Surface Andreev Bound States and Surface Majorana States on the Superfluid ^{3}He B Phase

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Collaboration with

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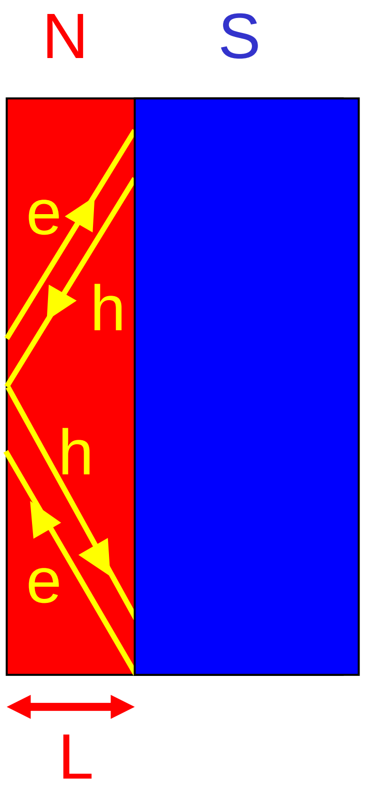
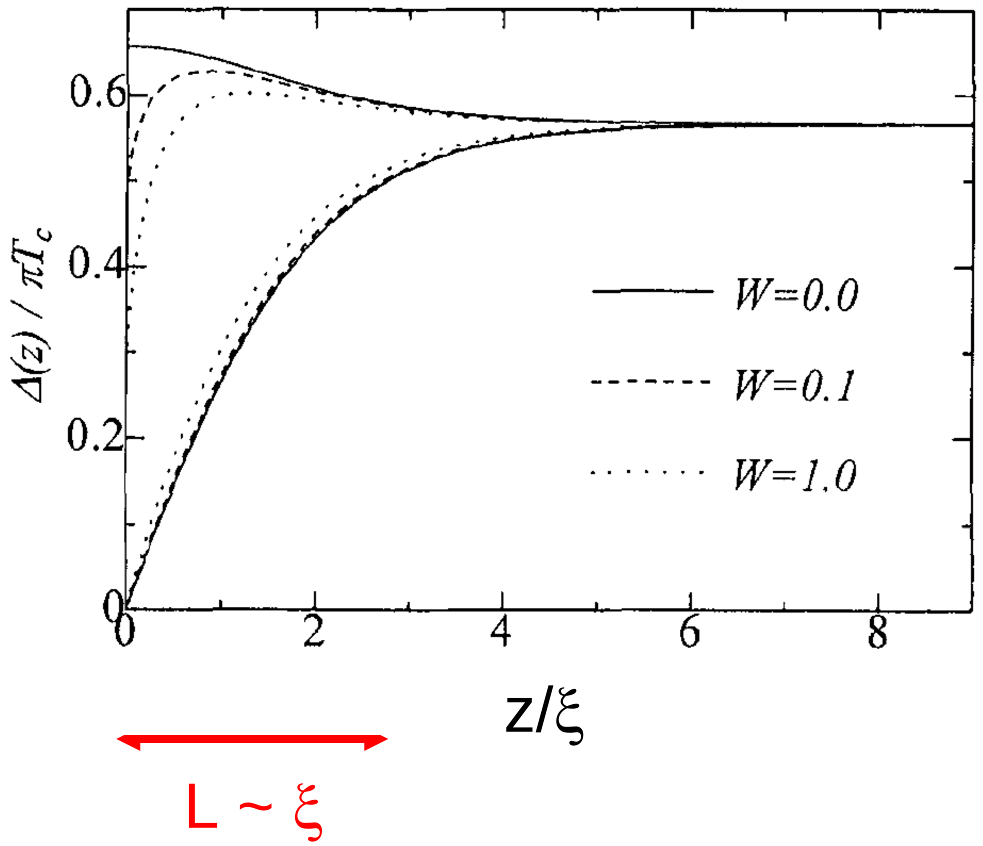
Andreev Bound States (ABS)

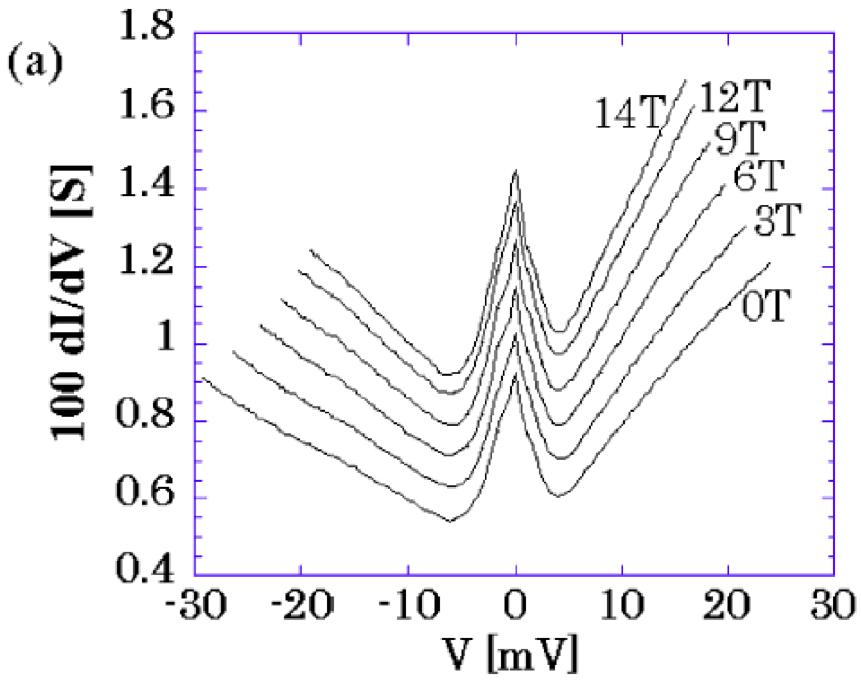


Resonant states in normal metal.



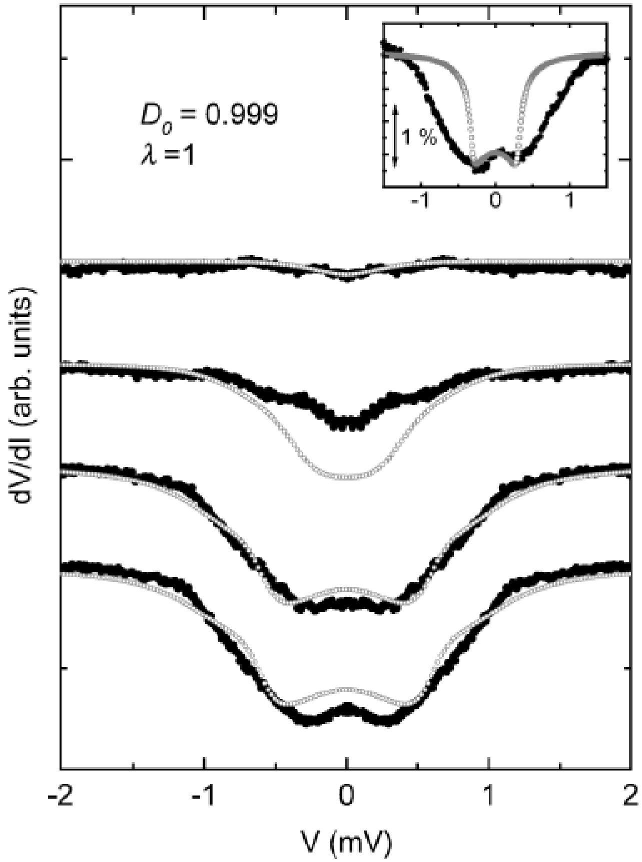
SABS are intrinsic to surface of anisotropic BCS states.

Zero bias conductance peak in unconventional superconductors



tunneling of YBCO junction

Kashiwaya *et al.*
PRB **70**, 094501
(2004)

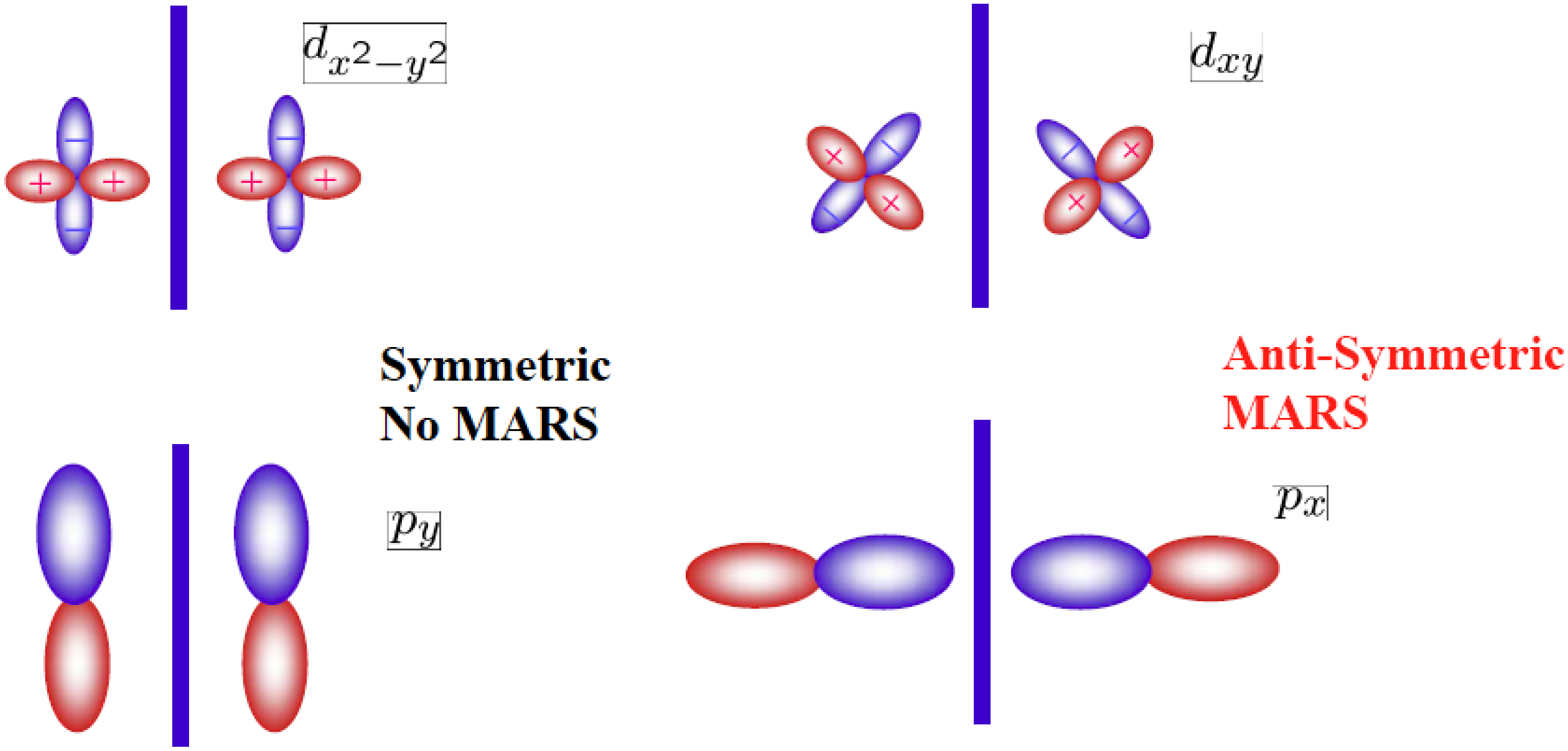


Sr2RuO4

Laube *et al.*
PRL 84,
1595
(2000)

Condition of the formation of mid gap Andreev resonant state(MARS)

Inversion at the plane parallel to the interface



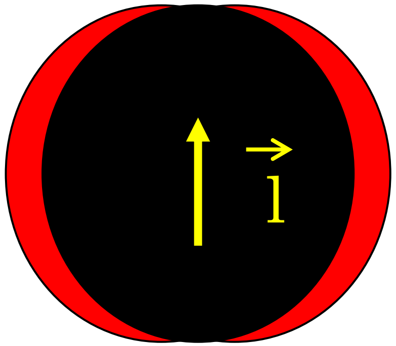
Symmetric
No MARS

Anti-Symmetric
MARS

By Yukio Tanaka, superclean (2005)

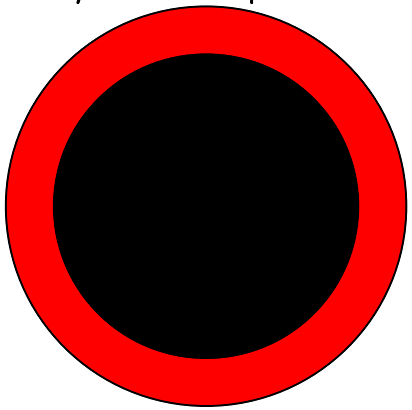
superfluid phases of 3He

$$|\text{A phase}\rangle = \Delta_A \left(p_x + ip_y\right)\left\{|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right\}$$



anisotropic gap

$$|\text{B phase}\rangle = \Delta_B \left\{\left(p_x + ip_y\right)|\downarrow\downarrow\rangle + \left(p_x - ip_y\right)|\uparrow\uparrow\rangle + p_z|\uparrow\downarrow + \downarrow\uparrow\rangle\right\}$$



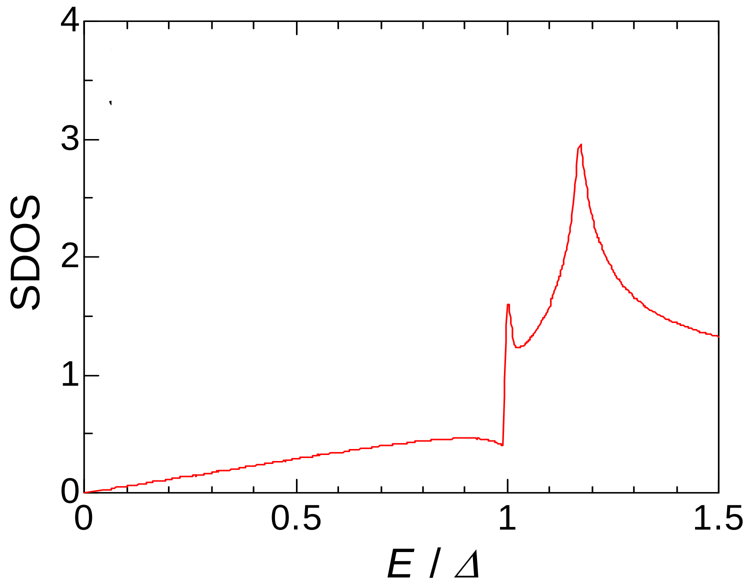
isotropic gap

In the BW state, anti-symmetry of the order parameter is broken.

Theoretically calculated SDOS in BW state on specular surface

angle resolved

angle averaged (Natato 1998)

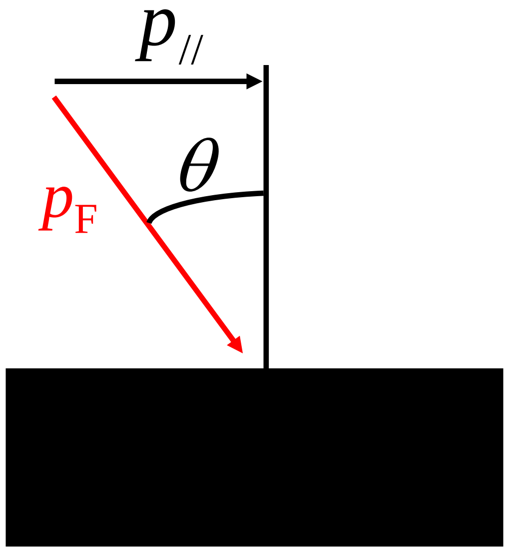


$$E = c_{//} p_{//}$$

$$N(E) \propto E$$

No sharp peak at zero energy but a broad SABS band appears within the bulk energy gap Δ.

“Dirac” cone on 3He-B



$$\theta = 0 \quad \mathit{\Delta}(\boldsymbol{p}_z) = -\mathit{\Delta}(-\boldsymbol{p}_z)$$

$$\Downarrow$$

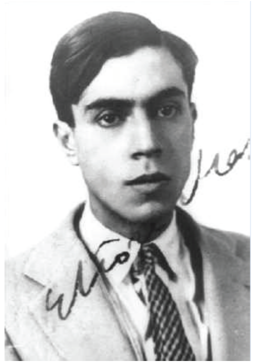
$$E = 0$$

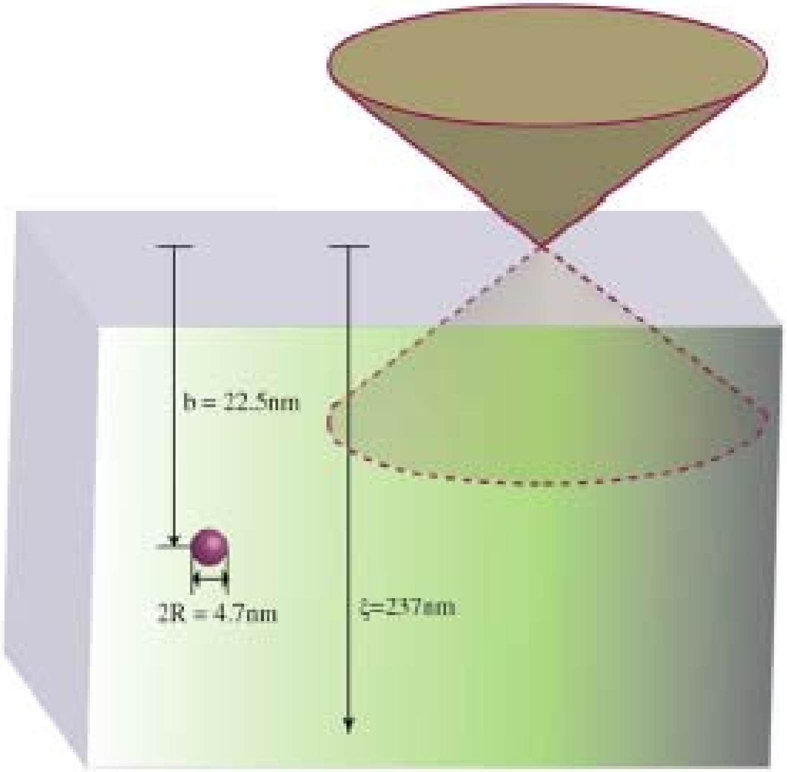
$$E = \Delta_{//} \sin\theta = c_{//}\, p_{//}$$

$$d_{\mu i} = \begin{pmatrix} \Delta_{\|} & 0 & 0 \\ 0 & \Delta_{\|} & 0 \\ 0 & 0 & \Delta_{\perp} \end{pmatrix}$$

particel = anti-particel

SABS: Majorana Fermion





“Majorana cone”

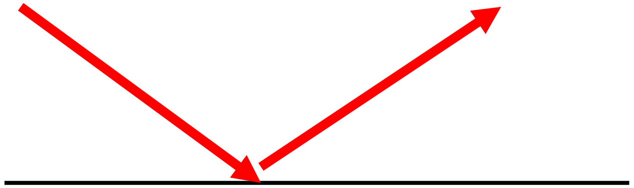
Chun, Zhan, PRL09

Recent theories on Majorana surface state in 3He-B

(1)Classification of topological insulators and superconductors in three spatial dimensions
A. P. Schnyder, S. Ryu, A. Furusaki, and A. W. W. Ludwig, Phys. Rev. B 78, 195125 2008
(2)Topological superfluids with time reversal symmetry
R. Roy, arXiv:0803.2868v1, 19 Mar 2008
(3)Time-Reversal-Invariant Topological Superconductors and Superfluids in Two and Three Dimensions
Xiao-Liang Qi, Taylor L. Hughes, S. Raghu, and Shou-Cheng Zhang, PRL 102, 187001 (2009)
(4) Detecting the Majorana fermion surface state of 3He-B through spin relaxation
S. B. Chung and S. C. Zhang, PRL 103, 235301 (2009)
(5) Fermion zero modes at the boundary of superfluid 3He-B
G.E. Volovik, Pis'ma ZhETF 90, 440-442 (2009)
(6) Topological invariant for superfluid 3He-B and quantum phase transitions
G.E. Volovik, Pis'ma ZhETF
(7) Fermi Surface Topological Invariants for Time Reversal Invariant Superconductors
X. L. Qi, Taylor, L. Hughes and S. C. Zhang, arXiv:0908.3550v1, 25 Aug 2009
(8) Strong Anisotropy in Spin Suceptibility of Superfluid 3He-B Film Caused by Surface Bound States
Y. Nagato, S. Higashitani and K. Nagai, J. Phys. Soc. Jpn., 78, 123603 (2009)

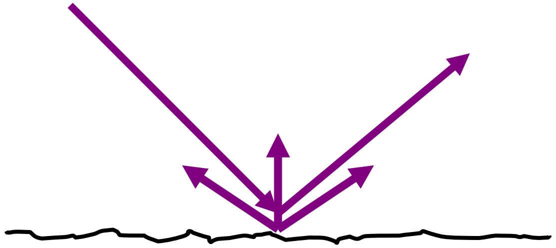
Quasiparticles scattering off a wall

Specular limit



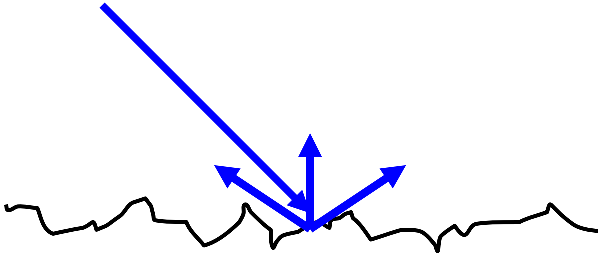
S = 1

Partially specular



1 > S > 0

Diffusive limit

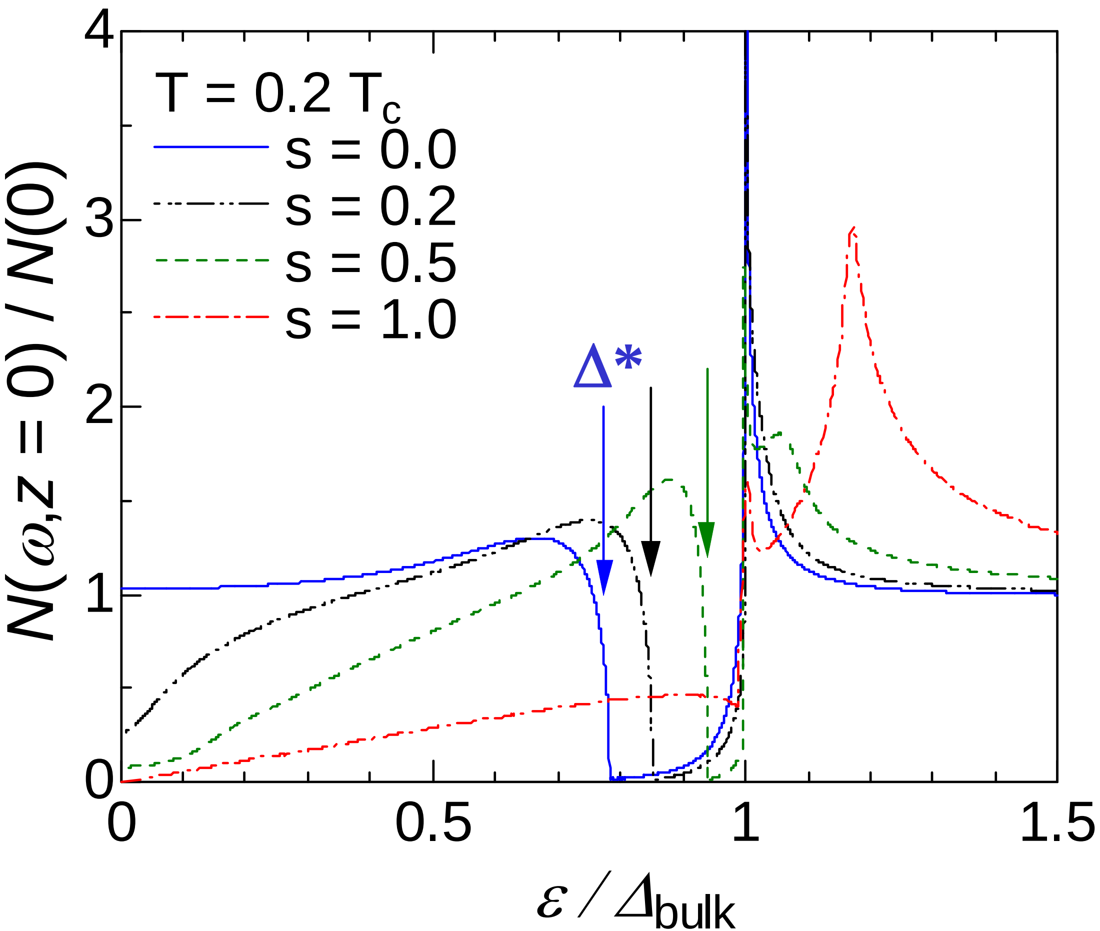


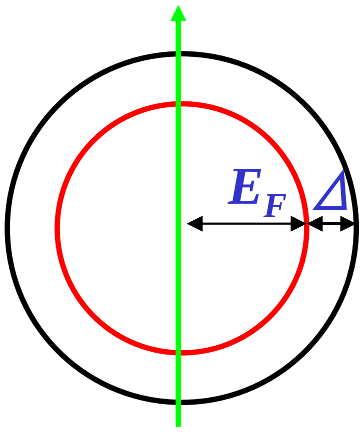
S = 0

S =0.5

S can be controlled continuously by thin ^{4}He layers on a wall.

Theoretically calculated SDOS in BW state at various S





Zero energy state is intrinsically suppressed at S > 0.

Bandwidth (Δ*) is broader at S > 0.

Flat surface bound states band at S = 0.

Nagato *et al*. JLTP 1998

Measurements

Transverse acoustic impedance of AC-cut quartz in liquid ^{3}He

$$Z = \frac{\Pi_{xz}}{u_x} = Z' + iZ''$$

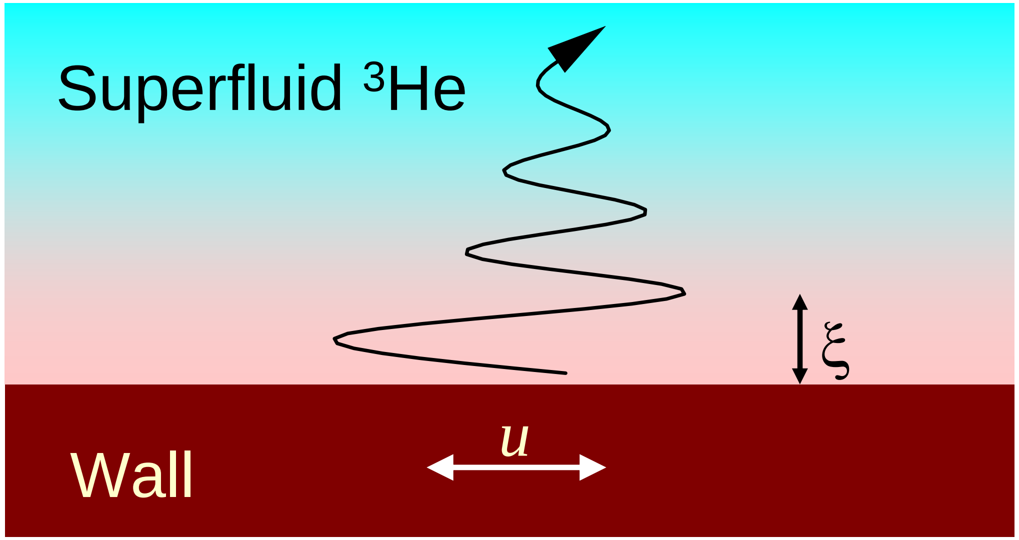
Π_{xz} Stress tensor of liquid on the wall

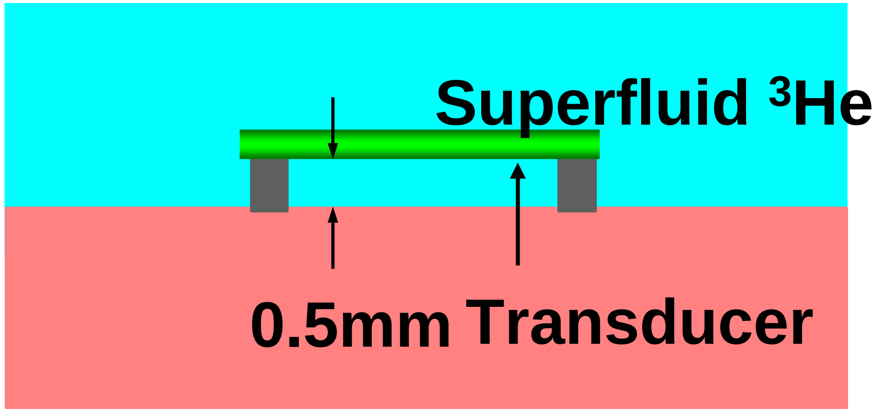
u_x Oscillation velocity

$$Z' - Z'_0 = \frac{1}{4} n\pi Z_q \left(\frac{1}{Q} - \frac{1}{Q_0} \right)$$

$$Z'' - Z''_0 = \frac{1}{2} n\pi Z_q \frac{f - f_0}{f_0}$$

$$Z_q = \rho_q c_q$$

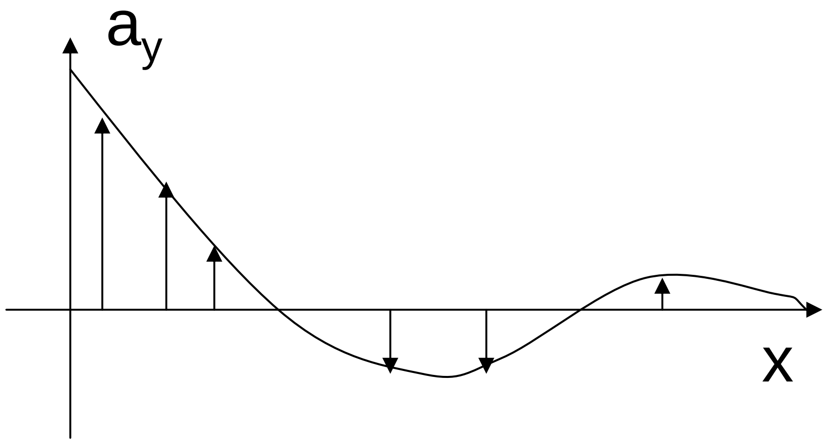




Hydrodynamics region $\omega\tau$ << 1, high temperature

$$Z = \sqrt{\frac{\omega\rho\eta}{2}}(1-i)$$

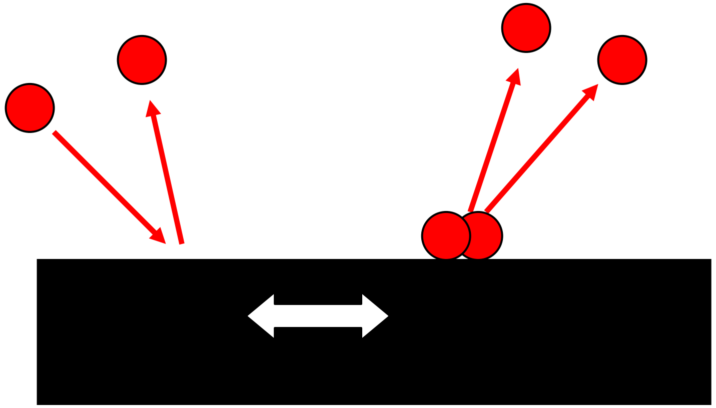
Equivalent to η viscosity measurements



critically damped

Collisionless region $\omega\tau$ >> 1, low temperature

$$Z = \frac{\Pi_{xz}}{u_x} = Z' + iZ''$$



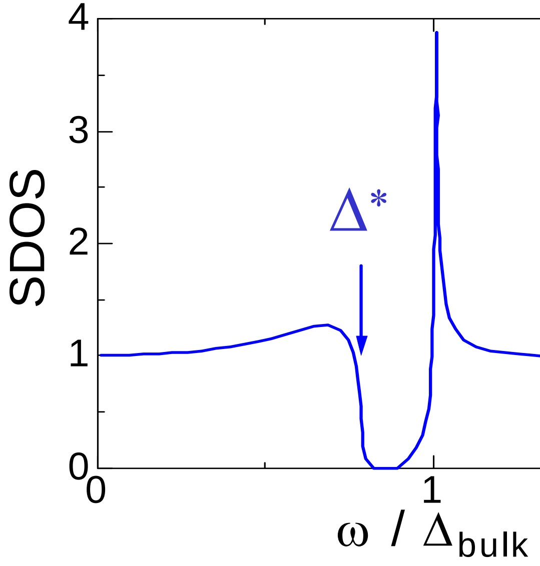
Quasiparticle scattering

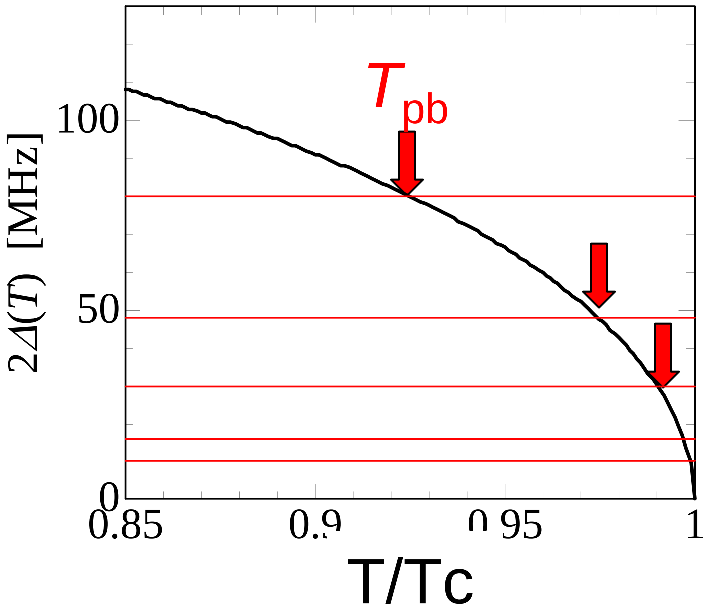
Pair breaking

$\omega \sim \Delta$ Spectroscopy of SDOS

Diffusive limit, S = 0

Pure ^{3}He without ^{4}He coating

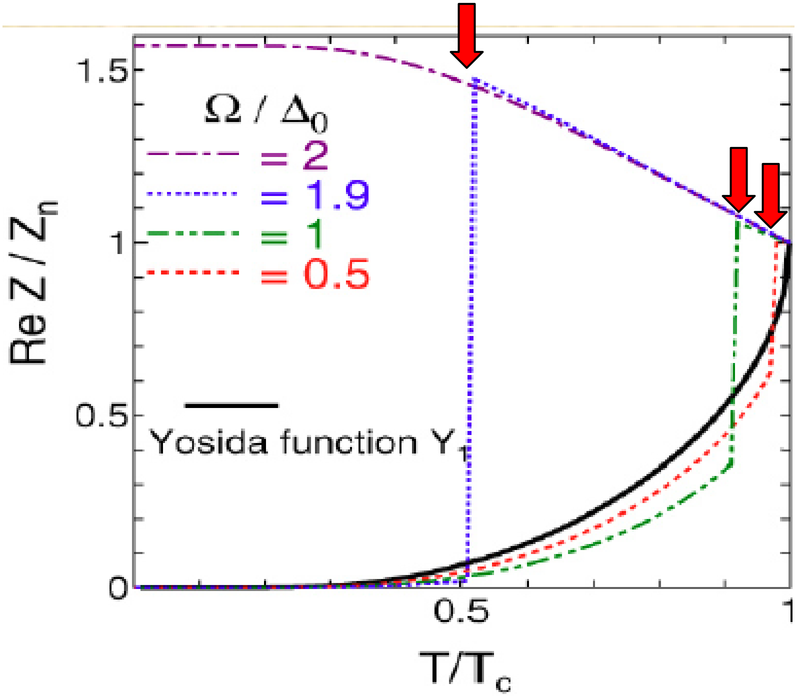




Pair breaking edge temperature T_{pb}

$$\hbar\omega \equiv 2\Delta(T_{pb})$$

In s-wave BCS superfluid (no SABS)



Drop in Z' at T_{pb}

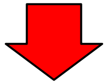
$$T \to 0 : Z \to 0$$

Small frequency dependence

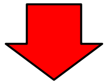
Only ρ_n responses

In B phase

No change in Z at T_c



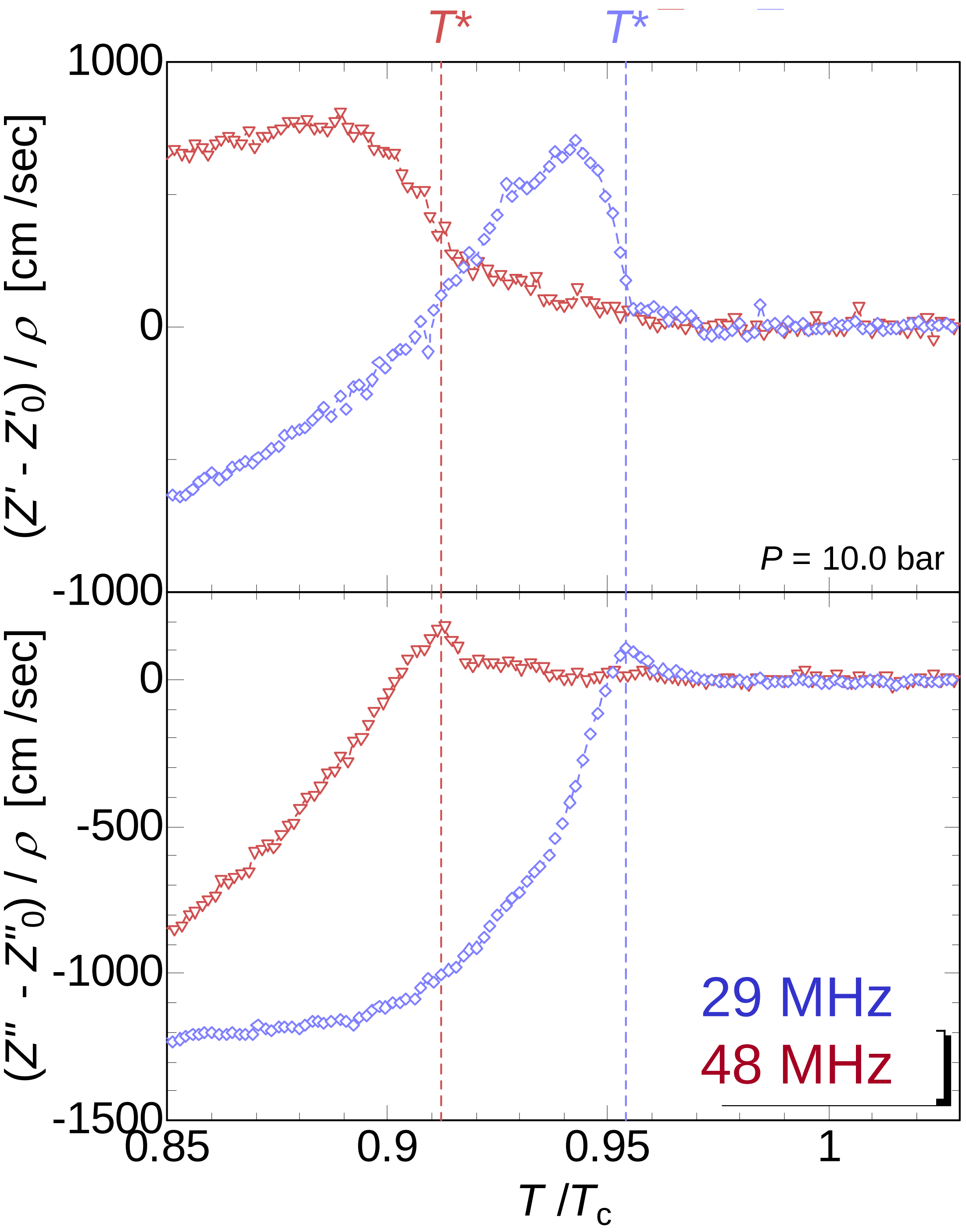
No drop in Z’ at T_{pb}.



peak in *Z”* and kink in *Z’* at *T**

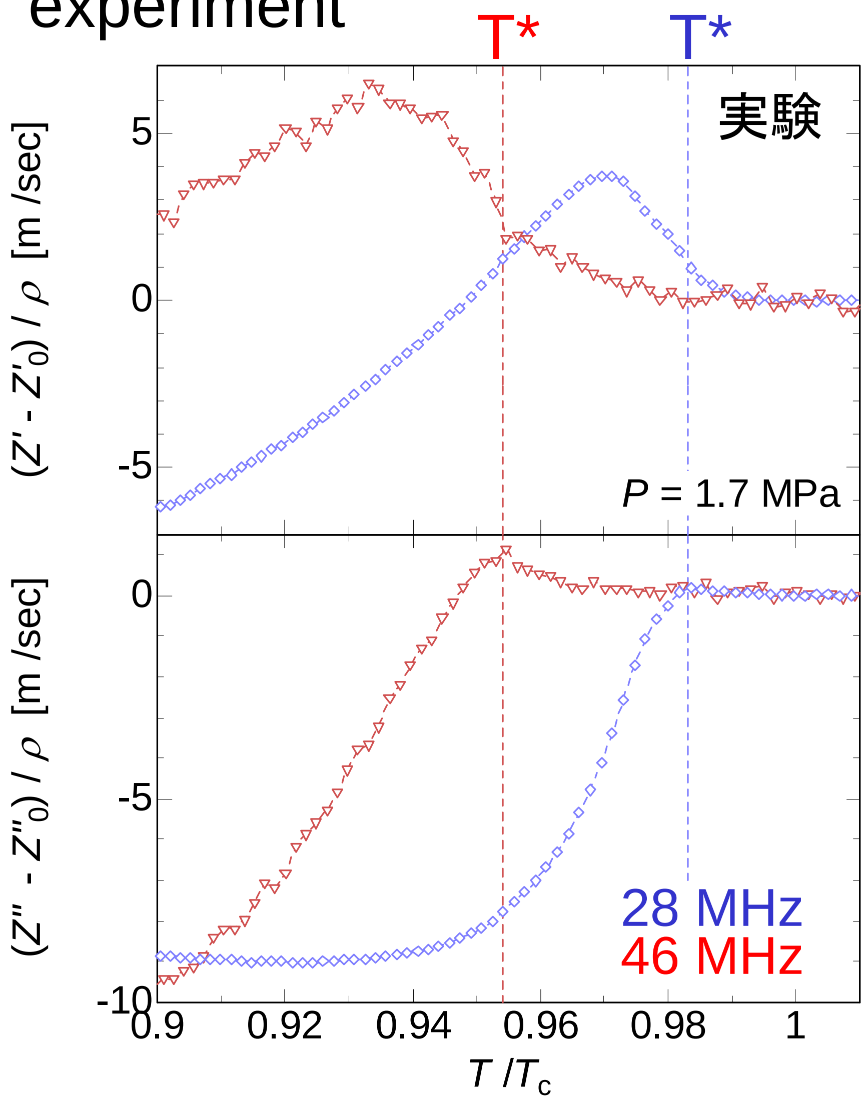
Structure appears below $T_{pb.}$

Low lying excitations !!

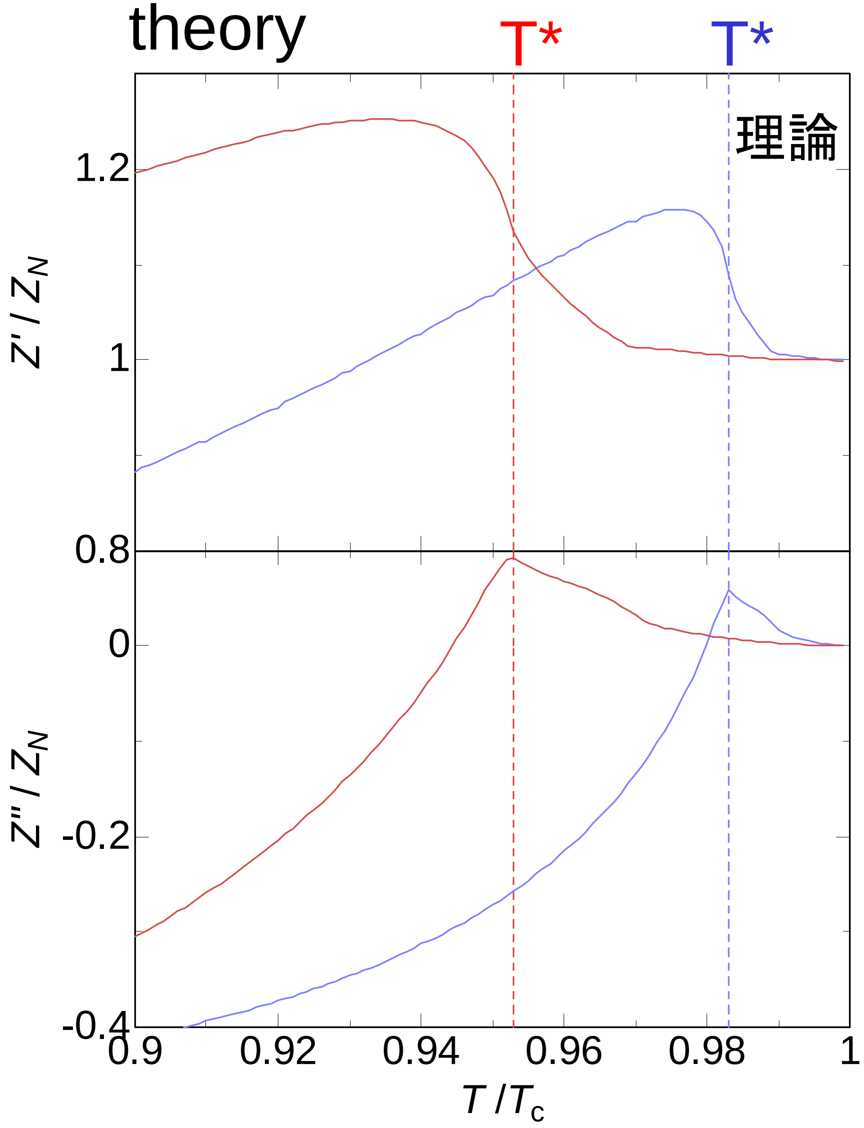


Z(T) at S = 0

experiment

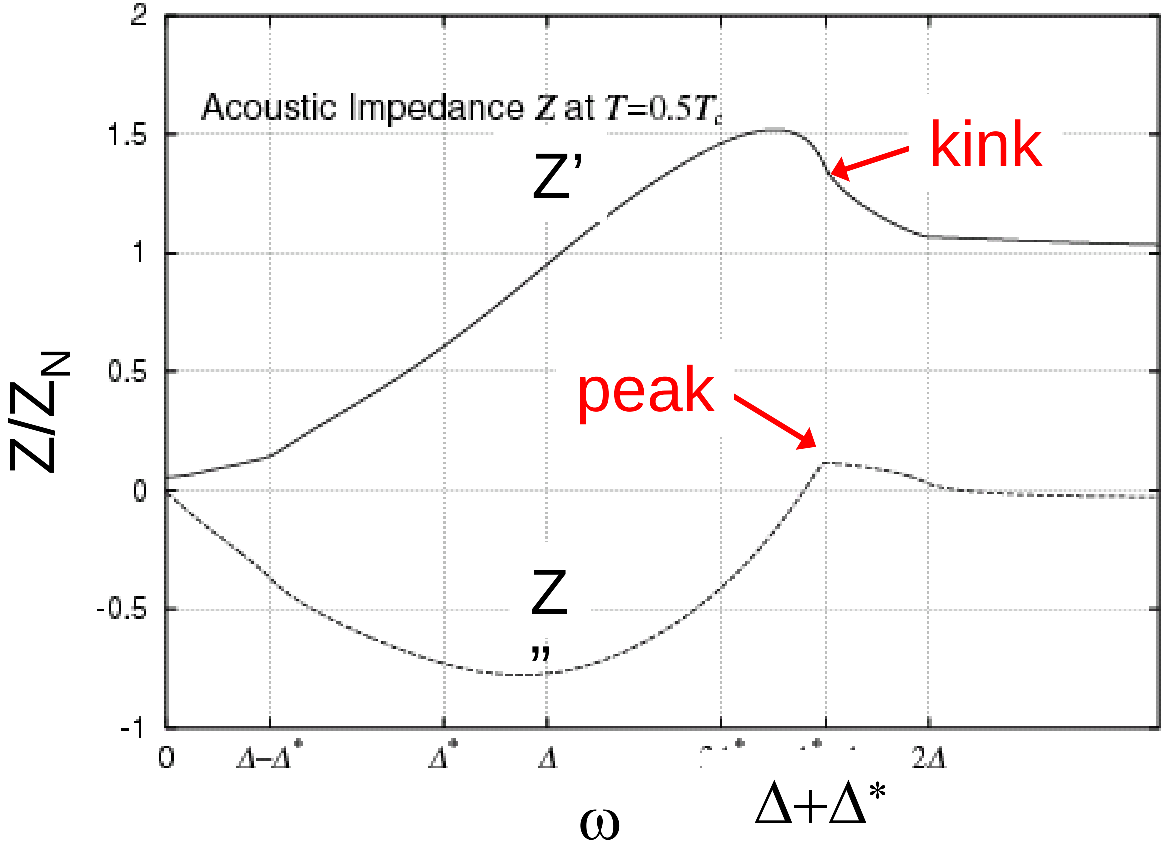


theory



Aoki *et al*. PRL (2005)

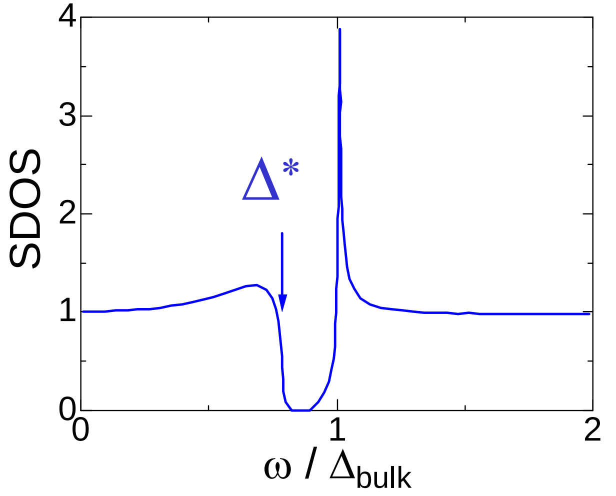
Z(ω) theory with SABS



Kink and peak
are anomaly
when $\hbar\omega = \Delta + \Delta^*$

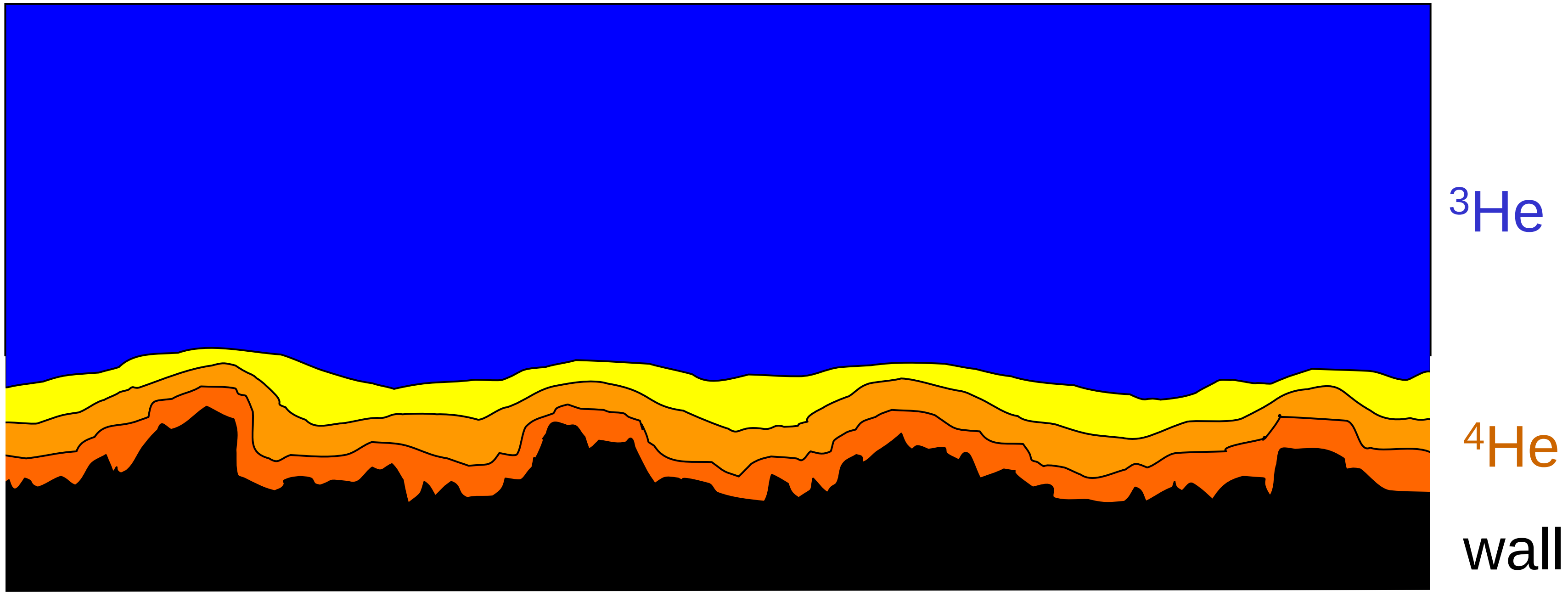
First experimental confirmation
of the sub-gap structure.

Aoki *et al*. PRL (2005)



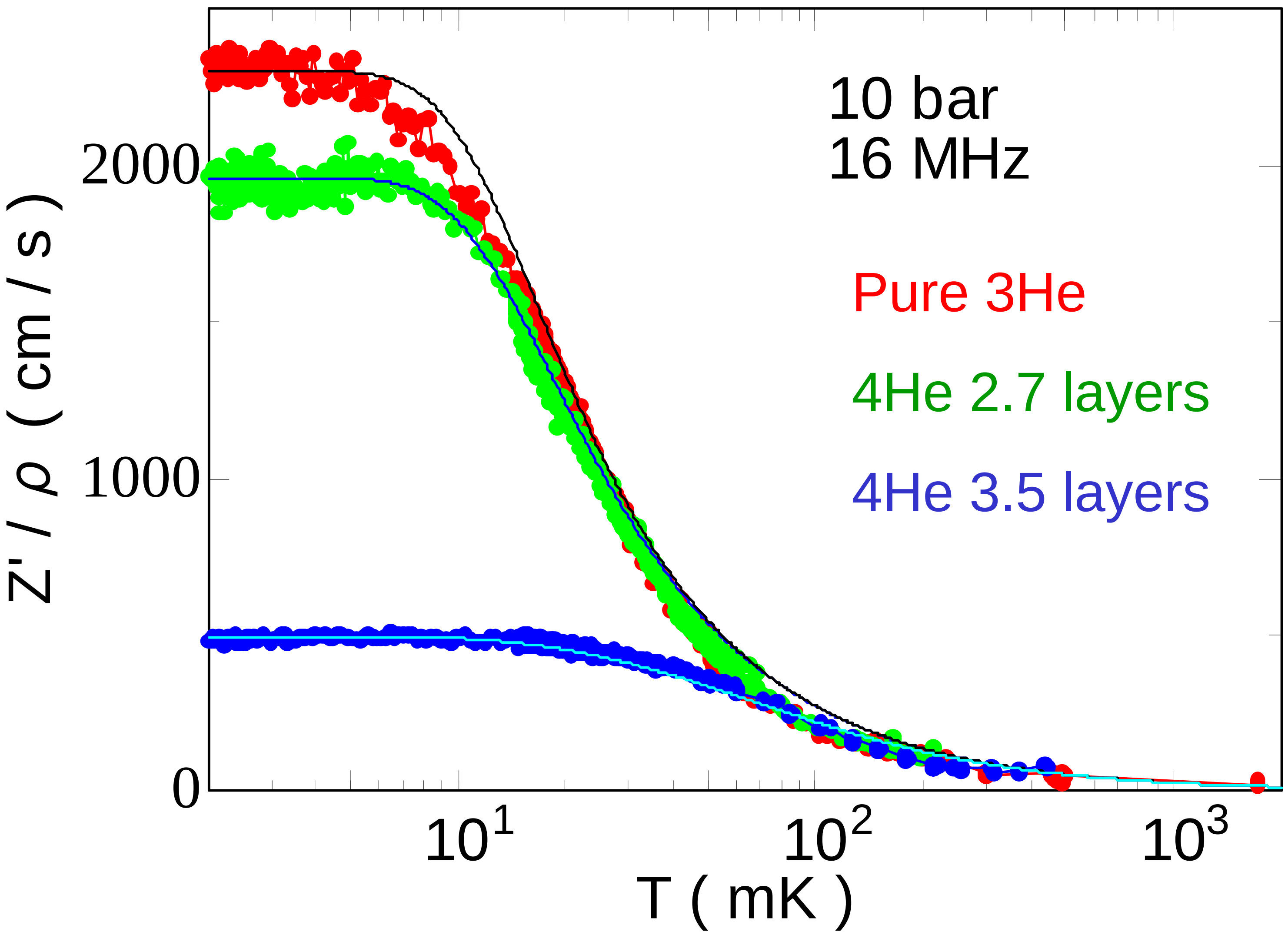
Partially specular wall; $0 < S < 1$

Coat a wall with ^{4}He layers



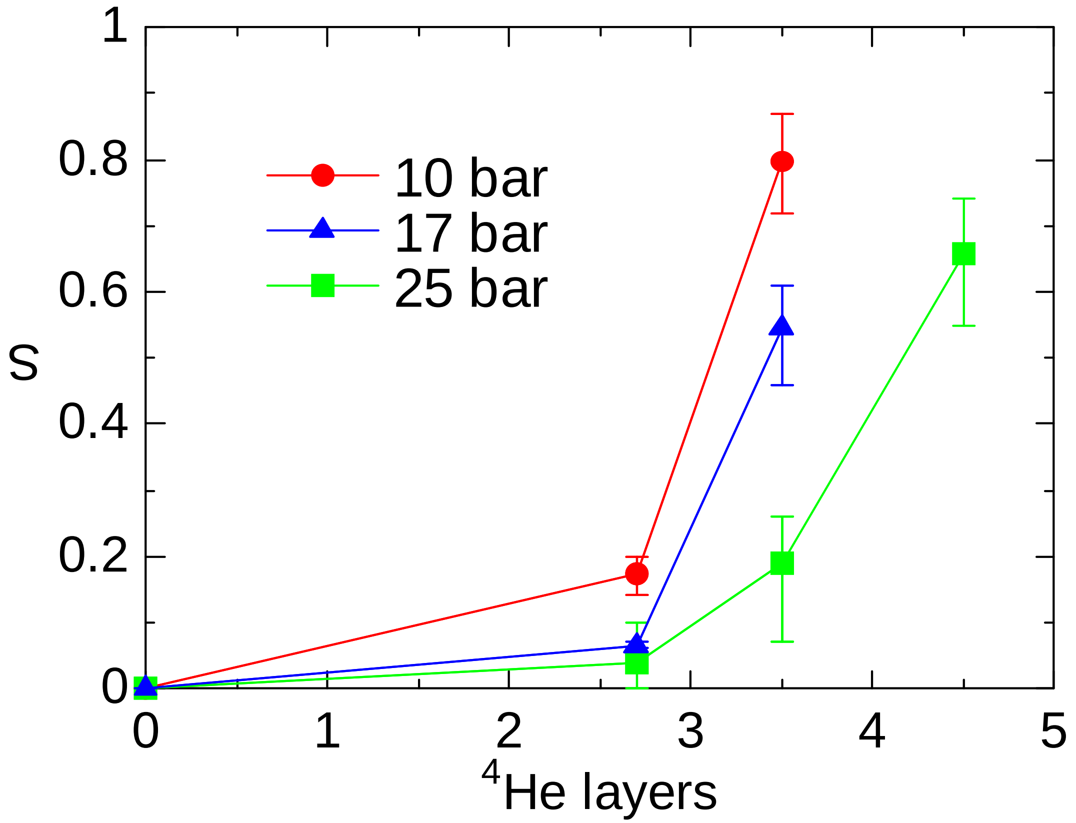
Cartoon

Evaluate S from *Z* in normal fluid



fitting at 16 MHz and 17 bar

S vs ^{4}He layers and P



S is larder for thicker ^{4}He.

is smaller at higher P.

Z(T) in B phase

S = 0.17、

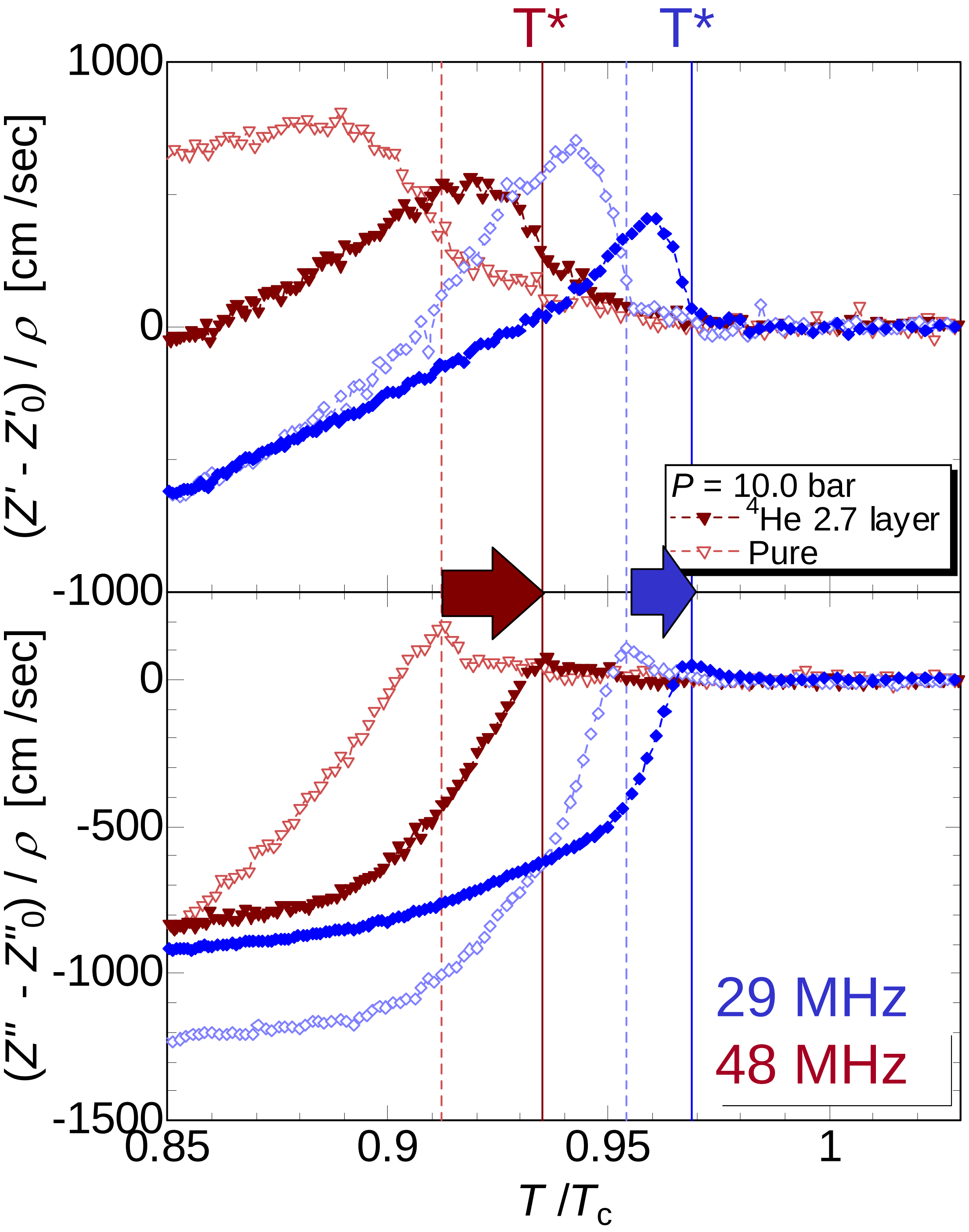
2.7 layers ^{4}He, 10bar

Compared to S = 0,

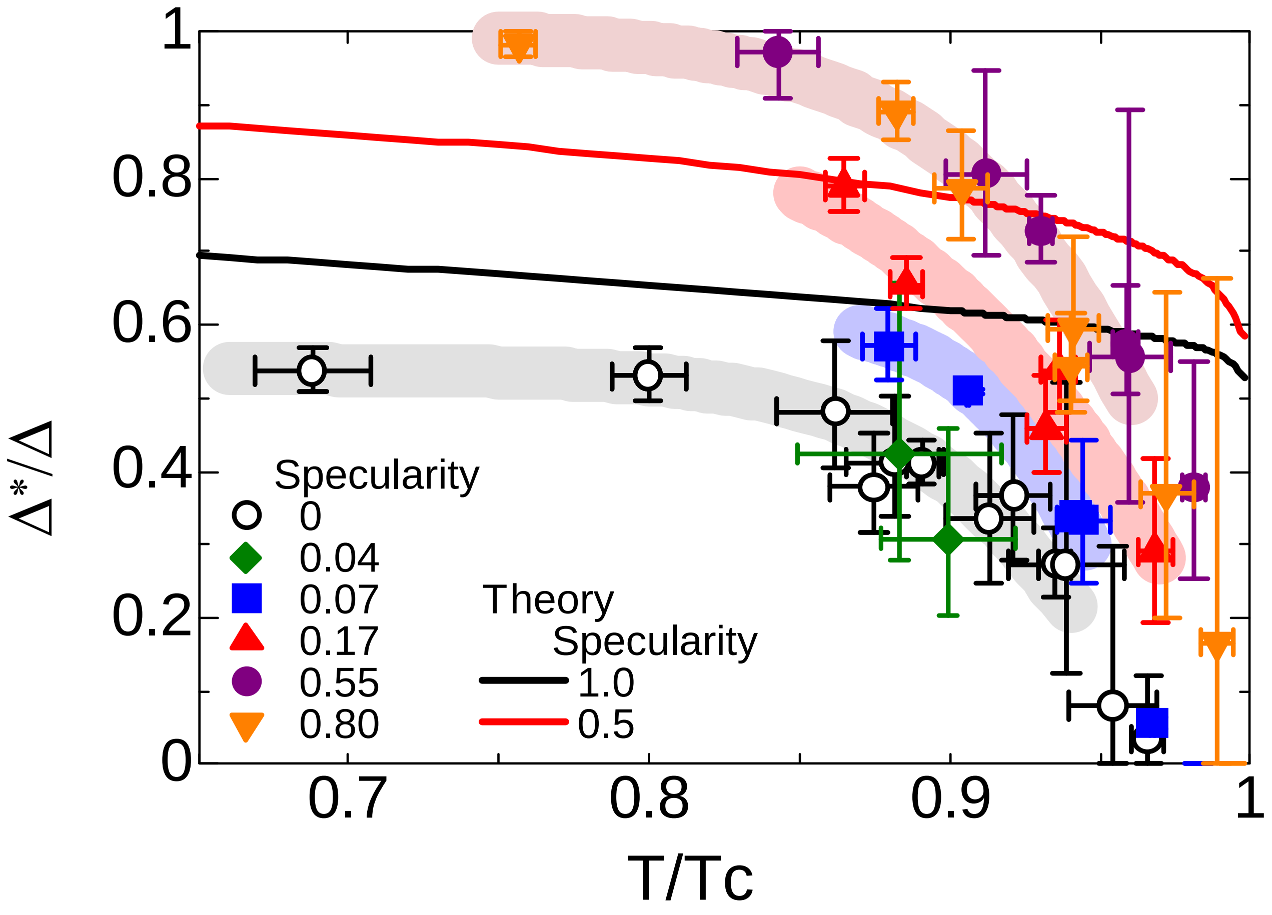
*T** shifts to higher.

Smaller temperature dependence Z(T).

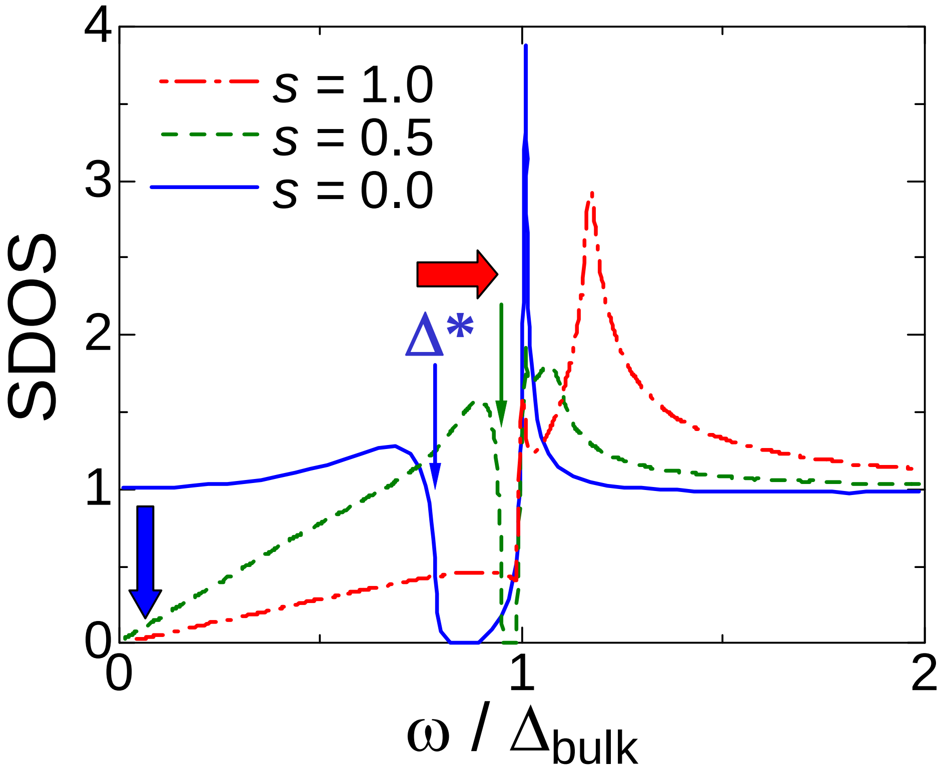
$$\Delta^* = \hbar\omega - \Delta(T^*)$$



S dependence of $\Delta^*(T)/\Delta(T)$



Saitoh, et al. PRB(R) 2006
Wada, et al. PRB 2008

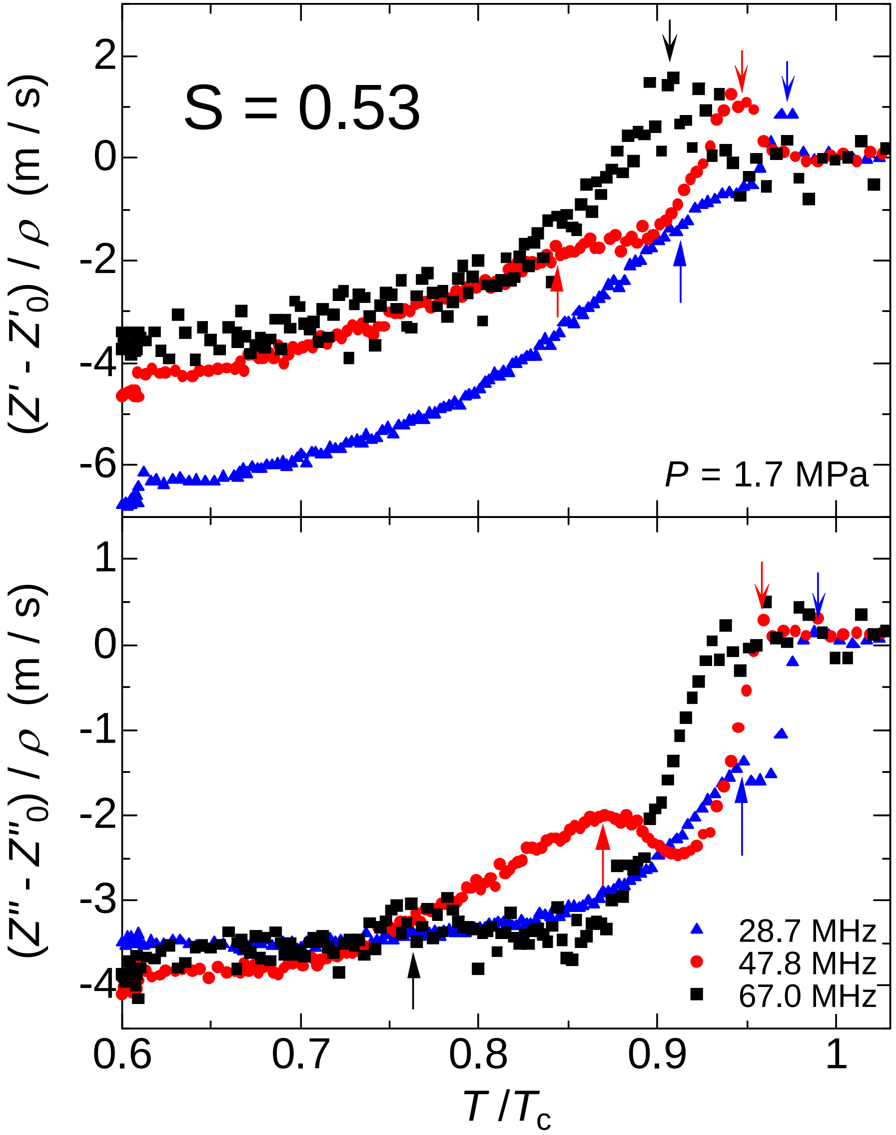


Broadening at larger S

Suppression of SDOS at zero-energy at larger S

Nagato *et al*. JLTP 1998

New low temperature peak at S > 0.

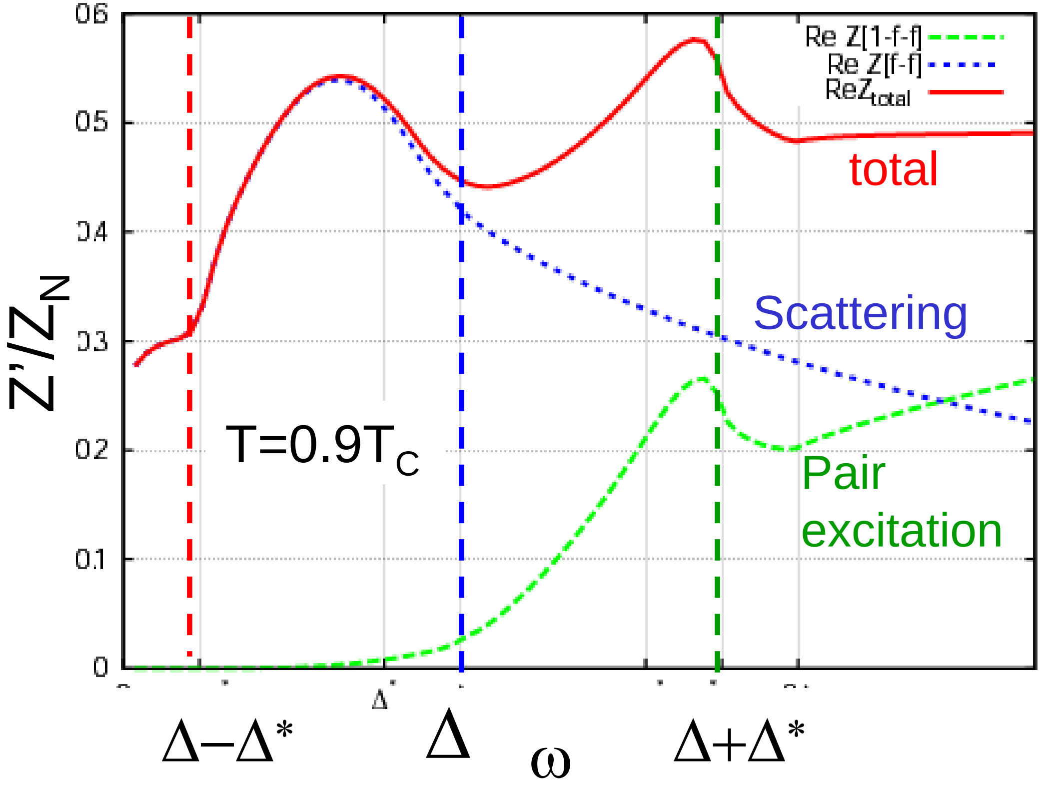


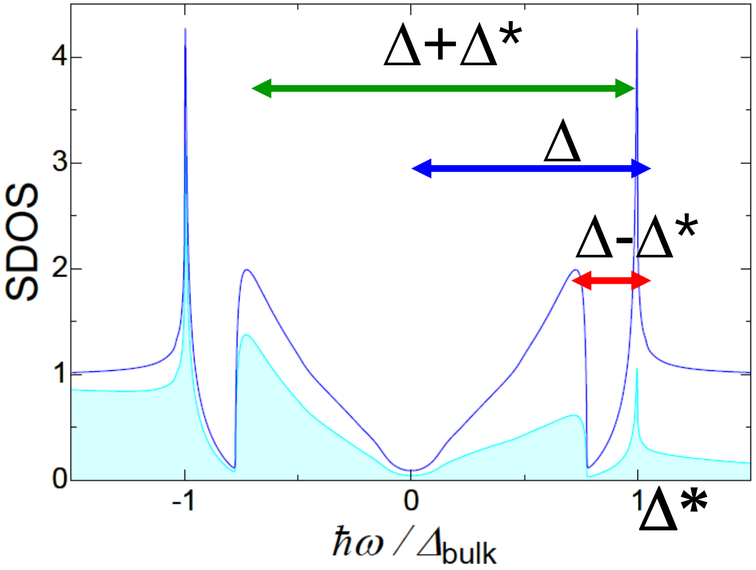
Murakawa *et al*., PRL 09

Scaled energy dependence of Z(ω/Δ) at various S

Low energy peak grows when S > 0 due to
the formation of the Majorana cone.

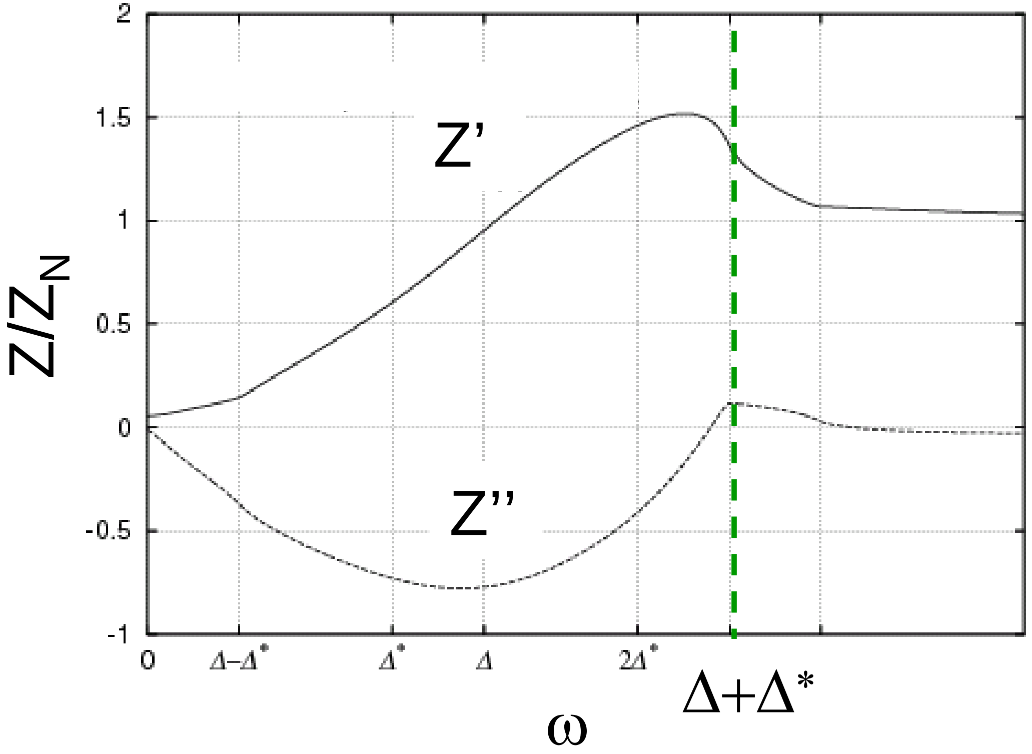
Z(ω) theory by Nagato et al. for S = 0.5

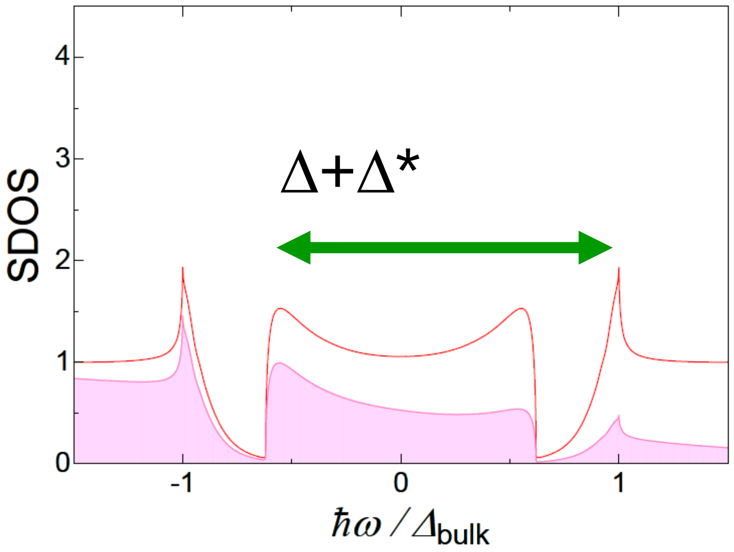




Two peaks in Z(ω) due to the formation of Majorana cone.

Z(ω) theory for S = 0





Flat below Δ*
Single peak in
Z(T)

Summary

Surface Andreev bound states in ^{3}He-B are detected by Z(T, ω) measurement.

Specularity S is controlled by ^{4}He layers.

On a partially specular wall

Bandwidth of bound states Δ^* becomes broader.

Growth of the low temperature peak in Z(T) as increasing S is due to the formation of the Majorana cone.

Our observation is an experimental indication of the Majorana cone on 3He-B.