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A Possible Approach from BCS through HTS to RTS

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OUTLINE

- Introduction
- Low Temperature Superconductivity
- High Temperature Superconductivity
- Room Temperature Superconductivity
  - it is possible and exciting
  - the holistic multidisciplinary enlightened empirical approach
  - several amusing claims
  - several interesting reports
  - several visionary predictions
  - common features of high temperature superconductivity
  - three examples at Houston
- concluding remarks

100 years of superconductivity

- The never-ending lure of superconductivity:
  intellectual challenges and technological promises
- The never-ending inspiration in frontier of science:
  quarks, neutron stars, superfluid He3, BE condensation,
  spontaneous symmetry breaking, Marjorana Fermions, etc.
- The major driving force:
  the search for superconductors of higher T_c
- The never-ending search will go on:

  God is kinder to physicists than to mountaineers to whom the final goal, Mt. Everest, was already granted and reached with the excitement ceased.

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Celebrations in Superconductivity in Recent Years

2006

- *20th anniversary of the discovery of cuprate HTSs*
- *50st anniversary of the Cooper pair*
- *(300th anniversary of the publication of Principia Mathematica)*

2007

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

2008

- *The discovery of the FeAs-Based Superconductors*

2011

100th anniversary of the discovery of superconductivity

When and what will the next celebration be? VHTS or RTS?

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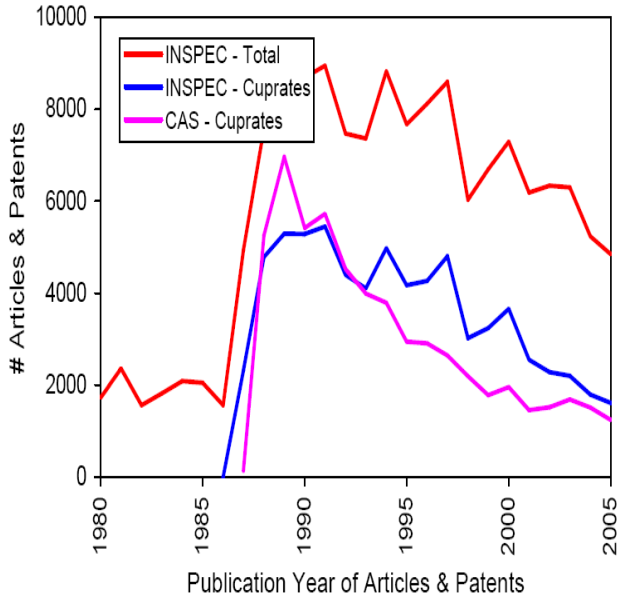
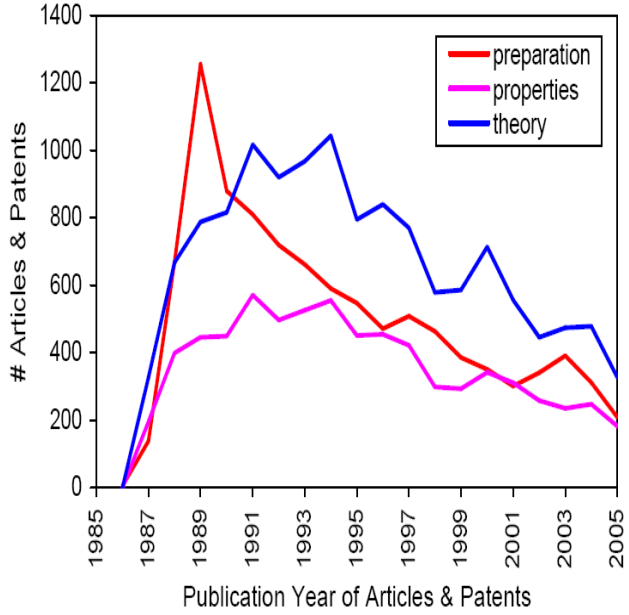
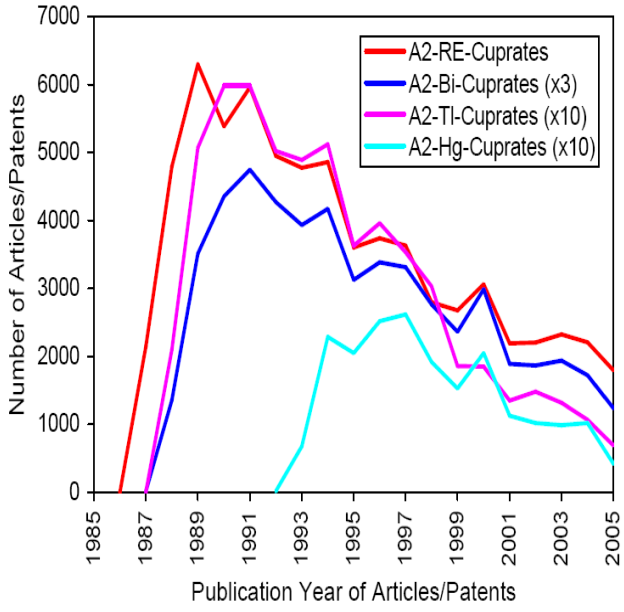
The Scientometrical Prediction

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







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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 die before in 1986-87.

The best response to the "sentence" by Barth and Marx is to discover a new HTS system or even better a VHTS/RTS.

Indeed, in 2008, Fe-based Arsenides and chalcogenides were discovered and RTS was chosen as the next grand challenge in HTS research by AFOSR and DOE.

Looking beyond the horizon can be most horrifying and yet exhilarating

- "The content of the future is what people are most insecure about." - *Isaac Asimov*

- "The excitement in the years ahead will spring from the answers to the questions we don't yet know enough to ask." - *John Maddox*

- "Discovery is man's noblest delight." - Mark Twain

Imagination, knowledge, courage and luck are the key to discovery.

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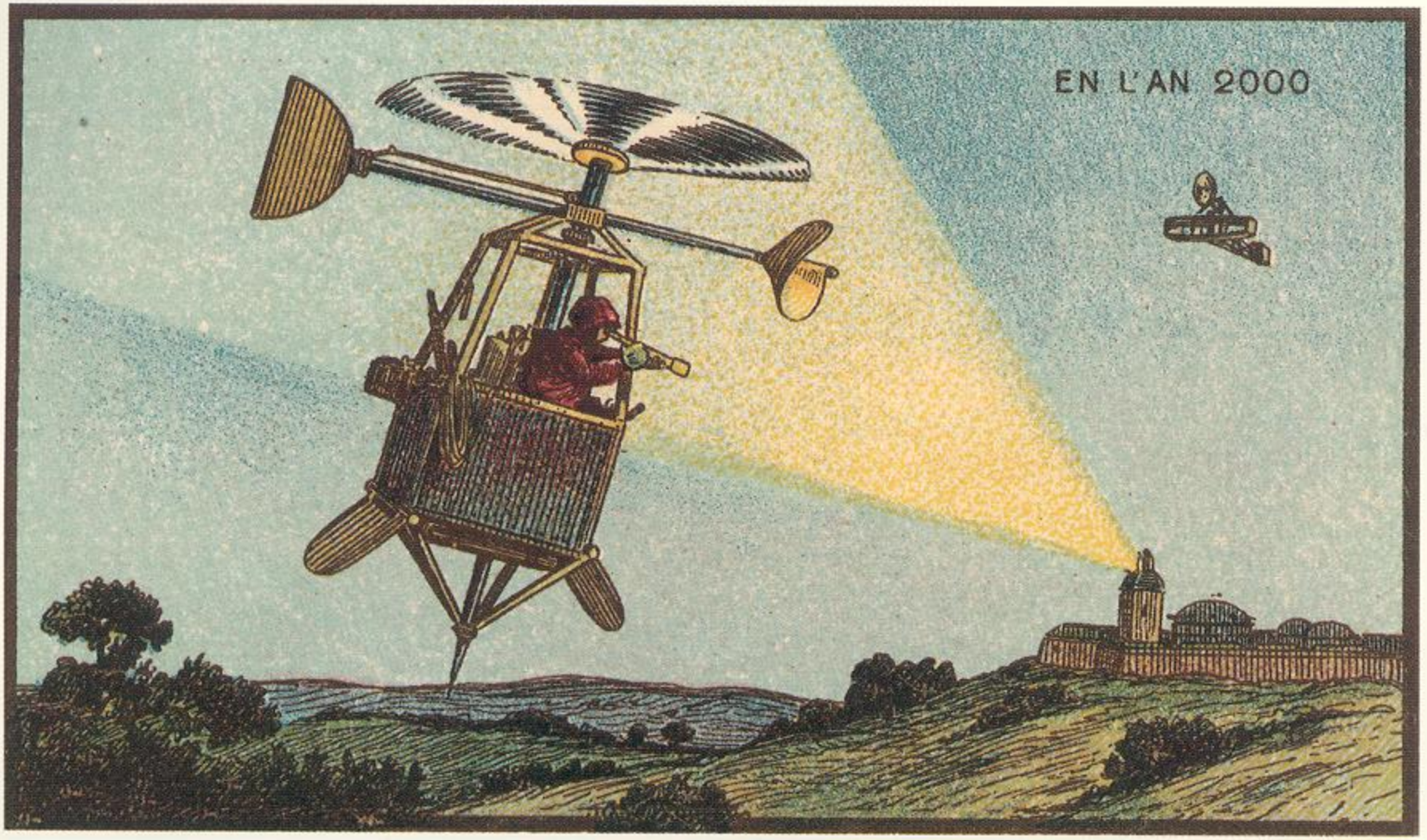
Vision of the Year 2000 by Jean Marc Cote in 1899



Advance Sentinel in a Helicopter

Bell Helicopter in 1899

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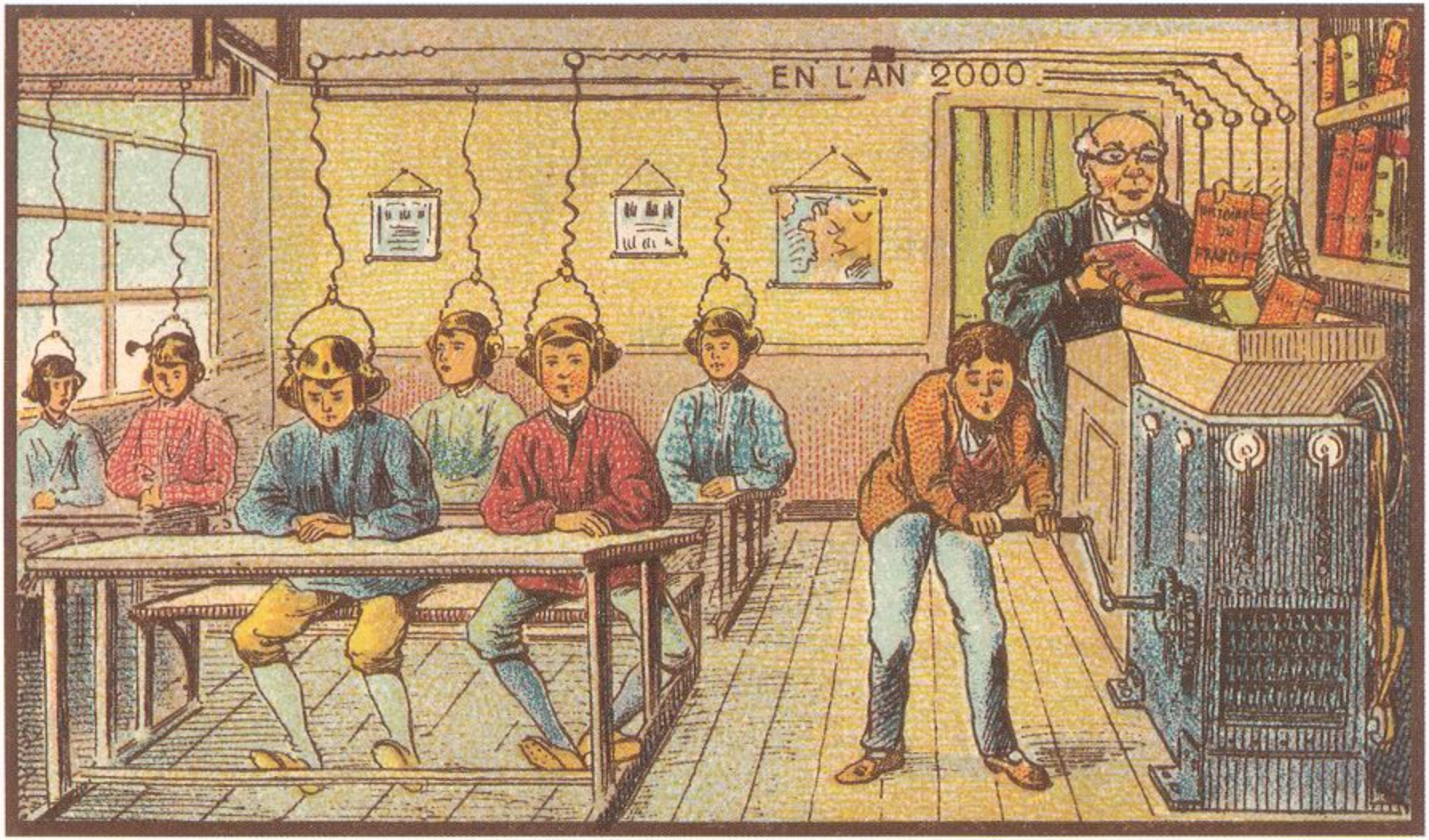
Vision of the Year 2000 by Jeane Marc Cote in 1899



At School

Microsoft in 1899

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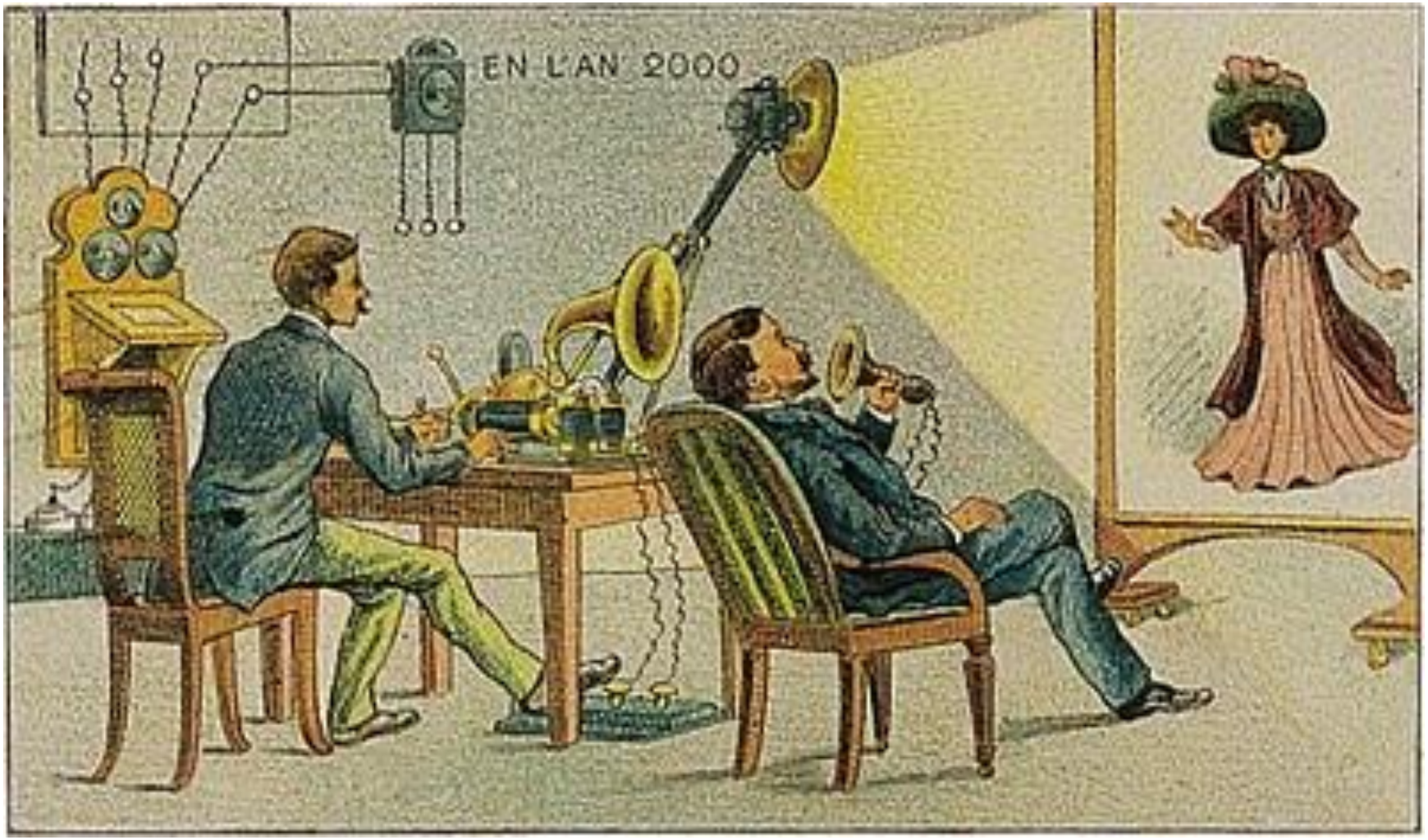
Vision of the Year 2000 by Jean Marc Cote in 1899



Skype in 1899

Ralph Waldo Emerson once said:

"Whatever course you decide upon, there is always someone to tell you that you are wrong. There are always difficulties arising that tempt you to believe that your critics are right. To map out a course of action and to follow it to the end requires courage."

“ Discovery is not a series of accidents but an organic growth, inevitable product of each development stage of scientific knowledge”

– Kurt Mendelssohm

LTS (Before 1986)

- **BCS APPROACH:**

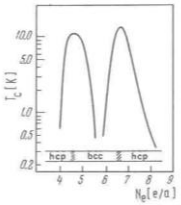
  Cooper Pair (1956)

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

  - To raise the T_c by enhancing θ_D, N(0) and/or V
  - Excellent descriptive power but little/no T_c- predictability

- **ENLIGHTENED 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

1950-70's

T_c ↑

↑

Physics ↗

Physics ↙

↑

T_c ←

1980's

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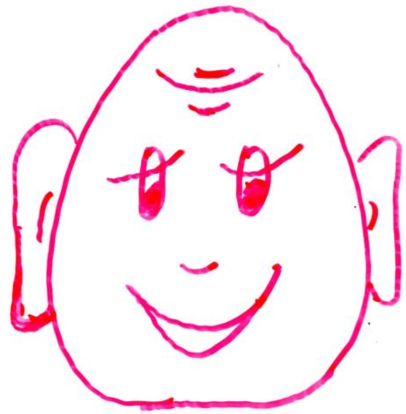
1950-70's

T_c ↑

$ ↑

Physics ↗



1980's

T_c →

↓

Physics ↗

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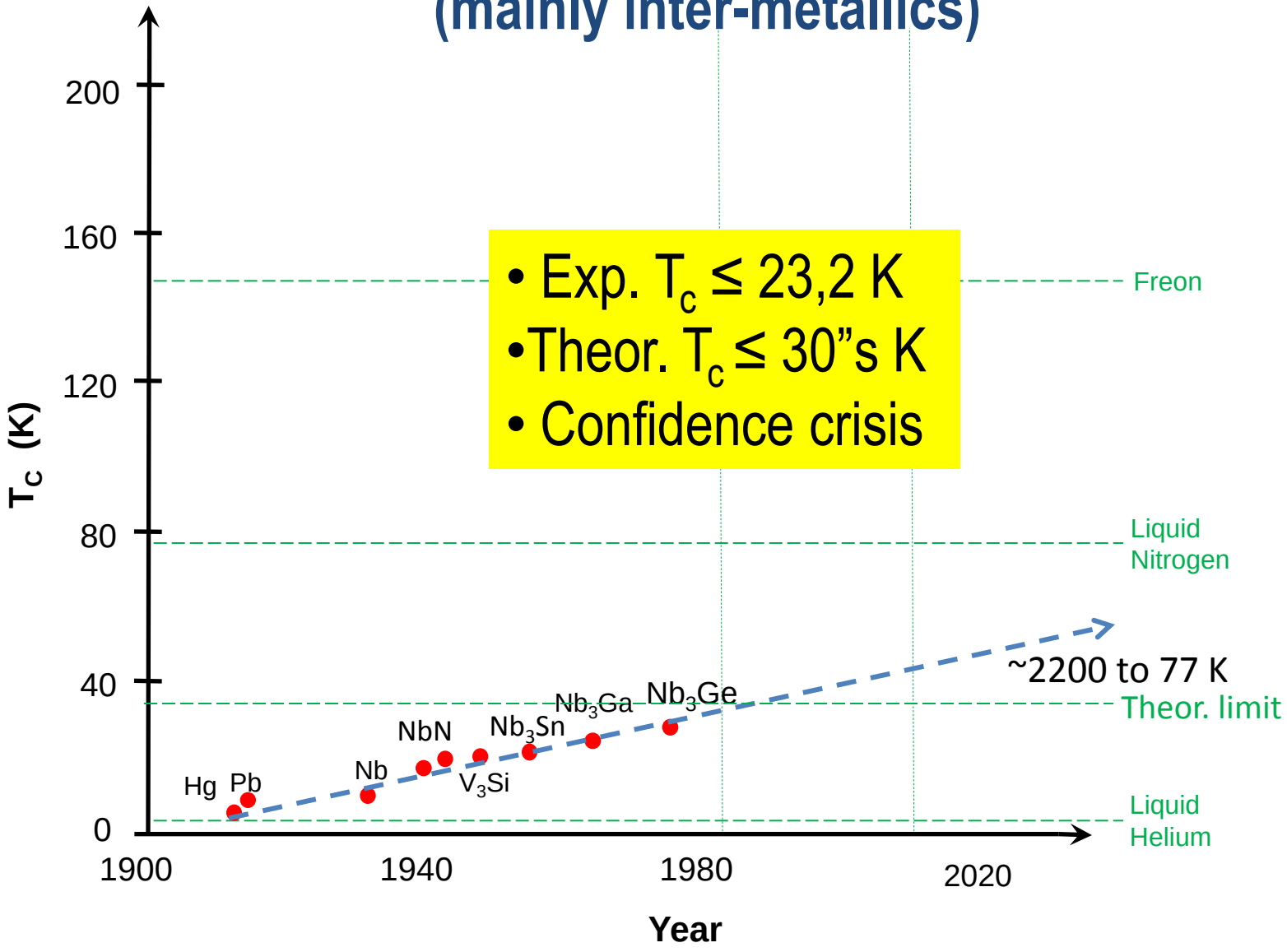
Confidence Crisis!

LTS - Before 1986
(mainly inter-metallics)



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Challenges & Hopes in LTS before 1986

- Matthias rule: stoichiometry, instability & defects
  - Nb_3Ge -film (23 K, 1973): Gavaler, Testardi

- BCS: Possible lattice instability limit to T_c to ≤ 30 K; and the confidence crisis - Martensitic lattice transformation

- The High pressure experiments & the confidence crisis :
  - only slight effect & incipient instability is good (1973, 1974, 1978): Chu, Diatchenko, Testardi
  - pressure a useful guide as a tuning parameter for higher T_c

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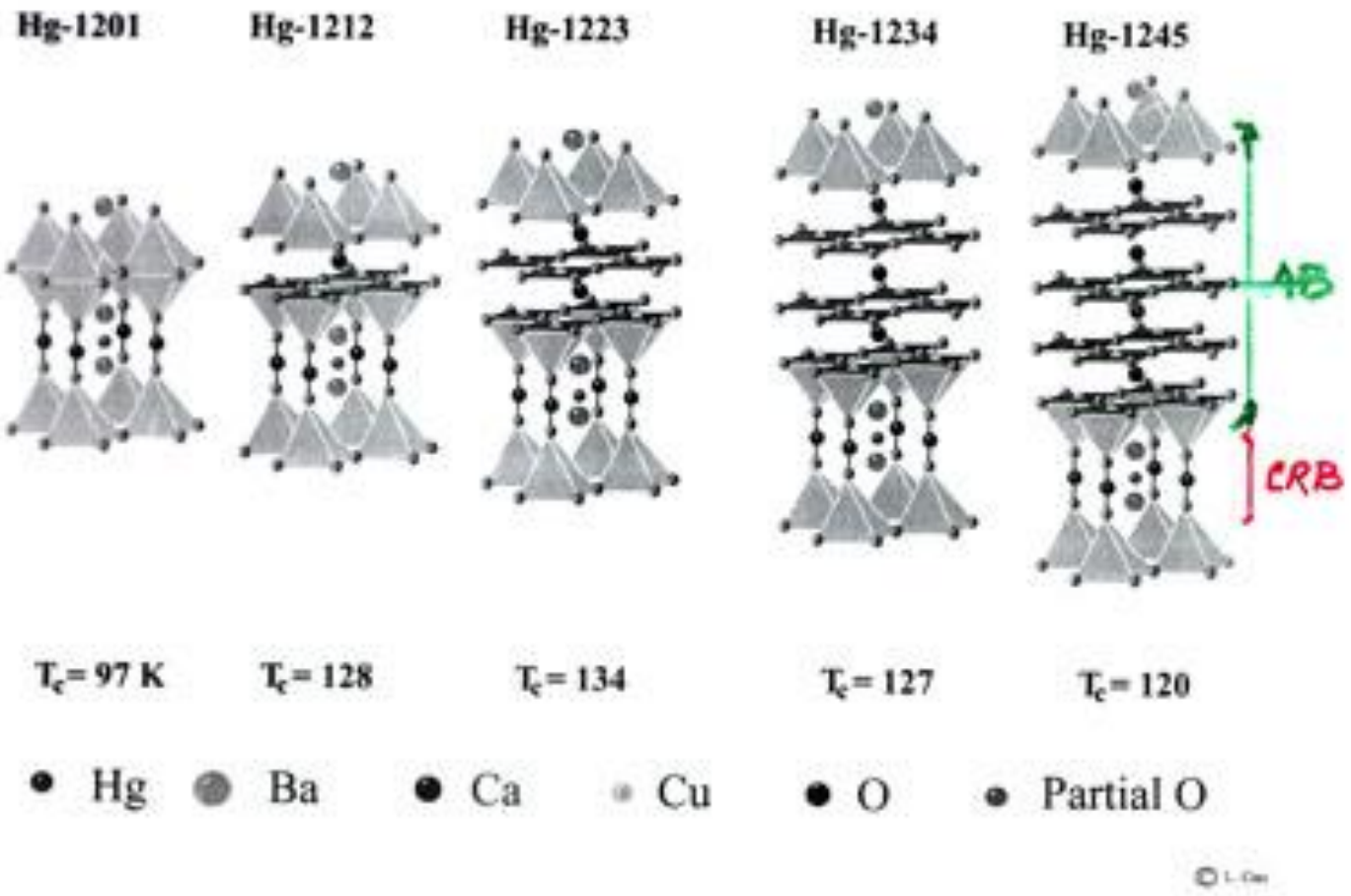
HTS - The Triumphs (1986-)

- **HTS: cuprates**
  - **(LB)CO [~ 35 K, 1986]:Mueller and Bednorz**
    BCS, Jahn-Teller, polarons; perovkite-type
  - **(YBCO) [~ 93 K, 1987]: Chu and Wu**
  - **(BSCCO) [~ 110 K, 1988]: Maeda et al.**
  - **(TBCCO) [~ 125 K,1988]: Sheng and Hermann**
  - **(HBCCO) [~ 134 K, 1993]: Schilling et al.**
  - (HBCCO) [~ 164 K, 30 Gpa, 1993]: Chu, Mao et al.

- **Fe-based arsonides and chalcogenides**
  - **(LFOA) [~ 56 K, 2008]: Hosono et al.**
  - **(FeSe) [~ 12 K, 2008]: Wu et al.**
  - **(KFSe) [~ 31 K, 2010]: Chen et al.**

Schematic Structures of the Hg-Compounds



Highly Anisotropic

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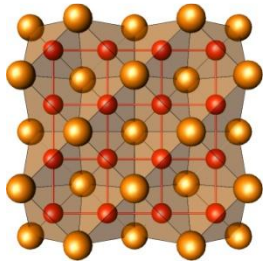
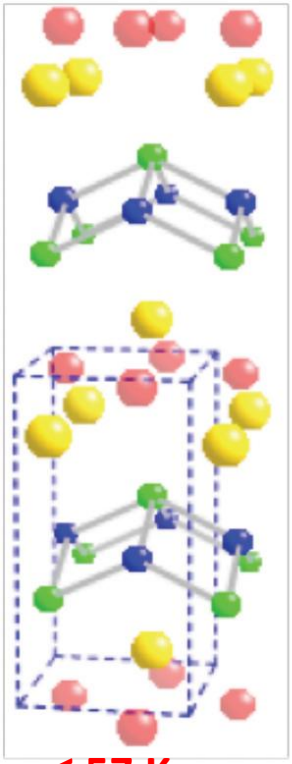
Fe- Pnictides & Fe-Chalcogenides

"1111" "122" "111" "11"

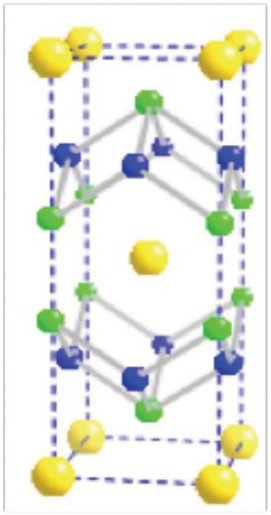
Perovskite-like
Fe-As layers or
Fe-Se layers





≤ 57 K

H. Hosono et al.

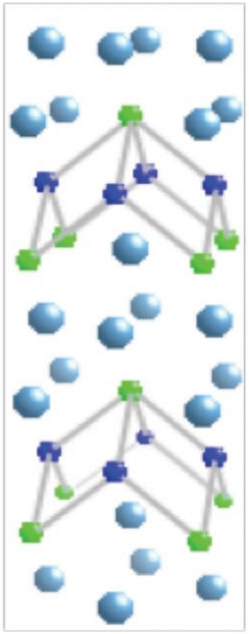


≤ 38 K

M. Rotter et al.

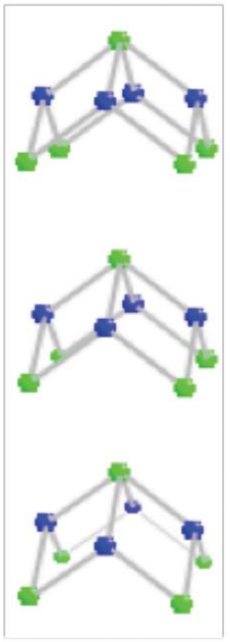
X. L Chen et al.

≤ 33 K



≤ 25 K

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



M. K. Wu et al.

≤ 10 K

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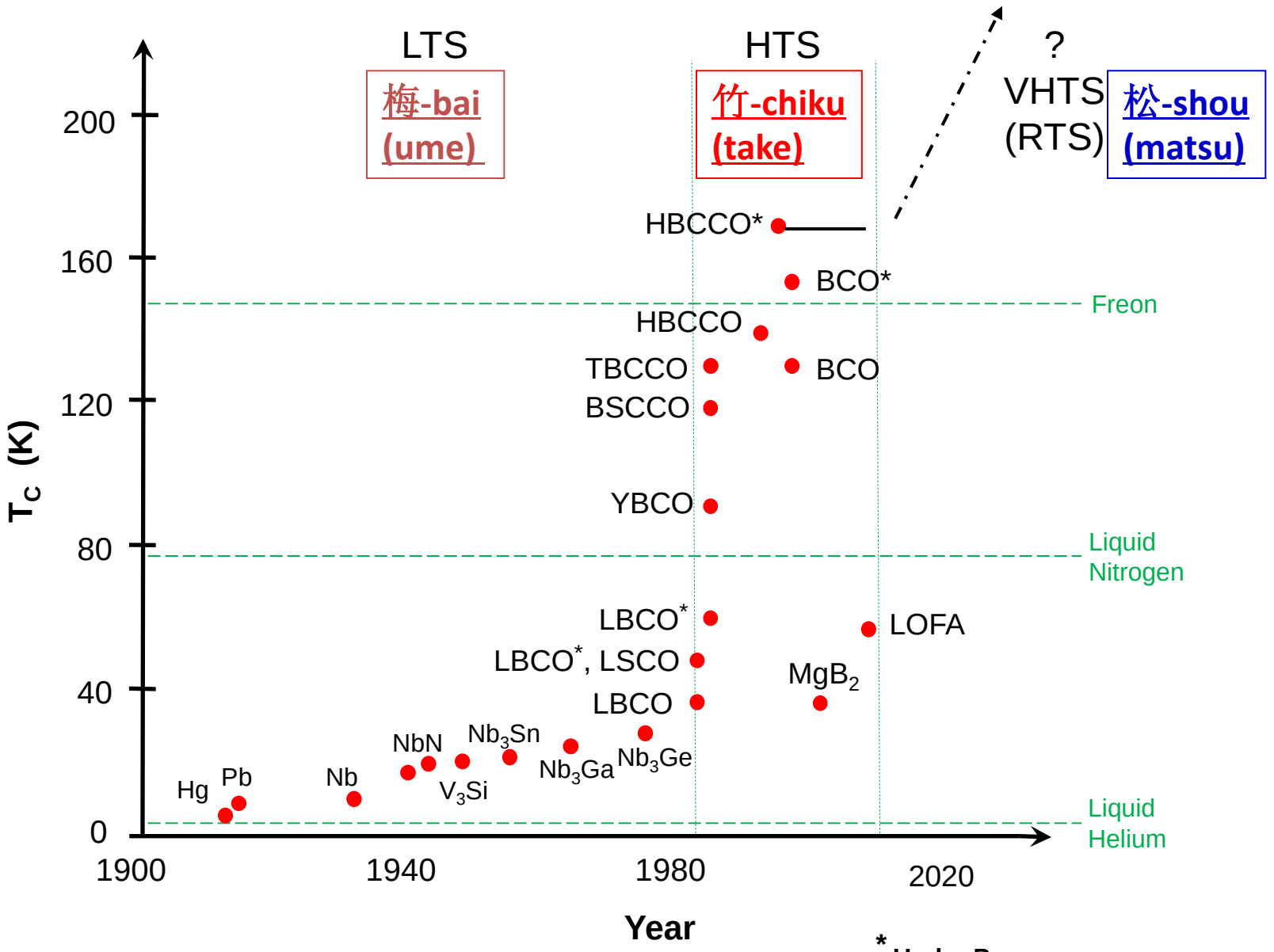
Three Stages of T_c- Evolution



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YBCO remains to be the compound of choice for HTS science and technology:

easier for doping, easier for single crystal, large grain and epi-film growths, high J_c & high H_i above 77 K, robust, less costly

"Honor the past, imagine the future!"

YBCO was included in the White House Millennium Time Capsule

Closing Ceremony - December 6, 2000 in the National Archives, Washington DC 050204CWC

The discovery of HTS has profoundly impacted science and technology.

- Gave new hope to superconductivity at higher temperatures
- Posed more challenges to physicists, material scientists, chemists and engineers
- Created a new subfield in physics
- Accelerated the development of materials science
- Brought superconductivity technology a giant step closer to reality

The next Grand Challenge in superconductivity science and technology research is to find a Room Temperature Superconductor (RTS) with a T_c ~ 300 K

(in public culture long before in science)

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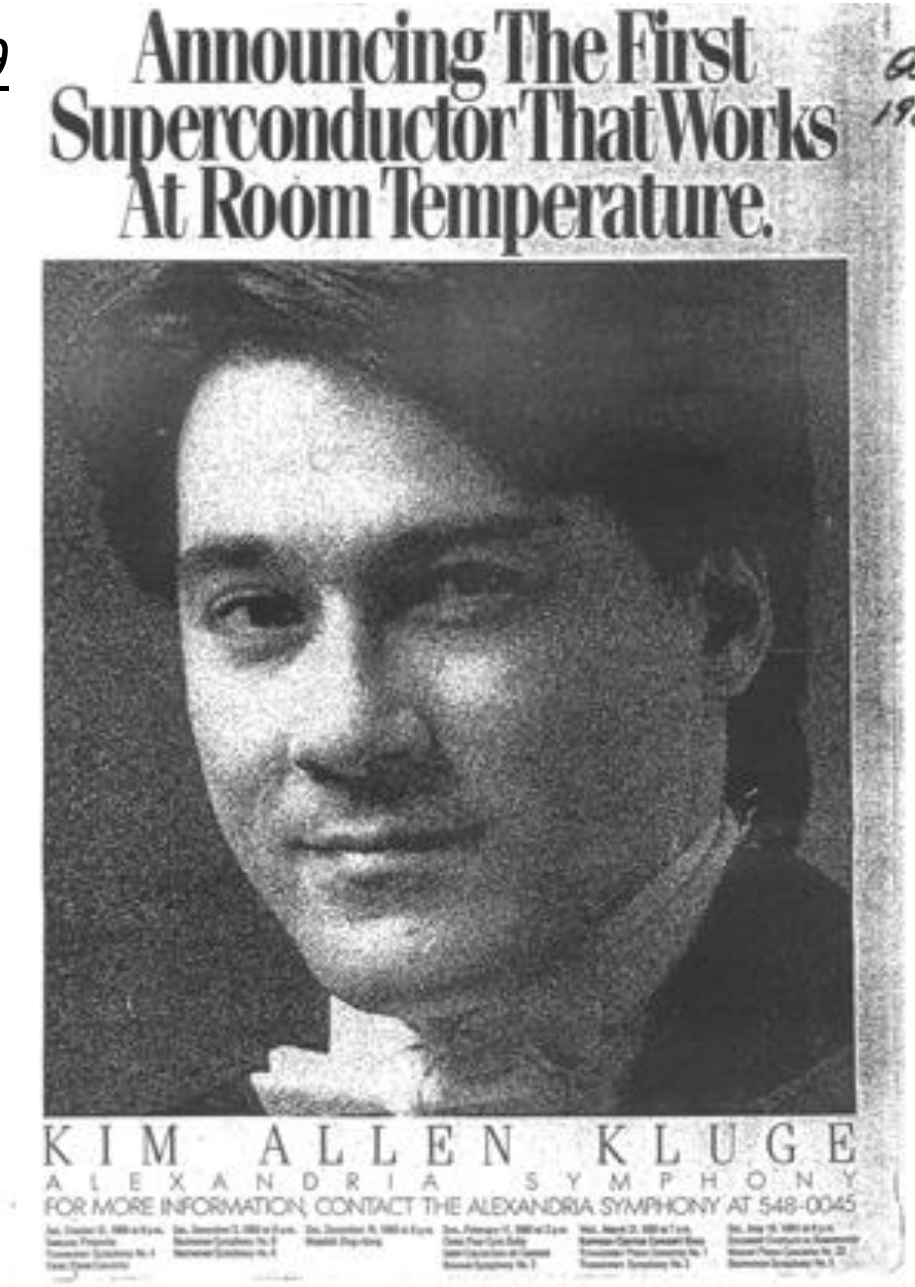
In October 1989



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20 years later, James Cameron announced in Avatar the discovery of a Room Temperature Superconductor in 2009

In 1968, Matthias told me where to find a room temperature superconductor:
"*go to the edge of the universe!*"

Room Temperature Superconductor (RTS) is a relative term:

i. e., $T_c = T_{operating\ environment}$

achieved by either raising the T_c or lowering the T_{op}

Targeted T_{op} suggested since 1911:

Liq. He – 4.2 K (Hg, 1911)

Liq. H_2 – 20.3 K [$Nb_3(Al,Ge)$, 1967]

Liq N_2 – 77 K (YBCO, 1987)

Shuttle – 100 K (BSCCO, 1988)

Liq. Natural Gas – 112 K (BSCCO,1988)

Liq. Freon CF_4 – 148 K (HBCCO,1993)

Solid CO_2 – 198 K (?)

Room Temperature – 300 K (??)

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300 K RTS is:

- Scientifically Exciting & Challenging

  - will provide a new paradigm to the understanding of solids

- Technologically Promising

  - will lead to a new industrial revolution: sustainable global economic development/ energy, environment and resource

- Is RTS possible? If yes, where and how to find it?

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.*

How do we get there?

["A possible path to RTS" - C. W. Chu, AAPPS 18, 9-21 (2008)]

Rational – reason is the source of knowledge

Empirical – experience is the source of knowledge

Enlightened Empirical – experience, intuition and reason are the sources of knowledge

Holistic Multidisciplinary Enlightened Empirical – holistic experience, intuition and reason from different fields are the sources of knowledge for RTS (past, present and future)

A few amusing claims of RTS

- A polymerical material from former USSR

- A piece of material from a former allegedly left behind by a Martian in the Arizona desert

- An oxide material from Croatia

Several Interesting Reports

- Na-amonia solution: Ogg [~ 180 K, 1946]
- CuCl: Rusakov & Brandt; Chu & Geballe [~ 170 K, 1978]
- USOs: Chen [~ 240 K, 1987], Lagues [~ 200 K, 1993], Tholence [~ 200 K, 1994]
- Na/WO_3: Reich [~ 91 K, 1999]

Some Visionary Predictions for RTS

- T_c ~ 300 K (W. A. Little 1964, V. L. Ginzburg 1964, Neil Ashcroft 1968, 1997, 2004)
- Enhanced T_c of interfacial SC (Allender, Bray, Bardeen, 1973)
- Why is the T_c so low? (Patrick Lee 1987)
- T_c may not have a ceiling. (Paul Chu 1988)
- T_c > 300 K (Maurice Rice 1997)
- T_c > 1000 K (J. R. Schrieffer 2004)
- T_c > 230 K (Peter Edward et al. 2006)

Unidentified Superconducting Objects (USO's)

too tantalizing to ignore; too fleeting to confirm

Possible Common Features of RTS

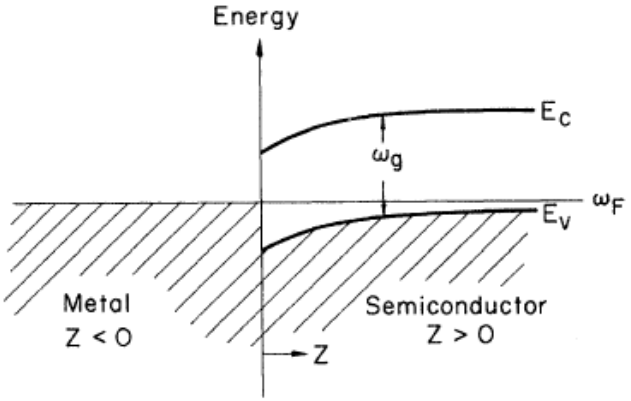
- Electron-pairing and phase-coherence
- Strongly correlated electron systems
- Multi-interactions
- Multi-structural
- Multi-energy scales
- Instabilities
- Proximity to M-I transition
- Quasi-2D
- Low carrier density
- High degree of co-valency
- Mixed valence
- ……..

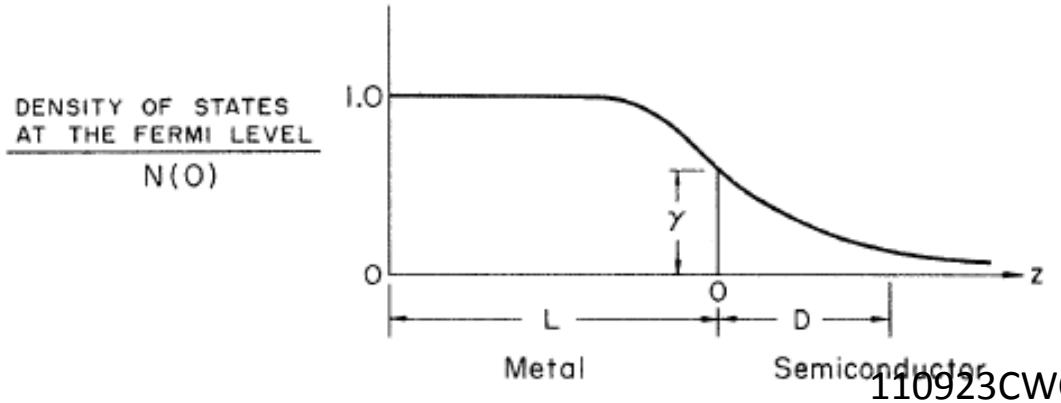
EX. I – Interfacial SC in (Ca,Pr)122

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

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

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





Interfacial superconductivity based on ABB?

-Perfect interface between metal and semiconductor

-Close coupling between the surfaces

-The Fermi energy of the metal has to match the energy gap of the semiconductor

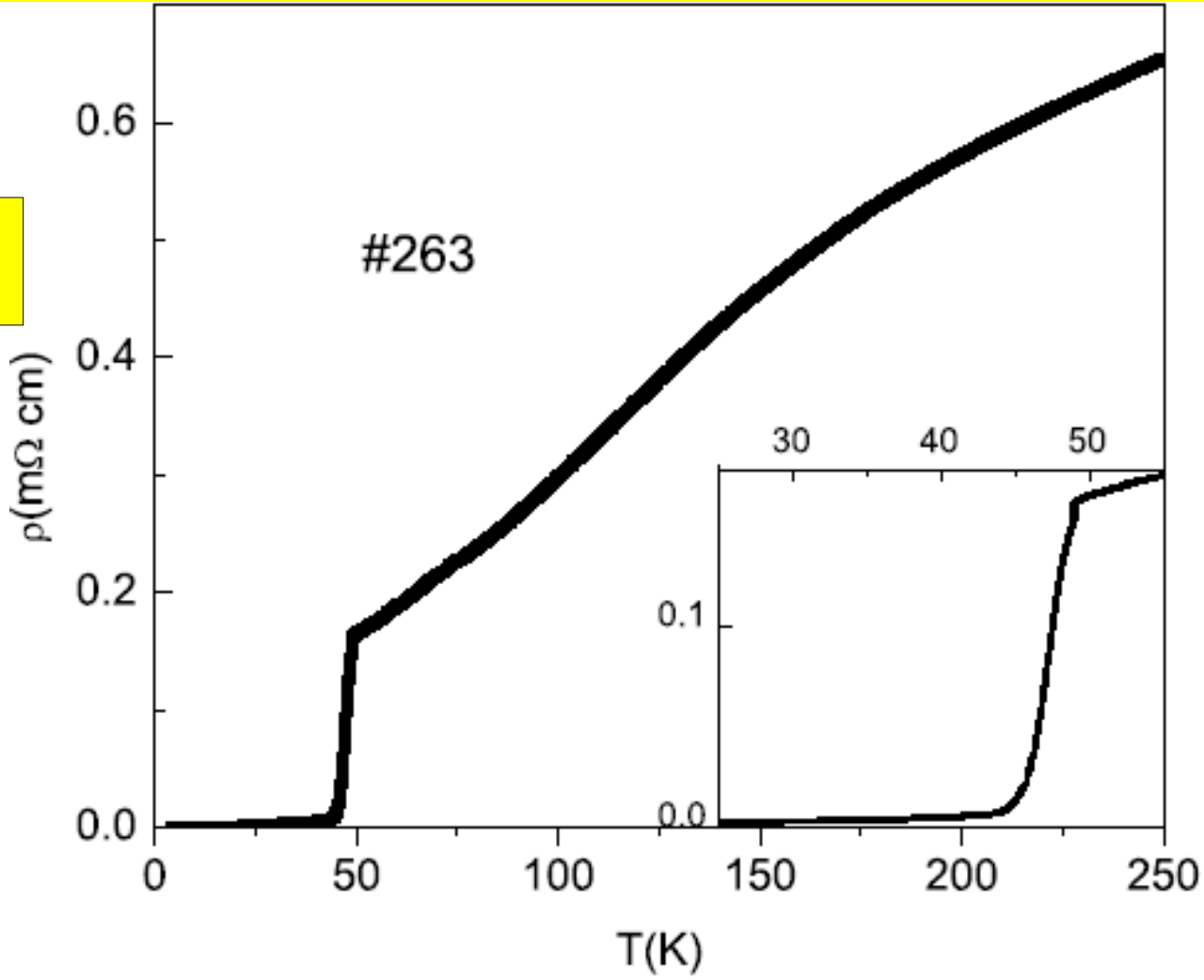
Possible candidates:

- Pb/PdTe?
- immiseable alloy?
- cuprates?
- topological superconductor?
- **Ca122?**
- ……

A possible candidate

The electron-doped single crystalline $(Ca,Pr)Fe_2As_2$ onset Tc ~ 49 K

Highest T_c of 38 K For doped Ca122



B. Lv/cwc et al. to appear in PNAS 2011

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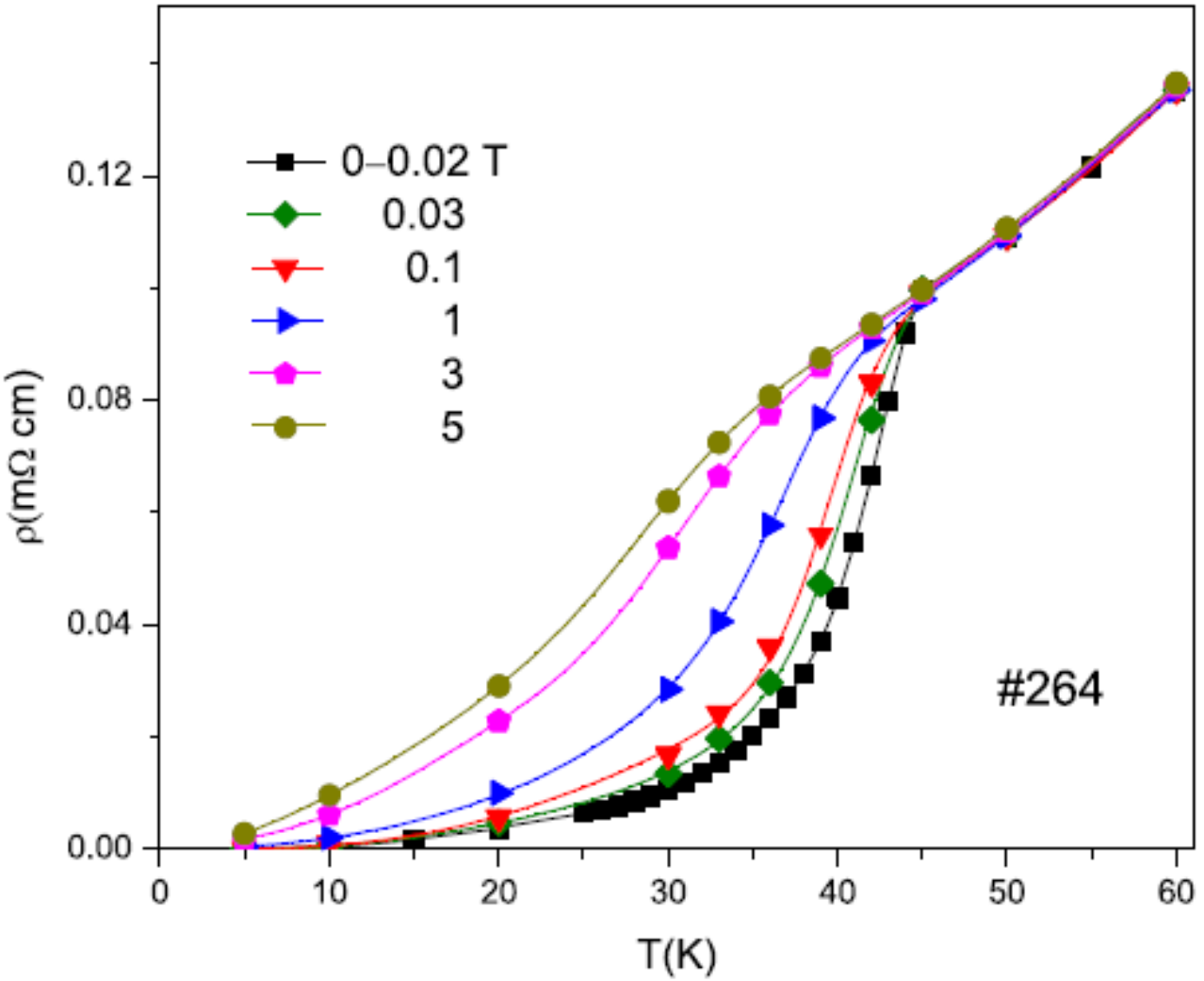
The electron-doped single crystalline $(Ca,Pr)Fe_2As_2$

H_{c2} > 5 T at 5 K



B. Lv/cwc et al. to appear in PNAS 2011

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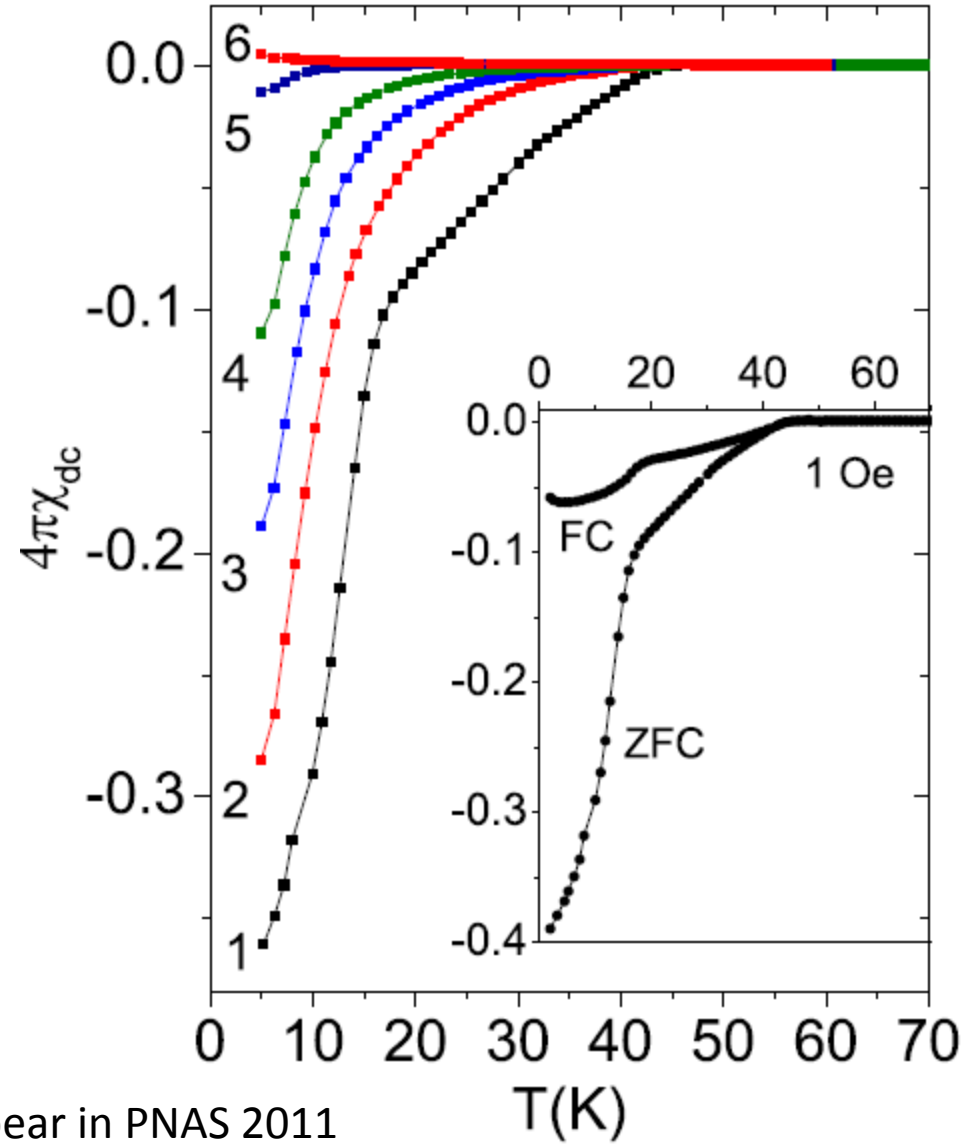
The electron-doped single crystalline $(Ca,Pr)Fe_2As_2$

Seems to suggest that $H_{c2} < 300$ Oe



B. Lv/cwc et al. to appear in PNAS 2011

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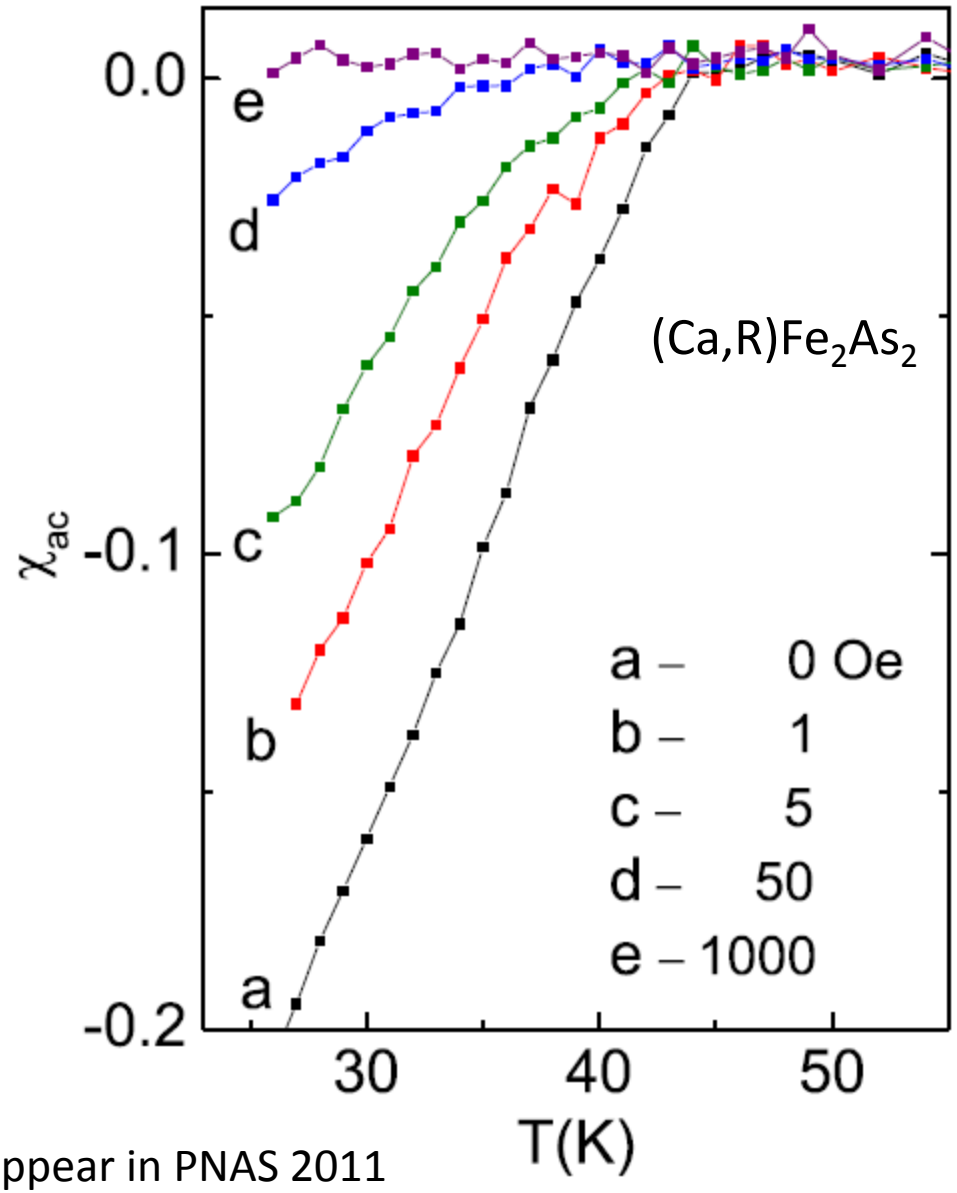
The field effect on the high temperature transition

Low H_c
High T_c phase



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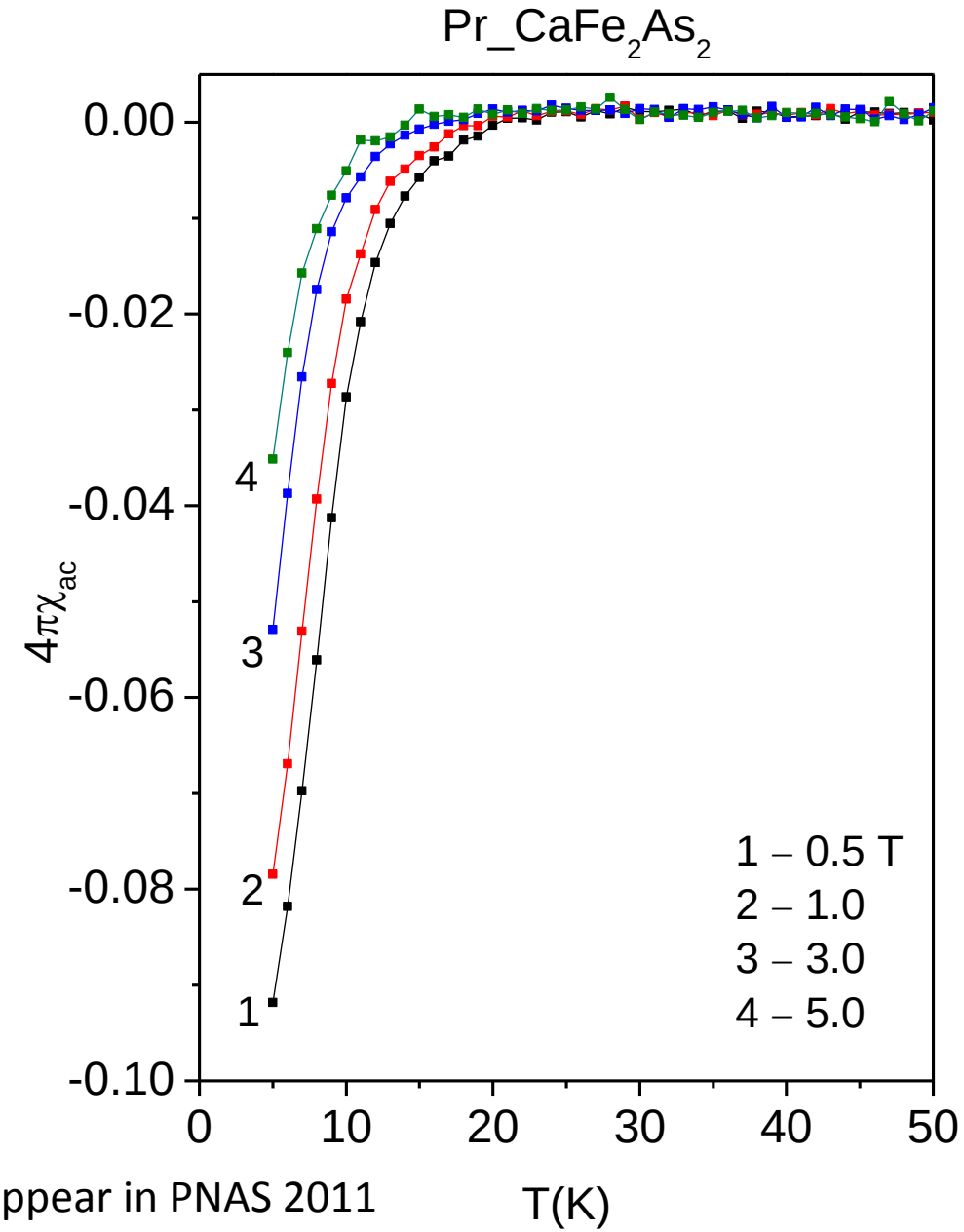
Smaller field effect on the low temperature transition

High Hc
Low Tc phase



B. Lv/cwc et al. to appear in PNAS 2011

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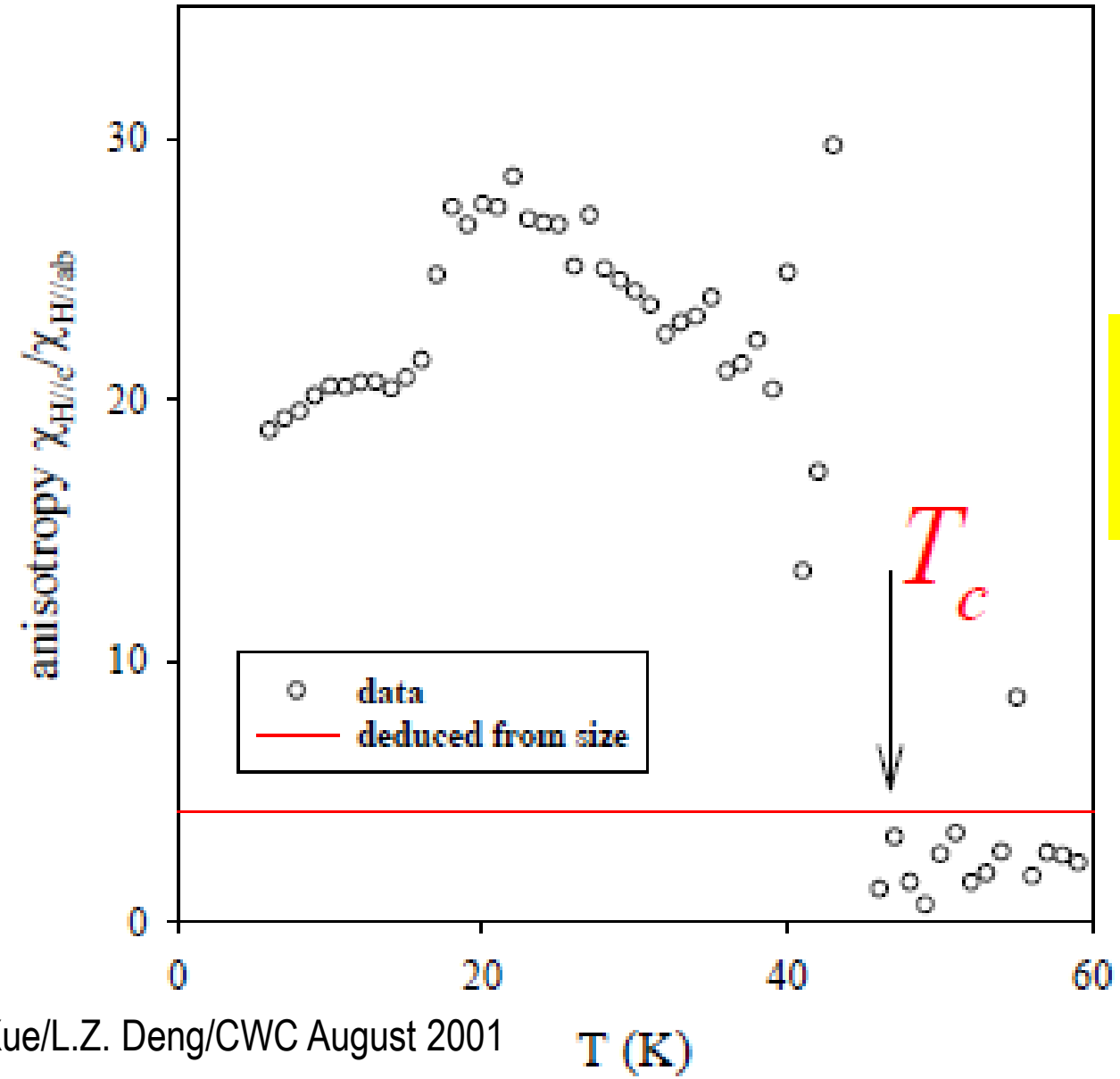
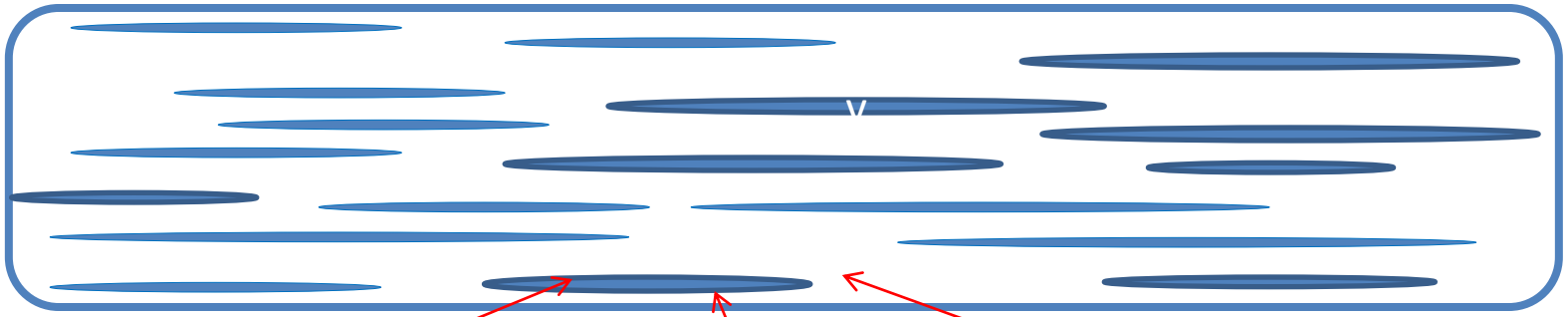
(Ca,Pr)122- possible interfacial sc highly anisotropic, filamentary



~30 for (Ca,Pr)122
vs.
~ 3 for bulk (Ba,K)122

Y. Xue/L.Z. Deng/CWC August 2001

Model of Interfacial SC in e-doped Ca122 and other materials (T_c can be higher than 49 K)



Semi-metallic
undoped Ca122

Enhance SC
an the interface

Sc doped Ca122

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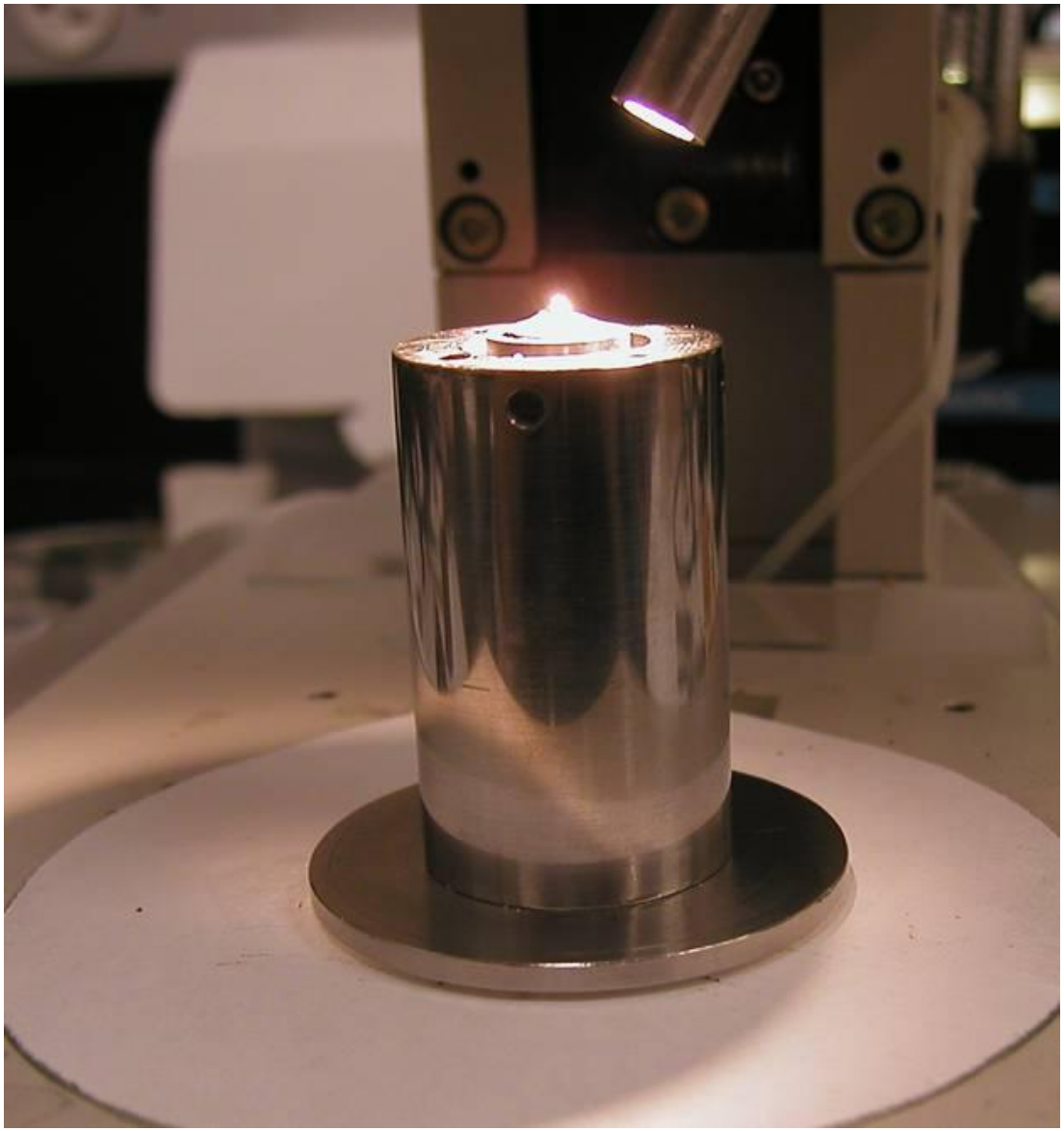
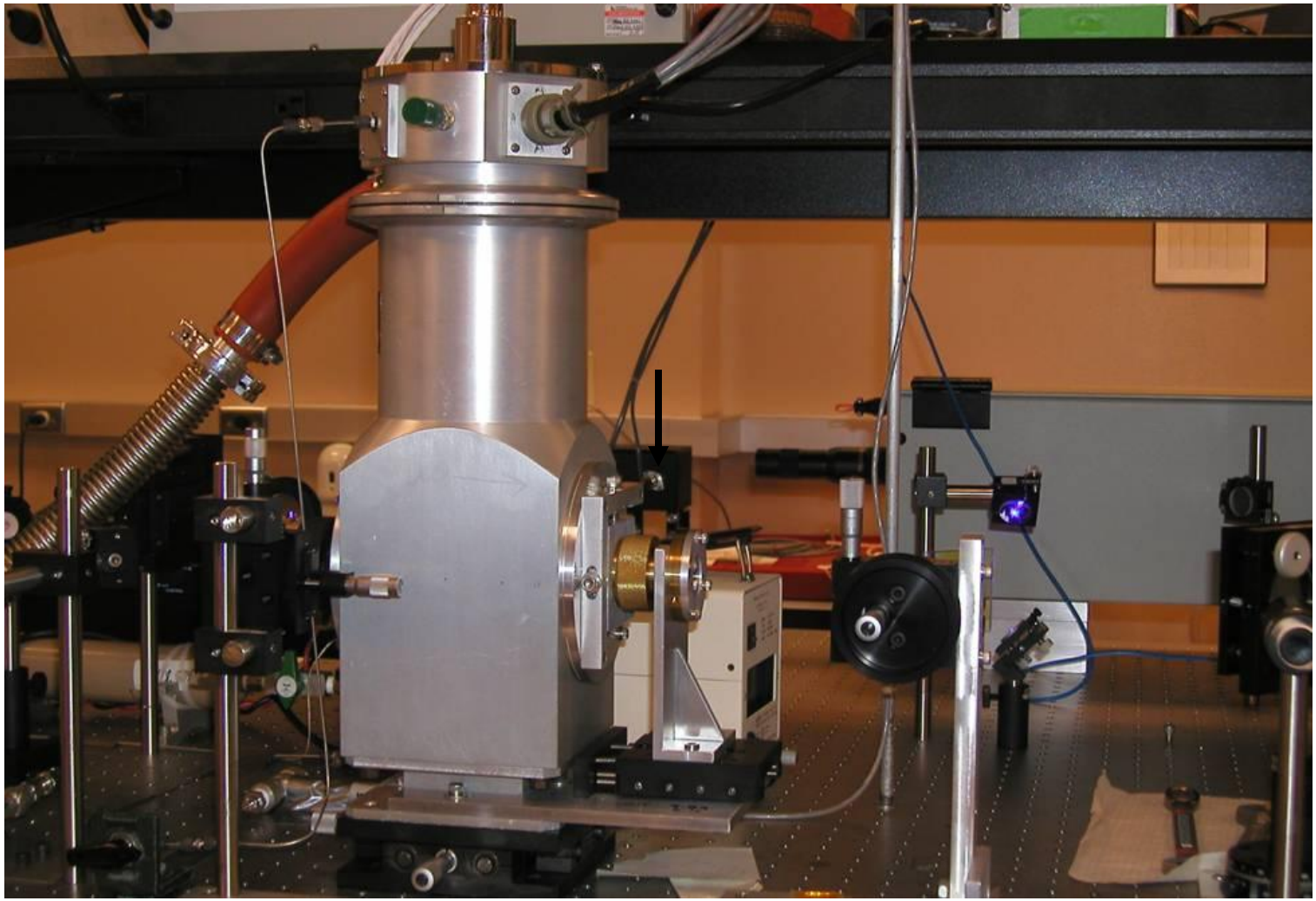
Ex. II - Stabilizing Meta-stable Phases at Low T

(Diatchenko/Chu,)



Search for Metastable Phases via Extreme conditions
(Diatchenko/Chu)



HPDC for in-situ synthesis, fast quenching and characterization

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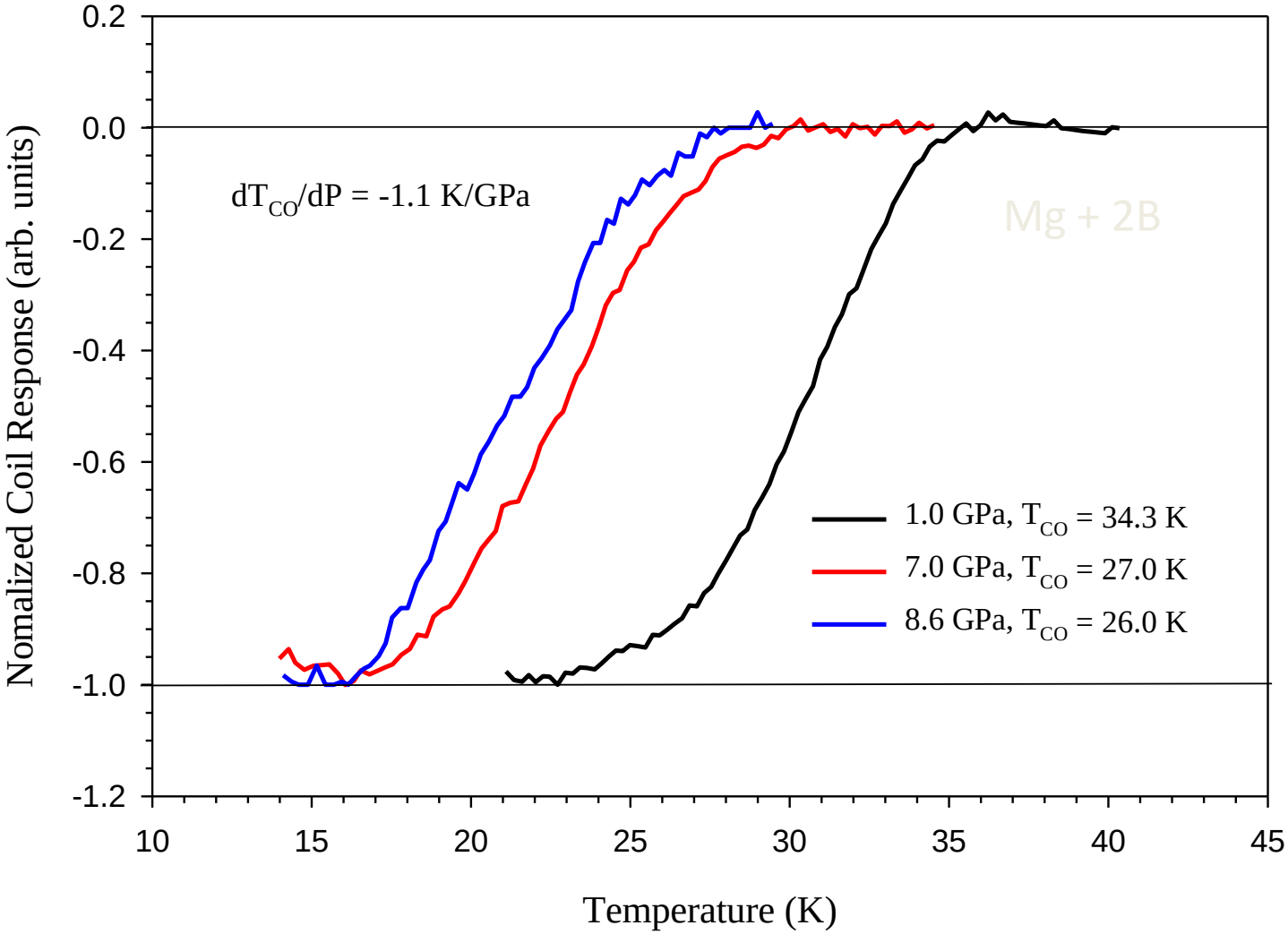
Search Metastable Phases

(Diatchenko/Chu, 2005)

Ex.II - Concept Demonstration - MgB_2



V. Diatchenko/CWC

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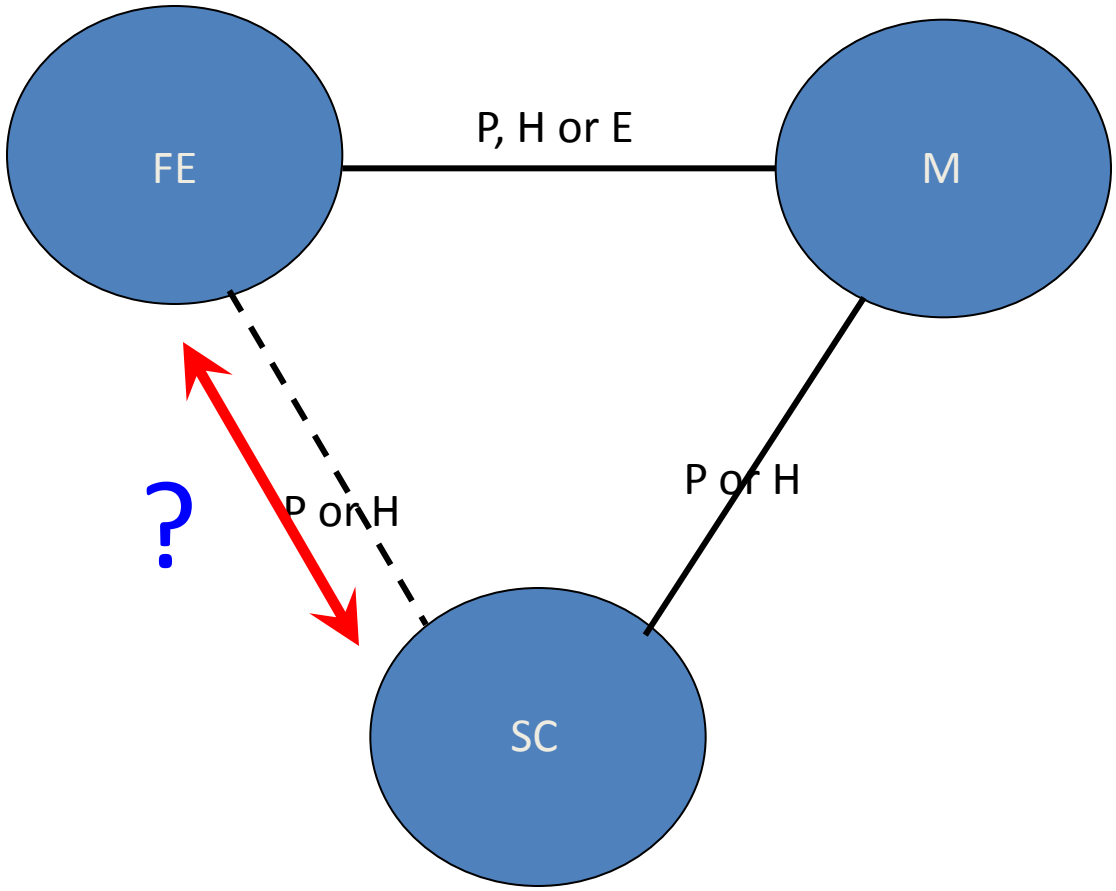
Figure 7

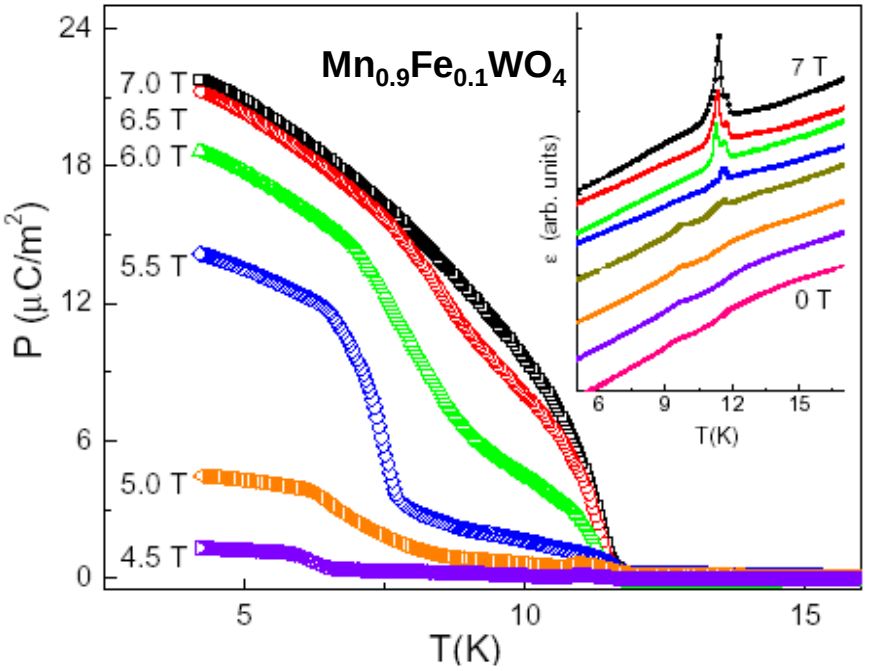
EX. III – Optimization of multiple interactions

Optimizing Multiple interactions in highly correlated electron systems with high ordering temperatures



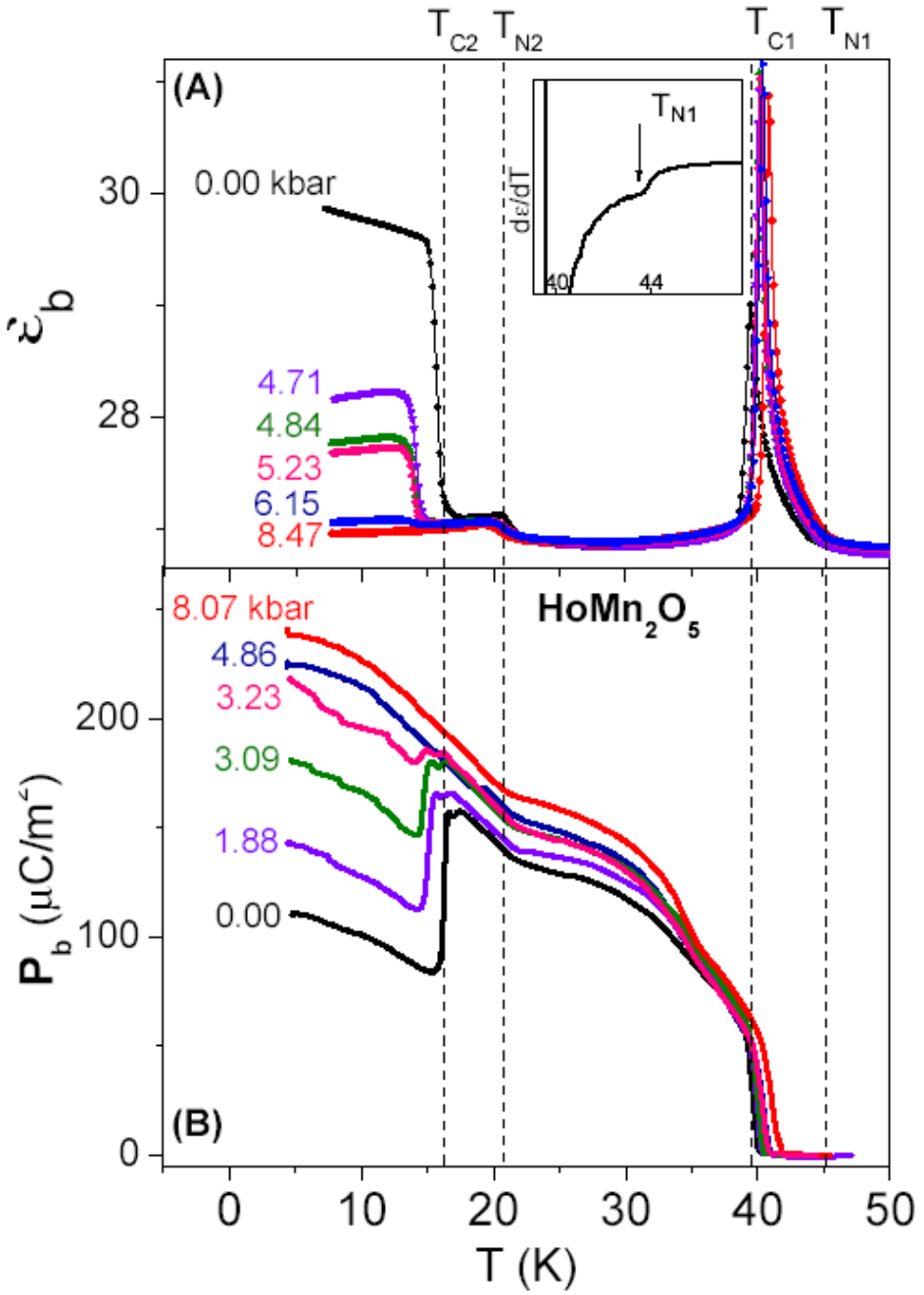
Superconductivity close to a ferroelectric instability ?

Field-Induced FE



Chaudhury/Lorenz/Chu et al. (2007)

De la Cruz/Lorenz/Chu et al. PRB (2007)



Pressure-Induced FE

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A few Lessons Learned

- Do watch what the experimentalists say but don't listen to what they say
- Do listen to the theorists but don't be intimidated by what they say
- Reviewed all past records and projects to think outside the box
- Holistic multidisciplinary enlightened empirical approach will be fruitful
- **Have faith** – "You really have faith in HTS." **-** *Alex Mueller*
- **Be optimistic** – in this world the optimists have it all, not because they are always right but because they are positive. Even when they are wrong, they are positive. – *David Lawdes*
- **Be cautious** – remember what was said in the 70"s

Several warnings in the 70's about RTS

- RTS *belongs to the domain of science fiction and to occur only at an astronomical distance under an astronomical pressure*

- *present theoretical attempts to raise the T_c are the opium in the real world of superconductivity. Unless we accept the fact and submit to a dose of reality, honest and not so honest speculations will persist until all that is left in this field will be these scientific opium addicts, dreaming and reading each other's absurdities in a blue haze.*

- *the deluge of idle speculations coming to us these days from all sides just won't do it – all it will manage to do is to widen the credibility gap instead of the energy gap.*

The future of SC science and technology Research and development will be exciting as new discoveries are continuously made!

Thank You!