Experiments on Superfluid ^{3}He in Controlled Nanofabricated Geometries: model systems for topological quantum matter

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EPSRC

European Microkelvin Collaboration

Cornell University Founded A.D. 1865

PTB

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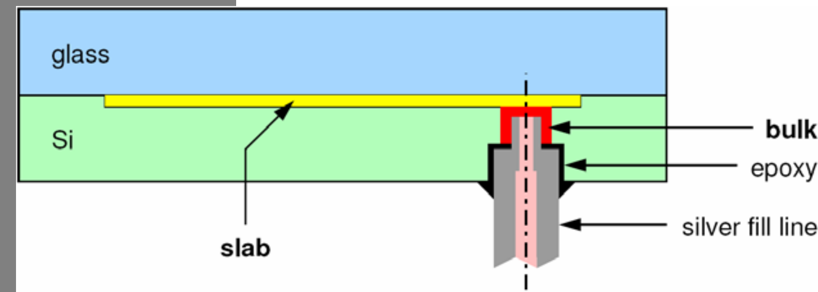
Experiments on Superfluid ^{3}He in Controlled Nanofabricated Geometries: model systems for topological quantum matter

Superfluid ^{3}He as a model material:

Perfect purity
Simple spherical Fermi surface
Isotropic normal state (but size quantization on confinement)
No crystal lattice
Spin-orbit coupling via dipolar interaction
Neutral: access to spin degrees of freedom and their manipulation by NMR
Different superfluid ground states

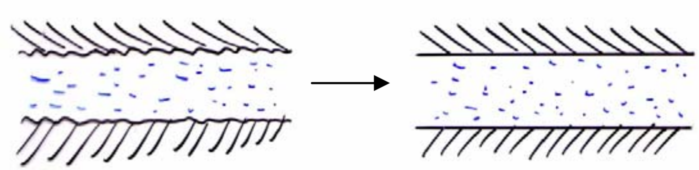


Confinement: Control parameters

Precise control of sample dimensions (through design of nanofluidic sample chamber)
Fully characterise surface roughness ⟶ effective disorder potential
Surface scattering tuneable by pre-plating with a ^{4}He film

Continuous pressure tuning of $\xi(p)$ and hence of effective confinement

Understanding disorder [theory: Tesanovic and Valls]



$Z = z - \zeta(x,y)$

$L + \zeta(x,y)$

Recent expts.arXiv.1010.5993
to appear Phys.Rev.Lett

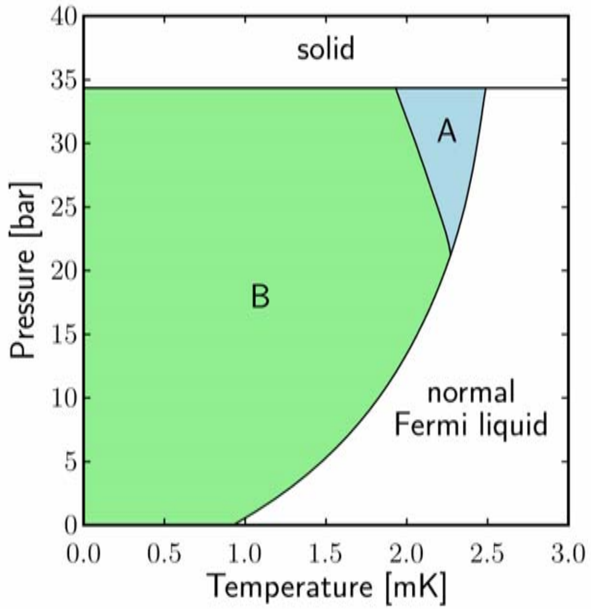
$\zeta(x,y)$ Determines an effective disorder potential within film, which is fully experimentally characterizable

Outline

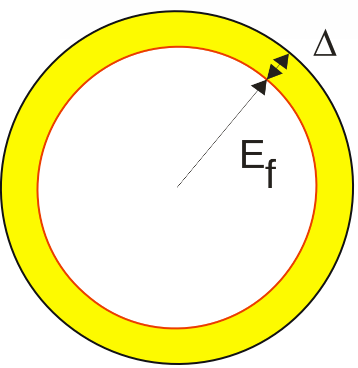
- Motivation
- Theoretical background: The order parameter at surfaces
- Superfluid ^{3}He films: previous work
- Our experiments:
  - NMR fingerprint of superfluid ^{3}He in a fully characterised nanofabricated slab geometry
- Future prospects:
  - Confinement as a control parameter
  - New p-wave states
  - Majorana excitations at surface, edges and defects

Motivation: topological superfluids (with known order parameter)

G Volovik
The Universe in a ^{3}He Droplet

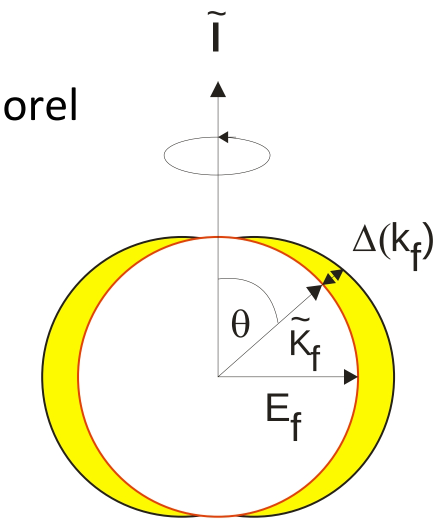


Pairs have L=1, S=1
9 component order parameter
L_z= -1, 0, +1 S_z= -1, 0, +1
Break symmetry of spherical Fermi surface
Multiple superfluid phases



Balian-Werthamer
(B) phase
Time reversal invariant
Preserves TRS

Anderson-Brinkman-Morel
(A) phase
Chiral superfluid
Breaks TRS
Stabilised by strong
Coupling at high p

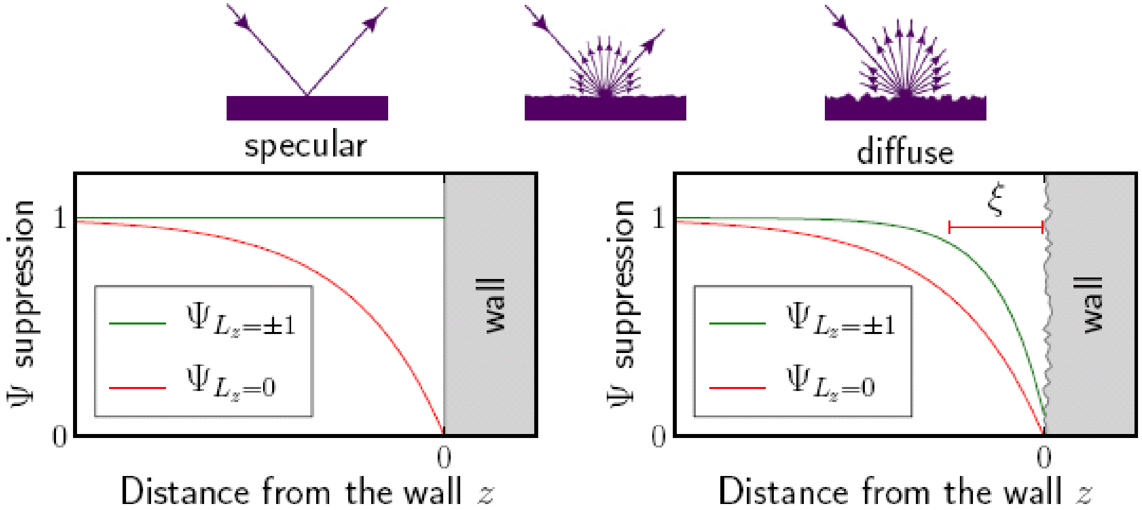


$$\mathbf{\Delta}(\mathbf{p}) = \Delta\left[(-\hat{p}_x + i\hat{p}_y)\left|\uparrow\uparrow\right\rangle + (\hat{p}_x + i\hat{p}_y)\left|\downarrow\downarrow\right\rangle + \hat{p}_z\left|\uparrow\downarrow + \downarrow\uparrow\right\rangle\right]$$

$$\mathbf{\Delta}(\mathbf{p}) = \Delta(\hat{p}_x + i\hat{p}_y)\left|\uparrow\uparrow + \downarrow\downarrow\right\rangle$$

What happens at a wall?

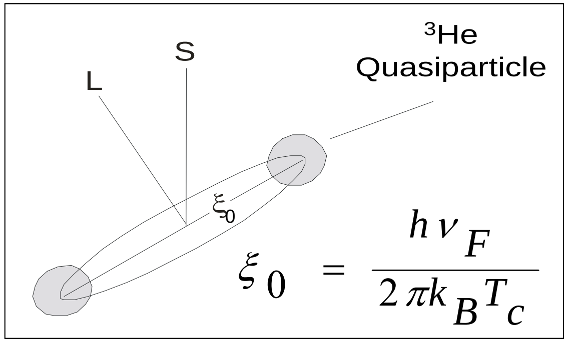
- Pairs with $\hat{l} \perp$ wall: $\Psi_{L_z=\pm1}$, pairs with $\hat{l} \parallel$ wall: $\Psi_{L_z=0}$ (wall in xy plane)
- Pairbreaking due to scattering of ^{3}He quasiparticles off the walls
- $\Psi_{L_z=0} = 0$ at the wall [AJ Leggett, *RMP* **47** (1975), V Ambegaokar, *et al.*, *PRA* **9** (1974)]
- Nature of scattering determines boundary conditions for $\Psi_{L_z=\pm1}$



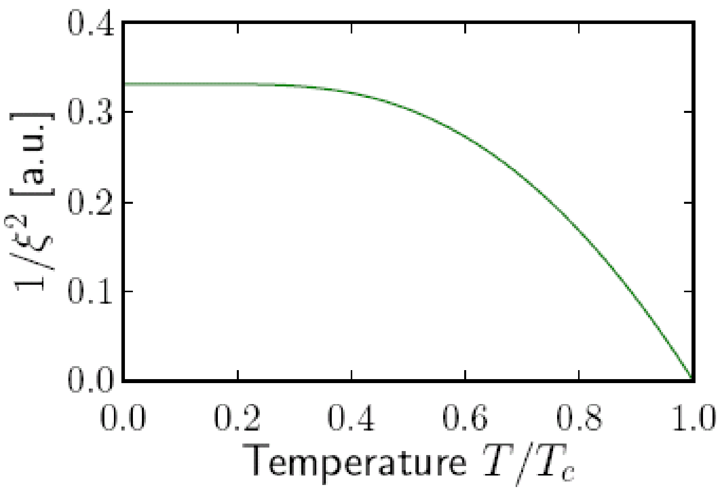
- Order parameter recovers over *coherence length* ξ
- Pairs with $\hat{l} \perp$ wall are suppressed less than pairs with $\hat{l} \parallel$ wall
- Specular scattering is enchanced by ^{4}He preplating [MR Freeman, RC Richardson, *PRB* **41** (1990)]

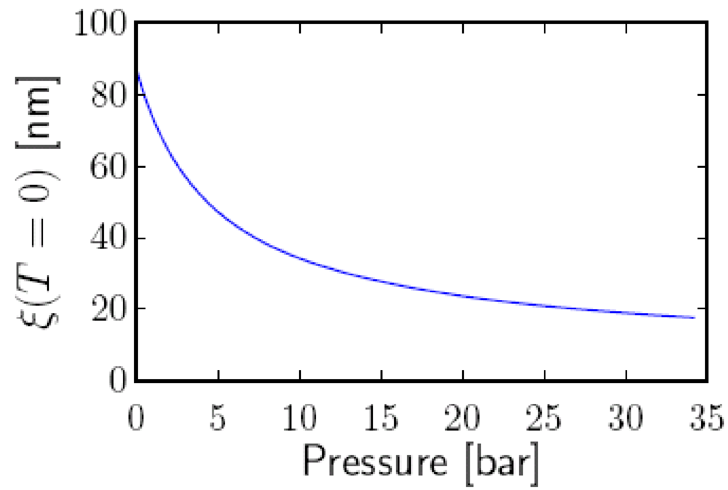
.........alters energy balance of A and B phases under confinement

Superfluid ^{3}He coherence length



Zero temperature coherence length
[Cooper pair diameter]



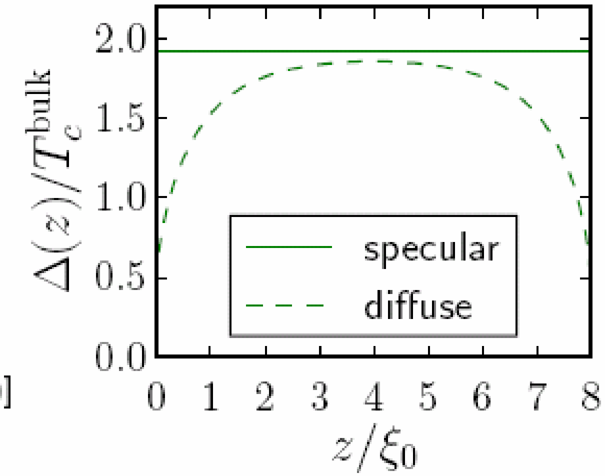


$$\xi_T = \left[\frac{7\zeta(3)}{20}\right]^{1/2} \frac{\hbar v_F}{2\pi T_c^{\mathrm{bulk}}} \left(1 - \frac{T}{T_c^{\mathrm{bulk}}}\right)^{-1/2} = \frac{\hbar v_F}{\Delta_B(T)\sqrt{10}}.$$

Order parameter distortion by surface

A Phase $\Delta(\mathbf{p}) = \Delta(\hat{p}_x + i\hat{p}_y)|\uparrow\uparrow + \downarrow\downarrow\rangle$

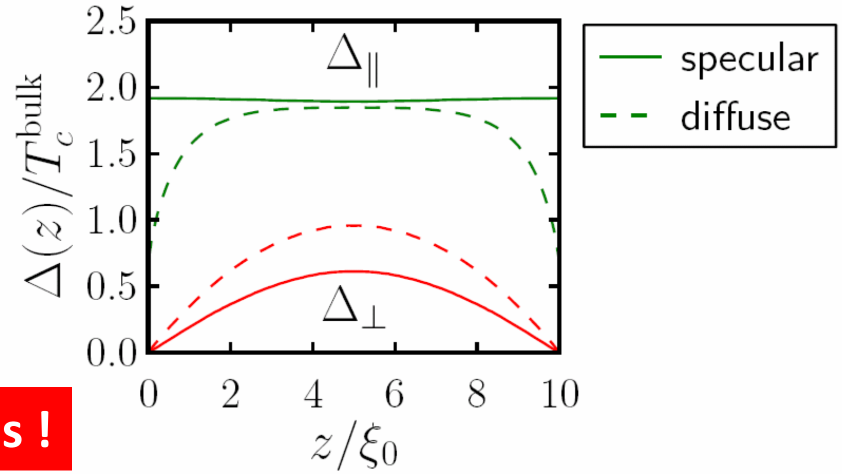
- Gap suppression is minimized by orienting $\hat{\mathbf{l}} \perp$ slab (slab in xy-plane)
- No suppression, if walls are specular
- Otherwise energy gap $\Delta(z)$ varies across the slab
- T_c suppression, if diffuse scattering is present



[AB Vorontsov and JA Sauls, *PRB* **68** (2003)]

B phase $\Delta(\mathbf{p}) = \left[\Delta_\parallel(-\hat{p}_x + i\hat{p}_y)|\uparrow\uparrow\rangle + \Delta_\parallel(\hat{p}_x + i\hat{p}_y)|\downarrow\downarrow\rangle + \Delta_\perp \hat{p}_z|\uparrow\downarrow + \downarrow\uparrow\rangle\right]$

- Planar distortion (spatially dependent)

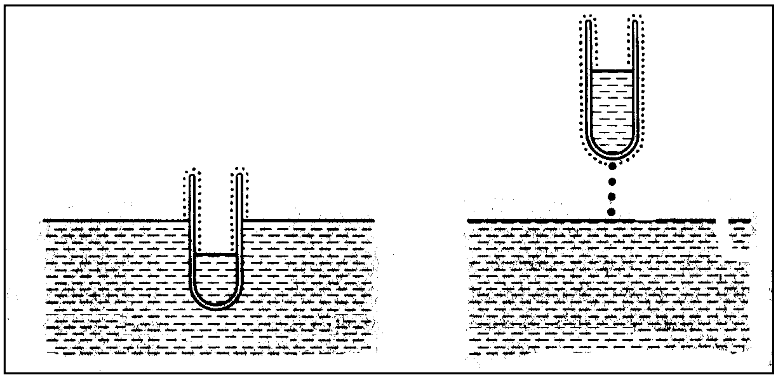


A-phase energetically favoured in thin slabs !

[Y Nagato and K Nagai, *Physica B* **284-288** (2000)]

Motivation: Superfluid helium films……^{4}He

Superfluid ^{4}He film flow
Daunt and Mendelssohn
Proc. R. Soc A170, 423, 439 (1939)



Berezinskii-Kosterlitz-Thouless (vortex-unbinding) transition in a 2D ^{4}He film
Bishop and Reppy 1978

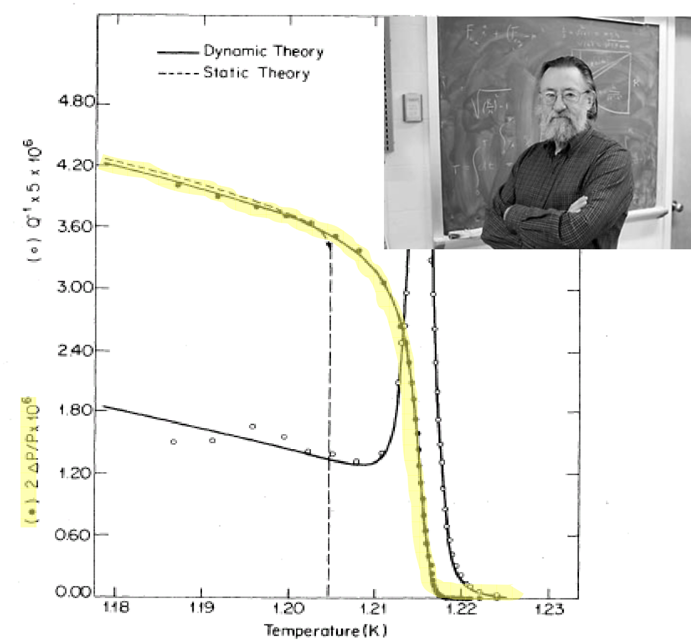


FIG. 2. The reduced period shift, $2\Delta P/P$, and dissipation Q^{-1} are shown for a superfluid transition temperature of 1.215 K. The solid lines are fits using the dynamic theory of AHNS (Ref. 6) and the dashed curve is the result of the static theory.

Superfluidity survives in atomically thin films on disordered surfaces

Since coherence length is of order 0.1 nm

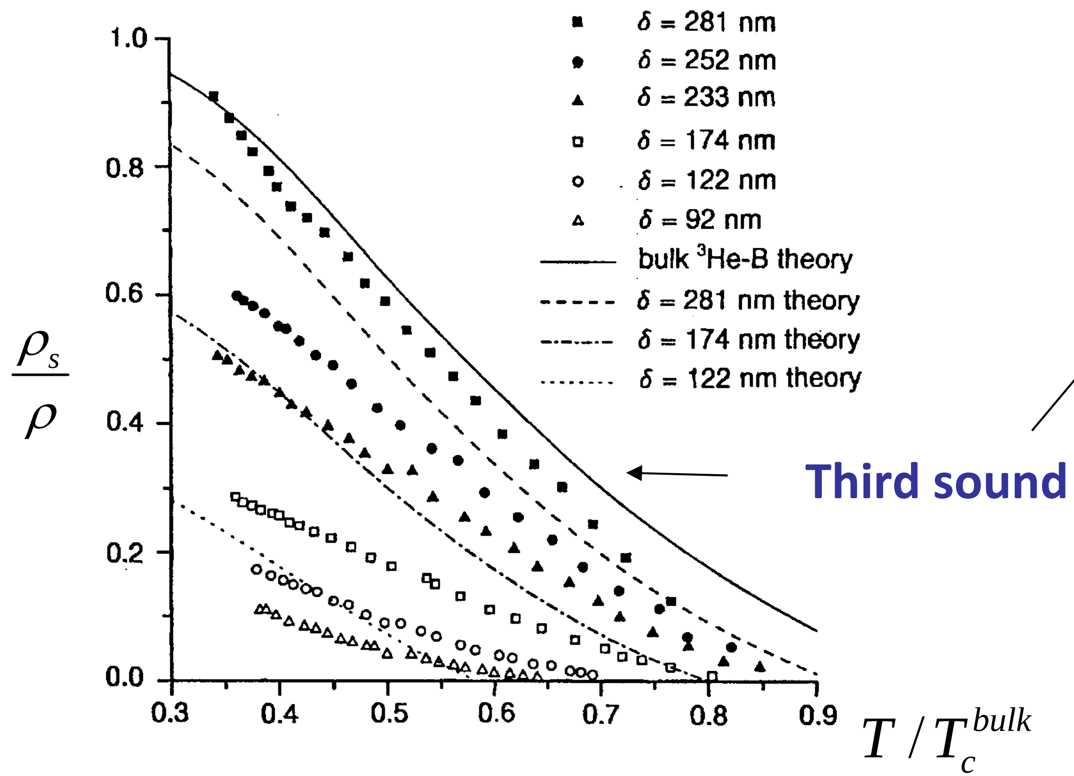
For atomically rough surfaces ^{3}He film must be relatively thick not to kill superfluidity

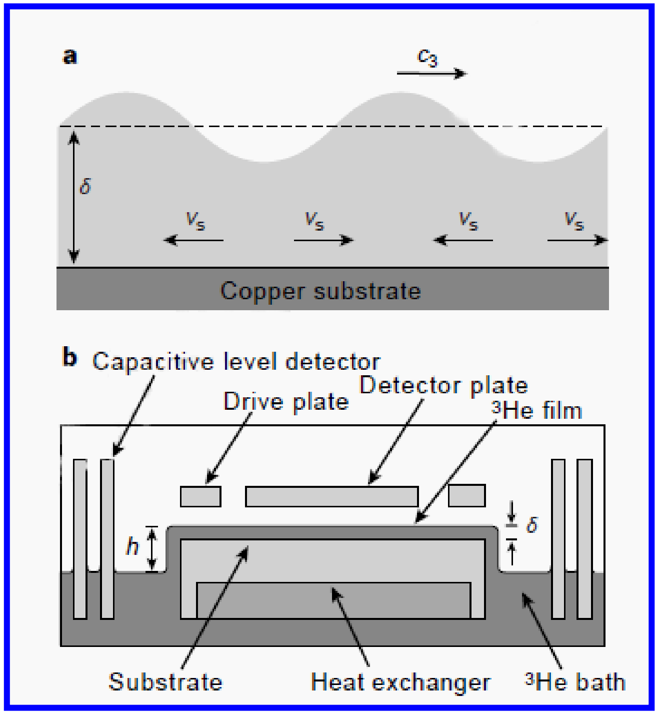
Superfluid ^{3}He film flow experiments

Film flow: S C Steel et al. J Low Temp. Phys. 95, 759 (1994)
A Sachrajda et al. Phys. Rev. Lett. 55, 1602 (1985)
J G Daunt et al. J Low Temp. Phys. 70, 547 (1988)

Third sound: A N R Schecter et al. Nature 554 (1998)

Torsional oscillator measurement of superfluid density: J Xu and C Crooker Phys. Rev. Lett. 65, 3005 (1990)
A Corcoles et al. unpub.





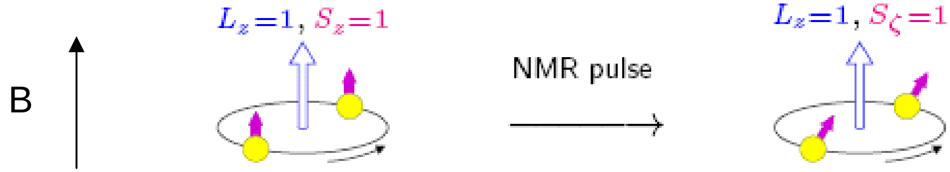
NMR on superfluid ^{3}He

NMR fingerprints the equilibium order parameter [A J Leggett Ann. of Phys. 85, 11 (1974)]

It determines the gap suppression and gap distortion arising from confinement.

Measure as a function of tip angle (non-linear response)

- Nuclear spins — degrees of freedom of cooper pairs
- Tipping the spin in NMR experiment modifies the order parameter:



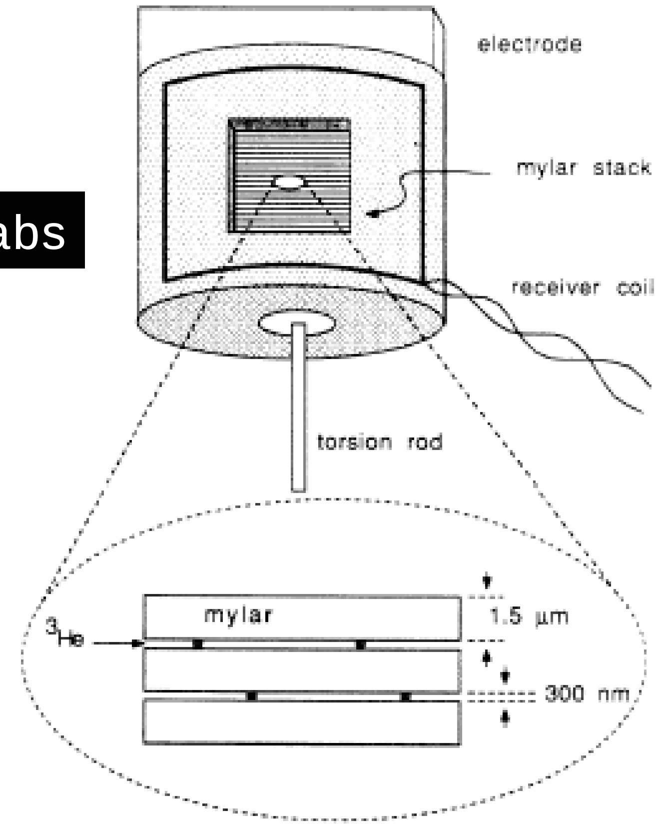
- Relative rotation of spins with respect to orbital momenta of pairs
- Condensation energy is invariant, but dipolar coupling between the spins is affected
- Dipolar torque on the spins $\longrightarrow$ frequency shift [AJ Leggett, *Ann. of Phys.* 85 (1974)]

$$\Delta f \propto \Delta^2$$

First NMR experiments on highly confined slabs

M R Freeman and R C Richardson
Phys. Rev. B41, 11011 (1990)

3000 x 300 nm slabs



Main conclusions:

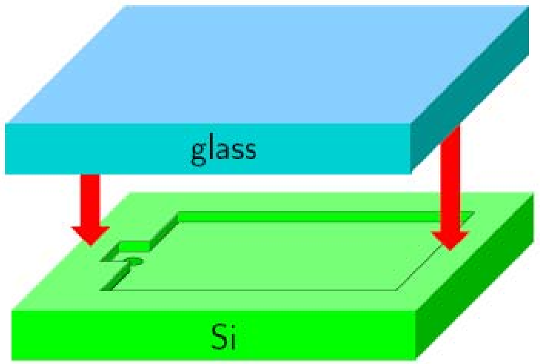
"A" phase at all pressures

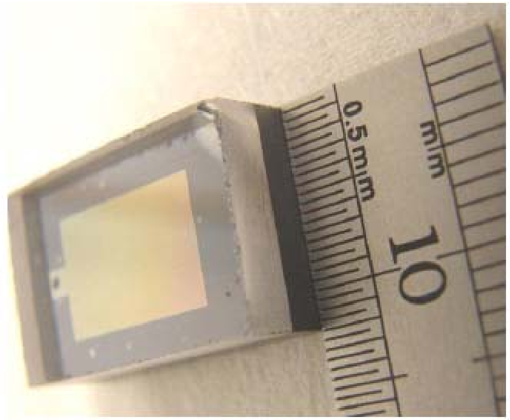
^{4}He coating on boundary → specular scattering

Confined superfluid ^{3}He (1)

Technical challenges:

- (1) controlled and well characterised confinement (single slab)
- (2) measurement sensitivity
- (3) cooling





650 nm x 10 mm x 7 mm

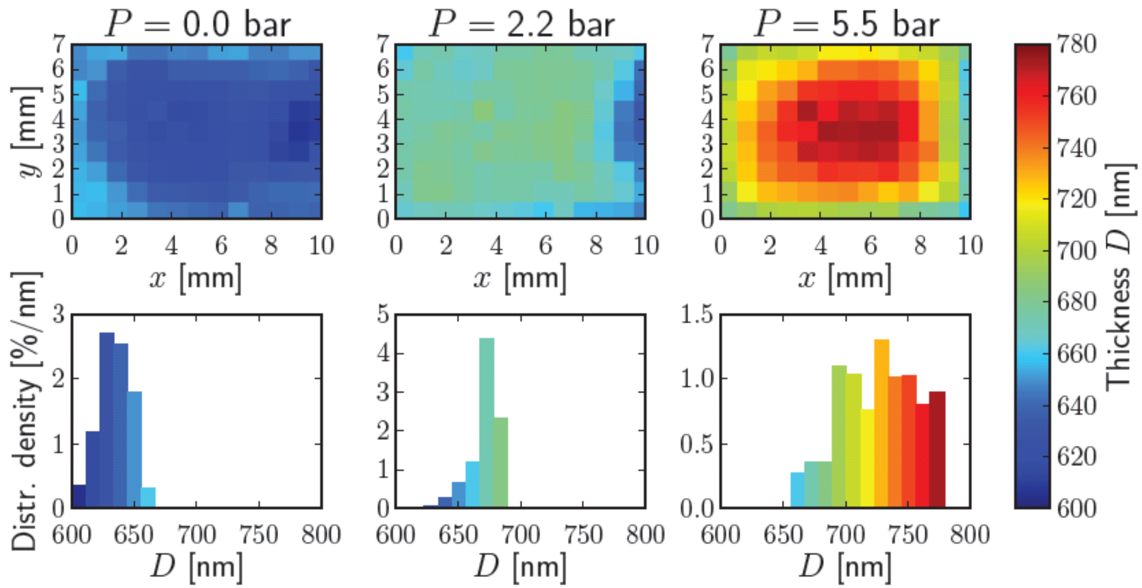
Fully characterise surface roughness (AFM)

[This cavity is unsupported:
Search for "striped phase"]

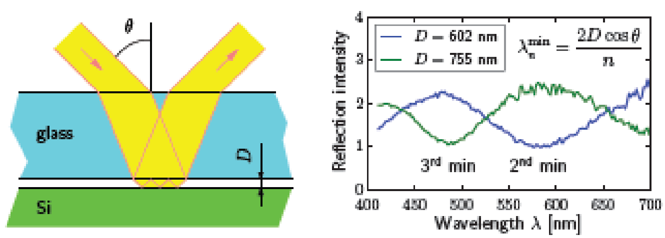
Optically characterise cavity thickness profile

Confined superfluid ^3He (1)

Optical characterization of cavity profile at low temperatures

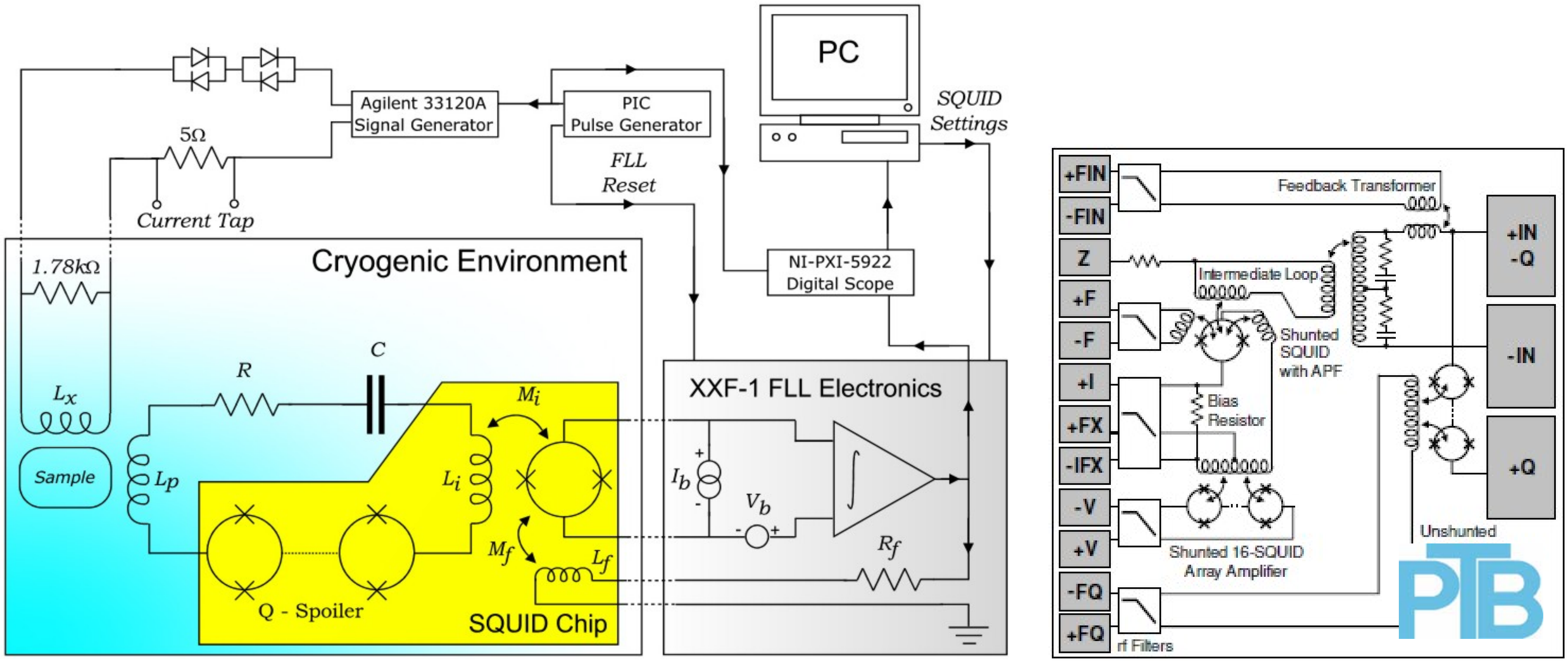


Optical Thickness Measurement



- Interferometry in the cavity cooled below 7 K.
- Analyse reflection of ⌀0.3 mm collimated white light beam
- Bowing due to differential thermal contraction. Stops at 30 K
- T-indep. inflation under pressure. 28 nm/bar in the centre

Detecting an NMR signal: Sensitive SQUID NMR spectrometer



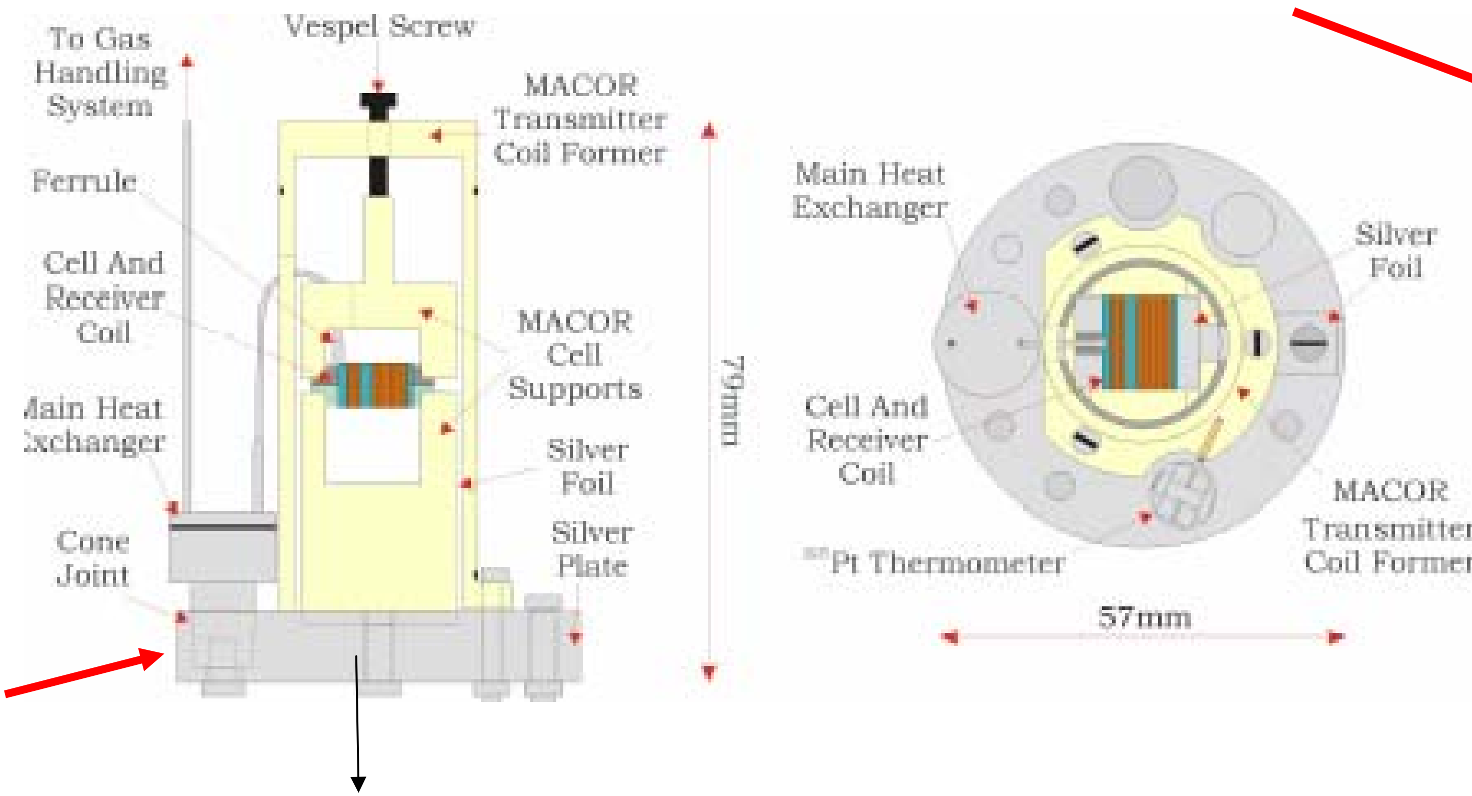
□ NMR probes the order parameter of ^{3}He: different phases show distinct shifts of the resonance away from the Larmor frequency

□ Integrated two stage DC SQUID energy sensitivity **20 h** achieved in this spectrometer. [5 mK noise temperature at 1 MHz)

Levitin *et al.*, Appl. Phys. Lett. **91**, 262507 (2007)

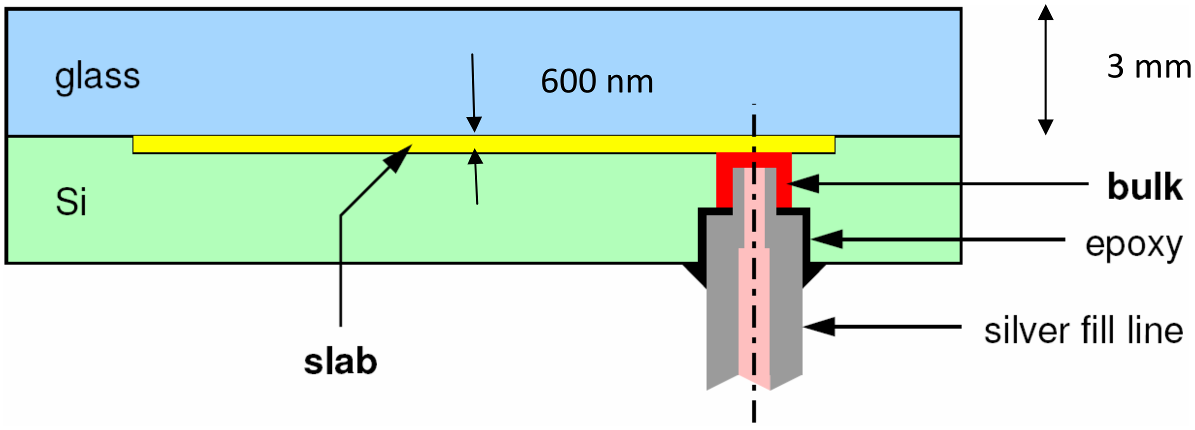
Cooling the ^{3}He sample

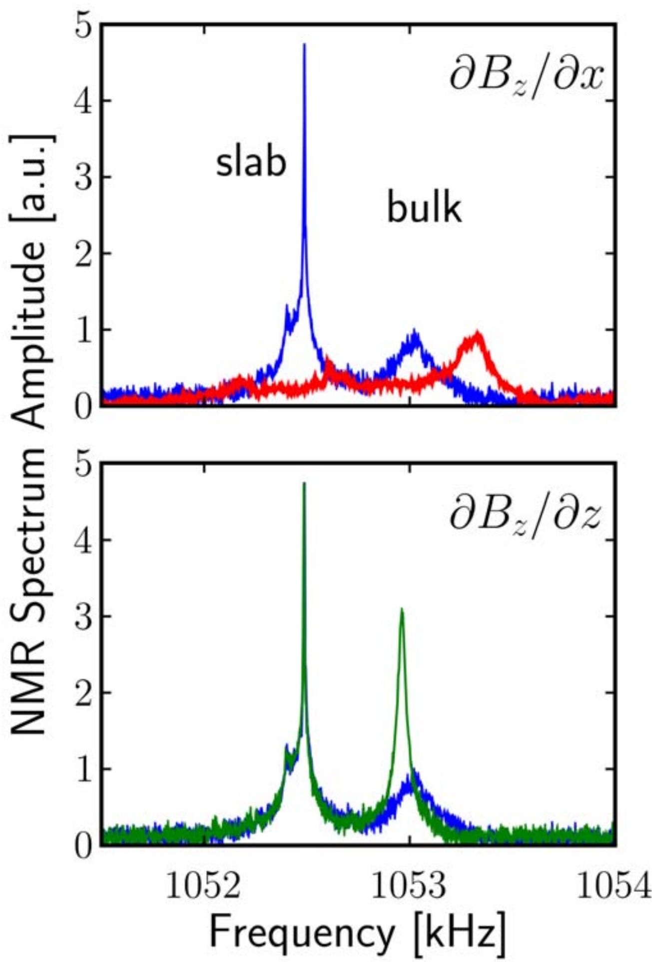
Sample is cooled through the "leads" = ^{3}He in fill line



to copper nuclear stage

NMR signals from slab

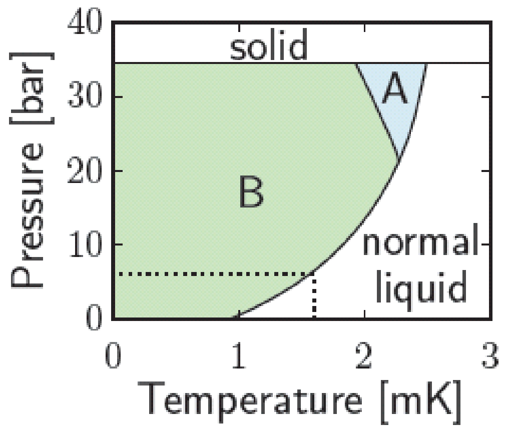




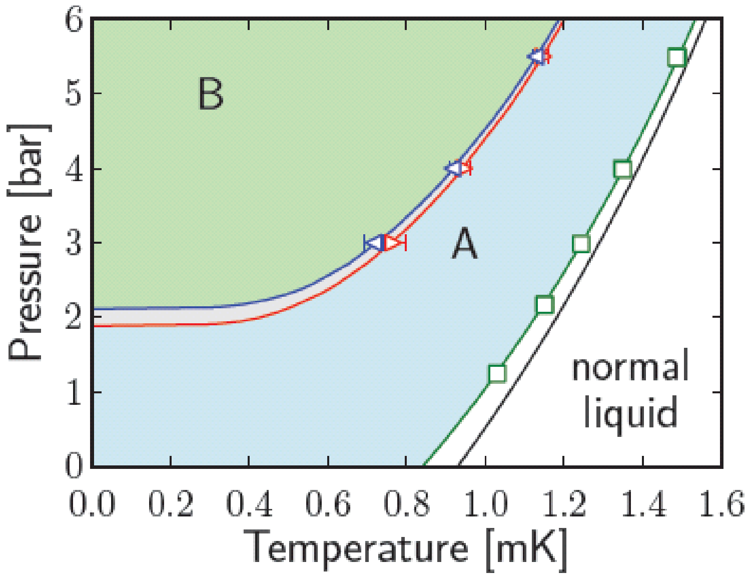
Apply field gradients, along or perpendicular to slab to clearly **image** slab and bulk signal

Profound influence of confinement on the phase diagram

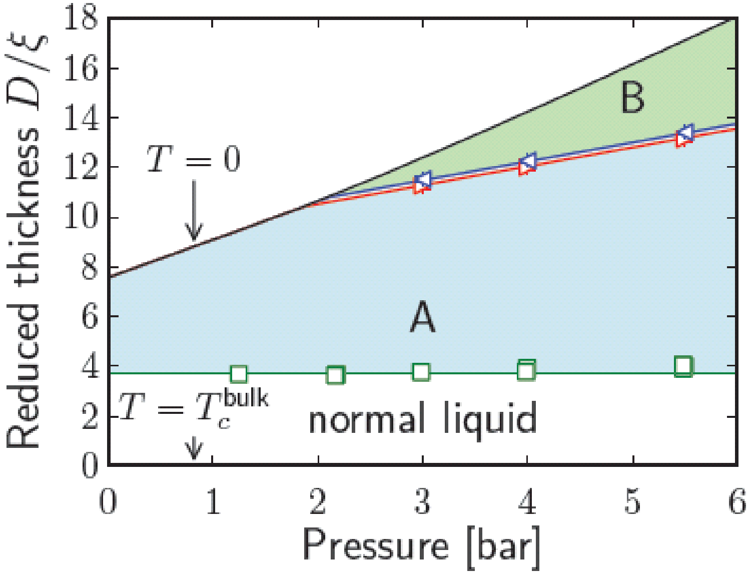
Bulk ^{3}He:



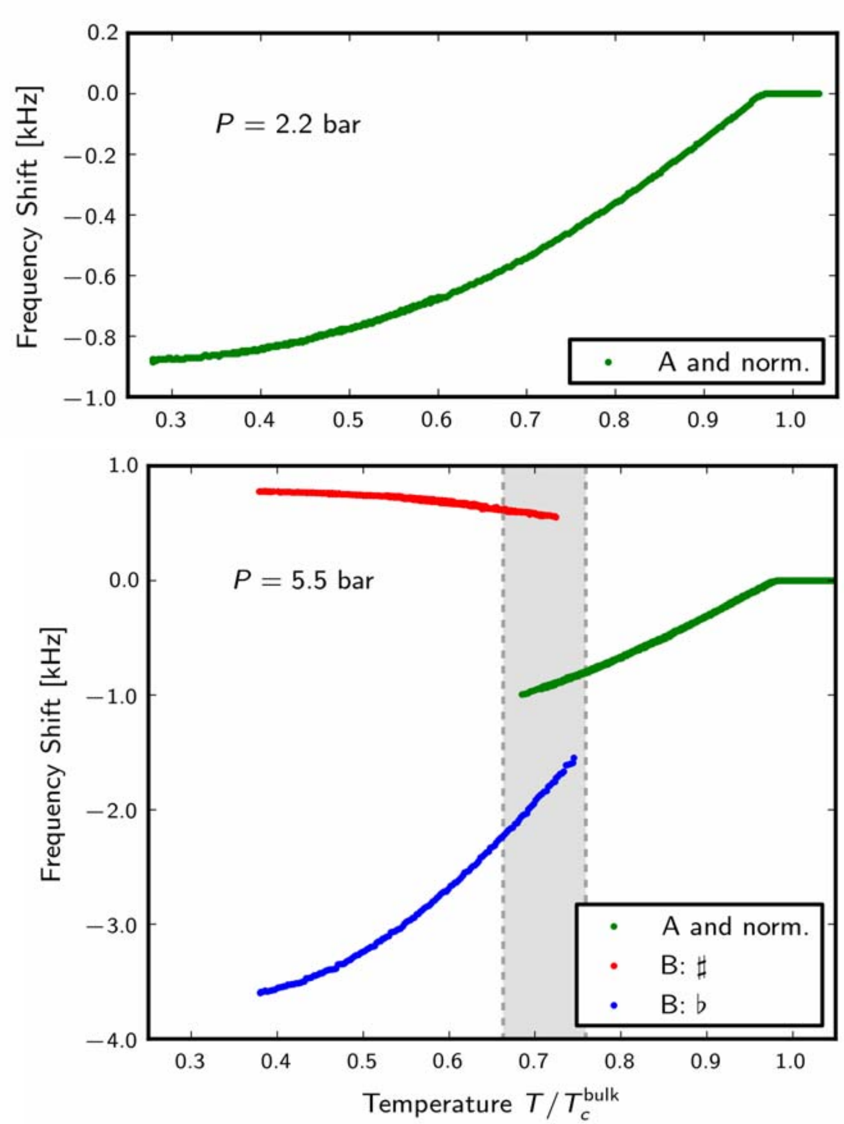
0.7 μm Slab:



- Two superfluid phases:
  - the A phase and
  - the B phase with a planar distortion
- Suppressed T_c
- Hysteresis at the AB transition
- Transitions at weakly P-dependent values of D/ξ



NMR signatures of superfluid: frequency shift



Lower pressures:
A phase

Higher pressures
A phase
then transition to
B phase with planar distortion

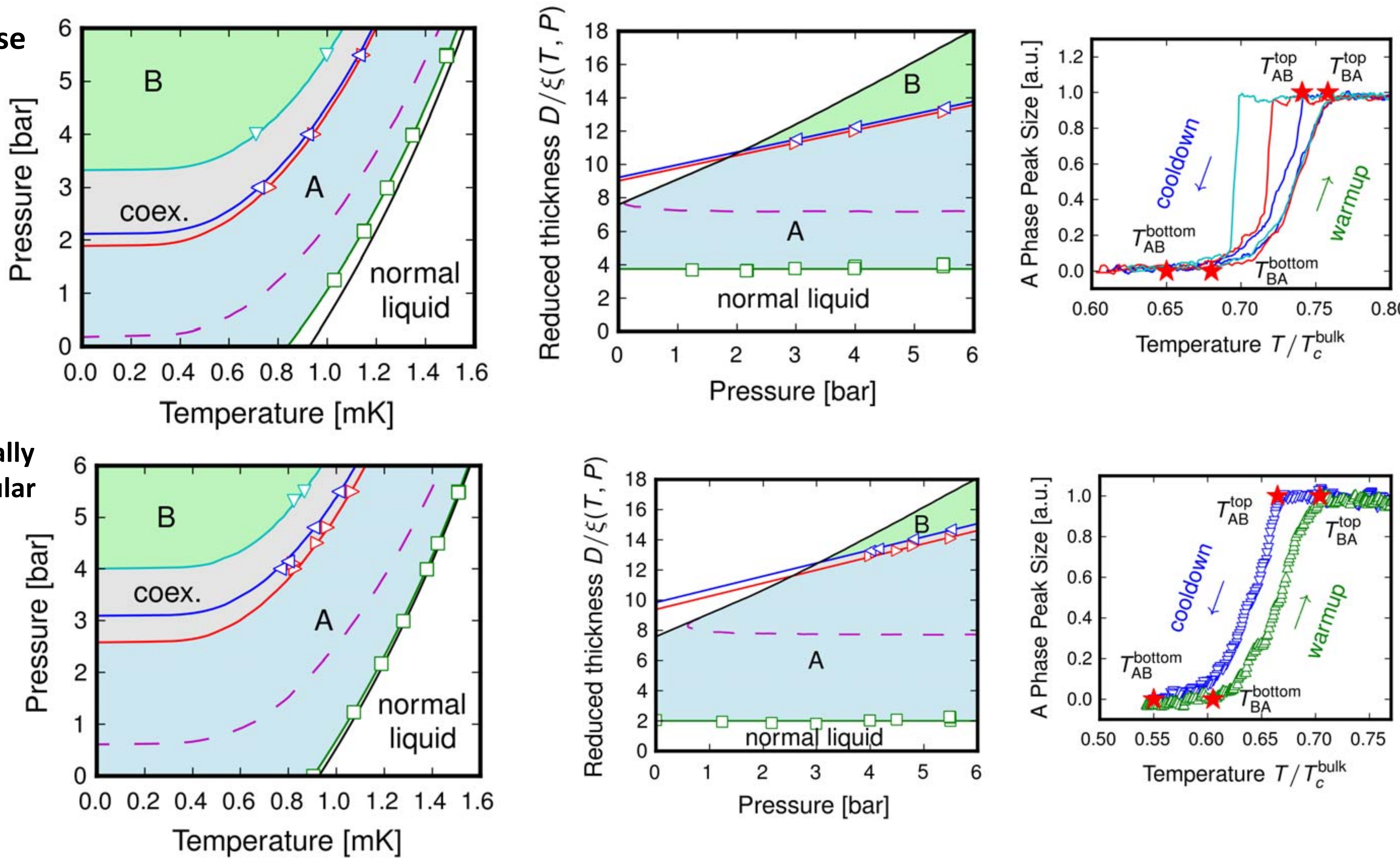
Pressure tunes effective confinement

$$\frac{D}{\xi_0}$$

Tuning boundary scattering in situ by coating surface with ^{4}He film

diffuse

Partially specular



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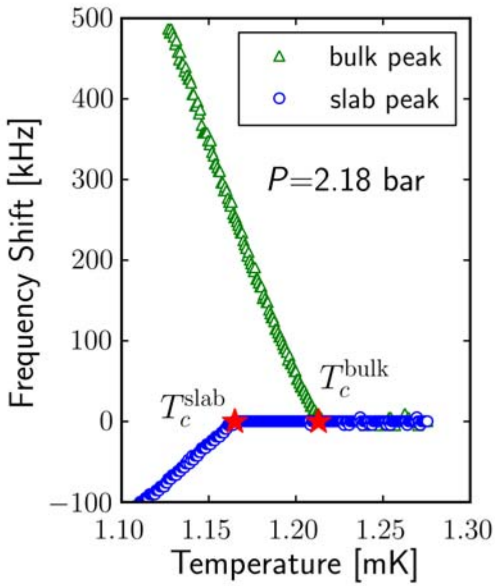
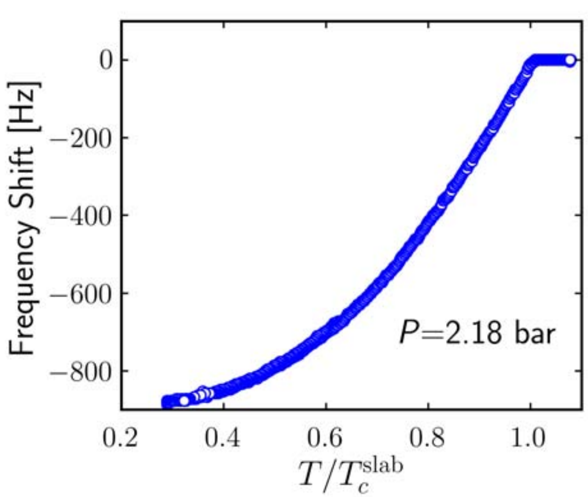
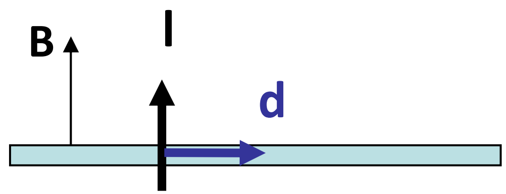
A- Phase in slab: NMR fingerprint (i) small angle pulsed NMR





$$|\Delta f| = \frac{g^2 \lambda_{\rm D} N_{\rm F}}{2\pi^2 \chi_{\rm N} f_{\rm L}} \langle \Delta^2(z) \rangle$$



L normal to surface

Zeeman energy orients

$\mathbf{d} \perp \mathbf{B}$

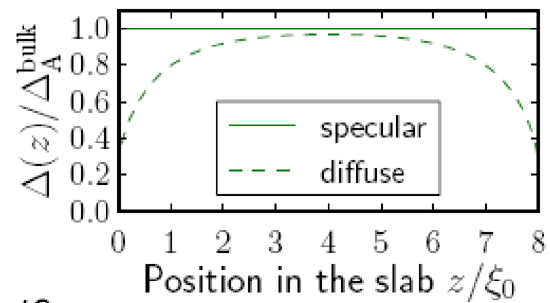
Dipole energy maximum

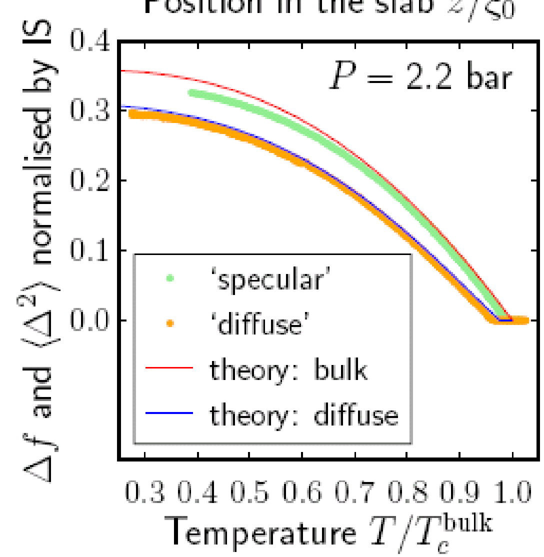
So -ve freq shift

Average gap:

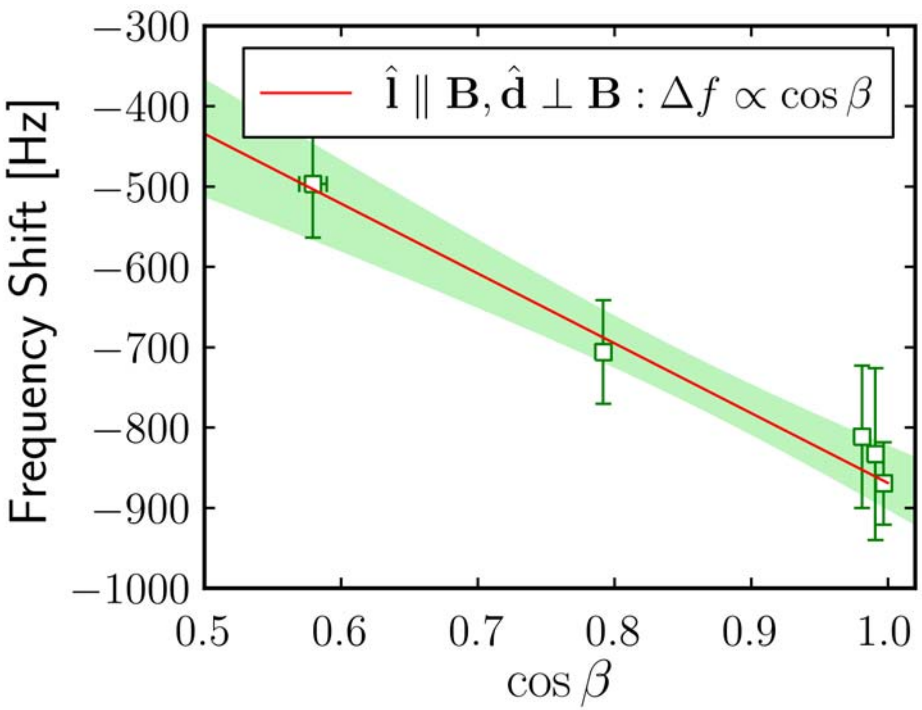
Diffuse and partially specular boundary

Comparison with quasiclassical theory (Vorontsov)





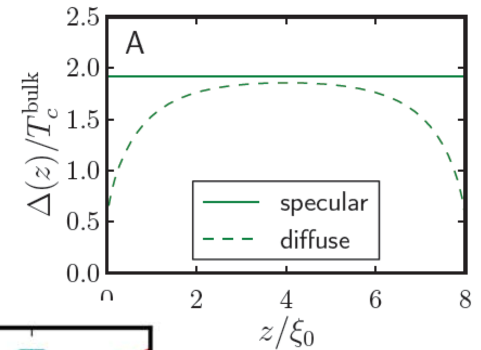
A- Phase in slab: NMR fingerprint (ii) large tip- angle pulsed NMR



Use large tip angle NMR to confirm the observation of the "dipole-unlocked" state of the A phase
Prediction: S Takagi *J Phys C* **8** (1975)

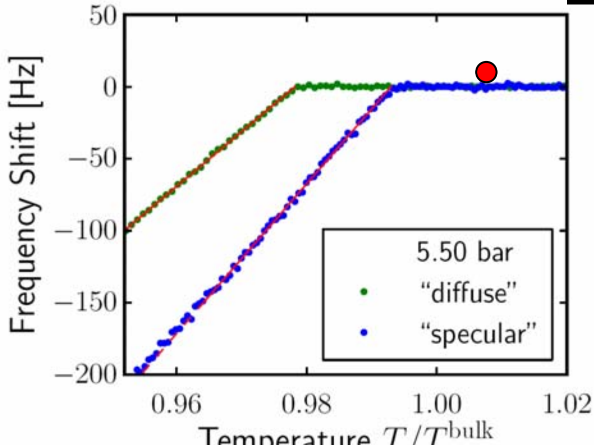
$$\Delta f(\beta) = -\frac{\nu_A^2}{2f_0}\cos\beta$$

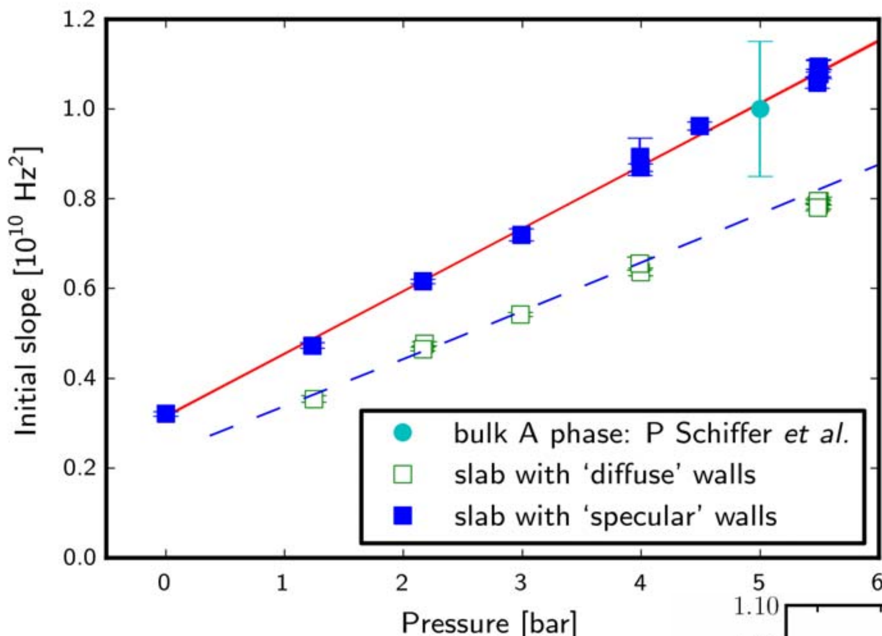
"A" phase: diffuse and specular surface scattering, measuring the gap

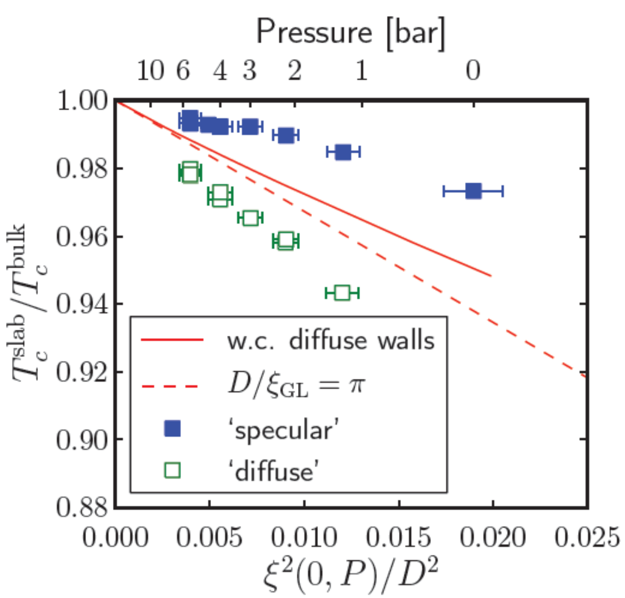


$$|\Delta f| = \frac{g^2 \lambda_D N_F}{2\pi^2 \chi_N f_L} \langle \Delta^2(z) \rangle$$

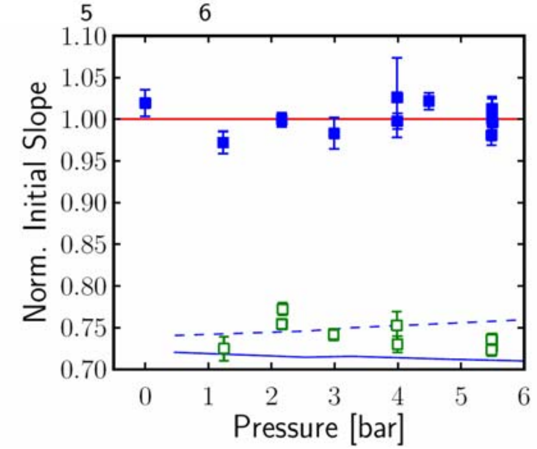
"Tune" surface scattering by ^{4}He plating: alters T_c suppression and gap suppression





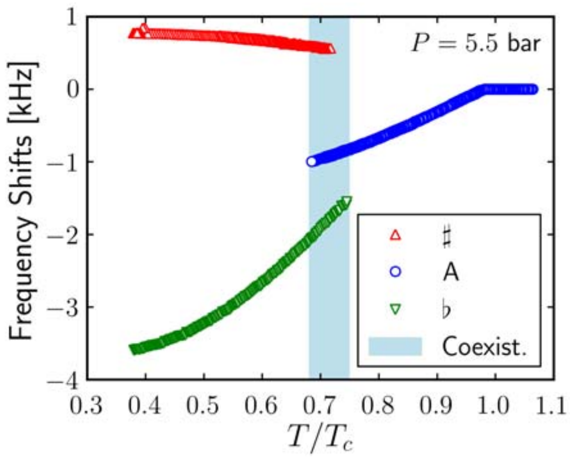


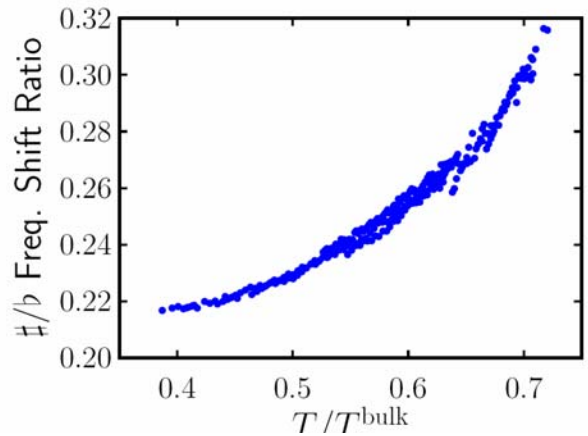
Comparison of A-phase gap suppression (diffuse walls) with ***quasi-classical theory***



NMR fingerprint of planar distorted B phase gap: (i) small angle tipping pulses

$$\mathbf{\Delta}(\mathbf{p}) = \left[\Delta_{\parallel}(-\hat{p}_x + i\hat{p}_y)\left|\uparrow\uparrow\right\rangle + \Delta_{\parallel}(\hat{p}_x + i\hat{p}_y)\left|\downarrow\downarrow\right\rangle + \Delta_{\perp}\hat{p}_z\left|\uparrow\downarrow + \downarrow\uparrow\right\rangle\right]$$





Indicates temperature dependence of

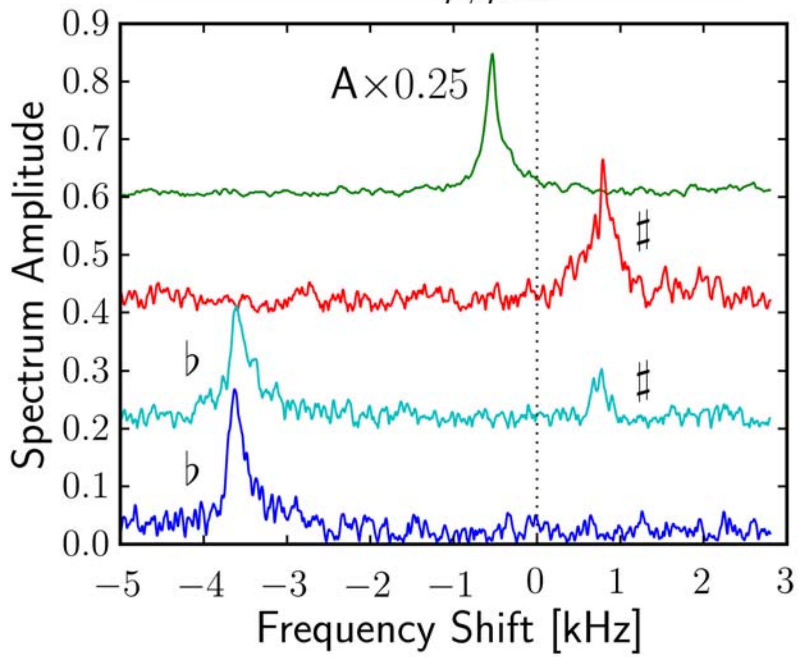
$$q = \frac{\Delta_{\perp}}{\Delta_{\parallel}}$$

Stable and metastable state

Gap anisotropy axis along z.

Susceptibility anisotropy axis is either
parallel or antiparallel

These two states have different dipole energy,



The B phase with a planar distortion: stable and metastable configuration

The gap anisotropy axis **l** is fixed || **z** by the walls of the slab

Order parameter with **l** || **z**:

$$\boldsymbol{A} = \boldsymbol{R} \begin{pmatrix} \Delta_{\parallel} & & \\ & \Delta_{\parallel} & \\ & & \Delta_{\perp} \end{pmatrix}$$

with a rotation matrix ***R***, determined by Zeeman and dipolar energy

Anisotropic magnetic susceptibility, axis **w = *R* l** due to planar distortion

Our experimental geometry: **H** || **z**, slab in *xy* plane, so **l** || **z**

Zeeman energy:

$$F_Z = -\frac{1}{2}\Delta\chi(\hat{\mathbf{w}} \cdot \mathbf{H})^2$$

has two minima: **w** = -**l**, **w** = +**l**.

Dipolar energy tends is minimised with **w** = **l**, hence **positive frequency shift**

The state **w** = -**l** is metastable, does not minimise dipole energy, and gives rise to a **negative frequency shift.** [confirmed by field cycling experiments]

NMR fingerprint of planar distorted B phase gap: (i) large angle tipping pulses

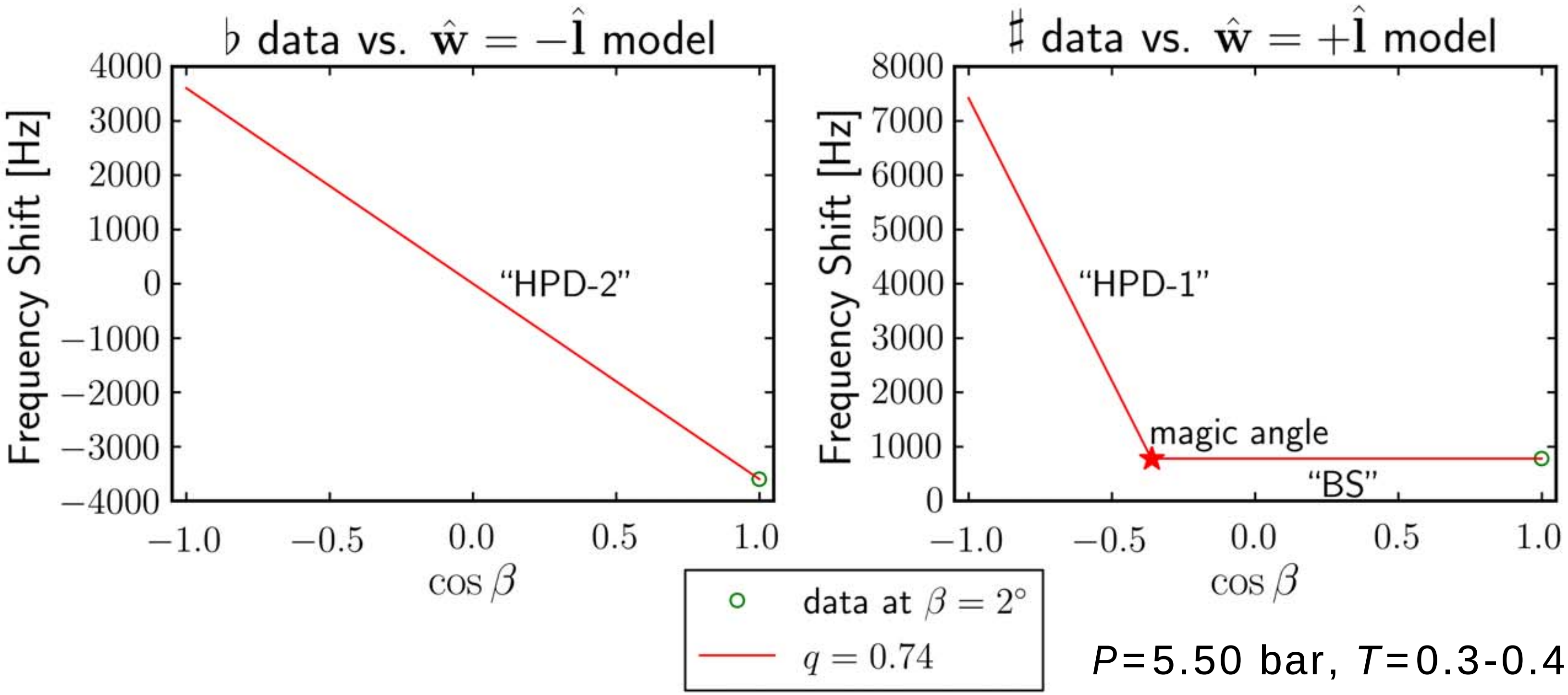
Theoretical **prediction** of NMR in the B phase with a uniform planar distortion by YuM Bunkov and GE Volovik, *JETP* **76** (1993)

Parameter of the theory, gap distortion parameter:

$$q = \frac{\Delta_\perp}{\Delta_\parallel}$$

Frequency shifts at small tip angle β determine q and yield a prediction for Δf(β)

GE Volovik JETP LETTERS Vol. 91 No. 4 (2010)



P=5.50 bar, T=0.3-0.4T_c

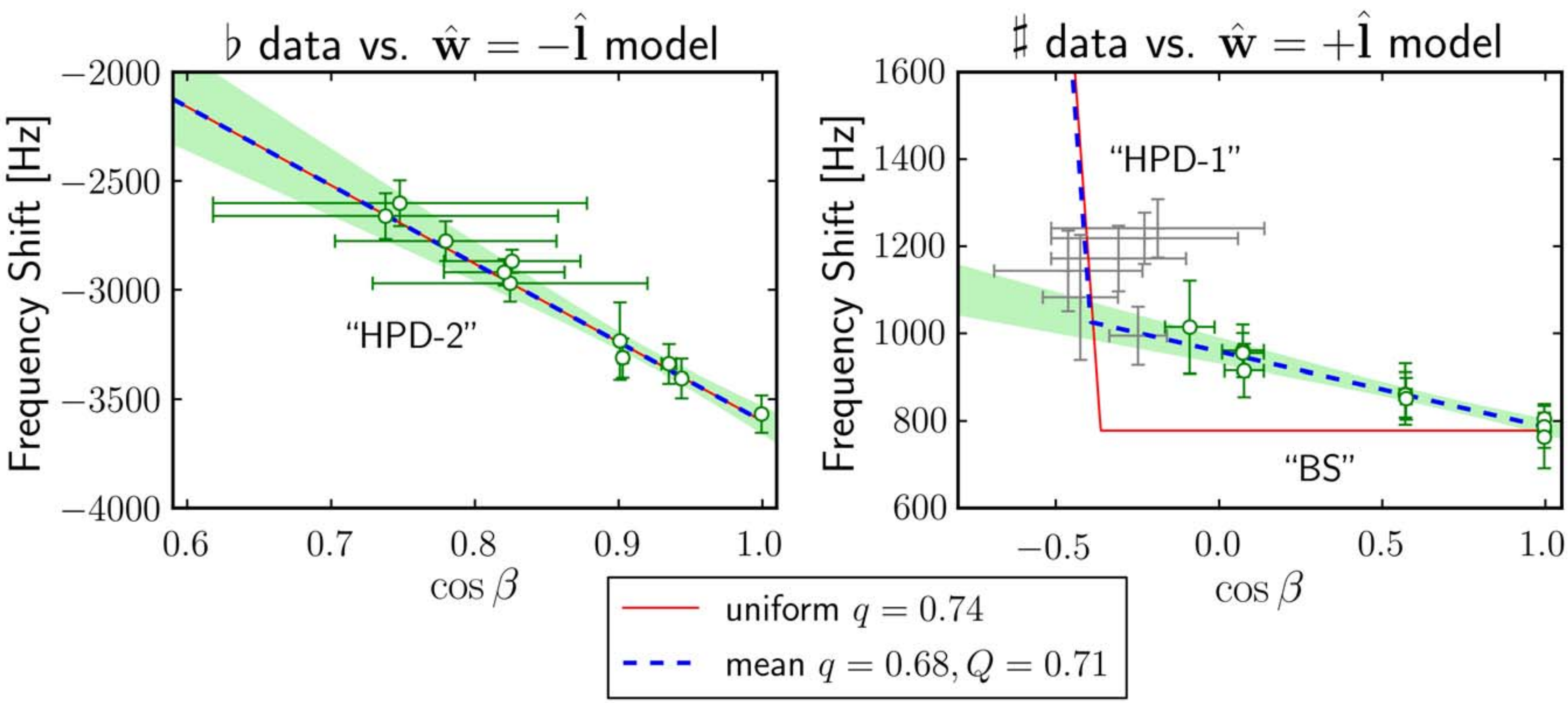
Large Tip Angle NMR on the confined B Phase: determining spatial variation of planar distortion

Modify theory to include spatial dependence of planar distortion:

$$q = \frac{\langle \Delta_\perp \Delta_\parallel \rangle}{\langle \Delta_\parallel^2 \rangle}, \quad Q = \sqrt{\frac{\langle \Delta_\perp^2 \rangle}{\langle \Delta_\parallel^2 \rangle}}$$

instead of just

$$q = \frac{\Delta_\perp}{\Delta_\parallel}$$



Measurements on 650 nm slab: summary of main results

1. Determine profound modification of superfluid phase diagram due to confinement.

2. “A” phase (not planar phase) stable at zero pressure

3. Determine T_{AB}, and conclude that strong coupling corrections exist at all p

4. No evidence, as yet, for striped phase (for good reason).

5. Identify both a stable and a metastable state of planar-distorted B-phase. Fully characterize by NMR.

6. Under confinement the gap is spatially dependent [due to wall suppression]. We can use ***NMR*** to ***measure averages of the gap*** and compare to predictions of quasi-classical theory.

7. We have ***in situ control*** of surface scattering by ^{4}He pre-plating.
   We can study this through (i) T_c suppression (ii) gap suppression

Future directions

•Discovering new order parameters

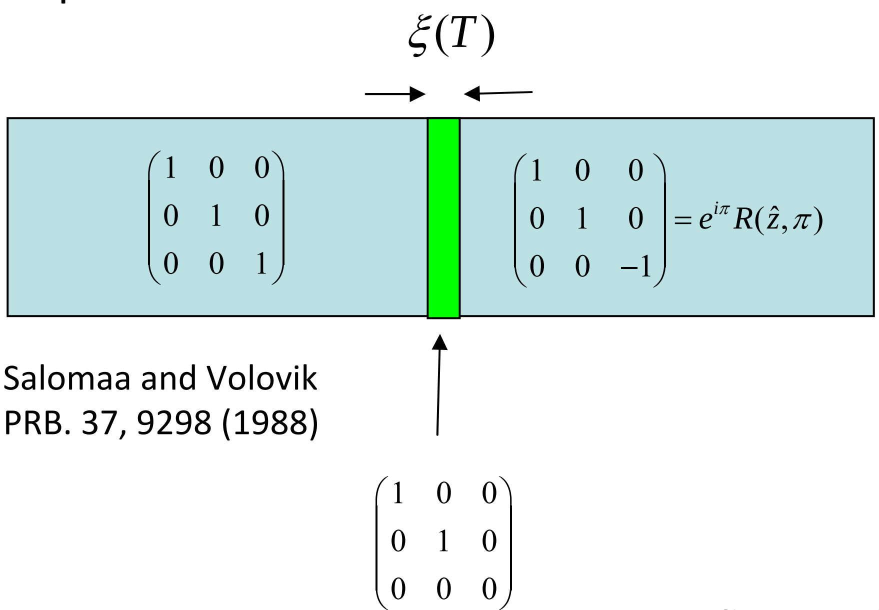
Prediction of spatially modulated B-phase (striped phase)
Gapped p+ip phase, arising from confinement (quantum size effect)

•Probing surface and edge excitations: the search for majorana fermions

Propagating majorana fermions at the surface of the B-phase
Chiral edge mode in the gapped A-phase (if stable)
Majorana zero-modes at core of HQV (if stable) in gapped A-phase

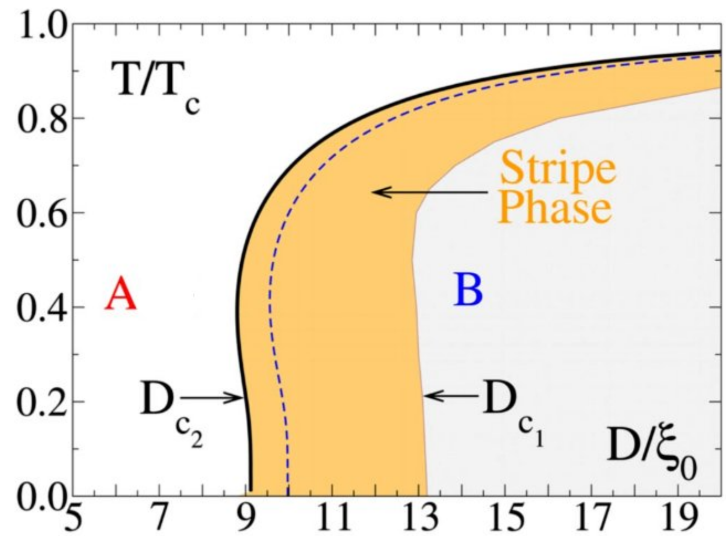
B phase domain walls and the striped phase

Domain wall (planar phase) between different B phase states

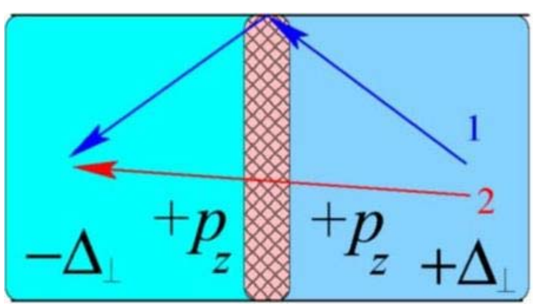


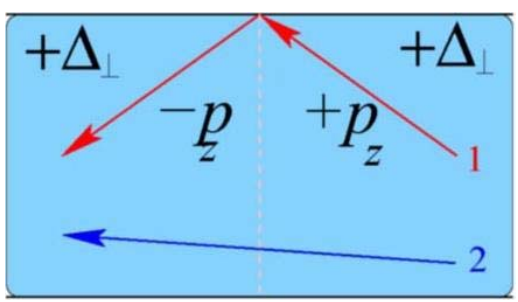
Salomaa and Volovik
PRB. 37, 9298 (1988)

Vorontsov and Sauls PRL 98, 045301 (2007)



Superfluid with spontaneously broken translational symmetry





Towards the two dimensional A phase

Gapped p + ip superfluid
Breaks TRI
cf candidate Sr_2RuO_4

→

Requires specular boundaries
Plate surfaces with superfluid ^{4}He film
Diagnostic is T_c suppression

slab geometry: Size quantization $$\varepsilon = \frac{1}{2m^*}[p_z^2 + q^2] \qquad p_z = \frac{\hbar \pi j}{L}$$

Number of discs $$j_0 = \frac{k_F L}{\pi}$$

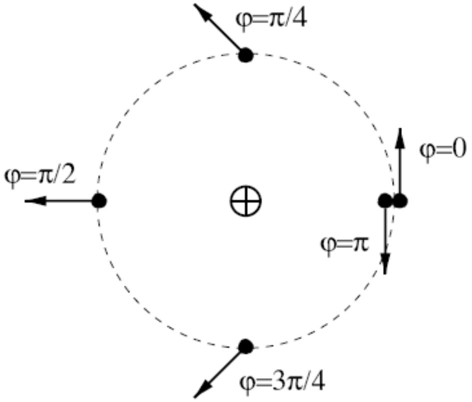
k_F=7.9 nm^{-1} so for L=100 nm: number of discs = 250

Note:
QSE show up clearly in transport in a 100 nm film. The transport relaxation time shows a *1/T* dependence.

Search for this state in slabs of thickness < 100nm

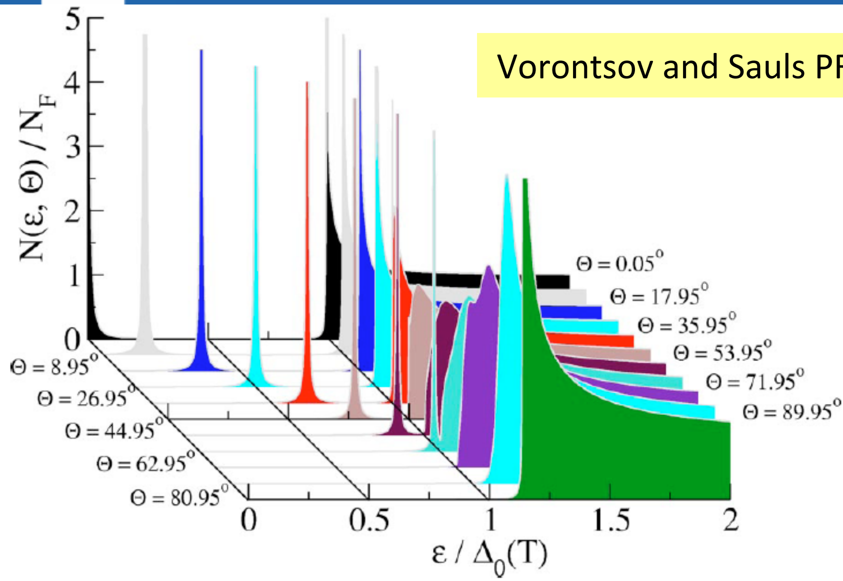
Consequences:
Quantum Hall analogues in transport of heat, spin, (mass?)
HQV in a gapped *p*+ *ip* superfluid (detection and manipulation?)

$$\kappa_{xy} = \frac{1}{2} N \frac{\pi^2 k_B^2}{3h} T$$

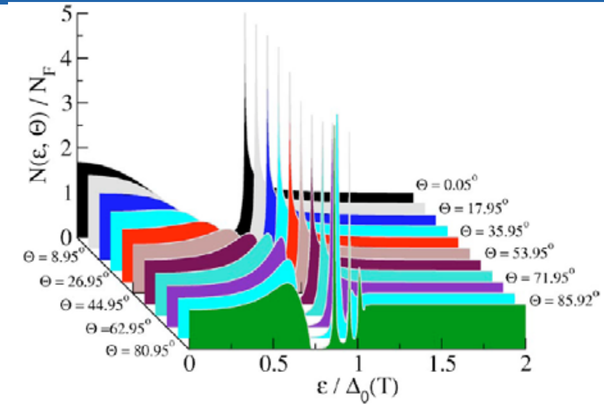


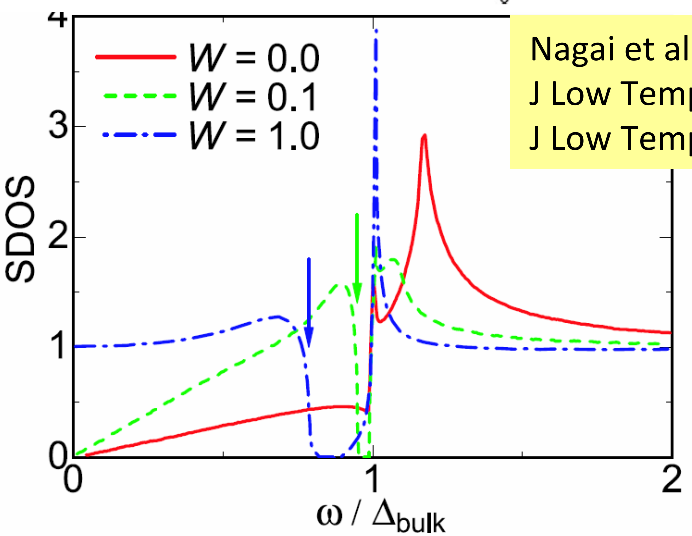
But…is this state stable relative to TRI planar phase?

Surface Andreev Bound States: B phase
Mid gap states and Majorana fermions



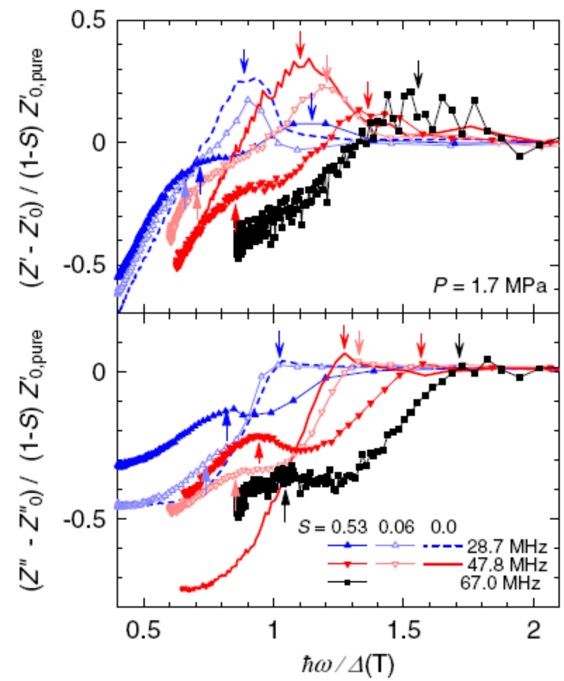
Vorontsov and Sauls PRB 68, 064508 (2003)





Nagai et al.
J Low Temp. Phys. 110, 1138 (1998)
J Low Temp. Phys. 149 294 (2007)

Transverse acoustic impedance



Murukawa et al.
JPSJ 80, 013602 (2011)
and refs. therein

Majoranas at surface of ^{3}He-B

Mizushima and Machida J. Low Temp.Phys.

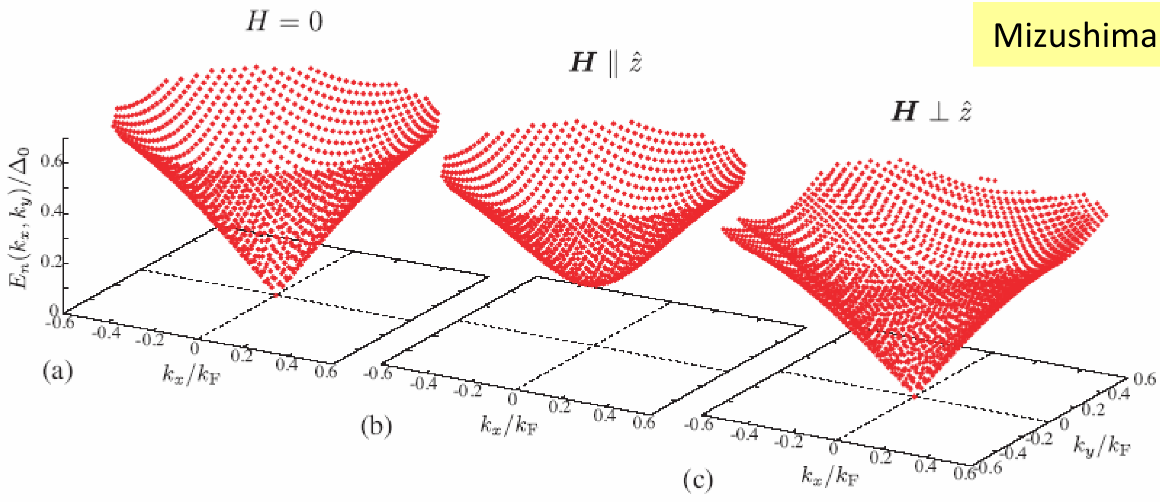
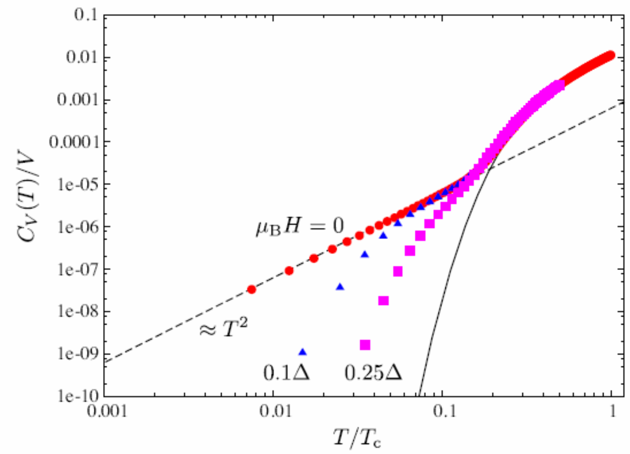


Fig. 1 (Color online) Low energy quasiparticle spectra in a plane of $\boldsymbol{K} = (k_x, k_y)$ parallel to the wall for the case of $H = 0$ (a), $\boldsymbol{H} \parallel \hat{z}$ (b), and $\boldsymbol{H} \perp \hat{z}$ (c). The zero energy corresponds to the Fermi energy and z-axis is set to be normal to the wall. Here, we use $k_F \xi = 5$. In (b) and (c), the Zeeman field is set to be $\gamma H/2 = 0.25\Delta_0$.

Thermodynamic signature:
Power law heat capacity
Thermal conductivity

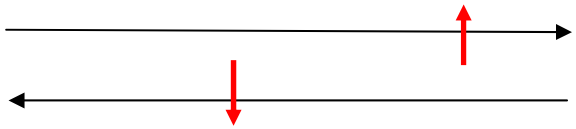


Distinctive feature of Majorana: spin-orbit coupling

S-B Chung and S-C Zhang Phys. Rev. Lett. 103, 235301 (2009)

QSH and TI analogue

$$H = v_F \boldsymbol{\sigma}.(\hat{\mathbf{z}} \times \mathbf{p})$$

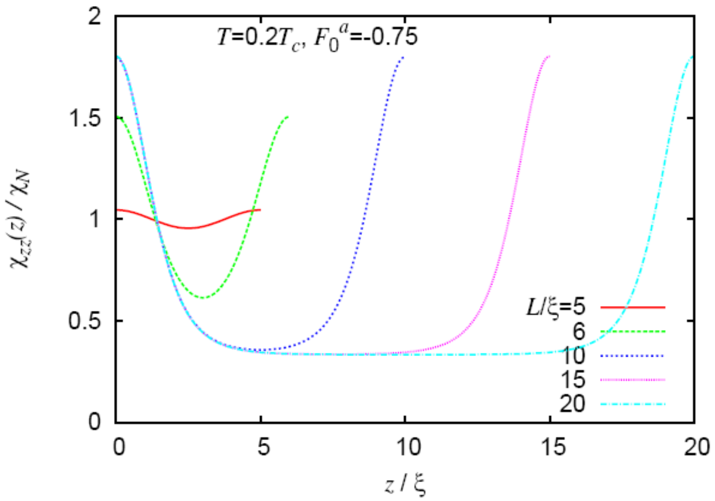


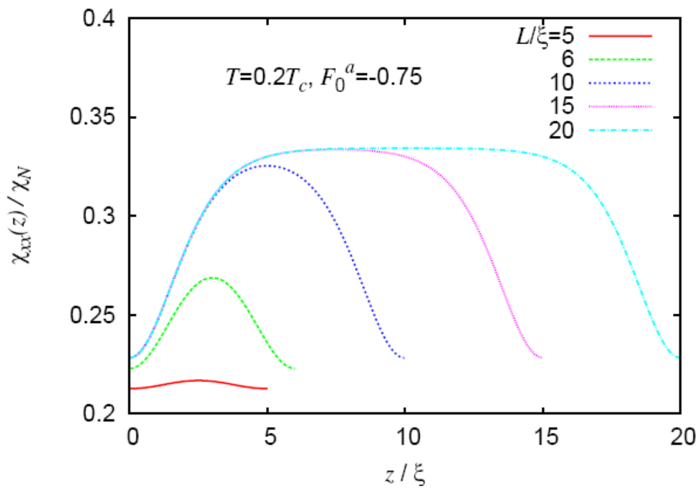
$$E = ck \qquad c = \frac{\Delta}{p_F}$$

They move slowly, at half Landau critical velocity

Nagato, Higashitani, Nagai JPSJ 78, 123604, 2009
Volovik JETP Lett. 2010
Kawakami, Tsutsumi, Ichioka, Machida

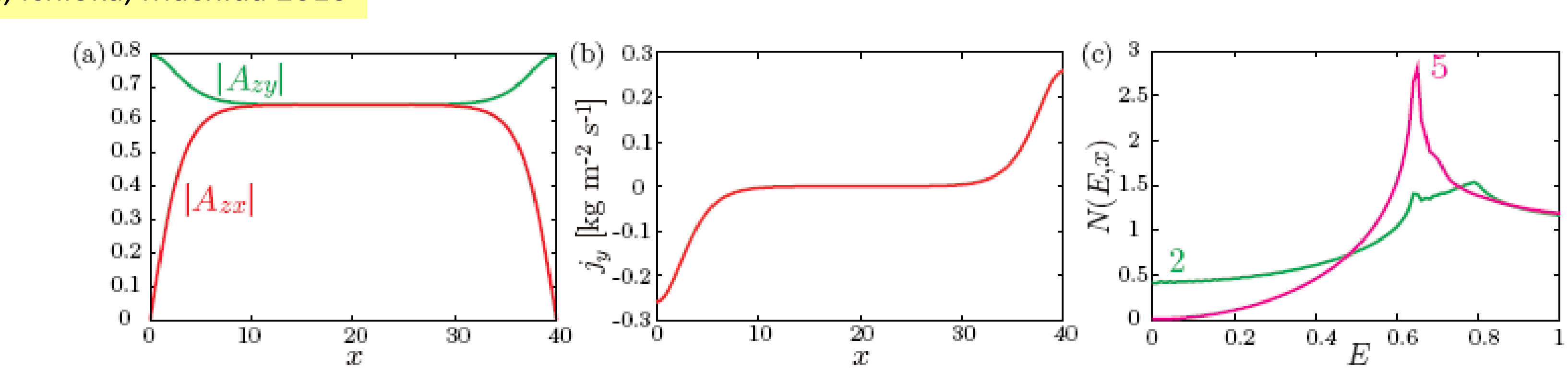
→ Anisotropy of spin susceptibility





Edge states in A phase

Tsutsumi, Ichioka, Machida 2010

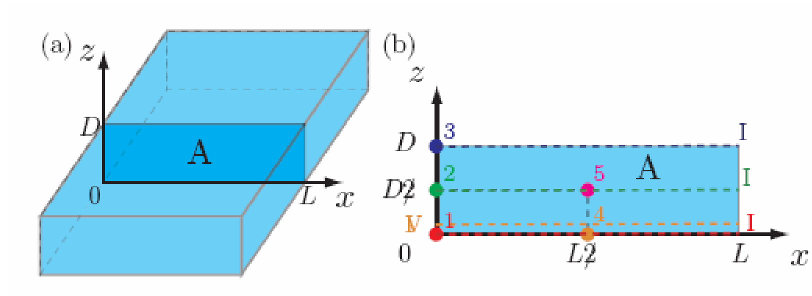


For specular walls:

No surface states on top and bottom surface of slab

Polar phase at edges

Counter-propagating mass currents



Hence intrinsic angular momentum in edge state of a mono-domain sample of ^{3}He-A.
Create mono-domain by cooling under rotation.
Detect edge state gyroscopically in the quietest vibrational environment in the world.

Also: can we stabilize HQVs in mono-domain sample?

Conclusion

Rob Bennett

Lev Levitin

Andrew Casey

New direction……Quantum nanofluidics

Confinement as a control parameter (+ pressure, magnetic field)

Explore richness of p-wave superfluid film

Search for new order parameters

Surface and edge excitations….majorana search

Develop new experimental probes