

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
• AND
JOURNAL OF SCIENCE.

—♦—
[FIFTH SERIES.]

OCTOBER 1897.

XI. *Cathode Rays.* By J. J. THOMSON, M.A., F.R.S.,
Cavendish Professor of Experimental Physics, Cambridge*.

THE experiments † discussed in this paper were undertaken in the hope of gaining some information as to the nature of the Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the æther to which—inasmuch as in a uniform magnetic field their course is circular and not rectilinear—no phenomenon hitherto observed is analogous: another view of these rays is that, so far from being wholly æthereal, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity. It would seem at first sight that it ought not to be difficult to discriminate between views so different, yet experience shows that this is

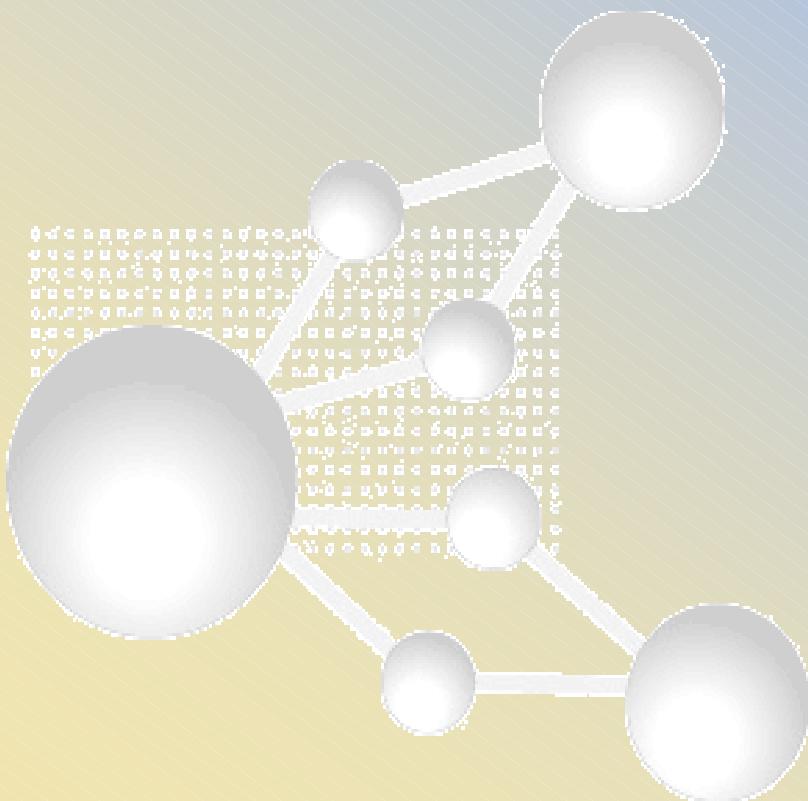


British physicist J. J. Thomson ushered in a new era of subatomic physics by discovering the electron in 1897. Here he is shown in the 1890s with the apparatus he used to determine the ratio of the electron's electrical charge to its mass.

J.J. Thomson

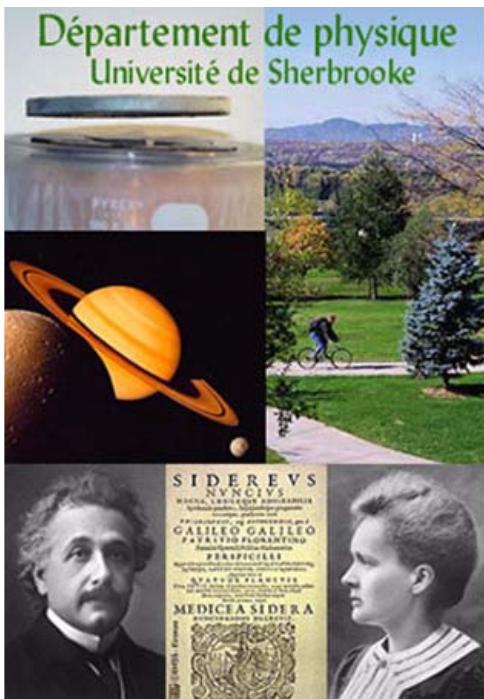
Superconductivity: the old and the new

A one hundred year voyage of discoveries

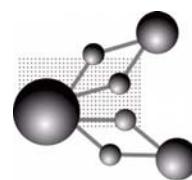


*André-Marie Tremblay
Département de Physique
Université de Sherbrooke*

<http://www.physique.usherb.ca/~tremblay>



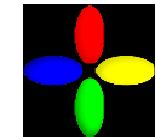
André-Marie Tremblay



CENTRE DE RECHERCHE SUR LES PROPRIÉTÉS
ÉLECTRONIQUES
DE MATÉRIAUX AVANCÉS



Commanditaires:



The old

- Looking for what happens to Ohm's law near absolute zero
- Quantum mechanics
- Looking for an explanation: a series of failures and a triumph
- A first golden age for superconductivity
- The vanishing act

The new

- The dream of high temperature superconductivity
- 1987: the revolution
- 17 years later, some of the mystery remains
- Strongly correlated electrons
- Lifting the veil. Some of what we did... (Part II)

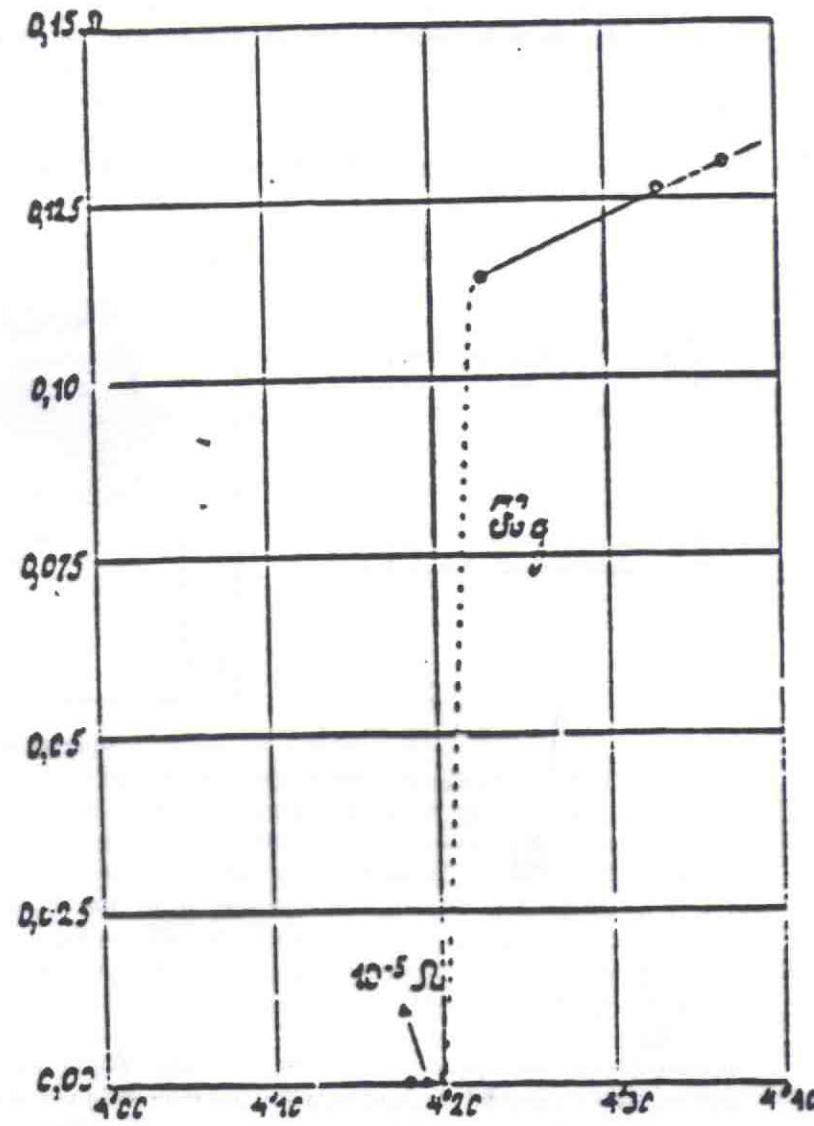
The old

- Looking for what happens to Ohm's law near absolute zero
-

- J.J. Thomson and the electron, october 1897
- Drude (1900) proposes a theory of metals
- Liquefaction of gases: moving closer to $T = 0 \text{ K}$
 - What happens to the resistance of metals at $T=0$?
 - Propositions: $R = 0$ or $R = \text{infinity}$.
- The Dutch Kamerlingh Onnes in 1911 just liquified Helium, which allows him to reach $T = 4\text{K}$

Kamerlingh Onnes 1911

Perfect conductivity



Temperature (°K)

History :

1911: Hg (used as a thermometer)



Many elements are superconductors.

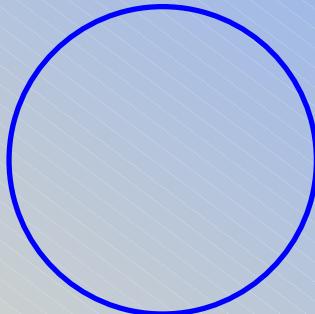
KNOWN SUPERCONDUCTIVE ELEMENTS																	
IA		IIA															
1	H	3	4														
2	Li	Be															
3	Na	Mg															
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
7	Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110	111	112					Rn
SUPERCONDUCTORS.ORG																	
* Lanthanide Series				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Superconducting elements :

Plomb (Pb)	7.2 K	Zinc	0.85 K
Niobium (Nb)	9.1K	Osmium	0.66 K
Lanthane (La)	4.9 K	Zirconium	0.61 K
Tantale	4.47 K	Americium	0.6 K
Mercure (Hg)	4.15 K	Cadmium	0.517 K
	(1 ^{er} superconducteur découvert - 1911)	Ruthenium	0.49 K
Étain (Sn)	3.72 K	Titane (Ti)	0.40 K
Indium (In)	3.40 K	Uranium	0.20 K
Thallium	1.70 K	Hafnium	0.128 K
Rhenium	1.697 K	Iridium	0.1125 K
Protactinium	1.4 K	Lutetium	0.1 K
Thorium	1.38 K	Beryllium	0.026 K
Aluminum (Al)	1.175 K	Tungsten	0.0154 K
Gallium	1.10 K	Platine	0.0019 K
Gadolinium	1.083 K	Rhodium	0.000325 K
	(ferromagnétique au-dessus T_c ; diamagnétique sous T_c)		
Molybdenum	0.915 K		

- No resistance to electrical current

- No dissipation of electrical energy into heat (No Joule effect)



A closed superconducting loop transports a current indefinitely

Immediate applications that come to mind:

Transmission lines

Electromagnets

<http://www.nobel.se>

1913: Physics Nobel Prize

To professor H. Kamerlingh Onnes from Leiden, for his experiments on the properties of matter at low temperature that lead, concomitantly to the production of liquid Helium.

The old

- Quantum mechanics

- Planck around 1900 and Einstein 1921:
Light (wave) sometimes behaves as if it was formed of packets of energy
$$h\nu$$
- de Broglie 1924: Matter sometimes behaves as if it had a wavelength
$$\lambda = \frac{h}{mv}$$
- Schrödinger 1926 : Wave equation,
- Heisenberg: matrix mechanics
- Bohr: complementarity principle
- Concept "quantum state"
- Allows a detailed understanding of the behavior of matter at the atomic scale (but not superconductivity).

Physics 1906

An irony of history: paradoxical prizes.

THOMSON, Sir JOSEPH JOHN, Great Britain, Cambridge University,
* 1856, † 1940:

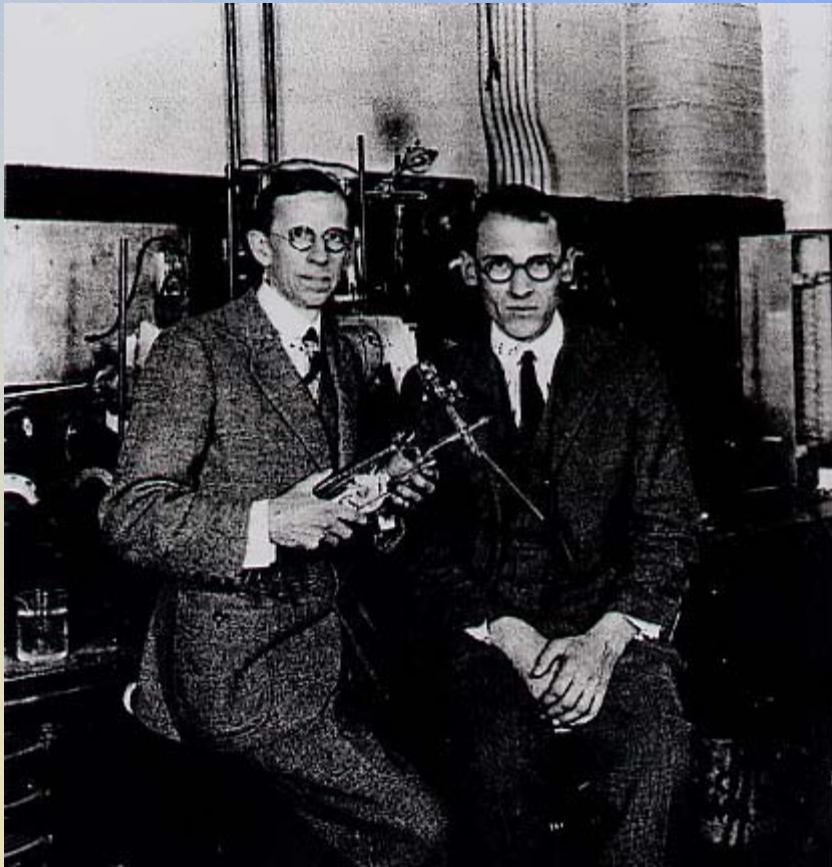
“recognizing the value of his theoretical and experimental studies of electrical conduction in gases ”

Physique 1937

DAVISSON, CLINTON JOSEPH, U.S.A., Bell Telephone Laboratories, New York, NY, * 1881, † 1958; and

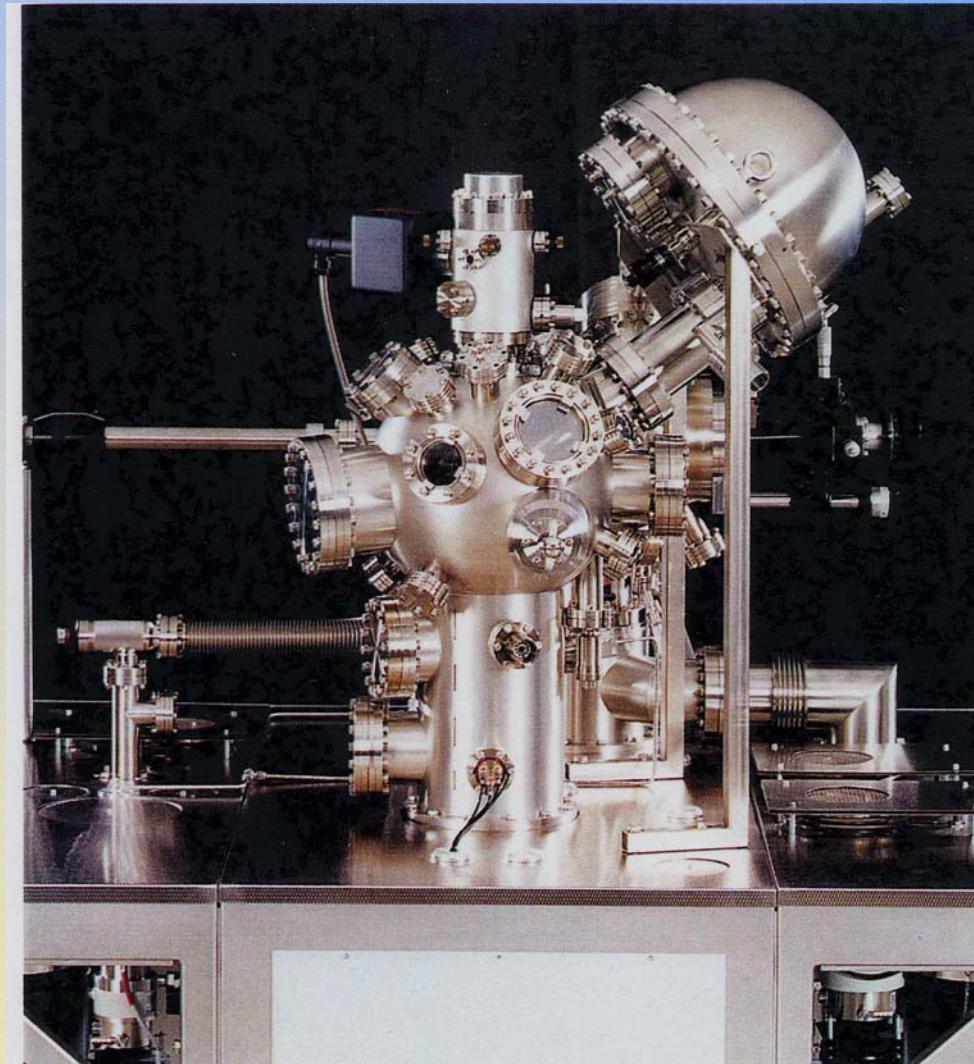
THOMSON, Sir GEORGE PAGET, Great Britain, London University,
* 1892, † 1975:

“for their experimental discovery of the diffraction of electrons by crystals ”



In 1927, Clinton Davisson (left) and Lester Germer provided convincing evidence for one of the strangest notions in the history of science, namely that moving particles behave like waves, with a wavelength that depends on their energy. One distinctive property of waves is diffraction, the bending of waves when they encounter an obstacle or aperture. Davisson and Germer showed that this happens to electrons striking a piece of metal. The effect is seen clearly if the electrons have an energy that makes their wavelengths similar to the spacing between layers of atoms in the metal crystal.

An electronic microscope of the last century



The old

- The Meissner effect
-

- 1933: a major discovery for superconductivity.
- W. Meissner and R. Ochsenfeld find that a superconductor is not only a perfect conductor, it also exhibits perfect diamagnetism.

Perfect diamagnetism is called the Meissner effect

The old

- Looking for an explanation: a series of failures and a triumph
-

- During 46 years, from 1911 to 1957, superconductivity remains unexplained.
- In 1950 it is the most important problem in theoretical Physics.
- Richard Feynman: « *No one is smart enough to explain it* »

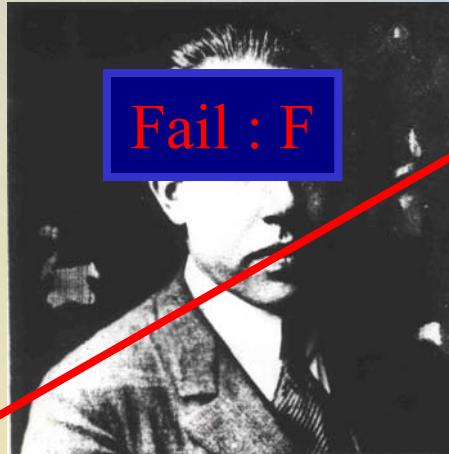


Feynman



Heisenberg

Bohr



NIELS BOHR (1885–1962) introduced the idea that the electron moved about the nucleus in well-defined orbits. This photograph was made in 1922, nine years after the publication of his paper

Einstein



Bose-Einstein Condensation of Trapped Electron
Pairs. Phase Separation and Super-
conductivity of Metal-Ammonia
Solutions

RICHARD A. OGG, JR.

Department of Chemistry, Stanford University, California

March 2, 1946

Phys. Rev. 69, 243 (1946)

“In Ogg’s theory it was his intent
That the current keep flowing, once sent;
So to save himself trouble,
He put them in double,
And instead of stopping, it went.”

- G. Gamow

The old

- BCS theory (1957)
-

Quantum behavior at the macroscopic scale

Leon Cooper



Nobel Prize : 1972

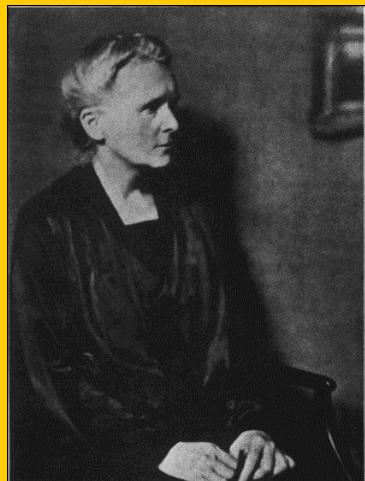
John Bardeen*

Robert Schrieffer

- John Bardeen :
- The only person to receive two Nobel prizes in Physics !!!

Invention : TRANSISTOR!

W. Shockley, J. Bardeen, W.H. Brattain



Marie Curie:

1903 Physics with H.A. Becquerel

1911 Chemistry (alone)

Juillet 1977, Wolfeboro, N.H. :

Gordon Research Conference on
"Nonequilibrium Phenomena in Superconductors and Superfluids",

John Bardeen

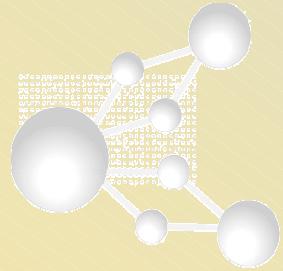
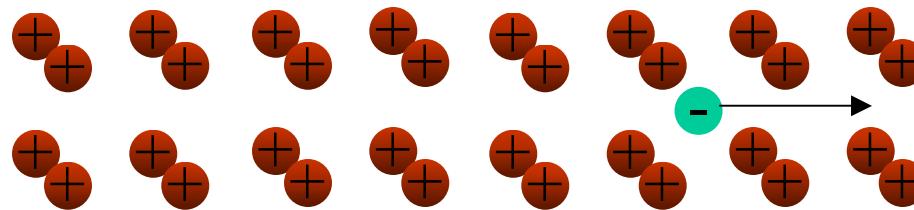


Forest Ranger

Bruce Patton

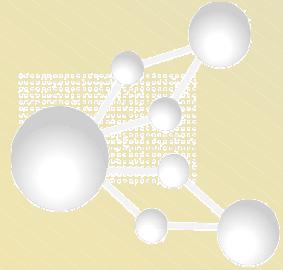
Tony Leggett

Resistance of a normal metal

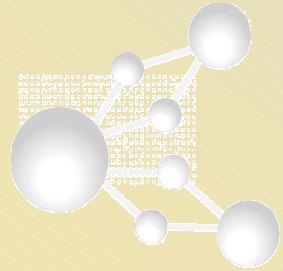
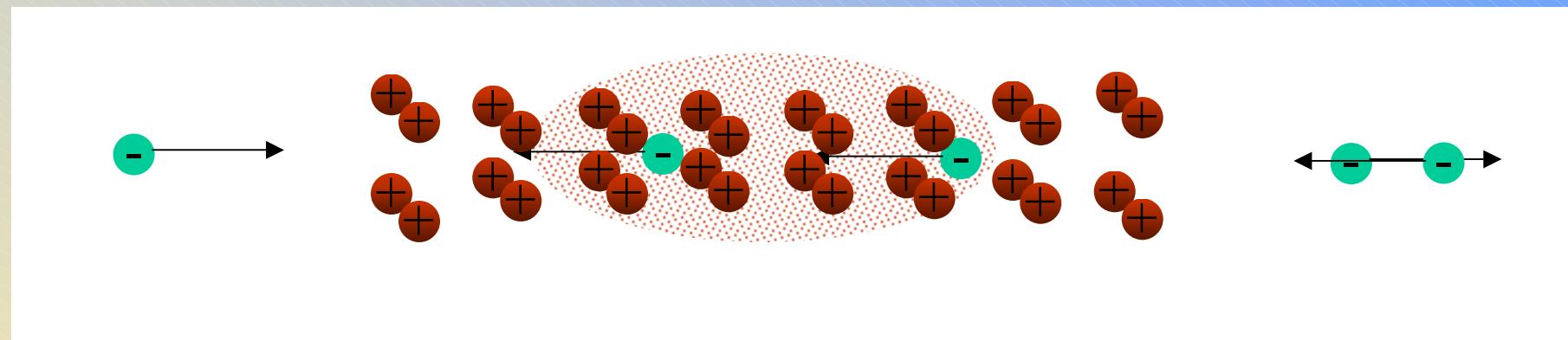


Ingredient #1

Attraction and formation of Cooper pairs



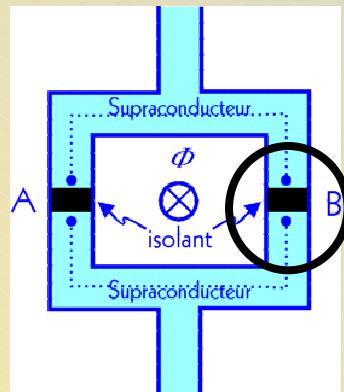
Cooper pairs or Prelude to supraconductivity



Ingredient #2 Coherence

Cooper form "bosons" that all "condense" in the same quantum state. Their wave functions all have the same quantum phase. Electrons are in a single coherent state (Like in a big atom!).

A spectacular application of coherence: Josephson effect



$$I = I_0 \sin (2\pi \phi)$$
$$d\phi/dt = 2eV/h$$

N.B. - Factor 2
- Standard for the Volt

Physics 1973

The Prize was divided in two

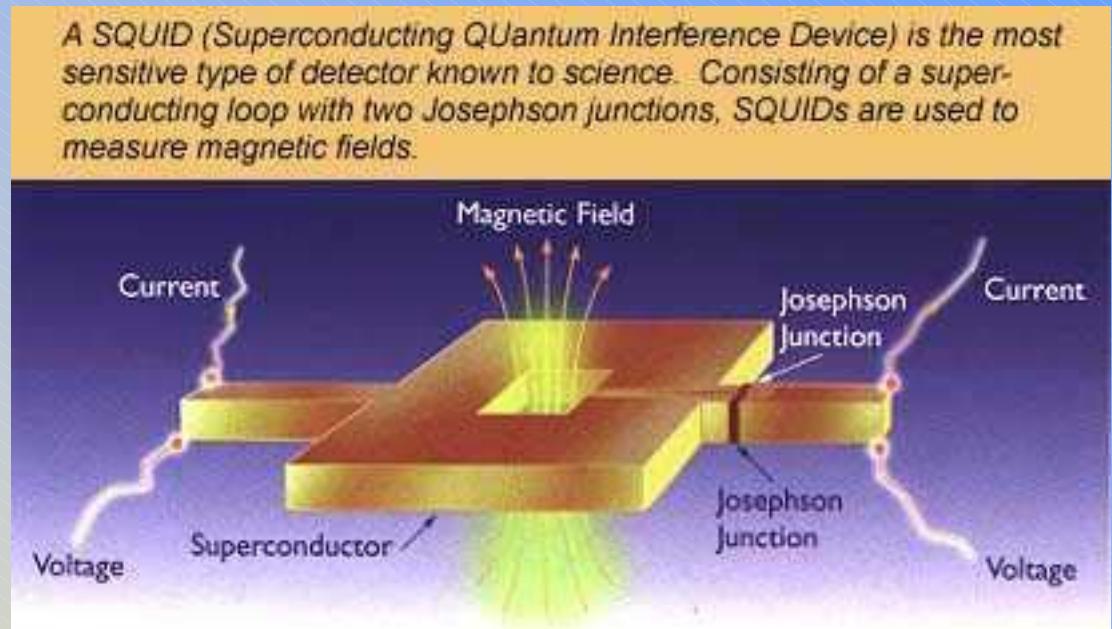
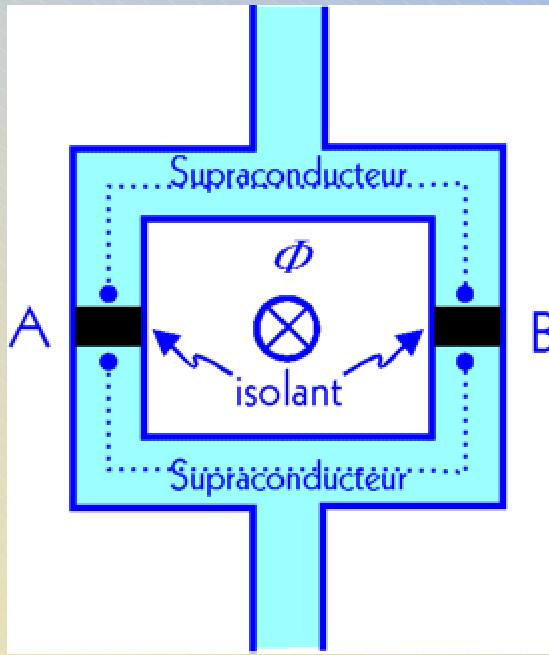
ESAKI, LEO, Japan, IBM Thomas J. Watson Research Center,
Yorktown Heights, NY, U.S.A., * 1925; and
GIAEVER, IVAR, U.S.A., General Electric Company, Schenectady,
NY, * 1929 (in Bergen, Norway),

“for their experimental discovery of the tunnel effect in semiconductors and superconductors respectively.”

JOSEPHSON, BRIAN D., Great Britain, Cambridge University,
Cambridge, * 1940:

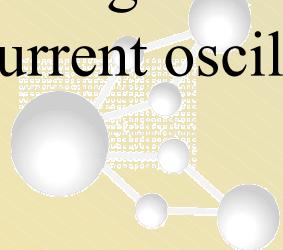
“For his theoretical predictions on supercurrents in tunnel barriers, in particular for the phenomena generally known as Josephson effects. ”

Detection of weak magnetic fields

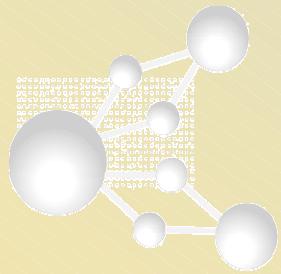
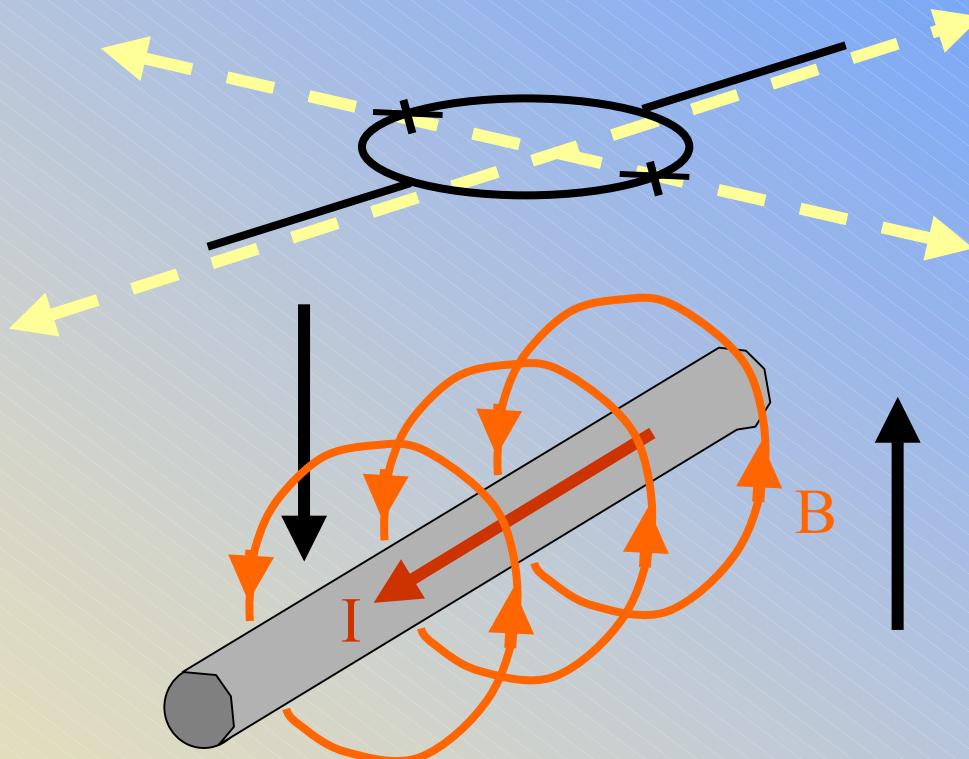


SQUID "Superconducting Quantum Interference Device"

A magnetic field modifies the phase of matter waves. By detecting current oscillations, one can detect very weak magnetic fields.



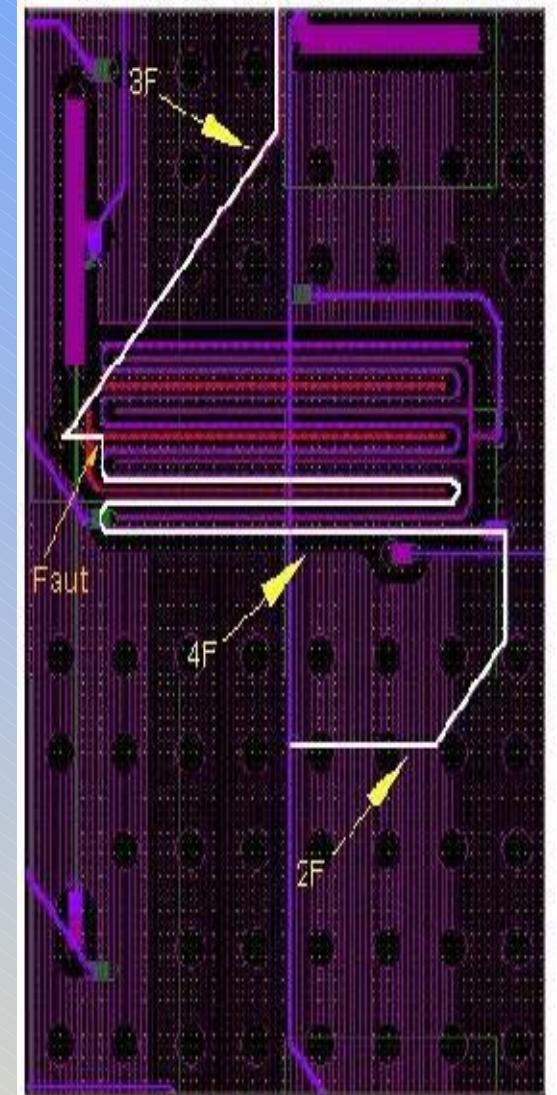
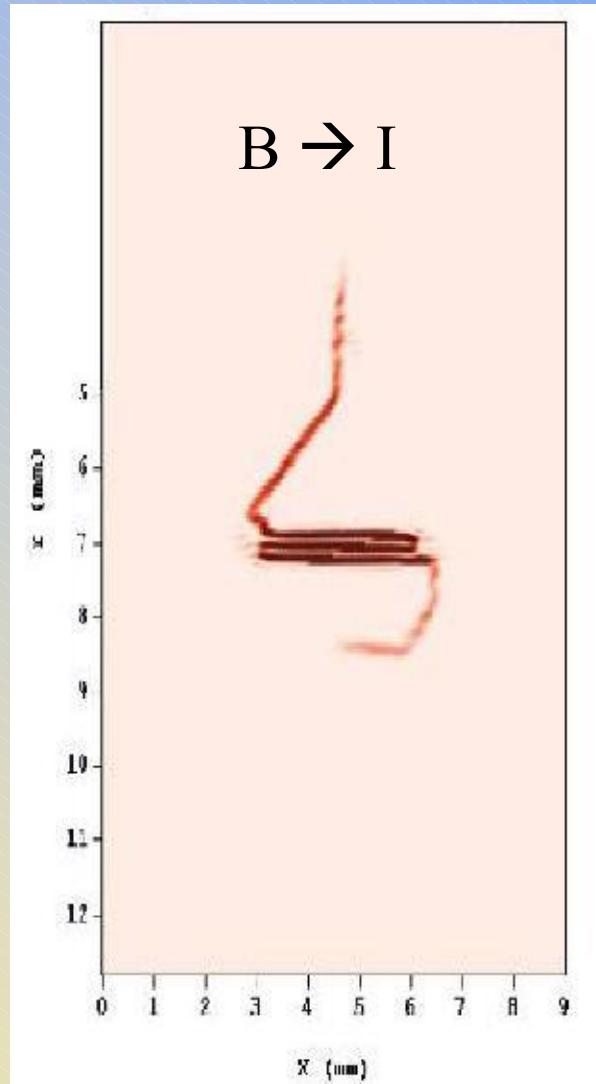
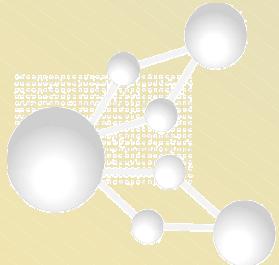
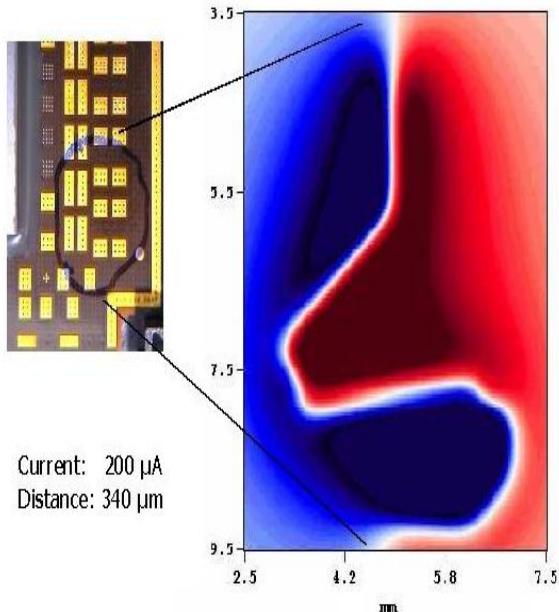
Detection of weak magnetic fields : Scanning SQUID microscope



Scanning SQUID microscope



<http://www.neocera.com>



The old

- A first golden age

- A first golden age for superconductivity began right after the BCS discovery and lasted for about 15 years.
- There was now a conceptual framework to allow people to
 1. Make theoretical predictions on the properties of superconductors.
 2. Design new experiments.

Applications : A short list

Market projections

\$90 billions in 2010 --- \$200 billions in 2020 !!!!

Technologie MAGLEV : TRAINS

MRI 300 appareils vendus pour un total de 600M\$

Aujourd'hui: Quelques milliards de \$ US.

Générateurs électrique - GE

(99% efficacité - 2 fois plus petit que les générateurs basés sur le cuivre)

Emmagasiner de l'énergie : “batteries” ---

“Distributed Superconducting Magnetic Energy Storage System” (D-SMES).

Hydro-Québec: Qualité de l'onde.

Lignes à transmission

Composants d'ordinateur

Ordinateurs plus rapides -- Nouvelles technologies basées sur le SQUID (Ordi quantique?)

Filtres (téléphone cellulaire) - TRW

Radars et détection (US : Army et Navy - détection de mines et sous-marins)

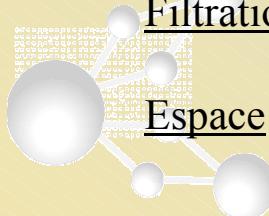
Plus petits moteurs sont fabriqués pour les bateaux de la NAVY

utilisant des fils et rubans supraconducteurs.

Séparation du charbon,

Filtration de l'eau

Espace (gyroscope et détecteur IR : bolomètres)



Martin Wood
1962



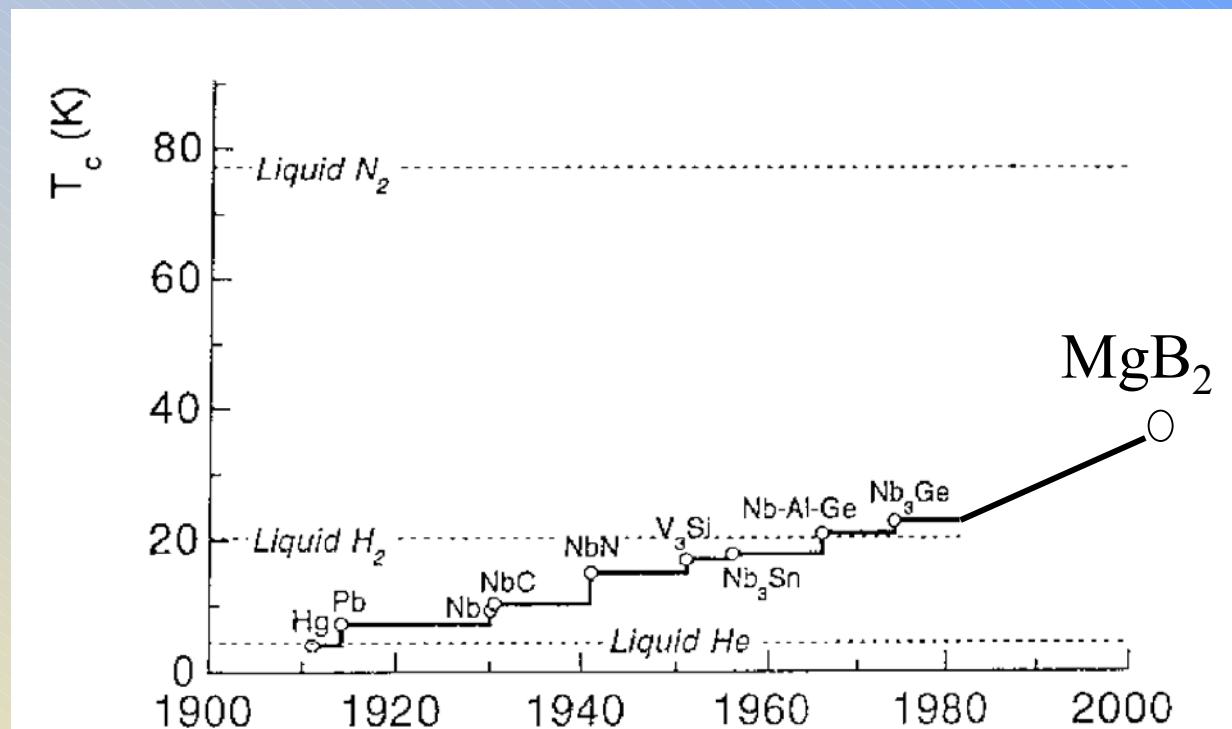
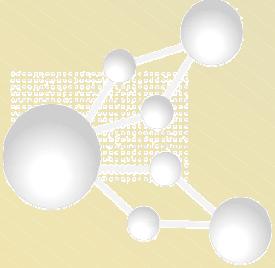
The old

- Vanishing act

- As early as 1970 many researchers had left the field
- Superconductivity is one of the best understood phenomena in all of Physics!
- In 1969, R.D. Parks edits a two volume treatise entitled "Superconductivity"
- One of the authors writing about the book: « *It is the last nail in the coffin of Superconductivity* »

“Psychological barrier” : 77K

Liquid Nitrogen
(The most abundant molecule in air!)



The new

1987 : the revolution

- **January 1986:**

Alex Müller and Georg Bednorz at IBM Zurich discover indications of superconductivity in the system *Ba-La-Cu-O*

-**September 1986** issue of de "Zeitschrift für Physik"
-(submitted April 17, 86)

"Possibility of high T_c superconductivity in the *Ba-La-Cu-O* system"

- This article is ignored... for good reasons:
 - transition towards $R=0$ is not sharp
 - The Meissner effect is not verified



1986 : Discovery of superconductivity in the La-Ba-Cu-O system

$T_c \sim 30\text{-}40\text{K}$

P. Chu's group (Houston)
Under high pressure : 50K!!!

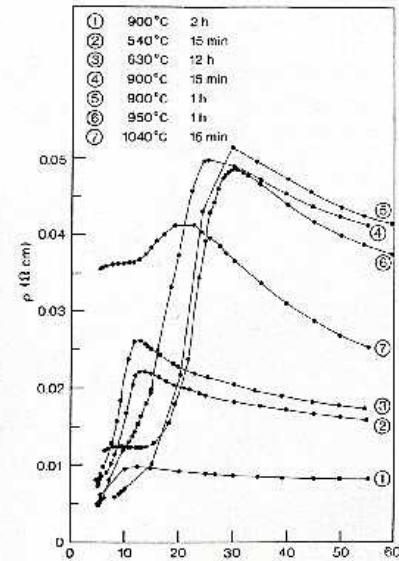
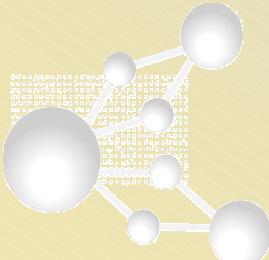


Fig. 2. Low-temperature resistivity of samples with $x(\text{Ba})=1.0$, annealed at O_2 partial pressure of 0.2 bar (curve ④) and 0.2×10^{-4} bar (curves ② to ⑦)

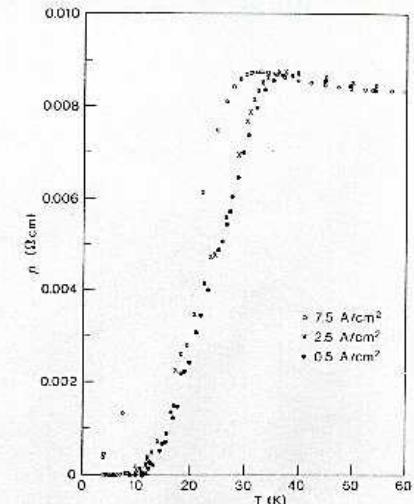


Fig. 3. Low-temperature resistivity of a sample with $x(\text{Ba})=0.75$, recorded for different current densities

towards the 30 K region. Curves ④ and ⑤, recorded for samples treated at 900 °C, show the occurrence of a shoulder at still lower temperature, more pronounced in curve ⑤. At annealing temperatures of 1,040 °C, the highly conducting phase has almost vanished. As mentioned in the Introduction, the mixed-valent state of copper is of importance for electron-phonon coupling. Therefore, the concentration of electrons was varied by the Ba/La ratio. A typical curve for a sample with a lower Ba concentration of 0.75 is shown in Fig. 1 (right scale). Its resistivity decreases by at least three orders of magnitude, giving evidence for the bulk being superconducting below 13 K with an onset around 35 K, as shown in Fig. 3, on an expanded temperature scale. The latter figure also shows the influence of the current density, typical for granular compounds.

III. Discussion

The resistivity behaviour of our samples, Fig. 1, is qualitatively very similar to the one reported in the Li–Ti–O system, and in superconducting

$\text{BaPb}_{1-x}\text{Bi}_x\text{O}_3$ polycrystalline thin films [5, 18]. Upon cooling from room temperature, the latter exhibit a nearly linear metallic decrease of $\rho(T)$, then a logarithmic type of increase, before undergoing the transition to superconductivity. One could, of course, speculate that in our samples a metal-to-metal structural phase transition occurs in one of the phases. The shift in the drop in $\rho(T)$ with increasing current density (Fig. 3), however, would be hard to explain with such an assumption, while it supports our interpretation that we observe the onset of superconductivity of percolative nature, as discussed below. In $\text{BaPb}_{1-x}\text{Bi}_x\text{O}_3$, the onset of superconductivity has been taken at the resistivity peak [18]. This assumption appears to be valid in percolative systems, i.e., in the thin films [18] consisting of polycrystals with grain boundaries, or when different crystalline phases with interpenetrating grains are present, as found in the Li–Ti–O [5] or in our Ba–La–Cu–O system. The onset can also be due to fluctuations in the superconducting wave functions. We assume one of the Ba–La–Cu–O phases exhibits this behaviour. Therefore, under the above premises, the peak in $\rho(T)$ at 35 K, observed for an $x(\text{Ba})=0.75$ (Fig. 1), has

- **Boston, "Materials Research Society"
December 1986**

Présentation of Koitchi Kitazawa and Shoji Tanaka from Tokyo convinces everyone.

Madness! These materials are easy to make. In China, India, everywhere everyone is trying.

Loss of sleep. The Nitrogen barrier has become much closer.

-
- **16 February 1987, Houston:**

Paul Chu and his group call a press conference to announce the discovery of *Y-Ba-Cu-O*

$$T_c = 93 \text{ K}$$

The Nitrogen barrier has been crossed ?

New York: March meeting of the American Physical Society.

-President Neil Ashcroft, (Cornell) hesitates

18 March 1987...

- New York Times title the next day:

"The Woodstock of Physics"

- 3000 people until 3 AM

"They began lining up outside the New York Hilton Sutton Ballroom at 5:30PM for an evening session that would last until 3:00 AM"



The "Woodstock of physics." On March 18, 1987, thousands of physicists crammed a ballroom at the New York Hilton to celebrate the coming of the age of superconductivity.

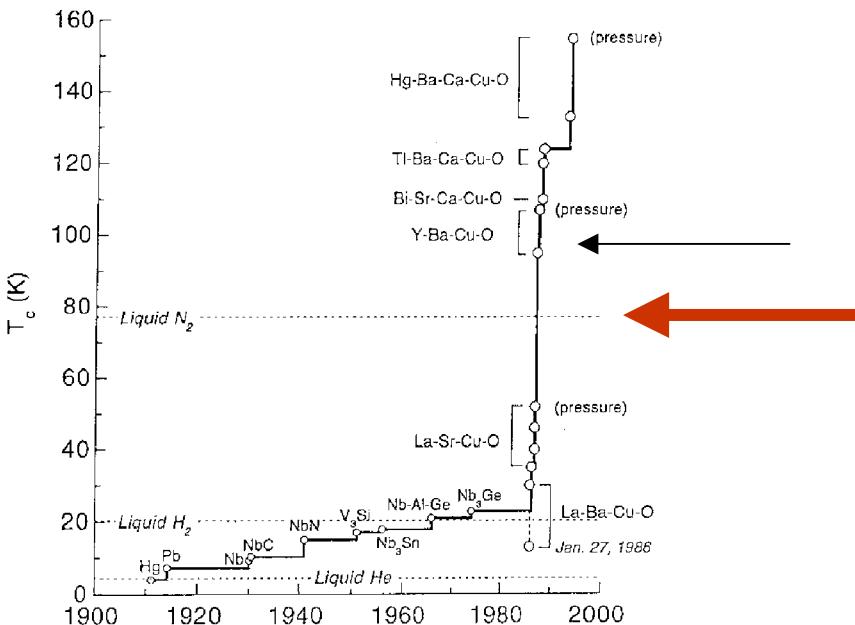
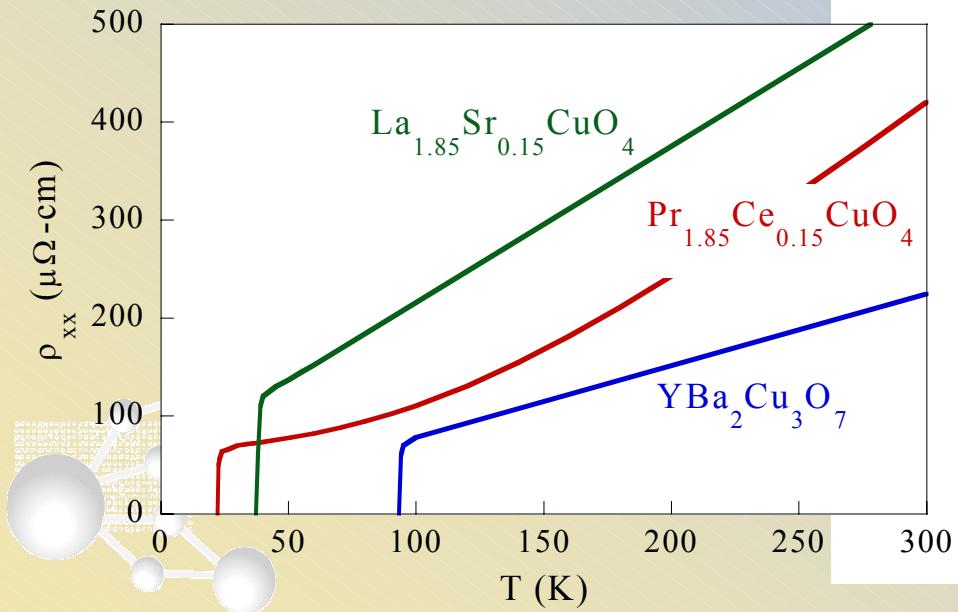
AMERICAN INSTITUTE OF PHYSICS

(right) Alex Müller, Paul Chu, and Shoji Tanaka, answering questions at the "Woodstock" meeting. Tanaka and Koichi Kitazawa were the first to confirm Bednorz and Müller's discovery, launching a worldwide race to find still better superconductors.

AMERICAN INSTITUTE OF PHYSICS



1987 : $\text{YBa}_2\text{Cu}_3\text{O}_7$ 93K
 --- $\text{LN}_2 = 77\text{K}$ ---
 Paul Chu : U. of Houston



Composé	Tc
$La_{2-x}Sr_xCuO_4$	~36
$YBa_2Cu_3O_7$	~96
$Bi_2Sr_2CaCu_2O_8$	~83
$Bi_2Sr_2Ca_2Cu_3O_{10}$	~115
$Tl_2Ba_2CuO_6$	~80
$Tl_2Ba_2CaCu_2O_8$	~120
$Tl_2Ba_2Ca_2Cu_3O_{10}$	~125
$HgBa_2Ca_2Cu_3O_8$	~133

Physique 1987

BEDNORZ, J. GEORG, Federal Republic of Germany, IBM Research Laboratory, Rüschlikon, Switzerland, * 1950;

MÜLLER, K. ALEXANDER, Switzerland, IBM Research Laboratory, Rüschlikon, Switzerland
* 1927:

“for the importance of the breakthrough represented by their discovery of superconductivity in the ceramics”

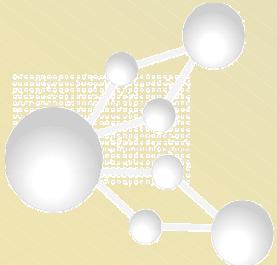


J. George Backman and K. Alex Müller in their laboratory at IBM's Zurich Re-



Why study HTCS ?

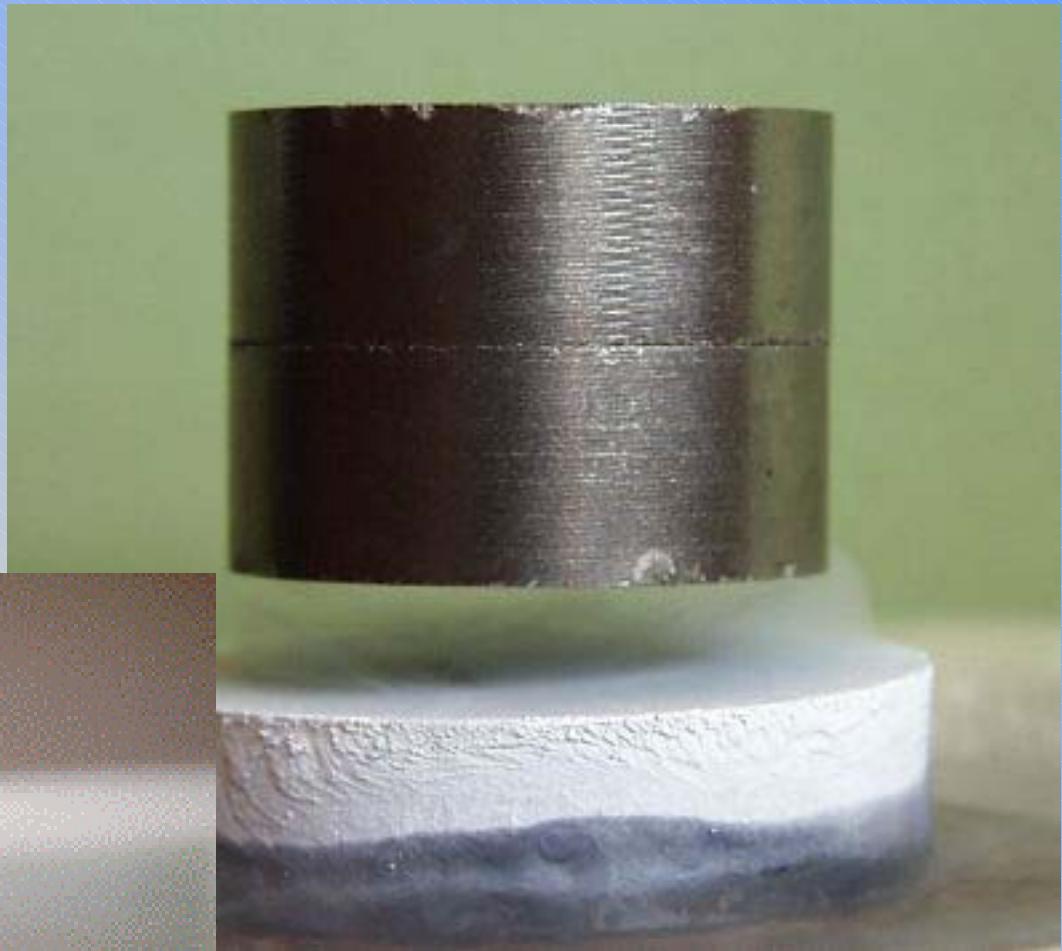
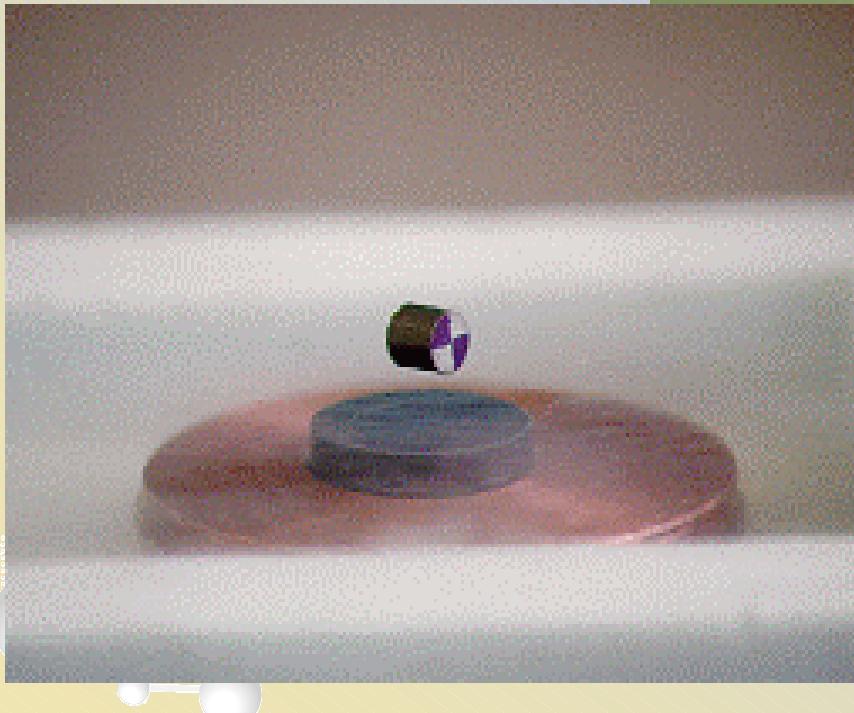
- 1) Spectacular
- 2) How to get higher T_c ? (understand the mechanism)
- 3) applications even at 77K



$$\chi = -1$$

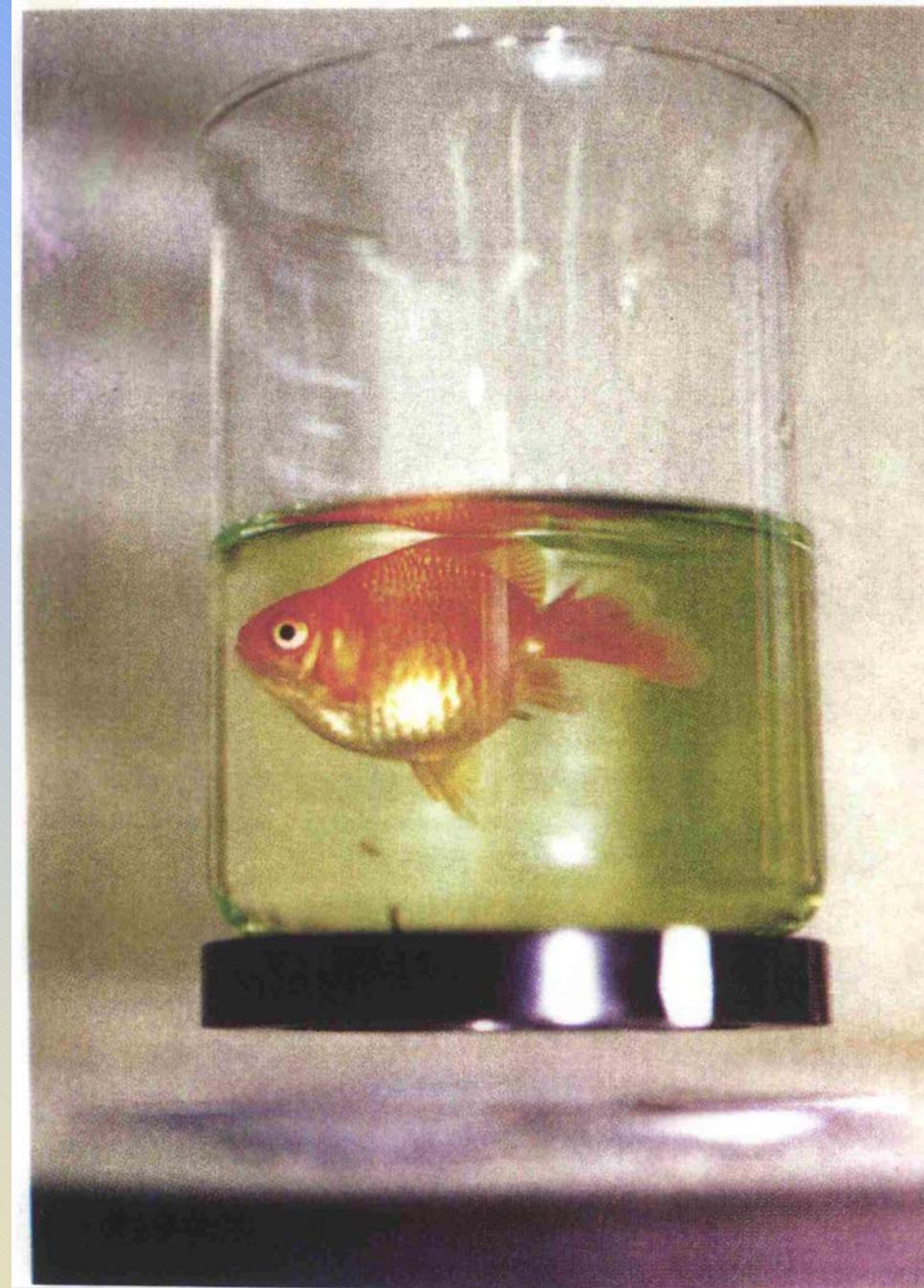
Perfect diamagnetism
(Shielding of
magnetic field)

(Meissner effect)



Disclaimer:

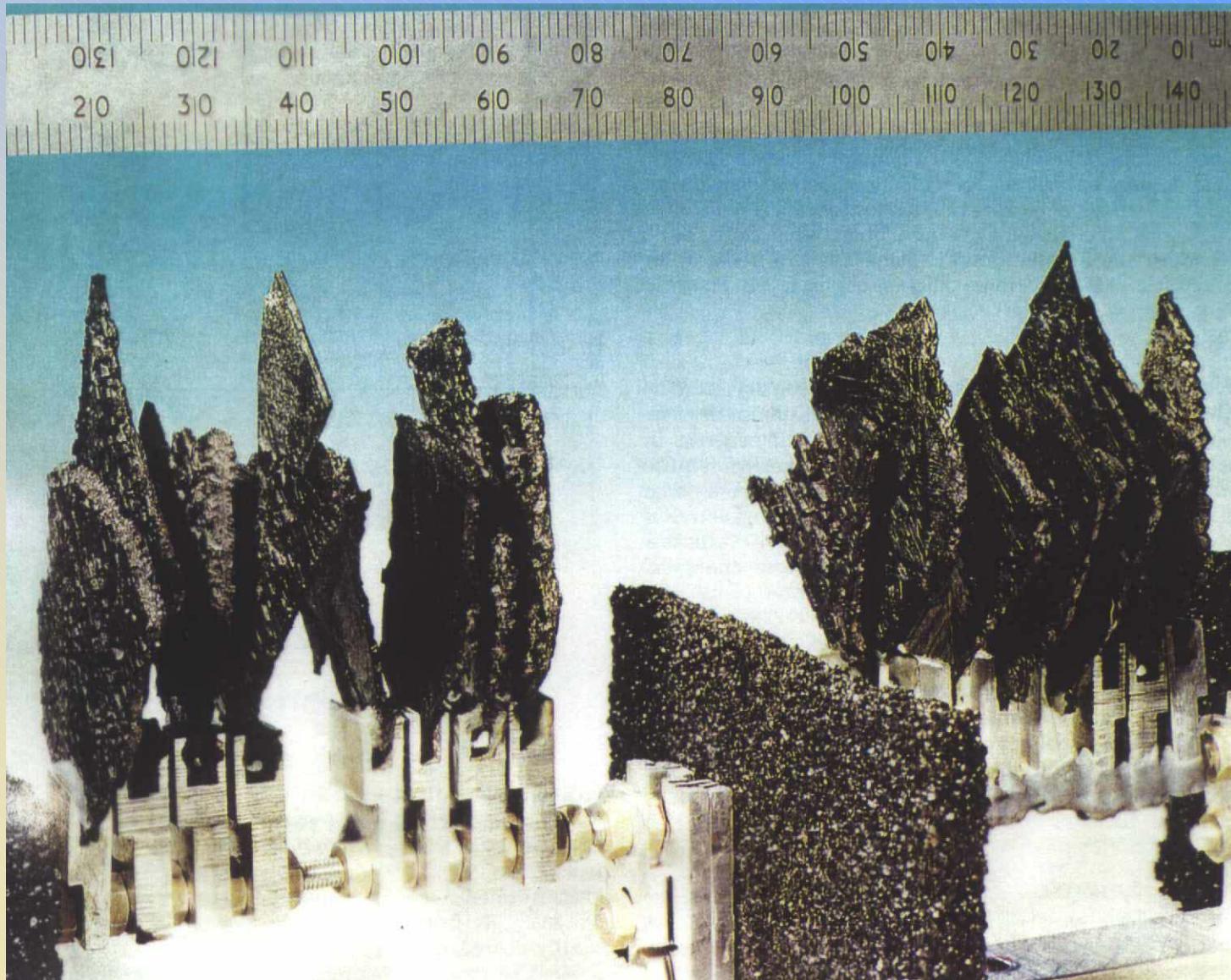
No harm has been
done to animals
during this
experiment.



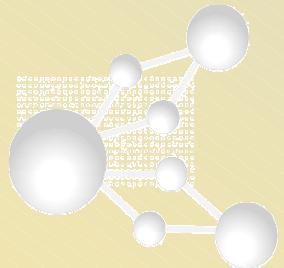
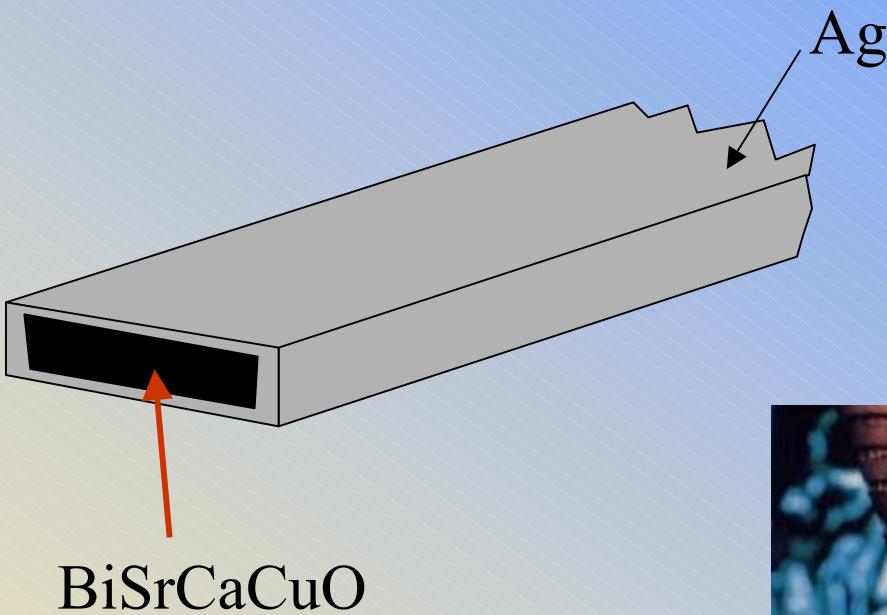
Warning:

The experimentalist
could be harmed
whenever this
experiment fails

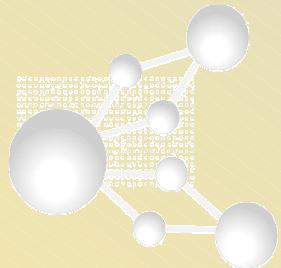




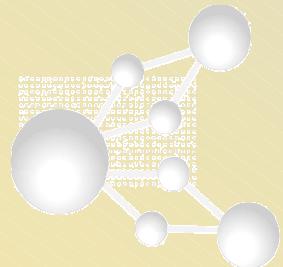
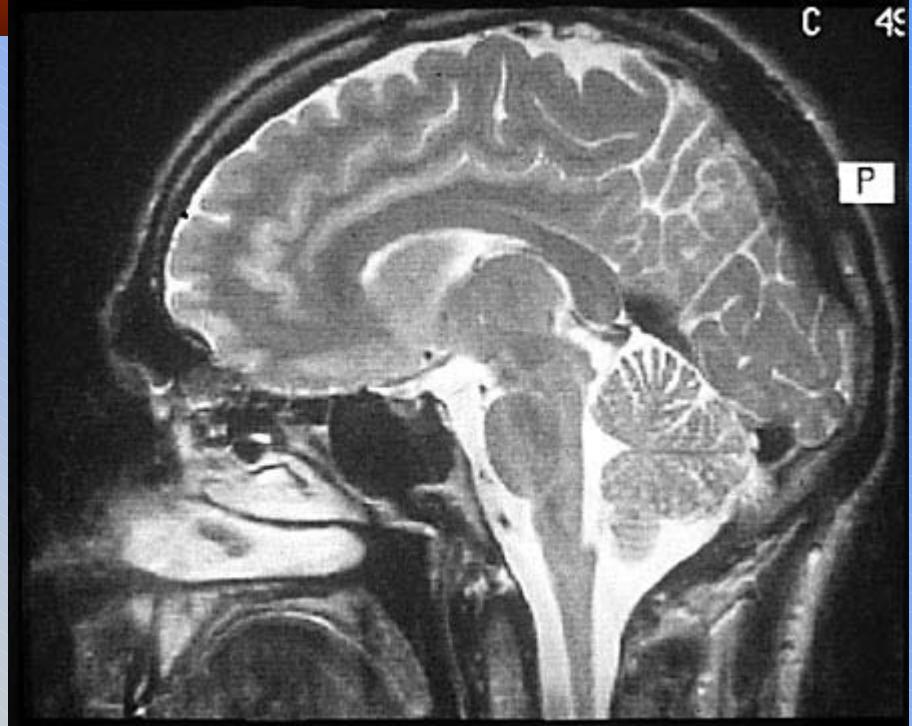
Transmission lines



MAGLEV

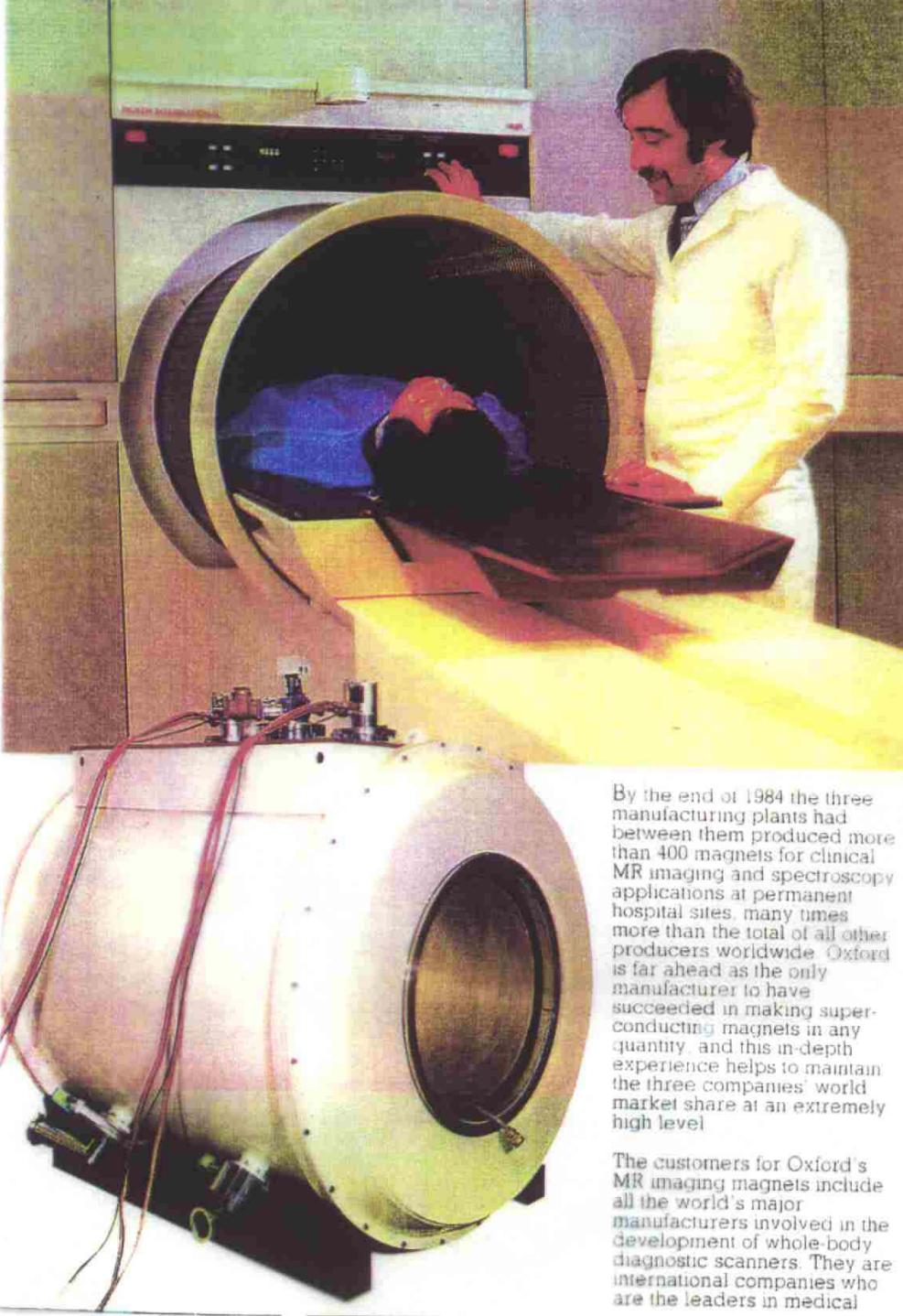


Magnetic resonance imaging (MRI)



Research :

- 1) Higher fields
- 2) New detectors (SQUID)

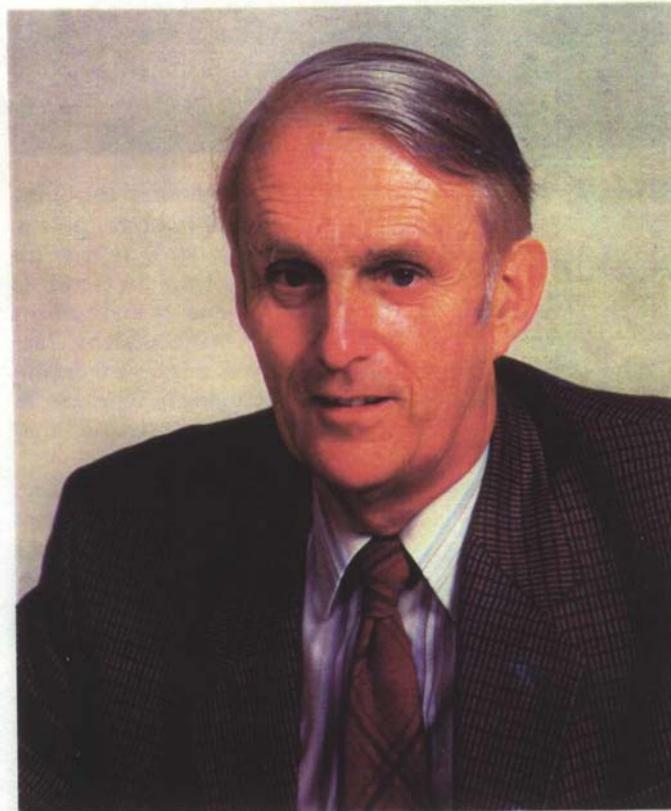
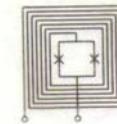


By the end of 1984 the three manufacturing plants had between them produced more than 400 magnets for clinical MR imaging and spectroscopy applications at permanent hospital sites, many times more than the total of all other producers worldwide. Oxford is far ahead as the only manufacturer to have succeeded in making superconducting magnets in any quantity, and this in-depth experience helps to maintain the three companies' world market share at an extremely high level.

The customers for Oxford's MR imaging magnets include all the world's major manufacturers involved in the development of whole-body diagnostic scanners. They are international companies who are the leaders in medical

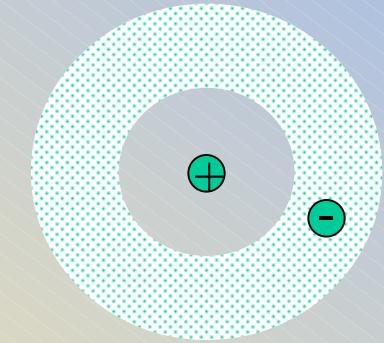
Supercurrents

The Superconductivity Magazine



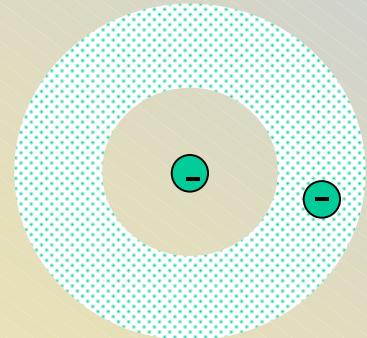
Sir Martin Wood
Founder, Oxford Instruments

Understanding the mechanism --- Where are we ?

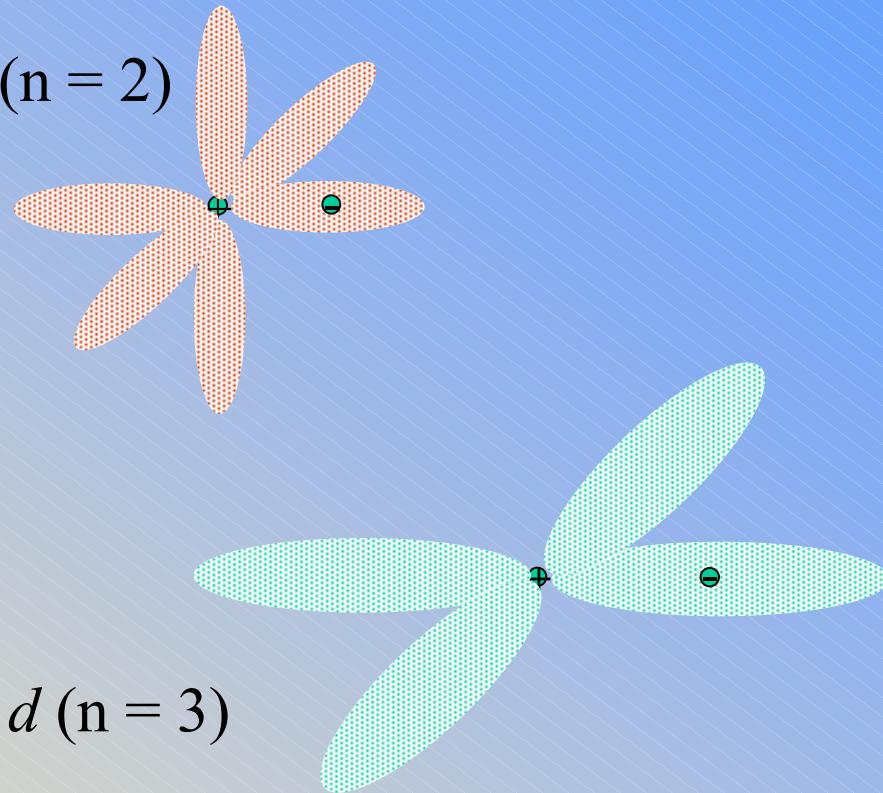
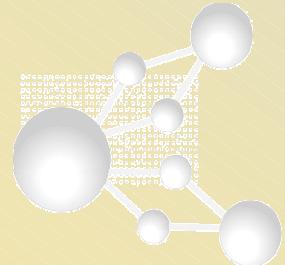


Type *s* ($n = 1$)

Type *p* ($n = 2$)



Type *d* ($n = 3$)



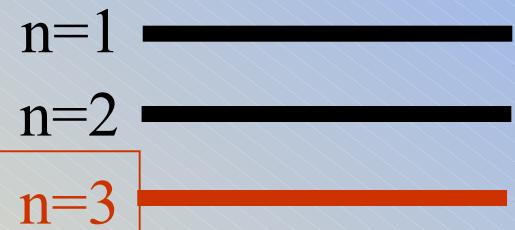
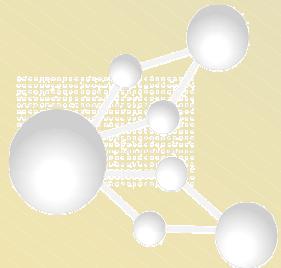
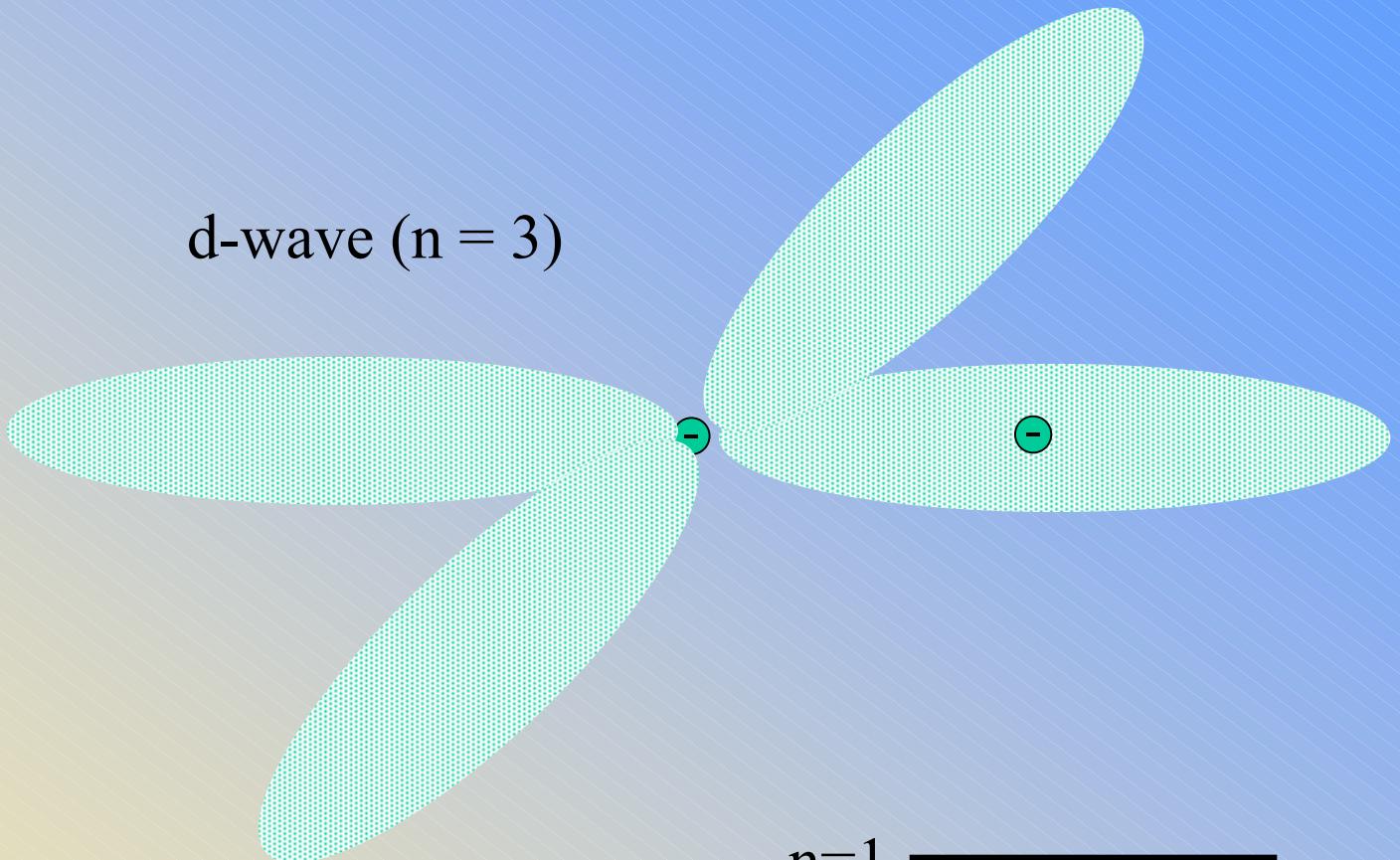
$n=3$ —————

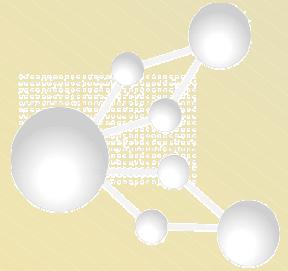
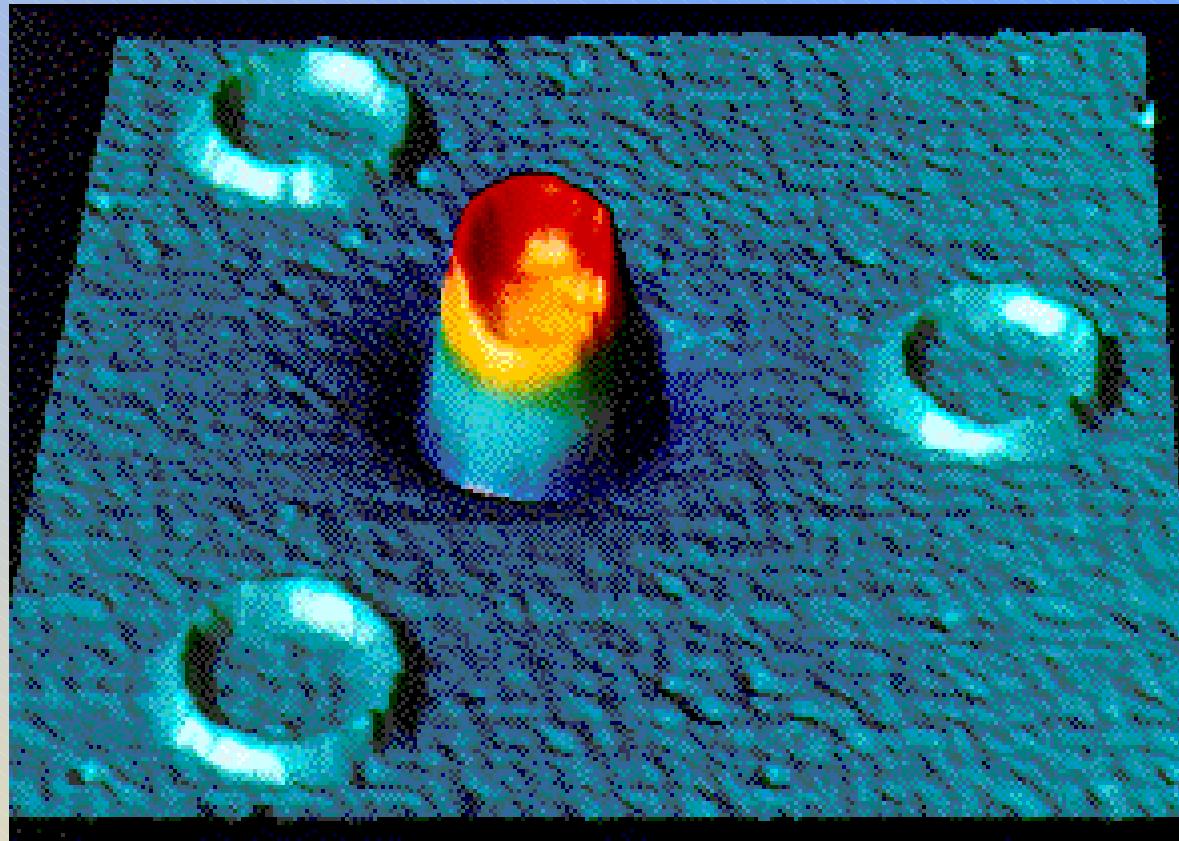
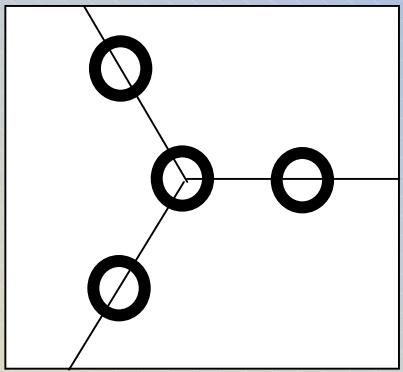
$n=2$ —————

$n=1$ —————

Understanding the mechanism --- Where are we ?

d-wave ($n = 3$)





A more microscopic view

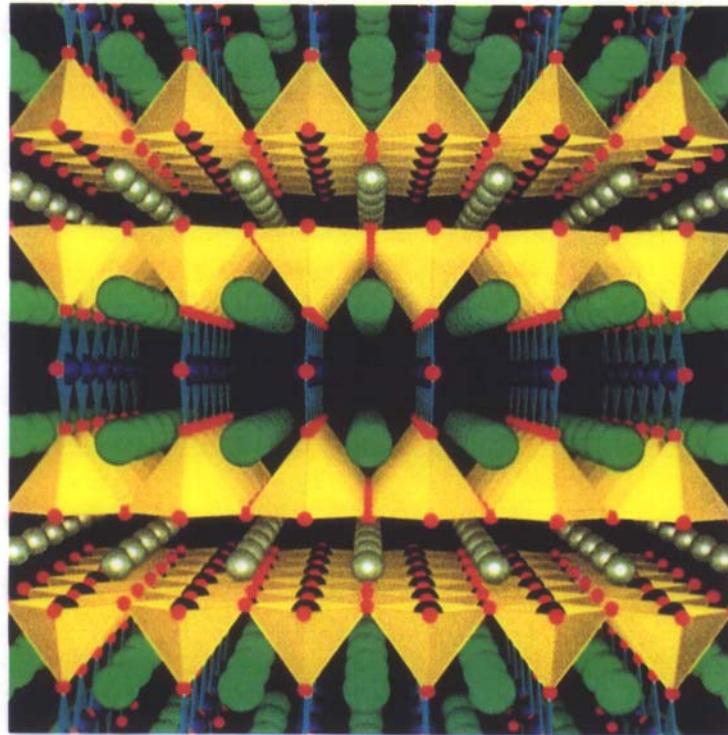
SCIENTIFIC AMERICAN

JUNE 1988
\$3.50

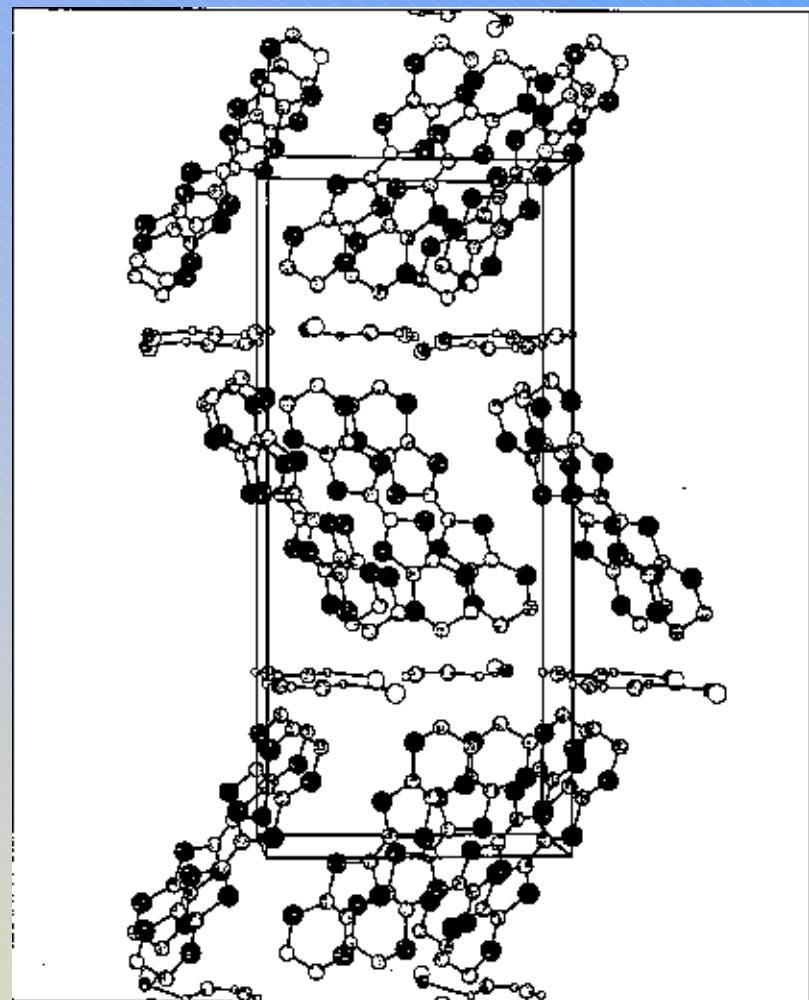
How nonsense is deleted from genetic messages.

Rx for economic growth: aggressive use of new technology.

Can particle physics test cosmology?



High-Temperature Superconductor belongs to a family of



Phase diagram

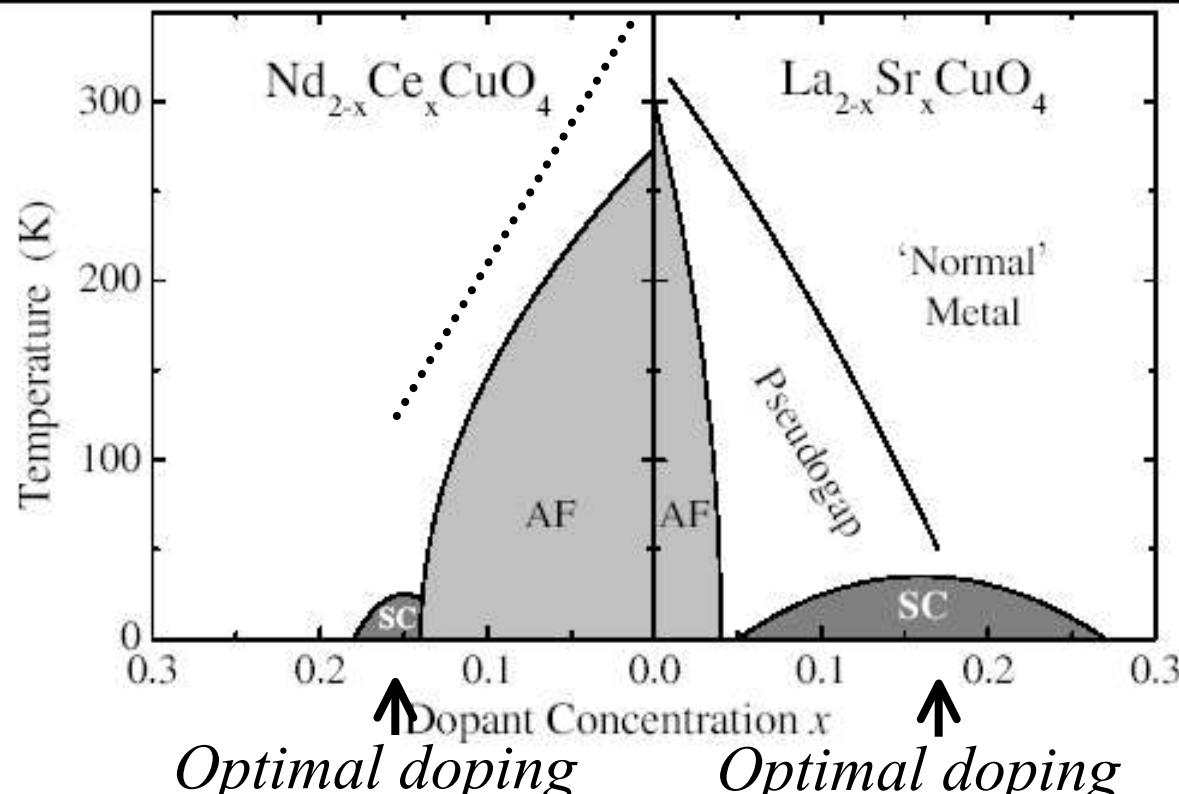
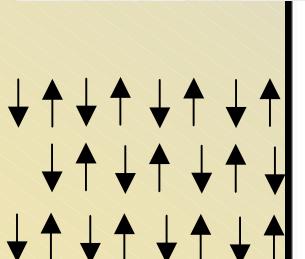
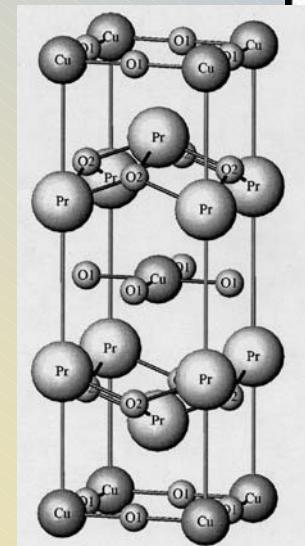
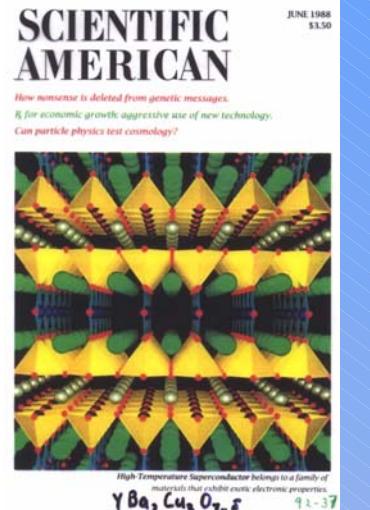


FIG. 1 Phase diagram of n and p-type superconductors.

n , electron density

Damascelli, Shen, Hussain, 2002.

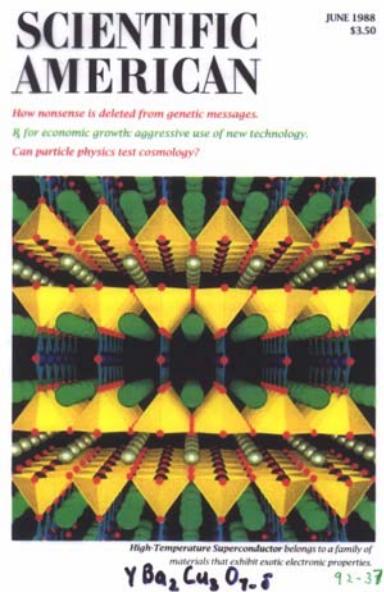


The normal state ($T > T_c$) of high temperature superconductors cannot be explained in the context of the band theory of metals or any of its extensions.

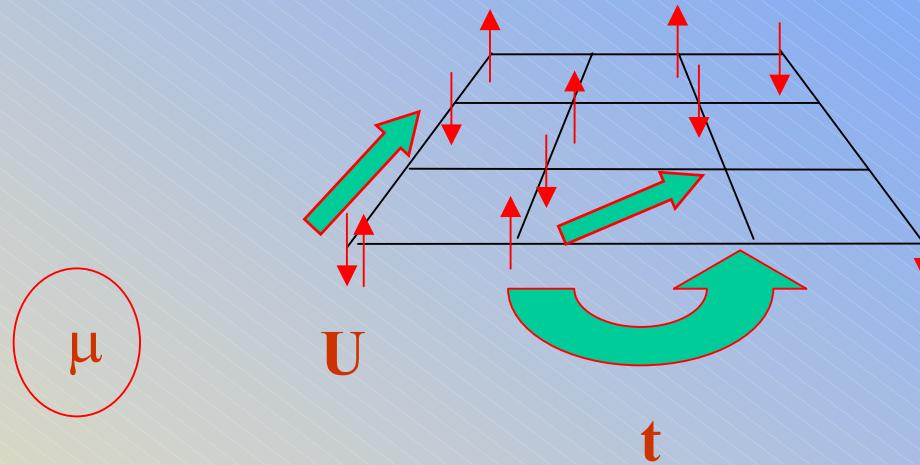
Two great mysteries:

1. The normal state (pseudogap).
2. The origin of the attraction leading to superconductivity (magnetic instead of phononic?)

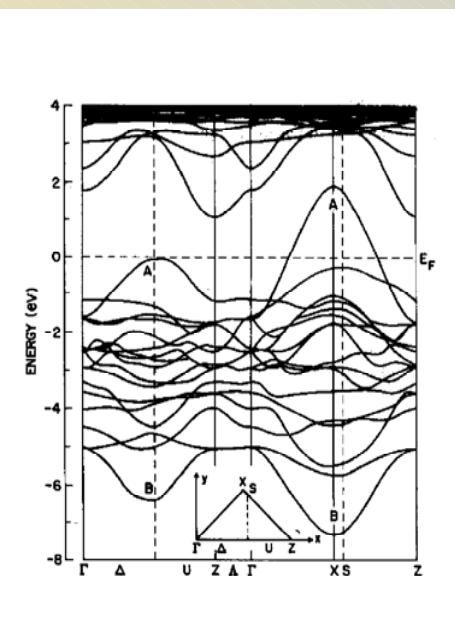
The « Hubbard model »



Simplest microscopic model for $Cu O$ planes.



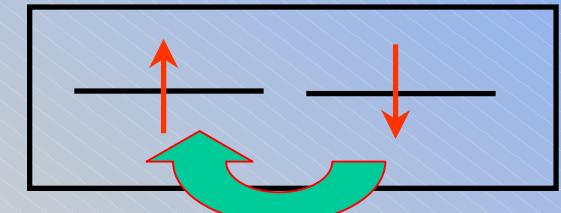
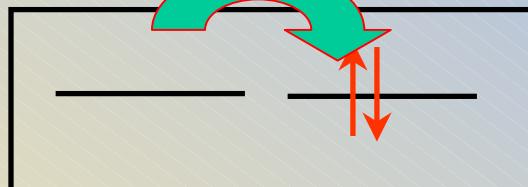
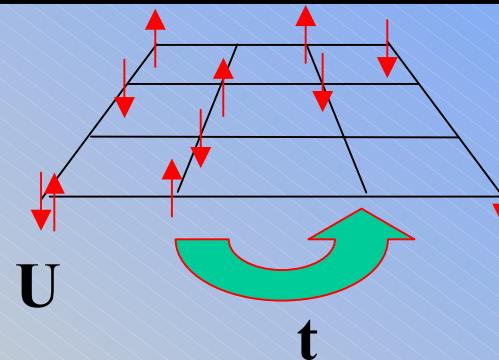
- Size of Hilbert space : 4^N ($N = 16$)
- With $N=16$, it takes 4 GigaBits just to store the states



Hubbard model (Kanamori, Gutzwiller, 1963) :

$$H = -\sum_{\langle ij \rangle \sigma} t_{i,j} (c_{i\sigma}^\dagger c_{j\sigma} + c_{j\sigma}^\dagger c_{i\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

- Screened interaction U
- U, T, n (or $\delta=1-n$)
- $a = 1, t = 1, \hbar = 1$



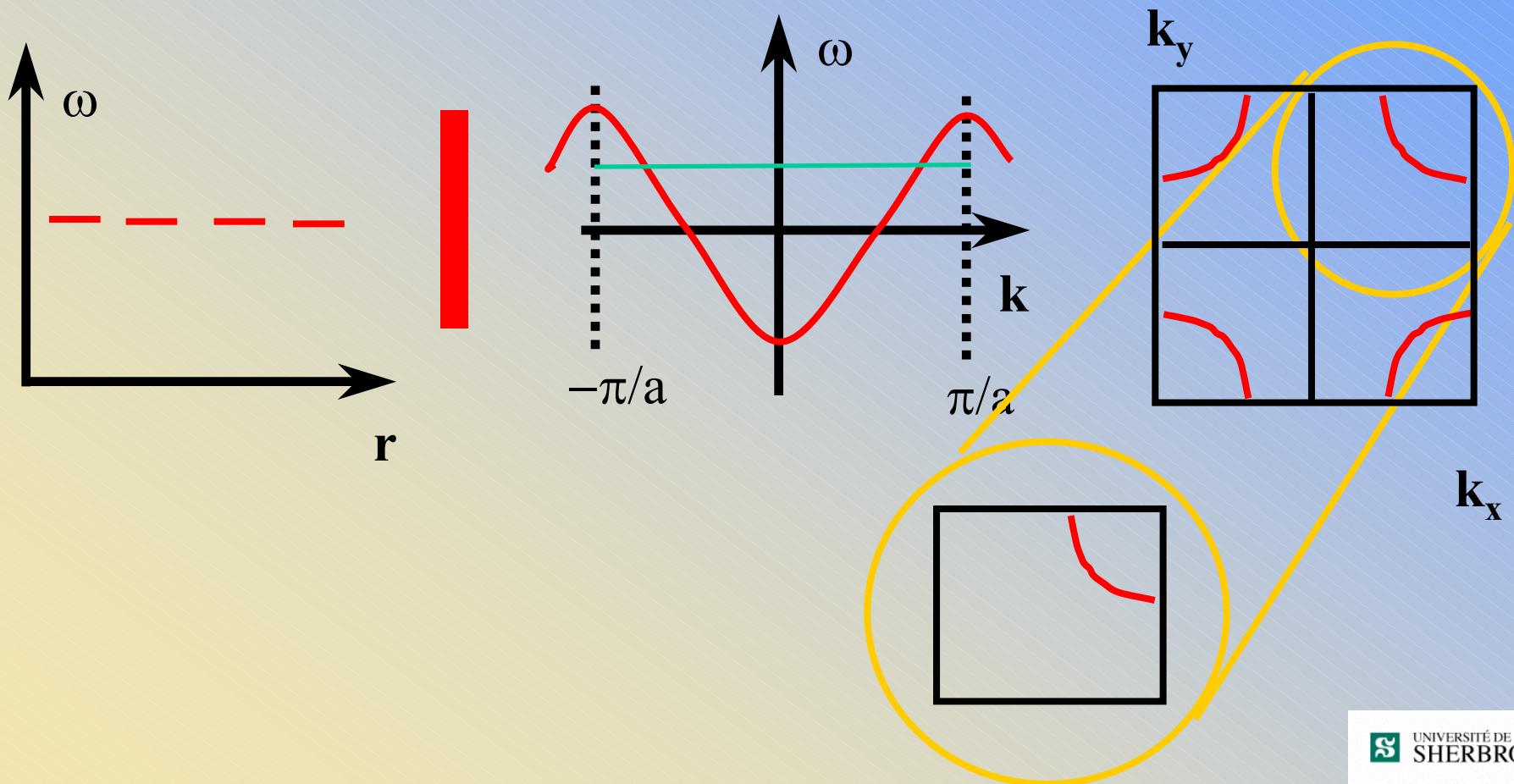
Effective model, Heisenberg: $J = 4t^2 / U$

t

- 2003 vs 1963: Numerical solutions to check analytical approaches

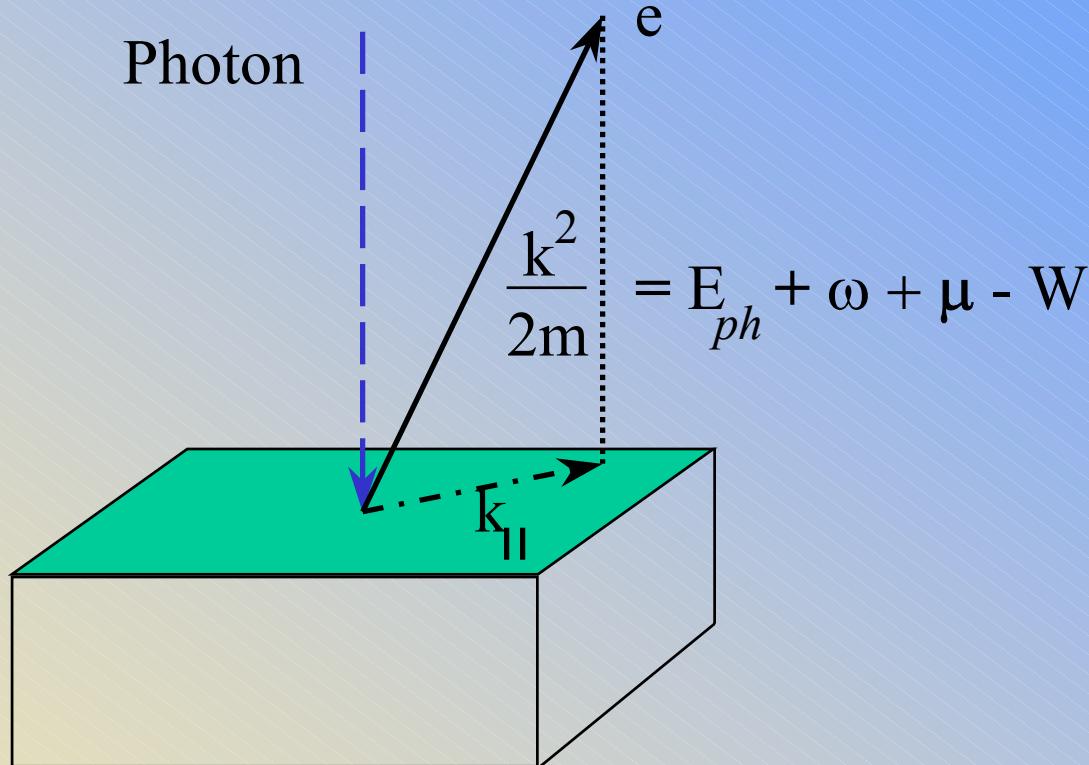
The Fermi surface

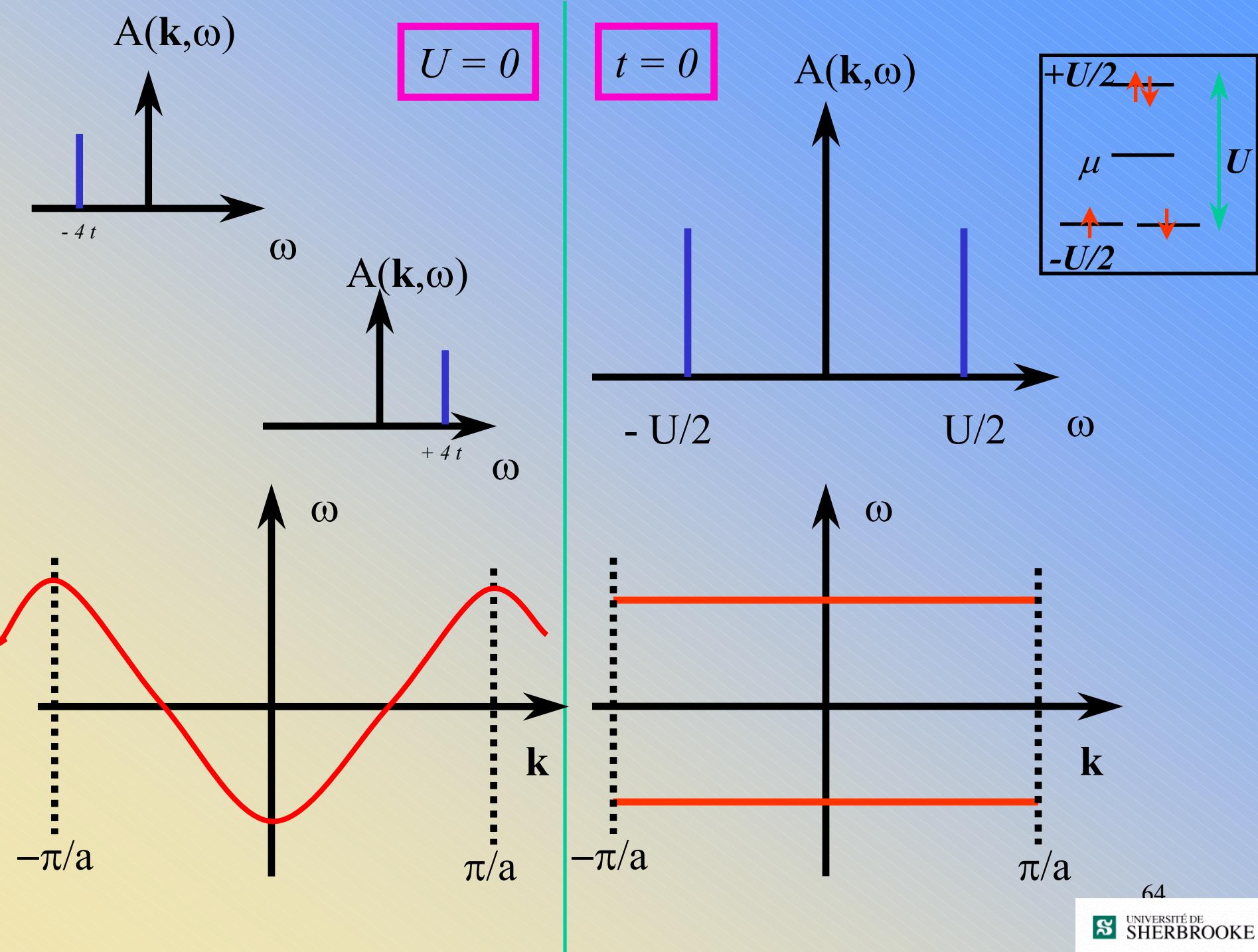
Some basic Solid State Physics



Measuring « band » properties in $d=2$

Photoemission



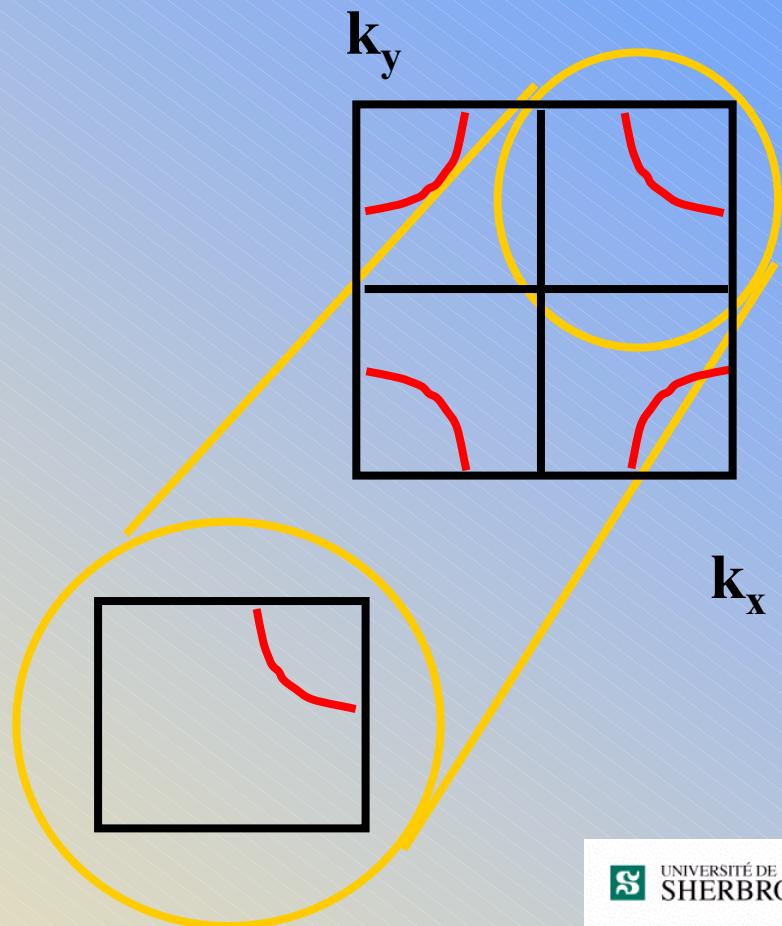


Part II : some of what we did

Pseudogap
Pairing

The Fermi surface

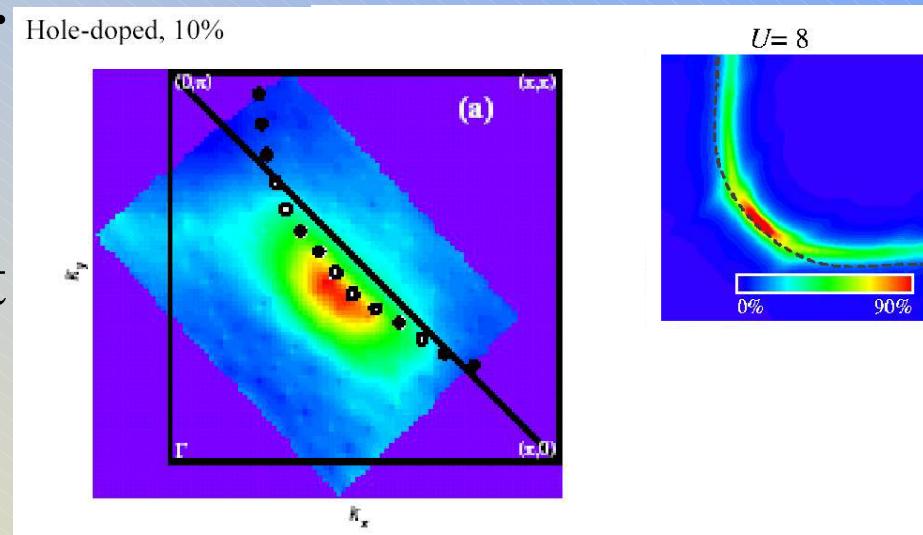
Some basic Solid State Physics



Destruction of the Fermi surface Strong coupling pseudogap

- When U is large enough, pseudogap is independent of cluster shape (and size) in CPT.
 - Short-range effect (few lattice spacings).
 - $\omega=0$ scattering largest at points separated by (π,π)
 - Scales like t .

Hole-doped systems

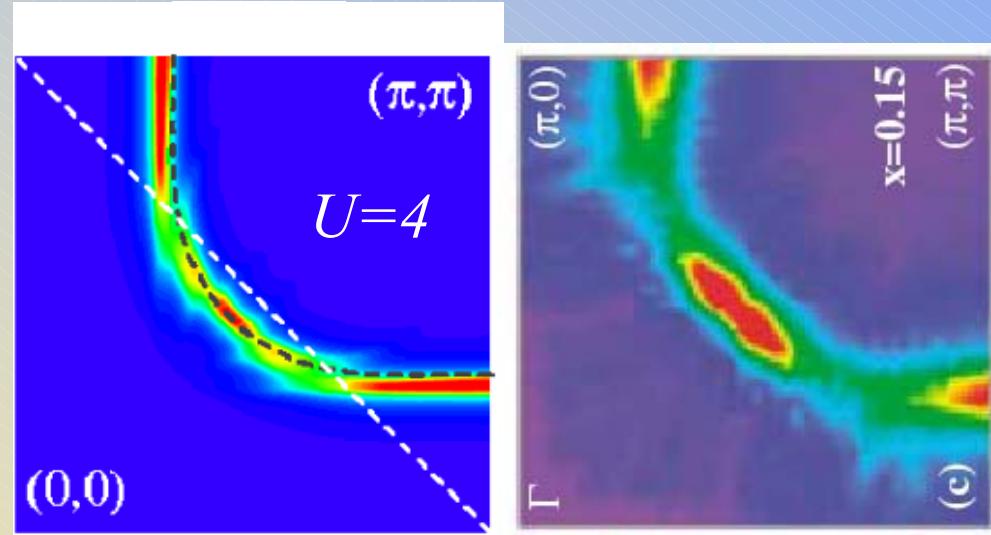


F. Ronning et al. Jan. 2002, $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

Destruction of the Fermi surface Weak-coupling pseudogap

- In CPT
 - is mostly a depression in weight
 - depends on system size and shape.
- Coupling weaker because better screened $U(n)$.

Electron-doped systems



Two-Particle Self-Consistent Approach

- How it works

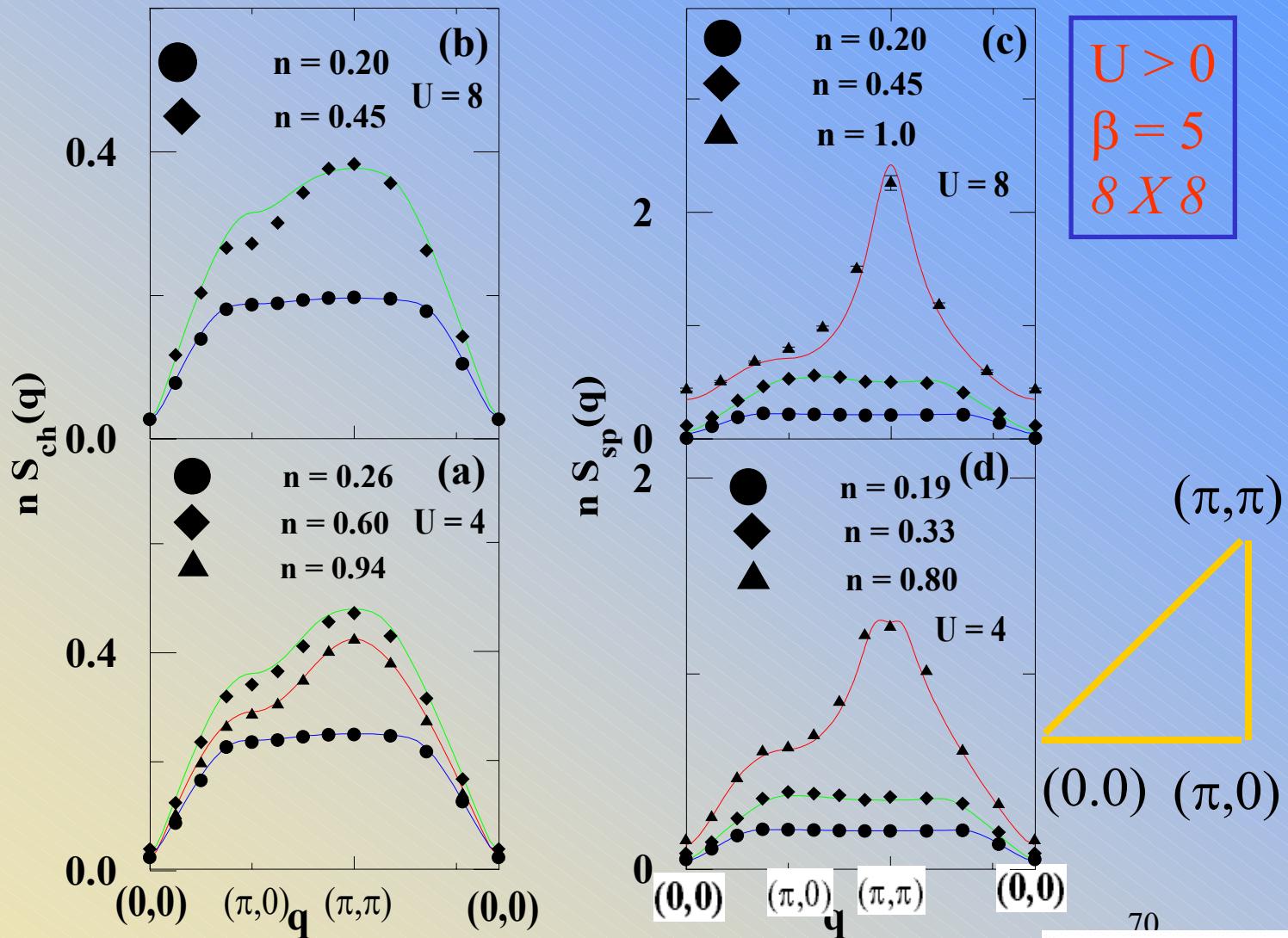
- General philosophy
 - Drop diagrams
 - Impose constraints and sum rules and try to satisfy them.
 - Pauli principle
 - Conservation laws
 - Mermin-Wagner theorem

Vilk, AMT J. Phys. I France, 7, 1309 (1997).

Proof that it works (comparisons with QMC)

Notes:

- F.L.
- parameters
- Self also
- Fermi-liquid

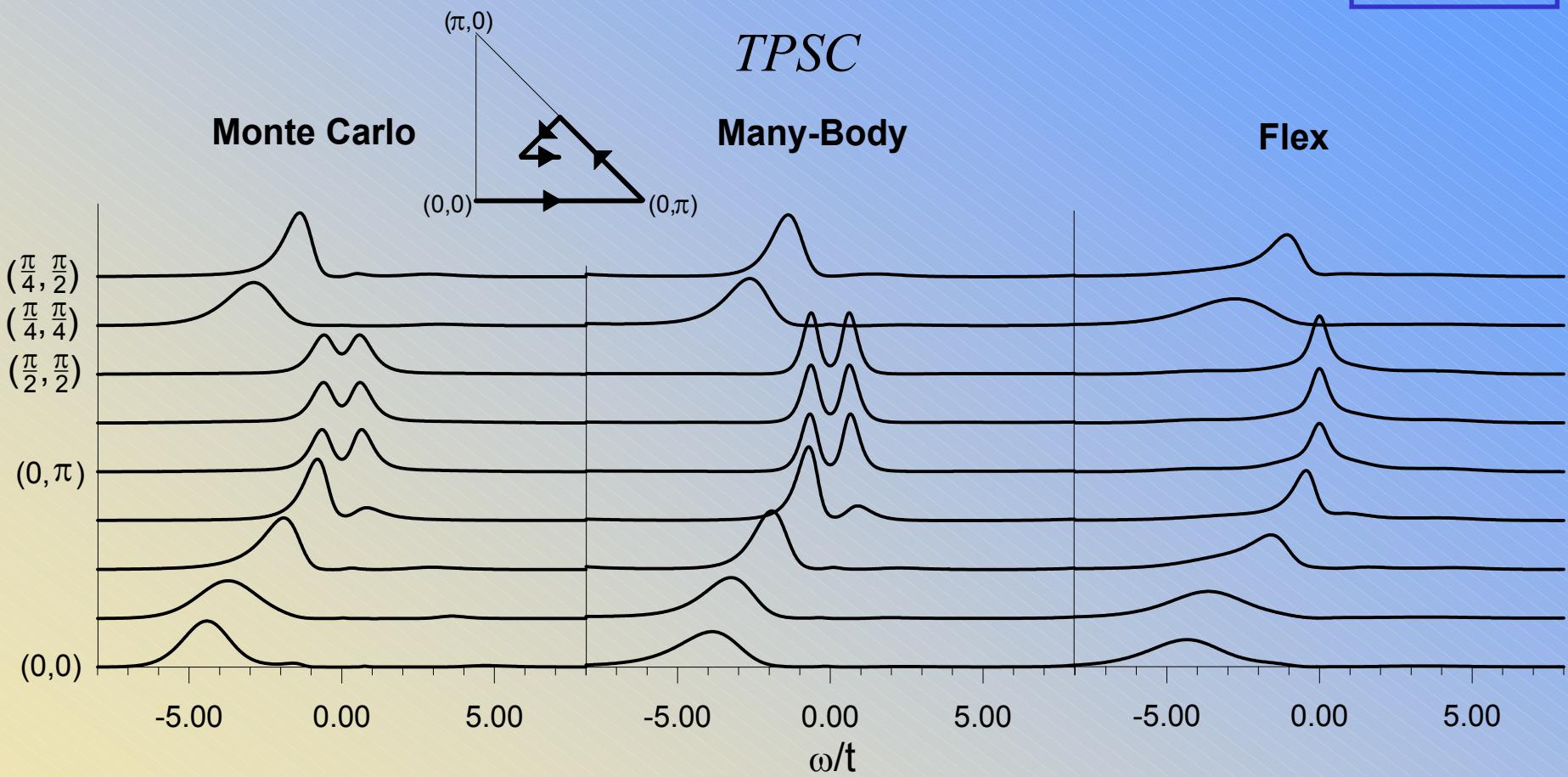


QMC + cal.: Vilk et al. P.R. B 49, 13267 (1994)



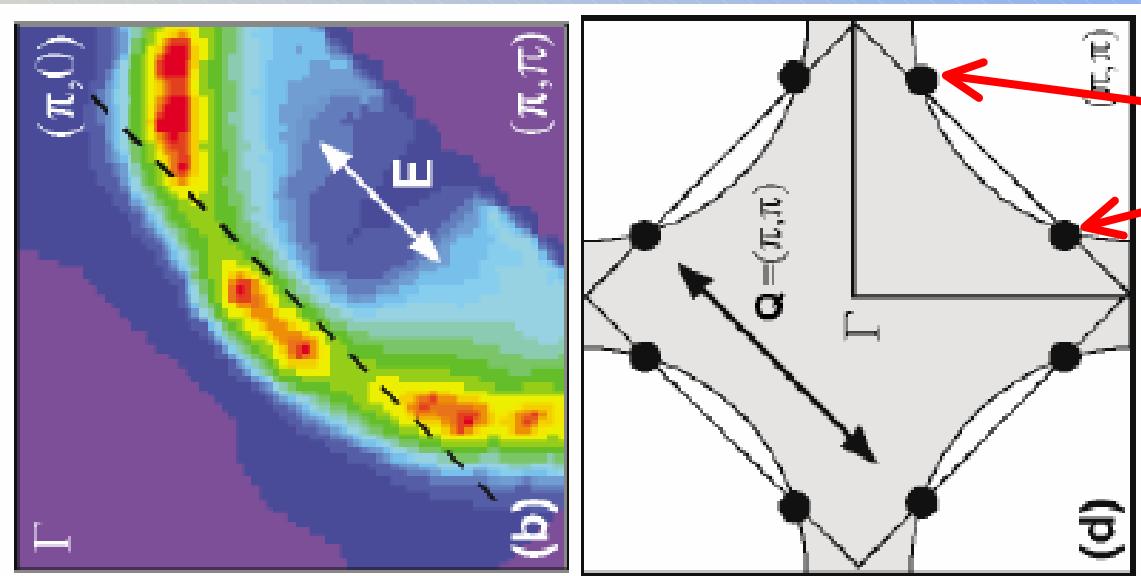
Proofs...

$U = +4$
 $\beta = 5$



Calc. + QMC: Moukouri et al. P.R. B 61, 7887 (2000).

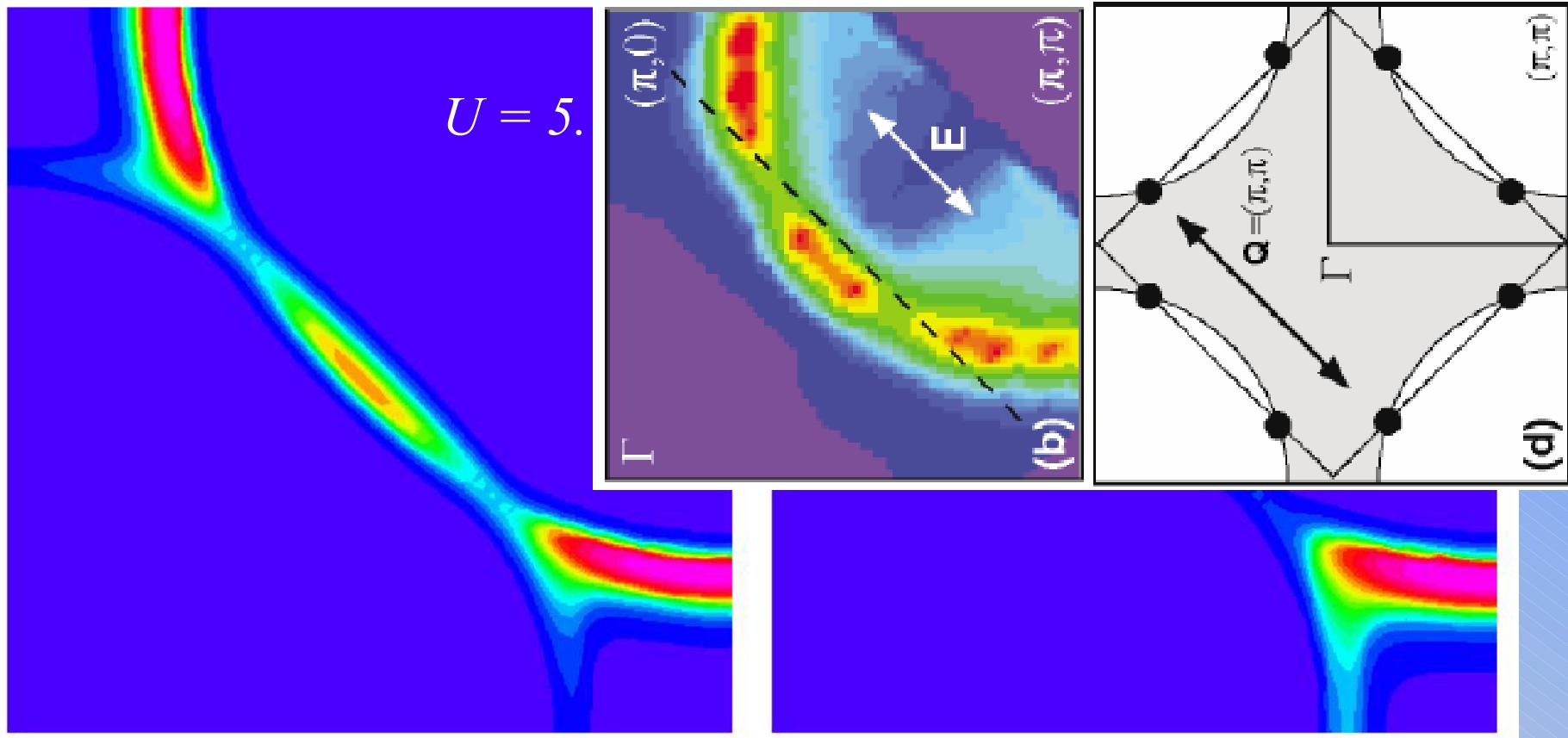
(π,π) collective excitations: a possible cause?



Armitage *et al.* PRL 87, 147003 (2001)

$$A(k, \omega) = \frac{-\Sigma''}{(\omega - \varepsilon_k - \Sigma')^2 + (\Sigma'')^2}$$

TPSC for electron-doped, 15%



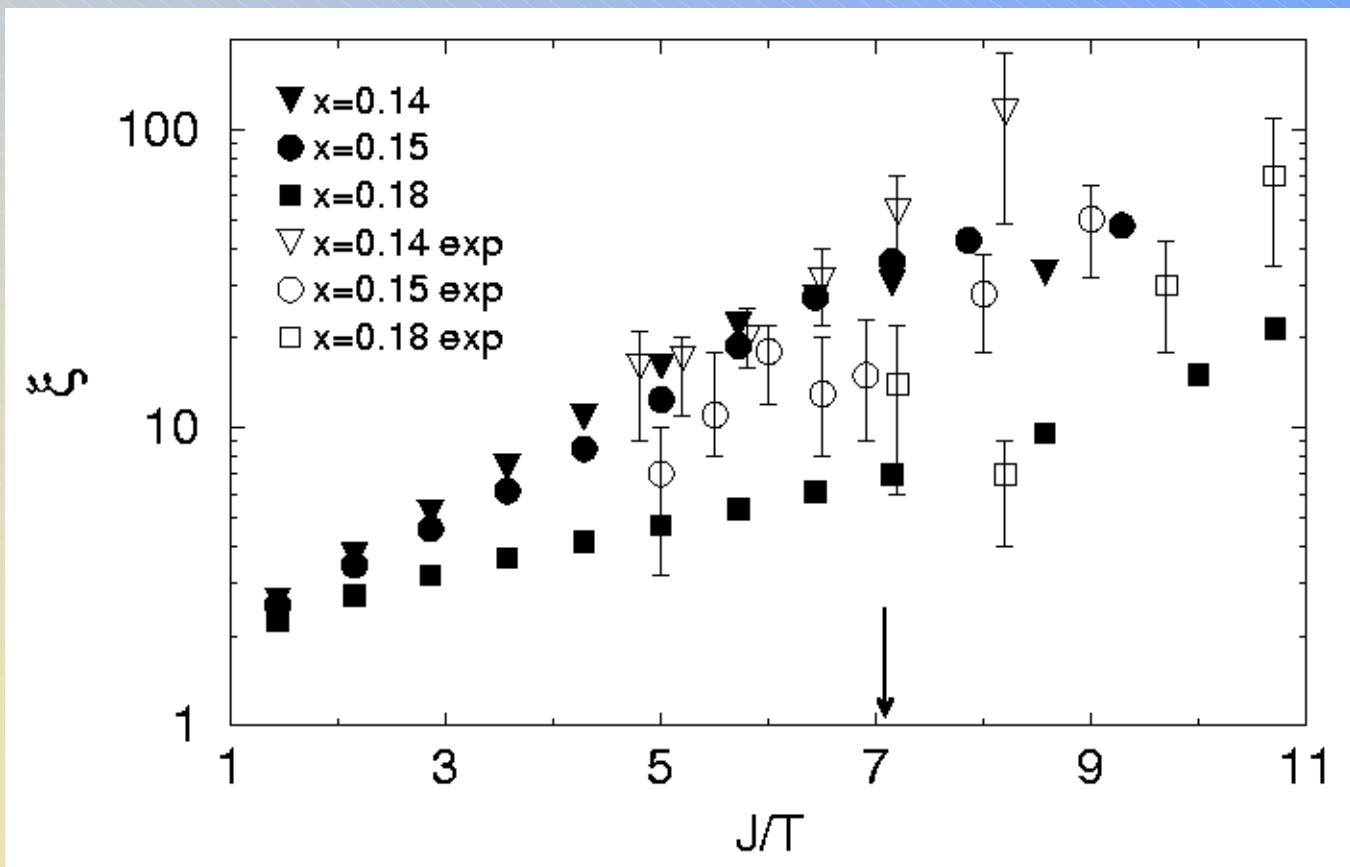
$t'=-0.175, t''=0.05$
 $n = 1.15$

$\beta = 40$

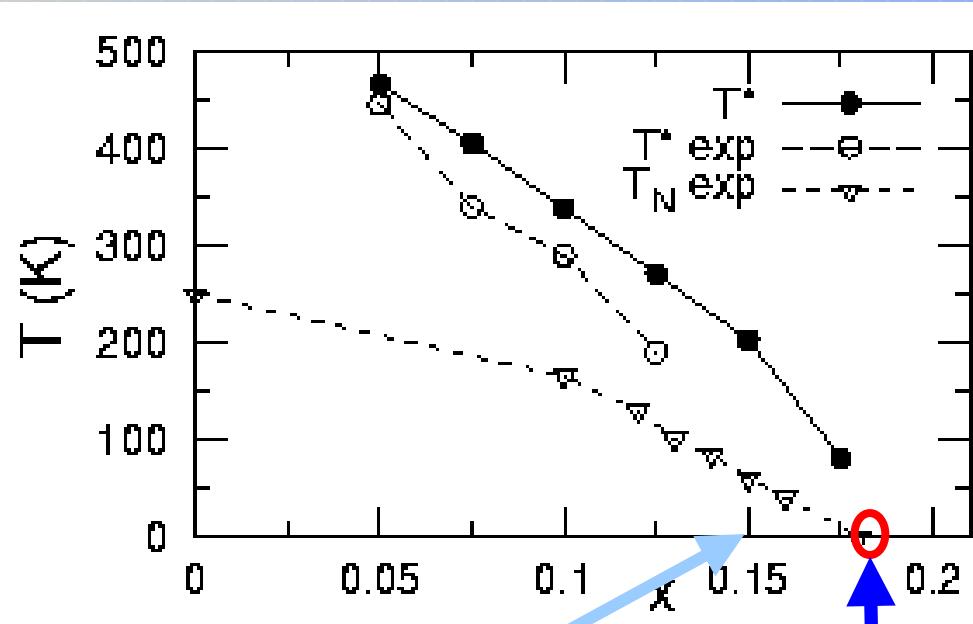
U cannot be too large to have three spots!

Kyung, Landry, AMT, cond-mat/0205165

AFM correlation length



Pseudogap temperature and QCP



➤ $\xi \approx \xi_{th}$ at PG temperature T^* ,
and $\xi > \xi_{th}$ for $T < T^*$



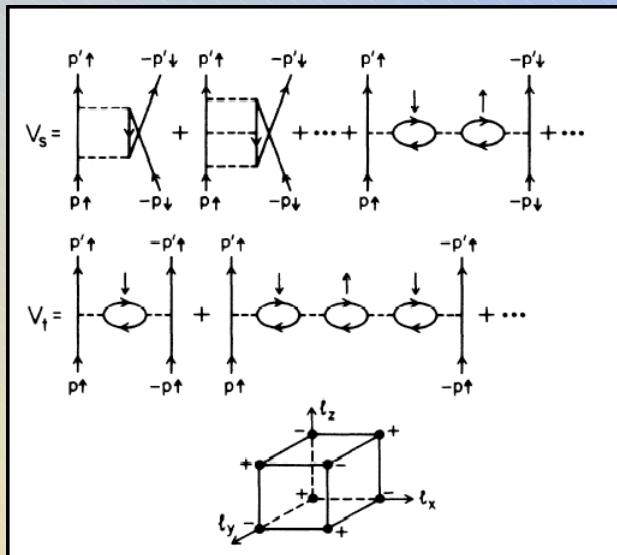
supports further AFM
fluctuations origin of PG

➤ ARPES to do:
when does PG disappear
with increasing T

- no PG in optics, and there is a PG in ARPES
TPSC agrees with ARPES
- $\Delta_{PG} \approx 10k_B T^*$ in agreement with optical measurements

Mechanism: A great prediction ? (Kohn-Luttinger mechanism)

d-wave superconductivity induced by antiferromagnetic fluctuations

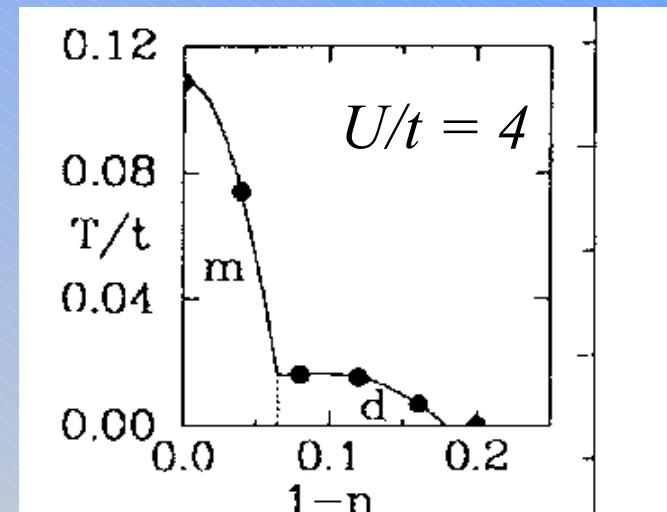


D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch
P.R. B **34**, 8190-8192 (1986).

Béal-Monod, Bourbonnais, Emery
P.R. B. **34**, 7716 (1986).

Miyake, Schmitt-Rink, and Varma
P.R. B **34**, 6554-6556 (1986)

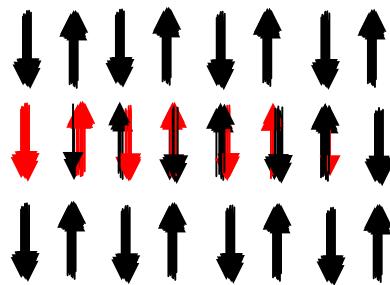
Kohn, Luttinger, P.R.L. **15**, 524 (1965).



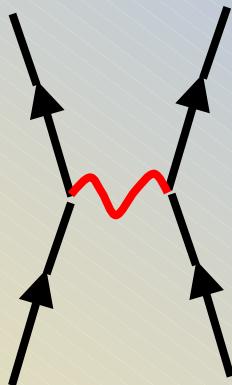
Bickers, Scalapino, White
P.R.L **62**, 961 (1989).

Recent review by Chubukov, Pines,
Schmalian.

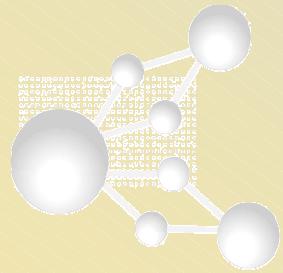
«Magnetic mechanism»

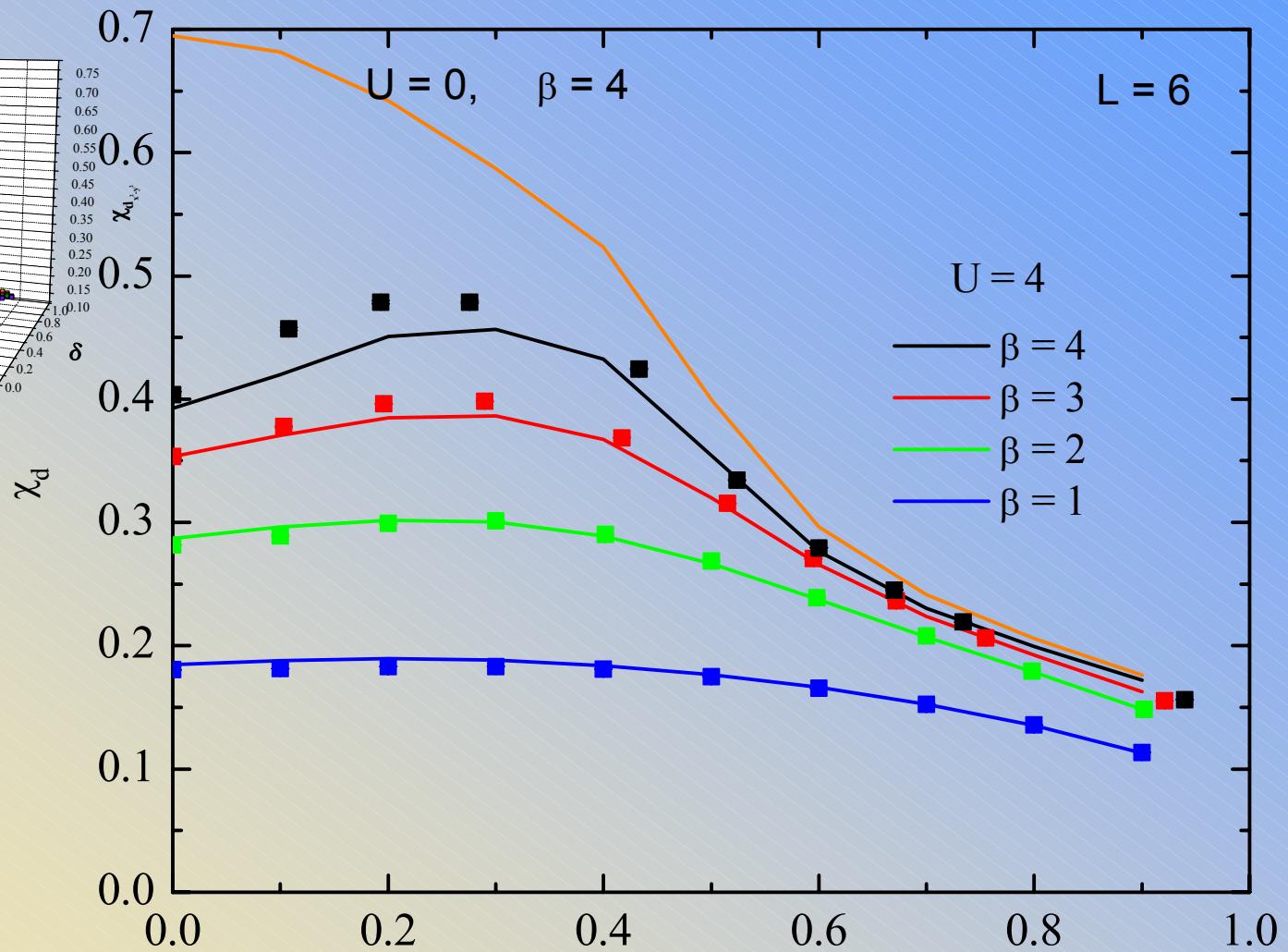
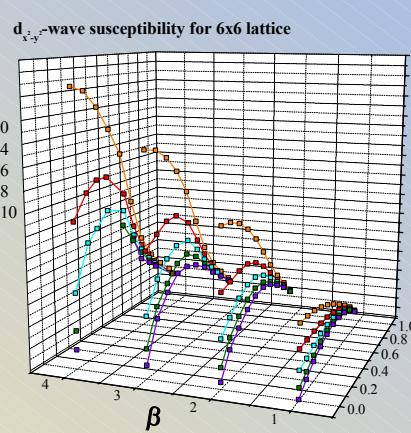


$t = T$



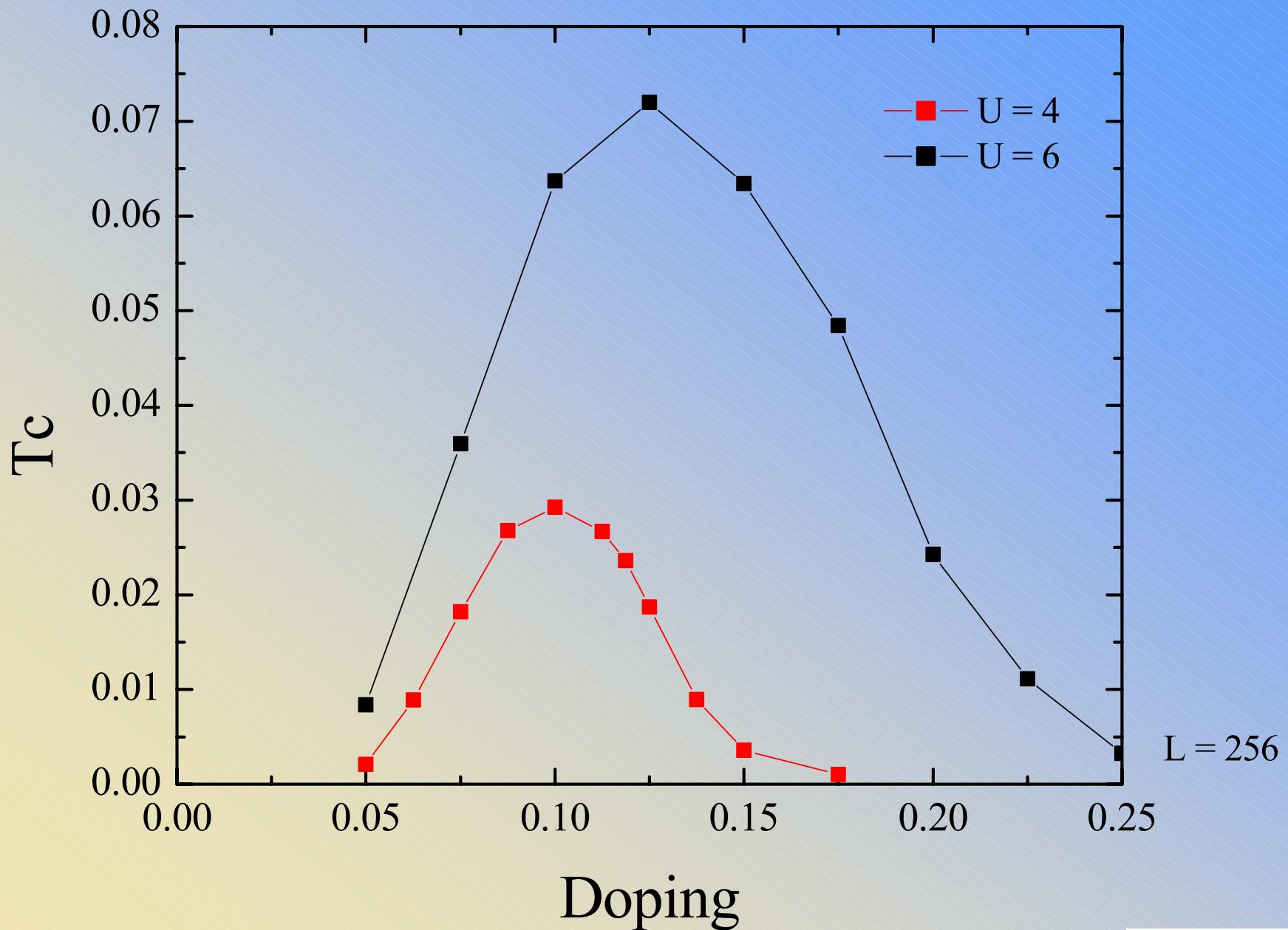
$t = 0$



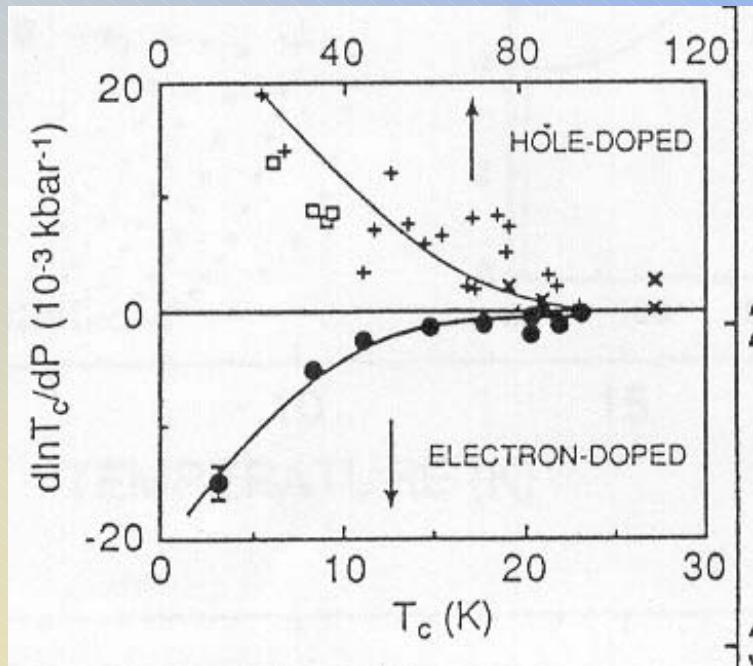


QMC: symbols.
Solid lines analytical.

Doping
Kyung, Landry, A.-M.S.T.



Electron doped:



M.B. Maple
MRS Bulletin,
June 1990

Armitage et al.
Phys. Rev. Lett.
87, 147003 (2001)

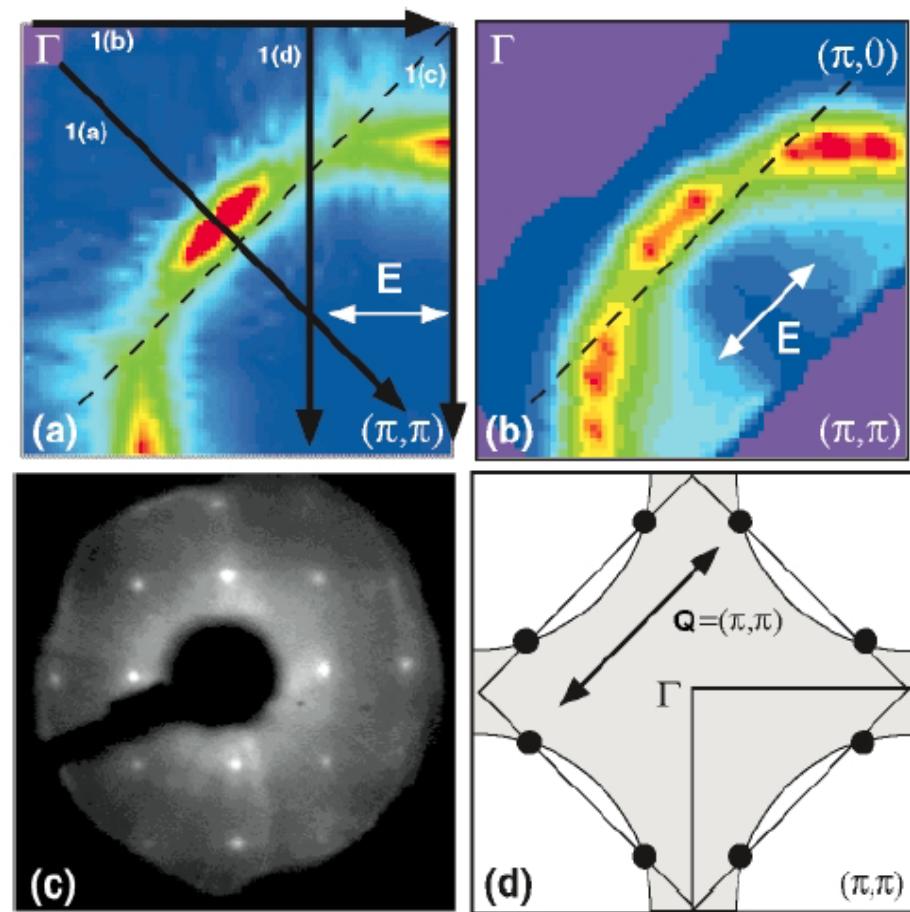
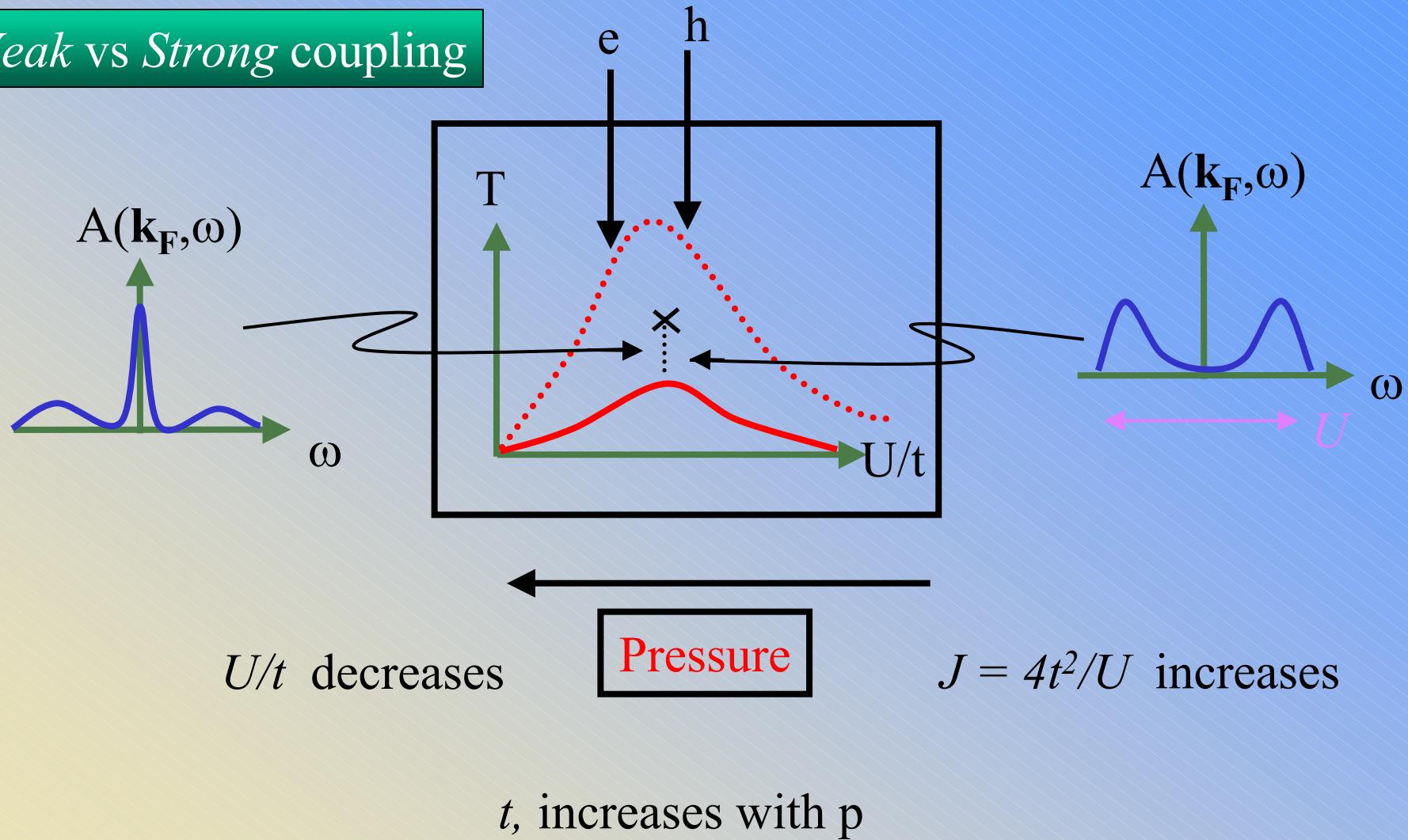


FIG. 2 (color). (a),(b) Fermi surface of the partial Brillouin zone of NCCO taken with $\hbar\omega = 16.5$ and 55 eV, respectively. The plotted quantity is a 30 meV integration about E_F of each EDC plotted as a function of \vec{k} . 16.5 eV data were taken over a Brillouin zone octant and symmetrized across the Γ to the (π, π) line, while the 55 eV data were taken over a full quadrant [6]. The polarization direction is denoted by the double ended arrow. The dotted line is the antiferromagnetic Brillouin zone boundary. (c) LEED spectra of NCCO cleaved *in situ* at 10 K. (d) Schematic showing only those regions of FS near the black circles can be coupled with a (π, π) scattering.

Weak vs Strong coupling



Conclusion to Part II

- Pseudogap in both hole and electron-doped compounds can be understood with a single model, but U is smaller for electron-doped
- At weak to intermediate coupling TPSC allows a rather detailed description of the electron-doped compounds. Both pseudogap and appearance of superconductivity can be understood.

Conclusion to Part I

- Conventional superconductivity – more than 70 years

Intimately related to the development of Physics
Applications under special conditions (4.2K)

- New HTC – **promising, exciting**

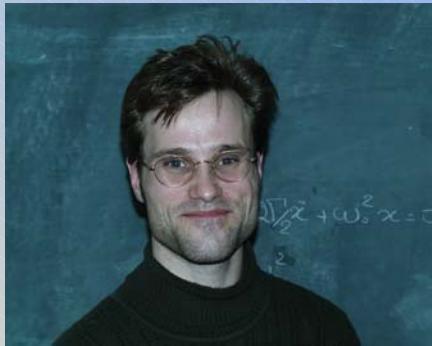
A major challenge for Physicist
77K for applications is already very good...

Room temperature superconductivity would be
INCREDIBLE !

Conclusion

Science and technology The inseparable....

- Steam engine, Watt (1765)
- Thermo, Carnot (1824)
- Electron, Thomson (1897)
- Television (1940...)
- Laser, (1960)
- CD-ROM (1980-90)
- Microelectronics and superconductivity
- Induction, Faraday (1831)
- Induction engine (1880)
- Quantum mechanics, (1926)
- Transistor, (1947)
- Computer revolution, m.-el. (1980)
- Superconductivity (1911)
- Medical imaging (1980-90)
- Quantum computer



Steve Allen



François Lemay



Liang Chen



Yury Vilk



Samuel Moukouri



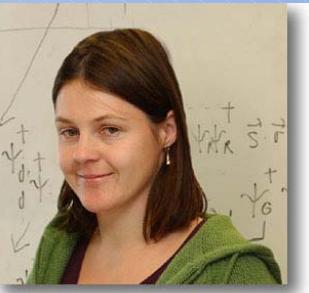
David Poulin



Hugo Touchette



J.-S. Landry



Alexis Gagné-Lebrun



A-M.T. Alexandre Blais Vasyl Hankevych



K. LeHur

C. Bourronnais



Sébastien Roy



R. Côté



D. Sénéchal

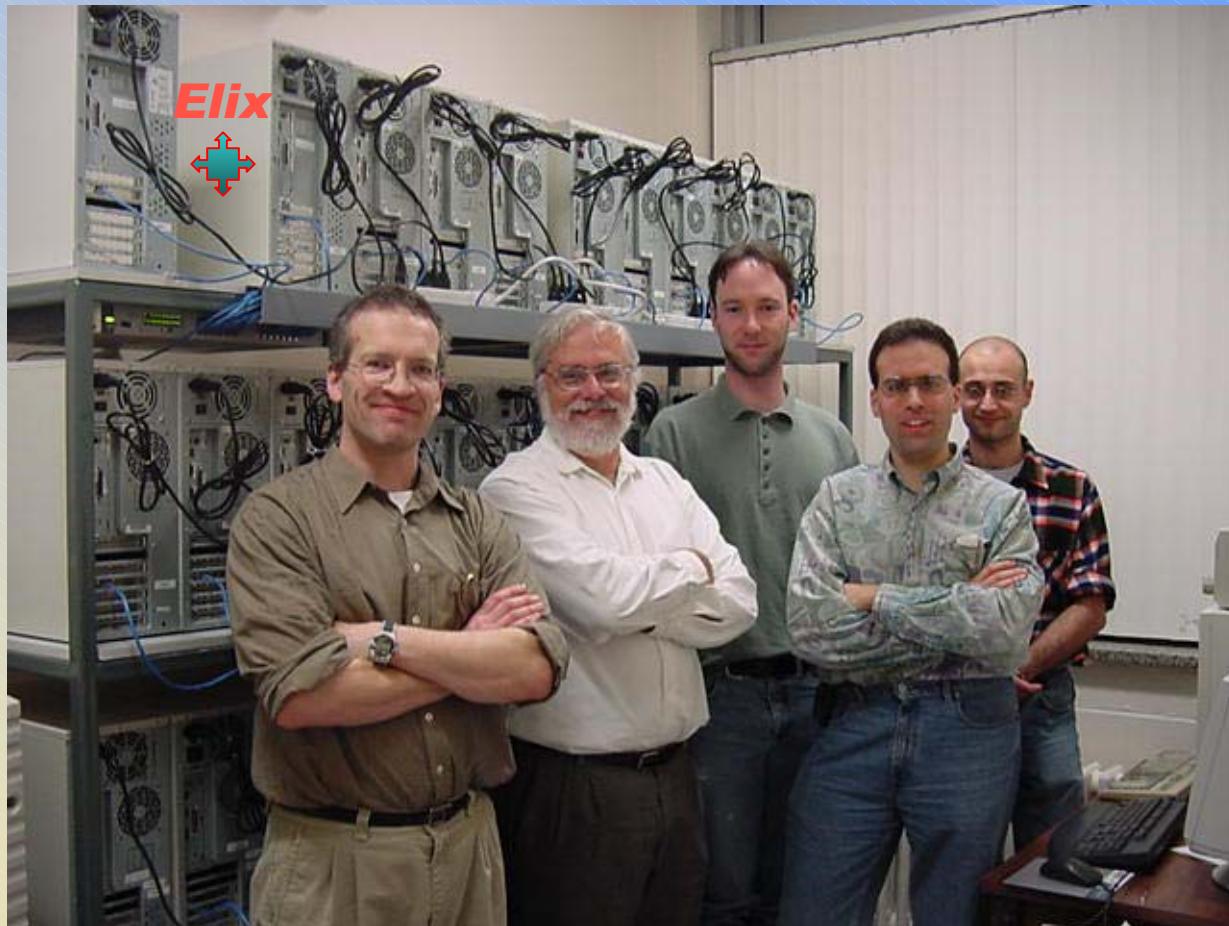
Sarma Kancharla

Bumsoo Kyung

Maxim Mar'enko

Michel Barrette

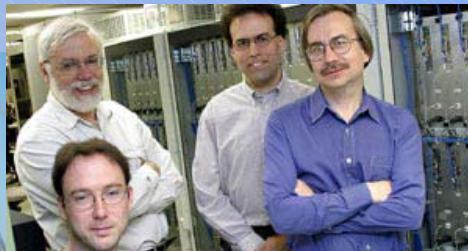
Mehdi Bozzo-Rey



David Sénéchal

A.-M.T.

Alain Veilleux



Un noeud d'Elix2

Carol Gauthier,
analyste en Calcul
du CCS en plein
machinage d'un
noeud d'Elix2



Elix2 vu de profil

Equipe du CCS devant Elix2. Al'arrière: Patrick Vachon, Minh-Nghia Nguyen, David Lauzon, Michel Barrette, Mehdi Bozzo-Rey, Simon Lessard, Alain Veilleux. A l'avant: Patrice Albaret, Karl Gaven-Venet, Benoît des Ligneris, Francis Giraldeau. Etait absent de la photo: Jean-Philippe Turcotte, Carol Gauthier, Xavier Barnabé Thériault et Mathieu Lutfy



De gauche à droite: Alain
Veilleux, Michel Barrette, Jean-
Phillipe Turcotte, Carol
Gauthier, Patrick Vachon et le
1er noeud d'Elix



Référence sur la découverte:

"The path of no resistance: The story of the revolution in Superconductivity"

Bruce Schechter
(Simon and Schuster, NY 1989)

Remerciements:

Jules Carbotte (McMaster)

Patrick Fournier (Sherbrooke)

Hyper-fréquences et ultrasons (Poirier)



Infra-rouge – Raman (Jandl)



Transport (Aubin)

Déposition laser (Fournier)

Quand l'électron se décompose:

- Par exemple en $d=1$, on a déjà prouvé la séparation spin-charge.
- Dans les structures MOSFET en champ magnétique ($d = 2$) l'électron se sépare en parties de charge $1/3, 1/5 \dots$ (Effet Hall quantique) (*Nobel 98*)
- Dans un supraconducteur, l'électron se décompose en deux parties qui sont chacune une combinaison linéaire de particule et de trou.