Superconductivity 101

A Primer for Engineers

Paul M. Grant

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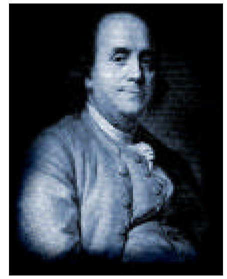
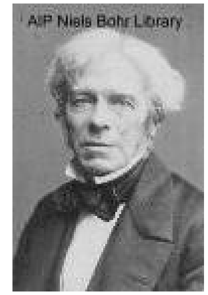
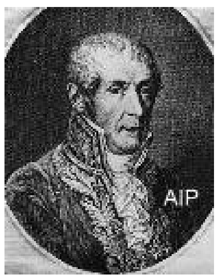
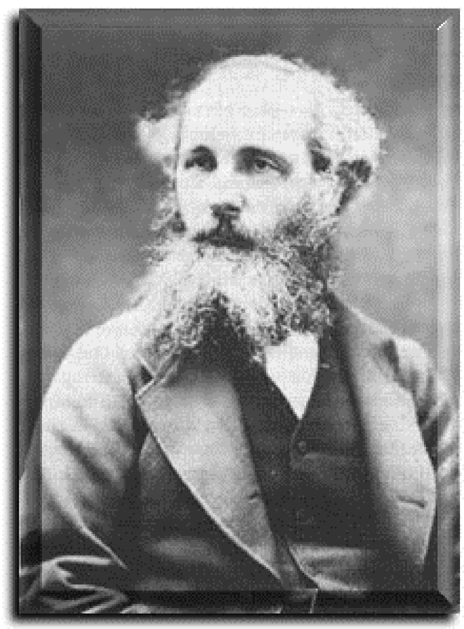
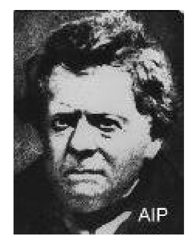
Fathers of Electricity







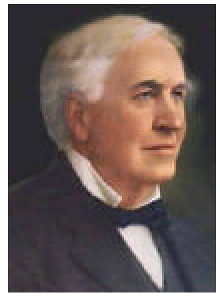


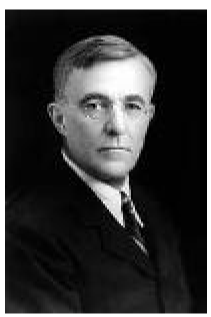


Discoverers

Fathers of Electricity

Practitioners

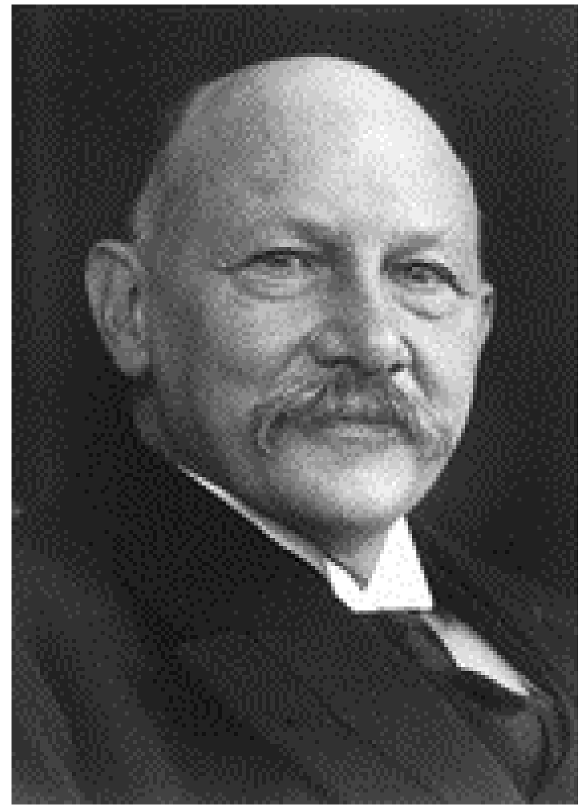




Fathers of Cryogenics

Dewar

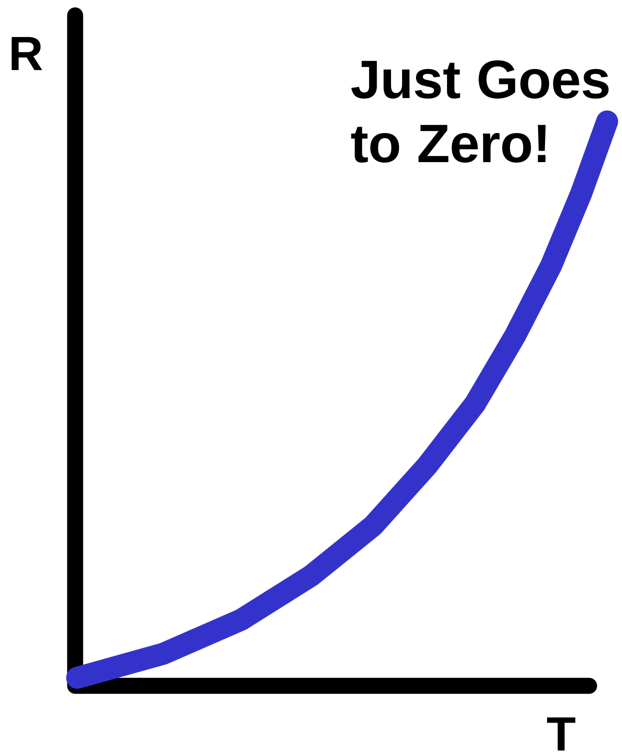
CH_4	112 K
O	90
N_2	77
Ne	27
H_2	20
He	4.2

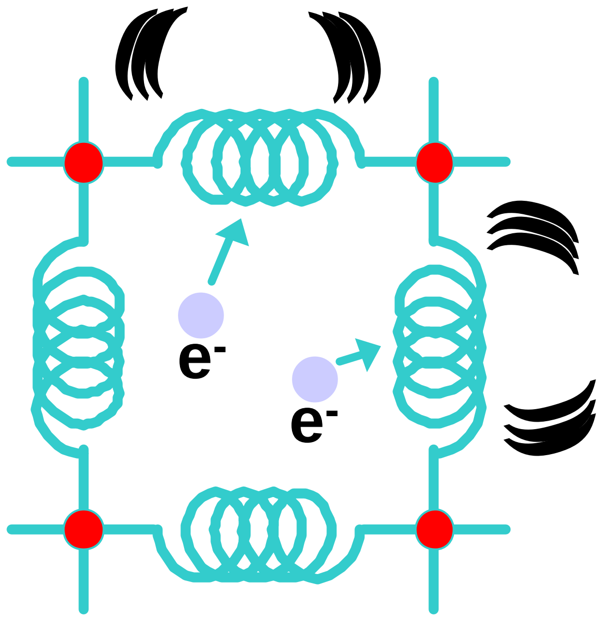


Kammerlingh-Onnes

Models of Electrical Conductivity

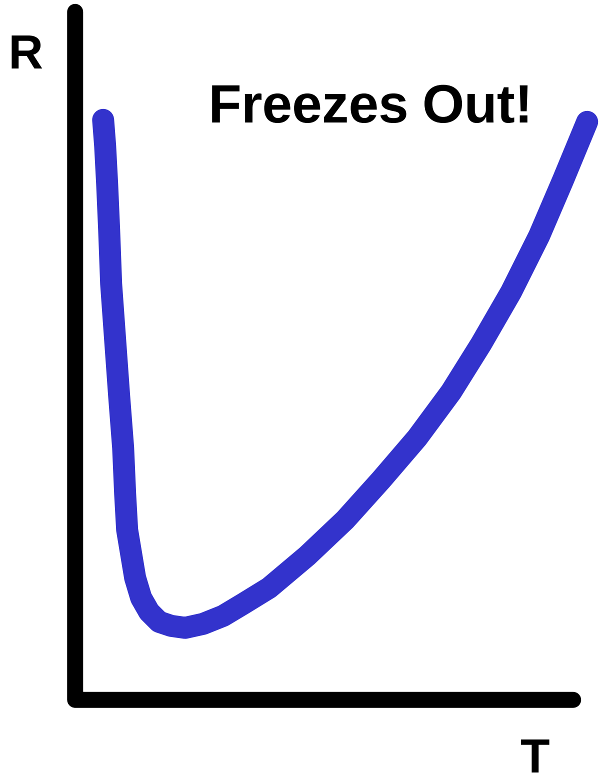
The First Idea:

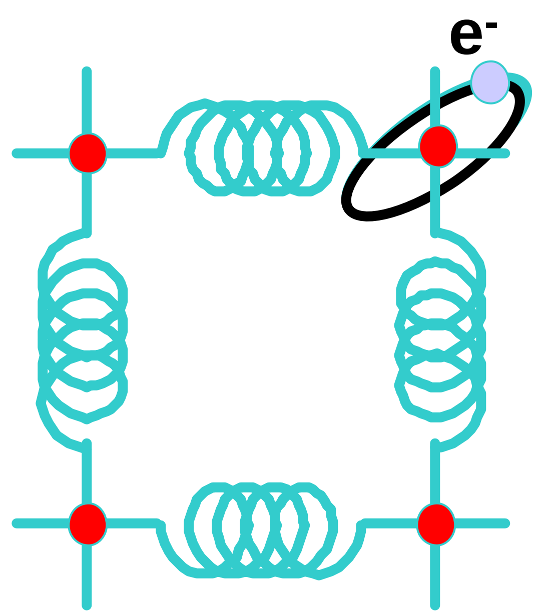




Models of Electrical Conductivity

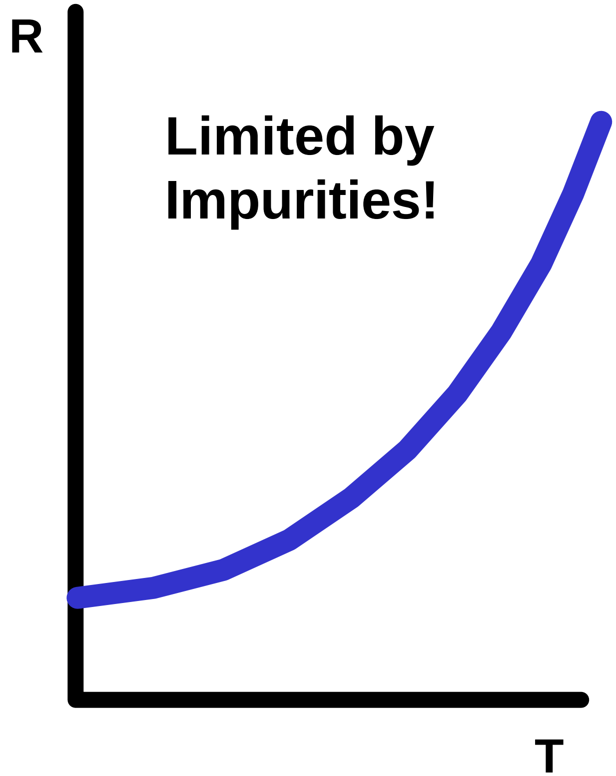
The Most Popular:

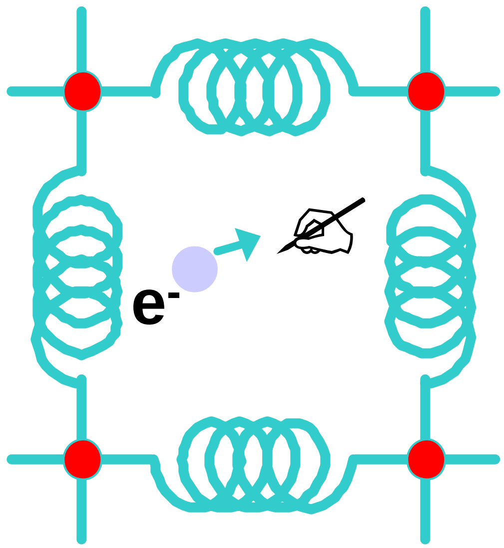




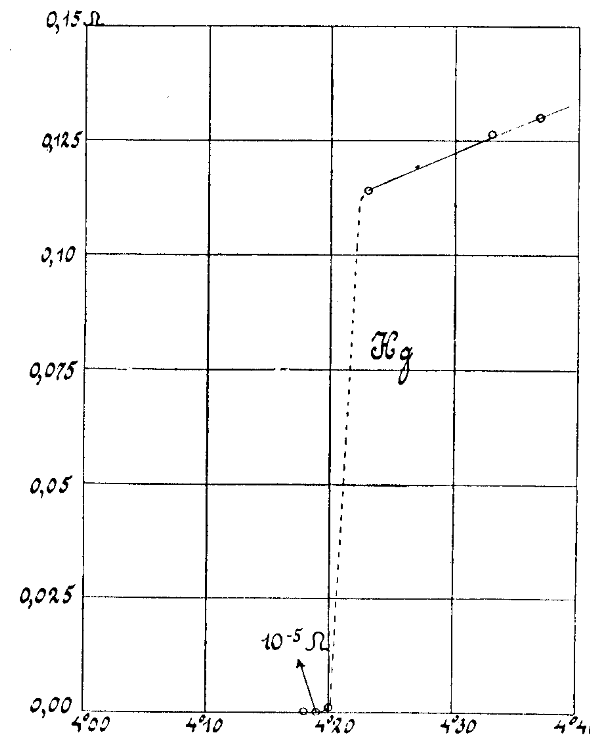
Models of Electrical Conductivity

Reality:





1911
A Big Surprise!



Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

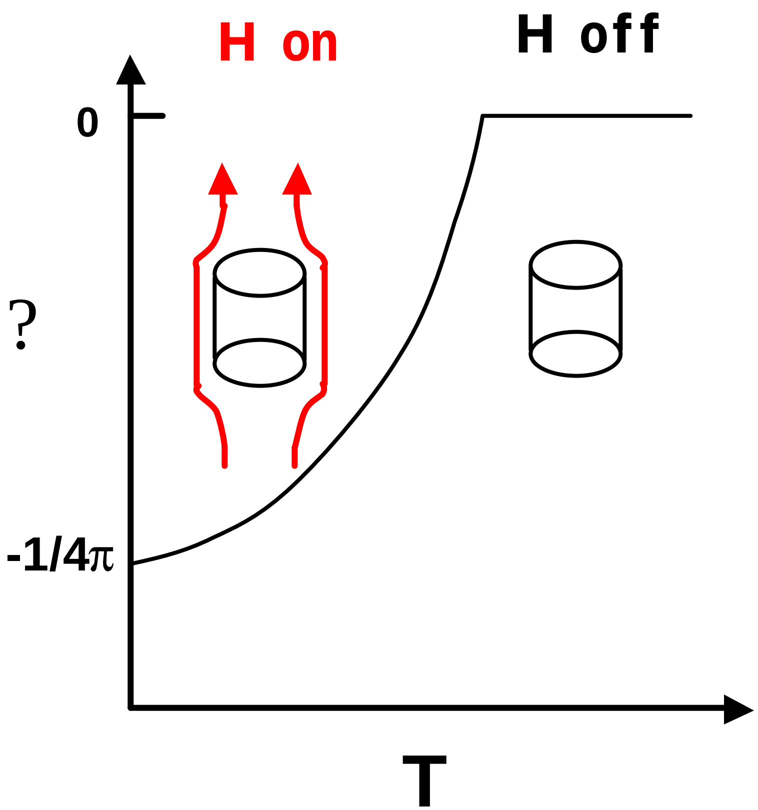
H. Kamerlingh-Onnes (1911)

IEEE Networking the World™

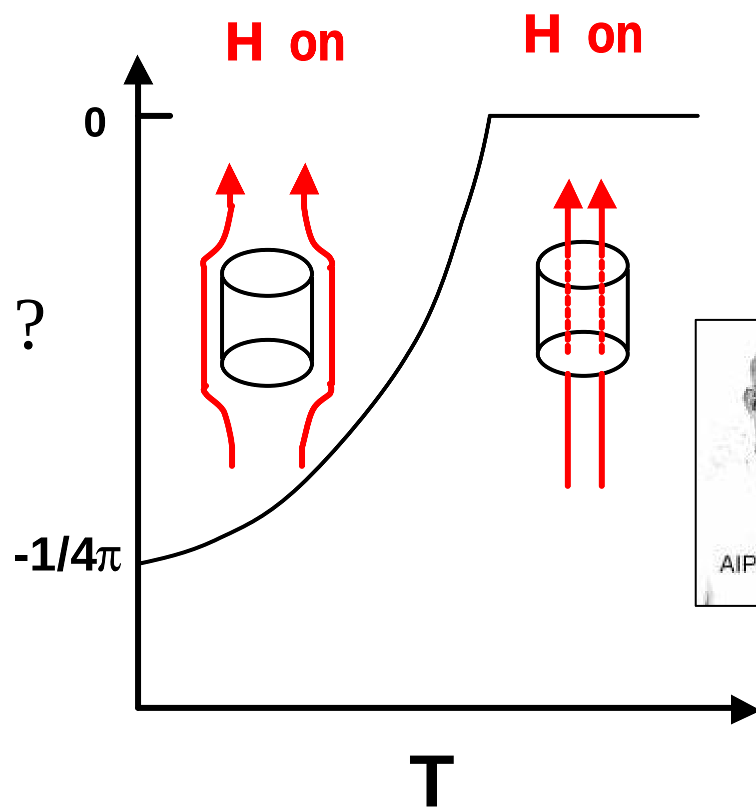
Superconductivity Workshop
Charlotte, 24 May 1999

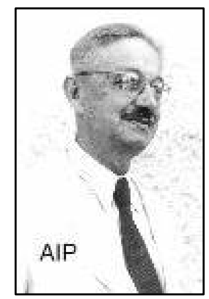
Insulated Conductors Committee

Magnetic Properties



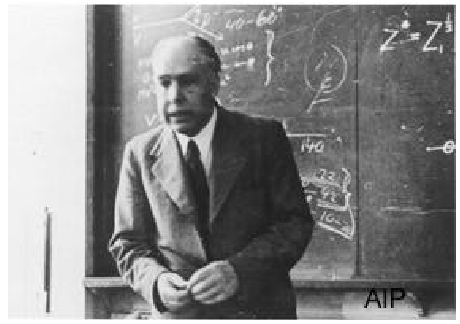
Expected (Lenz' Law)

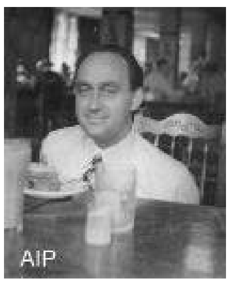


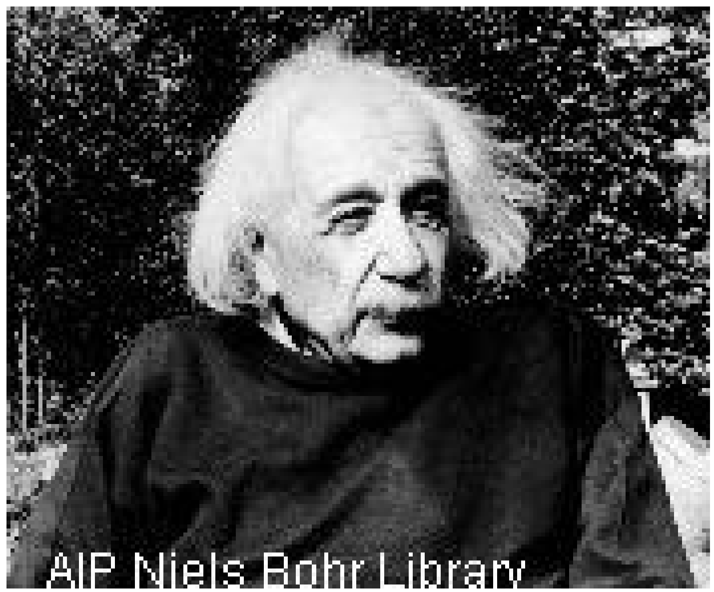


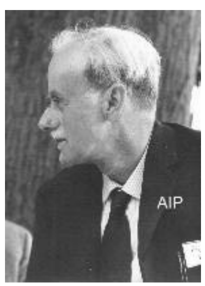
Weird ! (Meissner Effect)

They all tried…
and failed!

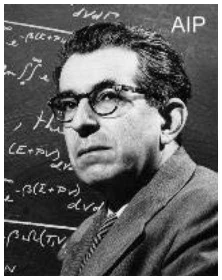








They came close...



Fritz London

"The B-field does penetrate."

$$E \sim \lambda^2 \, dJ/dt, \quad B \sim \lambda^2 \, \nabla \times J$$

Lev Landau

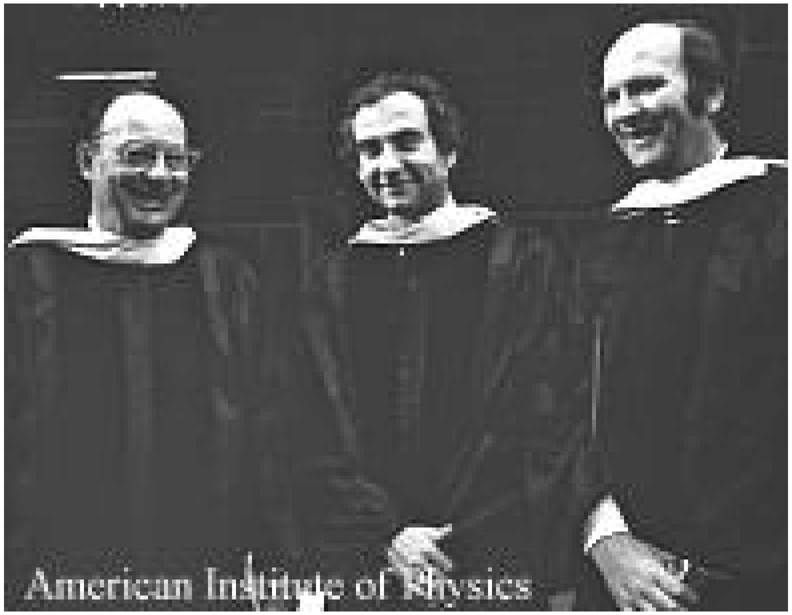
"Since SC is a second-order phase transition, there must be an order parameter involved."

Irwin Froehlich

"T_C depends on the mass of the atoms (isotope effect), so the SC must be tied to lattice vibrations (phonons)."

They Got It Right!

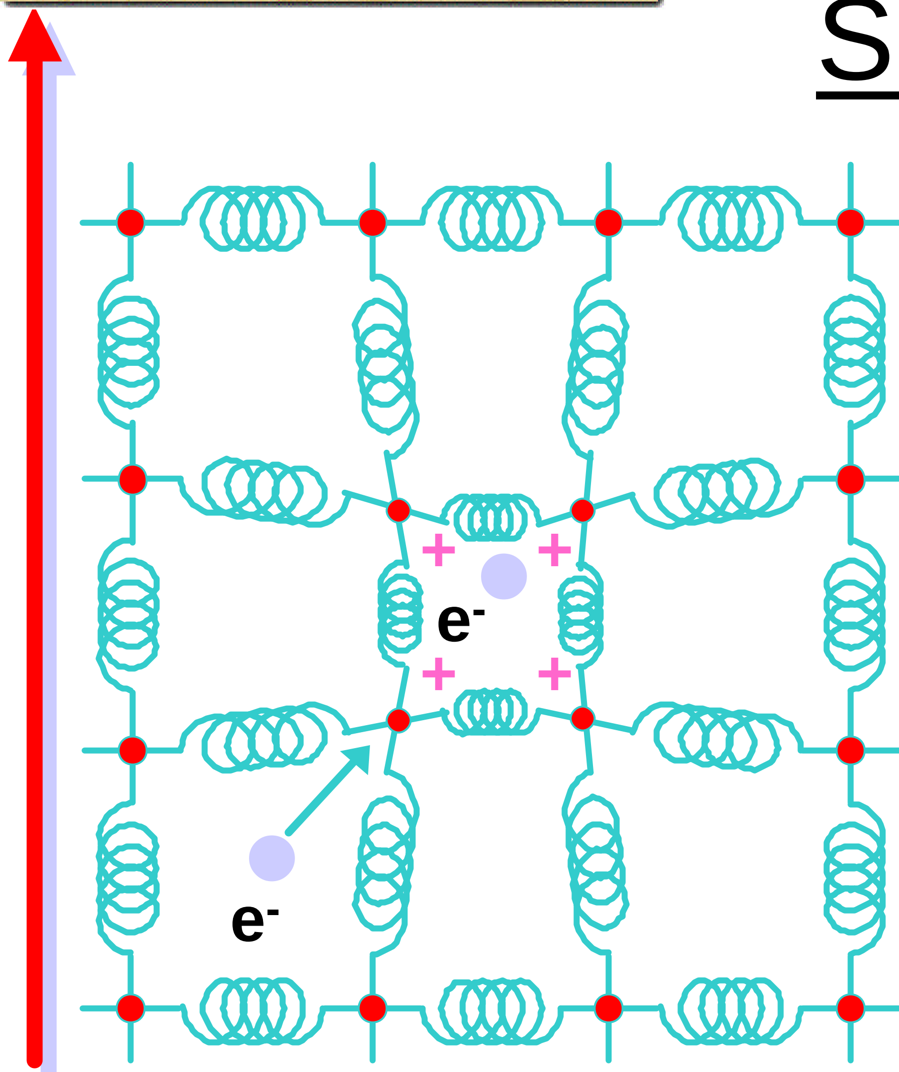
B ----- C ----- S



There has to be a regime where the lattice vibrations act to bind electrons together rather than scatter them with loss as given by Ohm's Law.

Bardeen: "It's a macroscopic quantum state"
Cooper: "It's got twice the charge you'd expect"
Schrieffer: "Ψ's a statistical wavefunction"

Physics of Superconductivity



Electrons Pair Off!

BCS Equation

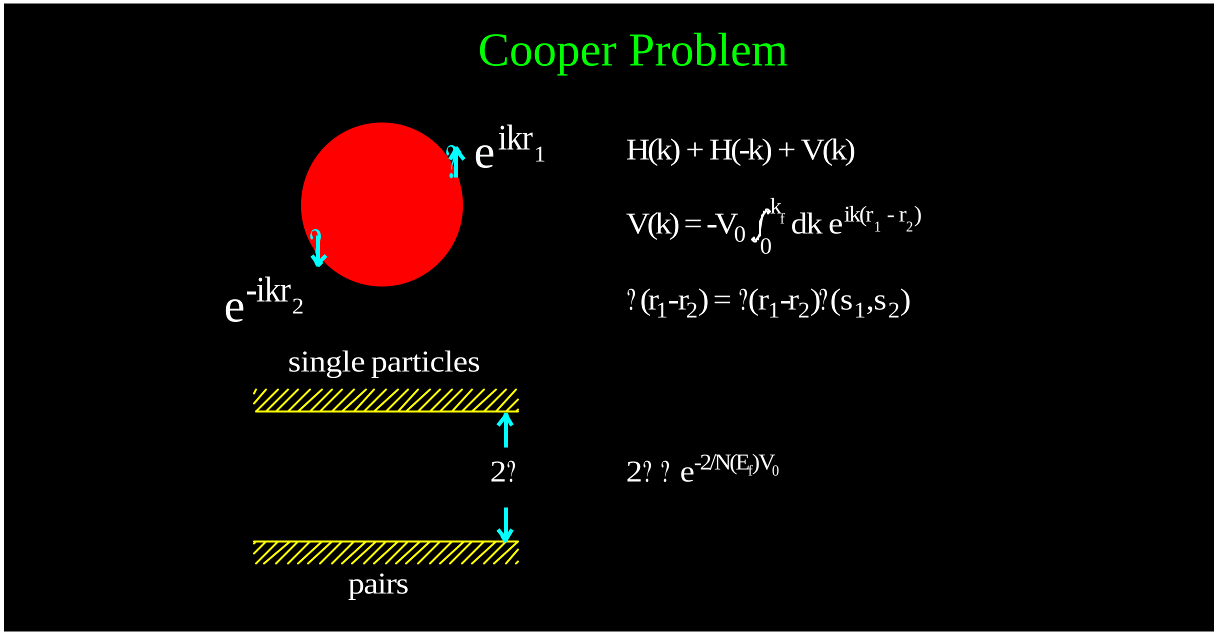
$$T_C \; ? \; 1.14 \, ?_D \, \exp(?1/?)$$

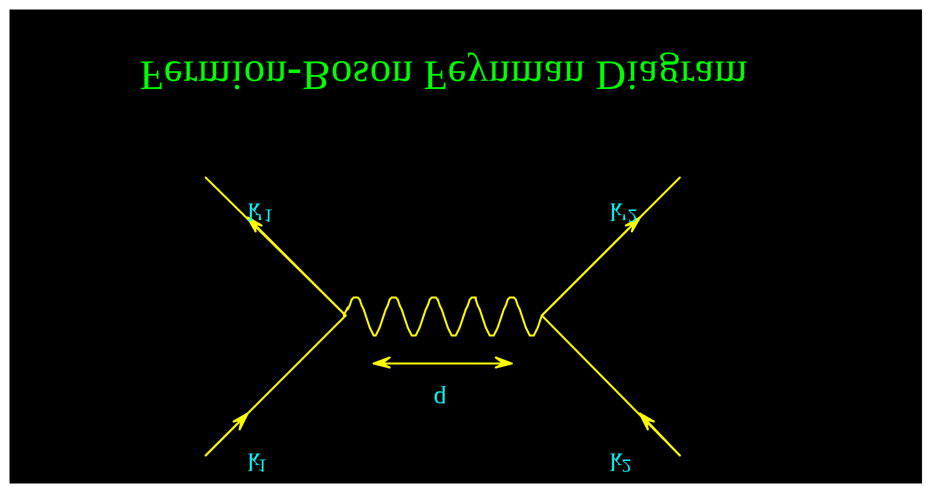
$?_D \; ? \; 275 \; K,$

$? \; ? \; 0.28,$

$? \; T_C \; ? \; \underline{9.5 \; K}$ (Niobium)

"Cooper's Problem"





Important Numbers in Superconductivity

Transition Temperature, T_C	Way below 300 K
Critical Current Density, J_C	10^{-2} - 10^{6} A/cm^2
Critical Magnetic Field, H_C	10^{-4} - 10 T
London Penetration Depth, λ	10 - >1000 Å
Pippard Coherence Length, ?	10 - >1000 Å
G-L Parameter, $\kappa = \lambda/$?	0.01 - 100

NB! All these numbers depend on each other. E.g., $H_C \sim \lambda$?

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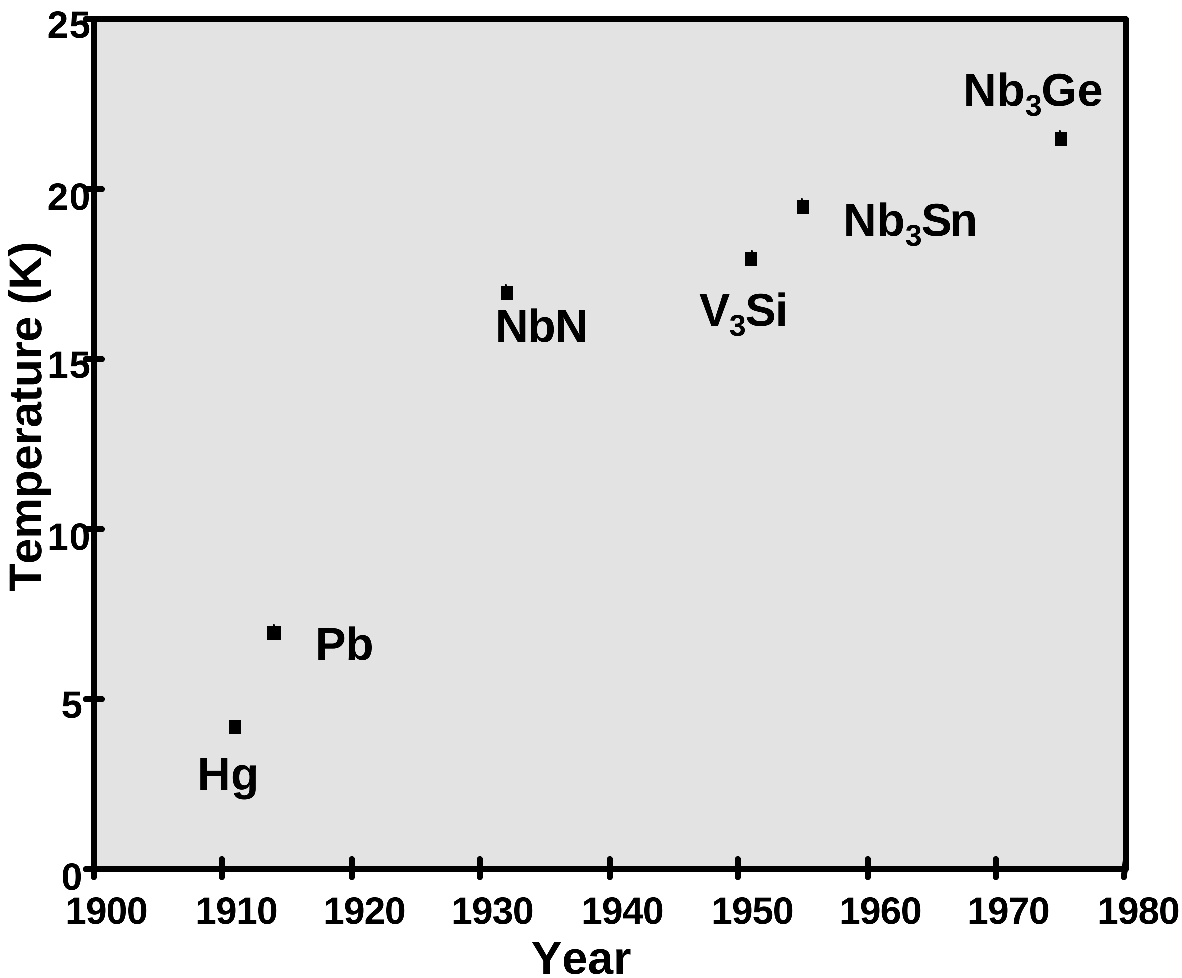
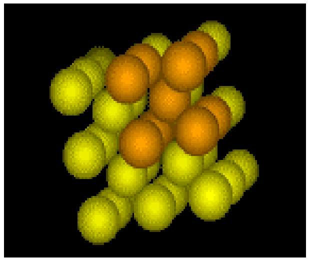
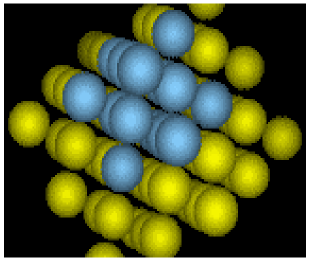
T_C vs. Year: 1911 - 1980







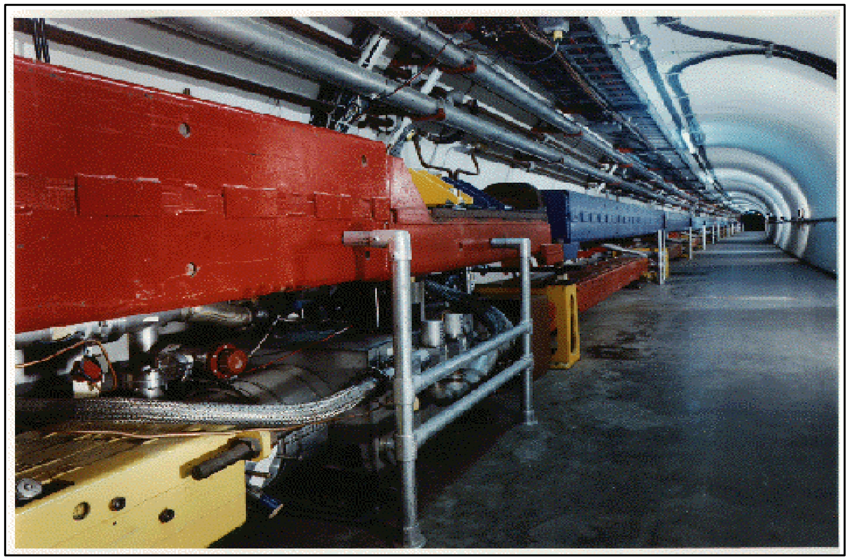
Cubic Metals

P. M. Grant

Superconductivity 101

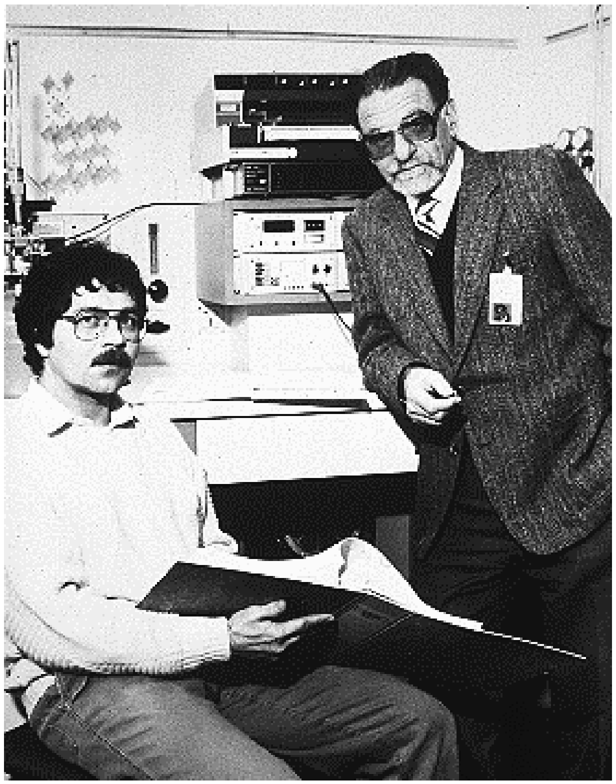
MRI & "Big Physics"

Magnetic Resonance Imaging
Philips

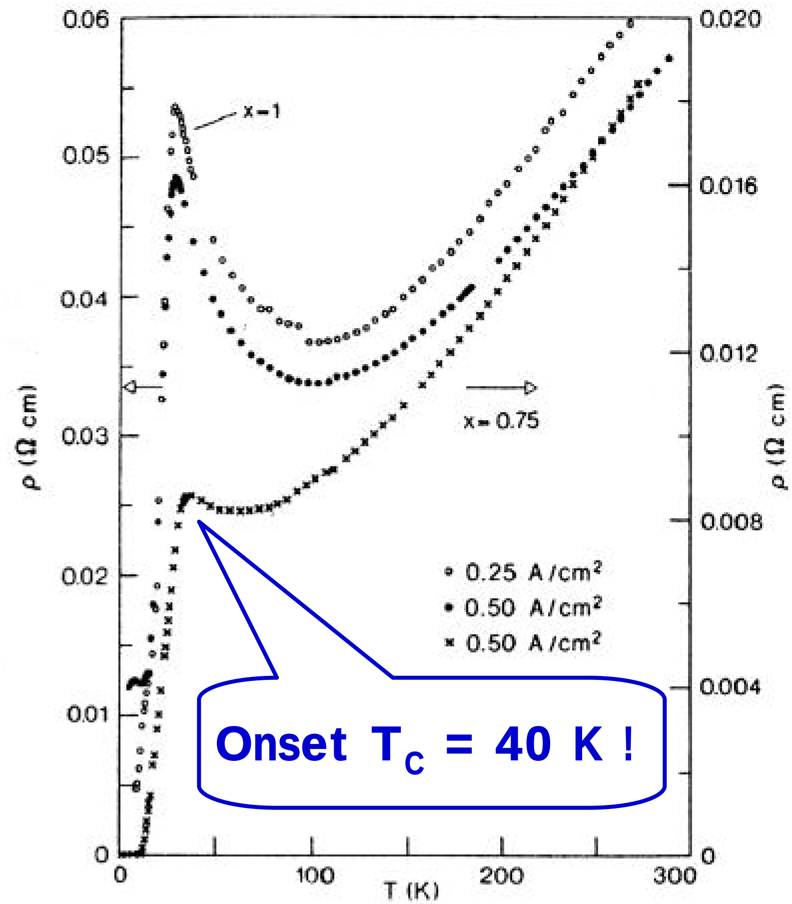


Tevatron
Fermi National Laboratory

1986
Another Big Surprise!



Bednorz and Mueller
IBM Zuerich, 1986



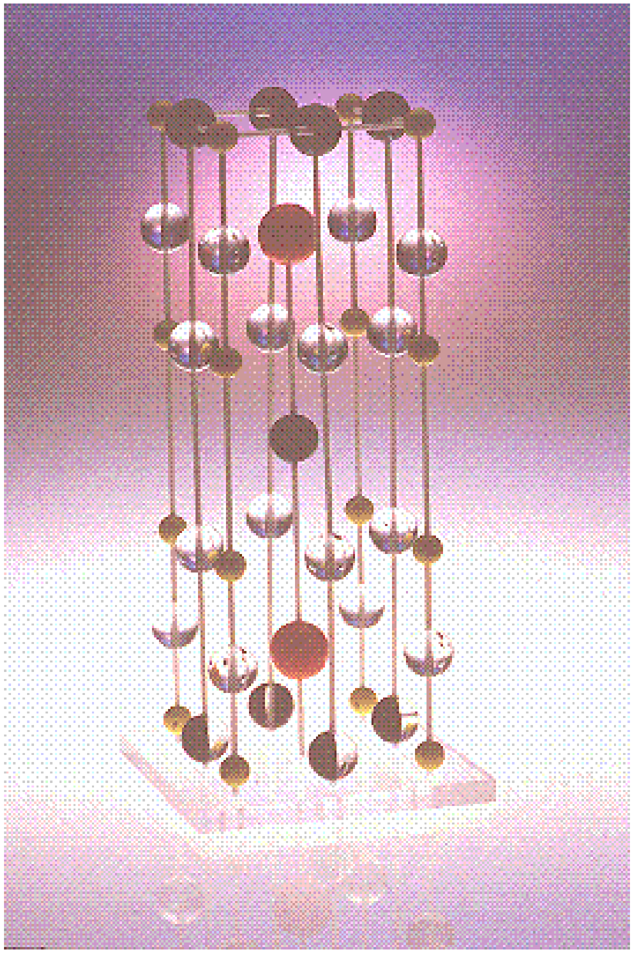
1987
"The Prize!"

Associated Press

J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

March 3, 1987
"123" Discovered



Woodstock of Physics NYC, 1987

Physicists' Night Out!

commentary

Woodstock of physics revisited

Ten years have passed since the now famous American Physical Society meeting that heard the first breathless accounts of high-temperature superconductivity. Now, in calmer times, practical applications are emerging.

Paul M. Grant

Snap quiz: who can tell me the winner of the 1987 Super Bowl? Not most physicists, I suspect, for whom it was certainly eclipsed by two events of far greater consequence that shared the early months of that year. One, the discovery of Supernova 1987A, perhaps portended the other: the announcement of superconductivity above liquid-nitrogen temperature on planet Earth — a dream fulfilled for many condensed-matter physicists like myself, whose careers had orbited around this elusive star.

The successful 'sighting' fell to W. K. Wu and C. W. (Paul) Chu and their teams of students and postdocs at the Universities of Alabama and Houston, following only five months after the publication in autumn 1986 by Georg Bednorz and Alex Müller' at IBM Zürich of their discovery of superconductivity in a previously unexplored class of compounds, the layered copper-oxide perovskites.

The 'inside' story of the hectic interval between the first week in January 1987 — when an announcement of the confirmation of Bednorz and Müller's discovery first brought 'high-temperature superconductivity' to wide public attention — and the week of the American Physical Society's March meeting, remains to be told. Suffice it to say that this period, and the last three months of 1986, were replete with incredulity, credulity, excitement, secrecy and a sense of immediacy in competition with one's peers, all of which resulted in, frankly, a substantial amount of intrigue and suspicion. All who participated surely came to understand, if they had not done so before, that physics is not only a science but, perhaps more significantly, an intensely human pursuit — something they do not teach you in graduate school.

The programme of the March meeting, held each year in a different US city, is 'cast in concrete' early the preceding December; thereafter, an absolute policy of no alterations prevails. By the deadline of 5 December 1986, for the 1987 meeting at the Hilton hotel in New York City, only one abstract had been accepted on the new materials: "Specific heat of Ba–La–Cu–O superconductors" by Rick Greene and his collaborators at IBM Yorktown. But the explosion of results that appeared in the new year prompted the meeting's organizers to take an unprecedented step. Brian Maple of the University of California, San Diego, was asked to put together a special post-deadline evening session devoted entirely to the discovery.

All those wishing to report results would be granted five minutes each, in order of the arrival of their request to take part — and did the requests rain in, reaching a downpour in the two weeks before the meeting, as confirmations of the Wu–Chu measurements were made. All in all, 51 presentations were to be given throughout the evening and early morning of Wednesday and Thursday, 18 and 19 March. That memorable and riotous session was to become our "Woodstock of physics", so named in honour of the village only 50 miles north where, in an obscure farmer's muddy field in 1969, the rock concert occurred that defined a generation of youth the world over.

Rising stars: Müller and Chu with Shoji Tanaka (right), whose Tokyo laboratory provided one of the first confirmations of Bednorz and Müller's discovery.

Fever pitch: the room filled to overflowing with physicists eager for news of superconductivity.

Opening act

A few personal observations and anecdotes may help to convey the colour of that week in midtown Manhattan. Excitement was running high even before Wednesday night. On Monday, the opening day, the press were already beginning to catch some of us to be interviewed. That noon my colleague Ed Engler and I went to lunch at a nearby Brew 'n' Burger and found Alex Müller sitting by himself in a corner booth, attempting to escape the turmoil at the Hilton. At the time he was not yet widely recognizable to those attending the meeting or to the press — a situation that would soon change.

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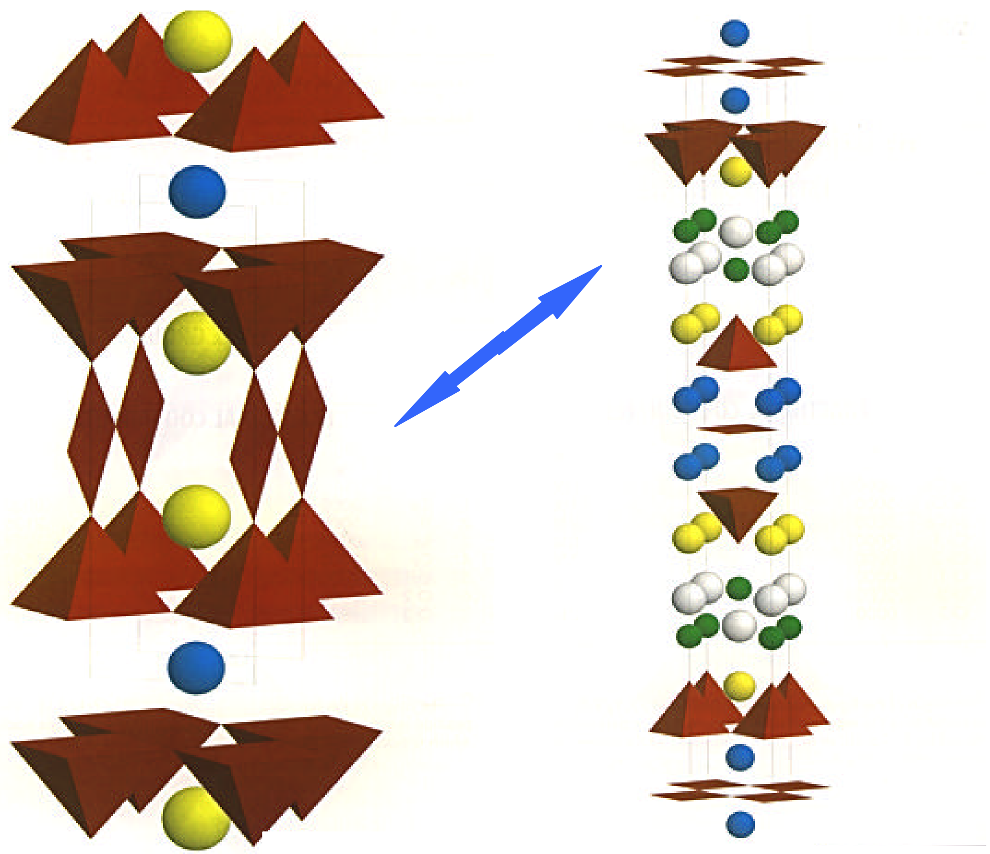
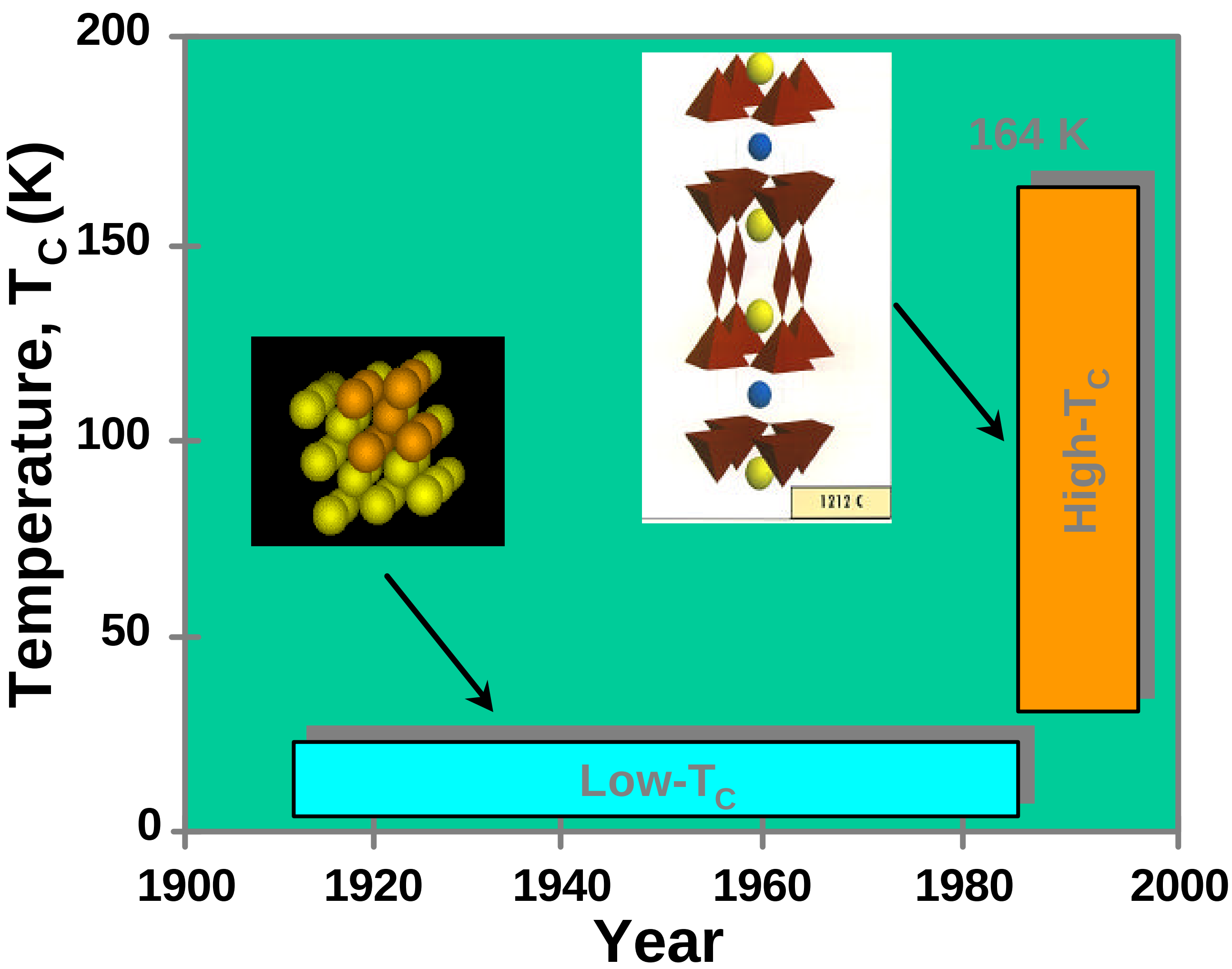
HTS Layered Perovskites

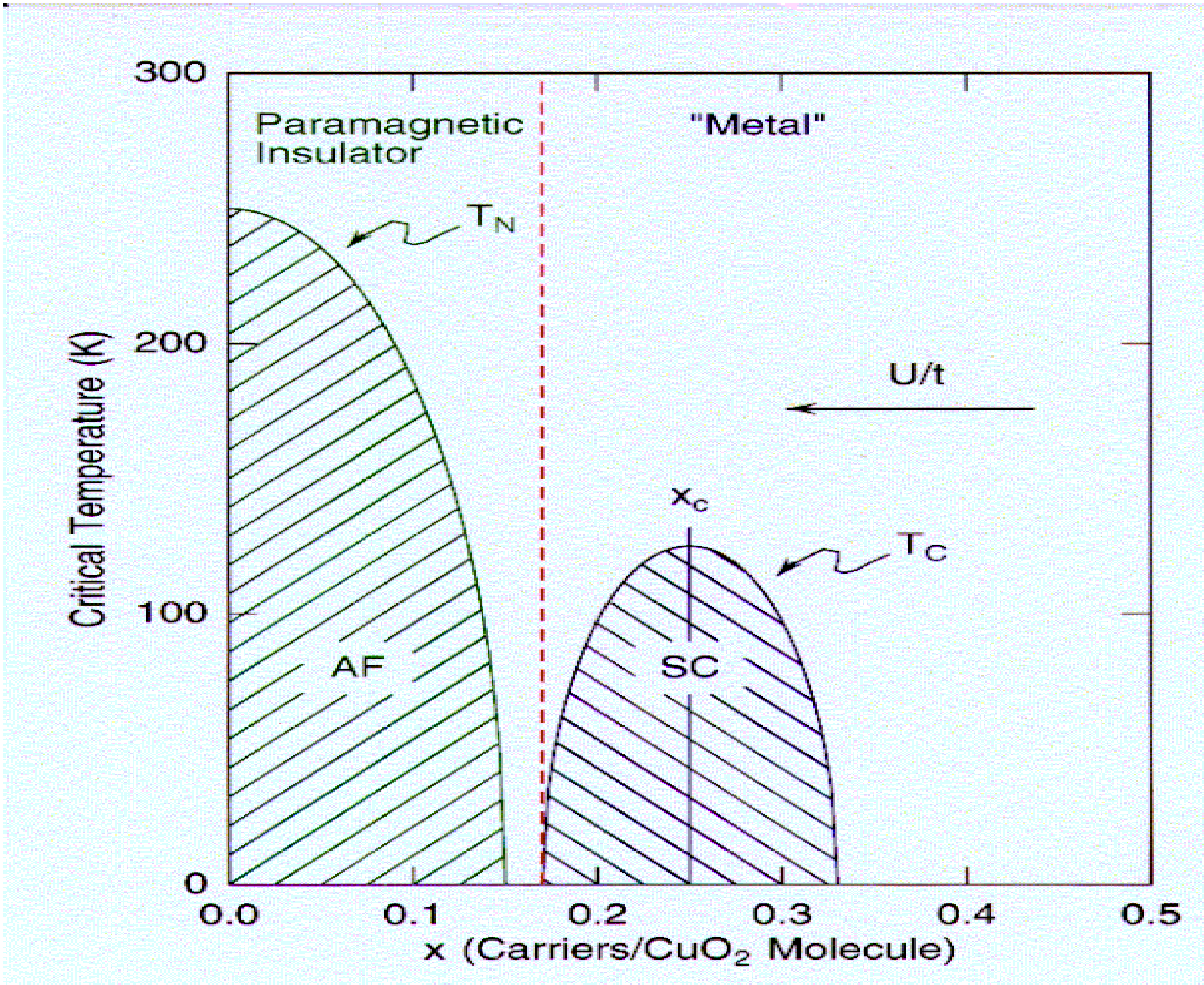
Y-123 **Bi-2223**



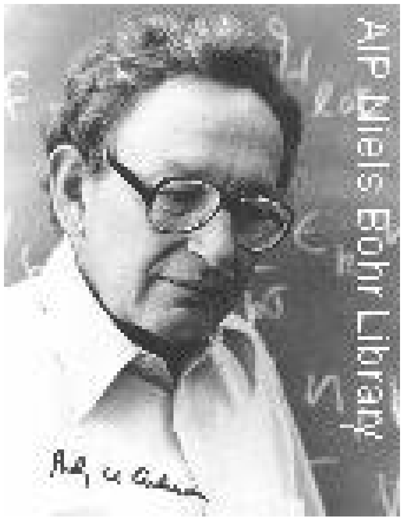
T_C vs. Year: 1911 - 1999



HTSC Phase Diagram



HTS Theories



Phil Anderson

"It can't be just an accident that high temperature superconductivity occurs in a host material whose insulating state is an antiferromagnet, and, which when doped with holes to a level where magnetic behavior disappears, we get superconductivity."

Current Situation:

- **The pair coupling is believed to be magnetically mediated.**
- **The normal conducting state is believed not to be a Landau liquid.**
- **The superconducting state is domain-like, occurring as electronic "stripes."**

However, there is yet no generally accepted model today!

Boson Flavors

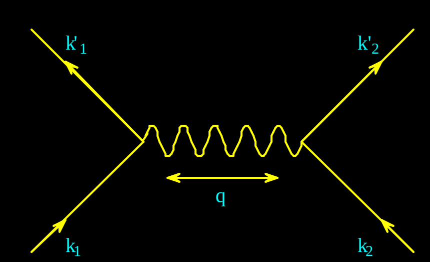
Hubbard Hamiltonian

$$H = \underset{i}{?}\,[t(c_i c^*_{i+1} + h.c.) + U n^{\uparrow}_i n^{\downarrow}_i]$$

t = Hopping Integral

U = Coulomb Repulsion

Fermion-Boson Feynman Diagram



Ultimate Boson

Put-ons!

GLAG

$$G[?] ? ?d^3r[\frac{1}{2m*}(?i□? ? e*A)?*(i□? ? e*A)? ? a??* ? \tfrac{1}{2}b??*??*]$$

$$? (i?? ? A)^2 f ? f(1? f^2) ? 0$$

$$?^2? ? (? ? A) ? ½i(f^*? f ? f? f^*) ? Af^2 ? 0$$

Lev Gor'kov

$$? ? (|a|/b)^{½} f$$

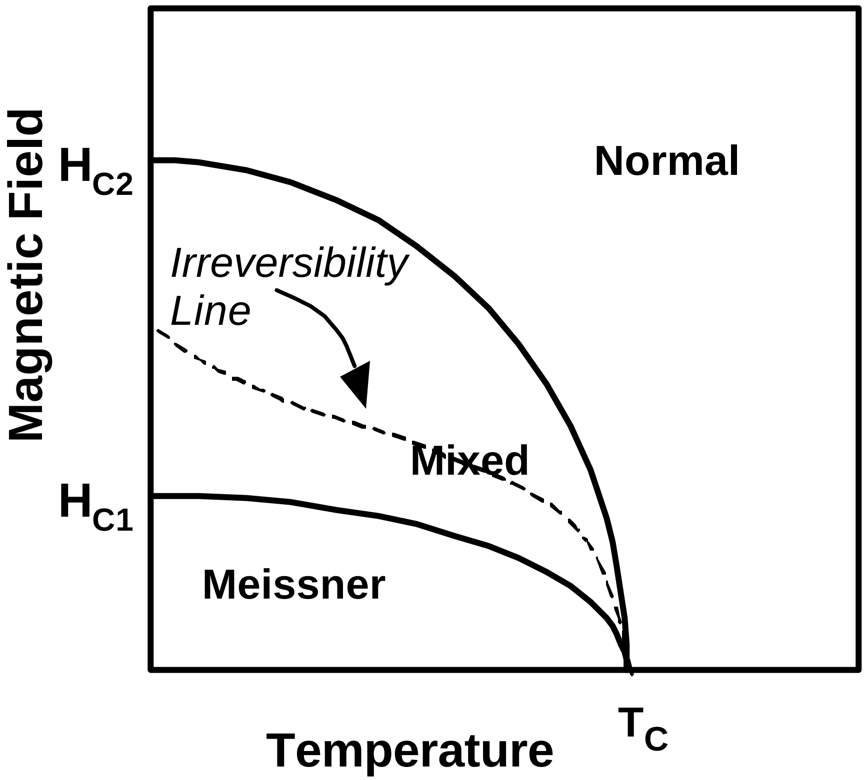
$$A ? (?_0 / 2??)A$$

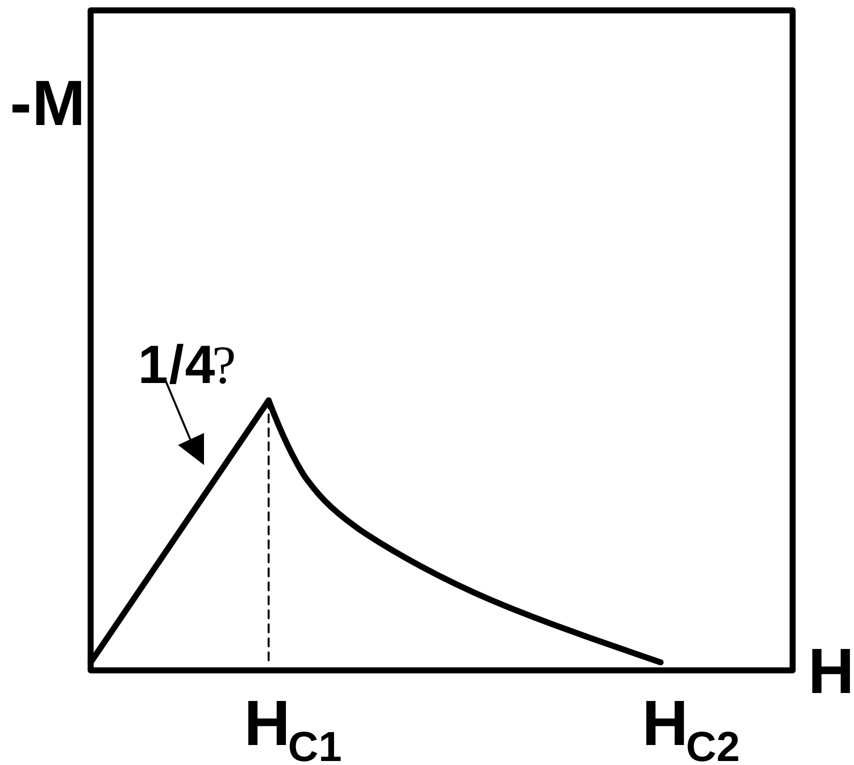
$$? ? ?_L / ?$$

$$? ? 1/\sqrt{2} \qquad \text{I}$$

$$? ? 1/\sqrt{2} \qquad \text{II}$$

Type II Superconductivity





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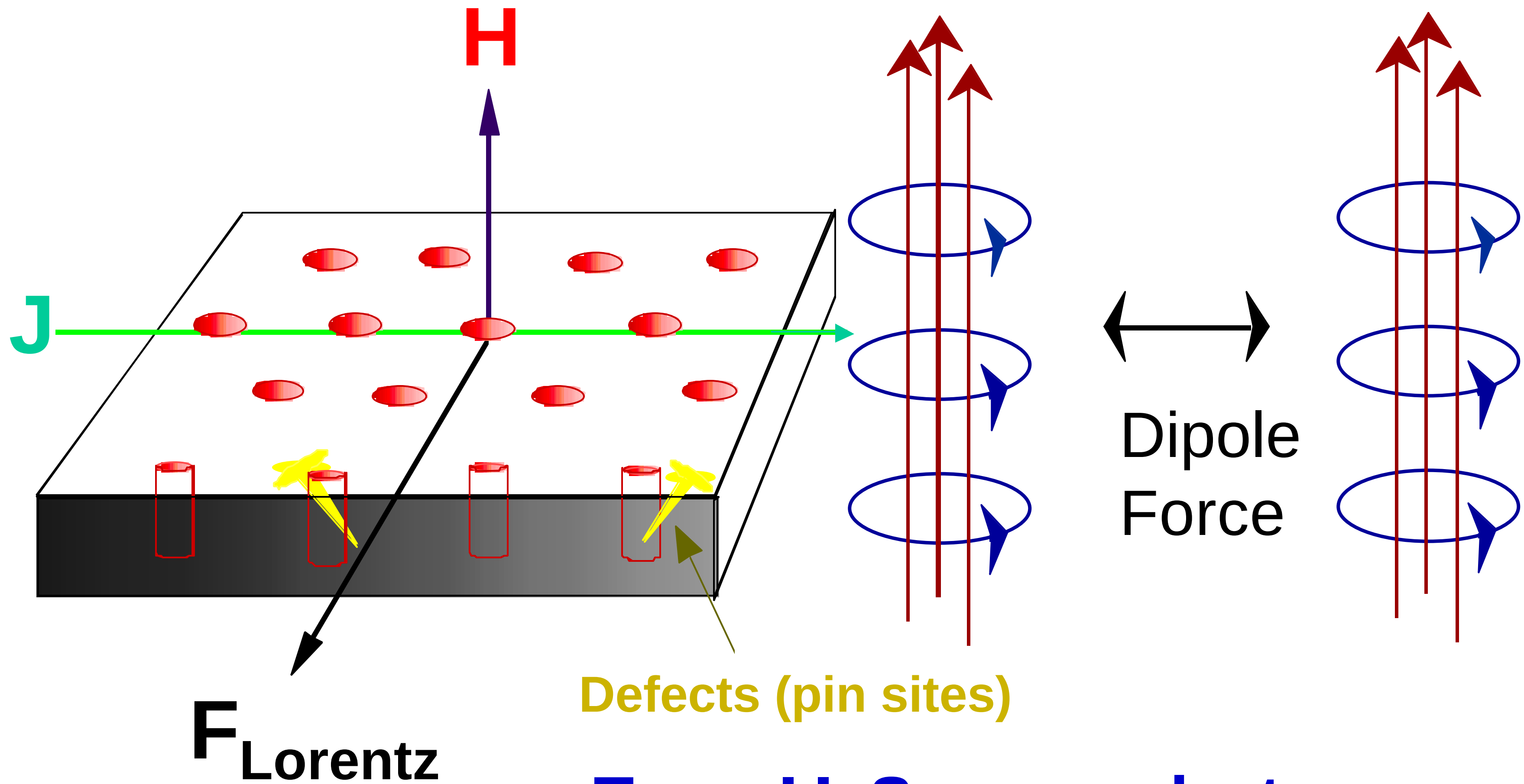
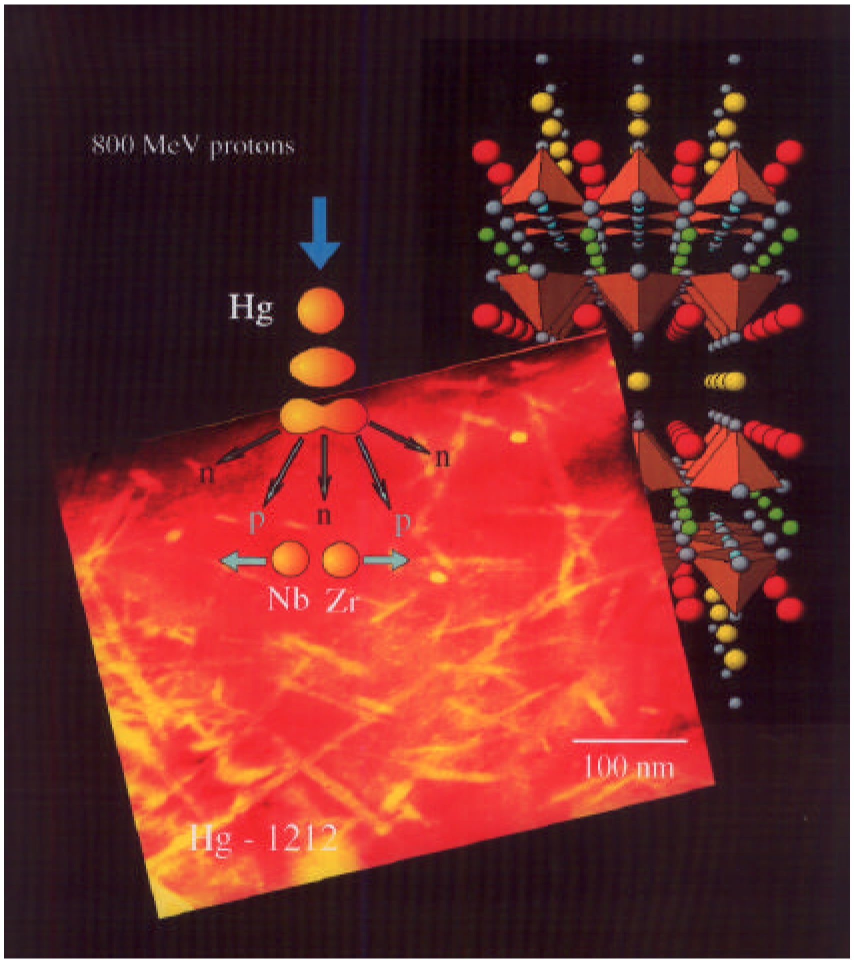
Abrikosov Vortex Lattice



Type II Superconductor in the Mixed State

Hg-1212: Fission-Induced Defects

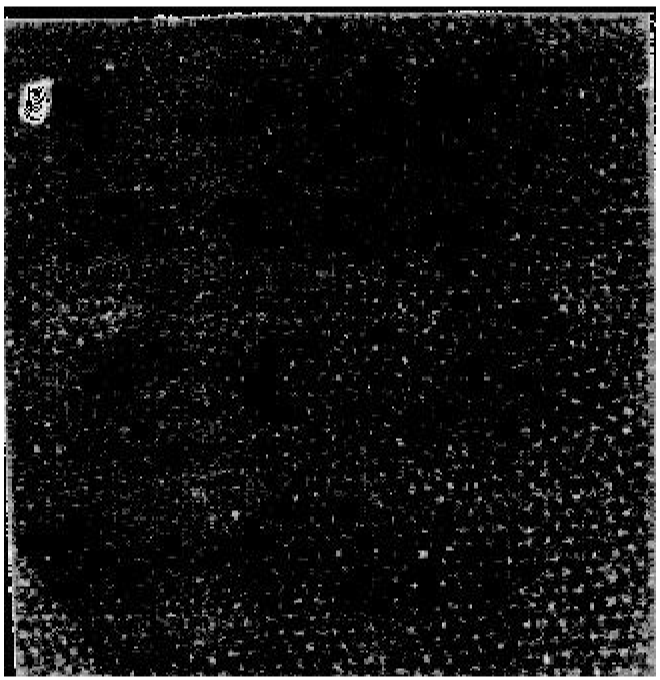


- L. Krusin-Elbaum, et al., Nature
- World record H_{irr} at 77 K in Hg-1212
- Hg-1212 Prototype Tapes made at TCSUH
- Potential for high-field magnet inserts

Extrinsic Pinning

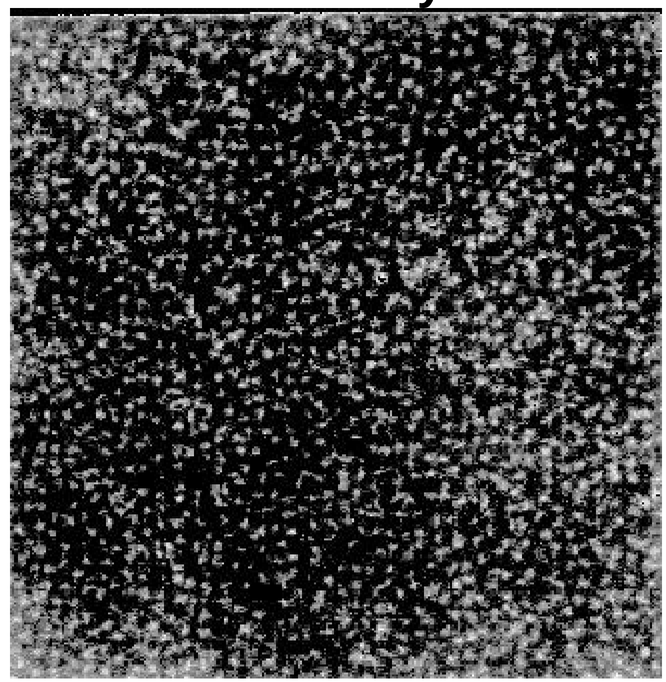
DECORATED VORTEX ARRAYS

clean



10 ?m

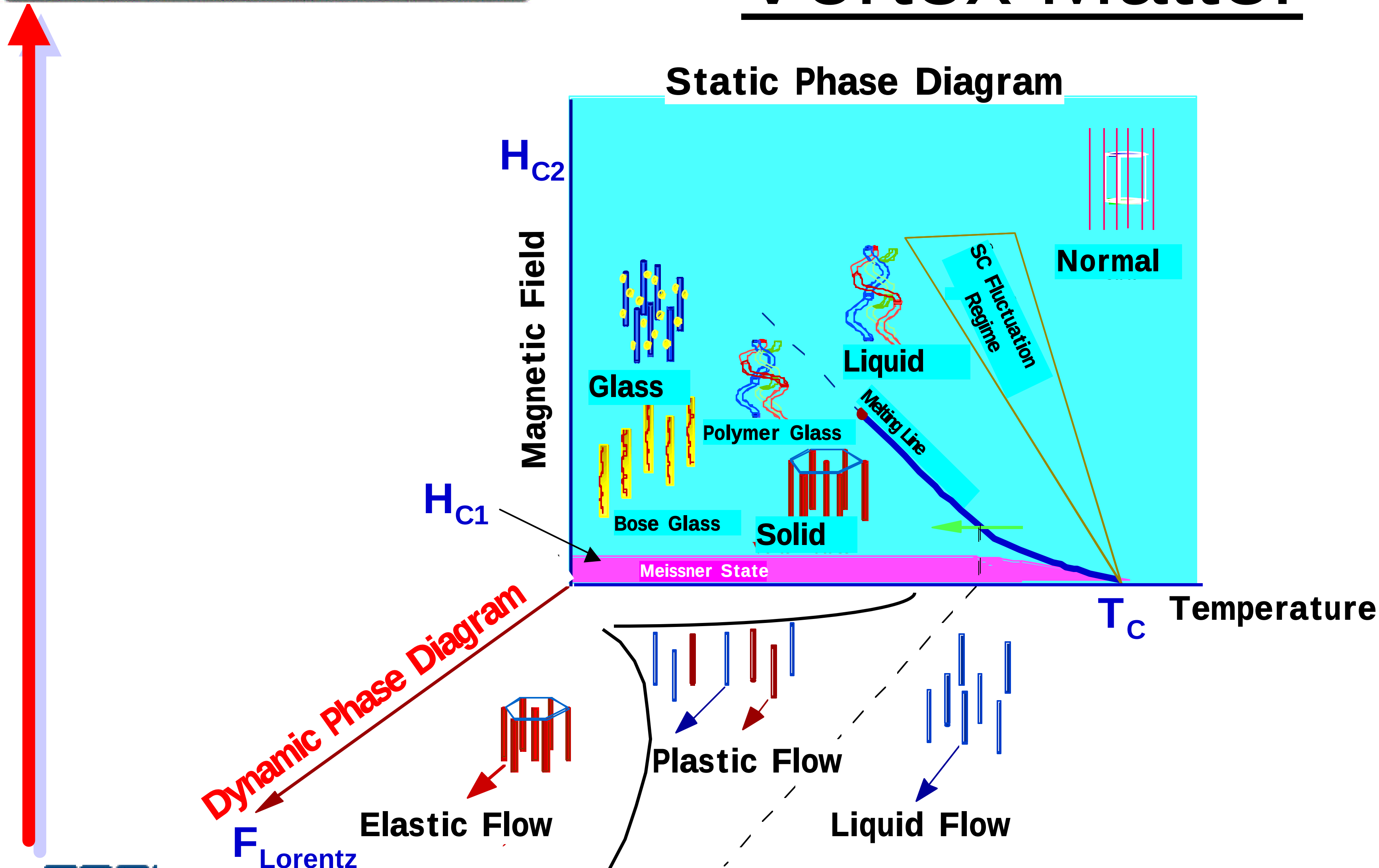
with random heavy ion tracks



10 ?m

M. Leghissa, et al. Phys. Rev. **B48**, 1341 (1993)

Vortex Matter



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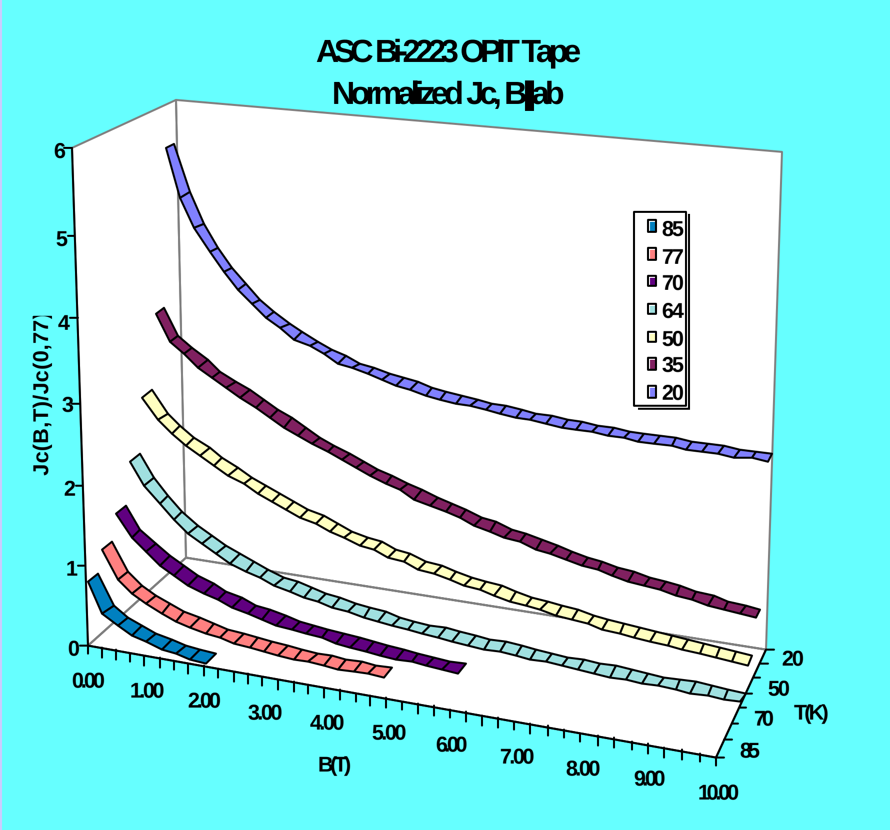
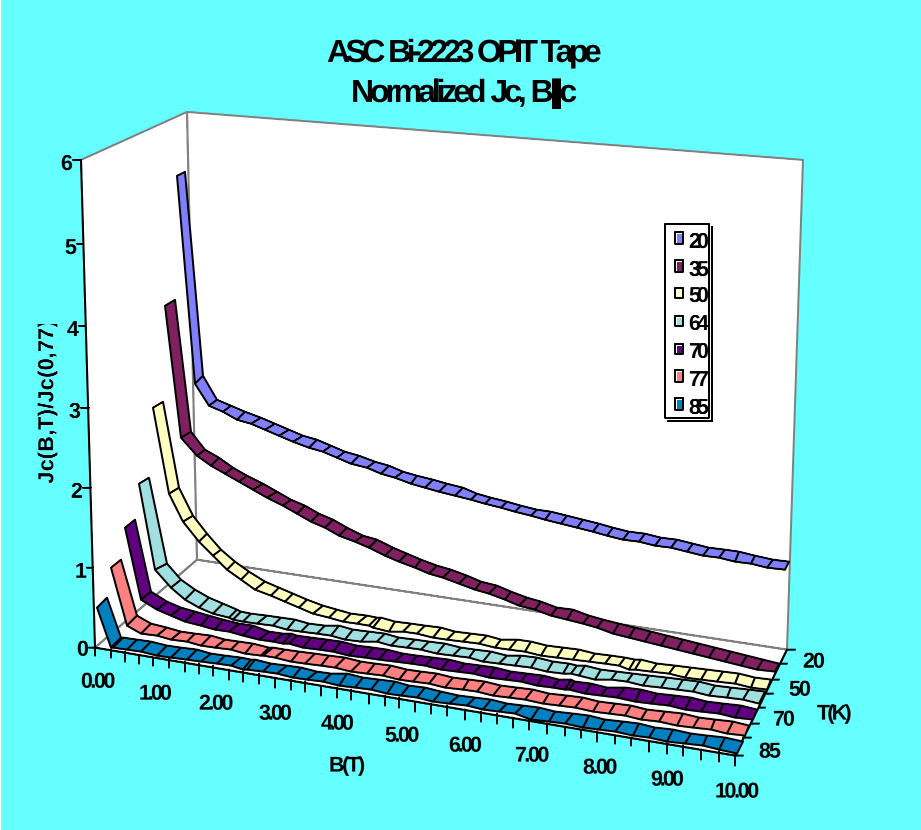
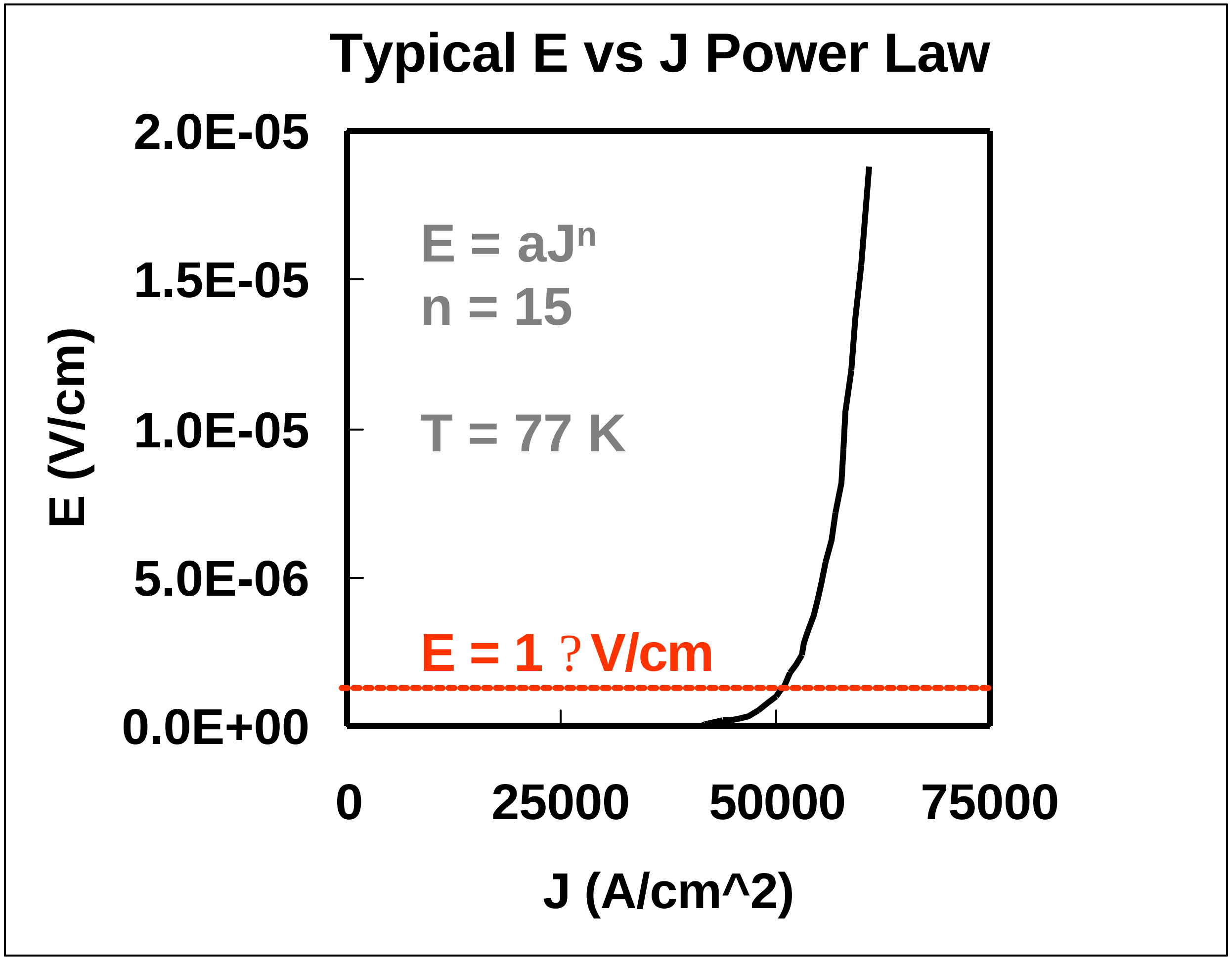
J_C(B,T) for BSCCO



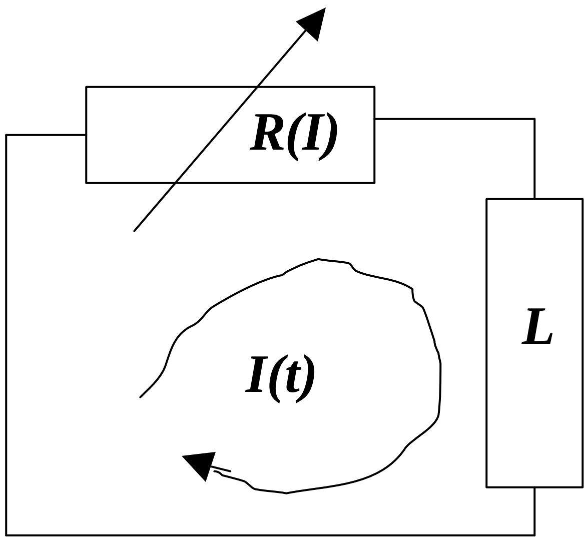


P. M. Grant
Superconductivity 101

BSCCO OPIT/Ag E-J Characteristic



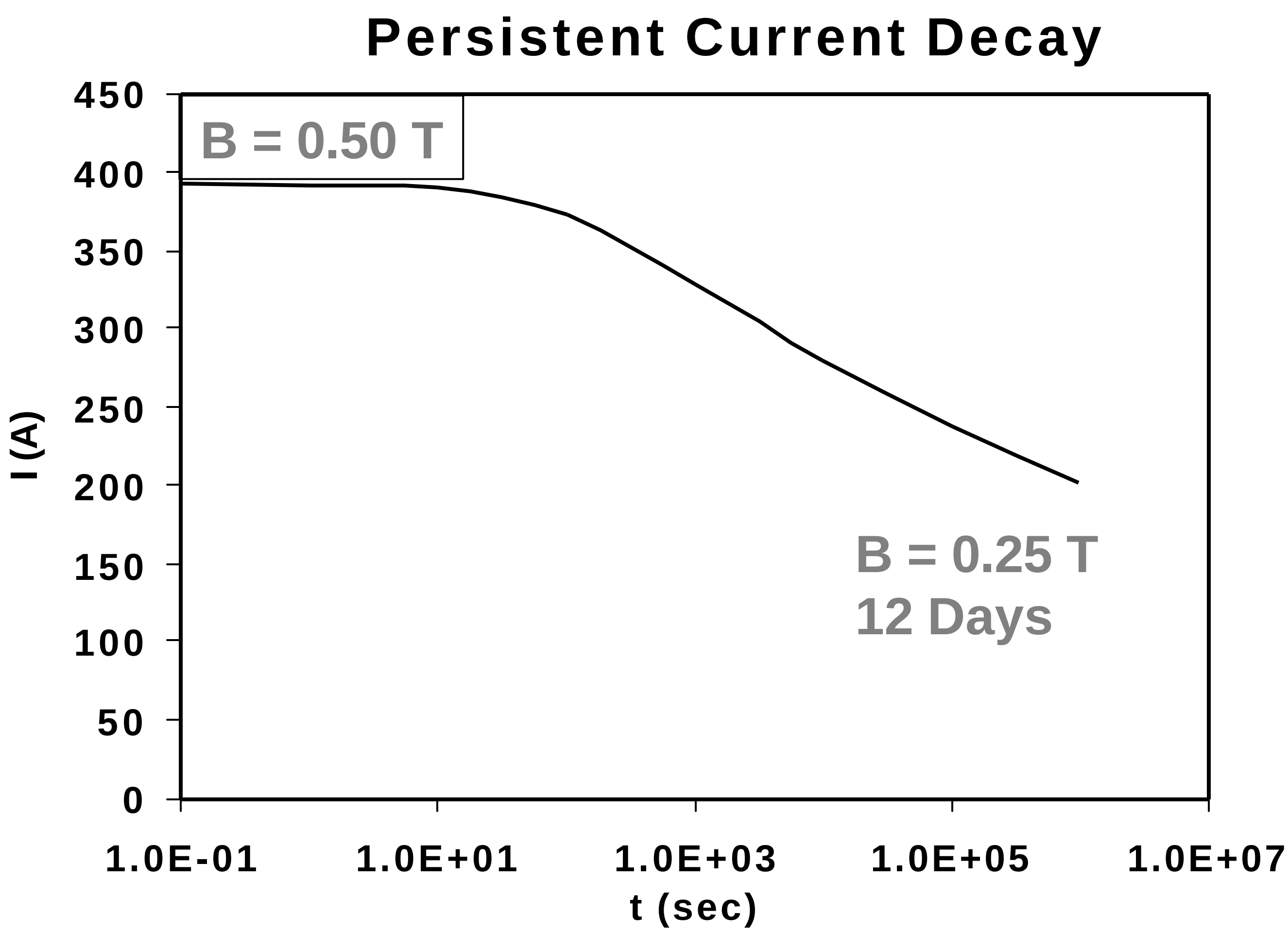
Solenoid Loop Current: $t > t_0$



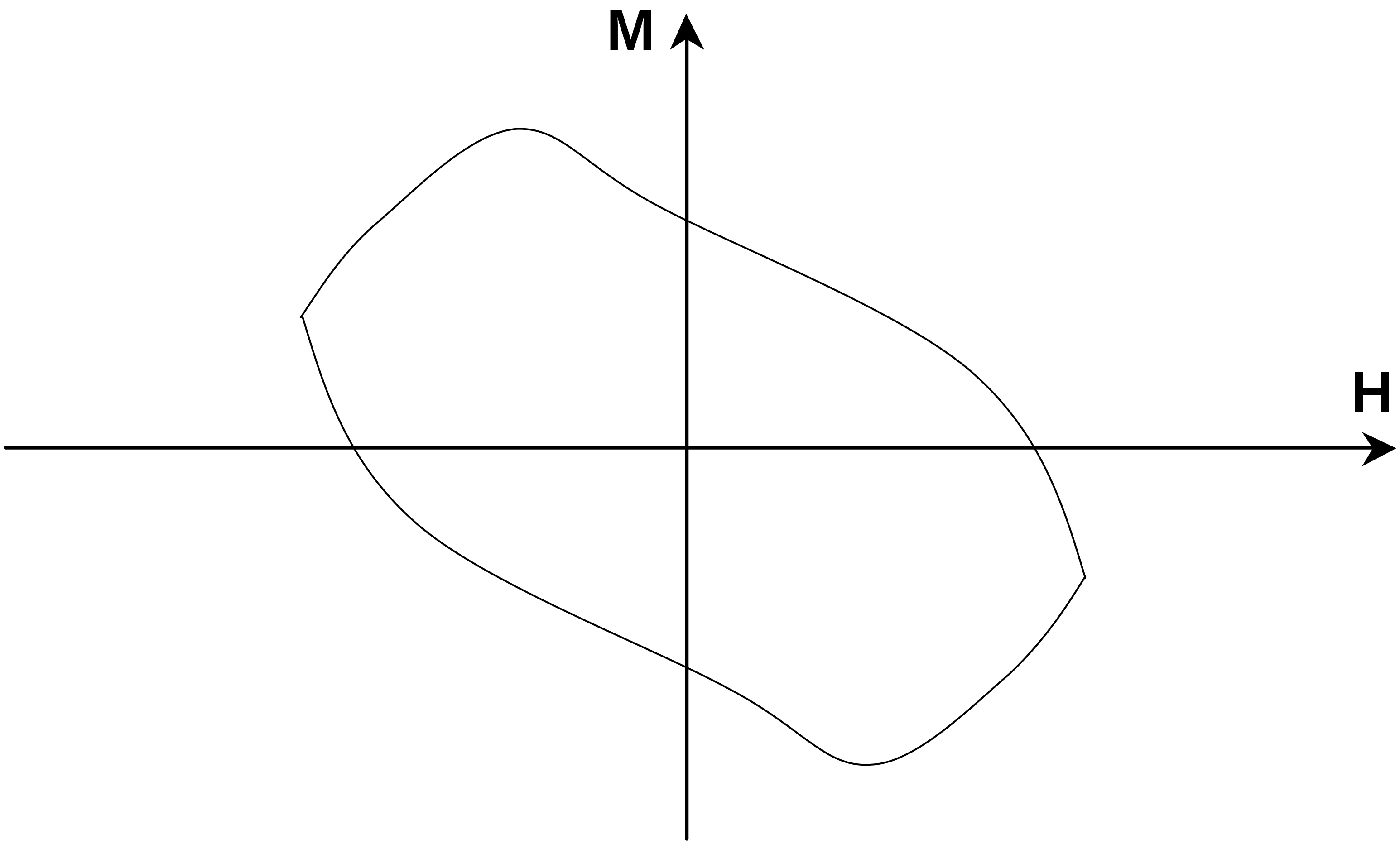
$$bI^n + L\frac{dI}{dt} = 0$$

$$I(t) = \left[\frac{b(n-1)}{L}(t - t_0) + I_0^{1-n}\right]^{\frac{1}{1-n}}$$

"Persistent" Current Decay



Type II Hysteresis



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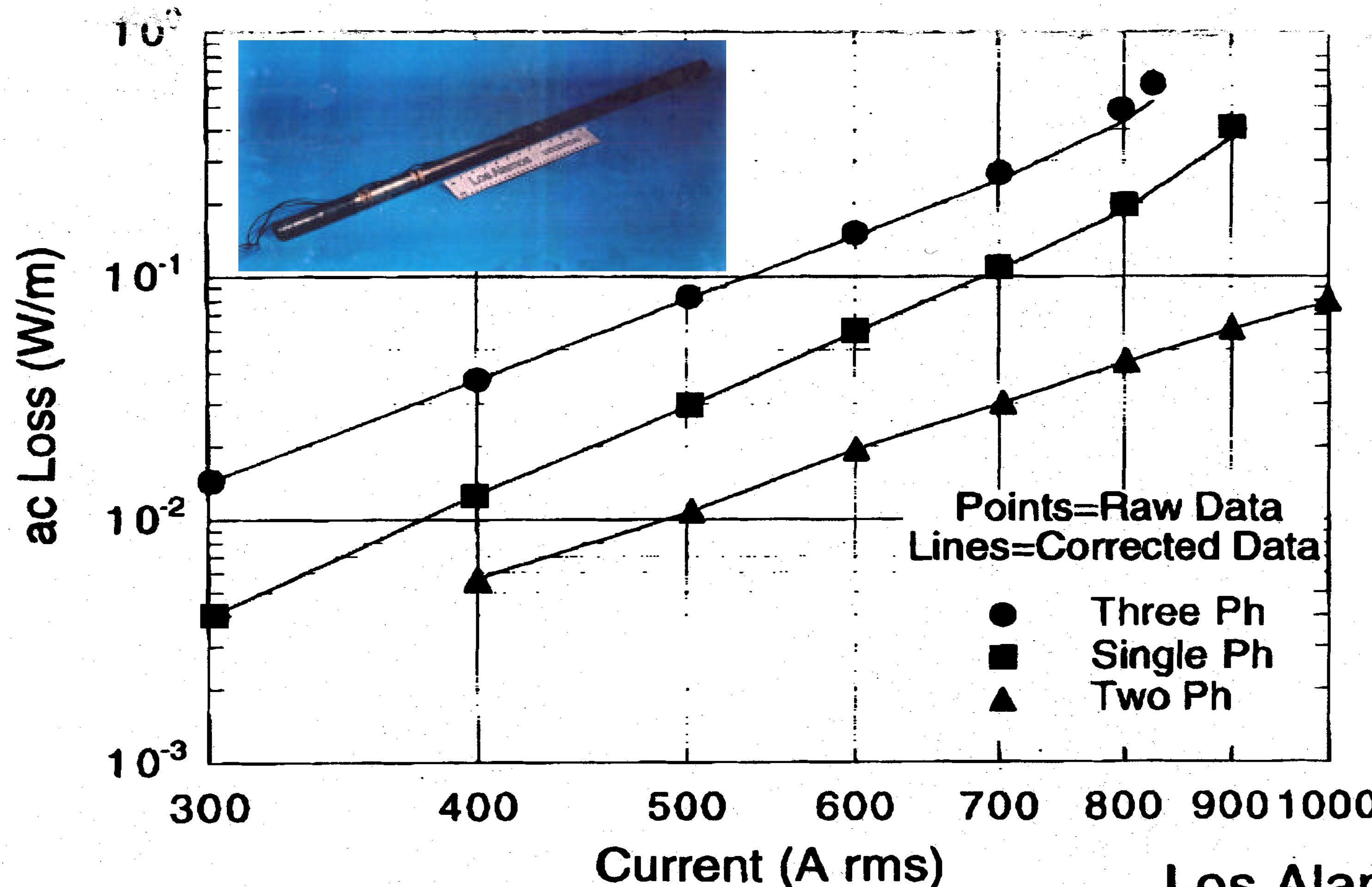
Hysteretic ac Loss



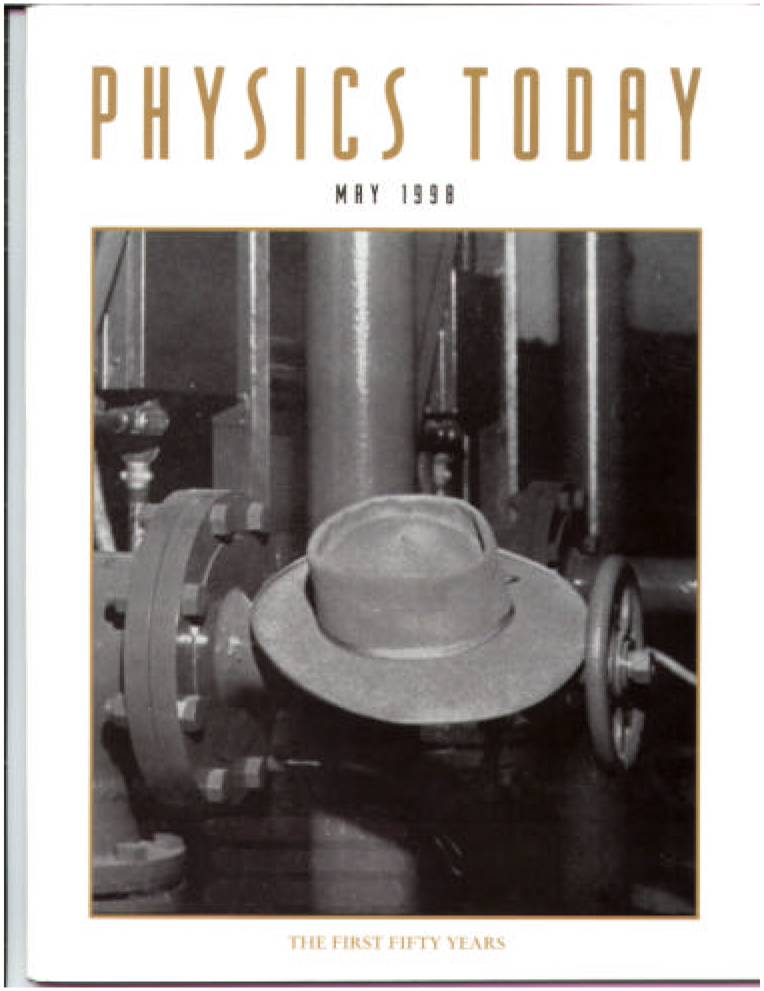
Los Alamos

Superconductivity Workshop

Charlotte, 24 May 1999

Insulated Conductors Committee

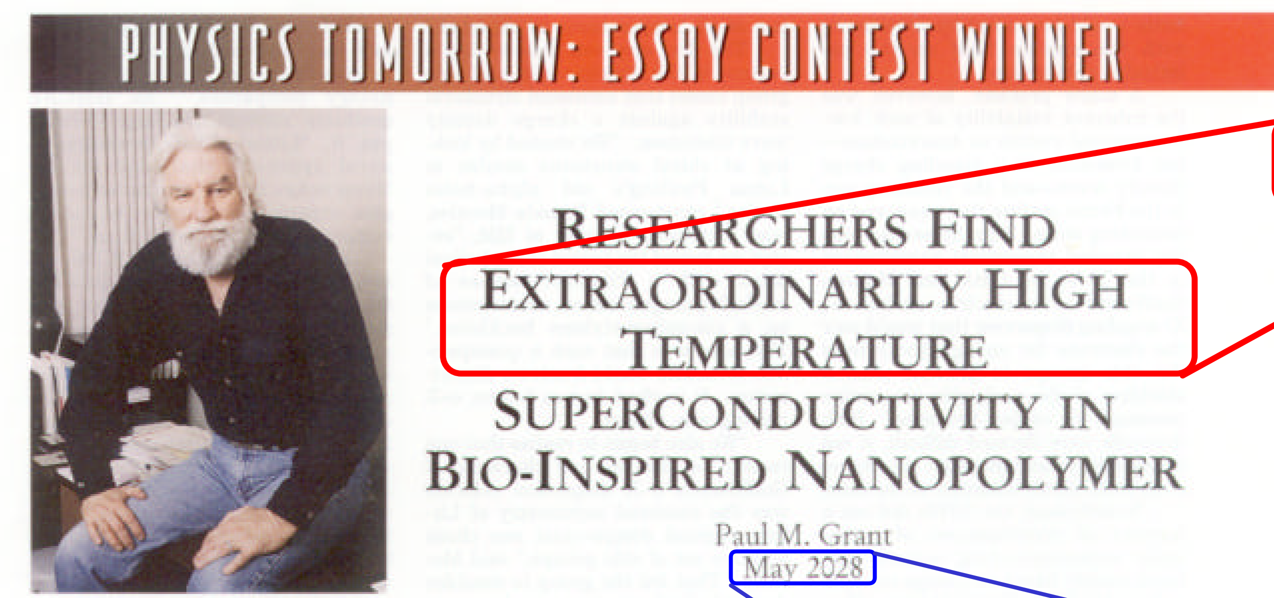
The Future 2028



P. M. Grant

Superconductivity 101

The Future


PHYSICS TOMORROW: ESSAY CONTEST WINNER

RESEARCHERS FIND EXTRAORDINARILY HIGH TEMPERATURE SUPERCONDUCTIVITY IN BIO-INSPIRED NANOPOLYMER

Paul M. Grant
May 2028

700 K !

May, **2028**

IEEE Networking the World™

Superconductivity Workshop
Charlotte, 24 May 1999

Insulated Conductors Committee

Electricity: A Life Necessity

California, Summer 1996

Sunday, August 11, 1996

Millions lose power

Half of PG&E's customers in Northern California affected; blackouts in 9 states

THE POWER PROBLEM

PG&E

Firms wonder: Is this the future?

U.S. says power will be bolstered

Substation explosion cuts PG&E service in South San Jose

Outage raises serious worries

More Outages Expected for Power Network

Increased demand strains regional transmission lines

Investigations planned after power grid falters

ELECTRICITY USERS FEELING POWERLESS

Shutoffs fray nerves in South San Jose

Quebec, Winter 1997

"You can't always get what you want..."

"…you get what you need!"