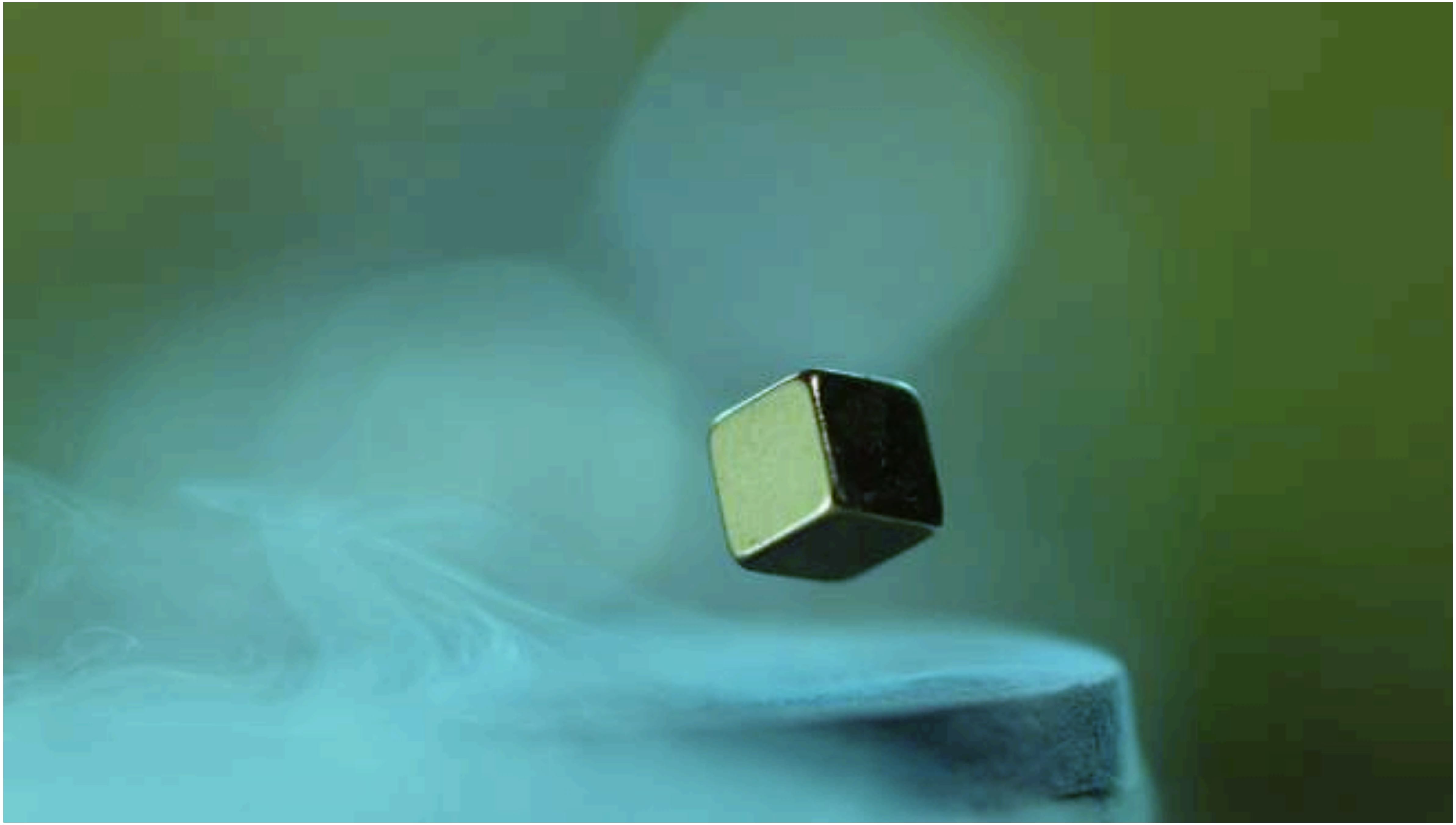
Aspects of Superconductivity



Aline Ramires
ETH Zurich → ICTP-SAIFR ↔ MPI-PKS

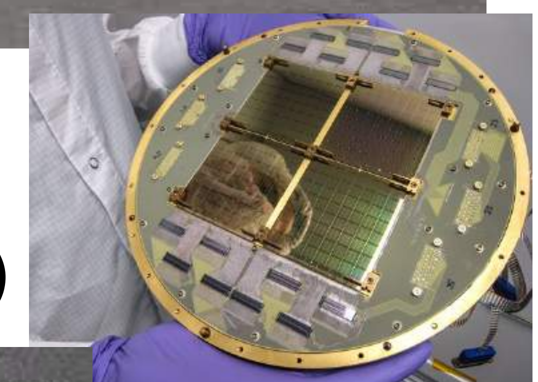
Image Credit: Department of Theoretical Physics at Ural University

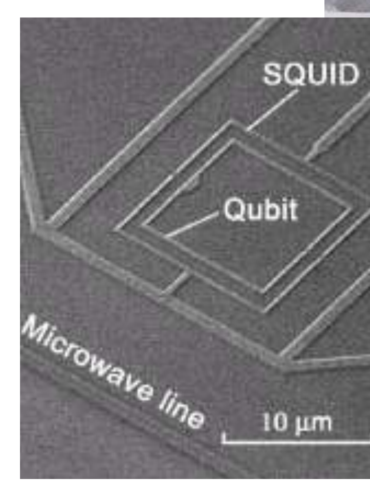
Applications?

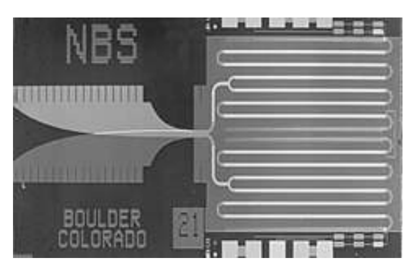
- Low loss power transmission lines
- Turbines and generators
- Maglev trains
- Magnetic resonance imaging (MRI)
- Tokamaks (for nuclear fusion)
- Bolometers (for particle detection in astronomy and cosmology)
- Particle accelerators/LHC (as beam-steering and focusing magnets)
- The basis of the most sensitive magnetometers (SQUIDs)
- The basis of Q-bits for quantum computation
- The basis of the VOLT standard
- …

Great impact on numerous areas:

- Power production/storage/distribution
- Transport
- Medicine
- Scientific instrumentation
- New quantum technologies
- …

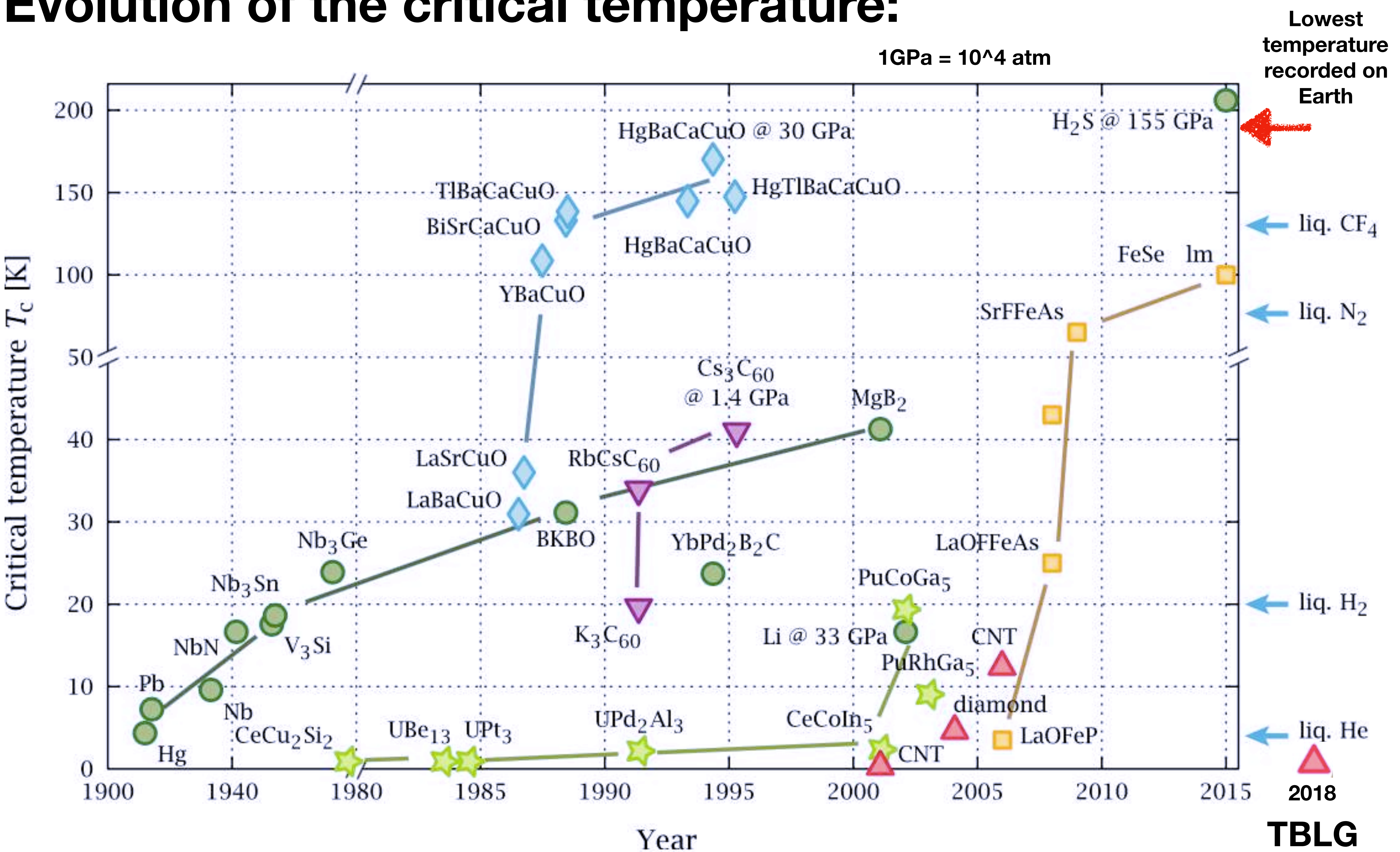




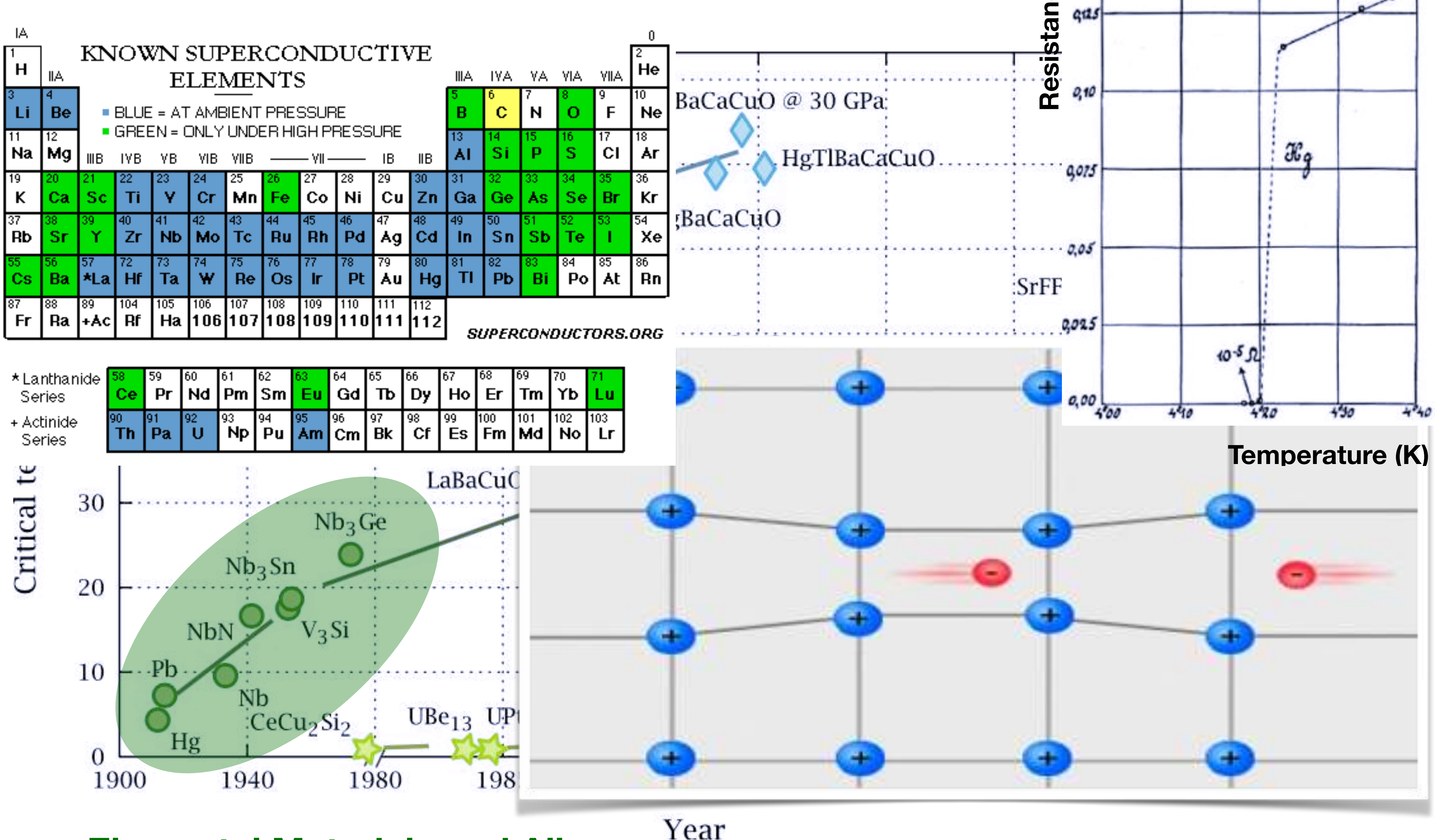


Main current limitation: SC only at very low temperatures!

Evolution of the critical temperature:



Evolution of the critical temperature:



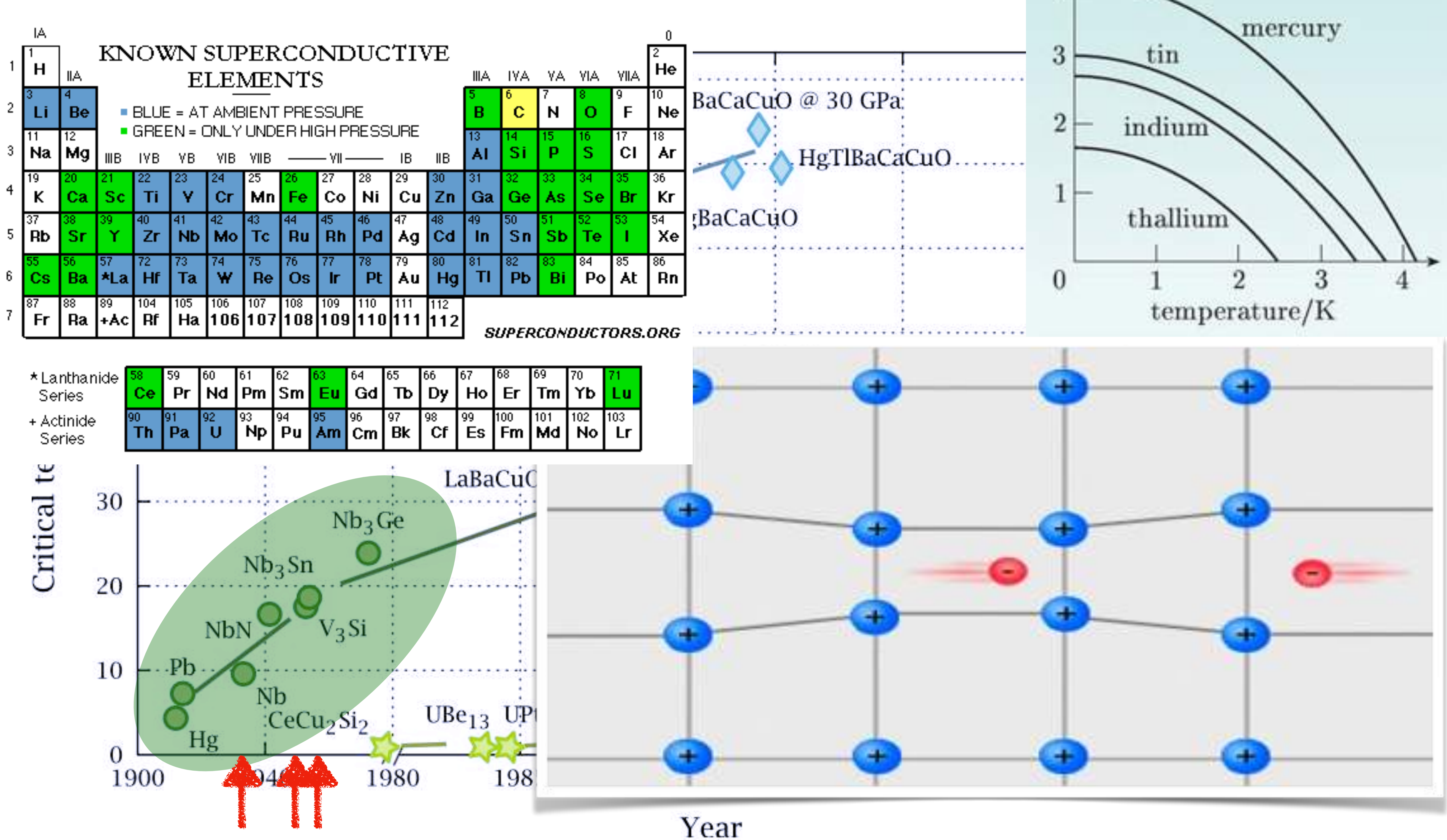
Elemental Materials and Alloys

- Conventional Superconductivity

- Well described by BCS theory. Phonon mediated.

Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)
superconductors.org

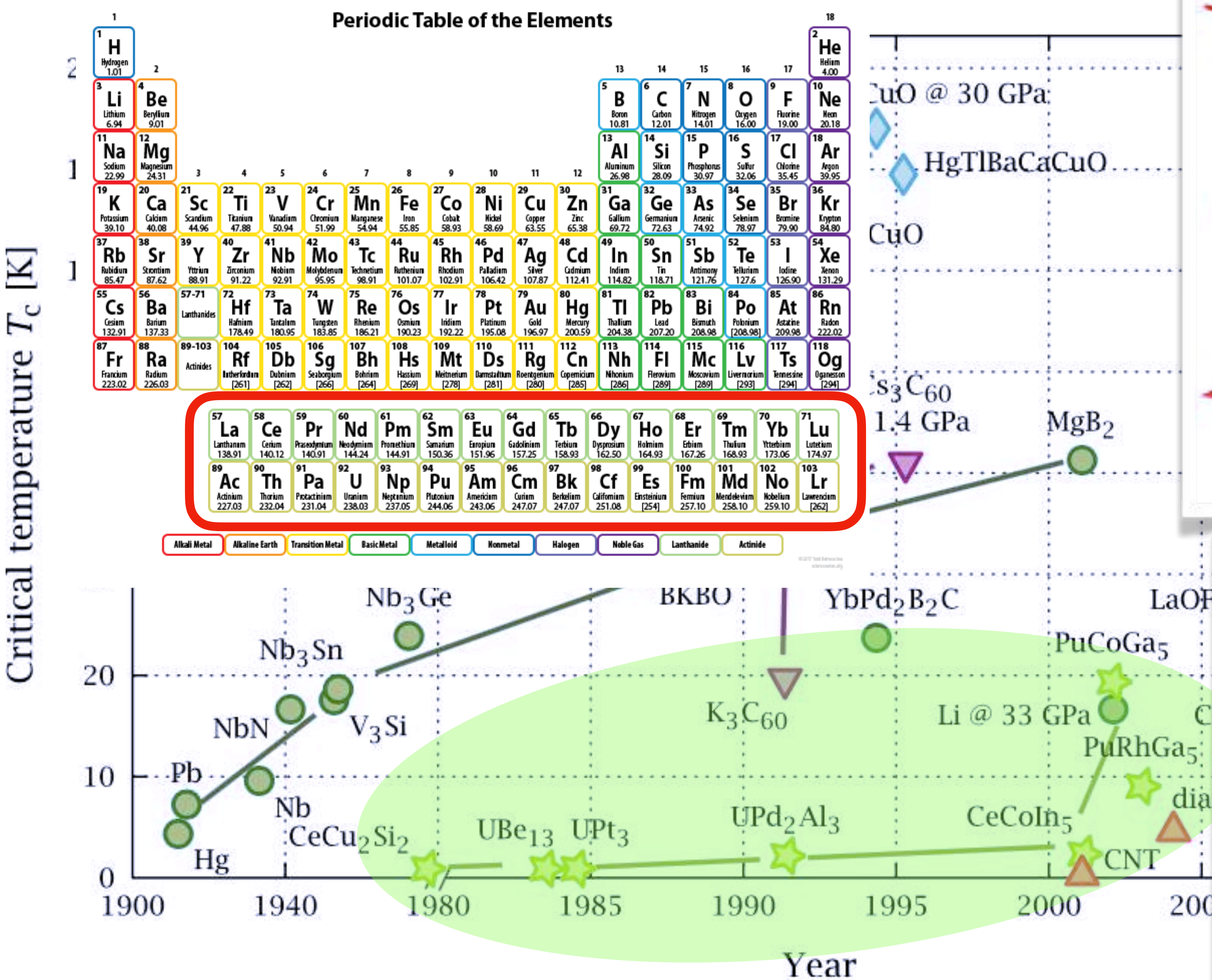
Evolution of the critical temperature:

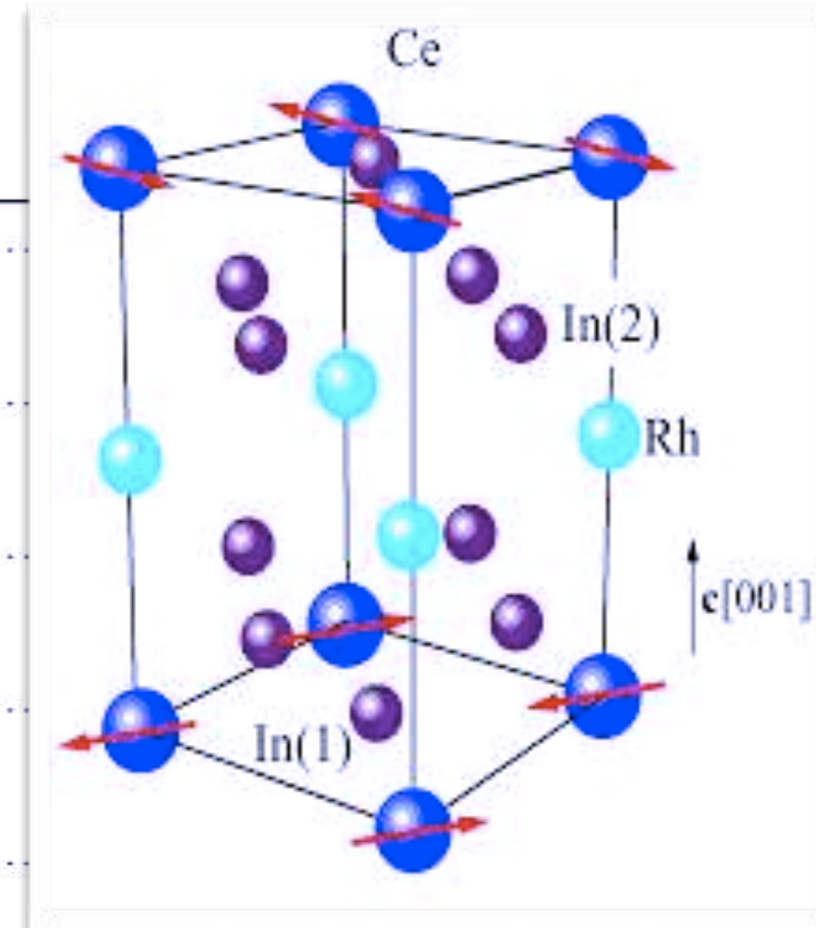


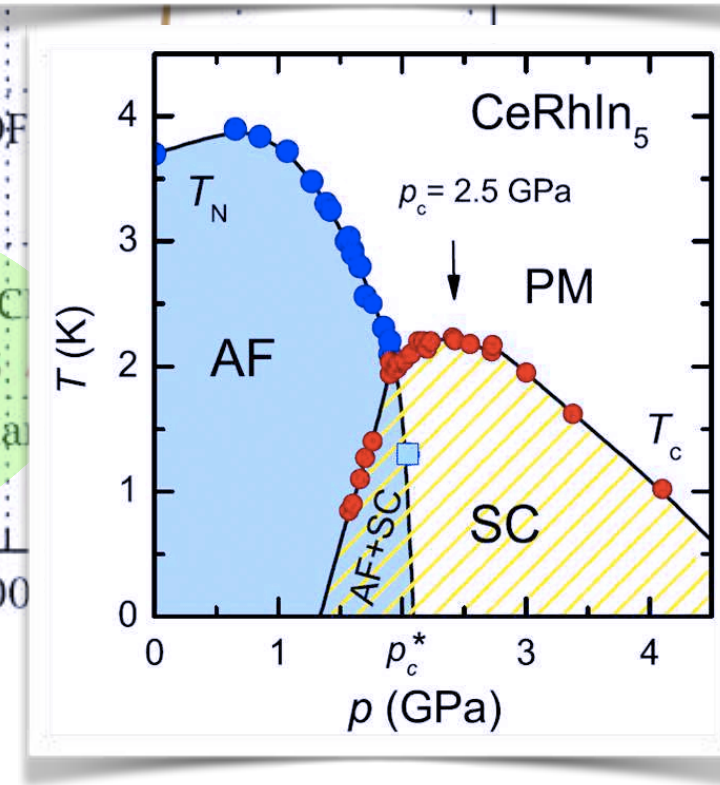
1935: London Theory
1950: Ginzburg-Landau Theory
1957: BCS Theory

Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)
www.superconductors.org
www.open.edu

Evolution of the critical temperature:





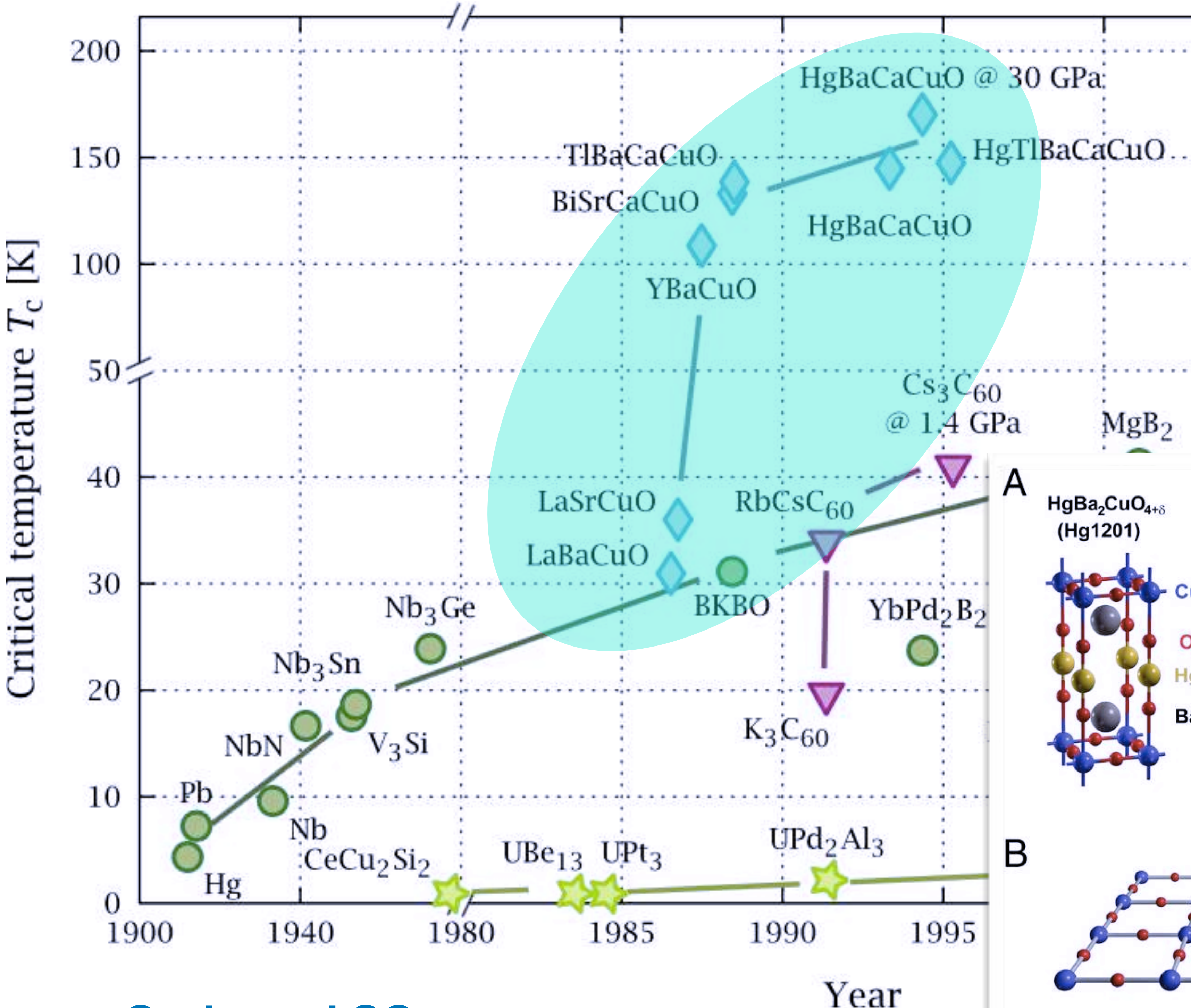


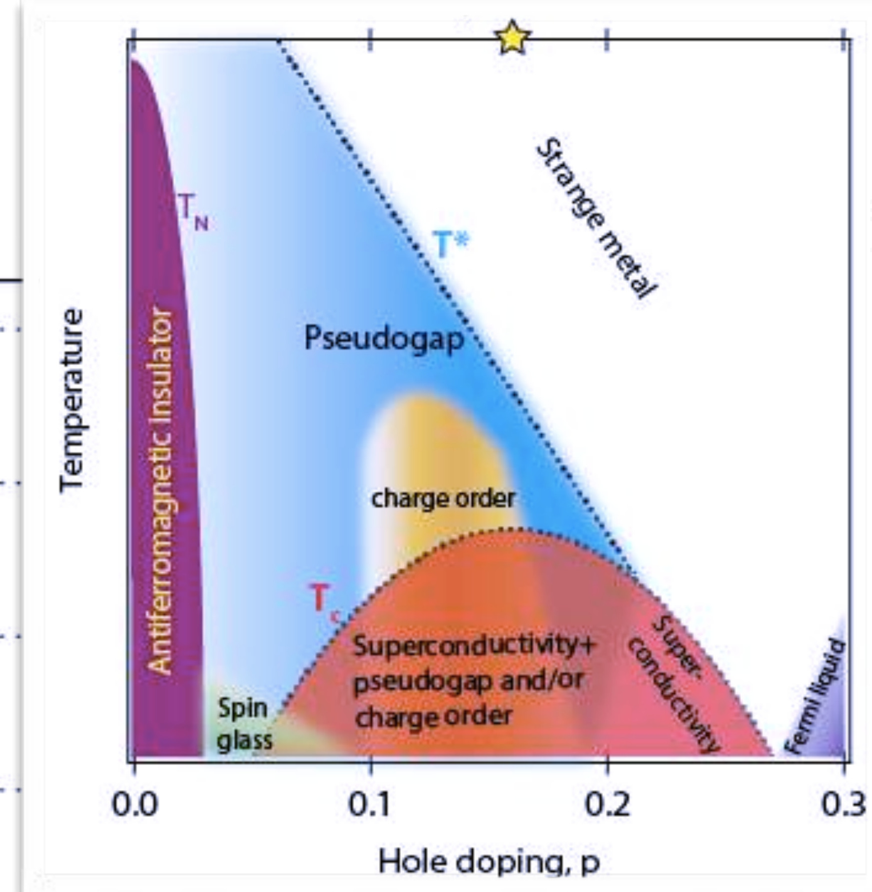
Heavy Fermions

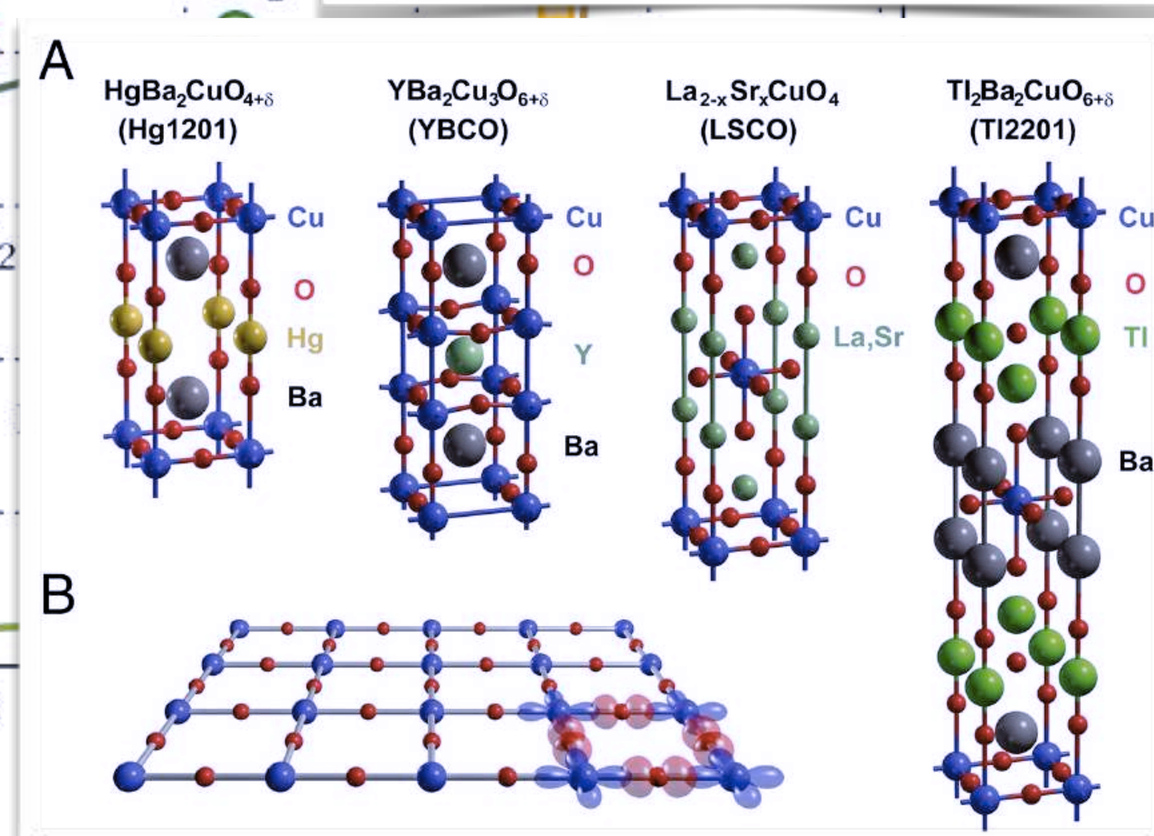
- **Strong correlations. Unconventional SC. Non-phonon mediated.**
- **Neighbouring magnetism?**

Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)
G. Knebel, arXiv 1105.3989

Evolution of the critical temperature:



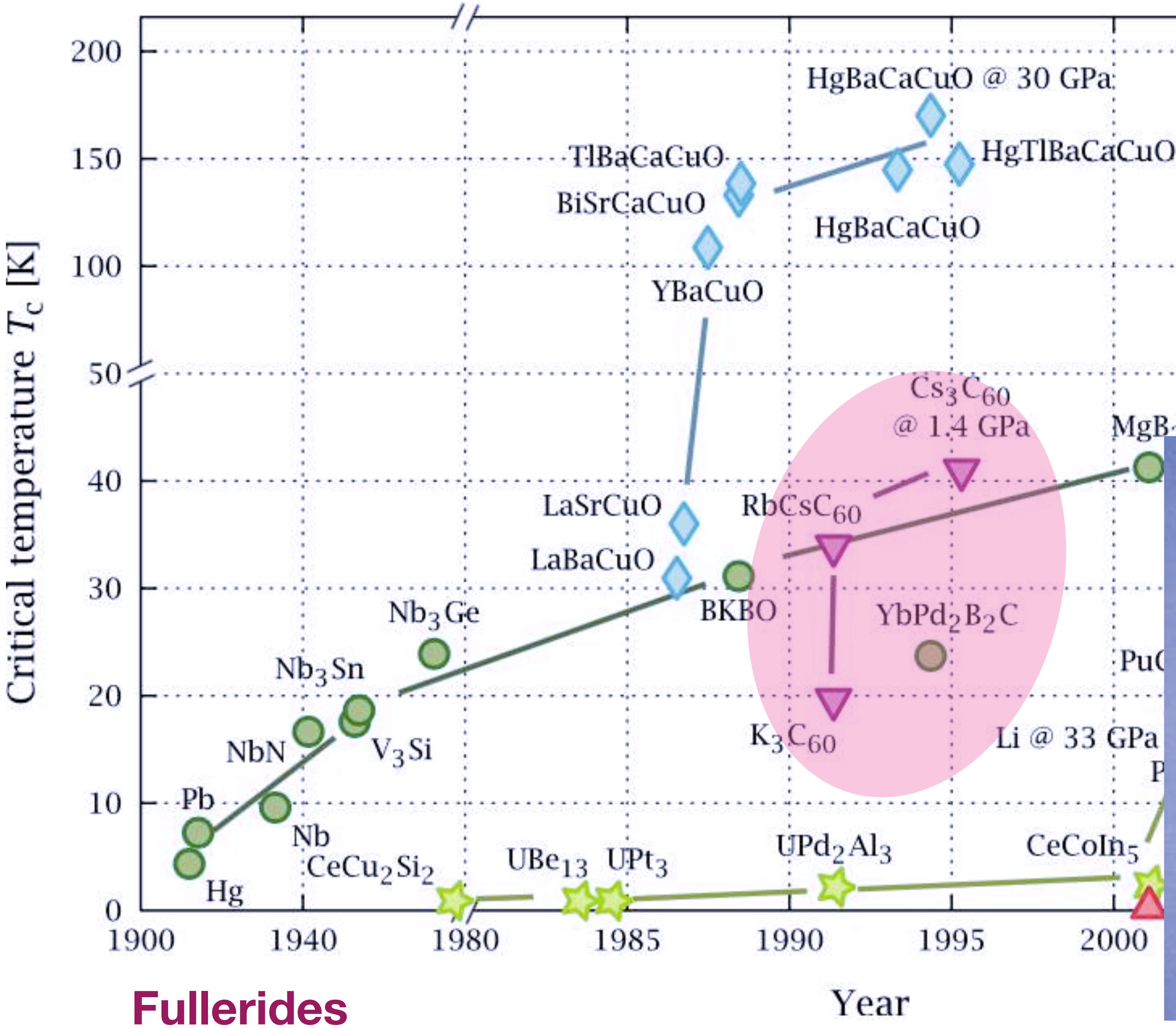


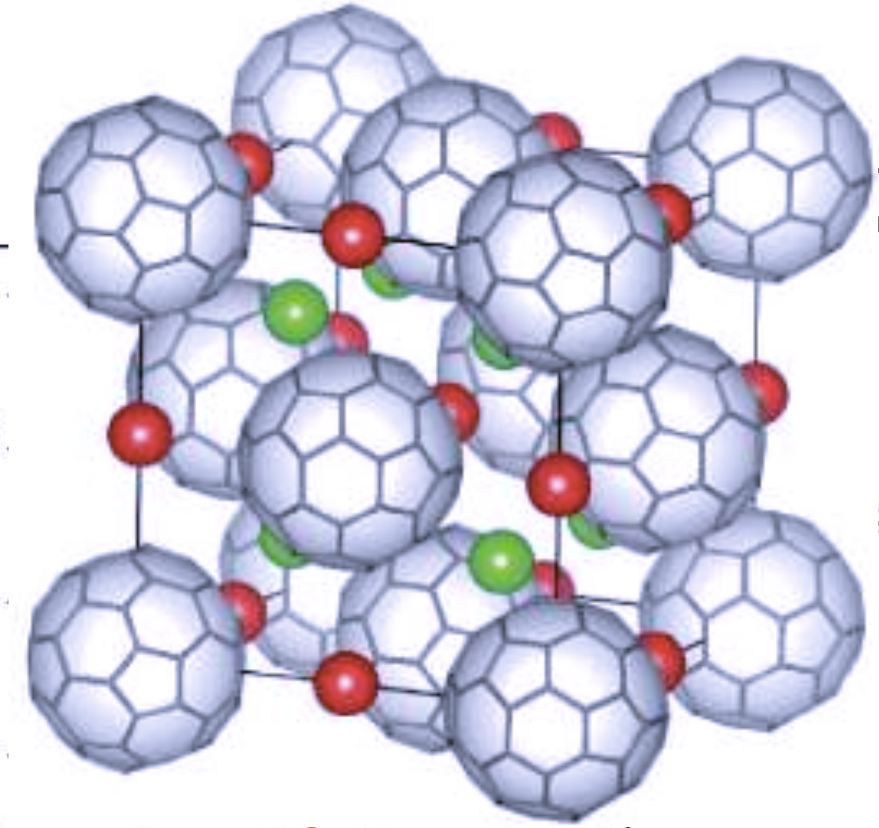


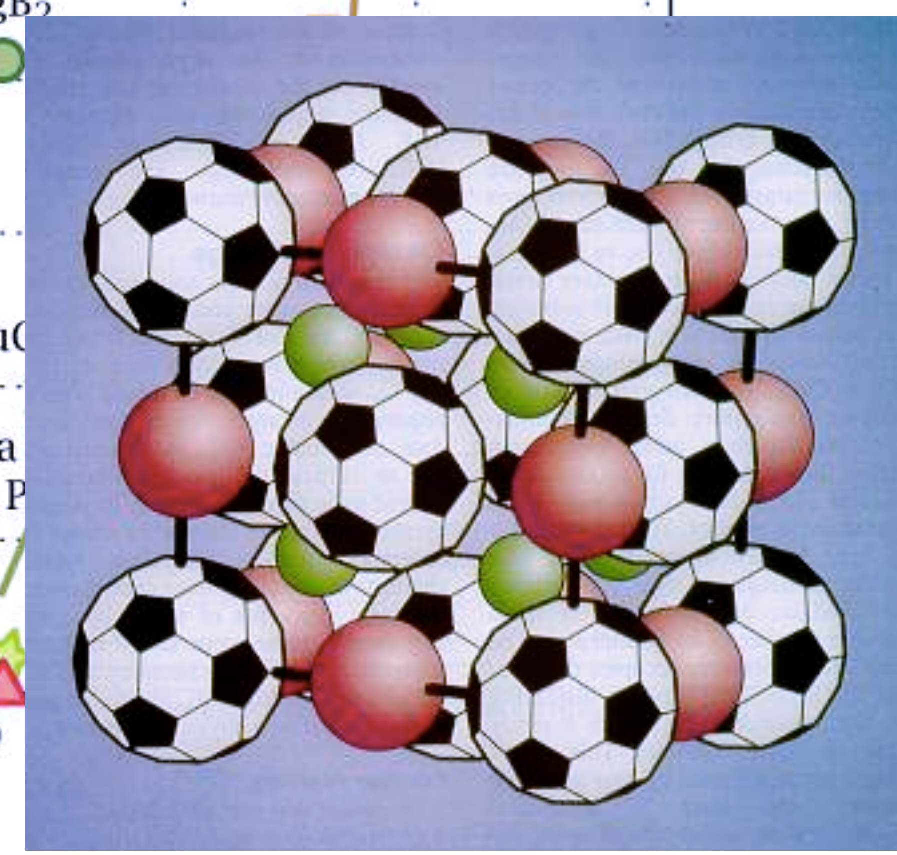
Cu-based SC

- Complex phase diagram. Unconventional SC. Non-phonon mediated.

Evolution of the critical temperature:





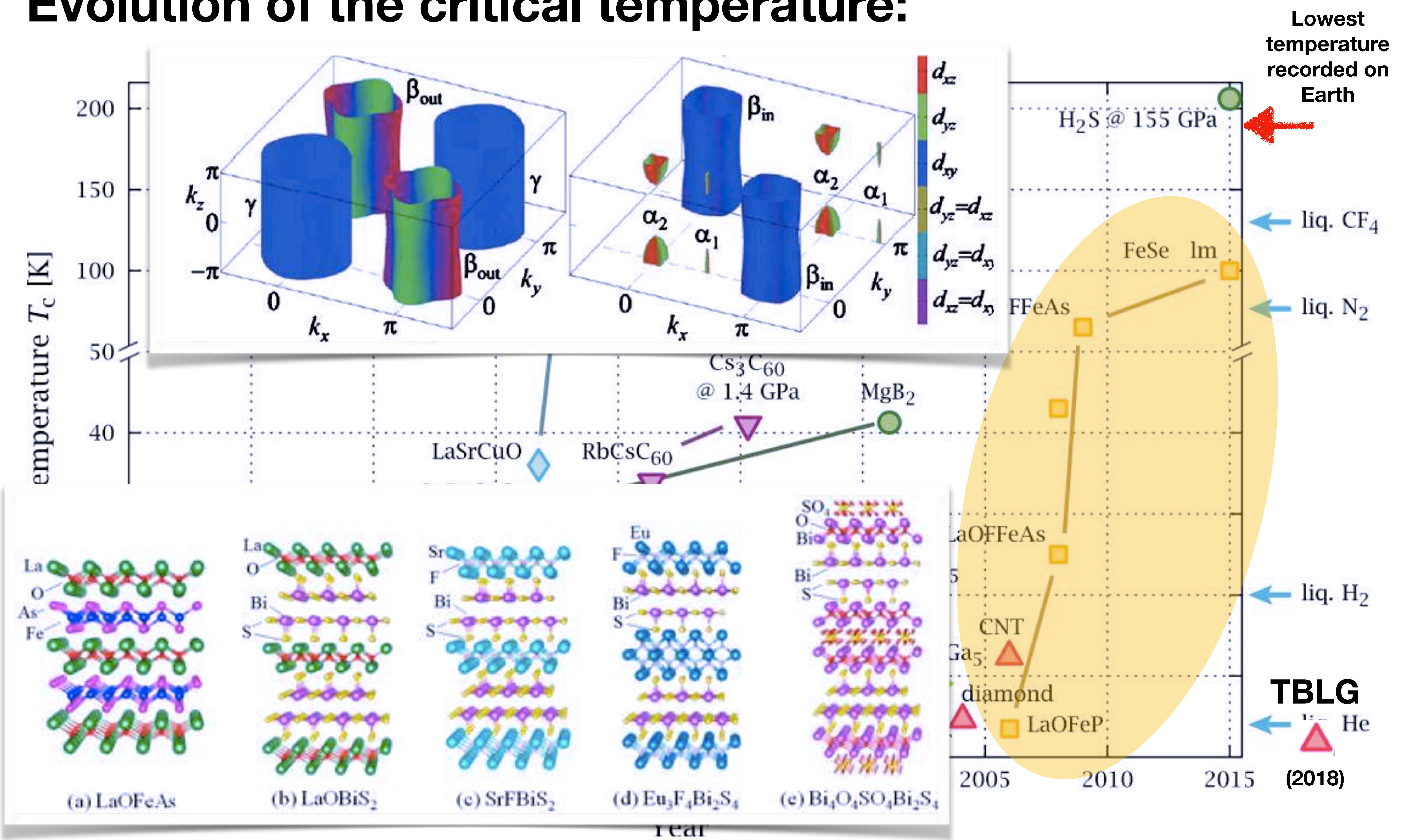


Fullerides

- **SC in organic/molecular solids**
- **Very sensitive materials. Conventional superconductors**

Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)
http://esperia.iesl.forth.gr/~lappas/A3C60c.jpg
R. H. Zadik, Science Advances (2015)

Evolution of the critical temperature:

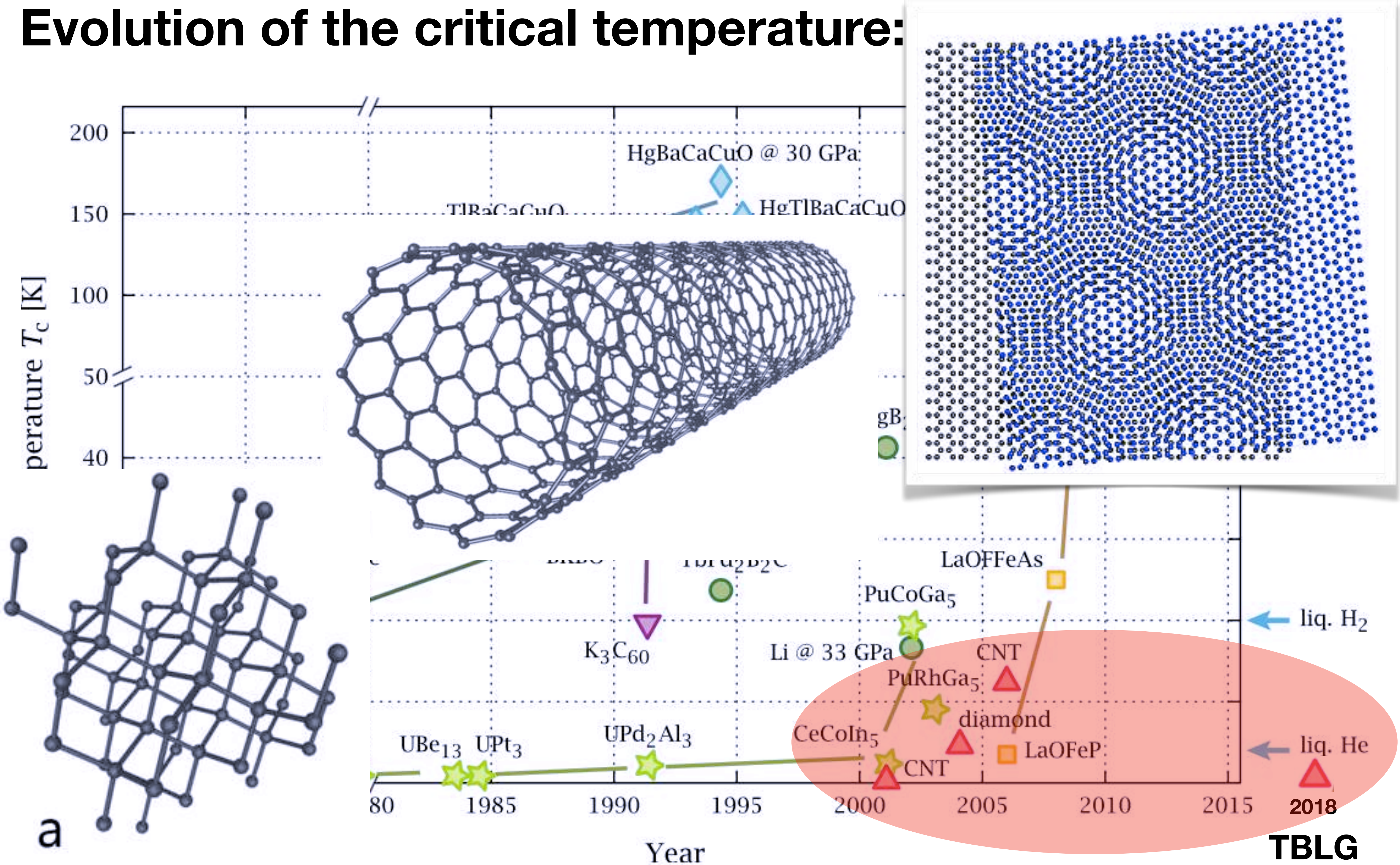


Fe-based SC

- Many orbitals and Fermi surfaces contribute to SC

Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)
Y. Mizuguchi, Condens. Matte. (2017)
Y. Wang, PRB (2013)

Evolution of the critical temperature:



Carbon-based

- Recent discoveries. Very clean materials!

Image credit: Wikipedia (created by P J Ray)
Wikipedia (Created by Michael Ströck)

Evolution of the critical temperature:

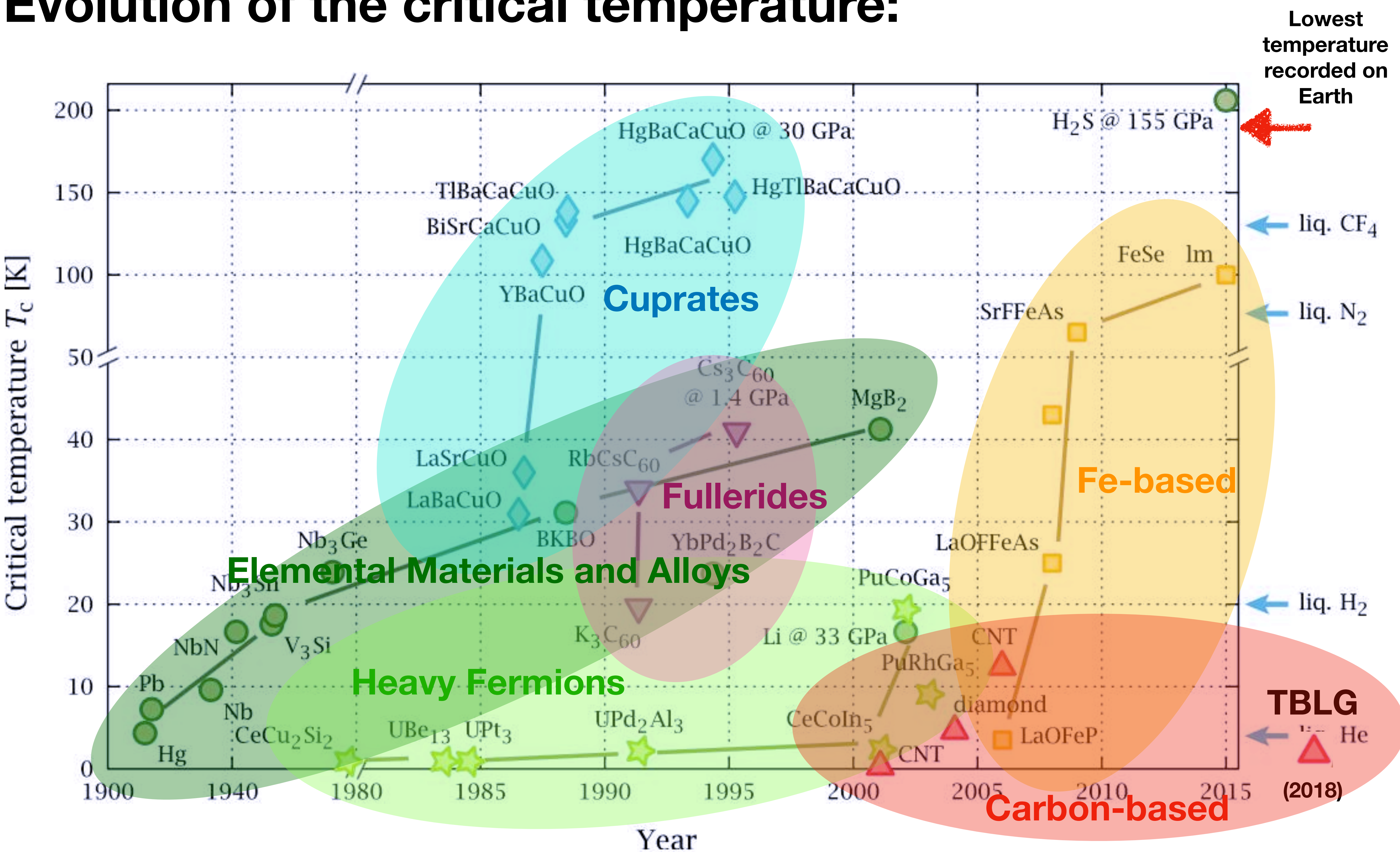
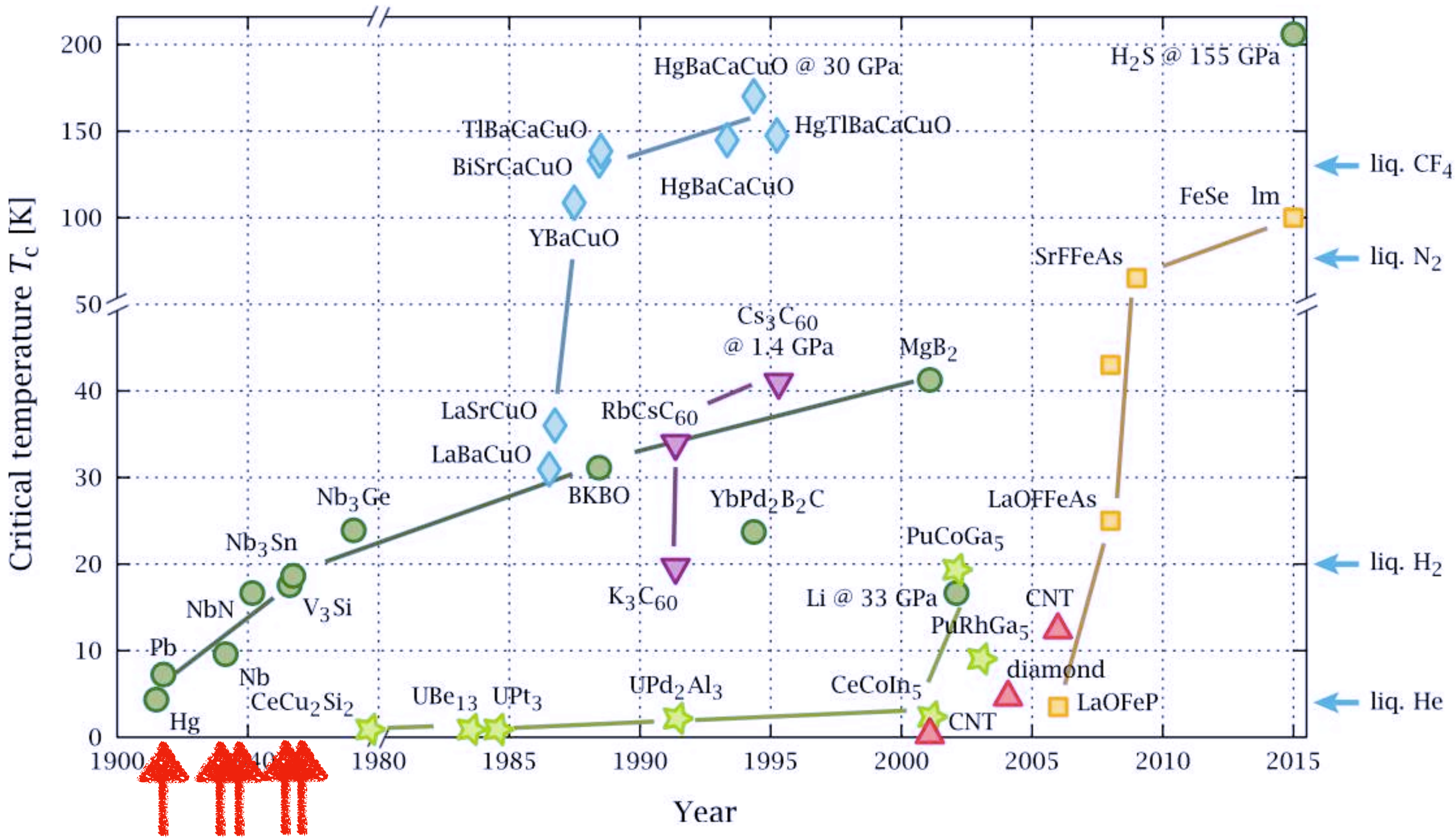


Image credit: Wikipedia (By PJRay - Own work, CC BY-SA 4.0)

SC was not predicted: it was discovered.

Some more historical remarks:

1911: Kamerlingh Onnes observed zero resistance of Hg below 4K
1933: Meissner and Ochsenfeld observed the phenomena of flux expulsion
1935: London Theory (Phenomenological)
1950: Ginzburg-Landau Theory (Phenomenological)
1957: BCS Theory (Microscopic)



46 years

Still some debate on the microscopic mechanism for pairing for unconventional SC

arXiv:1008.0447

Failed theories of superconductivity

Jörg Schmalian

Department of Physics and Astronomy, and Ames Laboratory, Iowa State University, Ames, IA 50011, USA

Almost half a century passed between the discovery of superconductivity by Kamerlingh Onnes and the theoretical explanation of the phenomenon by Bardeen, Cooper and Schrieffer. During the intervening years the brightest minds in theoretical physics tried and failed to develop a microscopic understanding of the effect. A summary of some of those unsuccessful attempts to understand superconductivity not only demonstrates the extraordinary achievement made by formulating the BCS theory, but also illustrates that mistakes are a natural and healthy part of the scientific discourse, and that inapplicable, even incorrect theories can turn out to be interesting and inspiring.

https://www.youtube.com/watch?v=2pB87H3_F_c&t=2s

https://www.youtube.com/watch?v=PqSgmCg1kew&t=1s

Outline

What are superconductors?
What are their defining properties?
Are superconductors simply perfect conductors?

London Theory
Landau Theory
Ginzburg-Landau Theory

Ginzburg-Landau Theory
- Flux Quantization\Recover London Theory

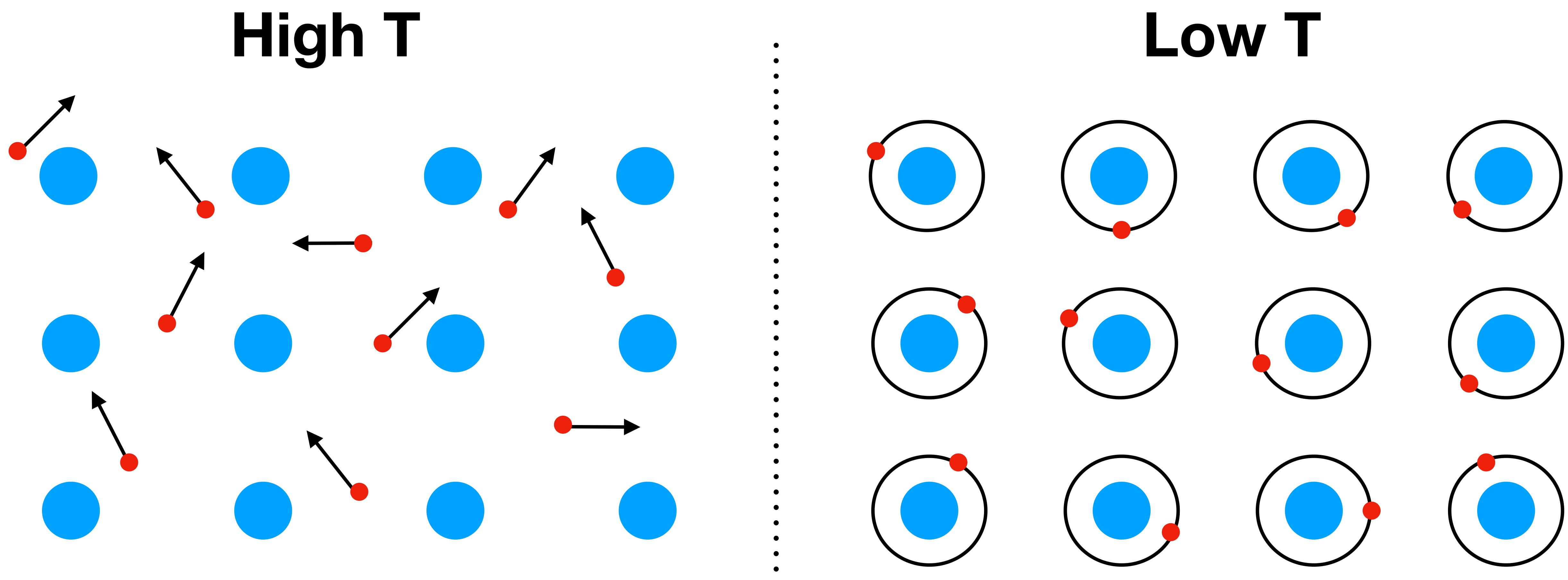
Josephson Junction
- SQUIDS

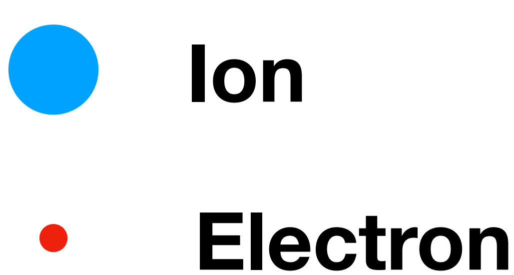
Back to the start…

Kamerlingh Onnes

How do metals behave at low T?

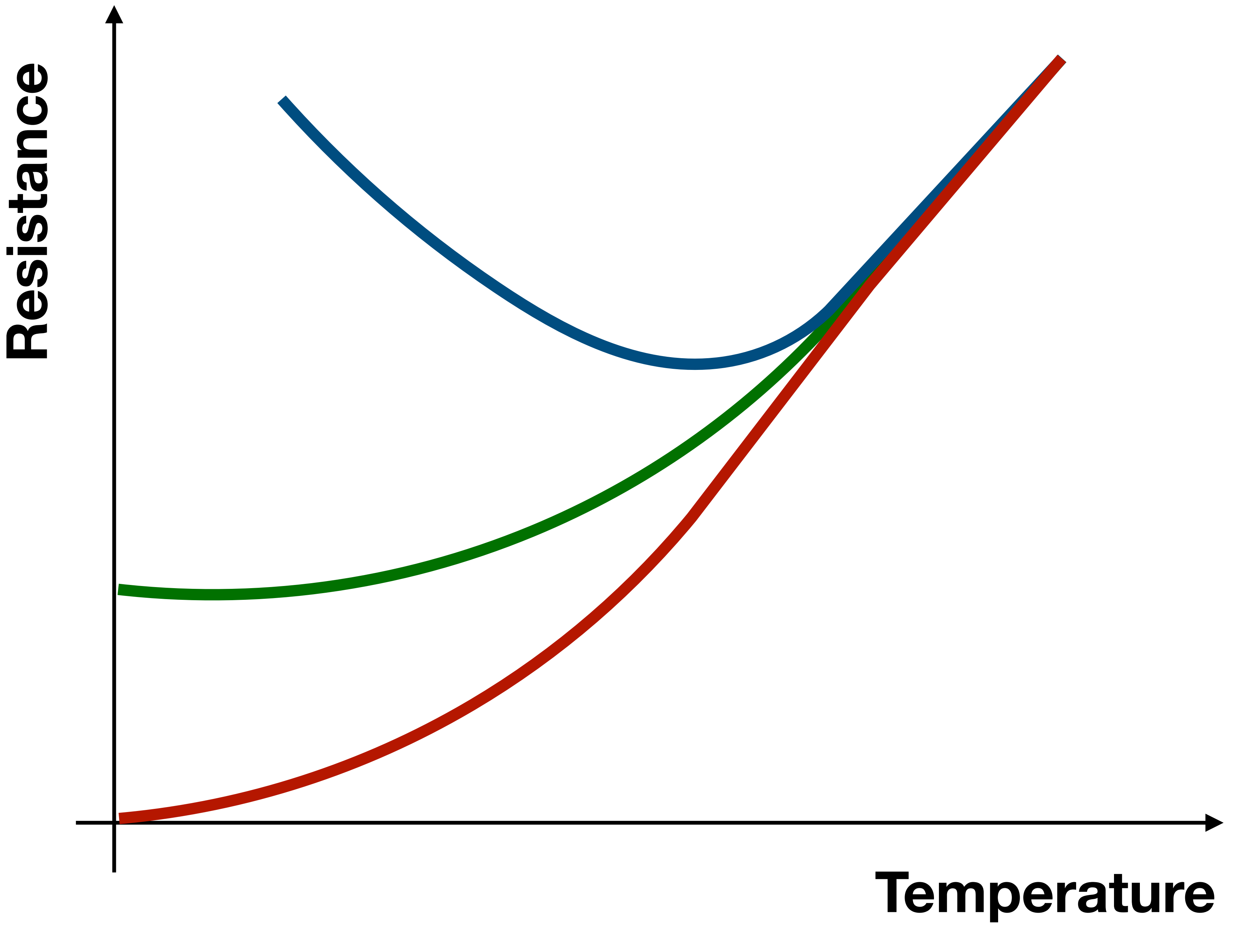
Naive early 1900's picture:





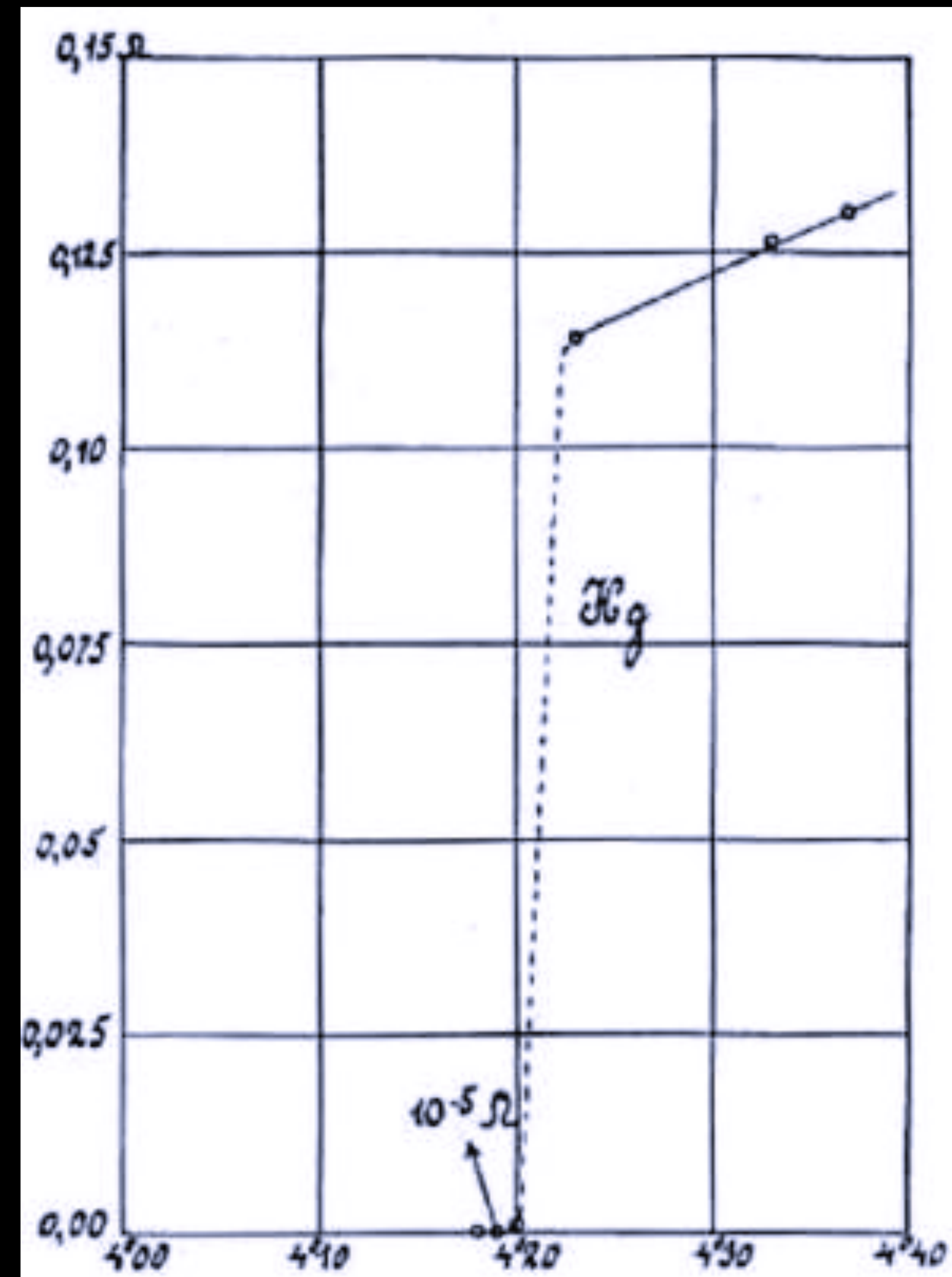
Q: What happens to the resistance of metals at low temperatures?

Q: How do metals behave at low T?



Kamerlingh Onnes (1911)

Resistance(Ω)



Temperature (K)

Let’s first describe metals…

Q: Are Superconductors simply perfect conductors?

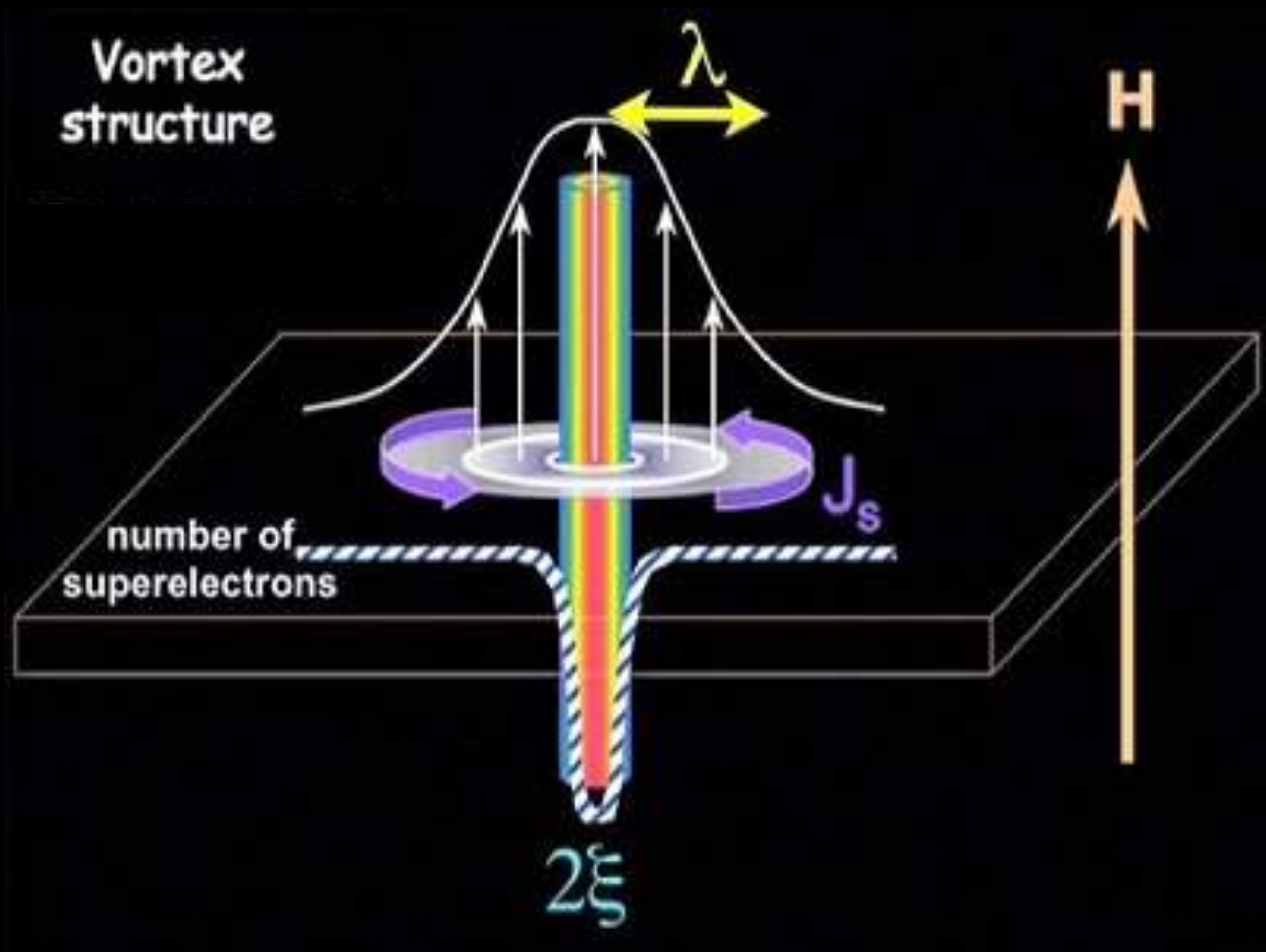
London Equations

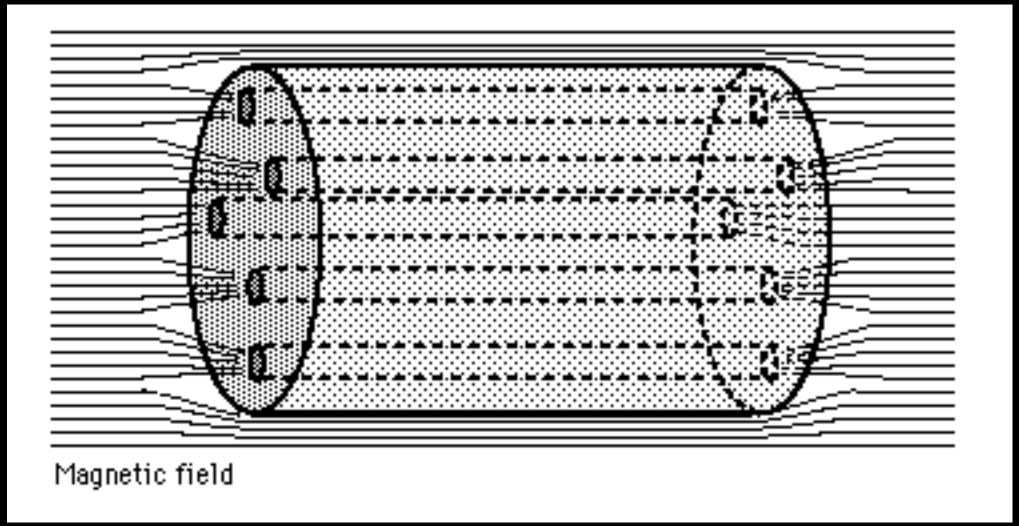
Landau Theory of Phase Transitions

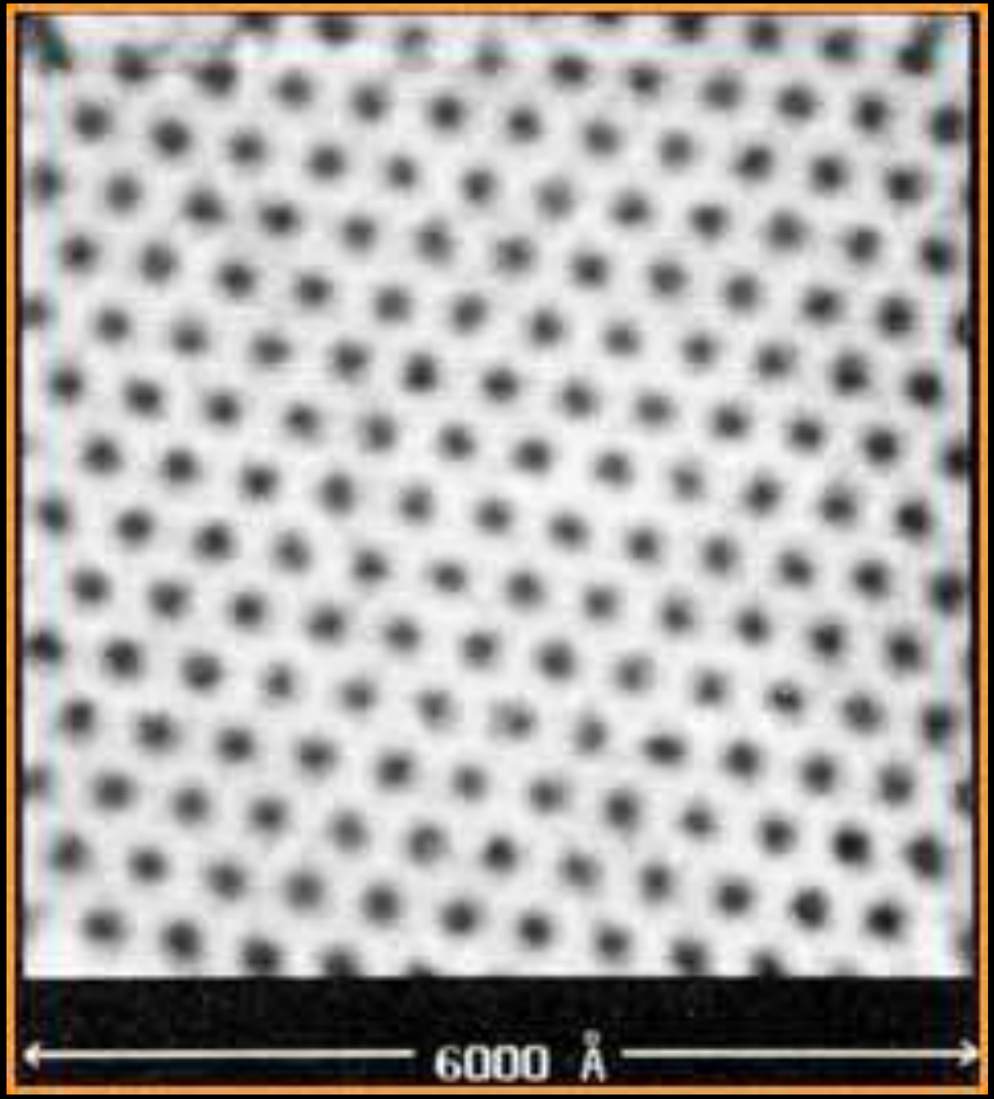
Ginzburg-Landau Theory

Ginzburg-Landau Theory + B

Vortices







Phys. Rev. Lett. 62, 214 (1989)
https://ascg.msm.cam.ac.uk/lectures/fundamentals/fluxpenetration.php

Josephson Effect

SQUIDS

Fun fact: That is what you get if you google SQUID

Image Credit: Wikipedia CC/© Hans Hillewaert

SQUID: Superconducting Quantum Interference Device

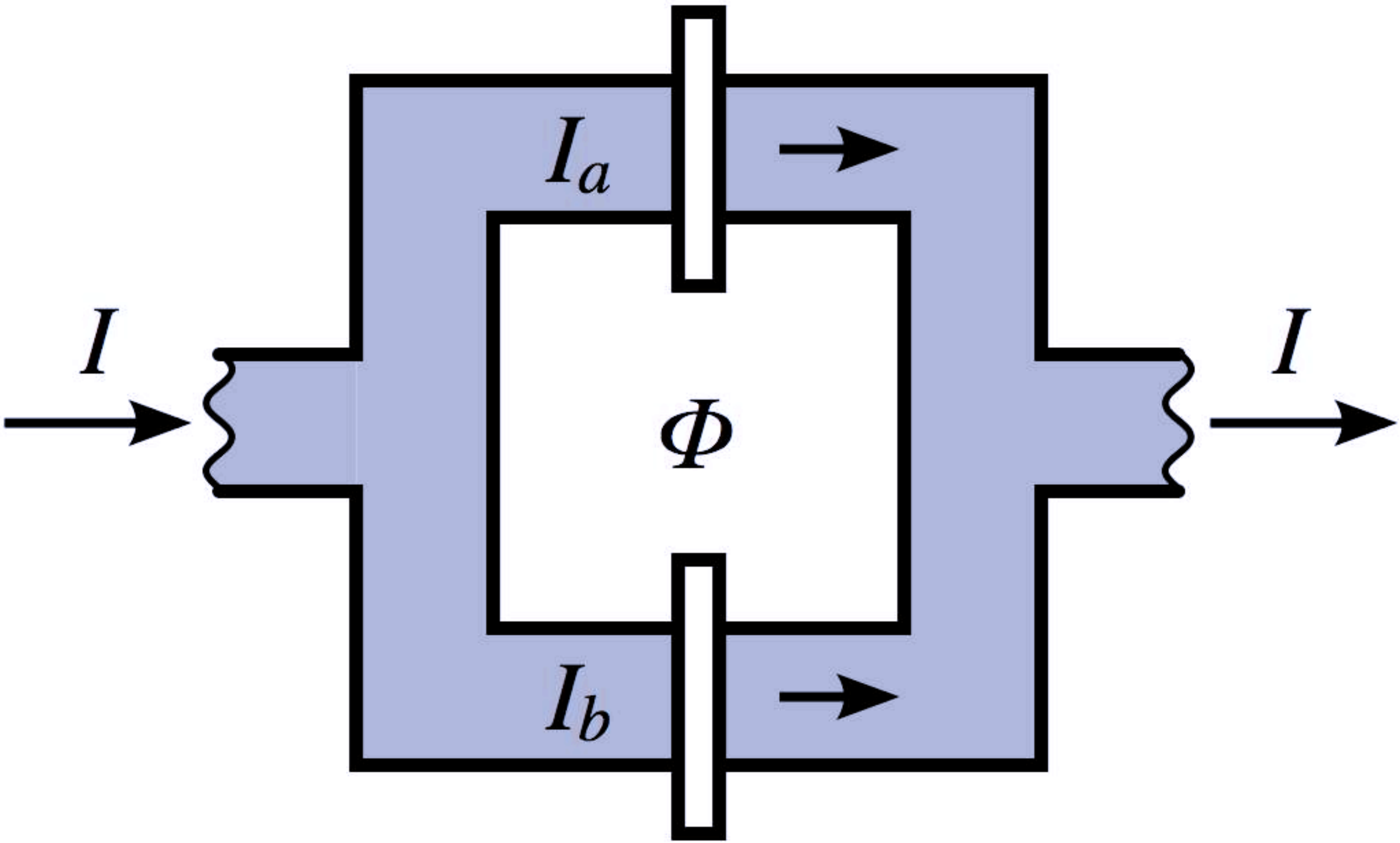


Image Credit: Wikipedia CC

Superconducting Q-bits

Some references:

N. W. Aschcroft and N. D. Mermin, Solid State Physics, Chapters 1 (Drude), 2 (Sommerfeld), and 34 (SC)

C. Kittel, Introduction to Solid State Physics, Chapter 12 (SC)

C. P. Poole, Superconductivity, Chapters 1 and 2 (Intro), 5 (GL), 6 (*BCS), 13.7 onwards (JJ) (note that the chapter numbers change for the latest edition of the book)

R. Feynman, Lecture Notes on Physics, Lecture 21: A Seminar on Superconductivity

P. Coleman, Introduction to Many-Body Physics, Chapters 11 (GL), 14 (*BCS)

Lecture videos:

S. Kivelson: Superconductivity and Quantum Mechanics at the Macro-Scale (https://www.youtube.com/watch?v=Yx666k2XH8E)

A. J. Millis: Microscopic Theory of SC (first 17 minutes for intro) (https://boulderschool.yale.edu/2014/boulder-school-2014-lecture-notes)

Further reading:

John M. Martinis, Kevin Osborne, Superconducting Qubits and the Physics of Josephson Junctions, Les Houches School Proceedings (https://arxiv.org/abs/cond-mat/0402415)

Jaw-Shen Tsai, Toward a superconducting quantum computer: Harnessing macroscopic quantum coherence, Proc Jpn Acad Ser B Phys Biol Sci. 2010 Apr; 86(4): 275–292 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3417795/)

G. Wendin and V. S. Shumeiko, Quantum bits with Josephson junctions (Review Article), Low Temperature Physics 33, 724 (2007) (https://aip.scitation.org/doi/full/10.1063/1.2780165)

Lecture videos:

A. Blais: Quantum Computing with Superconducting Qubits (Part 1) - CSSQI 2012 (https://www.google.com/url?hl=en&q=https://www.youtube.com/watch?v%3Dt5nxusm_Umk&source=gmail&ust=1532610408235000&usg=AFQjCNGYRSGU5EFyFPSfOZGalGFdRhOfkQ)

The first part of this video gives a good idea of how Josephson Junctions are important for SC-circuit based Q-Bits.