Title: Unconventional Pairing and Impurities in Superfluid Helium-3

Date: Apr 23, 2009 02:30 PM

URL: http://pirsa.org/09040026

Abstract: The growing fascination with unconventional pairing is driven in part by continuing discoveries of exotic superconductors. The first of these, superfluid 3He, was found by Osheroff, Richardson, and Lee in 1971. This was followed soon thereafter by superconductivity in the heavy fermion compound, UPt3. And then an explosion of interest accompanied the observation of superconductivity in cuprates, Sr2RuO4, and organic materials. The newest discoveries are sperconducting compounds of FeAs. These systems have been demonstrated (or in some cases it is just suspected) that they have pairing condensates with non-zero angular momentum, L= 1, 2, and even 3. But all of them have the common hallmark of a high degree of sensitivity to impurities. In this talk I will discuss impurity effects in the best known of these unconventionally paired systems, 3He, a paradigm for the other unconventional superconductors. Impurity scattering is deftly controlled in superfluid 3He by imbibing it into high porosity silica aerogel. We can understand the suppression of its superfluid state (the transition temperature), the effect on its order parameter (the pairing energy), the appearance of quasiparticle bound states (gaplessness), and possibly new phases, in the context of current theory. I will discuss experiments from many laboratories and their theoretical interpretation leading to the topical question of the day, â€œCan anisotropic scattering stabilize new anisotropic states?â€•

NORTHWESTERN
UNIVERSITY

Unconventional Pairing and Impurities in Superfluid ^{3}He

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Northwestern University
National Science Foundation DMR-0703656
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Outline:

Superfluid 3He in silica-aerogel

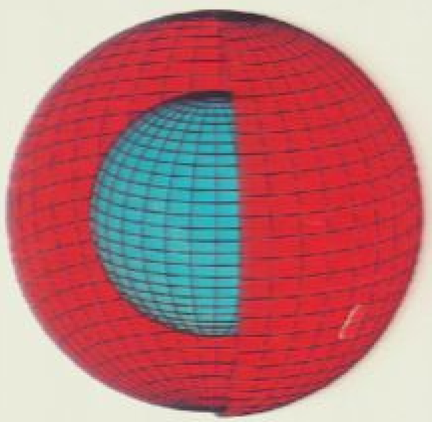
Impurity scattering models:
homogeneous or inhomogeneous?

Control of phase stability and nucleation with
global anisotropy

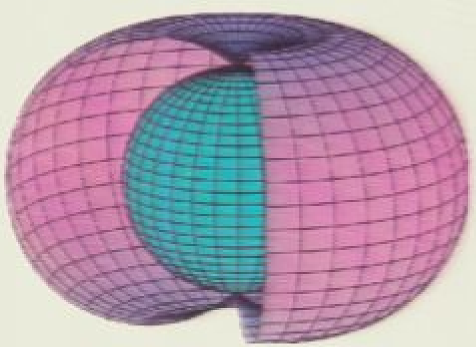
New phases?

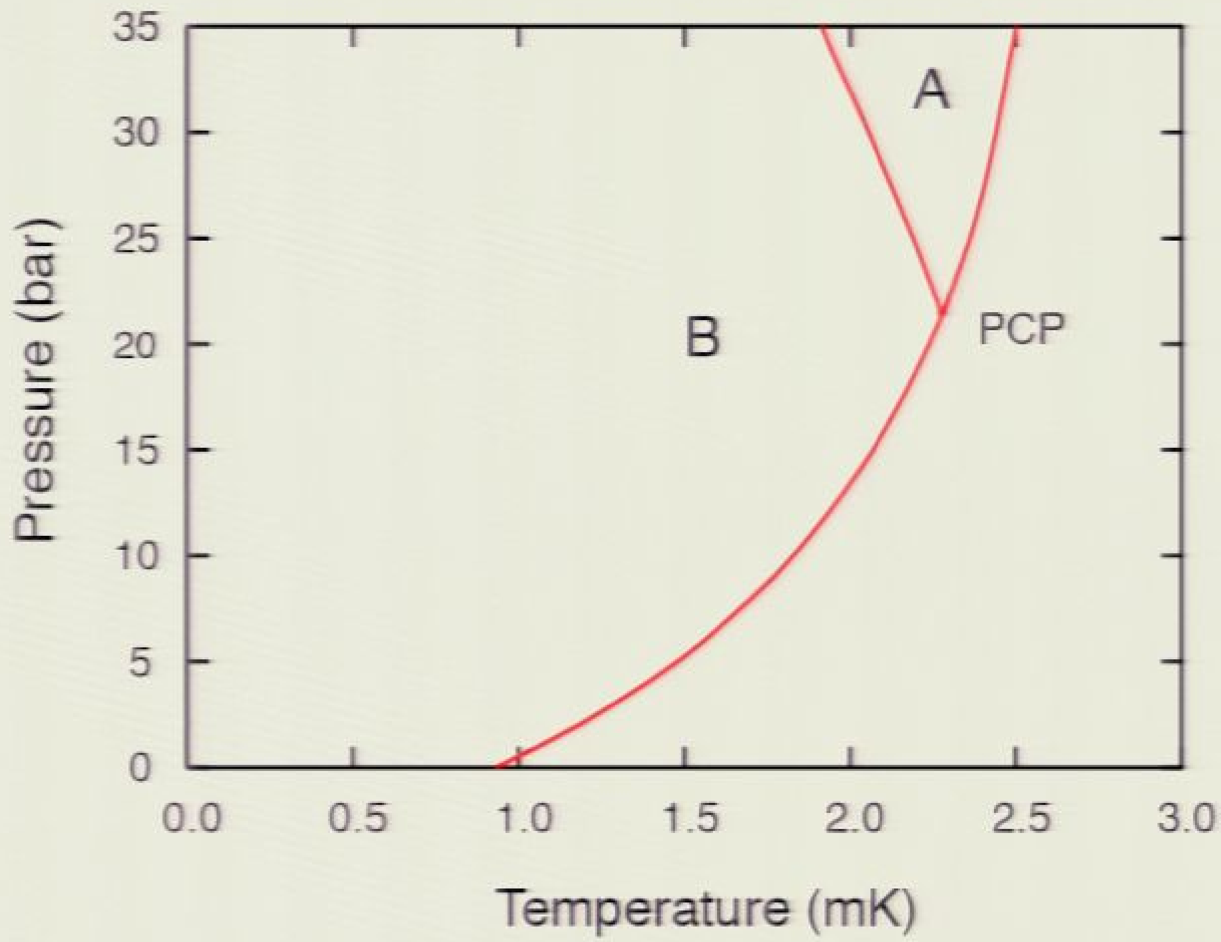
Superfluid ^{3}He : phase diagram

B - phase



A - phase





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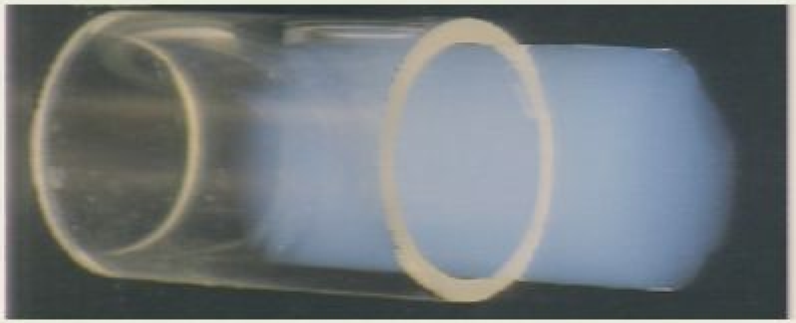
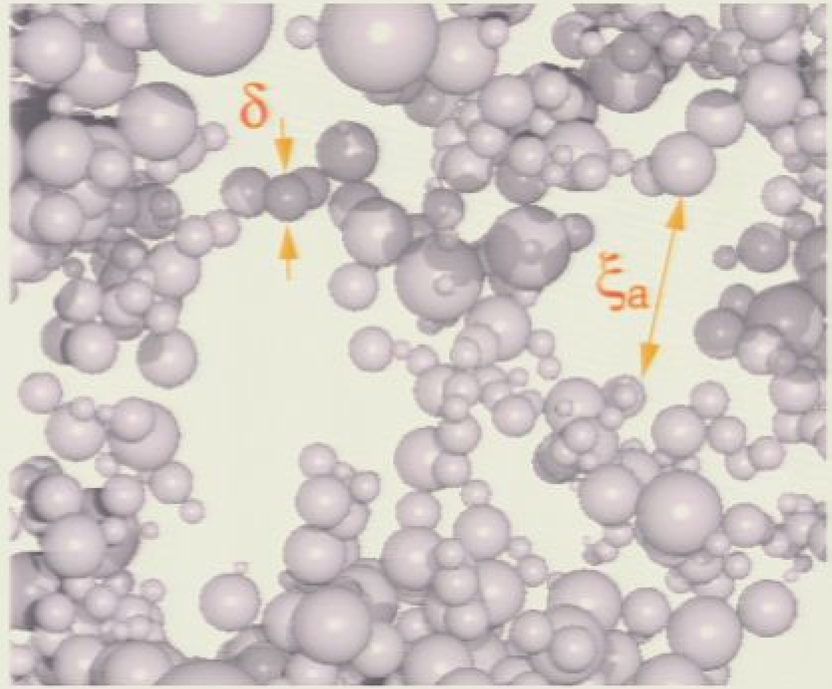
Silica aerogel:





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

particle diameter	$\delta \approx$	3 nm
mean free path	$\lambda \approx$	150 nm
correlation length	$\xi_a \approx$	20 nm

superfluid
coherence length: $\xi \approx$ 20 to 80 nm (34 to 0 bar)

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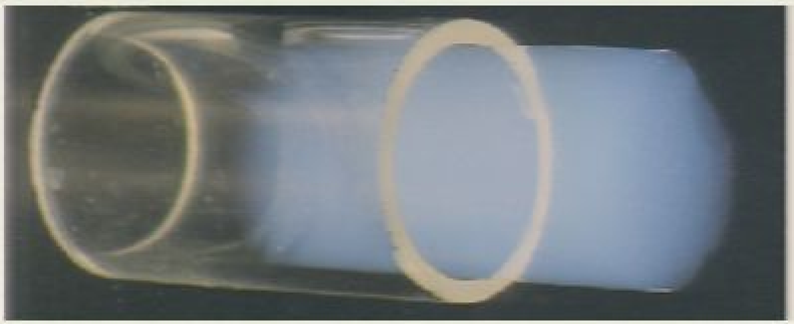

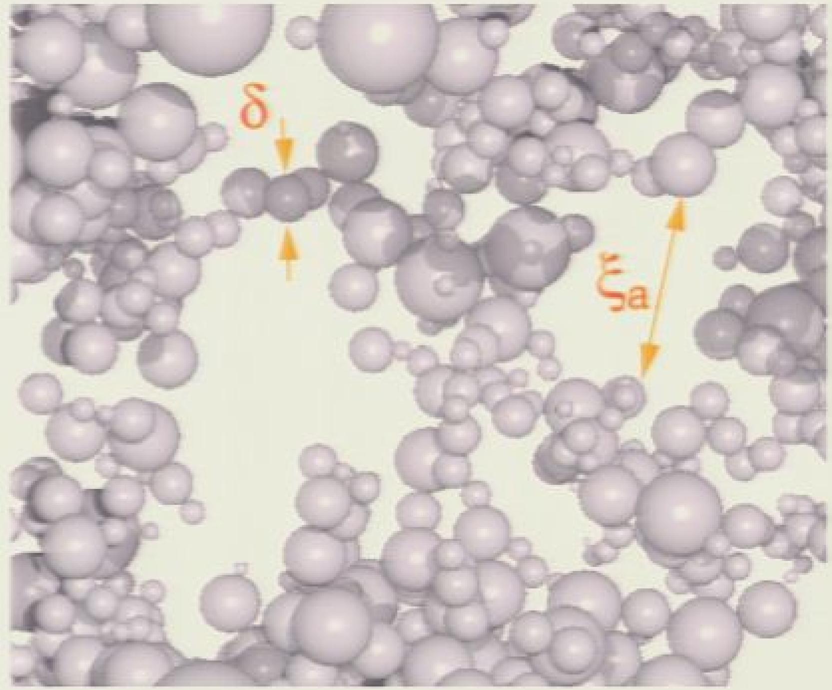

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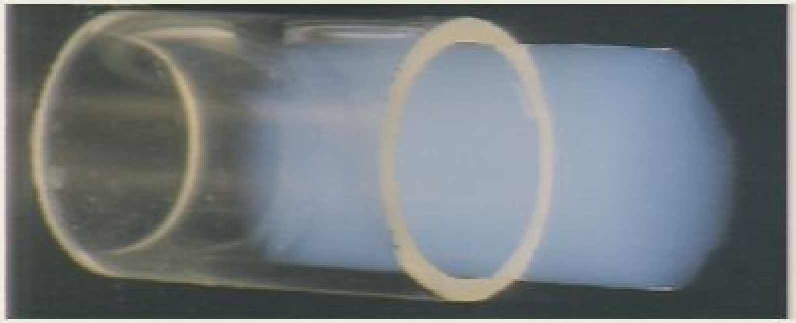

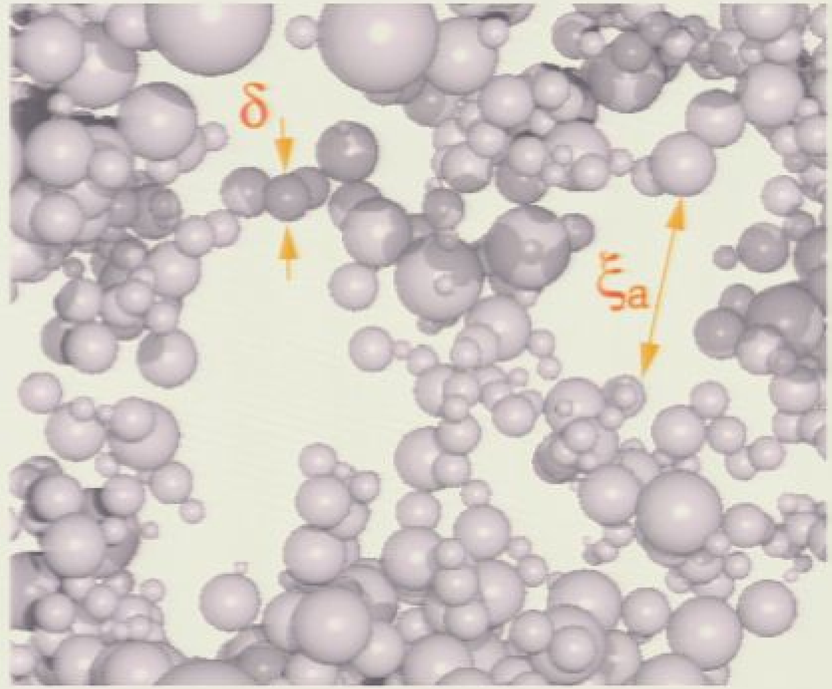

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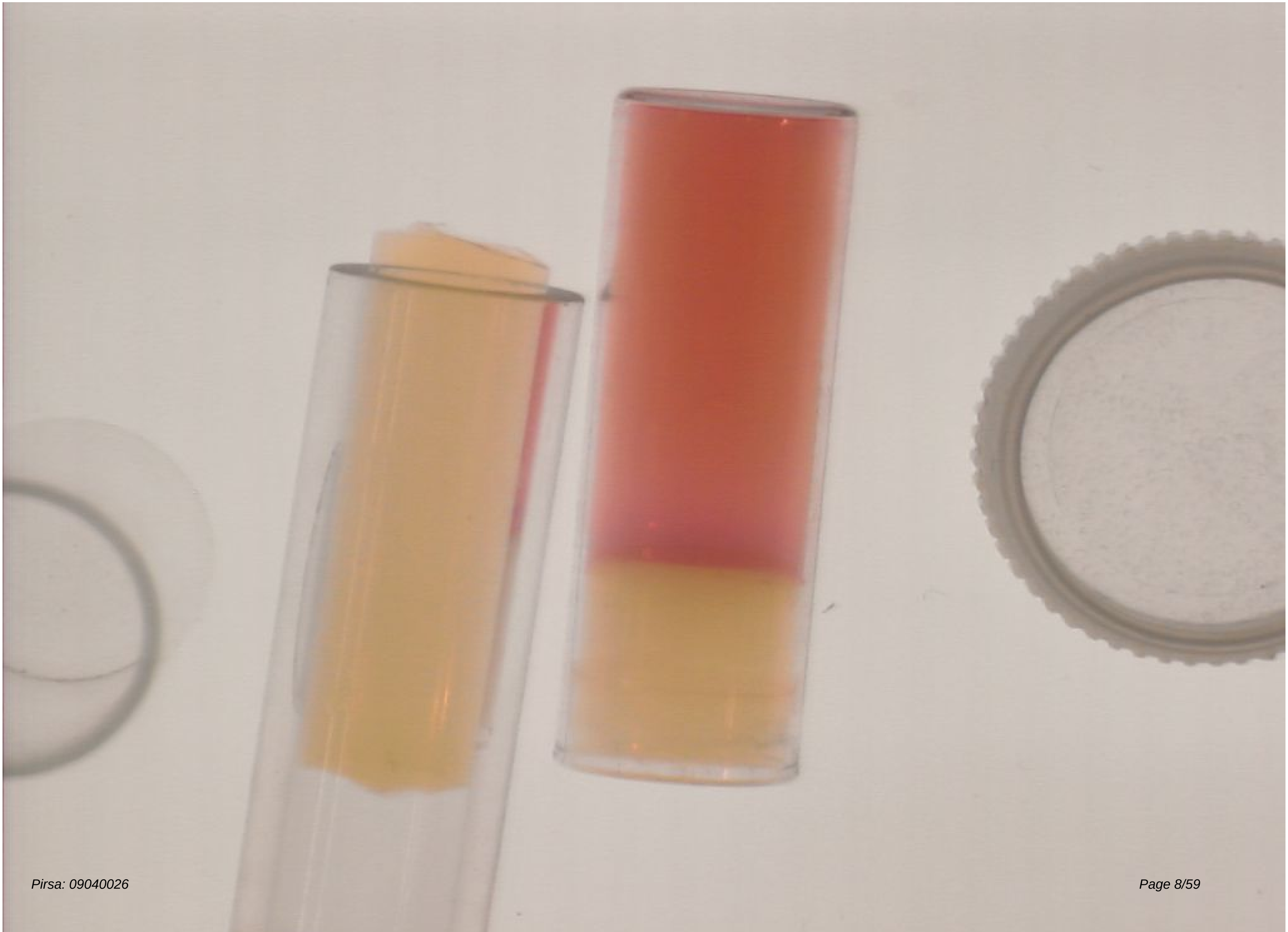
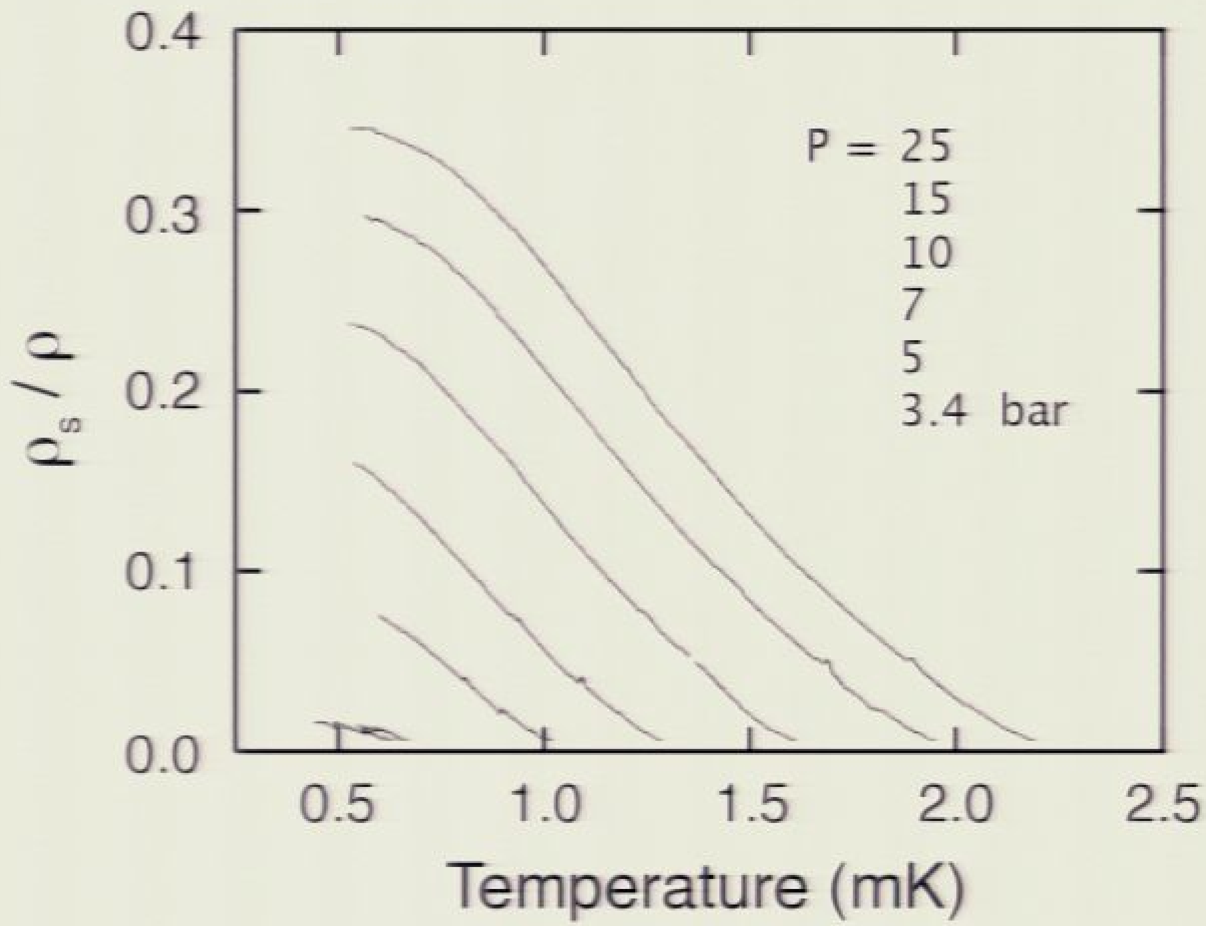


Superfluid density

Porto and Parpia
*PRL **74**, 4667 (1995)*



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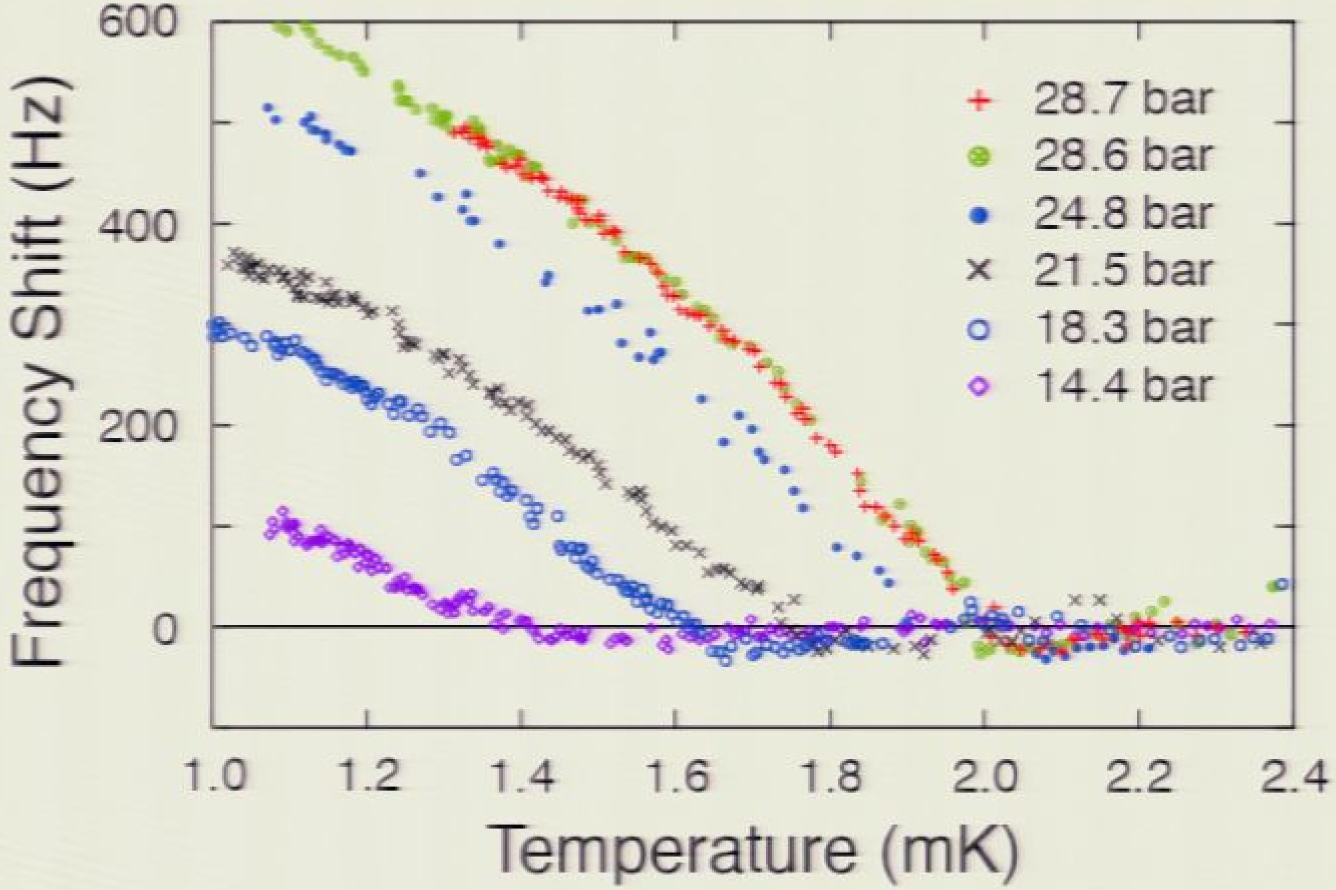
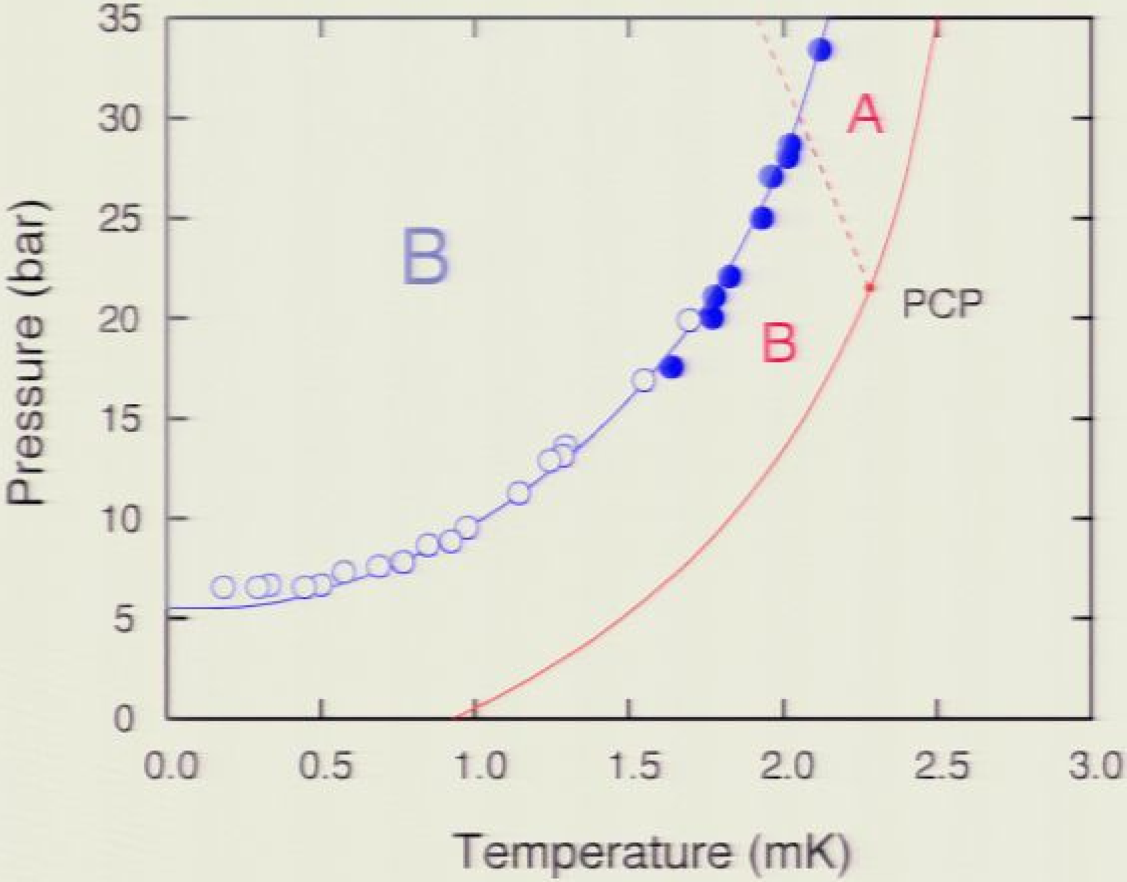
NMR frequency shift:

$\Delta\omega \;\propto\; \Delta^2$



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

Superfluid ^{3}He in aerogel: phase diagram



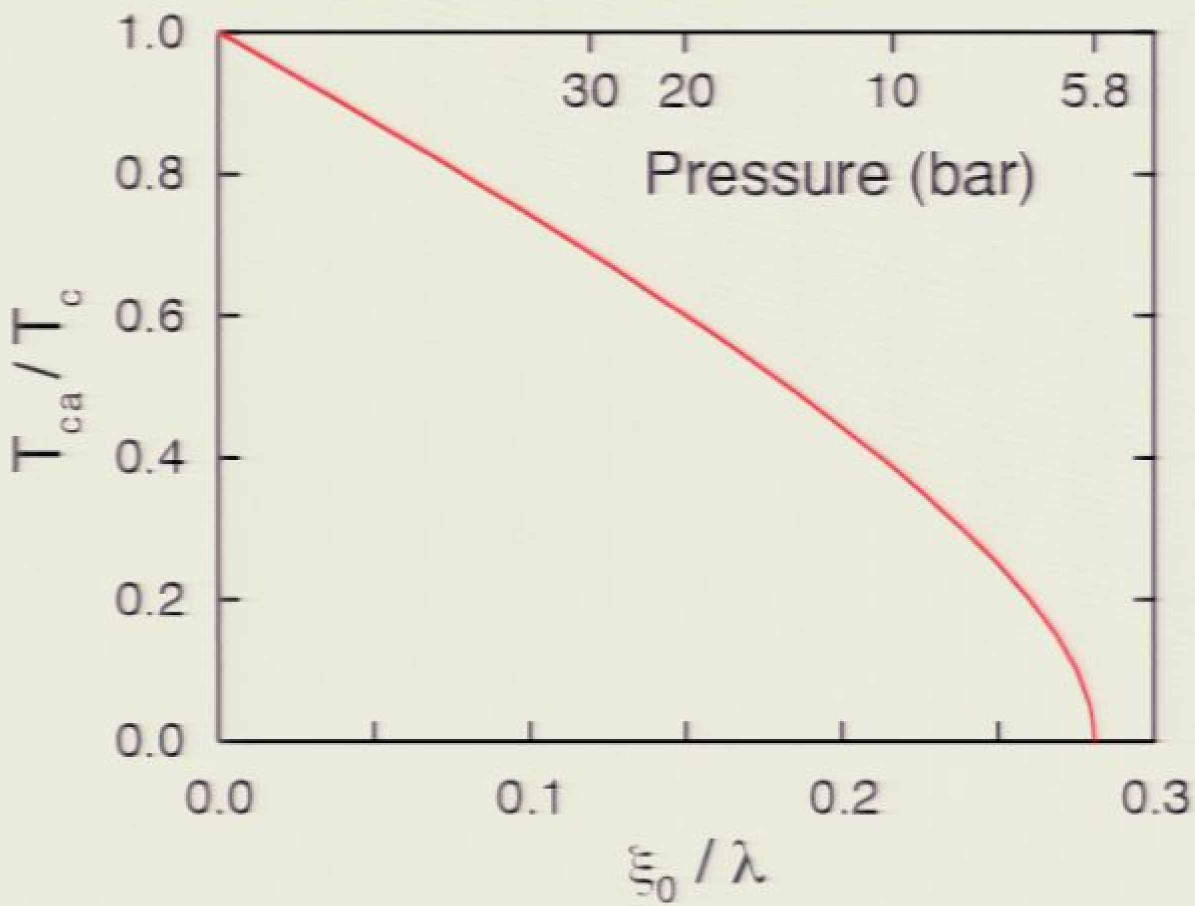
Torsional Oscillator
*Matsumoto et al. PRL **79**, 253 (1997);*

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

cw-NMR:
*Barker et al. PRL **85**, 2148 (2000).*

pulsed-NMR:
*Dmitriev et al. JETP Lett. **76**, 371 (2002).*

Abrikosov-Gorkov theory:



Abrikosov and Gorkov Soviet Phys. JETP ***12****, 1243 (1961)*

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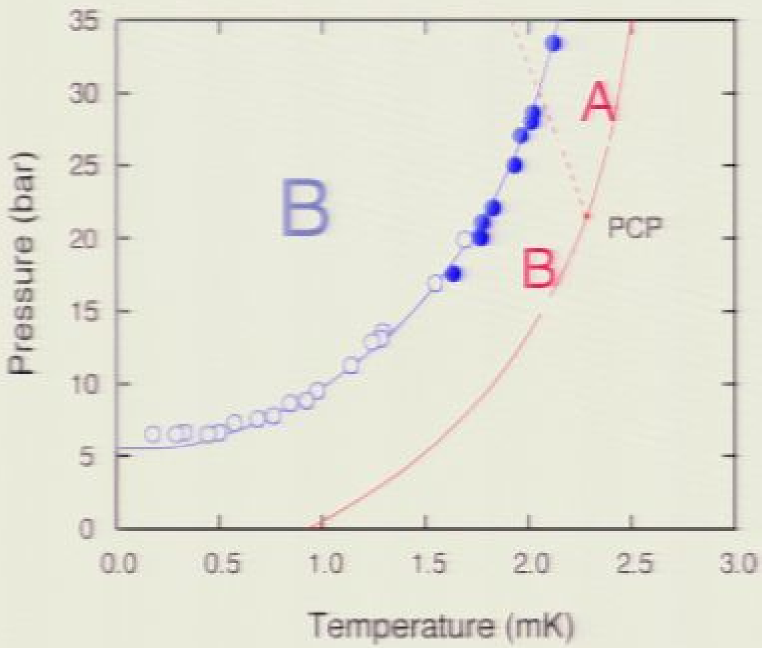
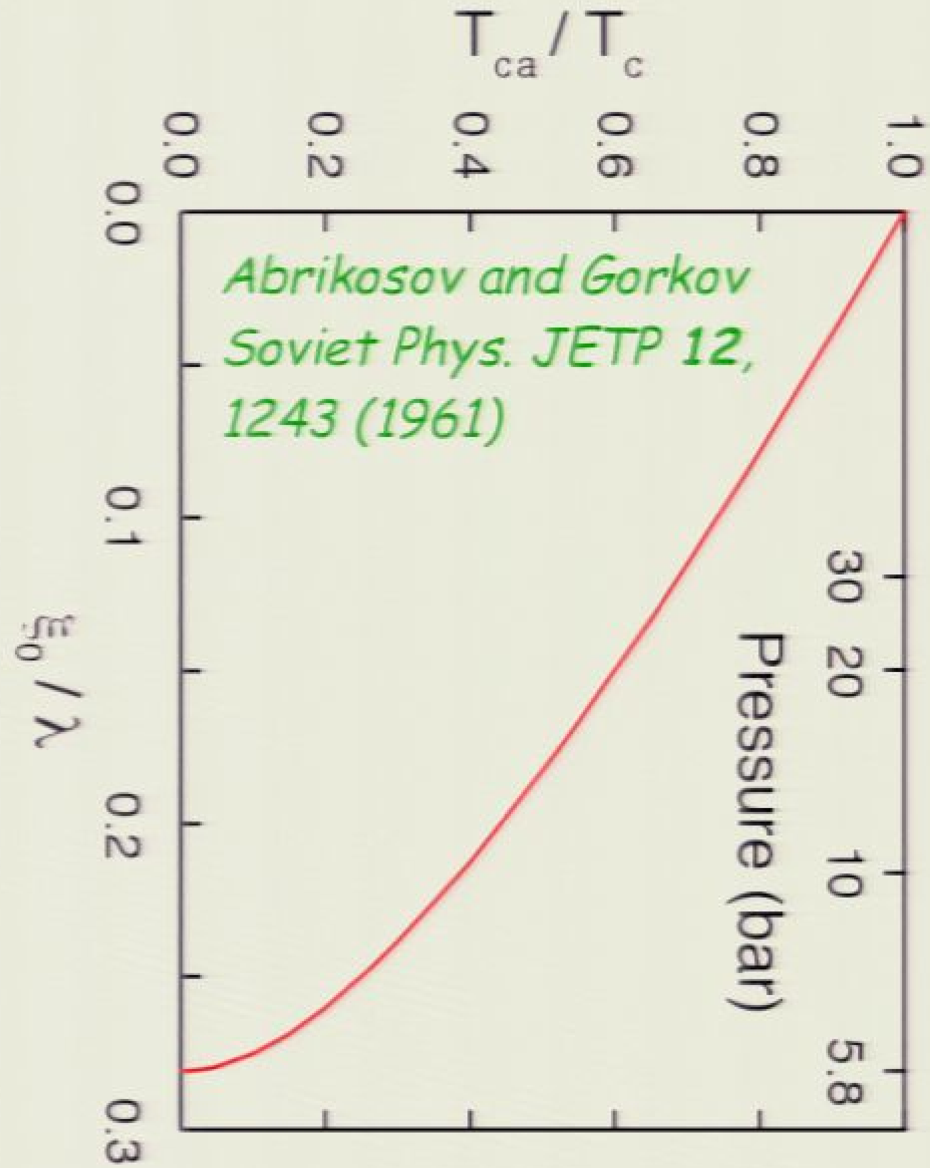
Abrikosov-Gorkov rotated:



Phase diagram critical pressure →



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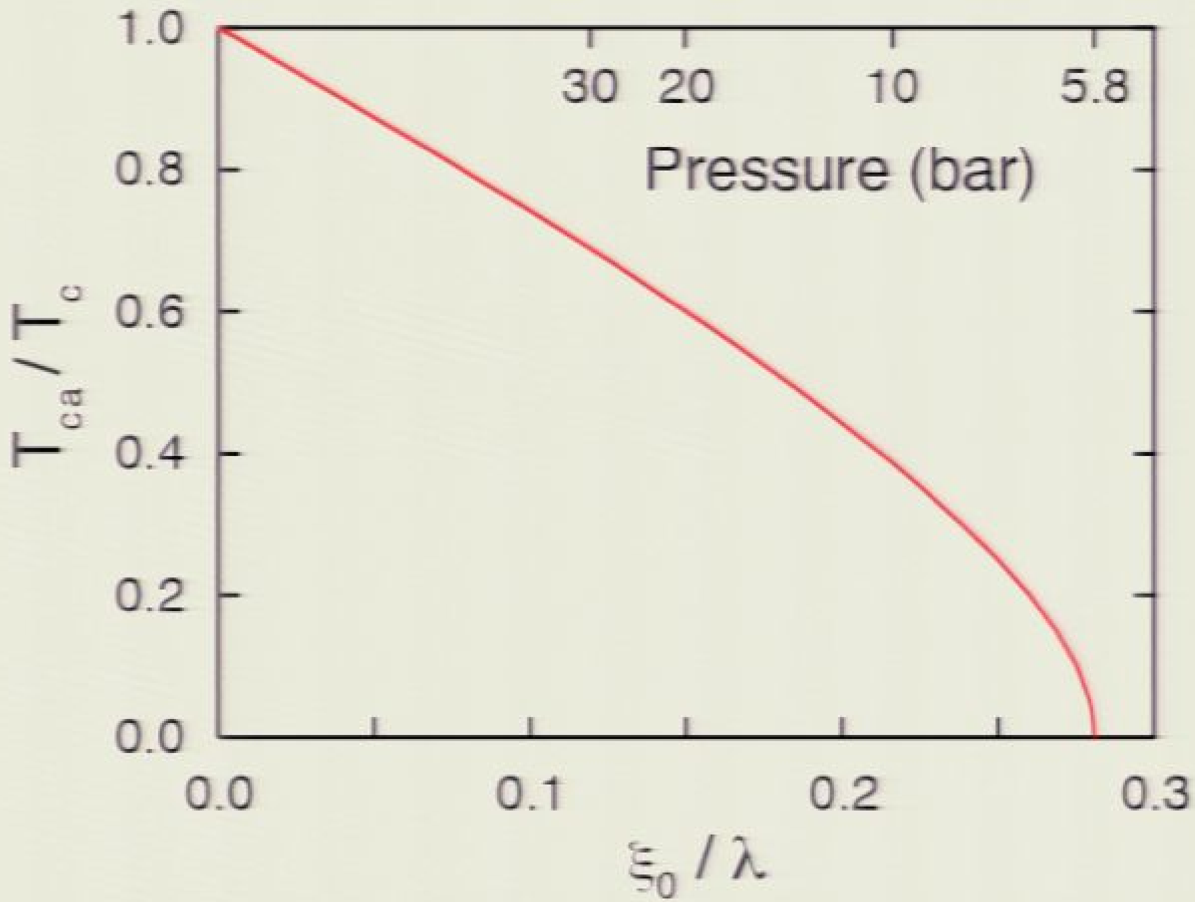

*Abrikosov and Gorkov Soviet Phys. JETP **12**, 1243 (1961)*

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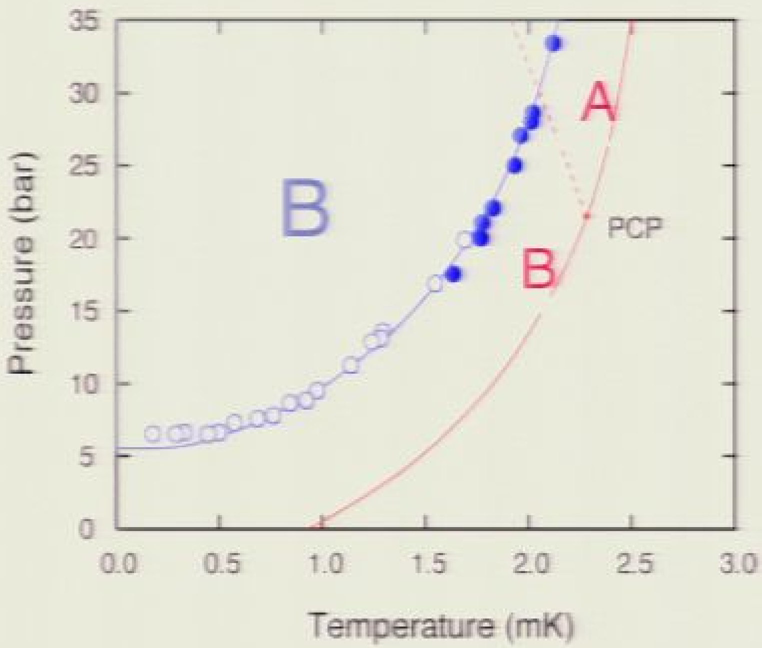
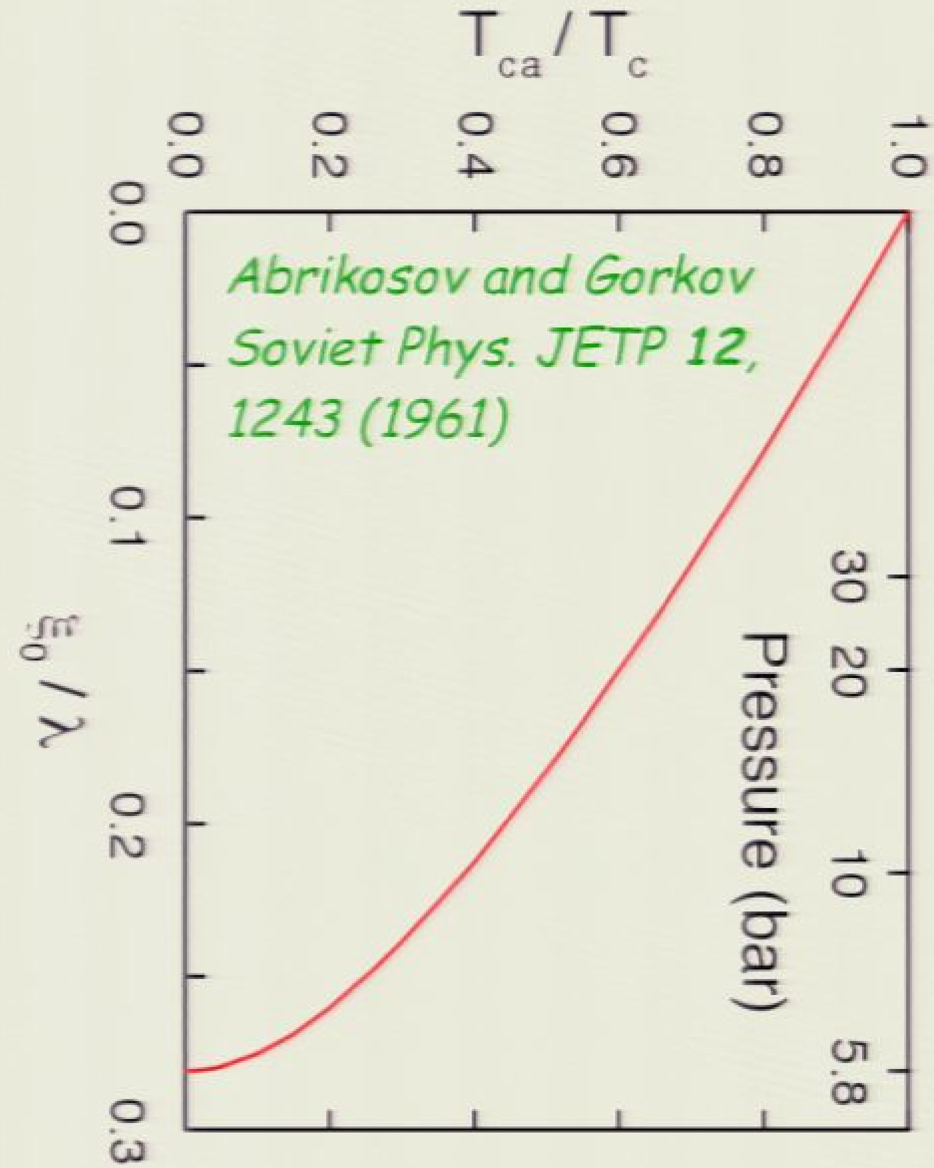
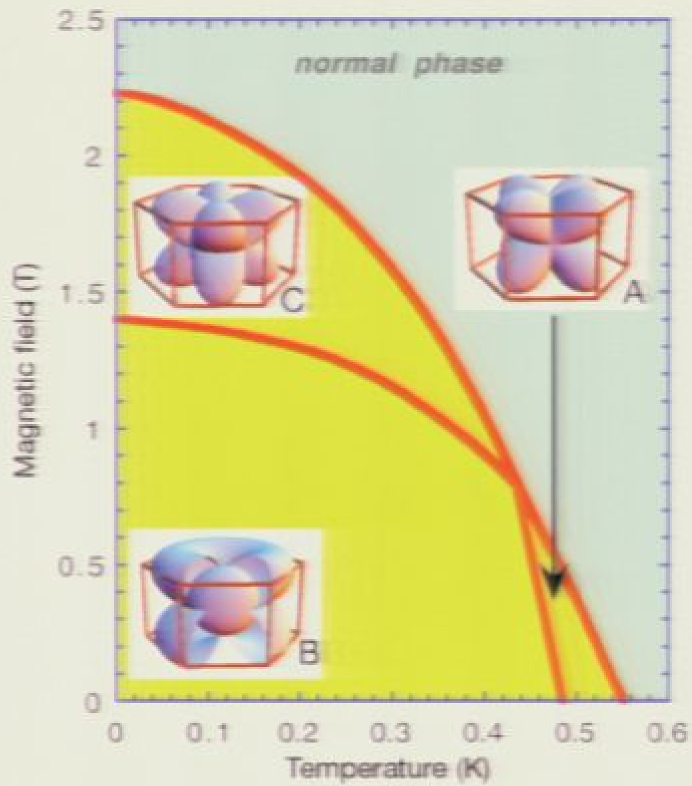


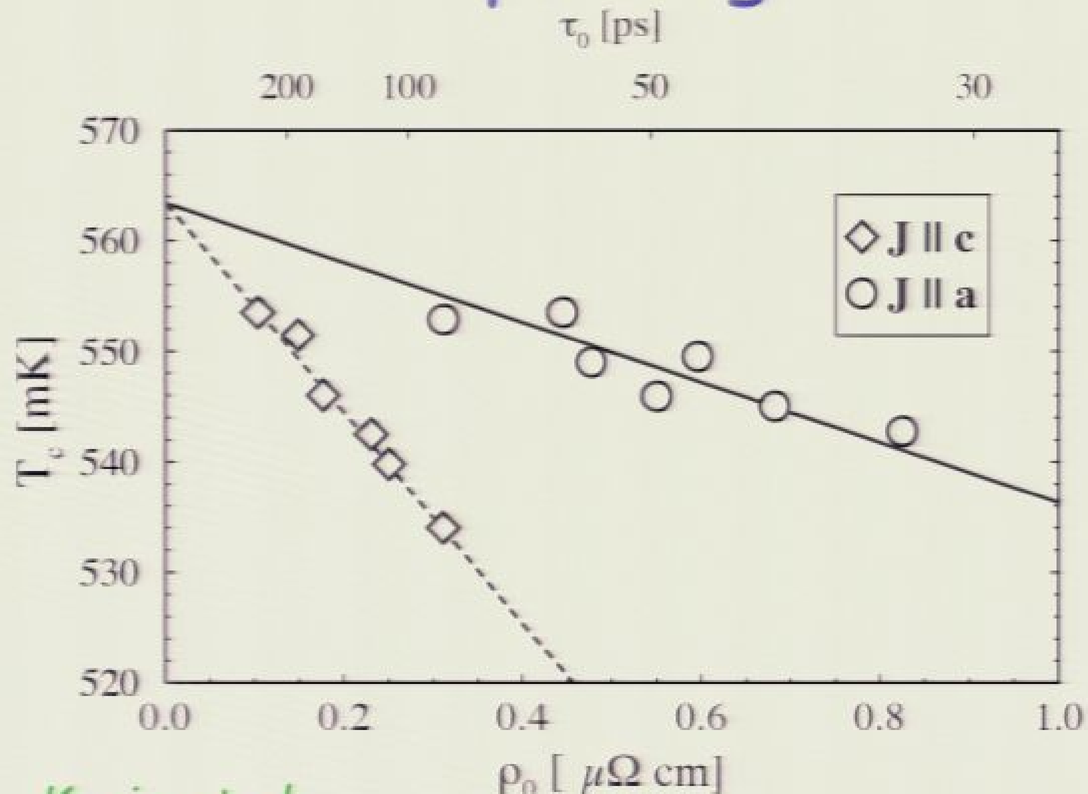


Phase diagram critical pressure →

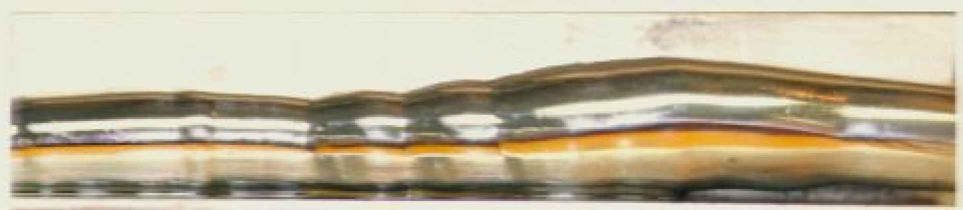
UPt$_3$ another unconventional pairing system:



Phase diagram



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



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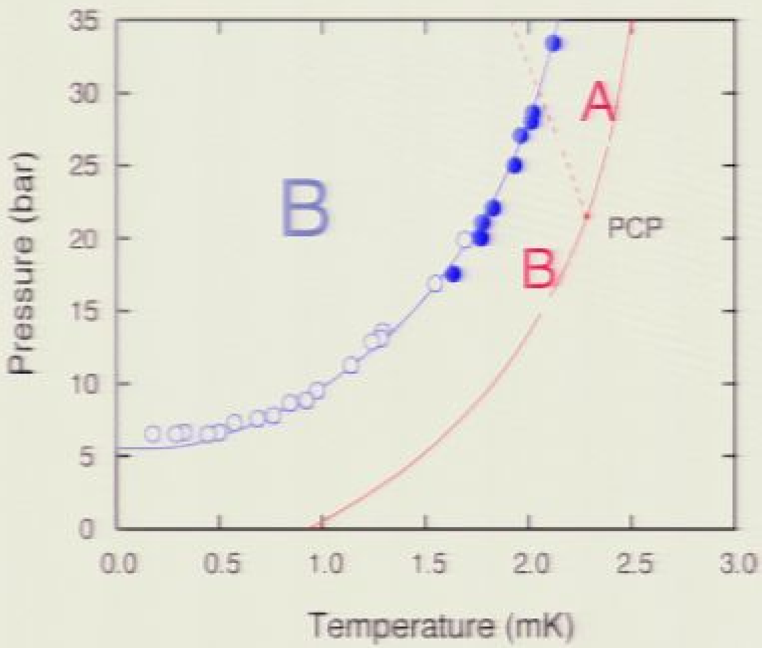
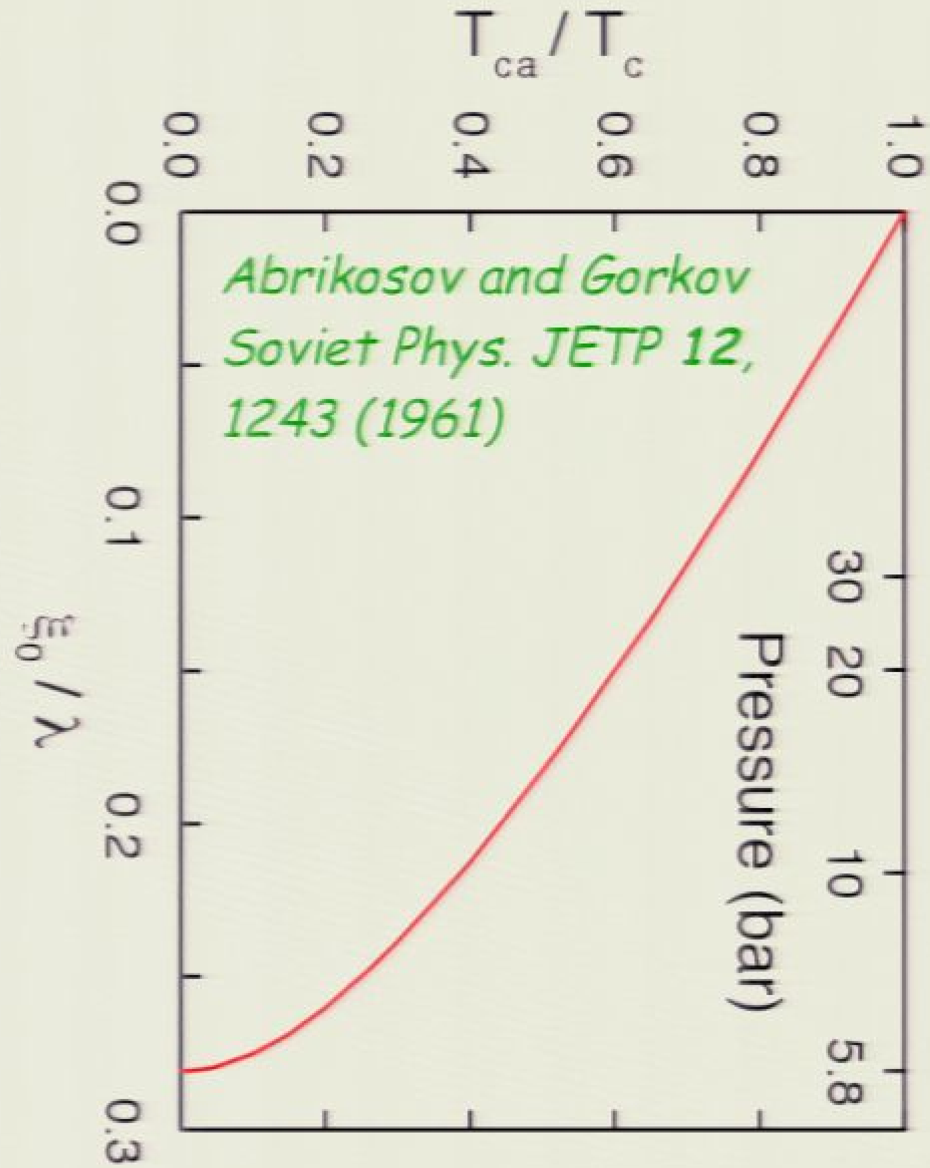


Phase diagram critical pressure



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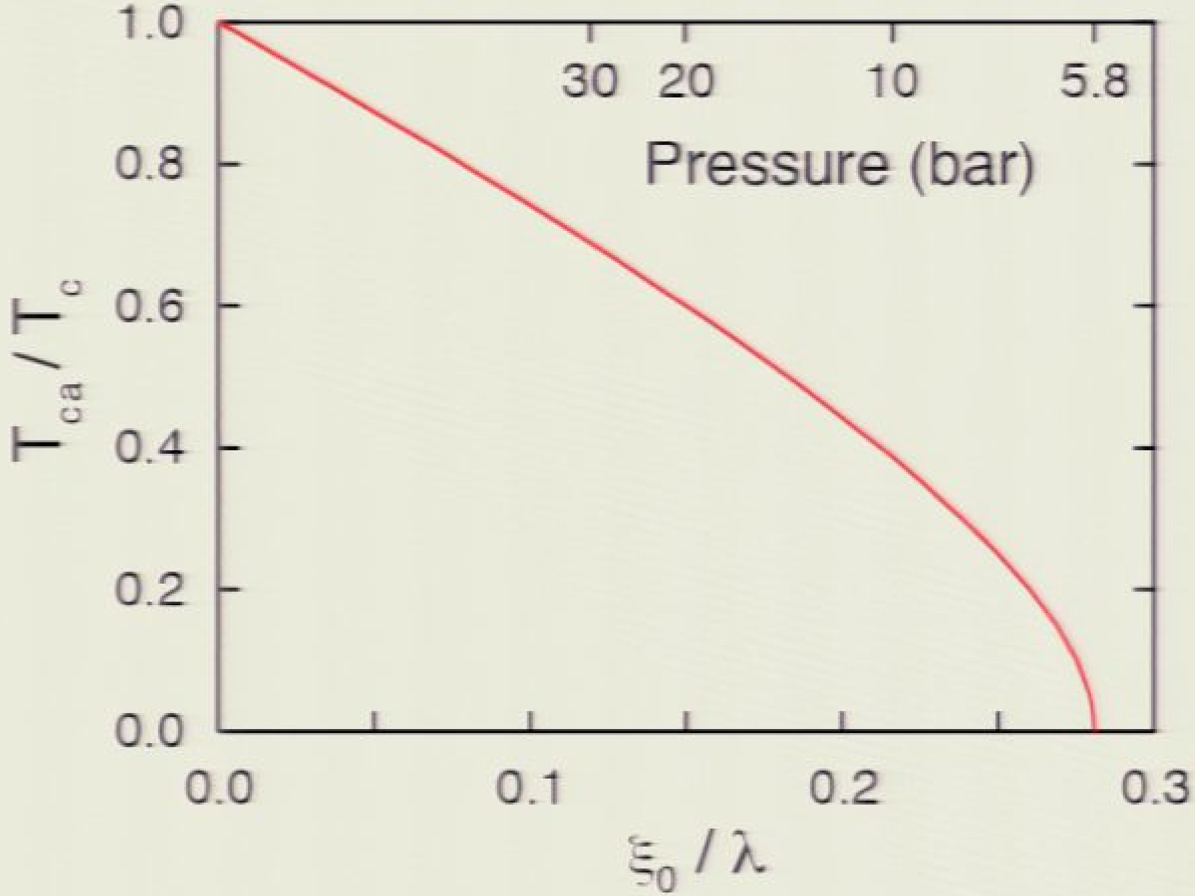

*Abrikosov and Gorkov Soviet Phys. JETP **12**, 1243 (1961)*

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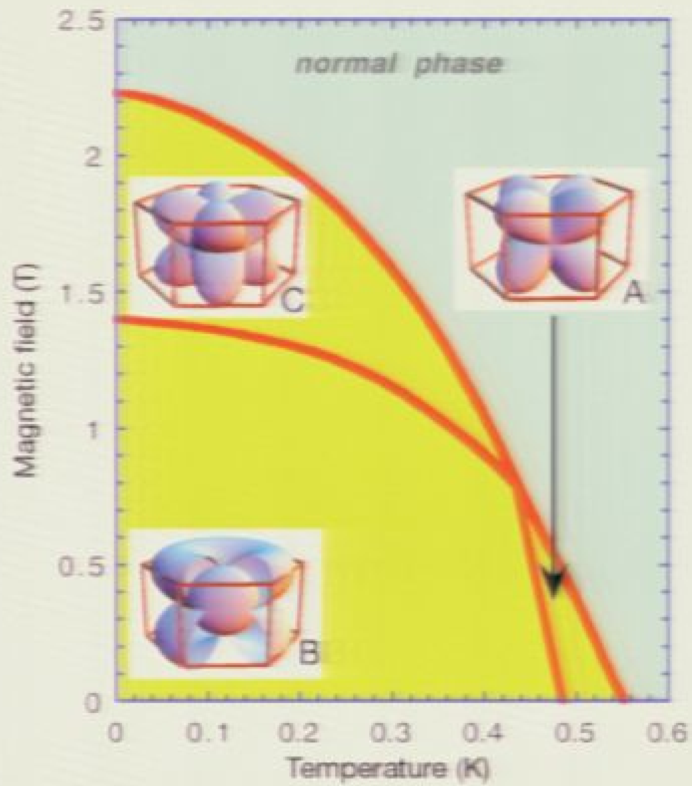
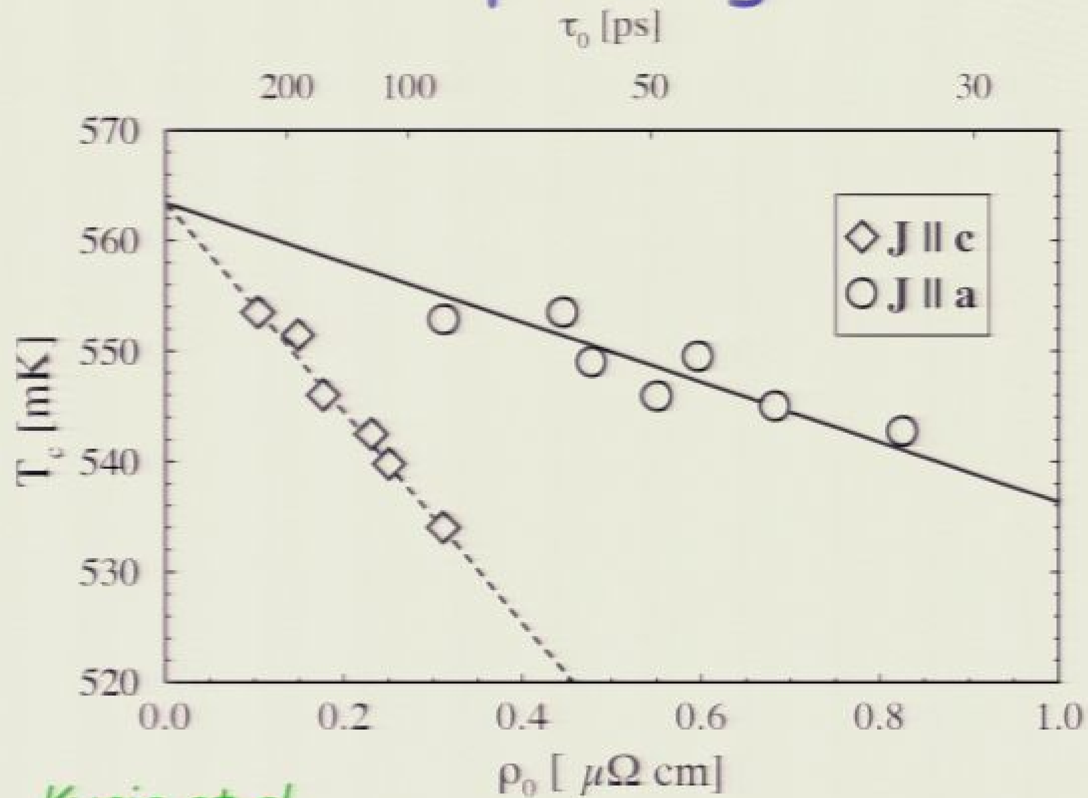
UPt_3 another unconventional pairing system:



Phase diagram



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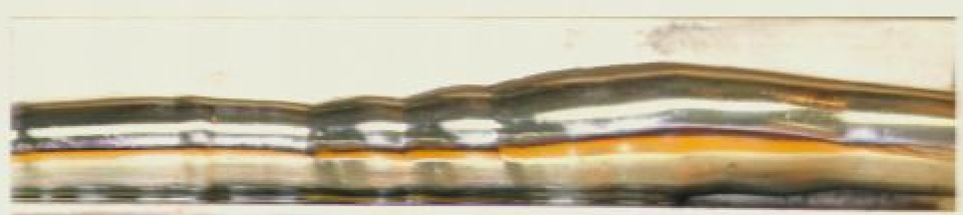

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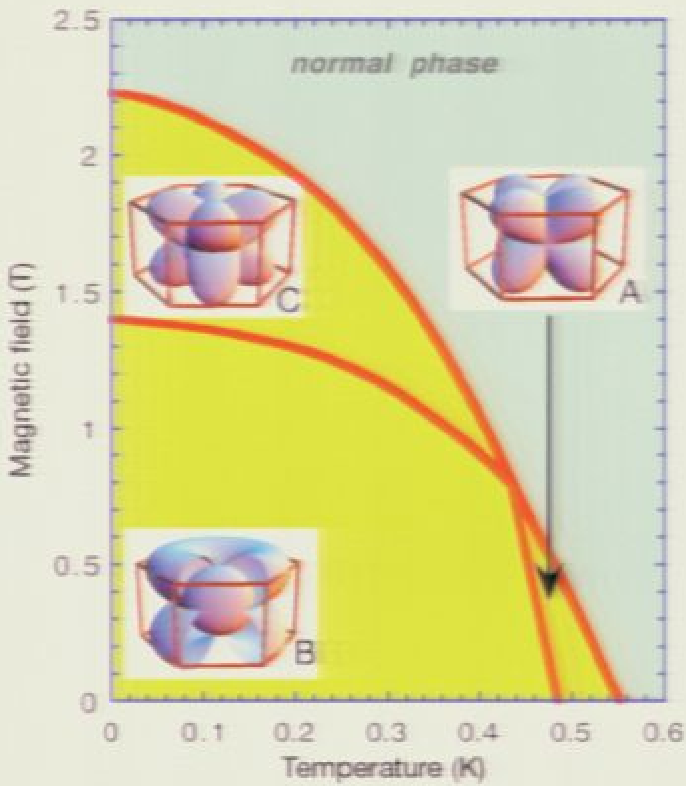

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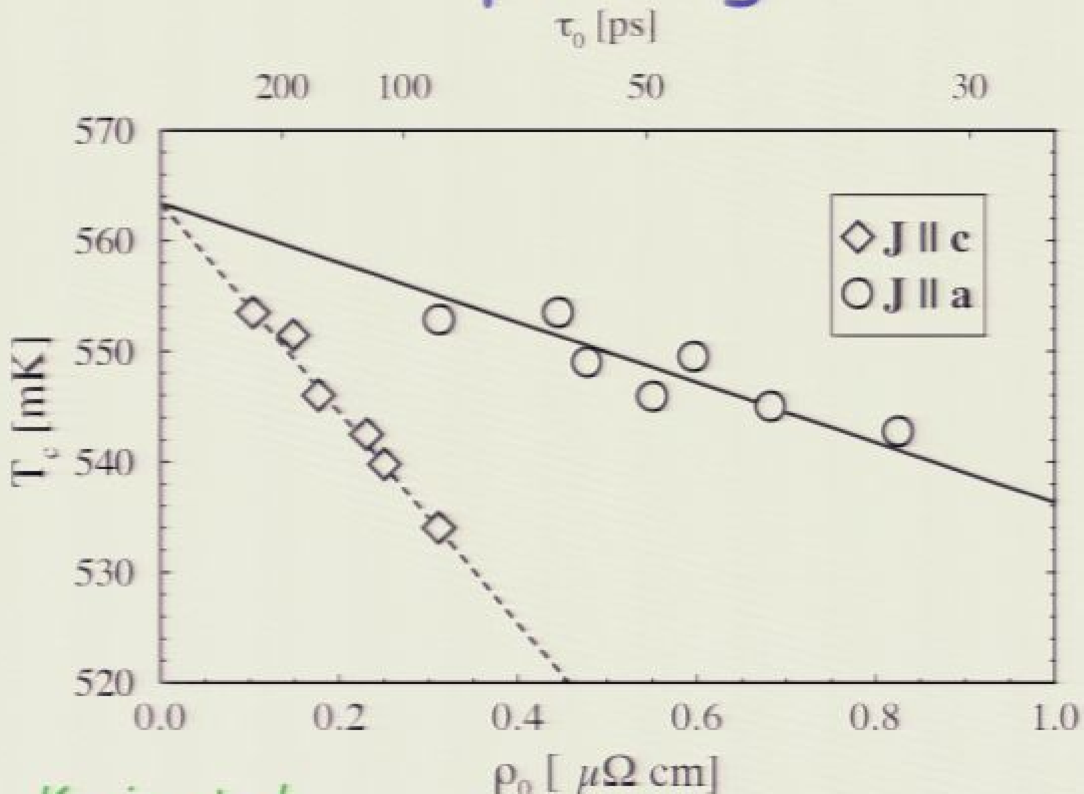

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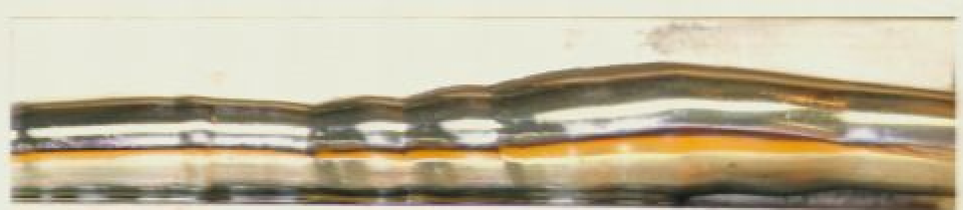
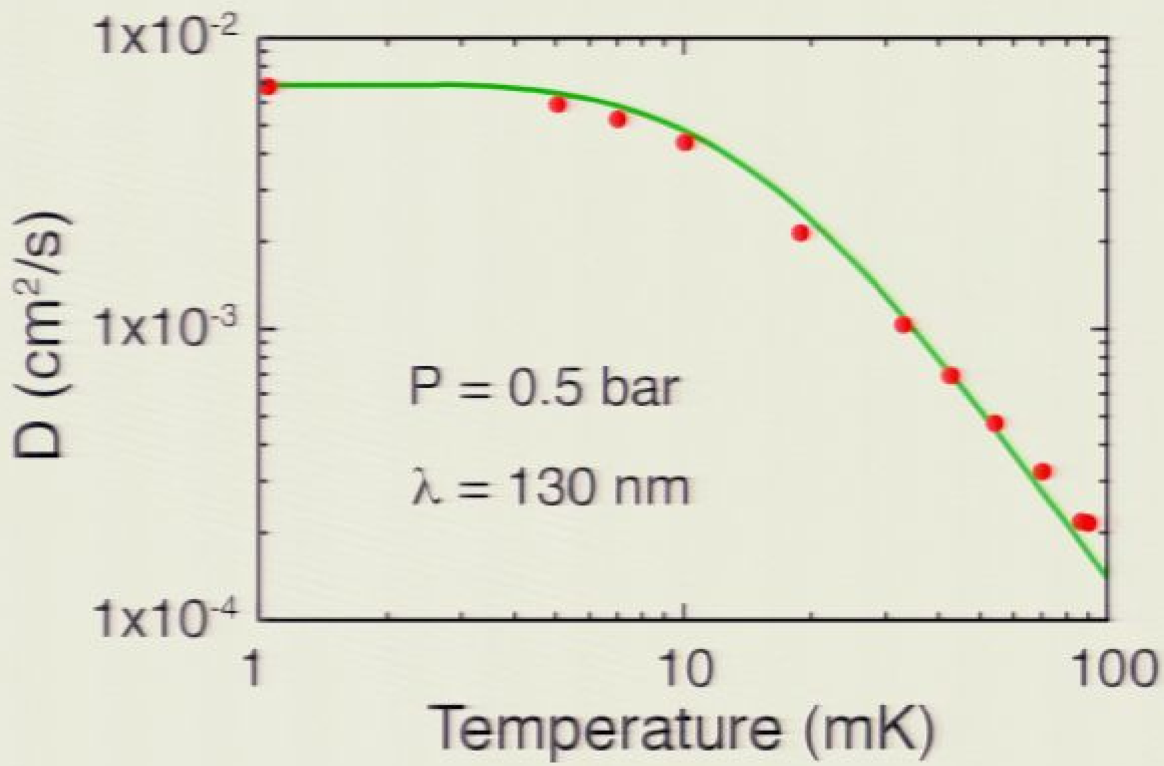


Transport mean-free-path λ:

For pure ^{3}He
in the Fermi liquid

$D \propto 1/T^2$



Collin, PhD thesis Univ. J. Fourier (2002); Bunkov et al JPChem **66**, 1325 (2005)

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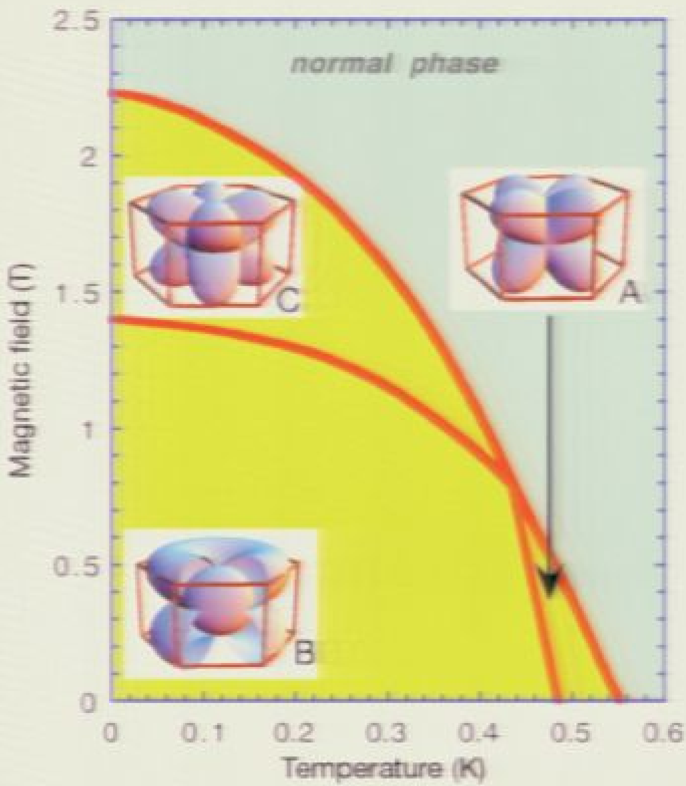

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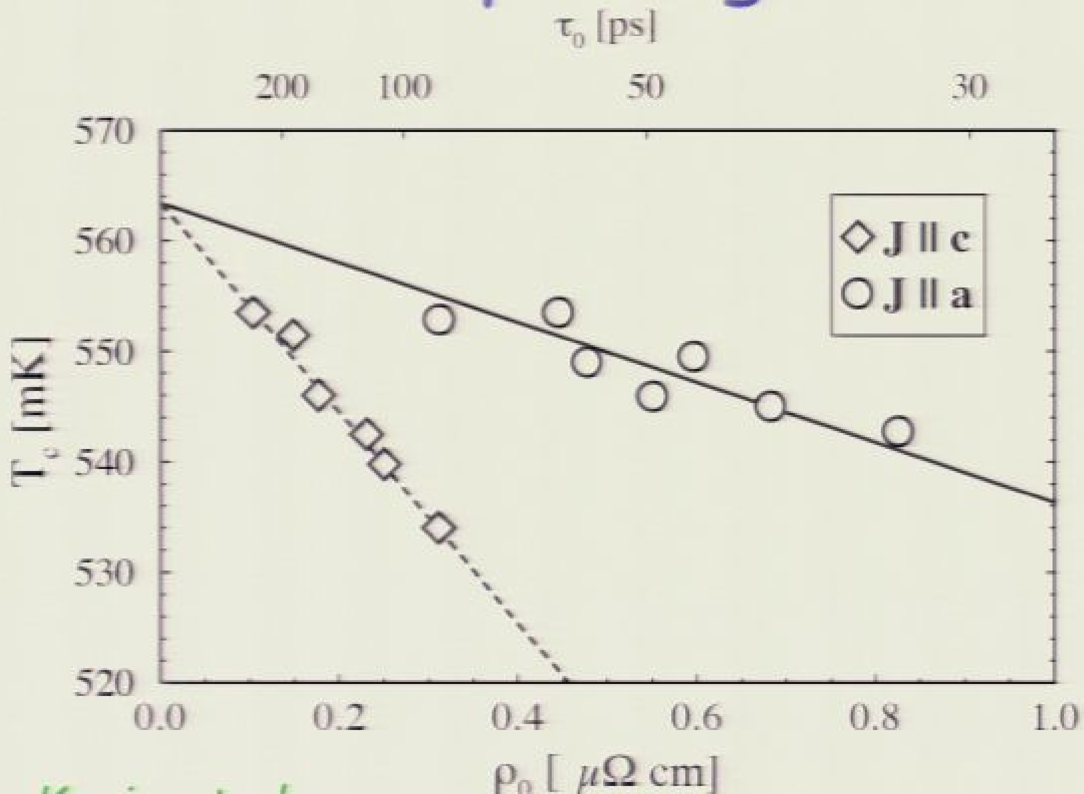

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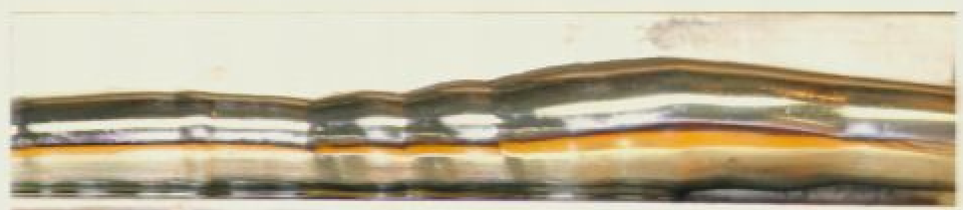

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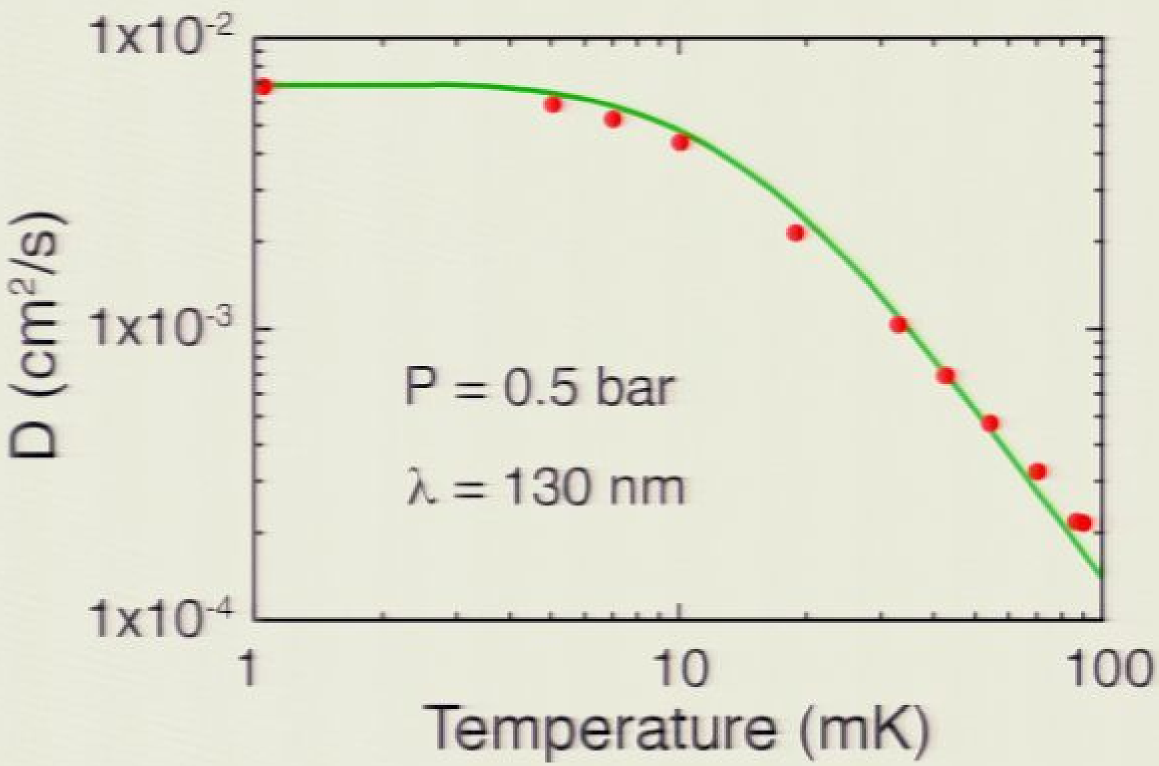

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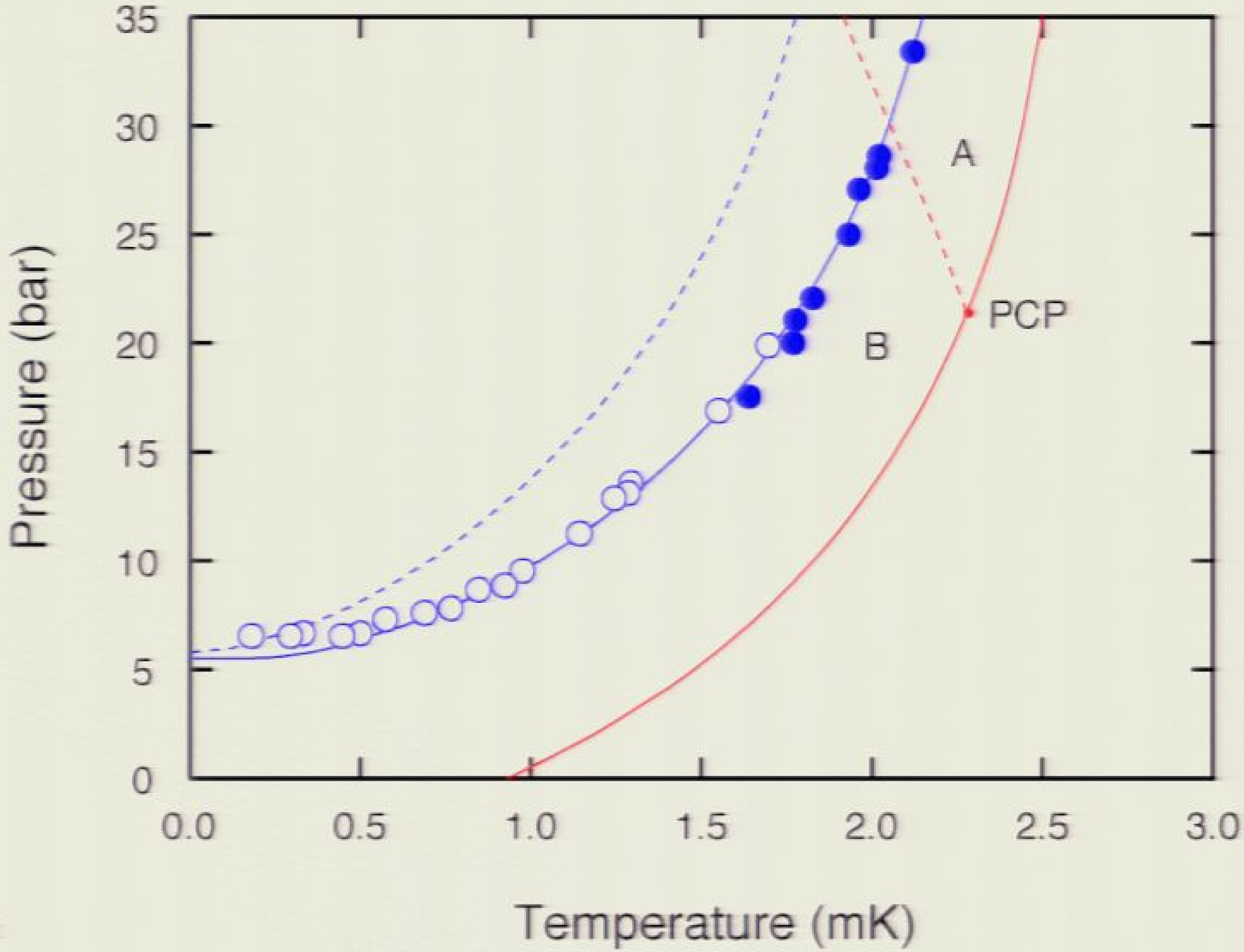
Phase diagram and AG theory:



4-corner

Ginzburg-Landau free energy:
(pure ^{3}He)

$$
\begin{aligned}
F \;=\; & -\alpha \mathrm{Tr}(AA^\dagger) + g_z H_\mu (AA^\dagger)_{\mu\nu} H_\nu + \beta_1 |\mathrm{Tr}(AA^T)|^2 \\
& + \beta_2 [\mathrm{Tr}(AA^\dagger)]^2 + \beta_3 \mathrm{Tr}(AA^T (AA^T)^*) \\
& + \beta_4 \mathrm{Tr}((AA^\dagger)^2) + \beta_5 \mathrm{Tr}(AA^\dagger (AA^\dagger)^*)
\end{aligned}
$$

$$
\alpha = \frac{N(0)}{3}\left(\frac{T}{T_c} - 1\right),
$$

$$
\frac{\beta_i}{\beta_0} = (-1, 2, 2, 2, -2), i = 1, \ldots, 5,
$$

$$
\beta_0 = \frac{7\zeta(3)}{120\pi^2} \frac{N(0)}{(k_B T_c)^2},
$$

Ginzburg-Landau theory for impurities:

Homogeneous Isotropic Scattering Model (HISM):

Silica aerogel is a system of point scatterers for ^3He

One parameter: the transport mean free path, λ (unitary limit).

Determines the pair-breaking parameter: $x = \xi / \lambda$.

$$\ln \frac{T_c}{T_{c,a}} = 2 \sum_{n=1} \left(\frac{1}{2n-1} - \frac{1}{2n-1+x} \right)$$

$$\begin{pmatrix} \beta_1^a \\ \beta_2^a \\ \beta_3^a \\ \beta_4^a \\ \beta_5^a \end{pmatrix} = \beta_0^a \begin{pmatrix} -1 \\ 2 \\ 2 \\ 2 \\ -2 \end{pmatrix} + b \begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \\ -1 \end{pmatrix} + \begin{pmatrix} \Delta\beta_1^{sc,a} \\ \Delta\beta_2^{sc,a} \\ \Delta\beta_3^{sc,a} \\ \Delta\beta_4^{sc,a} \\ \Delta\beta_5^{sc,a} \end{pmatrix}$$

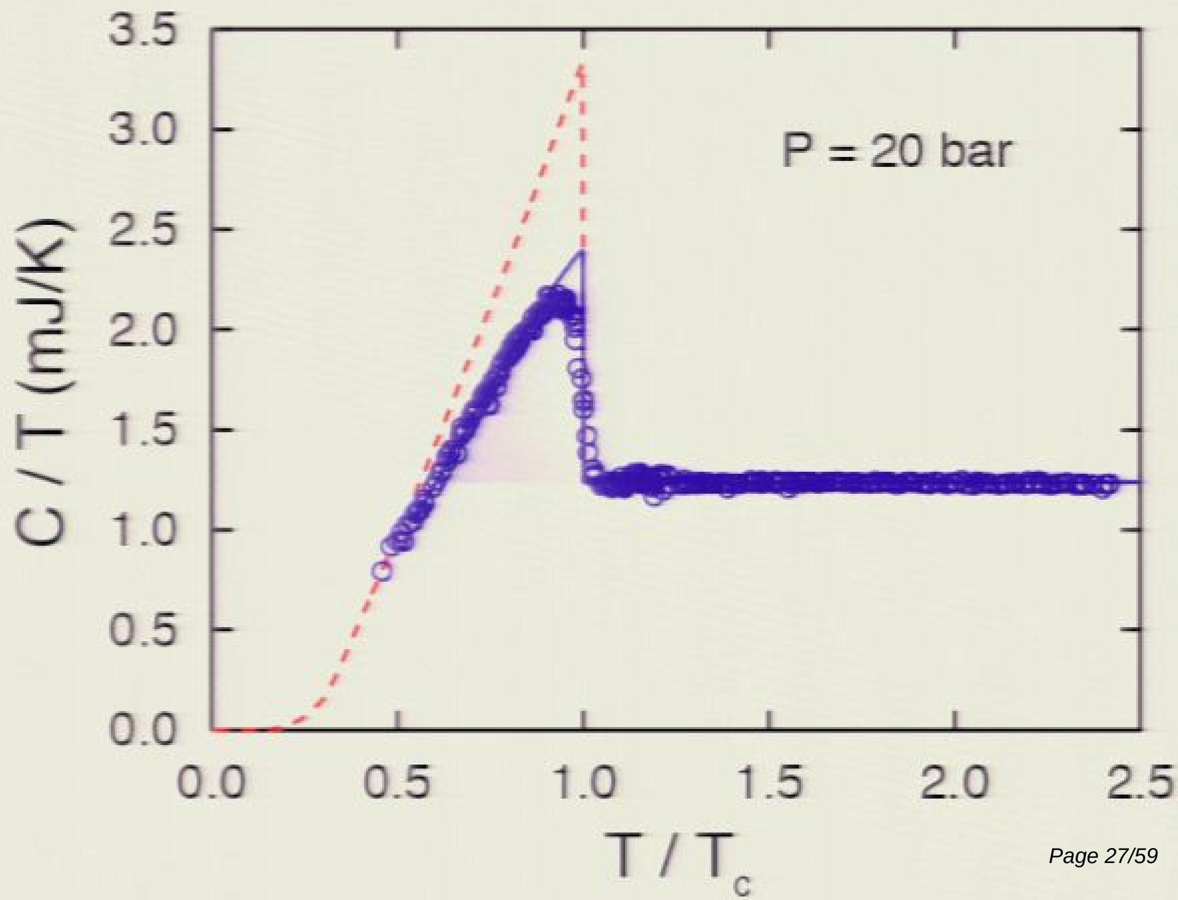
$$\beta_0^a = \frac{N(0)}{30(\pi k_B T_c)^2} \sum_{n=1} \frac{1}{(2n-1+x)^3},$$

$$b = \frac{N(0)}{9(\pi k_B T_c)^2} \left(\sin^2\delta_0 - \tfrac{1}{2}\right) \sum_{n=1} \frac{x}{(2n-1+x)^4}.$$

Thuneberg et al.
*PRL **80**, 2861 (1998);*

Specific heat jump:

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



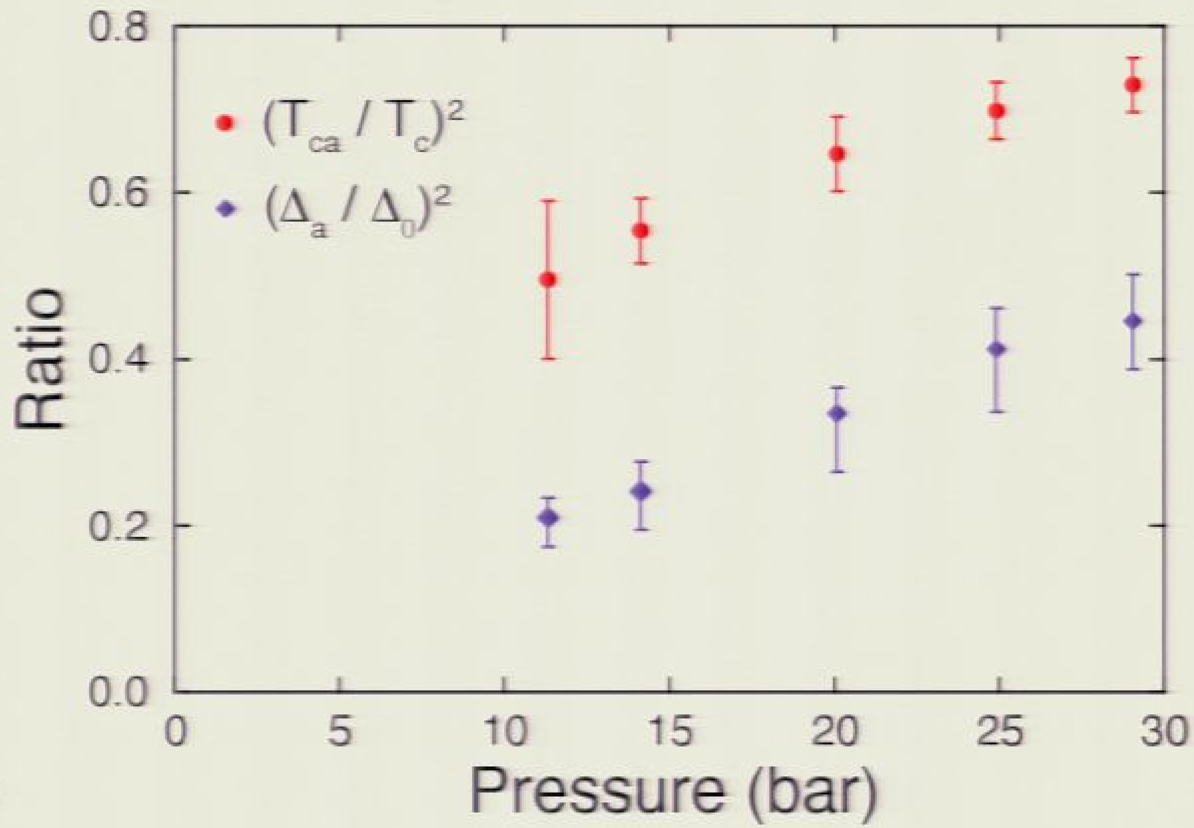
Choi et al.
*PRL **93**, 145301 (2004);*

Failure of HISM:

Gap from specific heat jump:

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

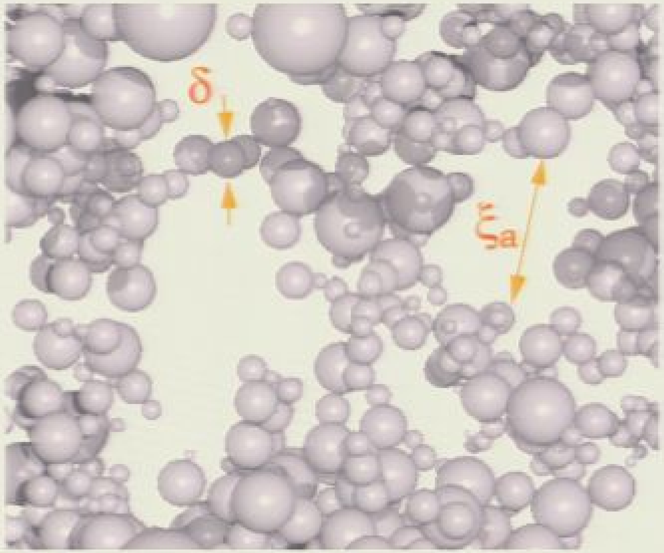
Homogeneous Isotropic Scattering Model (HISM): suppression ratio *must be the same* for the energy gap and Tc (unitary scattering)



4-corners 4

Ginzburg-Landau theory (cont'd):

Inhomogeneous Isotropic Scattering Model (IISM):



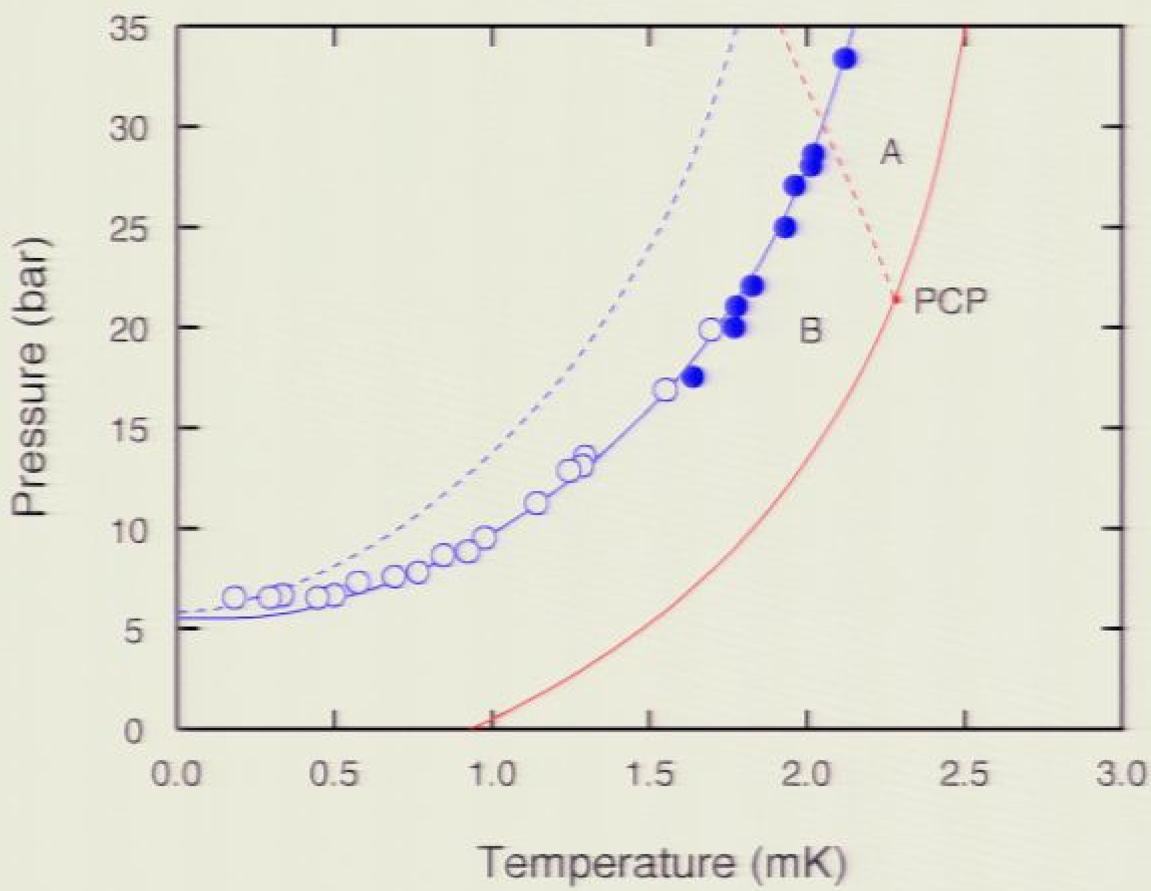
Define a new pair-breaking parameter:

$$x = (\xi/\lambda)/[1 + \xi_a^{\,2}/\lambda\xi]$$

in terms of a scattering correlation length ξ_a *, proposed by Sauls and Sharma and calculated by Fomin.*

Sauls and Sharma et al. PRB ***68****, 224502 (2003); Fomin, Pis'ma ZhETF* ***88****, 65 (2008); Surovtsev, arXiv:0810.1102; Hanninen and Thuneberg PRB* ***67****, 214507 (2003).*

Phase diagram with correlated disorder:



λ = 140 nm

ξ_a = 50 nm

ξ_a = 0 nm

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

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Ginzburg-Landau theory (cont'd):

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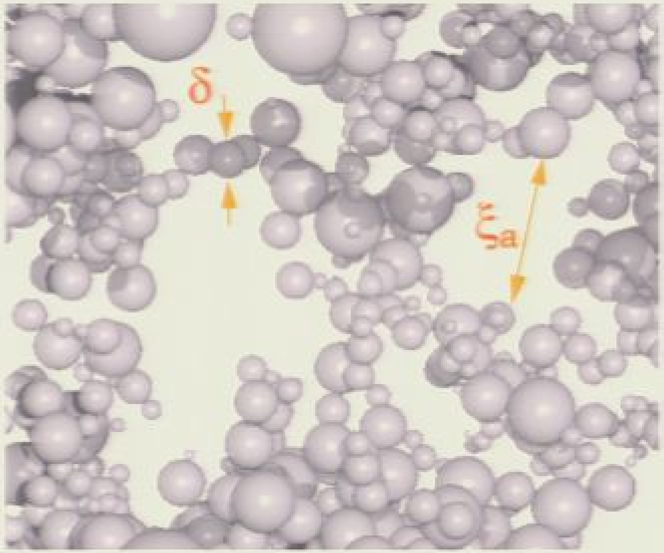

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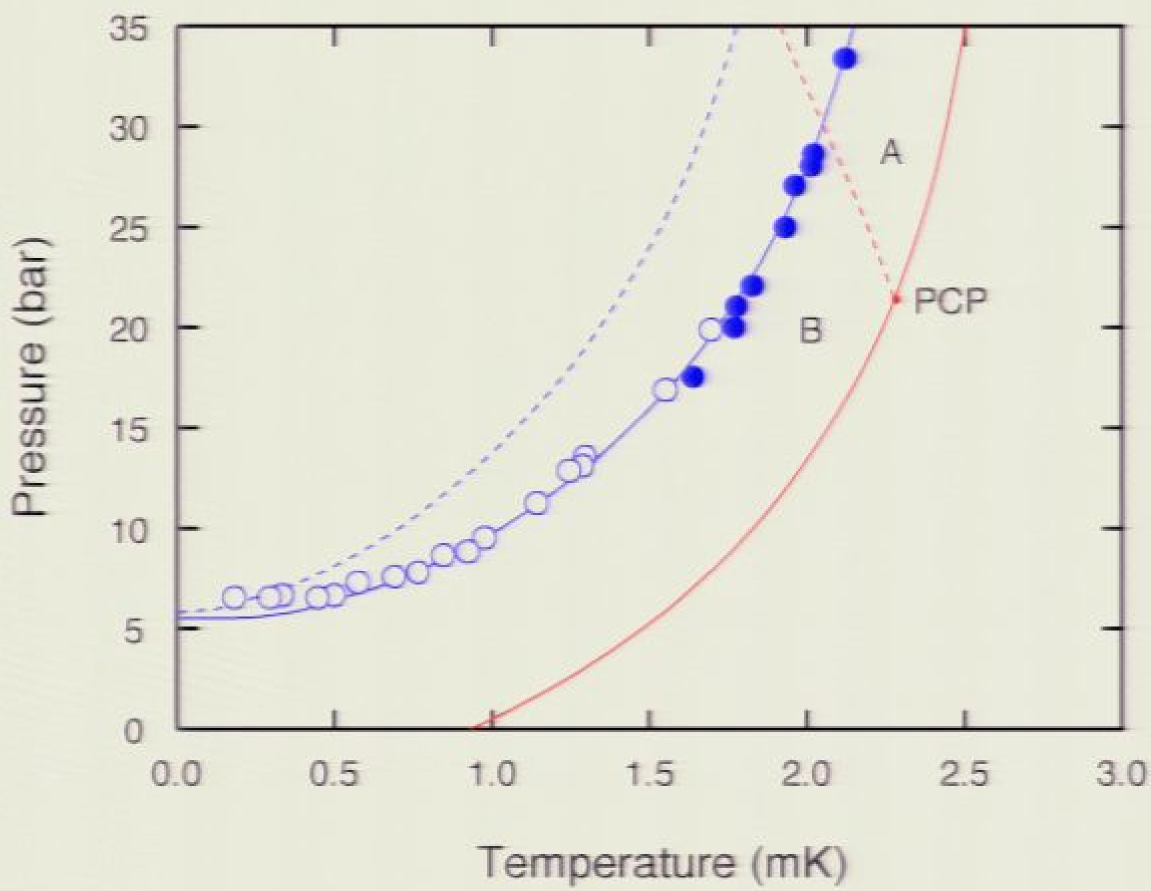

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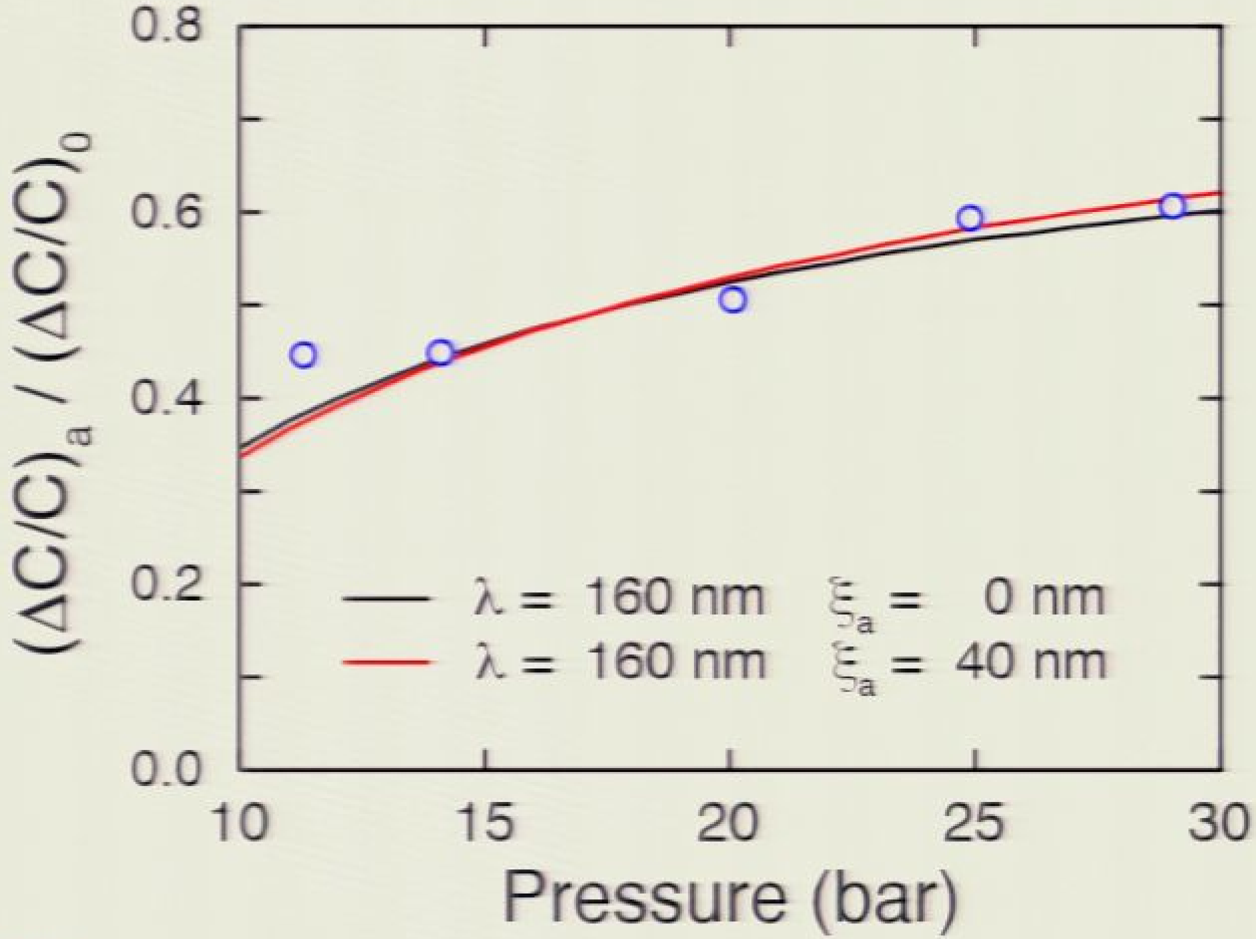
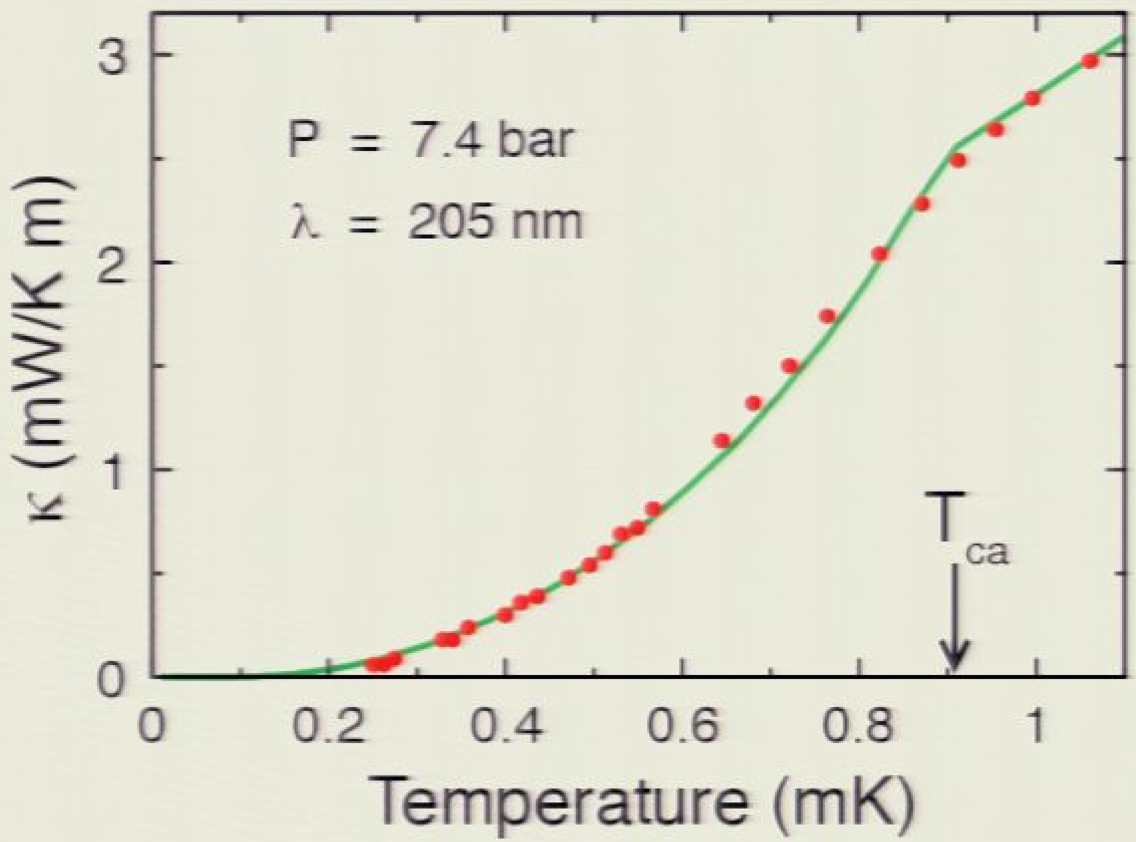


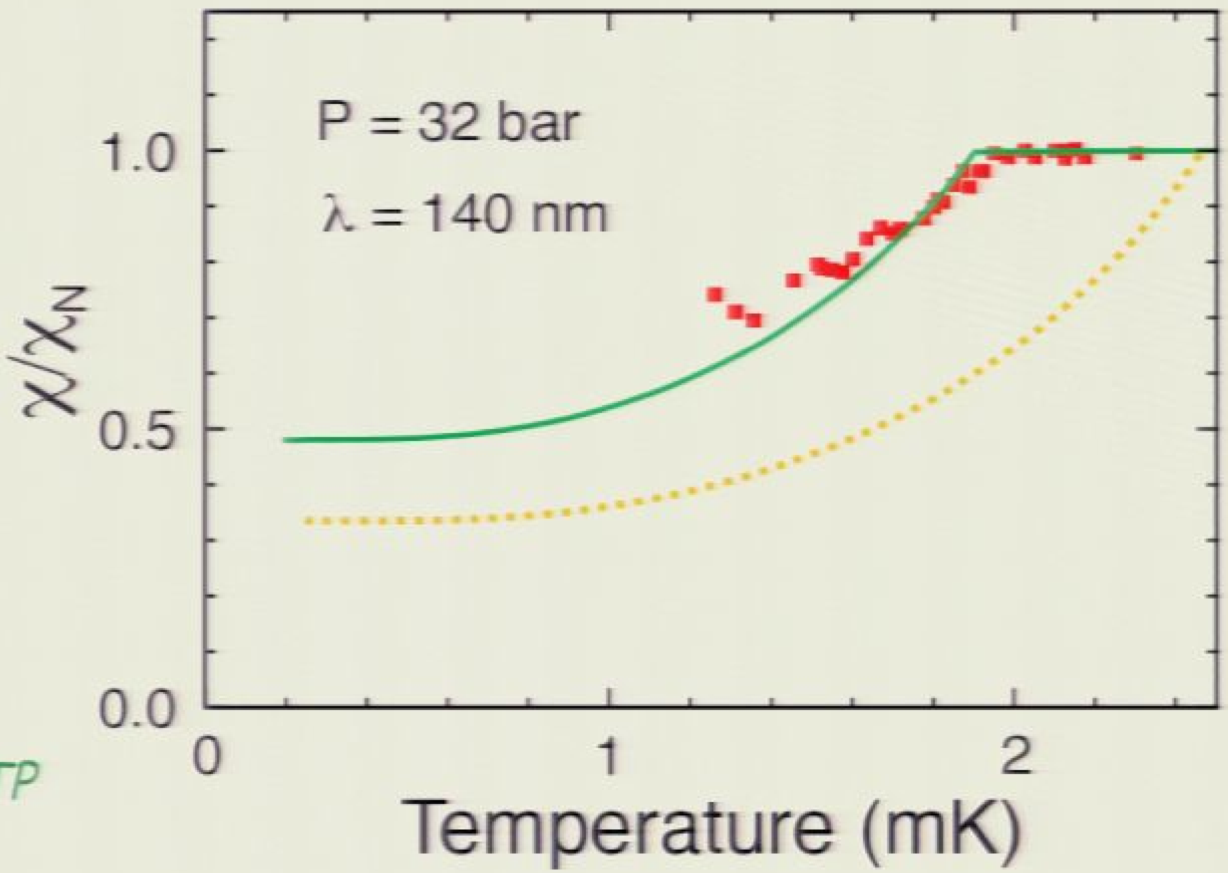
Choi et al.
PRL ***93****, 145301 (2004);*

Thermal conductivity:



Fisher et al.
*JLTP **126**, 673 (2001);*
Sharma and Sauls,
*PhysicaB **329**, 313 (2003).*

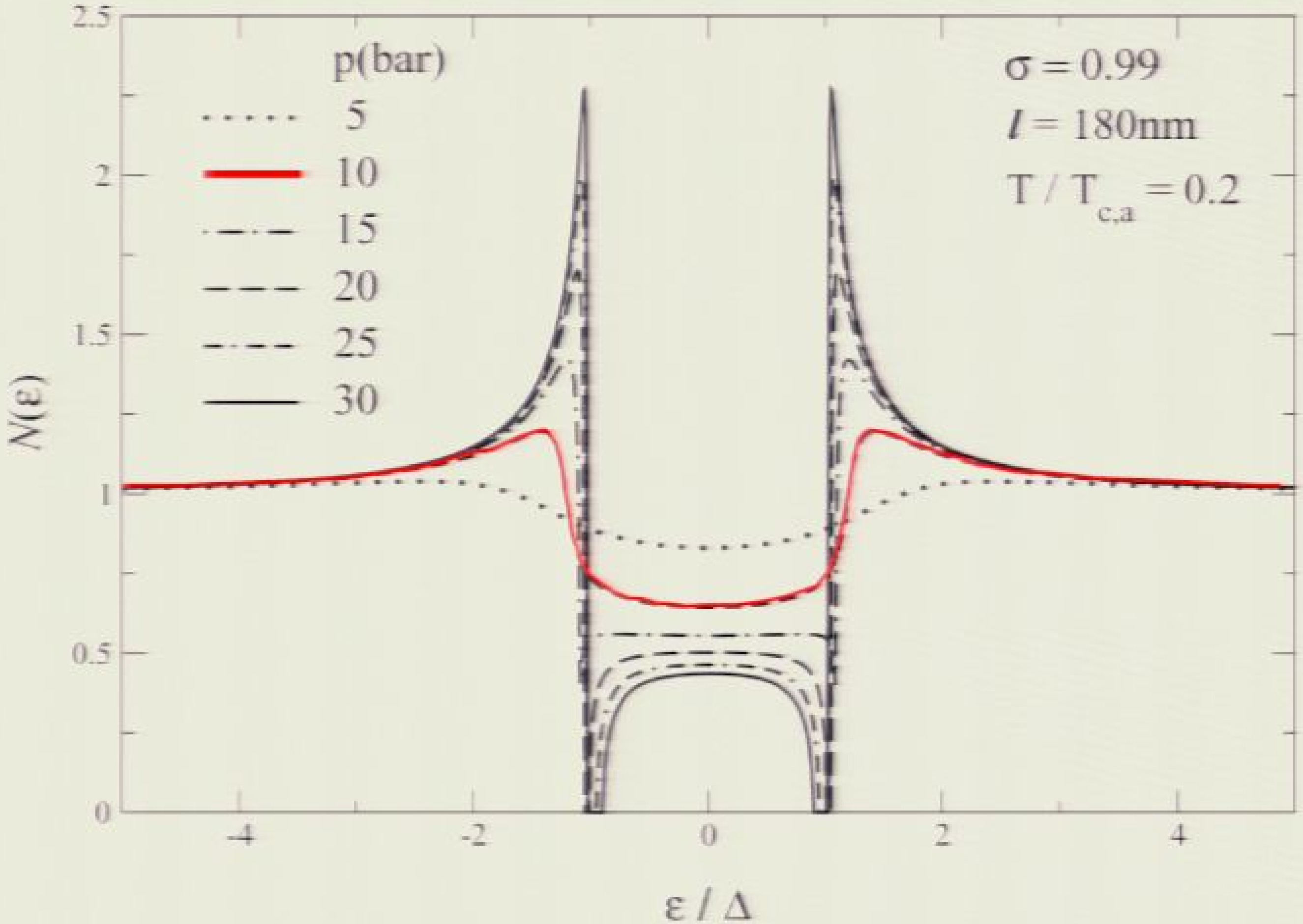
Magnetic susceptibility:

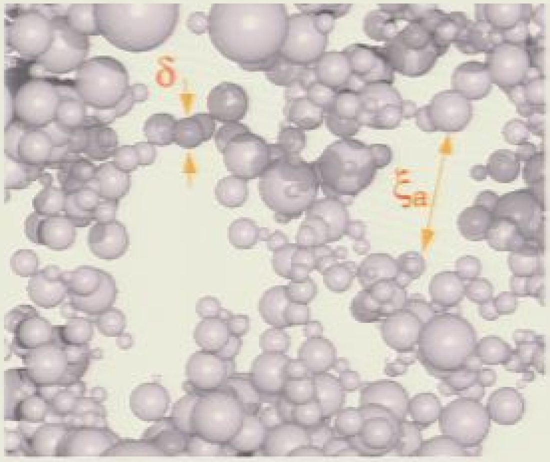


Barker et al.
PRL **85**, 2148 (2000);
Sharma and Sauls, JLTP
125, 115 (2001).

See also: Sprague et al.(1996); Collin (2002); Bunkov et al. (2005)

Gapless superfluidity: theory

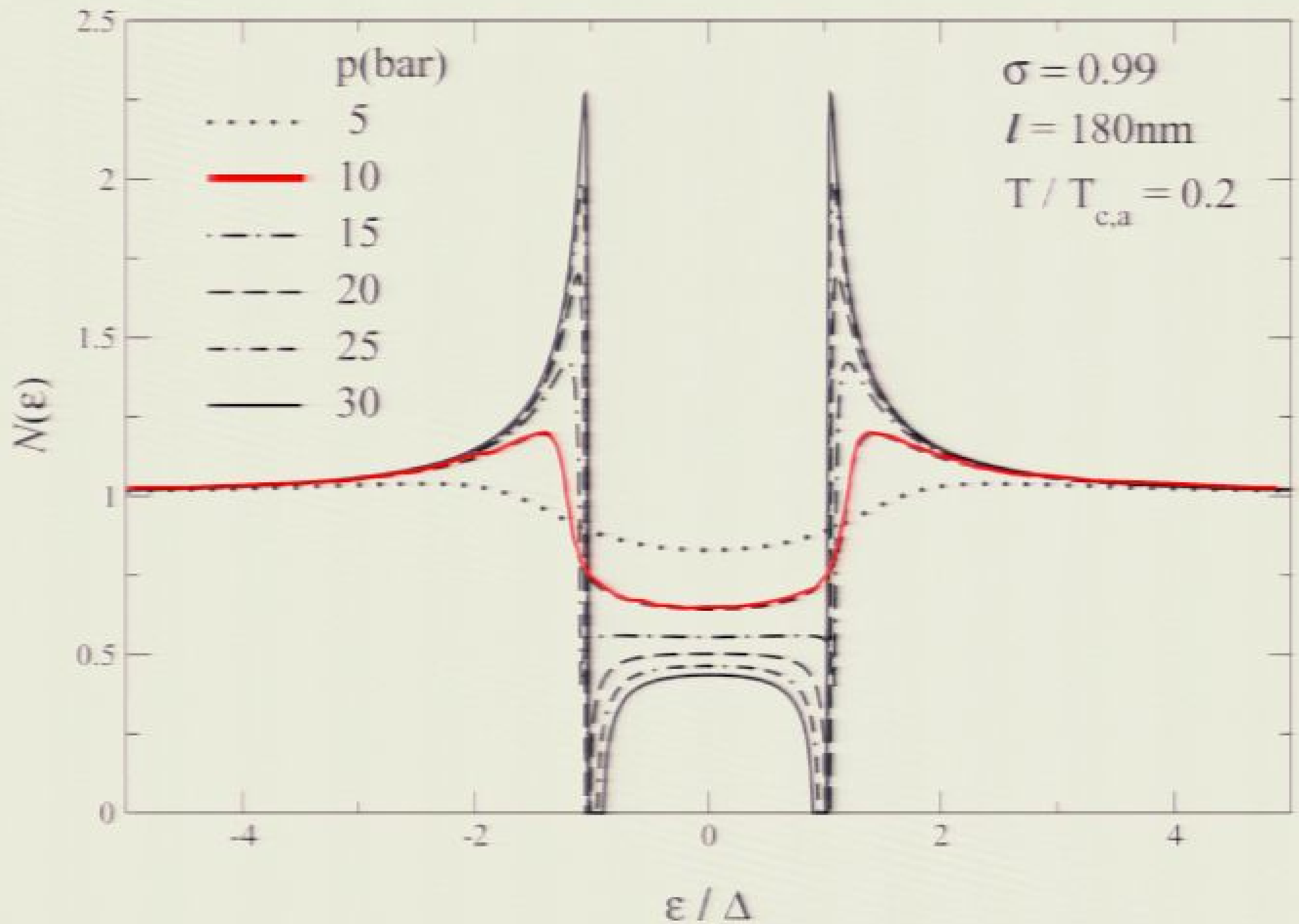


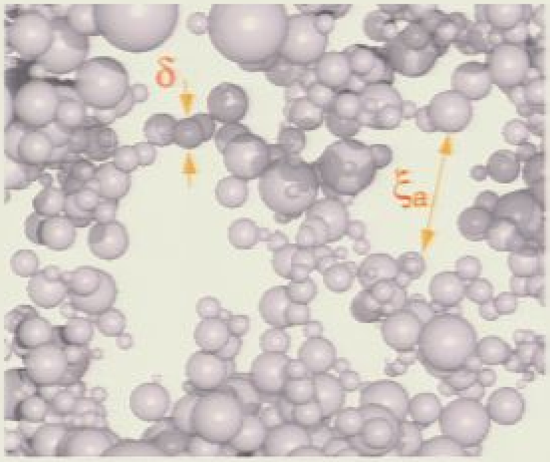


Sharma and Sauls.
JLTP **125**, 115 (2001);

[redacted]

Gapless superfluidity: theory



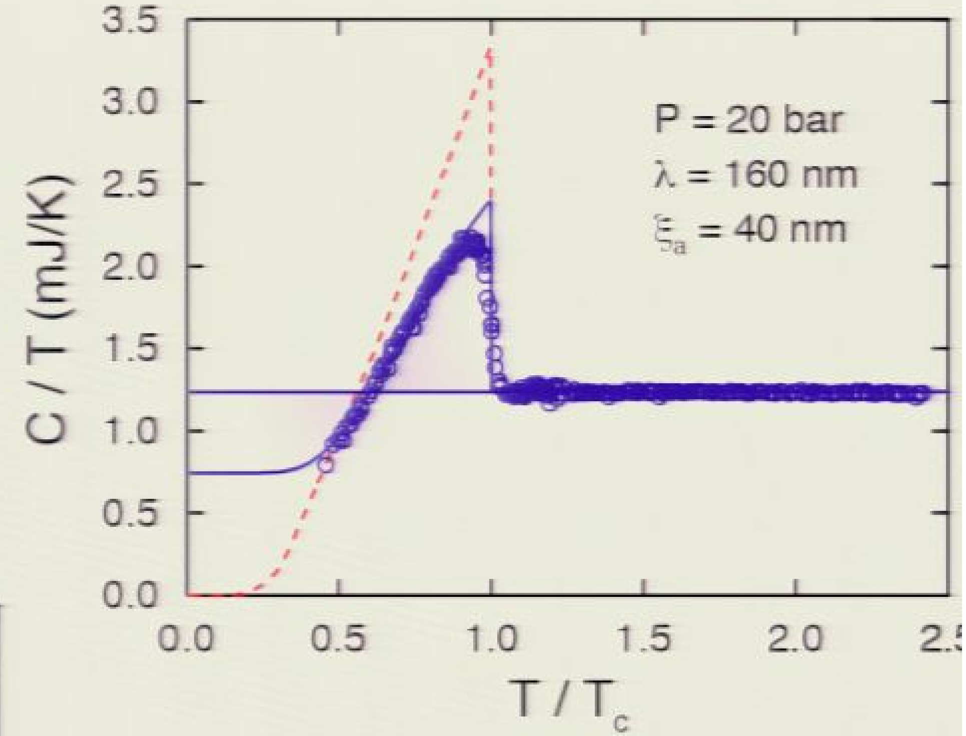


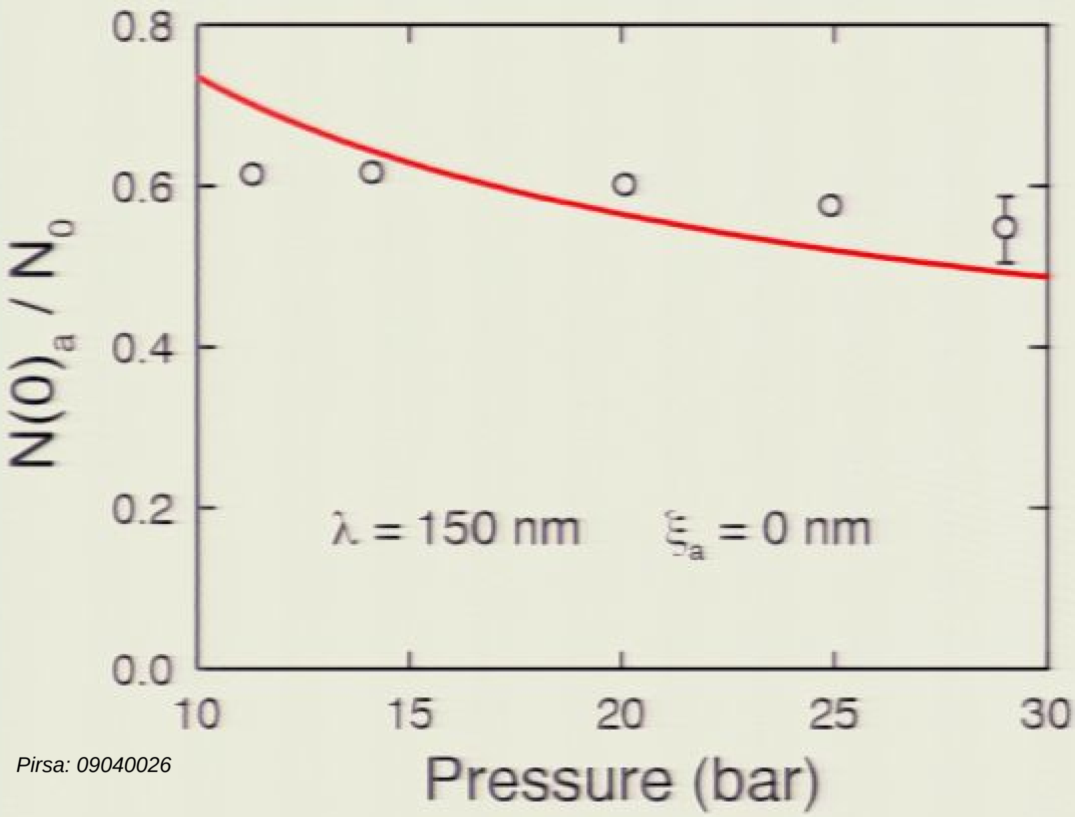
Sharma and Sauls.

JLTP **125**, 115 (2001);

4-corners 4/23/09

Gapless superfluidity $C(T)$:

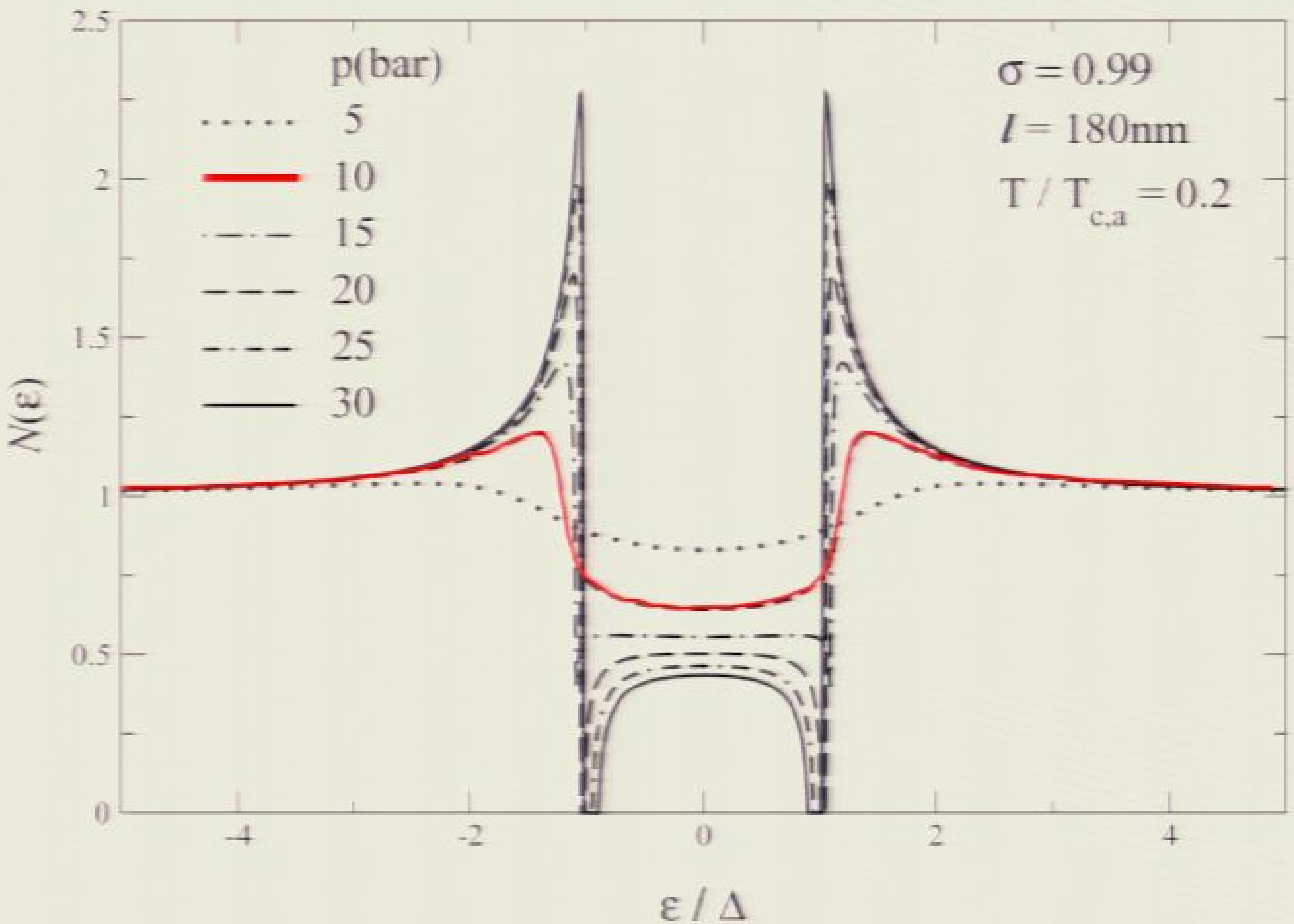


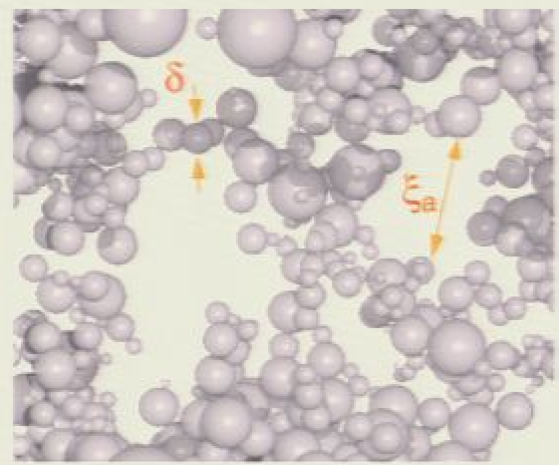


Choi et al. PRL ***93****, 145301 (2004);*

Also, attenuation of sound, $\alpha(T=0)$, H.C. Choi et al. PRL (2007)

Gapless superfluidity: theory





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JLTP **125**, 115 (2001);

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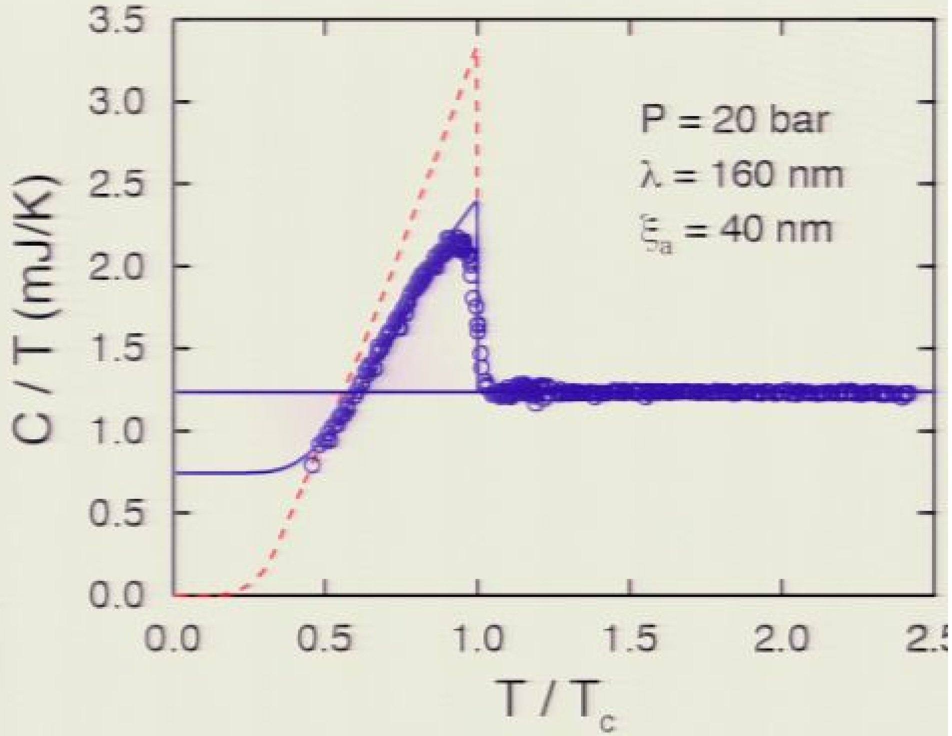

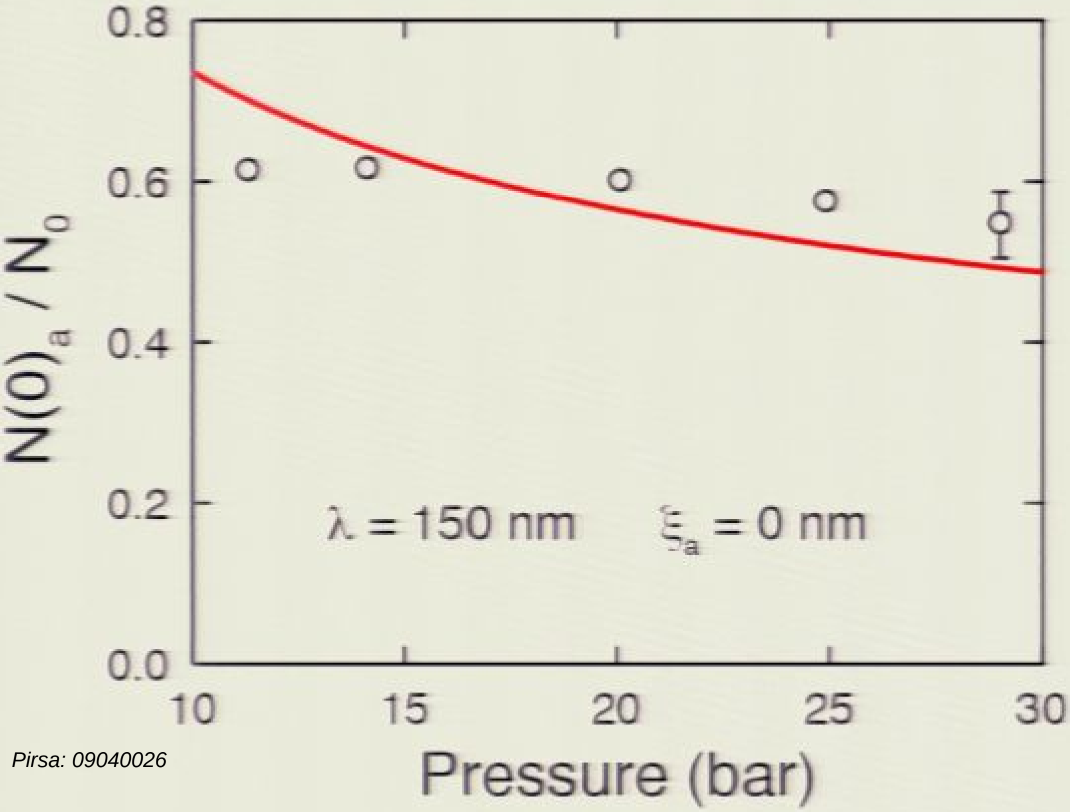

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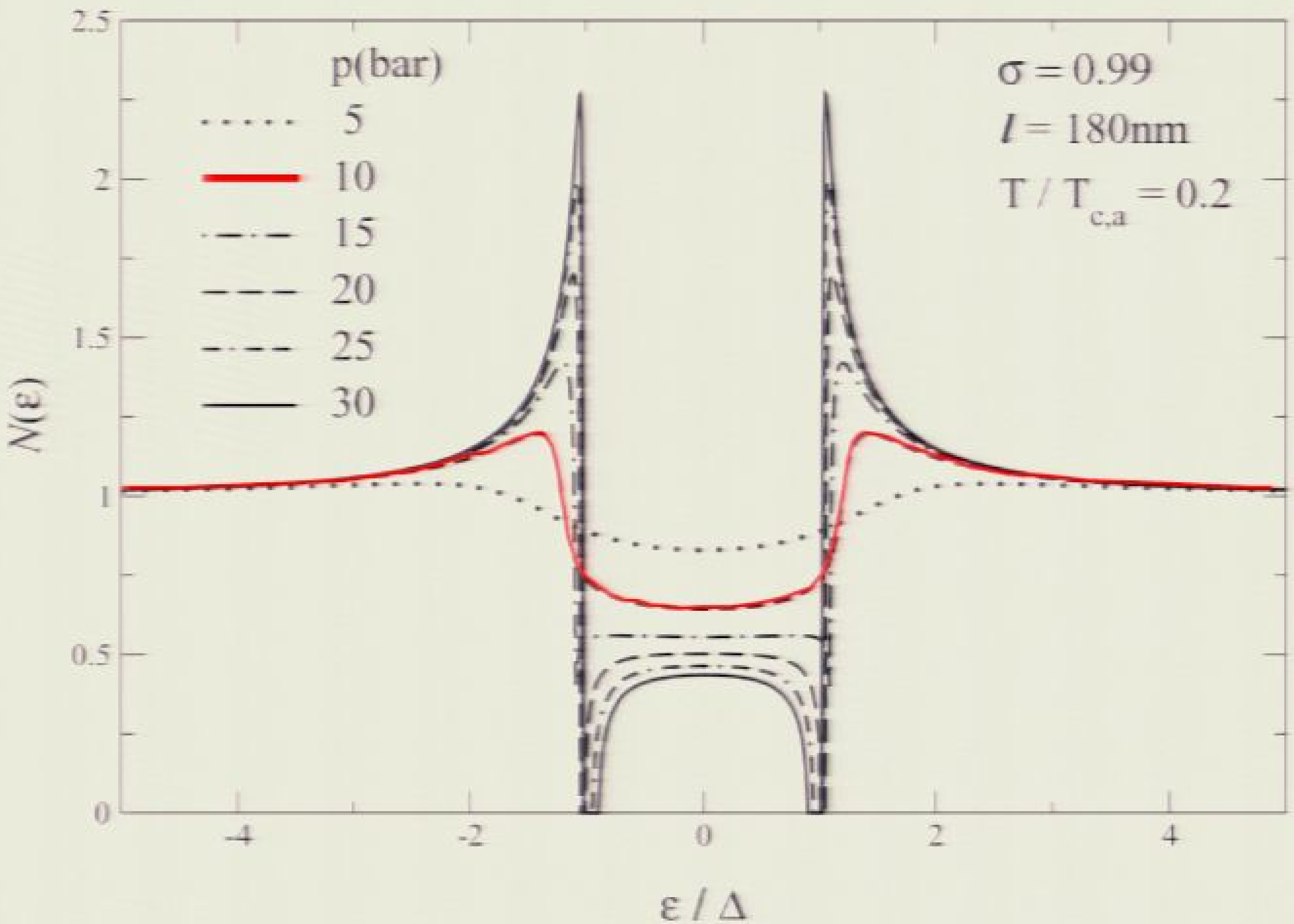

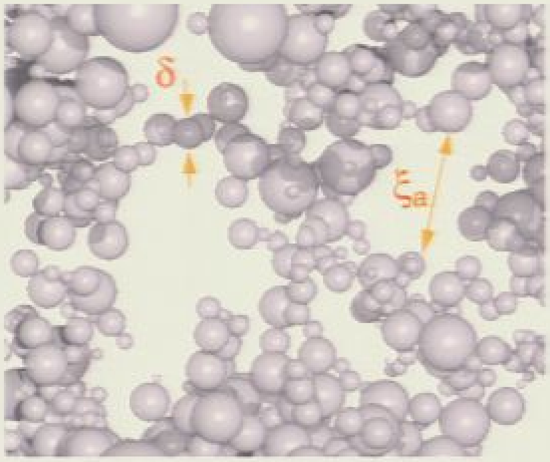

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JLTP **125**, 115 (2001);

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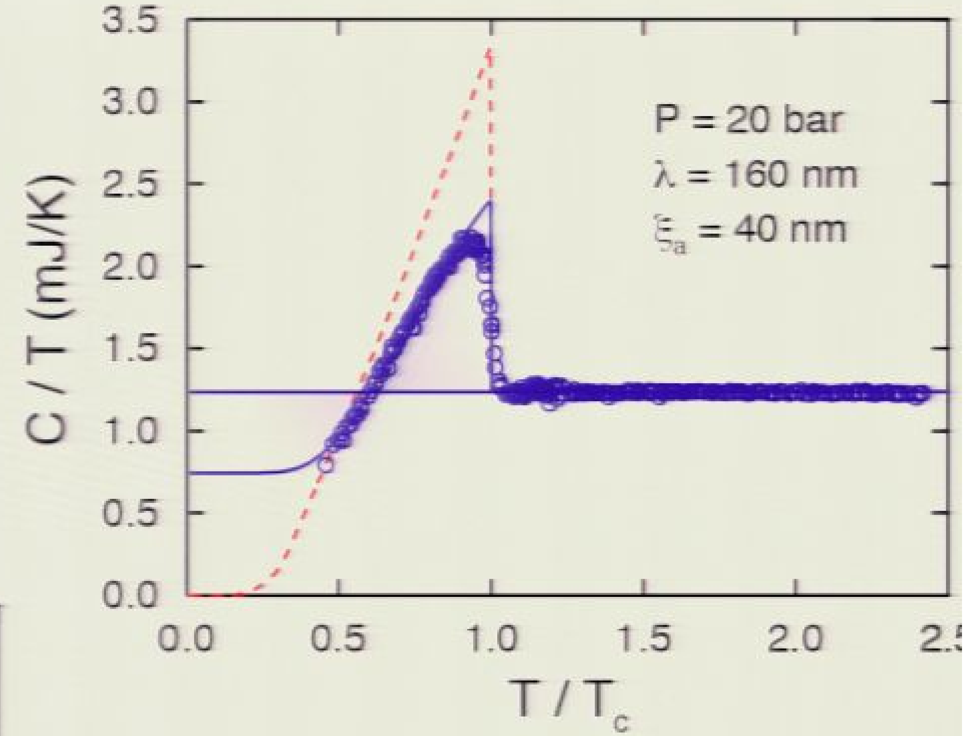
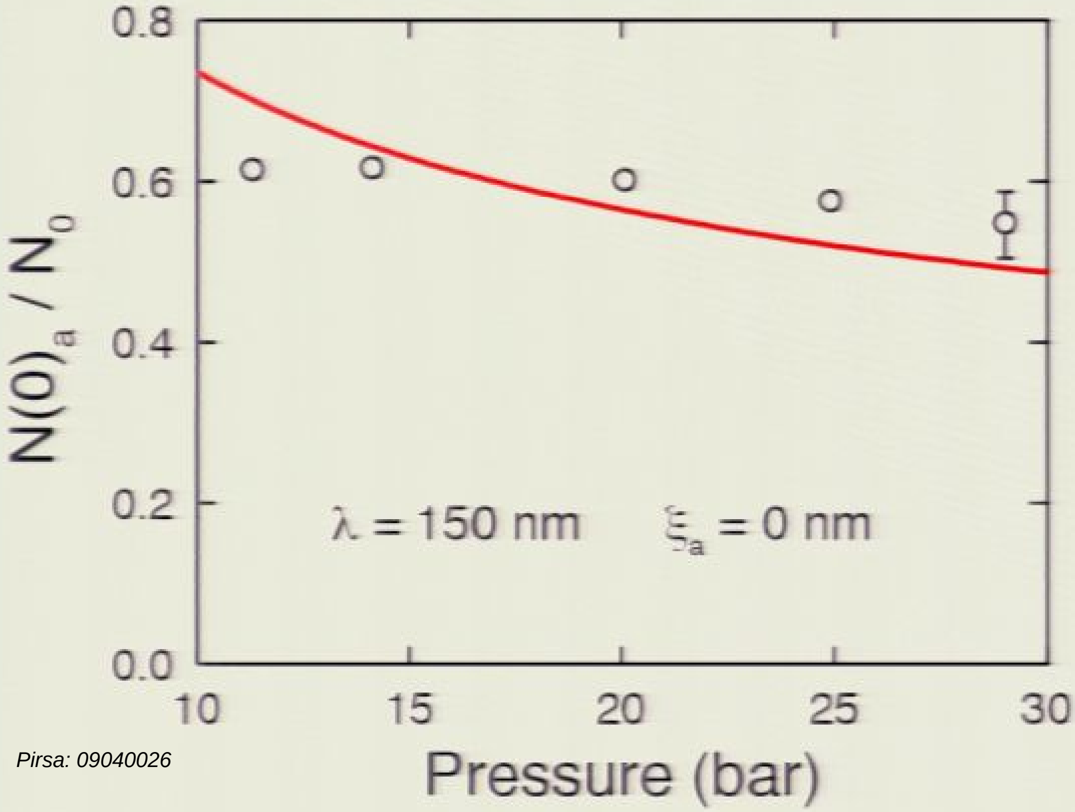




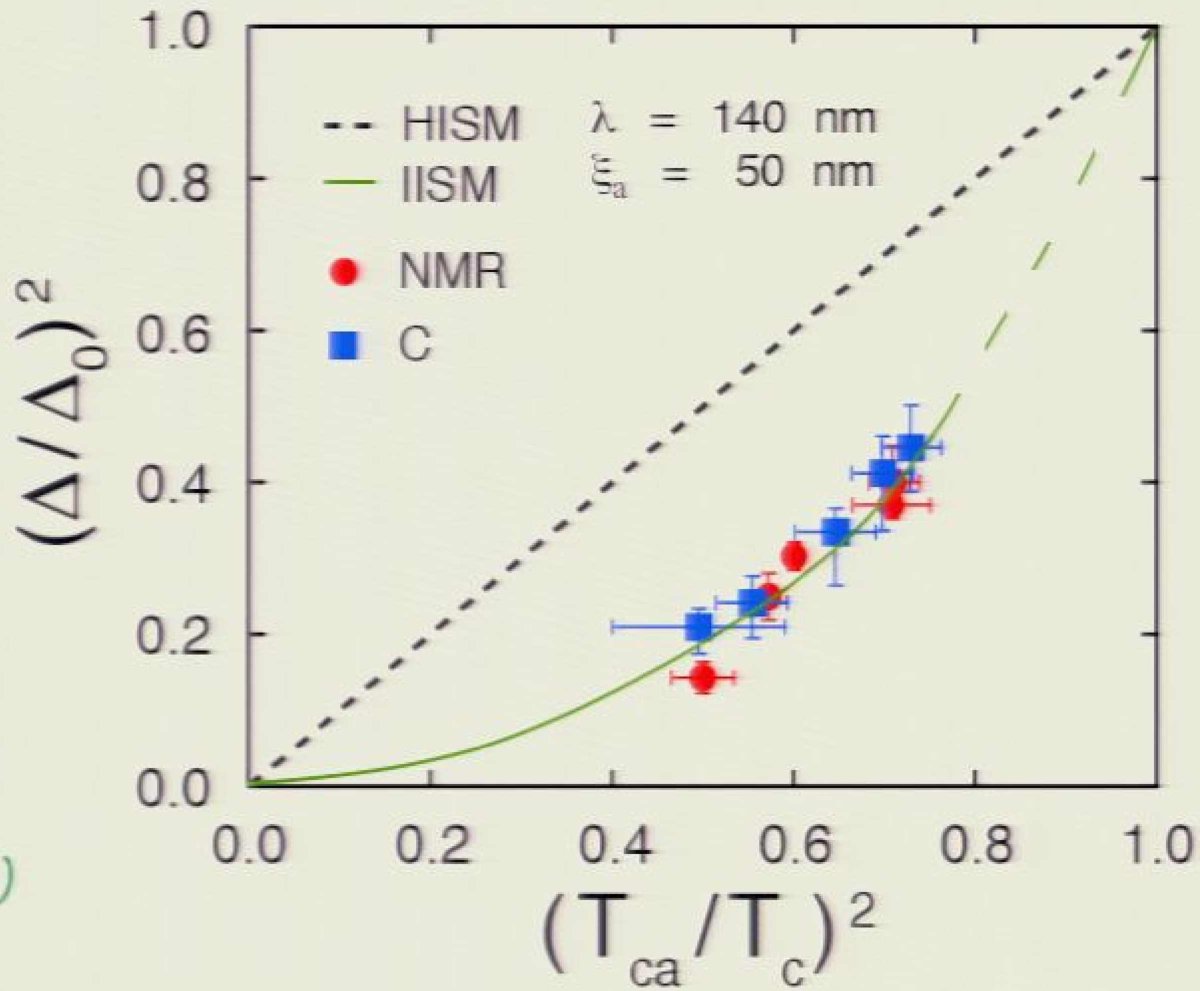
*Choi et al. PRL **93**, 145301 (2004);*

Also, attenuation of sound, $\alpha(T=0)$, H.C. Choi et al. PRL (2007)

Success of IISM:

$$\Delta\omega_{NMR} \propto \Delta^2$$

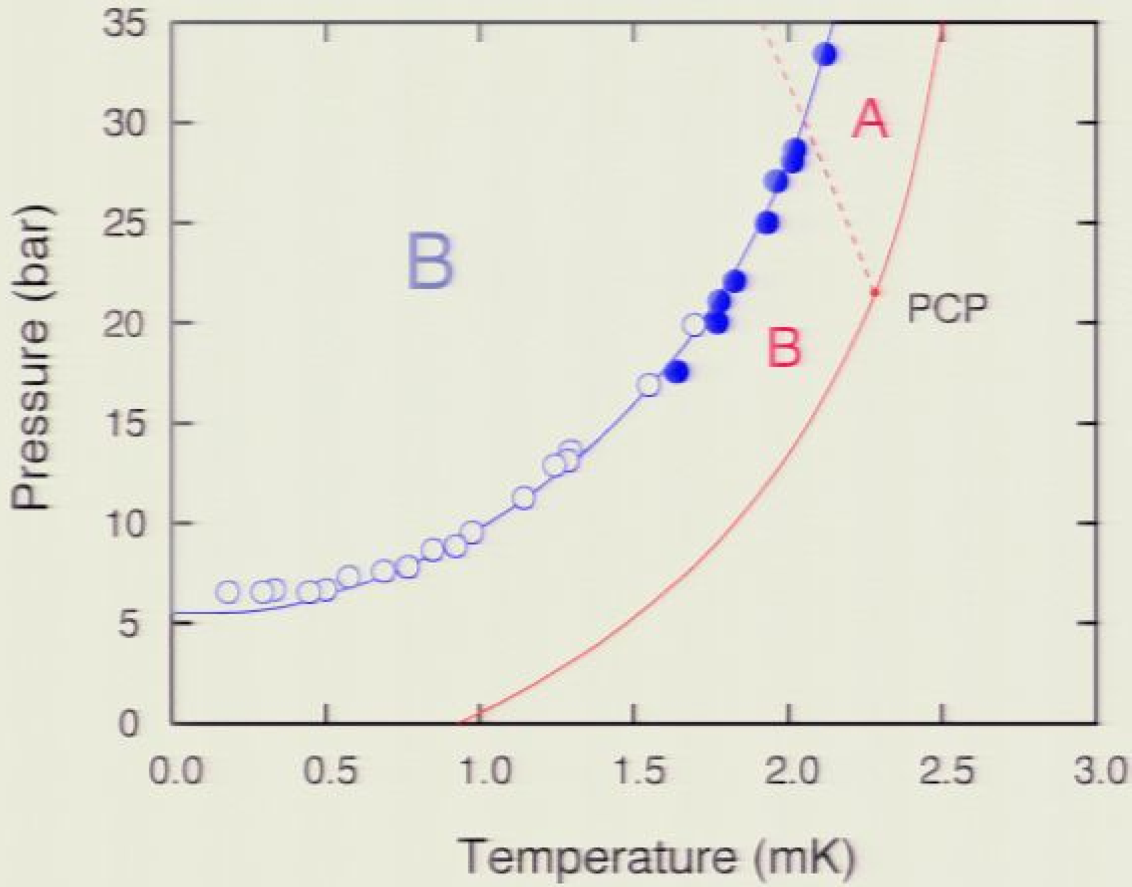
$$\frac{\Delta C}{C} \propto \Delta^2$$



Halperin et al.

*JPSJ **77** 111002 (2008)*

Superfluid ^{3}He in aerogel phase diagram

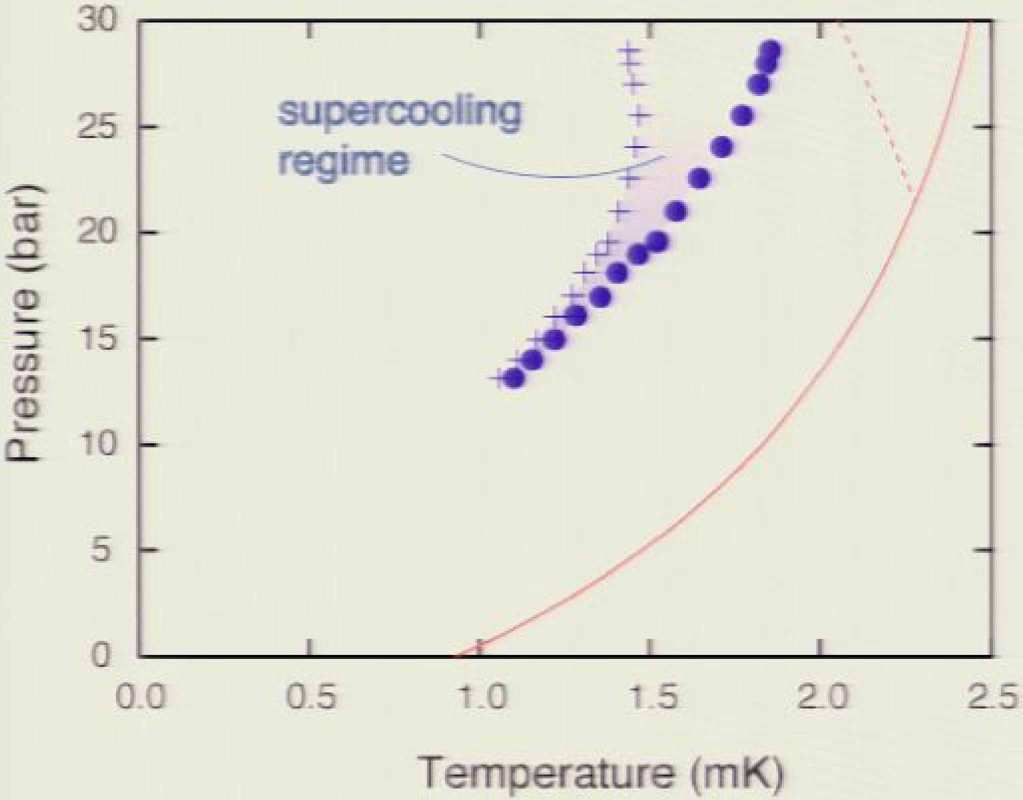


PCP ?

What happened to the polycritical point?

It's pushed up to high pressure.

Metastable phase:



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

The metastable A-like phase is an equal spin pairing state (ESP). But it's orbital structure is not known.

It could be the axial state like the A-phase (anisotropic) without long range orientational order, a Larkin-Imry-Ma state.

*Volovik JETP Lett **84**, 455 (2006).*

It could be a quasi-isotropic (robust) state with long range order

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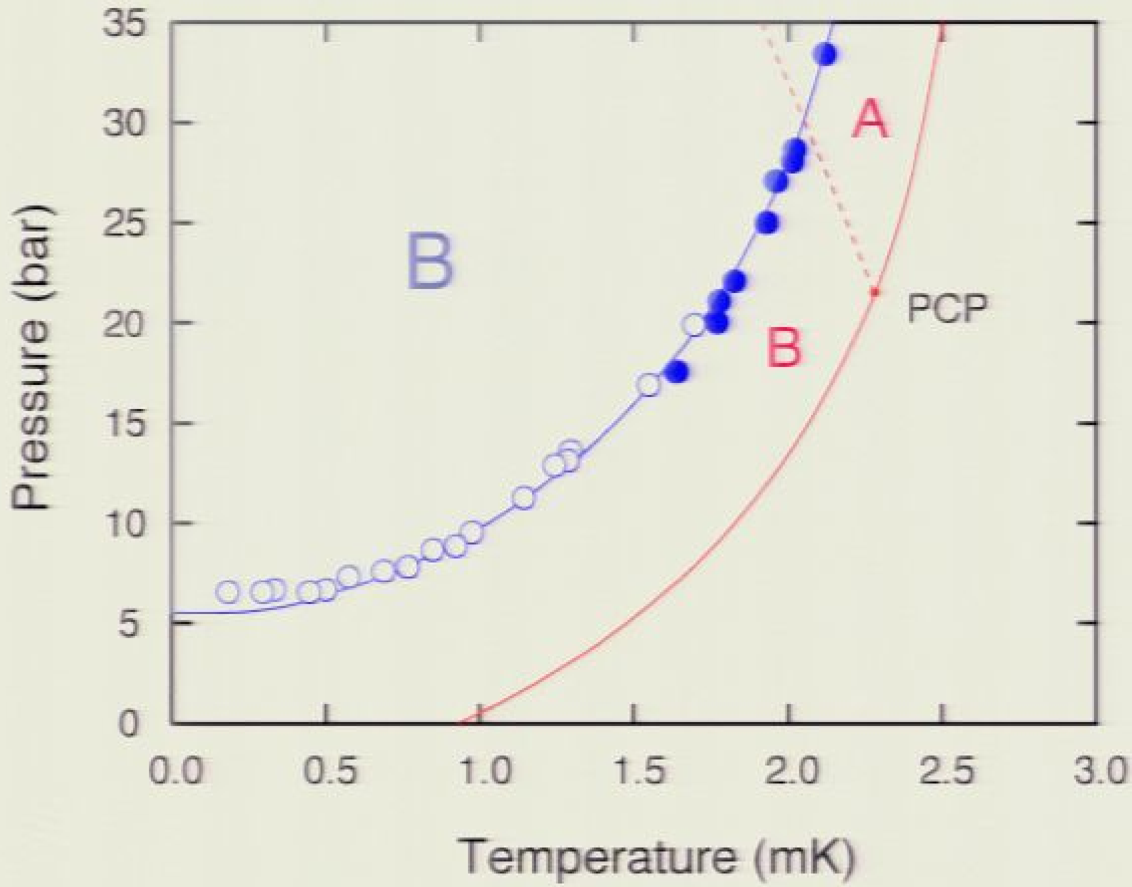

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4-corners 4/23/09

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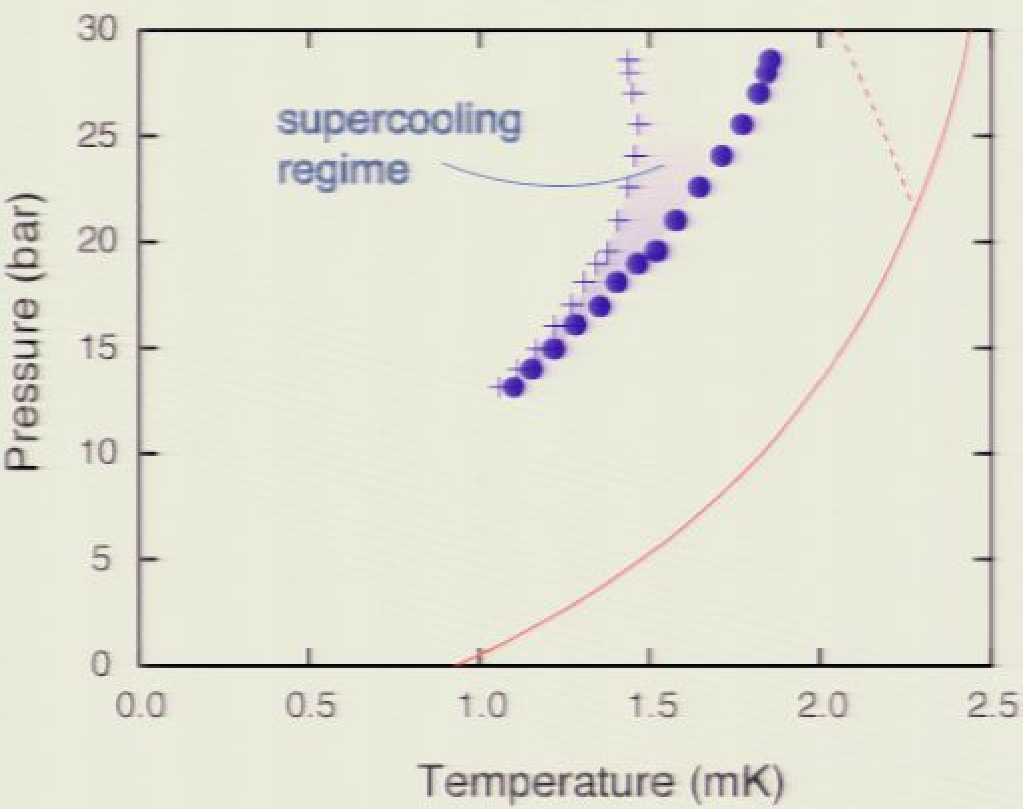

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Anisotropy:

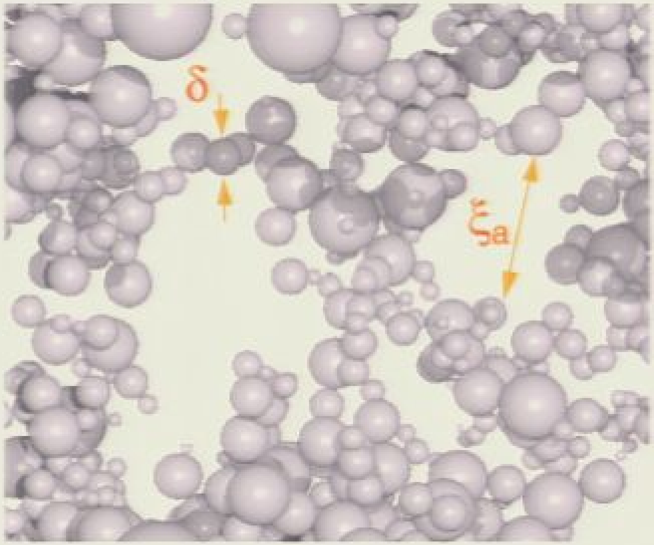
Anisotropic scattering favors anisotropic states (axial). Isotropic scattering favors isotropic phases: *Thuneberg et al. PRL **80**, 2861 (1998).*

The axial (LIM) state couples strongly to the anisotropic aerogel structure.

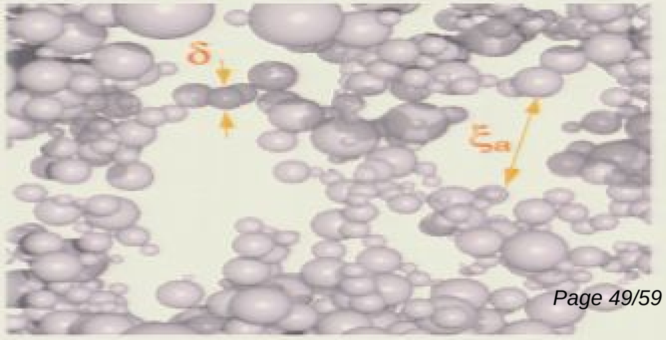
Can global anisotropy stabilize the A-like phase?

*Vicente et al. PRB **72**, 075301 (2005)*

local anisotropy



global anisotropy



Global Anisotropy- new phases :

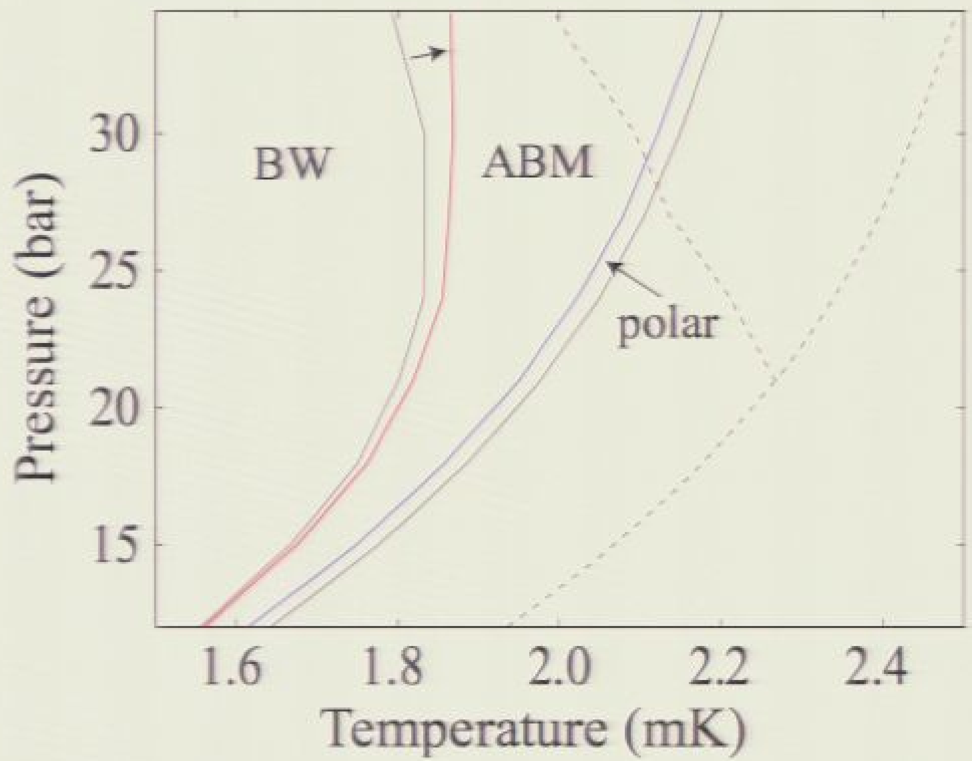
Aoyama and Ikeda PRB 76 104512 (2007).

Anisotropic scattering will stabilize (new) anisotropic states

Axial compression stabilizes the axial state

Radial compression stabilizes the polar state

radially compressed



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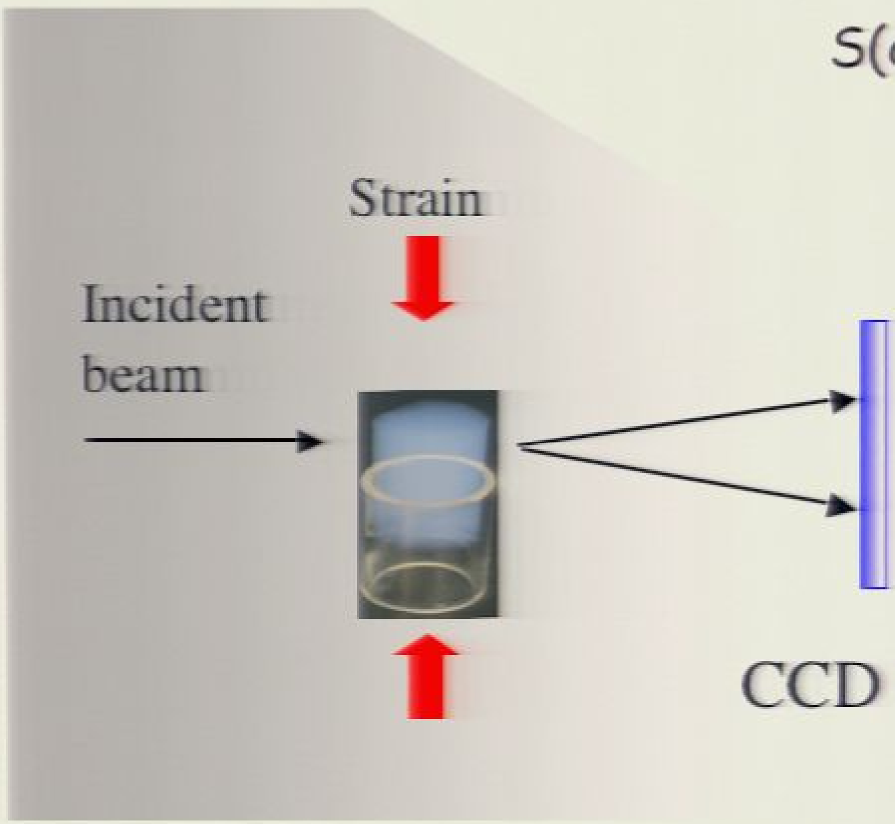
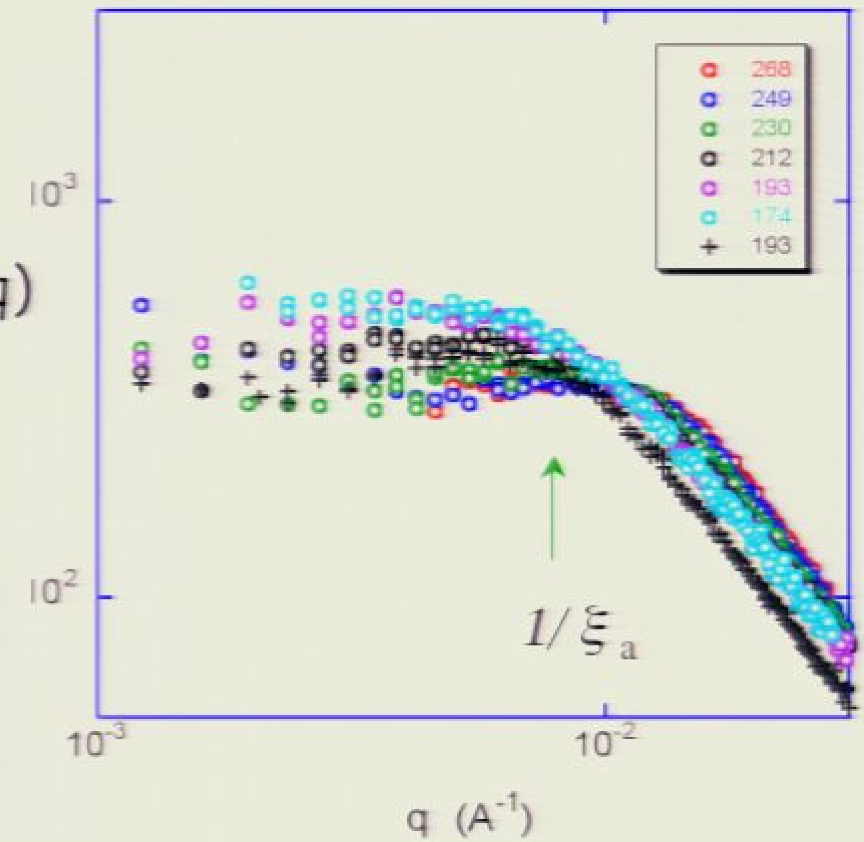
Controlled homogeneous anisotropic scattering:

SAXS: Advanced Photon Source (ANL)

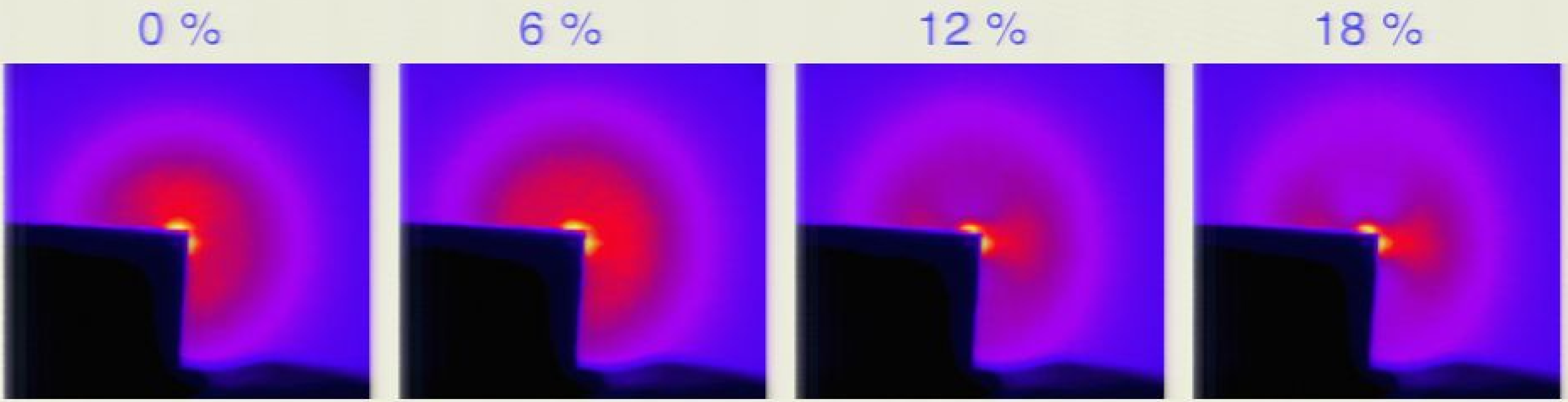




$$\frac{\lambda_{\perp}}{\lambda_{\|}} = \frac{\xi_{a\perp}}{\xi_{a\|}} \frac{2}{(1+\xi_{a\perp}/\xi_{a\|})}$$

Anisotropy (axial compression):

SAXS

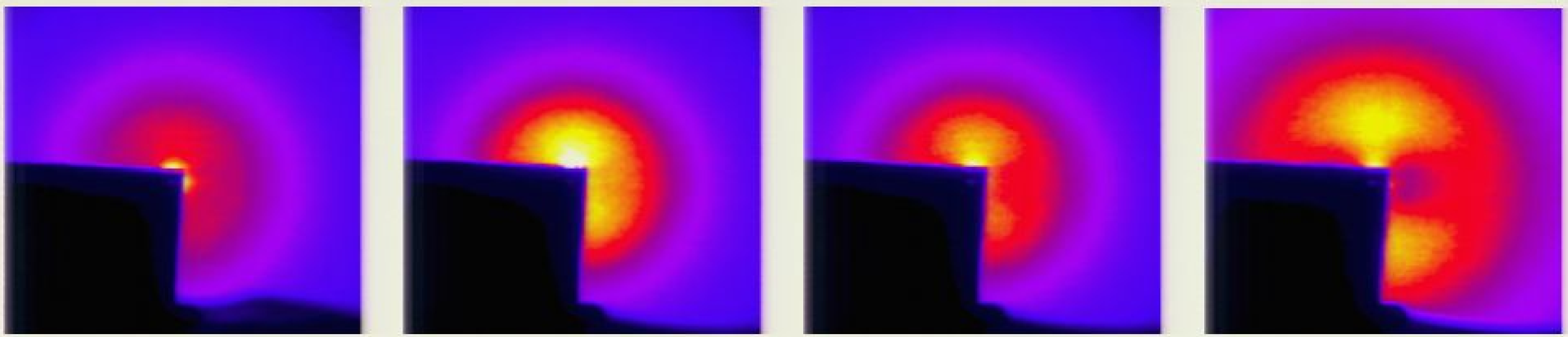


Pollanen et al. JNCS **354** 4668 (2008).

Anisotropy (radial compression):

SAXS

0 % 4.6 % 6.3 % 21 %

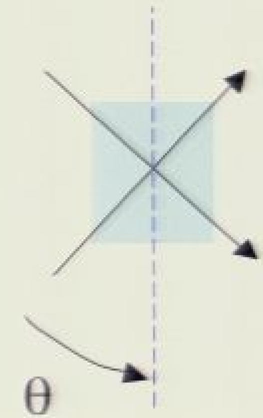


Pollanen et al. JNCS **354** 4668 (2008).

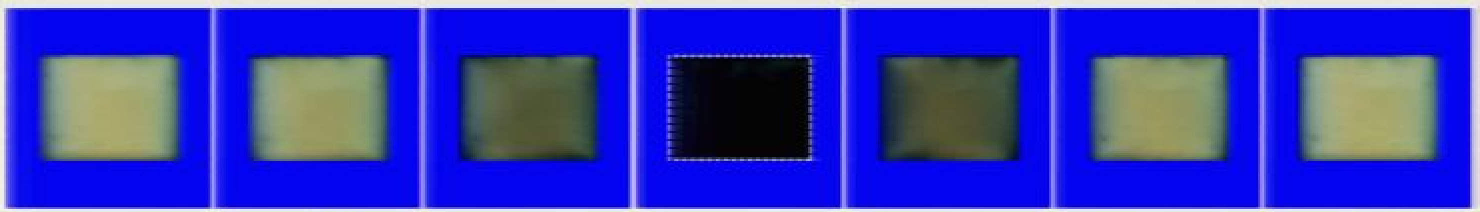
4-corners 4/23/09

Aerogel anisotropy characterization by optical birefringence:

crossed polarizer rotation

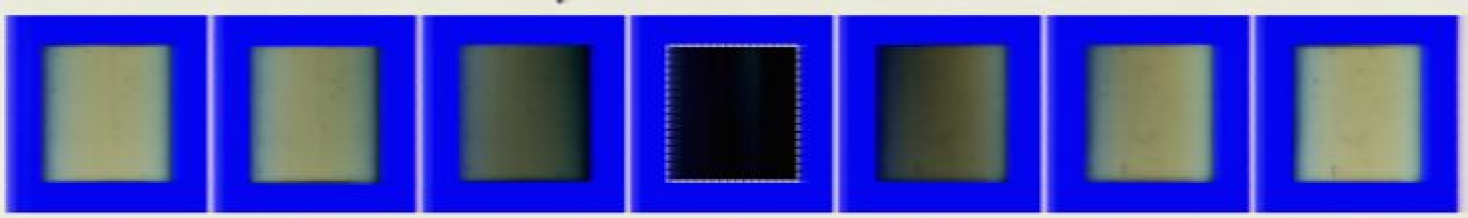


20.9% axial strain



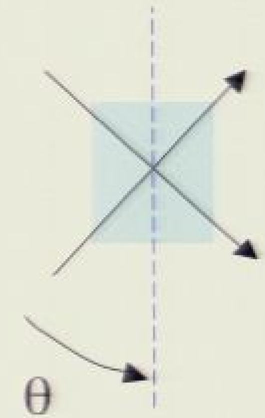
45° 60° 75° 90° 105° 120° 135°

12.7% radial compression



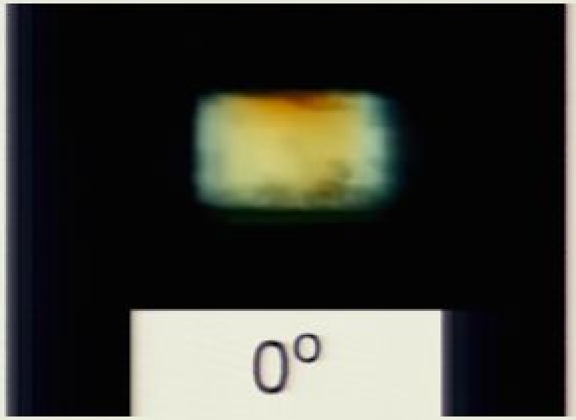
45° 60° 75° 90° 105° 120° 135°

Aerogel anisotropy characterization by optical birefringence:



Sample (N.Mulders) from
ISSP NMR experiment

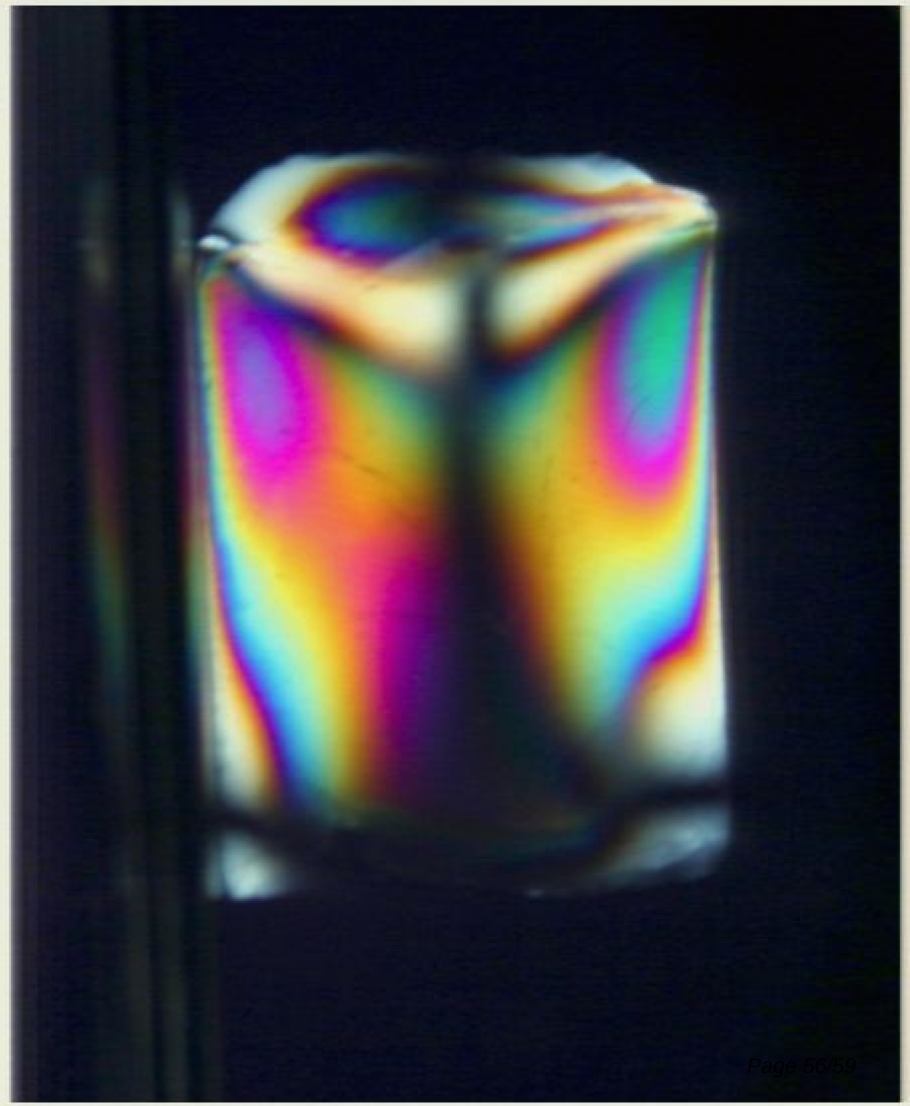
crossed polarizer at
45° to cylinder axis



Rotation about the
cylinder axis

Inhomogeneous aerogel:

....inhomogeneous
98% aerogel

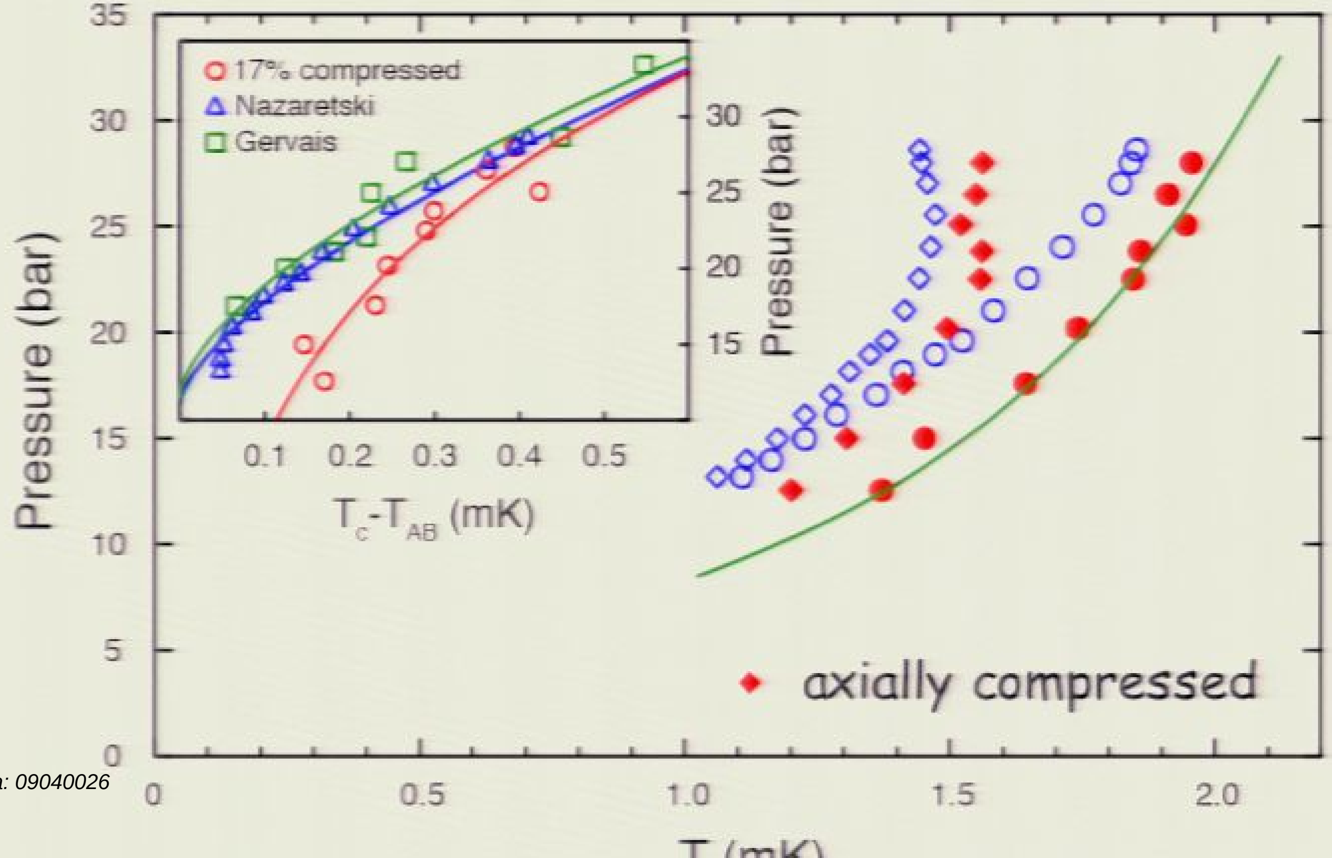


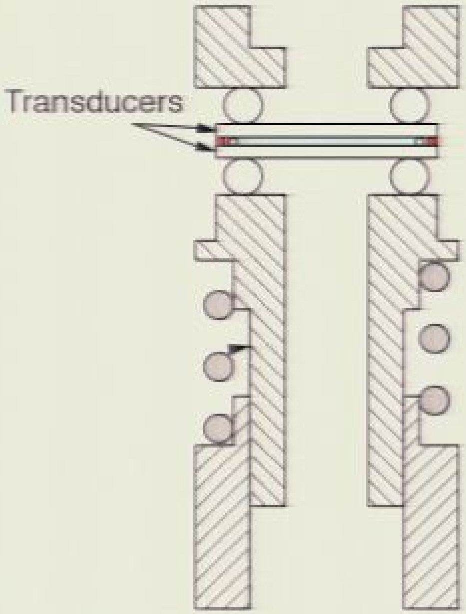
A-like phase stability: axial compression

Test of the Vicente *et al.* idea.....

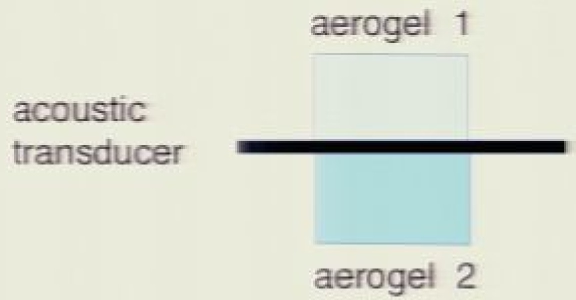
17% axial compression

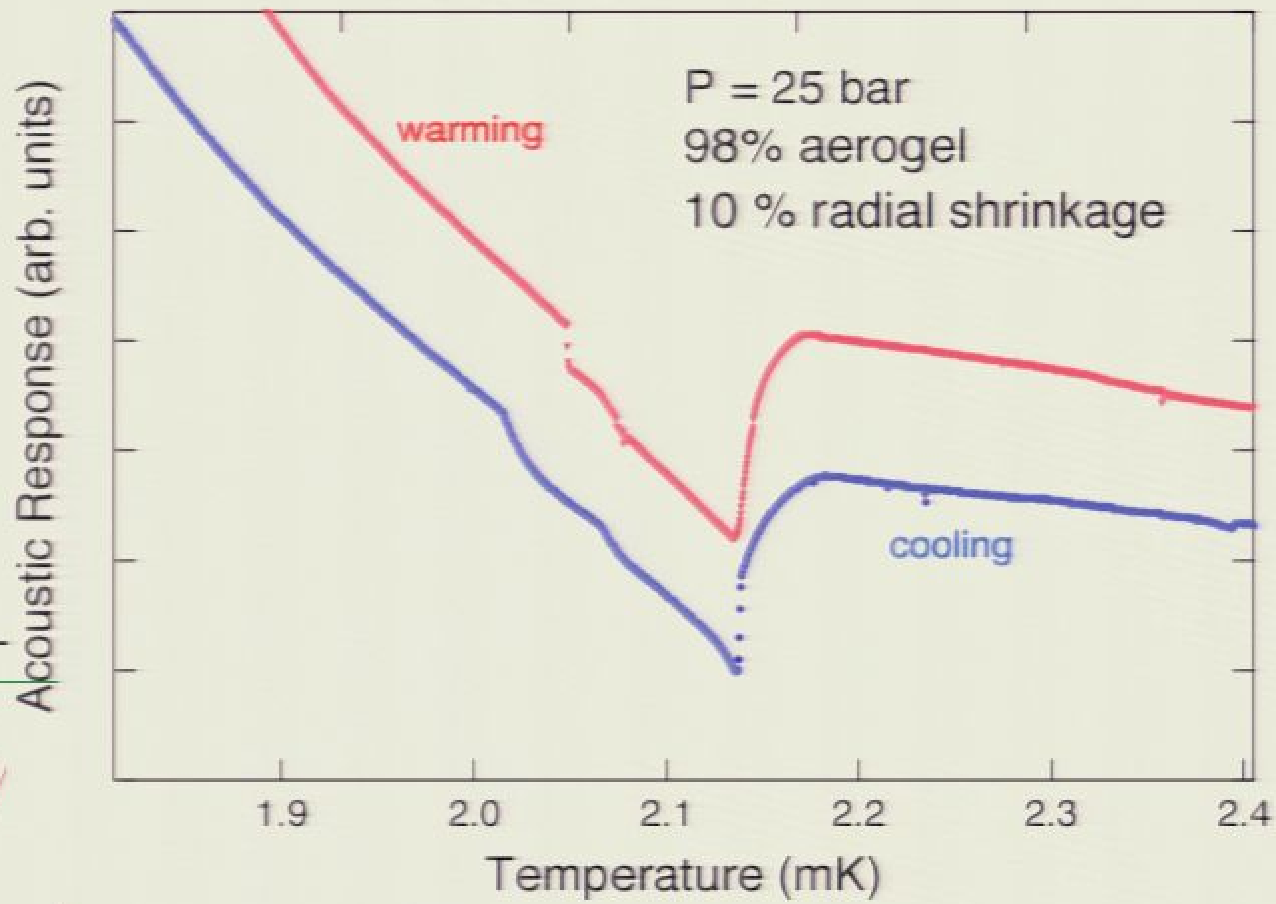
- *Davis et al.*
  *PRB **100**, 215304 (2008).*

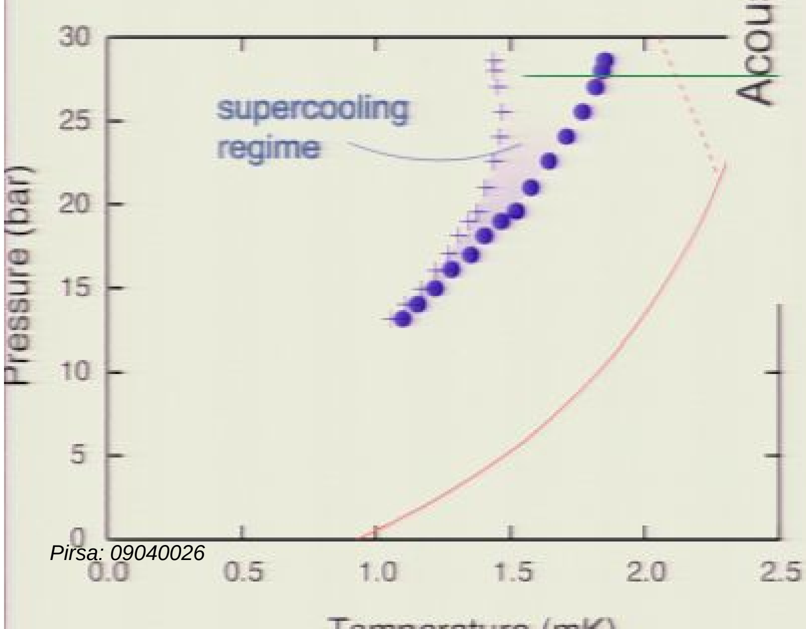




A-like phase stability: radial compression







Summary of ^{3}He in aerogel:

- *Correlated* impurity scattering models (IISM) work well
- Open question about the *A*-like phase orbital symmetry
- New phases?
- Possible control of phase stability and nucleation with global scattering anisotropy