Search for Novel Quantum Phenomena in ^4He Confined in Nano - Porous Media

（ヘリウムナノ構造における新しい量子多体現象）

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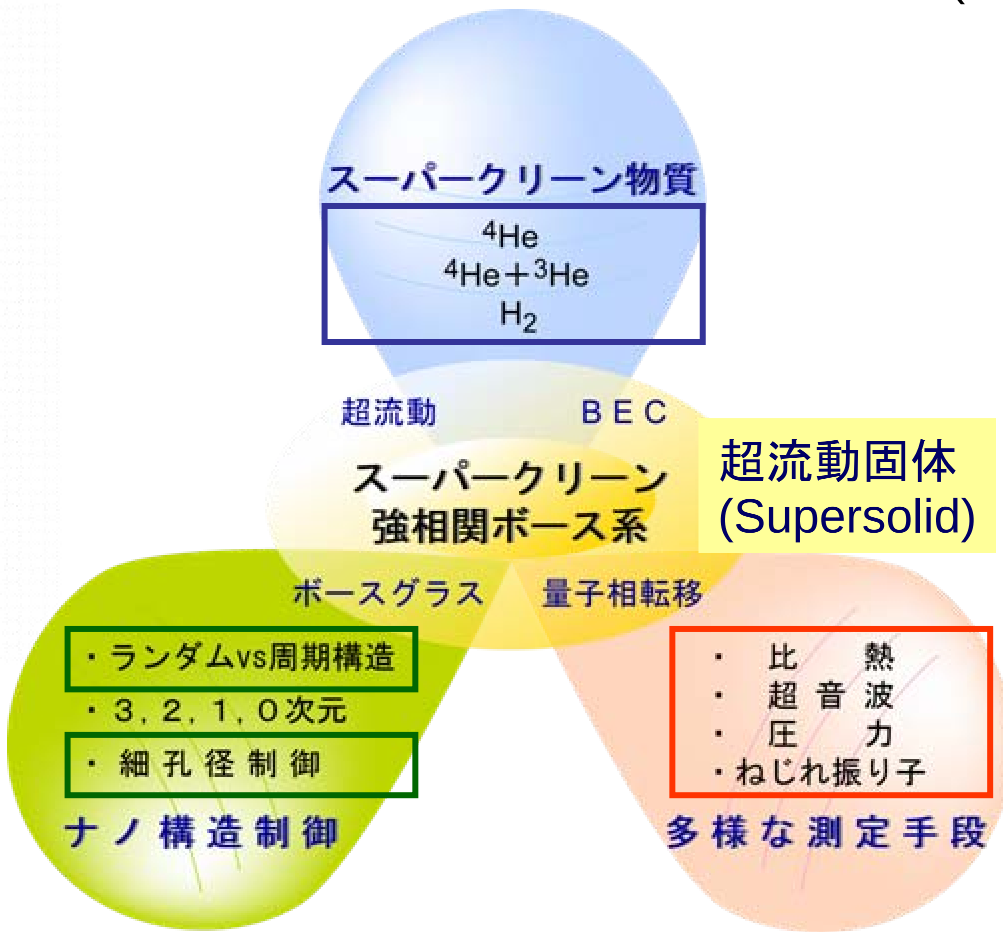
The Outline of Our Research

(科研費計画調書より)



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Outline

1. Helium Nanostructures
2. Quantum Phase Transition of ^4He
   in a Nano – porous Glass
3. Heat Capacity Measurement
4. H_2 Confined in the Nano – porous Glass
5. "Superfluidity" of Solid ^4He (Supersolidity)

Collaborators

Keio University (慶應義塾大学):

Y. Shibayama	(柴山義行)	^{3}He-^{4}He Mixtures
		Pore Control by Gas Adsorption
K. Yamamoto	(山本恵一)	Heat Capacity Measurement
Y. Sobage	(曽我部吉弘)	
Y. Ishii	(石井洋典)	Search for BEC of H_2
M. Kondo	(近藤大司)	Solid ^{4}He "Superfluidity"
S. Takada	(高田俊一)	

University of Electro-Communications (電気通信大学):

M. Suzuki	(鈴木勝)	Ultrasound Studies
J. Taniguchi	(谷口淳子)	Solid ^{4}He "Superfluidity"
T. Kobayashi	(小林利章)	
S. Fukazawa	(深沢聡)	

University of Delaware

H. Glyde & Coworkers	Neutron Scattering

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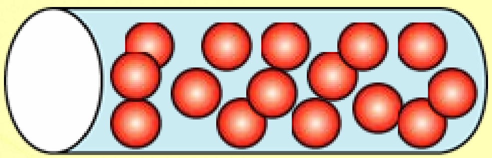
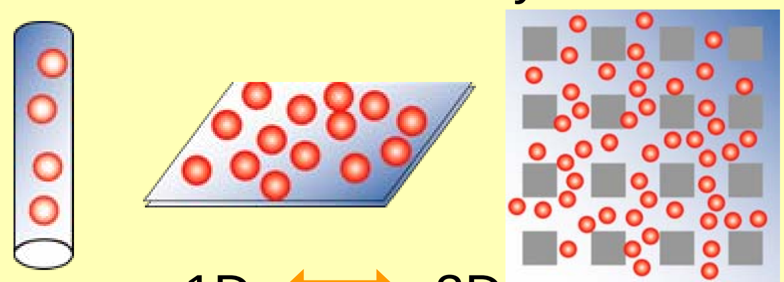
^{4}He Nanostructures: A model system of strongly correlated Bosons in a periodic or random potential

Interaction (Correlation)



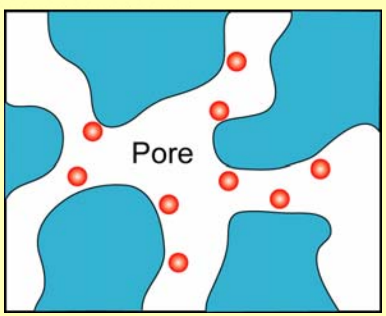
Dilute Gas ⟷ Dense Liq/Sol

Dimensionality

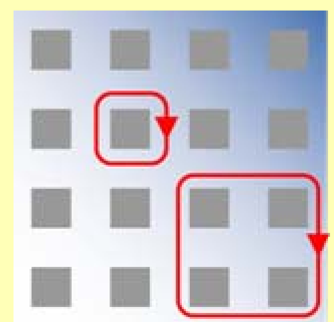


1D ⟷ 3D

Disorder



Topology



Novel Quantum Phases = Mott Insulator
Bose Glass
Supersolid….

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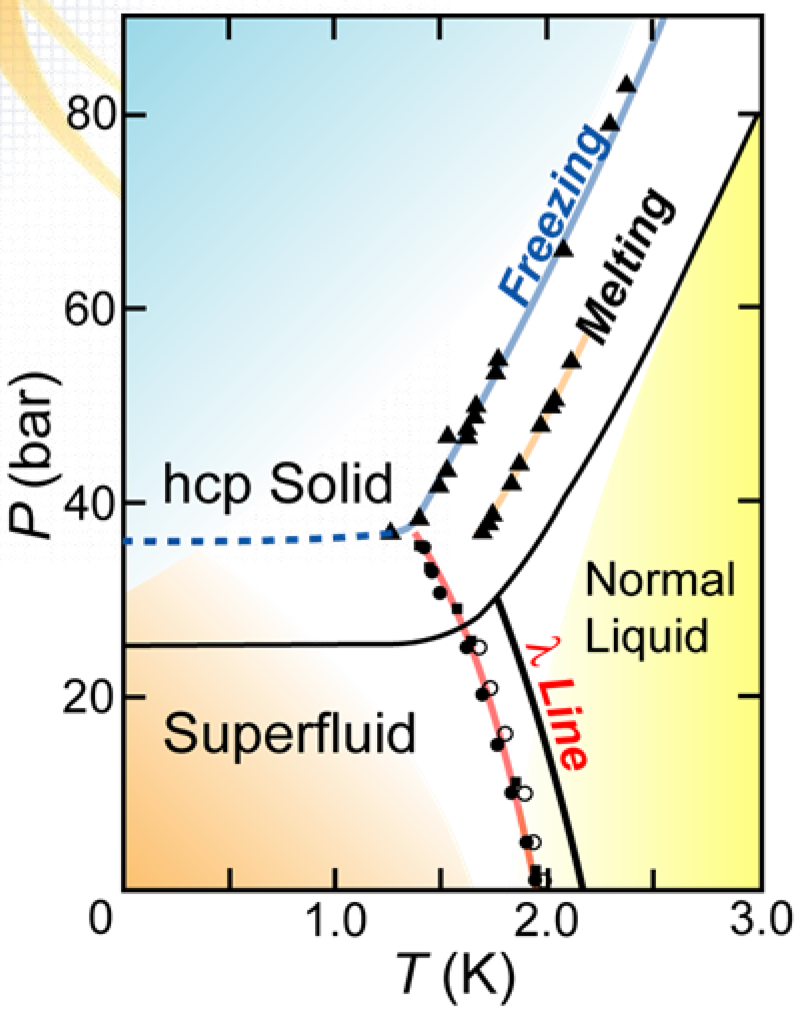
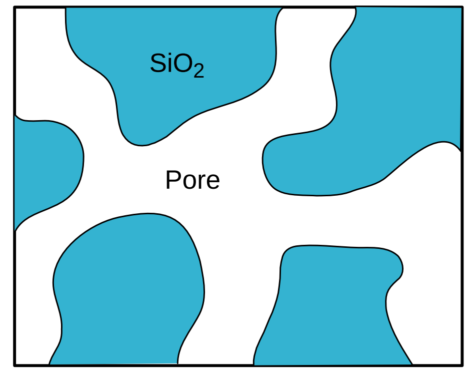
Physics of (Over) pressurized Liquid ^4He in Porous Media

Phase Diagram of ^4He in Porous Vycor Glass

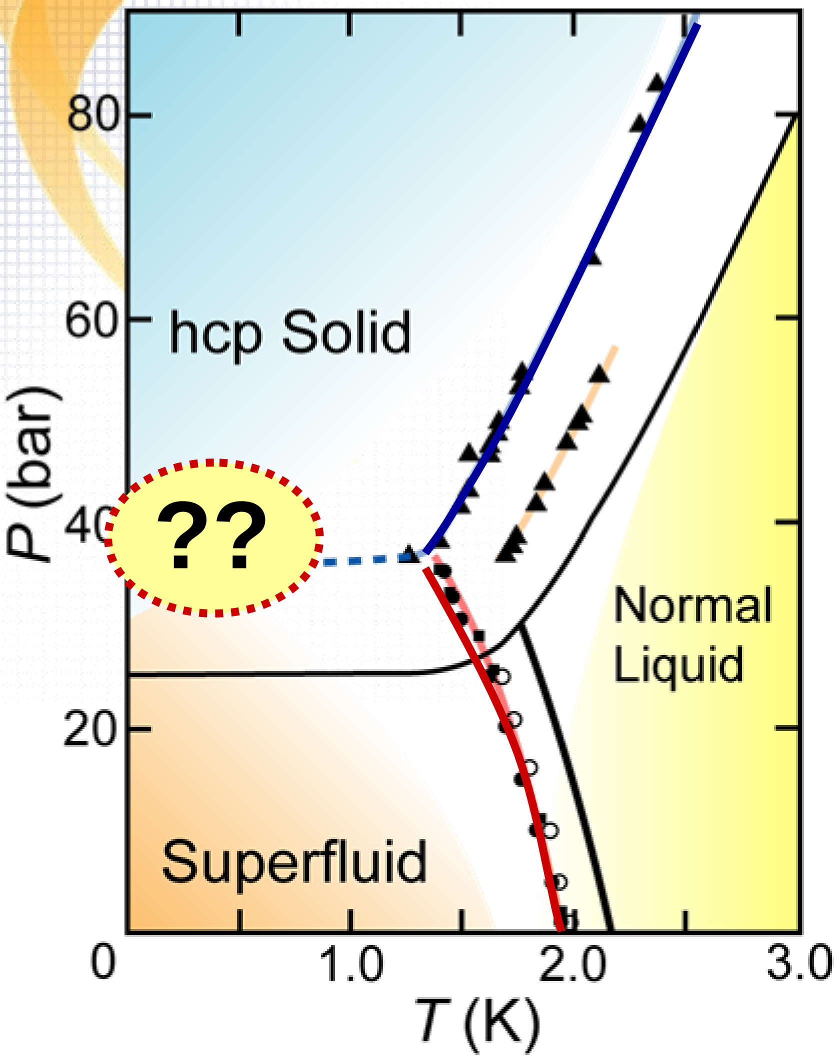




- 3D Random Network of Pores
- 7 nm in Pore Diameter

- Shift of **Freezing Curve**
- Shift of **the λ Line** (~0.2K)

Cao et al. *PRB* **33**, 106 (1986)
Adams et al. *PRL* **52**, 2249 (1984)

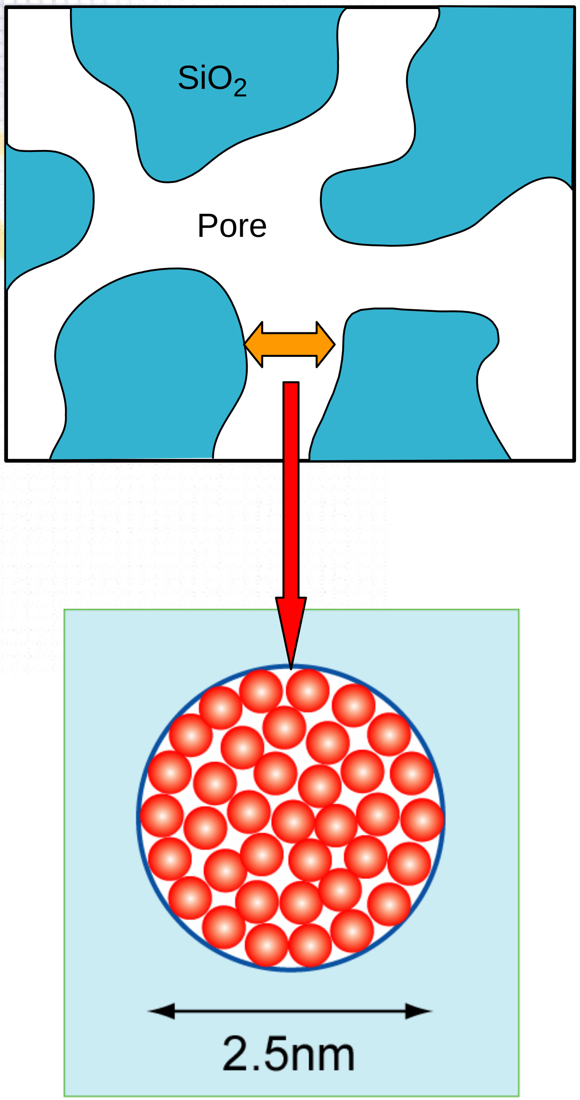


How is the superfluidity suppressed
as the Pore Size DECREASES ?

^{4}He in a Nano-porous Glass

- Superfluidity:
  Torsional Oscillator Study
  (*PRL* **93**, 075302 (2004))
- Liquid – Solid Phase Boundary:
  Pressure Study

^{4}He in Porous Gelsil Glass



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

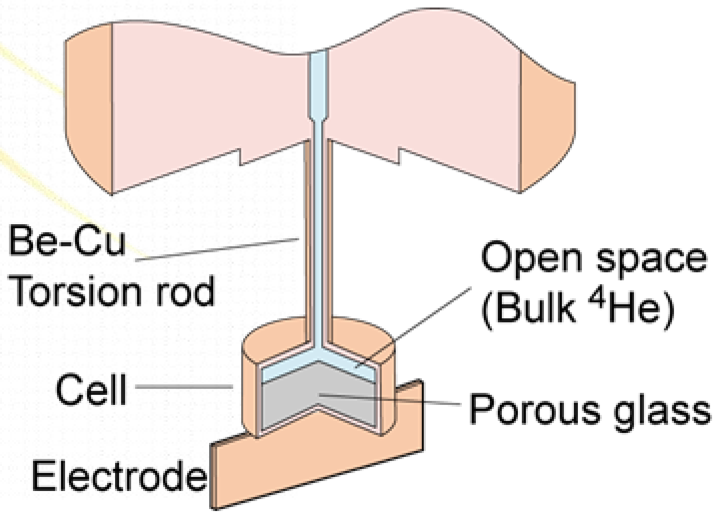
  1/3 of Vycor Pore
- ^{4}He atoms in Pores :

  7~8 atoms in radial

  40 atoms in cross section

Experimental Techniques

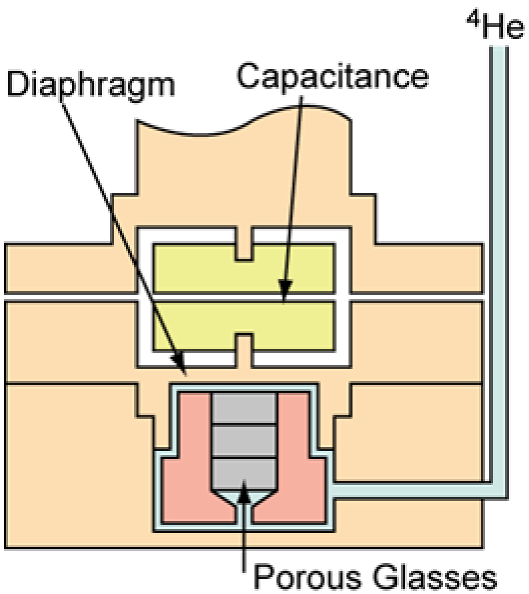
Torsional Oscillator



f ~ 1960 Hz

Superfluidity

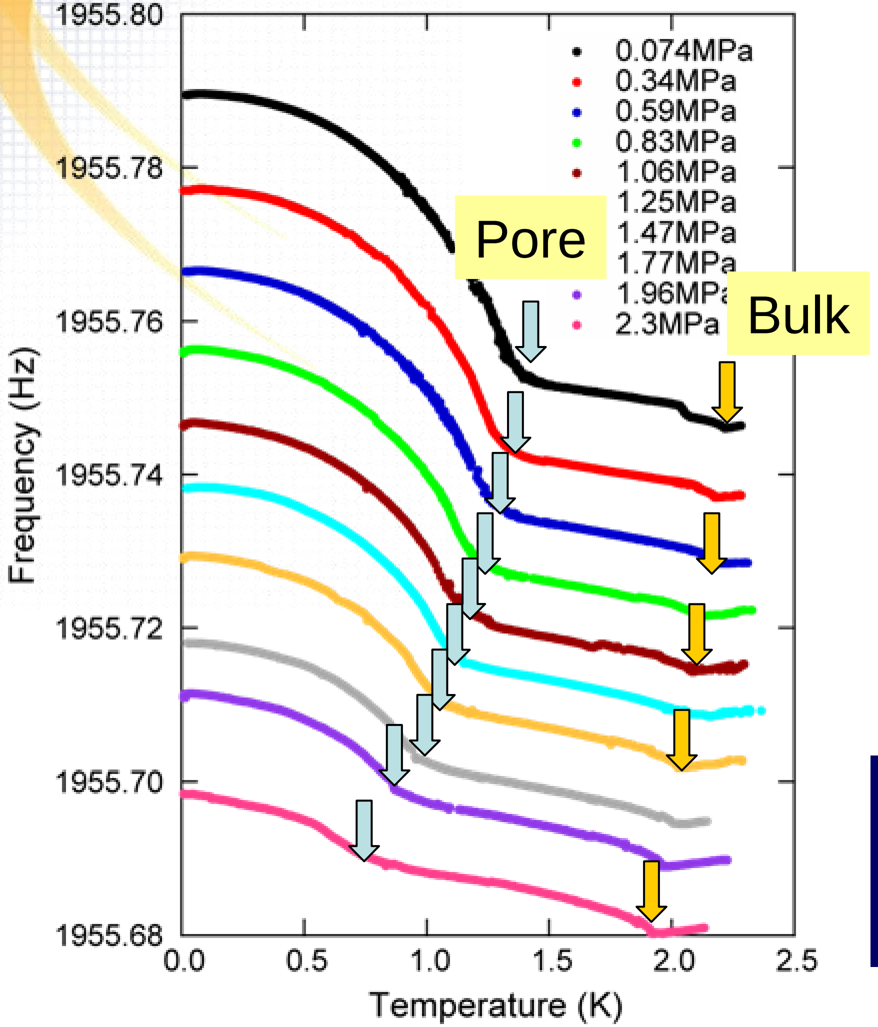
Isochoric Pressure



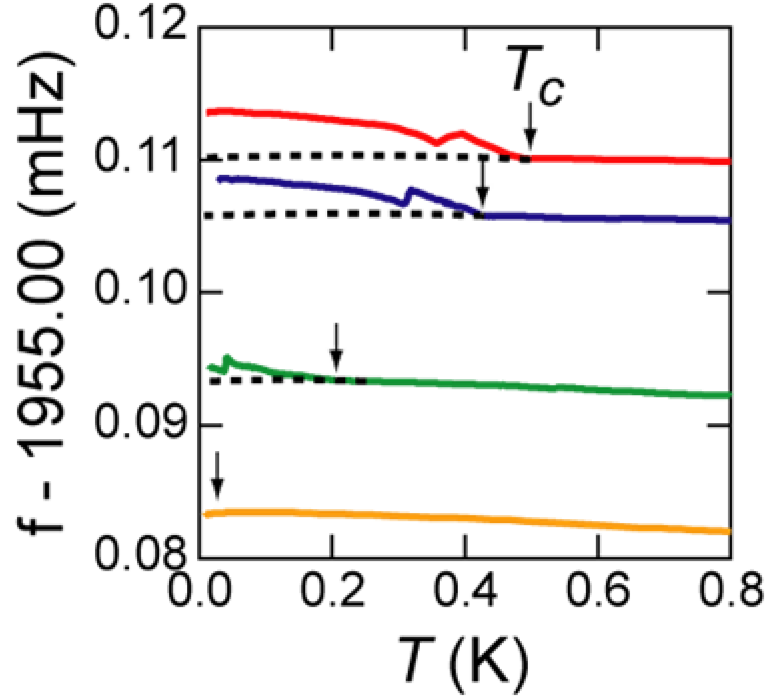
Liquid – Solid Phase Boundary

Suppression of Superfluidity

P < 2.5 MPa



Above bulk freezing pressure



- T_c decreases by pressurization
- Lowest T_c ~ 35 mK : at *P* ~ 3.3 MPa
- 3.5 < *P* < 5.0 MPa : No superfluidity

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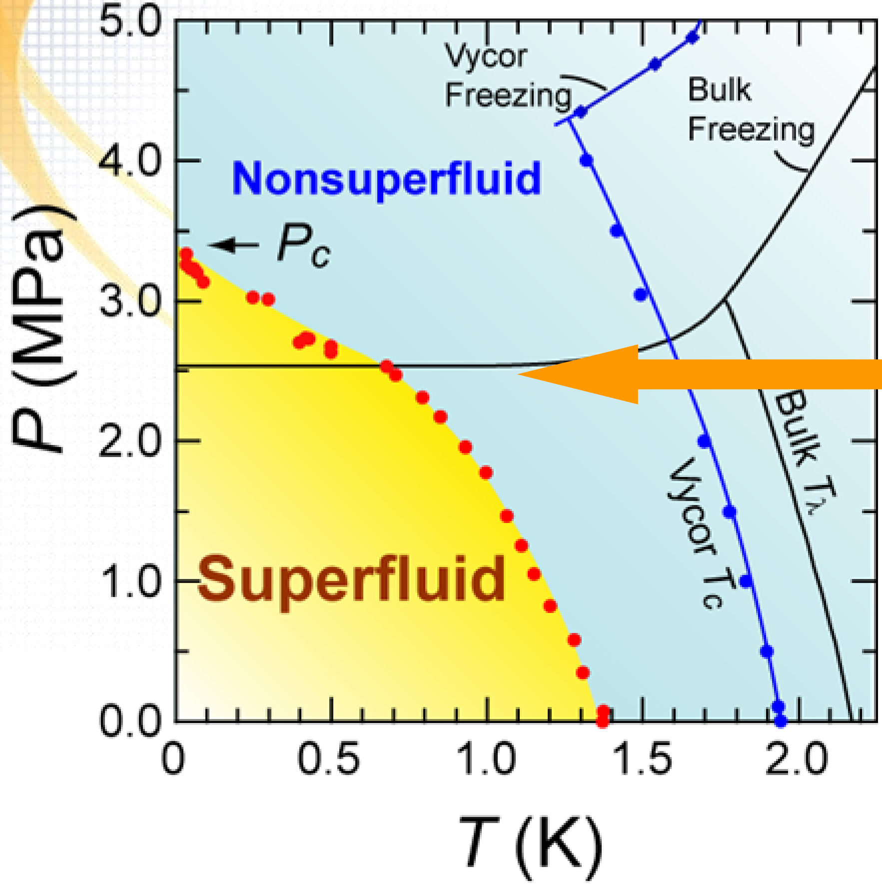
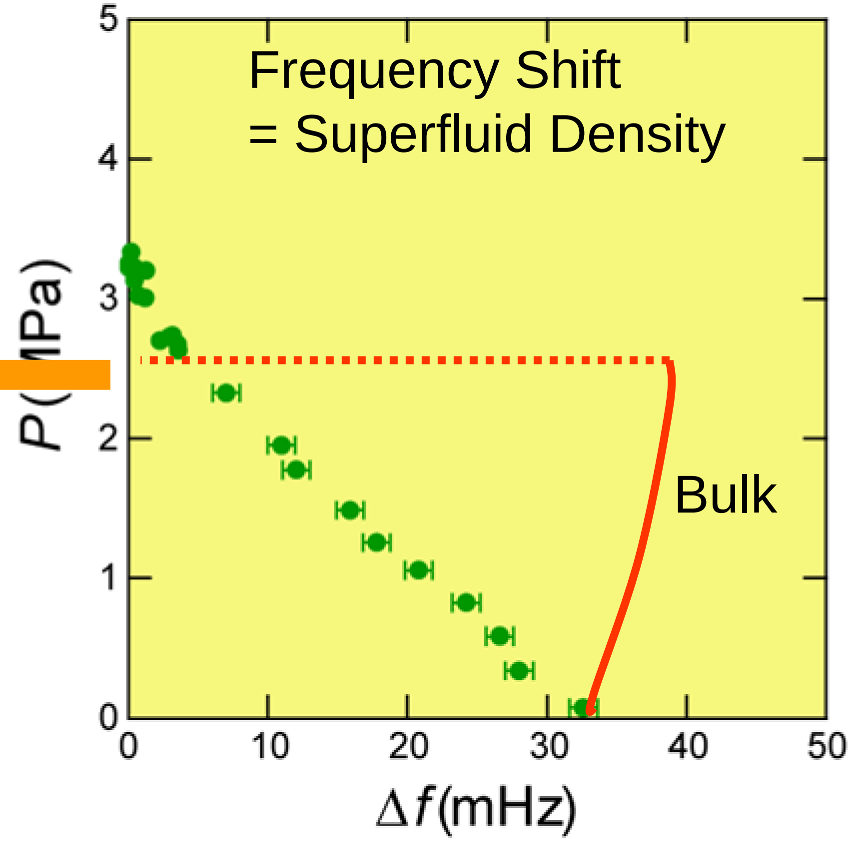
Continuous Reduction of T_c and ρ_s





T_c and ρ_s continuously decrease to zero, at $P_c \sim 3.4$ MPa.

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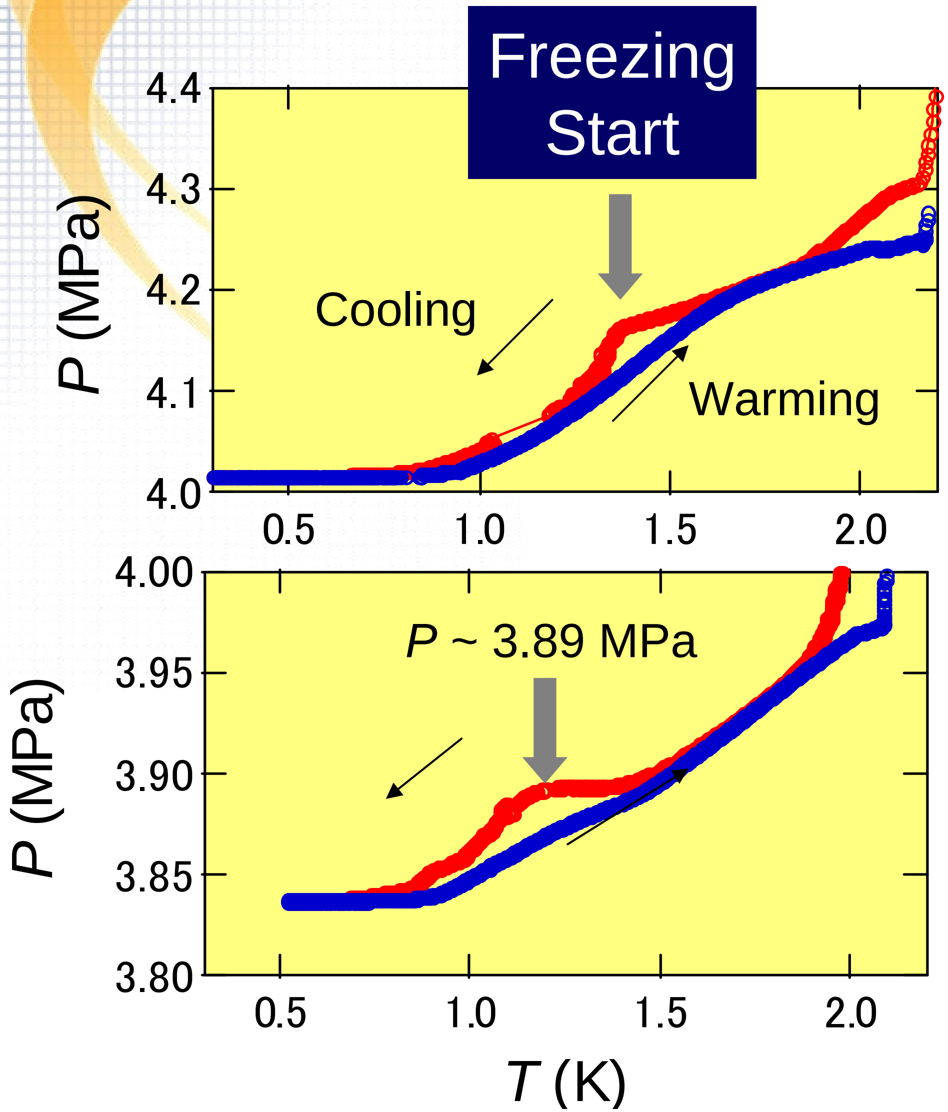
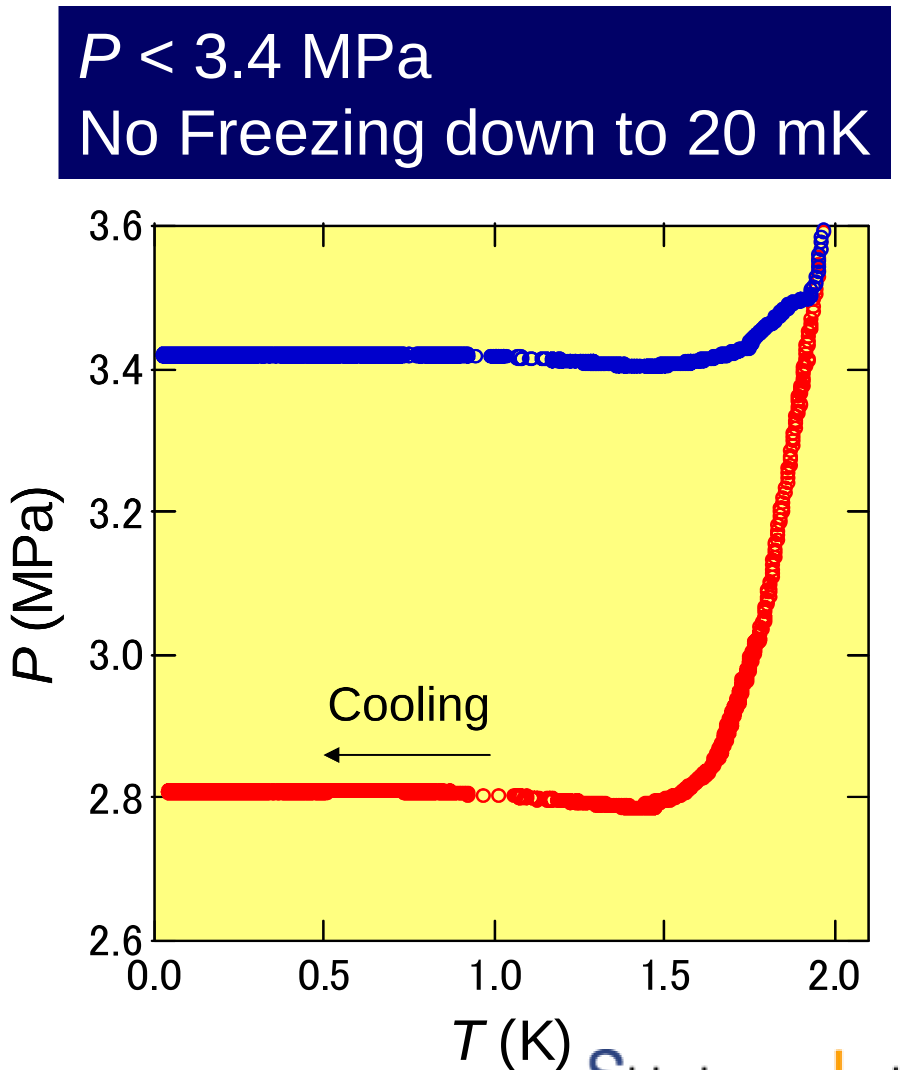
Determination of the Liquid – Solid Transition





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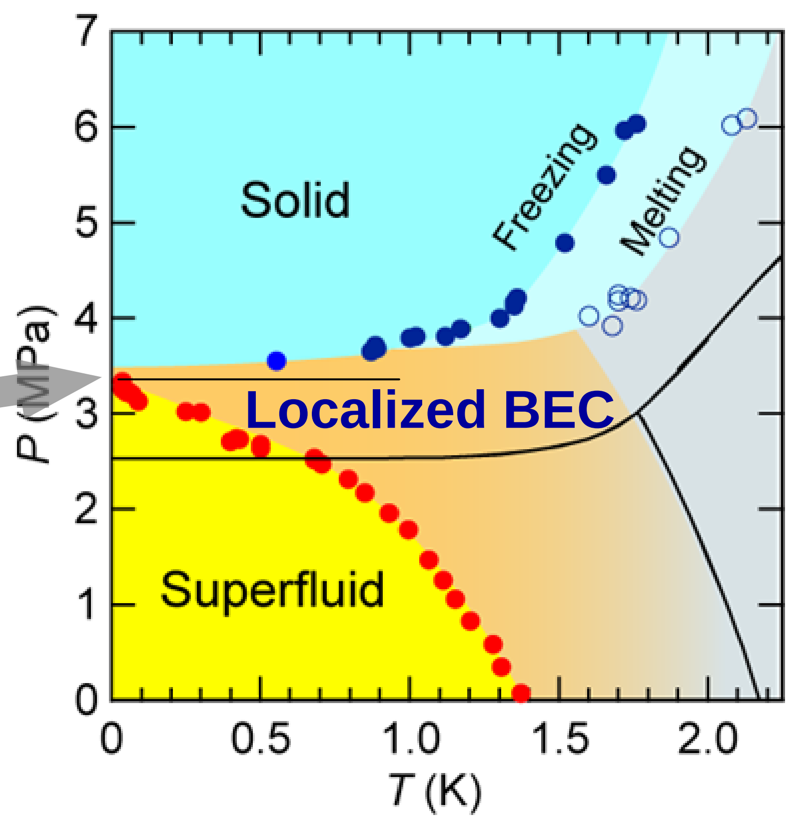
Phase Diagram

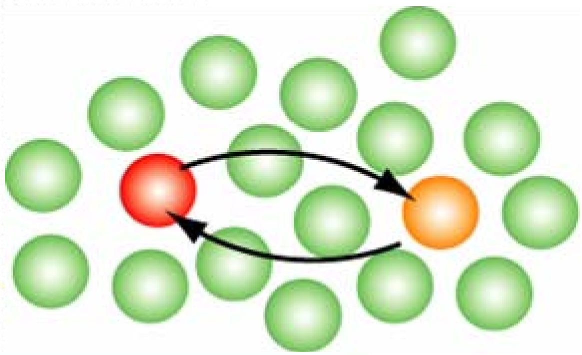
Present “Lower Limit” of the Solid Phase
P_{c2} ~ 3.42 MPa

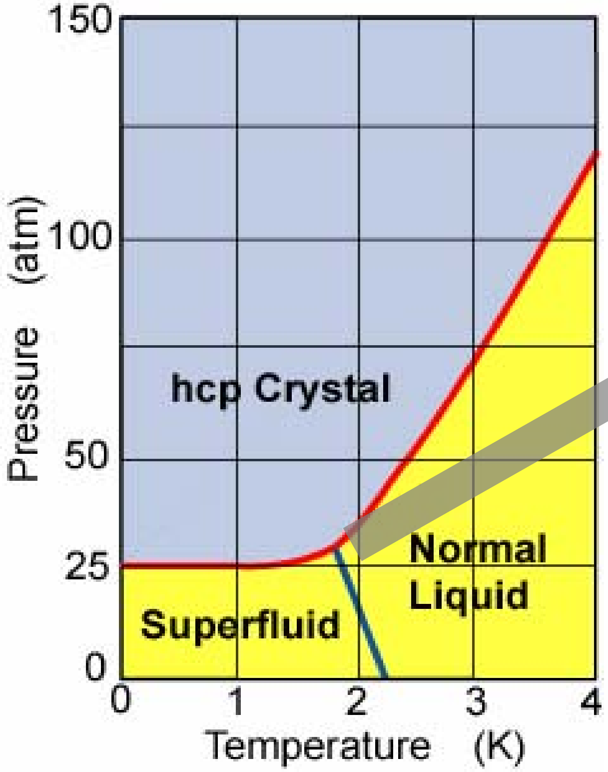


Flat solid phase boundary :
Adjacent “nonsuperfluid” phase has small entropy.

A Superfluid – Nonsuperfluid – Solid quantum phase transition is driven at 0 K, by increasing pressure (density)

Helium is a Strongly Correlated System





- "Hard Core" interrupts atom exchanges.
- Example : Negative Slope of the "Lambda" Line

Superfluidity = BEC + Correlation

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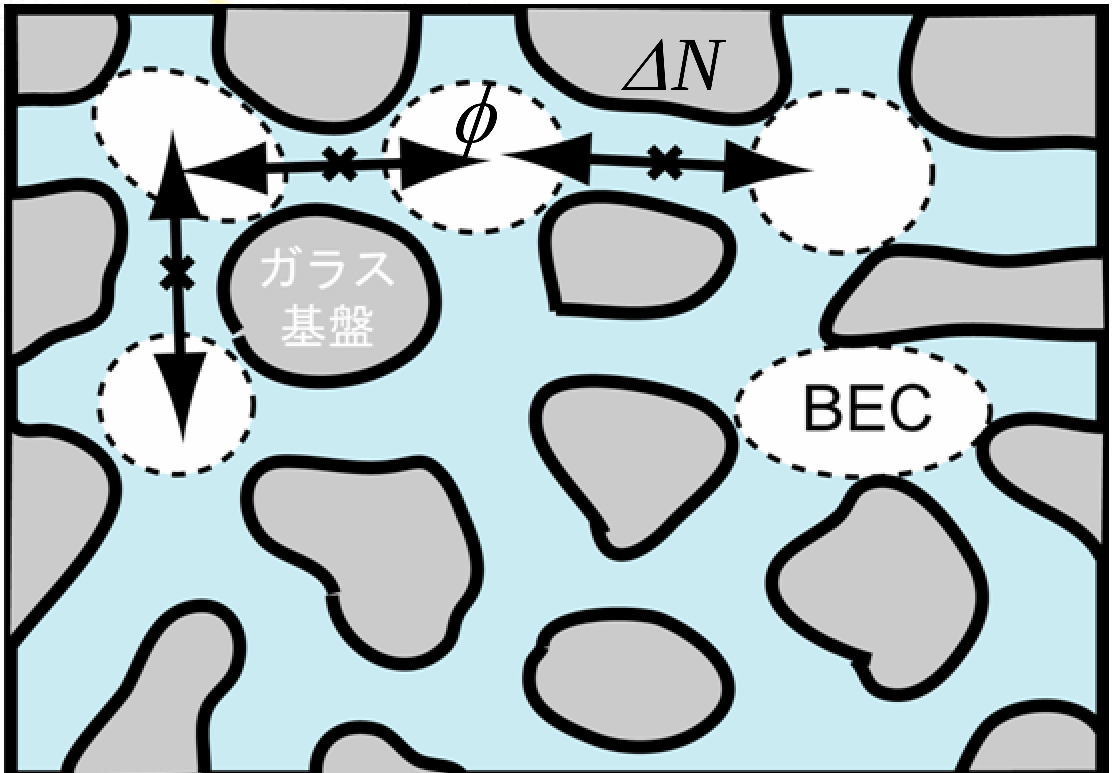
Possible Scenario: Phase Fluctuation and Localized BEC

Superfluid Order Parameter:

$$\Psi(\boldsymbol{r}) = A(\boldsymbol{r})\exp\{i\phi(\boldsymbol{r})\}$$

Amplitude   Phase



Number – Phase Relation:

$$\Delta N \cdot \Delta \phi \geq 1$$

Hard Core + High Density

↓

Exchanges of atoms are suppressed at the pores

↓

- **Phase Fluctuation**
- **Suppression of T_C**
- **Localized BEC**

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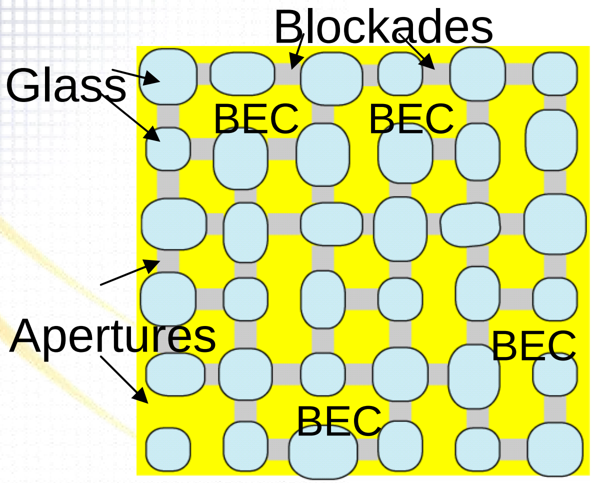
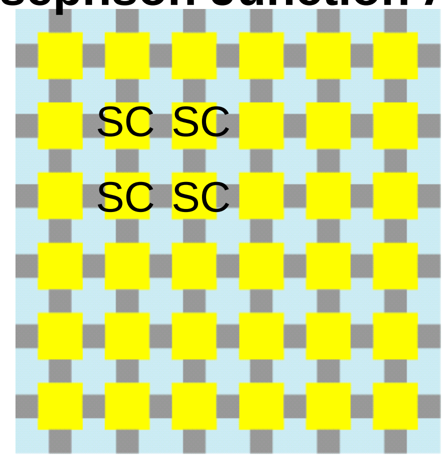
Analogy to Josephson – Junction Arrays

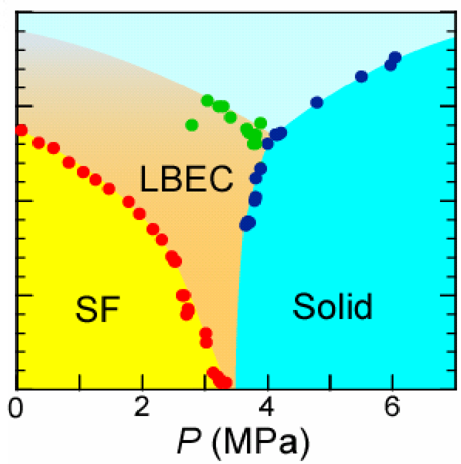


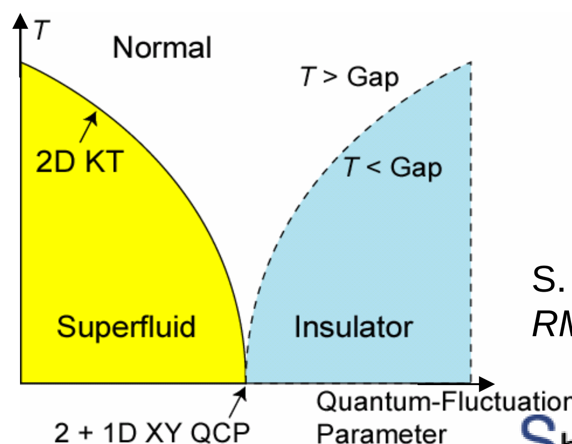
2D Josephson Junction Arrays



Interruption of **atom exchanges at the apertures** results in phase fluctuation.

Interruption of **the Cooper-pair tunneling by the Coulomb blockade** effect results in phase fluctuation.





S. L. Sondhi et al.
RMP **69**, 315 ('97)

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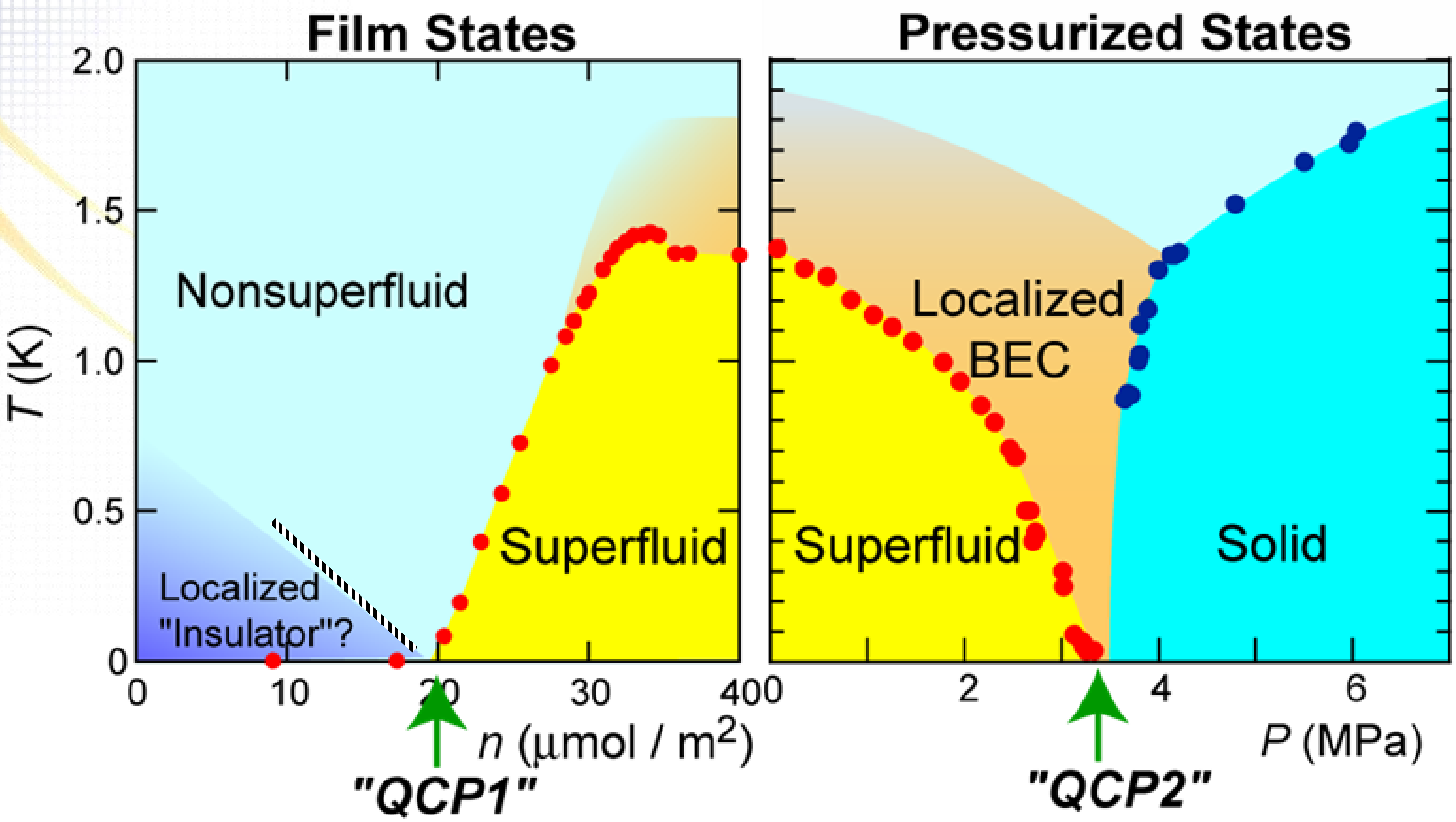
Global Phase Diagram



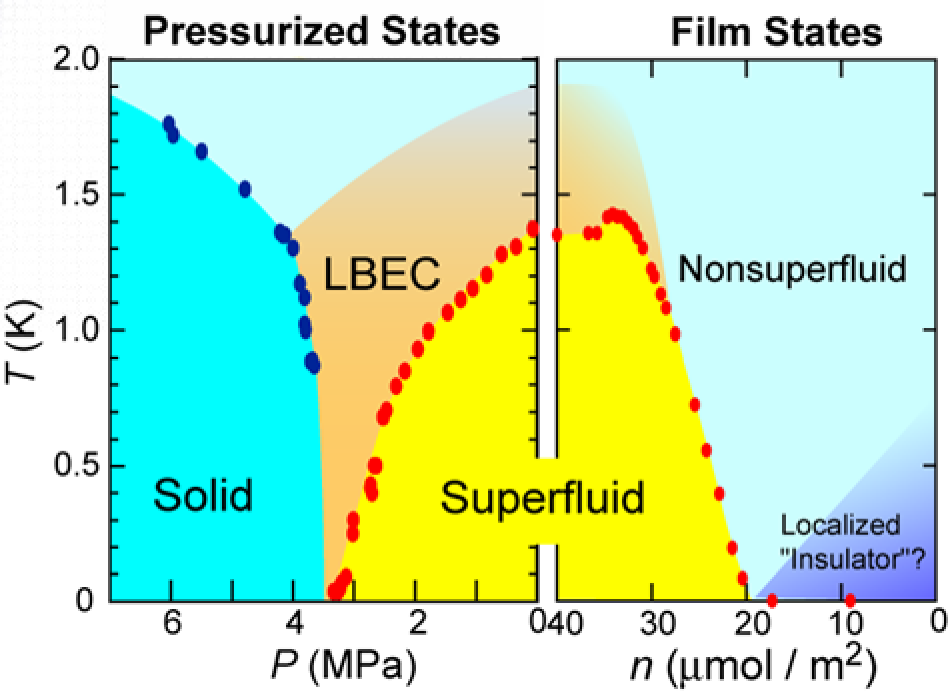
Crowell et al., *PRB* **55**,12620 (1997)

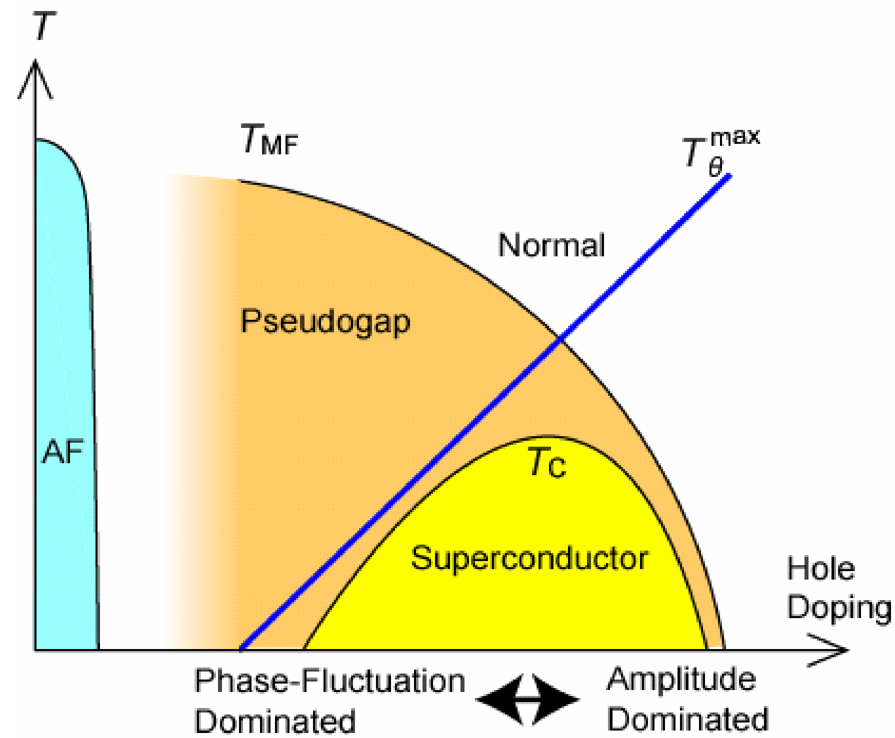
The ^4He – Nanopore system can be characterized by two quantum critical points.

Analogy to High - Tc Cuprates & Granular Superconductors

V. J. Emery, S. A. Kivelson, *Nature* **374**, 434 (1995)
L. Merchant, J. Ostrick, R. P. Barber, R. C. Dynes, *PRB* **63** 134508 (2001)

Localized BEC ⟷ Pseudo Gap State





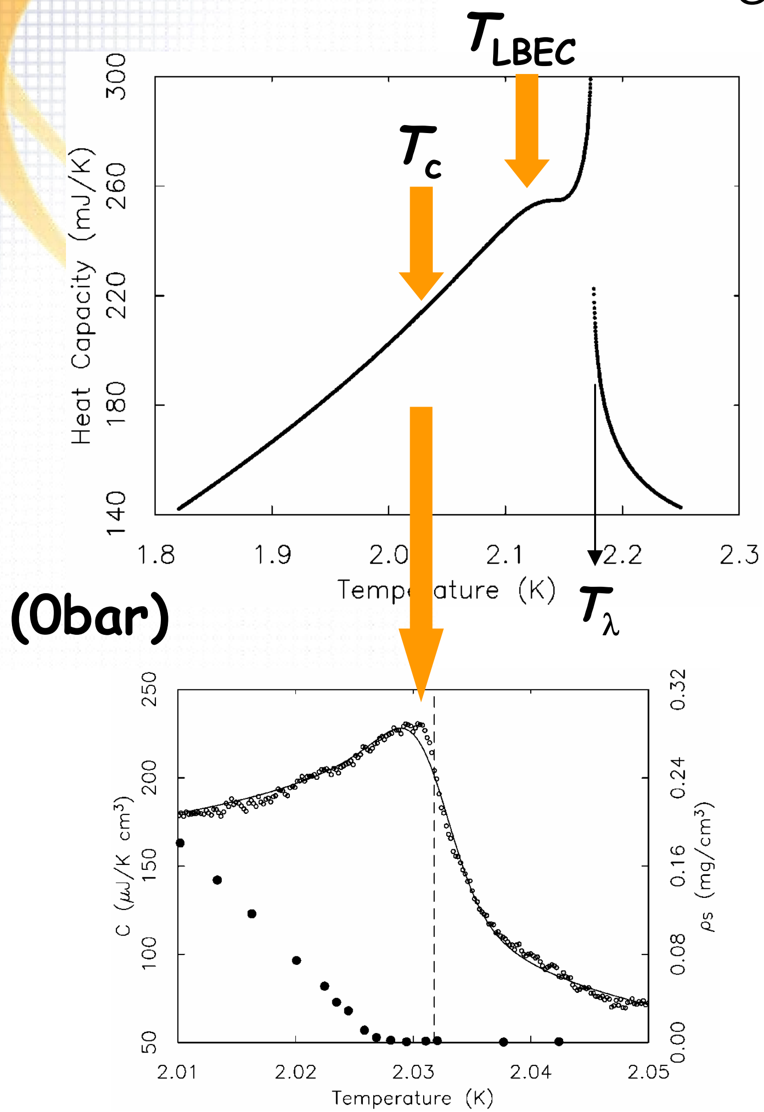
Elucidating the Nature of the Localized BEC

Ultrasound

Heat Capacity

Heat Capacity of ^{4}He in Porous Vycor Glass

G. Zassenhaus and J. D. Reppy, *PRL* **83**, 4800 (1999)



A broad peak below bulk T_λ

Evidence for Localized BEC ?

A small peak is observed at T_c which is determined by torsional oscillator.

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LBEC: Similar to ^{4}He Droplets and Clusters?

E. Syskakis, F. Pobell, H. Ullmaier, PRL 55, 2964 (1985)
S. Grebenev, J. P. Toennies, A. F. Vilesov, Science 279, 2083 (1998)

^{4}He Droplets(20~60A) in a Cu Foil

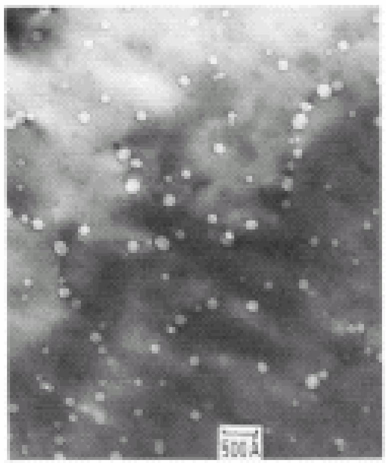

FIG. 2. A typical TEM picture of underfocused helium bubbles in Cu. The bubbles appear as light areas and are clearly faceted.

Rounded λ Peak below bulk T_λ

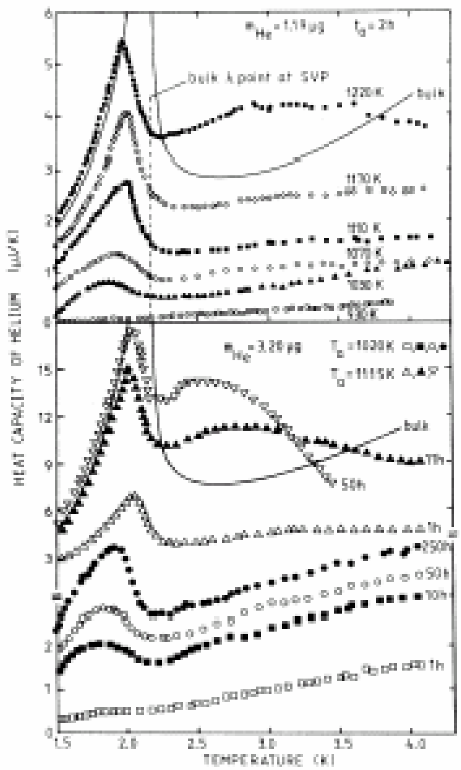

FIG. 1. Heat capacity of helium confined in bubbles in Cu after vacuum annealing of the specimens at the temperatures given in the figure. The continuous lines show the heat capacity of the corresponding mass of bulk liquid helium at saturated vapor pressure (SVP).

^{3}He/^{4}He(60atoms)/OCS

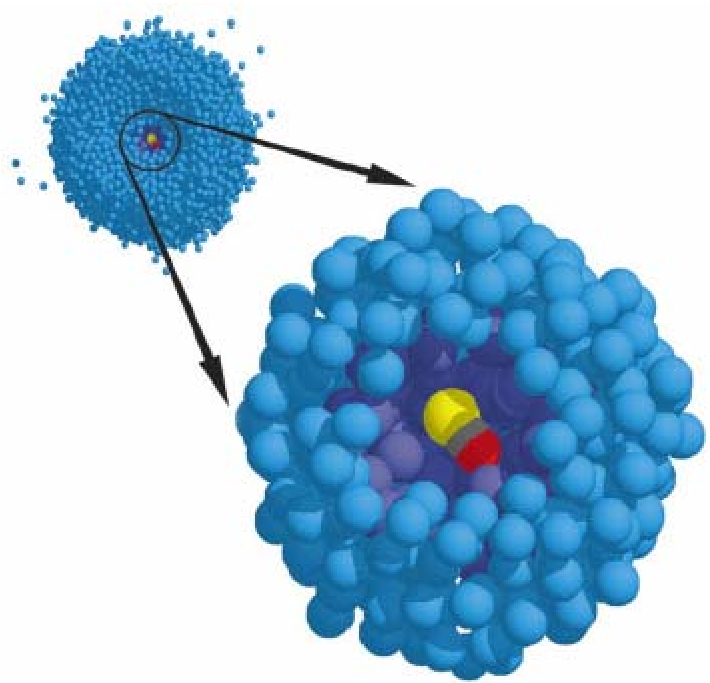

Fig. 3. Simple schematic picture of an OCS molecule (yellow, black, and red) with a surrounding cluster of 60 ^{4}He atoms (purple) inside a large ^{3}He droplet (blue). This model corresponds to the spectrum shown in Fig. 2E, where superfluidity becomes apparent.

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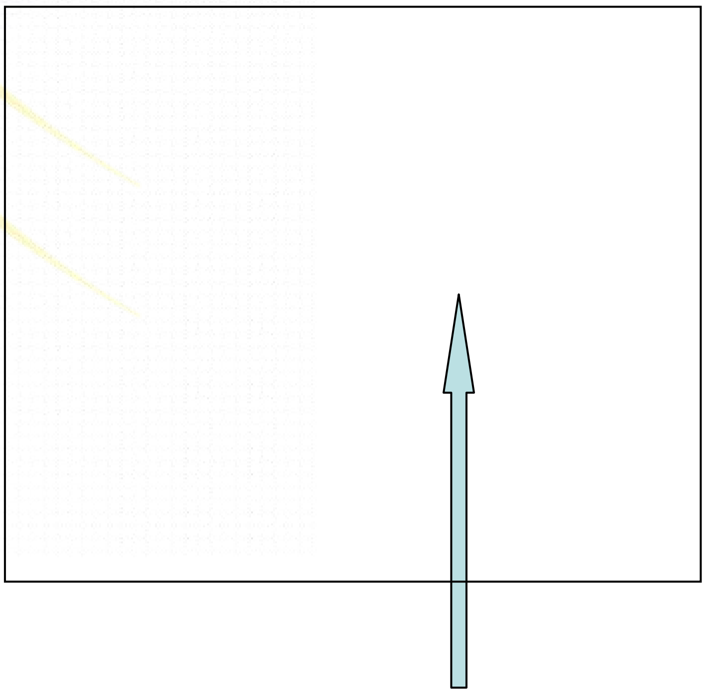
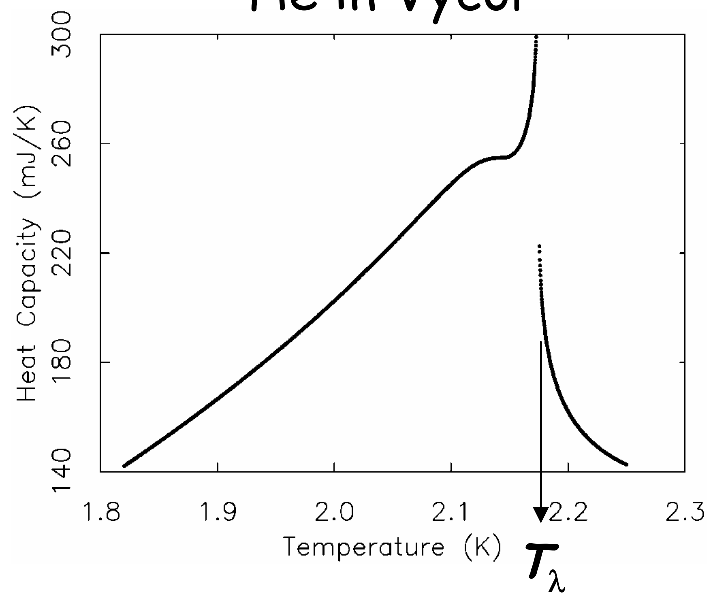
Heat Capacity of ^4He in the 25A Pores

山本恵一、ポスター発表



Hump?

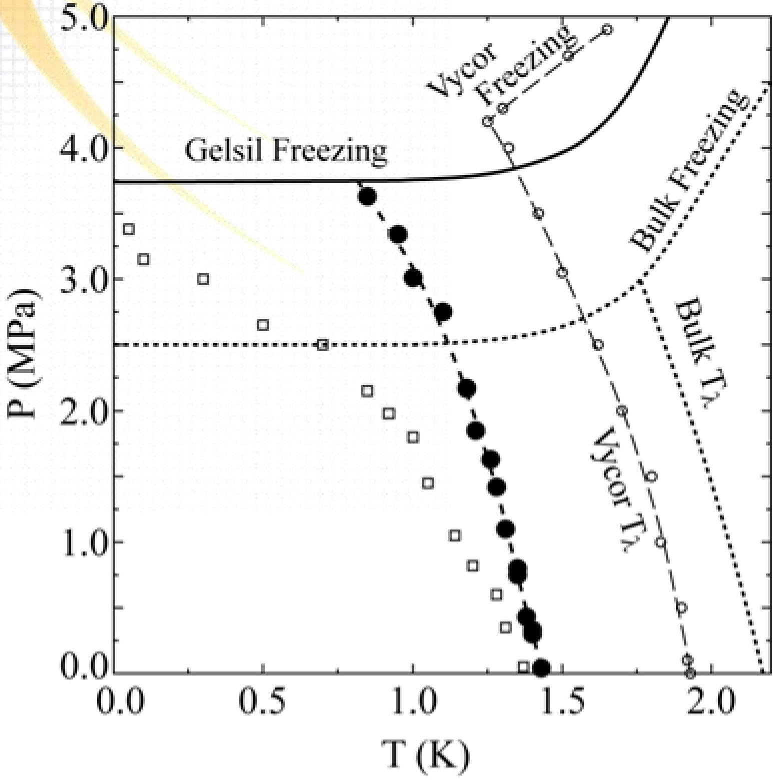
^4He in Vycor



Puzzle in Ultrasound Experiment

鈴木勝、次の講演
小林利章、ポスター発表

9 MHz Ultrasound Study



- Torsional Oscillator : *f* ~ 2 kHz
- Frequency: 3 orders of magnitude higher
- Same batch, but different heat treatment

- *Simultaneous measurement of Ultrasound and Tor. Osc.*
- *Measurement with new samples (2.5 and 3.3 nm)*

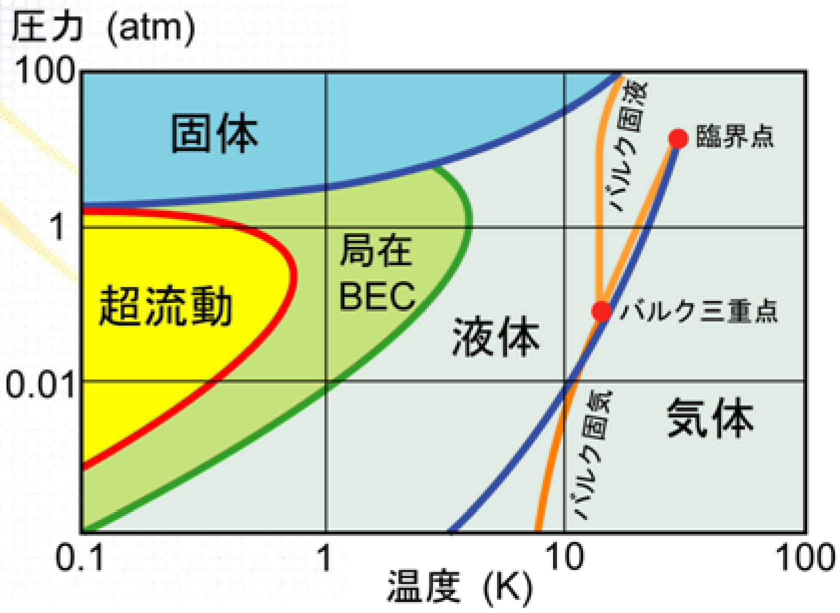
Quantum Fluids in Nanopores

1. Solidification is suppressed. (supercooling)
   Good for emergence of quantum phenomena (superfluidity)

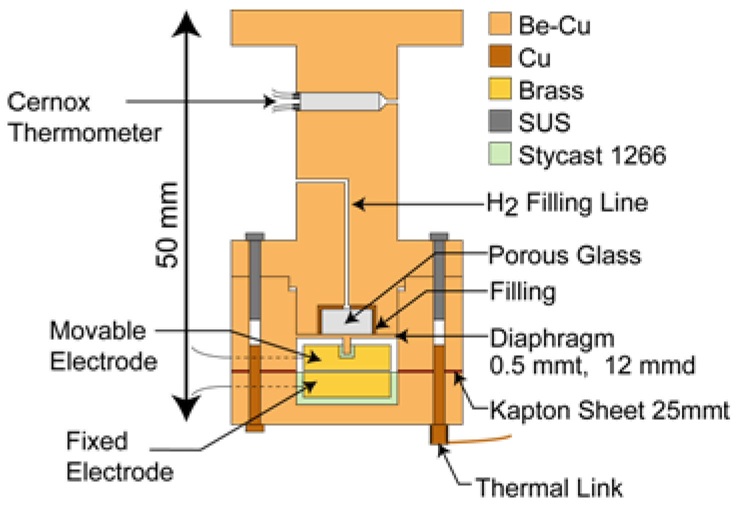
2. Superfluidity is also suppressed,
   but localized BEC's prevail.

Possible Phase Diagram of H_2 in Nanopores

石井洋典、ポスター発表



Pressure Cell



Suppression of Triple Point ?

No Superfluidity, but LBEC

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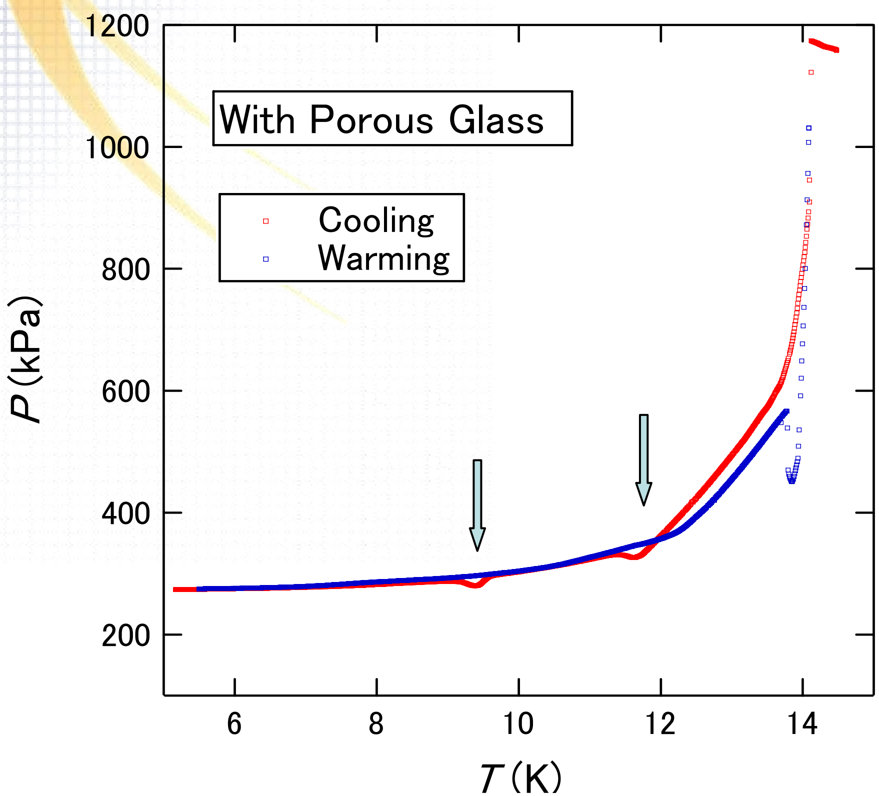
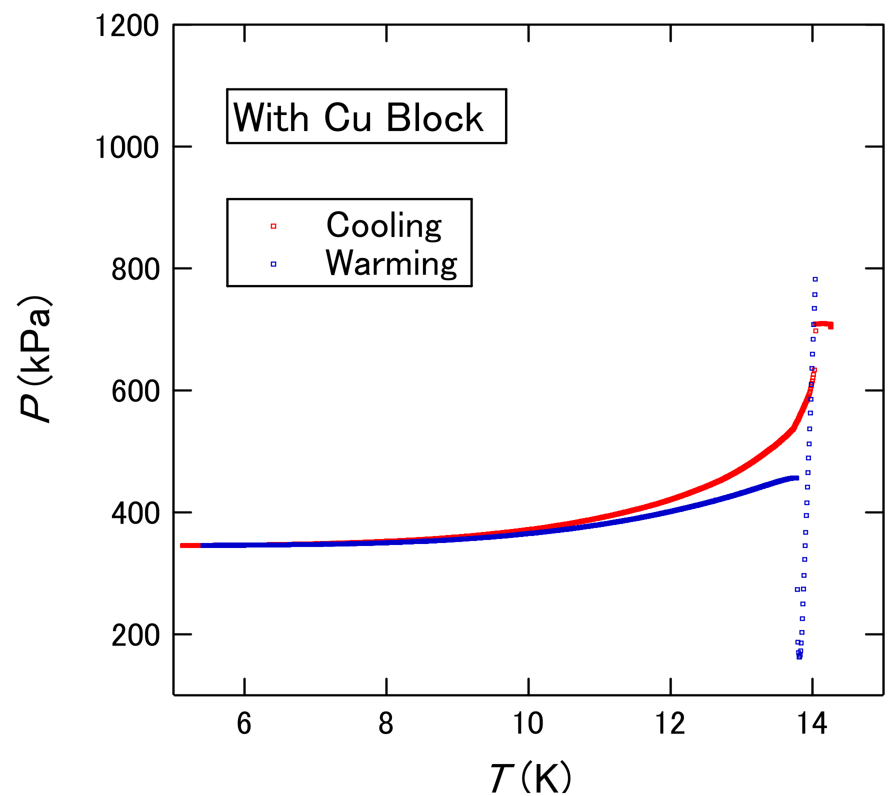
Pressure of H_2 in Nano – Porous Glass

石井洋典、ポスター発表

With 25A Porous Glass



Cu Block Replacing the Glass



The pressure cell is currently improved (Ishii, Suzuki)

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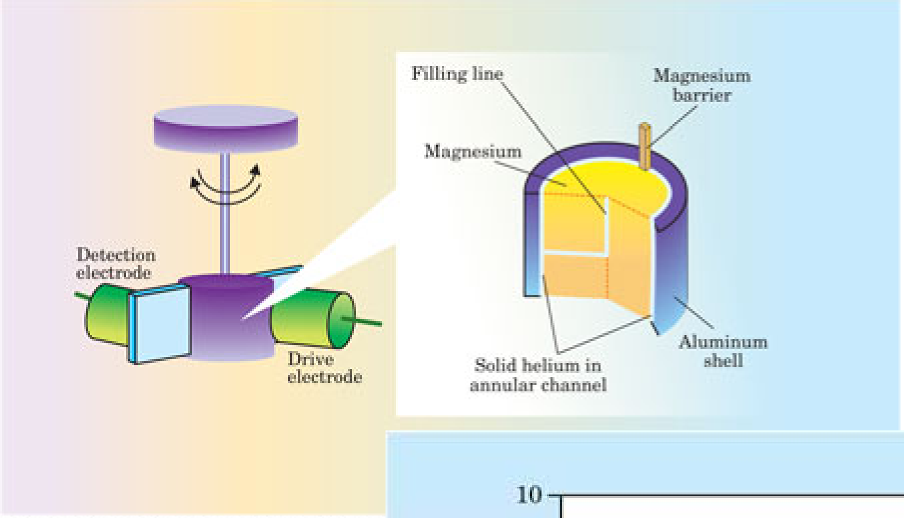
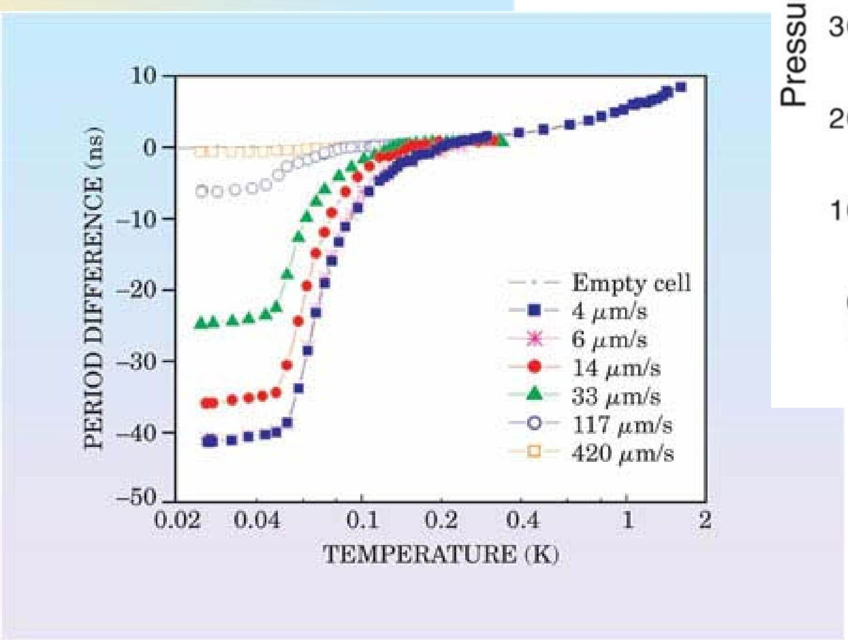
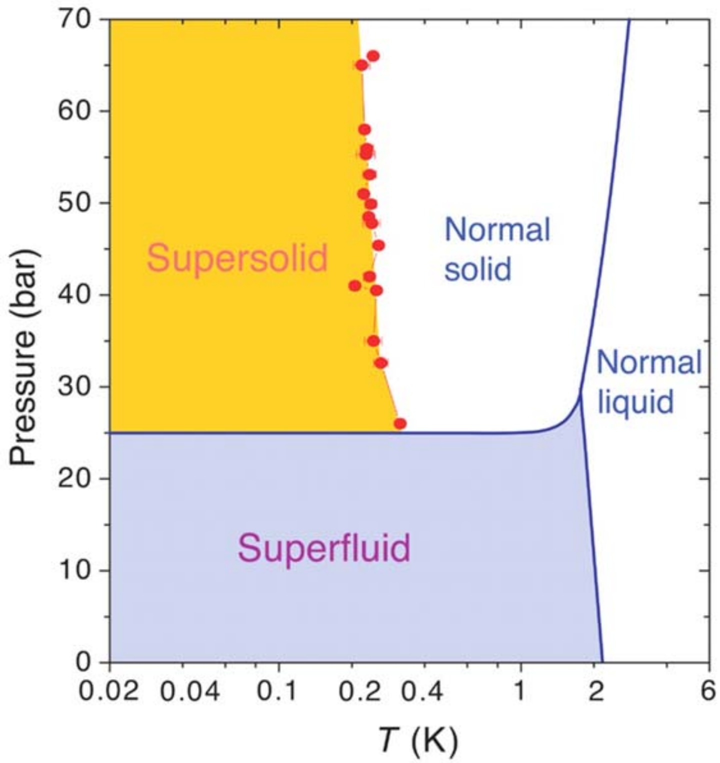
"Superfluidity" in Solid ^{4}He?

E. Kim and M. H. W. Chan, Nature **427**, 225 (2004); Science **305**, 1941 (2004)
Physics Today, April & November 2004, パリティ 2004/7, 2005/1月号 (白浜訳)







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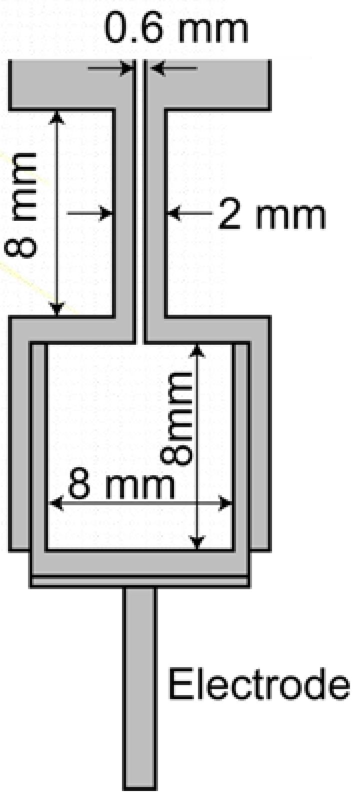
Observation of Non-Classical Rotational Inertia

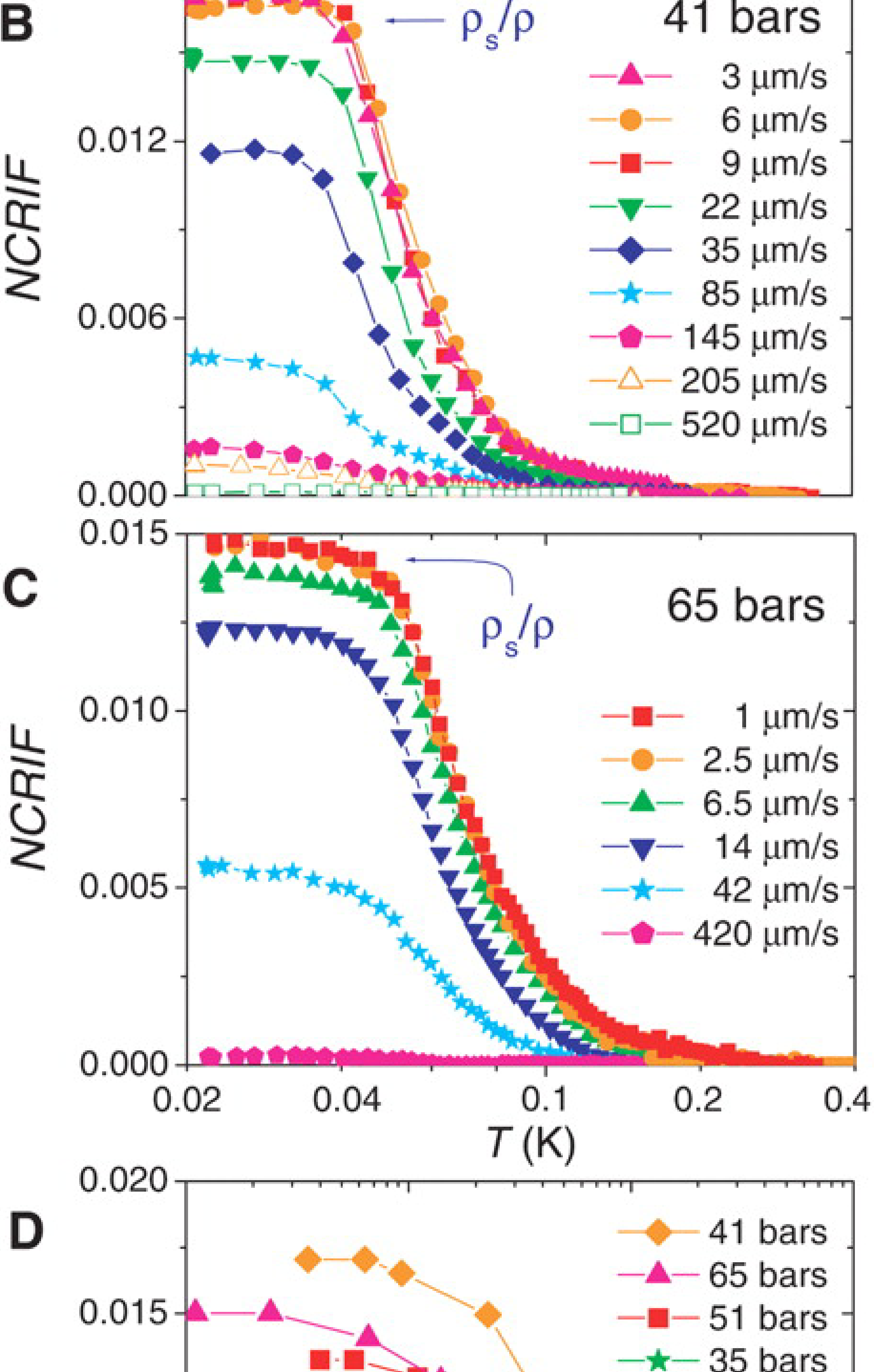
近藤大司、ポスター発表
M. Kondo and S. Takada

Bulk Solid ^{4}He (P ~ 52 bar)
in an Al – alloy Cylinder



Amplitude-Dependent Frequency Shift

"The first independent observation outside of Penn State" (H. Kojima)



B
ρs/ρ
41 bars
3 μm/s
6 μm/s
9 μm/s
22 μm/s
35 μm/s
85 μm/s
145 μm/s
205 μm/s
520 μm/s
NCRIF
0.012
0.006
0.000
0.015
C
ρs/ρ
65 bars
1 μm/s
2.5 μm/s
6.5 μm/s
14 μm/s
42 μm/s
420 μm/s
NCRIF
0.010
0.005
0.000
0.02
0.04
0.1
0.2
0.4
T (K)
0.020
D
41 bars
65 bars
51 bars
35 bars
0.015

Summary and Outlook

1. Quantum Phase Transition in ^{4}He Nanostructures
2. Localized BEC – Separation of Superfluidity and BEC –
3. Heat Capacity – LBEC, Excitation –
4. Ultrasound – Discrepancy with the Torsional Osc.
5. H_2 Experiment – Application of the LBEC concept –
6. Supersolid ^{4}He – Pressurized helium is intriguing !

1. Regular porous structure (HMM3, provided by S. Inagaki)
2. Pore size control by Kr absorption
3. Effect of ^{3}He