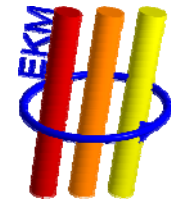




Center for Electronic Correlations and Magnetism
University of Augsburg



Superfluid Helium-3: From very low Temperatures to the Big Bang

Dieter Vollhardt

Dvořák Lecture
Institute of Physics, Academy of Sciences of the Czech Republic, Praha
June 8, 2011

Contents:

- The quantum liquids ^3He and ^4He
- Superfluid phases of ^3He
- Broken symmetries and long-range order
- Topologically stable defects
- Big Bang simulation in the low temperature lab

Helium

Two stable Helium isotopes:

^4He : air, oil wells, ...

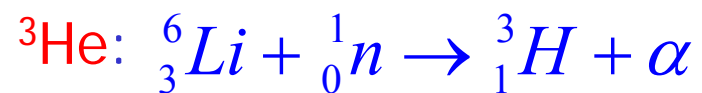
Janssen/Lockyer (1868)



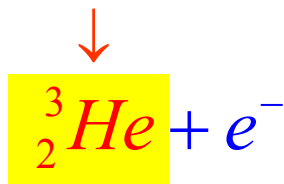
$\frac{\text{He}}{\text{air}} \approx 5 \times 10^{-6}$	$\frac{^3\text{He}}{^4\text{He}} \Big _{\text{air}} \approx 1 \times 10^{-6}$
---	---

Ramsay (1895)

Cleveit (UO_2)
from Jáchymov



(1939)



Research on macroscopic samples of ^3He since 1947

Helium

Atoms: spherical, hard core diameter $\sim 2.5 \text{ \AA}$

Interaction:

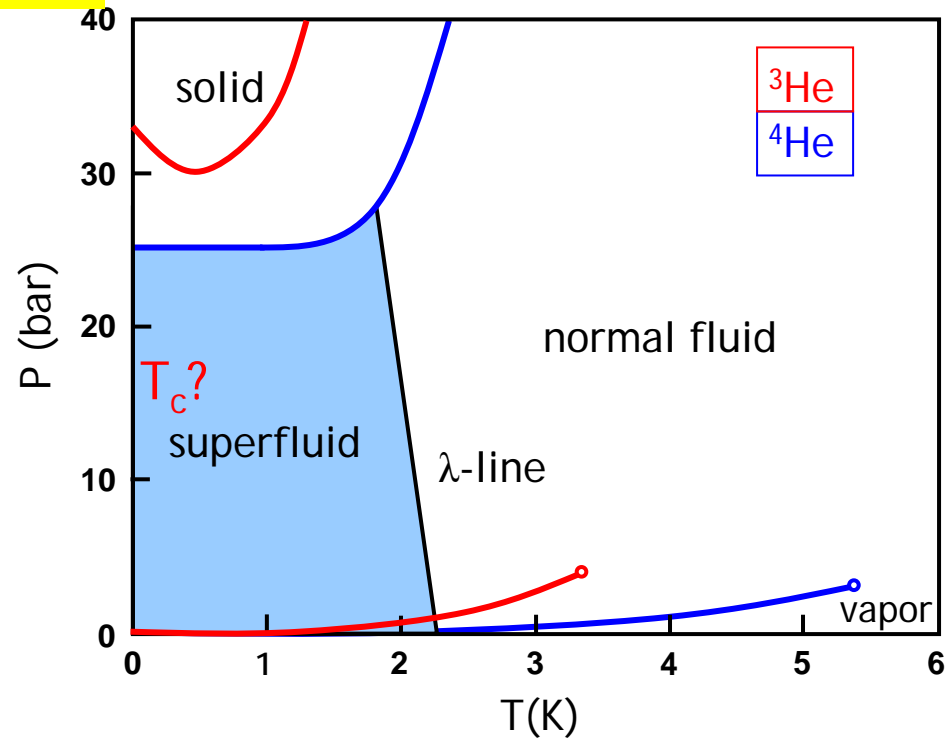
- hard sphere **repulsion**
- van der Waals dipole/multipole **attraction**

Boiling point: 4.2 K, ^4He Kamerlingh Onnes (1908)

3.2 K, ^3He Sydoriak *et al.* (1949)

Dense, simple liquid { isotropic
short-range interactions
extremely pure

Helium

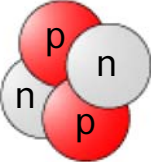
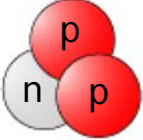


- Atoms:
- spherical shape \rightarrow weak attraction
 - low mass \rightarrow strong zero-point motion

$T \rightarrow 0$, $P \lesssim 30$ bar: Helium remains liquid

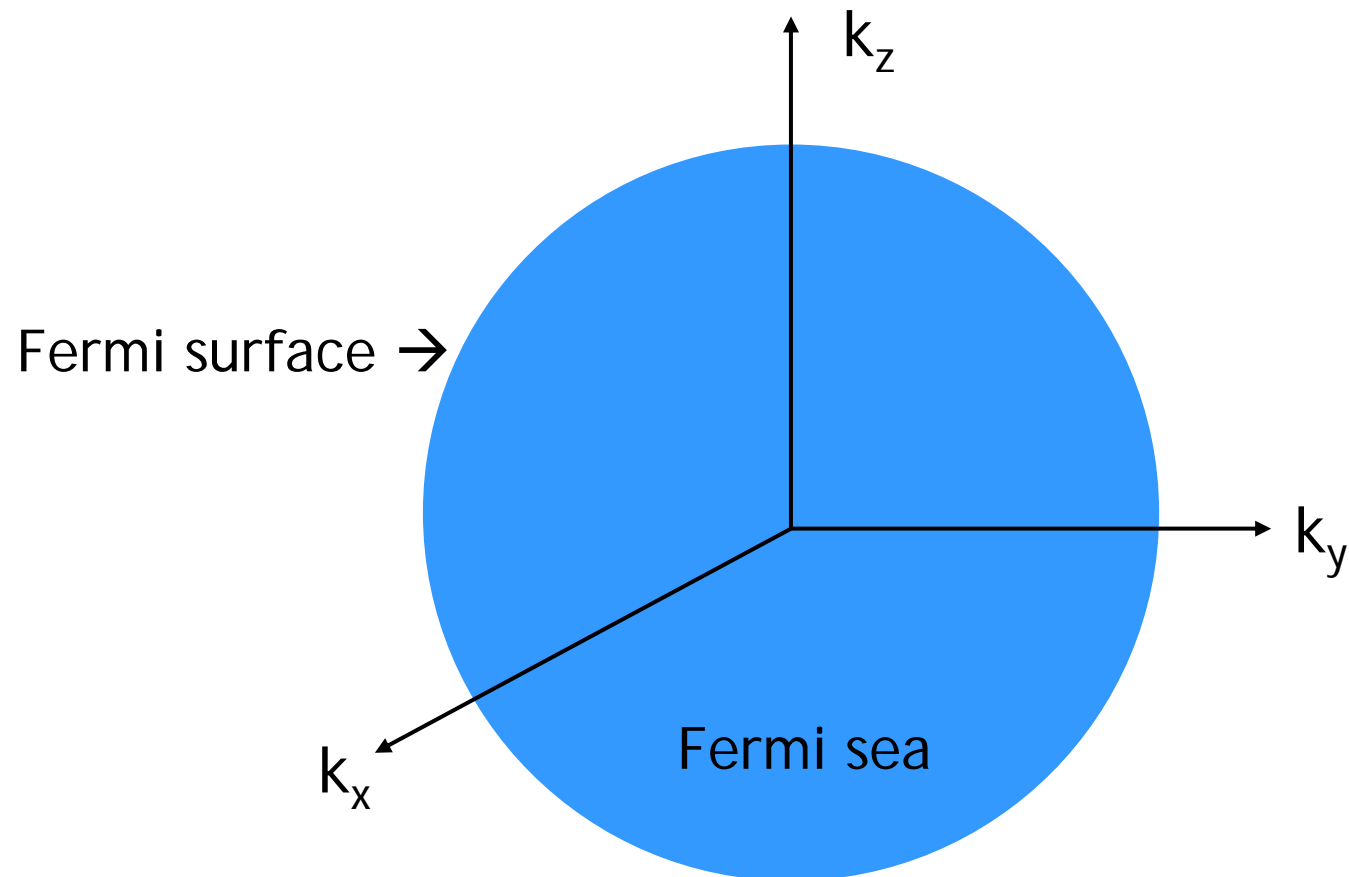
$$\lambda \propto \frac{\hbar}{\sqrt{k_B T}} \xrightarrow{T \rightarrow 0} \text{Macroscopic quantum phenomena}$$

Helium

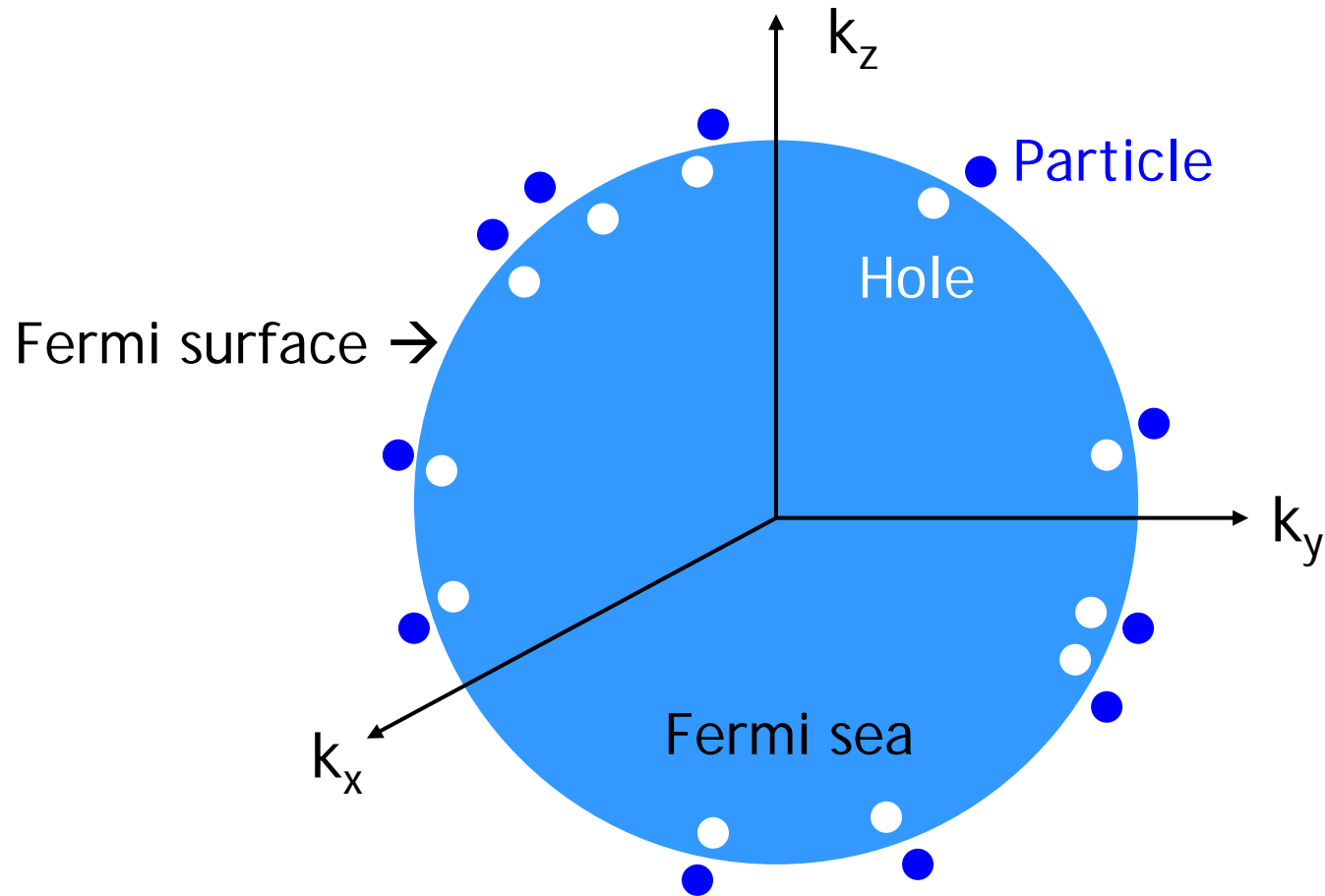
	^4He	^3He
Electron shell:	$2 e^{-}, S = 0$	
Nucleus:	 $S = 0$	 $S = \frac{1}{2}\hbar$
Atom(!) is a	Boson	Fermion
Phase transition	$T_{\lambda} = 2.2 \text{ K}$ ("BEC")	$T_c = ???$ Fermi liquid theory

Quantum liquids

Fermi gas: Ground state



Fermi gas: Excited states ($T > 0$)



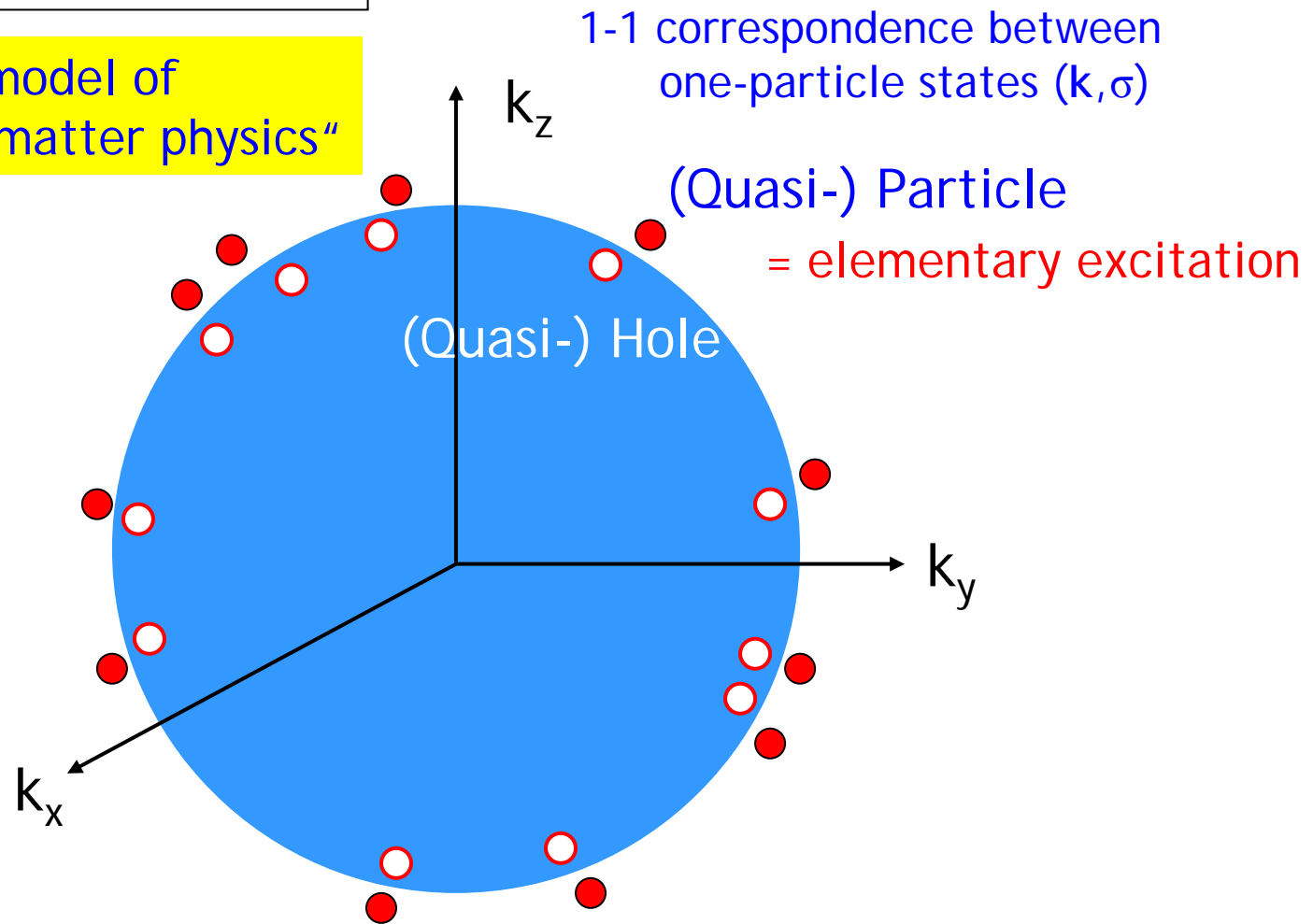
Exact k -states ("particles"): infinite life time

Switch on interaction adiabatically ($d=3$)

Landau Fermi liquid

Landau (1956/58)

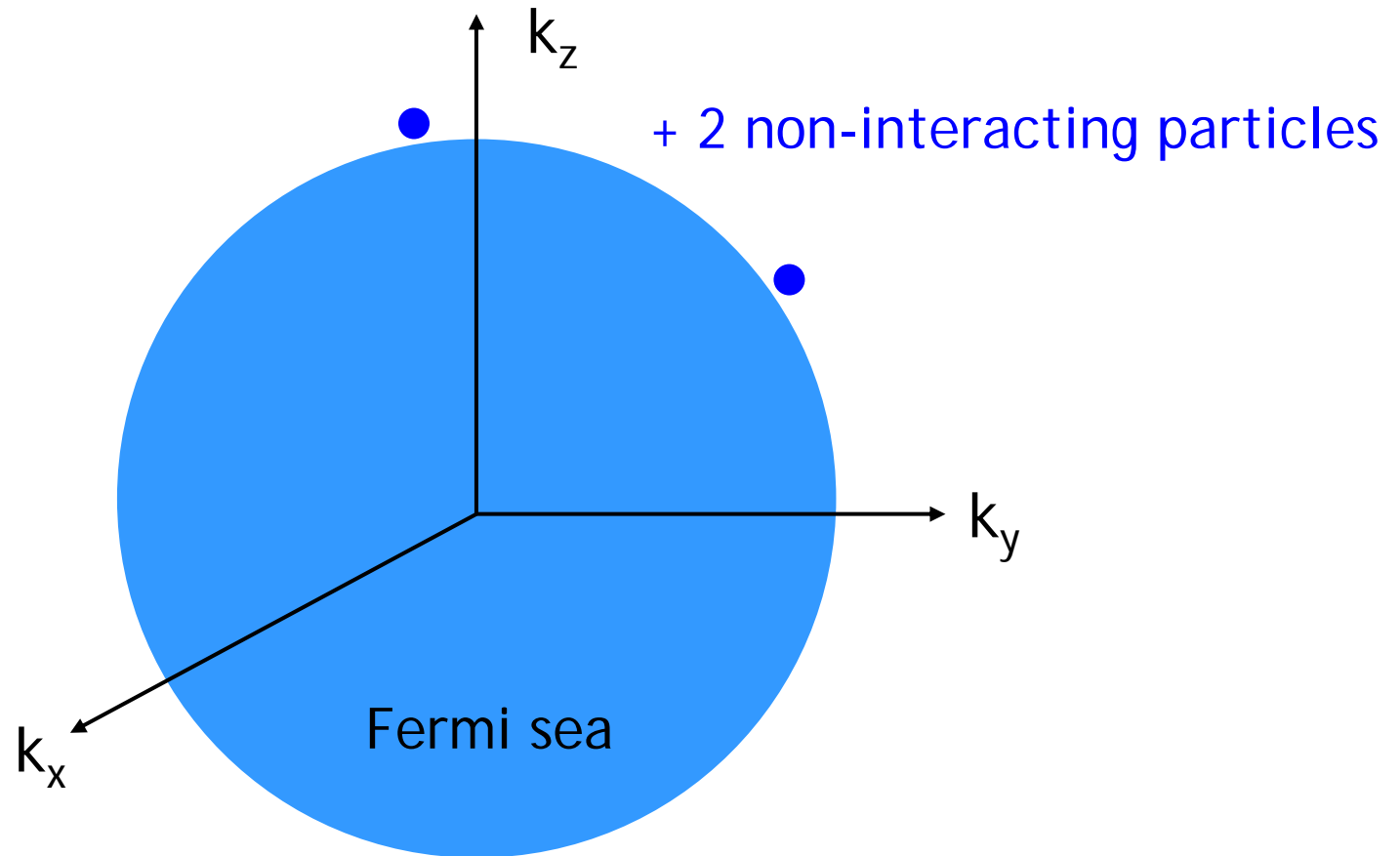
"Standard model of condensed matter physics"



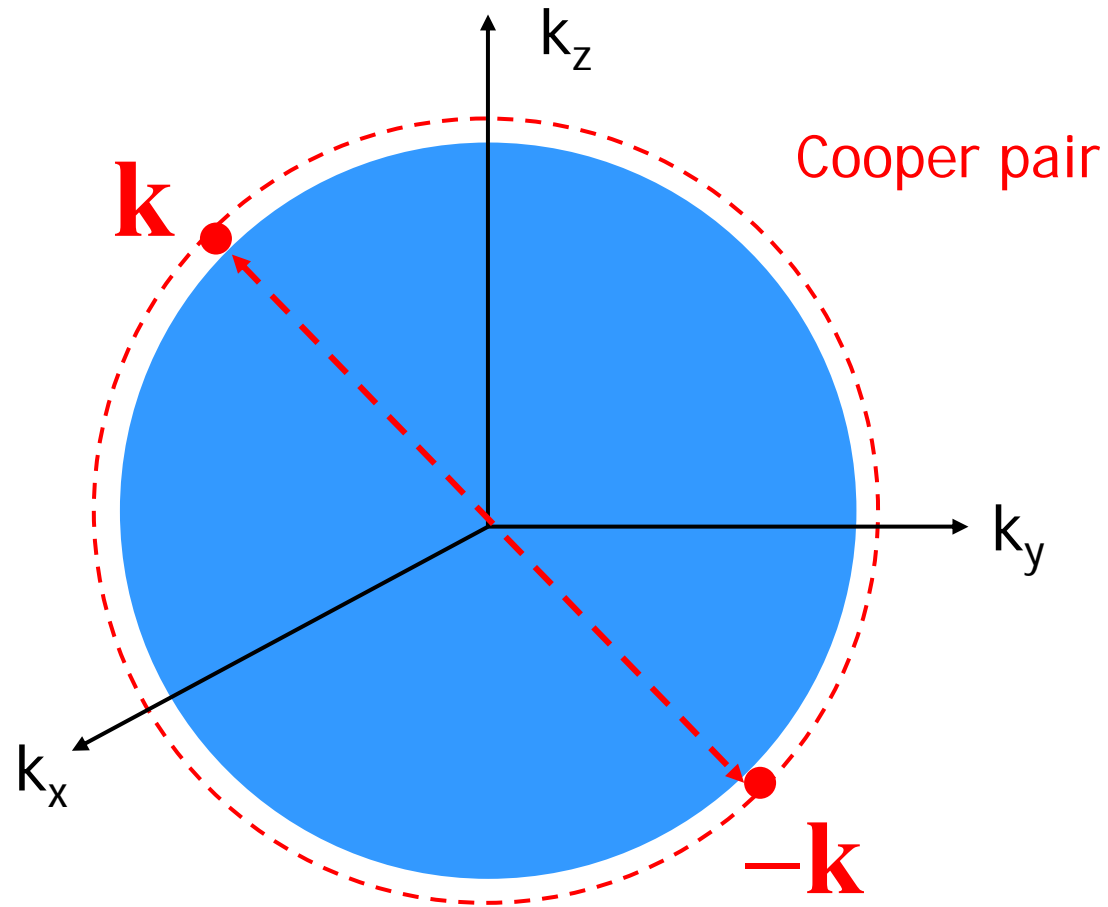
Prototype: Helium-3

- Large effective mass
- Strongly enhanced spin susceptibility
- Strongly reduced compressibility

Instability of Landau Fermi liquid

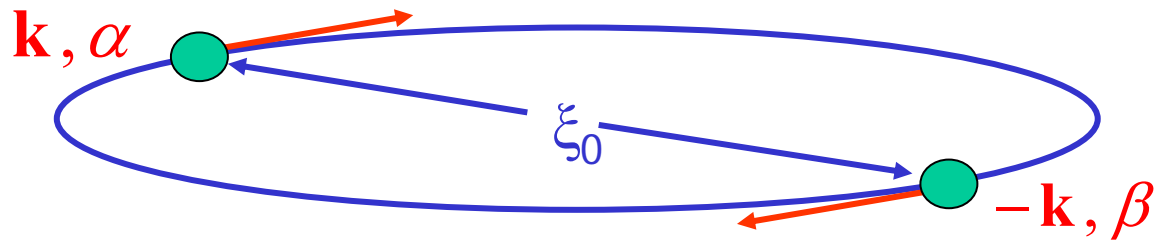


Arbitrarily weak attraction \Rightarrow Cooper instability



Universal fermionic property

Arbitrarily weak attraction \Rightarrow Cooper pair $(\mathbf{k}, \alpha; -\mathbf{k}, \beta)$



$$\Psi_{L=0,2,4,\dots} = \psi(\mathbf{r}) |\uparrow\downarrow - \downarrow\uparrow\rangle$$

S=0 (singlet)

$$\begin{aligned} \Psi_{L=1,3,5,\dots} = & \psi_+(\mathbf{r}) |\uparrow\uparrow\rangle \\ & + \psi_0(\mathbf{r}) |\uparrow\downarrow + \downarrow\uparrow\rangle \\ & + \psi_-(\mathbf{r}) |\downarrow\downarrow\rangle \end{aligned}$$

S=1 (triplet)

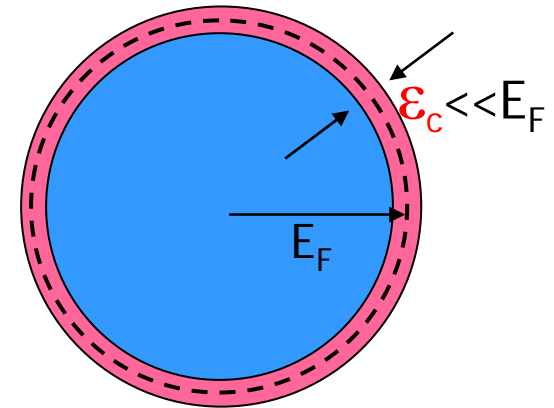
L = 0: isotropic wave function
L > 0: anisotropic wave function

Helium-3: Strongly repulsive interaction \rightarrow L > 0 expected

BCS theory

Bardeen, Cooper, Schrieffer (1957)

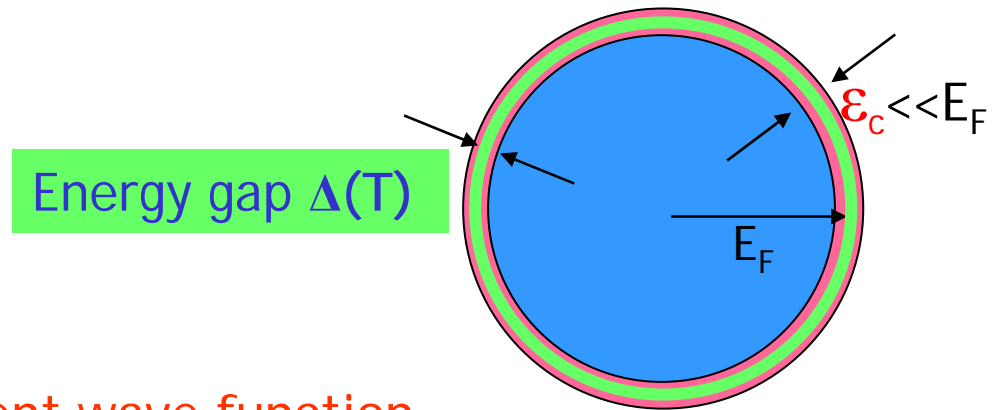
Generalization to macroscopically many Cooper pairs



BCS theory

Bardeen, Cooper, Schrieffer (1957)

Generalization to macroscopically many Cooper pairs



→ "Pair condensate"
with macroscopically coherent wave function

Transition temperature

$$T_c = 1.13 \epsilon_c \exp(-1 / N(0) |V_L|)$$

"weak coupling theory"

ϵ_c, V_L : Magnitude ? Origin ? → T_c ?

Thanksgiving 1971: Transition in ^3He at $T_c = 0.0026 \text{ K}$

Osheroff, Richardson, Lee (1972)

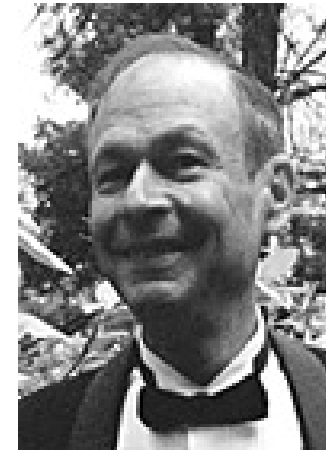
The Nobel Prize in Physics 1996
"for their discovery of superfluidity in helium-3"



David M. Lee
Cornell (USA)



Douglas D. Osheroff
Stanford (USA)



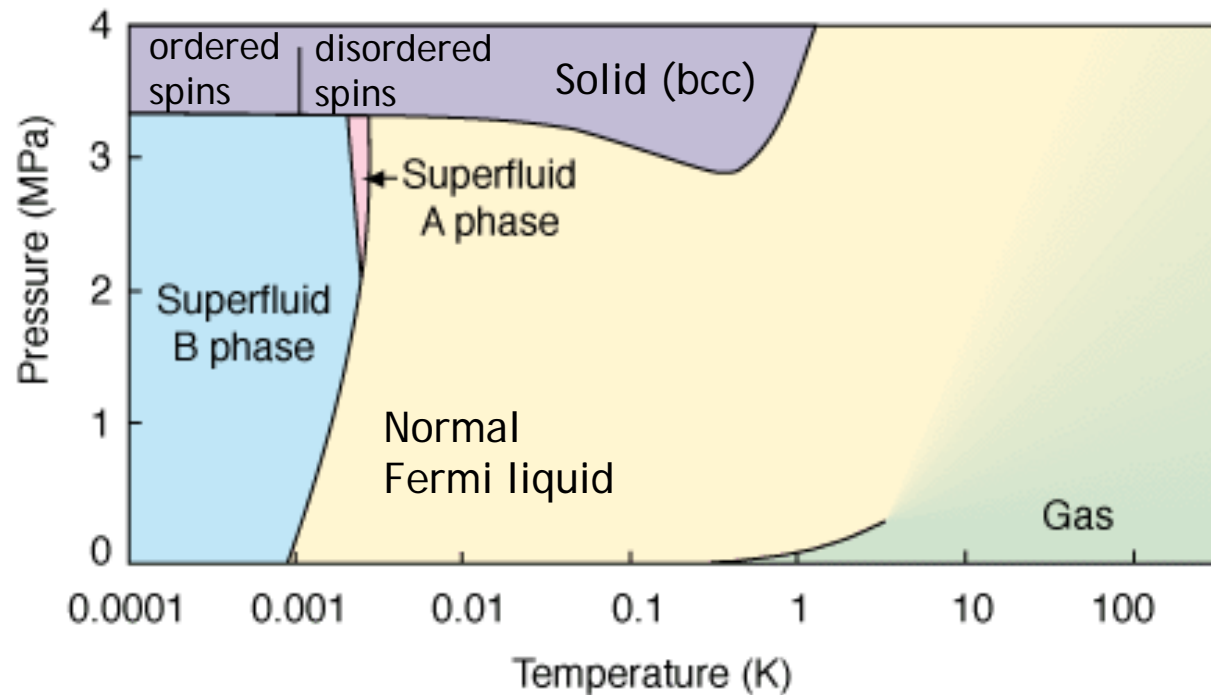
Robert C. Richardson
Cornell (USA)

Phase diagram of Helium-3

P-T phase diagram

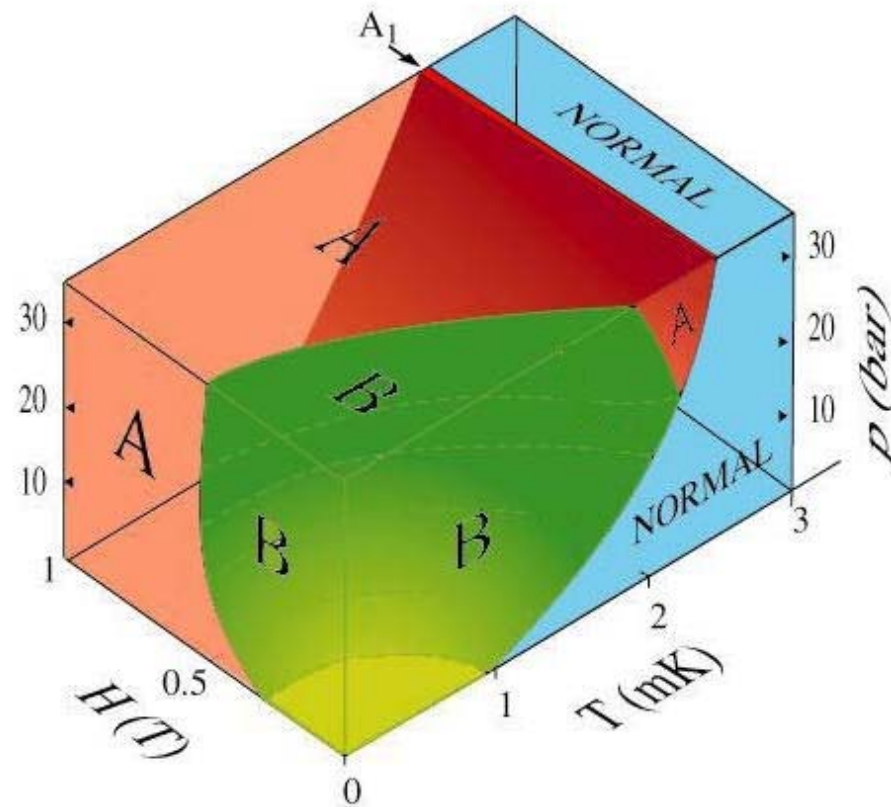
Dense, simple liquid

isotropic
short-range interactions
extremely pure
nuclear spin $S=1/2$



Phase diagram of Helium-3

P-T-H phase diagram



“Very low temperatures”: $T \ll T_{\text{boiling}} \sim 3\text{-}4 \text{ K}$
 $\ll T_{\text{backgr. rad.}} \sim 3 \text{ K}$

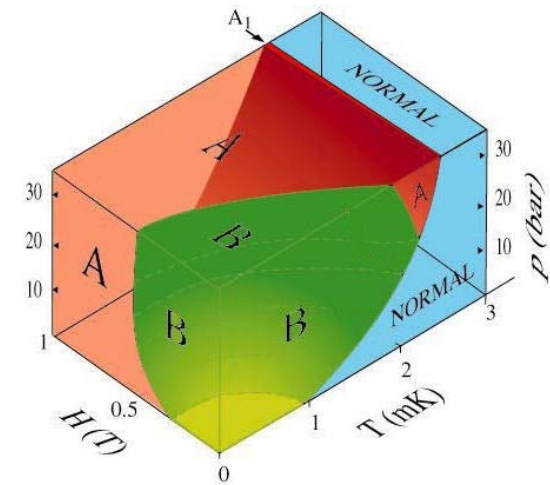
Superfluid phases of ^3He

Theory + experiment: $L=1$, $S=1$ in all phases

Leggett

Wölfle

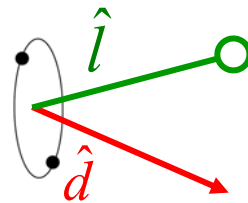
Mermin, ...



Attraction due to **spin fluctuations**

Anderson, Brinkman (1973)

→ anisotropy directions
in a ^3He Cooper pair



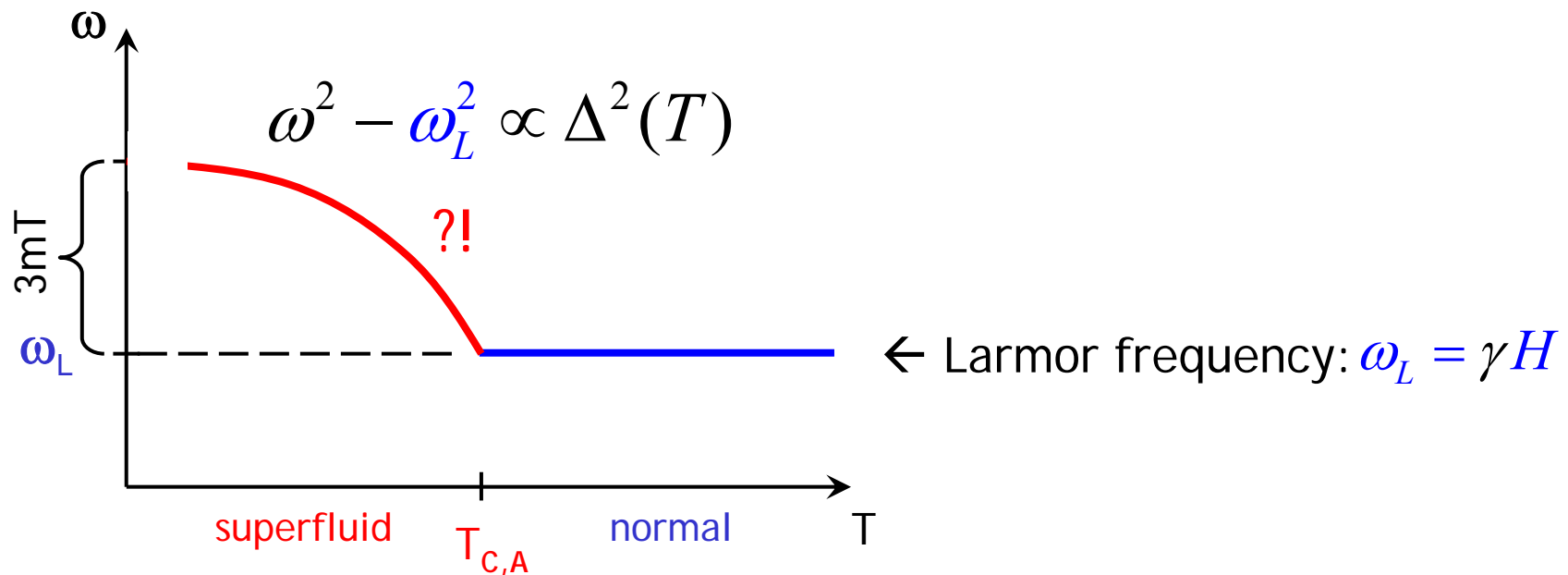
orbital part

spin part

... and a mystery!

NMR experiment on nuclear spins $I = \frac{1}{2}\hbar$

Osheroff *et al.* (1972)

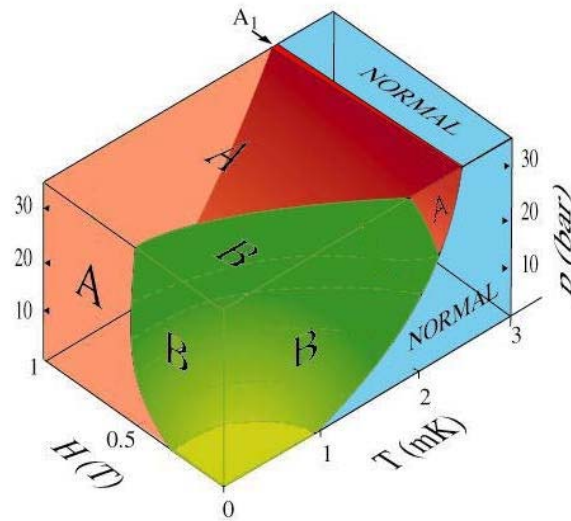


Shift of ω_L \Leftrightarrow spin-nonconserving interactions
→ nuclear dipole interaction $g_D \sim 10^{-7} K \ll T_C$

Origin of frequency shift ?!

Leggett (1973)

The superfluid phases of ^3He

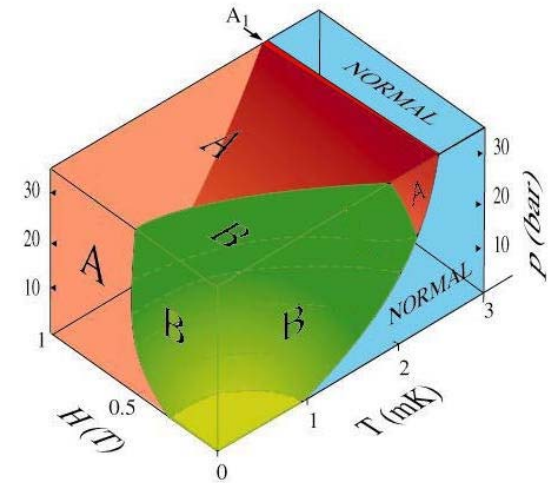
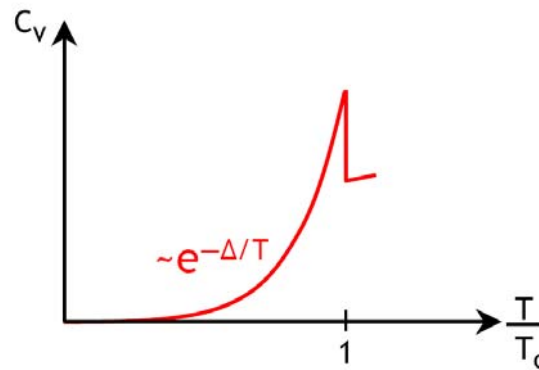
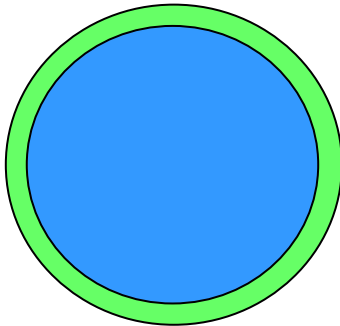


B-phase

$$\Psi = |\uparrow\uparrow\rangle + |\uparrow\downarrow + \downarrow\uparrow\rangle + |\downarrow\downarrow\rangle$$

$$\Delta(\mathbf{k}) = \Delta_0$$

Balian, Werthamer (1963)
Vdovin (1963)



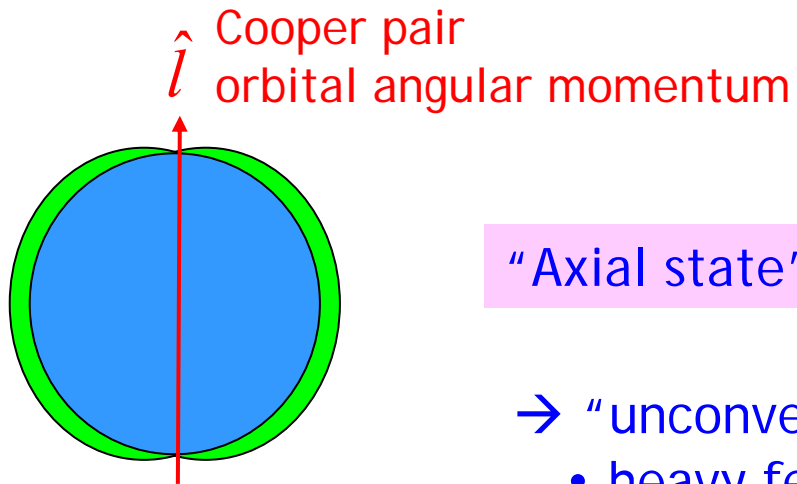
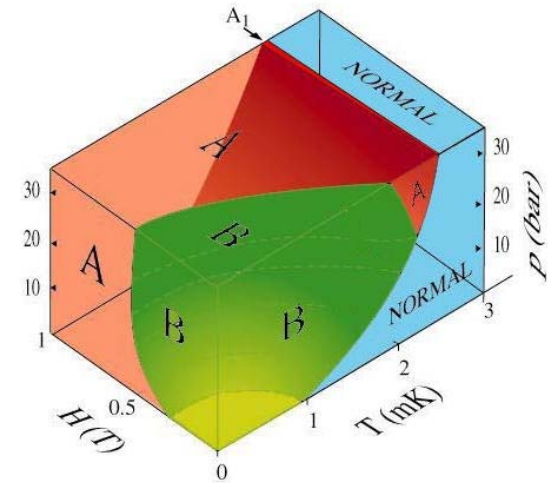
(pseudo-) isotropic state \leftrightarrow s-wave superconductor

Weak-coupling theory: stable for all $T < T_c$

A-phase

$$\Psi = |\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle \rightarrow \text{strong anisotropy}$$

$$\Delta(\hat{k}) = \Delta_0 \sin(\hat{k}, \hat{l}) \quad \text{Anderson, Morel (1961)}$$



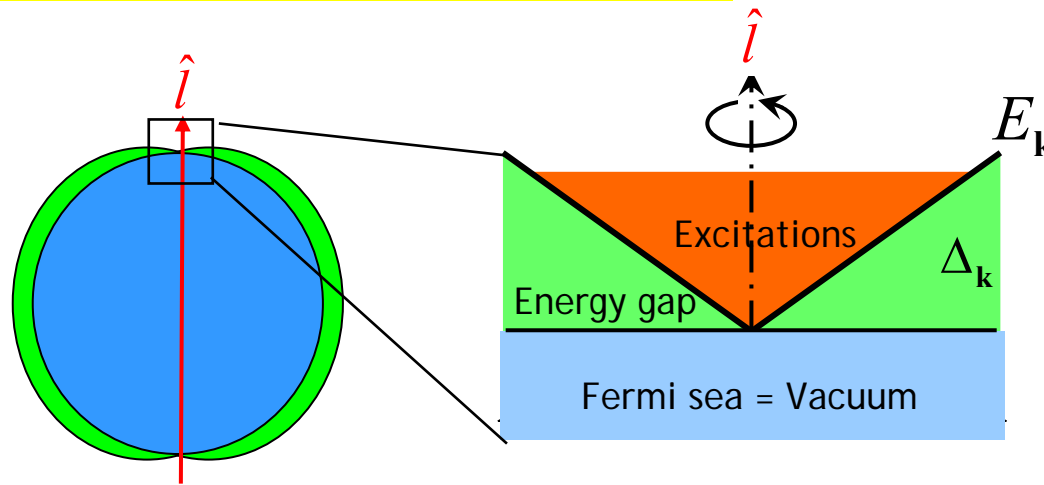
“Axial state” has point nodes

- “unconventional” pairing in
- heavy fermion/high- T_c superconductors
 - Sr_2RuO_4

Strong-coupling effect

³He-A: Spectrum near poles

Volovik (1987)



$$E_{\mathbf{k}}^2 = v_F^2 (k - k_F)^2 + \Delta_0^2 \sin^2(\hat{\mathbf{k}}, \hat{\mathbf{l}})$$

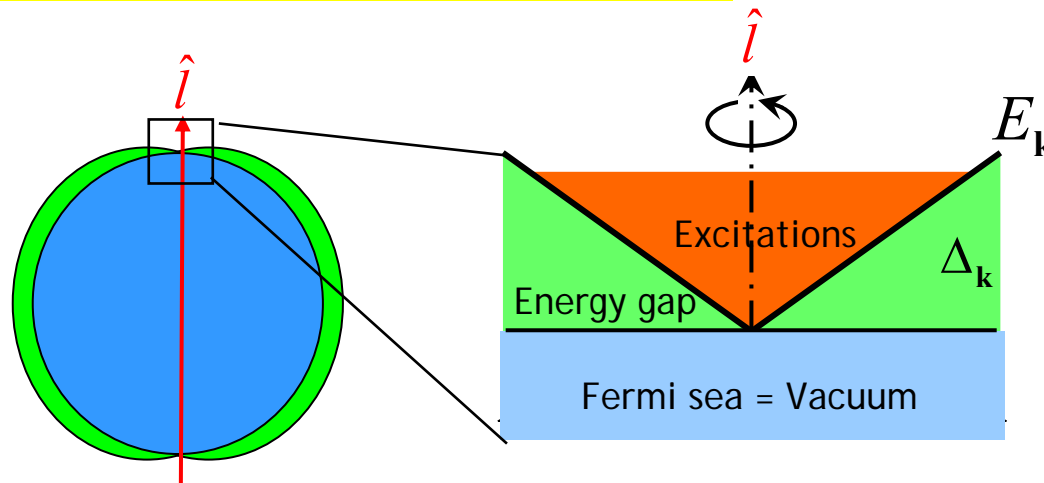
$$e = \begin{cases} +1 & \hat{\mathbf{k}} \parallel +\hat{\mathbf{l}} \\ -1 & \hat{\mathbf{k}} \parallel -\hat{\mathbf{l}} \end{cases} \quad \text{2 chiralities}$$

$$\mathbf{A} = k_F \hat{\mathbf{l}}$$

$$\mathbf{p} = \mathbf{k} - e\mathbf{A}$$

³He-A: Spectrum near poles

Volovik (1987)



$$E_{\mathbf{k}}^2 = v_F^2 (k - k_F)^2 + \Delta_0^2 \sin^2(\hat{\mathbf{k}}, \hat{\mathbf{l}}) = g^{ij} p_i p_j$$

$$e = \begin{cases} +1 & \hat{\mathbf{k}} \parallel +\hat{\mathbf{l}} \\ -1 & \hat{\mathbf{k}} \parallel -\hat{\mathbf{l}} \end{cases} \quad \text{2 chiralities}$$

$$g^{ij} = v_F^2 l_i l_j + \left(\frac{\Delta}{k_F} \right)^2 (\delta_{ij} - l_i l_j)$$

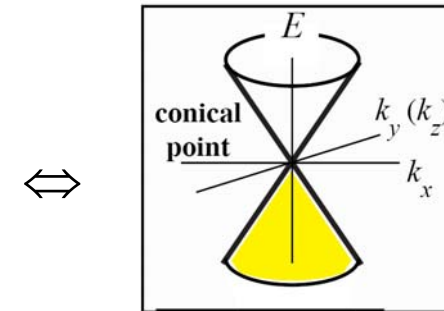
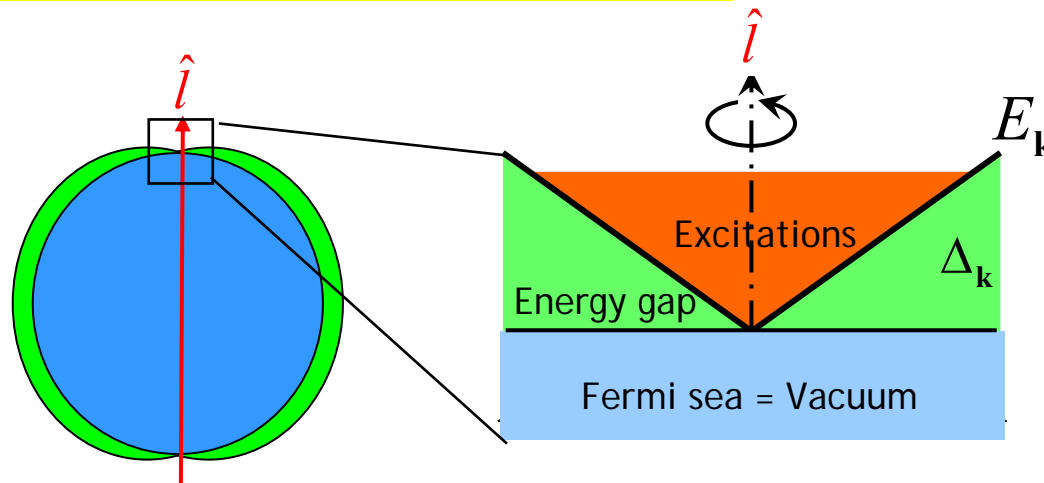
$$\mathbf{A} = k_F \hat{\mathbf{l}}$$

$$\mathbf{p} = \mathbf{k} - e\mathbf{A}$$

Lorentz invariance:
Symmetry enhancement
at low energies

³He-A: Spectrum near poles

Volovik (1987)



Fermi point:
spectral flow

$$E_{\mathbf{k}}^2 = v_F^2 (\mathbf{k} - \mathbf{k}_F)^2 + \Delta_0^2 \sin^2(\hat{\mathbf{k}}, \hat{\mathbf{l}}) = \mathbf{g}^{ij} p_i p_j$$

$$e = \begin{cases} +1 & \hat{\mathbf{k}} \parallel +\hat{\mathbf{l}} \\ -1 & \hat{\mathbf{k}} \parallel -\hat{\mathbf{l}} \end{cases} \quad \text{2 chiralities}$$

$$\mathbf{g}^{ij} = v_F^2 l_i l_j + \left(\frac{\Delta}{k_F} \right)^2 (\delta_{ij} - l_i l_j)$$

⇔ Massless, chiral leptons, e.g., neutrino $E(\mathbf{p}) = cp$

→ Chiral anomaly of standard model

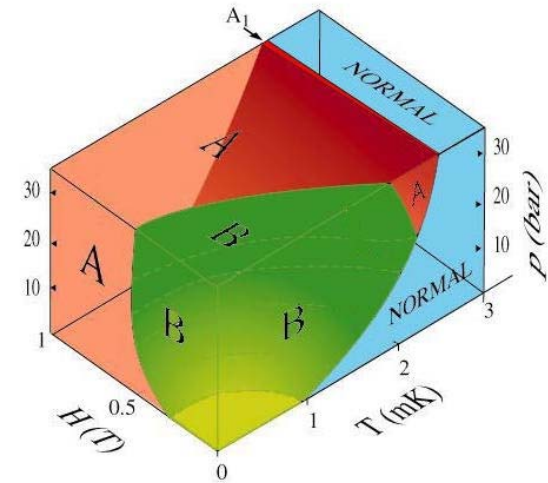
The Universe in a Helium Droplet,
Volovik (2003)

A_1 -phase

finite magnetic field

$$\Psi = |\uparrow\uparrow\rangle$$

Long-range ordered magnetic liquid

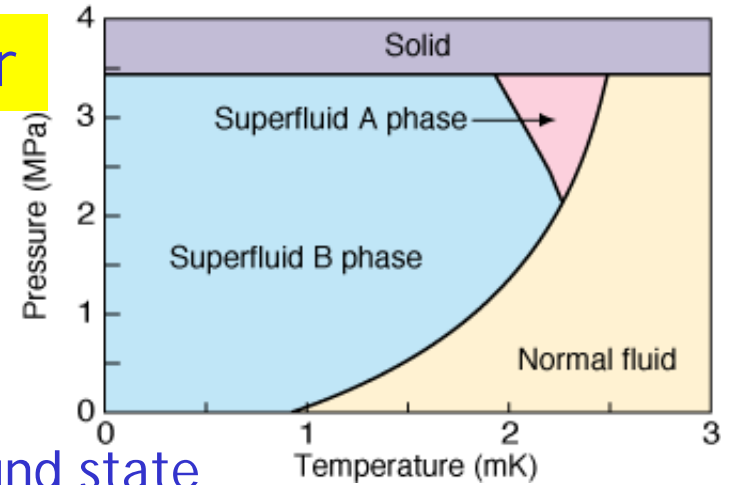


Broken Symmetries, Long Range Order



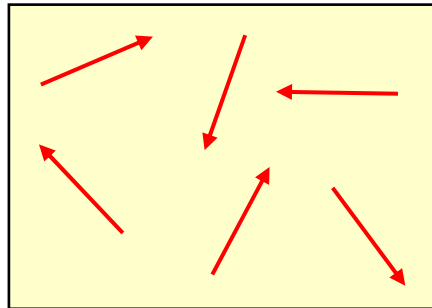
Broken Symmetries, Long Range Order

Normal $^3\text{He} \leftrightarrow ^3\text{He-A}, ^3\text{He-B}$:
 2. order phase transition



$T < T_c$: higher order, lower symmetry of ground state

I. Ferromagnet

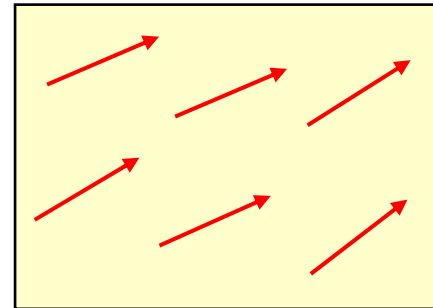


$T > T_c$

Average magnetization:
 Symmetry group:

$$\langle \mathbf{M} \rangle = 0$$

$$SO(3)$$



$T < T_c$

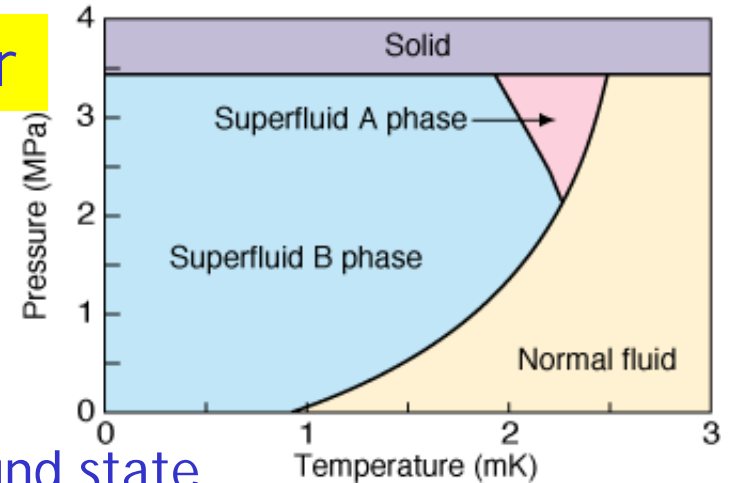
$$\langle \mathbf{M} \rangle \neq 0 \quad \text{Order parameter}$$

$$U(1) \subset SO(3)$$

$T < T_c$: $SO(3)$ rotation symmetry in spin space spontaneously broken

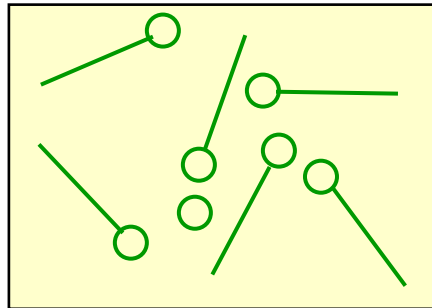
Broken Symmetries, Long Range Order

2. order phase transition

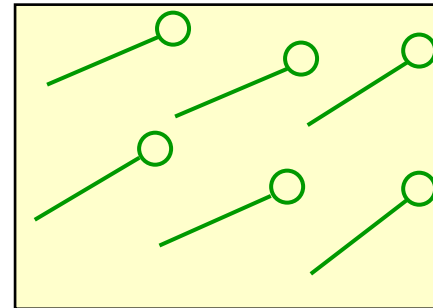


$T < T_c$: higher order, lower symmetry of ground state

II. Liquid crystal



$T > T_c$



$T < T_c$

Symmetry group:

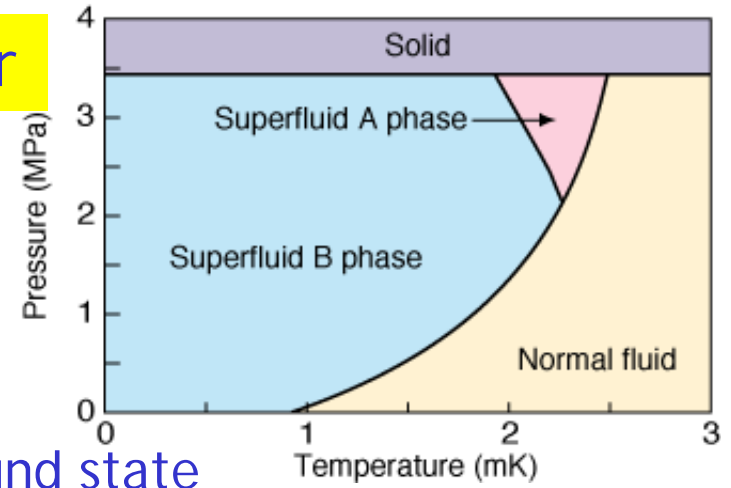
$SO(3)$

$U(1) \subset SO(3)$

$T < T_c$: $SO(3)$ rotation symmetry in real space spontaneously broken

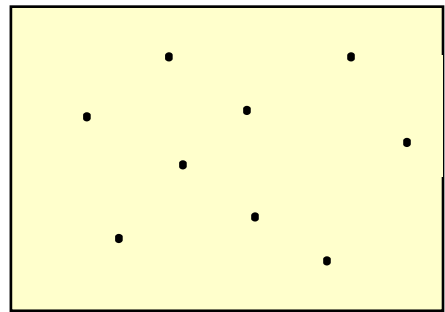
Broken Symmetries, Long Range Order

2. order phase transition

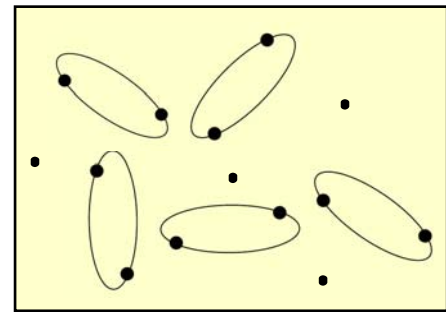


$T < T_c$: higher order, lower symmetry of ground state

III. Conventional superconductor



$T > T_c$



$T < T_c$

Pair amplitude $\langle c_{\mathbf{k}\uparrow}^\dagger c_{-\mathbf{k}\downarrow}^\dagger \rangle = 0$

$\Delta e^{i\phi}$ "Order parameter"

Gauge transf. $c_{\mathbf{k}\sigma}^\dagger \rightarrow c_{\mathbf{k}\sigma}^\dagger e^{i\varphi}$: gauge invariant

not gauge invariant

Symmetry group U(1)

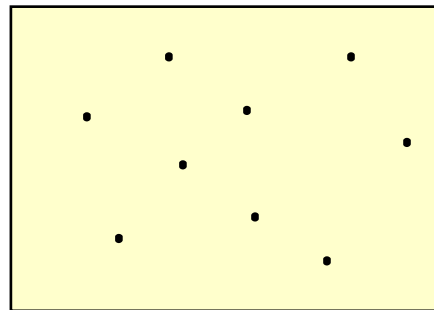
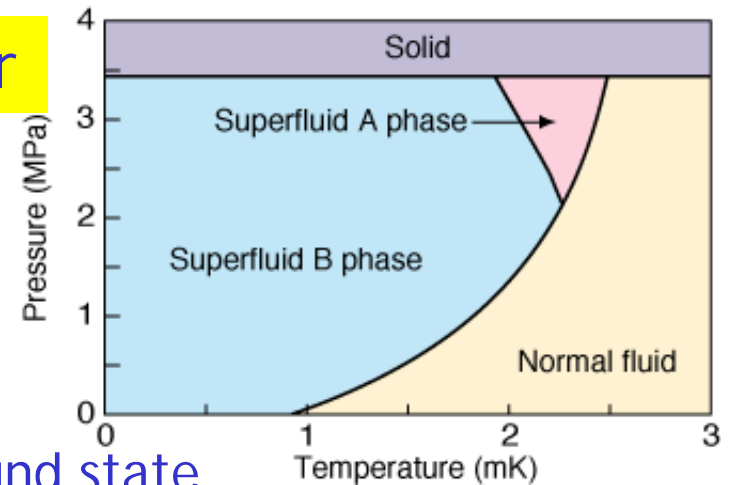
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Broken Symmetries, Long Range Order

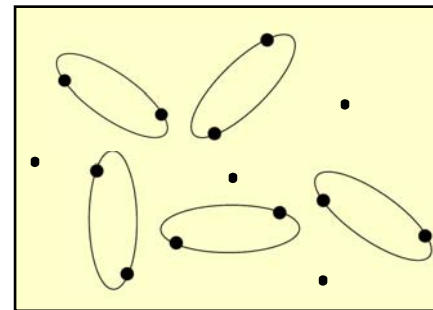
2. order phase transition

$T < T_c$: higher order, lower symmetry of ground state

III. Conventional superconductor



$T > T_c$



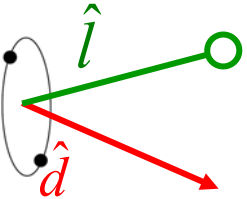
$T < T_c$

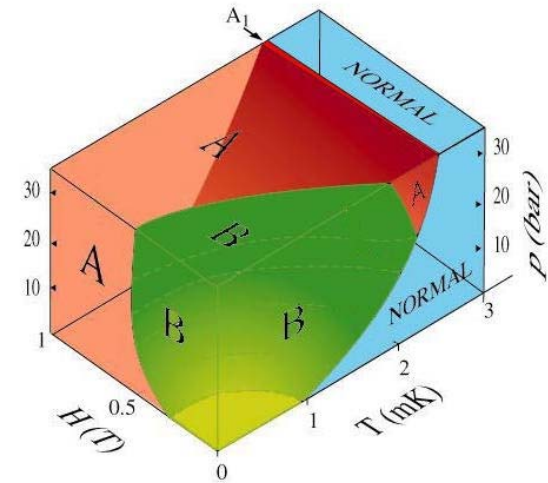
$T < T_c$: U(1) "gauge symmetry" spontaneously broken

→ U(1) gauge symmetry also broken in BEC

Broken symmetries in superfluid ^3He

$S=1$, $L=1$ in all phases

Cooper pair:  orbital part
spin part



Quantum coherence in $\left\{ \begin{array}{l} \text{anisotropy direction for spin} \\ \text{anisotropy direction in real space} \\ \text{phase} \end{array} \right.$ magnetic
liquid crystal
superfluid

Characterized by $(2S + 1) \times (2L + 1) \times 2 = 18$ real numbers

3x3 order parameter matrix $A_{i\mu}$

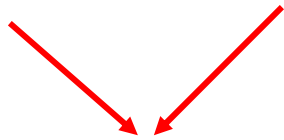
$\text{SO}(3)_S \times \text{SO}(3)_L \times \text{U}(1)_\varphi$ symmetry spontaneously broken Leggett (1975)

Broken symmetries in superfluid ^3He

Mineev (1980)
Bruder, DV (1986)

3He-B

$\text{SO}(3)_S \times \text{SO}(3)_L \times \text{U}(1)_\varphi$ symmetry broken

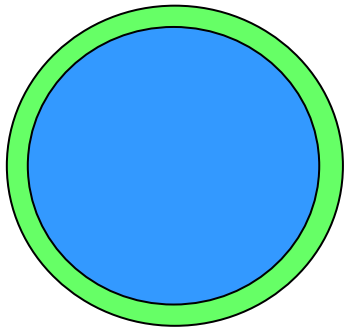


$\text{SO}(3)_{S+L}$



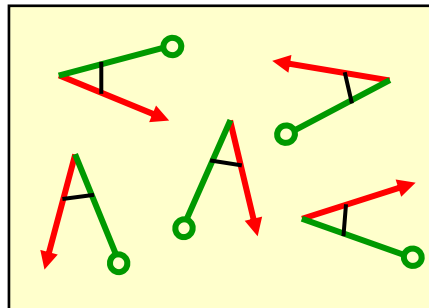
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„Unconventional“ superfluidity



Spontaneously broken spin-orbit
symmetry
Leggett (1972)

Cooper pairs



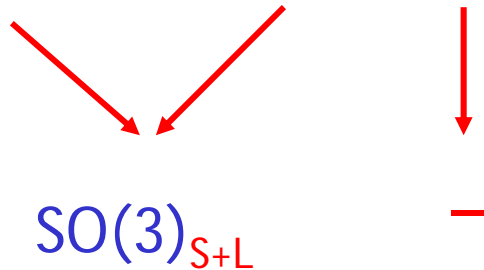
Fixed relative orientation

Broken symmetries in superfluid ^3He

Mineev (1980)
Bruder, DV (1986)

3He-B

$\text{SO}(3)_S \times \text{SO}(3)_L \times \text{U}(1)_\varphi$ symmetry broken



„Unconventional“ superfluidity

Relation to high energy physics

Isodoublet

$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_R$ chiral invariance

Global symmetry

$\text{SU}(2)_L \times \text{SU}(2)_R$



Goldstone excitations (bosons)

3 pions

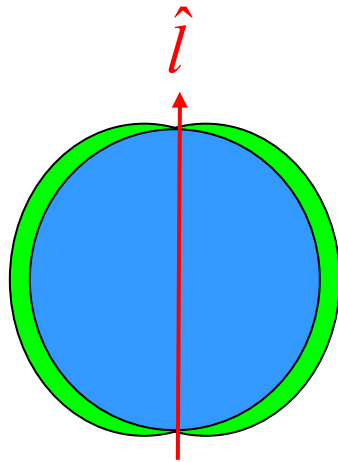
Broken symmetries in superfluid ^3He

Mineev (1980)
Bruder, DV (1986)

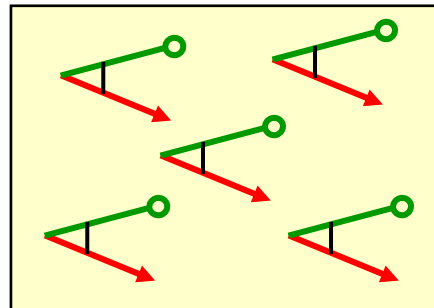
3He-A $\text{SO}(3)_S \times \text{SO}(3)_L \times \text{U}(1)_\varphi$ symmetry broken

$\text{U}(1)_{S_z} \times \text{U}(1)_{L_z - \varphi}$

„Unconventional“ pairing

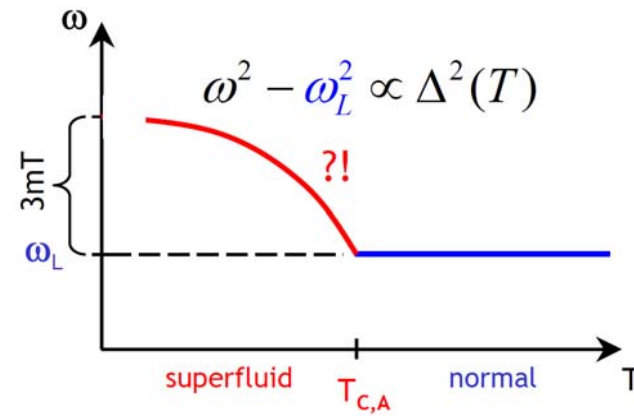


Cooper pairs



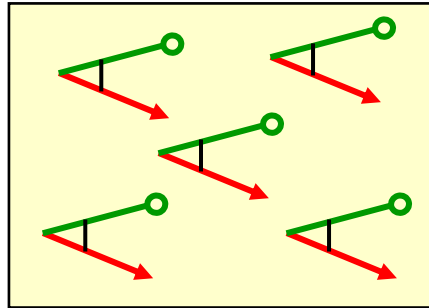
Fixed absolute orientation

Resolution of the NMR puzzle



Superfluid ^3He - a quantum amplifier

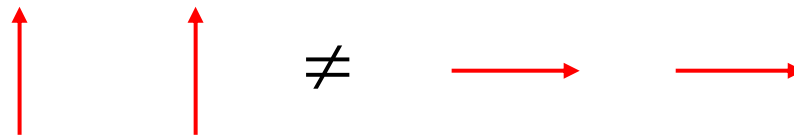
Cooper pairs in ^3He -A



Fixed **absolute** orientation

What determines the **actual** relative orientation of \hat{d} , \hat{l} ?

→ Anisotropic **spin-orbit interaction** of nuclear dipoles:

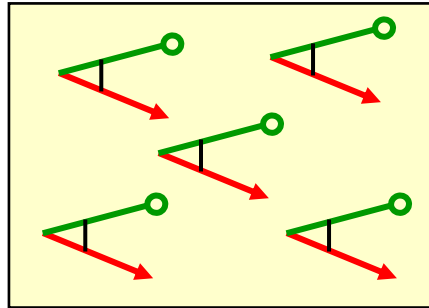


Dipole-dipole coupling of ^3He nuclei: $g_D \sim 10^{-7} K \ll T_C$

Unimportant ?!

Superfluid ^3He - a quantum amplifier

Cooper pairs in $^3\text{He-A}$



Fixed **absolute** orientation

- Long-range order in \hat{d}, \hat{l} due to Cooper pairing
- $g_D \sim 10^{-7} K$: tiny (but lifts degeneracy of relative orientation)

Quantum \Downarrow coherence

\hat{d}, \hat{l} locked in **all** Cooper pairs in the **same** way

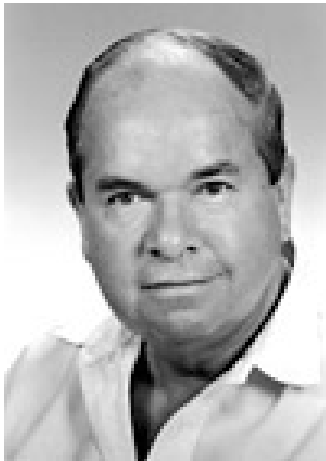


NMR frequency increases: $\omega^2 = (\gamma H)^2 + g_D \Delta^2(T)$ Leggett (1973)

→ Nuclear dipole interaction macroscopically measurable

The Nobel Prize in Physics 2003

"for pioneering contributions to the theory of superconductors
and superfluids"



Alexei A. Abrikosov
USA and Russia

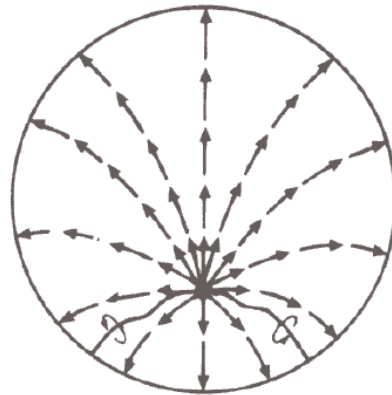


Vitaly L. Ginzburg
Russia



Anthony J. Leggett
UK and USA

Order parameter textures and topological defects

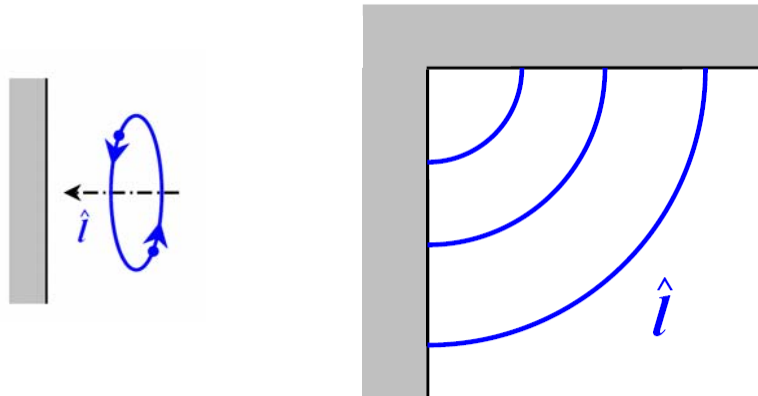


Order parameter textures

Orientation of anisotropy directions \hat{d}, \hat{l} in ${}^3\text{He-A}$?

Magnetic field $\rightarrow \hat{d}$

Walls $\rightarrow \hat{l}$

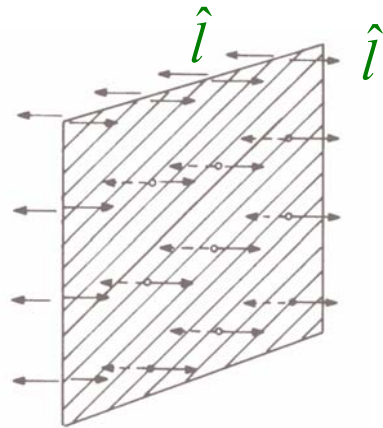


\rightarrow Textures in $\hat{d}, \hat{l} \leftrightarrow$ liquid crystals

\rightarrow Topologically stable defects

Order parameter textures and topological defects

D=2: domain walls in \hat{d} or \hat{l}



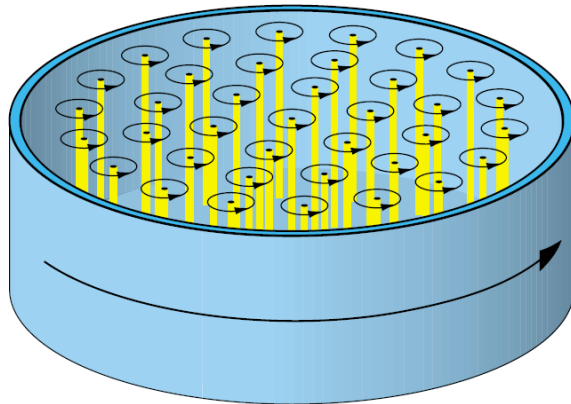
Single domain wall



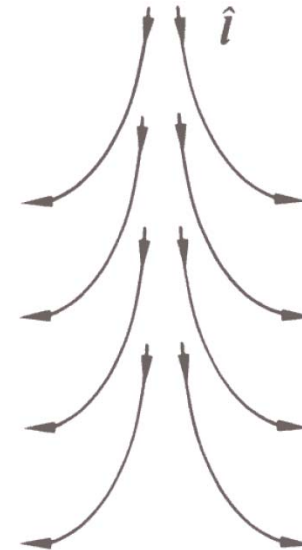
Domain wall lattice

Order parameter textures and topological defects

D=1: Vortices



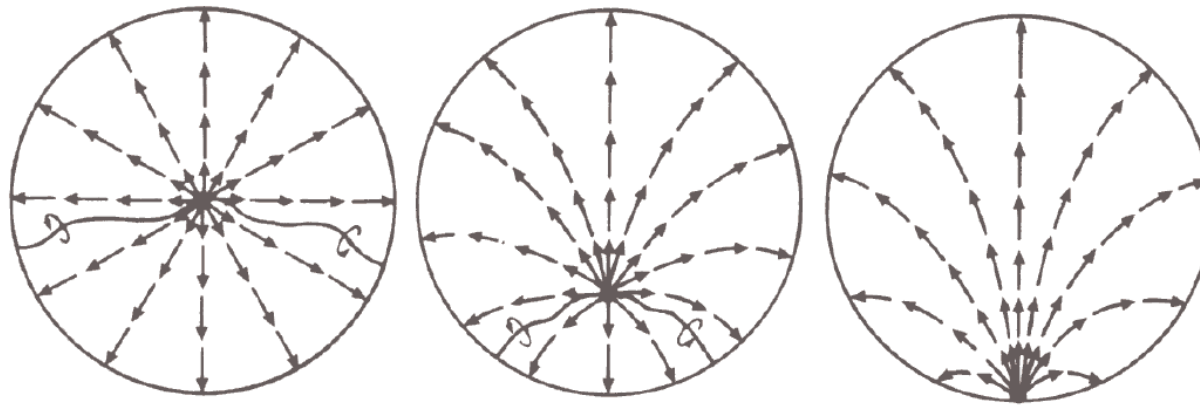
Vortex formation
(rotation experiments)



e.g., Mermin-Ho vortex
(non-singular)

Order parameter textures and topological defects

D=0: Monopoles



“Boojum” in \hat{l} -texture of ${}^3\text{He-A}$
(geometric constraint)

Defect formation by, e.g.,

- rotation
- geometric constraints
- rapid crossing through phase transition

Big bang simulation
in the low temperature lab



Universality in continuous phase transitions



High symmetry,
short-range order

$T > T_c$

Spins:
para-
magnetic

Helium:
normal
liquid

Universe:
Unified forces
and fields

$T = T_c$

Phase transition

Broken symmetry,
long-range order

ferromagnetic

superfluid

elementary
particles,
fundamental
interactions

Defects: domain
walls

vortices,
etc.

cosmic strings,
etc. Kibble (1976)

$T < T_c$

nucleation of galaxies?



Rapid thermal quench through 2. order phase transition

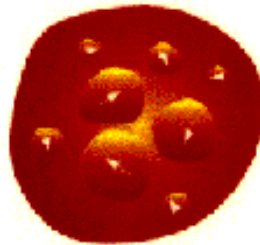
Kibble (1976)

1. Local temperature $T \gg T_C$



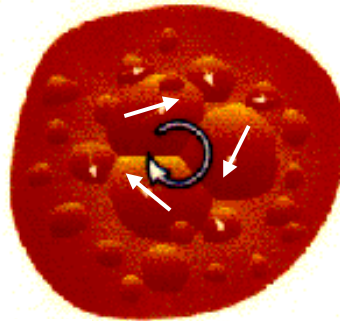
Expansion + rapid cooling

2. Nucleation of independently ordered regions

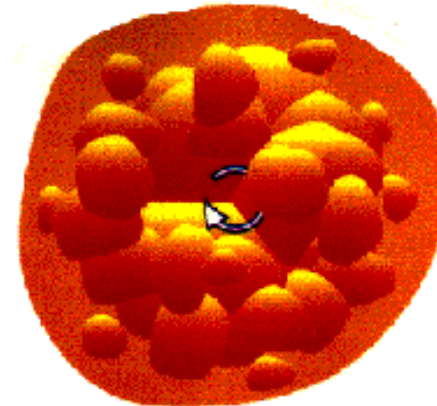


Clustering of ordered regions

→ Defects

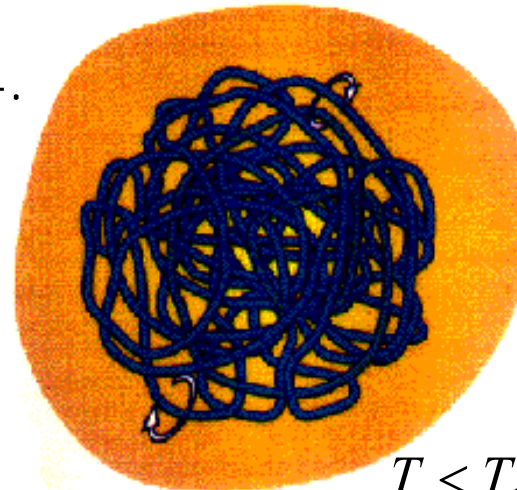


3.



Defects overlap

4.



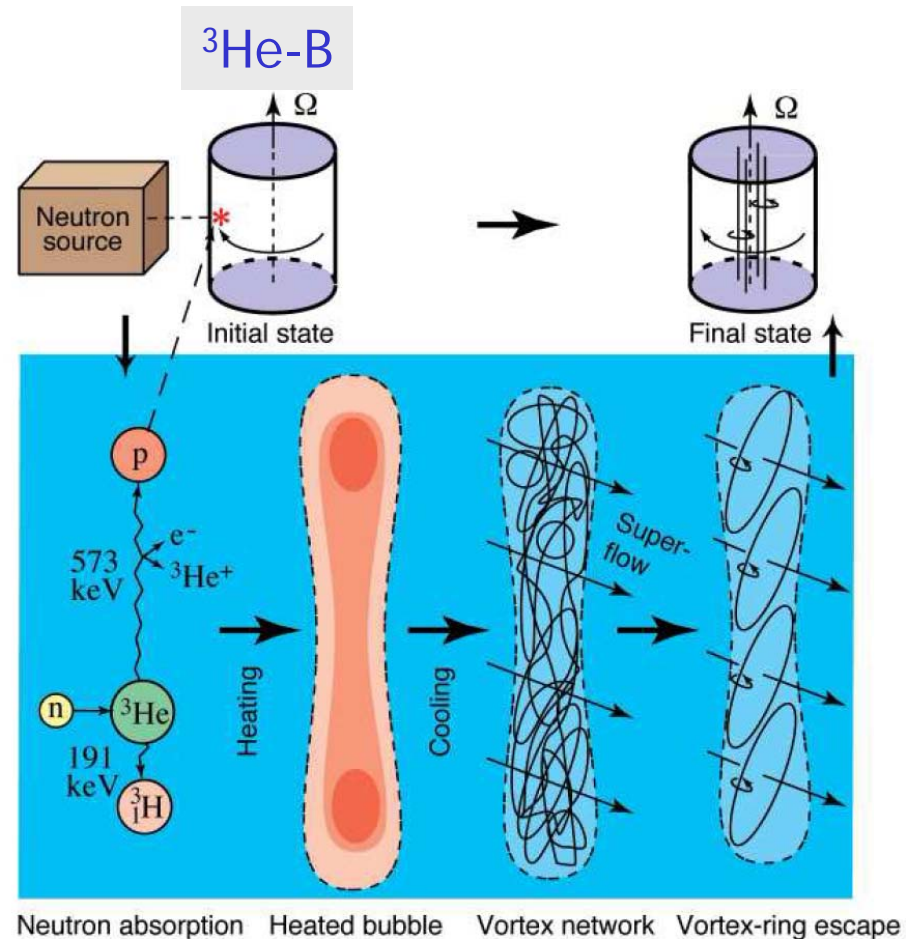
$T < T_C$: Vortex tangle

Estimate of density of defects Zurek (1985)

"Kibble-Zurek mechanism": How to test?

Big bang simulation in the low temperature laboratory

Grenoble: Bäuerle *et al.* (1996), Helsinki: Ruutu *et al.* (1996)



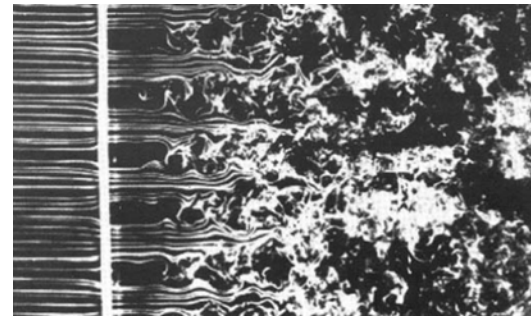
Measured vortex tangle density:
Quantitative support for Kibble-Zurek mechanism

Present research on superfluid ^3He : Quantum Turbulence

Classical Turbulence



Leonardo da Vinci (1452-1519)



Flow through grid

Quantum Turbulence = Turbulence in the absence of viscous dissipation (superfluid at $T \rightarrow 0$)

- What provides dissipation in the absence of friction?
- Why are quantum and classical turbulence so similar?

Test system: $^3\text{He-B}$

Vinen, Donnelly: *Physics Today* (April, 2007)

Conclusion

Superfluid Helium-3:

- Anisotropic superfluid
 - 3 different bulk phases
 - Cooper pairs with internal structure
- Large symmetry group broken
 - Close connections to particle theory
 - Zoo of topological defects
 - Kibble-Zurek mechanism quantitatively verified

