

Opportunities in Basic Science: Quantum Fluids and Solids ^3He

[key: blue is a challenge; red is a grand challenge]

- Brief introduction: solid and liquid ^3He
- ^3He as topological quantum matter
- Broken symmetry phases
- Quantum matter in extreme conditions
- Connections to hard quantum matter
- Connections to particle physics
- Connections to magnetism
- Low temperature technology

Brief introduction: solid and liquid ^3He



Osheroff

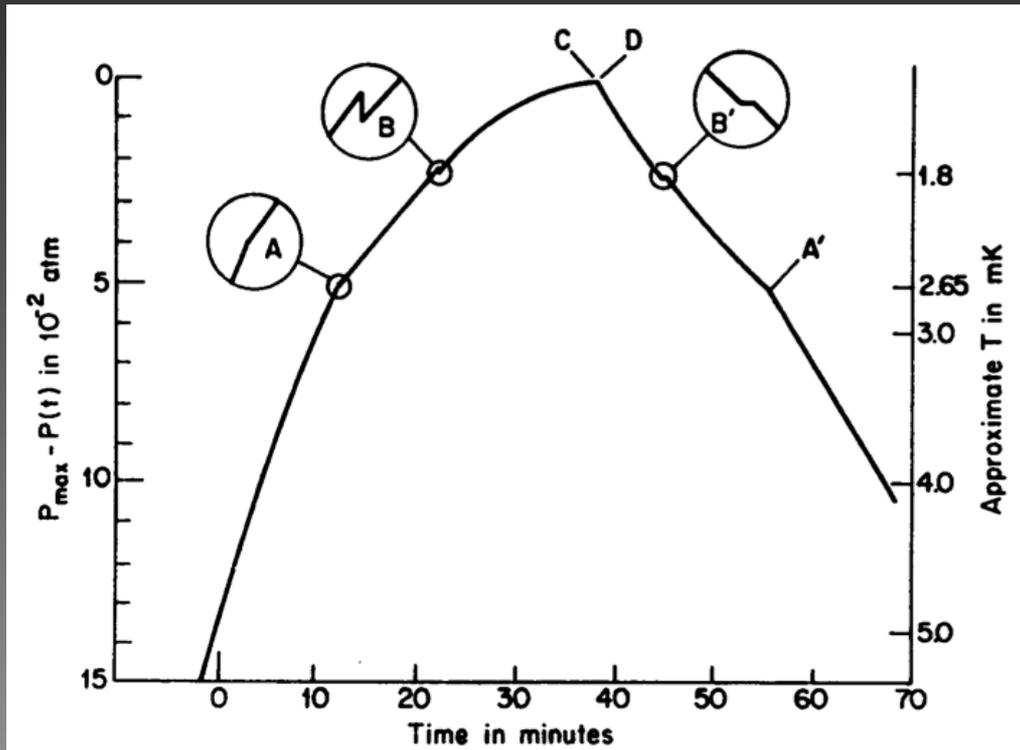


Richardson



Lee

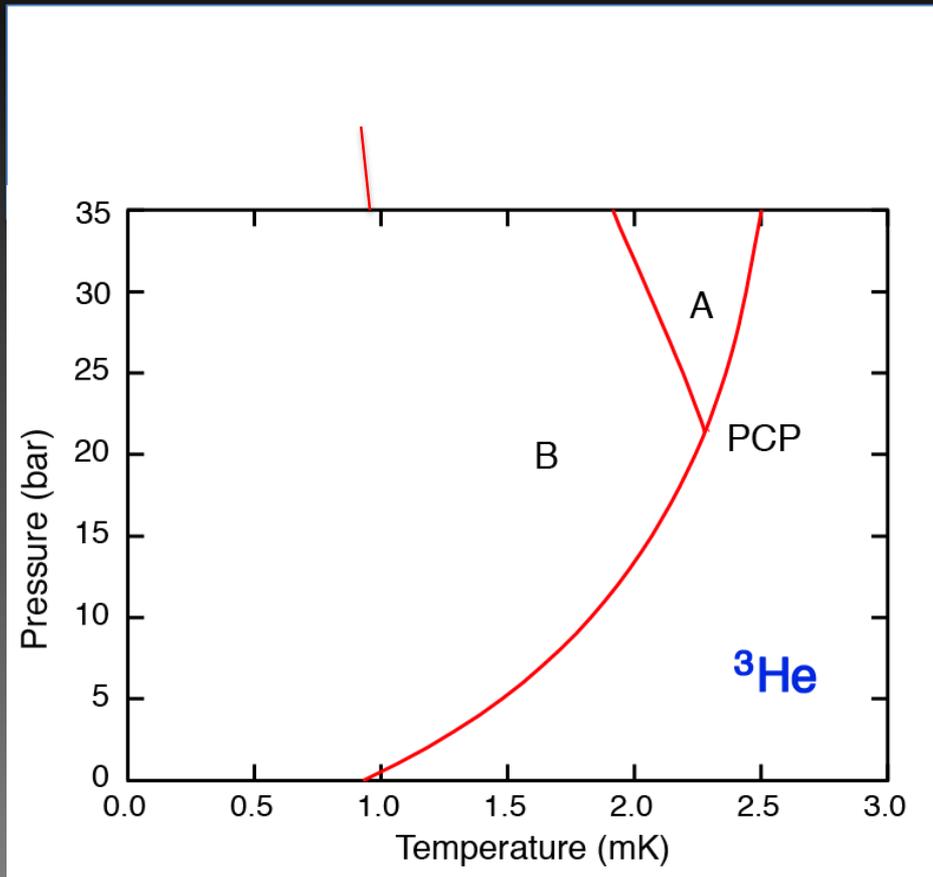
Nobel prize 1996



Leggett
Nobel prize
2003



Brief introduction: solid and liquid ^3He



Nuclear magnetic order 1974
Halperin, Richardson et al.

Superfluid order in 1972
Osheroff, Richardson, Lee

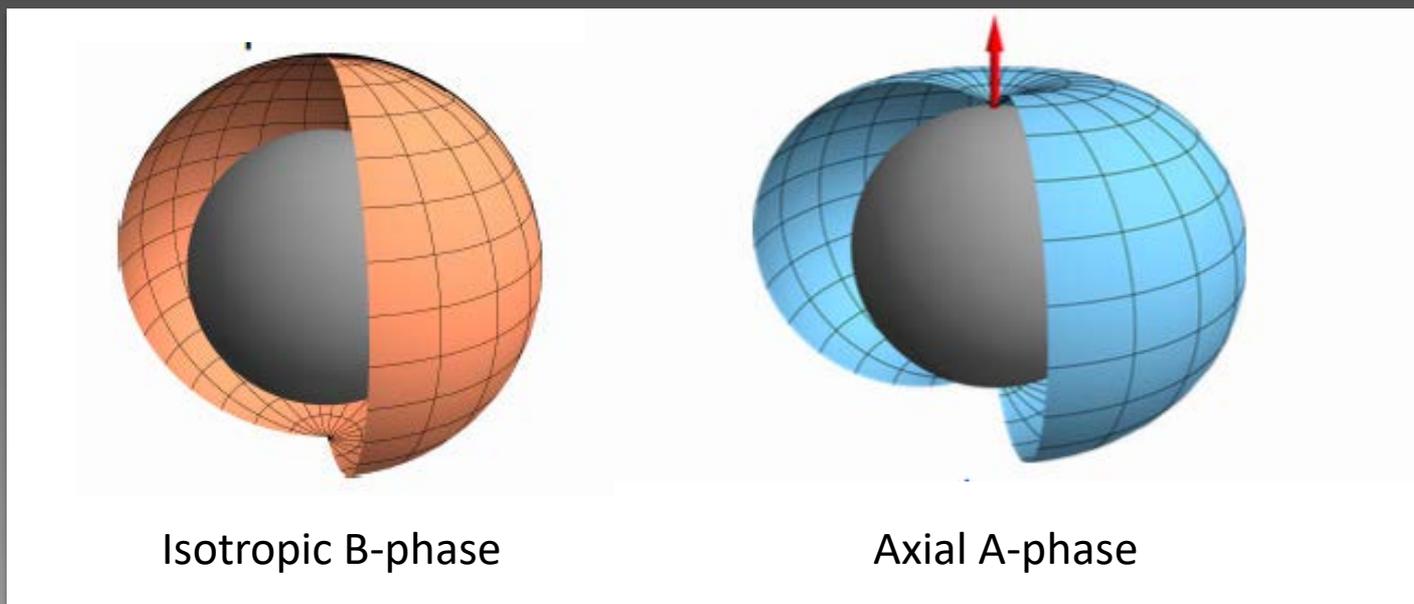
Superfluid ^3He as topological quantum matter

Majorana fermionic excitations at $^3\text{He-B}$ surfaces (confinement, A-B interface)

Majorana fermionic excitations $^3\text{He-A}$ vortex cores

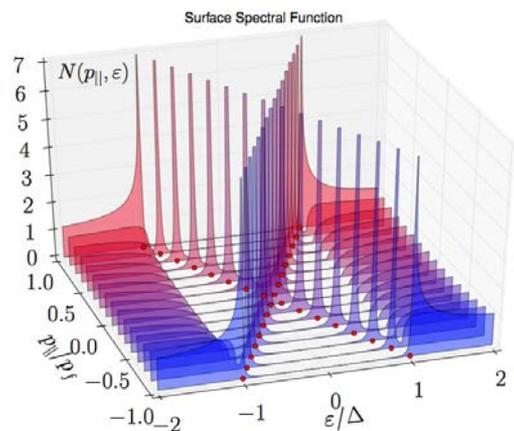
Chiral edge currents in $^3\text{He-A}$

Intrinsic angular momentum of $^3\text{He-A}$

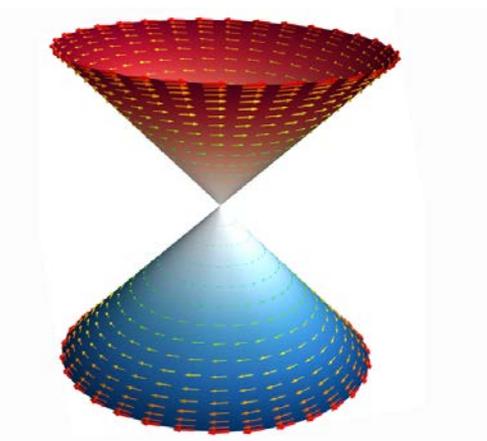


Superfluid ^3He as topological quantum matter

Majorana fermionic excitations at $^3\text{He-B}$ surfaces
(confinement, A-B interface)



Surface Dispersion $^3\text{He-B}$



Spin helical modes $^3\text{He-B}$

Superfluid ^3He as topological quantum matter

Majorana fermionic excitations at $^3\text{He-B}$ surfaces:

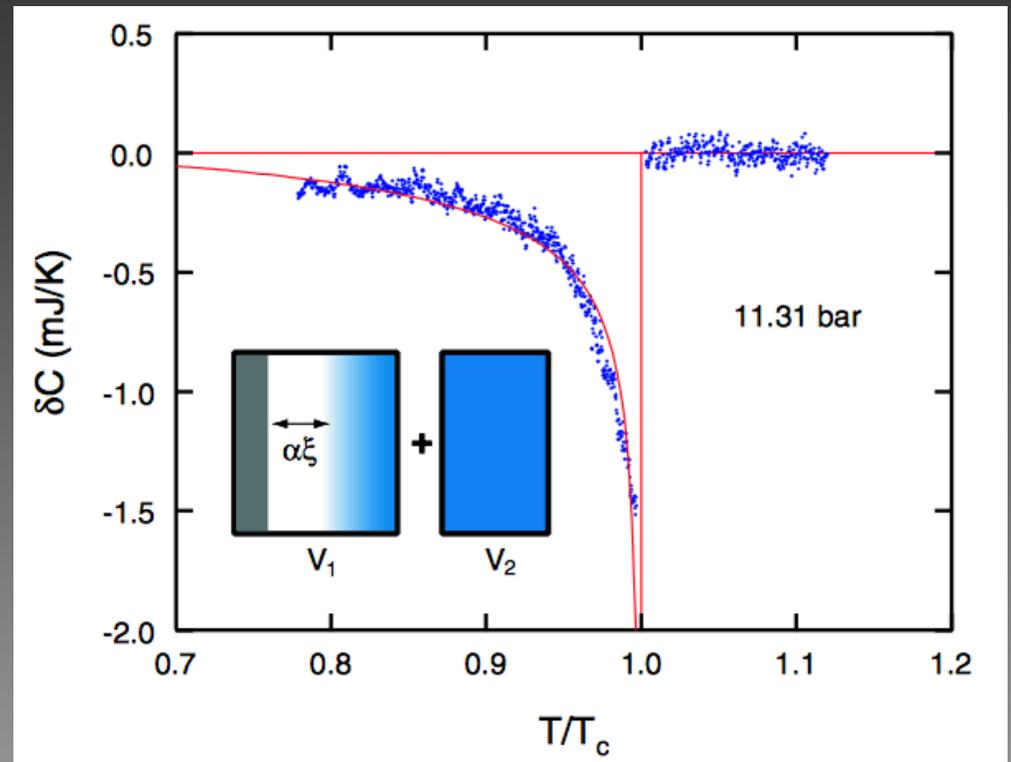
Heat capacity of surface

Andreev bound states . . . Majoranas.

Choi *et al.* PRL **96**, 125301 (2006).

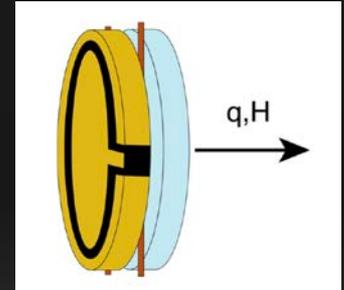
Here - δC is the heat capacity of the Andreev bound states occupying a volume $\sim \alpha A \xi(T)$
 A is the surface area of the sample cell.

Extend to $T=0$ and compare with theory.



Superfluid ^3He as topological quantum matter

Majorana fermionic excitations at $^3\text{He-B}$ surfaces:

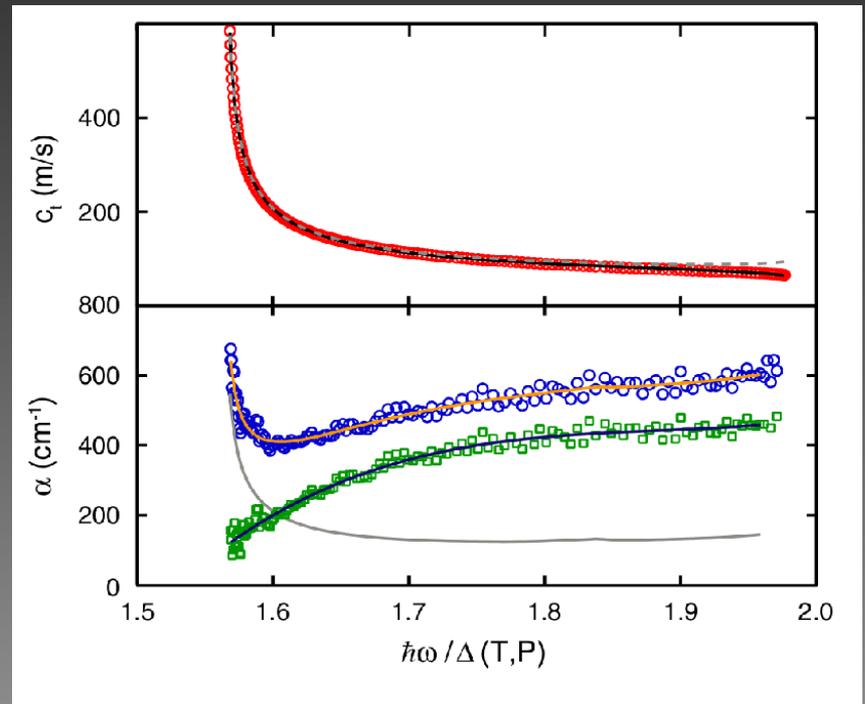


acoustic cavity

Spectroscopy for
surface Andreev-Majorana bound states
from transverse sound in a thin slab.

Acoustic impedance at the surface:
Y. Aoki et al, PRL 95, 075301 (2005)
Murakawa *et al.* PRL **103**, 155301 (2009)

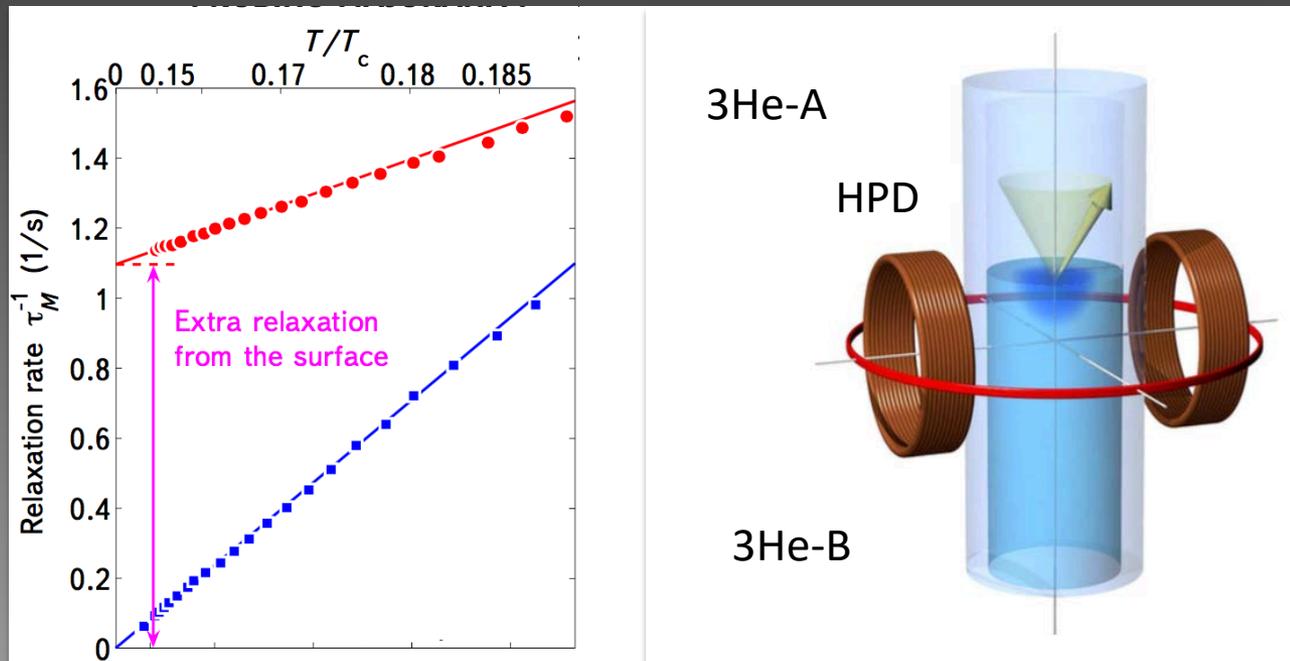
Attenuation of transverse sound from
surface bound states
Davis *et al.* PRL **101**, 085301 (2008).



Superfluid ^3He as topological quantum matter

Majorana fermionic excitations at $^3\text{He-B}$ surfaces:

Majorana states at the AB interface should relax the homogeneous precession domain
Efitov et al., *Grand Challenges Workshop, Buffalo, NY (2015)*
(Aalto University)

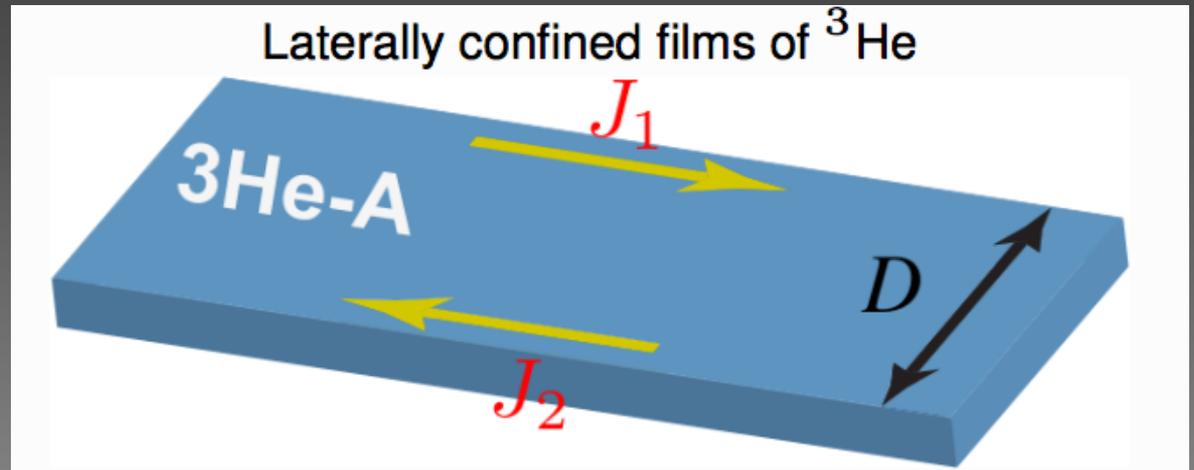


Superfluid ^3He as topological quantum matter

Surface states, edge currents, and the angular momentum of chiral p-wave superfluids,
Sauls, Phys. Rev. B 84, 214509 (2011) (Northwestern)

Chiral edge currents in $^3\text{He-A}$

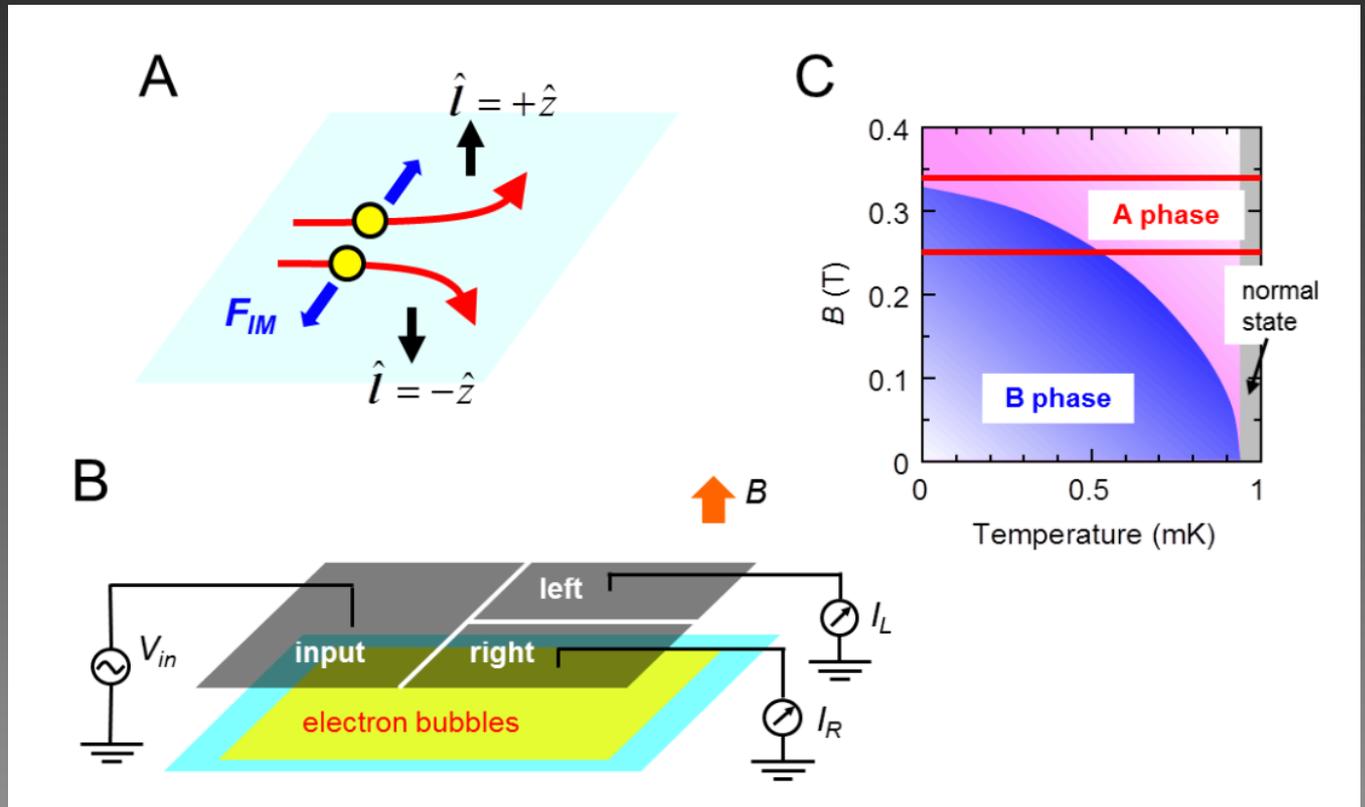
Intrinsic angular momentum of $^3\text{He-A}$: $N\hbar/2$



Broken symmetry phases

A-phase is chiral and breaks time reversal symmetry.

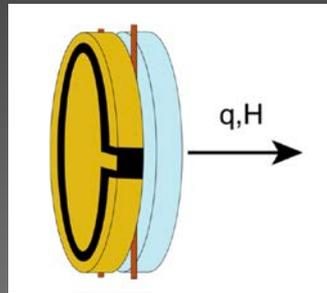
The first direct observations by Ikegami, Tsutsumi, and Kono (RIKEN)
Science **341**, 59 (2013)



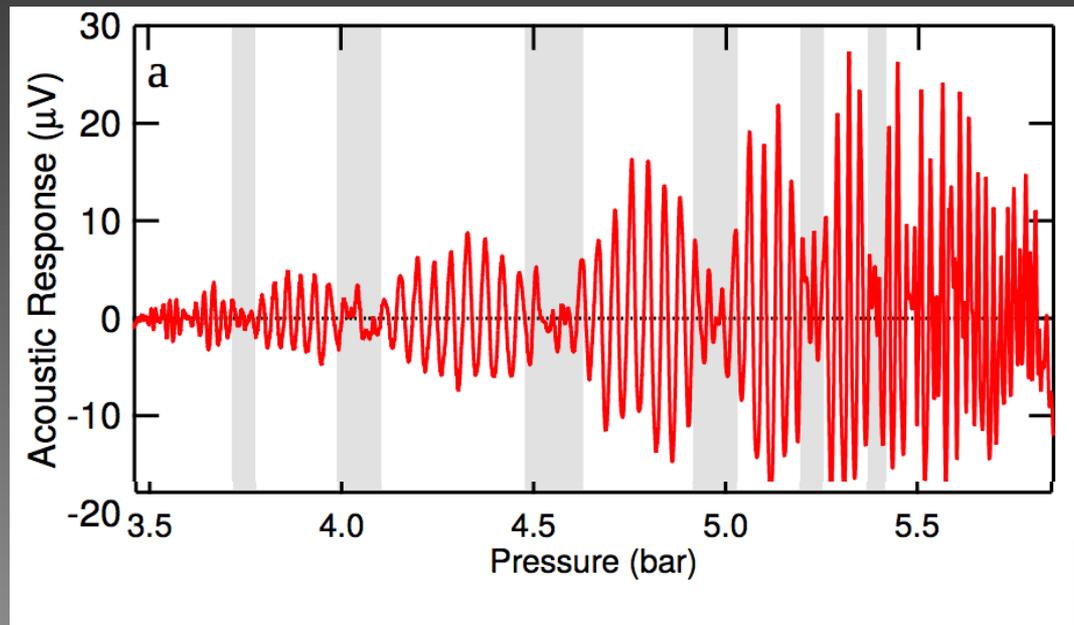
Broken symmetry phases

B-phase is time reversal symmetric with a broken rotational symmetry that preserves relative spin - orbit symmetry (like the predicted color flavor locking symmetry predicted by Wilczek in the quark – gluon plasma).

First direct observations of this characteristic symmetry by Lee *et al.*
Nature **400**, 431 (1999) in the acoustic Faraday effect in an acoustic cavity



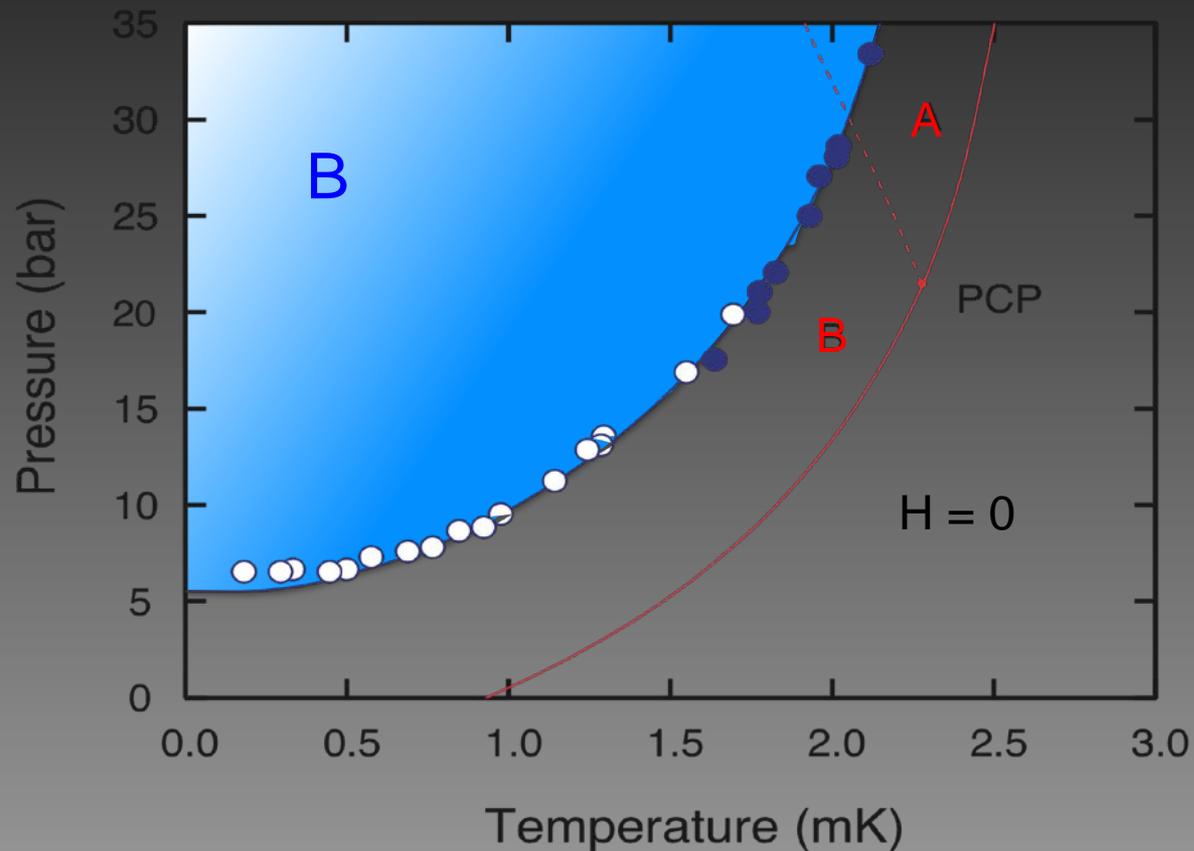
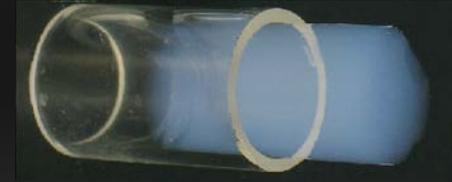
acoustic cavity



Broken symmetry phases

Isotropic silica aerogel:

Pollanen *et al.*, (Northwestern)
PRL **107**, 195301 (2011)



Broken symmetry phases

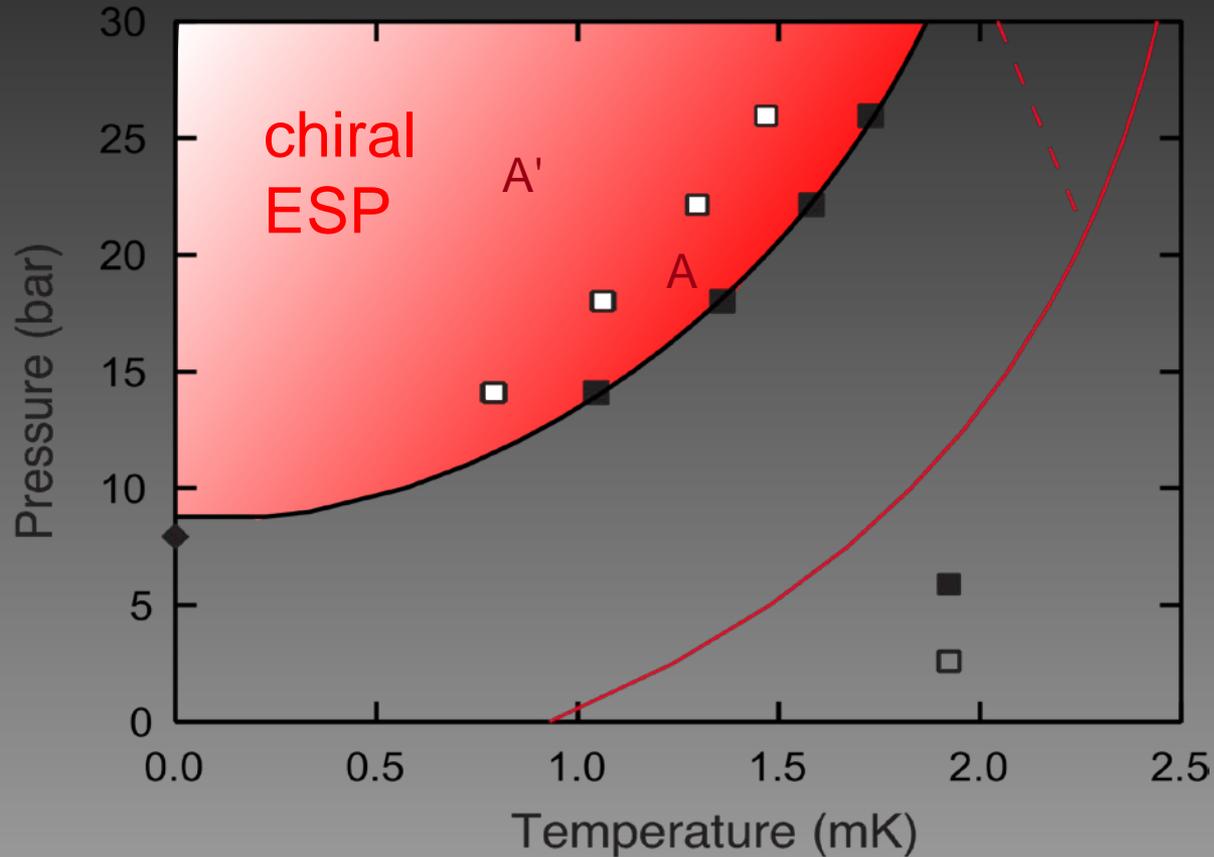
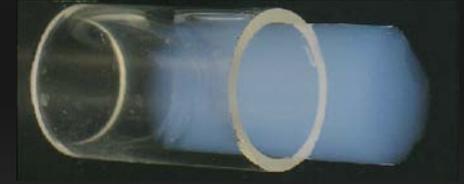
Anisotropic (stretched) silica aerogel:

Pollanen *et al.* (Northwestern)

Nature Phys. **8**, 317 (2012)

Two chiral equal spin pairing phases (ESP), aligning $\ell \parallel$ or \perp to the strain axis

Theory? Sauls PRB Phys. Rev. B **88**, 214503 (2013).



Broken symmetry phases

Anisotropic (compressed) silica
aerogel:

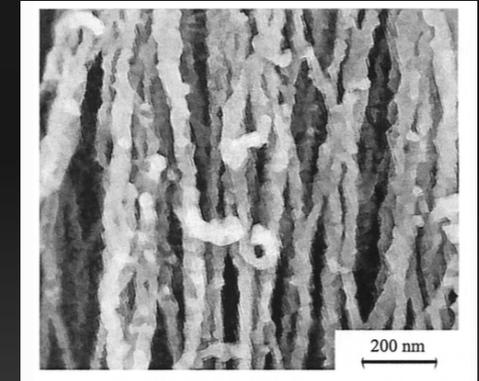


A new type of anisotropic B-phase
trumps the A-phase . . . work in
progress (Northwestern)

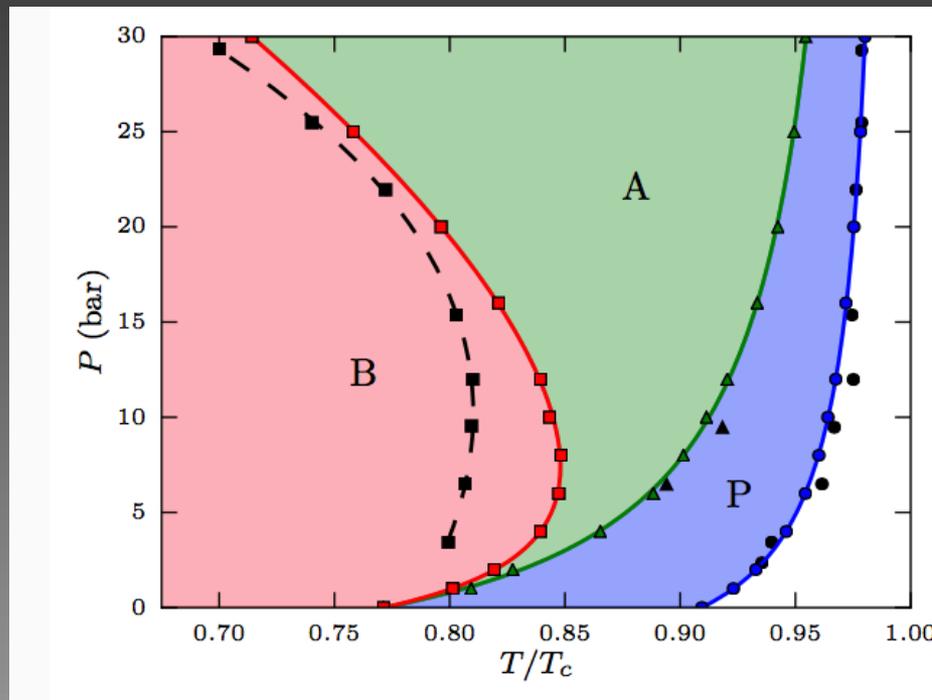
Broken symmetry phases

Anisotropic (nematic) aerogel:

Discovery of the polar phase
Ashkadullin *et al.* JETPL **100**, 662 (2014)
(Moscow) PRL to appear



"Nefen" aerogel
Al₂O₃ strands



Theory (colored curves): Wiman and Sauls, to be published.

The polar phase is an Equal Spin Pairing time reversal symmetric phase (not chiral).

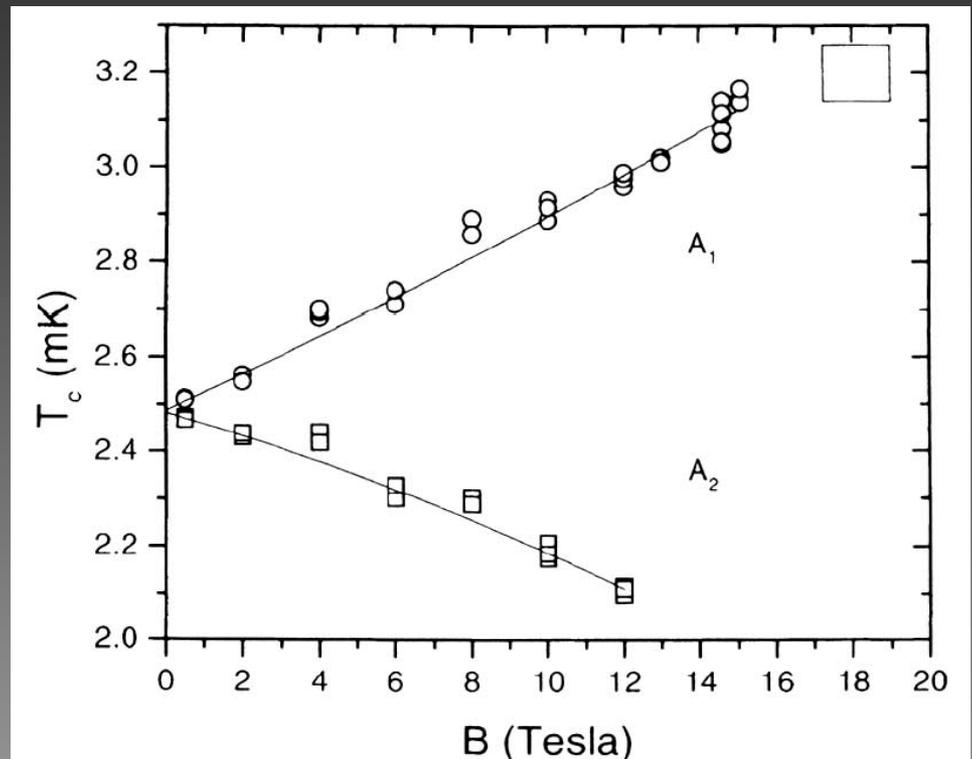
Extreme conditions

Superfluid ^3He in High Magnetic Field, Remeijer *et al.* JLTP **111**, 119 (1998). (Leiden)

Superfluid ^3He should double its transition temperature in $H = 50\text{ T}$

What is the Critical Field for superfluid ^3He ? Theory?

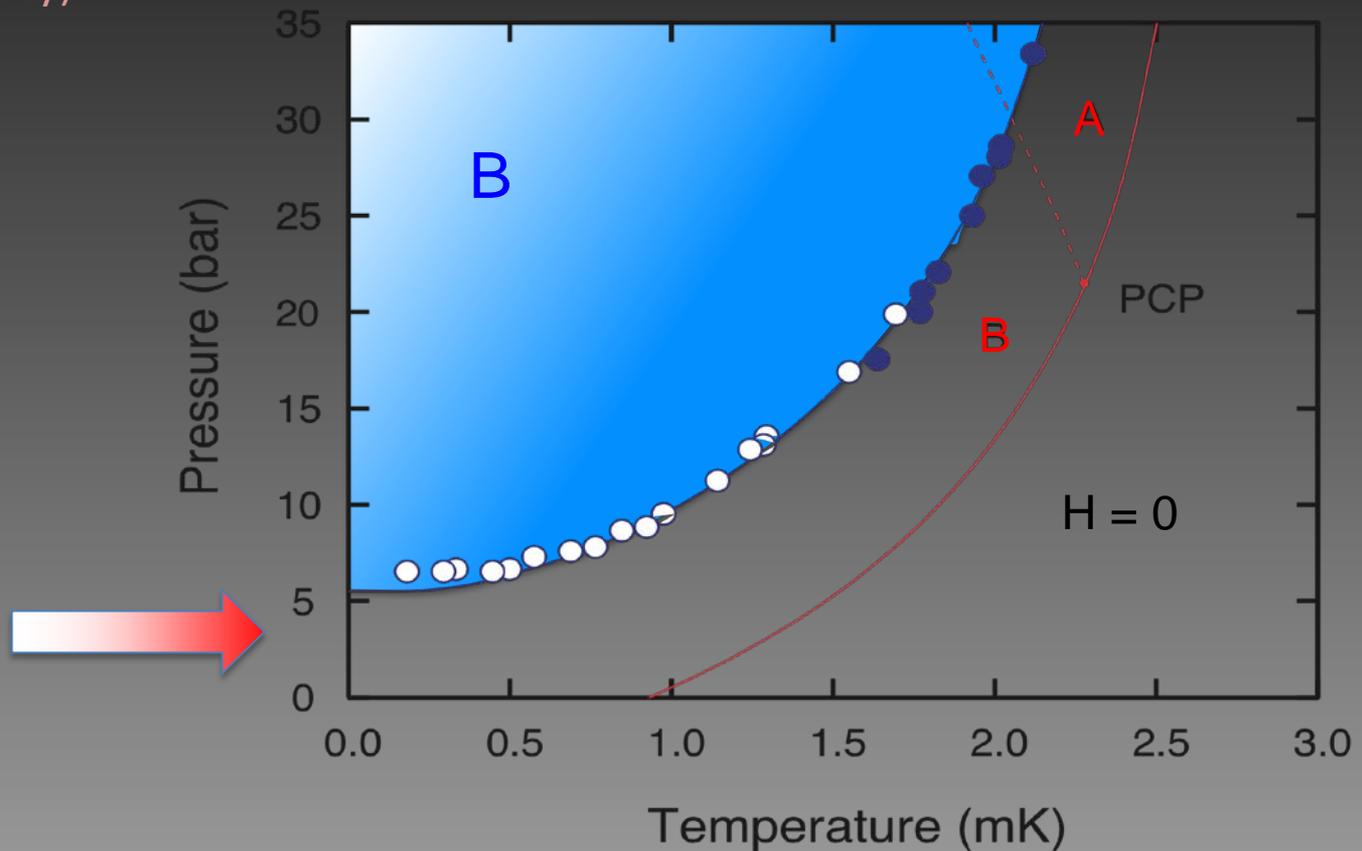
Could be 1000 T . We need to measure the quadratic piece.



Extreme conditions

Superfluid ^3He at ultra low temperatures:

Too much entropy . . . suggests ordering below $250\ \mu\text{K}$ (Lancaster University)



Connections to hard quantum matter



UPt3

Stewart, 1984



SrRuO4

Maeno, 1994

Superfluid $^3\text{He-A}$ and chiral superconductors :

Sr_2RuO_4 and UPt3 are the principal players and candidates for chiral superconductivity (100 papers/year for 10 years; 11,000 citations)

Questions about Sr_2RuO_4 and UPt3 :

What is the symmetry of the order parameter?

What are the stable phases?

What is the role of magnetism to superconductivity?

Are there edge currents?

What is the intrinsic angular momentum?

Connections to hard quantum matter

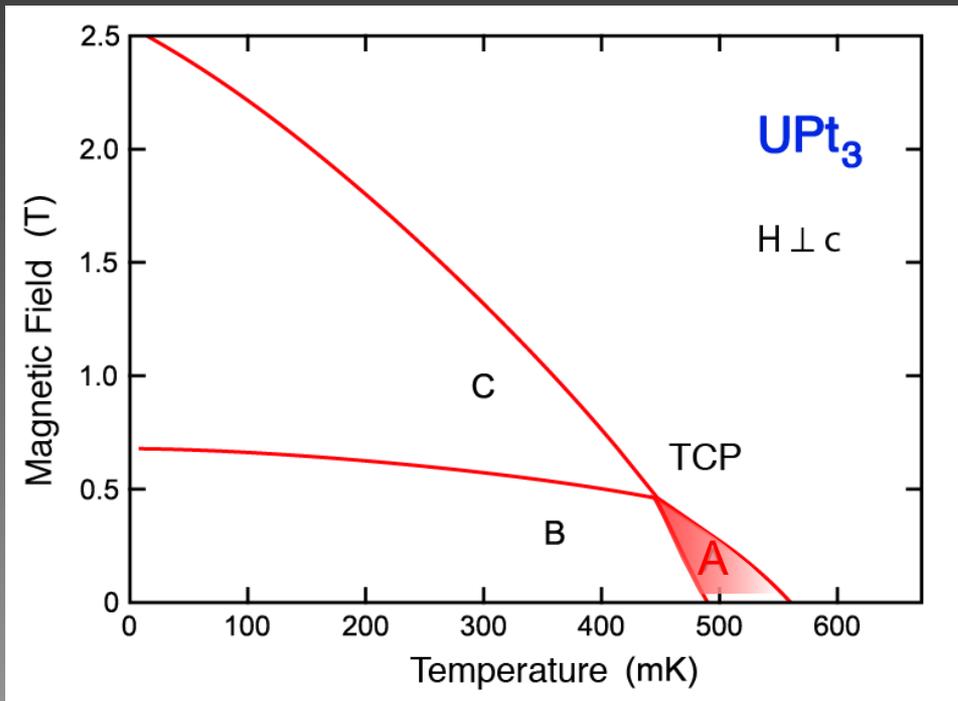
Superfluid ^3He and UPt_3

Multiple phases: unconventional superconductivity

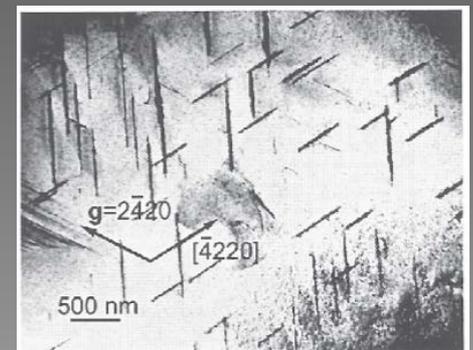
The anisotropic A phase is stabilized by anisotropic quasiparticle scattering (stacking faults) – just like ^3He .



Single crystals:
RRR 1,500
(Northwestern)



TEM stacking faults



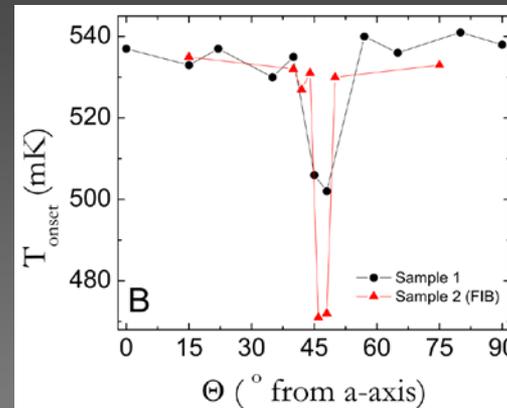
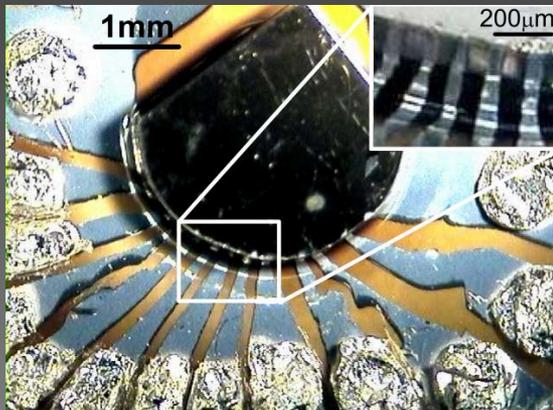
Connections to hard quantum matter

Superfluid ^3He and UPt_3

Directional tunneling identification of gap nodes in A-phase :
Strand *et al.* Science 328, 1368 (2010)
consistent only with E_{2u} symmetry
(Univ. Illinois Urbana-Champaign)



Single crystals:
RRR 1,500
(Northwestern)



Bottom line: ^3He is indeed a paradigm for unconventional pairing with both time reversal and chiral phases and informs us about hard quantum materials

Connections to hard quantum matter

Superfluid ^3He and UPt_3

Phase sensitive Josephson tunneling: Chern number 2
Strand *et al.* PRL **103**, 197002 (2009).
(Univ. Illinois Urbana-Champaign)

Polar Kerr effect onset proves BTRS in the B-phase
Schemm *et al.* Science **345**, 190 (2014). (Stanford)

Linear temperature dependence of the penetration depth,
quadratically dispersed polar nodes, Gannon *et al.*
NJP **17**, 023041 (2015) (Northwestern)

The chiral ^3He A-phase is analogous to UPt_3 chiral B-phase.



Single crystals
4 cm, 15 gm
(Northwestern)

Connections to hard quantum matter

Superfluid ^3He is topological quantum matter with broad implications for hard condensed matter applications of topological materials, notably Dirac - Weyl excitations in topological insulators.

"Discoveries of superfluid phases in ^3He , high T_c superconductors, graphene and topological insulators have brought into focus materials where quasiparticles are described by the same Dirac equation that governs behavior of relativistic particles. This class of materials, called Dirac materials, exhibits unusual universal features: Klein tunneling, chirality and impurity resonances. These similarities inform the unique role of symmetries that protect the Dirac spectrum. Dirac materials can be quantum imaged and ripples in the Dirac sea are generated by defects inducing fascinating features in local magnetism and Kondo effect. We can use modern theoretical tools to design Dirac Materials that host bosonic Dirac excitations impossible in particle physics."

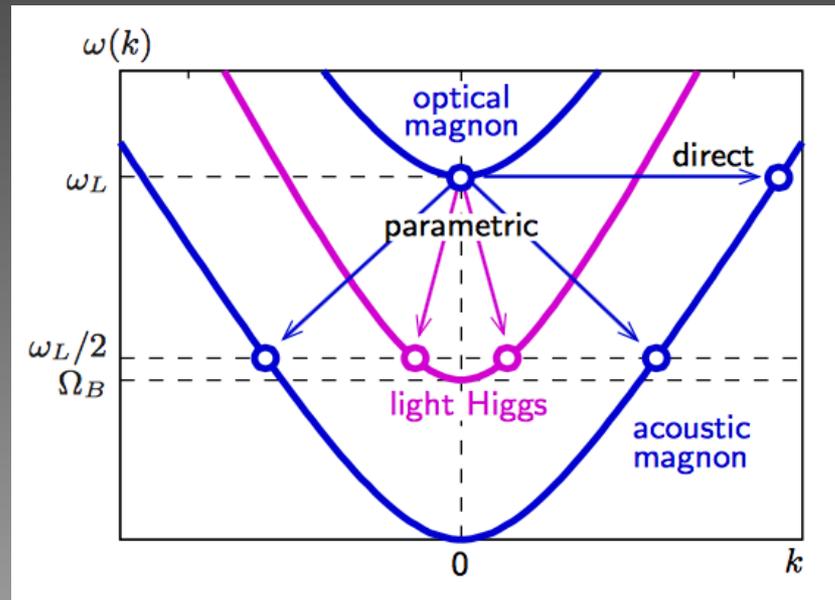
- Sasha Balatsky, Los Alamos/Nordita

Connections to particle physics

Superfluid ^3He bosonic excitations: collective modes of the order parameter in the B-phase are Higgs modes and satisfy the Nambu-Goldstone sum rule. (Northwestern, Cornell)

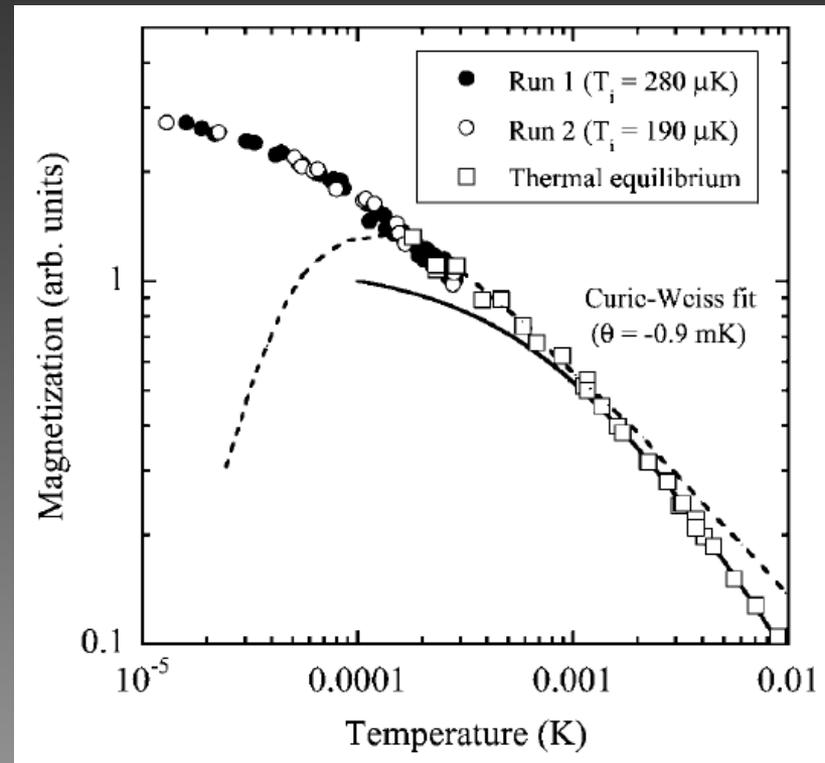
Recent observations of the little Higgs in superfluid $^3\text{He-B}$ have prompted, by analogy, prediction of a new Higgs particle at 325 GeV.

Zavjalov, Volovik, Eltsov *et al.* [arXiv:1411.3983](https://arxiv.org/abs/1411.3983)
and to be published in Nat. Comm. (Aalto Univ.)



Connections to magnetism

Solid ^3He adsorbed on graphite is a two dimensional quantum spin liquid phase with no gap larger than $10\ \mu\text{K}$.
Matsutomi, Ishimoto PRL 92, 035201 (2004).

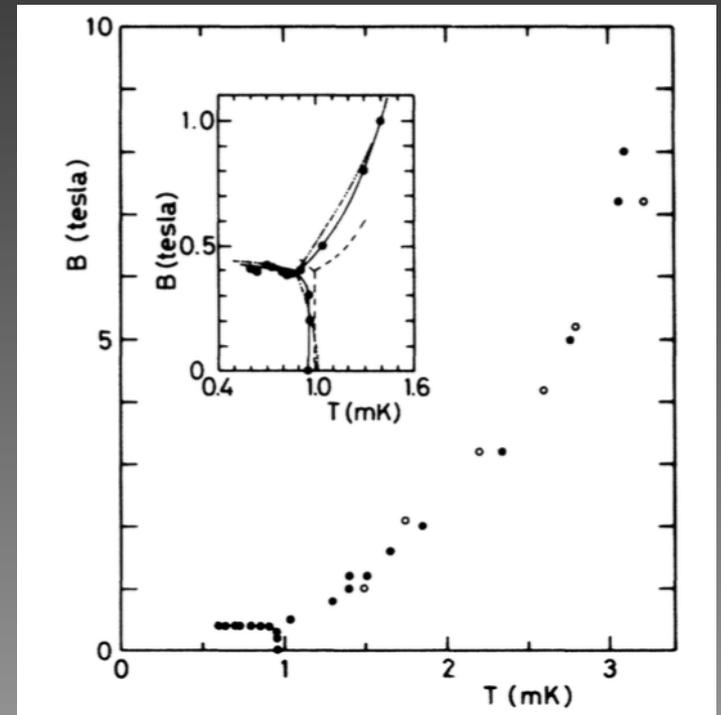


Connections to magnetism

Solid ^3He in High Magnetic Field, Sawada *et al.* PRL **56**, 1587 (1986).
(Nagoya)

What is the Critical Magnetic Field for solid ^3He ?
an accessible theoretical problem

Could be 20 T !



Low temperature technology driven in large part by Quantum Fluids and Solids

push button technology to 10 mK, huge increase in DR sales

hold 1 mK for more than 1 month, proven technology

push button technology to 1 mK

SQUID arrays for measurement and thermometry at < 1 mK

Measurement and thermometry at $100 \mu\text{K}$

Summary:

Research on Quantum Fluids and Solids is
an essential component of
research on quantum matter