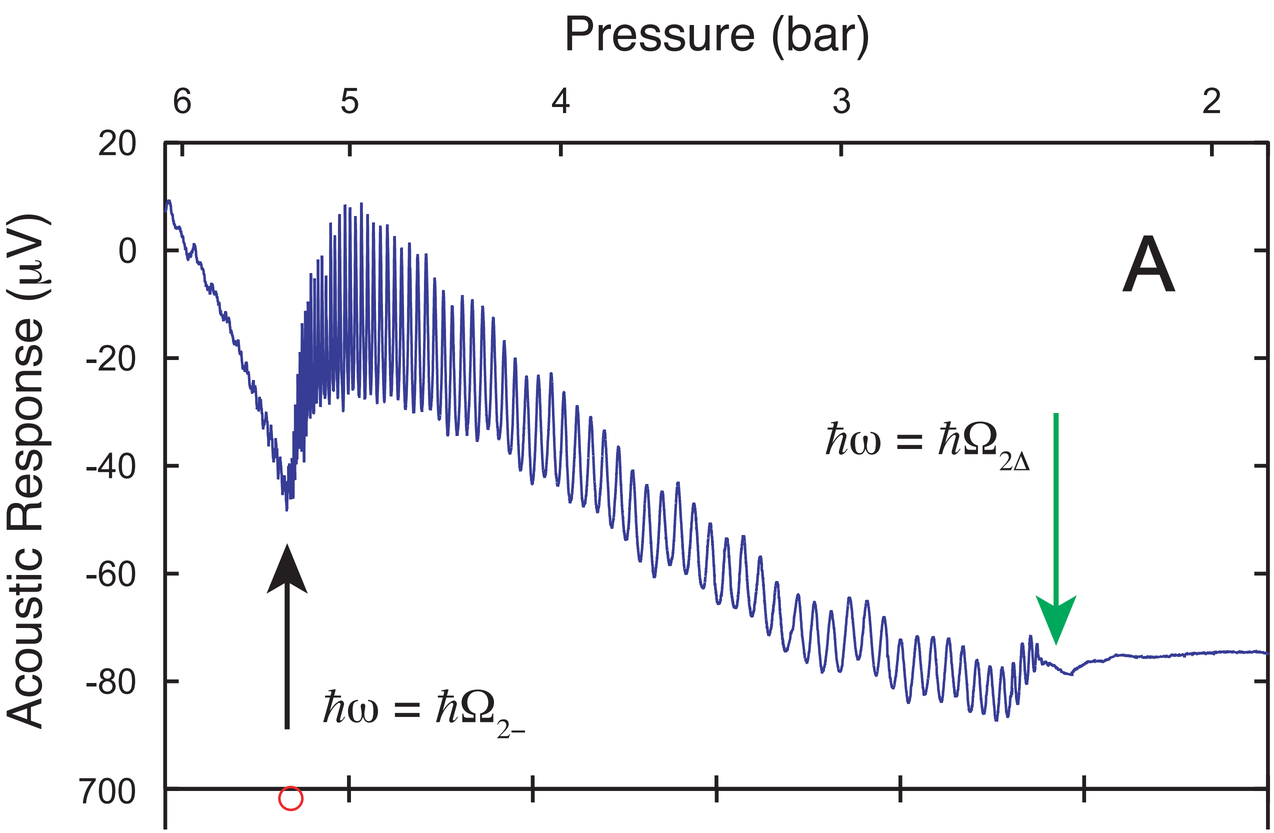
Sounds of Broken Symmetry

in

Superfluid ^{3}He

Jim Sauls

Northwestern University



Transverse Sound Cavity Modes in ^{3}He-B

John Davis et al. (2007)

Bill Halperin (ULT @ NU)

Collisionless Sound Modes in Normal ^{3}He

Deformation of the Fermi Surface

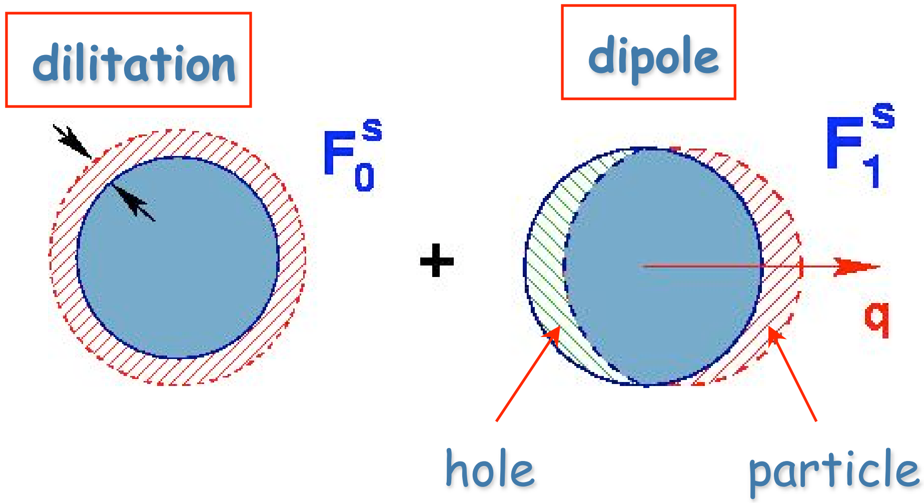
$$\omega\tau(T) > 1$$

$$\delta\Phi(\hat{p}) = \sum_{lm} \delta\Phi_{lm}\, P_l^m(\cos\vartheta)\, e^{im\varphi}$$

$$\delta\varepsilon(\hat{p}) = \sum_{lm} \mathbf{F}_l\, \delta\Phi_{lm}\, P_l^m(\cos\vartheta)\, e^{im\varphi}$$

$$\delta\Phi_{00} \propto \delta n$$

$$\delta\Phi_{10} \propto \hat{\mathbf{q}} \times \delta\vec{\mathrm{j}}$$



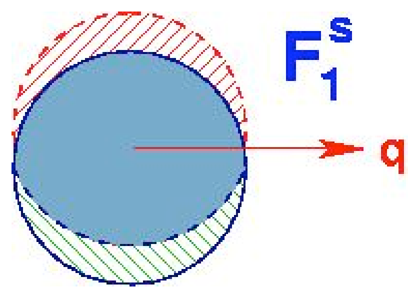
Longitudinal (zero) sound

$$\frac{c_0 - c_1}{c_1} \simeq \frac{4}{5}\left(\frac{1}{F_0^s}\right)$$

Transverse (zero) sound

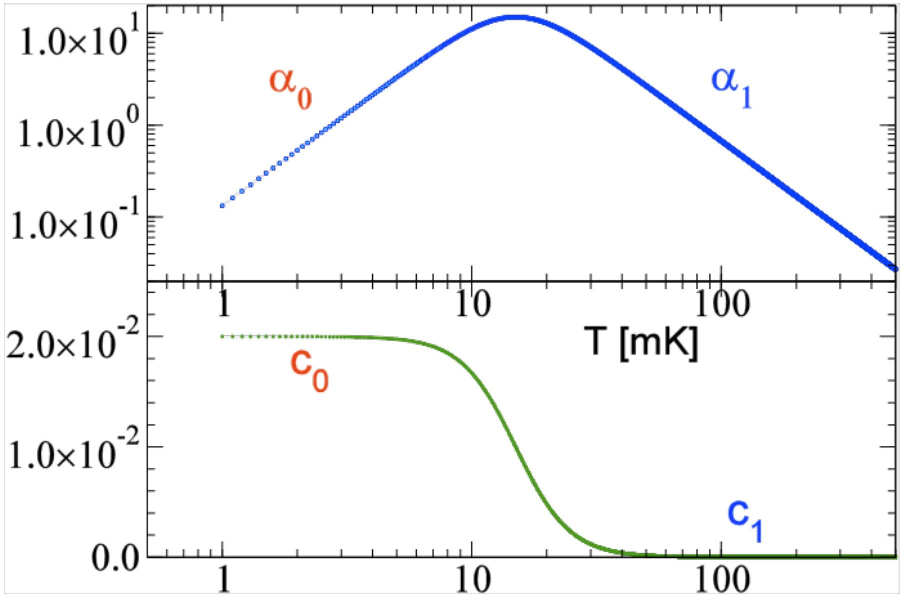
$$\frac{c_t}{v_f} \simeq \frac{F_1^s}{15}$$

$$\left.\begin{array}{l} \delta\Phi_{1,+1} \propto \delta\,\mathrm{j}_{\mathrm{RCP}} \\ \delta\Phi_{1,-1} \propto \delta\,\mathrm{j}_{\mathrm{LCP}} \end{array}\right\} \longleftrightarrow$$



Landau (1958)

Longitudinal (zero) sound



Abel, Anderson & Wheatley (1966)

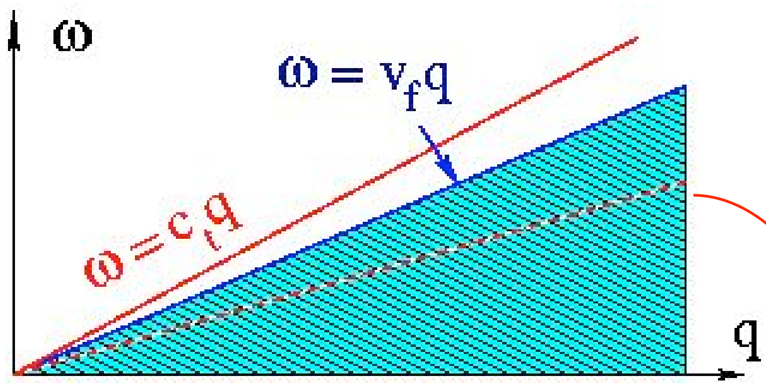
$$\alpha_0 \;;\; \frac{1}{c_0\tau} \propto T^2$$

$$\alpha_1 \;;\; \omega^2\eta \propto T^{-2}$$

$$\frac{c_0 - c_1}{c_1} \;;\; \frac{4}{5}\left(\frac{1}{F_0^s}\right) \approx 10^{-2}$$

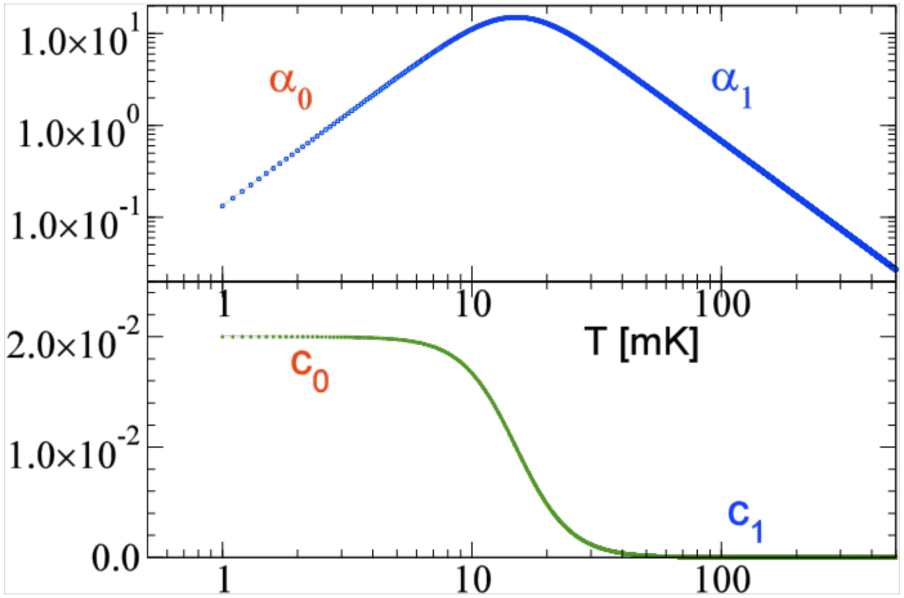
Transverse (zero) sound

No conclusive Observation of TZS in normal ^{3}He so far.



particle-hole continuum

Longitudinal (zero) sound



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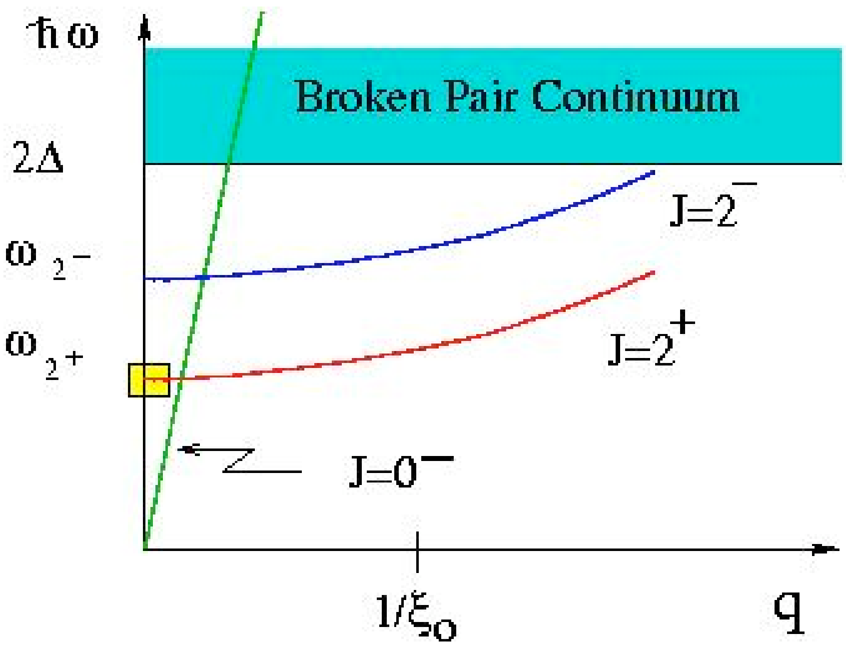
Transverse (zero) sound



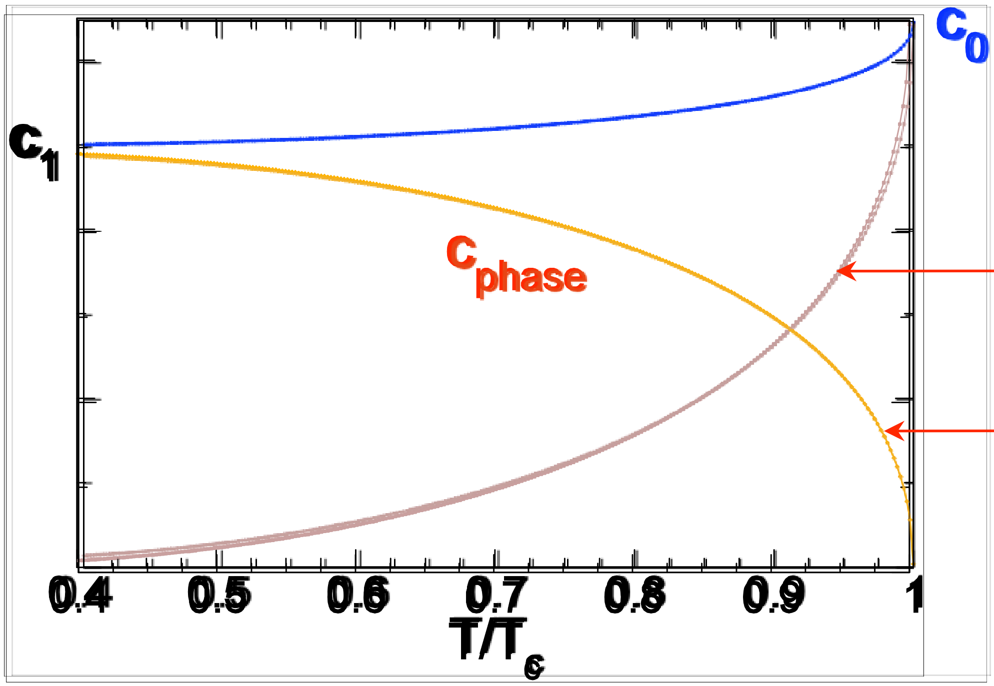
TZS in superfluid ^{3}He-B

Restoring Force - coupling to Collective mode - “pair exciton”

(G. Moores and JAS 1992)

Observed (Y. Lee et al. 1999)

What is the Fate of Zero Sound for $T<T_c$?



qp restoring force

$$E_p \geq \Delta$$

Energy Gap

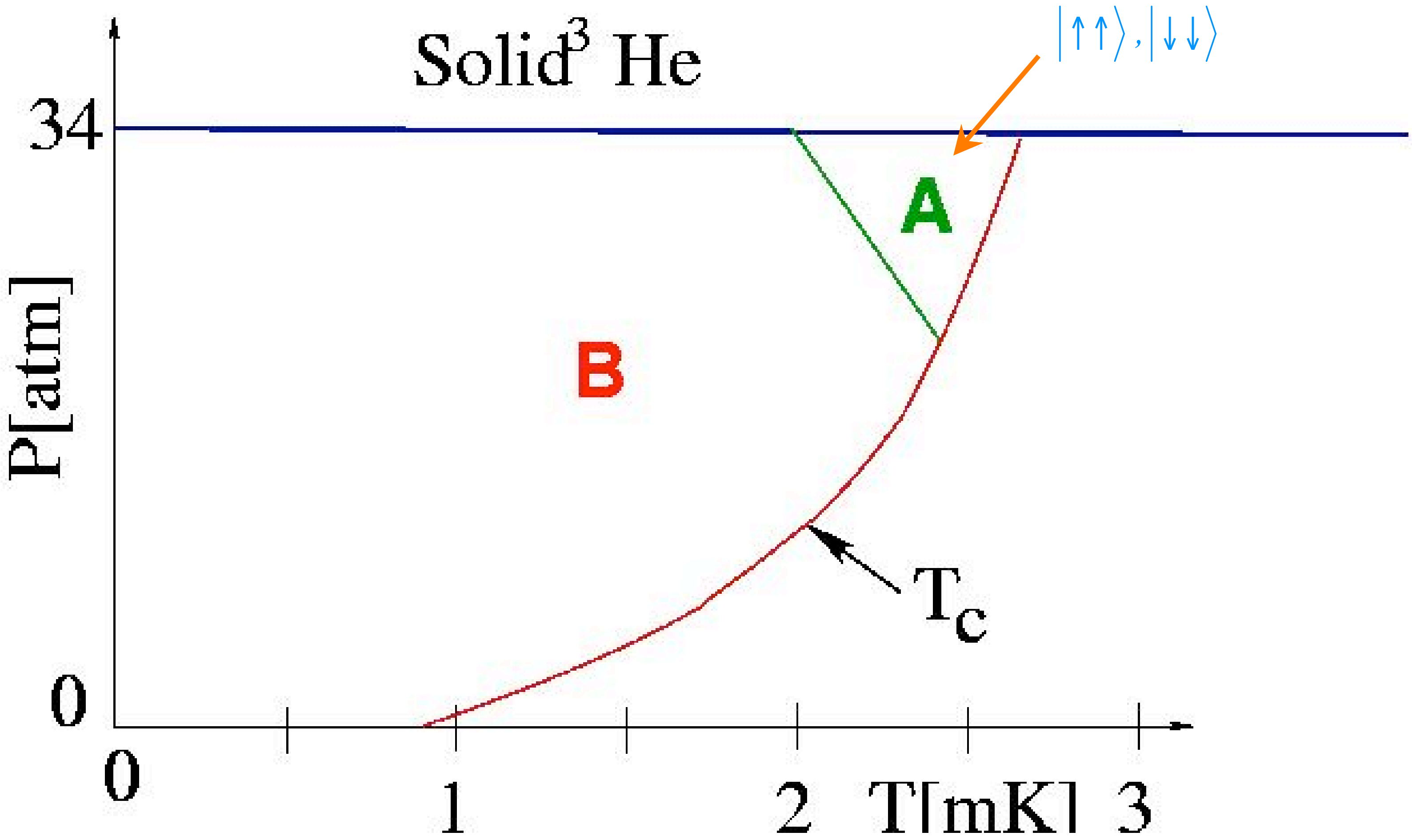
Collective Mode

(Anderson-Bogoliubov)

$$\Delta(\boldsymbol{R},\boldsymbol{t}) = \Delta_0 \, e^{i\varphi(\boldsymbol{R},\boldsymbol{t})} \longrightarrow \delta\varphi(\boldsymbol{q},\omega) = \frac{\omega}{\omega^2 - \frac{1}{3}\boldsymbol{q}^2\boldsymbol{v}_f^2}\,\delta\mu$$

$$\vec{\nabla}\cdot\vec{j} + \partial_t \rho = 0 \qquad \vec{j} = \rho\,\vec{\nabla}\varphi$$

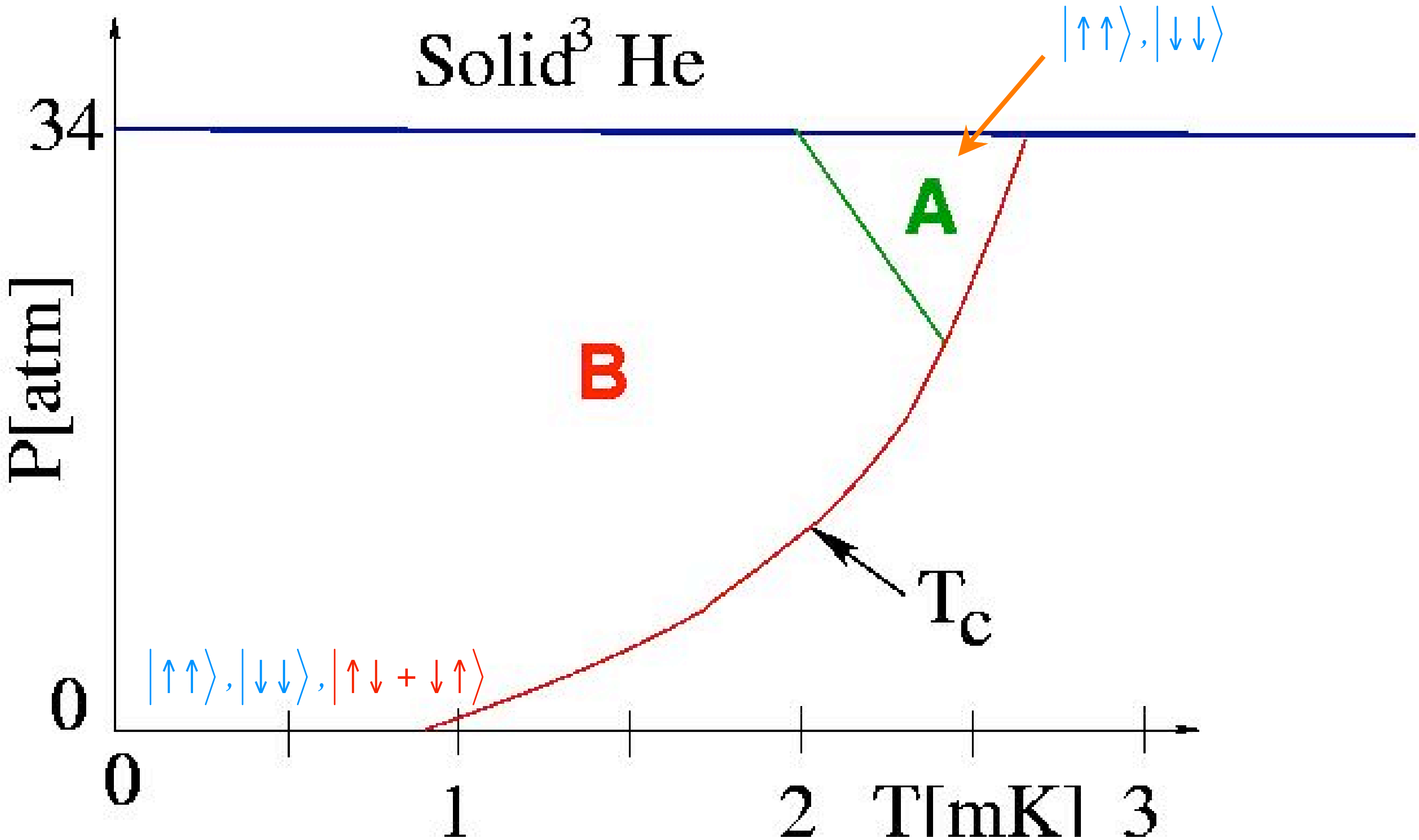
Superfluid Phases of ^3He



BCS pair condensates with:

$S_{pair} = \hbar$ ("triplet") & $L_{pair} = \hbar$ ("p-wave")

Superfluid Phases of ^{3}He



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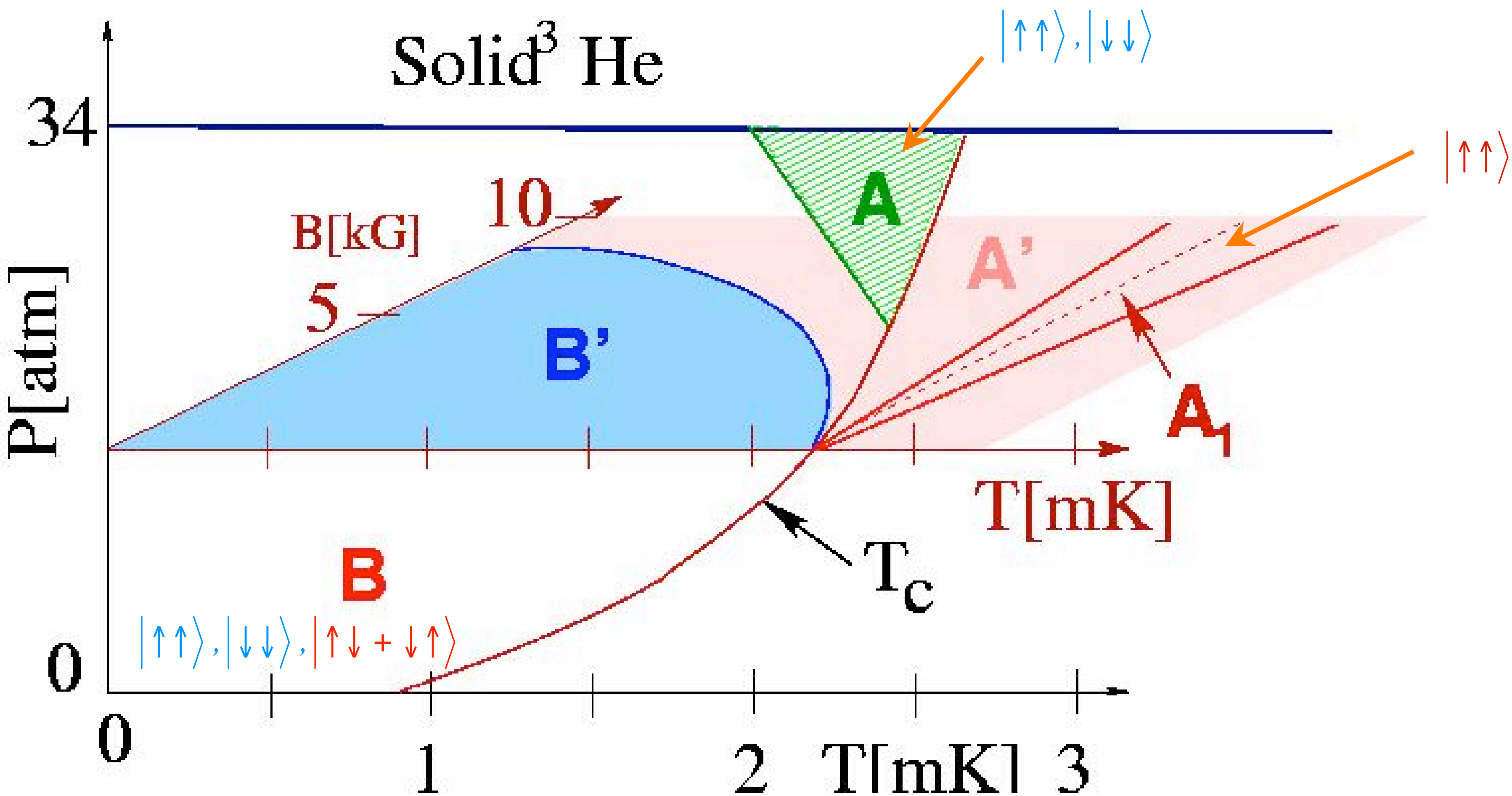


BCS pair condensates with:

$S_{pair} = \hbar$ ("triplet") & $L_{pair} = \hbar$ ("p-wave")

Superfluid ^{3}He-B

$$|\mathbf{B}\rangle = \Delta_B \left\{\frac{\hat{p}_x + i\hat{p}_y}{\sqrt{2}}\right\}|\downarrow\downarrow\rangle + \left\{\frac{\hat{p}_x - i\hat{p}_y}{\sqrt{2}}\right\}|\uparrow\uparrow\rangle + \hat{p}_z|\uparrow\downarrow + \downarrow\uparrow\rangle$$

- Balian & Werthamer (1963)

$$\left.\begin{matrix} L = 1 \\ S = 1 \end{matrix}\right\} \Rightarrow J = 0$$

$$G = SO(3)_S \times SO(3)_L \times U(1)_{gauge} \times P \times T \times C$$

$$G_B = SO(3)_{L+S} \times T$$

$$\vec{J} = \vec{L} + \vec{S}$$

Broken relative spin-orbit symmetry

Acoustic Birefringence

Approximate particle-hole symmetry

violation: $(T/E_f)^2$ » 10^{-5}

Neglect Nuclear Dipole Energy

violation: E_{dip}/E_f » 10^{-7}

NMR frequency shifts

A. Leggett

Collective Mode Dynamics in ^{3}He-B

Goldstone Mode w/ J=0$^-$ → $D^{(-)}_{00} = i|\Delta|\,\varphi(q,\omega)$

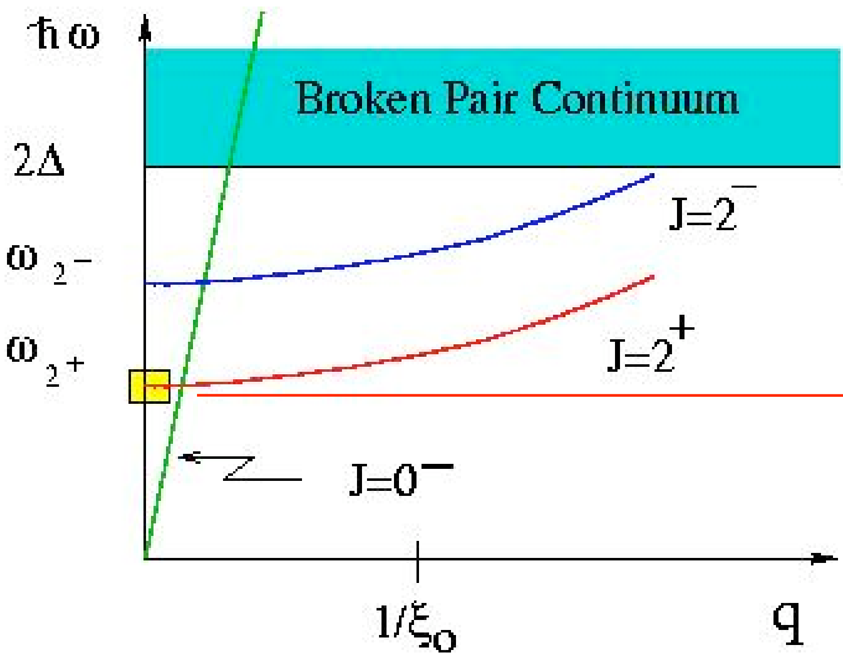
phase mode

$$\left(\omega^2 - \frac{1}{3}q^2 v_f^2\right) D^{(-)}_{00} = \dots$$

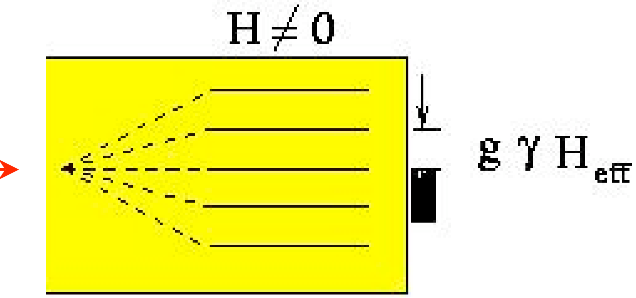
Pair Excitons w/ J=2$^{+/-}$

$$\left(\omega^2 - \omega^2_{J^CM}(q)\right) D^{(C)}_{JM} = \dots$$

coupling to internal & external fields



Nuclear Zeeman levels



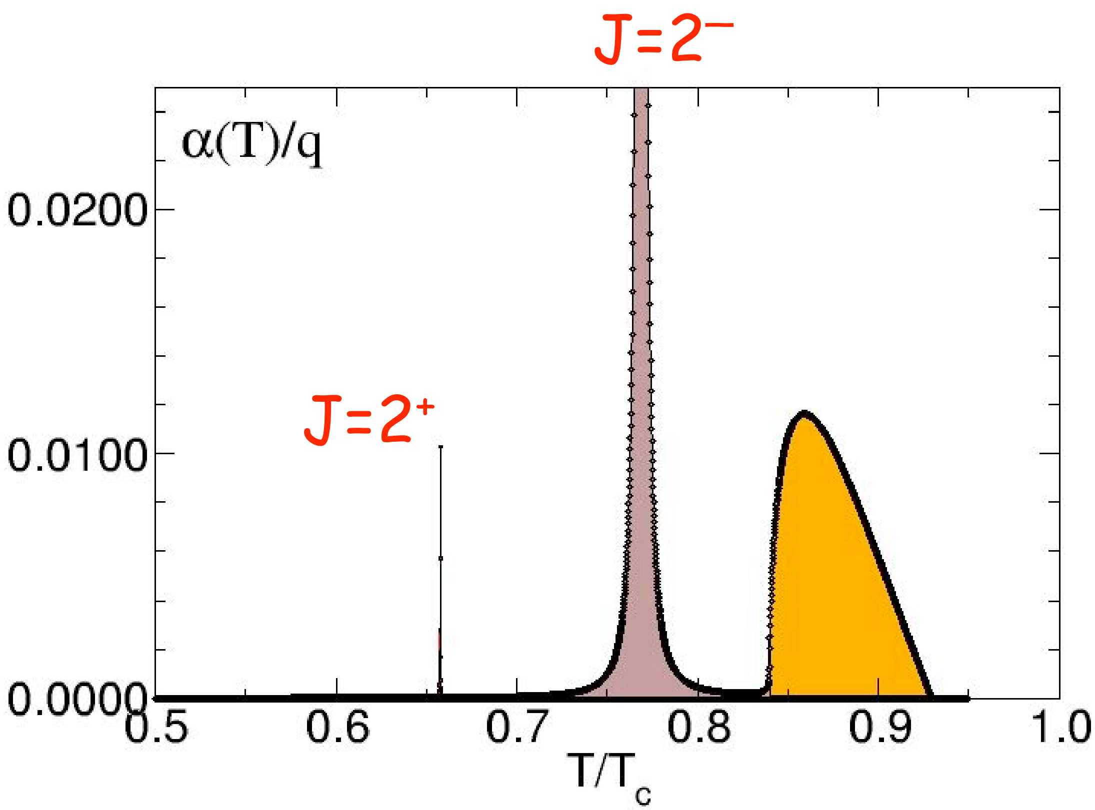
Schopohl   Serene & JAS

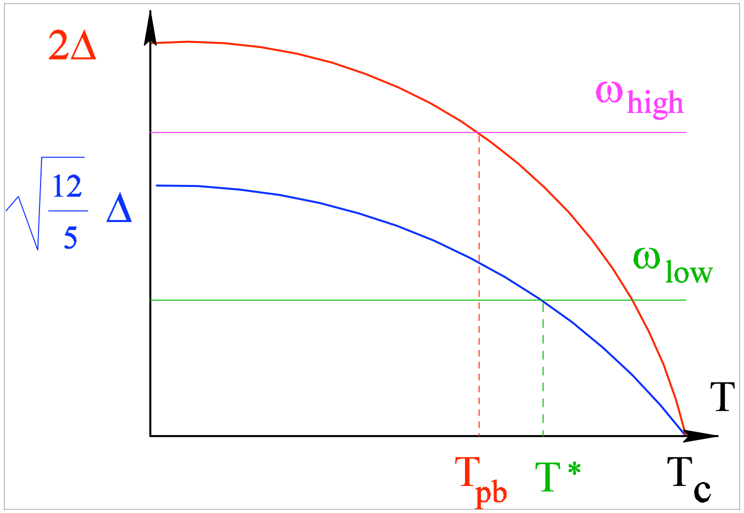
Absorption of Longitudinal Sound in ^{3}He-B

Pairbreaking Absorption $\alpha_{pb} \propto \sqrt{\omega - 2\Delta}\; \Theta(\omega - 2\Delta)$

Resonant absorption by J=2$^{+/-}$ modes; **Linewidth** $\Gamma \approx \Gamma_N\, e^{-\Delta/T} = \Delta$

Particle-hole asymmetry $\int \alpha_{2^+}\, dT \,/\, \int \alpha_{2^-}\, dT = \mathbf{a}^2 \approx 10^{-4}$ (Koch & Wolfle)





What is the Fate of Transverse Zero Sound for $T<T_c$?

Transverse Zero Sound in ^{3}He-B

$$\frac{\partial \vec{j}_t}{\partial t} + \vec{\nabla} \cdot \overleftrightarrow{\Pi} = 0 \longrightarrow$$ **Dispersion Relation**

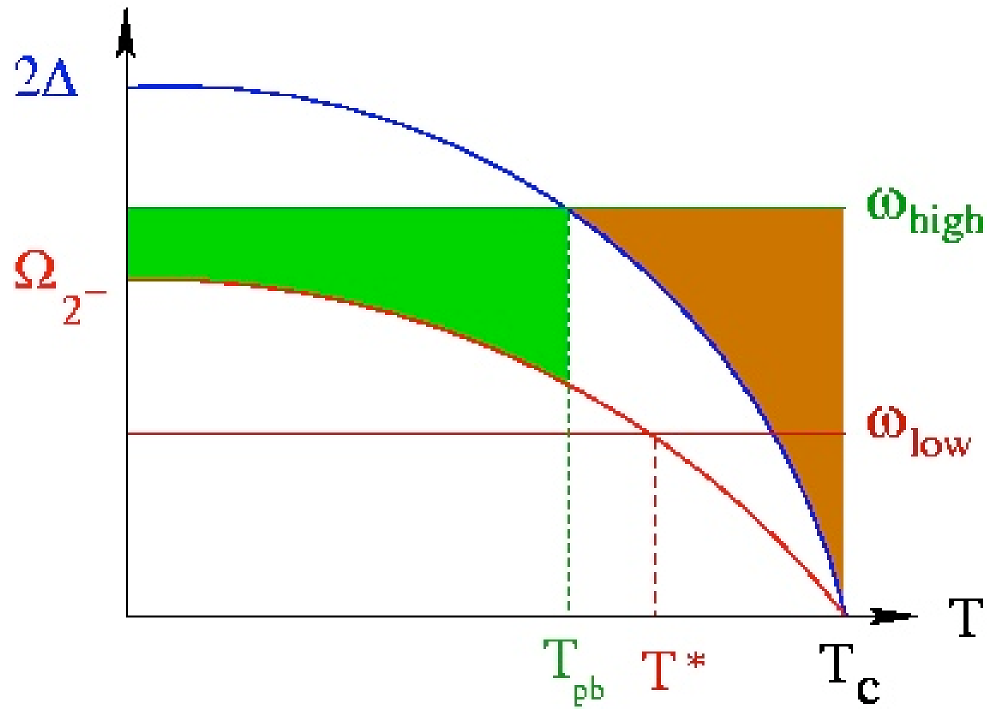
$$\left(\frac{\omega}{q v_f}\right)^2 = \underbrace{\left(\frac{c_t}{v_f}\right)^2 \rho_n(\omega)}_{\text{quasiparticle stiffness}} + \underbrace{\frac{2}{5}\left(\frac{c_t}{v_f}\right)^2 \rho_s(\omega) \left\{\frac{\omega^2}{(\omega + i\Gamma)^2 - \Omega_{2^-}^2}\right\}}_{\text{condensate stiffness}}$$

quasiparticle stiffness

condensate stiffness

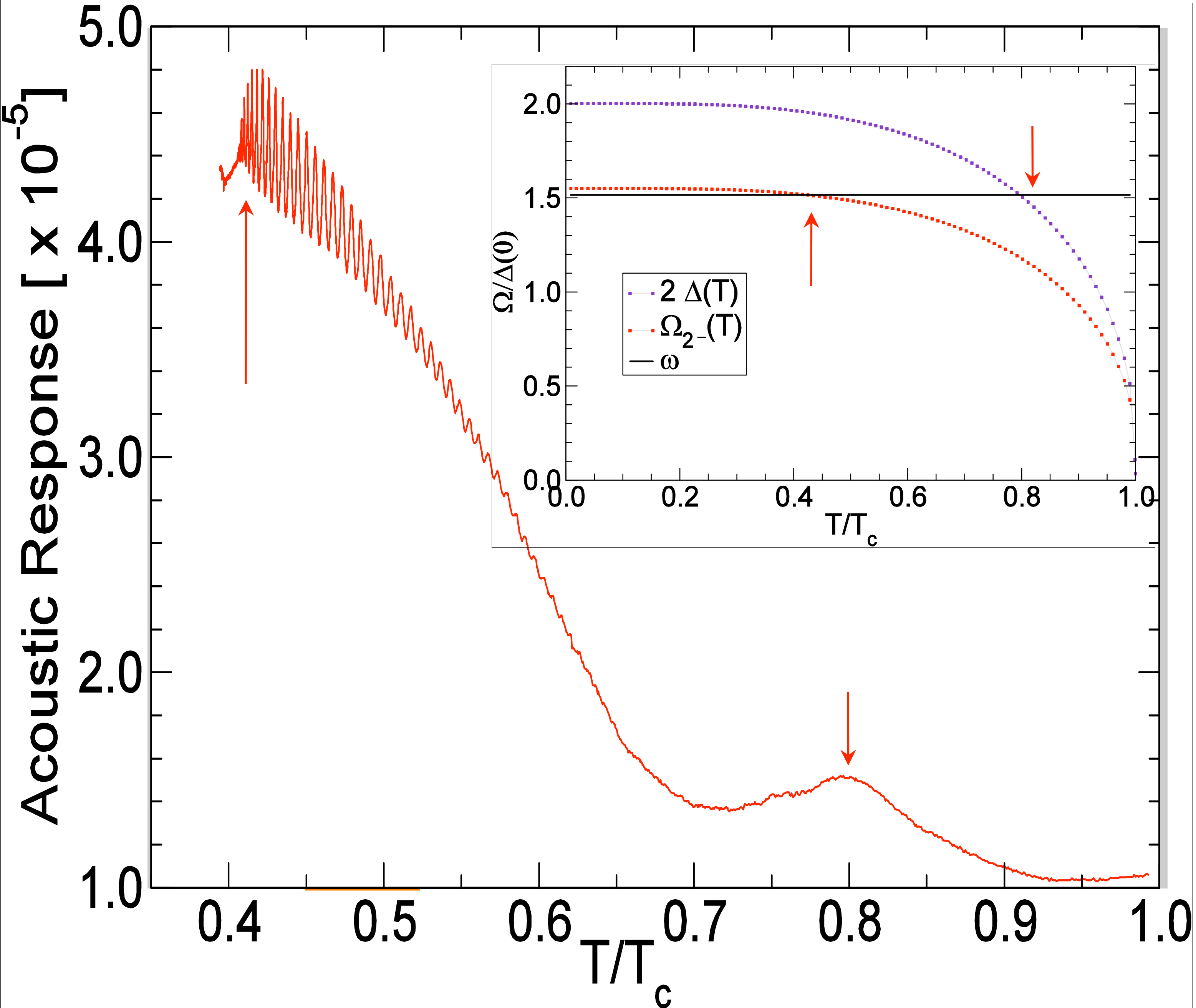
Propagation for $\Omega_{2^-} < \omega < 2\Delta$

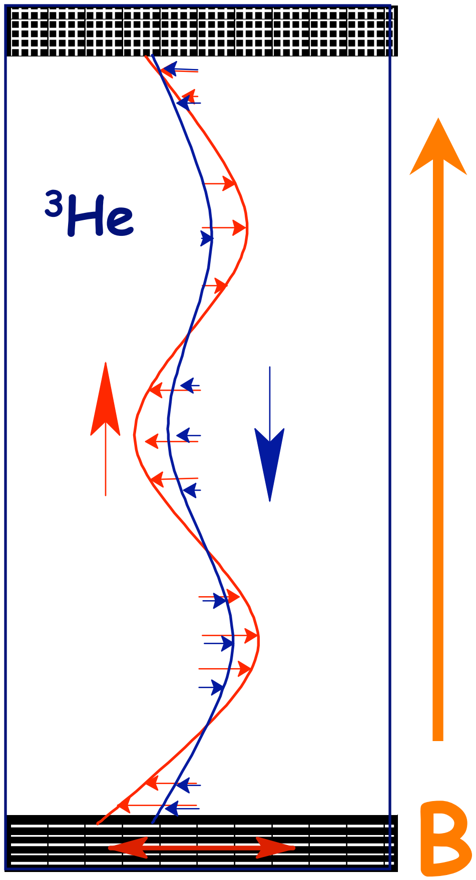
Extinction for $\omega \le \Omega_{2^-}$



G. Moores & JAS

Transverse Cavity Waves in ^{3}He-B





transverse excitation

Y. Lee et al., Nature 400, 431 (1999)

Optical Faraday Effect

$$\vartheta = V B_0 l$$

Verdet's constant

$$V \approx 2^{\circ}\ \mathrm{cm}^{-1}\mathrm{T}^{-1}$$

e.g. in glass

$$V = \frac{e}{2mc^2}\,\omega\left(\frac{dn}{d\omega}\right)$$

Becquerel (1897)
(Rosenfeld, Kramers, Heisenberg)

Acoustic Faraday Effect

$$\vec{E} \leftrightarrow \vec{j}$$ (transverse mass current)

$$V_A = \underbrace{g_{2^-}}_{g-factor}\ \overbrace{\gamma_{^3He}}^{Nuclear\ gyro-magnetic\ ratio}\ \underbrace{f}_{Fermi-liquid\ factor}(T)\ \omega \frac{d}{d\omega}\left(\frac{1}{\underbrace{C_t}_{transverse\ velocity}}\right)$$

JAS (1999)

$$V_A \approx 10^4\ \mathrm{deg}-\mathrm{cm}^{-1}\mathrm{T}^{-1}$$ in ^3He

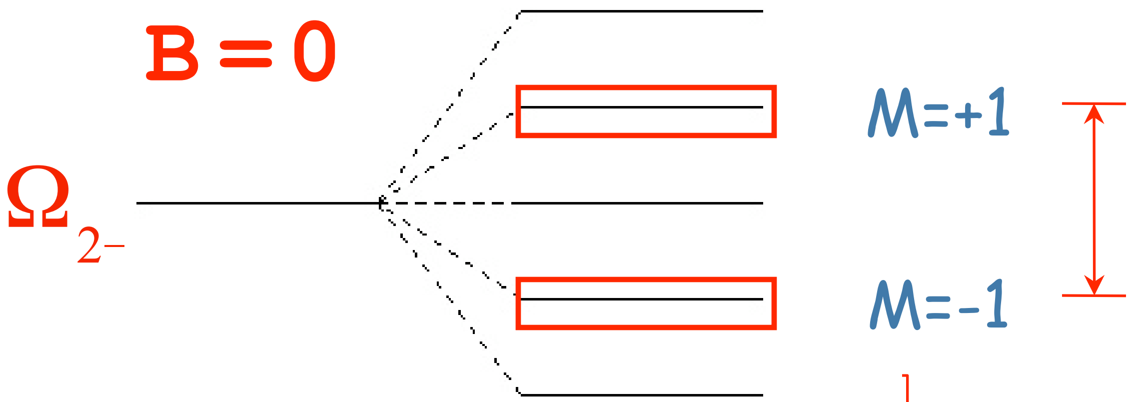
Field-induced acoustic birefringence in ^{3}He-B

$j_{RCP(+)}, j_{LCP(-)} \leftrightarrow \mathbf{D}^{(-)}_{2,\, M=+1},\ \mathbf{D}^{(-)}_{2,\, M=-1}$

$\vec{B} \neq 0$ Time-inversion (broken)

$\vec{B} \,||\, \vec{q}$ Axial symmetry (preserved)

B = 0



$$\Delta\omega = 2 \underbrace{g_{2^-}}_{g-factor} \overbrace{\gamma_{^3He}}^{Nuclear\ gyro-magnetic\ ratio} \mathbf{B}$$

$$\frac{C_{RCP} - C_{LCP}}{\bar{C}} \approx \frac{g_{2^-}\gamma_{^3He}\mathbf{B}}{\omega}$$

Acoustic Faraday Rotation

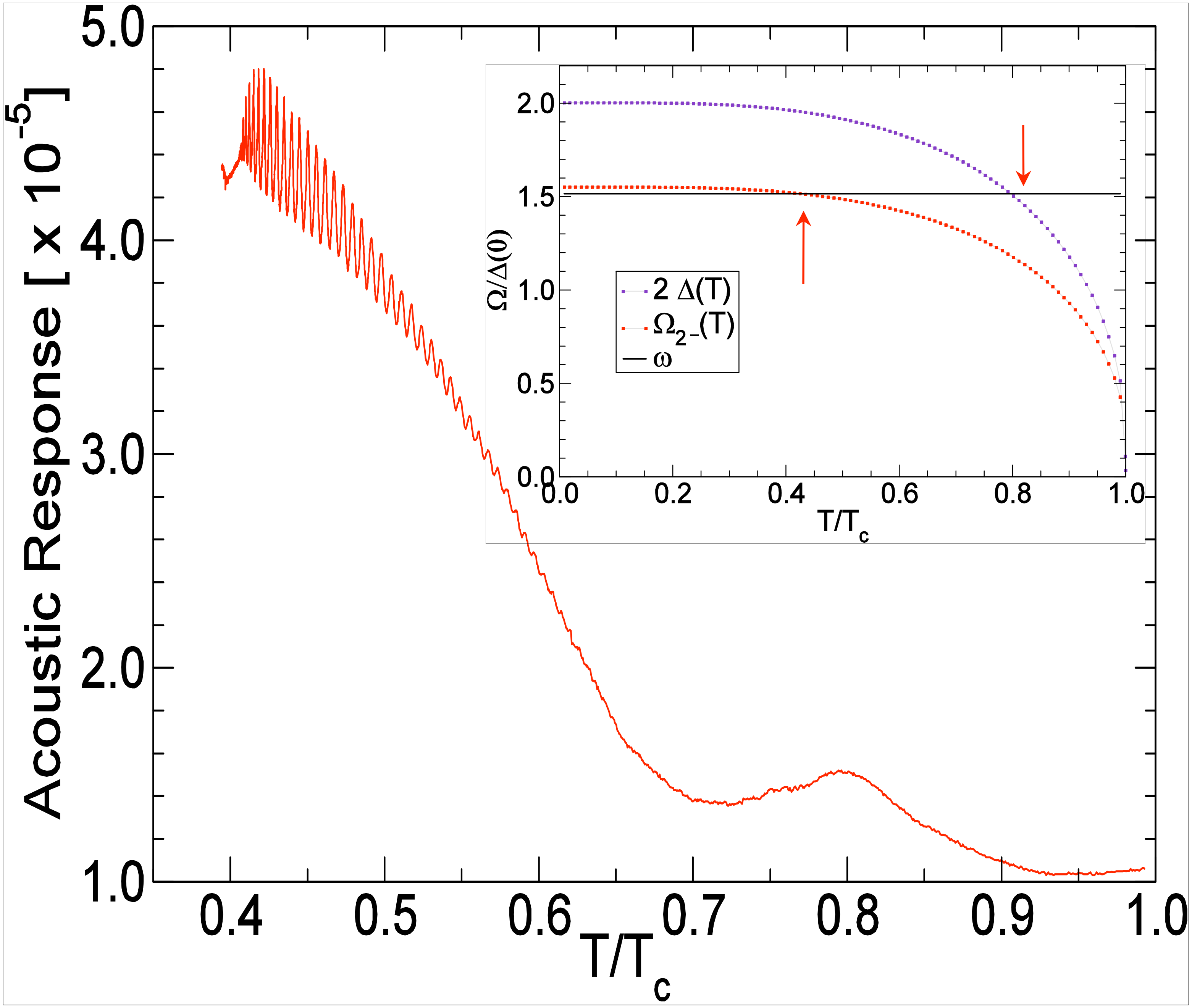
linear polarization

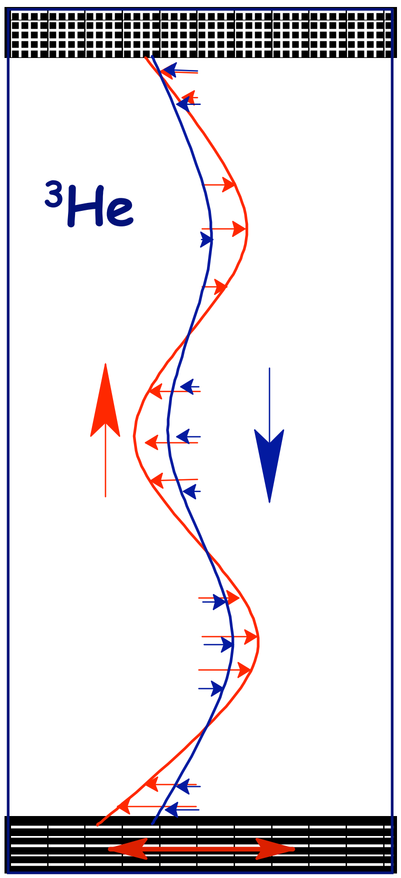
circular birefringence

$$\vartheta = V_A \mathbf{B}\, l$$

$$V_A = g_{2^-}\, \gamma_{^3He} \underbrace{f(T)}_{Fermi-liquid\ factor} \omega \frac{d}{d\omega} \underbrace{\left(\frac{1}{C_t}\right)}_{transverse\ velocity} \approx 10^4\ \mathbf{deg - cm^{-1}\, T^{-1}}$$

Transverse Cavity Waves in ^{3}He-B

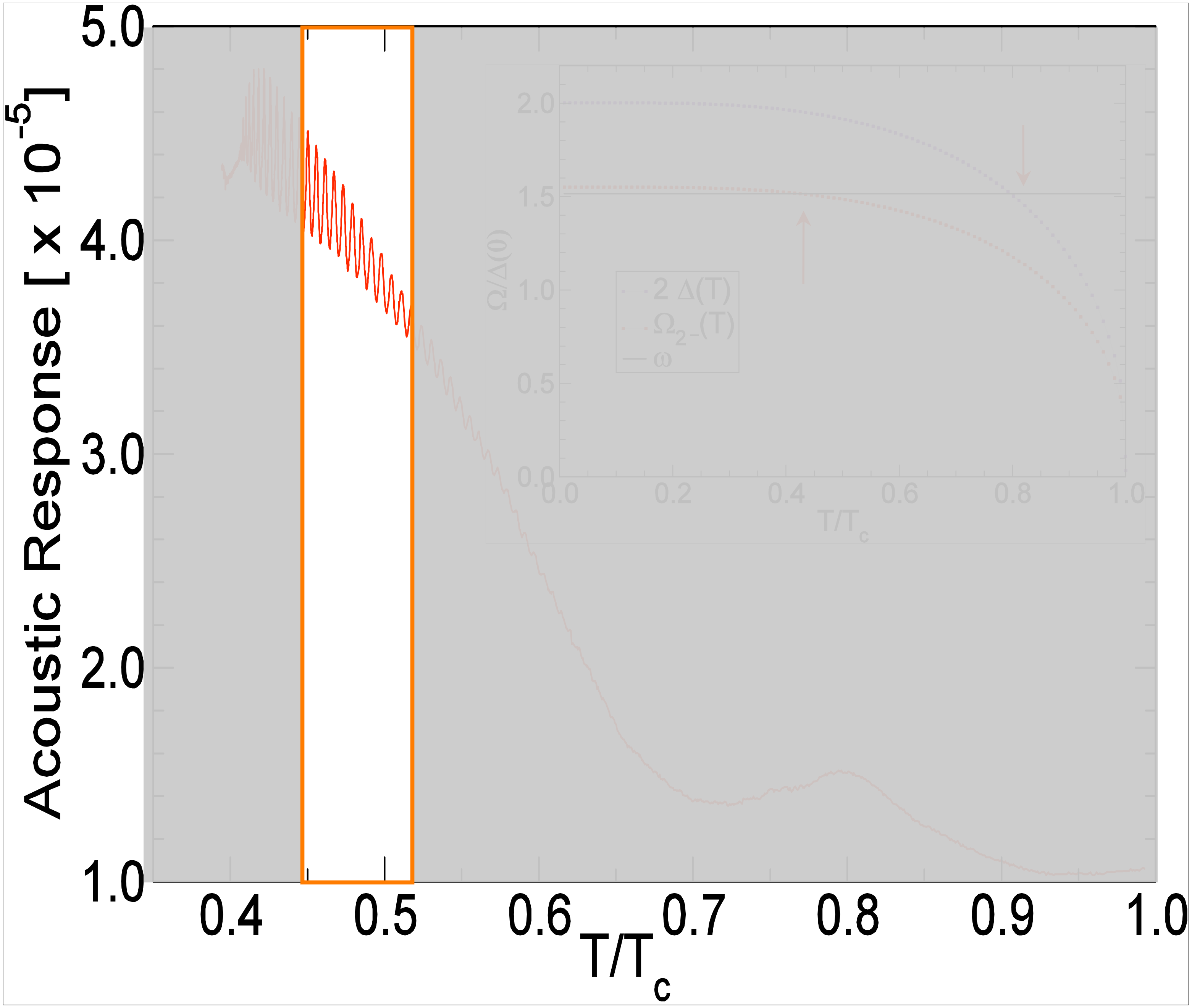


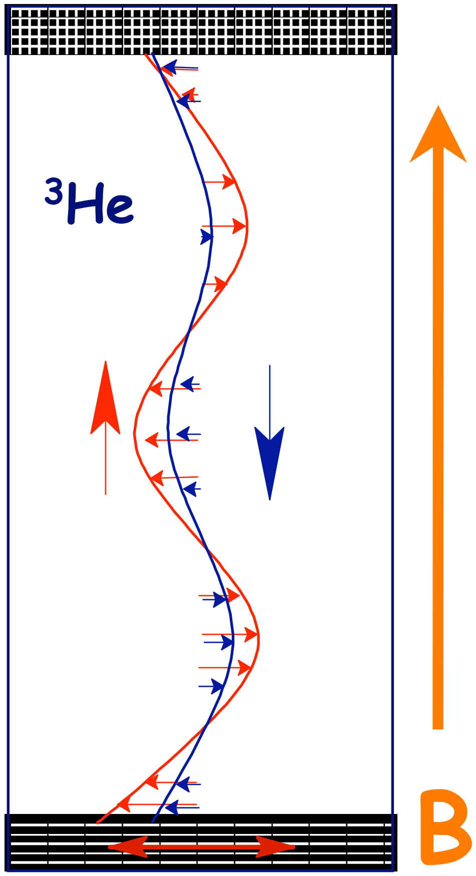


transverse excitation

Y. Lee et al., Nature 400, 431 (1999)

Transverse Cavity Waves in ^{3}He-B

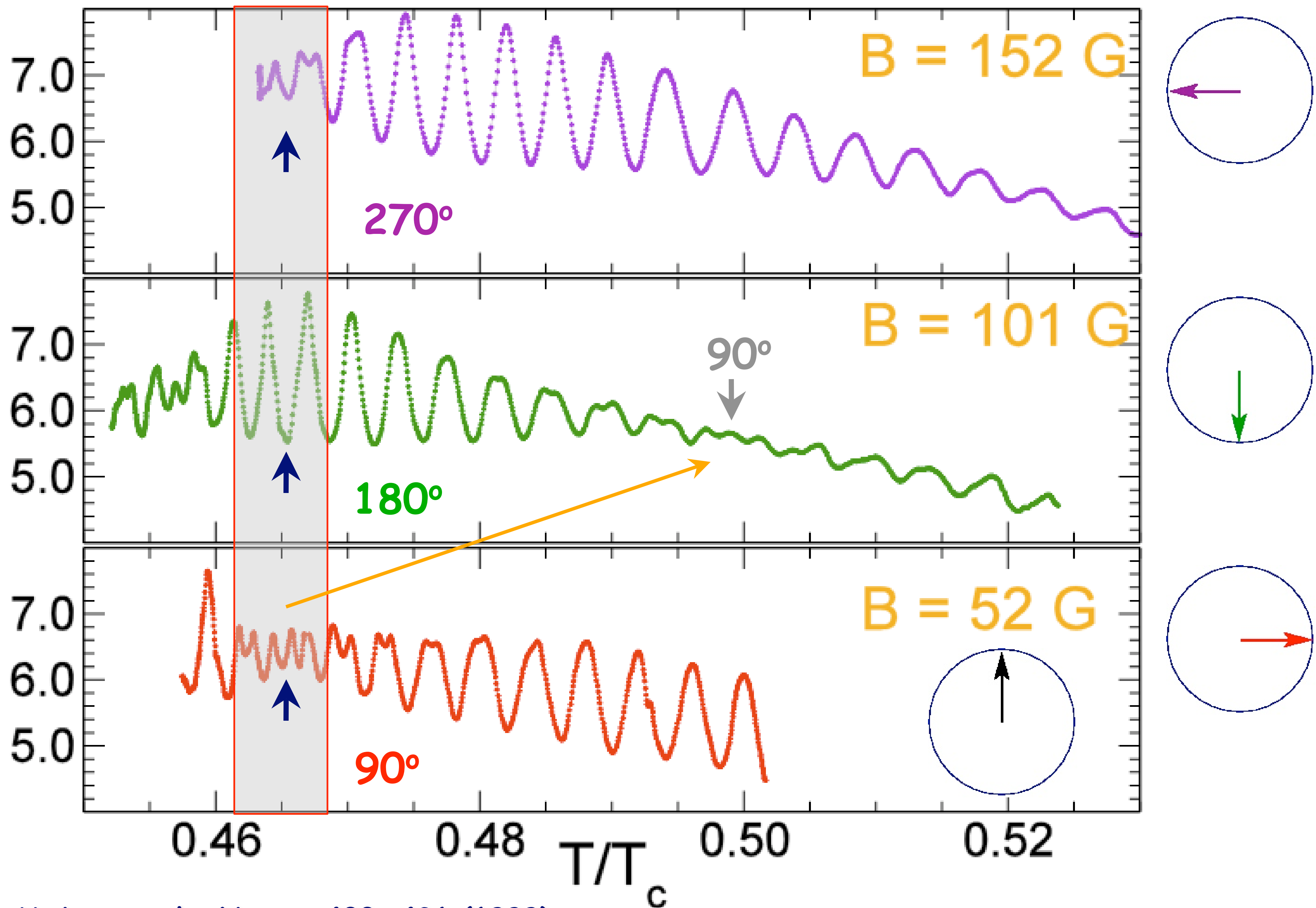




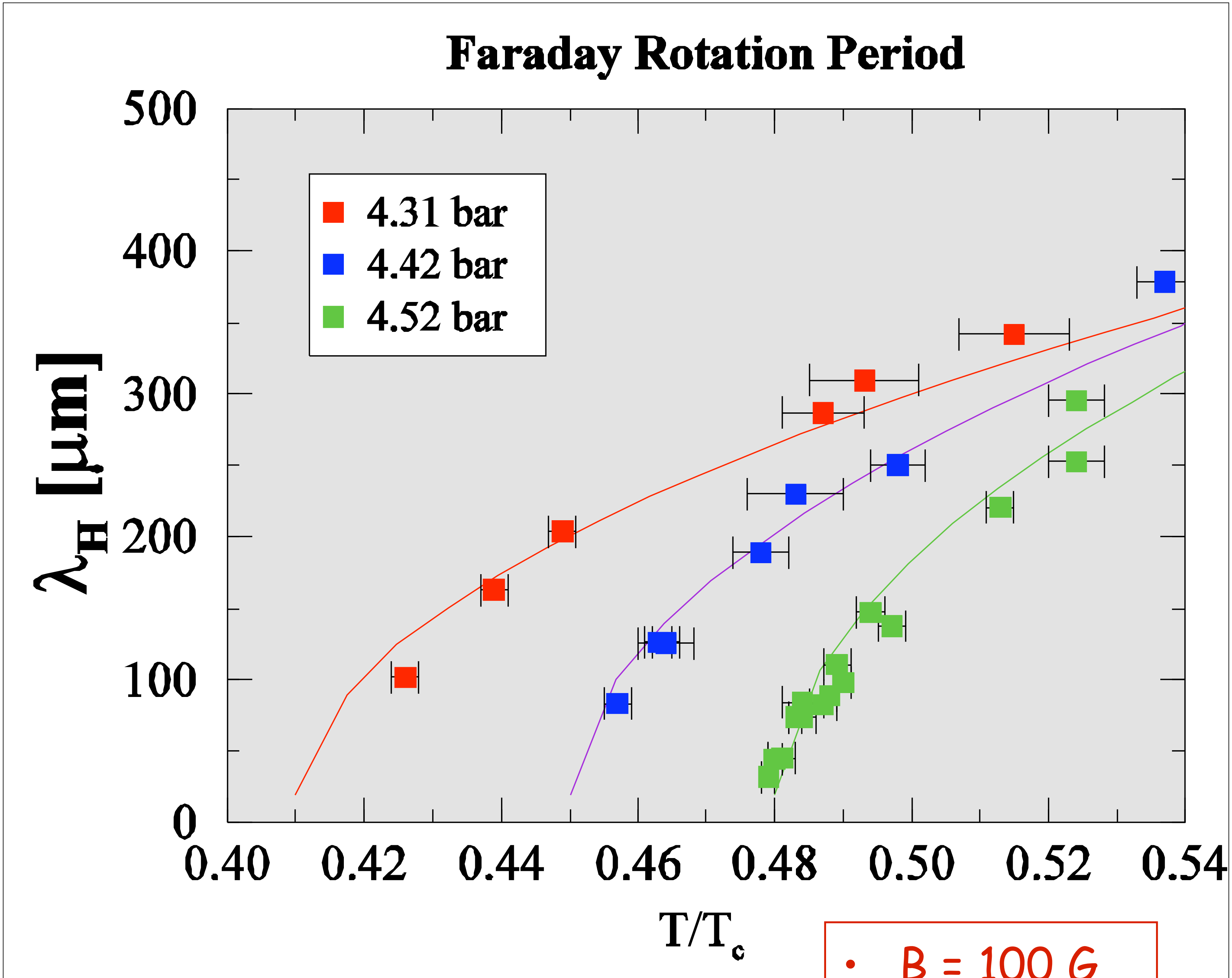
transverse excitation

Y. Lee et al., Nature 400, 431 (1999)

Faraday "Beats" in the Transverse Impedance



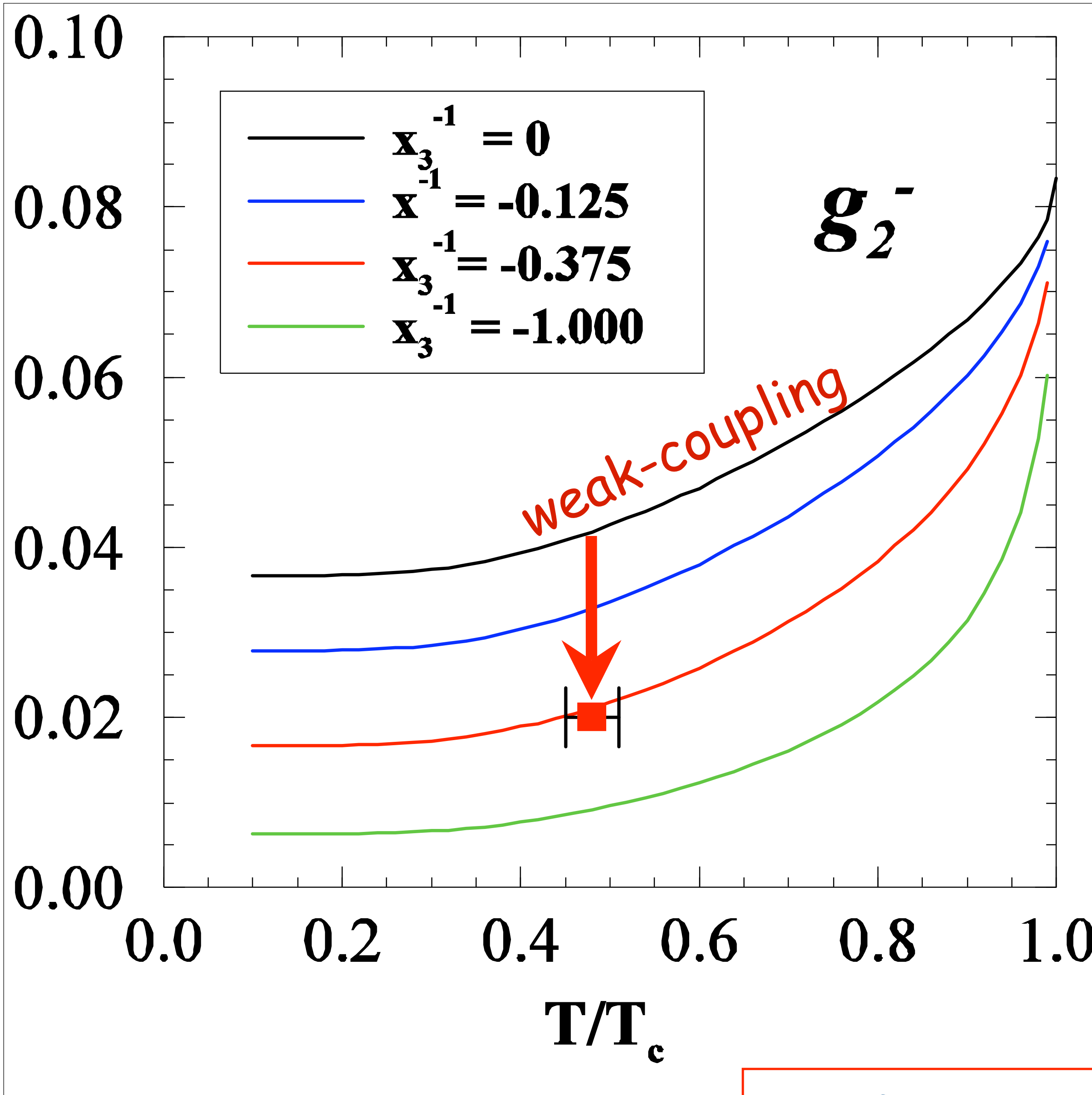
Y. Lee et al., Nature 400, 431 (1999)



Faraday Rotation Period
4.31 bar
4.42 bar
4.52 bar
λH [μm]
T/Tc
0
100
200
300
400
500
0.40
0.42
0.44
0.46
0.48
0.50
0.52
0.54

- $B = 100\ G$
- $g(T_+) = 0.02$

g-factor for the J=2- modes



$g(T_+) = 0.02$

f-wave pairing

$x_3^{-1} = -0.375$

$T_{cf} = 0.07\ T_c$

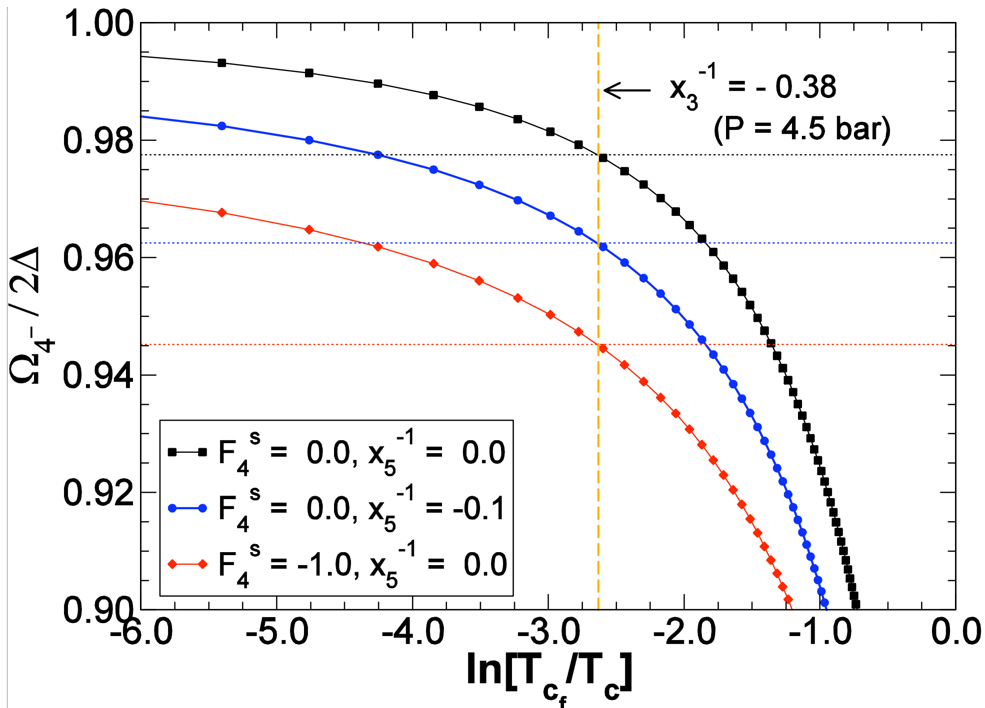
JAS & J. W. Serene, PRL 49, 1183 (1982)

Implications of f-wave pairing

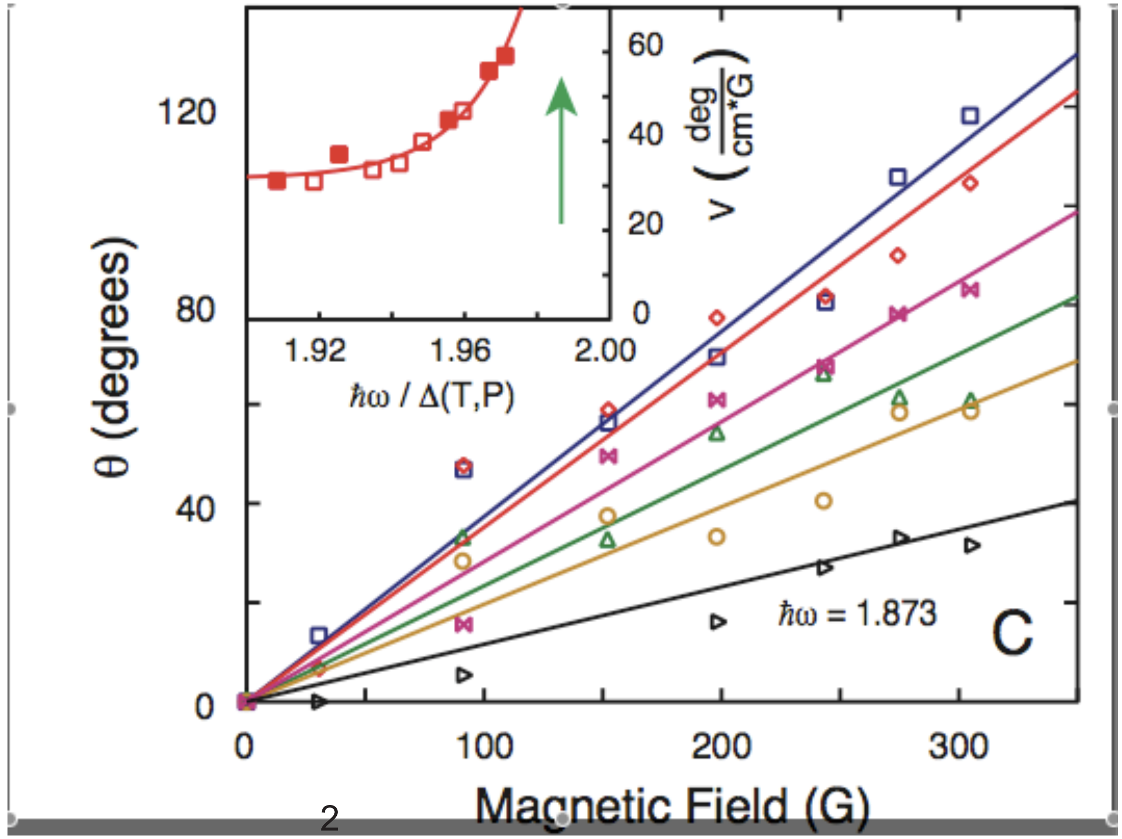
Superfluid ^{3}He-A: is p-wave/f-wave mixture

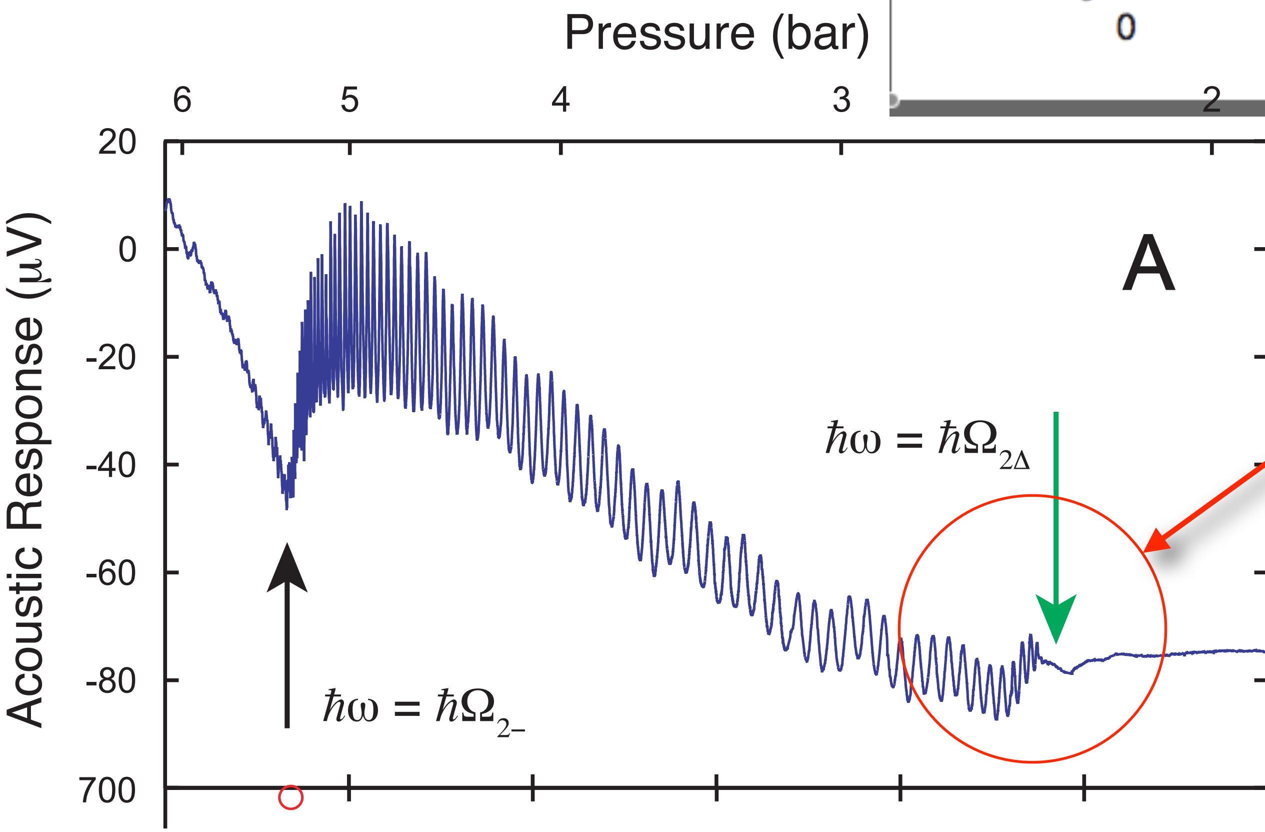
- f-wave pairing & strong-coupling effects on A-B transition
- Inhomogenous phases (vortices) with f-wave ``cores"
- Surface phases with f-wave pairing correlations

Superfluid ^{3}He-B: new collective modes



$$\left.\begin{array}{l} L = 3 \\ S = 1 \end{array}\right\} \Rightarrow \quad J = 4$$





Transverse Sound Cavity Modes in ^{3}He-B

New Collective Mode

- Circular Birefringence
- $J=4^-$, $M=+/-1$

John Davis et al. (submitted 2007)

What about the A-phase?

Superfluid ^{3}He-A

$$|\mathbf{A}\rangle = \frac{1}{2}\Delta_A\left(\hat{p}_x \pm i\hat{p}_y\right)\left\{|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle\right\}$$

- Anderson & Morel (1962)

$$\left.\begin{array}{l} L=1 \\ S=1 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} L_z = \pm 1 \\ S_z = 0 \end{array}\right.$$

$$G = SO(3)_S \times SO(3)_L \times U(1)_{gauge} \times P \times \not{T} \times C$$

$$G_{AM} = U(1)_{S_z} \times U(1)_{N-L_z}$$

S_z $\quad$ $N - L_z$

Broken relative spin-orbit symmetry

Broken relative gauge-orbit symmetry

Broken time-reversal symmetry

↓

Ground state orbital current

↓

Spontaneous Acoustic Birefringence