Outline

1. Motivation
2. 1D nanoporous media FSM16
3. Superfluid response in the film state
   (Nagoya University group)
4. Superfluid response in the liquid state
   (UEC group)
5. Future challenges

Motivation

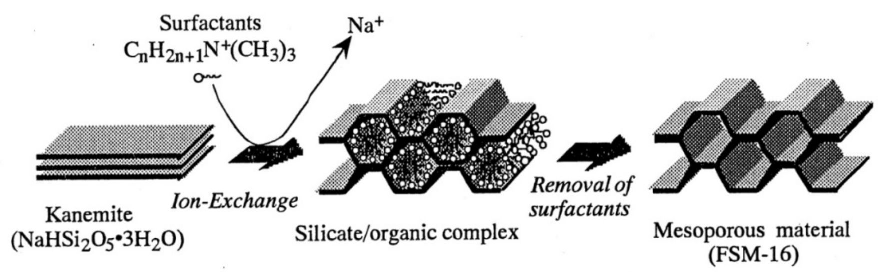
- Relation between ODLRO and superfluidity

	3D	2D	1D
ODLRO	yes	no	no
Quasi-LRO	-	yes	no
Superfluidity	yes	yes	?

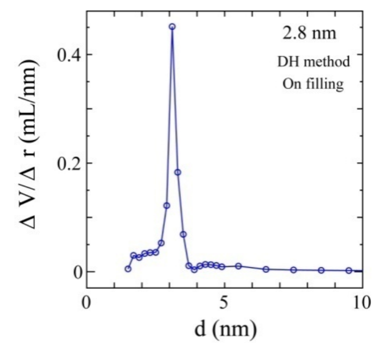
- Does superfluidity appears in 1D even without LRO?

1D nanoporous media <FSM16>

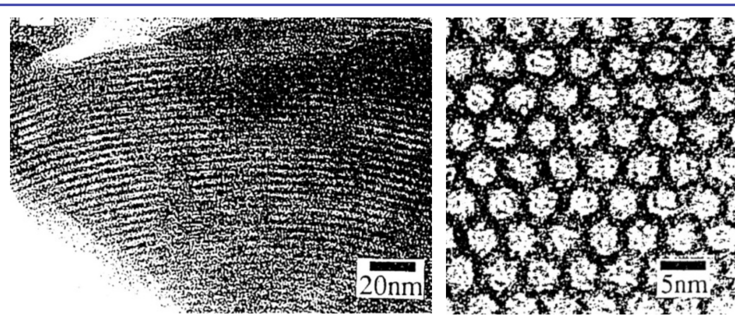
S. Inagaki et al., Toyota Central R & D Lab.



Synthesis of FSM16



Distribution of pore size

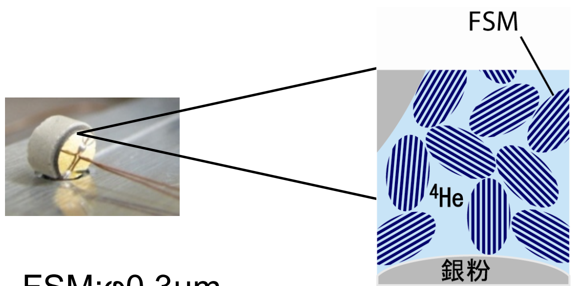


TEM of FSM16 (2.8 nm)

FSM16 has uniform hexagonal silicate channels.

- **FSM16 has uniform hexagonal slicate channels.**
- **Its diameter can be controlled by ~0.3 nm step.**

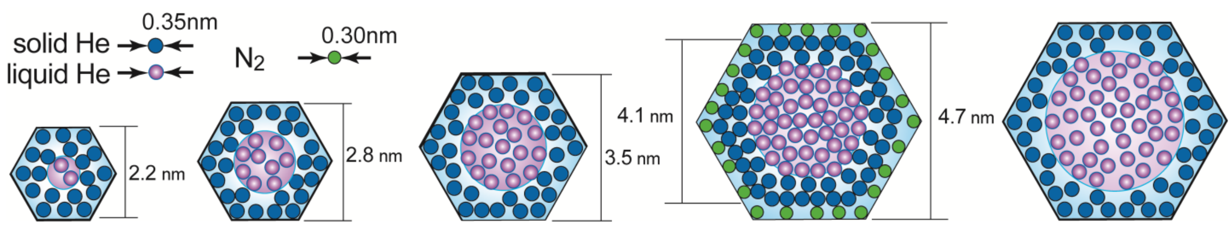
Sample preparation



FSM:φ0.3μm
Ag:φ60μm

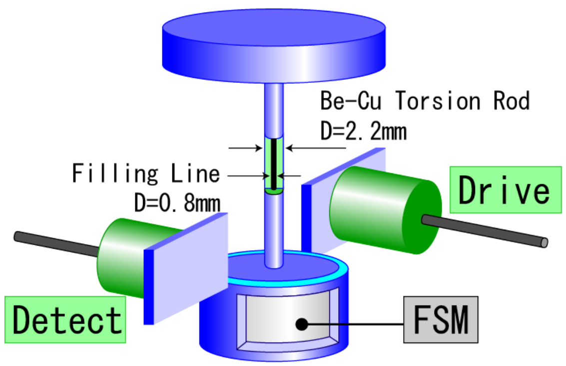
Pellets were prepared by sintering FSM16 and silver powder.

Thermal de Broglie wavelength for ^{4}He atoms is 0.9 nm at 1 K, 2.8 nm at 0.1 K.



Channel diameter		2.2 nm	2.8 nm	3.5 nm	4.1 nm	4.7 nm
Total surface area (outer surface area of powder)		91 m^2 (16m^2)	114 m^2 (12m^2)	83 m^2 (7 m^2)	88 m^2	101 m^2 (11 m^2)
Porosity	In the channel	25%	44%	40%	38%	49%
	Outside powder	**46%**	**18%**	**34%**	**26%**	**27%**

Detection of superfluid by torsional oscillator



Resonance frequency

$$f = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I_{cell}+I_{He}}}$$

Superfluidity of ^4He in 1D channel was measured by means of a torsional oscillator.

When the superfluid transition takes place, the resonance frequency increases because of decoupling of the superfluid fraction from the oscillation.

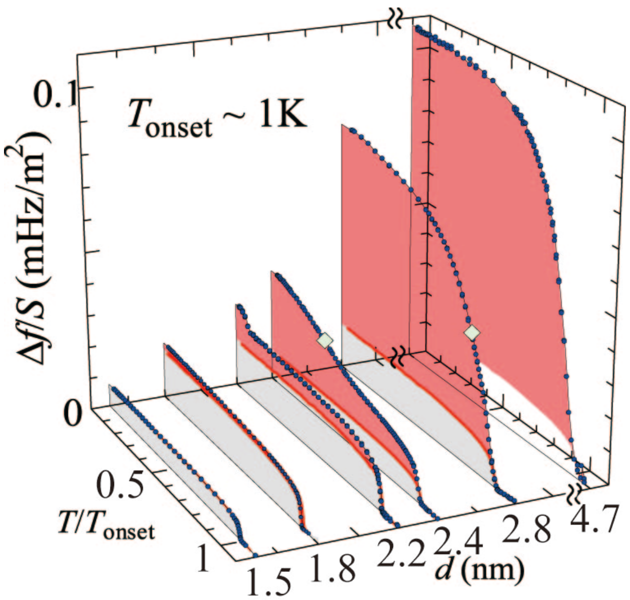
$$\triangle f \cong \frac{f_{cell}}{2}\frac{I_{He}}{I_{cell}}\frac{\rho_s(T)}{\rho}$$

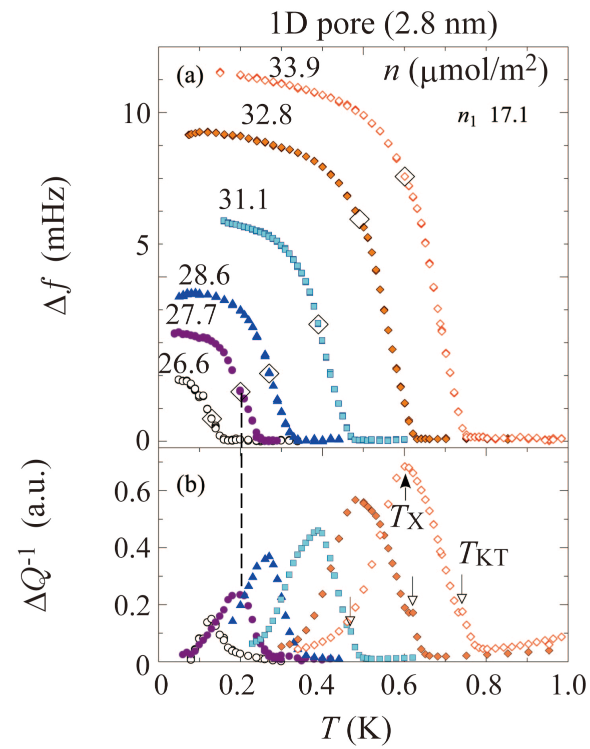
FILM STATE

(Nagoya Univ. Group)

Channel diameter dependence of superfluid

N. Wada et al., *Low Temp. Phys.* 39 9 786-792 (2013).



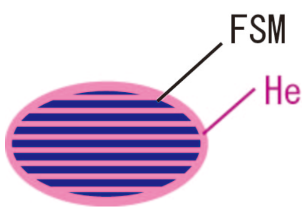


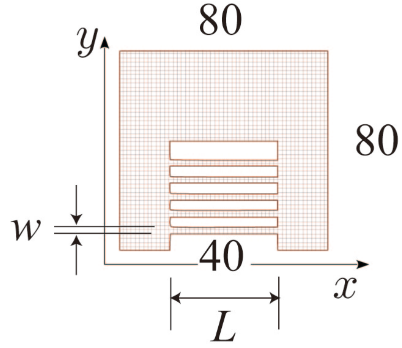
- Superfluid response appears above 1.8 nm.
- The growth of superfluid fraction is gradual, compared with the one of KT transition, and is accompanied by a broad dissipation.
- The growth becomes more gradual with decreasing diameter.

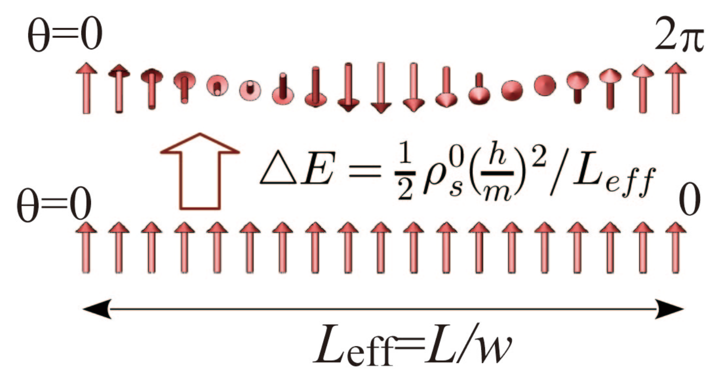
Explanation by Helicity modulus

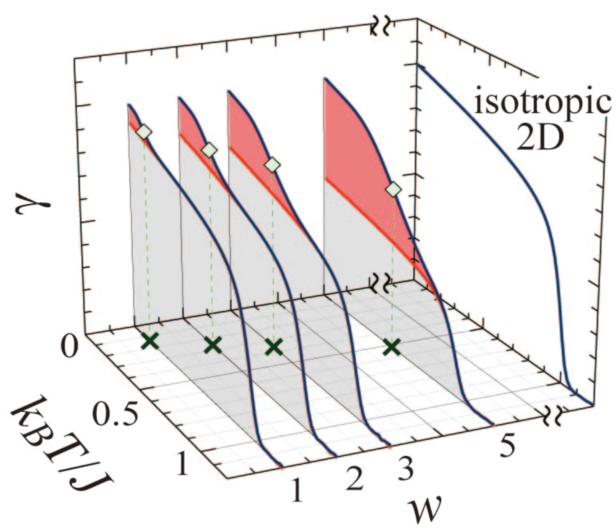
anoistropic 2D XY model

Yamashita and Hierashima, *PRB* 79 014501 (2011).
N. Wada et al., *Low Temp. Phys*. 39 9 786-792 (2013).







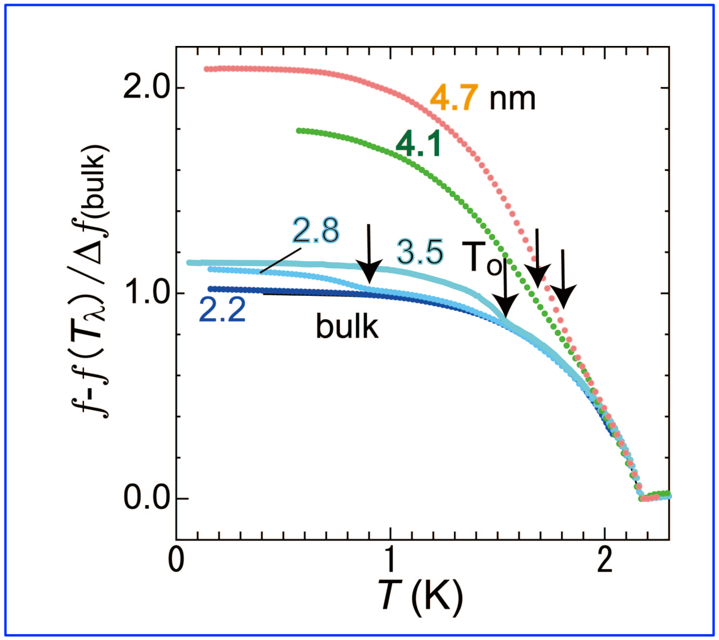


- Hirashima's group calculated hellicity modulus in an anistropic two-dimensional (quasi-1D) classical XY model.
- In finite anisotropic 2D lattices, helicity modulus vanishes due to proliferating phase slippage.
- Since $\Delta E \propto 1/L_{eff}$, superfluid onset Tx changes as $1/L_{eff}$.

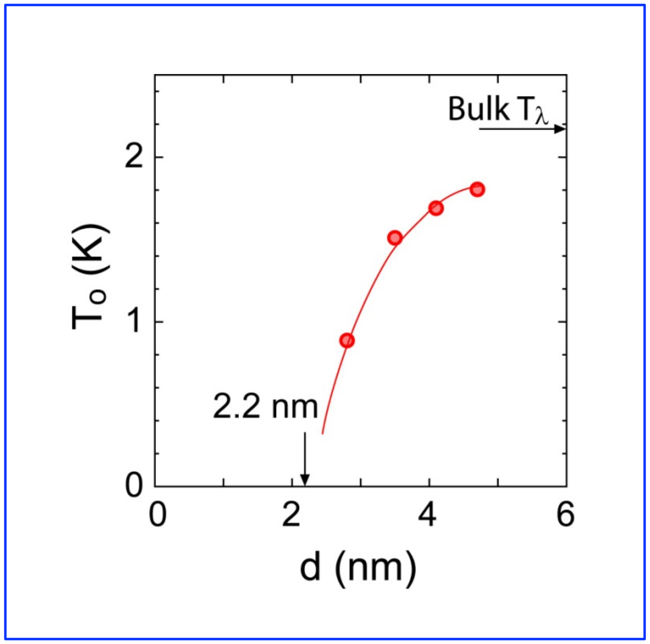
LIQUID STATE

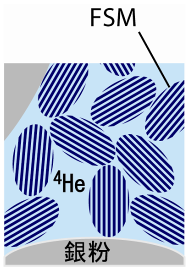
(UEC Group)

Size dependence of superfluid response for liquid ^{4}He



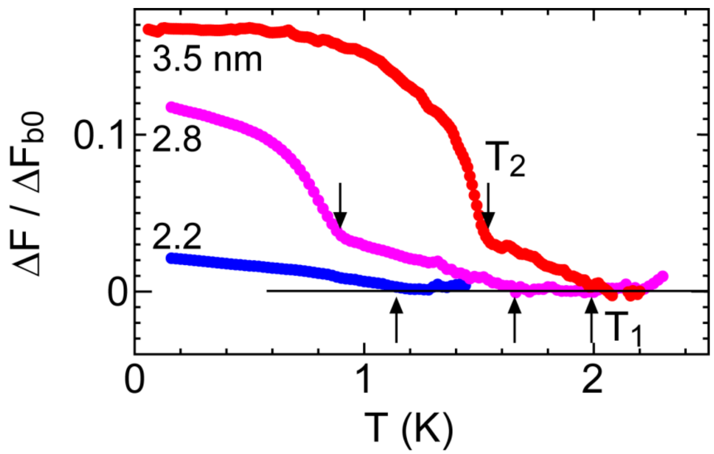
Taniguchi et al., PRB **82**, 104509 (2010).

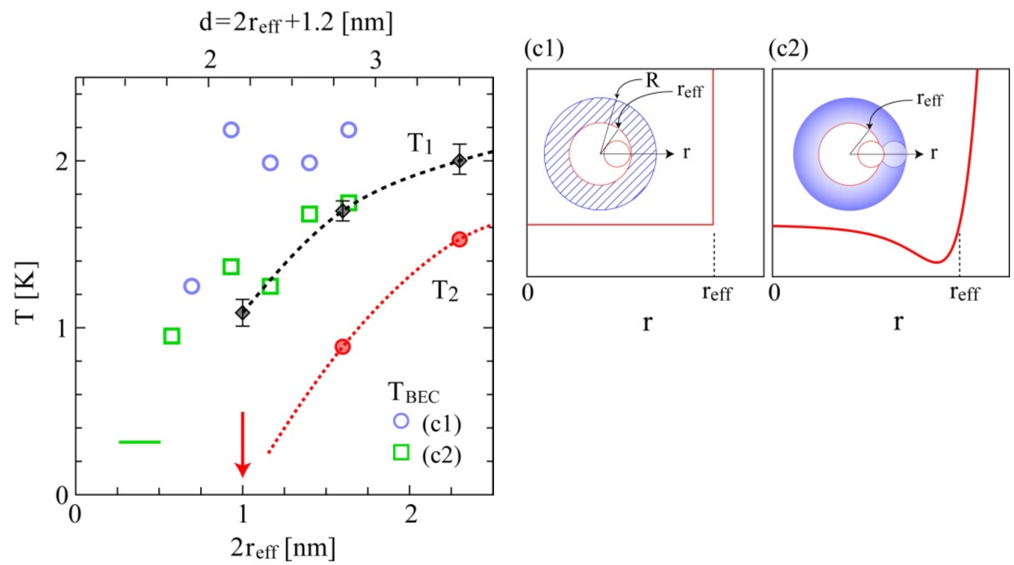




- **A clear rise due to the superfluid response in the channel is observed above 2.8 nm in addition to the bulk one.**

Two –stage growth of superfluid (2.8 nm)

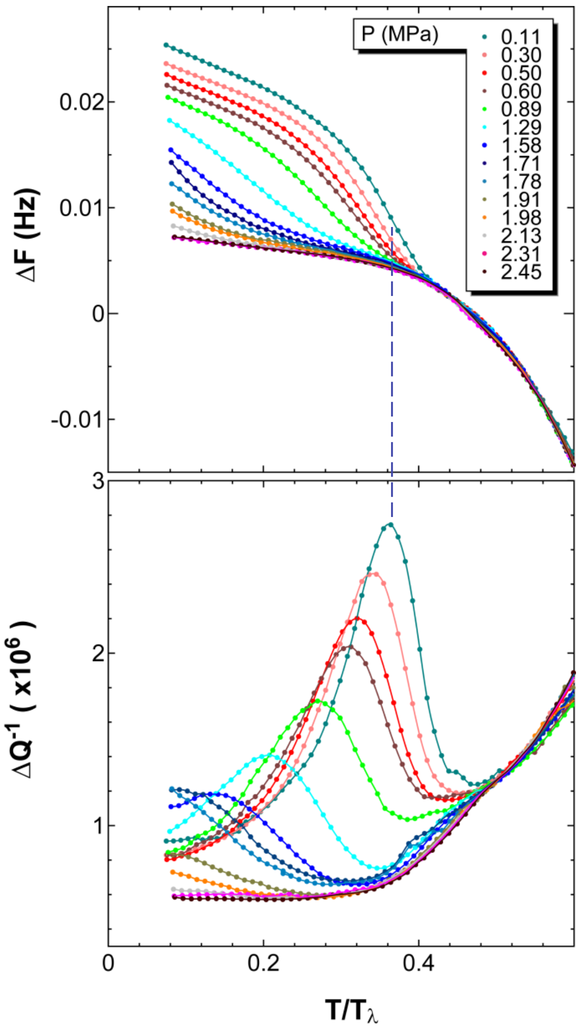


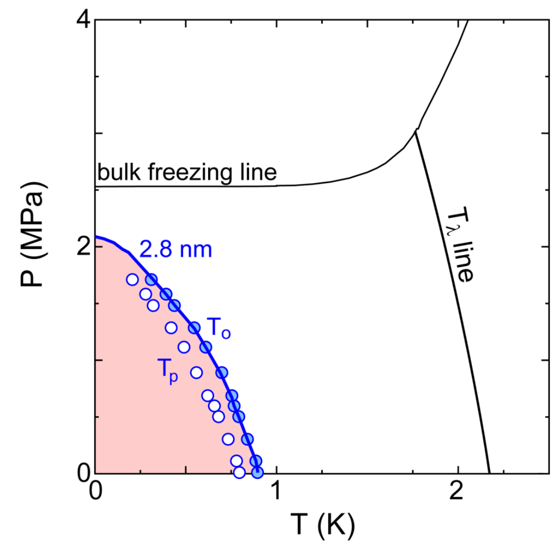


kiriyama et al., JPSJ **82**, 104509 (2010).

- **In the channel, liquid ^{4}He shows a two-stage growth.**
- **The temperature of 1st growth corresponds to T_{BEC}!?**
- **The 2nd rapid growth is not observed for 2.2-nm channel.**

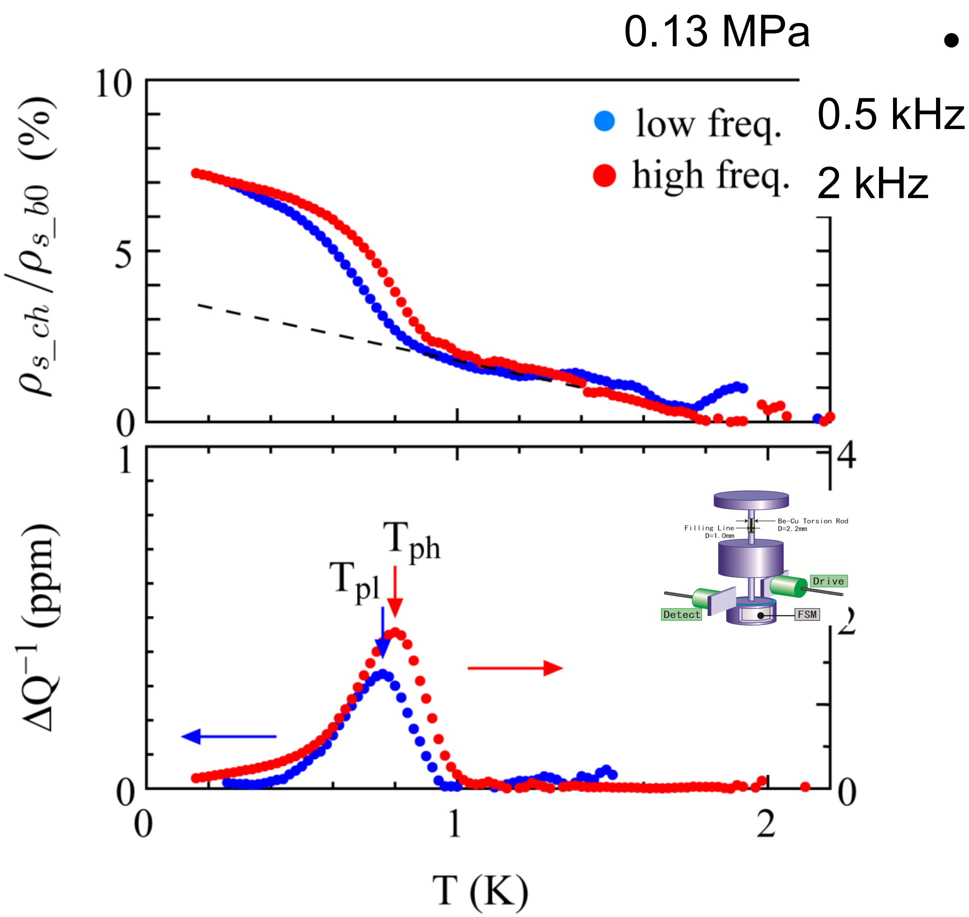
Pressure dependence of superfluid response (2.8 nm)





- **Superfluid response is accompanied by a large and broad dissipation.**
- **Superfluid response disappears above 2.1 MPa., which is below the bulk freezing line.**

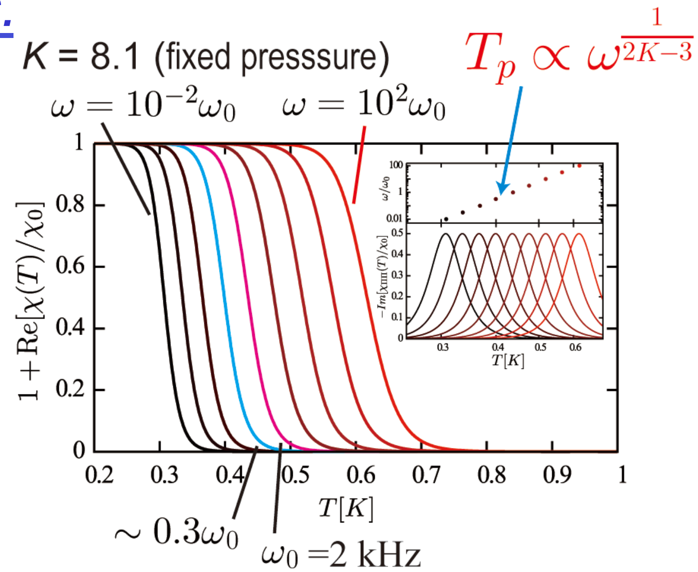
Frequency dependence of superfluid response



- The rapid growth and the dissipation peak shift to low temperature by ~40 mK.
  cf.)2D ^{4}He film
  KT theory shows only a 4 mK shift of dissipation peak.
- **Large frequency dependence**
- **The observed decoupling and dissipation comes from the dynamical superfluid response.**

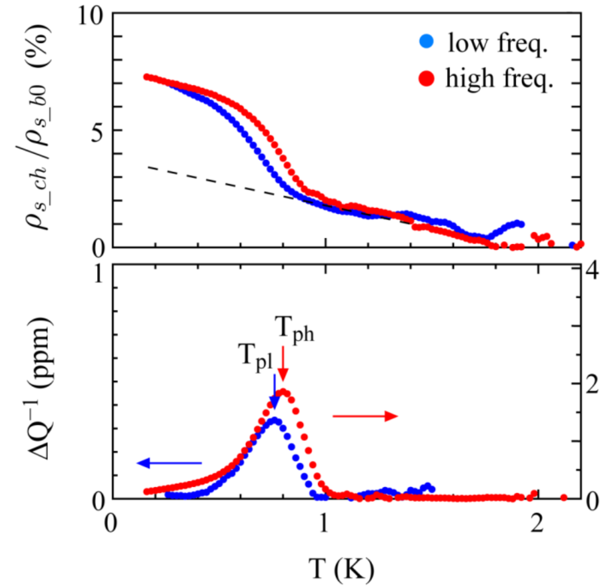
A Possible TL liquid state in the channel

Calc.



- Superfluid onset decreases with lowering ω.

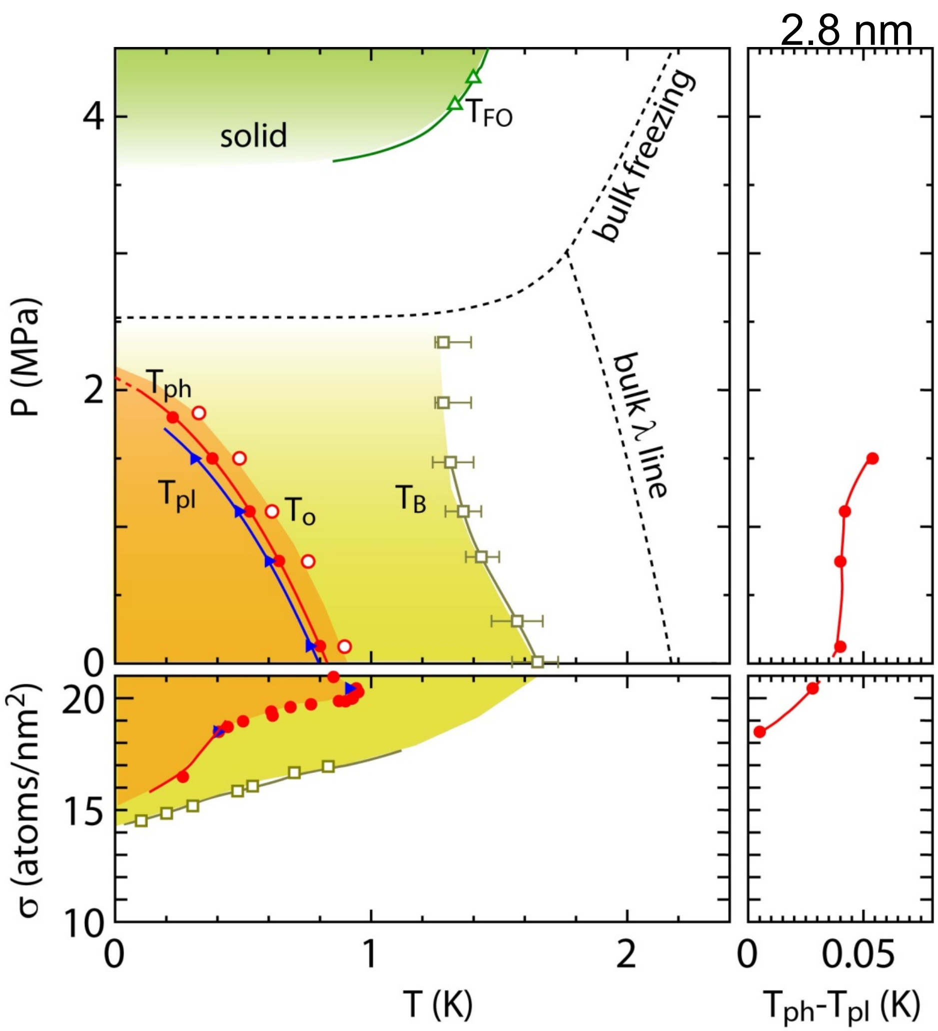
Exp.



T. Eggel et al. PRL **107**, 275302 (2011).

- **The temperature dependence of observed decoupling and dissipation is quite similar to the calculation based on the Tomonaga-Luttinger liquid theory.**

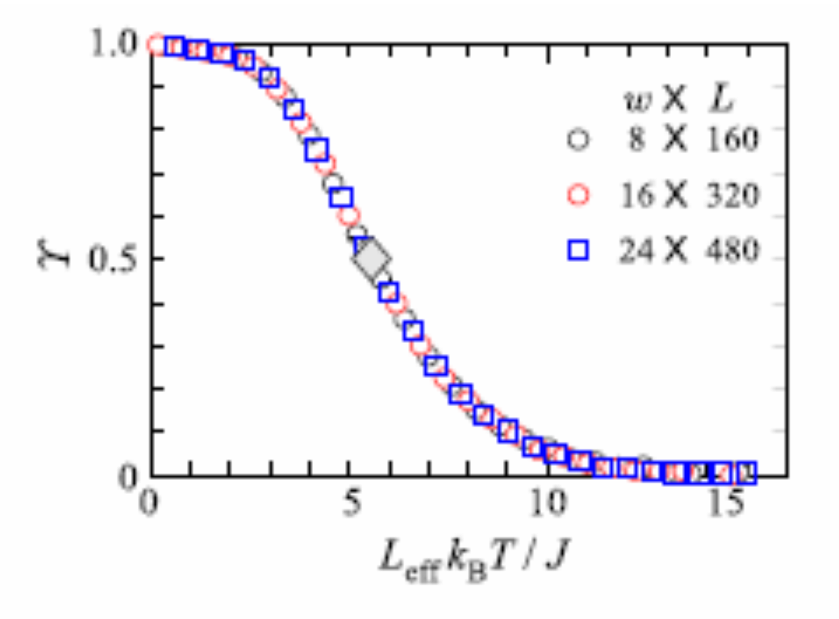
Total phase diagram & dynamical superfluid region



- Common properties over the film and liquid region
  - superfluid response takes place at far below temperature than that of heat capacity anomaly.
  - The superfluid growth is accompanied by a dissipation peak.
- Different property
  - The frequency dependence is not observed in the region of thin film, within the experimental error. It is likely to appear after the channel is filled with liquid ^4He.

FUTURE CHALLENGES

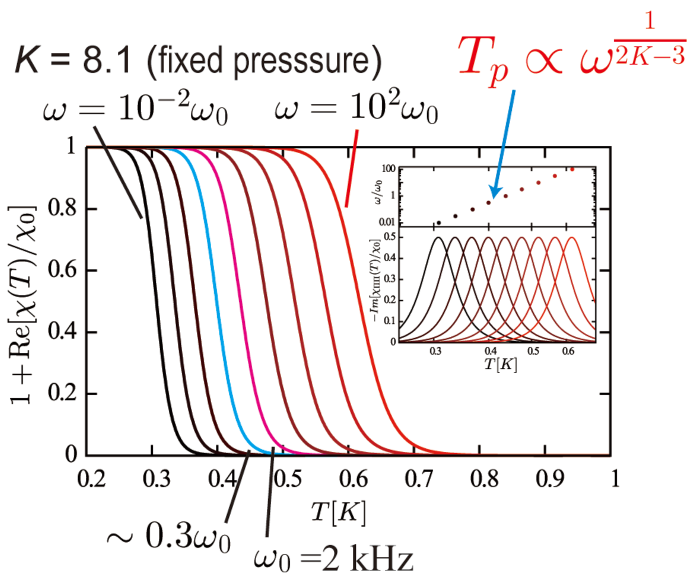
Experimental verification of "Helicity modulus" model



Yamashita and Hierashima, *PRB* 79 014501 (2011).

- In the "Helicity modulus" theory, T_x is determined by L_{eff} (aspect ratio).
- Experimental verification
  - TO measurements using the channel the same in diameter and larger in length
  - TO measurements using the channel with the same aspect ratio and larger in diameter
- Experimental difficulty
  - Control of the aspect ratio

Search for the distinct signature of TLL realization

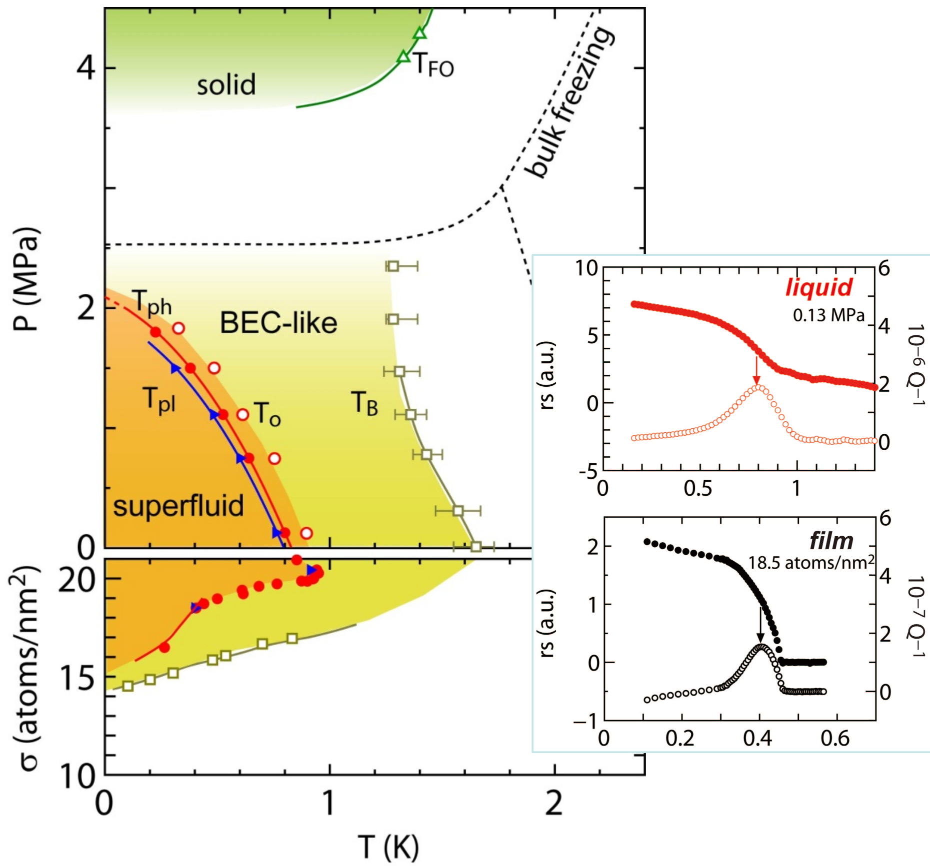


T. Eggel et al. PRL **107**, 275302 (2011).

As a signature of TL liquid, the dissipation peak is expected to have a power-law dependence on frequency.

- Experimental verification
  - Measurements in a wide range of frequency
- Experimental difficulty
  - Development of detection technique in the high frequency range

Unified understanding from thin film to dense liquid



- Phase diagram connects very smoothly from the film to the liquid region.
- Dissipation peak is also similar.

- Unified understanding of superfluid response in the film and the liquid regions is possible?

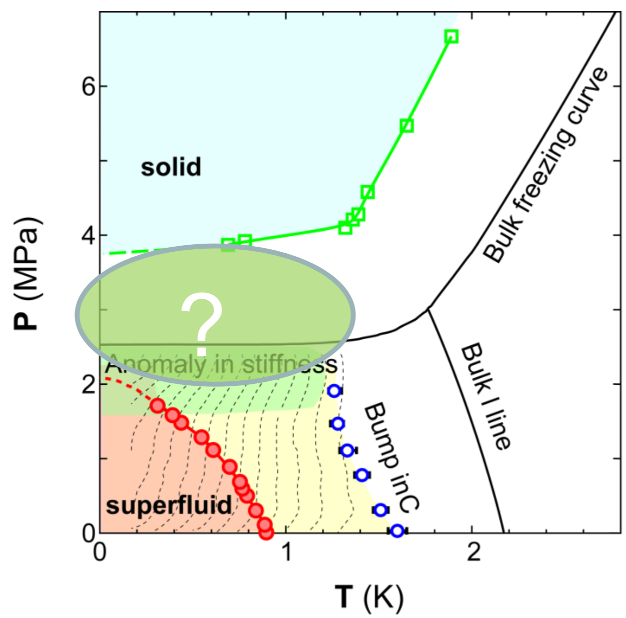
Summary

- Highlighted feature of superfluid in1D mezoporous media.
  - Superfluid response takes place at the temperature much lower than T_{KT} in the film state and than T_{λ} in the liquid state.
  - Superfluid response takes place at far below the temperature of BEC.
  - Superfluid response occurs down to the diameter of 1.8 nm.
  - Superfluid response is accompanied by a dissipation peak.
  - The temperature of dissipation peak has a frequency dependence, when the channel is filled with liquid ^{4}He.
  - The frequency dependence shows the possibility that TLL state is realized in the liquid 4He confined in the channel.

Summary

- Future challenges
  - Difference in frequency dependence between the film and the liquid state
  - Experimental confirmation of whether the superfluid response is ruled by not the channel diameter but the aspect ratio
  - Experimental confirmation of realization of TLL in the nanometer-size channel
  - Unified understanding of superfluid response throughout the film and the liquid state.

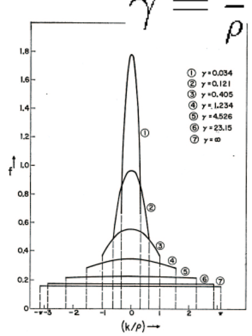
Property of non-superfluid ground state above 2.1 MPa



- Non-superfluid ground state above 2.1 Mpa
- A gradual hardening in stiffness at around 2 Mpa.

Interacting 1D Bose gas

$$\gamma = \frac{c}{\rho}$$



γ

0 — Ideal Bose gas

Large (13.3[2]) — No superfluid transition at finite T. But show superfluidlike response.

∞ — Tonks-Girardeau gas[1]

Exhibit Fermionic property

[1]L. Tonks, Phys. Rev. **50**, 955 (1936) [2]A. Y. Cherny, J. Brand, Phys. Rev. A **73**, 023612 (2006)