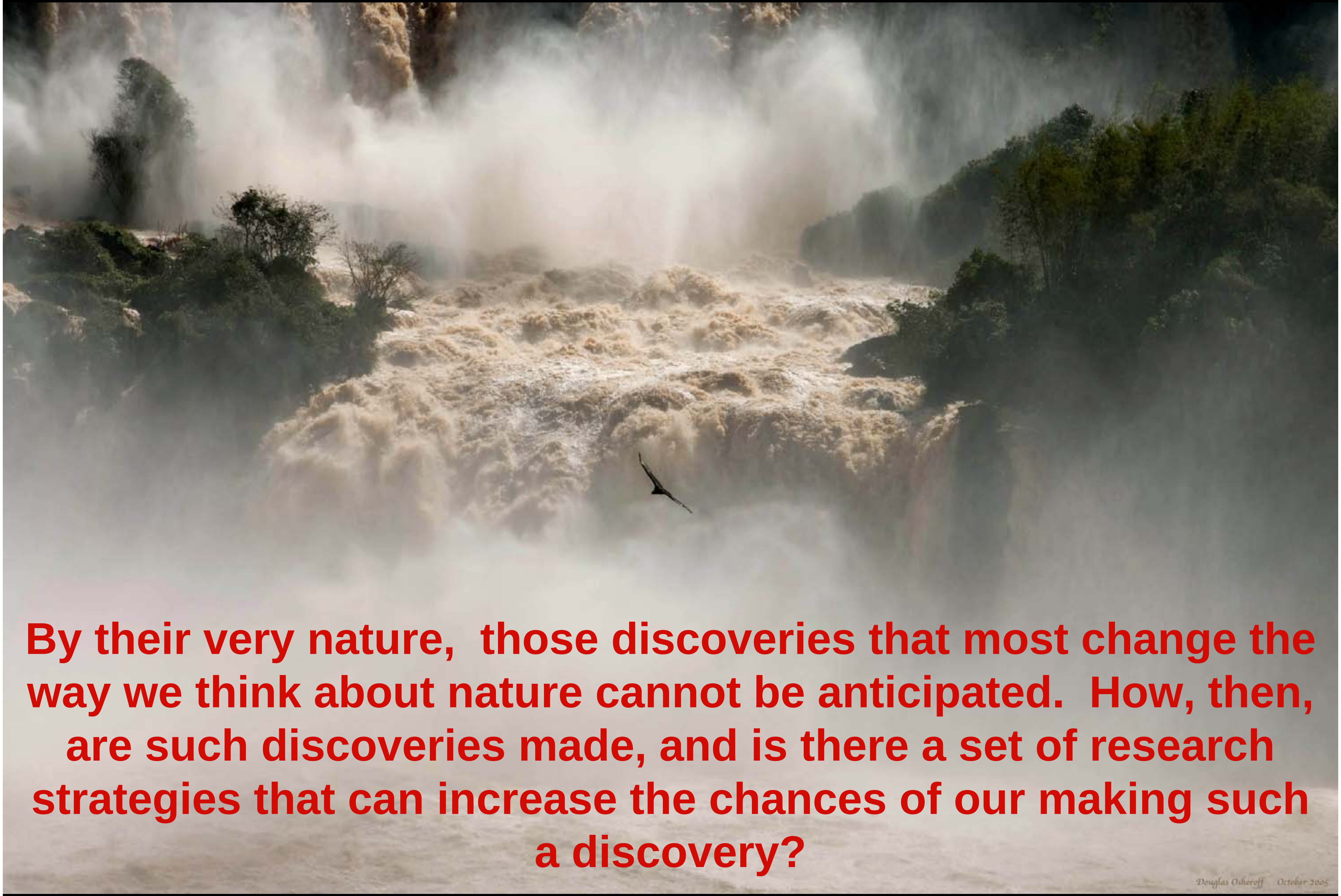
How Advances in Science Are Made

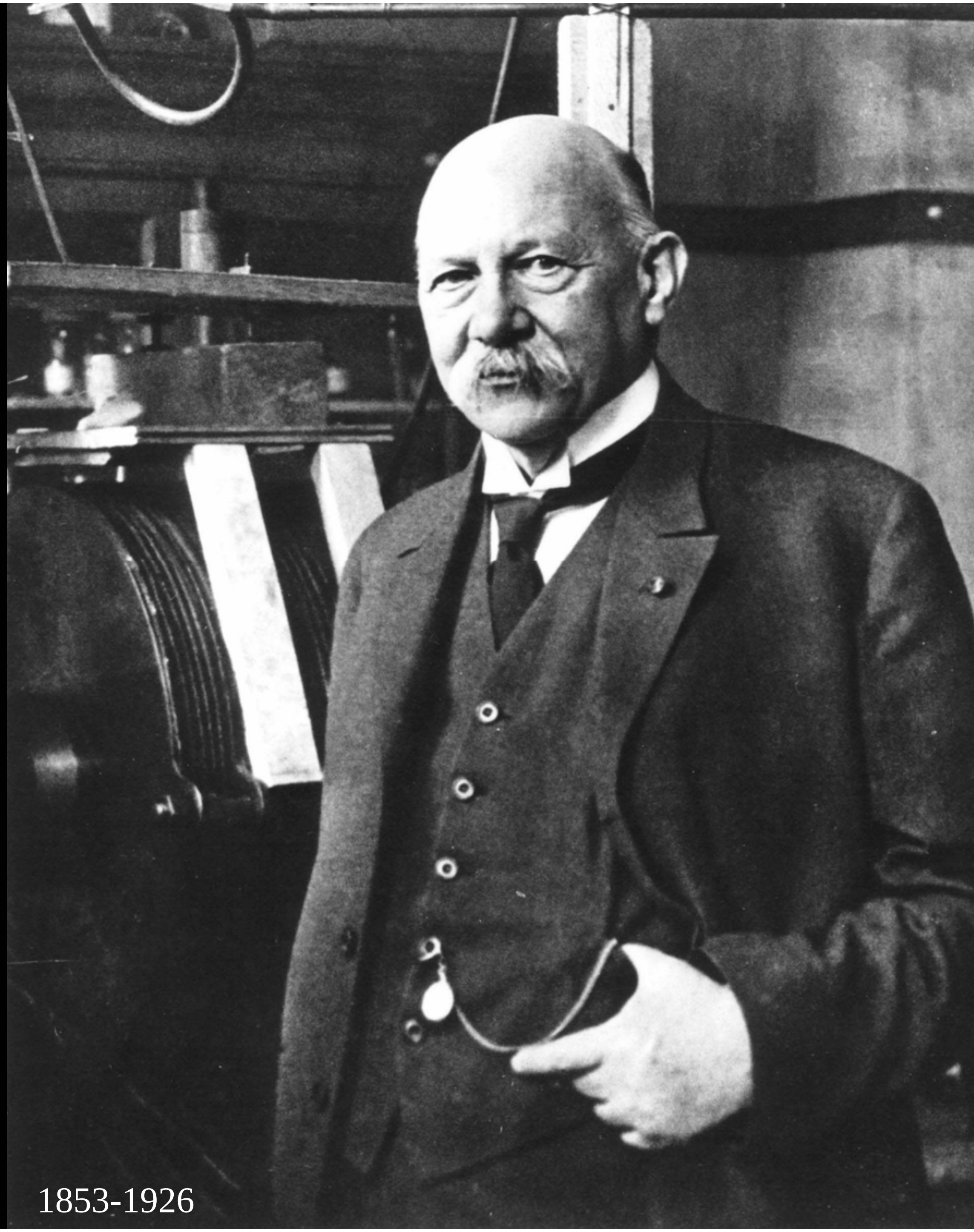
Stanford Matters

Douglas Osheroff
Stanford University

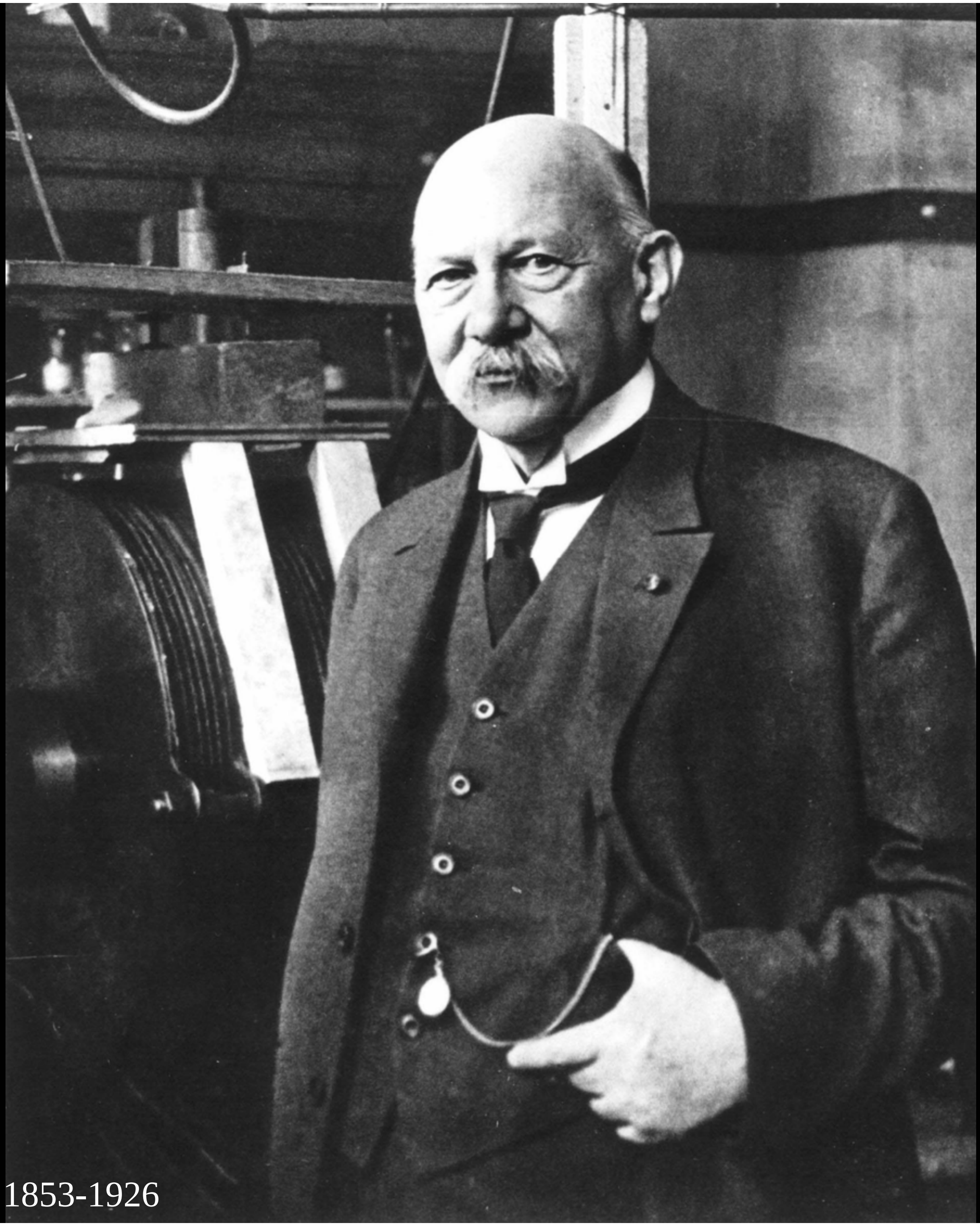
Stanford Day - East Bay
11 March 2006


By their very nature, those discoveries that most change the way we think about nature cannot be anticipated. How, then, are such discoveries made, and is there a set of research strategies that can increase the chances of our making such a discovery?
Douglas Osheroff October 2005

A Linked Chain of Discoveries and Inventions


1853-1926

Heike Kammerlingh Onnes



Nobel Prize for Physics 1913

The Discovery of Superconductivity

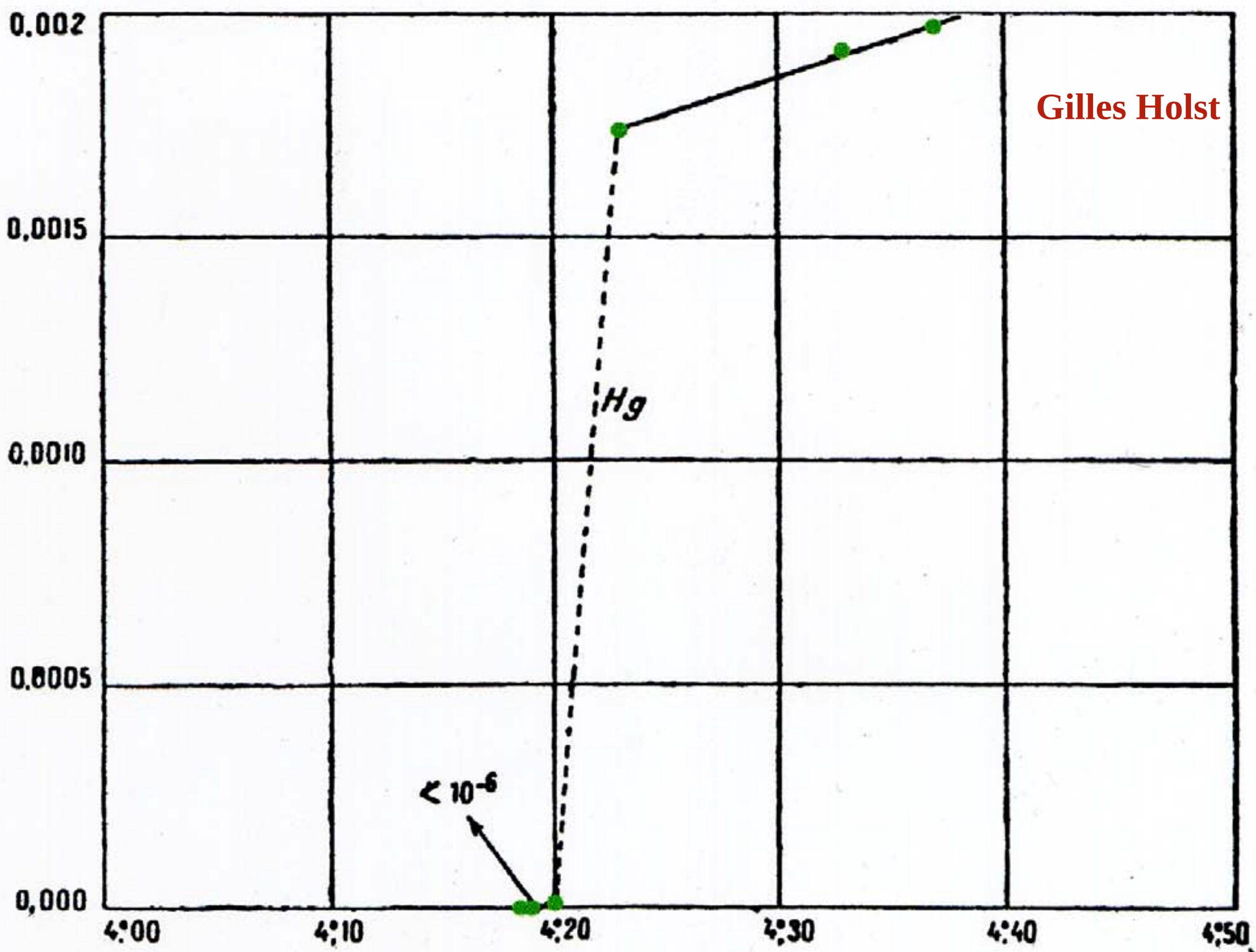
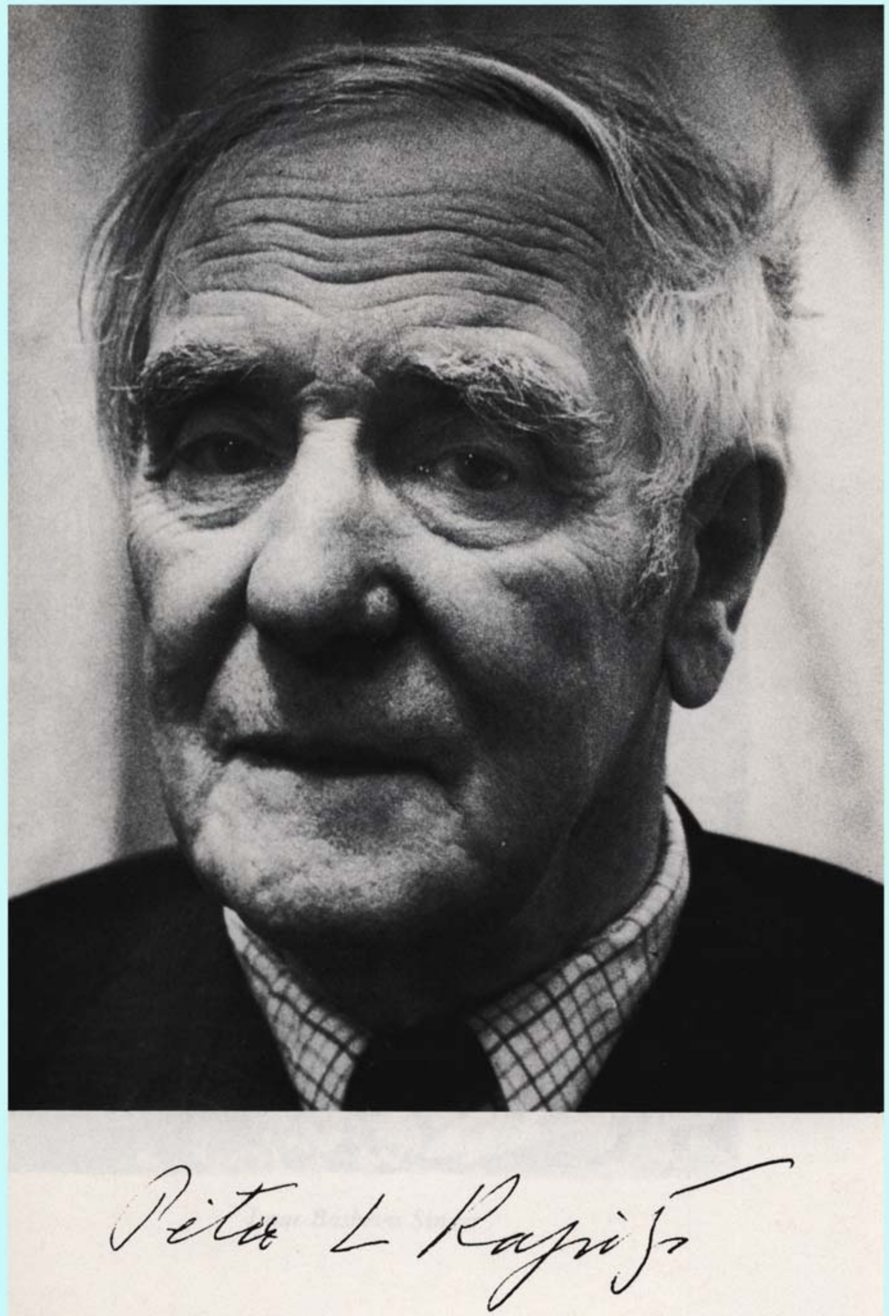


Figure 1. Onnes's graph plotting electrical resistance of a mercury sample versus temperature in kelvins. At 4.2 K, the resistance drops abruptly to a value no greater than 10^{-5} Ohms. (Reproduced from the proceedings of the First Solvay Conference, October 30 - November 3, 1911)

David and Judith Goldstein

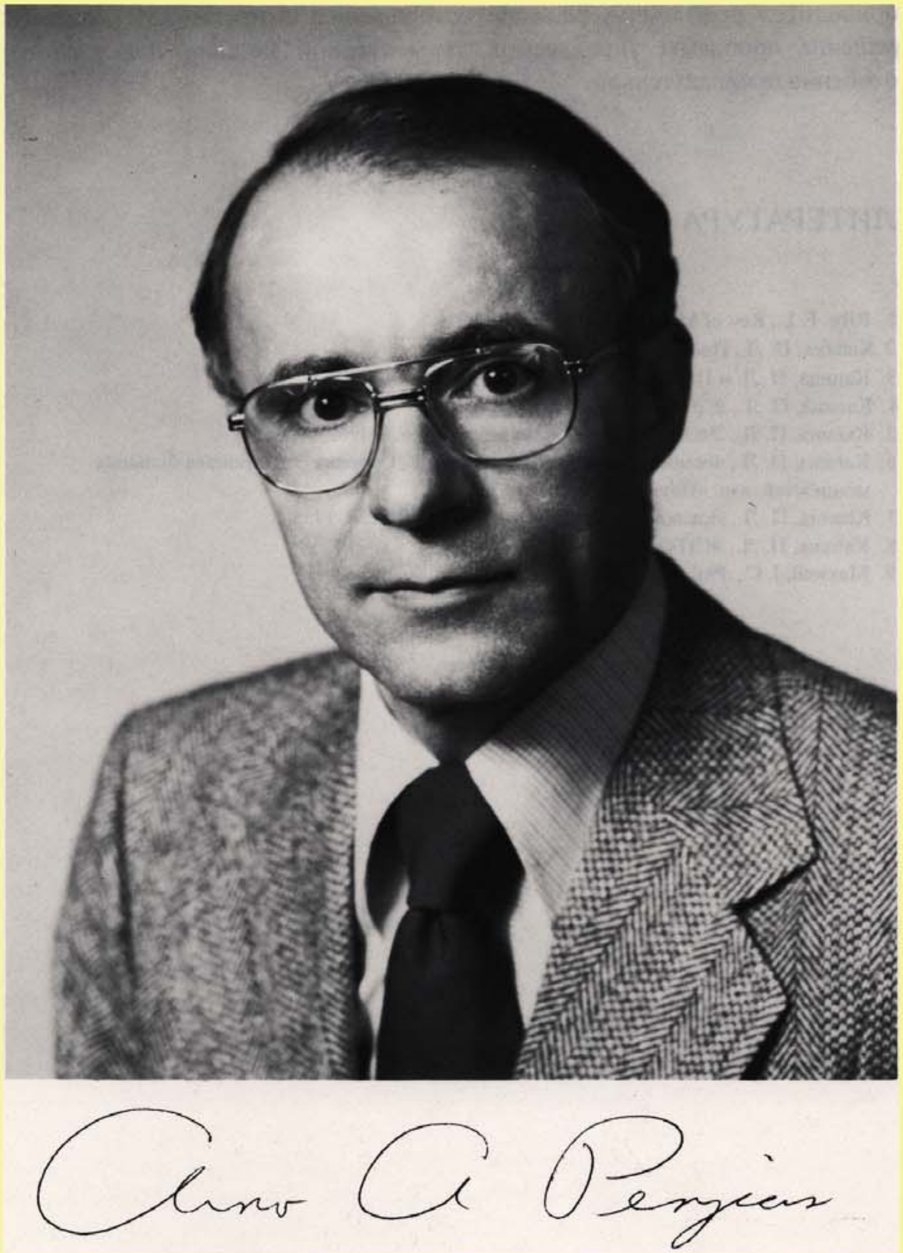
Relevant Research Strategies

- Use the best instrumentation available
- Don’t re-invent: Borrow the technologies you can
- Look in an unexplored region of the landscape
- Failure might be an invitation to try something new
- Be aware of subtle unexplained behavior, don’t dismiss it!



1894-1984 NL 1978

Arno Penzias



Robert Wilson

1954

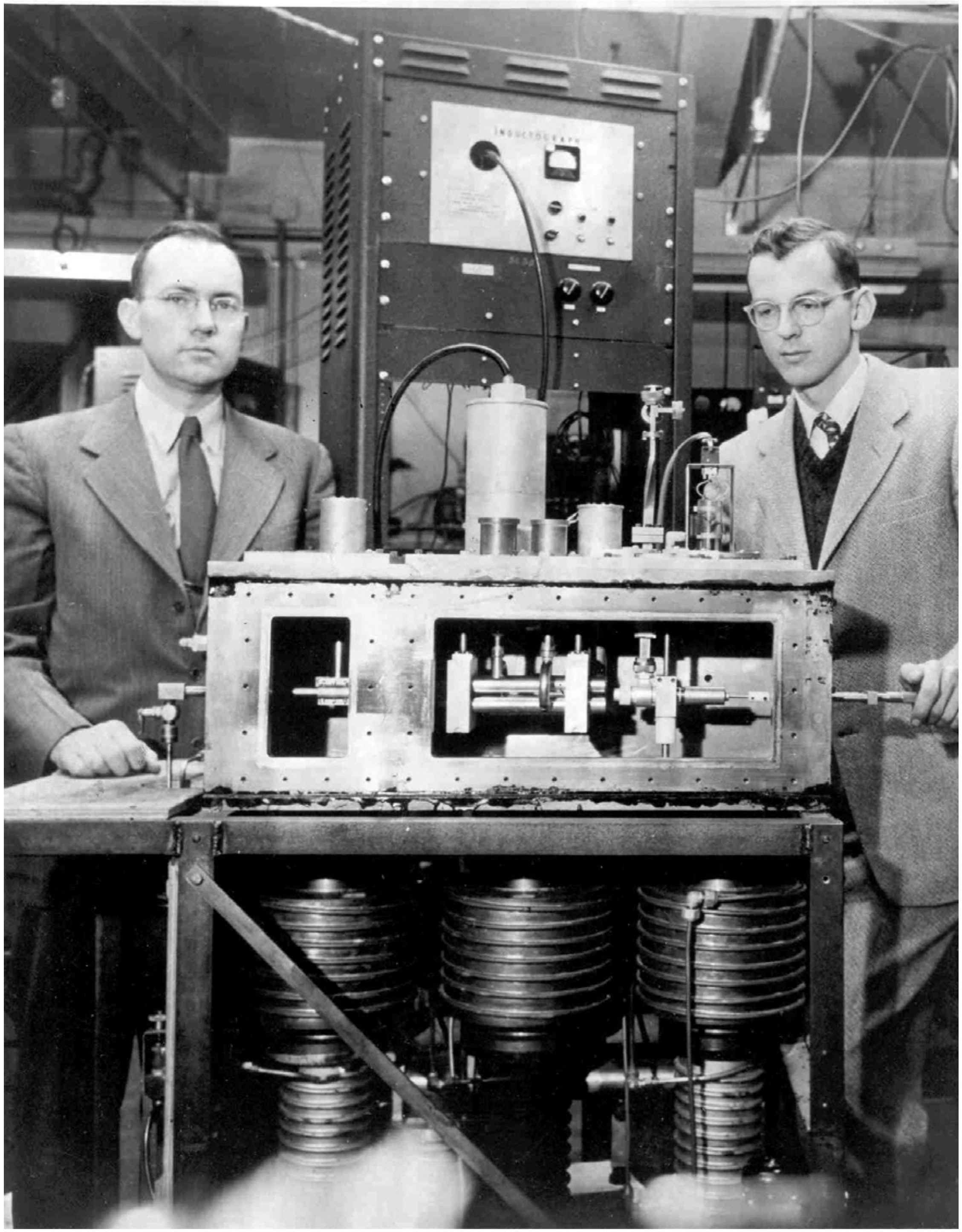
Columbia University

Charles Townes
Jim Gordon

The Ammonia Maser II

—> *Maser parametric amplifier*

Townes Nobel Prize 1964



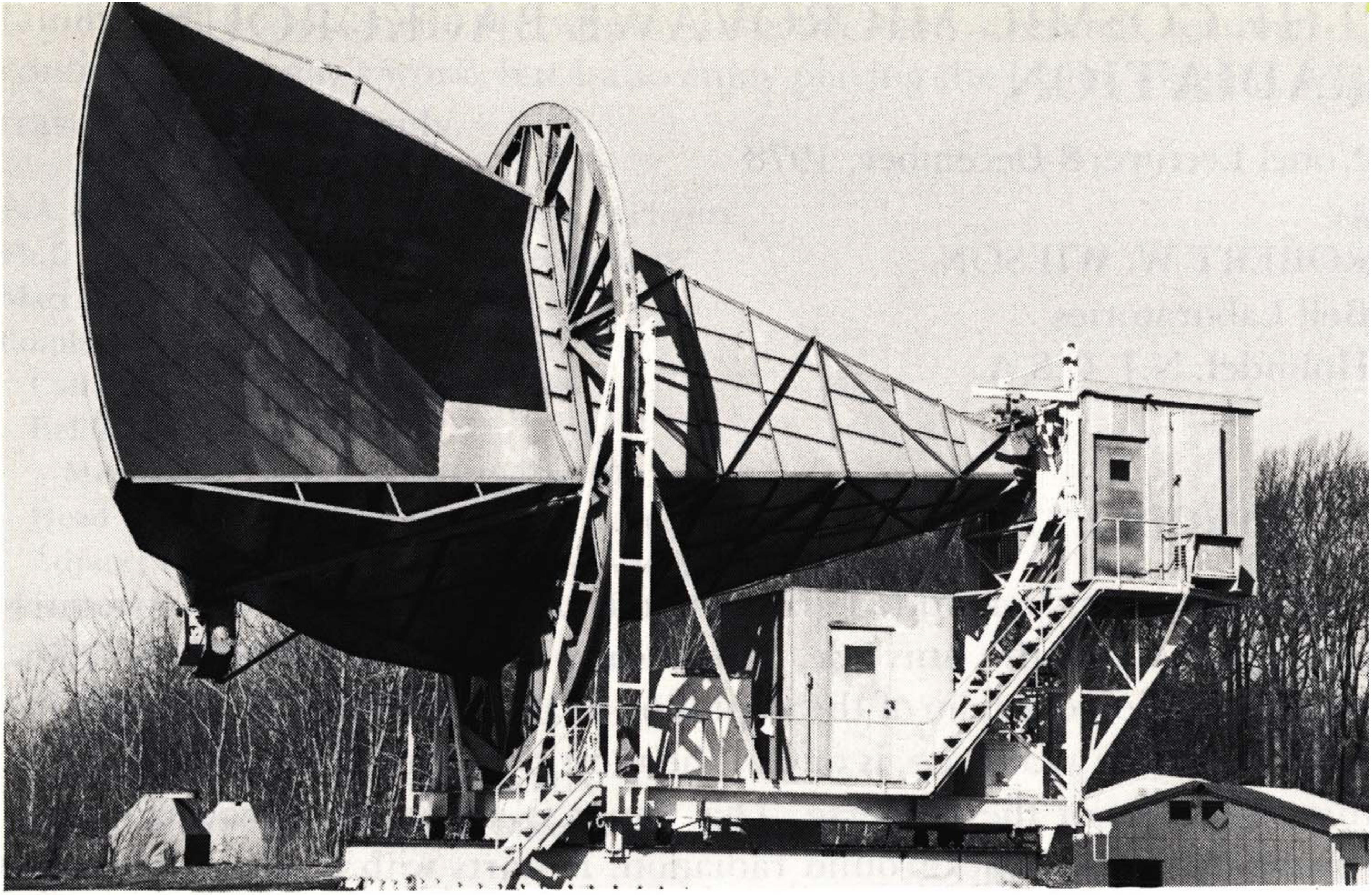
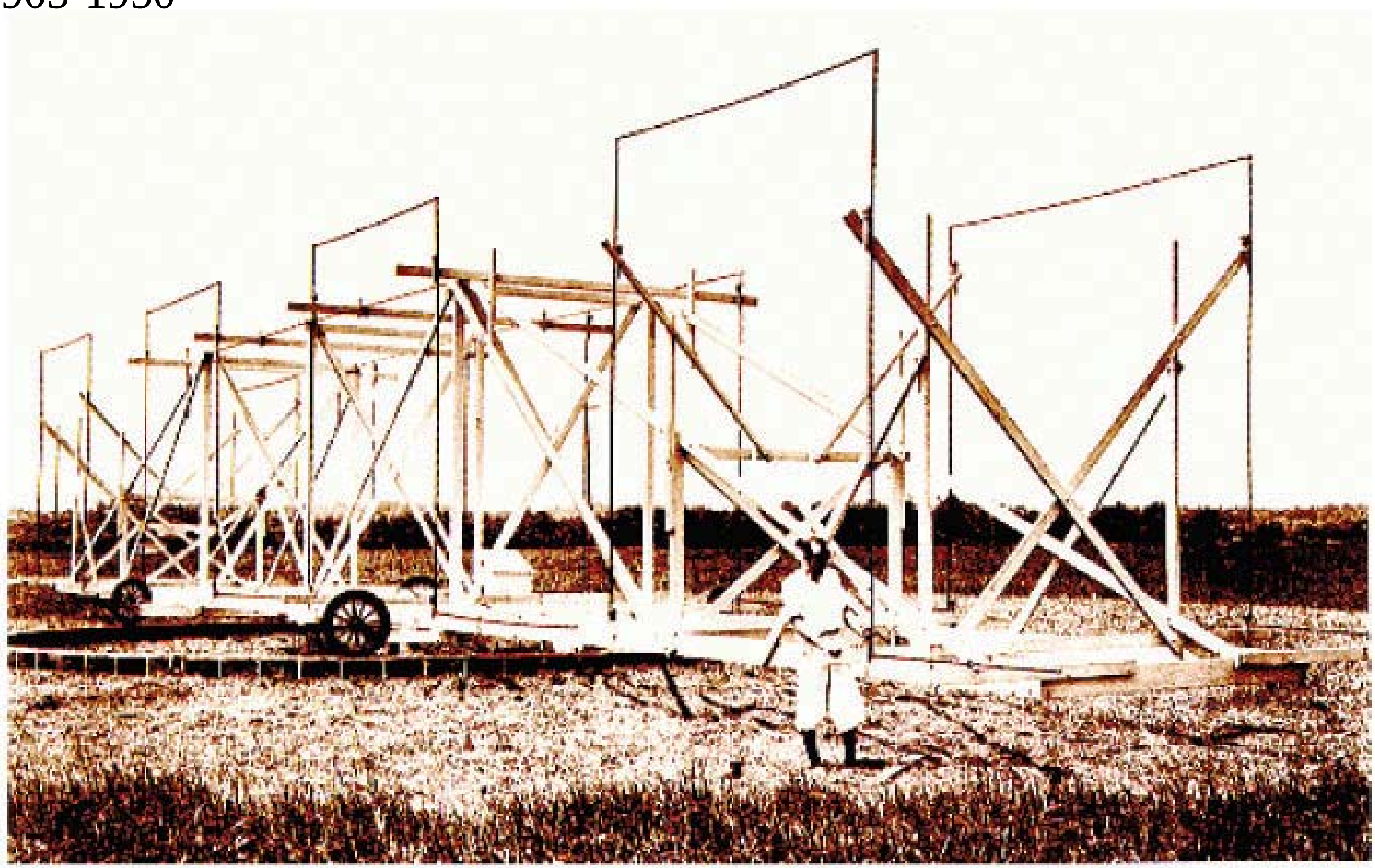


Fig. 1 The 20 foot horn-reflector which was used to discover the Cosmic Microwave Background Radiation.

Karl Jansky At Bell Laboratories in 1933

1905-1950



First Evidence of CMBR

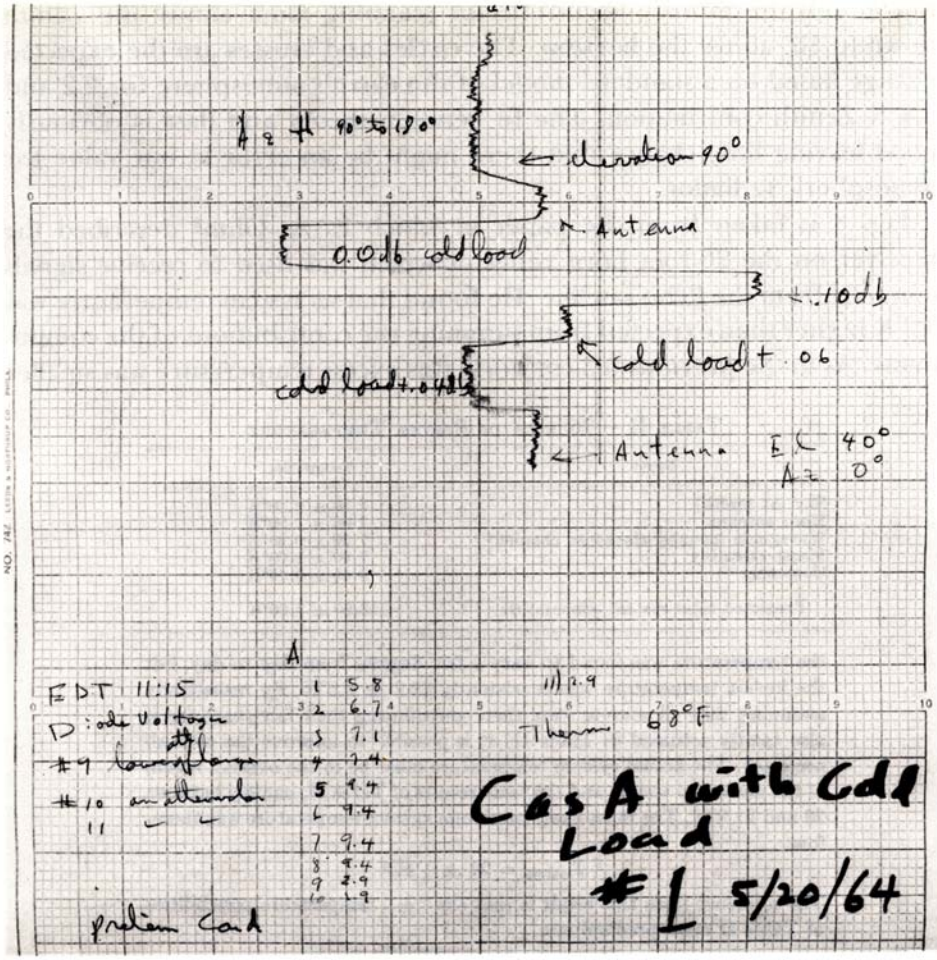
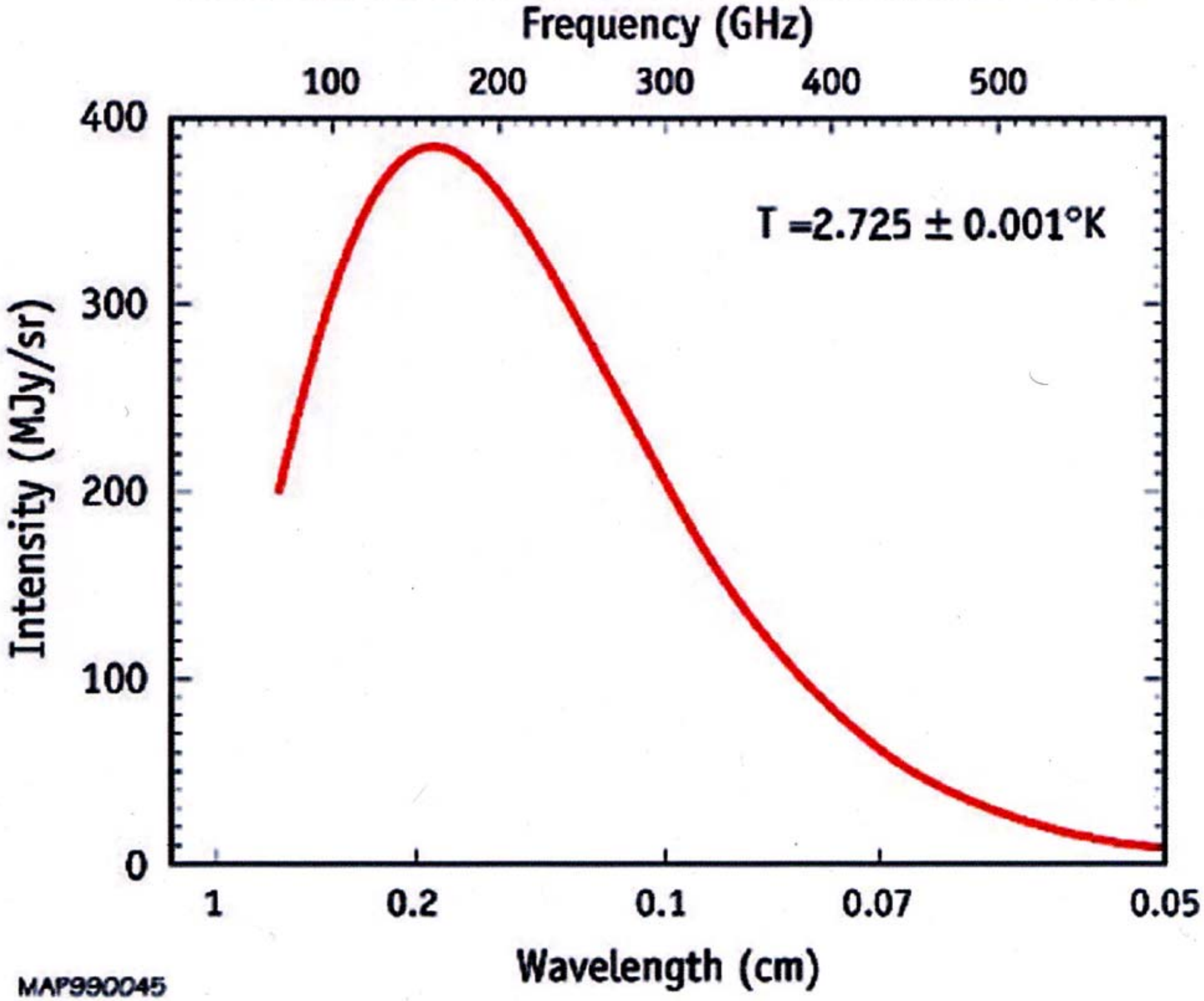


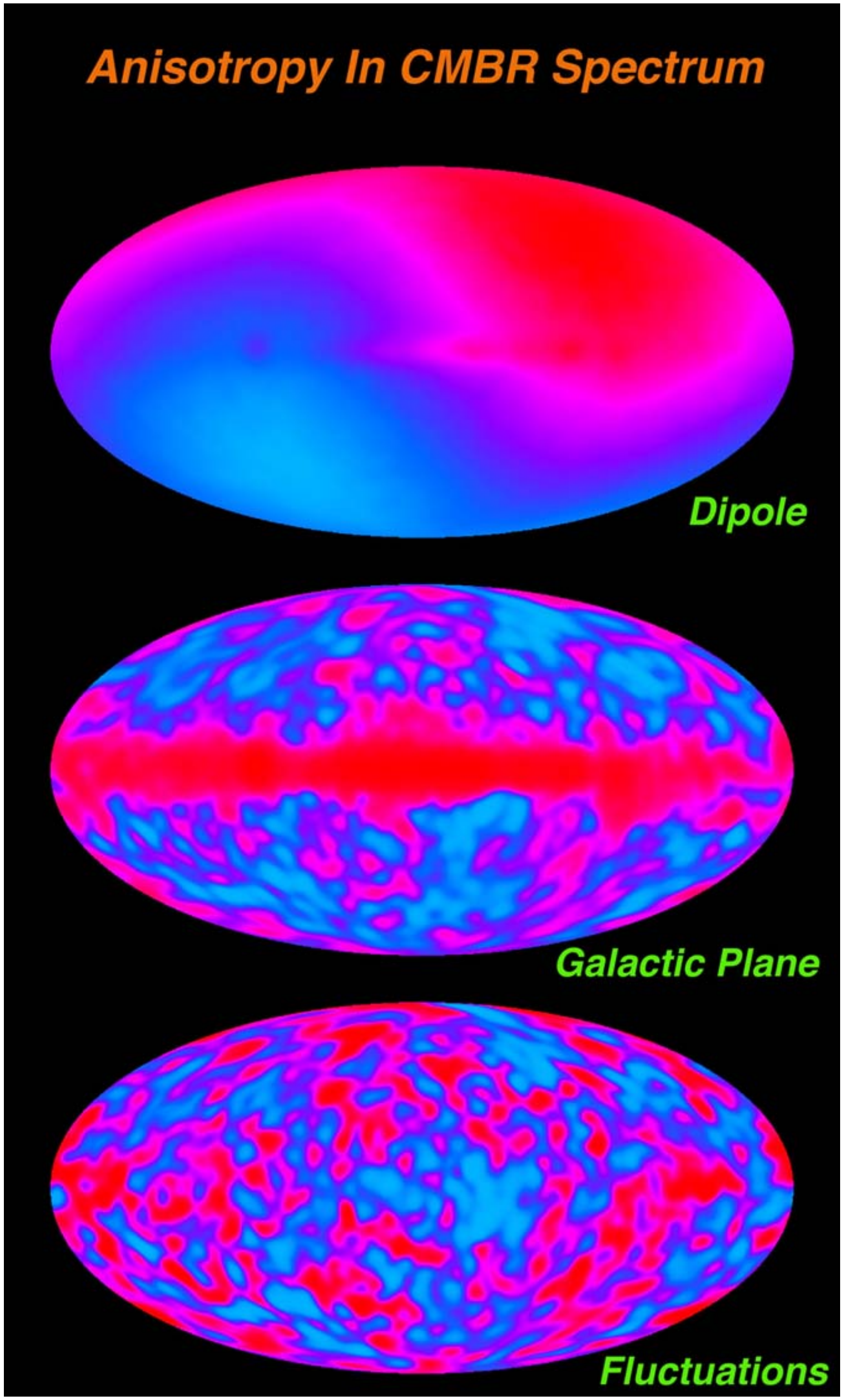
Fig. 9 The first measurement which clearly showed the presence of the microwave background. Noise temperature is plotted increasing to the right. At the top, the antenna pointed at 90° elevation is seen to have the samt noise temperature as the cold load with 0.04 db attenuation (about 7.5K). This is considerably above the expected value of 3.3K.

Wilkinson

May 20, 1964

Spectrum of the Cosmic Microwave Background




Anisotropy In CMBR Spectrum
Dipole
Galactic Plane
Fluctuations

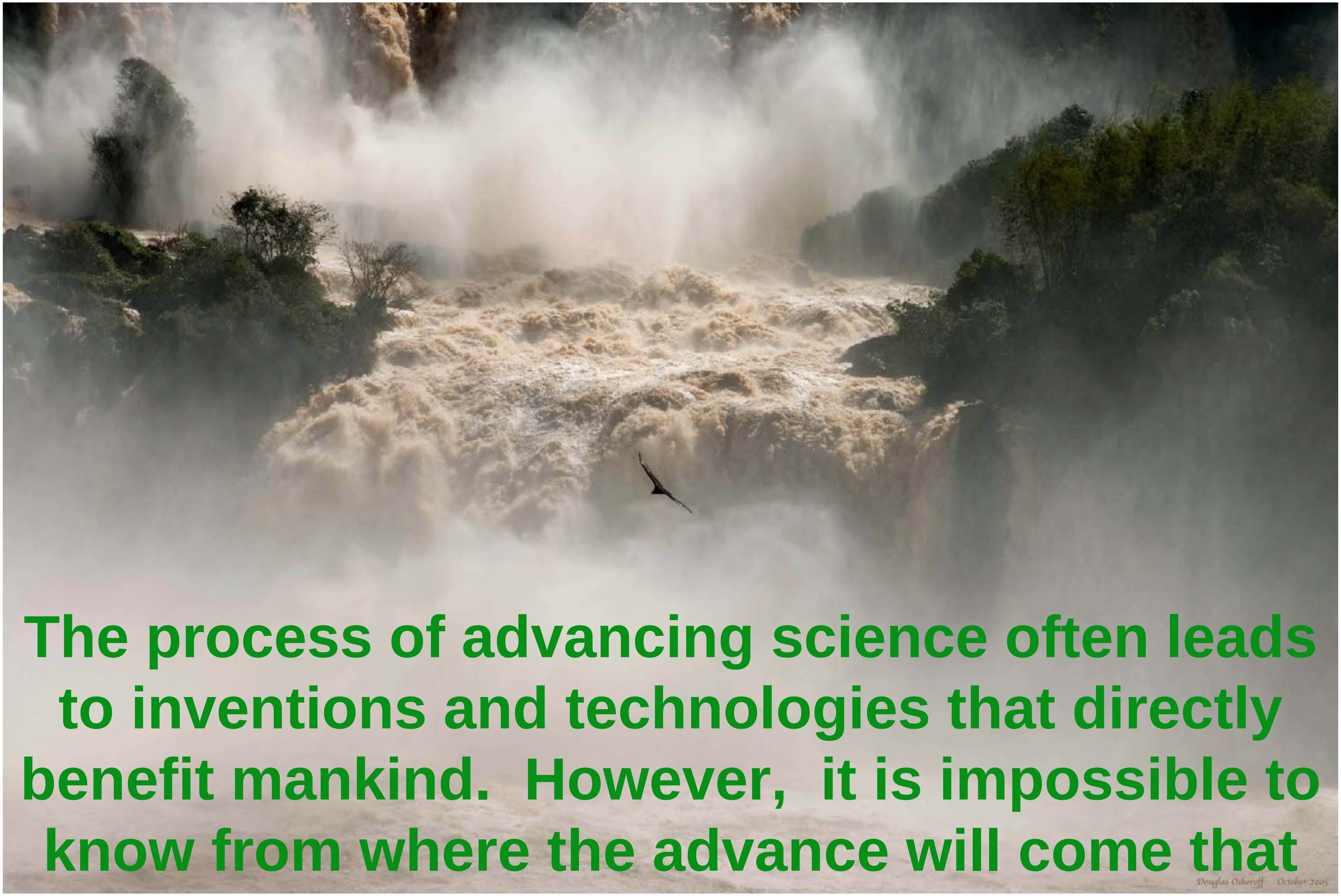
Relevant Research Strategies

1. Use the best technology available.

2. Don't re-invent the wheel, borrow if possible.

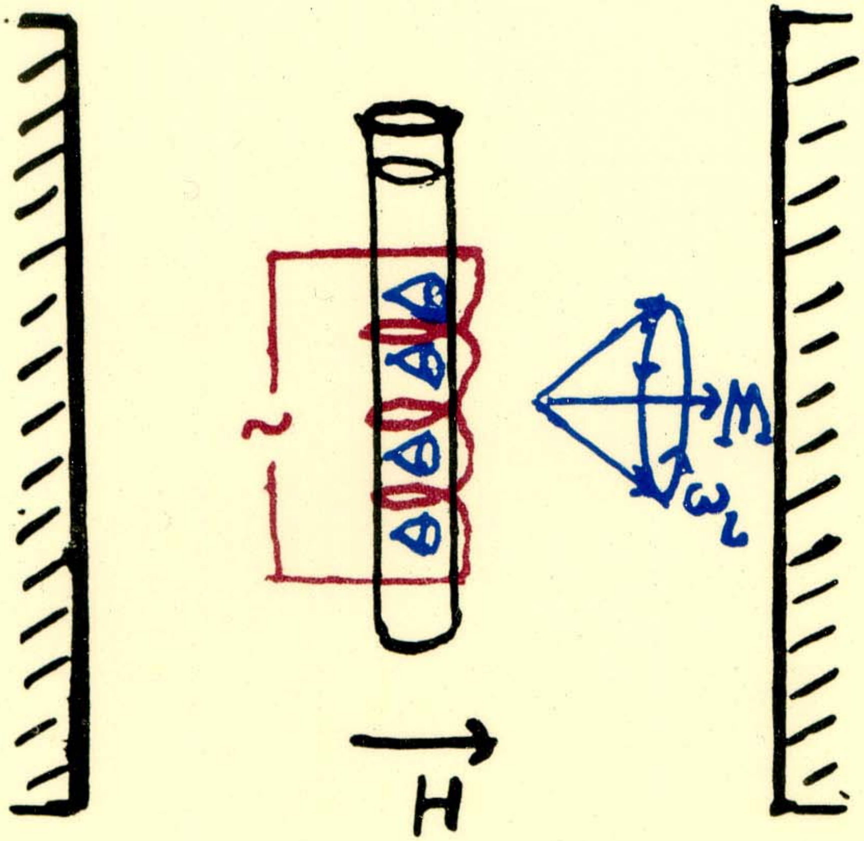
3. Look in a region of parameter that is unexplored.

4. Understand what your instrumentation is measuring.



The process of advancing science often leads to inventions and technologies that directly benefit mankind. However, it is impossible to know from where the advance will come that might solve a problem facing mankind.

"nmr" 1946



$$M_0 = N \frac{H\mu^2}{3kT} \frac{I+1}{I}$$

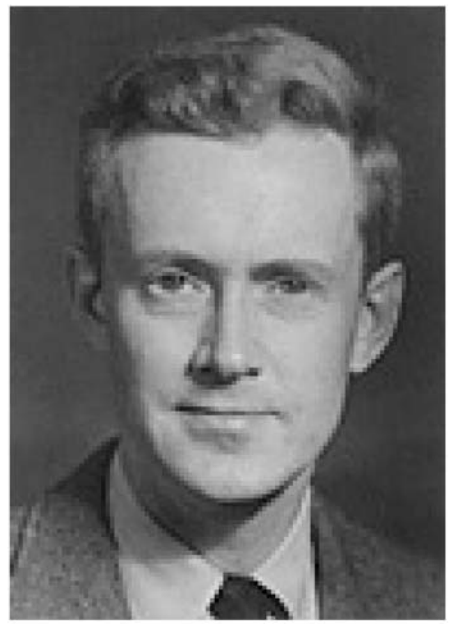
$$\omega_L = \gamma H$$

$$\gamma = \frac{\mu}{I\hbar}$$

The Nobel Prize in Physics 1952

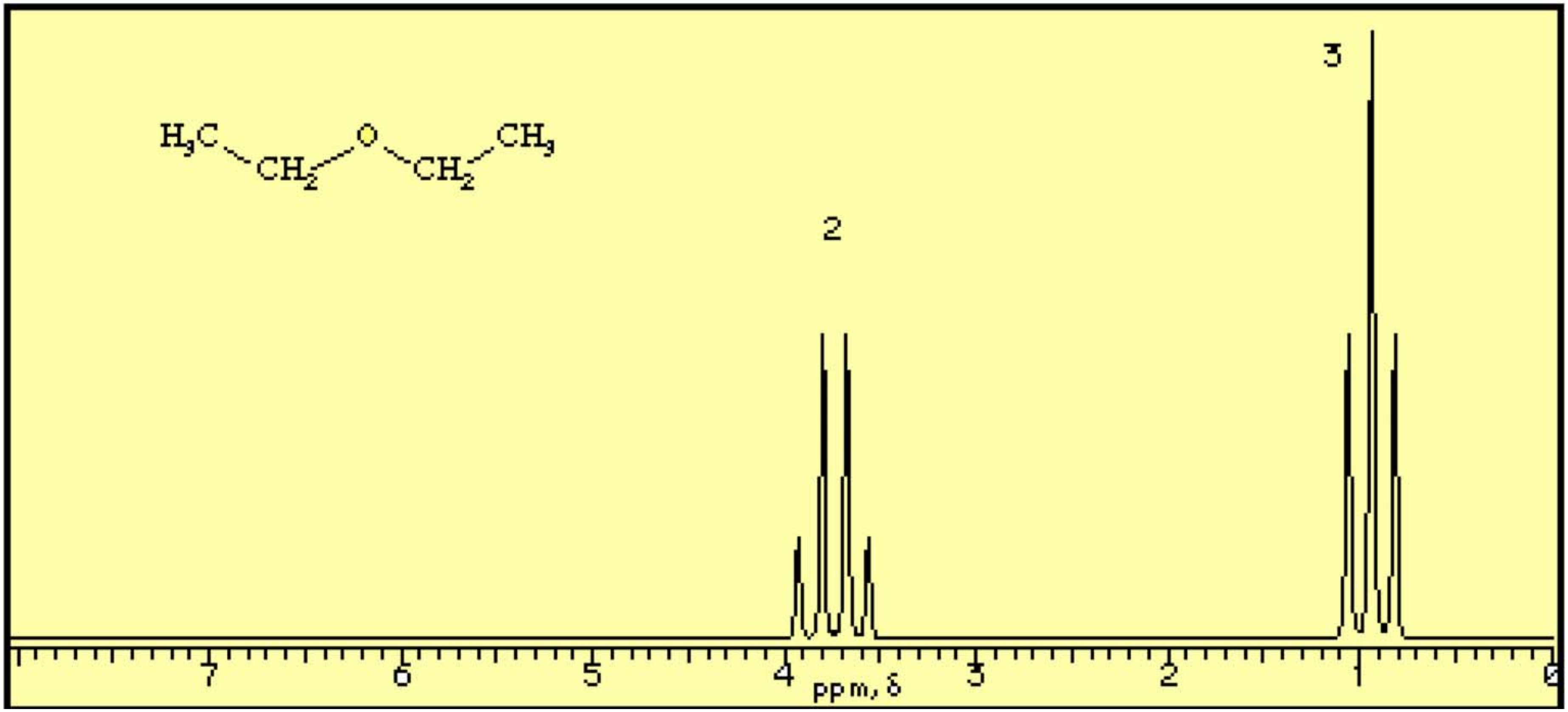
"for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith"

Felix Bloch



Edward Mills Purcell

Chemical and Spin Shifts in NMR



Fourier Transform and 2D NMR

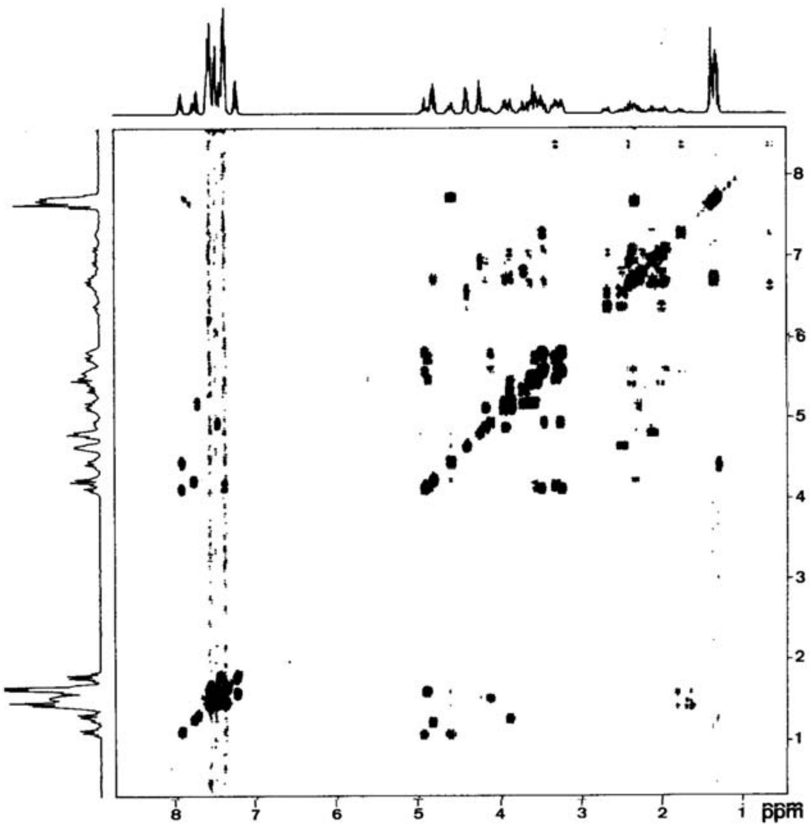


Figure 8. Phase-sensitive 400 MHz proton resonance COSY spectrum of antamanide in chloroform solution (at 250 K) in a contour-line representation. Positive and negative contours are not distinguished. The spectrum has been recorded by Dr. Martin Blackledge.

Richard R. Ernst 25

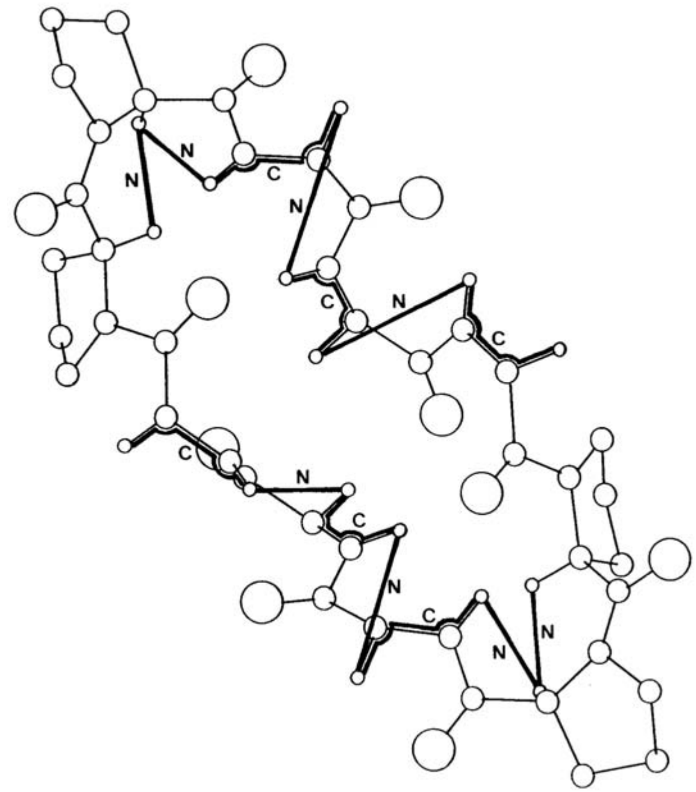
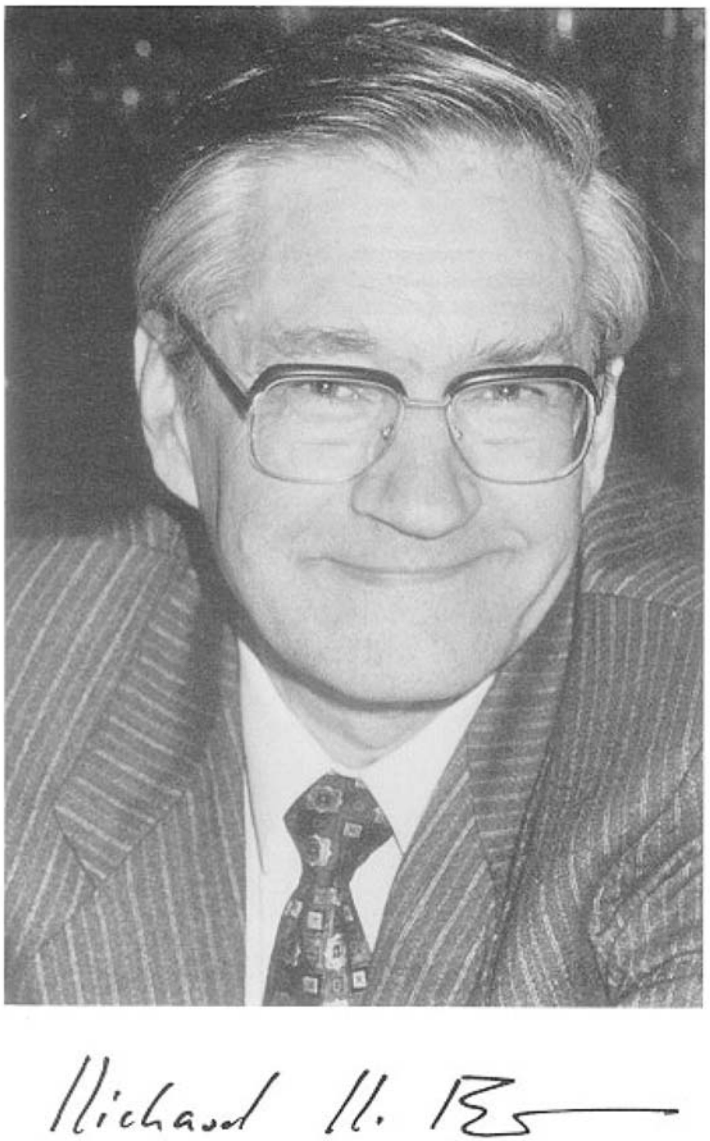


Figure 9. Assignment of backbone protons in antamanide by the combination of COSY (C) and NOESY (N) cross peaks. The missing NH protons in the four proline residues break the chain of sequential C,N connectivities.



Richard Ernst

Nobel Prize
Chemistry
1991

Three Dimensional Conformation of Organic Molecules

Kurt Wütrich

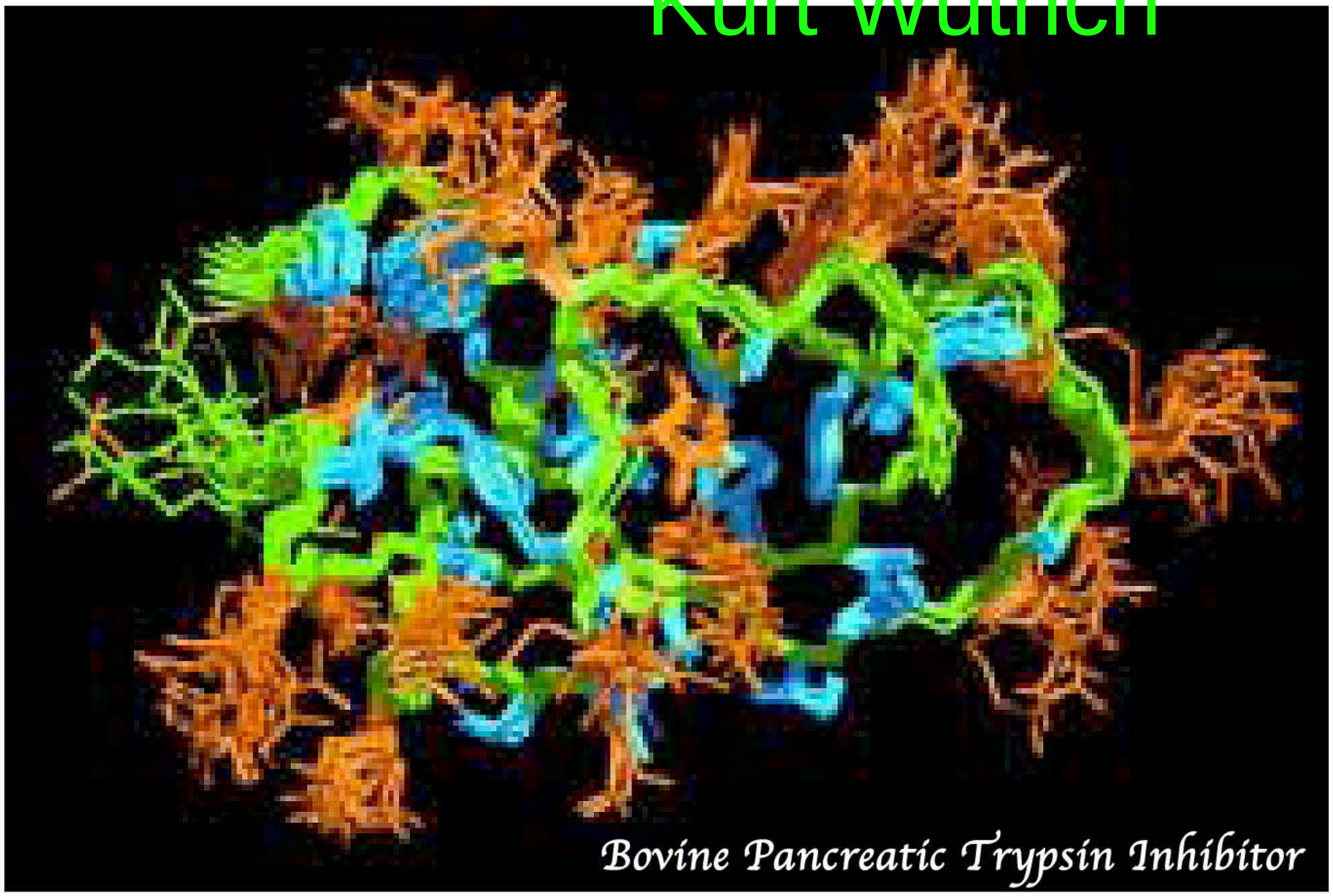


Figure 27. NMR structure of BPTI represented by a bundle of 20 conformers superimposed for best fit of the polypeptide backbone. The polypeptide backbone is green, core side-chains are blue, and solvent-accessible surface side-chains are red.

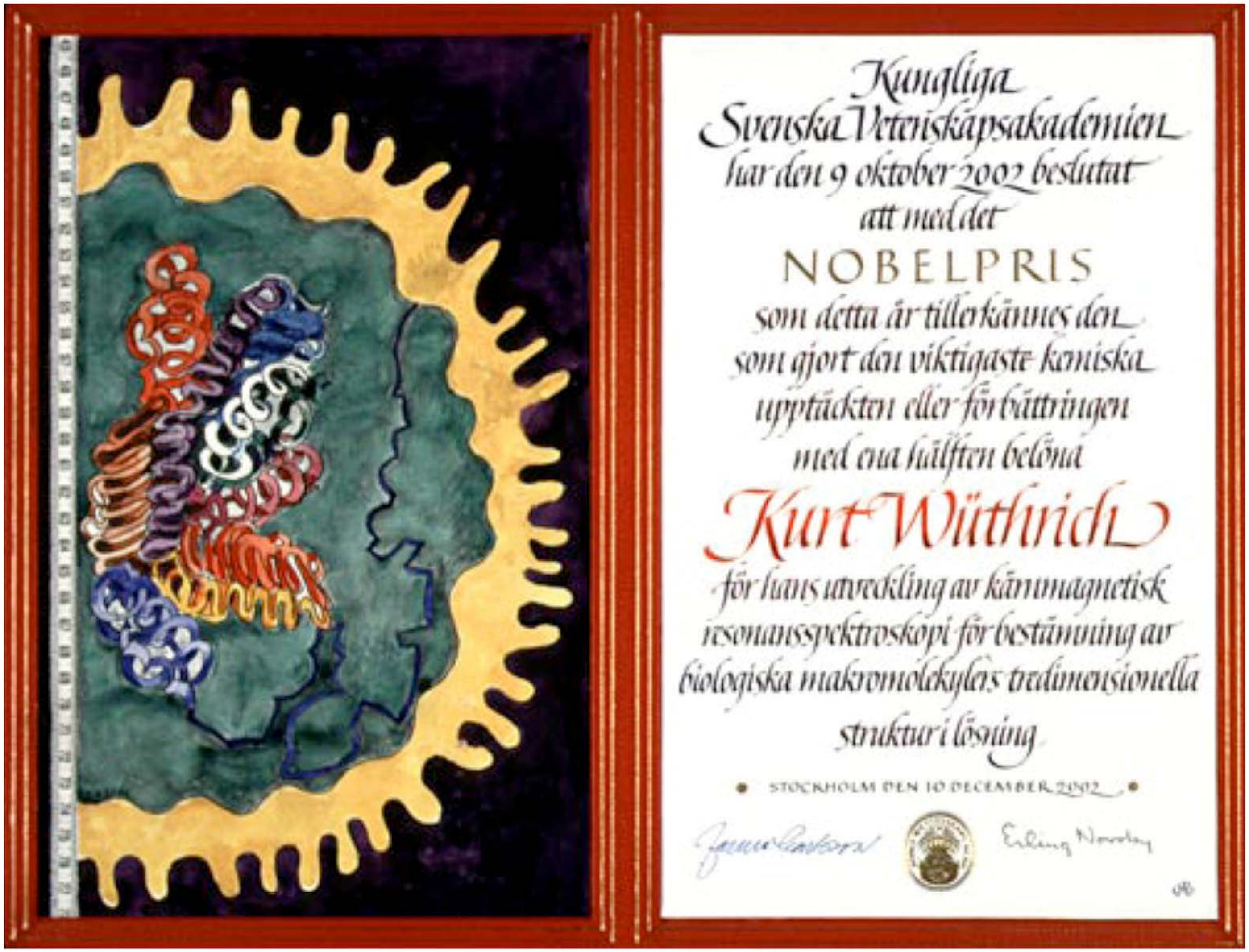
…in Aqueous Solutions

Kurt Wütrich

Nobel Prize for Chemistry

2002

Kurt Wüthrich – Nobel Diploma



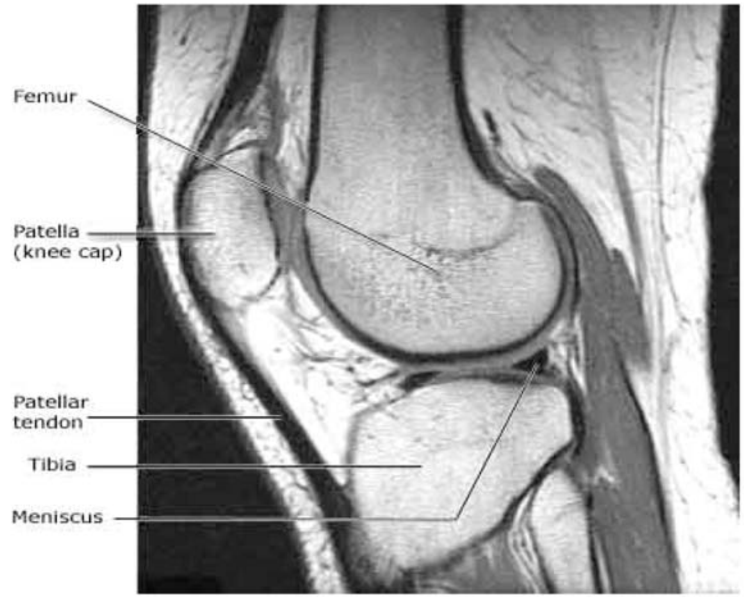
Artist: Nils G. Stenqvist
Calligrapher: Annika Rücker

Magnetic Resonance Imaging: MRI

RADIOLOGYINFO™
The radiology information resource for patients

Image Gallery

Magnetic Resonance (MR) - Body



Sample image: MR of the knee - side (lateral) view, showing distal or lowest part of femur, the patella (knee cap) and proximal (upper) tibia. The lateral meniscus is seen as a dark bow-tie like structure. The patellar tendon is also clearly seen at the front of the knee connecting the patella with the tibia.

- Return to procedure
- View more images related to this procedure

The Nobel Prize in Physiology or Medicine 2003

"for their discoveries concerning magnetic resonance imaging"

Paul C. Lauterbur

1/2 of the prize

USA

University of Illinois
Urbana, IL, USA

b. 1929

Sir Peter Mansfield

1/2 of the prize

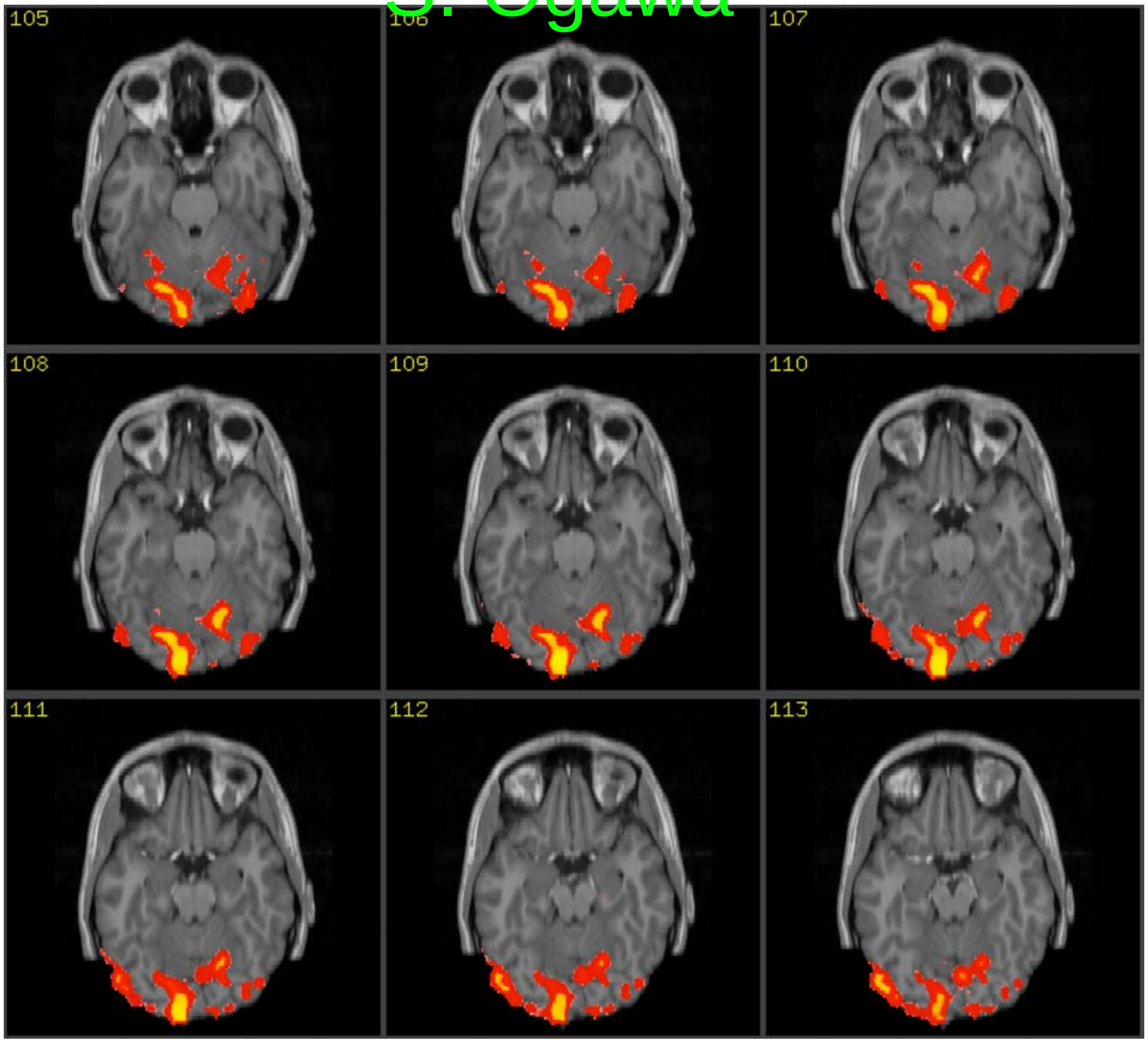
United Kingdom

University of Nottingham, School of Physics and Astronomy
Nottingham, United Kingdom

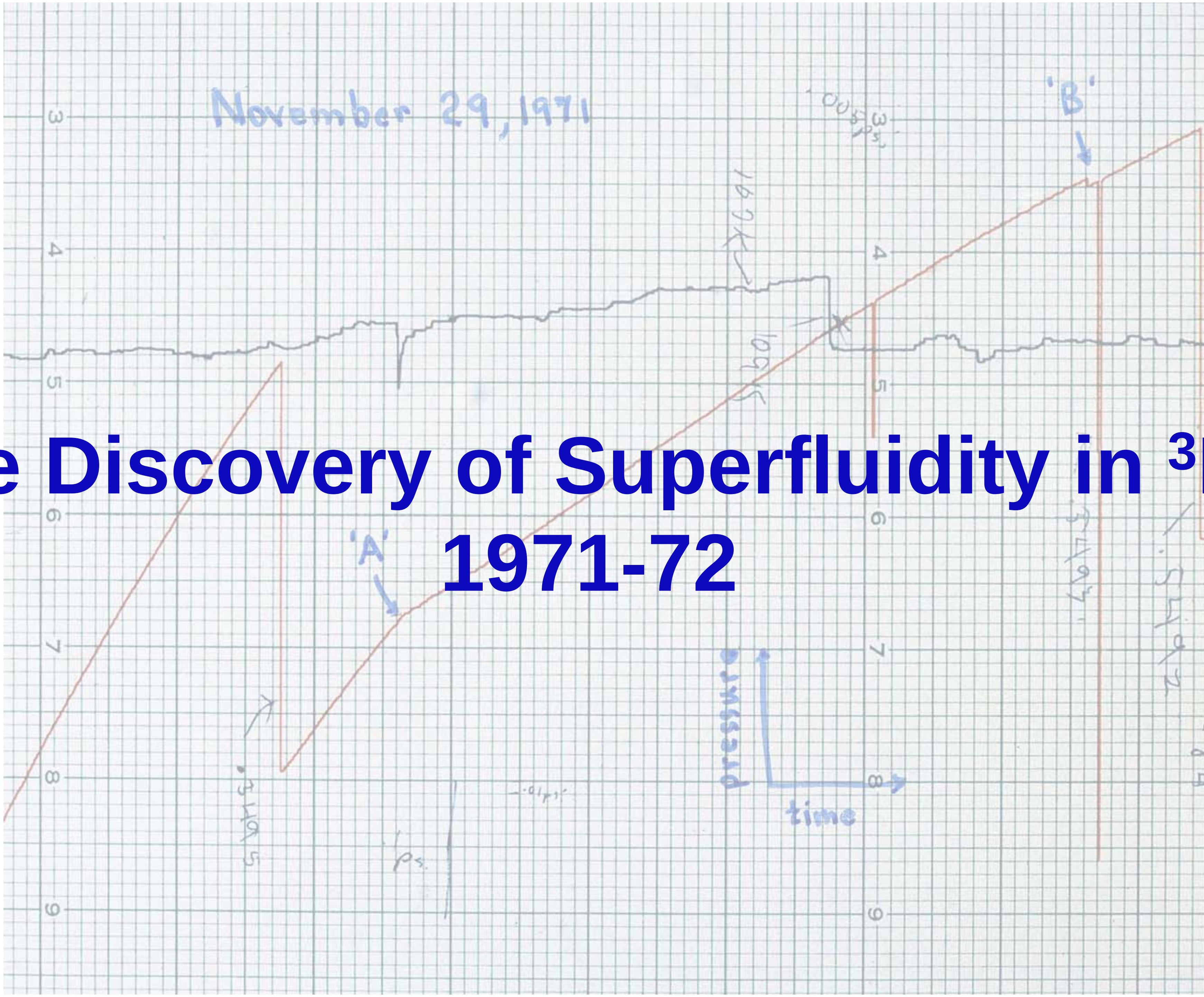
b. 1933

Functional Magnetic Resonance Imaging: FMRI

S. Ogawa



he Discovery of Superfluidity in ^{3}He
1971-72



The History:

- 1948 Ed Hammel led a group at Los Alamos who first liquified ^3He

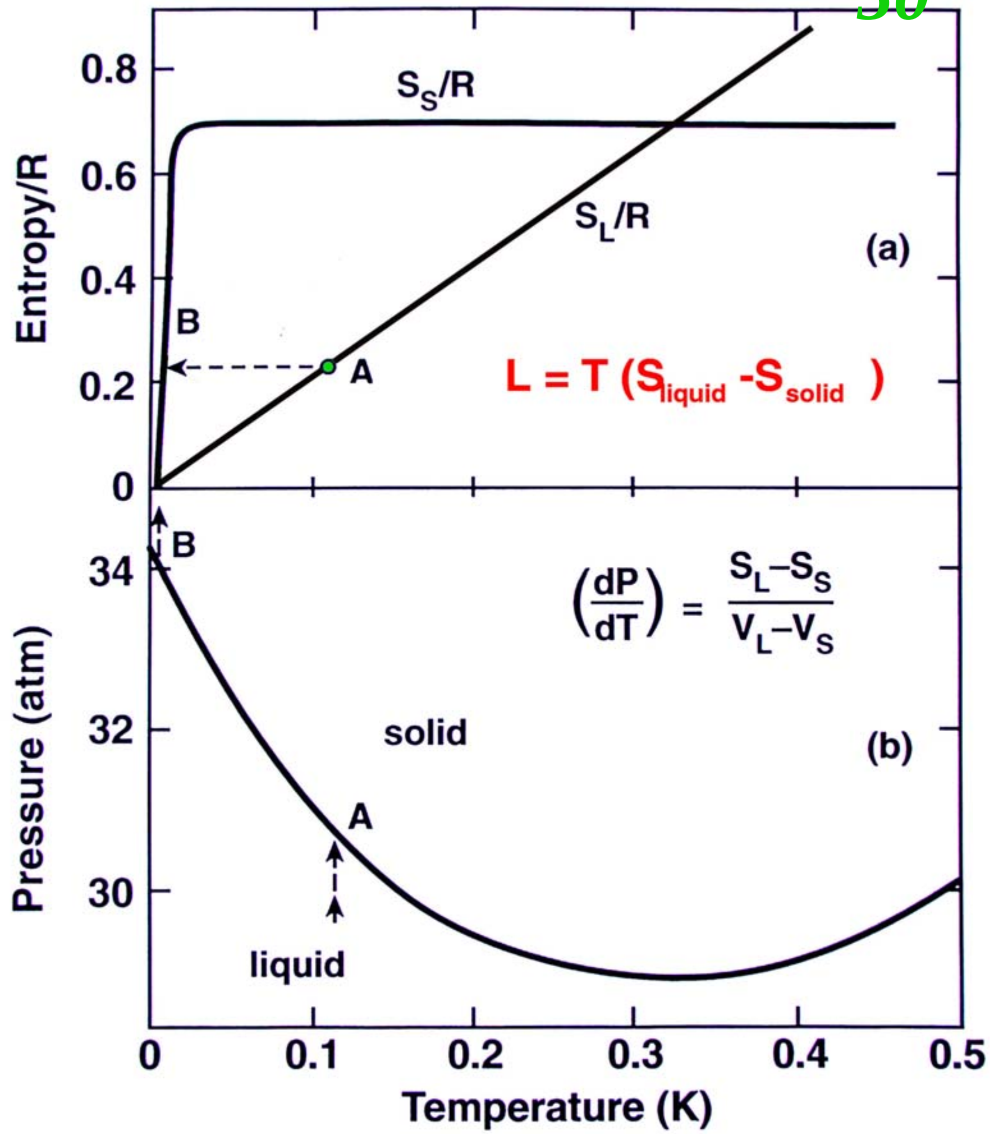
- 1950's Physicists study normal liquid behavior of ^3He (Wheatley+Landau)

- 1957 Bardeen, Cooper and Schrieffer explain superconductivity (BCS)

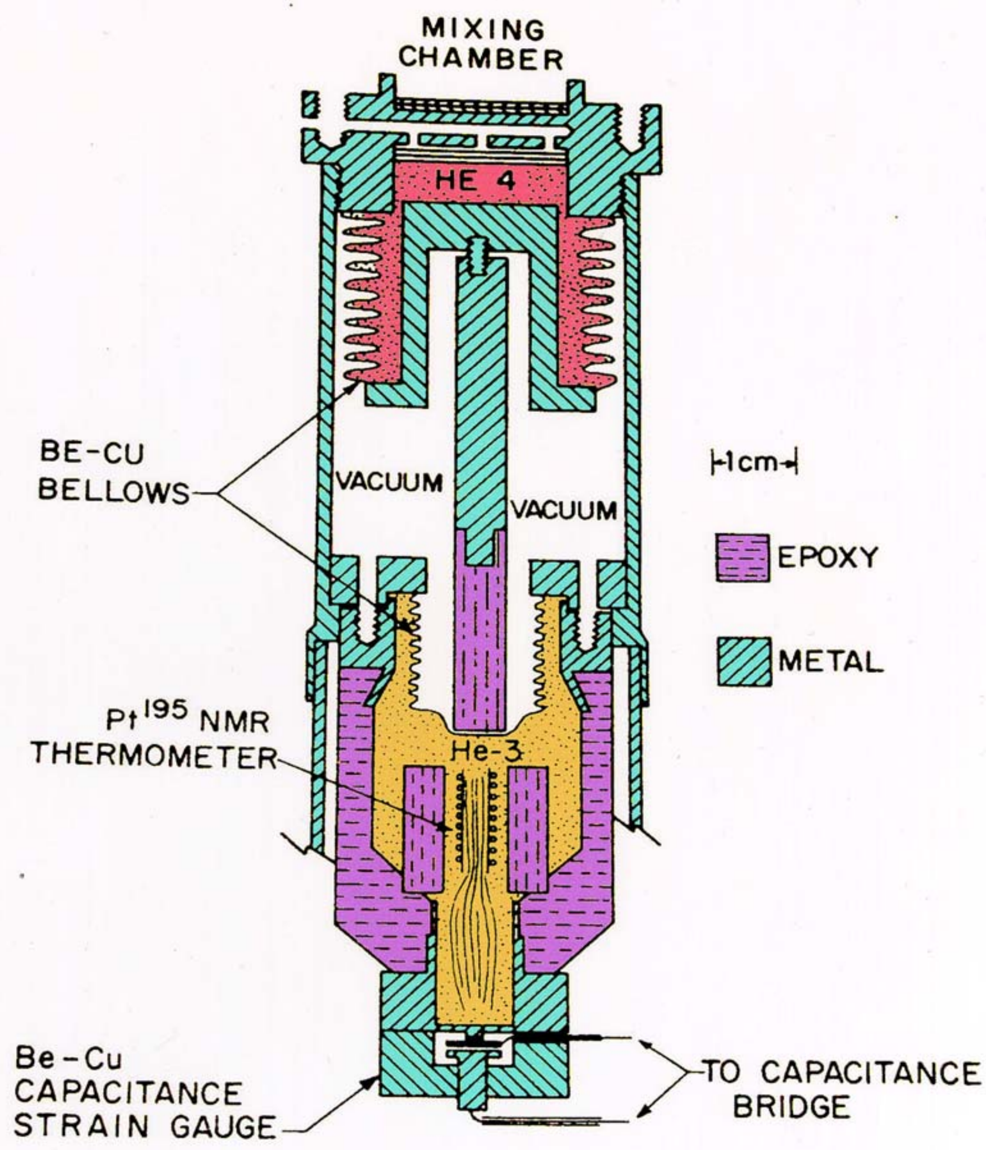
- 1959 Theorists predict ^3He would become a BCS superfluid at ~80 mK

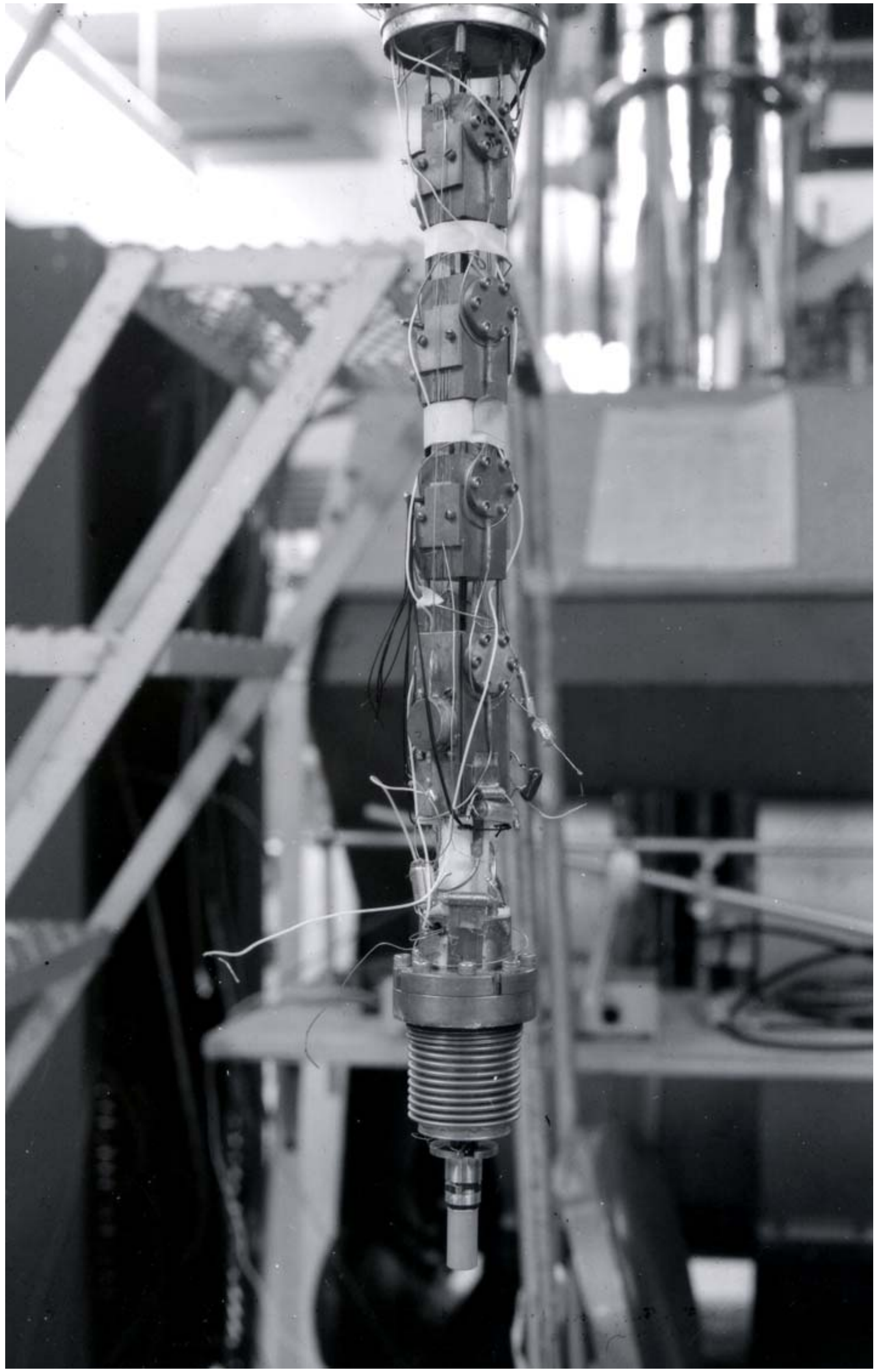
Christmas

Pomeranchuk's Conjecture: *1950*



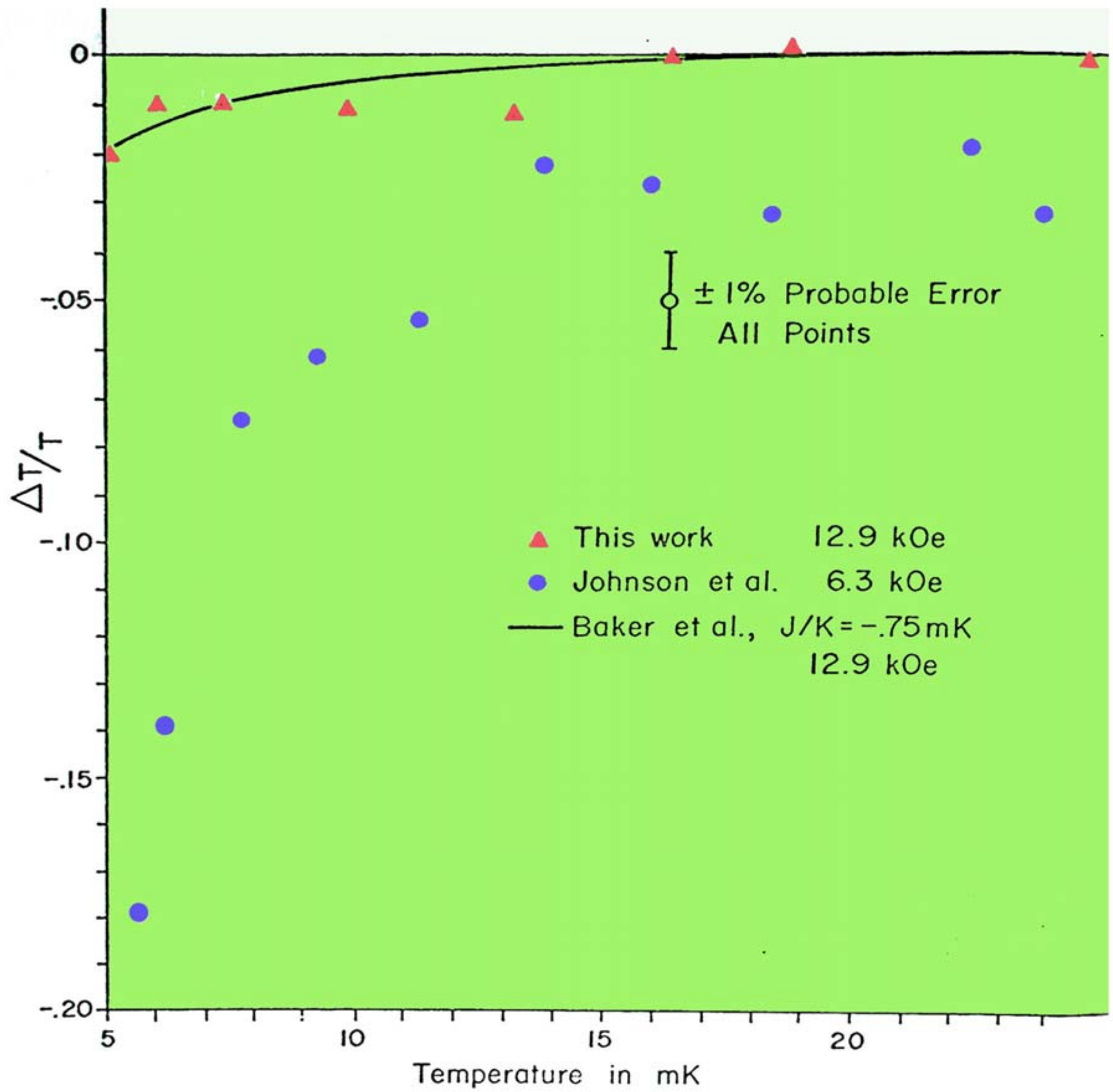
Osheroff's Pomeranchuk Cell

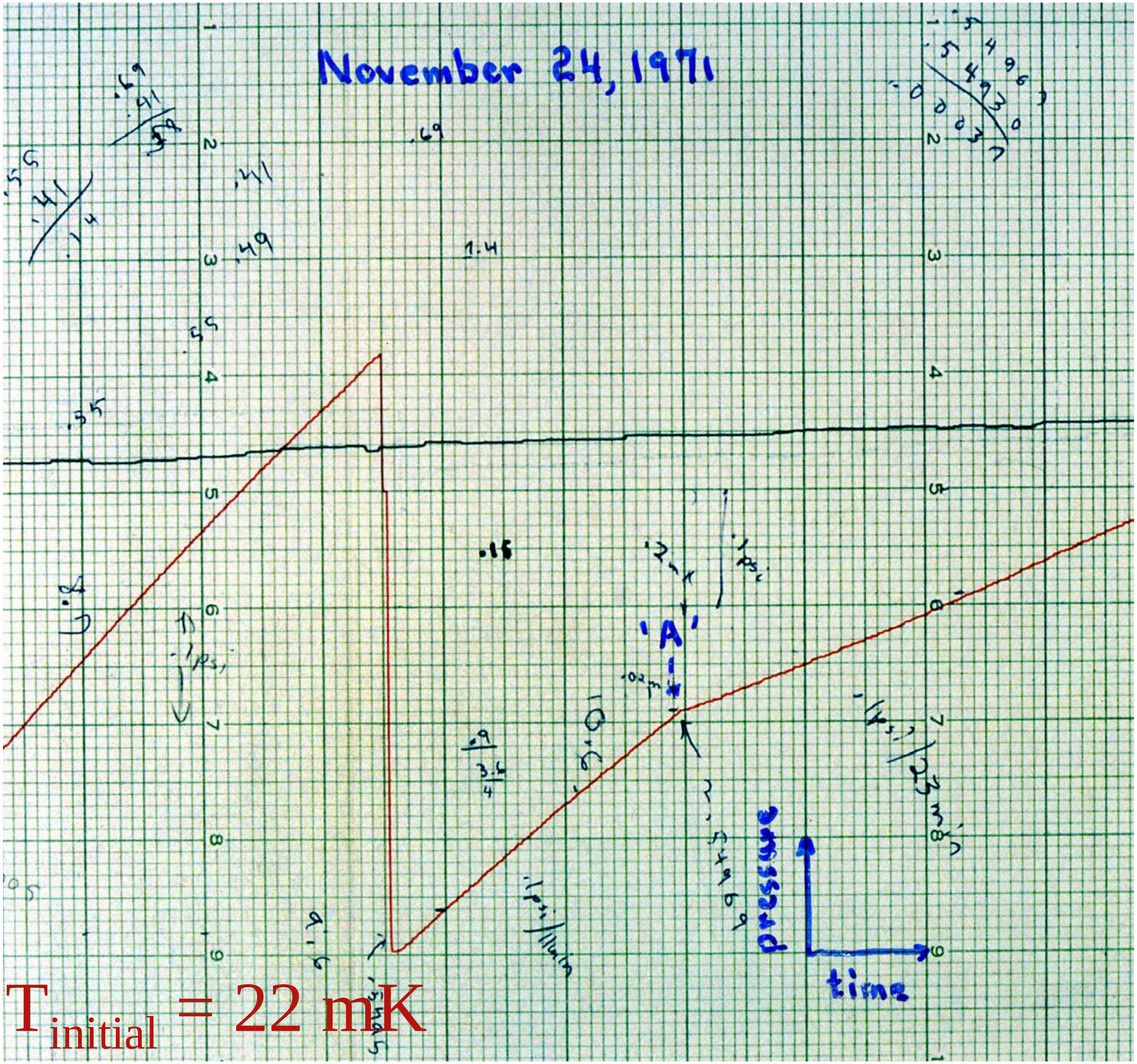




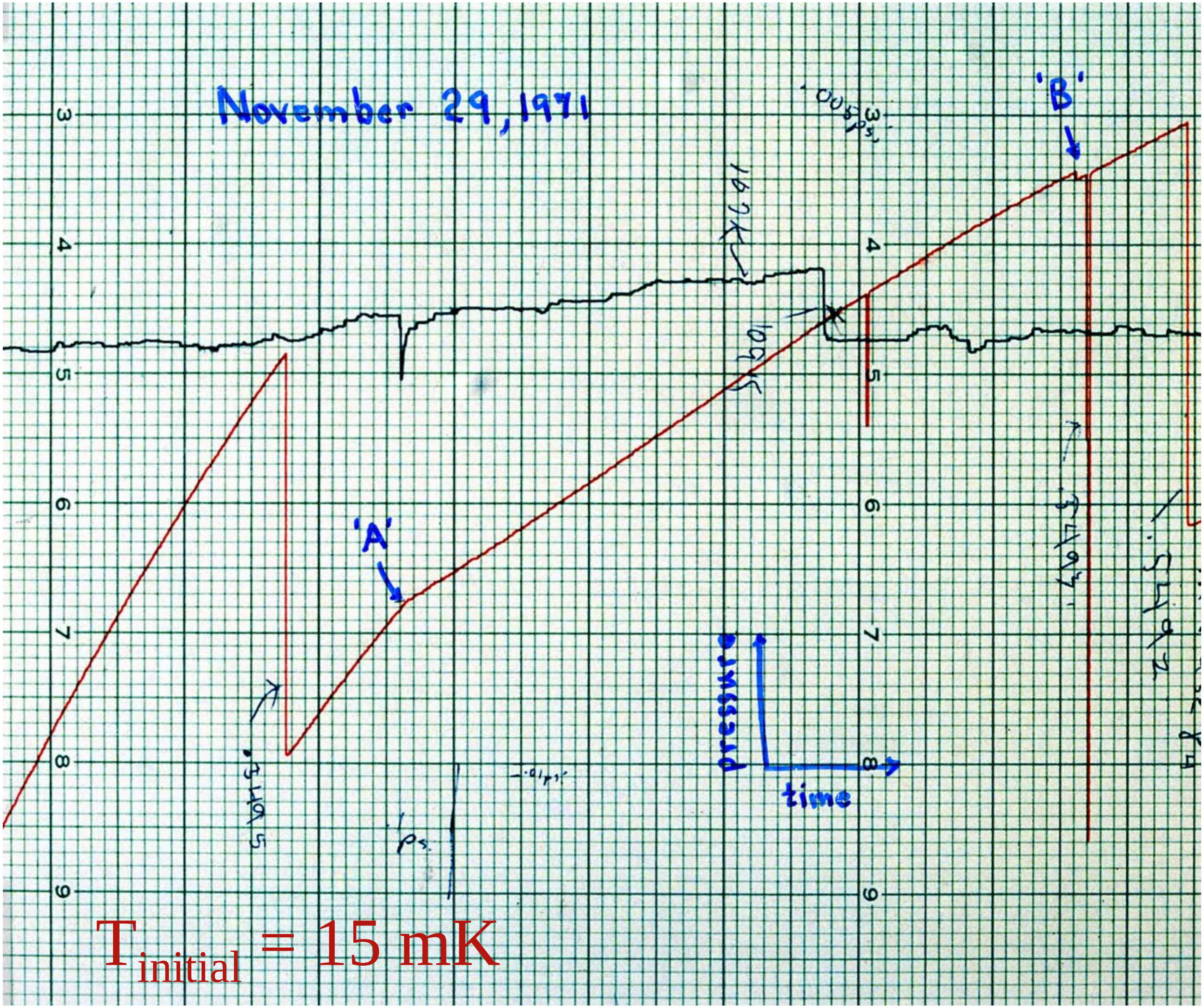

Conversational Chinese

Magnetic Field Supression of Melting Pressure



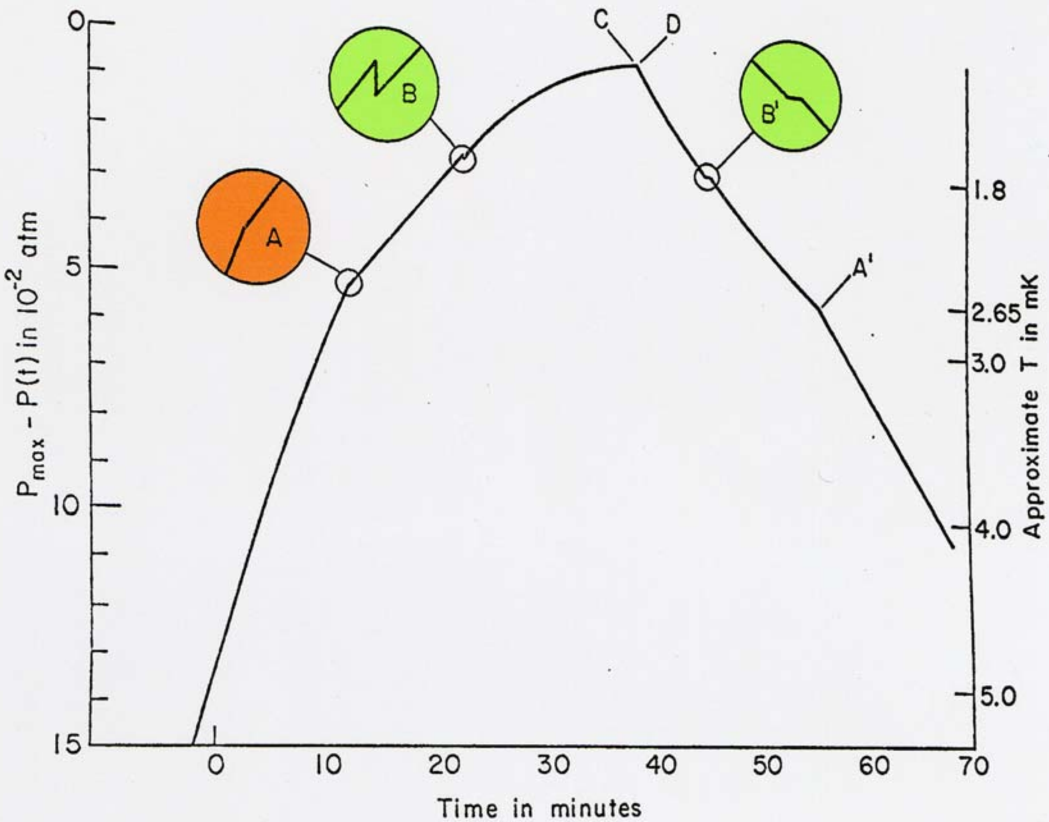


$T_{initial} = 22\ mK$



$T_{initial}$ = 15 mK

Full Pressurization Curve



$$\Delta P \sim (1/\Delta V) \int_{T_i}^{T_f} S_{solid}(T)\,dT$$

PRL 28, 885 (1972)

Evidence for a New Phase of Solid He^3 †

D. D. Osheroff, R. C. Richardson, and D. M. Lee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 10 February 1972)

Measurements of the melting pressure of a sample of He^3 containing less than 40-ppm He^4 impurities, self-cooled to below 2 mK in a Pomeranchuk compression cell, indicate the existence of a new phase in solid He^3 below 2.7 mK of a fundamentally different nature than the anticipated antiferromagnetically ordered state. At lower temperatures, evidence of possibly a further transition is observed. We discuss these pressure measurements and supporting temperature measurements.

On the basis of measured values of the solid-He^3 spin exchange energy J, defined by $\mathcal{H}_{ex} = -2J \times \sum_{i<j} I_i \cdot I_j$, it has been assumed that near 2.0 mK solid He^3 would order antiferromagnetically by a second-order phase transition.[1] In this Letter we present evidence that at 2.7 mK solid He^3 undergoes a phase transition of a nature fundamentally different from that which had been expected, and that the ordered state is most probably not the simple antiferromagnetic one assumed. The refrigeration device, pressure transducer, and thermometry employed in our measurements are described, the evidence is presented, and a brief discussion follows.

The method of compressional cooling of He^3 to obtain temperatures as low as 2 mK is by now well established.[2-4] The present apparatus, shown in Fig. 1, employs a pressure amplifier which consists of a set of beryllium-copper bellows connected by a rigid piston. The pressure amplifier enables a moderate He^4 pressure (< 10 atm) in the upper chamber, generated externally, to compress and solidify the He^3 in the lower chamber. Although sufficient volume changes can be generated to solidify the entire 12-cm^3 He^3 sample, seldom was over 40% solid ever formed in the experiments to be discussed.

The apparatus was attached directly to the mixing chamber of a dilution refrigerator for precooling and thermal isolation.[5] Above about 5 mK the compression process was highly revers-

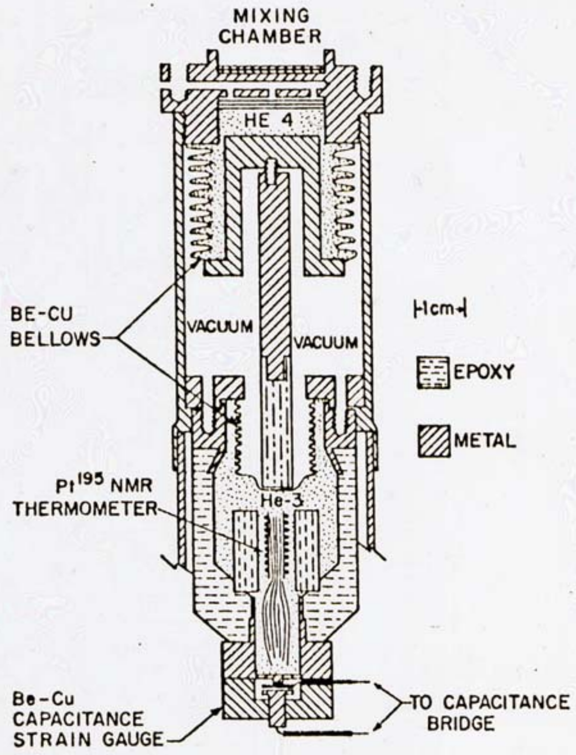
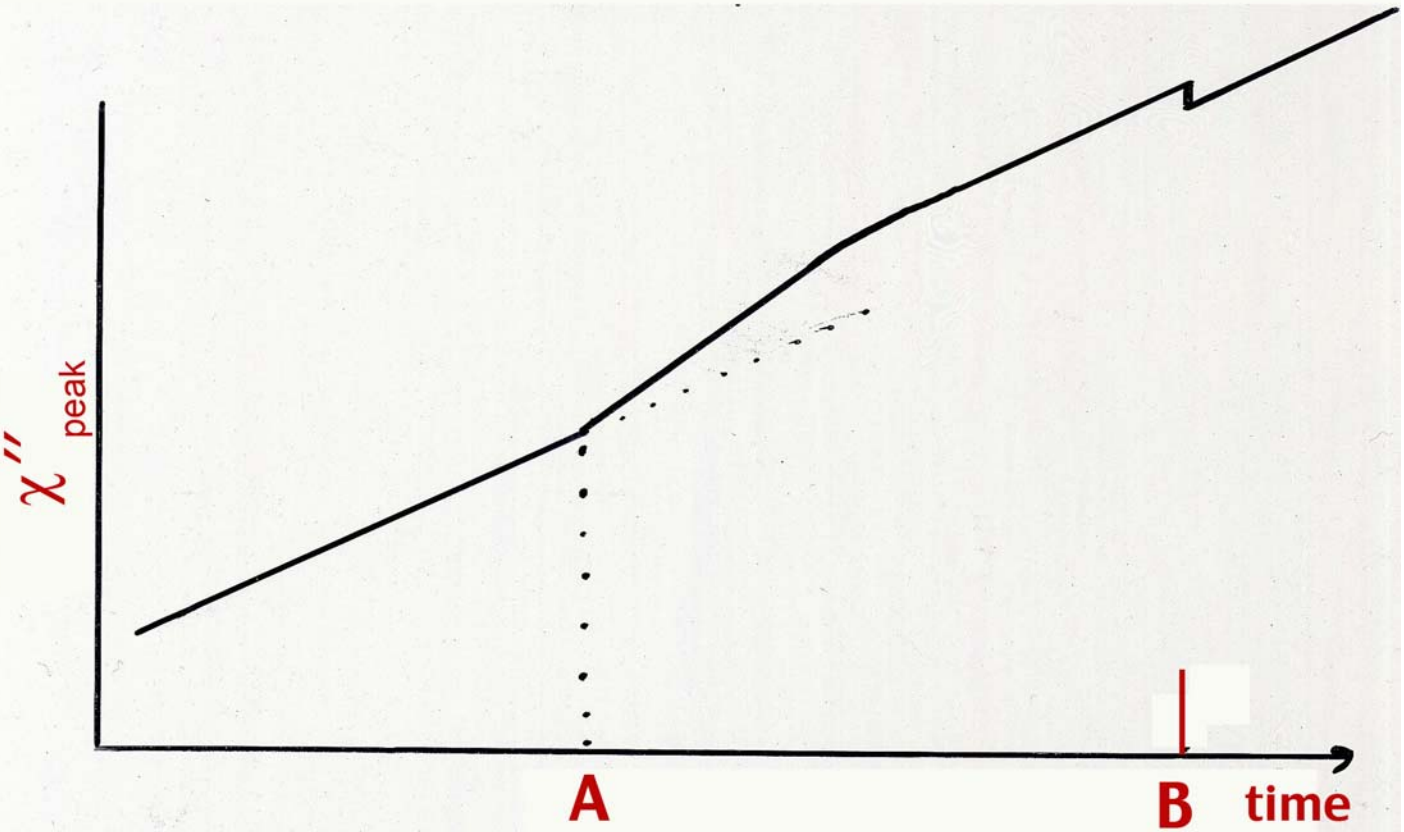
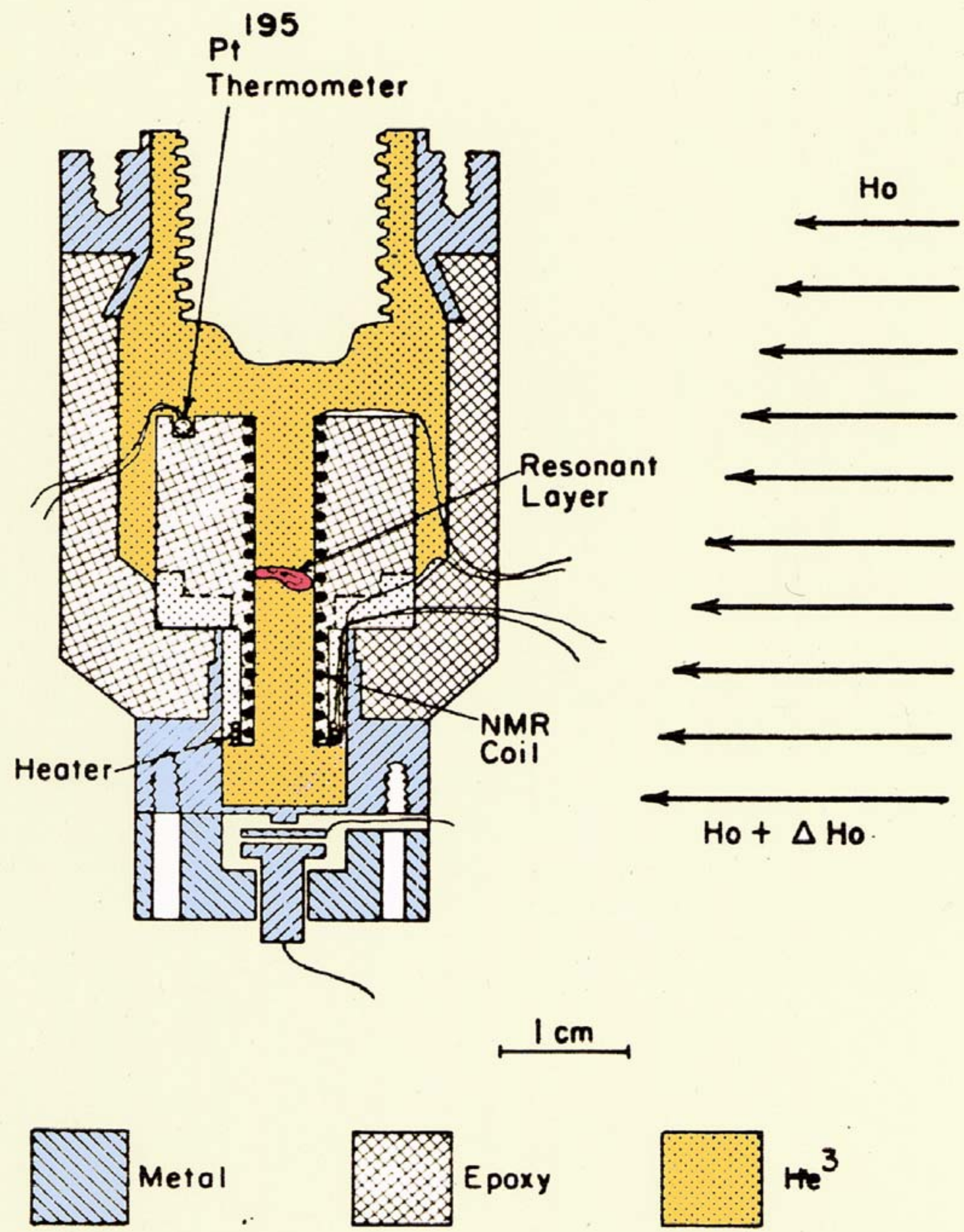


FIG. 1. Pomeranchuk cooling and pressure-measuring apparatus.

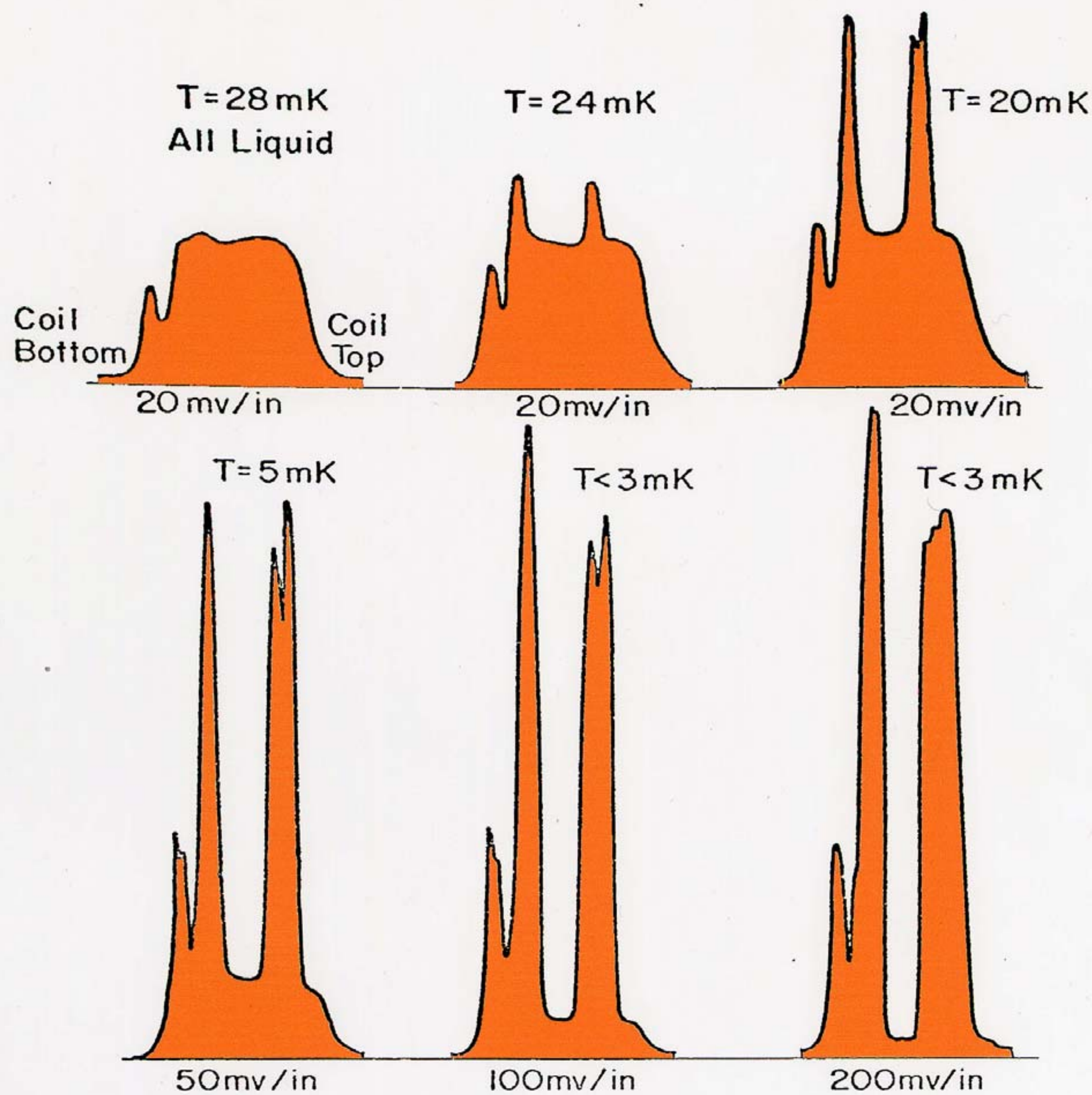
Behavior of Solid NMR Peaks at A Transition

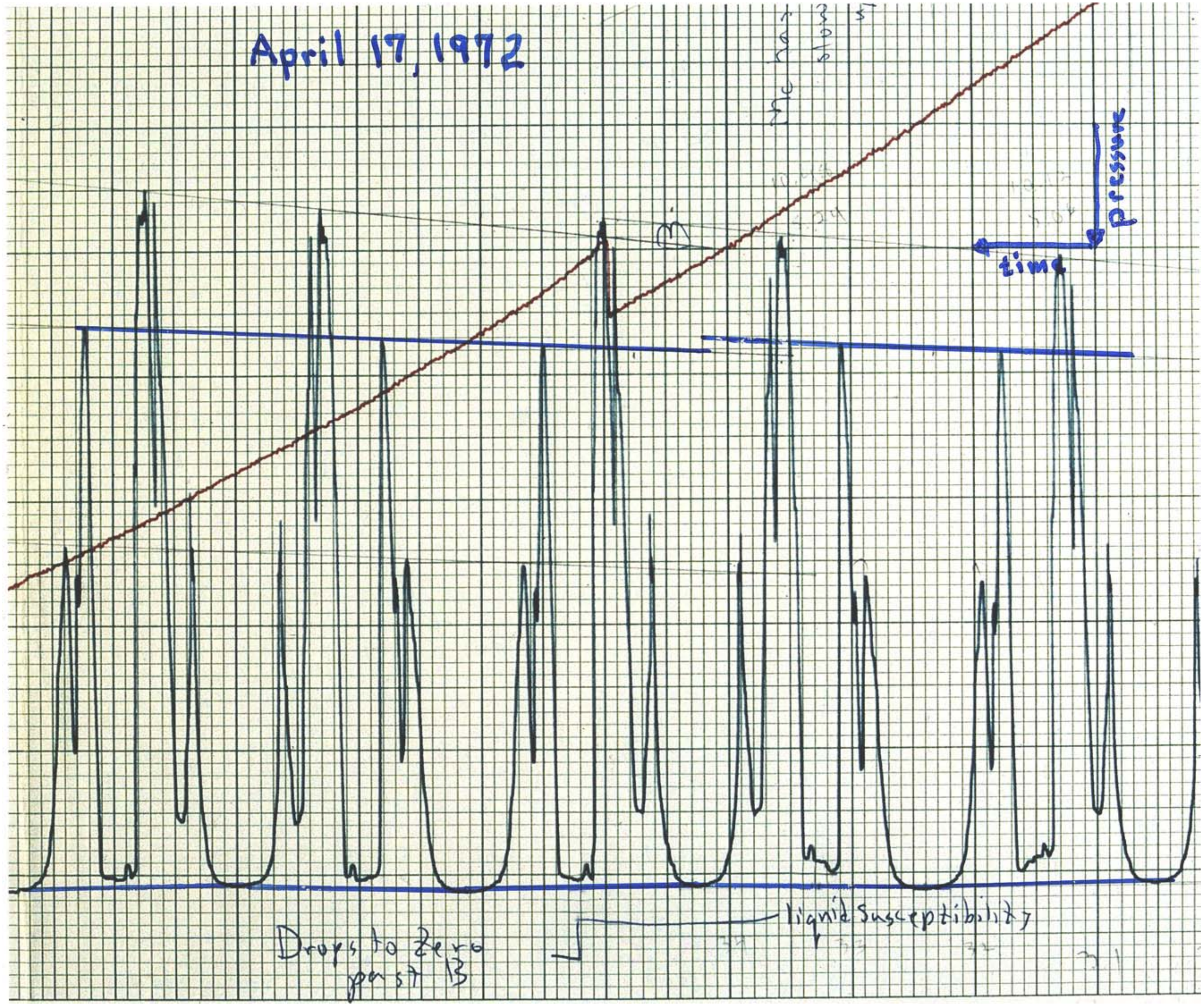


Change in magnetization slope small, but highly correlated with A-transition as seen in pressurization curves.



Pt^{195}
Thermometer
Ho
Resonant
Layer
NMR
Coil
Heater
Ho + ΔHo
1 cm
Metal
Epoxy
He^3


T=28 mK
All Liquid
Coil
Bottom
Coil
Top
20 mv/in
T=24 mK
20mv/in
T=20mK
20mv/in
T=5 mK
50mv/in
T<3 mK
100mv/in
T<3 mK
200mv/in


April 17, 1972
B
pressure
time
liquid susceptibility
Drops to zero past B

Apr 20 '72

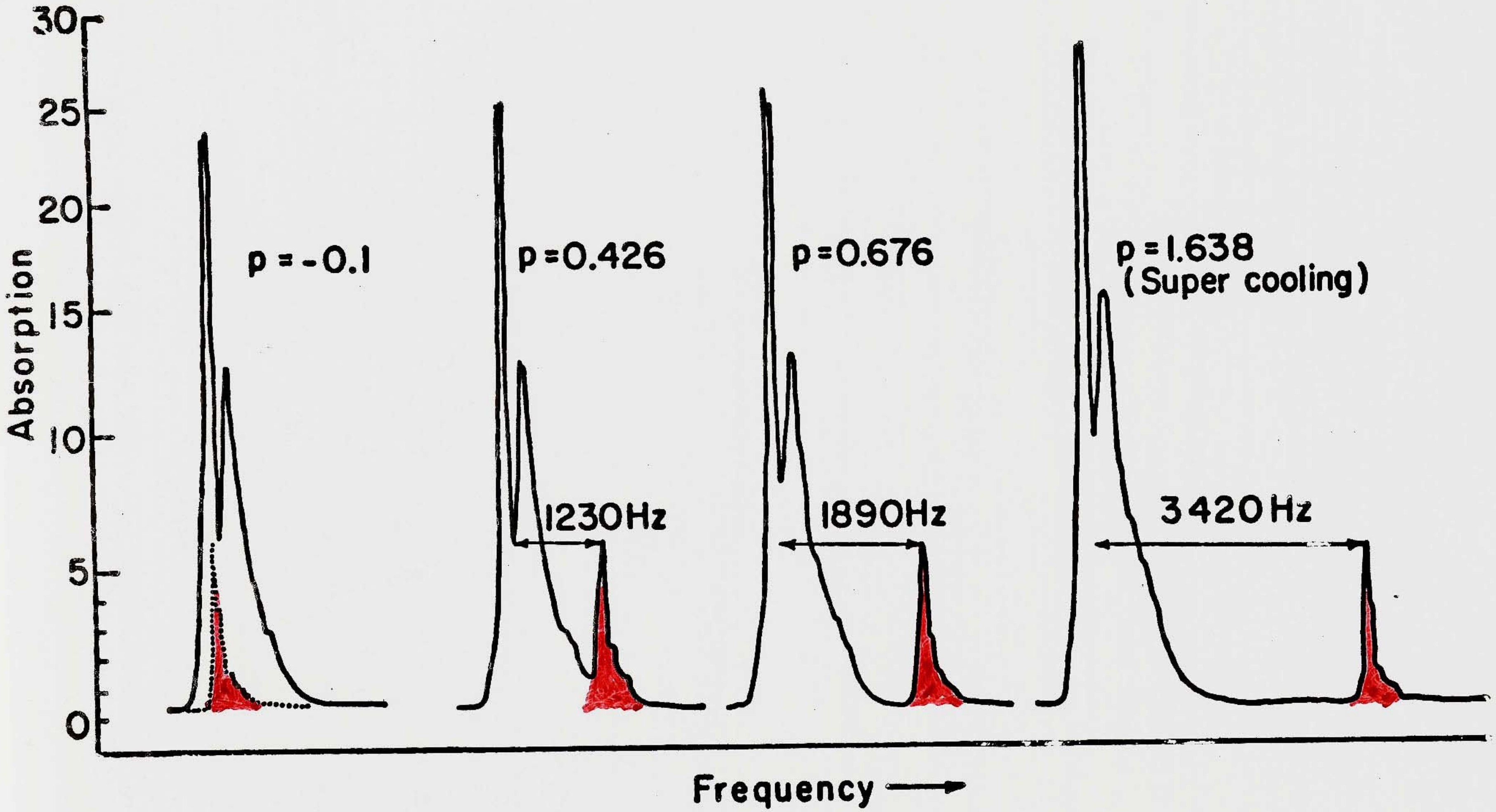
Decided to fool with sweep to try to "sit"
on a peak.

1:15 retransf, fill pot

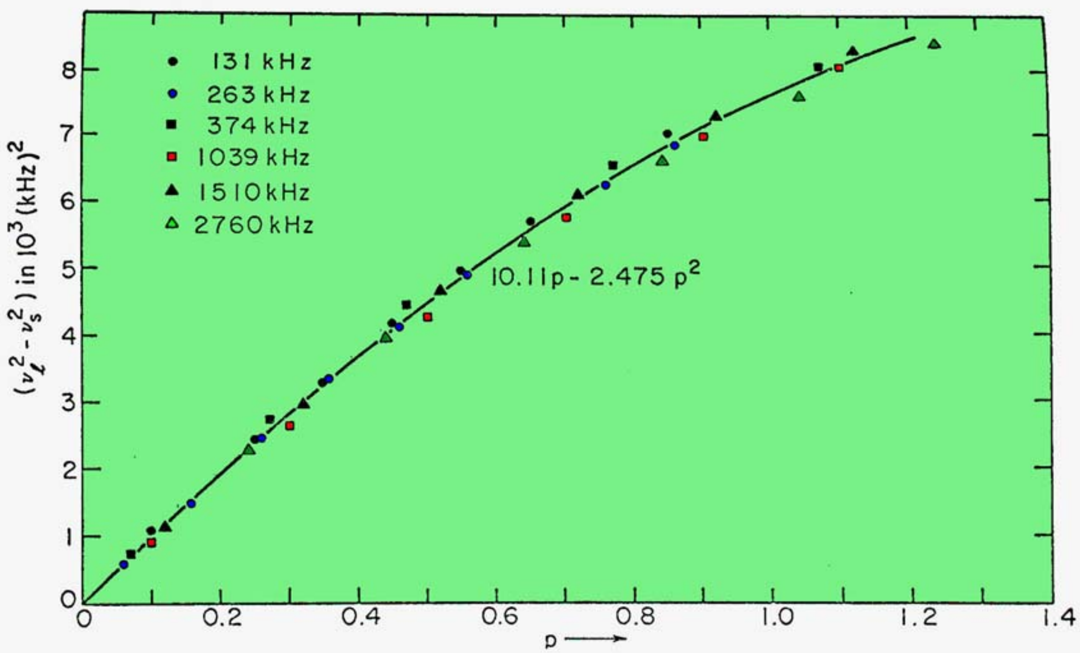
2:40 Have discovered the BCS transition in
liquid ^3He tonite. The pressure phenomena
associated with B & B' are accompanied
by changes in the He^3 susceptibility both
on & off the peaks approximately equal to the
entire liquid susceptibility.

17:40 MC = 51K

NMR Frequency Spectra: 4 June 1972

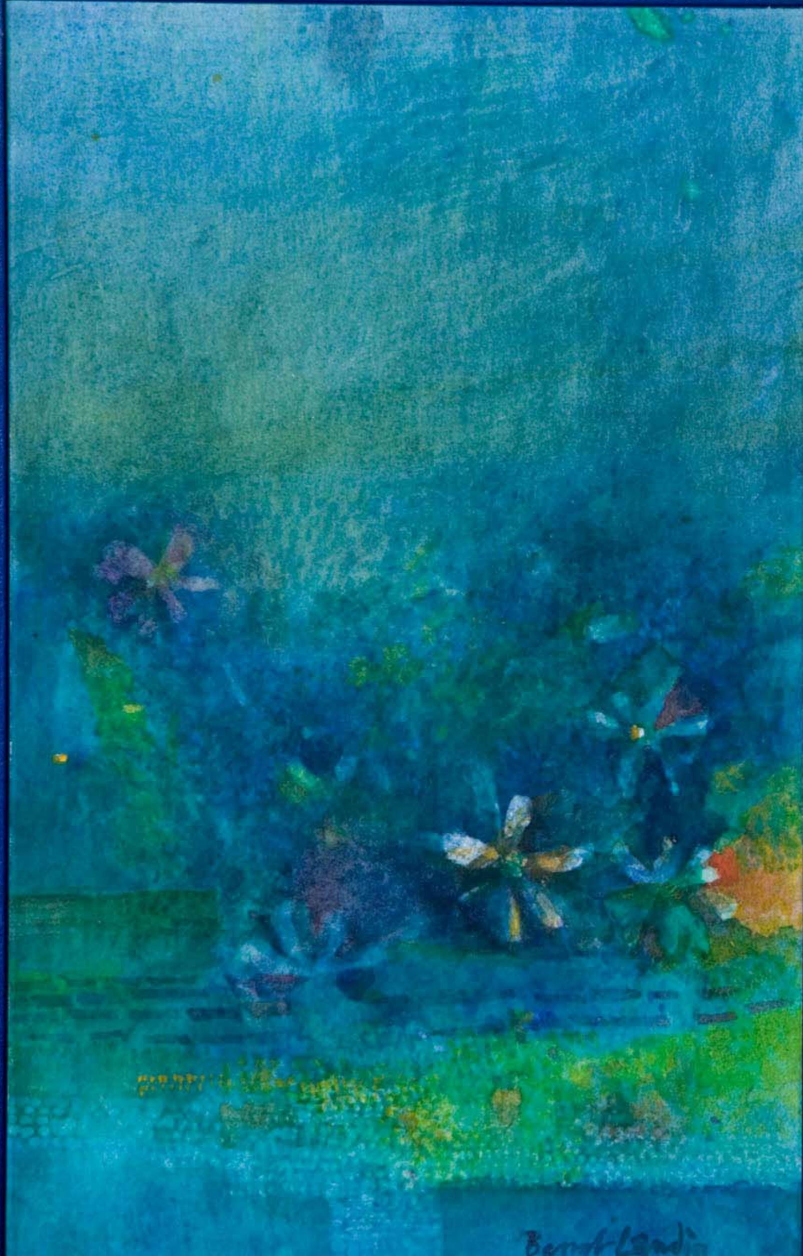


A Phase Frequency Shifts Collapsed



------A. J. Leggett

$$\nu_\ell^2 - \nu_s^2 = \text{Function (T)}$$



Kungliga
Svenska Vetenskapsakademien
har den 9 oktober 1996 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den
som inom fysikens område gjort
den viktigaste upptäckten eller
uppfinningen gemensamt belöna

Douglas D Osheroff

David M Lee och Robert C Richardson
för upptäckten av suprafluiditet
i helium-3

STOCKHOLM DEN 10 DECEMBER 1996

Strategies:

1. Utilize new technologies.

    • *View nature from a new perspective or in a different realm.*

2. Don’t give up when things are going badly.

    • *Failure may be an invitation to try something new.*

3. Spend a little time doing something

Basic Research At Bell Laboratories 1977:

Good research was research that taught us something new about Nature.

Joe Burton….Try something else.

Nuclear Antiferromagnetism in Solid ^{3}He

Weak Localization in Two Dimensions

Strategies:

1. Change the subject of your research occasionally.

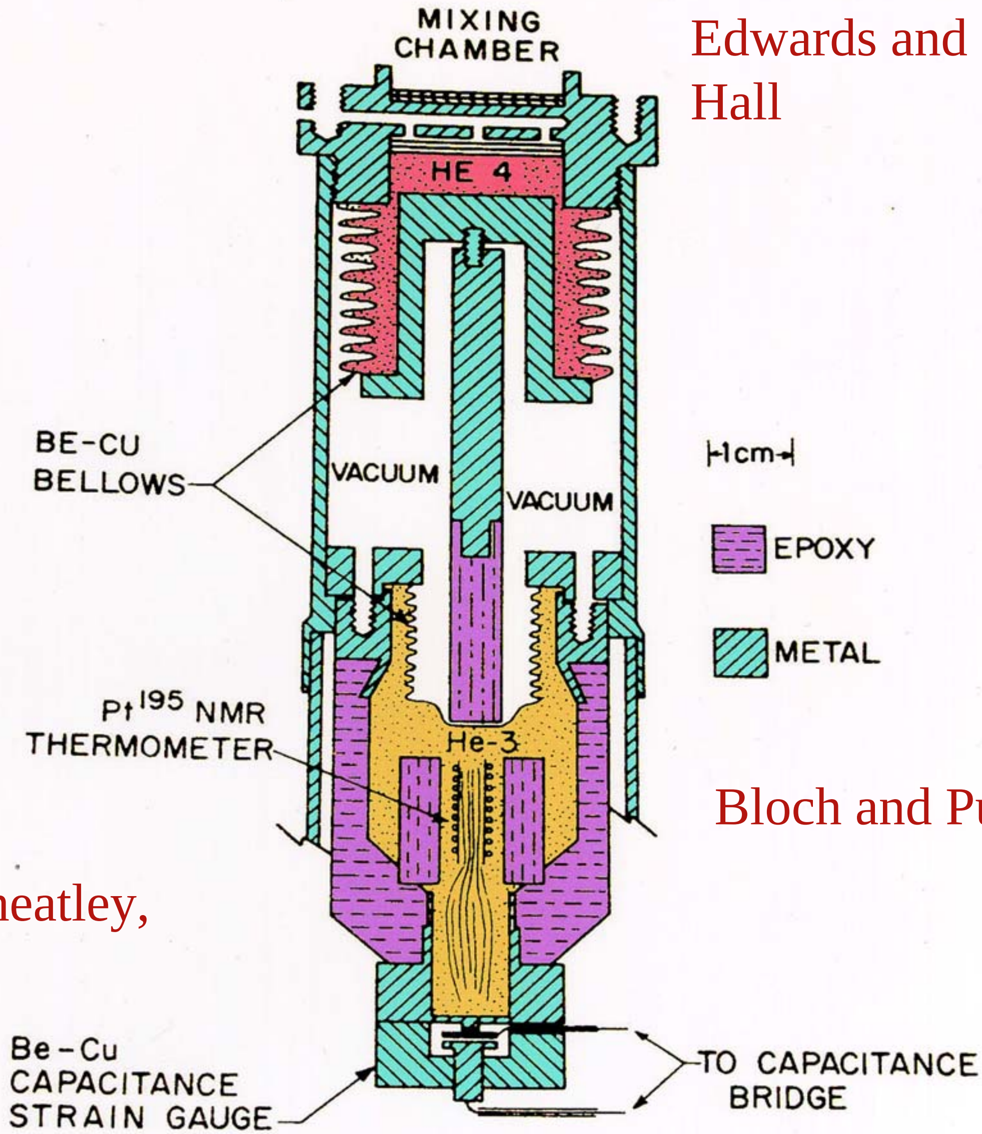
    • *After a while we lose perspective as well as run out of ideas.*

2. Note the predictions of theorists, but don't trust them to be correct.

    • *Good theorists have a nose for interesting physics, but we should not expect them to have all the details correct.*

Osheroff's Pomeranchuk Cell

Edwards and Hall



Bloch and Purcell

Hammel, Wheatley, Landau …

Stratey and Adams

to answer those questions, and sharing their results and their ideas with others. To have rapid progress, one must support scientific research broadly, and encourage scientists to interact with one another and to spend some of their time satisfying their own curiosities.

….This is How Advances in Science Are Made