CERN Seminar
May 7, 2015

A Long March to Room Temperature Superconductivity

C. W. Chu

TCSUH, University of Houston,
Lawrence Berkeley National Laboratory and
Taiwan Comprehensive University System

Supported by AFOSR, DoE, State of Texas, Temple Foundation, Moores Foundation, etc.

The Long March

- 1911 – 1987 (LTS-Inter-metallics)
- 1987 – 2006 (HTS-Cuprates)
- 2006 – 2015 (Fe-pnictides &
  challcogneies)
- 2015 - (Hydrides ???)
- Conclusion

- Superconductivity is a 104 YOUNG vibrant subject.

- It has lured numerous great minds in physics.

- It has also humbled many:

  "Failed theories of superconductivity"- J Schmalian, <u>BCS:50</u>

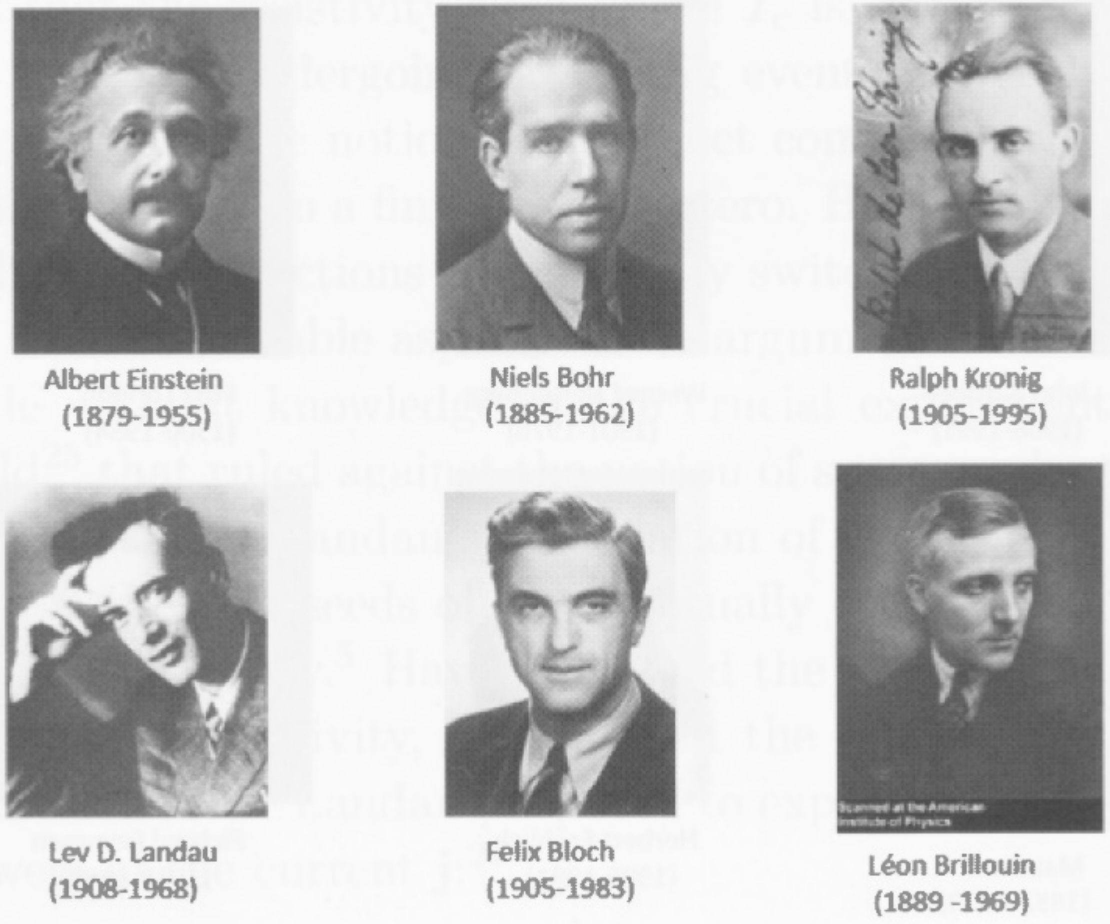
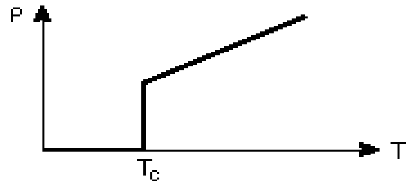


Fig. 1. Einstein, Bohr, Kronig, Landau, Bloch and Brillouin made proposals for microscopic theories of superconductivity prior to the groundbreaking experiment by Meissner and Ochsenfeld in 1934.

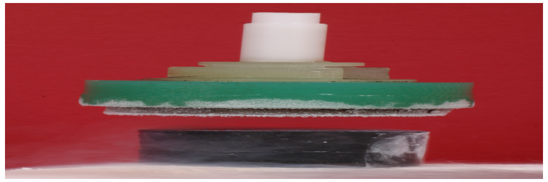
Fig. 2. Between 1941 and the formulation of the BCS theory, unsuccessful attempts to formulate microscopic theories of superconductivity were made by Bardeen, Heisenberg, London, Born, Fröhlich and Feynman.

BASIC PROPERTIES OF A SUPERCONDUCTOR

- **COMPLETE DISAPPEARANCE OF ELECTRICAL RESISTANCE (1911)**



- **COMPLETE EXPULSION OF EXTERNALLY APPLIED MAGNETIC FIELD (1933)**



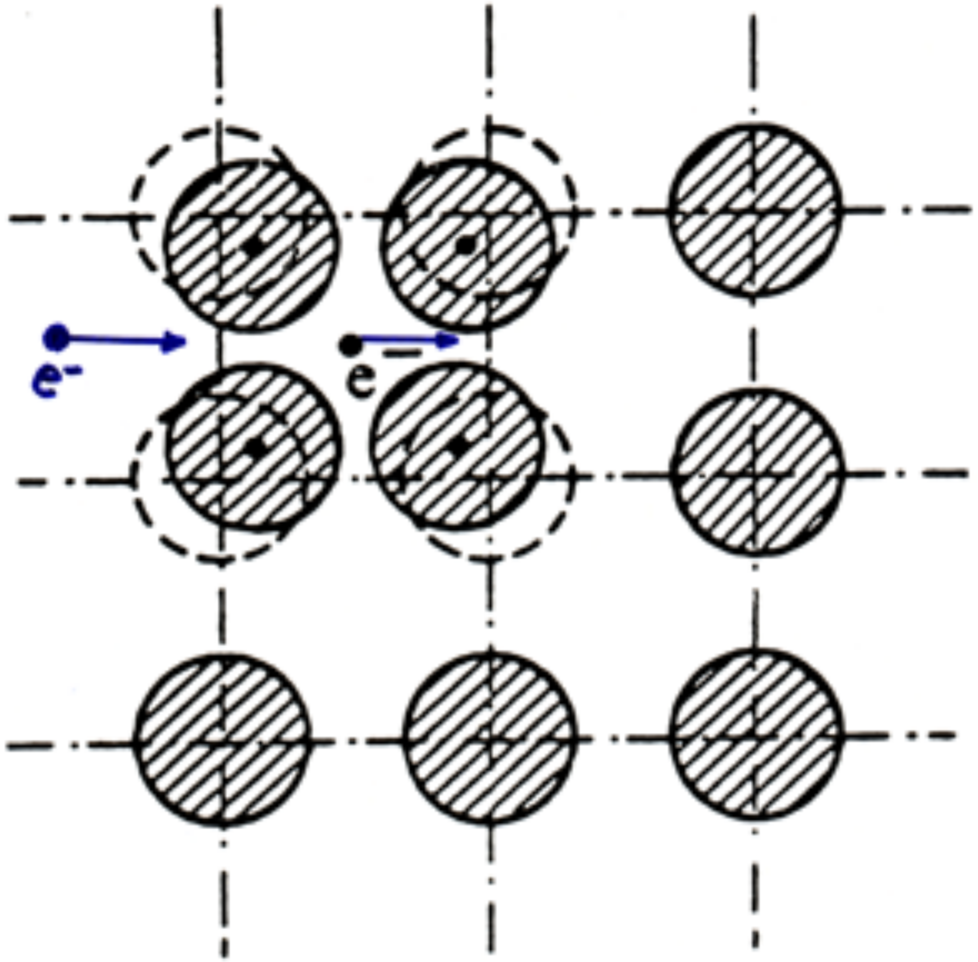
- **MACROSCOPIC QUANTUM PHENOMENON (1930's, 1962)**

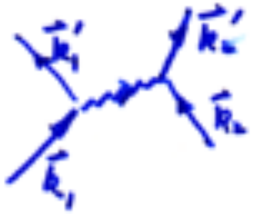
T_c - SC Transition Temperature
J_c - Critical Current Density
H_c - Critical Magnetic Field

The BCS Theory: T_c ∞ $\Theta_D$exp(1/NV)

Electron Pairing (1956)

BCS Theory (1957)





$T_c = 1.14\,\Theta_D \exp(-1/NV)$

BCS Theory (1957)

Superconductor finds its common ground with Dalai Lama

Nothingness （空）
&
Harmony （諧）

Humanity's Top Ten Problems for next 50 years

1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003	**6.3**	**Billion People**
2050	**9-10**	**Billion People**

(Rick Smalley)

The Future Global Sustainable Development in This Millennium

The Constraints:

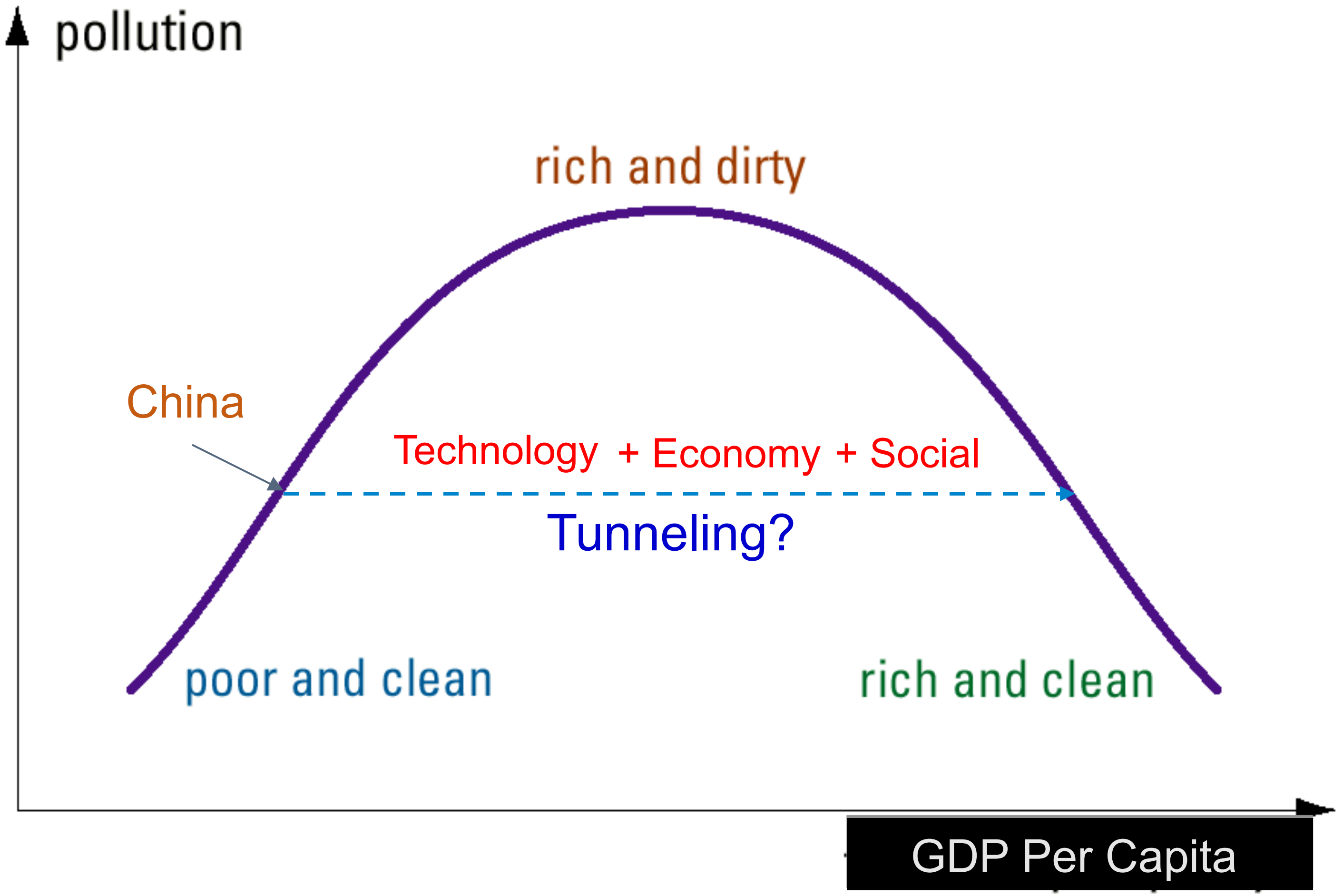
Energy, Environment and Resources

The 4R-Paradigm:

Reduce, Reuse, Recycle, Remanufacture

(energy)

Traditional Path for Industrialization



(Xu K. D., Former President, CAE)

The Most Environmentally Friendly Secondary Energy Source:

Electricity

Electricity and Economic Growth

"If the electricity infrastructure of this country is inadequate or in some way excessively costly, it will undermine economic growth, and is therefore a major issue that must be addressed." ***(G. W. Bush, 2004)***

Alan Greenspan
Chairman of the Federal Reserve Board
January 26, 2001

Without electric power the ~$17 trillion U.S. economy will come to a halt.

Asia at Night

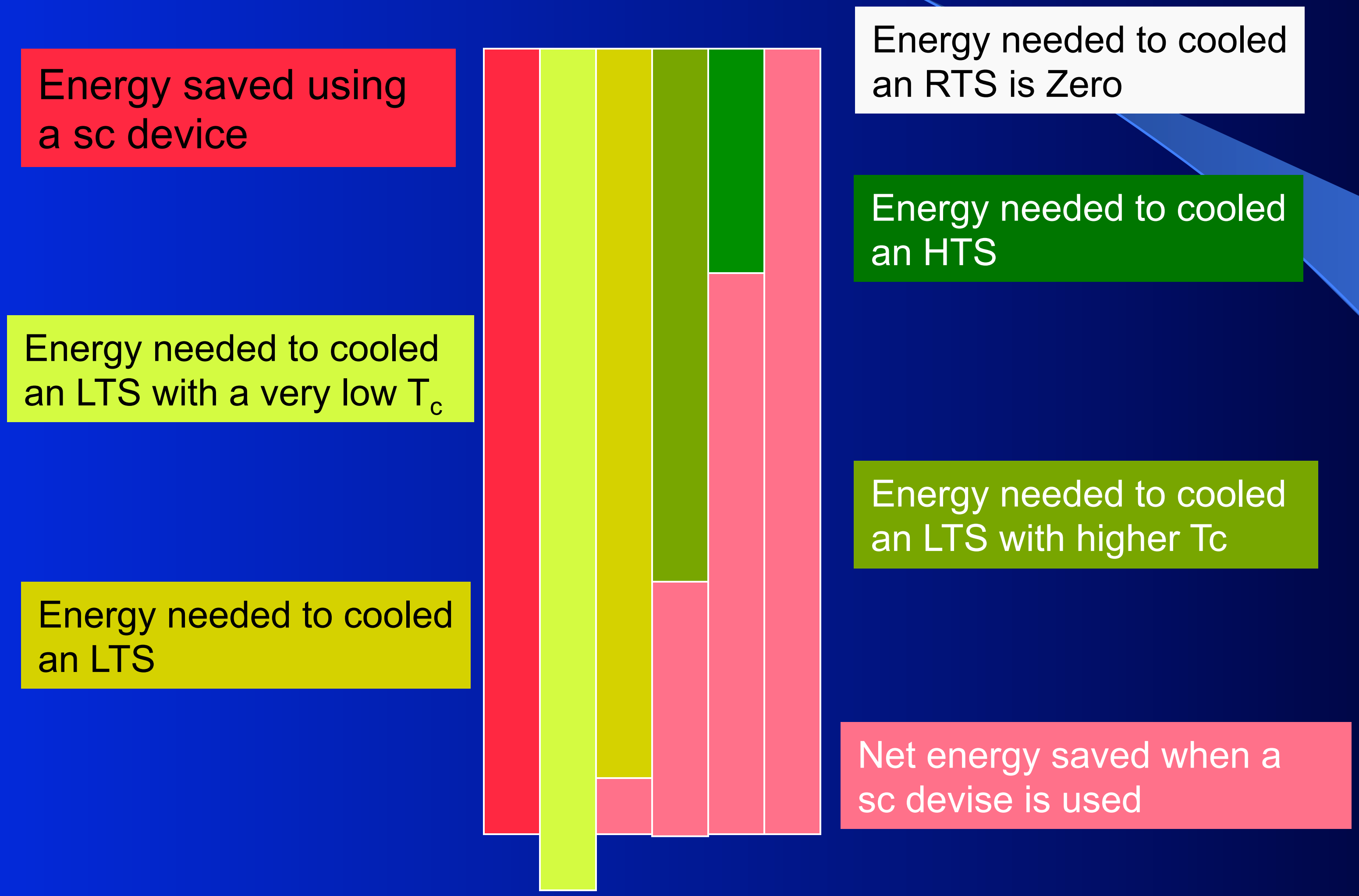
Where there is light, i. e. electricity there is prosperity!

The Most Efficient Electricity Carrier:

Superconductor

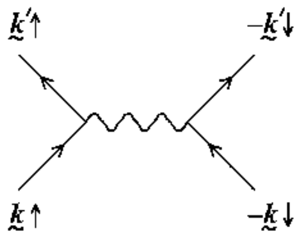
To Search for Superconductors with High T_c

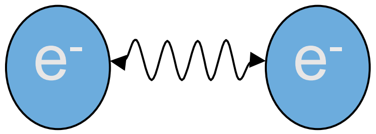
- *to save more energy* -



General Principles

1. Superconductivity needs electrons pairing & phase coherence (BCS)
2. Electrons pairing requires an effective attraction (BCS)





T_c

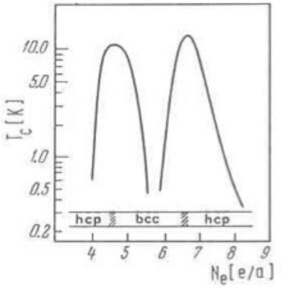
3. At high temperatures, thermal excitation energy grows
4. If the thermal excitation energy exceeds the pairing energy, the pairs breakup and superconductivity disappears
5. Higher T_c needs greater pairing potential
6. Greater pairing potential often leads to instabilities and even catastrophic instabilities

The challenge is to enhance the pairing potential without triggering catastrophic instabilities.

To raise T_c (before 1986)

- **MATTHIAS EMPIRICAL APPROACH:**

Matthias e/a Rule (1953)



- Highest T_cs at e/a ~ 4.75 & 6.4

- Works well for crystalline inter-metallic materials but not for amorphous materials or oxides

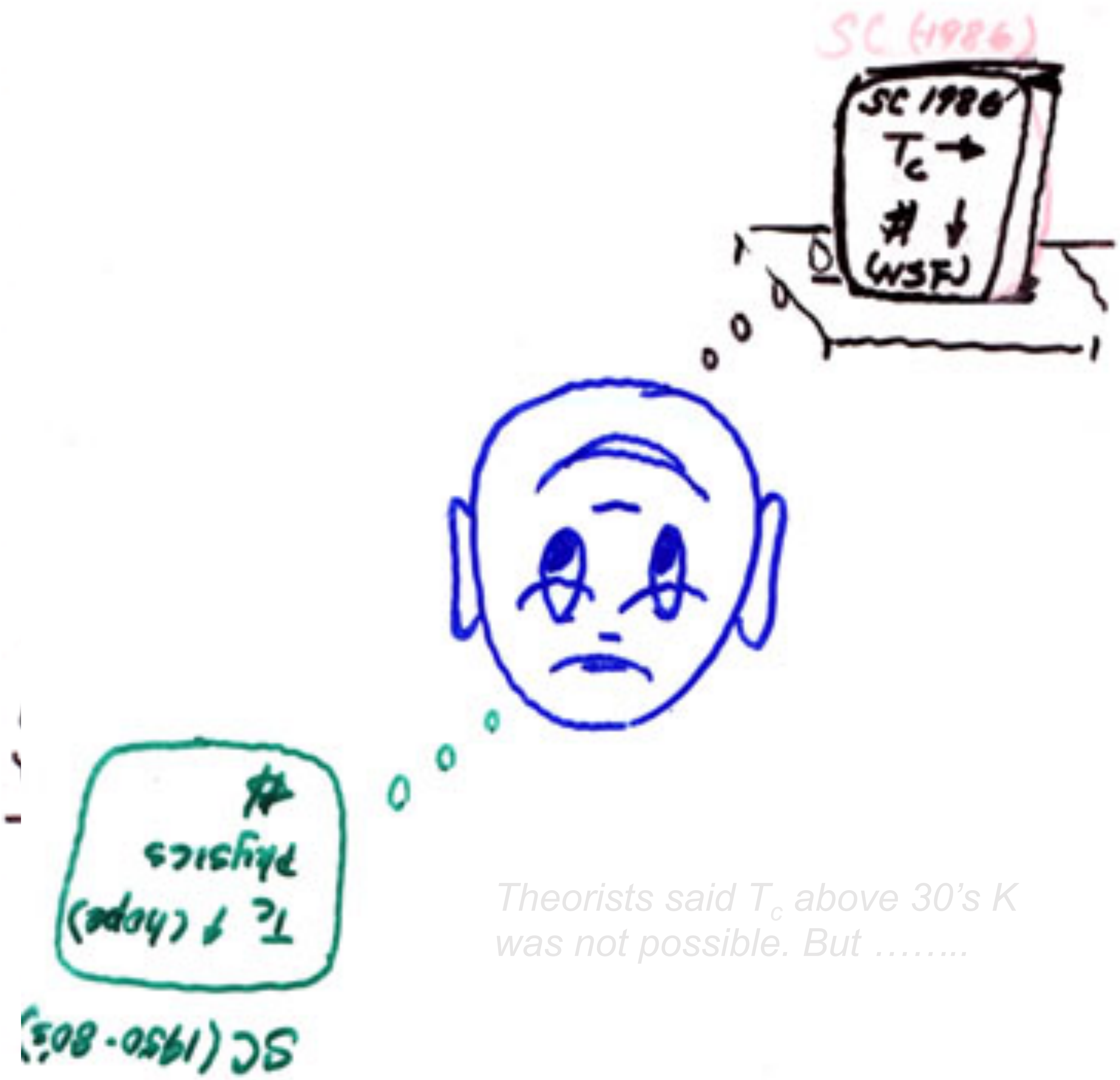
- **BCS RATIONAL APPROACH:**

Cooper Pair (1956)

$T_c = 1.14\Theta_D \exp(-1/NV)$ (1957)

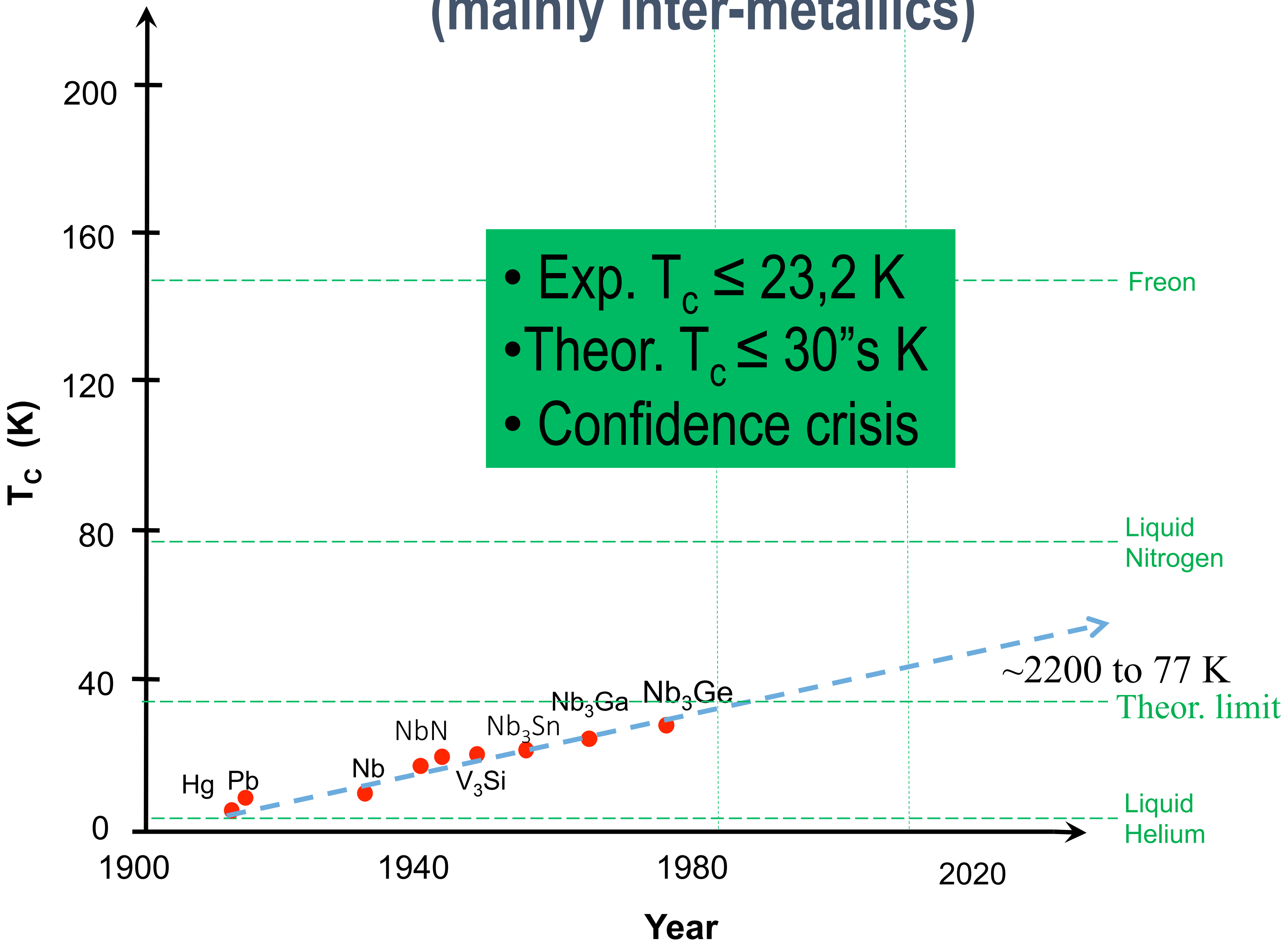
- To raise the T_c - enhance θ_D, N(0) & V

- Excellent descriptive power but little T_c- predictability



Theorists said T_c above 30's K was not possible. But ……..

T_c - Before 1986 (mainly inter-metallics)



20120726CWC

The confidence crisis

- BCS: Lattice instability limits T_c to the 30s K

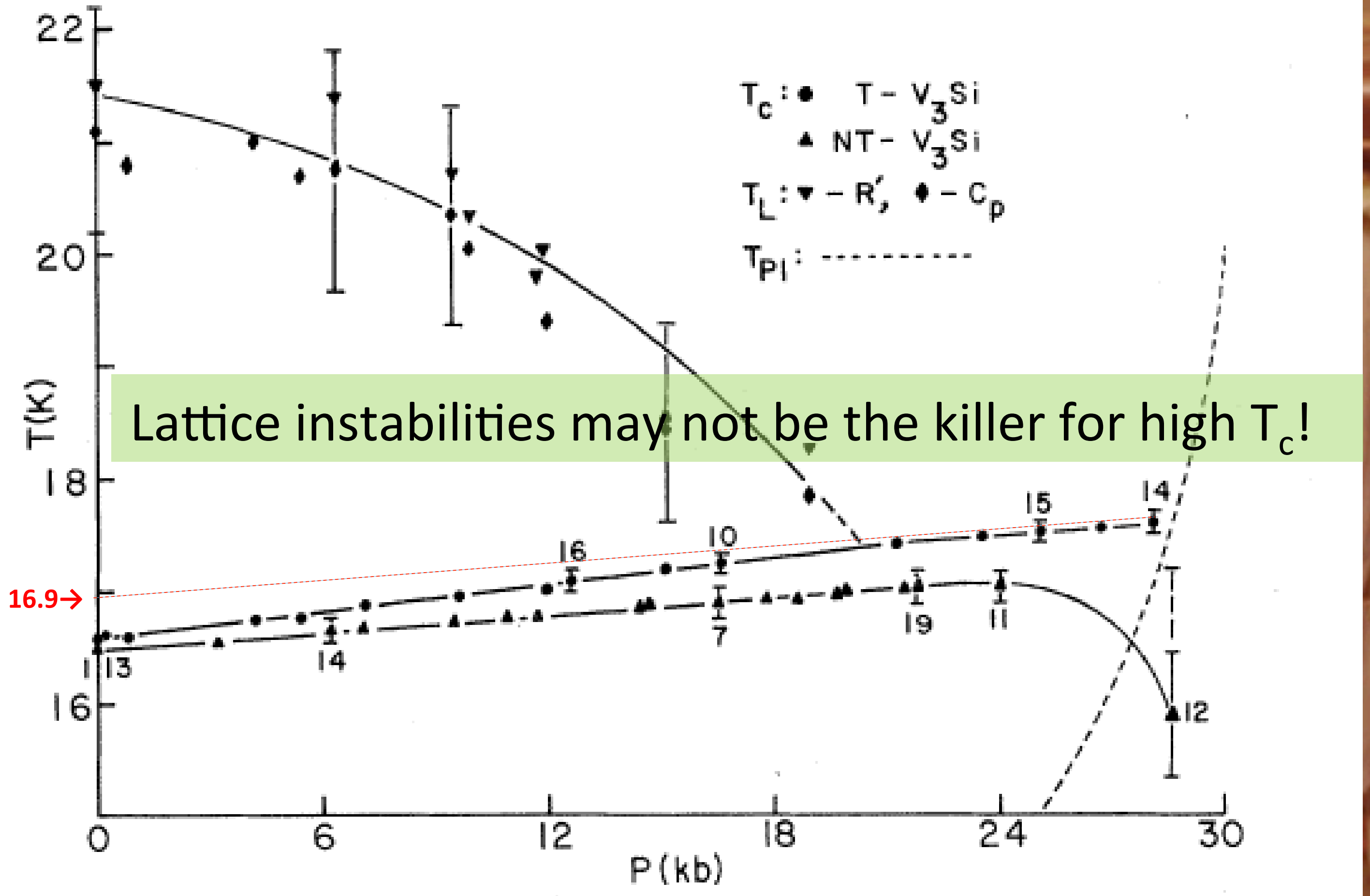
High pressure to test the basis for the crisis

- only slight effect & incipient instability is good (1973, 1974, 1978): Chu, Diatchenko, Testardi
- not a serious problem
- pressure a useful guide as a tuning parameter for higher T_c

VOLUME 41, NUMBER 8 PHYSICAL REVIEW LETTERS 21 AUGUST 1978

Study of Transforming and Nontransforming V_3Si up to 29 kbar

C. W. Chu and V. Diatschenko
Department of Physics and Solar Energy Laboratory, University of Houston, Houston, Texas 77004
(Received 5 June 1978)



1986: the critical year

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

Condensed Matter
Zeitschrift für Physik B

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

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

Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba–La–Cu–O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from 2*D* superconducting fluctuations of double perovskite layers of one of the phases present.

Ba-doped La_2CuO_4 – new T_c record at 35 K in a new oxides

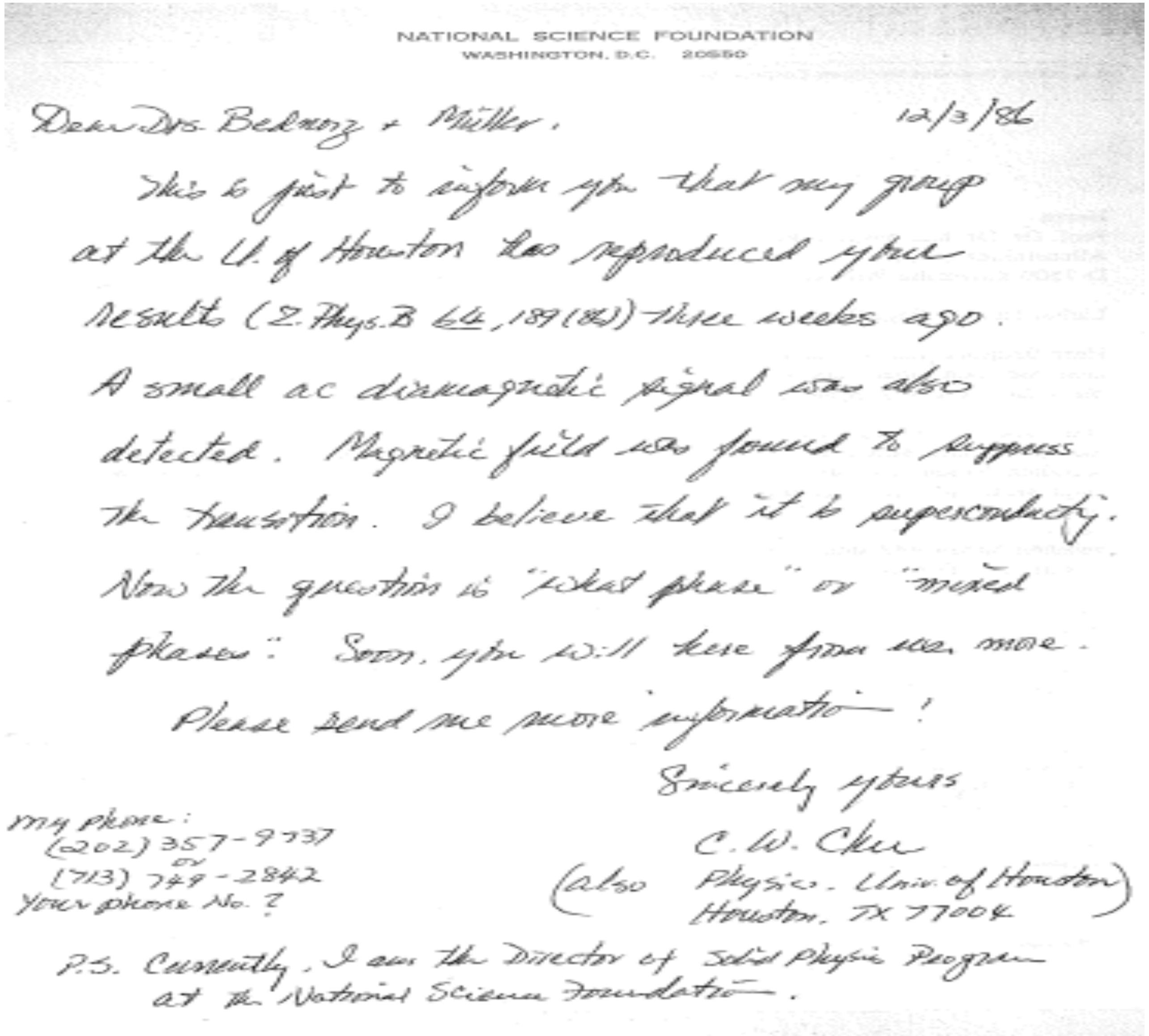
070919CWC

• The paper was initially greeted with skepticism
by most except a few groups
(Tokyo, Houston, IBM-Yorktown, Beijing)

• We confirmed their results in late November and
more

• The 1986 Fall MRS Meeting (Dec. 4):
- invited M. K. Wu to join the search and showed him
all our data, including possible sc at 70 K
- showed our preliminary resistive data at the Meeting
- learned Tokyo's magnetic and structure data

The original note to B&M from GB:
later AM called CW Chu thank and comment on CWC's confidence on T_c = 77 K


NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

Dear Drs. Bednorz + Müller, 12/3/86

This is just to inform you that my group at the U. of Houston has reproduced your results (Z. Phys. B 64, 189 (86)) three weeks ago. A small ac diamagnetic signal was also detected. Magnetic field was found to suppress the transition. I believe that it is superconductivity. Now the question is "what phase" or "mixed phases". Soon, you will hear from us more. Please send me more information!

Sincerely yours
C. W. Chu
(also Physics, Univ. of Houston
Houston, TX 77004)

my phone:
(202) 357-9737
or
(713) 749-2842
Your phone No.?

P.S. Currently, I am the Director of Solid Physic Program at the National Science Foundation.

VOLUME 58, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1987

Evidence for Superconductivity above 40 K in the La-Ba-Cu-O Compound System

C. W. Chu,[a] P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, and Y. Q. Wang
Department of Physics and Magnetic Information Research Laboratory
University of Houston, Houston, Texas 77004
(Received 15 December 1986)

An apparent superconducting transition with an onset temperature above 40 K has been detected under pressure in the La-Ba-Cu-O compound system synthesized directly from a solid-state reaction of La_2O_3, CuO, and $BaCO_3$ followed by a decomposition of the mixture in a reduced atmosphere. The experiment is described and the results of effects of magnetic field and pressure are discussed.

PACS numbers: 74.70.Ya

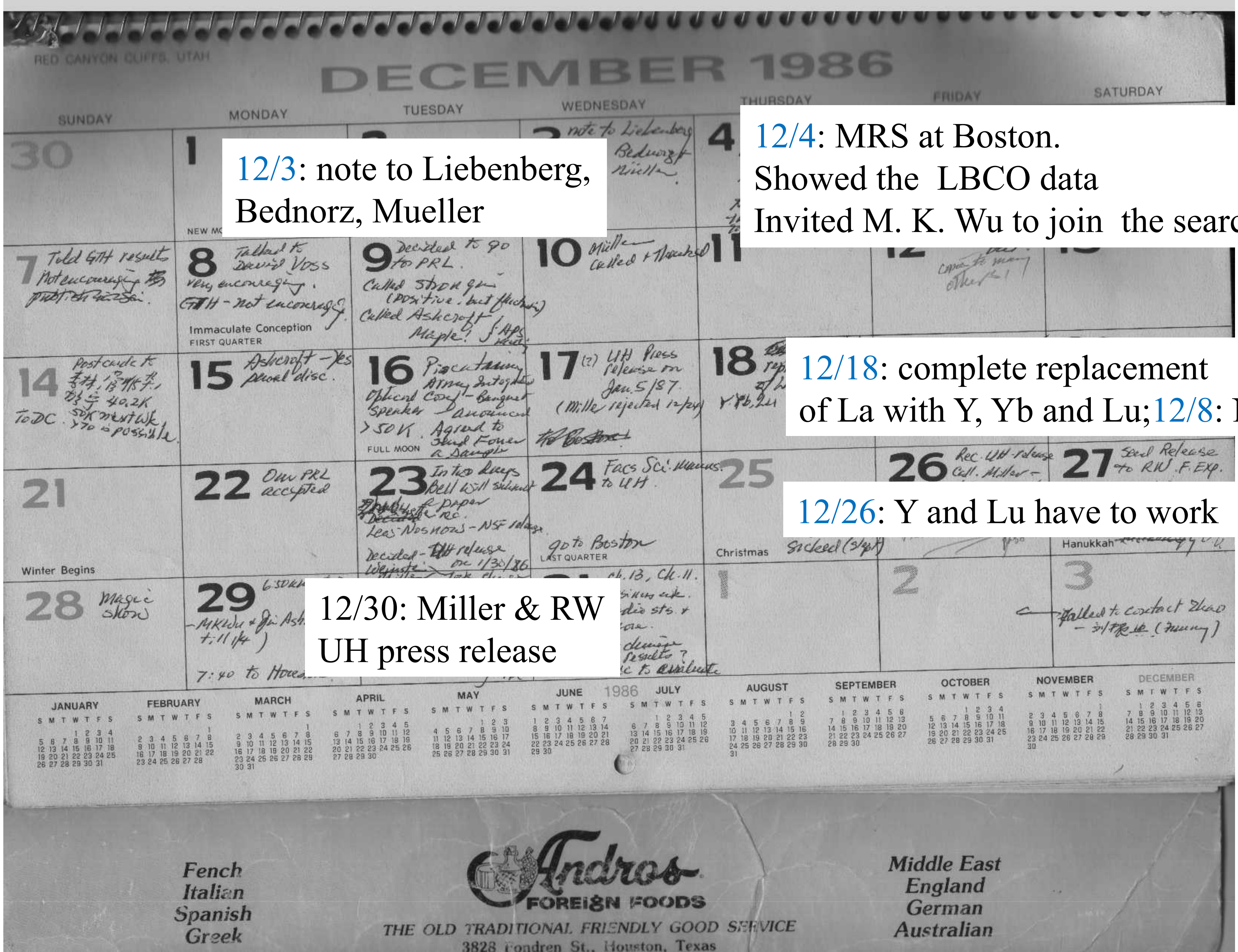
Superconductivity at 52.5 K in the Lanthanum-Barium-Copper-Oxide System

Science235,567(1987)

C. W. CHU,* P. H. HOR, R. L. MENG, L. GAO, Z. J. HUANG

A superconducting transition with an onset temperature of 52.5 K has been observed under hydrostatic pressure in compounds with nominal compositions given by $(La_{0.9}Ba_{0.1})_2\ CuO_{4-y}$. Possible causes for the high-temperature superconductivity are discussed.

- *Enhanced T_c to 40.2 and then to 52.4 K*
- *A T_c > 40 K defies the then theoretical prediction*
- *The unusually large pressure effect on T_c => cuprates are unusual and warrant further study*
- *Proposed to replace Ba by Sr & Ca; La by Y & Lu.*



12/3: note to Liebenberg, Bednorz, Mueller

12/4: MRS at Boston.
Showed the LBCO data
Invited M. K. Wu to join the search

12/18: complete replacement of La with Y, Yb and Lu; 12/8: No Y

12/26: Y and Lu have to work

12/30: Miller & RW
UH press release

The New York Times

pyright © 1986 The New York Times — NEW YORK, WEDNESDAY, DECEMBER 31, 1986

Front Page

2 Groups Report a Breakthrough In Field of Electrical Conductivity

By WALTER SULLIVAN

After a dozen years of futile efforts to raise the temperature at which materials become superconducting, researchers at the University of Houston and at

….at the University of Houston and at AT&T Bell Laboratories….

transmission and generation, energy storage and the generation of fusion energy.

Possible Applications

The achievements also mean that superconductivity, in which materials lose all resistance to electricity, can be more widely applied for scientific research and could substantially reduce the cost of the proposed superconducting atom smasher with a 60-mile acceleration ring.

In the early 1970's researchers at Bell Laboratories and Westinghouse found substances that became superconducting when cooled to 23 degrees Kelvin, 23 degrees above absolute zero. Absolute zero, the total absence of heat, occurs at minus 273 degrees Celsius, or 460 degrees below zero Fahrenheit: 23 Kelvin is equal to minus 250 Celsius,

Dr. Paul C. W. Chu at the University of Houston reported that under high pressure, hundreds of thousands of pounds per square inch, a compound of lanthanum, barium, copper and oxygen becomes superconducting at 40.2 degrees Kelvin.

However, A.T.&T. Bell Laboratories, following a similar line of research, yesterday reported production of an alloy that at normal pressure begins its transition to superconductivity at 40 degrees Kelvin and becomes fully superconducting when cooled to 36 degrees. Participants in that project, while reluctant to provide details until

Continued on Page A13, Column 1

1987: The Exciting Year

ARNOLD, WHITE & DURKEE
P.O. BOX 4433
HOUSTON, TX 77210

UNITED STATES DEPARTMENT OF COMMERCE
Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231

MAILED
MAR 2 1987
APPLICATION BRANCH

Applicant(s): CHING W. CHU
Serial Number: 002,089
Filing Date: 1/12/87
Title: SUPERCONDUCTING COMPOSITION AND METHOD

SEE UNIA: 011

NOTICE TO FILE MISSING PARTS OF APPLICATION—FILING DATE GRANTED

Docket # UNIA: 011

A filing date has been granted to this application. However, the following parts have been found missing.

If all missing parts ...
☒ large entity, ☐ sm...

1. ☒ The statutory ...
☐ small entity, ...
THE SURCHA...

2. ☒ Additional clai... multiple deper... fees or cancel t... FOR THIS ITE...

3. ☐ The oath or dec...
☐ is missing.
☐ does not cove...
An oath or dec... above Serial N... SUBMITTED ...

4. ☐ The oath or de... declaration in ... Serial Number a... AS INDICATE...

5. ☐ The signature ... other than the inventor or a person qualified under 37 CFR 1.42, 1.43, or 1.47. A properly signed oath or declaration in compliance with 37 CFR 1.63, identifying the application by the above Serial Number and Filing Date is required. A SURCHARGE MUST ALSO BE SUBMITTED AS INDICATED BELOW.

6. ☐ The signature of the following joint inventor(s) is missing from the oath or declaration: ________ Applicant(s) should provide, if possible an oath or declaration signed by the omitted inventor(s), identifying this application by the above Serial Number and Filing Date. A SURCHARGE MUST ALSO BE SUBMITTED AS INDICATED BELOW.

7. ☐ The application was filed in a language other than English. Applicant must file a verified English translation of the application and a fee of $26.00 under 37 CFR 1.17(k), unless this fee has already been paid NO SURCHARGE UNDER 37 CFR 1.16(e) IS REQUIRED FOR THIS ITEM.

8. ☐ Other:

-17-

WHAT IS CLAIMED IS:

1. A superconducting composition having a superconducting transition temperature above about 40° Kelvin.

This was the basis for our work to discover the Y-BaCuO

2. ... wherein said compositio... metal that has interatomi...

... oup

... oup

... bismuth, titanium, tungsten, zirconium, tantalum, niobium, and vanadium or a mixture of one or more of these elements;

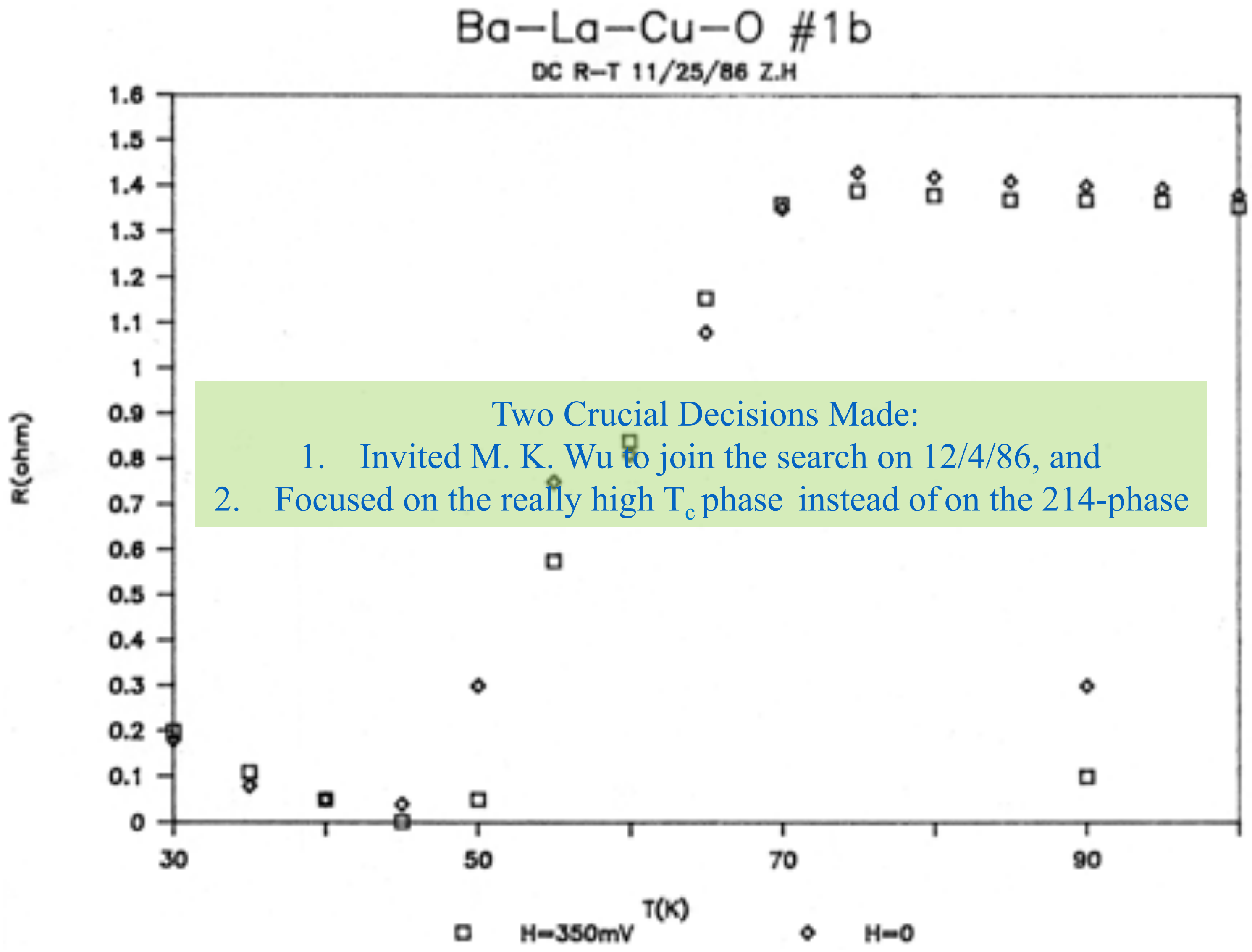
wherein M is an element selected from the group consisting of barium, strontium, calcium and magnesium or a mixture of one or more of these elements; and

wherein L is an element selected from the group consisting of **lanthanum, lutetium and yttrium**

or

a mixture of one or more of these elements

even with a formula $(Y_{0.6}Ba_{0.4})_2CuO_4$



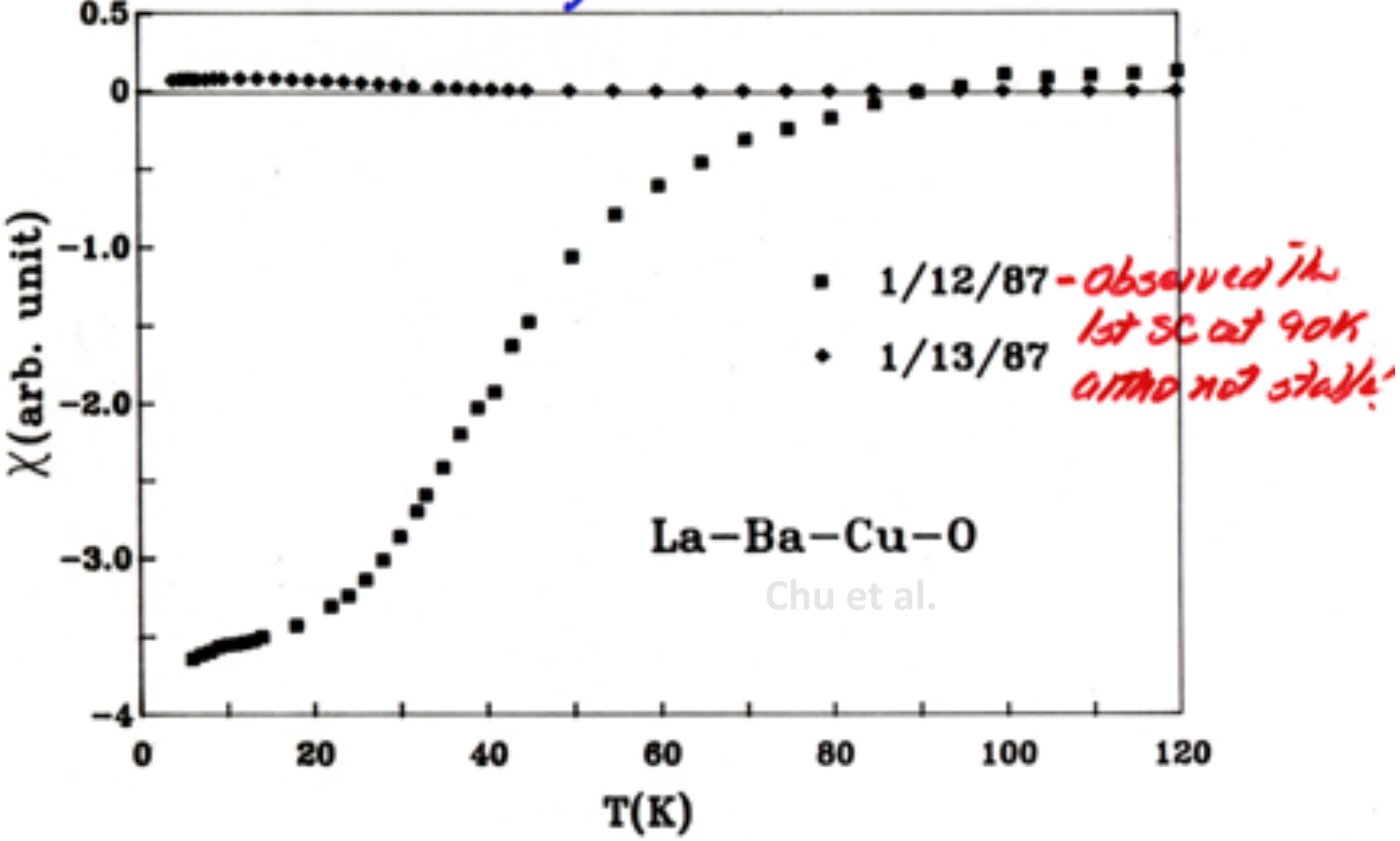
Two Crucial Decisions Made:

1. Invited M. K. Wu to join the search on 12/4/86, and
2. Focused on the really high T_c phase instead of on the 214-phase

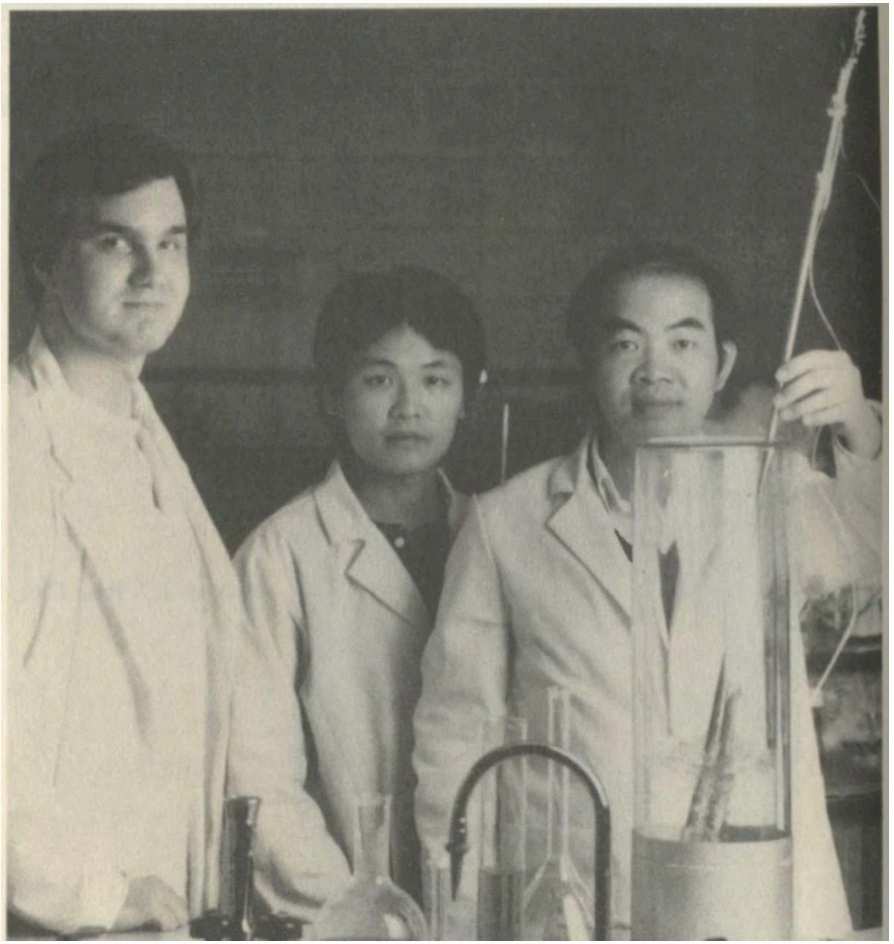
- ***First sign of SC slightly < 77 K was detected on November 25, 1986 in multi-phased but not pure 214 samples!***
- ***Conclude the real high T_c phase cannot be 214***
- ***Wanted to stabilize the phase by replacing La with Y & Lu !***

1987: the exciting year

⇒ SC up to 90K must exist!
But stability remains an issue!



- *First 90 K - SC was unambiguously observed, although not yet stable.*
- *Later analysis of the X-ray data showed it was $LaBa_2Cu_3O_7$ (123 or LBCO)*

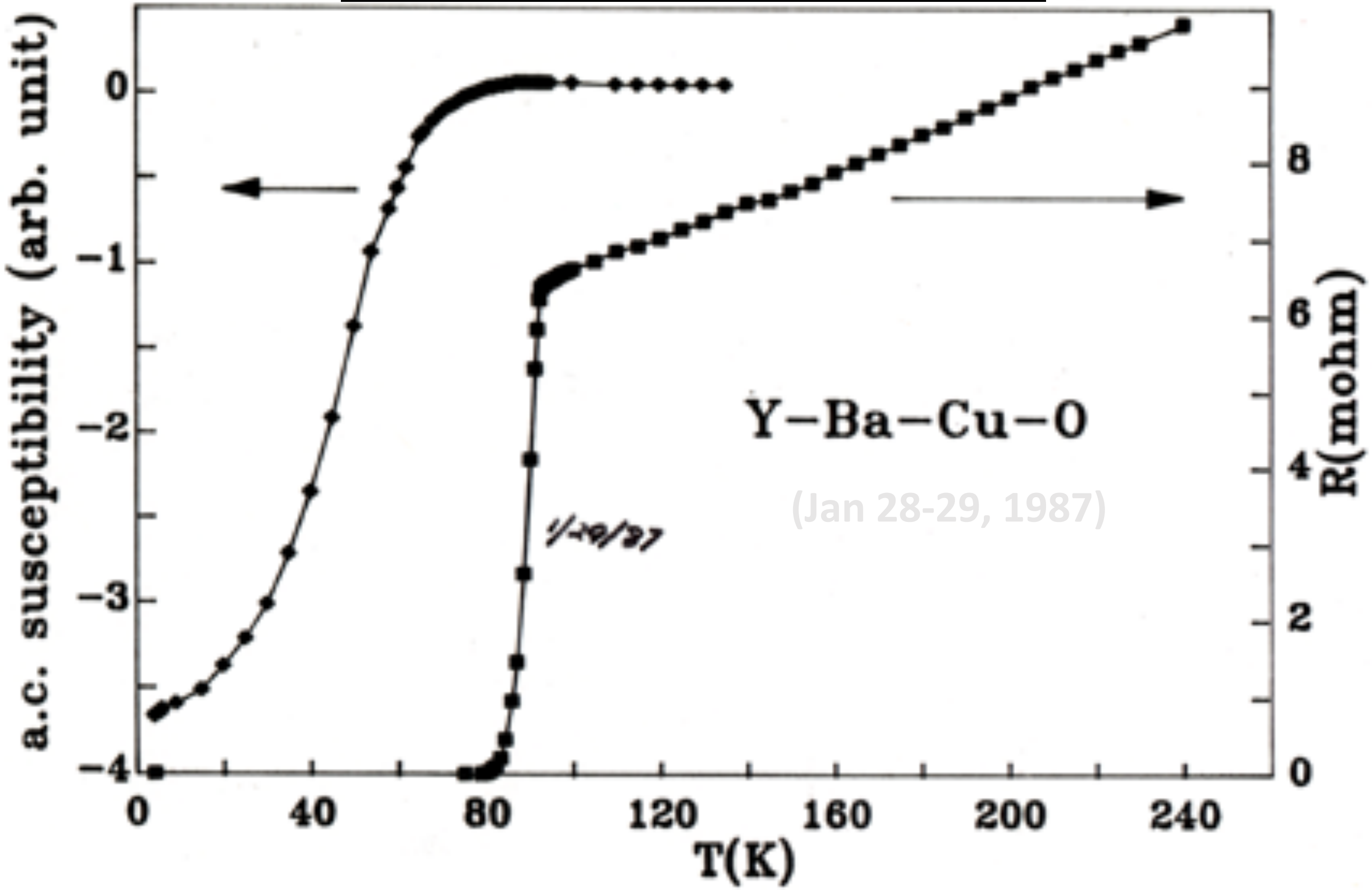


Chu’s group at UH:
R. L. Meng, C. W. Chu, L. Gao, P. H. Hor,
Y. Q. Wang, A. Testa, Z.J. Huang， D. Camball, J. Bechtold

Wu’s group at UAH:
J。 Ashburn, J. C. Torng, M. K. Wu

1987: The Exciting Year

M. K. Wu et al./C. W. Chu et al.



• SC above 77 K was finally stabilized.

• $YBa_2Cu_3O_7$ (123 or YBCO)

the first stable liquid-nitrogen-temperature superconductor.

070714CWC

Front page 2/16/87 NYT

Team Reports Breakthrough In Conductivity of Electricity

By WALTER SULLIVAN

In a scientific advance with potentially valuable commercial application, researchers at the University of Houston and the University of Alabama in Huntsville have produced a superconductive compound that loses all resistance to electricity when cooled to the temperature of liquid nitrogen, the National Science Foundation announced yesterday.

The work could have vast application in the generation and transmission of electricity, medical diagnosis and other uses including powering trains with magnets. The superconductivity was achieved at normal atmospheric pressure and at temperatures that can be produced with relatively cheap and easy-to-use coolants.

Wire made of the new compound could be in use within a few years, according to the researchers, Dr. Paul C.W. Chu at Houston and Dr. Mau-Kuen Wu, one of his former students, now at the Alabama university. The two led groups that worked together on the compound.

The researchers said wire or other electrical conductors made from the compound could transmit electricity great distances without loss of power. The compound could be used in magnets strong enough to move trains or guide particles around the huge ring of the superconducting supercollider, an atom smasher whose construction has recently been approved.

Scientists have long sought to create compounds that would be superconductive when cooled with liquid nitrogen instead of liquid helium, the cooling agent now widely used to achieve superconductivity. Liquid nitrogen costs a tenth as much, is 20 times more efficient and is much less volatile. Existing superconductors have limited commercial value because of the cost and handling problems associated with the helium cooling agent. Nitrogen liquefies at 321 degrees below zero Fahrenheit, or 77 degrees above absolute zero on the Kelvin scale.

The researchers whose work was announced yesterday achieved superconductivity at 283 degrees below zero Fahrenheit, or 98 degrees Kelvin. They

Continued on Page 10, Column 4

Front page 1/26/57 NYT

Basic Concept in Physics Is Reported Upset in Tests

Conservation of Parity Law in Nuclear Theory Challenged by Scientists at Columbia and Princeton Institute

By HAROLD M. SCHMECK Jr.

Experiments shattering a fundamental concept of nuclear physics were reported yesterday by Columbia University.

The concept, called the "principle of conservation of parity,"

The text of Columbia report will be found on Page 24.

has been accepted for thirty years. It must now be discarded, according to the Columbia scientists.

The principle of parity states that two sets of phenomena, one of which is an exact mirror of the other, behave in an identical fashion except for the mirror image effect.

The principle might be explained this way:

Assume that one motion picture camera is photographing a given set of actions and that another camera simultaneously is photographing the same set of actions as reflected in a mirror.

If the two films are later screened, a viewer would have no way, according to the principle of parity, of telling which of the two was the mirror image. The recently completed experiments indicate that there is a way of determining which of the two images is the mirror image.

In communicating with people in an intelligent civilization on another world, the Columbia report explained, it would be impossible, with the principle of parity in effect, to tell whether or not they and we meant the same thing by right-handed or left-handed. This could be true and still the basic physical laws in both worlds would behave ex-

1987: The Exciting Year

VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

M. K. Wu, J. R. Ashburn, and C. J. Torng
Department of Physics, University of Alabama, Huntsville, Alabama 35899

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu[a]
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004

(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

YBCO ($YBa_2Cu_3O_7$, or 123)
[was originally intended to be a one sentence paper]

March 2, 1987 was a super-day for physics – >90K SC, supernova, SSC!!!

1987: The Exciting Year

VOLUME 58, NUMBER 18 PHYSICAL REVIEW LETTERS 4 MAY 1987

Superconductivity above 90 K in the Square-Planar Compound System $ABa_2Cu_3O_{6+x}$ with A = Y, La, Nd, Sm, Eu, Gd, Ho, Er, and Lu

P. H. Hor, R. L. Meng, Y. Q. Wang, L. Gao, Z. J. Huang, J. Bechtold, K. Forster, and C. W. Chu[(a)]
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004
(Received 16 March 1987; revised manuscript received 13 April 1987)

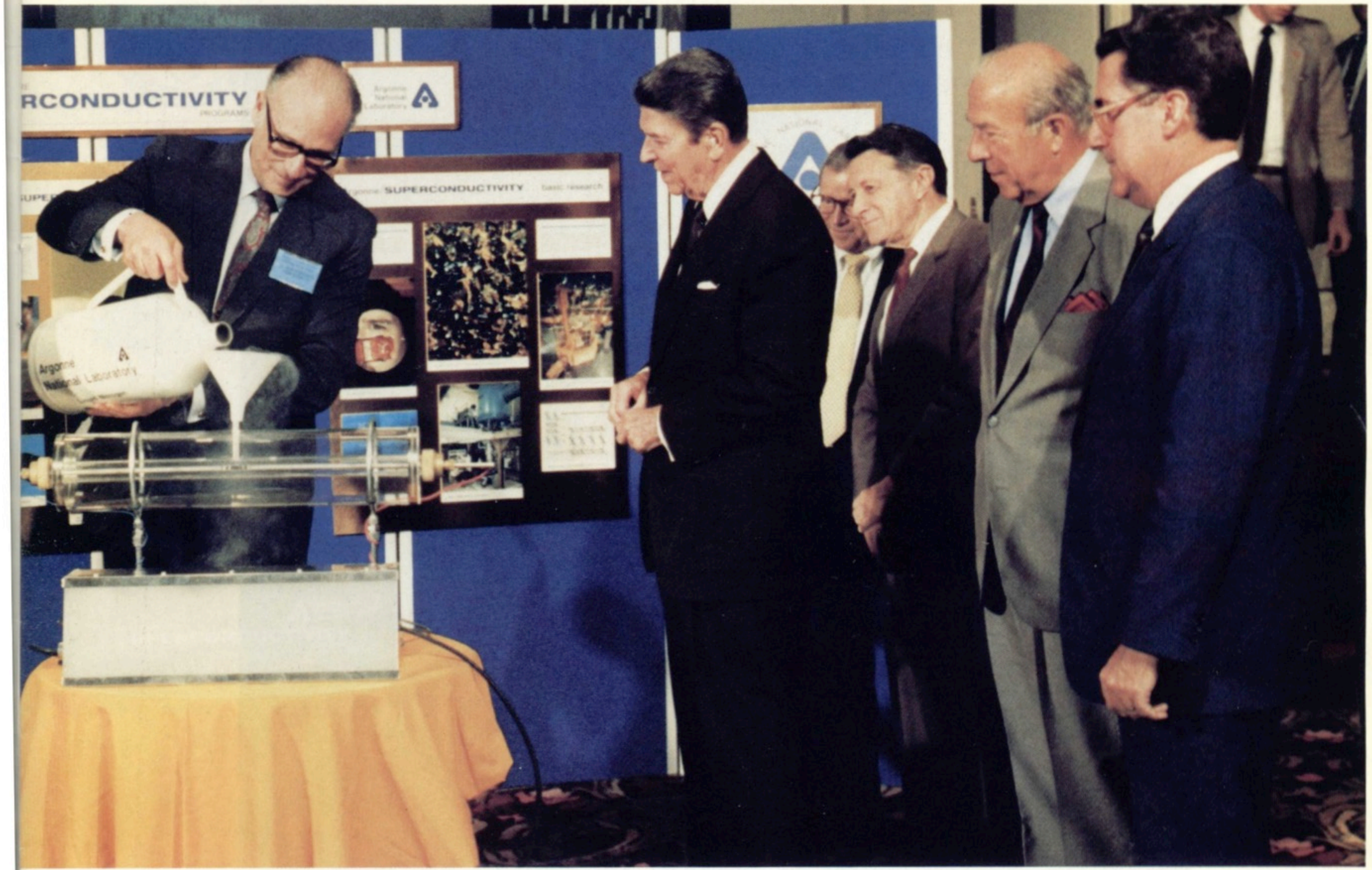
We have found superconductivity in the 90-K range in $ABa_2Cu_3O_{6+x}$ with A = La, Nd, Sm, Eu, Gd, Ho, Er, and Lu in addition to Y. The results suggest that the unique square-planar Cu atoms, each surrounded by four or six oxygen atoms, are crucial to the superconductivity of oxides in general. In particular, the high T_c of $ABa_2Cu_3O_{6+x}$ is attributed mainly to the quasi two-dimensional assembly of the CuO_2-Ba-CuO_{2+x}-Ba-CuO_2 layers sandwiched between two A layers, with particular emphasis in the CuO_{2+x} layers. Higher-T_c oxides are predicted for compounds with bigger assemblies of CuO_2 layers coupled by Ba layers.

PACS numbers: 74.10.+v, 74.70.Ya

New York Hilton Hotel, evening of March 18, 1987

Woodstock of Physics

Figure 1.3 Some of the protagonists of the special session on superconductivity (March 1987, APS Meeting, Hilton Hotel, New York City). From left to right: Alex Müller, Paul Chu, and Shoji Tanaka. (Courtesy of the American Institute of Physics Niels Bohr Library.)



Alan Schriesheim, Director of Argonne National Laboratory, demonstrates superconductivity to the President, Chief of Staff Howard Baker, Secretary of Defense Caspar Weinberger, Secretary of State George Shultz and Secretary Herrington.

Federal Conference on Superconductivity, July 1997

A New High-T_c Oxide Superconductor without a Rare Earth Element

Hiroshi MAEDA, Yoshiaki TANAKA, Masao FUKUTOMI and Toshihisa ASANO

T_c ≤ 110 K
$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$
Jpn.J.Appl. Phys. 27, L209 (1988)

Bulk superconductivity at 120 K in the Tl–Ca/Ba–Cu–O system

Z. Z. Sheng & A. M. Hermann

T_c ≤ 125 K
$Tl_2Ba_2Ca_{n1}Cu_2O_{2n+4}$
Nature 332, 138 (1988)

Superconductivity above 130 K in the Hg–Ba–Ca–Cu–O system

A. Schilling, M. Cantoni, J. D. Guo & H. R. Ott

T_c ≤ 134 K
$HgBa_2Ca_{2n-1}Cu_nO_{3+2n-\delta}$
Nature 363, 56 (1993)

Superconductivity up to 164 K in $HgBa_2Ca_{m-1}Cu_mO_{2m+2+\delta}$ (m=1, 2, and 3) under quasihydrostatic pressures

L. Gao, Y. Y. Xue, F. Chen, Q. Xiong, R. L. Meng, D. Ramirez, and C. W. Chu
J. H. Eggert and H. K. Mao

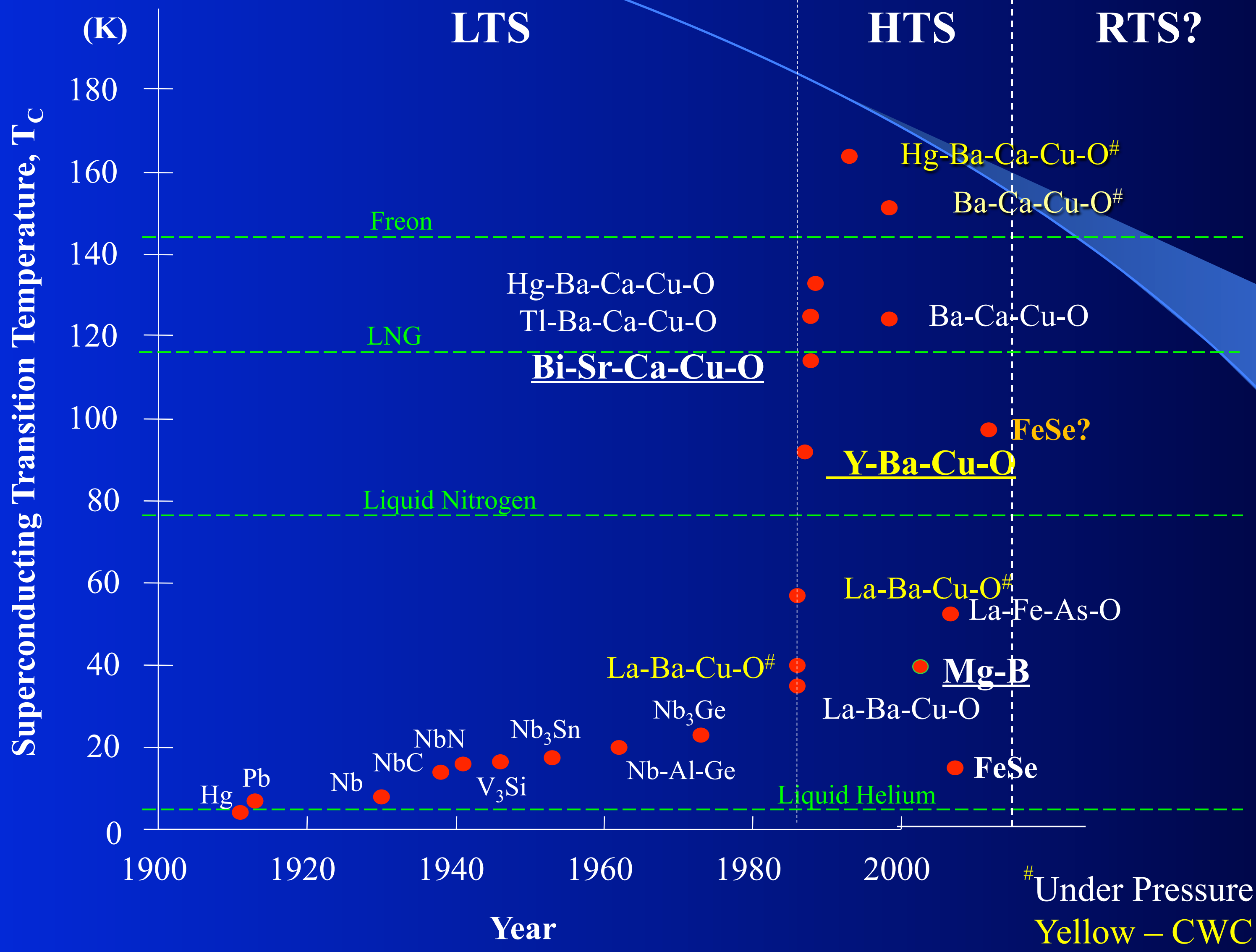
T_c ≤ 164 K
$HgBa_2Ca_{2n-1}Cu_nO_{3+2n-\delta}$
Phys. Rev. B (R) 50, 4260(1994)

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ (x = 0.05–0.12) with T_c = 26 K

Yoichi Kamihara,[*,†] Takumi Watanabe,[‡] Masahiro Hirano,[†,§] and Hideo Hosono[†,‡,§]

Tc ≤ 57 K
R(O,F)FeAs
JACS 130, 3296 (2008)

HTS: Past, Present and Future



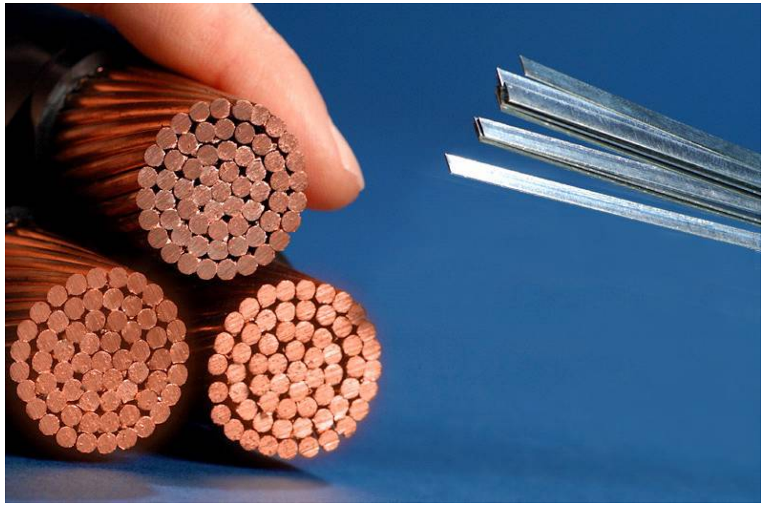
#Under Pressure

Yellow – CWC et al.

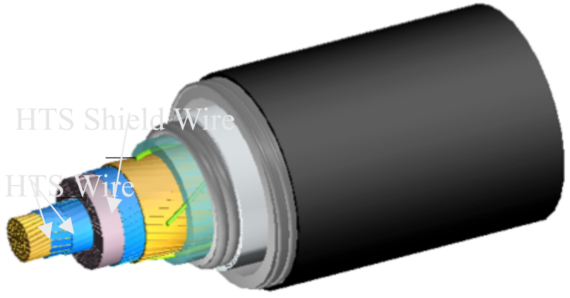
050921CWC

HTS Cables are Ready!

AMSC HTS wire plant



High Power Density
~ 140 × copper



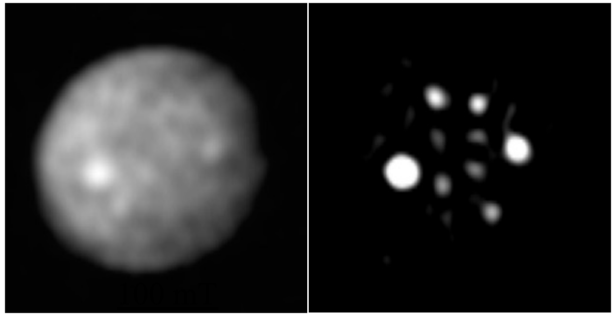
VLI Superconductor Cable

Many HTS prototype devices have been made and tested with superior performance than their non superconducting counterparts..

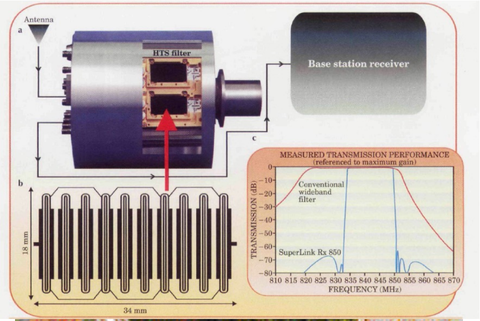
HTS Technology Works

(although more work is needed for commercialization)

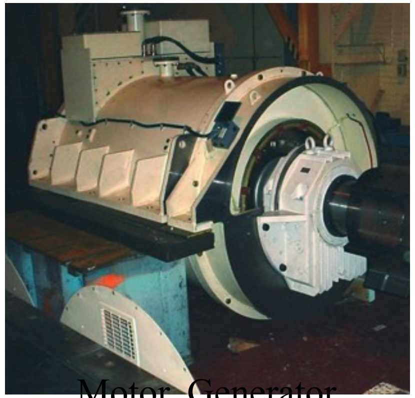
SQUID MRI of water columns by J. Clarke



MCG by Brzdeikis



Flywheel, W. K. Chu



Motor, Generator

Fault Current Limiter

Maglev in Japan

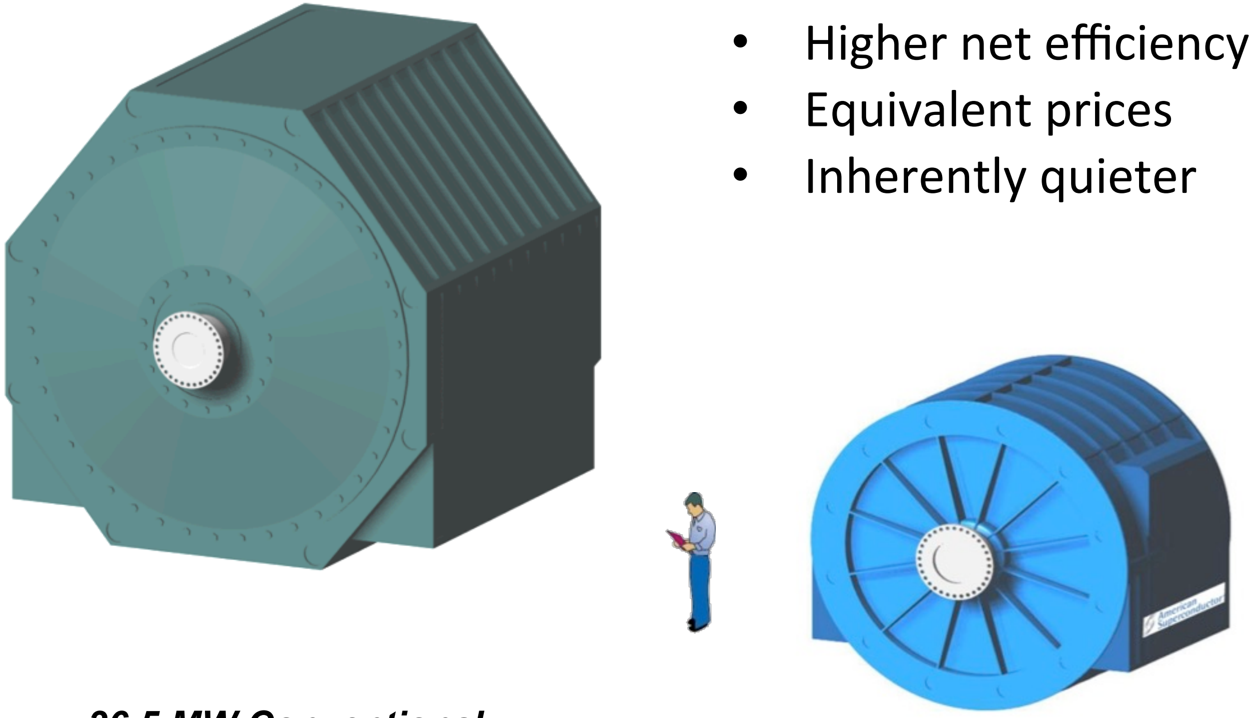
Biomag. Sensing
A. Brazdekis

5 MW Ship Propulsion Motor for US Navy
by AMSC

Synchronous Condensers

Ship Propulsion Motors

- Less than half the size
- Less than one-third the weight
- Higher net efficiency
- Equivalent prices
- Inherently quieter

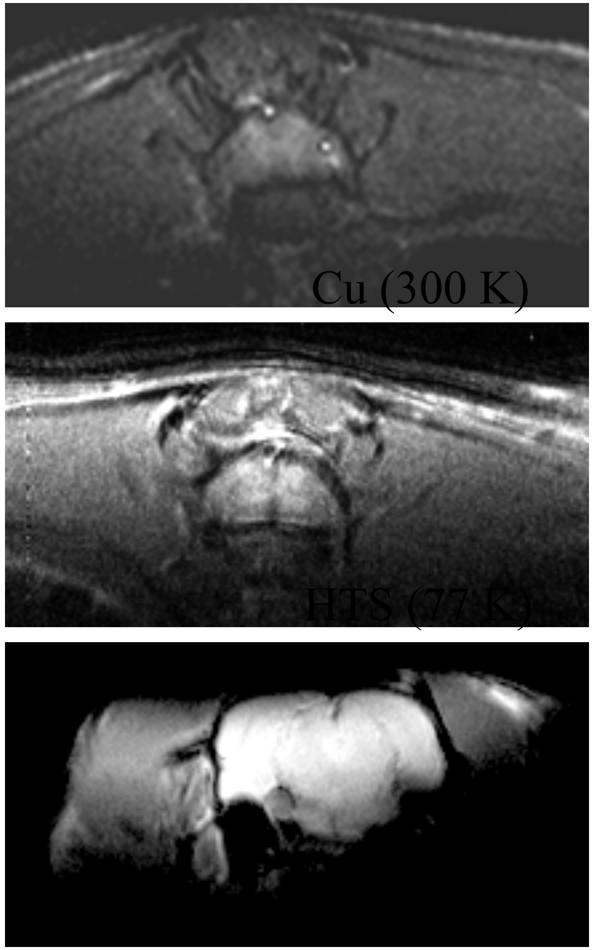


36.5 MW HTS
(75 tons)

36.5 MW Conventional
(300 tons)

AMSC

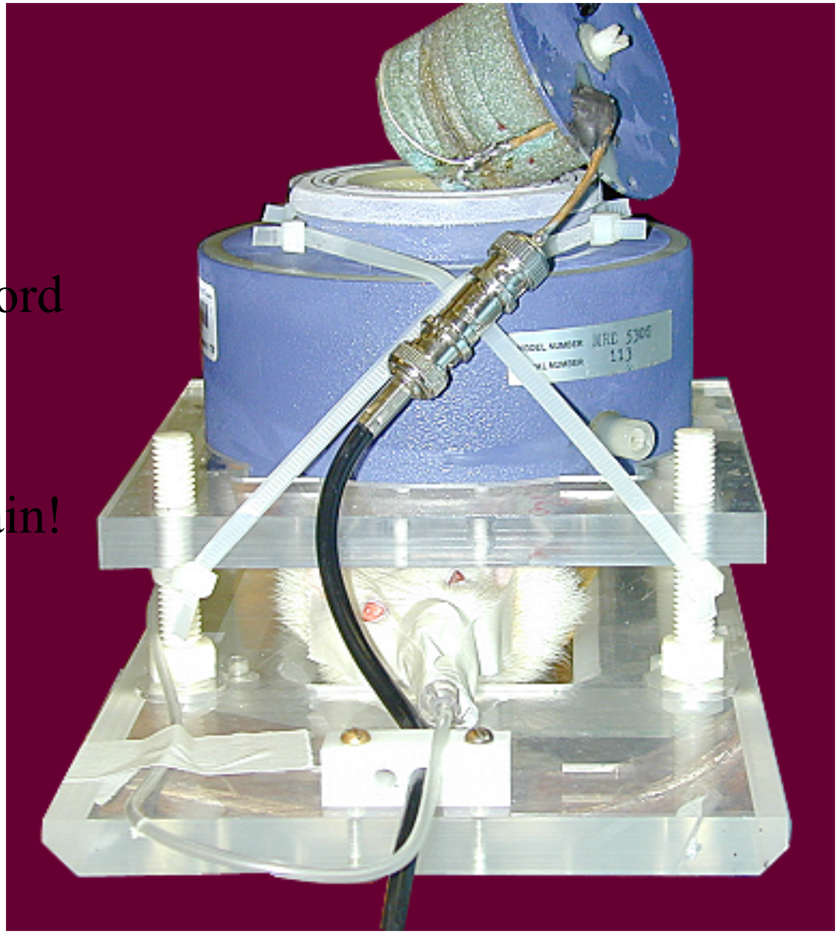
2-Tesla MRI of a Rat (under anesthesia)



spine-cord

4 dB gain!

brain



Wosik et al.

YBCO:

- *quality epi-films*
- *robust*
- *high J_c & high H_{ir} above 77 K*

↓

The best material for HTS science & technology

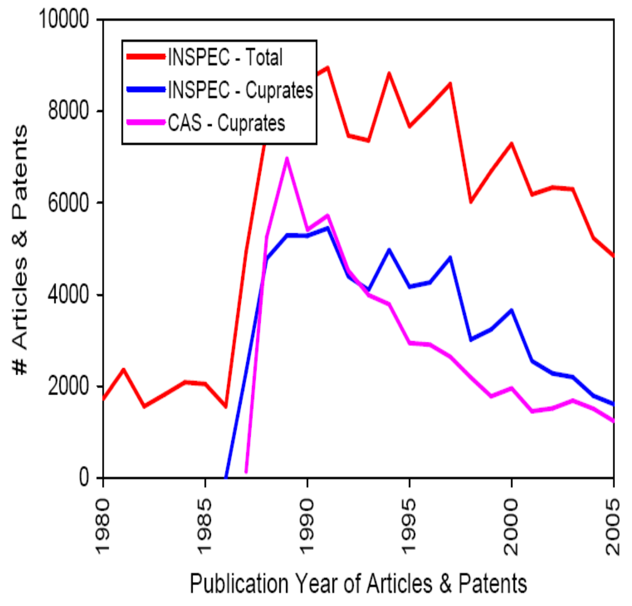
YBCO was included in the White House Millennium Time Capsule

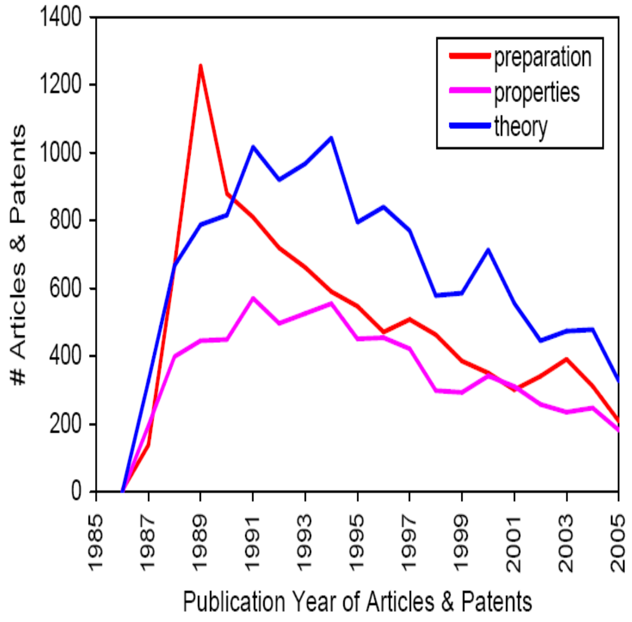
Closing Ceremony - December 6, 2000 in the National Archives, Washington DC

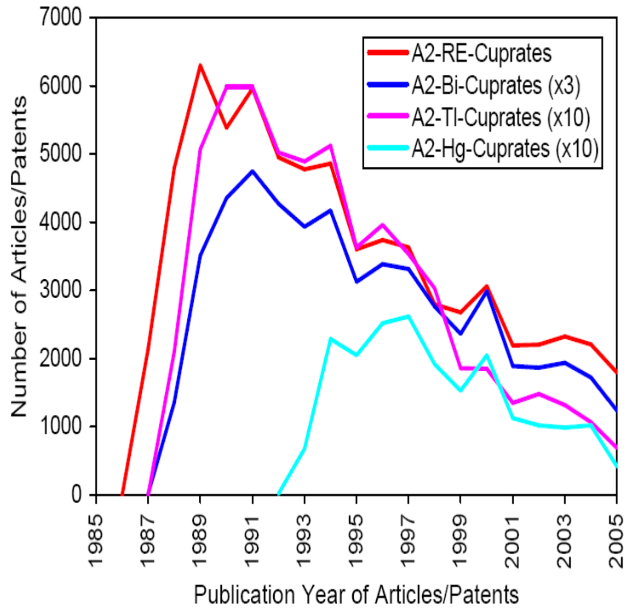
060327CWC

The winter of HTS S&T in 2006

A.Barth and W. Marx analyzed the HTS science publication statistics scientometrically in 2006, and sentenced it to die in 2010-2015 by extrapolation.







However, new discoveries cannot be predicted from past statistics

Mark Twain (Benjamin Disraeli):

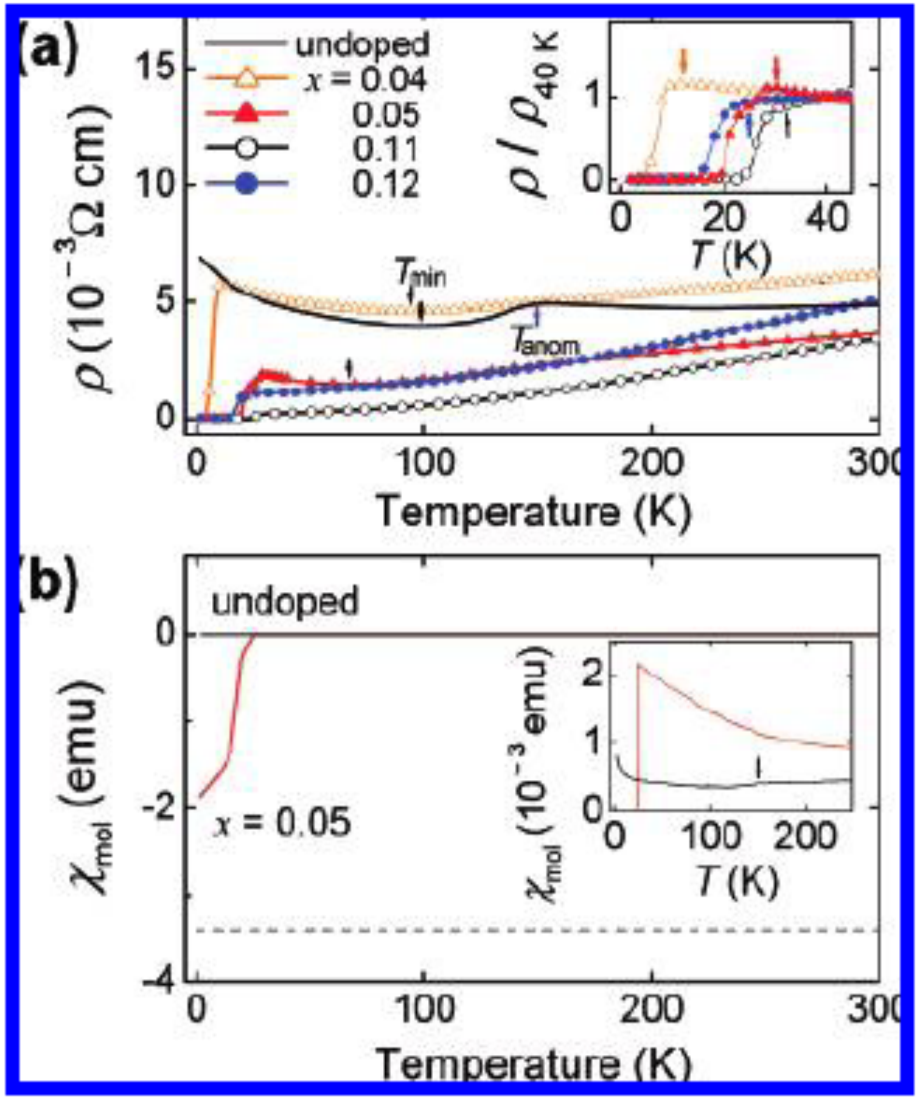
There are lies,
there are damned lies and
there are statistics.

SC was once sentenced to death before in 1986-87.

Fe-pnictides superconductors were discovered in 2008

Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs (x = 0.05−0.12) with T_c = 26 K

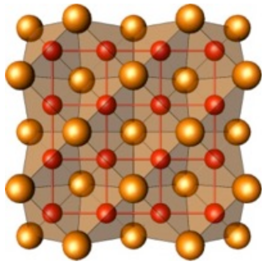
Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§



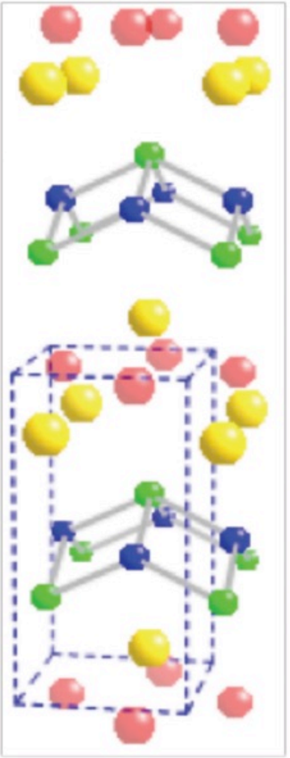
Tc ≤ 57 K
R(O,F)FeAs
JACS 130, 3296 (2008)
1111, 11, 122, 111

Fe- Pnictides & Fe-Chalcogenides

Perovskite-like
Fe-As layers or
Fe-Se layers



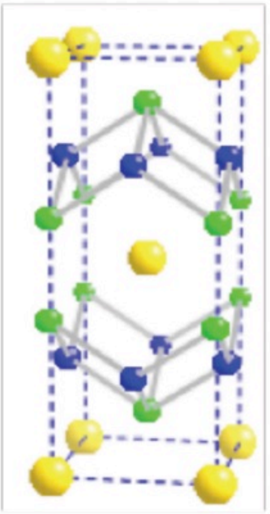
"1111"



≤ 57 K

H. Hosono et al.

"122"



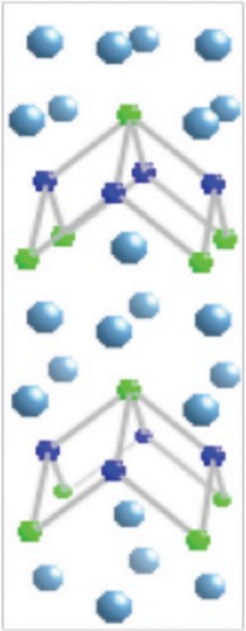
≤ 38 K

M. Rotter et al.

X. L Chen et al.

≤ 33 K

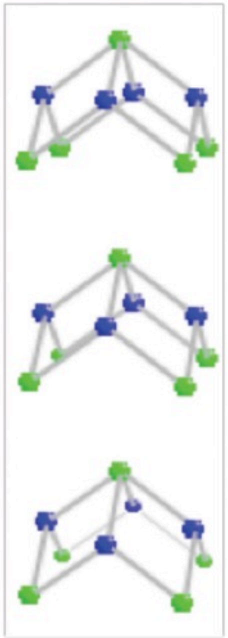
"111"



≤ 20 K

C. W. Chu et al.
C. Q. Jin et al.

"11"



M. K. Wu et al.

≤ 10 K
100 K?

Is room temperature superconductivity achievable?

104 years after the discovery of superconductivity,
57 years after the development of BCS &
27 years after the discovery of YBCO,
we have learned:

- *There is no evidence, experimental or theoretical, that prevents room temperature superconductivity from happening.*

- *Whatever physics law doesn't say won't happen will happen.*

- *RTS will be the next grand challenge in SC research – DoE, AFOSR*

BUT HOW and WHERE?

Search for and study of Novel Superconductors with Higher T_c and Unusual Superconducting States at TCSUH

the holistic multidisciplinary enlightened empirical approach*: *knowledge, imagination, experience, courage and luck

[“A possible path to RTS”, AAPPS Bulletin 16, 8 (2008); and “The evolution of HTS: Tc-experiment perspective”, BCS: 50 Years, P391 (2011)]

• by realizing novel SC mechanisms predicted theoretically,

e.g. interfacial mechanisms:

$(Ca,R)Fe_2As_2$ single crystals; ultrathin FeSe Films

• by discovering novel materials empirically,

e.g. anti-phase, new structural class:

$(Ba,Na)Ti_2Sb_2O$; (LiFe)OHFeSe; Zr_5Sb_3; $SrPt_6P_2$; $SrPt_{10}P_4$;

AFe_2As_2; FeSe

•by metalizing insulating phases via physical and/or chemical means,

$TeZr_3$

• by optimizing the multiple interactions in complex material systems,

e.g. superconducting, magnetic, ferroelectric

La_2CuO_{4-x}; CuO; $(Mn_{0.85}Co_{0.15})WO_4$; $TmAl_3(BO_3)_4$

• by stabilizing the metastable phases physically and chemically

$YBa_2Cu_3O_7$; [H_2S]

• by exploring novel states in solids

•$Cu_xBi_2Se_3$, $Bi_2Se_{2.1}Te_{0.9}$, $Pb_{1-x}Sn_xTe$, 1T-TaS_2; BAs

•Minerals

Covellite, Urvantsevite, Froodite

- The T_c record has stagnated at 164 K since 1994.
- Is it time to look into other directions?

Recent exciting observations in HTS

- Rare-earth doped - Ca122 up to 49 K

[B. Lv et al. PNAS USA 108, 15705 (2011); S. R. Saha et al. PRB 85, 024525 (2012);

L. Z. Deng et al. PRB(R)90, 214513 (2014)]

- FeSe up to 100 K

[Q. Y. Wang et al. Chin. Phys. Lett. 29, 037402 (1911); L. Z. Deng et al. PRB in press (2015)]

- H_2S up to 190 K above 200 GPa

[A. P. Drozlov et al. arX (2015)]

Naturally Assembled Compound System

PNAS USA 108, 15705 (2011)

Unusual superconducting state at 49 K in electron-doped $CaFe_2As_2$ at ambient pressure

Bing Lv[a], Liangzi Deng[a,b], Melissa Gooch[a], Fengyan Wei[a,b], Yanyi Sun[a], James K. Meen[a,c], Yu-Yi Xue[a,b], Bernd Lorenz[a,b], and Ching-Wu Chu[a,b,d,1]

[a]Texas Center for Superconductivity, University of Houston, Houston TX 77204-5002; [b]Department of Physics, University of Houston, Houston TX 77204-5005; [c]Department of Chemistry, University of Houston, Houston TX 77204-5003; and [d]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley CA 94720

Contributed by Ching-Wu Chu, July 26, 2011 (sent for review June 23, 2011)

PHYSICAL REVIEW B **85**, 024525 (2012)

Structural collapse and superconductivity in rare-earth-doped $CaFe_2As_2$

S. R. Saha,[1] N. P. Butch,[1] T. Drye,[1] J. Magill,[1] S. Ziemak,[1] K. Kirshenbaum,[1] P. Y. Zavalij,[2] J. W. Lynn,[3] and J. Paglione[1,*]

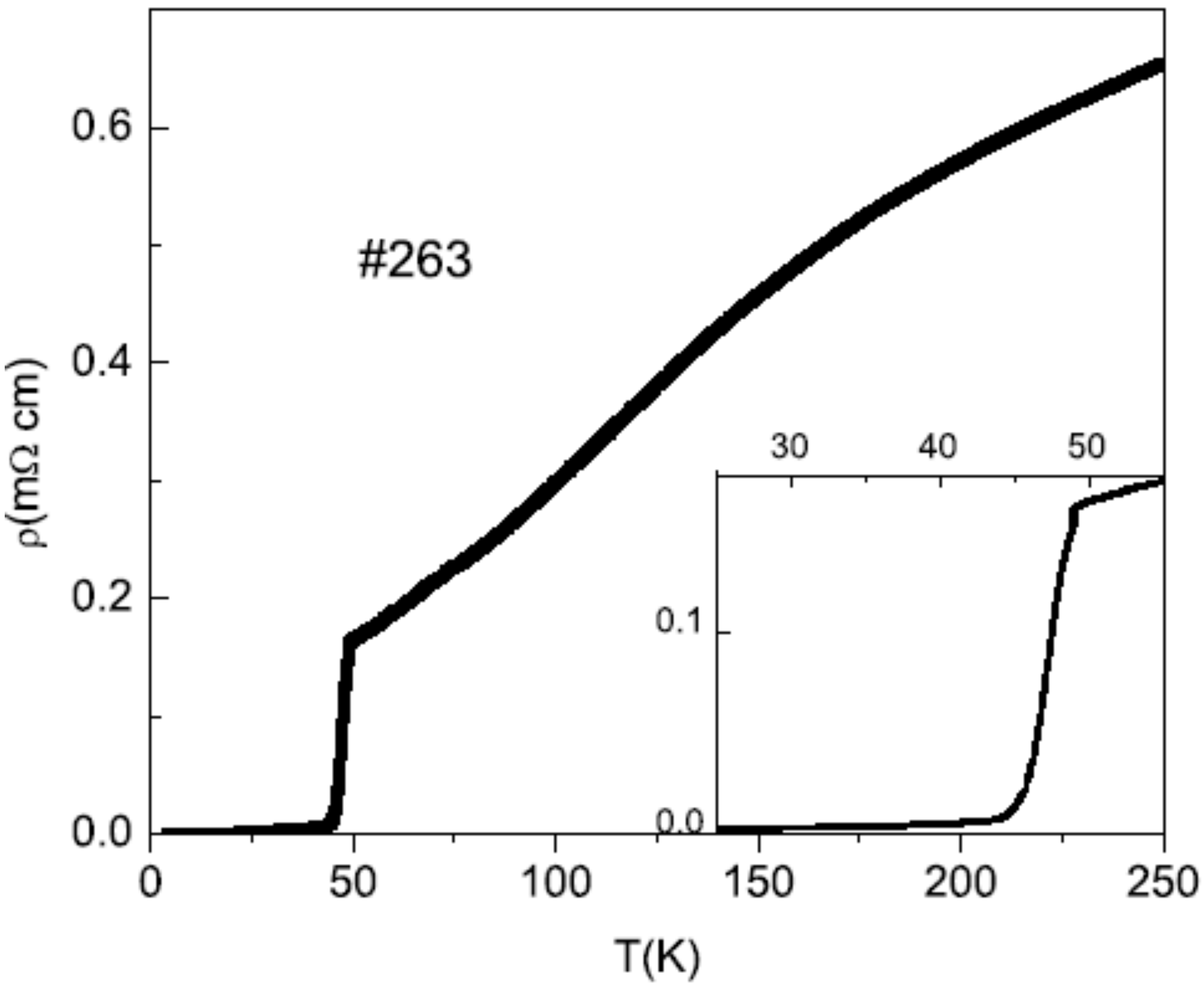
[1]*Center for Nanophysics and Advanced Materials, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

[2]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*

[3]*Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

(Received 3 November 2011; revised manuscript received 5 December 2011; published 13 January 2012)

$(Ca_{0.87}Pr_{0.13})Fe_2As_2$ onset T_c ~ 49 K, higher than any other 122 SCs



B. Lv/cwc et al. , PNAS 2011

20120726CWC

The 49 K superconductivity in rare-earth doped Ca122

•is non-bulk with a Tc higher than any other A122

•Is not rare earth specific

•displays a large magnetic anisotropy

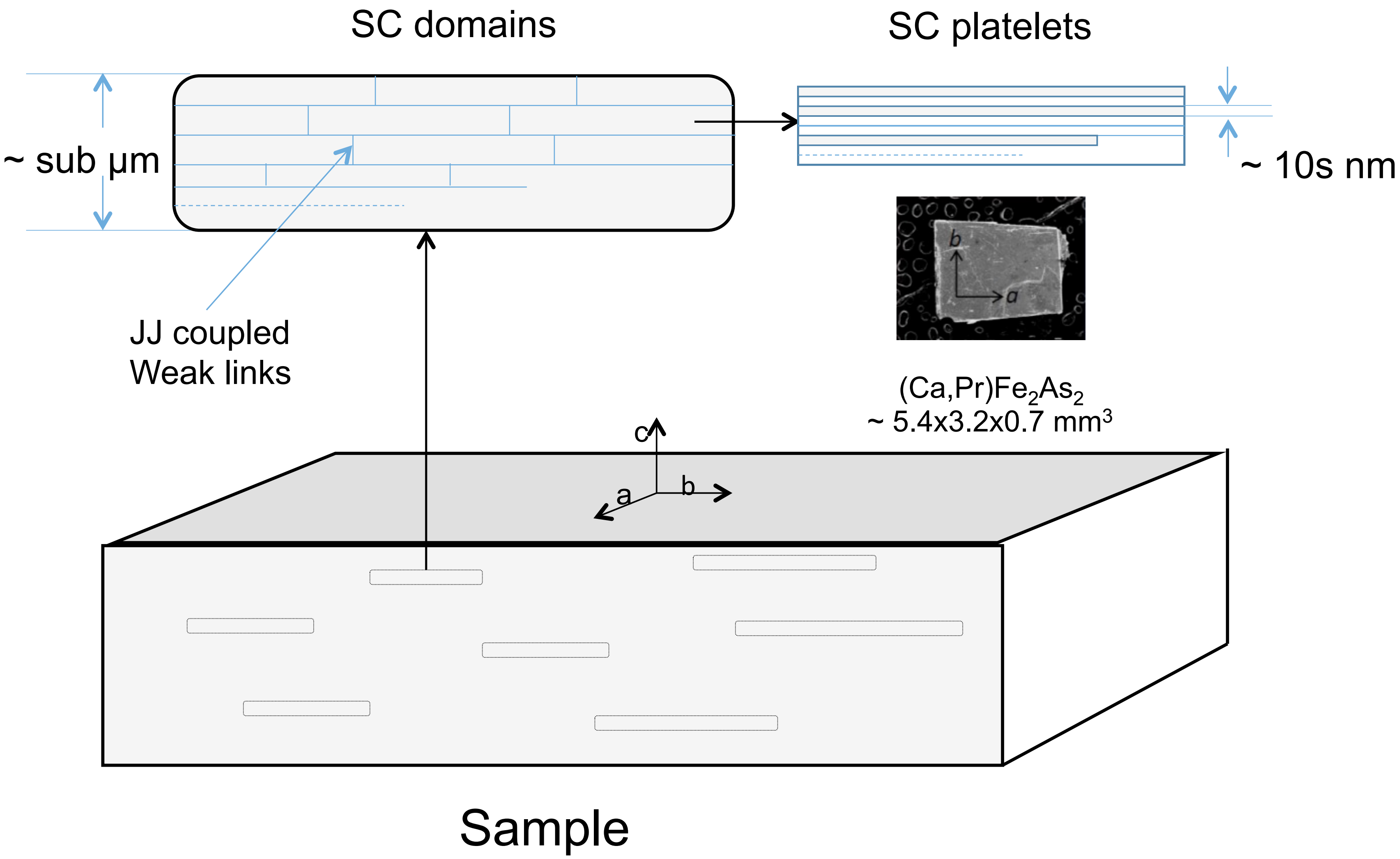
•is independent of doping-levels

•cannot be due to trivial artifacts, such as collapsed phase, or minute inclusions of optimally doped phase or the 1111 phase

•is closely related to the doping-induced defects

•The observations have provided clear evidence for possible interface-enhanced T_c in self-assembled material and led us to the proposition of a model that facilitates the formation of interfaces for the enhanced T_c

• All evidence is not direct to date.



SC domains
SC platelets
~ sub μm
~ 10s nm
JJ coupled
Weak links
b
a
(Ca,Pr)Fe_2As_2
~ 5.4x3.2x0.7 mm^3
c
a
b
Sample

Nature 501, 474 September 26, 2013

PHYSICS

Interface superconductivity found in single crystal

Iron-based compound revives search for room-temperature superconductors.

BY EUGENIE SAMUEL REICH

The provocative result comes from a superconducting pioneer: Paul Chu of the University of Houston in Texas. In the 1980s, he helped to discover the first high-temperature superconductors, a family of copper-containing compounds (see 'All in the family'). In a paper posted on the arXiv preprint server on 30 August[1], Chu and his colleagues now report their work on an iron-based crystal that generally superconducts at 30 kelvin — but that contains small regions that superconduct at 49 kelvin. Chu proposes that the effect is the result of many interfaces forming tens of nanometres apart within these regions (see 'At the interface').

Artificially Assembled Ultrathin Films

CHIN. PHYS. LETT. Vol. 29, No. 3 (2012) 037402

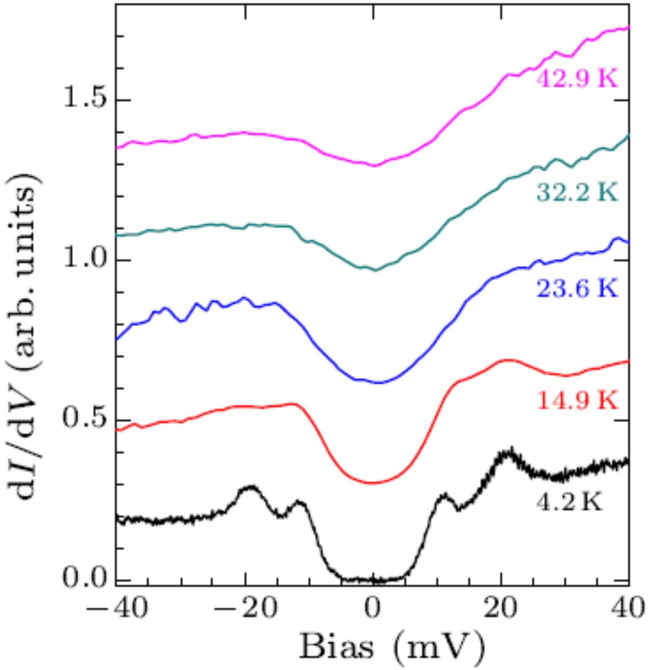
Interface-Induced High-Temperature Superconductivity in Single Unit-Cell FeSe Films on $SrTiO_3$ *

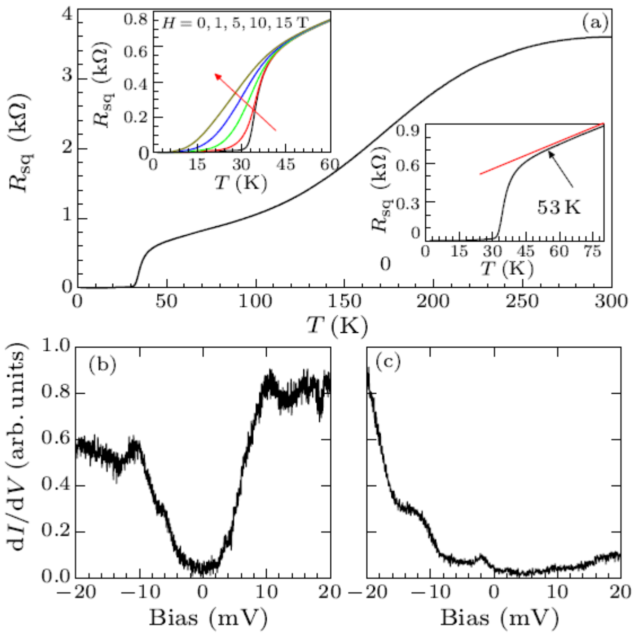
WANG Qing-Yan(王庆艳)[1,2†], LI Zhi(李志)[2†], ZHANG Wen-Hao(张文号)[1†], ZHANG Zuo-Cheng(张祚成)[1†], ZHANG Jin-Song(张金松)[1], LI Wei(李渭)[1], DING Hao(丁浩)[1], OU Yun-Bo(欧云波)[2], DENG Peng(邓鹏)[1], CHANG Kai(常凯)[1], WEN Jing(文竞)[1], SONG Can-Li(宋灿立)[1], HE Ke(何珂)[2], JIA Jin-Feng(贾金锋)[1], JI Shuai-Hua(季帅华)[1], WANG Ya-Yu(王亚愚)[1], WANG Li-Li(王立莉)[2], CHEN Xi(陈曦)[1], MA Xu-Cun(马旭村)[2**], XUE Qi-Kun(薛其坤)[1**]

[1] *State Key Lab of Low-Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084*

[2] *Institute of Physics, Chinese Academy of Sciences, Beijing 100190*

(Received 1 February 2012 and accepted by ZHU Bang-Fen)





- Superconducting Gap
  - Bulk FeSe, Δ= 2.2 meV, T_c-9.4 K
  - 1UC FeSe, Δ=20.1meV,T_c→80K(?)
- Resistance drop
  - transition ` 32 – 42 K

vs.

- T_c ~ 8 K (bulk)
- T_c ~37 K (8.9 GPa): β- $Fe_{1.01}Se$
- T_c ~18 K (Te substitution): $FeSe_{0.5}Te_{0.5}$

Significant scientifically and technologically

- *High T_c*
- *Simple structure*
- *Nano-electronics*

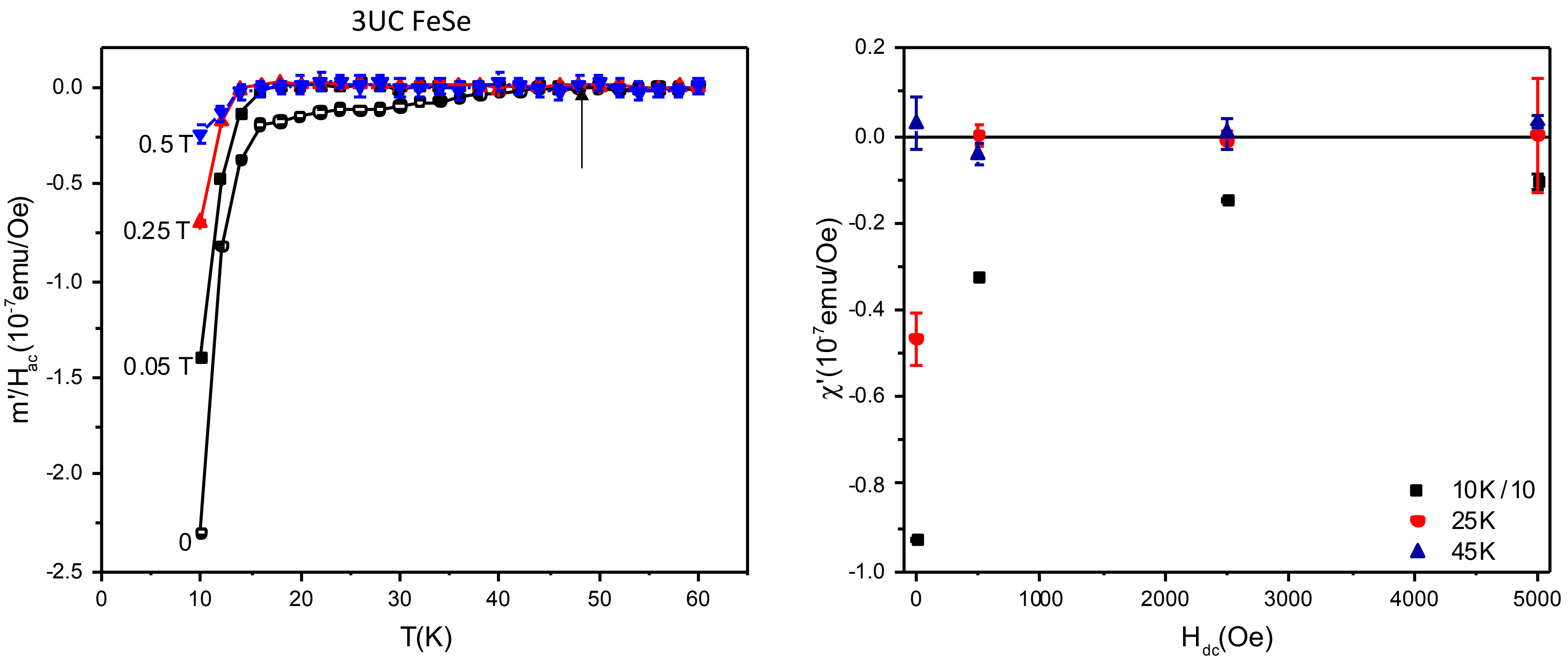
- *1UC vs 2UC?*
- *So few lab can do it?*
- *No hole-pocket?*
- *T_c?*
- *SC?*

Search for the Meissner state in ultrathin FeSe samples- the necessary and sufficient condition for SC

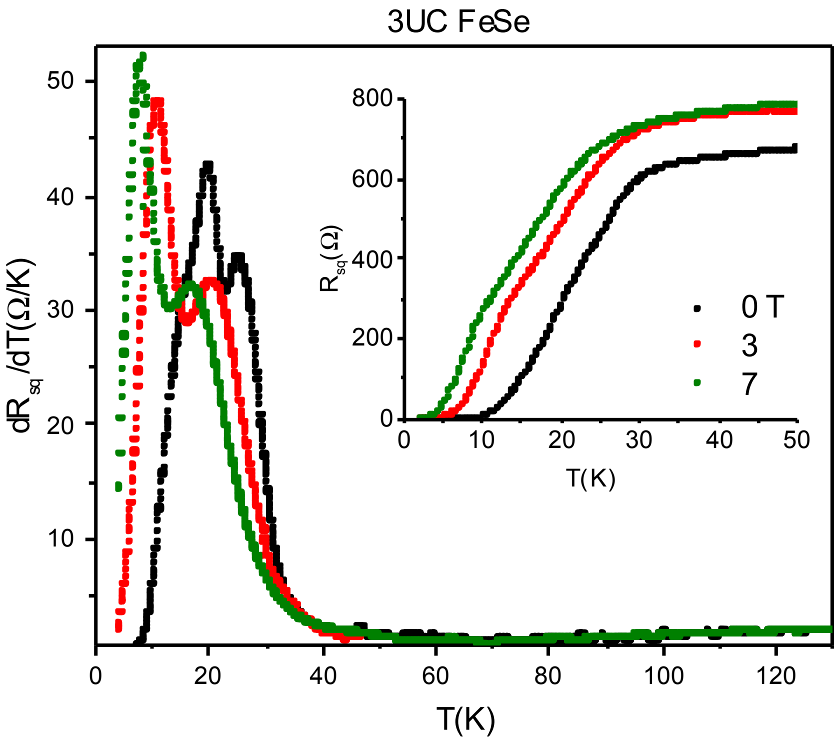
- It is a challenge to measure the magnetization of such a small mass ~ n x 26 ng.
- The large demagnetization factor (~ 10^6) does help but poses challenges to determine the SC volume fraction.
- We have developed a technique to acquire meaningful data on the SC temperature and morphology.

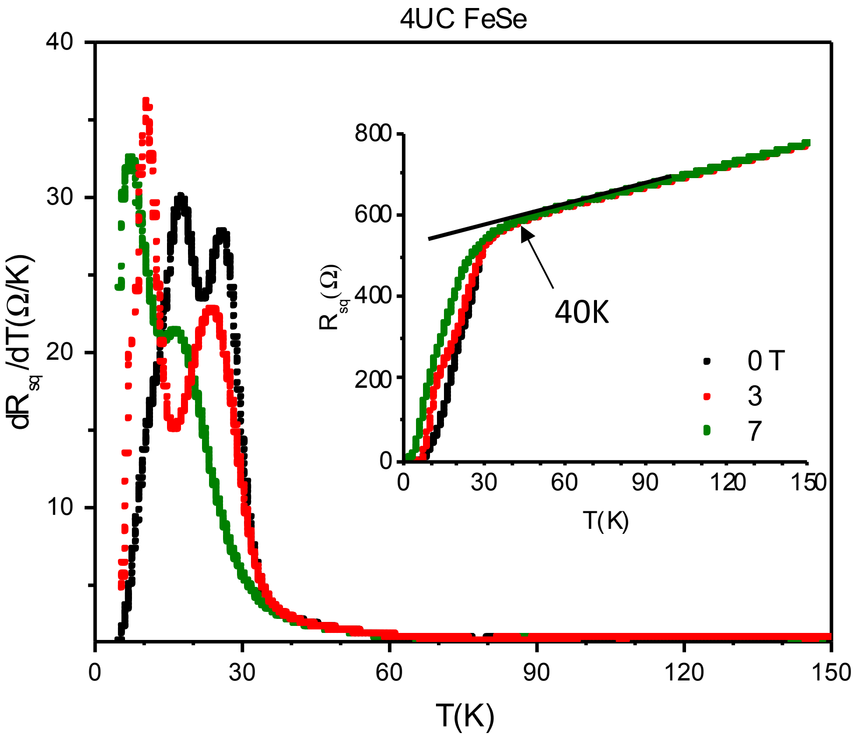
8 Samples (Si/10UC FeTe/n FeSe/STO) with n = 1-4 of size 2mmx5mm over one and half years

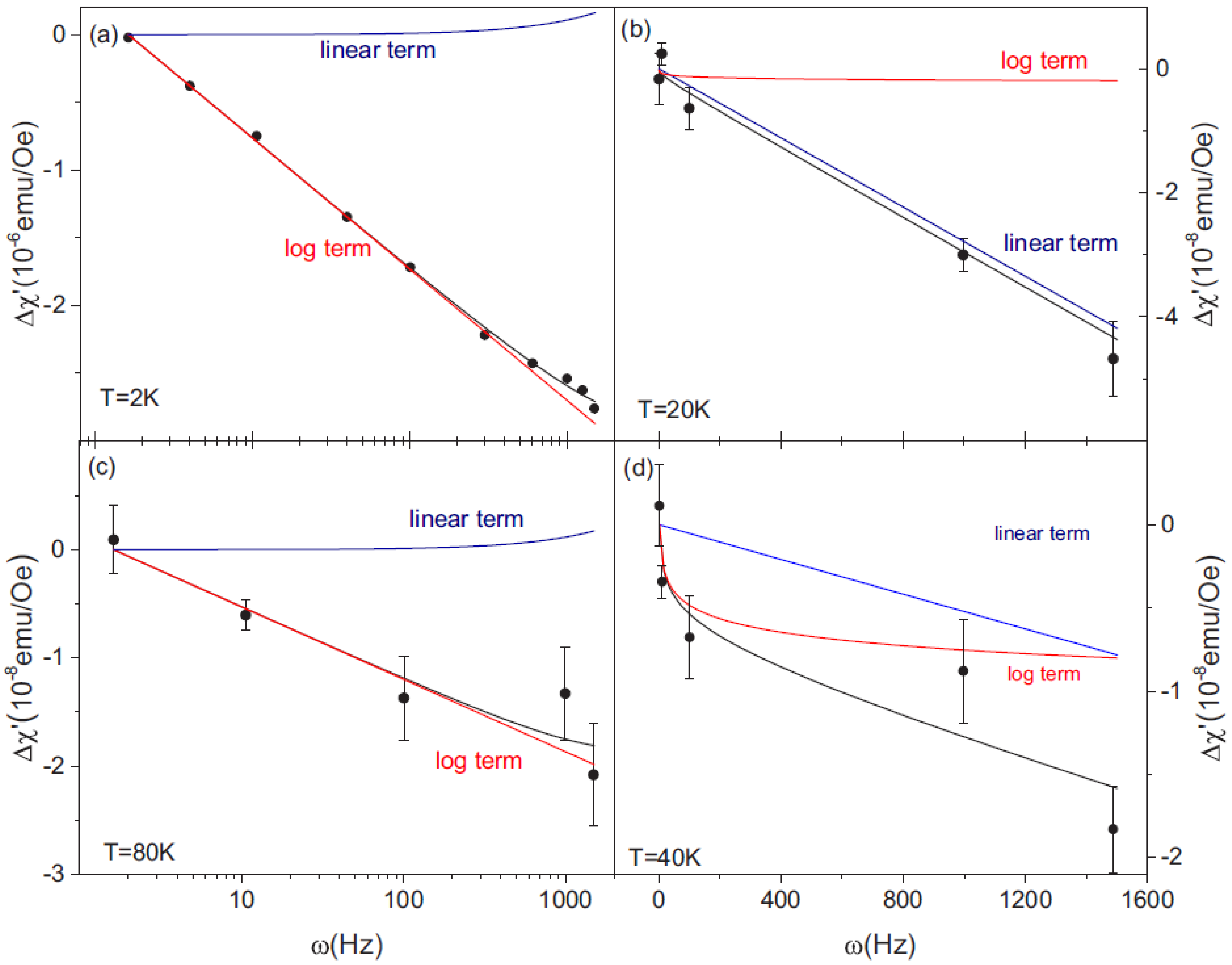
➢ Magnetic field effect and Meissner state



➢ RT measurement



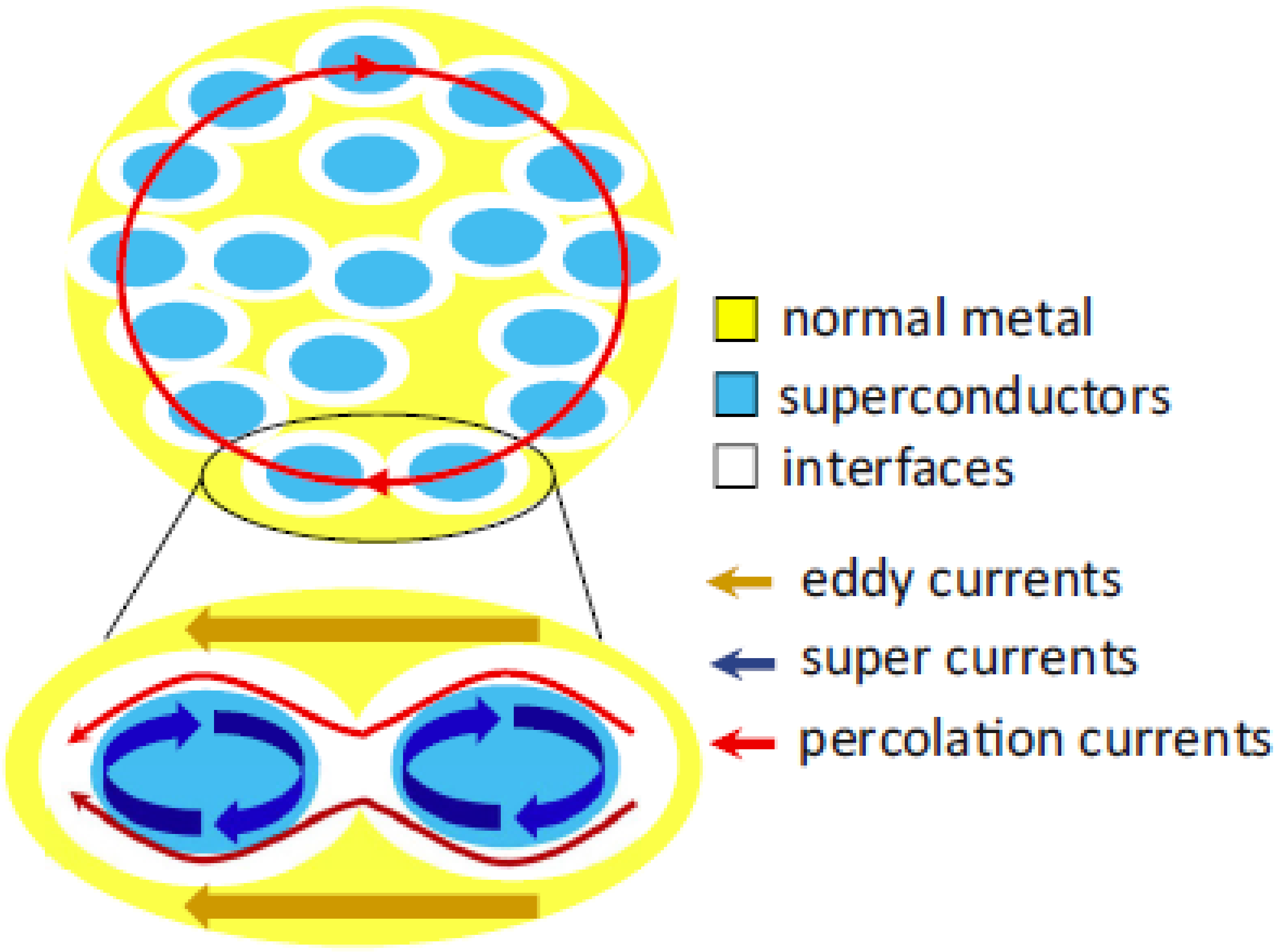




(a)
linear term
log term
T=2K
(b)
log term
linear term
T=20K
(c)
linear term
log term
T=80K
(d)
linear term
log term
T=40K
Δχ'(10^-6emu/Oe)
Δχ'(10^-8emu/Oe)
Δχ'(10^-8emu/Oe)
Δχ'(10^-8emu/Oe)
0
-1
-2
-3
-4
10
100
1000
0
400
800
1200
1600
ω(Hz)
ω(Hz)

A Defect-Dependent Complex SC state in Ultrathin FeSe Films

- Meissner state exists below 20 K
- Mesoscopic sc state exists up to 45 K
- Collective excitations exists up to 100 with nature yet to be determined
- Cannot address the n-dependent SC yet

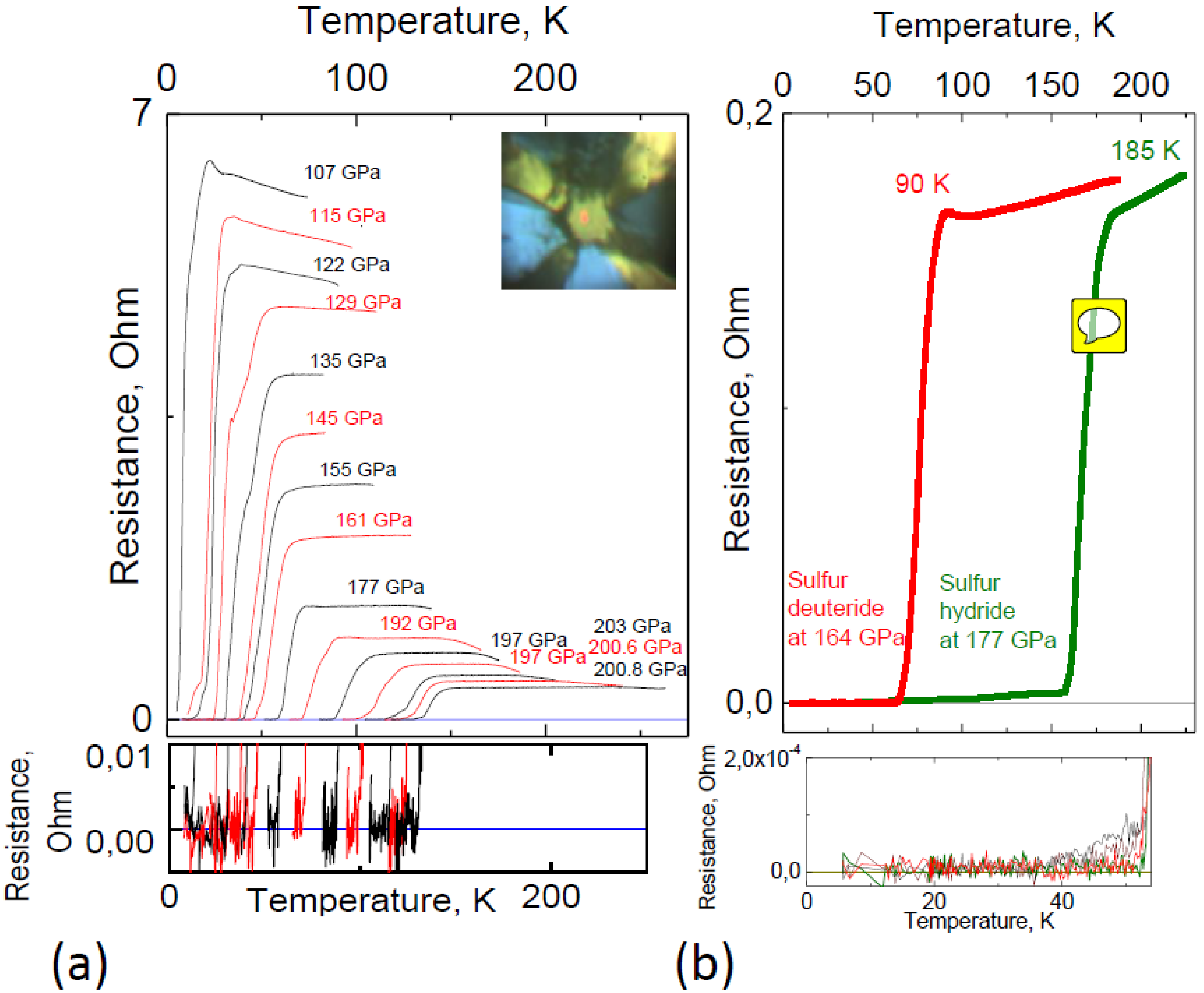

normal metal
superconductors
interfaces
eddy currents
super currents
percolation currents

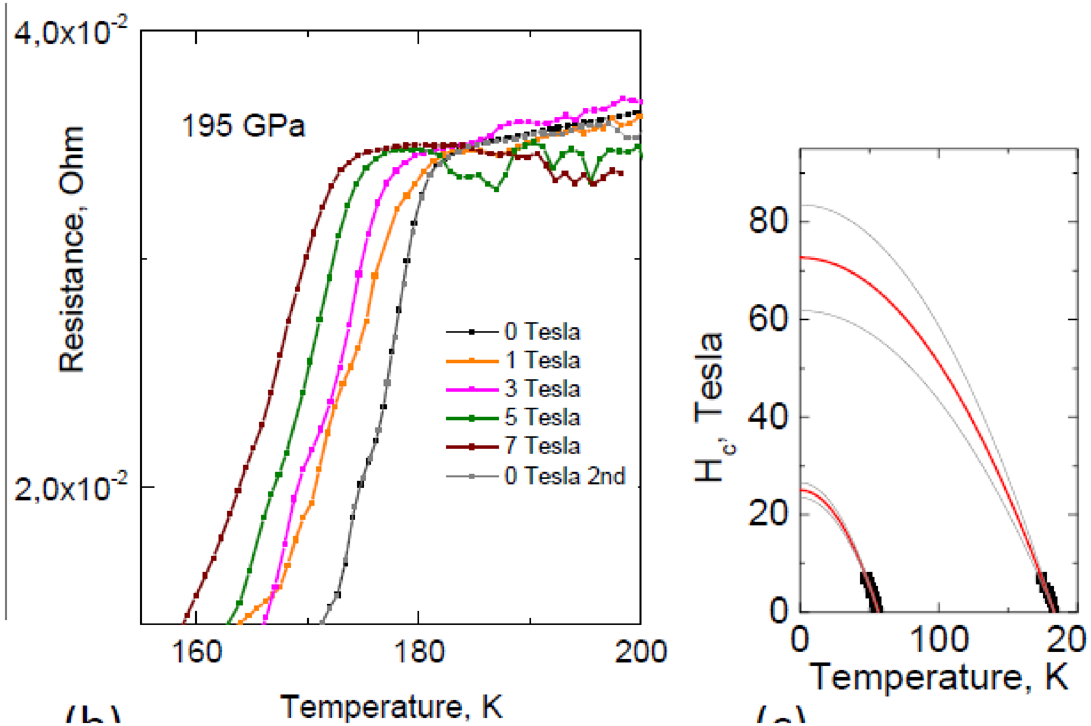
Conventional superconductivity at 190 K at high pressures

A.P. Drozdov, M. I. Eremets*, I. A. Troyan

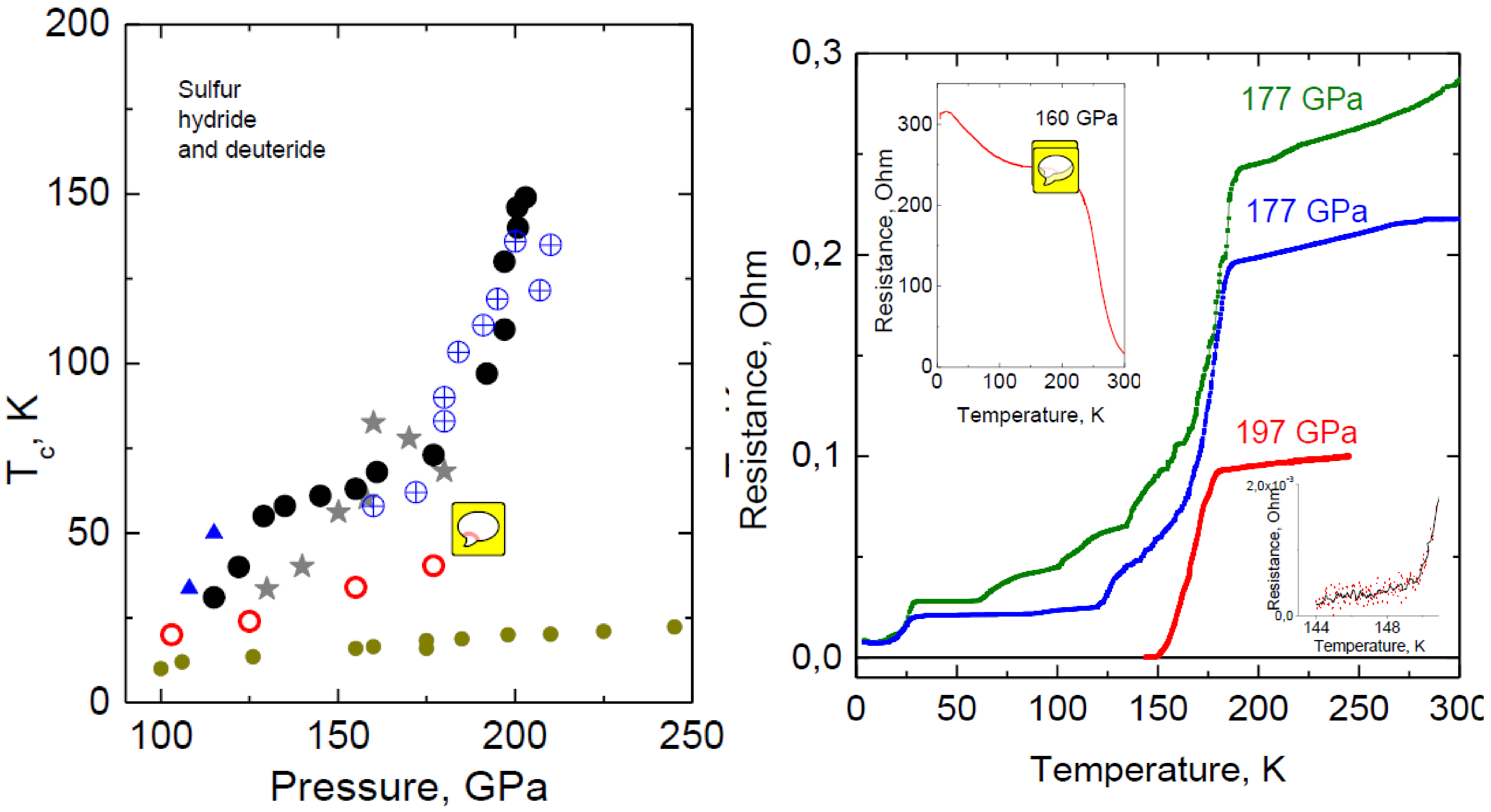
Max-Planck Institut fur Chemie, Chemistry and Physics at High Pressures Group

Postfach 3060, 55020 Mainz, Germany





BCS conventional sc
Electron-phonon

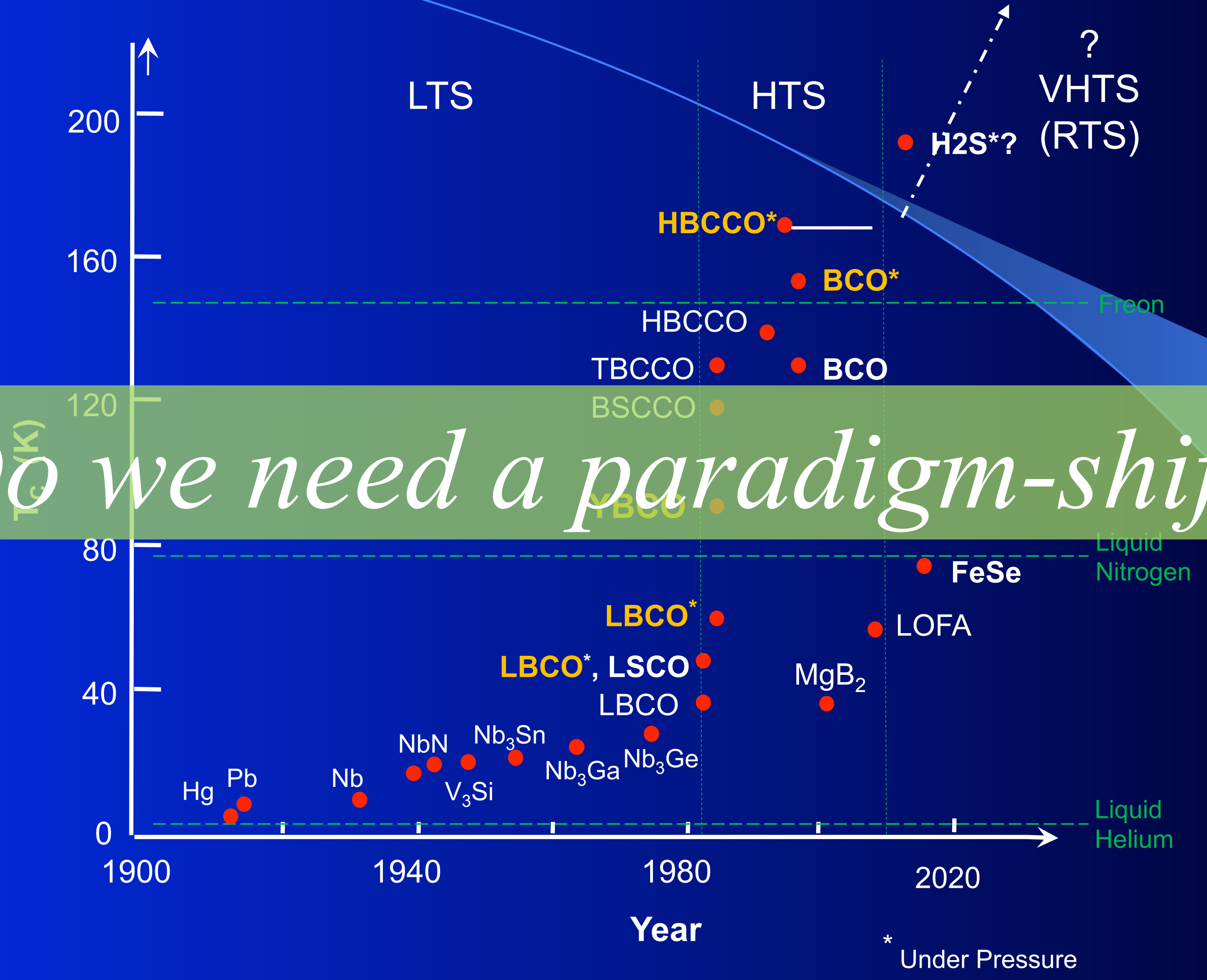


Sulfur
hydride
and deuteride
200
150
100
50
0
T_c, K
100
150
200
250
Pressure, GPa
0,3
0,2
0,1
0,0
Resistance, Ohm
0
50
100
150
200
250
300
Temperature, K
177 GPa
177 GPa
197 GPa
160 GPa
300
200
100
0
Resistance, Ohm
0
100
200
300
Temperature, K
2,0x10^{-3}
0,0
Resistance, Ohm
144
148
Temperature, K

- BCS - $T_c \sim M^{-\alpha}$, $\alpha = 0.5$
- H_2S - $\alpha = 12$ or 3
- Type I superconductor
- History-dependent
- Magnetic signature

???

Three Stages of T_c- Evolution



Do we need a paradigm-shift?


April 10, 2015, MPI Mainz, Germany

- One possible common theme

Interface may play an important role in the unusually high T_c in all three cases. i.e. Ca122, FeSe, H_2S and CuCl

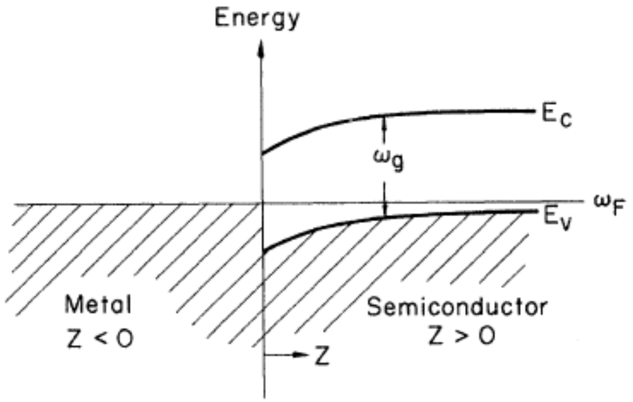
- Could be a paradigm shift (2D, correlation, applications)

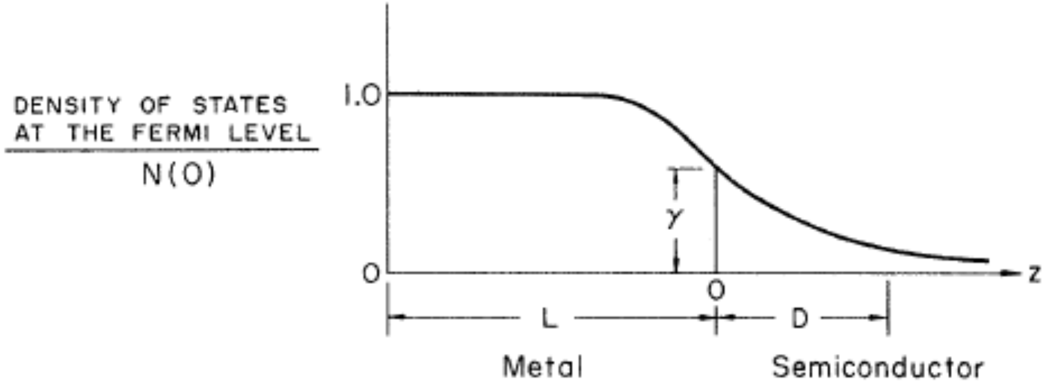
- But no direct magnetic evidence yet

Interfacial SC in (Ca,Pr)122

•Search for high T_c via novel mechanisms: bosonic excitations with high characteristic temperatures – phonons, polarons excitons, magnons, plasmons, bipolarons, spinons, anyons, morons,..

•A possible route via inter-facial superconductivity by the exchange of excitons: **Allender, Bray and Bardeen PRB 7, 1020 (1973)**



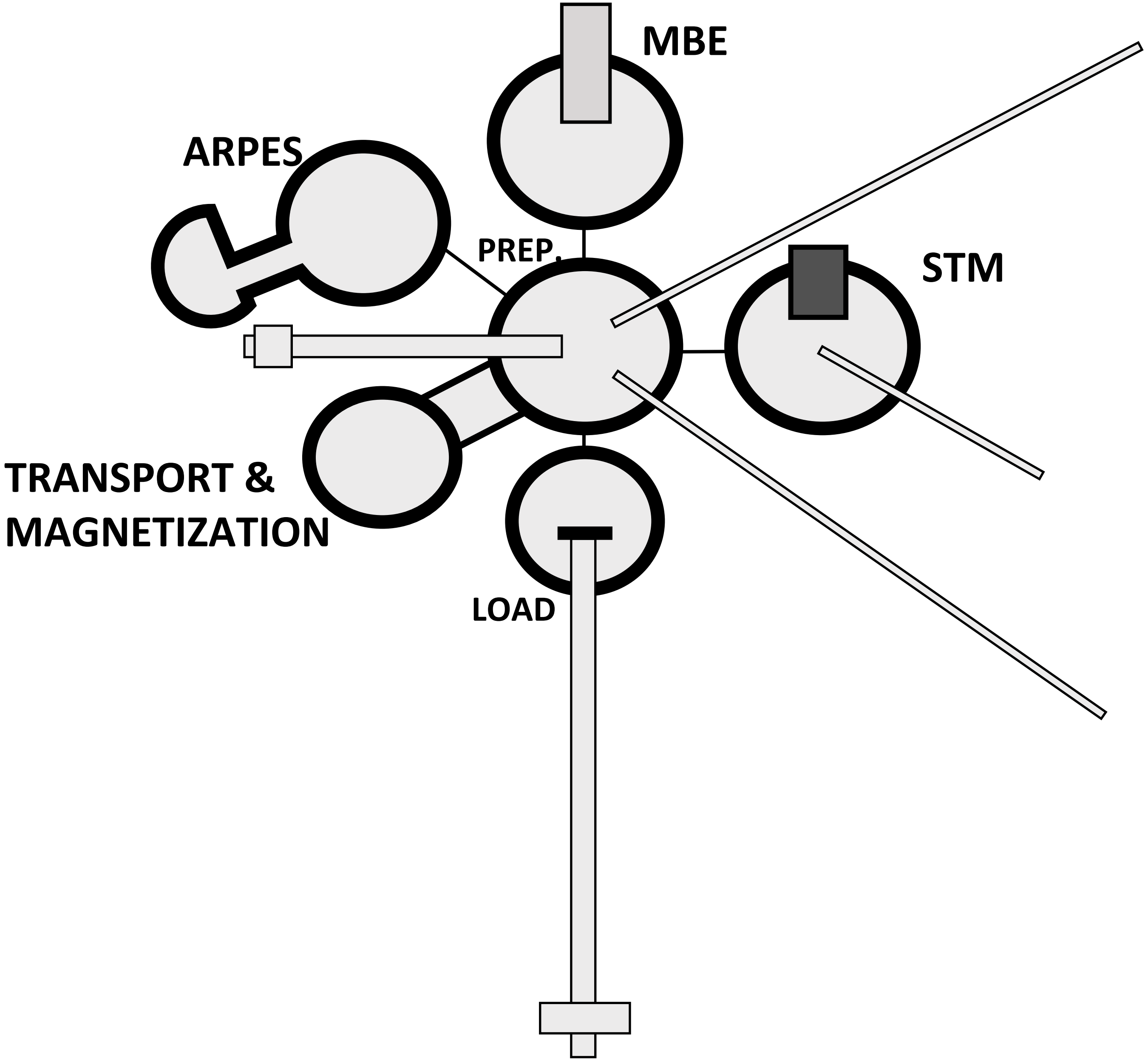


• Challenges: Where and How to find and realize them?
Theoretical guidance and method of negation

To address the issues, two new projects are in progress at TCSUH:

- The integrated MBE/TEM/ARPES/MR system
- Magnetization etc. under ultrahigh pressure

(in collaboration with Mikhail Eremets & Xiaojie Chen)


MBE
ARPES
PREP.
STM
TRANSPORT &
MAGNETIZATION
LOAD

Is it possible to find a room temperature superconductor?

Yes, it is possible, because
over the last 100 years, we have learned:

- *There is no evidence, experimental or theoretical, that prevents room temperature superconductivity from taking place.*

- *Whatever physics law doesn't say won't happen will happen.*

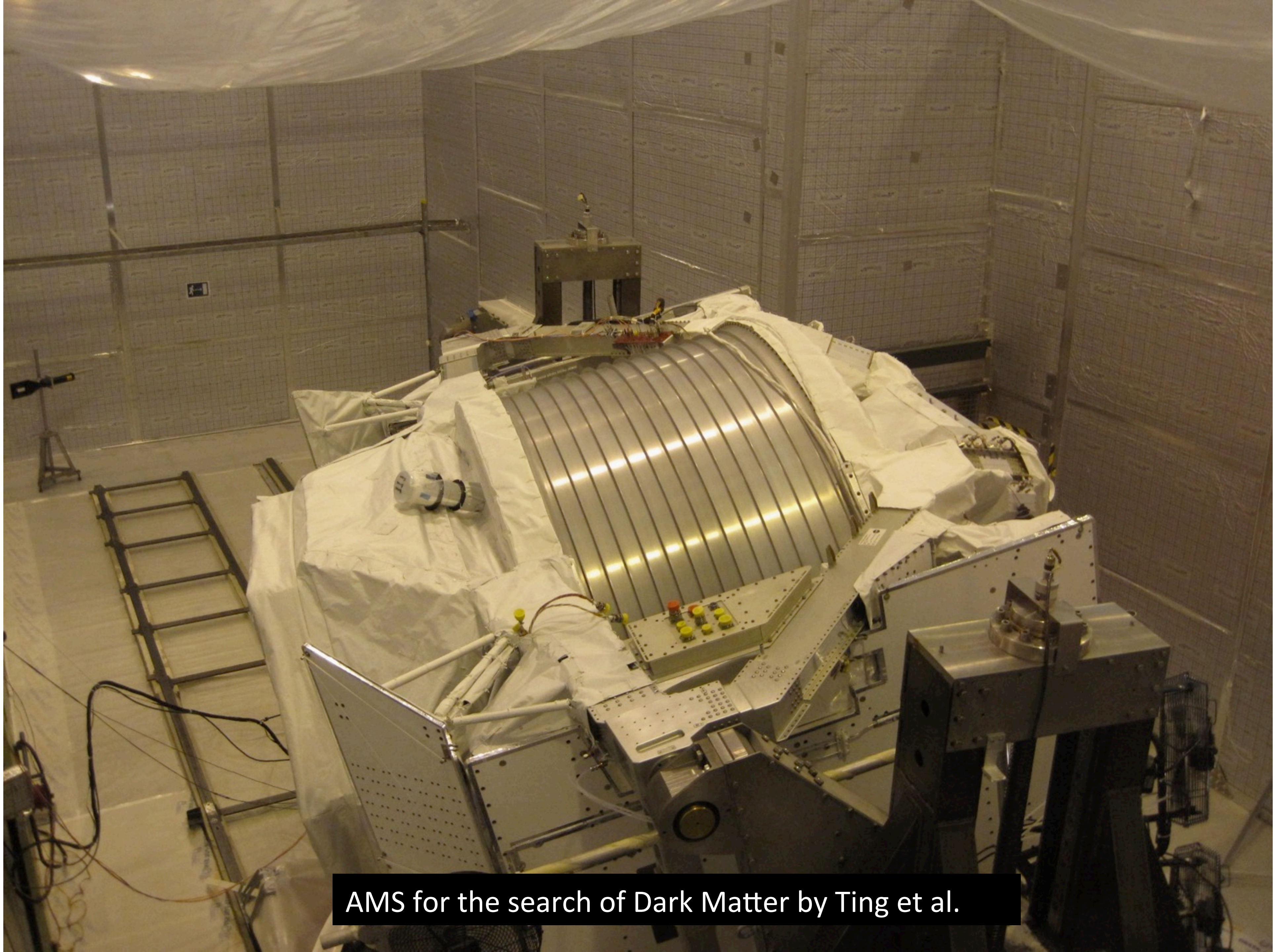
- *Be prepared to expect the unexpected - history repeats itself always.*

- The search for high Tc will go on:

God is kinder to physicists than to mountaineers to whom the final goal of Mt. Everest is already granted and reached, and the excitement ceases once they get there.

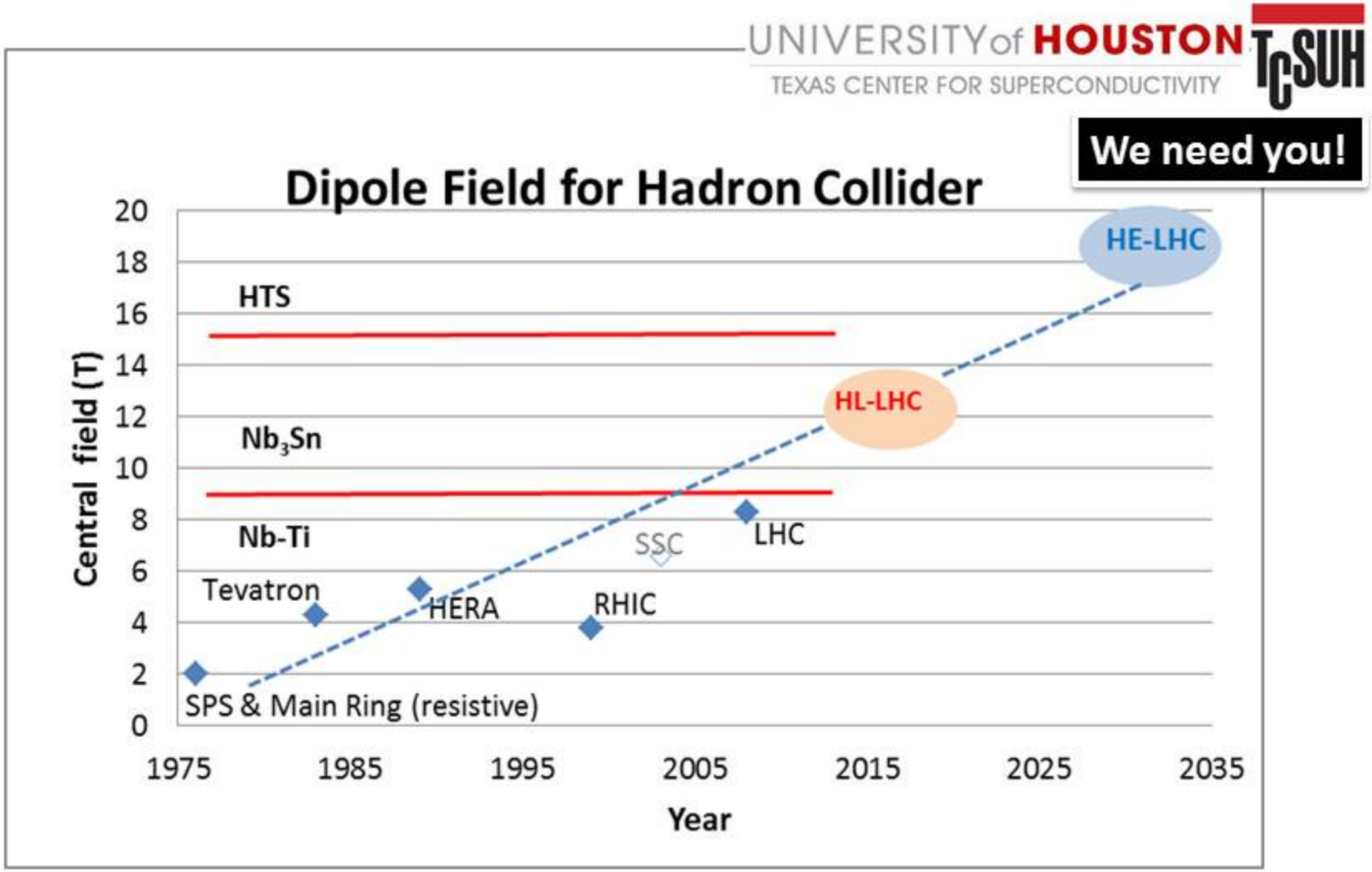
Edmund Hillary & Tenzing Norgay May 29 1953

A "Room Temperature Superconductor" was found in 2009 by James Cameron



AMS for the search of Dark Matter by Ting et al.

WITH HI-LUMI LHC WE PREPARE THE 2025-2035 RUN: AND AFTER?



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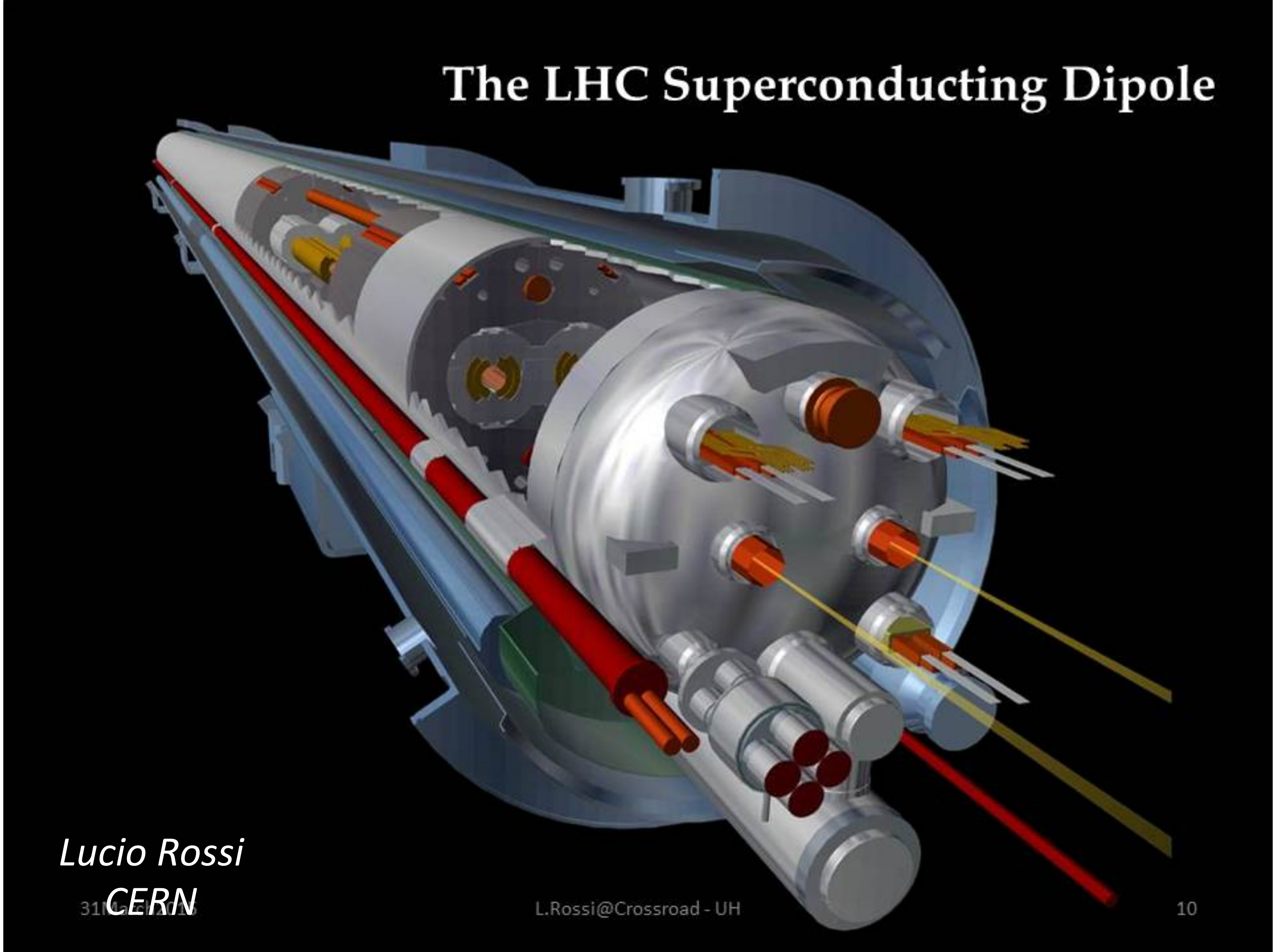
CERN


The LHC Superconducting Dipole
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Thank You!