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Superfluid ^{3}He in Aerogel

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CosLab 2004; Chamrousse, *December 18, 2004*

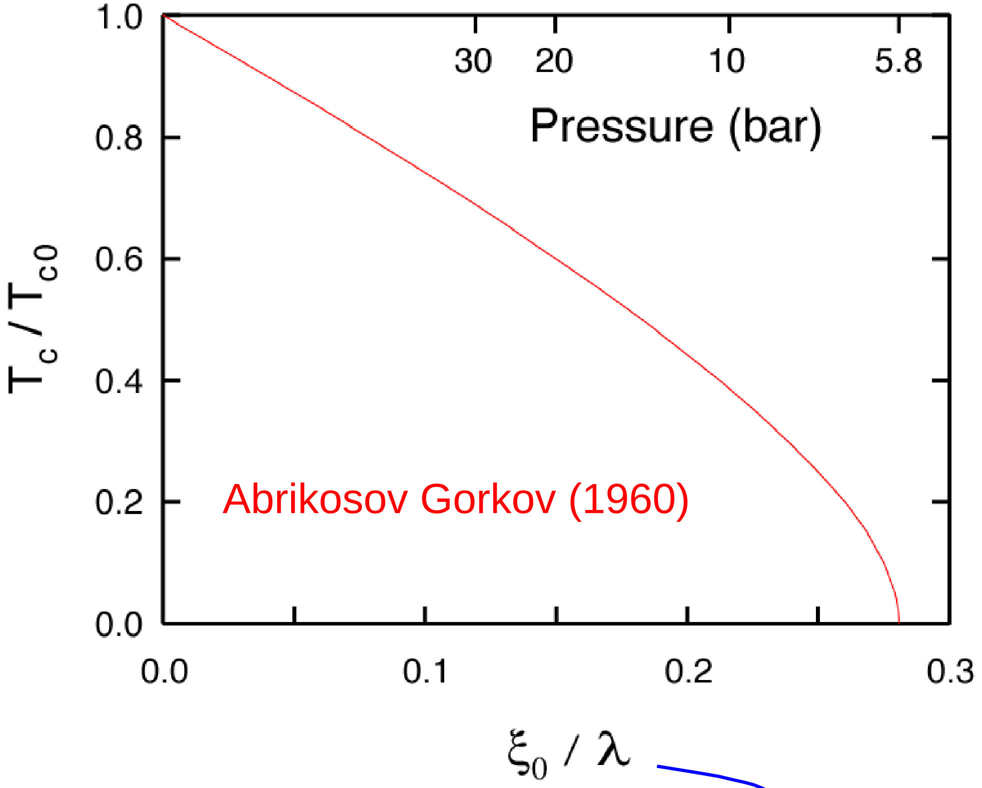
Impurities ⇨ *Disorder*

Unconventional Superfluids :

- heavy fermions (UPt_3), ruthenates, ….
- cuprates
- ^{3}He

Impurity suppression
of *unconventional*
superfluidity

(λ = 140 nm)

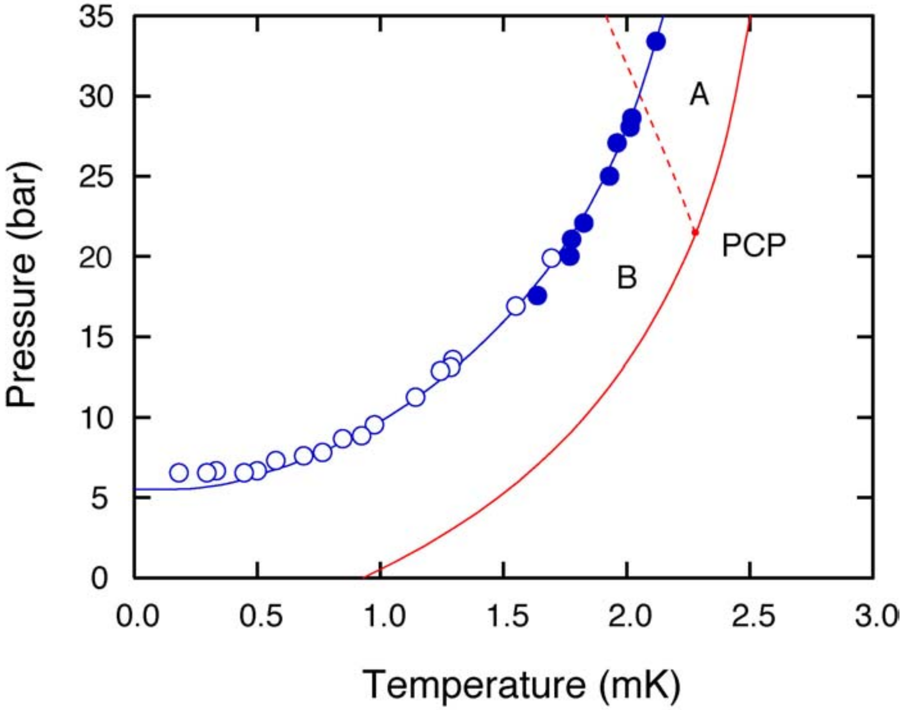


impurity
mean-free-path

Disorder can be introduced in
superfluid ^{3}He by
high porosity silica aerogel

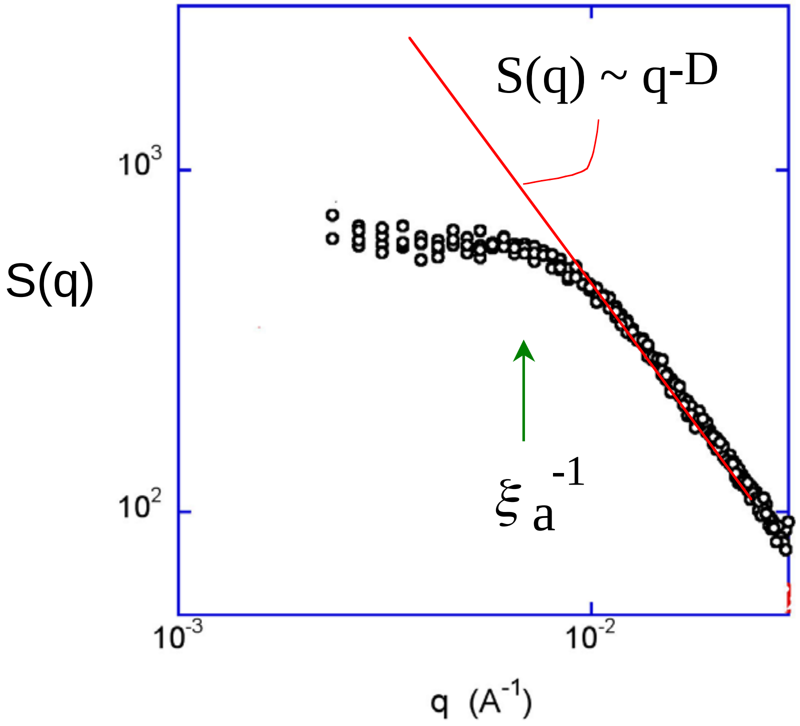
Why Superfluid ^{3}He in Aerogel ?

- Superfluid ^{3}He in aerogel; hopelessly complex, or *perturbatively simple*?
- Can we learn about *pure* superfluid ^{3}He by introducing spatial disorder?
- Do the aerogel superfluids show *new phenomena*? new phases, metastability, and nucleation.



Matsumoto et al. PRL **79**, 253 (1997)
Gervais et al. PRL **87**, 035701 (2001);
PRB **66**, 054528 (2002).

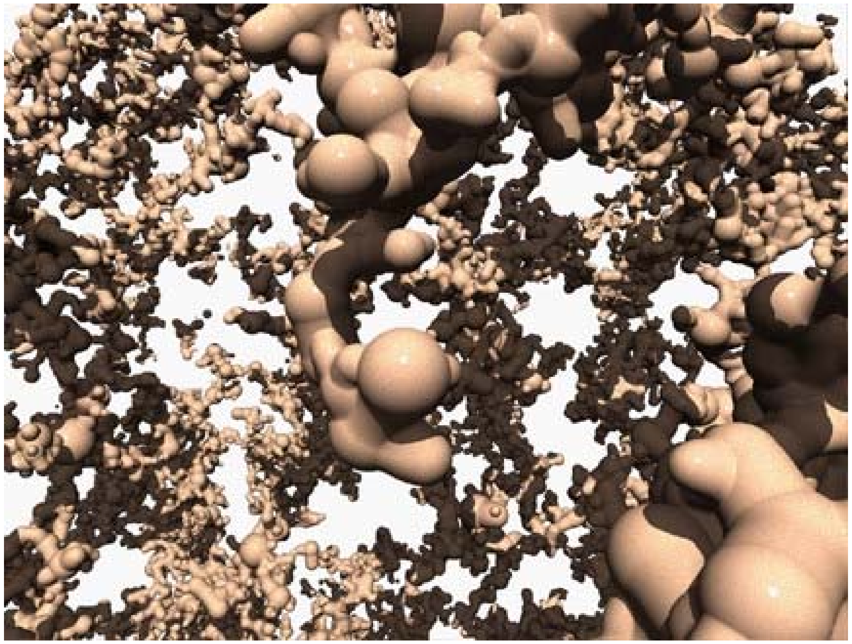
Silica Aerogel:



SAXS,
porosity, ϕ = 98%, *Norbert Mulders*

$S(q) \sim q^{-D}$, $q > \xi_a^{-1}$
$S(0) \sim \xi_a^3 (1-\phi)^2$

DLCA Calculation,
porosity, ϕ = 98%, *Tom Haard*

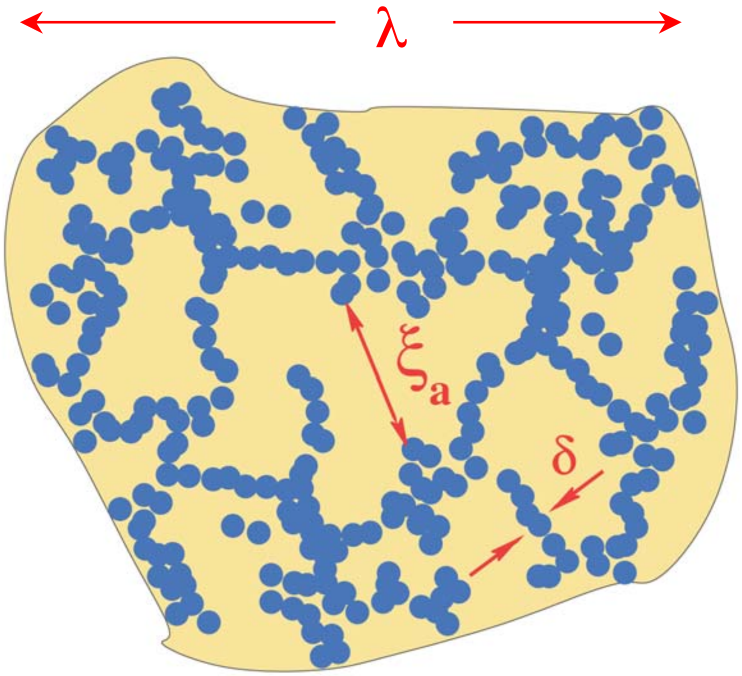


particle diameter $\delta \approx$ 3 nm
mean free path $\lambda \approx$ 200 nm
Fractal cutoff $\xi_a \approx$ 30 - 50 nm
Fractal dimension $D \approx$ 1.8

Compare these length scales with the superfluid coherence length:

$\xi_o \approx$ 20 to 80 nm (34 to 0 bar)

The coherence length is larger than the silica particle size diameter, δ;
it is of order the correlation length, ξ_a;
and smaller than the mean free path, λ (superfluid is not completely suppressed)



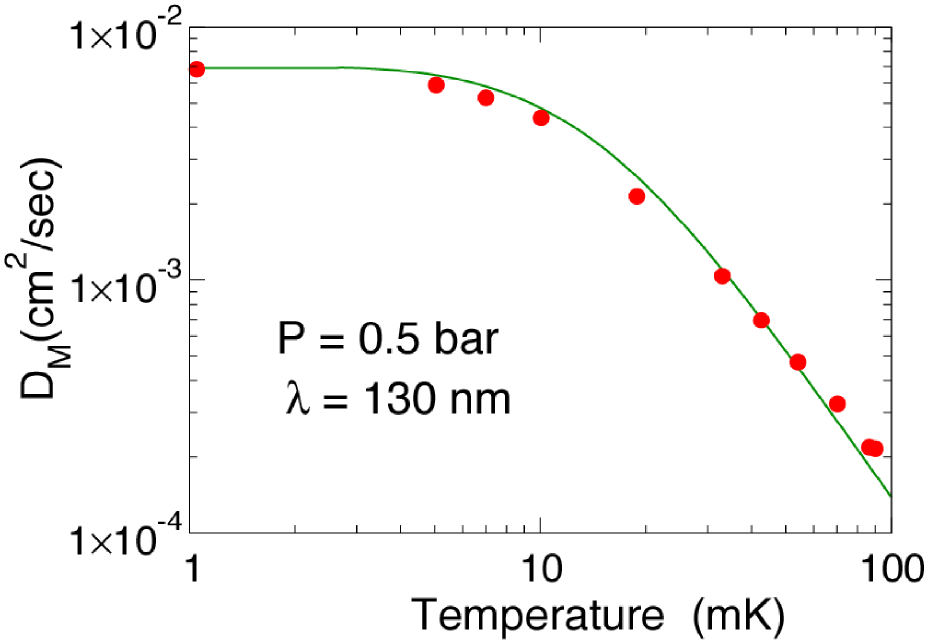
The mean free path can be determined in the normal state of ^{3}He in aerogel from transport measurements:

- spin diffusion (U. Mass., Grenoble)
- thermal conductivity (Lancaster)
- attenuation of sound (Northwestern)

Normal State

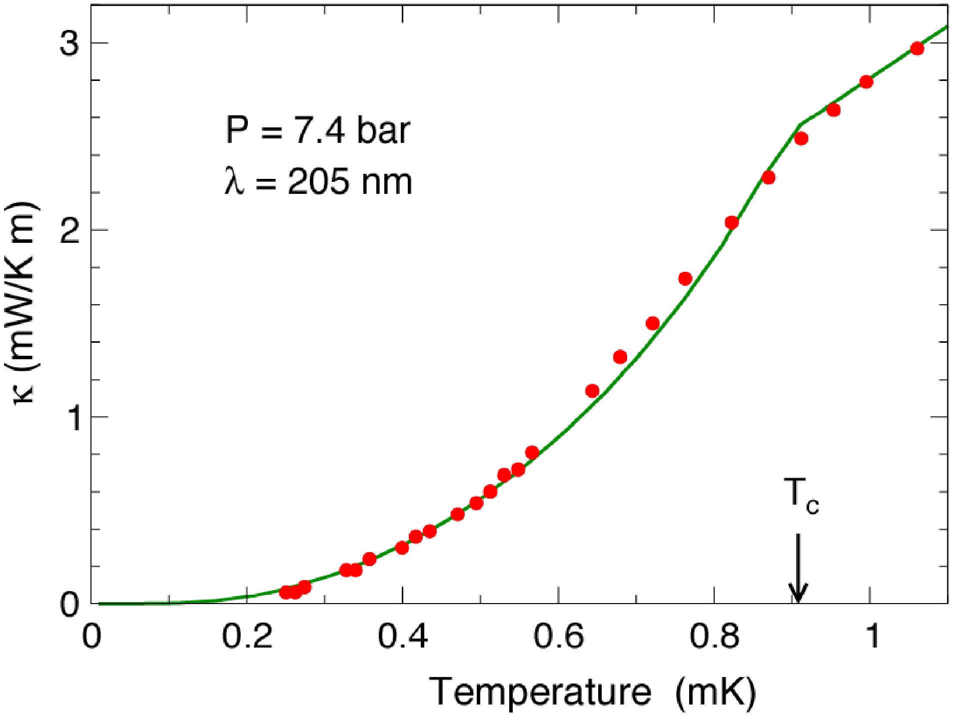
Spin diffusion

Collin, thesis (2002);
Sauls *et al.* cond-mat/0408492



Thermal conductivity

Fisher *et al.* JLTP (2001)



Scattering Models for the Superfluid State:

Thuneberg et al. PRL **80**, 2861 (1998); *Sauls, Sharma*, PRB (2003); *Hanninen,Thuneberg* PRB (2003).

The simplest model for aerogel: a random distribution of point isotropic scatterers.

Arbitrarily small anisotropy leads to orientational disorder of the vector order parameter, according to fundamental arguments by Imry and Ma, PRL(1975). For the axial state (bulk A-phase), this forces spatial inhomogeneity of the orbital state which Volovik JETPL (1997) calls a superfluid glass.

Fomin JETPL (2003); JLTP (2004) has suggested that instead of the axial state an aerogel A-phase, could be a *homogeneous* equal spin pairing state, but one of a class of "robust" *p*-wave states not constrained by above arguments to be a glass.

The free energy, density of states, thermal conductivity, attenuation of sound, spin diffusion, magnetic susceptibility have been calculated. Note: *Thuneberg, Sauls, Khardze, Nagai, Mineev, Fomin.*

Ginzburg-Landau theory:

For *pure* ^{3}He the free energy $F[A]$ is expanded as a function of the five fourth-order invariants of the 3x3 complex *p*-wave order parameter, ***A***:

$$F\left[A\right] = \frac{1}{3}\alpha\,(T)\,Tr\,(AA^{\dagger}) + g_z\,B(AA^{\dagger})B +$$
$$\beta_1\left|Tr\,(AA^{T})\right|^2 + \beta_2\left(Tr\,(AA^{T})\right)^2 + \beta_3\,Tr\,[AA^{T}(AA^{T})^*]$$
$$\beta_4\,Tr\,[(AA^{\dagger})^2] + \beta_5\,Tr\,[AA^{\dagger}(AA^{\dagger})^*]$$

Rainer and Serene PRB **13**, 4745 (1976); **17**, 2901 (1978).

where $\beta_{ijk} = \beta_i + \beta_j + \beta_k$

axial state (A-phase) heat capacity jump: $\dfrac{\Delta C_A}{C} = 1.19\,\dfrac{2}{\beta_{245}}$

isotropic state (B-phase)heat capacity jump: $\dfrac{\Delta C_B}{C} = 1.43\,\dfrac{5}{3\beta_{12} + \beta_{345}}$

A_1- A_2 field splitting ratio: $r = \dfrac{T_{A1} - T_c}{T_c - T_{A2}} = -\dfrac{\beta_5}{\beta_{245}}$

T_{AB} suppression by magnetic field:

$$1 - \frac{T_{AB}(B)}{T_c} = g(\beta)\ (B/B_o)^2$$

$$g(\beta) = \frac{\beta_{245}}{2(-3\,\beta_{13} + 2\,\beta_{345})}\left(1 + \sqrt{\frac{(3\,\beta_{12} + \beta_{345})(2\,\beta_{13} - \beta_{345})}{\beta_{245}\beta_{345}}}\right)$$

GL-theory for Superfluid ^{3}He in Aerogel

Homogeneous Isotropic Scattering Model (HISM):

Treat the silica aerogel as a system of point scatterers for ^{3}He quasiparticles. There is one parameter: the transport mean free path, λ, assuming strong scattering (unitary limit). The pair breaking parameter is $x = \xi_o / \lambda$.

Homogeneous Isotropic Scattering Model (HISM) *Thuneberg et al. PRL* **80**, 2861 (1998); *Sauls (2002)*, includes strong coupling corrections:

$$\beta_i^{aero} = a_1(T_{ca},\lambda)\,\beta_i^{wc} + \frac{T_{ca}}{T_{c0}}\,\beta_i^{sc\text{-}bulk}$$

Inhomogeneous Isotropic Scattering Model (IISM):

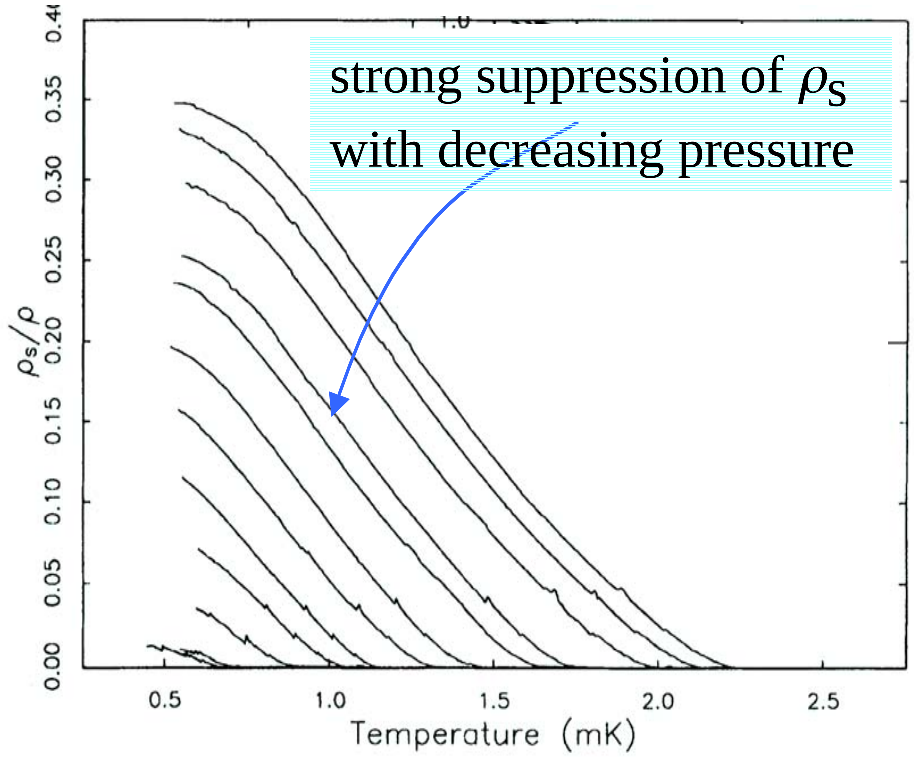
According to Sauls and Sharma (2003), include the particle-particle correlation length, ξ_a, in a new pair breaking parameter, $x = (\xi_o / \lambda)/[1 + (\xi_a / \xi_o)^2]$.

$$\beta_i^{aero} = a_1(\lambda, \xi_a)\, \beta_i^{wc} + \frac{T_{ca}}{T_{c0}} \beta_i^{sc\text{-}bulk}$$

Experiments for Superfluid ^{3}He in Aerogel:

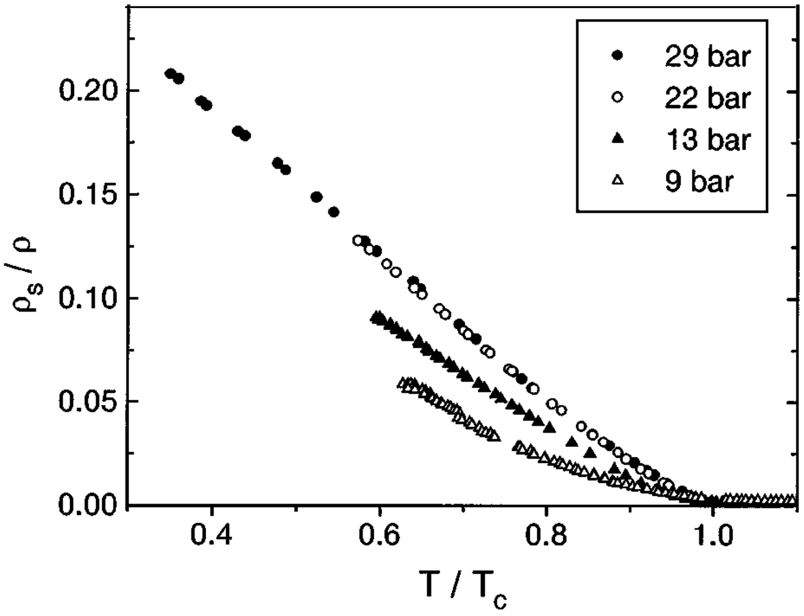
Superfluid density *Porto and Parpia PRL* **74**, 4667 (1995). *Golov et al. PRL* **82**, 3492 (1999).

torsional oscillator



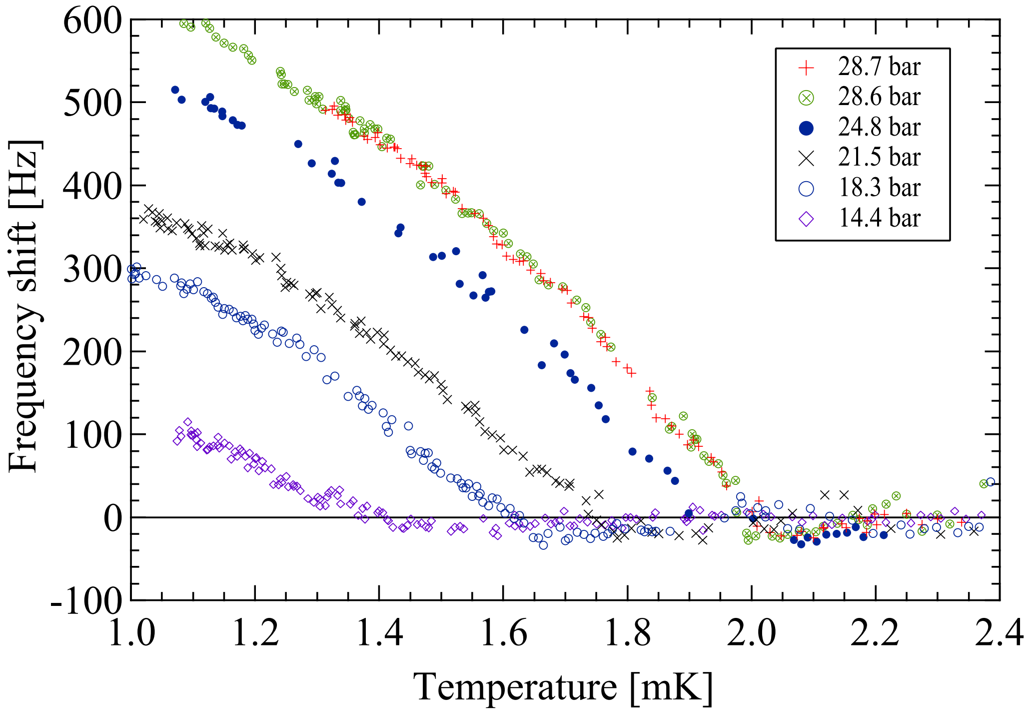
strong suppression of ρ_S with decreasing pressure

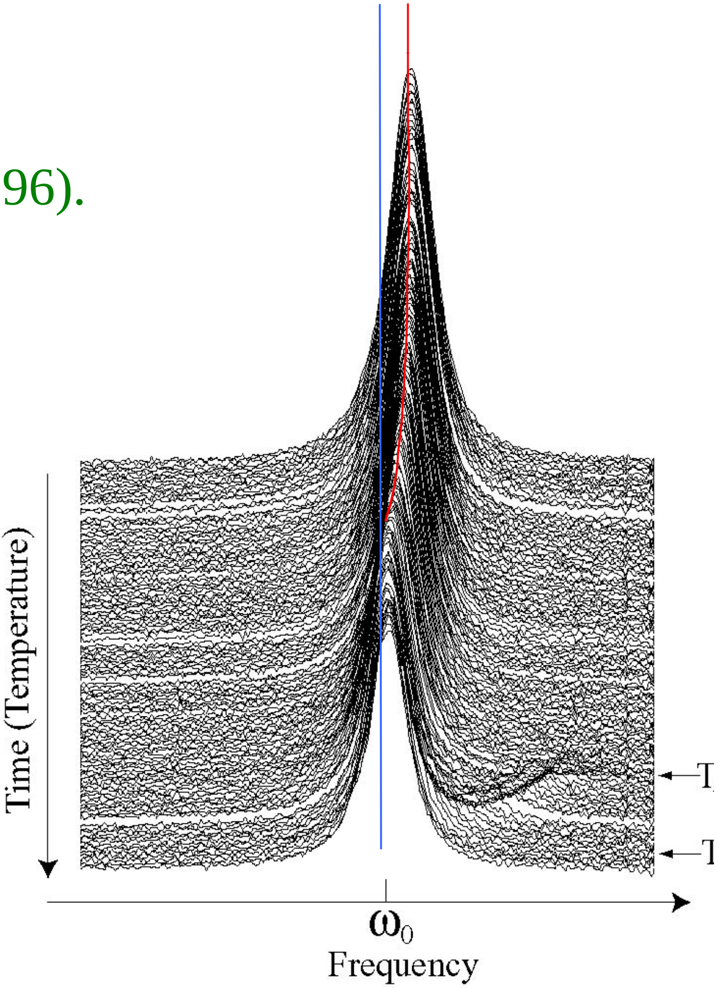
sound velocity



NMR

Sprague et al.PRL **75**, 661 (1995); *PRL* **77**, 4568 (1996).

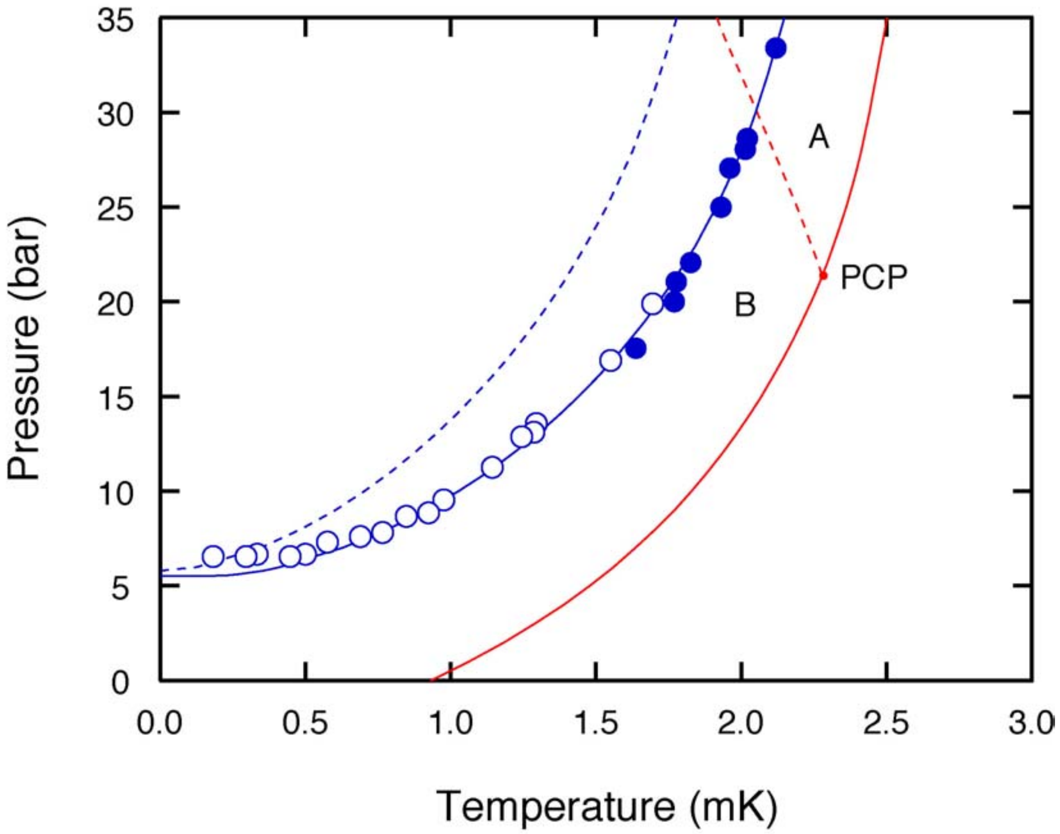




P = 28.7 bar

More recently: *Osheroff (Stanford), Hata (Osaka),*
Bunkov/Godfrin, (Grenoble), Dimitriev (Moscow)

Phase Diagram with correlated scattering (IISM)



λ = 140 nm

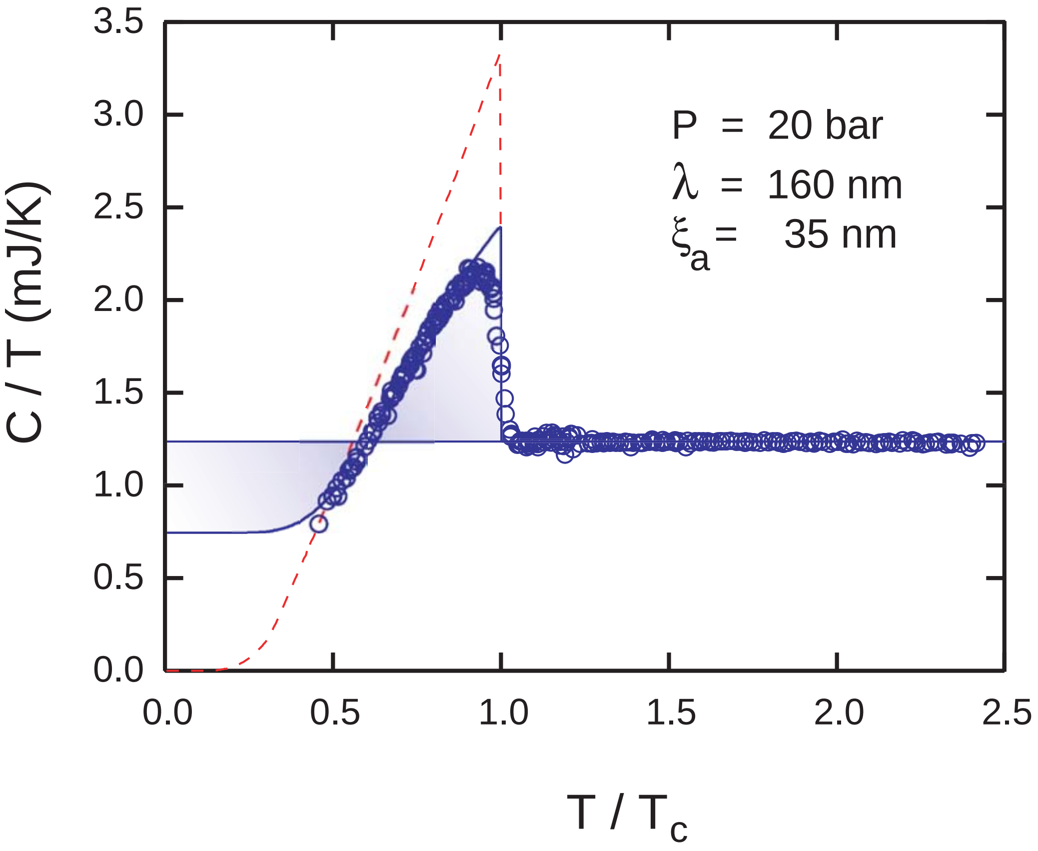
— ξ_a = 50 nm

····· ξ_a = 0

- Is this a well-defined thermodynamic transition?
- Is the phase boundary field dependent?
- What are the phases of this aerogel/superfluid: axial (A), isotropic (B), planar, polar, axi-planar,…?

Heat Capacity:

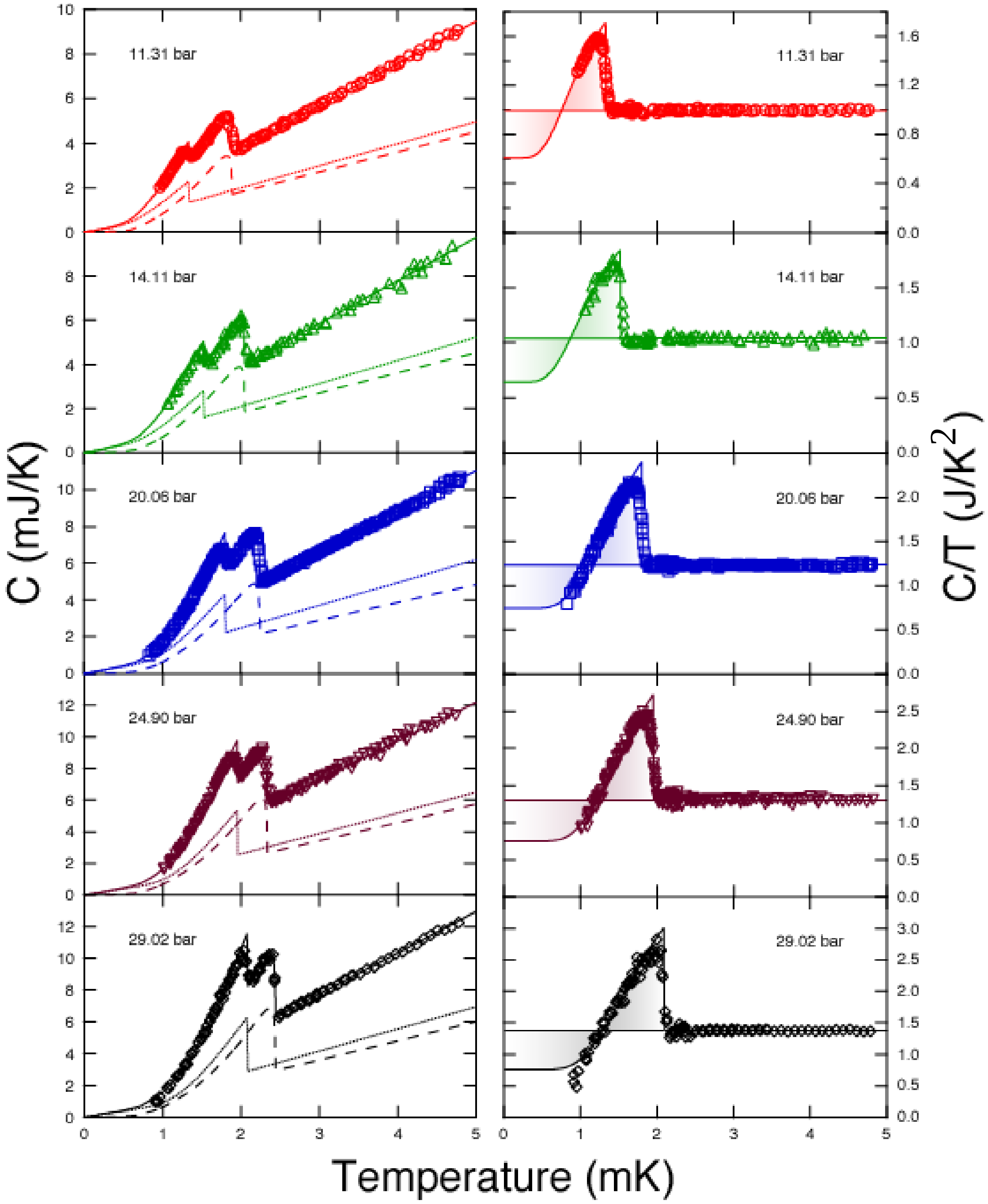
Aerogel-Superfluid heat capacity at P = 20 bar
(98% porosity aerogel) Choi *et al.*PRL **93**, 145301 (2004).



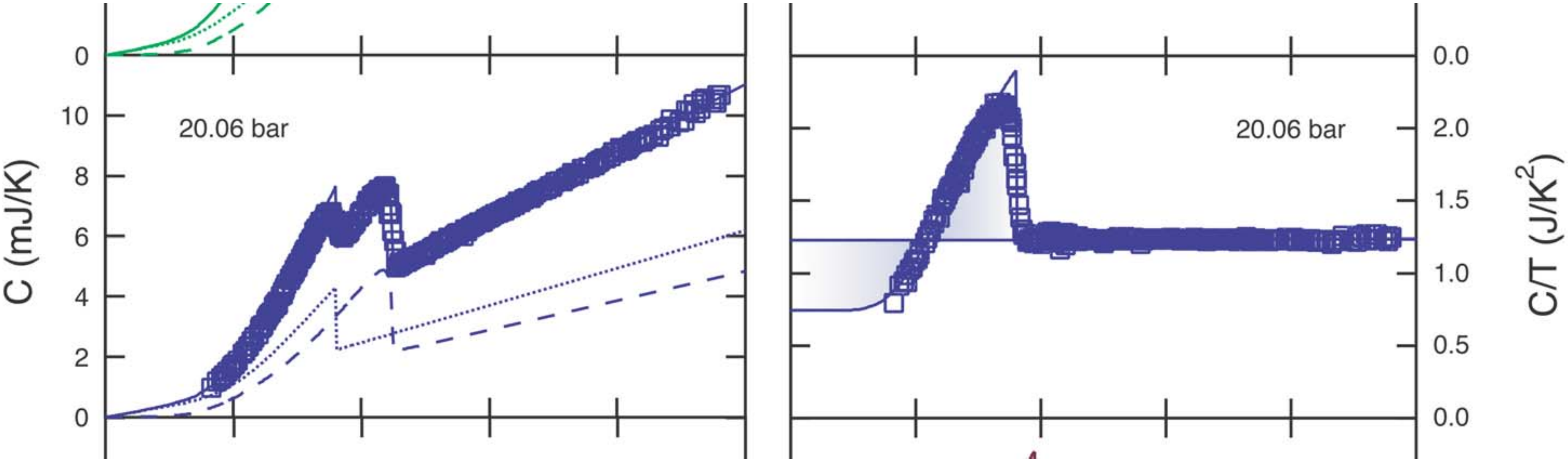
$$\Delta(T) = \pi\, k_B T_c \left[\frac{2}{3}\left(\frac{T_c}{T} - 1\right) \frac{\Delta C}{C} \right]^{1/2}$$

ΔC/C = 1.0 ±0.1 compared to 1.82 for pure ^{3}He at P = 20 bar.

the order parameter is suppressed.

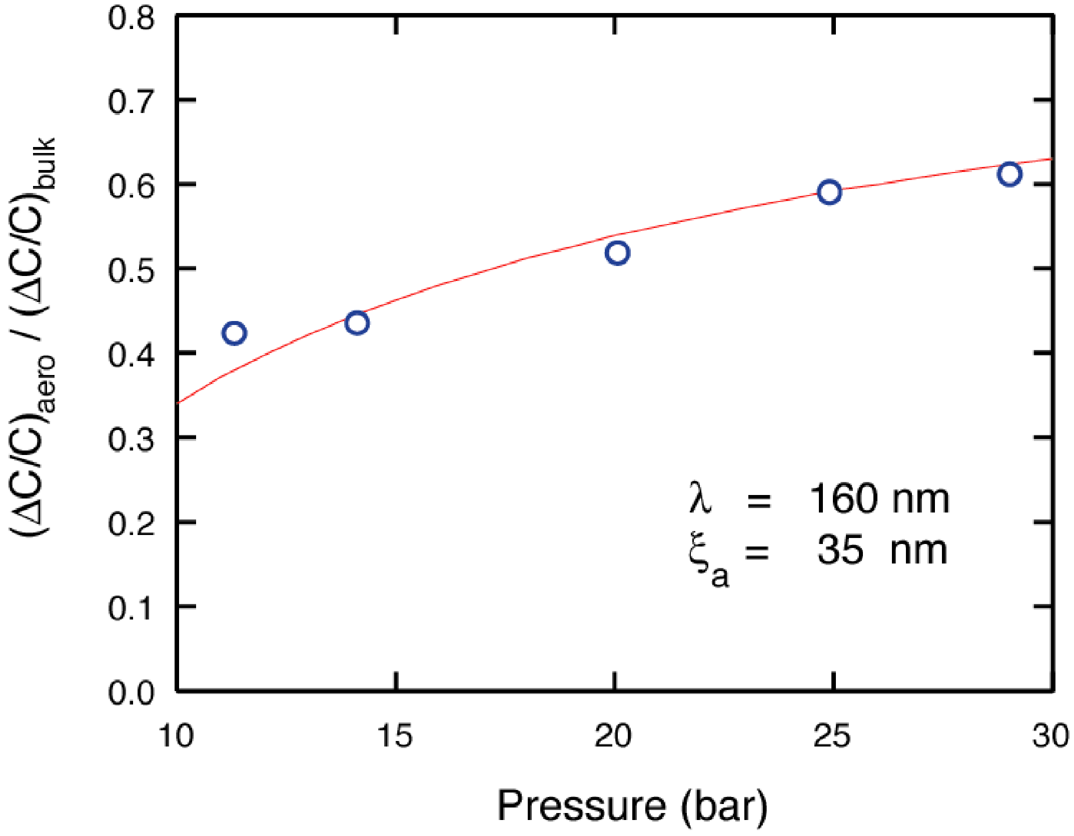


CosLab 2004; Chamrousse


0
10
8
6
4
2
0
C (mJ/K)
20.06 bar
20.06 bar
0.0
2.0
1.5
1.0
0.5
0.0
C/T (J/K^2)

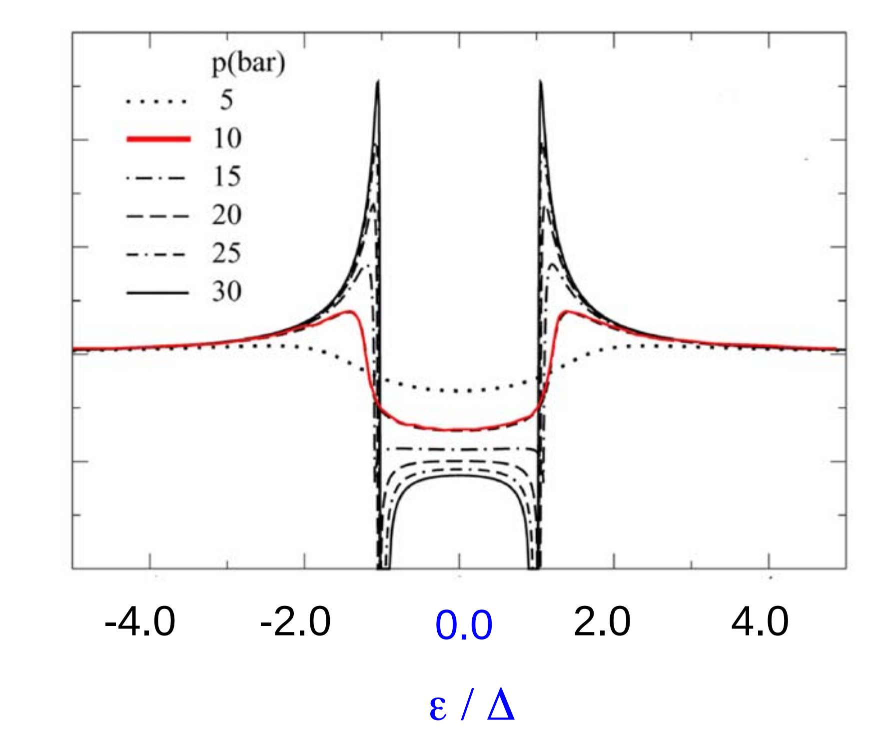
Strong suppression of the amplitude of the order parameter:

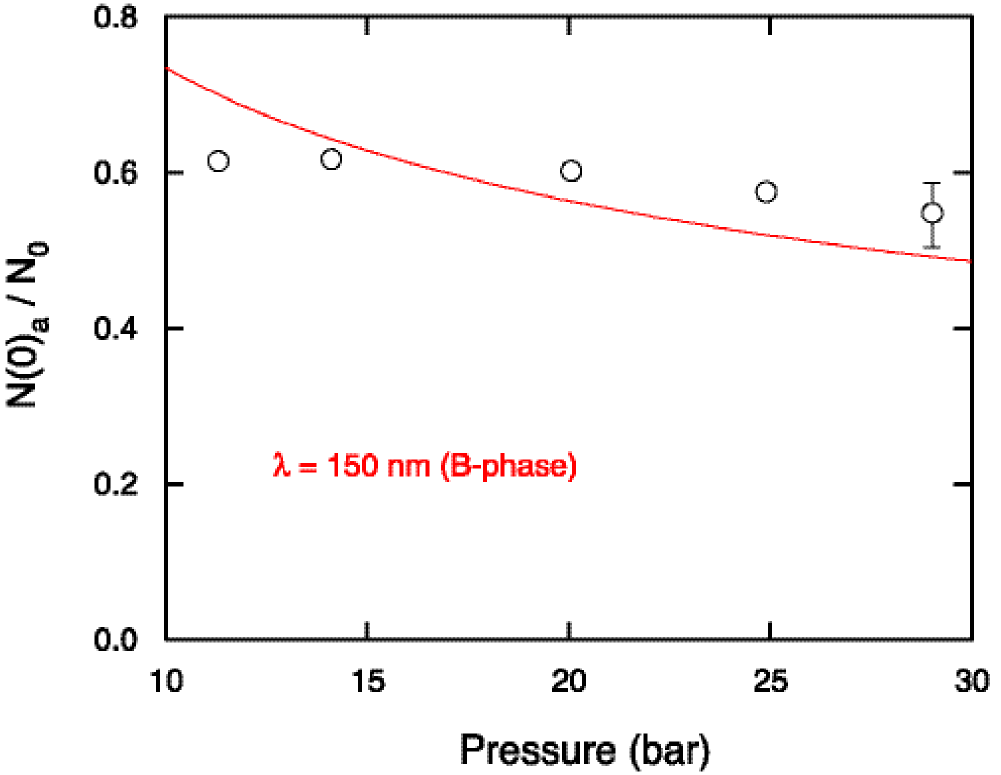
$$\Delta(T) = \pi\, k_B T_c \left[\frac{2}{3}\left(\frac{T_c}{T} - 1\right) \frac{\Delta C}{C} \right]^{1/2}$$



Density of Andreev bound states at ε = 0

Sharma and Sauls
JLTP (2001).





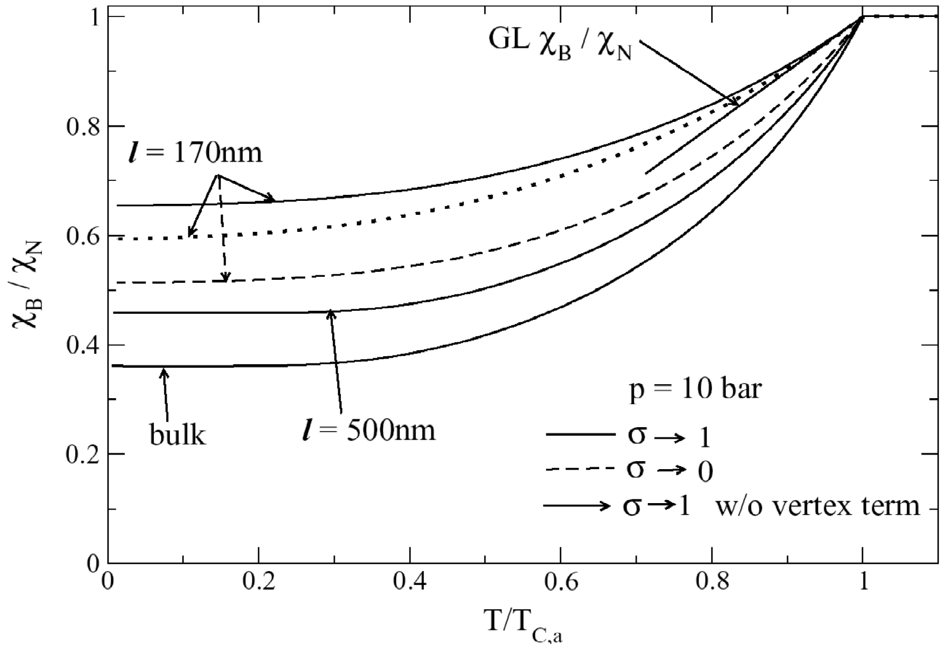
From heat capacity,
Choi et al. PRL (2004).

Disorder induces gapless superfluidity

CosLab 2004; Chamrousse, *December 18, 2004*

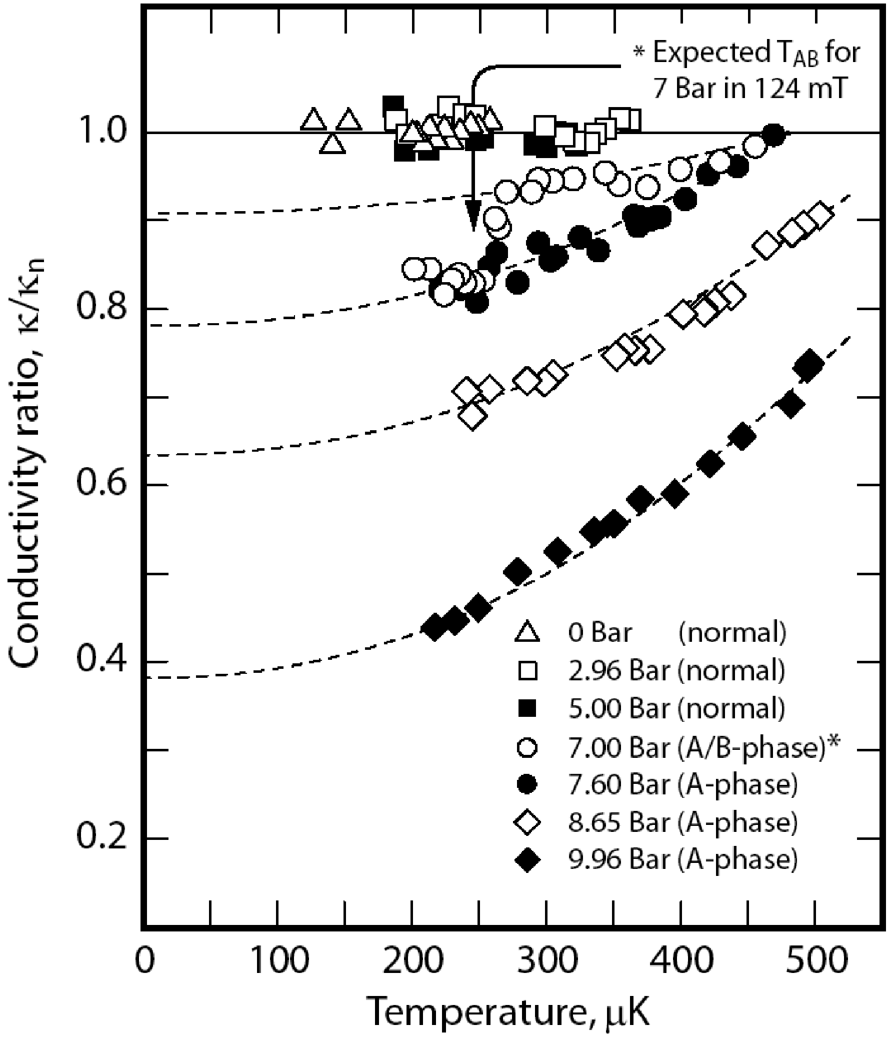
Magnetic Susceptibility

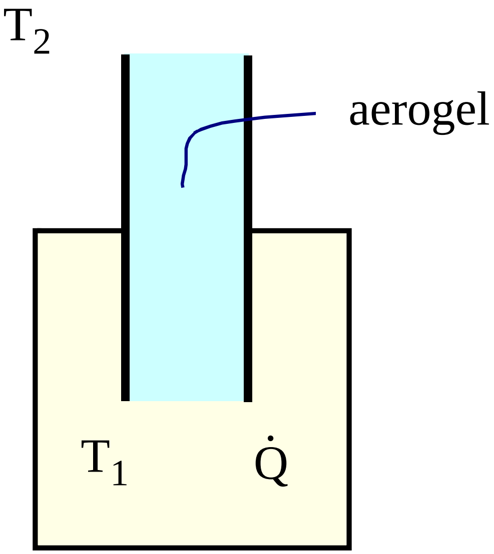
Sharma and Sauls, JLTP **125**, 115 (2001).



Thermal Conductivity

Fisher et al. PRL **91**, 105303 (2003)



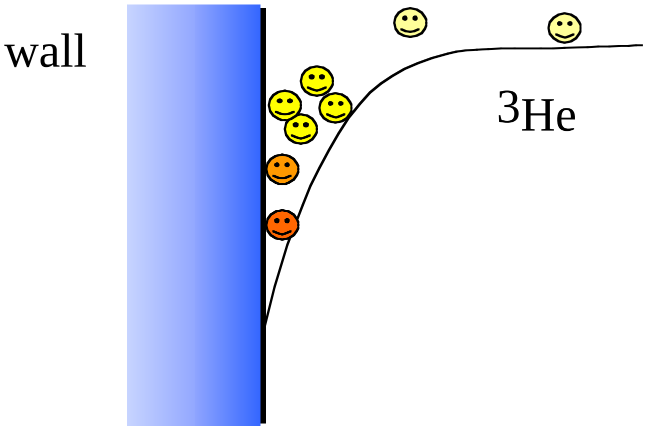


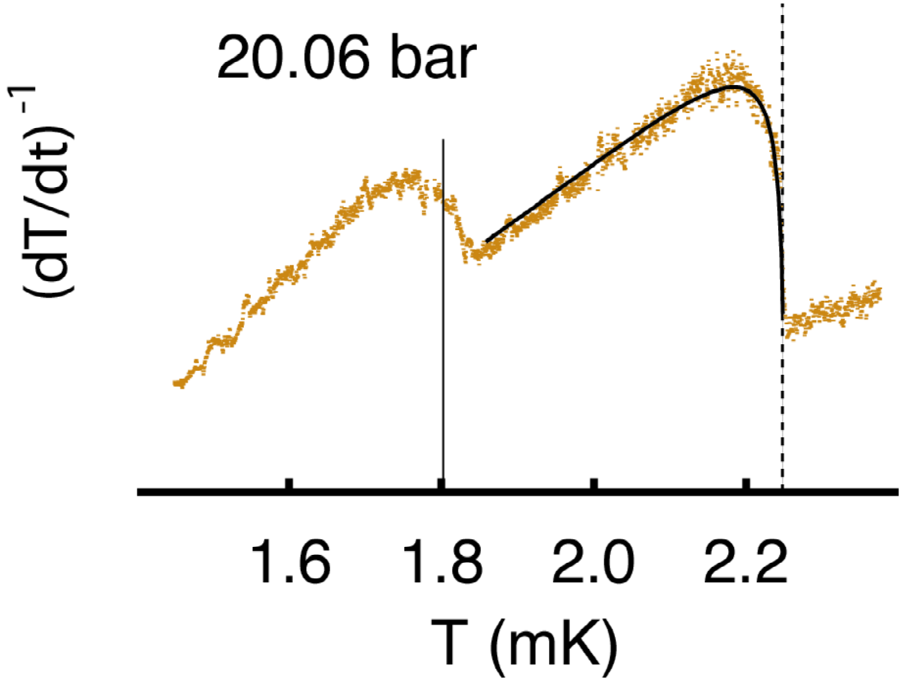
Andreev surface bound states from bulk specific heat:

Andreev bound states have been predicted at surfaces in ^{3}He by many workers including: Kjaldman, Kukijarvi, Rainer; Buchholz, Rainer; Zhang; Vorontsov and Sauls;…

We have measured the heat capacity of Andreev *surface* bound states at the bulk transition temperature (dashed line) showing rounding from the temperature dependence of the coherence length:

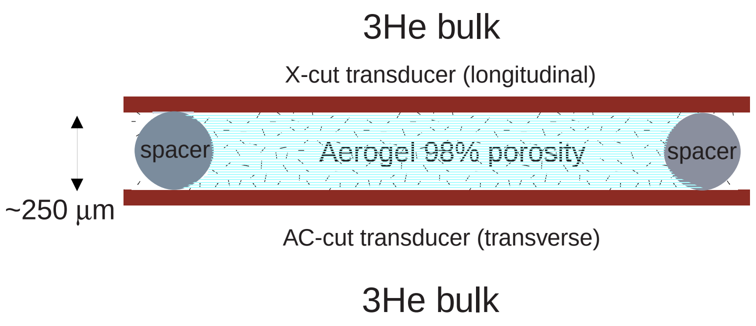
Slow warm-up specific heat:





Phase Diagram:

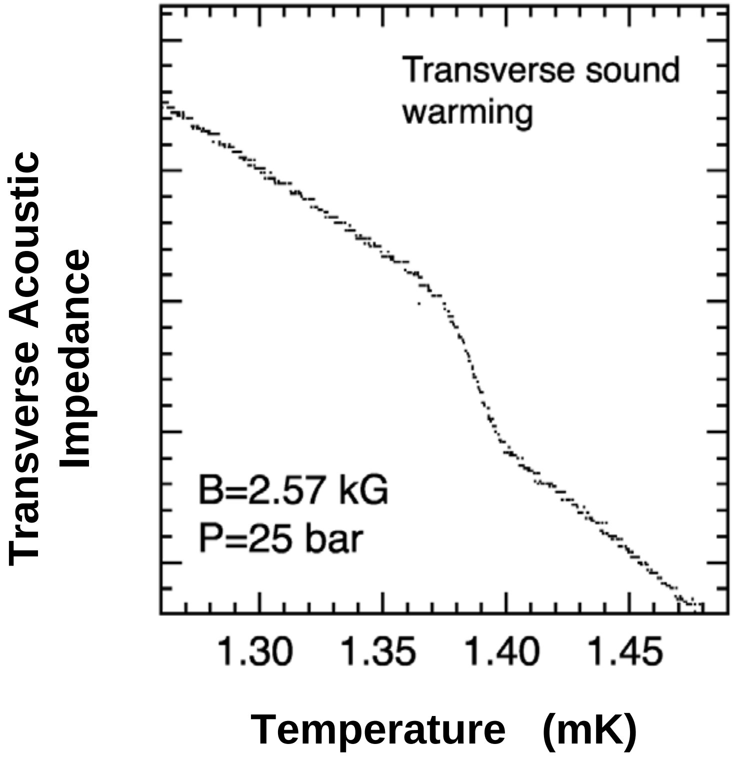
Aerogel/Superfluid ^{3}He phase diagram from transverse acoustic impedance:



We measure the acoustic impedance and find a response at all known phase transitions: bulk and aerogel superfluids. Measurement from zero applied magnetic field up to 0.8 T.

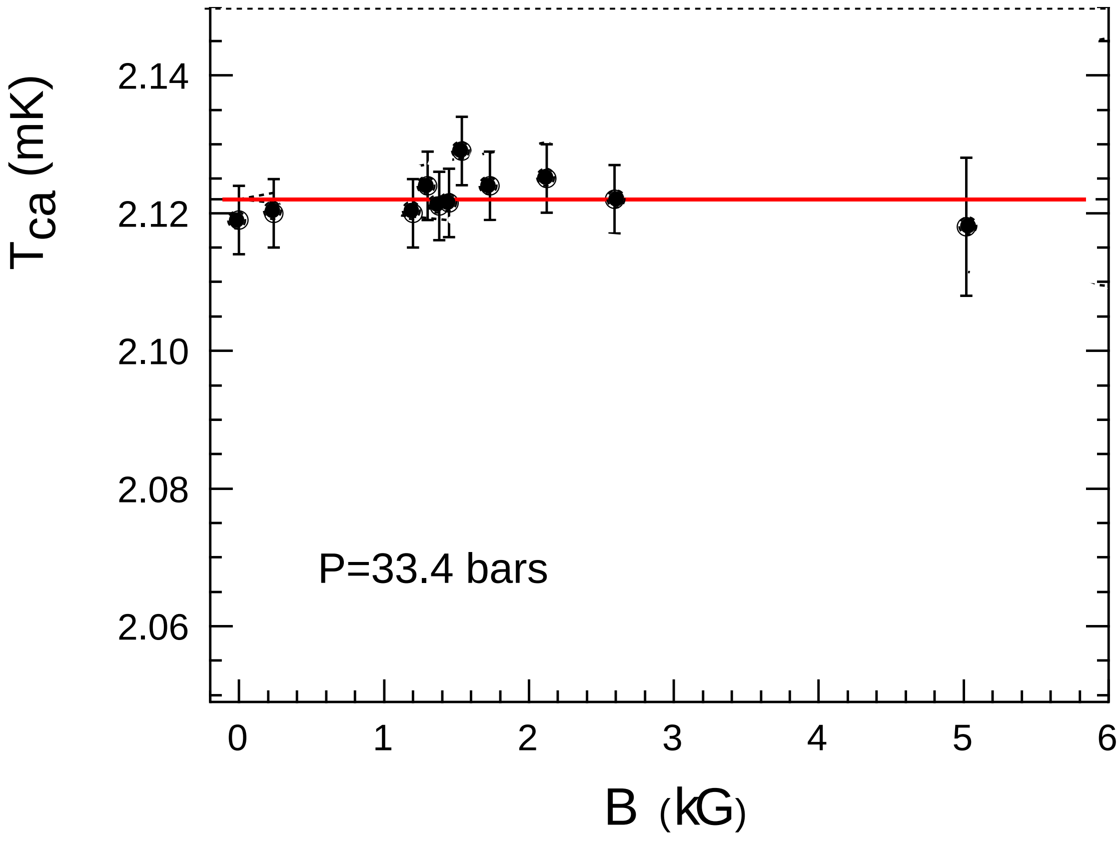
Gervais et al. PRL **87**, 035701 (2001);
PRB **66**, 054528 (2002).

B- to A-transition in a magnetic field

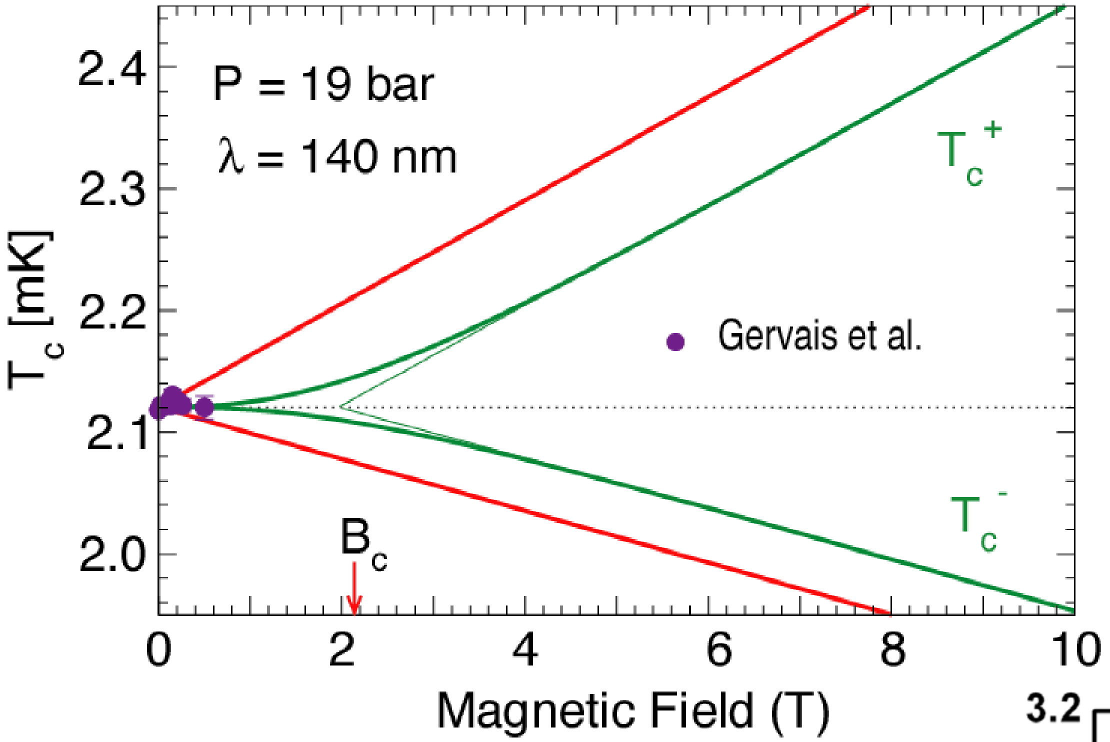


Normal to superfluid transition in a magnetic field:

No field dependence to the aerogel/superfluid transition observed by *Gervais et al. PRB* **66**,054528 (2002) up to 0.5 T and no splitting up to 0.8 T



Indicates an equal spin pairing state (ESP).

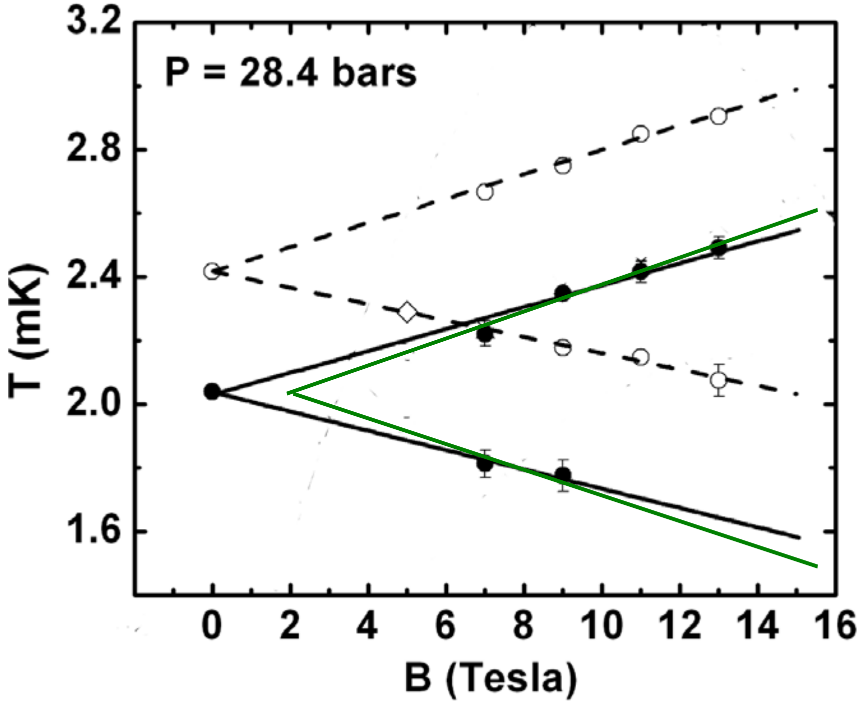


Antiferromagnetic exchange between liquid ^{3}He and solid ^{3}He adsorbed on aerogel give the green curve; *Sauls and Sharma*, PRB **68**, 224502 (2003).

Also Baramidze and Kharadze, cond-mat/0307612

Splitting for aerogel-superfluid discovered at high field:

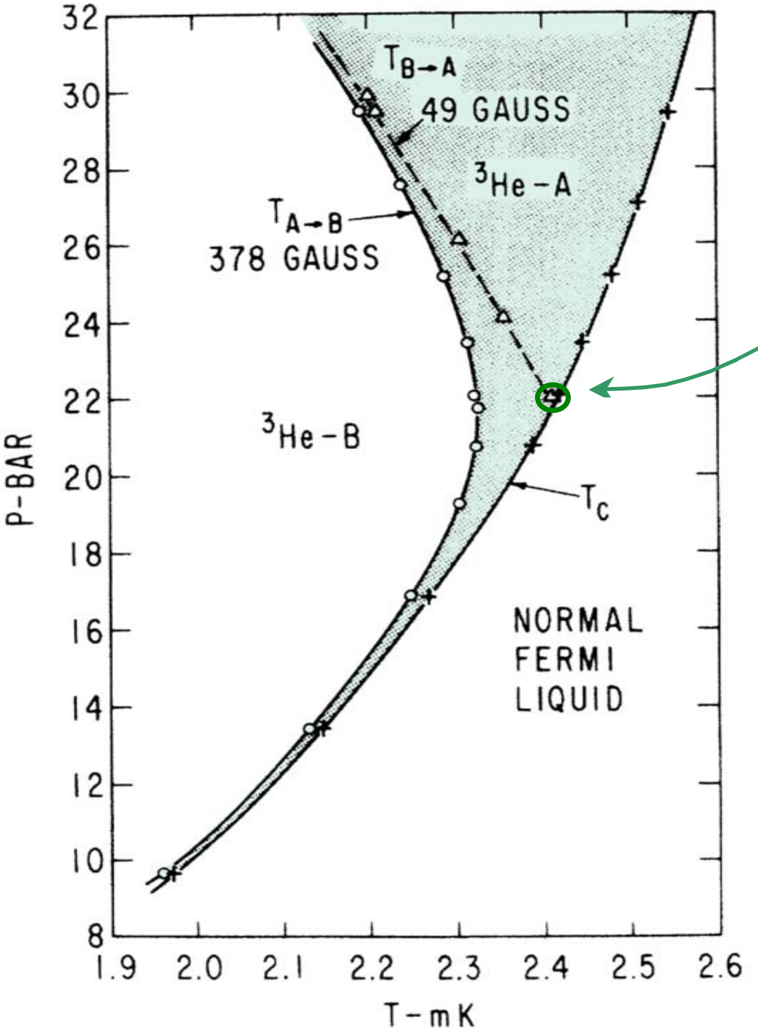
Choi et al. (Univ. Florida)
PRL **93**, 145302 (2004)



AB-transition:

pure superfluid ^{3}He:

Paulson et al. PRL **32**, 1098 (1974).



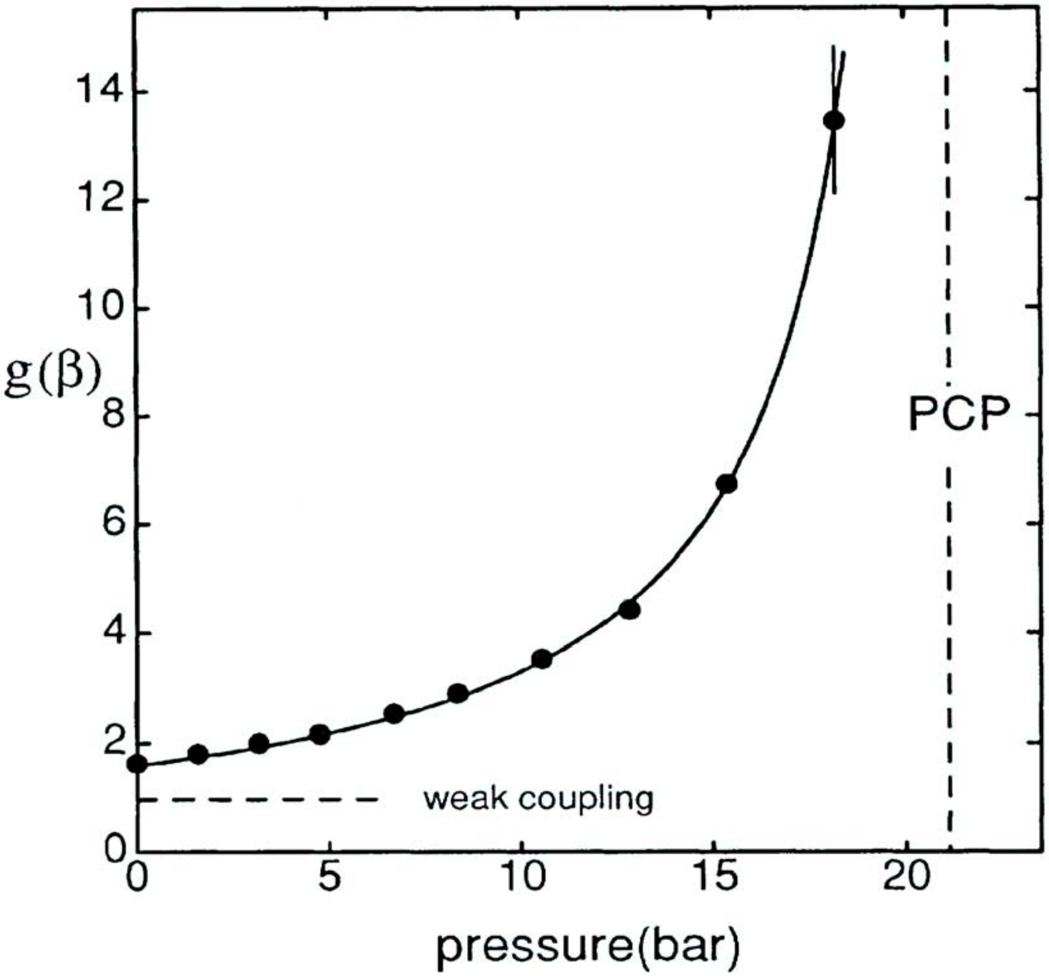
Poly-Critical Point

Strong suppression of the B-phase by a magnetic field

⇨ spin triplet state.

$$1 - \frac{T_{AB}(B)}{T_c} = g(\beta)\ (B/B_o)^2$$

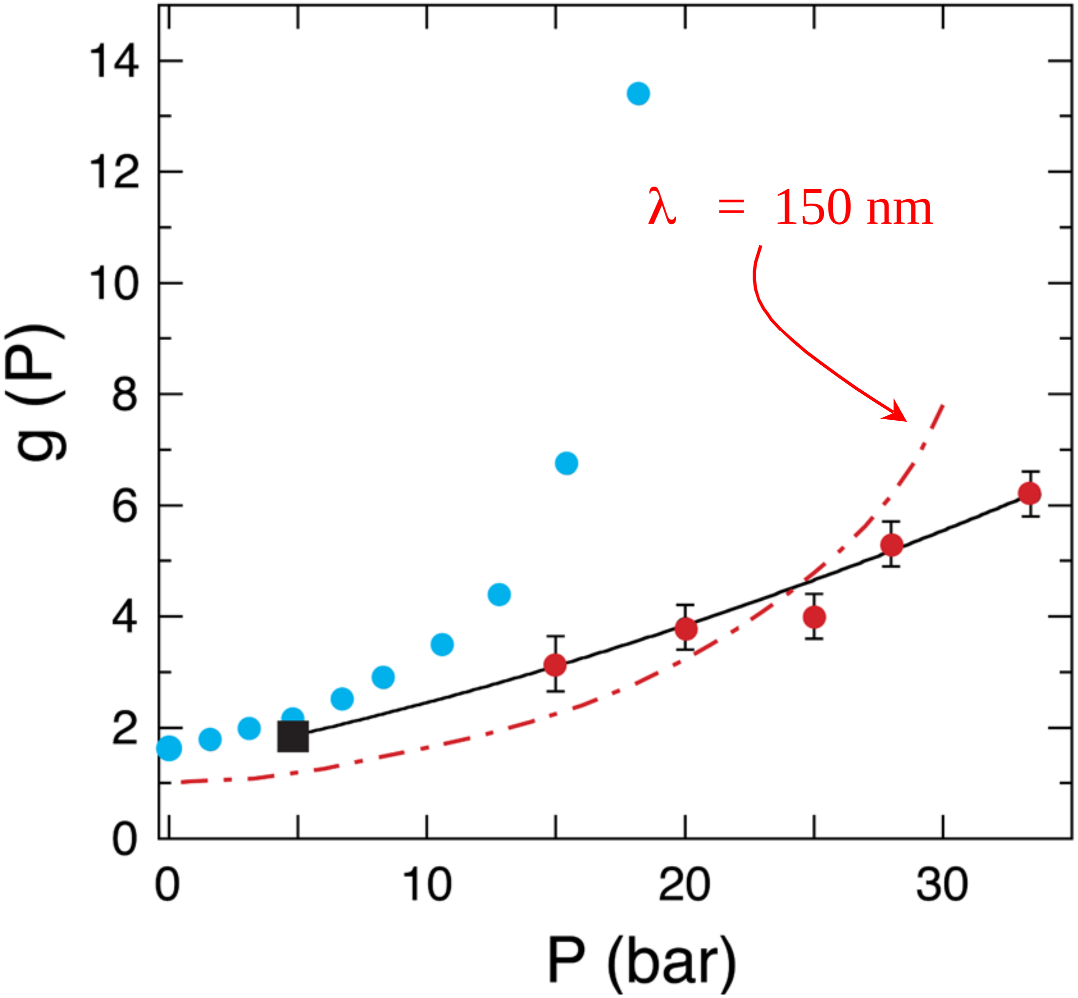
Later detailed study: *Tang, Hahn, Bozler, Gould PRL* **67**, 1775 (1991) was performed to determine strong coupling effects: (β_1 , β_2 , … β_5 , g_Z)



The HISM *including strong coupling* is in agreement with a vanishing PCP.

- ● *Gervais et al. PRL* **87**, 035701 (2001); *PRB* **66**, 054528 (2002)
- ■ *Brussaard et al. PRL* **86**, 4580 (2001)

The B-phase is stabilized by disorder and strong coupling effects are reduced by T_{ca} suppression.

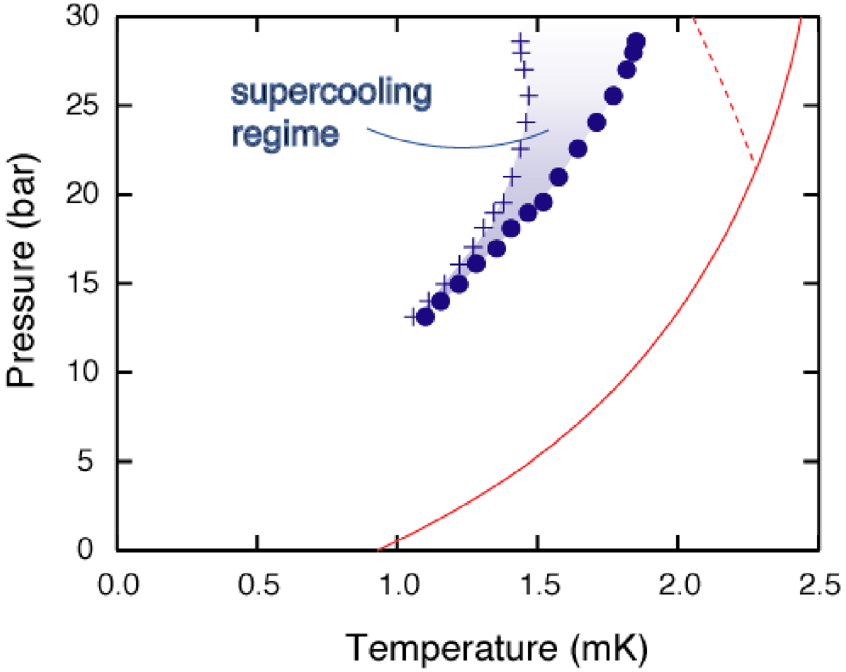


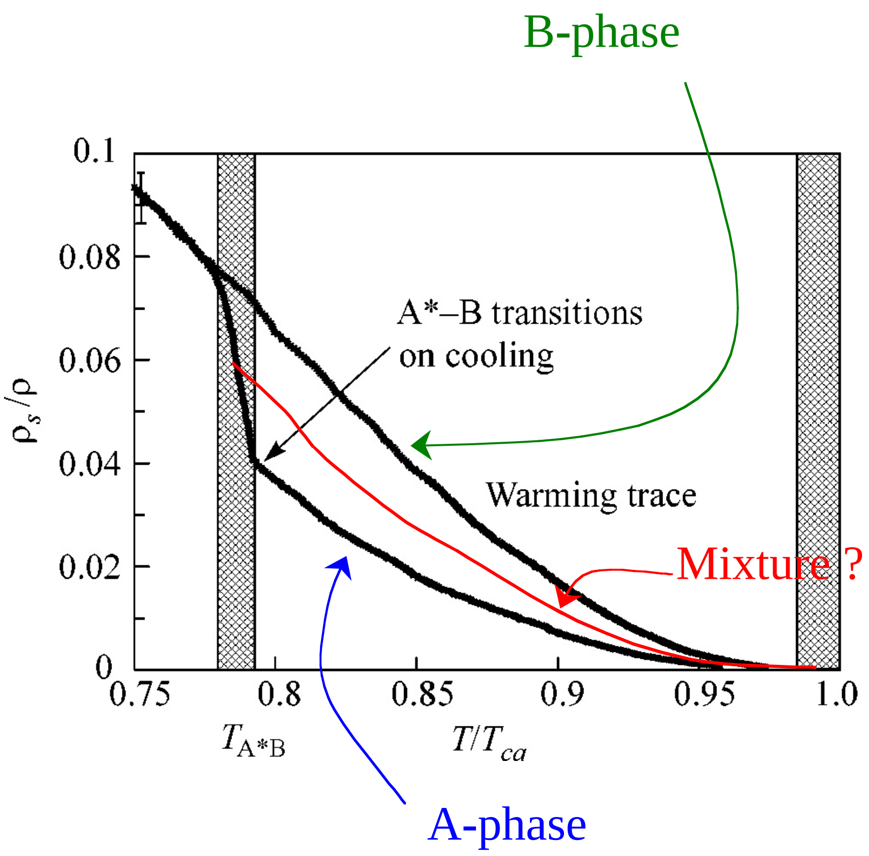
Metastability and Supercooling:

Barker et al., *PRL* **85**, 2148 (2000); *Gervais et al.*, *PRL* **87**, 035701 (2001); *PRB* **66**, 054528 (2002); *Baumgardner et al.*, *PRL* **85**, 2148 (2000); *PRL* **93**, 155301 (2004).

Nazaretski et al., JETP Lett. **79** 383 (2004).

98 % aerogel

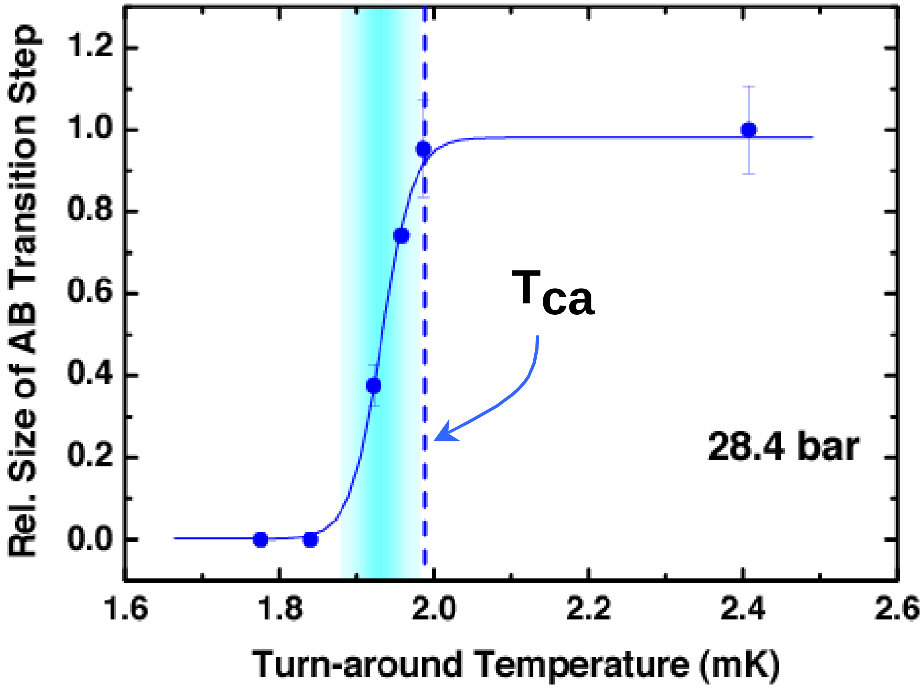




CosLab 2004; Chamrousse, *December 18, 2004*

The role of anisotropic scattering:

Vicente et al. (Univ. of Florida), submitted.
From transverse acoustic impedance.



There are new terms in the Ginzburg-Landau free energy owing to broken orbital symmetry from anisotropic scattering. *Rainer*, *Vuorio* J.Phys.C (1977); *Thuneberg et al.*, cond-mat/980204; *Sauls* (2004); *Fomin* (2004).

Magnetic field suppression by **B**: $f_z = g_z B_\mu A_{\mu i} A^*_{\nu i} B_\nu$

Anisotropic scattering direction ***a***: $f_a = \alpha_1 a_i A_{\mu i} A^*_{\mu j} a_j$

scale is given by an effective field: $B_e = (\alpha_1 / g_z)^{1/2} \approx 0.1\ \mathrm{T}$

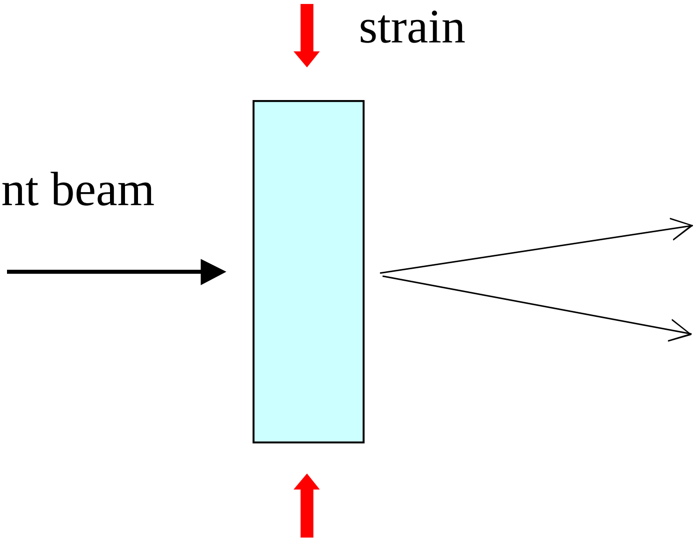
PCP is pushed to unobservably high pressure, scattering anisotropy (locally inhomogeneous) will stabilize the A-phase, Y. Lee (Univ. Florida).

Controlled homogeneous anisotropic scattering:

Introduce uniaxial strain into the aerogel to stabilize the A-phase:

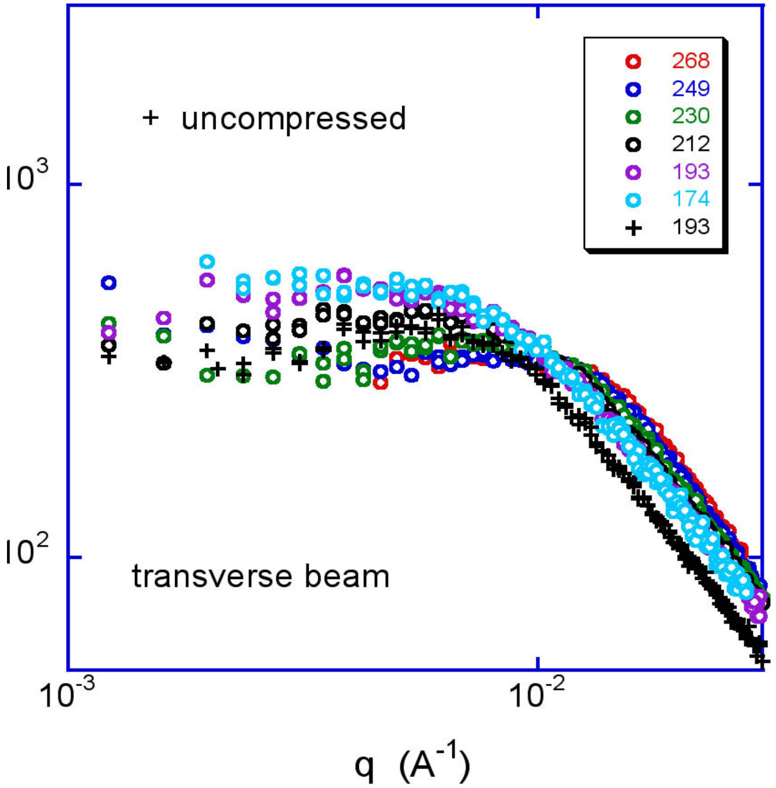
98% aerogel, 30 % strain:
SAXS Norbert Mulders (2004)

SAXS:



strain

Incident beam

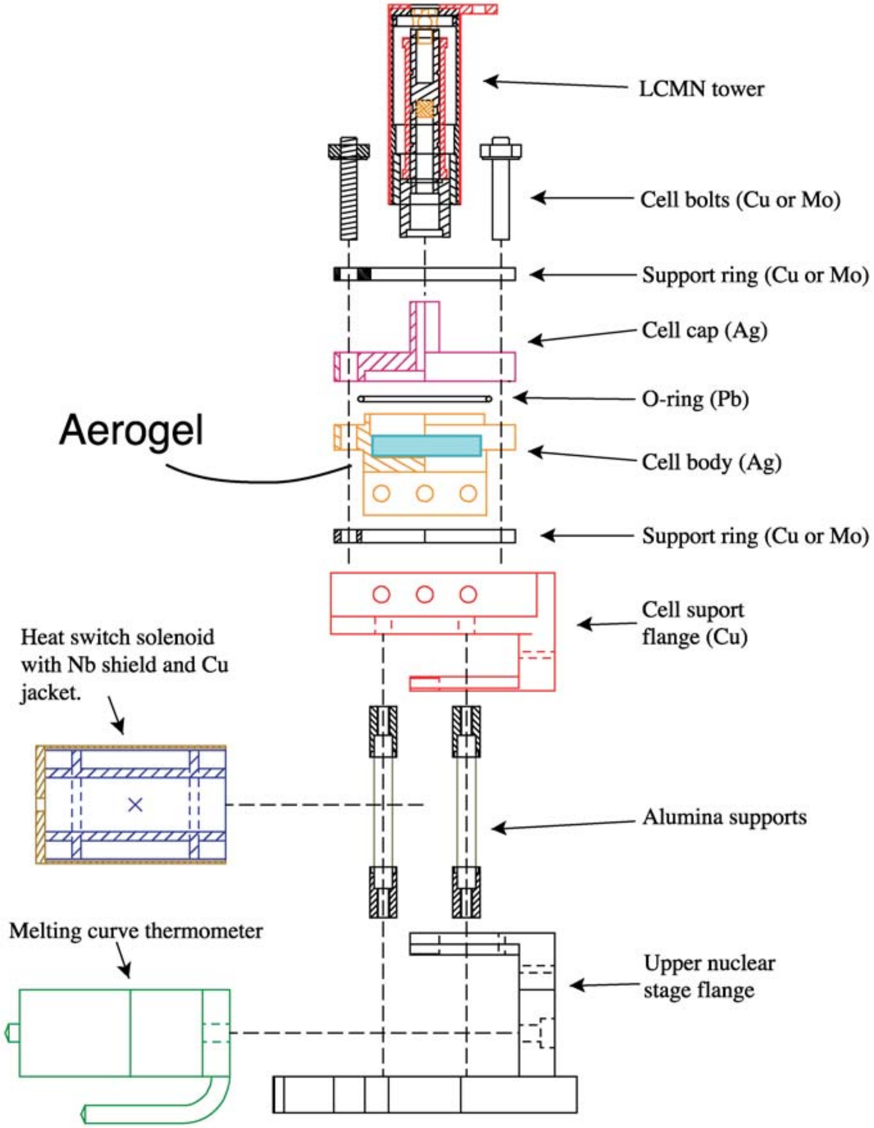


Summary:

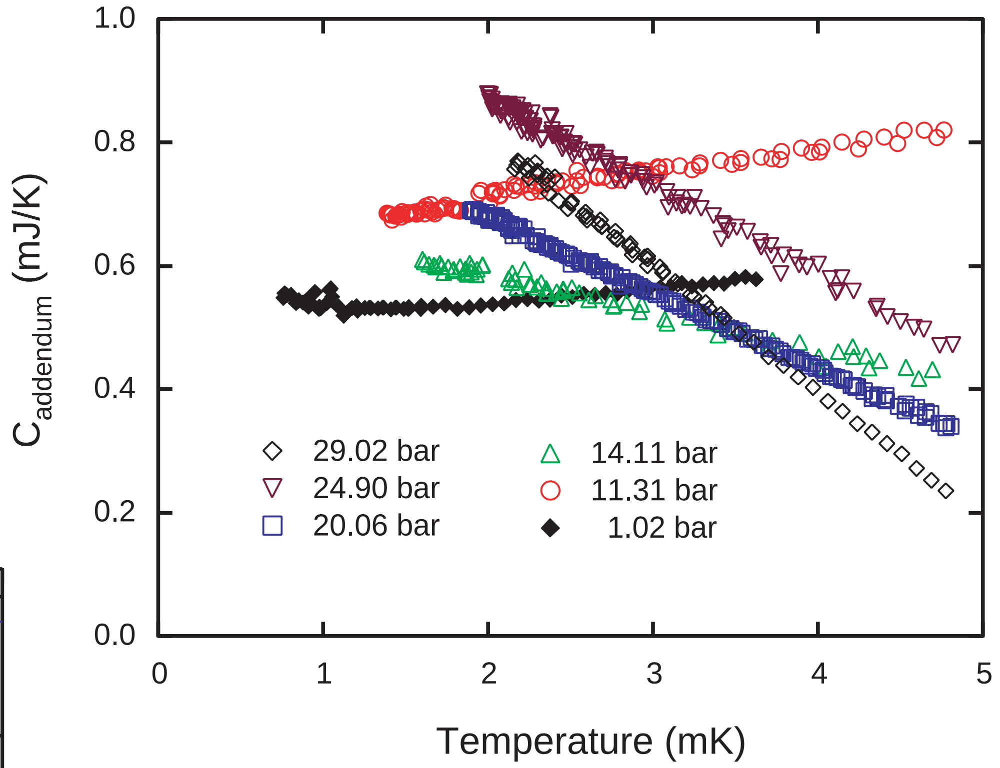
- Phase diagram for 98% aerogel/superfluid ^{3}He is the B phase at zero field at all pressures except close to T_c.
- The PCP has vanished for 98% aerogel.
- The Inhomogeneous Isotropic Scattering Model is consistent with the B-phase in aerogel, effect of magnetic field and heat capacity with $\lambda \approx 150$ nm; $\xi_a \approx 40$ nm.
- Heat capacity indicates that quenched disorder from aerogel produces gapless superfluidity (Andreev bound states).
- Scattering anisotropy may stabilize the equal-spin pairing state, ie A-phase, and proposal for stabilizing this phase macroscopically by uniaxial strain.

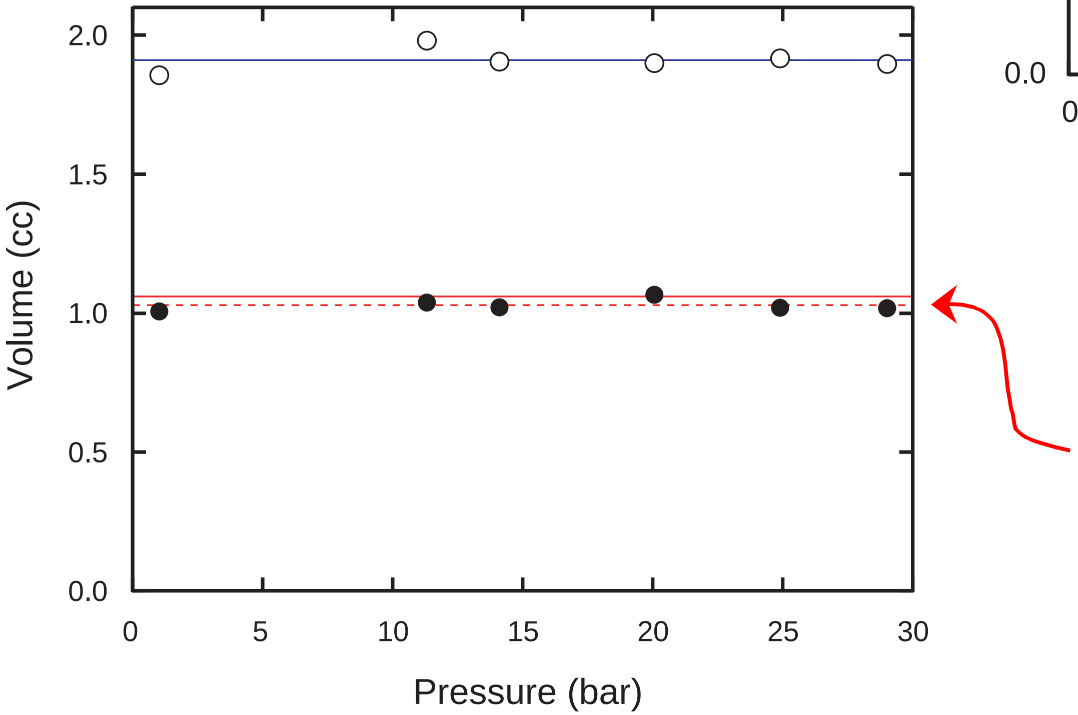
Aerogel/Superfluid ^{3}He Heat Capacity:

Calorimeter



Addendum from paramagnetic adsorbed solid ^{3}He



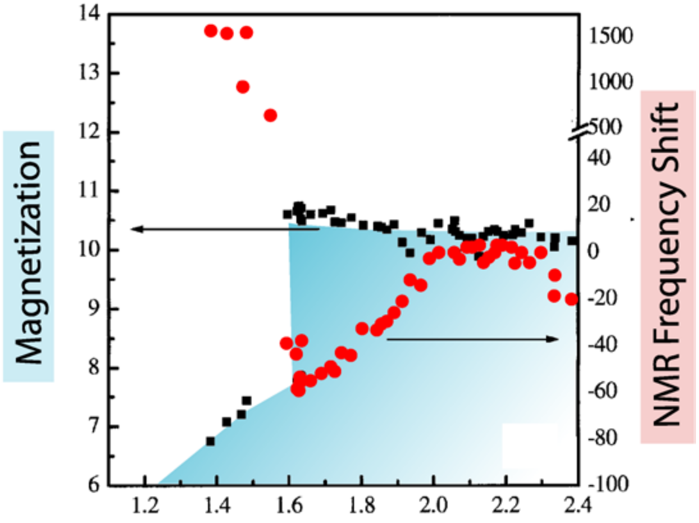


Geometric volume of the aerogel sample compared to the measured volume are within 3%.

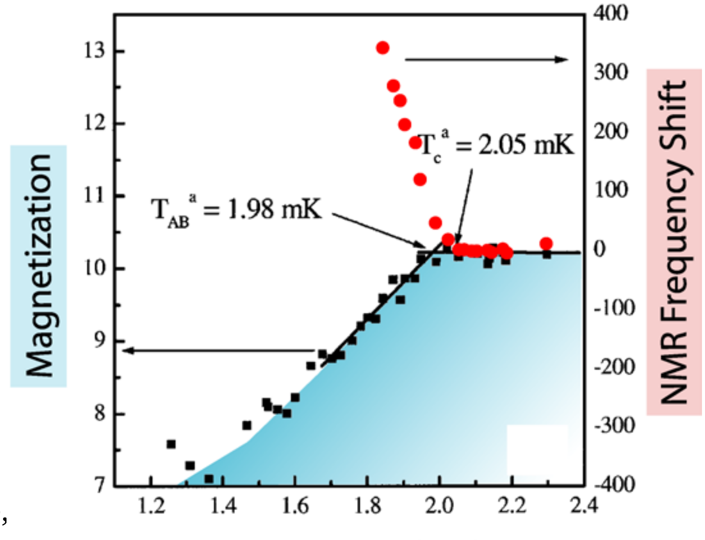
Is there an AB transition for superfluid ^{3}He in aerogel ?

First observed on supercooling by the Stanford group *Barker et al. PRL* 85, 2148 (2000), from NMR magnetization and frequency shift.

Cooling
P = 32 bar
B = 284 G



Warming
P = 32 bar
B = 284 G



Similar NMR results from,

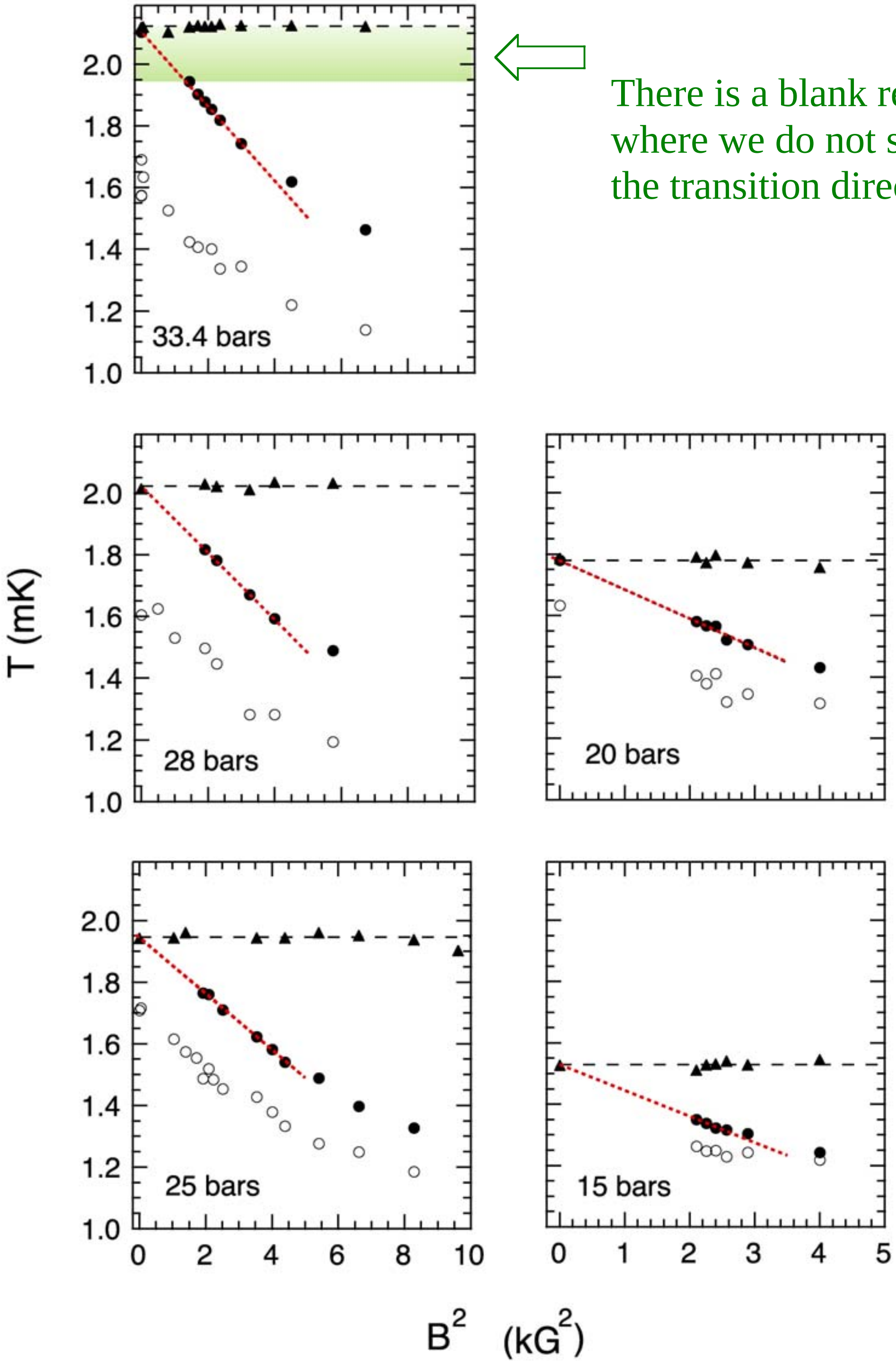
Northwestern, *Sprague et al. PRL* **77**, 4568 (1996);

and Grenoble (*E. Collin*, PhD *thesis, 2002*)

Aerogel superfluid ^{3}He:

AB transition was first observed by *Barker et al.* PRL **85**, 2148 (2000) from NMR susceptibility and frequency shift

Transverse acoustic impedance, Gervais et al. PRL **87**, 035701 (2001); *PRB* **66**, 054528 (2002)



There is a blank region where we do not see the transition directly

Metastable Phase Mixtures

Detail of how the tracking method allows exploration of the phase mixture near T_c

Gervais et al., PRL **87**, 035701 (2001);
PRB **66**, 054528 (2002);