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Boundary and Impurity Effects on Anisotropic Superfluids and Superconductors

広島大学　綜合科学部　永井　克彦

共同研究者

東谷誠二、長登　康、山本幹雄
三浦　真毅

1. Transverse Acoustic Impedance of Superfluid ^{3}He-B
2. Sound Propagation in Liquid ^{3}He in Aerogel
3. Electronic Raman Scattering of Sr_2RuO_4
4. Future Problems

Transverse Acoustic Impedance of Superfluid ^{3}He-B

Acoustic Impedance

$$Z = \Pi_{xz}/v$$

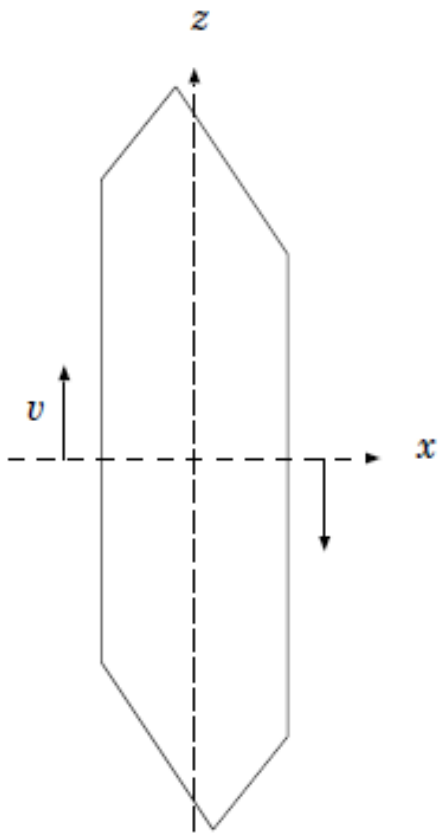
Π_{xz} : Stress Tensor of Liquid

Resonance Frequency of Quartz

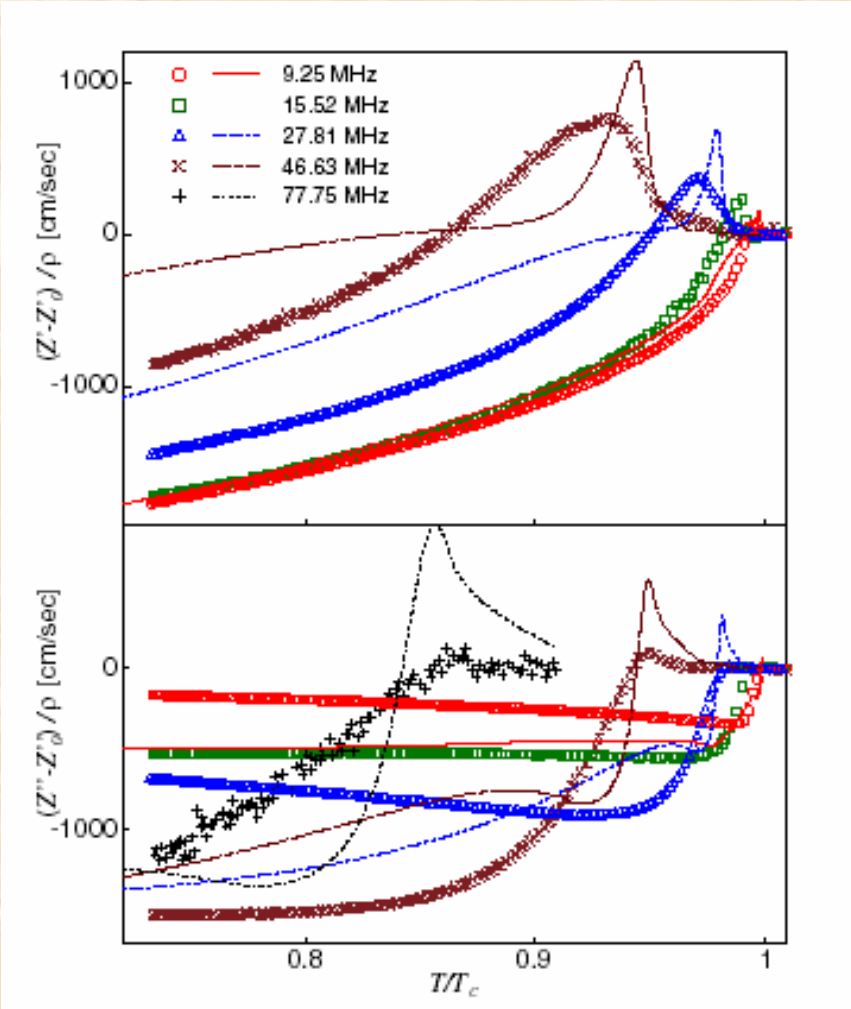
$$Z' = \frac{\pi}{4} Z_Q \frac{1}{Q}$$

$$Z'' = \frac{\pi}{2} Z_Q \delta\omega$$

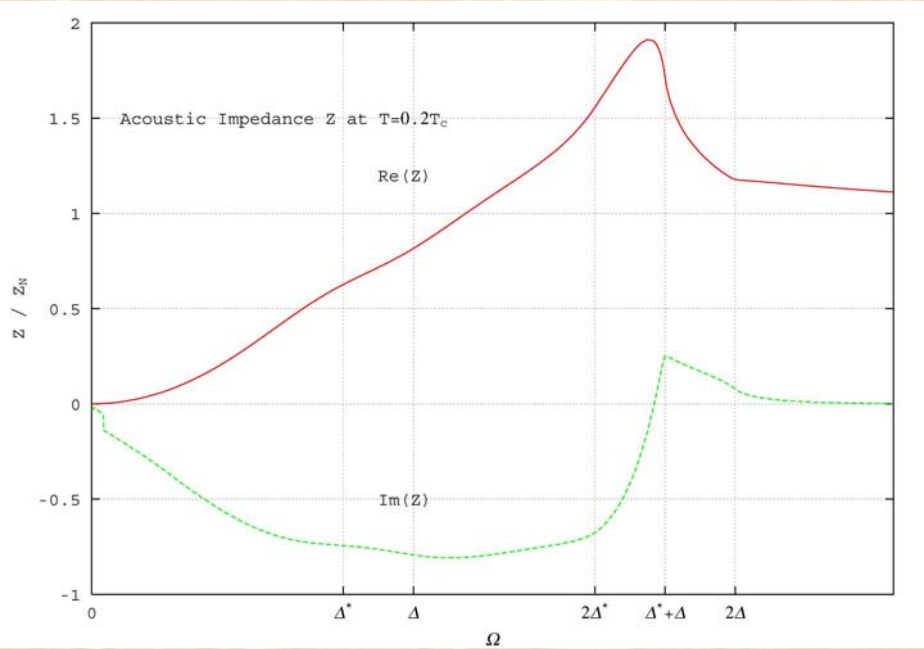
$$Z_Q = \rho_Q c_t$$

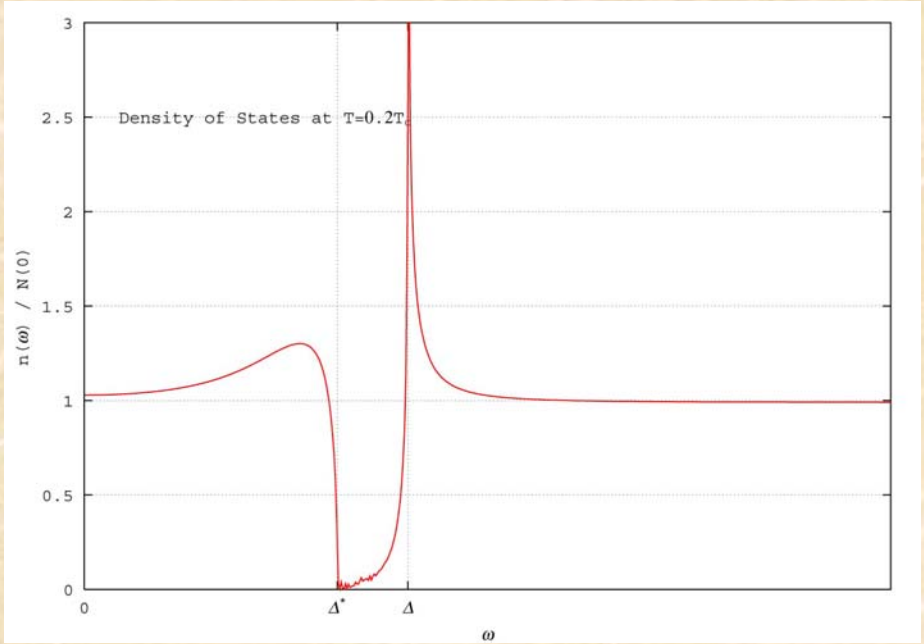


Aoki et al., Phys. Rev. Letters **95**, 075301 (2005)



Frequency Dependence of $Z=Z'+iZ''=P_{xz}/u_{wall}$





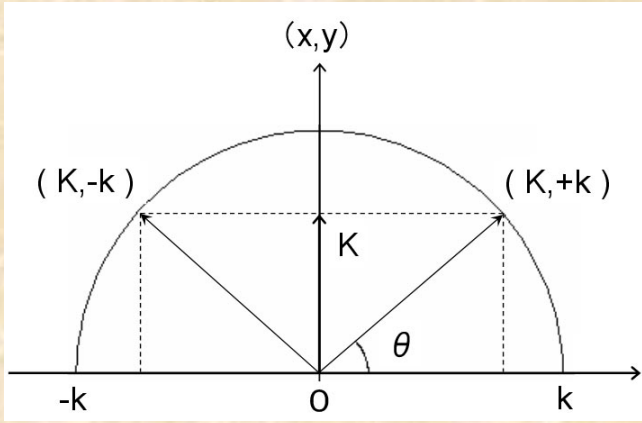
Structure in the acoustic impedance can be related to the pair excitations of midgap quasi-particle and propagating quasi-particle.

Acoustic Surface Spectroscopy

Random S-matrix Model

Nagato et al. (1996)

$$S = -\frac{1 - i\eta}{1 + i\eta} \quad (\eta_{KQ}\text{: Hermite matrix})$$



η : Random variable to describe the surface roughness

$$\overline{\eta_{KQ}} = 0$$

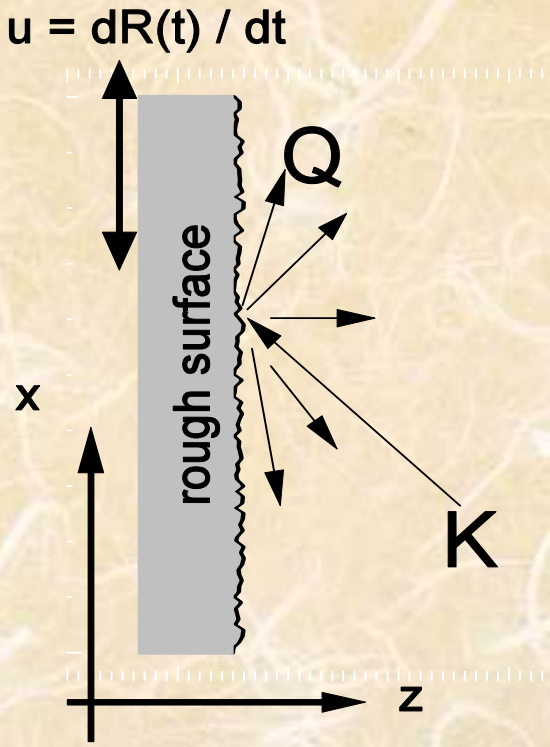
$$\overline{\eta^*_{KQ}\eta_{K'Q'}} = \eta^{(2)}(K - Q)\delta_{K-Q,K'-Q'}$$

$$\eta^{(2)}(K - Q) = \frac{2W}{\Sigma_Q 1}$$

W: Parameter to describe the roughness of the surface

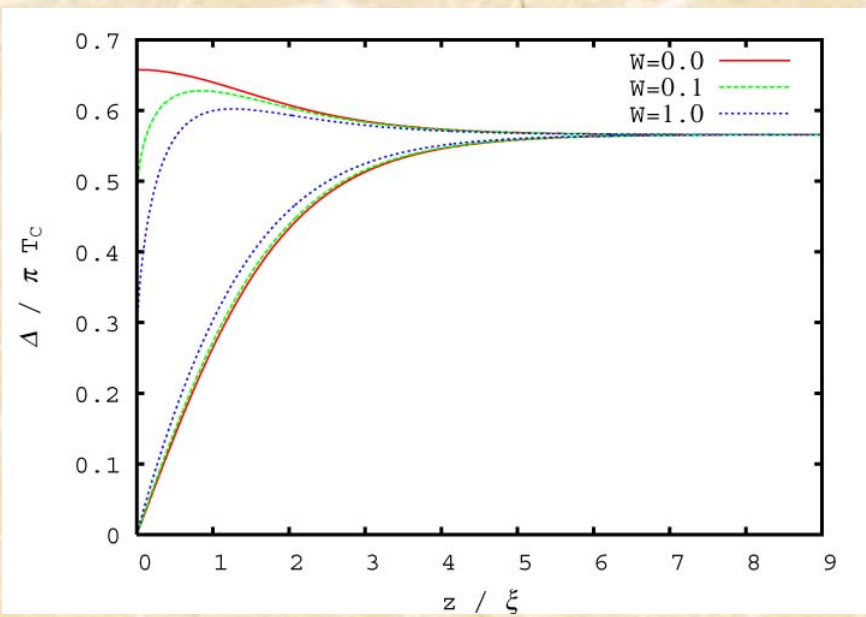
$$W = 0 \longleftrightarrow W = 1$$

Specular — Diffusive

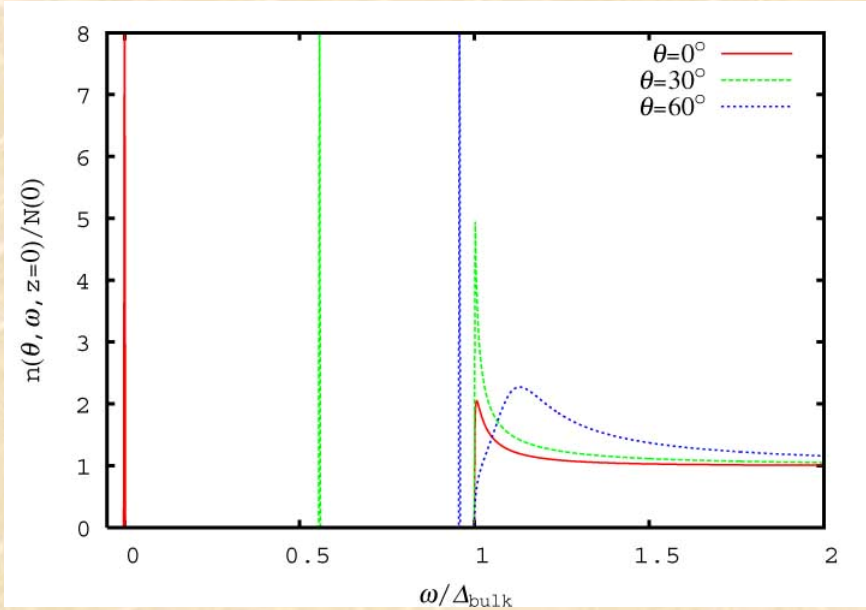


Surface Effects on BW State

Orderparameter

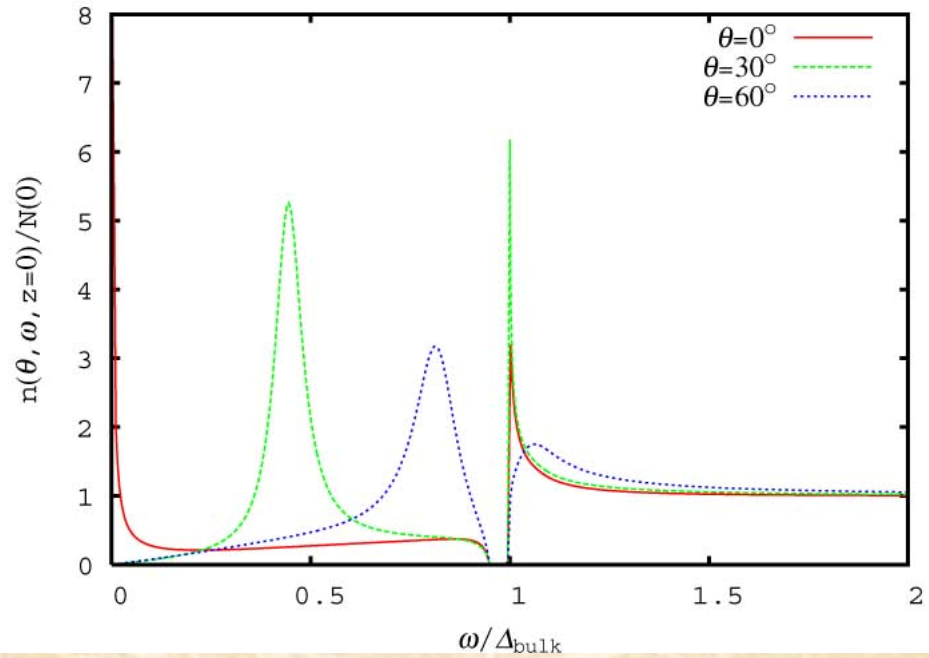


Angle Resolved Density of States at Surface

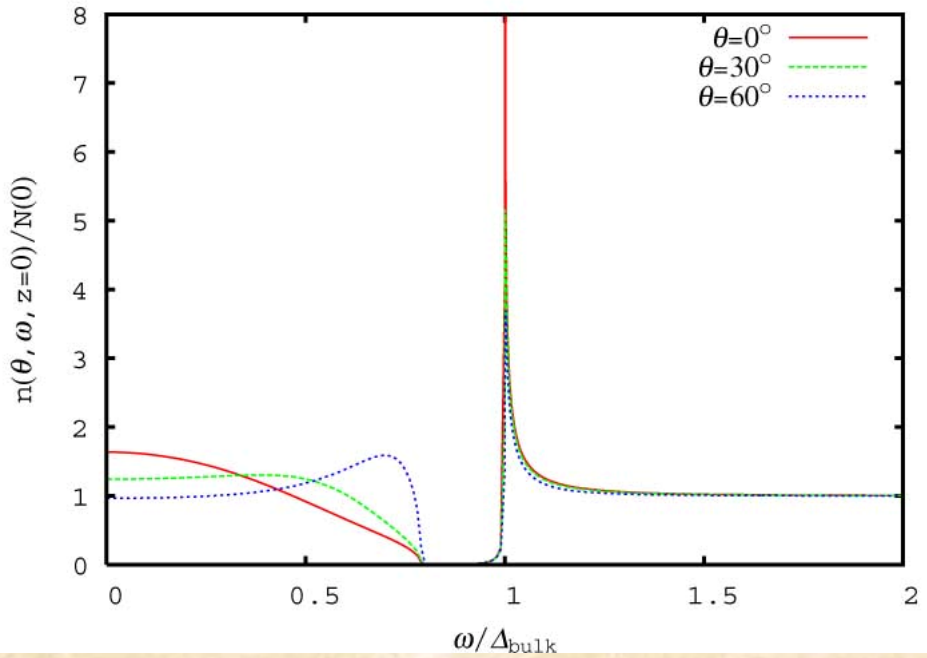


W=0

Density of States at Surface with Roughness

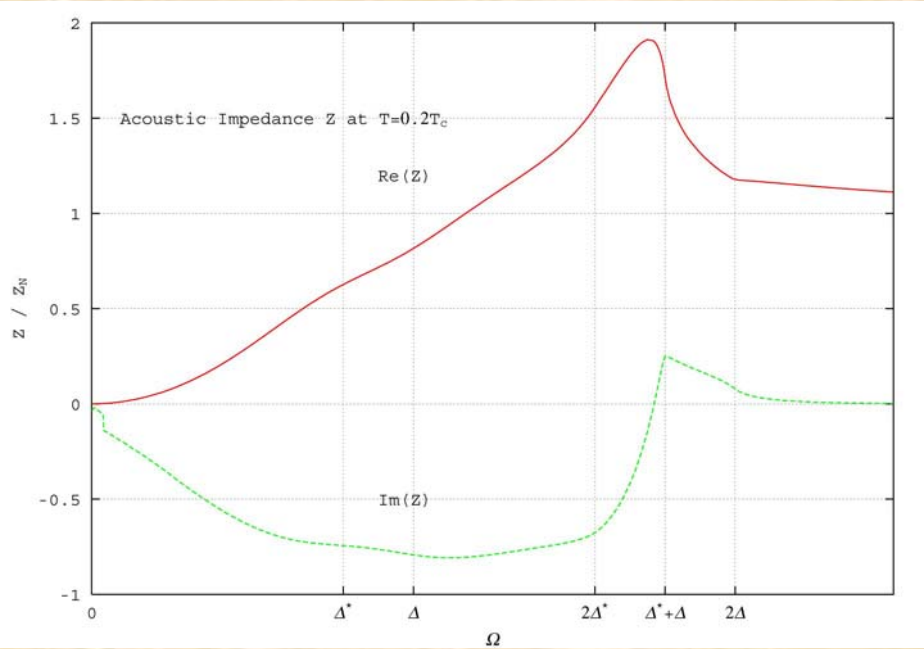


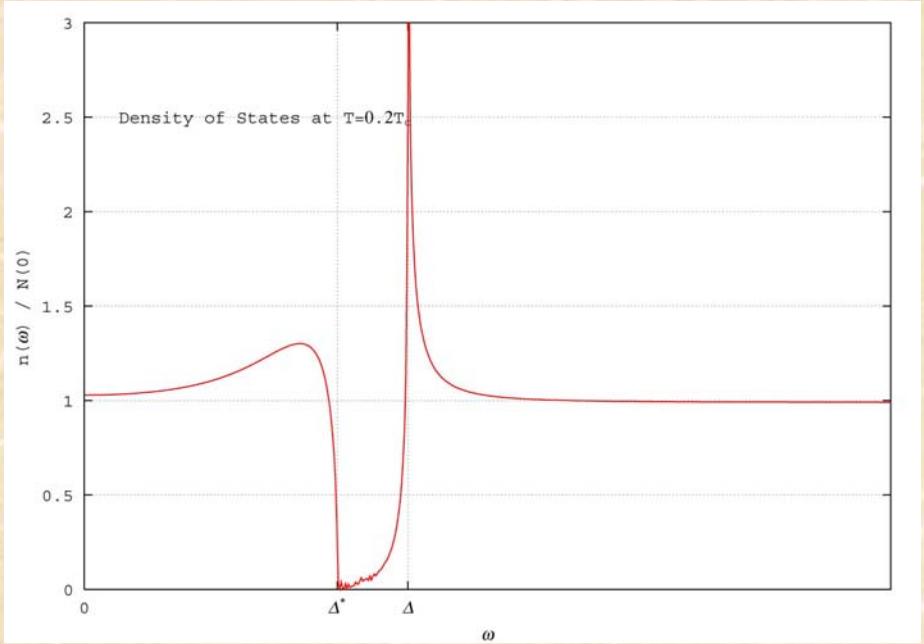
W=0.1



W=1.0

Frequency Dependence of $Z=Z'+iZ''=P_{xz}/u_{wall}$





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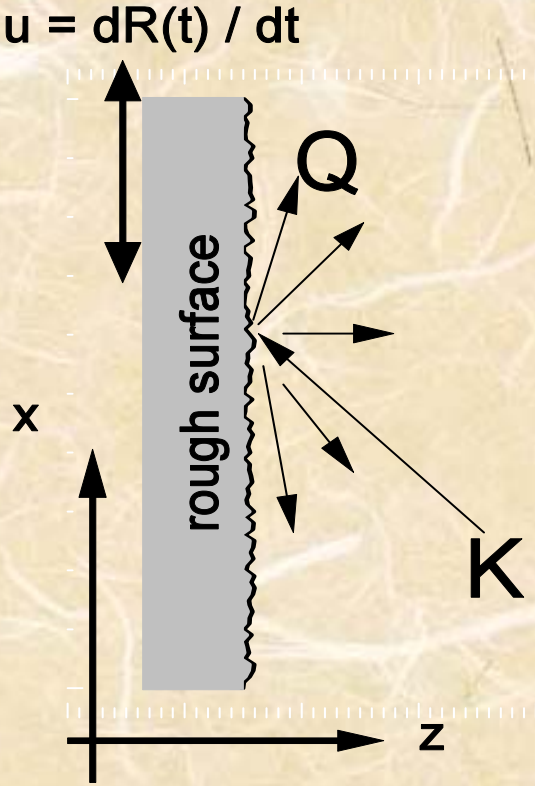
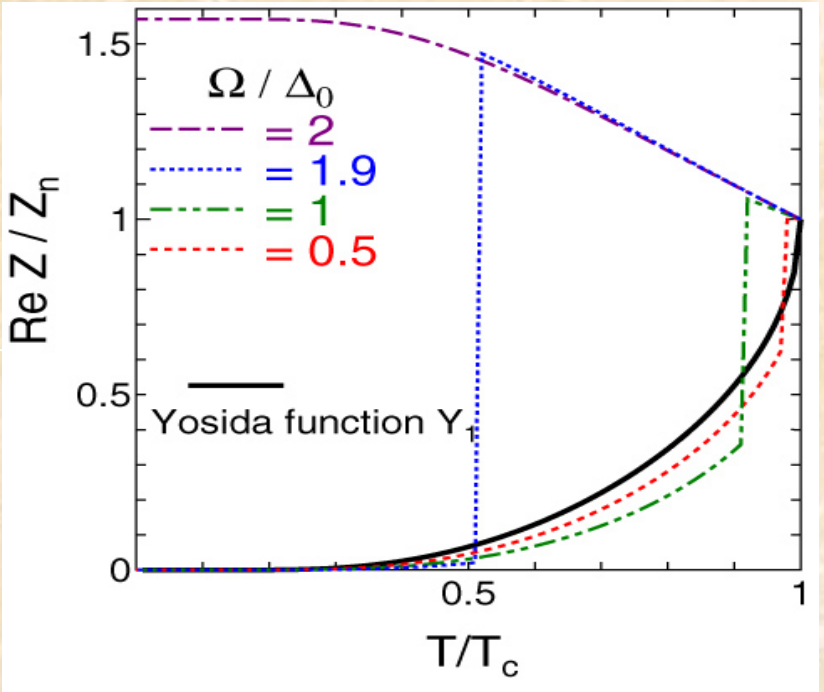
Acoustic Surface Spectroscopy

Boundary Condition for Oscillating Wall



$$S_{KQ} \rightarrow e^{-iKR(t)} S_{KQ} e^{iQR(t')}$$

Analytic Result for s-wave pairing System



Unsolved Problems

1. Origin of the upper edge of the surface states band.

2. Fermi liquid effects

$$\frac{\partial}{\partial t} J_x(z) = -\frac{\partial}{\partial z} \Pi_{xz}$$
$$\Pi_{xz}(0) = -i\omega \int_0^\infty dz J_x(z)$$

$$J_x(z) = J_0(z) + F_1^s \int_0^\infty dz' K(z, z') J_x(z')$$

How the momentum of wall is transferred to the superfluid and how the transverse wave motion develops as it is away from the wall?

Sound Propagation in Liquid ^{3}He in Aerogel

Aerogel SiO_2 の鎖状ネットワーク

エアロジェル (98%) の特徴的な長さ

- SiO_2 粒子　a=3nm,　$k_F a \sim 20$
- 平均鎖間距離　35nm
- フラクタル相関長　100nm
  フラクタル次元　$D = 1.8,\ 3 - D = 1.2 > 1$
- ^{3}He の平均自由行程　200nm
- ^{3}He のコヒーレンス長　15nm~80nm

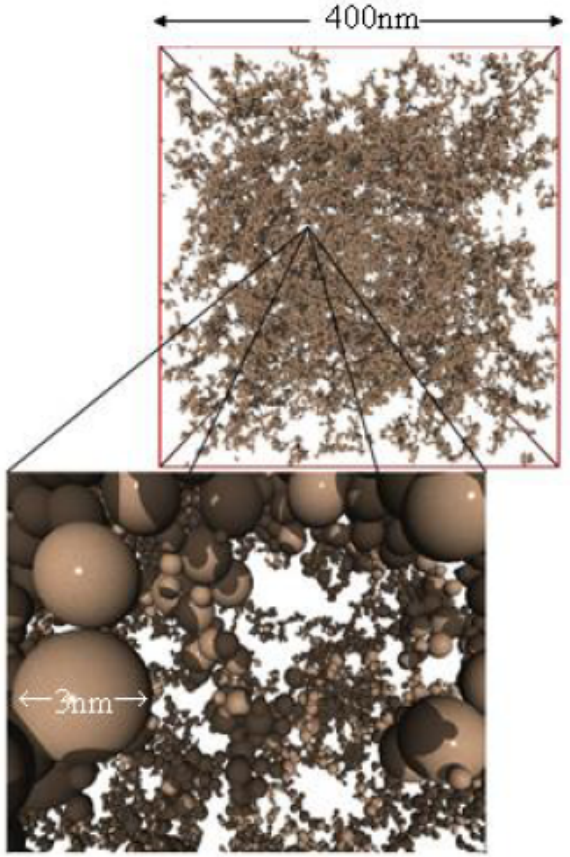
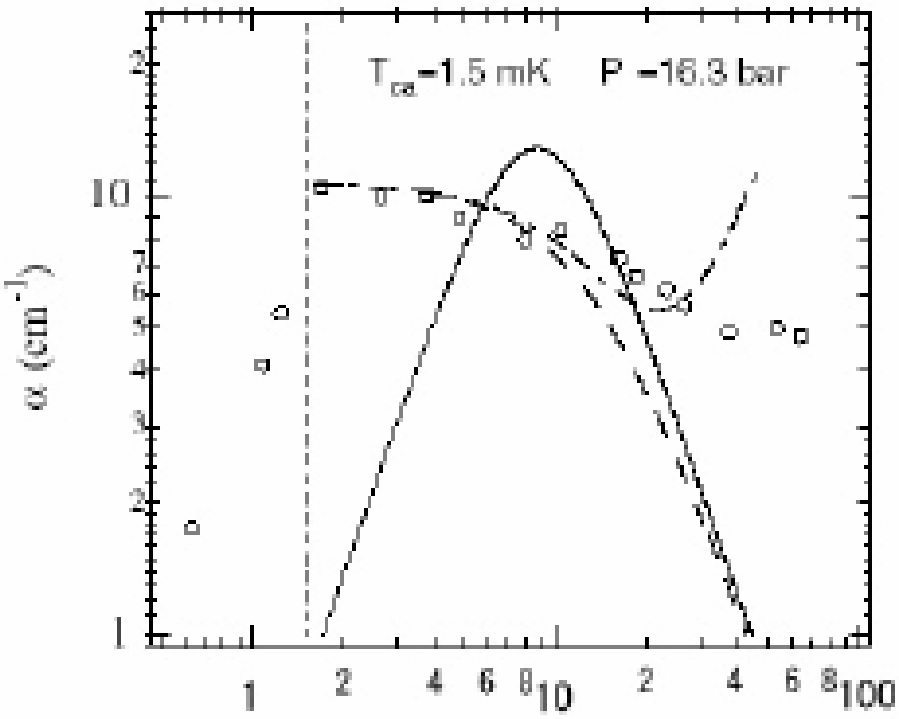


図:シミュレーションにより描かれた
エアロジェルの構造
(http://spindry.phys.nwu.edu/DLCA)

Sound Propagation

Nomura et al. Phys. Rev. Lett, **85**, 4325 (2000).

15MHz, $\lambda \sim 20\mu$m



Momentum Conservation Law in Aerogel

$$\frac{\partial J_i}{\partial t} + \frac{\partial \Pi_{ij}}{\partial x_j} + F_i = 0$$

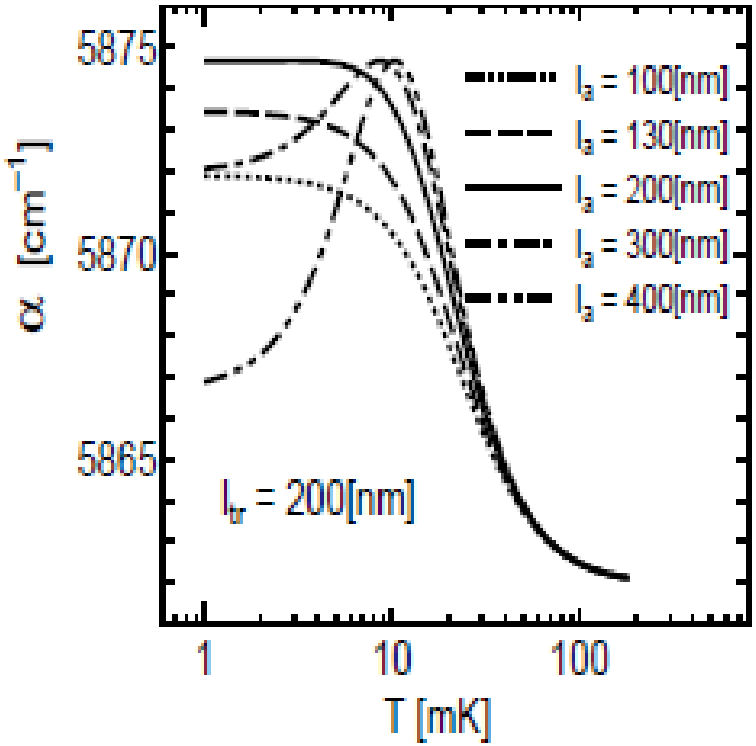
$$\Pi_{ij} \leftarrow \eta$$

Viscoelastic Model

$$\eta \rightarrow \eta(\omega) = \frac{\eta}{1+\omega\tau}$$

$$\frac{1}{\tau} = \frac{1}{\tau_\eta} + \frac{1}{\tau_a}$$

$$F_i = \frac{1 + F_1^S/3}{\tau_{\rm tr}} J_i$$



Aerogel Motion

Equation of motion of aerogel

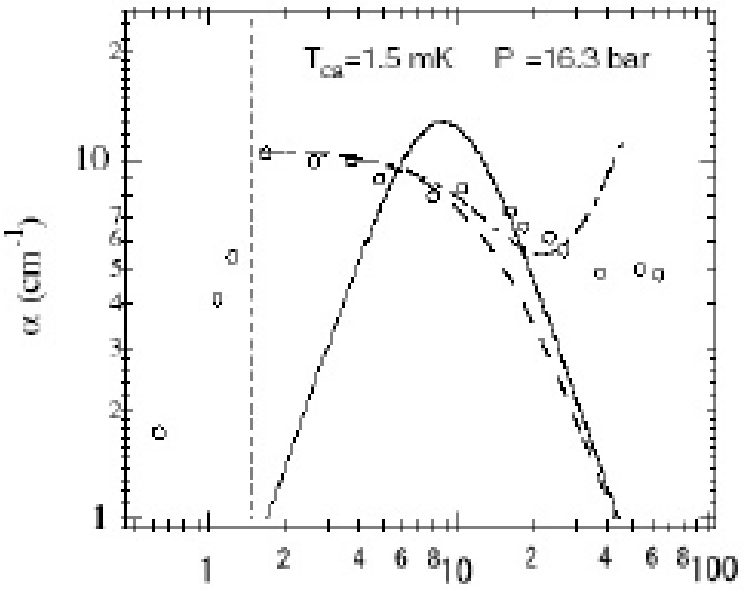
$$\rho_a \left(\frac{\partial^2}{\partial t^2} \boldsymbol{u}_a - c_a^2 \Delta \boldsymbol{u}_a \right) = \boldsymbol{F}, \quad \boldsymbol{v}_a = \frac{\partial}{\partial t} \boldsymbol{u}_a$$

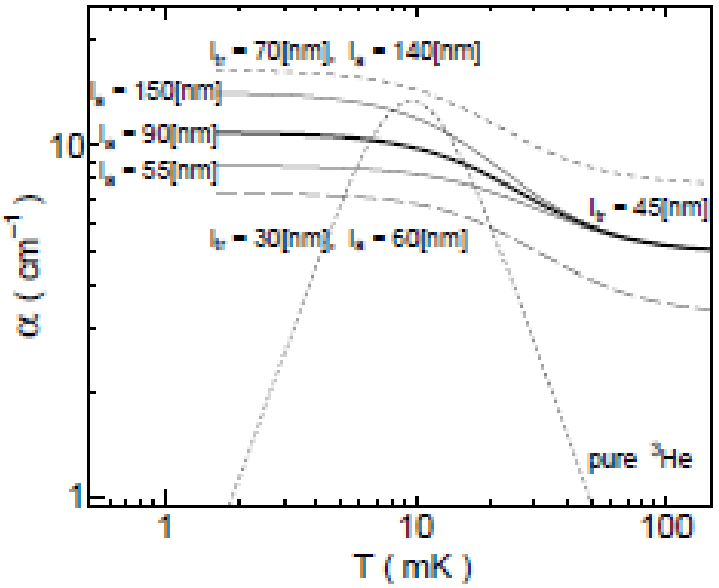
Collision drag force (Pippard, Holstein)

$$\boldsymbol{F} = -\sum_{\boldsymbol{p}} \boldsymbol{p} I_{\mathrm{imp}} = \frac{1 + F_1^S/3}{\tau_{\mathrm{tr}}} \rho (\boldsymbol{v} - \boldsymbol{v}_a)$$

$$\begin{aligned} \boldsymbol{J} &= \rho \boldsymbol{v} \\ \frac{\partial J_i}{\partial t} &= -\frac{\partial \Pi_{ij}}{\partial x_j} - F_i \end{aligned}$$

Ichikawa et al. JPSJ 70,3483 (2001).





$$\omega = 2\pi \times 15\mathrm{MHz}, \quad \omega\tau_{\mathrm{tr}} \sim 0.7$$

Electronic Raman Scattering from Sr_2RuO_4

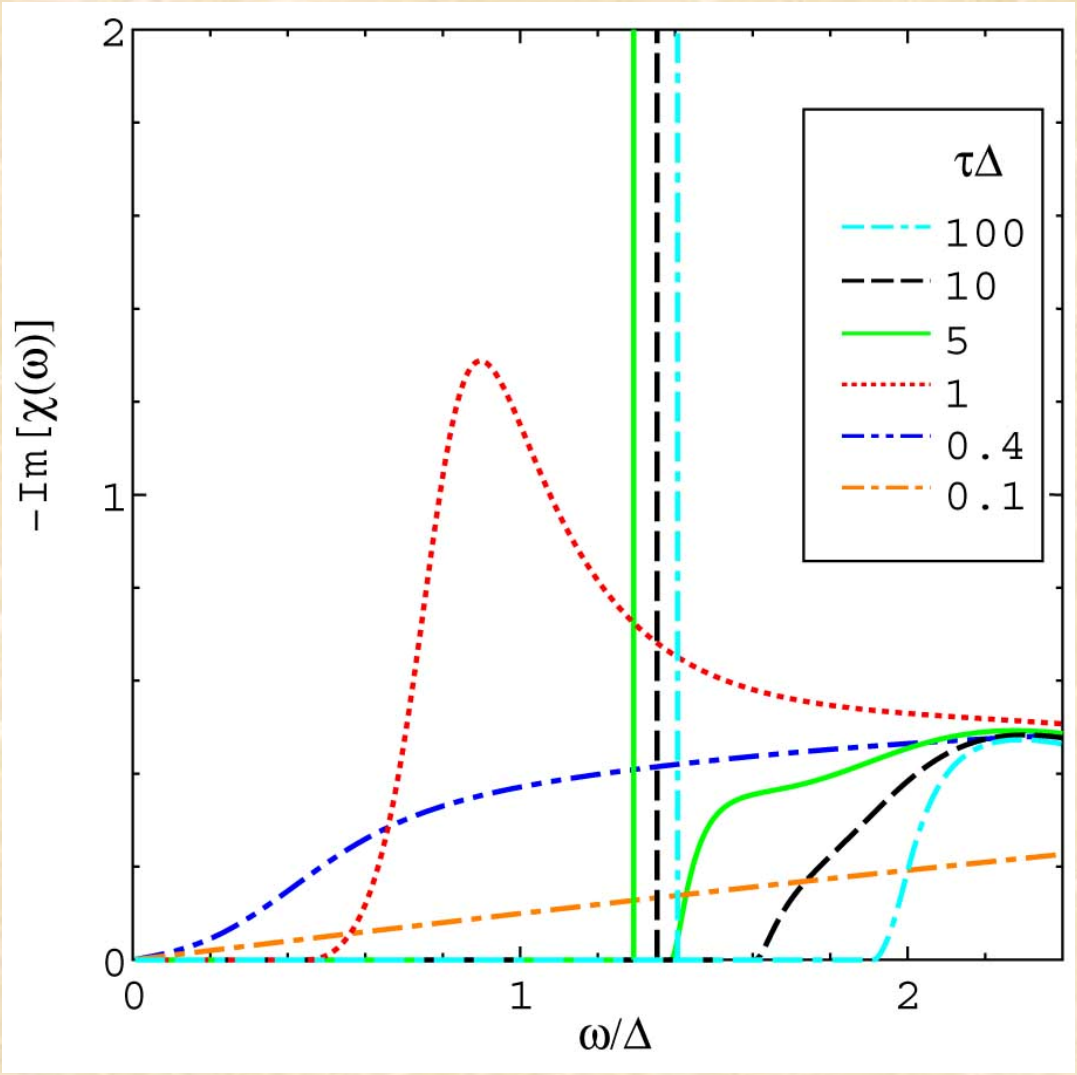
- Pair excitations
- Order Parameter Collective Modes

$$k_x \pm i k_y$$

$$\sin k_x \pm i \sin k_y$$

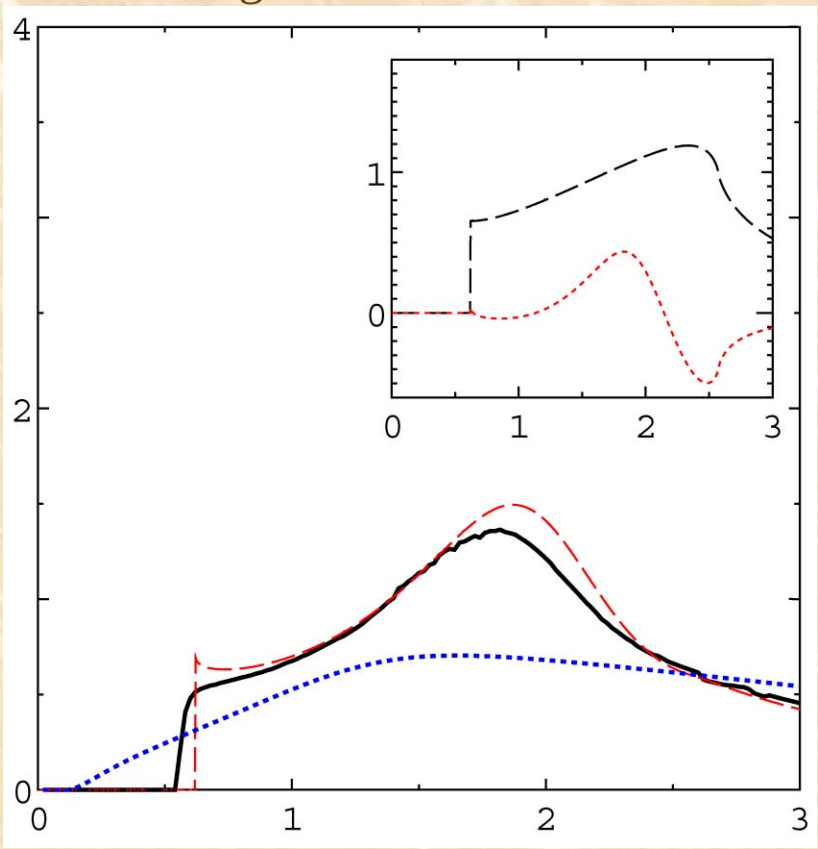
c.f. clapping mode in ^{3}He-A

$k_x + ik_y$

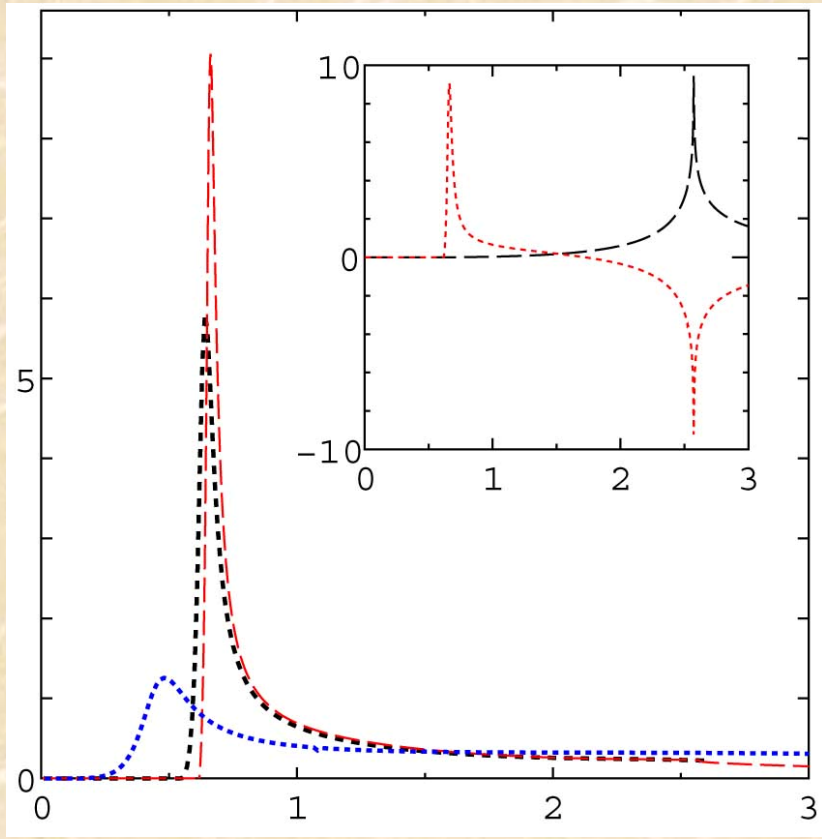


$sin\ k_x + \ i\ sin\ k_y$

B_{1g} mode



B_{2g} mode



$\tau\Delta = \infty,\ \tau\Delta = 10,\ \tau\Delta = 1$

Future Problems to Study

- quantitative study of acoustic impedance of superfluid ^{3}He
- dynamics of systems with boundary
  optical conductivity of superconductors contacts
- proximity effects of superfluid ^{3}He in aerogel
  in contact with pure superfluid ^{3}He