Superconductivity: The magic of the quantum world in front of your eyes.

André-Marie Tremblay

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VERITATEM IN CHARITATE

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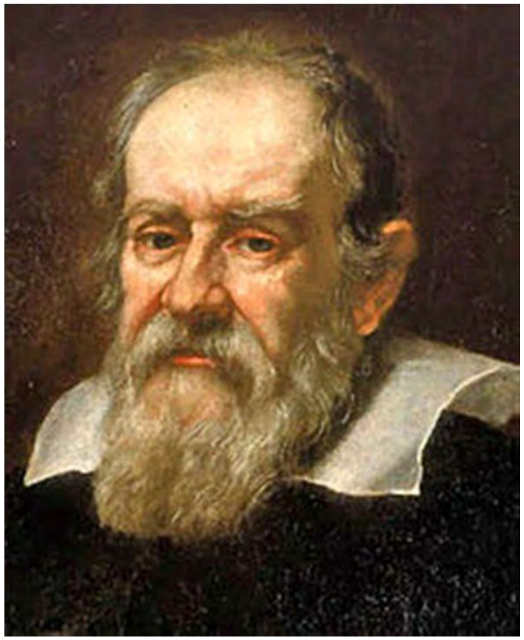
Galileo Galilei



1564-1642

Richard Feynman

1918-1988

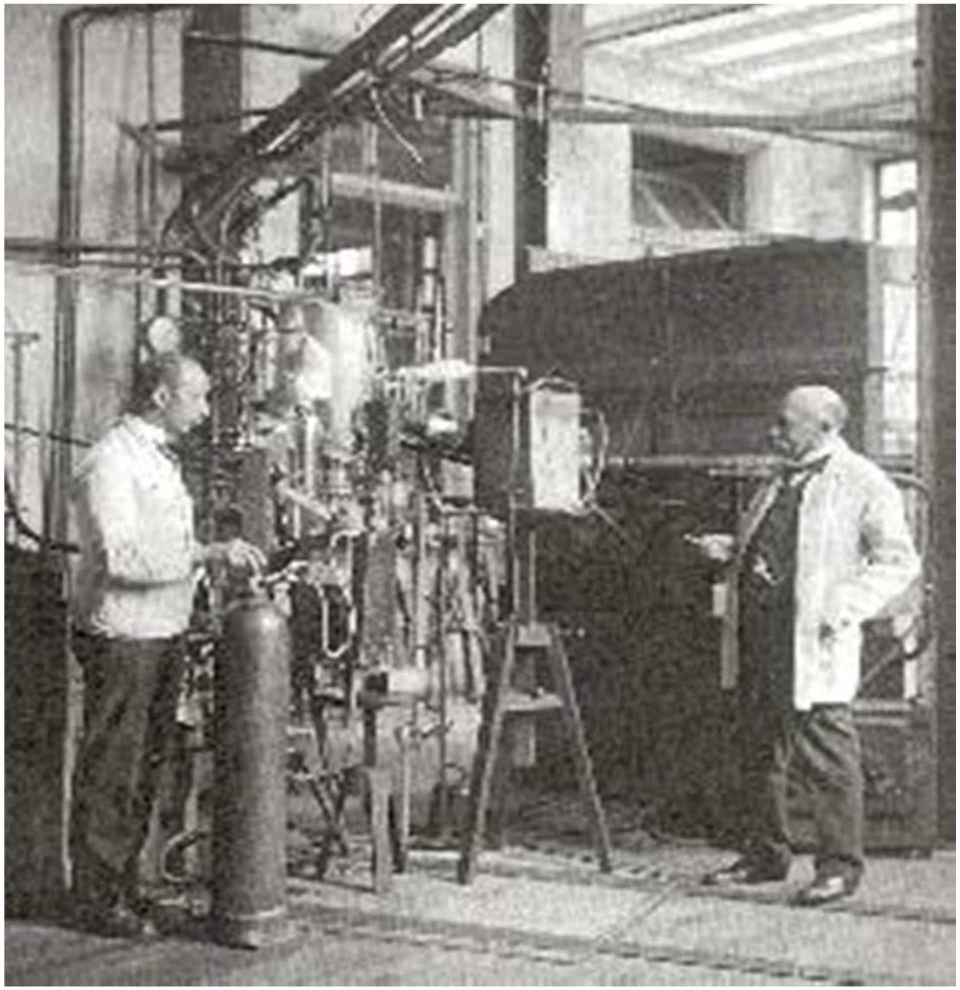
The race for absolute zero temperature

An important step towards zero temperature

- Heike Kamerlingh Onnes
  (Leiden) (1853/1926)

The beginnings of team work in research

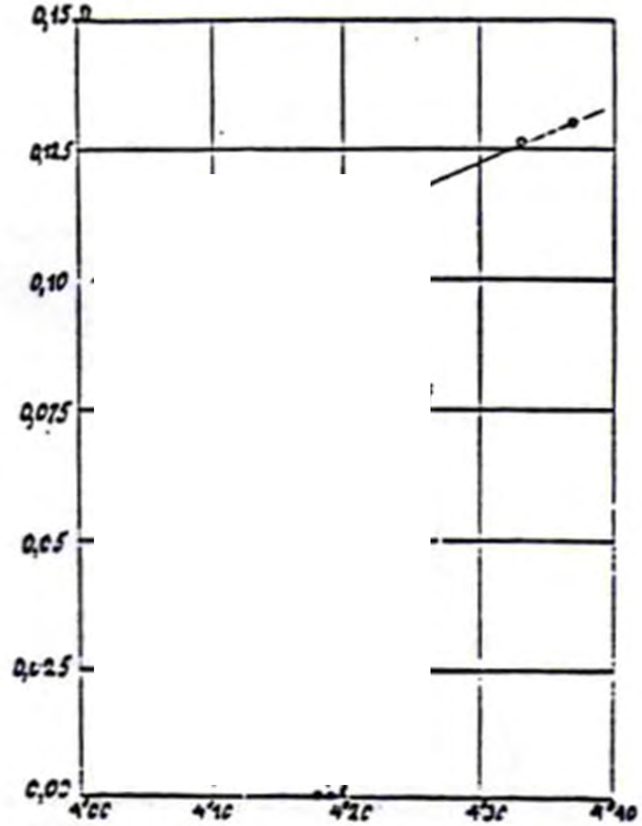
J.G.. Flim, cryogeny
G. Dorsma: thermometry
G. Holst: electronics
Glass blower



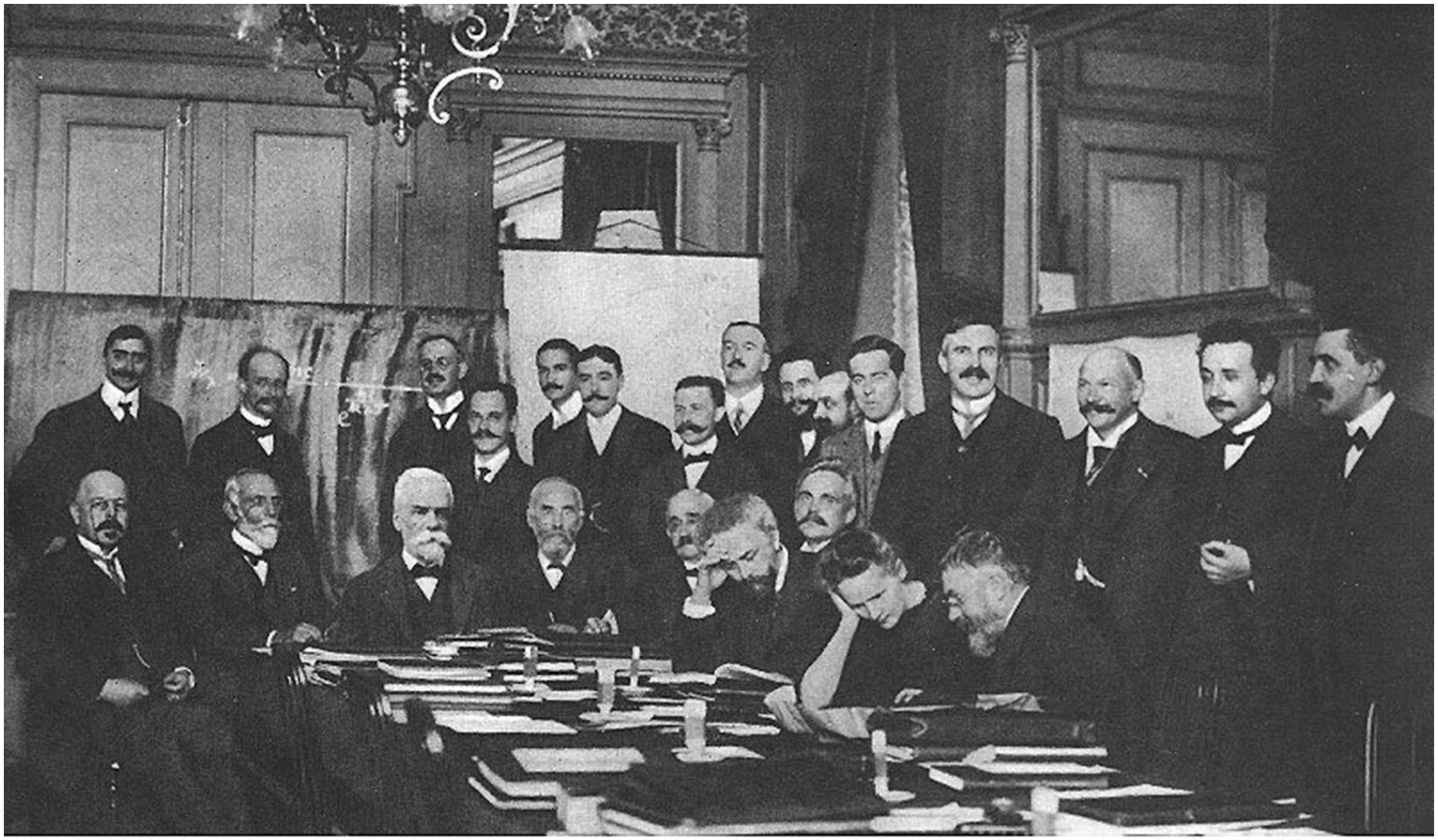
And so what?

- What happens to electrical resistance?

8 April 1911



Solvay Congress, 1911



GOLDSCHMIDT PLANCK RUBENS LINDEMANN HASENOHRL
NERNST BRILLOUIN SOMMERFELD M. DE BROGLIE HOSTELET
SOLVAY KNUDSEN HERZEN JEANS RUTHERFORD
LORENTZ WARBURG WIEN EINSTEIN LANGEVIN
PERRIN Madame CURIE POINCARÉ KAMERLINGH ONNES

DE
ROOKE

And the winner is

- Heike Kamerlingh Onnes (Leiden) (1853/1926)

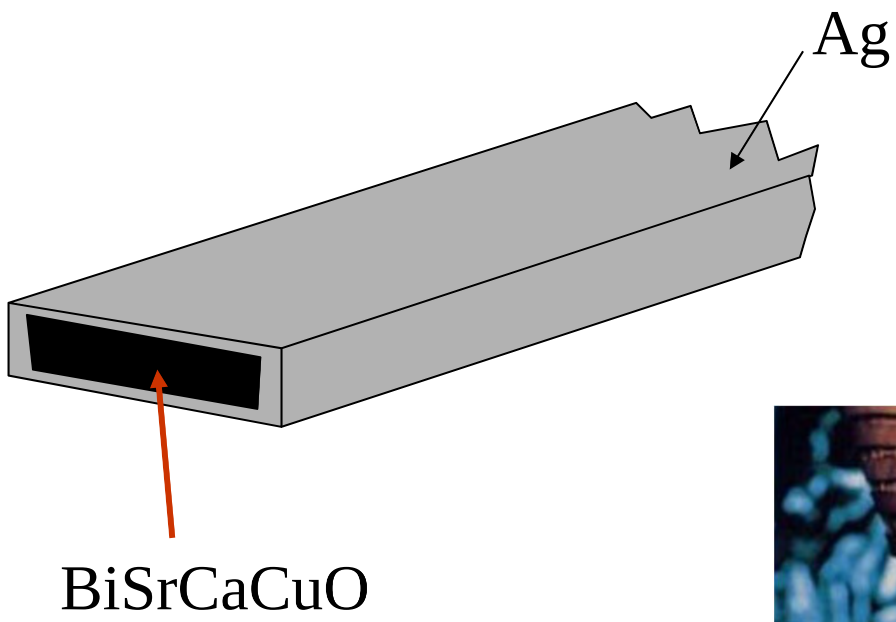
http://www.nobel.se

1913: Nobel in Physics

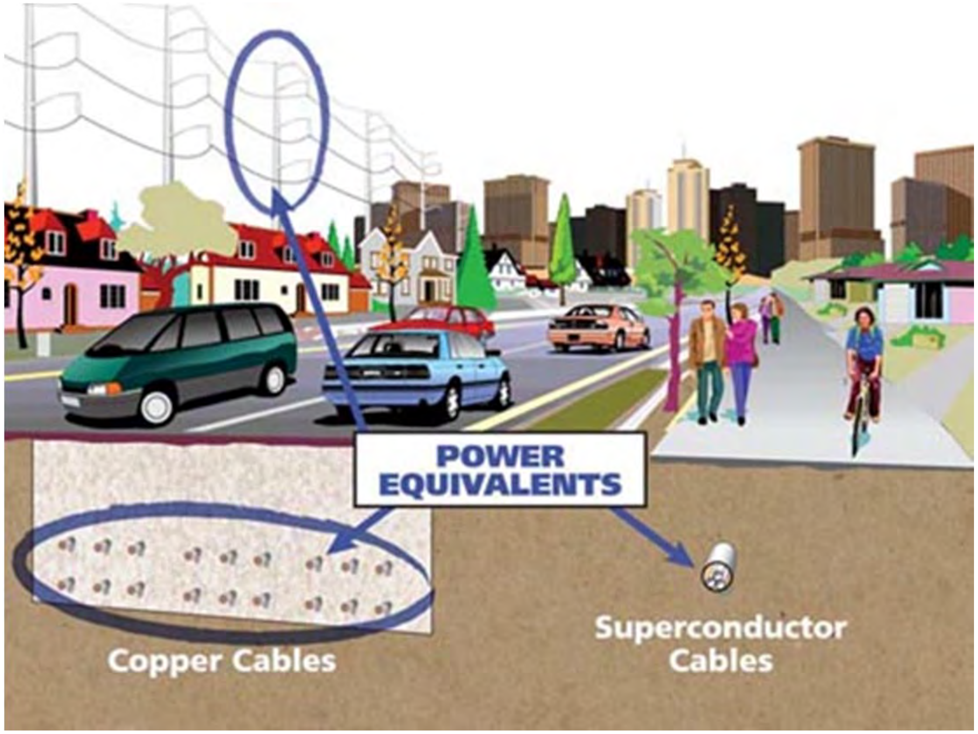
To Professor H. Kamerlingh Onnes from Leiden, for his experiments on the properties of matter at low temperature that have led, concomitantly, to the production of liquid Helium.

Power transmission

Transmission cables

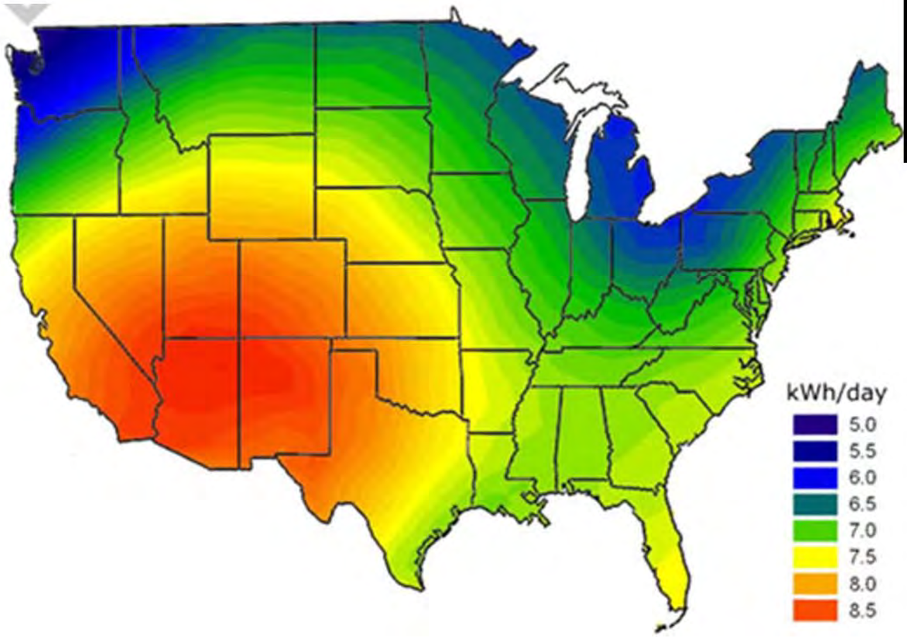


7 Octobre 2010, American Superconductors

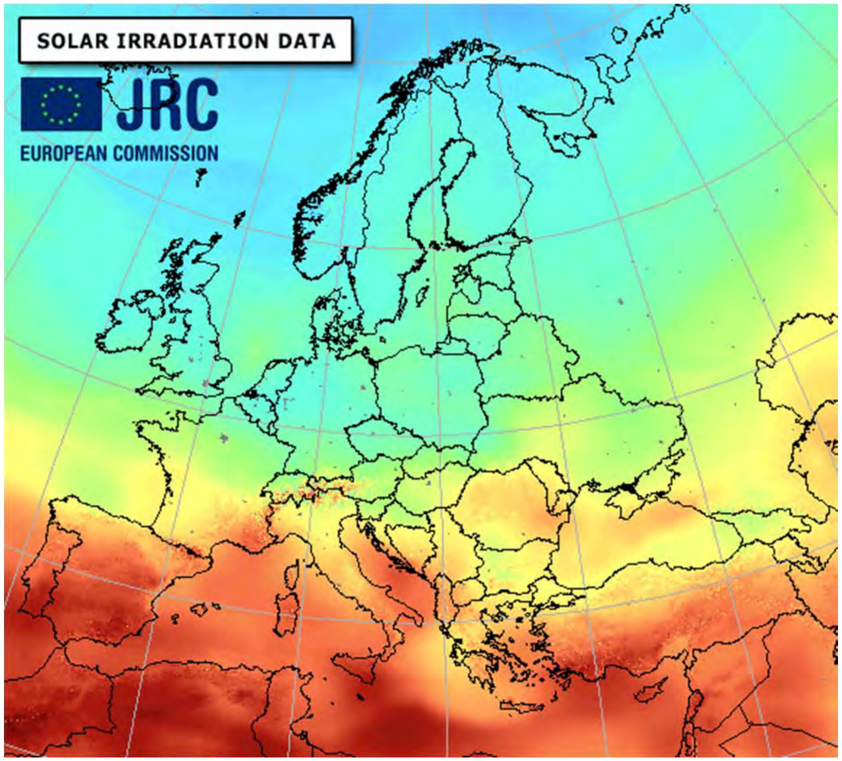


3,000 km of superconducting cables for South Korea

Power generation vs need



Power generation vs need



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Going around in circles while doing something useful

André-Marie Ampère

1775 - 1836

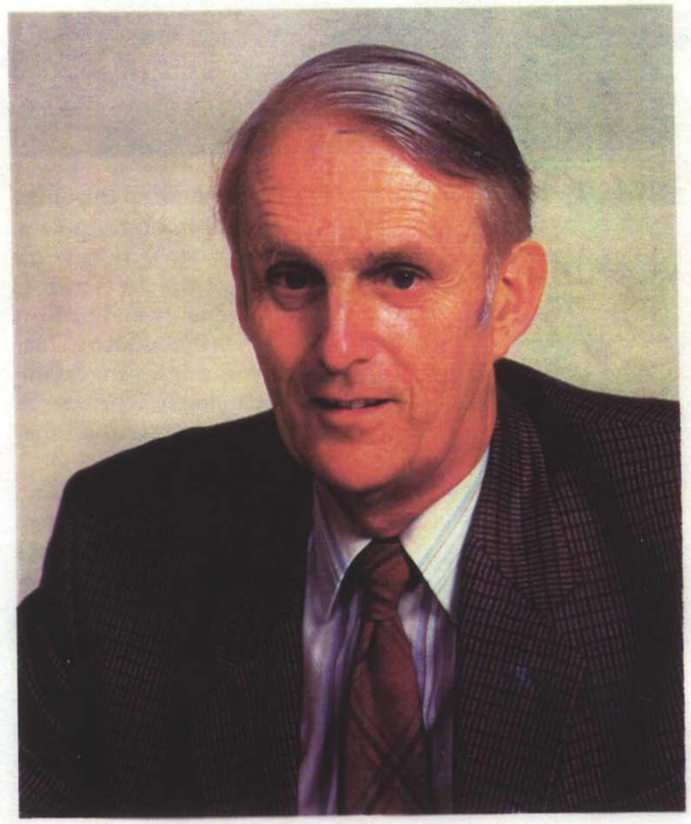
The first superconduting magnet

Martin

Wood, 1962

Supercurrents

The Superconductivity Magazine



Sir Martin Wood
Founder, Oxford Instruments

Transportation

Maglev, Shangai airport

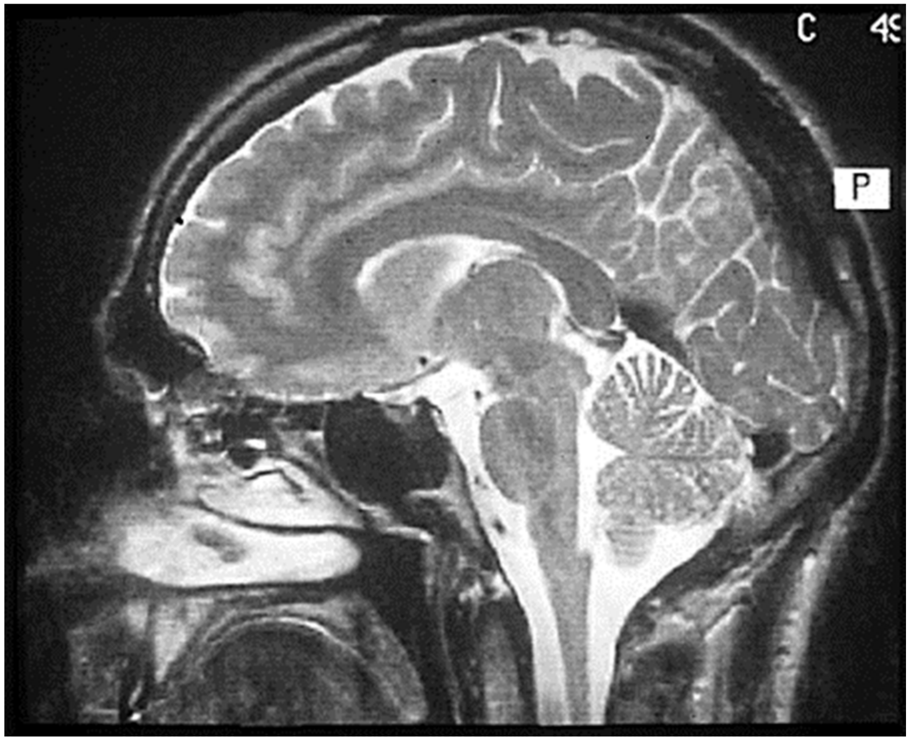
350 km/h (220 mph) in 2 minutes,
Maximum speed 431 km/h (268 mph).
Record 12 November 2006, 501 km/h (311 mph).

Test, magnetic levitation train, Japan Rail

JR-MLX01 maglev train at Yamanashi test track

In medecine

Magnetic medical imaging



And where you least expect it

Back to levitation

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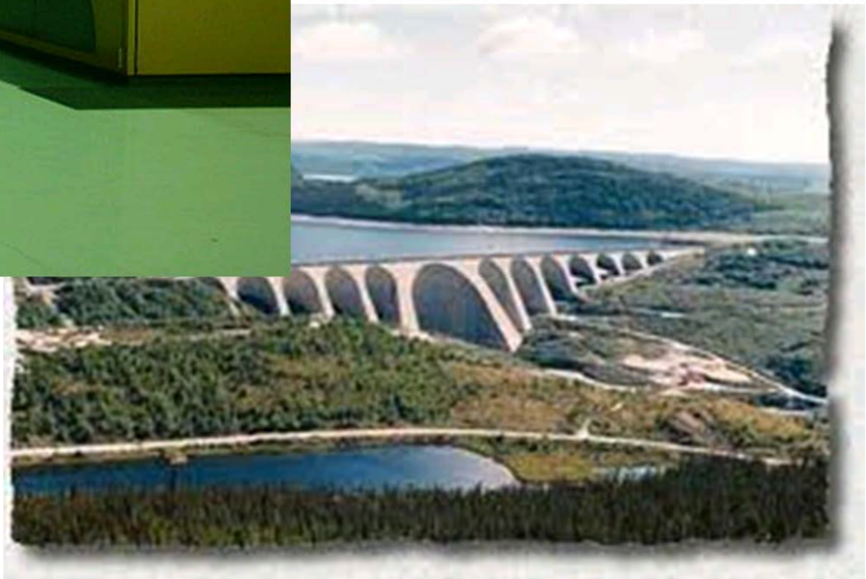
Michael Faraday

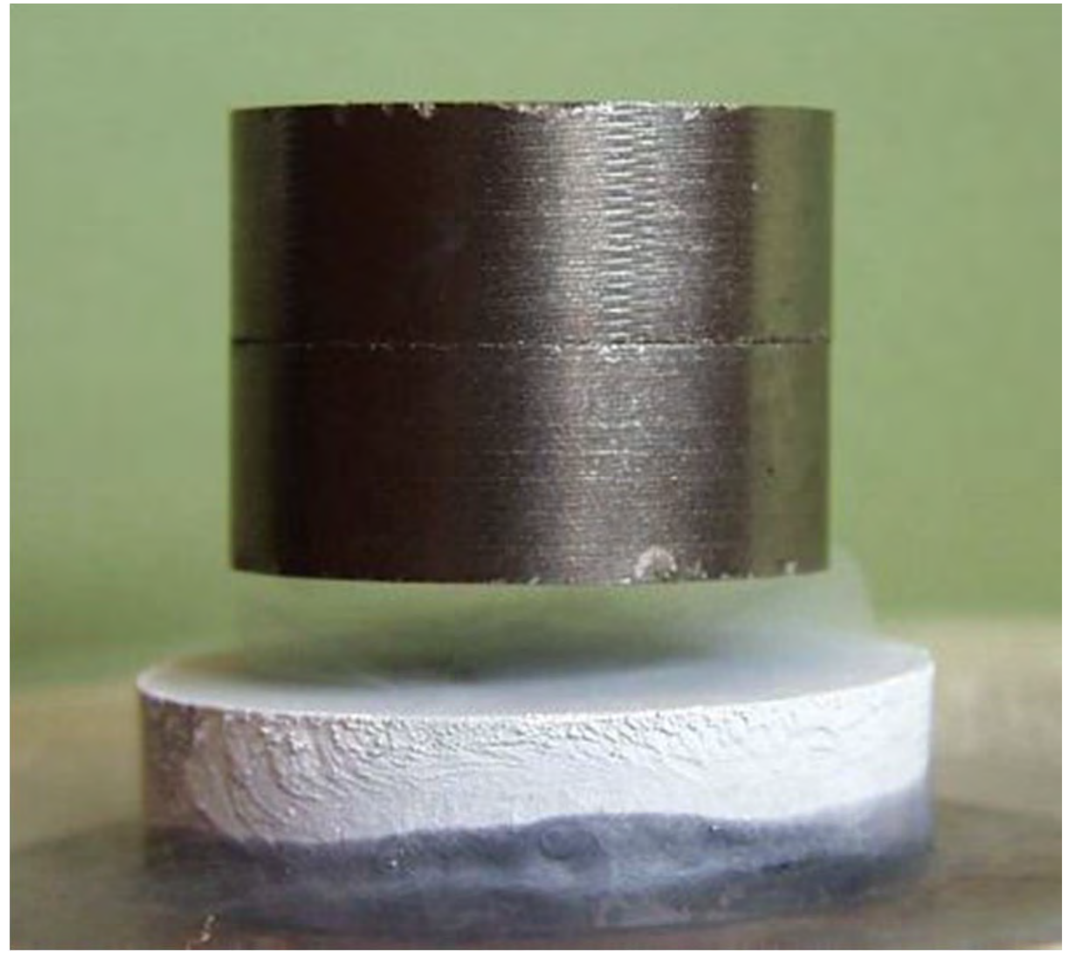
1791-1867

Induction



Walther Meissner
(1882-1974)

R. Ochsenfeld (1900-1992)

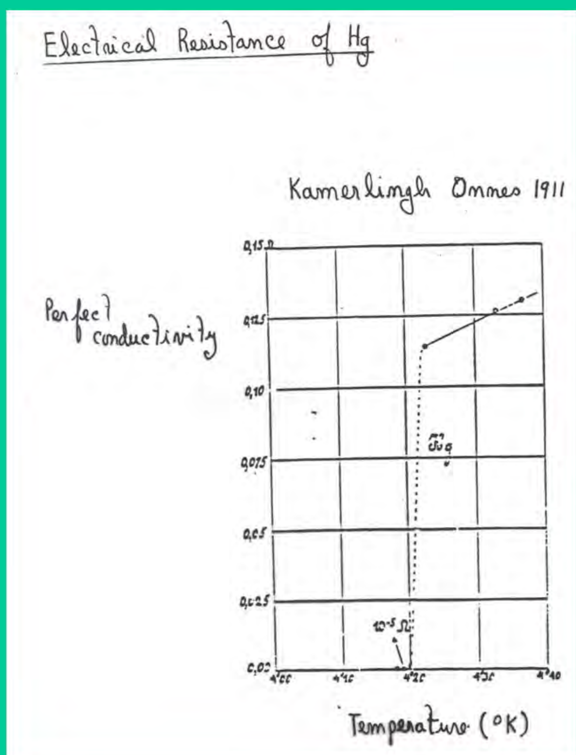


http://www.magnet.fsu.edu/education/tutorials/pioneers/meissner.html

http://kvphysics.blogspot.com/

Two important properties

1. Zero resistance (if **B=0**)



2. Diamagnetism

OOKE

How do we explain superconductivity?

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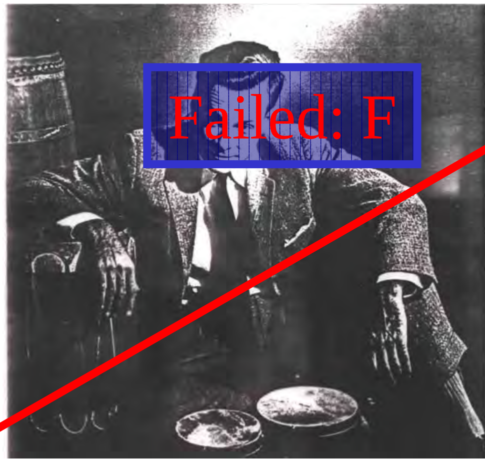
Bloch's theorem: 1930

- All theories of superconductivity can be proven false.
- Feynman: no one is bright enough to find the solution.

Some unccessful attempts

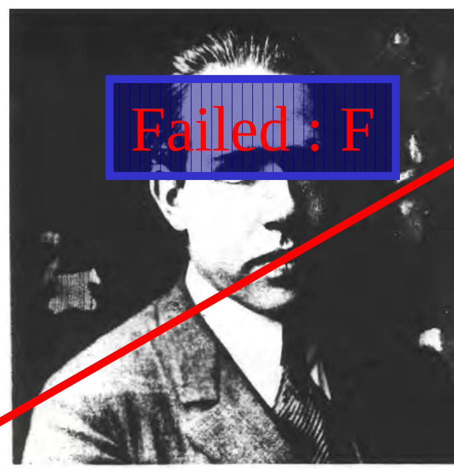


Feynman

WERNER HEISENBERG (1901–) introduced matrix mechanics, which, like the Sch

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

An analogy

- Broken symmetry
- Rigidity

A simple example from statistical physics

$$E = -\sum_{i,j} J_{i,j} S_i S_j$$

$$S_i = \pm 1$$

$$E = -\sum_{i,j} J_{i,j} (S_i \langle S_j \rangle + \langle S_i \rangle S_j)$$

$$= -\sum_{i} h_{eff} S_i$$

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BCS 1957

Quantum behavior at the macroscopic scale

Leon Cooper

John Bardeen*

Robert Schrieffer

Nobel Prize : 1972

•John Bardeen :

•Only one to have received 2 Nobel Prizes in Physics !!!

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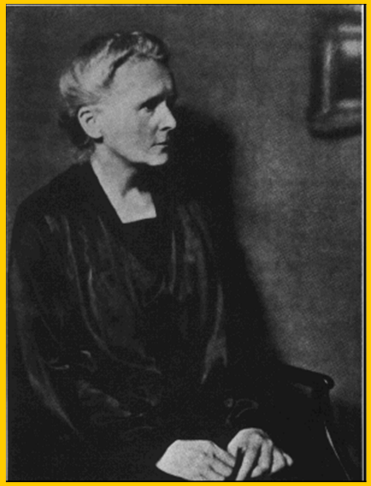
Invention : TRANSISTOR!

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



Marie Curie:

1903 Physics with H.A. Becquerel

1911 Chemistry (alone)

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What was known

- Resistance vanishes
- Meissner effect
- Transparent to low frequency microwaves
- Isotopic effect

http://users-phys.au.dk/philip/pictures/physicsfigures/physicsfigures.html

Attraction mechanism in the metallic state

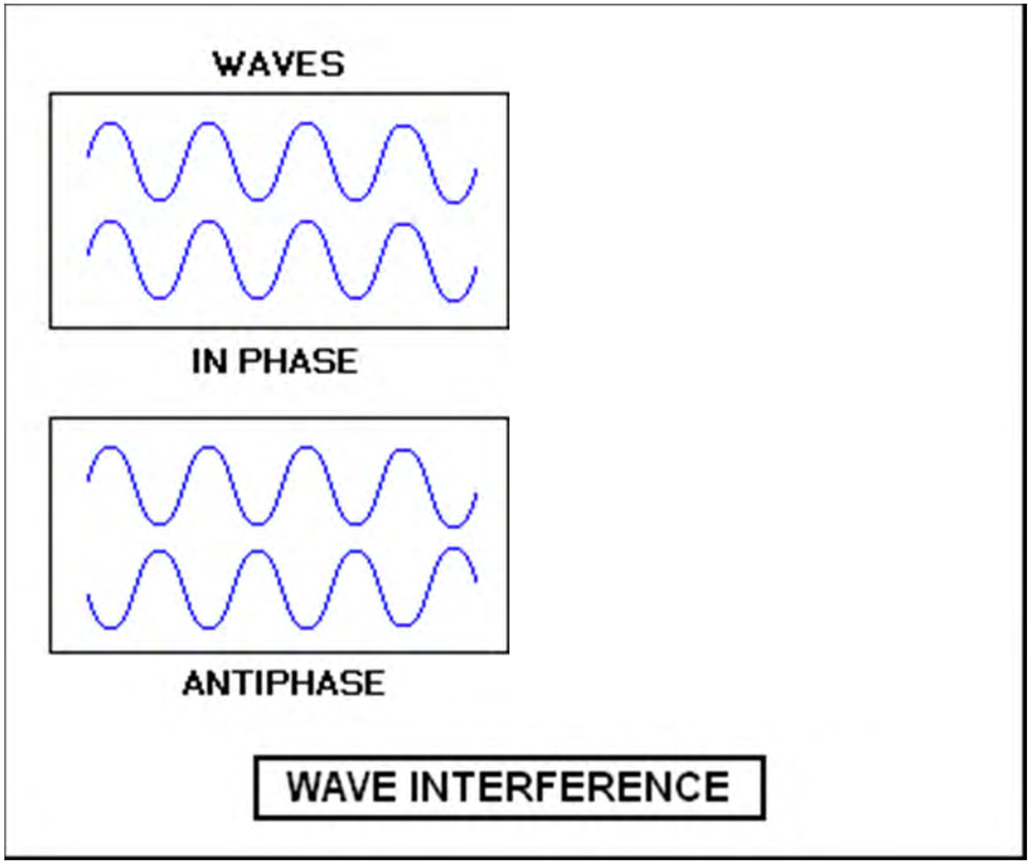
#1 Cooper pair, #2 Phase coherence

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow}$$

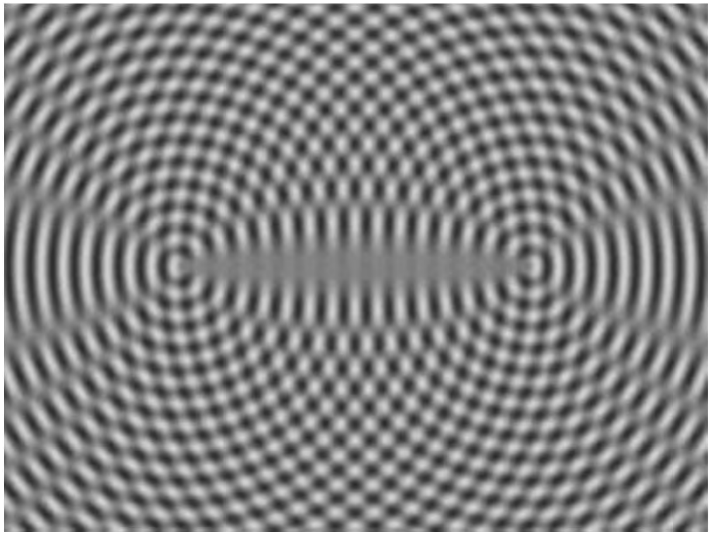
$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \left(\langle \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \rangle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} + \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \left\langle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \right\rangle \right)$$

$$|\mathrm{BCS}(\theta)\rangle = \ldots + e^{iN\theta}|N\rangle + e^{i(N+2)\theta}|N+2\rangle + \ldots .$$

Waves



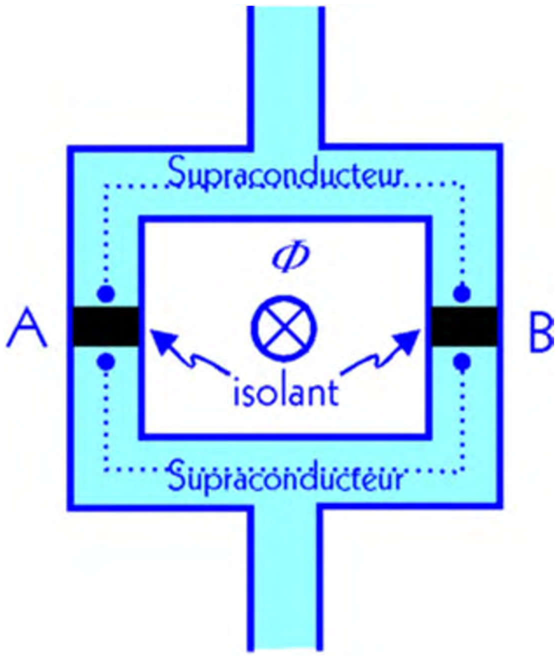
Interference

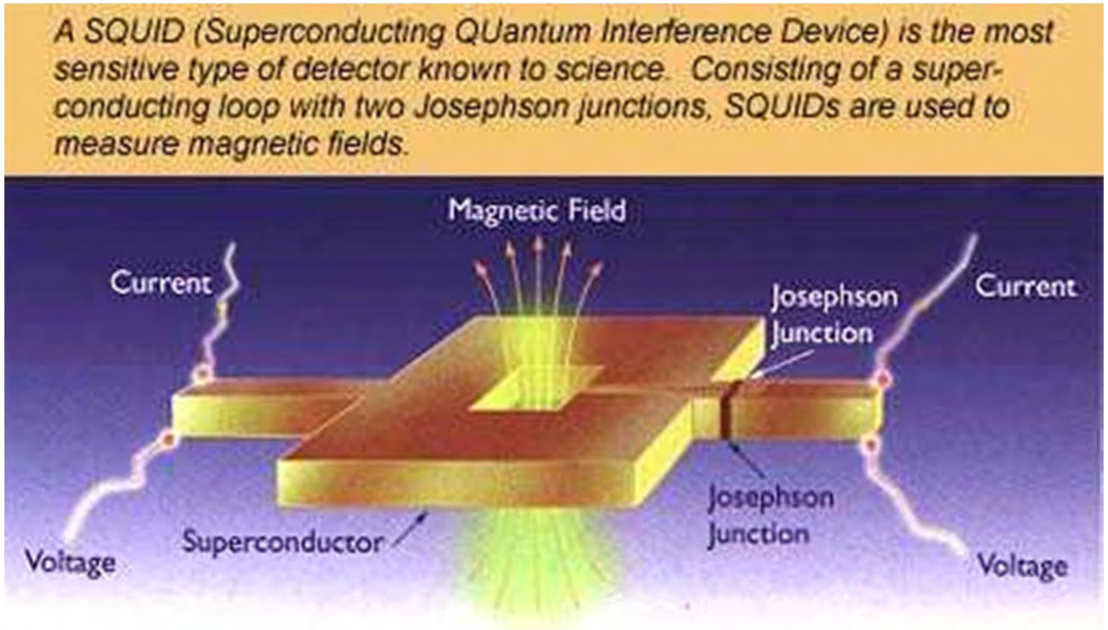


Applications of the Josephson effect

Nobel 1973

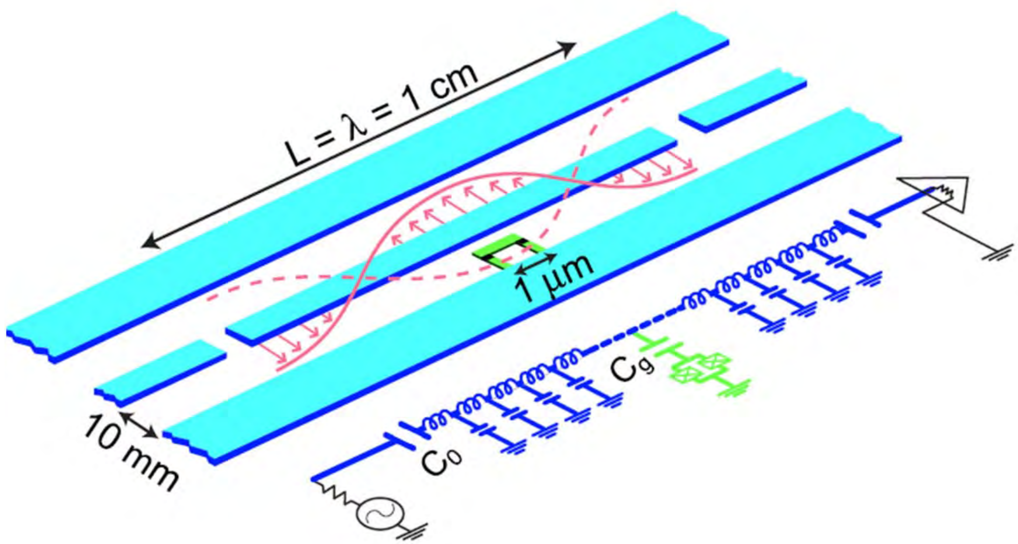
SQUID





SQUID "Superconducting Quantum Interference Device"

The quantum computer



Alexandre Blais, et al. Phys. Rev. A **69**, 062320 (2004)

Quantum processor

Informatique

L'ordinateur quantique se matérialise

Mise à jour le mardi 22 mars 2011 à 16 h 45

Commenter (37) » Partager Imprimer T+ T-

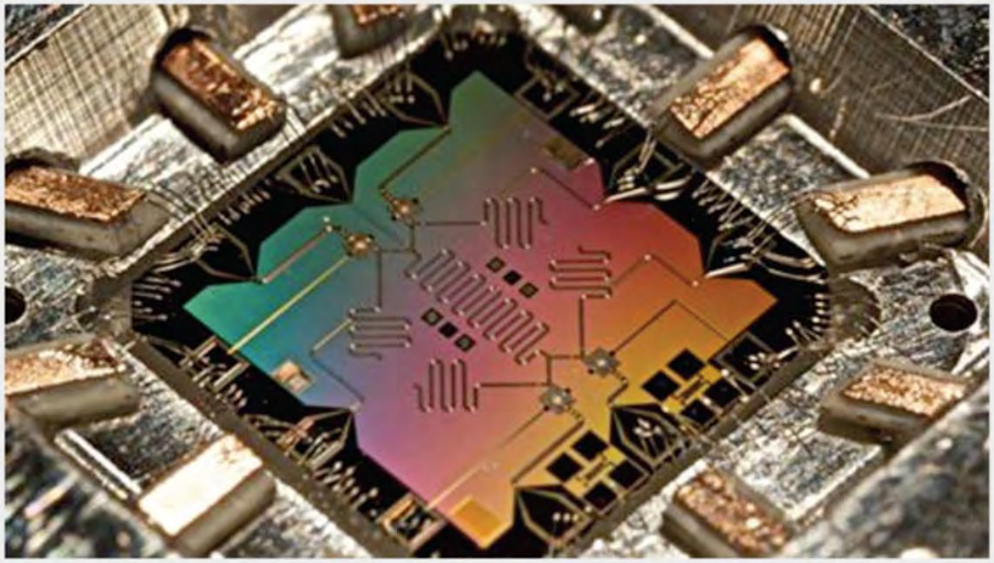


Photo: Erik Lucero
Puce contenant des circuits quantiques de 4 Qubits chacun

L'une des percées les plus concrètes dans la perspective de la création d'ordinateurs quantiques performants a été présentée lors de la rencontre annuelle de l'American Physical Society qui se tient à Dallas, aux États-Unis.

Le chercheur Erik Lucero et ses collègues de l'Université de la Californie ont créé des puces de 6 cm par 6 cm contenant des circuits quantiques de 4 Qubits chacun. Le Qubit est l'unité de base du calcul quantique et, contrairement au bit classique, il peut changer de nature. Ainsi, il peut être 1,0 ou même les deux à la fois, ce qui augmente de beaucoup les capacités de calcul d'un ordinateur.

M. Lucero pense qu'il sera possible d'inclure sur une puce jusqu'à 10 Qubit d'ici la fin de

“

We're right at the bleeding edge of actually having a quantum processor”

Erik Lucero

University of California, Santa Barbara

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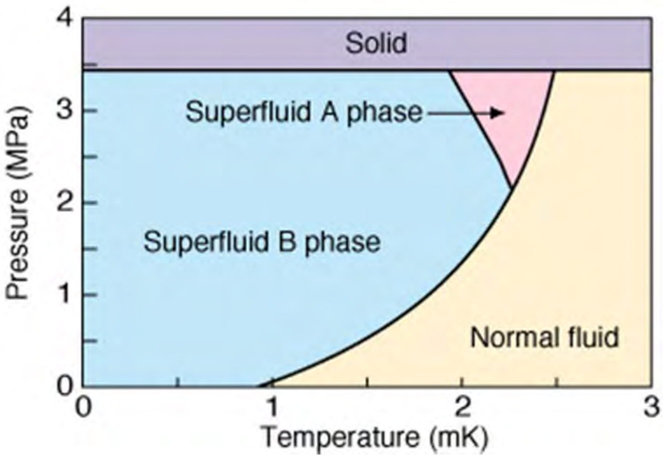
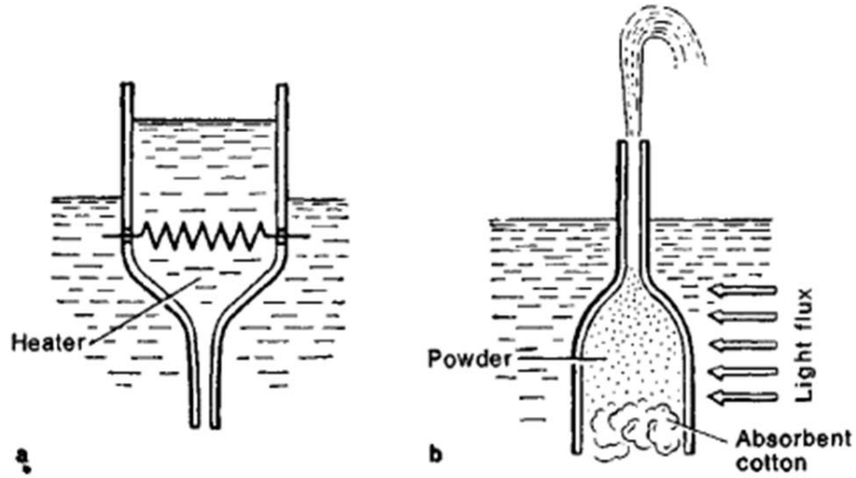
Superconductivity everywhere…

Superfluid ^{3}He





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Atomic nucleus (discovered: Rutherford 1911)

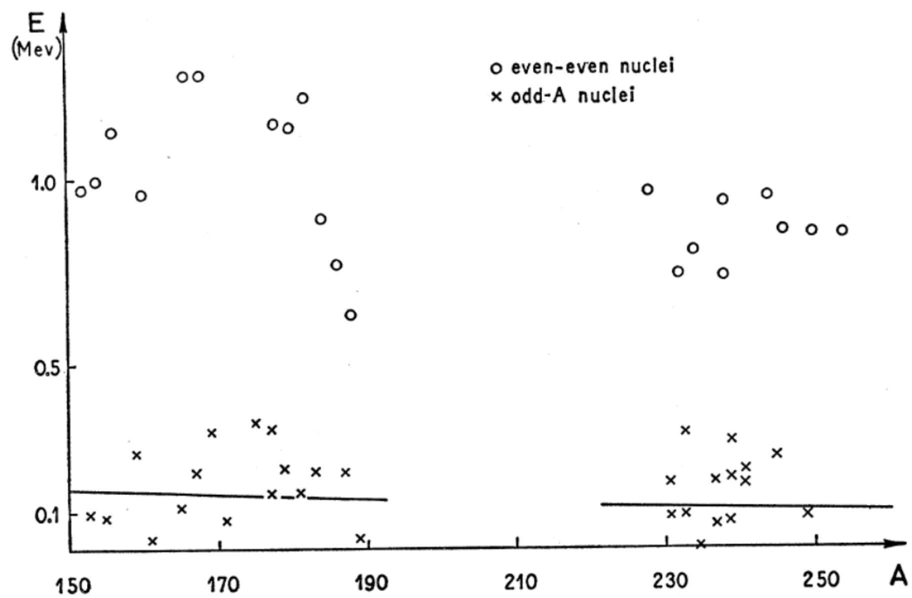
PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State

A. Bohr, B. R. Mottelson, and D. Pines*
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark, and Nordisk Institut for Teoretisk Atomfysik, Copenhagen, Denmark

(Received January 7, 1958)

The evidence for an energy gap in the intrinsic excitation spectrum of nuclei is reviewed. A possible analogy between this effect and the energy gap observed in the electronic excitation of a superconducting metal is suggested.



Neutron stars

The Crab Nebula (4 July 1054) in Blue and White
Credit & Copyright: Jay Gallagher (U. Wisc.), WIYN, AURA, NOAO, NSF

Ultracold atoms

Vol 443 | 26 October 2006 | **doi:10.1038/nature05224** nature

LETTERS

Evidence for superfluidity of ultracold fermions in an optical lattice

J. K. Chin[1], D. E. Miller[1], Y. Liu[1], C. Stan[1]†, W. Setiawan[1], C. Sanner[1], K. Xu[1] & W. Ketterle[1]

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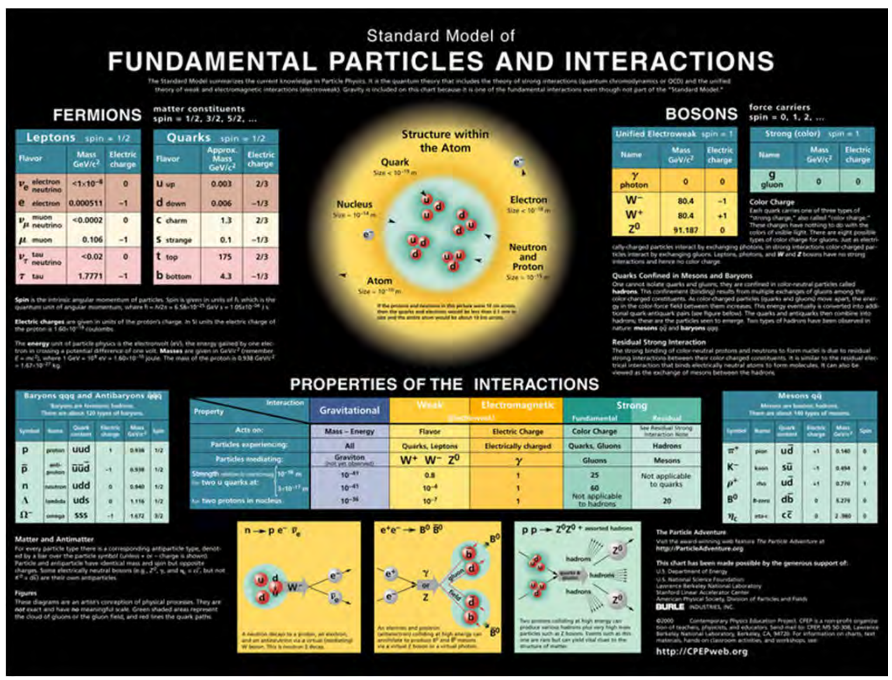
Standard model of elementary particles (unifying electro-weak interactions)

$$SU(2) \otimes U(1) \rightarrow U(1)$$

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}$$



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Return to history

Fortunately not everything was known

- Zero resistance (except if magnet nearby)
- Meissner effect (not perfect)
- Sometimes not transparent to microwaves
- Isotope effect (sometimes wrong way)

The best understood theory

- In 1969, R.D. Parks two volumes « Superconductivity »

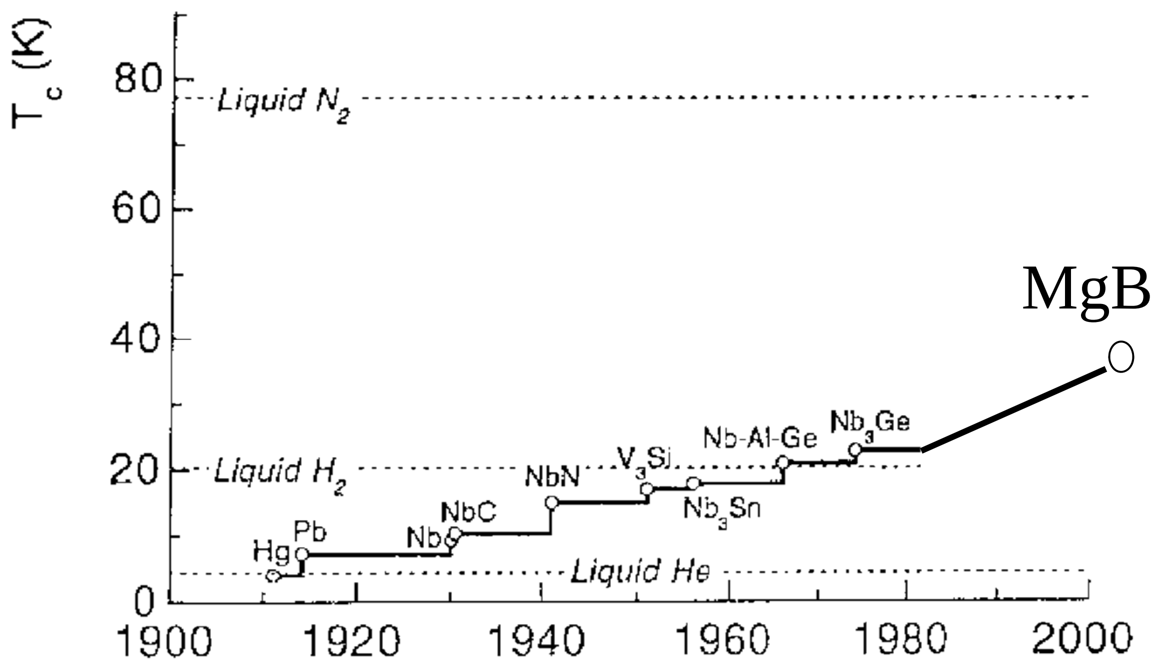
- From one of the authors : *« It is the last nail in the coffin of superconductivity »*

The search for new materials

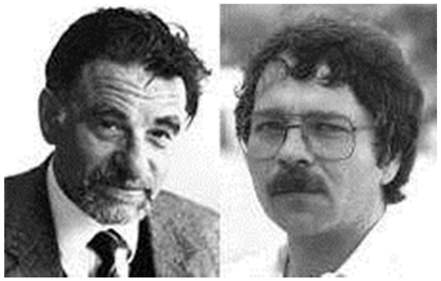
The goal: liquid nitrogen temperature!

It was generally believed that

- Cu,Au,Fe not a good idea
- Cubic is good
- Stay away from
  - O
  - Magnets
  - Insulators



January 1986



USO

1986 : Bednorz and Muëller,
IBM Zurich
La-Ba-Cu-O $T_c \sim 30\text{-}40K$

Group of P. Chu (Houston)
Under high pressure : 50K!!!

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It goes quickly…

- Boston, "Materials Research Society" December 1986
  - Koitchi Kitazawa and Shoji Tanaka Tokyo convince everyone.
- 16 Feb.1987, Houston:
  - Press conference by Paul Chu to announce discovery of *Y-Ba-Cu-O*
  - $T_c = 93$ *K*

March meeting APS

- Title of the New York Times the following day:
"The Woodstock of Physics"

- 3000 people until three in the morning

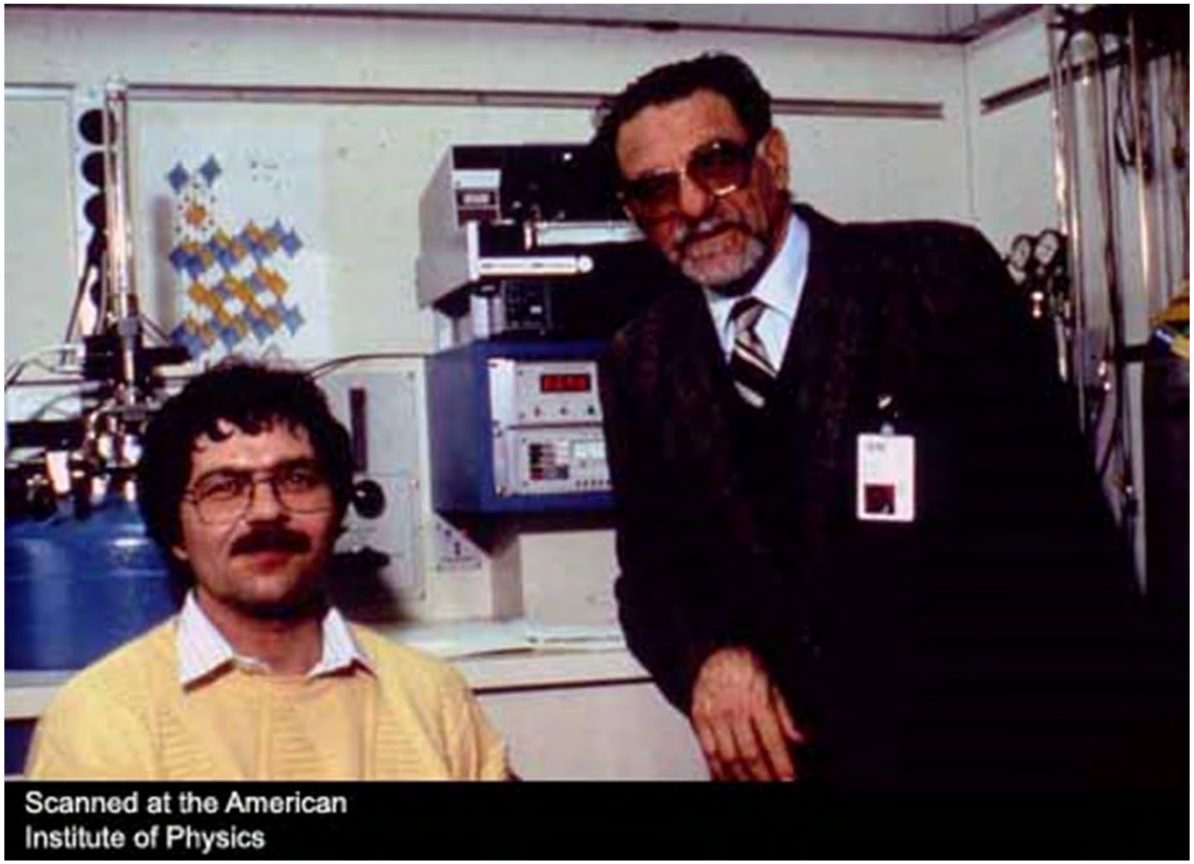
"They began lining up outside the New York Hilton Sutton Ballroom at 5:30PM for an evening session that would last until 3:00 AM"

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



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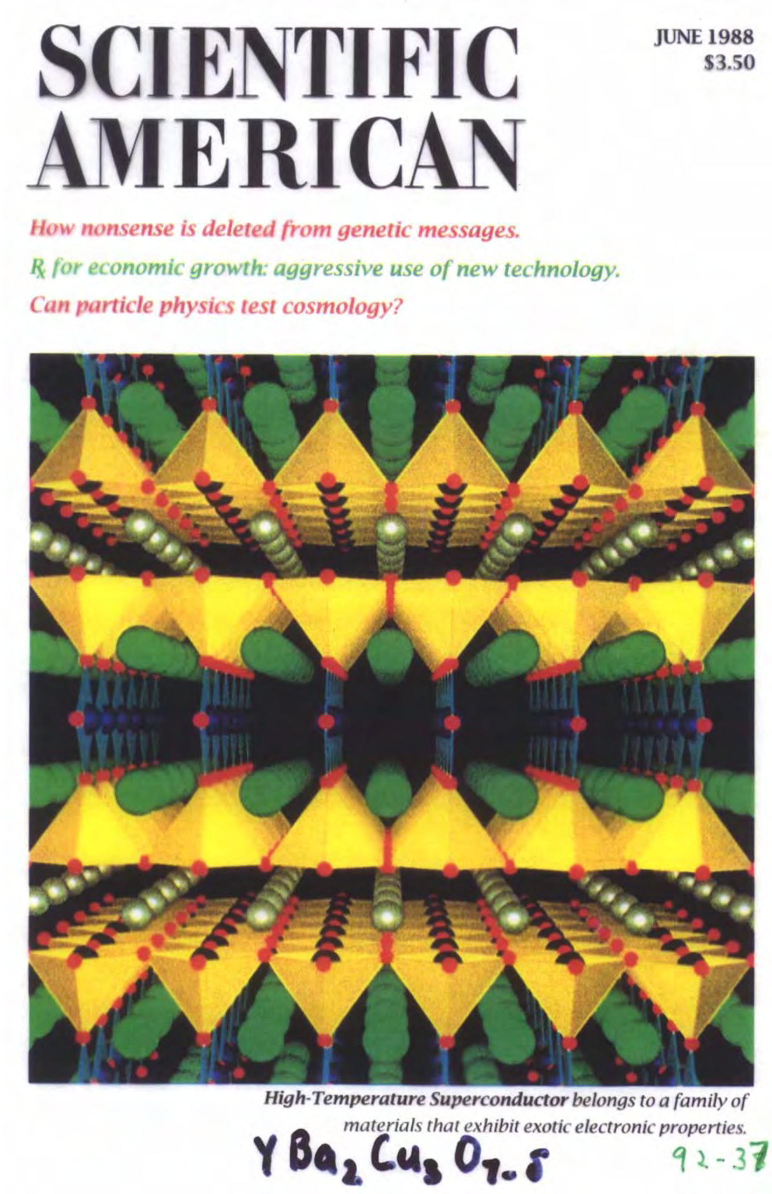
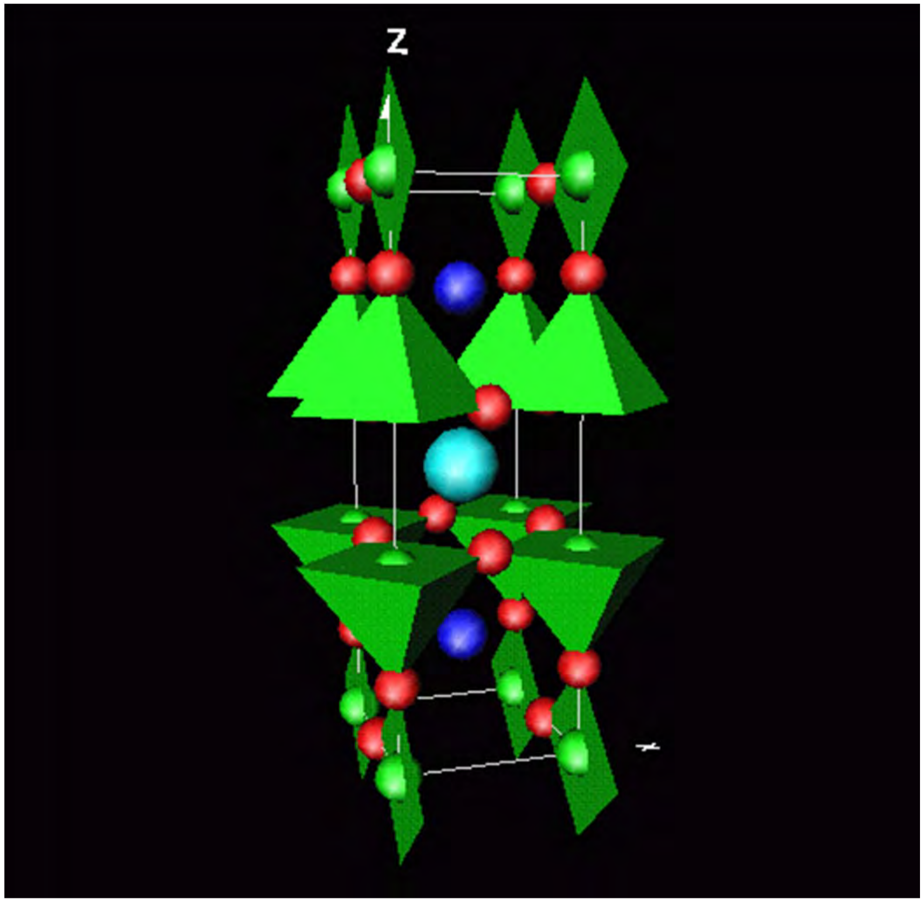
What is special about these superconductors?

Atomic structure





What is special

- Cu, Au, Fe not good
- Cubic
- Stay away from
  - O
  - Magnets
  - Insulators

- Cu
- Layered
- Stay close to
  - O
  - Magnets
  - Insulators

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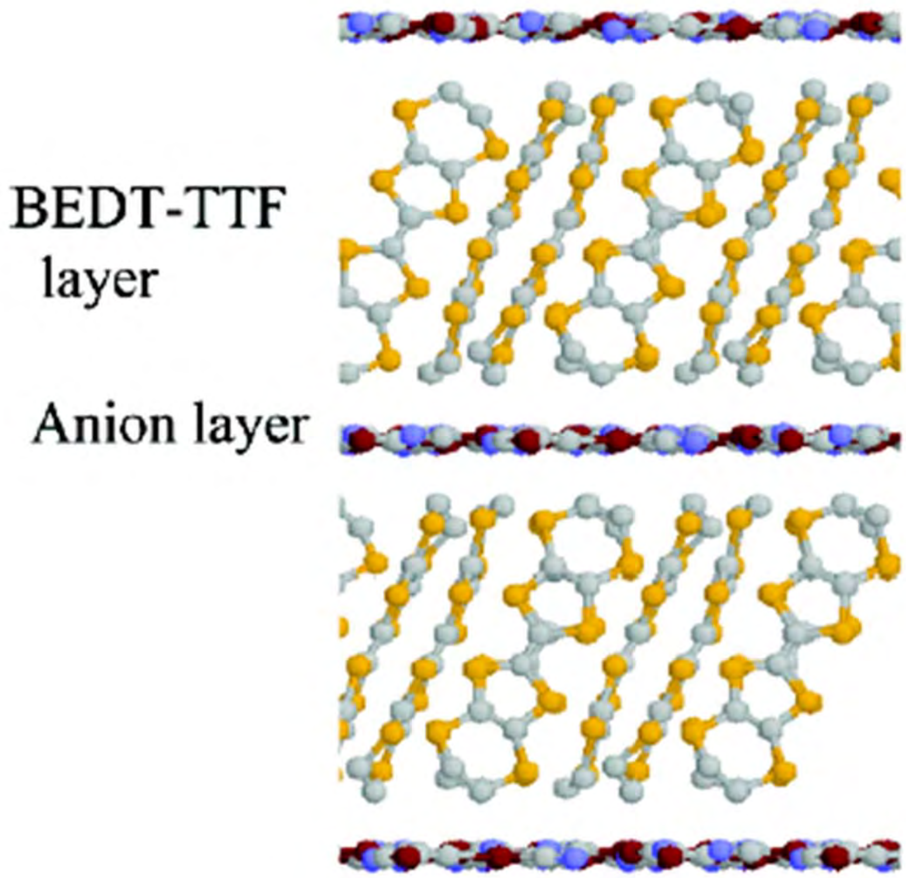
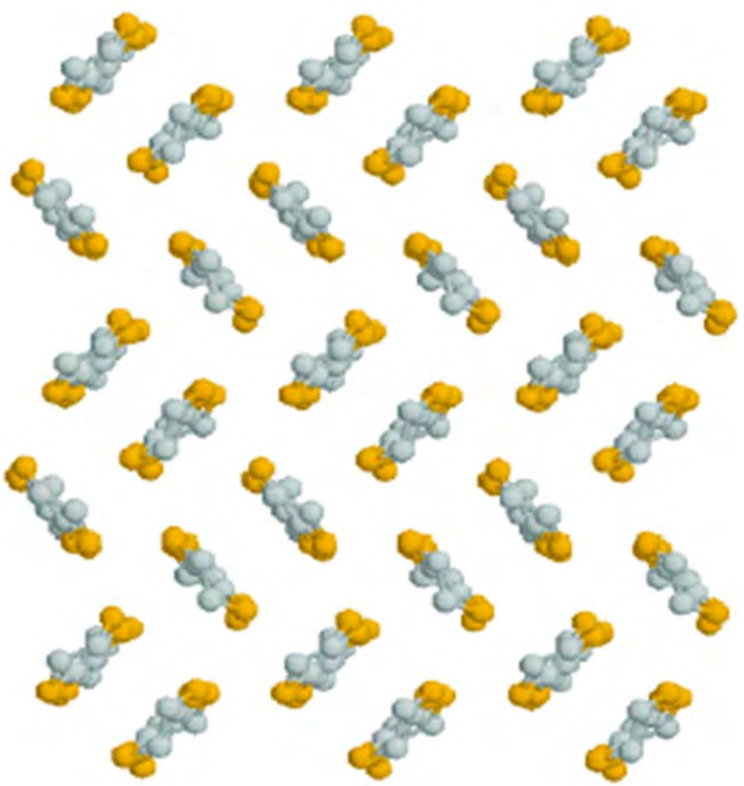
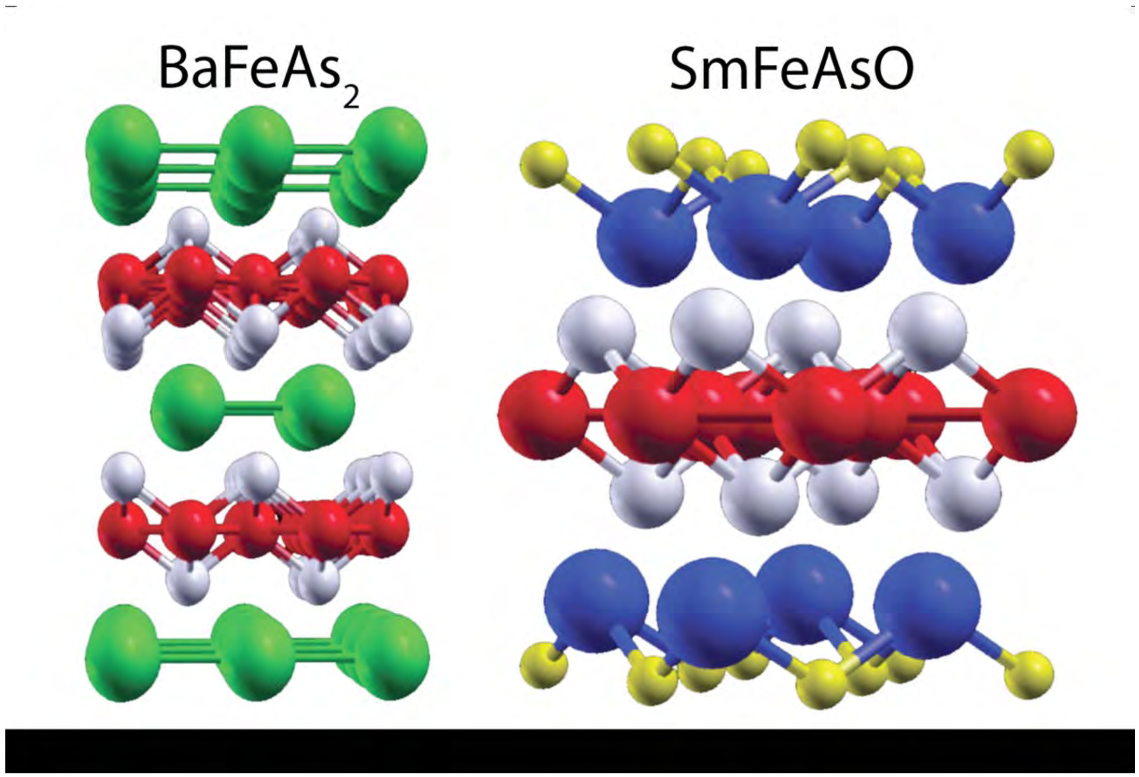
Layered organic conductors(κ–BEDT-X family)





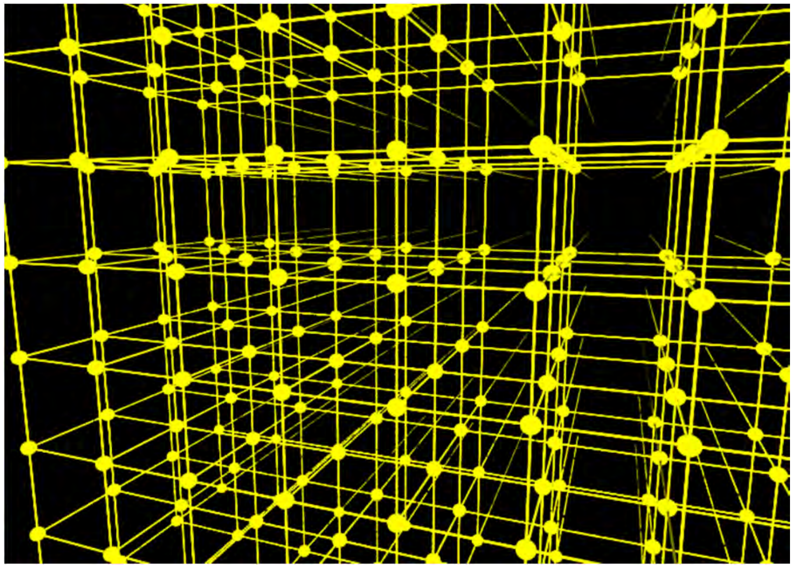
Pnictides (2008)

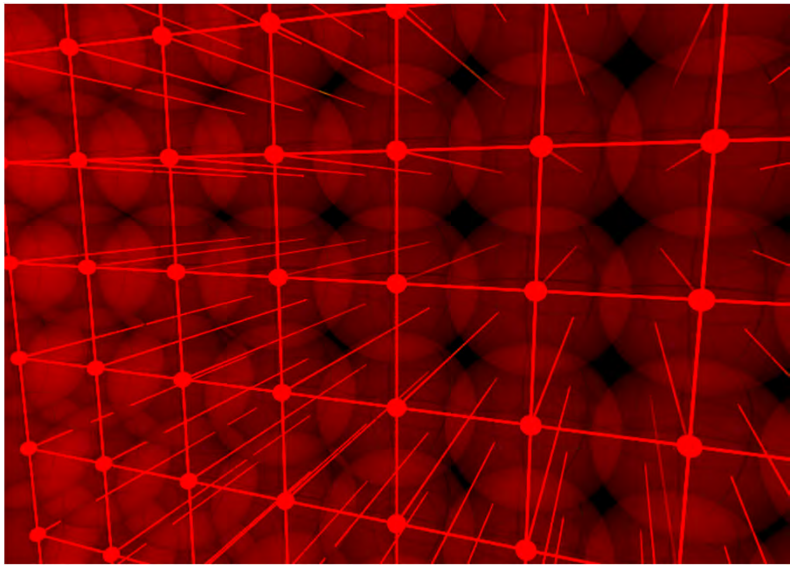


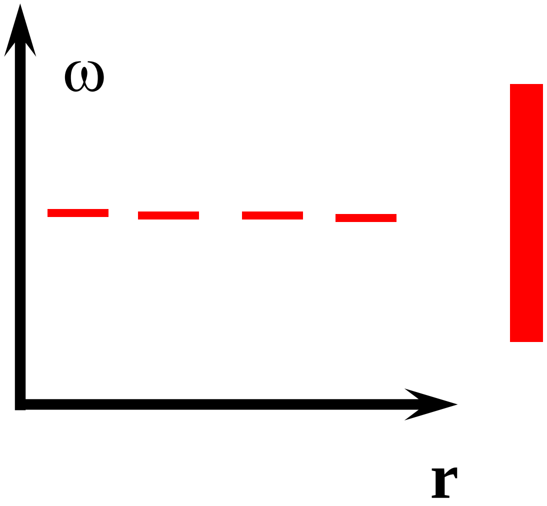
http://www.stanford.edu/~tpd/research_hightc.html

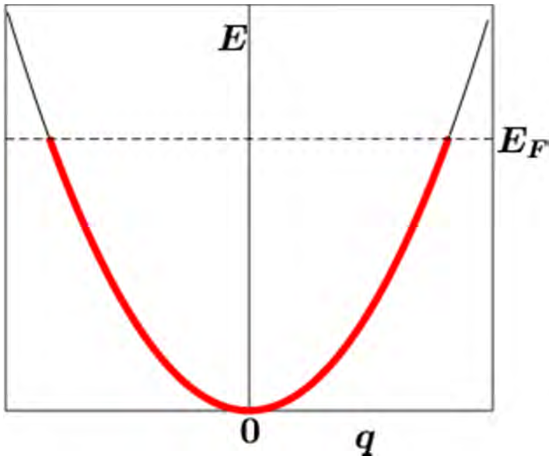
Strong correlations

How to make a metal



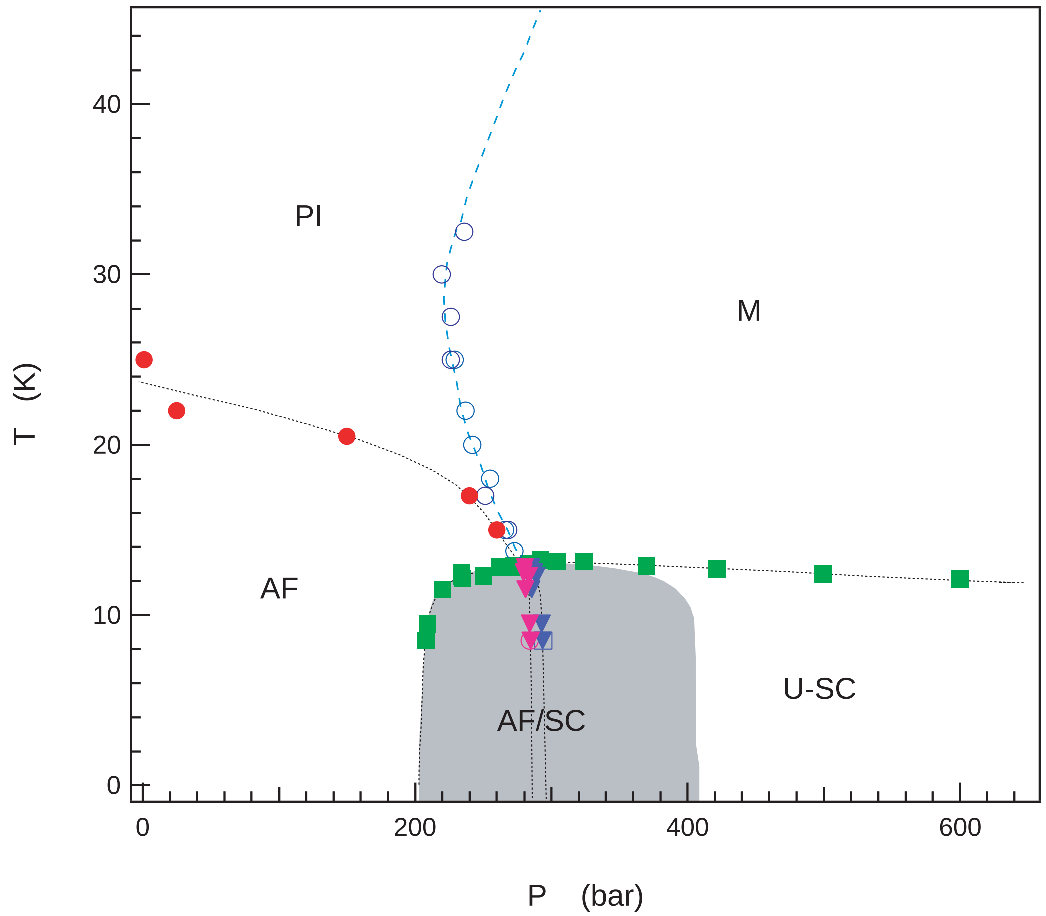






Courtesy, S. Julian

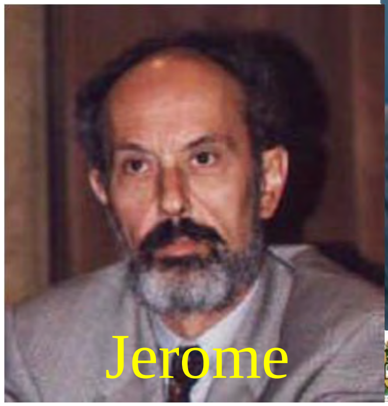
Experimental phase diagram BEDT-X



Phase diagram (X=Cu[N(CN)$_2$]Cl)

S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et

CIAR The Canadian Institute for Advanced Research



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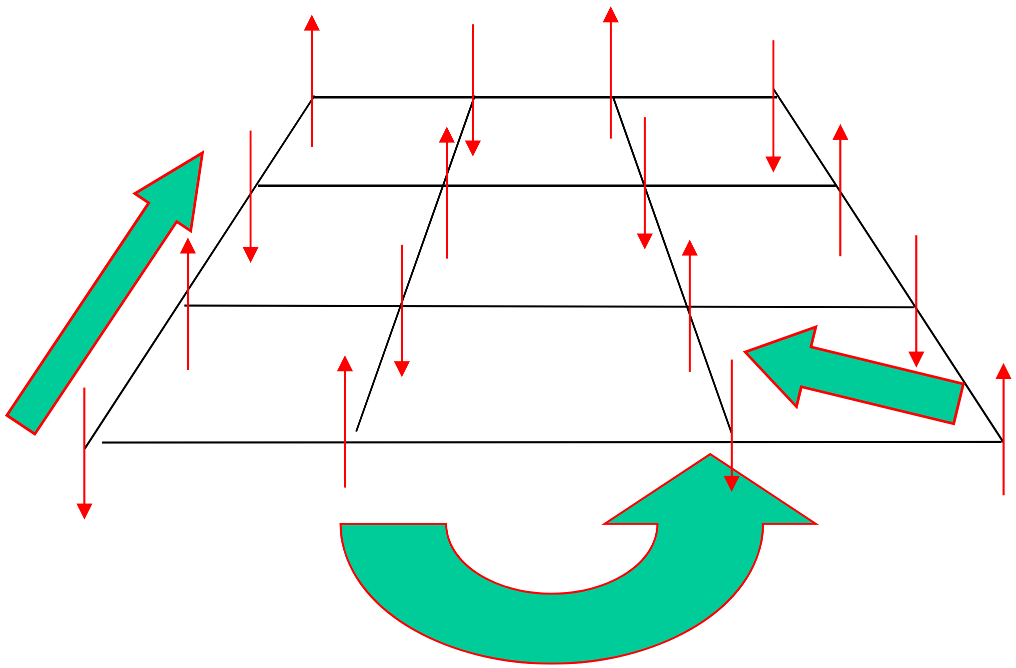
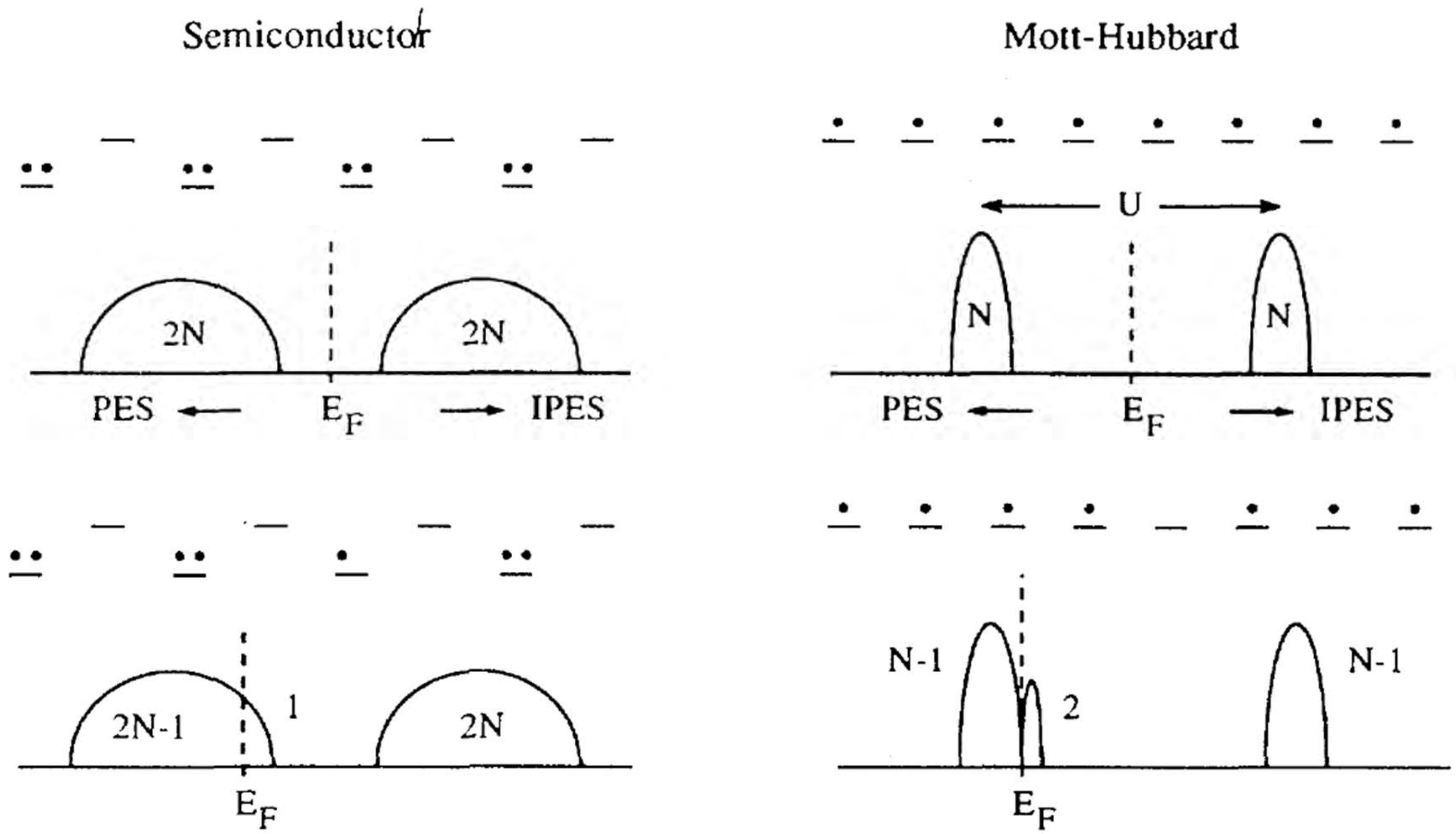
A quantum traffic jam (A.P.): Mott insulator



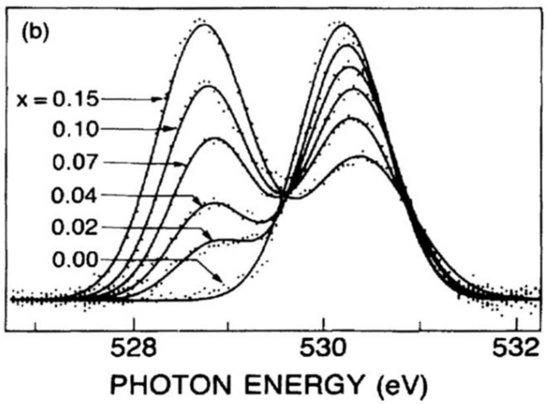
Spectral weight transfer



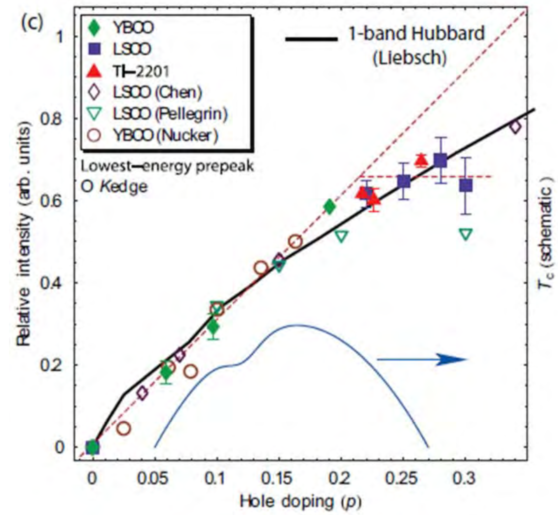
Meinders *et al.* PRB **48**, 3916 (1993)

Cuprates as doped Mott insulators

Experiment: X-Ray absorption



Chen et al. PRL **66**, 104 (1991)



Peets et al. PRL **103**, (2009), Phillips, Jarrell arXiv

Number of low energy states above ω = 0 scales as *2x* +
Not as 1+x as in Fermi liquid

Meinders *et al.* PRB **48**, 3916 (1993)

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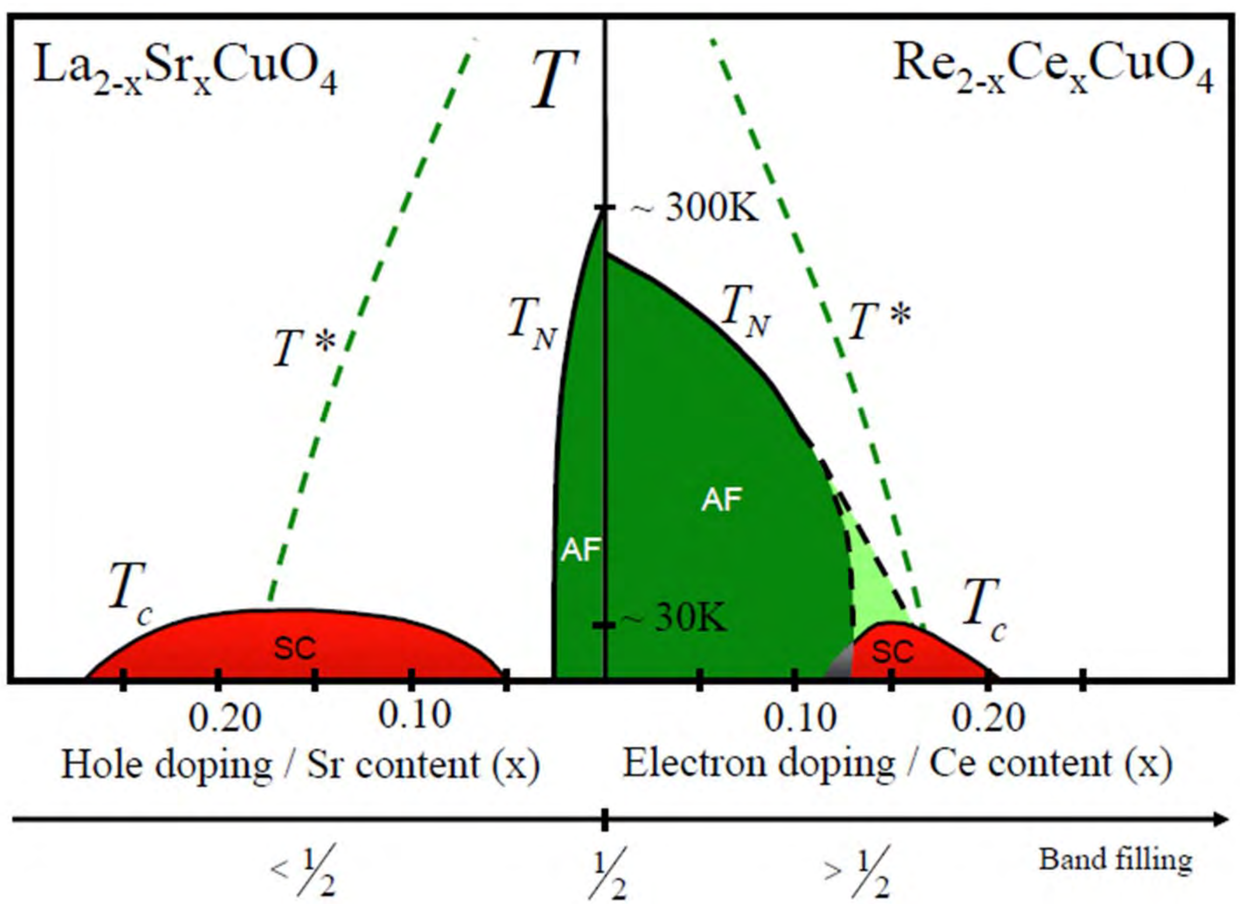
Phase diagram

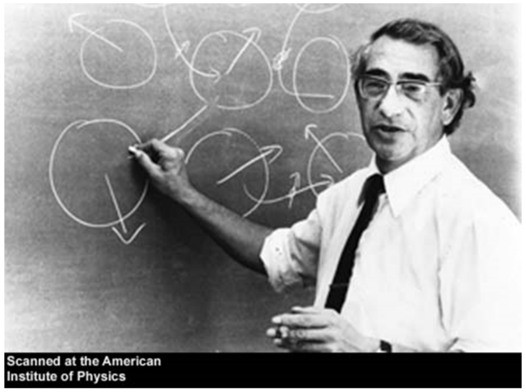
Insulator even if *n=1*

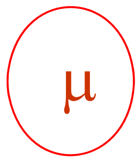


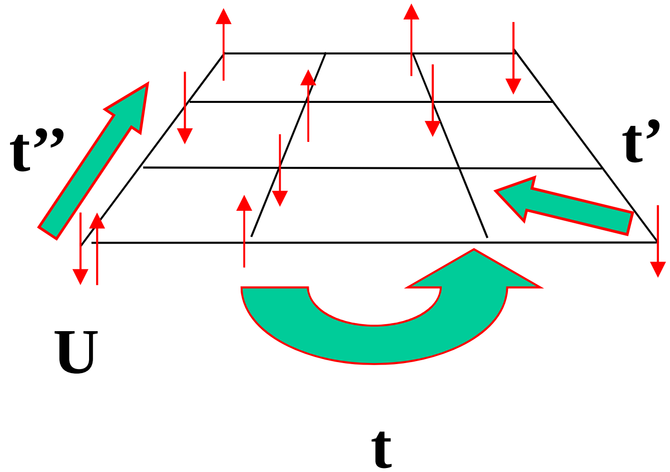
Armitage, Fournier, Greene, RMP (2009)

Theoretical method

Hubbard model

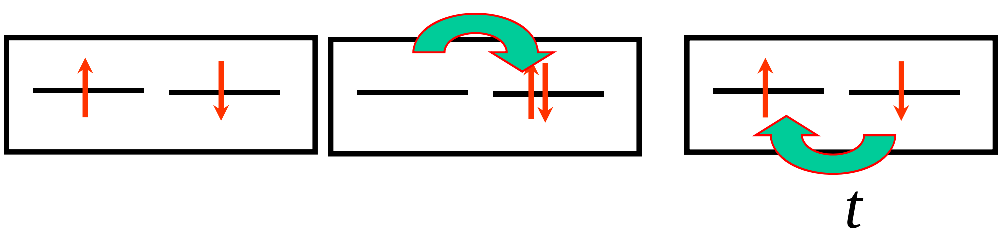






1931-1980

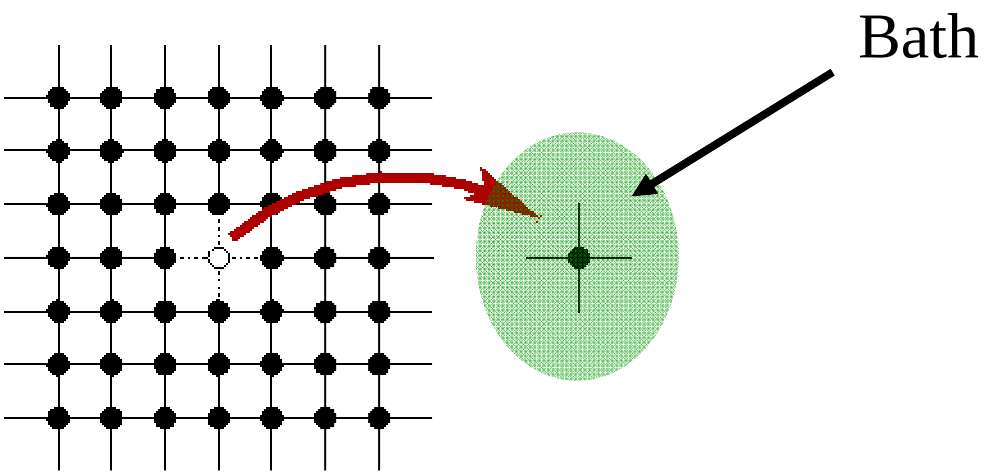
$$H = -\sum_{<ij>\sigma} t_{i,j} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$



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

Mott transition and Dynamical Mean-Field Theory. The beginnings in *d = infinity*

- Compute scattering rate (self-energy) of impurity problem.
- Use that self-energy (ω dependent) for lattice.
- Project lattice on single-site and adjust bath so that single-site DOS obtained both ways be equal.



W. Metzner and D. Vollhardt, PRL (1989)
A. Georges and G. Kotliar, PRB (1992)
M. Jarrell PRB (1992)

DMFT, (*d = 3)*

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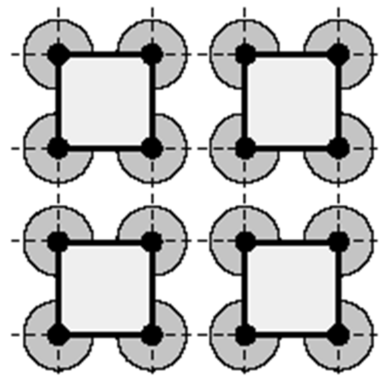
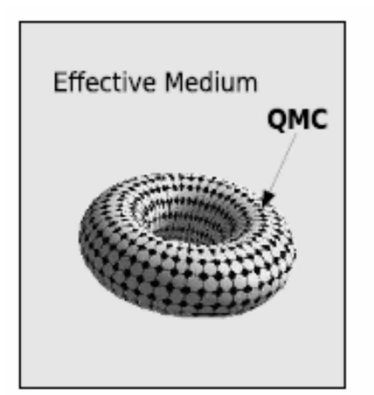
2d Hubbard: Quantum cluster method

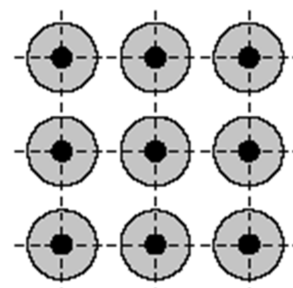
C-DMFT





DCA

DMFT



Hettler …Jarrell…Krishnamurty PRB **58** (1998)
Kotliar et al. PRL **87** (2001)
M. Potthoff *et al.* PRL **91,** 206402 (2003).
Maier, Jarrell et al., Rev. Mod. Phys. **77**, 1027 (2005)

Solving cluster in a bath problem

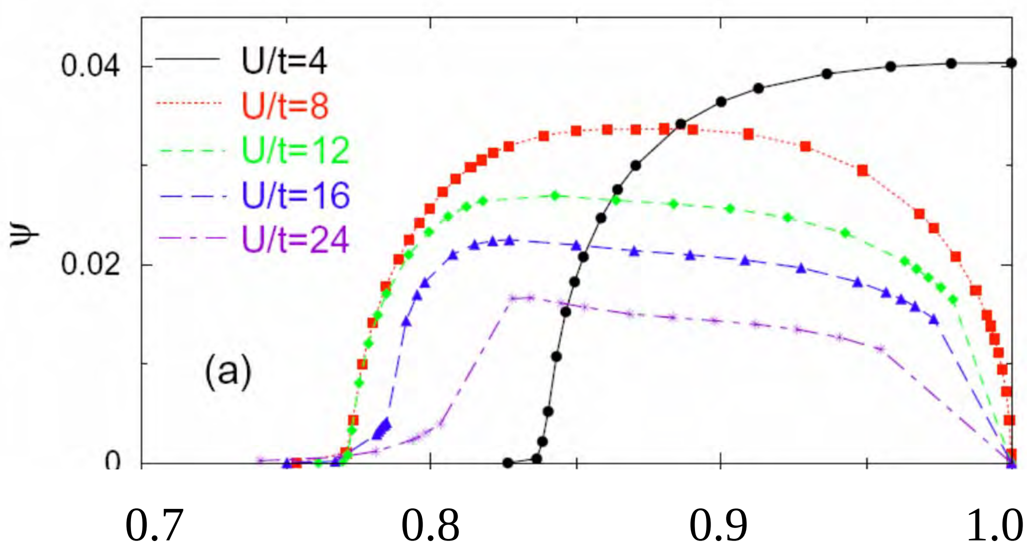
- Continuous-time Quantum Monte Carlo calculations to sum all diagrams generated from expansion in powers of hybridization.
  - P. Werner, A. Comanac, L. de' Medici, M. Troyer, and A. J. Millis, Phys. Rev. Lett. **97**, 076405 (2006).
  - K. Haule, Phys. Rev. B **75**, 155113 (2007).

Strongly Correlated Superconductivity

Phase diagram

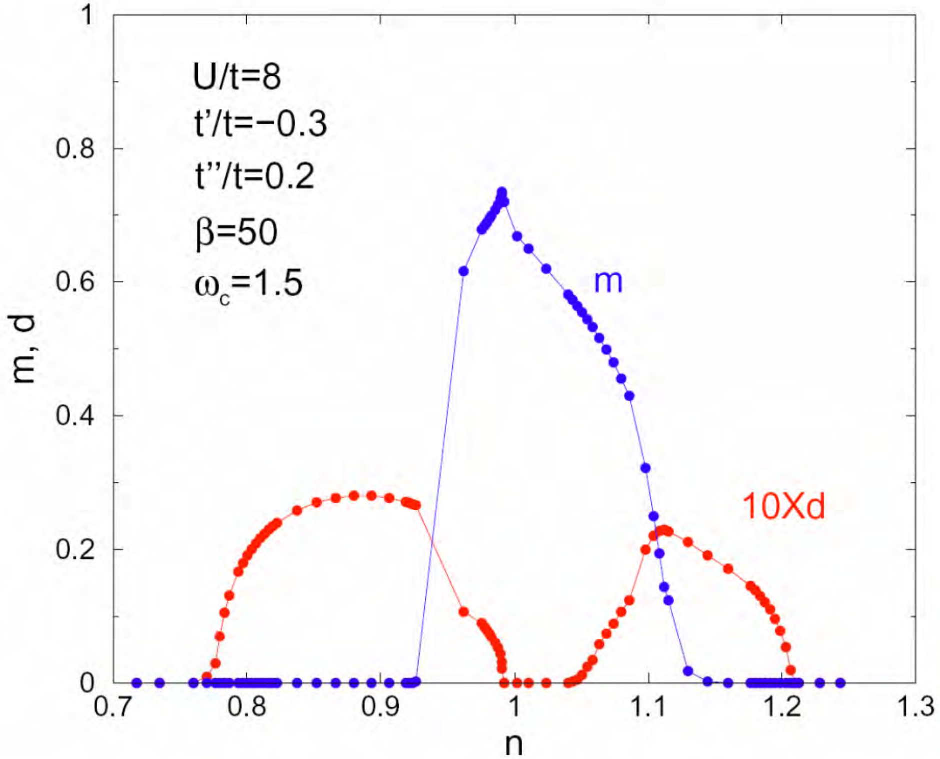
Exact diagonalization as impurity solver ($T=0$).

Dome vs Mott (CDMFT)

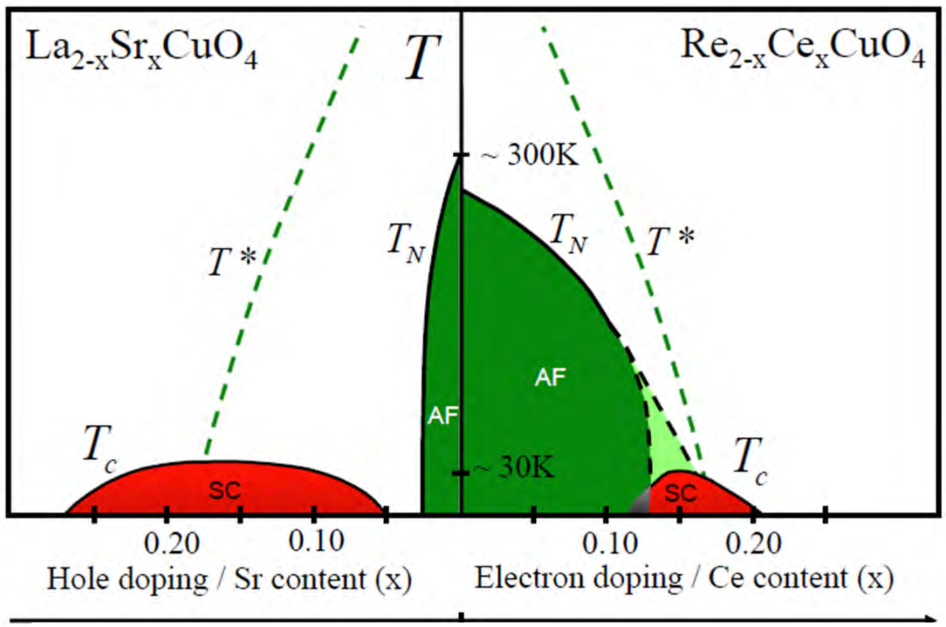


Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)

CDMFT global phase diagram



Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)

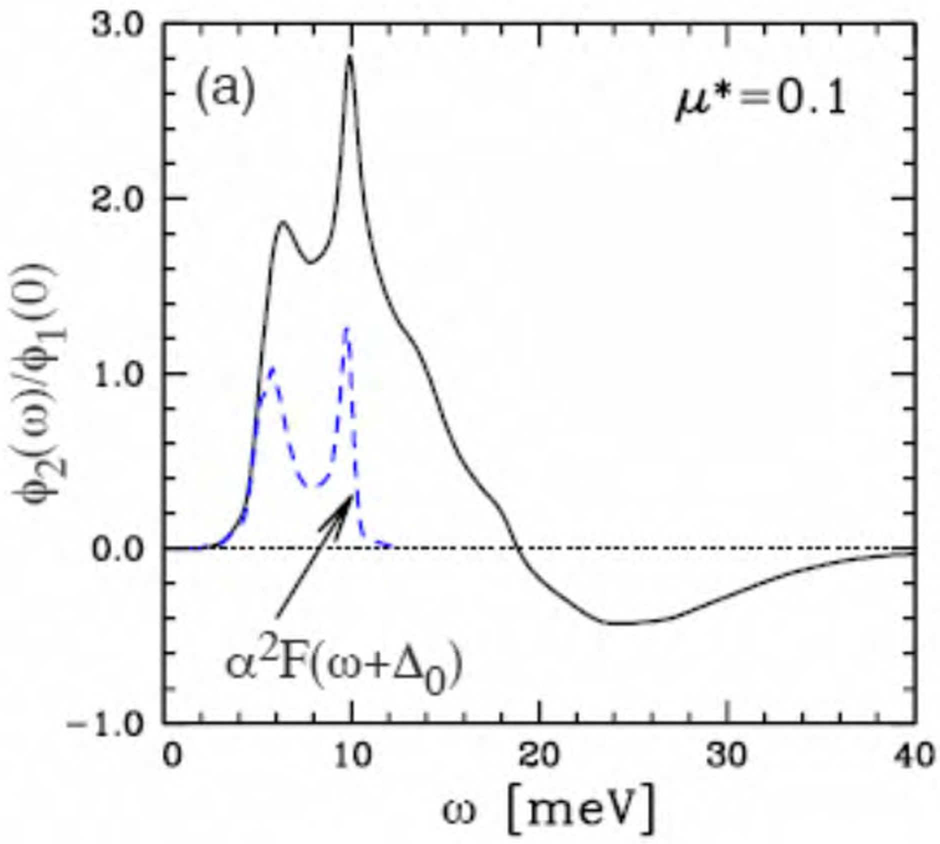


Armitage, Fournier, Greene, RMP (2009)

The glue

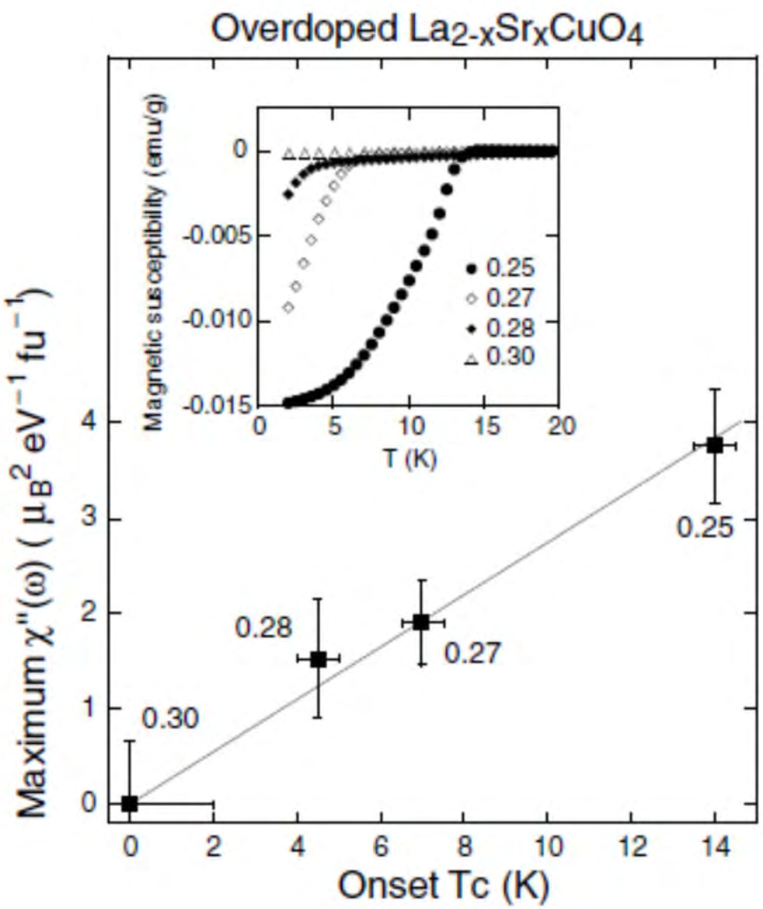
Im Σ_{an} and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)

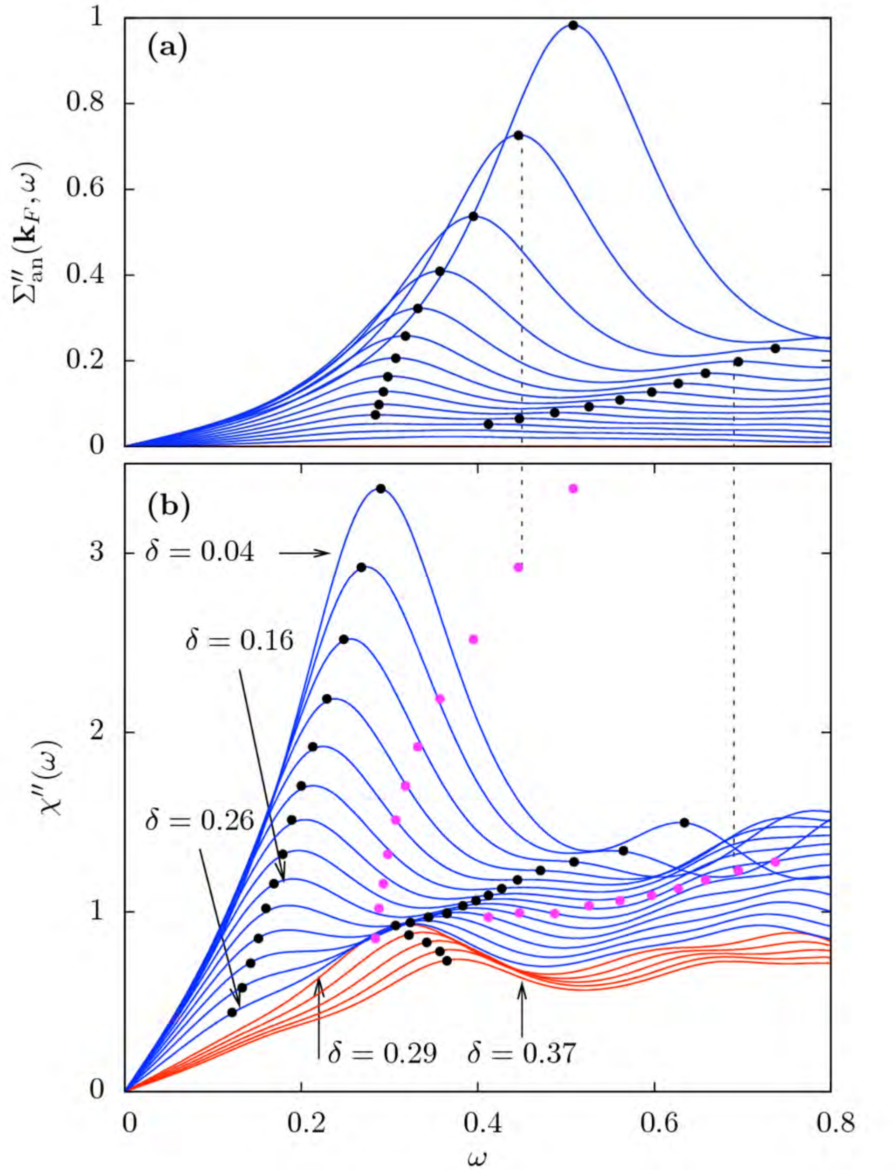


The glue

Kyung, Sénéchal, Tremblay, Phys. Rev. B **80,** 205109 (2009)



Wakimoto … Birgeneau PRL (2004)



The glue and neutrons

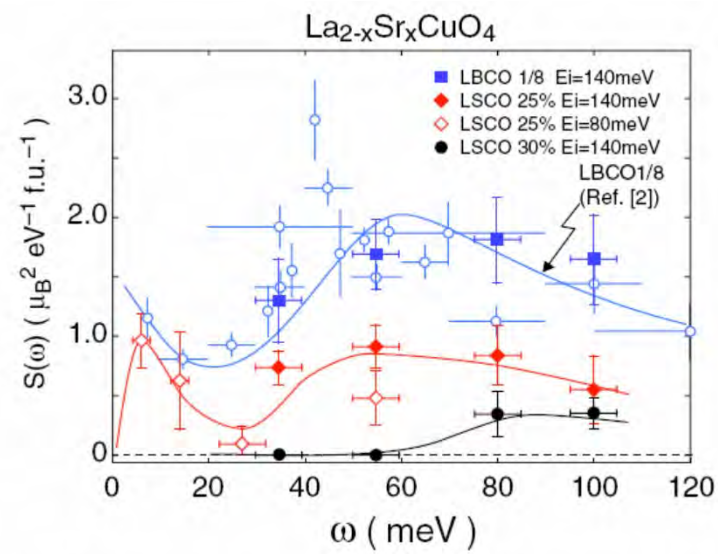
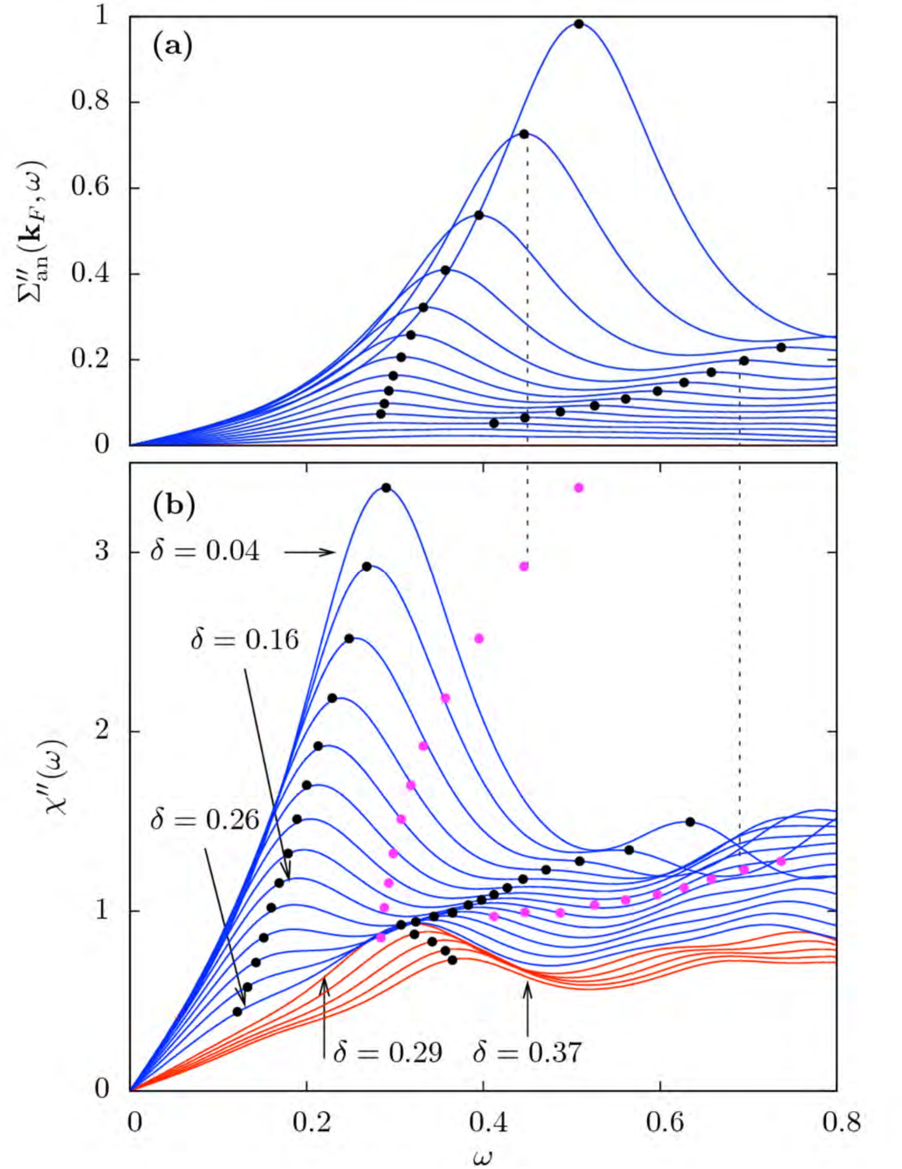


FIG. 3 (color online). **Q**-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-H integrated profiles for LBCO 1/8 (squares), LSCO $x = 0.25$ (diamonds; filled for E_i = 140 meV, open for $E_i = 80$ meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 1/8 (open circles) from [2]. The solid lines following data of LSCO $x = 0.25$ and 0.30 are guides to the eyes.

Wakimoto … Birgeneau PRL (2007);
PRL (2004)



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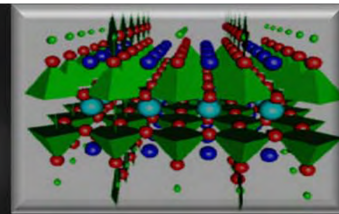
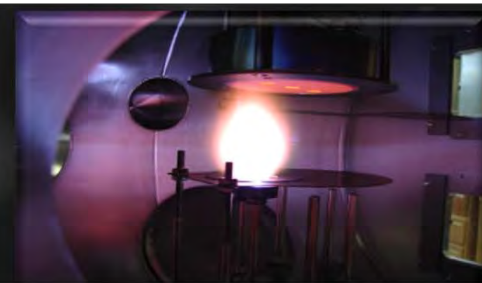
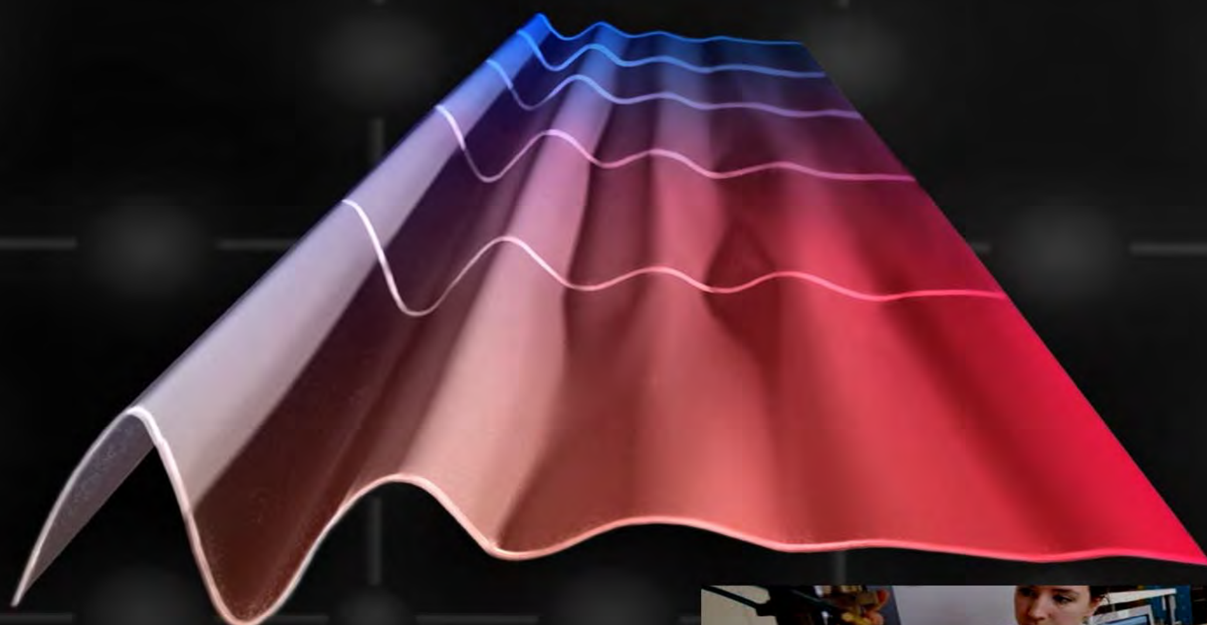


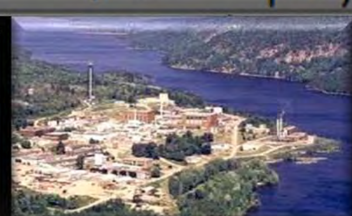


$$H(t) = -\sum_{ij\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} e^{-i\int_i^j d\mathbf{r}_{ij}\cdot\mathbf{A}(\mathbf{r},t)} + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

$$\Delta_{\mathbf{p}} = \frac{1}{V}\sum_{\mathbf{p}'} U\left(\mathbf{p}-\mathbf{p}'\right)\langle c_{-\mathbf{p}'\downarrow}c_{\mathbf{p}'\uparrow}\rangle$$



$$|BCS(\theta)\rangle = \cdots + \mathrm{e}^{iN\theta}|N\rangle + \mathrm{e}^{i(N+2)\theta}|N+2\rangle + \ldots$$



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Conclusion

The dream

room-temperature superconductors

50–50

They would transform the grid—if they can exist at all *By Michael Moyer*

You can build a coal-fired power plant just about anywhere. Renewables, on the other hand, are finicky. The strongest winds blow across the high plains. The sun shines brightest on the desert. Transporting that energy into cities hundreds of kilometers away will be one of the great challenges of the switch to renewable energy.

The most advanced superconducting cable can move those megawatts thousands of kilometers with losses of only a few percent. Yet there is a catch: the cable must be kept in a bath of liquid nitrogen at 77 kelvins (or −196 degrees Celsius). This kind of deployment, in turn, requires pumps and refrigeration units every kilometer or so, greatly increasing the cost and complexity of superconducting cable projects.

Superconductors that work at ordinary temperatures and pressures would enable a truly global energy supply. The Saharan sun could power western Europe via superconducting cables strung across the floor of the Mediterranean Sea. Yet the trick to making a room-temperature superconductor is just as much of a mystery today as it was in 1986, when researchers constructed the first superconducting materials that worked at the relatively high temperatures of liquid nitrogen (previous substances needed to be chilled down to 23 kelvins or less).

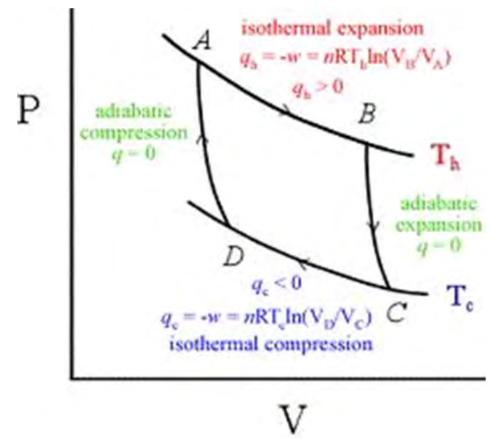
Two years ago the discovery of an entirely new class of superconductor—one based on iron—raised hopes that theorists might be able to divine the mechanism at work in high-temperature superconductors [see "An Iron Key to High-Temperature Superconductivity?" by Graham P. Collins; Scientific American, August 2009]. With such insights in hand, perhaps a path toward room-temperature superconductors would come into view. But progress has remained slow. The winds of change don't always blow on cue.

http://www.physique.usherbrooke.ca/taillefer/Vulgarisation.html

Science and technology, hand in hand

Steam engine and thermodynamics

Watts 1765

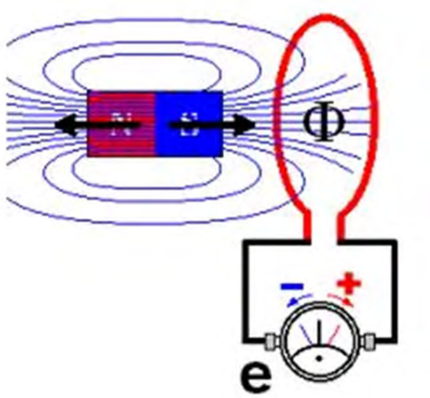


Carnot 1824

Induction and electric motor

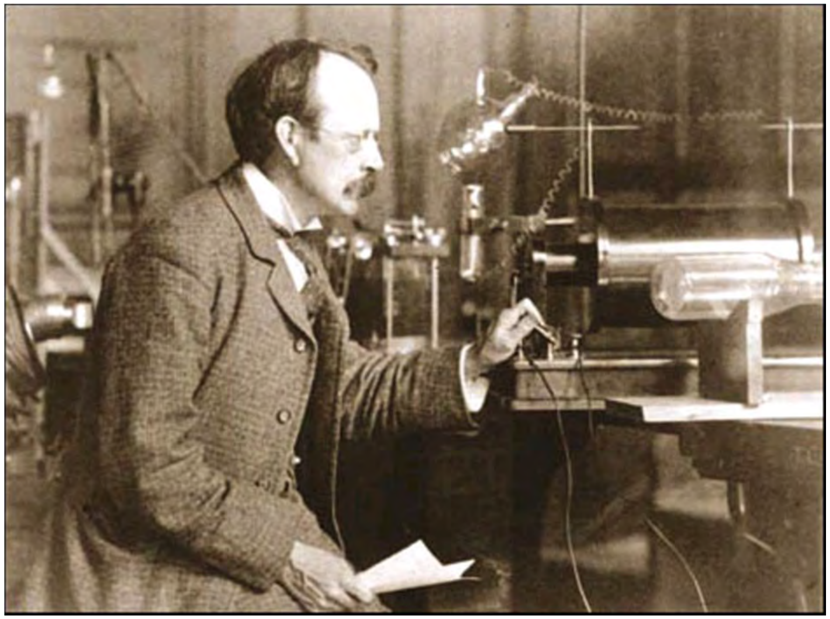
Electric motor, Tesla(1880)

Induction, Faraday (1831)



Induction

Electron and television



Thomson, 1897

Television, 1940

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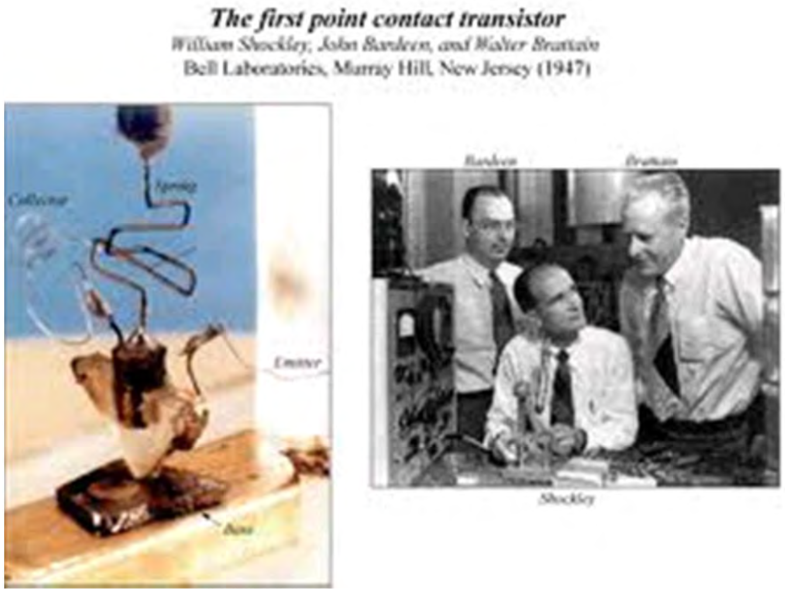
Quantum mechanics and the transitor



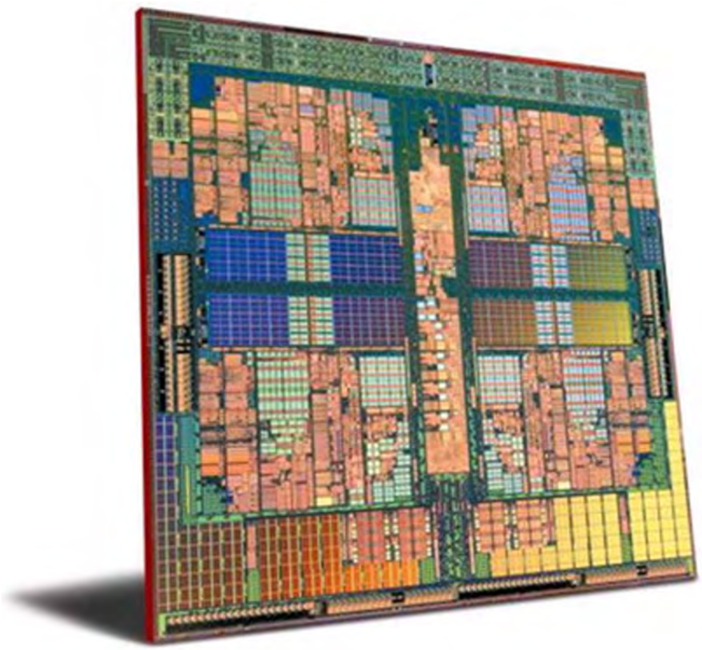
Schrödinger

Heisenberg

Transistor 1947

Quantum mechanics 1926

Quantum mechanics and the transitor



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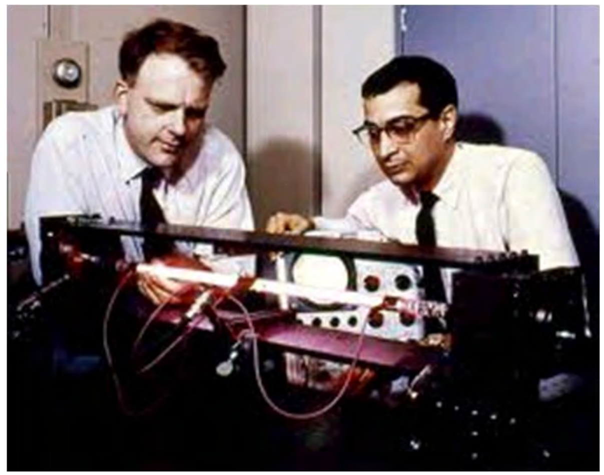
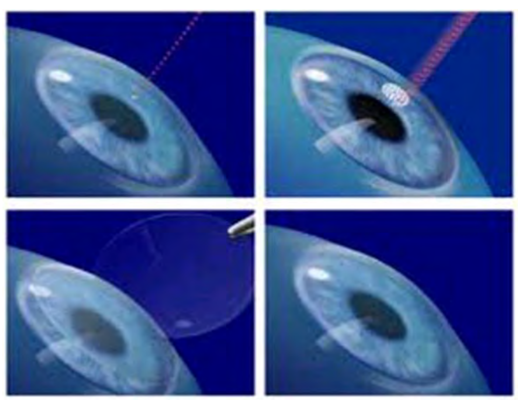
Laser and CD-ROM

Stimulated emission 1925



Laser 1960

CD-ROM (1980-90)



Eye surgery

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Edward Bellamy (USA) 1887

- Novel: « Looking backward » 2000-1887
- If we could have devised an arrangement for providing everybody with music in their homes, perfect in quality, unlimited in quantity, suited to every mood, and beginning and ceasing at will, we should have considered the limit of human felicity already attained, and ceased to strive for further improvements.
- Edward Bellamy, Looking Backward, (1887) p.67 Boston: Ticknor and Company, 1888, www.forgottenbooks.org

Merci

http://sweetladiesbakery.com/gallery/female-cakes/