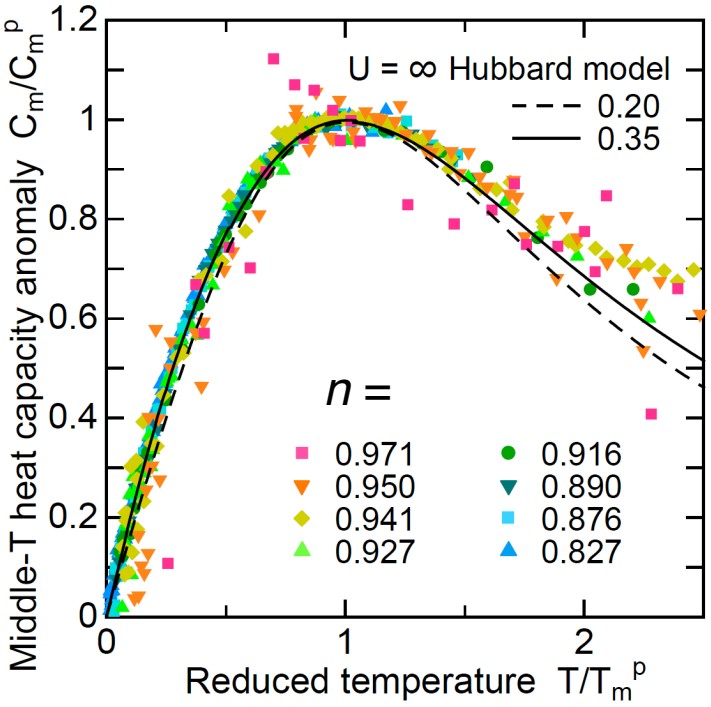
order-disorder transition
- 4/7 phase ⇆ fluid

relative density: $n \equiv \rho/\rho_{4/7}$

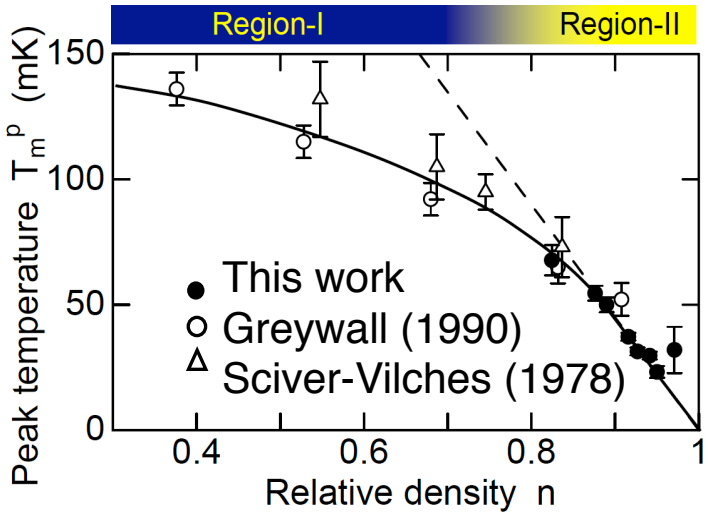
$\rho_{4/7} = 6.86\ \mathrm{nm}^{-2}$ $A = 556\ \mathrm{m}^2$

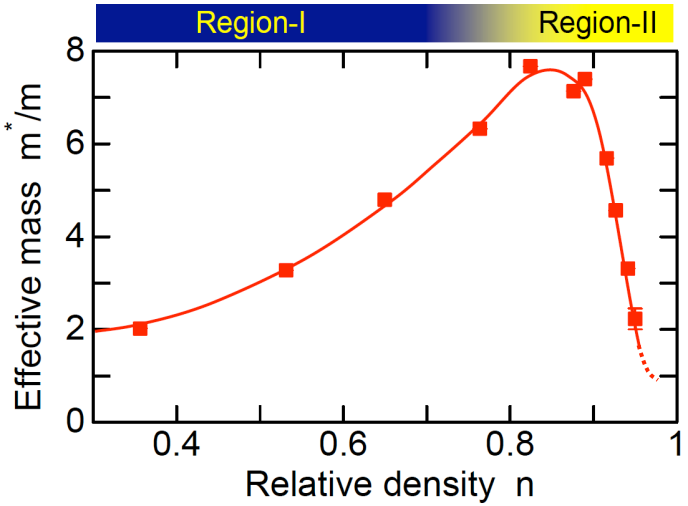
MT-anomalies of heat capacity in Region-II





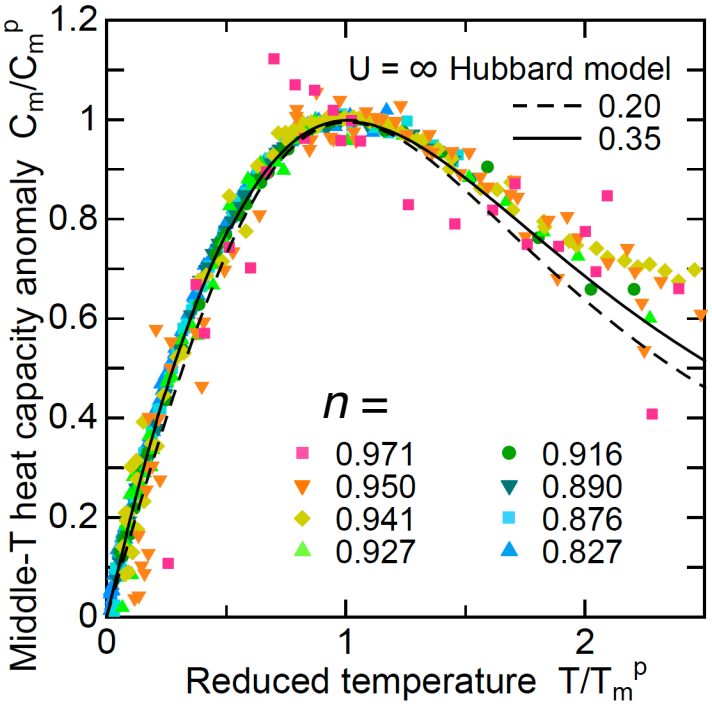
- T_m^p shifts to higher-T with decreasing n.
- C/C_m^p scales with T/T_m^p.





- $T_m^p \propto \delta \equiv (1 - n)$
- γ value turns around at $n \approx 0.8$.

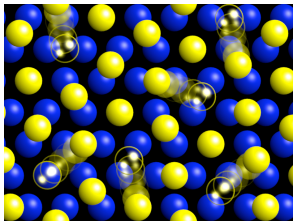
2D hole (ZPV) band picture for Region-II

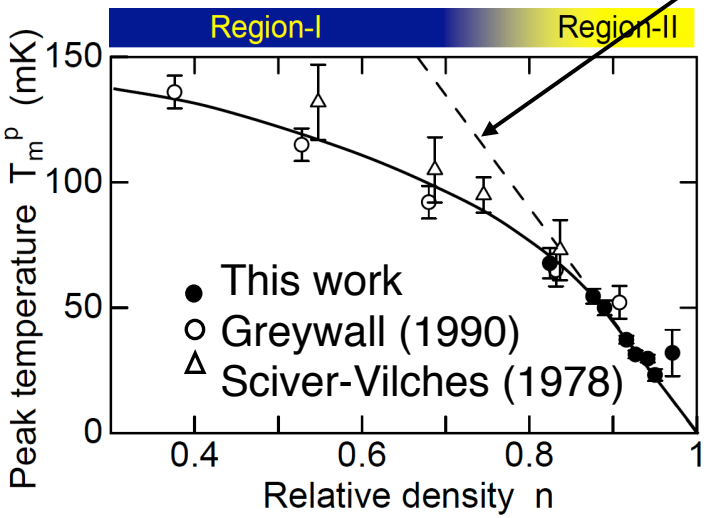


$U = \infty$ Hubbard model* for low particle densities gives good description for measured $C_m(T)$ at high particle densities.

*Koretsune-Ogata (2006)

- 2D hole (ZPV) band is created as a result of strong correlation effects near localization.
- Lattice models are applicable.





- $T_m^p \approx t\delta$ → t = 430 mK
- tight binding cal. → t = 320 mK (Koretsune-Ogata)
- $J = 4t^2/U^*$ → t = 200 mK

consistent each other.

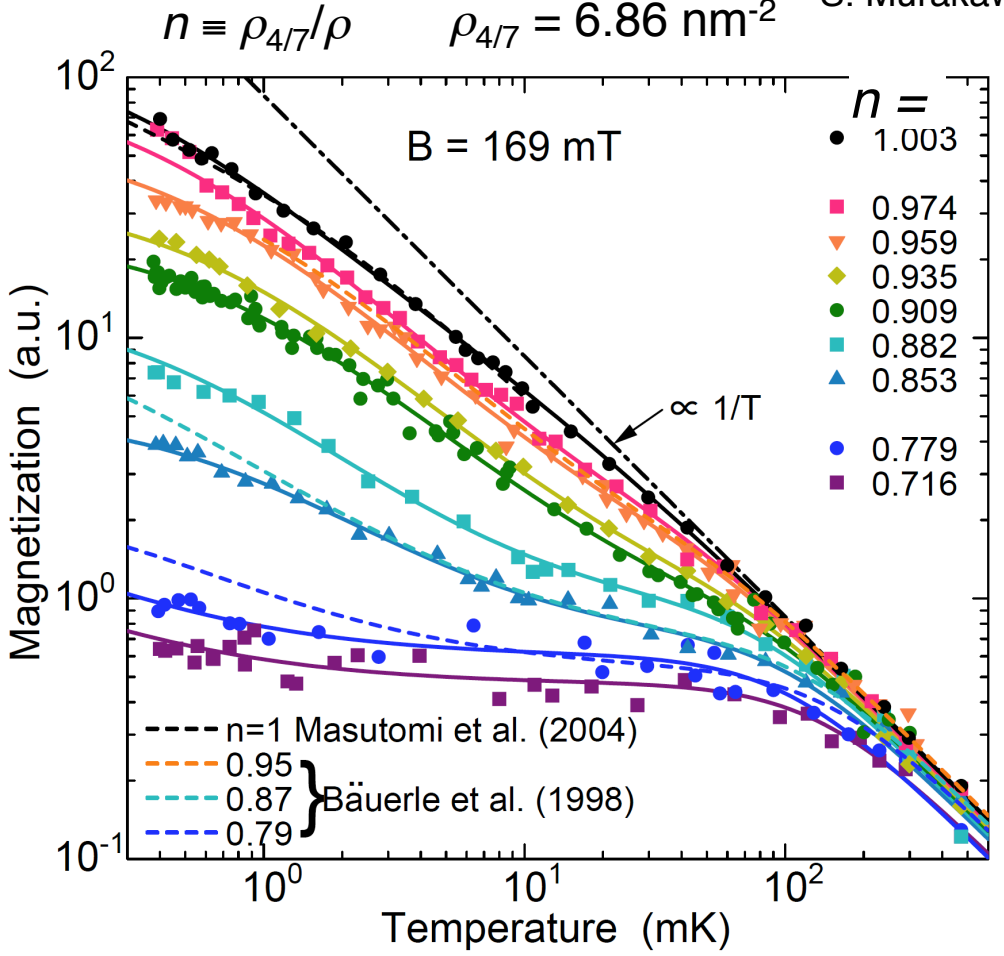
$U^* \approx$ 1-10 K (short-range repulsion)
:density fluctuations such as layer promotion or interstitial creation

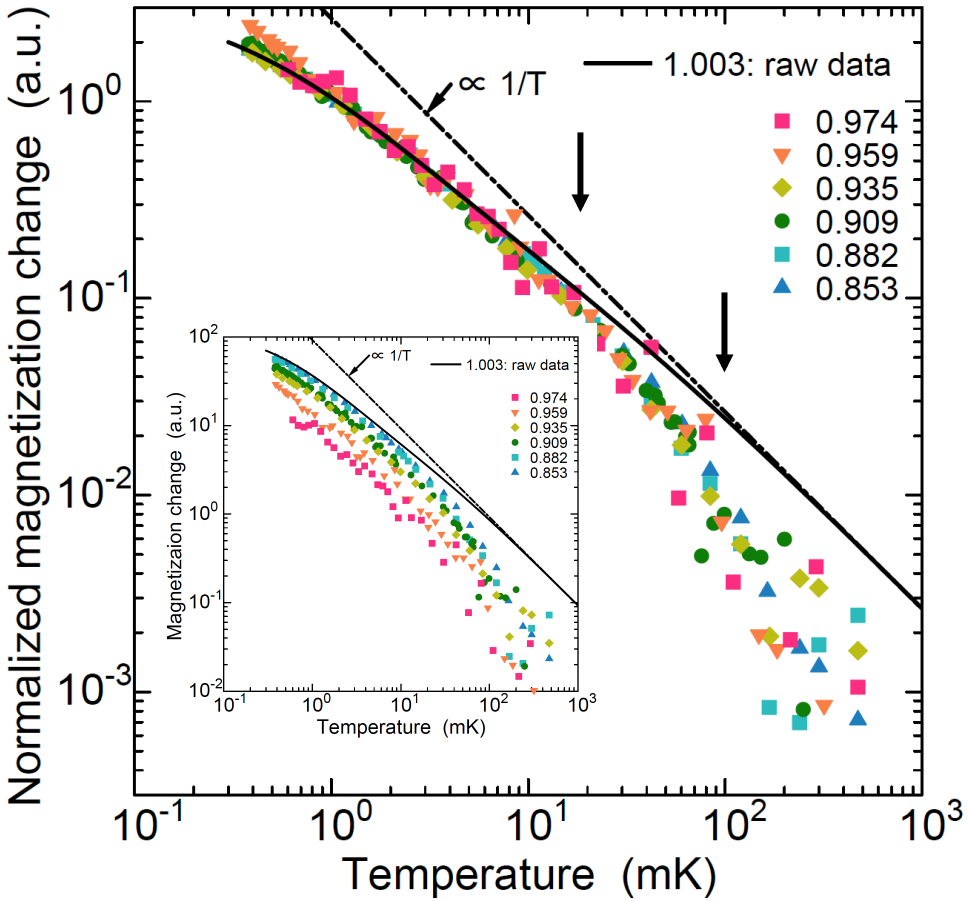
J = 10-20 mK > T_l^p : due to frustration

$U^*/t \approx 50$

Magnetization of Region-II

S. Murakawa et al., AIP Conf. Proc. **850**, 311-312 (2006); to be published



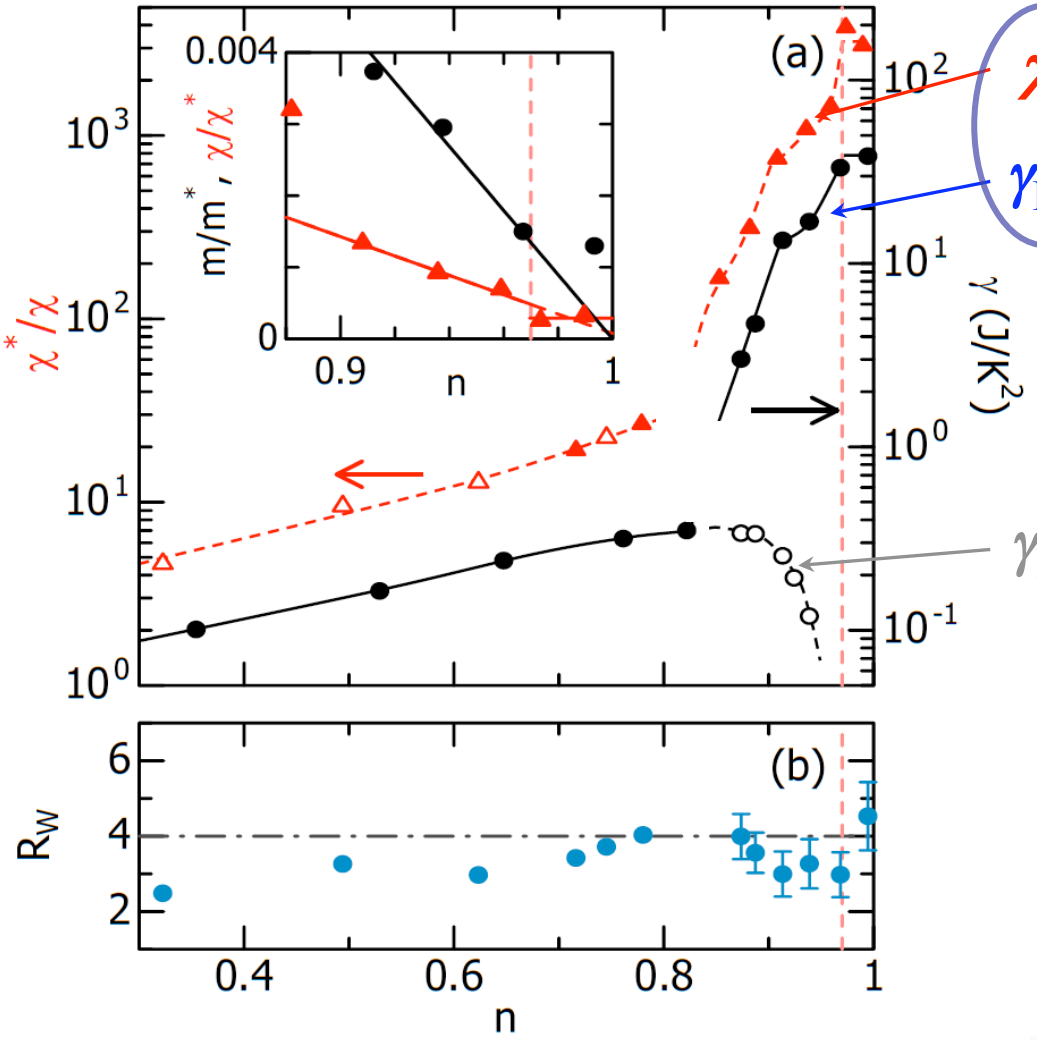


$\Delta M(\rho, T) \equiv M(\rho_{4/7}, T) - M(\rho, T)$

All $\Delta M(\rho, T)$ have the same T-dependence.

→ phase separation?! •••• **contradicts heat capacity data**

Wilson ratio in Region-II

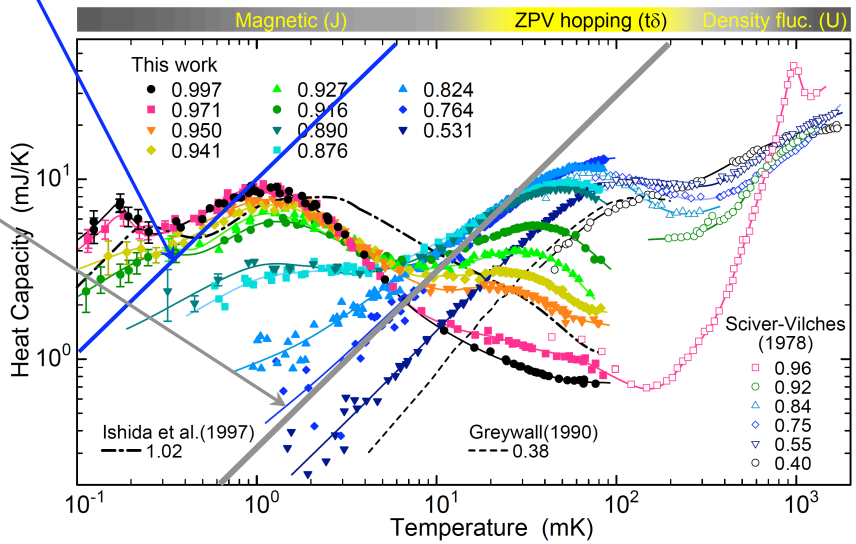


χ

γ_{LT}

γ_{MT}

m*/m* ≈ 830 !



Wilson ratio (R_W) = 3 -4 at the lowest T.

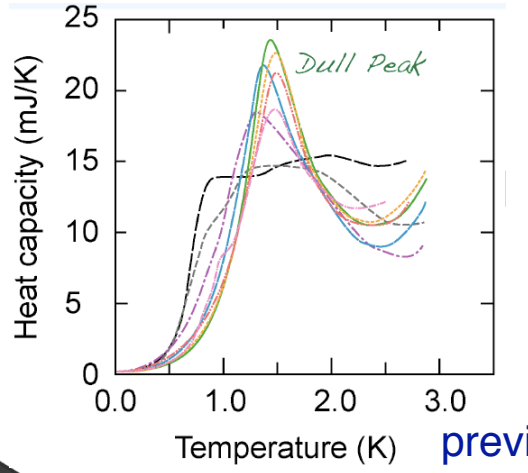
→ **spinon Fermi surface**? or **super heavy fermions**?

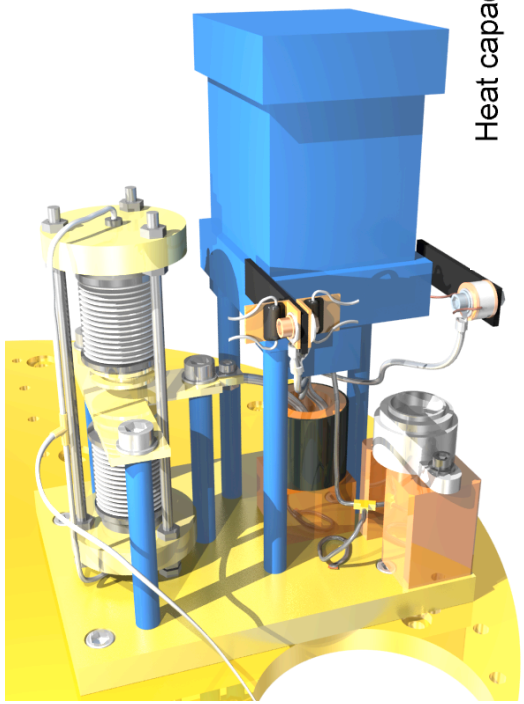
Future experiments

High-*T* HC measurements

- 30 mK ≤ *T* ≤ 2 K
- ZYX graphite (10 time larger platelet size than Grafoil)

previous HC data

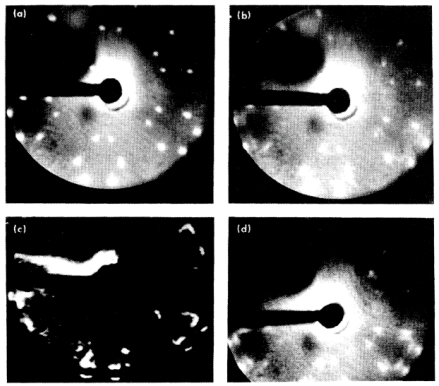


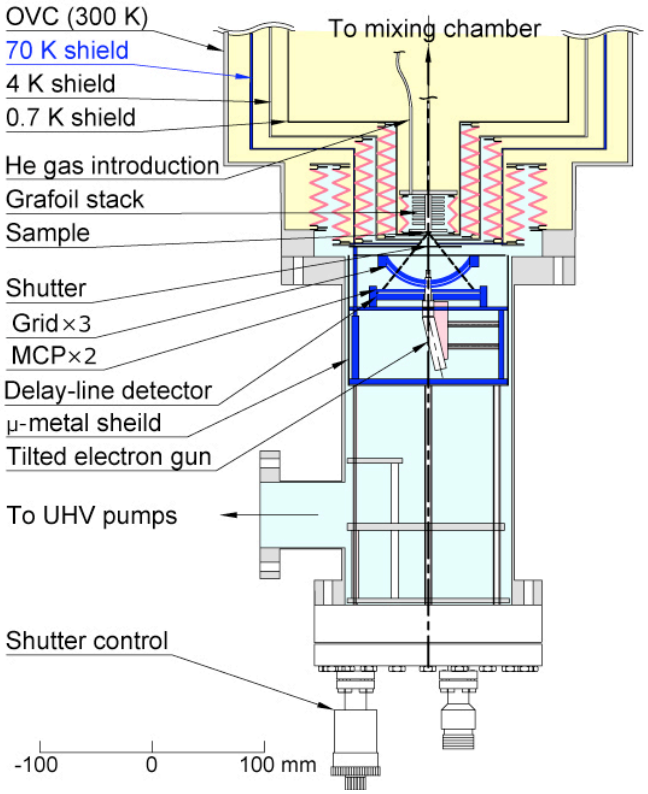


LEED measurements

- *T* ≥ 100 (300) mK
- I < 1 pA
- micro channel plates (MCP) × 2
- delay-line detector (DLD)

previous LEED data for bilayer D_2 on graphite





Summary

1. We found puddle formation in 3rd layer

- The newly added particles are promoted into 3rd layer forming FL puddles.

2. We found simple two-phase coexistence between the 4/7 phase and the high density IC solid in the 2nd layer.

3. Density dependences of the MSE parameters in ^{3}He /^{4}He/gr look similar to those in ^{3}He /^{3}He/gr.

4. We found a curious density dependence of HC in "hole doped" region.

- possible ZPV phase? spin-mass separation? or two-phase coexistence?
- T_2 data support single phase (ZPV phase) at least at high-T ($\geq$ 20 mK).