``Enseigner la recherche en train de se faire''

COLLÈGE DE FRANCE
1530

Chaire de
Physique de la Matière Condensée

PETITS SYSTEMES THERMOELECTRIQUES: *CONDUCTEURS MESOSCOPIQUES ET GAZ D'ATOMES FROIDS*

Cycle « Thermoélectricité »
2012 - 2014

Antoine Georges

Séance du 18 décembre 2013
Cours 6

SUPERFLUIDS:

When entropy propagates as a wave

(« First » and « second » sound

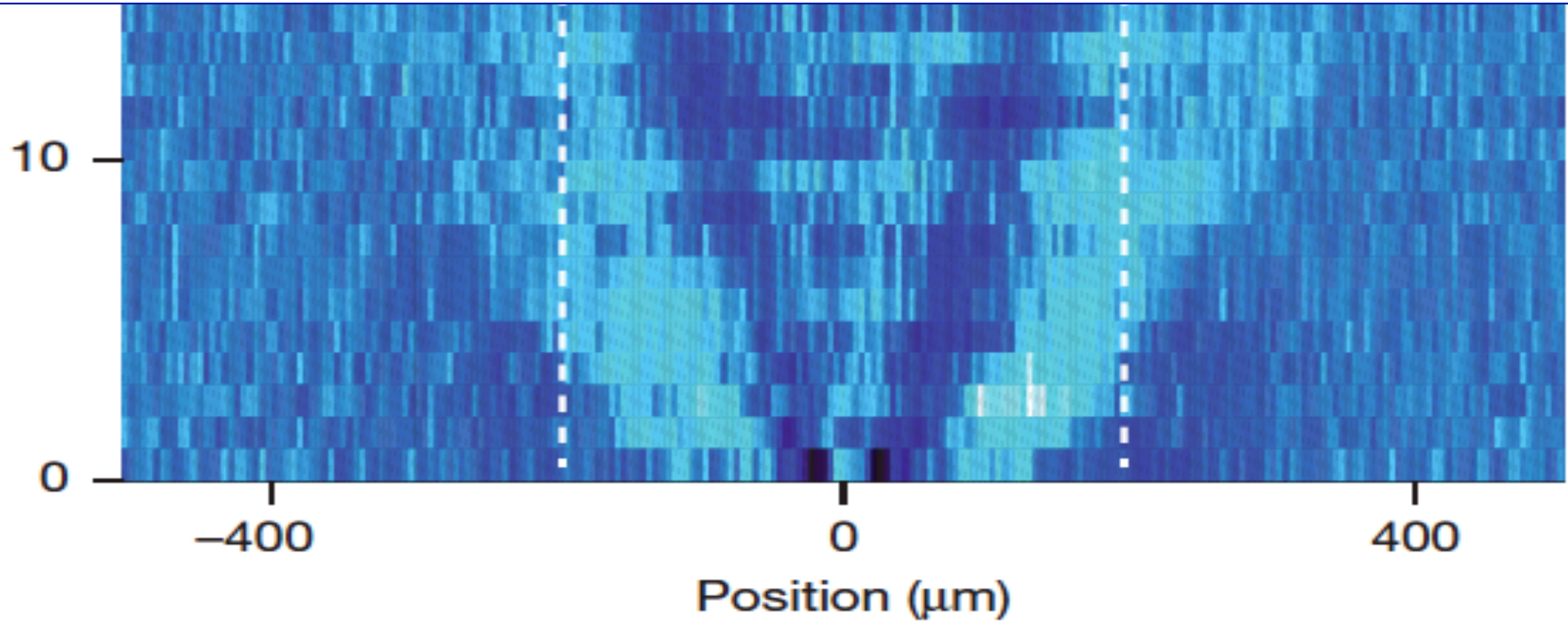
and their possible coupling)

Séminaire - 18/12/12013

Rudolf Grimm

(Institut für Experimental Physik, Universität Innsbruck)

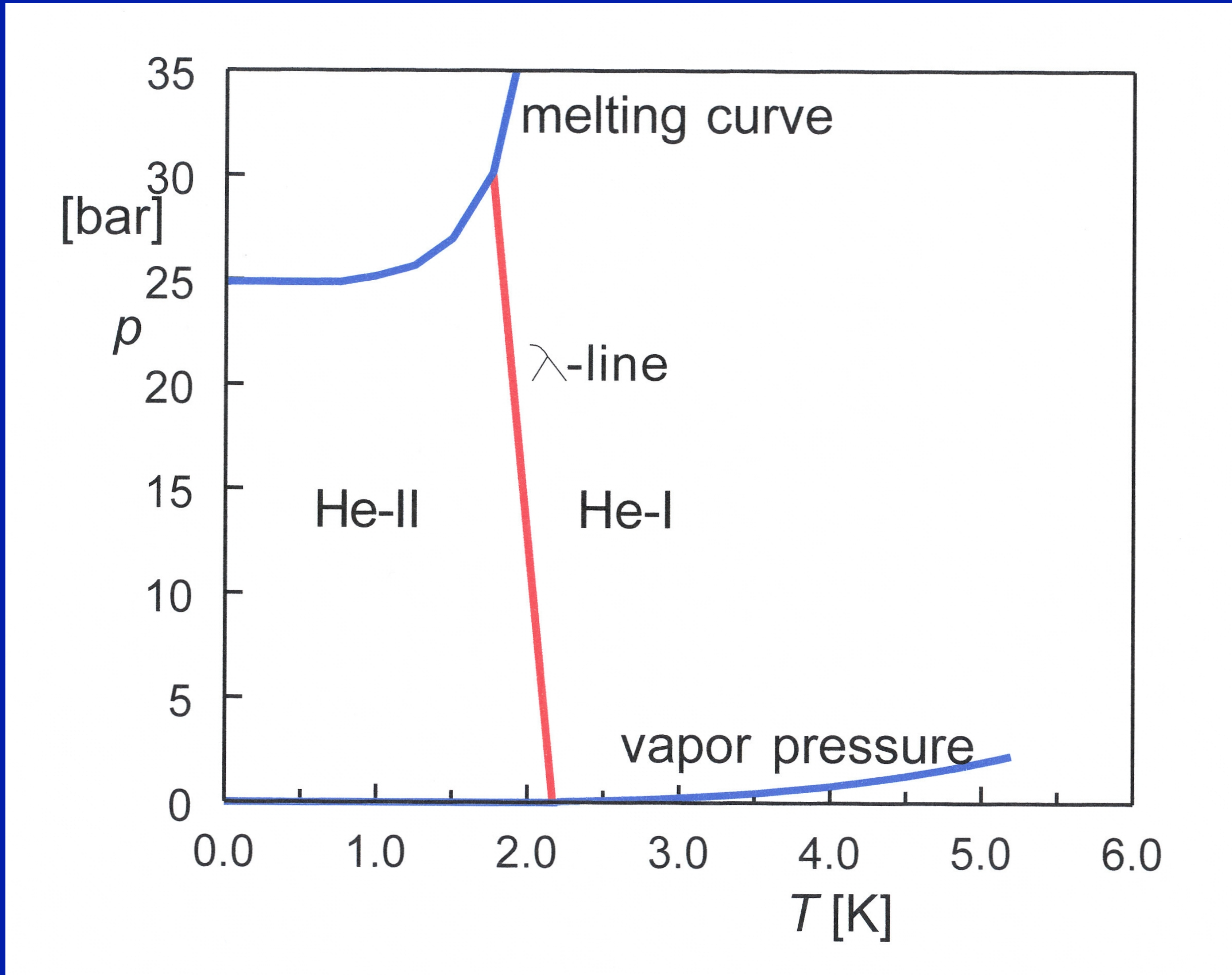
Observation of second sound and more recent developments in ultracold Fermi gases



SUPERFLUIDS

- For a long time, only known example: Helium 4 below 2.17 K (1937)
- Much later (1970's) superfluidity of the fermionic isotope Helium 3 (~2.5 <u>mK</u>)
- The discovery and study of Bose-Einstein condensation in ultra-cold atomic gases, and of superfluidity in two-component Fermi gases, <u>have rejuvenated the field since the mid-1990's</u>

Helium 4: Some reminders



The "lambda"-transition

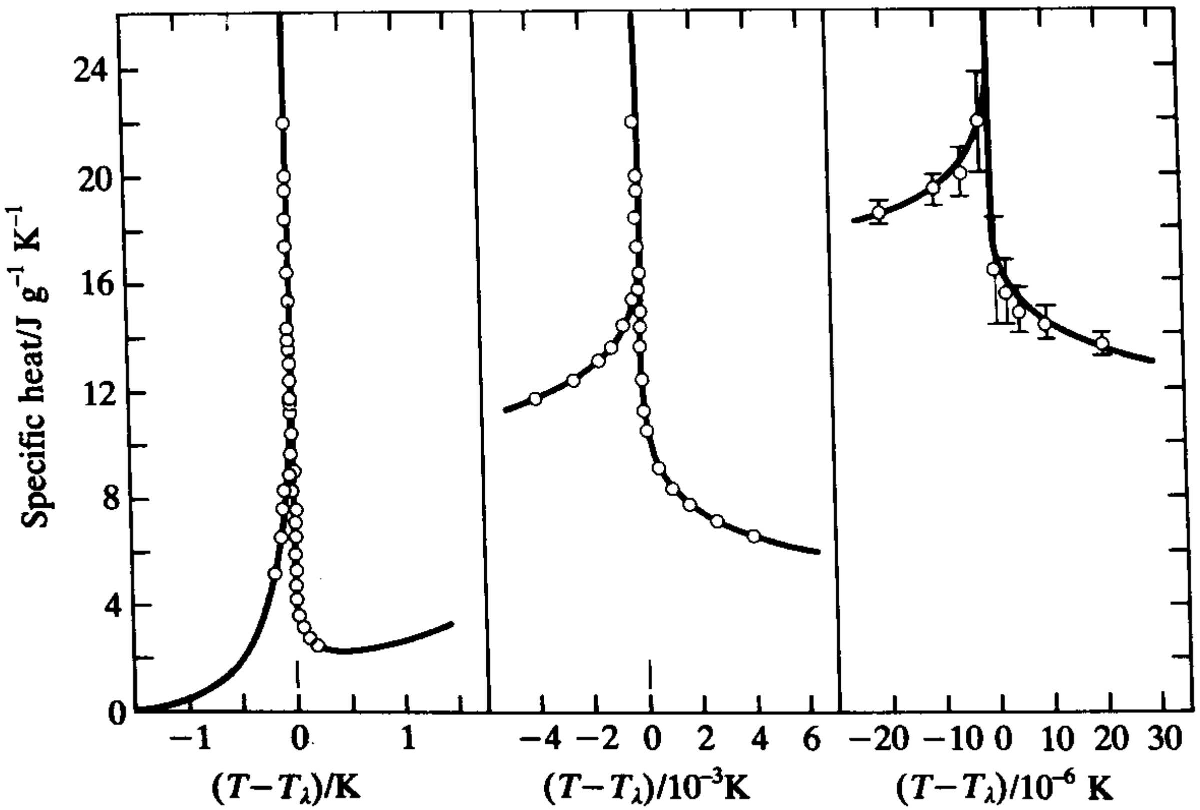


Fig. 15.3. The specific heat of liquid ^{4}He under the saturated vapour pressure as a function of $T - T_\lambda$. The width of the small vertical line just above the origin indicates the portion of the diagram shown expanded (in width) in the curve directly to the right (after Buckingham and Fairbank [193].)

The Fascinating History of the Discovery of Superfluidity

- *Scientific discovery as a collective process*
- See:
- Sébastien Balibar:
- J. Low Temp Phys 146, 441 (2007)
- La pomme et l'atome (Odile Jacob, 2005)
- Slides on website @ENS
- Also: A.Griffin, J.Phys. Cond. Mat. 21, 164220 (2009)

The experimental discovery of superfluidity ...1927-32
(slide: courtesy S.Balibar)

Several steps :

1927-32: W.H. Keesom, M. Wolfke and K. Clusius (Leiden): liquid He has two different states which they call « helium I » above 2.2K and « helium II » below 2.2K. A singularity in the specific heat at 2.2 K (the « lambda point »)

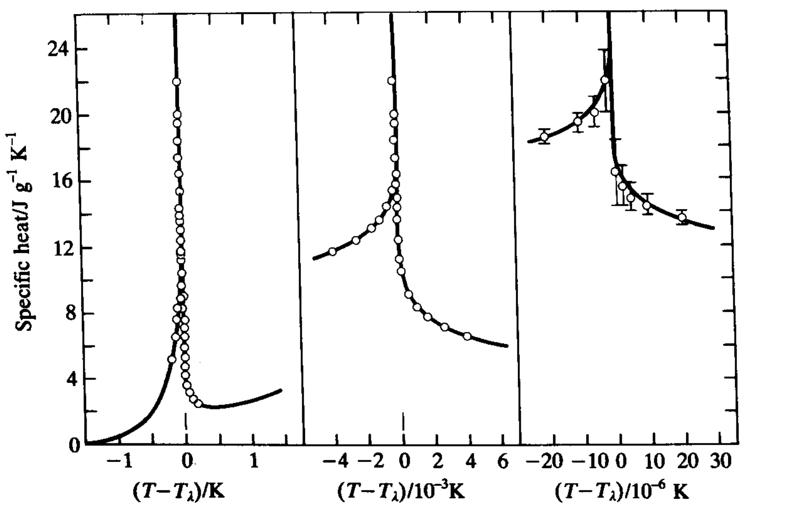
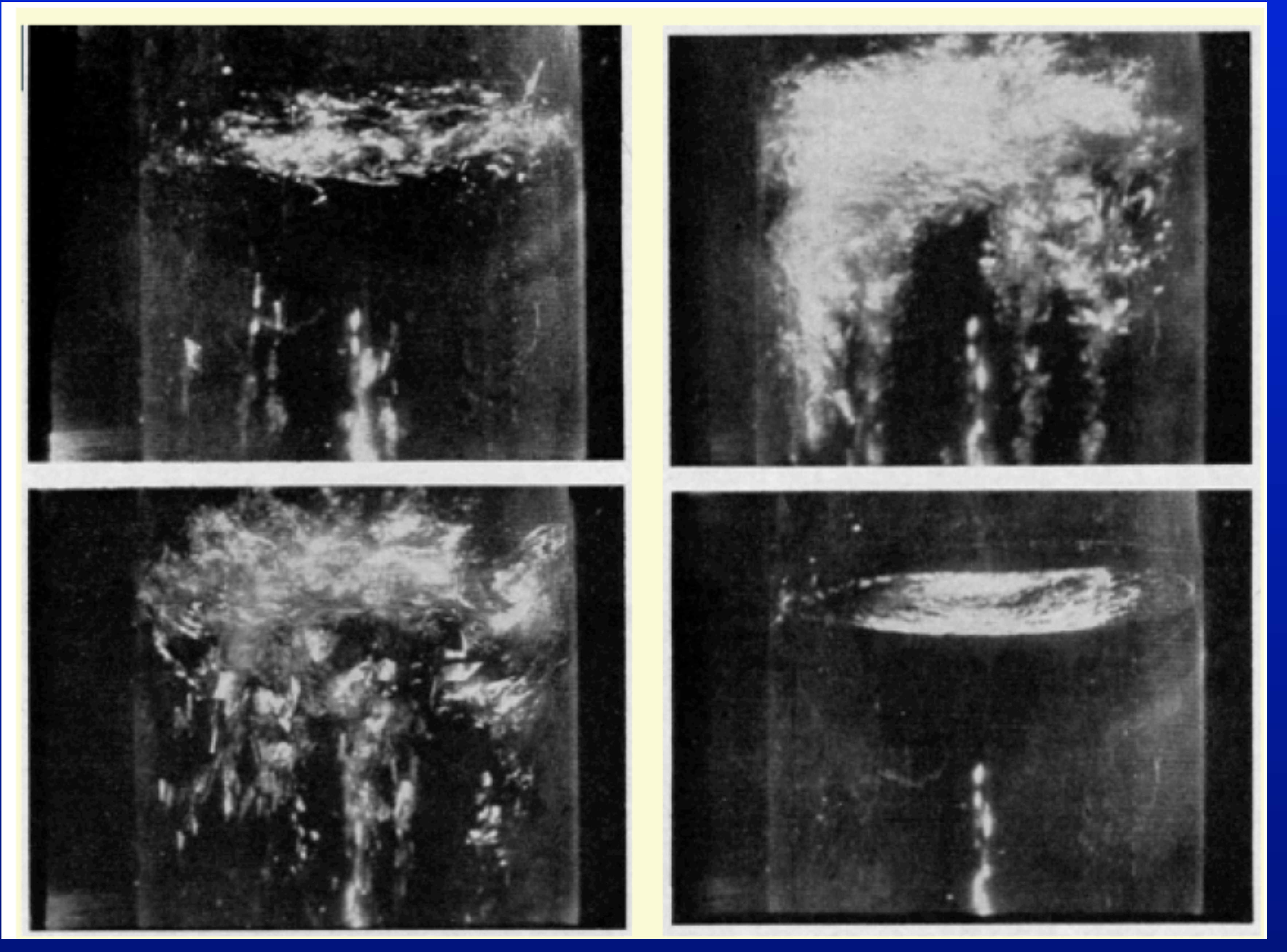


Fig. 15.3. The specific heat of liquid ^{4}He under the saturated vapour pressure as a function of $T - T_\lambda$. The width of the small vertical line just above the origin indicates the portion of the diagram shown expanded (in width) in the curve directly to the right (after Buckingham and Fairbank [193].)

1930: W.H. Keesom and J.N. van der Ende (Leiden): liquid He flows vey easily through narrow slits (superleaks)

1932: McLennan et al. (Toronto): liquid He stops boiling below 2.2K



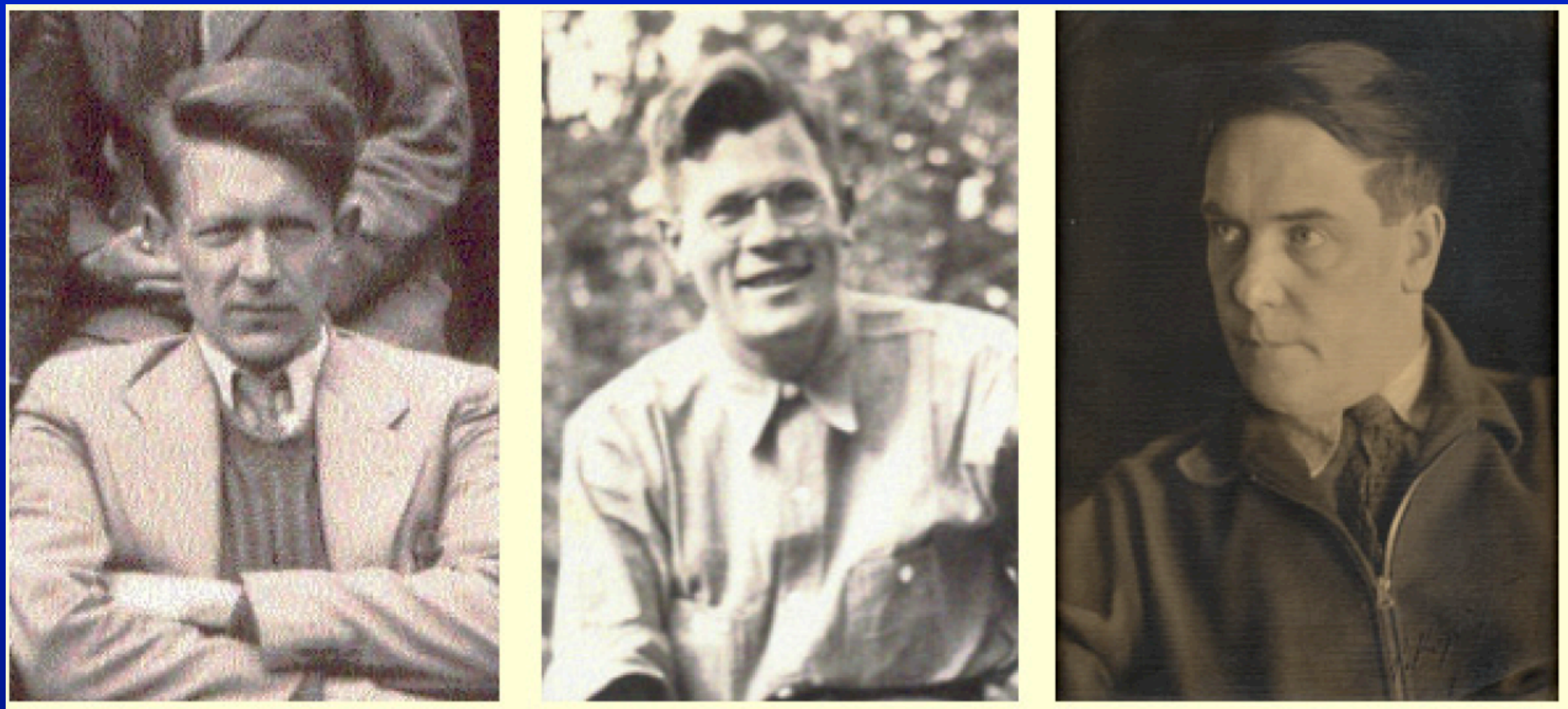
From Khalatnikov, Int.Sci.Tech, 1964

The experimental discovery of superfluidity ...1935-37
(slide: courtesy S.Balibar)

J.O. Wilhem, A.D. Misener and A.R. Clark (Toronto, 1935):
the viscosity of liquid He drops down below 2.2 K

B.V. Rollin (Oxford, 1935)
W.H. Keesom and A. Keesom (Leiden, 1936)
J.F. Allen R. Peierls and M.Z. Uddin (Cambridge, 1937) :
the thermal conductivity of liquid He increases below 2.2 K

December 1937: two articles side by side in Nature
(« THE DISCOVERY »)
P. Kapitza (Moscow)
J.F. Allen and A.D. Misener (Cambridge, UK)



Pictures from:
A.Griffin’s article (op. cit.)

1938: Annus Mirabilis, Annus Horribilis

- Dec 3, 1937: Letter by Kapitza sent to Nature
- Dec 22, 1937: Letter by Allen and Misener sent to Nature
- Nature 141, 243 (1938): Allen and Jones report the fountain effect (see lecture 5, Dec 10)
- Nature 141, 643 (1938): Fritz London proposes that superfluidity is related to BEC
- Nature 141, 913 (1938) and Comptes Rendus Académie des Sciences 207; 1035, 1186 (1938): Laszlo Tisza proposes 2-fluid model

Fritz London and Laszlo Tisza find shelter in Paris

(Institut Henri Poincaré and Collège de France)

Paul Langevin, Jean Perrin, Frédéric Joliot, Edmond Bauer take action to host scientists fleeing nazism, fascism and antisemitism

Finalement je tiens à remercier M. Paul Langevin qui a bien voulu m'accepter dans son laboratoire.

Je remercie vivement M. E. Bauer pour l'intérêt constant qu'il a porté au présent travail et pour ses nombreuses remarques critiques.

Je remercie MM. F. London et F. Simon pour les discussions fructueuses que j'ai eues avec eux.

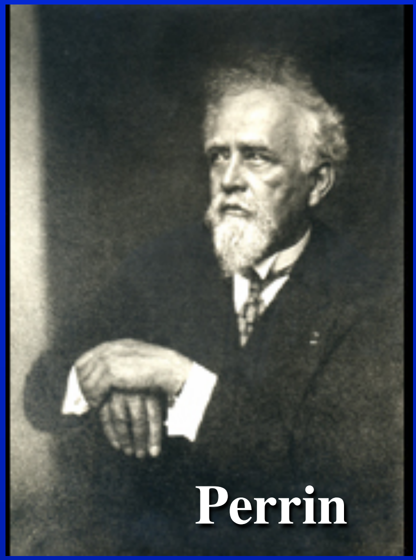
Je remercie le « Comité français pour l'accueuil et l'organisation du travail des savants étrangers » qui m'a aidé à poursuivre mes recherches à Paris.

Manuscrit reçu le 23 octobre 1939.

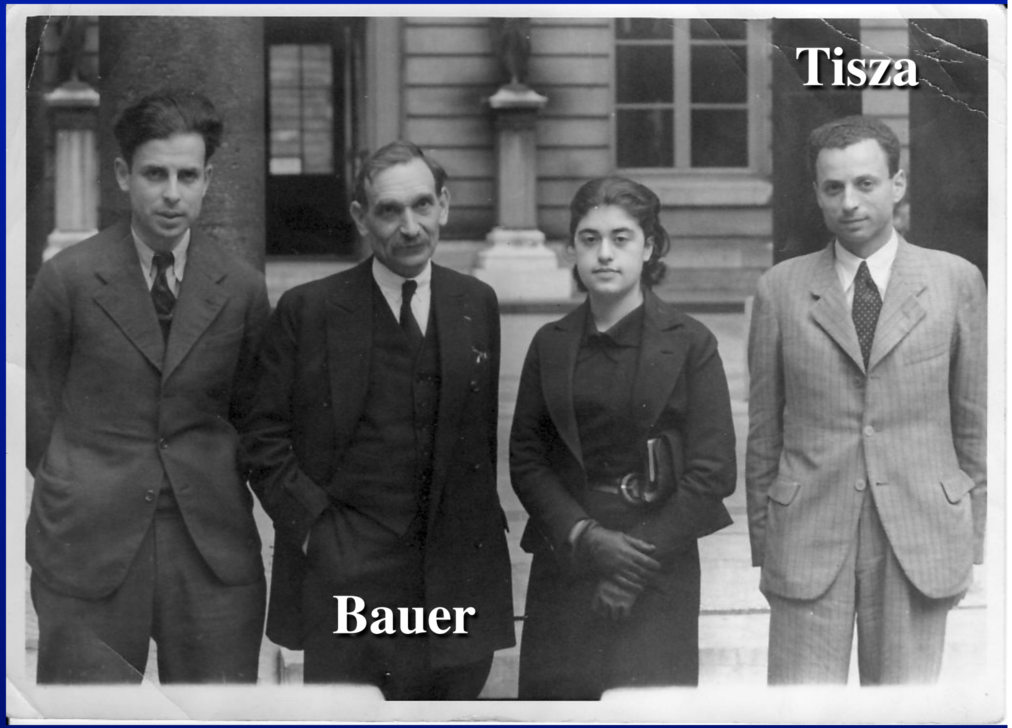
Laszlo Tisza, Journal de Physique et Le Radium, 1, 164 et 350 (1939)
In these two articles as well as Nature 141, 913 (1938), Laszlo Tisza sets the basis of the two-fluid description !

Tisza meets London in Paris

1937 : a group of French intellectuals (Paul Langevin, Jean Perrin (Nobel 1926, and secretary of Research in the Front Populaire), Frederic Joliot-Curie (Nobel 1935) and Edmond Bauer welcome foreign scientists escaping from antisemitism in Eastern Europe



This is where Tisza (Collège de France) meets Fritz London (Institut Henri Poincaré, 500 m distance) who had recommended him to Langevin

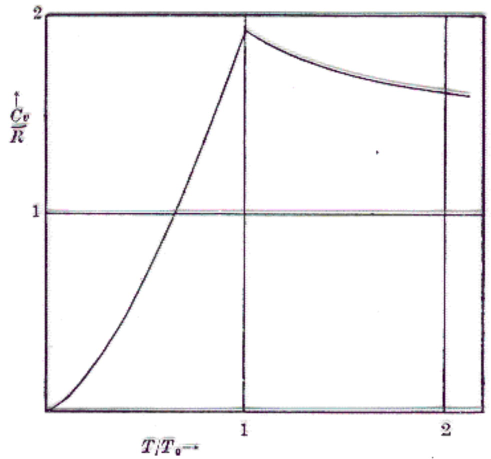


Slide: courtesy S.Balibar

5 mars 1938, Institut Henri Poincaré :

Fritz London:
Bose-Einstein Condensation may explain superfluidity !

Landau apparently always rejected this idea…
But it is now clearly validated
by the discoveries on cold gases



SPECIFIC HEAT OF AN IDEAL BOSE-EINSTEIN GAS.

(4) Though actually the λ-point of helium resembles rather a phase transition of second order, it seems difficult not to imagine a connexion with the condensation phenomenon of the Bose-Einstein statistics. The experimental values of the temperature of the λ-point (2·19°) and of its entropy ($\sim 0 \cdot 8\,R$) seem to be in favour of this conception. On the other hand, it is obvious that a model which is so far away from reality that it simplifies liquid helium to an ideal gas, cannot, for high temperatures, yield but the value $C_v = 3/2\,R$, and also for low temperatures the ideal Bose-Einstein gas must, of course, give too great a specific heat, since it does not account for

the effective mass m^* being of the order of magnitude of the mass of the atoms. But in the present case we are obliged to apply Bose-Einstein statistics instead of Fermi statistics.

(3) In his well-known papers, Einstein has already discussed a peculiar condensation phenomenon of the 'Bose-Einstein' gas; but in the course of time the degeneracy of the Bose-Einstein gas has rather got the reputation of having only a purely imaginary existence. Thus it is perhaps not generally known that this condensation phenomenon actually represents a discontinuity of the derivative of the specific heat (phase transition of third order). In the accompanying figure the specific heat (C_v) of an *ideal* Bose-Einstein gas is represented as a function of T/T_0 where

$$T_0 = \frac{h^2}{2\pi m^* k}\left(\frac{n}{2,615}\right)^{2/3}.$$

With m^* = the mass of a He atom and with the mol. volume $\frac{N_l}{n} = 27 \cdot 6$ cm.³ one obtains $T_0 = 3 \cdot 09°$. For

expected to furnish quantitative insight into the properties of liquid helium.

The conception here proposed might also throw a light on the peculiar transport phenomena observed with He II (enormous conductivity of heat[5], extremely small viscosity[6] and also the strange fountain phenomenon recently discovered by Allen and Jones[2]).

A detailed discussion of these questions will be published in the *Journal de Physique*.

F. LONDON.

Institut Henri Poincaré,
Paris.
March 5.

[1] Fröhlich, H., *Physica*, **4**, 639 (1937).
[2] Allen, J. F., and Jones, H., NATURE, **141**, 243 (1938).
[3] Simon, F., NATURE, **133**, 529 (1934).
[4] London, F., *Proc. Roy. Soc.*, A, **153**, 576 (1936).
[5] Rollin, *Physica*, **2**, 557 (1935); Keesom, W. H., and Keesom, H. P., *Physica*, **3**, 359 (1936); Allen, J. F., Peierls, R., and Zaki Uddin, M., NATURE, **140**, 62 (1937).
[6] Burton, E. F., NATURE, **135**, 265 (1935); Kapitza, P., NATURE, **141**, 74 (1938); Allen, J. F. and Misener, A. D., NATURE, **141**, 75 (1938).

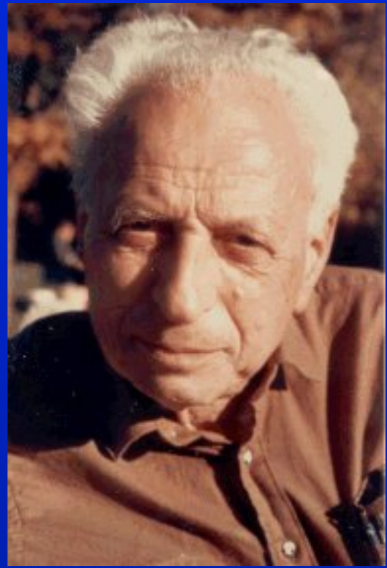
Slide: courtesy S.Balibar

Laszlo Tisza 1938 :
le « modèle à deux fluides »

A detailed discussion of the problem will be given in the *Journal de Physique*. I am greatly indebted to Dr. F. London for the opportunity of seeing his paper before publication.

L. Tisza.

Laboratoire de Physique Expérimentale,
Collège de France,
Paris. April 16.



Slide: courtesy S.Balibar

deux fluides: le condensat et les atomes non-condensés

le condensat est à T=0 , ne transporte pas d'entropie et ne peut participer à la dissipation (viscosité nulle)

les atomes non-condensés constituent un « fluide normal » qui transporte de l'entropie et peut échanger de l'énergie (viscosité non-nulle)

il existe deux champs de vitesse indépendants: v_s et v_n

la température détermine le rapport entre les les densités des deux fluides
la dissipation dépend de la géométrie de l'expérience

si le superfluide seul s'écoule (à travers un poreux), T diminue
un gradient de T produit un effet thermomécanique inverse, un écoulement du superfluide vers la région chaude (effet fontaine)

Walking together...

L. Tisza (ENS-Paris, June 14, 2001 + e-mail to SB Sept. 4, 2001):

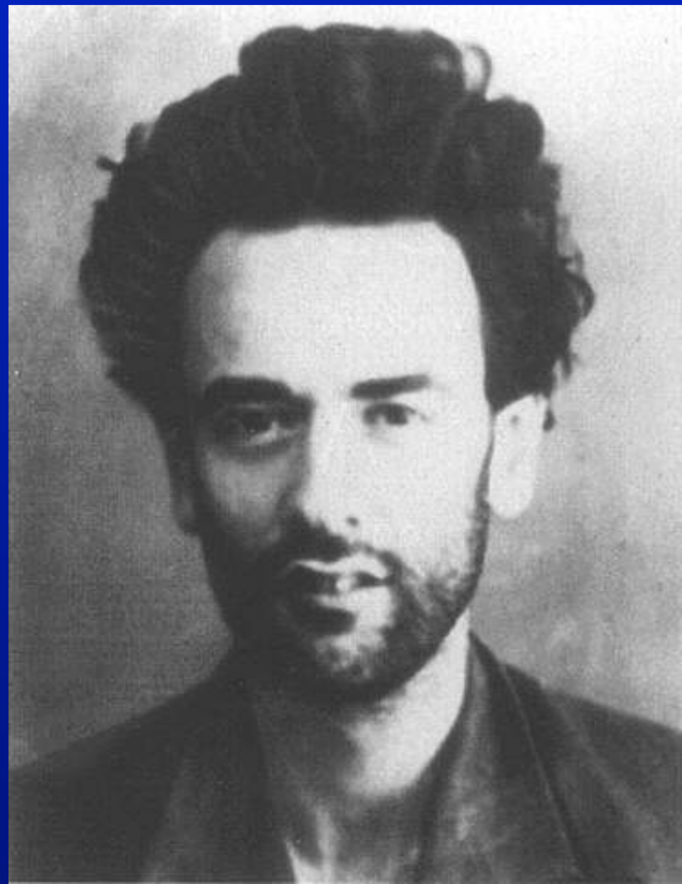
January 1938. On a Sunday we took a walk in the Bois de Verrières

The novelty of the effect became strikingly apparent in the Allen-Jones fountain effect that started London and myself on our speculative spree... He jumped on me the BEC. I was at once delighted...

There followed a sleepless night and by morning a rough outline of two fluid idea was in place. My idée fixe was that no value of viscosity however small could reconcile the capillary flow experiments with those on oscillating disks of Toronto...There had to be two fluids and to my mind this became evident in the fountain effect. One of the fluids had to be superfluid , the other viscous...

The next morning, I proudly reported my contribution to Fritz. He was outraged. I assigned to the two Bose Einstein components their own velcity field. Here London demurred...

Kapitza rescues Landau out of Stalin's jails
(where he spent ~ 1 year from mid-1938 till mid-1939…).
Landau builds his famous theory of superfluidity (1941)



Kapitza, Landau, ca. 1938

Bose-Einstein Condensation: Long-Range Order and Condensate Wave-Function

(Bogoliubov 1947→, Penrose and Onsager, 1951,1956)

One-body density matrix:

$$n_1(\mathbf{r},\mathbf{r}') \;\equiv\; \langle \Psi^\dagger(\mathbf{r})\Psi(\mathbf{r}')\rangle$$

(Off-Diagonal) Long-Range Order: As r and r’ are separated, n_1 tends to a non-zero value``<ψ>”

$$n(\mathbf{p}) \;=\; N_0\,\delta(\mathbf{p}) + \overline{n}(\mathbf{p})$$

Condensed fraction: $$n_0 \equiv \frac{N_0}{N}$$

Eigenfunctions of 1-body density matrix:

$$\hat{n}_1 \, |\phi_\alpha\rangle \; = \; n_\alpha |\phi_\alpha\rangle$$

$$\hat{\Psi}(\mathbf{r}) \; = \; \phi_0(\mathbf{r}) a_0 + \sum_{\alpha \neq 0} \phi_\alpha(\mathbf{r}) a_\alpha \simeq \Psi_0(\mathbf{r}) + \delta\hat{\Psi}$$

Wave-function of the condensate (macroscopic part of field operator):

$$\Psi_0(\mathbf{r}) = \sqrt{N_0}\, \phi_0(\mathbf{r})$$

Amplitude and Phase:

$$\Psi_0(\mathbf{r}) \; = \; |\Psi_0(\mathbf{r})| \, e^{i\Phi(\mathbf{r})}$$

Evolution in the Heisenberg representation→ chemical potential

$$\Psi_0(\mathbf{r}, t) \; = \; \Psi_0(\mathbf{r}, 0) \, e^{-i\mu t/\hbar}$$

The gradient and time-derivative of the phase

From the Heisenberg equation of motions, one can deduce a relation between the condensate wave-function in the frame where the fluid is at rest and the laboratory frame where the superfluid component has velocity v_s:

$$\Psi_{lab}(\mathbf{r},t) = |\Psi_0(\mathbf{r}-\mathbf{v}_s t)|\, e^{i\Phi(\mathbf{r},t)}$$

$$\Phi(\mathbf{r},t) = \frac{1}{\hbar}\left[m\,\mathbf{v}_s\cdot\mathbf{r} - \left(\frac{1}{2}mv_s^2+\mu\right)t\right]$$

Irrotational Flow
Φ: potential

$$\boxed{\mathbf{v}_s = \frac{\hbar}{m}\nabla\Phi \;\;,\;\; \hbar\frac{\partial\Phi}{\partial t} = -\mu - \frac{1}{2}mv_s^2}$$

First (~Josephson) relation also follows from superfluid current

$$\frac{\hbar}{m}\mathrm{Im}\Psi_0^*\nabla\Psi_0$$

The Two Sounds of Superfluids

SUR LA THÉORIE DES LIQUIDES QUANTIQUES. APPLICATION A L'HÉLIUM LIQUIDE [1]. II

Par L. TISZA.

Laboratoire de physique expérimentale du Collège de France.

Sommaire. — La théorie du liquide de Bose-Einstein est étendue aux cas où les deux « phases » (définies dans I) ont des vitesses différentes. En général, ces courants se compensent en ce qui concerne le flux de matière, mais ils sont toujours accompagnés d'un flux de chaleur (effet thermomécanique). Quant à la transition des atomes d'une phase à l'autre, elle comporte un échange de chaleur avec l'entourage. Ce mécanisme peut rendre compte de la supraconductibilité thermique observée dans l'He II. La théorie prévoit sous certaines conditions une vitesse de propagation des inégalités de température (ondes de température). La compensation du flux de matière n'est pas complète au voisinage des parois solides. Cet *effet thermomécanique proprement dit* permet de comprendre les phénomènes capillaires observés dans l'He II (le phénomène de la fontaine d'hélium, l'écoulement non hydrodynamique, etc.).

Laszlo Tisza, Journal de Physique et Le Radium, 1, 164 et 350 (1939)

5° Les différences de température à pression constante provoquent des courants opposés des deux phases, accompagnés d'un transport important de chaleur, mais se compensant en général quant au transport de matière. (Effet thermomécanique.) La théorie prévoit sous certaines conditions la propagation d'ondes de température. Une transition entre les deux phases n'a lieu en premier approximation qu'aux lieux d'échange de chaleur avec l'entourage.

The two-fluid model and its hydrodynamics
(Tisza 1938-39, Landau 1941)

Assumption: the motion of the fluid can be described as the coupled motion of two components: a superfluid component with velocity v_s and a `normal' component with velocity v_n

In the following: ρ_s and ρ_n designate respectively the mass density of the superfluid and normal component (ρ_s not to be confused with the condensed fraction n_0)

Total mass density and mass current (= momentum density)

$$\boxed{\rho = \rho_n + \rho_s \quad , \quad m\mathbf{j} = \rho_s \mathbf{v}_s + \rho_n \mathbf{v}_n}$$

Coupled equations for mass density and pressure

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(mj) = 0$$

Conservation of particle number

$$m\frac{\partial j}{\partial t} = -\nabla p$$

Equation of motion under pressure force

$$\boxed{\frac{\partial^2 \rho}{\partial t^2} = \nabla^2 p}$$

Together with equation of state p=p(ρ) this leads to usual sound-waves in a conventional fluid

Coupled equations for entropy and temperature

All irreversible processes and dissipation are assumed to be negligible here (viscosity of normal part = 0). We assume that the hydrodynamic regime applies, and linearize all equations.

$$\frac{\partial s}{\partial t} + \mathrm{div}(s_V \, v_n) = 0$$

Conservation of entropy (s_V: per unit volume)
The superfluid component does not carry any entropy !

Change variable to entropy per unit mass $s=s_V/\rho$ in the following.
After simple algebra:

$$\boxed{\frac{\partial s}{\partial t} + \frac{s\rho_s}{\rho}\,\mathrm{div}(v_n - v_s) = 0}$$

We see here that the RELATIVE velocity between superfluid and normal components appears.

Using the dynamical equations for the phase (above):

$$\mathbf{v}_s = \frac{\hbar}{m}\nabla\Phi \ , \ \hbar\frac{\partial\Phi}{\partial t} = -\mu - \frac{1}{2}mv_s^2$$

$$\rightarrow \ m\frac{\partial v_s}{\partial t} + m(v_s.\nabla)v_s \simeq m\frac{\partial v_s}{\partial t} = -\nabla\mu$$

Thermodynamics allows to relate the gradient of chemical potential to that of pressure and temperature:

$$\frac{\rho}{m}\nabla\mu = -s\nabla T + \nabla p$$

So that one obtains the second equation of motion as:

$$\boxed{\rho_n\frac{\partial}{\partial t}(v_n - v_s) + \rho s\nabla T = 0}$$

Temperature gradient controls the RELATIVE flow !

5° Les différences de température à pression constante provoquent des courants opposés des deux phases, accompagnés d'un transport important de chaleur, mais se compensant en général quant au transport de matière. (Effet thermomécanique.)

Finally, combining:

$$\frac{\partial s}{\partial t} + \frac{s\rho_s}{\rho}\,\mathrm{div}(v_n - v_s) = 0$$

$$\rho_n\,\frac{\partial}{\partial t}(v_n - v_s) + \rho s\,\nabla T = 0$$

One obtains the second evolution equation linking entropy (per unit mass) and temperature:

$$\boxed{\frac{\partial^2 s}{\partial t^2} = \frac{\rho_s}{\rho_n}\,s^2\,\nabla^2 T}$$

In summary:

$$\boxed{\frac{\partial^2\rho}{\partial t^2} = \nabla^2 p \;\;,\;\; \frac{\partial^2 s}{\partial t^2} = \frac{s^2\rho_s}{\rho_n}\nabla^2 T}$$

These two equations have to be supplemented by the thermodynamic equation of state, leading to wave-like solutions

A priori, $\rho = \rho(p,T) \;\;,\;\; s = s(p,T)$

So that the (pressure,temperature) and (density,entropy) variations are coupled: these waves are a priori not pure pressure and temperature waves.
In practice however, this depends on the superfluid we consider

Matrix of thermodynamic coefficients:

$$\begin{pmatrix} \delta\rho \\ \delta s \end{pmatrix} = \begin{pmatrix} \frac{\partial \rho}{\partial p}|_T & \frac{\partial \rho}{\partial T}|_p \\ \frac{\partial s}{\partial p}|_T & \frac{\partial s}{\partial T}|_p \end{pmatrix} \begin{pmatrix} \delta p \\ \delta T \end{pmatrix} \equiv M \begin{pmatrix} \delta p \\ \delta T \end{pmatrix}$$

Wave-like solutions:

Also define:

$$N \equiv \begin{pmatrix} 1 & 0 \\ 0 & \frac{s^2 \rho_s}{\rho_n} \end{pmatrix}$$

Look for wave-like solutions of the form $e^{i(kx-\omega t)} = e^{-i\omega(t-x/c)}$:

$$\det\left[c^2\, M - N\right] = 0$$

$$c^4 \left[\frac{\partial \rho}{\partial p}|_T \frac{\partial s}{\partial T}|_p - \frac{\partial s}{\partial p}|_T \frac{\partial \rho}{\partial T}|_p\right] - c^2 \left[\frac{\partial s}{\partial T}|_p + \frac{s^2 \rho_s}{\rho_n}\frac{\partial \rho}{\partial p}|_T\right] + \frac{s^2 \rho_s}{\rho_n} = 0$$

Using thermodynamic identities:

$$c^4 - \left[\frac{\partial p}{\partial \rho}|_s + \frac{kT\rho_s s^2}{\rho_n c_v}\right] c^2 + \frac{kT\rho_s s^2}{\rho_n c_v}\frac{\partial p}{\partial \rho}|_T = 0$$

More on the thermodynamics of the reservoirs: including the non-diagonal terms

$$\begin{pmatrix} \Delta N \\ \Delta S \end{pmatrix} = \underline{K} \begin{pmatrix} \Delta \mu \\ \Delta T \end{pmatrix} = \begin{pmatrix} \kappa & \kappa\alpha_r \\ \kappa\alpha_r & C_\mu / T \end{pmatrix} \begin{pmatrix} \Delta \mu \\ \Delta T \end{pmatrix}$$

$$K_{11} \equiv \kappa = \frac{\partial N}{\partial \mu}\Big|_T = -\frac{\partial^2 \Omega}{\partial \mu^2}$$

$$K_{12} = K_{21} \equiv \alpha_r \kappa = \frac{\partial N}{\partial T}\Big|_\mu = -\frac{\partial^2 \Omega}{\partial \mu \partial T} = \frac{\partial S}{\partial \mu}\Big|_T$$

$$K_{22} \equiv \frac{C_\mu}{T} = \frac{\partial S}{\partial T}\Big|_\mu = -\frac{\partial^2 \Omega}{\partial T^2}$$

Grand-potential: $\Omega \equiv -k_B T \ln Z_{gc}\ , \quad S = -\frac{\partial \Omega}{\partial T}\Big|_\mu\ , \quad N = -\frac{\partial \Omega}{\partial \mu}\Big|_T$

(Almost-) uncoupled case: Helium

dilatation coefficient $\frac{\partial s}{\partial p}|_T \simeq 0$:

$$\left[c^2 \frac{\partial \rho}{\partial p}|_T - 1\right] \left[c^2 \frac{\partial s}{\partial T}|_p - \frac{s^2 \rho_s}{\rho_n}\right] = 0$$

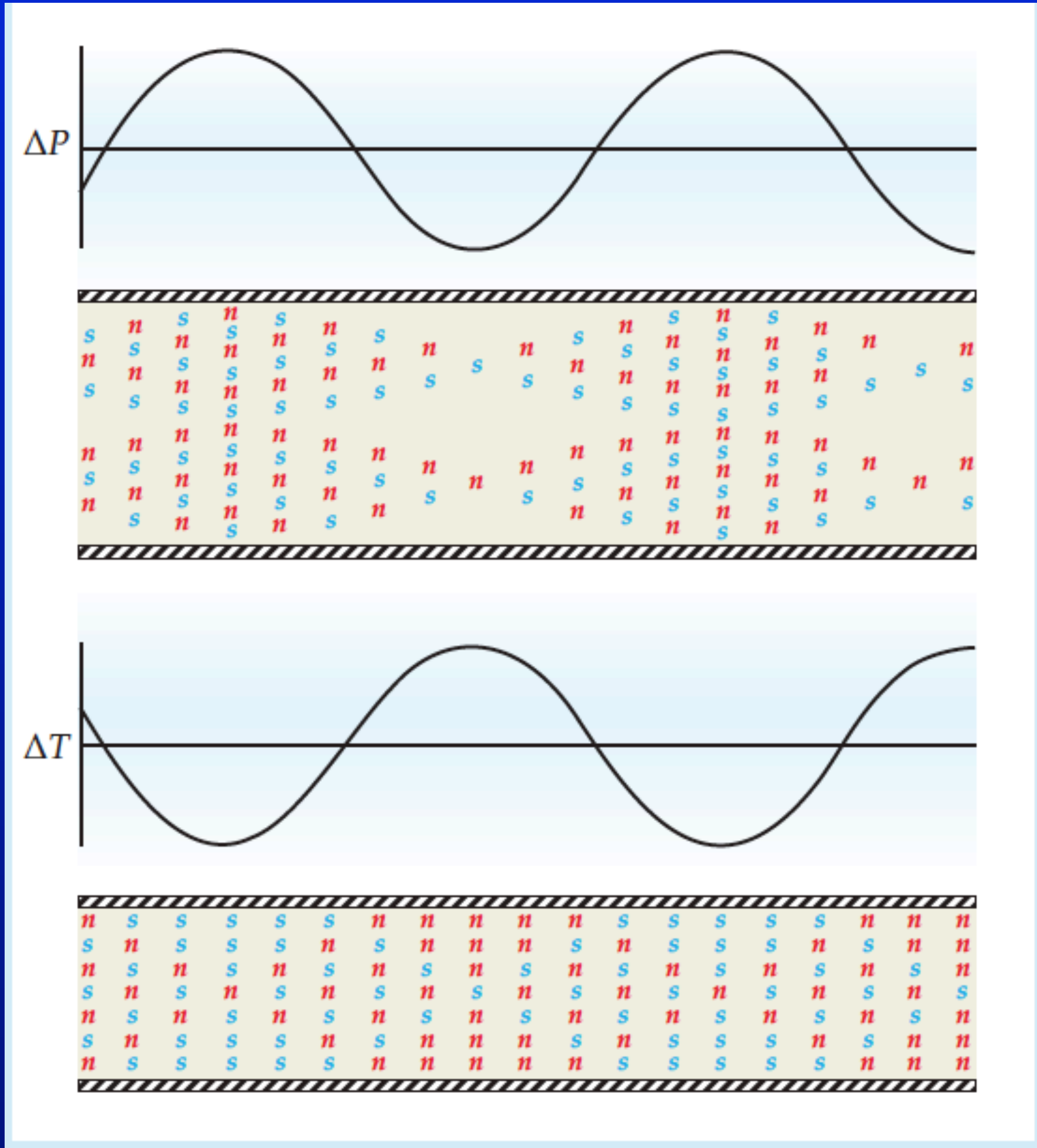
$$c_1^2 = \frac{\partial p}{\partial \rho}|_T \simeq \frac{\partial p}{\partial \rho}|_s \propto \frac{1}{\kappa} \quad , \quad \boxed{c_2^2 = \frac{s^2 \rho_s}{\rho_n} \frac{T}{c_p}}$$

Contains superfluid fraction !

In this case:

- \`First sound': conventional pressure/density wave
- Second sound: pure temperature/entropy wave

Relative motion (v_n-v_s) of supefluid vs. normal component, out of phase



Donnelly, Physics Today, 10/2009

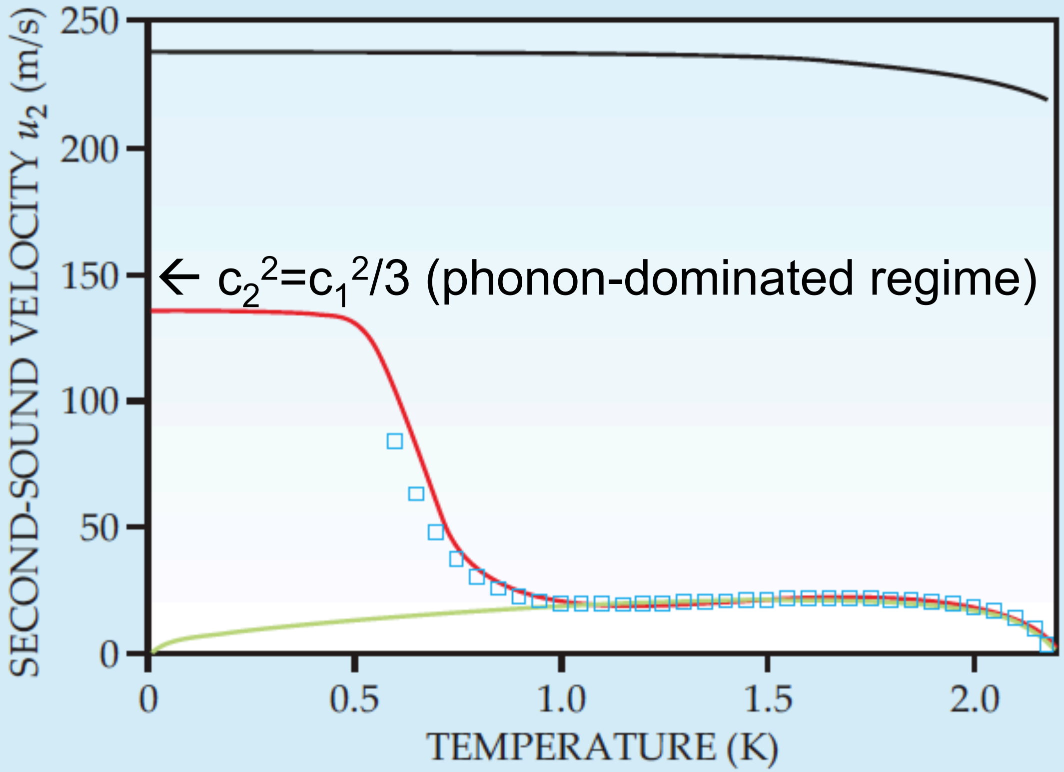


Figure 2. The velocity of second sound as computed by Evgeny Lifshitz (red curve) and by Laszlo Tisza (green curve); for comparison, the upper, black curve shows the velocity of first sound. The blue points are today's accepted values of second-sound velocity. Box 2 describes why Tisza's formula did not work.

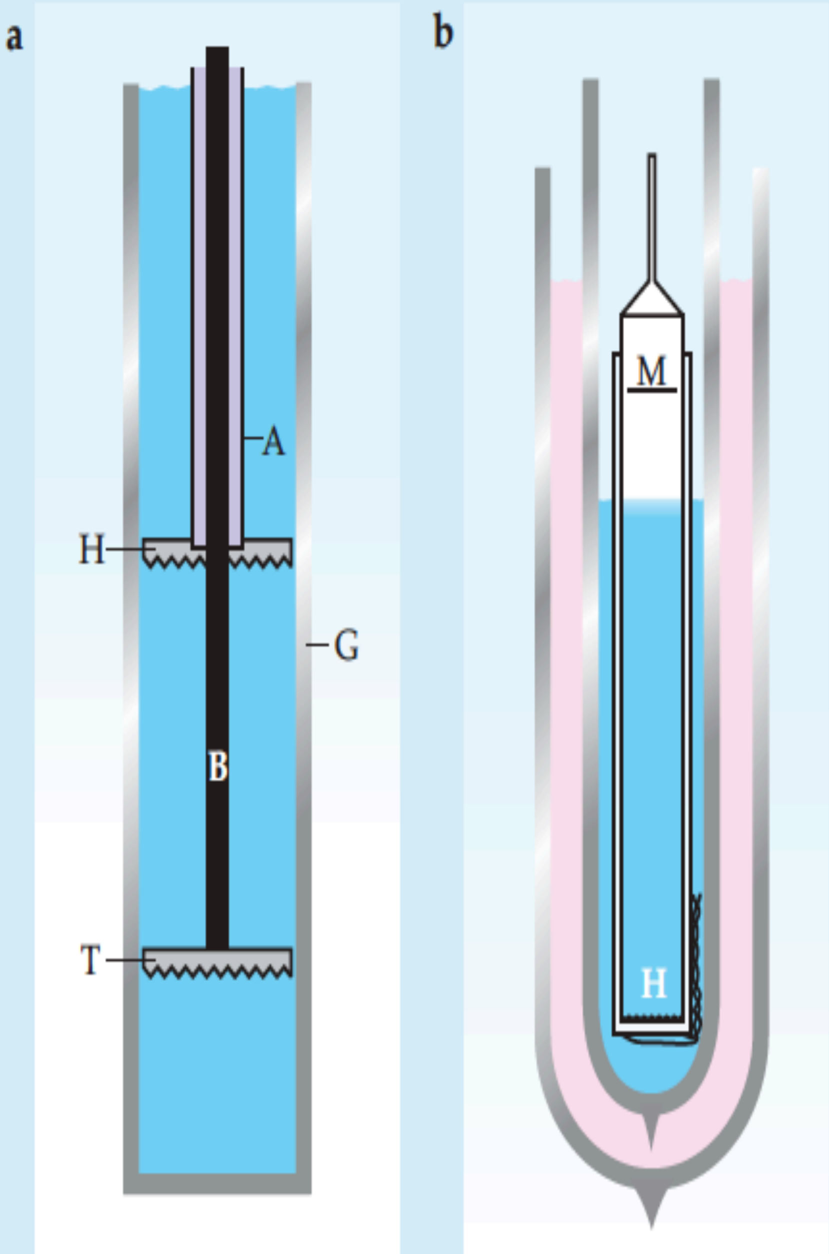
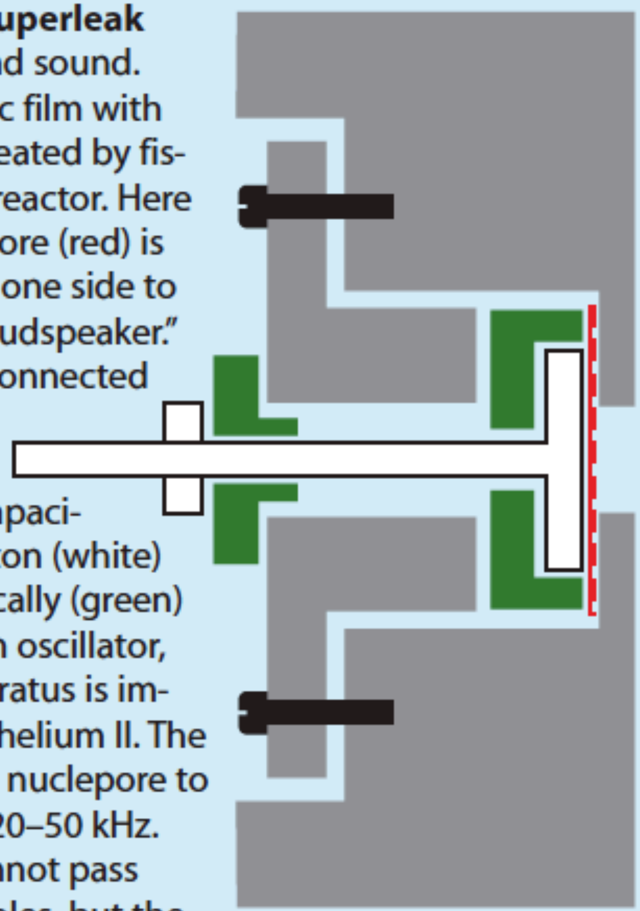


Figure 4. Modern superleak transducer for second sound. Nuclepore is a plastic film with micron-size holes created by fission fragments in a reactor. Here a thin film of nuclepore (red) is plated with gold on one side to make a capacitor "loudspeaker." The frame (gray) is connected to a bias voltage and connected to ground by a large capacitor, the rod and button (white) are insulated electrically (green) and connected to an oscillator, and the whole apparatus is immersed in a bath of helium II. The oscillator causes the nuclepore to vibrate, typically at 20–50 kHz. The normal fluid cannot pass through the film's holes, but the superfluid can, and the transducer can act as a generator or detector for second sound.



tuned to 2 kHz and its signal rectified. As the liquid helium bath evaporated, the free surface fell and resonant peaks appeared from the microphone output, from which the velocity of second sound could be deduced. (Adapted from ref. 7.)

Dilute Bose Gases

(dilatation not negligible → coupling)

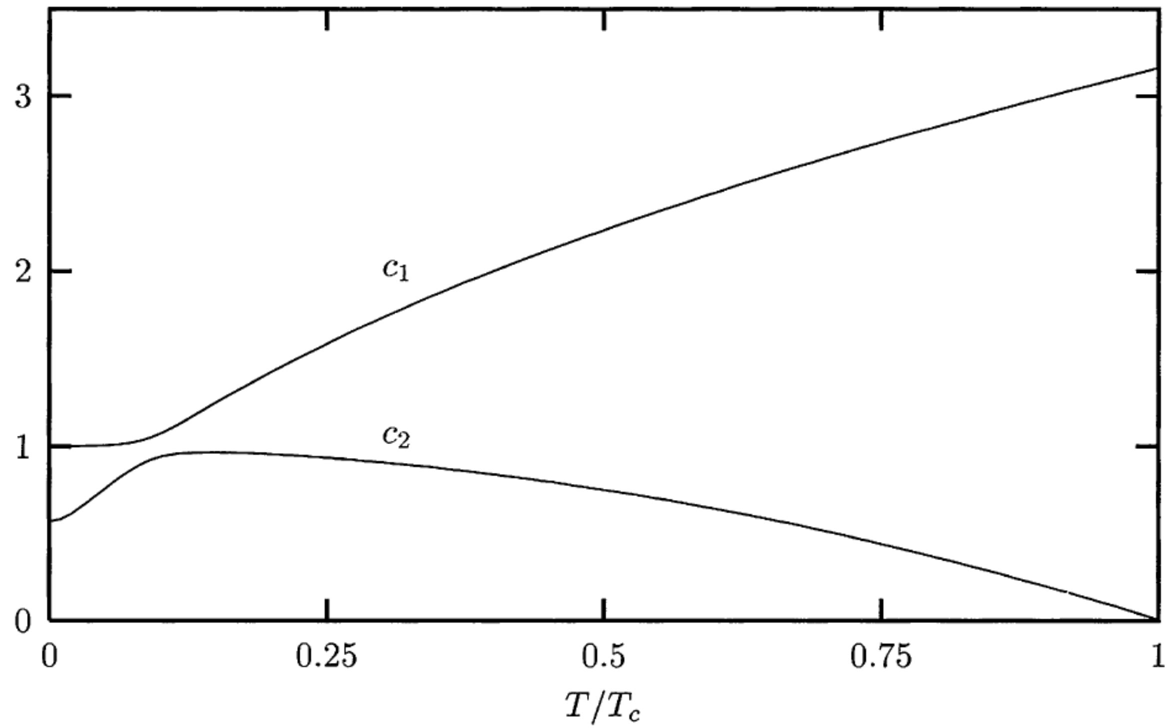


FIG. 6.1. Schematic representation of the velocity of first and second sound in a dilute Bose gas as a function of temperature. The figure points out the effect of hybridization between the two modes taking place at low temperature. Above T_c only the first sound survives

From: Pitaevskii and Stringari, Bose-Einstein Condensation (Oxford)

Second-sound in solids

(Suggestion: Ward and Wilks, 1951)

Schematically:

$$c_v \frac{\partial T}{\partial t} + \mathrm{div} j_Q = 0 \ , \ \ \frac{\partial}{\partial t} j_Q + \frac{1}{\tau} j_Q + \frac{c^2}{3} c_v \nabla T \simeq 0$$

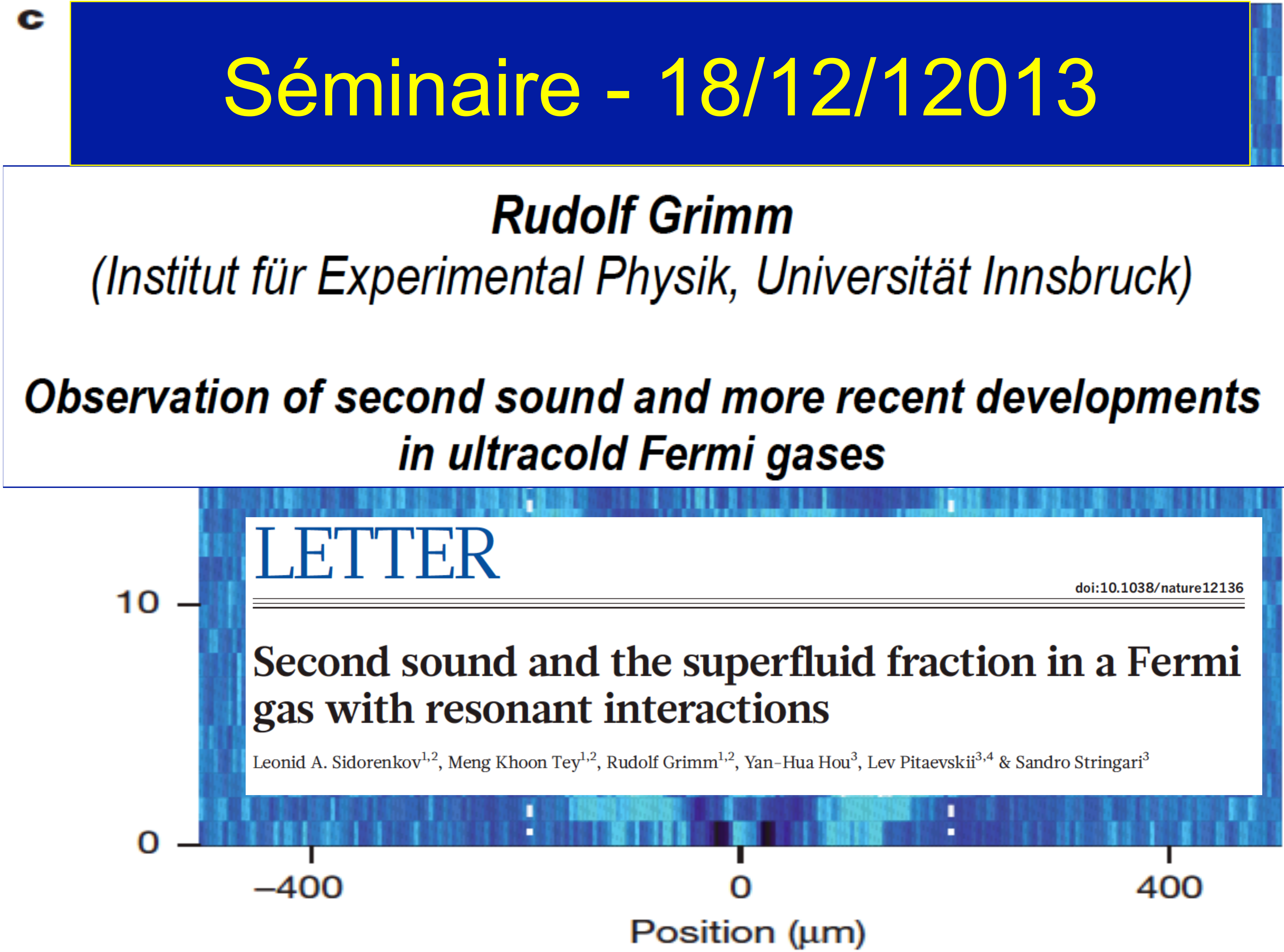
When all anharmonic phonon coupling and scattering can be neglected: wave-like propagation of temperature fluctuation (rather than Fourier diffusive law)

For an early review, see:
Ackerman and Guyer, Annals of Physics 50, 128 (1968)
Observation in solid He:
Ackerman et al. Phys Rev Lett 16, 789 (1966)

Séminaire - 18/12/12013

Rudolf Grimm
(Institut für Experimental Physik, Universität Innsbruck)

Observation of second sound and more recent developments in ultracold Fermi gases



LETTER

doi:10.1038/nature12136

Second sound and the superfluid fraction in a Fermi gas with resonant interactions

Leonid A. Sidorenkov[1,2], Meng Khoon Tey[1,2], Rudolf Grimm[1,2], Yan-Hua Hou[3], Lev Pitaevskii[3,4] & Sandro Stringari[3]