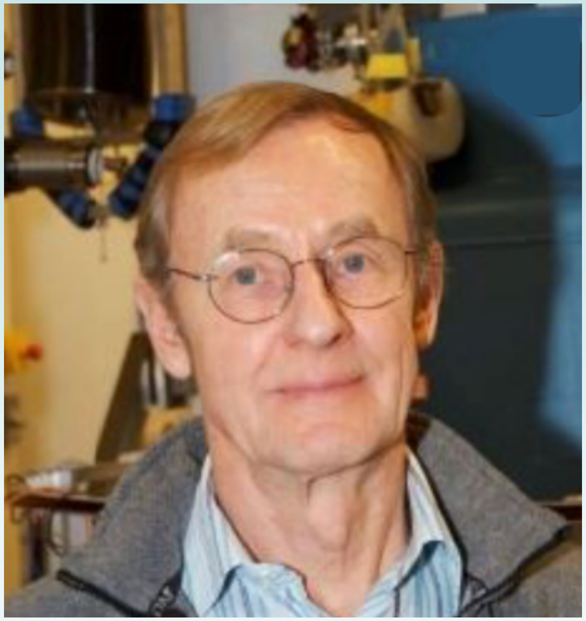
Paljon Onnea Matti



one of my favorites

Phase-Diagram of the 1st-Order Vortex-Core Transition in Superfluid He-3-B
Pekola, Simola, Hakonen, Krusius, Lounasmaa, Nummila, Mamniashvili, Packard, Volovik

50 Years of Superfluid ^{3}He

Odd-Parity Symmetry
in
Topological Superconductors

Bill Halperin
Northwestern University

NORTHWESTERN UNIVERSITY

National Science Foundation
Directorate for Mathematical & Physical Sciences (MPS/DMR)

U.S. DEPARTMENT OF ENERGY
Office of Science

Topological Superconductors

^3He — 50 Years of Superfluid ^3He

UPt_3

Sr_2RuO_4 (?)

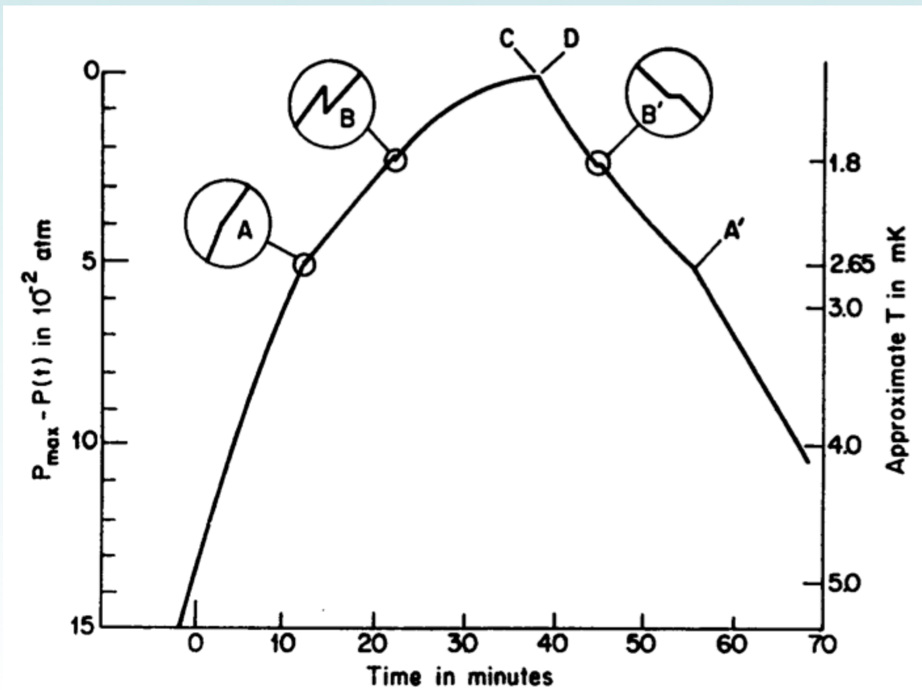
URu_2Si_2, UGe_2, UCoGe

$RbEuFe_4As_4$

UTe_2

Superfluid ^{3}He

Nobel prize 1996



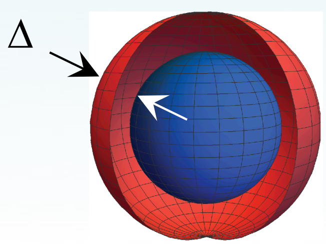
Nobel prize 2003

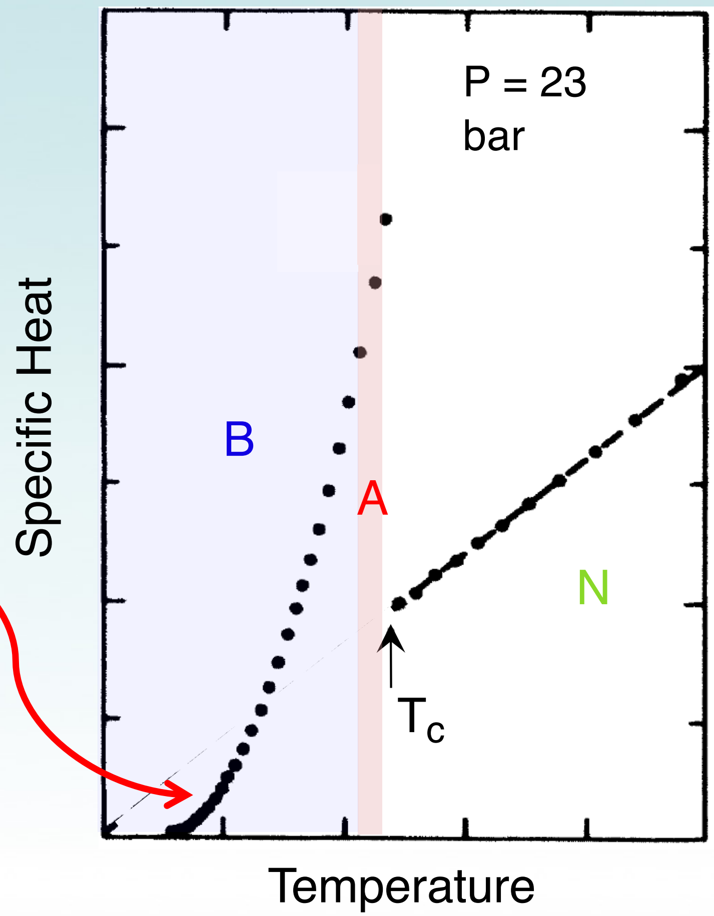
Basic properties of the superfluid

^{3}He Specific heat

Greywall, PRB **33** 7520 (1986)

evidence of an isotropic energy gap Δ in the B-phase



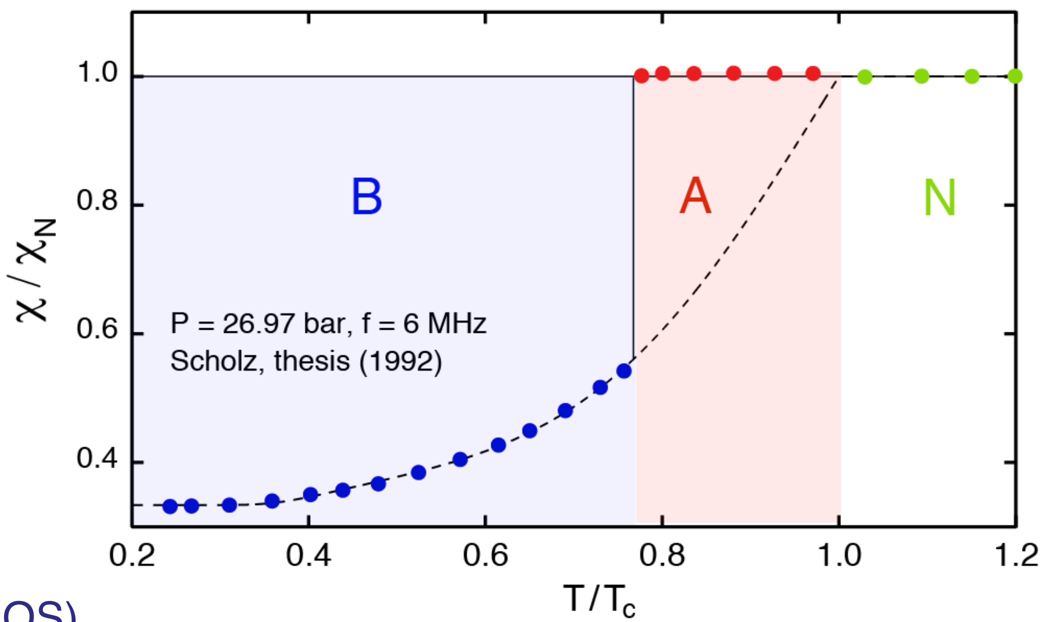


Basic Properties of the Superfluid

A-phase:
equal spin pairing: ↑↑, ↓↓
triplet spin state : L = 1, S = 1
odd parity
chiral, broken time-reversal symmetry

B-phase:
same transition as the A-phase
same pairing state manifold: L = 1, S = 1
non-equal spin pairing: ↑↑, ↓↓ , ↑↓+↓↑
time reversal symmetric
broken relative spin-orbit symmetry (SBSOS)

^{3}He Susceptibility

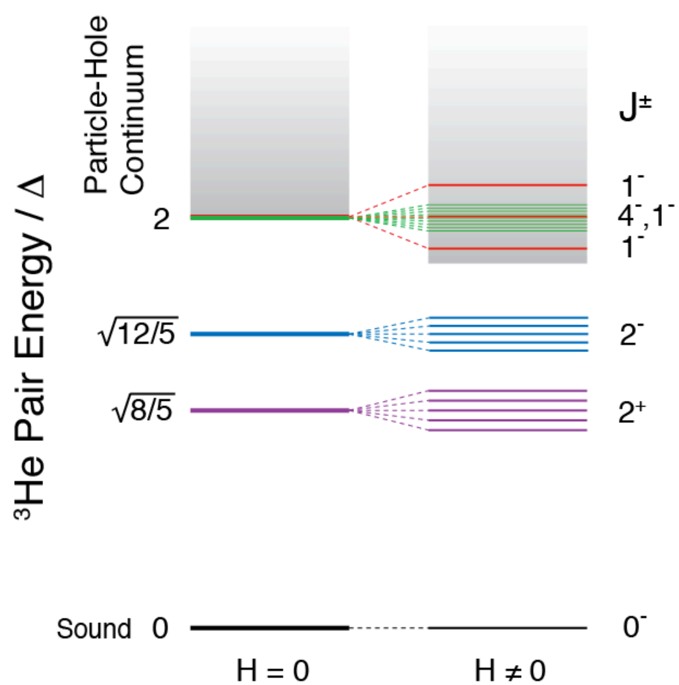


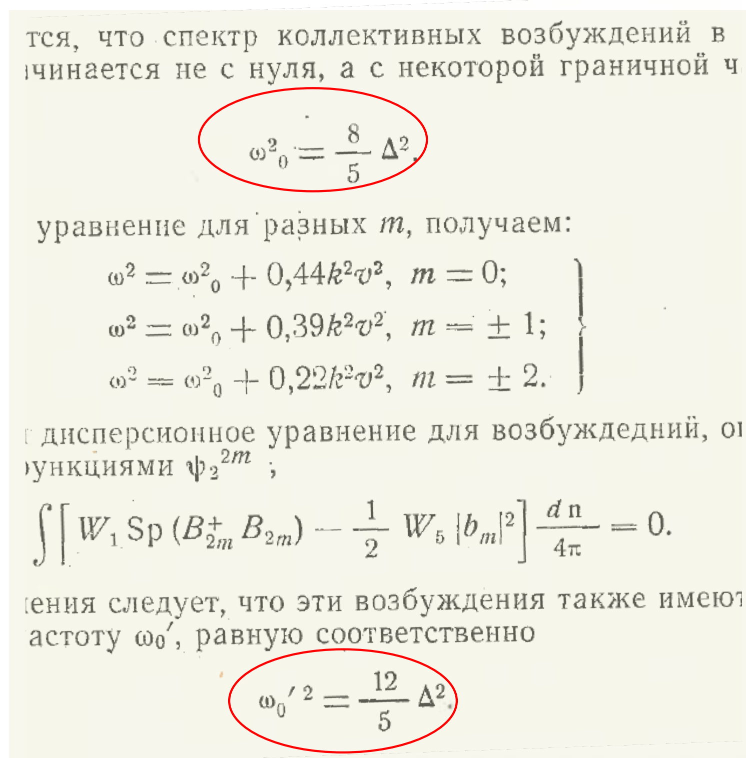
Superfluid ^{3}He-B order parameter

J = 2, bosonic Higgs collective modes

The highest symmetry odd parity state is the L = 1 isotropic state.

Balian/Werthamer,
PRB **131** 1353 (1963)
Vdovin, GOS ATOM ISDAT, p94 (1963)





тся, что спектр коллективных возбуждений в
ıчинается не с нуля, а с некоторой граничной ч

$$\omega^2{}_0 = \frac{8}{5}\Delta^2,$$

уравнение для разных m, получаем:

$$\left.\begin{aligned} \omega^2 &= \omega^2{}_0 + 0{,}44k^2v^2, \quad m = 0; \\ \omega^2 &= \omega^2{}_0 + 0{,}39k^2v^2, \quad m = \pm 1; \\ \omega^2 &= \omega^2{}_0 + 0{,}22k^2v^2, \quad m = \pm 2. \end{aligned}\right\}$$

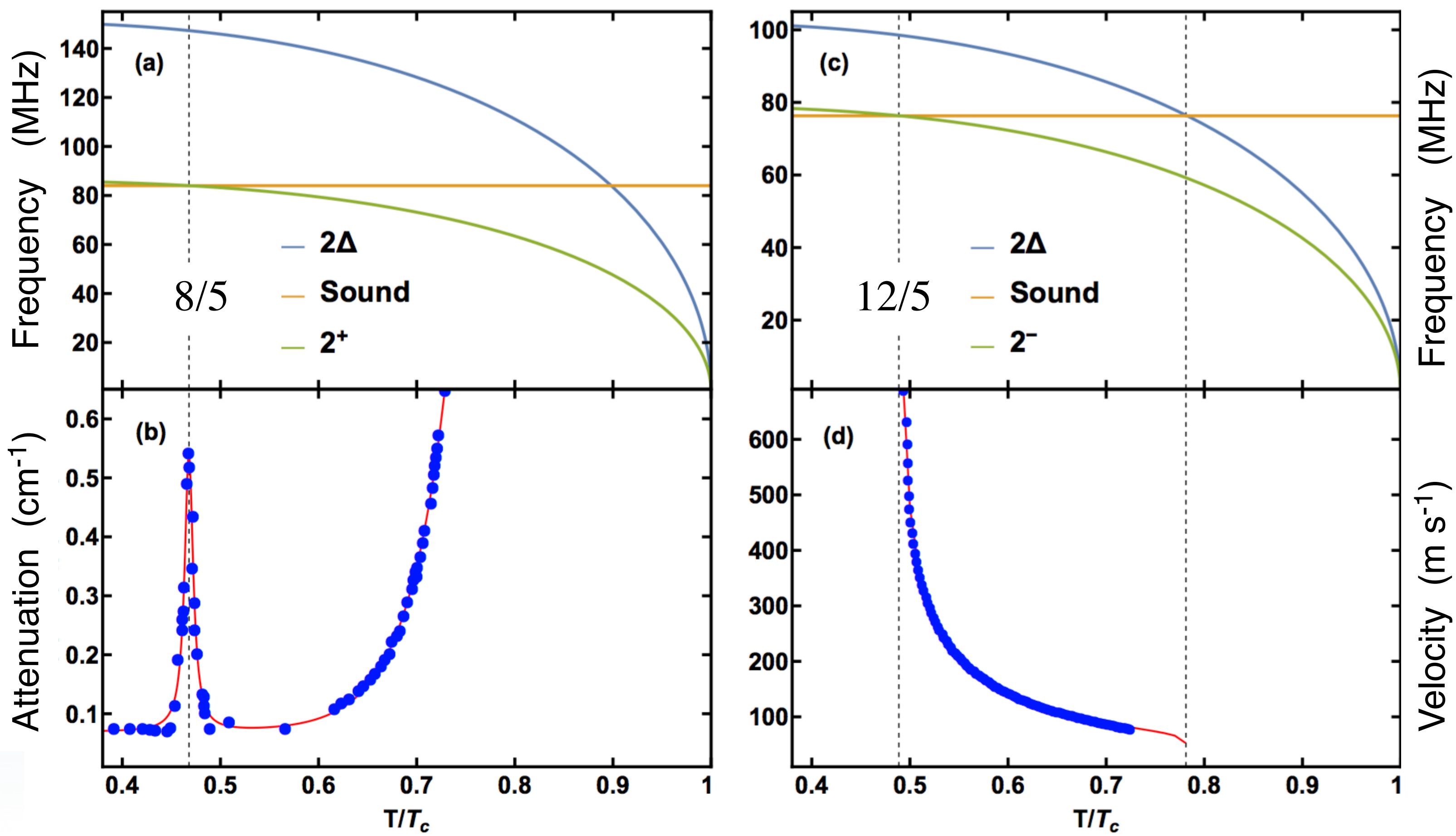
ı дисперсионное уравнение для возбуждедний, о
ıункциями $\psi_2{}^{2m}$;

$$\int\left[W_1\,\mathrm{Sp}\,(B^+_{2m}B_{2m}) - \frac{1}{2}W_5\,|b_m|^2\right]\frac{d\,\mathrm{n}}{4\pi} = 0.$$

ıения следует, что эти возбуждения также имеют
астоту ω_0', равную соответственно

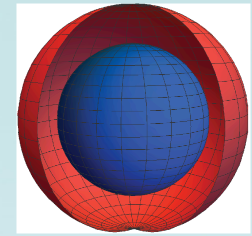
$$\omega_0'^{\,2} = \frac{12}{5}\Delta^2.$$

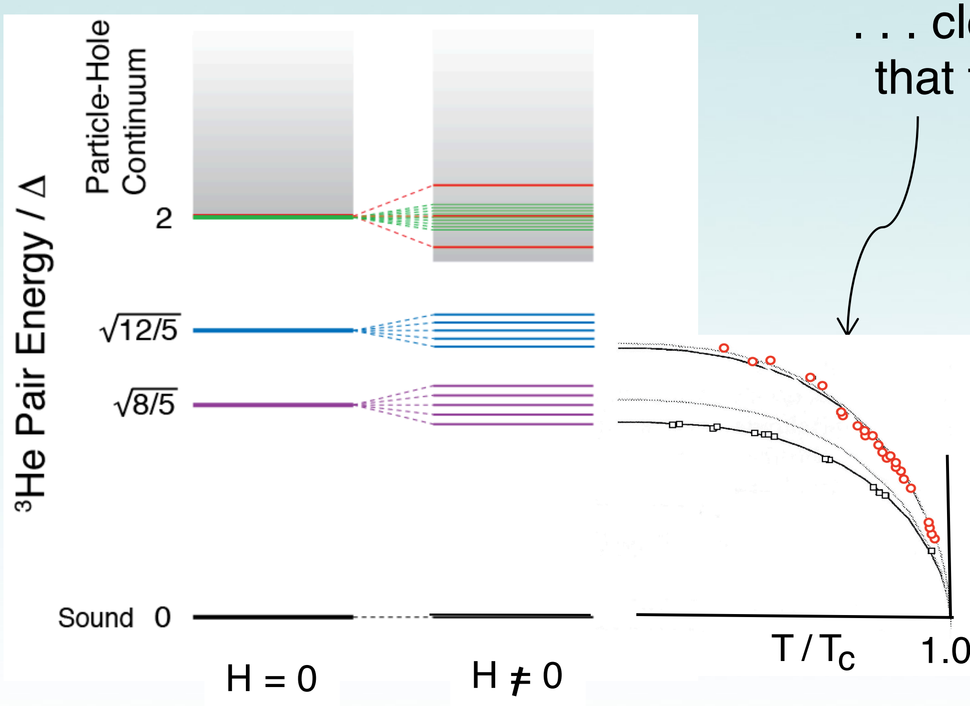
Longitudinal sound modes B-phase



Mast *et al.*
PRL **45**, 266 (1980)

B-phase order parameter collective modes





. . . clear evidence from acoustics that the B-phase is the BW-state

spontaneously broken relative spin-orbit rotation symmetry
Leggett PRL **29** 1227 (1972)

$$\boldsymbol{d}(\boldsymbol{k}) = \Delta(T)\, e^{i\phi}\ \mathbf{R}(\hat{\boldsymbol{n}}, \theta)\ \hat{\boldsymbol{k}}$$

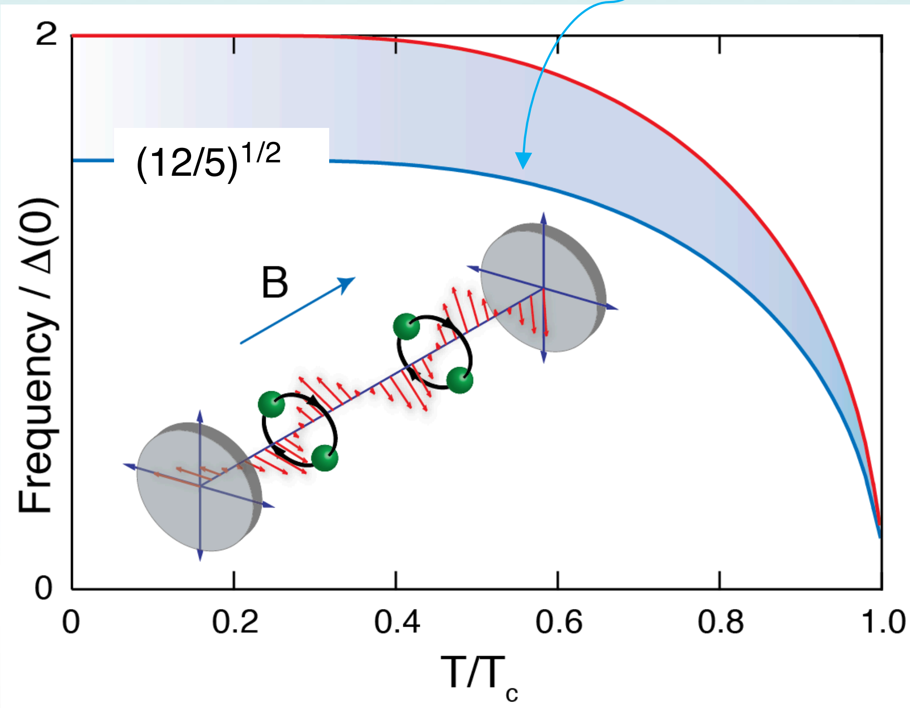
$$\theta_L = 104^\circ$$

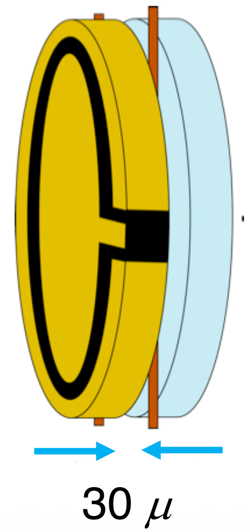
"Leggett angle"

Transverse sound

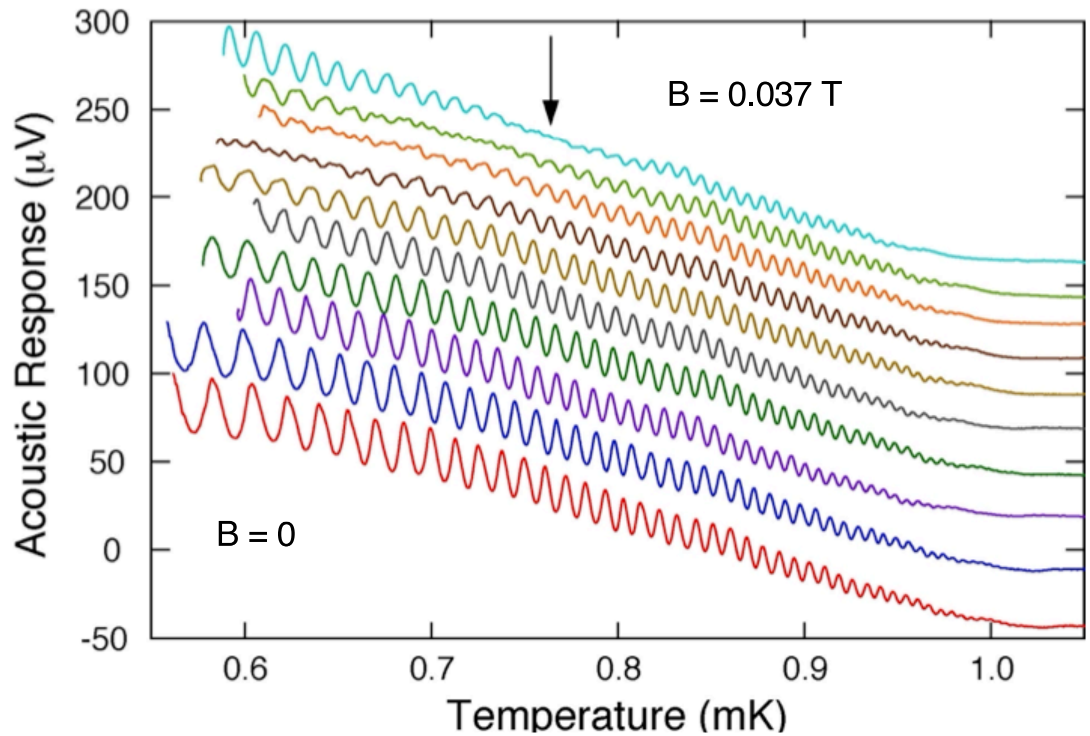
normal fluid prediction:
Landau, Sov. Phys. JETP **5**, 101 (1957)
. . . not yet observed
threshold m*/m > 3

superfluid prediction:
off resonant coupling to 12/5 collective mode
Moores and Sauls JLTP **91** 13 (1993). . . . and discovery
. . . Y. Lee *et al.* Nature **400** 431 (1999)



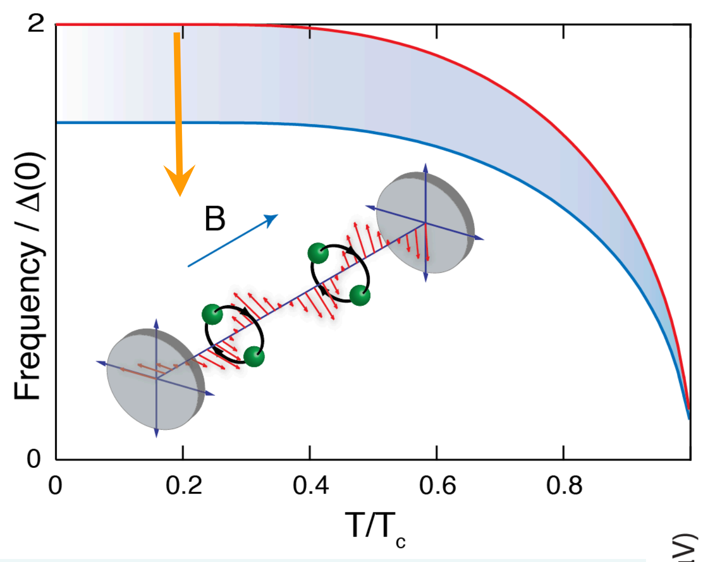


Transverse sound in superfluid ^{3}He-B



Y. Lee *et al*.
Nature **400** 431 (1999)
J.P. Davis, *et al*.
PRL **101**, 085301 (2008).

Transverse sound and Faraday rotation in Superfluid ^{3}He-B

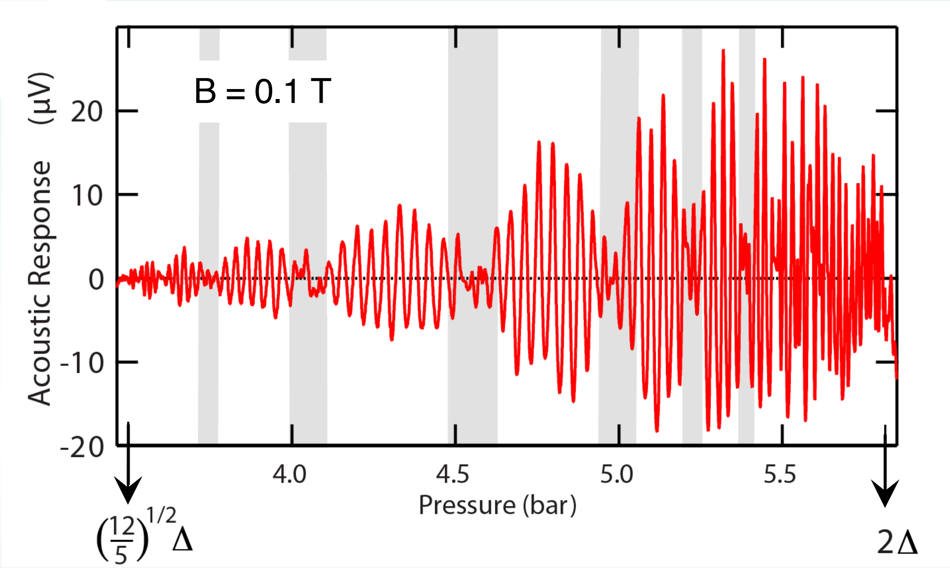


normal fluid prediction:
Landau, Sov. Phys. JETP **5**, 101 (1957)
. . . not yet observed!

superfluid prediction:
Moores and Sauls, JLTP **91** 13 (1993)

$$\boldsymbol{d}(\boldsymbol{k}) = \Delta(T)\, e^{i\phi}\ \mathbf{R}(\hat{\boldsymbol{n}}, \theta)\, \hat{\boldsymbol{k}}$$

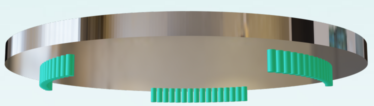
Y. Lee *et al.*
Nature **400** 431 (1999)
J.P. Davis, *et al.*
PRL **101**, 085301 (2008)
C. A. Collett *et al.*
PRB **87**, 024502 (2013)

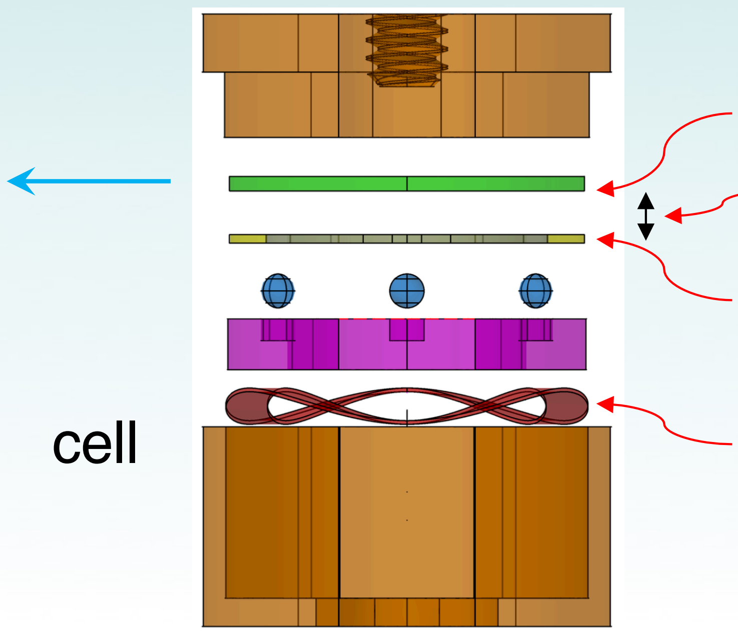


Search for transverse sound in the normal fluid?

predicted by L. D. Landau, Sov. Phys. JETP **5**, 101 (1957)

nanofabricated acoustic cavities
Man Nguyen *et al.*
. . . . amplitude resolution improvement > 400





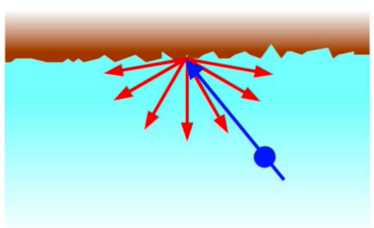
Surface states in ^{3}He-B (Andreev and Majorana)

Background

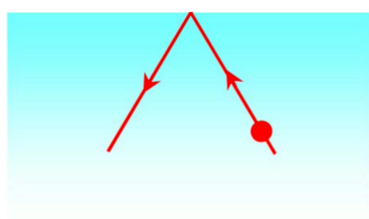
Chung and Zhang, PRL **103**, 235301 (2009)
Volovik, JETPL **90**, 398 (2009)
Nagato, Higashitani, Nagai, JPSJ **78**, 123603 (2009)
Murakawa *et al.* PRL **103**, 155301 (2009)
Wu and Sauls, PRB **88**. 184506 (2013)
Tsutsumi, PRL **118**, 145301 (2017)
Ikegami and Kono, JLTP **195**, 343 (2019)
Heikkinen *et al.* Nature Com.**12**, 1574 (2021)

Sauls arXiv:2203.16698 (2022)

diffusive scattering

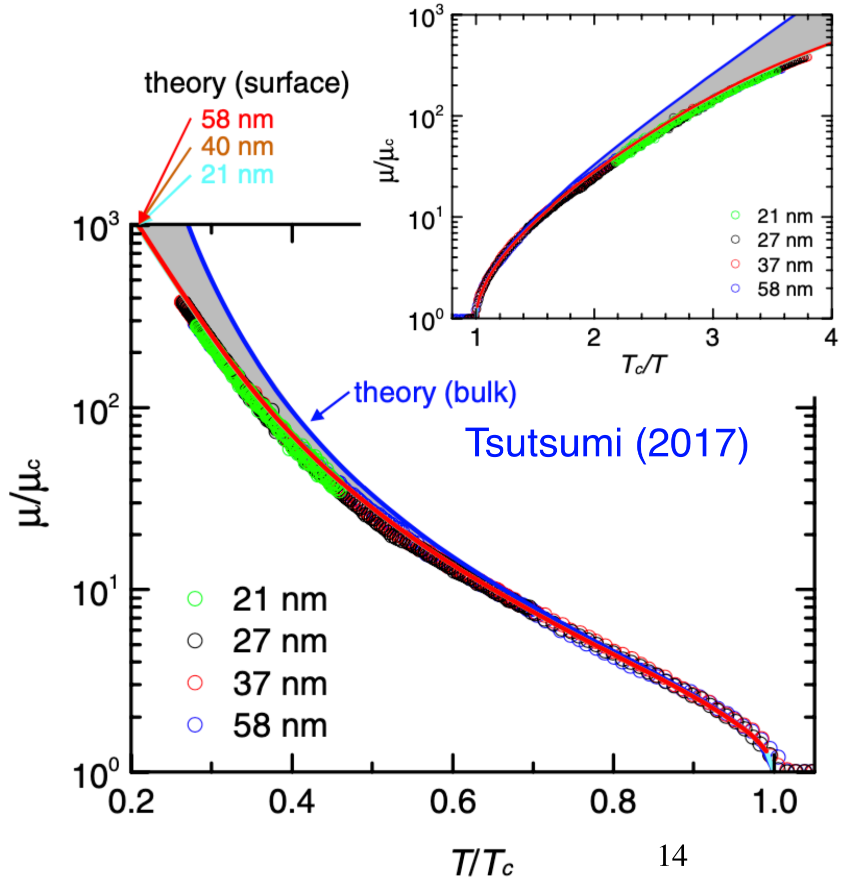


specular free surface



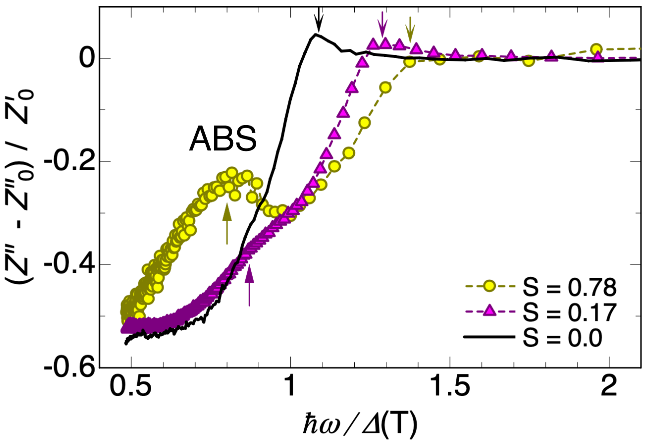
Compare with confinement between silicon slabs
Heikkinen *et al.* Nature Com.**12**, 1574 (2021)

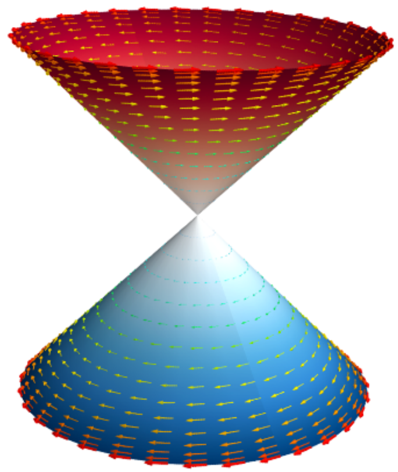
Ikegami and Kono, JLTP **195**, 343 (2019)
negative ion mobility below the
free surface of ^{3}He-B



Surface states in ^{3}He-B

Acoustic Impedance



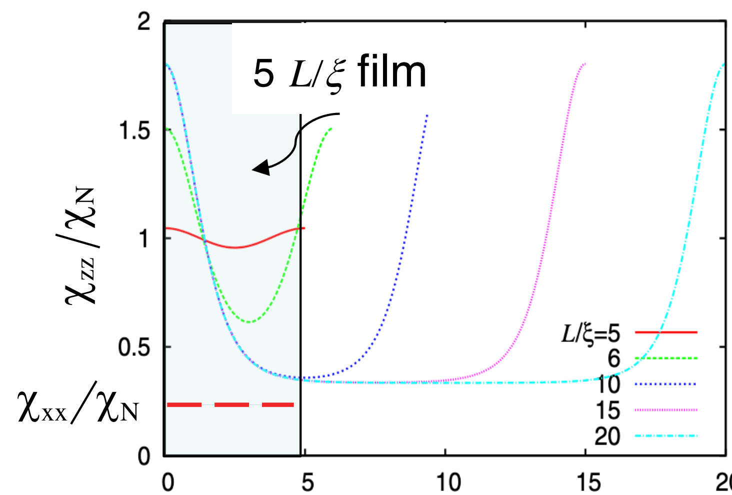


Sauls (2022)

Murakawa *et al.* PRL **103**, 155301 (2009)
Okuda, Nomura, *J. Phys: Con. Mat.* **24** 343201 (2012)

“Proving the Majorana nature of surface Andreev bound states is an important next step. One potential way of achieving this is to detect the Ising-like behavior of the spin of surface Andreev bound states” Ikegami and Kono, JLTP **195**, 343 (2019)

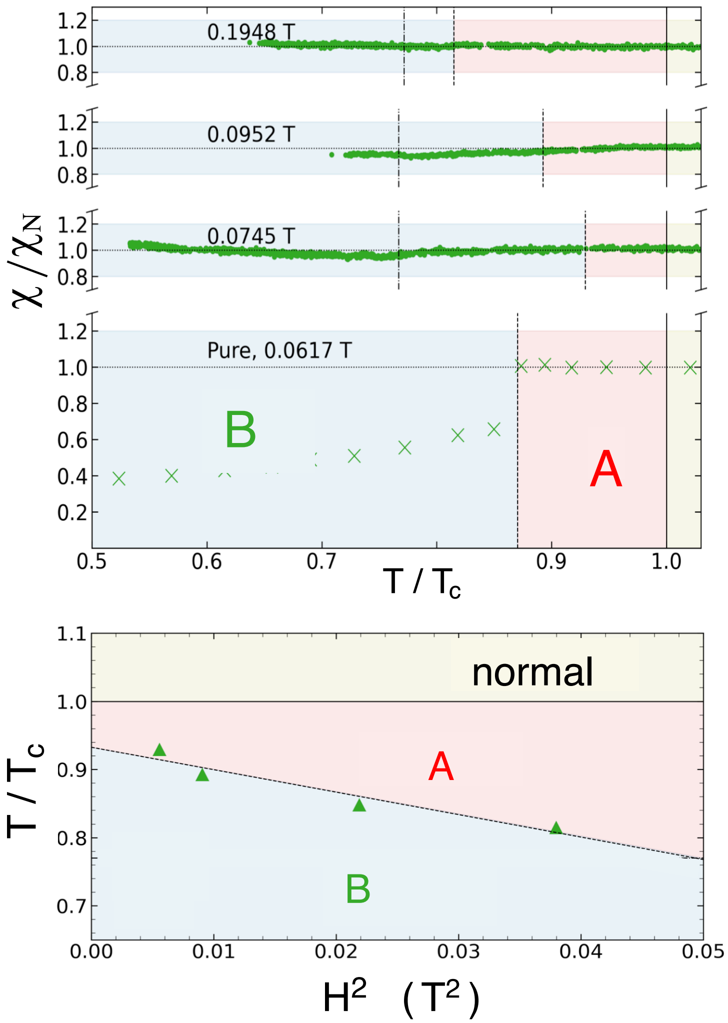
anisotropic susceptibility



Nagato, *et al.* JPSJ, **78**, 123603 (2009)

Magnetic surface states in ^{3}He-B

Scott *et al.* LT29 poster: P22-SF1-12

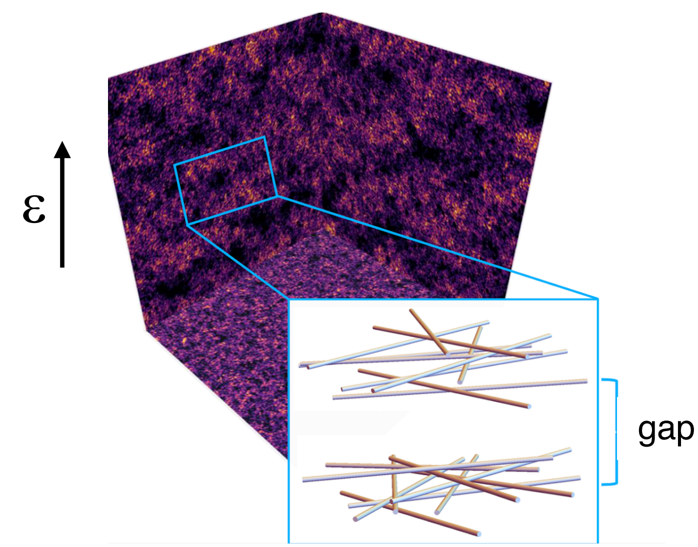


stretched silica aerogel, ε = 16% strain, P = 26 bar
^{4}He coverage completely removes the ^{3}He surface solid

discovery: both ^{3}He-A and ^{3}He-B appear to be equal spin pairing states for H $\parallel$ ε

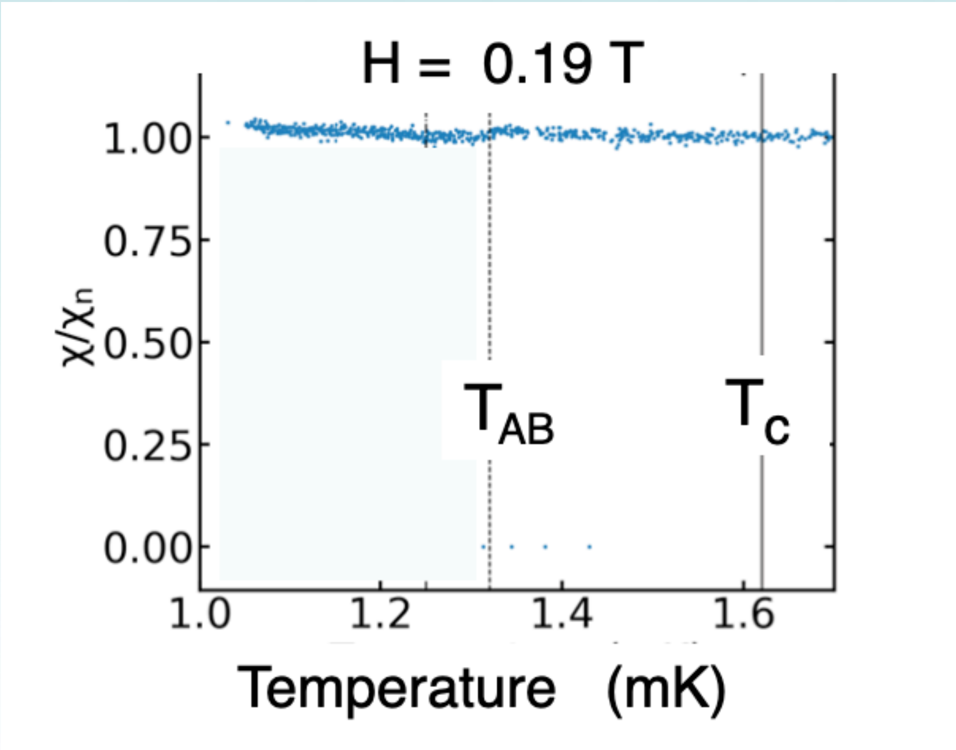
Ising surface states are a signature of Majoranas:
Nagato *et al.* JPSJ **78**, 123603 (2009)

planar-like structure from simulation of anisotropic aerogel
Nguyen *et al.*
ArViv: (2022)



- future: measure H $\perp$ ε

Anisotropic aerogel: ^4He preplated specular surface



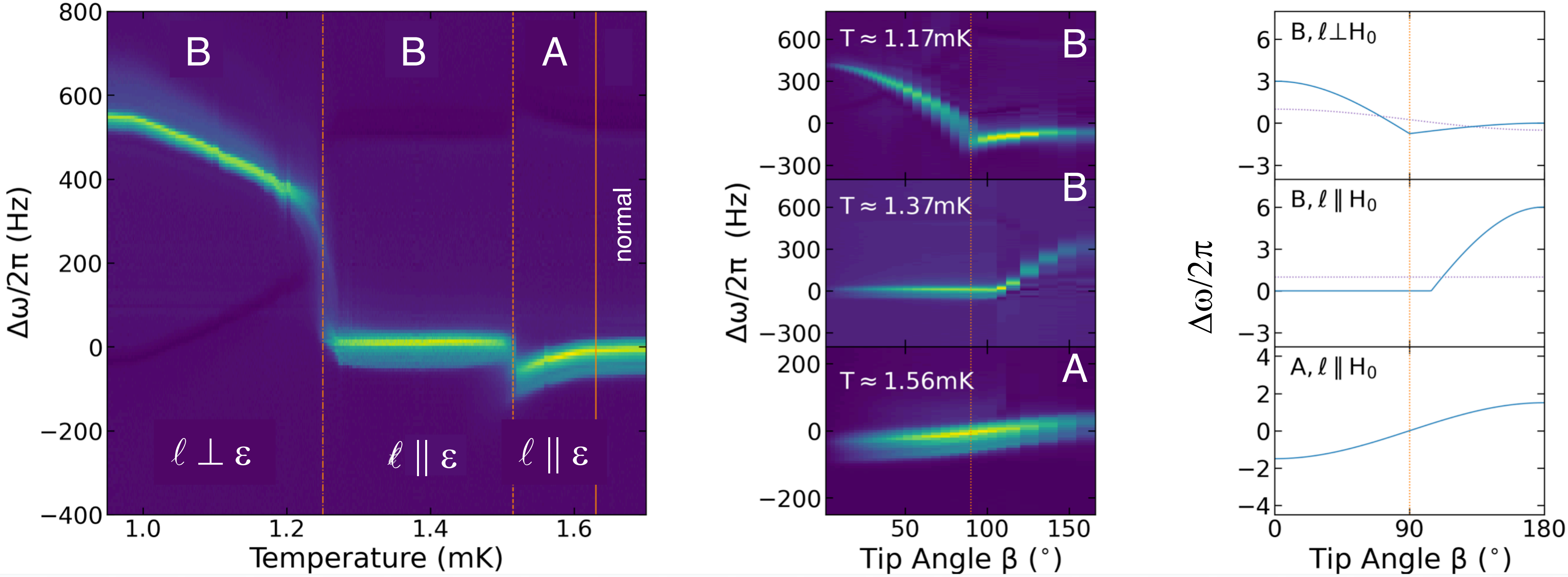
P = 26.6 bar
Strain 16% stretched

No susceptibility reduction in the B-phase; J. Scott, M.Nguyen, D. Park,WPH (2022)

Evidence for Andreev bound states with Majorana character. Nagato *et al.* JPSJ. 78, 123603 (2009).

Magnetic surface states in ^{3}He-B preplated-stretched silica aerogel

Identification of the A and B-phases



Chiral order in ^{3}He-A from confinement: anisotropic aerogel

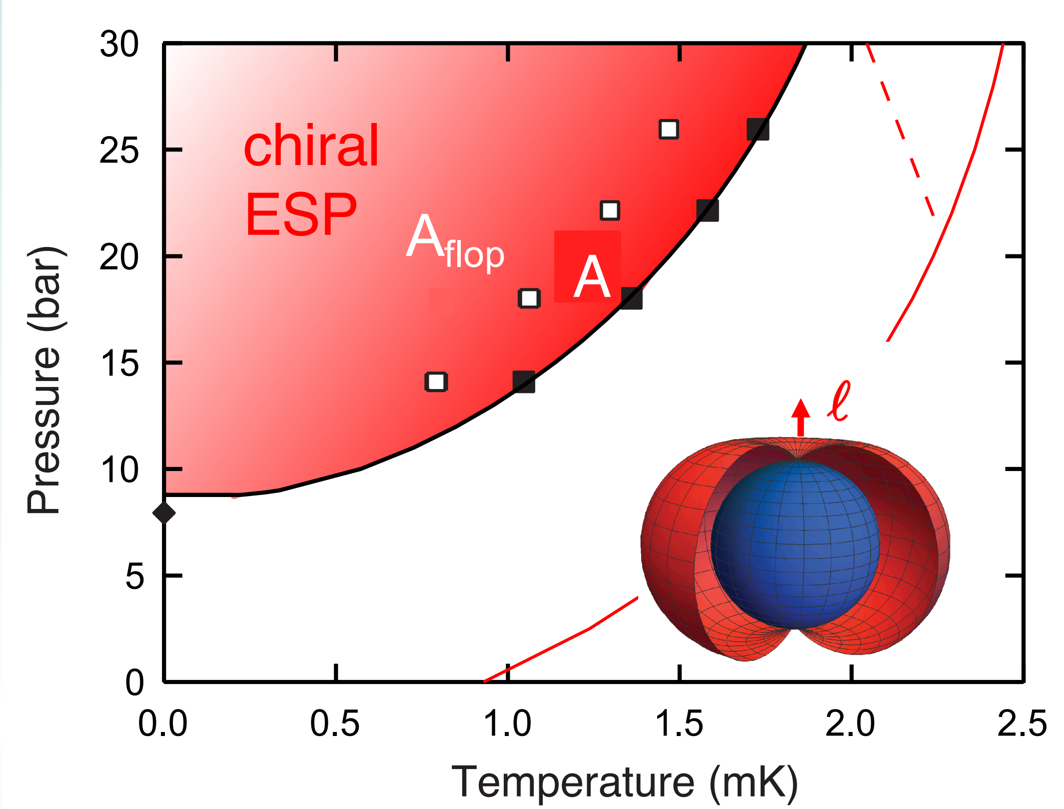
Stretched Aerogel
P-T Phase Diagram:

98% aerogel
strain $\varepsilon = 14\%$

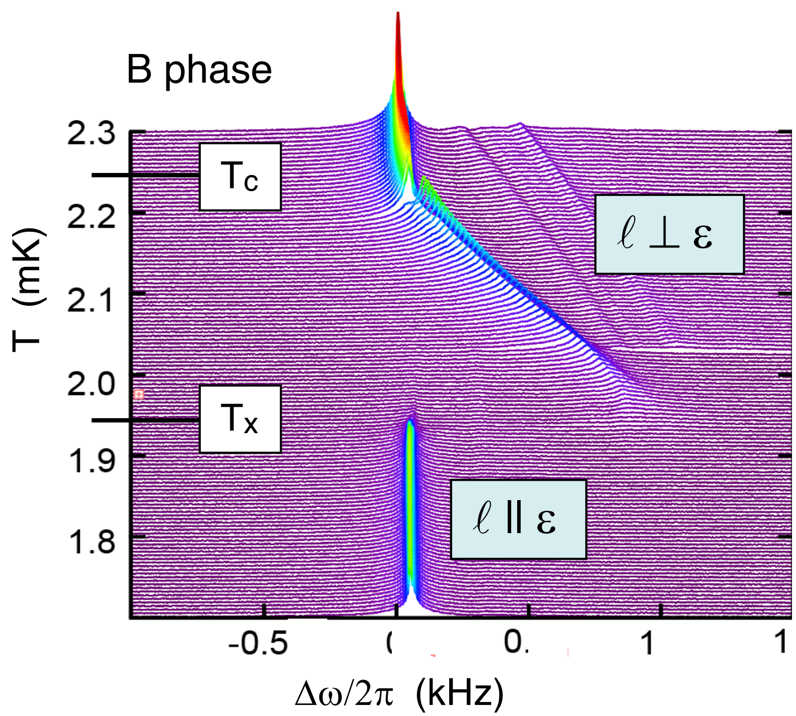
Pollanen *et al.*, Nat. Phys. **8** 317 (2012)

A and A_{flop} are axial
A : $\ell \parallel$ strain
A_{flop} : $\ell \perp$ strain
"orbital flop"

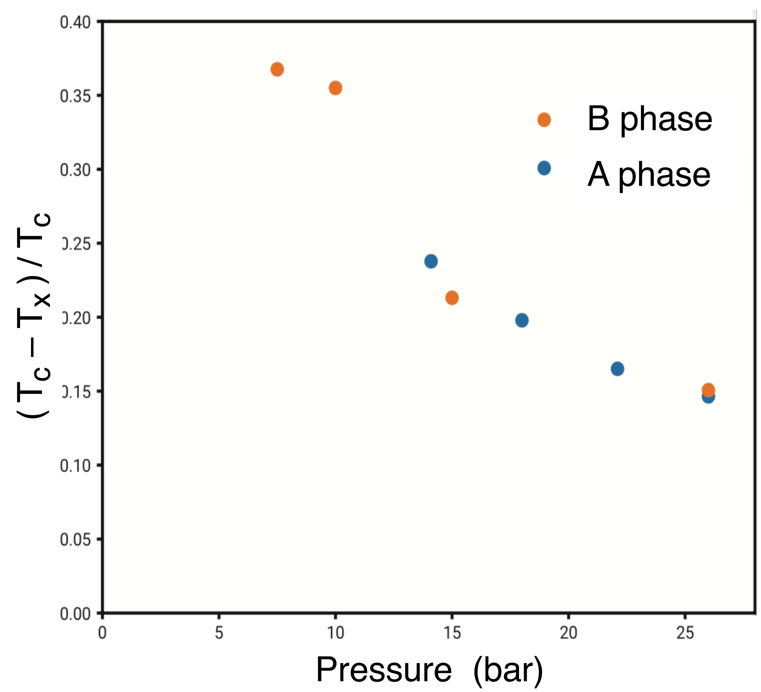
Zimmerman *et al.*
PRL **121** 255303 (2018):
Li *et al.*
JLTP **175**, 331 (2014)
Scott, *et al.*
LT29 poster: P22-SF1-12



Orbital-flop texture in ^{3}He-A and ^{3}He-B



Flop of the orbital axis in A and B phases



Topological Superconductors

^3He

UPt_3

Sr_2RuO_4 (?)

URu_2Si_2, UGe_2, UCoGe

$RbEuFe_4As_4$

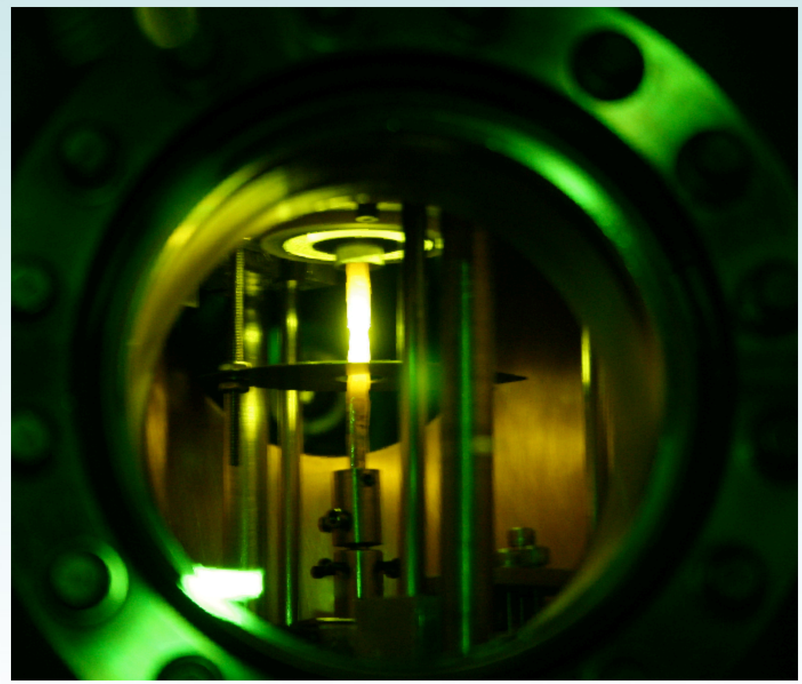
UTe_2

UPt_3 ultra-high vacuum, e-beam, float-zone refining

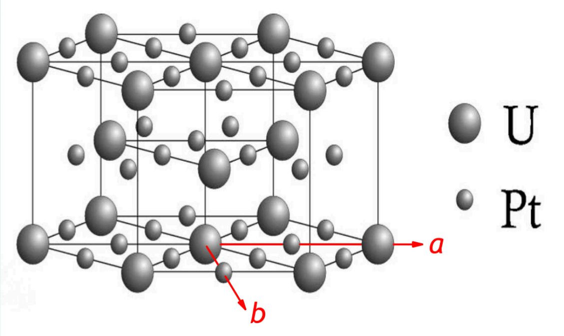
high quality:
RRR_c = 1,460
$\Delta T_c / T_c$ = 1.3 mK

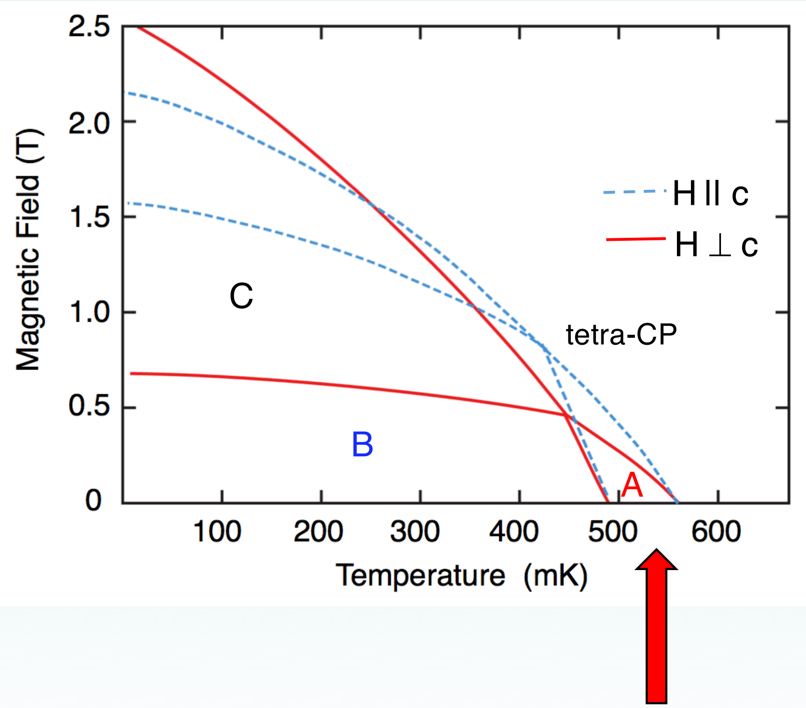
Kycia thesis (97)

4 cm,
15 gm



UPt_3 A, B, C : a phase triplet





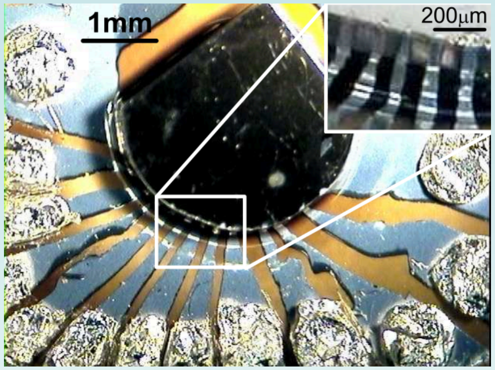
Stewart *et al.* PRL **52** 679 (1984);

unconventional
superconductor.

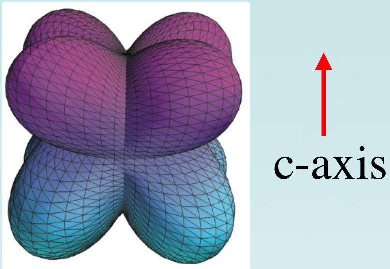
Sauls, E_{2u} symmetry
Adv. in Phys. **43**, 11(1994)

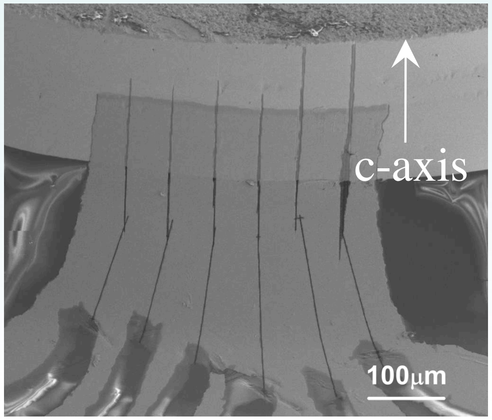
symmetry breaking field

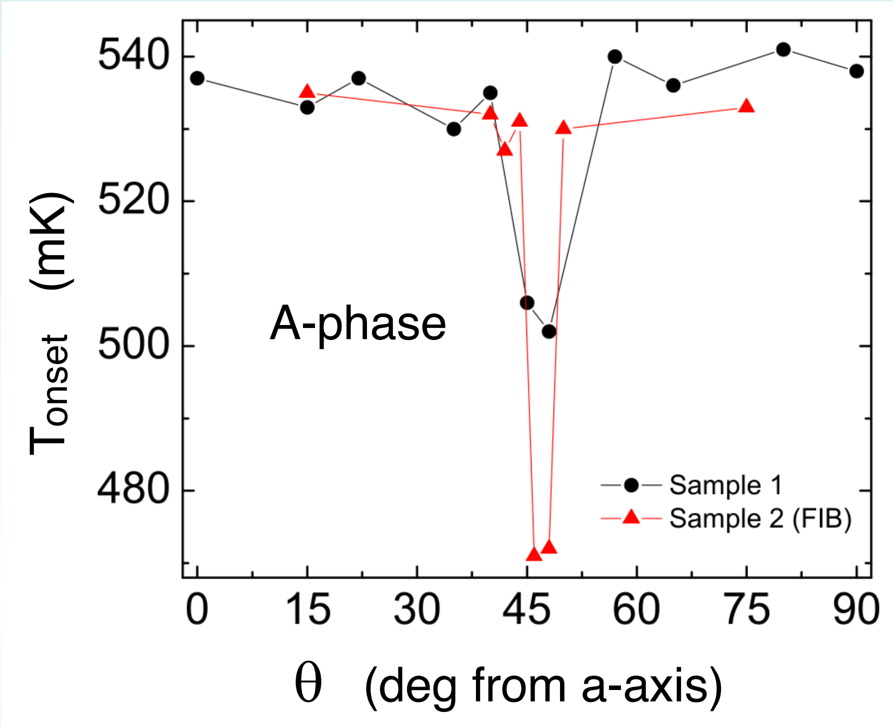
Nodal structure of UPt_3 A-phase



Strand, Van Harlingen *et al.*
Science **328** 1368 (2010)

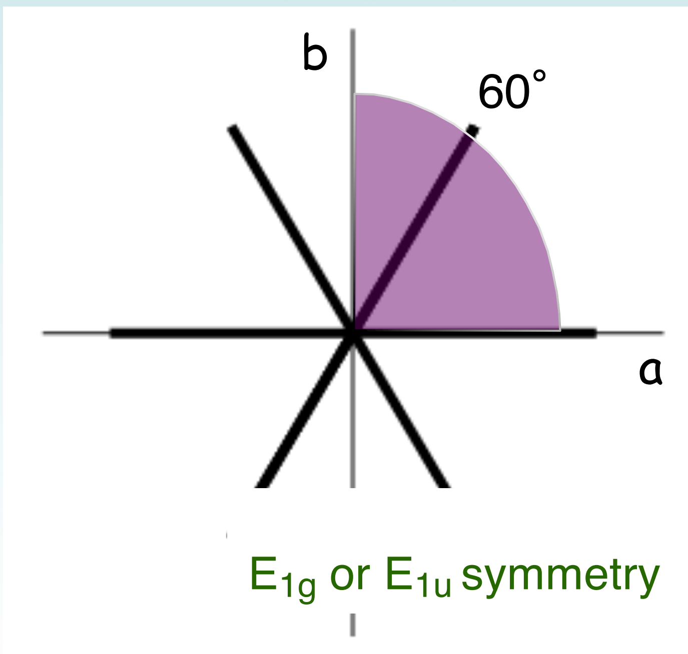


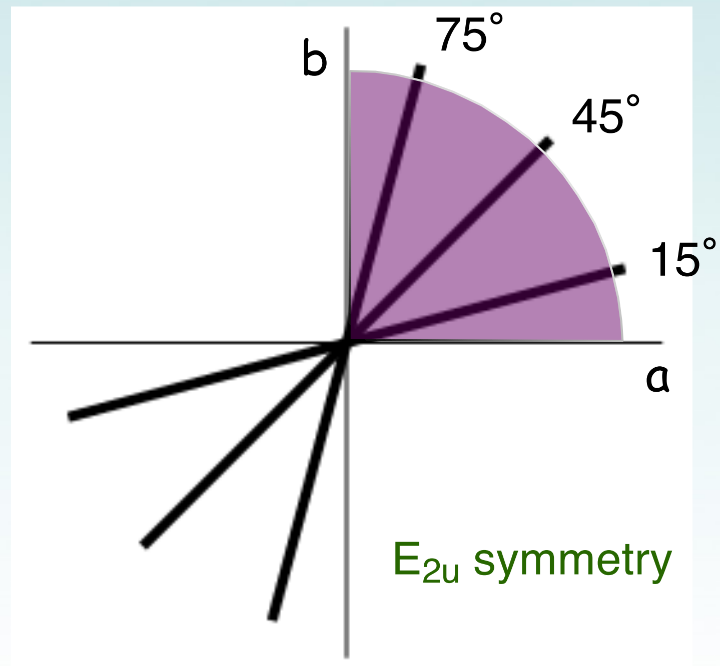




Directional tunneling experiment: A-phase

possible nodal directions for A-phase
in the field of view of the crystal basal plane





consistency with E_{2u} symmetry
single order parameter domain.

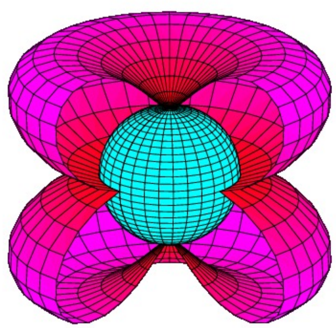
Superconductivity in the B-phase

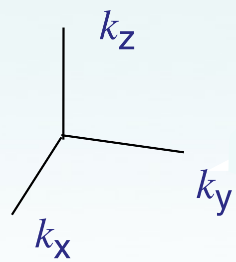
Broken mirror and time reversal symmetries in the B-phase

E_{2u} f - wave state proposed by: Sauls, Adv. in Phys. **43**, 113 (1994)

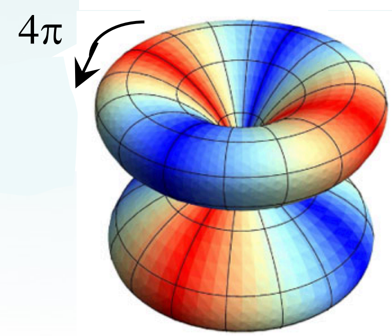
$$\Delta(\hat{\boldsymbol{k}}) = \Delta(T)\, \hat{k}_z\, (\hat{k}_x \pm i\, \hat{k}_y)^2$$

amplitude of $\Delta(k)$

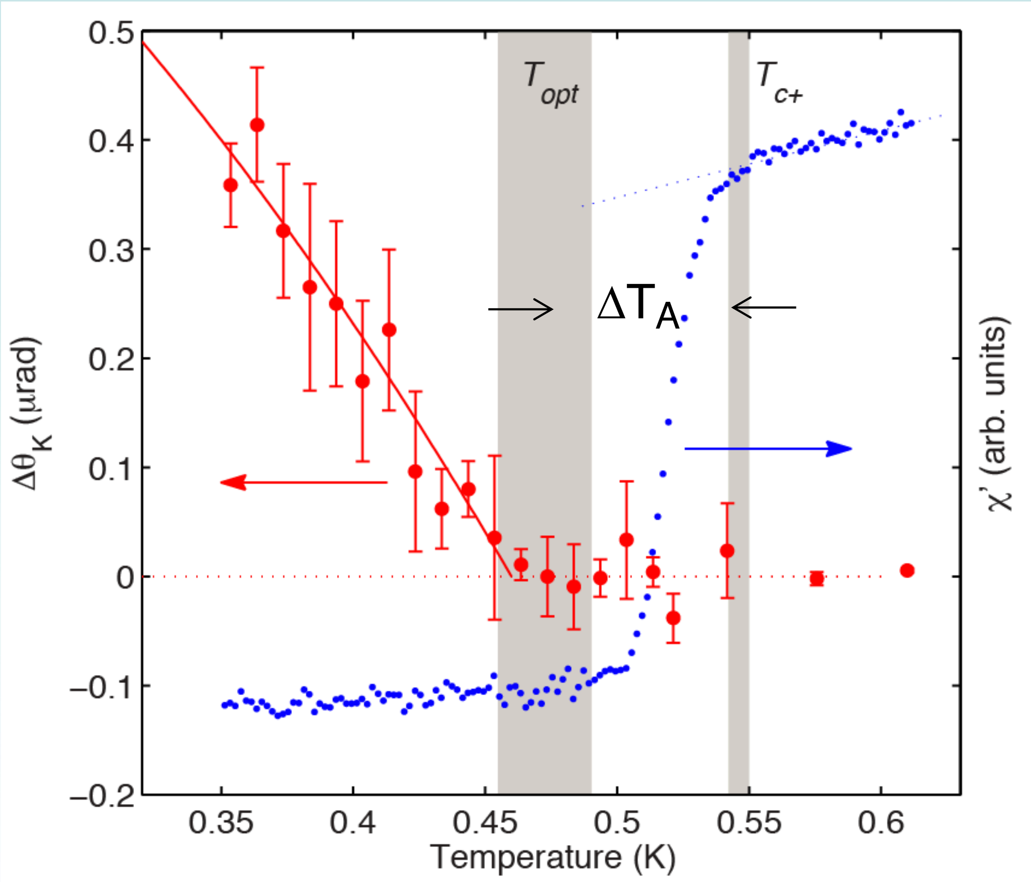




phase of $\Delta(k)$



Polar Kerr effect onset in the B-phase



Schemm and Kapitulnik *et al.*
Science **345**, 190 (2014)

c-axis facet

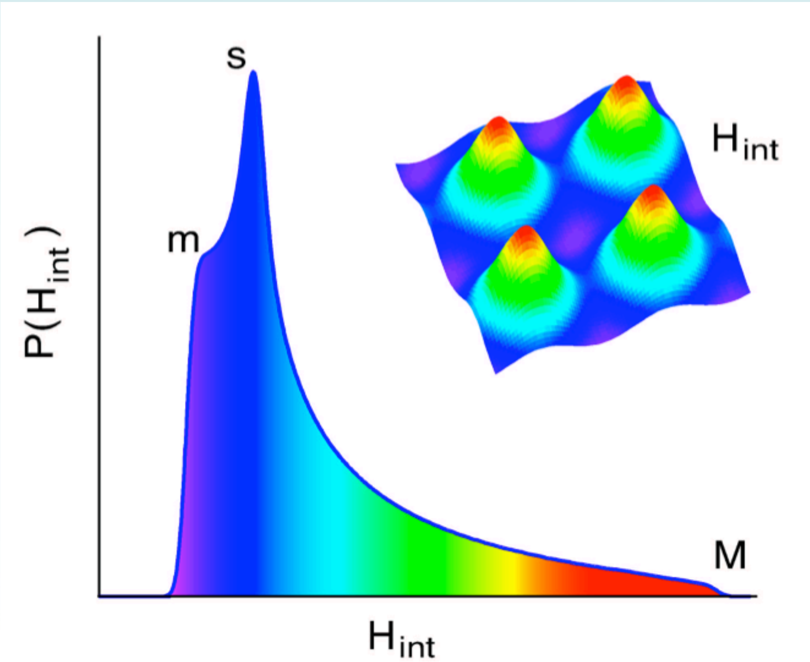
RRR = 870
ΔT_c = 9 mK

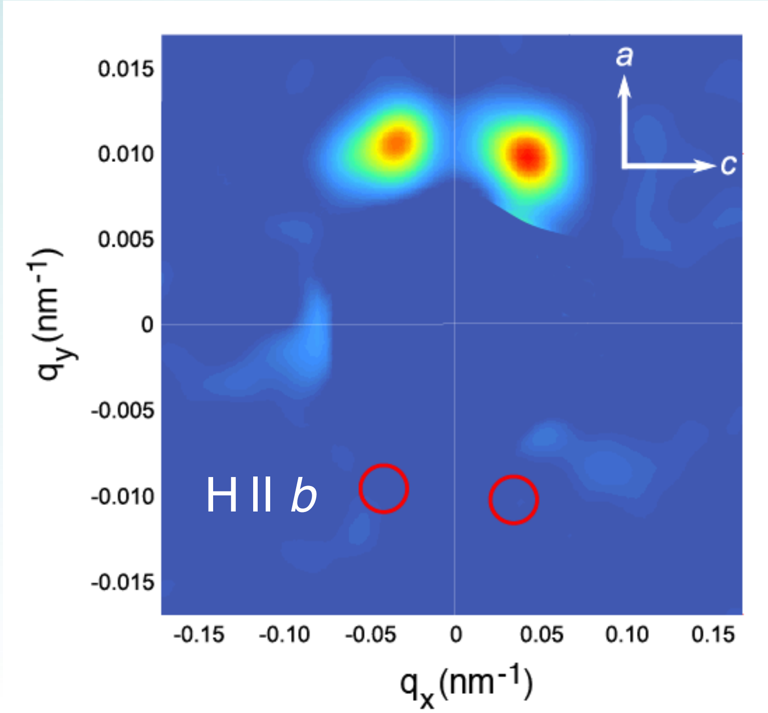
B-phase breaks time-reversal symmetry. The A-phase does not; consistent with E_{2u} symmetry as predicted by Sauls (1994).

Vortex phases of UPt_3

small angle neutron scattering (SANS)
from vortices B-phase.

Gannon *et al.*
NJP **17** 023041 (2015)
Avers *et al.* Nature Physics **16**, 531(2020)

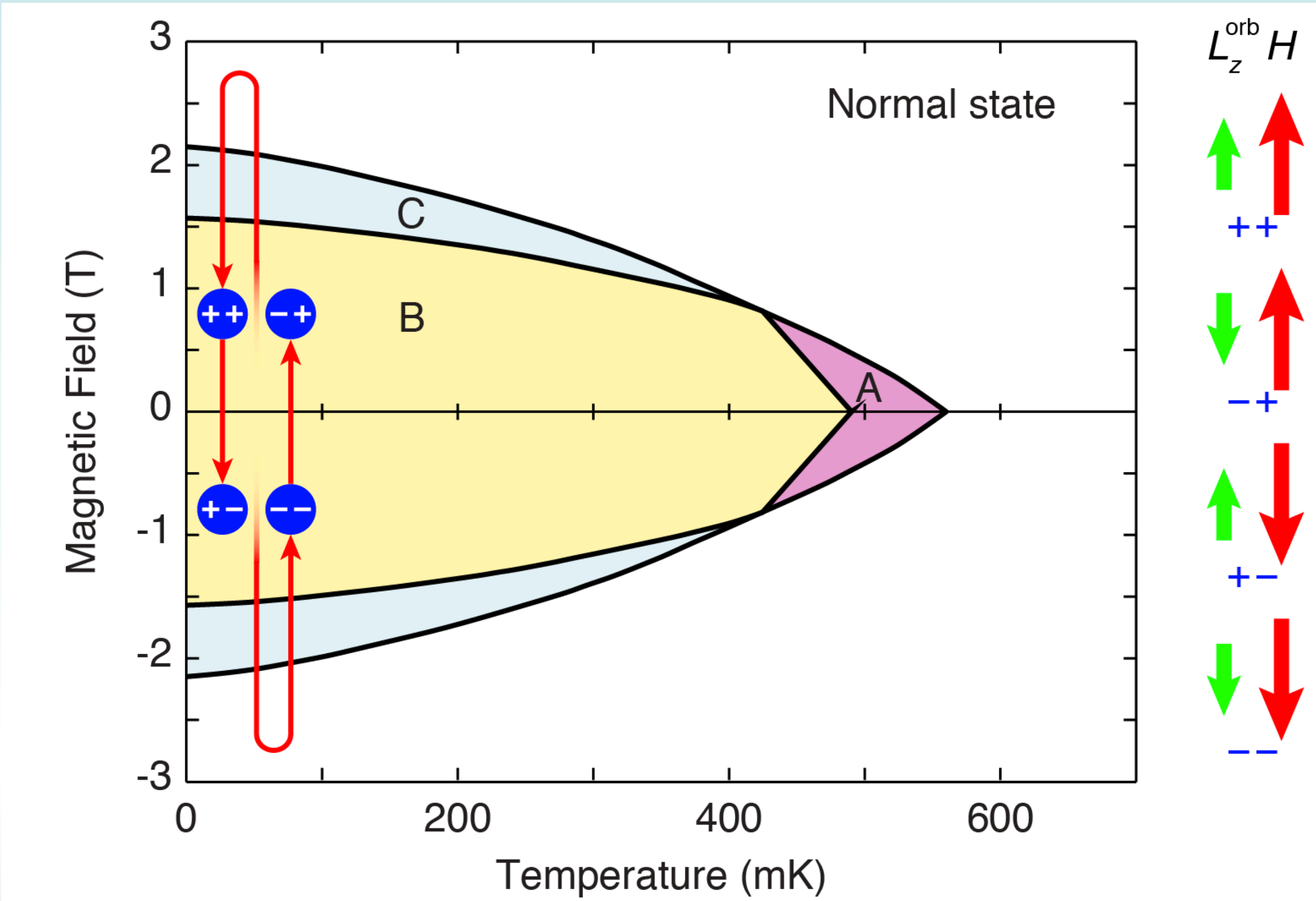




from:
Mitrovic *et al.,* Nature **413** 501 (2001)

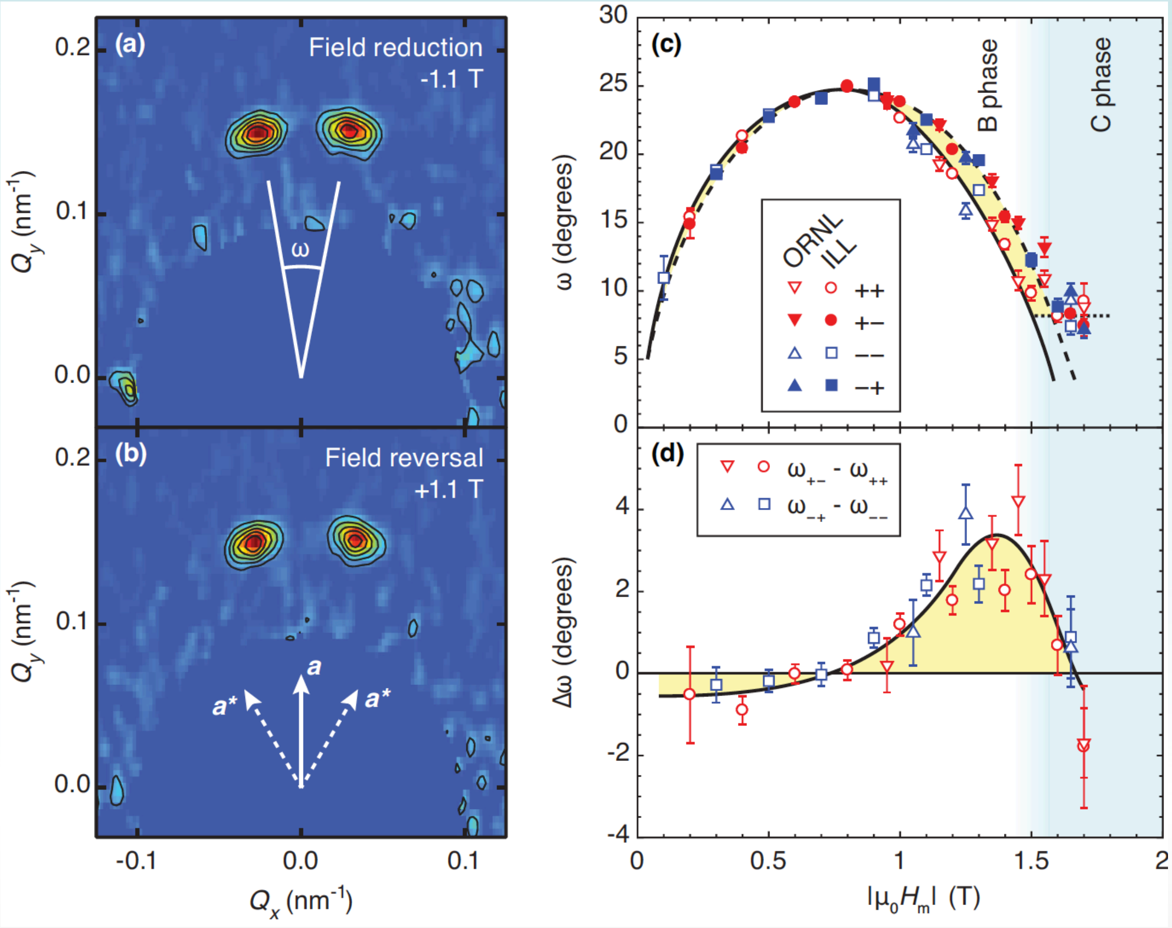
UPt_3 B-phase: broken time-reversal symmetry

Avers *et al.* Nature Physics **16**, 531(2020)
Tokuyasu and Sauls, PRB **165**, 347 (1990)



Vortex phases of UPt_3 B-phase

evidence for broken mirror and time reversal symmetry

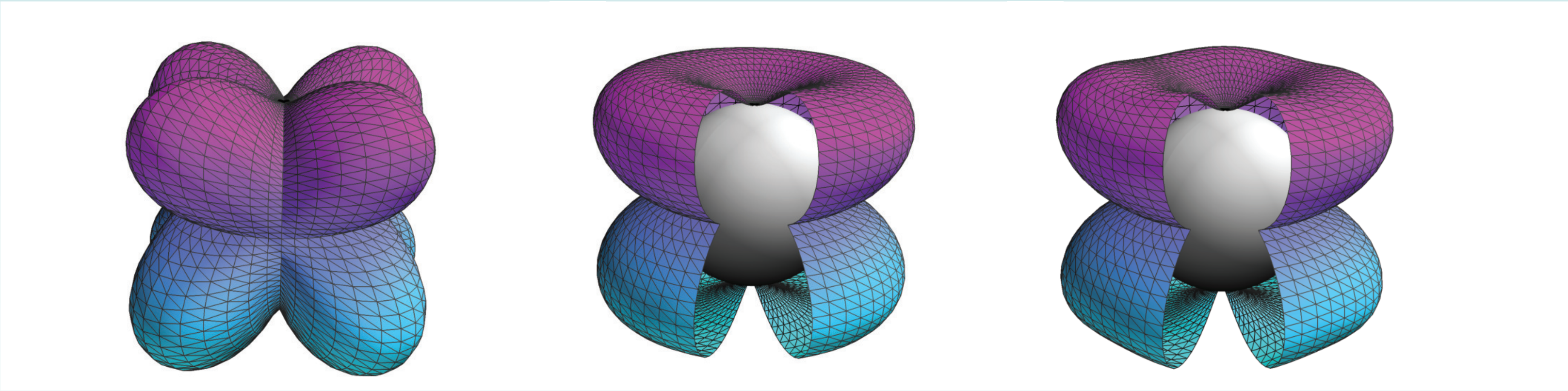


H II *c*

Avers *et al*. (2020)

Similar to ^{3}He-A
Walmsey, Golov, PRL
109 215301 (2012)

The symmetry breaking field in UPt_3



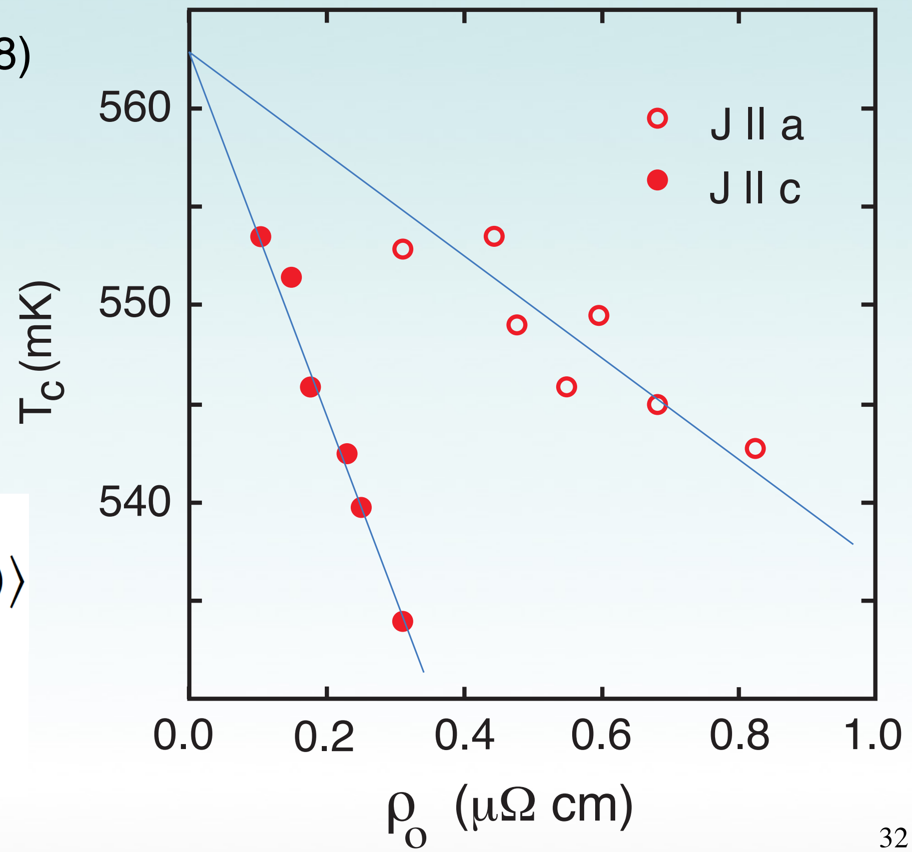
A-phase B-phase B-phase with symmetry breaking field (?)

UPt_3 Transport (residual resistivity)

anisotropic elastic scattering:

Kycia *et al.* PRB **58**, R603 (1998)

Abrikosov/Gorkov,
extended by Larkin (1963)



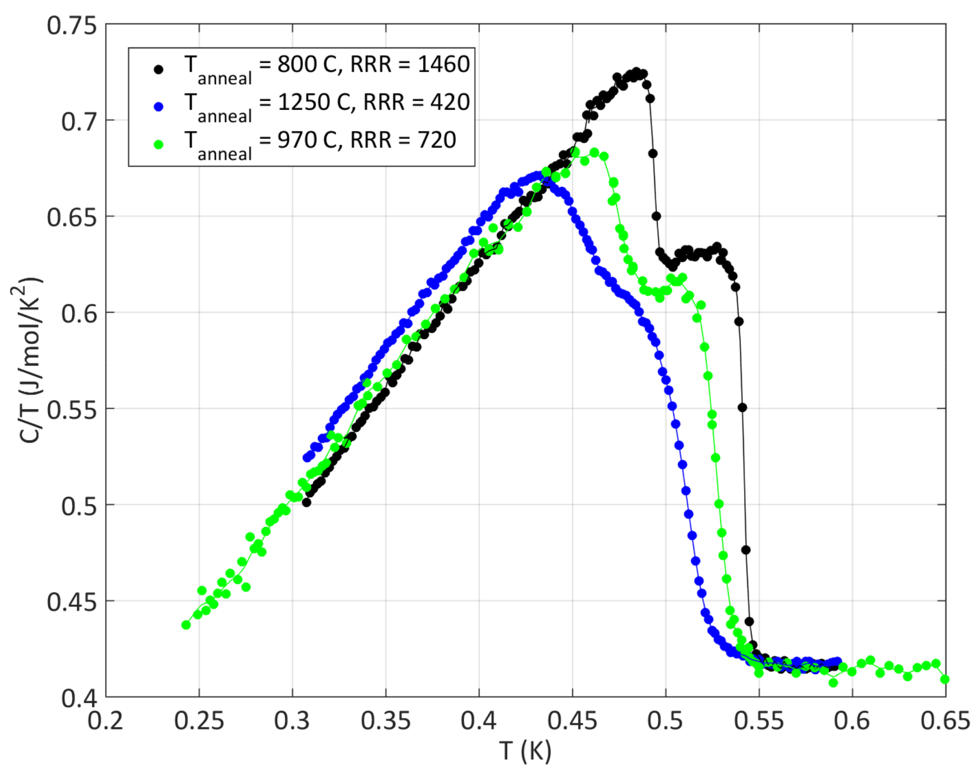
$$\rho_{0i}^{-1} = \frac{3}{\pi^2}\left(\frac{e}{k_B}\right)^2 \gamma_S \langle v_{fi}^2(\boldsymbol{p}_f)\,\tau(\boldsymbol{p}_f)\rangle$$

$$\frac{\tau_c}{\tau_a} = \frac{\rho_{0a} A_c}{\rho_{0c} A_a} = 1.3 \pm 0.1$$

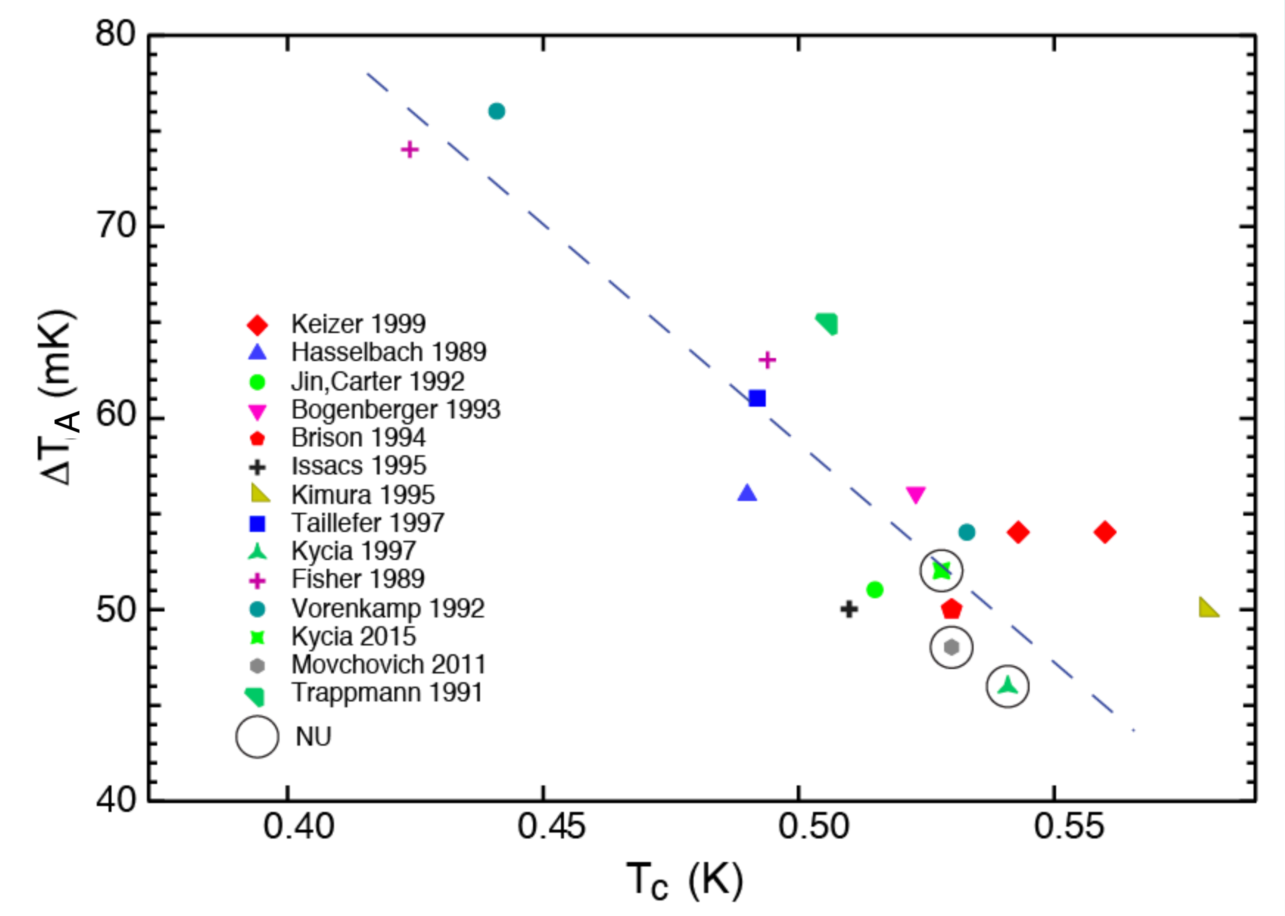
UPt_3: Specific heat

Correlation between ΔT_A and T_c ?
$\Delta T_A \propto$ Symmetry breaking field

Mitchelitis, Pomaranski, Kycia, (Waterloo)



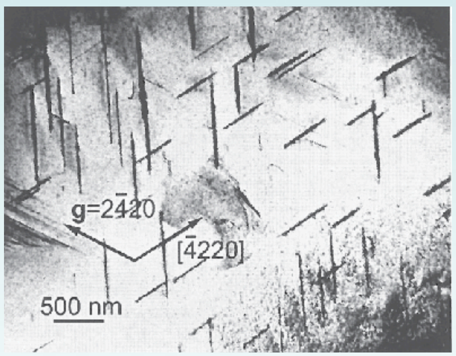
UPt_3 Specific heat



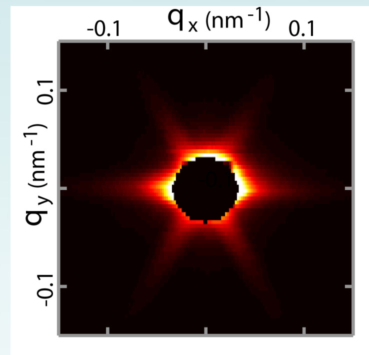
Prism-plane stacking faults

anisotropic elastic scattering, spin-orbit: Gannon *et al.* PRB 2017

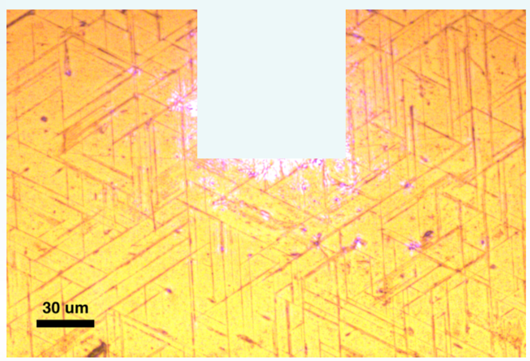
TEM: Hong and Seidman



SANS: Avers, Eskildsen, WPH



c - axis
facet

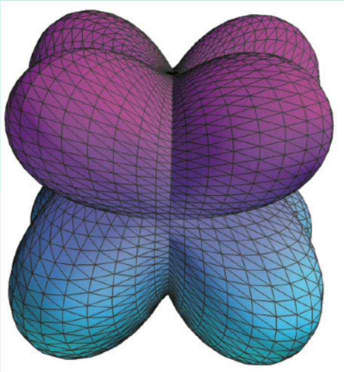


Optical: Schemm, Kapitulnik

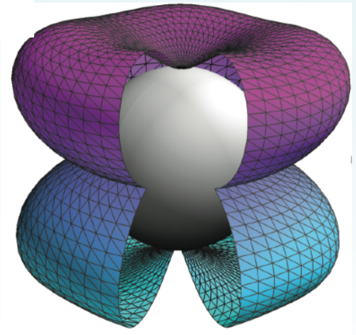
UPt_3: phase stability and the symmetry breaking field

Thuneberg *et al.* PRL (1998) for ^{3}He aerogel:
Anisotropic quasiparticle scattering favors anisotropic phases.

A-phase



B-phase

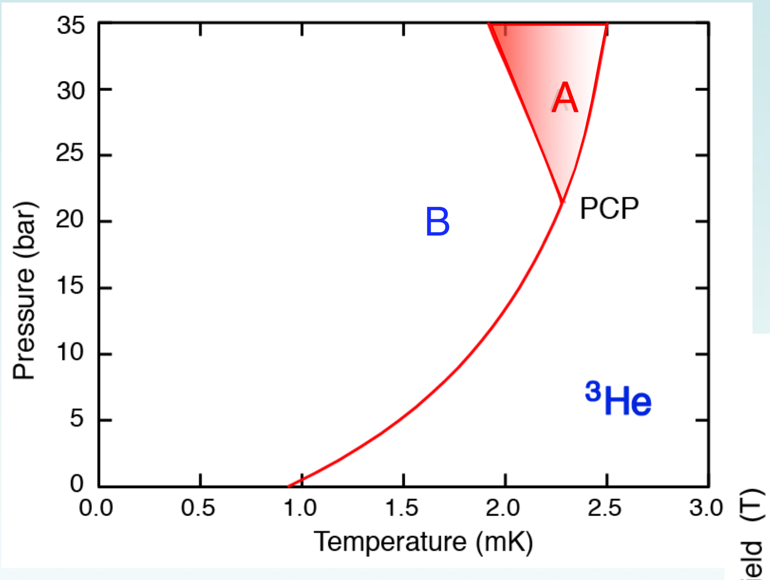


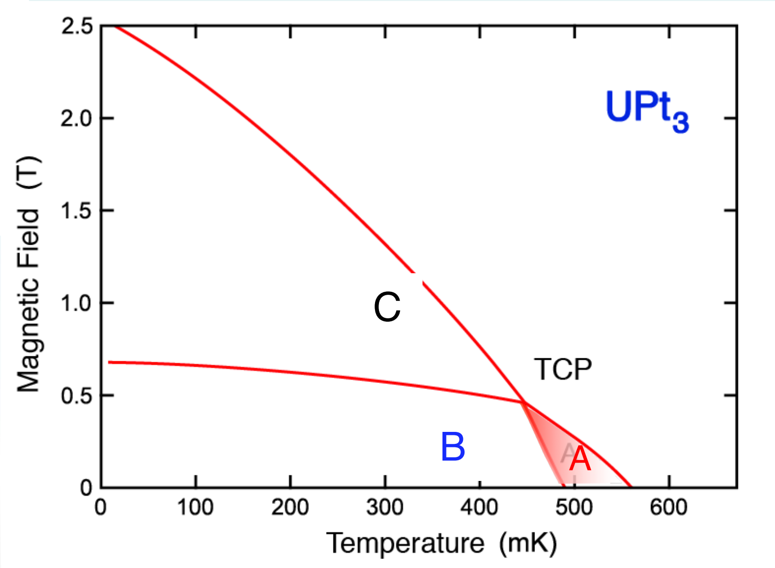
A-phase is more anisotropic than B.
Anisotropic scattering favors A.

Likely the symmetry breaking field is anisotropic quasiparticle scattering

Summary

- triplet superconductivity:
- multiple phases with BTRS
- ^{3}He and UPt_3 are odd parity





Thank You