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Workshop on Supersolid 2008

18 - 22 August 2008

Search for supersolid behaviors in 2-D Solid He-4 and He-4 in nanoporous media

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Search for supersolid behaviors in 2-D Solid ^{4}He and ^{4}He in nanoporous media

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Design the Future

Shirahama Lab.

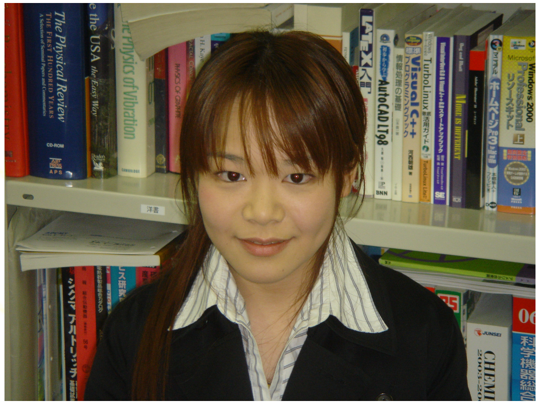
Outline

Torsional Oscillator Studies for :

1. Solid ^{4}He confined to a Nanoporous Glass
 (Pore Diameter : 25 A)
   Supersolid behavior observed

2. Two-dimensional ^{4}He adsorbed on Graphite
(Second layer solid on first-layer ^{4}He + Graphite)
   Supersolid behavior observed
   Velocity-dependent frequency shift

1. Supersolid ^{4}He in 25-A Nanopores



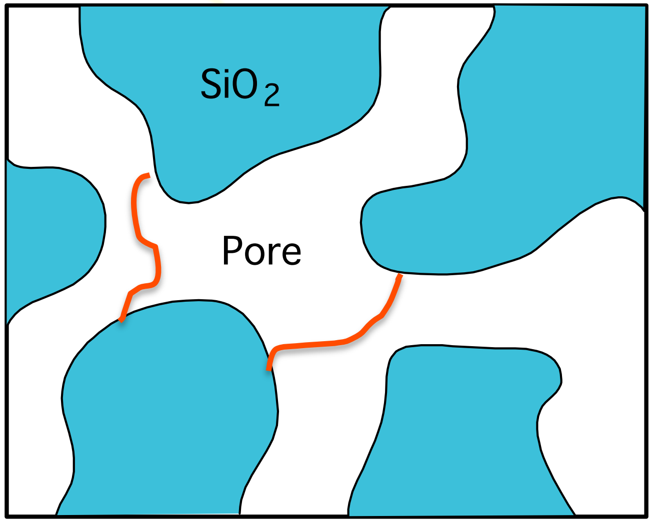
Hitomi Yoshimura
Shunichi Takada
Rama Higashino
Yoshiyuki Shibayama
Keiya Shirahama

Supersolid ^{4}He in Porous Media
Why interesting and important (even now) ?

Whatever mechanism underlies solid helium's odd behavior must also be able to explain Kim and Chan's original experiment, which looked at helium trapped in the tiny pores of Vycor glass.

Johanna Miller, Physics Today, Feb. 2008

Cartoon of porous glass



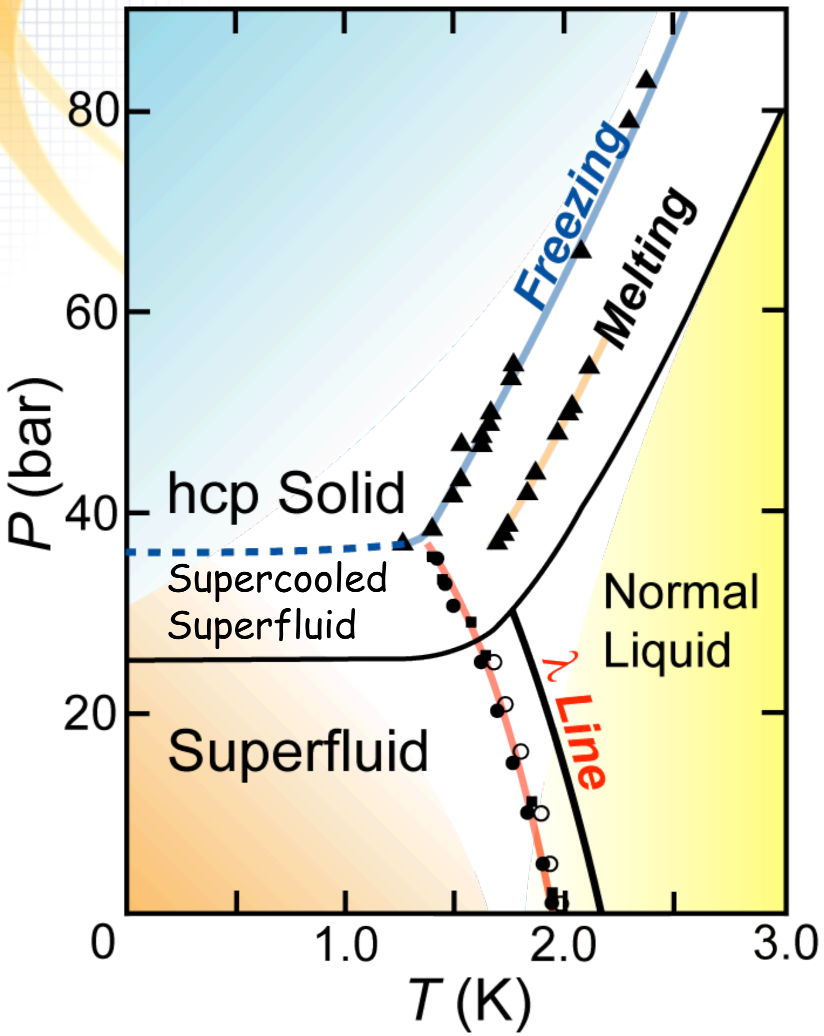
Dislocation lines or vortex lines must be terminated at the wall. Their core sizes must be smaller than the pore sizes.

can discriminate theories and models.

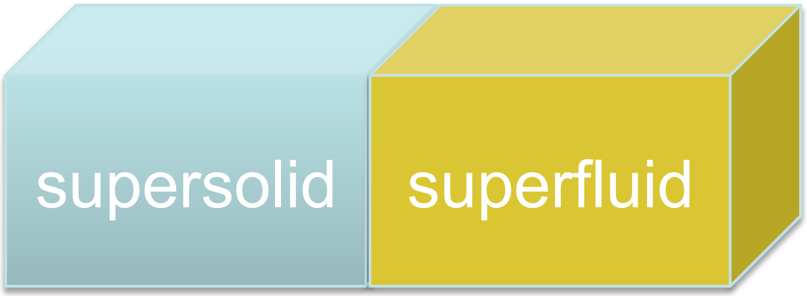
Superfluid – Supersolid Junction

(Ray and Hallock, PRL 2008)

Phase Diagram of ^{4}He in Porous Vycor Glass



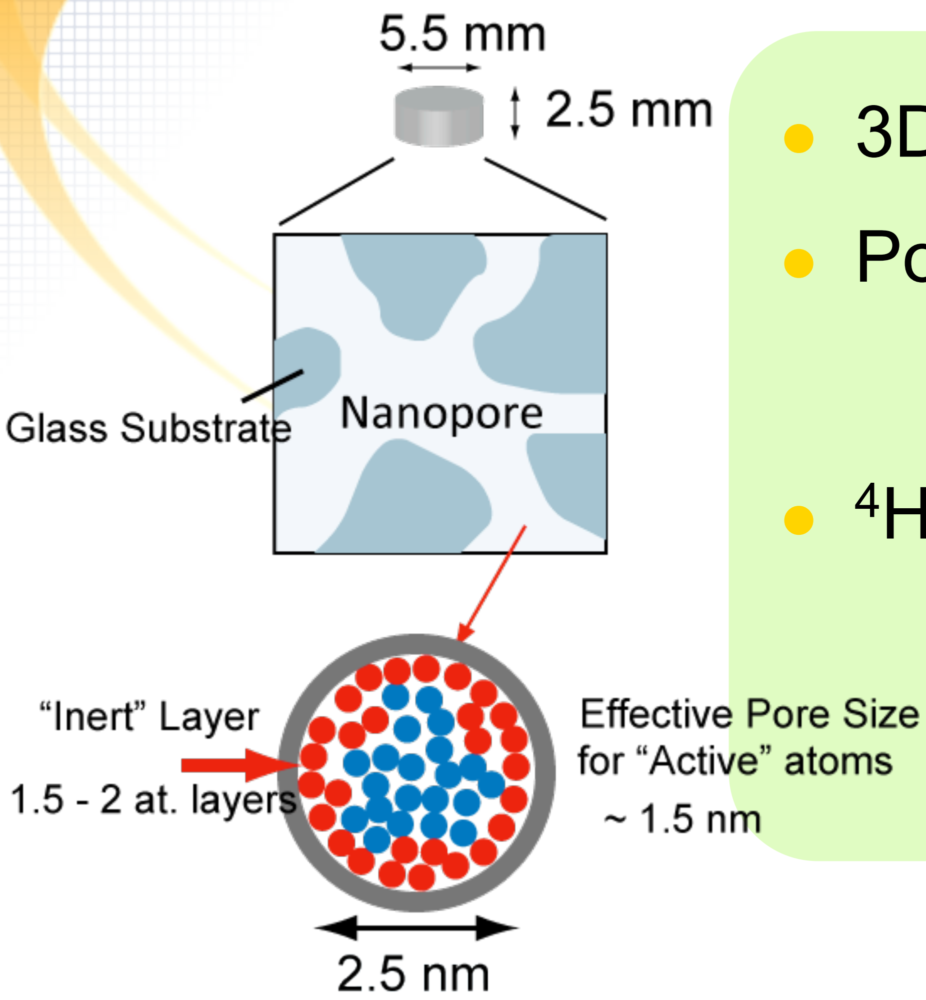
Bulk Porous material



Phase coherence between superfluid and supersolid ?

Hallock
Kim
Davis, …

^{4}He in Nanoporous Gelsil Glass



- 3D Network of Nanopores
- Pore Diameter : 2.5 nm

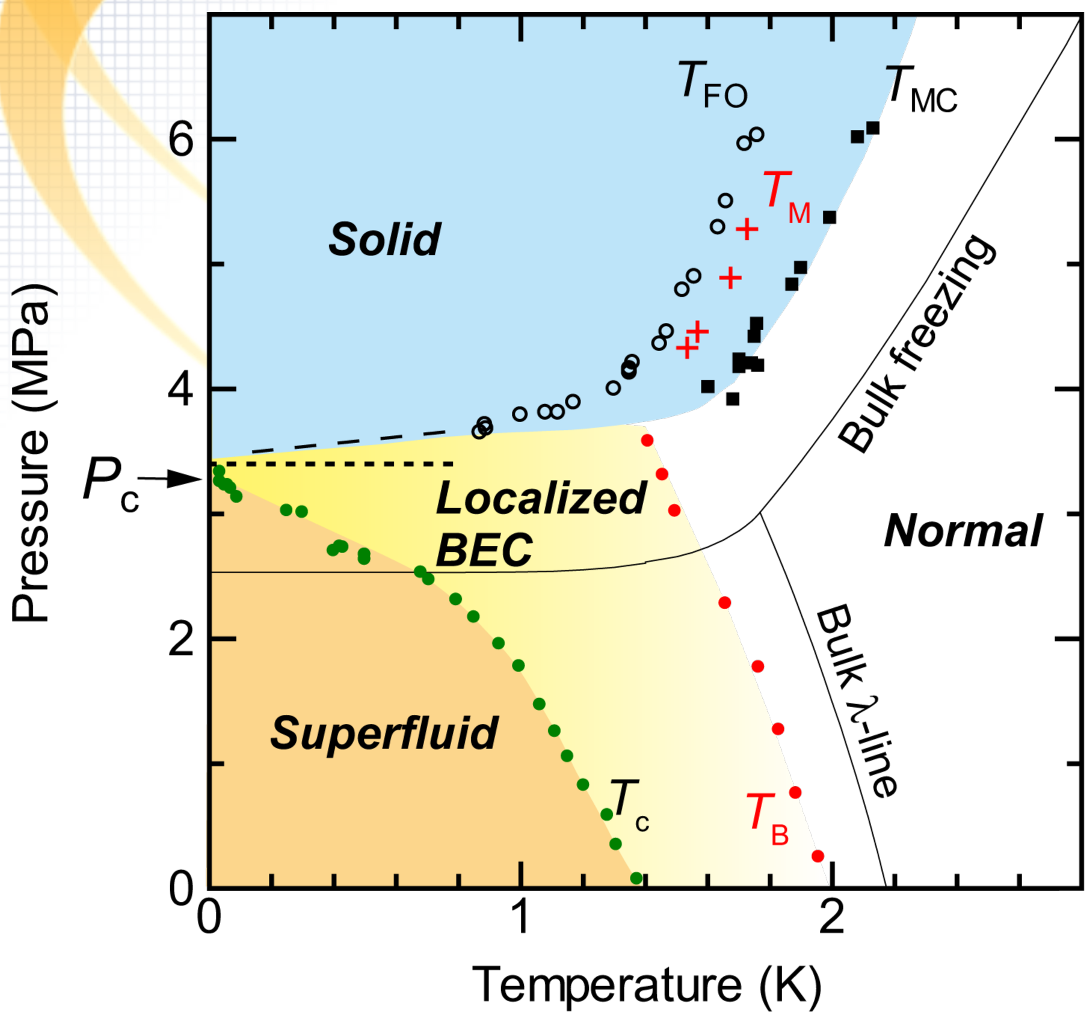
  1/3 of Vycor Pore
- ^{4}He atoms in Pores :

  "Inert" Layer near wall

  "Active" atoms inside

Phase Diagram of ^4He in 25A Gelsil

PRL **93**, 075302 (2004)
JPSJ **77**, 013601 (2008)
(Editors' Choice)
PRL **100**, 195301 (2008)
(Editors' Suggestions)

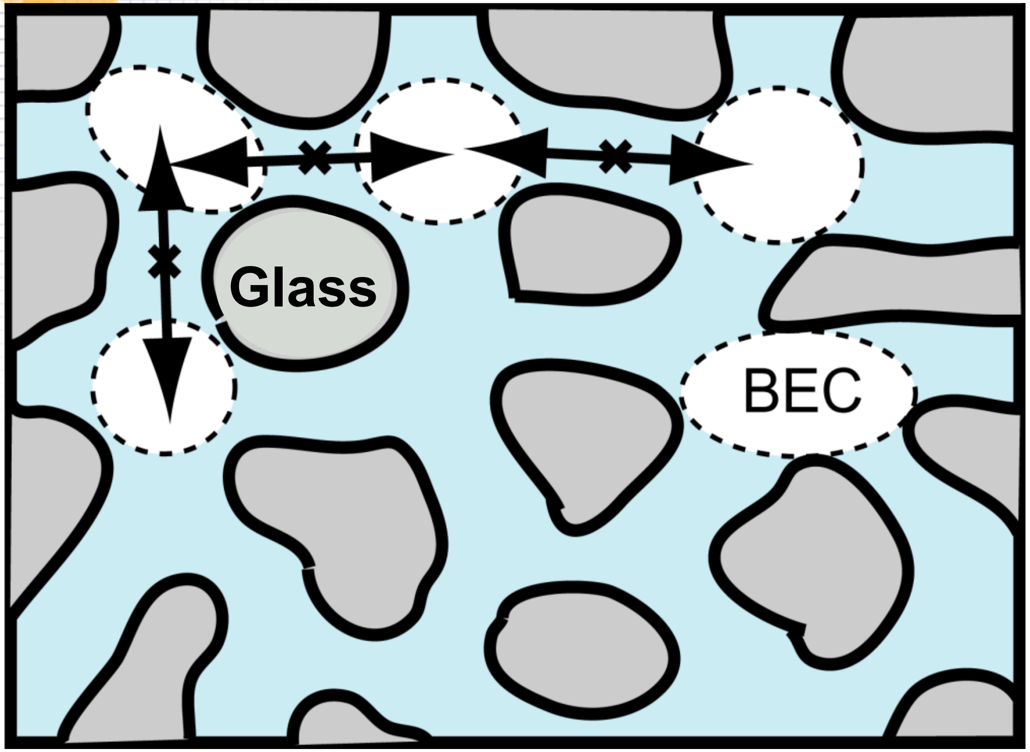


Superfluidity is
Strongly suppressed.

Localized (Nanoscale) BEC
$Tc \not\approx T_{BEC}$

Localized BEC State of ^{4}He in Nanopores

(Henry Glyde, 2000)

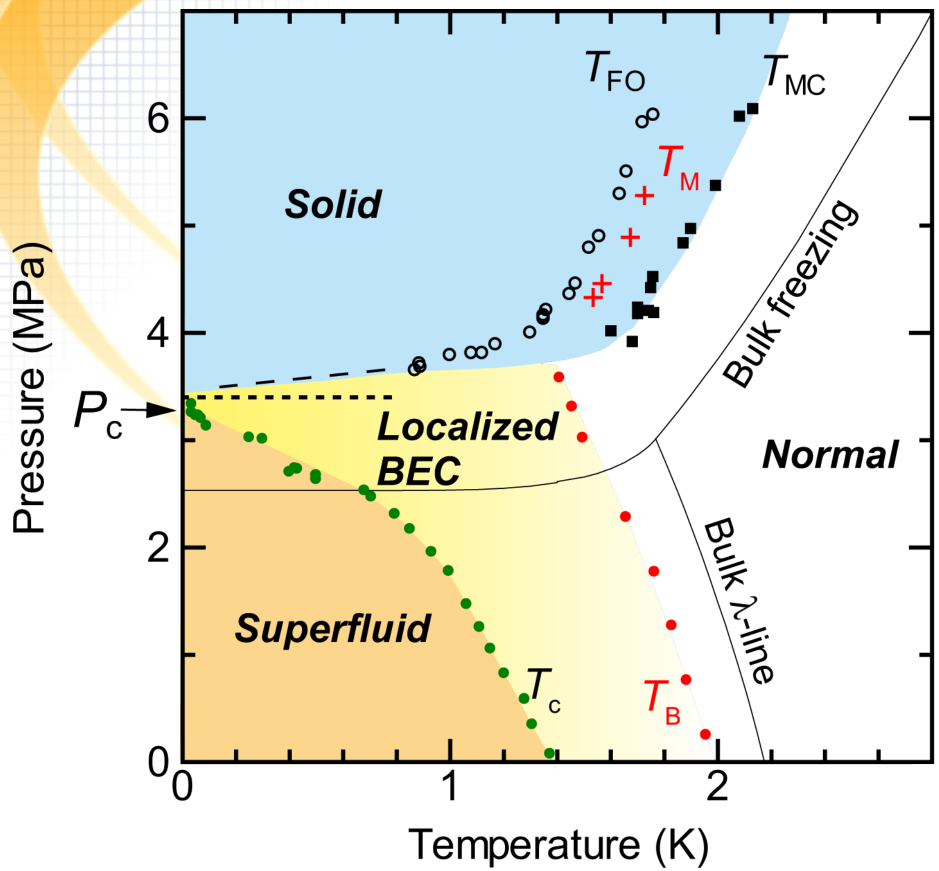


“Seeds” of BEC are created near T_λ, but they are not phase coherent in macroscopic scale.

Atom exchanges between the BEC's are suppressed by nanopores.

No macroscopic superfluidity
(detected by torsional oscillator)

Evidences of Localized BEC



1. Flat Freezing Line Below 1K

JPSJ **77**, 013601 (2008) (Editors' Choice)

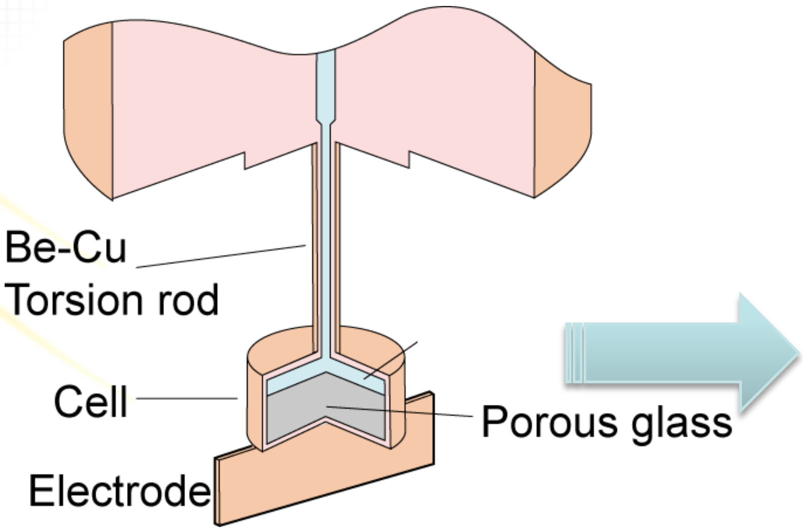
2. Heat Capacity Peak Just below λ - line

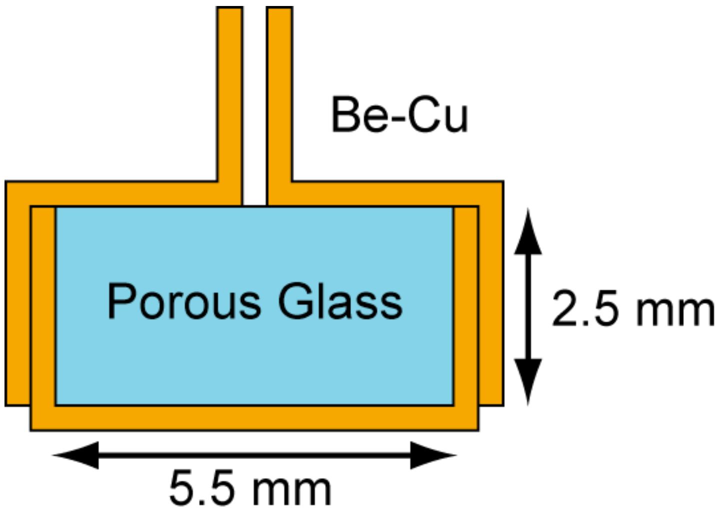
PRL **100**, 195301 (2008) (Editors' Suggestions)

3. Roton signal above Tc Neutron studies

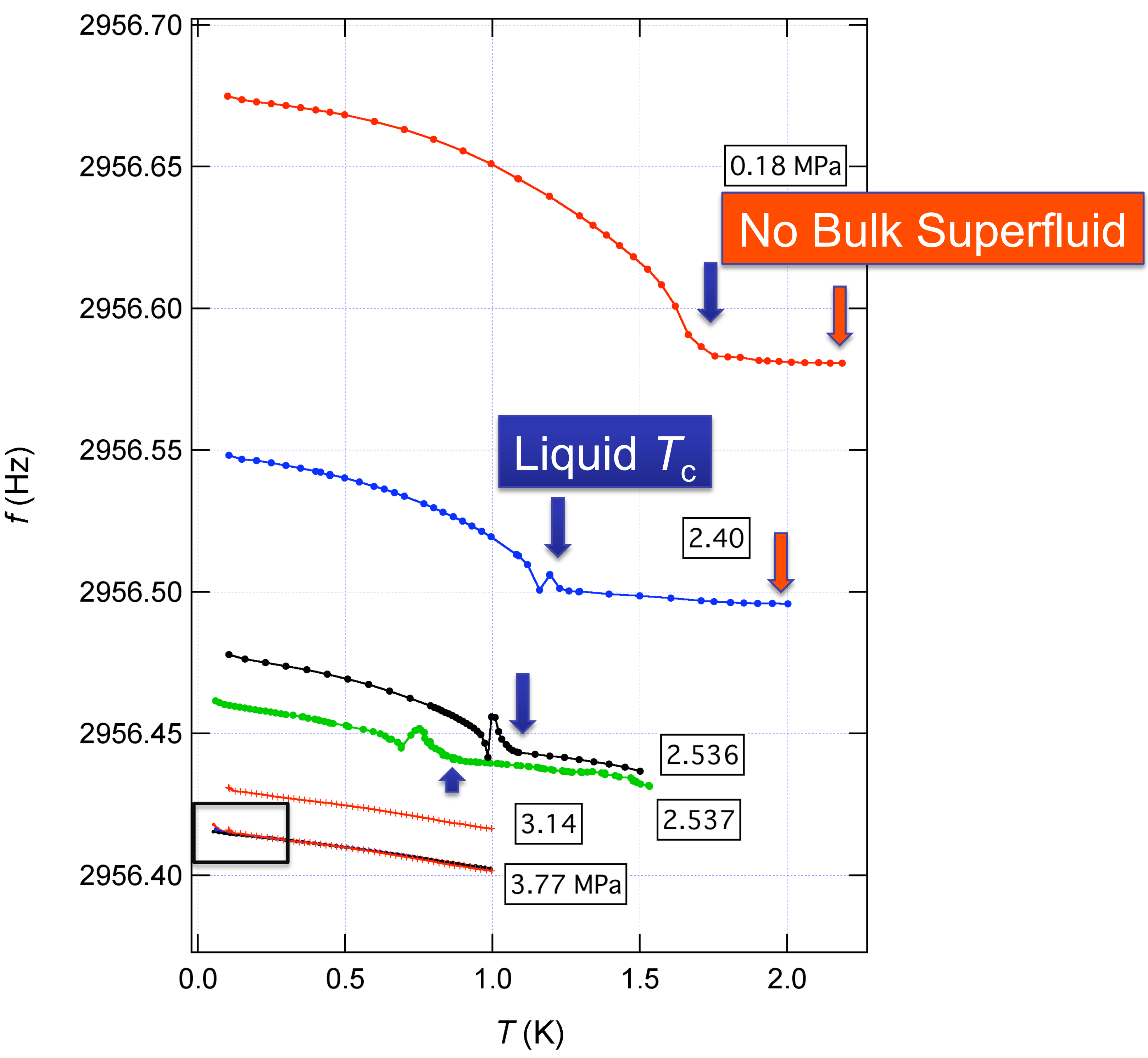
J. Bossy, H. R. Glyde et al. Preprint

Torsional Oscillator



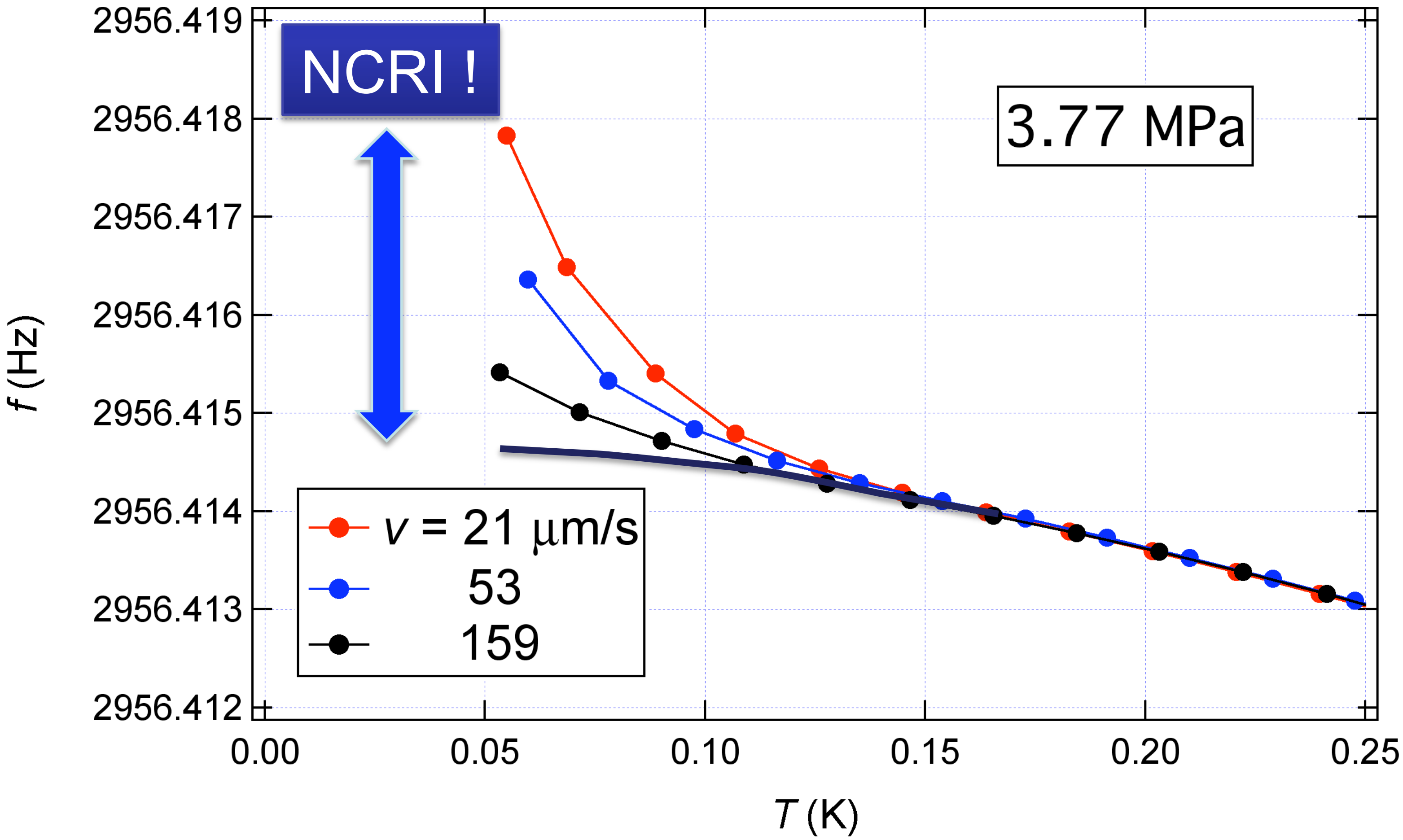


No space for bulk helium inside the cell

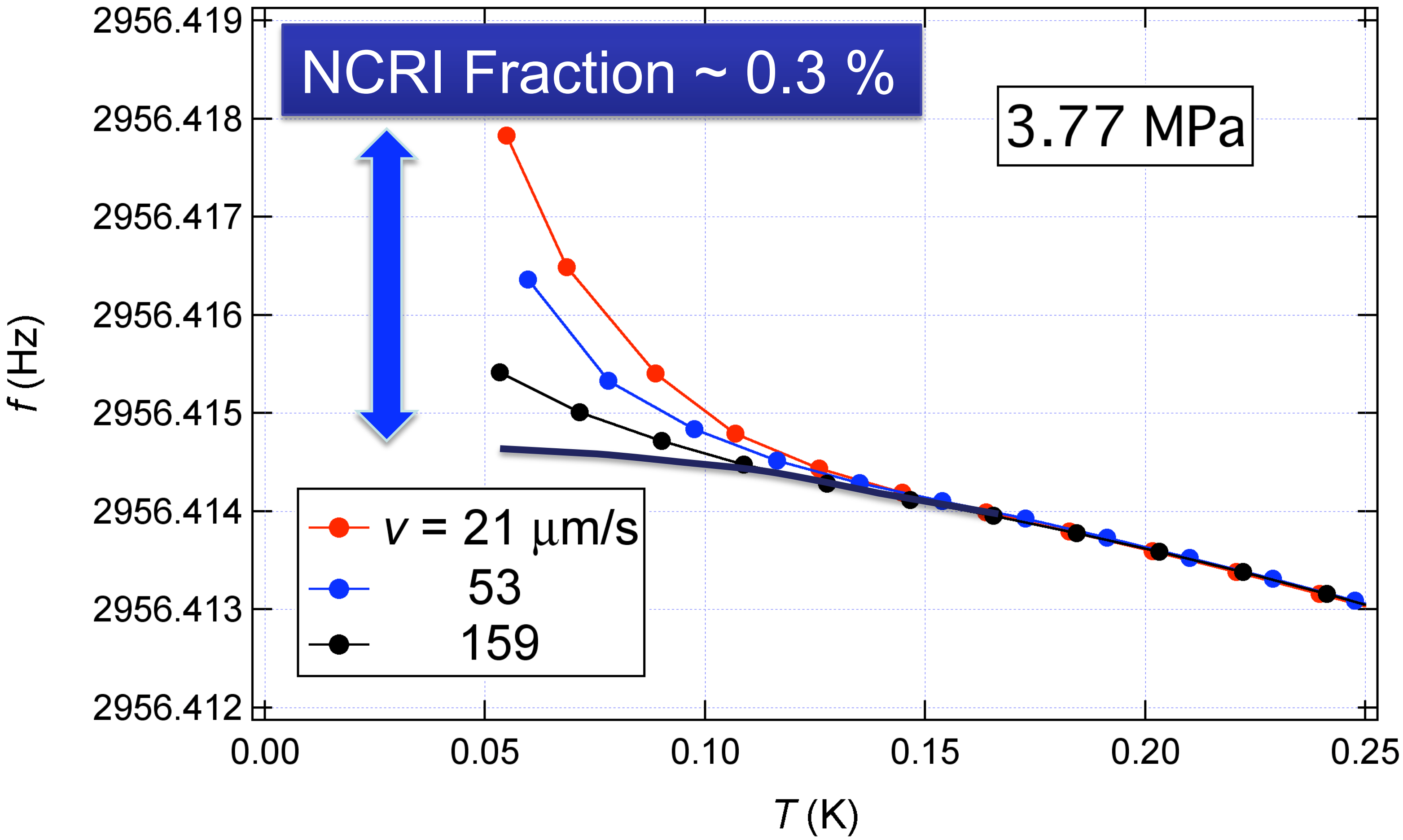


2956.70
2956.65
2956.60
2956.55
2956.50
2956.45
2956.40
f (Hz)
0.0
0.5
1.0
1.5
2.0
T (K)
0.18 MPa
No Bulk Superfluid
Liquid T_c
2.40
2.536
2.537
3.14
3.77 MPa

V-dependent frequency at 3.77 MPa



Rough Estimation of NCRI Magnitude

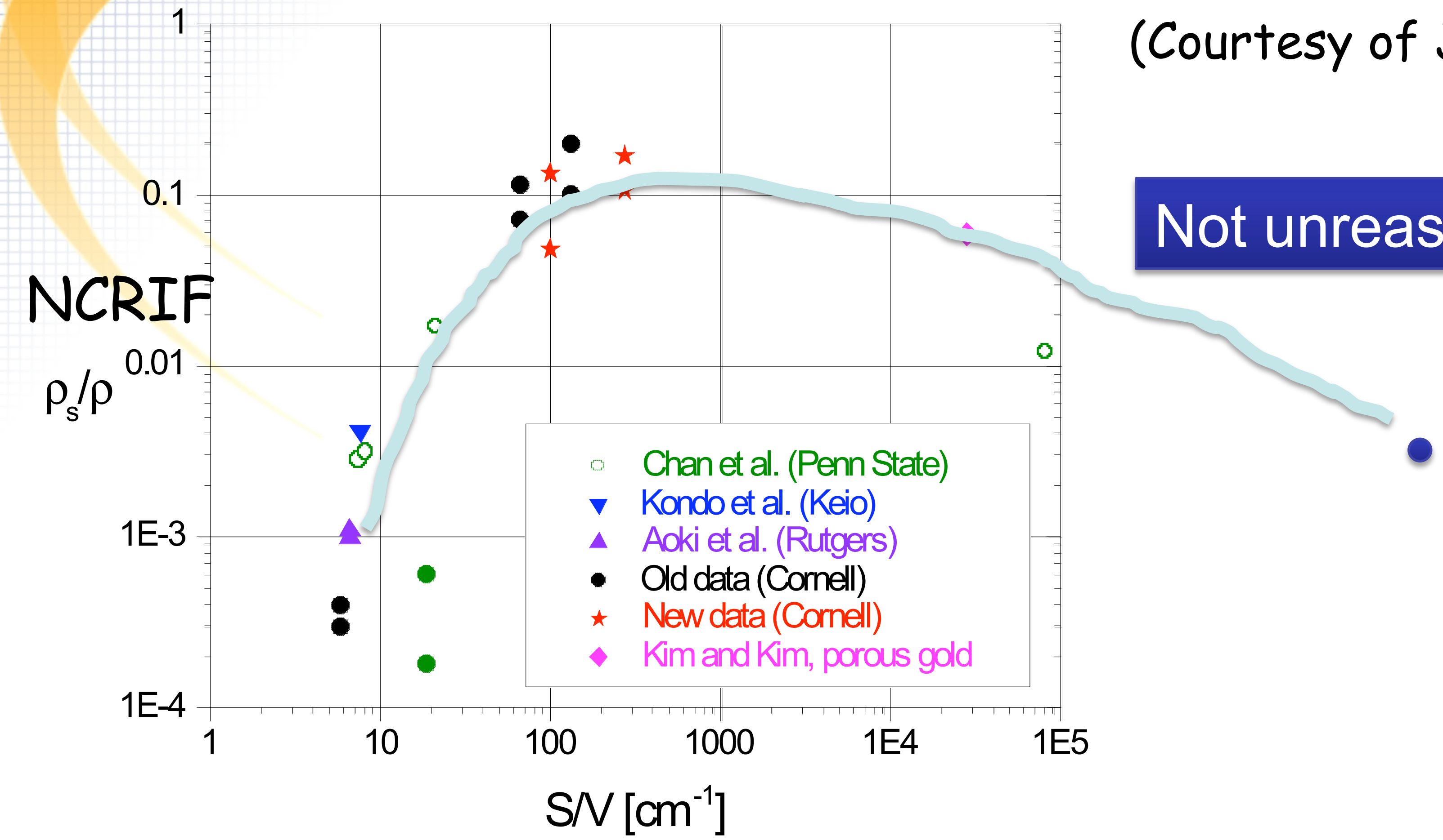


Comparison of NCRI Magnitude with Other Exp.

Material	Characteristic Size	Approx. NCRIF (%)	Group
Gelsil	2.5 nm	0.3	Yoshimura et al.
Vycor	7 nm	2	Kim&Chan
Porous Gold	180 nm	7	Kim et al.
Aerogel		0.03	West, Mulders
Bulk, Annulus	< 100 μm	20	Rittner & Reppy
Bulk, Cylinder	~ cm	0.04 - 1	Many groups

"Rittner - Reppy S/V Plot"

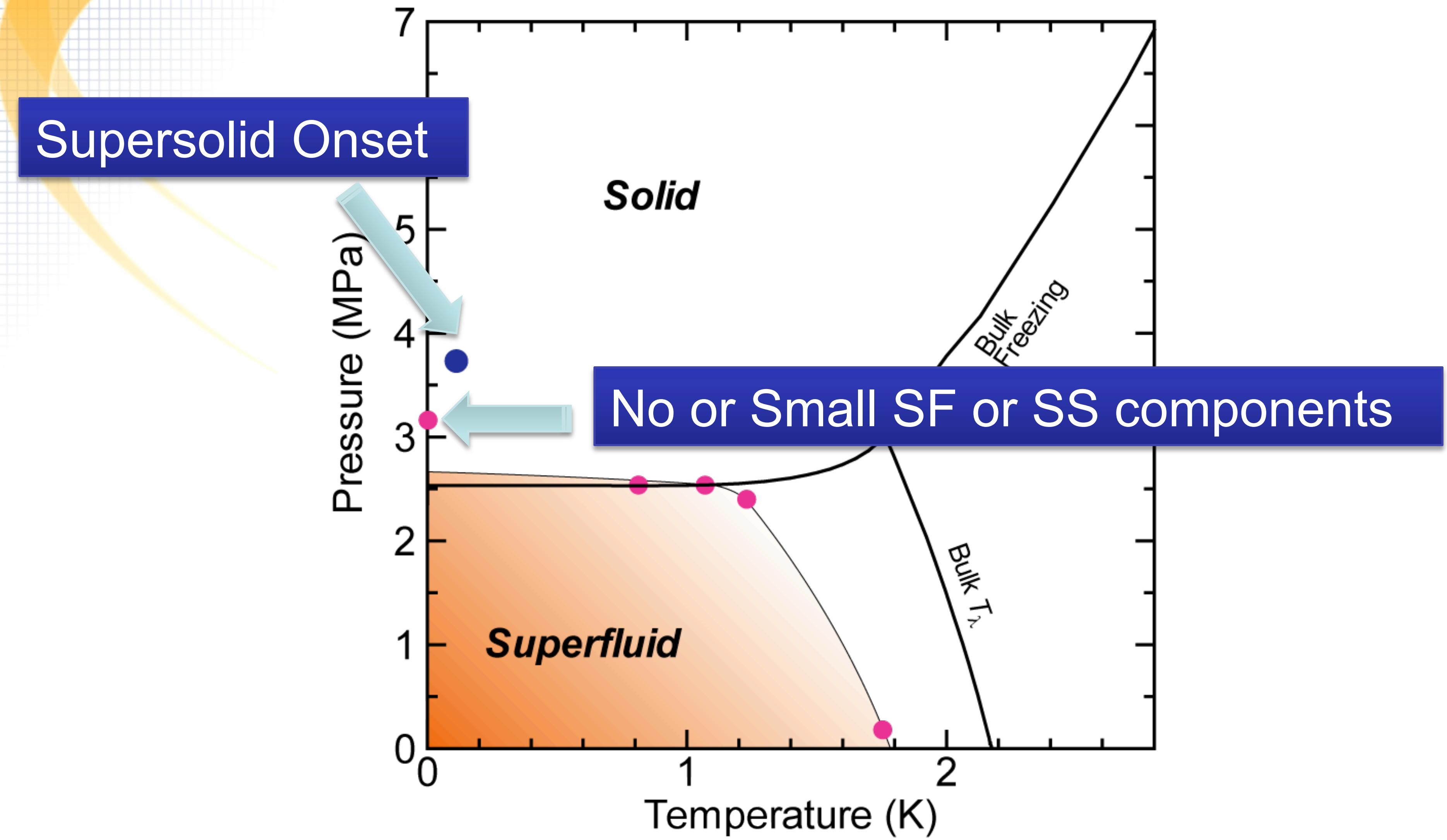
(Courtesy of John Reppy)



(Surface area) / (Sample Volume)

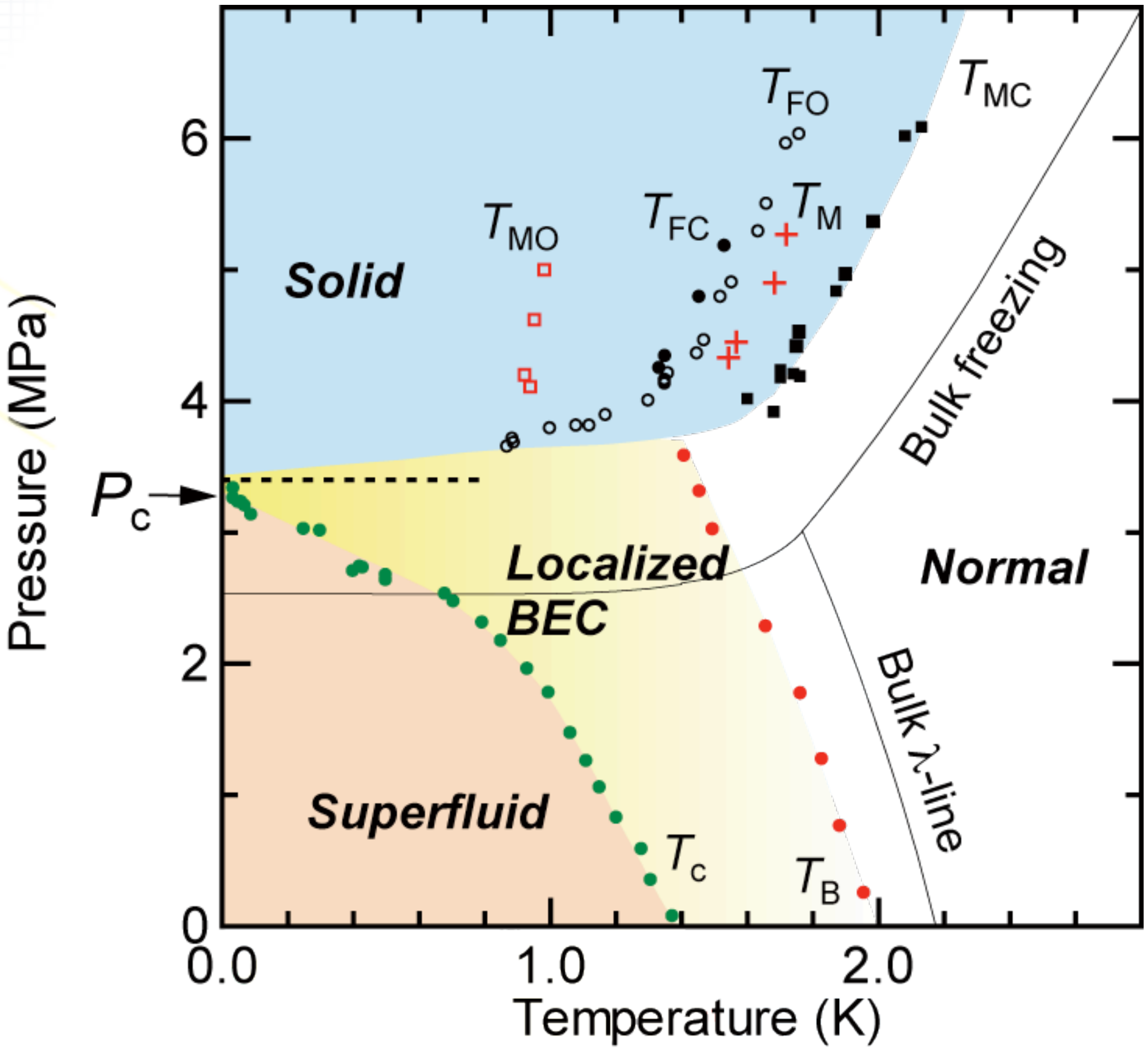
Not unreasonable

Phase Diagram



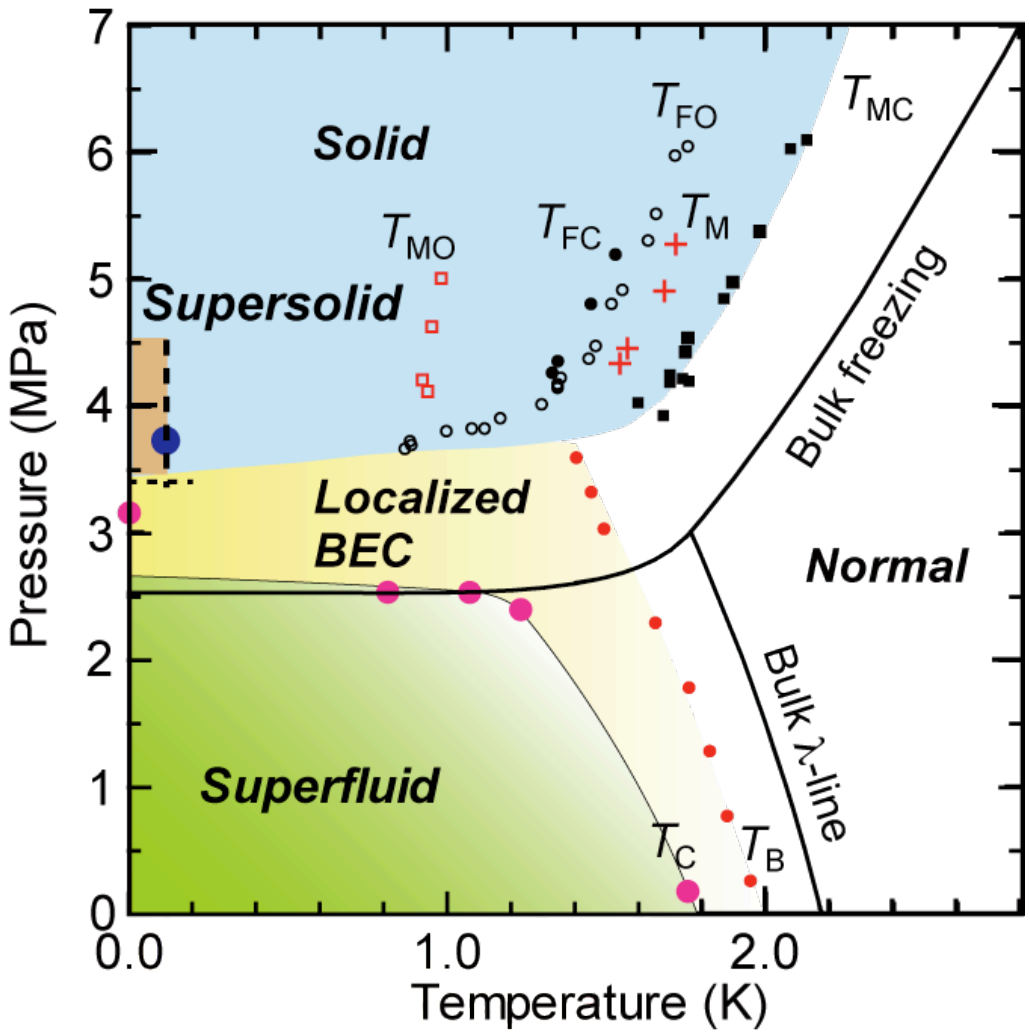
Phase Diagram

PRL **93**, 075302 (2004)
JPSJ **77**, 013601 (2008)
PRL **100**, 195301 (2008)

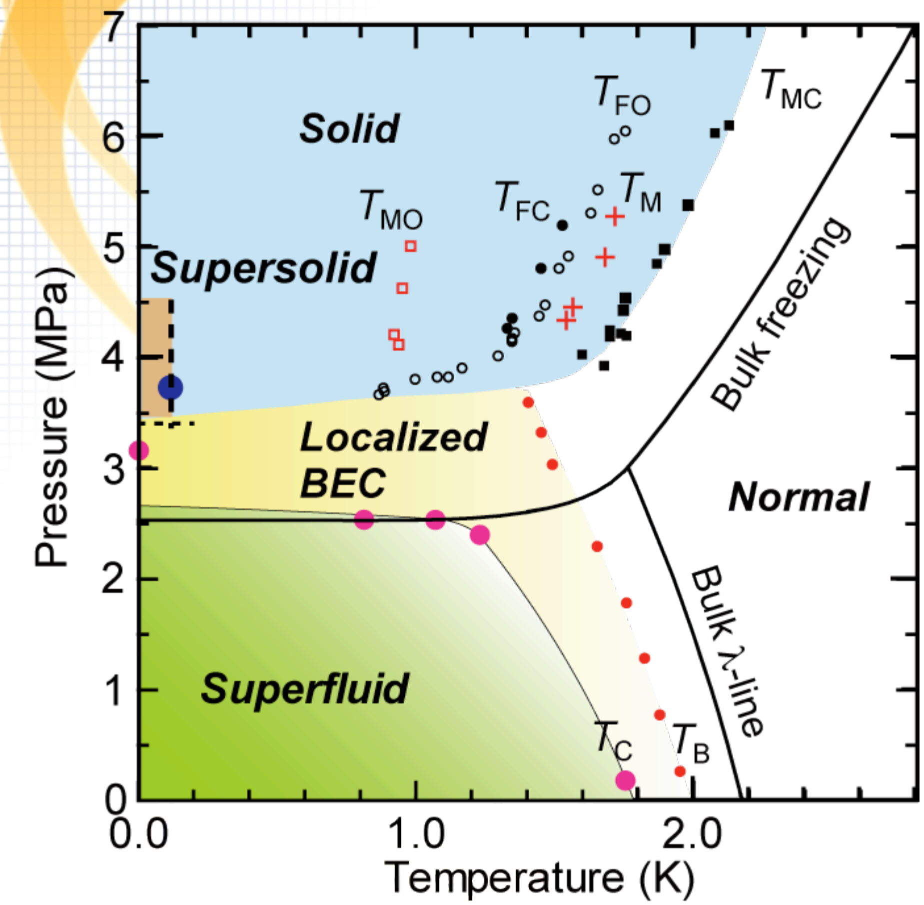


Possible Phase Diagram

PRL **93**, 075302 (2004)
JPSJ **77**, 013601 (2008)
PRL **100**, 195301 (2008)



Remarks

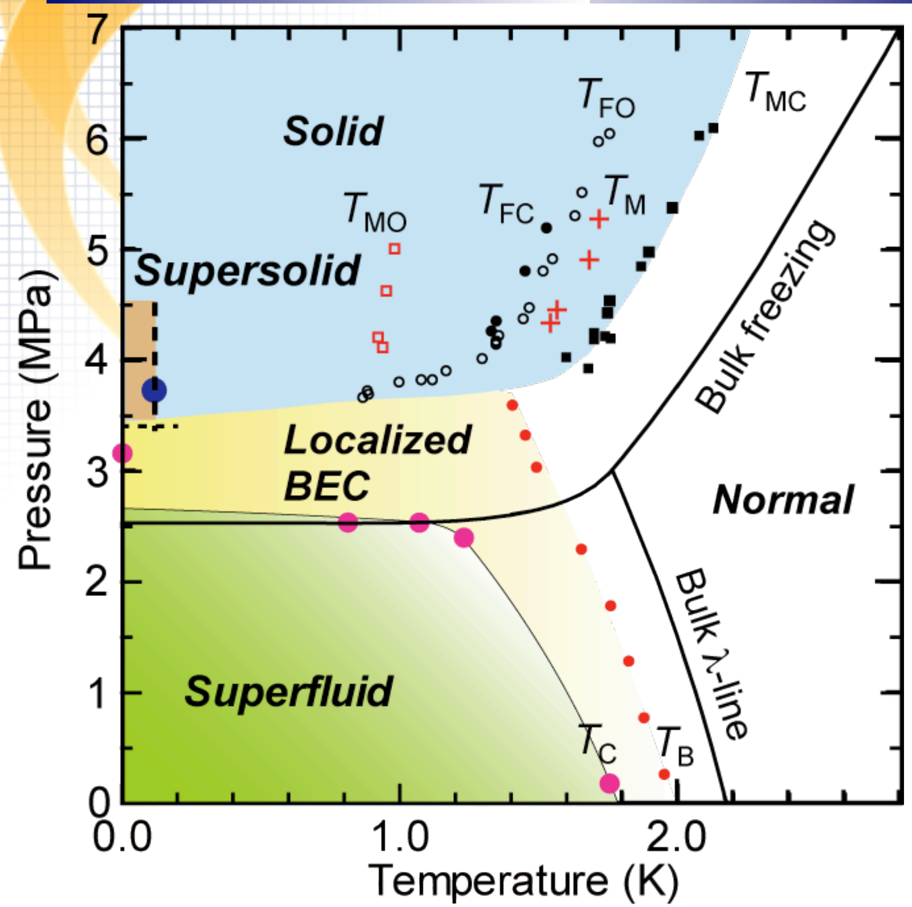


1. NCRI comes from solid ^{4}He in approx. 15 A pores.

2. No evidence of crystallization is found in neutron studies for 25, 31 and 44 A Gelsil glasses.
(Henry Glyde, private comm.)

Amorphous Solid ?

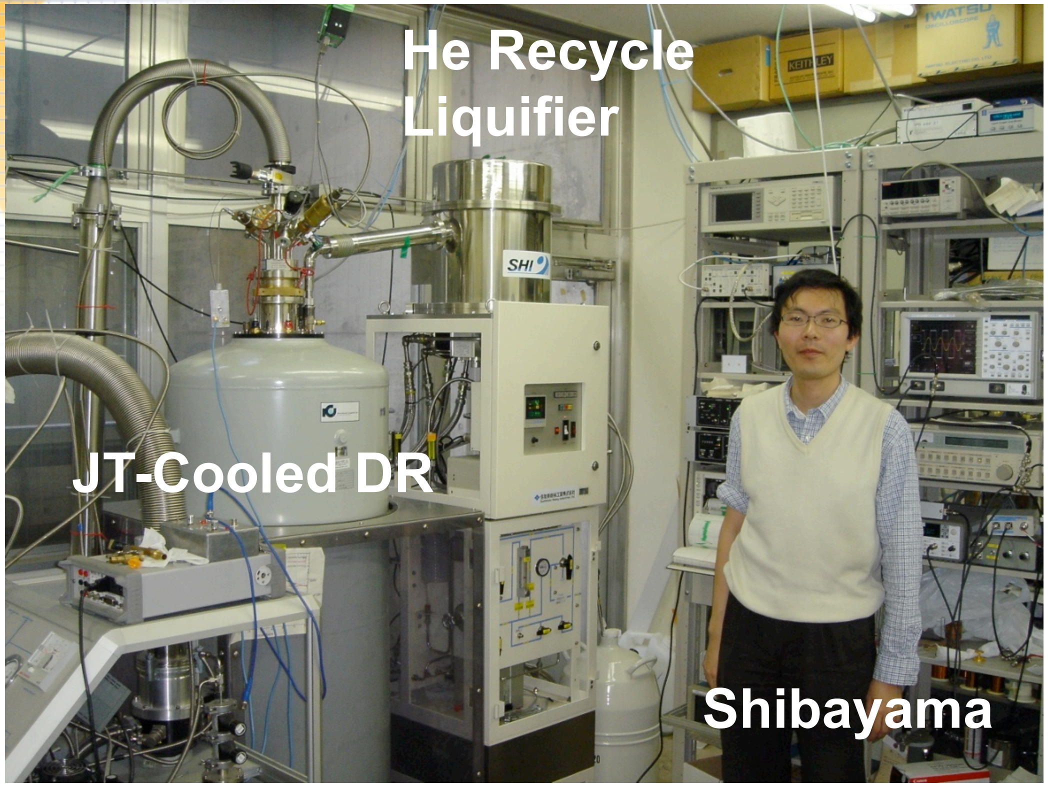
Summary - 1



NCRI of ~ 0.3 % of the total mass is observed in 25 A nanopores at 3.77 MPa.

^{3}He effect ?
Coexists with LBEC ?

2. Two-dimensional solid ^{4}He on Graphite



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(Univ. Tokyo)

Motivations for 2D Solid Experiments

1. Superfluid Behavior in Second-layer (possibly solid) ^4He on Graphite (Crowell and Reppy, 1993)

2. Evidence for Zero-Point Vacancies in Second-layer ^3He on Graphite (Matsumoto, Fukuyama, et al.)

2D solid ^4He on Graphite:
Zero-point vacancies are much more favorable than 3D bulk

Supersolidity induced by Vacancies in 2-D solid ^4He?

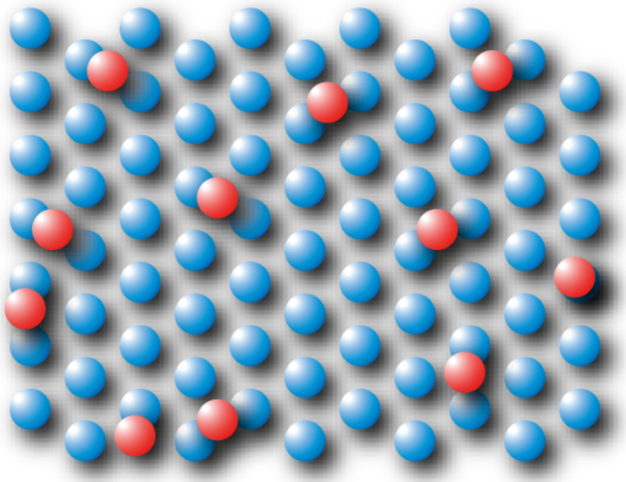
Zero-Point Vacancies in 2-D ^{3}He on graphite

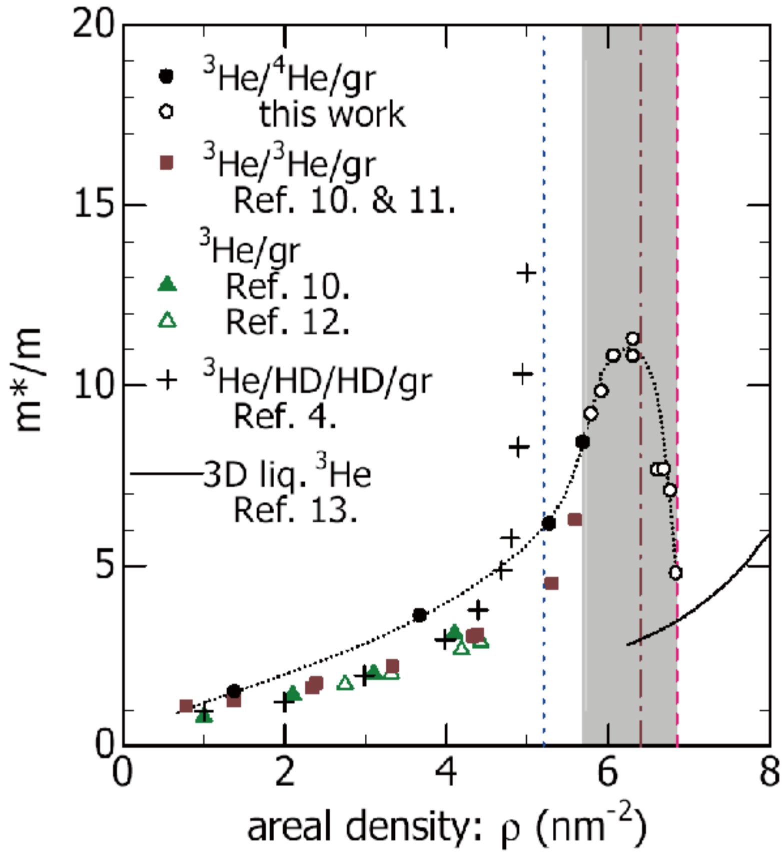
Y. Matsumoto et al., *JLTP*, **138**, 271 (2005) and submitted.

The existence of ZPVs has been proposed in 2D ^{3}He on graphite

2D ^{3}He system on graphite

- 1st layer : ^{4}He monolayer of 12.03 nm^{-2}
- 2nd layer : **^{3}He** submonolayer





Low ^{3}He densities: 2D Fermi fluid with strong interparticle correlation
Effective mass m^* is enhanced by the correlation

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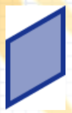
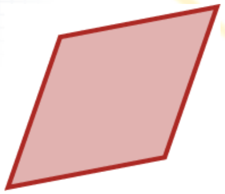
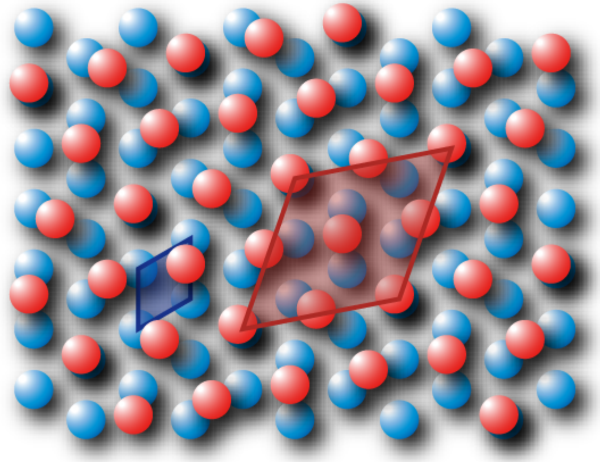
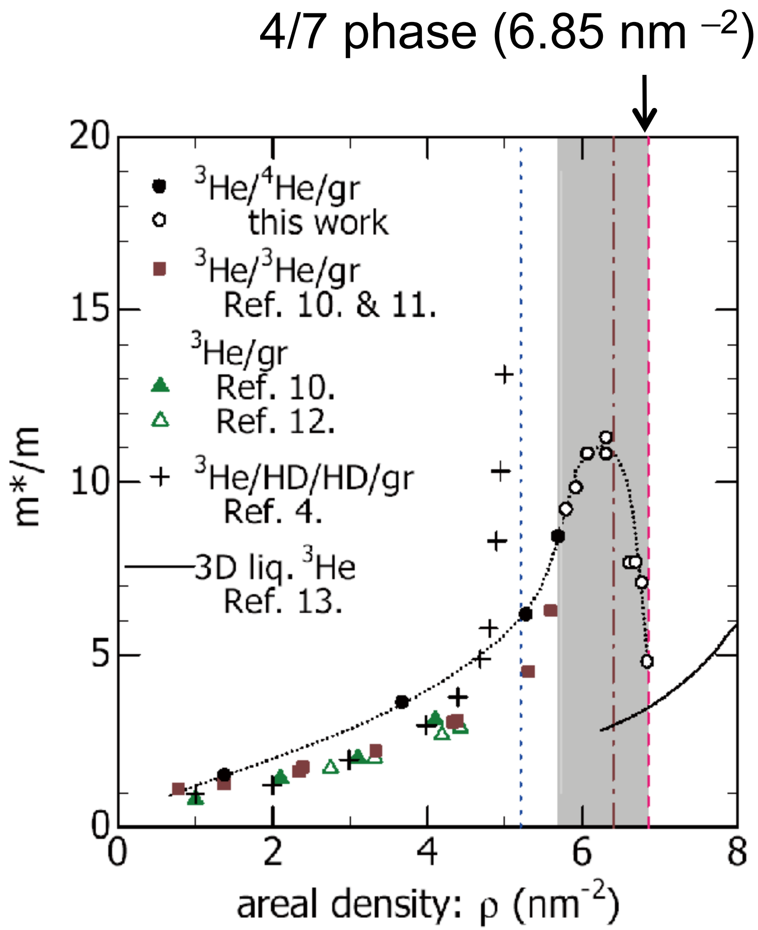
At the four seventh density $\rho_{4/7}$ of the preplated ^{4}He layer:
A registered “4/7 phase”


unit cell for the preplated ^{4}He layer

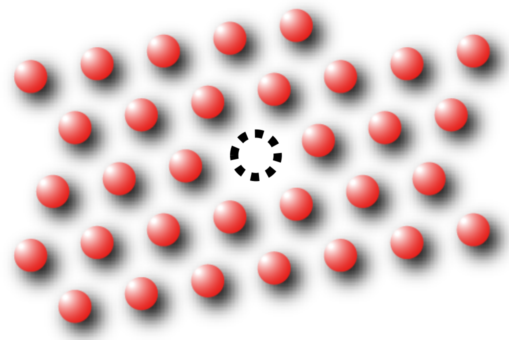

unit cell for ^{3}He 4/7 phase





・Just below $\rho_{4/7}$ (gray region in the figure)
A “**Mott localized phase**” **doped with ZPVs**.

・The thermodynamic properties of the 4/7 phase : **a quantum hopping of ZPVs**



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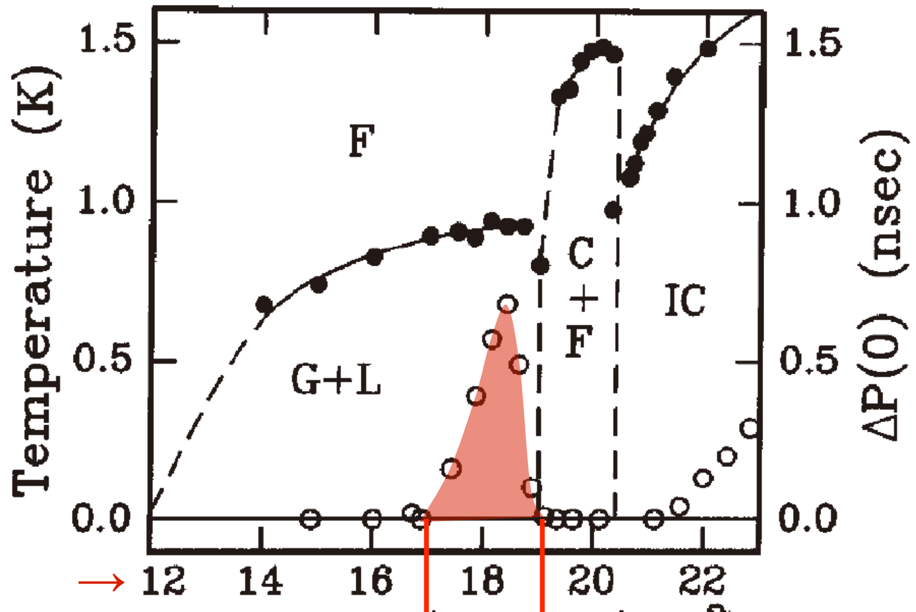
Mobile ZPVs in 2D ^{3}He solid strongly suggests that **ZPVs also form and are mobile in 2D ^{4}He solid**. Moreover, because the ZPVs in solid ^{4}He is Bose particle, it is expected that **their quantum motion results in superfluidity of ZPVs**, namely **supersolidity**.

Crowell and Reppy (CR) have found a peculiar superfluid behavior for the ^{4}He films on graphite at the coverages between 17 and 19 nm^{-2}

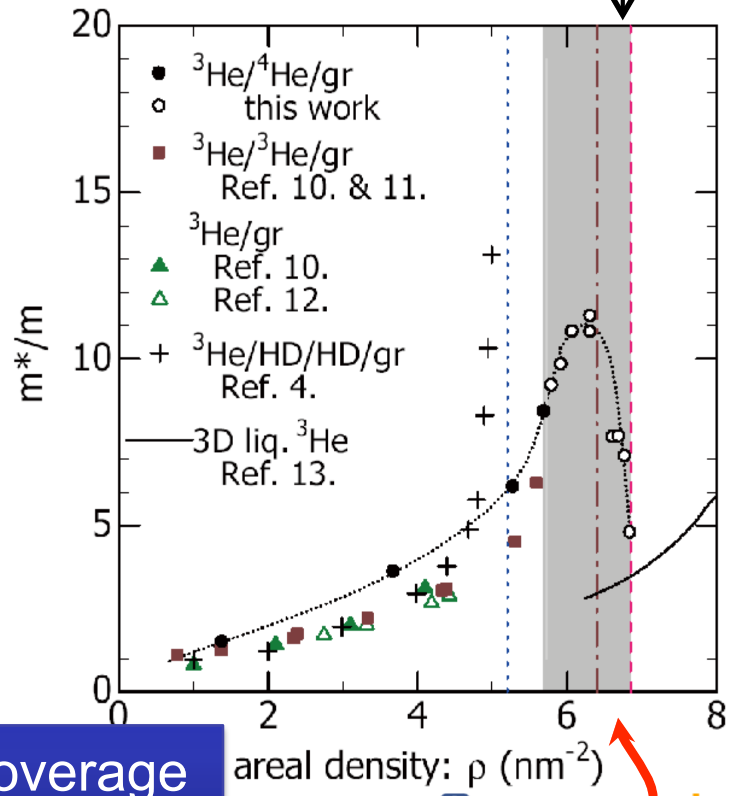
(Crowell and Reppy, *PRL* **70**, 3291 ('93); *PRB* **53**, 2701 ('96))

4/7 phase (6.85 nm $^{-2}$)



→ for total

0 2 4 6 8 10 ← for only the 2nd layer



corresponding coverage

ZPV-induced supersolid?

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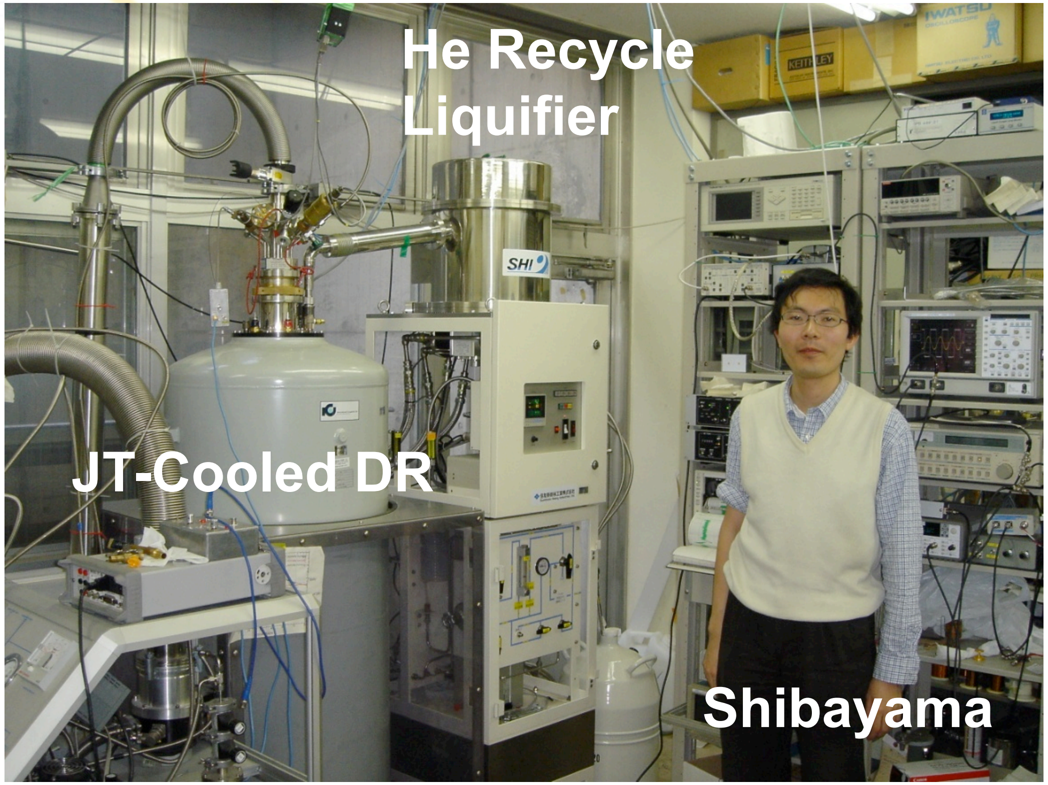
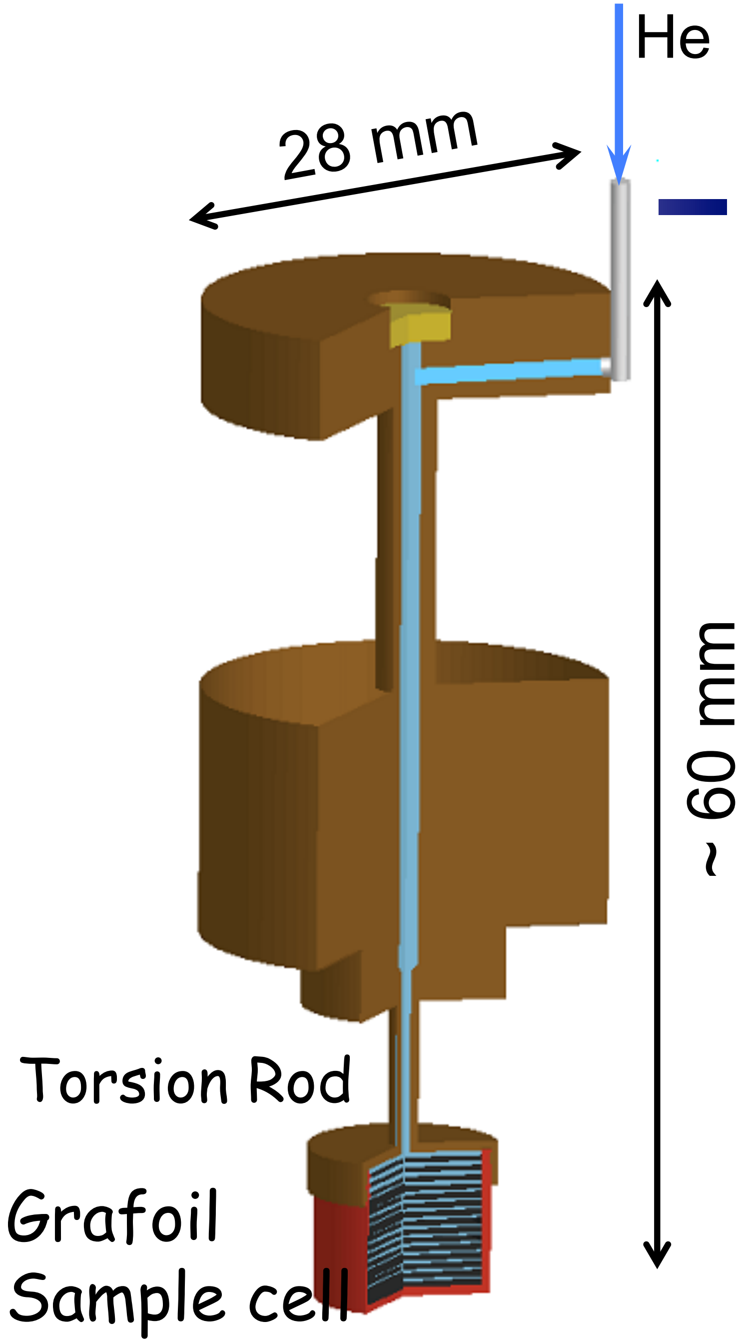
● Experimental

- Grafoil (Exfoliated graphite)
- Commercial ^{4}He (0.3 ppm ^{3}He?)
- BeCu Torsional Oscillator

  The resonance frequency : $f \sim$ 1016.4 Hz

  Q-value : $Q = 1.5 \times 10^6$ at 10 mK





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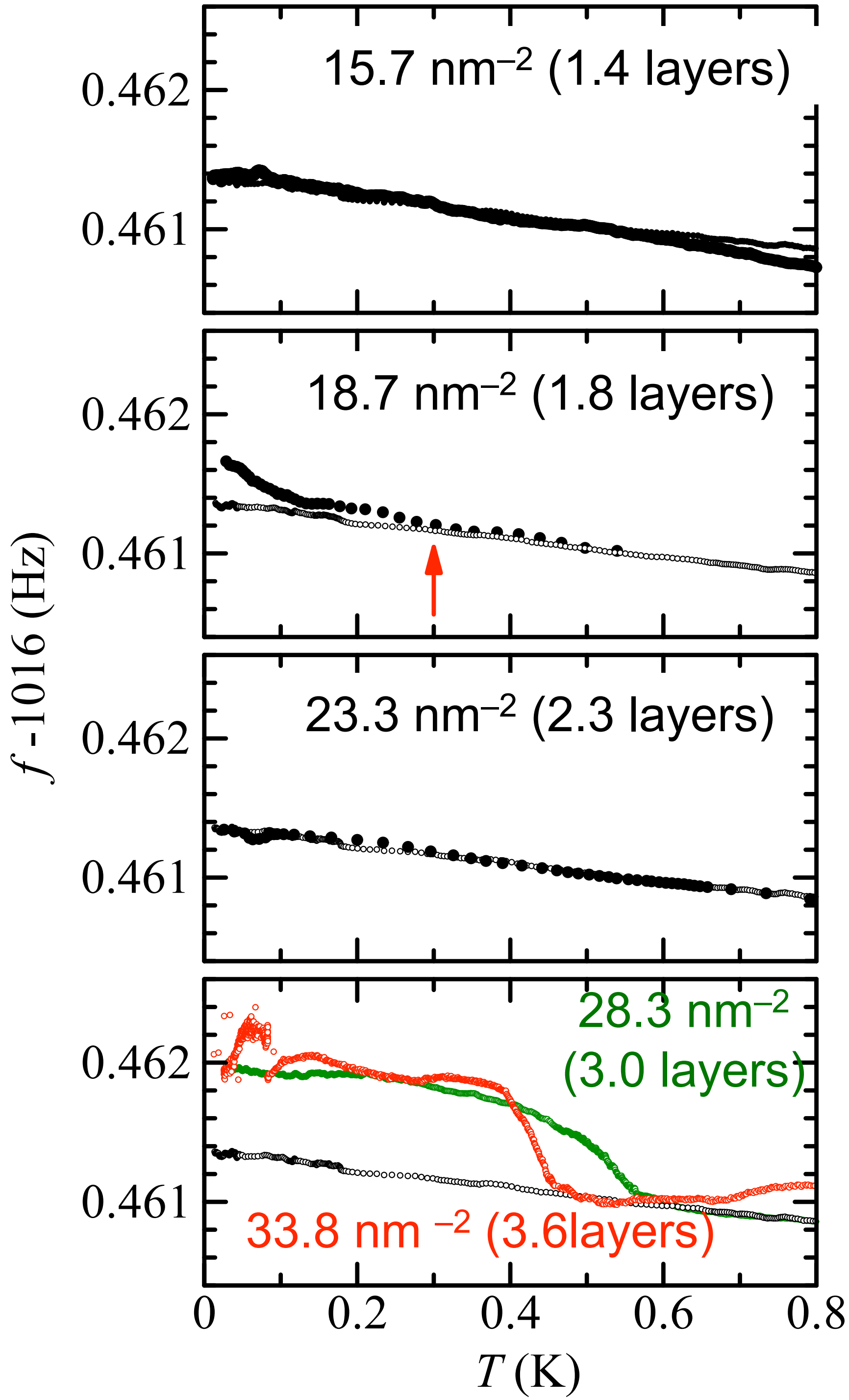
Frequency shift

・At 1.4 layers, no frequency shift was observed.
→ an inert layer state

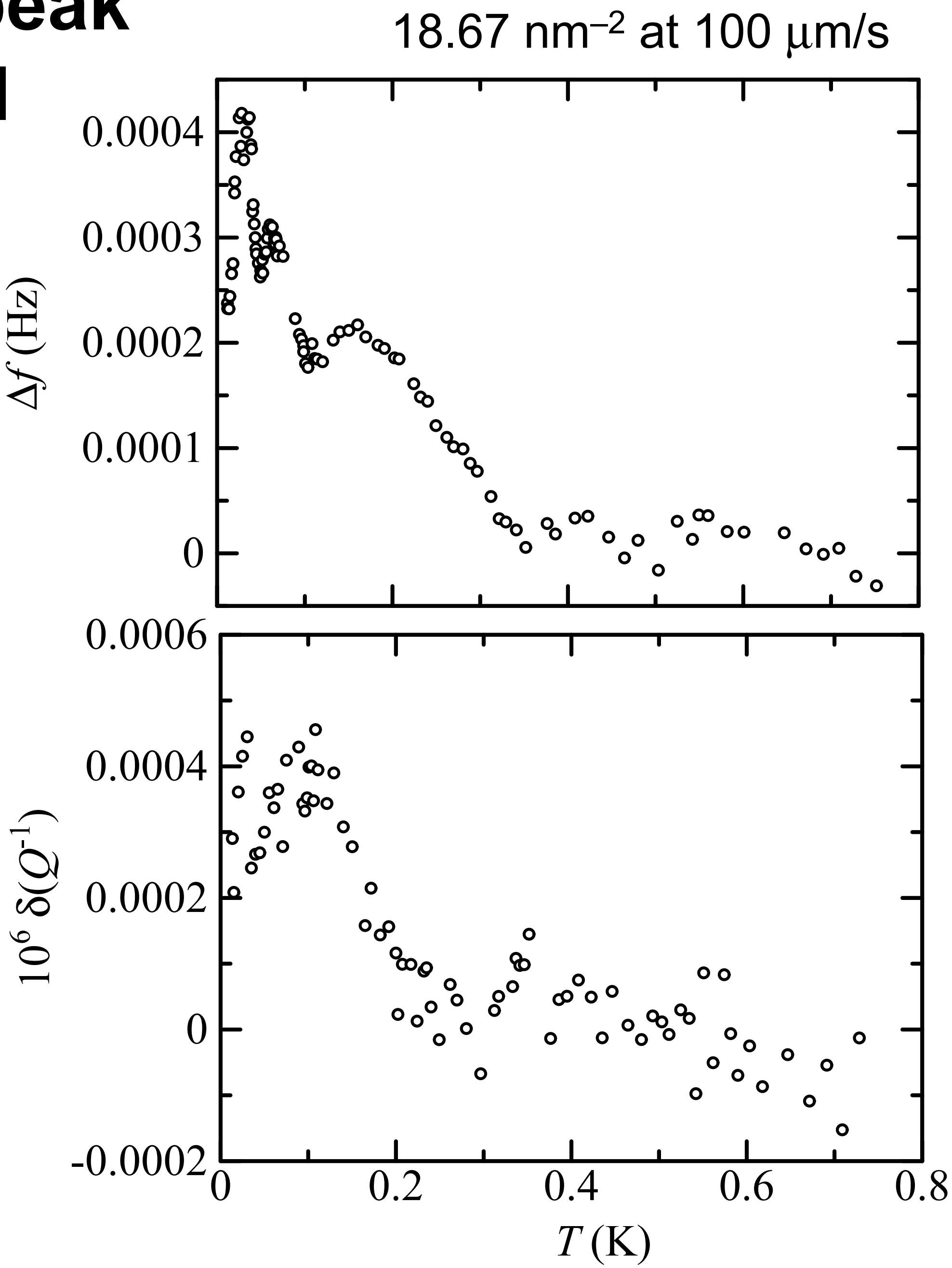
・At 1.8 layers, a positive frequency shift was observed below ～300 mK.

・At 2.3 layers, the shift disappeared once

・Over 3.0 layers, ordinary superfluidity of adsorbed liquid films were observed around 500 mK.



○NCRI and dissipation peak by a new (improved) cell



・Substantial NCRI at 18.67 nm^{-2}

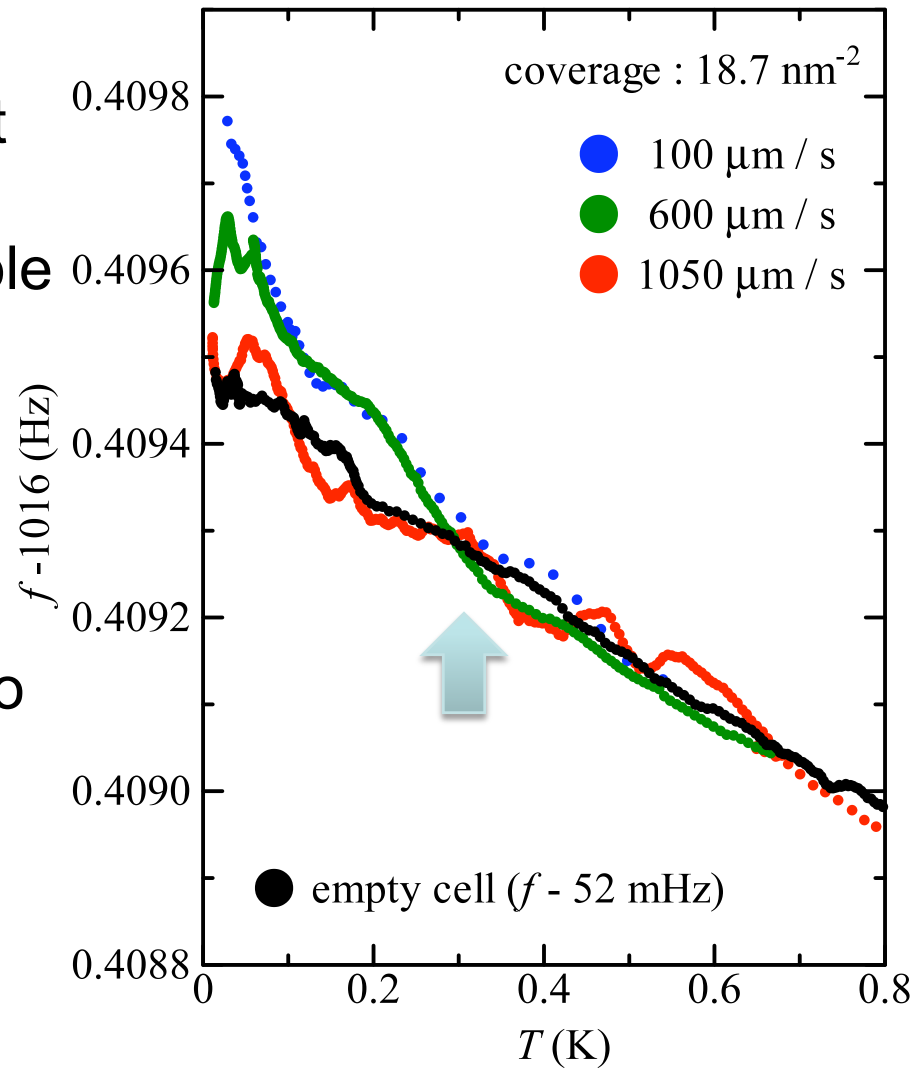
・A small dissipation (peak) at 100 mK

● Frequency shift of the 18.7 nm^{-2} sample at various oscillation velocity

With the increase in the oscillation velocity, the size of the frequency shift below 300 mK decreases.
At 1050 μm/s, f(T) is not distinguishable from the empty cell data.

・The velocity-dependent frequency shift is a common feature to the case of bulk solid ^{4}He.

・The present coverage corresponds to the one of **the novel superfluidity of ^{4}He (by CR)** and of **the novel ZPVs state in ^{3}He (by Matsumoto *et al.*)**



↓

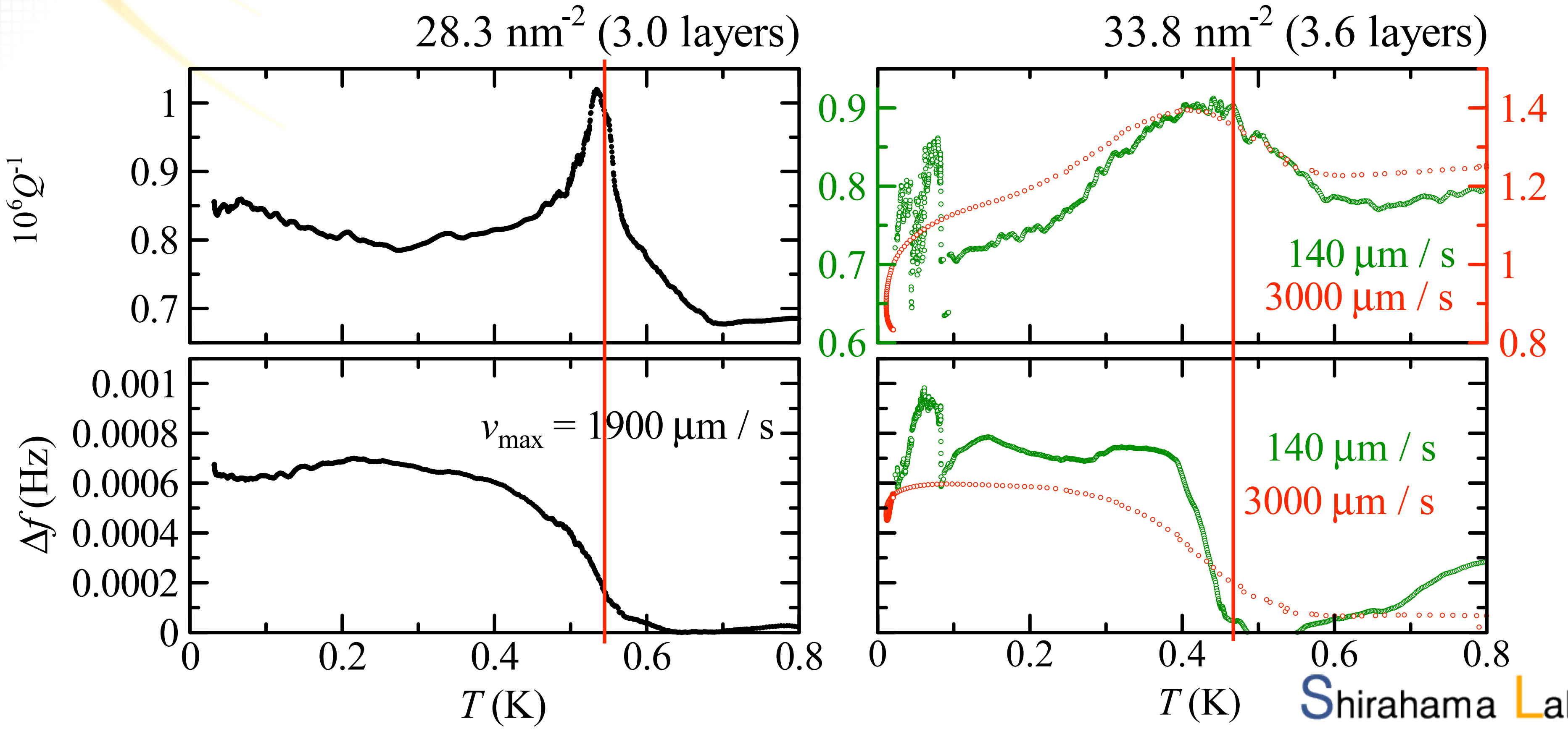
The observation can be associated with **superfluidity of ZPVs** in 2D solid ^{4}He, namely **a 2D supersolid state** of ^{4}He.

● **In the region over 3 layers** (28.3 and 33.8 nm^{-2})

・We observed both frequency shifts and the dissipation peak, which are attributed to **ordinary superfluidity of liquid ^{4}He films**

・For the 33.8 nm^{-2} sample, the magnitude of the frequency shift is independent of the oscillation velocity up to 3000 μm / s.

→ The frequency shifts are not associated with supersolidity.



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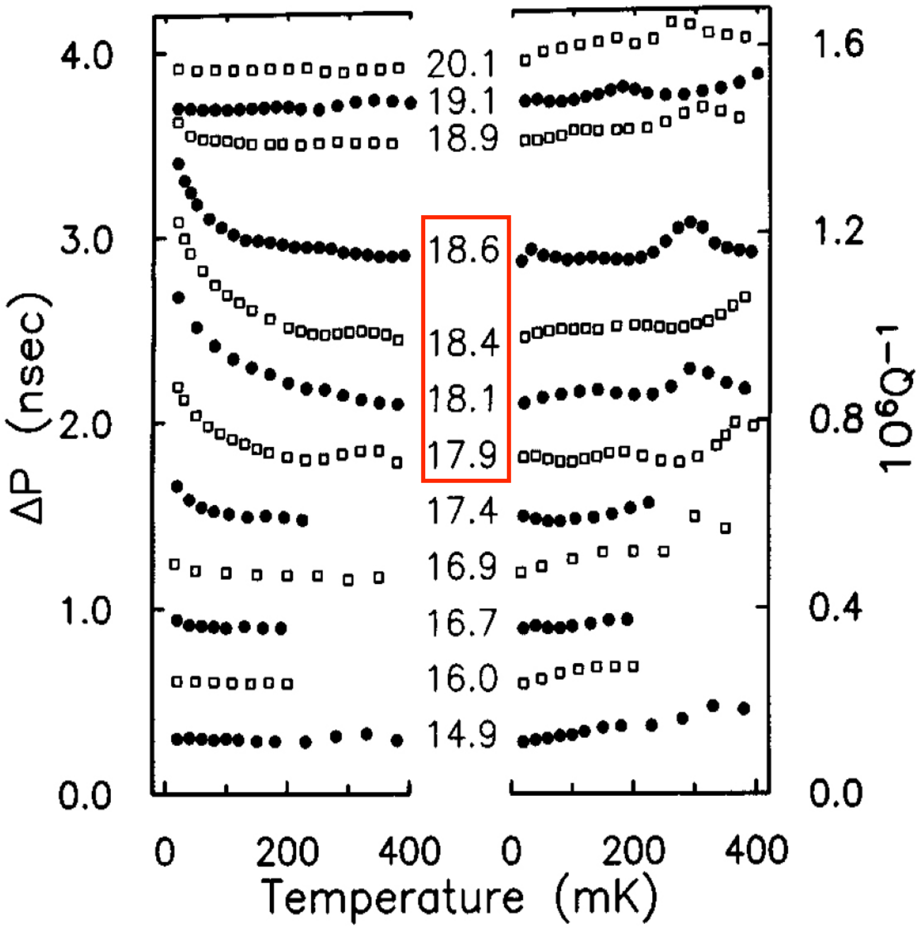
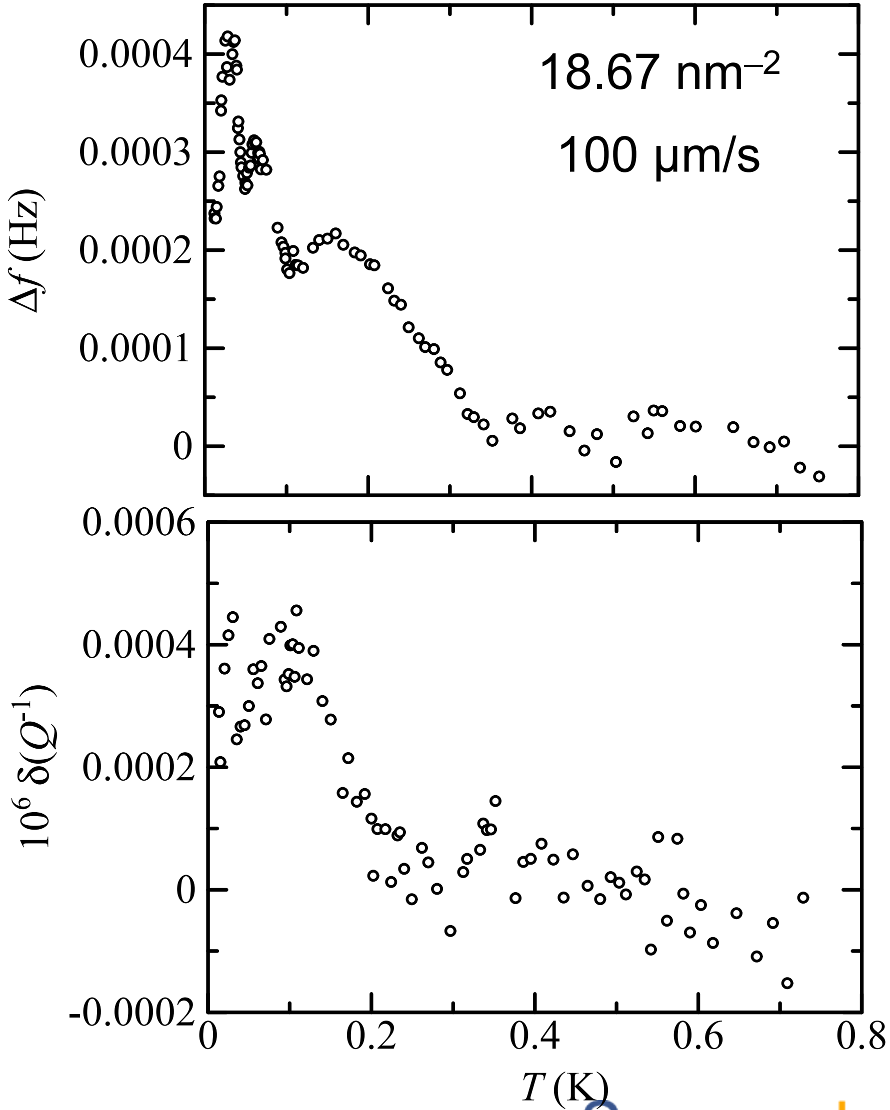
Comparison: Crowell & Reppy *PRB*53, 2701 (1996)

Oscillation velocity: 200 – 900 μm/s





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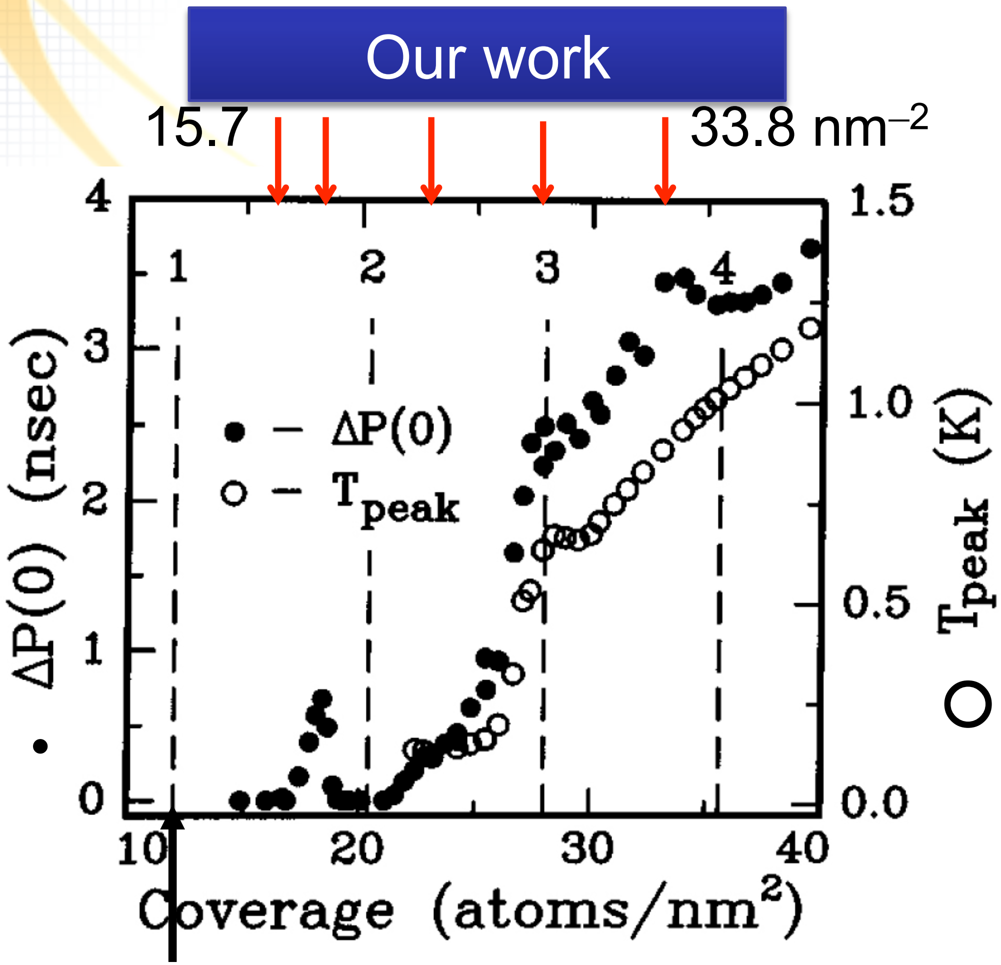
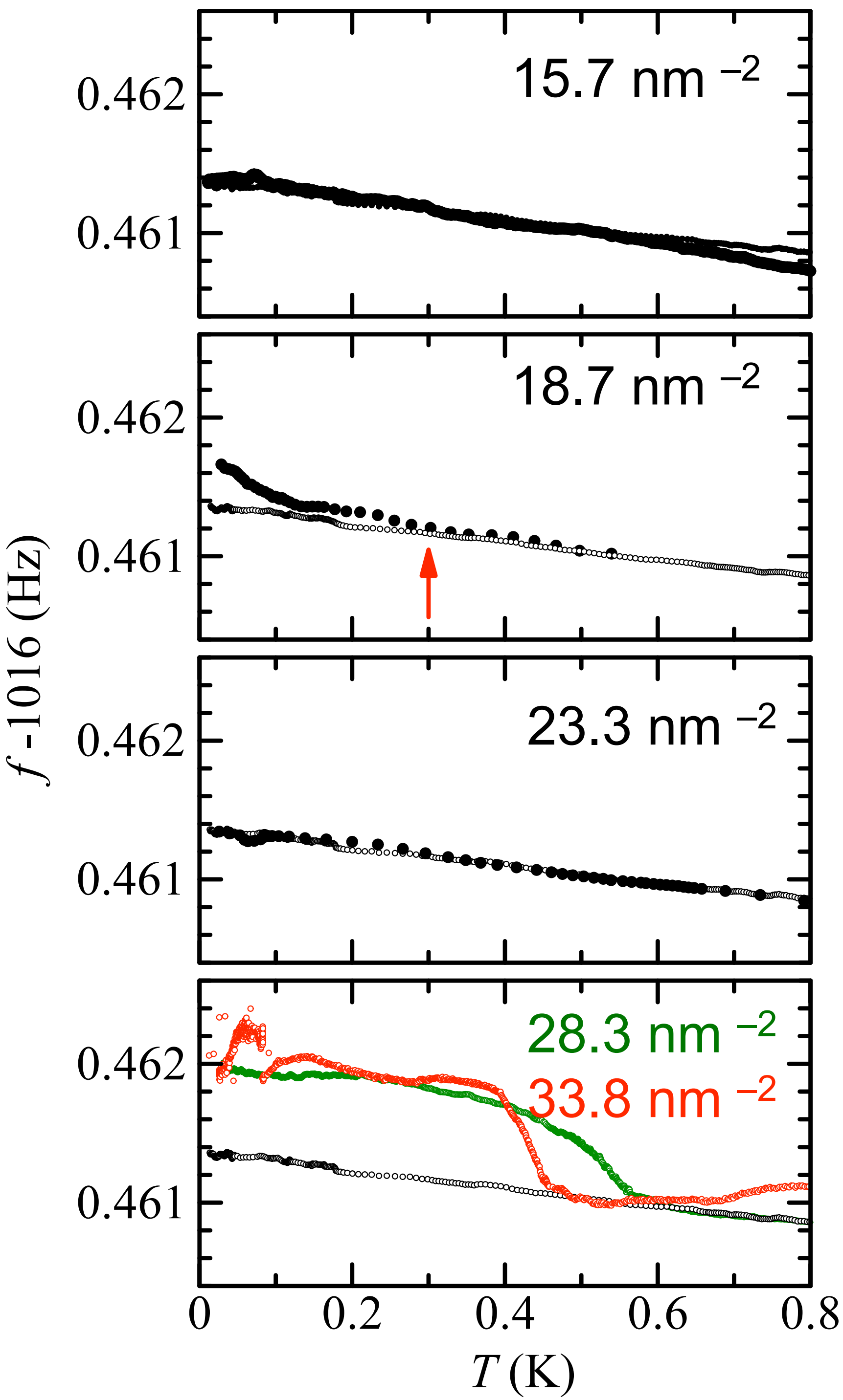
Comparison: Crowell and Reppy (*PRB* **53**, 2701 (1996))

We confirmed the results of CR

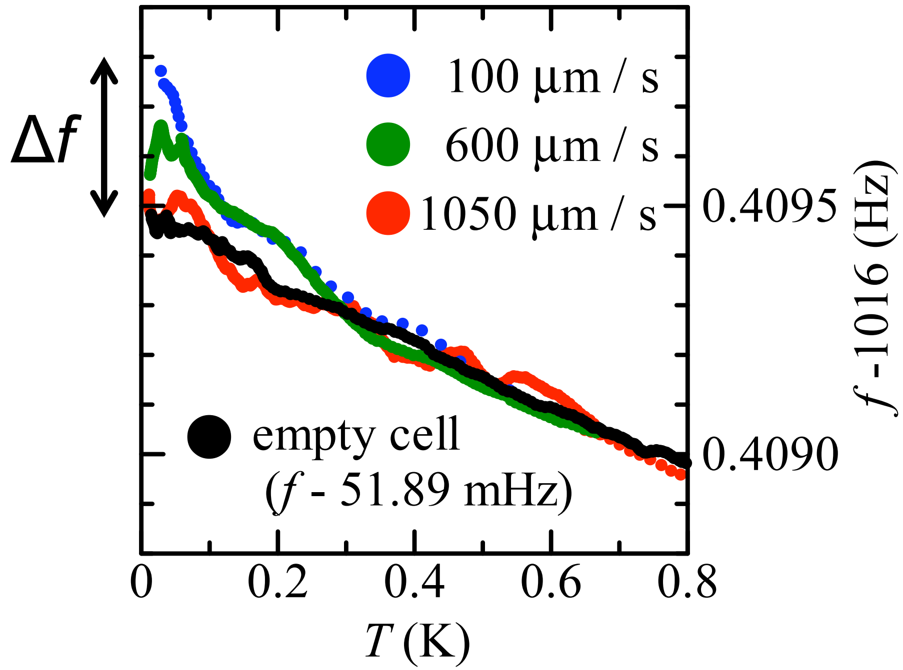


The 2nd layer begins to fill at 12 nm^{-2}



○ The size of NCRI fraction

	coverage	reduction in f by ^{4}He adsorption
Total	18.7 nm^{-2}	51.89 mHz
1st layer	12.0 nm^{-2}	33.30 mHz
2nd layer	6.7 nm^{-2}	18.59 mHz



The frequency shift at 0 K Δf : ~ 0.3 mHz $\rightarrow$ NCRI fraction : $\dfrac{0.3\ \mathrm{mHz}}{18.59\ \mathrm{mHz}} \approx 1.6\%$

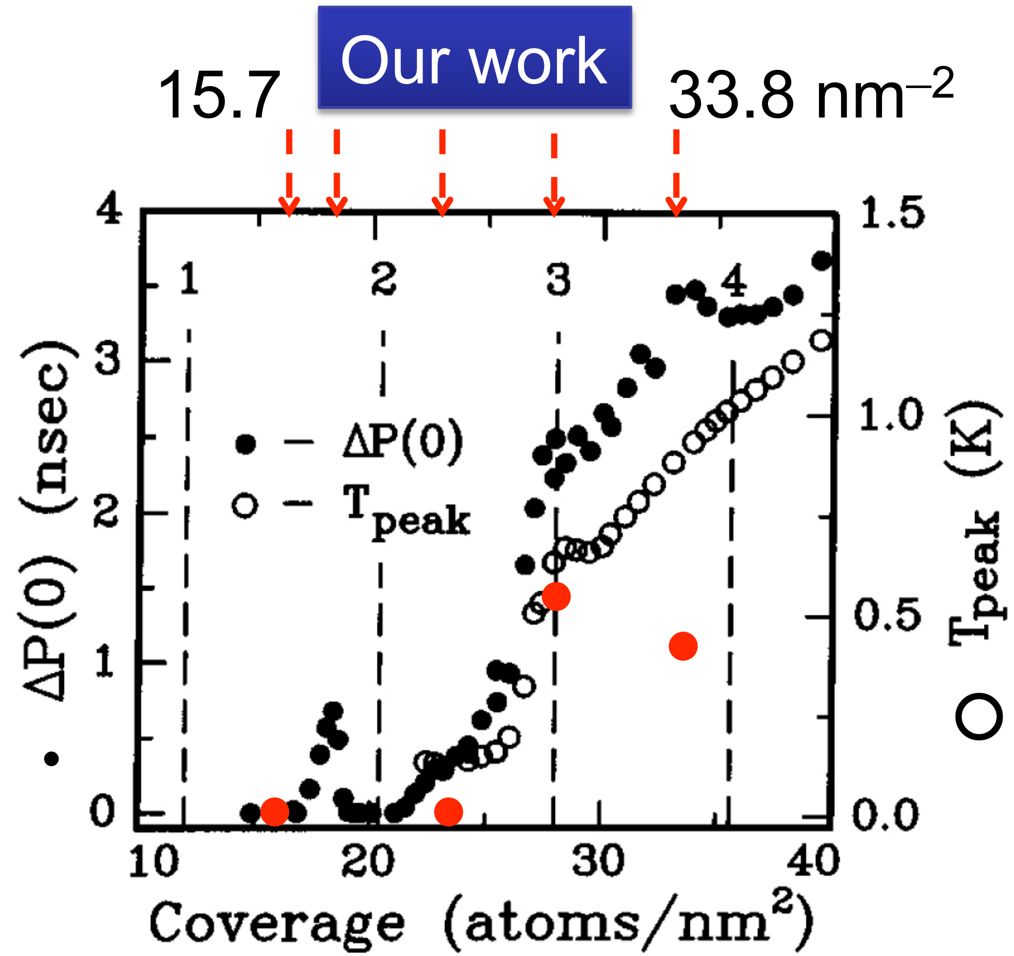
・The surface tortuosity factor χ of Grafoil is 0.98 for ^{4}He superfluid films.(Crowell and Reppy, *PRB* **53**, 2701 ('96))

This means that only 2% of total NCRI value is observable.

If the χ factor for the present system is same size, the observed NCRI fraction 1.6% implies that **the almost all the second layer ^{4}He can be a superfluid (supersolid).**

Summary - 2

1. Confirmed the Crowell-Reppy "reentrant" superfluidity
2. Velocity dependence similar to bulk solid
3. If it is NCRI, its magnitude is order of 10 – 100 % ?



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