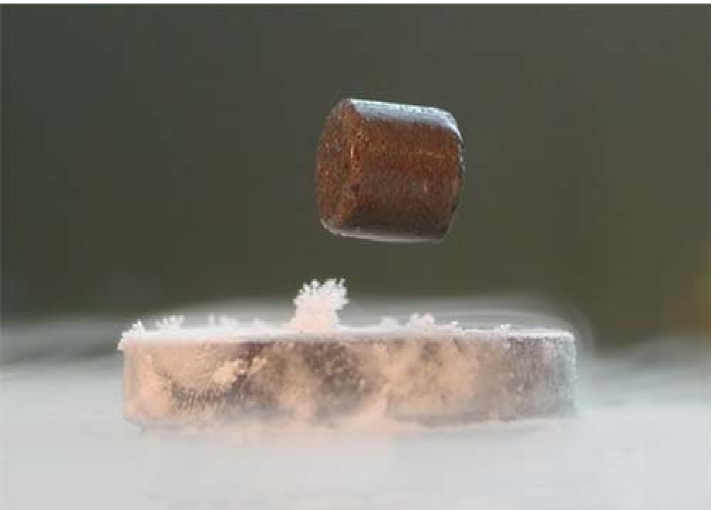
CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH
CRSNG NSERC
Fondation canadienne pour l'innovation
Fonds de recherche Nature et technologies Québec
VERITATEM IN CHARITATE

Supraconductivité: La mécanique quantique devant vos yeux.

André-Marie Tremblay



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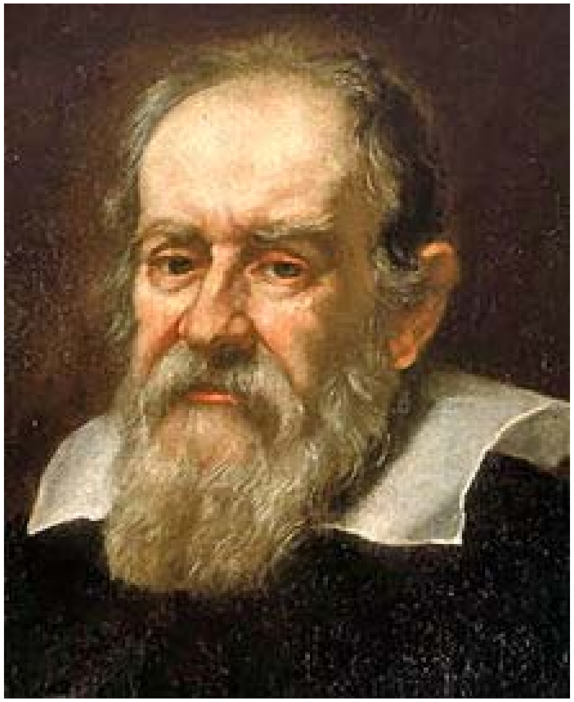
Galileo Galilei



1564-1642

Richard Feynman

1918-1988

Quelle serait la phrase qui contiendrait le plus d’information dans le moins de mots?

Atomes - température

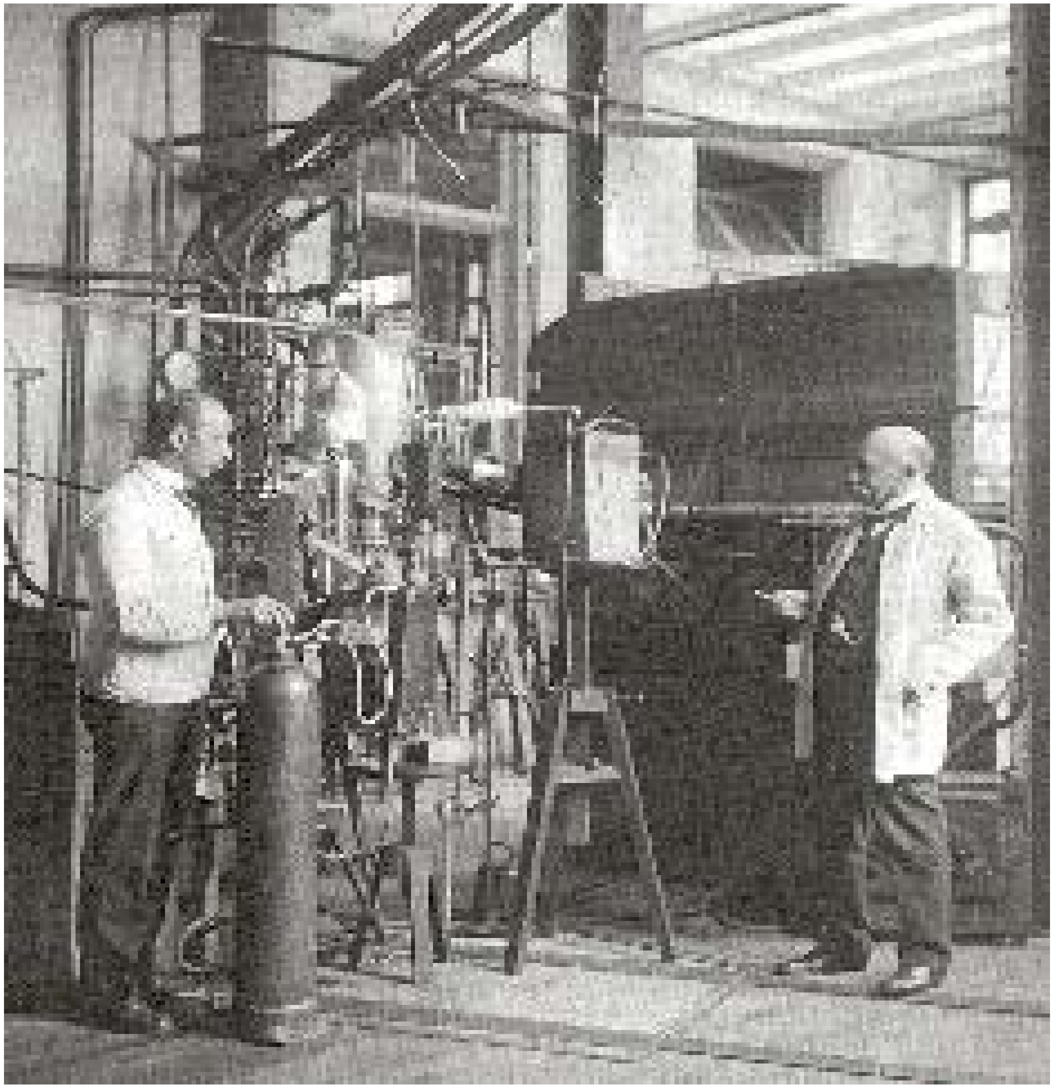
La course vers la température zéro

Un pas important vers *T = 0*

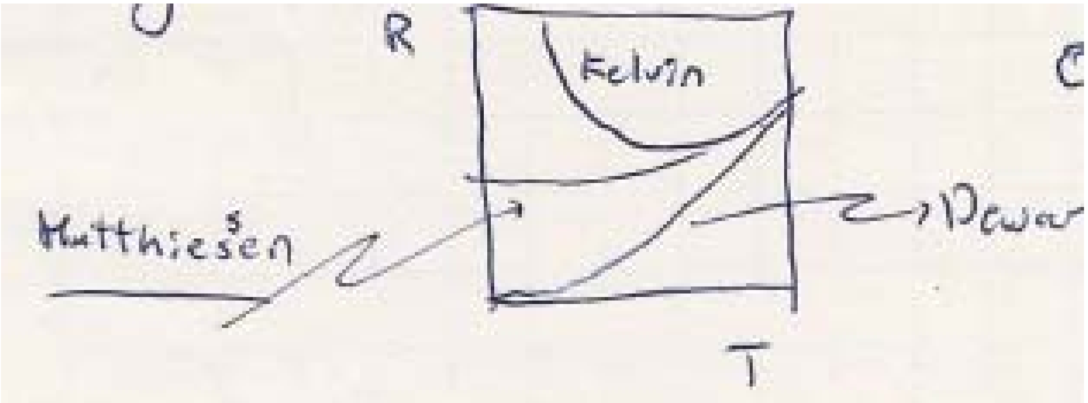
- Heike Kamerlingh Onnes (Leiden) (1853/1926)

Les débuts du travail d'équipe en recherche

J.G. Flim, cryogénie
G. Dorsma: thermométrie
G. Holst: électronique
Souffleur de verre



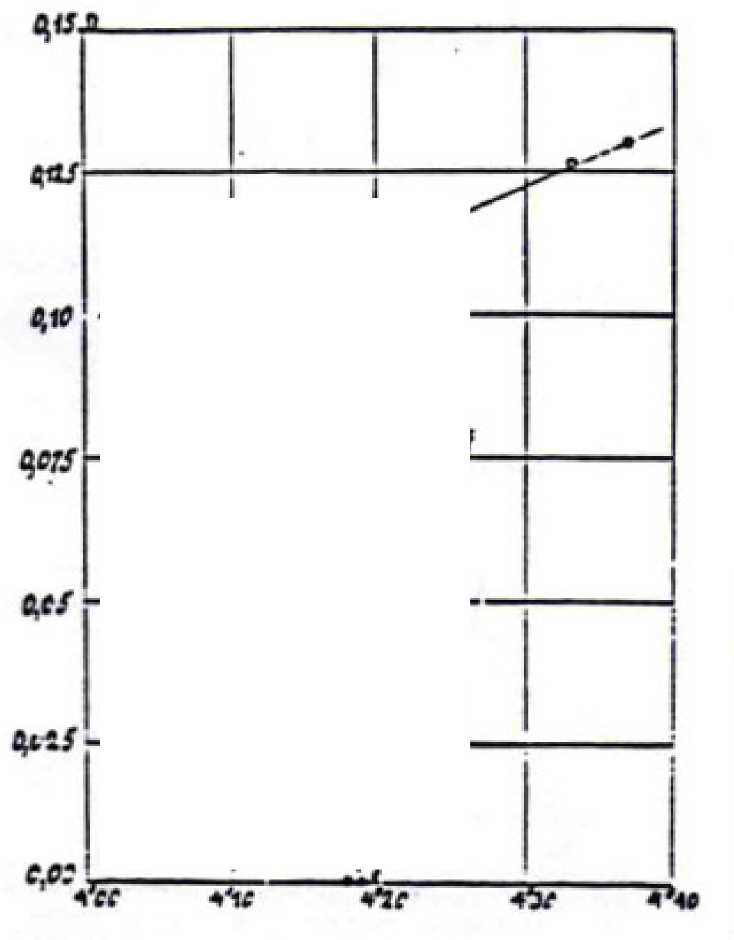
Et quoi encore?



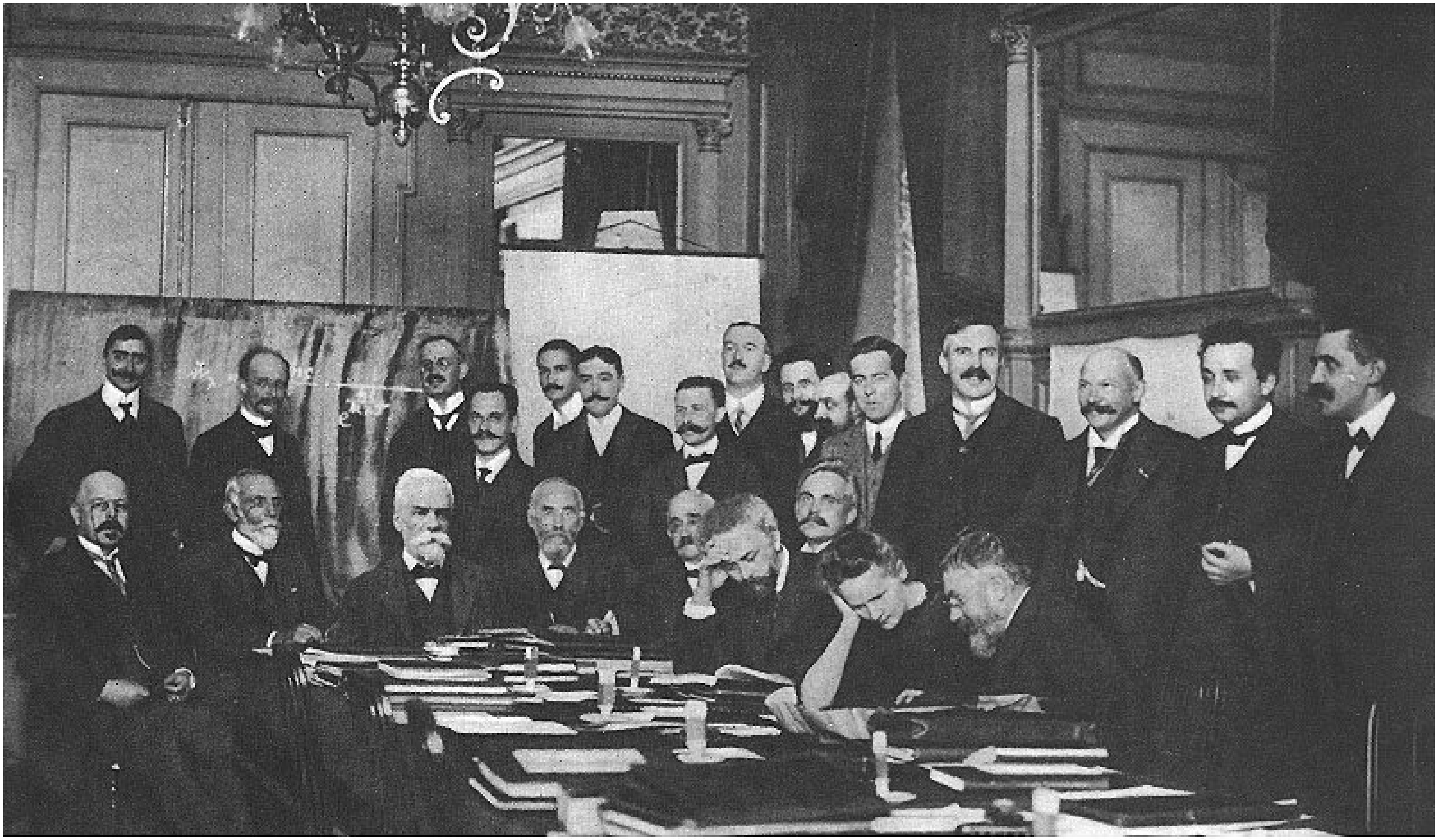
Et alors?

- Qu'arrive-t-il à la résistance électrique?

8 avril 1911



Congrès Solvay, 1911



Et le gagnant est…

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

http://www.nobel.se

1913: Prix Nobel de physique

Au Professeur H. Kamerlingh Onnes de Leiden, pour ses expériences sur les propriétés de la matière à basse température qui ont conduit, concomitament à la production de l'hélium liquide.

Transmission de l’électricité

UNIVERSITÉ DE SHERBROOKE

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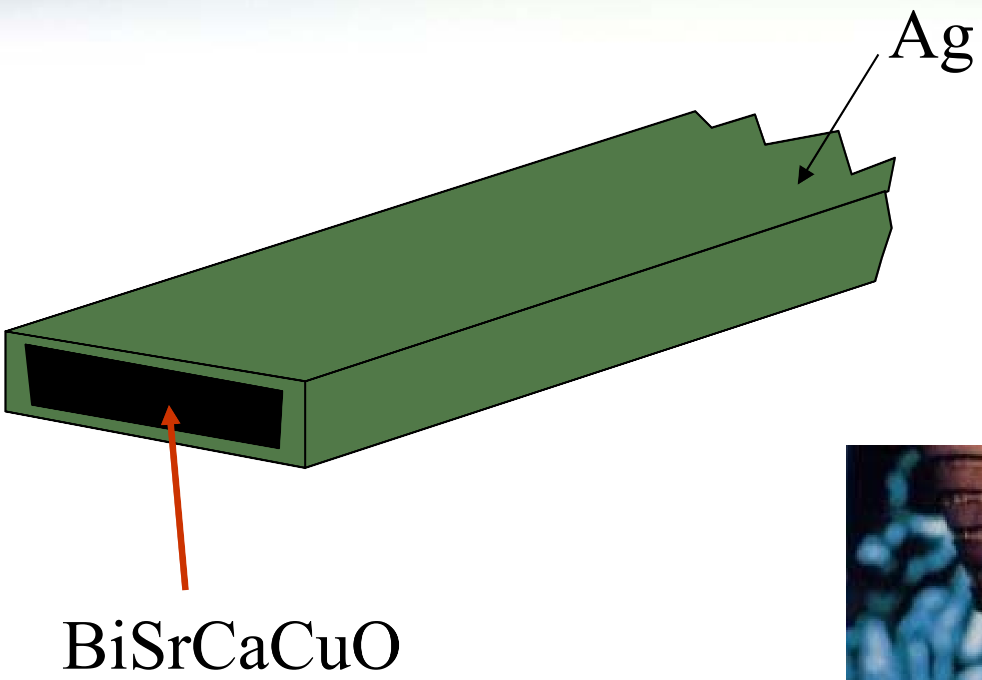
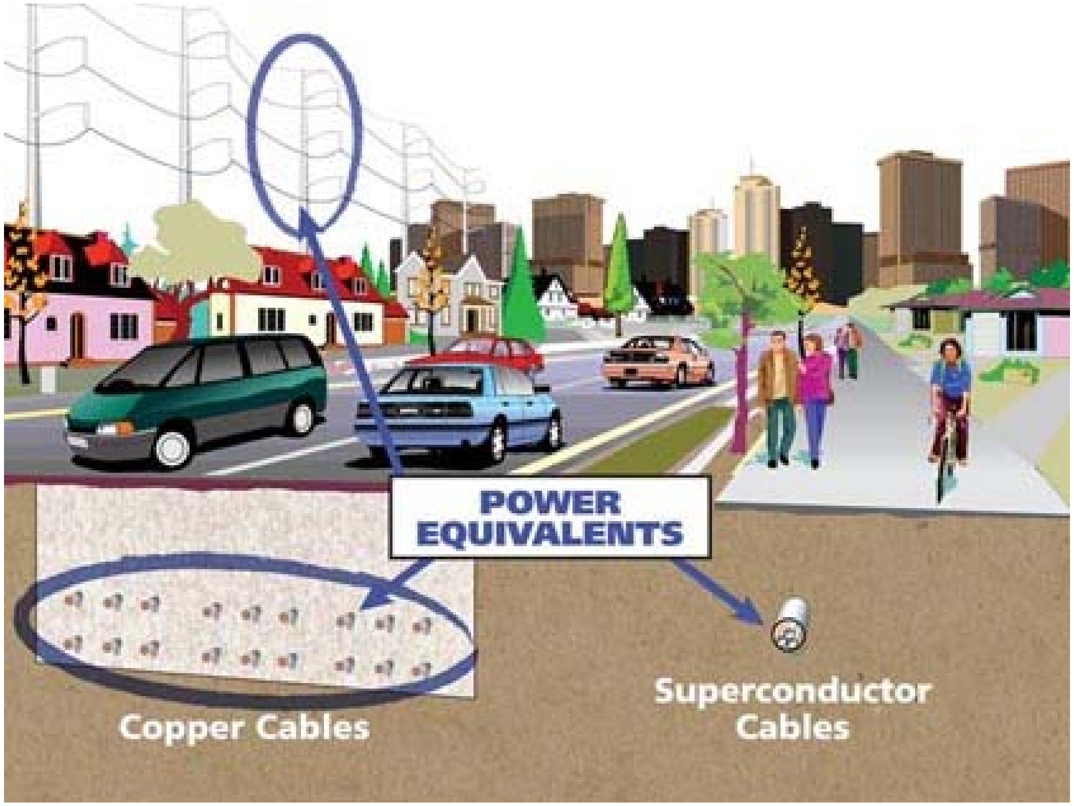
Câbles

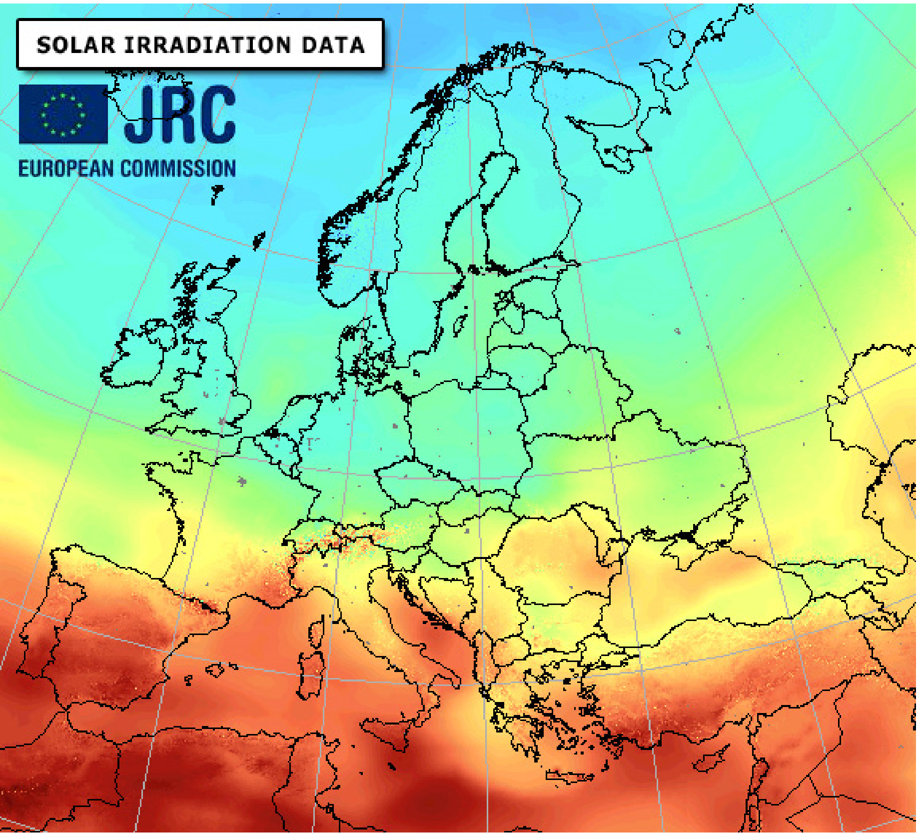


7 octobre 2010, American Superconductors



3,000 km de câbles pour la Corée du sud

Production et besoin



Regional Agenda | SDG 07: Affordable and Clean Energy | Electricity | Oil and Gas

Could the Sahara turn Africa into a solar superpower?

A promising theory, but could it work in reality?

Image: Unsplash/Nicolas Jehly

Tourner en rond tout en faisant quelque chose d'utile

André-Marie Ampère

1775 - 1836

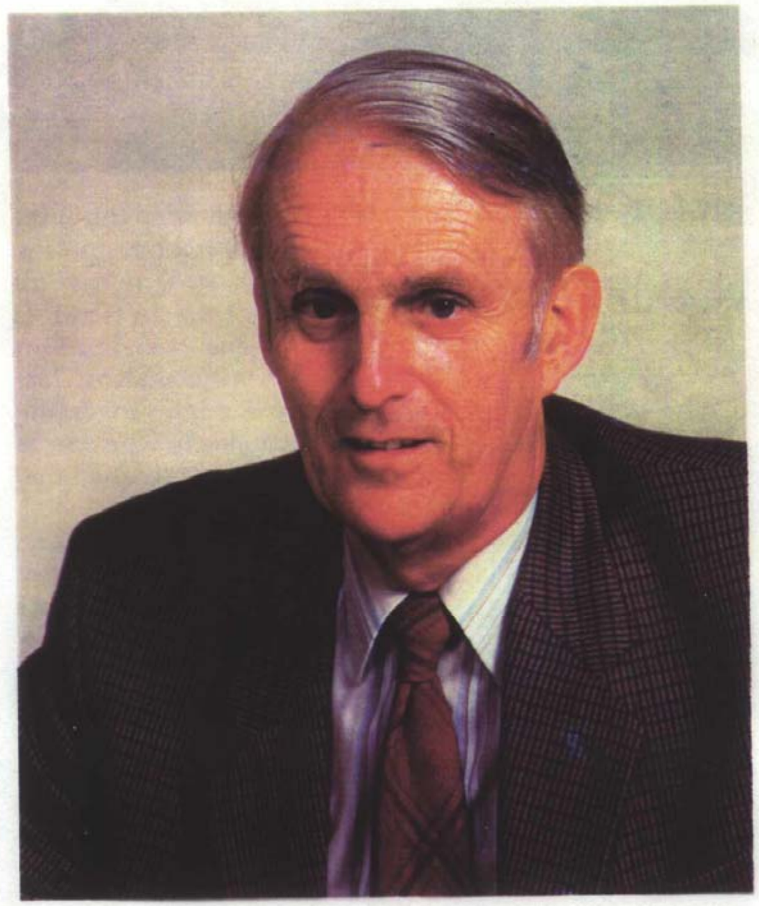
Le premier aimant supraconducteur

Martin

Wood, 1962

Supercurrents

The Superconductivity Magazine



Sir Martin Wood
Founder, Oxford Instruments

Transport des personnes

UNIVERSITÉ DE SHERBROOKE

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Maglev, aéroport de Shangai

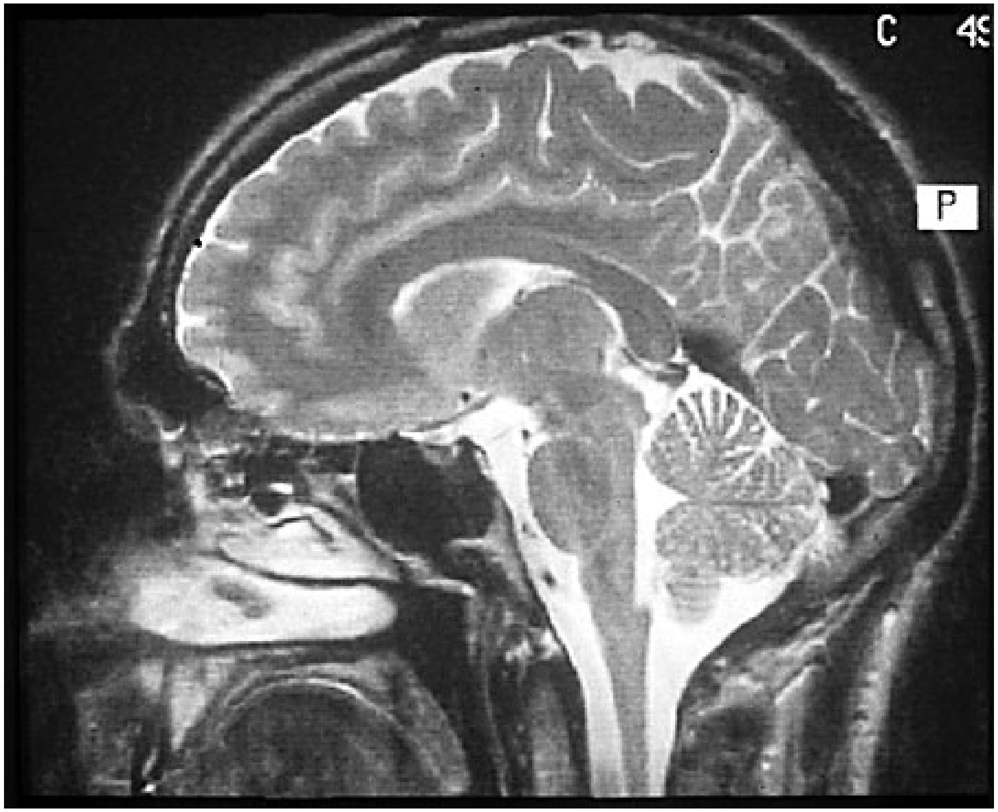
350 km/h (220 mph) en 2 minutes,
Vitesse maximale 431 km/h (268 mph).
Record 12 novembre 2006, 501 km/h (311 mph).

Test, train à lévitation magnétique, Japan Rail

JR-MLX01 maglev train at Yamanashi test track (630 km/h 2015)

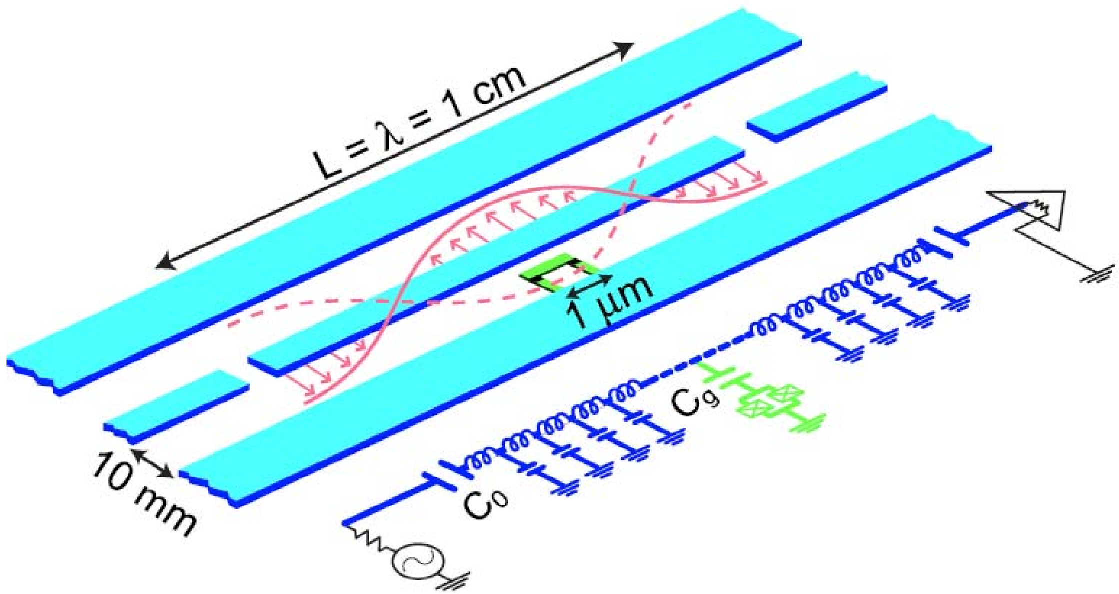
En médecine

Imagerie par résonnance magnétique



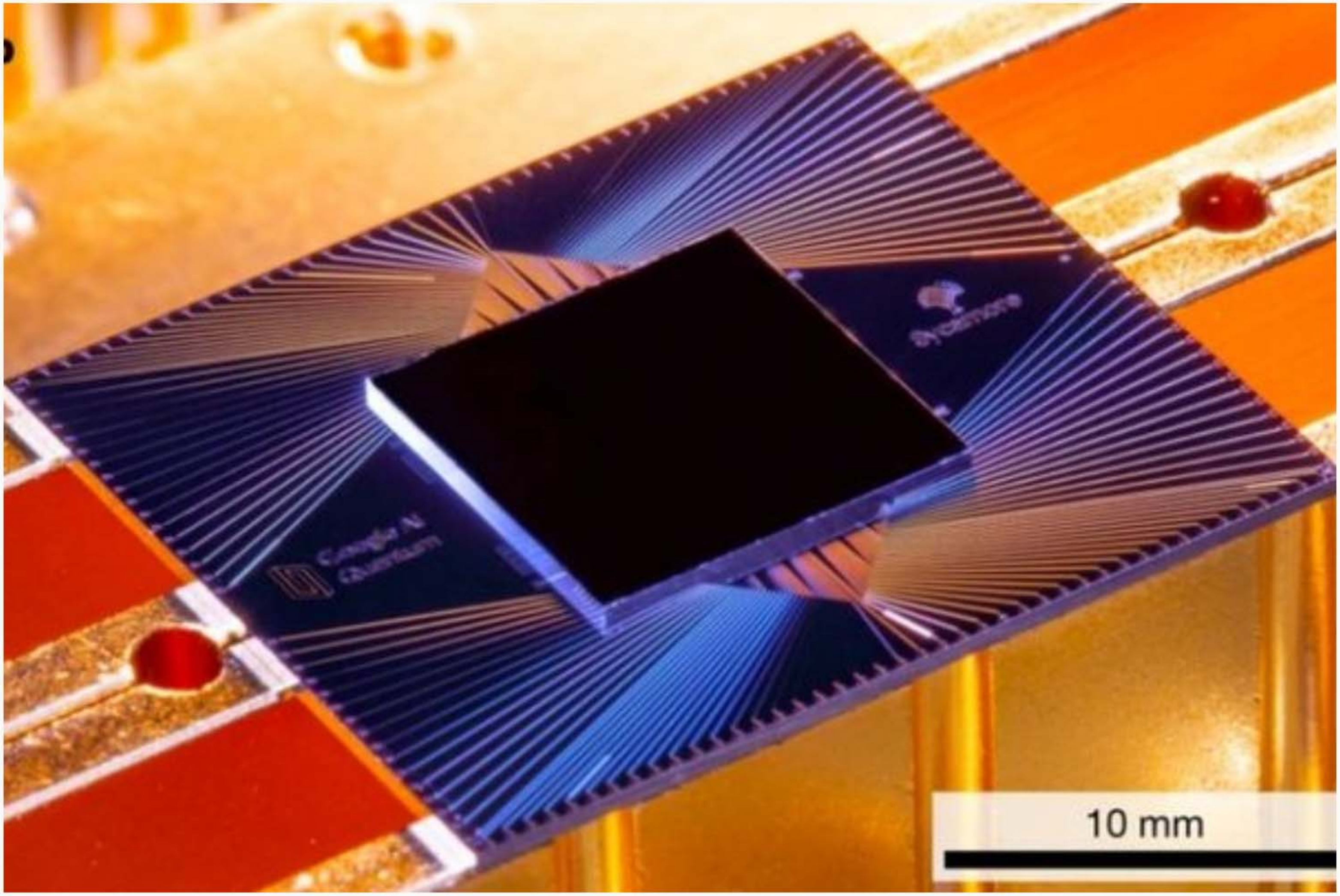
Et là où vous l'attendez le moins

L’ordinateur quantique



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

Google franchit un cap vers la «suprématie quantique»



GOOGLE

Le processeur Sycamore parvient à réaliser un calcul en 200 secondes, là où un supercalculateur «classique» aurait mis «environ 10 000 ans».

De retour à la lévitation

Michael Faraday

1791-1867

Induction

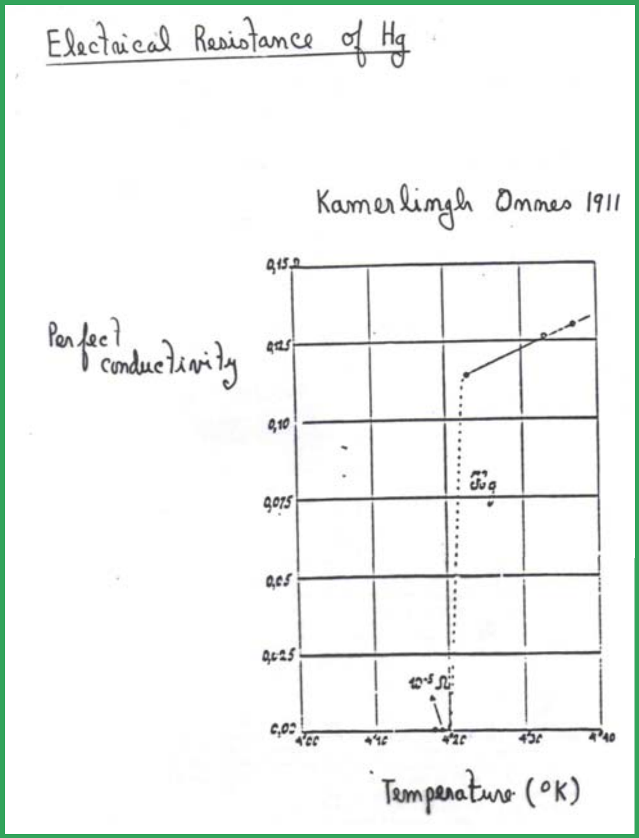
R. Ochsenfeld (1900-1992)

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

http://kvphysics.blogspot.com/

Deux propriétés importantes

1. Résistance zéro (si **B=0**)



2. Diamagnetism

Un état de la matière

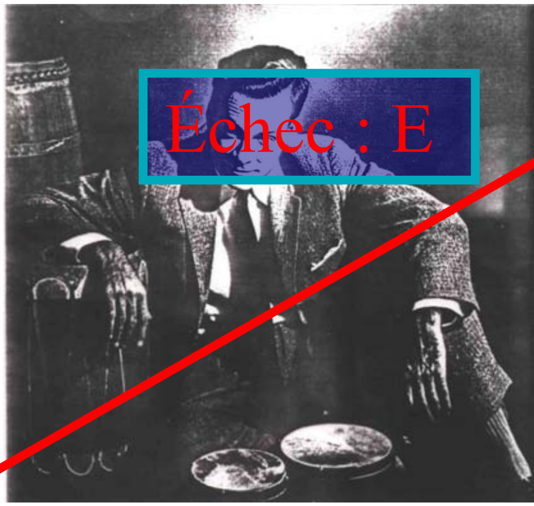
par Alexis Reymbaut, 2014

Comment explique-t-on la supraconductivité?

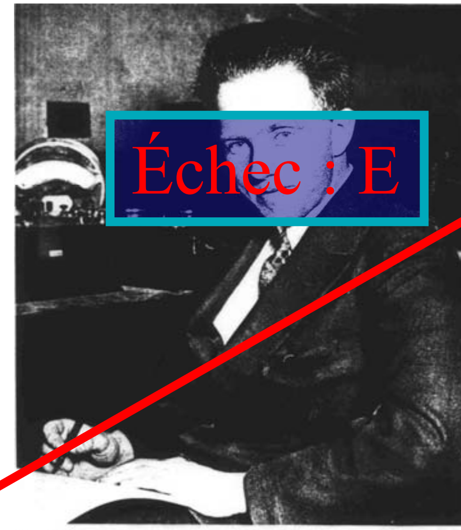
Théorème de Bloch, 1930

- On peut prouver que toutes les théories de la supraconductivité sont fausses.
- Feynman: personne n’est assez brillant pour trouver la solution.

Quelques essais infructueux



Feynman



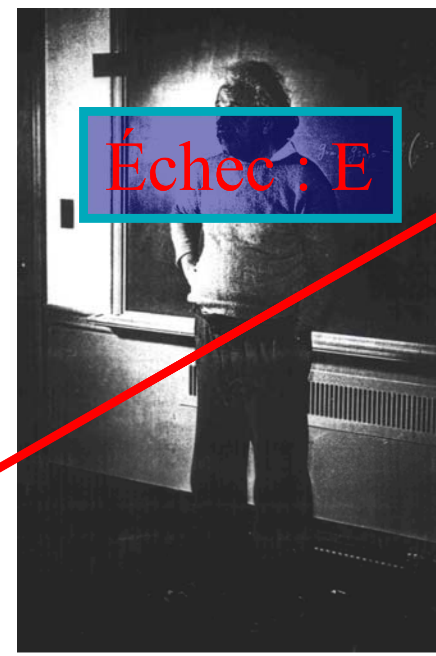
WERNER HEISENBERG (1901–) introduced matrix mechanics, which, like the Sch

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



BCS 1957

Comportement quantique à l'échelle macroscopique

Leon Cooper

John Bardeen*

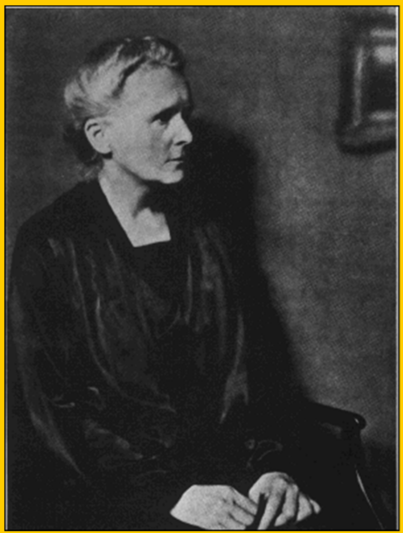
Robert Schrieffer

Prix Nobel : 1972

- John Bardeen :
- Le seul à avoir obtenu deux prix Nobel en physique!!!

Invention : TRANSISTOR!

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



Marie Curie:

1903 Physique with H.A. Becquerel

1911 Chimie (seule)

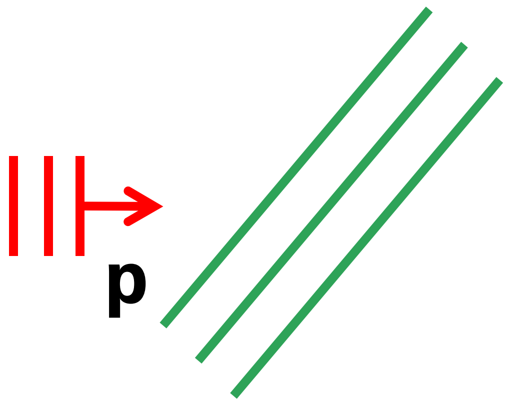
Ce qui était connu

- La résistance s'annulle
- L'effet Meissner
- Transparent aux microondes basse fréquence
- Effet isotopique

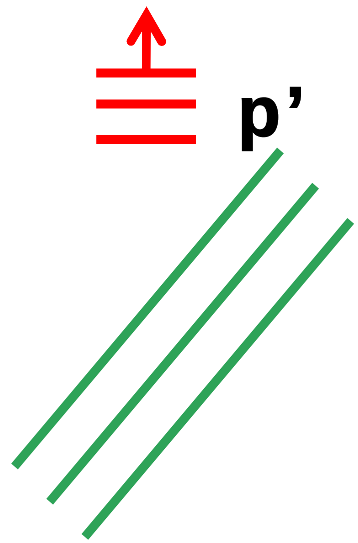
http://users-phys.au.dk/philip/pictures/physicsfigures/physicsfigures.html

L’explication: Un premier phénomène: les électrons peuvent s’attirer

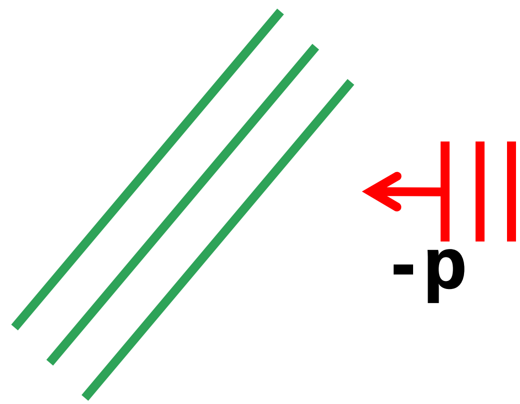
Mécanisme d’attraction dans l’état métallique



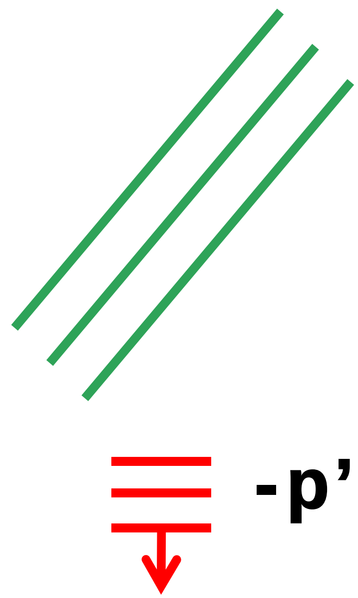
Mécanisme d'attraction dans l'état métallique



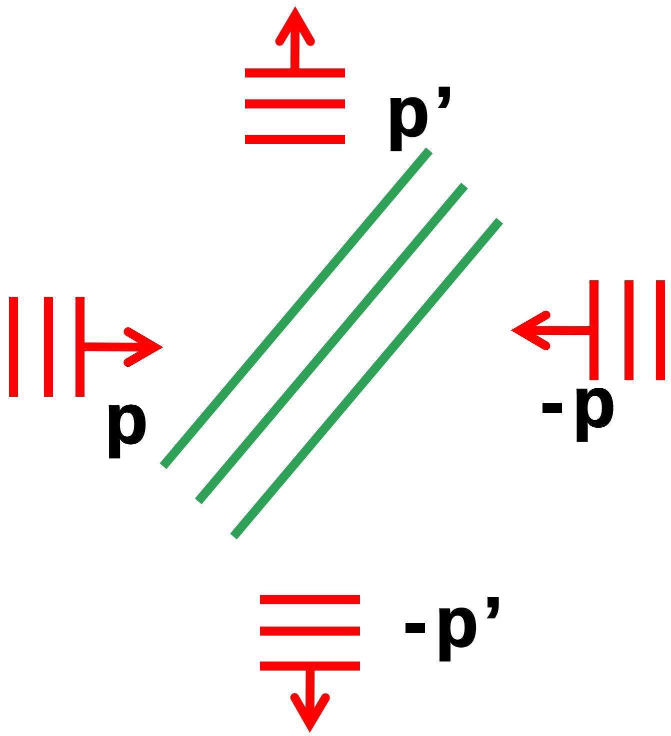
Mécanisme d'attraction dans l'état métallique



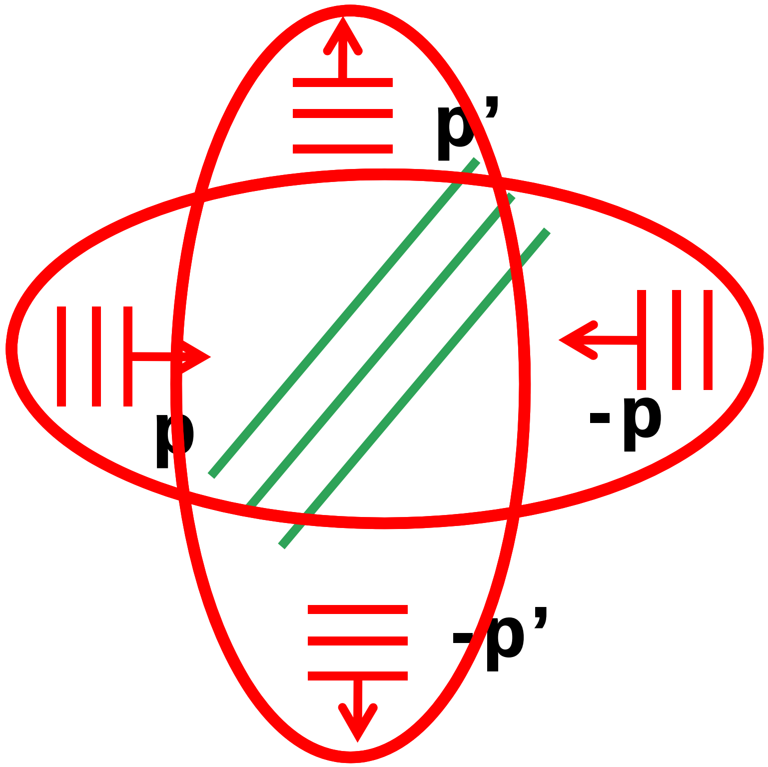
Mécanisme d’attraction dans l’état métallique



Mécanisme d'attraction dans l'état métallique



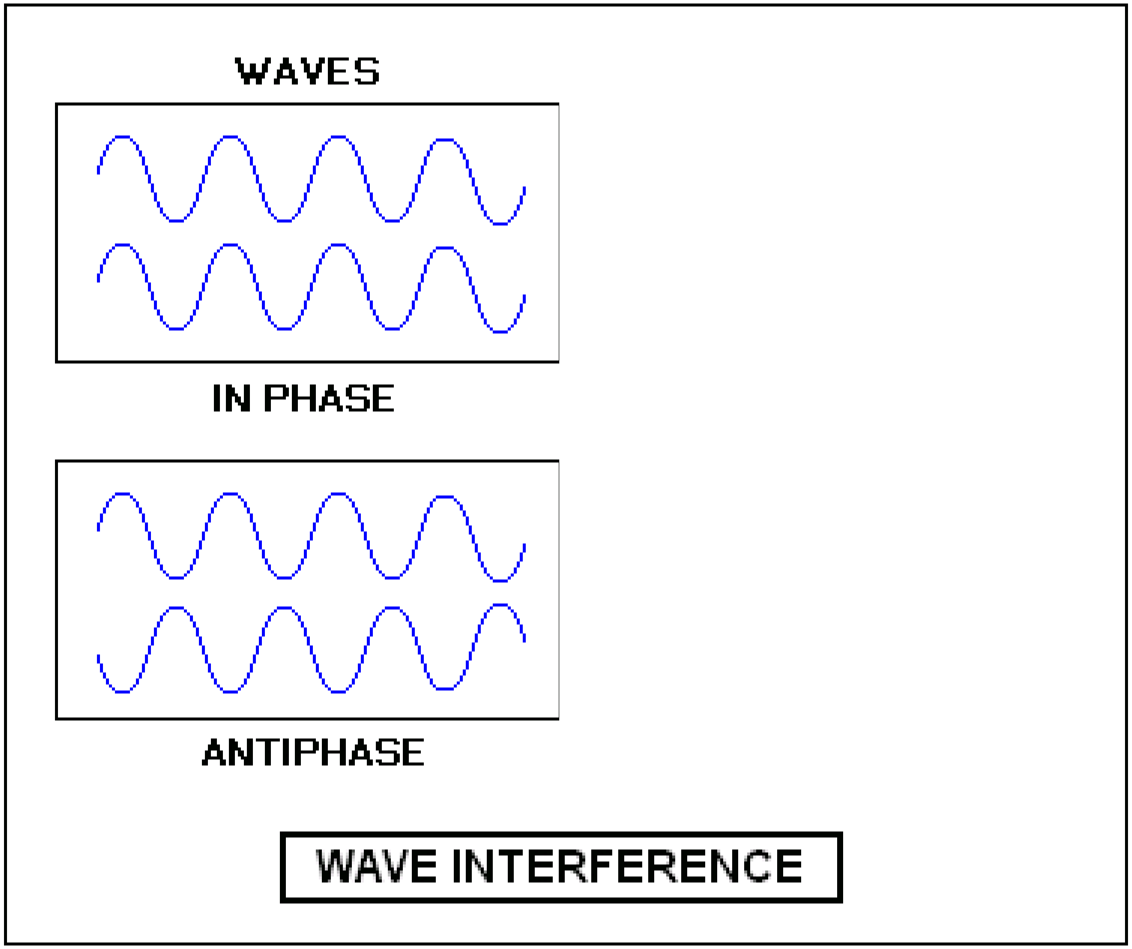
Mécanisme d’attraction dans l’état métallique



Paires de Cooper

Un deuxième phénomène, la cohérence

Ondes



Une analogie

- Symétrie brisée
- Rigidité

Rigidité de phase, état cohérent

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

La supraconductivité partout

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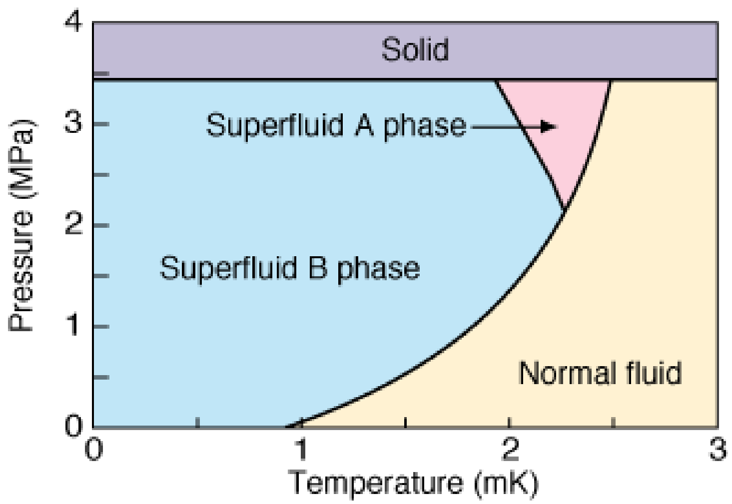
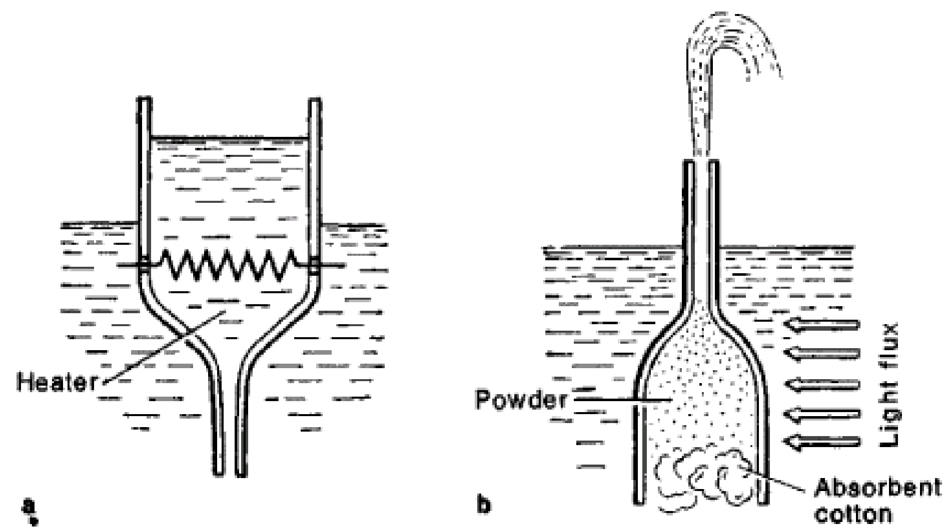
^{3}He superfluide





Le noyau des atomes (Rutherford 1911)

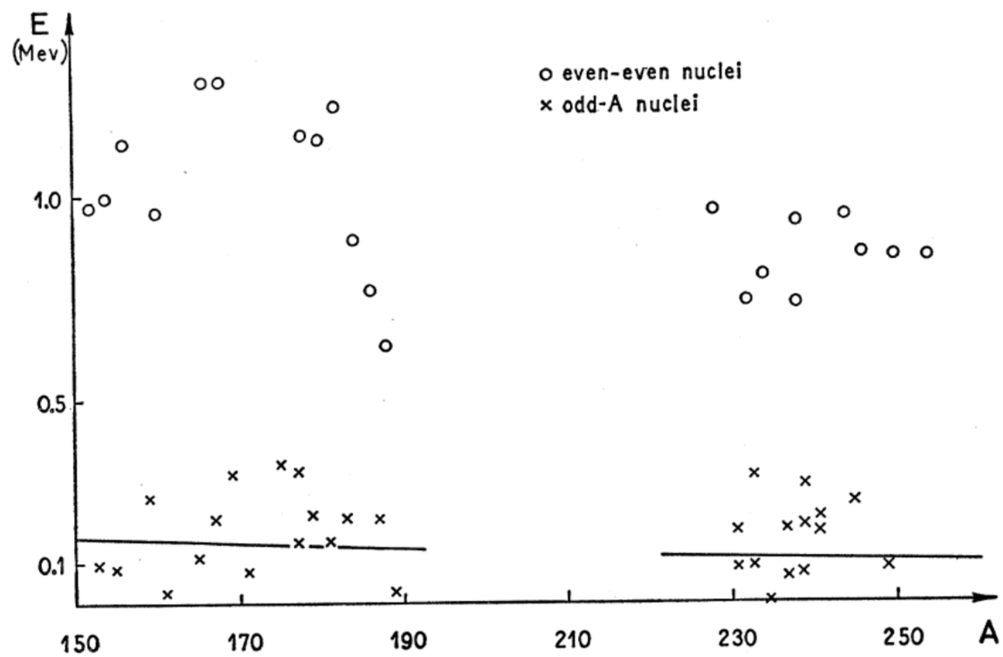
PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

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.



Les étoiles à neutron

La nébuleuse du crabe (4 juillet 1054) en bleu et blanc
Credit & Copyright: Jay Gallagher (U. Wisc.), WIYN, AURA, NOAO, NSF

Les atomes ultra-froids

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

nature

LETTERS

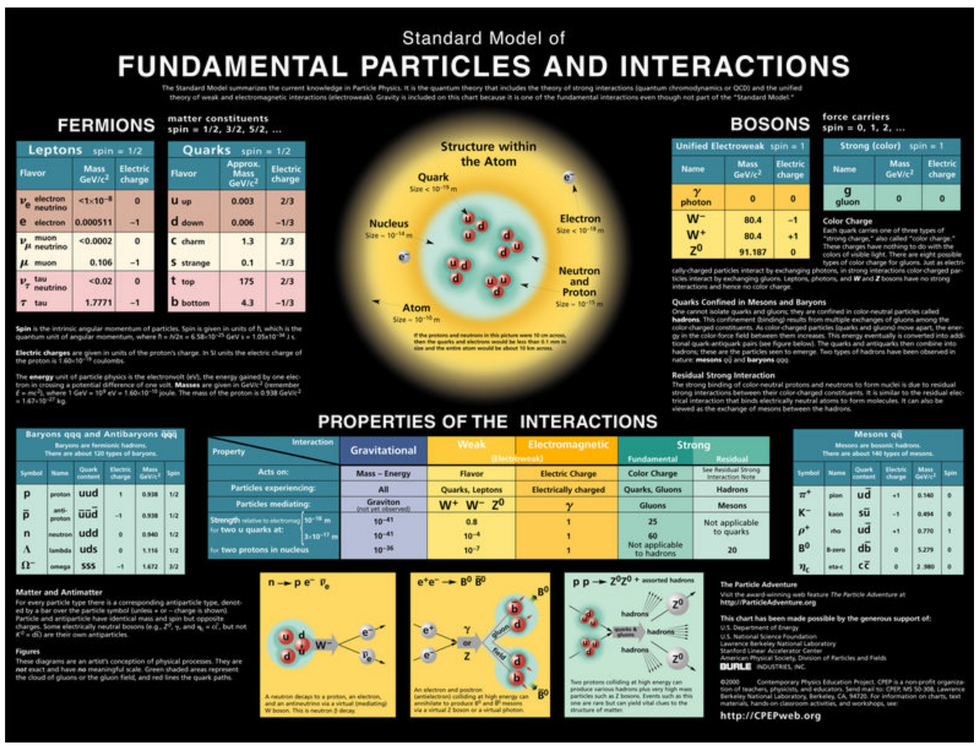
Evidence for superfluidity of ultracold fermions in an optical lattice

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]

Le modèle standard des particules élémentaires (unification des interactions électro-faibles)

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

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

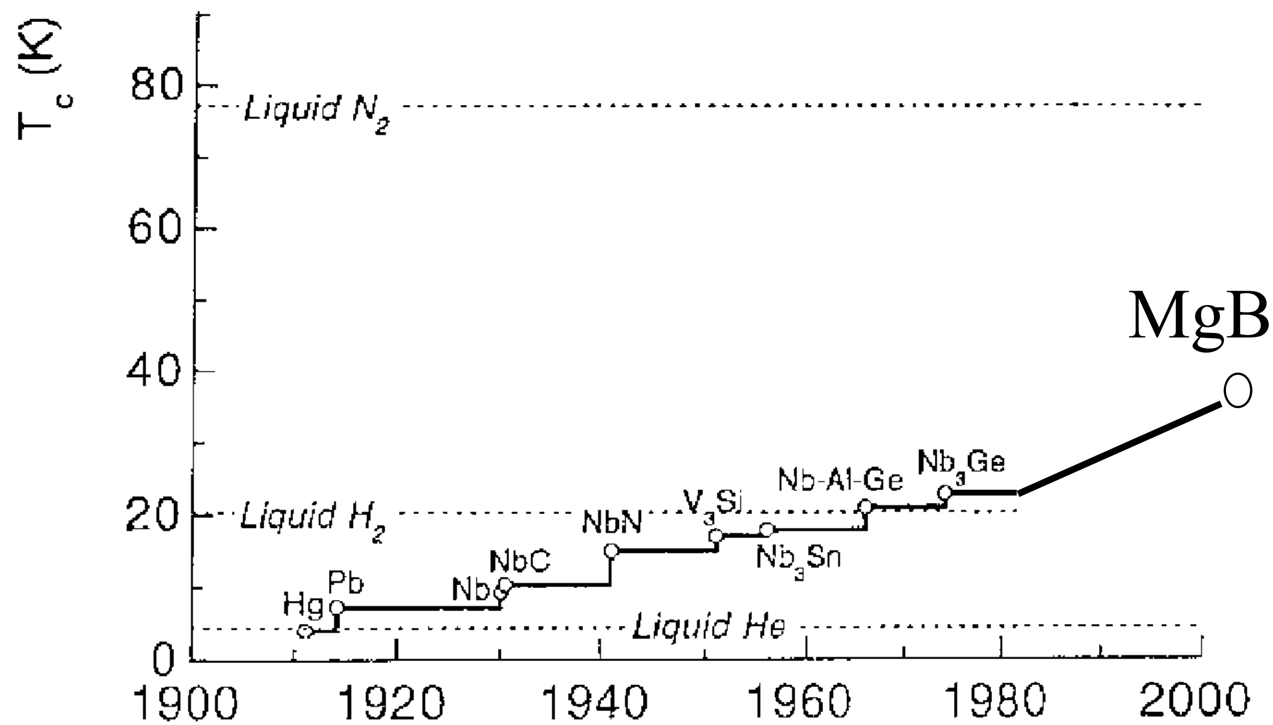


La quête de nouveaux matériaux

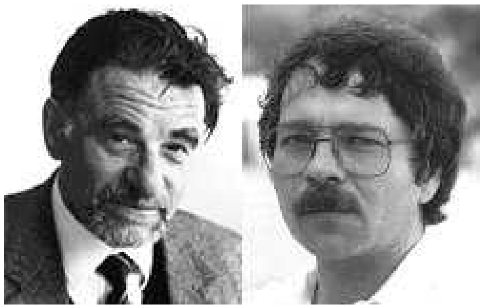
- Le but: la température de l’azote liquide!

On croyait généralement que (1952)

- Métaux de transition (pas Cu,Au,Fe)
- Cubique
- Ne pas s'approcher de
  - O
  - Aimants
  - Isolants



Janvier1986



OSNI

1986 : Bednorz et Muëller, IBM Zurich

La-Ba-Cu-O $T_c \sim 30\text{-}40K$

Effet Meissner ?

Ça va vite…

- Boston, "Materials Research Society" Décembre 1986
  - Koitchi Kitazawa et Shoji Tanaka Tokyo convainquent tout le monde.
- 16 février1987, Houston:
  - Conférence de presse par Paul Chu pour annoncer la découverte de *Y-Ba-Cu-O*
  - $T_c = 93\ K\ (vs\ 77\ K)$

March meeting APS, 1987

- Titre du New York Times le lendemain:
"The Woodstock of Physics"

- 3000 personnes jusqu'à 3 heures du matin

"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"

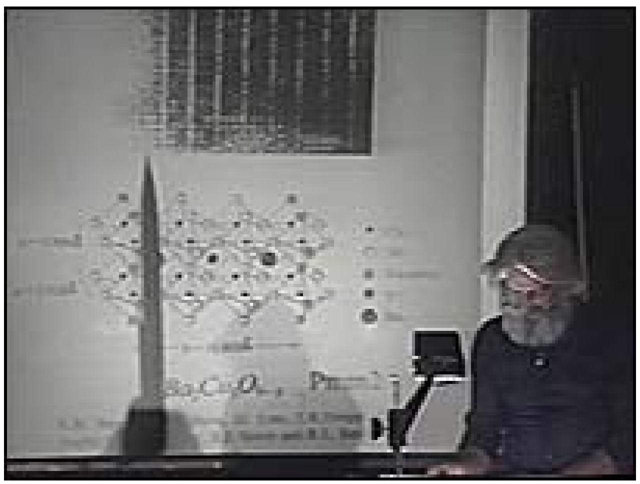
15-18 Aug. 1969
500,000 participants

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.

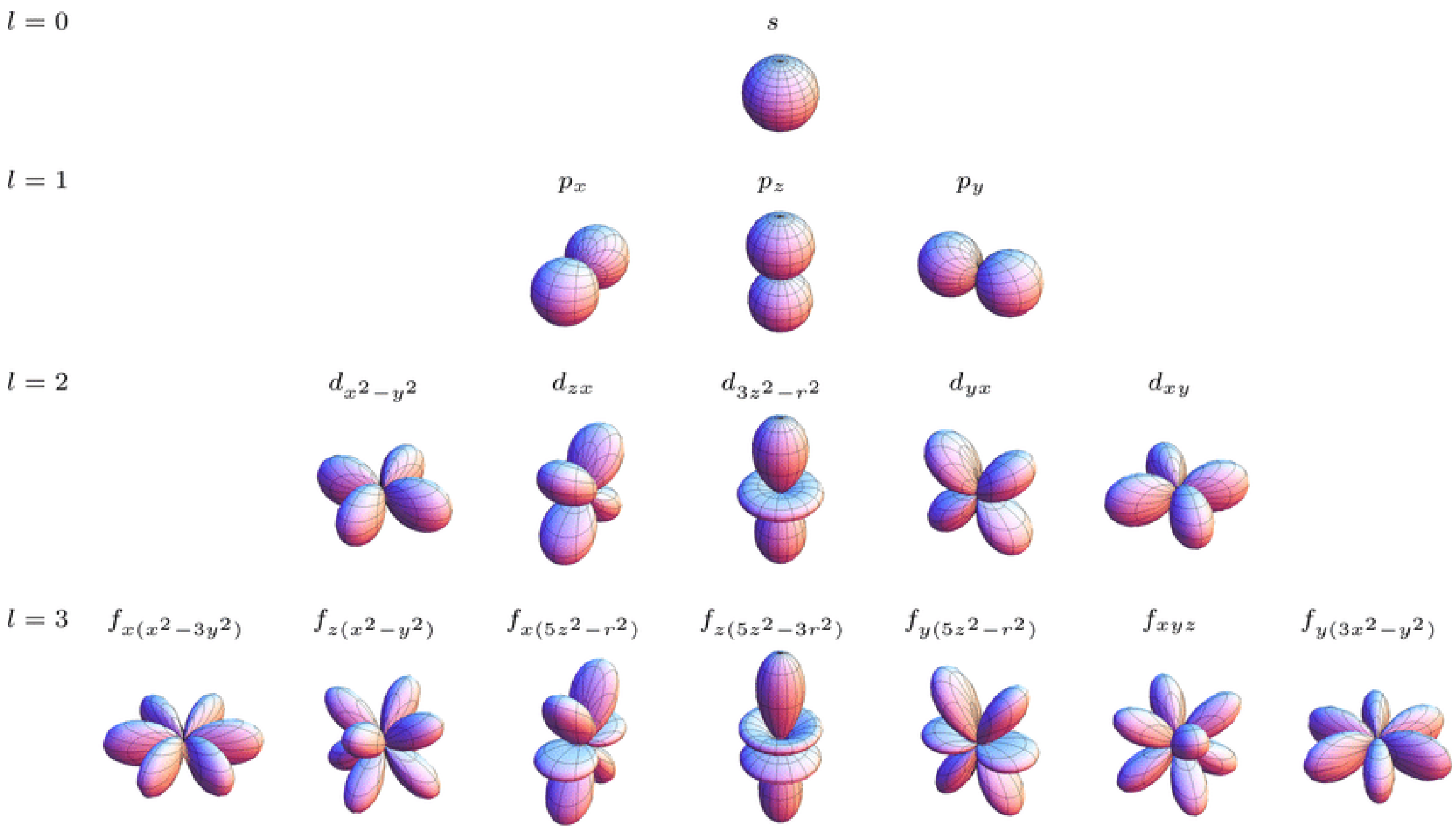
AMERICAN INSTITUTE OF PHYSICS



Ce qu'il y a de particulier avec ces supraconducteurs:

Ce qu'il y a de particulier

- Il y a des paires de Cooper, mais les vibrations cristallines n'expliquent pas leur présence.
- Les paires sont dans un état « *d* »



Structure atomique

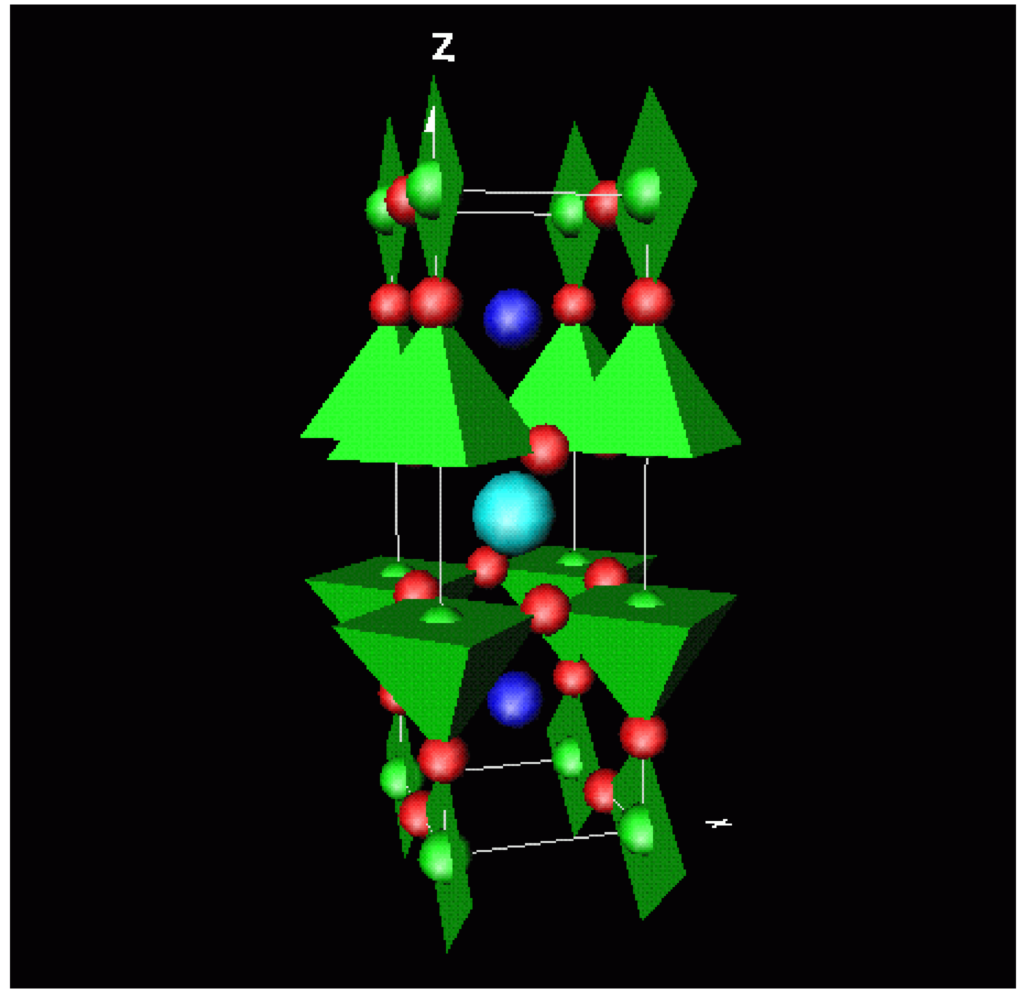
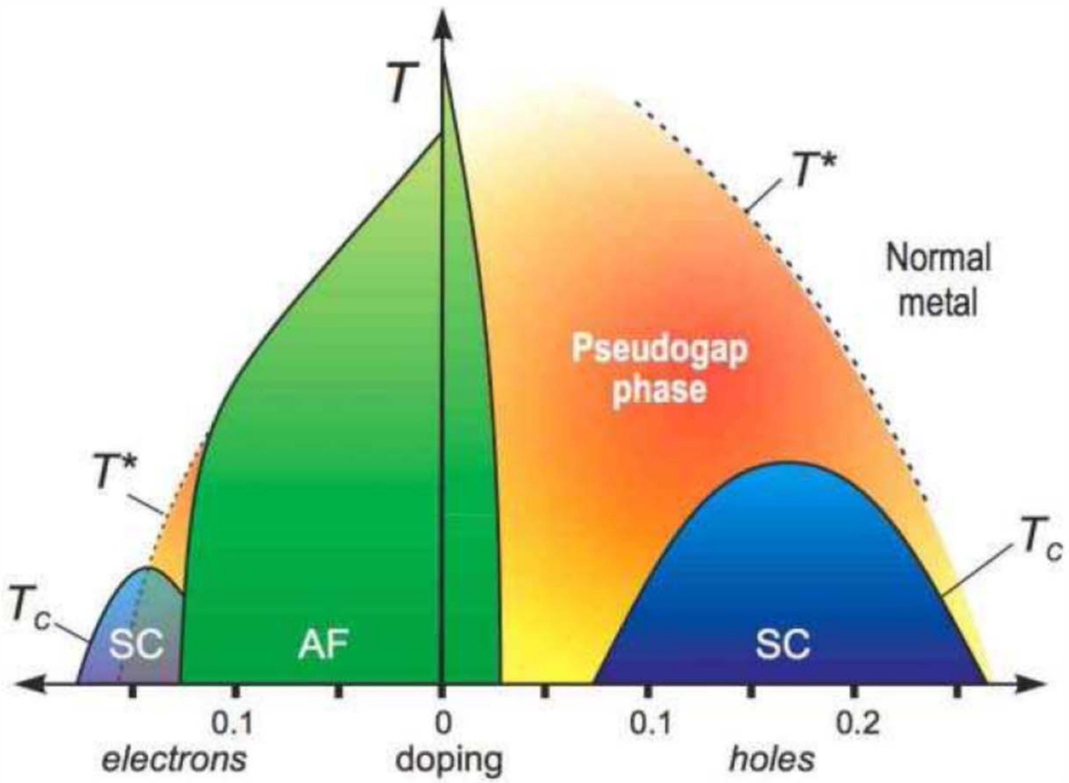


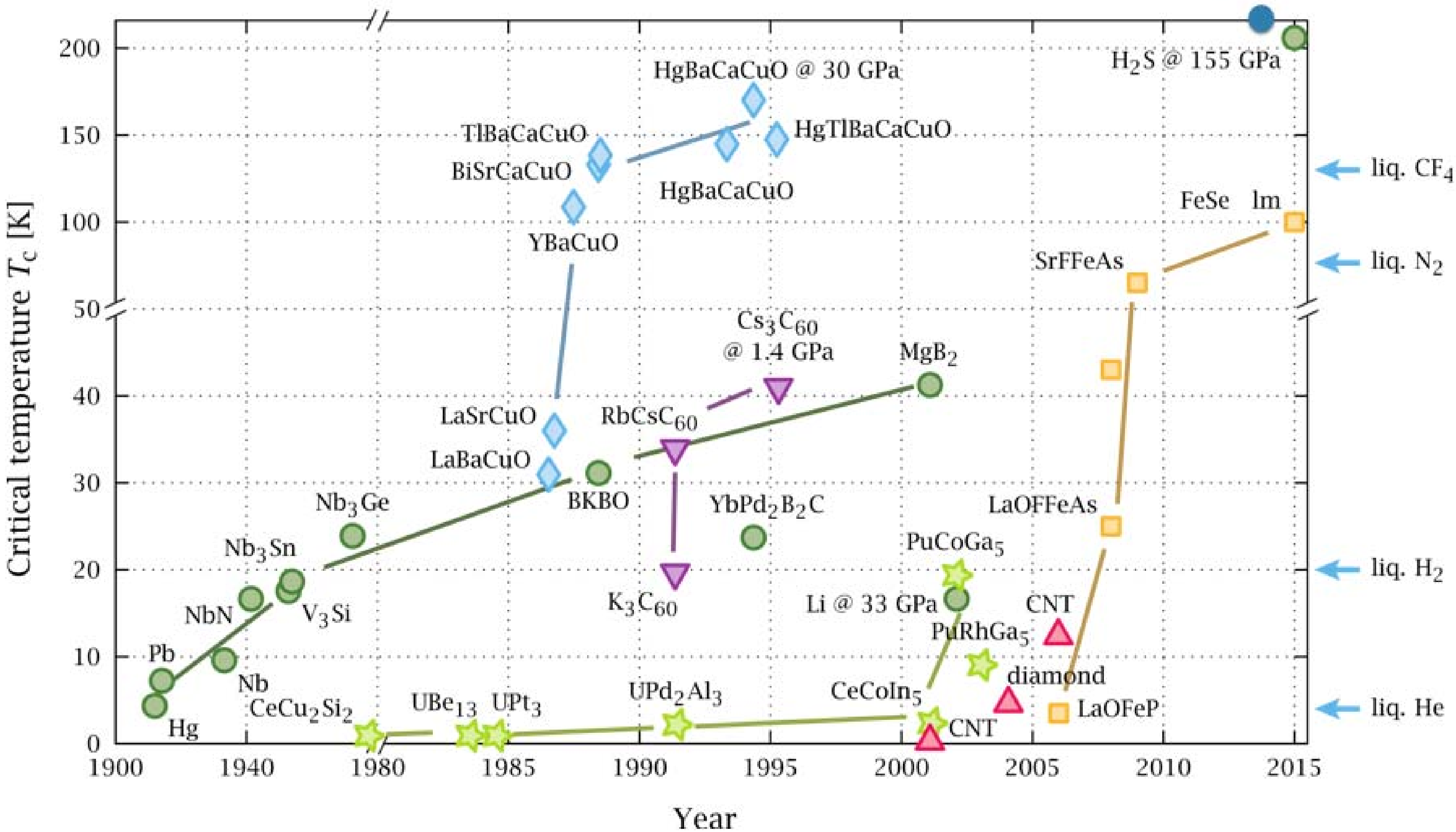
Diagramme de phase



Fischer et al. Rev. Mod. Phys. 79, 353 (2007)

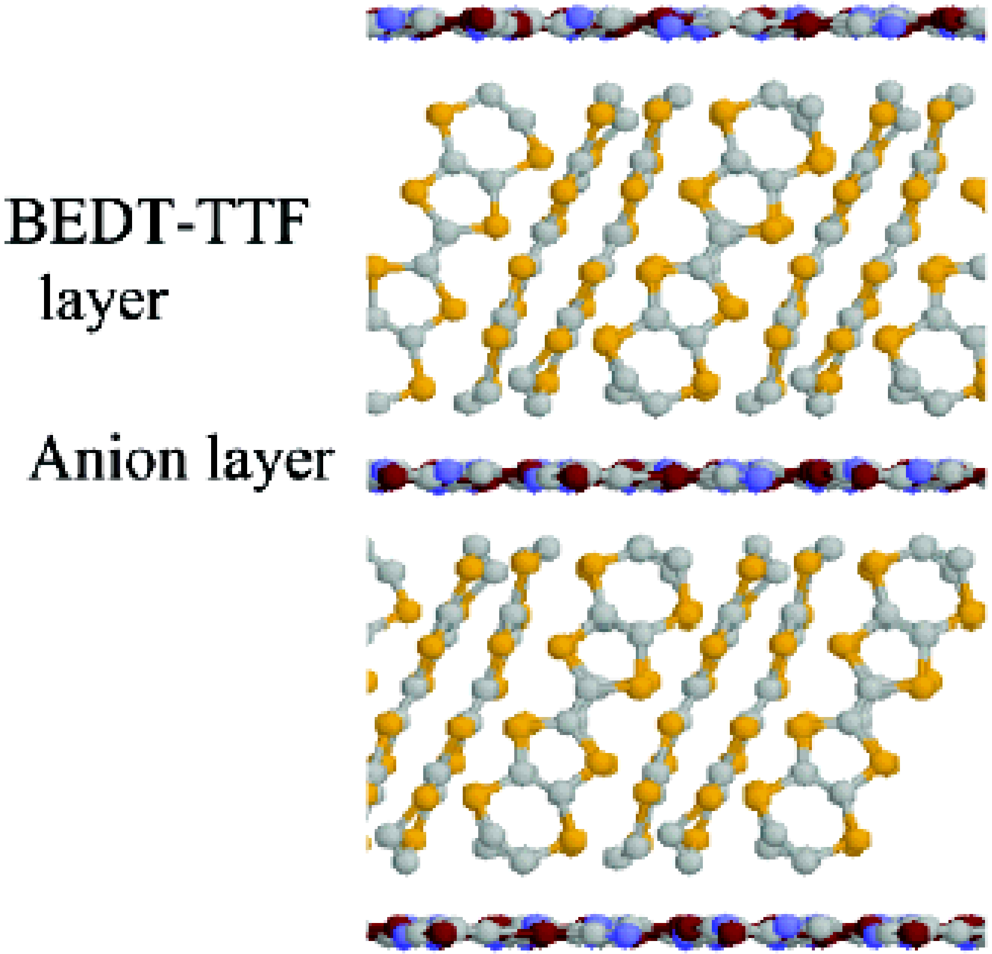
Température critique en fonction de l'année

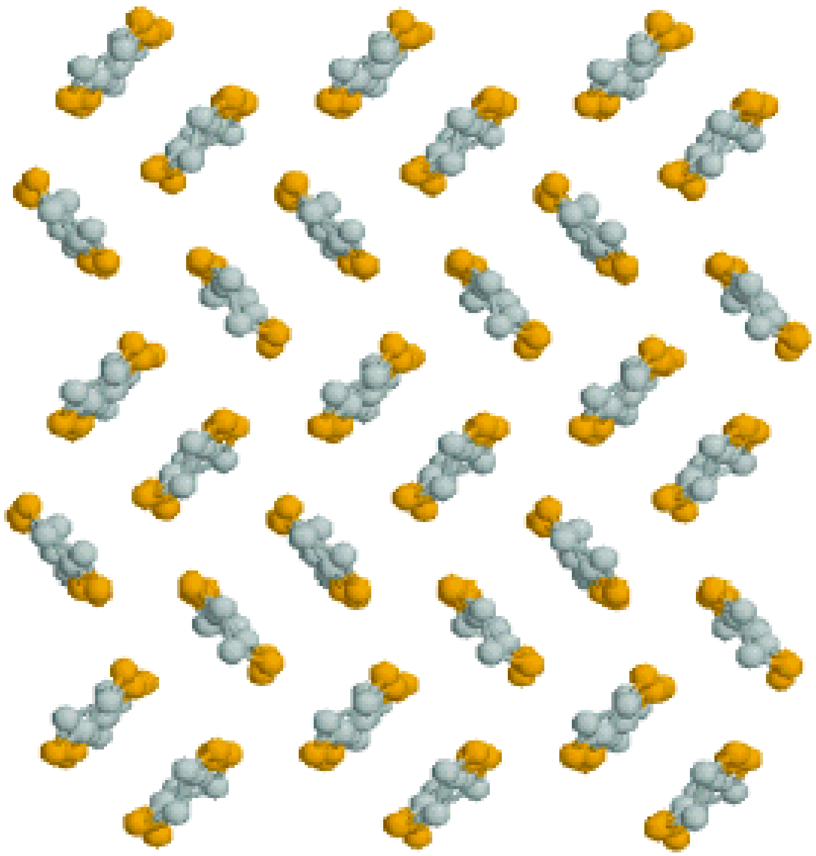
LaH10 Tc=250K @155GPa (2019)



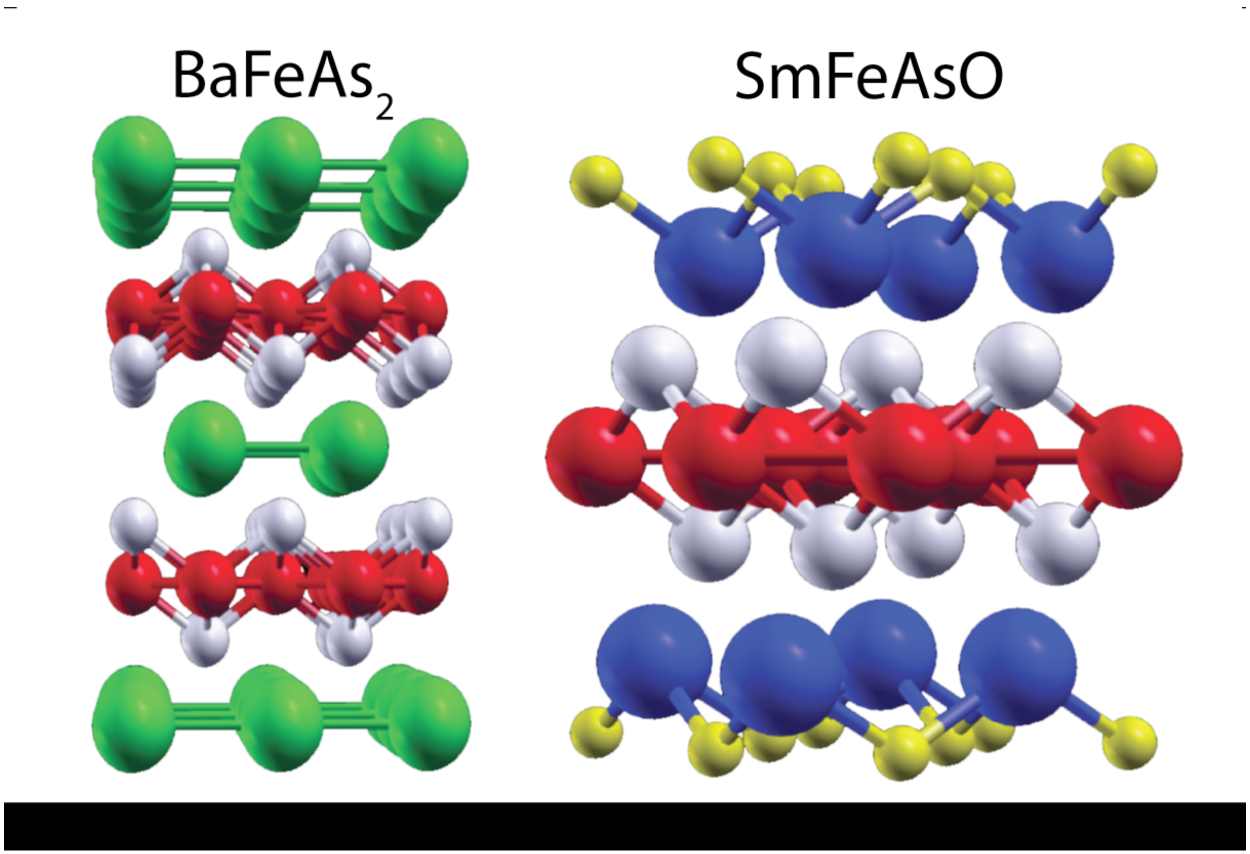
Pia Jensen Ray, Mémoire de Maîtrise

Conducteurs organiques en couches (κ–BEDT-X)





Pnictures (2008)



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

Couches de graphène à l'angle magique

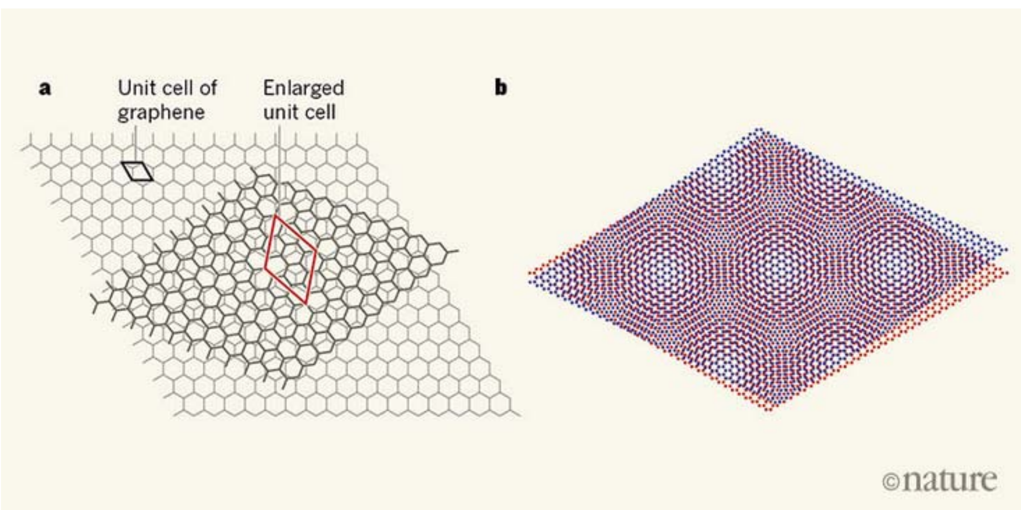
nature Accelerated Article Preview

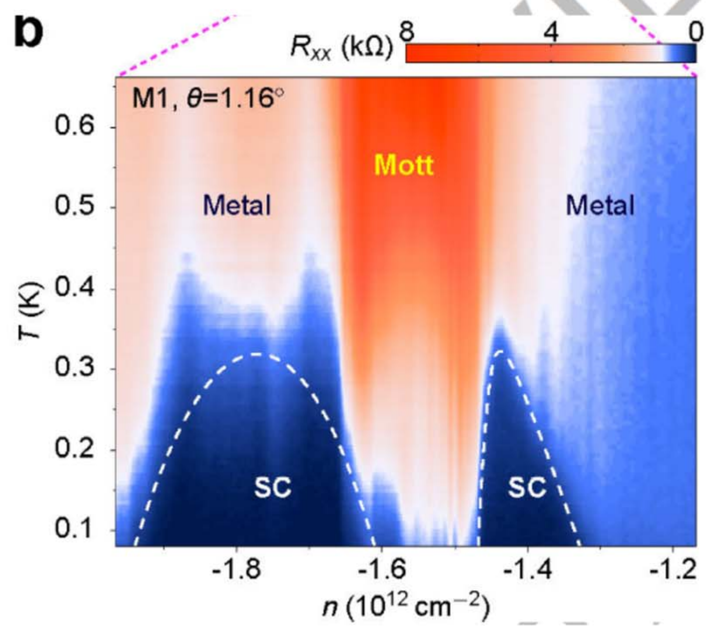
ARTICLE

doi:10.1038/nature26160

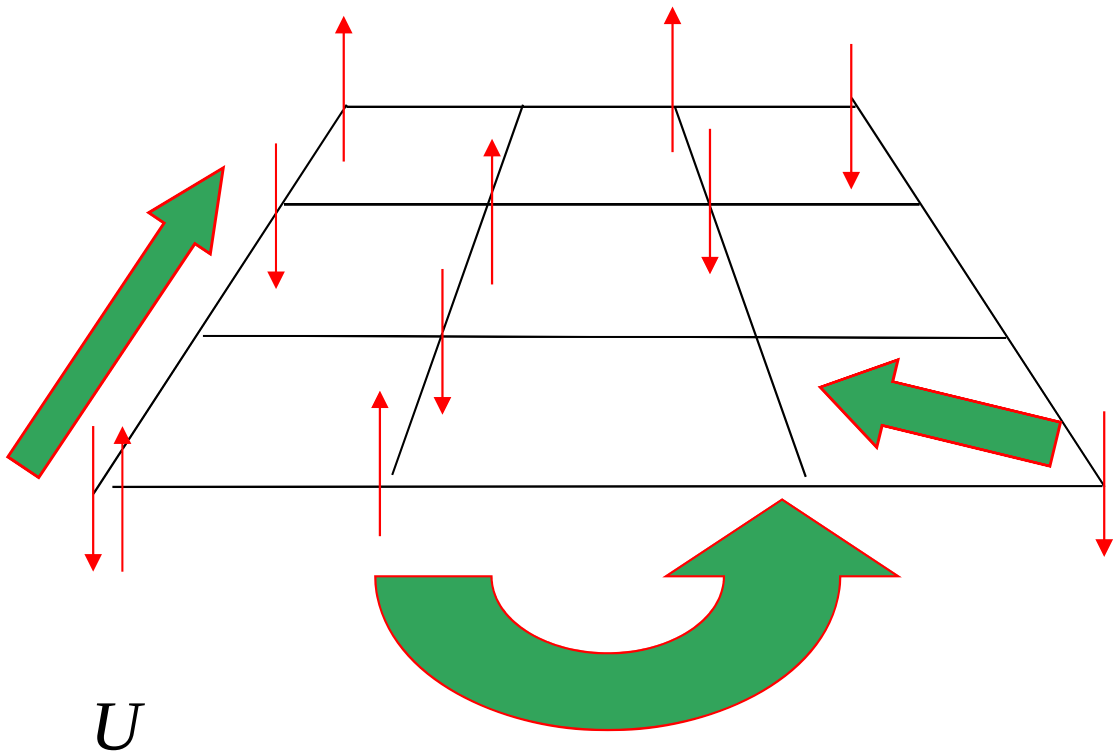
Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao, Valla Fatemi, Shiang Fang, Kenji Watanabe, Takashi Taniguchi, Efthimios Kaxiras & Pablo Jarillo-Herrero

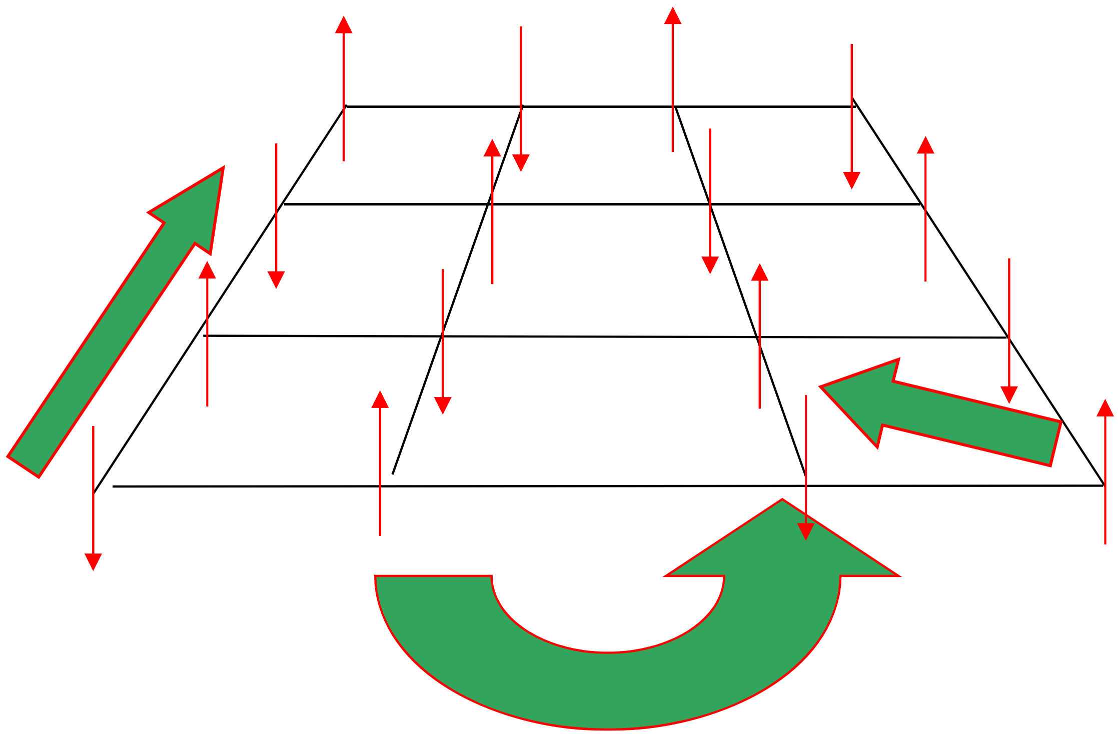




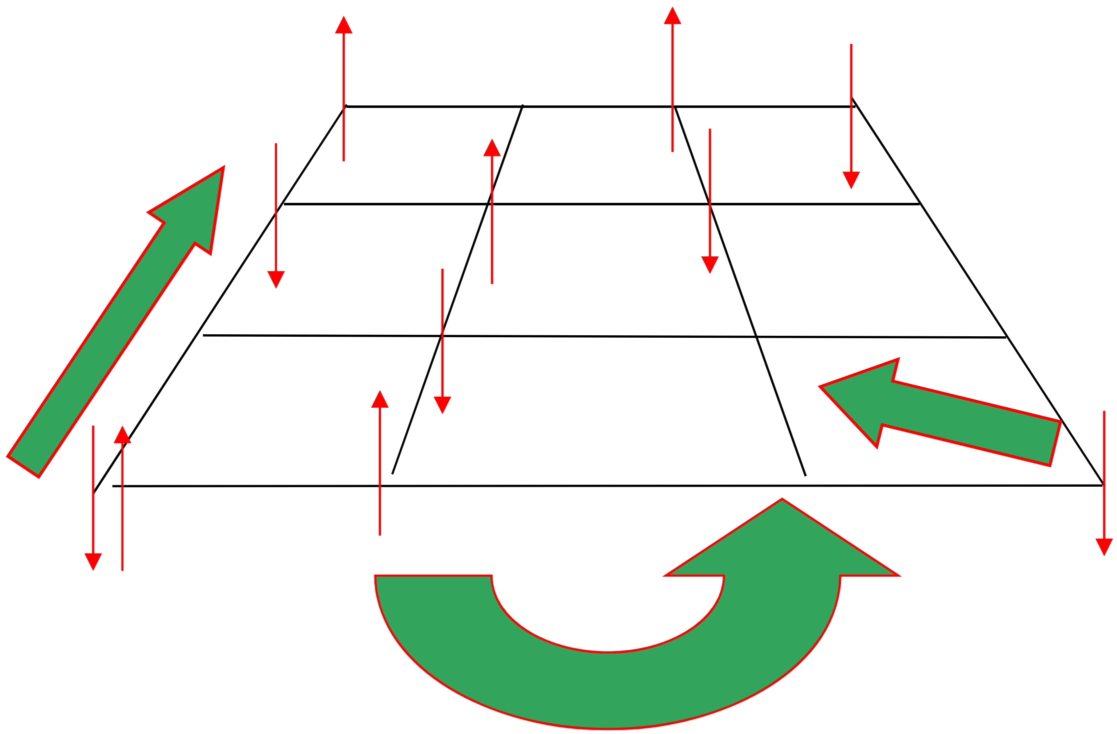
Pourquoi est-ce si difficile à comprendre?



Isolant



Pourquoi est-ce si difficile à comprendre?



Quoi faire?

Quoi faire?

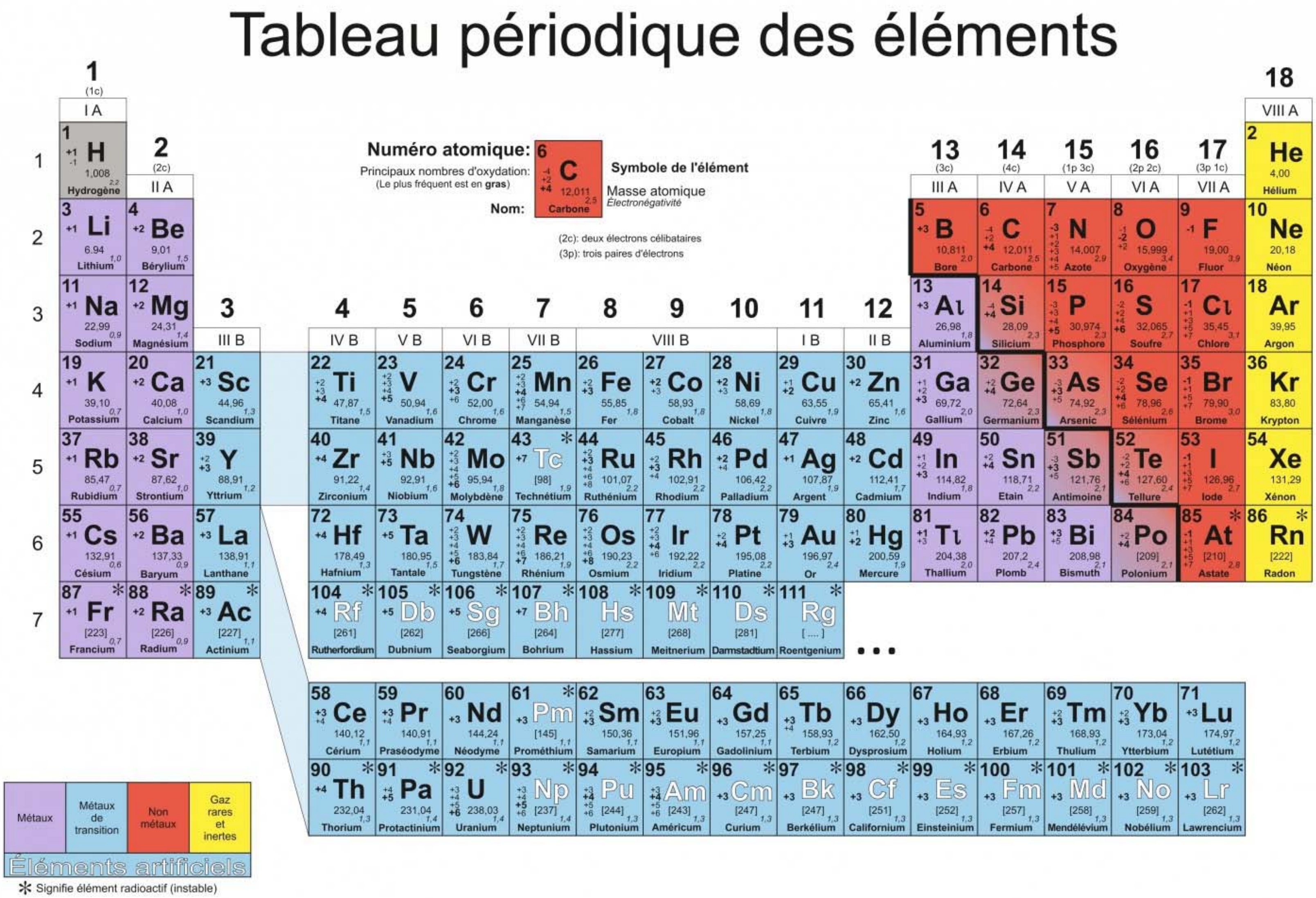
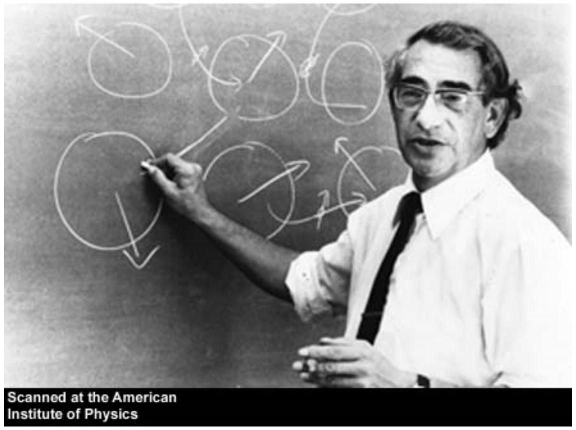
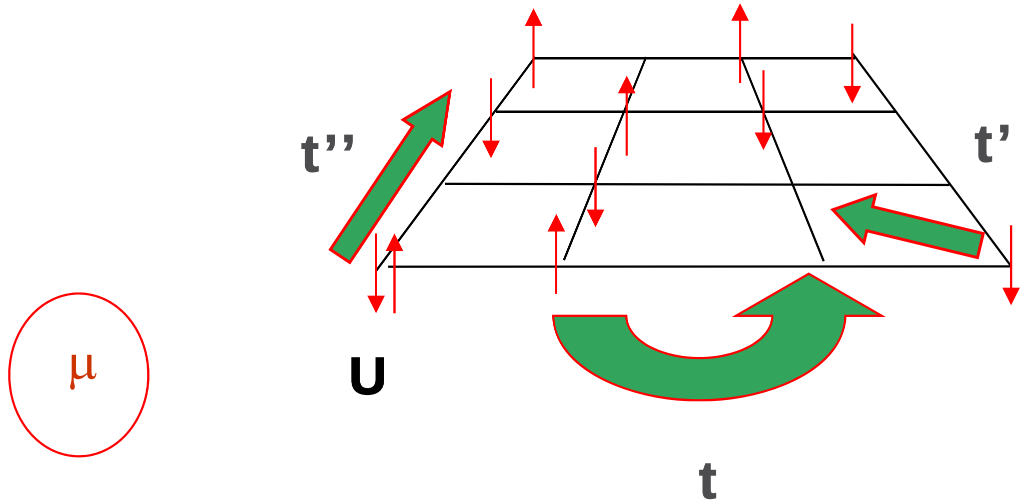


Tableau périodique des éléments
Numéro atomique:
Principaux nombres d'oxydation:
(Le plus fréquent est en gras)
Nom:
Symbole de l'élément
Masse atomique
Électronégativité
(2c): deux électrons célibataires
(3p): trois paires d'électrons
Métaux
Métaux de transition
Non métaux
Gaz rares et inertes
Éléments artificiels
* Signifie élément radioactif (instable)

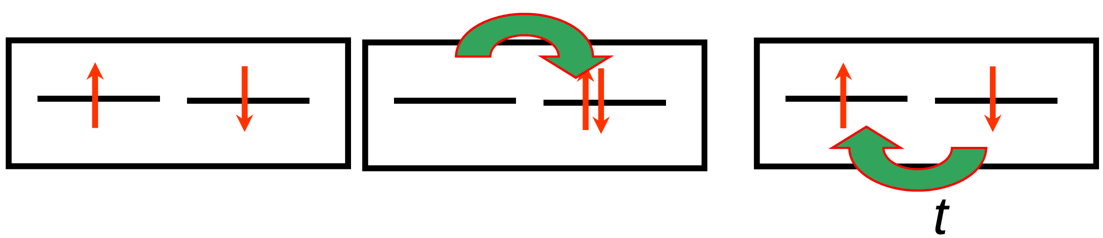
Le modèle de Hubbard





1931-1980

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



Modèle effectif, Heisenberg: *$J = 4t^2 / U$*

Attn: Isolant à transfert de charge

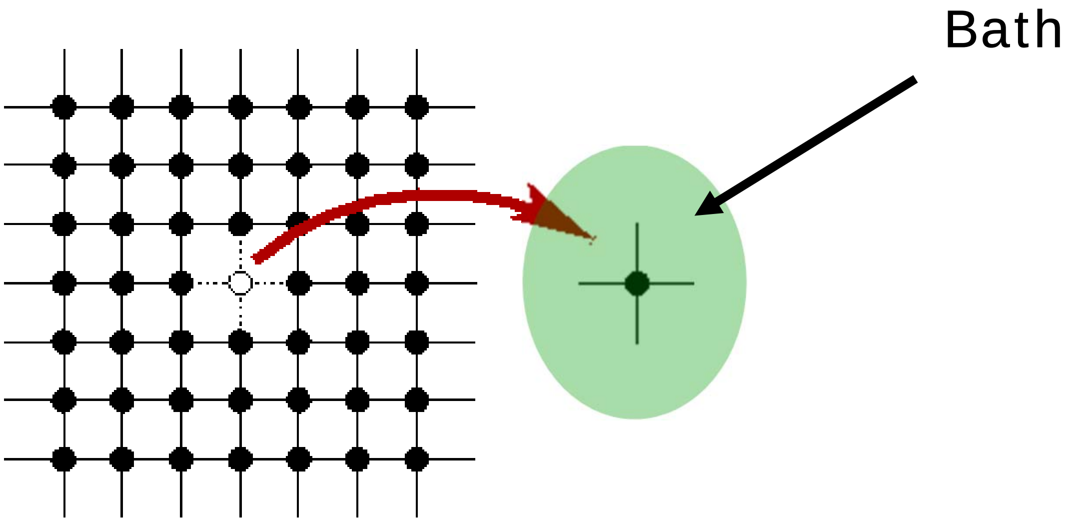
Méthode

- Théorie de champ moyen dynamique
  - amas
- Concept: corrélations atomiques localisées, cohérentes avec les aspects délocalisés

REVUES
Maier, Jarrell et al., RMP. (2005)
Kotliar *et al.* RMP (2006)
AMST *et al.* LTP (2006)

Hettler *et al*, PRB 1998
Lichtenstein *et al.*,PRB 2000
Kotliar *et al.*, PRB 2000
M. Potthoff, EJP 2003

Théorie de champ moyen dynamique
Les débuts en *d = infini*

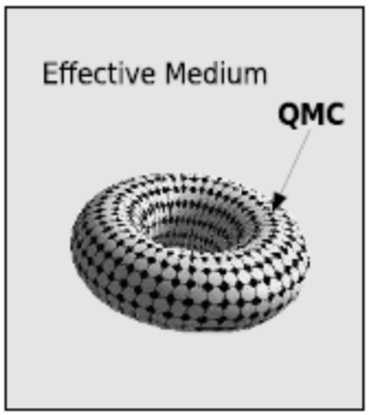


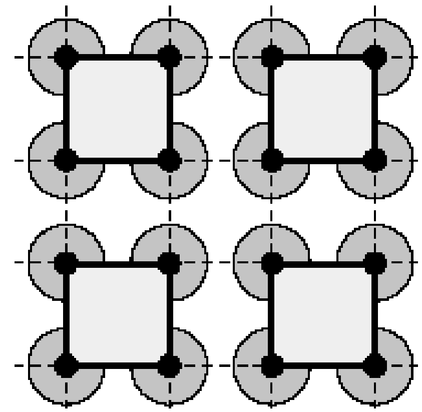
W. Metzner and D. Vollhardt, PRL (1989)
A. Georges and G. Kotliar, PRB (1992)
M. Jarrell PRB (1992)

DMFT, (*d = 3*)

2d Hubbard: Amas quantiques

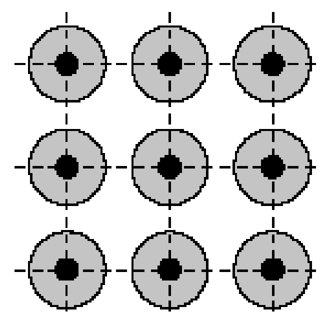
C-DMFT





DCA

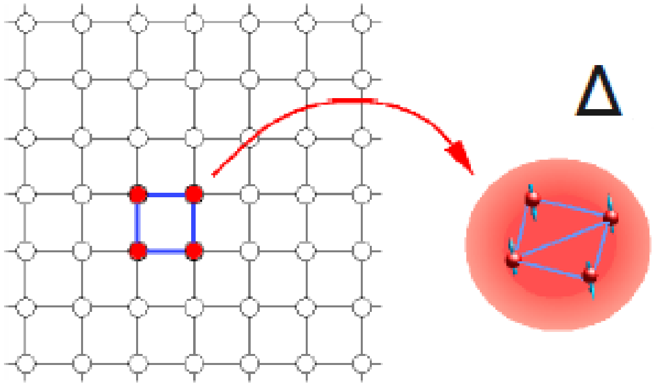
DMFT



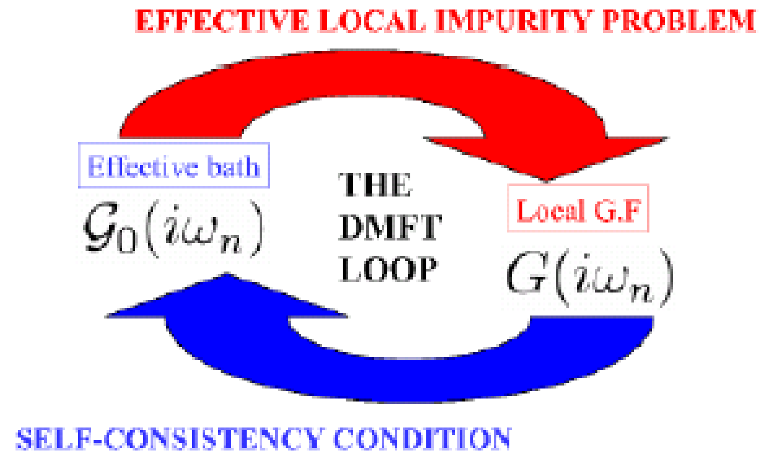
Hettler …Jarrell…Krishnamurty PRB **58** (1998)
Kotliar et al. PRL **87** (2001)
M. Potthoff *et al*. PRL **91,** 206402 (2003).

REVIEWS
Maier, Jarrell et al., RMP. (2005)
Kotliar *et al.* RMP (2006)
AMST *et al.* LTP (2006)

Solutionneur



$$Z = \int \mathcal{D}[\psi^\dagger, \psi]\, e^{-S_c - \int_0^\beta d\tau \int_0^\beta d\tau' \sum_{\mathbf{K}} \psi^\dagger_{\mathbf{K}}(\tau)\Delta_{\mathbf{K}}(\tau,\tau')\psi_{\mathbf{K}}(\tau')}$$



Mean-field is not a trivial problem! Many impurity solvers.

Here: continuous time QMC

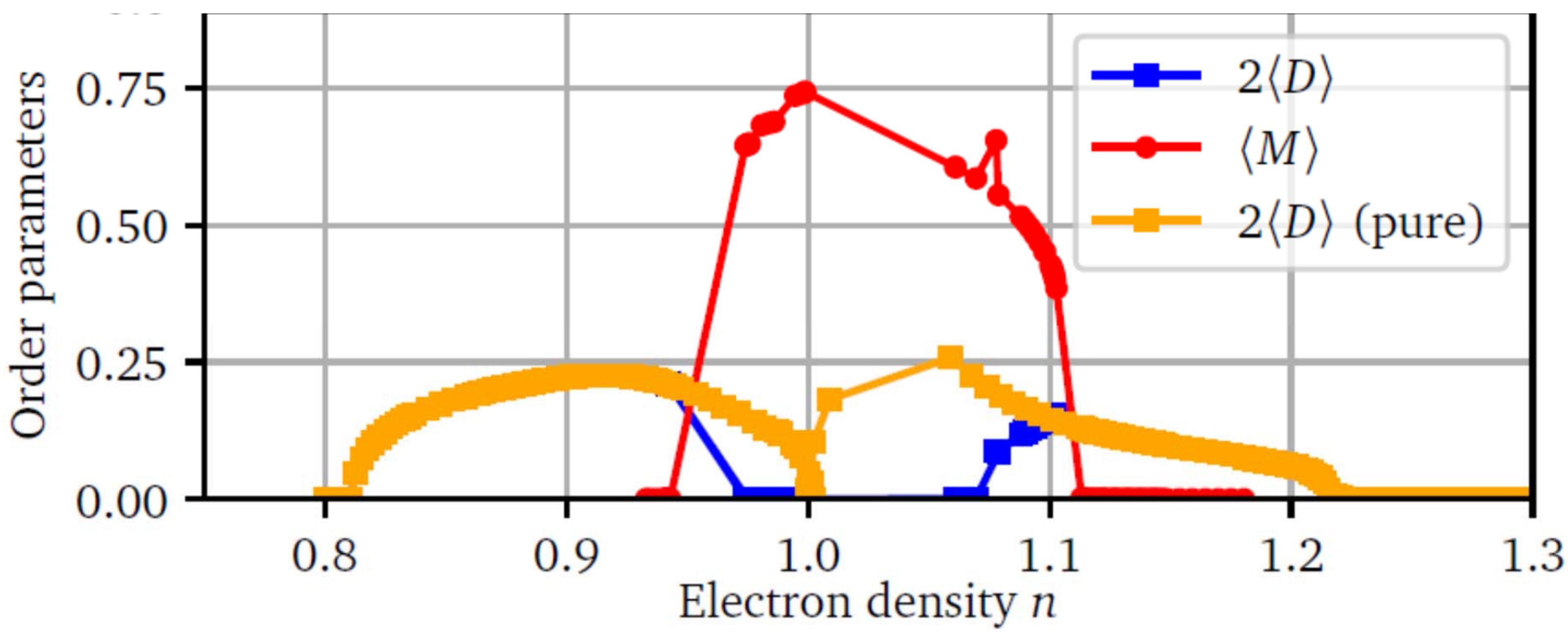
P. Werner, PRL 2006
P. Werner, PRB 2007
K. Haule, PRB 2007

$$\Delta(i\omega_n) = i\omega_n + \mu - \Sigma_c(i\omega_n) - \left[\sum_{\tilde{k}} \frac{1}{i\omega_n + \mu - t_c(\tilde{k}) - \Sigma_c(i\omega_n)}\right]^{-1}$$

Diagramme de phase, *T = 0*

Diagramme de phase *T = 0*

$U = 8t, t' = -0.3t, t'' = 0.2t$



A. Foley *et al.* Phys. Rev. B **99**, 184510 (2019)
S. S. Kancharla, *et al.* Phys. Rev. B **77**, 184516 (2008)
D. Sénéchal, *et al.* Phys. Rev. Lett. **94**, (2005)
M. Jarrell *et al.* EPL **56** 563, (2001)

CDMFT 4 sites

D. Sénéchal

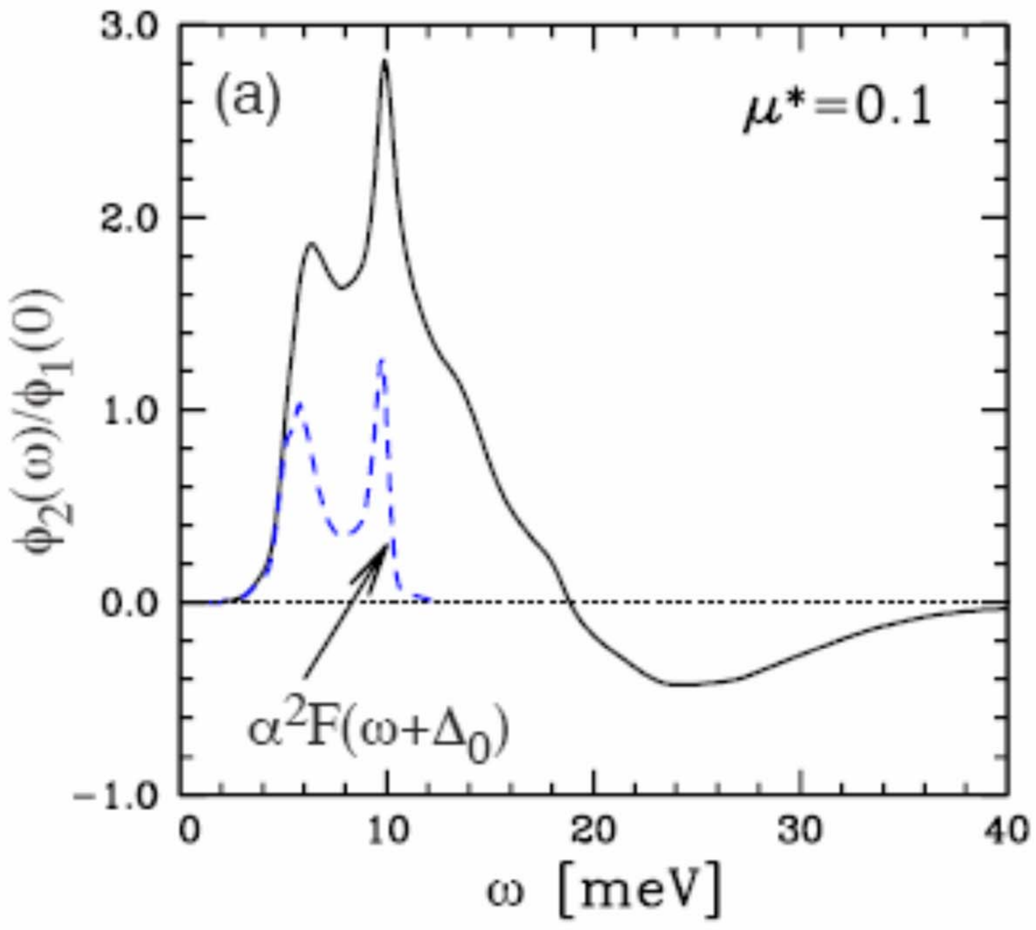
Bumsoo Kyung

La colle

Kyung, Sénéchal, Tremblay, Phys. Rev. B **80,** 205109 (2009)
Sénéchal, Day, Bouliane, AMST, Phys. Rev. B **87**, 075123 (2013)
A. Reymbaut *et al.* PRB **94** 155146 (2016)

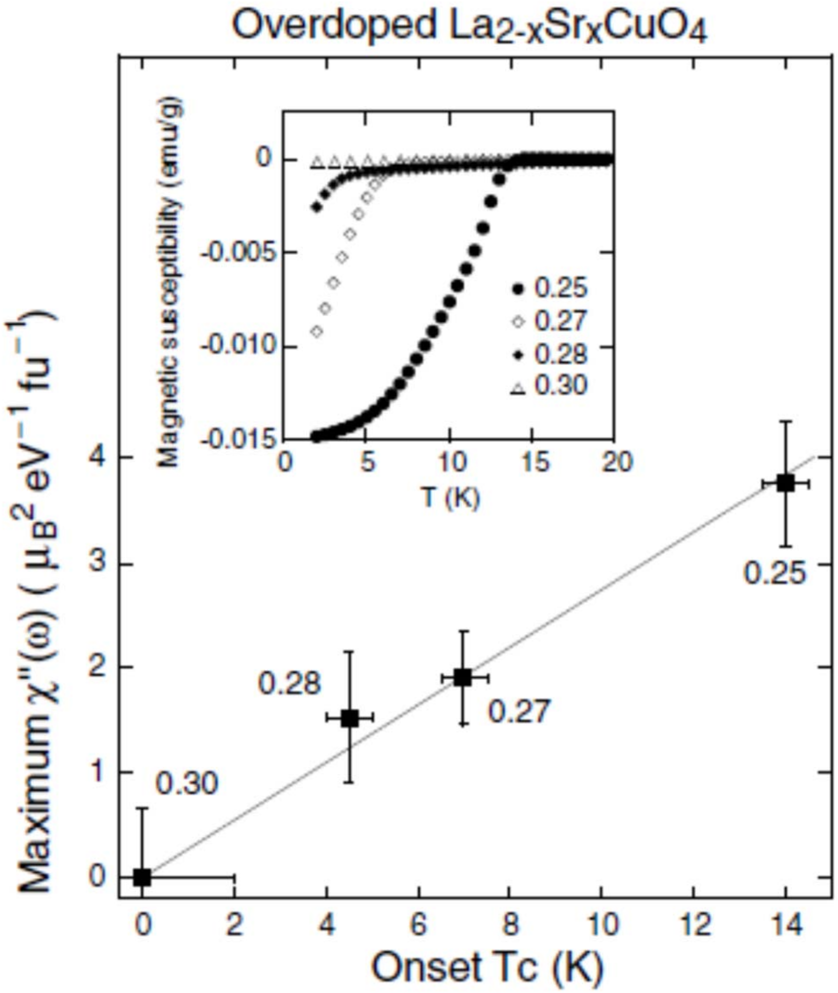
Im Σ_{an} électron-phonon dans Pb

Maier, Poilblanc, Scalapino, PRL (2008)

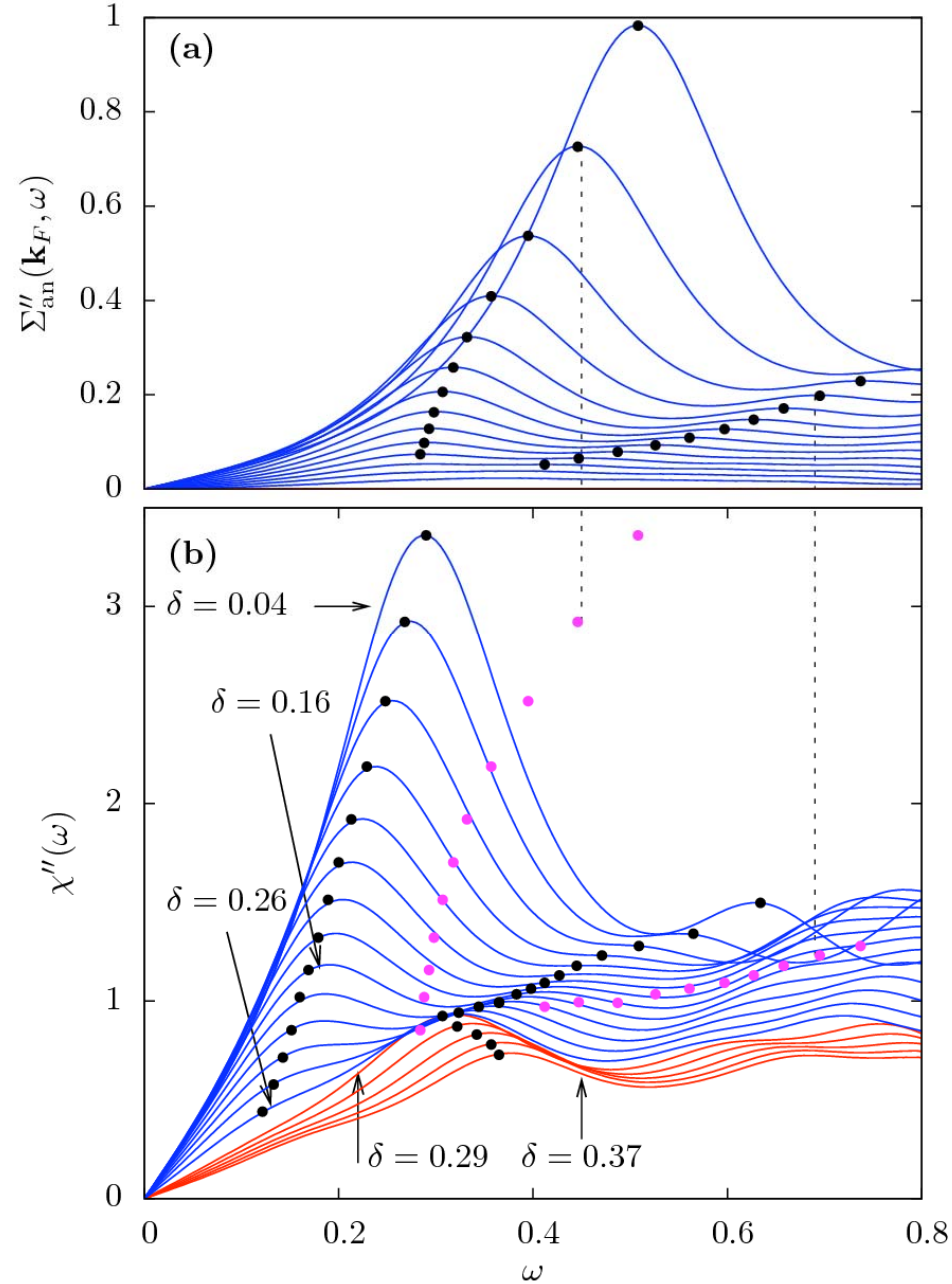


La colle

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



Wakimoto … Birgeneau PRL (2004)



La colle et les neutrons

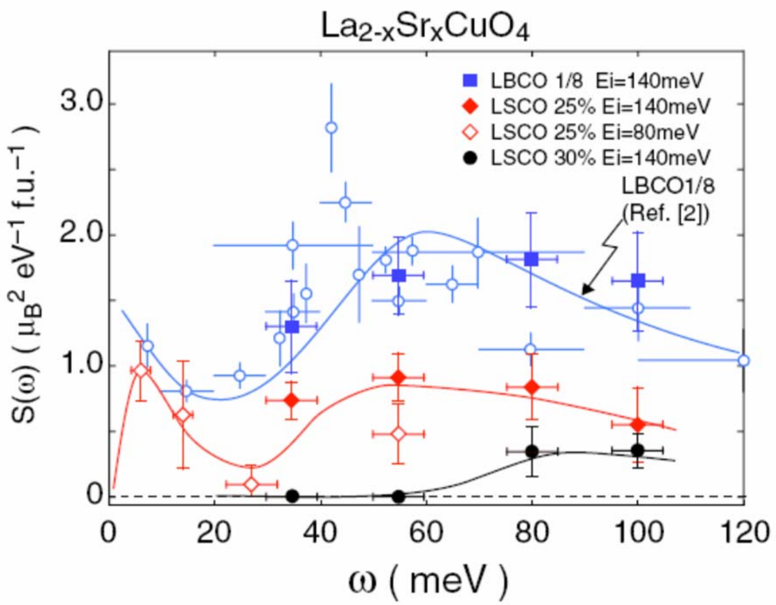
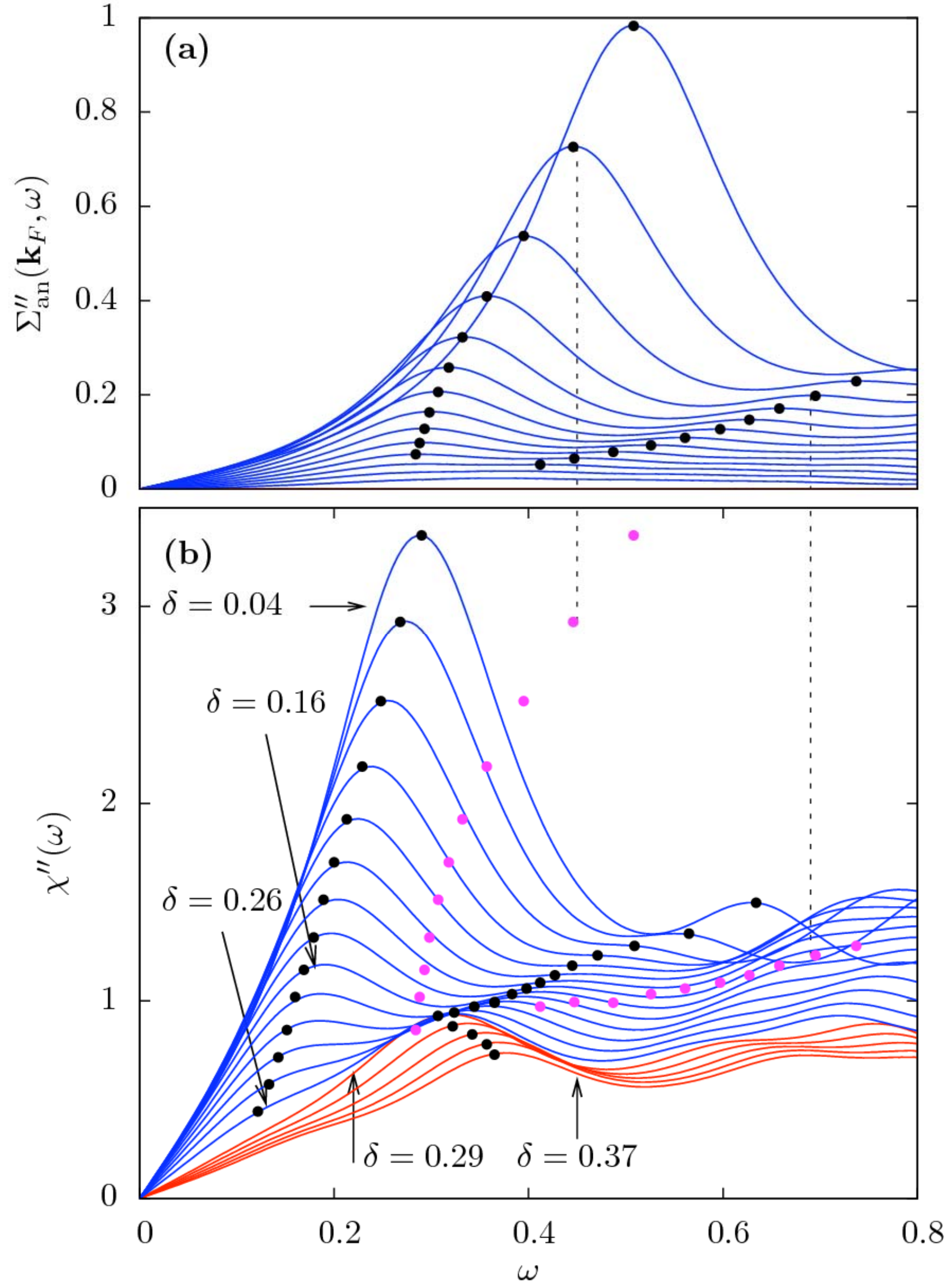


FIG. 3 (color online). **Q**-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-H integrated profiles for LBCO 1/8 (squares), LSCO $x = 0.25$ (diamonds; filled for E_i = 140 meV, open for E_i = 80 meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 1/8 (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)

Conclusion

Le rêve

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).

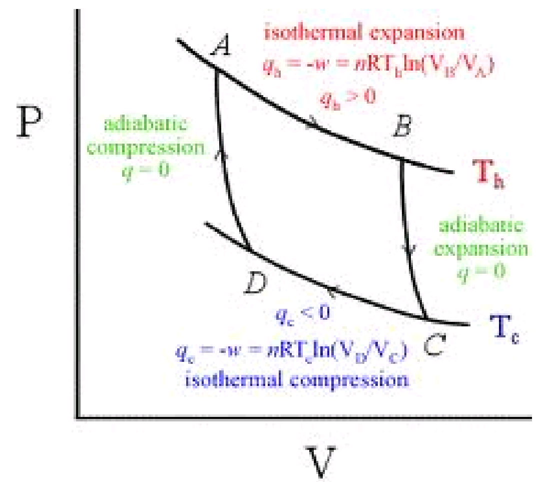
Two years ago the discovery of an entirely new class of superconductor—one based on iron—raised hopes that theorists might be able to divine the mechanism at work in high-temperature superconductors [see "An Iron Key to High-Temperature Superconductivity?" by Graham P. Collins; Scientific American, August 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 et technologie, main dans la main

Machine à vapeur et thermodynamique

Watts 1765

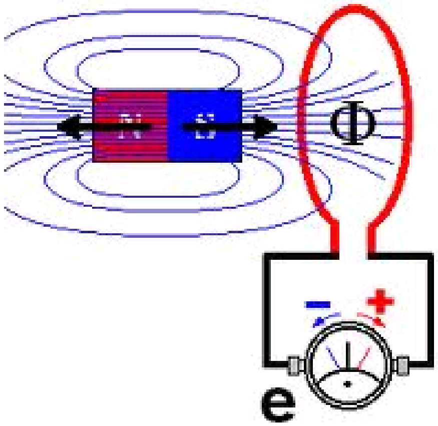


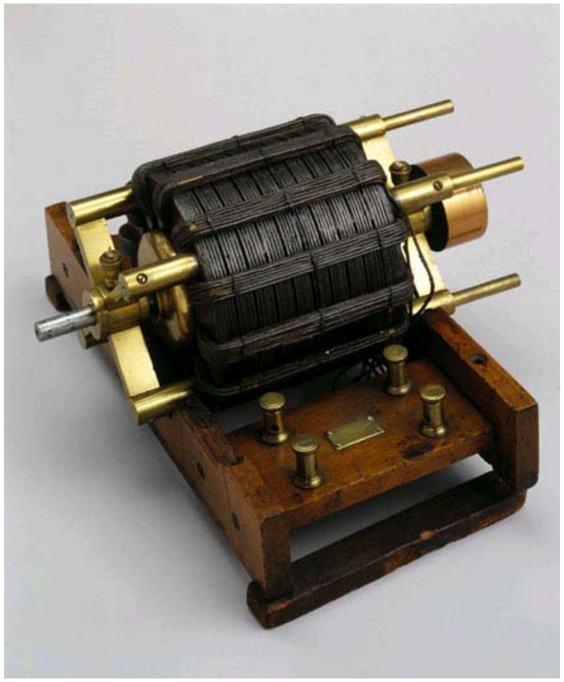
Carnot 1824

Induction et le moteur électrique

Moteur électrique, Tesla(1880)

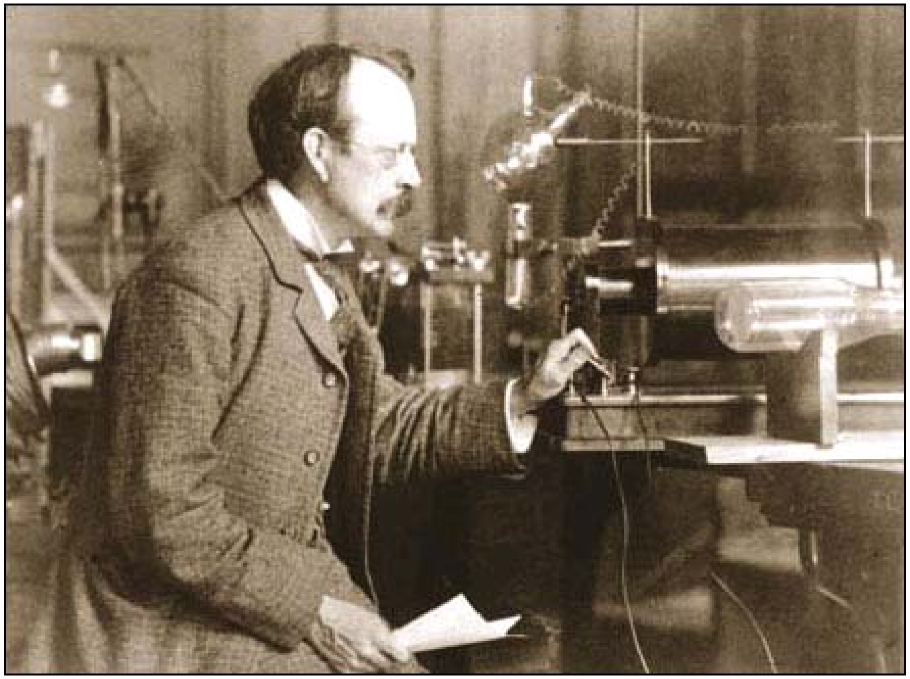
Induction, Faraday (1831)





Induction

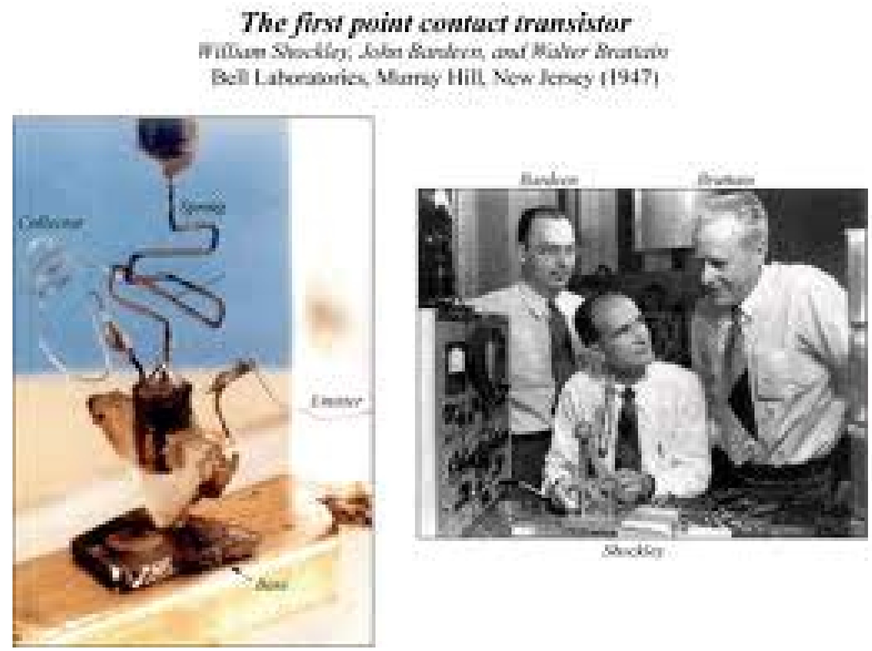
Électron and television



Thomson, 1897

Télévision, 1940

Mécanique quantique et le transistor



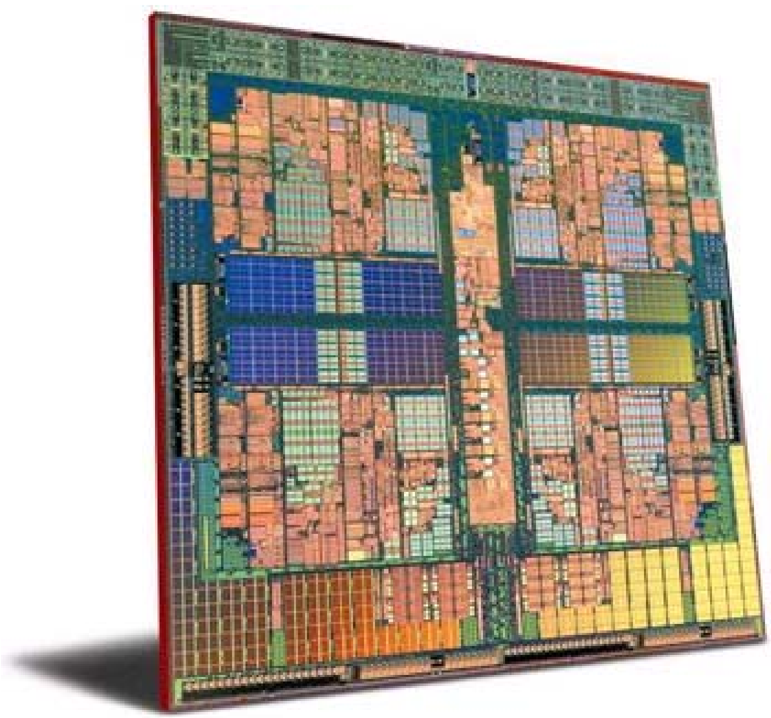
Schrödinger

Heisenberg

Transistor 1947

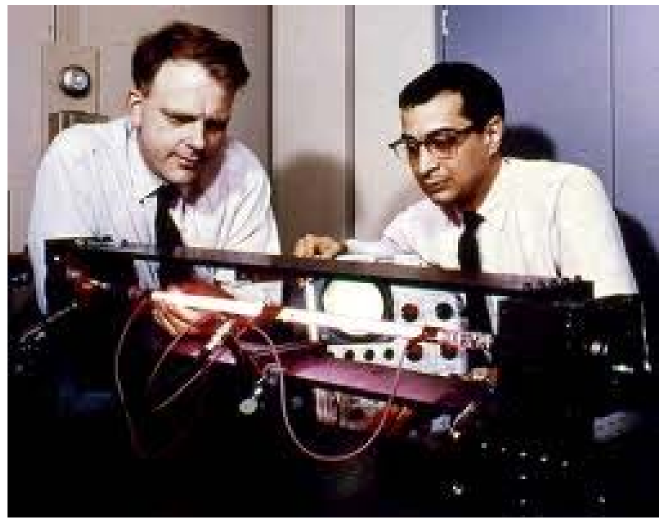
Mécanique quantique 1926

Mécanique quantique et le transistor



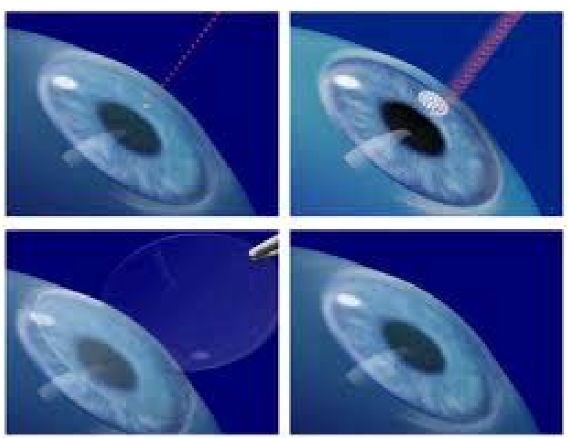
Laser et CD-ROM

Stimulated emission 1925



Laser 1960

CD-ROM (1980-90)



Chirurgie occulaire

Edward Bellamy (USA) 1887

- Roman: « Looking backward » 2000-1887
- Si nous pouvions inventer un dispositif pour offrir à tous de la musique dans leur maison, qui serait de qualité parfaite, de quantité illimitée, pour toutes les humeurs et qui commencerait et s'arrêterait lorsqu'on voudrait, alors nous aurions atteint la limite du bonheur pour l'humanité et nous pourrions cesser de chercher des améliorations.

Merci