

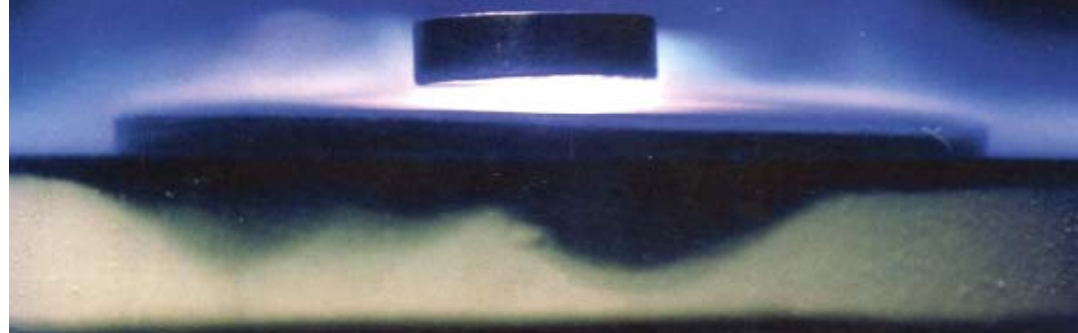
physicsworld

physicsworld.com

Volume 24 No 4 April 2011

SUPERCONDUCTIVITY

THE
FIRST
100
YEARS



100 Years and Counting- The Continuing Saga of Superconductivity

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IBM Physicist, Emeritus



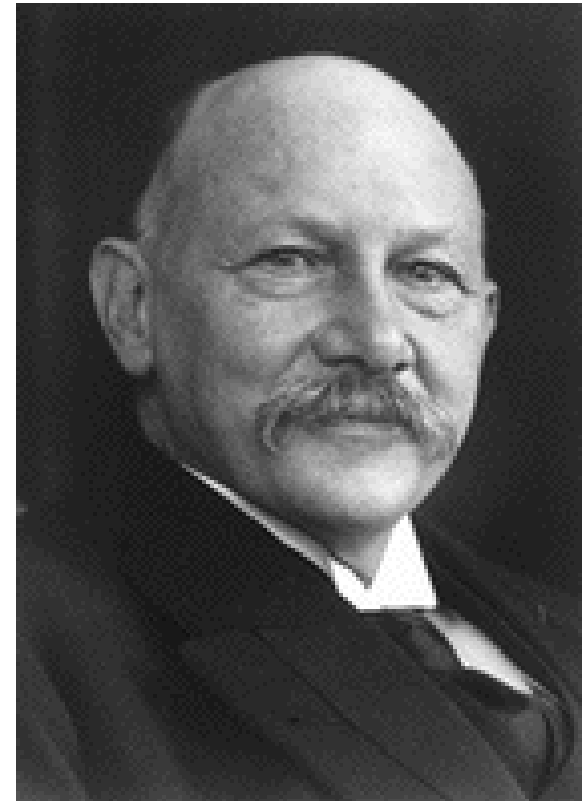
It takes two to Tango

Fathers of Cryogenics

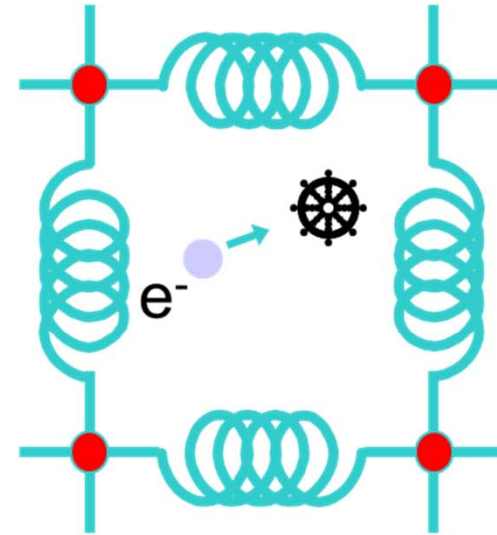
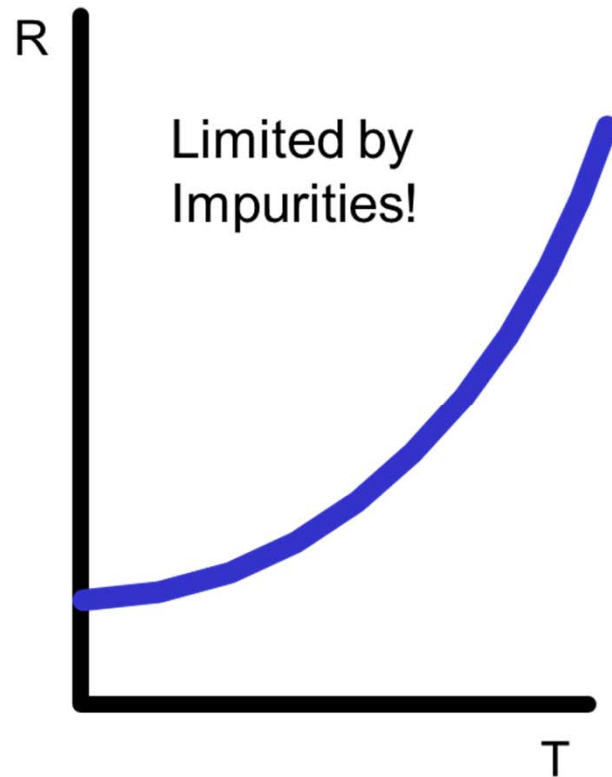


Dewar

CH ₄	112 K
O	90
N ₂	77
Ne	27
H ₂	20
He	4.2



Kammerlingh-Onnes



Resistance vs Temperature

At room temperature their relationship is linear. At low temperatures The resistivity is inversely proportional to the mean free path between collisions. At extremely low temperatures, the mean free path is dominated by impurities or defects in the material and becomes almost constant with temperature

How cold is too cold?

•Room temperature	298 K
•Freezing point of water	273 K
•Cold winter at Lake Tahoe	247 K
•Sublimation point of dry ice at 1 atm	194.5
•Coldest place on earth (Antarctica)	184 K
•Boiling point of liquid nitrogen	77 K
•Boiling of liquid hydrogen	21 K
•Boiling point of liquid helium	4.2 K



conductor



Semiconductor

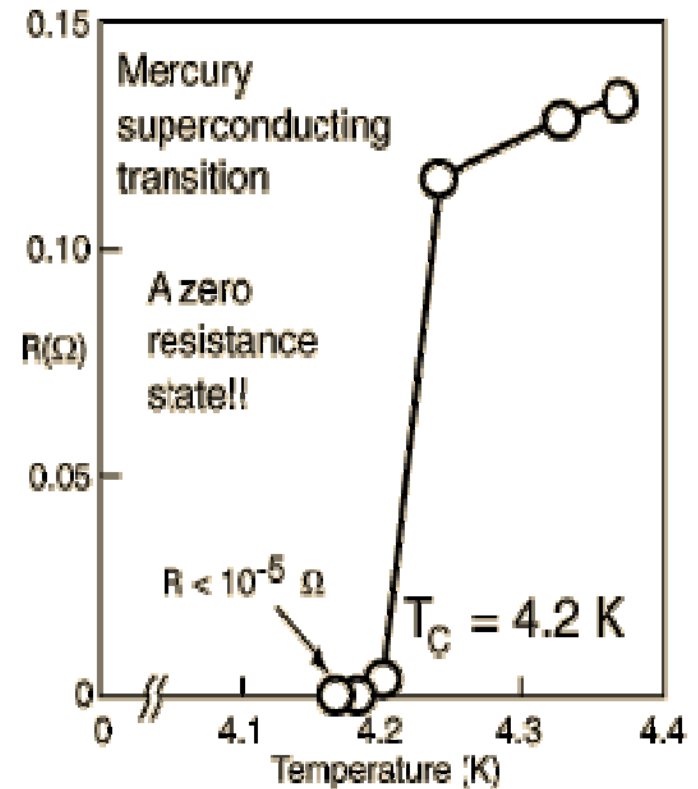
1911



H. Kamerlingh-Onnes



Gilles Holst



“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)



SUPERCONDUCTOR

H	superconductors at ambient pressure																He						
Li	Be																	B	C	N	O	F	Ne
Na	Mg	superconductors at high pressure																Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr						
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe						
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn						
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt															
*		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu							
**		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr							

Over the last 100 years, an ever bigger range of elements in the periodic table has been found to superconduct. Shown here are those elements that superconduct at ambient pressure, shaded according to when this ability was first unearthed (yellow/orange), and those elements that superconduct only at high pressure (purple).

Adapted from *Superconductivity: A Very Short Introduction* by Stephen Blundell (2009, Oxford University Press)

How does superconductivity happen?

It was not until the mid-1950s that the theoretical web surrounding superconductivity was finally unravelled, having frustrated attempts by some of the 20th century's brightest and best physicists, including Dirac, Einstein, Feynman and Pauli.

This feat was eventually accomplished by John Bardeen, Leon Cooper and Robert Schrieffer, leading to what is now called **BCS theory**.

the trio shared the 1972 Nobel Prize for Physics

The Meissner Effect

When a material makes the transition from the normal to [superconducting](#) state, it actively excludes [magnetic fields](#) from its interior; this is called the Meissner effect.

This constraint to zero magnetic field inside a superconductor is distinct from the [perfect diamagnetism](#) which would arise from its zero electrical resistance.

Zero resistance would imply that if you tried to magnetize a superconductor, current loops would be generated to exactly cancel the imposed field ([Lenz's law](#)).

But if the material already had a steady magnetic field through it when it was cooled through the superconducting transition,

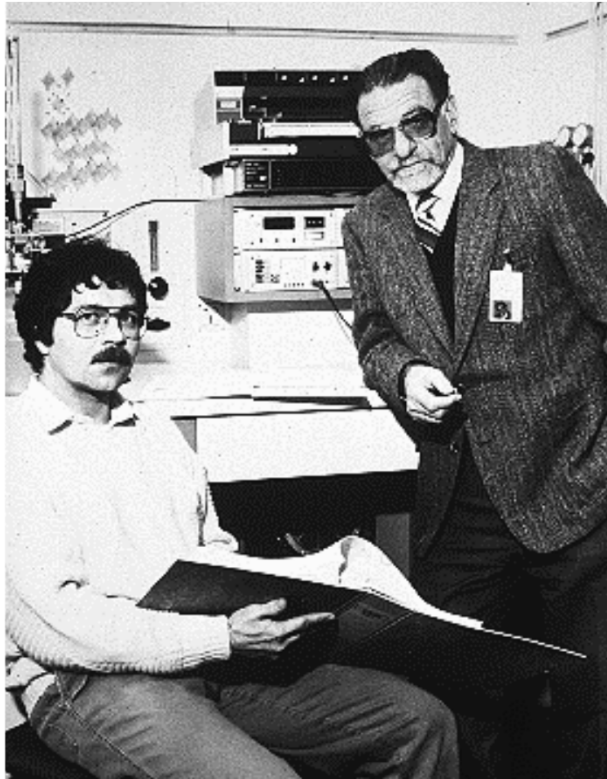
the magnetic field would be expected to remain.

If there were no change in the applied magnetic field, there would be no generated voltage ([Faraday's law](#)) to drive currents,

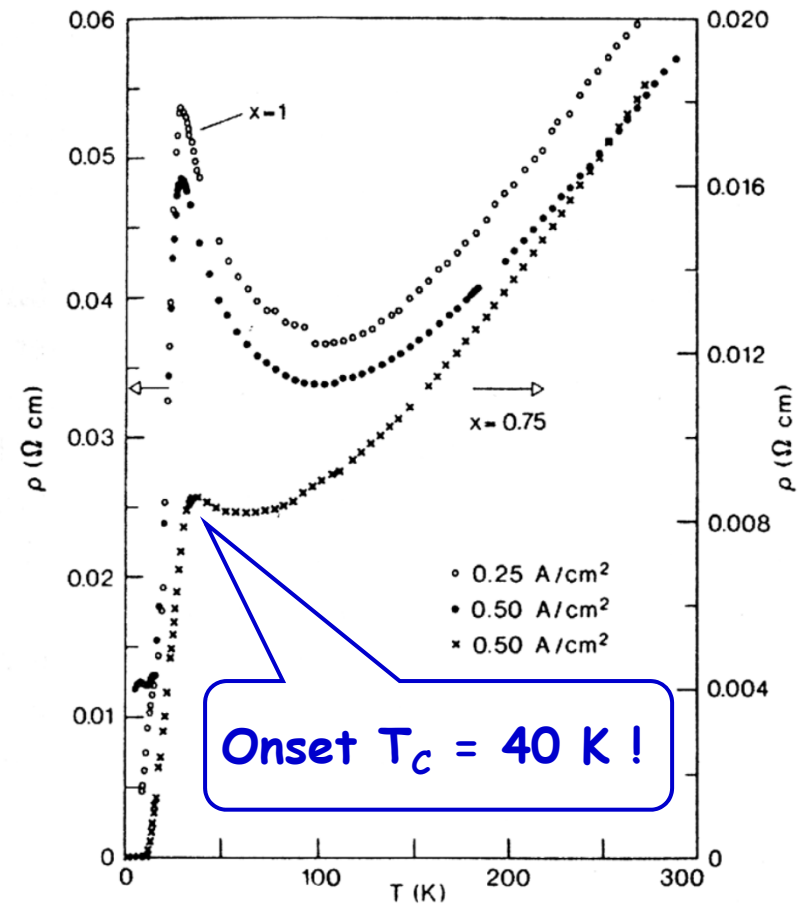
even in a perfect conductor. Hence the active exclusion of magnetic field must be considered to be an effect distinct from just zero resistance.

Racing for higher T SC

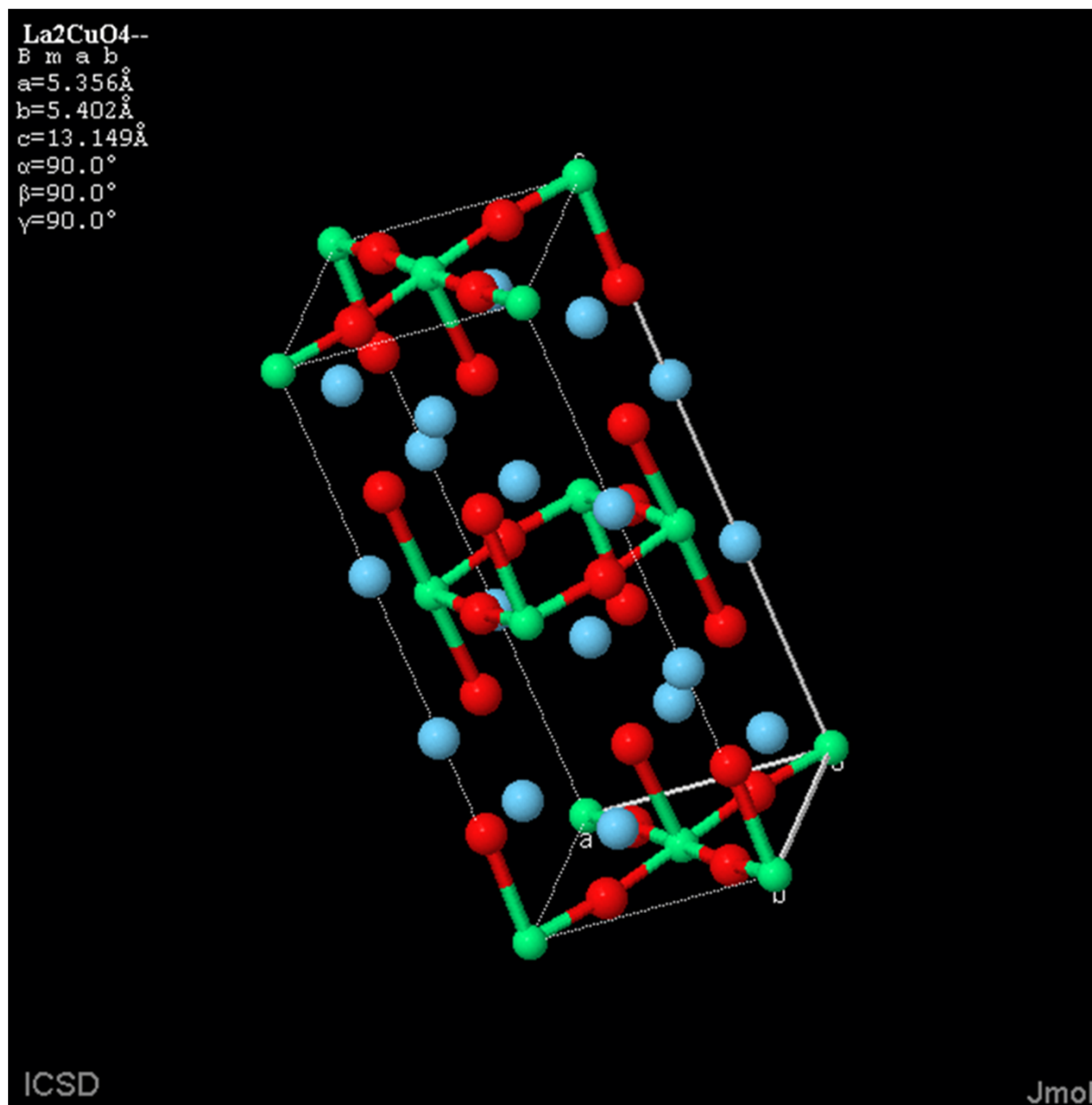
1986



Bednorz and Mueller
IBM Zuerich, 1986



La_2CuO_4 (doped with Ba)



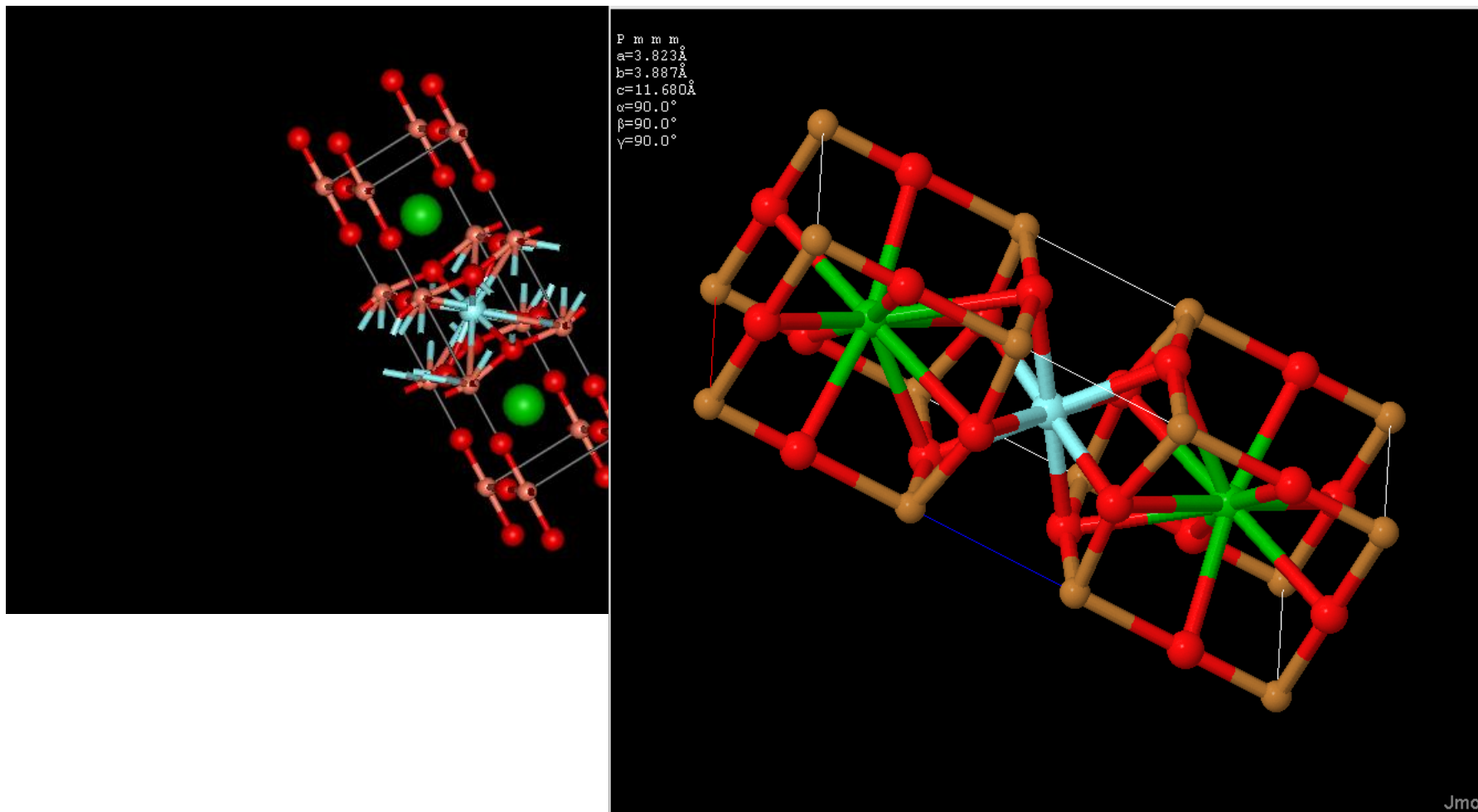


2011

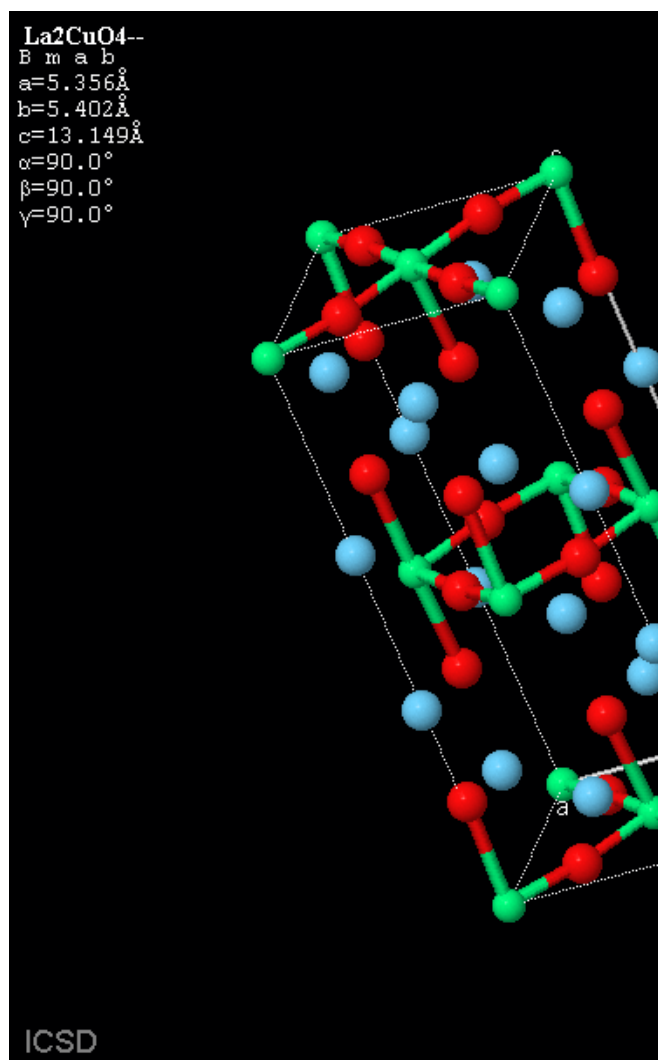
In February of 1987, a perovskite ceramic material was found to superconduct at 90 K.

Because these materials superconduct at significantly higher temperatures they are referred to as **High Temperature Superconductors**.

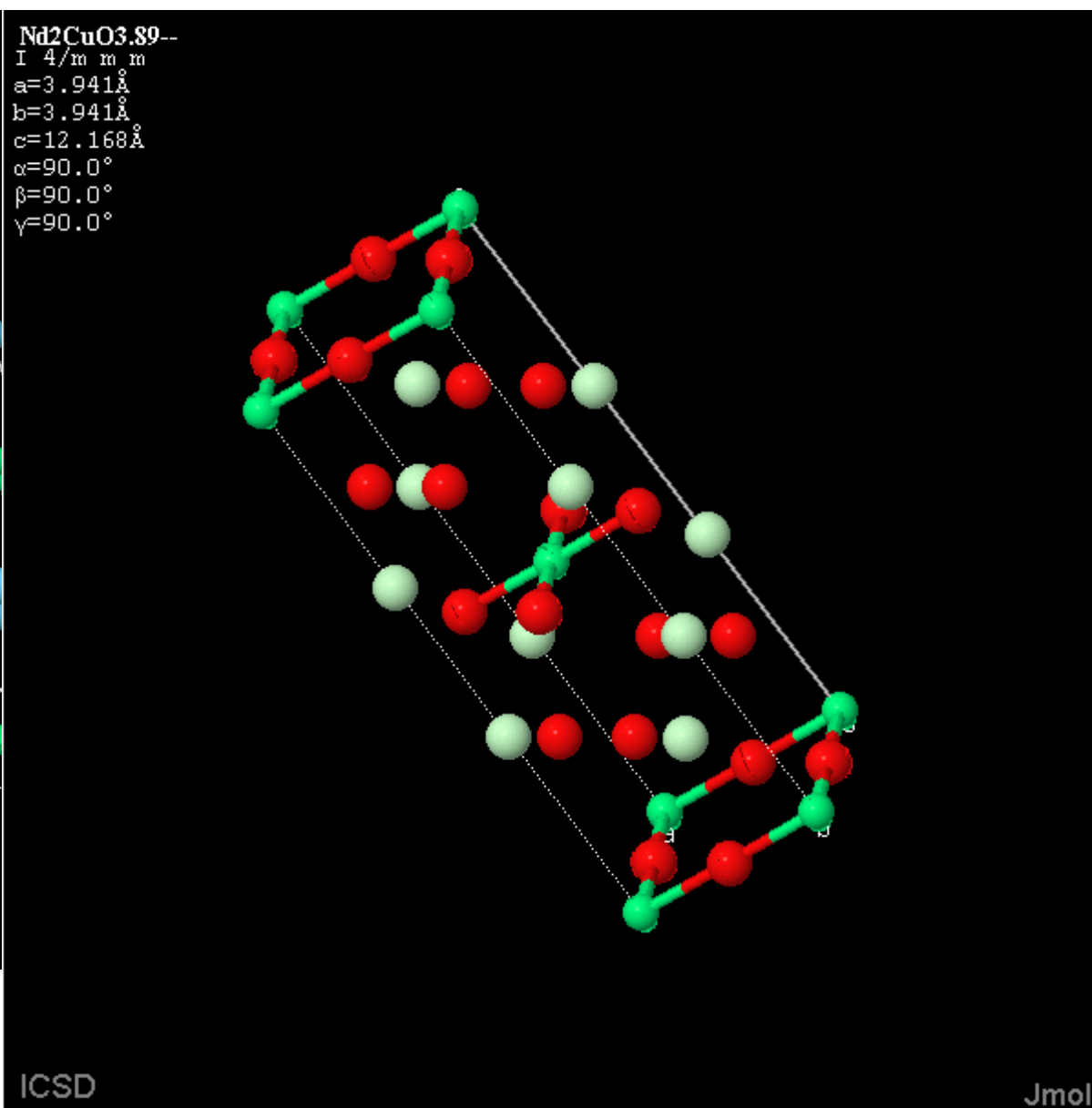
This discovery was very significant because now it became possible to use liquid nitrogen as a coolant.



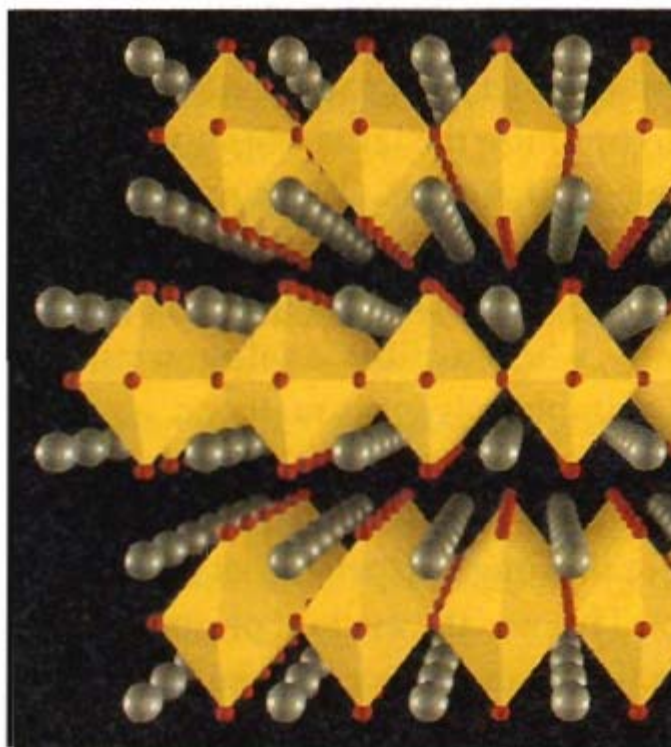
Y123



La214



Nd214



Figs. 1–6. Crystal structures of the generic copper compounds. Unless otherwise noted, the colors and size reflect scaled ionic radii, designate the following: blue = copper, grey = lanthanide (La, Y, Gd, Eu). To indicate the copper coordination in the presence of planar coordinated copper is shown by the La_2CuO_4 ; alkaline earth substitution occurs on sites at the body centers of the bipyramids.

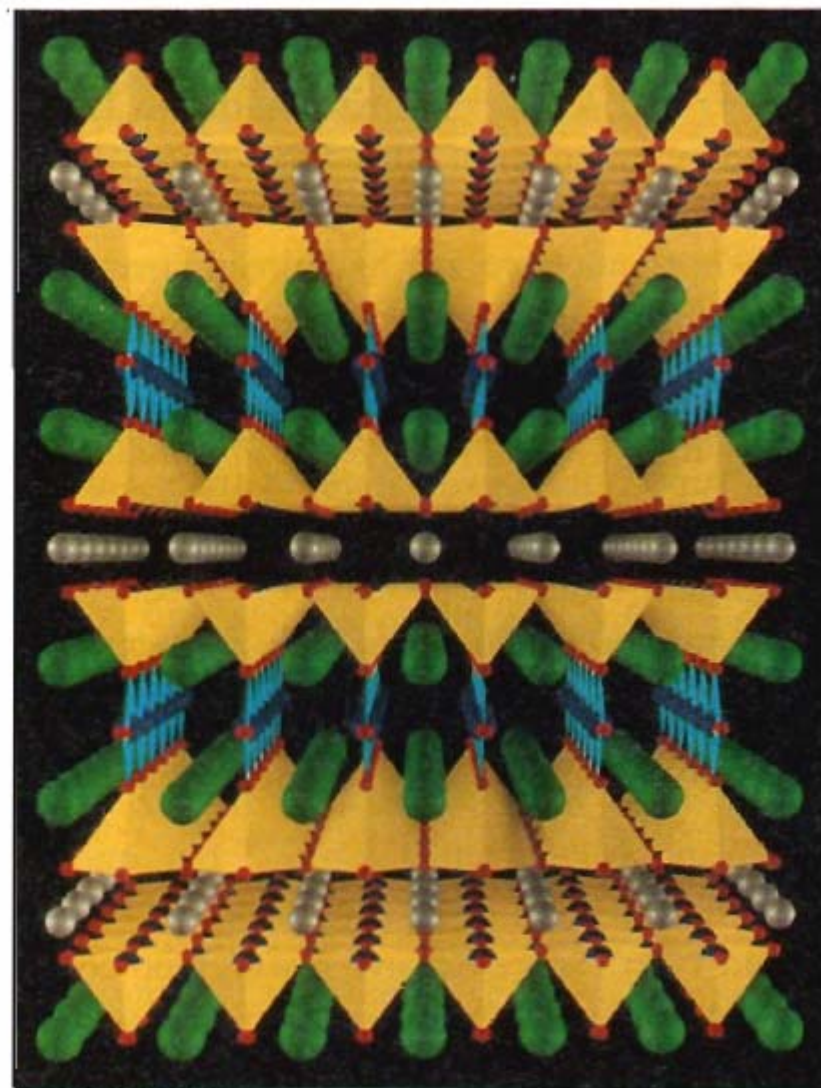


Fig. 3. $\text{YBa}_2\text{Cu}_3\text{O}_7$, the green spheres represent barium. For color coding see Figure 1.

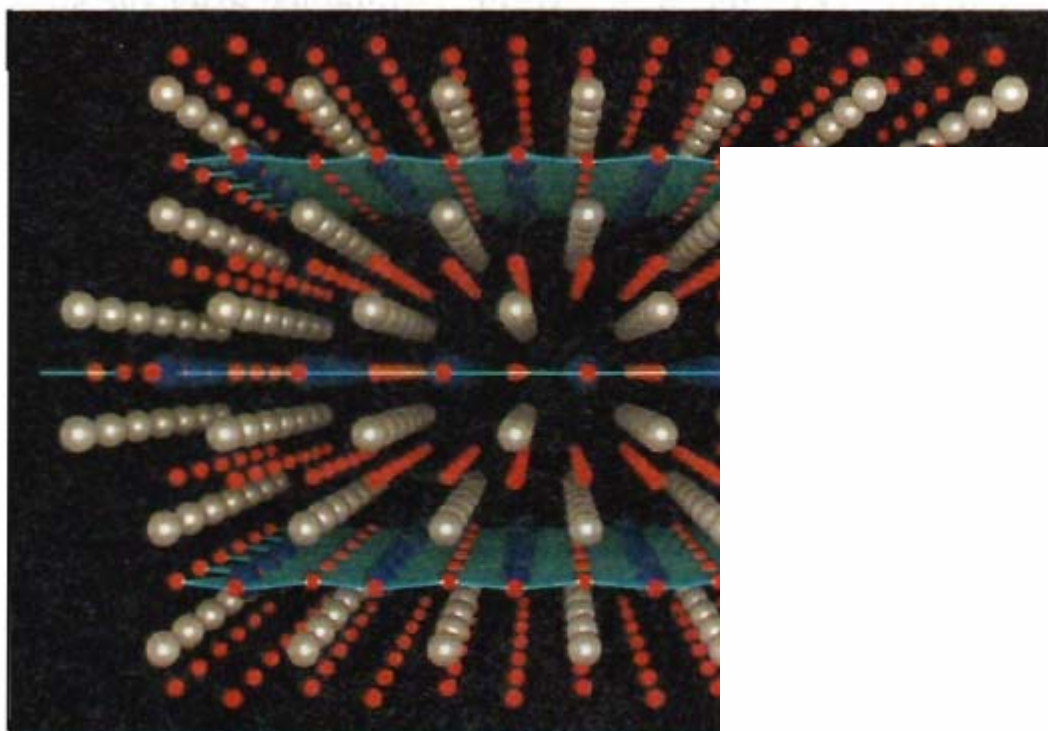


Fig. 2. Nd_2CuO_4 ; cerium or thulium substitution occurs on an oxygen site coordinated to neodymium (Figure 1).

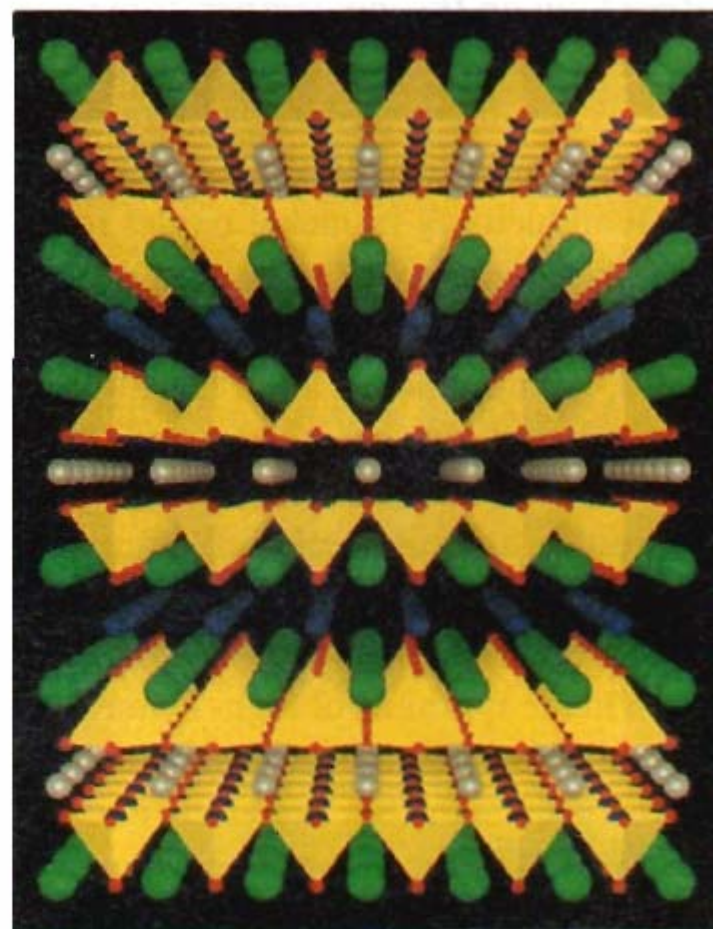


Fig. 4. $\text{YBa}_2\text{Cu}_3\text{O}_6$; note the complete absence of oxygen in the inter-barium plane, resulting in a purely tetragonal structure. For color coding see Figure 1.

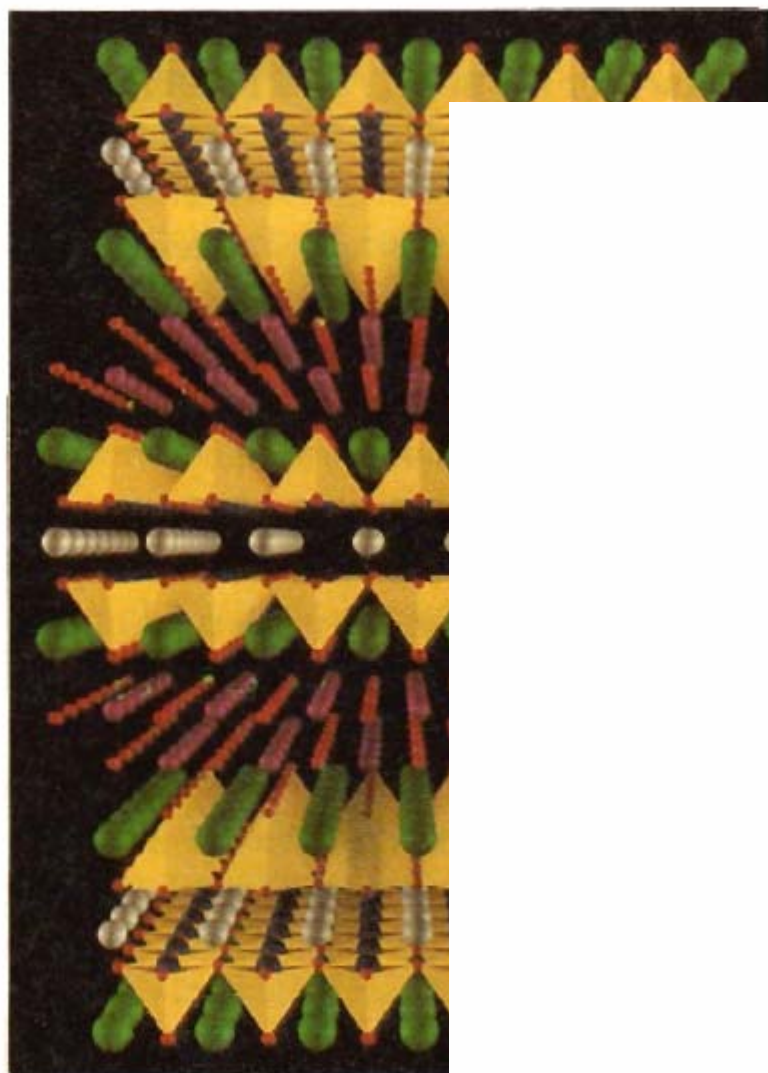


Fig. 5. $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_{8+y}$; the magenta spheres represent the green barium as in $\text{YBa}_2\text{Cu}_3\text{O}_7$; however, in this structure they are calcium, which can also be substituted by yttrium, at low concentration. For other color coding see Figure 1.

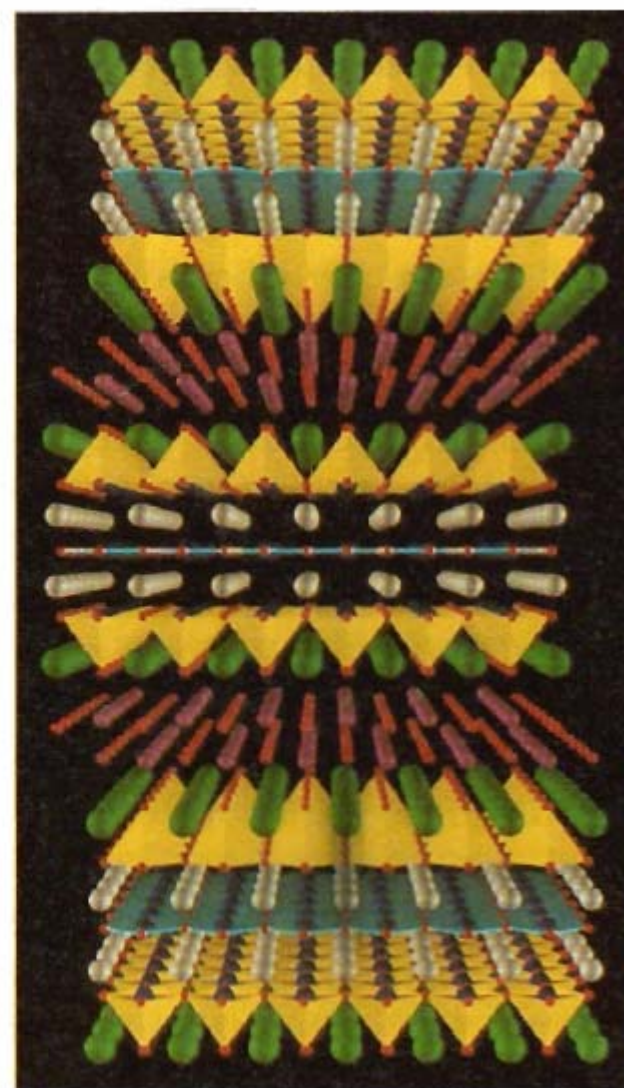
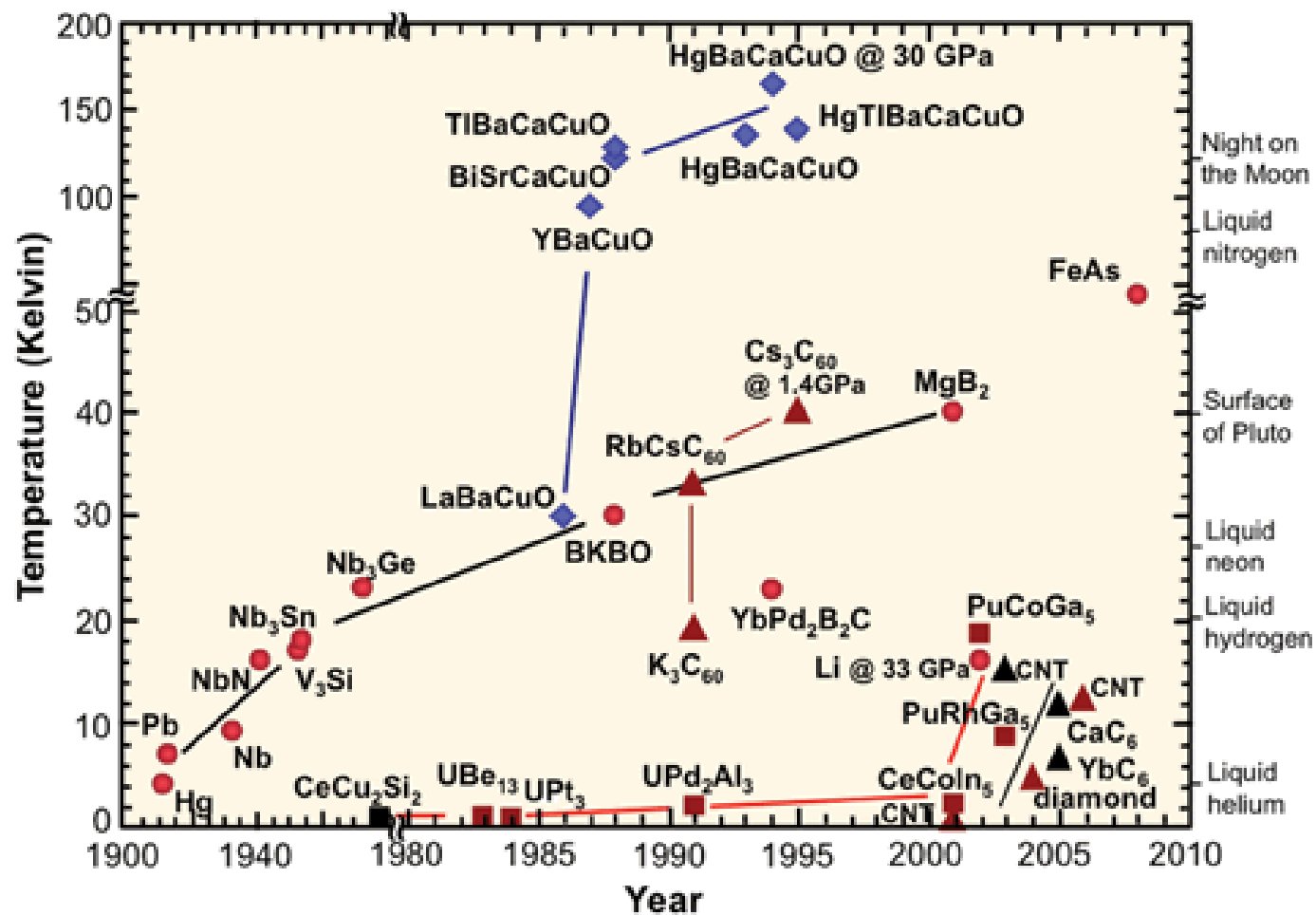
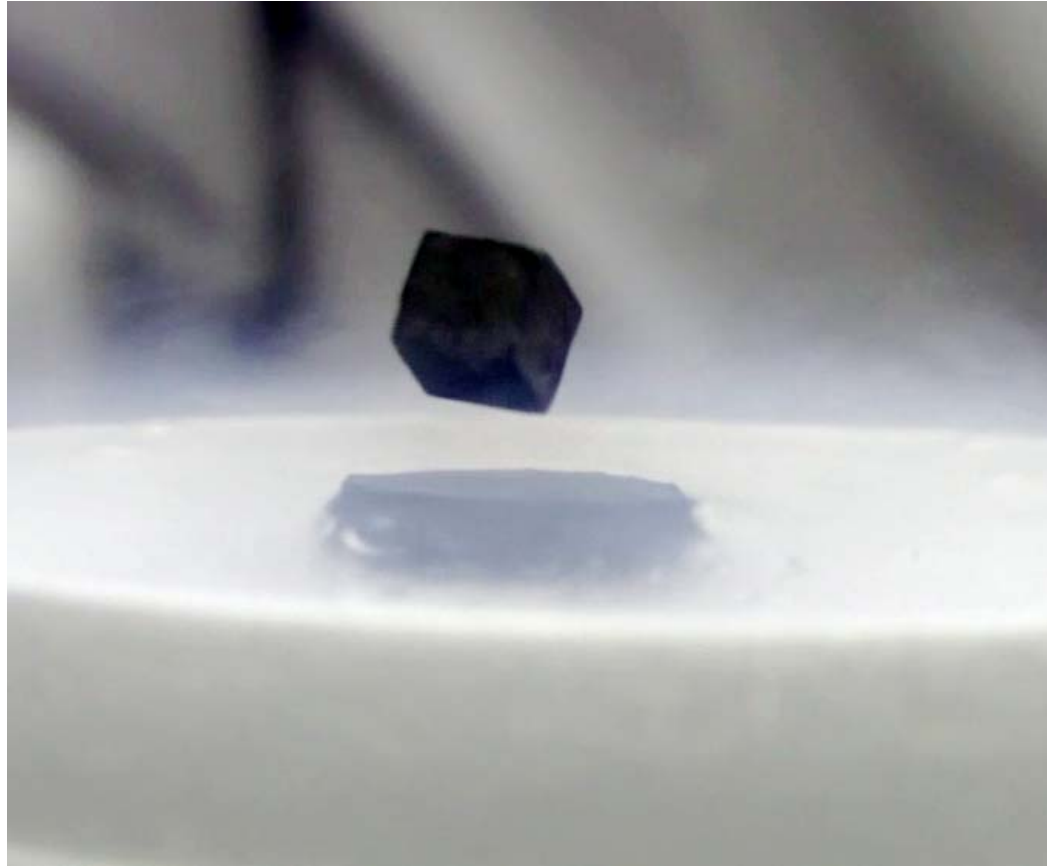


Fig. 6. $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+y}$; same representation as $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_{8+y}$ (Fig. 5). For the remaining color coding see Figure 1.



As of today the highest-temperature superconductor (at ambient pressure) is (HgBa₂Ca₂Cu₃O_x), at 135 K , reaching 164 K under high pressure.



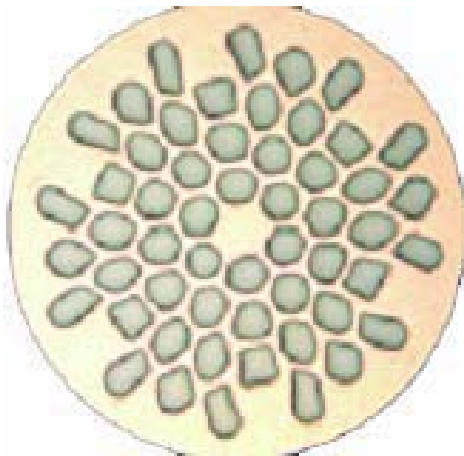
**Levitation of a magnet over a
superconductor**

Whither Applications of Superconductivity?

- Today & Tomorrow -

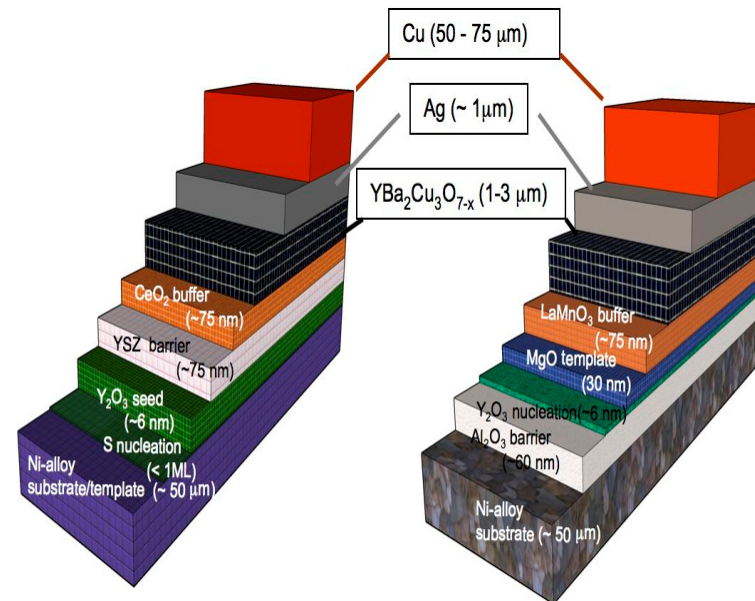
Wires & Films

LTSC



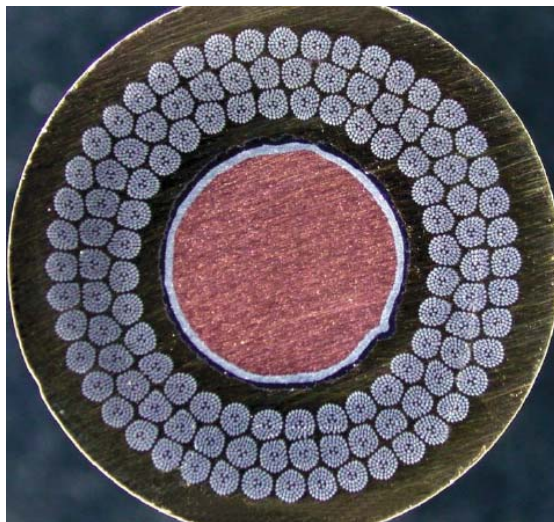
NbTi/Cu
Oxford

HTSC



Rolling-Assisted Biaxially
Textured Substrates
(RABiTS)

Ion-Beam-Assisted Deposition
(IBAD)



Nb₃Sn
Supercon

American
Superconductor

SuperPower

Medical Imaging



Altars to the Almighty - Yesterday

Giza



Teotihuacan



Chartes



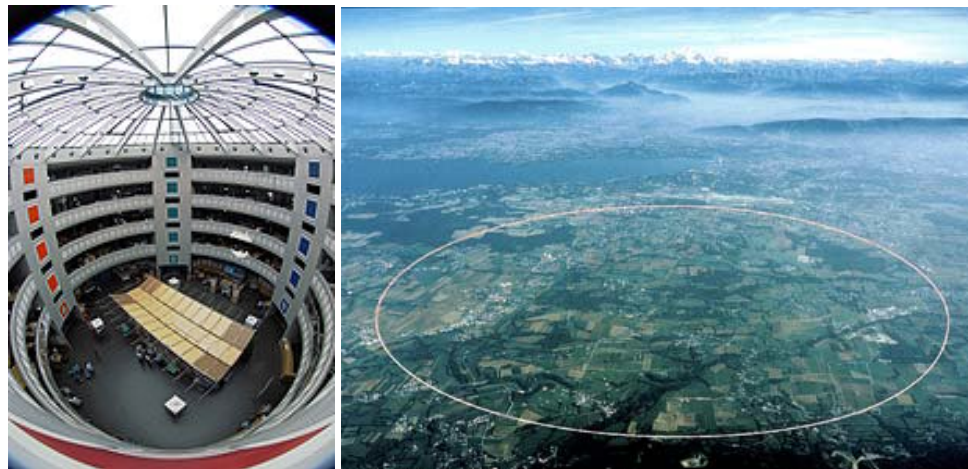
**Notre-Dame
de Paris**

Altars to the Almighty - Today

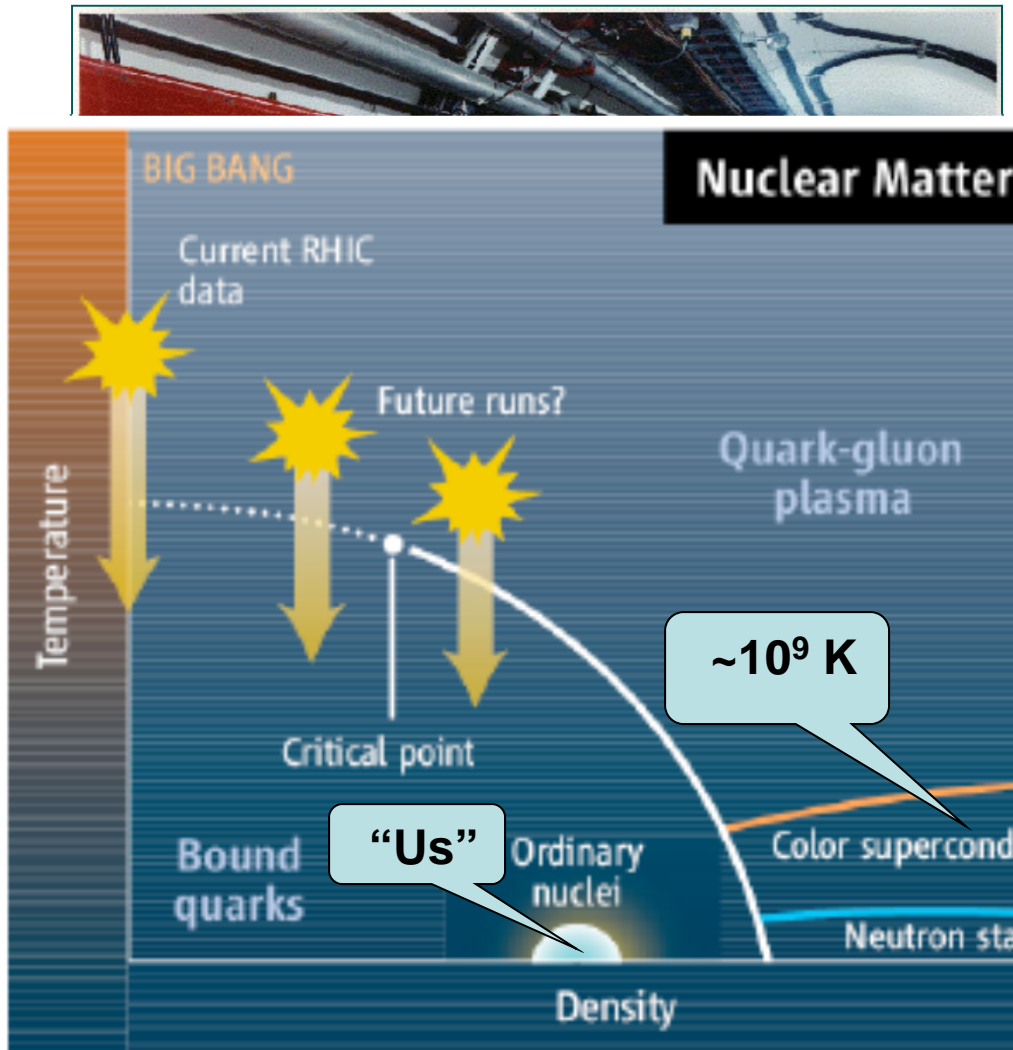
Fermilab



CERN - LHC

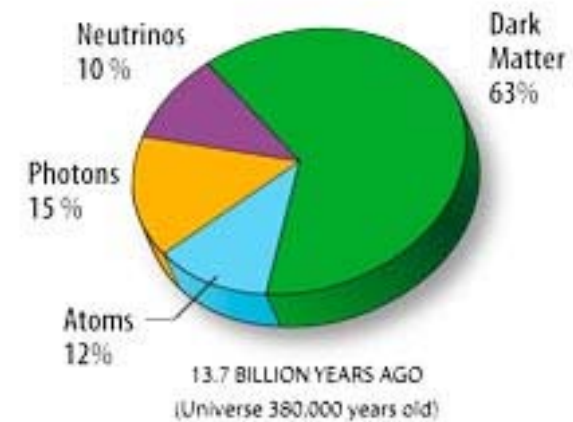
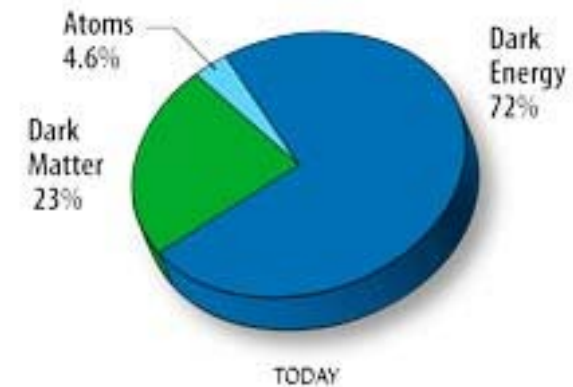
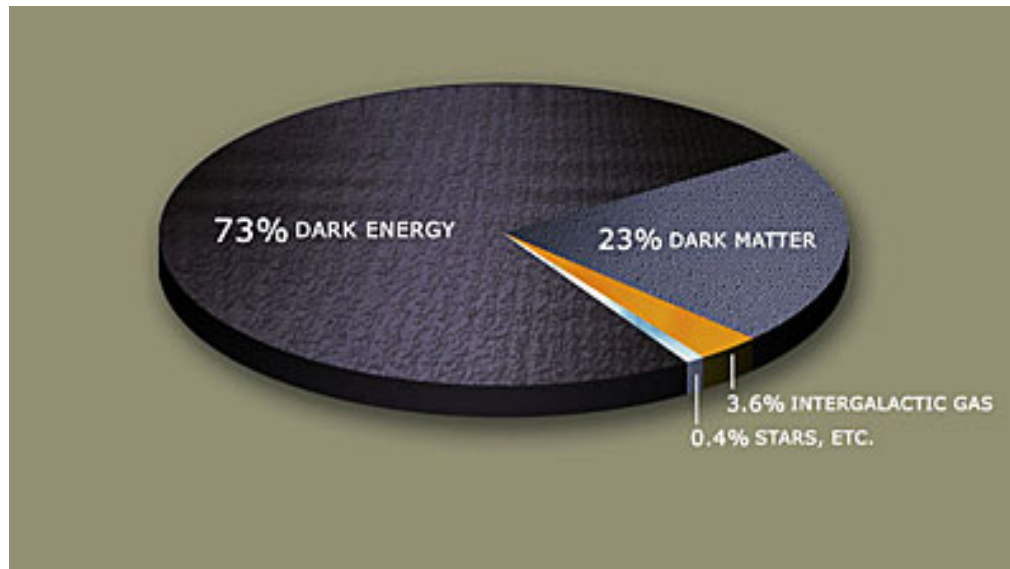


High Energy Physics

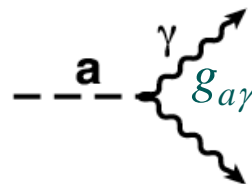
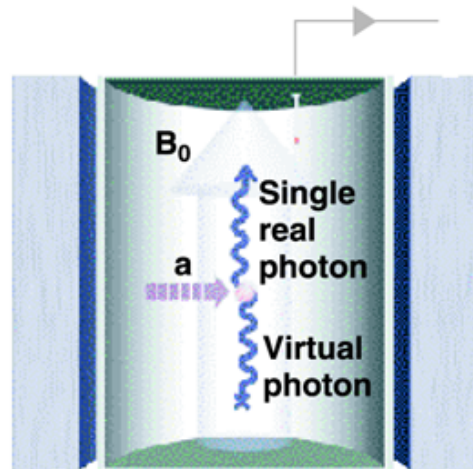


Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force
Leptons				Bosons (Forces)

Dark Matter



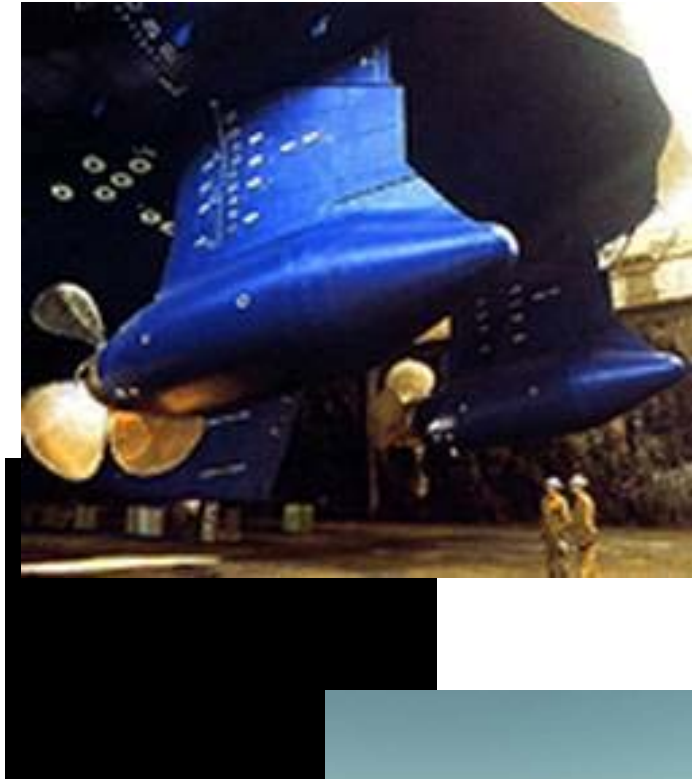
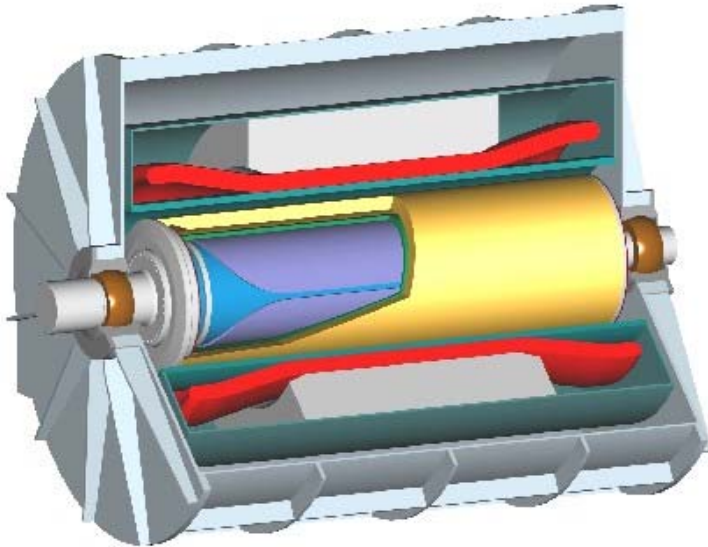
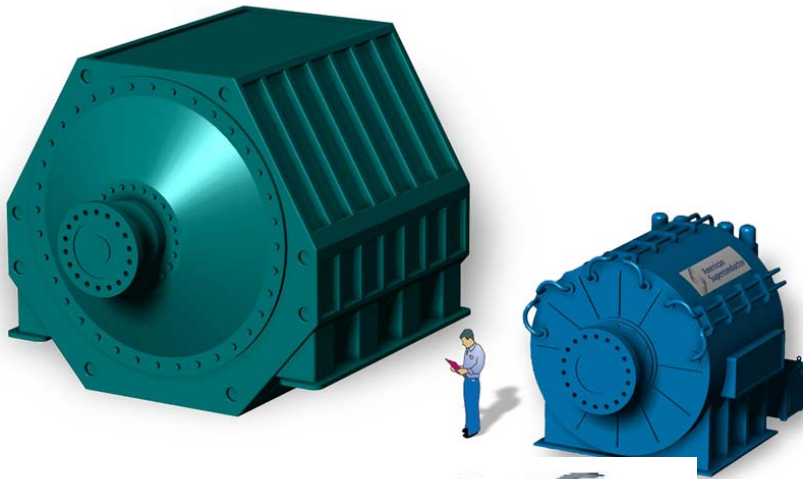
Primakoff Conversion



Primakov model predicts axion decay into a (presumably) detectable photon in a sufficiently large magnetic field contained in a superconducting solenoid and resonant cavity

Rotating Machinery

Courtesy AMSC



Major Players:

- AMSC
- SEI

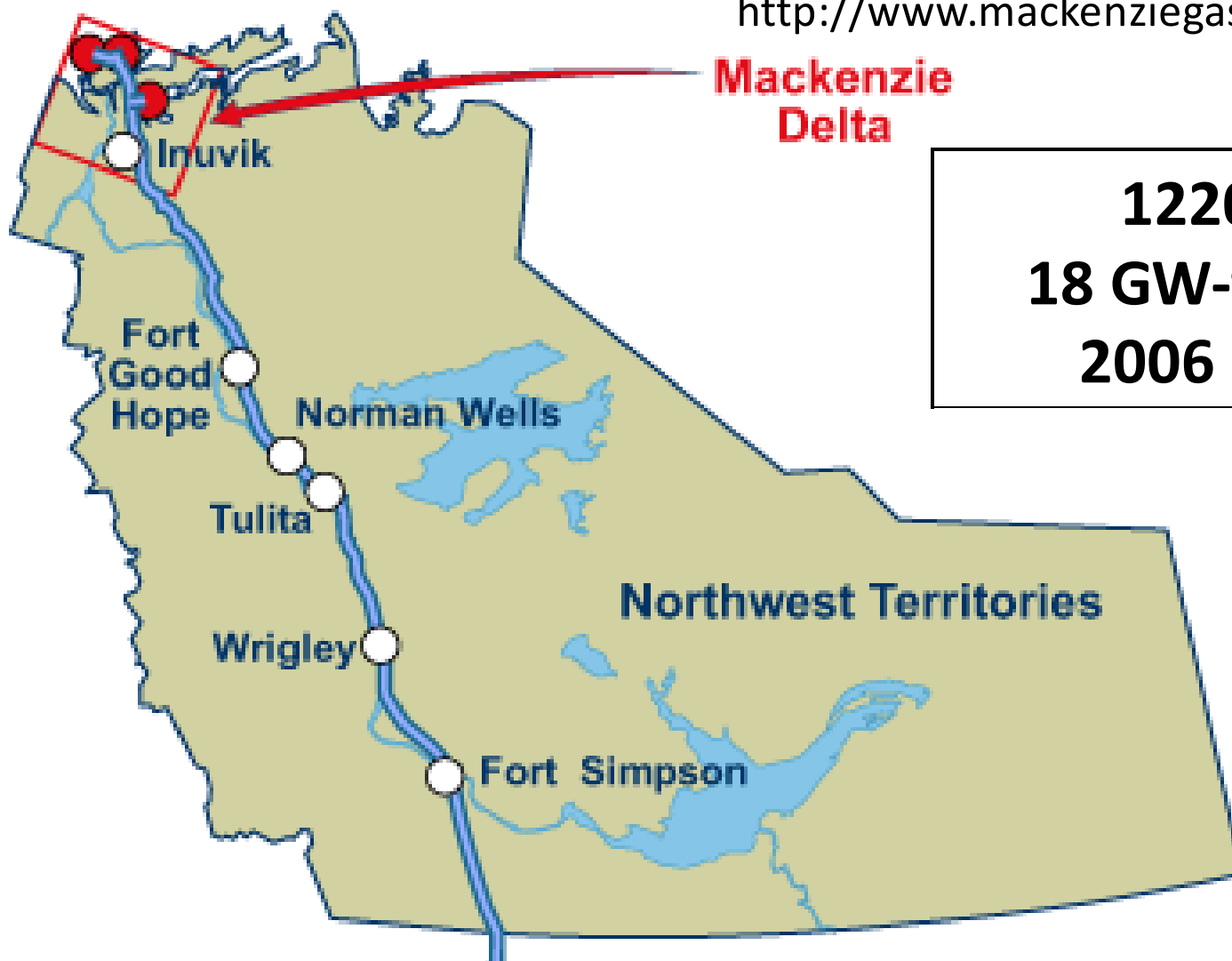


A Canadian's View of the World



The Mackenzie Valley Pipeline

<http://www.mackenziegasproject.com>



**Mackenzie
Delta**

**1220 km
18 GW-thermal
2006 - 2010**

Transporting Tens of Gigawatts to the **Green** Market

12 – 13 May 2011

Institute for Advanced Sustainability Studies
Potsdam, Germany



Go Where the Sun Shines



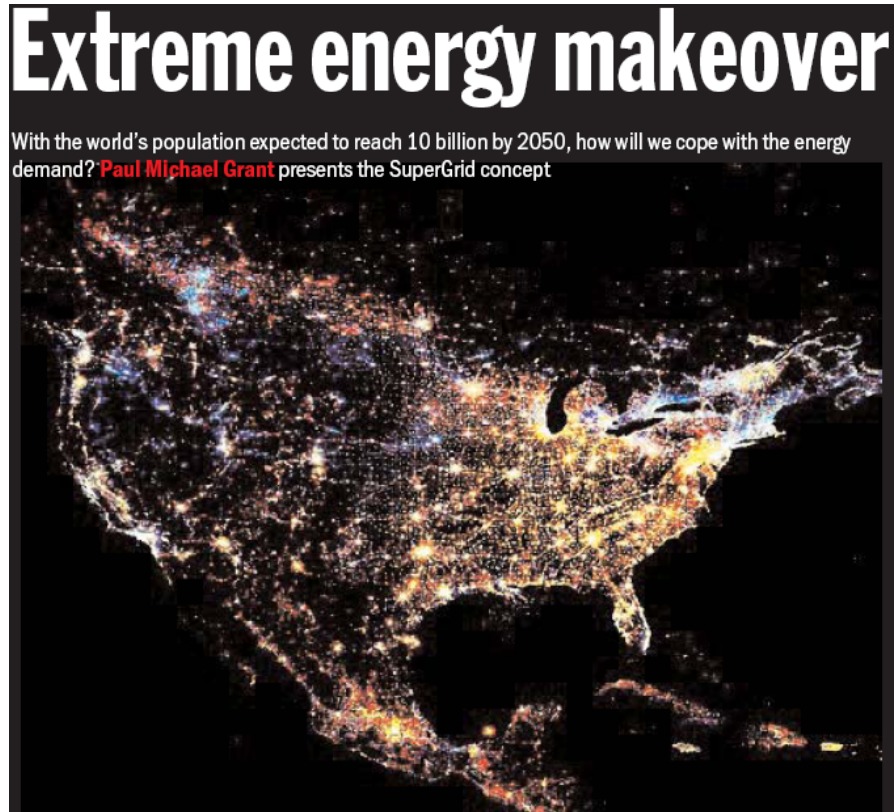
Solar – PV & Thermal



Superconducting SolarPipe



Physics World, October 2009



From The Times

October 3, 2009

Science: Stand by for the Supergrid

Why the world needs an 'extreme energy makeover'

Anjana Ahuja



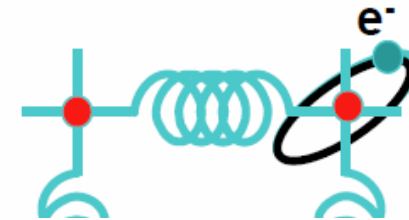
...a future editor of
Nature...?

Models of Metallic Conduction

The Most Popular:

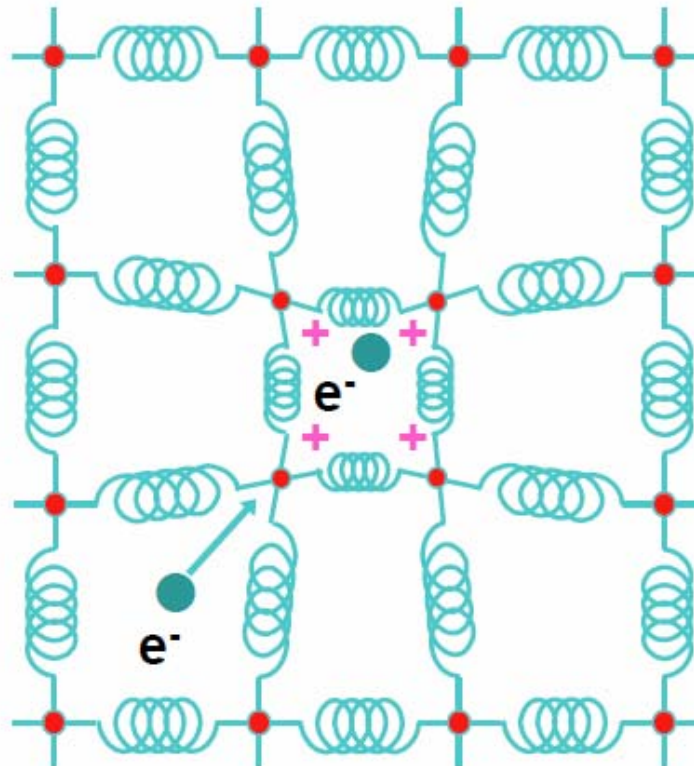
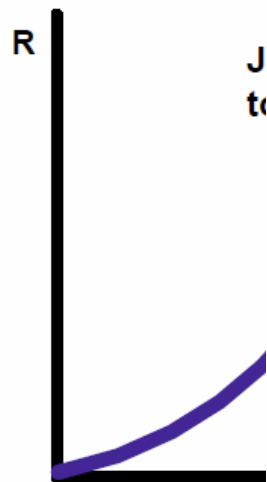
Models of E_R

Freezes Out!



Electrons Pair Off!

One Idea:



BCS Equation

$$T_C = 1.14 \theta_D \exp(-1/\lambda)$$

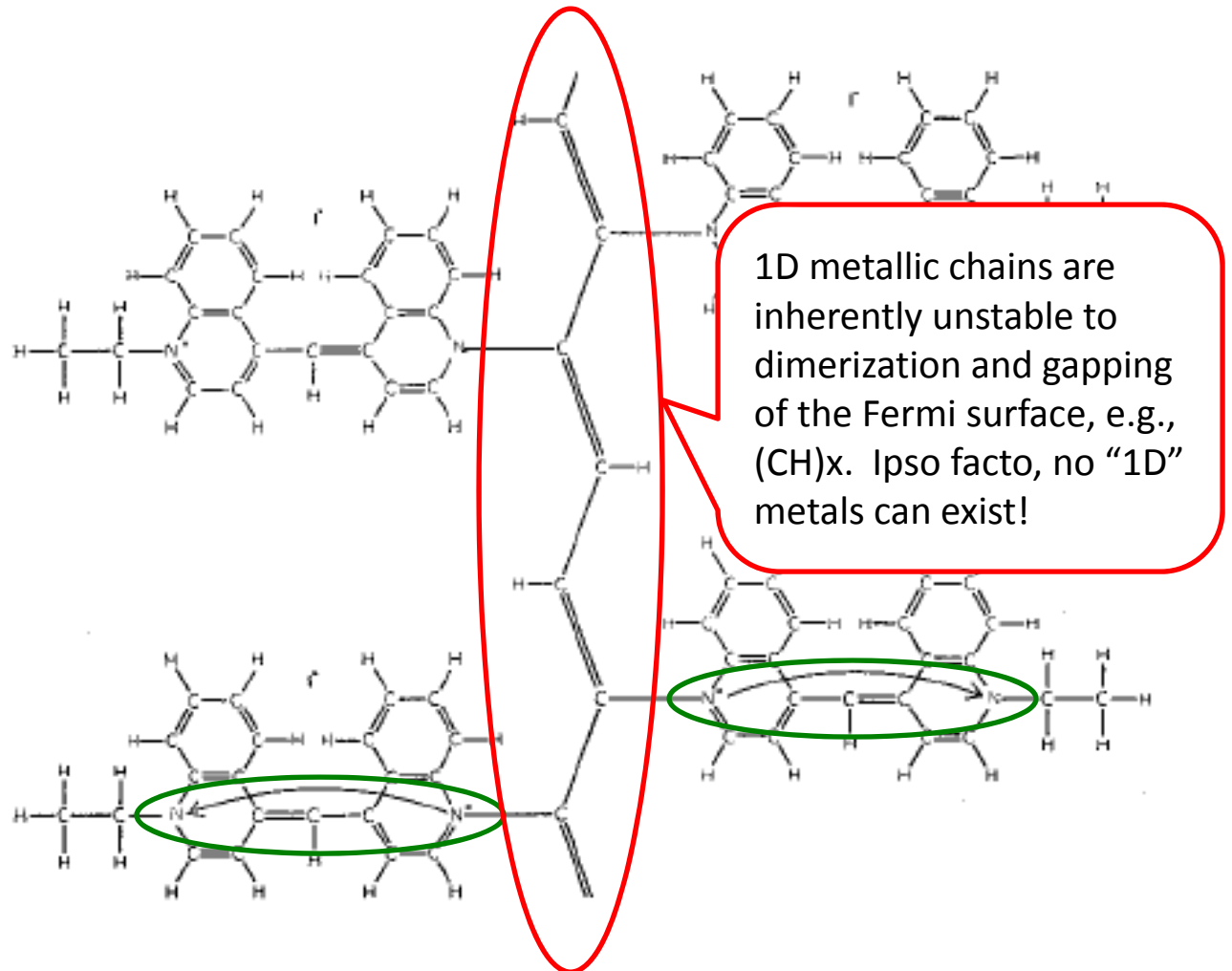
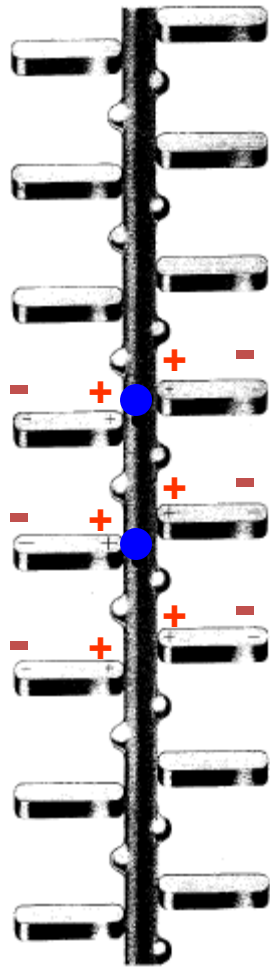
$$\theta_D = 275 \text{ K},$$

$$\lambda = 0.28,$$

$$\therefore T_C = \underline{9.5 \text{ K}} \text{ (Niobium)}$$

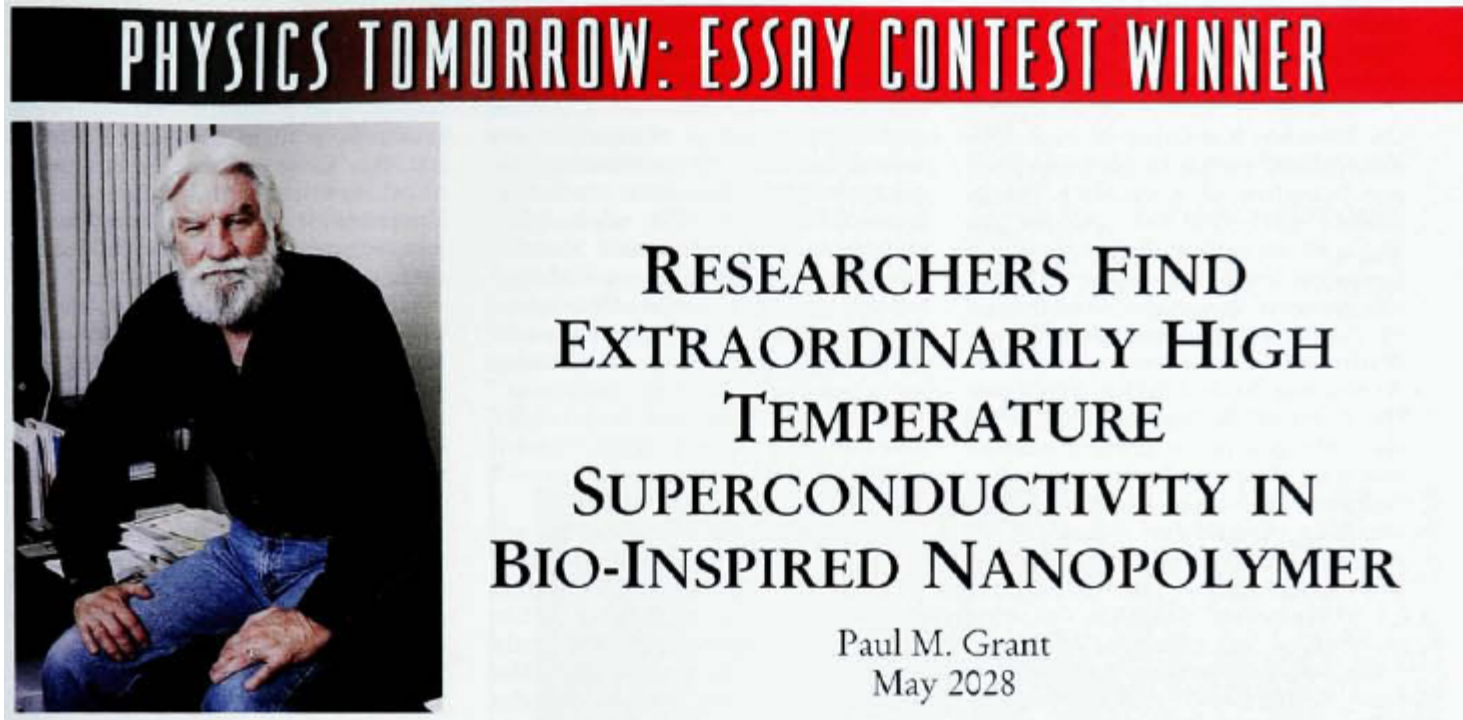
Room Temperature Superconductor

Little, Ginzburg, 1963



Diethyl-cyanine iodide

Does the **DA VINCI CODE** Hold the Key to Room Temperature Superconductivity?



50th Anniversary of Physics Today, May 1998

“You can’t always get what you want...”



“...you get what you need!”

