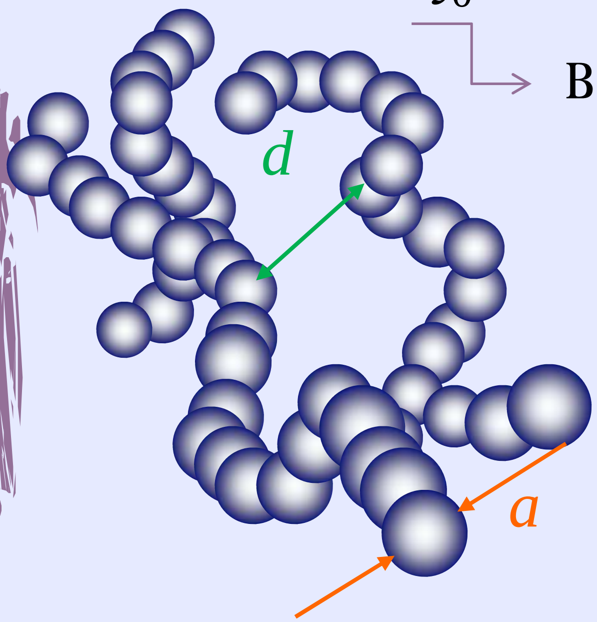
Study on Superfluid ^3He in Aerogel using the Fourth Sound Resonance

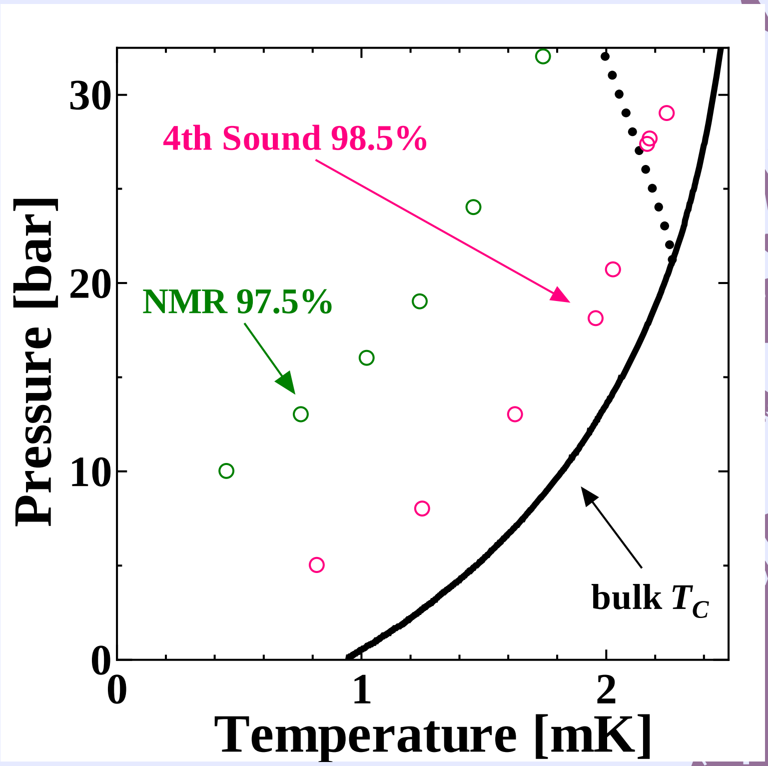
K. Obara, T. Matsukura, C. Kato, Y. Nago,
H. Yano, O. Ishikawa and T. Hata

^{3}He in Aerogel

diameter a $< \xi_0 <$ mean distance d

BCS coherence length





Aerogel :
not a wall
but a
scatterer

The Fourth Sound

The fourth sound is the pressure wave that propagates in a superleak. In an ideal straight superleak, only ρ_s can oscillate, so that it is an inviscid → loss less flow.

superleak :
the structure which blocks the motion of ρ_n due to its finite viscosity η and allows ρ_s to pass through.

effective radius of path

$$R \ll \delta_v = \sqrt{\frac{2\eta}{\rho\omega}}$$

viscous penetration depth

4th Sound in Viscous Regime

Under a fixed boundary condition, ρ_n is forced to oscillate in an opposite phase of $\boldsymbol{v}_s$ in order to compensate the pressure gradient. Motion of ρ_n → energy loss

$$\omega^2 = c_4^2 q^2 - i\omega q^2 \frac{\rho_n}{\rho} c_1^2 \frac{1}{8} R^2 \frac{\rho_n}{\eta} \left[1 + \frac{4\zeta}{R}\right]$$

$$C_4^2 = \mathrm{Re}\ \omega^2/q^2 \implies \frac{\rho_s}{\rho} = \left(\frac{C_4}{C_1}\right)^2$$

q: wave number
ζ: slip length
R: pore radius
C_1: ordinary compression wave velocity
η: shear viscosity

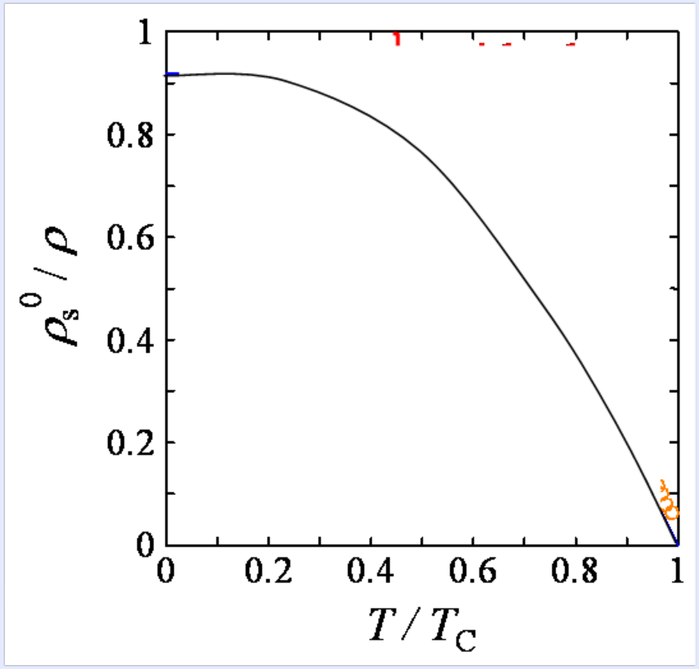
Energy Loss : $Q^{-1} = -\arg\ \omega^2 = \frac{1}{4} \frac{\rho_n}{\rho_s} \left(\frac{R}{\delta_\nu}\right)^2 \left[1 + \frac{4\zeta}{R}\right].$

Jensen, JLTP 55,469(1984), JLTP 51,81(1983)
Nagai, JLTP 42,227(1981), JLTP 41,473 (1980)

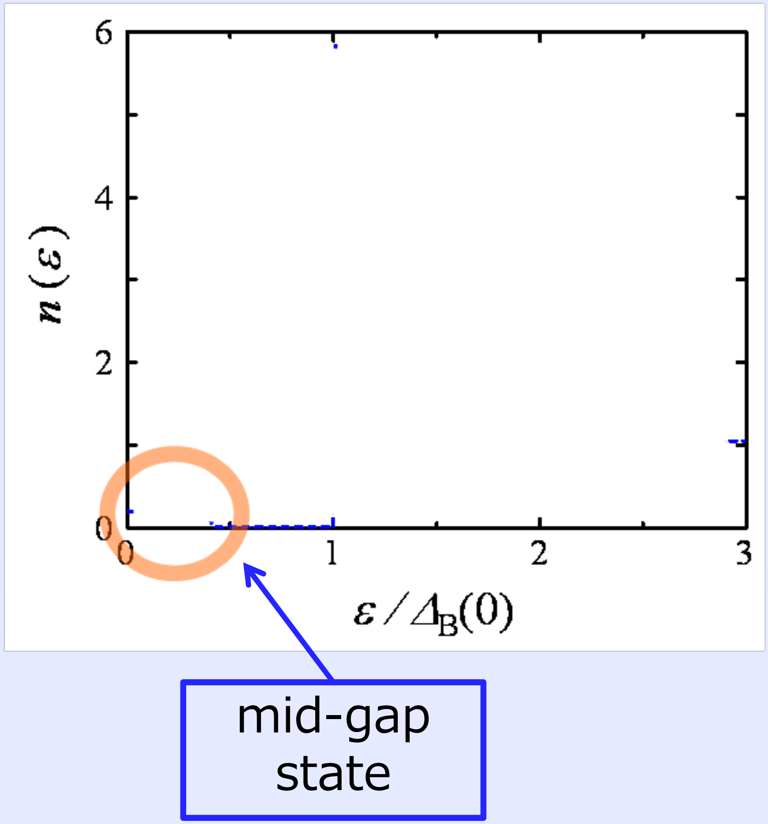
Energy loss can be obtained from FWHM of the spectrum.

Motivation

bare superfluid density fraction



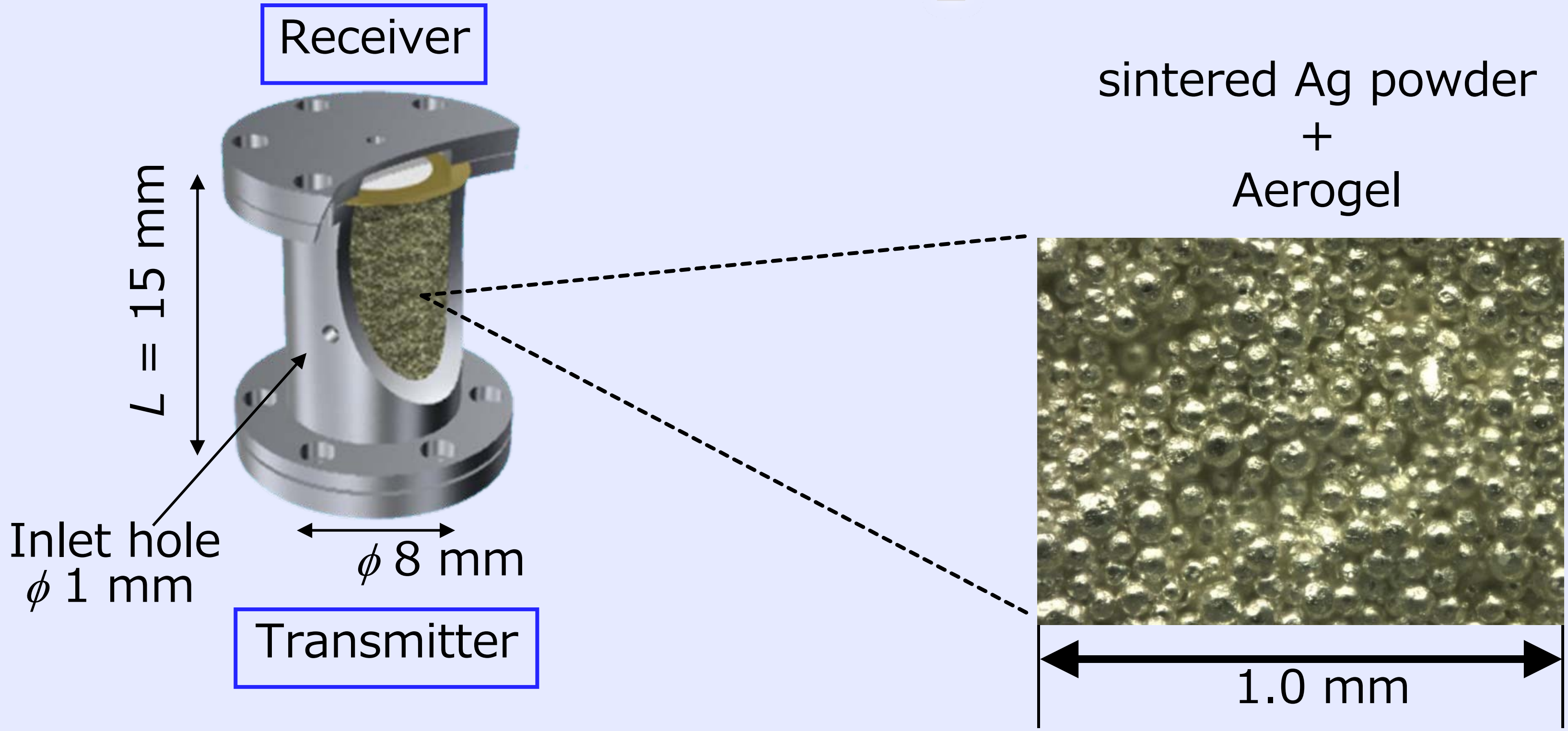
DOS @ T → 0



solid line : numerical calculation (Hiroshima Univ. S. Higashitani private comm.)

→ To study the influence of the mid-gap state QP on the normal fluid motion.

Setup



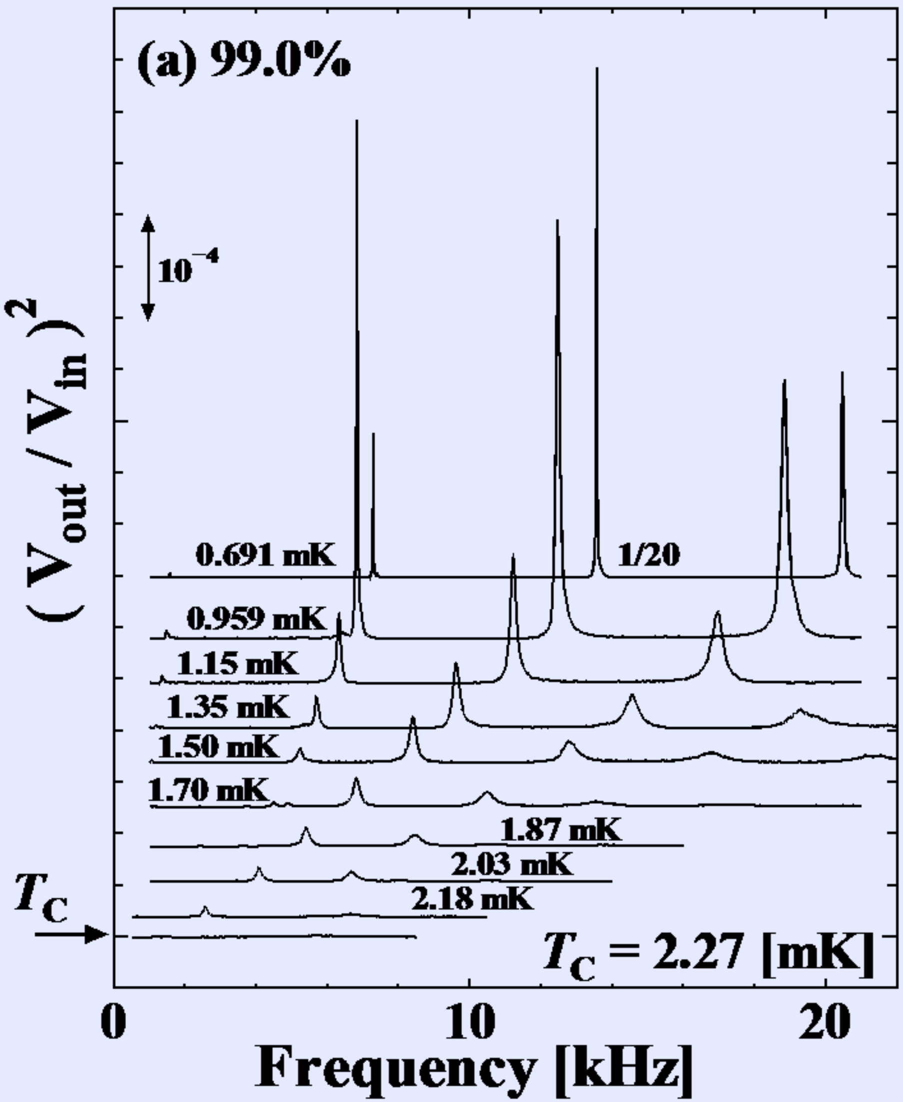
Resonance method (4^{th} sound standing wave, 2^{nd} mode)

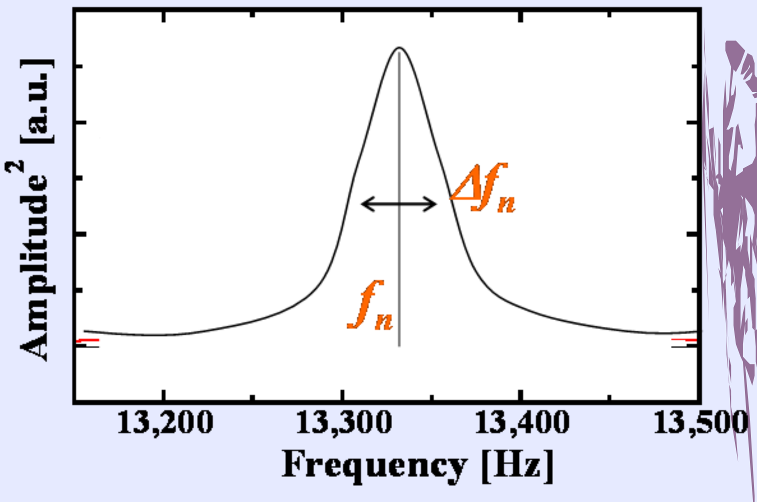
Aerogel ： porosity 99.0 % ※grown directly into pores

Zero Magnetic Fields

ambient pressure 29, 23, 10 [bar]

Frequency Spectrum





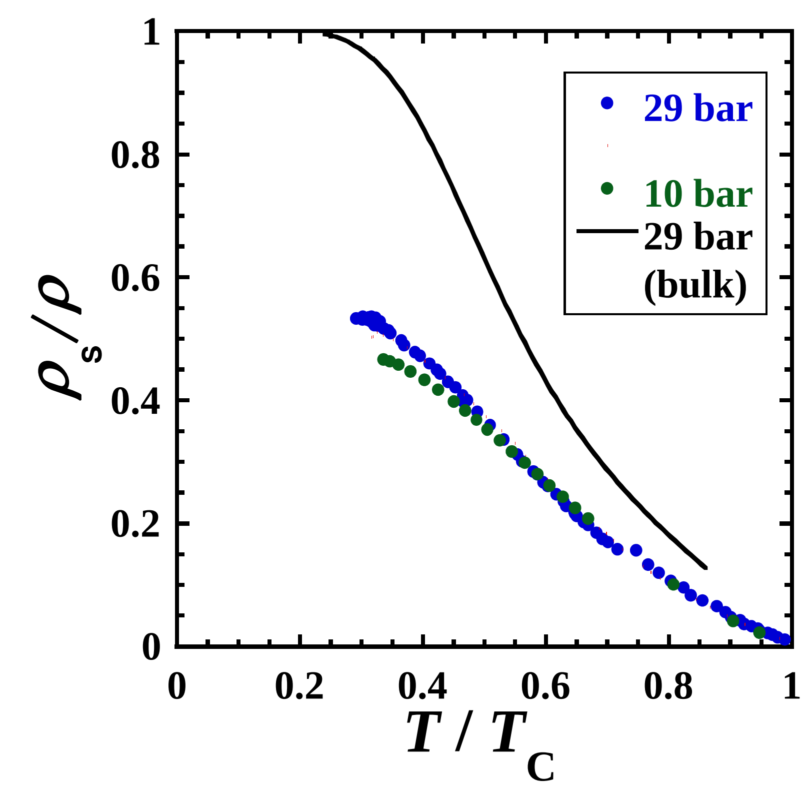
$$C_4 = \frac{2L^*}{n} f_n$$

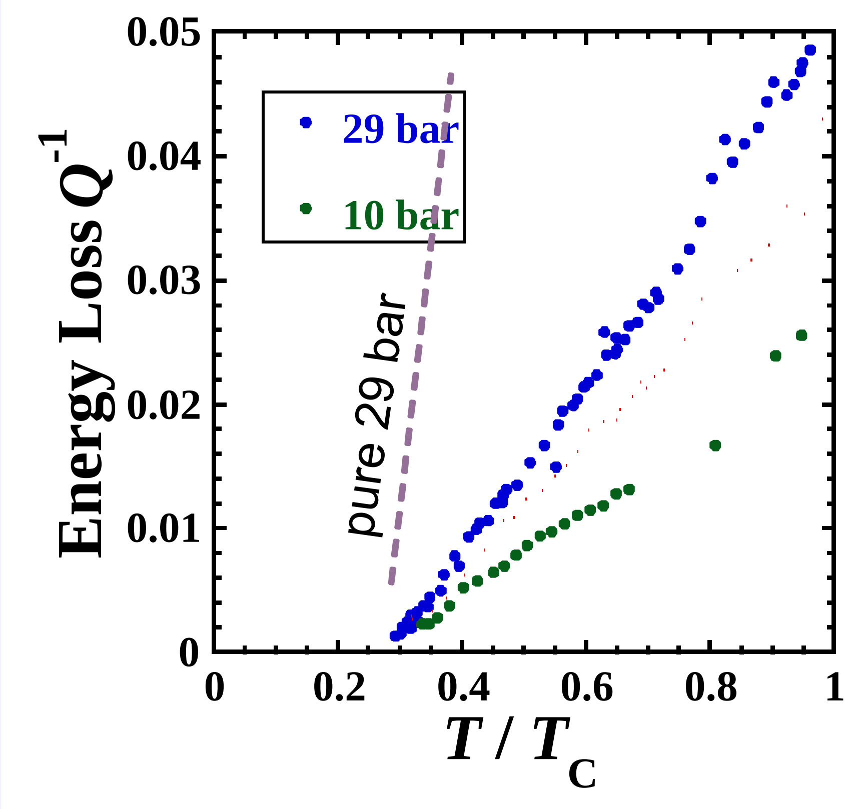
L* : effective path length

$$\frac{\rho_s}{\rho} = \left(\frac{C_4}{C_1}\right)^2$$

$$Q^{-1} \equiv \frac{\Delta f_n}{f_n}$$

Result & Discussion





suppression of ρ_s due to the pair breaking.

Finite ρ_n at $T \rightarrow 0$

Pressure insensitive.

Pressure sensitive.

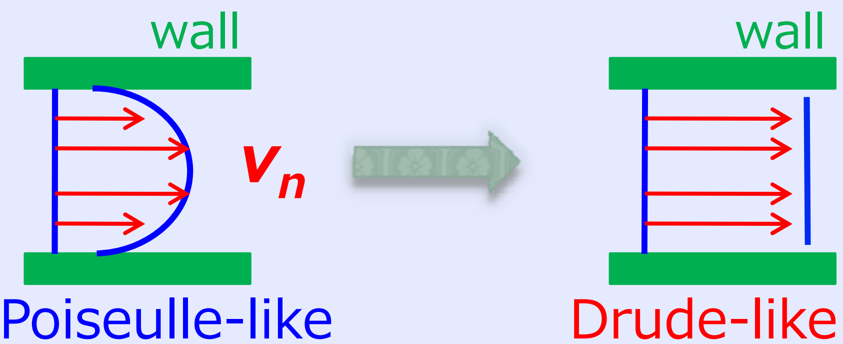
Energy Loss of the 4th sound in aerogel is smaller than that of pure case. ? ? ?

Why not viscosity but Friction ?

In the **viscous** regime,

$$\delta_\nu = \sqrt{\frac{2\eta}{\rho_n \omega}}, \quad \eta = \frac{1}{5} n p_F \lambda_{tr}.$$

the viscosity should be suppressed due to the contraction of λ_{tr} by aerogel



Einzel & Parpia, PRL 81, 3896(1998)

$\rho_n^{aero} > \rho_n^{aero}$ and $\delta_v^{aero} < \delta_v^{aero}$ means…

Q^{-1}_{aero} should be larger than Q^{-1}_{pure} in the viscous regime

$$Q^{-1} = \frac{1}{4}\frac{\rho_n}{\rho_s}\left(\frac{R}{\delta_\nu}\right)^2\left[1 + \frac{4\zeta}{R}\right].$$

Going back to raw data, spectra were Lorentzian and Q^{-1} showed no amplitude dependence.

→the damping force is prop to velocity.

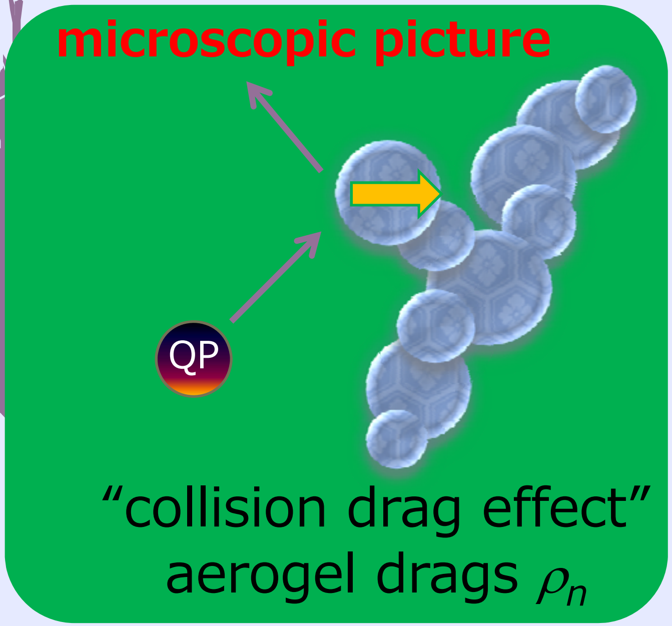
If not **viscous**, **friction** is a candidate.

frictional damping force

$$\boldsymbol{F}_d = \frac{\rho_n}{\tau_f}\left[\boldsymbol{v}_n - \boldsymbol{v}_a\right]$$

Collision Drag Effect

Virtually allows the minutes oscillation of the aerogel strands
in a macroscopic picture: flow of "**superfluid** & **normal fluid + aerogel complex**"



$$\boldsymbol{J} = \rho \left[Y(\omega) \boldsymbol{v}_a + (1 - Y(\omega)) \boldsymbol{v}_s \right]$$

using quasiclassical Green's function theory,

$$Y(\omega) = \frac{m^*}{m} \frac{1 - K_1(\omega)}{1 + (1/3)F_1^s(1 - K_1(\omega))}$$

$$K_1(0) = \frac{\rho_s^0}{\rho}, \quad Y(0) = \frac{\rho_n}{\rho}$$

and then, take the decoupling limit
(i.e. rigid aerogel)

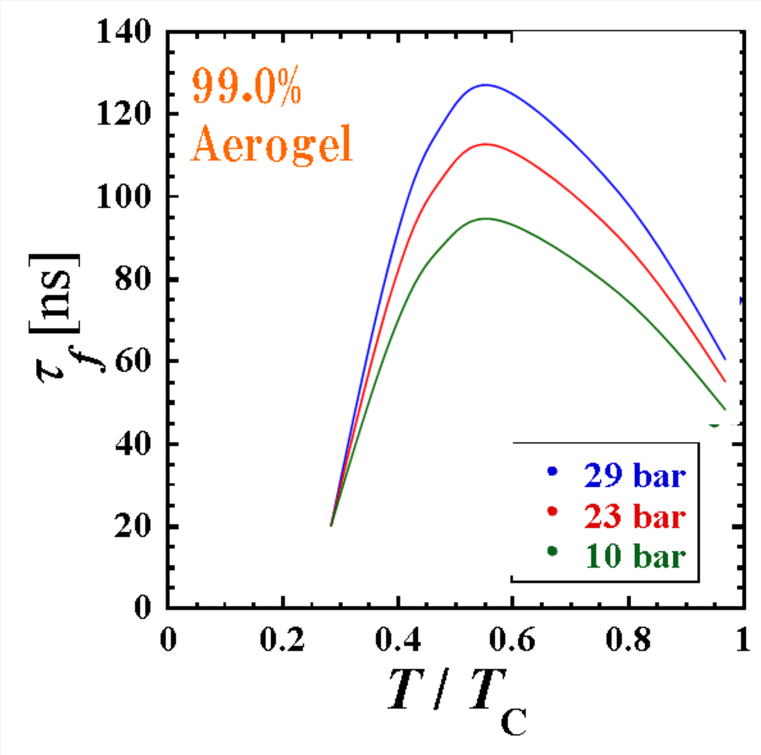
$$\left(z^2 - c_1^2\right)\left(z^2 - c_2^2\right) + i\left(\frac{4\eta_n \omega}{3\rho_n} + \frac{z^2}{\omega \tau_f}\right)\left(z^2 - c_4^2\right) = 0$$

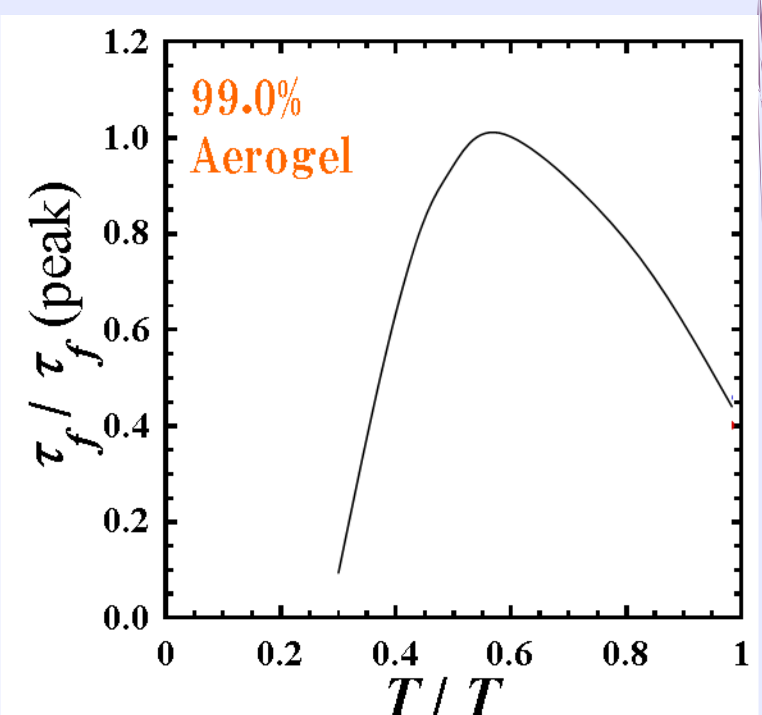
$$Q^{-1} = \frac{\rho_n}{\rho_s} \omega \tau_f$$

M. Miura, S. Higashitani, M. Yamamoto, and K. Nagai, JLTP **134**, 843 (2004).
S. Higashitani, M. Miura, M. Yamamoto, and K. Nagai, PRB **71**, 134508 (2005).
S. Higashitani, M. Miura, M. Yamamoto, and K. Nagai, JLTP **138**, 147 (2005).

Result & Discussion

Frictional relaxation time $\tau_f = \frac{\rho_s}{\rho_n} Q^{-1}$





scaled by peak value

- The lower *P*, the shorter τ_f
- ρ_n strongly trapped by aerogel @ $T \to 0$

τ_f (peak) & T_C same coherence length dependence

Compare with Theory

This broad peak structure has already predicted by the numerical study.

the absolute value is 30 times lager, though…

$$\tau_f = \lim_{\omega \to 0} \frac{1 - Y(0)/Y(\omega)}{i\omega}$$

[S. Higashitani et. al., PRB,71,134508(2005)]

※modification $\tau_f / \tau_f\,(T_C)$ → $\tau_f / \tau_f\,(\text{peak})$

competition between $Y(0)$ & $Y(\omega)$ leads the peak

Summary

- The fourth sound experiment in 99.0% open aerogel.
  B-like phase only.
- ρ_s depends only weakly on pressure,
  but $Q^{-1}(T)$ or $\tau_f(T)$ depends on pressure.
- $\tau_f(T)$ are scaled by T_C and τ_f^{peak} (or hopefully $\tau_f(T_C)$?)
- $\tau_f(T)$ shows a broad peak, which is predicted by the quasiclassical
  Green's function study.
- The origin of the energy loss of the 4th sound resonance is
  the momentum transfer during the scattering
  between QP at mid-gap state and the aerogel,
  which is characterized by $\tau_f(T)$.

Future works

- Porosity dependence
- Simple geometry