2008 American Physical Society April Meeting
St. Louis MO, April 14, 2008

HTS 20 Years later:

Achievements, Promises, Challenges plus the New Fe-Based HTS System

Paul C. W. Chu

University of Houston
&
Hong Kong University of Science & Technology


AFES2005


Hong Kong University of Science & Technology
080328CWC


Hong Kong University of Science & Technology
080328CWC

Hong Kong University of Science & Technology

2007 was a special year

- *20th anniversary of the discovery of the YBCO*
- *50th anniversary of non-conservation of parity*
- *50th anniversary of the development of BCS theory*

- *21st anniversary of the discovery of the 30 K sc*
- *51st anniversary of the Cooper pair*
- *301st Principia Mathematica*

2008 may be equally special

- *the newly discovered R(OF)FeAs with a T_c up to 53 K*

High Temperature Superconductivity is:

- Scientifically Challenging

- offers new paradigms for our understanding of solids & physics

- Technologically Promising

- holds the key to the sustainable development of the worlds and others

Constraints for Future global economic growth:

Energy, Environment and Resources

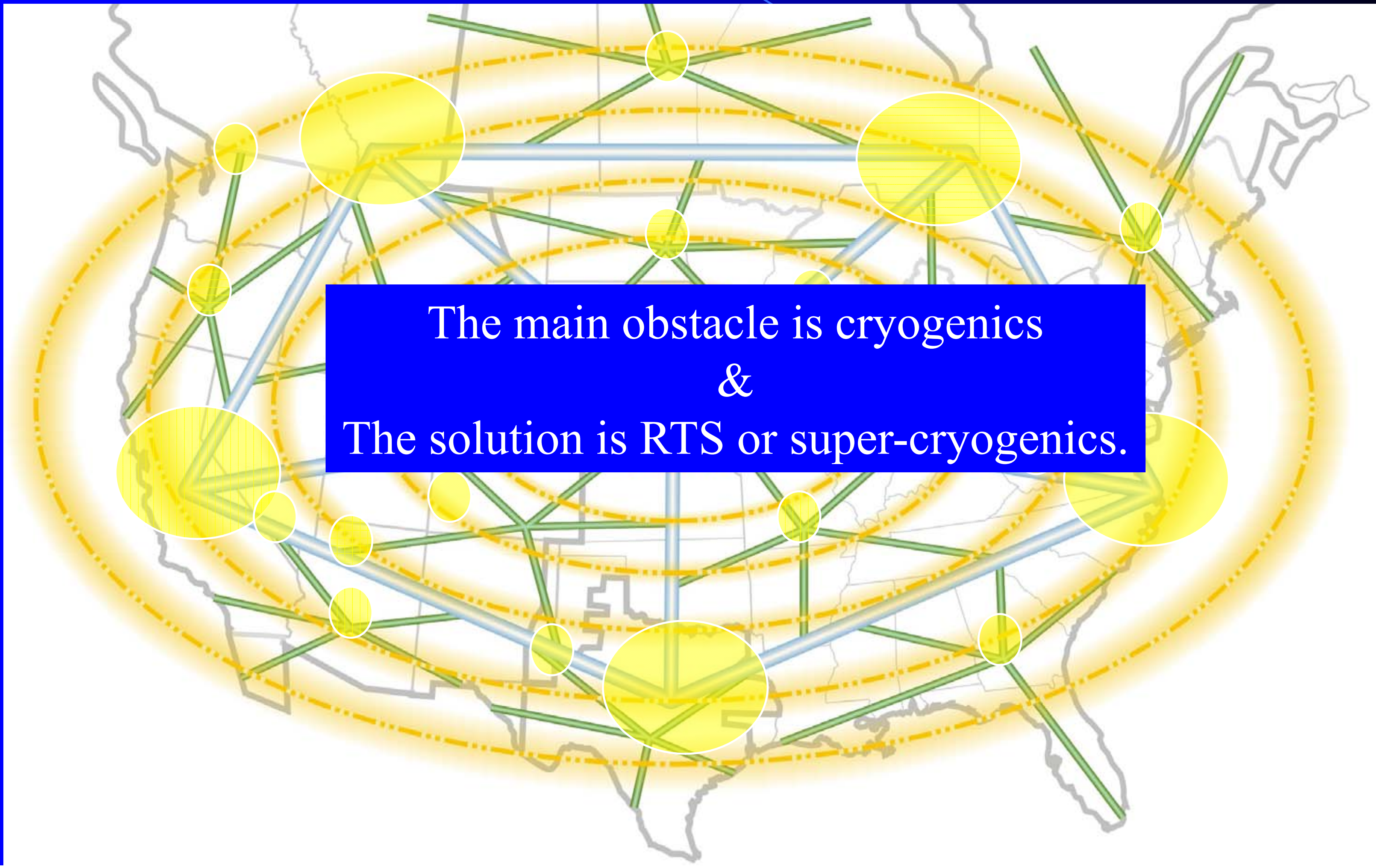
Energy is the key
and HTS can play a crucial role in electricity use, and electric power quantity delivery and quality control.

Asia at Night

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

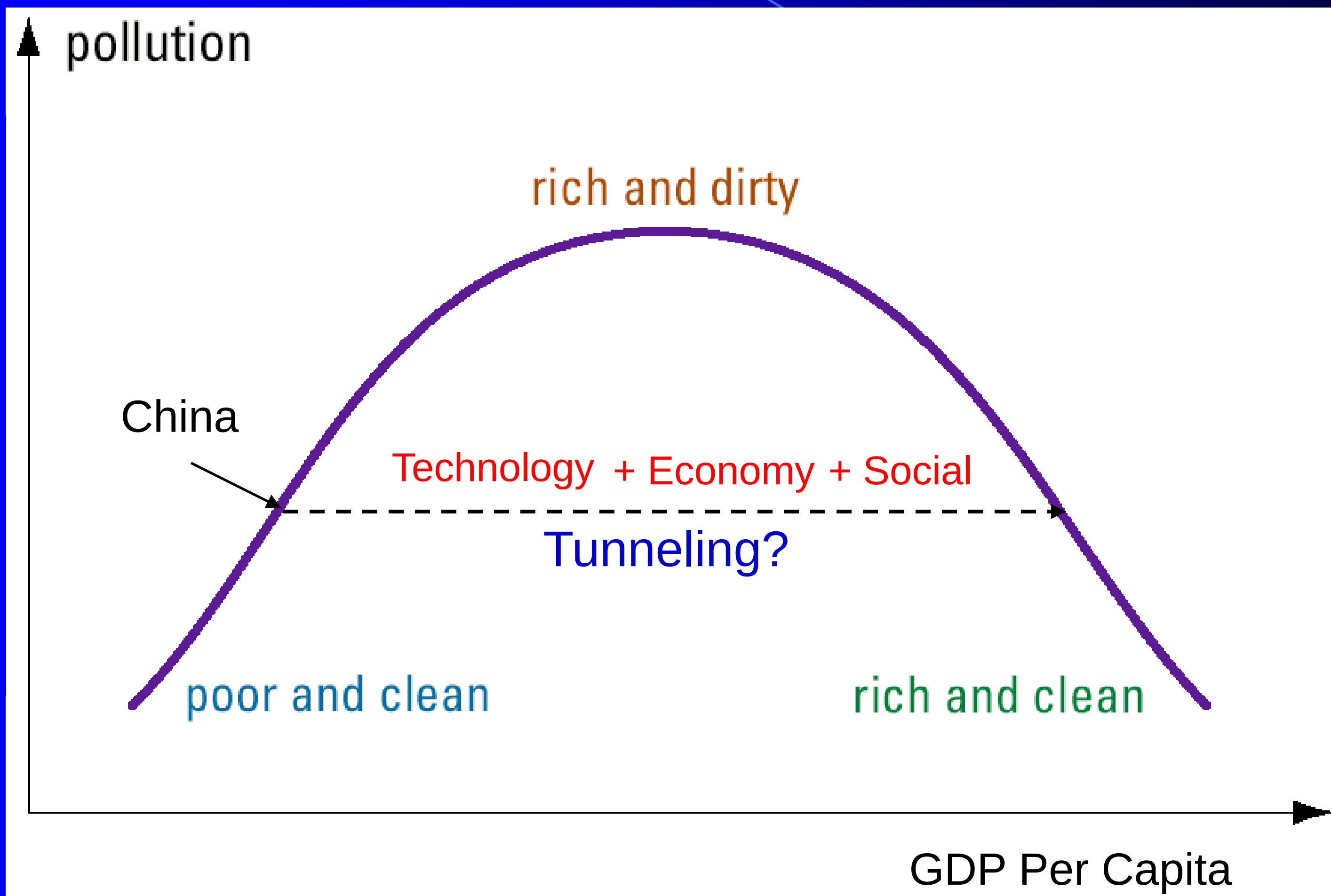
080328CWC

SuperGrid in North America (Jimmy Glotfelty) backbone, regional, micro and IT



The main obstacle is cryogenics
&
The solution is RTS or super-cryogenics.

Traditional Path for Industrialization



(Xu K. D., President, CAE)

Searching for a new superconductor with a higher T_c has long been the driving force for superconductivity research

The BCS theory is simple, elegant and descriptive but lacks the predictive power for high T_c.

Before 1986

- Experimentally:
  - $T_c \leq 23.2$ K (1973 - 1986)
  - search for novel materials

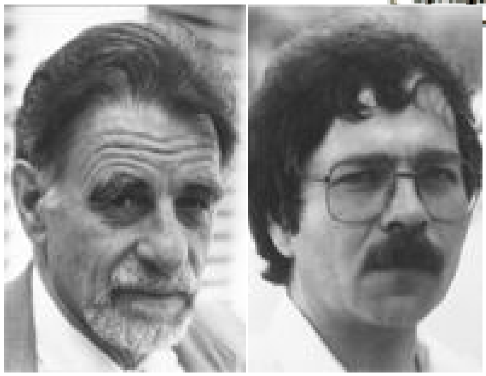
- Theoretically:
  - $T_c <$ 30's K (instabilities)
  - propose novel mechanisms

Confidence crisis in the search for higher T_c

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.

$La_{2-x}Ba_xCuO_4$ (214) – new T_c record to 35 K in a new oxides

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.

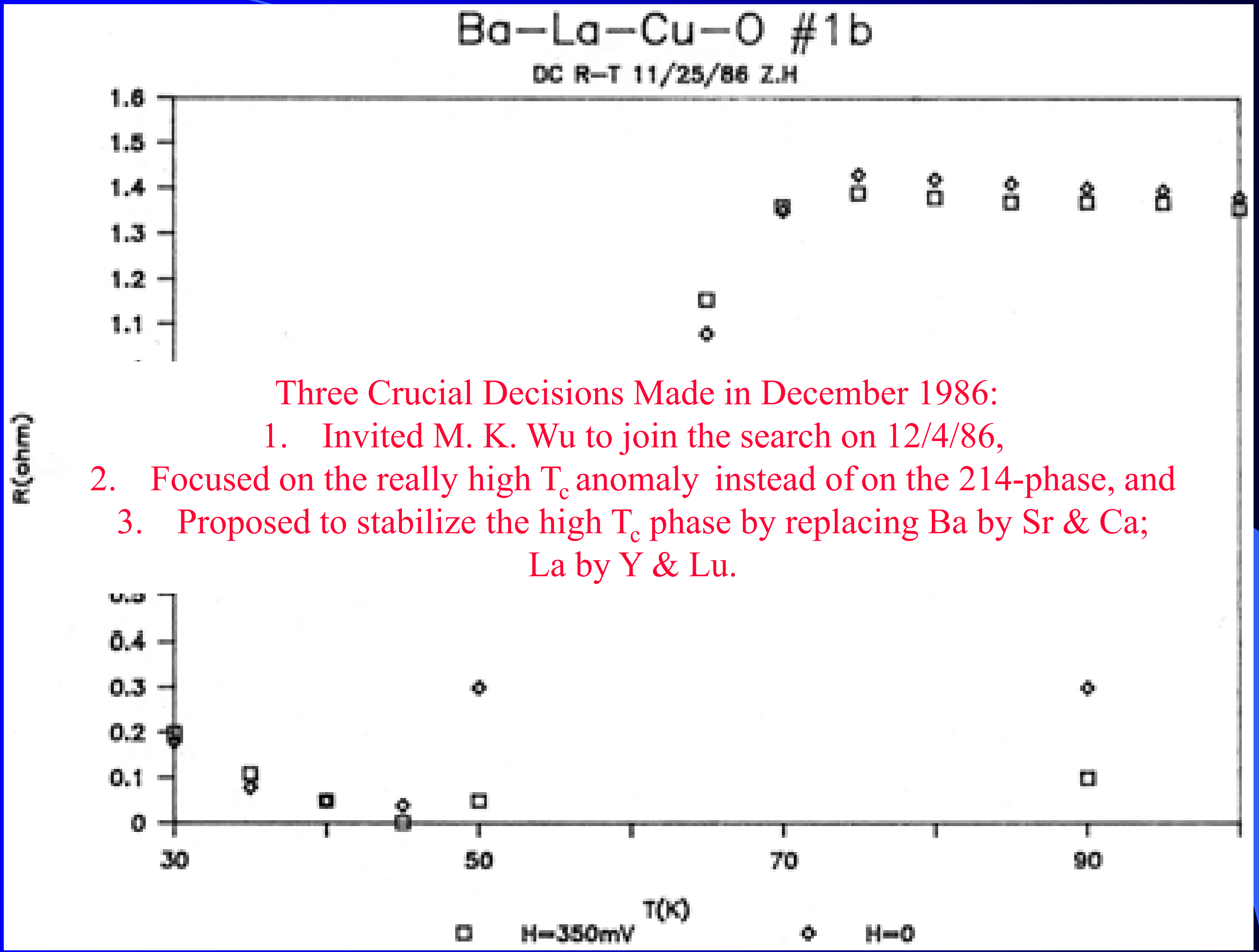
Superconductivity at 52.5 K in the Lanthanum-Barium-Copper-Oxide System

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*

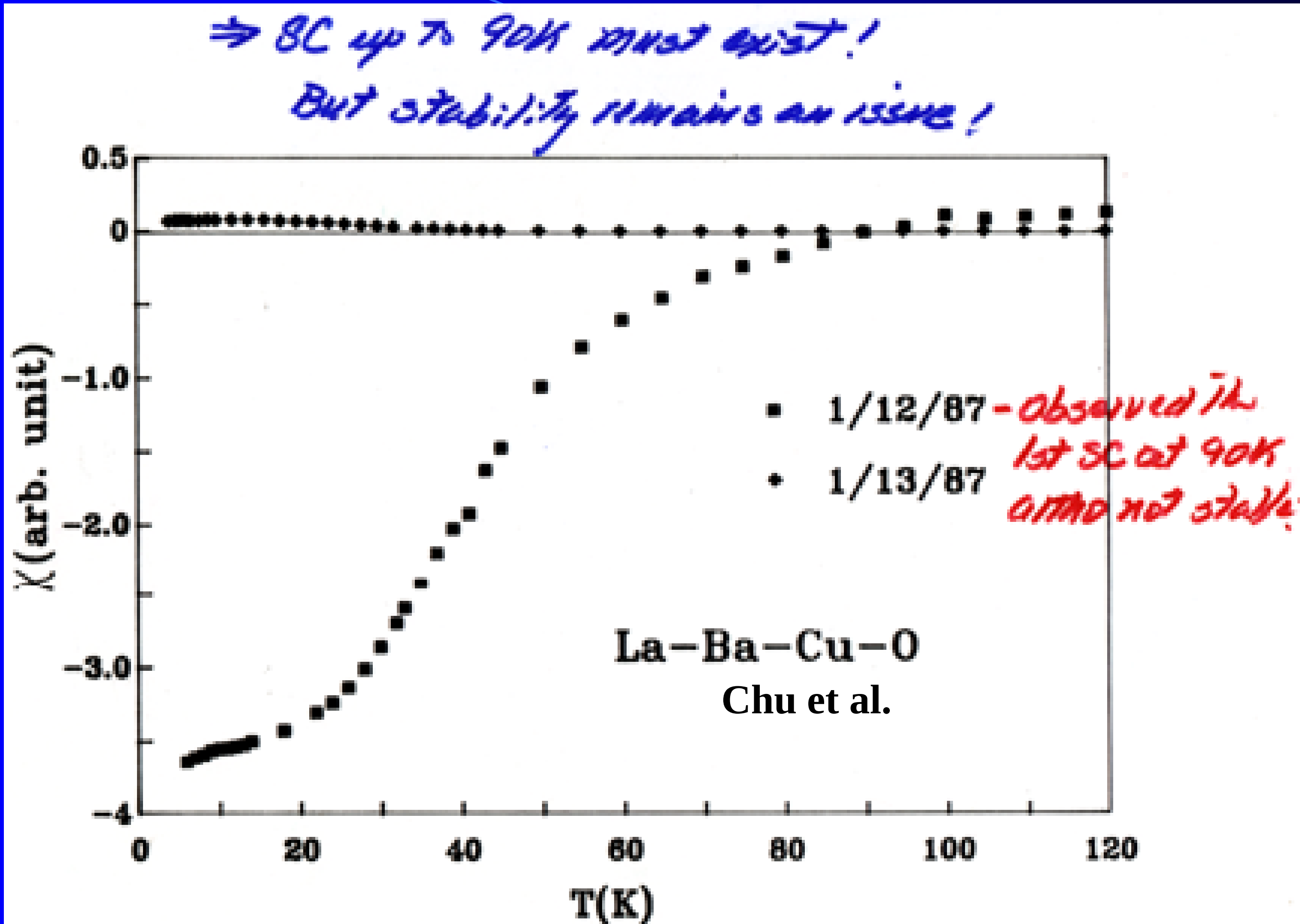


Three Crucial Decisions Made in December 1986:

1. Invited M. K. Wu to join the search on 12/4/86,
2. Focused on the really high T_c anomaly instead of on the 214-phase, and
3. Proposed to stabilize the high T_c phase by replacing Ba by Sr & Ca; La by Y & Lu.

- ***First sign of SC slightly ~ 77 K was detected on November 25, 1986 in multi-phased but not pure 214 samples!***
- ***Concluded that the real high T_c phase cannot be 214***

1987: the exciting year

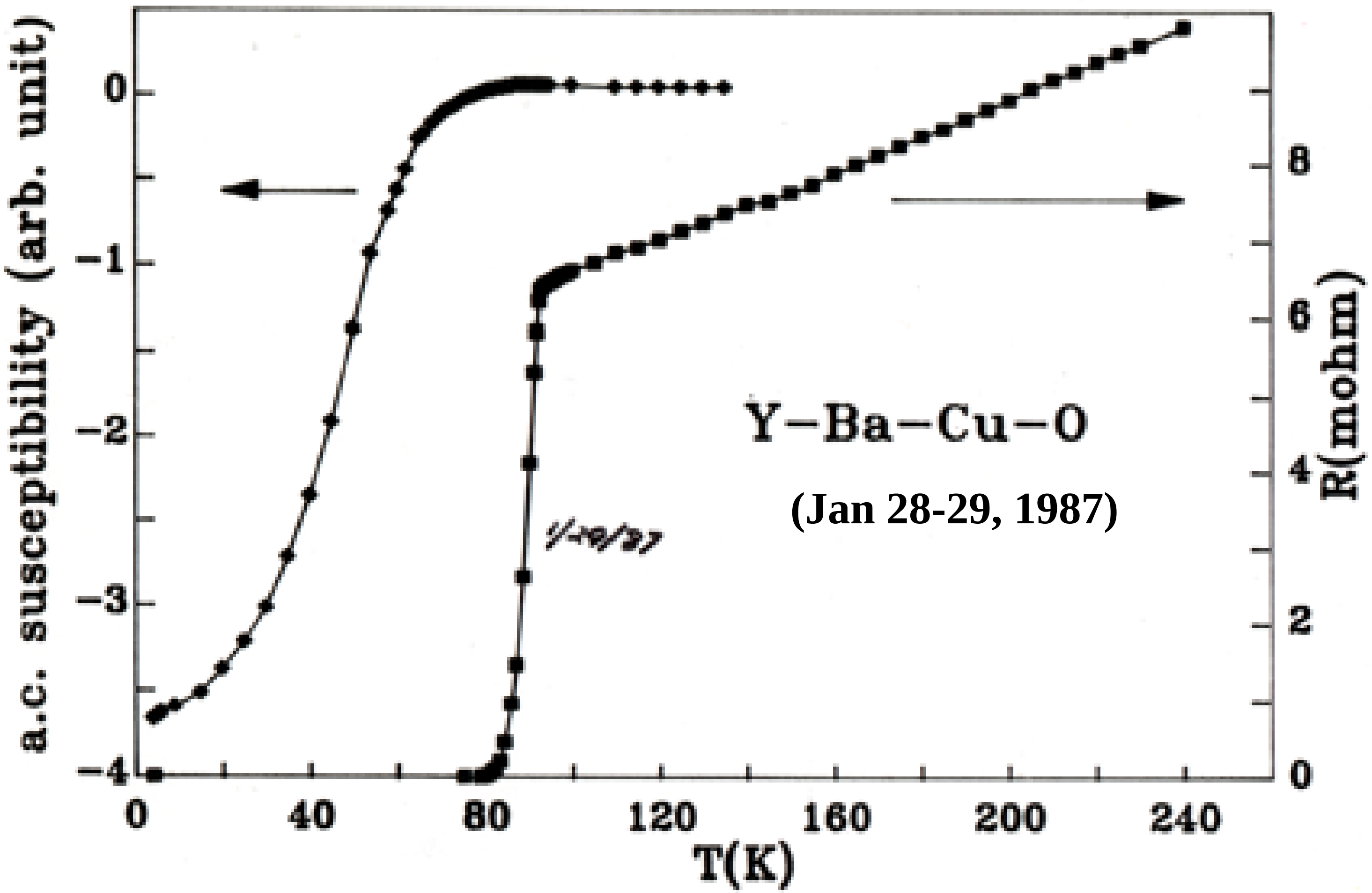


• *First 90 K - SC was unambiguously observed, although not yet stable.*

• *Later analysis of the X-ray data showed it was $LaBa_2Cu_3O_7$ (123 or LBCO)*

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.

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.

$YBa_2Cu_3O_7$ (YBCO or 123)

[was originally intended to be a one sentence paper]

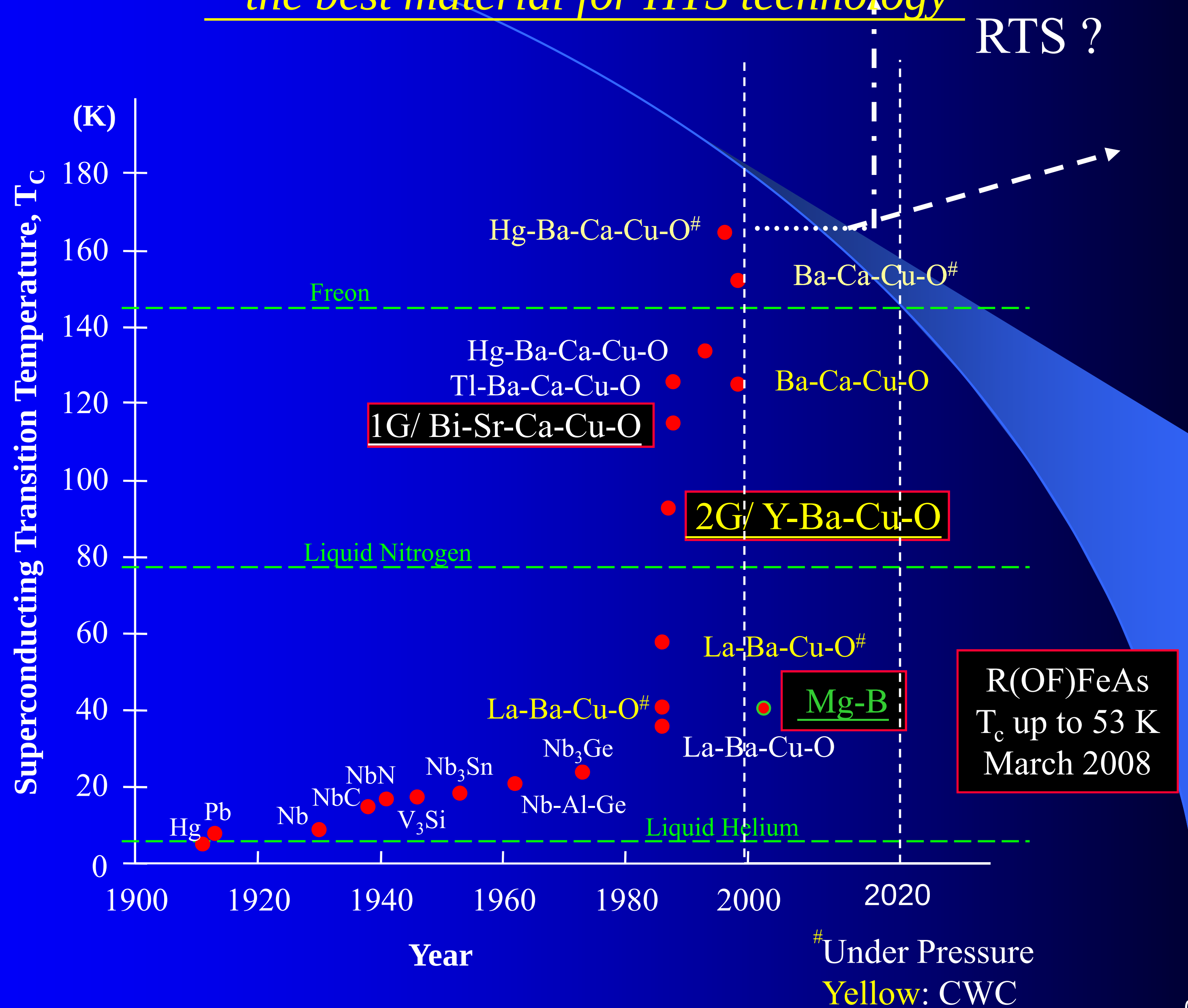
March 2, 1987 was a super-day for physics – >90K SC, supernova, SSC!!!

Current Status – *Known*

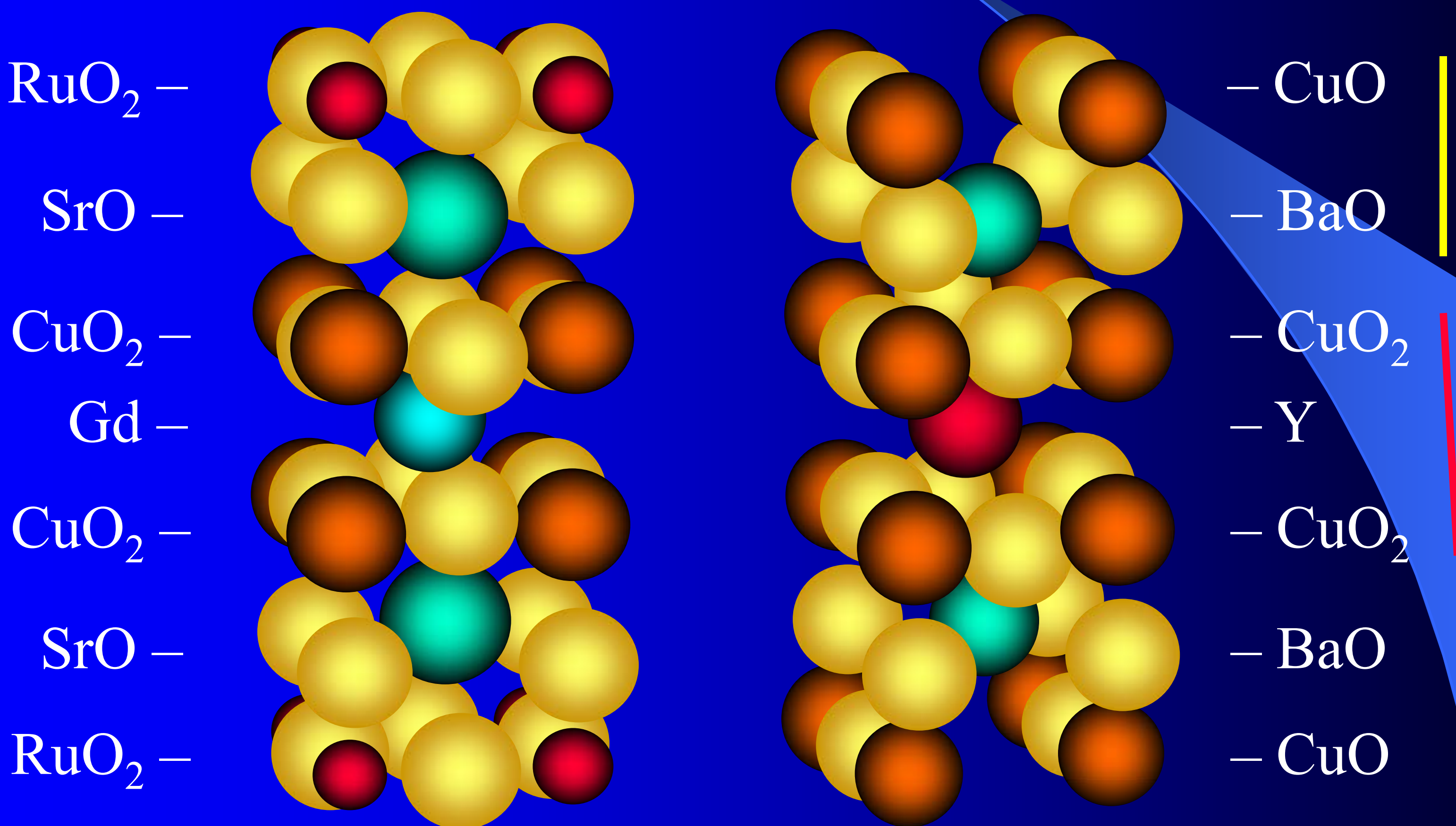
HTS - a new paradigm for condensed matter physics

- More than 150 non-intermetallics with $T_c > 23$ K (Cuprates, Bismuthates, and Fullerites, MgB_2)
- All HTSrs with $T_c > 77$ K belong to Layered Cuprates
- $H_{c2} \geq 150$ T (~ 3×10^6 H_{earth})
- J_c (77 K) ~ 5×10^6 A/cm^2 (film) and 5×10^5 A/cm^2 (bulk)
- J_c (4.2 K) ~ 10^7 A/cm^2 at 0 T and >> LTSrs Above 15 T
- R_s (77 K) ~ R_s of Nb at 7 K and 10-10^3 times better than Cu at 77 K
- $HgBa_2Ca_2Cu_3O_{8+\delta}$ Has the Highest T_c = 134 K (at ambient), 164 K (at 30 GPa)
- Intriguing generic phase diagram and magnetic phase diagram

YBCO: high J_c & high H_i, robust, less costly
- the best material for HTS technology-



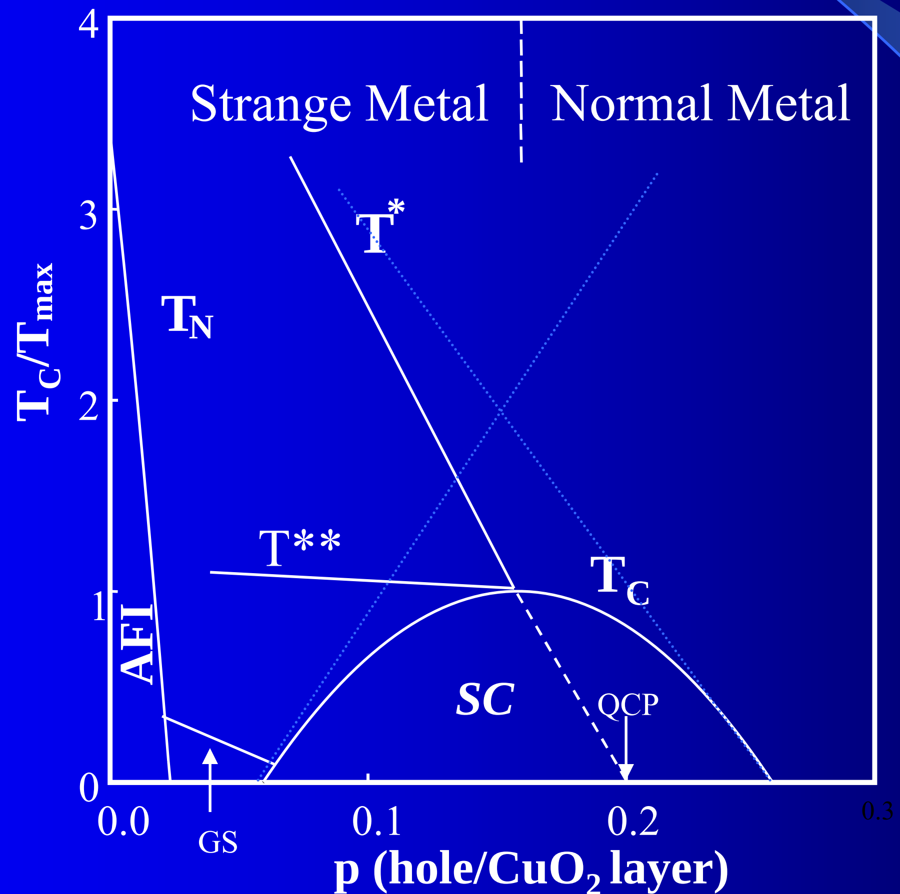
Ru –1212 YBCO



KNOWN

- **The Generic Phase Diagram**

***-The Quadratic Universal** $\{T_c = T_c^{max} [1-82.6(p-0.16)^2]\}$*

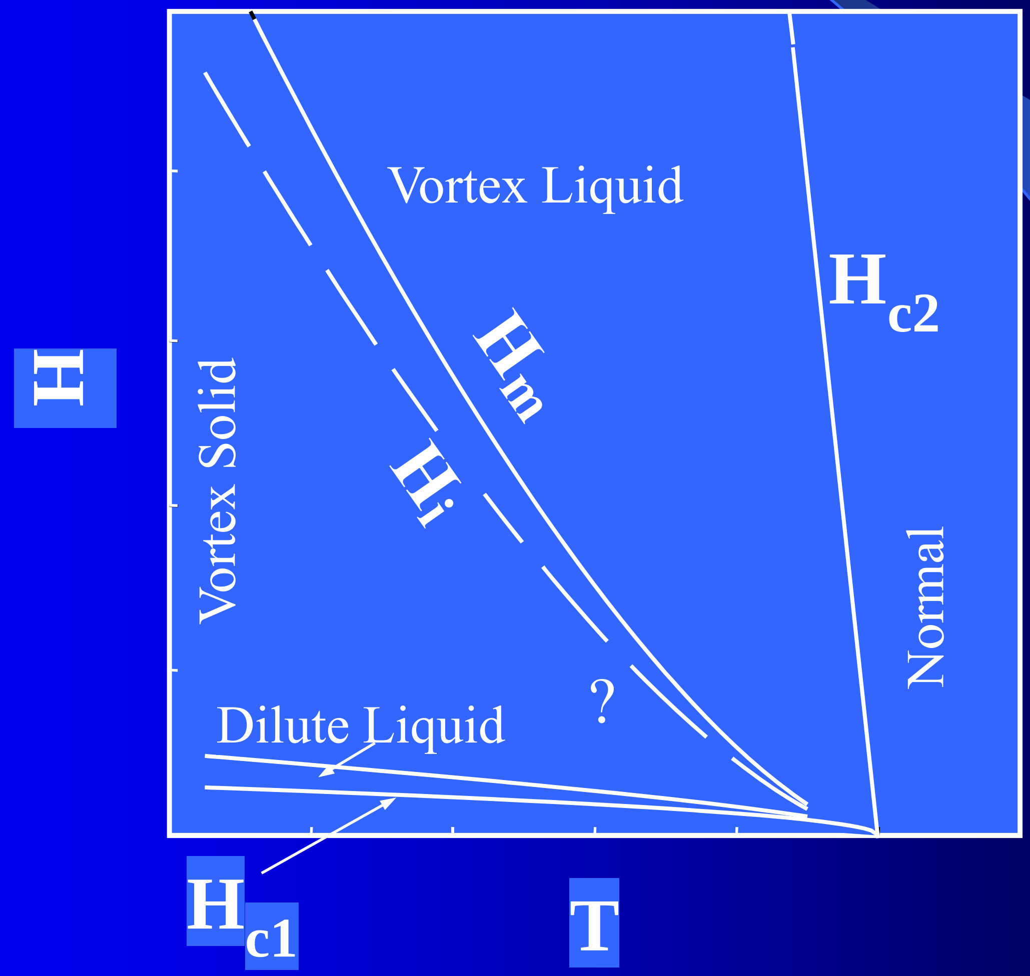


Doping:
- **chemical**
- **pressure**
- **photon**
- **electrical**

The Complex H(T) Phase Diagram

- rich in physics

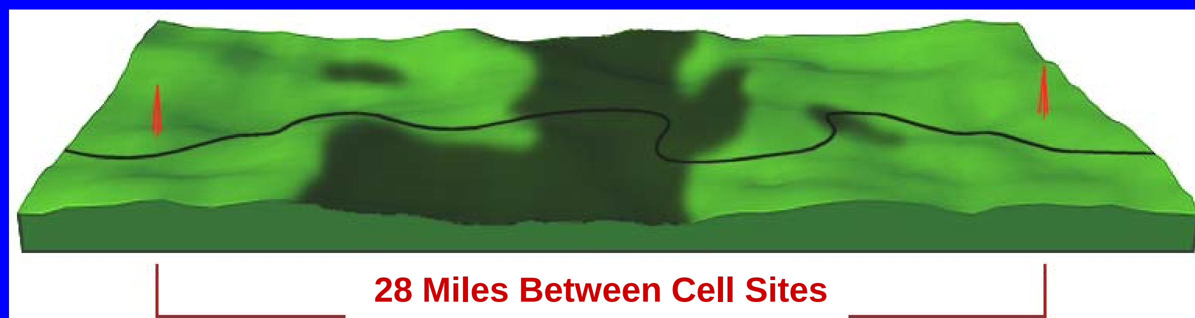
- crucial to applications



071102CWC

Wireless Communication
Base-Station Filters

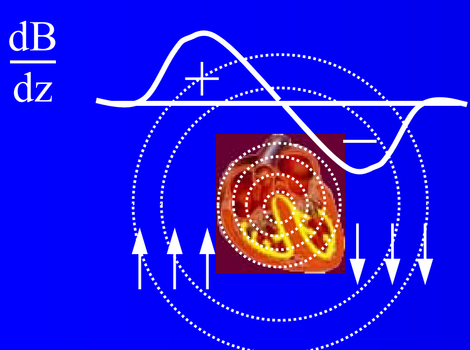
Before HTS



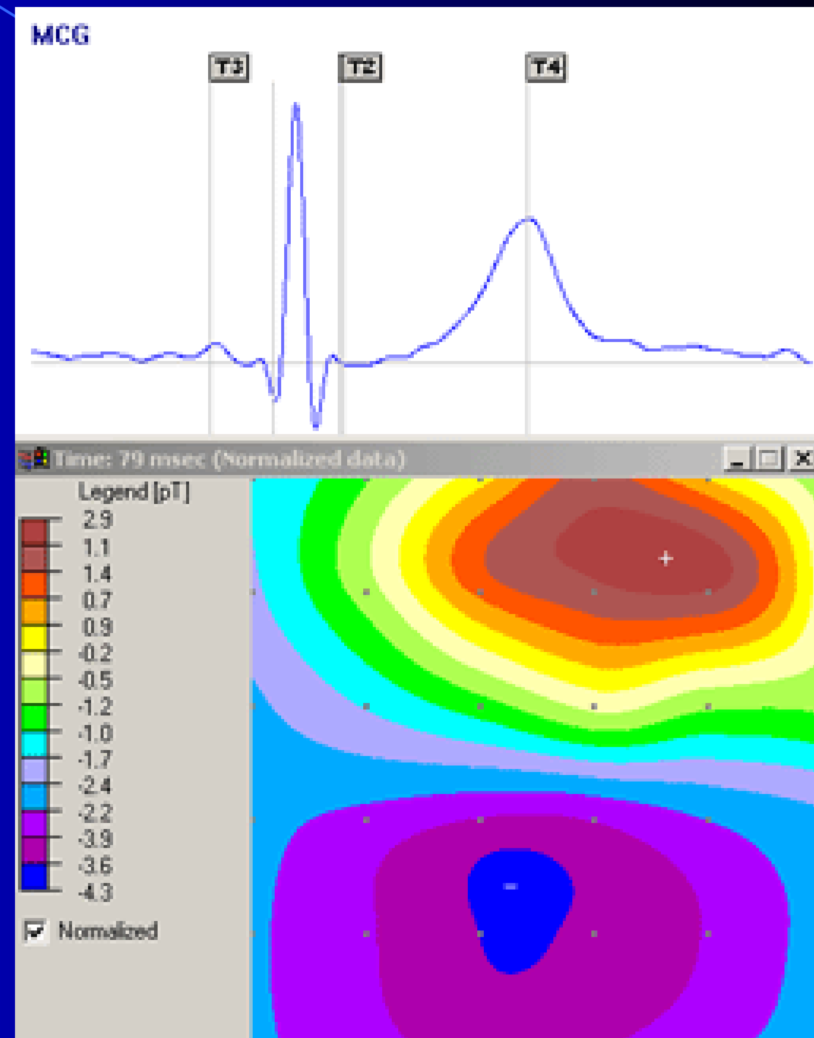
HTS Deployed

Increase Range/Coverage

MagnetoCardioGram (MCG)

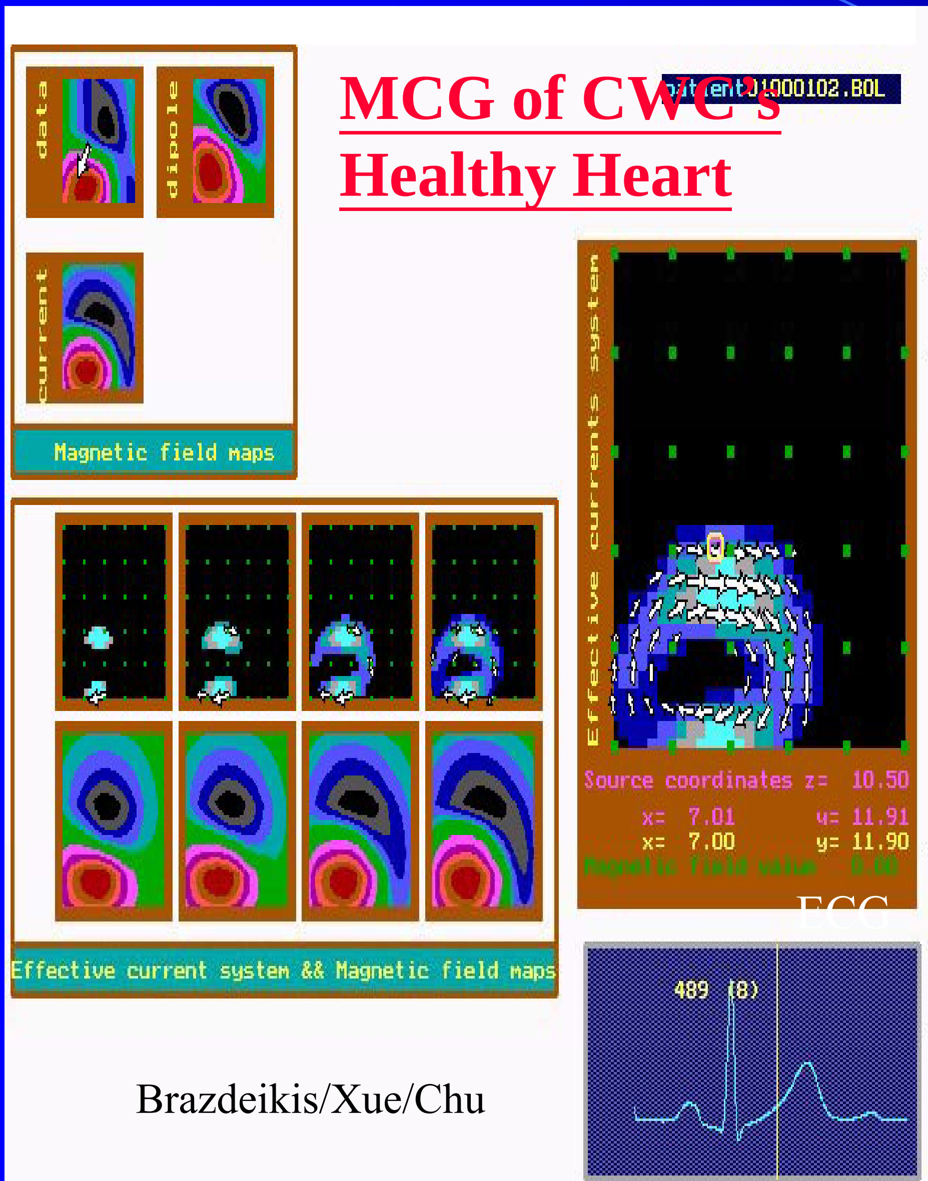


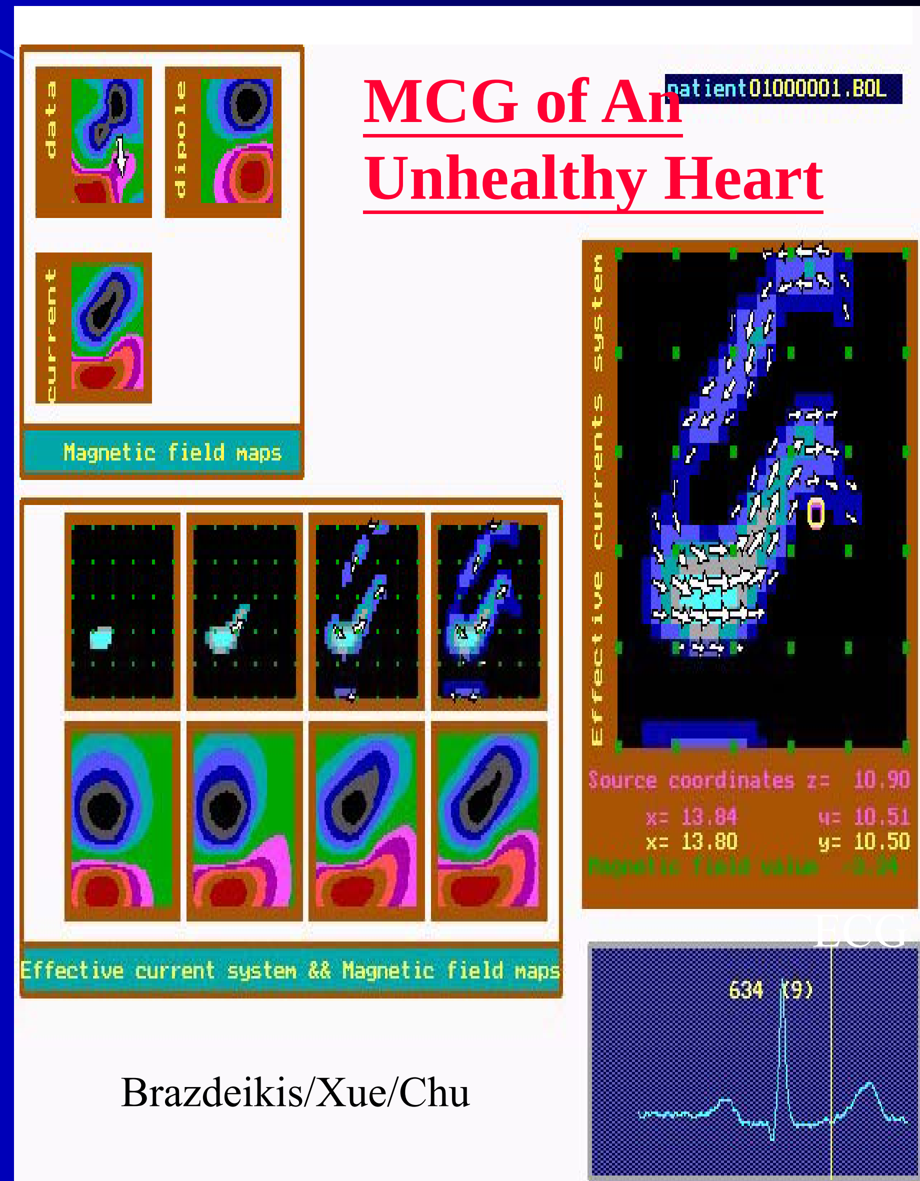
Mapping normal (B_Z) component distribution shows a dipolar pattern (MFM)



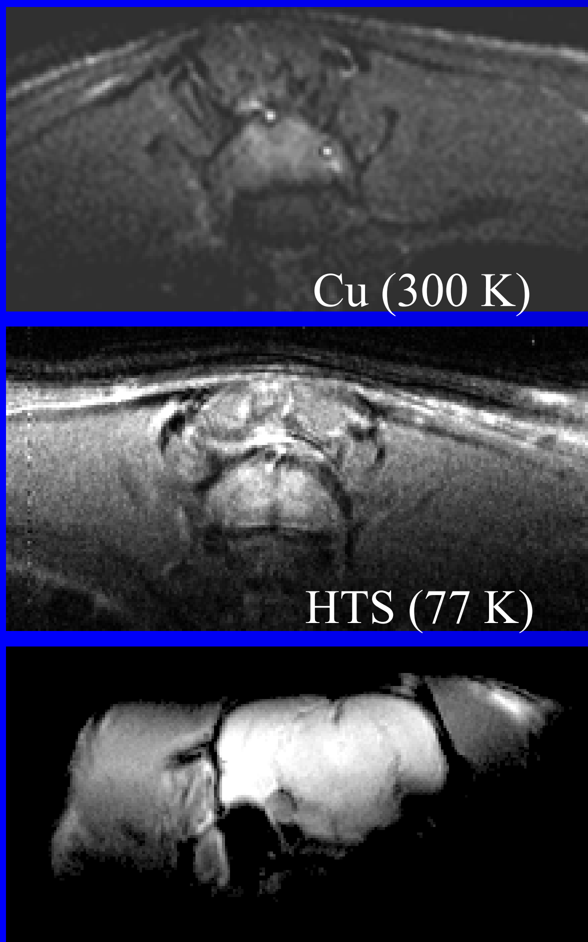
Brazdeikis/Chu et al.

Comparisons between MCG and ECG of Two Subjects





2-Tesla MRI of a Rat (under anesthesia)



spine-cord

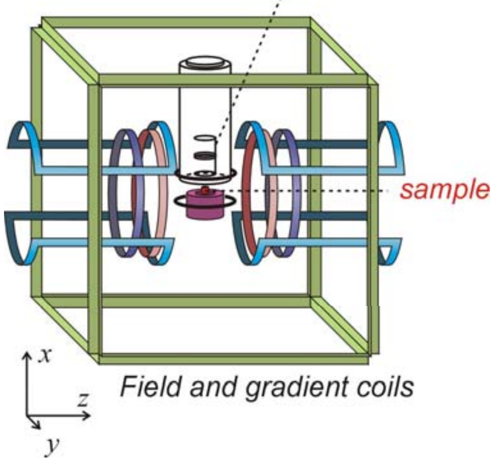
4 dB gain!

brain

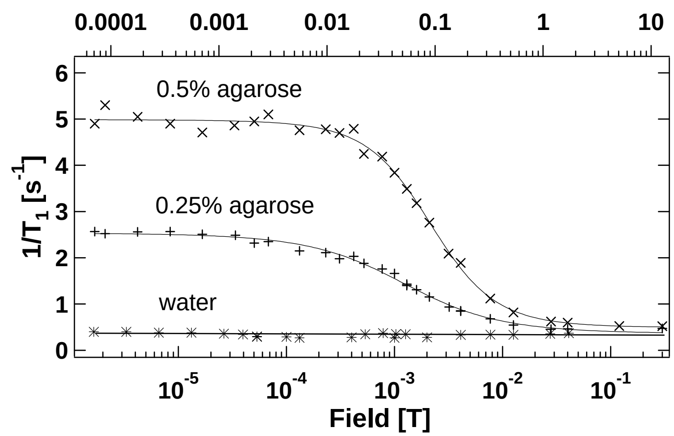
Wosik et al.

SQUID-detected Microtesla MRI

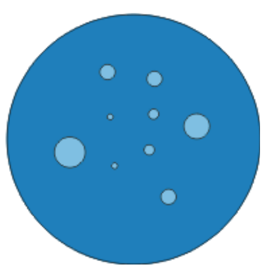
Microtesla MRI System



Relaxation rate $1/T_1$ vs. Magnetic Field

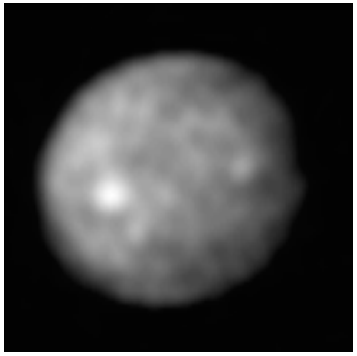


Phantom

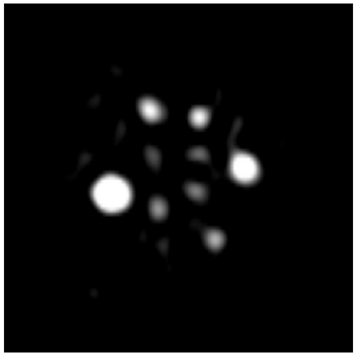


Water columns in agarose

T_1 contrast at 100 mT



T_1 contrast at 132 μT



- T_1-contrast greatly enhanced at microtesla fields
- Potential application: tumor imaging

John Clarke
LBNL & UCB

070126CWC

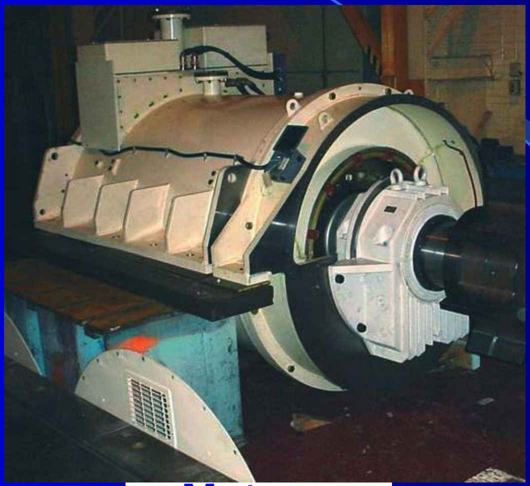
Flywheel

- Levitated 42 lb flywheel in 10^{-6} Torr vacuum
- Spun up to 6000 RPM
- Coasted down to stop in 6 days
- HTS used 14 pieces
    - 1-1½" diameter
    - ¼- ½" thick

W. K. Chu et al.

A Wide Array of Efficient, Compact, Environmentally Friendly Electric Power Equipment

Power Cables



Motors, Generators

Synchronous Condensers

Fault Current Limiters

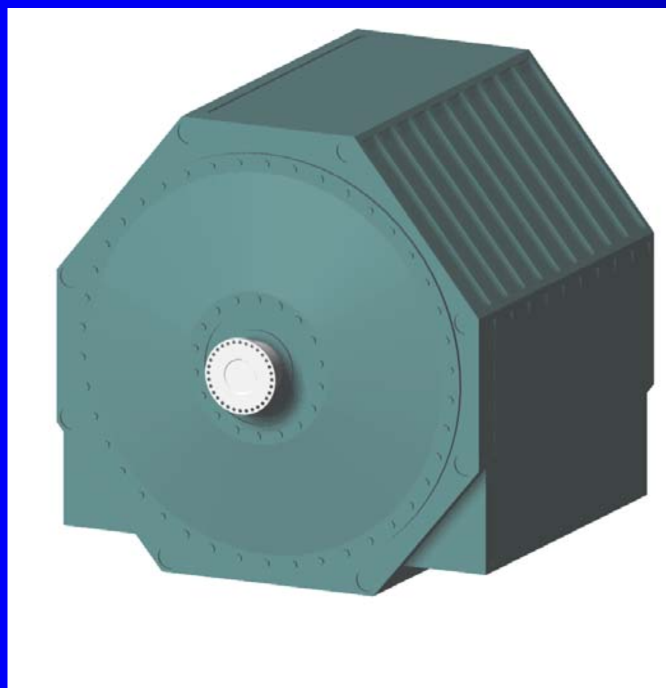
A 630-kVA demonstration HTS transformer resulting from an earlier ABB project. (ABB)

Transformer

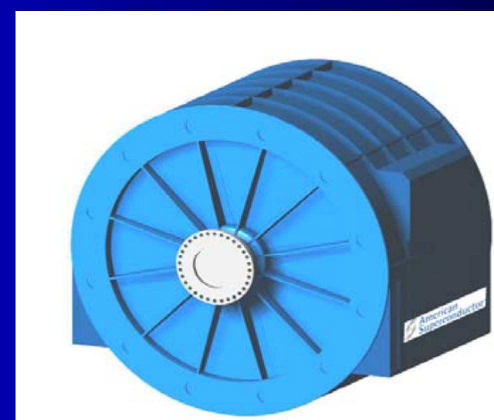
Maglev

Ship Propulsion Motors

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

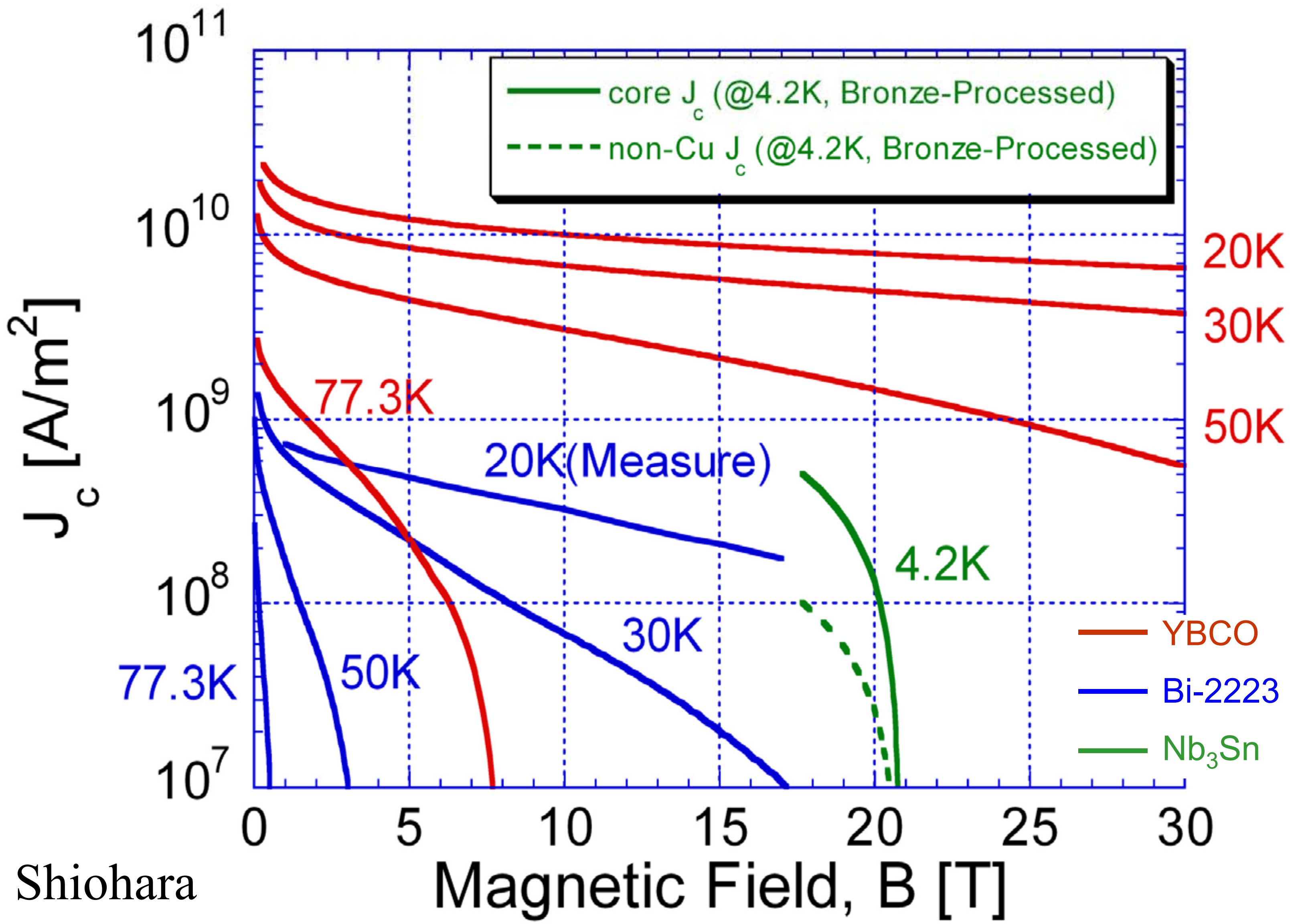


36.5 MW Conventional
(300 tons)



36.5 MW HTS
(75 tons)

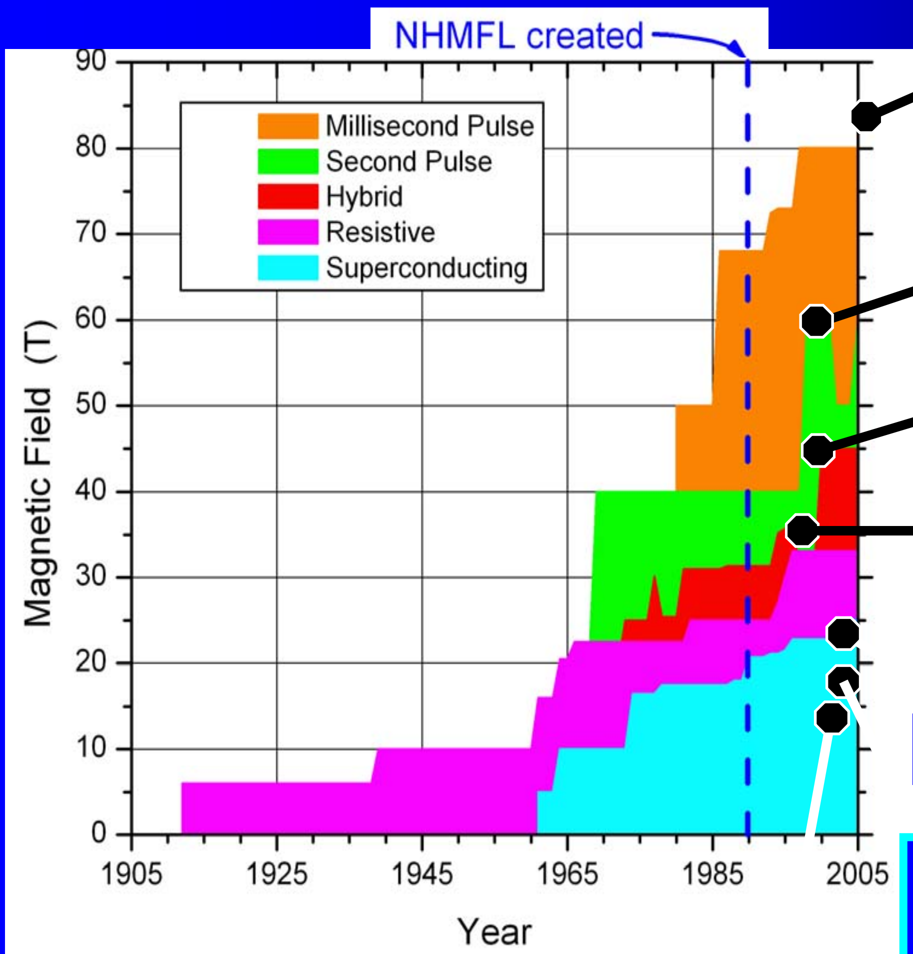
AMSC



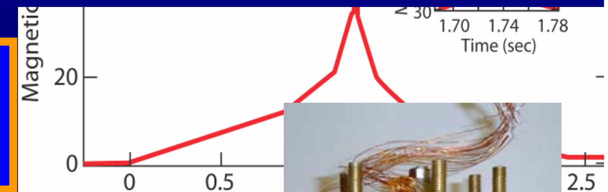
core J_c (@4.2K, Bronze-Processed)
non-Cu J_c (@4.2K, Bronze-Processed)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
J_c [A/m^2]
20K
30K
50K
77.3K
20K(Measure)
4.2K
30K
50K
77.3K
YBCO
Bi-2223
Nb_3Sn
0
5
10
15
20
25
30
Magnetic Field, B [T]

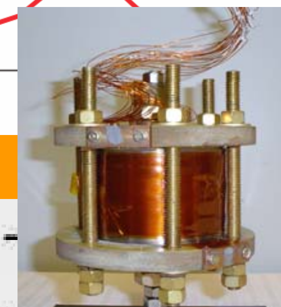
Shiohara

World record non-destructive magnets

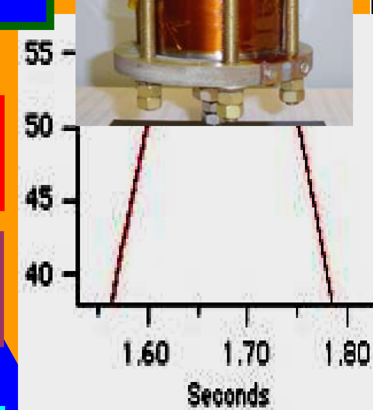


2006: 90T Multi-shot Magnet (world record)





1998: 60T Controlled-Pulse Magnet (world record) (rebuild in 2006)

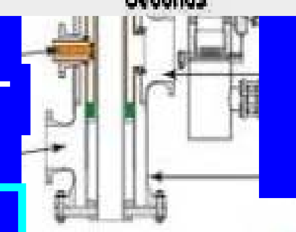


1999: 45T DC Hybrid Magnet (world record)

2003: 35T DC Resistive Magnet (world record)

2003: 25 T in 38mm bore

2007 NEW RECORD: 26.8 T



2004: 900 MHz (21.1T) NMR magnet with unique 105mm warm bore (world record)

2004: 14.5T Ion Cyclotron Resonance magnet to measure molecular mass with 0.1ppm accuracy (world record)

G. Boebinger

HTS Material Challenges *for Science*

Need to determine the intrinsic properties, but the materials are *physically intricate, chemically complex and chemically unstable*

- higher T_c
- sensitive to doping
- highly anisotropic
- inhomogeneity
- sample perfection
- good sample size
- material base

HTS Material Challenges
for Technology

Need high performance at low cost, and
the materials have to be in the proper forms for devices

- T_c, J_c, ξ
- intrinsic property dependent
- improved properties via processing & modification
- cryogenic efficiency
- impurity and grain boundary sensitive
- tedious processing
- auxiliary material compatibility
- lifetime

Challenges in HTS Science

- *What is the mechanism responsible for HTS?*
- *When will there be a comprehensive microscopic theory?*
- *Do HTSs form a class of materials of their own?*
- *Can there be a room temperature superconductor?*

No generally accepted microscopic theory yet!

The “Holy Grail” in
HTS science and technology
is to find
Room Temperature Superconductivity.

- *There is no reason why it does not exist.*
- *Whatever physics law does not say it won’t happen will.*

We have learned from HTS in the last two decades:

• **electron-pairing; phase coherence**

(in k or real space, at same or different T's)

• **strongly correlated electron systems**

(strong interaction between electrons of unfilled d-shell, many phase transitions)

• **instabilities**

(many electronically induced transitions implies different types of interactions, controllable by physical and/or chemical means, fluctuations}

• **layered structure with two different sub-components**

$(A_mE_2R_{n-1}Cu_nO_{2n+m+2}) = [(EO)(AO)_m(EO)]+\{(CuO_2)[R(CuO_2)]_{n-1}\}$

Active block + Charge reservoir

e.g. ß-HfNCl/$Li_x(THF)_y$ – 25.5K vs HfN – 8.8K

• **near the Metal-Insulator Phase Boundary**

Cuprates, BKBO, BPBO, LTO – large Pauli susceptibility

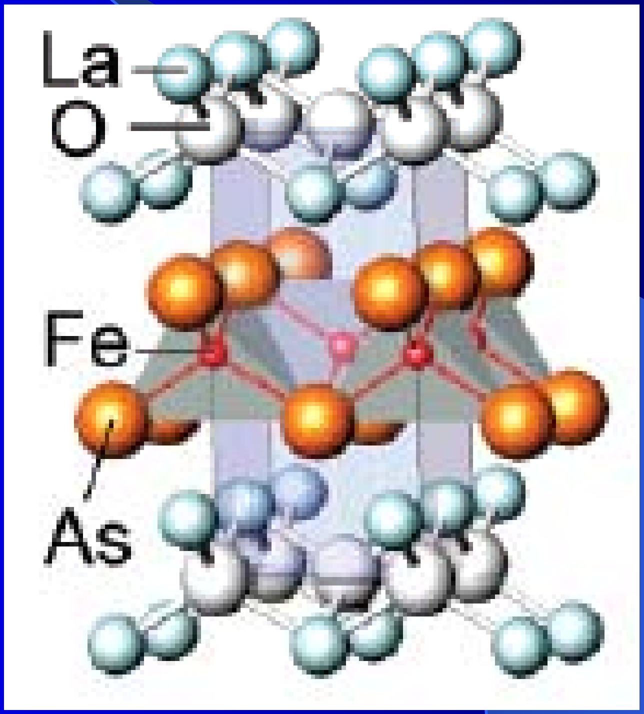
• **mixed valence**

Cu^{2+}&Cu^{3+}, Bi^{3+}&Bi^{5+}, Ti^{3+}&Ti^{4+}, W^{4+}&W^{6+}

•**Magnetism or Spin = ½**

The Newly Discovered Fe-Based HTSs with a T_c up to 52 K

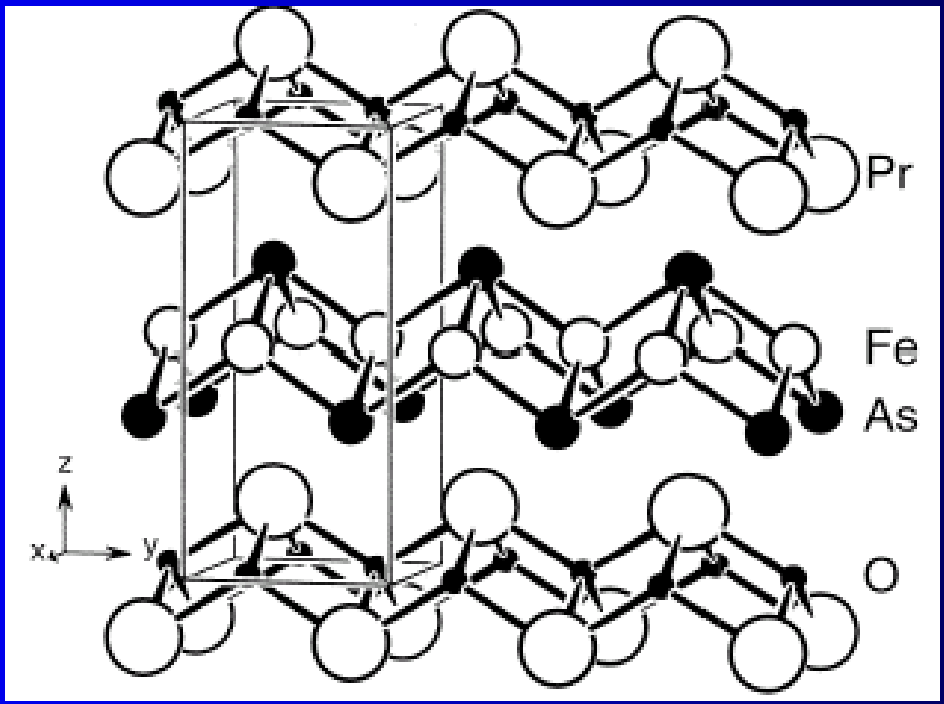
$R(O_{1-x}F_x)FeAs$ [R = rare earth]
F-doped rare-earth Fe oxyarsenides



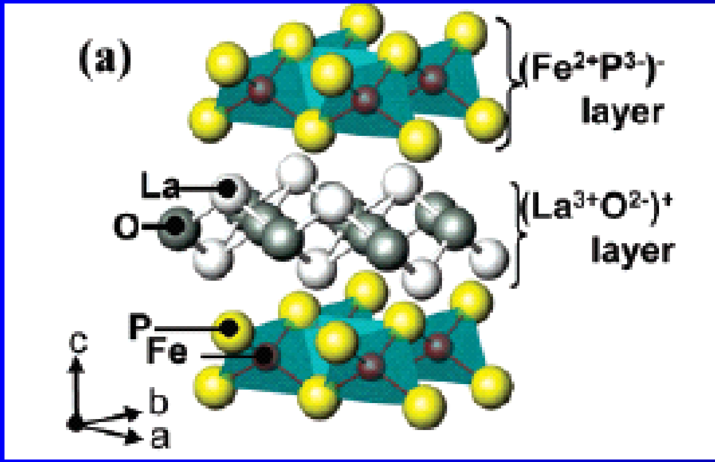
Rare-Earth Transition Metal Oxypnictides ROTPn

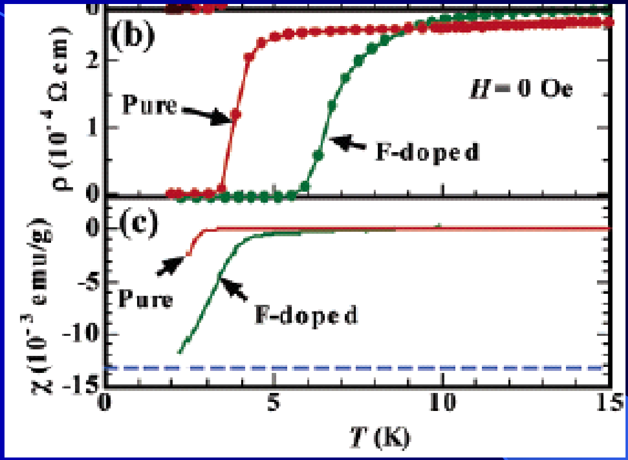
- 1995 ROTP – ZrCuSiAs structure - Zimmer et al

- 2000 ROTAs – Quebe et al.

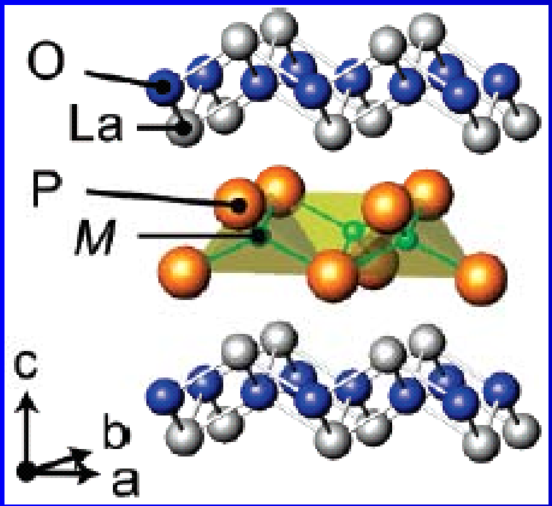


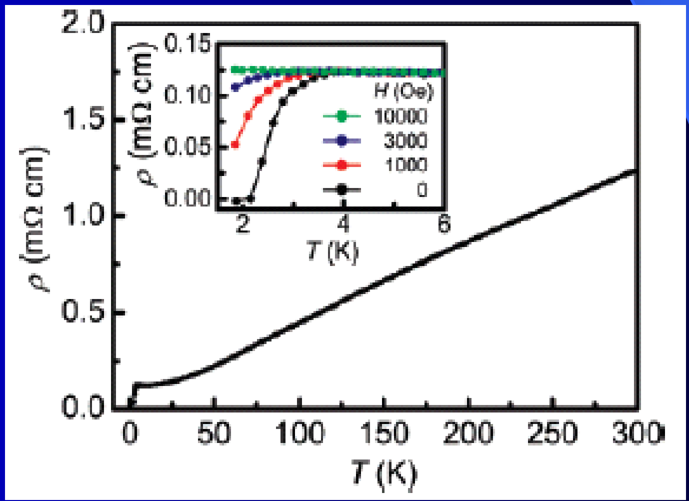
• 2006 La(O,F)FeP (5-12 K) – Kamihara/Hosona et al.





• 2007 LaONiP (3 K) – Wntanabe/Hosona et al





The rapid T_c- rise & Euphoria a

- 20080325 Sm(OF)FeAs (43 K) – X. H. Chen
- 20080326 Ce(OF)FeAs (41 K) – G. F. Chen/N. L. Wang
- 20080328 Pr(OF)FeAs (52 K) – Z. A. Ren/Z. X. Zhao
- 20080328 Nd(OF)FeAs (52 K) – Z. A. Ren/Z. X. Zhao

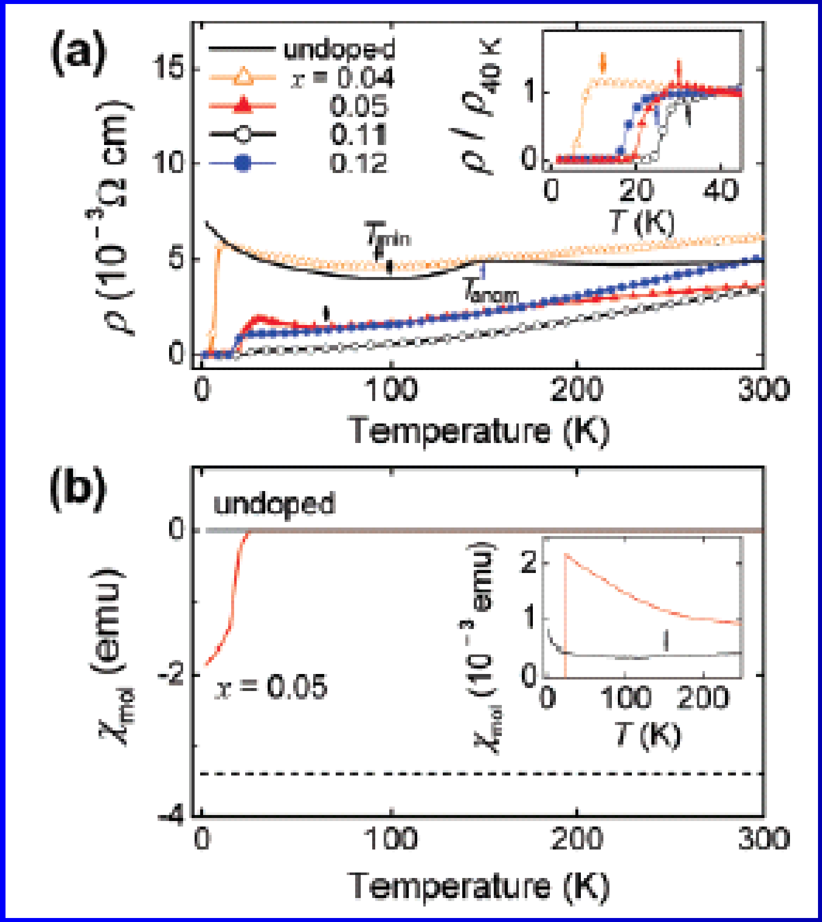
- 20080304 Singh and Du: F–doping and P suppress SDW and enhance T_c
- 20080306 Wen et al. – Nodal gap
- 20080324 Dong/Wang – FS nesting, SDW gap,
- 20080330 Ou/Feng – SDW gap forms, AFM ground state, large ungapped sc region
- 20080331 Zhang et al. – FS nesting, inter-band paring, orbital degeneracy
- 20080331 Masiglio & Hirsch – hole, two band, critical role of As, F and P enhance T_c
- 200800331 Wen – Hole doping is possible in (LaSr)FFeAs
- 20080328 Zhao et al. - positive dT_c/dP for La(OF)FeAs (+ 1.2 K/GPa)
- …………………
- 20080407 Lorenz/Chu et al. – dT_c/dP for Sm(OF)FeAs (+ or – depends on n)
- ………………

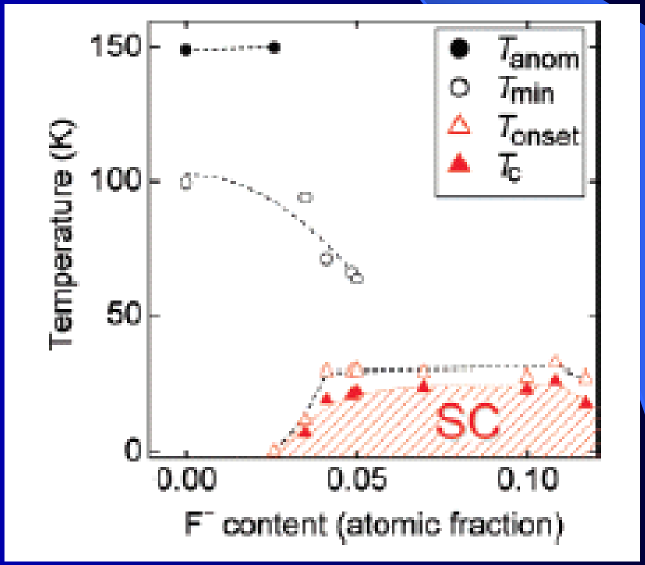
By working on R(OF)FeAs

- mechanism of HTS will be unraveled
- sky will be the limit to T_c

The great excitement didn't occur until R(OF)FeAs was discovered

- 20080109 $R(O_{1-x}F_x)FeAs$ (26 K) Kamihara/Hosona





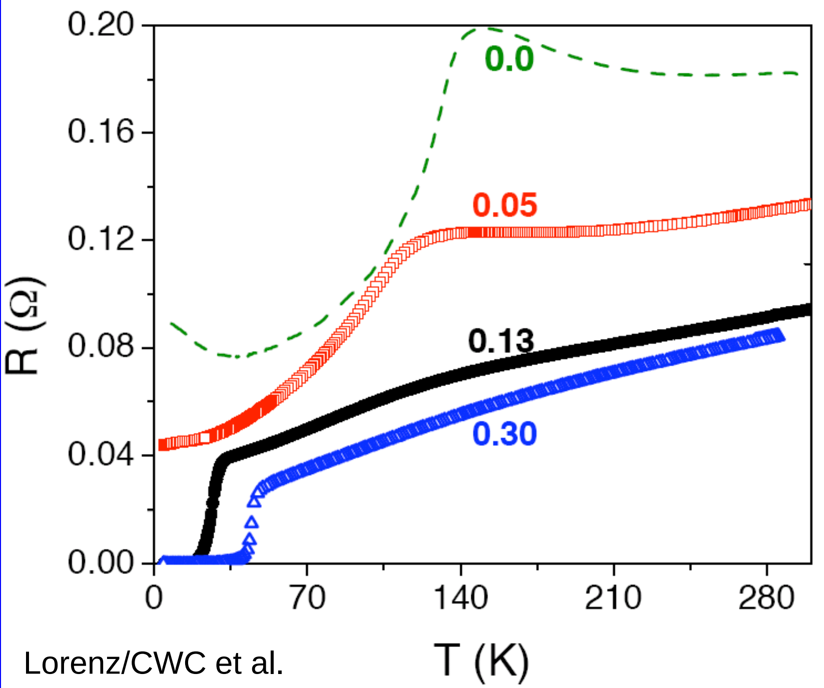
Pressure Effects on the Superconducting and Spin-Density-Wave States of the Newly Discovered $Sm(O_{1-x}F_x)FeAs$

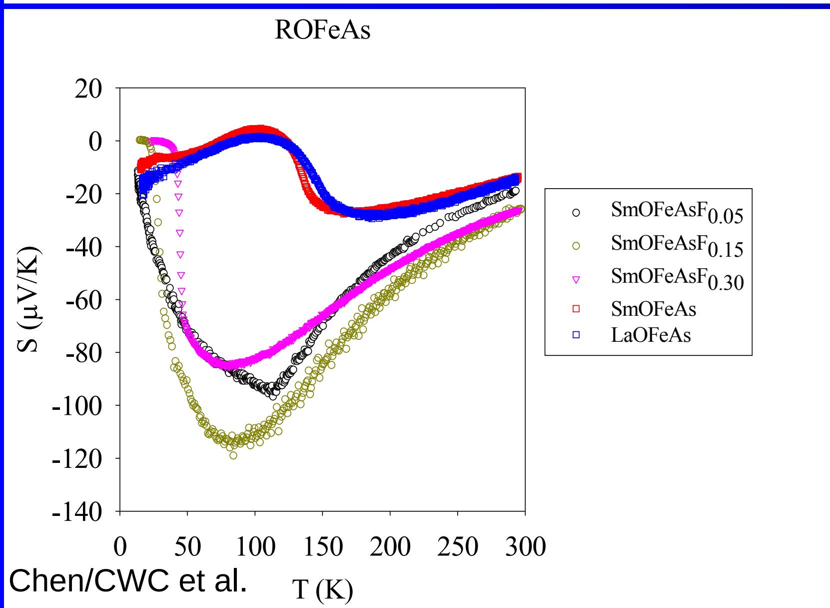
B. Lorenz,[1] K. Sasmal,[1] R. P. Chaudhury,[1] X. H. Chen,[2] R. H. Liu,[2] T. Wu,[2] and C. W. Chu[1,3,4]

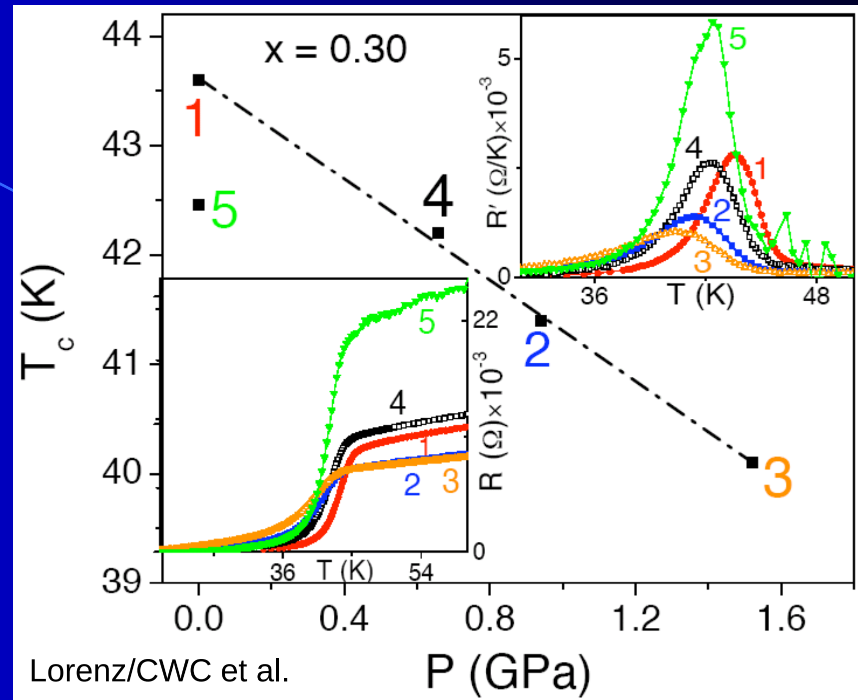
(April 4,2008 UH, HKUST, USTC)

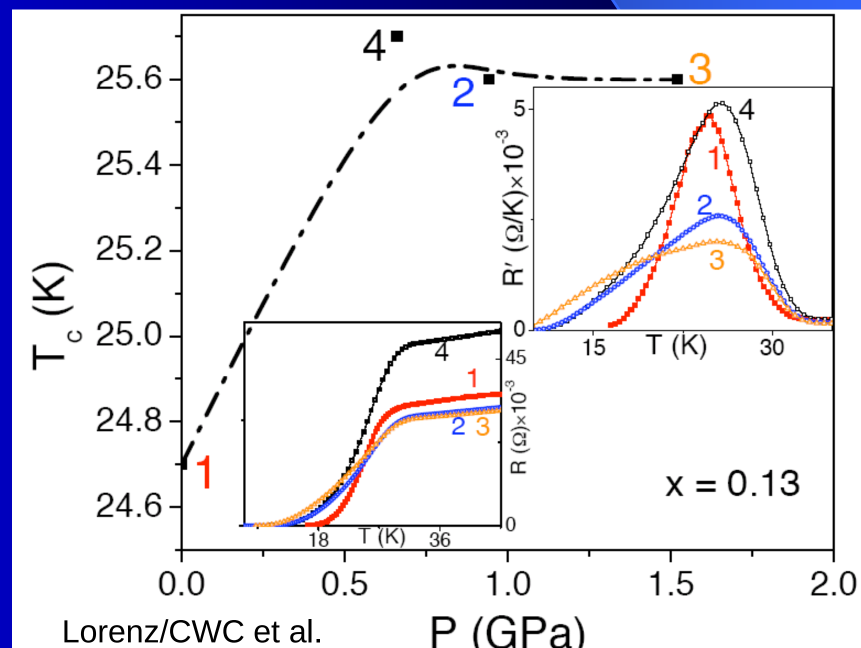
arXiv:0804.1582

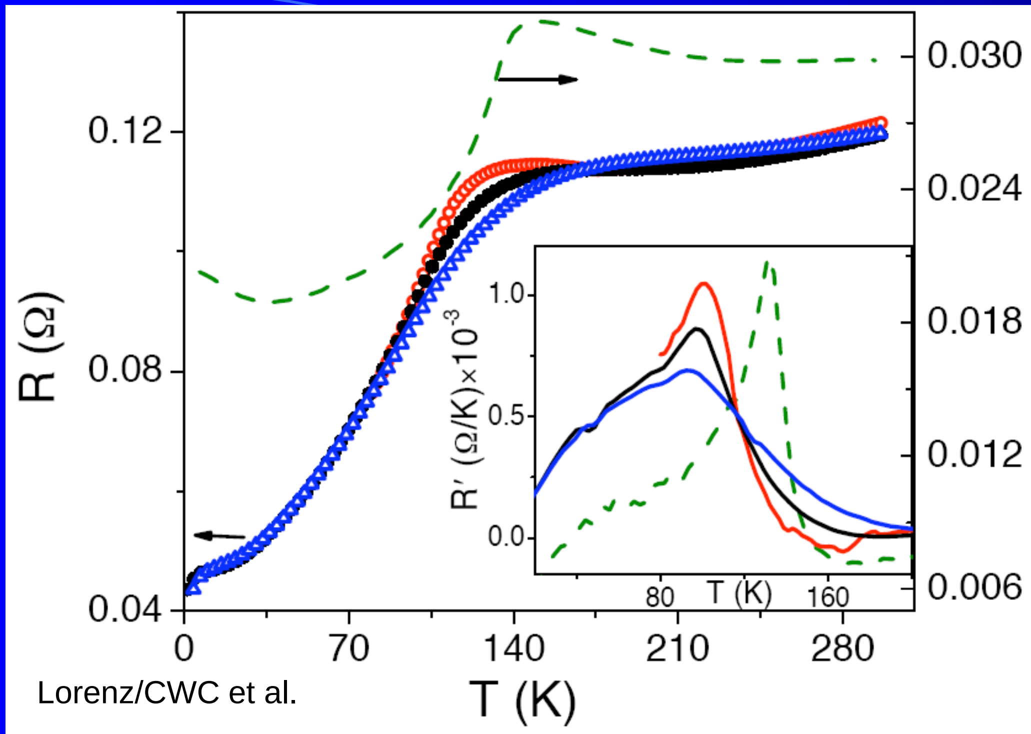
$Sm(O_{1-x}F_x)FeAs$

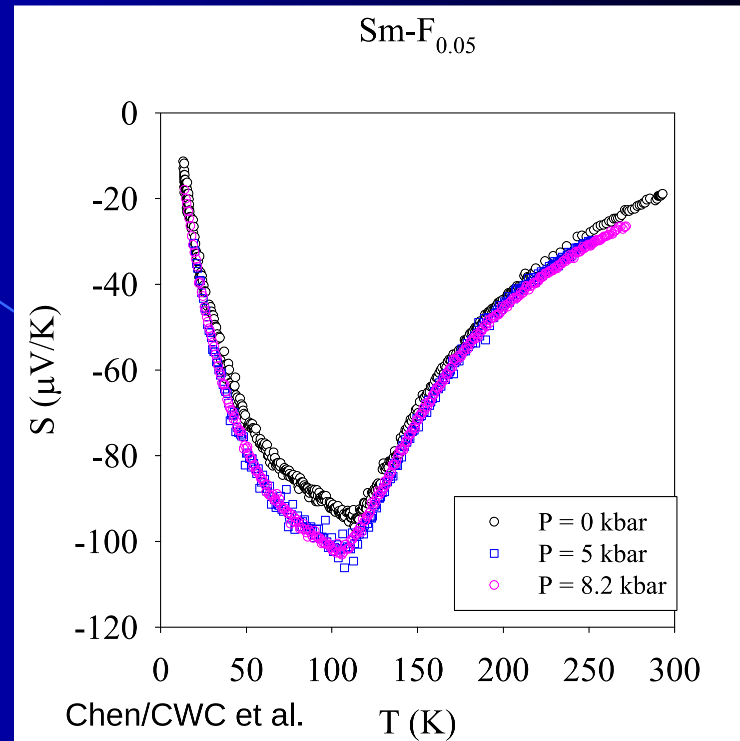


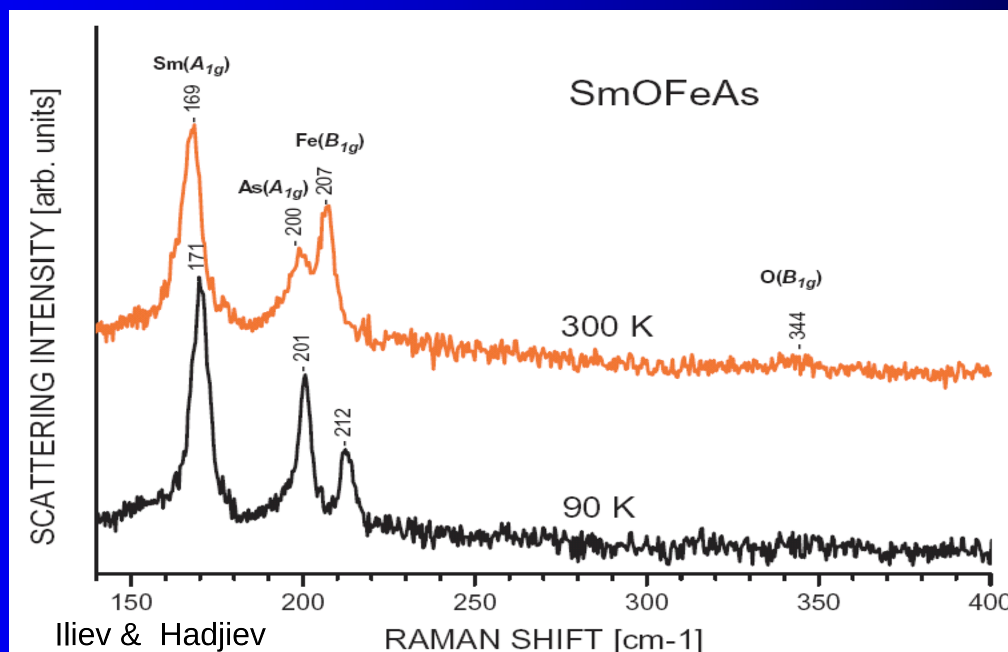







R (Ω)
0.12
0.08
0.04
0.030
0.024
0.018
0.012
0.006
0
70
140
210
280
T (K)
R′ (Ω/K)×10^-3
1.0
0.5
0.0
80
T (K)
160
Lorenz/CWC et al.


Sm-F0.05
S (μV/K)
0
-20
-40
-60
-80
-100
-120
0
50
100
150
200
250
300
T (K)
P = 0 kbar
P = 5 kbar
P = 8.2 kbar
Chen/CWC et al.


SmOFeAs
Sm(A1g)
169
171
As(A1g)
200
201
Fe(B1g)
207
212
O(B1g)
344
300 K
90 K
SCATTERING INTENSITY [arb. units]
150
200
250
300
350
400
RAMAN SHIFT [cm-1]
Iliev & Hadjiev

R(OF)FeAs is similar to RBCO

- P can enhance but also suppress Tc
- Follow a universal T_c-n independent of R
- Maximum T_c is ~ 50's K for all R
- T_c's of La(FO)FeAs, Ce(OF)FeAs and Sm(FO)FeAs may be raised to ~ 50's K
- For T_c higher than ~ 50's K, examine similar to but different from the R(FO)FeAs systems
- Many interesting experiments are waiting for us

Thank you!