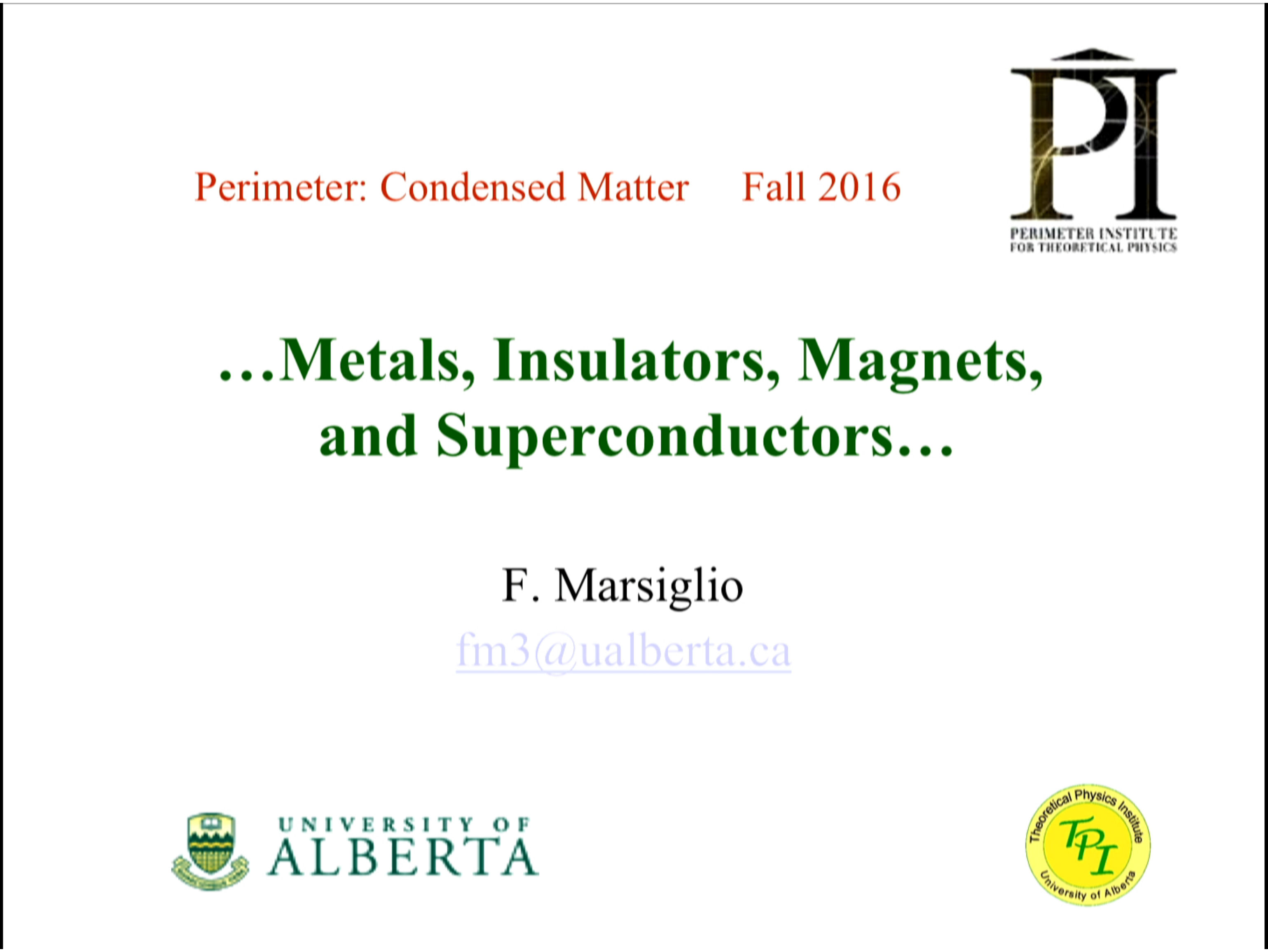
Title: PSI 2016/2017 Condensed Matter - Lecture 1

Date: Nov 07, 2016 10:45 AM

URL: http://pirsa.org/16110052

Abstract:



Perimeter: Condensed Matter Fall 2016

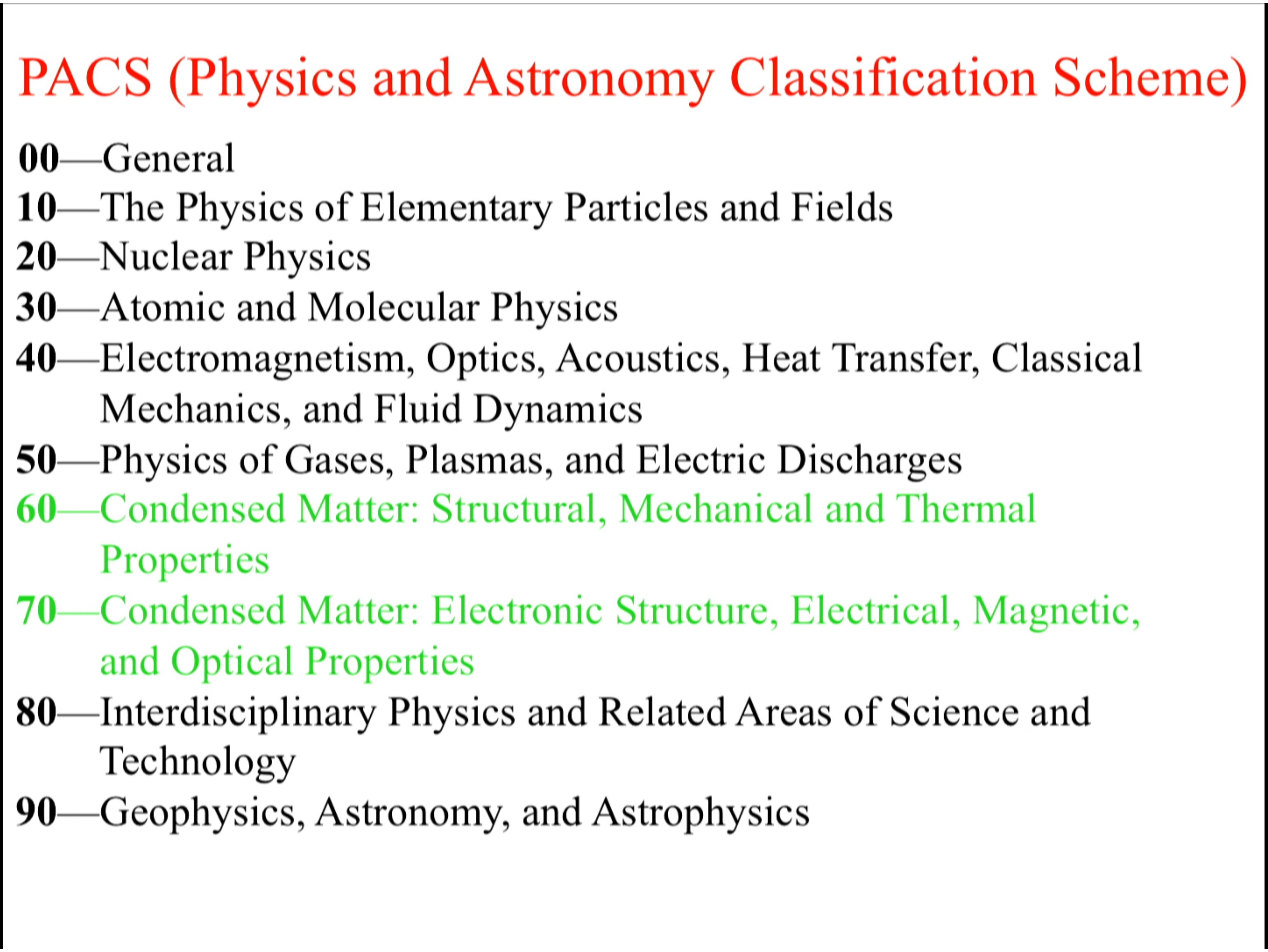
PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

…Metals, Insulators, Magnets, and Superconductors…

F. Marsiglio
fm3@ualberta.ca

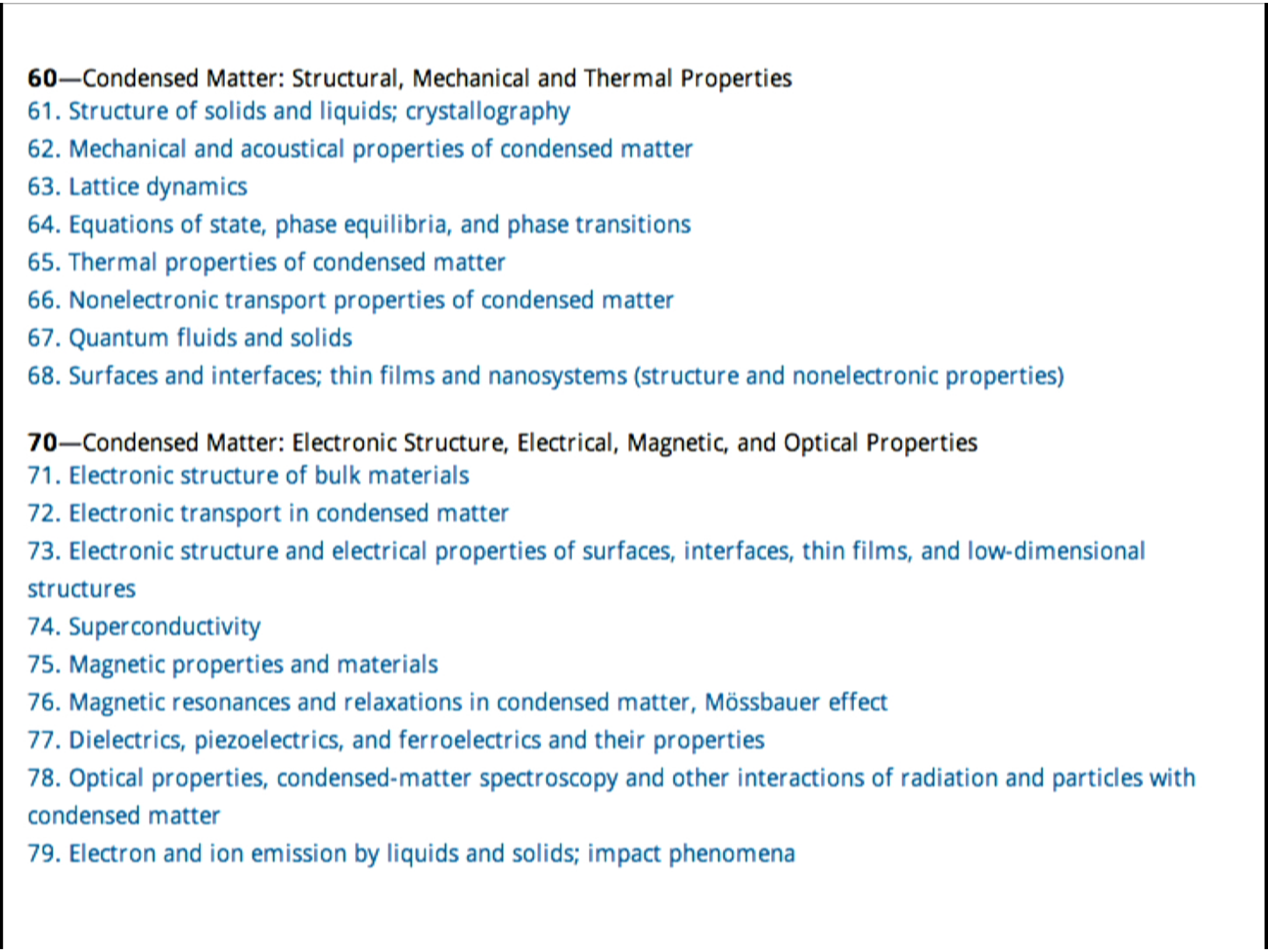
UNIVERSITY OF ALBERTA

Theoretical Physics Institute
TPI
University of Alberta



PACS (Physics and Astronomy Classification Scheme)

00—General
10—The Physics of Elementary Particles and Fields
20—Nuclear Physics
30—Atomic and Molecular Physics
40—Electromagnetism, Optics, Acoustics, Heat Transfer, Classical Mechanics, and Fluid Dynamics
50—Physics of Gases, Plasmas, and Electric Discharges
60—Condensed Matter: Structural, Mechanical and Thermal Properties
70—Condensed Matter: Electronic Structure, Electrical, Magnetic, and Optical Properties
80—Interdisciplinary Physics and Related Areas of Science and Technology
90—Geophysics, Astronomy, and Astrophysics

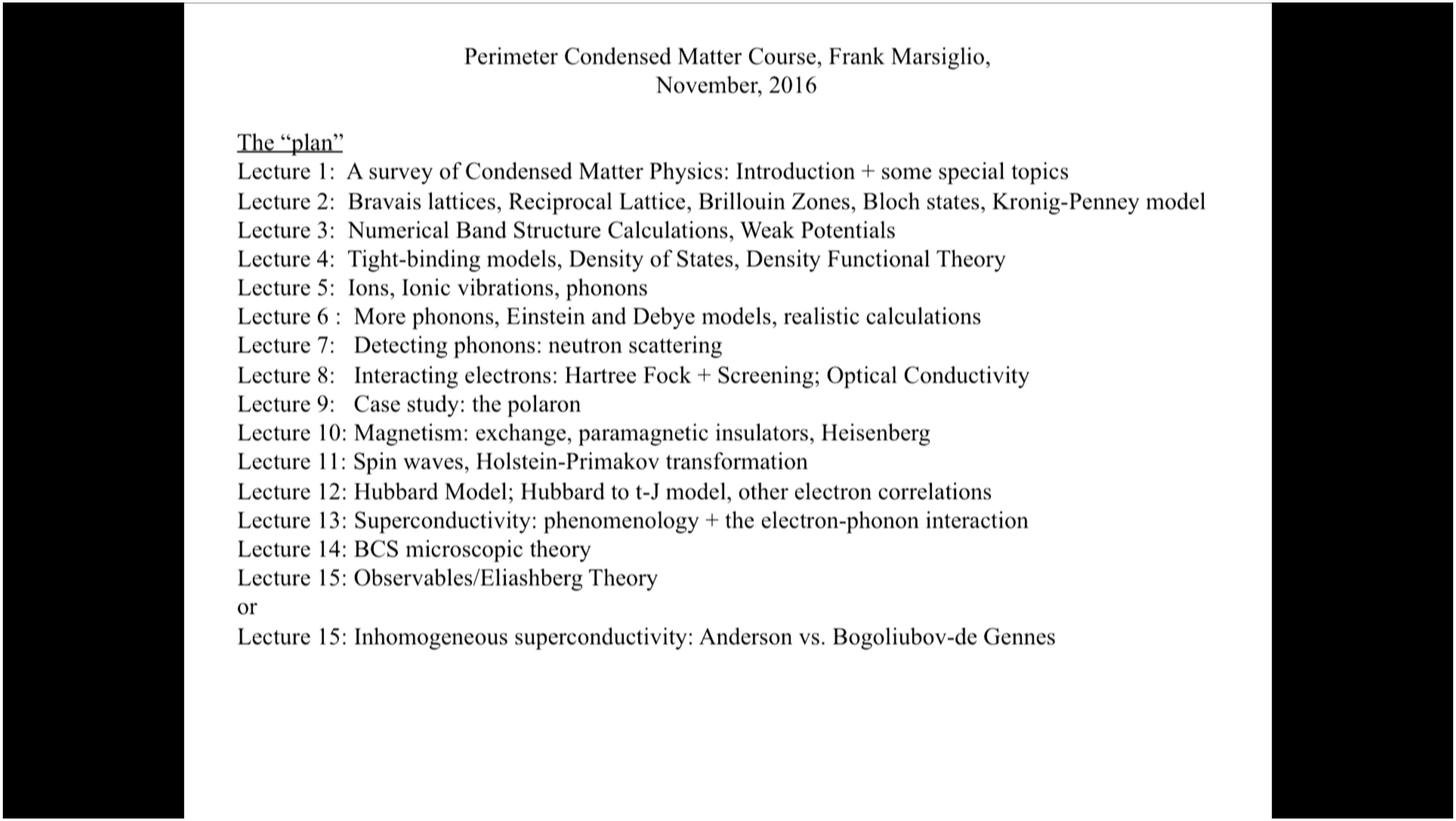


60—Condensed Matter: Structural, Mechanical and Thermal Properties

61. Structure of solids and liquids; crystallography
62. Mechanical and acoustical properties of condensed matter
63. Lattice dynamics
64. Equations of state, phase equilibria, and phase transitions
65. Thermal properties of condensed matter
66. Nonelectronic transport properties of condensed matter
67. Quantum fluids and solids
68. Surfaces and interfaces; thin films and nanosystems (structure and nonelectronic properties)

70—Condensed Matter: Electronic Structure, Electrical, Magnetic, and Optical Properties

71. Electronic structure of bulk materials
72. Electronic transport in condensed matter
73. Electronic structure and electrical properties of surfaces, interfaces, thin films, and low-dimensional structures
74. Superconductivity
75. Magnetic properties and materials
76. Magnetic resonances and relaxations in condensed matter, Mössbauer effect
77. Dielectrics, piezoelectrics, and ferroelectrics and their properties
78. Optical properties, condensed-matter spectroscopy and other interactions of radiation and particles with condensed matter
79. Electron and ion emission by liquids and solids; impact phenomena

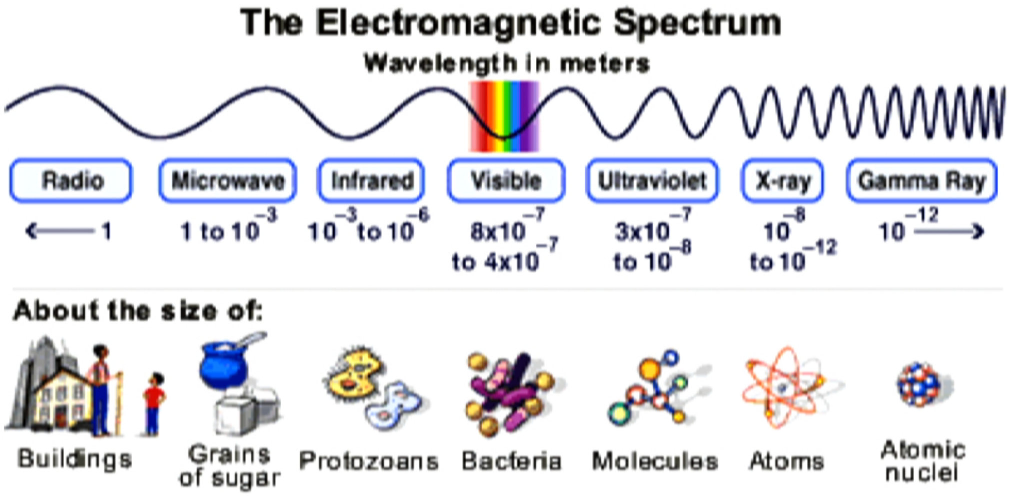


Perimeter Condensed Matter Course, Frank Marsiglio,
November, 2016

The “plan”

Lecture 1: A survey of Condensed Matter Physics: Introduction + some special topics
Lecture 2: Bravais lattices, Reciprocal Lattice, Brillouin Zones, Bloch states, Kronig-Penney model
Lecture 3: Numerical Band Structure Calculations, Weak Potentials
Lecture 4: Tight-binding models, Density of States, Density Functional Theory
Lecture 5: Ions, Ionic vibrations, phonons
Lecture 6 : More phonons, Einstein and Debye models, realistic calculations
Lecture 7: Detecting phonons: neutron scattering
Lecture 8: Interacting electrons: Hartree Fock + Screening; Optical Conductivity
Lecture 9: Case study: the polaron
Lecture 10: Magnetism: exchange, paramagnetic insulators, Heisenberg
Lecture 11: Spin waves, Holstein-Primakov transformation
Lecture 12: Hubbard Model; Hubbard to t-J model, other electron correlations
Lecture 13: Superconductivity: phenomenology + the electron-phonon interaction
Lecture 14: BCS microscopic theory
Lecture 15: Observables/Eliashberg Theory
or
Lecture 15: Inhomogeneous superconductivity: Anderson vs. Bogoliubov-de Gennes

Units

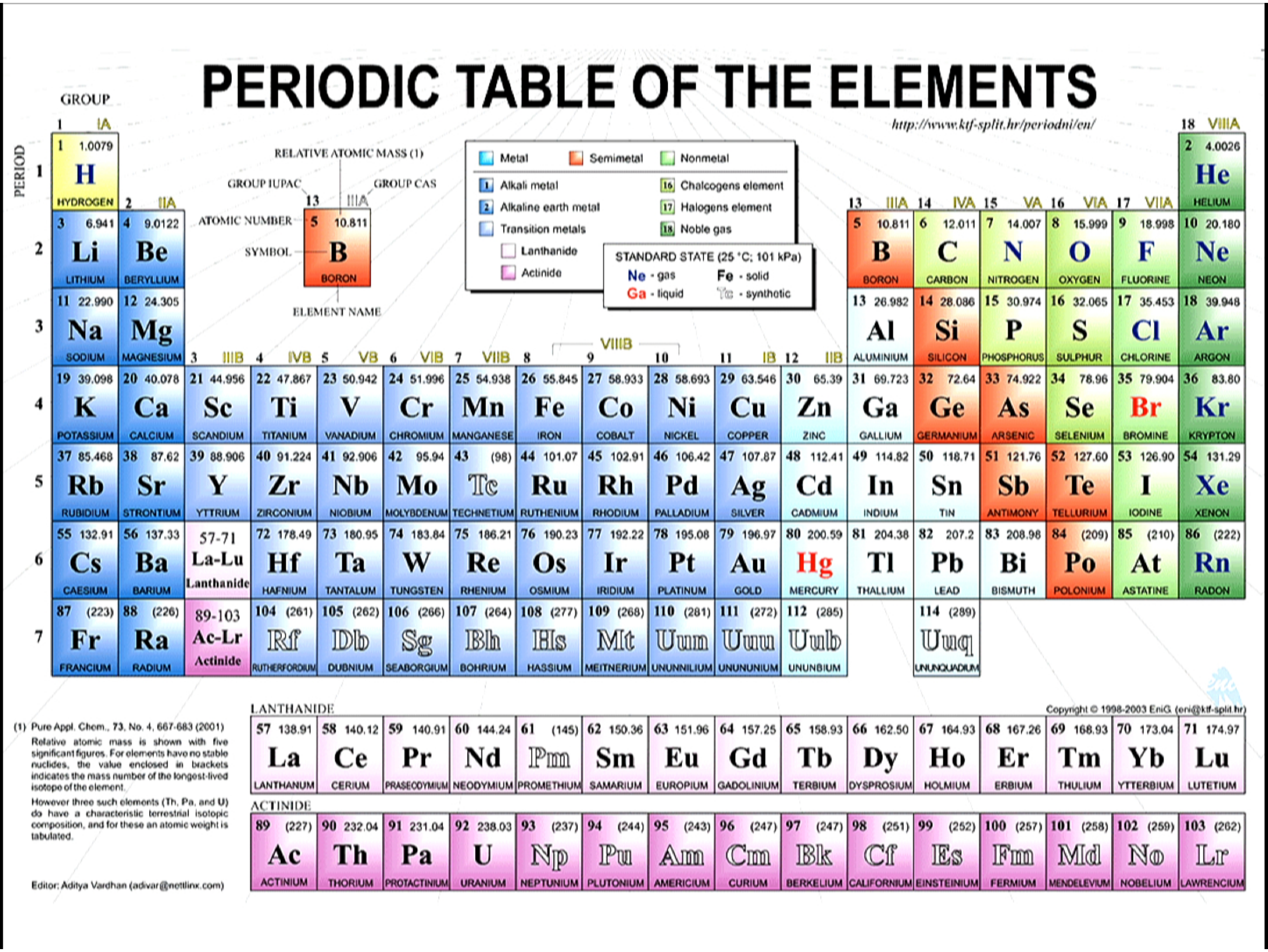


Units: 1 meV = 0.24 THz

8.066 cm^{-1}

11.605 K

1.73 $[\Omega\text{-cm}]^{-1}$



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME
13 IIIA
5 10.811
B
BORON

🟦 Metal 🟥 Semimetal 🟩 Nonmetal
1 Alkali metal
2 Alkaline earth metal
🟦 Transition metals
☐ Lanthanide
☐ Actinide
16 Chalcogens element
17 Halogens element
18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

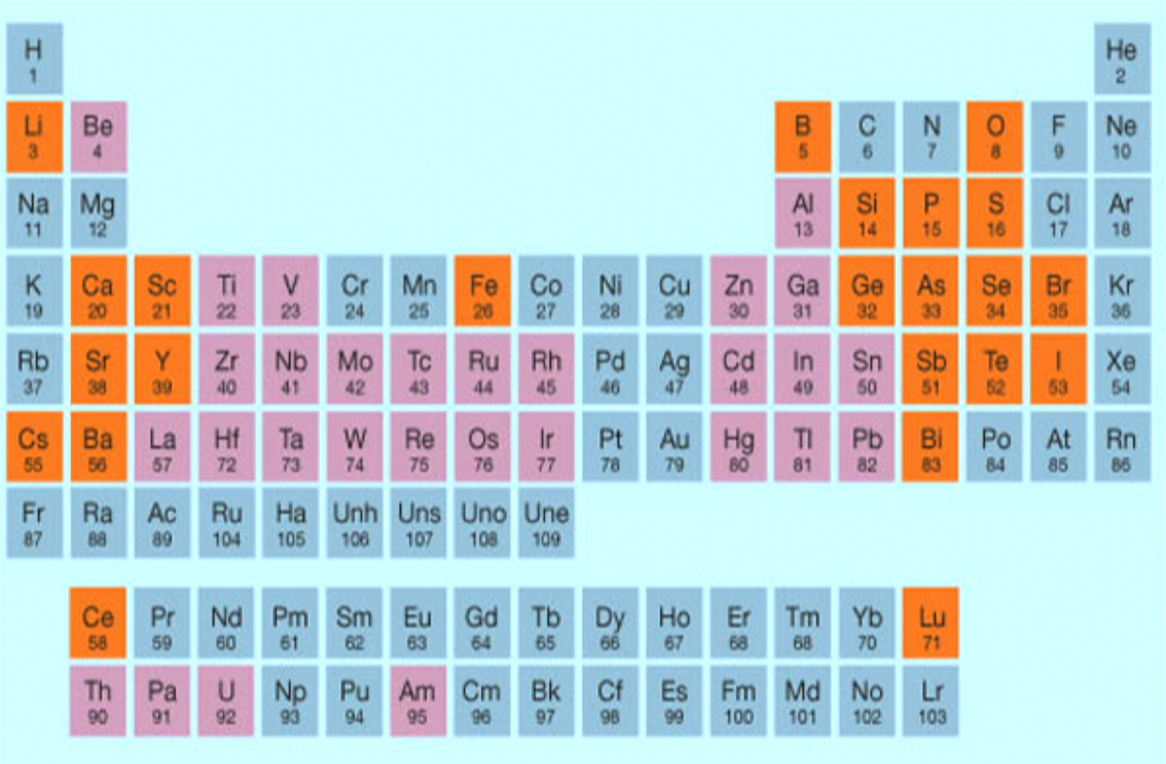
89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

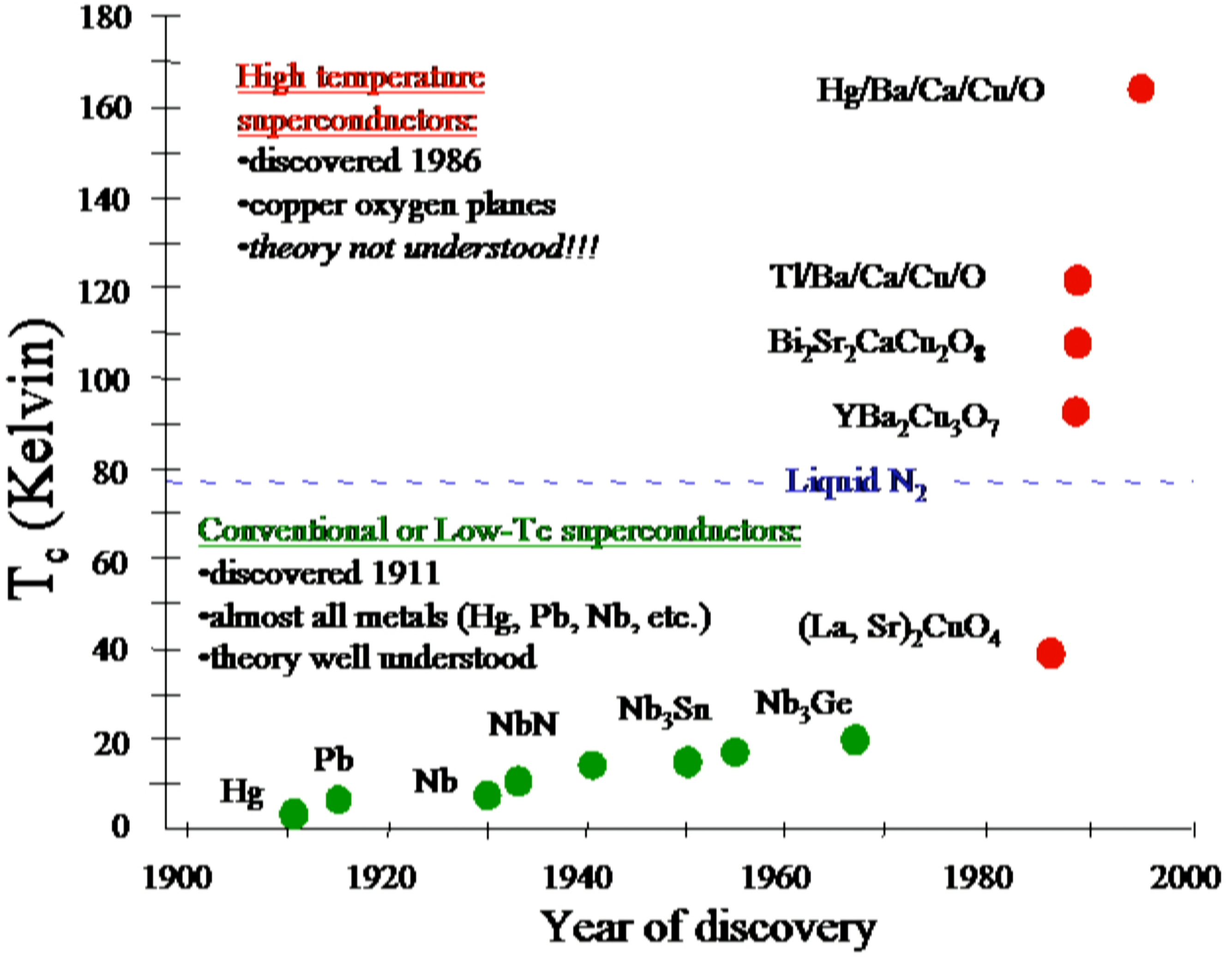
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@nettlinx.com)

N.W. Ashcroft, Nature
News and Views, 2002



H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Ru 104	Ha 105	Unh 106	Uns 107	Uno 108	Une 109									
	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 68	Yb 70	Lu 71			
	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103			



High temperature superconductors:

- discovered 1986
- copper oxygen planes
- *theory not understood!!!*

Conventional or Low-Tc superconductors:

- discovered 1911
- almost all metals (Hg, Pb, Nb, etc.)
- theory well understood

http://spot.colorado.edu/~dessau/HighTc.shtml

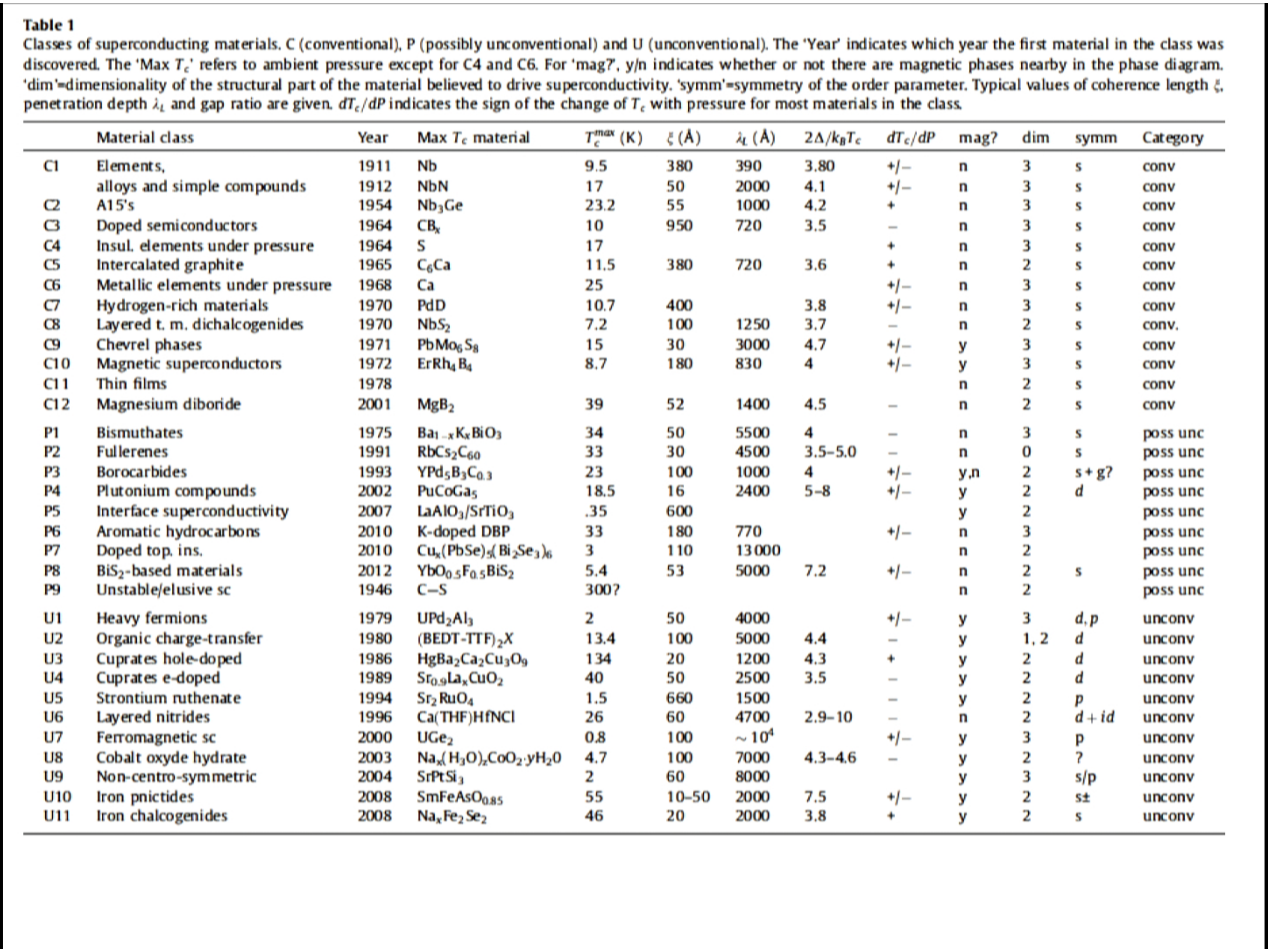
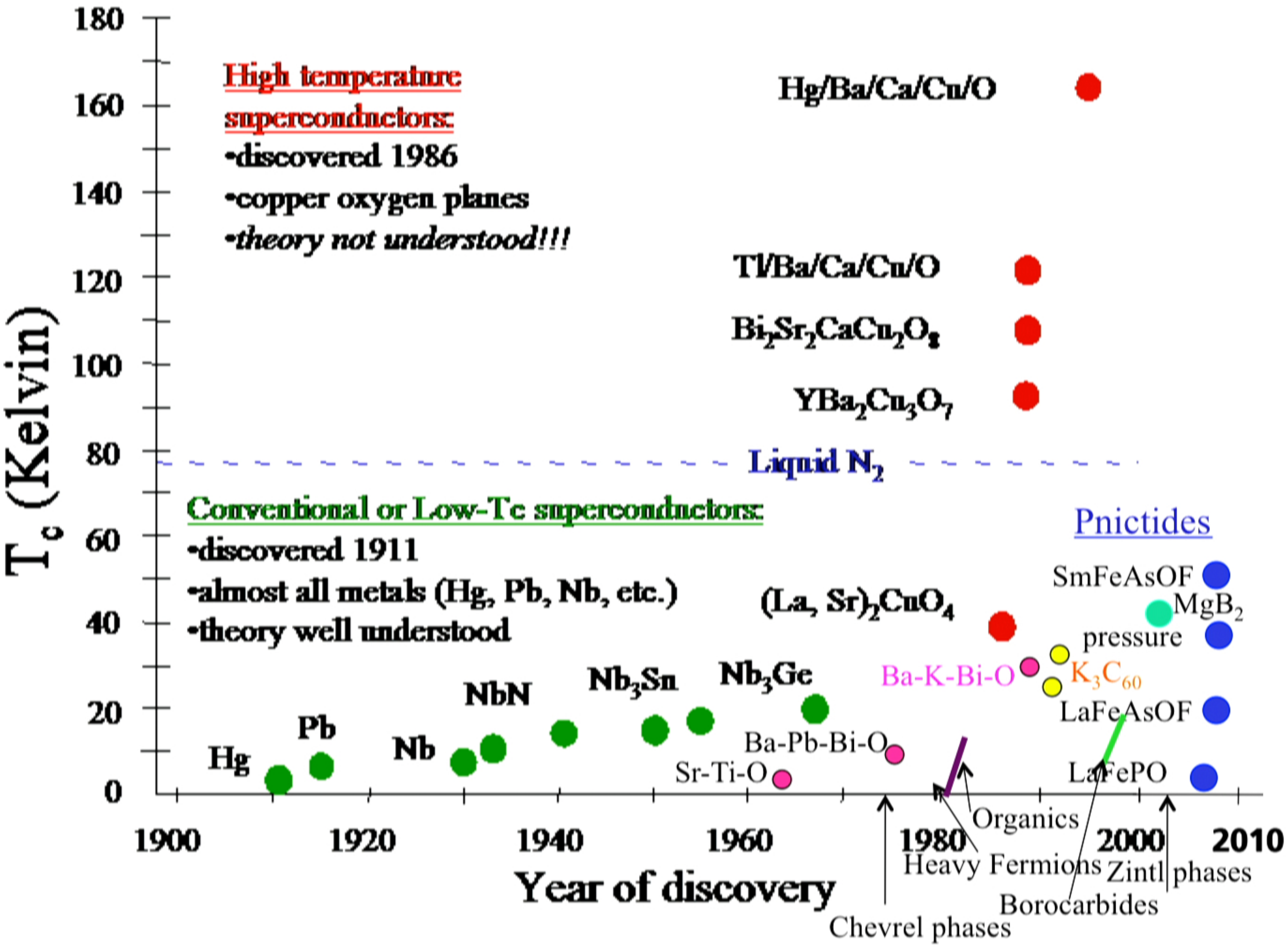


Table 1

Classes of superconducting materials. C (conventional), P (possibly unconventional) and U (unconventional). The 'Year' indicates which year the first material in the class was discovered. The 'Max T_c' refers to ambient pressure except for C4 and C6. For 'mag?', y/n indicates whether or not there are magnetic phases nearby in the phase diagram. 'dim'=dimensionality of the structural part of the material believed to drive superconductivity. 'symm'=symmetry of the order parameter. Typical values of coherence length ξ, penetration depth λ_L and gap ratio are given. dT_c/dP indicates the sign of the change of T_c with pressure for most materials in the class.

	Material class	Year	Max T_c material	T_c^{max} (K)	ξ (Å)	λ_L (Å)	$2\Delta/k_BT_c$	dT_c/dP	mag?	dim	symm	Category
C1	Elements,	1911	Nb	9.5	380	390	3.80	+/–	n	3	s	conv
	alloys and simple compounds	1912	NbN	17	50	2000	4.1	+/–	n	3	s	conv
C2	A15's	1954	Nb_3Ge	23.2	55	1000	4.2	+	n	3	s	conv
C3	Doped semiconductors	1964	CB_x	10	950	720	3.5	–	n	3	s	conv
C4	Insul. elements under pressure	1964	S	17				+	n	3	s	conv
C5	Intercalated graphite	1965	C_6Ca	11.5	380	720	3.6	+	n	2	s	conv
C6	Metallic elements under pressure	1968	Ca	25				+/–	n	3	s	conv
C7	Hydrogen-rich materials	1970	PdD	10.7	400		3.8	+/–	n	3	s	conv
C8	Layered t. m. dichalcogenides	1970	NbS_2	7.2	100	1250	3.7	–	n	2	s	conv.
C9	Chevrel phases	1971	$PbMo_6S_8$	15	30	3000	4.7	+/–	y	3	s	conv
C10	Magnetic superconductors	1972	$ErRh_4B_4$	8.7	180	830	4	+/–	y	3	s	conv
C11	Thin films	1978							n	2	s	conv
C12	Magnesium diboride	2001	MgB_2	39	52	1400	4.5	–	n	2	s	conv
P1	Bismuthates	1975	$Ba_{1-x}K_xBiO_3$	34	50	5500	4	–	n	3	s	poss unc
P2	Fullerenes	1991	$RbCs_2C_{60}$	33	30	4500	3.5–5.0	–	n	0	s	poss unc
P3	Borocarbides	1993	$YPd_5B_3C_{0.3}$	23	100	1000	4	+/–	y,n	2	s + g?	poss unc
P4	Plutonium compounds	2002	$PuCoGa_5$	18.5	16	2400	5–8	+/–	y	2	*d*	poss unc
P5	Interface superconductivity	2007	$LaAlO_3/SrTiO_3$	.35	600				y	2		poss unc
P6	Aromatic hydrocarbons	2010	K-doped DBP	33	180	770		+/–	n	3		poss unc
P7	Doped top. ins.	2010	$Cu_x(PbSe)_5(Bi_2Se_3)_6$	3	110	13000			n	2		poss unc
P8	BiS_2-based materials	2012	$YbO_{0.5}F_{0.5}BiS_2$	5.4	53	5000	7.2	+/–	n	2	s	poss unc
P9	Unstable/elusive sc	1946	C–S	300?					n	2		poss unc
U1	Heavy fermions	1979	UPd_2Al_3	2	50	4000		+/–	y	3	*d, p*	unconv
U2	Organic charge-transfer	1980	$(BEDT\text{-}TTF)_2X$	13.4	100	5000	4.4	–	y	1, 2	*d*	unconv
U3	Cuprates hole-doped	1986	$HgBa_2Ca_2Cu_3O_9$	134	20	1200	4.3	+	y	2	*d*	unconv
U4	Cuprates e-doped	1989	$Sr_{0.9}La_xCuO_2$	40	50	2500	3.5	–	y	2	*d*	unconv
U5	Strontium ruthenate	1994	Sr_2RuO_4	1.5	660	1500		–	y	2	*p*	unconv
U6	Layered nitrides	1996	Ca(THF)HfNCl	26	60	4700	2.9–10	–	n	2	$d + id$	unconv
U7	Ferromagnetic sc	2000	UGe_2	0.8	100	$\sim 10^4$		+/–	y	3	p	unconv
U8	Cobalt oxyde hydrate	2003	$Na_x(H_3O)_zCoO_2 \cdot yH_20$	4.7	100	7000	4.3–4.6	–	y	2	?	unconv
U9	Non-centro-symmetric	2004	$SrPtSi_3$	2	60	8000			y	3	s/p	unconv
U10	Iron pnictides	2008	$SmFeAsO_{0.85}$	55	10–50	2000	7.5	+/–	y	2	s±	unconv
U11	Iron chalcogenides	2008	$Na_xFe_2Se_2$	46	20	2000	3.8	+	y	2	s	unconv



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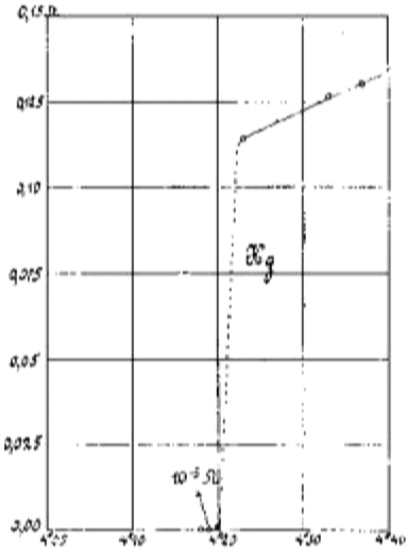
Superconductivity

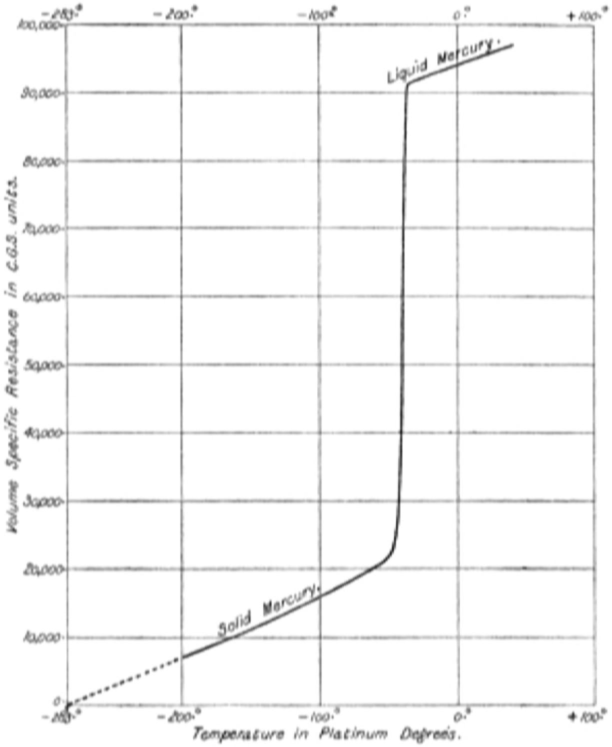
Heike Kamerlingh Onnes

Kamerlingh Onnes, H.,
"The Superconductivity of Mercury."
Comm. Phys. Lab. Univ. Leiden; Nos. 122 and 124, 1911.



Superconductivity

Fig. 1.

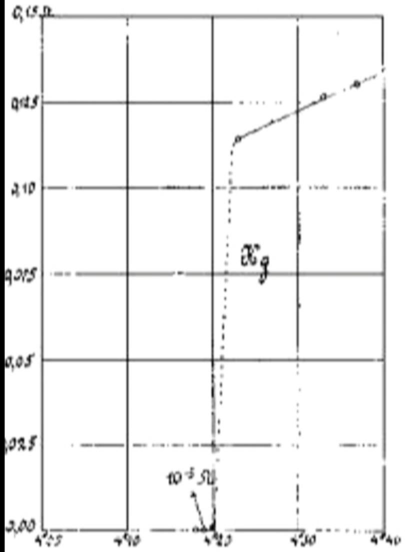


On the Electrical Resistivity of Pure Mercury at the Temperature of Liquid Air

James Dewar and J. A. Fleming

Proceedings of the Royal Society of London,
Vol. 60 (1896 – 1897), pp. 76-81

Aside: Gilles Holst, the student



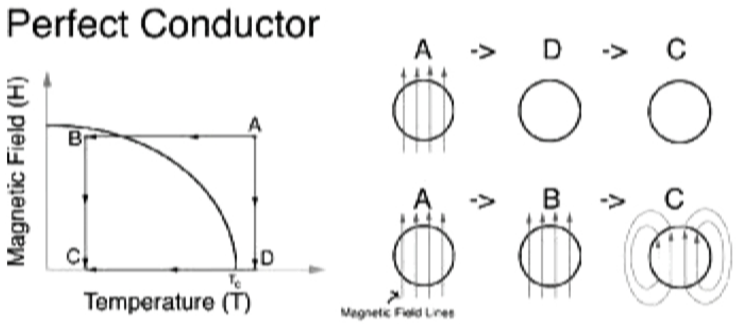
- Really the discoverer of superconductivity
- Founding director of Philips labs in Netherlands
- Holst Memorial Lectures, started 1977
- Acknowledged by Kamerlingh-Onnes in papers, and in a letter for membership in Royal Dutch Academy

> “***As a research director at Philips, according to Casimir, Holst would never insist on being coauthor, let alone sole author of papers based essentially on the work of others.***”

As quoted from Casimir, in Dahl: *Superconductivity*

Walther Meißner
1882 - 1974

Meissner-Ochsenfeld Effect

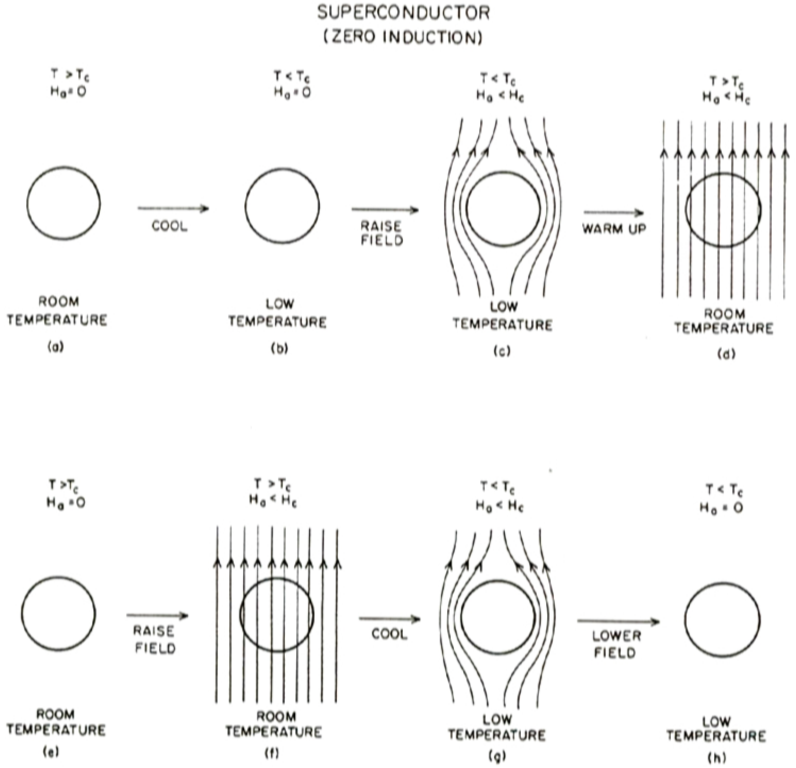


Robert Ochsenfeld
1901 - 1993

Walther Meißner
1882 - 1974

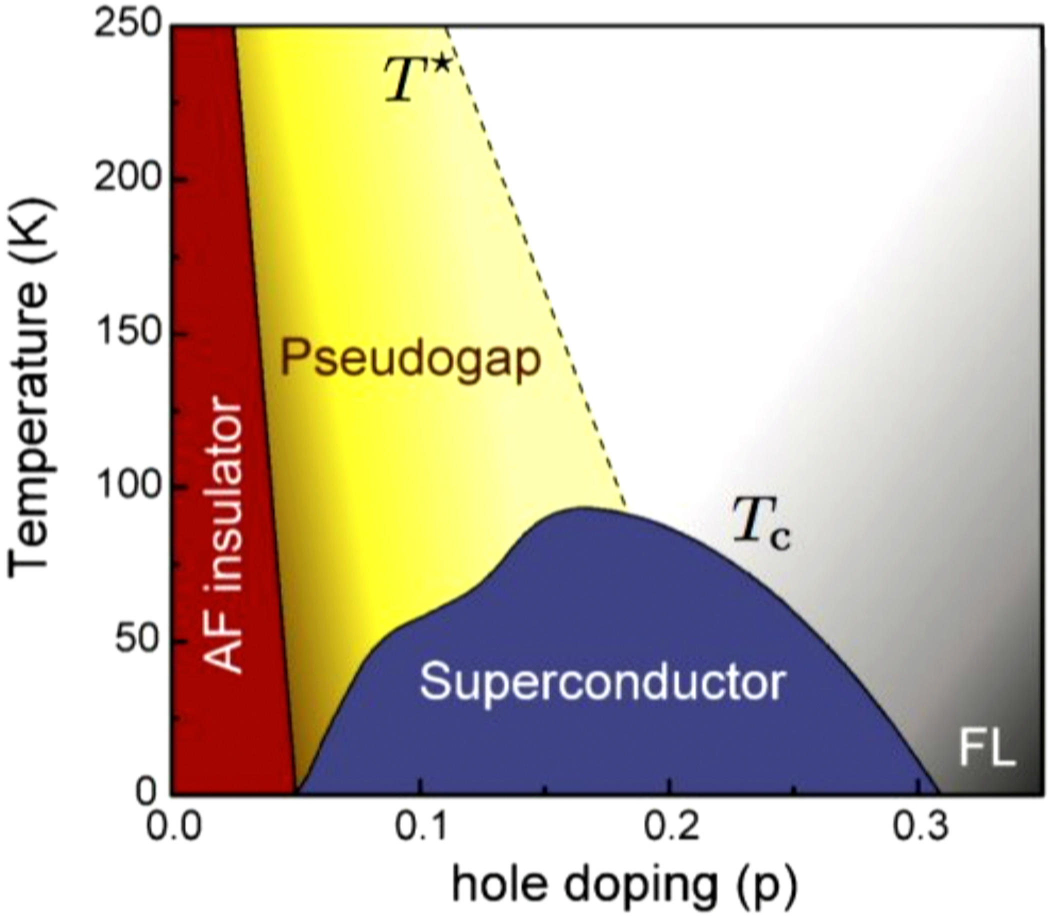
Meissner-Ochsenfeld Effect

Robert Ochsenfeld
1901 - 1993

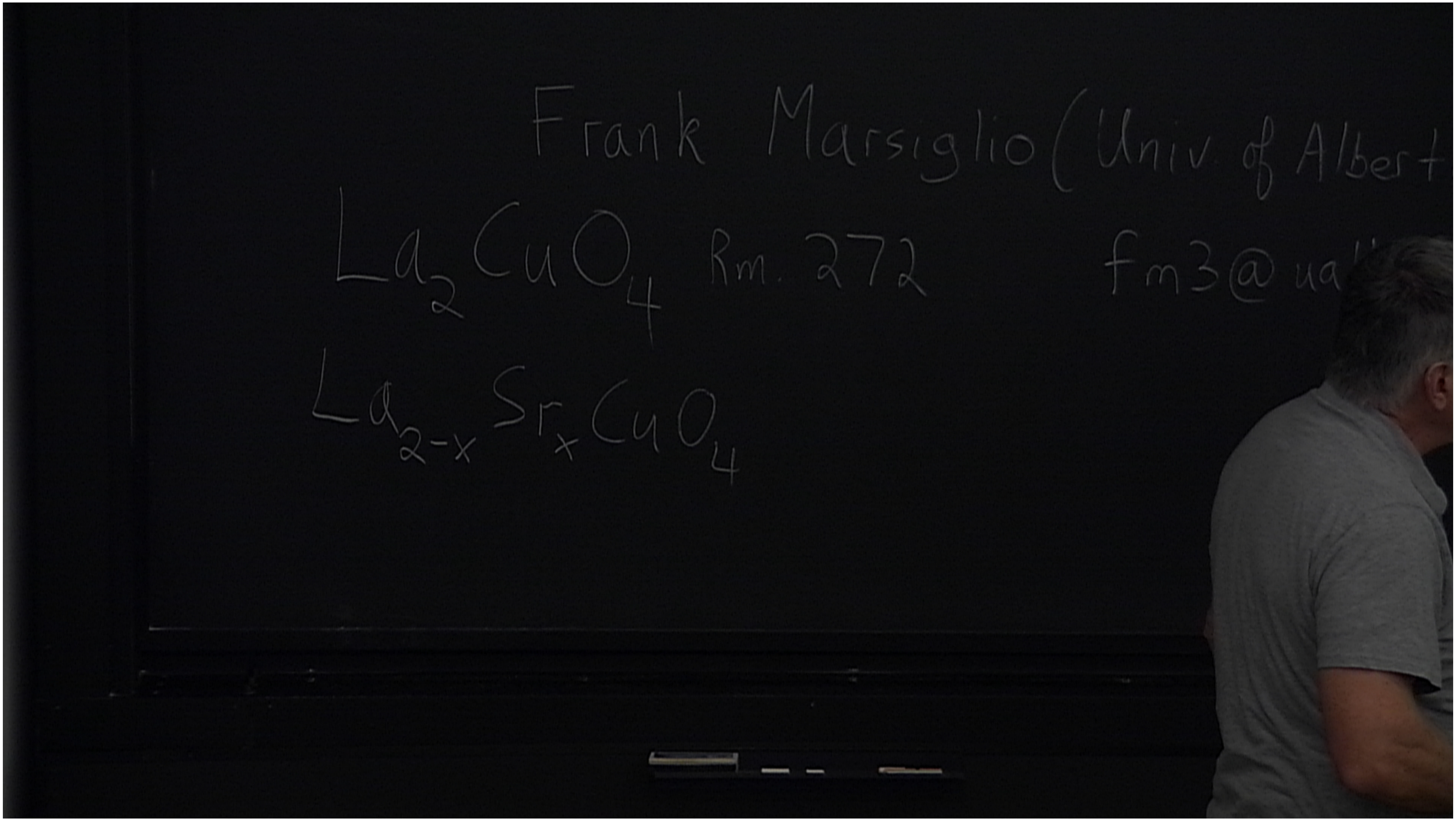


Dahl, p.180

“high T_c” cuprates



http://www.toulouse.lncmi.cnrs.fr/spip.php?rubrique149&lang=en



Frank Marsiglio (Univ. of Albert

La_2CuO_4 Rm. 272 fm3@ual

$La_{2-x}Sr_xCuO_4$

How we view electronic properties in Condensed Matter

The Theory of Everything

R. B. Laughlin* and David Pines†‡§


Bob Laughlin


David Pines

28–31 PNAS **January 4, 2000** vol. 97 no. 1

$$i\hbar \frac{\partial}{\partial t} |\Psi> \; = \mathcal{H} |\Psi> \qquad \textbf{[1]}$$

where

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}. \qquad \textbf{[2]}$$

> ‵We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance.’

The Theory of Everything

R. B. Laughlin* and David Pines†‡§

Bob Laughlin

David Pines

28–31 PNAS **January 4, 2000** vol. 97 no. 1

$$i\hbar \frac{\partial}{\partial t} |\Psi > \; = \mathcal{H}|\Psi > \qquad \textbf{[1]}$$

See also; P.W. Anderson's 'More is Different' in Science, 1972

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}. \qquad \textbf{[2]}$$

> ` We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance.'

A big “rug”: Fermi Liquid Theory

nothing very exceptional about the normal state of electrons in a metal

(pretend they don’t interact)

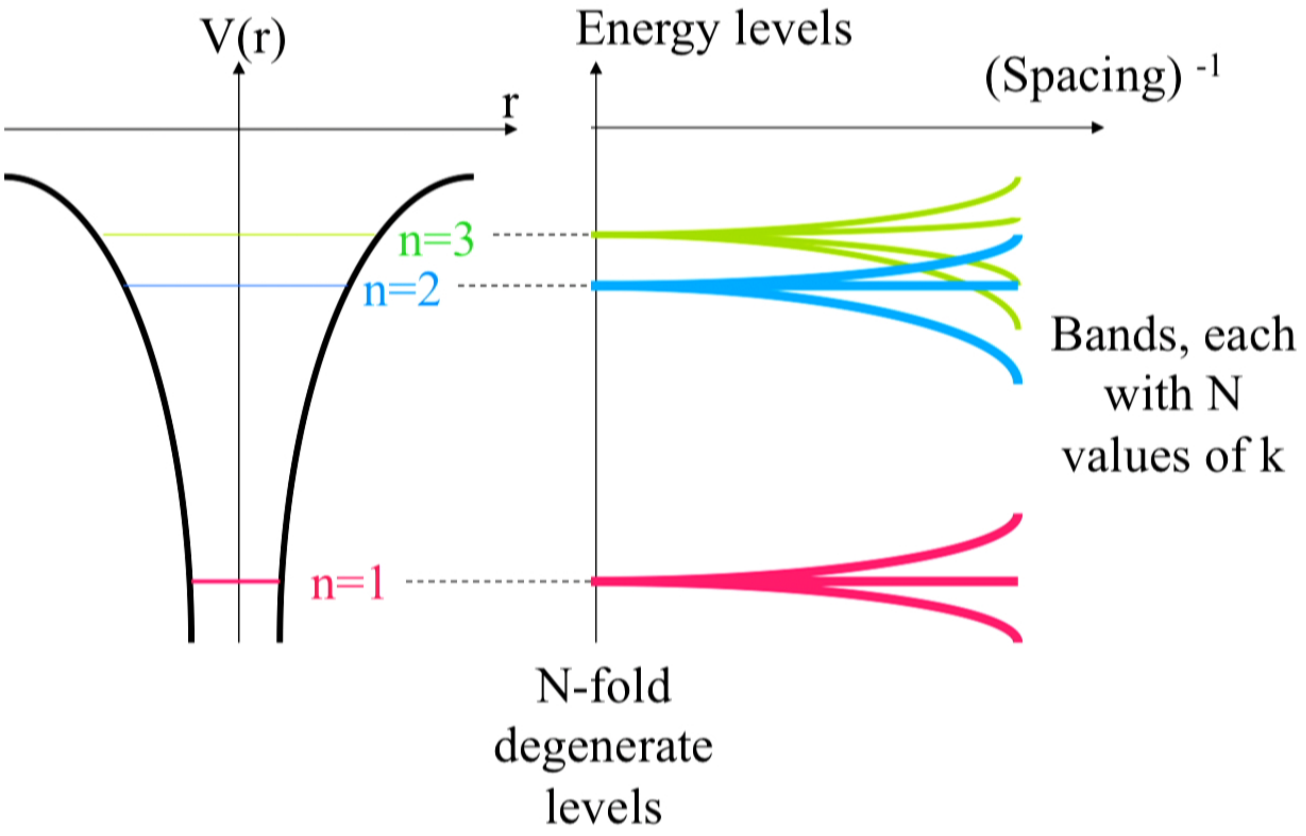
A big “rug”: Fermi Liquid Theory

nothing very exceptional about the normal state of electrons in a metal

(pretend they don’t interact)

… a premise for ‘conventional’ superconductivity

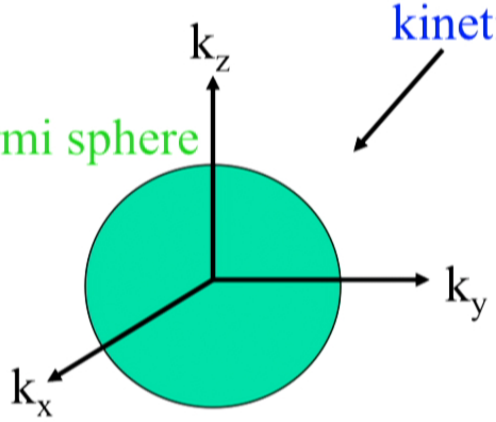
Band theory of metals

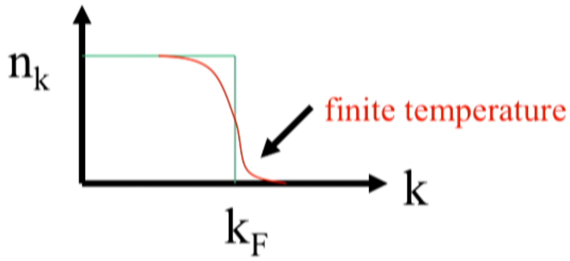


Electrons in solids

kinetic vs. potential energy

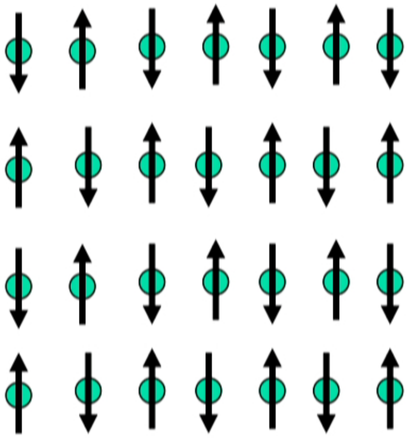
Fermi sphere





$$E_{kin} = 2\,\Sigma \varepsilon_k n_k$$

Mott insulator



why ? Coulomb:
keep electrons away from one another !

$_4$

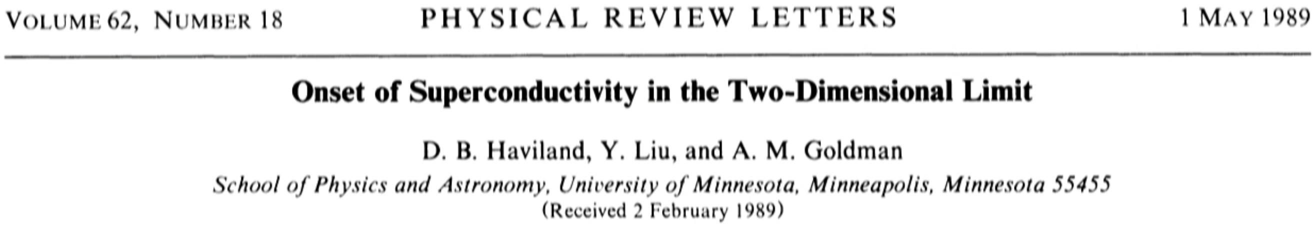
uO_4

Rm. 272

fm3@ualberta.ca

$$\varepsilon_k = \frac{\hbar^2 |\vec{k}|^2}{2m}$$

Ultrathin films



VOLUME 62, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 1989

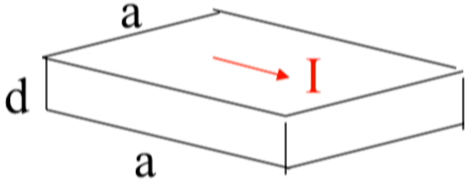
Onset of Superconductivity in the Two-Dimensional Limit

D. B. Haviland, Y. Liu, and A. M. Goldman
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

(Received 2 February 1989)

$R=\rho L/A$

$R_s=\rho a/(ad) = \rho/d$



sheet resistance
resistance/sheet

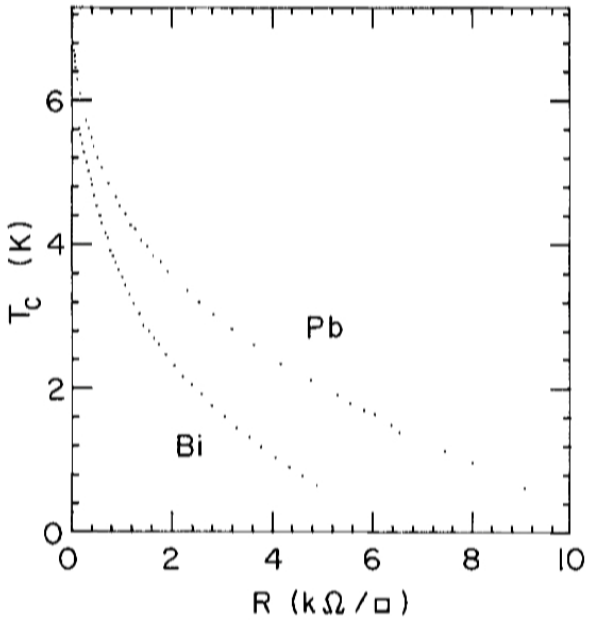


FIG. 3. Dependence of the mean-field transition temperature of Bi and Pb films on sheet resistance.

$$\frac{h}{4e^2}=6.45\mathrm{k}\Omega$$

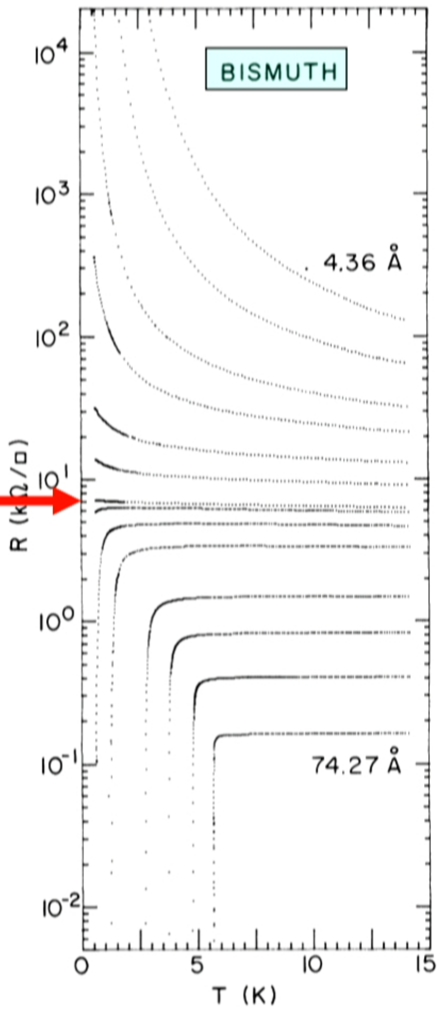


FIG. 1. Evolution of the temperature dependence of the sheet resistance $R(T)$ with thickness for a Bi film deposited onto Ge. Fewer than half of the traces actually acquired are shown. Film thicknesses shown range from 4.36 to 74.27 Å.

not as close in Pb

decreasing
film
thickness

http://www.jst.go.jp/sicp/ws2009_ge3rd/presentation/14.pdf

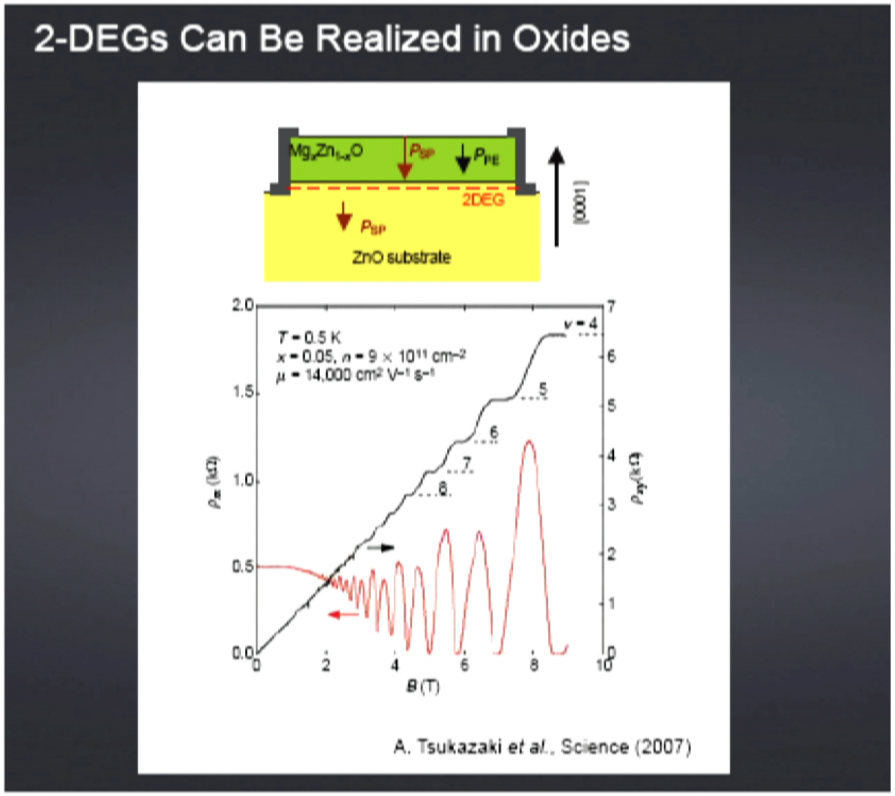
Two Dimensional Electron Gases at Oxide Interfaces

Jochen Mannhart

Center for Electronic Correlations and Magnetism
University of Augsburg

JST-DFG Workshop on Nanoelectronics, Kyoto, Jan. 21, 2009

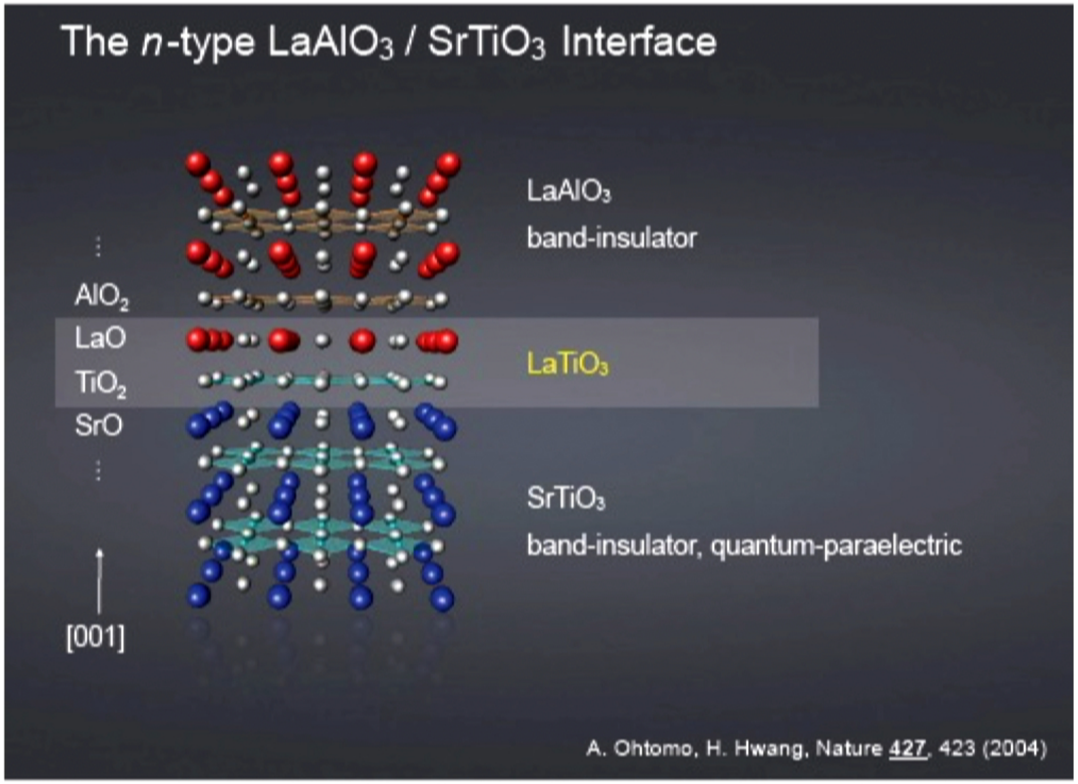
Slide from Mannhart Kyoto talk



2-DEGs Can Be Realized in Oxides

A. Tsukazaki *et al.*, Science (2007)

Slide from Mannhart Kyoto talk



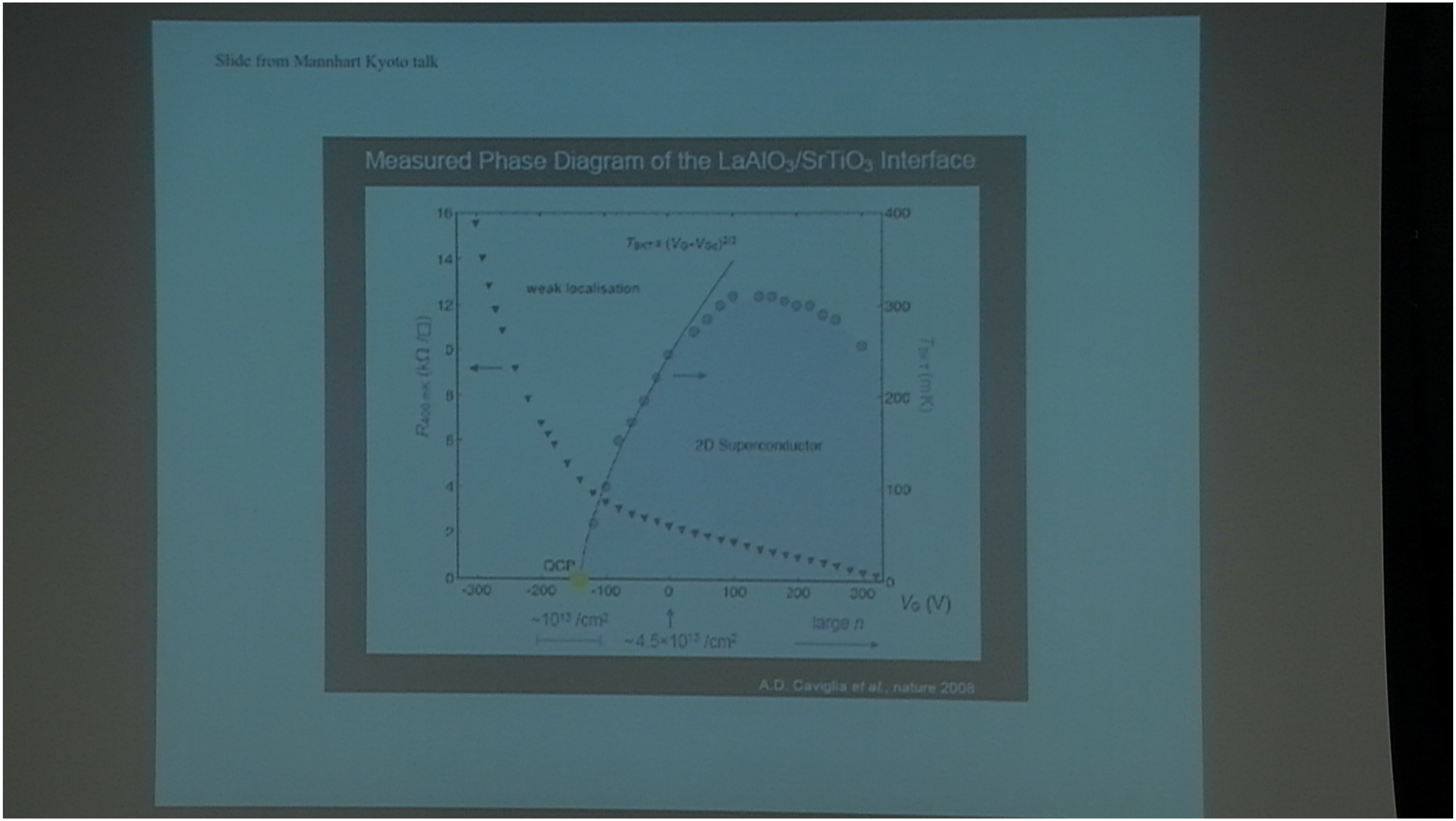
The n-type $LaAlO_3$ / $SrTiO_3$ Interface

$LaAlO_3$
band-insulator

$LaTiO_3$

$SrTiO_3$
band-insulator, quantum-paraelectric

A. Ohtomo, H. Hwang, Nature **427**, 423 (2004)



Slide from Mannhart Kyoto talk

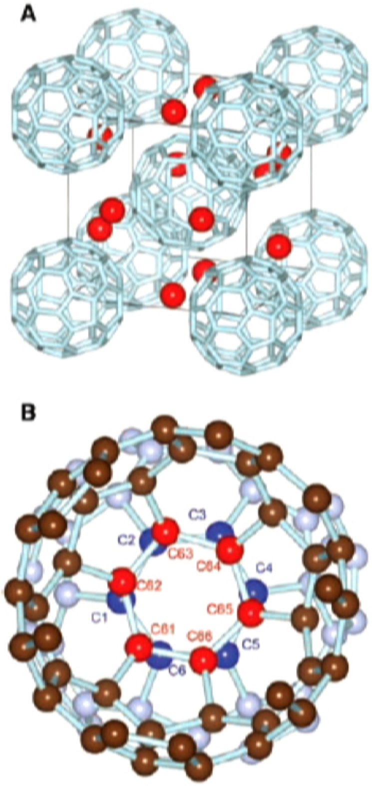
Measured Phase Diagram of the $LaAlO_3/SrTiO_3$ Interface

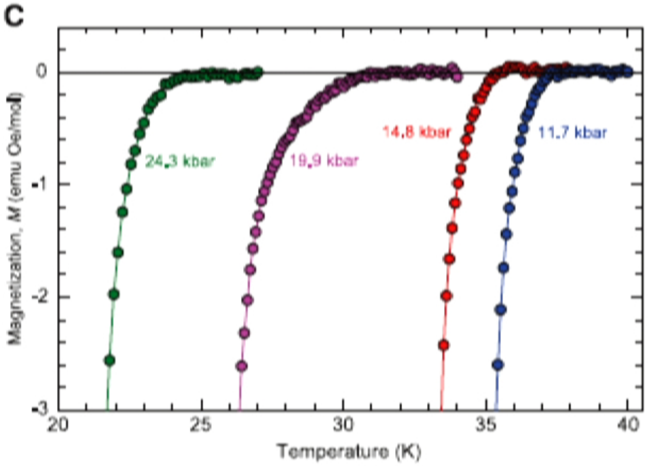
A.D. Caviglia *et al.*, nature 2008

www.sciencemag.org SCIENCE VOL 323 20 MARCH 2009

The Disorder-Free Non-BCS Superconductor Cs_3C_{60} Emerges from an Antiferromagnetic Insulator Parent State

Yasuhiro Takabayashi,[1]* Alexey Y. Ganin,[2]* Peter Jeglič,[3] Denis Arčon,[3,4]
Takumi Takano,[5] Yoshihiro Iwasa,[5] Yasuo Ohishi,[6] Masaki Takata,[6,7]
Nao Takeshita,[8] Kosmas Prassides,[1]† Matthew J. Rosseinsky[2]†





A.F. Hebard et al. Nature 350, 600 (1991)

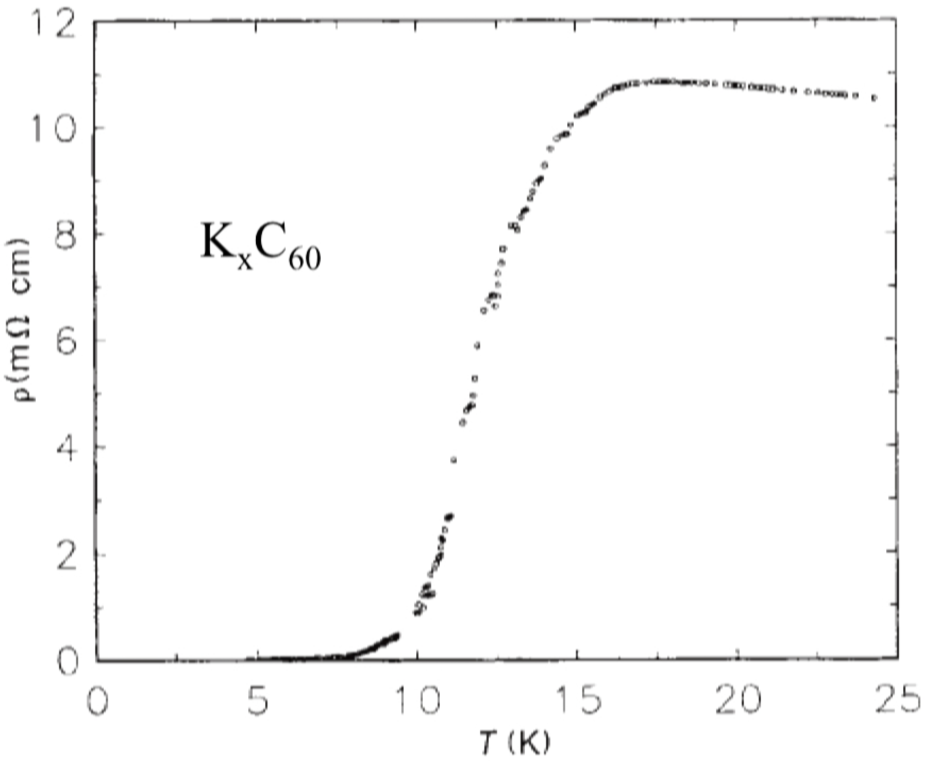
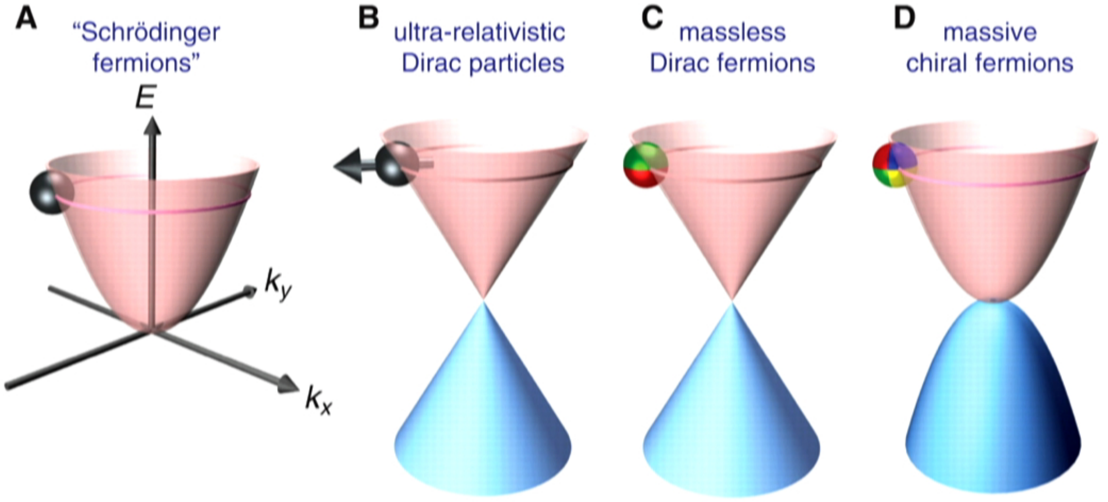


Fig. 2 Quasi-particle zoo



$\hat{H} = \hat{p}^2 / 2m^*$ $\hat{H} = c\,\vec{\sigma} \cdot \hat{p}$ $\hat{H} = v_F\,\vec{\sigma} \cdot \hat{p}$ $\hat{H} = \vec{\sigma} \cdot \hat{p}^2 / 2m^*$

A. K. Geim Science 324, 1530 -1534 (2009)

Fig. 2 Quasi-particle zoo. (**A**) Charge carriers in condensed matter physics are normally described by the Schrödinger equation with an effective mass m^* different from the free electron mass (is the momentum operator). (**B**) Relativistic particles in the limit of zero rest mass follow the Dirac equation, where c is the speed of light and is the Pauli matrix. (**C**) Charge carriers in graphene are called massless Dirac fermions and are described by a 2D analog of the Dirac equation, with the Fermi velocity vF 1 x 106 m/s playing the role of the speed of light and a 2D pseudospin matrix describing two sublattices of the honeycomb lattice (*3*). Similar to the real spin that can change its direction between, say, left and right, the pseudospin is an index that indicates on

Published by AAAS

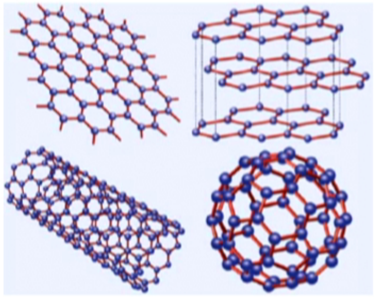


FIG. 1. (Color online) Graphene (top left) is a honeycomb lattice of carbon atoms. Graphite (top right) can be viewed as a stack of graphene layers. Carbon nanotubes are rolled-up cylinders of graphene (bottom left). Fullerenes (C_{60}) are molecules consisting of wrapped graphene by the introduction of pentagons on the hexagonal lattice. From Castro Neto *et al.*, 2006a.

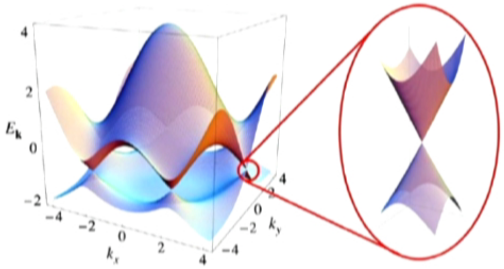
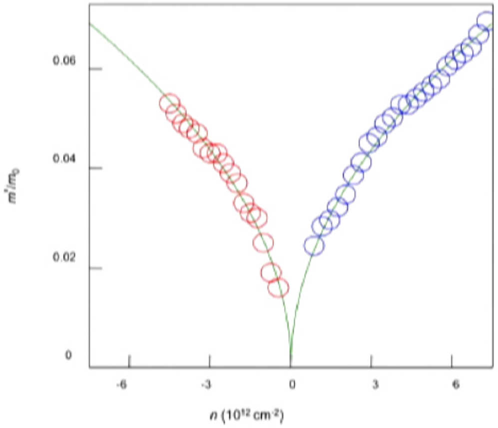
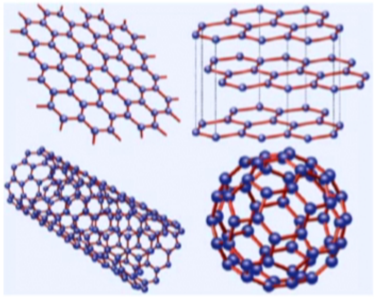


FIG. 3. (Color online) Electronic dispersion in the honeycomb lattice. Left: energy spectrum (in units of t) for finite values of t and t', with $t=2.7$ eV and $t'=-0.2t$. Right: zoom in of the energy bands close to one of the Dirac points.



$$m^* = \frac{\sqrt{\pi}}{v_F}\sqrt{n}. \tag{13}$$

perature dependence of the SdH oscillations; solid curves are the best fit by Eq. (13). m_0 is the free-electron mass. Adapted from Novoselov, Geim, Morozov, *et al.*, 2005.



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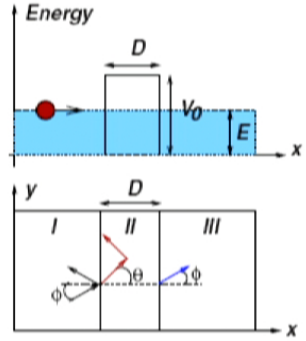
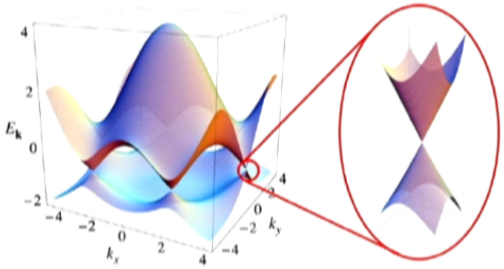


FIG. 6. (Color online) Klein tunneling in graphene. Top: schematic of the scattering of Dirac electrons by a square potential. Bottom: definition of the angles ϕ and θ used in the scattering formalism in regions I, II, and III.



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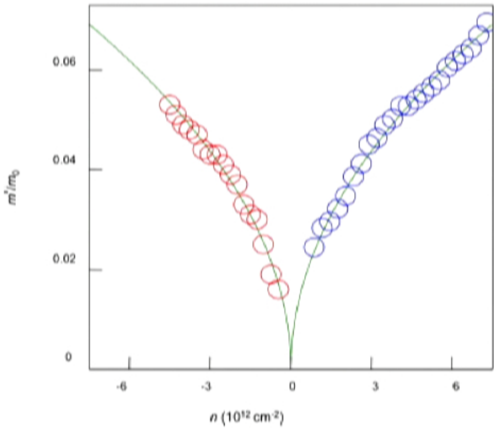

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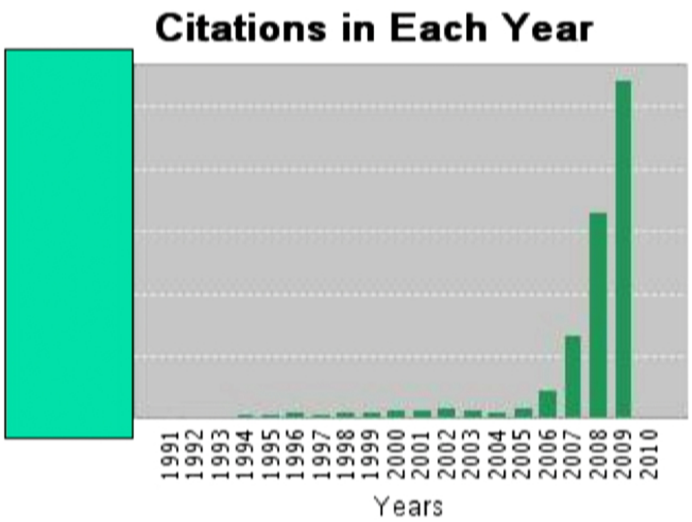
A.K. Geim



citations

2004 Science paper:
2005 Nature paper:
2007 Nature Materials:
2009 Rev. Mod. Phys:

[redacted]

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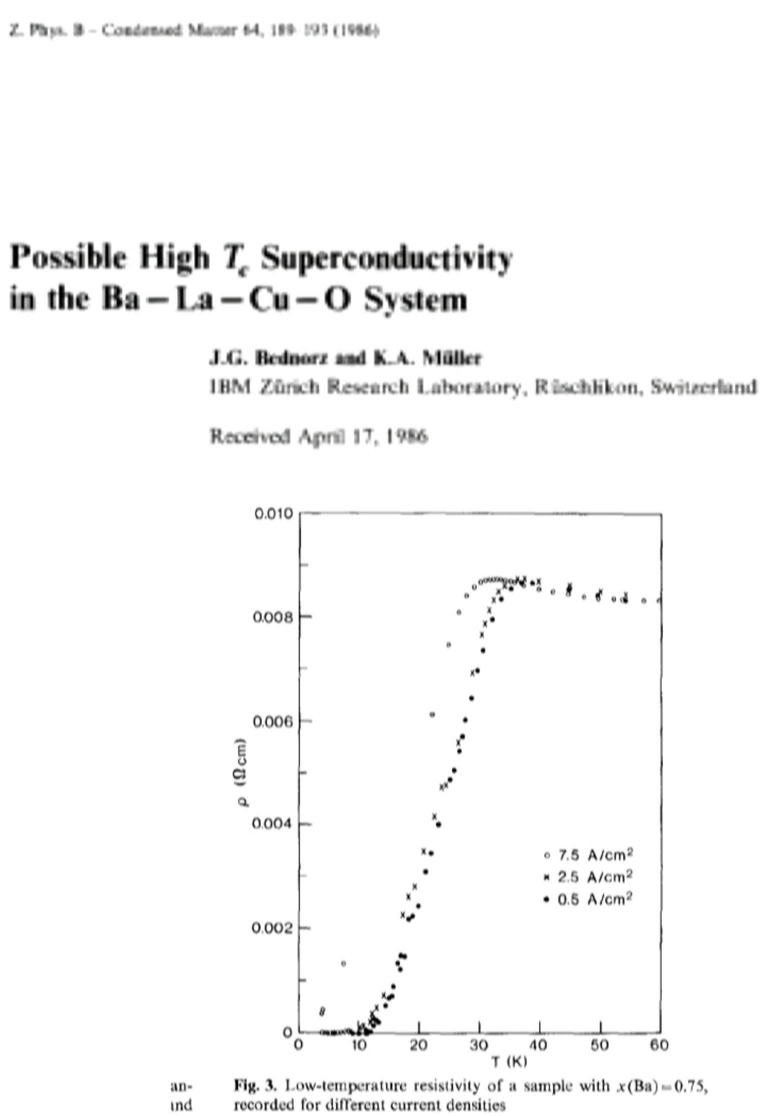
	12517	**13479**	**14545**	**8941**	**0**	**143820**	**3344.65**
☐ 1. **Generalized gradient approximation made simple** By: Perdew, JP; Burke, K; Ernzerhof, M PHYSICAL REVIEW LETTERS Volume: 77 Issue: 18 Pages: 3865-3868 Published: OCT 28 1996	5780	6465	7459	4835	0	50556	2407.43



Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Condensed Matter
Zeitschrift für Physik B

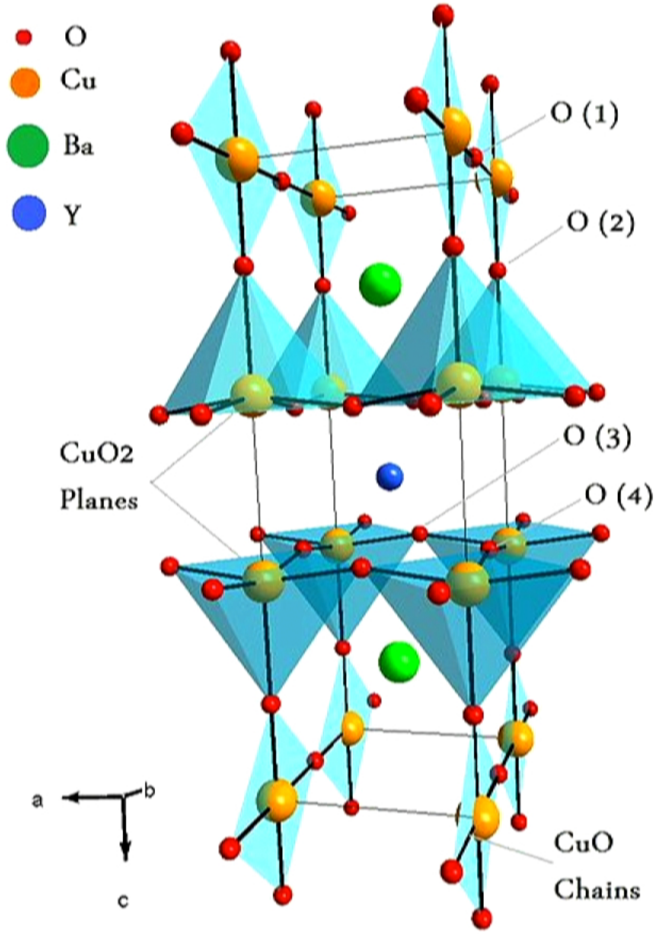
Possible High T_c Superconductivity in the Ba – La – Cu – O System

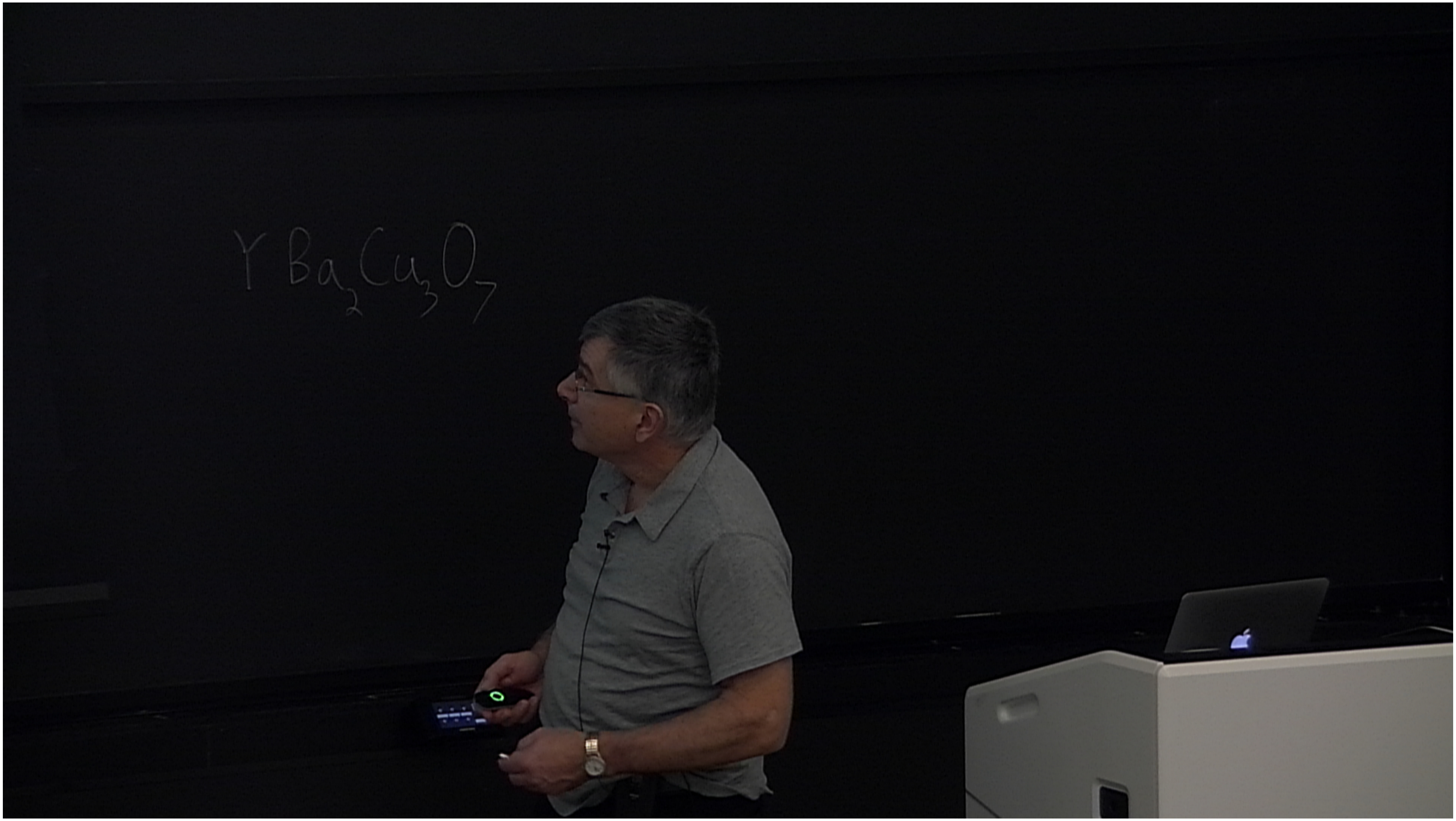
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

an-
ınd

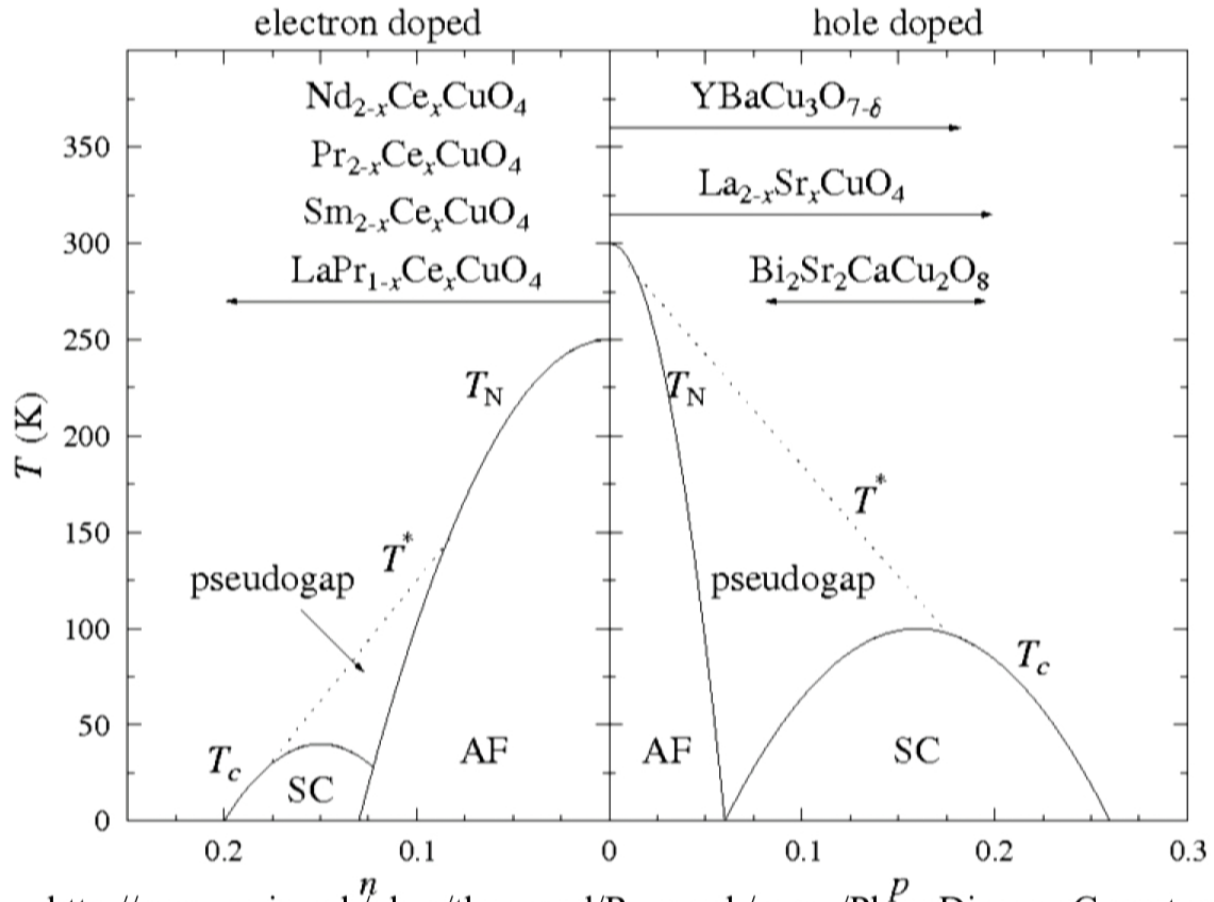
Fig. 3. Low-temperature resistivity of a sample with $x(\mathrm{Ba}) = 0.75$, recorded for different current densities





$YBa_2Cu_3O_7$

Phase diagram for cuprate materials



http://www.unine.ch/phys/theocond/Research/supra/PhaseDiagramCuprates.gif

http://en.wikipedia.org/wiki/File:Cuphasediag.png

BCS formalism vs. Pairing Mechanism

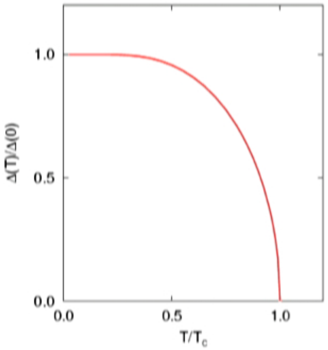
$$\Delta = |V| \frac{1}{N} \sum_k \frac{\Delta}{2E_k}$$

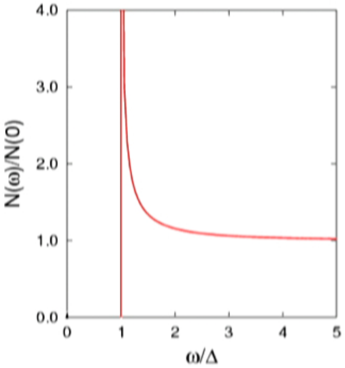
Tc equation (useless)

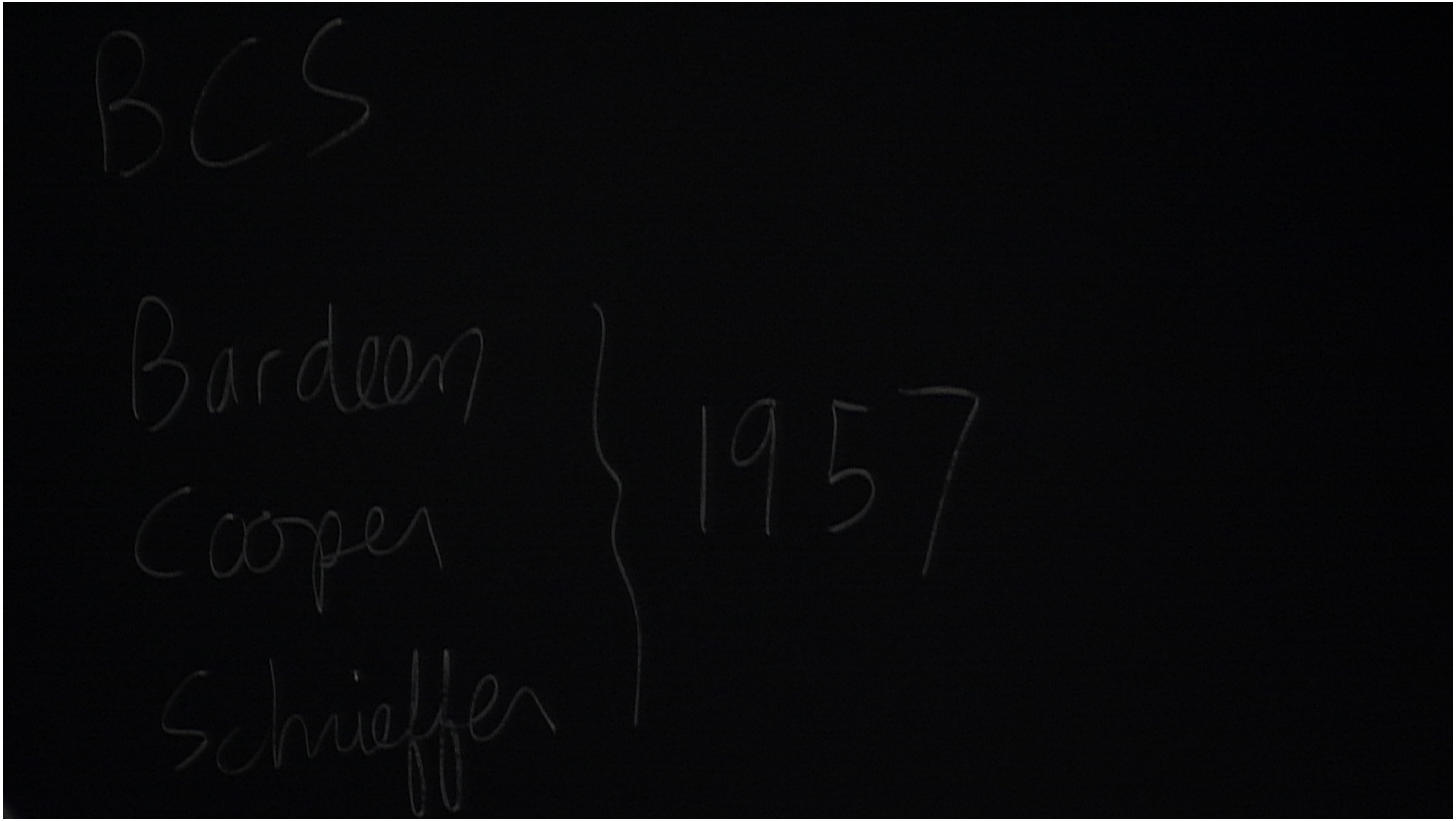
$$\frac{2\Delta}{k_B T_c} = 3.53$$

Universality

$$\frac{\Delta C}{\gamma T_c} = 1.43$$

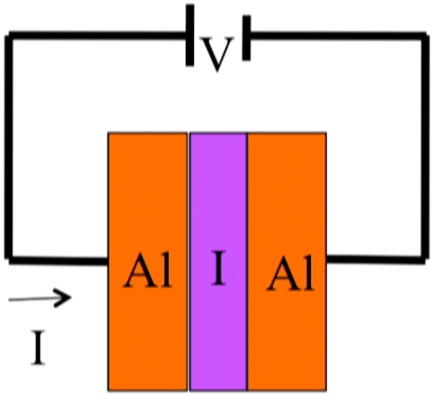


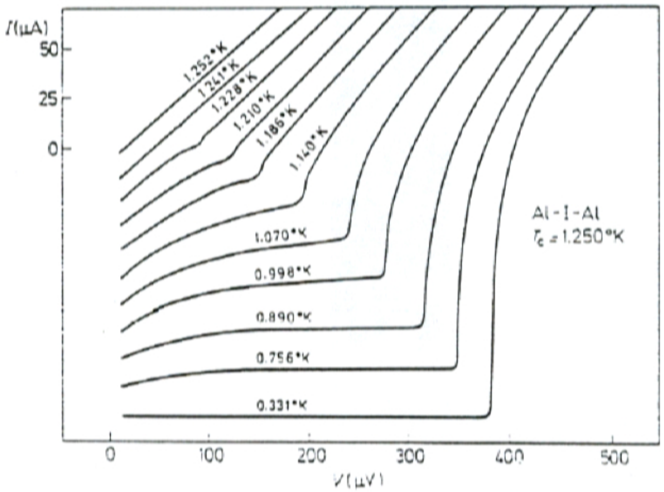




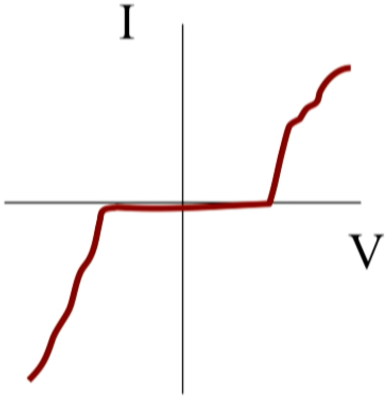
BCS

$$\left.\begin{array}{l}\text{Bardeen}\\ \text{Cooper}\\ \text{Schrieffer}\end{array}\right\} 1957$$

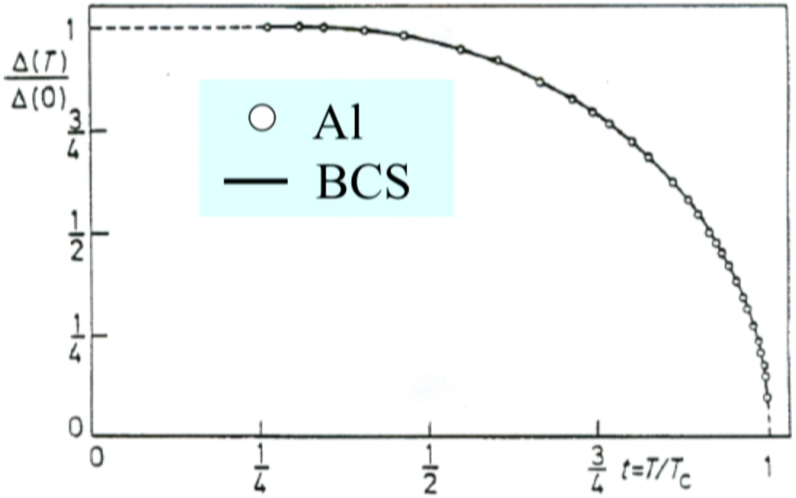




B.L. Blackford and R.H. March, Can. J. Phys. 46, 141 (1968)

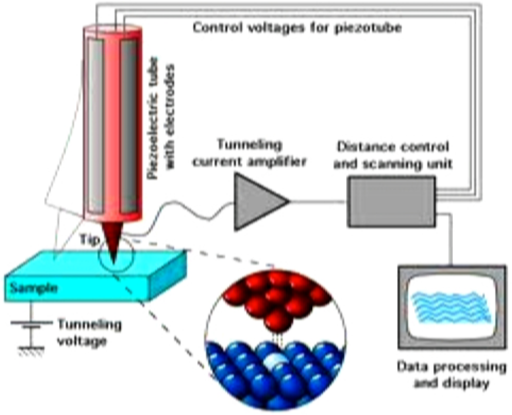


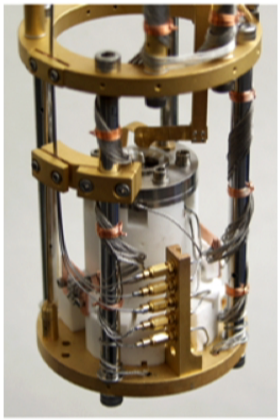
$$\frac{dI}{dV} \propto N(V)$$

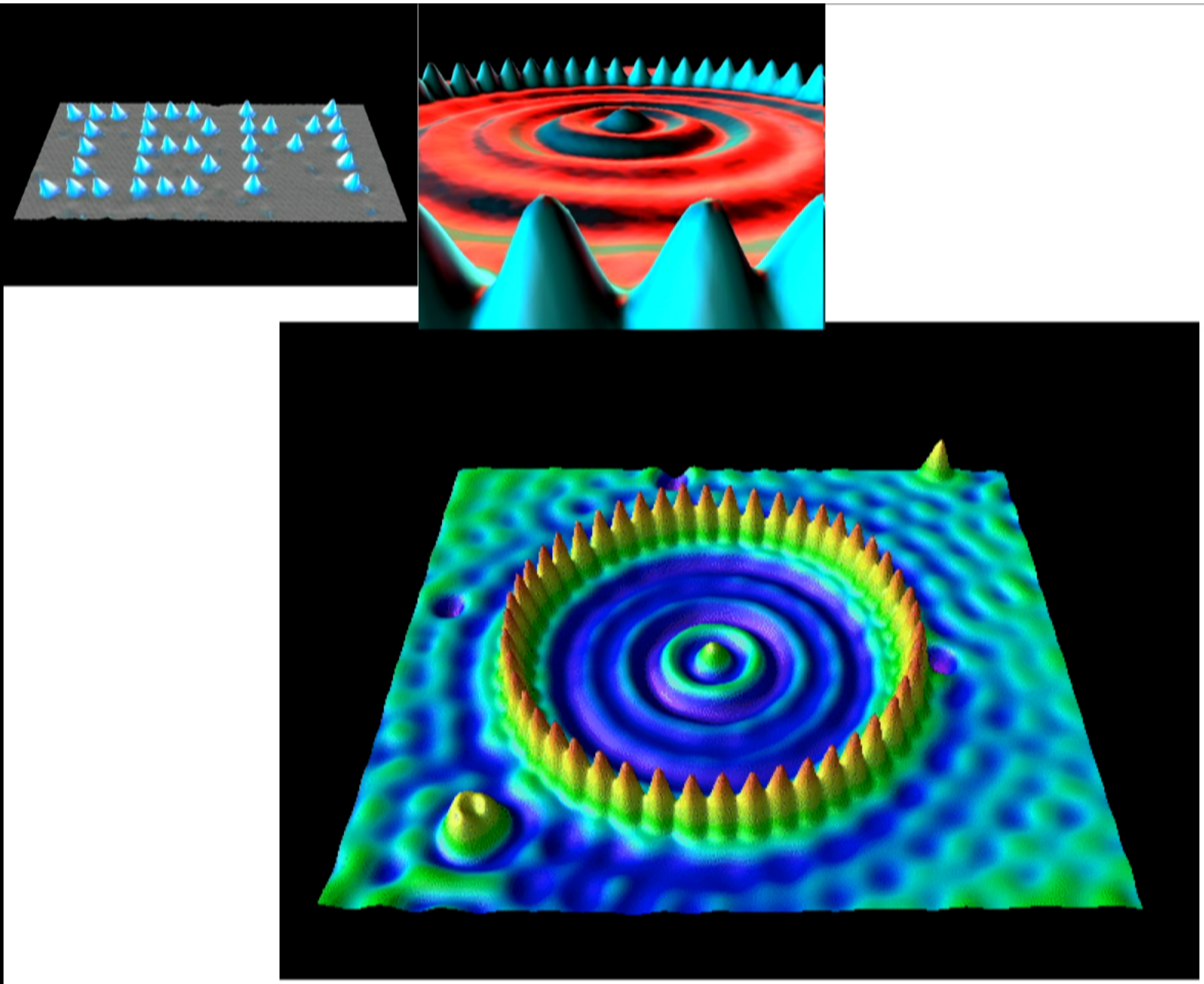


Nowadays…

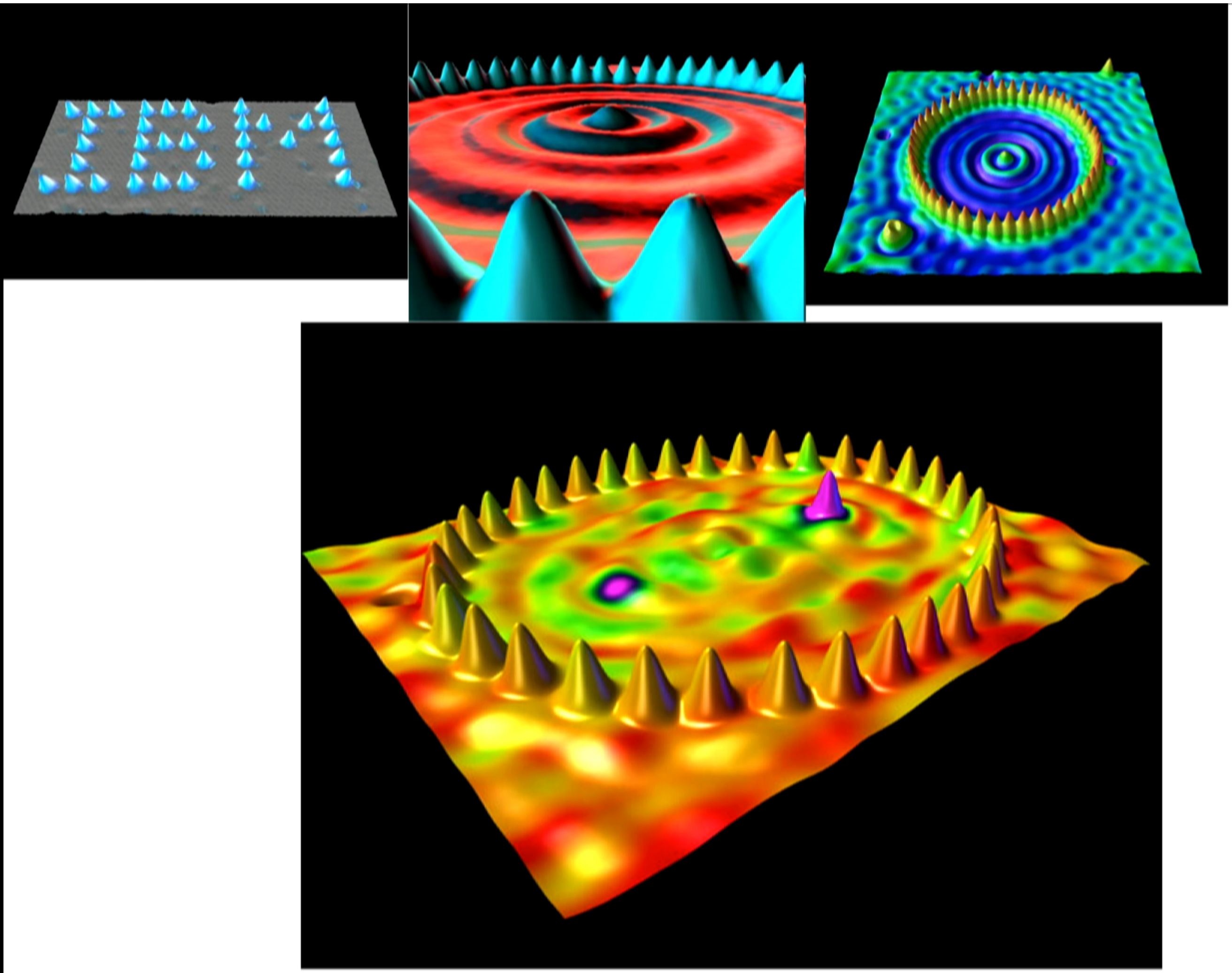
Scanning Tunneling Microscope (STM)







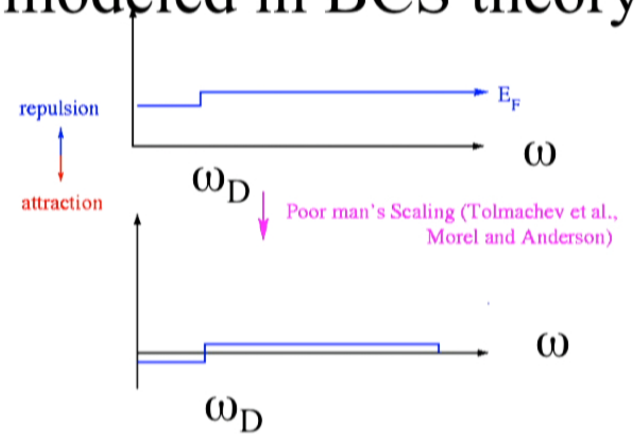
Crommie, Lutz, and Eigler   http://www.almaden.ibm.com/vis/index.html

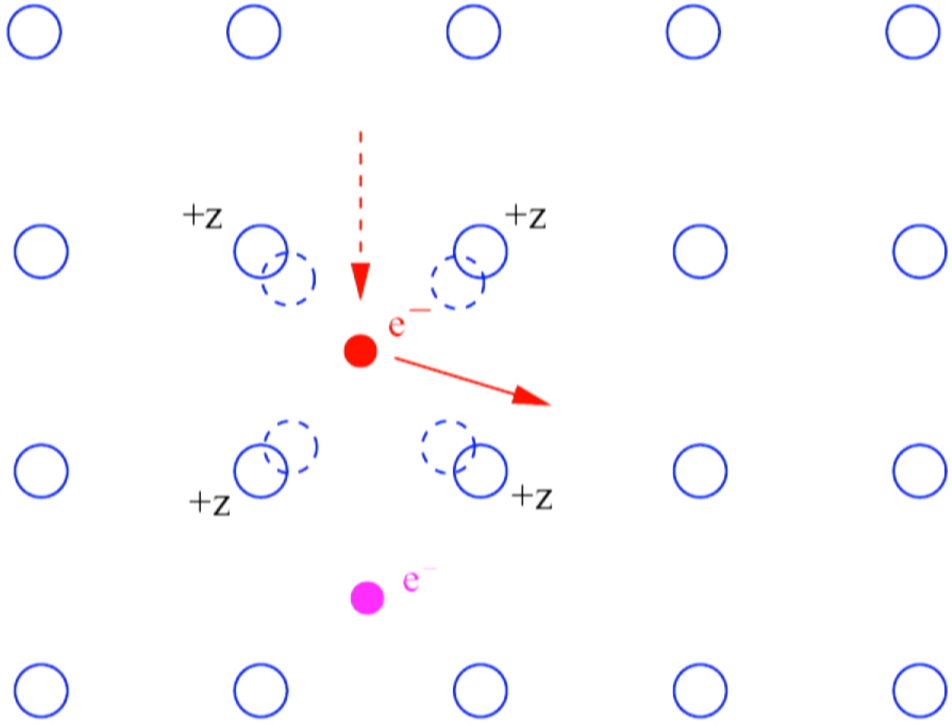


Crommie, Lutz, and Eigler http://www.almaden.ibm.com/vis/index.html

Eliashberg Theory

- Extension of BCS formalism to include dynamical electron-phonon interaction
- builds on Migdal theory in the normal state
- loosely modeled in BCS theory





effective attraction

PHYSICAL REVIEW B, VOLUME 63, 115415

Direct measurements of the *L*-gap surface states on the (111) face of noble metals by photoelectron spectroscopy

F. Reinert,* G. Nicolay, S. Schmidt, D. Ehm, and S. Hüfner

Photoemission

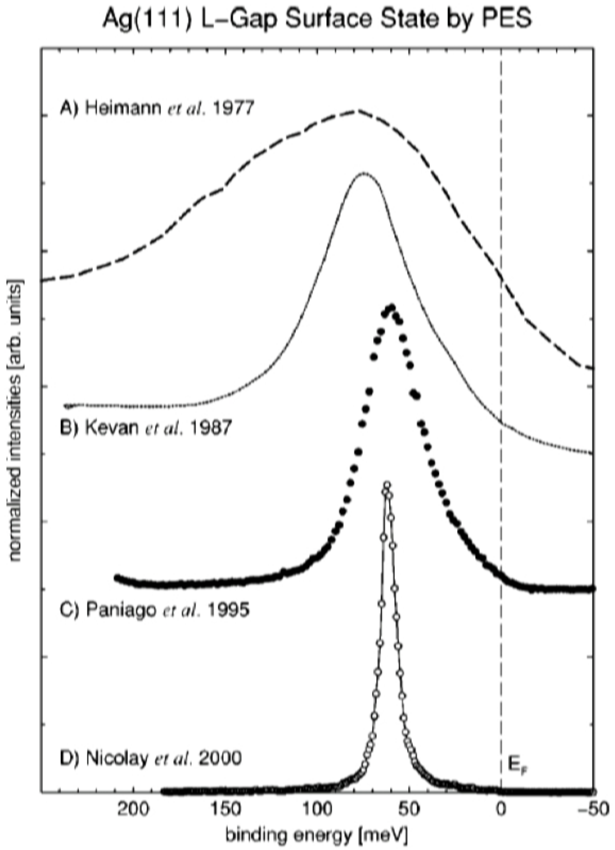
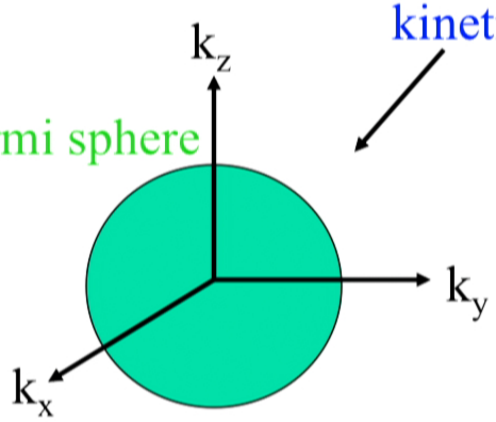


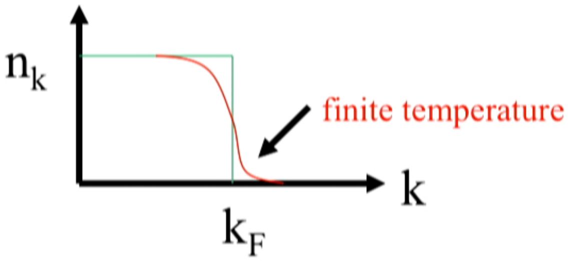
FIG. 1. Technological development in PES since the first observation of the Ag(111) surface state in photoemission spectra: (A) from Ref. 2 measured at room temperature (RT) with Ar I ($h\nu = 11.83\,\mathrm{eV}$), angular integrated; (B) from Ref. 30 at RT with $h\nu = 13\,\mathrm{eV}$, $\Delta E \approx 60\,\mathrm{meV}$ and $\Delta\theta = 1°$; (C) from Ref. 13 at $T = 56\,\mathrm{K}$ with Ar I, $\Delta E = 21\,\mathrm{meV}$, and $\Delta\theta = 0.9°$; (D) present data at $T = 30\,\mathrm{K}$ with He I ($h\nu = 21.23\,\mathrm{eV}$), $\Delta E = 3.5\,\mathrm{meV}$ and $\Delta\theta = \pm 0.15°$.

Electrons in solids

kinetic vs. potential energy

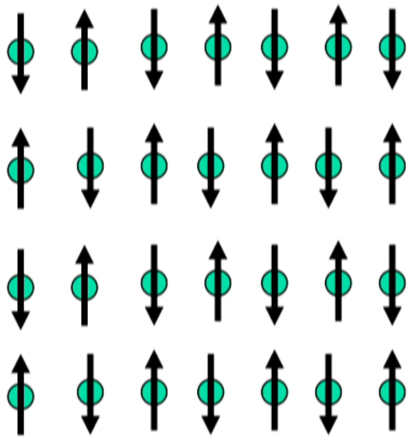
Fermi sphere





$$E_{kin} = 2\,\Sigma \varepsilon_k n_k$$

Mott insulator



why ? Coulomb:
keep electrons away from one another !

The conventional scenario: BCS


J. Bardeen


L.N. Cooper


J.R. Schrieffer

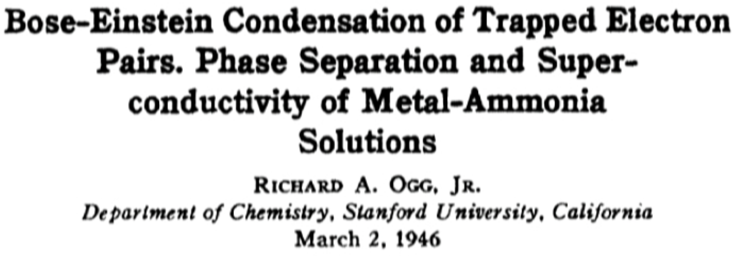
$$\psi_{\mathrm{BCS}} = \pi_{k} (u_k + v_k c^{\dagger}_{k\uparrow} c^{\dagger}_{-k\downarrow})|0\rangle$$

$$\psi_{2\nu} = \int_0^{2\pi} \frac{d\theta}{2\pi} e^{-i\nu\theta} \pi_{k} (u_k + e^{i\theta} v_k c^{\dagger}_{k\uparrow} c^{\dagger}_{-k\downarrow})|0\rangle$$

It’s all about pairs…

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.

George Gamow

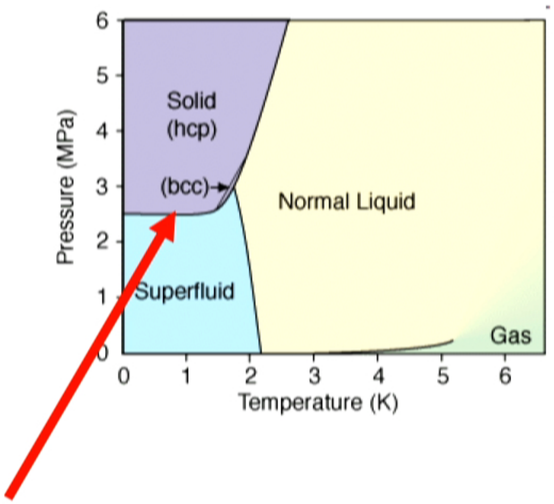


Bose-Einstein Condensation of Trapped Electron Pairs. Phase Separation and Superconductivity of Metal-Ammonia Solutions

RICHARD A. OGG, JR.
Department of Chemistry, Stanford University, California
March 2, 1946

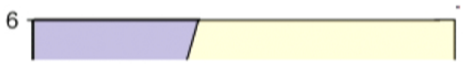
…Cooper pairs

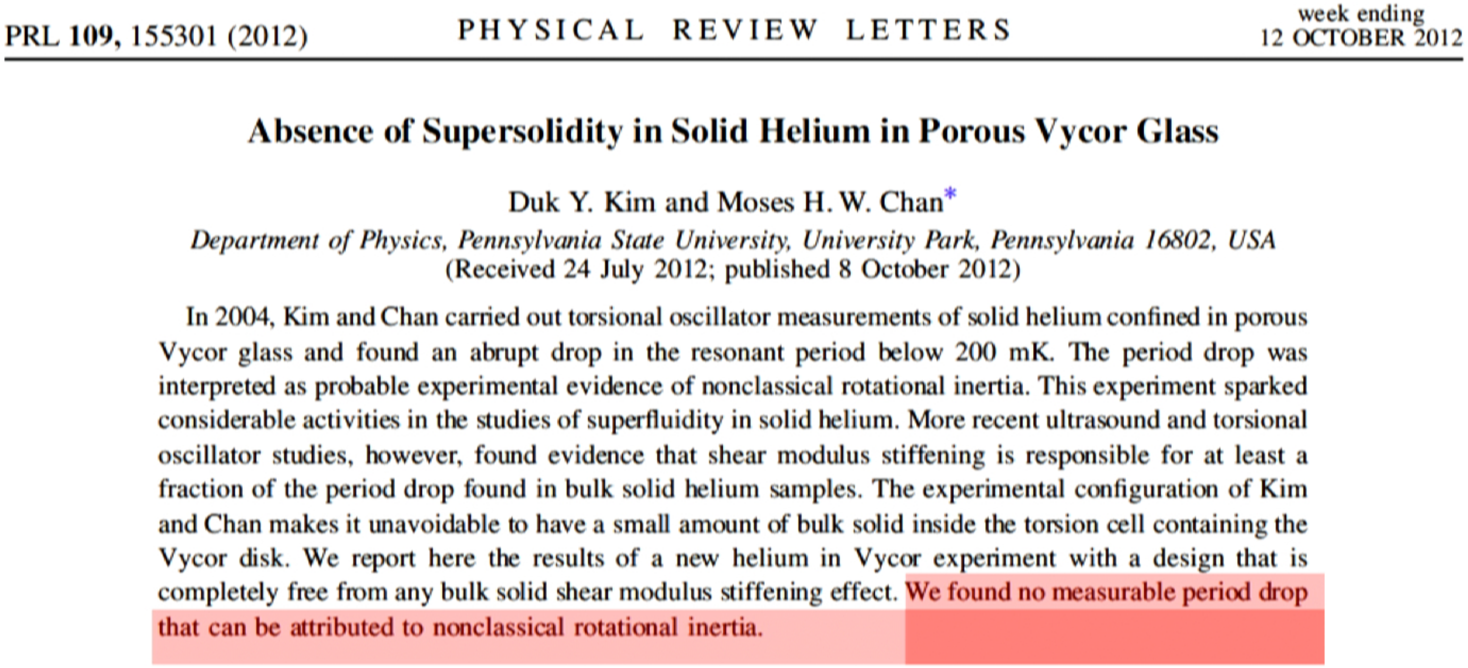
Supersolid phase in He^4?



Supersolid phase here?

Supersolid phase in He^4?




PRL **109**, 155301 (2012) PHYSICAL REVIEW LETTERS week ending 12 OCTOBER 2012

Absence of Supersolidity in Solid Helium in Porous Vycor Glass

Duk Y. Kim and Moses H. W. Chan*
Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA

(Received 24 July 2012; published 8 October 2012)

In 2004, Kim and Chan carried out torsional oscillator measurements of solid helium confined in porous Vycor glass and found an abrupt drop in the resonant period below 200 mK. The period drop was interpreted as probable experimental evidence of nonclassical rotational inertia. This experiment sparked considerable activities in the studies of superfluidity in solid helium. More recent ultrasound and torsional oscillator studies, however, found evidence that shear modulus stiffening is responsible for at least a fraction of the period drop found in bulk solid helium samples. The experimental configuration of Kim and Chan makes it unavoidable to have a small amount of bulk solid inside the torsion cell containing the Vycor disk. We report here the results of a new helium in Vycor experiment with a design that is completely free from any bulk solid shear modulus stiffening effect. We found no measurable period drop that can be attributed to nonclassical rotational inertia.

Topological Superconductivity

See http://www.princeton.edu/~psscmp/ss2010/Lecture_Notes_files/Lecture3.pdf

(Charlie Kane)

Cold Atoms
and
Optical Lattices

BCS-BEC Crossover