Helium in restricted geometries: some “nuts and bolts”

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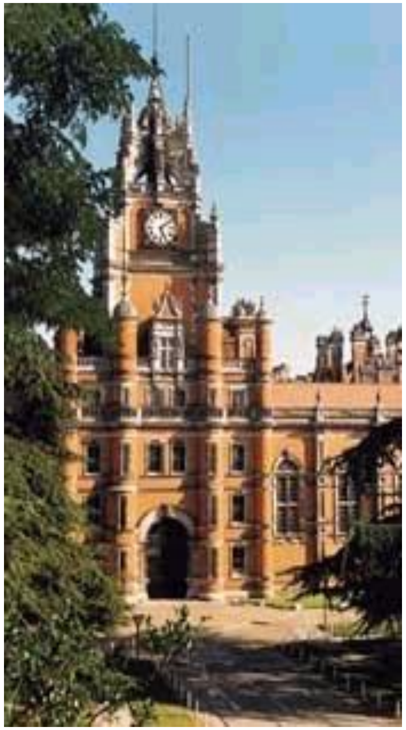


Material: ^{3}He superfluid ^{3}He phases; normal ^{3}He

Confine ^{3}He in precisely engineered nanofluidic geometries

Superfluid ^{3}He: topological superfluid surface and edge states

Hybrid nanostructures

Control parameters: Confinement , structure, surface, symmetry breaking fields

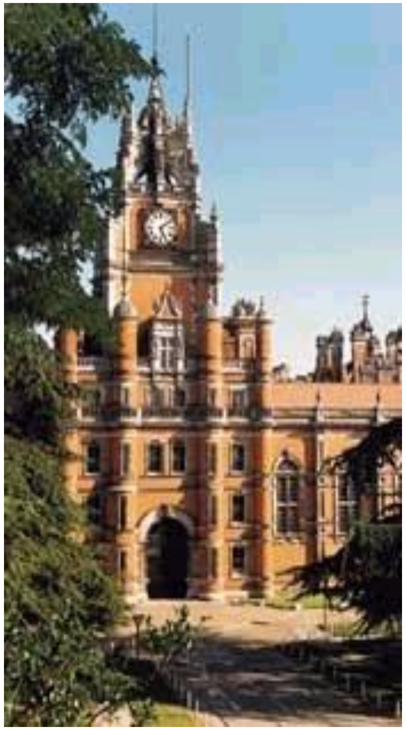
EMP

EPSRC Engineering and Physical Sciences Research Council

PTB

CORNELL UNIVERSITY FOUNDED A.D. 1865

CNF Cornell NanoScale Science and Technology Facility



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Control parameters: Confinement , structure, surface,
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Restricted geometry (context): porous medium (sinter, vycor, porous gold, nanotubes, aerogel, thin films (including atomically layer films on graphite)

Helium in restricted geometries: some “nuts and bolts”

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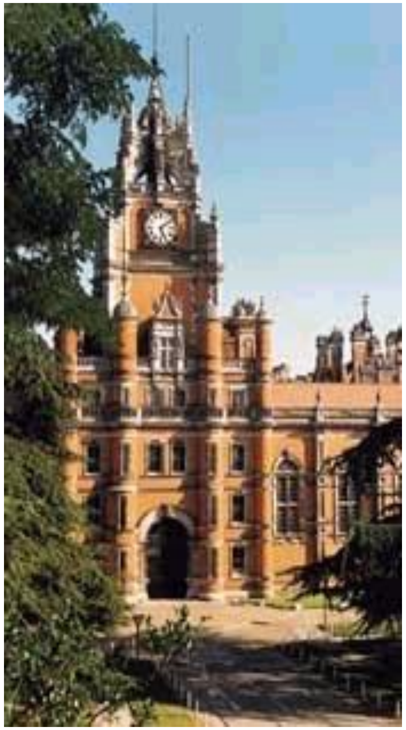

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Hybrid nanostructures

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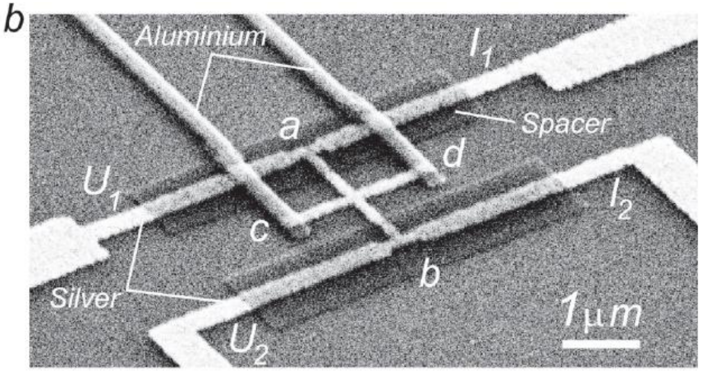
Topological mesoscopic superfluidity

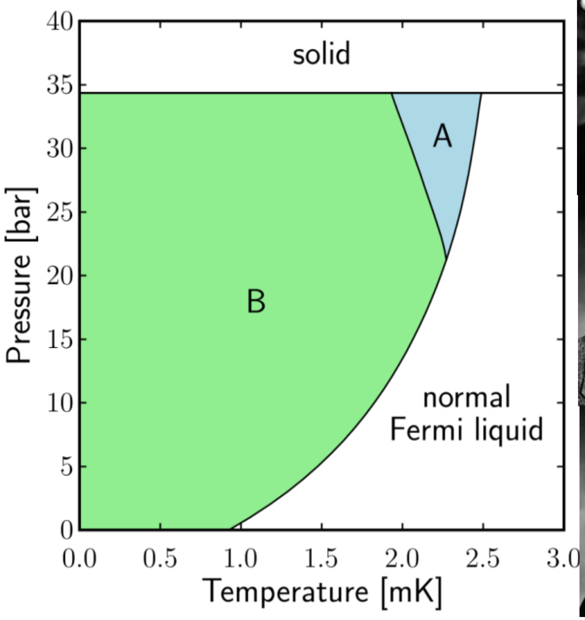
EMP

EPSRC
Engineering and Physical Sciences Research Council

PTB

b





Superfluid ^{3}He as a model material:

Perfect purity

Simple spherical Fermi surface $SO(3)_L \times SO(3)_S \times U(1) \times T \times P$

Isotropic normal state (but size quantization on confinement)

No crystal lattice

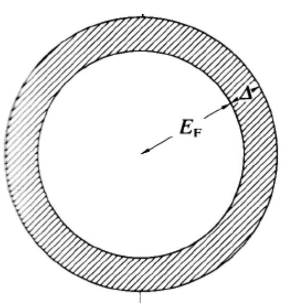
Pairs have L=1, S=1

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

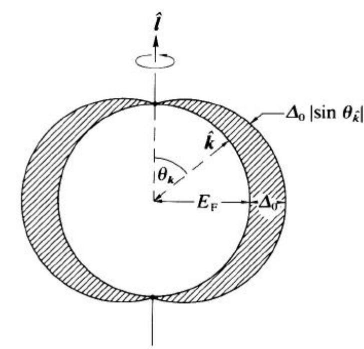
Anderson-Brinkman-Morel

(A) phase

Chiral superfluid

Breaks TRS

Stabilised by strong coupling at high p

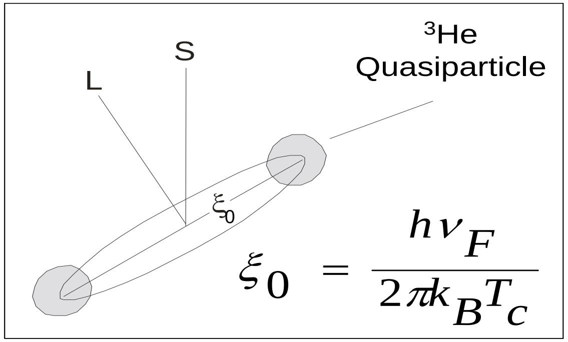


$$\mathbf{\Delta}(\mathbf{p}) = \Delta\left[(-\hat{p}_x + i\hat{p}_y)\left|\uparrow\uparrow\right\rangle + (\hat{p}_x + i\hat{p}_y)\left|\downarrow\downarrow\right\rangle + \hat{p}_z\left|\uparrow\downarrow + \downarrow\uparrow\right\rangle\right]$$

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

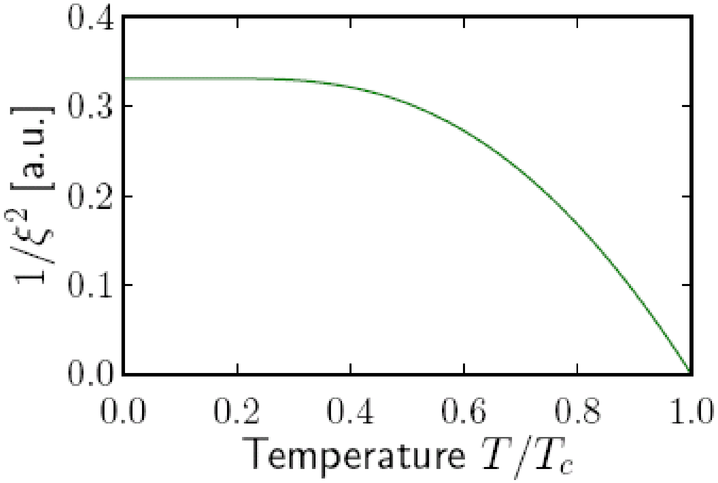
Coherence Length

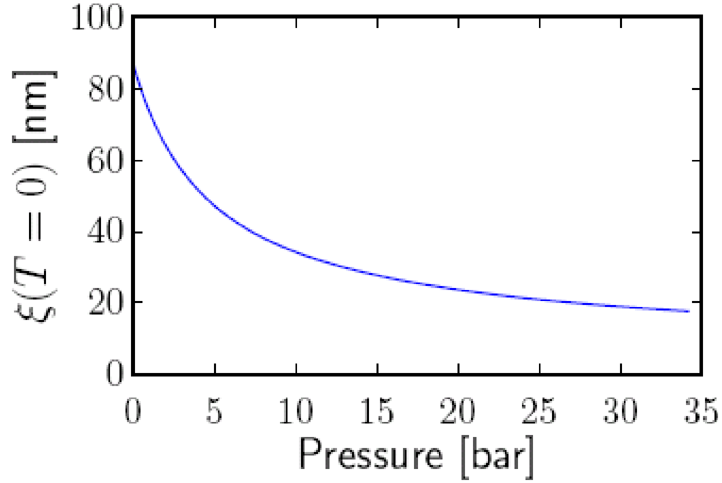
Sets the required length scale of confinement



$$\xi_0 = \frac{h v_F}{2\pi k_B T_c}$$

Zero temperature coherence length
[Cooper pair diameter]

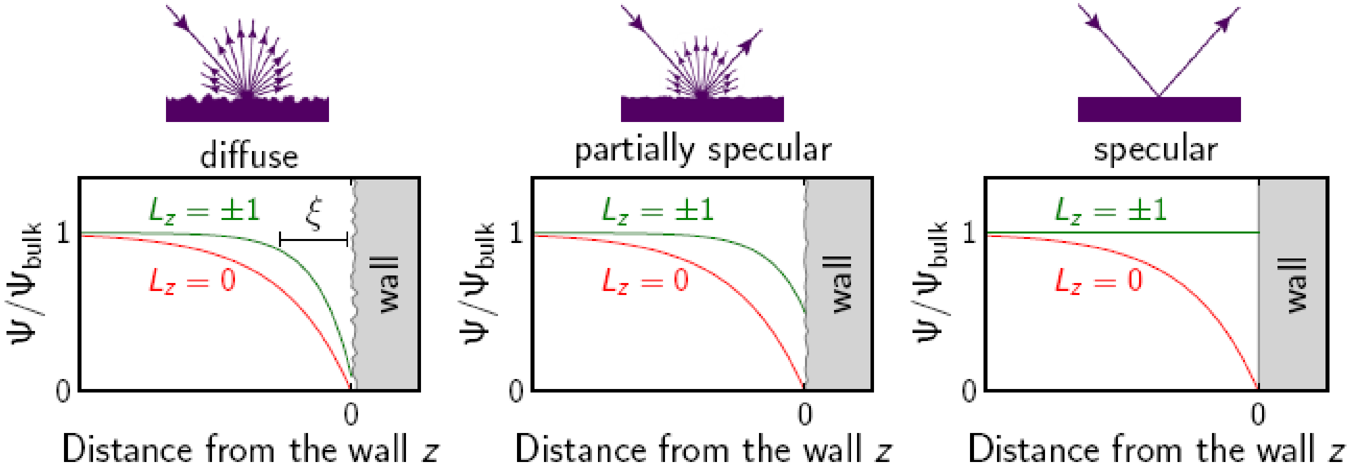




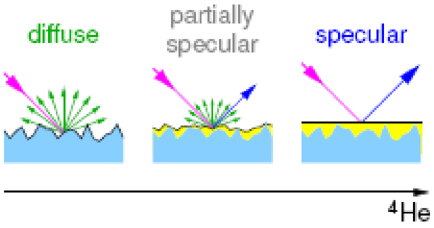
$$\xi_T = \left[\frac{7\zeta(3)}{20}\right]^{1/2} \frac{\hbar v_{\mathrm{F}}}{2\pi T_c^{\mathrm{bulk}}} \left(1 - \frac{T}{T_c^{\mathrm{bulk}}}\right)^{-1/2} = \frac{\hbar v_{\mathrm{F}}}{\Delta_{\mathrm{B}}(T)\sqrt{10}}.$$

Suppression of pairing depends on orientation of pair orbital angular momentum and can be tuned from diffuse to specular by coating surface (in situ) with a superfluid ^{4}He film

- Suppression of $\Psi_{L_z=\pm1}$ is determined by the nature of surface scattering [V Ambegaokar, *et al.*, *PRA* **9** (1974)]



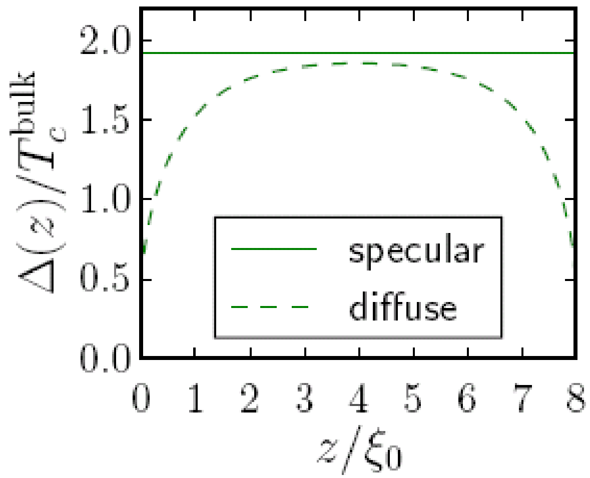
- Specular scattering is enhanced by ^{4}He preplating [DA Ritchie *et al.*, *PRB* **59** (1987), MR Freeman and RC Richardson, *PRB* **41** (1990)]



Order parameter distortion by surface: Implications for ^{3}He-A (chiral) and ^{3}He-B (time-reversal-invariant)

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

- Gap suppression is minimized by orienting $\hat{\mathrm{l}} \perp$ 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

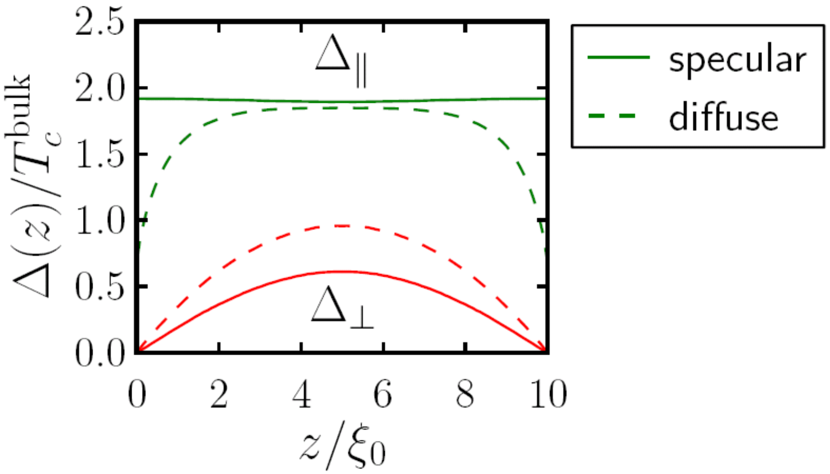


[AB Vorontsov and JA Sauls, *PRB* **68** (2003)]

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

- Planar distortion (spatially dependent)

$$A_{\mu m} = \Delta e^{i\varphi} R_{\mu m}$$



Strong gap anisotropy is induced by surface
Hence strong susceptibility anisotropy

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

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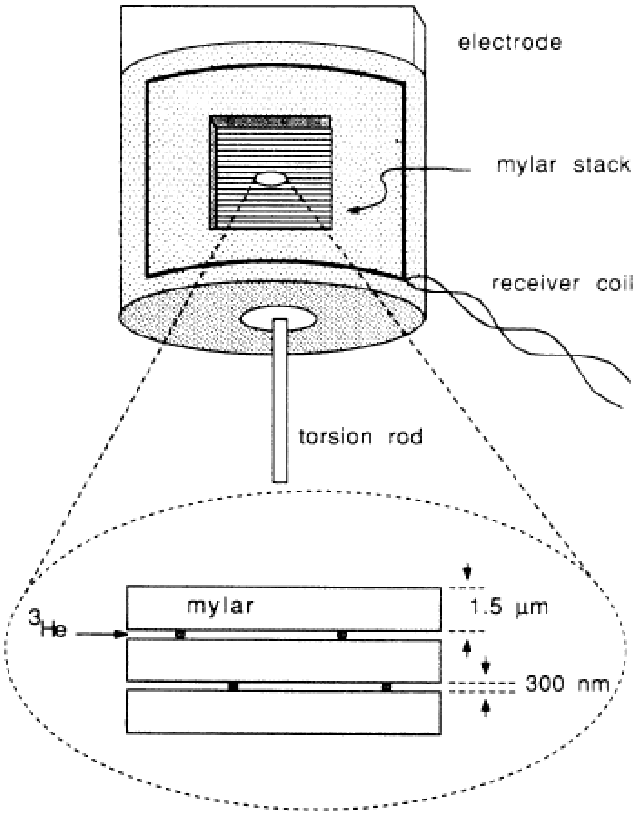
Cornell: "Size Effects in Thin Films of ^{3}He"

M.R.Freeman, R.S.Germain, E.V.Thuneberg and R.C.Richardson, PRL **60**, 596 (1988)



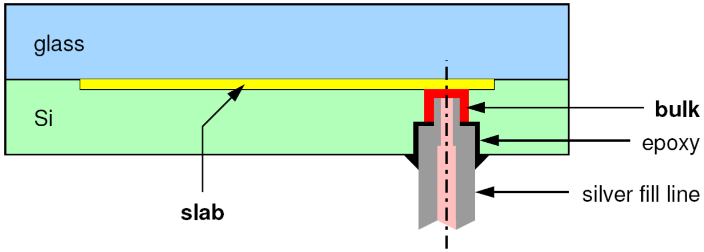
Large ensemble of slabs
Distribution of slab height, which is hard to characterize
Other inherent limitations

Challenges:

(1) controlled and well characterised confinement (single slab)

(2) High measurement sensitivity of NMR spectrometer

(3) Cooling ^{3}He in slab

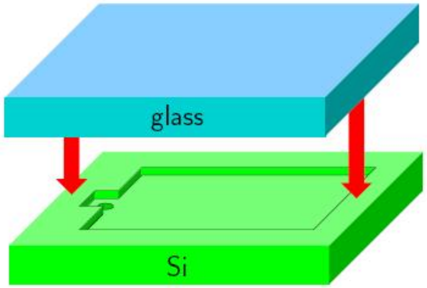


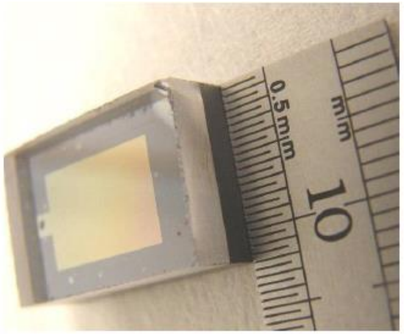
Our first attempt:

650 nm x 10 mm x 7 mm

Unsupported cavity

Cell walls 3 mm thick



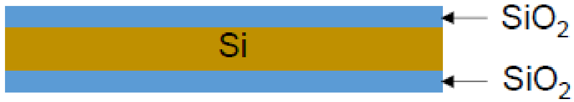


Glass (Hoya) anodically bonded to Si
Cavity fabricated in Si wafer

Defining the cavity

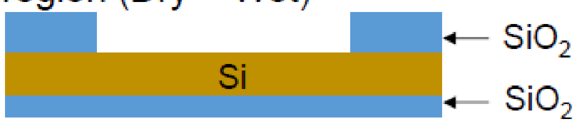
Fabrication Process Flow

1. Grow thick thermal oxide



2. Deposit more oxide by PECVD

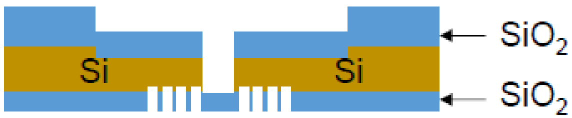
3. Etch the oxide in the cavity region (Dry + Wet)



4. Thermally oxidize the wafer

5. Using DRIE, etch a series of concentric circles around the fill line

6. Etch through the wafer to define the fill line hole



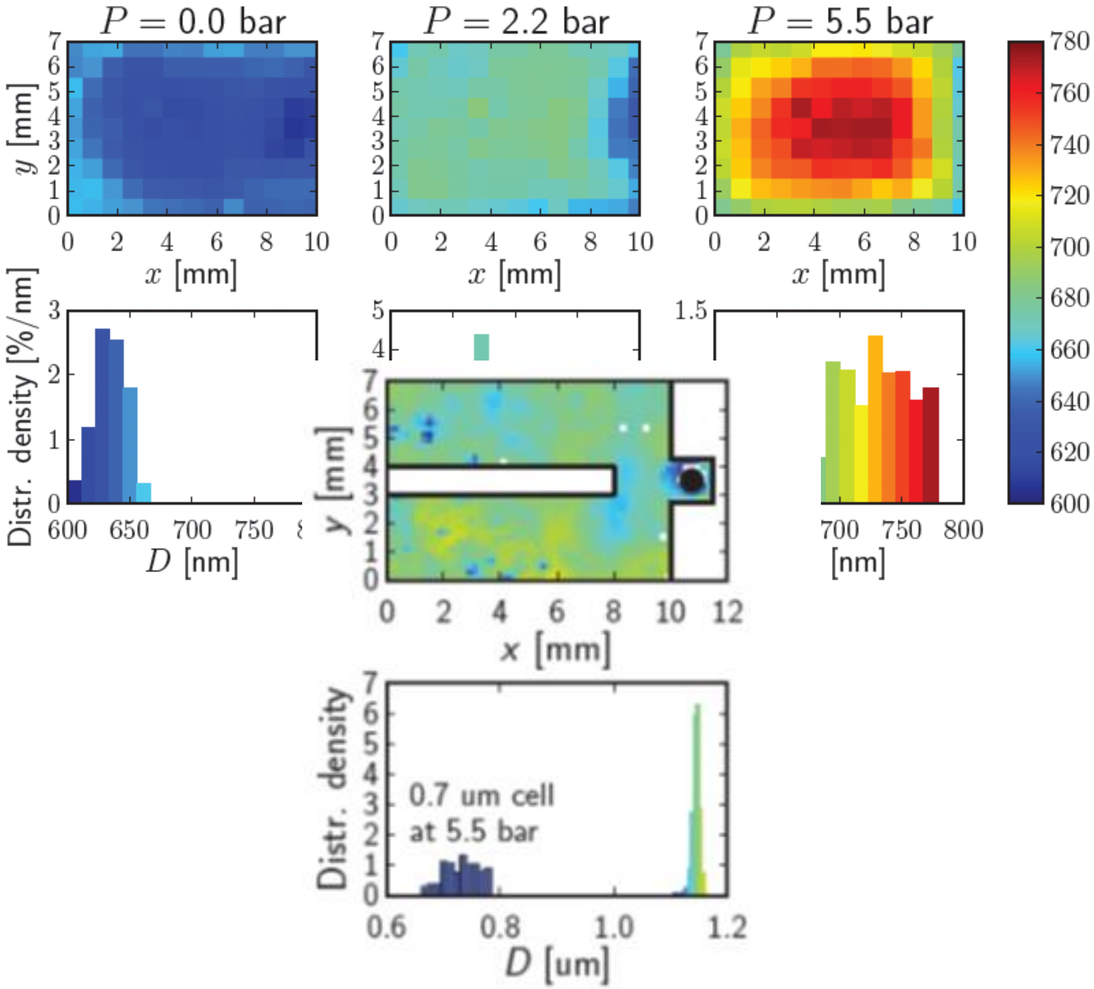
7. Remove all oxide using HF

8. Bond to a matching glass piece

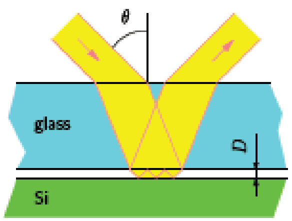
9. Deposit silver film on the outside surfaces (Sputter Deposition)

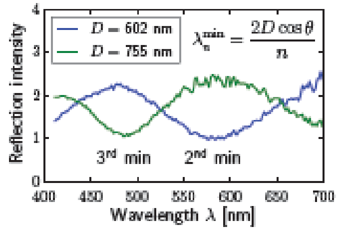
Characterize nanofluidic confinement (1)

Optical characterization of cavity profile at low temperatures



Optical Thickness Measurement

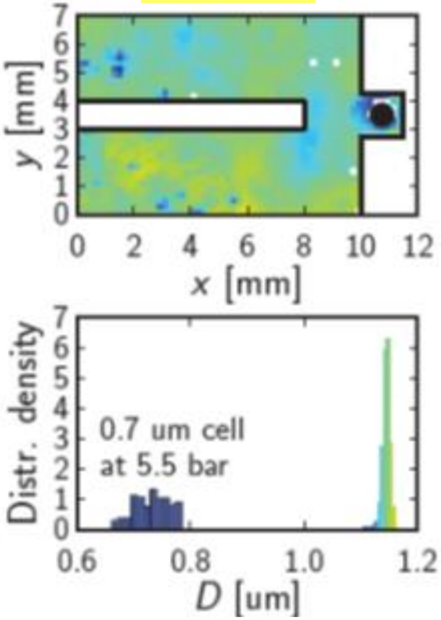


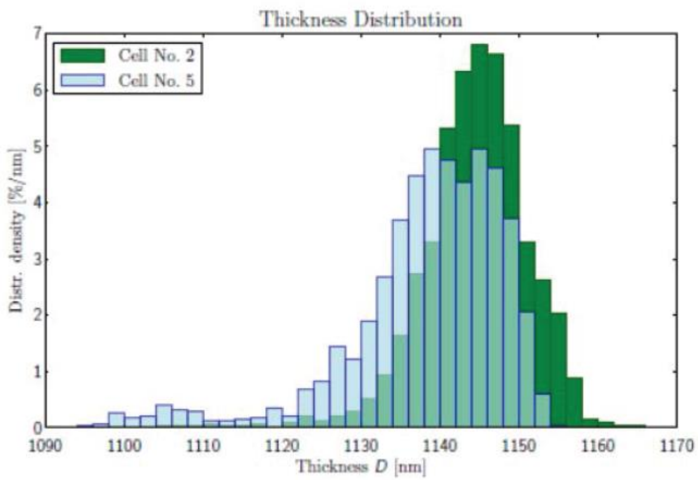


- Interferometry in the cavity cooled below 7 K.
- Analyse reflection of ⌀0.3 mm collimated white light beam
- Bowing due to differential thermal contraction. Stops at 30 K
- T-indep. inflation under pressure. 28 nm/bar in the centre

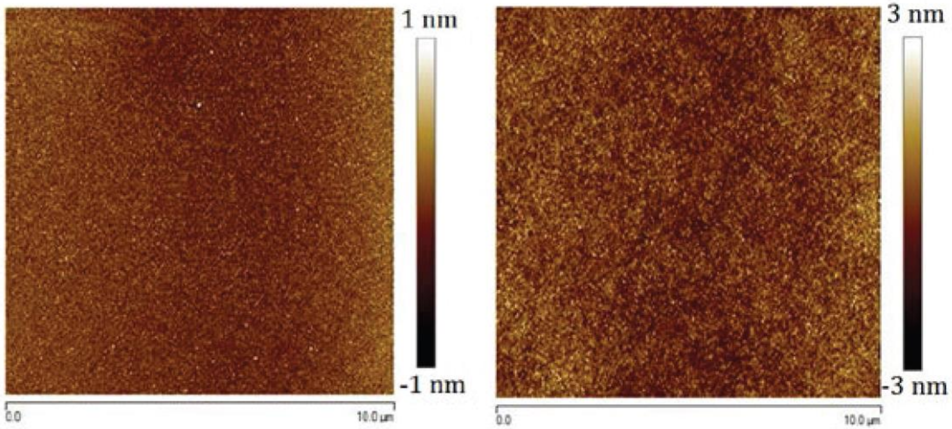
Characterize nanofluidic confinement (2)

optical

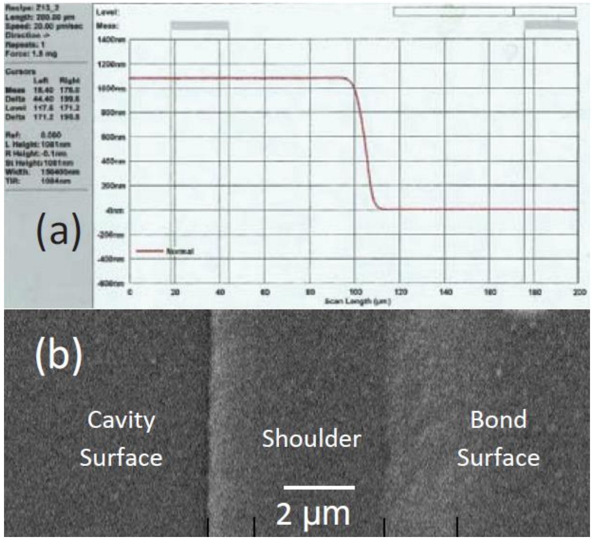




AFM



profilometer



Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

L. V. Levitin,[1] R. G. Bennett,[1*] A. Casey,[1] B. Cowan,[1] J. Saunders,[1†] D. Drung,[2] Th. Schurig,[2] J. M. Parpia[3]

Science **340**, 841 (2013)

ULT + confinement + NMR

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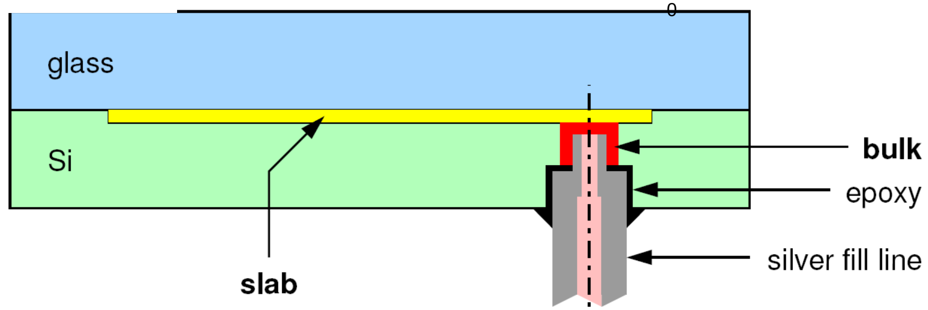
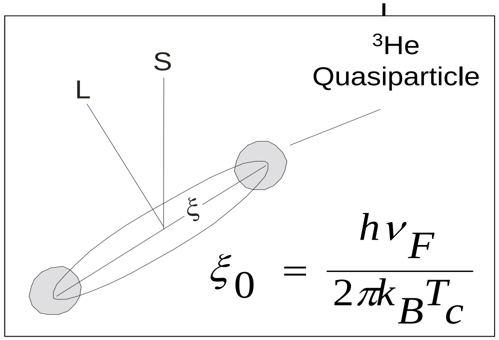
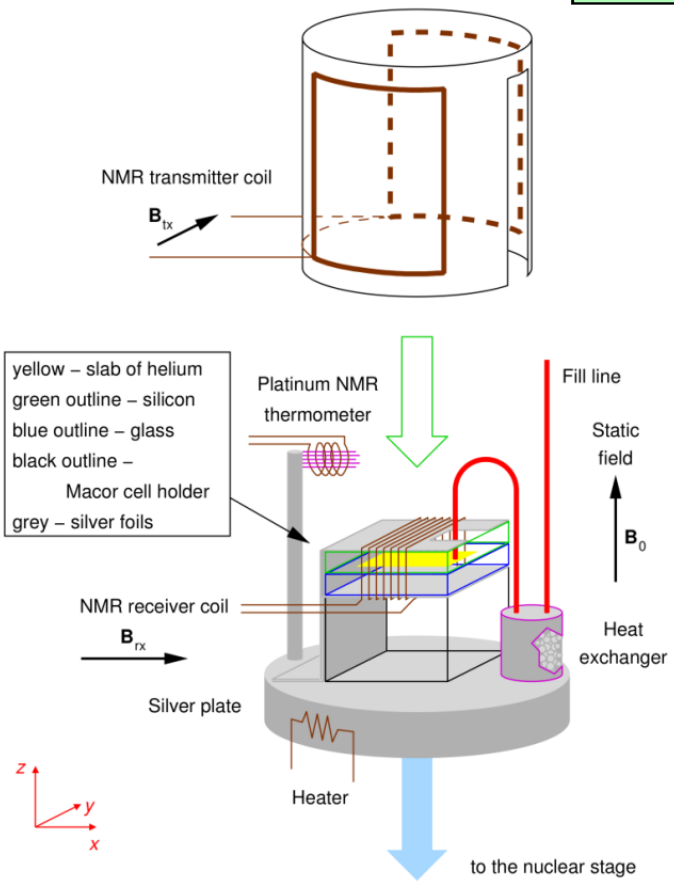






J. Low Temp. Phys. **175**, 667-680 (2014)

L. V. Levitin · R. G. Bennett · A. Casey · B. Cowan · J. Saunders · D. Drung · Th. Schurig · J. M. Parpia · B. Ilic · N. Zhelev

Study of superfluid ^{3}He under nanoscale confinement

A new approach to the investigation of superfluid ^{3}He films

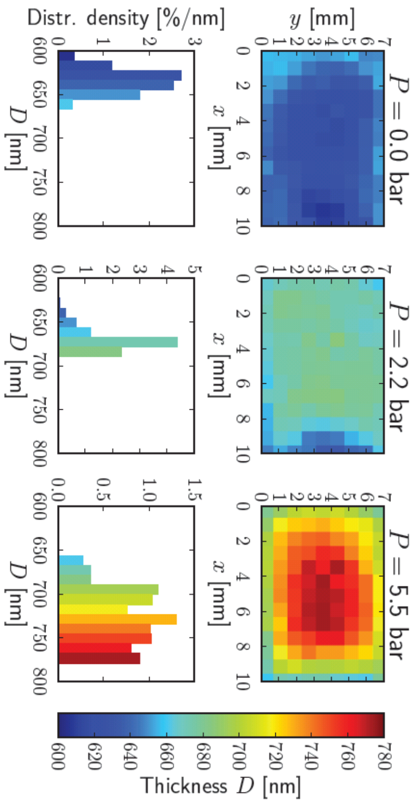
Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

Science AAAS

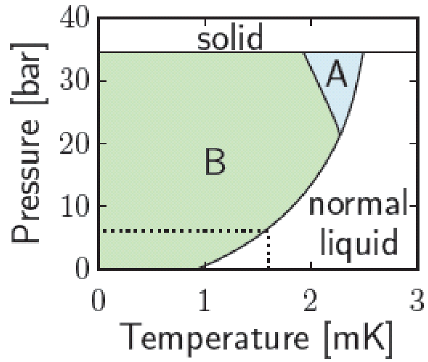
L. V. Levitin,[1] R. G. Bennett,[1*] A. Casey,[1] B. Cowan,[1] J. Saunders,[1†] D. Drung,[2] Th. Schurig,[2] J. M. Parpia[3]

Science **340**, 841 (2013)

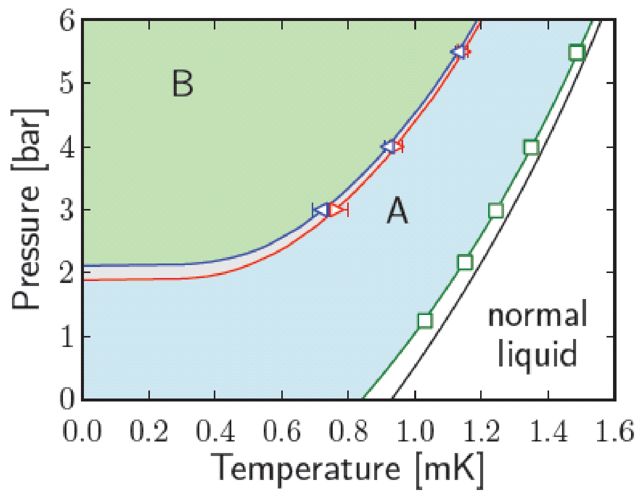
D = 0.7µm



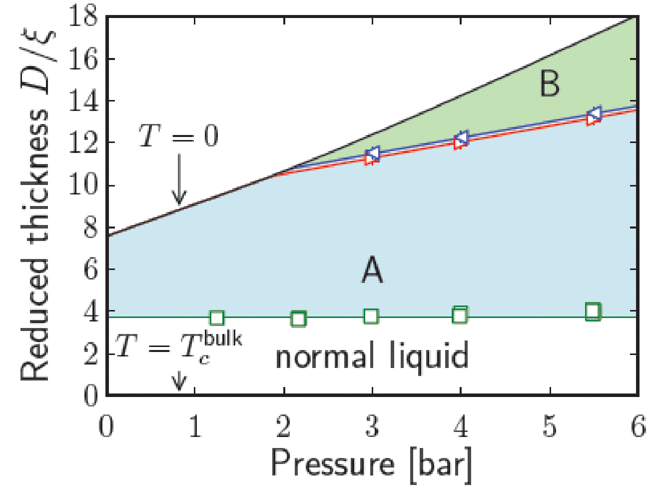
Bulk ^{3}He:



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

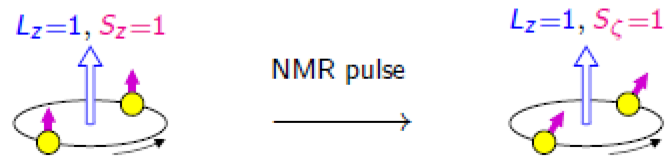


Fingerprint order parameter by NMR

NMR on superfluid ^{3}He in a (small) nutshell

The nuclear spin is the S=1/2 spin of the ^{3}He fermion

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



- NMR frequency shift [AJ Leggett, *Ann. of Phys.* 85 (1974)]

$$\Delta f = f - f_L \propto \Delta^2$$

Additional torque from coherent nuclear dipole-dipole energy of pairs

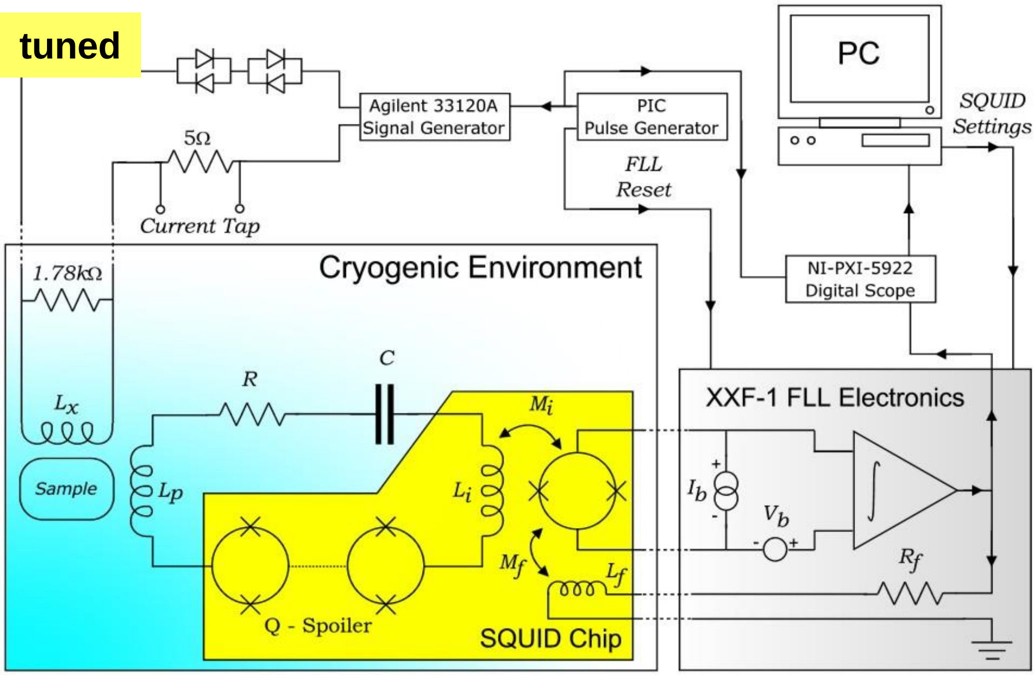
Measurements

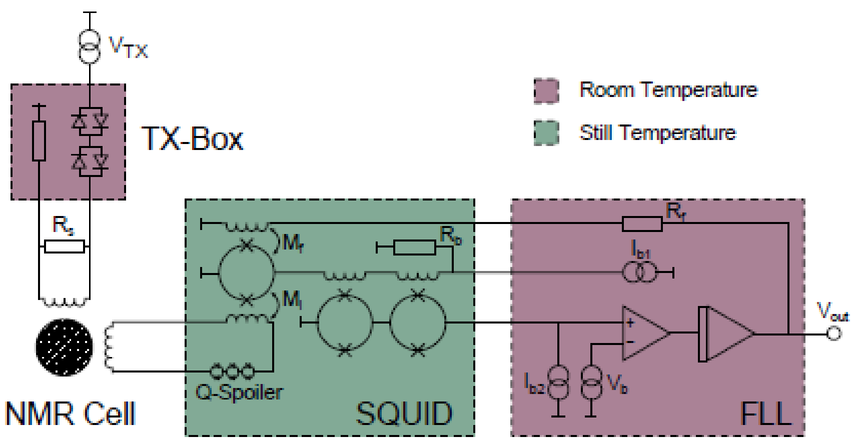
- Map the phase diagram with small tipping angle ($\beta \sim 1^\circ$) pulses
- Phase identification and order parameter characterisation with large pulses: $\Delta f = \Delta f(\beta)$

This is **very different from NMR studies of quantum materials**, where the focus is on Knight shift and T_1.
There the nuclei are bystanders (to different degrees);
hyperfine coupled to the strongly correlated electron system.
Also in ^{3}He, no Meissner effect (or skin depth), so probe throughout the sample.

New technique: SQUID NMR (Tuned or Broadband)

tuned

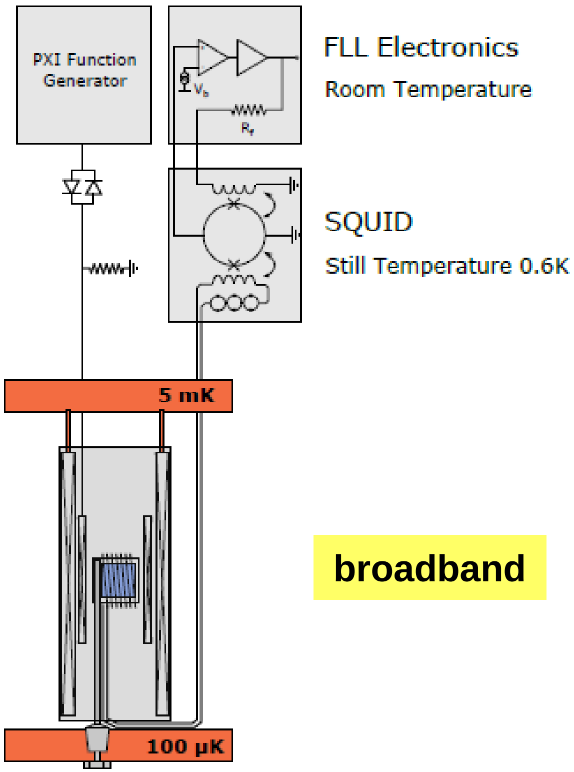




APPLIED PHYSICS LETTERS 91, 262507 (2007)

A nuclear magnetic resonance spectrometer for operation around 1 MHz with a sub-10-mK noise temperature, based on a two-stage dc superconducting quantum interference device sensor

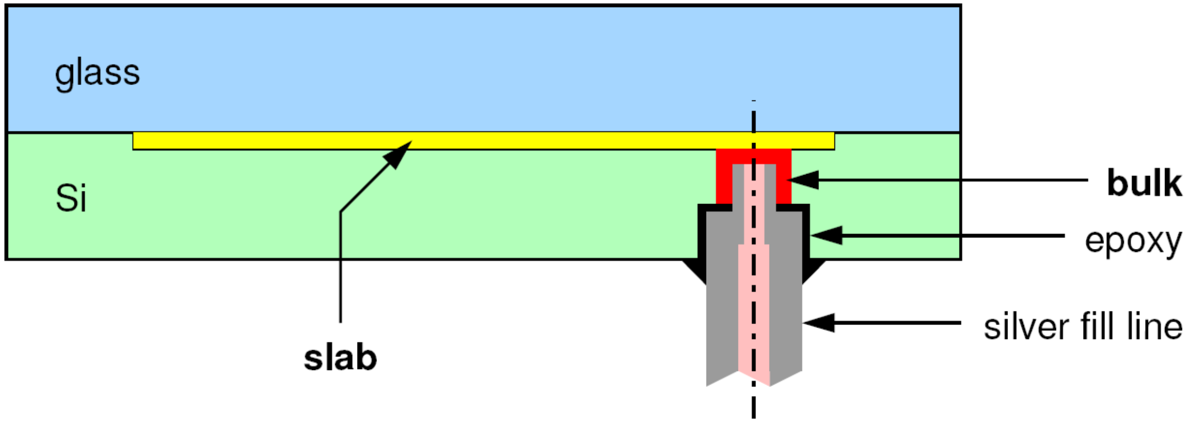
L. V. Levitin, R. G. Bennett, A. Casey,[a] B. P. Cowan, C. P. Lusher,[b] and J. Saunders
Department of Physics, Royal Holloway University of London, Egham, Surrey TW20 0EX, United Kingdom
D. Drung and Th. Schurig
Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, D-10587 Berlin, Germany

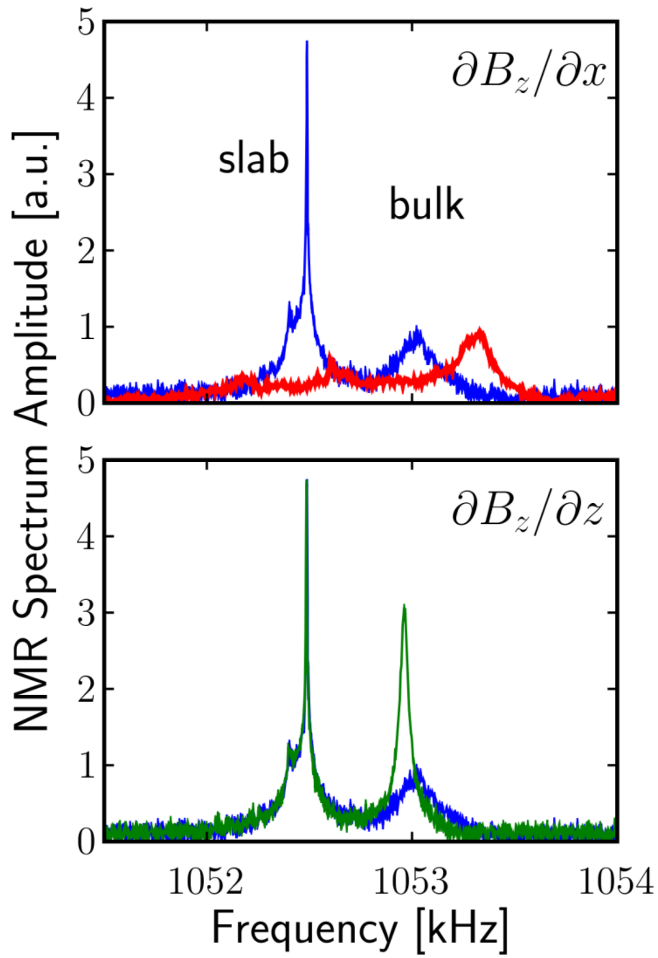


broadband

NMR signals from slab: simple 1D imaging to decode signal

Distinguish slab and bulk contributions to signal



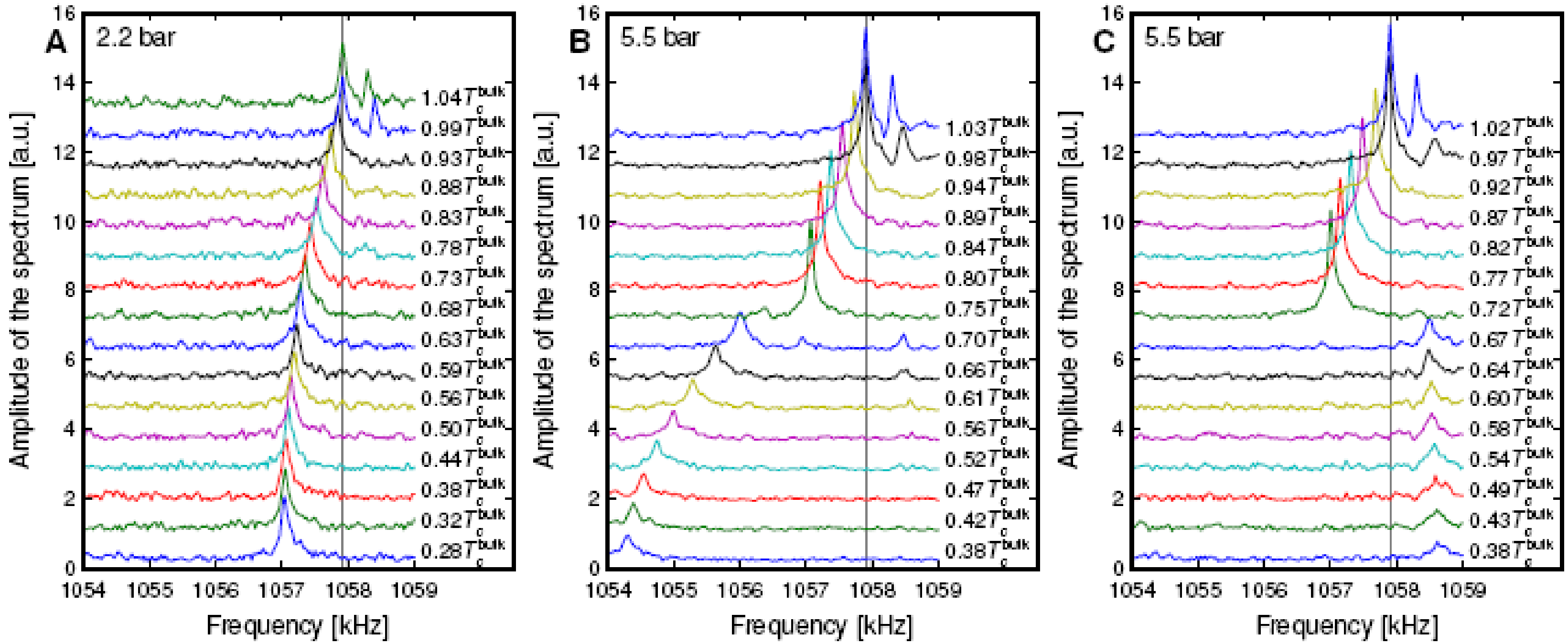


Apply field gradients, along or perpendicular to slab to clearly **image** slab and bulk signal

1D magnetic resonance imaging (zeugmatography)

Gallery of NMR signals from superfluid

D = 0.7μm



Negative frequency shift
[A-phase]

Negative frequency shift
[A-phase]
Transition to another state
Also with negative shift
[planar-distorted B phase]

Negative frequency shift
[A-phase]
Transition to another state
Now with positive shift
[planar-distorted B phase]

Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

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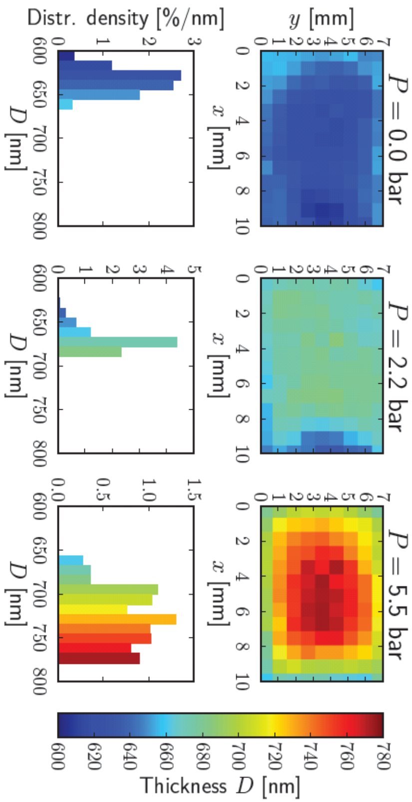
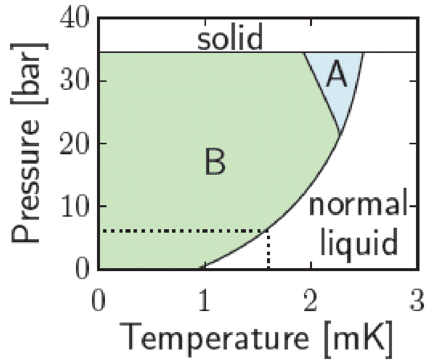
Science **340**, 841 (2013)

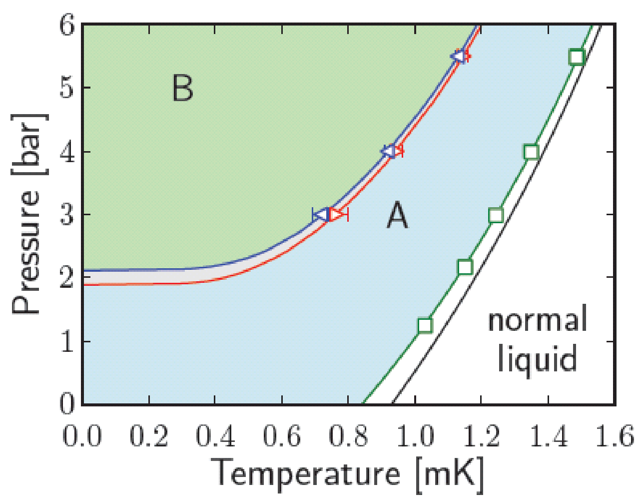
D = 0.7μm



Bulk ^{3}He:



0.7 μm Slab:



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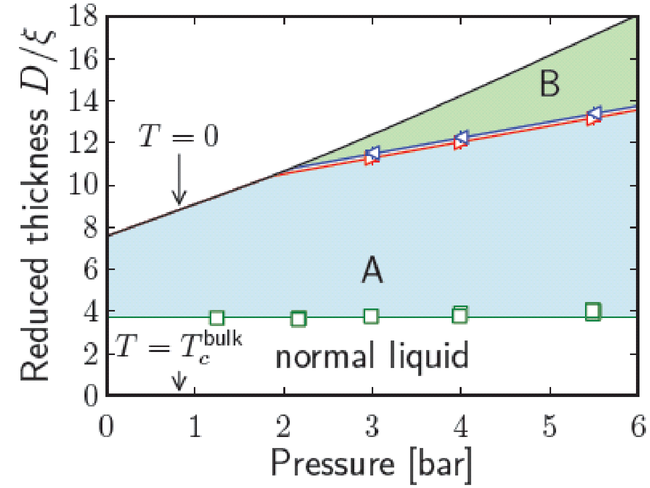


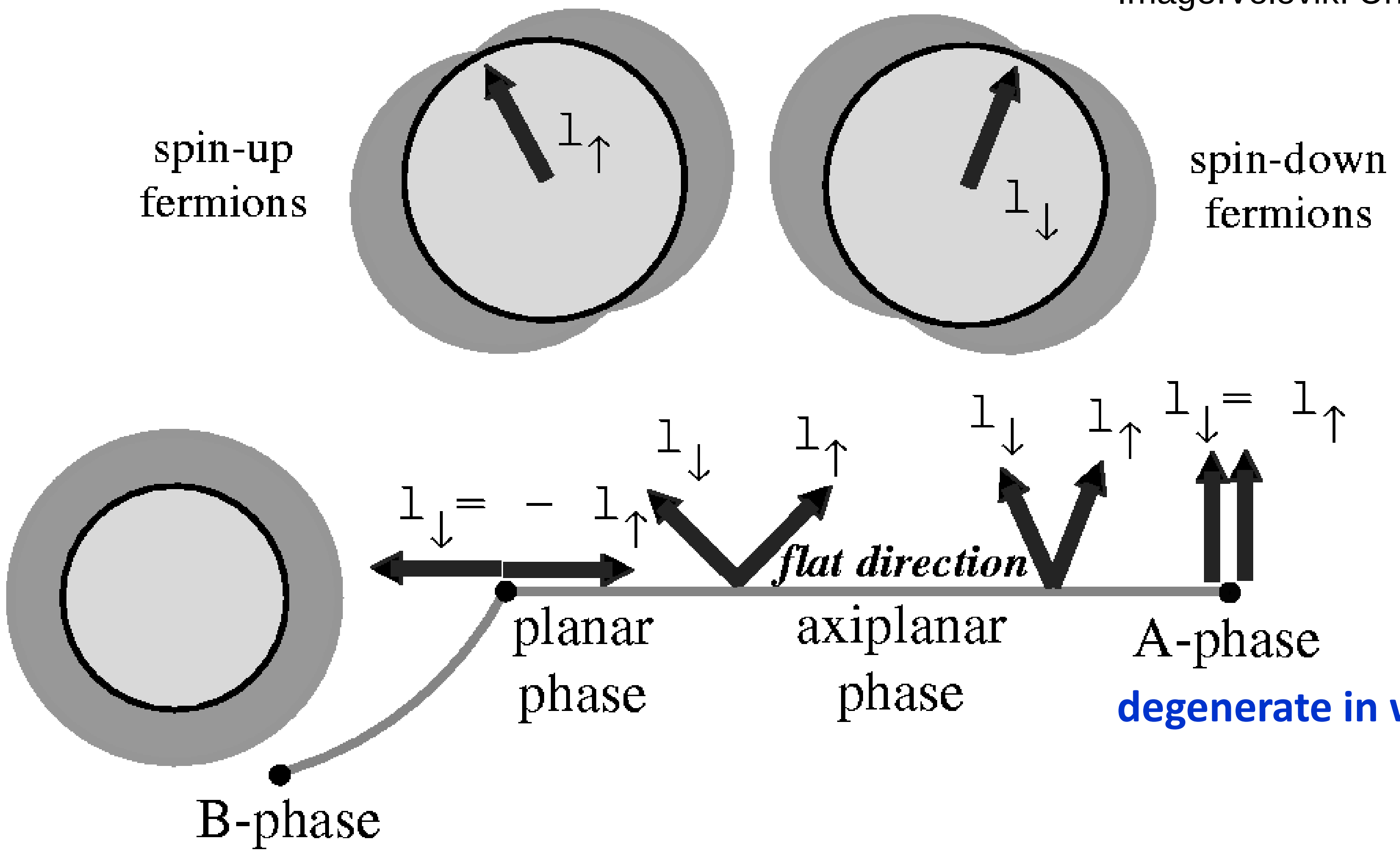
"order parameter sculpture by confinement"

1. **Spatially modulated superfluid phase ("stripe-phase")**
   new phase predicted to arise
   spontaneously in a slab geometry near A-B boundary

2. **Does chiral A phase survive as we increase confinement?**
   planar vs A phase
   approaching the quasi-2D limit

3. **New states arising from structured confinement**

Image:Volovik: Universe in a ³He droplet



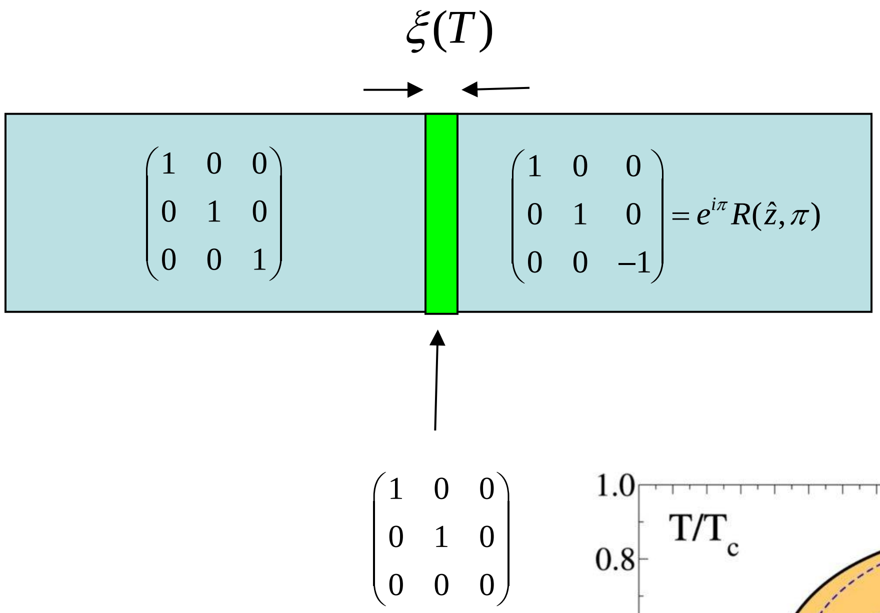
degenerate in weak-coupling limit

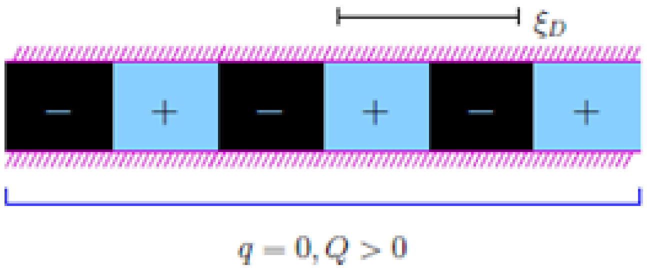
$$\mathbf{\Delta(p)} = \Delta\left[(-\hat{p}_x + i\hat{p}_y)\left|\uparrow\uparrow\right\rangle + (\hat{p}_x + i\hat{p}_y)\left|\downarrow\downarrow\right\rangle + \hat{p}_z\left|\uparrow\downarrow + \downarrow\uparrow\right\rangle\right]$$

A vs Planar phase = Chiral vs Time reversal invariant

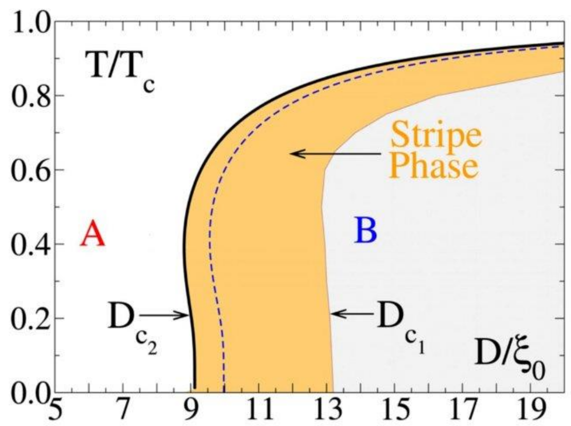
"order parameter sculpture by confinement"

1. Spatially modulated superfluid phase ("stripe-phase")





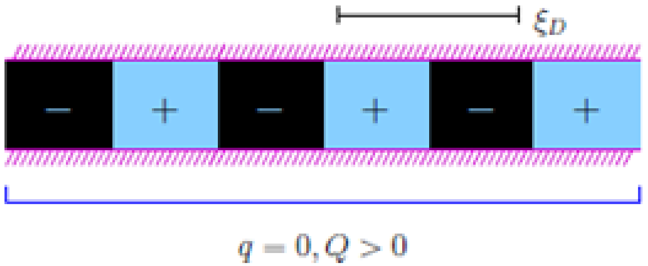
Analogue of FFLO superconductor:
Sought in organic and heavy fermion superconductors and fermionic ultracold atoms



Stripes: signature in non-linear NMR

Averages of components of order parameter define:

$$\overline{q} = \frac{\langle \Delta_{\parallel}(\mathbf{r})\Delta_{\perp}(\mathbf{r})\rangle}{\langle \Delta_{\parallel}^2(\mathbf{r})\rangle}, \qquad \overline{Q} = \left[\frac{\langle \Delta_{\perp}^2(\mathbf{r})\rangle}{\langle \Delta_{\parallel}^2(\mathbf{r})\rangle}\right]^{1/2}$$

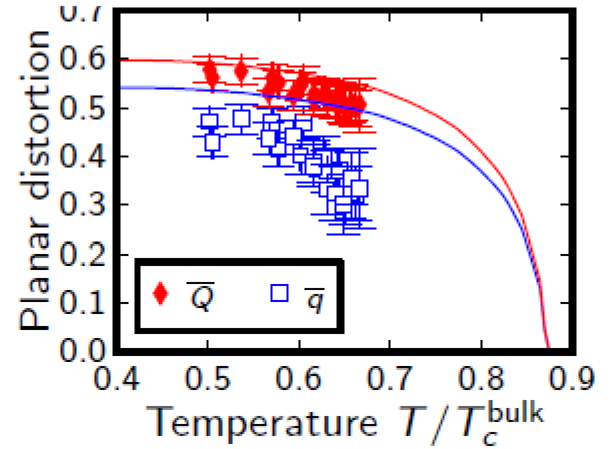


Determine these parameters from tip-angle dependent frequency shift

$$\Delta f_+(\beta) = \frac{\gamma^2 \lambda_{\mathrm{D}} N_{\mathrm{F}}}{10\pi^2 \langle \chi_{\parallel}\rangle f_L} \langle \Delta_{\parallel}^2 \rangle \qquad (5)$$

$$\times \begin{cases} 1 - \overline{q}^2 + 2(\overline{q}^2 - \overline{Q}^2)\cos\beta, & \text{at } \cos\beta > \cos\beta^*, \\ -1 - \overline{q} - 2(1 + 2\overline{q} + \overline{Q}^2)\cos\beta, & \text{at } \cos\beta < \cos\beta^*. \end{cases}$$

$$\Delta f_-(\beta) = -\frac{\gamma^2 \lambda_{\mathrm{D}} N_{\mathrm{F}}}{10\pi^2 \langle \chi_{\parallel}\rangle f_L} \langle \Delta_{\parallel}^2 \rangle [1 + 2\overline{Q}^2] \cos\beta. \qquad (6)$$



New measurements from 1 μm cavity

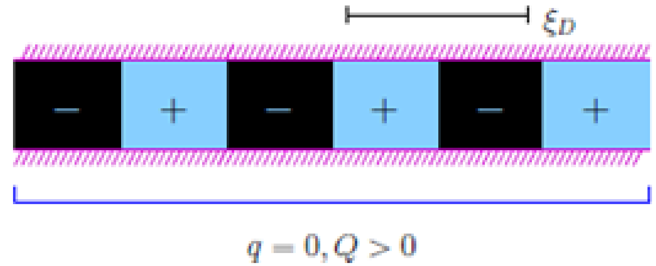
PRL **111,** 235304 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

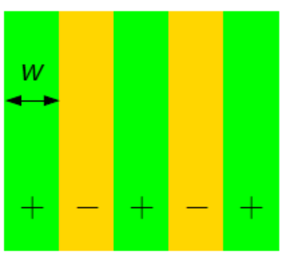
Surface-Induced Order Parameter Distortion in Superfluid ^{3}He-*B* Measured by Nonlinear NMR

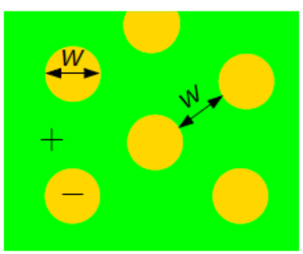
Lev V. Levitin,[1,†] Robert G. Bennett,[1,2,*] Evgeny V. Surovtsev,[3] Jeevak M. Parpia,[2] Brian Cowan,[1]
Andrew J. Casey,[1] and John Saunders[1]

Averages of components of order parameter define:

$$\overline{q} = \frac{\langle \Delta_{\parallel}(\mathbf{r}) \Delta_{\perp}(\mathbf{r}) \rangle}{\langle \Delta_{\parallel}^2(\mathbf{r}) \rangle}, \qquad \overline{Q} = \left[\frac{\langle \Delta_{\perp}^2(\mathbf{r}) \rangle}{\langle \Delta_{\parallel}^2(\mathbf{r}) \rangle} \right]^{1/2}$$

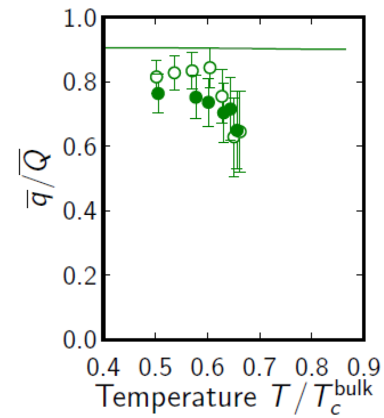


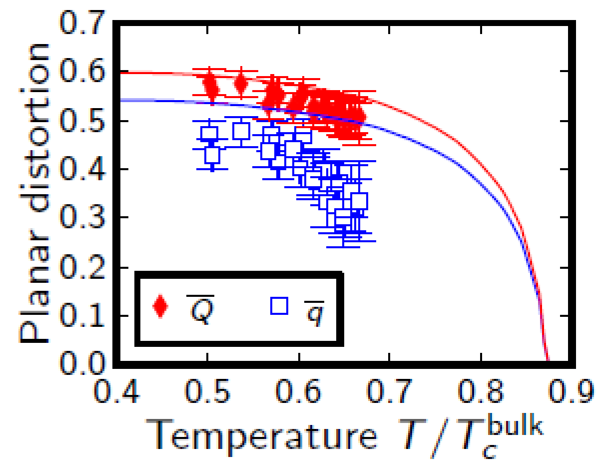




Stripes	Polka Dots
50% / 50%	≈ 75% / ≈ 25%
$\overline{q} = 0$	$\overline{q} \approx 0.5\overline{Q}$

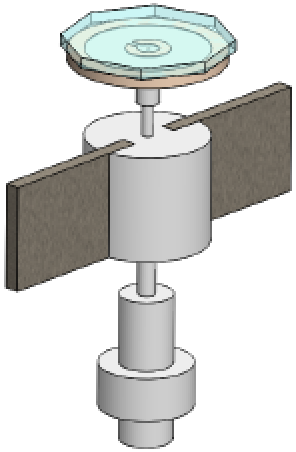
Two scenarios for spatial modulation



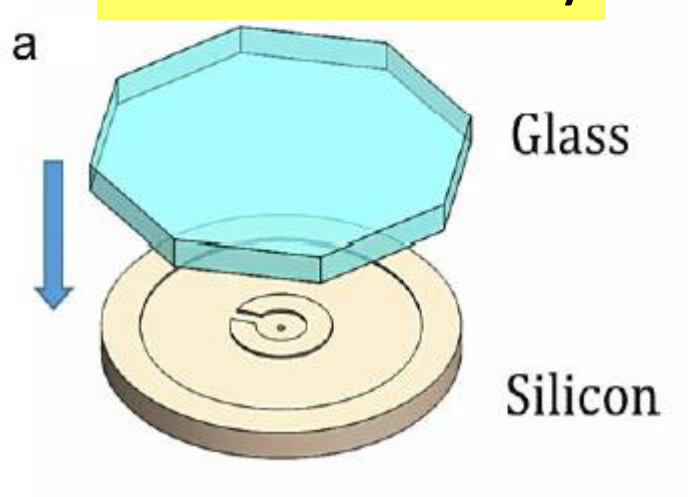


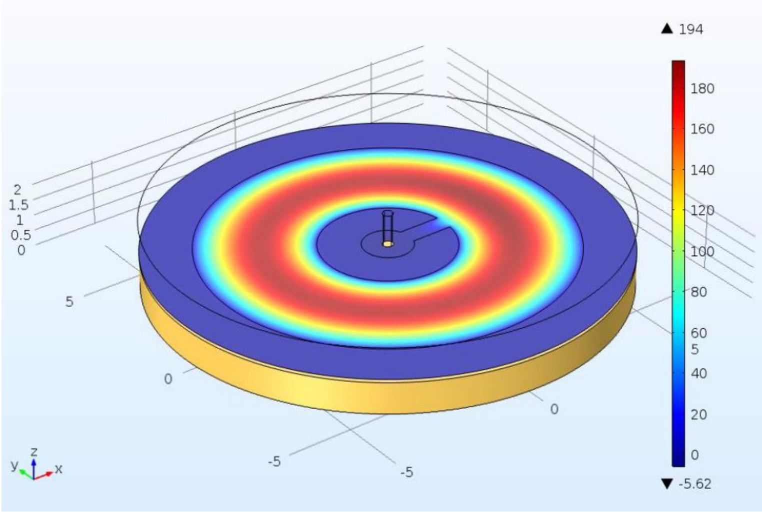
New measurements from 1 μm cavity

Torsion pendulum



1080 nm annular cavity



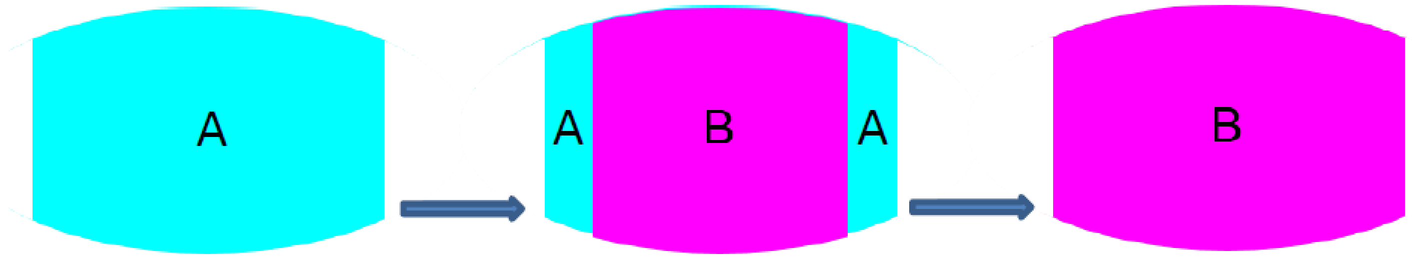


Bowing of cavity under ^{3}He pressure of 5 bar

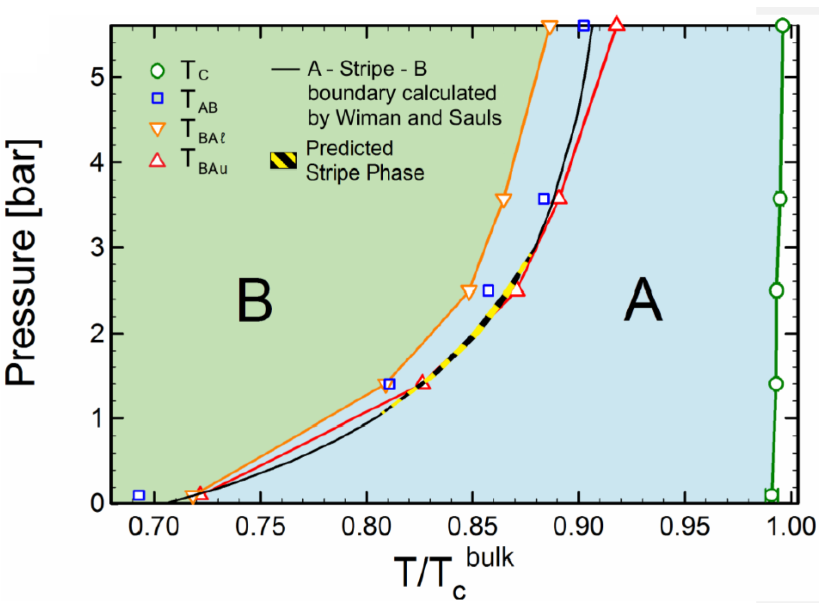
N. Zhelev, T. S. Abhilash, E. N. Smith, R. G. Bennett, X. Rojas, L. Levitin, J. Saunders, J. M. Parpia
In preparation

Nucleation of B phase: evidence for an intrinsic mechanism

Bowing creates clean "bottle" in which B phase nucleates



Supercooling of A phase is tiny (in bulk it is "huge")



Stability of stripe phase strongly influenced by strong coupling corrections

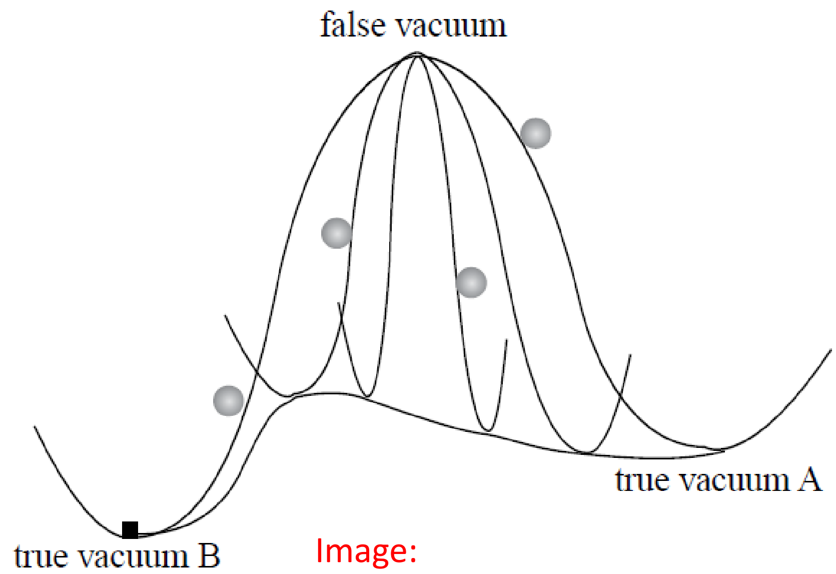


Image:
Bunkov: Phil. Trans, R. Soc. A. 366, 2821 (2008)

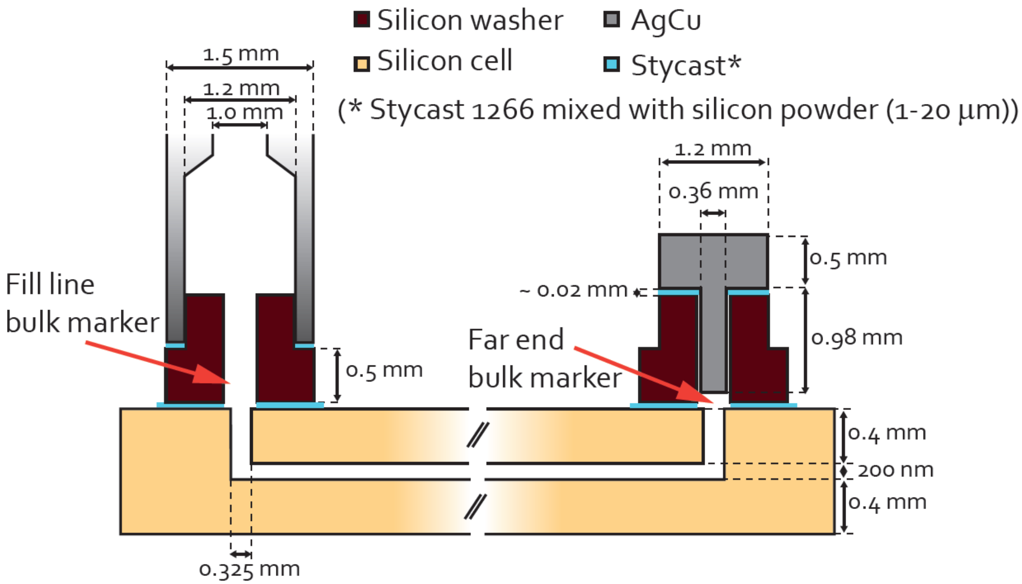
Under confinement energy landscape is changed by proximity of stripe phase.
Nucleation by "resonant tunnelling" hypothesis

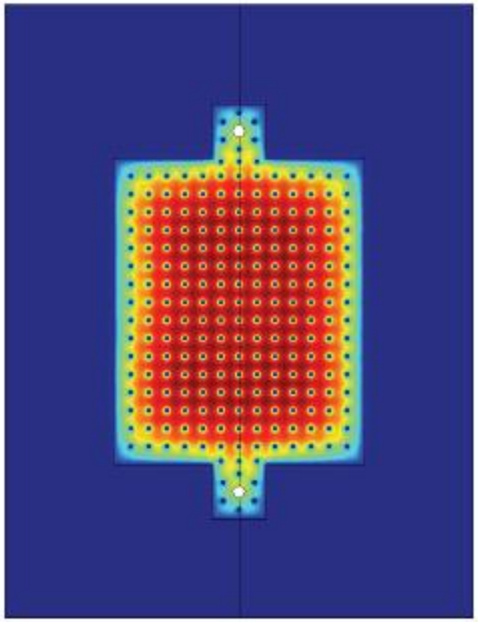
Does chiral A phase remain stable as confinement is increased?

Methodology

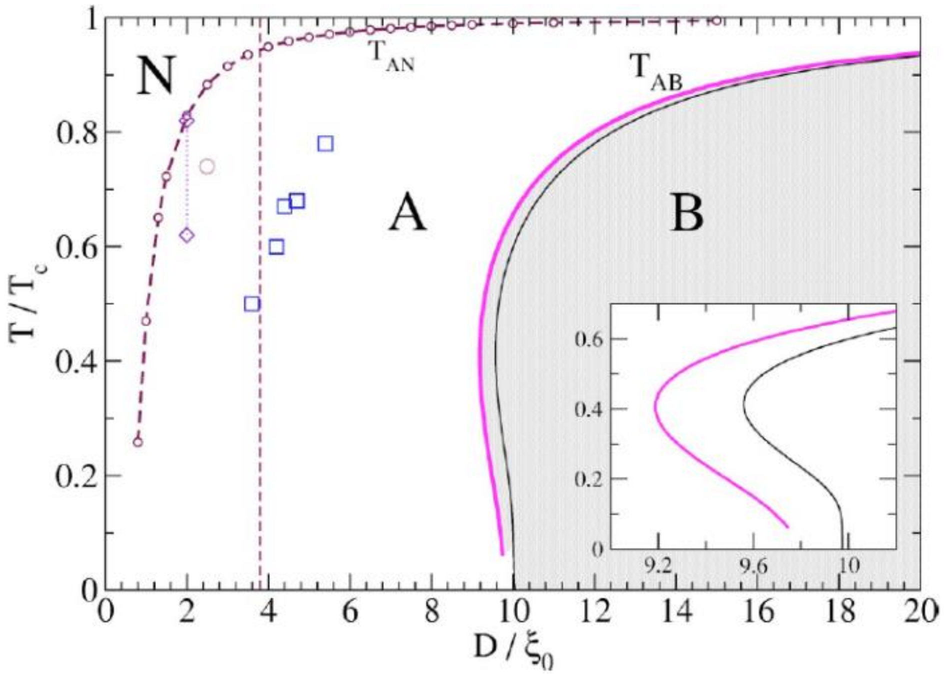
1. **Switch to direct wafer bonding of all silicon cells**
2. **Fully characterize T_c suppression**
3. **Create fully specular surfaces**
4. **Progressively increase confinement**

200 nm silicon cell





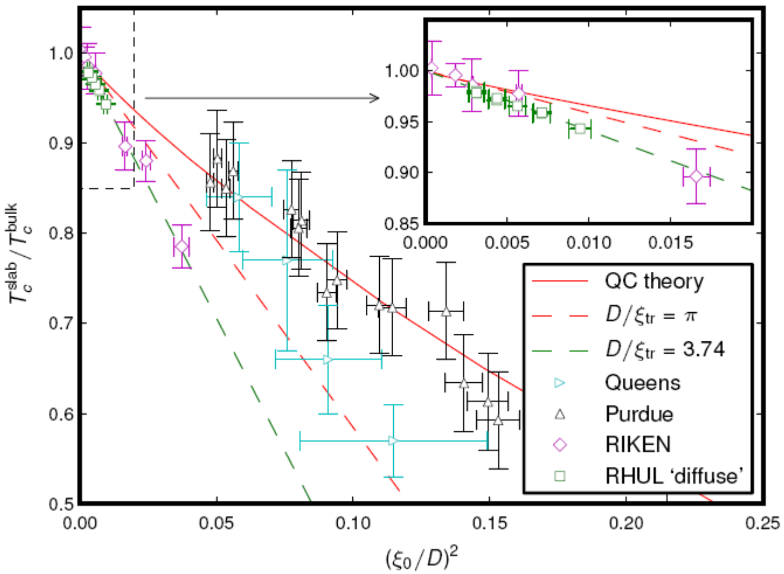
Suppression of T_c by diffusively scattering walls



theory

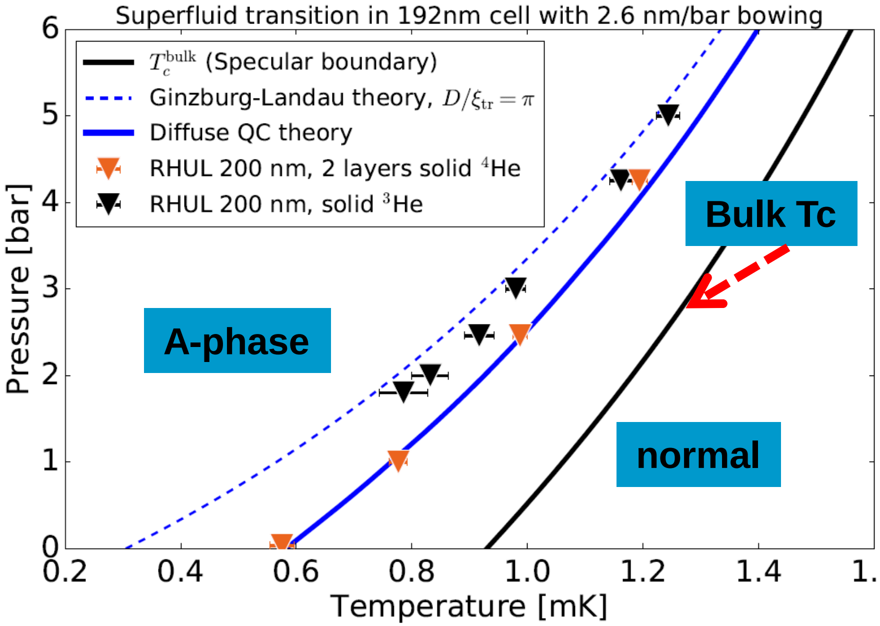
Previous experiment

Measurements on unsaturated films
(Film thickness difficult to characterise)

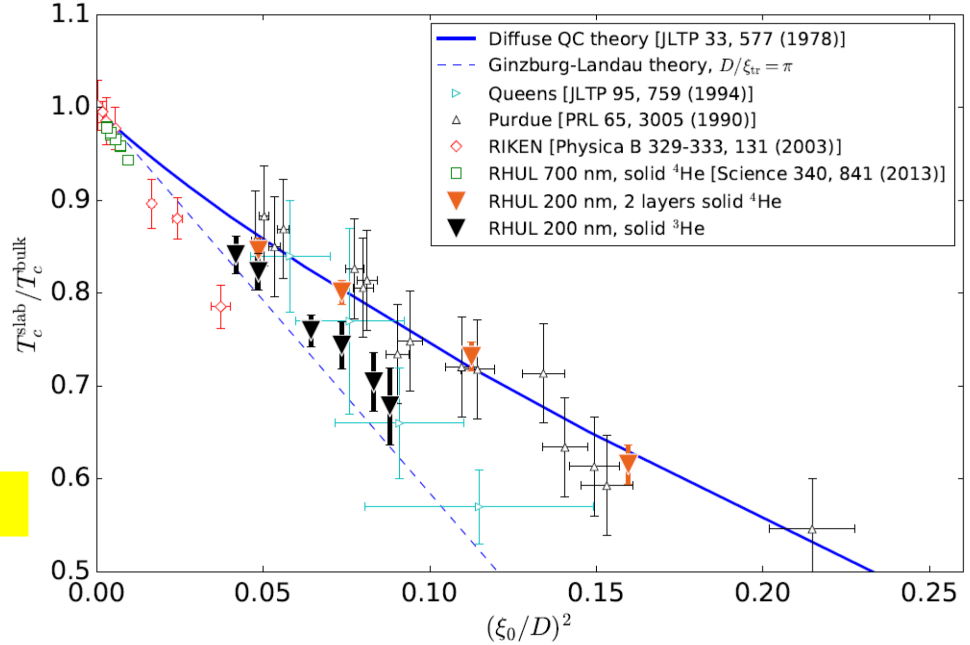


Suppression of *Tc*

Phase diagram



Suppression of slab T_c relative to bulk

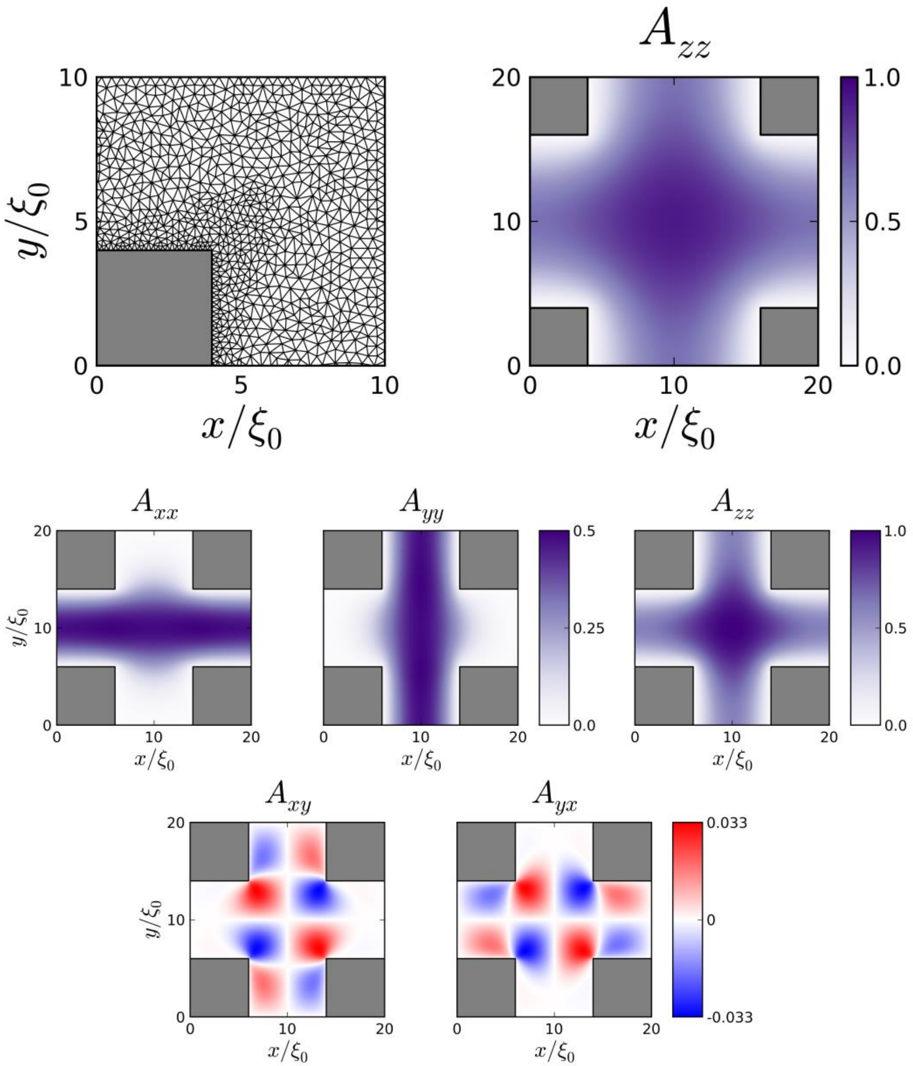


Spin dependent scattering with surface ^{3}He: enhance suppression of T_c

Diffuse scattering, surface solid ^{4}He: suppression agrees with quasi-classical theory prediction

T_c suppression should be eliminated by superfluid ^{4}He film on surface

Structured confinement: Order parameter sculpture (1)

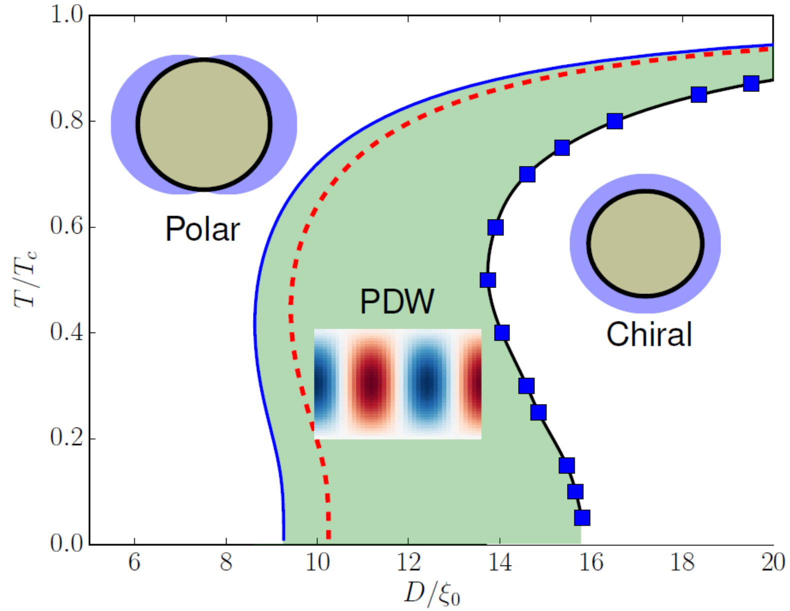


Near T_c ($0.9T_c$), only A_{zz} component survives. Polar Phase

At lower temperatures, A_{zz}, A_{xx}, A_{yy}, components and off diagonal elements appear .

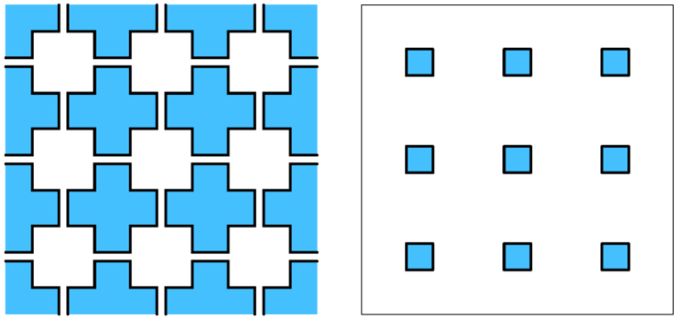
$B_{\square}$ Phase.

Structured confinement: Order parameter sculpture (2)

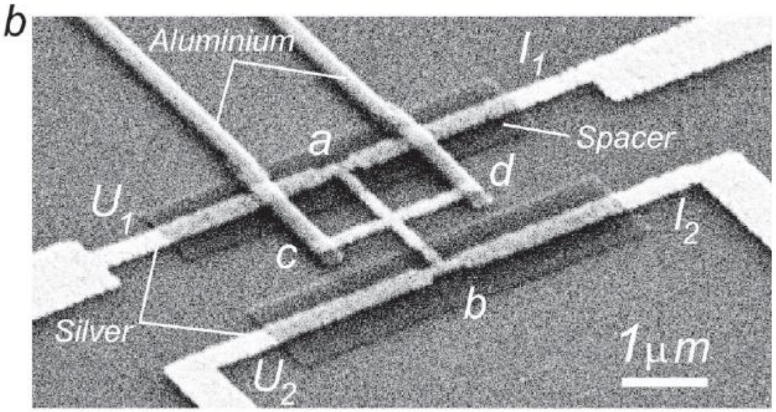


Predicted phase diagram in narrow channels
Polar Phase stabilised

Periodic array of channels and islands
Tune width of channel and height of island cavity

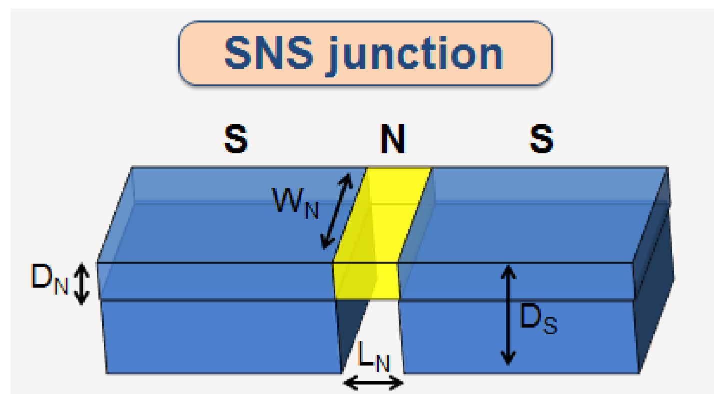


Hybrid nanostructures from topological superfluids



Hybrid metallic nanostructures
Petrashov and co-workers

Create clean SN interface <u>within the ^{3}He</u>, engineered by stepped confinement



…….the disorder story

Surface and edge states

Key outstanding problems in topological superfluidity/superconductivity:

Detect Majoranas
Detect Majorana-Weyl excitations
Demonstration of bulk-surface correspondence
Manipulation of Majoranas

Surface of ^{3}He-B: dispersing Majoranas [specular surface]:

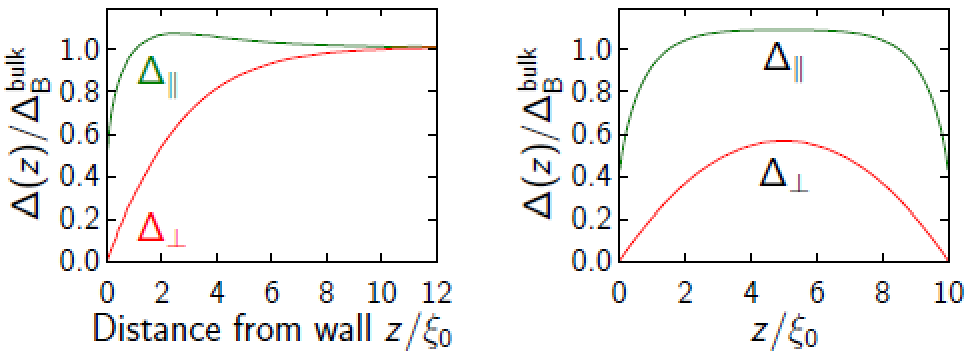
Superfluid density [Helmholtz resonator or torsional oscillator]
Heat capacity
Thermal conductivity
Detect helicity of surface states [ground state spin currents]
Probe non-local response arising from quantum entanglement of surface states
Coupling of surface excitations to gap [Anderson-Higgs] modes

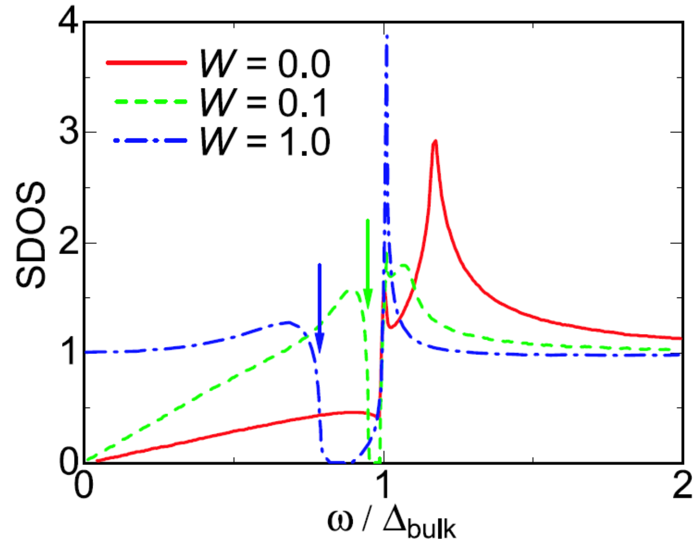
Chiral 3He-A: dispersing Majorana-Weyl edge states:

Ground state mass current [torsional oscillator gyroscope]
Thermal conductivity of edge states [QSH analogue]
Quantum Hall analogues in 2D A-phase [if stable]
Majorana at cores of half-quantum vortices [need to detect HQVs first!]

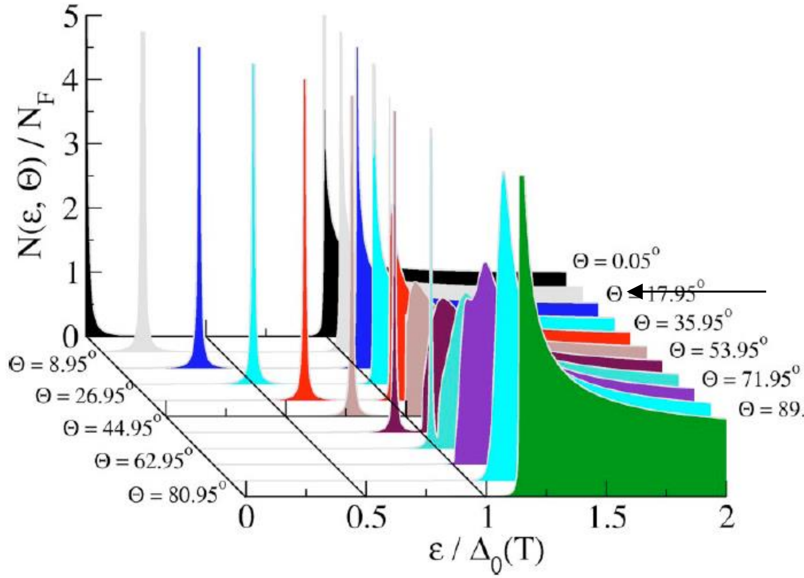
Suppression of ^{3}He-B order parameter at surface
Surface-bound excitations

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





Specular wall eliminates suppression of $\Delta_{\parallel}$

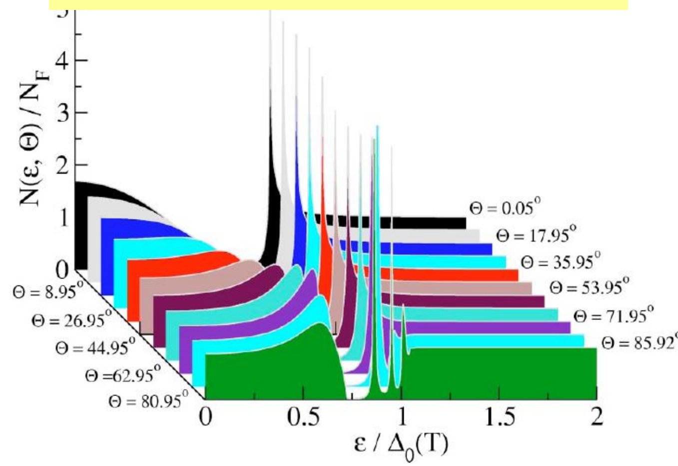


specular

diffuse

Quasi-classical theory

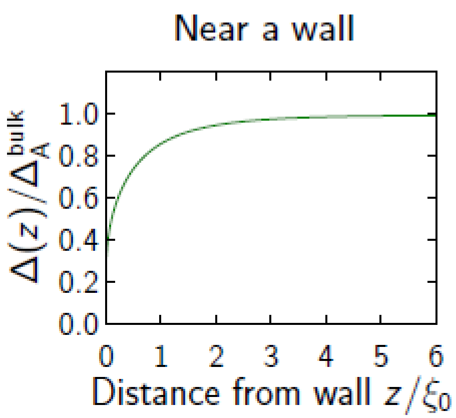
Nagai et al.
J Low Temp. Phys. 110, 1138 (1998)
J Low Temp. Phys. 149 294 (2007)



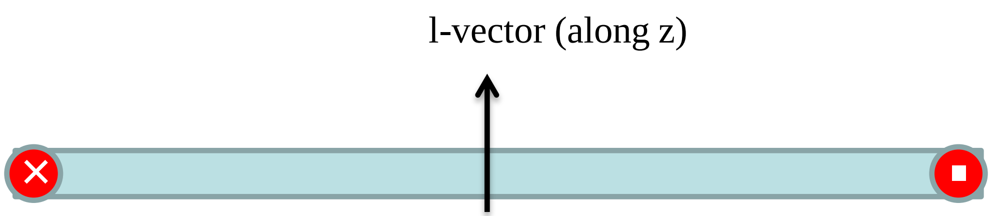
Vorontsov and Sauls PRB 68, 064508 (2003)

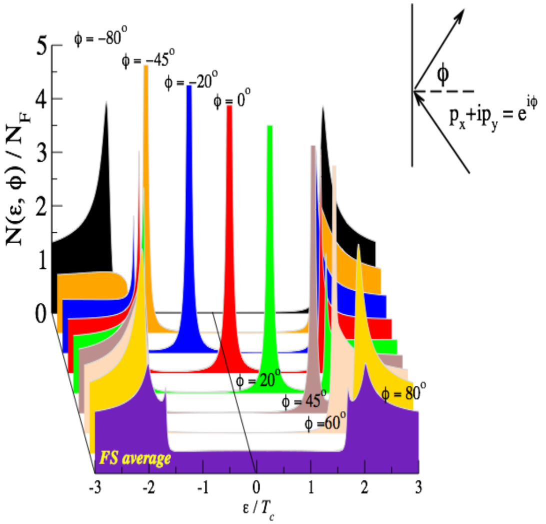
(Chiral) A-phase

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

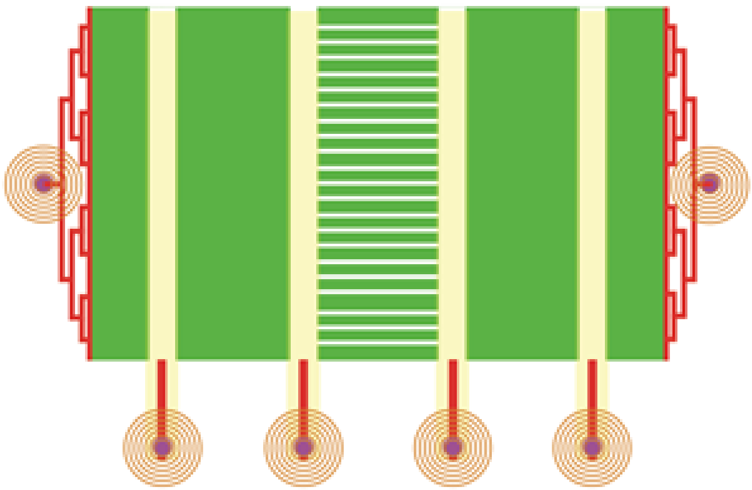


Gap suppression eliminated if walls are specular





Chiral edge currents if sample is single domain



Conclusions: Topological mesoscopic superfluidity

^{3}He is the only established topological "superconductor"

We can manipulate its order parameter by confinement, and measure it by NMR

Surface excitations of ^{3}He-B are majoranas (with strong s-o coupling)

^{3}He-A is chiral with majorana-weyl edge modes

There are numerous possiblities for engineering surfaces and interfaces

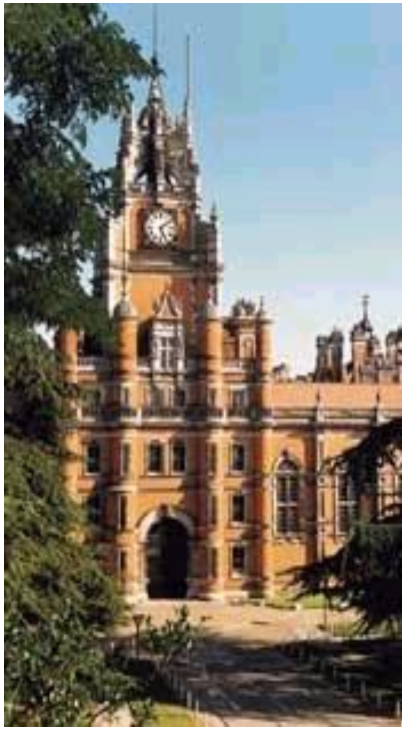
Developing new techniques to study of mesoscopic ^{3}He

Symmetry protected topological superfluids and superconductors- from the basics to ^{3}He
T. Mizushima et al. J. Phys. Soc. Jpn. 85, 74 (2016)

Symmetry Protected Topological Superfluid ^{3}He-B

Takeshi Mizushima, Yasumasa Tsutsumi, Masatoshi Sato, Kazushige Machida

Topical Review:
J.Phys. Cond. Matter 27, 113203 (2015))



A Casey, LV Levitin, **X Rojas**, **P Heikinnen**
R.G. Bennett, B Yager

European Microkelvin Collaboration (FP7 Research Infrastructures)

DC SQUID fabrication

RHUL-Cornell partnership
Nik Zhelev, T.S. Abhilash, Jeevak Parpia

Jim Sauls

Evgeny Surovtsev, Grisha Volovik, Anton Vorontsov, Takeshi Mizushima, Rob Ilic, Mika Fogelstrom, Erkii Thuneberg, Hao Wu, Josh Wiman, Matthias Eschrig

Reduce cavity height

Spherical Fermi surface → **Fermi discs**

Size quantization

$$\varepsilon = \frac{1}{2m^*}[p_z^2 + q^2] \qquad p_z = \frac{\hbar \pi j}{L} \qquad j_0 = \frac{k_F L}{\pi}$$

Number of discs

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

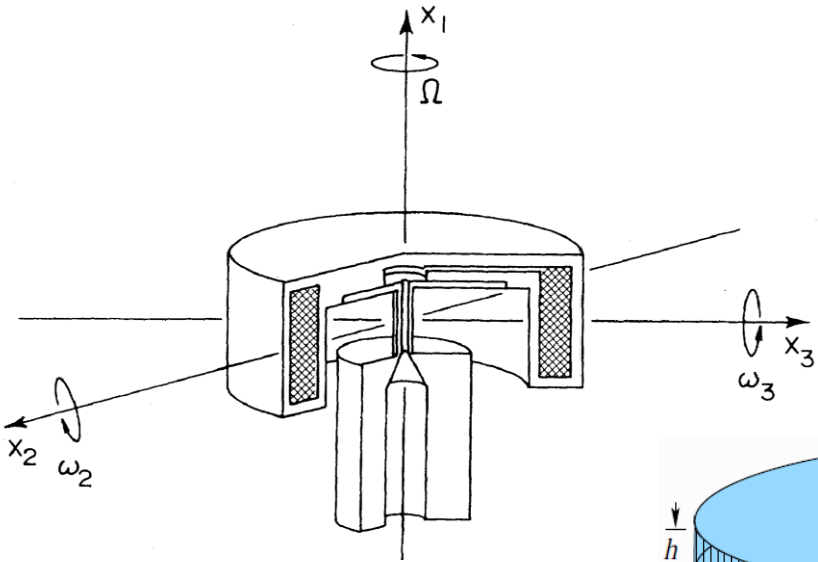
Note:
QSE show up clearly in transport in a 100 nm film. The transport relaxation time shows a *1/T* dependence.
PRL 107, 196805 (2011)

gapped p + ip superfluid, breaking TRS [But…is this state stable relative to TRI planar phase?]
cf Sr_2RuO_4

Chiral phase
Quantum Hall analogues in transport of heat, spin, (mass?)
HQV in a gapped *p+ ip* superfluid (detection and manipulation?)
Ground state angular momentum

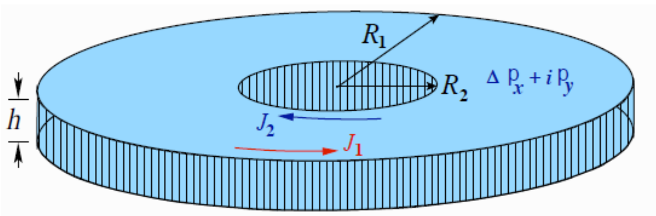
$$\kappa_{xy} = \frac{1}{2} N \frac{\pi^2 k_B^2}{3h} T$$

The torsional oscillator gyroscope



P. L. Gammel, H. E. Hall and J. D. Reppy
Persistent Currents in Superfluid ^{3}He-B
Phys. Rev. Lett., **52**, 121-124 (1984)

J. Sauls Phys. Rev. B 84, 214509 (2011)



$$L = \frac{N\hbar}{2} \times \left(\frac{f_1 - r f_2}{1 - r} \right)$$

$$0 \leq f \leq 1 \qquad r = (R_2 / R_1)^2$$

Requirements:
1. Single chiral domain
2. Adequate sensitivity and low mechanical noise environment
3. To understand quasi-2D A vs. 2D A

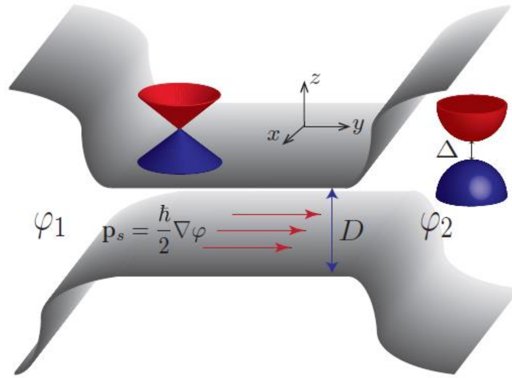
Mass current experiment in ^{3}He-B to detect surface majoranas

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Superflow exhibits a reduction due to backflow of Majoranas

Equivalently

Surface excitation contribution to normal density



Hao Wu and Sauls Phys. Rev. B88, 184506 (2013)

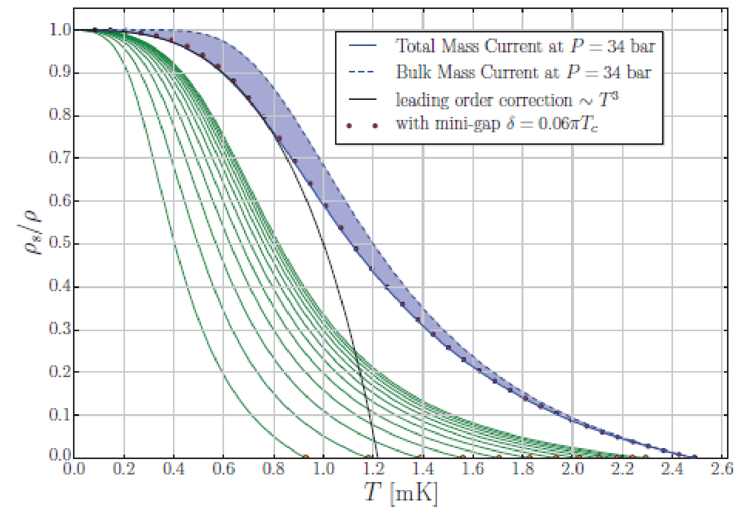
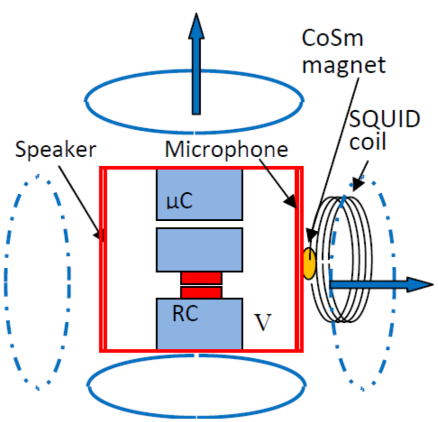


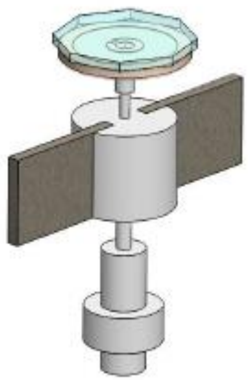
FIG. 8. (Color online) Superfluid mass fraction for a ^{3}He-B film of width $D = 7.5\,\xi_\Delta$ ($D \approx 13.2\,\xi_0$) for pressures $p = 0 \ldots 22$ bars in steps of 2 bars (green) and $p = 34$ bars (solid blue). T_c at each pressure is indicated by the orange circles. The bulk superfluid fraction at 34 bars is shown for comparison (dashed blue), and the shaded region represents the reduction in supercurrent from thermal excitation of the surface Majorana states. For $T \lesssim 0.9$ mK these excitations give a T^3 power law (black) for the reduction in mass current. The effect of the minigap, $\delta = 0.06\pi T_c$, in the surface spectrum on the superfluid fraction is shown for $p = 34$ bars (red circles).

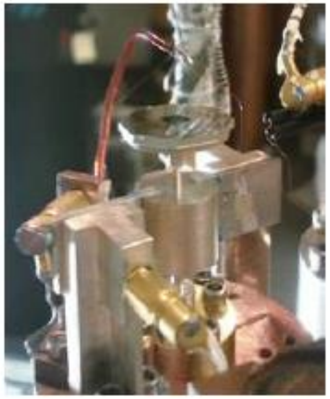
$$\omega^2 = 2c^2 V\left(\frac{A_1}{l_1} + \left(\frac{\rho_s}{\rho}\right)\frac{A_2}{l_2}\right)$$

Helmholtz resonator

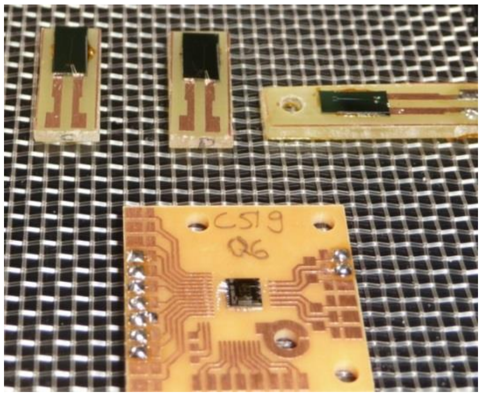


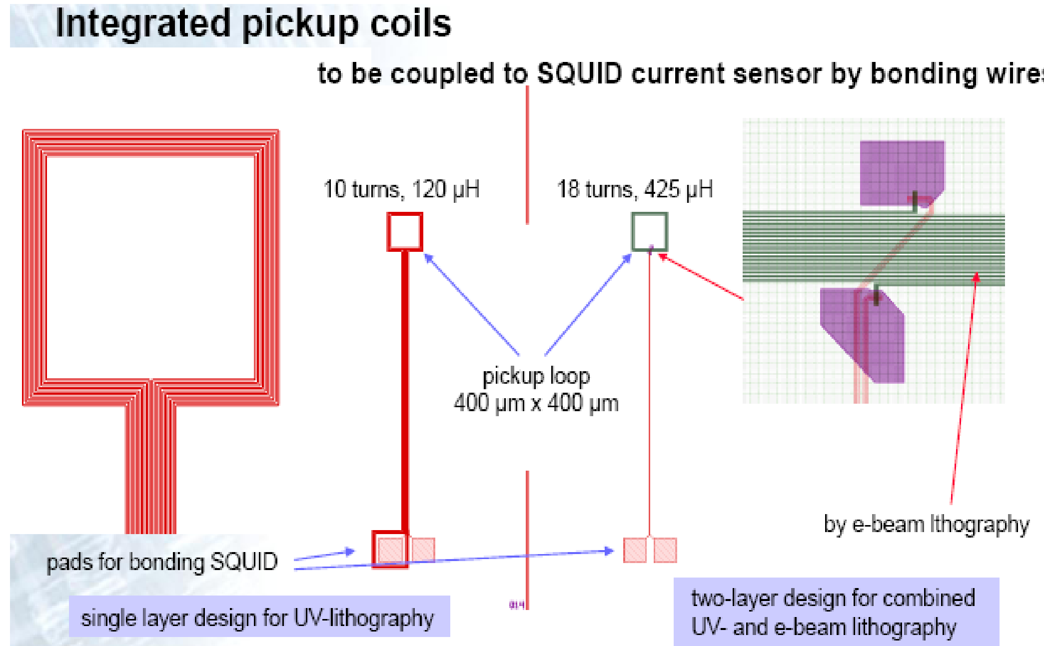
Torsional oscillator (Cornell)



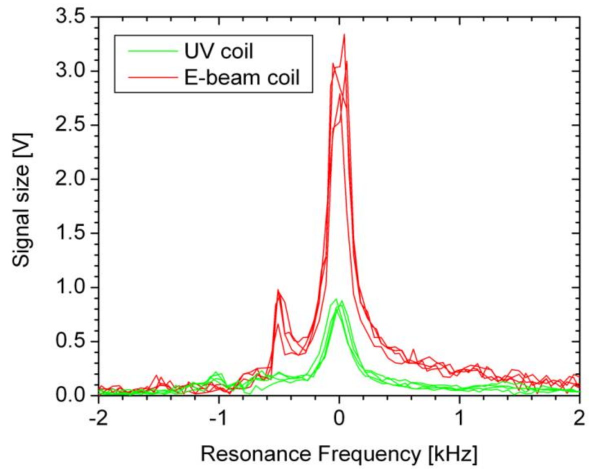


400 micron x 400 µm micro-coils for NMR

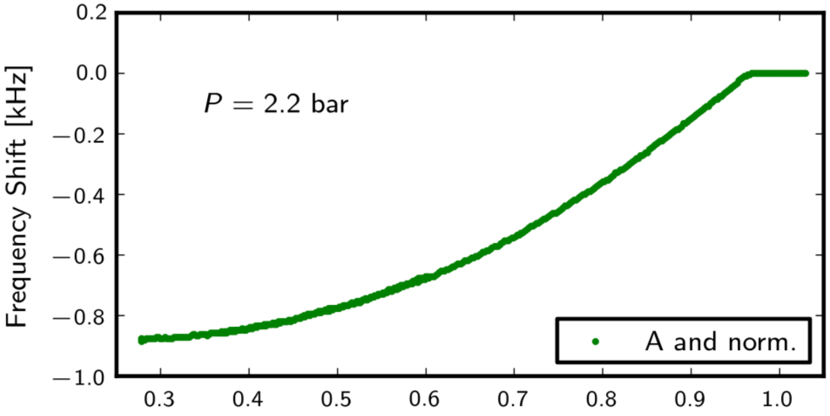




Signals from 3He gas at 4K helium gas test cell



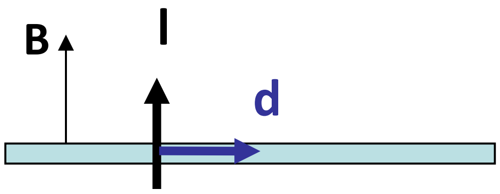
NMR signatures of superfluid: frequency shift vs T



Lower pressures:

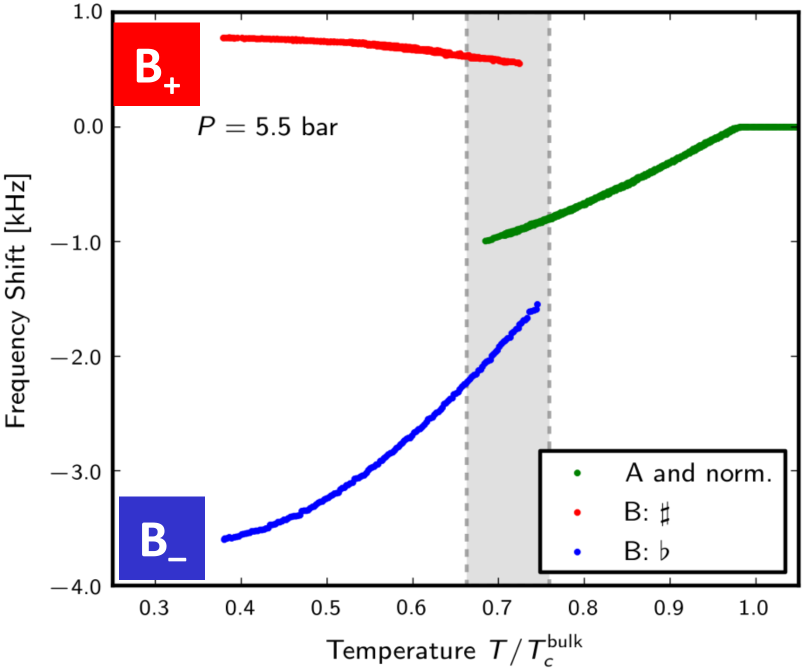
A phase

D = 0.7μm



Minimises Zeeman energy

Maximises dipole energy



Higher pressures

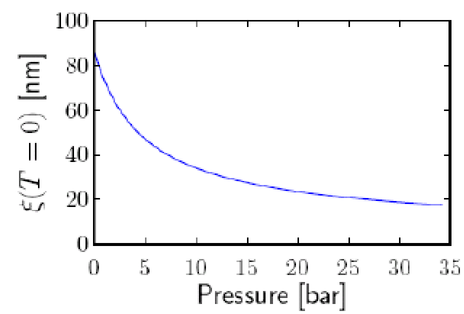
A phase

then transition to

B phase with planar distortion

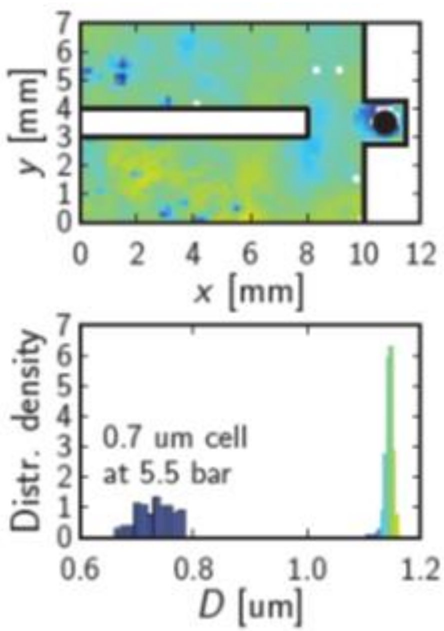
Pressure tunes effective confinement $\dfrac{D}{\xi_0}$

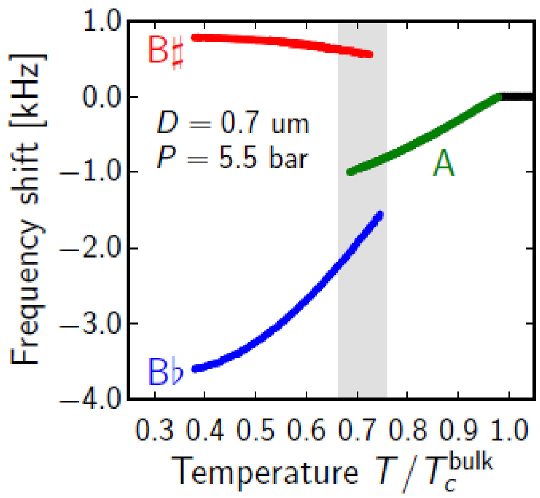
$$\xi_0 = \frac{\hbar v_F}{2\pi k_B T_c}$$

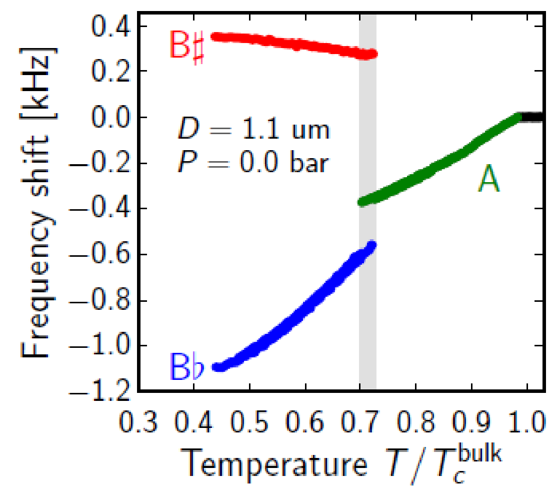


Stabilize planar distorted B phase at zero pressure
[comparison of results from 1.1 and 0.7 μm cavities]

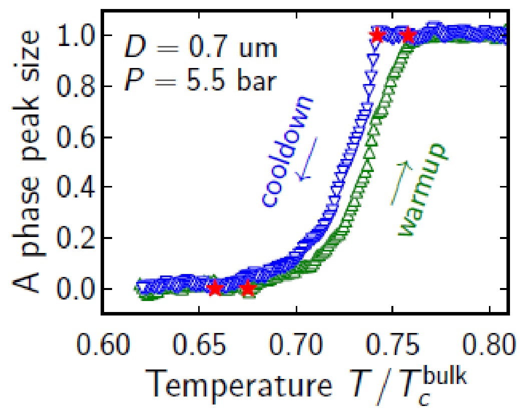
D = 0.7 and 1.1 μm

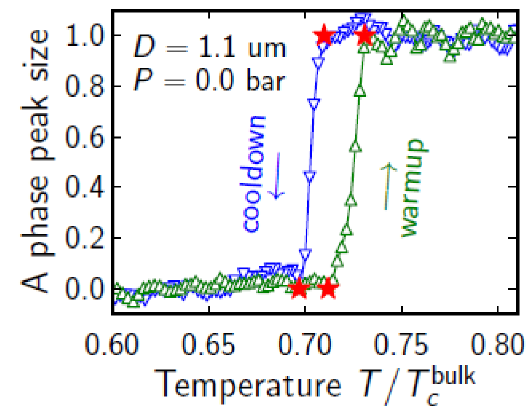


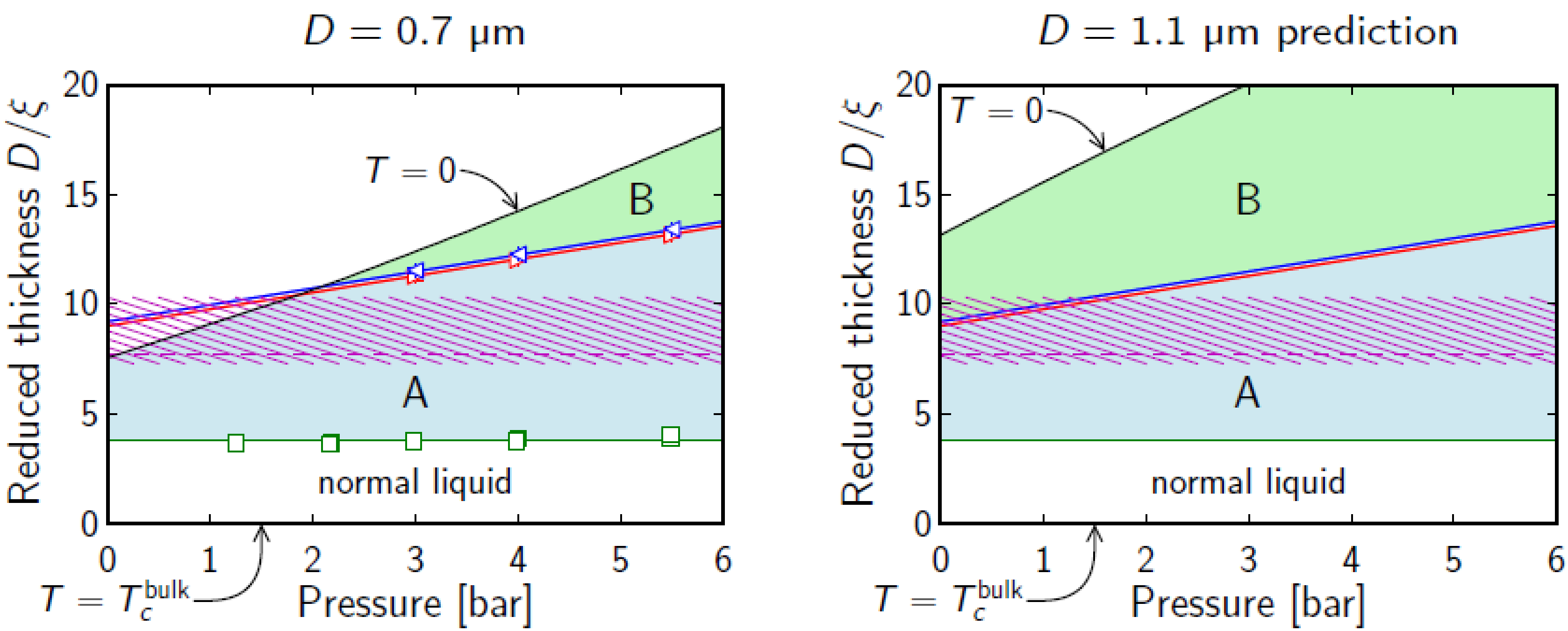




- AB transition is observed at $P = 0$
- AB transition width is reduced



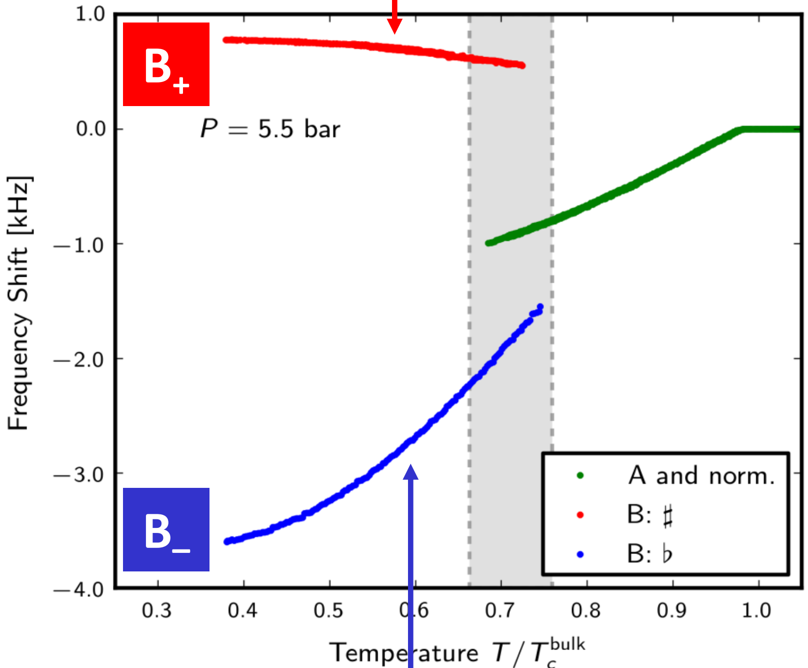


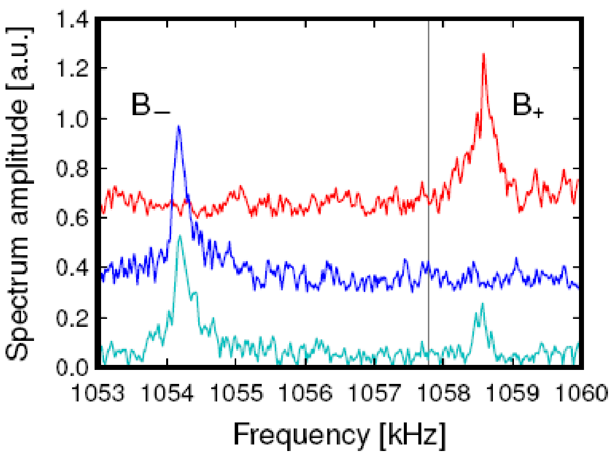

$D = 0.7$ μm
$D = 1.1$ μm prediction
Reduced thickness D/ξ
Pressure [bar]
$T = 0$
$T = T_c^{\mathrm{bulk}}$
B
A
normal liquid
0
5
10
15
20
0
1
2
3
4
5
6

Planar distorted B phase in cavity: NMR fingerprint

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

$$f_{\mathrm{B}_+}^2 - f_{\mathrm{L}}^2 = \frac{\gamma^2 \lambda_{\mathrm{D}} N_{\mathrm{F}}}{5\pi^2 \chi}\left(\Delta_{\parallel}^2 - \Delta_{\perp}^2\right)$$





$$f_{\mathrm{B}_-}^2 - f_{\mathrm{L}}^2 = -\frac{\gamma^2 \lambda_{\mathrm{D}} N_{\mathrm{F}}}{5\pi^2 \chi}\left(\Delta_{\parallel}^2 + 2\Delta_{\perp}^2\right)$$

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

PRL **111,** 235304 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Surface-Induced Order Parameter Distortion in Superfluid ^{3}He-B Measured by Nonlinear NMR

Lev V. Levitin,[1,†] Robert G. Bennett,[1,2,*] Evgeny V. Surovtsev,[3] Jeevak M. Parpia,[2] Brian Cowan,[1] Andrew J. Casey,[1] and John Saunders[1]

[1]*Department of Physics, Royal Holloway University of London, Egham, TW20 0EX Surrey, United Kingdom*
[2]*Department of Physics, Cornell University, Ithaca, New York 14853, USA*
[3]*Kapitza Institute for Physical Problems, ul. Kosygina 2, Moscow 119334, Russia*

(Received 30 July 2013; published 6 December 2013)

The B phase of superfluid ^{3}He is a three-dimensional time-reversal invariant topological superfluid, predicted to support gapless Majorana surface states. We confine superfluid ^{3}He into a thin nanofluidic slab geometry. In the presence of a weak symmetry-breaking magnetic field, we have observed two possible states of the confined ^{3}He-B phase manifold, through the small tipping angle NMR response. Large tipping angle nonlinear NMR has allowed the identification of the order parameter of these states and enabled a measurement of the surface-induced gap distortion. The results for two different quasiparticle surface scattering boundary conditions are compared with the predictions of weak-coupling quasiclassical theory. We identify a textural domain wall between the two B phase states, the edge of which at the cavity surface is predicted to host gapless states, protected in the magnetic field.

Confinement → strong planar distortion of order parameter, along surface normal.

$$\hat{\mathbf{o}} = \pm\hat{\mathbf{z}}$$

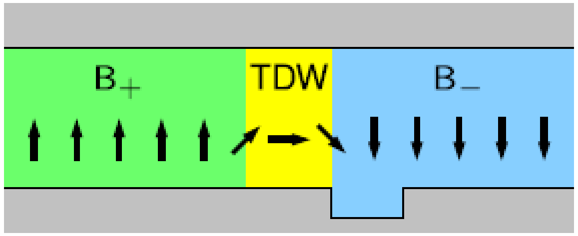
Surface induced susceptibility anisotropy.

$$\hat{\mathbf{w}} = R\,\hat{\mathbf{o}}$$

Minimize Zeeman energy.

$$\hat{\mathbf{w}} = \pm\hat{\mathbf{H}}$$

These states have different dipole energies (one is metastable)
→ domain walls [host gapless states], can be pinned and manipulated.

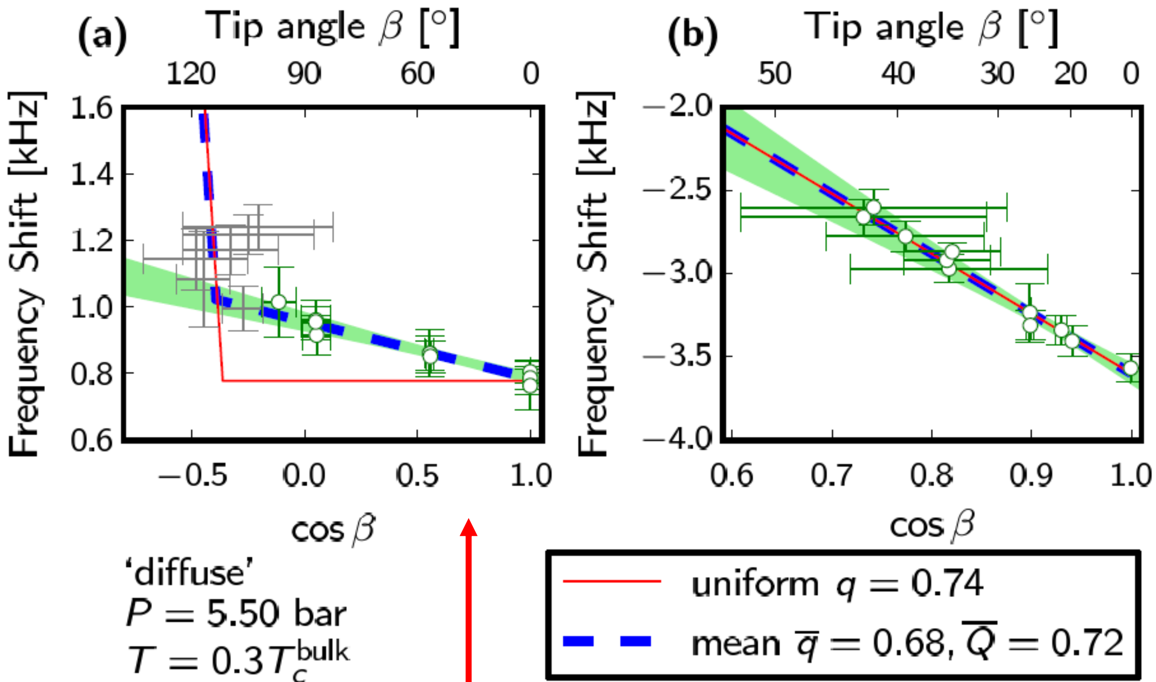


Large Tip Angle NMR on the confined B Phase: determining planar distortion

Non-uniform gap distortion

$$\overline{x}^2 = \frac{\langle \Delta_\parallel^2(\mathbf{r})\rangle}{\Delta_\mathrm{B}^2}, \qquad \overline{q} = \frac{\langle \Delta_\parallel(\mathbf{r})\Delta_\perp(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}, \qquad \overline{Q}^2 = \frac{\langle \Delta_\perp^2(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}$$

Generalisation of
Bunkov, Volovik
JETP 76, 794 (1993)



$$\Delta f = \frac{2\nu_\mathrm{B}^2}{15 f_\mathrm{L}} \overline{x}^2 \frac{\chi_\mathrm{B}}{\overline{\chi}_\parallel} W(\beta)$$

B_+

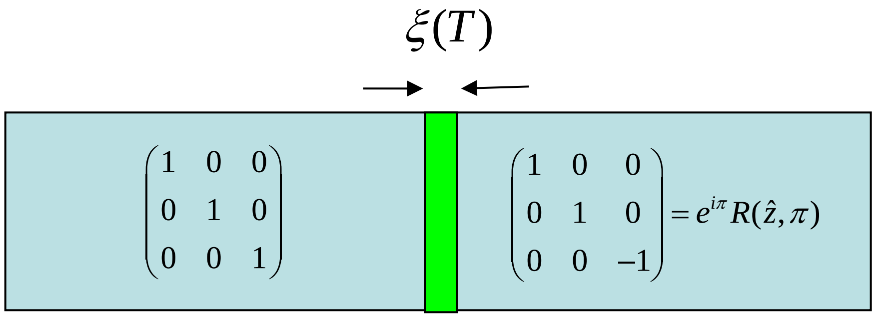
$$W(\beta) = \begin{cases} 1 - \overline{q}^2 + 2(\overline{q}^2 - \overline{Q}^2)\cos\beta, & \text{at } \cos\beta \geq \hat{w}_z^* \\ -1 - \overline{q} - 2(1 + 2\overline{q} + \overline{Q}^2)\cos\beta, & \text{at } \cos\beta \leq \hat{w}_z^* \end{cases}$$

B_-

$$W(\beta) = -(1 + 2\overline{Q}^2)\cos\beta$$

New order parameter:
B phase domain walls and the striped phase

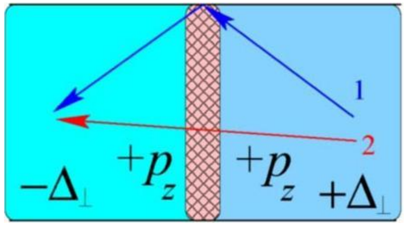
Domain wall (planar phase) between different B phase states

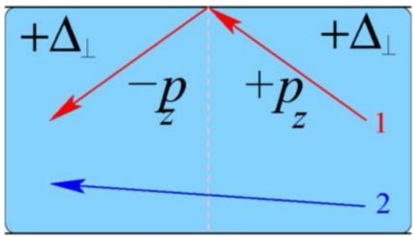


$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} = e^{i\pi} R(\hat{z}, \pi)$$

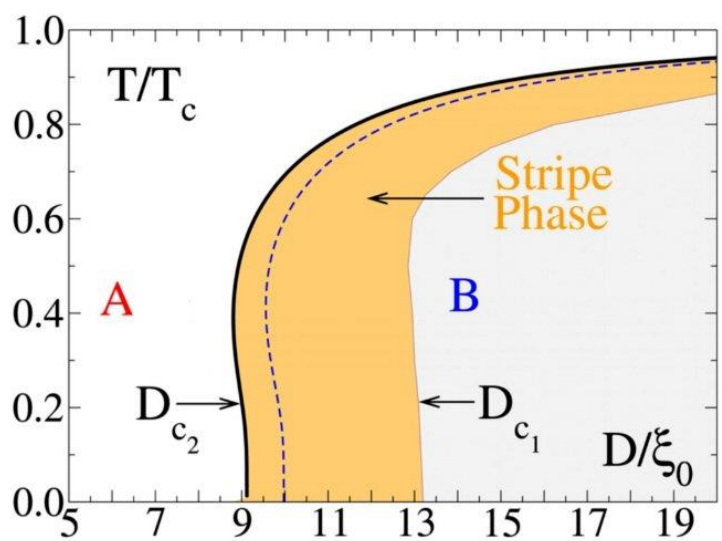
Salomaa and Volovik
PRB. 37, 9298 (1988)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$





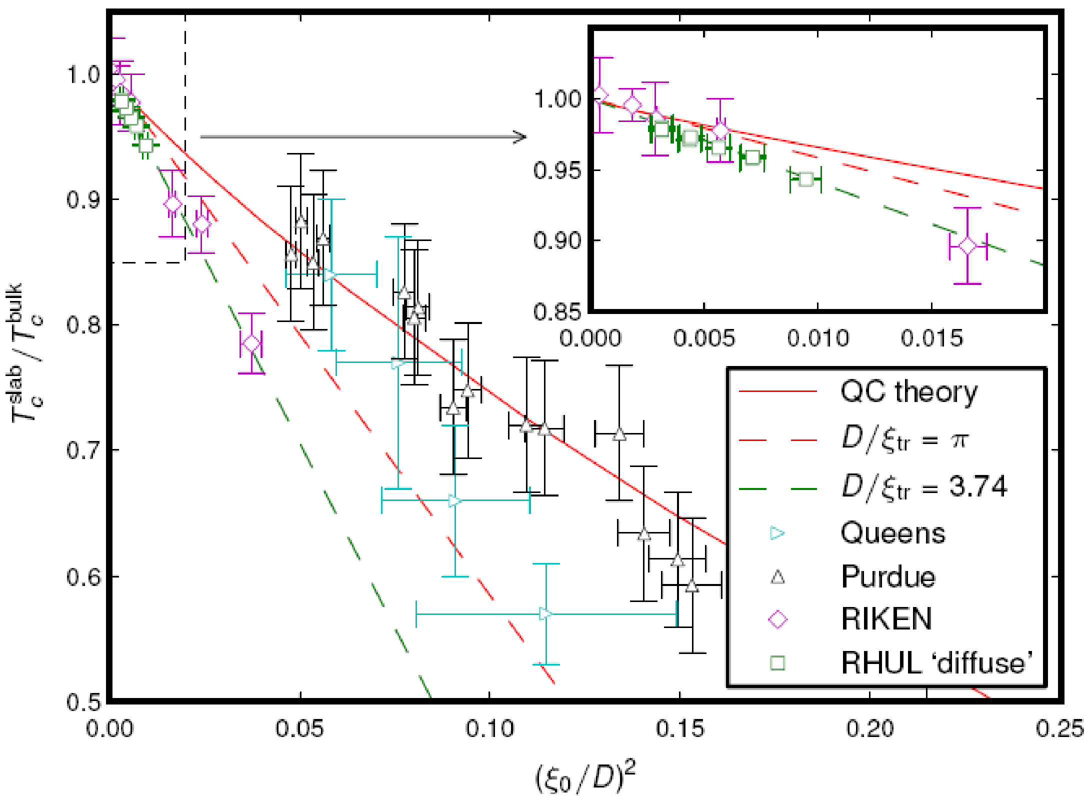
Such domain walls become energetically favourable in a slab



Prediction (in weak coupling limit) of a superfluid with spontaneously broken translational symmetry

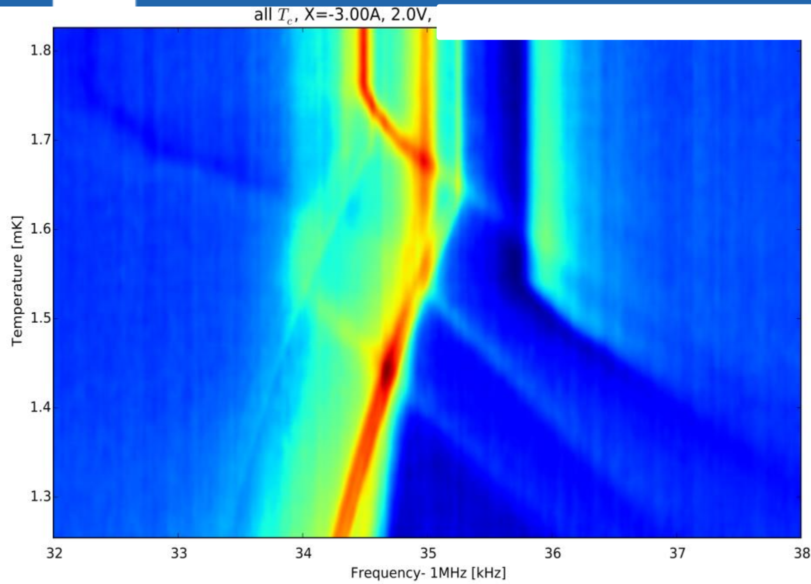
Vorontsov and Sauls PRL 98, 045301 (2007)

test of quasi-classical theory

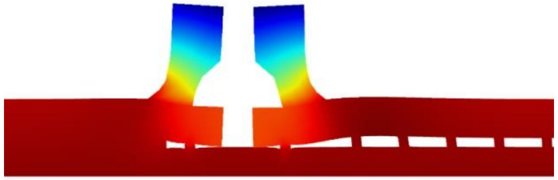


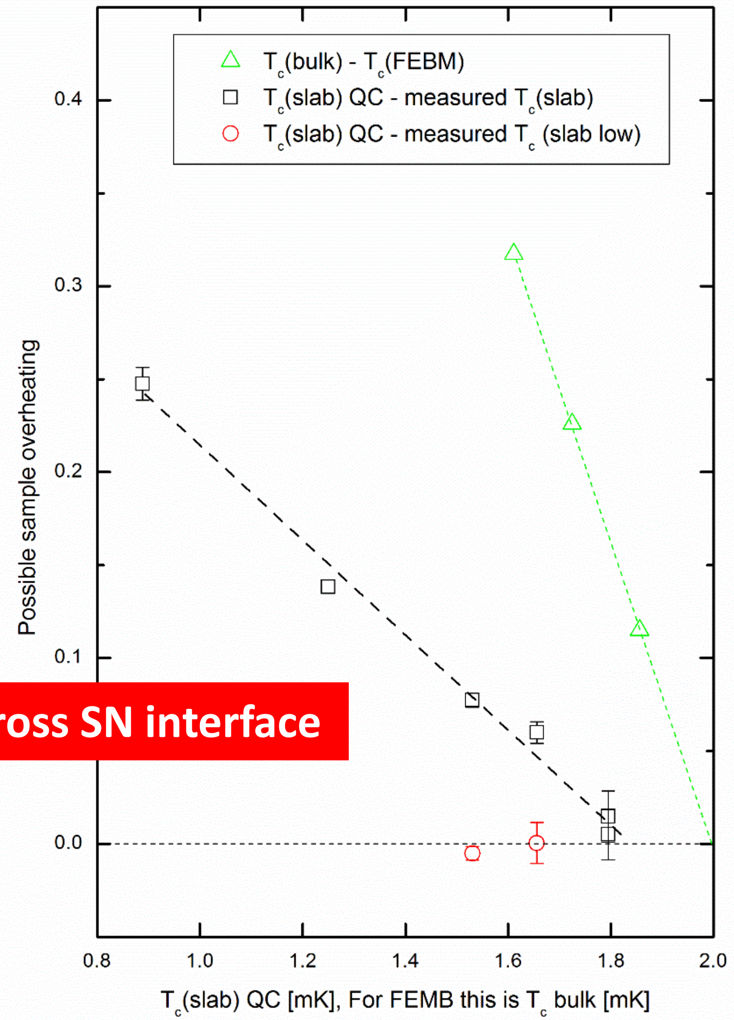
Phenomenological boundary conditions:
Specular
Diffuse
Retroflection (maximally pair-breaking)

Recent results from a 300 nm cavity



Temperature gradients across SN interface





Sculpture of a p-wave superfluid order parameter in a nanofluidic environment

Our new tuning parameters are:

Symmetry breaking

Geometry	eg flat slab
Scale	eg thickness of slab
Surface	eg tailor surface profile or coat with a superfluId ^{4}He film
Flow	
Magnetic field	

This will influence:

Equilibrium Order Parameter
distorted
periodic

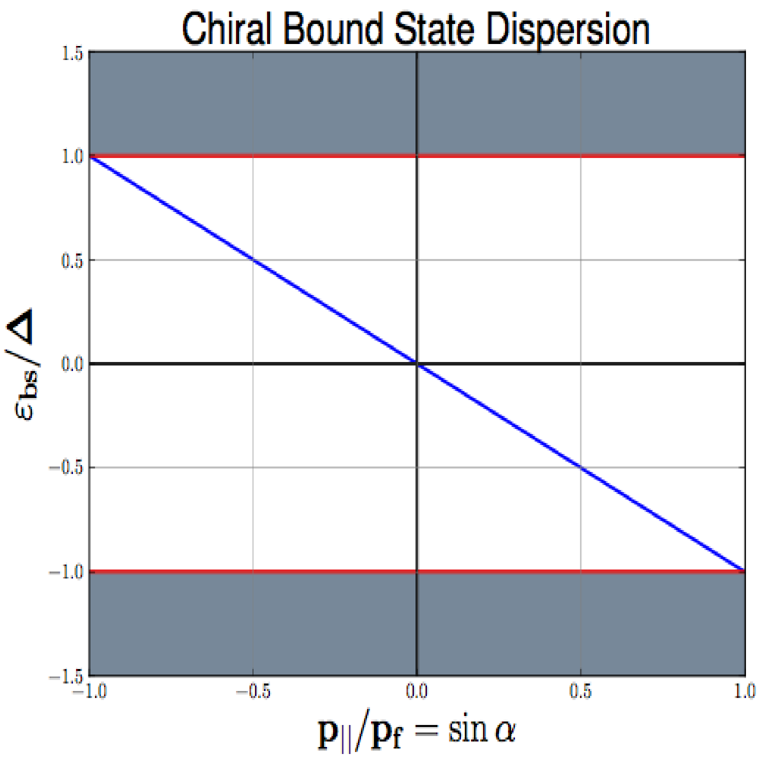
Surface states
eg Majorana fermions at surface of 3He-B

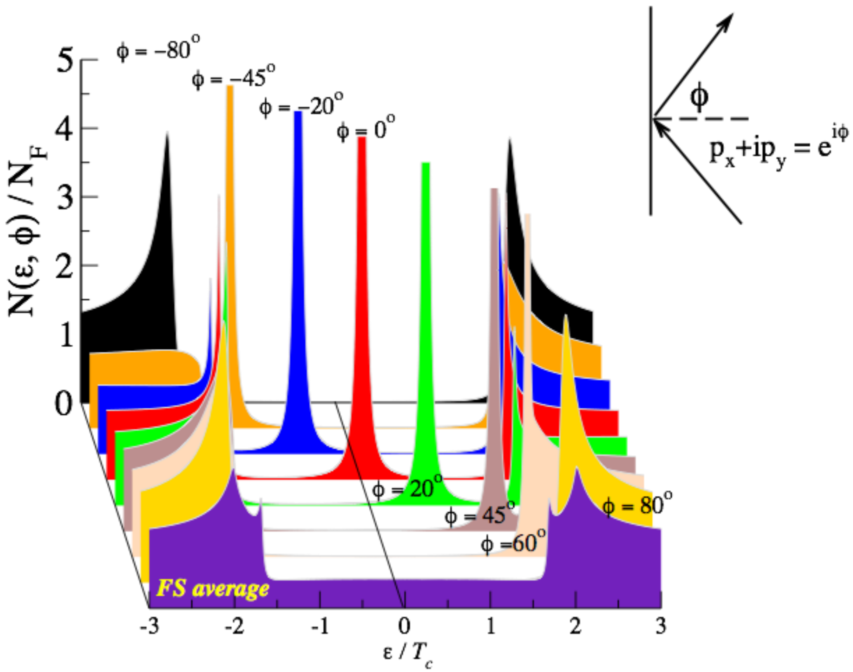
Edge states
eg at edge of chiral A-phase slab

Entirely new order parameters:
Striped phases
Gapped 2D A-phase
Planar Phase
Polar Phase
Periodic phases in periodic structures

Topological defects:
vortices (eg half quantum vortex)
domain walls

Gapped Chiral Phase: Towards 2D A phase [2D p + ip]





Size quantization:

Fermi surface → Fermi discs

$$\varepsilon = \frac{1}{2m^*}[p_z^2 + q^2] \qquad p_z = \frac{\hbar \pi j}{L} \qquad j_0 = \frac{k_F L}{\pi}$$

Fully gapped chiral phase

Edge currents in chiral A-phase: thermal transport

PHYSICAL REVIEW B VOLUME 61, NUMBER 15 15 APRIL 2000-I

Paired states of fermions in two dimensions with breaking of parity and time-reversal symmetries and the fractional quantum Hall effect

N. Read and Dmitry Green

G.E. Volovik, Zh. Éksp. Teor. Fiz. **94**, 123 (1988) [Sov. Phys. JETP **67**, 1804 (1988)].

G.E. Volovik and V.M. Yakovenko, J. Phys.: Condens. Matter **1**, 5263 (1989).

G.E. Volovik, Physica B **162**, 222 (1990).

G.E. Volovik, Zh. Éksp. Teor. Fiz. **51**, 111 (1990) [JETP Lett. **51**, 125 (1990)].

G.E. Volovik, Zh. Éksp. Teor. Fiz. **55**, 363 (1992) [JETP Lett. **55**, 368 (1992)].

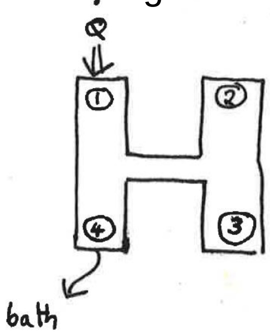
$$\kappa_{xx} = \frac{\pi^2 k_B^2 T}{3\hbar} \tilde{\kappa}_{xx}$$

$$\kappa_{xy} = \frac{\pi^2 k_B^2 T}{3\hbar} \tilde{\kappa}_{xy}$$

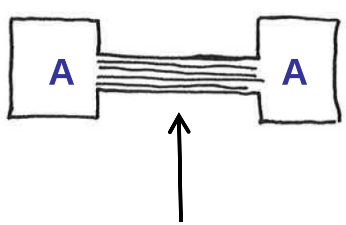
$$c = N/2$$

Thermal (quantized) Hall effect

Control geometry



Amplify edge current, [and turn on/off]



A→ striped → polar

The future (2)

Our approach:

<u>Nano-engineering is the key new development in quantum fluids research</u>
match this to intrinsic high sample quality and purity

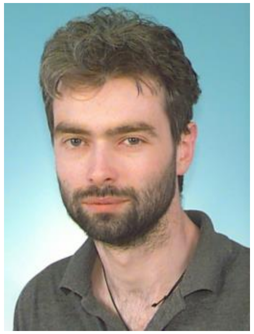
<u>Confinement is our new control parameter</u>. Use this in device engineering. [eg SNS, or $S_1S_2S_1$]
Fabrication of hybrid mesoscopic devices based on quantum fluids
We anticipate good control over surface scattering.

<u>Quantum nanofluidics requires new experimental techniques</u>:
Local nanoscale probes:
(eg nano-mechanical resonators, microcoils, graphene, tunnelling, optical-mechanical transducers)
[Need to understand back action]
High frequency ($\sim\Delta$) probes
Leads and thermometers [how do they couple to surface and edge states?]….understood by Quantum Hall Community?

<u>Understanding the basics:</u>
Ensure that we have a complete understanding of surface scattering processes, including the influence of size quantization effects in the film.
Quantum fluids in a nanofluidic environment is new; there will be surprises (engineering detail or fundamental?]

The ND3 team

Ben Yager



Andrew Casey

Xavier Rojas,
arriving March

Lev Levitin

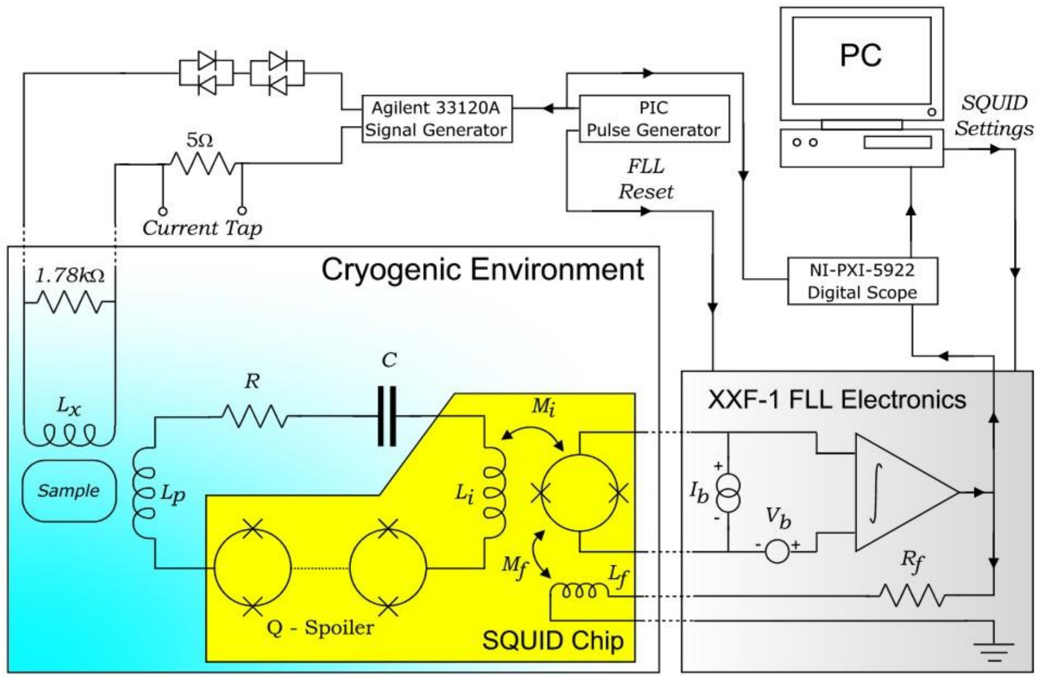
Topological superfluids under engineered nanofluidic confinement: New order parameters and exotic excitations
EPSRC grant EP/J022004/1 (October 2012- March 2017)
Investigators: Saunders, Casey, Cowan, Eschrig
International Project Partners: **Parpia/Davis** Cornell (USA); **Sauls**, Northwestern (USA), **Drung/Schurig** PTB (Berlin),

Contact j.saunders@rhul.ac.uk

Rob
Bennett

London Low Temperature Laboratory
www.royalholloway.ac.uk/lltl
European Microkelvin Platform
www.emplatform.eu

NMR “fingerprint” of order parameter: Sensitive SQUID NMR spectrometer

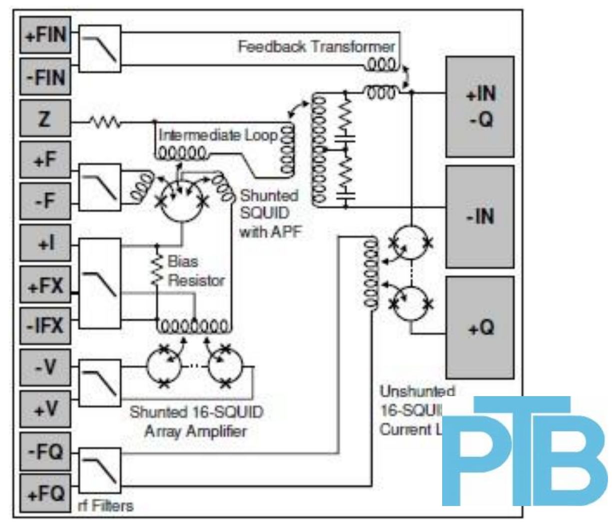


APPLIED PHYSICS LETTERS **91**, 262507 (2007)

A nuclear magnetic resonance spectrometer for operation around 1 MHz with a sub-10-mK noise temperature, based on a two-stage dc superconducting quantum interference device sensor

L. V. Levitin, R. G. Bennett, A. Casey,[a] B. P. Cowan, C. P. Lusher,[b] and J. Saunders
Department of Physics, Royal Holloway University of London, Egham, Surrey TW20 0EX, United Kingdom

D. Drung and Th. Schurig
Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, D-10587 Berlin, Germany



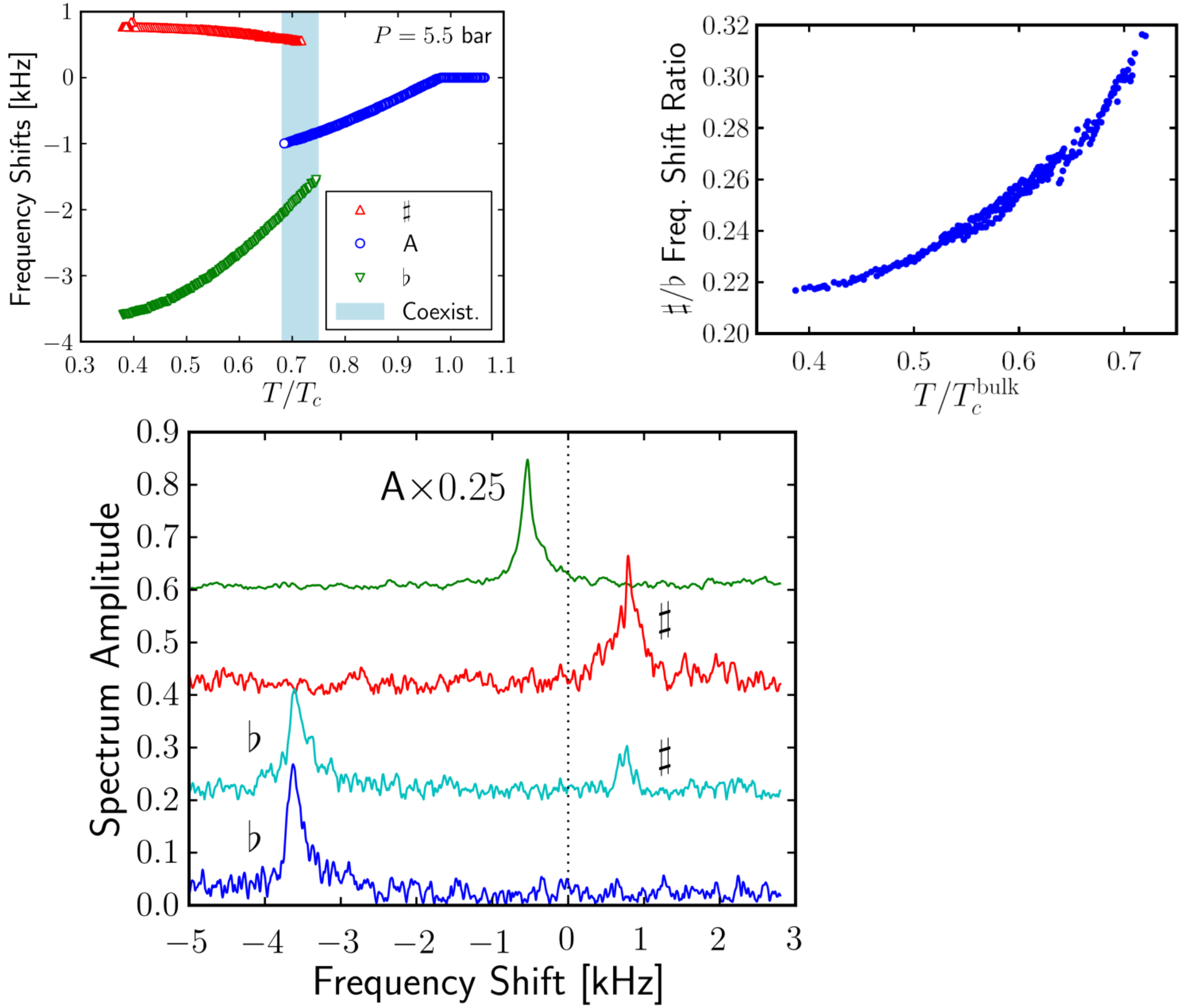
NMR probes the order parameter of ^{3}He: different phases show distinct shifts of the resonance away from the Larmor frequency

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)

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

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

Two planar distorted B phase states, differing only by spin-orbit energy: details

Neglecting spin-orbit interaction: degenerate manifold of states, wrt relative rotation of spin and orbital part

$$A_{\mu m} = \Delta e^{i\varphi} R_{\mu m} \qquad d_{\mu} = A_{\mu m} k_m \qquad R = R(\hat{\mathbf{n}}, \theta)$$

$$\mathbf{J} = \mathbf{L} + \mathbf{R}\mathbf{S}$$

Surface induces gap distortion along surface normal $\hat{\mathbf{o}} = \pm\hat{\mathbf{z}}$

$$A_{\mu j} = e^{i\phi} R_{\mu m} [\Delta_{\parallel}(z)\delta_{mj} + (\Delta_{\perp}(z) - \Delta_{\parallel}(z))\hat{o}_m \hat{o}_j]$$

Gap distortion results in strong magnetic susceptibility anisotropy along axis $\hat{\mathbf{w}} = \boldsymbol{R}\hat{\mathbf{o}}$

In a magnetic field Zeeman energy is

$$\overline{F}_H = -\frac{1}{2}\overline{\chi}_{\perp} H^2 - \frac{1}{2}\overline{\Delta\chi}(\hat{\mathbf{w}} \cdot \mathbf{H})^2$$

It dominates spin-orbit energy for field bigger than about 3 mT, then $\hat{\mathbf{w}} = \pm\hat{\mathbf{H}}$

This allows two configurations which minimize Zeeman energy, but with different spin-orbit energy

B_+ minimises Spin-orbit energy

$$\hat{\mathbf{w}} = \hat{\mathbf{o}} = \hat{\mathbf{z}} \qquad \hat{\mathbf{n}} = \hat{\mathbf{z}} \qquad \theta = \arccos(-\Delta_{\perp}/4\Delta_{\parallel})$$

B_ metastable state not minimising dipole energy

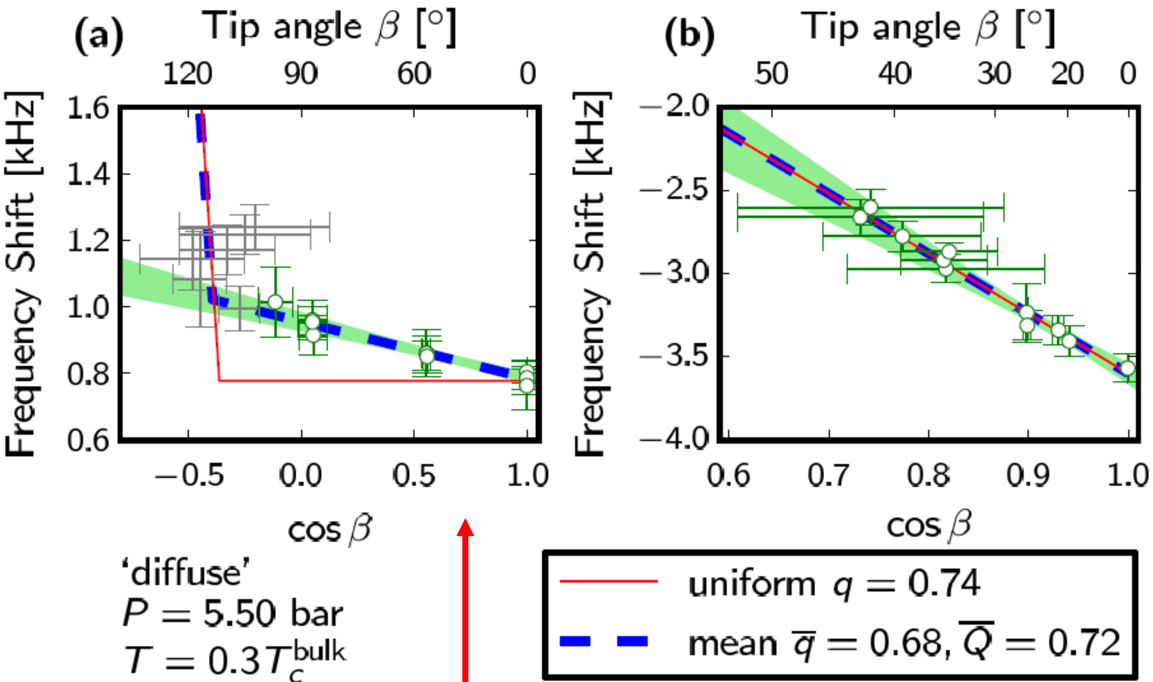
$$\hat{\mathbf{w}} = -\hat{\mathbf{o}} \qquad \hat{\mathbf{n}} = \perp \hat{\mathbf{z}} \qquad \theta = \pi/2$$

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

Non-uniform gap distortion

$$\overline{x}^2 = \frac{\langle \Delta_\parallel^2(\mathbf{r})\rangle}{\Delta_\mathrm{B}^2}, \qquad \overline{q} = \frac{\langle \Delta_\parallel(\mathbf{r})\Delta_\perp(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}, \qquad \overline{Q}^2 = \frac{\langle \Delta_\perp^2(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}$$

Generalisation of
Bunkov, Volovik
JETP 76, 794 (1993)



$$\Delta f = \frac{2\nu_\mathrm{B}^2}{15 f_\mathrm{L}} \overline{x}^2 \frac{\chi_\mathrm{B}}{\overline{\chi}_\parallel} W(\beta)$$

B$_+$

B$_-$

$$W(\beta) = \begin{cases} 1 - \overline{q}^2 + 2(\overline{q}^2 - \overline{Q}^2)\cos\beta, & \text{at } \cos\beta \ge \hat{w}_z^* \\ -1 - \overline{q} - 2(1 + 2\overline{q} + \overline{Q}^2)\cos\beta, & \text{at } \cos\beta \le \hat{w}_z^* \end{cases}$$

$$W(\beta) = -(1 + 2\overline{Q}^2)\cos\beta$$

NMR on ^{3}He-B with a non-uniform planar distortion

$$\overline{x}^2 = \frac{\langle \Delta_\parallel^2(\mathbf{r})\rangle}{\Delta_B^2}, \qquad \overline{q} = \frac{\langle \Delta_\parallel(\mathbf{r})\Delta_\perp(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}, \qquad \overline{Q}^2 = \frac{\langle \Delta_\perp^2(\mathbf{r})\rangle}{\langle \Delta_\parallel^2(\mathbf{r})\rangle}$$

$$\overline{F}_D = \langle F_D(\hat{\mathbf{r}})\rangle = \frac{2\chi_B\Omega_B^2}{15g^2}\overline{x}^2\overline{\tilde{F}}_D,$$

$$\overline{\tilde{F}}_D = -\hat{w}_z + \cos^2\Phi(1+\hat{w}_z)^2 + \overline{q}\cos\Phi(1+\hat{w}_z)(2\hat{w}_z-1) + \overline{Q}^2\hat{w}_z^2.$$

$$\Delta f = \frac{2\nu_B^2}{15 f_L}\overline{x}^2\frac{\chi_B}{\overline{\chi}_\parallel}W(\beta)$$

$$W = \partial\overline{\tilde{V}}_D/\partial\cos\beta$$

$\hat{\mathbf{w}} = \hat{\mathbf{o}} = \hat{\mathbf{z}}$

$$W(\beta) = \begin{cases} 1-\overline{q}^2 + 2(\overline{q}^2 - \overline{Q}^2)\cos\beta, & \text{at } \cos\beta \geq \hat{w}_z^* \\ -1-\overline{q} - 2(1+2\overline{q}+\overline{Q}^2)\cos\beta, & \text{at } \cos\beta \leq \hat{w}_z^* \end{cases} \qquad \hat{w}_z^* = \cos\beta^* = (\overline{q}-2)/(2\overline{q}+2)$$

$\hat{\mathbf{w}} = -\hat{\mathbf{o}}$

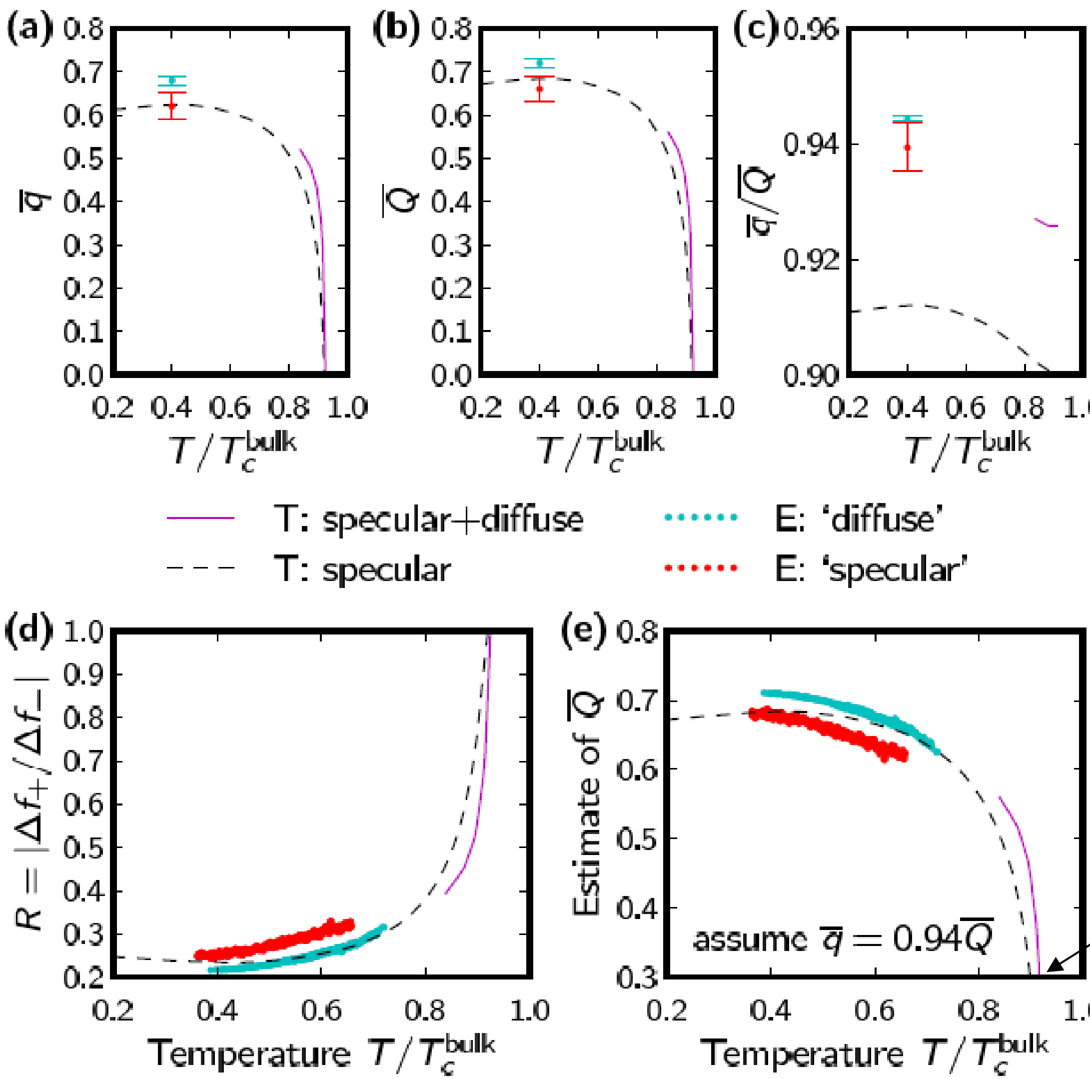
$$\overline{\tilde{V}}_D = \frac{3}{4} + \frac{1}{2}(1+2\overline{Q}^2)\cos^2\beta$$

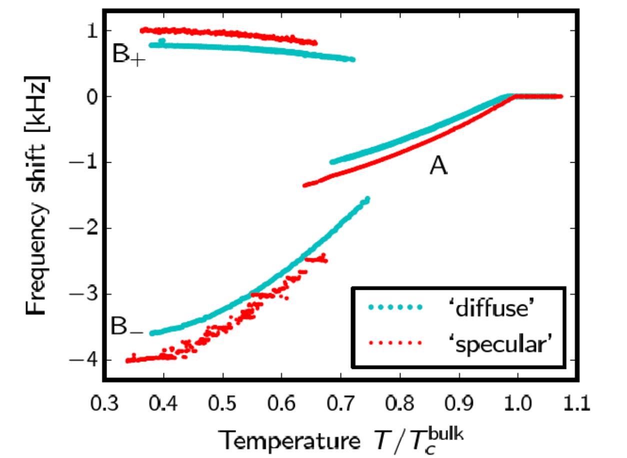
$$W(\beta) = -(1+2\overline{Q}^2)\cos\beta$$

Temperature dependence of planar-gap distortion: Comparison with quasiclassical theory

ROYAL HOLLOWAY UNIVERSITY OF LONDON

$$\Delta f_+(\beta = 0)/|\Delta f_-(\beta = 0)| = (1 + \bar{q}^2 - 2\bar{Q}^2)/(1 + 2\bar{Q}^2)$$



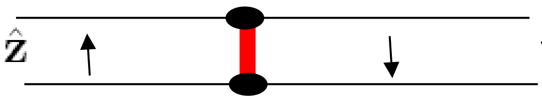


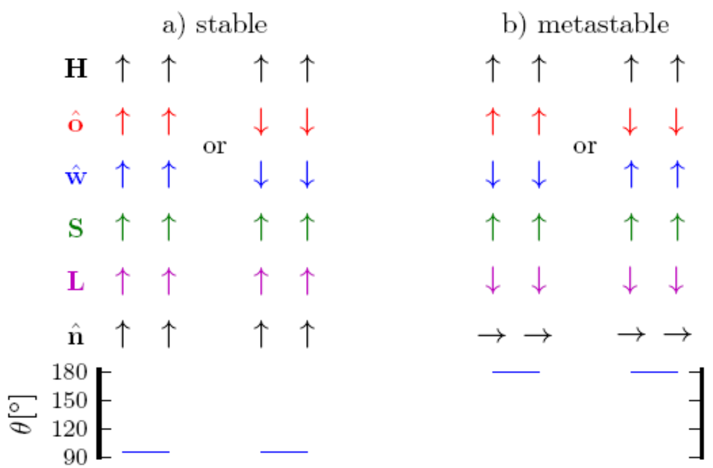
Transition (weak coupling theory)
from
Planar distorted B-phase
to Planar phase
(degenerate with A-phase)

$\Delta_\perp \to 0$

Domain wall, between the two B phase states: protected fermion zero modes at surface

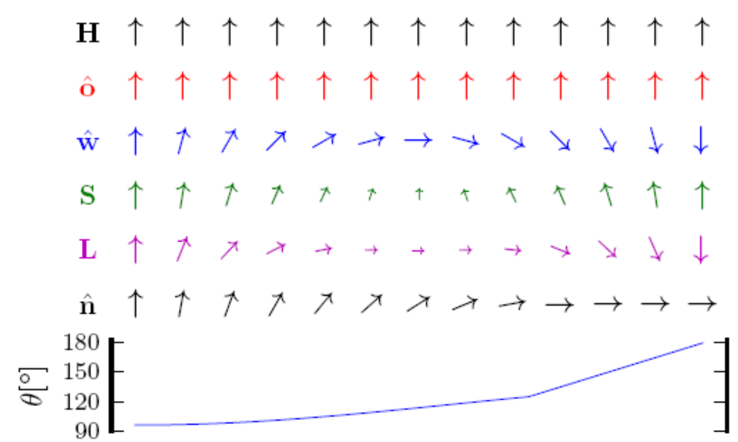
$\hat{w} = \hat{o} = \hat{z}$ $\hat{w} = -\hat{o}$

$\hat{w} = \hat{o} = \hat{z}$  $\hat{w} = -\hat{o}$



Magnetic field breaks TRI. It induces a weak orbital angular momentum. This points in opposite directions on opposite sides of domain wall. Surface modes, at wall, remain gapless at intersection of domain wall and surface.

$$\xi_H = \xi_0 \sqrt{N_F \Delta_{\parallel}^2 / \Delta\chi H^2}$$



$$E(\boldsymbol{k}_{\parallel}) = \pm\sqrt{[E_0(\boldsymbol{k}_{\parallel})]^2 + [\mu_n H \hat{\ell}_z(\hat{\boldsymbol{n}}, \varphi)]^2},$$

Topological Superfluid ^{3}He-B in Magnetic Field and Ising Variable¶

G. E. Volovik

Low Temperature Laboratory, Aalto University, FI-00076 AALTO, Finland
Landau Institute for Theoretical Physics, Russian Academy of Sciences, Moscow, 119334 Russia
e-mail: volovik@boojum.hut.fi

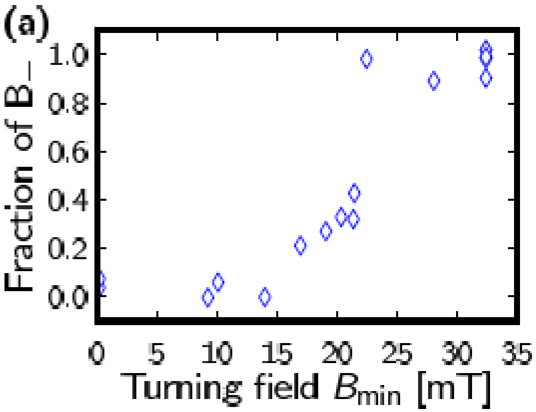
PRL **109,** 165301 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

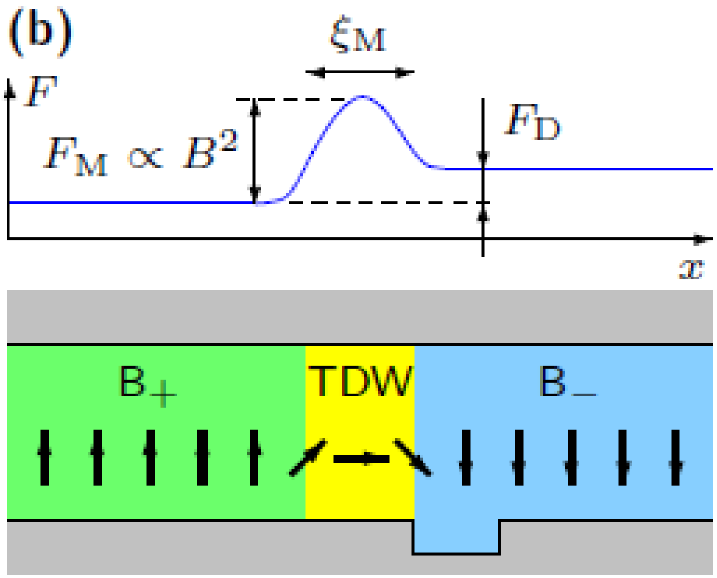
Symmetry Protected Topological Order and Spin Susceptibility in Superfluid ^{3}He-*B*

Takeshi Mizushima,[1,*] Masatoshi Sato,[2,†] and Kazushige Machida[1]

[1]*Department of Physics, Okayama University, Okayama 700-8530, Japan*
[2]*The Institute for Solid State Physics, The University of Tokyo, Chiba 277-8581, Japan*

Pinning and possible manipulation of domain walls

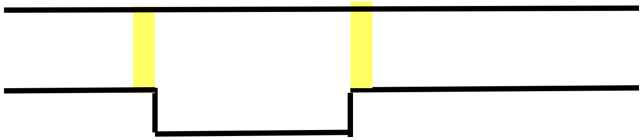




Energy difference of domains = dipole energy

Domain wall costs Zeeman energy

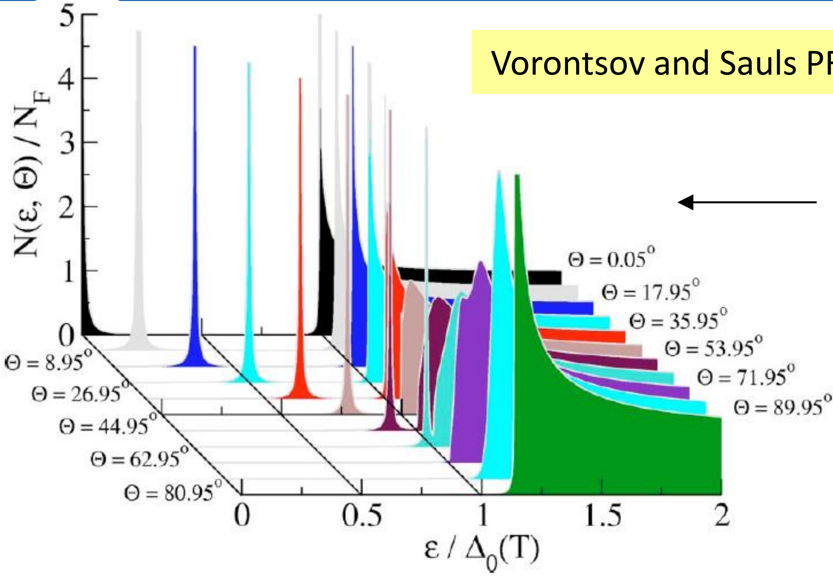
Hence energy cost for DW to enter crack



Fabricate nano-channel to locate DWs

Reduce field to fuse DWs

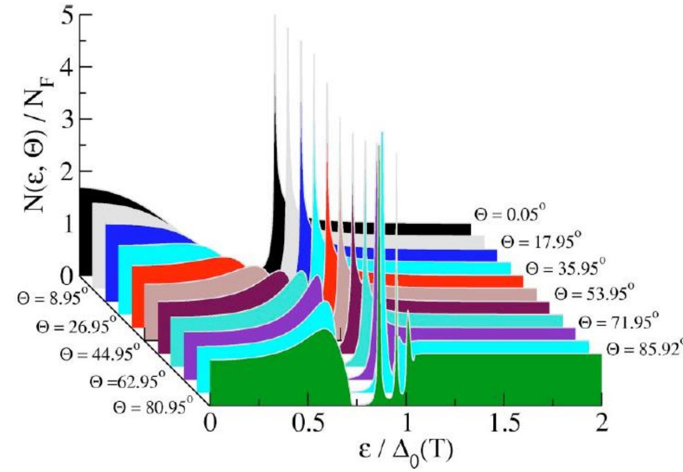
Surface States in ^{3}He-B phase: Majorana fermions
Detailed predictions of quasiclassical theory



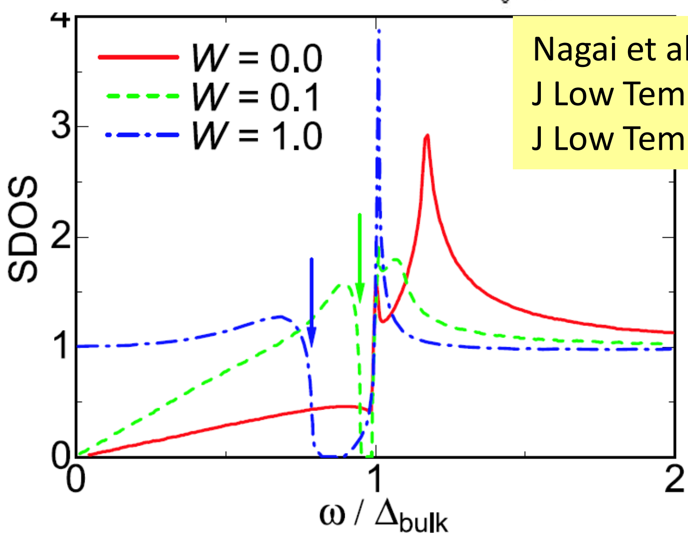
Vorontsov and Sauls PRB 68, 064508 (2003)

← specular

diffuse →



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

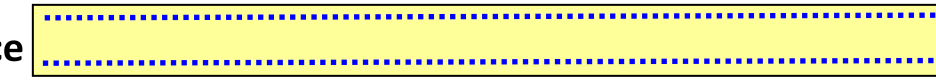


Nagai et al.
J Low Temp. Phys. 110, 1138 (1998)
J Low Temp. Phys. 149 294 (2007)

Quasi-classical theory

Surface bound excitations
Majorana fermions

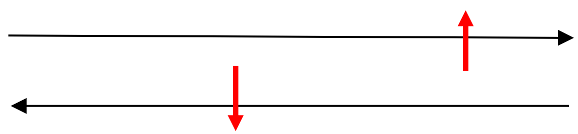
Surface modes live within coherence length of surface
Satisfy Majorana condition
Superfluid is fully gapped away from surface



$$\Psi^{\dagger}(\mathbf{r}) = \Psi(\mathbf{r})$$

Gapless surface excitations in a fully gapped superfluid gives a <u>power law contribution</u> to heat capacity thermal conductivity, or normal fraction which dominates at sufficiently low temperatures

Majorana fermions have a strong spin orbit coupling of surface bound excitations

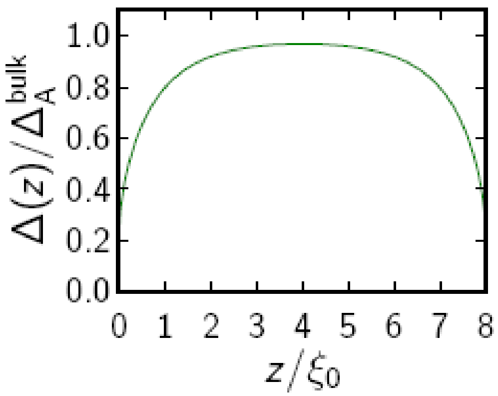


Determining the B-phase gap suppression by NMR

The A phase

Suppressed in the slab.
One gap component $\Delta(z)$

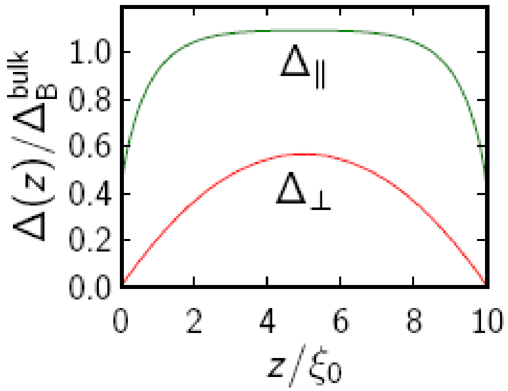
$$\Delta f \propto \langle \Delta^2 \rangle$$



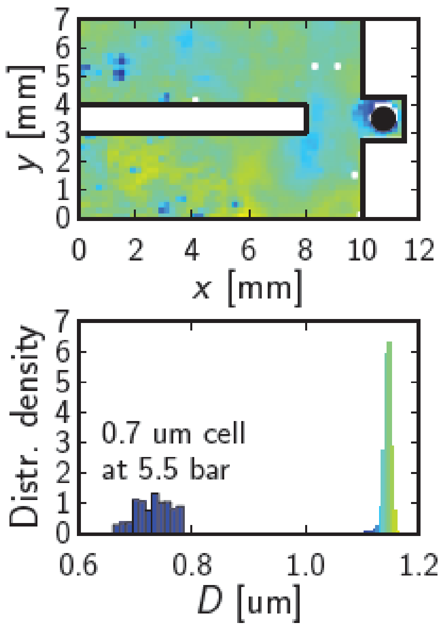
The B phase

Suppressed and distorted in the slab.
Two gap components $\Delta_\parallel(z)$ and $\Delta_\perp(z)$

$$\Delta f = \Delta f\left(\langle \Delta_\parallel^2 \rangle, \langle \Delta_\parallel \Delta_\perp \rangle, \langle \Delta_\perp^2 \rangle\right)$$

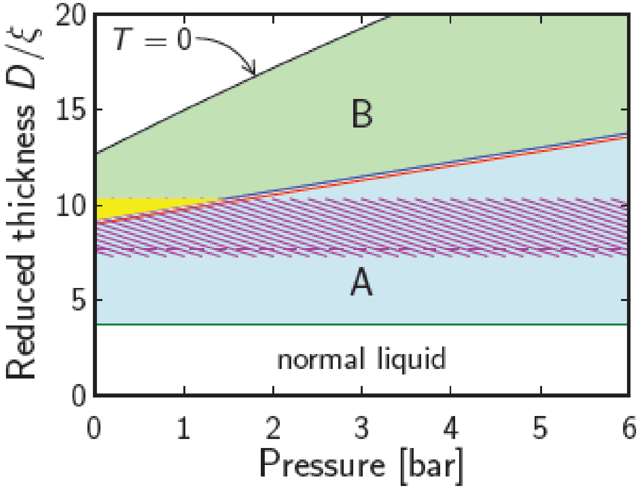


- Si&glass cell with a 1.1 µm cavity
- Partition wall in the middle
- Improved uniformity of D
- Reduced bowing due to thermal contraction and inflation under pressure



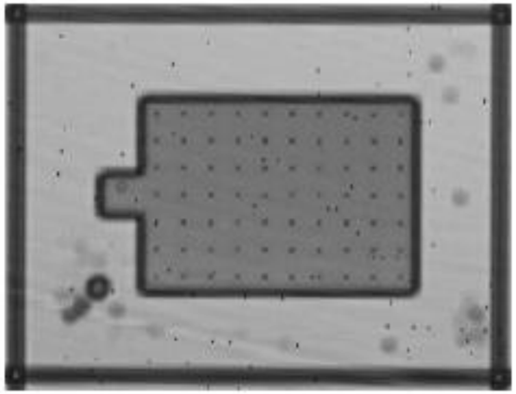
- Increase D to 1.1 µm
- Expect A-B transition at $P = 0$ bar
- Stripe phase?

Predicted phase diagram in a 1.1 µm slab



Gapped Chiral Phase: Towards 2D A phase [2D p + ip]

- New cell with 100 nm spacing
- Fully silicon, 0.4 mm wafers
- Pillars to maintain the spacing



Acoustic microscopy scan

- Interrupt the fill line with a cryogenic valve below 10 mK: lock thick ^{4}He films $\Longrightarrow$ specular walls

Size quantization:

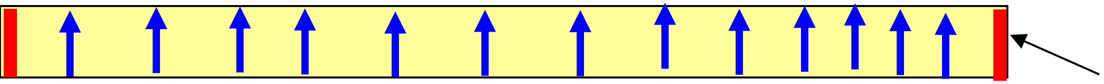
Fermi surface → Fermi discs

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

$$j_0 = \frac{k_F L}{\pi}$$

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

^{3}He-A: broken time reversal symmetry

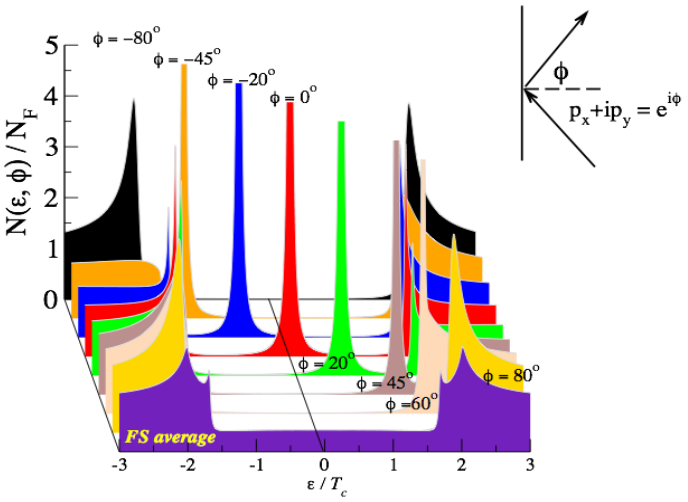


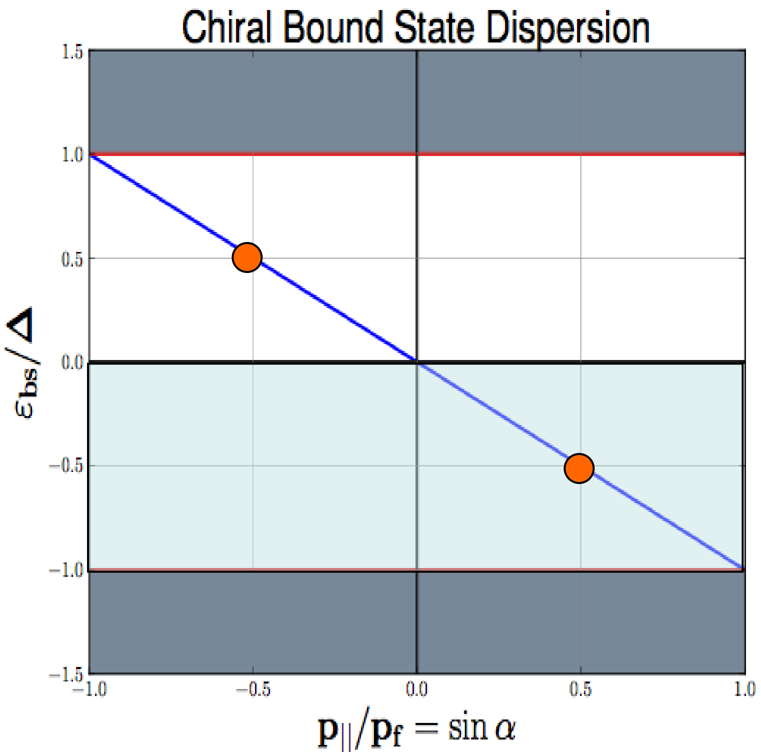
Chiral edge states (Majorana-Weyl)
→Ground state angular momentum

$$L_z = \frac{N\hbar}{2}\left(\frac{\Delta}{E_F}\right)^p \qquad p=0,\ 1,\ 2\ ?$$

McClure-Takagi theorem PRL (1979)
Stone and Roy, PRB 2006
Sauls PRB 2011

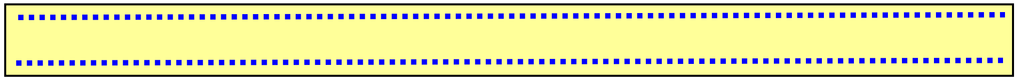
$$\widehat{L}_z |\, \Phi_N \,\rangle = \frac{N}{2}\hbar |\, \Phi_N \,\rangle$$





Surface modes satisfy Majorana condition

$$\Psi^{\dagger}(\mathbf{r}) = \Psi(\mathbf{r})$$



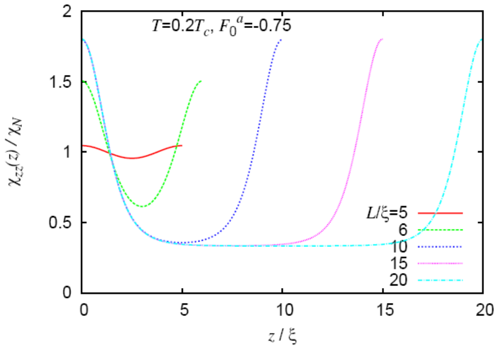
Superfluid is fully gapped away from surface

Gapless surface excitations in a fully gapped superfluid gives a power law contribution to heat capacity (thermal conductivity) which dominates at sufficiently low temperatures

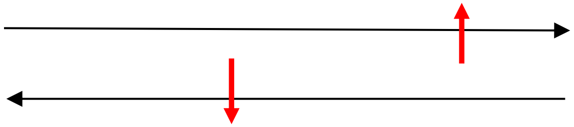
proposed experiments by Bunkov

Demonstrate strong spin orbit coupling of surface bound excitations
Proposed experiments by Okuda, Nomura on anisotropy of susceptibility:
by Kono group on anisotropy of T1

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

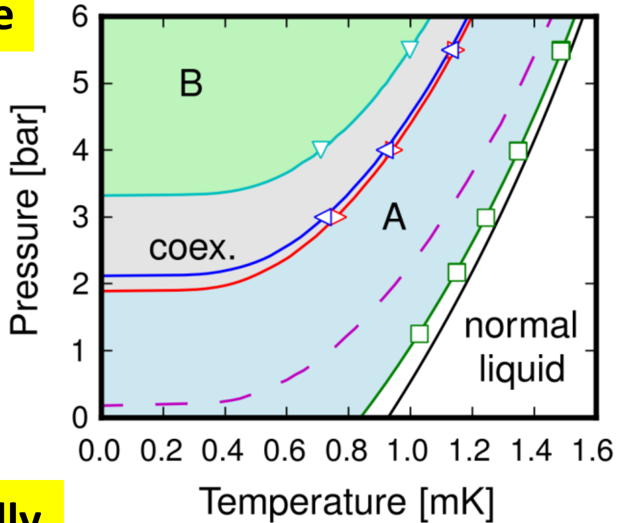


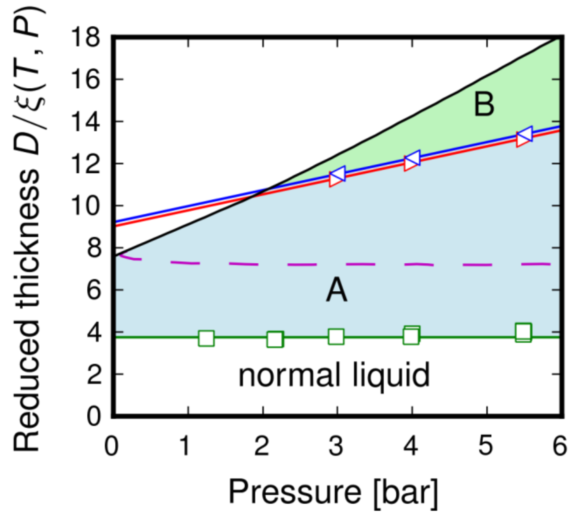
Demonstrate helicity of surface bound excitations

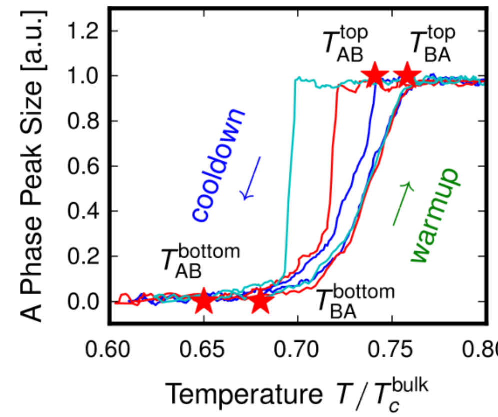


Tuning boundary scattering in situ: coating surface with a superfluid ^{4}He film

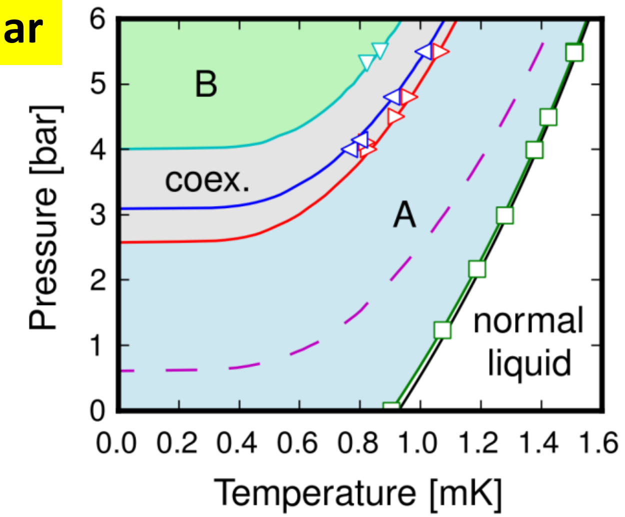
diffuse

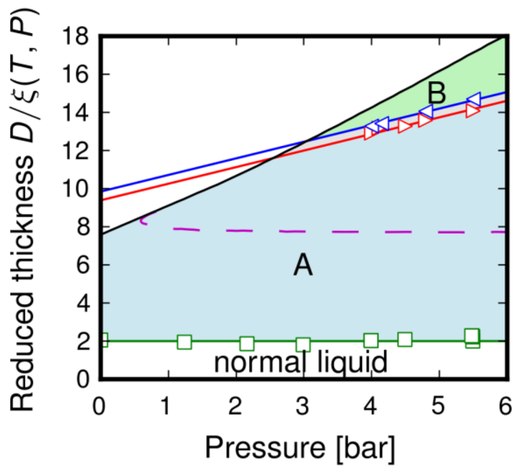


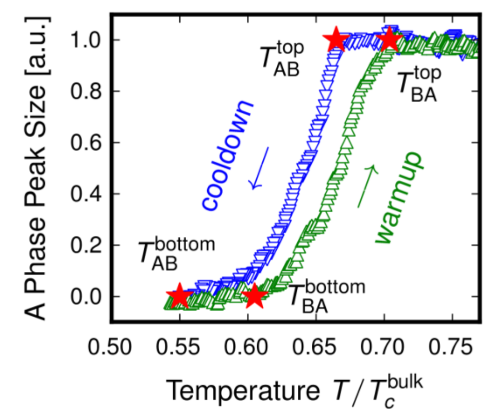




Partially specular

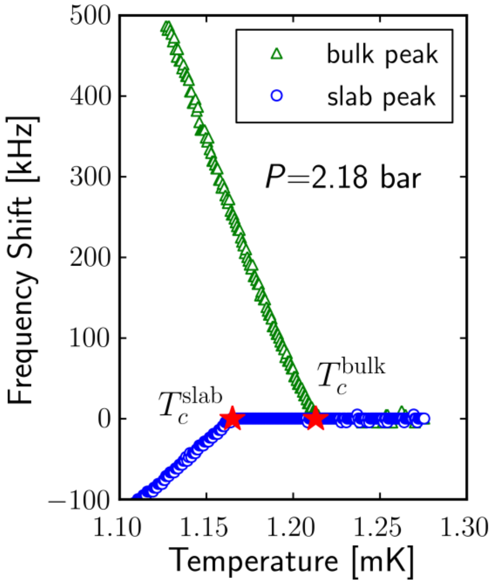


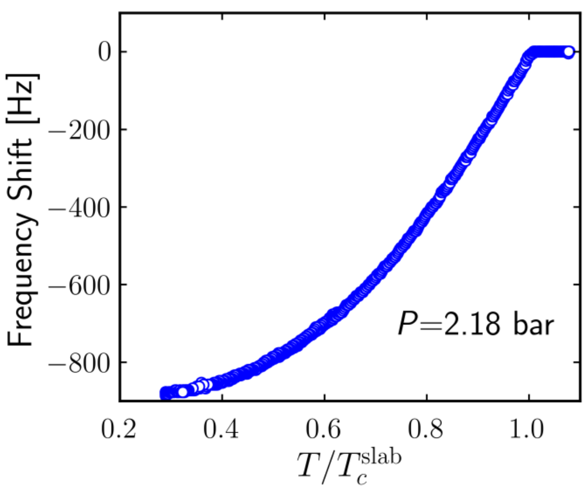




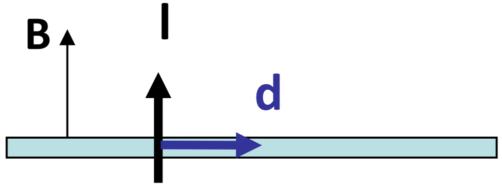
Dashed line = weak-coupling AB phase boundary

A- Phase in slab: NMR fingerprint





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



L normal to surface

Zeeman energy orients

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

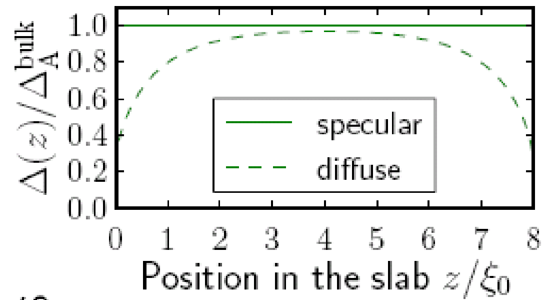
Dipole energy maximum

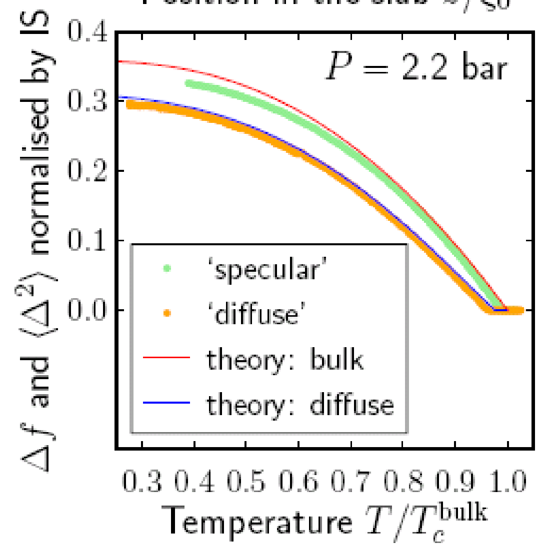
So -ve freq shift

Average gap:

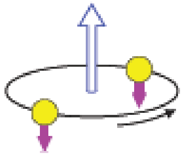
Diffuse and partially specular boundary

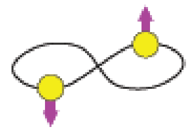
Comparison with quasiclassical theory (Vorontsov)

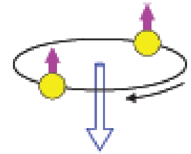




The B phase with a planar distortion: stable and metastable configuration

- B♮: $\Psi = \Delta_\parallel$ 

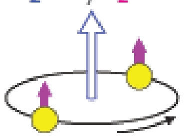
$+ \Delta_\perp$ 

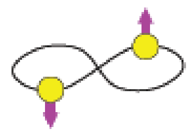
$+ \Delta_\parallel$ 

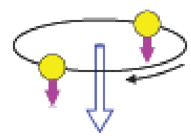
, $\quad L_z = -S_z$

(simplified) This is the minimum of magnetic and dipole energies

flip the spins of the pairs:

- B♭: $\Psi = \Delta_\parallel$ 

$+ \Delta_\perp$ 

$+ \Delta_\parallel$ 

, $\quad L_z = +S_z$

Also a minimum of magnetic energy, dipole energy out of equilibrium

Two states correspond to different relative orientations of spin and orbital part
Large susceptibility anisotropy arising from planar distortion

$$A_{\mu j} = e^{i\phi} R_{\mu m}\left[\Delta_\parallel \delta_{mj} + (\Delta_\perp - \Delta_\parallel)\hat{o}_m \hat{o}_j\right]$$

$$\hat{\mathrm{o}} = \pm\hat{\mathrm{z}}.$$

$$\hat{\mathrm{w}} = R\,\hat{\mathrm{o}}.$$

$$\overline{F}_H = -\tfrac{1}{2}\overline{\chi}_\perp H^2 - \tfrac{1}{2}\overline{\Delta\chi}(\hat{\mathrm{w}}\cdot\mathbf{H})^2 \qquad \hat{\mathrm{w}} = \pm\hat{\mathbf{H}}$$

Established: Classify new states of matter by their broken symmetries

New: Classify new states of matter by non-trivial topological invariant

↓

Protected surface and edge states

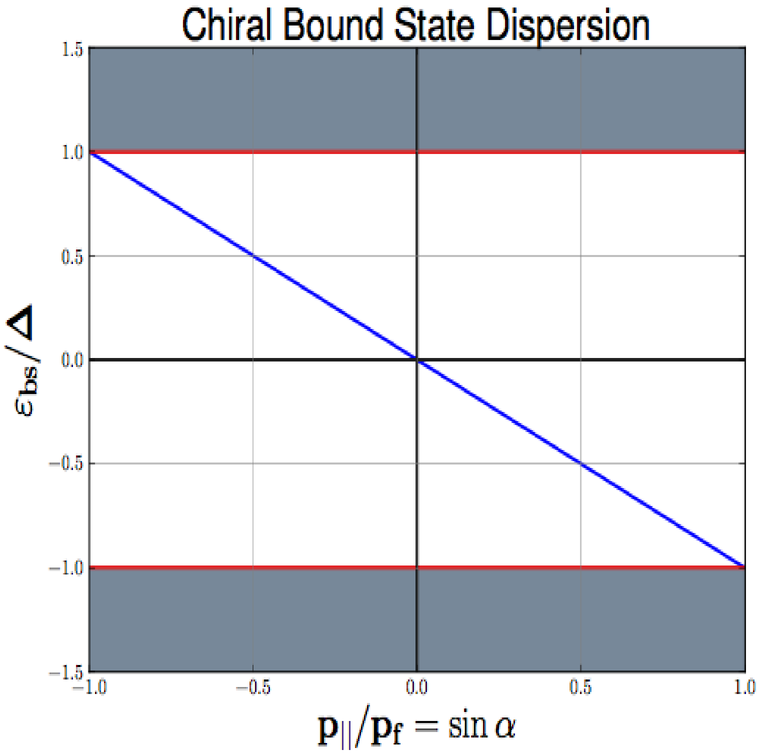
Quantum Hall Effect [Thouless 1982]
Quantum Spin Hall Effect [Kane/Mele 2005, Bernevig/Hughes/Zhang 2006, Molenkamp et al. 2007: HgTe/CdTe]
Topological Insulators [Fu/Kane/Mele, Moore/Balents 2007, Hasan et. al ; $Bi_{1-x}Sb_x$ (2008), Bi_2Se_3 (2009)]

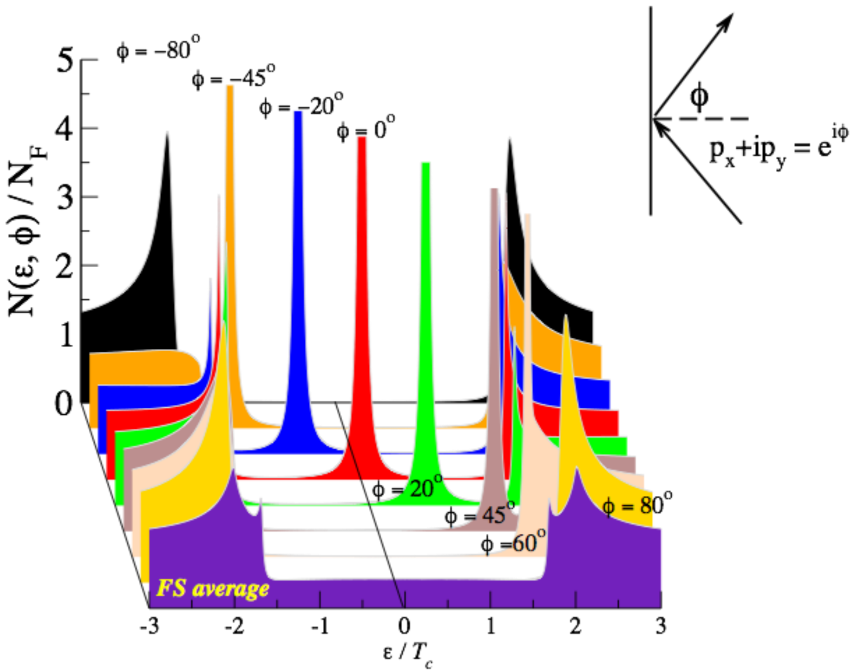
Topological Superconductors [Volovik 1988……, Roy 2008, Schnyder/Ryu/Furusaki/Ludwig 2008, Kitaev 2009, Qi/Hughes/Raghu/Chung/Zhang 2009]

→ Need to identify examples in nature [1. chiral 2. time reversal invariant]

Reviews: Hasan/Kane Rev. Mod. Phys.2010, Qi/Zhang Rev. Mod. Phys. 2011, Hasan/Moore Ann. Rev. Cond. Matter Phys. 2011

Gapped Chiral Phase: Towards 2D A phase [2D p + ip]





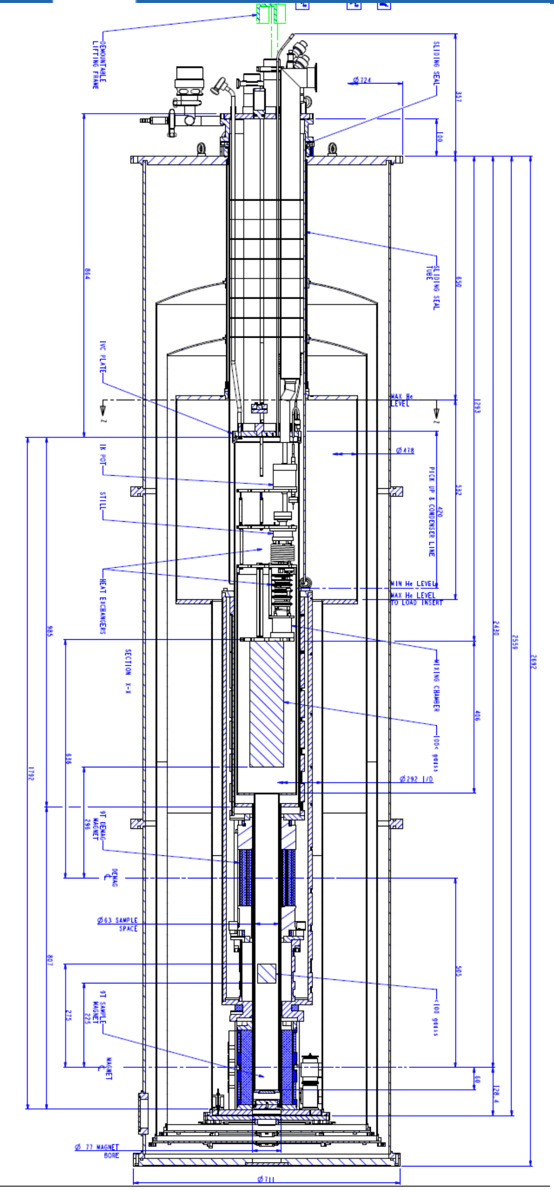
Size quantization:

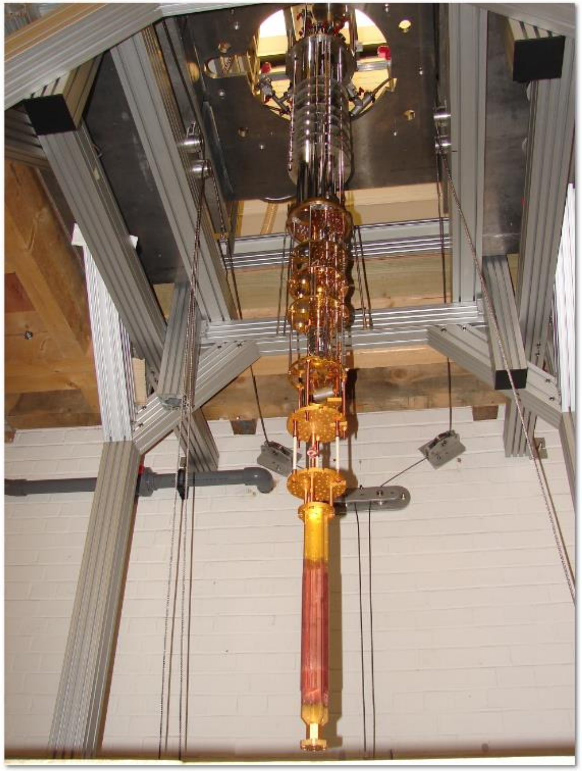
Fermi surface → Fermi discs

$$\varepsilon = \frac{1}{2m^*}[p_z^2 + q^2] \qquad p_z = \frac{\hbar\pi j}{L} \qquad j_0 = \frac{k_F L}{\pi}$$

Fully gapped chiral phase

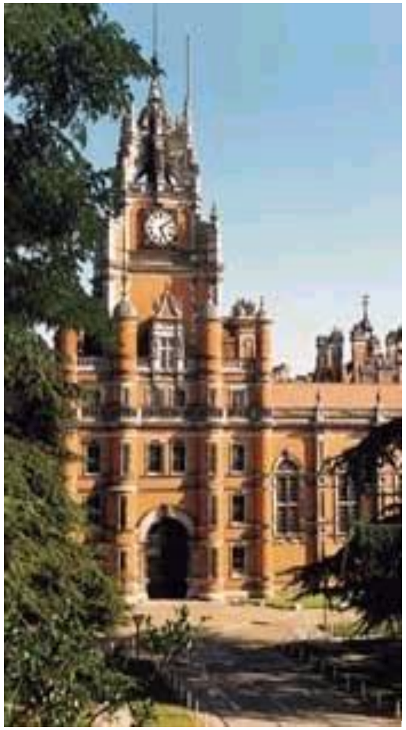
ND3: cooling semiconductor nanostructures and quantum matter





Helium in restricted geometries

ROYAL HOLLOWAY UNIVERSITY OF LONDON



EPSRC
Engineering and Physical Sciences Research Council

F Arnold, K Kent, **A Casey, LV Levitin**, B Yager
R Bennett, **J Nyeki**, **X Rojas**, **A Waterworth, B Cowan, JS**
+
M Eschrig, P Coleman, A Ho

European Microkelvin Collaboration (FP7 Research Infrastructures)

DC SQUID fabrication

RHUL-Cornell partnership
Nik Zhelev, Jeevak Parpia

Jim Sauls

CNF Cornell NanoScale Science and Technology Facility

Evgeny Surovtsev, Grisha Volovik, Anton Vorontsov, Takeshi Mizushima, Rob Ilic, Mika Fogelstrom, Erkii Thuneberg, Hao Wu, Josh Wiman, Derek Lee

Roadmap for confined superfluid 3He

^{3}He is the only established topological "superconductor"

We can manipulate its order parameter by confinement, fingerprint it, and measure the surface induced distortion by non-linear NMR. PRL 111, 235304 (2013)

Confinement can be used to sculpture and stabilize new order parameters (theory by Sauls). Polar phase, phase with 4-fold symmetry induced by array of posts.

We can reduce slab thickness, inducing stronger size quantization in normal state, to approach 2D limit "top-down". Planar or gapped A phase stable?

We envisage mesoscopic superfluid physics with ^{3}He in nanofluidic structures (including perfect SN, SS' interfaces).

Surface excitations of ^{3}He-B are **majoranas** (with strong s-o coupling), supporting ground state spin currents.

^{3}He-A is chiral with majorana-weyl edge modes, supporting ground state mass currents to be detected gyroscopically.